Spin-photon interfaces and quantum transduction

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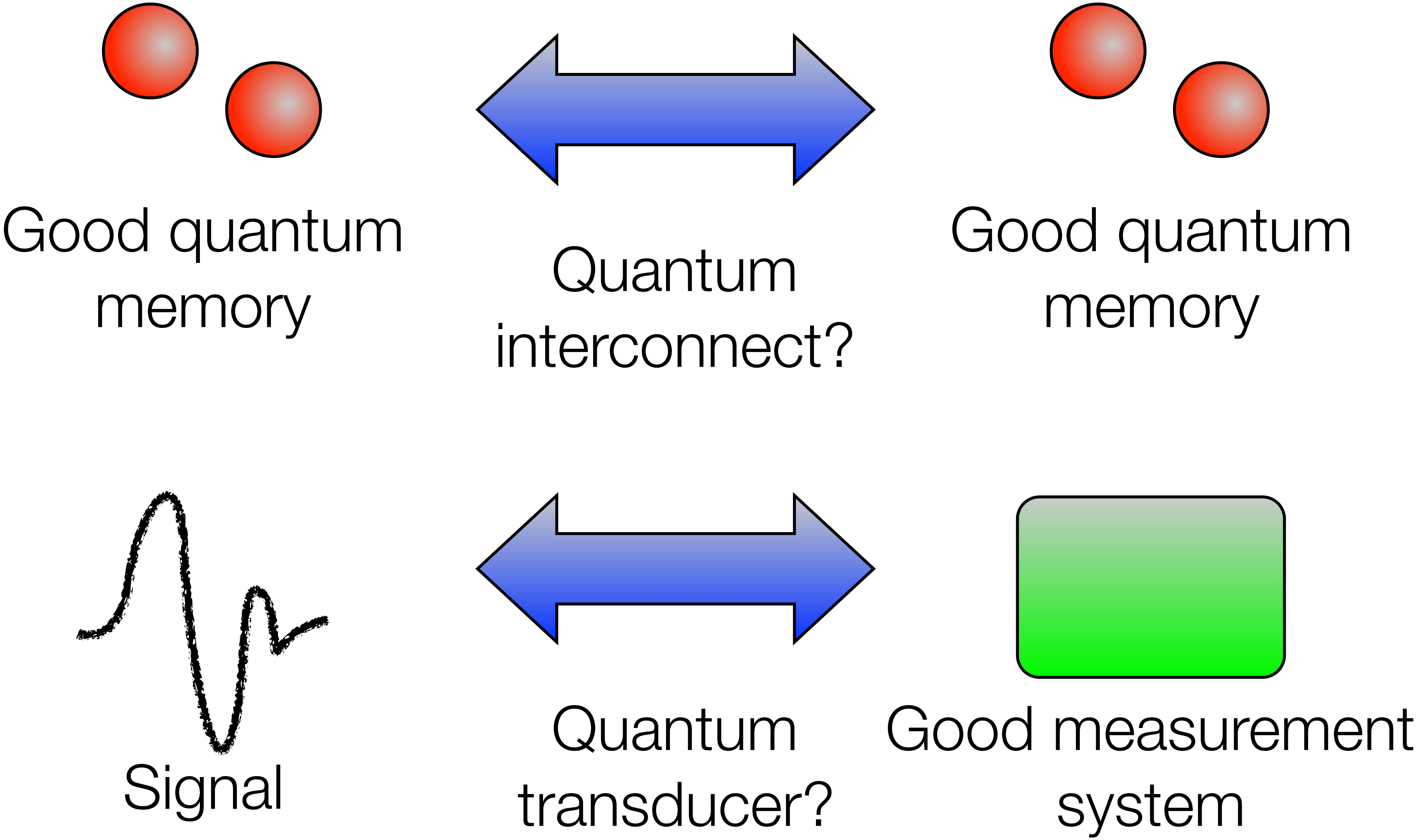
Why quantum transduction?

Quantum systems, entangled at a distance, provide…

Fundamental physics tests (Bell's inequality)
New approaches for metrology (clock syncronization)
Shared randomness at distance
Distributed quantum computing
And more (homomorphic/blind compute)?

Quantum networks provide these opportunities,
but we need a way to get Q information from A to B

Applications of linear systems: quantum interfaces



Good quantum memory

Quantum interconnect?

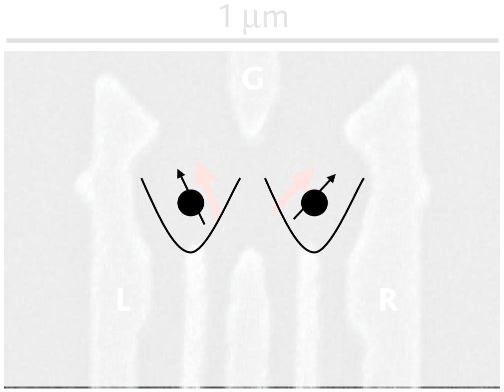
Good quantum memory

Signal

Quantum transducer?

Good measurement system

Spins in quantum dots



Local confinement in a semiconductor

- Trap single electrons in controlled potentials
- Electron spin provides a quantum bit

[Loss & DiVincenzo 1998]

$$|\text{``0''}\rangle = |\uparrow\rangle\,, |\text{``1''}\rangle = |\downarrow\rangle$$

Why solid-state atoms?

- Stability
- Local manipulation
- Possibility of large-scale integration

Why spins?

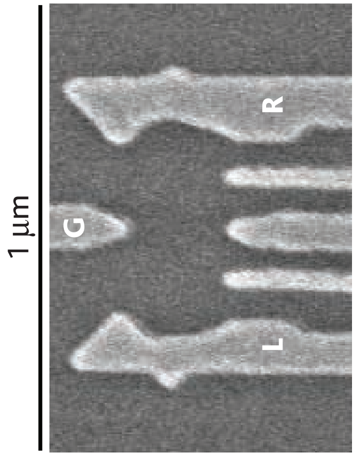
- Avoids charge relaxation
- Reduced coupling to 1/f
- *But*...

magnetic dipole coupling
***weak*, hard to localize**

Quantum memory

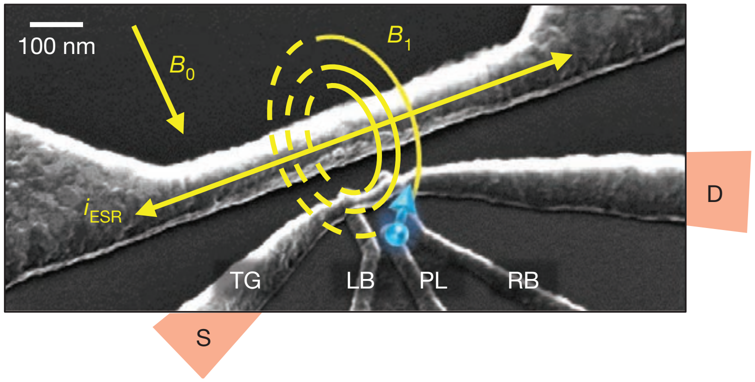
Electron spin in a quantum dot

Coherence time ~ 1-100 μs
Fast gates ~ 1-100 ns
Length scale ~ 100 nm



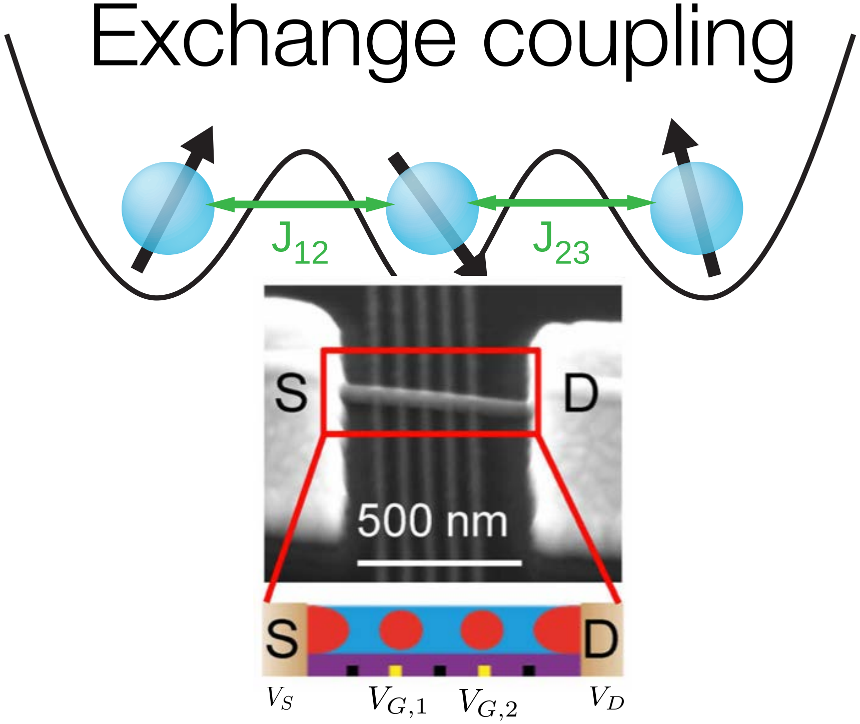
Single phosphorous impurity nuclei

Coherence time ~ 10^4 s
Slow gates ~ 0.1-10 ms
Length scale ~ 5 nm



Spin-based computing in silicon

Exchange coupling



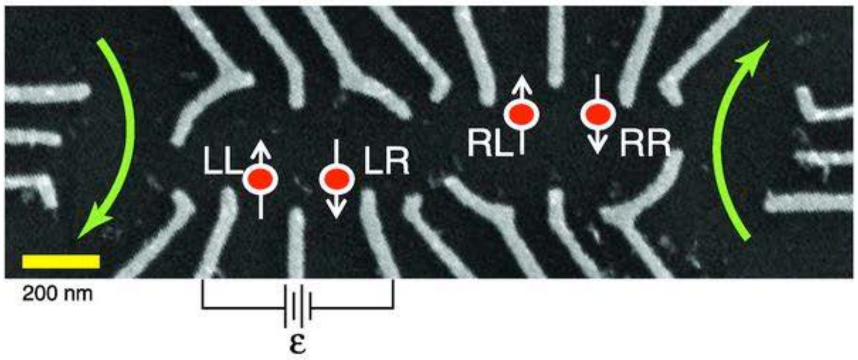
Operating parameters:

Low temperature (mK)

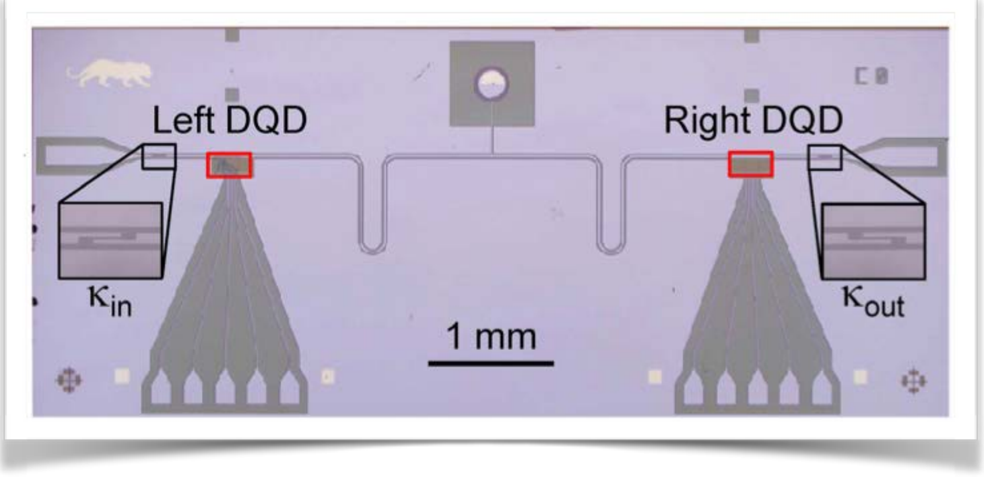
Microwave control and measurement

Small qubits (nm scale)

electrostatic coupling

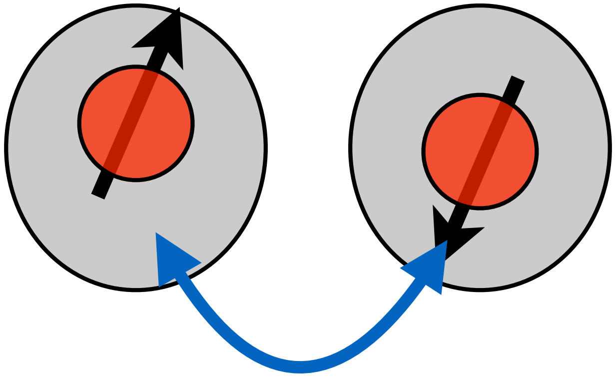


electrodynamic coupling



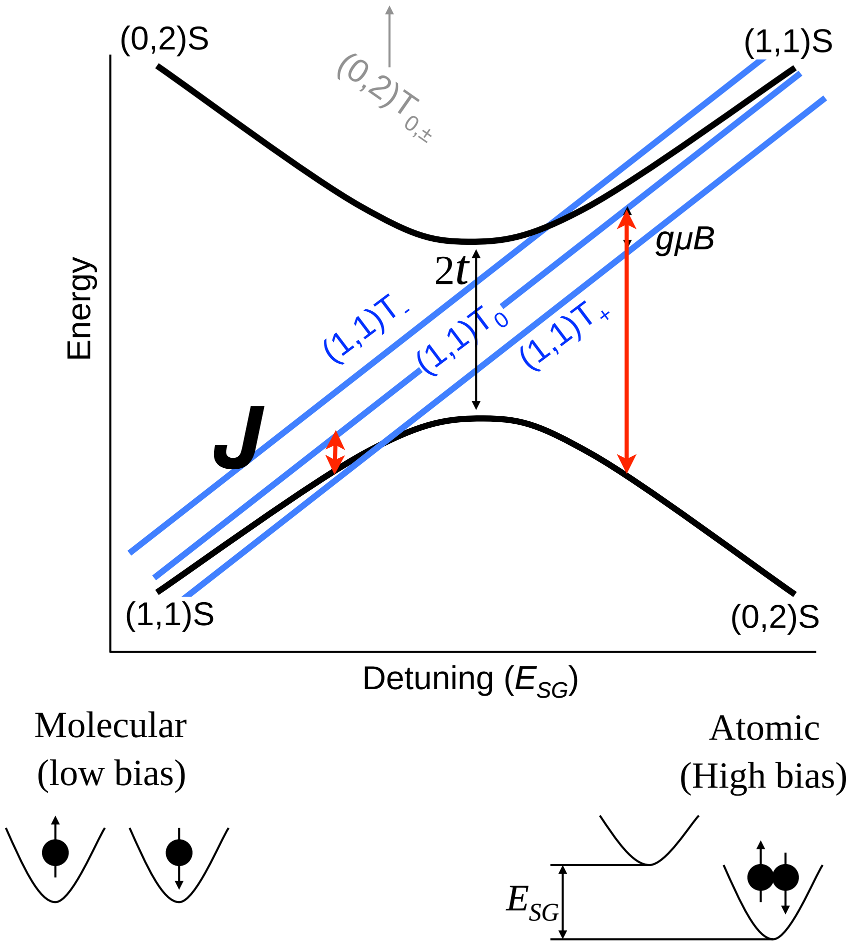
Short-range coupling: exchange

Overlap of wavefunctions

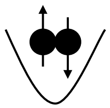


Spin singlet and spin triplet:
different energies (like molecular bonds)

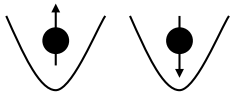
Double dot-based exchange interaction



- Hubbard model (t-U)
  - same QD: large exchange



$$|S_0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$



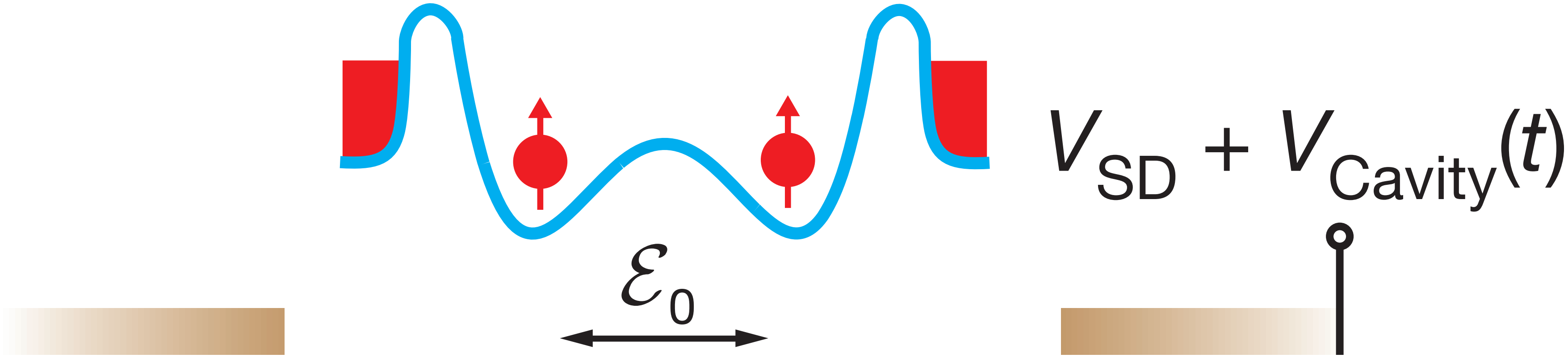
  - separated quantum dots: small exchange *J*, singlet–triplet degeneracy

$$|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$$

  - separated electrons can enter same quantum dot iff singlet
  - control exchange with voltage
  - measure charge state with nearby electrometer

Coupling a spin to microwaves

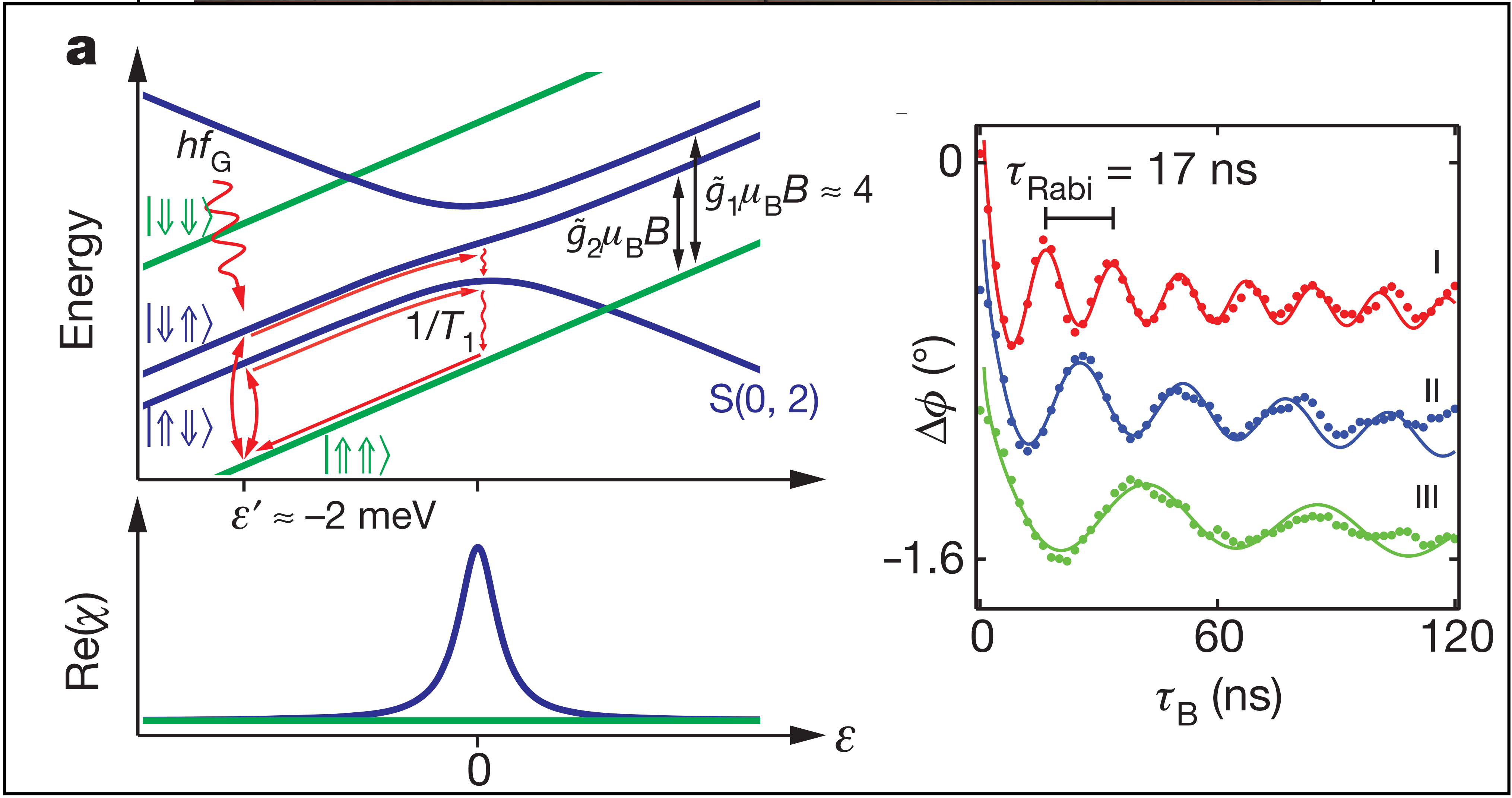
Double quantum dot in an
InAs nanowire (two electrons)



Voltage induces charge oscillations...
spin-orbit leads to spin rotations

Coupling a spin to microwaves

Double quantum dot in an

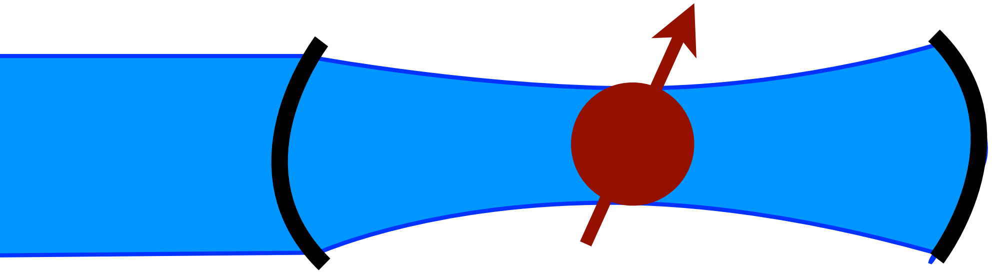


[Taylor, Lukin (2006); Petersson *et al.* Nature (2012)]

Cavity QED and beyond

[Haroche, Kimble, Rempe, …]

Goal: coupling *magnetic* dipoles to photons



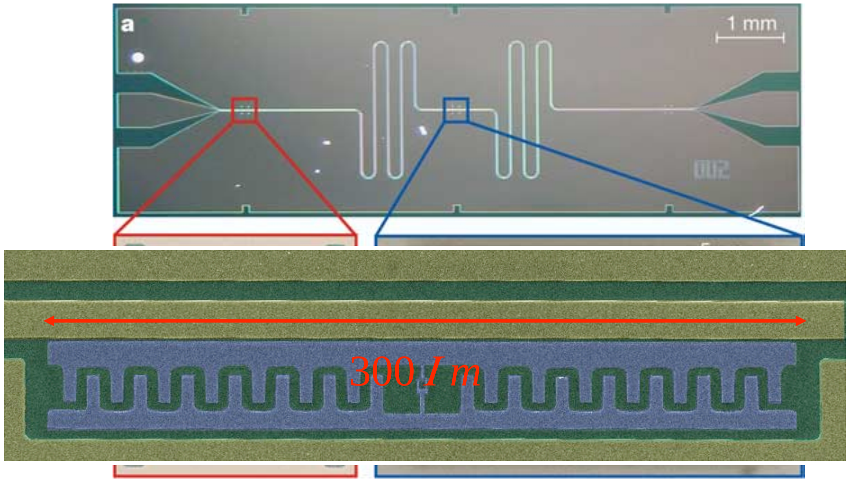
- decrease the volume
- increase the dipole moment
- decouple the magnetic and electric fields

$$\frac{\text{Vacuum Rabi coupling}}{\text{Resonance frequency}}$$

$$\frac{g}{\omega} \sim \sqrt{\alpha}\frac{\mathcal{D}}{ea_0}\sqrt{\frac{\lambda a_0^2}{V}}$$

$$\frac{g_\mu}{\omega} \sim \alpha^{3/2}\frac{\mu}{\mu_B}\sqrt{\frac{\lambda a_0^2}{V}}$$

[Schoelkopf group]

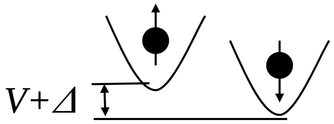


Spin-“orbit” and electric dipole transitions

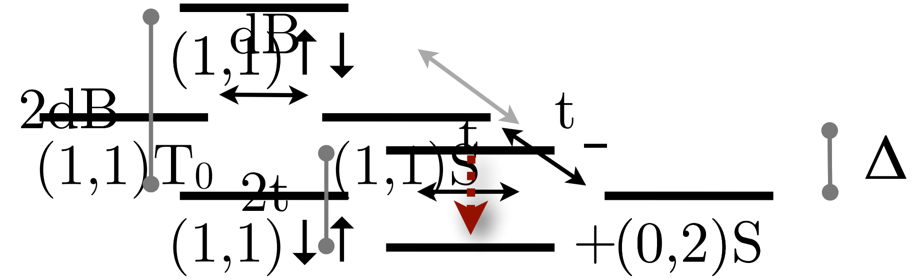
Different working regime:

- large gradient
- intermediate exchange

Electric field drives transitions between qubit states



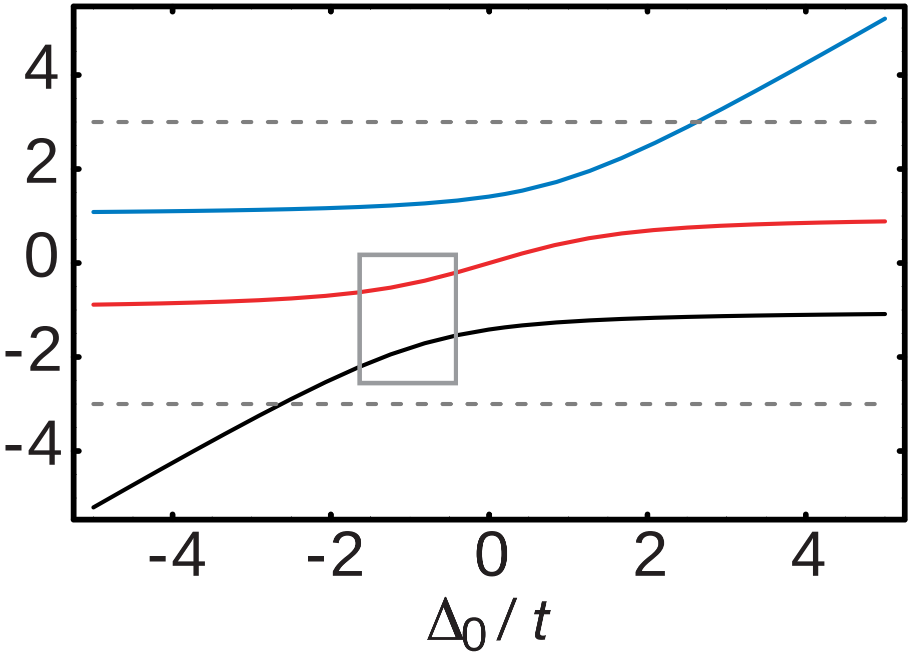
$V \propto (\hat{a}+\hat{a}^\dagger)$



Magnetic field gradient (dB) mixes singlet and triplet

Tunnel coupling (t) mixes (1,1) and (0,2)

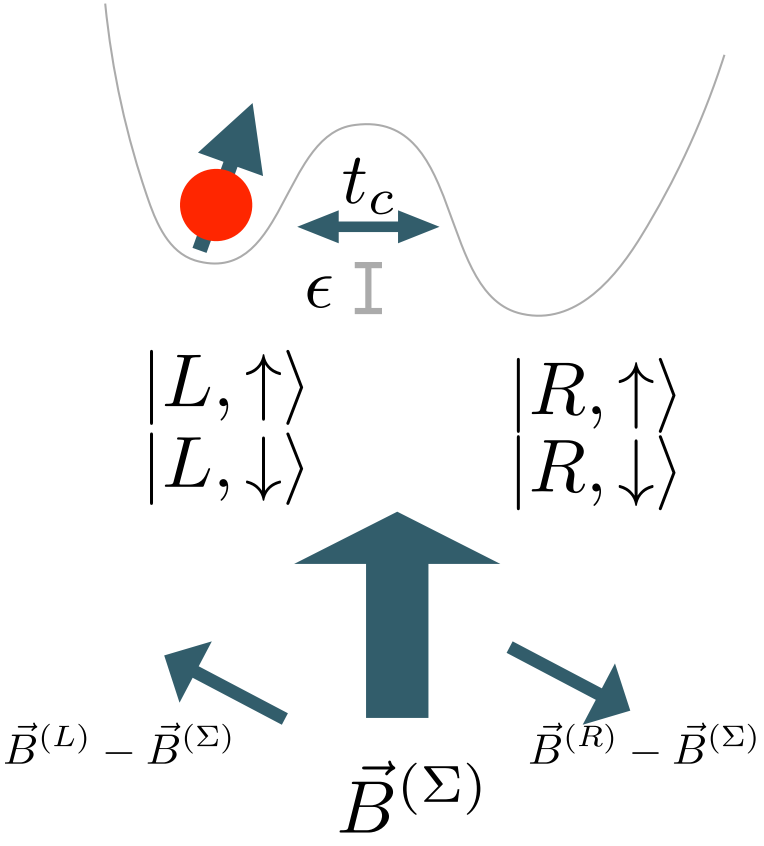
Resonator photon



[Burkard & Imamoglu, PRB 2007,
Taylor & Lukin, cond-mat/0605144]

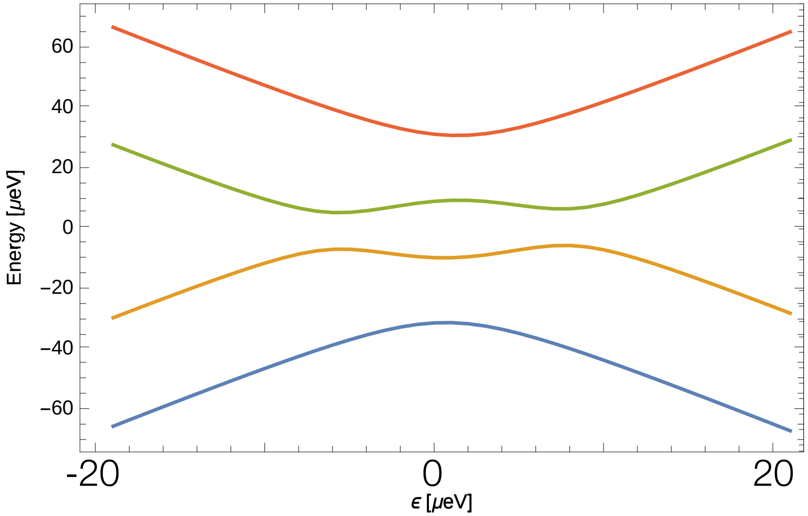
Single spin coupling approach: mix in charge

[Srinivasa et al. (2013)]

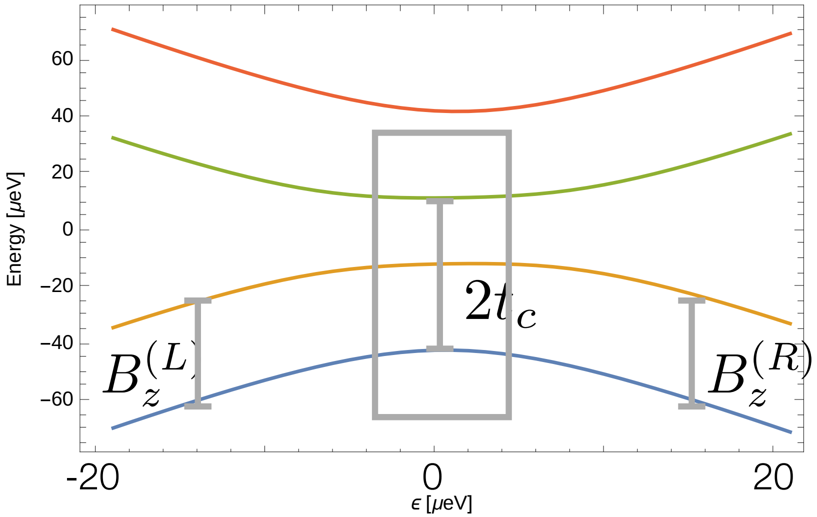


$$dB_x \equiv B_\perp^{(L)} - B_\perp^{(R)}$$

$$2t_c < B_Z^{(\Sigma)}$$



$$2t_c > B_Z^{(\Sigma)}$$



The Lambda system at zero detuning for spin-charge-photon coupling

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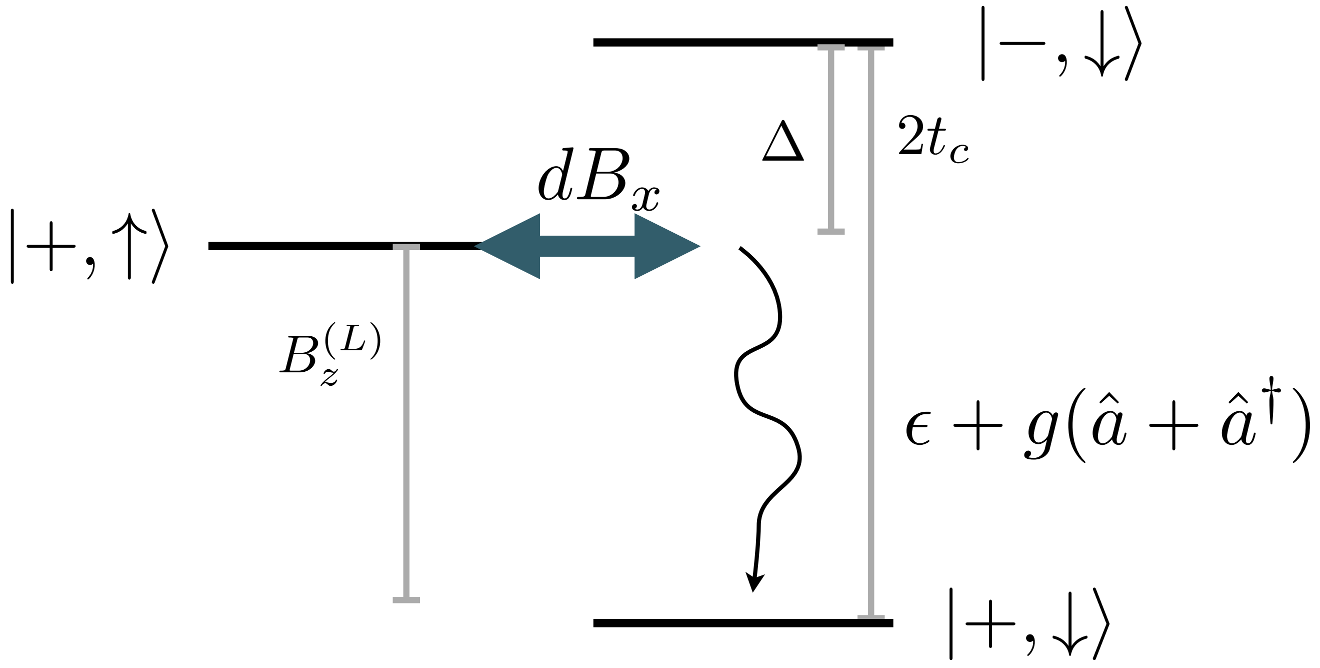
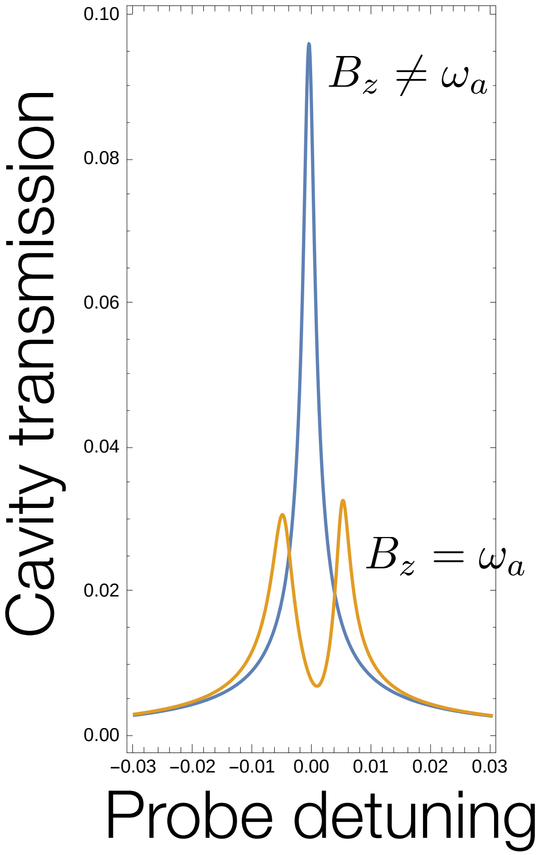
[Benito González et al. PRB 2018]



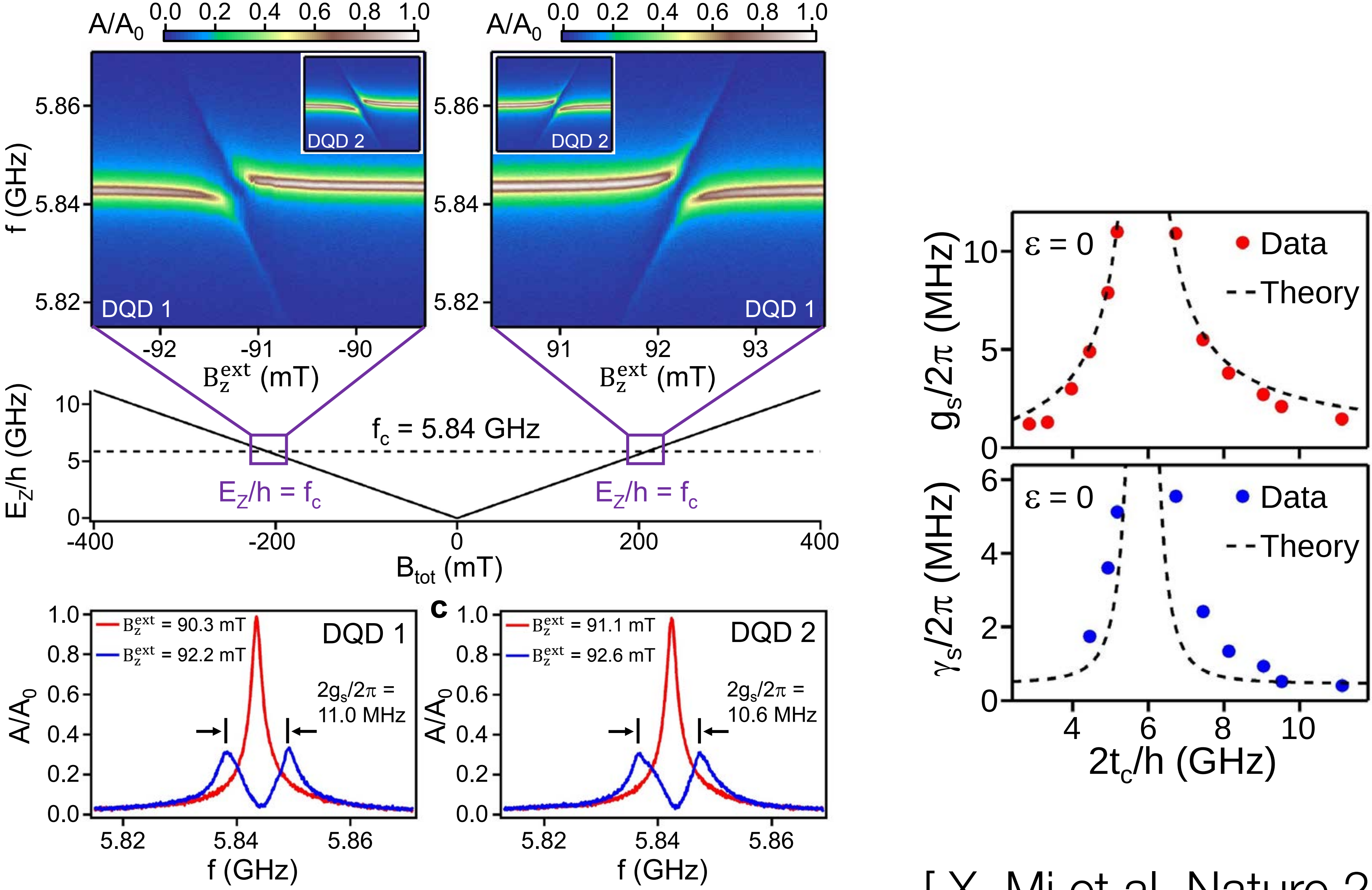


Key features: adiabatic elimination $g_{\text{eff}} \approx \dfrac{dB_x g}{\Delta}$

Key features: dark state/bright state $|B\rangle \propto \left(g a^\dagger \,|+,\downarrow\rangle + dB_x \,|+,\uparrow\rangle\right) |\text{vac}\rangle$

dark state: *no* decay through charge!

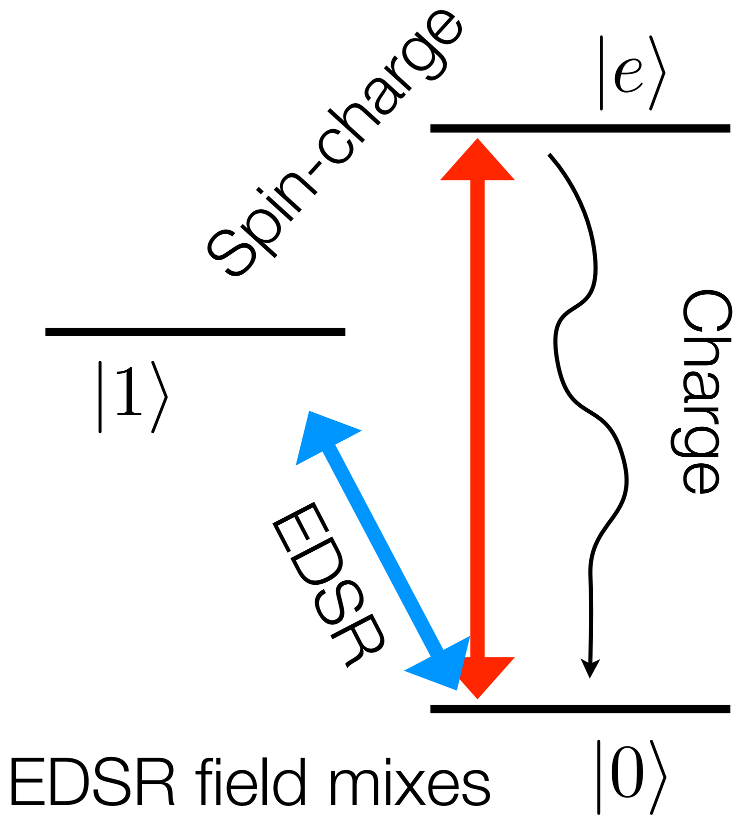
Experimental evidence for strong coupling



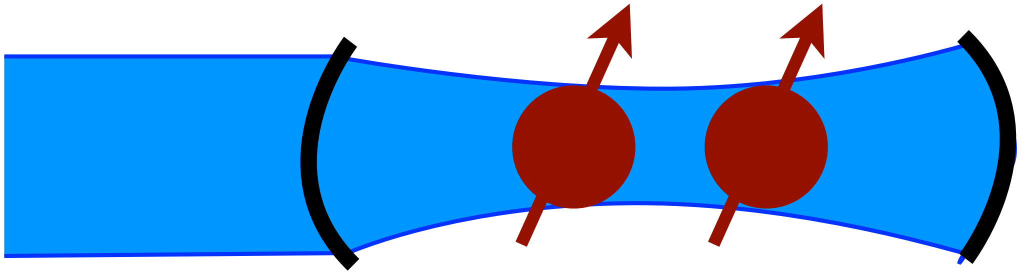
[X. Mi et al. Nature 2018]

Entanglement generation using a resonator

Two atoms, one resonator: destructive and constructive interference

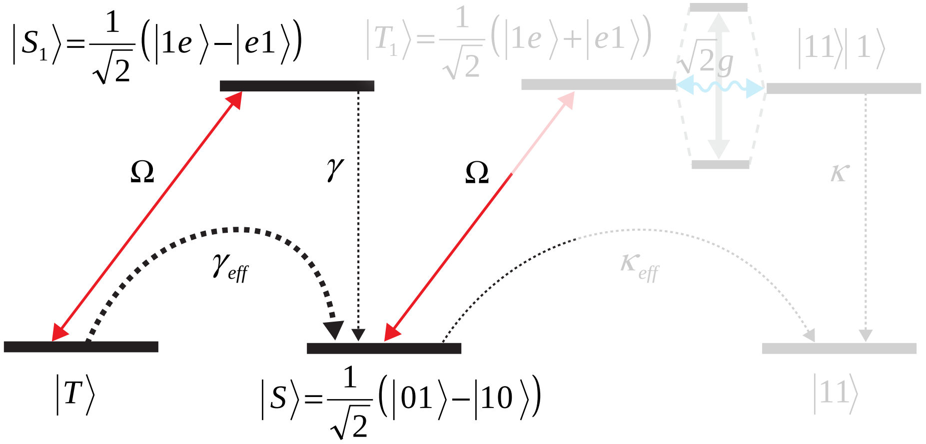


EDSR field mixes triplet states



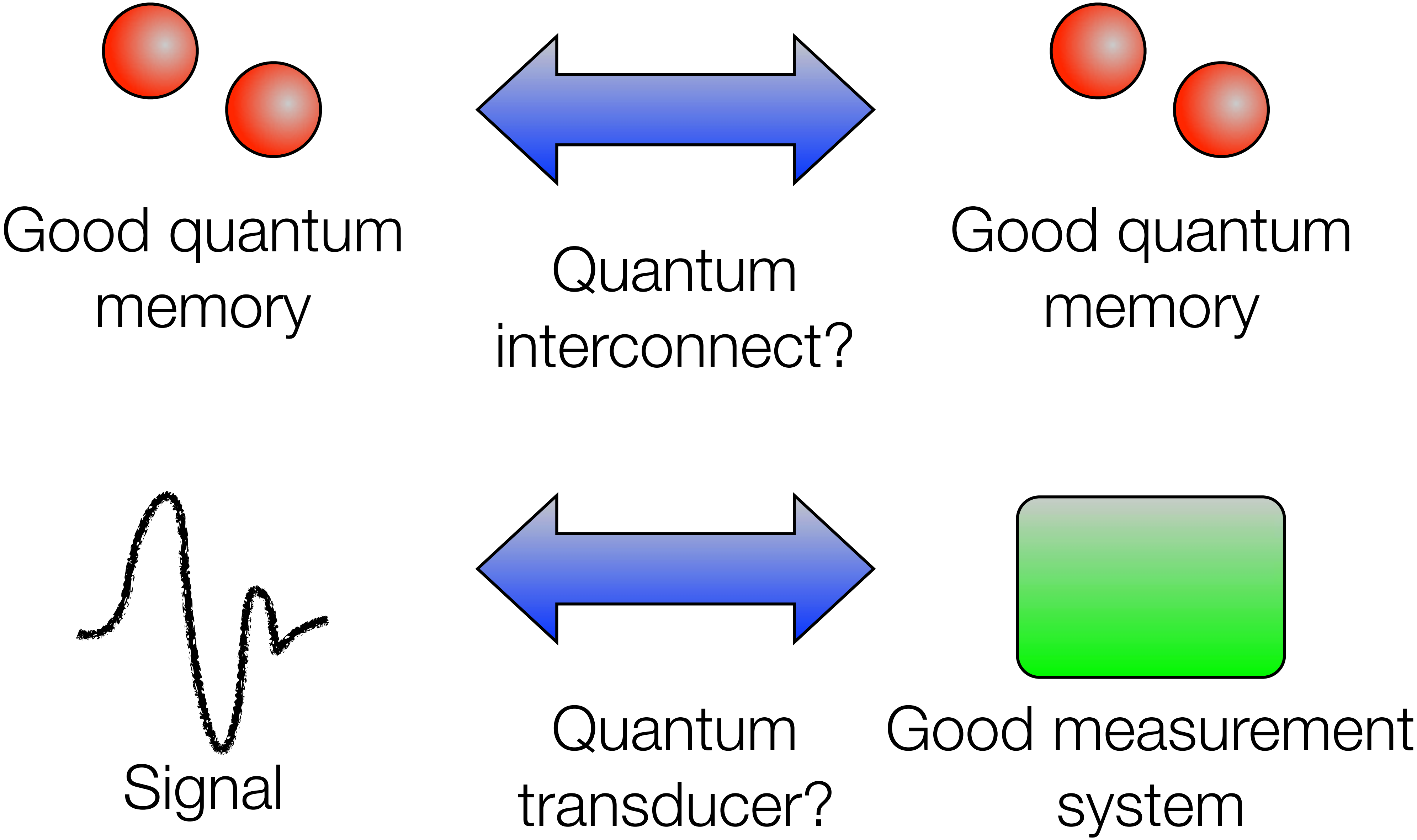
Driving two atoms in an optical cavity into an entangled steady state using engineered decay

Florentin Reiter[1], Michael J Kastoryano and Anders S Sørensen



Steady state reached in time $\gg \frac{\gamma}{g^2}$, infidelity ~ $\frac{1}{C} \sim \frac{\gamma\kappa}{4g^2}$

Applications of linear systems: quantum interfaces



Good quantum memory

Quantum interconnect?

Good quantum memory

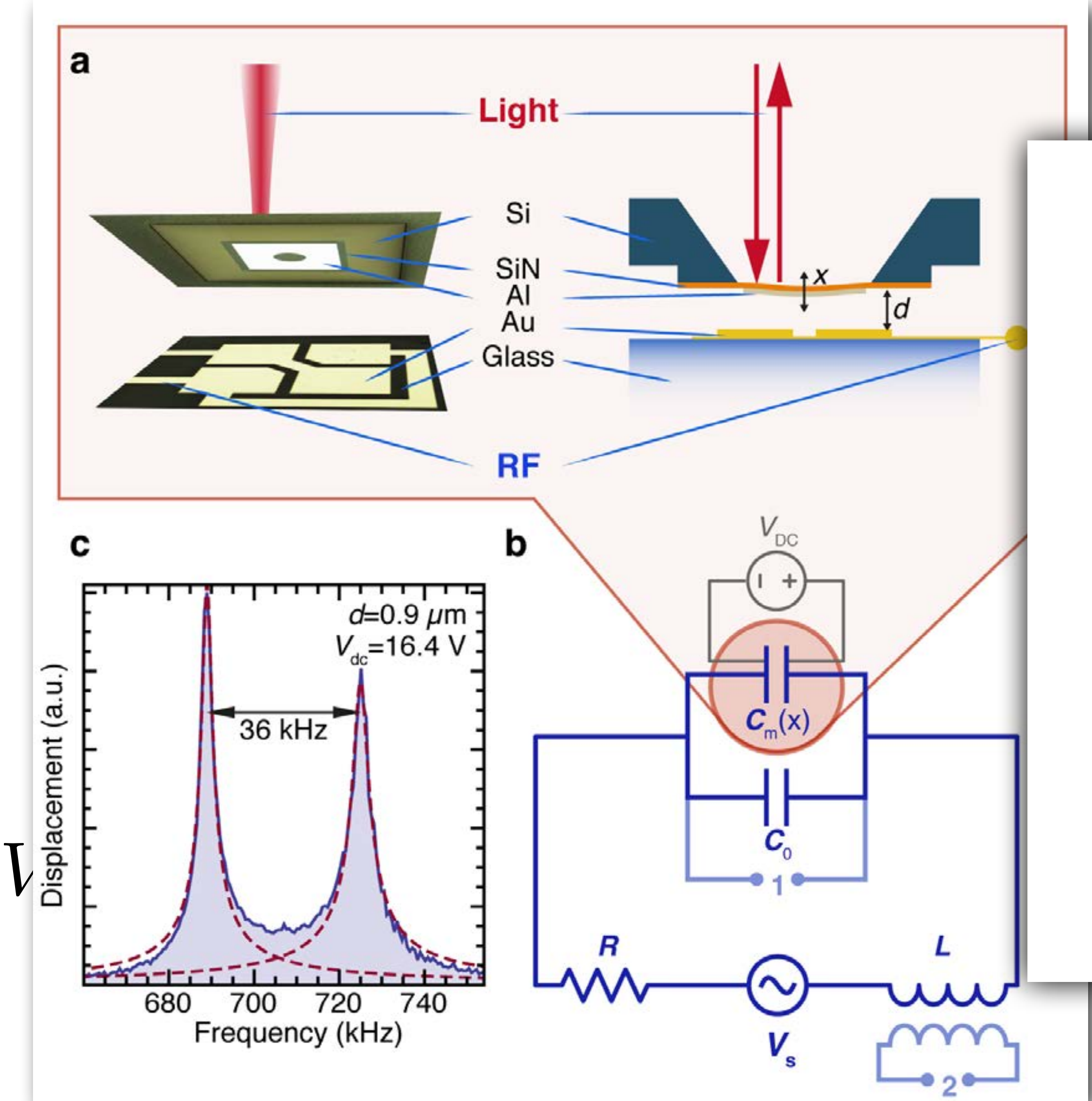
Signal

Quantum transducer?

Good measurement system

A universal interface?

[JMT et al PRL (2013)]
[Bagci et al Nature (2014)]
[Regal, Lehnert (2015)]
[Usami group (2017)]

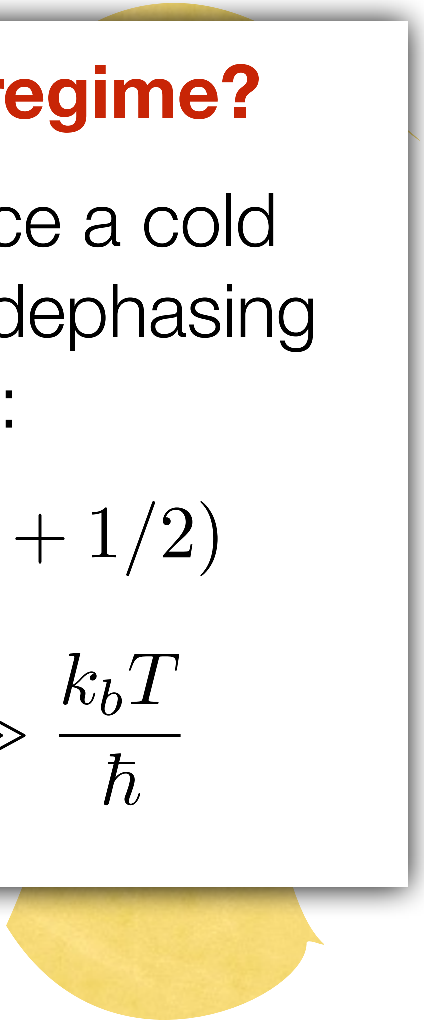


Quantum regime?

Can transduce a cold source when dephasing slow:

$$\omega > \gamma(n_{\rm th} + 1/2)$$

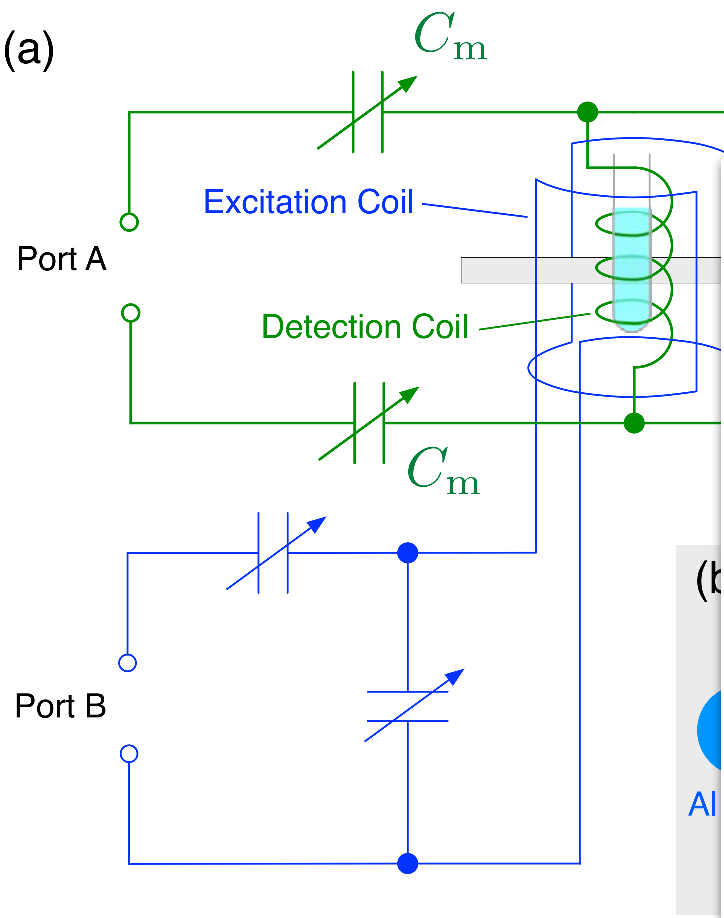
or $$\frac{\omega}{\gamma}\omega \gg \frac{k_b T}{\hbar}$$

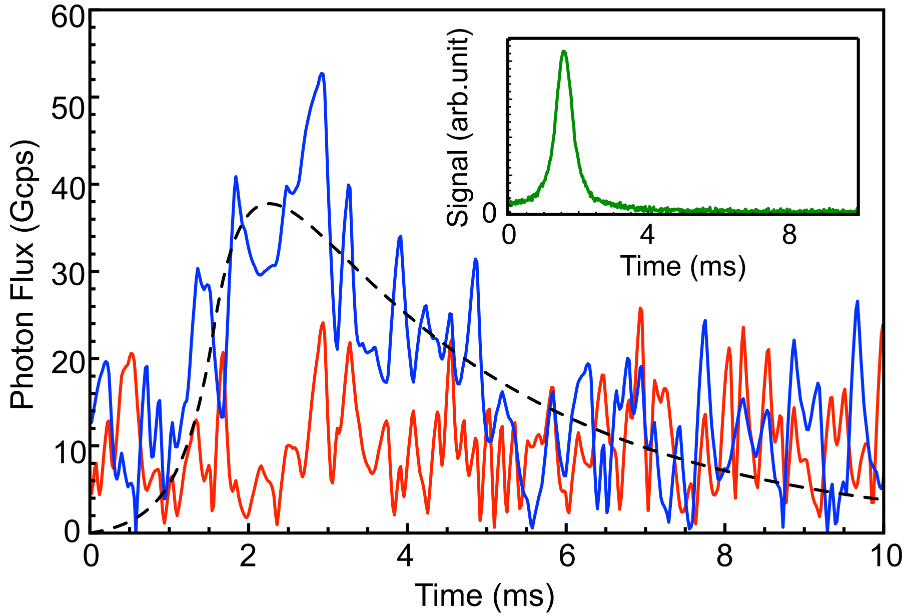


Versatile optical interface

Enhanced NMR via optical readout

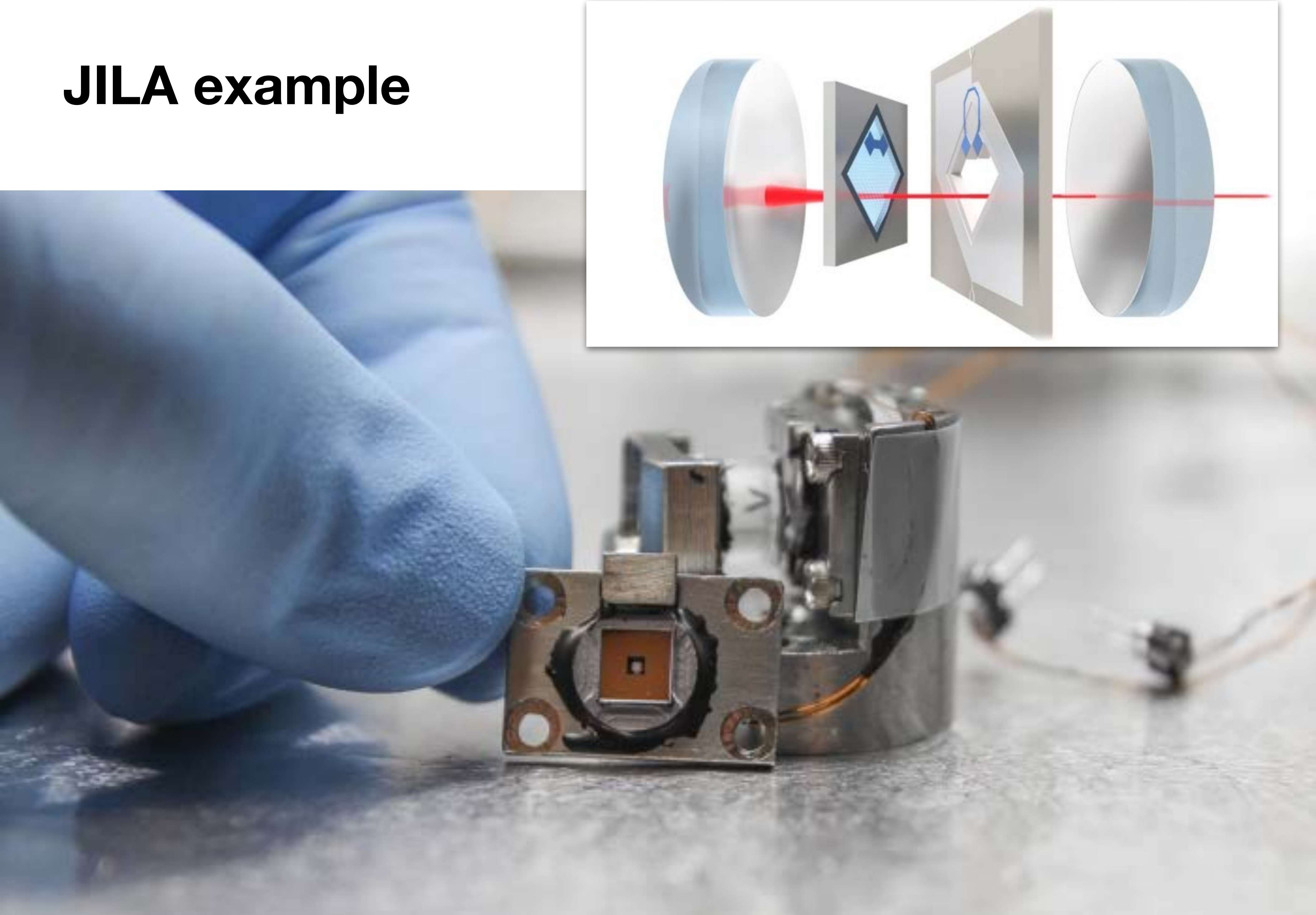
[Takeda et al., Optica 2018]



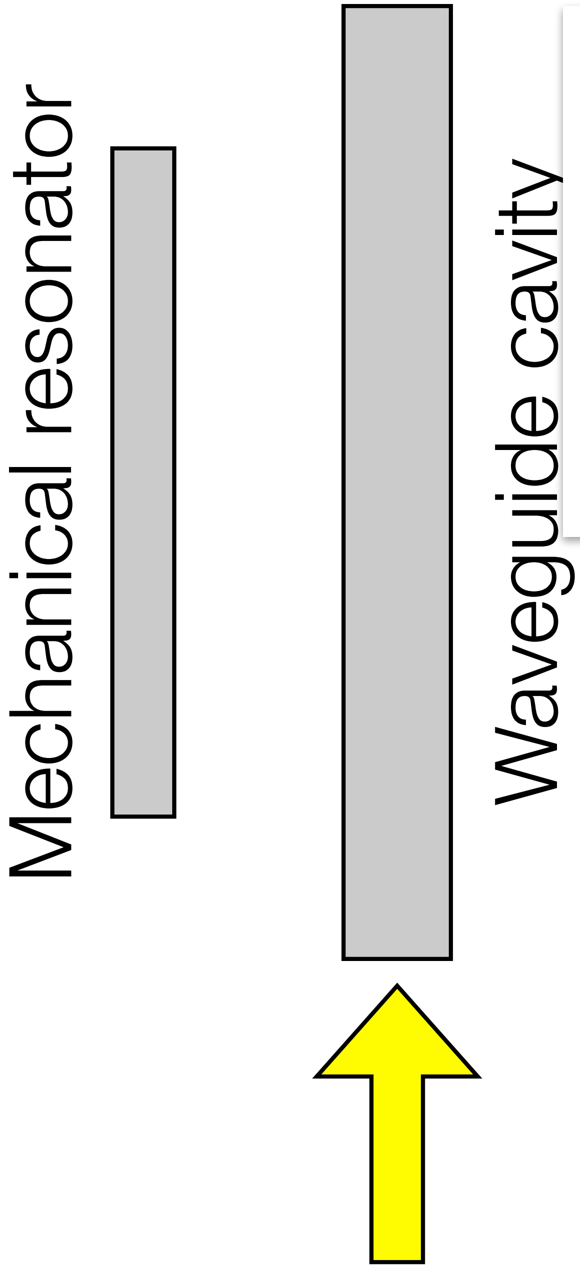


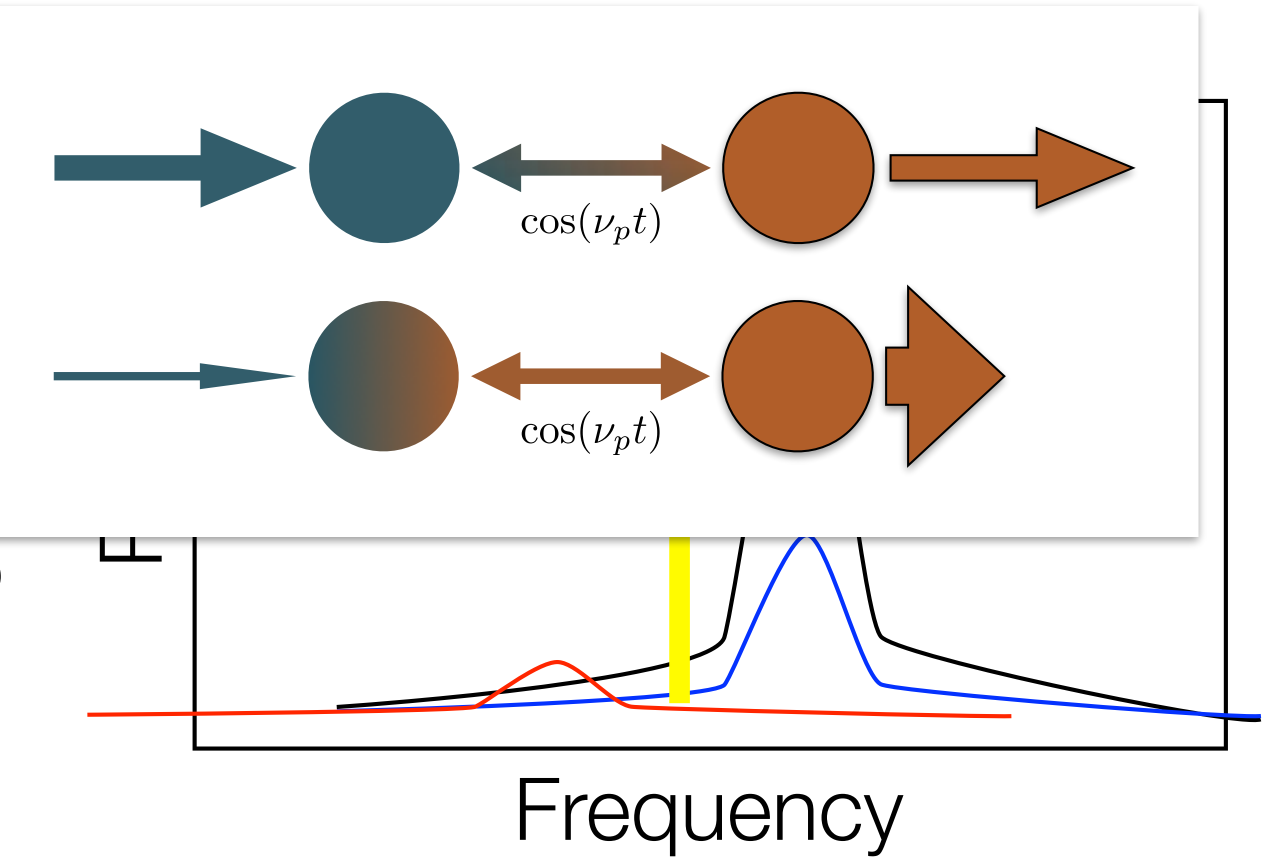
Observation of proton spin echo via transduction

JILA example



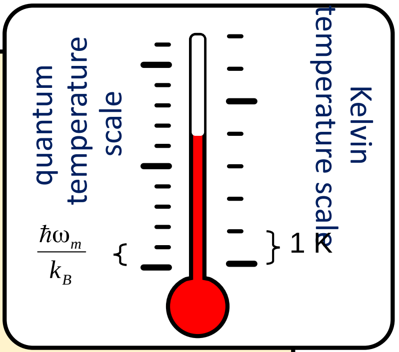
Sideband cooling





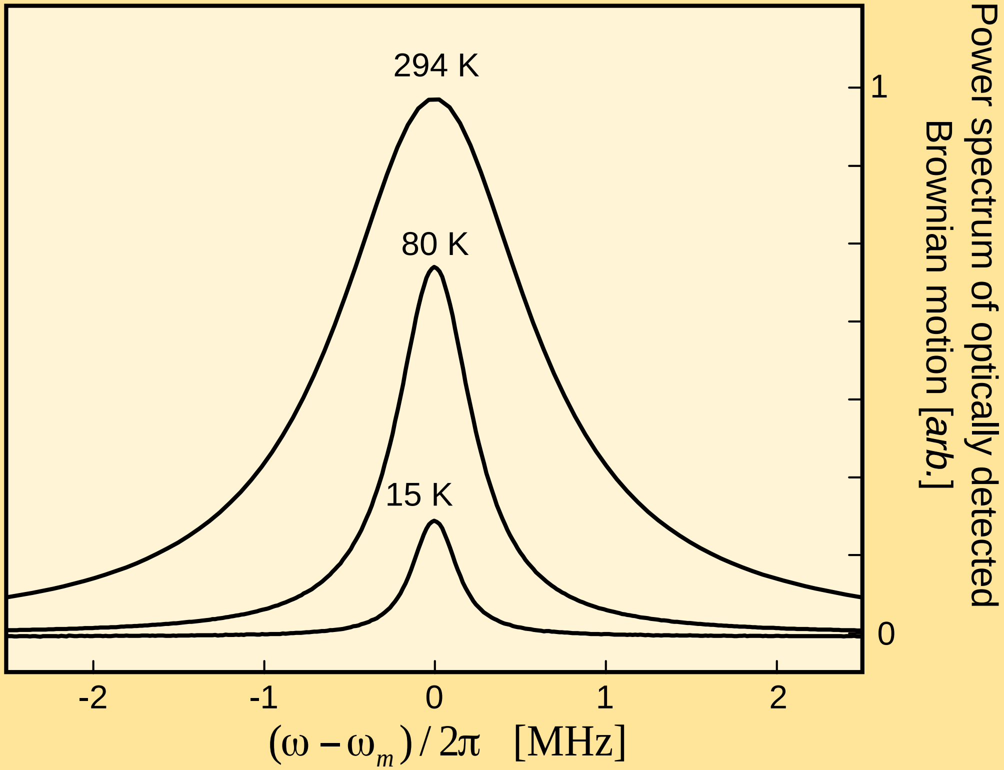
Phonons convert into outgoing photons if cavity line width is narrow

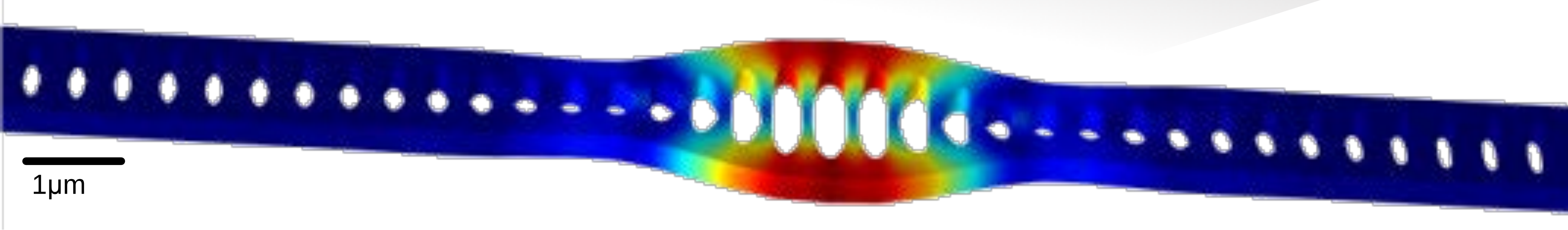
Optomechanical Quantum Correlation Thermometry



- Brownian motion is an absolute noise thermometer (like Johnson noise) but is hard to calibrate
- Use quantum fluctuations as intrinsic force standard
- Look at optical correlations to distinguish thermal from quantum backaction force (similar to Raman sideband asymmetry, but technically easier)
- Goals:
  - Build on-chip, photonic integrated primary thermometer
  - Develop methods to observe quantum measurement backaction at room temperature

Optically Detected Brownian Motion

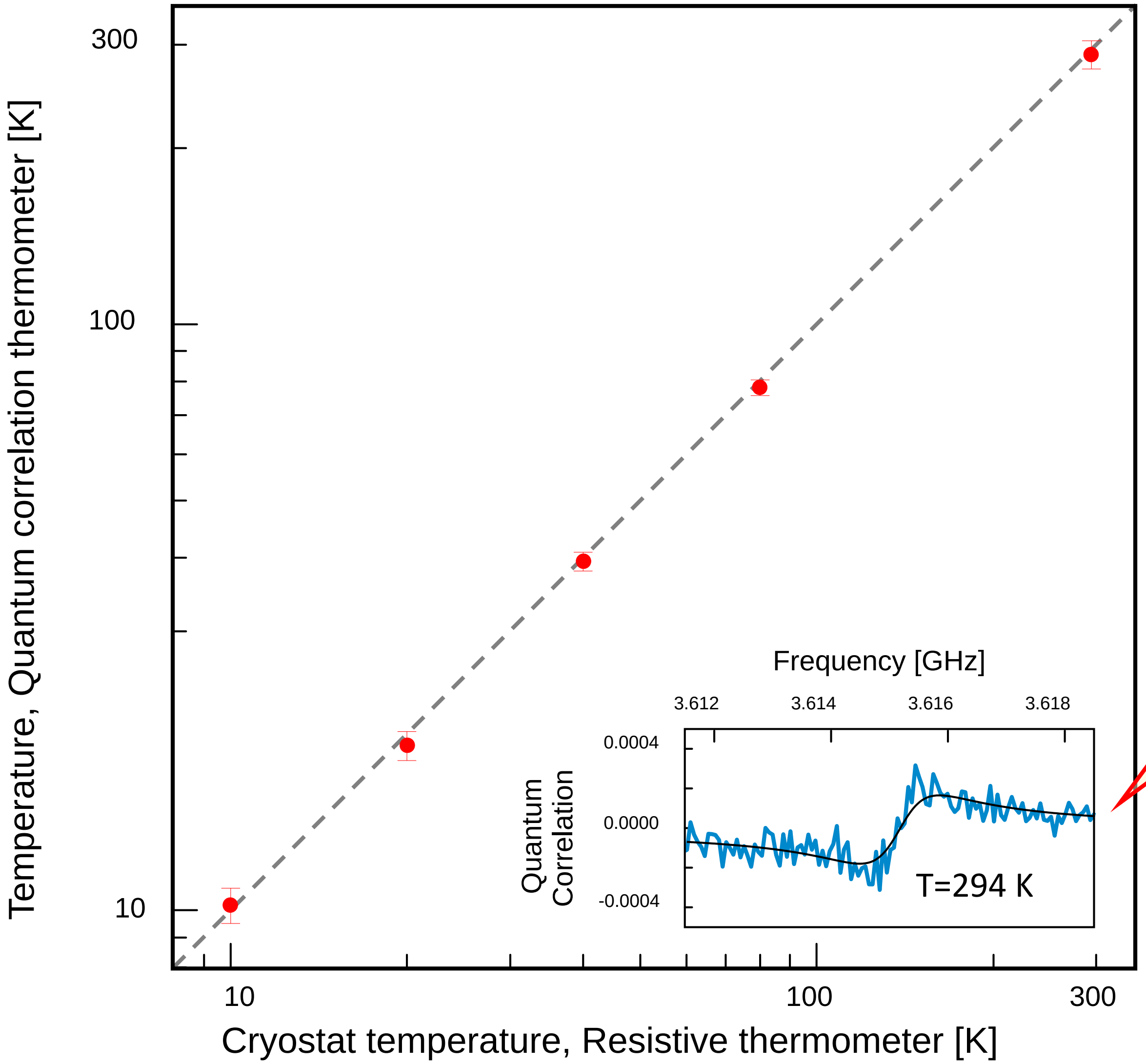




3.6 GHz vibrational mode of Si_3N_4 nanobeam

Optomechanical Quantum Correlation Thermometry

Proof-of-principle demonstration of quantum correlation thermometry



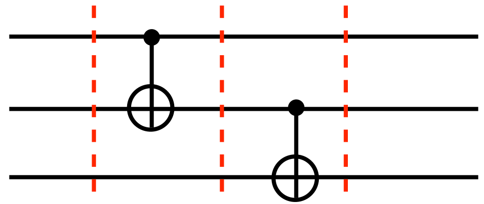
Room temperature signature of quantum measurement backaction

T. P. Purdy, K. E. Grutter, K. Srinivasan, J. M. Taylor, *Science* 2017

Using entanglement: deterministic distributed computation

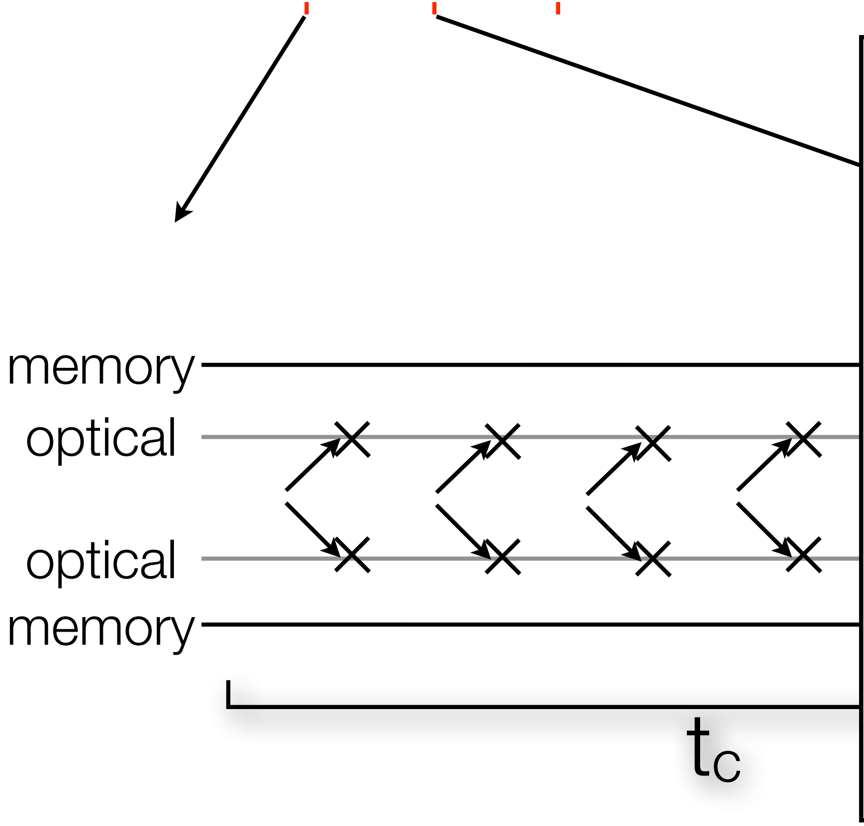
[Gottesman & Chuang (1999); **L. Jiang et al. (2007);** Yao et al. (2013); Monroe et al. (2014)]

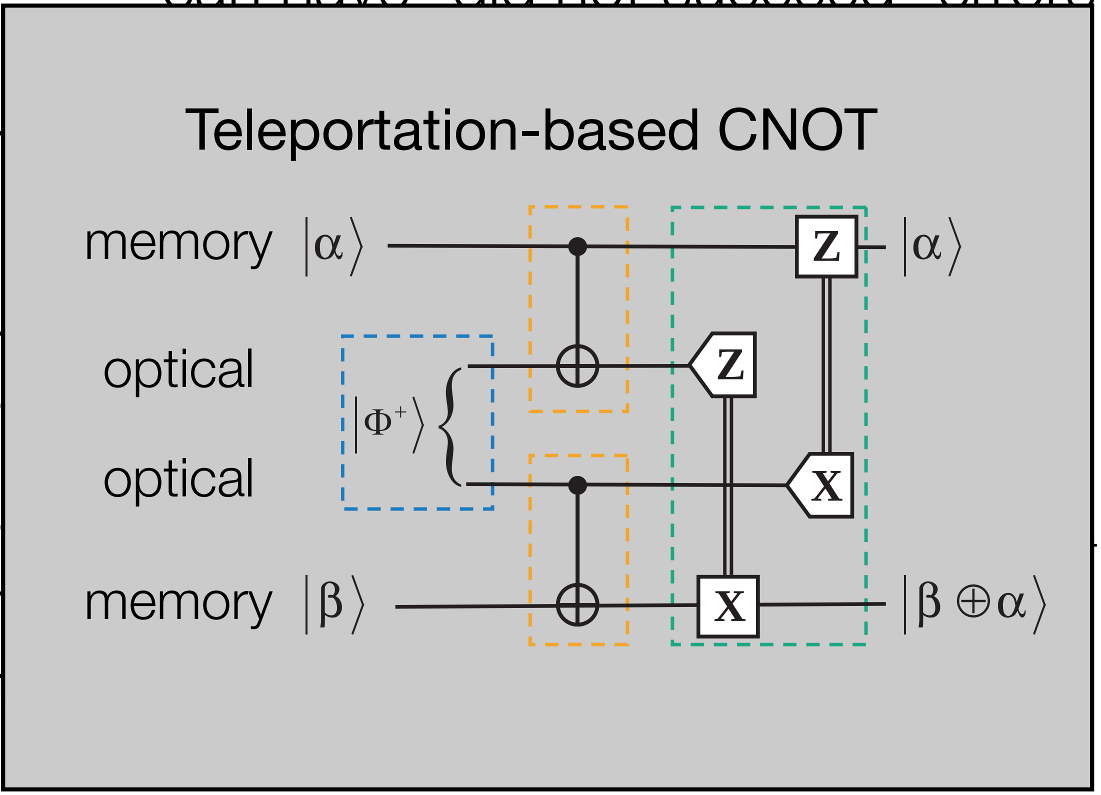
desired (logical) circuit



Idea:

- Break into pairwise gates
- Set a “clock cycle” time
  – can have “did not succeed” errors





Teleportation-based CNOT

Dealing with imperfections: 3 more spins

[Dür & Briegel (2003); Jiang et al. (2007); Jiang et al. (2009)]

Robust measurement

- imperfect initialization, measurement (p_I,p_M ~ 5%)
- near-perfect local operation (p_L ~ 0.01%)

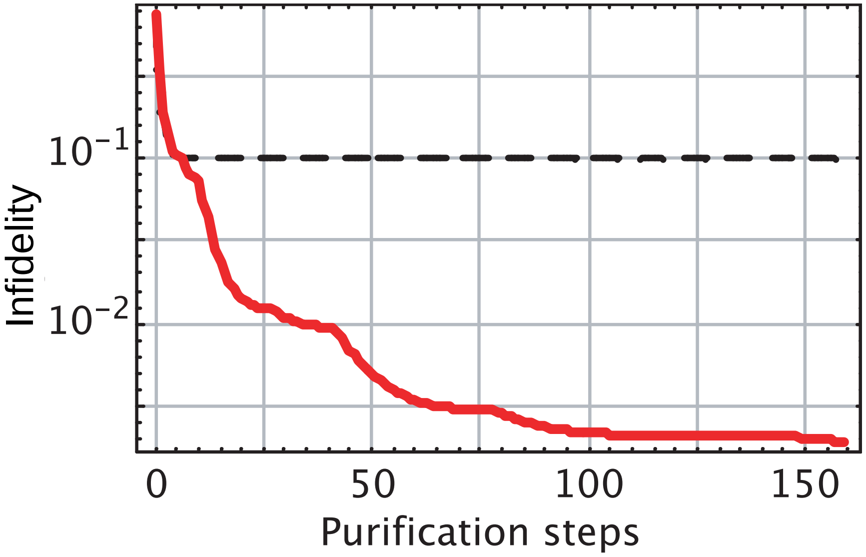
$$\tilde{\varepsilon}_M \approx \binom{2m+1}{m+1} (p_I + p_M)$$

$$\tilde{t}_M = (2m+1)\,(t_I + t_L + t_M$$

Further improvements:
better collection efficiency via cavities (Purcell effect)
— improves both speed and fidelity

Robust entanglement generation

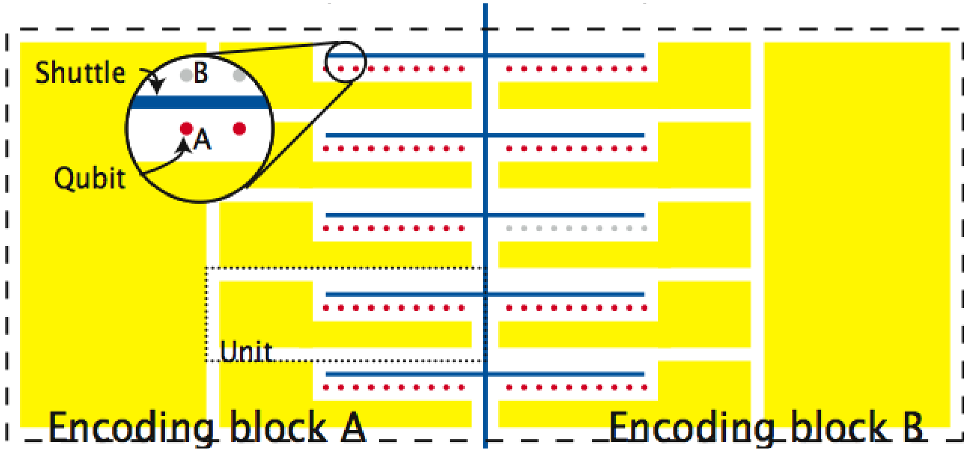
- Large time overhead
  (t_C ~100–1000 t_L)
- Initial *F*=0.9 gives final *F*>0.995
  (N_{eff} ~ 20)
- Good quantum memory *critical*



[Oskin et al. (2002); Copsey et al. (2003);
Metodi et al., (2005, 2008); Jiang et al. (2007);
DiVincenzo (2009); Fowler et al. (2010);
Monroe et al. (2014); Veldhost et al. (2016);

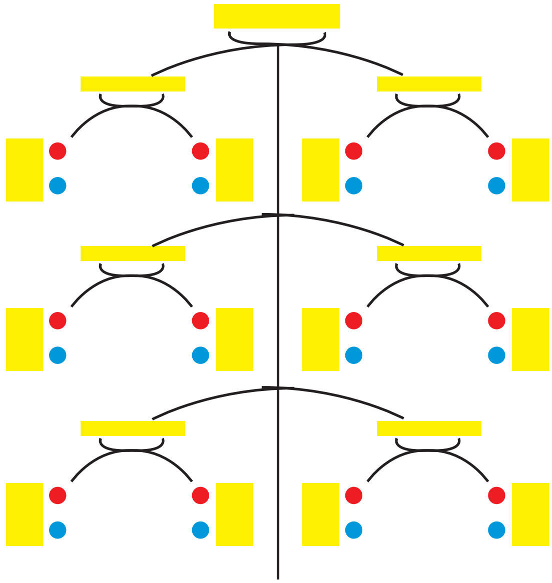
Large-scale processors

Shuttling and neighbors

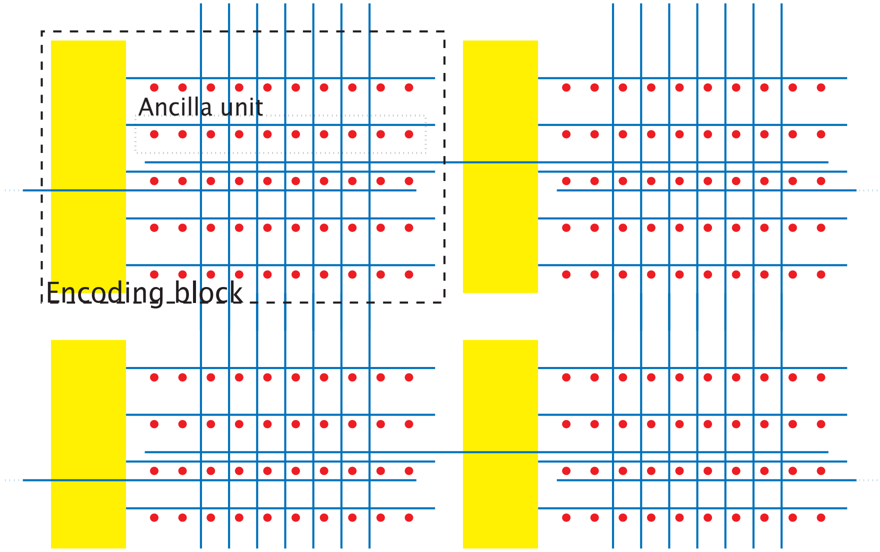


In all cases: quantum error correction dominates over logical operations.

Distributed computation: registers and links

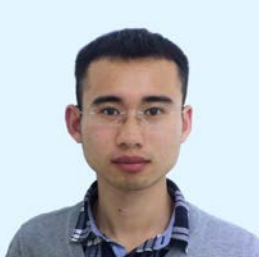


Deterministic resonator coupling and control



Thanks!

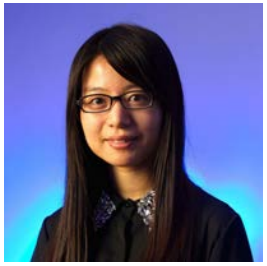
quics.umd.edu
@quantum_jake

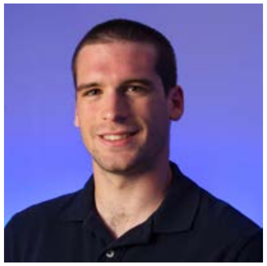

X. Wu


J. Zwolak


M. Gullans


S. Ragole


C.-H. Wang


A. Glaudell


M. Tran


B. Richman


S. Guo

UTokyo/RIKEN: K. Usami,
Y. Nakamura
Kyoto U: K. Takeda

Mónica Benito González, Guido Burkard,
Xiao Mi, Jason Petta