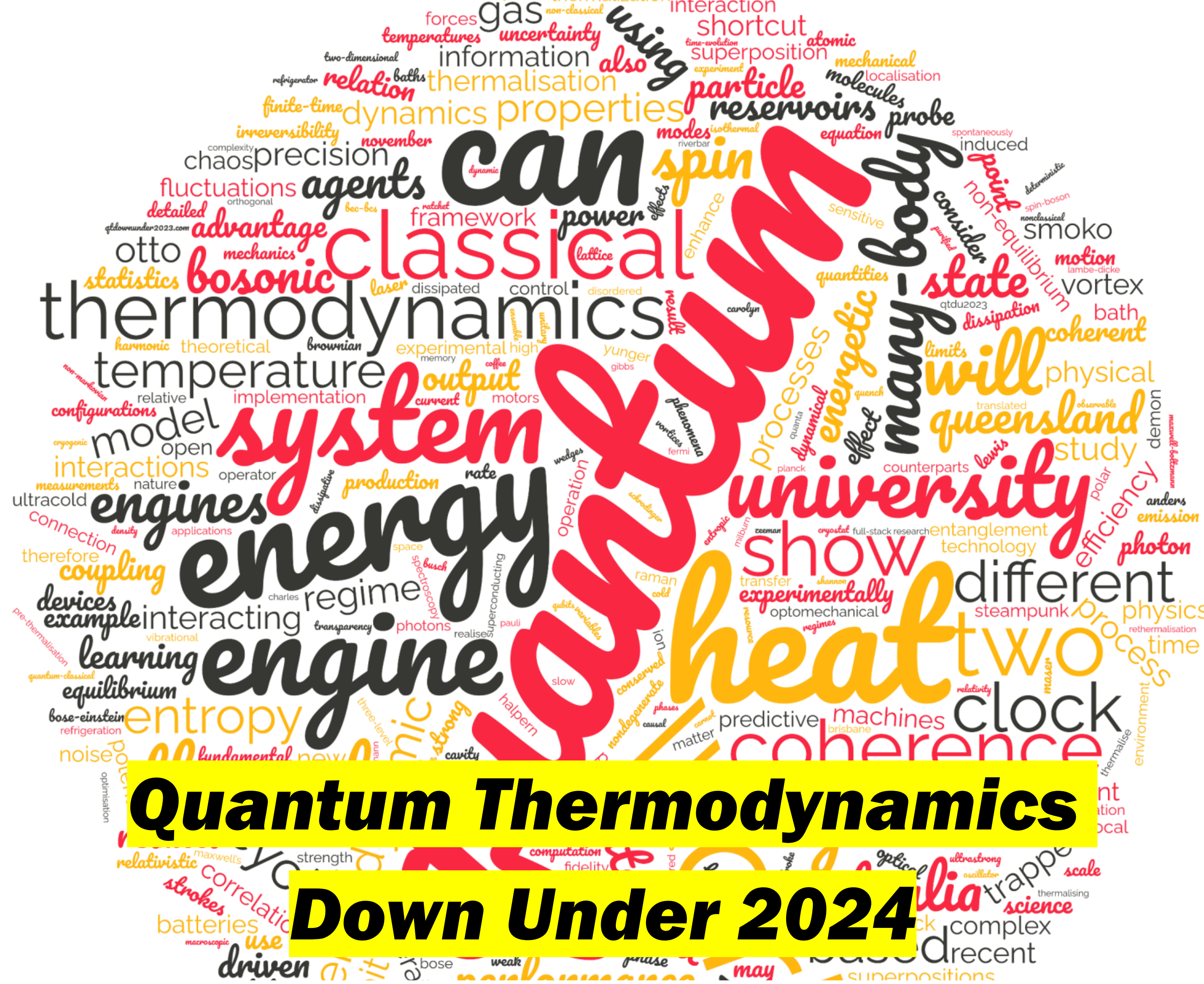

Quantum Thermodynamics Down Under 2024

The University of Queensland (City Campus),
Brisbane, Australia

12th –15th November 2024

qtdownunder2024.com

Welcome to QTDU2024!

How do notions of heat and irreversibility emerge from unitary microscopic dynamics? Can distinct quantum features such as entanglement or coherence improve heat engine operation? Can a fundamental understanding of thermodynamics at the quantum scale inspire new technologies, or help improve existing technologies?

These are all important questions in the emerging field of Quantum Thermodynamics. QTDU2024 brings together researchers in this field from around Australia, and abroad, to get to know each other, our work, and to foster new connections and collaborations.

Useful Information

The conference venue is the University of Queensland's City Campus at **308 Queen Street**, Brisbane.

Talks will be held in **Room 1M16**. Enter the building from the Queen Street entrance (see purple arrow right), where staff will greet you and swipe you up to the room.

If at any time you need to get back up to our floor, building staff or members of the organising committee will be able to help. (No swipe card is needed to exit the floor or building.)

Lunch and coffee breaks ("smoko") will be held in the foyer area just outside Room 1M16 (in which the talks are held).

The **conference dinner** will be held at Riverbar & Kitchen, looking out across the Brisbane River.

Wifi will be available during the conference through either:

- **UQ wifi**, for UQ staff,
- **Eduroam**, using the credentials you normally use to connect at your home institution, or
- The **UQ Guest** network, for attendees who cannot connect to the above.

For further information visit this link: https://my.uq.edu.au/information-and-services/information-technology/internet-and-wifi/visitor-and-conference-internet-access

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Sponsors

This conference was made possible by funding from the School of Mathematics and Physics (SMP) at the University of Queensland, and Australian Research Council Centre of Excellence for Engineered Quantum Systems (EQUS).

Code of Conduct

QTDU2024 is committed to providing a discrimination and harassment-free experience for all attendees. All speakers and participants are expected to comply with the EQUS Code of Conduct: https://equs.org/centre-code-conduct.

Timetable[1]

Keynote or Invited Talk · Breaks · Discussions · Social Event

Tuesday, 12th of November

8:00–8:50	Registration	
8:50–9:00	Opening & Welcome	
9:00–10:00	Alexia Auffèves	Quantum energetics: foundations, applications, and back
10:00–10:30	Nathan Shettel	Entropic Cost of Statistical Inference
10:30–11:00	Smoko	
11:00–11:30	Mile Gu	The Thermodynamic Cost of Misaligned Expectations and Its Consequences
11:30–12:00	Kiarn Laverick	Quantum Fluctuation Theorems using Optimal State Estimation
12:00–13:30	Lunch	
13:30–14:30	Federico Cerisola	Exploring nanoscale thermodynamics on suspended carbon nanotubes
14:30–15:00	Liam McClelland	A proof-of-concept memory powered heat engine with trapped Yb+ ions
15:00–15:30	Rose Manakil	Information Erasure with Spin-polarised atoms
15:30–16:00	Smoko	
16:00–17:30	Discussion Time	

Wednesday, 13th of November

8:30–9:00	Arrival	
9:00–10:00	James Quach	Quantum batteries – from information to energy
10:00–10:30	Josephine Dias	Strategies for charging open quantum batteries
10:30–11:00	Smoko	
11:30–12:00	Arnab Mukherjee	Enhancement in the performance of a Unruh-DeWitt battery through velocity tuning
11:00–11:30	Cassandra Bowie	The Quantum Tolman-Ehrenfest effect
12:00–13:30	Lunch	
13:30–14:30	Jayne Thompson	Scaling advantages for quantum thermodynamic advantage in agents
14:30–15:00	Sahil	Post-Markovian master equation via microscopic collisional model
15:00–15:30	William McEniery	Thermally induced correlations in gas of spin-half quantum particles bathed in thermal light
15:30–16:00	Smoko	
16:00–17:30	Discussion Time	

18:00–22:00	Conference Dinner

[1] All times are in Australian Eastern Standard Time (UTC+10)

Thursday, 14th of November

8:30–9:00	Arrival	
9:00–10:00	Masahito Ueda	Roles of locality and range of interactions on quantum thermalization
10:00–10:30	Matthew Davis	Thermalisation of a Spin-1 Bose Gas in a Double-Well
10:30–11:00	Smoko	
11:00–11:30	Lewis Williamson	The Jarzynski equality in a microcanonical ensemble and connections with the Eigenstate Thermalization Hypothesis
11:30–12:00	David Strachan	Non-Markovian Quantum Mpemba Effect
12:00–13:30	Lunch	
13:30–14:30	Dario Poletti	Many-body quantum systems out of equilibrium: relaxation and emergence of steady states
14:30–15:00	Stephen Sanderson	Machine learning a time-local fluctuation theorem for classical nonequilibrium steady states
15:00–15:30	Jesse Slim	Chiral thermal transport induced by optomechanically-mediated synthetic magnetism
15:30–16:00	Smoko	
16:00–17:30	Discussion Time	

Friday, 15th of November

8:30–9:00	Arrival	
9:00–10:00	Karen Kheruntsyan	Glauber's second-order correlation and quantum thermodynamics
10:00–10:30	Vishnu Muraleedharan Sajitha	Thermal machine regimes in the transverse-field Ising model.
10:30–11:00	Smoko	
11:00–11:30	Nicole Luu	Thermodynamic driving of superfluid helium thin films
11:30–12:00	Raymon Watson	A nonequilibrium quantum Otto cycle fuelled by chemical work
12:00–12:30	Wrap Up & Close	
12:30–	Social Activity (TBD)	

Abstracts – Tuesday 12th

Quantum energetics: foundations, applications, and back

Alexia Auffèves
CNRS Grenoble, MajuLab, & National University of Singapore, France & Singapore

Quantum energetics is the study of the flows of energy, entropy and information in the quantum realm. It is a cousin of quantum thermodynamics, but the game does not necessarily involves a temperature. In this talk I will present two fundamental outcomes of the field. Firstly, I will focus on measurement-powered engines and what they teach us about the theory of quantum measurement. Secondly, I will introduce a new framework to analyse energy exchanges between two quantum systems that are otherwise isolated, and present recent experimental results where such analyses were performed. I will conclude on the potential of quantum energetics to bring out meaningful results regarding the energy cost of quantum technologies.

Entropic Cost of Statistical Inference

Nathan Shettel
MajuLab, Center for Quantum Technology, Singapore

Inferring an unknown quantity can be bisected into two tasks: a physical task of measuring an observable(s), and an information theoretic task of transforming the measurement results into an estimate, formally known as estimator [1]. The quality of an estimator is typically gauged by the means of a mathematical tool known as a statistical cost function (e.g. expected mean-squared error). This measure of efficacy is solely dependent on the measurement results, completely overlooking the fact that measurements implicate the use of some sort of physical meter, wherein the preparation, usage and subsequent reset of the meter invokes an energetic cost [2]. This energetic cost is not reflected in the value of the statistical cost function, despite being relevant given real-world limitations of finite resources.

To remedy this absence we propose a framework where the cost of measurements is reflected in the overall assessment of a statistical inference strategy. We attribute the energetic cost of using a meter, and the subsequent reset, to the bounds derived by Sagawa and Ueda: wherein the minimum cost is proportional to the change of entropy of the meter(s) [2]. We showcase our framework with a classical toy-model, where a noisy bit is used to infer the state of a secondary unknown bit: a statistical advantage arises by adopting a more energetically efficient measure-and-reset protocol. Our framework is especially useful for comparing two or more estimators which make use of different measurements. This is common practice in the realm of quantum metrology, where entangling qubits can lead to a statistical advantage [3]. However, the difference in cost of measuring entangled versus separable states is not addressed.

[1] David Roxbee Cox. Principles of statistical inference. Cambridge university press, 2006.

[2] Takahiro Sagawa and Masahito Ueda. Minimal energy cost for thermodynamic information processing: Measurement and information erasure. Physical review letters, 102(25):250602, 2009.

[3] Vittorio Giovannetti, Seth Lloyd, and Lorenzo Maccone. Advances in quantum metrology. Nature photonics, 5(4):222– 229, 2011.

The Thermodynamic Cost of Misaligned Expectations and Its Consequences

Mile Gu
Nanyang Technological University, Singapore

When we make decisions about how best to achieve our goals, we generally do so based on our expectations. For example, when getting from A to B, the expectation of rain induces us to carry an umbrella. Meanwhile, in optimizing communication rates, expecting the letter 'z' to appear rarely in English allows us to encode it in a longer bitstring. However, when our expectations are misaligned with reality, such optimizations reduce efficiency.

References:
Paul Riechers and Mile Gu. "Initial-state dependence of thermodynamic dissipation for any quantum process." Physical Review E 103, no. 4, 042145.
Paul Riechers and Mile Gu. "Impossibility of achieving Landauer's bound for almost every quantum state." Physical Review A 104.1, 012214.
Paul Riechers, C. Gupta, A. Kolchinsky and Mile Gu. Thermodynamically ideal quantum-state inputs to any device. arXiv preprint arXiv:2305.00616. (accepted in PRX Quantum)

Quantum Fluctuation Theorems using Optimal State Estimation

Kiarn Laverick
MajuLab, Center for Quantum Technology, Singapore

In fluctuation theorems, the key idea is to compare how likely a given dynamical process is to occur both forward and backward in time, often leading to an exponential difference in favour of the forward process [1]. Importantly, these theorems reproduce the second law when applied to thermodynamical systems. When moving to a quantum treatment of fluctuation theorems, there have been numerous different approaches [2] depending on the physical scenario. In particular, the approach we are interested in is when we have an open quantum system undergoing an (imperfect) continuous-in-time measurement [3]. In this scenario, the conditional forward-evolving state that is used in the fluctuation theorem is more commonly known, in the field of quantum state estimation, as the filtered state [3]. This state has been shown in recent years [4] to be an optimal Bayesian estimator, that is, it minimizes the expected relative entropy with the actual underlying pure quantum state of the system. While usual approaches [3] to this problem make use of the time-reversal operator to construct the backward-in-time conditional trajectory, from an estimation theory perspective, this is not the optimal way to reverse the conditional dynamics. From the Bayesian estimation theory framework, it is possible to derive [6] such an estimator that minimizes the average relative entropy with the true state, called the "retrofiltered state". With this alternative method for computing the reverse process, it is interesting to see what implications this has on the fluctuation theorem. From an informational perspective, intuition suggests that this estimate will yield a more accurate representation of the likelihood of the reverse trajectory occurring, which when applied to a thermodynamic system, would have interesting implications on the second law.

[1] F. Buscemi and V. Scarani, Phys. Rev. E 103, 052111 (2021)
[2] K. Funo, M. Ueda, and T. Sagawa. "Quantum fluctuation theorems." Thermodynamics in the Quantum Regime: Fundamental Aspects and New Directions (2018): 249-273.
[3] J. M. Horowitz, Phys. Rev. E 85, 031110 (2012).
[4] V. P. Belavkin, Commun. Math. Phys. 146, 611 (1992).
[5] K. T. Laverick, I. Guevara, H. M. Wiseman, Phys. Rev. A 104, 032213 (2021).
[6] K. T. Laverick and H. M. Wiseman, Optimal State Estimation using Past, Future and Past-Future Information, In Preparation.

Exploring nanoscale thermodynamics on suspended carbon nanotubes

Federico Cerisola
University of Exeter, United Kingdom

State of the art nanoscale electromechanical devices provide exciting platforms to explore and test thermodynamics at small scales, where fluctuations dominate and quantum effects become relevant. In particular, suspended carbon nanotubes (CNTs) are a very rich and promising platform which features a wide range of phenomena, from quantised electron transport through quantum dots, to spin qubits and mechanical motion. In this talk, I will discuss recent experiments where we have measured ultra-strong coupling between the charge transport along the CNT and the mechanical motion. Furthermore, through precise measurement of the quantum dot's population and CNT displacement, we estimate the energy and entropy of the different degrees of freedom. In this way, we explore the entropy to energy conversion between the charge state of the dot and the mechanical displacement. A thorough understanding of these exchanges naturally leads to a generalised formulation of the Landauer bound that takes into account the non-equilibrium nature of these devices and strong coupling to the reservoirs. Moreover, the coupling between mechanics and electron transport can lead to non-equilibrium steady states that can exhibit long lived self-sustained oscillations. Finally, I will discuss the first observation of coupling between a spin qubit and mechanical motion of the CNT. We have further developed a detailed theoretical model to understand the origin and nature of this coupling and estimate its strength. The observation of the spin-mechanics coupling further opens the doors to a new range of experimental tests of thermodynamics involving energetic coherences.

A proof-of-concept memory powered heat engine with trapped Yb+ ions

Liam J. McClelland
Griffith University, Australia

Using a trapped $^{171}\mathrm{Yb}^{+}$ ion, we intend on showing that memory can be used as a resource during a heat engine cycle. By coupling the ion's motion with the internal electronic states using stimulated Raman transitions, we can coherently transfer heat energy out of the heat bath through a usable (low-entropy) photon, at the expense of fidelity in the electronic states.

This is a realisation of Maxwell's demon, where the demon's memory of whether or not a particle in a thermally equalised gas passes through a hole in a dividing wall is used as a resource to separate hot and cold particles. In our case, the thermal gas and the demon's memory are represented by the ion's motion and the electron's energy states respectively. Much like the thought experiment, the resetting of the demon's memory keeps our proof-of-concept within the bounds of the second law of thermodynamics.

To prove that such a demon can physically be realised, we intend to: measure the entropy transfer from the heat bath to the electronic state, measure the heat energy converted into usable energy in the form of a higher energy photon, and control and manipulate the trap potential. We utilize techniques including (but not limited to) motional sideband resolved Raman spectroscopy state tomography, machine learning and sub-MHz interferometry to achieve these goals.

Information Erasure with Spin-polarised atoms

Rose Manakil
Griffith University, Australia

We present a novel theoretical framework for information erasure in quantum heat engines using spin-polarized atoms. A Raman laser pulse converts the thermal energy of source atoms into coherent light, serving as useful optical work. This technique involving collisions with a reservoir of spin-polarized atoms, where the erasure of information occurs at the cost of spin angular momentum, leading to a loss of spin polarization of the reservoir. Our framework extends classical thermodynamics to quantum systems, emphasizing multiple conserved quantities. The concept of free entropy is integrated with the Generalized Gibbs Ensemble (GGE), providing a measure of the effective number of accessible microstates when multiple constraints are considered. This relation is essential for understanding the broader entropy landscape and state accessibility in complex quantum systems. The novelty of our approach lies in the separation of spins through a carefully controlled process, ensuring minimal entropy change. Gibbs' theorem, which states that the entropy of a mixture of ideal gases is the sum of the entropies of the individual gases, is crucial in understanding why the total thermodynamic entropy remains unchanged during the spin separation process. This principle is applied to describe the entropy dynamics when erasing information through spin-polarized atoms, highlighting the interplay between energy, particle number, and other conserved quantities. This approach demonstrates how heat can be converted into coherent light with high efficiency, with potential applications in enhancing the performance of quantum heat engines.

Abstracts – Wednesday 13th

Quantum batteries-–from information to energy

James Quach
CSIRO, Australia

Much of recent development in quantum technologies have been built around the quantum advantages afforded through the science of quantum information, such as quantum computers. However, there is a deep connection between information and energy, and so one may envisage adopting these quantum advantages in an energy context to develop novel energetic systems. In this talk I will discuss the link between quantum information and energy, leading to the idea of quantum batteries. I will review the recent developments in quantum batteries and discuss their potential to address future energy challenges and opportunities.

Strategies for charging open quantum batteries

Josephine Dias
The University of Queensland, Australia

With recent advancements in hybrid quantum systems, we can engineer both the system and the environment to perform the task we are interested in. Such hybrid systems can involve many different elements, from solid state to atomic, molecular and optical. Hybrid quantum systems naturally provide a rich environment to study complex phenomena in open quantum systems. Recently, a novel quantum battery protocol utilizing hybrid quantum systems was proposed that achieved super extensive capacity and charging. In this protocol, the quantum battery is an ensemble of spins in contact with a thermal reservoir at some temperature. The charging process is performed by bringing a larger ensemble of spins in the excited state into the reservoir. Through the collective coupling of all the spins, in the charger and the battery, to the reservoir, the spins in the battery relax to the excited state as the entire system reaches its steady state. Interestingly, this effect can happen even if the reservoir is at zero temperature. In this work, we extend upon this novel open quantum battery system to specifically examine some possible strategies for utilizing this protocol to efficiently charge many quantum batteries.

Enhancement in the performance of a Unruh-DeWitt battery through velocity tuning

Arnab Mukherjee
S. N. Bose National Centre for Basic Sciences, Kolkata, India

Investigating the relativistic effect on the performance of a quantum battery through estimating some important parameters in the open quantum framework is the primary concern of this work. For doing so, we consider a Unruh-DeWitt (UDW) detector driven by a coherent classical pulse as a quantum battery. The battery is coupled with a massless quantum scalar field and moving along a trajectory characterized by a combination of a uniformly accelerated motion in the x direction and constant velocities in the orthogonal directions to x. From the results, we found that the accelerated motion degrade the performance of the quantum battery rapidly in the absence of constant velocities in the y and z direction. For a fixed value of acceleration, performance of the battery remains unchanged when we increase the velocity in the nonrelativistic regime. Furthermore, it is also observed that the performance of the quantum battery can be enhanced by tuning the velocities in the relativistic regime.

The Quantum Tolman-Ehrenfest effect

Cassandra Bowie
The University of Queensland, Australia

The Tolman-Ehrenfest effect describes the relationship between local temperature and spacetime curvature when considered in thermodynamic equilibrium. In short, in the presence of gravity, local temperature is not constant at equilibrium, but is instead proportional to the spacetime norm of the timelike Killing vector field. We investigate this phenomena through a two level detector described using Open Effective Field Theories, with emphasis on the notion of thermal time, and application to relativistic quantum heat engines.

Scaling advantages for quantum thermodynamic advantage in agents

Jayne Thompson
A*STAR, Singapore

AI has a growing energy foot print, the energetic cost of generating responses to user input is growing exponentially year on year as we seek to automate ever more complex tasks. Here we discuss interactive protocols which involve an agent interacting with its environment, to execute some task. We discuss the potential to get to smaller scale implementations with a quantum agent, and the capacity for this to change the fundamental lower bounds on the energetic cost of exhibiting a behaviour or executing a task. We show that this leads to quantum agents having fundamentally lower energetic cost to exhibit a particular behaviour, and that the gap between quantum and classical energetic cost can scale unboundedly.

Post-Markovian master equation via microscopic collisional model

Sahil
The Institute of Mathematical Sciences, Chennai, India

We derive a completely positive post-Markovian master equation (PMME) from a microscopic Markovian collisional model (CM) framework, incorporating bath memory effects via a probabilistic single-shot measurement approach. This phenomenological master equation is both numerically tractable and analytically solvable. Depending on the choice of the memory kernel function, the PMME can be reduced to either a non-Markovian or Markovian master equation. We have investigated thermalization using the derived equation and performed a comparative analysis with both Markovian and non-Markovian dynamics. Several physical examples are considered and discussed with the appropriate forms of memory kernel. Our derivation of PMME via CM strengthens the widely believed claim that "collisional model can simulate any quantum dynamics".

Thermally induced correlations in gas of spin-half quantum particles bathed in thermal light.

William McEniery
The University of Queensland, Australia

Densely-spaced dipoles can interact via the collective scattering of photons. These light-mediated interactions may produce correlations between the dipoles, resulting in subradiant and superradiant emission spectra, with broad applications in quantum information and sensing. So far, most of this exploration has focussed on dipoles interacting with coherent light. We show how thermal light can also enhance correlations amongst densely-spaced dipoles. Employing the mean-force Gibbs state formalism [1], we calculate the thermal state of a gas of spin-half quantum particles in a bath of thermal light. We show how thermal light induces interactions between the particles, resulting in correlations that would be absent in a naive calculation of the thermal state of the gas. Our results demonstrate both the potential utility of densely-spaced dipoles driven by thermal light, and the use of the mean-force Gibbs state formalism in studying finite-temperature many-body quantum systems.

[1] J. D. Cresser and J. Anders, Phys. Rev. Lett. 127, 250601 (2021)

Abstracts – Thursday 14th

Roles of locality and range of interactions on quantum thermalization

Masahito Ueda
University of Tokyo, Japan

In this talk, I will address the question of the roles of locality and range of interactions on quantum thermalization. We verify that the eigenstate thermalization hypothesis (ETH) holds for locally interacting quantum many-body systems. We employ random matrix theory to demonstrate that an overwhelming majority of pairs of local Hamiltonians and observables satisfy the ETH. We also test the strong ETH for systems with power-law interactions. We numerically demonstrate that the strong ETH typically holds for systems with the Coulomb, monopole-dipole, and dipole-dipole interactions. However, we find that Srednicki's ansatz for interactions longer than the Coulomb interaction, at least for relatively large system sizes. Finally, we identify rigorous upper and lower bounds on the m-body observables such that all m-body operators with m smaller than a certain value m□ satisfy the ETH in fully chaotic systems. Thermalization of typical systems for any few-body operators is thus rigorously proved.

Thermalisation of a Spin-1 Bose Gas in a Double-Well

Matthew Davis
The University of Queensland, Australia

We consider the dynamics of an isolated spin-1 Bose gas in a double-well potential undergoing a quench from an unmagnetized to a magnetised phase The system is generally nonintegrable, but becomes integrable in the limits that the tunnelling between the wells is either very small or very large. Using exact diagonalisation, we consider how the Eigenstate Thermalization Hypothesis to this system as it transitions from integrability to non-integrability, and examine the signatures of thermalisation and spontaneous symmetry breaking that arise.

The Jarzynski equality in a microcanonical ensemble and connections with the Eigenstate Thermalization Hypothesis

Lewis Williamson
The University of Queensland, Australia

The Jarzynski equality is a prominent fluctuation theorem that connects non-adiabatic work fluctuations to the work output of an isothermal process. The conventional Jarzynski equality assumes the initial state is in a canonical ensemble. We show that the equality does not hold for a system prepared in a microcanonical ensemble. We derive a modified equality that connects microcanonical work fluctuations to entropy production, in an analogous way to the Jarzynski equality, but with reference to an inverse temperature that depends on the path of the work protocol [1]. We then explore what happens as the microcanonical ensemble is reduced to a single quantum state in a system of interacting spins. This system can conveniently be tuned from integrable to non-integrable, providing insights into the role of the Eigenstate Thermalization Hypothesis in fluctuation theorems.

[1] L. A. Williamson, arXiv:2409.10810 (2024)

Non-Markovian Quantum Mpemba Effect

David Strachan
University of Bristol, United Kingdom

Since its rediscovery in the twentieth century, the Mpemba effect, where a far-from-equilibrium state may relax faster than a state closer to equilibrium, has been extensively studied in classical systems and has recently received significant attention in quantum systems. Many theories explaining this counter-intuitive behavior in classical systems rely on memory effects. However, in quantum systems, the relation between the Mpemba effect and memory has remained unexplored. In this work, we consider general non-Markovian open quantum systems and reveal new classes of quantum Mpemba effects, with no analog in Markovian quantum dynamics. Generically, open quantum dynamics possess a finite memory time and a unique steady state. Due to non-Markovian dynamics, even if the system is initialized in the steady state it can take a long time to relax back. We find other initial states that reach the steady state much faster. Most notably, we demonstrate that there can be an initial state in which the system reaches the steady state within the finite memory time itself, therefore giving the fastest possible relaxation to stationarity. We verify the effect for quantum dot systems coupled to electronic reservoirs in equilibrium and non-equilibrium setups at weak, intermediate and strong coupling, and both with and without interactions. Our work provides new insights into the rich physics underlying accelerated relaxation in quantum systems.

Many-body quantum systems out of equilibrium: relaxation and emergence of steady states

Dario Poletti
Singapore University of Technology and Design, Singapore

Large quantum systems typically thermalize, which is in itself a very interesting problem. On their way to thermalization, we show that large quantum systems can manifest different dynamics which can be classified depending on their symmetries and the observables we are considering. We will also present how non-equilibrium steady states can be understood as a prethermal state emerging while the system is on the path towards thermalization, and how this can help their experimental study in today's quantum processors.

Machine learning a time-local fluctuation theorem for classical nonequilibrium steady states

Stephen Sanderson
AIBN, The University of Queensland, Australia

Fluctuation theorems (FTs) quantify the thermodynamic reversibility of a system, and for deterministic systems they are defined in terms of the dissipation function. However, in a nonequilibrium steady state of deterministic dynamics, the phase space distribution is unknown, making the dissipation function difficult to evaluate without extra information. As such, steady state FTs for deterministic systems to date have required either that the trajectory segment of interest is relatively long, or that information is available about the entire trajectory surrounding that segment. In this work, it is shown that a simple machine learning model trained to predict whether a given steady state trajectory segment is being played forward or backward in time calculates a function which satisfies an FT and relies solely on information within the segment of interest. The FT is satisfied even for very short trajectory segments where the approximate relation derived from theory breaks down, for systems far from equilibrium, and for various nonequilibrium dynamics. It is further demonstrated that any function which is a well-calibrated predictor of time's arrow must satisfy an FT, and that a local FT can be derived which depends only on local dissipation and its correlations with the surrounding nonlocal dissipation.

Chiral thermal transport induced by optomechanically-mediated synthetic magnetism

Jesse Slim
The University of Queensland, Australia

Magnetic fields allow nonreciprocal transport of energy by breaking time-reversal symmetry (TRS). In an optomechanical system, modulated radiation pressure allows the generation of strong effective interactions between phonon modes that imprint nonreciprocal Peierls phases, breaking TRS. For mechanical modes coupled in a loop, these interaction phases establish a synthetic magnetic flux, akin to the Aharonov-Bohm effect for electrons.

Here we demonstrate synthetic magnetism for thermal acoustic transport in an optomechanical nanobeam photonic crystal. The nanobeam supports a localized optical resonance at telecom frequency, simultaneously coupled to multiple mechanical overtones at MHz frequencies. Superimposed intensity modulations of a drive laser then enable a flexible, optically configurable nanomechanical network, with tunable hopping interactions between frequency-resolved mechanical modes. In this network, we track the flow of heat by resolving correlations in the optically transduced Brownian motion of the resonators. When a non-trivial flux breaks TRS, we reveal chiral circulation of the thermal fluctuations in the loop. Finally, we utilize the different, frequency-dependent Bose occupations of the thermal baths that couple to the resonators to induce flux-controlled redistribution of thermal energy, heating and cooling.

Our results provide new perspectives to control the thermal environment at the nanoscale and enable fundamental, real-time studies of stochastic thermodynamics and microscopic heat engines.

Abstracts – Friday 15th

Glauber’s second-order correlation and quantum thermodynamics

Karen Kheruntsyan
The University of Queensland, Australia

Glauber’s second-order correlation function plays an important role in the understanding of various phenomena in radio and optical astronomy, quantum and atom optics, high-energy particle physics, condensed matter physics, and quantum many-body theory. However, its relevance to quantum thermodynamics has so far been elusive, given the fact that such a correlation function is simply a two-body observable, also known as the reduced two-body density matrix. In this talk, I will consider examples of many-body quantum systems with short-range interactions, for which Glauber’s local second-order correlation is a thermodynamic quantity and hence becomes relevant to quantum thermodynamic processes and concepts. More specifically, I will discuss quantum many-body thermal machines utilising ultracold atomic gases as their working medium, whose operation is enabled by Glauber’s local atom-atom correlation function. I will also introduce a new set of Maxwell relations that relate the same correlation function to various thermodynamic quantities, such as pressure, entropy, chemical potential, heat capacity, etc. These Maxwell relations offer a new experimental method to deduce these thermodynamic quantities directly from the measurements of atom-atom correlations which are often relatively easy to conduct in ultracold atom experiments. Beyond ultracold atomic gases, the Maxwell relations introduced here can be related to the static structure factor used in the study of condensed matter systems. Finally, I will show how a set of similar Maxwell relations can be derived for a large class of spin Hamiltonians; I will illustrate this for the transverse field Ising model, allowing one to deduce its thermodynamic properties from spin-spin correlations. The Maxwell relations derived here highlight the profound role that the calculation and measurement of particle-particle or spin-spin correlation functions may play in the future for determining the thermodynamic properties of unsolved models of quantum many-body theory, which in turn can help identify novel phases of quantum matter.

Thermal machine regimes in the transverse-field Ising model

Vishnu Muraleedharan Sajitha
The University of Queensland, Australia

We identify and interpret the possible thermal machine regimes with a transverse-field Ising model as the working substance. In general, understanding the emergence of such regimes in a many-body quantum system is hard due to the dependence on the many energy levels in the system. By considering infinitesimal work strokes, we can understand the operation from equilibrium properties of the system. We find that infinitesimal work strokes enable both heat engine and accelerator operation, with efficiencies and boundaries of operation described by macroscopic properties of the system, in particular net transverse magnetization and energy. This understanding generalises to larger work strokes when the temperature difference between the hot and cold reservoirs is sufficiently large. For hot and cold reservoirs close in temperature, a larger work stroke can reverse the flows of heat and refrigerator and heater regimes can emerge. Our results and method of analysis will prove useful in understanding the possible regimes of operation of quantum many-body thermal machines more generally.

Thermodynamic driving of superfluid helium thin films

Nicole Luu
The University of Queensland, Australia

Previously, average thermodynamic properties have limited the measurement of phonon excitations due to dissipation. However, employing cavity optomechanics allows us to study and control phonon-phonon interactions in real time [1]. By utilizing the entropic forces of the superfluid fountain pressure effect in thin films [2], it is possible to optically induce surface waves called third sound. The driving of these waves resembles the mechanics of a microscale thermodynamic heat engine and is quantum-limited to the heat generated by single photon absorption and the cooling power of the cryostat. Through advanced fabrication techniques, we have been able to create a microscale platform for studying thermodynamic fluctuations such as hydrodynamic wave asymmetry and multisolition fission, as well as more chaotic behaviour such as quantized vortices [3].

[1] G. Harris et al., Nature Physics, 12, 788–793 (2016).
[2] A. Sawadsky et al., Science Advances, 21, 9 (2023).
[2] Y. P. Sachkou et al., Science 366, 1480 (2019).

A nonequilibrium quantum Otto cycle fuelled by chemical work

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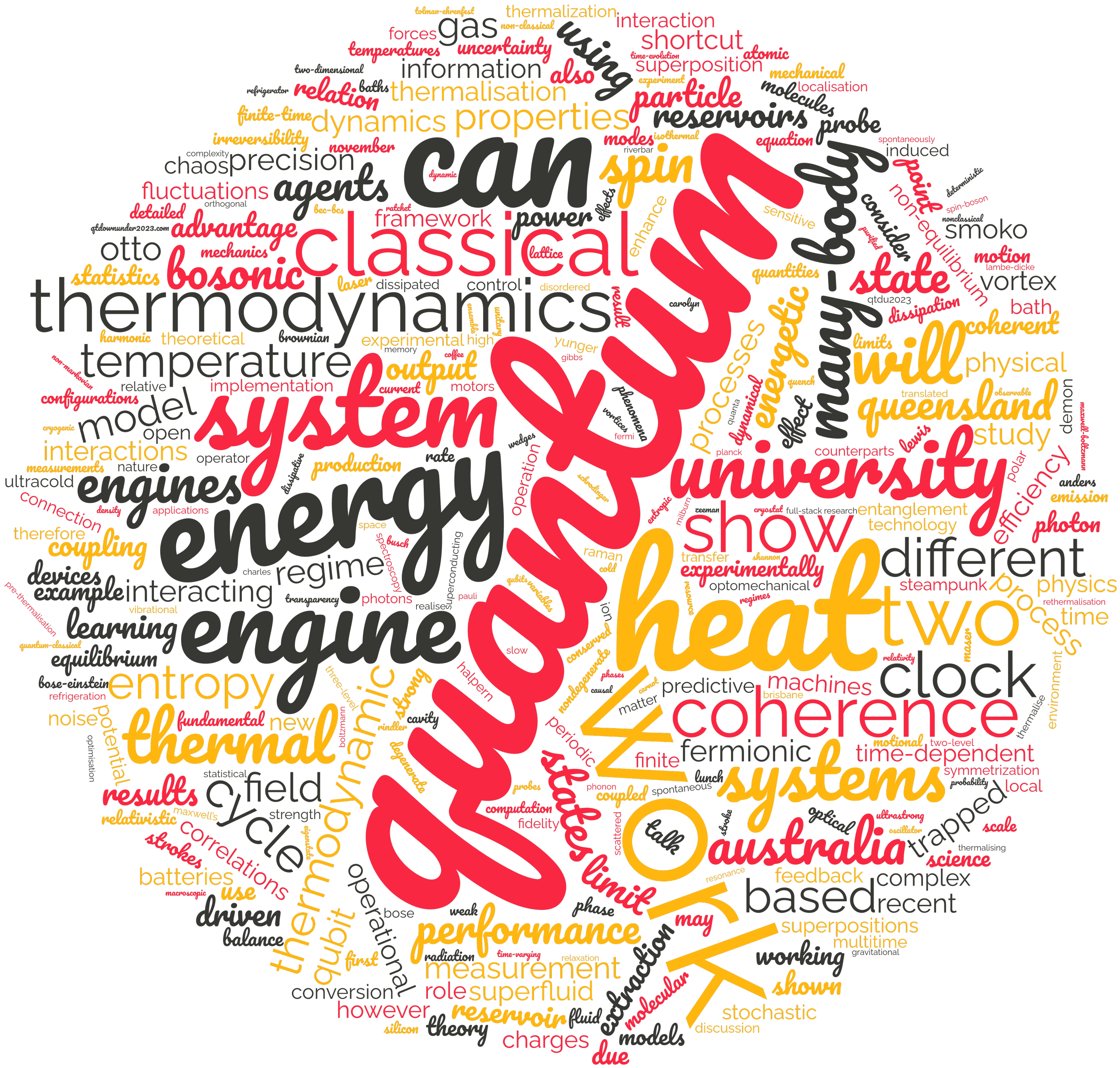
The study of nonequilibrium thermodynamics in many-body interacting systems is often restricted by the complexity of simulating the real-time dynamics of such systems, starting from a finite-temperature thermal equilibrium state. Integrable systems are one of few exceptions to this, with the recently developed theory of generalized hydrodynamics (GHD) capable of capturing the finite-temperature dynamics of integrable and nearly intergrable systems on large scale, and in parameter regimes not accessible by other microscopic theories. We demonstrate the utility GHD to the field of nonequilibrium quantum thermodynamics through its application in an Otto engine cycle for an experimentally realistic harmonically trapped one-dimensional (1D) Bose gas. In particular, we analyse a thermochemical Otto engine cycle where the unitary work strokes are driven by a quench of interactomic interactions, while the equilibration strokes with hot and cold reservoirs are faciliated via diffusive contact that allows for particle exchange. We numerically evaluate the performance of this engine cycle in both the weakly interacting quasicondensate regime and the strongly interacting near-Tonks-Girardeau regime of the 1D Bose gas. We further make connections with two previous studies: one in the limit of a sudden quench where approximate analytic results are known at finite temperatures, and the other in the limit of an adiabatic engine cycle at zero temperature, which in turn provides an upper bound to the net work and efficiency of this engine cycle at nonzero temperatures.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