

# Transport, metastability, and neuromorphic applications in quantum networks (QNet)

**Call topic:** Quantum Phenomena and Resources  
**Project start date** – July 31, 2024  
**Duration** – 36 months  
**Budget** ~ 1.2 mil eur

<https://qnet.ifs.hr/>

## QNet

## Consortium

**DFG** Deutsche Forschungsgemeinschaft  
German Research Foundation

**Universität des Saarlandes**  
Saarlandes, Germany

**Federal Institute of Technology**  
Zurich, Switzerland

**ETH zürich**  
Swiss National Science Foundation

**Aalto University**  
Aalto, Finland

**A''**  
Aalto University

**Institute of Physics**  
Zagreb, Croatia

**INSTITUT ZA FIZIKU**

**HRZZ**  
Croatian Science Foundation

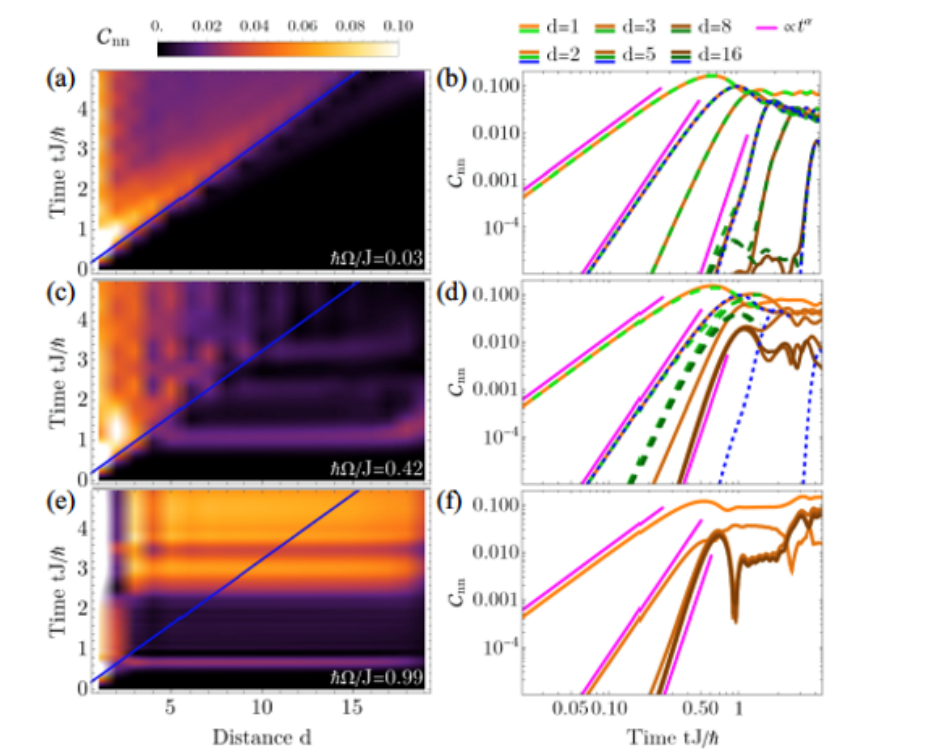
**IFISC**

**CSIC**

**University of the Balearic Islands/Institute for Cross-Disciplinary Physics and Complex Systems**  
Palma de Mallorca, Spain

**We study the out-of-equilibrium dynamics of quantum networks with long-range interactions under noise, focusing on applications in quantum associative memories and quantum reservoir computing.**

**Published**  
From Light-Cone to Supersonic Propagation of Correlations by Competing Short- and Long-Range Couplings

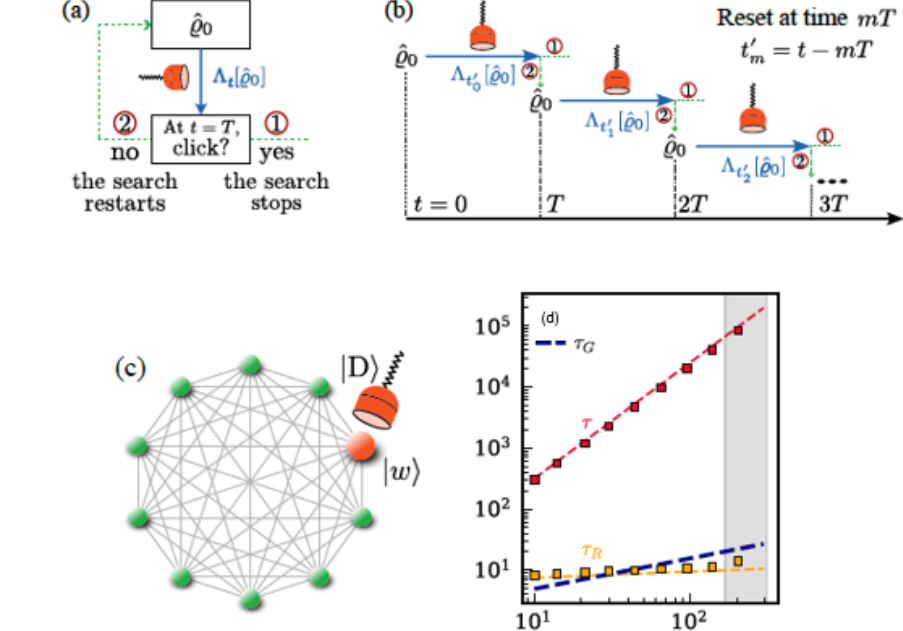


We monitor the nonequilibrium dynamics of the correlations following a quench.

For strong short-range couplings the propagation of correlations is dominated at short and intermediate distances by a causal, light-cone dynamics.

Phys. Rev. Lett. 135, 190402 (2025)

**Preprint**  
Time complexity of a monitored quantum search with resetting



We determine the time complexity of the quantum analog of a randomized algorithm, which implements feedback in a simple form (a,b). The search is a continuous-time quantum walk on a complete graph, where the search target is continuously monitored by a detector(c).

The quantum state is reset if the detector does not click within a specified time interval (b).

We optimize the search time as a function of the hopping amplitude, detection rate, and resetting rate, and determine the time complexity.

arXiv:2601.20560

**USAAR, Saarland University**

Emma King, Sayan Roy, Francesco Mattiotti, G. Morigi

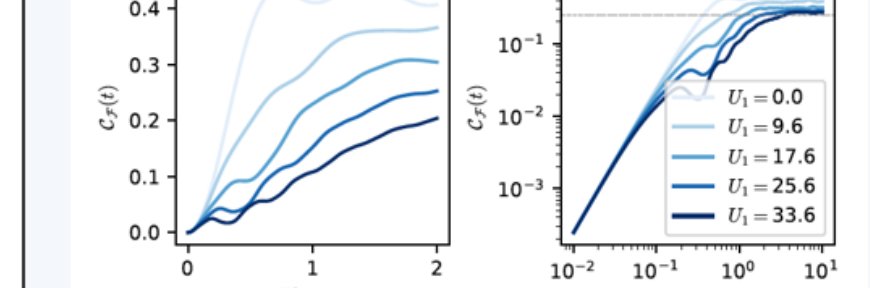
**Collaborations within QNet**  
Tijana Ban and collaborators, Zagreb  
quantum transport of photonic excitations in multimode cavity QED

Tobias Donner and collaborators, ETH

metastability and relaxation in many-body QED

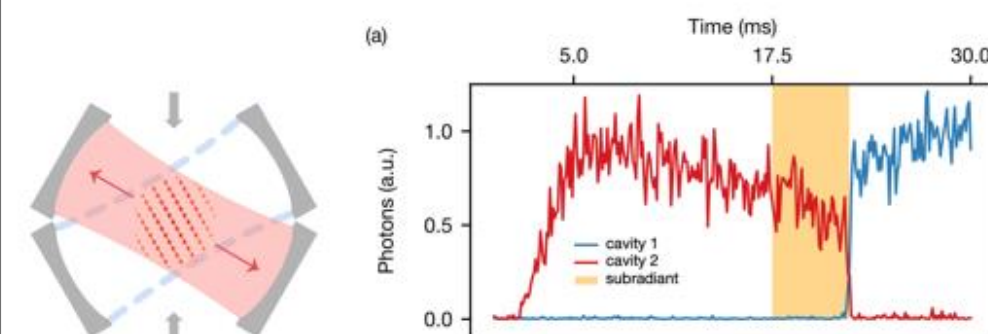
**Ongoing project:**  
Quantum information scrambling for competing short- and long-range Couplings

$$H = -J \sum_{i,j} \left( \hat{b}_{i+1}^\dagger + \hat{b}_i \right) + \frac{U}{2} \sum_i \hat{b}_i^\dagger (\hat{b}_i - 1) - \frac{U}{2} \sum_i (\hat{b}_i^\dagger - 1) \hat{b}_i$$
$$C_T(t) = \frac{1}{L} \sum_{i,j} \left( \langle \hat{b}_i^2(t) \rangle - \langle \hat{b}_i(t) \rangle^2 \right)$$



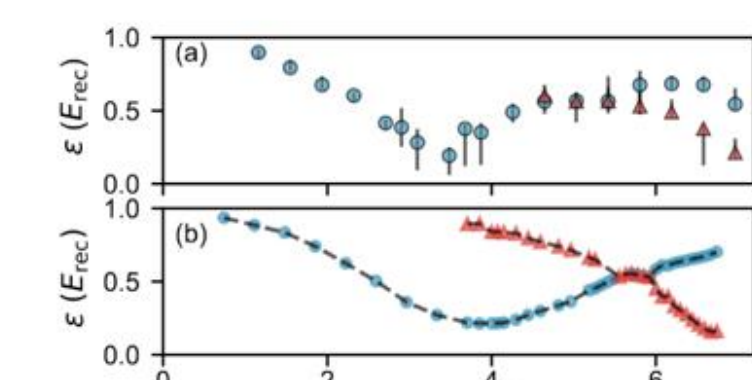
The long-range interactions confine the dynamics into an energy band with gaps of  $\sim U$  with the rest of the spectrum. Inside the band, the effective hopping is much smaller than the on-site interaction, realizing an effective hard-core bosonic system.

**Phase transitions to superradiant and subradiant states of matter, Observation of Metastability**



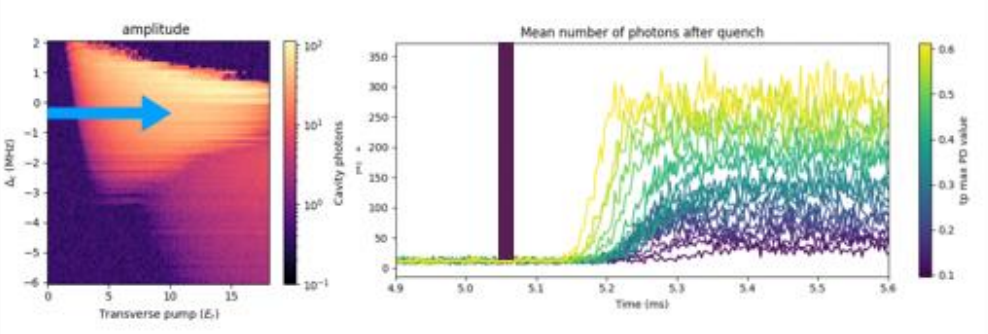
Joint work with Giovanna Morigi  
Science Adv. 11, eadw0299 (2025)

**Synchronization of Quasi-Particle Excitations in a Quantum Gas with Cavity-Mediated Interactions**



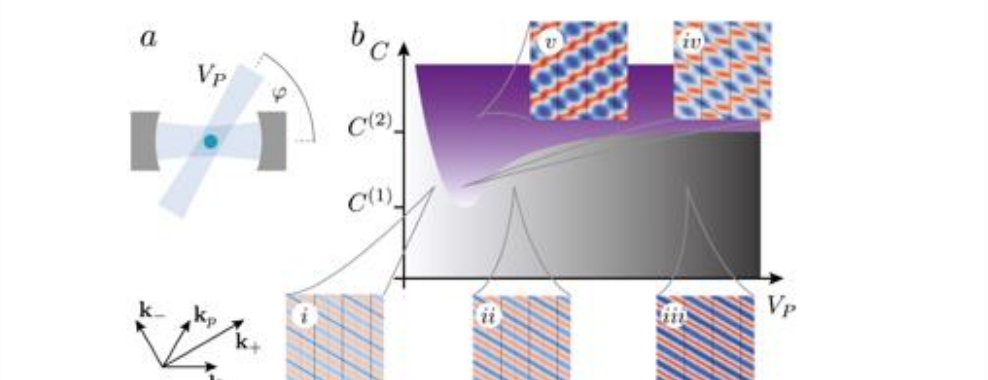
Phys. Rev. Lett. 136, 140401 (2026)

**Ongoing project:**  
Dynamics after rapid quenches into self-ordered states of matter



Joint work with Giovanna Morigi  
Visiting PhD student  
Marin Dujic from Zagreb

**Ongoing project:**  
Universality of re-entrant superradiance



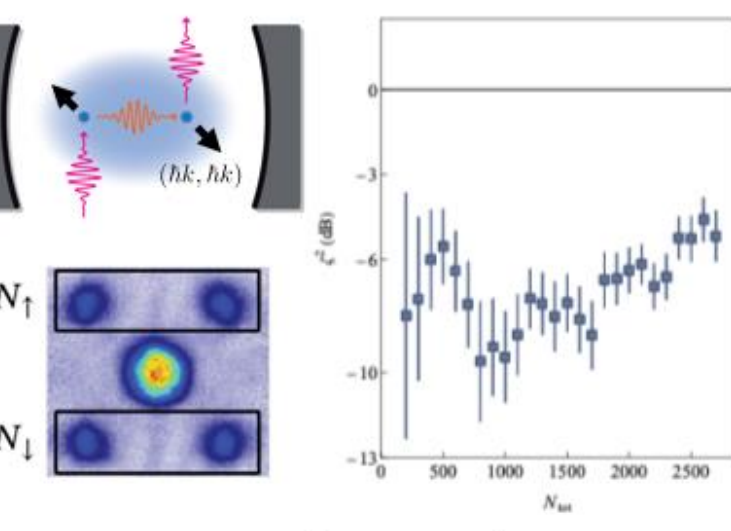
Joint work with Giovanna Morigi



Nicola Montalti Tobias Donner

**ETH zürich**

**Ongoing project:**  
Pair correlations seeded by quantum fluctuations: Observation of squeezing

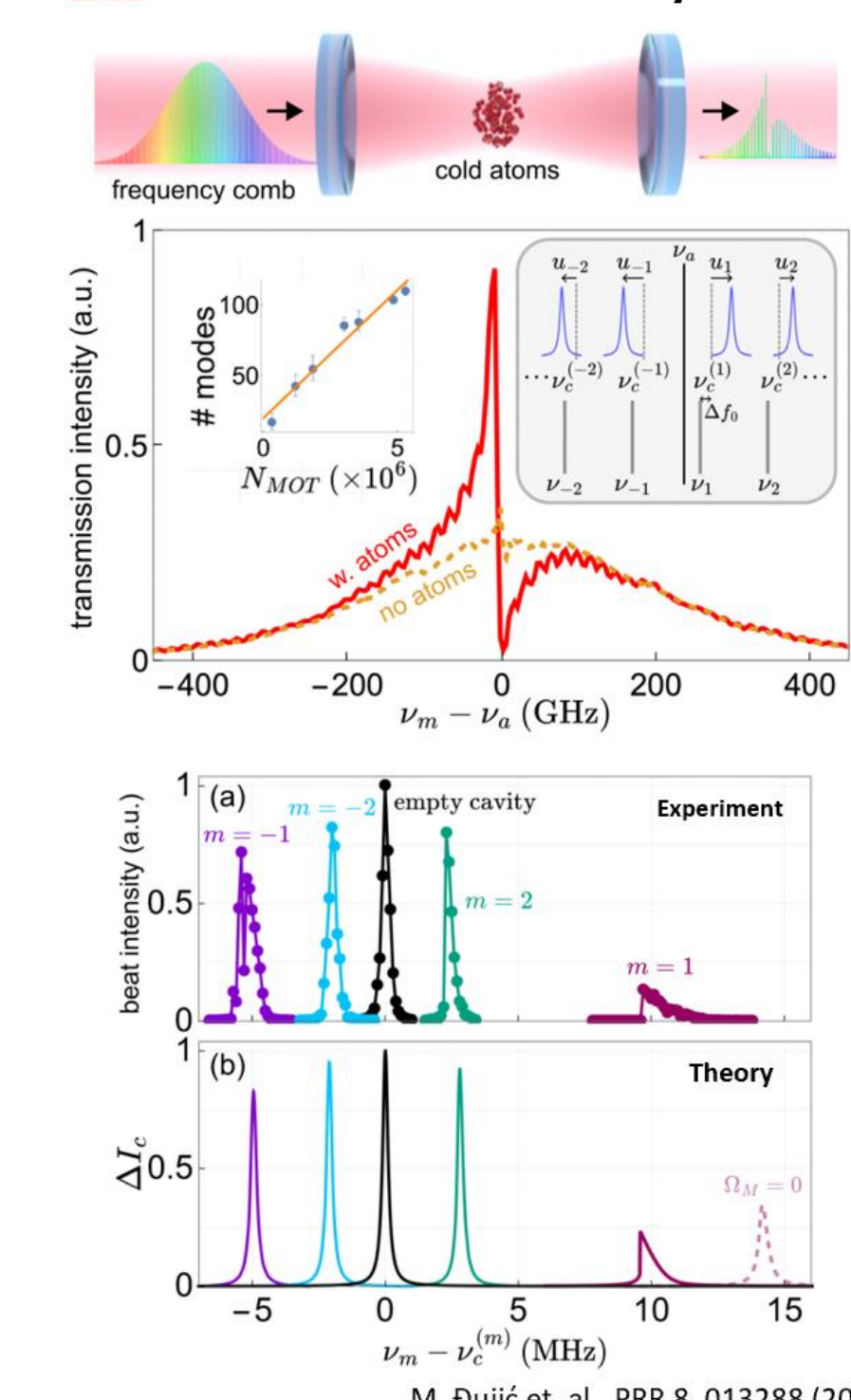


$$\xi_V^2 = \frac{\text{Var}[N_\uparrow - N_\downarrow]}{\langle N_\uparrow + N_\downarrow \rangle} < 1$$

## Objectives

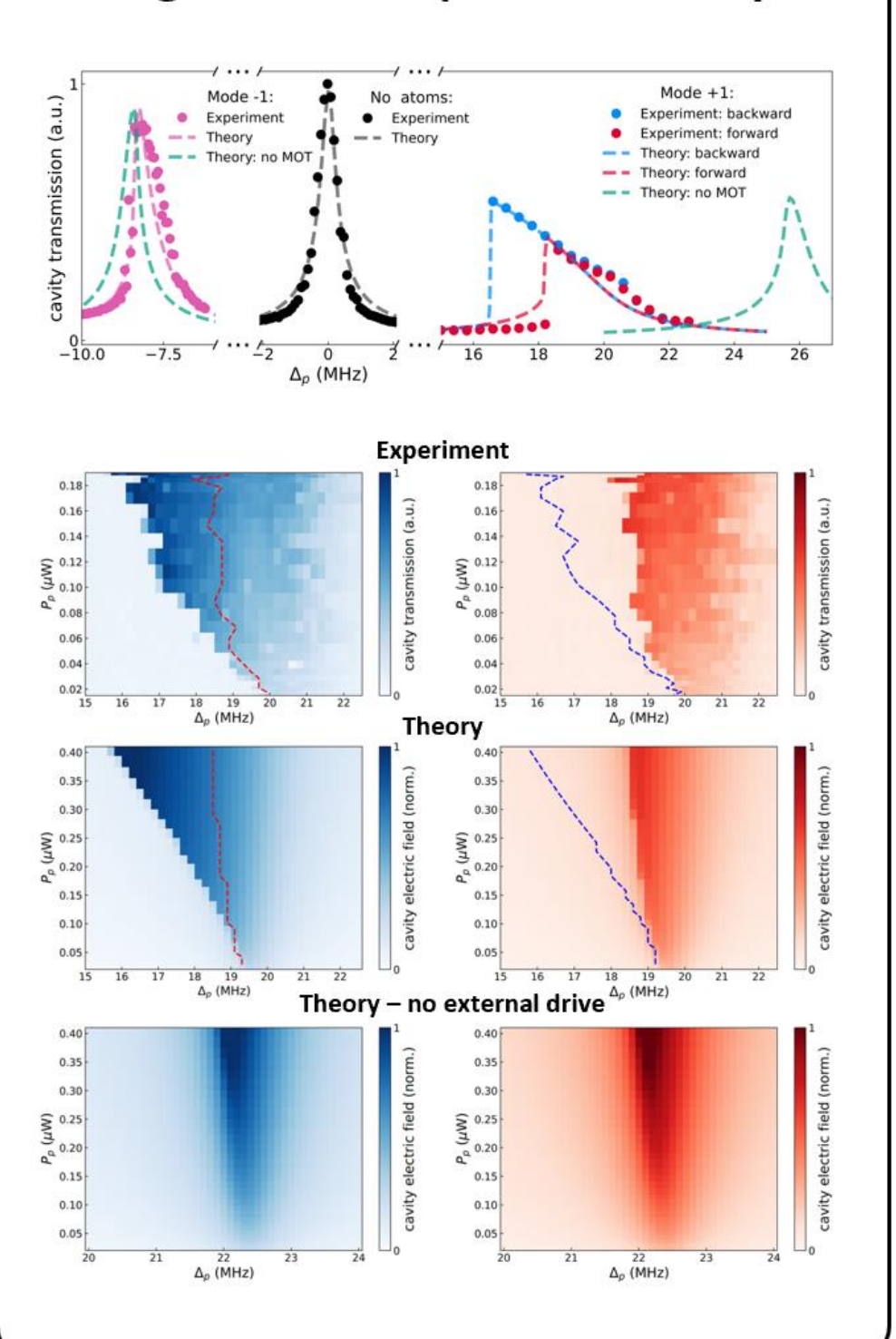
- ❖ Quantum transport of energy and propagation of information, entanglement in the presence and as a function of the dissipation, disorder and temperature.
- ❖ Quantum metastability and information scrambling in noisy and dissipative environments.
- ❖ Theoretical framework and proof-of-principle implementation of neuromorphic-inspired computing in atomic and superconducting systems.
- ❖ **Experimental platforms:** ultracold atoms in a high-finesse cavities & superconducting quantum circuits that are coupled to on-chip mesoscopic heat baths
- ❖ **Theory:** open quantum system theory & neural networks

**Published**  
Multi-color excitation of cavity modes



M. Dujic et al., PRR 8, 013288 (2026).

**Ongoing work**  
Programmable Optical Bistability

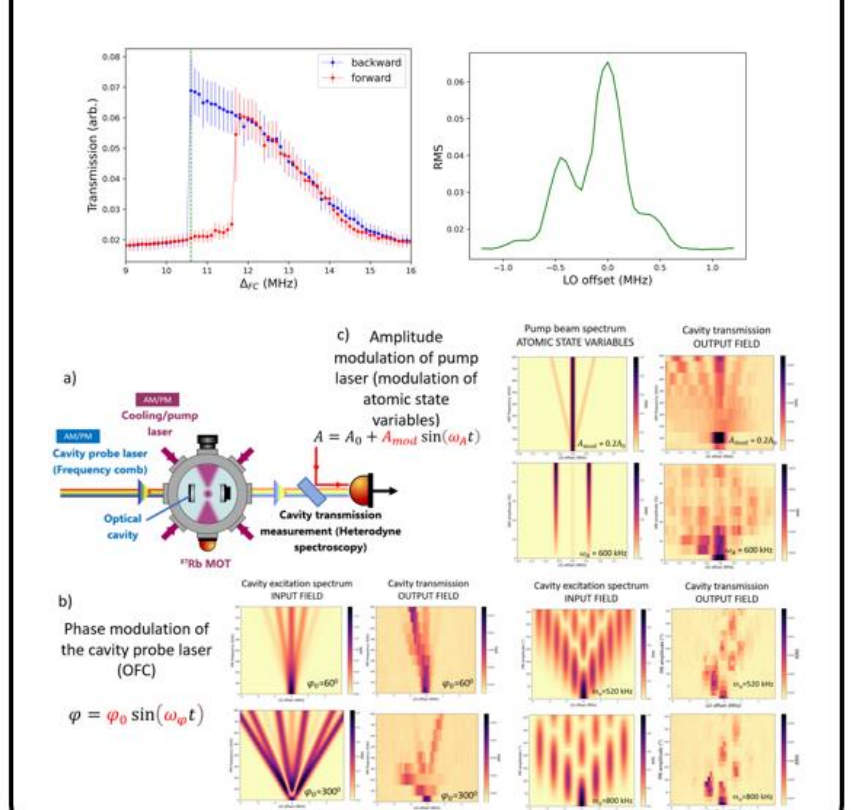


Marin Dujic Juraj Gajovic Ivor Kresic Tijana Ban

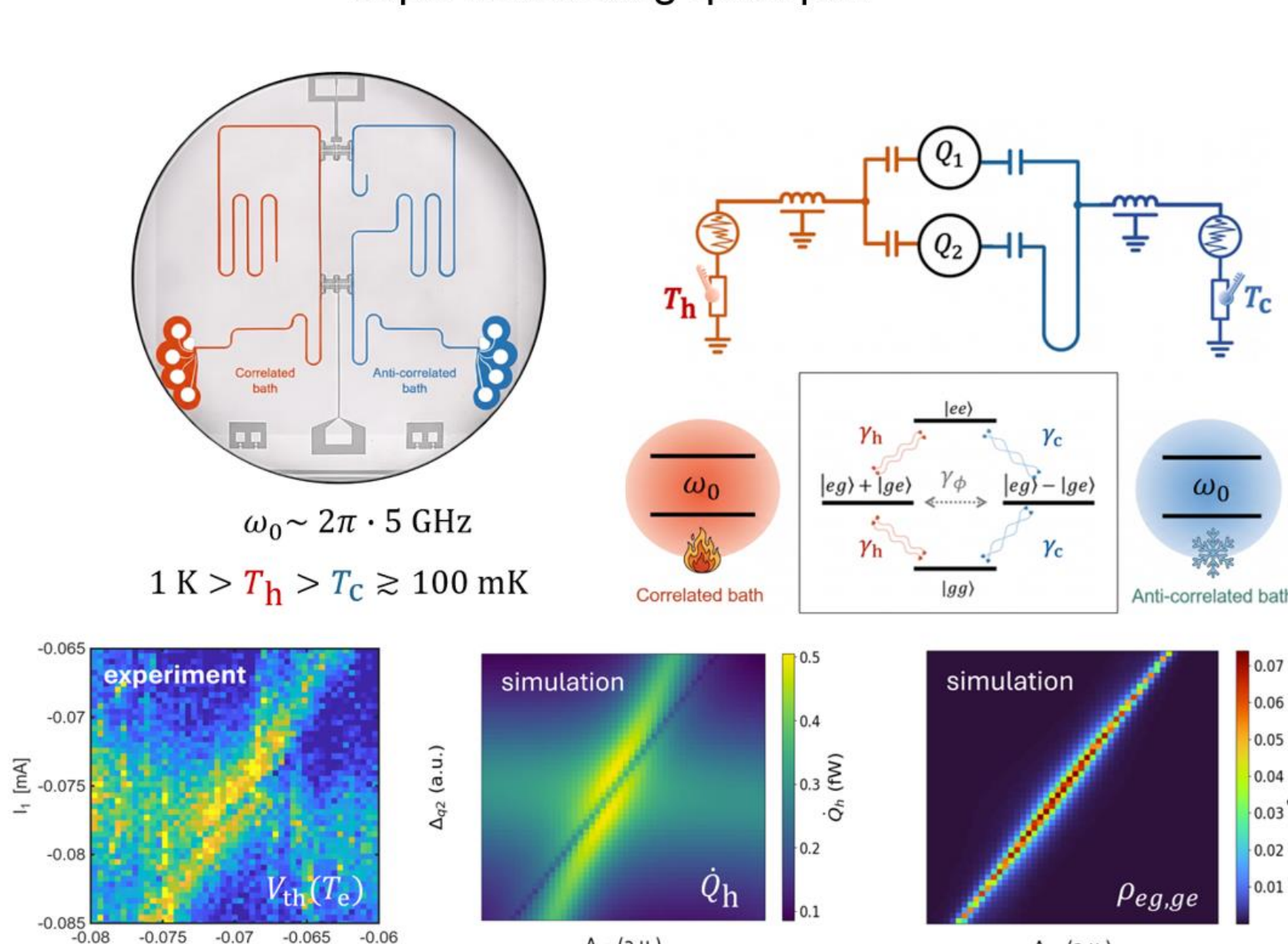
**INSTITUT ZA FIZIKU**

**INSTITUTE OF PHYSICS**  
Zagreb, Croatia

**Ongoing work**  
Sideband Generation and Atom-Mediated Phase Modulation



Autonomous collective coherence between a superconducting qubit pair



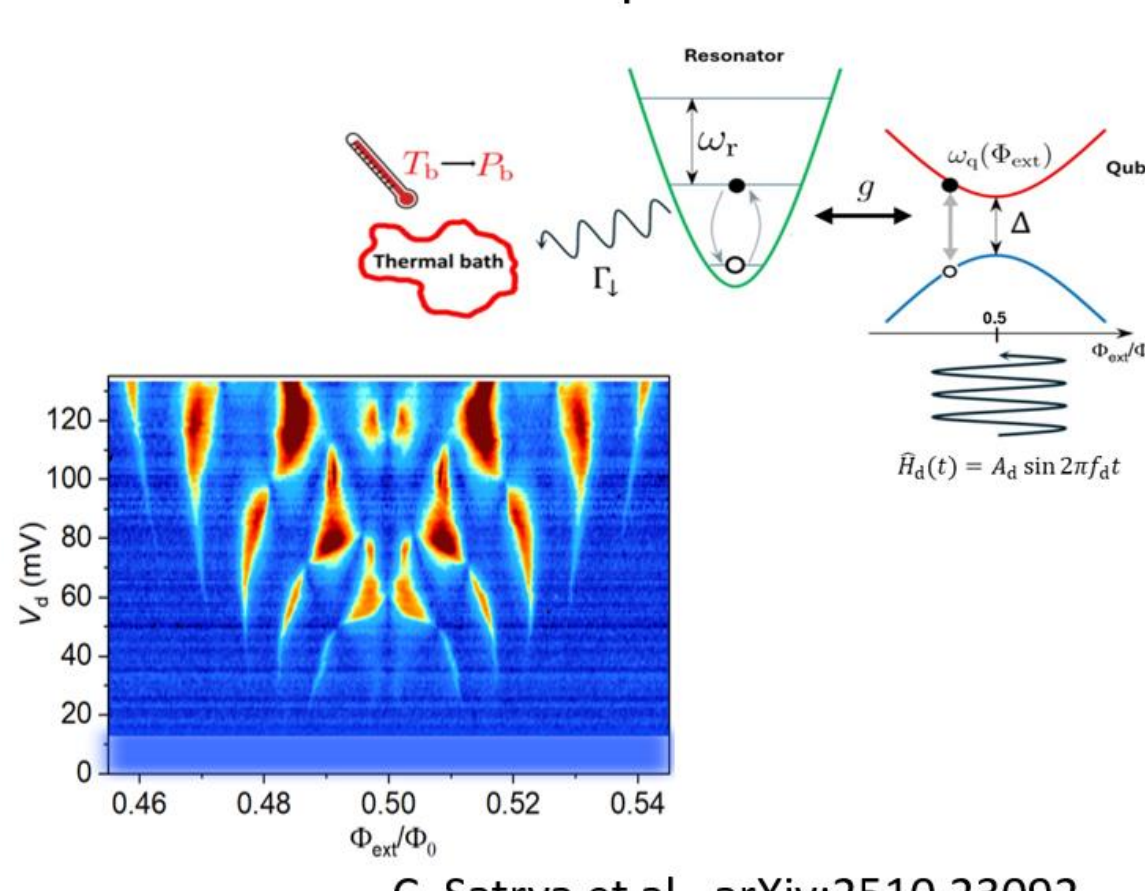
K.-H. Chiang, F. Chowdhury, G.M. Andolina, P.A. Erdman, Marco Schirò and J. Pekola.



Kuan-Hsun Chiang Jukka Pekola

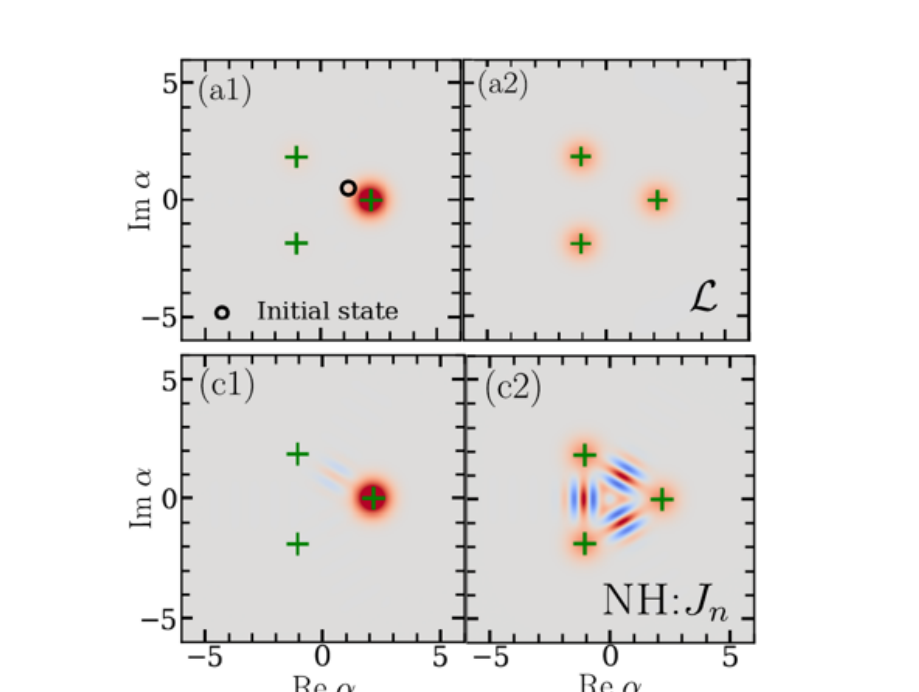
**A!**  
Aalto University

Heat measurement of quantum interference



C. Satrya et al., arXiv:2510.23092

**Ongoing work**  
Unraveling-dependent metastability in monitored quantum systems and associative memories

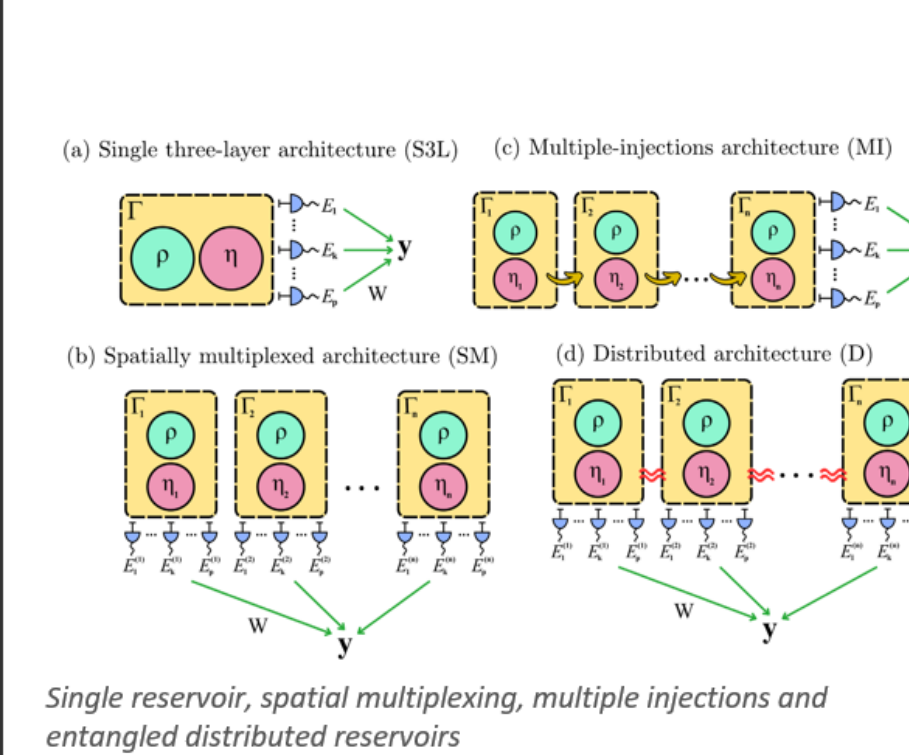


Wigner functions: Liouvillian (top) vs. no-click evolution with the displaced jump operator (bottom)

- Same master equation, different unravelings: Liouvillian gap alone does not fix the trajectory-level fate of a metastable memory
- No-click non-Hermitian dynamics retrieves the branch only at finite time (survival selects the least-decaying mode)
- Retention requires compatibility between monitored channel, record and memory manifold

M. Malakar, R. Zambrini, G. L. Giorgi  
arXiv:2609.06056 (2026)

**Published**  
Learning functions of quantum states with distributed architectures



Single reservoir, spatial multiplexing, multiple injections and entangled distributed reservoirs

- Quantum extreme learning machines that learn linear and nonlinear functions of input states from computational-basis measurements
- Entangled small reservoirs reach polynomial functionals, Rényi entropy and entanglement measures
- Higher-order nonlinearity from more interacting units, not a larger single reservoir: scalable, hardware-efficient

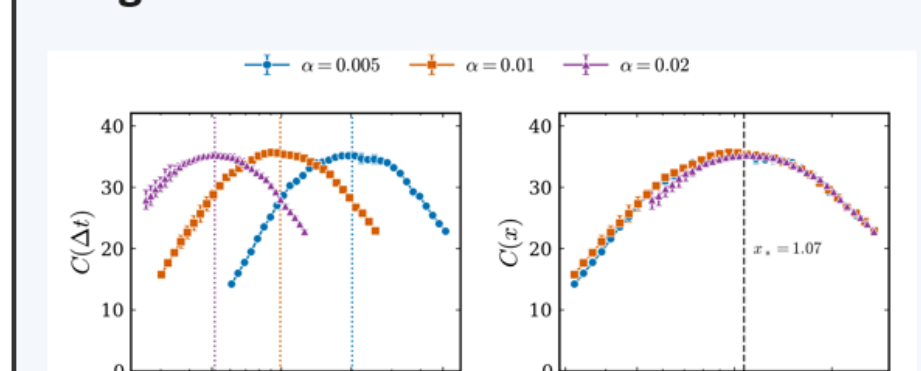
M. Gili, E. Fiorelli, A. Blázquez-García, G. L. Giorgi, R. Zambrini  
Quantum Mach. Intell. 8, 63 (2026)

Joint work at IFISC (UIB-CSIC), Palma de Mallorca



Manali Malakar Roberta Zambrini Marta Gili Gian Luca Giorgi

**Ongoing project:**  
Quantum reservoir computing with fragmented ETH



Memory capacity collapses onto one curve when time is scaled by the band width

- Long-range Ising chain: weak perturbation of a collective ( $\alpha = 0$ ) symmetry creates chaos inside bands, before bands mix
- Reservoir clock set by the band width:  $\Delta t^* \approx x^*/W(\alpha)$ ,  $x^* = 1.07$
- Next: size scaling and concentration of outputs