

Heat and Entropy Management in Superconducting Devices

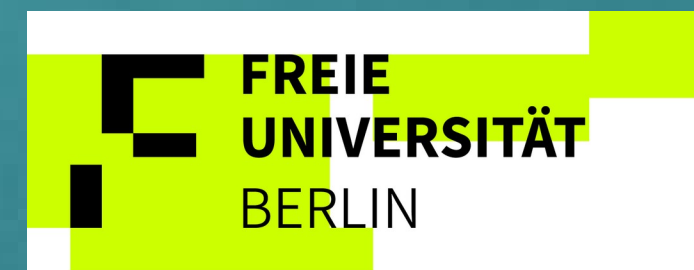
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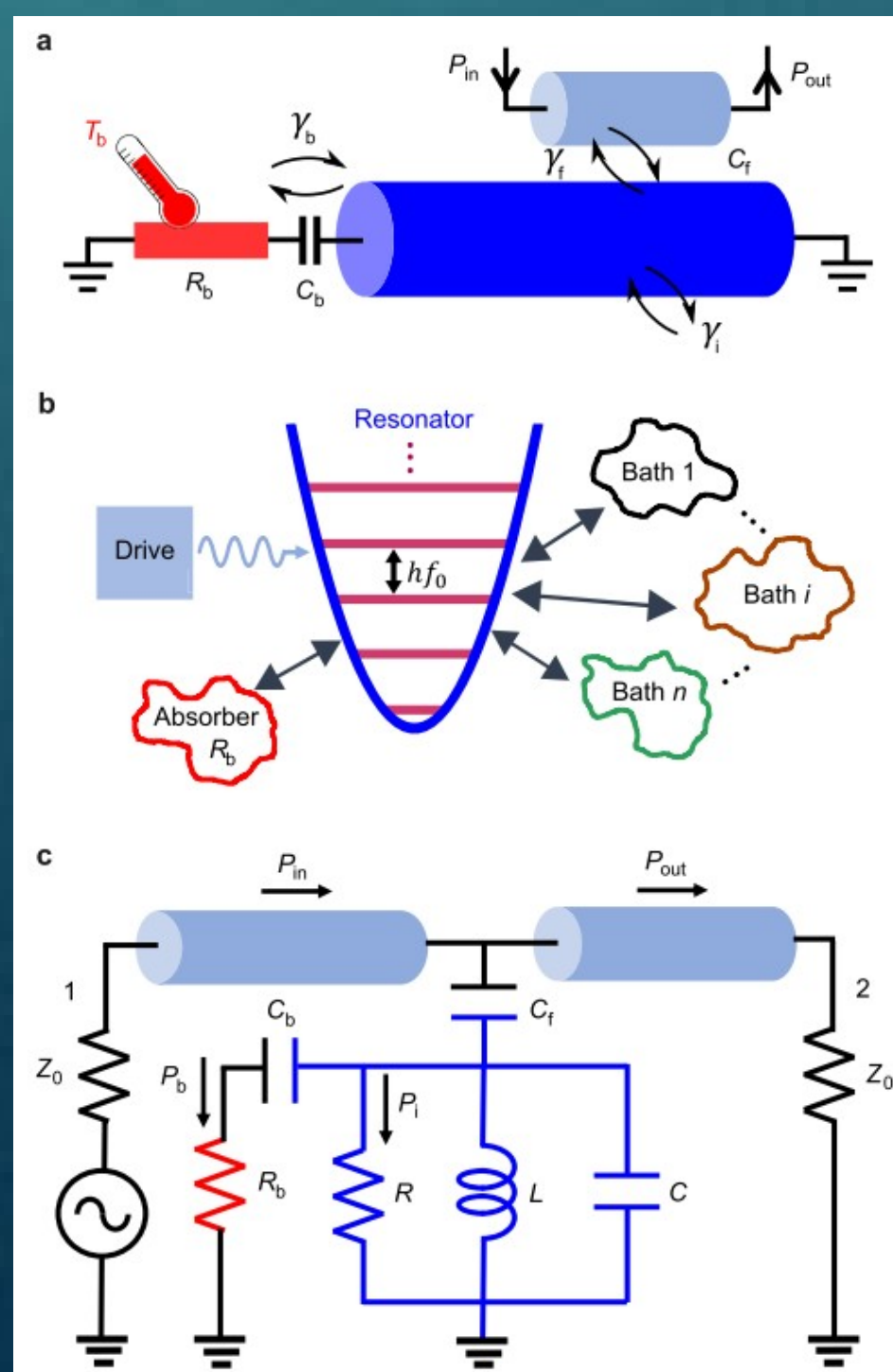


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Superconducting circuits have become a leading platform for exploring fundamental light–matter quantum physics and developing quantum technologies. Major bottlenecks persist when scaling laboratory devices toward error-corrected full-stack quantum computers. Challenges arise in designing scalable gate control, achieving fast and accurate read-out and reset, and handling the quantum–classical interface where entropy is continuously produced. Preserving coherence requires efficient entropy removal, a problem still unsolved at the hardware level. **HEMS aims to develop strategies for efficient entropy and heat management in superconducting devices.** Our approach separates each device into high-purity regions for storing and processing quantum information, and dedicated entropy sinks that can interface with refrigeration without disturbing the qubits. This requires **local, well-integrated mechanisms for transporting heat and entropy**, supported by a **microscopic understanding of energy-transfer and thermalization channels**. **HEMS** exploits **strong driving** to access **nonlinear cQED regimes** for rapid entropy removal and apply **optimal control theory** to design pulse sequences with minimal detrimental impact on device performances.

Principle of thermal spectrometry and bolometry



The driven quantum system can be monitored by detecting the heat due to photon in-flux into the bolometer (red element).

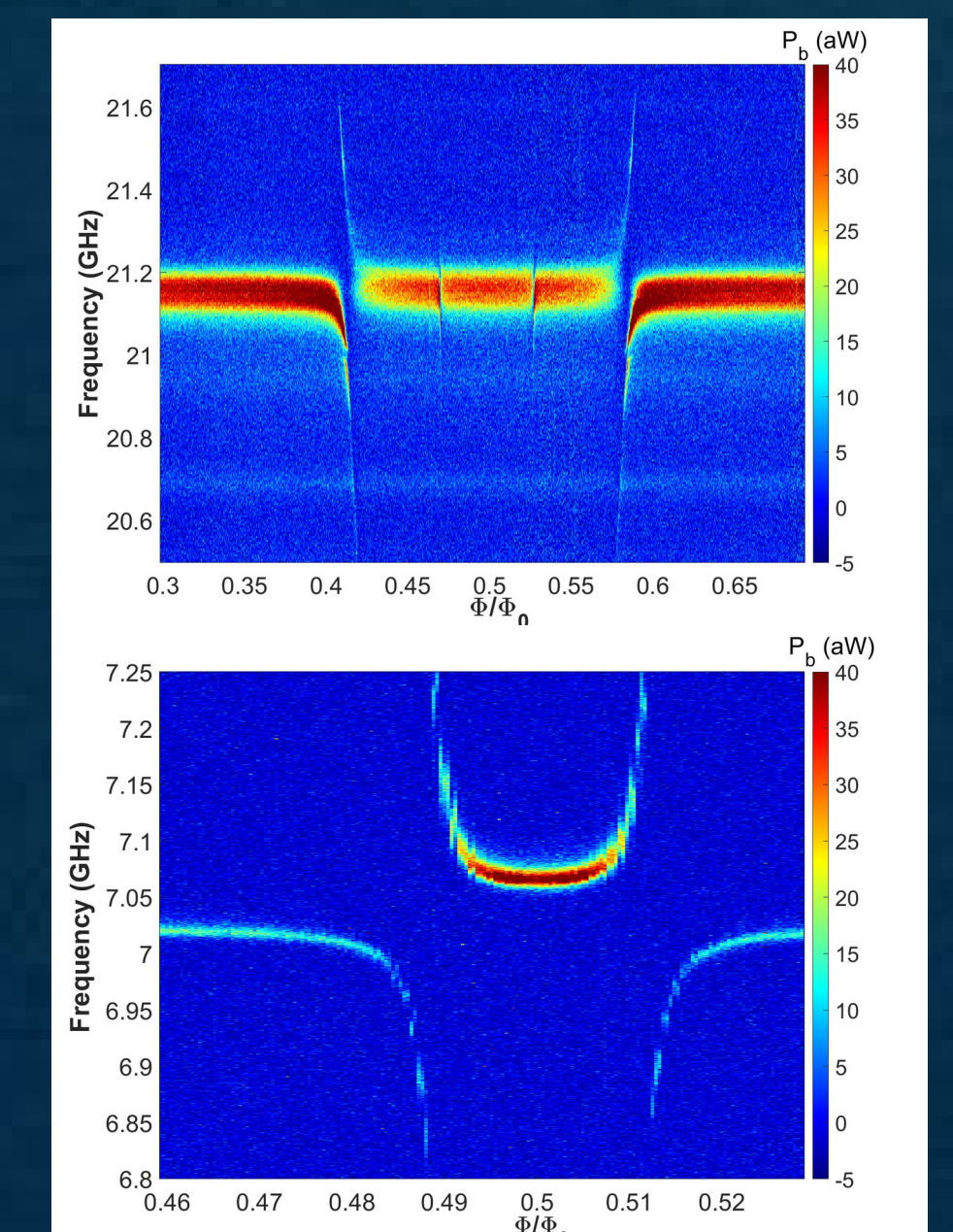
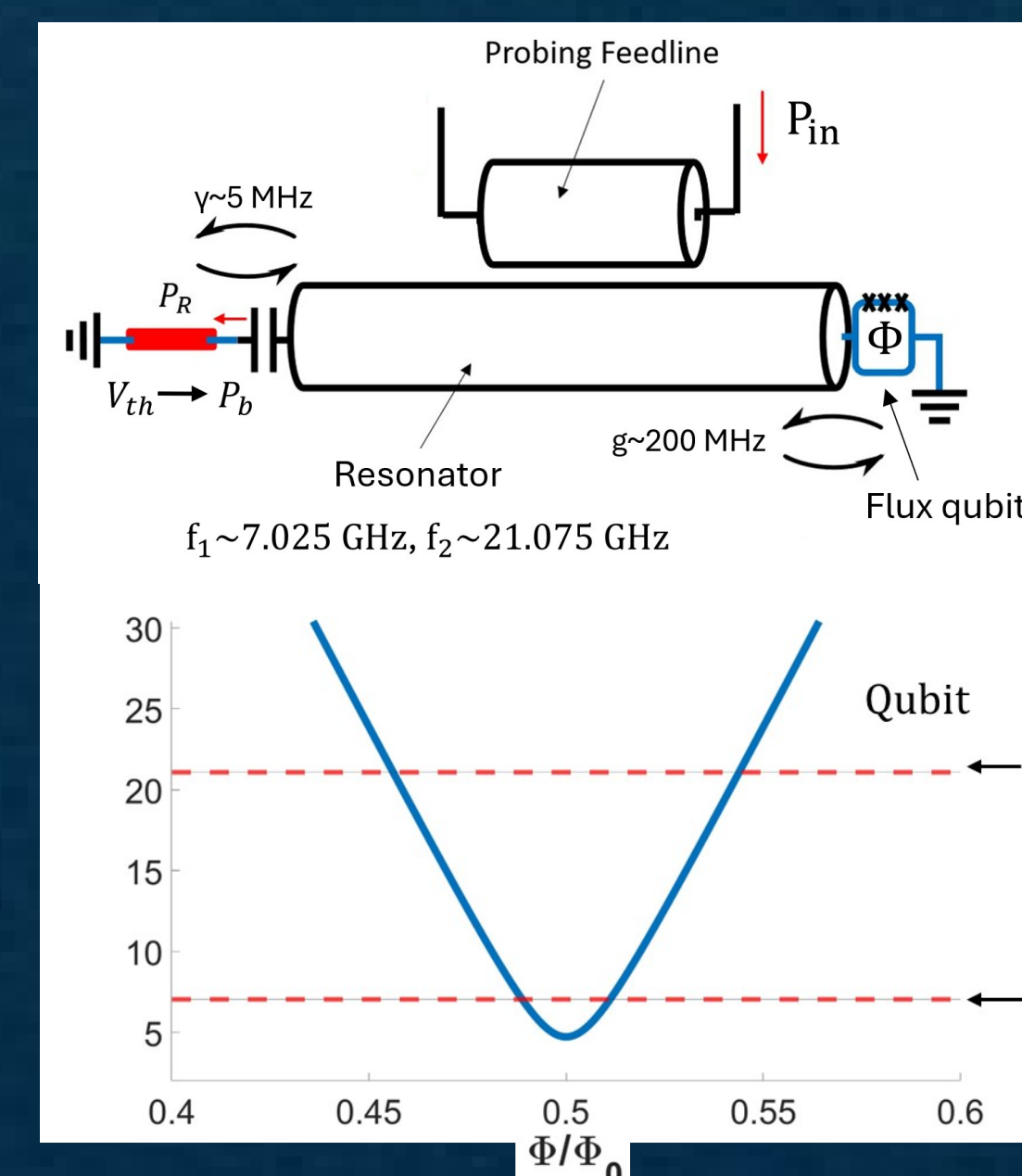
In HEMS we apply it in:

- Strongly driven and strongly coupled systems
- Two-bath cyclic quantum refrigerators

C. Satrya, Yu-Cheng Chang et al., Nat. Commun. 16, 4435 (2025)

Example:

Thermal spectroscopy of qubit resonator above 30 GHz



C. Satrya et al. unpublished (2026)

Concept and Methodology

Energy and heat flow main channels: **electromagnetic radiation in the microwave domain, quasi-particles, defects and phonons** - different microscopic origins, coupling strengths, characteristic time scales and they simultaneously affect quantum operations.

Approaches exploited in HEMS:

- Separation of strongly coupled “relevant” degrees of freedom or **primary bath** - to be incorporated into the system - from the remaining ones treated perturbatively as a **secondary bath** guided by time-scale and coupling hierarchies.

G. Falci et al, PRL 94, 167002 (2005),

E. Paladino et al. RMP 86, 361 (2014), D. Reich et al Sci. Rep. 5, 12430 (2015)

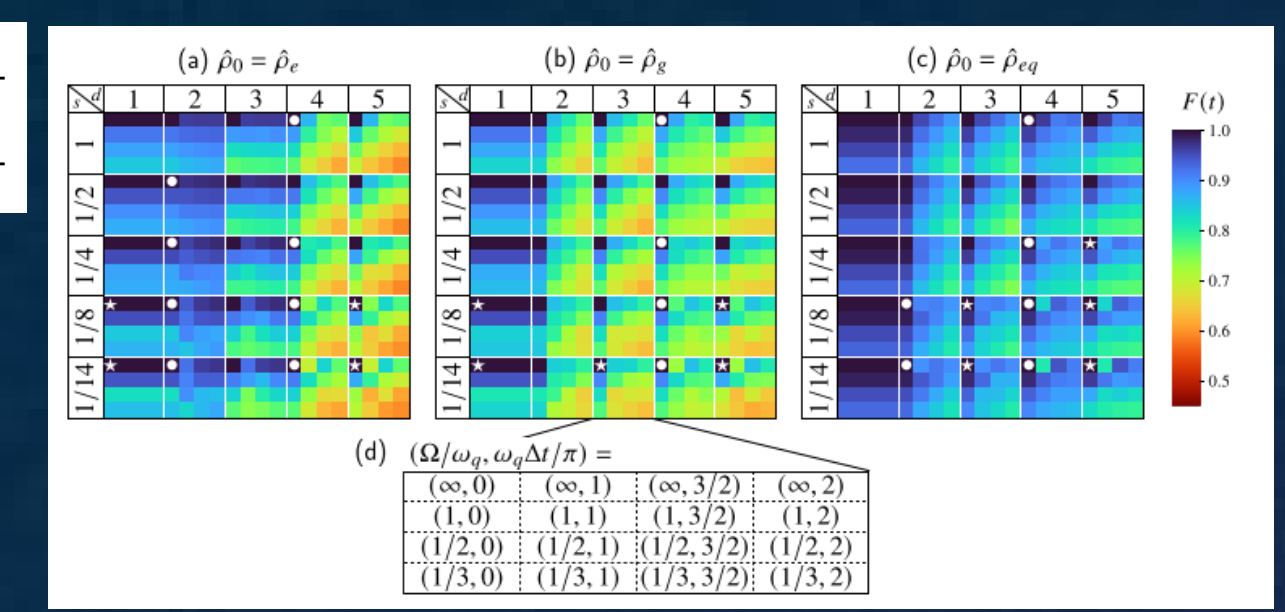
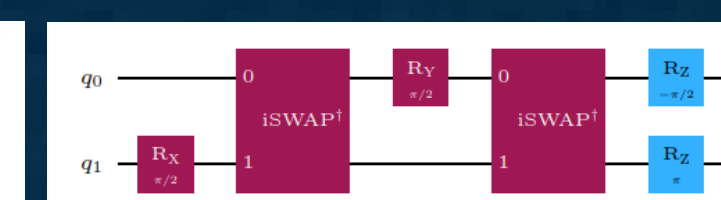
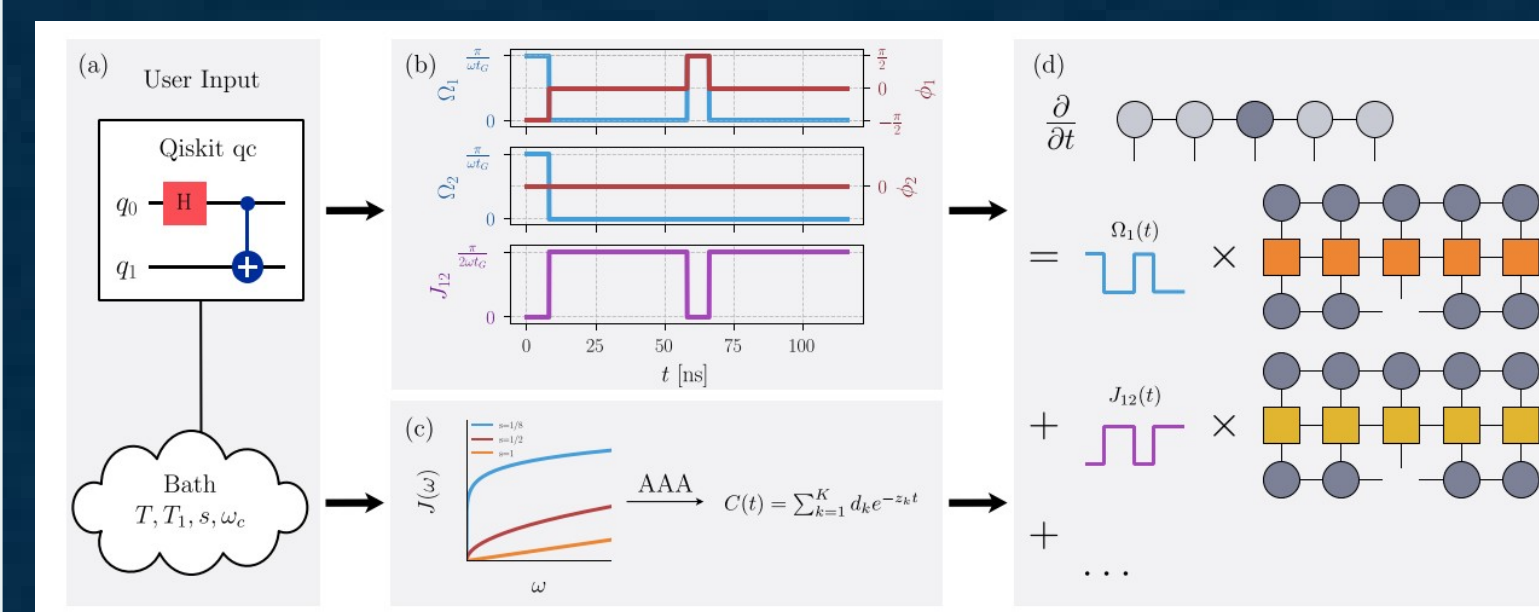
- Reservoir: „Few“ effective damped harmonic modes from bath spectral noise power: Time-local dynamics in extended Hilbert space: non-perturbative, numerically efficient, versatile, long-time stability (**QD-MESS**).

Xu et al, RMP 98, 021002 (2026)

Combined with advanced optimal-control techniques, generalizing qubit reset in structured environments toward a microscopic theory for HEMS

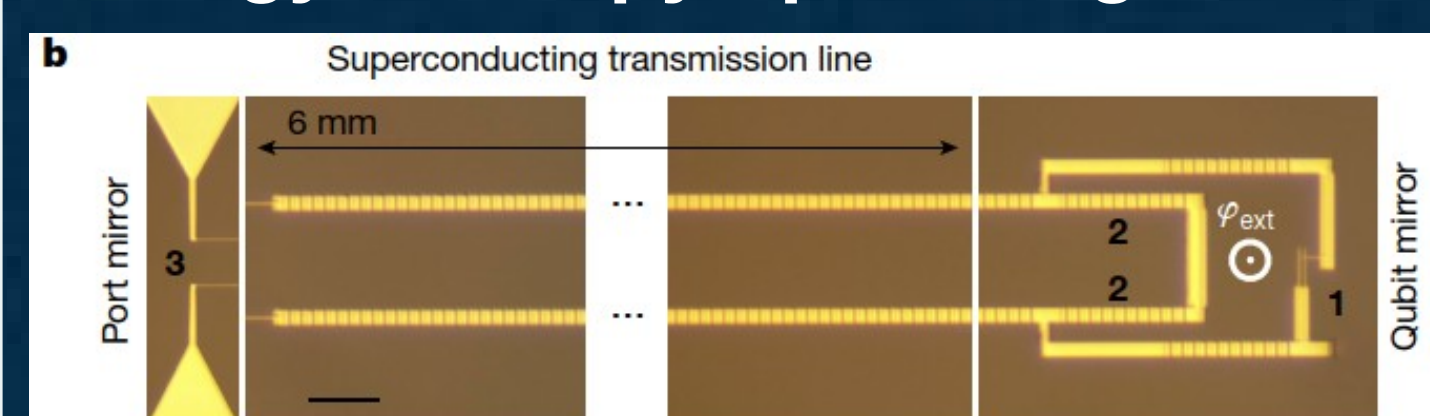
D.I. Basilewitsch et al. New J Phys 21, 093054 (2019)

QD-MESS – toolkik for superconducting qubit platform



K. Nakamura et al. PRR 6, 033215 (2024) K. Nakamura et al, PRR 8, 013337 (2026). K. Nakamura et al, unpublished (2026)

Energy+Entropy spreading for nonlinear oscillators



Mehta et al, Nature 613, 650 (2022)

Thermal rectification from weak to ultra-strong coupling

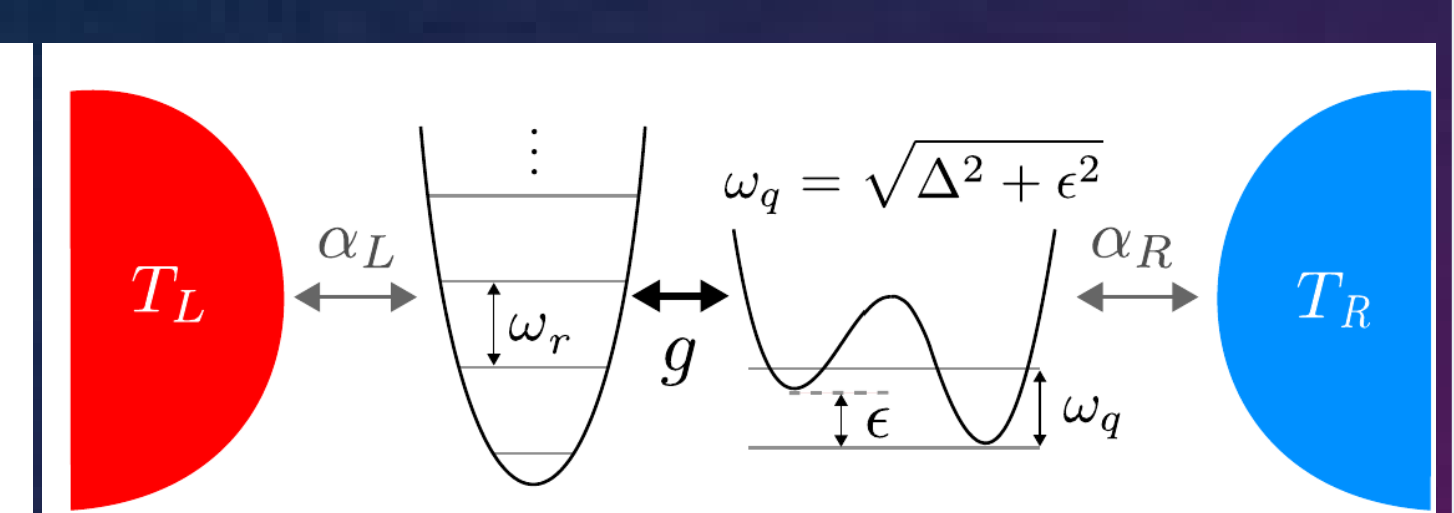
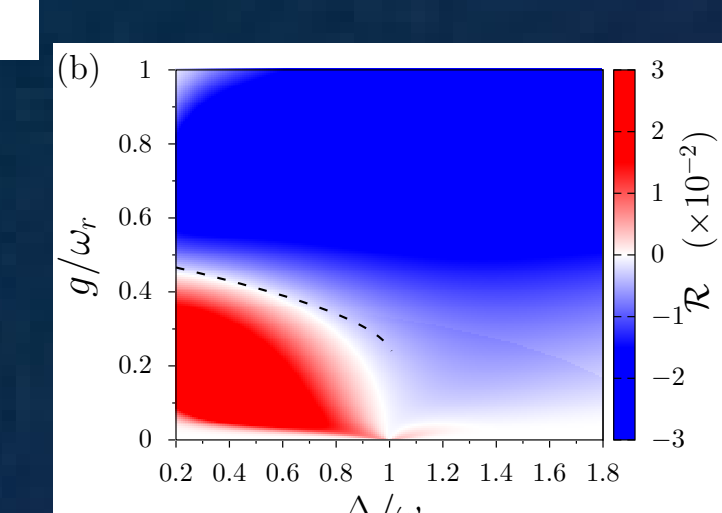
L. Magazzù et al, PRR 7, 043102 (2025)

L. Magazzù et al, Quantum Sci. Technol 10, 025013 (2025)

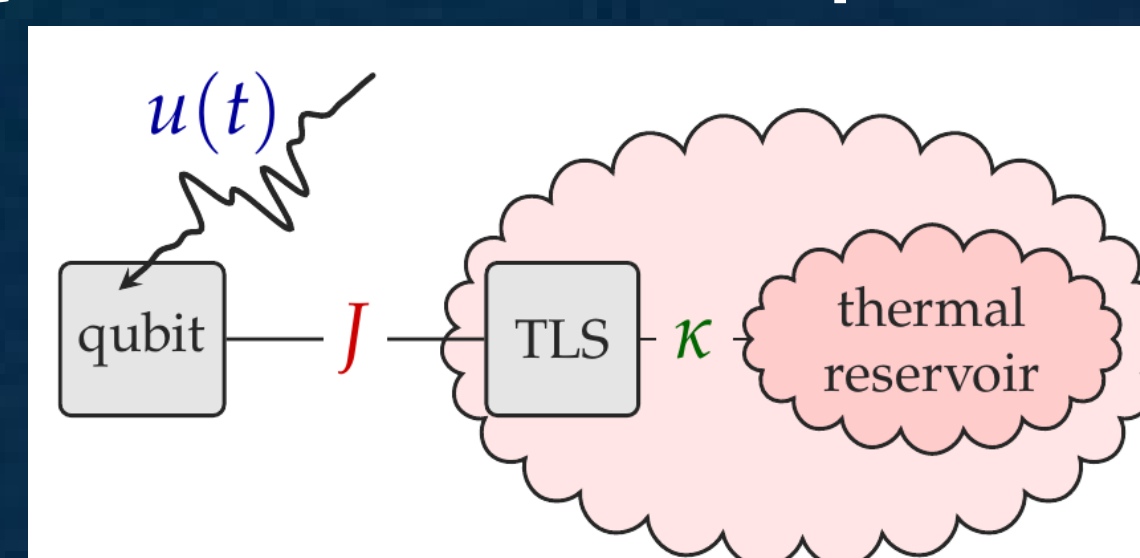
Uconventional thermalization in a three-wave mixing model

Pekola et al, PRR 6, L042023 (2024)

Varvelis, J.Ankerhold, arXiv: 2607.27028 (2026)



Quantum control – exploit the environment as entropy sink



Primary bath – TLS strong J for fast reset

Thermal reservoir – weak coupling for thermalization

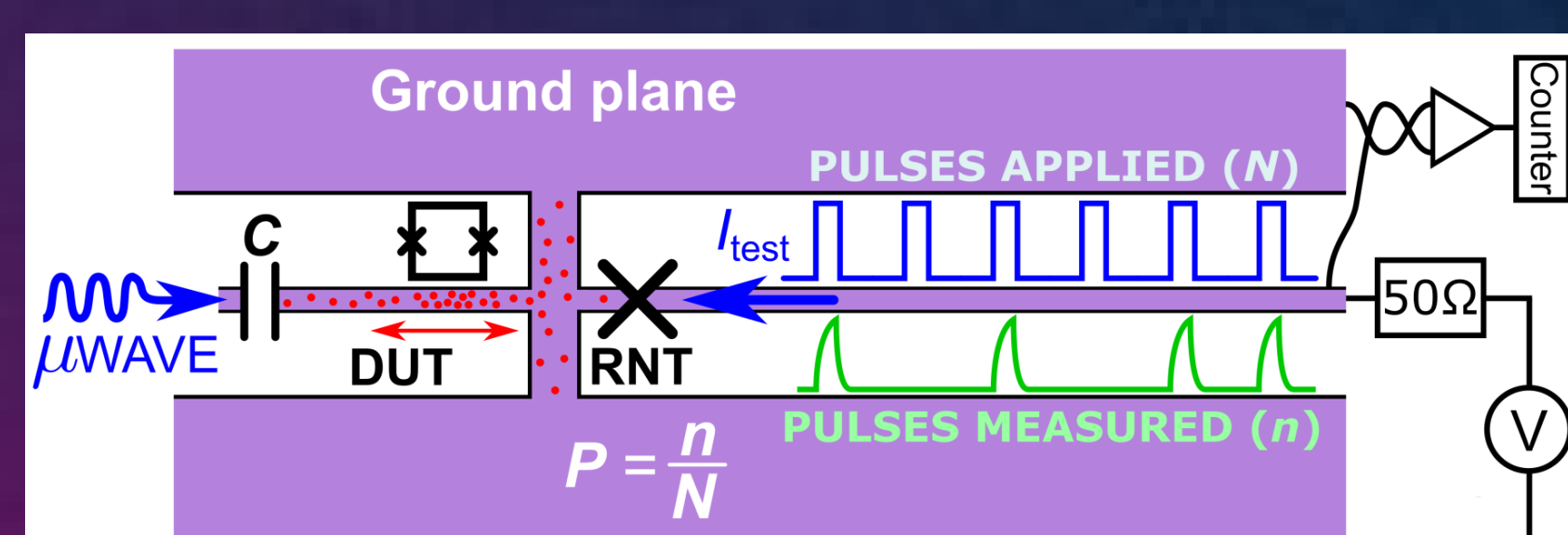
D.I. Basilewitsch et al. New J Phys 19, 113042 (2017)

D.I. Basilewitsch et al. PRR 3, 013110 (2021)

J. Langhehn et al. ArXiv:2506.11964

F. Gago-Encinas, C. Koch SciPost Phys. 20, 046 (2026)

Thermal detection via switching thermometry

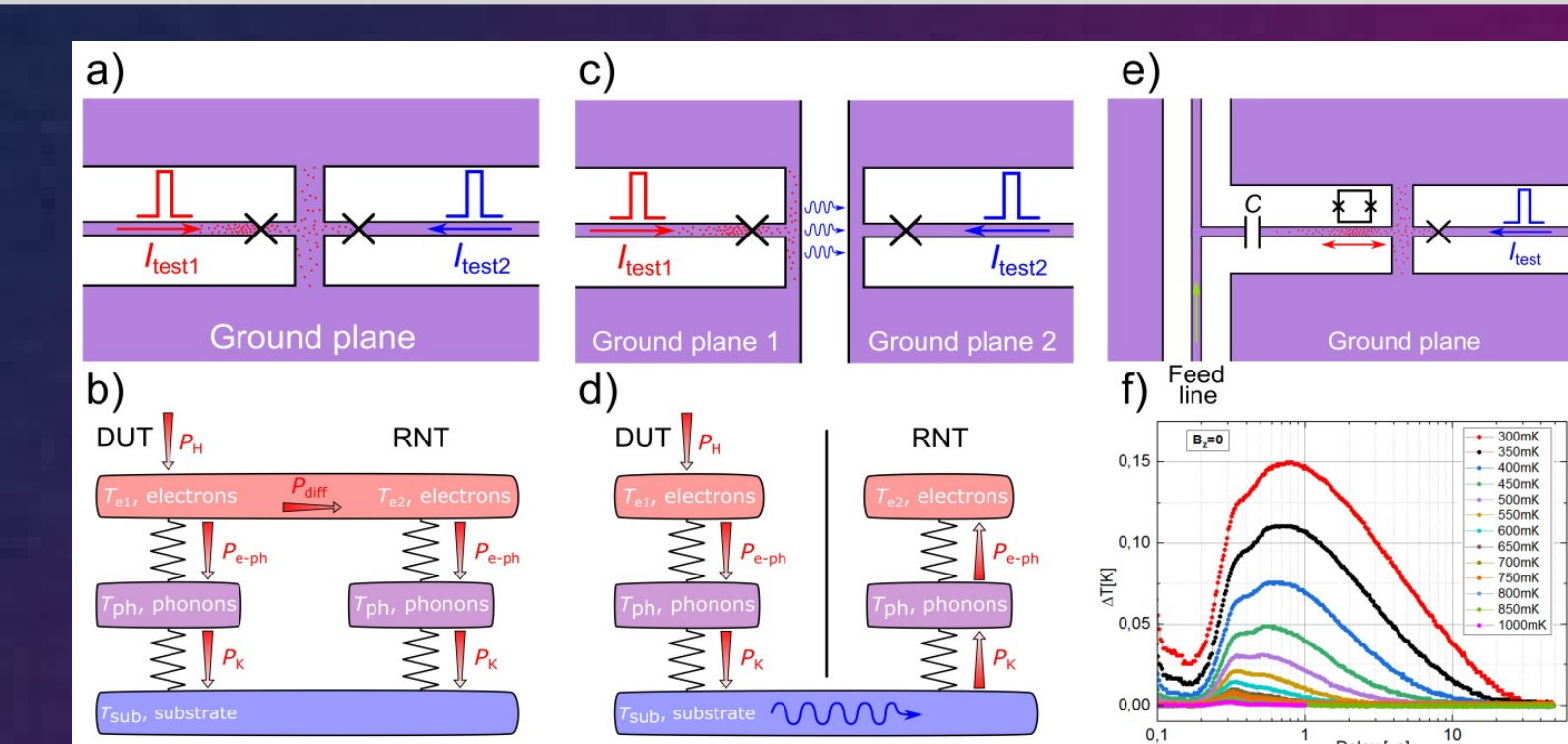


The remote nanothermometer (RNT) is a Josephson junction tested with current pulses to find its temperature-dependent switching probability P . Pulses are synchronized with the microwave signal applied to the resonator yielding the temporal trace of temperature. The device under test (DUT) and RNT are electromagnetically decoupled but they can exchange quasiparticles (red dots). The RNT provides direct thermal signatures of defect-related resonator losses producing quasiparticles

M. Zgirski et al. Phys. Rev. Appl. 10, 044068 (2018); M. Zgirski et al., Phys. Rev. Appl. 11, 054070 (2019);

M. Zgirski et al. Phys. Rev. Appl. 14, 044024 (2020); M. Zgirski et al. Phys. Rev. B 104, 014506 (2021);

K. Norowski et al., Phys. Rev. B 113, 214512 (2026)



Thermal detection mechanisms: a) Quasiparticle-mediated and c) phonon-assisted read-out of a current-biased Josephson junction (crosses indicate the CBJJ and RNT). b,d) Thermal diagrams showing the two channels responsible for quasiparticle excitation in the RNT due to remote dissipation: b) diffusion of nonequilibrium quasiparticles and d) absorption of phonons propagating from the heater through the silicon substrate. e) Quasiparticle-mediated read-out of the temperature of a microwave-driven resonator coupled to a qubit. f) Temporal evolution of the electron temperature of an Al nanobridge following short Joule dissipation in a galvanically isolated Cu nanowire (DUT). The thermal coupling occurs through the two channels shown in b) and d); the initial signal corresponds to the arrival of ballistic substrate phonons, while the longer delays reflect the thermal contribution of quasiparticles.

M. Zgirski et al unpublished 2026

