Single microwave photon detectors for ADMX

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Fermilab

Collaborators: Akash Dixit, David Schuster (U.Chicago) and ADMX-G2

ADMX-G2, an Axion Dark Matter Radio

Tests QCD axion models which would solve the strong-CP problem

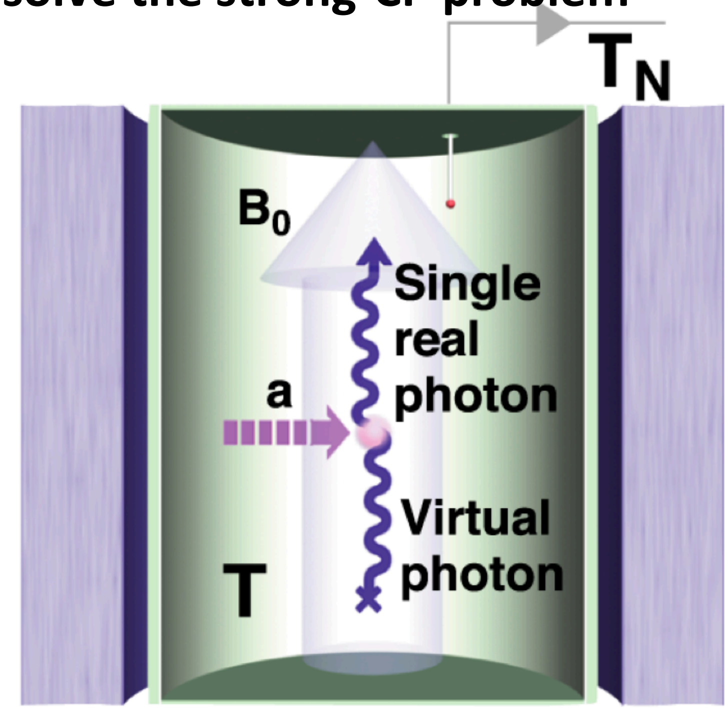
Coherently scatter classical axion dark matter wave (10^{20} axions/m^3 coherent state) on DC magnetic field.

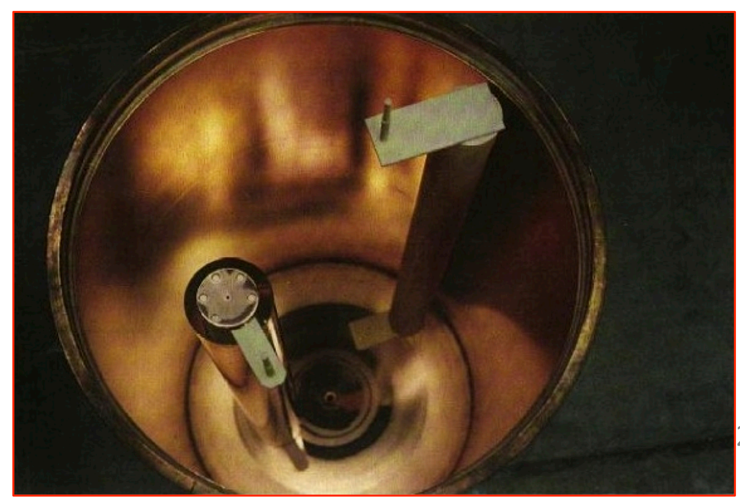
Resonantly enhance scattering cross section using tunable high-Q microwave cavity as the "antenna."

Use quantum-limited amplifier with "irreducible" single photon readout noise.

At each radio tuning, look for tiny excess power by averaging away noise over $>10^5$ measured power spectra.

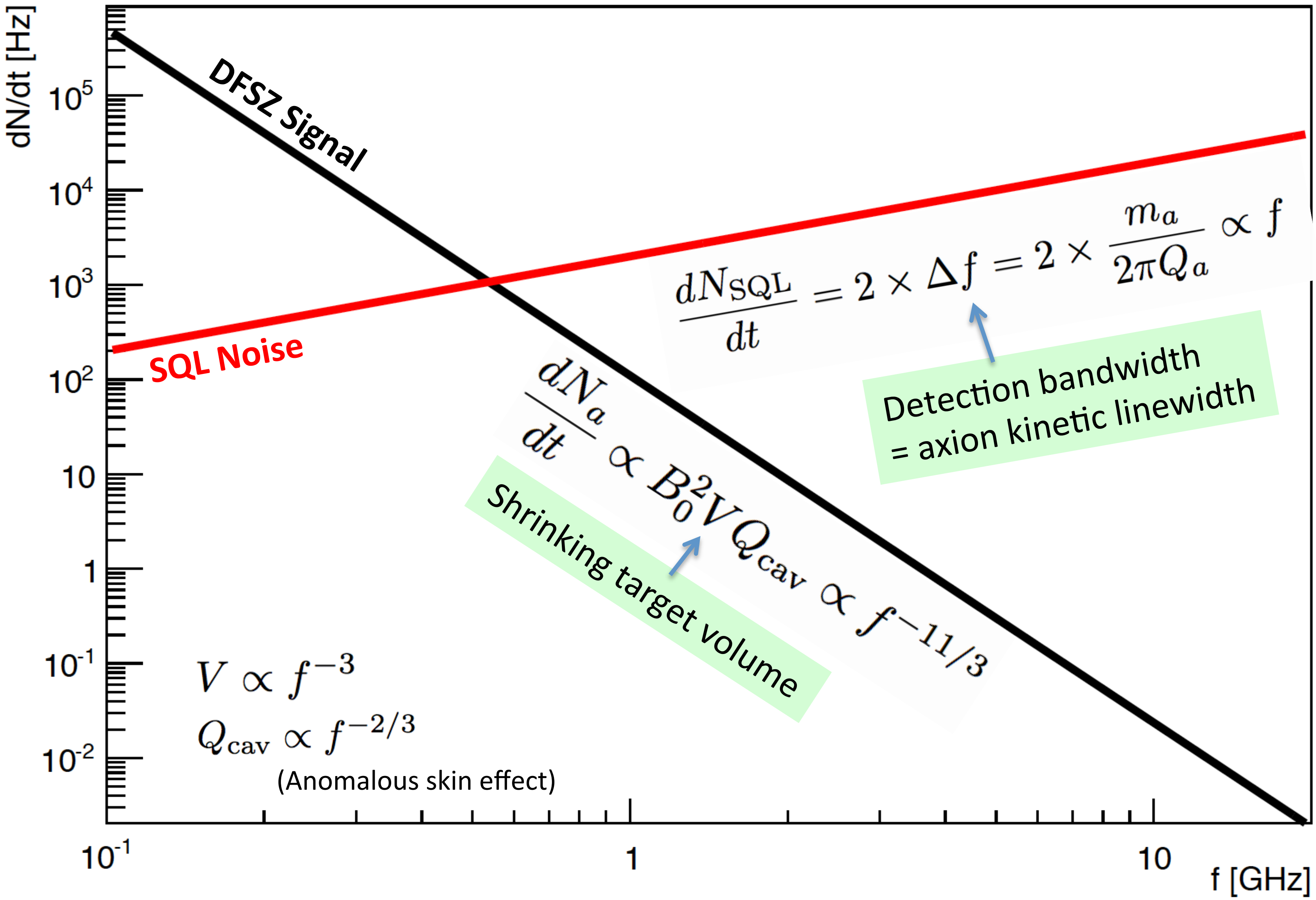
Confirm/exclude the predicted axion-photon coupling at that frequency.



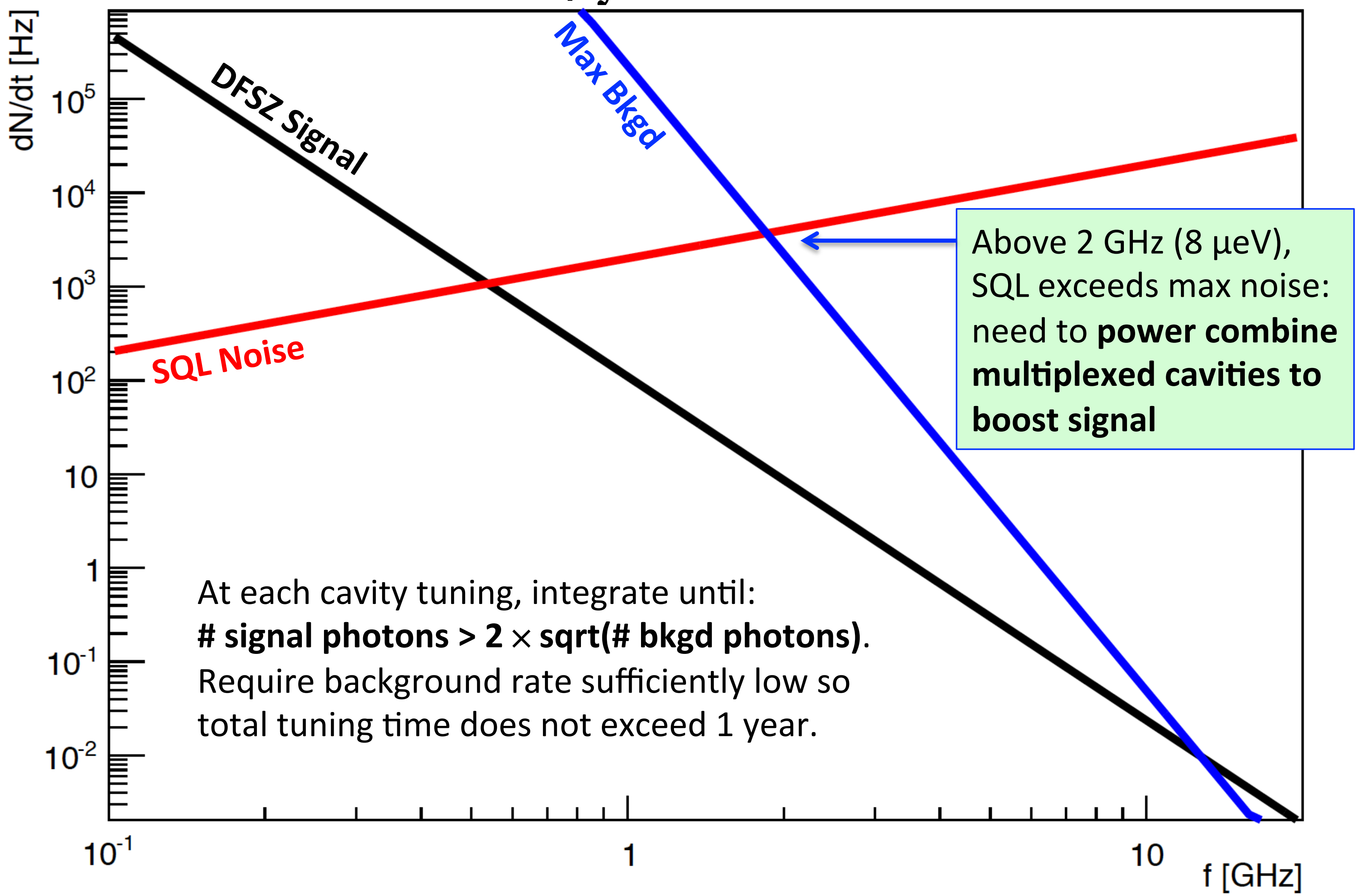

ADMX copper cavity

Aaron S. Chou (FNAL), ICHEP 2016

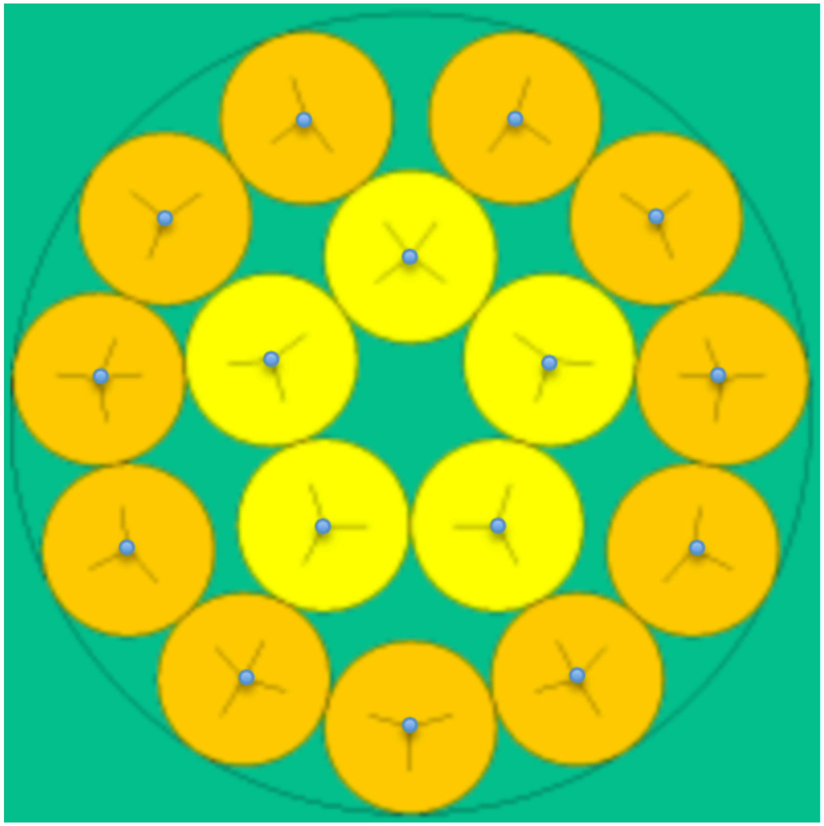
DFSZ signal photon rate for single volume=λ^3 cavity vs. **Standard Quantum Limit** readout noise

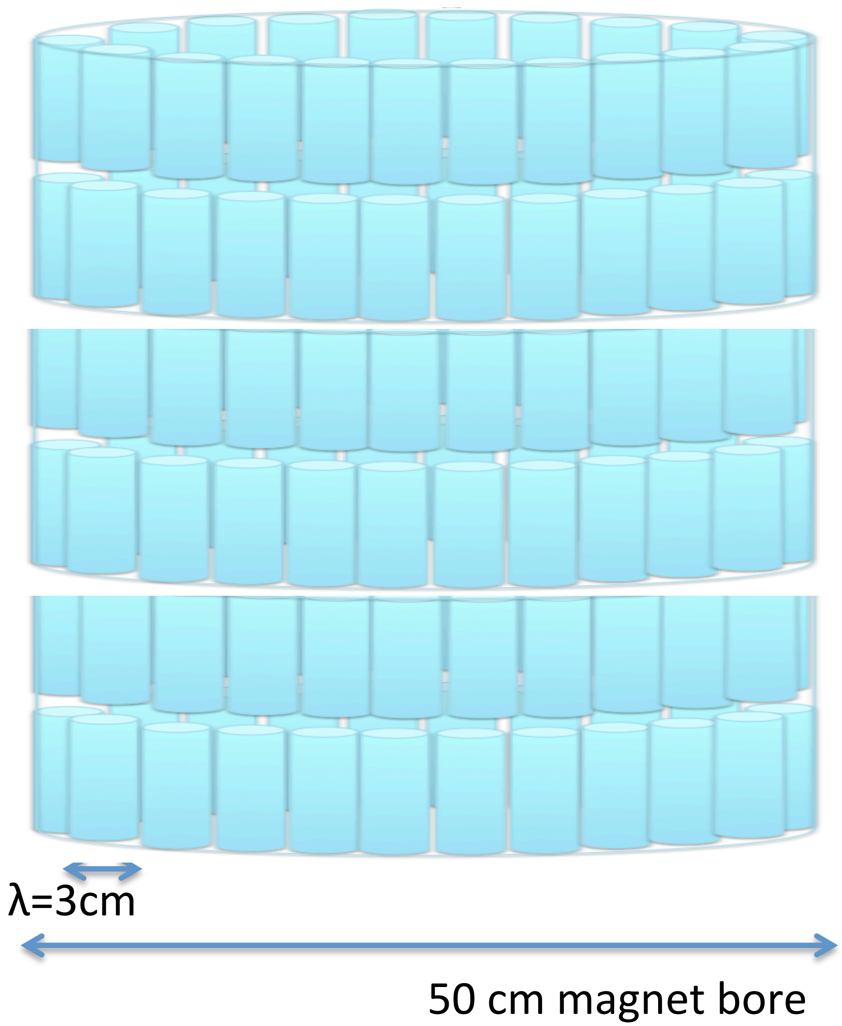


Maximum tolerable background photon rate for 1 octave/year scan rate



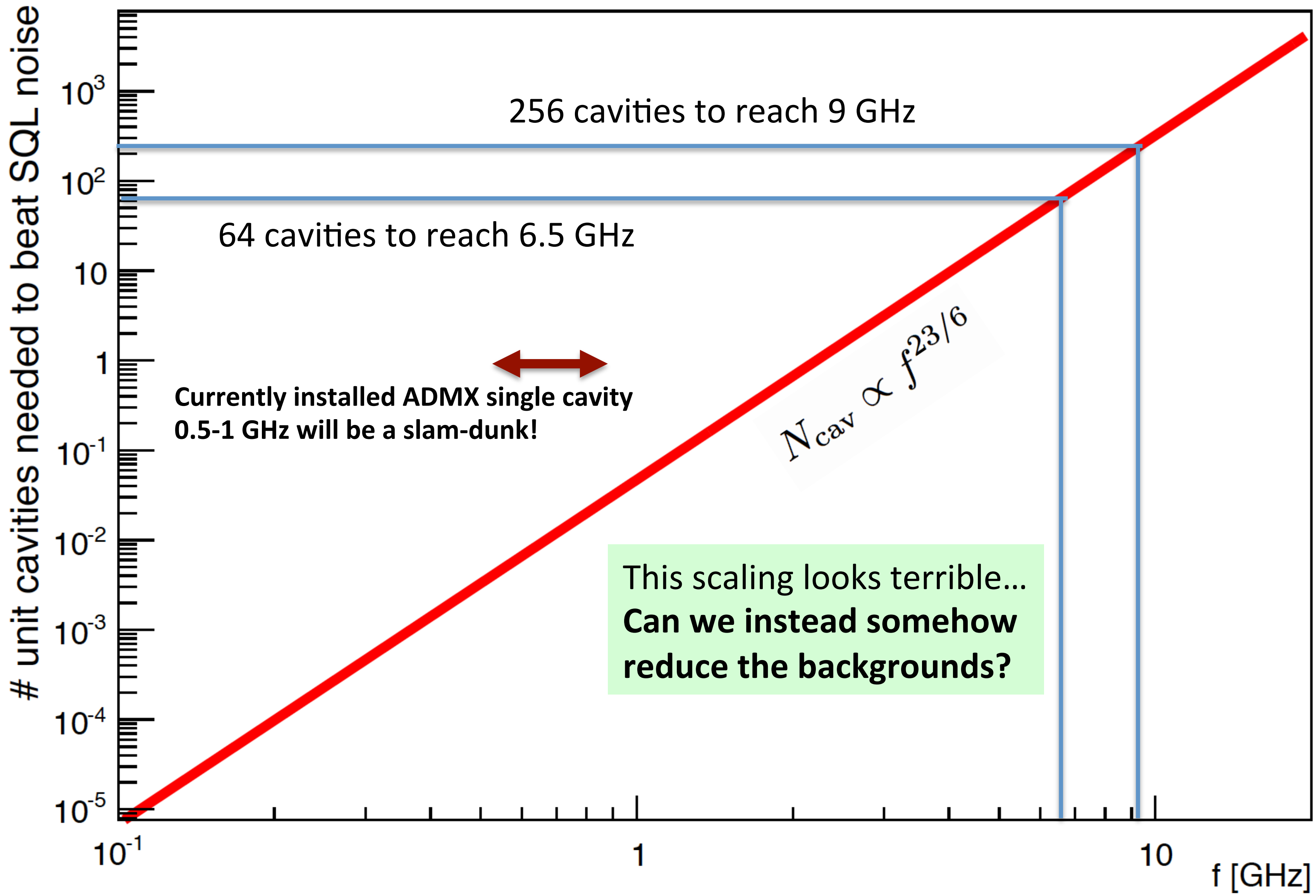
Swiss watch problem: Many resonant elements must be simultaneously tuned to the same frequency



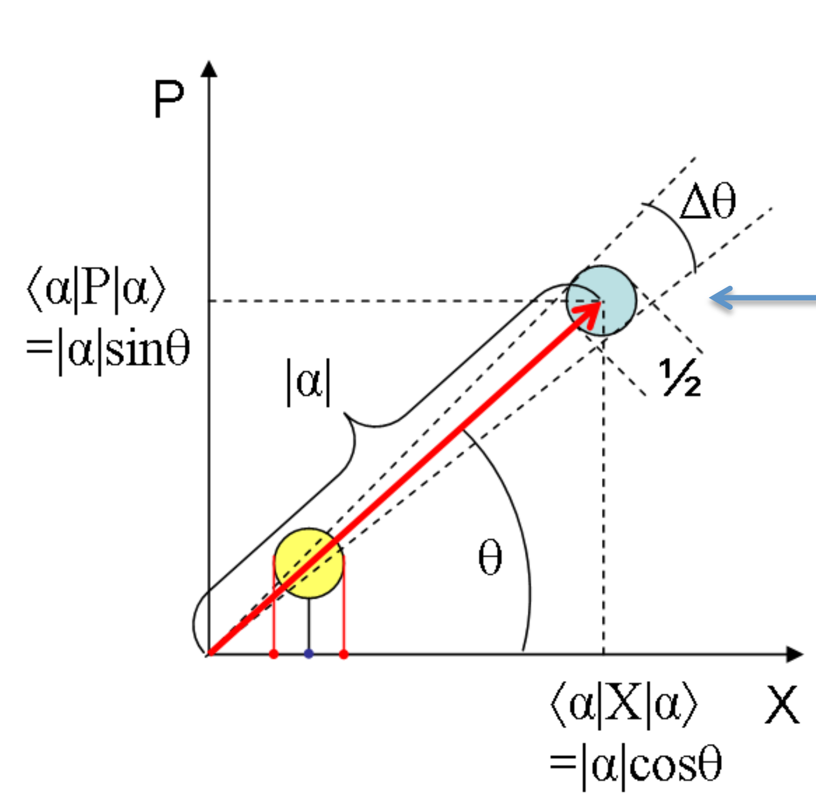


Cost and complexity scale at least linearly with N_{cav}

How many cavities are needed to cover 1 octave/year?



Quantum-limited amplifiers suffer from zero-point readout noise – the Standard Quantum Limit (SQL)



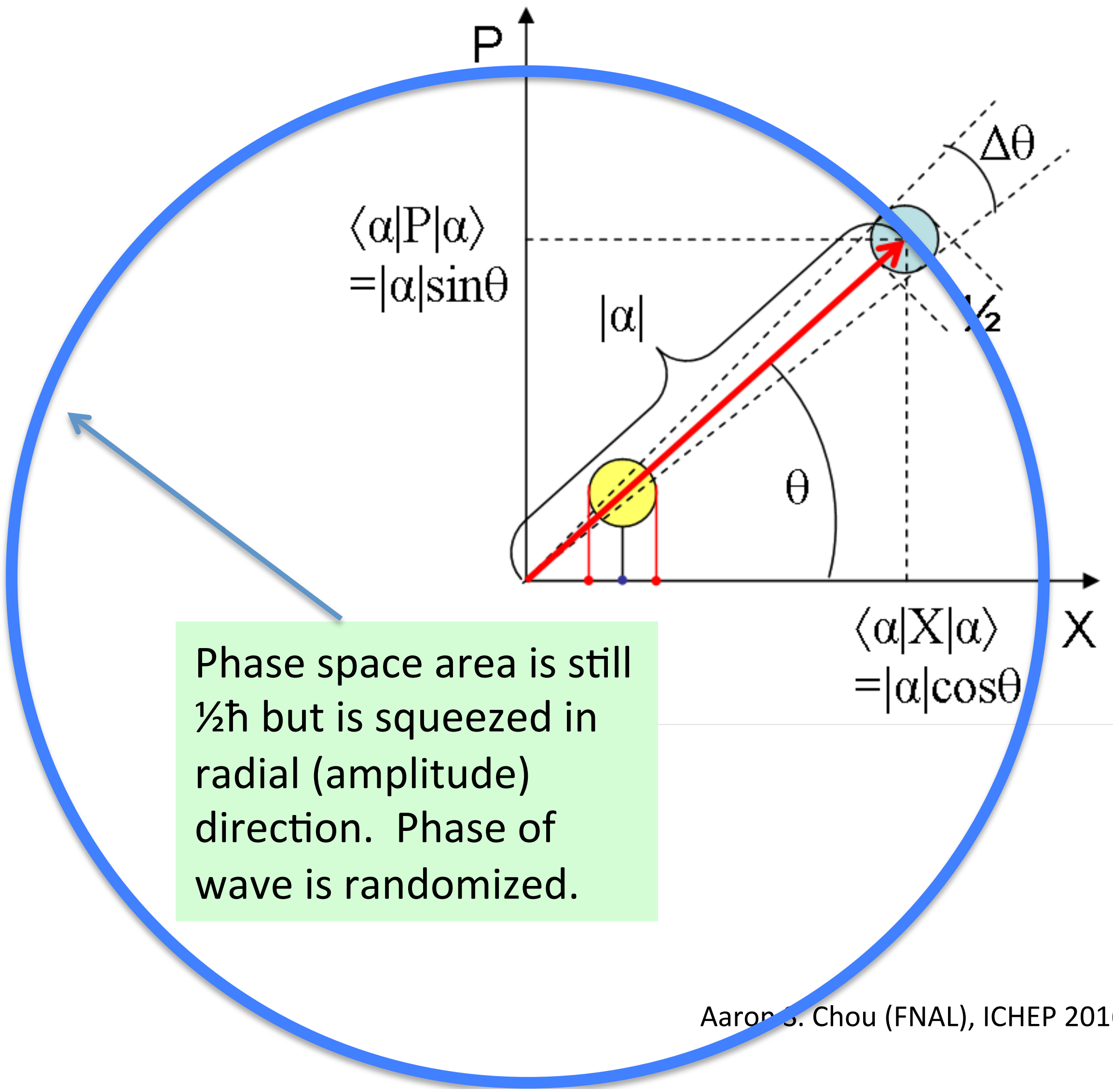
½ ħ= quantum of phase space area.
Simultaneous measurement of wave amplitude and phase gives irreducible zero-point noise in measurement.
(Caves, 1982)

Thermal noise = kT of energy per resolved mode
→ Quantum noise = 1 photon per resolved mode in the T=0 limit.

Noise photon rate exceeds signal rate in high frequency dark matter axion searches.
Need new sensor technology….

Quantum non-demolition (QND) single photon detection can do much better

Number operator commutes with the Hamiltonian→ all backreaction is put into the phase.
Measure exact photon number. Noise = shot noise, thermal backgrounds, read noise.



Demonstrated with Rydberg atoms, (Haroche/Wineland Nobel Prize 2012)

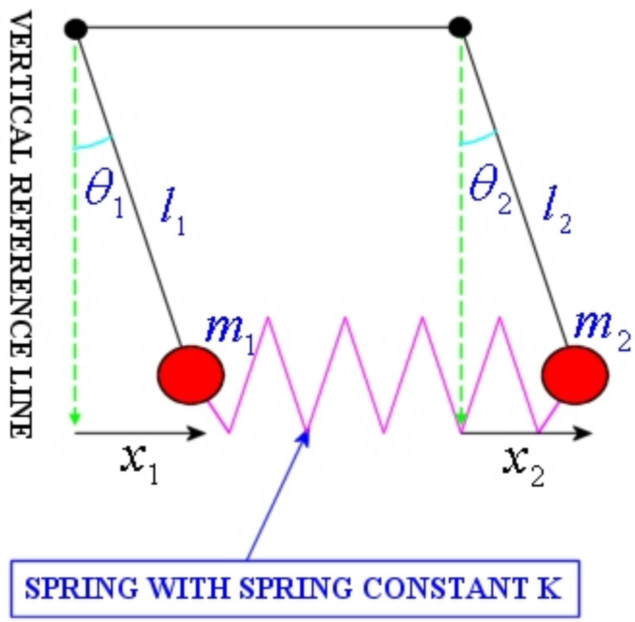
Implementation using solid state artificial atom qubits, (D.Schuster et.al, 2007)

Proposed for axion search: (Lamoreaux, et.al, 2013, Zheng, et.al, 2016)

Note: different from Carrack technique of non-QND single photon counting using Rydberg atoms (Ogawa, Matsuki,Yamamoto, 1996) .

What does a QND single microwave photon detector look like?

Coupled oscillators



Energy stored in the spring

$$H = \begin{pmatrix} \omega_1 & g \\ g & \omega_2 \end{pmatrix}$$

Mixing angle to diagonalize:

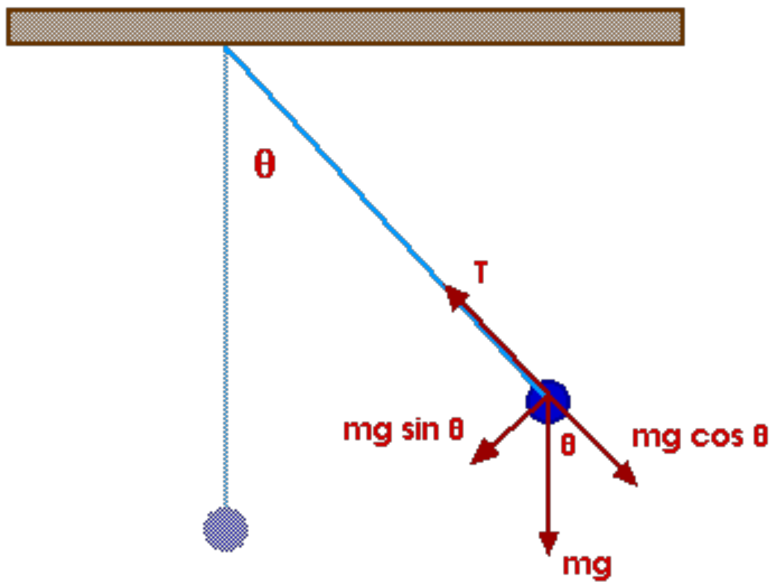
$$\tan 2\theta = 2g/(\omega_1 - \omega_2)$$

Normal mode frequencies for small g

$$\tilde{\omega}_1 = \omega_1 + \frac{2g^2}{\omega_1 - \omega_2}$$

$$\tilde{\omega}_2 = \omega_2 - \frac{2g^2}{\omega_1 - \omega_2}$$

Suppose one oscillator has non-linear restoring force



For example:
Resonant frequency of a real-world pendulum increases with oscillation amplitude

$$\omega_2 = \omega_2(A_2)$$

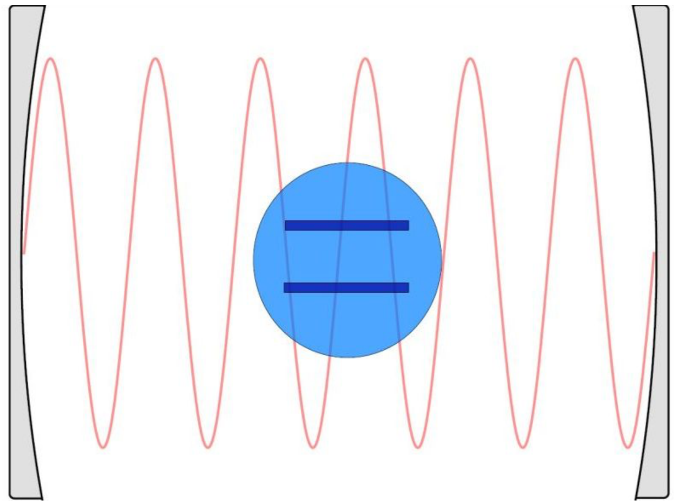
Then the instantaneous resonant frequency of **linear** oscillator 1 depends weakly on the amplitude or occupation number of **nonlinear** oscillator 2

$$\tilde{\omega}_1 = \omega_1 + \frac{2g^2}{\omega_1 - \omega_2(A_2)}$$

Measuring the frequency of oscillator 1 performs a QND measurement on the number of quanta stored in oscillator 2 (and vice-versa)

Cavity QED:
Use 2-level atom to measure cavity photon population

Linear cavity
Bosonic oscillator,
Number operator = $a^\dagger a$



2-level "atom"
Fermionic oscillator,
Number operator = σ_z

The 1st order non-linearity in (number operator)^2 in the undiagonalized Hamiltonian is:

$$H \approx \hbar\omega_{\rm r}\left(a^\dagger a + 1/2\right) + \frac{\hbar}{2}\left(\omega_{\rm a} + \boxed{\frac{2g^2}{\Delta}a^\dagger a} + \frac{g^2}{\Delta}\right)\sigma_{\rm z}$$

$\Delta = \omega_r - \omega_a$

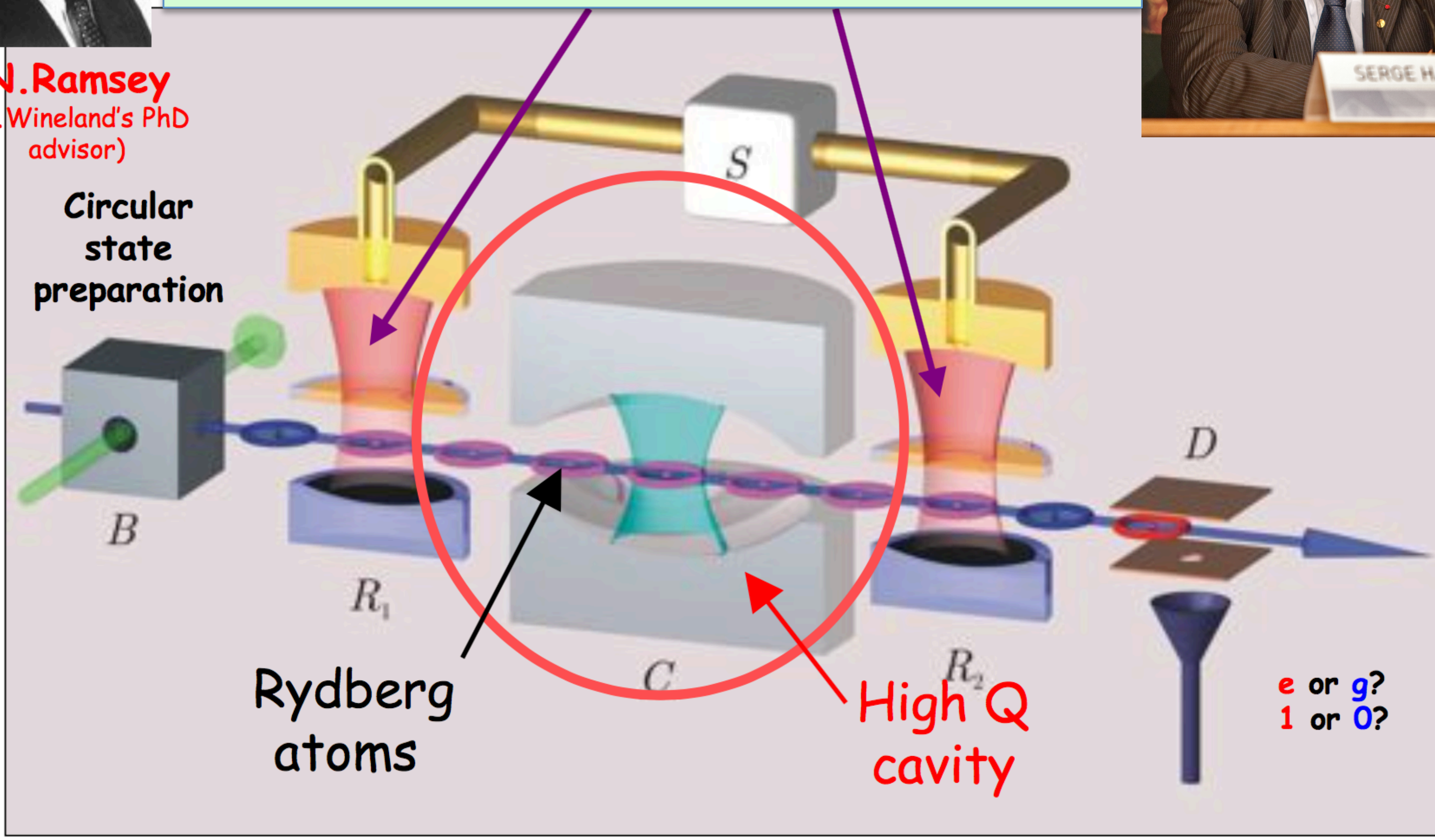
The atom frequency depends on the cavity resonator's occupation number!

This product of number operators commutes with H and allows QND measurement.

N.Ramsey
(D.Wineland's PhD advisor)

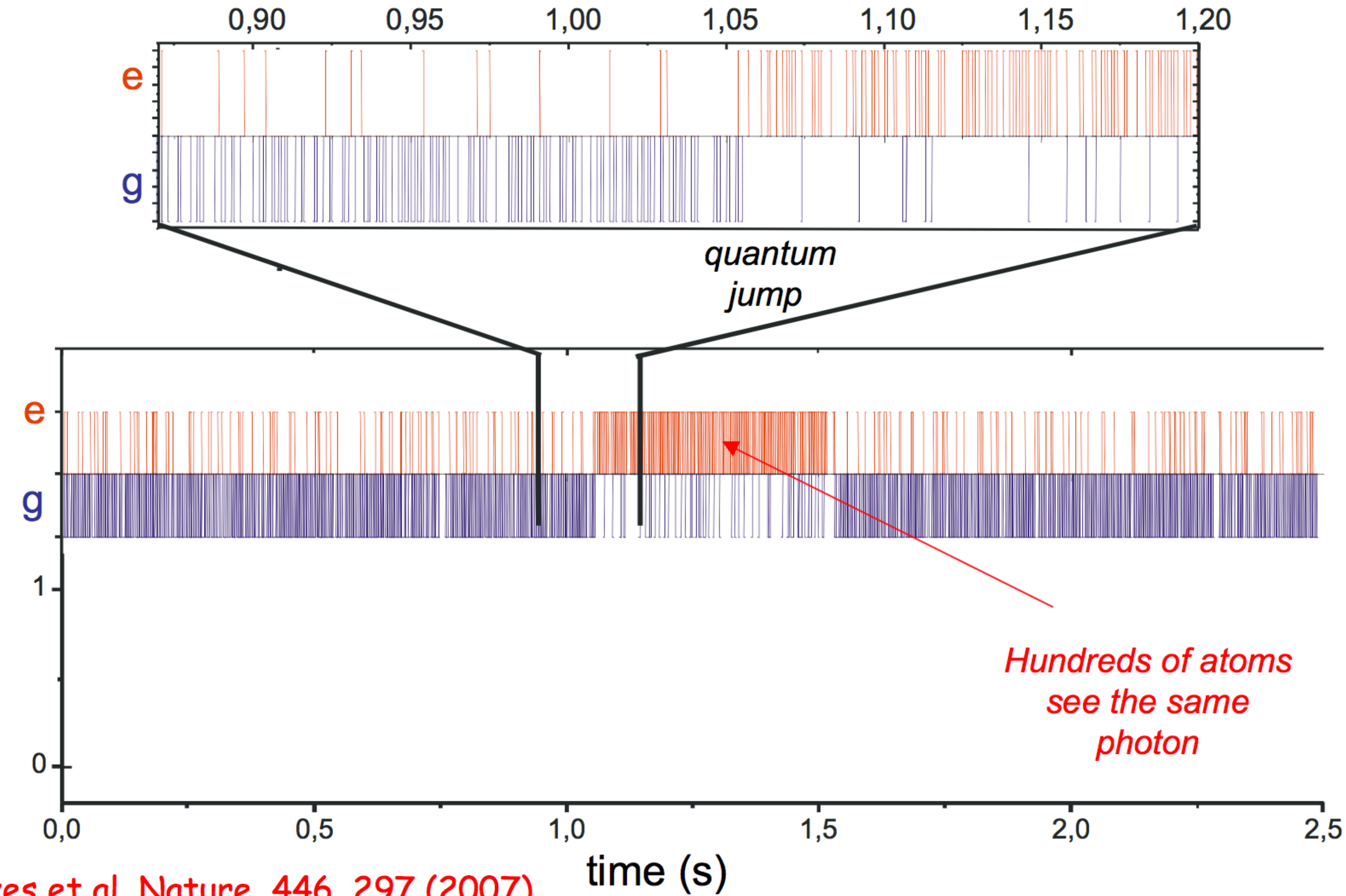
Serge Haroche 2012 Nobel Prize:

Atoms acts an amplitude→ frequency transducers.
They probe the cavity photon number without any net absorption of photons. **QND measurement!**



An atomic clock delayed by photons trapped inside

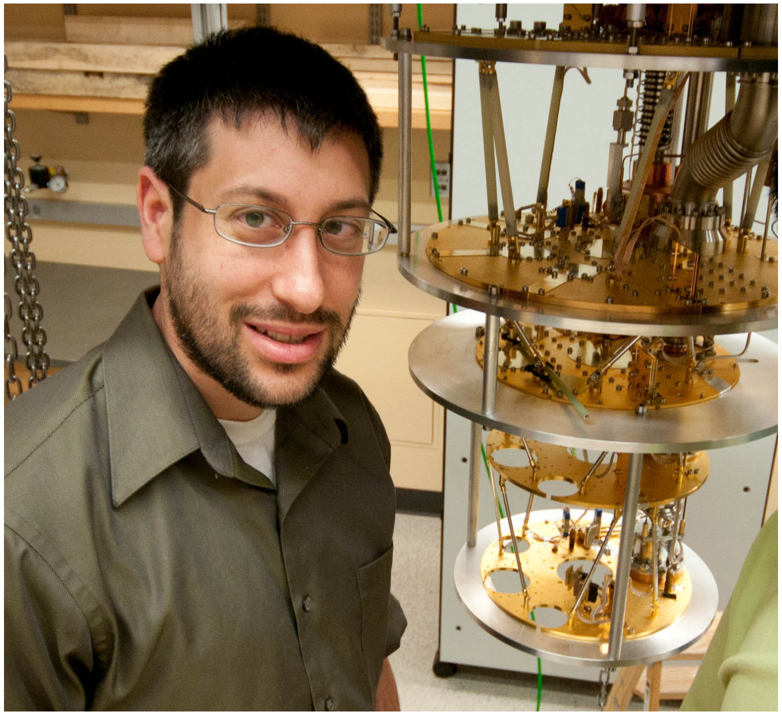
Birth, life and death of a photon



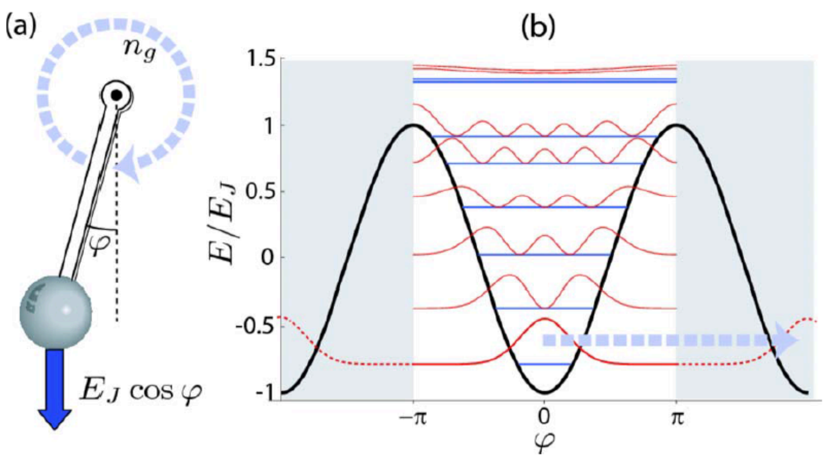
S.Gleyzes et al, Nature, 446, 297 (2007)

Nonlinear circuit oscillators have non-degenerate energy level spacings and hence behave just like 2-level atoms

Slides from Dave Schuster (U.Chicago)



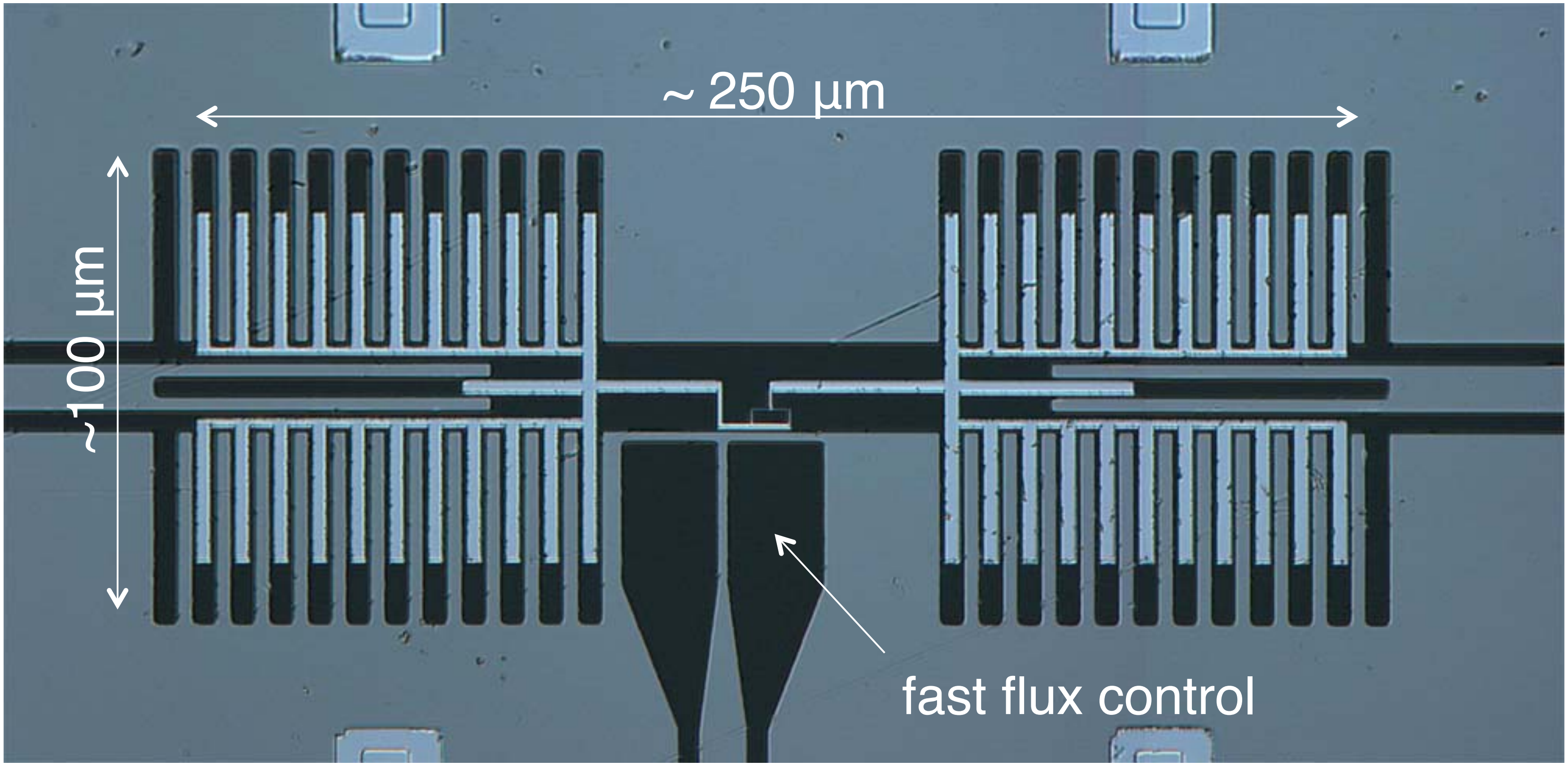
Transmon qubit based on the Cooper pair box
J.Koch, e.al, Phys.Rev.A76, 042319 (2007)



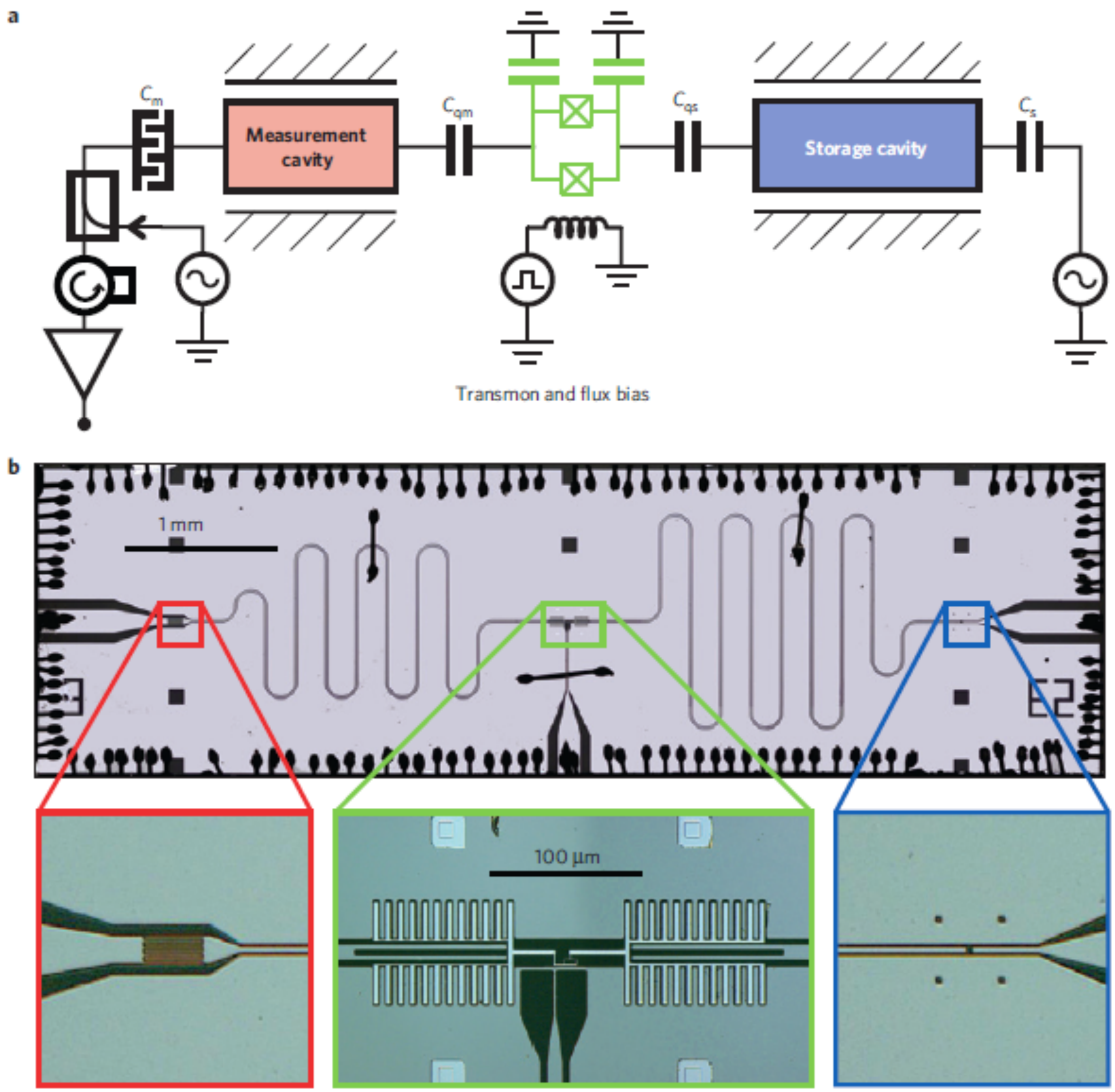
QND detectors developed for high fidelity quantum computing qubit readout.
B.R. Johnson, et.al, Nature Physics 6, 663-667 (2010)

The sarantapede

- An end-coupled "transmon" qubit with ~40 legs

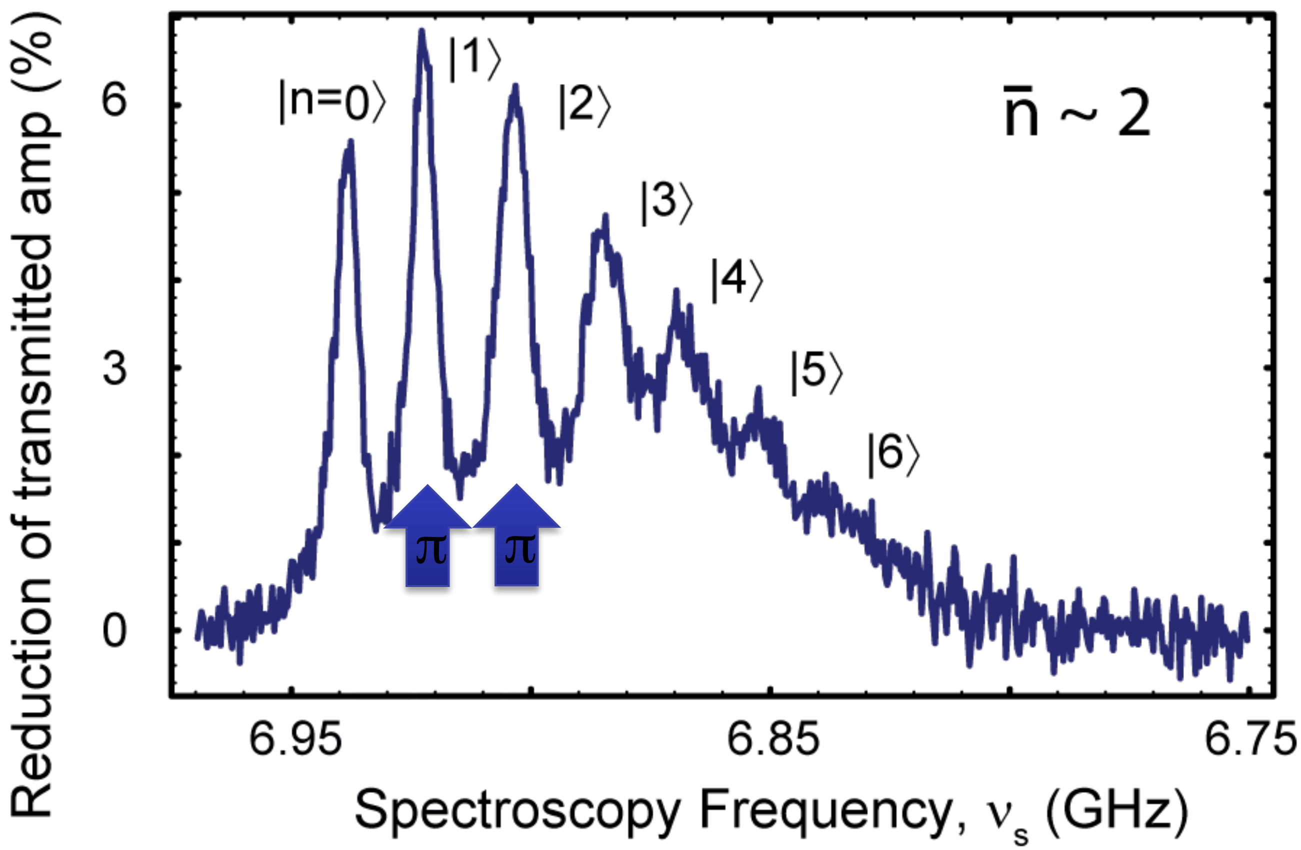


QND Detector = qubit + fast cavity



Sensing photon number with a qubit

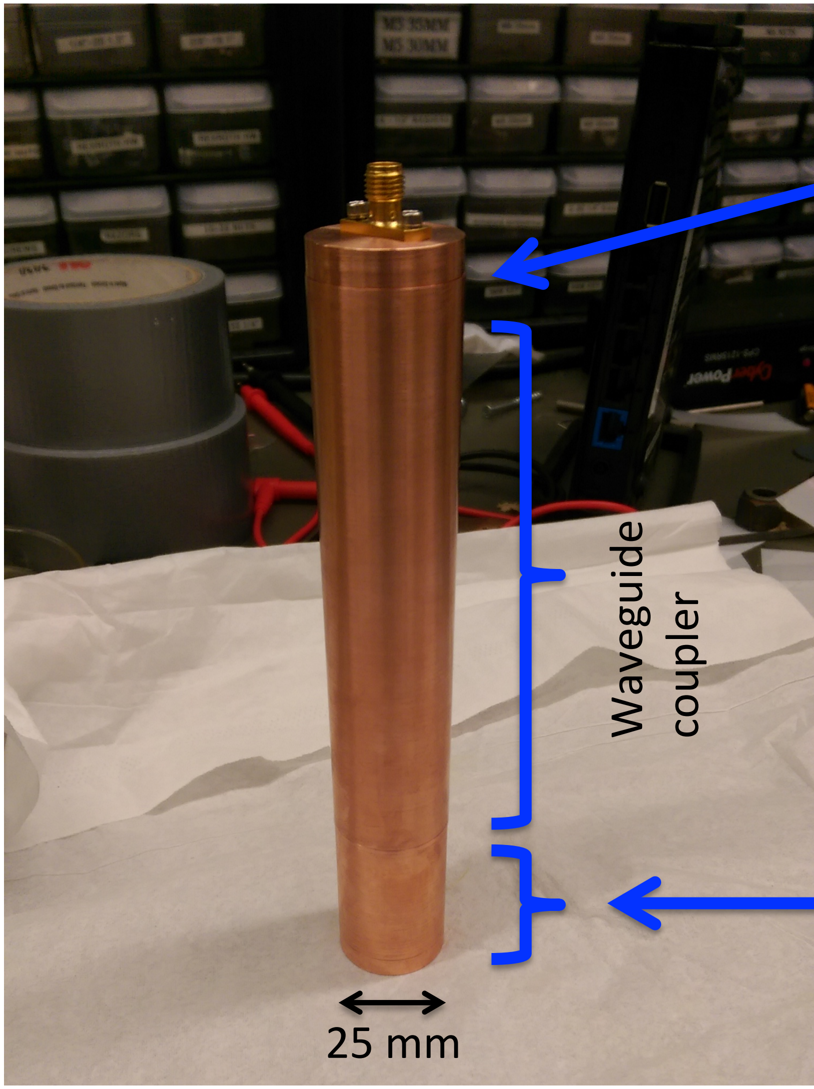
$$H \approx \hbar\omega_r a^\dagger a + \frac{\hbar}{2}(\omega'_a + 2\chi a^\dagger a)\sigma_z$$

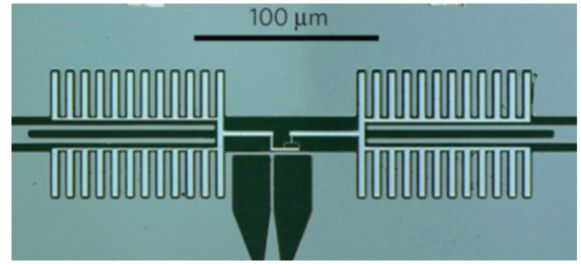


- Qubit transition frequency depends on photon number in cavity

Theory: J. Gambetta, A. Blais, …, S. Girvin, and R. J. Schoelkopf, *PRA 94 123602 (2005)*
Experiment: D. I. Schuster, … , S. M. Girvin, R. J. Schoelkopf, Nature (London) **445** 515 (2007)

Prototype for 10 GHz axion QND detector





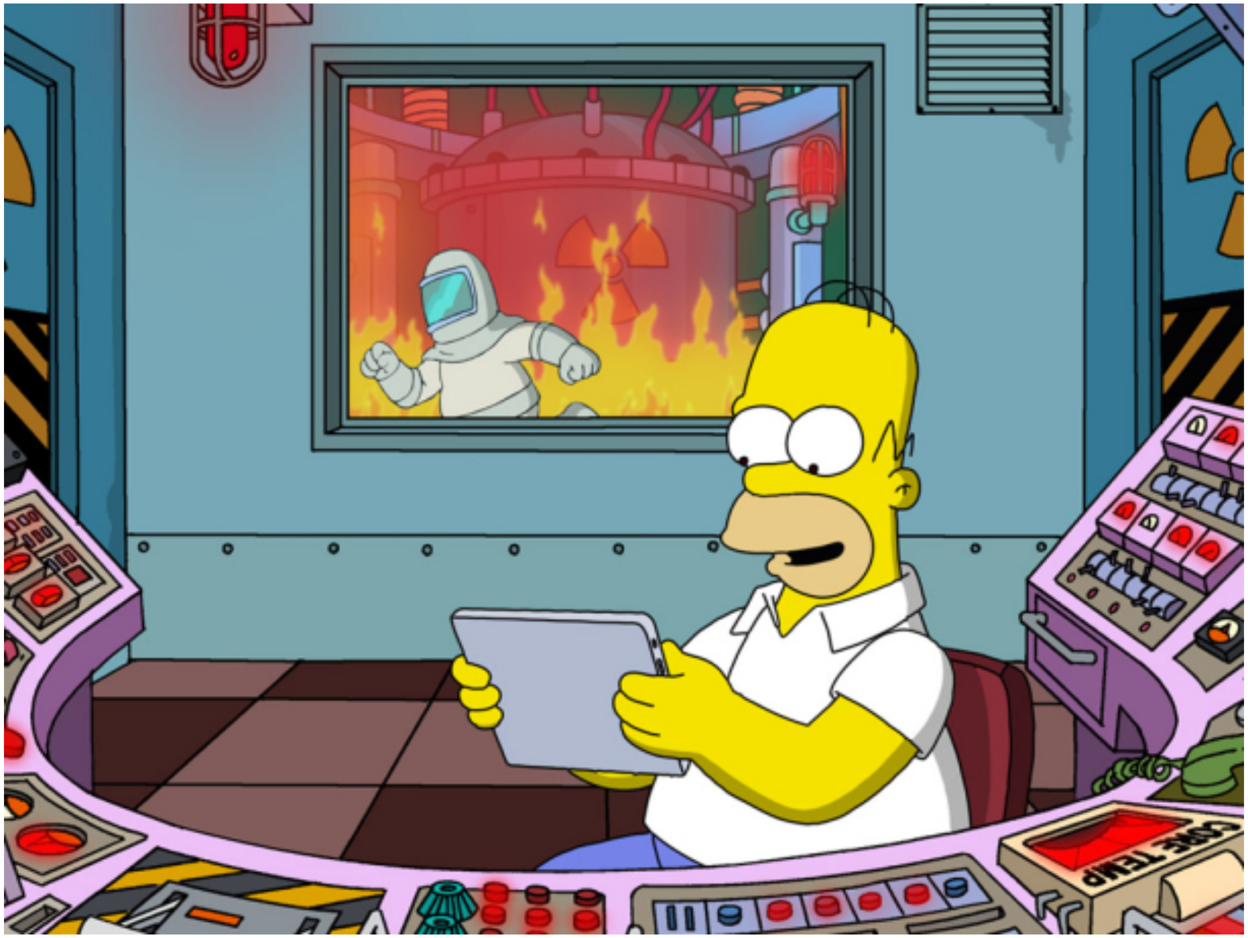
Superconducting qubit in field-free bucking coil region acts as an amplitude→frequency transducer for QND measurements.

Qubit frequency shifts by 10 MHz per photon deposited in axion cavity. **Successful "spin-flip" of qubit confirms presence of cavity photon.**

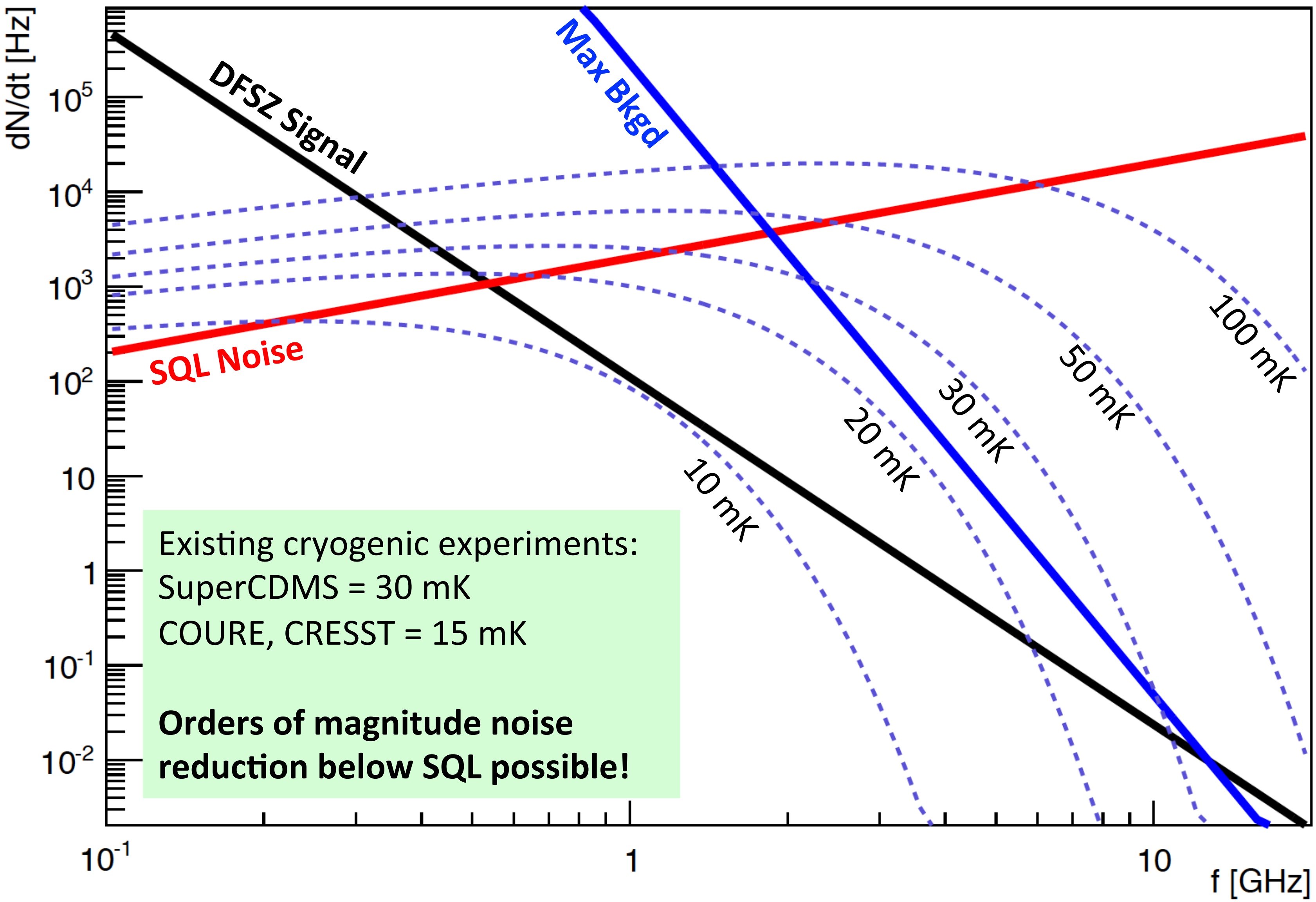
Axion scattering cavity dipped into high B-field region

Akash Dixit, Aaron Chou, David Schuster, R&D in progress

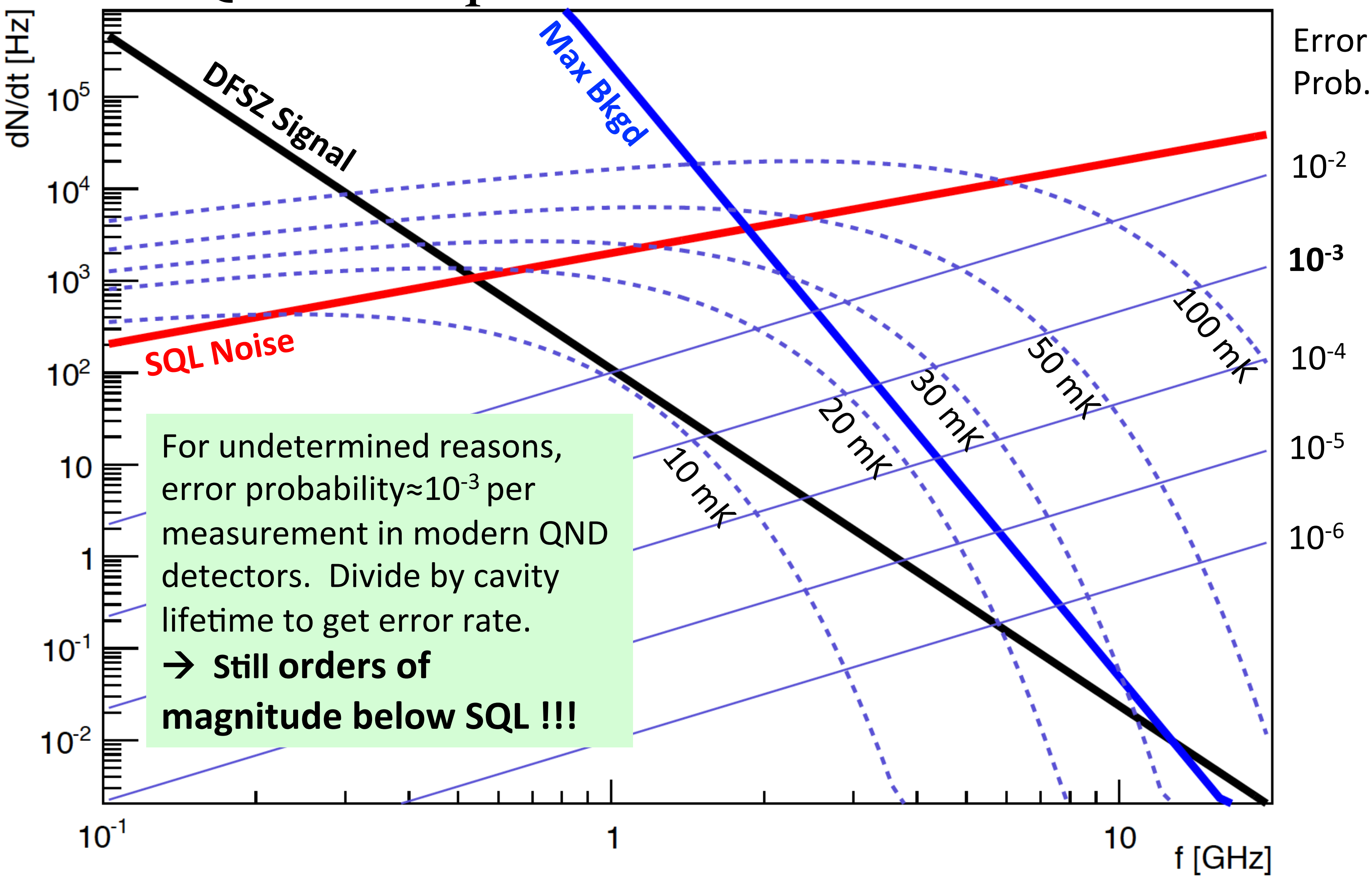
What are the improvements one can realistically expect from qubit-based QND readout for high frequency axion detectors?



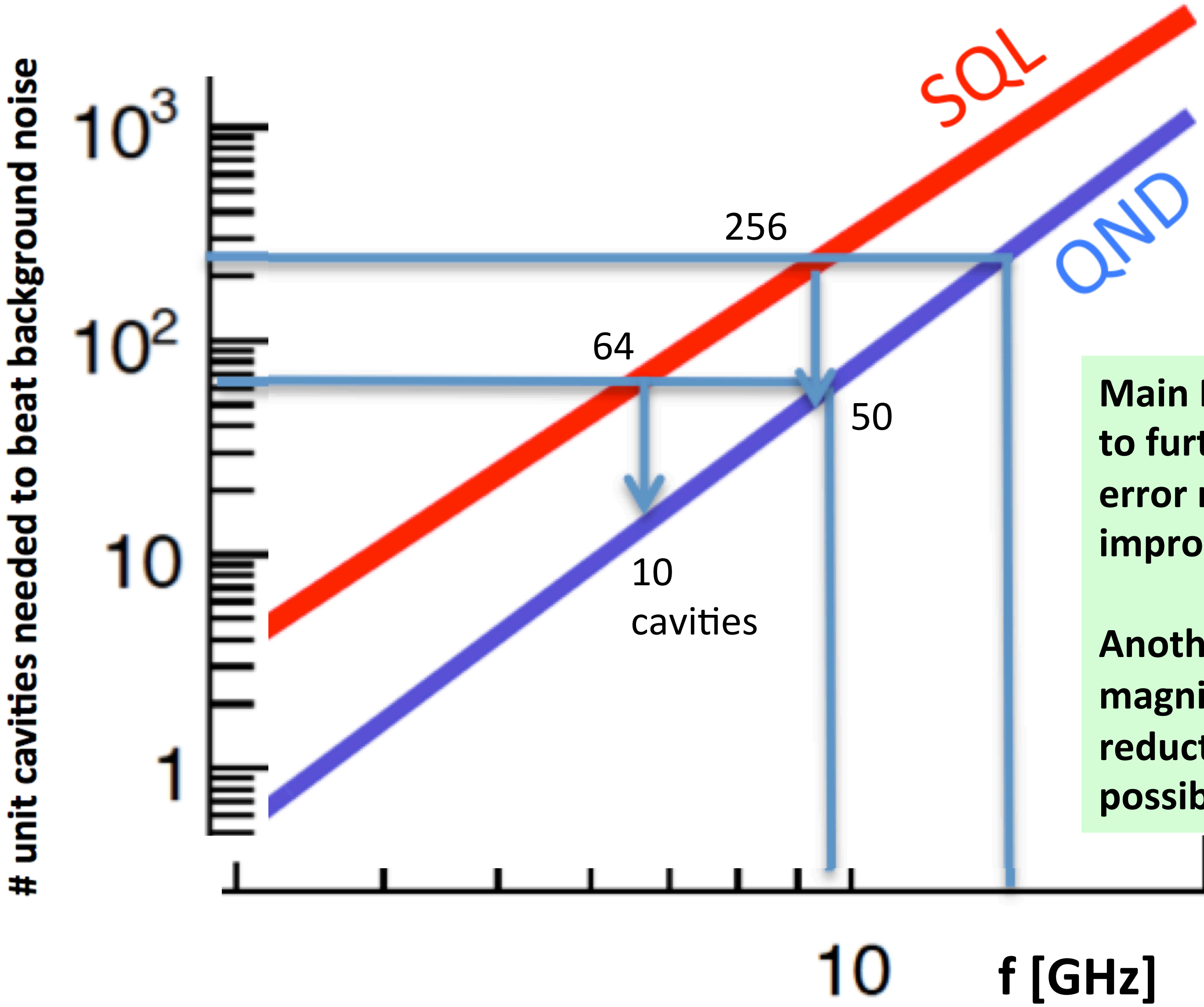
Thermal photon emission rates are negligible



Another background "photon" source: QND false positives from read errors



QND reduces required N_{cav} by factor of 6, or alternatively extends frequency range for fixed N_{cav}



Main R&D focus should be to further reduce the QND error rate, which limits the improvement.

Another order of magnitude background reduction should be possible.

Reducing noise is cheaper than increasing signal

A fun summer at Fermilab!