Quantum Thermo Dynamics 2025 SINGAPORE 7–11 JULY

Book of Abstracts

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Talks titles and abstracts — Monday, 7th July to Friday, 11th July

7th of July, Morning Session 1
9:00-10:30

1. Optimal time estimation at the nanoscale: frenetic and thermodynamic aspects

Presenter: **Mark Mitchison** (*King's College London*)

The problem of optimal time estimation is as follows. An observer, who lacks a clock, records a sequence of random events. How can they use this data (together with some model of the dynamics) to estimate the elapsed time with the highest accuracy and precision? This problem is important, not only for unlucky castaways who have lost their watch, but also for the construction and calibration of any clock or time standard. I will present a remarkably intuitive and elegant solution to this problem for classical Markovian jump processes [1], and also for some quantum-jump dynamics [2]. This result has consequences beyond time estimation: it implies a tight bound on the fluctuations of arbitrary counting observables in far-from-equilibrium systems, and can be used to detect the presence of hidden states from observable data. I will also present the results of a recent experiment by the ASPECTS consortium [3], where we performed optimal time estimation by monitoring electrons tunnelling across a double quantum dot [4]. We measured two different sources of dissipation underlying this quantum clock's operation: the generation of ticks, and their readout as a classical signal. Our results show that the entropy produced by the measurement process is the most important and fundamental thermodynamic cost of timekeeping at the nanoscale.

References:

[1] K. Prech, et al., arXiv:2406.19450

[2] K. Macieszczak, arXiv:2407.09839

[3] https://www.aspects-quantum.com

[4] V. Wadhia, F. Meier, et al., arXiv:2502.00096

2. Precision is not limited by the second law of thermodynamics

Presenter: **Florian Meier** (*Technische Universität Wien*)

Physical devices operating out of equilibrium are inherently affected by thermal fluctuations, limiting their operational precision. This issue is pronounced at microscopic and especially quantum scales and can only be mitigated by incurring additional entropy dissipation. Understanding this constraint is crucial for both fundamental physics and technological design. For instance, clocks are inherently governed by the second law of thermodynamics and need a thermodynamic flux towards equilibrium to measure time, which results in a minimum entropy dissipation per clock tick. Classical and quantum models and experiments often show a linear relationship between precision and dissipation, but the ultimate bounds on this relationship are unknown.

In this talk I will present our recent theoretical discovery of a quantum many-body system that achieves clock precision scaling exponentially with entropy dissipation. This finding demonstrates that coherent quantum dynamics can surpass the traditional thermodynamic precision limits, showing clocks may not be fundamentally limited by the second law. Moreover, the system we find to exhibit this behavior is robust to imperfections and it is based on an extensible spin-chain model with nearest neighbor interactions, making it a particularly interesting candidate for experimental realization. We conclude the talk with an outlook on possible applications that quantum ticking clocks may have beyond foundational thermodynamic considerations.

3. Fully quantum stochastic entropy production from quantum Bayes rule

Presenter: **Ge Bai** $\to$ **Valerio Scarani** (*Nagoya University* $\to$ *CQT and National University of Singapore*)

Entropy production plays a fundamental role in non-equilibrium thermodynamics, yet its extension to quantum systems presents profound conceptual and mathematical challenges. Classical stochastic entropy production is typically defined as the log-ratio of forward and reverse trajectory probabilities, forming the foundation of fluctuation theorems. However, the quantum generalization of this expression remains an open problem, particularly due to the absence of well-defined joint probability distributions for quantum processes.

In this work, we introduce a fully quantum notion of stochastic entropy production, grounded in Bayesian retrodiction. Our approach extends classical formulations by leveraging the Petz recovery map as a quantum Bayes' rule to define a reverse quantum process. We construct an entropy production operator formulated in terms of quantum analogs of the classical joint input-output distributions for the forward and reverse processes. This construction ensures that entropy production takes real values, avoiding complications from quasi-probabilities. Moreover, we prove that its expectation value is non-negative, thereby recovering the Second Law in its standard form without the need for ad hoc modifications.

Our framework retains key desiderata of classical stochastic thermodynamics:

1. Classical Limit: When applied to commuting observables, our entropy production operator reproduces the classical expression exactly.

2. Fluctuation Theorems: The fully quantum detailed and integral fluctuation theorems emerge naturally as mathematical consequences of our definition.

3. Locality in Time: In the classical limit, entropy production decomposes into input and output contributions, a hallmark of Bayesian inference.

4. Superadditivity and Mutual Information Interpretation: Our entropy production satisfies a superadditivity property when decomposed into sequential processes, suggesting a connection to information-theoretic measures.

We illustrate our results using quantum collisional models, demonstrating how our definition generalizes classical thermalization processes and captures distinctively quantum effects. In particular, we explore cases where entropy production remains positive but deviates from standard formulations due to quantum coherence and measurement incompatibility.

This work contributes to the broader goal of establishing a unified framework for quantum thermodynamics that explicitly incorporates the role of inference and knowledge. Our approach paves the way for a systematic understanding of entropy production in quantum processes, with implications for both foundational studies and emerging quantum technologies.

This is work done in collaboration with Ge Bai and Valerio Scarani. Preprint available at https://arxiv.org/abs/2412.12489.

7th of July, Morning Session 2
11:00-12:30

4. Effect of Measurement Backaction on Quantum Clock Precision Studied with a Superconducting Circuit

Presenter: **Arkady Fedorov** (*University of Queensland*)

We theoretically and experimentally study the precision of a quantum clock near zero temperature, explicitly accounting for the effect of continuous measurement. We theoretically find an equality for the precision of the clock in each regime and derive a kinetic uncertainty relation for the precision. We experimentally verify that our quantum clock obeys the kinetic uncertainty relation for the precision, thus making an explicit link between the (kinetic) thermodynamic behavior of the clock and its precision, and achieving an experimental test of a kinetic uncertainty relation in the quantum domain.

Another way for a quantum clock precision to be affected by the measurement is through feedback which is one of the most common ways to engineer limit cycles for clocks. Although the measurement backaction cannot be avoided, the effect of the feedback noise can be mitigated by using coherent quantum feedback. We experimentally implement the model using two superconducting cavities with incorporated Josephson junctions and microwave circulators for the realisation of the quantum feedback. We confirm the appearance of the limit cycle and study the clock accuracy both in frequency and time domains. Under specific conditions of noisy driving, we observe that the clock oscillations are more coherent than the drive, pointing towards the implementation of a quantum autonomous clock.

5. Emergence of a second law of thermodynamics in isolated quantum systems

Presenter: **Maximilian Lock** (*Atominstitut, Technische Universität Wien*)

The second law of thermodynamics states that the entropy of an isolated system can only increase over time, thereby distinguishing the past from the future. This seems to conflict with the reversible evolution of isolated quantum systems, which preserves the von Neumann entropy. However, counterintuitively, many observables in large isolated systems do reach equilibrium, despite the unitary evolution of the system's state. We characterise the extent to which any observable exhibits this emergent irreversibility, as determined by the relationship between the microstates associated with the reversible evolution and the macrostates associated with the observable. We demonstrate how a version of the second law of thermodynamics can be recovered in isolated quantum systems, and analyse the fluctuations from equilibrium that reveal the underlying reversible dynamics, finding that these fluctuations diminish as the system size increases. We illustrate our findings using numerical results from the paradigmatic example of a quantum Ising model on a chain of spins. There, we observe entropy increasing up to equilibrium values, as well as fluctuations in accordance with the derived bounds.

6. The impact of finite-precision instruments on quantum thermodynamics laws

Presenter: **Giulia Rubino** (*University of Bristol*)

In both classical and quantum thermodynamics, physical quantities are typically assigned objective values defined independently of our observations. We then refer to the 'work performed by a gas', or the 'entropy of the gas', regardless of how they are evaluated. Here, we question this conception, estimating

how experimental instruments of limited precision affect the definition of pivotal thermodynamic quantities. We find that (i) coarse-graining involves a thermodynamic cost from the viewpoint of a fine-grained agent, and (ii) the coarse-grained thermodynamic quantities frequently lead to different conclusions from those drawn in fine-grained scenarios. For instance, the irreversibility of a process, or its work payoff can significantly vary with the instrument's precision. We show nonetheless that coarse-grained thermodynamic quantities satisfy the same relations (i.e., the second law inequality, the relation between dissipation and distinguishability of a process from its time-reverse, and the quantum work fluctuation theorems) as their fine-grained counterparts. These results highlight the observation-independence of relations linking thermodynamic quantities which are themselves observation-dependent.

7th of July, Afternoon Session
14:00-15:15

7. The thermodynamic nature of the energy provided by a measuring apparatus

Presenter: **Cyril Elouard** (*Université de Lorraine*)

Measurement is known to constitute a thermodynamic resource. First, the information acquired when measuring a system can be turned into work as known since the resolution of the Maxwell demon paradox. In the quantum world, there is in addition the measurement backaction (a.k.a the wave-function collapse) which turns out to constitute an energy source of purely quantum origin, able to fuel engines and refrigerators. Despite many proposals (and experimental implementations) of measurement-fueled machines, the thermodynamic nature of the energy provided by the measurement remains unclear : it behaves as pure work in some ideal limits (ideal projective measurements, Zeno regime), but it is also stochastic and carry entropy in the general case, in a way reminiscent to heat. We address this question by analyzing microscopic models of measuring apparatuses coupled to a quantum system of interest. We evaluate the energy flows accompanying the measurement process (work cost to power the apparatus, heat flows dissipated in the apparatus) and relate them to the energy received by the system [1,2,3]. Importantly, we find that the thermodynamic nature of the energy received by the system strongly depends on some microscopic parameters of the apparatus. We illustrate this result on the case of an electronic measurement-driven refrigerator [1], where a continuous charge measurement of a double quantum dot triggers cold-to-hot heat transport between two electron reservoirs. We find that the average measurement-induced dynamics (i.e. the system's master equation) is not enough to unambiguously evaluate the coefficient of performance of the machine. We then use a microscopic model of charge detection apparatus based on an electronic tunnel junction to reveal the overall thermodynamic balance of the machine. We find that the measurement (and therefore the refrigerator) can be fueled either by heat, by work, or a combination of both, depending on the chosen junction parameters (its potential bias and the reservoirs' temperature). Surprisingly, the overall efficiency is very different in the heat-fueled and work-fueled regime, and presents a trade-off with the measurement efficiency, quantified for instance by the signal-to-noise ratio [1]. Our analysis offers a new perspective on the nature of the energy exchanges occurring during a quantum measurement, paving the way for energy optimization in quantum protocols and quantum machines that rely on measurements.

[1] Cyril Elouard, Sreenath K. Manikandan, Andrew N Jordan and Geraldine Haack, Revealing the fuel of a quantum continuous measurement-based refrigerator, arXiv:2502.10349 (2025). [2] Camille Latune and Cyril Elouard, A thermodynamically consistent approach to the energy costs of quantum measurements, Quantum 9, 1614 (2025). [3] Lorena Ballesteros Ferraz and Cyril Elouard, weak continuous measurements cost more work than strong ones, arXiv:2502.09732 (2025).

8. Cost analysis of strong versus weak continuous measurements in quantum systems

Presenter: **Ballesteros Ferraz** (*LPCT - Université de Lorraine and LPTM - CY Cergy Paris Université*)

The primary objective of this work is to quantify the fundamental energetic costs associated with quantum measurements [1]. To this end, we develop and analyze a minimal model that captures the essential aspects of the measurement process. Our framework accounts for scenarios in which partial or complete information is obtained from a quantum system during the measurement protocol, encompassing a spectrum of measurements ranging from weak to strong, and varying in detection efficiency from ideal (fully efficient) to highly lossy (inefficient). Our model consists of a quantum system of interest, S, and an auxiliary system, A, which serves as an ancilla to facilitate information extraction. The measurement process unfolds in several key stages: the ancilla is first initialized, then coupled to the system, allowing information transfer through their interaction modelled via a unitary, enabling measurements ranging from weak to strong. We consider the irreversibility of the quantum measurement process by assuming that the ancilla undergoes pure dephasing induced by inaccessible degrees of freedom of the measuring apparatus. The ancilla is then read out, transferring the measurement result to a classical memory, which is reset, after utilizing the extracted information, alongside the ancilla to ensure the process remains repeatable. Unlike previous studies on the energetics of measurements, our model explicitly incorporates weak measurements. To characterize the quality of this protocol, we introduce three figures of merit that we found essential in this case, the strength characterizing the amount of information that can be extracted from the system, the detection efficiency characterizing the amount of information that has left the system and could be found in the accessible degrees of freedom of the ancilla and the normalized classical mutual information, which quantifies how much information about a specific observable is available in the accessible degrees of freedom of the ancilla. We found that the three of them were essential to characterize the quality of the measurement. We determine a fundamental lower bound on the work cost of this protocol and contrast it with an alternative approach in which dissipation, rather than dephasing, is used to convert quantum information into classical form [2]. Our analysis reveals that the energetic cost in the dephasing case is always greater than or equal to that in the dissipation case. We have also analyzed the role of coarse-graining of the ancilla outputs in the quality and cost of this setup and we have found that the lower work bound is not modified by coarse-graining as long as the coarse-graining spaces remain orthogonal between themselves. Furthermore, we explore different routes to achieving strong and efficient measurements. One approach is to implement a single strong measurement via an intense/long interaction with the ancilla, while another relies on a long sequence of consecutive weak measurements. By comparing their energetic costs, we find that the work bound for multiple successive weak measurements significantly exceeds that of a single strong measurement. Our findings shed light on the interplay between energy expenditure and measurement performance, offering insights into the thermodynamic constraints governing quantum measurements. [1] Ballesteros Ferraz, Lorena, and Elouard, Cyril. ""Weak continuous measurements require more work than strong ones"" arXiv:2502.09732. [2] Latune, Camille L., and Elouard, Cyril. ""A thermodynamically consistent approach to the energy costs of quantum measurements."" Quantum 9 (2025): 1614.

9. Dynamics of Open Quantum Systems in the Weak-Memory Regime: A Mathematical Framework Beyond the Markov Approximation

Presenter: **Kay Brandner** (*University of Nottingham*)

Memory effects are ubiquitous in small-scale systems. They emerge from interactions between accessible degrees of freedom, which form the observable system of interest, and inaccessible ones, which cannot be directly observed or controlled. In thermodynamics, the accessible degrees of freedom typically belong to working systems performing certain thermodynamic tasks like power generation or cooling, while the inaccessible ones form thermal reservoirs acting, for example, as heat sources. On the mathematical level, memory effects usually give rise to time evolution equations that are non-local in time, such as the well-known Nakajima–Zwanzig equation, which can be systematically derived with projection operator techniques. If the characteristic time scales of accessible and inaccessible degrees of freedom are sharply separated, locality in time can be restored through the standard Markov approximation, which is commonly used in the derivation of quantum master equations with time-homogeneous generators. Here, we show that this approach can be rigorously extended to a precisely defined weak-memory regime, where the relevant time scales can be of comparable order of magnitude. We derive explicit bounds on the error of the local approximation and a convergent perturbation scheme for its systematic construction. In lowest the order of this perturbation theory, we recover the standard Redfield equation. Being applicable to any autonomous open system with a finite-dimensional Hilbert space, our theory provides a unifying framework for the systematic description of weak but significant memory effects. At the same time, our results show that the validity of various established quantum master equation can be rigorously traced back to a few physically transparent and mathematically well-defined conditions.

References:

[1] K. Brandner, Dynamics of Microscale and Nanoscale Systems in the Weak-Memory Regime, Phys. Rev. Lett. 134, 037101 (2025).

[2] K. Brandner, Dynamics of microscale and nanoscale systems in the weak-memory regime: A mathematical framework beyond the Markov approximation, Phys. Rev. E 111, 014137 (2025).

8th of July, Morning Session 1
9:00-10:30

10. Investigating Quantum Thermodynamics via Nuclear Spin Qubits: Quantum Battery, Ergotropy Estimation, and Entanglement Certification

Presenter: **T.S. Mahesh** (*Indian Institute of Science Education and Research (IISER), Pune*)

A molecular network of nuclear spin qubits offers long coherence times and allows precise quantum control via nuclear magnetic resonance (NMR), making it an excellent testbed for quantum information studies. We describe recent experiments investigating key aspects of quantum thermodynamics, beginning with the concept of a quantum battery, which enables faster charging than classical counterparts. Using star-topology spin systems with up to 38 qubits, we demonstrate quantum-enhanced charging of a quantum battery, which can controllably release energy into a load qubit over a duration of up to two minutes. A central quantity in this context is ergotropy, the maximum amount of work that can be extracted from a quantum system via unitary operations. We recently proposed and experimentally implemented a feedback-based algorithm to estimate ergotropy and discharge a quantum battery (or de-energize a general quantum system) from an arbitrary state to its passive state, from which no further unitary work can be extracted. Notably, ergotropy also serves as a witness of entanglement by comparing the extractable work under global and local unitaries. We experimentally demonstrated this entanglement certification protocol on quantum registers of up to 10 qubits.

11. Quantum enhancement of precision in non-gaussian energy harvesters

Presenter: **Beatriz Polo** (*The Institute of Photonic Sciences (ICFO)*)

We investigate the process of quantum energy harvesting, i.e. the conversion of some external potential applied to a quantum system into useful work, which can in turn be stored in a battery or used to power a thermal machine. In particular, we are not concerned about optimizing the performance of these so-called energy harvesters in terms of power, but in terms of precision, thus targeting nanotechnological applications with high-accuracy requirements, where fluctuations at the quantum level play a crucial role. Our study focuses on multimode continuous-variable (CV) quantum systems, which provide a natural framework for describing and manipulating energy fluctuations at the quantum scale.

We address this problem by establishing a hierarchy of analytical upper bounds on the signal-to-noise (SNR) ratio of the harvested energy depending on the nature of the applied external potential. Our results reveal that when the energy source exhibits nonclassical properties, significant enhancements in precision can be achieved. Moreover, if the source is also non-Gaussian, entanglement can be leveraged to further improve the SNR, with greater degrees of non-gaussianity leading to better performances. This suggests that non-Gaussian quantum correlations serve as a resource not only for quantum computation and communication but also for energy processing.

Although applicable to any form of potential, our theoretical framework focuses on a specific ansatz of non-gaussian states which can be experimentally realized with current photonic technologies, making it feasible for near-term implementations in quantum laboratories.

By bridging concepts from quantum thermodynamics, quantum optics, and information theory, our proposal of a novel platform for energy-efficient technologies highlights the potential of energy-harvesting systems that leverage quantum properties to revolutionize the way energy is distributed and utilized at the nanoscale.

12. Experimentally probing entropy reduction via iterative quantum information transfer

Presenter: **Toshihiro Yada** (*University of Tokyo*)

Thermodynamic principles governing energy and information are essential tools for understanding and controlling a system's dynamics and have been intensively investigated since the thought experiment of Maxwell's demon. However, the role of quantum information flow in thermodynamics remained experimentally unexplored, despite its relevance to various tasks in quantum experiments. In this work, we experimentally investigate the interplay between thermodynamic costs and information flow in a quantum system undergoing iterative quantum measurement and feedback. Our study employs a state stabilization protocol involving repeated measurement and feedback on an electronic spin qubit in a silicon-vacancy center in diamond, which is strongly coupled to a diamond nanocavity. This setup allows us to verify fundamental principles of nonequilibrium quantum thermodynamics, including the second law and the fluctuation theorem, both incorporating measures of quantum information flow induced by iterative measurement and feedback. We further assess the reducible entropy based on the feedback's causal structure and quantitatively demonstrate the thermodynamic advantage of non-Markovian feedback over Markovian feedback. To this end, we extend the theoretical framework of quantum thermodynamics to incorporate the causal structure of the applied feedback protocol. Our work lays the foundation for investigating the entropic and energetic costs of real-time quantum control in various quantum systems.

(A preprint of this work can be found on https://arxiv.org/abs/2411.06709)

8th of July, Morning Session 2
11:00-12:30

13. Autonomous demon exploiting heat and information: stochastic trajectories and current fluctuations

Presenter: **Juliette Monsel** (*Chalmers University*)

Nanoscale devices have access not only to heat, like usual heat engines, but also to other resources such as information – like in Maxwell demon-based engines – or nonthermal distributions. Furthermore, since fluctuations can be sizeable at the nanoscale, precision – namely how much the noise of the output power is suppressed – is a key performance quantifier for such devices. In this talk, I will present a refrigerator-type device exploiting the thermoelectric effect but fed by a nonthermal resource. The device generates a heat flow from cold to hot in the working substance in the absence of any average particle or energy flow from the resource region, thereby acting as a “demon”. Specifically, the device consists of three capacitively coupled quantum dots, one of which is tunnel-coupled to two electronic reservoirs at different temperatures (the working substance) while the other two dots are respectively in contact with a hot and a cold reservoir (the demonic resource). In such a setup, a finite cooling power can be obtained in the working substance, while the energy exchange with the resource region exactly cancels out on average. At the same time, information is always exchanged, even on average, due to the capacitive coupling between the working substance and resource region. The proposed system therefore implements an autonomous demon with fully vanishing heat extraction from the resource. I will give a comprehensive description of the thermodynamic performance of the proposed autonomous demon by using two complementary approaches: stochastic trajectories and full counting statistics. I will first show that the precision of the cooling power strongly depends on the operation principle of the device. More precisely, the interplay of information flow and counter-balancing heat flows at the trajectory level dramatically impacts the trade-off between cooling power, efficiency, and precision [1]. I will then provide further insights on the operation of the device by analyzing the noise in the input heat flow and cross-correlations between heat currents, evidencing in particular that the output noise – namely cooling power fluctuations – can be made much smaller than the input noise [2]. These results are of relevance for guiding the design of energy-conversion processes exploiting nonthermal resources.

[1] J. Monsel, M. Acciai, R. Sánchez, and J. Splettstoesser, Autonomous demon exploiting heat and information at the trajectory level, Phys. Rev. B 111, 045419 (2025).

[2] J. Monsel, M. Acciai, N. Chiabrando, R. Sánchez, and J. Splettstoesser, Precision of an autonomous demon exploiting heat and information, in preparation.

14. Symmetry induced enhancement in finite-time thermodynamic trade-off relations

Presenter: **Ken Funo** (*Department of Applied Physics, The University of Tokyo*)

In finite-time thermodynamics, a central objective is achieving high-speed operation with low energetic costs. Recent advances in the fields of stochastic thermodynamics and quantum thermodynamics have revealed universal trade-off relations between the operation speed and the entropy production (energetic cost). Active research is exploring how quantum effects contribute to overcoming this trade-off relation. In particular, quantum heat engines that provide non-zero output power while asymptotically reaching the Carnot efficiency, which is not possible for classical heat engines [1], have been discovered [2]. Despite these findings, the fundamental limit of the enhancement of the performance of thermodynamic devices via quantum effects has not been clarified.

By constructing a unified theoretical framework based on the symmetry of the model, we analytically derived a general inequality that gives an upper bound on the quantity called activity or the average jump rate [3]. Note that, according to the thermodynamic trade-off relation, increasing the activity implies that a combination of higher speed and lower entropy production can be realized. We have further identified the optimal symmetry condition on open quantum systems that maximizes the activity. By applying our general framework to permutation-invariant N qubit systems, we find that the optimal scaling of the activity is exponential, at the expense of designing finite-tuned nonlinear system-bath couplings. We have further constructed a heat engine model that asymptotically reaches Carnot efficiency while the power scales ranging from quadratic to exponential with respect to the number of qubits, going far beyond the scaling realized by the conventional super-radiant heat engine model.

This research establishes a theoretical framework for analyzing how symmetry affects quantum thermodynamics. The findings are expected to lead to design principles for thermodynamic devices and quantum information processing devices that operate at high speed with low energetic costs. In particular, we have obtained a model that has better scaling than the conventional super-radiant model, having direct application to heat engines and quantum emitters.

References:

[1] N. Shiraishi, K. Saito, and H. Tasaki, Phys. Rev. Lett. 117, 190601 (2016).

[2] H. Tajima and K. Funo, Phys. Rev. Lett. 127, 190604 (2021).

[3] K. Funo and H. Tajima, accepted in Phys. Rev. Lett. (arXiv:2408.04280)

15. Measuring Work Fluctuations in Quantum Thermodynamics

Presenter: **Jefferson Diniz** (*Universidade Federal do ABC (UFABC)*)

If precision is a key goal in quantum technologies, understanding and controlling work fluctuations becomes crucial. The two-point measurement (TPM) scheme, which relies on projective measurements at two distinct times, is widely used to study various scenarios, as it correctly recovers fluctuation relations for quantum systems. While TPM correctly conserves energy for initially incoherent quantum systems, the role of the destroyed coherence at the end of the protocol is often overlooked. Alternative approaches, such as quasiprobability distributions for work or treating work as an observable, have been proposed, both ensuring energy conservation even for initially coherent states. In this study, we experimentally investigate work fluctuations using a nuclear magnetic resonance (NMR) spectrometer, performing measurements across a range of driving speeds, from the adiabatic regime—where the Jarzynski equality holds for incoherent initial states—to the sudden quench limit. We employ three different approaches to quantify work: the traditional TPM scheme, quasiprobability distributions for work, and the work operator framework. By contrasting TPM with these alternative methods, we provide a broader perspective on work fluctuations and energy conservation in quantum thermodynamics, highlighting the impact of coherence in fluctuation relations.

8th of July, Afternoon Session
14:00-15:15

16. The quantum thermodynamics of many-body quantum systems with long-range interactions

Presenter: **Andrea Solfanelli** (*Max Planck Institute for the Physics of Complex Systems*)

Long-range interactions, where two-body potentials decay as a power law, $V(r) \propto r^{-\alpha}$, with r being the inter-particle distance, are a fundamental feature of several experimental platforms relevant to quantum technologies. These include Rydberg atom arrays, dipolar quantum gases, polar molecules, quantum gases coupled to optical cavities, and trapped-ion systems [1].

While the impact of long-range interactions on classical statistical mechanics has been extensively explored, revealing their ability to modify thermodynamic properties and alter universal behavior at criticality [2], their role in quantum thermodynamics remains largely uncharted. In this talk, we investigate the quantum thermodynamics of many-body quantum systems with long-range interactions, focusing on the universal features of the quantum work statistics when the system is driven out-of-equilibrium across a quantum critical point. We analyze the system's response to different external driving protocols [3], unveiling the distinctive resilience of long-range systems against finite-time drivings. This resilience significantly mitigates energy losses due to defect generation in non-adiabatic evolution, thereby enhancing the power-to-efficiency ratio of quantum thermal devices featuring long-range couplings [4].

To establish a comprehensive framework for these phenomena, we employ the effective dimension approach, which maps the universal properties of a system with long-range interactions in d-dimensional space to those of a short-range system in an effective fractal dimension d_{eff} [5]. Thanks to this powerful method our findings can be drawn in full generality and, then, specified to different experimentally relevant scenarios.

References:

[1] N. Defenu, T. Donner, T. Macrì, G. Pagano, S. Ruffo, and A. Trombettoni, Long-range interacting quantum systems, Rev. Mod. Phys. 95, 035002 (2023).

[2] A Campa, Thierry Dauxois, D Fanelli, and S Ruffo, Physics of long-range interacting systems. Oxford Univ. Press, (2014).

[3] A. Solfanelli, N. Defenu, Universal work statistics in long-range interacting quantum systems, Phys. Rev. Lett. 134, 030402 (2025).

[4] A. Solfanelli, G. Giachetti, M. Campisi, S. Ruffo, N. Defenu, Quantum heat engine with long-range advantages, New J. Phys. 25 033030 (2023).

17. Unconventional thermalization patterns in quantum many-body systems: Almost complete revivals and scarred dynamics

Presenter: **Igor Ermakov** (*Steklov Institute of Mathematics AND Russian Quantum Center*)

Abstract: In this talk, I will discuss two novel mechanisms that slow down thermalization in quantum many-body systems. Both mechanisms arise in relatively generic physical systems and are associated with specific initial states. The first mechanism involves special initial states that exhibit almost complete revivals of local observables to their original values at predetermined moments in time. Such states can be found in a wide range of quantum systems and have significant implications for quantum sens-

ing, quantum tomography, and the realization of so-called "quantum time capsules," where classical information can be retrieved only at specific times and not before. The second mechanism is quantum many-body scars, a phenomenon recently observed in a number of physical systems. We will explore the connection between quantum many-body scars and unstable periodic trajectories, revisiting the original concept of scars introduced by Heller in 1986. In many-body systems with large spins, there are scarred quantum states that can strongly influence the thermalization dynamics of fully polarized states.

The talk is mainly based on the following papers:

https://arxiv.org/pdf/2011.02848, https://arxiv.org/pdf/2409.00258

18. Expanding Possible Measurements in 1D Quasicondensates for Studying Thermalization Near Integrability

Presenter: **Taufiq Murtadho** (*Nanyang Technological University*)

The equilibration of quantum many-body systems near integrability is a long-standing problem in quantum thermodynamics. A hallmark experiment in this field involves coherently splitting 1D quasicondensates and probing local relative phase fluctuations through matter-wave interference. The subsequent dynamics leads to phenomena such as pre-thermalization where the properties of the split gas are consistent with generalized Gibbs ensembles. However, further characterizing equilibration in this system, especially over long time scales, is hindered by the limited observables that could be measured. In this work, we expand the space of possible measurements by extracting the local total phase fluctuations - the sum of phase fields of the two gases - from density ripple analysis after time of flight. We benchmark our method with numerical simulation and experimental data in and out of equilibrium. The total phase fluctuations can be understood as thermally populated modes whose interaction with the relative modes provides a mechanism for thermalization. Our work enlarges read-out capabilities in 1D ultracold atoms experiments by revealing correlation functions between the two gases which are challenging to compute theoretically, paving the way to study thermalization in isolated and near-integrable quantum systems.

9th of July, Morning Session 1
9:00-10:30

19. Finite-Resource Thermal Operations: Collision Models and Gaussian Constraints

Presenter: **Xueyuan Hu** (*Shandong University*)

The resource-theoretic approach to quantum thermodynamics provides a framework for characterizing state transformations under physically motivated constraints. In this talk, I present two recent advances that incorporate practical limitations into models of thermal operations. For continuous variable systems, we focus on Gaussian-preserving operations and establish the equivalence between axiomatic and physically realizable models. For discrete systems, we introduce finite-complexity thermal operations based on the collision model, where the system interacts with small, uncorrelated bath particles via energy-conserving unitaries. We identify a necessary condition for cooling below the bath temperature and demonstrate a protocol achieving such cooling without a machine. Introducing a minimal qubit machine further improves both cooling performance and energy efficiency. These results highlight new possibilities for thermodynamic control under realistic constraints.

20. Optimizing energy conversion in quantum devices exploiting non-thermal resources

Presenter: **Elsa Danielsson** (*Chalmers University of Technology*)

A typical heat engine exploits a hot, thermal resource for power production, by coupling to a cold reservoir with a different potential. However, when reaching the nanoscale, particles might no longer equilibrate with their thermal surroundings. The question is, what happens if the resource is not in thermal equilibrium? This is a particularly relevant query in nanoelectronic devices, where one could envision waste energy recovery on-chip. Consequently, to investigate energy conversion processes, non-thermal distributions become highly relevant descriptors of the particles' environment.

I will present how a non-thermal resource can be exploited to generate power or cool another reservoir, and how to maximize the efficiency for these processes. Utilizing coherent electron scattering, the optimization is made by adjusting the transmission probabilities of electrons at different energies. Importantly, we also address the issue of how to define an efficiency as the energy current cannot be neatly divided into heat and work, due to the presence of a non-thermal resource. Based on this, we show that for either a fixed input or output current, the optimal transmission function is a series of band-passes in the energy spectrum, depending on the shape of the non-thermal distribution.

21. Improving Quantum Machine Learning via Heat-Bath Algorithmic Cooling

Presenter: **Nayeli A. Rodriguez Briones** (*Technische Universität Wien*)

In this talk, I will present a novel application of quantum thermodynamics to improve sampling efficiency in quantum machine learning (QML). Drawing inspiration from heat-bath algorithmic cooling, we propose a quantum refrigeration protocol that enhances polarization and reduces entropy in quantum-supervised learning tasks. By alternating entropy compression and thermalization steps, our method effectively increases polarization toward the dominant bias, which is initially unknown—without requiring Grover iterations or quantum phase estimation, as in conventional methods. This thermodynamic approach minimizes the computational overhead associated with estimating classification scores and gradients, making it a practical and efficient solution for QML algorithms on noisy intermediate-scale quantum (NISQ) devices. Our findings suggest a new perspective on the role of thermodynamic cooling in quantum information processing, with potential implications beyond QML.

Ref. NA Rodríguez-Briones, DK Park. arXiv preprint arXiv:2501.02687.

9th of July, Morning Session 2
11:00-12:55

22. Complexity in thermodynamics: From the complexity entropy to maximum-entropy quantum channels

Presenter: **Philippe Faist** (*Freie Universität Berlin*)

I will present techniques based on the resource theory of thermodynamics and quantum information theory to quantify operational physical properties of many-body systems which might be undergoing complex dynamics. In particular, I will discuss how the resource-theoretic picture can accommodate the concept of complexity. Quantum circuit complexity measures the difficulty of realizing a quantum process, such as preparing a state or implementing a unitary. I will consider the prototypical task of information erasure, or Landauer erasure, where an n-qubit memory is reset to the all-zero state. In this setting, I'll show that the trade-off between the thermodynamic work and computational complexity required for erasure is determined by the complexity entropy, which quantifies the entropy a system appears to have to an observer of limited computational power. In a second part of my talk, I will introduce maximum-entropy methods for quantum channels and I will discuss their use as a toolbox to learn and model complex quantum dynamics.

23. Investigating Thermodynamic Resources in Quantum Cooling: Focus on Finite-resource Scenarios

Presenter: **Pharnam Bakhshinezhad** (*Technische Universität Wien*)

Quantum cooling is a fundamental process in quantum thermodynamics, with implications ranging from foundational principles to practical quantum technologies. In this talk, we investigate the thermodynamic resources required for cooling across different regimes, integrating insights from asymptotic, finite but large, and strictly finite resource scenarios. By analyzing various thermodynamic resources in both finite and asymptotic cases, we aim to understand their fundamental role in thermodynamic processes under constraints.

We first explore the role of control complexity in quantum cooling, addressing the trade-off between energy, time, and unitary complexity in achieving low-temperature states. In particular, we discuss how Landauer's principle connects to cooling when infinite time or control resources are available, and how constraints on available operations lead to the emergence of new thermodynamic limits [1]. The study of optimal unitary trajectories under commuting observables further improves our understanding of structural and dynamical complexity in cooling protocols [2].

Furthermore, we investigate initial correlations as a thermodynamic resource, deriving fundamental bounds on anomalous energy flow in the absence of external work [3]. We also explore finite-memory effects in quantum thermal machines, demonstrating that memory-assisted protocols can lead to exponential improvements in cooling efficiency over memoryless methods [4]. In large but finite systems, we derive resource requirements for optimal energy transfer and cooling processes, establishing a thermodynamic framework that accounts for real-world constraints [5].

Our results unify various aspects of quantum cooling, providing a comprehensive resource-theoretic perspective on the interplay between time, energy, and complexity in quantum thermodynamics.

[1] Philip Taranto, P. B., Andreas Bluhm, Ralph Silva, Nicolai Friis, Maximilian PE Lock, Giuseppe Vitagliano, Felix C Binder, Tiago Debarba, Emanuel Schwarzhans, Fabien Clivaz, Marcus Huber, Lan-

dauer versus Nernst: What is the true cost of cooling a quantum system?, PRX QUANTUM 4, 010332 (2023).

[2] Ralph Silva, P. B., Fabien Clivaz, Optimal unitary trajectories under commuting target and cost observables; applications to cooling, arXiv:2412.07291 (2024).

[3]Patryk Lipka-Bartosik, Giovanni Francesco Diotallevi, P.B., Fundamental limits on anomalous energy flows in correlated quantum systems, Phys. Rev. Lett. 132, 140402 (2024).

[4] Philip Taranto, Faraj Bakhshinezhad, Philipp Schüttelkopf, Fabien Clivaz, Marcus Huber, Exponential Improvement for Quantum Cooling through Finite-Memory Effects, Phys. Rev. Applied 14, 054005 (2020).

[5] Philip Taranto, Patryk Lipka-Bartosik, Nayeli A. Rodríguez-Briones, Martí Perarnau-Llobet, Nicolai Friis, Marcus Huber, and P.B., Efficiently cooling quantum systems with finite resources: Insights from thermodynamic geometry, arXiv:2404.06649 (Accepted in PRL).

24. A trilemma for thermodynamically consistent efficient measurements

Presenter: **Hamed Mohammady** (*Slovak Academy of Sciences*)

This work investigates the consequences of assuming that the quantum measurement process—the physical realization of a measurement through an interaction between the system to be measured with a measuring device—is thermodynamically closable, and thus subject to thermodynamic analysis. Our results highlight that this assumption gives rise to a fundamental tension between the following three statements: (i) the measurement process is consistent with the second and third laws of thermodynamics; (ii) the measurement process is decomposed into two autonomous sub-processes—unitary interaction between system and measuring device, followed by a readout mechanism on the measuring device; and (iii) the measurement on the system is efficient, i.e., is characterized by operations that are completely purity-preserving and represented by a single measurement operator. Any two of the above statements necessarily precludes the third. In particular, efficient measurements can be implemented without violating the laws of thermodynamics, but only if we abandon the unitary interaction measurement model and accept as fact the existence of non-purifiable, thermodynamically closed processes.

25. Coherent Charging of Quantum Batteries by Incoherent Source

Presenter: **Pawel Mazurek** (*University of Gdansk*)

The transfer of energy from a coherent source (e.g. a laser) to a quantum battery is of significant technological importance. However, a bounded transfer of energy from an incoherent source (e.g. a thermal bath) to a quantum battery, and its storage in a coherent form (active states) is also possible. In this study, we propose a novel approach to utilize thermal reservoirs for battery charging. Our method involves utilizing a system of non-interacting two-level fermions as the fundamental units of the quantum battery, interacting collectively with a shared reservoir.

Exploiting algebra of angular momentum, we provide analytic formulas for a stationary state of the system of N fermions interacting with a shared reservoir of a given temperature. The non-ergodicity of the evolution plays a crucial role in enforcing second law of thermodynamics, limiting maximal ergotropy one can extract from a single bath. Furthermore, we observe that, by increasing the number of cells in the battery, a linear increase of ergotropy extracted can be observed, with a fixed gap between ergotropy and energy. Our analysis reveals that the charging power of the battery experiences an enhancement with an increase in the temperature of the reservoir. Exploring evolution dependence on the initial state, we show that for the most experimentaly friendly initializations of fermions in a product of Gibbs states, the ergotropy extracted per battery cell is a monotonic function of temperature difference between local baths preparing the state and the shared reservoir, and that for finite temperaures it achieves its maximum at a specific size N of the system.

With possible implementations of the scheme in the current state-of-the-art quantum photonic systems or microwave superconducting circuits, the investigated setup may be of practical interest for extraction and processing energy in the nano- and microscale.

10th of July, Morning Session 1
9:00-10:30

26. Quantum Kinetic Uncertainty Relations in Mesoscopic Conductors

Presenter: **Geraldine Haack** (*University of Geneva*)

Kinetic Uncertainty Relations (KURs) establish quantum transport precision limits by linking signal-to-noise ratio (SNR) to the system's dynamical activity, valid in the weak-coupling regime where particle-like transport dominates. At strong coupling, quantum coherence challenges the validity of KURs and questions the meaning of the concept of activity itself.

In this talk, I will introduce a generalized dynamical activity valid at arbitrary coupling and discuss steady-state quantum KUR (QKUR) expressed in terms of this generalized activity. Explicit expressions are obtained within Green's function and Landauer-Büttiker formalisms. This QKUR ensures that uncertainty relations are valid across all coupling strengths, offering a general framework for out-of-equilibrium quantum transport precision analysis.

These concepts will be illustrated with paradigmatic quantum-coherent mesoscopic devices: a single quantum channel pinched by a quantum point contact and open single- and double-quantum dot systems. These result establish a general theoretical framework for quantifying precision limits in open quantum systems far from equilibrium.

27. Fundamental Bounds on Precision and Response for Quantum Trajectory Observables

Presenter: **Tan Van Vu** (*Yukawa Institute for Theoretical Physics, Kyoto University*)

The precision and response of trajectory observables offer valuable insights into the behavior of nonequilibrium systems. For classical systems, trade-offs between these characteristics and thermodynamic costs, such as entropy production and dynamical activity, have been established through uncertainty relations. Quantum systems, however, present unique challenges, where quantum coherence can enhance precision and violate classical uncertainty relations. In this study, we derive trade-off relations for stochastic observables in Markovian open quantum systems. Specifically, we present three key results: (i) a quantum generalization of the thermokinetic uncertainty relation, which bounds the relative fluctuations of currents in terms of entropy production and dynamical activity; (ii) a quantum inverse uncertainty relation, which constrains the relative fluctuations of arbitrary counting observables based on their instantaneous fluctuations and the spectral gap of the symmetrized Liouvillian; and (iii) a quantum response kinetic uncertainty relation, which bounds the response of general observables to kinetic perturbations in terms of dynamical activity. These fundamental bounds, validated numerically using a three-level maser and a boundary-driven XXZ spin chain, provide a comprehensive framework for understanding the interplay between precision, response, and thermodynamic costs in quantum systems.

28. Precision bounds for multiple currents in open quantum systems

Presenter: **Marco Radaelli** (*Trinity College Dublin*)

Thermodynamic (TUR) and kinetic (KUR) uncertainty relations are fundamental bounds constraining the fluctuations of current observables in classical, non-equilibrium systems. Several works have verified, however, violations of these classical bounds in open quantum systems, motivating the derivation of new quantum TURs and KURs that account for the role of quantum coherence. Here, we go one step further by deriving multidimensional KUR and TUR for multiple observables in open quantum systems undergoing Markovian dynamics. Our derivation exploits a multi-parameter metrology approach, in which the Fisher information matrix plays a central role. Crucially, our bounds are tighter than previously derived quantum TURs and KURs for single observables, precisely because they incorporate correlations between multiple observables. We also find an intriguing quantum signature of correlations that is captured by the off-diagonal element of the Fisher information matrix, which vanishes for classical stochastic dynamics. By considering two examples, namely a coherently driven qubit system and the three-level maser, we demonstrate that the multidimensional quantum KUR bound can even be saturated when the observables are perfectly correlated.

10th of July, Morning Session 2
11:00-12:30

29. Thermodynamic bound on current fluctuations in coherent conductors

Presenter: **Keiji Saito** (*Kyoto University*)

We derive a universal thermodynamic uncertainty relation for Fermionic coherent transport, which bounds the total rate of entropy production in terms of the mean and fluctuations of a single particle current. This bound holds for any multi-terminal geometry and arbitrary chemical and thermal biases, as long as no external magnetic fields are applied. It can further be saturated in two-terminal settings with boxcar-shaped transmission functions and reduces to its classical counterpart in linear response. Upon insertion of a numerical factor, our bound also extends to systems with broken time-reversal symmetry. As an application, we derive trade-off relations between the figures of merit of coherent thermoelectric heat engines and refrigerators, which show that such devices can attain ideal efficiency only at vanishing mean power or diverging power fluctuations. To illustrate our results, we work out a model of a coherent conductor consisting of a chain of quantum dots. We also discuss the large deviation properties.

30. Experimental Investigation of Quantum Heat Engines using NMR Quantum Platform

Presenter: **Krishna Moreshwar Shende** (*Indian Institute of Science Education and Research (IISER) Mohali*)

We present an experimental study of quantum heat engines using a nuclear magnetic resonance (NMR) quantum processor. First, we implement a quantum SWAP engine and explore its ability to function as both a heat engine and a refrigerator. By preparing a Gibbs thermal state in two distinct ways—either directly from thermal equilibrium or via a pseudopure state initialization—we analyze the thermodynamic uncertainty relations (TURs) governing the system. Our results confirm that a generalized TUR holds in all operational regimes of the SWAP engine, whereas a tighter TUR is violated in specific regimes. In a second experiment, we realize a quantum Otto heat engine using spin-1/2 nuclei and investigate the effects of finite-time operation on efficiency and power. To mitigate the efficiency-power trade-off caused by non-adiabatic transitions, we implement a shortcut-to-adiabaticity (STA) protocol via counter-adiabatic driving. By incorporating the cost of implementing STA, we evaluate the engine's performance using two different efficiency metrics and experimentally determine the most suitable measure for the NMR platform. Our findings demonstrate a significant enhancement in the engine's performance with STA compared to a non-adiabatic counterpart. These results provide valuable insights into the role of coherence, thermodynamic uncertainty, and quantum control in optimizing quantum thermal machines.

References:

1) https://arxiv.org/abs/2410.16230

2) https://arxiv.org/abs/2412.20194

31. Violation of the Thermodynamic Uncertainty Relation in Quantum Collisional Models

Presenter: **Ahana Ghoshal** (*University of Siegen*)

The thermodynamic uncertainty relation (TUR) is a fundamental principle in non-equilibrium thermodynamics that relates entropy production to fluctuations in a system, establishing a trade-off between the precision of an observable and the thermodynamic cost. Investigating TUR violations challenges classical thermodynamic limits, offering the potential for improved precision-entropy trade-offs, which is crucial for enhancing performance and optimization in quantum technologies. In this work, we investigate the thermodynamic uncertainty relation within a quantum collisional model, which offers the advantage of discretizing interactions into successive collisions with auxiliaries, allowing for precise tracking of dynamics and the incorporation of memory effects and non-Markovian behavior. We consider three types of dynamics in the collisional model: one is Markovian evolution, achieved by taking the continuous time limit and imposing the stability condition, while the other two are non-Markovian dynamics—one arising from increasing the collision time between the system and the auxiliaries, and the other from incorporating interactions between the auxiliaries. For the Markovian dynamics, we examine the classical and quantum TUR bounds in the non-equilibrium steady-state regime, and also the finite-time TUR bound. We demonstrate that the classical TUR bound is violated once a certain threshold of collisions with the auxiliaries is exceeded, with the maximum violation observed at the steady state. For the two non-Markovian approaches, we find that the violation of the finite-time TUR bound is more pronounced and highly dependent on the type of non-Markovianity, warranting a detailed comparison.

10th of July, Afternoon Session 1
14:00-15:15

32. Direct Experimental Observation of Quantum Mpemba Effect in Thermalization of Nuclear Spins Without Bath Engineering

Presenter: **Arijit Chatterjee** (*Indian Institute of Science Education and Research (IISER), Pune*)

The Mpemba effect is believed to be known from ancient times as the bizarre incident where an object, heated to a much higher temperature, cools down faster than when initiated in relatively cooler states. The quantum analog of this, known as the Quantum Mpemba Effect, is a counterintuitive phenomenon in quantum thermodynamics where a system initially prepared in a state much closer to the steady thermal state relaxes to equilibrium faster than a system that starts much nearer to it under the same external conditions. To this date, although few experiments have reported the observation of this effect in highly controlled settings, the existence of the Mpemba effect during the thermalization of a quantum system in interaction with an actual environment remains yet to be seen. We experimentally investigate the Quantum Mpemba effect in nuclear spin systems, as they thermalize naturally without any bath engineering. We first characterize the noise elements responsible for decoherence in single, double, and multi-qubit nuclear spin systems by performing quantum process tomography at different time scales, along with a spectral analysis of the noise. These experiments provide enough insight about the spectrum of the overall Liouvillian causing the dissipations. Identifying the relatively slower decay modes, which dominate the relaxation timescale, we prepare an initial state far from equilibrium in zero overlaps with these modes. We experimentally observe that such a state relaxes back to equilibrium much faster than the states living nearer to the steady state but having overlap with almost all the decay modes, confirming the presence of the Mpemba effect in the actual thermalization of quantum systems. We also identify the key role of quantum coherences in the above phenomena. As all slow decay modes contain primarily coherent terms, their presence leaves no effect if all initial states are prepared as only population ensembles. We experimentally verify this by putting the initial states under a strong dephasing after preparation, which destroys all coherences in the initial states. An identical run of the experiments shows no Mpemba speed up this time, thereby confirming the quantum nature of the effect. Finally, we theoretically investigate the regions in the space of control parameters where the Mpemba effect can be observed and where it is absent and discuss the possibility of a dynamical phase transitions at their boundary. The direct experimental observation of the quantum Mpemba effect demonstrates the potential of achieving faster thermalization in the presence of a real bath. Since, with the advancement of quantum information technologies, any method that offers a shortcut to relaxation is highly valued for reducing the wait time between two consequtive runs of a quantum device , our work will pave the way for new research in this area, along with deepening the theoretical understanding of this fascinating quantum phenomenon.

33. Informational non-equilibrium concentration

Presenter: **Chung-Yun Hsieh** (*University of Bristol*)

Informational contributions to thermodynamics can be studied in isolation by considering systems with fully-degenerate Hamiltonians. In this regime, being in non-equilibrium — termed informational non-equilibrium — provides thermodynamic resources, such as extractable work, solely from the information content. The usefulness of informational non-equilibrium creates an incentive to obtain more of it, motivating the question of how to concentrate it: can we increase the local informational non-equilibrium of a product state $\rho\otimes\rho$ under a global closed system (unitary) evolution? We fully solve this problem analytically, showing that it is impossible for two-qubits, and it is always possible to find states achieving this in higher dimensions. Specifically for two-qutrits, we find that there is a single unitary achieving optimal concentration for every state, for which we uncover a Mepmba-like effect. We further discuss the notion of bound resources in this framework, initial global correlations' ability to activate concentration, and applications to concentrating purity and intrinsic randomness.

Reference: C.-Y. Hsieh, B. Stratton, H.-C. Weng, V. Scarani, arXiv:2409.12759

34. Information geometry approach to quantum stochastic thermodynamics

Presenter: **Laetitia Paula Bettmann** (*Trinity College Dublin*)

Recent advancements have revealed new links between information geometry and classical stochastic thermodynamics, particularly through the Fisher information (FI) with respect to time. Recognizing the nonuniqueness of the quantum Fisher metric in Hilbert space, we exploit the fact that any quantum Fisher information (QFI) can be decomposed into a metric-independent incoherent part and a metric-dependent coherent contribution. We demonstrate that the incoherent component of any QFI can be directly linked to entropic acceleration, and for GKSL dynamics with local detailed balance, to the rate of change of generalised thermodynamic forces and entropic flow, paralleling the classical results. Furthermore, we tighten a classical uncertainty relation between the geometric uncertainty of a path in state space and the time-averaged rate of information change and demonstrate that it also holds for quantum systems. We generalise a classical geometric bound on the entropy rate for far-from-equilibrium processes by incorporating a nonnegative quantum contribution that arises from the geometric action due to coherent dynamics. Finally, we apply an information-geometric analysis to the recently proposed quantum-thermodynamic Mpemba effect, demonstrating this framework's ability to capture thermodynamic phenomena.

10th of July, Afternoon Session 2
15:45-17:00

35. Estimation of Hamiltonian Parameters from Thermal States

Presenter: **Kishor Bharti** (*A*STAR*)

We upper bound and lower bound the optimal precision with which one can estimate an unknown Hamiltonian parameter via measurements of Gibbs thermal states with a known temperature. The bounds depend on the uncertainty in the Hamiltonian term that contains the parameter and on the term's degree of noncommutativity with the full Hamiltonian: higher uncertainty and commuting operators lead to better precision. We apply the bounds to show that there exist entangled thermal states such that the parameter can be estimated with an error that decreases faster than $1/\sqrt{n}$, beating the standard quantum limit. This result governs Hamiltonians where an unknown scalar parameter (e.g., a component of a magnetic field) is coupled locally and identically to n qubit sensors. In the high-temperature regime, our bounds allow for pinpointing the optimal estimation error, up to a constant prefactor. Our bounds generalize to joint estimations of multiple parameters. In this setting, we recover the high-temperature sample scaling derived previously via techniques based on quantum state discrimination and coding theory. In an application, we show that noncommuting conserved quantities hinder the estimation of chemical potentials.

Reference: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.133.040802

36. From the limits of thermal metrology to the Planckian time of thermalization

Presenter: **Paolo Abiuso** (*IQOQI - Vienna*)

We present results on fundamental operational limits descending from the standard rules of (nonrelativistic) quantum mechanics applied on thermal states. Namely, we assess the following questions:

1. What are the ultimate precision bounds for the estimation of parameters encoded in thermal states?

2. What is the minimum time required by the most general machine to thermalize a given system?

Formally, in [1] we consider the estimation of an unknown parameter θ encoded in a system at thermal equilibrium. This means the system is assumed to be in a Gibbs state according to its Hamiltonian $H(\theta)$, which is divided into a parameter-encoding term $H_P(\theta)$ and an additional, parameter-independent, control H_C. Given a fixed $H_P(\theta)$, we find the maximal Quantum Fisher Information (QFI) attainable via arbitrary H_C, which provides a fundamental bound on the estimation precision. We elucidate the role of quantum non-commutativity between encoding and control, and prove that, when the latter is unconstrained, no fundamental advantage is offered by quantum coherence in terms of the maximum attainable QFI. A coherence-advantage is instead recovered when assuming additional constraints on the control, such as a minimum energy gap between the ground state and the first excited level: this scenario naturally converges to ground state metrology in the limit of low temperature. For the case of locally-encoded parameters, the optimal sensitivity presents a Heisenberg-like N^2-scaling in terms of the number of particles, which for finite temperature can be reached with local measurements and no entanglement. We apply our results to paradigmatic spin chain models and we discuss some consequences for critical systems and Hamiltonian learning. Remarkably, these findings of Ref.[1] become instrumental to the derivation and intuition behind the results on thermalization bounds.

Via the Boltzmann constant k and the Planck constant $\hbar$, each temperature T naturally defines a Planckian timescale as $\tau_P = \hbar/(kT)$. Due to its appearance in several quantum many-body dissipative systems,

τ_P has been conjectured to intrinsically constrain the thermal relaxation of any system. Going beyond model-dependent arguments that have been discussed in the literature, in [2] we provide a formal operational proof of this bound, considering thermalization as a task assigned to the most general machine E that receives as input a system S with local Hamiltonian H_S, and satisfies two conditions: (i) (Validity of Quantum Mechanics) The evolution of the compound $S+E$ is well described by unitary Hamiltonian evolution, which includes the local H_S as well as arbitrary additional terms/interactions fixed by the machine. After time t, the machine E is traced out to return the output state of S. (ii) (Nontrivial Thermalization) The output should be approximately the thermal ensemble, i.e., the Gibbs state, for the given T and H_S. This requirement has to be satisfied for a nontrivial set of Hamiltonians (at least 2, but more generally some continuous ball); otherwise, the thermalization for a single H_S could be performed arbitrarily fast by a machine storing copies of the fixed target Gibbs state. Using the geometry induced by the QFI (Bures distance), we prove that under (i) and (ii), it always holds $t \geq \tau_P \chi$, where χ is a dimensional function of the tolerated error and the set of Hamiltonians to thermalize. For standard systems, we show $\chi \approx 0.5$. Finally, in the limit of low temperature or ground state, we show that $\chi \propto kT/\Delta$, (Δ being the energy gap of S), connecting our results to adiabatic relaxation. We corroborate our sharp bounds via exact numerical simulations of a qubit thermalizing via interaction with a fermionic bath.

[1] Abiuso P, Sekatski P, Calsamiglia J, Perarnau-Llobet M. Fundamental limits of metrology at thermal equilibrium. Physical Review Letters. 2025;134(1):010801.

[2] (To appear) Abiuso P et al, “An information-theoretic proof of the Planckian bound for thermalization".

37. Double-bracket quantum algorithms for quantum imaginary-time evolution

Presenter: **Jeongrak Son** (*Nanyang Technological University*)

The Boltzmann factor $e^{-\beta H}$ is an operator ubiquitous in thermodynamics: from the partition function and the Gibbs state to the path integral formalism and thermal Green’s functions. It is also known as imaginary-time evolution due to its formal similarity to the usual Hamiltonian evolution, but with time as an imaginary-valued number. As the name suggests, imaginary-time evolution does not naturally occur in physical systems. However, if successfully implemented, it unlocks challenging tasks such as preparing Gibbs and ground states or measuring partition functions.

We introduce a quantum algorithm that coherently implements imaginary-time evolution, i.e. given any initial pure state $|\psi\rangle$, our algorithm prepares a normalised pure state $|\psi(\beta)\rangle$ that is proportional to $e^{-\beta H}|\psi\rangle$. Our approach is based on the insight that quantum imaginary-time evolution is an analytical solution to Brockett’s double-bracket flow, in the special case where the derivative of the density matrix of the system is given by the nested commutator of the density matrix itself and the Hamiltonian. To synthesise a circuit that implements this flow, we first discretise the continuous evolution and then approximate each discrete step using three unitary operations: two real-time Hamiltonian evolutions and an exponentiation of the state’s density matrix. The latter can also be compiled using real-time Hamiltonian evolutions and the unitary transformation that prepares the initial state $|\psi\rangle$ from a fiducial state $|\theta\rangle$. The resulting algorithm, which we call Double-Bracket Quantum Imaginary-Time Evolution (DB-QITE), is guaranteed to be a good approximation of the desired imaginary-time evolution. In particular, at each step:

i) the average energy decreases by an amount proportional to the energy variance of the previous state and

ii) the distance to the ground state reduces exponentially.

Our algorithm does not contradict the QMA-hardness of the ground state preparation problem. The caveat is that the step size of a discretisation must depend on the spectral gap of the Hamiltonian and vanishes when the Hamiltonian is gapless.

The main application of DB-QITE is the approximate preparation of ground states using shallow circuits. In other words, our method cools down any pure state by any amount along the trajectory of imaginary-time evolution. Compared to prior methods, DB-QITE offers several advantages:

i) Unlike other cooling processes, DB-QITE does not require thermal baths or measurements and feedback.

ii) Unlike other imaginary-time evolution algorithms, DB-QITE does not require variational optimisation or auxiliary qubits.

Furthermore, DB-QITE's equivalence to the double-bracket flow allows insights from dynamical systems theory to inform our cooling process:

i) The evolution is optimal since its connection to the double-bracket flow implies a steepest-descent process that minimises average energy.

ii) Even when the initial state is a noisy state ρ that is not pure, our algorithm converges to a state isospectral to ρ and passive, i.e. the eigenvectors of the final state are in the energy eigenbasis and their eigenvalues are ordered non-increasingly with energy.

This work is based on the preprint: https://arxiv.org/abs/2412.04554

11th of July, Morning Session 1
9:00-10:30

38. Quantum energetic advantage for agents responding in real-time

Presenter: **Jayne Thompson** (*A*STAR, Singapore*)

Agents employ complex strategies, dynamically adjusting responses to current inputs depending on past circumstances. As society pushes to automate ever more complex tasks, the computational resource requirements of such agents are growing in tandem. In particular sequence-to-sequence transduction, which requires agents to convert input symbol sequences into corresponding output sequences, has seen recent rapid progress – causing resource demands to double every 3-4 months and energy costs to rise accordingly.

Here we derive the fundamental minimal energetic cost on the task of sequence to sequence transduction. In particular we focus on scenarios where an agent processes L input symbols and generates L output symbols per cycle. We determine the most memory and energetically efficient constructions for executing this task classically. We then link this fundamental energetic costs to the requirement of generating the sequences in an online format, where at each time step we need to respond to current stimuli before we can see the upcoming inputs. We show this lack of being able to see upcoming inputs, fundamentally imposes a minimum energetic cost for this task.

We also explore quantum sequence-to-sequence models, which outperform classical models in energy and memory efficiency. We establish the necessary and sufficient conditions for quantum advantage in these metrics, demonstrating that quantum implementations are generally more energy efficient. We show the quantum advantage can scale without bound with parameters in the task.

39. Quantum Chaos and Volumetric Spatiotemporal Correlations

Presenter: **Kavan Modi** (*Singapore University of Technology and Design*)

Chaotic systems are highly sensitive to a small perturbation, and are ubiquitous throughout biological sciences, physical sciences and even social sciences. Taking this as the underlying principle, we construct an operational notion for quantum chaos. Namely, we demand that the future state of a many-body, isolated quantum system is sensitive to past multitime operations on a small subpart of that system. By 'sensitive', we mean that the resultant states from two different perturbations cannot easily be transformed into each other. That is, the pertinent quantity is the complexity of the effect of the perturbation within the final state. From this intuitive metric, which we call the Butterfly Flutter Fidelity, we use the language of multitime quantum processes to identify a series of operational conditions on chaos, particularly the scaling of the spatiotemporal entanglement. Our criteria already contain routine notions and well-known diagnostics for quantum chaos. We then extend the criteria to include projected process ensembles, motivated by studies on deep thermalisation. Our results account for previous attempts to make sense of quantum chaos, such as the Peres-Loschmidt Echo, Dynamical Entropy, Tripartite Mutual Information, and Local-Operator Entanglement. Finally, we will present numerical results using the XXZ model and discuss how chaos leads to equilibration, Markovianisation, and thermalisation.

40. Statistical mechanics of random density matrices

Presenter: **Harry Miller** (*University of Manchester*)

Random states are an important concept in quantum theory for quantifying the typical properties of quantum systems. In practice, a random state may be acquired by uniformly sampling a point from the manifold of density matrices, or alternatively sampling a random pure state on an enlarged projective Hilbert space and taking a partial trace. Here I investigate the distribution of random states under additional average energy constraints with respect to a Hamiltonian. Such constraints naturally impose a statistical mechanical structure on the state distribution and I derive the properties of both canonical and microcanonical distributed density matrices, such as the ensemble-averaged state, energy fluctuations and average purity. This is applied to a number of different systems including a single spin-n/2 particle and many non-interacting spin-1/2 particles. One notable feature is that the microcanonical distribution can exhibit phase transitions below the thermodynamic limit. I discuss the application of these mixed state ensembles to the foundations of statistical mechanics, many-body chaotic systems, random matrix theory, quantum state inference and quantum thermodynamics.

11th of July, Morning Session 2
11:00-12:30

41. Thermodynamic Computing: Harnessing Nonequilibrium Systems for Computation

Presenter: **Patryk Lipka-Bartosik** (*Center for Theoretical Physics, Polish Academy of Sciences (CTP PAS) and Jagiellonian University*)

As traditional computing approaches its fundamental limits, thermodynamic computing emerges as a promising new paradigm that harnesses the innate equilibration dynamics of physical systems to drive energy-efficient computation. In this talk, I will introduce a physics-based model of computation inspired by quantum transport phenomena. In this thermodynamic computing framework, computation is modeled as the flow of information through a network of coupled reservoirs—each defined by macroscopic variables such as chemical potential, temperature, or capacitance—and connected by transport channels realized through classical or quantum mechanisms. While the structure resembles that of a neural network, computation emerges not from discrete logical operations, but from the system's natural evolution toward equilibrium. Importantly, this framework inherently supports learning through physically grounded techniques like equilibrium propagation, enabling both inference and training to unfold through the system's intrinsic equilibration dynamics. Beyond its theoretical appeal, the model provides a versatile platform for developing energy-efficient AI architectures, paving the way toward more sustainable machine-learning hardware. By mapping neural network operations onto thermodynamic variables, it uncovers fundamental links between machine learning and nonequilibrium statistical physics—offering not only greater interpretability, but also deeper insights into the physical principles underlying computation itself.

42. Energy-Consumption Advantage of Quantum Computation

Presenter: **Hayata Yamasaki** (*University of Tokyo/NanoQT*)

Energy consumption in solving computational problems has been gaining growing attention as one of the key performance measures for computers. Quantum computation is known to offer advantages over classical computation in terms of various computational resources; however, proving its energy-consumption advantage has been challenging due to the lack of a theoretical foundation linking the physical concept of energy with the computer-scientific notion of complexity for quantum computation. To bridge this gap, we introduce a general framework for studying the energy consumption of quantum and classical computation, based on a computational model conventionally used for studying query complexity in computational complexity theory. Within this framework, we derive an upper bound for the achievable energy consumption of quantum computation, accounting for imperfections in implementation appearing in practice. As part of this analysis, we construct a protocol for Landauer erasure with finite precision in a finite number of steps, which constitutes a contribution of independent interest. Additionally, we develop techniques for proving a nonzero lower bound of energy consumption of classical computation, based on the energy-conservation law and Landauer's principle. Using these general bounds, we rigorously prove that quantum computation achieves an exponential energy-consumption advantage over classical computation for solving a paradigmatic computational problem – Simon's problem. Furthermore, we propose explicit criteria for experimentally demonstrating this energy-consumption advantage of quantum computation, analogous to the experimental demonstrations of quantum computational supremacy. These results establish a foundational framework and techniques to explore the energy consumption of computation, opening an alternative way to study the advantages of quantum computation. This presentation is based on the following preprint. https://arxiv.org/abs/2305.11212

43. Work and entropy of mixing in isolated quantum systems

Presenter: **Dominik Safranek** (*Institute for Basic Science*)

The mixing of two different gases is among the most common natural phenomena, with key environmental applications, such as CO2 capture, desalination, and purification of water supply. Most mixing scenarios, whether classical or quantum, involve thermal baths. We address this issue for isolated quantum systems, where a bath is not present, initial states can be fundamentally non-equilibrium, and only macroscopic information is known about the system. We define the entropy of mixing in the context of observational entropy, where different observers have different macroscopic measurements to perform and, as a result, different associated amounts of energy to extract. This naturally resolves the Gibbs mixing paradox in quantum systems: while an observer would experience a discontinuous increase in entropy if they became aware of two particle types, this knowledge does not provide an advantage if particles remain indistinguishable in their measurements. Finally, we derive a Landauer-like formula for the difference in energy extracted by two observers, where "observational temperature" emerges, defined by the knowledge accessed by the measurement.

Poster Session I — Monday, 7 July, 3:45 PM – 5:00 PM

I.1 Power-efficiency trade-off in quantum information engines

Presenter: **Milton Aguilar** (*Stuttgart University*)

Efficiency and power are two essential figures of merit of thermal machines. We here investigate the power-efficiency trade-off in a finite-time quantum Carnot information engine, in which an information reservoir replaces the usual cold bath of a quantum Carnot engine. We analytically evaluate mean and variance of the work output for a working medium consisting of a qubit, and demonstrate that maximum efficiency can be reached at both finite work output and finite work output fluctuations. We additionally show that the relative work output fluctuations may be smaller than those of the corresponding Carnot heat engine. This result implies that the quantum Carnot information engine can be more stable than the quantum Carnot heat engine, an important property for practical applications.

I.2 Emergent non-Markovianity and dynamical quantification of the quantum switch

Presenter: **Vishal Anand** (*International Institute of Information Technology Hyderabad(IIIT H)*)

We investigate the dynamical aspects of the quantum switch and find a particular form of quantum memory emerging out of the switch action. We first analyze the loss of information in a general quantum evolution subjected to a quantum switch and propose a measure to quantify the switch-induced memory. We then derive an uncertainty relation between information loss and switch-induced memory. We explicitly consider the example of depolarizing dynamics and show how it is affected by the action of a quantum switch. For a more detailed analysis, we consider both the control qubit and the final measurement on the control qubit as noisy and investigate the said uncertainty relation. Further, while deriving the Lindblad-type dynamics for the reduced operation of the switch action, we identify that the switch-induced memory actually leads to the emergence of non-Markovianity. Interestingly, we demonstrate that the emergent non-Markovianity can be explicitly attributed to the switch operation by comparing it with other standard measures of non-Markovianity. Our investigation thus paves the way forward to understanding the quantum switch as an emerging non-Markovian quantum memory. (arXiv:2307.01964v2)

I.3 Irreversibility (of linear maps) in terms of Subjectivity

Presenter: **Clive Cenxin Aw** (*Centre for Quantum Technologies, Singapore*)

In both classical and quantum physics, irreversible processes are described by maps that contract the space of states. The change in volume has often been taken as a natural quantifier of the amount of irreversibility. In Bayesian inference, loss of information results in the retrodiction for the initial state becoming increasingly influenced by the choice of reference prior. In this paper, we import this latter perspective into physics, by quantifying the irreversibility of any process with its Bayesian subjectivity—that is, the sensitivity of its retrodiction to one's prior. We show that this measure not only coheres with other figures of merit for irreversibility, but also has joint monotonicities with physically noteworthy, information geometric measures.

I.4 Dephasing Enabled Fast Charging of Quantum Batteries

Presenter: **Prasanna Venkatesh B** (*Indian Institute of Technology (IIT), Gandhinagar*)

We propose and analyze a universal method to obtain fast charging of a quantum battery by a driven charger system using controlled, pure dephasing of the charger. While the battery displays coherent underdamped oscillations of energy for weak charger dephasing, the quantum Zeno freezing of the charger energy at high dephasing suppresses the rate of transfer of energy to the battery. Choosing an optimum dephasing rate between the regimes leads to a fast charging of the battery. We illustrate our results with the charger and battery modeled by either two-level systems or harmonic oscillators. Apart from the fast charging, the dephasing also renders the charging performance more robust to detuning between the charger, drive, and battery frequencies for the two-level systems case.

I.5 Fundamental constraints on quantum prediction

Presenter: **Graeme Berk** (*Nanyang Technological University*)

For many important tasks in quantum thermodynamics, high efficacy can only be guaranteed if the quantum system's behaviour can be accurately predicted. Here, we study the scenario where a quantum system cannot be accurately predicted using a simple large-bath Markov approximation, but can be accurately predicted when properly accounting for its non-Markovian nature. Non-Markovian models require the use of quantum memory, leading to a theoretically and practically important question: how much does one need to remember about the past to faithfully predict the future? These fundamental constraints have been well studied for models of classical processes in the field of computational mechanics. A key concept employed in this theory is causal equivalence of future morphs (CEFM): histories of observations that lead to the same future observation statistics are assigned to the same memory state. Invoking CEFM leads to provably minimal unifilar classical models of classical processes, known as epsilon-machines. Unfortunately, it is known that not all quantum processes can be efficiently classically simulated, even with the best classical models. However, numerous challenges make a generalisation of computational mechanics to quantum models of quantum processes highly nontrivial. These include the non-passivity of quantum observation, the continuous nature of Hilbert spaces, and fact that quantum superpositions render CEFM insufficient to construct minimal quantum models. Leveraging the process tensor formalism — which has demonstrated its utility at describing discrete time non-Markovian processes — we formulate a quantum generalisation of computational mechanics. The fundamental object in this theory is the conditional future process tensor. We show that CEFM can be generalised to linear dependence of future morphs (LDFM) using linear dependence of the vector space of Hermitian operators, or the vector space of state vectors, leading to two distinct classes of models. Using the former notion, we provide a lower bound on the memory required to model a process in terms of the number of distinct statistical behaviours the process can exhibit. We also study how the prediction of quantum and classical processes differs. Epsilon-machines have the property that all memory states yield different statistics for future outcomes. We show that this property is sufficient, although not necessary for a quantum model to be minimal. This is a fundamental memory redundancy in predicting quantum processes with no classical analogue. Another beneficial property possessed by Epsilon-machines is unifilarity, which implies that the memory states do not drift into uncertainty over time. We characterise unifilar quantum processes, and find that quantum unifilarity is significantly more difficult to satisfy than classical unifilarity, which makes quantum processes intrinsically more difficult to predict. Additionally, we show that classical models and classical processes can be described within our framework. This allows us to characterise the memory advantage of models that use quantum memory. Collectively, our results illustrate that quantum prediction is inherently more complex than classical prediction, requiring a re-evaluation of basic assumptions. However, the utilisation of non-Markovian quantum models that minimise memory redundancy is likely to improve performance at quantum thermodynamics tasks on a wide range of physical systems.

I.6 Dynamical invariant-based shortcut to equilibration in open quantum systems

Presenter: **Mohamed Boubakour** (*University of Lorraine*)

We propose using the dynamical invariant also known as the Lewis-Riesenfeld invariant, to speed-up the equilibration of a driven open quantum system. This allows us to reverse engineer the time-dependent master equation that describes the dynamics of the open quantum system and systematically derive a protocol that realizes a shortcut to equilibration. The method does not require additional constraints on the timescale of the dynamics beside the Born-Markov approximation and can be generically applied to boost single particle quantum engines significantly. We demonstrate it with the damped harmonic oscillator, and show that our protocol can achieve a high-fidelity control in shorter timescales than simple non-optimized protocols. We find that the system is heated during the dynamics to speed-up the equilibration, which can be considered as an analogue of the Mpemba effect in quantum control. Reference: M. Boubakour, S. Endo, T. Fogarty and T. Busch, 2025 Quantum Sci. Technol. 10 025036

I.7 Quantum control of heat current

Presenter: **Subhadeep Chakraborty** (*Centre for Quantum Technologies, Singapore*)

We study the steady-state, internal current circulation of local thermal currents in a bosonic trimer with a geometric phase inside it. Driven by two external reservoirs at different temperatures, the system exhibits a nonreciprocal current between two of its sites in thermal equilibrium, without violating the zeroth law of thermodynamics. Notably, our study explores both the limits where the internal hopping amplitude falls within weak- and strong-coupling regimes, relative to the system's dissipation rates. While nonreciprocity persists in the strong-coupling regime, we observe a novel phase reversal in the nonequilibrium current. We discuss its experimental feasibility and propose exciting new possibilities for implementing quantum-controlled heat devices.

I.8 Information Structure of Multi-time Quantum Processes

Presenter: **Derek Chang** (*Nanyang Technological University*)

Information processing and control of quantum systems with non-classical correlations over multiple time steps are the subjects of intense focus in recent years. Such tasks can greatly benefit from accounting for the intrinsic informational structures in the quantum process involved. For example, an observer whose goal is to predict a quantum process's future outputs seeks to minimize the uncertainty of their predictions while using the least resources possible. This begs the following question: What are the fundamental limits of predictability of a quantum process? By imposing the lens of input-output processes from computational mechanics onto the framework of process tensors which is an operationally consistent multi-time characterization of non-Markovian quantum processes, we define and quantify structural features along the lines of randomness and complexity in stationary quantum processes. The central object quantifying the intrinsic randomness is the process Choi state entropy rate which is shown to have a conditional form for stationary processes and further leads to a notion of process memory as the quantum excess entropy. Our results provide foundational tools to examine and compare quantum processes, and opens up possibilities in obtaining fundamental limits in operational contexts such as quantum predictive modelling, quantum communication and cryptography, and quantum thermodynamic work extraction.

I.9 Petz Map Realization In Linear Optics

Presenter: **Jinyan Chen** (*Centre for Quantum Technologies, Singapore*)

The Petz recovery map is known for its near-optimal performance in recovering quantum information. Though the Petz recovery map has been widely explored in theory, it still lacks experimental implementations. In this work, we provide an experimentally accessible method to realize the Petz recovery map using linear optics. In our model, quantum information is lost due to interaction with environment via a single beam splitter. We have proved that the Petz recovery map can be realized by another beam splitter with certain constraints when the environment state and the reference state are both Gaussian states. Finally, we use thermal state, general Gaussian state, cat state and qubit state as inputs to show the fidelity of the Petz recovery map.

I.10 Non-Markovian refrigeration and heat flow in the quantum switch

Presenter: **Jian Wei Cheong** (*Nanyang Technological University*)

The quantum switch is a composition of channels where a pair of quantum channels are placed in a coherent superposition of alternating orders, and features various advantages to communication and thermodynamic tasks. While these advantages are typically attributed to its indefinite causality and coherent superposition, we show that the quantum switch also has non-Markovian memory effects, which can contribute to heat extraction and thus refrigeration tasks. Particularly, we showed that refrigeration is still possible even when the working body begins at a temperature that is hotter than the interacting baths, provided that non-Markovian memory effects are present. We achieve this by generalizing the quantum switch such that its non-Markovianity can be varied, showing that the coefficient of performance of the refrigeration cycle depends on the presence and amount of non-Markovianity. Our work demonstrates that non-Markovian effects in quantum compositions with indefinite causal order is an important factor to account for when studying their advantages and resources.

I.11 Dynamical blockade of a reservoir for optimal performances of a quantum battery

Presenter: **Dario Ferraro** (*University of Genova*)

The development of fast and efficient quantum batteries is crucial for the prospects of quantum technologies. We show that both requirements are accomplished in the paradigmatic model of a harmonic oscillator strongly coupled to a highly non-Markovian thermal reservoir. At short times, a dynamical blockade of the reservoir prevents the leakage of energy towards its degrees of freedom, promoting a significant accumulation of energy in the battery with high efficiency. The possibility of implementing these conditions in LC quantum circuits opens up new avenues for solid-state quantum batteries. F. Cavaliere, G. Gemme, G. Benenti, D. Ferraro, M. Sassetti, Communications Physics 8, 76 (2025).

I.12 Inverse Current in Coupled Transport: A Quantum Thermodynamic Framework for Energy and Spin-polarized Particle Currents

Presenter: **Shuvadip Ghosh** (*Indian Institute of Technology (IIT), Kanpur*)

The phenomenon of inverse current in coupled transport (ICC), where one induced current flows counter to two parallel thermodynamic forces, represents a strikingly counterintuitive behavior in transport processes [Phys. Rev. Lett. 124, 110607 (2020)]. Through an exactly solvable model of strongly coupled quantum dots, we provide a quantum thermodynamic framework to describe ICC in energy and spin-polarized particle currents, highlighting its potential applications for unconventional and autonomous nanoscale thermoelectric engines and refrigerators. Our analysis establishes a link between the microscopic and macroscopic descriptions of the entropy production rate, emphasizing the crucial role of thermodynamic forces and their conjugate fluxes in accurately characterizing genuine ICC. Here, the paradoxical behavior of ICC emerges from the symmetry breaking between particle and energy transitions, identified as the sufficient condition, while the attractive interaction between the coupled quantum dots is determined to be the necessary criterion for the ICC effect.

I.13 Transport in open quantum systems in the presence of lossy channels

Presenter: **Katha Ganguly** (*Indian Institute of Science Education and Research (IISER), Pune*)

Transport in low-dimensional open quantum systems with boundary drives has been an active area of research both theoretically and experimentally. Such quantum systems can potentially have additional dissipative effects which arise due to inevitable imperfections in experimental platforms. In this work, we have studied the nonequilibrium steady-state transport in a boundary-driven one-dimensional fermionic lattice setup subjected to particle loss dissipative channels. By analyzing the system size scaling of conductance at zero temperature for different values of the chemical potential of the boundary reservoirs, we show that these dissipative channels are not necessarily always detrimental. We consider a variety of loss channel configurations: (i) single loss at the middle site of the lattice, (ii) multiple but nonextensive lossy channels, and (iii) extensive lossy channels. For the cases (i) and (ii), the conductance scaling with system size remains robust (i.e., same as the case with no loss) for chemical potential within and outside the lattice band, while at the band edge rich anomalous conductance scaling emerges including the enhancement of conductance. For case (iii), we find the conductance scaling becomes ballistic in the thermodynamic limit for any value of chemical potential. We explain the emergence of these different system size scalings of conductance by analyzing the spectral properties of the associated non-Hermitian transfer matrices of the underlying lattice. We demonstrate that the emergence of anomalous scaling is deeply connected to the existence of exceptional points of transfer matrices. Our study unravels that by carefully optimizing the loss mechanism configurations, one can in principle realize systems with rich transport properties in low-dimensional open quantum systems.

I.14 Cyclic solid-state quantum battery: Thermodynamic characterization and quantum hardware simulation

Presenter: **Giulia Gemme** (*University of Genoa*)

We have introduced a cyclic quantum battery model, based on an interacting bipartite system, weakly coupled to a thermal bath. The working cycle of the battery consists of four strokes: system thermalization, disconnection of subsystems, ergotropy extraction, and reconnection. The thermal bath acts as a charger in the thermalization stroke, while ergotropy extraction is possible because the ensuing thermal state is no longer passive after the disconnection stroke. Focusing on the case of two interacting qubits, we have shown that phase coherence, in the presence of non-trivial correlations between the qubits, can be exploited to reach working regimes with efficiency higher than 50% while providing finite ergotropy.

Our protocol is illustrated through a simple and feasible circuit model of a cyclic superconducting quantum battery. Furthermore, we have simulated the considered cycle on superconducting IBM quantum machines. The good agreement between the theoretical and simulated results strongly suggests that our scheme for cyclic quantum batteries can be successfully realized in superconducting quantum hardware.

I.15 Local injection of quantum particles in quasi-periodic lattice

Presenter: **Sparsh Gupta** (*International Centre for Theoretical Sciences (ICTS), Bangalore*)

In this work, our objective is to investigate the response of a quasiperiodic system's dynamics when coupled with an environment, contrasting it with the isolated quantum dynamics of the system. We study the dynamics of filling an empty Aubre-Andre-Harper lattice (in different phases of the lattice) by connecting it locally with a non-interacting bath that injects non-interacting bosons or fermions into the lattice. We use exact quantum dynamics to evolve the whole setup and investigate various quantities of interest such as spatial density profile and the total number of bosons/fermions in the lattice. To complement this, we employ hydrodynamic methods to analytically compute these observables in the clean limit of this setup. We observe that the spatial spread is ballistic, diffusive, and logarithmic in the Delocalized, Critical, and Localized phases respectively and the local occupation eventually settles down owing to equilibration. However, the time scales of equilibration vary differently in different regimes. We also observe the same scaling in different phases when the system's dynamics are evolved using the Lindblad Equation. The difference between bosons and fermions shows up in the early time growth rate and the saturation values of the profile.

I.16 Fundamental Scaling Limit in Critical Quantum Metrology

Presenter: **Ju-Yeon Gyhm** (*Seoul National University*)

Critical quantum metrology seeks to exploit the enhanced sensitivity near quantum phase transitions to improve the precision of parameter estimation. However, a fundamental limitation arises due to critical slowing down, which restricts the precision achievable within a finite evolution time. In this work, we address this challenge by establishing a fundamental scaling limit of critical quantum metrology with respect to the total evolution time. We uncover that the winding number of the system's trajectory in phase space plays a central role in determining the scaling bound of the quantum Fisher information (QFI). Specifically, we demonstrate that QFI scaling is fundamentally governed by this topological quantity, and that an exponential enhancement of QFI can be realized if the winding number increases linearly with total evolution time. To achieve this optimal scaling, we construct an explicit, time-dependent control scheme. Remarkably, the control is simple: an on-off modulation based solely on the phase of the system. This control not only enables exponential scaling but also reveals the topological nature of the underlying metrological enhancement. Furthermore, we show that the exponential scaling of QFI persists even in the absence of exact criticality and under the influence of thermal dissipation, albeit with a reduced exponent. This robustness highlights the practical viability of the proposed approach in realistic settings. Our results establish a novel connection between quantum criticality, topological dynamics, and metrological precision, offering a fundamentally new perspective on how to overcome the limitations of critical slowing down in finite-time quantum sensing.

I.17 Experimental Realization of Self-Contained Quantum Refrigeration

Presenter: **Keyi Huang** (*Southern University of Science and Technology*)

In the context of two-level systems, the most compact refrigerator necessitates the involvement of three entities, operating under self-contained conditions that preclude the use of external work sources. Here, we build such a smallest refrigerator using a nuclear spin system, where three distinct two-level carbon-13 nuclei in the same molecule are involved to facilitate the refrigeration process. The self-contained feature enables it to operate without relying on the net external work, and the unique mechanism sets this refrigerator apart from its classical counterparts. Through full thermodynamic characterization—including measurements of energy, entropy, and temperature—we confirm that the cooling is achieved in a self-contained manner. Additionally, we investigate the working conditions and efficiency limits of the refrigeration cycle, showing how heat flow between the other two spins powers the cooling of the target.

I.18 Quantum state-agnostic work extraction (almost) without dissipation

Presenter: **RuoCheng Huang** (*Nanyang Technological University*)

Given sequential access to finite copies of an identical, unknown quantum state, what is the optimal approach to extract work to charge a battery? A natural strategy might involve first performing tomography to estimate the unknown state, then using this estimate to extract work. However, with only finite copies, any estimate will contain errors, leading to heat dissipation during work extraction. We investigate how this cumulative dissipation scales with the number of available copies, addressing whether adaptive strategies can simultaneously learn the unknown state and maximize the work transferred to the battery system. We establish a link between sequential work extraction from unknown quantum states and the exploration-exploitation trade-off, a core concept in reinforcement learning. In these protocols, each interaction accesses one copy of the unknown state at a time: exploration involves learning about the unknown state to enable greater work extraction in future rounds, while exploitation focuses on maximizing work extraction based on the current state knowledge. Our protocols are inspired by multi-armed bandit algorithms, particularly optimistic algorithms that apply the principle of optimism in the face of uncertainty. These belong to the family of upper confidence bound (UCB) algorithms, with finite-time analysis pioneered in the seminal work [Aurer 2002]. We relate the physical heat dissipation in our protocols to a concept known as "regret" in reinforcement learning, which quantifies the loss of potential reward—or in our case, work extracted—due to the agent's incomplete information. Crucially, when the unknown state is a pure qubit, our protocols achieve an upper bound on cumulative work dissipation that scales as polylog(N), where N is the number of available unknown pure qubit states. We emphasize that in our setting, a straightforward protocol, which allocates a portion of the copies for quantum state tomography and then extract work based on that estimate, will achieve at best a sqrt(N) scaling. This is due to the fundamental limits on how accurate the estimate is compared to the actual state, given the finite number of samples. Our problem aligns with the quantum state tomography problem with minimal regret introduced in, where the objective is to learn an unknown pure quantum state by performing minimally disruptive measurements, i.e., measurements that closely align with the unknown state. In that setting, orthogonal measurements increase regret, which we connect to work dissipation. We explicitly show the bound for two models: the uniform energy ladder battery, based on the Jaynes-Cummings model, and a semi-classical battery system with operations requiring only average energy conservation. We are first to frame sequential work extraction in terms of exploration-exploitation and quantified the cumulative dissipation in the finite copy regime. We have not only established an upper bound on the cumulative dissipation but also provided the explicit algorithm that achieves it. Our approach also opens the door to extending this framework to investigate the extraction of other resources considered in other quantum resource theories beyond free energy, such as entanglement and quantum "magic".

I.19 Deep Thermalization in Gaussian Continuous-Variable Systems: Universality and Maximum Entropy Principles

Presenter: **Qi Huang** (*National University of Singapore*)

We study deep thermalization—a form of emergent universality in quantum dynamics extending beyond conventional thermalization—in multimode bosonic Gaussian systems. For a highly entangled global Gaussian state, we demonstrate that the ensemble of pure states on a small subsystem, induced by Gaussian measurements on its complement (the "bath"), attains a universal form: unsqueezed coherent states with normally and isotropically distributed displacements. This universality depends solely on the global particle-number density and is independent of the measurement basis. We show that this universal distribution of Gaussian states, dubbed the "Gaussian Scrooge distribution", aligns with a generalized maximum entropy principle, which endows the ensemble with a special quantum information-theoretic property: it minimizes its accessible information to outside observers. Our results generalize the concept of deep thermalization—previously confined to discrete-variable systems like quantum spins—to continuous-variable systems. Furthermore, they highlight how quantum information-theoretic frameworks can uncover novel physical phenomena and principles in quantum dynamics and statistical mechanics.

I.20 Ergotropic advantage in measurement-based quantum heat engine

Presenter: **Sidhant Jakhar** (*Indian Institute of Science Education and Research (IISER), Mohali*)

This study investigates a five-stroke single-reservoir measurement-based quantum heat engine (QHE) with the working medium based on a single qubit and two coupled qubits. Qubits are coupled through a 1D isotropic Heisenberg exchange interaction. It is an extension of the four-stroke model proposed by Yi et al. in 2017, in which the authors studied a single-reservoir modified quantum Otto cycle. When the working medium is a single qubit, we have taken two types of general (weak) measurements in the 2-D plane for the quantum measurement stroke. For coupled qubits, we have taken four measurement cases. These are when spins of qubits A and B are measured along z direction, x and y directions respectively, y and z directions respectively, and x direction. For coupled qubits, we have explored the high J regime for now. Our objective is to explore efficiency improvements over the model proposed by Yi and coworkers, and also to find the class of measurement operators that gives maximum efficiency. We have found that for a single qubit, introducing an ergotropic stroke enhances the efficiency compared to earlier models with specific measurement operator parameters, leading to optimal performance. For coupled qubits, we have found that our model have clear advantages in terms of efficiency over the conventional four-stroke model for all the four cases mentioned above. Our results indicate a direct relationship between the measurement operators design and ergotropic work extraction.

I.21 The Jaynes-Cummings model as an autonomous Maxwell demon

Presenter: **Yashovardhan Jha** (*University of Lorraine*)

Progress in experimental physics allows nowadays to study quantum machines with great detail. Specifically, research on autonomous quantum machines is increasing gradually since they play a significant role in thermodynamics. Autonomous machines are known to work without any external control, which helps the machines overcome the effect of decoherence due to the external environment. When these controllers perform thermodynamic tasks, such as work extraction or cooling, they are called autonomous

Maxwell demons. A thorough characterization of these machines is of major fundamental interest, as it is linked to the long-standing question of how the dynamics induced by quantum measurements and the laws of thermodynamics emerge in an entirely quantum framework. In a recent article [1], we study a two-level atom resonantly interacting with a harmonic oscillator via the Jaynes-Cummings interaction, where the cavity or the harmonic oscillator is initialized in a coherently displaced thermal state. We focus on the limit of very large coherent displacement, where the cavity is expected to behave as a classical drive. We observe that this model actually exhibits different behaviors depending on the time scale, which divides the evolution into three regimes. The first regime, or the unitary regime, indeed corresponds to a quasi-ideal work source behavior of the cavity, where the cavity induces a classical drive on the atom, which performs Rabi oscillations. Both the atom and cavity evolve almost unitarily. Using a framework of thermodynamics introduced for autonomous quantum systems [2], we quantify the residual heat exchange, showing that it goes to zero in the classical limit. However, this regime breaks down on a time scale set by the qubit-cavity coupling constant, on which the Rabi oscillations start to collapse. This second regime corresponds to an autonomous measurement performed by the cavity on the atom. The cavity performs this measurement in a basis that is set by the initial phase of the field. During this measurement, the mutual information between the cavity and qubit rises as measurement results become available in the phase of the field. Ultimately, we identify a third regime where the cavity provides autonomous feedback on the atom. The field in the cavity becomes dependent upon the measurement result, consequently leading to a conditional drive on the atom. This feedback appears to purify the atom, whatever its initial state, by driving it towards a specific pure state set by the initial phase of the field. Owing to our thermodynamic framework, we show that the cavity behaves as an autonomous Maxwell demon [1], trading mutual information for cooling power. This behavior emerges autonomously in the Jaynes-Cummings interaction. Our analysis demonstrates the potential of consistent thermodynamic approaches to understanding complex quantum dynamics. References: [1] Yashovardhan Jha, Dragi Karveski, and Cyril Elouard. The Jaynes Cummings Model as an Autonomous Maxwell Demon (2025), arXiv:2502.10344 [2] Cyril Elouard and Camille Lombard Latune. Extending the Laws of Thermodynamics for Arbitrary Autonomous Quantum Systems. PRX Quantum, 4(2):020309, April 2023.

I.22 Estimating Observational Entropy on a Quantum Computer through Shadow State Framework

Presenter: **Caesnan Leditto** (*Monash University*)

Observational entropy (OE) represents a unified framework for understanding various entropy concepts in physics. It not only offers a natural approach to quantum thermodynamics but also facilitates the examination of important dynamical properties in many-body systems, such as (de)localization and quantum chaos. Despite its potential, the computation of OE can be resource-intensive. In this work, we present a novel fault-tolerant quantum algorithm, enabling efficient estimation of OE in quantum many-body systems. To do so, we employ an improved quantum algorithm for von Neumann entropy (vNE) estimation of the shadow state of related observables. This establishes a close relation between OE and vNE of the shadow state. As a future work, we anticipate that this algorithm will also be applicable in uncovering exotic features of quantum processes through OE.

I.23 Retrodictive approach to quantum state smoothing

Presenter: **Mingxuan Liu** (*Centre for Quantum Technologies, Singapore*)

Smoothing is a technique for estimating the state of an imperfectly monitored open system by combining both prior and posterior measurement information. In the quantum regime, current approaches to smoothing either give unphysical outcomes, due to the non-commutativity of the measurements at different times, or require assumptions about how the environment is measuring the system, which with current technology is unverifiable. We propose a novel definition of the smoothed quantum state based on quantum Bayesian retrodiction, which mirrors the classical retrodictive approach to smoothing. This approach always yields physical results and does not require any assumption of the environment. We show that this smoothed state has, on average, greater purity than the state reconstructed using just the prior information.

I.24 Thin Film Diamond Nano-photonics and its quantum Application

Presenter: **Sunil Kumar Mahato** (*University of Hamburg Faculty of Mathematics, Informatics and Natural Sciences Department of Physics Institute for Quantum Physics*)

Exploiting quantum effects of light matter entanglement has been limited to a small number of qubits and has only been performed in tabletop experimental setups consisting of a large number of macroscopic components, Diamond is a potential candidate for the realization of quantum information technology because it encompasses optically active color centers with long-lived spin coherence and material properties that permit the efficient use of photons and phonons as quantum information carriers. It has a large bandgap, allowing for optical transitions in defect centers. Also, diamond naturally has a low number of nuclear background spins (98.9% in natural diamond is spin 0), realizing a magnetic vacuum

I.25 Shortcuts to adiabaticity in open quantum critical systems

Presenter: **Shishira Mahunta** (*Indian Institute of Science Education and Research (IISER), Berhampur*)

Shortcuts to adiabaticity (STAs) is a control protocol that has been proposed to realize effectively adiabatic dynamics in quantum systems driven by Hamiltonians changing at a finite rate in time. In this work we focus on implementing STA in quantum critical systems in presence of dissipation. We consider a dissipative transverse Ising model as a working ensemble that is made to evolve in a desired path by engineering the unitary and dissipator terms. The strength of the dissipator control terms show universal scaling close to criticality. We show that exact STA takes a simple form in the momentum space, which changes to multi-spin interactions in the real space and in contrast to closed quantum critical system systems, here STA may require multi-body interaction terms, even away from criticality, owing to change in entropy of the time-dependent target state. Further, the associated heat current shows extremum, while power dissipated changes curvature, close to criticality, and analogous to unitary control, no operational cost is associated with implementation of the exact counterdiabatic(CD) Hamiltonian. We expect that the protocol studied here can be of fundamental importance in understanding STA in many-body open quantum systems and can be highly relevant in quantum technologies, such as designing high-performing many-body quantum heat engines.

I.26 Using non-Markovian dynamics in effective-negative-temperature-based transient quantum Otto engines

Presenter: **Arghya Maity** (*Harish Chandra Research Institute*)

We demonstrate that the efficiency of effective-negative-temperature-based quantum Otto engines, already known to outperform their traditional counterparts operating with positive-temperature thermal

reservoirs, can be further improved by terminating the isochoric strokes before the working substance reaches perfect equilibrium with its environment. Our investigation encompasses both Markovian and non-Markovian dynamics during these finite-time isochoric processes while considering a weak coupling between the working substance and the reservoirs. We assess the performance of these engines as they undergo a transition from the Markovian to the non-Markovian regime using two figures of merit: maximum achievable efficiency at a certain finite time during the isochoric heating stroke, and overall performance of the engine over an extended period during the transient phase of this stroke. We show that the maximum efficiency increases with the increase of non-Markovianity. However, the overall engine performance decreases as non-Markovianity increases. Additionally, we discover the existence of effective-negative-temperature-based necessarily transient quantum Otto engines. These engines operate within an extended operational domain, reaching into temperature ranges where conventional effective-negative-temperature-based quantum Otto engines, which rely on perfect thermalization during the isochoric strokes, are unable to function. Furthermore, this extended operational domain of an effective-negative-temperature-based necessarily transient quantum Otto engine increases as non-Markovianity becomes more pronounced.

I.27 Thermodynamics of Hamiltonian anyons with applications to quantum heat engines

Presenter: **Daniel Manzano** (*University of Granada*)

The behavior of a collection of identical particles is intimately linked to the symmetries of their wavefunction under particle exchange. Topological anyons, arising as quasiparticles in low-dimensional systems, interpolate between bosons and fermions, picking up a complex phase when exchanged. Recent research has demonstrated that similar statistical behavior can arise with mixtures of bosonic and fermionic pairs, offering theoretical and experimental simplicity. We introduce an alternative implementation of such statistical anyons, based on promoting or suppressing the population of symmetric states via a symmetry generating Hamiltonian. The scheme has numerous advantages: anyonic statistics emerge in a single particle pair, extending straightforwardly to larger systems; the statistical properties can be dynamically adjusted; and the setup can be simulated efficiently. We show how exchange symmetry can be exploited to improve the performance of heat engines, and demonstrate a reversible work extraction cycle in which bosonization and fermionization replace compression and expansion strokes. Additionally, we investigate emergent thermal properties, including critical phenomena, in large statistical anyon systems.

I.28 A Finite-Time Quantum Otto Engine subject to Control Noise and Enhancement Techniques

Presenter: **Theodore McKeever** (*The University of Manchester*)

With the development of any quantum technology comes a need for precise control of quantum systems. Here, we evaluate the impact of control noise on a quantum Otto cycle. Whilst it is postulated that noiseless quantum engines can approach maximal Otto efficiency in finite times, the existence of white noise on the controls is shown to negatively affect average engine performance. Two methods of quantum enhancement, counterdiabatic driving and quantum lubrication, are implemented and found to improve the performance of the noisy cycle only in specified parameter regimes. To gain insight into performance fluctuations, projective energy measurements are used to construct a noise-averaged probability distribution without assuming full thermalisation or adiabaticity. From this, the variances in thermodynamic currents are observed to increase as average power and efficiency improve, and are also shown to be consistent with known bounds from thermodynamic uncertainty relations. Lastly, by comparing the average functioning of the unmonitored engine to a projectively-measured engine cycle, the role of coherence in work extraction for this quantum engine model is investigated.

I.29 Thermodynamical applications of the pseudomode framework in non-Markovian open quantum systems

Presenter: **Paul Menczel** (*RIKEN*)

The pseudomode framework describes the dynamics of an open quantum system coupled to a non-Markovian environment. It provides a Markovian embedding, where the open system is coupled to a finite number of unphysical pseudomodes that follow a Lindblad-like master equation. The influence of the pseudomodes on the system is exactly the same as that of the original non-Markovian environment. We show that thermodynamical observables such as heat currents and their fluctuations, multi-time correlation functions and response functions are also naturally represented on the pseudomode space. Hence, the framework provides an opportunity to study thermodynamical observables in non-Markovian open systems in a physically intuitive way. As a concrete application, we demonstrate how this physical intuition can be leveraged to engineer efficient ground-state cooling protocols.

I.30 The impact of quantum correlations on parameter estimation in a spin reservoir

Presenter: **Ali Raza Mirza** (*University Of Surrey*)

We study the impact of quantum correlations existing within the system-environment thermal equilibrium state while estimating the parameters of the spin reservoir. By employing various physical situations of interest, we present results for the reservoir temperature and its coupling strength with the central two-level system. The central system (probe) interacts with the bunch of randomly oriented spin systems and attains a thermal equilibrium state. We consider a projective measurement which prepares the probe's initial state, and then the global system (probe and reservoir) evolves unitarily. The reduced density operator encapsulates the information about the spin reservoir which can be extracted by doing measurements on the probe. The precision of such measurement is quantified by quantum Fisher information. We repeat this process if the probe-reservoir initial state is not correlated (product state). We compare the estimation results for both with and without the outturn of initial correlations. In the temperature estimation case, our results are promising as one can significantly improve the accuracy of the estimates by including the effect of initial correlations. A similar trend prevails in the case of coupling strength estimation especially at low temperatures.

I.31 Distributing Entanglement over Separable Quantum Networks

Presenter: **Karthik Mohan** (*Korea Advanced Institute of Science & Technology (KAIST)*)

Entanglement is a fundamental resource for quantum communication, cryptography, and resource-sharing protocols. Consequently, its efficient distribution across networks is both a critical challenge and an immediate need. In this paper, we introduce a protocol that distributes distillable entanglement among neighboring nodes via the transmission of a qubit. While previous studies have demonstrated that entanglement can be distributed through the transmission of a qubit that remains separable with respect to the communicating parties, our work advances this concept by characterizing the specific qubit states that facilitate such distribution while maintaining separability. Furthermore, we demonstrate how our scheme can be generalized to networks of arbitrary structure.

I.32 Memory-minimal quantum generation of stochastic processes

Presenter: **Magdalini Zonnios** (*Trinity College Dublin*)

Stochastic processes abound in nature and accurately modeling them is essential across the quantitative sciences. They can be described by hidden Markov models (HMMs) or by their quantum extensions (QHMMs). These models explain and give rise to process outputs in terms of an observed system interacting with an unobserved memory. Although there are infinitely many models that can generate a given process, they can vary greatly in their memory requirements. It is therefore of great fundamental and practical importance to identify memory-minimal models. This task is complicated due to both the number of generating models, and the lack of invariant features that determine elements of the set. In general, it is forbiddingly difficult to ascertain that a given model is minimal. Addressing this challenge, we here identify spectral invariants of a process that can be calculated from any model that generates it. This allows us to determine strict bounds on the quantum generative complexity of the process – its minimal memory requirement. We then show that the bound is raised quadratically when we restrict to classical operations. This is an entirely quantum-coherent effect, as we express precisely, using the resource theory of coherence. Finally, we demonstrate that the classical bound can be violated by quantum models.

Poster Session II — Tuesday, 8 July, 3:45 PM – 5:00 PM

II.1 Efficiently Estimating Order Parameters in Higher-Order Coupled Oscillators

Presenter: **Kavan Modi** (*Singapore University of Technology and Design*)

The urge to capture complex phenomena in complex systems has led to the rapid development of higher-order networks that encode multi-way interactions among nodes. Particularly, the recent application of a higher-order model in Kuramoto Models (KM) gives interesting observations of the presence of explosive synchronisation. The key idea behind this novel feature of the dynamics lies in the topological structure of higher-order networks, which is modelled as a simplicial complex or, more generally, a hypergraph. Here, we use quantum topological information processing to estimate order parameters in this dynamical system.

II.2 Statistical entropy of quantum systems

Presenter: **Smitarani Mishra** (*Indian Institute of Technology (IIT), Tirupati*)

Let D_1 and D_2 be the Hilbert space dimensions of two subsystems of a quantum system of total Hilbert space dimension $D = D_1 D_2$. In the thermodynamic limit (with $1 \ll D_1 \ll D_2$), we know from the works of Page and Sen that the average von Neumann (VN) entropy of the first subsystem is $\mathbb{E}(S^{sb}_{VN}) = \ln(D_1) + O(D_1/D_2)$ if the full system is in a random pure state. Here, it is argued that this result can be strengthened for a thermalized quantum system. Consider the subspace $\mathscr{H}_E$ of the total Hilbert space corresponding to a narrow shell around the energy E. We find that the result of Page and Sen holds for each of these subspaces, that is, the VN entropy, when averaged over the states in $\mathscr{H}_E$, is given by $\overline{S}^{sb}_{VN} \approx \ln \widetilde{d}_1$, where $\widetilde{d}_1$ represents the dimension of the effective Hilbert space of the first subsystem relevant to $\mathscr{H}_E$. If $d_E = \dim(\mathscr{H}_E)$, we estimate that $\widetilde{d}_1 = D_1^{\gamma}$, where $\gamma = \ln(d_E)/\ln(D)$. This finding has significant implications, as it suggests an equivalence between the VN entropy and the thermodynamic (TH) entropy of a subsystem within a much larger thermalized quantum system. For completeness, we also discuss in this work the issue of equivalence between the VN entropy and TH entropy for isolated system (as a whole) and open system. For numerical demonstration of our important results, we here consider a one-dimensional spin-1/2 chain with next-nearest neighbor interactions.

II.3 Quantum thermal machines in black hole spacetime

Presenter: **Dimitris Moustos** (*Newcastle University*)

We study an Otto thermodynamic cycle where the working medium is a qubit Unruh-DeWitt detector interacting with a massless, conformally coupled scalar field in the Hartle-Hawking vacuum of a (2+1)-dimensional BTZ black hole spacetime. The thermal properties of the field are employed to model the heat and cold reservoirs driving the cycle. Treating the detector as an open quantum system, we use a master equation to study its finite-time dynamics during each cycle stroke. We evaluate the output performance of the Otto heat engine and refrigerator by computing, respectively, the total work output and the cooling power. Additionally, we evaluate the optimal performance of the thermal machine by analyzing its efficiency at maximum power output and ecological impact. Our study presents a general framework for understanding the finite-time operation of relativistic quantum thermal machines, focusing on their energy optimization.

II.4 Integrable Path to Fast and Stable Quantum Batteries

Presenter: **Hanlin Nie** (*Centre for Quantum Technologies, Singapore*)

We introduce two integrable fermionic spin-$\frac{1}{2}$ chains that provide a genuine extensive quantum advantage in battery charging. Exact closed-form solutions reveal that boundary- and mediated-hopping Hamiltonians can realize near-N^2 charging power while remaining compatible with quantum speed limits. By further incorporating weighted couplings (without breaking integrability) or harnes collective noise, we stabilize both stored energy and ergotropy, thereby suppressing the large discharge oscillations typical of integrable dynamics. These findings, valid at arbitrarily large system sizes, establish a rigorous and experimentally testable framework for fast and robust quantum batteries.

II.5 Efficient measure of information backflow with quasi-stochastic process

Presenter: **Kelvin Onggadinata** (*Nanyang Technological University*)

Characterization and quantification of non-Markovian dynamics in open quantum systems is a topical issue in the rapidly developing fields of quantum communication and quantum computation. A standard approach, based on the notion of information backflow, detects the flow of information from the environment back to the system. Numerous measures of information backflow have been proposed using different definitions of distinguishability between pairs of quantum states. These measures, however, require optimization over the state space, which can be analytically challenging or numerically demanding. Here, we propose an alternative witness and measure of information backflow that is explicitly state-independent by utilizing the concept of quasiprobability representation and recent advances in the theory of majorization for quasiprobabilities. We illustrate its applicability through several paradigmatic examples, demonstrating consistent non-Markovian conditions with known results and reported the necessary and sufficient condition for a qutrit system in a random unitary channel. Furthermore, the witness provides insights on the reversibility of a process leading to the backflow of information and the connection with negativity.

II.6 Promoting Fluctuation Theorems into Covariant Forms

Presenter: **Jihui Pei** (*Peking University*)

The principle of covariance, a cornerstone of modern physics, asserts the equivalence of all inertial frames of reference. Fluctuation theorems, as extensions of the second law of thermodynamics, establish universal connections between irreversibility and fluctuation in terms of stochastic thermodynamic quantities. However, these relations typically assume that both the thermodynamic system and the heat bath are at rest with respect to the observer, thereby failing to satisfy the principle of covariance. In this study, by introducing covariant work and heat that incorporate both energy-related and momentum-related components, we promote fluctuation theorems into covariant forms applicable to moving thermodynamic systems and moving heat baths. We illustrate this framework with two examples: the work statistics of a relativistic stochastic field and the heat statistics of a relativistic Brownian motion. Although our study is carried out in the context of special relativity, the results can be extended to the nonrelativistic limit. Our work combines the principle of covariance and fluctuation theorems into a coherent framework and may have applications in the study of thermodynamics relevant to cosmic microwave background as well as the radiative heat transfer and noncontact friction between relatively moving bodies.

II.7 Physical implementations of Petz map for single-qubit decoherence channel.

Presenter: **Wen Han Png** (*Centre for Quantum Technologies, Singapore*)

This work investigates the physical implementation of the Petz map for a single-qubit decoherence channel, specifically focusing on dephasing, amplitude damping, and the depolarizing channel. We construct the unitary operations of the Petz map for a single-qubit channel with an ancillary qubit. The two-qubit Petz unitary is adapted to a qubit-quantum harmonic oscillator (QHO) system, and the validity of this adaptation is discussed. The study further extends the investigation of the Petz map to the decoherence of a marginal state of a Bell state, providing the entanglement fidelity for the corresponding Petz maps. Inspired by dynamical decoupling, we also explore the existence of universal sequence of Petz maps that may recover a non-pure single-qubit state without prior knowledge of the error.

II.8 Measurement and feedback-driven adaptive dynamics in the classical and quantum kicked top

Presenter: **Mahaveer Prasad** (*Singapore University of Technology and Design*)

In classical dynamical systems, a chaotic map can be stochastically controlled onto unstable periodic orbits leading to controlled and uncontrolled phases as a function of the rate at which the control is applied. Recent work on classical and quantum Bernoulli maps demonstrates that these control transitions persist in the quantum regime, where local measurements and unitary feedback serve as quantum proxies for classical control. This work applies these control protocols to the classical and quantum kicked top model, a paradigmatic model of quantum chaos. A key feature of this model is its manifestation of classical, semiclassical, and quantum dynamics, with wave packet interference evident after the Ehrenfest timescale. The interplay of control protocols with quantum interference effects offers an intriguing playground to test the controllability of quantum chaotic dynamics in the presence of these effects. Such stochastic control has not been investigated for Hamiltonian dynamics lacking analytical knowledge of fixed points or periodic orbits. We show that the classical and quantum dynamics of the kicked top can be controlled using stochastic protocols, and the spin size is the effective $\hbar$ parameter that interpolates between the classical, semi-classical, and quantum limits controlled via the Ehrenfest time scale. One of the striking results of this work is that the control protocols can tame the quantum interference effects on their way to controlling the quantum dynamics.

II.9 Advanced collision models for Quantum Energetics in Quantum Technologies

Presenter: **Samyak Pratyush Prasad** (*Centre for Quantum Technologies, Singapore*)

Waveguide QED refers to the physics of quantum emitters coupled to reservoirs of light modes confined in one dimension, such as superconducting and photonic circuits [1,2]. Owing to constant technological improvements it is now possible to measure the state of the light with high efficiency. These new experimental capacities mandate to update theoretical tools, to close formerly open quantum systems. This is the purpose of Autonomous Collisional Models (ACM). They model the emitter-field interaction as repeated interactions in a closed manner, with no external influence. An ACM captures the unitary dynamics of the emitter and the light modes, unlocking access to their correlations. Moreover, they are energy-conserving and give rise to a thermodynamics framework with symmetric and accurate energy balances between quantum systems. In this talk, we build an ACM to describe a qubit coupled to a displaced thermal field - the regime of the Optical Bloch Equations (OBE) [3]. We track fundamental correlations created within each collision and find that each sub-system is driven by an effective

Hamiltonian while a remnant term captures the effect of the correlations. They respectively impact the field amplitude and fluctuations, resulting in a physically observable splitting. We explore the thermodynamic consequences of our framework by developing a general paradigm [4,5,6,7] valid for any isolated bipartite system, i.e., bipartite quantum energetics (BQE) [8]. Exploiting global energy conservation, we define work-like (heat-like) flows as the energy changes stemming from the effective Hamiltonian dynamics (the dynamics induced by the correlations). We show that these quantities are accessible through dyne or spectroscopic measurements [9]. Our approach yields a tighter expression of the second law that we quantitatively relate to the extra knowledge about the field, compared with usual treatment of the emitter as an open system. Moreover, to extract intuitions, we apply BQE to refrigeration processes, that we model via a two-mode interaction between fields. It reveals that the energies exchanged are directly measurable in the fields' phase-space distributions. We find that the field is deformed whenever heat-like energy is exchanged, while displacements are caused through transfer of work-like energy. We again find a tightening of the second law and show that squeezing can transfer heat from a colder to a hotter field, while maintaining a positive entropy production. The concepts and effects we introduce deepen our understanding of thermodynamics in the quantum regime and its potential for energy management at quantum scales.[1] Loredo, J. C., et al. "Generation of non-classical light in a photon-number superposition." Nature Photonics 13.11 (2019): 803-808.[2] Gu, Xiu, et al. "Microwave photonics with superconducting quantum circuits." Physics Reports 718 (2017): 1-102. [3] Elouard, Cyril, et al. "Thermodynamics of optical Bloch equations." New Journal of Physics 22.10 (2020): 103039. [4] Weimer, Hendrik, et al. "Local effective dynamics of quantum systems: A generalized approach to work and heat." Europhysics Letters 83.3 (2008): 30008.[5] Hossein-Nejad, et al. "Work, heat and entropy production in bipartite quantum systems." New Journal of Physics 17.7 (2015): 075014. [6] Monsel, Juliette, et al. "The energetic cost of work extraction." Physical review letters 124.13 (2020): 130601.[7] Maffei, Maria, et al. "Probing nonclassical light fields with energetic witnesses in waveguide quantum electrodynamics." Physical Review Research 3.3 (2021): L032073.[8] Prasad, Samyak Pratyush, et al. "Tracking light-matter correlations in the Optical Bloch Equations: Dynamics, Energetics" arXiv preprint arXiv:2404.09648 (2024). [9] Maillette de Buy Wenniger, I., et al. "Experimental analysis of energy transfers between a quantum emitter and light fields." Physical Review Letters 131.26 (2023): 260401.

II.10 Dephasing enabled charging of multiple quantum batteries

Presenter: **Chayan Purkait** (*Zhejiang University*)

An efficient method of fast charging a quantum battery by driving and controlling the charger's dephasing was recently proposed [1]. A weak dephasing of the charger results in coherent under-damped oscillations of the battery's energy, whereas a high dephasing results in quantum Zeno freezing of the charger's energy, inhibiting energy transfer to the battery. An optimal dephasing rate between these two regimes helps us get faster battery charging. In the present work, we explore the charging of multiple quantum batteries in the setup of a central spin system. The central spin serves as a charger, which is driven and also experiences dephasing, and all the surrounding spins play the role of batteries. We show how the extractable form of energy of the total charge of the battery can be improved with an increasing number of batteries. We discuss further the behavior of the battery from the perspective of the correlation between the charger and the battery.

II.11 Exploring quasiprobability approaches to quantum work in the presence of initial coherence: Advantages of the Margenau-Hill distribution

Presenter: **Haitao Quan** (*Peking University*)

In quantum thermodynamics, the two-projective-measurement (TPM) scheme provides a successful description of stochastic work only in the absence of initial quantum coherence. Extending the quantum work distribution to quasiprobability is a general way to characterize work fluctuation in the presence of initial coherence. However, among a large number of different definitions, there is no consensus on the most appropriate work quasiprobability. In this article, we list several physically reasonable requirements including the first law of thermodynamics, time-reversal symmetry, positivity of second-order moment, and a support condition for the work distribution. We prove that the only definition that satisfies all these requirements is the Margenau-Hill (MH) quasiprobability of work. In this sense, the MH quasiprobability of work shows its advantages over other definitions. As an illustration, we calculate the MH work distribution of a breathing harmonic oscillator with initial squeezed states and show the convergence to classical work distribution in the classical limit. Ref. Ji-Hui Pei, Jin-Fu Chen, and H. T. QuanPhys. Rev. E 108, 054109 (2023)

II.12 Optimal Landauer Erasure in Finite-Time Thermodynamics

Presenter: **Alberto Rolandi** (*Technical University of Vienna*)

I will present multiple approaches to obtain finite-time bounds on the thermodynamic cost of the erasure of information. With the framework of geometric thermodynamics we can obtain the minimal amount of energy that has to be dissipated into the environment during a slow out-of-equilibrium thermodynamic process. We apply this framework to different erasure scenarios that give us insight into a fundamental bound on the cost of finite-time erasure and the third law of thermodynamics.

II.13 Probing Bilayer Superfluid with 2D Bose Gases.

Presenter: **Erik Rydow** (*University of Oxford*)

We use ultracold gases trapped in multiple-RF-dressed potentials [1] to experimentally study such coupled bilayer systems where thermal excitations are naturally expressed in terms of shared properties of both layers, i.e., the relative and common phases of coupled Bose gases. We prepare a bilayer system of two 2D Bose condensates with a variable interlayer coupling strength and probe the spatial coherence of both the relative and common phase using matter wave interferometry and density noise measurements. This allows us to investigate the physics of strongly coupled bilayers, providing an avenue to detect and study the dynamics of an anti-symmetric superfluid phase, a possible mechanism for high-temperature superconductivity [2]. In addition to coupled bilayer physics, I will also present preliminary data demonstrating how the BKT critical point shifts when introducing speckle disorder of varying strength.[1] Sunami, Shinichi, et al. Physical Review Letters 128.25 (2022): 250402.[2] Homann, Guido, et al. Physical Review Letters 132.9 (2024): 096002

II.14 Thermalization in open many-body systems and KMS detailed balance

Presenter: **Matteo Scandi** (*Instituto de Física Teórica (IFT)*)

A key question in statistical mechanics is how macroscopic irreversibility emerges from microscopic reversible dynamics. In quantum systems, this transition is often modeled using master equations that rely on the rotating wave approximation (RWA), such as Davies' construction, which satisfies GNS detailed balance. However, the RWA breaks down in many-body systems due to their dense energy spectra, making such models inadequate for realistic thermalization scenarios. In this work, we derive a quantum master equation from first principles that remains valid for many-body systems and satisfies KMS detailed balance—a weaker yet physically meaningful condition that ensures convergence to the Gibbs state. Our approach bypasses the RWA and is inspired by recent dissipative quantum algorithms for Gibbs state preparation. We show that the resulting Lindbladian dynamics not only reproduces thermal equilibrium but also approximates the true system evolution with an error that grows only linearly in time—significantly improving upon previous bounds. This master equation provides a rigorous and physically grounded model for quantum thermalization in many-body systems, bridging a gap in the theory of open quantum systems and offering new insights into non-equilibrium quantum dynamics.

II.15 Asymptotic Fate of Continuously Monitored Quantum Systems

Presenter: **Finn Schmolke** (*Institute for Theoretical Physics, Universität Stuttgart*)

A quantum trajectory is the natural response of a quantum system subject to external perturbations due to continuous indirect measurement. We completely characterize the asymptotic behavior of continuously monitored quantum systems in arbitrary finite dimensions and show that generically, spontaneous irreversible localization transitions on the level of individual realizations occur, where the evolution becomes effectively constrained to one of the irreducible components of the total Hilbert space. More generally, localization can be either complete, where the strongest possible confinement is achieved, or incomplete, where localization terminates prematurely. The full description contains, but is not restricted to, asymptotic purification, the abelian structure of symmetries, and classical noise. On the trajectory level, symmetries and conserved quantities are no longer respected and localization transitions occur concurrently with violations of ergodicity. As a result, a generalized update rule emerges, that effectively projects the system onto one of several possible time evolutions. The update comes equipped with a generalized Born rule that assigns probabilities to these irreversible events. Spontaneous transitions thus occur probabilistically and can deviate considerably from the behavior of the ensemble. In particular, time and ensemble average no longer commute which gives rise to global violations of ergodicity, while on a local level, ergodicity can be restored. We show that these violations are captured by the mean fidelity between the time and ensemble averaged states, resulting in a participation ratio which depends solely on the effective distribution of the initial state over the substructures of the Hilbert space. We explicitly illustrate the asymptotic behavior of continuously monitored systems in a series of examples demonstrating, among other phenomena, stabilization of many-body scar states and generation of Bell states from local measurement. Finally, we present an algorithm that identifies all the minimal orthogonal subspaces of the Lindblad equation and all the extremal stationary states which are supported on them.

II.16 Crooks Fluctuation Theorem for Random Density Matrices

Presenter: **Charlie Shakeshaft** (*University of Manchester*)

We study the non-equilibrium work distributions of mixed quantum states sampled randomly from the set of density matrices. By sampling according to a unitarily invariant measure such as the Hilbert-Schmidt or Bures-Hall ensembles of random matrices, we derive an analogue of the Crooks fluctuation theorem for ensembles of states driven out of equilibrium via a time-reversal invariant Hamiltonian protocol. A Crooks relation holds for (i) microcanonically distributed mixed states with fixed energy expectation values $\mathrm{Tr}[H_0\rho] = E$, and (ii) canonically distributed mixed states with a continuous Gibbsian measure. The work cumulants for the two-level Rabi model are computed, and we compare and contrast the predictions when sampling from different choices of random state ensembles. As a second example we study a quench process applied to a pair of non-interacting spins, where an interaction between them is suddenly switched on, and investigate signatures of criticality in the work fluctuations.

II.17 Lorentz Transformation of the Energy Spectrum of the Equilibrium State of Massive Free Fields

Presenter: **Tingzhang Shi** (*Peking University*)

In previous studies of relativistic thermodynamics, the temperature of a static system, as perceived by a moving observer, has traditionally been treated as a scalar. This assumption has also been extended to the research on the cosmic microwave background. However, the validity of this assumption is a consequence of the massless nature of photons. More generally, when an observer is in relative motion to a system, the thermal equilibrium state is characterized by a four-vector temperature. In this article, we study the non-interacting massive Bosonic and Fermionic field systems. We derive the Lorentz transformation of the energy spectral density in the equilibrium state of these fields. In the massless limit for bosonic field, our results recover the transformation of black body radiation [G. W. Ford and R. F. O'Connell., Phys. Rev. E, 88,044101(2013)], which corresponds to a scalar temperature with dipole anisotropy. For the massive fields, the moving equilibrium state cannot be characterized by a corresponding scalar temperature. This result shows the necessity of introducing four-vector temperature in relativistic thermodynamics.

II.18 Concentration of Athermality

Presenter: **Peter Sidajaya** (*Centre for Quantum Technologies, Singapore*)

The central role of athermal resources in quantum thermodynamics leads to the question of whether they can be concentrated into a single copy using energy-preserving unitaries. Here, we explore this problem for two-qubit systems, identifying the optimal method for concentrating athermality and analysing the usefulness of concatenating multiple concentration steps to further concentrate athermality. We determine the necessary conditions on both the state and the unitary operation and examine the role of quantum coherence in the process. Finally, we discuss the implications for deterministic work extraction and other applications.

II.19 Conditions of Tabletop Reversibility: when can a Petz recovery map be implemented in a cost-effective way?

Presenter: **Min Jeong Song** (*Centre for Quantum Technologies, Singapore*)

A Petz recovery map offers a near optimal recovery although open quantum dynamics are inherently irreversible. However, its experimental implementation has been found challenging due to its innate complex definition. In this work, we present conditions when the Petz recovery map can be realized in not only experiment friendly but also cost effective way.

II.20 Operational constraints in quantum Otto engines: Interplay of energy-gap modulation and majorization

Presenter: **Sachin Sonkar** (*Indian Institute of Science Education and Research (IISER), Mohali*)

We study constraints on the performance of a quantum Otto engine based on modulation of energy gaps compatible with the relative changes in probability distributions at the two given heat reservoirs. We observed that a well-defined change in energy gaps aligns with the majorization relation, thus characterizing the operation of the engine. A detailed analysis of a three-level system as a working medium reveals that an Otto engine is feasible if at least one energy gap shrinks during the first quantum adiabatic stage. The operating regimes are derived for the allowed energy gap modulations. Otto efficiency is enhanced when the probability distributions fulfill the majorization condition. Finally, we show that our formalism applies to swap engine operations with a working medium composed of two three-level systems.

II.21 Geometric Bound for Trade-off Relation in Quantum Tricycle

Presenter: **Shanhe Su** (*Xiamen University*)

In this work, we establish a finite-time external field-driven quantum tricycle model. Within the framework of slow driven cycle, the perturbation expansion of heat in powers of time can be derived during the heat exchange processes. Besides, we explore the geometric bounds for trade-off relations in quantum tricycles, specifically focusing on the implications of thermodynamics in slow dynamics. By examining the interplay between thermodynamic length and thermodynamic processes, we derive fundamental limits on the efficiency and performance of quantum tricycles. Our findings demonstrate that the geometric framework serves as a powerful tool for understanding the trade-offs between energy dissipation and the speed of thermodynamic processes. This research not only enhances our broader understanding of quantum thermodynamics but also provides valuable insights for future advancements in quantum technologies.

II.22 Bayesian retrodiction of the isothermal drive

Presenter: **Yi Da Tan** (*National University of Singapore*)

Systems undergoing a driving process while in contact with a heat bath have been known to obey Crooks' fluctuation theorem, with some appropriate definition of the ”reverse driving process”. If viewing the process as some sequence of stochastic and deterministic steps, it is shown here that a composition of Bayesian retrodicted steps as a "reverse driving process" recovers the fluctuation theorem. Crucially, there is not a need for explicit imposition of detailed balance in this method. An alternate scheme of retrodiction is also studied, where the process is retrodicted as a whole instead of at each step. In general, these two schemes do not give the same result and the situations where they can be equal are explored.

II.23 On the Two-Scenario Relativistic Quantum Heat Engine

Presenter: **Muhammad Taufiqi** (*Institut Teknologi Sepuluh Nopember*)

This work evaluates a two-scenario relativistic quantum heat engine as an extension of our previous study in [10.4236/jamp.2016.47144]. In that study, two fermions were used as the working substance. However, the evaluation treated the two particles semi-classically. Here, we modify that assumption and recalculate the engine efficiency. Our results show that neither scenario occurs.

II.24 Squeezing light to get non-classical work in quantum engines

Presenter: **Álvaro Tejero** (*Universidad de Granada*)

Light can be squeezed by reducing the quantum uncertainty of the electric field for some phases. We show how to use this purely quantum effect to extract net mechanical work from radiation pressure in a simple quantum photon engine. Along the way, we demonstrate that the standard definition of work in quantum systems is not appropriate in this context, as it does not capture the energy leaked to these quantum degrees of freedom. We use these results to design an Otto engine able to produce mechanical work from squeezing baths, in the absence of thermal gradient. Interestingly, while work extraction from squeezing generally improves for low temperatures, there exists a nontrivial squeezing-dependent temperature for which work production is maximal, demonstrating the complex interplay between thermal and squeezing effects.

II.25 Path integral approach to work beyond the two-point measurement scheme

Presenter: **Nicolás Torres Domínguez** (*Chalmers University of Technology*)

The conventional approach to characterize work statistics in driven quantum systems is the two-point measurement scheme (TPMS), where work is defined as the difference between two projective energy measurements performed at the beginning and end of an evolution protocol. This scheme has been shown to be consistent with classical stochastic thermodynamics [1], and to enable the identification of a work functional that converges to its classical counterpart in the semiclassical limit [2].

Despite its importance, since the initial projective energy measurement suppresses coherences in the initial state, the TPMS is not suited to assess the role of initial coherence in quantum thermodynamics. In this work we present a path integral formulation of two alternative schemes that preserve initial coherences and are consistent with the TPMS for incoherent states described by quasi-probability distributions: i) the Margenau-Hill (MH) scheme [3], where the explicit introduction of the initial projective measurement is avoided introducing an estimation of the initial Hamiltonian based on end projective measurements only, and ii) the so-called full counting statistics scheme [4], where the characteristic function is related to the phase accumulated by a detector coupled to the system.

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II.26 Dynamics of first-order phase transition in quantum tilted Ising model

Presenter: **Chiao Wang** (*Peking University*)

We studied the dynamics of first-order phase transitions in the quantum tilted Ising model. We found that when a first-order phase transition occurs from one ferromagnetic state to another at a finite speed, the point at which the double-well potential transforms into a single-well potential is crucial. The behavior of the system near this point resembles that of a second-order phase transition. An effective Hamiltonian and critical exponents can be introduced, and an extra work scaling was observed. Numerical simulations support our findings.

II.27 Quantum thermodynamics of adiabatic processes

Presenter: **Gentaro Watanabe** (*Zhejiang University*)

Adiabatic processes, processes during which a system does not exchange heat with its environment, are fundamental in thermodynamics. In stochastic thermodynamics of classical systems, adiabatic processes are described by the system's Hamiltonian dynamics. Similarly, in quantum thermodynamics, such processes are conventionally modeled as unitary evolution governed by the system Hamiltonian. In the present work, we explore the possibility of a new class of adiabatic processes in quantum systems, where there is no heat exchange with the environment, yet the system is not isolated and undergoes non-unitary evolution. We further discuss the implications of this new class of adiabatic processes on the performance of quantum thermodynamic systems.

II.28 Stochastic Physical Neural Networks

Presenter: **Matt Woolley** (*UNSW Canberra*)

Machine learning algorithms have demonstrated a significant and growing technological impact. A learning machine, by contrast with a machine learning algorithm, is an analogue physical system that learns. The study of physical learning machines may provide insight into the dynamics and thermodynamics of learning, while also suggesting pathways to energy-efficient implementations of learning. One type of learning machine developed recently is a so-called physical neural network, a machine in which the weights, inputs, and neurons of the network are physical rather than digital. We consider learning in physical neural networks where the neurons are implemented as stochastic switches; that is, stochastic physical neural networks. The dynamics of the neuron weights and biases are described in both discrete-time and continuous-time via stochastic difference equations and differential equations, respectively. The learning (that is, weight and bias update) is implemented by feeding back the labelled training data and physical stochastic switch output onto the drift term in the weight and bias dynamics. This provides both an elementary framework for incorporating noise into a physical neural network model and a plausible model of physical implementations. Possible quantum photonic implementations of stochastic switches as elements of stochastic physical neural networks are given. Physics-aware training of a stochastic physical neural network is studied analytically and numerically, working through canonical problems: learning the NOT and XOR gates, vowel classification, and handwritten digit recognition trained with the MNIST dataset. Backpropagation-free training of a stochastic physical neural network is also studied. Physics-aware training of a stochastic physical neural network with a classification accuracy above 90% for more than five trials on the MNIST-trained model was achieved. This performance demonstrates the potential capability of intrinsically noisy and quantum-limited physical systems to complement current implementations of deep neural networks on conventional digital computers.

II.29 Performance Limits of Quantum Systems under Feedback Control

Presenter: **Hayato Yunoki** (*The University of Tokyo*)

Quantum feedback control regulates quantum dynamics by applying control operations based on measurement outcomes. This technique is crucial from both practical and theoretical standpoints. Two key trade-off relations in quantum mechanics—quantum speed limit and quantum thermodynamic uncertainty relation—set fundamental bounds on non-equilibrium quantum systems. We formulate these trade-offs within the framework of quantum feedback control using the continuous matrix product state method. Our analytical results include the exact form of quantum dynamical activity under feedback control, which appears as a cost term in the inequalities. Numerical simulations show that feedback control can enhance the quantum speed and measurement accuracy. We also explore connections to quantum error correction as an application. Our findings highlight the role of feedback in optimizing fundamental performance limits in quantum systems.

II.30 Noise induced Quantum Mpemba effect

Presenter: **Mingrui Zhao** (*University of Science and Technology of China*)

Being an intriguing anomalous relaxation phenomenon, quantum mpemba effect(QMPE) has gain a lot of attention recently. It has been widely analyzed for open quantum system under the hypothesis that the effect of environment can be seen as white noise, which allow people to use Markovian quantum master equation. However, diverse non-Gaussian noises (e.g., telegraph noise)in realistic systems may significantly alter relaxation dynamics. A critical open question is whether such noise can induce or eliminate QMPE, challenging the Markovian paradigm. Here we study the relaxation dynamics of an open quantum system under the influence of telegraph noise and show that quantum Mpemba effect can be both induced and eliminated after applying the external noise. It is due to the deceleration effect induced by the extra mode of the system dynamics introduced by external noise, which is totally different from the usual picture. Also, we find that this effect can lead to deceleration of decoherence process. The conditions under which external noise can induce or eliminate the quantum Mpemba effect are presented simultaneously.