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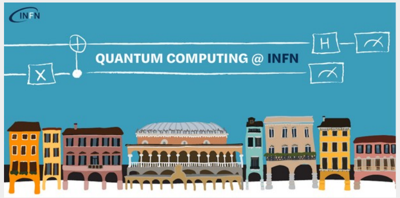
Uni ct FISICA E ASTRONOMIA "ETTORE MAJORANA"
INFN

Noise in superconducting quantum computing devices

a very partial overview of old and new results



Quantum Computing @ INFN
October 29-31 2024, Padova • Italy

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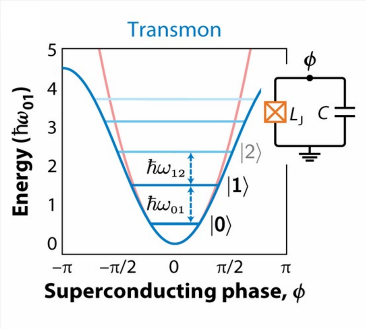
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
NQSTI National Quantum Science and Technology Institute

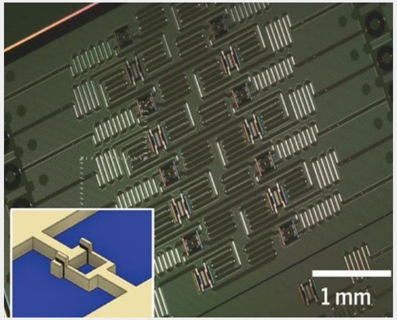
Superconducting hardware

- Qubits based on Josephson Ju ctions (JJ)
  - Wirable artificial atoms
  - Flexibility in design solutions
  - All-superconducting & hybrid systems
  - Prototype circuit: rf-SQUID

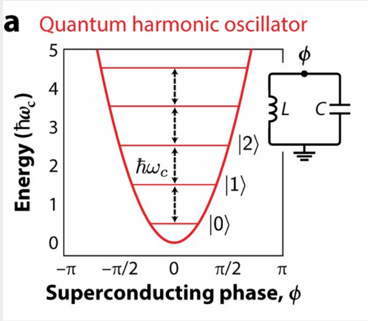
$$H_0 = \frac{(Q - Q_x)^2}{2C} - E_J \cos\frac{2\pi\Phi}{\Phi_0} + \frac{(\Phi - \Phi_x)^2}{2L}$$

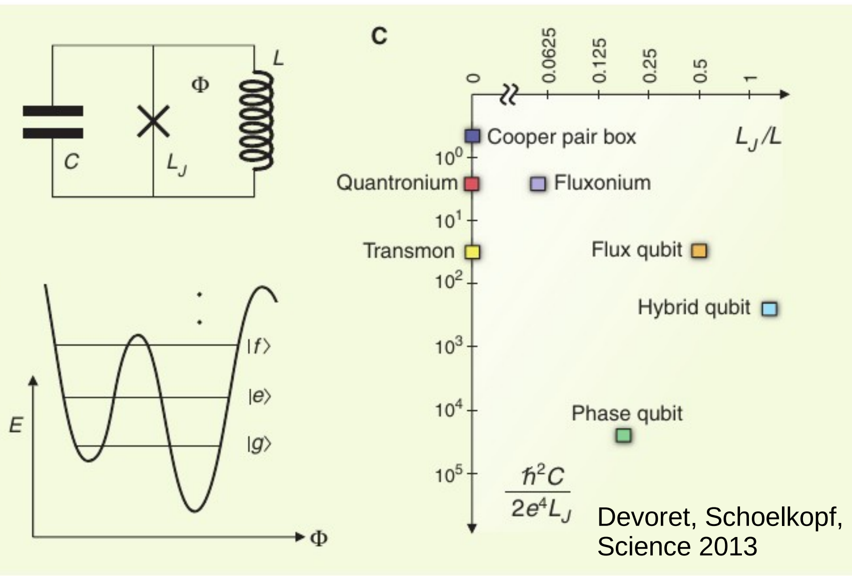
- Resonators
  - Superconducting microstrip transmission line
  - JJ-based LC circuit
  - Superinductors





De Leon et al., Science 2021

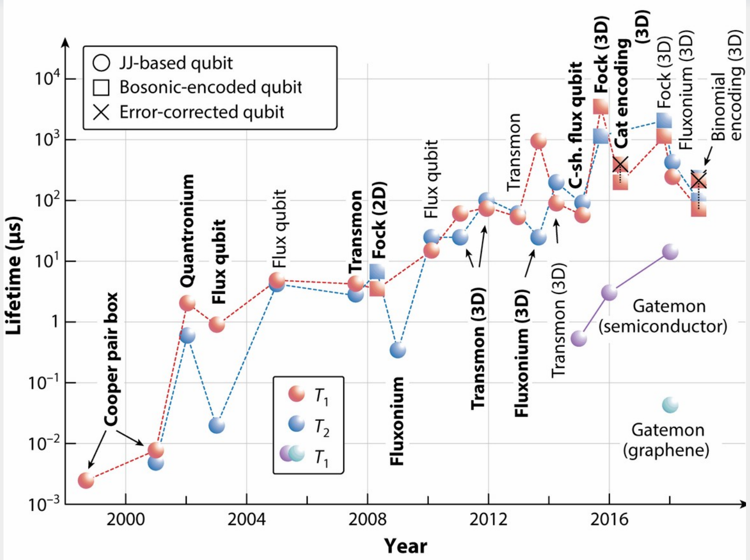




Devoret, Schoelkopf, Science 2013

Decoherence

- What: loss of coherence in an open system
  - Physically due to additional degrees of freedom to be traced out
  - Reduction to a DM, in the basis of the observable coupling to the “pointer”
  - General treatments
- Trend in one and two qubits
  - Single qubit coher. times > 1 ms
    - rather well understood, optimized device design
  - scalable manufacturing
  - Upscaling: NISQ, what about QEC ? $\approx 1\,\mu s$
- Trend in Resonators
  - Larger coherence times → cat state qubits

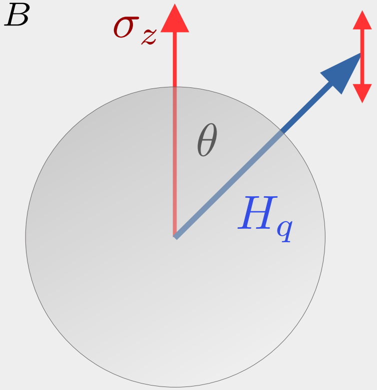


Kjaergaard et al.,   Annu. Rev. Condens. Matter Phys. 2020

Requirement for scalability	Desired capability margins	Estimated current capability	Demonstrated successful performance
QI operation			
Reset qubit	10^2 to 10^4	50	Fidelity ≥ 0.995 (*17*)
Rabi flop	10^2 to 10^4	1000	Fidelity ≥ 0.99 (*69, 70*)
Swap to bus	10^2 to 10^4	100	Fidelity ≥ 0.98 (*71*)
Readout qubit	10^2 to 10^4	1000	Fidelity ≥ 0.98 (*51*)
System Hamiltonian			
Stability	10^6 to 10^9	?	$\delta f/f$ in 1 day < 2×10^{-7} (*43*)
Accuracy	10^2 to 10^4	10 to 100	1 to 10% (*43*)
Yield	$>10^4$	?	?
Complexity	10^4 to 10^7	10?	1 to 10 qubits (*61*)

Markovian Master Equation → single-qubit noise metrics

- **Quantum Markovian ME** (Bloch, Wangness, Redfield) $H = H_q + \frac{1}{2}\sigma_z \otimes \hat{B} + H_B$



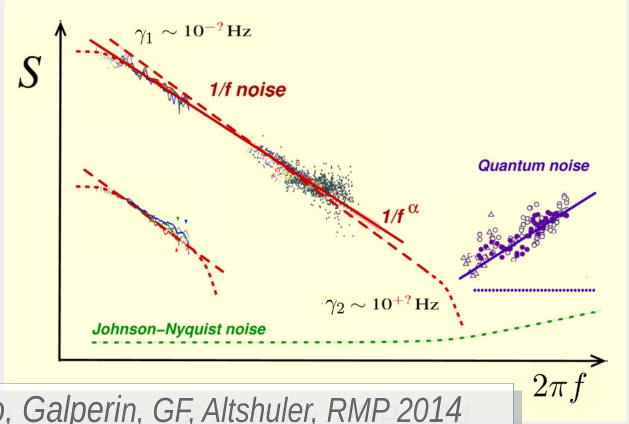
  - von Neumann + **Born-Markov** approx ($b\tau_c \ll 1$) $\frac{d\rho_{ij}(t)}{dt} \approx -i\omega_{ij}\rho_{ij}(t) + \sum_{lm} \mathcal{R}_{ijlm}\rho_{lm}(t)$
  - secular approximation
    - Non-secular **dephasing** $1/T_\phi = \frac{1}{2}\cos\theta\, S(0)$
    - **Relaxation** $1/T_1 = \frac{1}{2}\sin\theta\, S(\Omega)$

    → **overall dephasing** $1/T_2 = 1/(2T_1) + 1/T_\phi$

  - FT of the symmetrized correlation functions ↔ **noise power spectrum**

$$S(\omega) = \frac{1}{2}\langle \hat{B}(t)\hat{B}(0) + \hat{B}(0)\hat{B}(t)\rangle_\omega = J(\omega)\coth\frac{\omega}{2k_BT}$$

- 1/f noise → failure of Born-Markov
  - Non-secular dephasing rate $\propto S(0)$ **diverges**
  - "phase diffusion" dephasing time T_ϕ calculated beyond Born-Markov
  - **Tansverse noise** $\theta = \pi/2$ pure **dephasing is minimized** → **sweet spot**



Paladino, Galperin, GF, Altshuler, RMP 2014
adapted from Bylander et al., Nat. Phys 2011

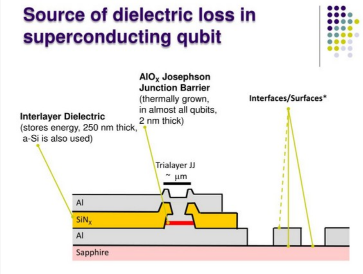
Phenomenological Hamiltonian

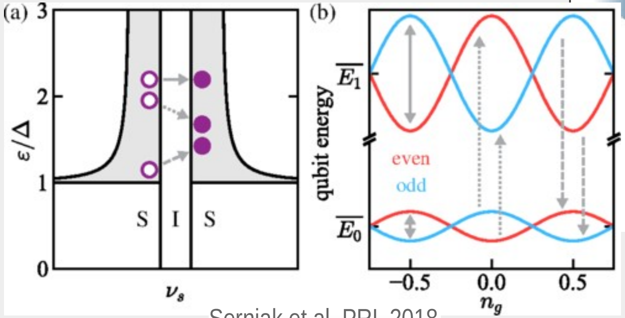
- Tunability **opens "ports"** to decoherence
- Convenient sufficiently general form $H_{tot} = H_0 + H_c(t) + H_n(t) + H_B + H_{int}$
- System $H_0[\mathbf{q}] = \sum_i \epsilon_i(\mathbf{q}) \, |\phi_i(\mathbf{q})\rangle\langle\phi_i(\mathbf{q})|$
  - **Bias** parameters $\mathbf{q}$ and **coupling constants**
    - eg. SQUID design $H_0 = \frac{(Q - Q_x)^2}{2C} - E_J \cos\frac{2\pi\Phi}{\Phi_0} + \frac{(\Phi - \Phi_x)^2}{2\,L}$
- Control $\mathbf{q} \to \mathbf{q}(t)$; $H_0[\mathbf{q}(t)] =: H_0[\mathbf{q}] + H_c(t)$
- Classical noise: add $\delta\mathbf{q}_{sl}(t) + \delta\mathbf{q}_f(t) \quad \to \quad H_0[\mathbf{q}(t) + \delta\mathbf{q}_{sl}(t)] + H_f(t)$
- Environment: add a "quantized" $H_c(t) \to \sum_\alpha \hat{Q}_\alpha \, \hat{B}_\alpha + H_B$
  - eg. flux noise in SQUID $\to \hat{\Phi} \, \hat{B}_\alpha + H_B$

Paladino, Galperin, GF, Altshuler, RMP 2014

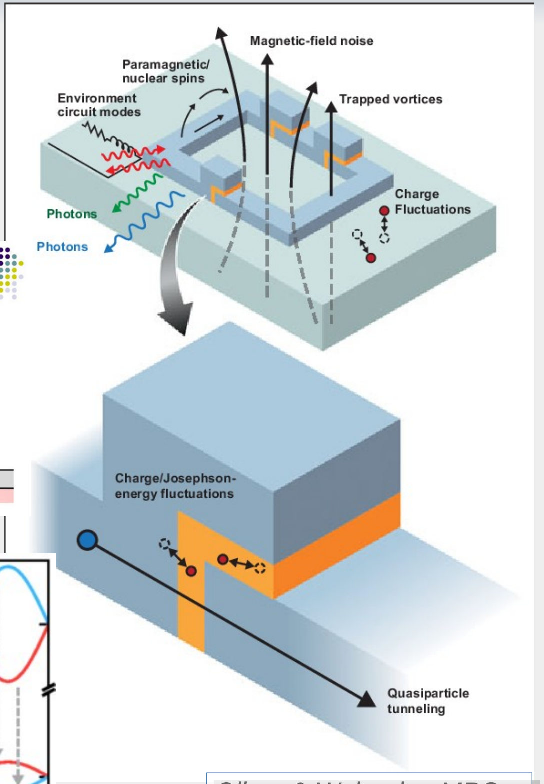
Noise sources in superconductin q-circuits

- Physical source → noise injected from a “port” of the device
- Impurities (coherent, incoherent → 1/f)
  - In the junction 1/f, offset drift
- Dielectric loss
  - Electric field in the dielectric ↔ capacitance fluctuations
  - Via two-level fluctuator in the (glassy) substrate
  - Relevant for resonators
- Quasiparticles
  - Nonequilibrium & leakage
- Upscale architectures: leakage from computational space





Serniak et al. PRL 2018

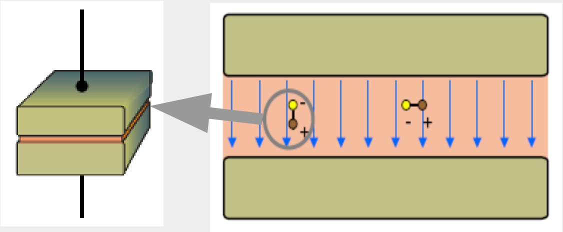


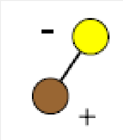
Oliver & Welander. MRS Bulletin 2013

Paladino, Hakkonen, GAF, Enc. Cond Mat. Phys. 2024

Non-Markovian environment: coherent impurities

- In the **tunnel oxide** – may couple resonantly to the qubit

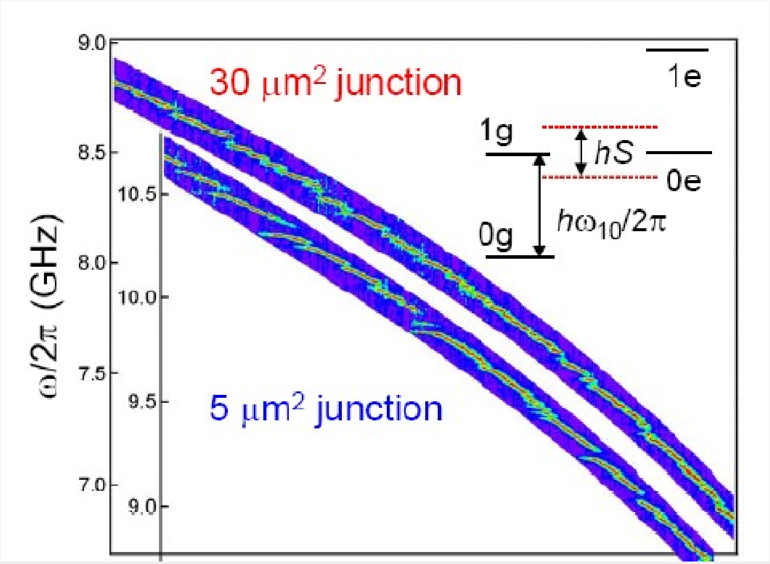




electrical dipole
bistable fluctuator

- **Q-coherent *impurities*** entangled with the device

***Experiments in phase qubit**:*
Cooper et al. PRL 04, Simmonds et al. PRL 04,
Johnson et al. PRL 05, Lisenfeld et al. PRB '10
see also Paladino et al. RMP 2014



avoided crossings ↔ resonant quantum impurities

- Fluctuating E_J → critical current noise
  - Reducing junction size

- In the graphene layer of a **hybrid JGJ gatemon**

Pellegrino, GAF, Paladino, Comm. Phys. 2020 & 2022

VOLUME 88, NUMBER 22 PHYSICAL REVIEW LETTERS 3 JUNE 2002

Decoherence and $1/f$ Noise in Josephson Qubits

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(Received 24 January 2002; published 20 May 2002)

We propose and study a model of dephasing due to an environment of bistable fluctuators. We apply our analysis to the decoherence of Josephson qubits, induced by background charges present in the substrate, which are also responsible for the $1/f$ noise. The discrete nature of the environment leads to a number of new features which are mostly pronounced for slowly moving charges. Far away from the degeneracy this model for the dephasing is solved exactly.

Gaussian vs non-Gaussian

Paladino, Faoro, GAF, Fazio PRL 2002;
Paladino, Galperin, GAF, Altshuler, RMP 2014

- Effects of noise involve bath equilibrium **correlations higher than second**

  ↔ The **Markovian ME** describes **no effect of non-Gaussianity** of the environment

- Example: incoherent impurities in the surface oxides or in the substrates
  - Fano-Anderson impurity

    PHENOMENOLOGICAL description of **non-Gaussian QUANTUM** environment ↔ Caldeira Legget

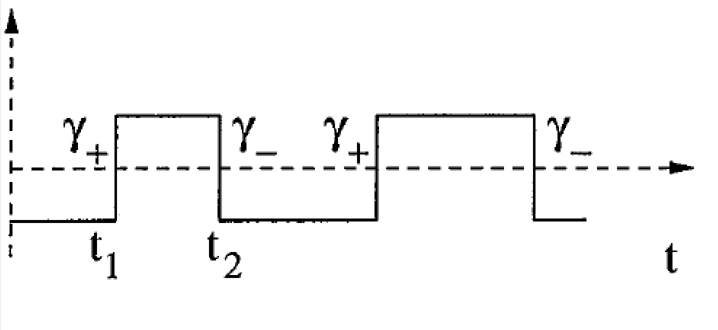
$$H = -\frac{\Omega}{2}\sigma_3 + \frac{v}{2}\sigma_z\tau_z + \left[\tau_+ \sum_k T_k c_k + \text{h.c.}\right] + \sum_k \xi_k\, c_k^\dagger c_k$$

  - Semiclassical counterpart: RTN $\quad H = -\frac{\Omega}{2}\sigma_3 + \frac{v}{2}\sigma_z\, x(t)$

$$x(t) = \pm 1 \qquad \gamma_\pm$$

$$\gamma_+ = e^{-\beta E}\gamma_- \qquad \gamma_+ + \gamma_- =: \gamma$$

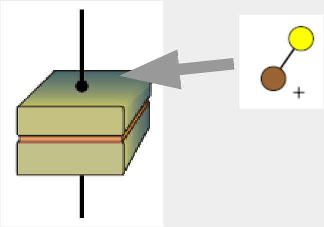
$$\langle x(t)x(0)\rangle = e^{-\gamma t} \qquad S_x(\omega) = \frac{x_+ - x_-}{4\cosh(E/2k_BT)}\mathcal{L}_\gamma(\omega)$$



  - Slow impurities → 1/f noise

Non-Markovian environment: incoherent impurities

- In the surface oxide or in the substrates



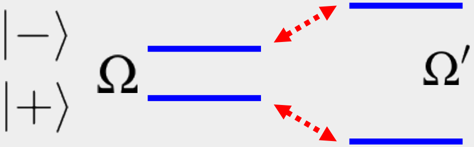
$$\mathcal{H}_0 = -\frac{\Omega}{2}\sigma_z - \frac{v}{2}X(t)\sigma_z$$

$X(t)$

γ

- Decoherence

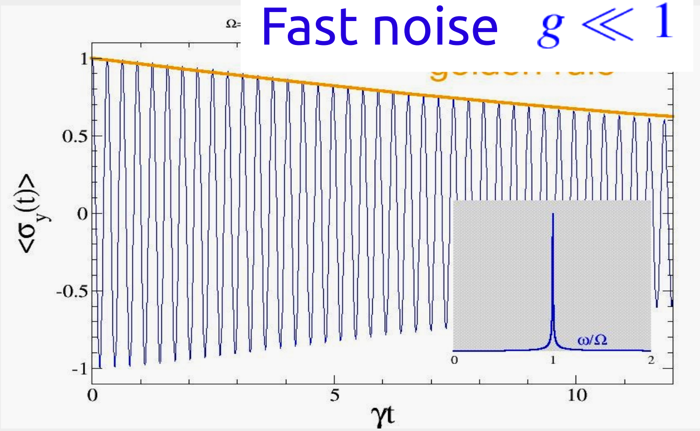
$$\rho_{+-}(t) \sim A(t)e^{i\Omega t} + A'(t)e^{i\Omega' t}$$



$$g = \frac{\Omega' - \Omega}{\gamma} = \frac{v}{\gamma}$$

visibility of the induced splitting

Fast noise $g \ll 1$

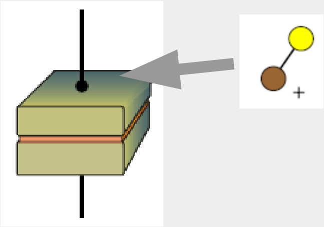


$g \ll 1$ Weak coupling

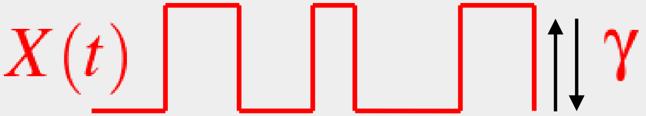
Markovian $T_2^* = S(0)/2$

Non-Markovian environment: incoherent impurities

- In the surface oxide or in the substrates



$$\mathcal{H}_0 = -\frac{\Omega}{2}\sigma_z - \frac{v}{2}X(t)\sigma_z$$

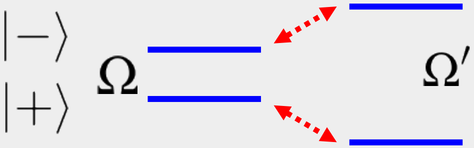


$$g = \frac{\Omega' - \Omega}{\gamma} = \frac{v}{\gamma}$$

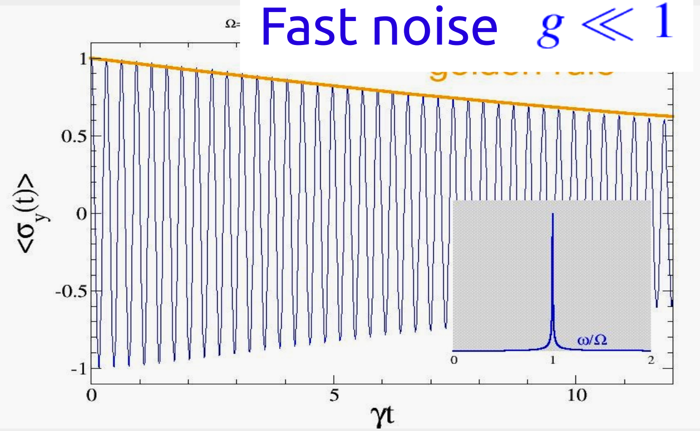
visibility of the induced splitting

- Decoherence

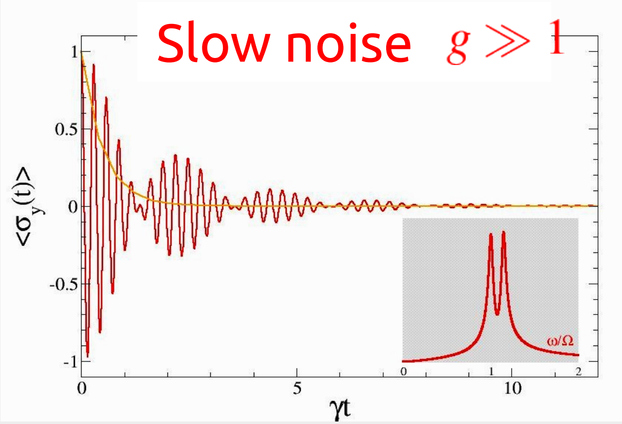
$$\rho_{+-}(t) \sim A(t)e^{i\Omega t} + A'(t)e^{i\Omega' t}$$



Fast noise $g \ll 1$

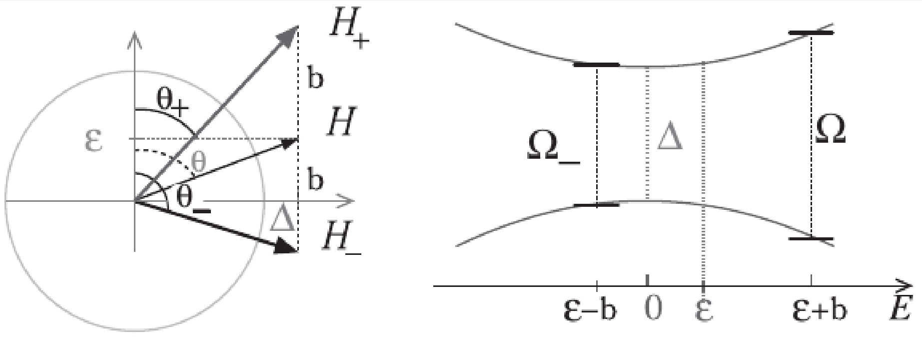


Slow noise $g \gg 1$



General working point & Markovianity

Paladino et al., Adv. Sol. State Phys. 2003
Paladino et al. RMP 2014



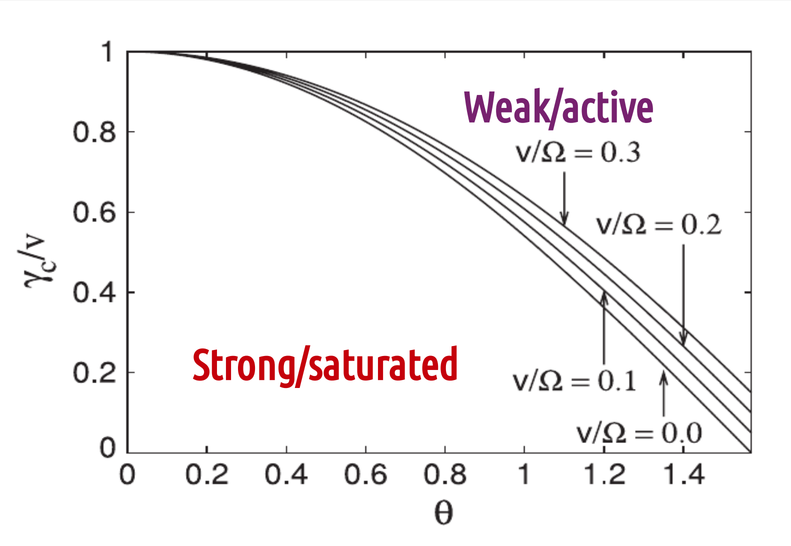
Dynamics at arbitrary working point

- Approximate solution with Fano-Anderson model
- **Threshold for strongly/weakly coupled** behavior

$$g = \frac{\Omega_+ - \Omega_-}{\gamma} \qquad \Omega_\pm = \sqrt{(\varepsilon \pm b)^2 + \Delta^2}$$

also depends on the qubit's working point

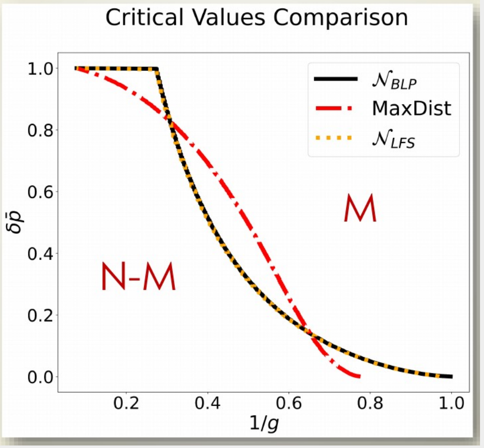
→ **changing bias of the computer "activates" fluctuators**



Markovianity

- A **non-secular** → **Lindblad** approach
- BLP, LFS, FT measures
- Metrics for **upscaled systems**?

Chiatto, GAF et al. Preprint 2024



RTN → 1/f noise

REVIEWS OF MODERN PHYSICS, VOLUME 86, APRIL–JUNE 2014

1/f noise: Implications for solid-state quantum information

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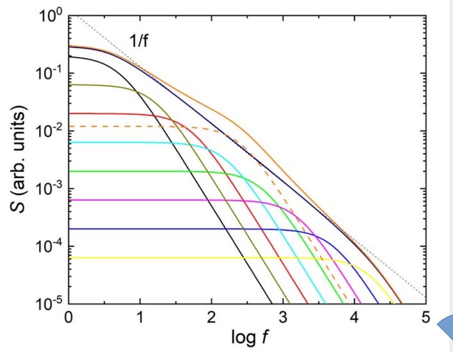
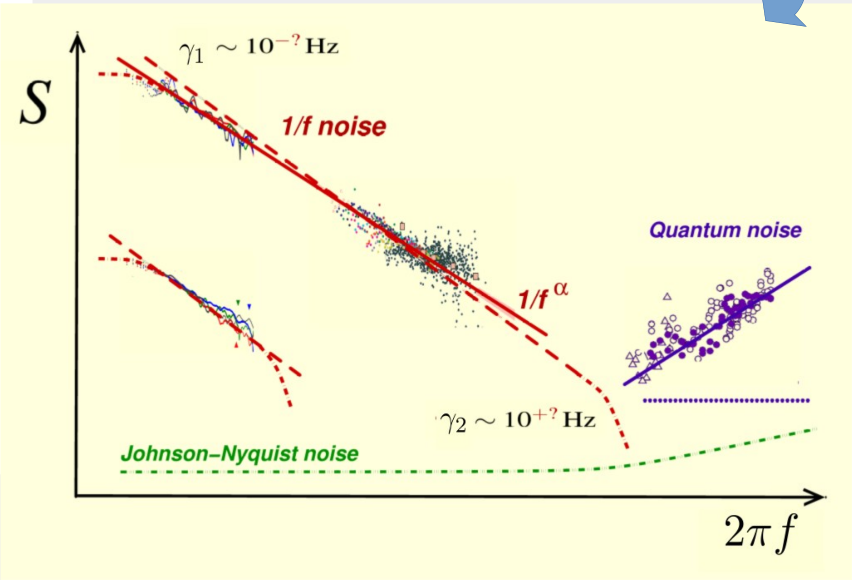
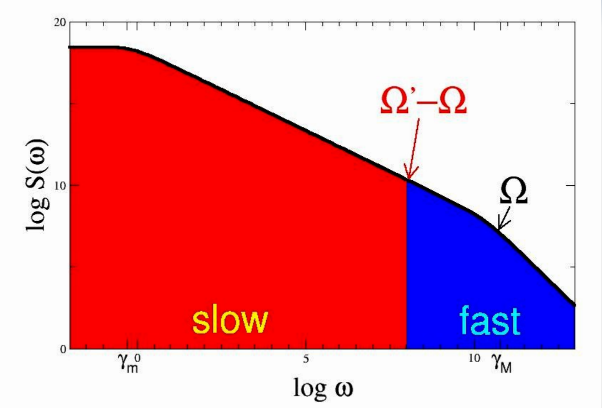
(published 3 April 2014)





1/f noise @ pure dephasing
exact results

Paladino, Faoro, GF, Fazio PRL 2002
Paladino, Galperin, GF, Altshuler, RMP 2014

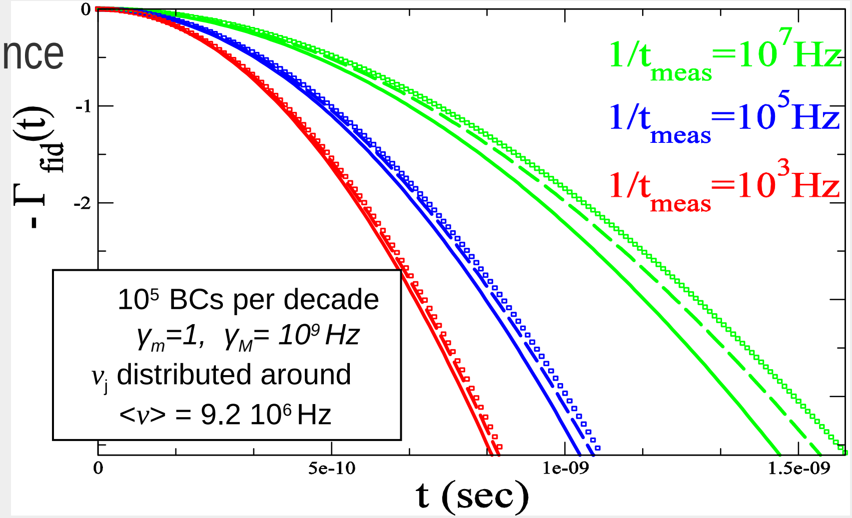


- Ensemble of fluctuators with distribution of switching rates

$$\frac{\rho_{+-}(t)}{\rho_{+-}(0)} = e^{-i\varepsilon t} \prod_j \left\{ A_j e^{-\frac{\gamma_j}{2}(1-\alpha_j)t} + (1-A_j) e^{-\frac{\gamma_j}{2}(1+\alpha_j)t} \right\} = ¿$$

¿

- About nonequilibrium of the environment of slow fluctuators
  - some of them thermalize during the whole measurement
  - The slowest do not termalize but have little effect on decoherence



- Partial-equilibrium which depends on the whole procedure including preparation and measurement

  → non-Gaussianity provides
  an effective low-frequency cutoff

Fluctuator initially at equilibrium for $\gamma > 1/t_m$

PRL **94,** 167002 (2005) PHYSICAL REVIEW LETTERS week ending 29 APRIL 2005

Initial Decoherence in Solid State Qubits

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(Received 20 September 2004; published 27 April 2005)

We study decoherence due to low frequency noise in Josephson qubits. Non-Markovian classical noise due to switching impurities determines inhomogeneous broadening of the signal. The theory is extended to include effects of high-frequency quantum noise, due to impurities or to the electromagnetic environment. The interplay of slow noise with intrinsically non-Gaussian noise sources may explain the rich physics observed in the spectroscopy and in the dynamics of charge based devices.

Adiabatic + Longitudinal + static path approx

GF et al. PRL 2005
Paladino et al. RMP 2014

- H1/f spectrum by slow fluctuators → **semiclassical Adiabatic approximation**
- Phase fluctuations accumulate in time → retain *only* fluctuations of the **length** of the Hamiltonian (**longitudinal approximation**)

$$\rho_{ij}(\tau) = \rho_{ij}(0) \int \mathcal{D}[x(\tau')] P[x(\tau')] \exp\left\{ i \int_0^{\tau'} d\tau'' \omega_{ij}[x(\tau'')] \right\}$$

instantaneous eigen-splittings

- Static Path Approximation (SPA) inhomogeneous broadening $x(\tau) \to x(0) \equiv x$

$$\rho_{ij}(\tau) = \rho_{ij}(0) \int dx\, P(x)\, e^{i\tau\omega_{ij}(x)}$$

Relevant cases central limit theorem → Gaussian distributed x $\quad P(x) = \dfrac{e^{-\frac{x^2}{2\Sigma^2}}}{\sqrt{2\pi}\Sigma}$

Large number of impurities $\Sigma = \int_{\gamma_m}^{\gamma_M} \dfrac{d\omega}{\pi} S(\omega) \qquad S(\omega) = \dfrac{\pi\Sigma^2}{\ln(\gamma_M/\gamma_m)} \dfrac{1}{\omega}$

Also Ithier et al. PRB 2005

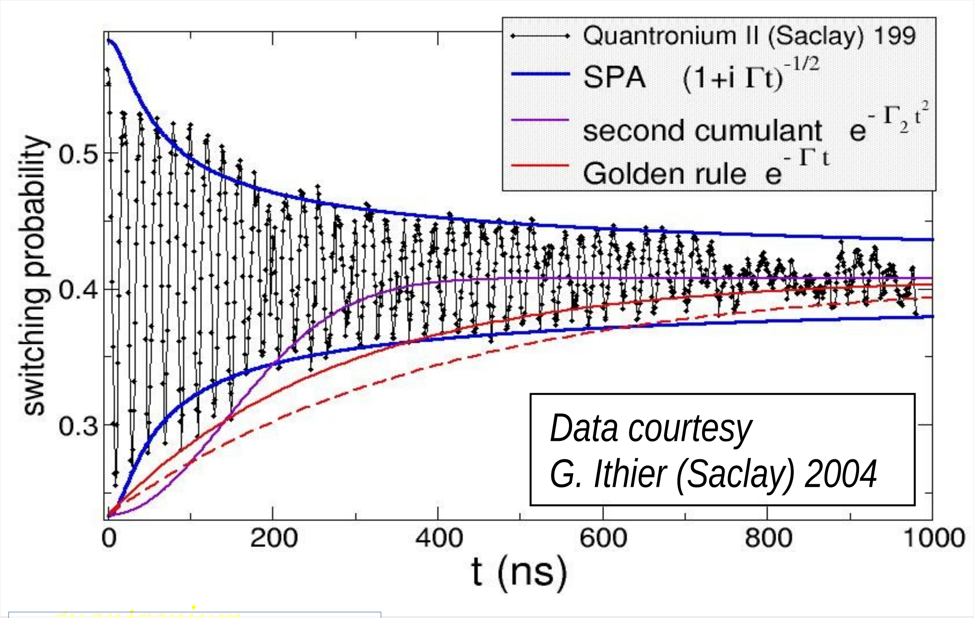
Experiments @ optimal points

$$\rho_{10}(t) = \rho_{10}(0) e^{-i\Omega t} \left(1 + i \frac{\Sigma_x^2 t}{\Delta}\right)^{-\frac{1}{2}} \propto t^{-\frac{1}{2}}$$

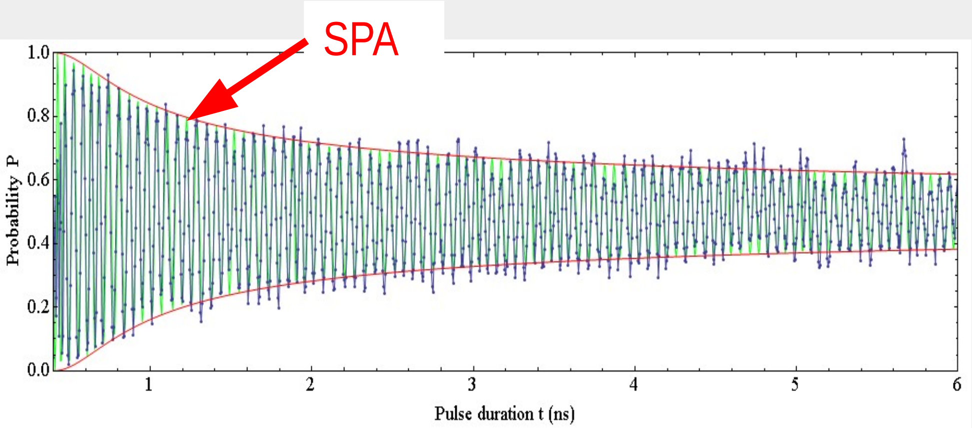
$$\Sigma_x = \int_{\gamma^*}^{\gamma_M} \frac{d\omega}{\pi} S_x^{1/f}(\omega)$$

One-parameter theory!

GF et al. PRL 2005
Ithier et al. PRB 2005

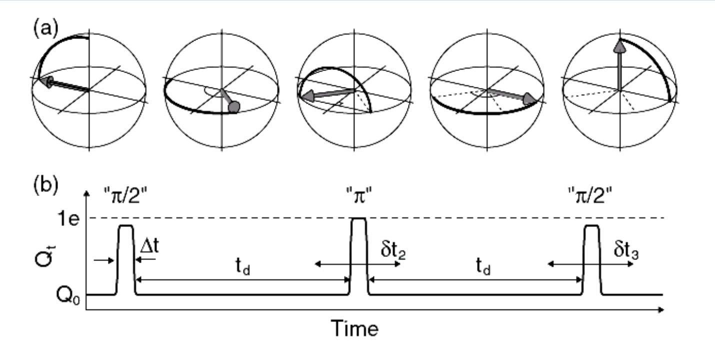


Ithier et al. PRB 2005



Chiarello, Paladino, Castellano, Cosmelli, D'Arrigo, Torrioli, GAF NJP 2012

Pulsed control → dynamical decoupling & noise sensing



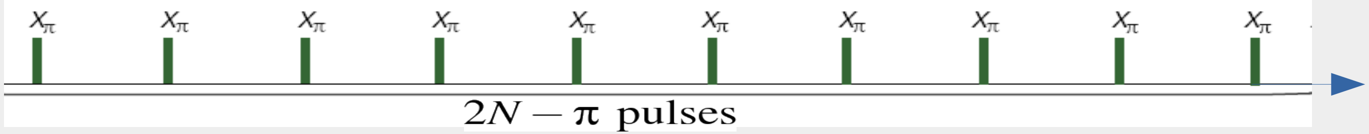
Spin echo

$t_{echo} = 2t_d$ cancels noise at frequencies $\omega << 1/t_d$

Bang-bang control

longer sequences $t_{tot} = 2N\, t_d$ cancel noise at larger frequencies $\omega << 1/(Nt_d)$ for the same t_{tot}

PDD, CMPG, Uhrig sequences

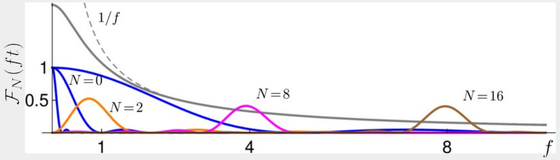


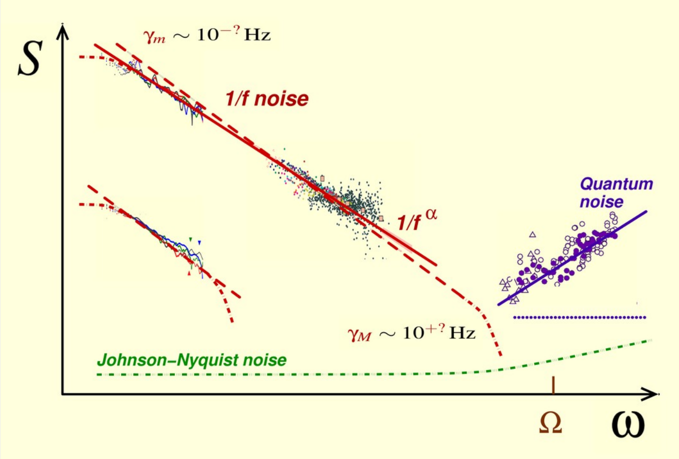
Filters out single qubit dephasing $\rho_{01}(t) = \rho_{01}(0)e^{-\Gamma_N(t) - i\Sigma_N(t)}$

$$\Gamma_N(t) = \int \frac{d\omega}{\omega^2} S(\omega) F_N(\omega t)$$

Filter function

→ Noise sensing





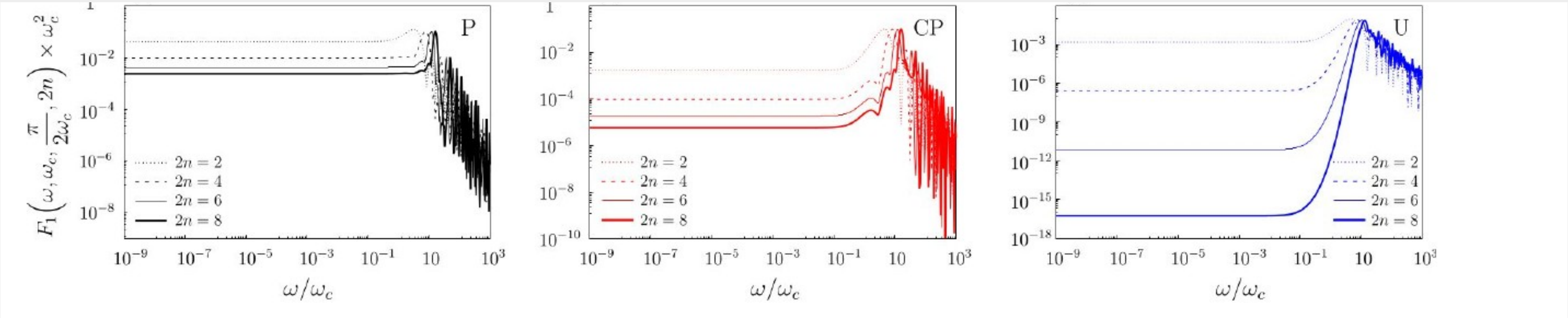
Two-qubit decoupling while processing!

- Dynamical decoupling protocol for mitigating error of a two-qubit entangling-gate with longitudinal local noise while processing

- Magnus expansion for analytical expression of the gate error.

- Derivation of a generalized filter function theory: decoherence while processing

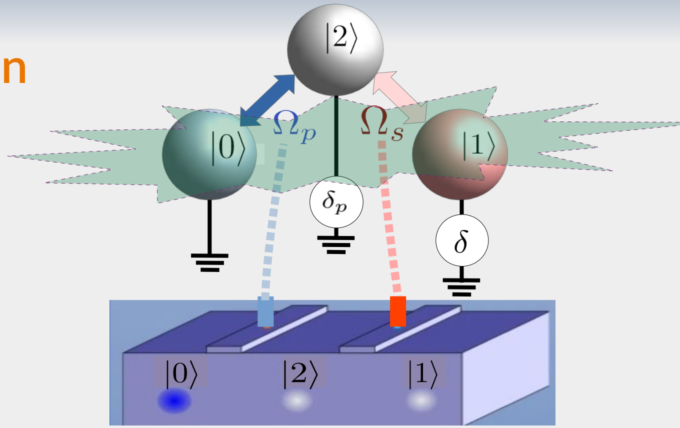
- Quantum sensing:
  - **higher order cumulants**: Gaussian vs non-Gaussian
  - **Spatial correlations**



D'Arrigo, Piccitto, GAF, Paladino Sci. Rep 2024

Coherent Transport by Adiabatic Passage

- 3 single-level qdots Hamiltonian coupled in the **Λ configuration**
  - "Stokes" and "pump" **tunneling amplitudes** Ω_k and **local bias** δ_k



$$H \equiv \begin{bmatrix} 0 & 0 & \frac{1}{2}\Omega_p^*(t) \\ 0 & \delta & \frac{1}{2}\Omega_s^*(t) \\ \frac{1}{2}\Omega_p^*(t) & \frac{1}{2}\Omega_s(t) & \delta_p \end{bmatrix}$$

- **@ two-photon** resonance $\delta := \delta_p - \delta_s = 0$ → **trapped** eigenstate $|D\rangle = \frac{\Omega_s(t)|0\rangle - \Omega_p(t)|1\rangle}{\sqrt{|\Omega_s|^2 + |\Omega_p|^2}}$

Population **coherently trapped** in the subspace $\text{span}\{|0\rangle, |1\rangle\}$

Coherent Transport by Adiabatic Passage

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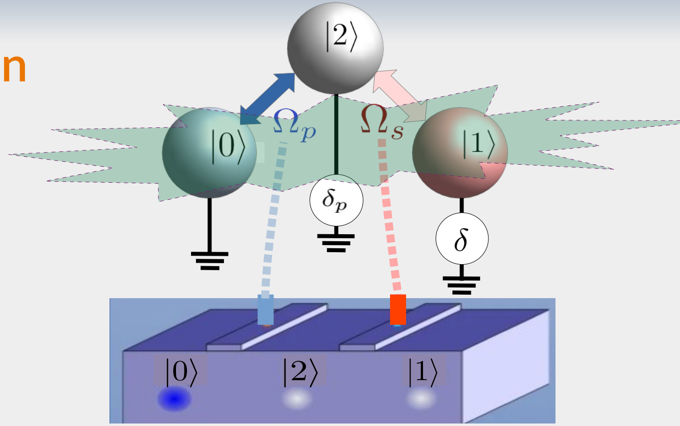

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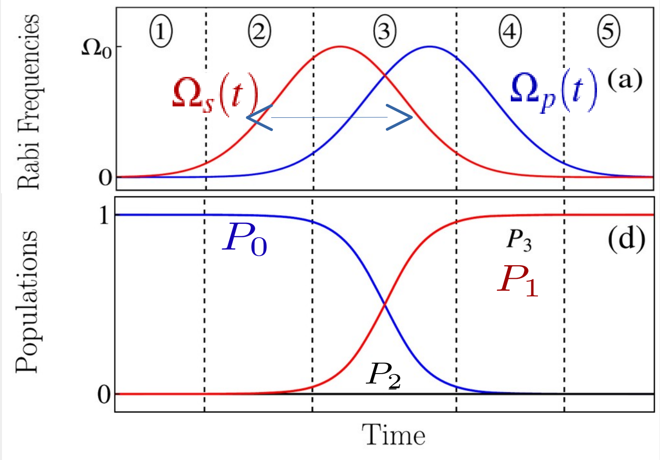


- Switching couplings in **counterintuitive** sequence → **CTAP**
  - **100% robust population transfer** $|0\rangle \rightarrow |1\rangle$ while $|2\rangle$ always empty
  - Ac-driven 3LS in rot-frame → **STIRAP**

Vitanov, Rangelov, Shore, Bergmann, RMP (2017)

Menchon-Enrich, Greentree et al., Rep. Prog. Phys. (2016)
Huneke, Platero, Koler, PRL (2013)
Gullans & Petta, PRB (2020)

Noise classification in a 3-LS by supervised learning

- CTAP/STIRAP + **pure dephasing** classical noise $\tilde{x}_i(t)$
  - Simulate **fluctuations of the energy spectrum** of the system
  - Effective model of the leading decoherence effects in most AAs

$$H \equiv \begin{bmatrix} 0 & 0 & \frac{1}{2}\Omega_p(t) \\ 0 & \delta + \tilde{x}_1(t) & \frac{1}{2}\Omega_s(t) \\ \frac{1}{2}\Omega_p(t) & \frac{1}{2}\Omega_s(t) & \delta_p + \tilde{x}_2(t) \end{bmatrix}$$

- Goal: **classification** among 4/5 types of noise (**labels**)
  - **Multilevel correlation parameter η**

- **Non-Markovian quasistatic:**
  1. correlated noise: $x_2(t) = \eta x_1(t)$, with $\eta > 0$,
  2. anti-correlated noise: $x_2(t) = \eta x_1(t)$, with $\eta < 0$,
  3. uncorrelated noise: $x_2(t)$ and $x_1(t)$, are independent from each other.

Samples generated by Stochastic Schrödinger equation

- **Markovian:**
  - 4a. correlated noise: $x_2(t) = \eta x_1(t)$, with $\eta > 0$,
  - 4b. anti-correlated noise: $x_2(t) = \eta x_1(t)$, with $\eta < 0$.

  OR

  - 4. correlated noise: $x_2(t) = \eta x_1(t)$, with no conditions on η.

Samples generated by Markovian Master equation

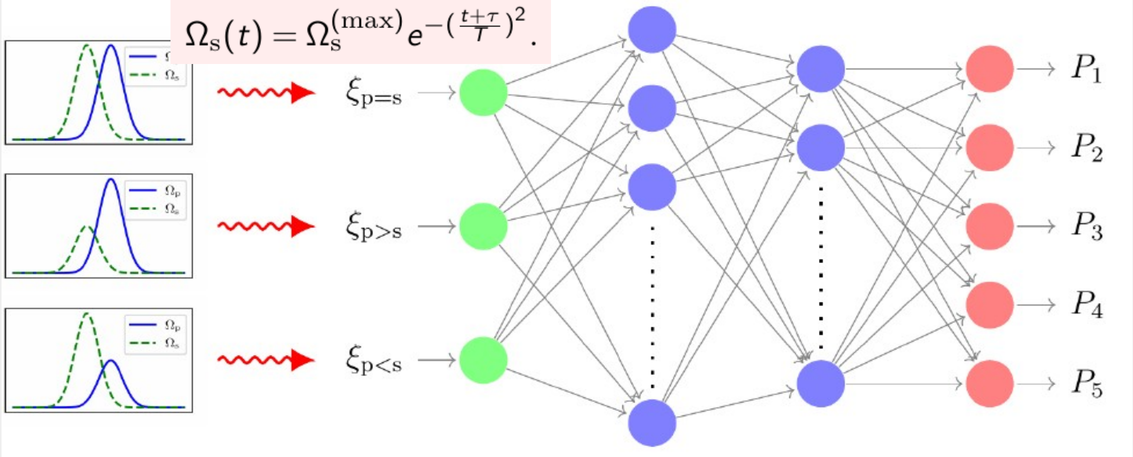
Mukharjee, GAF, Giannelli et al., Machine Learning: Science and Technology 2024

Dataset generation → output

- We exploit sensitivity of CTAP/STIRAP to **asymmetries in the peak amplitudes**
  - For each **label** $i = 1, \ldots, 5$
    - Extract correlation coefficient **η** ($\leftrightarrow$ device) **in the proper range**
    - Run STIRAP with **3 combinations of amplitudes**

$$\Omega_\mathrm{p}(t) = \Omega_\mathrm{p}^{(\max)} e^{-(\frac{t-\tau}{T})^2},$$
$$\Omega_\mathrm{s}(t) = \Omega_\mathrm{s}^{(\max)} e^{-(\frac{t+\tau}{T})^2}.$$

1. $\Omega_\mathrm{p}^{(\max)} = \Omega_\mathrm{s}^{(\max)} \quad (50/T, 50/T),$
2. $\Omega_\mathrm{p}^{(\max)} > \Omega_\mathrm{s}^{(\max)} \quad (20\sqrt{10}/T, 10\sqrt{20}/T),$
3. $\Omega_\mathrm{p}^{(\max)} < \Omega_\mathrm{s}^{(\max)} \quad (10\sqrt{20}/T, 20\sqrt{10}/T),$



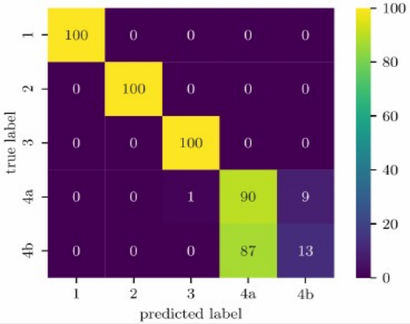
    - Take 3 efficiencies $\{\xi\}$ as the **NN input**
    - Train the NN to maximize probabilities $\{P_i\}$ of correct output for each label $i = 1, \ldots, 5$

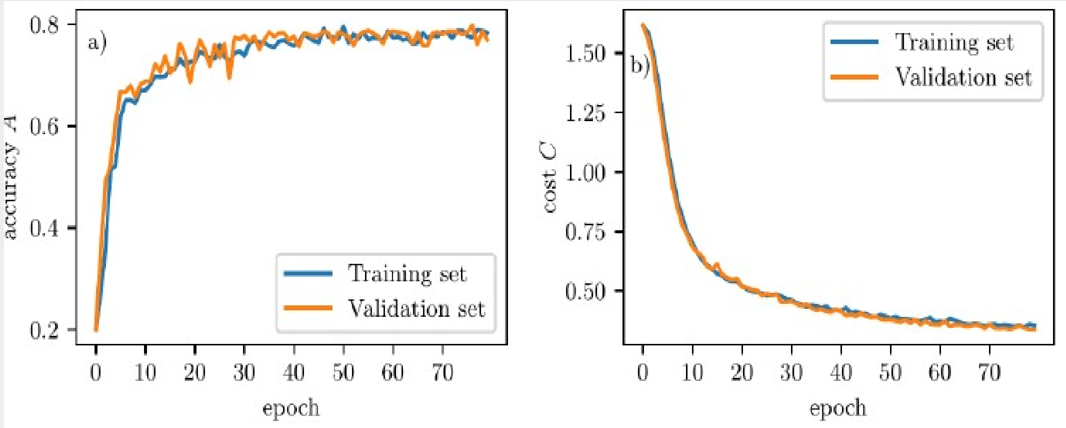
- Each dataset has 500 samples

Mukharjee, GAF, Giannelli et al., Machine Learning: Science and Technology 2024

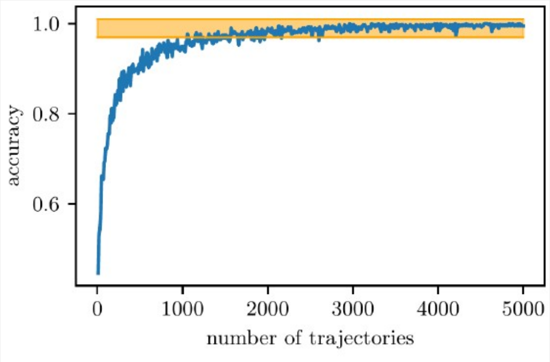
Results for supervised learning

- Discriminates **Markovian/non-Markovian**
  - ~ 100% accuracy in discrimination of **correlations of non-Markovian noises**
  - Unable to discriminate correlations of Markovian noises
  - Ideal situation: each sample from averaging an **infinite set** of identical experiments





  - Each sample from averaging over a **finite set** of (simulated) identical experiments

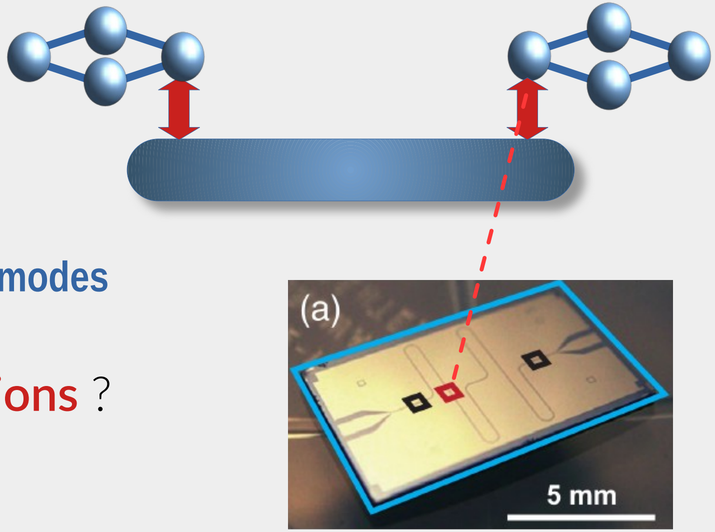


- **Amazing** sensitivity to amplitude's asymmetry
- developing **tailored clustering algorithms for unsupervised learning** → ICSC
- Design of quantum devices specific for sensing

Mukharjee, GAF, Giannelli et al., Machine Learning: Science and Technology 2024

Modular computing ↔ USC quantum interconnect

- Post-NISQ **modular architectures** combine quantum gates with communication between separate quantum cores
  - Complexity of control, cooling and power infrastructure, crosstalk, component reliability, upscaled decoherence, …
  - Developed on **various platforms:** semiconductor, superconductor, impurities
  - Prototype model: **mutiqubit nodes interconnected by quantized harmonic modes**



- A **USC coupled** interconnect → **ultrafast intercore q-operations** ?
  - USC achieved in semi/superconductor architectures

Theory: *Ciuti et al. (2005),*
Experiments: *Aanappara et al., PRB (2009)*
Niemczyck, et al., Nat.Phys. (2010)
Reviews*: Kockum, Nori et al., Nat. Phys Rev. (2019)*
Forn-Diaz et al. Rev. Mod. Phys (2020)

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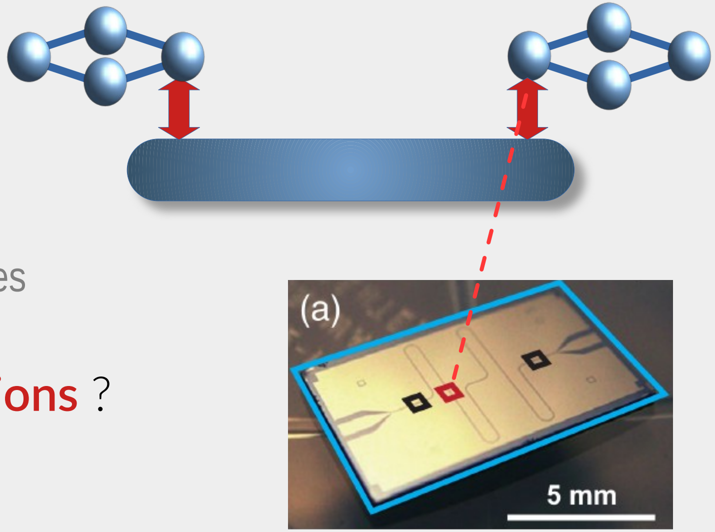


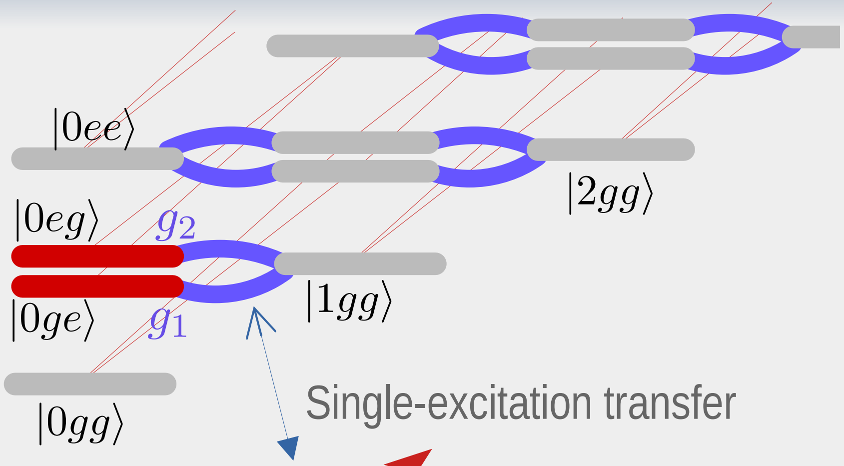
- A **USC coupled** interconnect → **ultrafast intercore q-operations** ?
  - USC achieved in semi/superconductor architectures

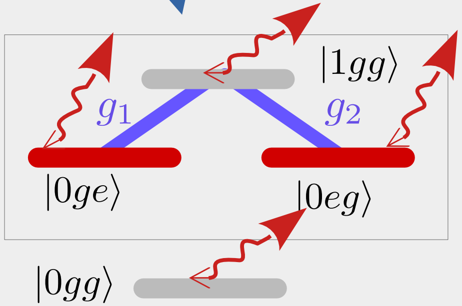
- Faster dynamics **costs fidelity**!
  - in USC fundamental limitation: **Dynamical Casimir Effect** (DCE)

Benenti, D'Arrigo et al. , PRA (2014)
Hoeb, Benenti et al. PRA (2017)

- Our result: **faithful, robust fast quantum operations** via "**modulated CTAP**"

Mode as quantum interconnect: USC





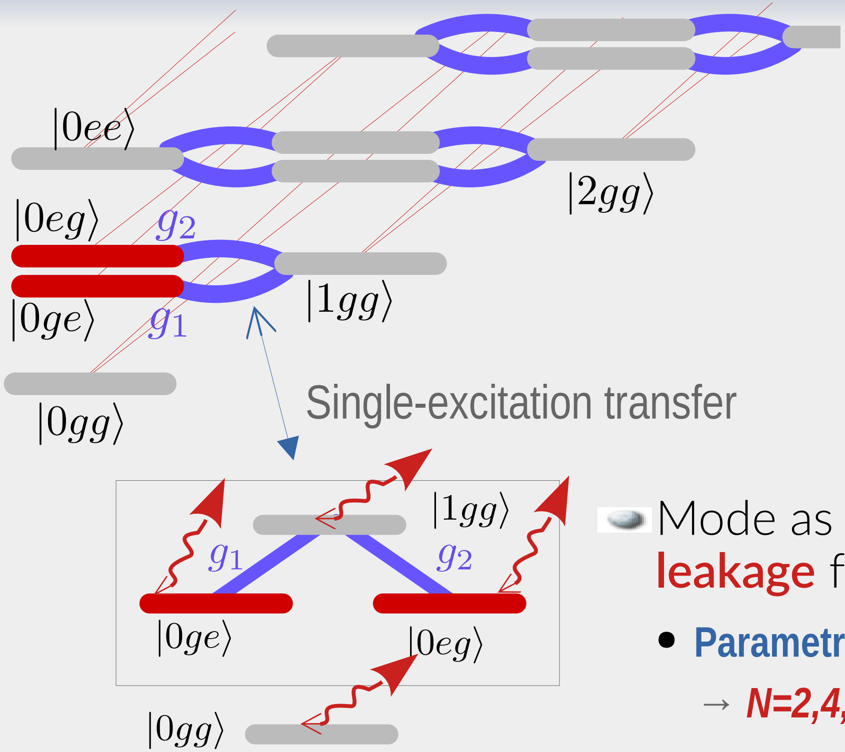
- Two atoms + single em. cavity mode **RABI**

$$H = \omega_c\, a^\dagger a - \frac{1}{2}\sum_{i=1}^{2} \epsilon_i \sigma_3^i + \sum_{i=1}^{2} g^i(t)\,\left[a^\dagger\,\sigma_-^i + a\,\sigma_+^i\right]$$
$$+ \sum_{i=1}^{2} g^i(t)\,\left[a^\dagger\,\sigma_+^i + a\,\sigma_-^i\right] \quad \text{CR (counterrotating)}$$

- *N* is **NOT conserved**

- Mode as a **quantum interconnect ?**
  leakage from *N*=0,1 computational subspace by **DCE**
  - **Parametrically time-dependent** H-Rabi conserves the parity of *N*
    → ***N*=2,4,6,… photons production**

Mode as quantum interconnect: USC



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$$+\sum_{i=1}^{2} g^i(t)\,[a^\dagger\,\sigma_+^i + a\,\sigma_-^i]$$ **CR (counterrotating)**

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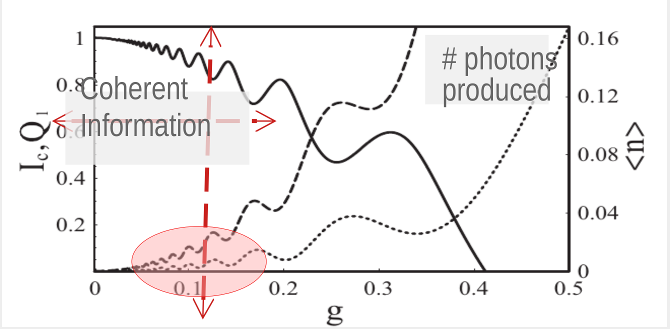
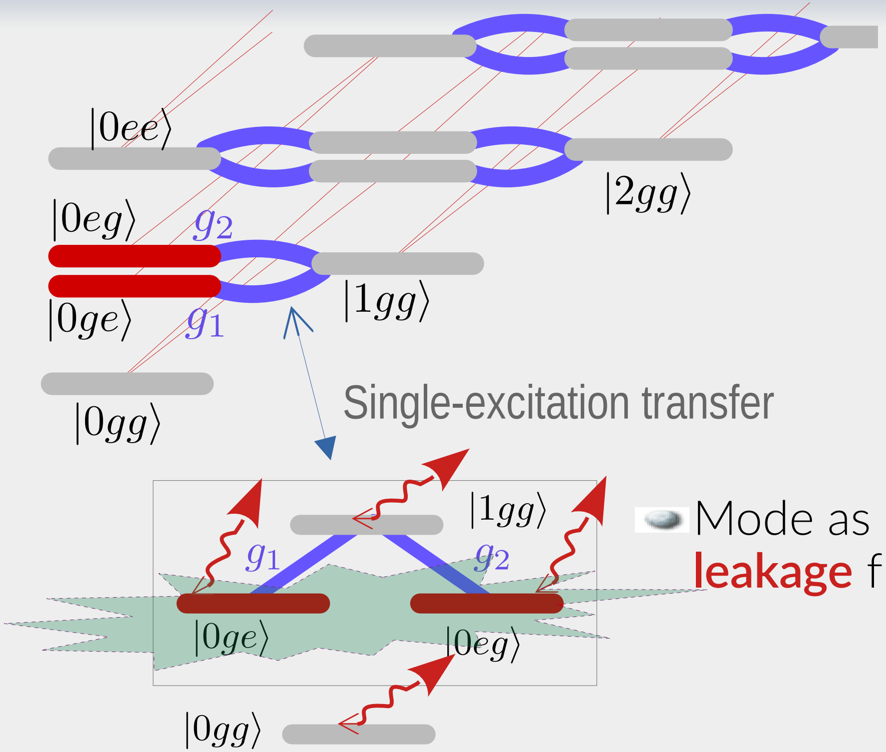


- Fidelity **drastically deteriorates** for faster dynamics

Benenti, D'Arrigo et al. , PRA (2014)
Hoeb, Benenti et al. PRA (2017)

Mode as quantum interconnect: USC



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$$+\sum_{i=1}^{2} g^i(t)\left[a^\dagger \sigma_+^i + a\,\sigma_-^i\right]$$ **CR** (counterrotating)

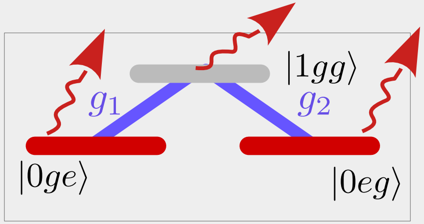
- *N* is **NOT conserved**

- Mode as a **quantum interconnect ?**
  leakage from *N=0,1* computational subspace by **DCE**

- Our work: quantized mode as a **virtual quantum interconnect** by CTAP
  - does it **suppress DCE** → Ideal clock scaling as $T \sim \pi/g$?

Single-excitation transfer: the building block

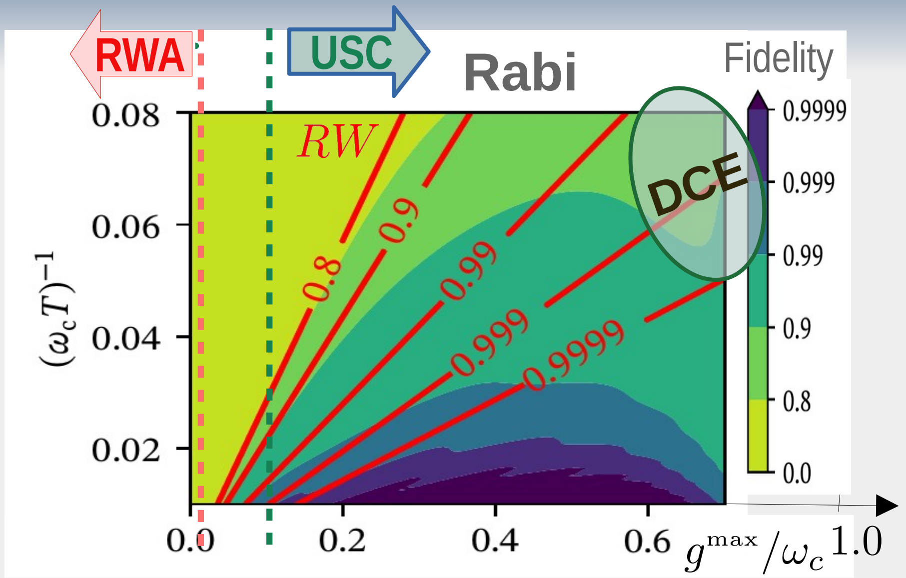
- Benchmark: fidelity for **N-conserving** interaction ideally depends on $g^{\max}T$

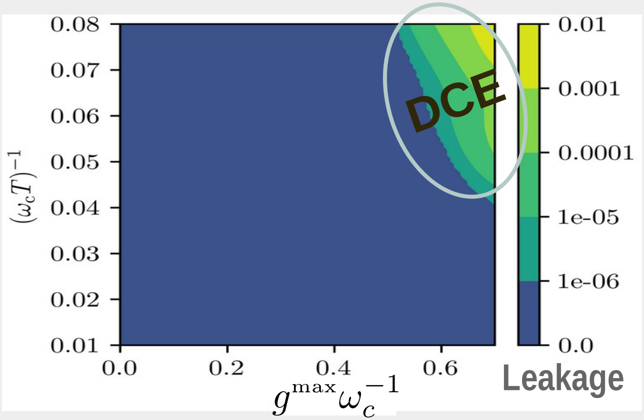


- **Virtual interconnect** protects from **DCE**

Stramacchia, et al. MDPI (2019)
Giannelli, et al. Nuovo Cim. C (2022)

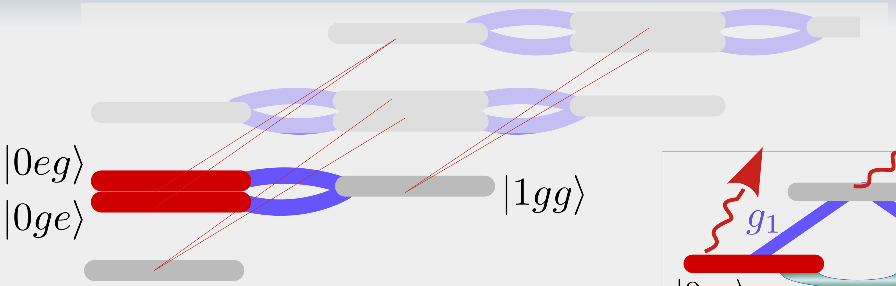
- Ideal only up to $g^{\max}/\omega_c \approx 0.1$. What at **intermediate g**?

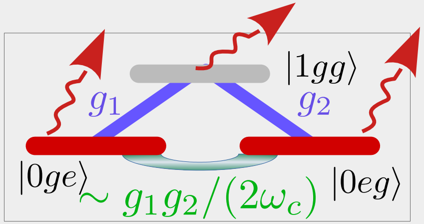


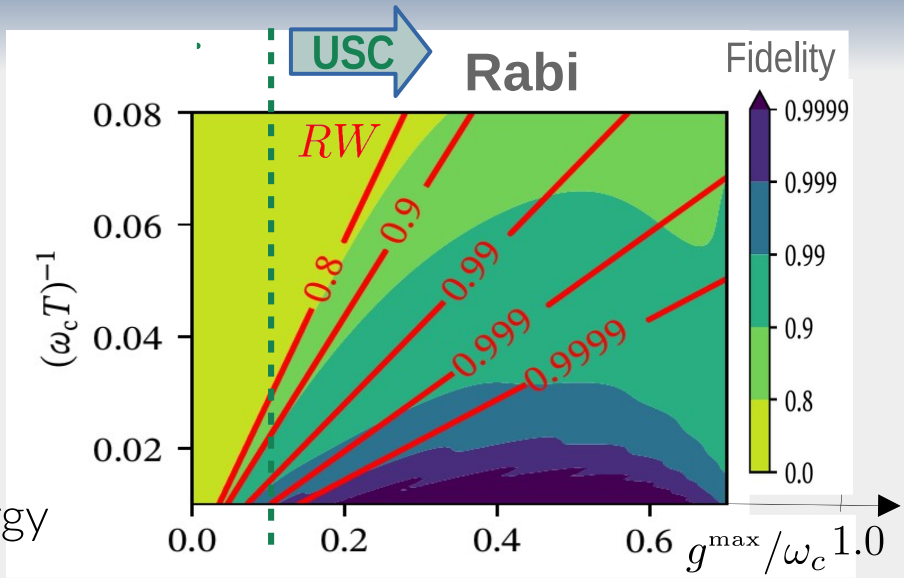


GAF, Giannelli, Benenti, Montangero, Paladino, 2024

Single-excitation transfer: renormalization

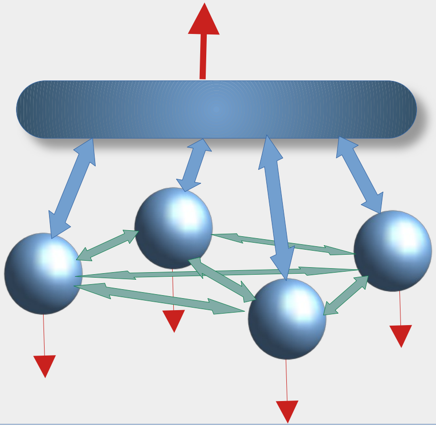






- **CR terms** → renormalized **fully connected** low-energy effective Hamiltonian

$$H_{eff} = H_0 + \sum_{j=1}^{2} \frac{g_j^2}{\epsilon_j \omega_c}\left[(a^\dagger a + \frac{1}{2})\sigma_3^j\right] + \sum_{j\neq k} \frac{g_j g_k}{\epsilon_j + \omega_c}[\sigma_-^j \sigma_+^k + \text{h.c.}] + H_{RW}$$



GAF, Giannelli, Benenti, Montangero, Paladino, 2024

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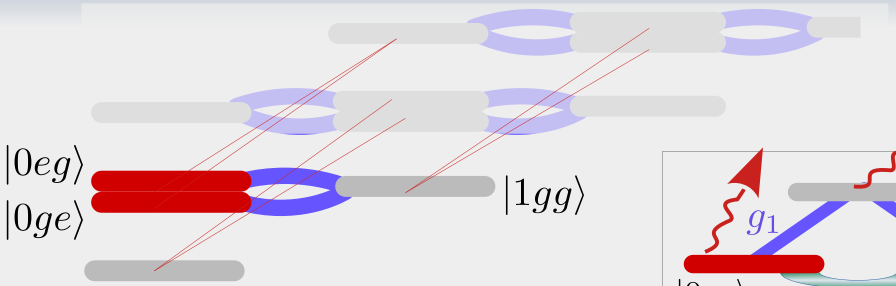
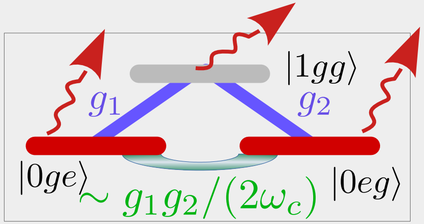
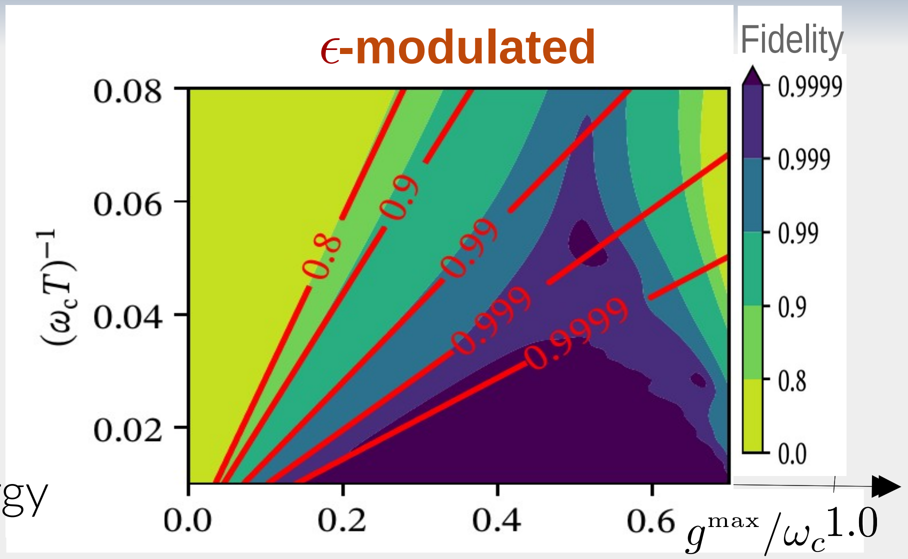




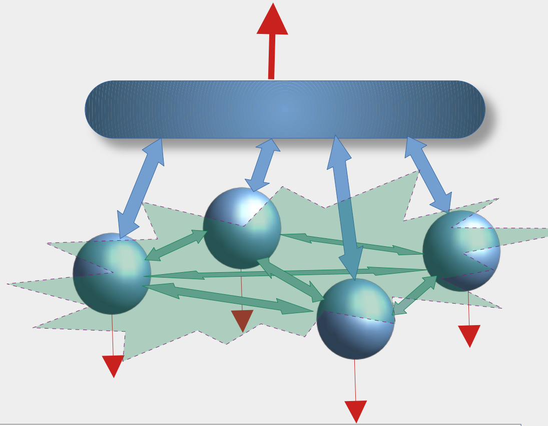


- **CR terms** → renormalized **fully connected** low-energy effective Hamiltonian

- A new **trapped eigenstate** solution *Pope, GAF et al., J. Stat. Mech. (2019)* allows the design of an adiabatic pattern yielding efficient and robust population transfer by a simple **local modulation** of the qubits splittings

$$\epsilon_2 - \epsilon_1 \approx \left[g_2(t) - g_1(t)\right]/(2\omega_c)$$

  - **ideal RW is outperformed! H**ow comes?

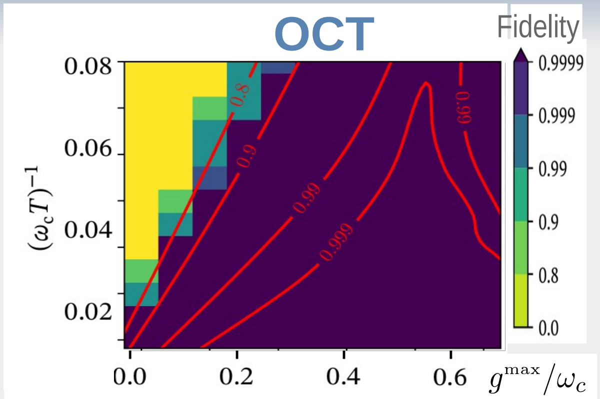


GAF, Giannelli, Benenti, Montangero, Paladino, 2024

Optimization, state-transfer, resilience, ….

- Optimizing ϵ-modulation → populationtransfer **error ~ 10^-7**

- **Theorem:** in the absence of DCE & within a state-independent local unitary, the error for state-transfer is maximized by the **efficiency** of excitation transfer → **fidelity of state-transfer**



GAF, Giannelli, Benenti, Montangero, Paladino, 2024

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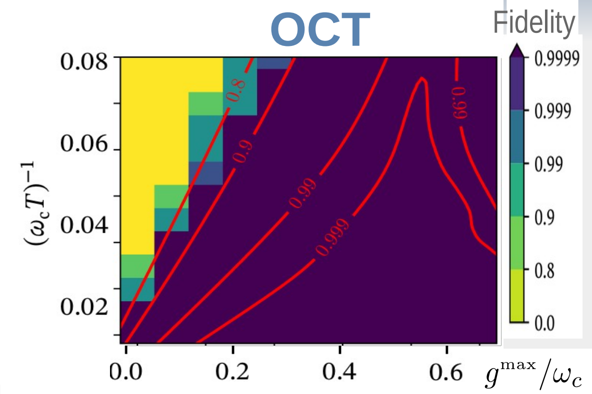
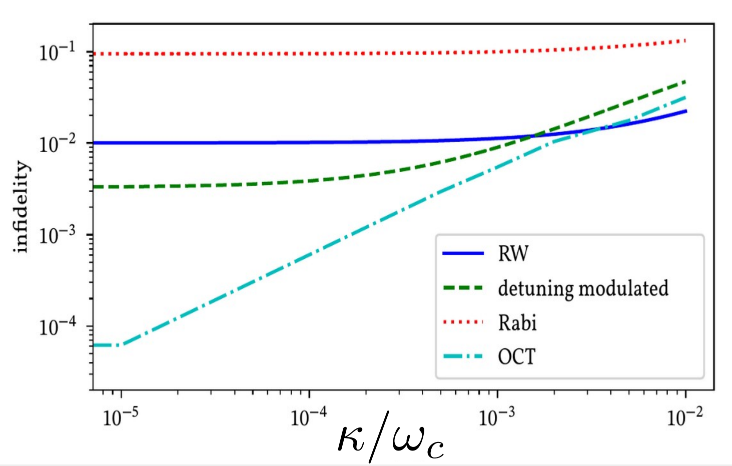


- Bottleneck: interconnect **decoherence** rather than USC

- Remarks on hardware and architectures
  - Operation **time scale: intercore ~ intracore**
    - In **noisy** superconducting q-circuits: infidelities $1-\mathcal{F} \gtrsim 10^{-5}$ for a protocol duration $T_{tot} \sim 6T \approx 30\,ns$ @ $g^{max}/\omega_c = 0.5$
  - Natural **unidirectional** photon emission/routing necessary in communication
  - **Available switchable** components in flux-based superconducting circuits

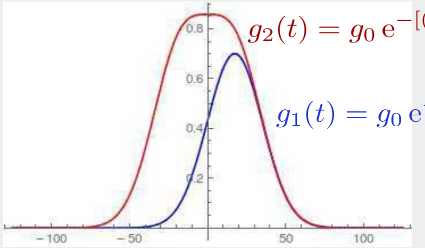


Kannan et al., Nat. Phys. (2023)

GAF, Giannelli, Benenti, Montangero, Paladino, 2024

Intercore communication: entanglement generation/sharing

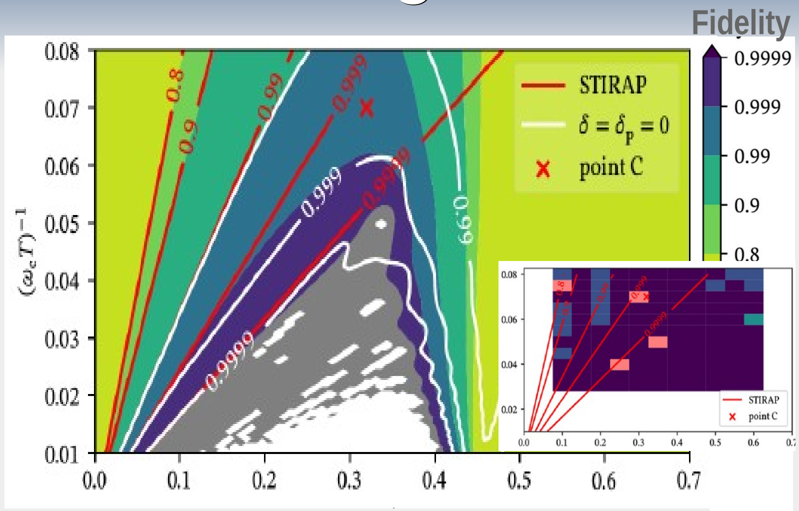
- Entanglement **generation by "half-CTAP"**



$g_2(t) = g_0\, e^{-[(t+\tau)/T]^2} + g_0\, e^{-[(t-\tau)/T]^2}$

$g_1(t) = g_0\, e^{-[(t-\tau)/T]^2}$

$$|0\rangle\, |eg\rangle \to \frac{g_2\, |0eg\rangle - g_1\, |0ge\rangle}{\sqrt{g_1^2 + g_2^2}} = |0\rangle\, \frac{|eg\rangle - |ge\rangle}{\sqrt{2}}$$



GAF, Giannelli, Benenti, Montangero, Paladino, 2024

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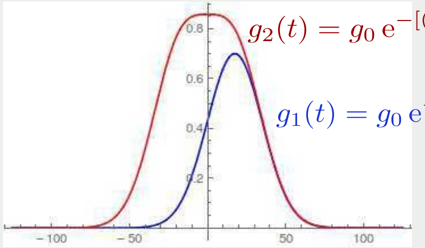

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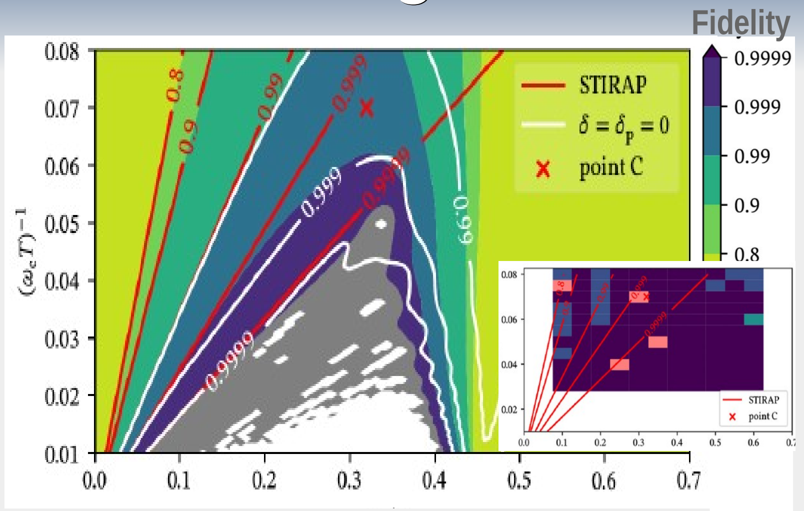
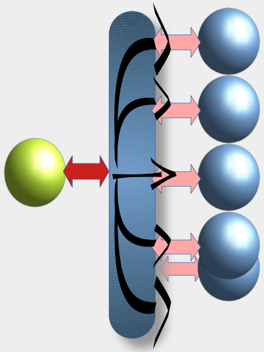


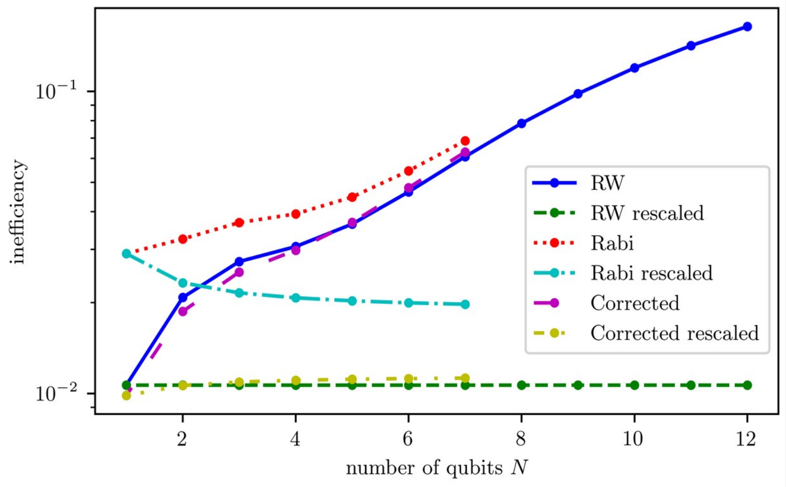
- **ancillary qubit** → entanglement **sharing/multipartite**



  - One excitation coherently transferred at once
    qubit 0 → (1,...,N) = **W state**

$$|0\rangle_c\,|g\rangle^{\otimes N}|e\rangle_0 \xrightarrow{\mathscr{S}^{\otimes N}} |0\rangle_c\,\frac{1}{\sqrt{N}}\left[|egg\ldots\rangle + |geg\ldots\rangle + \cdots + |g\ldots ge\rangle\right]|g\rangle_0$$

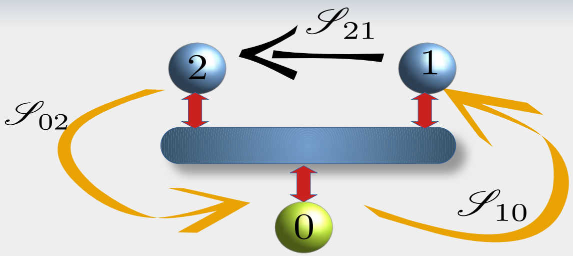
  - Rescaling of interactions $g^0 \sim \sqrt{N} g^i$ → **USC** g^0 necessary for N>>1
  - **ϵ-modulated** protocol **mets** the benchmark of **N-conserving** system



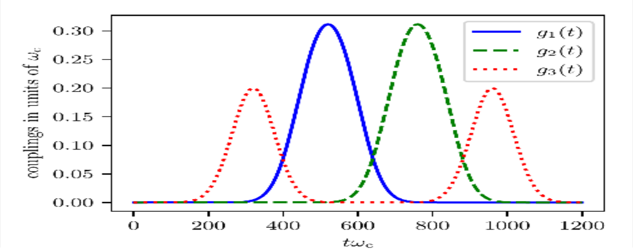
GAF, Giannelli, Benenti, Montangero, Paladino, 2024

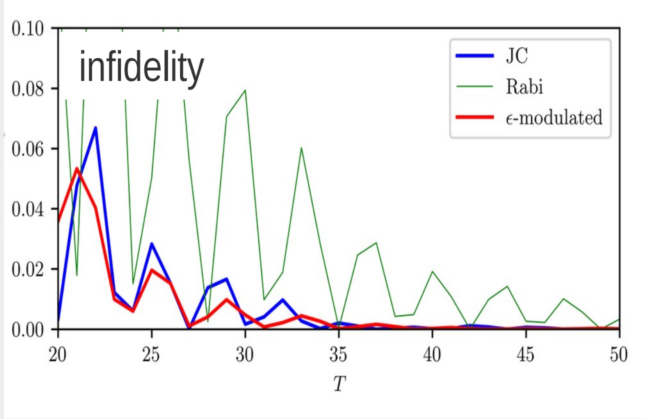
Intercore computation

- Two-qubit remote computing
  - by entanglement teleportation
  - by remote SWAP+ local entangling gates

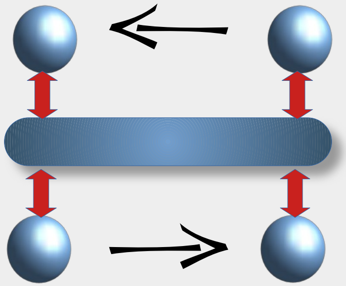


- SWAP by **ancillary qubit**
  - 3 ϵ-modulated sequences $\mathscr{S}_{02}\,\mathscr{S}_{21}\,\mathscr{S}_{10}$
  - Implemented by **4 composite pulses**
  - **Error smaller than the N-conserving (RW) benchmark**





- SWAP by **two-particle CTAP**
  - Two excitations transferred at once → SWAP
  - Transfer of entangled states



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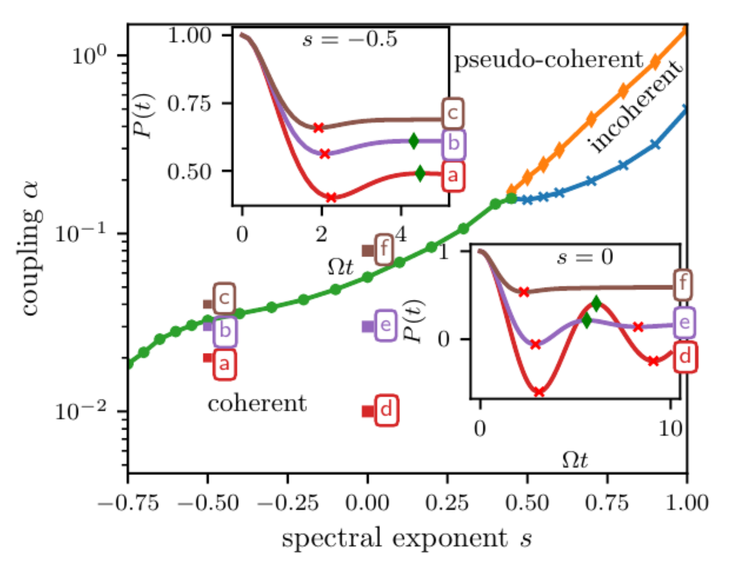
A quantum theory of low-frequency noise

- With Gaussian noise ↔ **spin-boson**



Otterpohl, Nalbach, Thorwart 2024 + GAF

$$J(\omega) = \sum_j \frac{c_j^2}{2\omega_j}\delta(\omega-\omega_j) = 2\alpha\frac{\omega^s}{\omega_c^{s-1}}e^{-\frac{\omega}{\omega_c}}\Theta(\omega-\omega_{\mathrm{ir}}).$$

- Coherent, incoherent, **pseudocoherent**
- negative s (highly non-Markovian):
  - Pseudocoherent region widens
  - Strong dependence on initial conditions

- Non-Gaussian noise ↔ **spin-bath**