# DECOHERENCE IN THE NISQ-ERA

*Dr. Jekyll or Mr. Hyde*


**ARCHANA KAMAL**

Department of Physics and Astronomy

Northwestern University



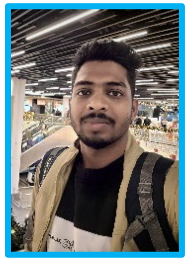
**International Conference on Quantum Information Science and Technology (ICQIST), 2025**

CQuERE, TCG CREST, Kolkata, India

December 10, 2025

# QUEST group and Collaborators

## Postdocs


Sudhir Sahu
(w/ NIST Boulder)


Debsuvra Mukhopadhyay

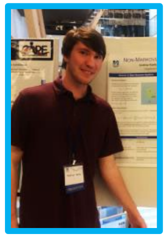

Jiru Liu


Le Hu

### Alums

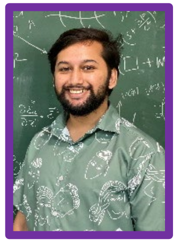
Zhihao Xiao
Taewan Noh (Yale/Quantum Circuits Inc.)
Juzar Thingna (APS Editorial, PRX-Q)
Carlos Gutierrez (Faculty @UNAM Mexico)
Emery Doucet (UMaryland)
Tristan Brown (MIT-LL)
Alvin Kow (UMass Boston)

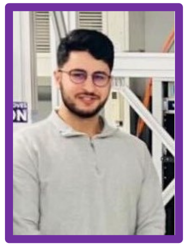
## Graduate Students

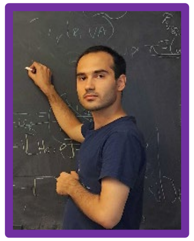

Andrew “Red” Keefe


Tarush Tiwari


Vedant Kashyap


Pawan Goswami


Ennis Mawas


Boran Kuzhan


Aakash Lakshmanan

## Collaborators

**Theory**

N. Agarwal (UML)
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**Expt.**

J. Aumentado (NIST)
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K. Murch (WUSTL)
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L. Ranzani (BBN)

G. Ribeill (BBN)
D. Riste (BBN → Keysight)
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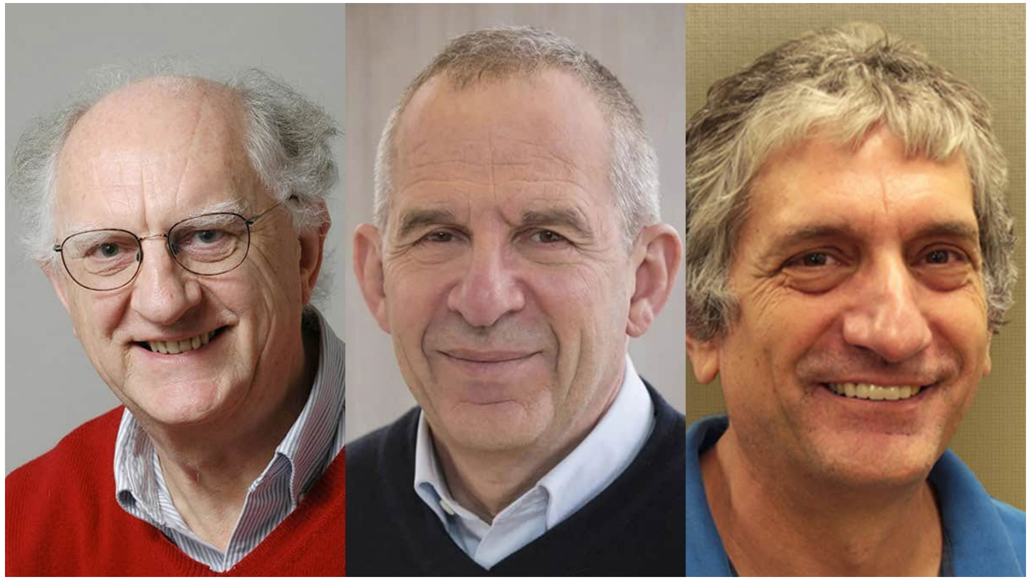
# The Legacy of Engineered Quantum Systems: from fundamental to applied

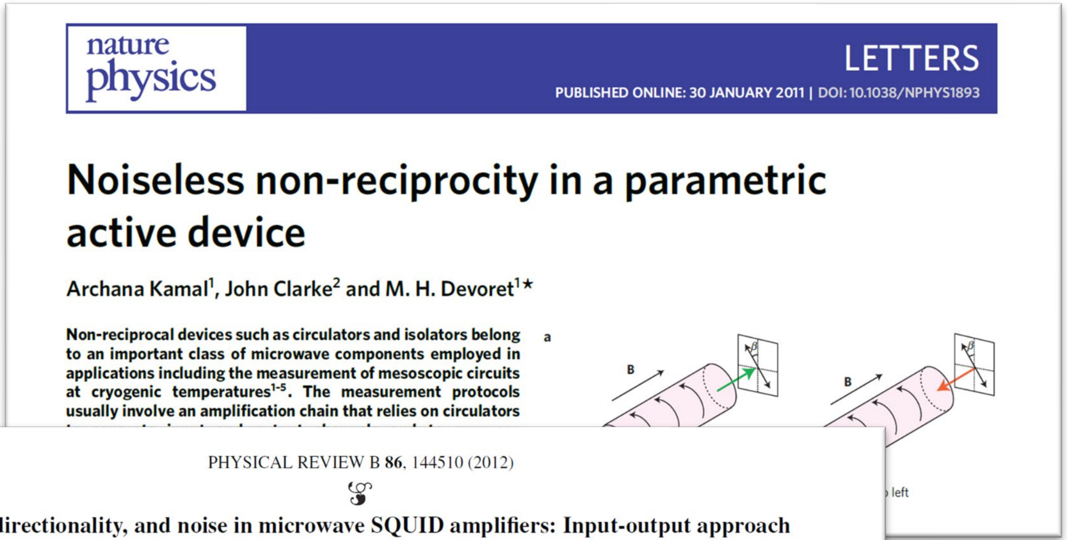
## Nobel Prize in Physics 2025



**John Clarke** **Michel Devoret** **John Martinis**

"Great research requires a combination of inspired faith and masochistic doubt."

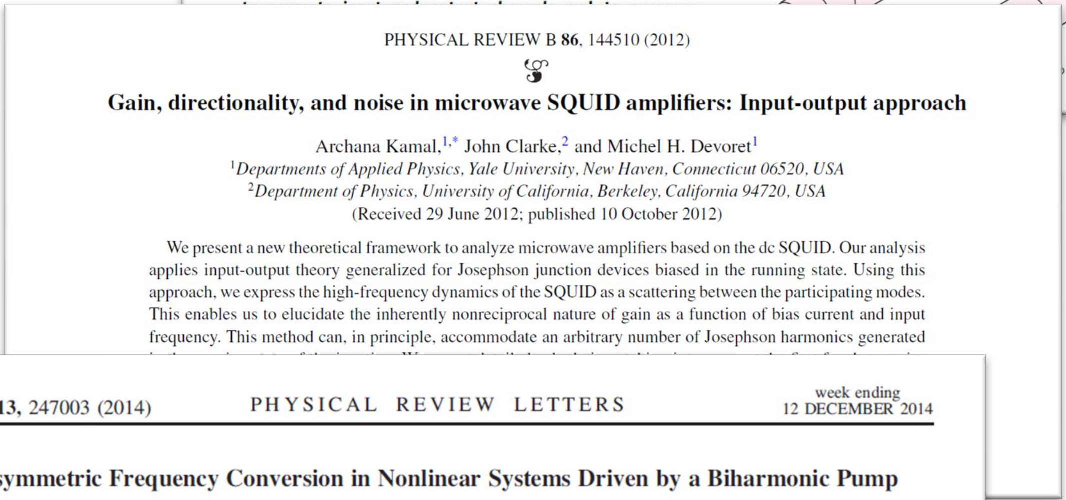
- M. Devoret, c. 2010


nature physics LETTERS
PUBLISHED ONLINE: 30 JANUARY 2011 | DOI: 10.1038/NPHYS1893

Noiseless non-reciprocity in a parametric active device

Archana Kamal[1], John Clarke[2] and M. H. Devoret[1]*

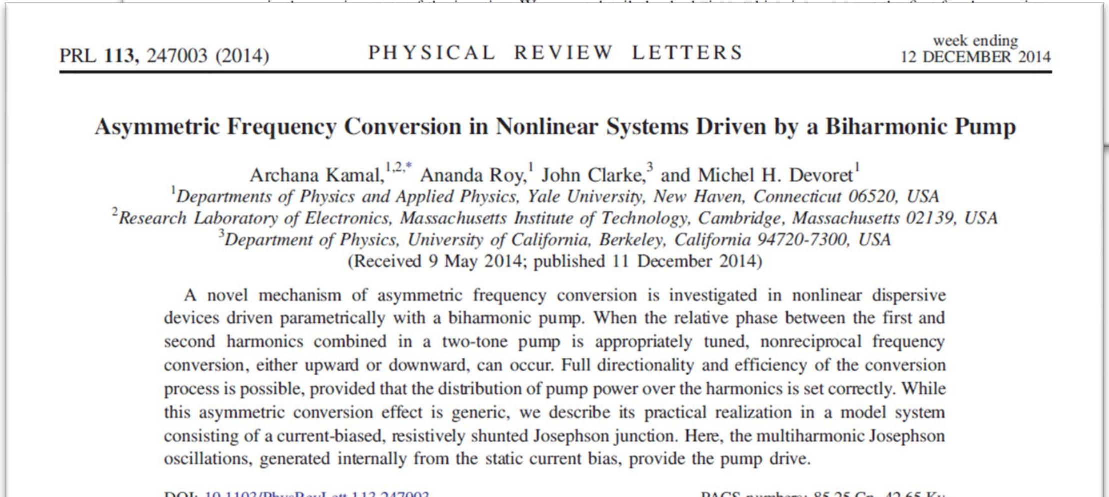
**Non-reciprocal devices such as circulators and isolators belong to an important class of microwave components employed in applications including the measurement of mesoscopic circuits at cryogenic temperatures[1-5]. The measurement protocols usually involve an amplification chain that relies on circulators**


PHYSICAL REVIEW B **86**, 144510 (2012)

**Gain, directionality, and noise in microwave SQUID amplifiers: Input-output approach**

Archana Kamal,[1,*] John Clarke,[2] and Michel H. Devoret[1]
[1]*Departments of Applied Physics, Yale University, New Haven, Connecticut 06520, USA*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*
(Received 29 June 2012; published 10 October 2012)

We present a new theoretical framework to analyze microwave amplifiers based on the dc SQUID. Our analysis applies input-output theory generalized for Josephson junction devices biased in the running state. Using this approach, we express the high-frequency dynamics of the SQUID as a scattering between the participating modes. This enables us to elucidate the inherently nonreciprocal nature of gain as a function of bias current and input frequency. This method can, in principle, accommodate an arbitrary number of Josephson harmonics generated


PRL **113,** 247003 (2014) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2014

**Asymmetric Frequency Conversion in Nonlinear Systems Driven by a Biharmonic Pump**

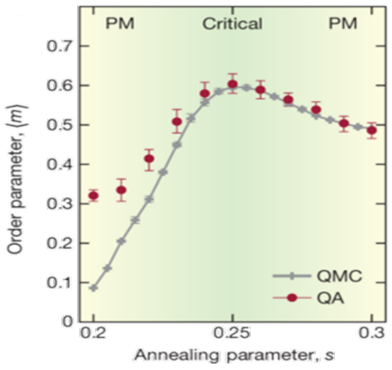
Archana Kamal,[1,2,*] Ananda Roy,[1] John Clarke,[3] and Michel H. Devoret[1]
[1]*Departments of Physics and Applied Physics, Yale University, New Haven, Connecticut 06520, USA*
[2]*Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[3]*Department of Physics, University of California, Berkeley, California 94720-7300, USA*
(Received 9 May 2014; published 11 December 2014)

A novel mechanism of asymmetric frequency conversion is investigated in nonlinear dispersive devices driven parametrically with a biharmonic pump. When the relative phase between the first and second harmonics combined in a two-tone pump is appropriately tuned, nonreciprocal frequency conversion, either upward or downward, can occur. Full directionality and efficiency of the conversion process is possible, provided that the distribution of pump power over the harmonics is set correctly. While this asymmetric conversion effect is generic, we describe its practical realization in a model system consisting of a current-biased, resistively shunted Josephson junction. Here, the multiharmonic Josephson oscillations, generated internally from the static current bias, provide the pump drive.

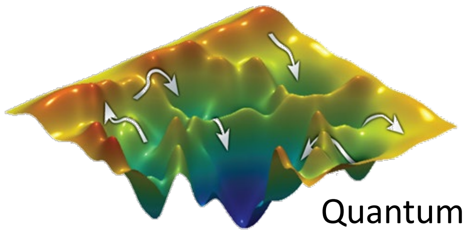
# NISQ era, c. 2025

Noisy Intermediate-Scale Quantum (NISQ) systems

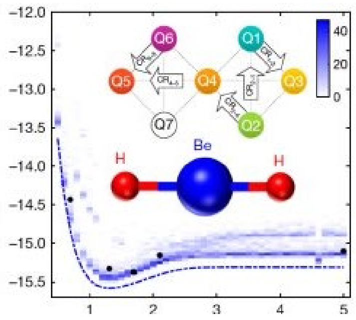
Useful applications <u>before</u> we have access to… a universal quantum computer




Quantum many-body simulation

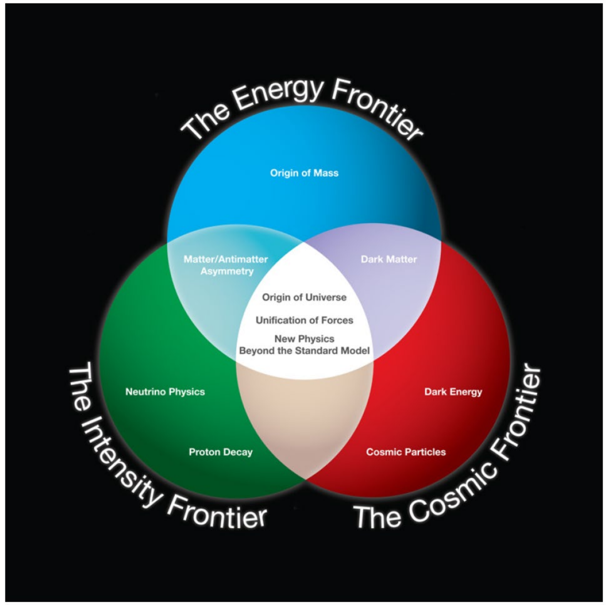


Quantum annealing and optimization




Quantum chemistry

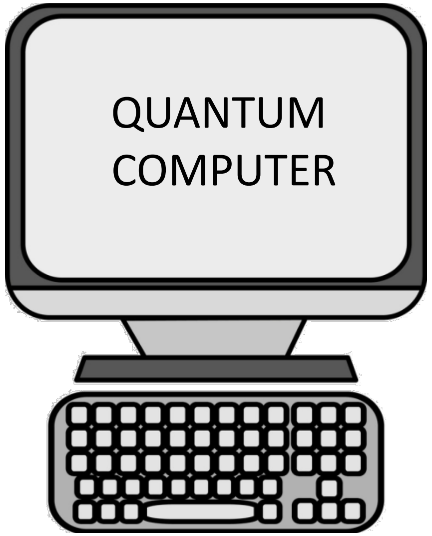
…




Strongly-interacting QFTs
Non-Abelian gauge fields,
(…beyond lattice QCD)

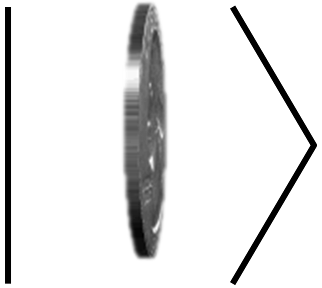
- Both analog and digital versions (QAOA, hybrid classical/quantum algorithms etc.)
- Boost using quantum ("enhanced") machine learning and neural networks..

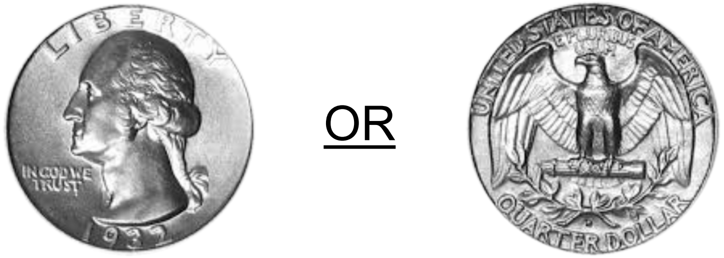
# *Decoherence challenge in the NISQ era*




ENVIRONMENT
(Uncontrolled
degrees of
freedom)

**Conflicting requirements**:
We need to protect quantum systems
while coupling them strongly to external agents



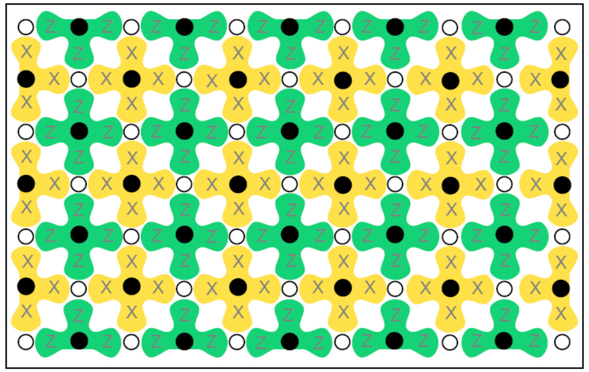


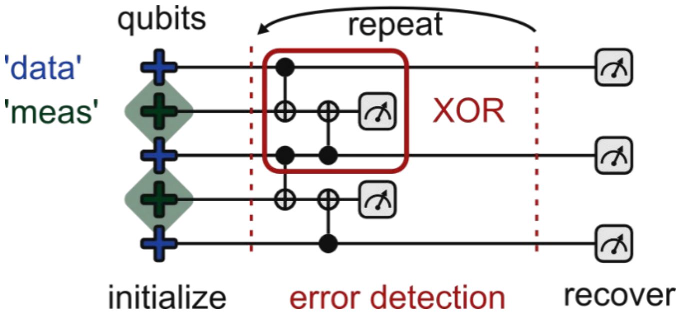

Decoherence washes out quantum effects and ultimately limits the scale of computations that can be executed accurately.

# *Decoherence challenge in the NISQ era*


**CHALLENGE**: Scaling up quantum processors while maintaining coherence and controllability

Reason we believe this can be done: **Quantum Error Correction**





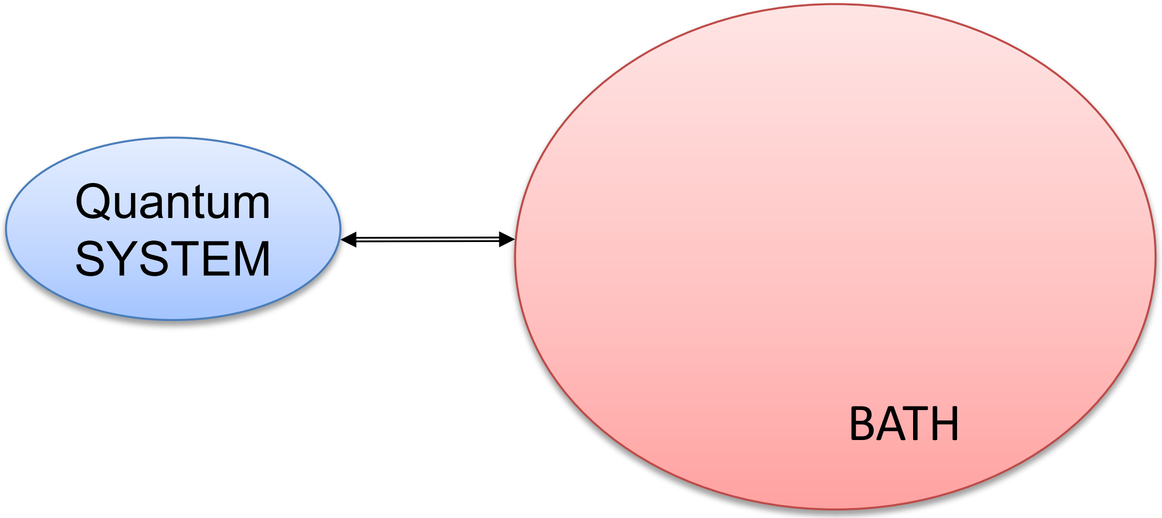

**BOTTLENECK**: Very large overhead, 1 logical qubit ↔ $10^4$ physical qubits

[Fowler, Mariantoni, Martinis, 2002]

**ALTERNATIVE/COMPLEMENTARY STRATEGIES**:

- Protected, noise-resilient qubit designs
- Advanced quantum control (Dynamical decoupling)
- Autonomous error correction

# AUTONOMOUS QEC: Quantum reservoir engineering (QRE)

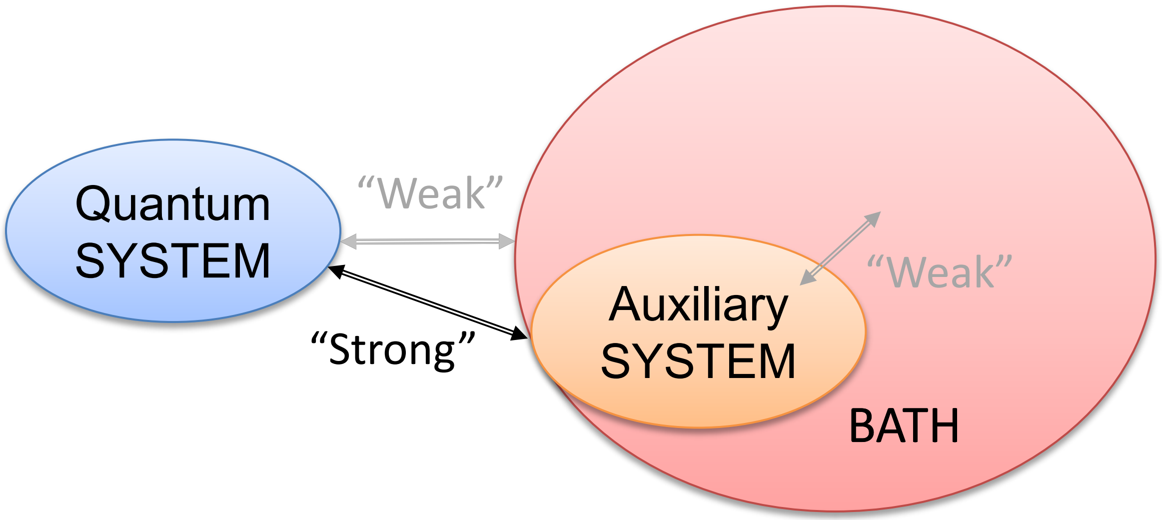




**Hamiltonian engineering:**
Beating decoherence

Suppress effect of bath via fast (than deoherence) control

and/or correct for decoherence-induced dynamics (DD, gate-based QEC)

# AUTONOMOUS QEC: Quantum reservoir engineering (QRE)




**Hamiltonian engineering:**
Beating decoherence

Suppress effect of bath via fast (than deoherence) control

and/or correct for decoherence-induced dynamics (DD, gate-based QEC)

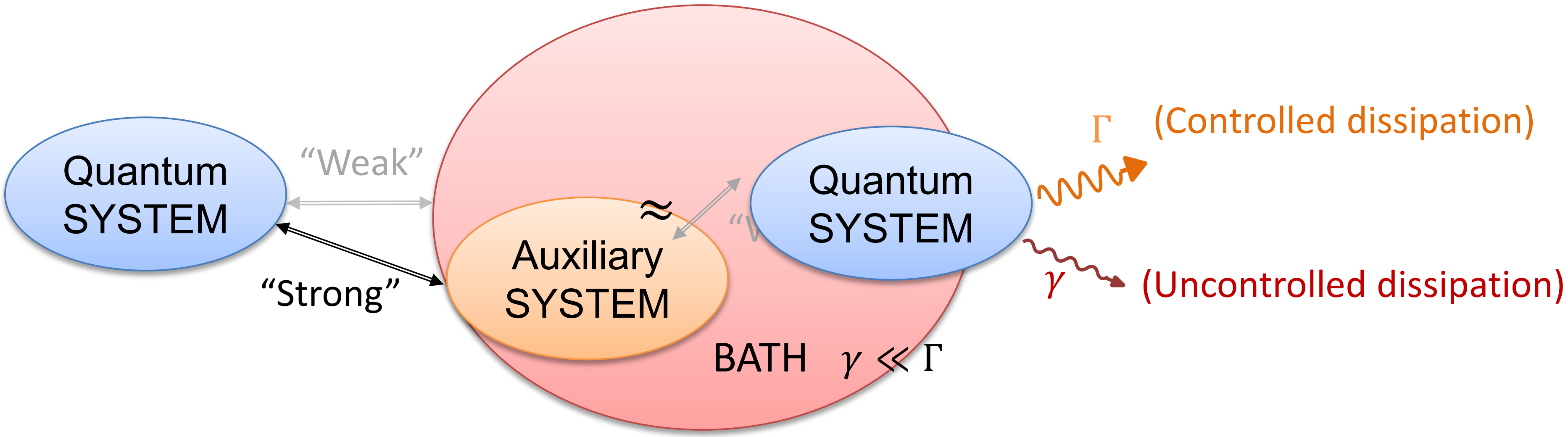
**Reservoir engineering:**
Controlled decoherence can help

Engineer dissipation work for us to steer the quantum system

$$\rho(t \to \infty) \equiv \rho_{ss} = |\Psi_D\rangle\langle\Psi_D|$$

Hopefully a non-trivial pure state!

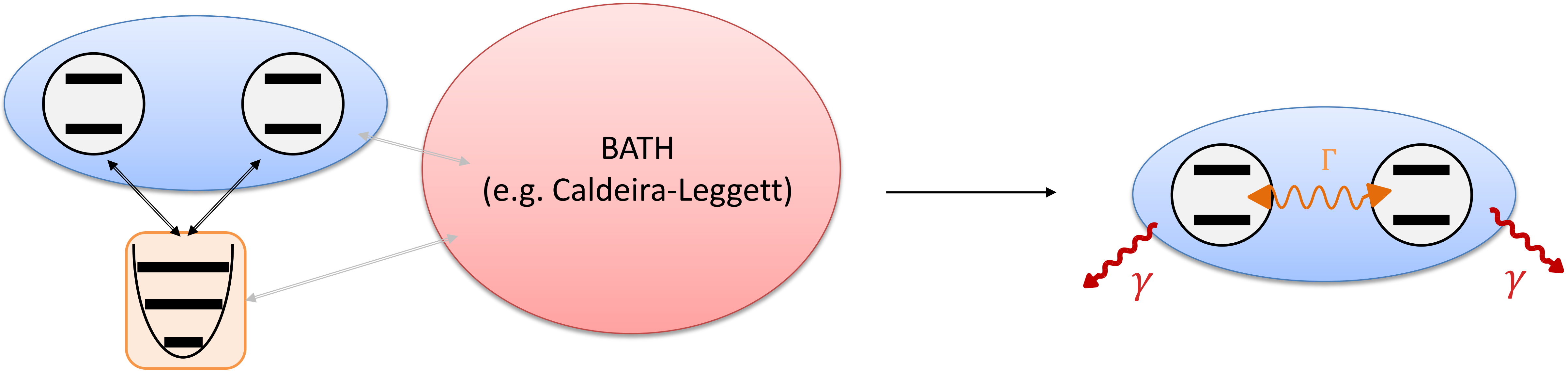
# AUTONOMOUS QEC: Quantum reservoir engineering (QRE)



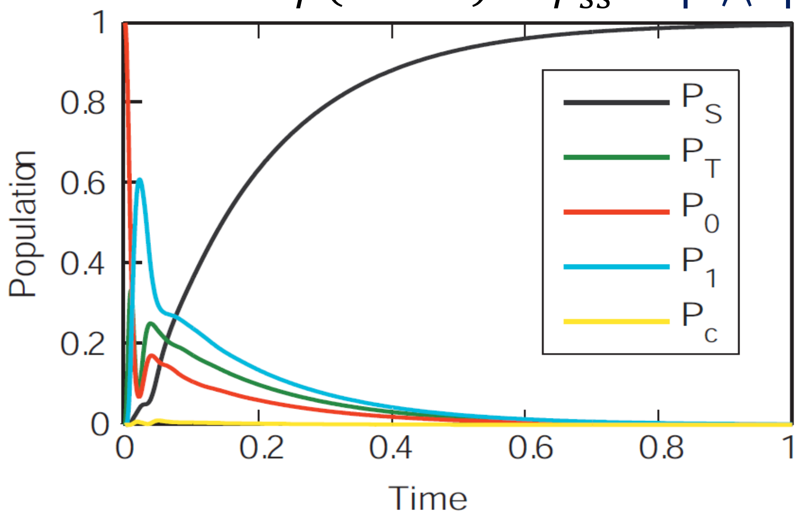

- Collective dissipation as a resource to generate non-local correlations
- The prepared state is **stable** over time and **robust** to initialization errors
- No active control or pulse engineering required → autonomous quantum error correction

Superconducting circuits
Trapped ions
Cavity-QED
Rydberg atoms
Atomic ensembles
…

# Simplest QRE: linear dissipation via a lossy bosonic mode




$\rho(t \to \infty) \equiv \rho_{ss} = |S\rangle\langle S|$

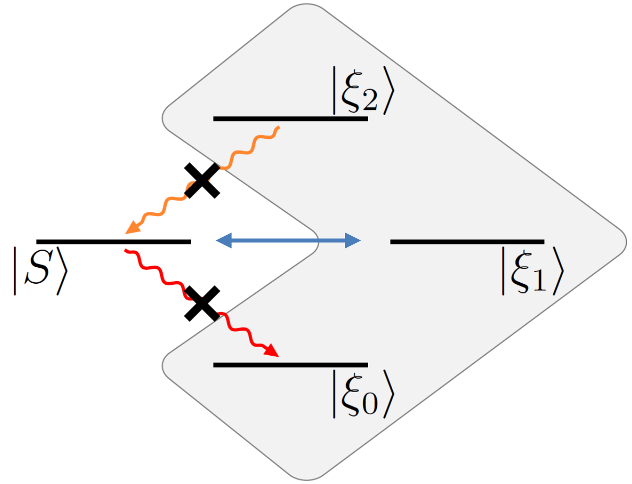



$$\dot{\rho} = -i[H, \rho] + \gamma \mathcal{D}(L)\,\rho + \sum_k \Gamma_k \mathcal{D}[c_k^{\text{eng}}]\rho(t)$$

# Perturbative approach to Dissipation Engineering

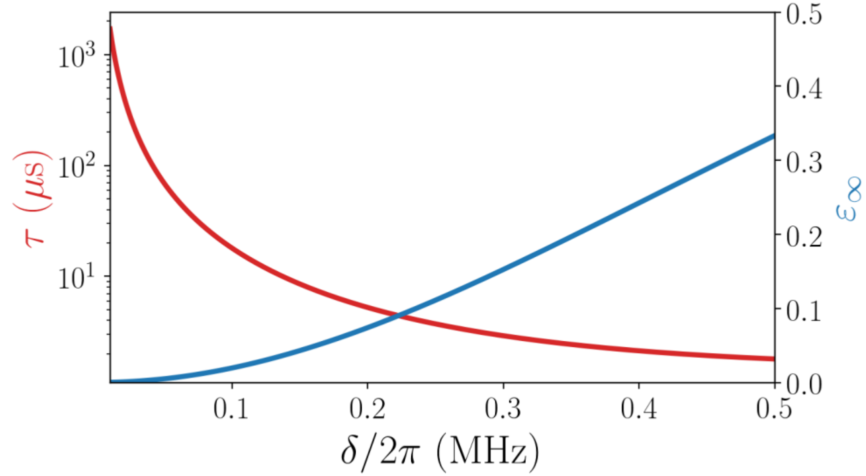
Approximate stabilization schemes involve a coherent coupling into target state to break symmetries in computational space

Wang & Schirmer, 2010; Stannigel, Rabl & Zoller, 2012



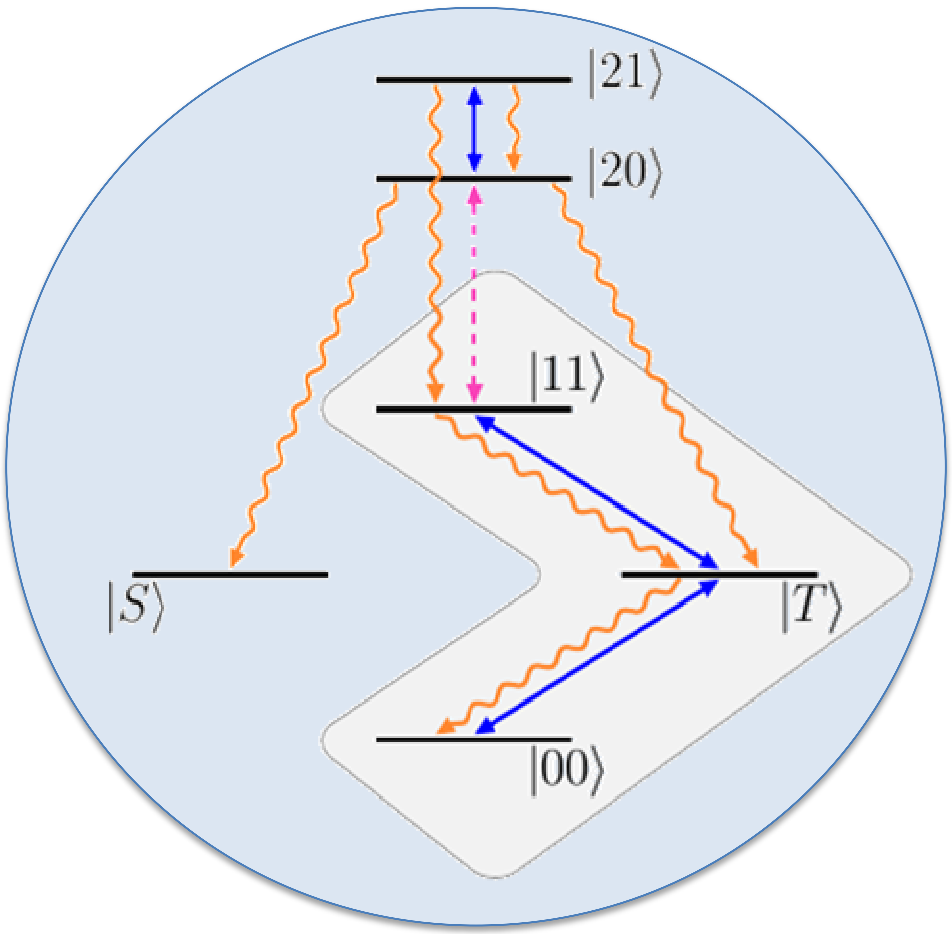

Trade-off between "speed" and "quality" of entanglement preparation

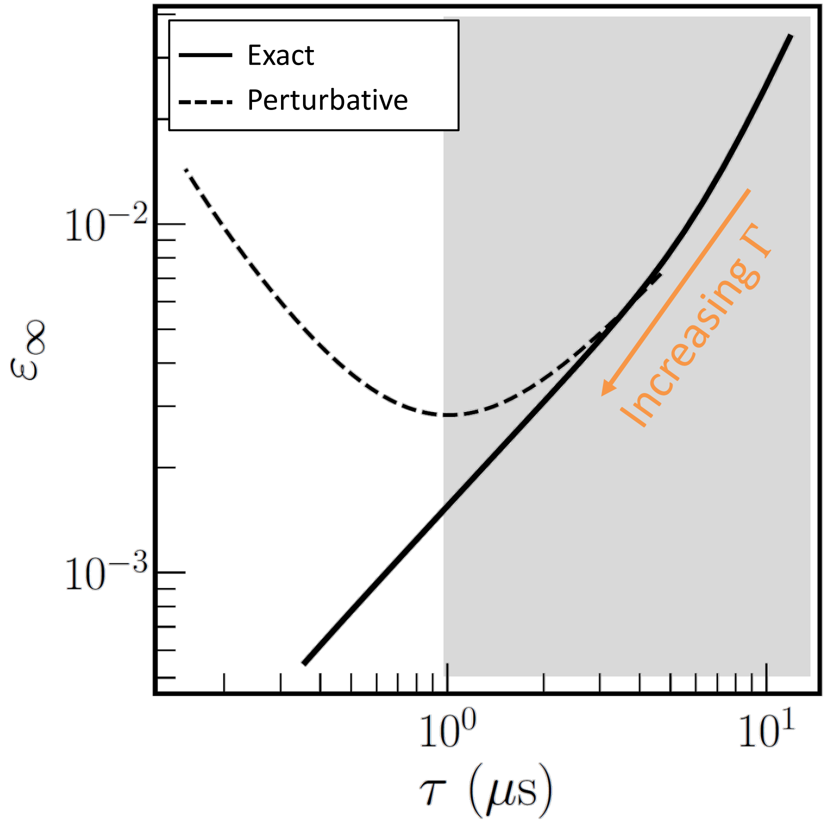
$$\varepsilon_\infty \tau \approx const.\ \gamma_T$$



# EXACT Dissipation Engineering

Breaking symmetries outside the computational space – simplest possible extension (2 x 3 = 6D $\mathcal{H}_s$)

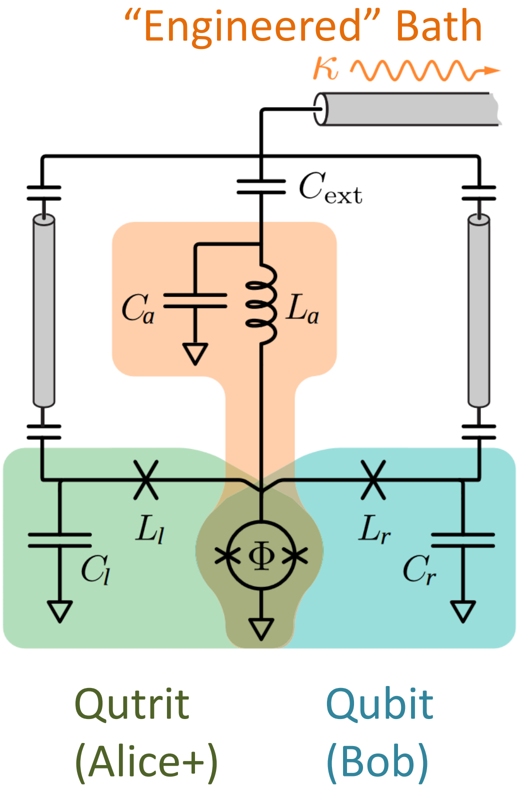


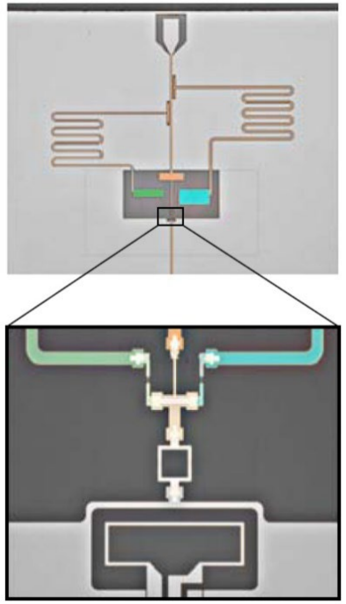



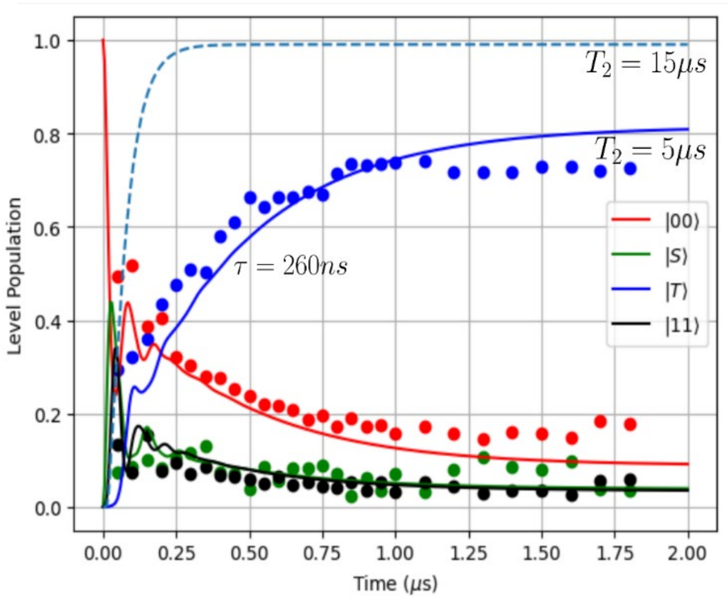

Fast *and* deterministic entanglement generation

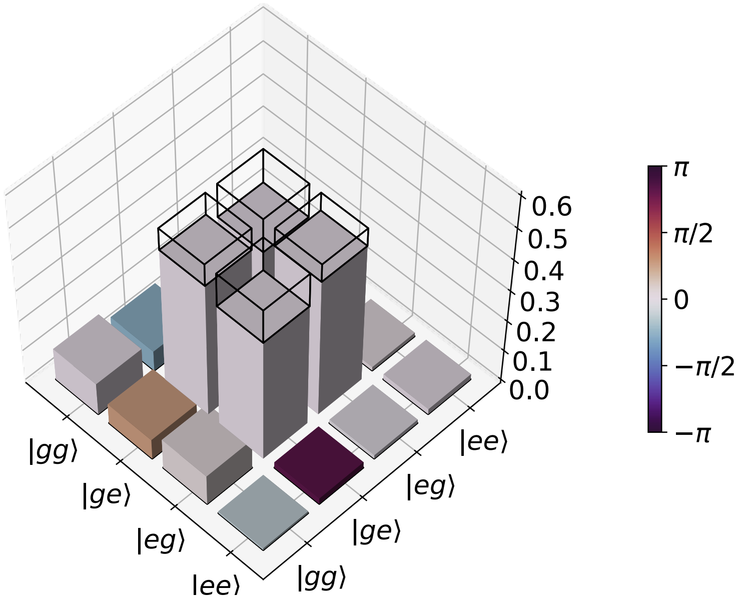
# EXACT Dissipation Engineering: circuit-QED Implementation

Experiment: Raytheon-BBN Technologies
Chip design w/ NIST Boulder






[**THY**: Doucet, Phys. Rev. Res. (2020)
**EXPT**: Brown, Nat. Comm. (2022)]

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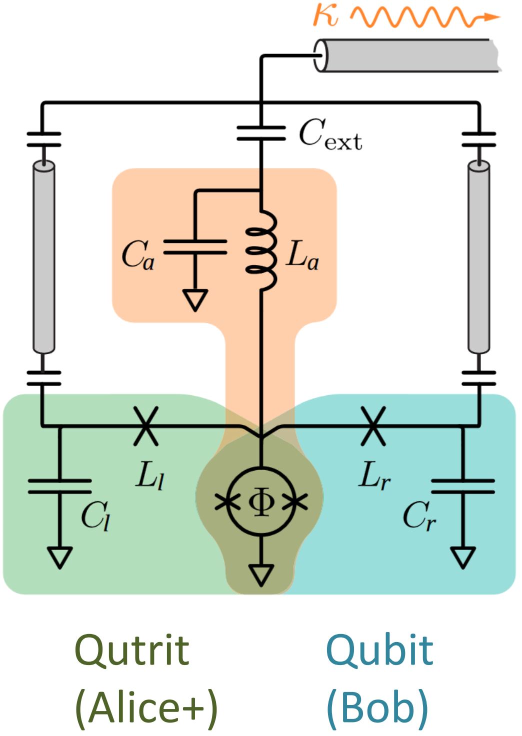
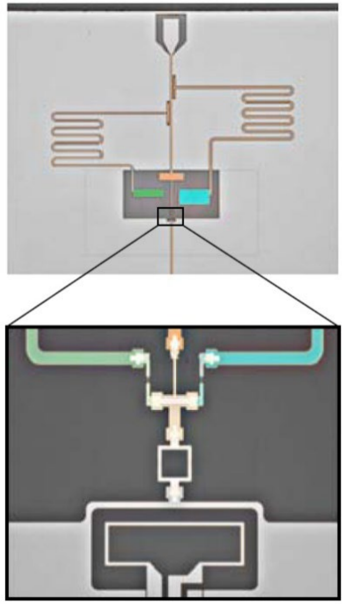
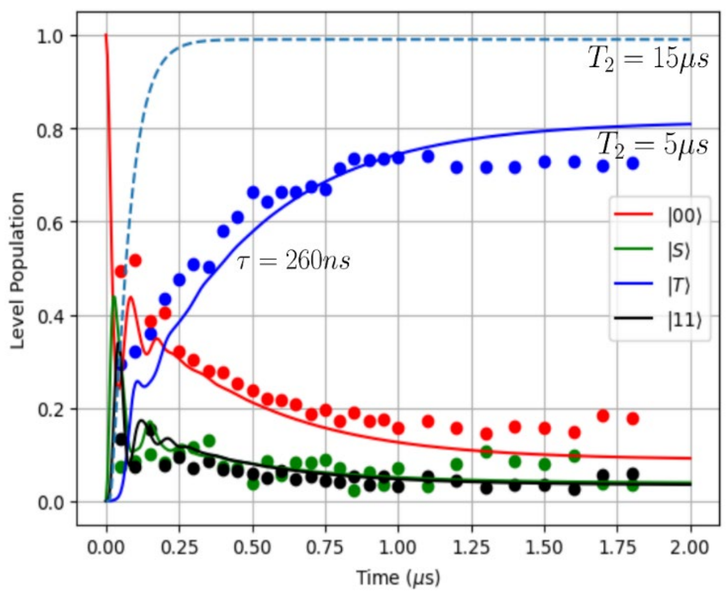
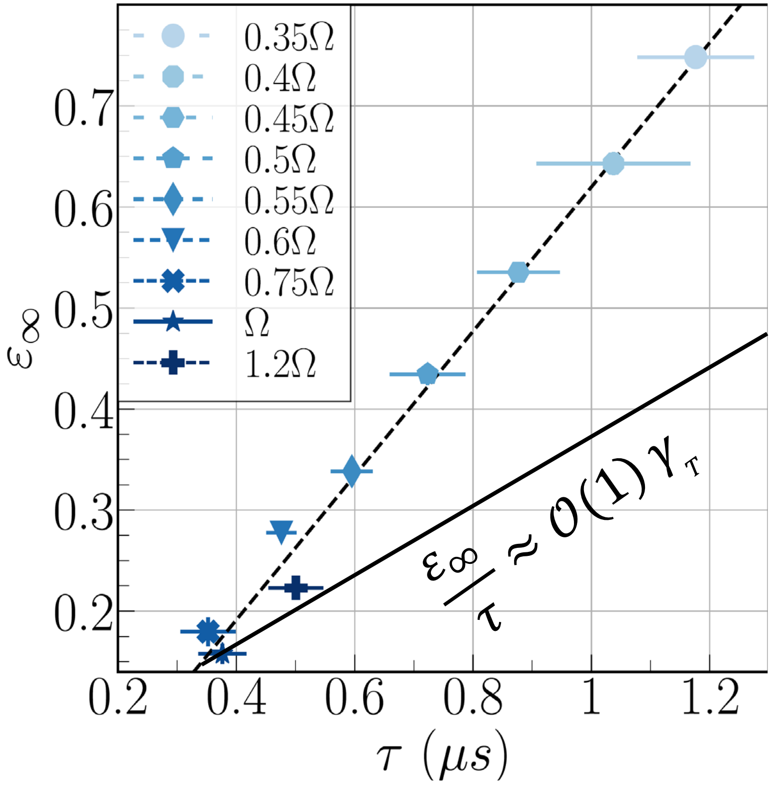




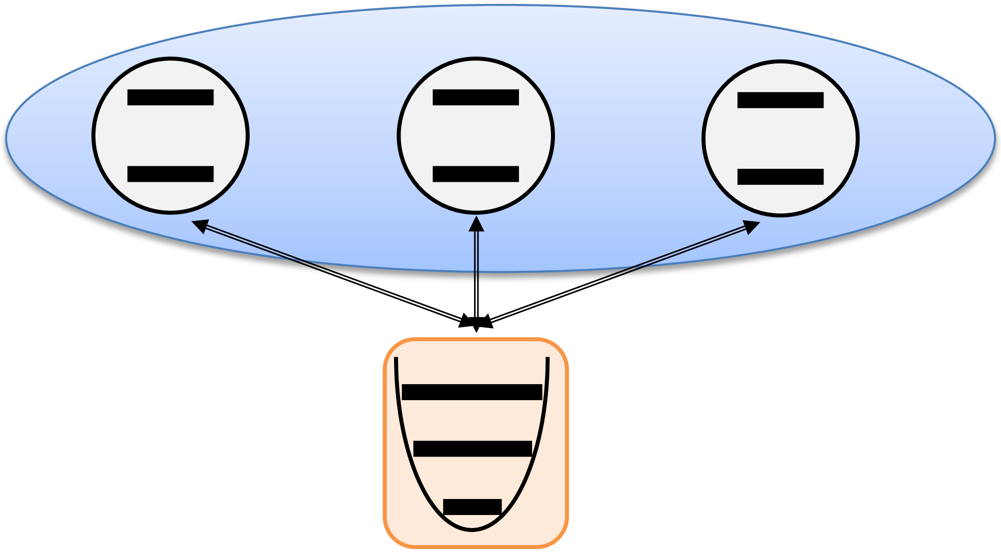

Steady state error-time scaling

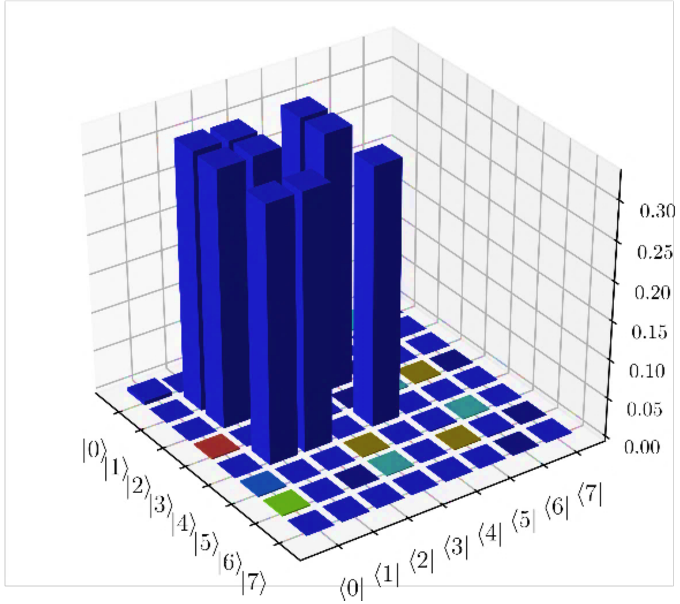


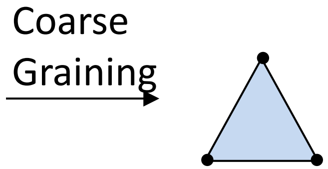

Min. error-time product in solid-state QIP platforms $\varepsilon_\infty\ \tau$ = 55 ns

[**THY**: Doucet, Phys. Rev. Res. (2020)
**EXPT**: Brown, Nat. Comm. (2022)]

# Extensions to Multipartite Entanglement





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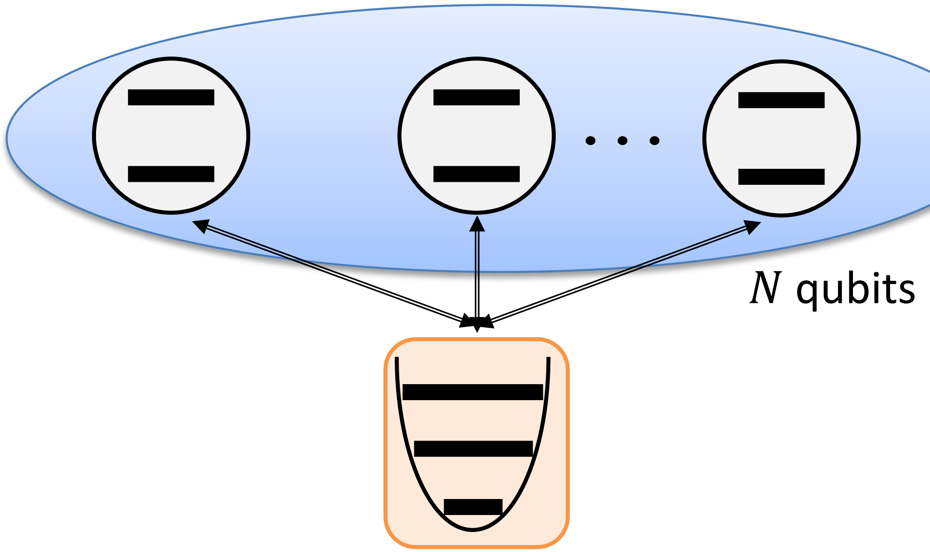
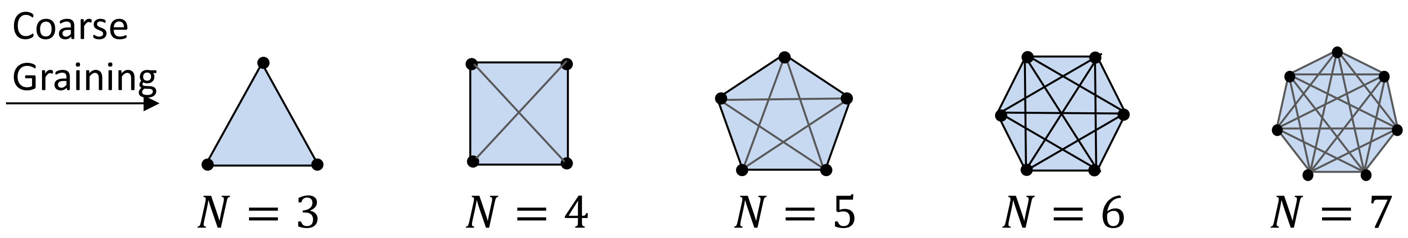
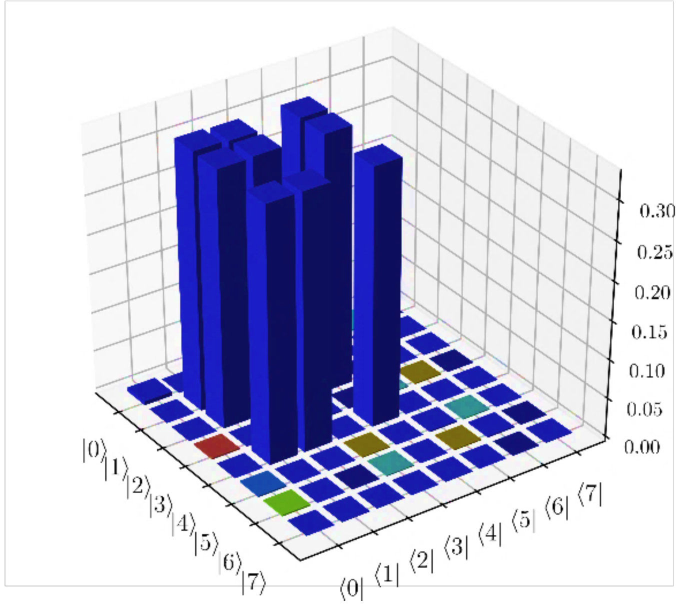
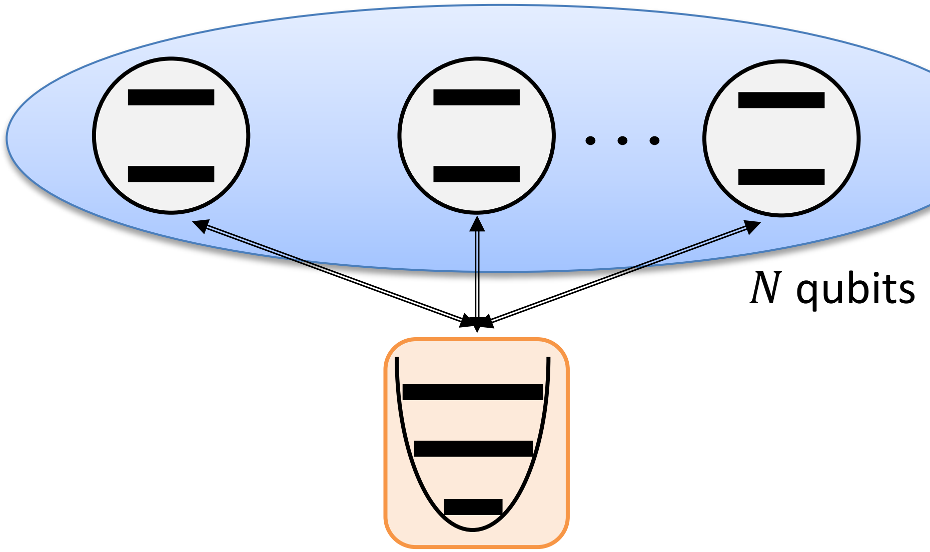
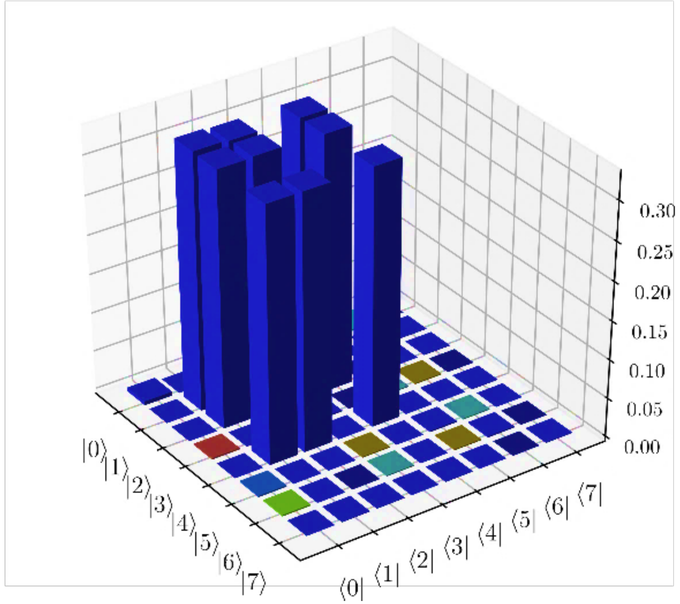


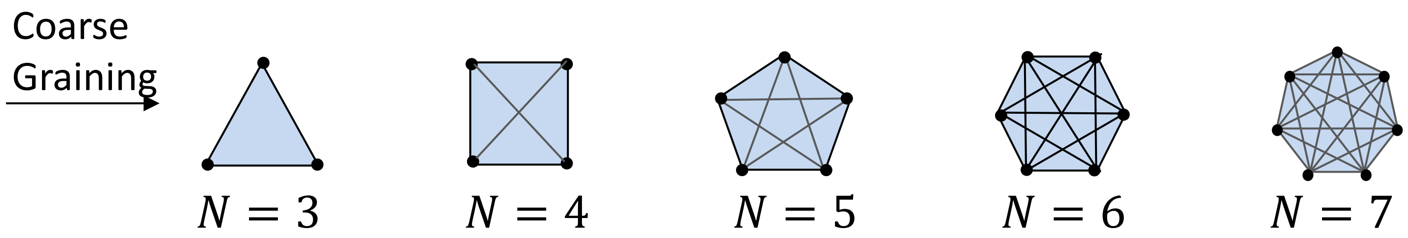



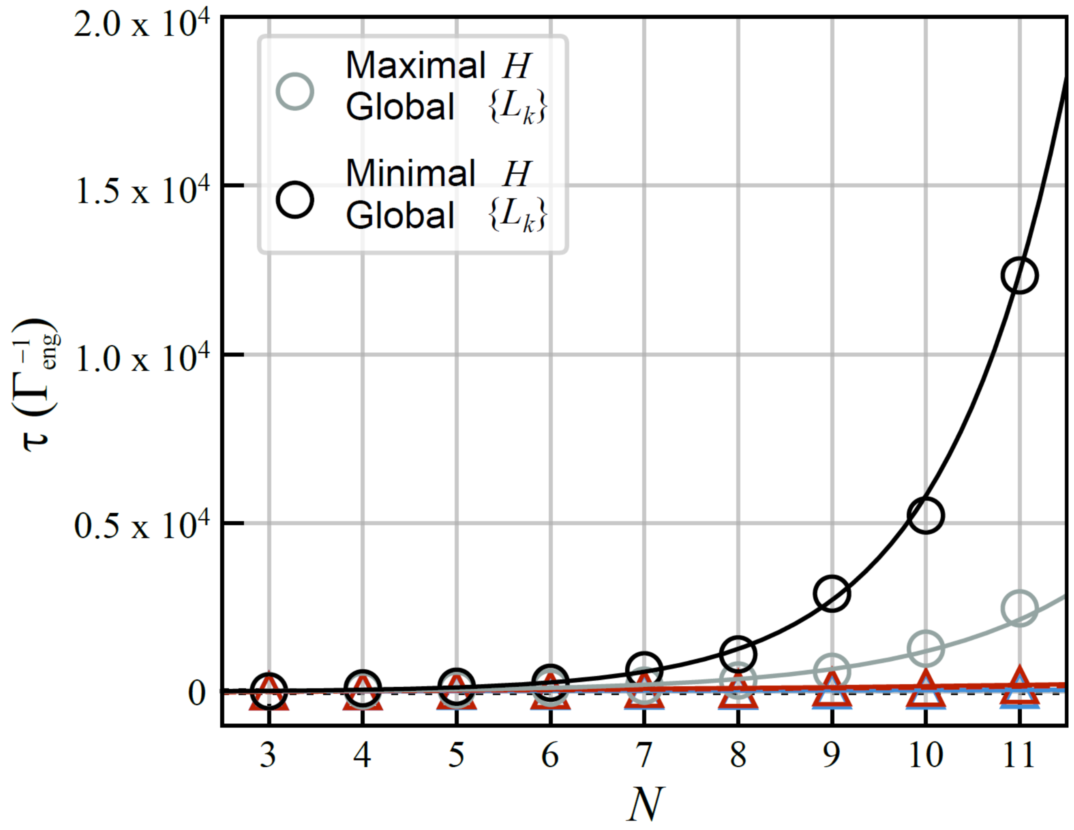



# Extensions to Multipartite Entanglement



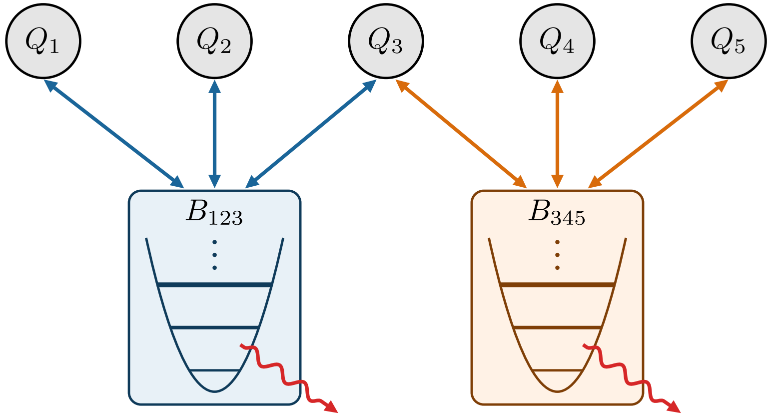






Dissipation "width", $k = N$

# Modular quantum reservoir engineering (Fixed Dissipation width)



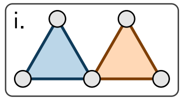

**Example**: $N = 5, k = 3$ (min. width using qubits)

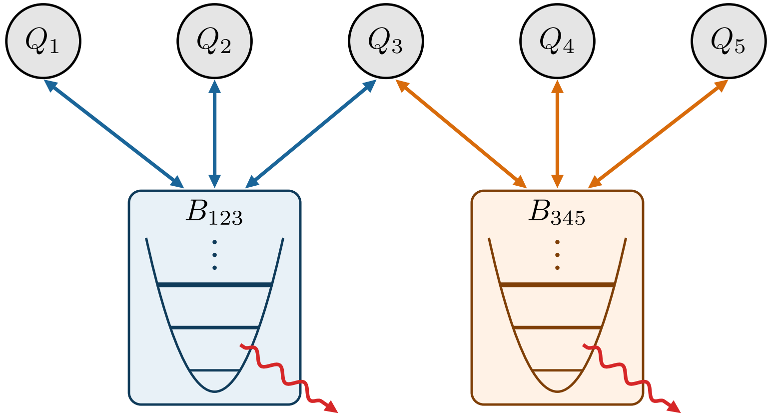
$$\mathcal{D}[r_1\hat{\sigma}_1 + r_2\hat{\sigma}_2 + r_3\hat{\sigma}_3] + \mathcal{D}[s_3\hat{\sigma}_3 + s_4\hat{\sigma}_4 + s_5\hat{\sigma}_5]$$

[Doucet, arXiv (2023)]

# Modular quantum reservoir engineering (Fixed Dissipation width)

$N_q = 5$

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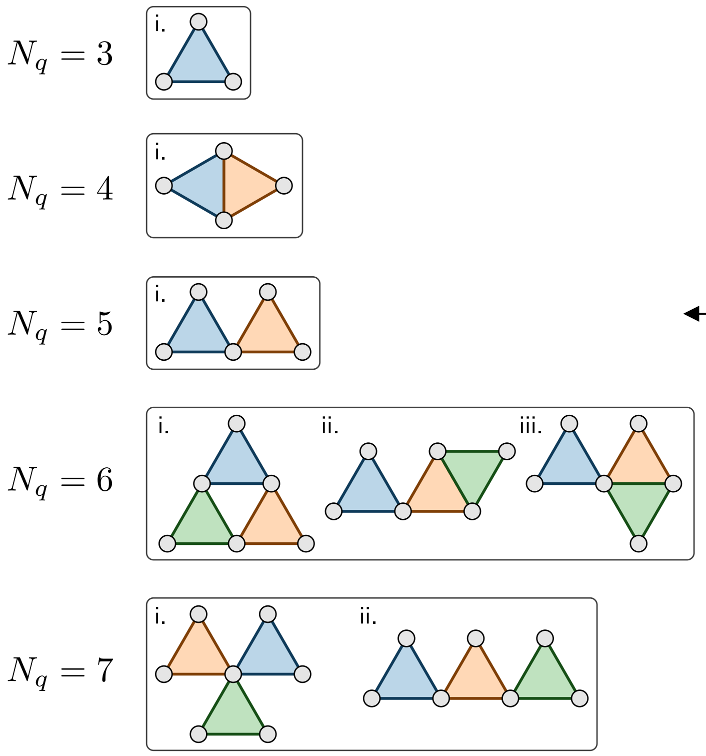


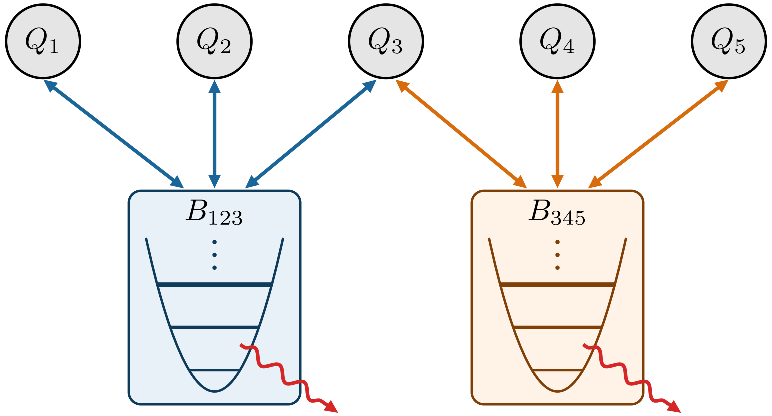


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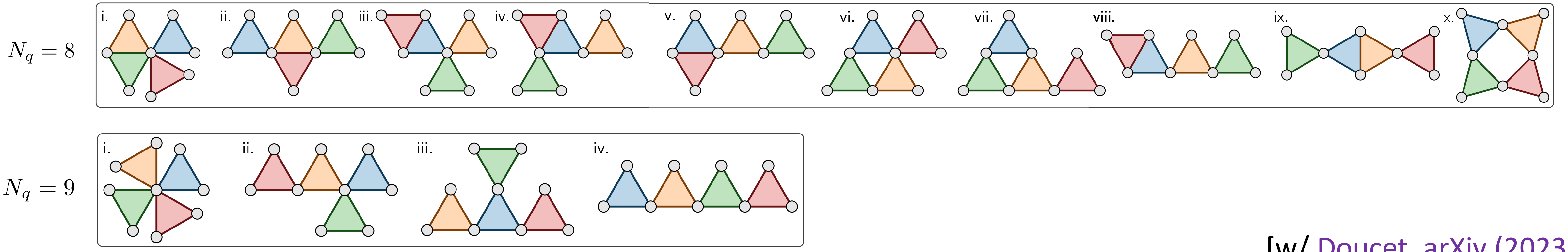
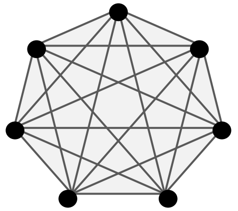


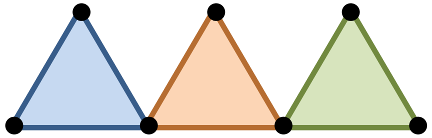

[w/ Doucet, arXiv (2023)]

# Scalable entanglement generation

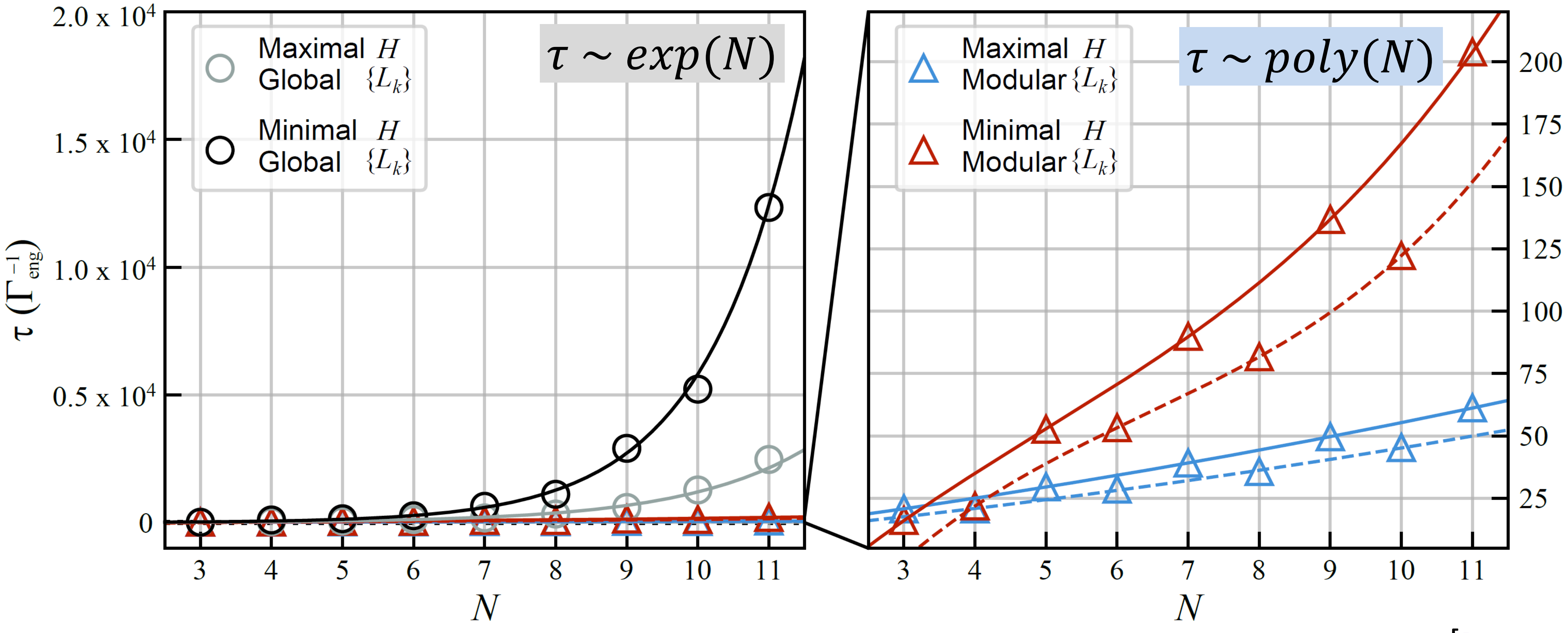
Width $k = N$



vs

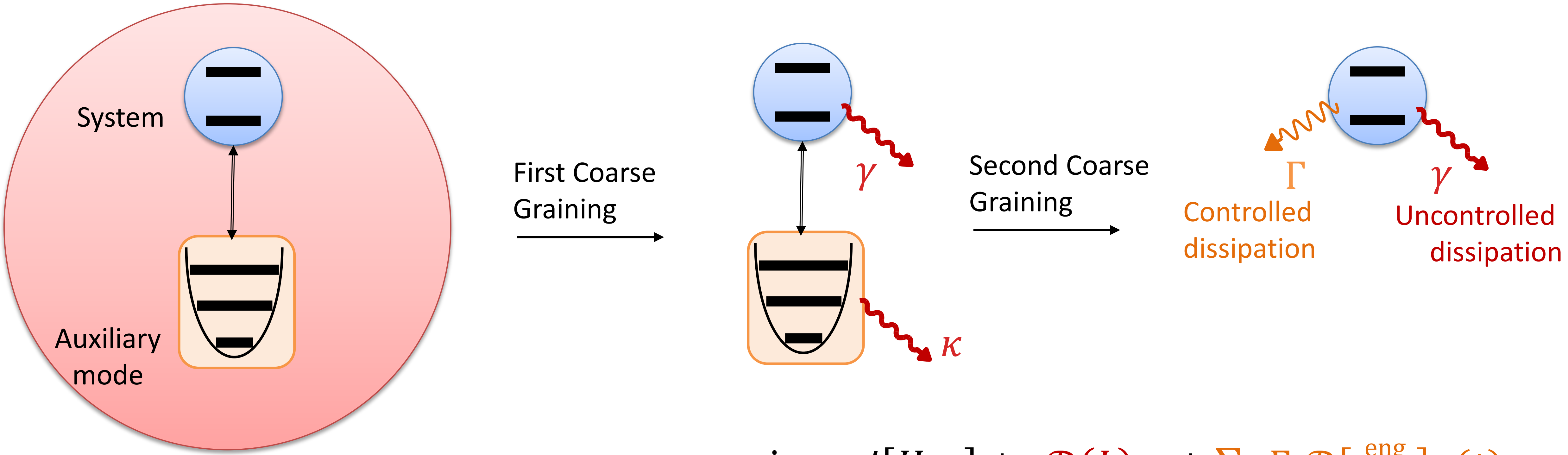


Width $k = 3$




[Doucet, arXiv (2023)]

# Simplest QRE revisited: *return of Mr. Hyde*

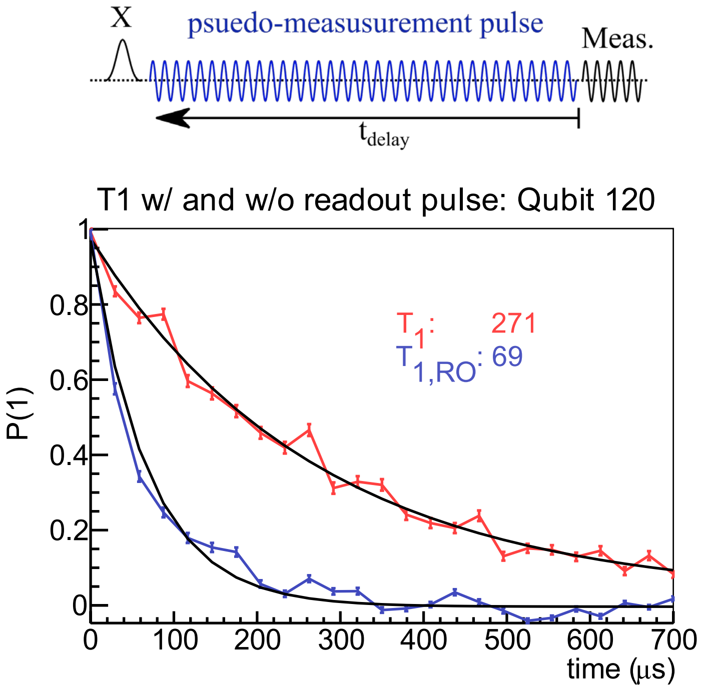



$$\dot{\rho} = -i[H,\rho] + \gamma\mathcal{D}(L)\,\rho + \sum_k \Gamma_k \mathcal{D}[c_k^{\mathrm{eng}}]\rho(t)$$

Decoherence channels interact

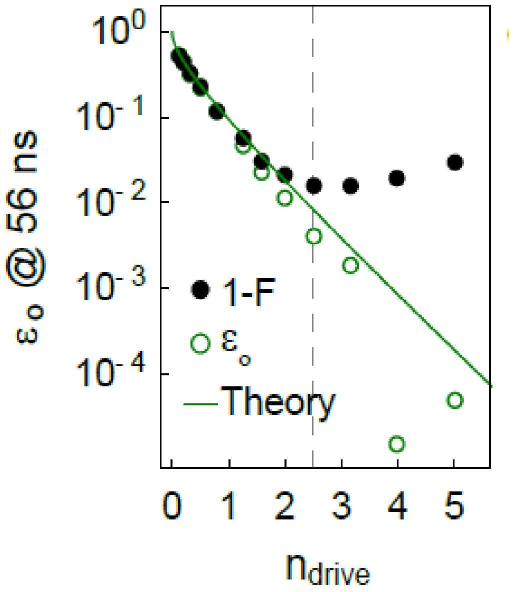
# T1 anomaly in dispersive circuit-QED

$T_1$ often changes during readout: **non-QND readout even in dispersive regime**!



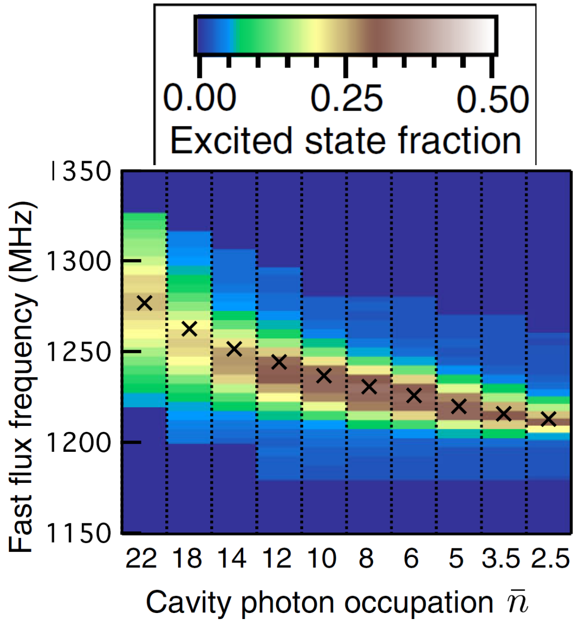

**IBM Quantum, Device: Sherbrooke**

Modified T1 with readout (usually worsens!)




**ETH 2017**

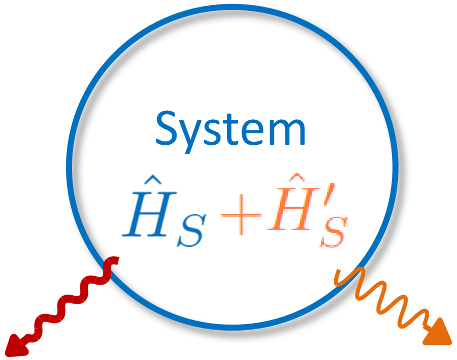
Non-monotonic scaling of SNR w/ readout strength




**Berkeley 2012**

Spurious qubit excitation

# **DISCO**: **D**issipation-**I**ncorporated **S**elf-**CO**nsistent QME




$$\gamma_s \mathcal{D}[\hat{O}_s] \qquad \Gamma_S(\gamma_s)\mathcal{D}[\hat{O}'_s]$$

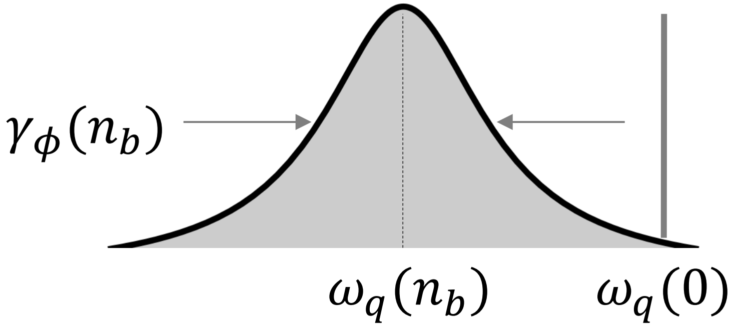

- Self-consistent treatment incorporating **ALL** intrinsic decoherence and coherent channels for quantum master equation construction
- Specifically relevant to cQED type scenarios where ancilla systems implement strong dissipation on a target quantum system
- QME takes standard CPTP form

[w/ Lakshmanan and Xiao, 2026.xxxx]

# DISCO with dispersive readout

Two effects of measurement: Stark shift **and** linewidth broadening

Qubit Dephasing: analogous to continuous measurement, entirely sets the amplitude of filter function

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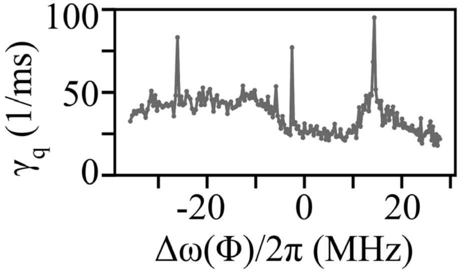


Environmental DOS

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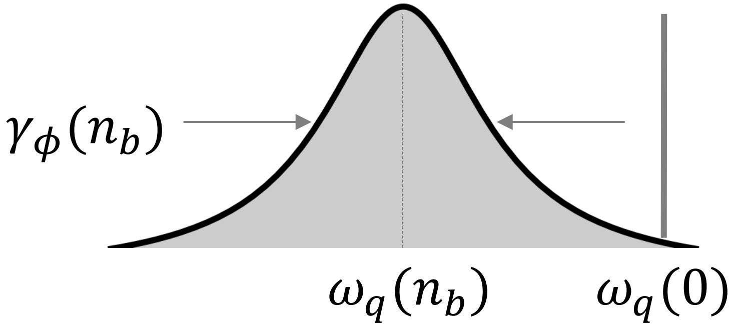


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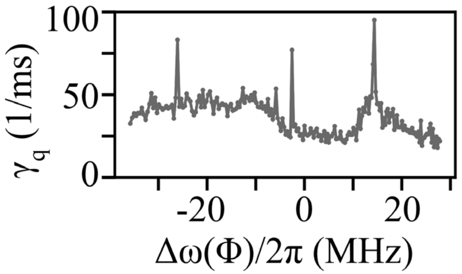
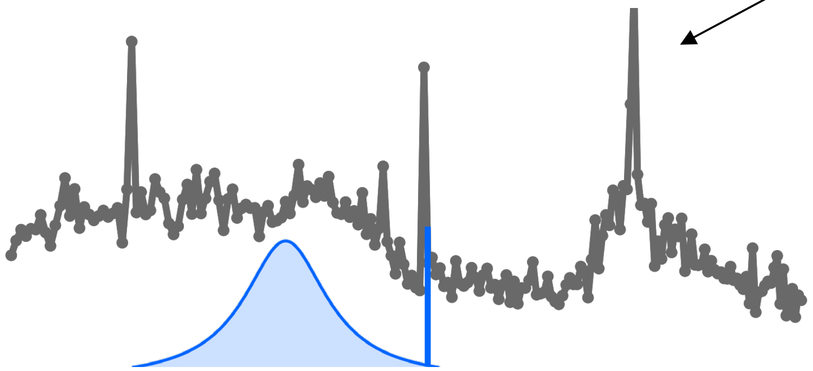
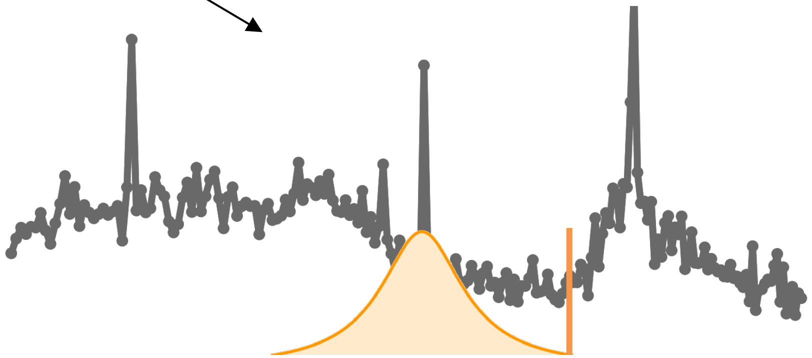



Environmental DOS





Qubit near hot spot
→ Zeno due to measurement

Qubit away from hot spot
→ Anti-Zeno due to measurement

# DISCO with dispersive readout

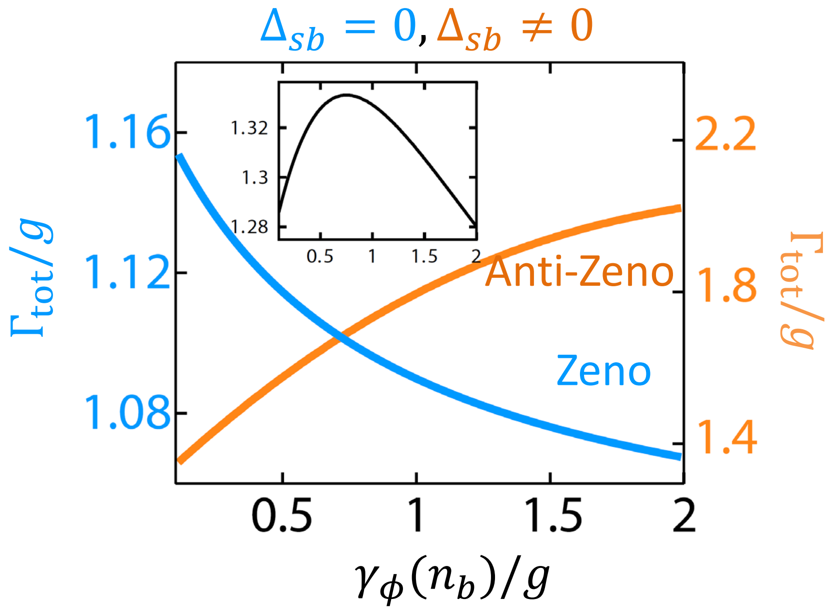
**QZE induced corrections manifest** even for undriven two-level approximation – distinct from multi-level ionization

$$\Gamma_s = 4g^2 \frac{(4\gamma_\phi + \gamma_b)}{(4\gamma_\phi + \gamma_b)^2 + 4(\omega_b - \omega_s)^2}$$

$\sim \frac{g^2}{\gamma_\phi}$ Near resonant w/ bath mode

$\sim 4\gamma_\phi \frac{g^2}{\Delta^2}$ Off resonant w/ bath mode

T1 modification due to readout is like a dephasing-mediated self-Purcell




[Thorbeck, Phys. Rev. Lett. (2024); New review: arXiv:2506.12679 – signatures of A/QZE on quantum trajectories]

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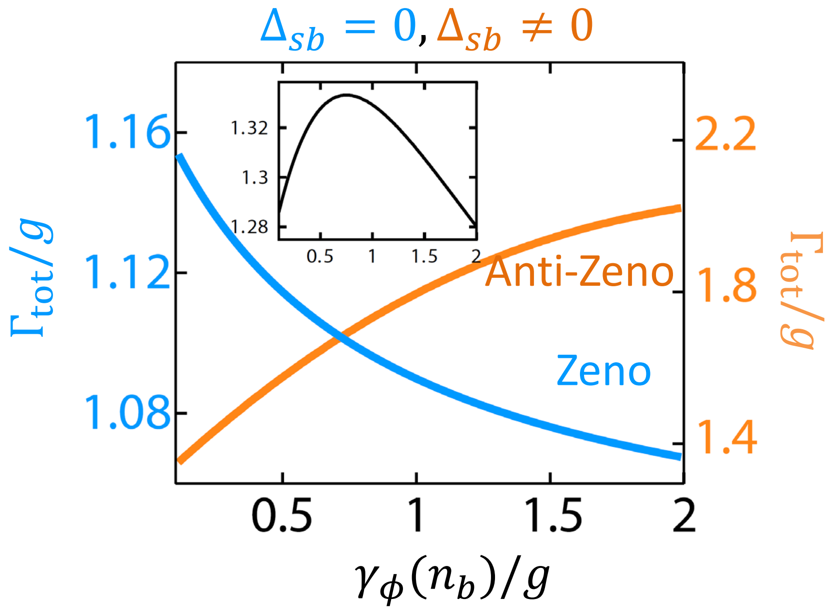
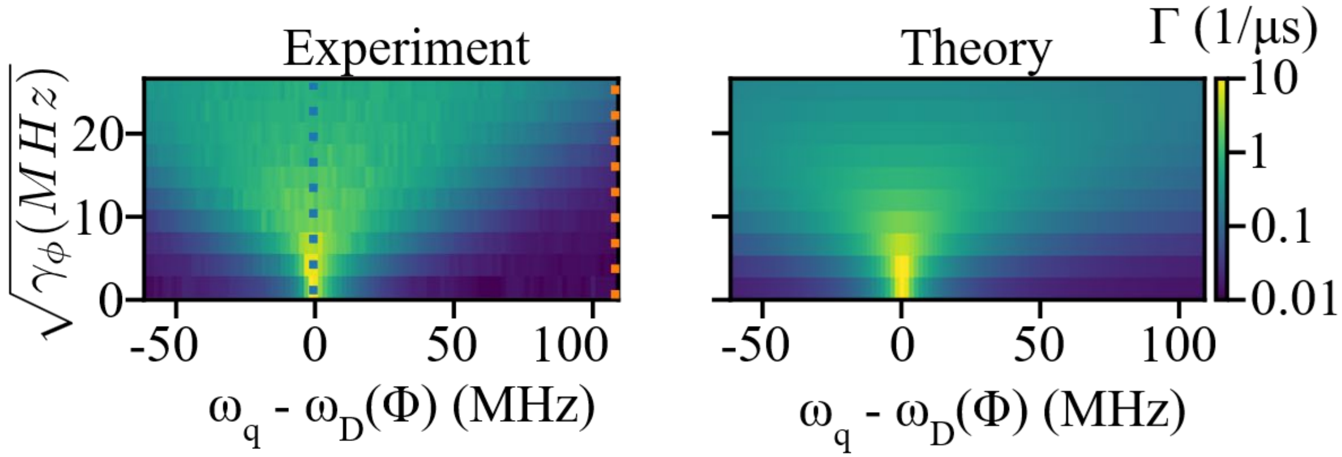
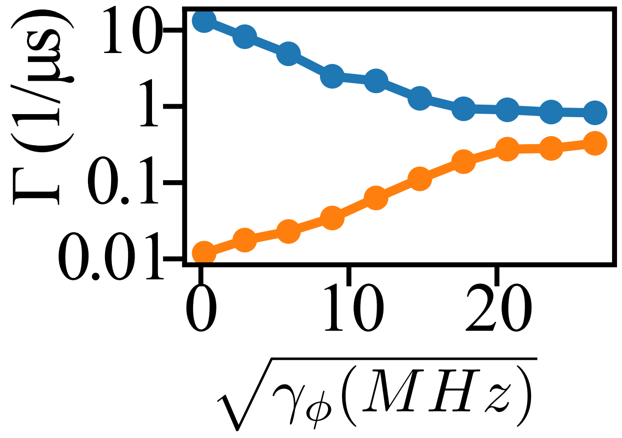



**Experiment**: IBM Quantum




[Thorbeck, Phys. Rev. Lett. (2024); New review: arXiv:2506.12679 – signatures of A/QZE on quantum trajectories]

**Q**. Is decoherence good or evil?

**Answer**. Yes

Thanks for your attention.