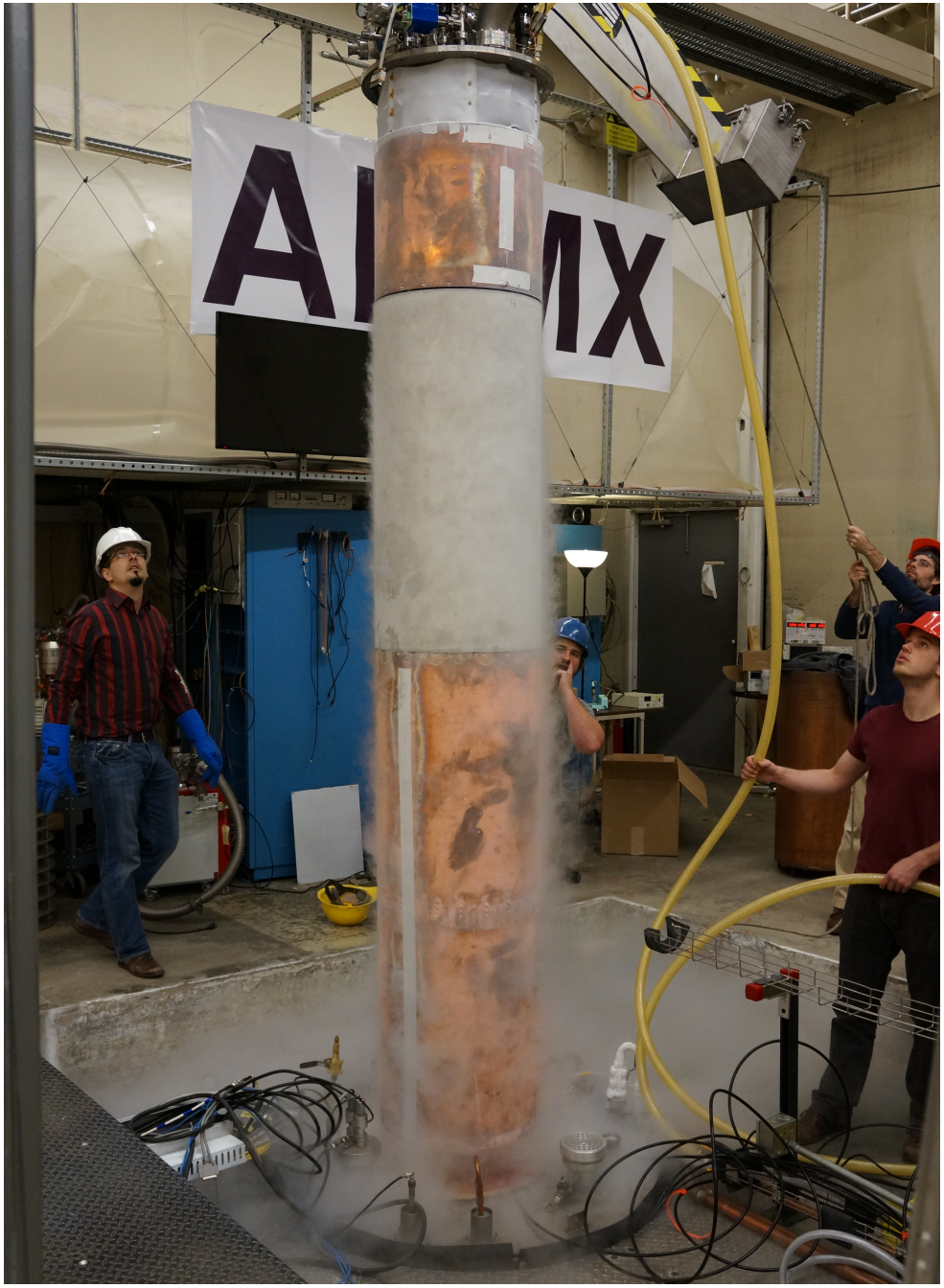
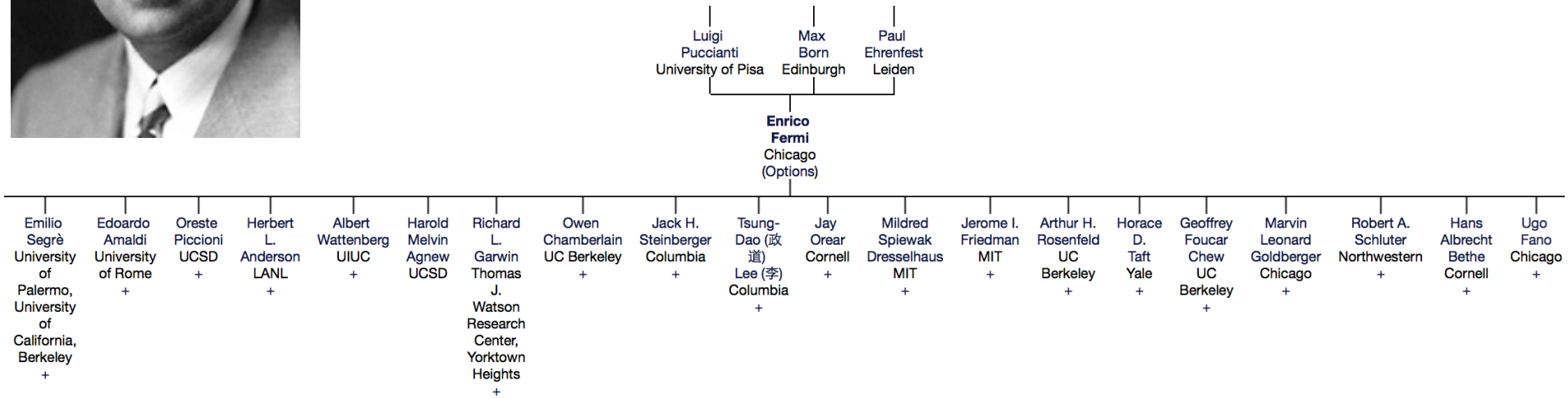


Axion Dark Matter: From Fermi to Rabi

Aaron S. Chou
FNAL

Simplicity II
Fermilab
9/8/16

Clan Fermi (i.e our guys)

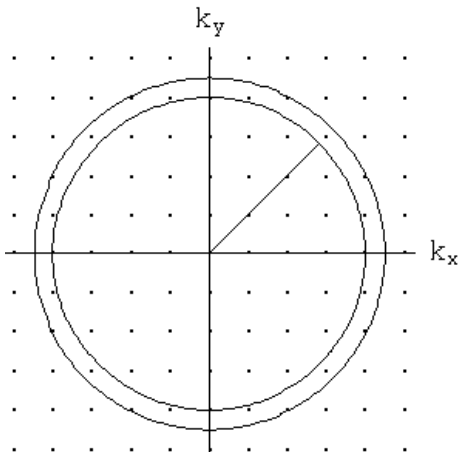


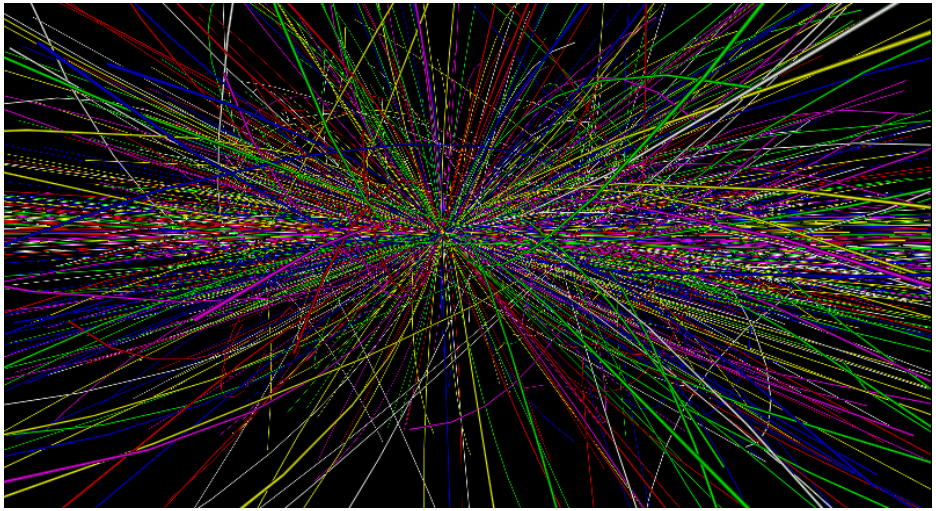
12 Nobel prizes: ***Fermi***, **Bethe**, ***Segre***, ***Chamberlain***, **TD.Lee**, ***Steinberger***, ***M.Schwartz***, ***Koshiba***, ***J.Friedman***, **S.Weinberg**, **Gross**, **Wilczek**

Bold = part of HEP community
Blue = theorist,
Red = experimentalist

Fermi's Golden Rule guides HEP research

- Golden Rule:
  - Lots of accessible final states
    → **Irreversible processes**
  - Integrate over final state phase space to get cross-section





CMS event

"No one would design experiments like this if they had a choice."
-- unnamed CDF graduate student

Clan Rabi (i.e. the other guys)

Albert Potter Wills, Columbia
Arnold Johannes Wilhelm Sommerfeld, University of Munich
Niels Bohr, University of Copenhagen
Otto Stern, Universität Hamburg

Isidor Isaac Rabi, Columbia (Options)

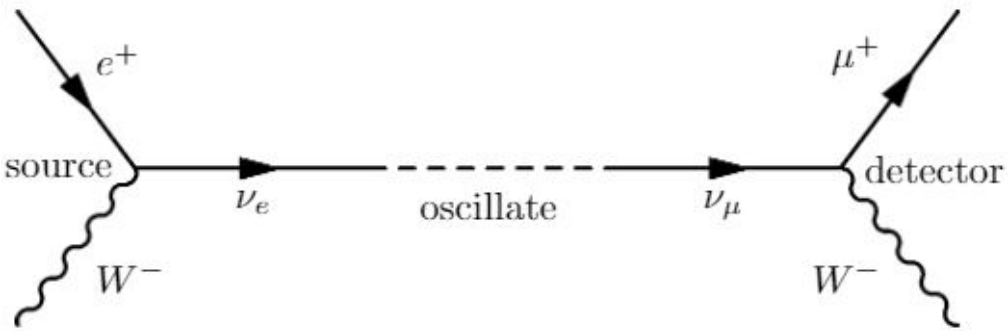
- Lloyd Motz, Columbia +
- Henry Cutler Torrey, Rutgers +
- Julian Schwinger +
- Donald Ross Hamilton, Princeton +
- Norman F. Ramsey, Harvard +
- William Aaron Nierenberg, UCSD +
- Harold Brown, Johns Hopkins
- Vernon W. Hughes, Yale +
- Herbert J. Zeiger, MIT +
- Daniel Isadore Bolef, Washington University +
- Gabriel Weinreich, Bell Labs +
- Martin L. Perl, Stanford +

14 Nobel prizes: *Rabi*, *Ramsey*, *Wineland*, **Schwinger**, Glauber, **Glashow**, Mottelson, ***Perl***, ***Ting***, *Cornell*, *Ketterle*, *Wieman*, *Phillips*, Kohn

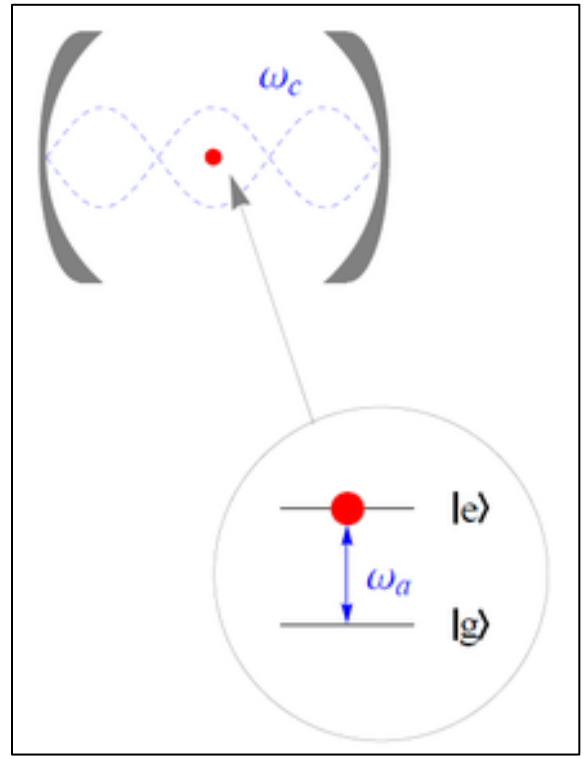
Bold = part of HEP community
Blue = theorist
Italics = experimentalist

The Rabi school (mostly) works in the other extreme

- Rabi Limit:
  - Finite number of accessible states
    → **Reversible processes**
  - Semiclassical phenomena of oscillations, flavor mixing



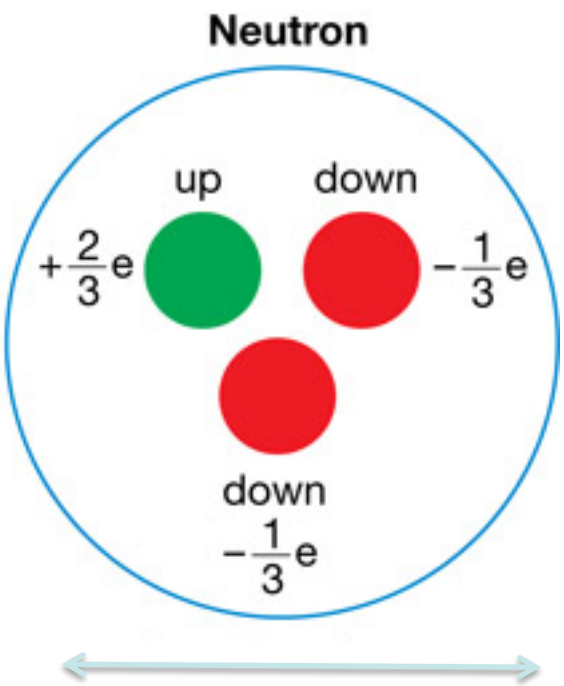
Neutrino oscillations



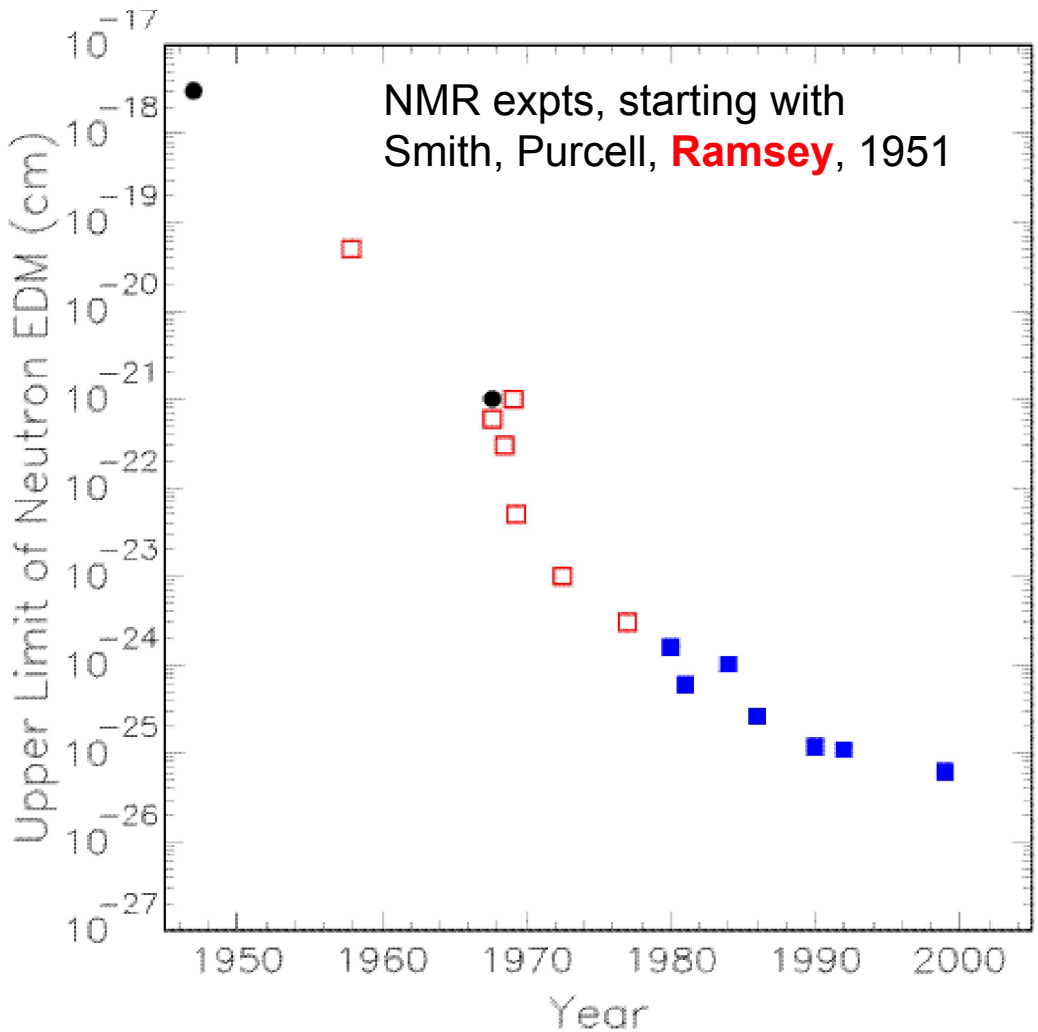
Rabi oscillations between atom and cavity mode

The axion story begins in the Rabi school:

Naive estimate of neutron EDM gives
$d_n \approx 10^{-16}$ e-cm



10^{-15} m



The CP Problem of Strong Interactions

Characterizes degenerate QCD ground state (Θ vacuum)

Phase of Quark Mass Matrix

Standard QCD Lagrangian contains a CP violating term

$$L_{CP} = -\frac{\alpha_s}{8\pi}\underbrace{(\Theta - \arg\det M_q)}_{0\leq\bar{\Theta}\leq 2\pi}\,\mathrm{Tr}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$$

Induces a neutron electric dipole moment (EDM) much in excess of experimental limits

$$d_n \approx \bar{\Theta}\,10^{-16}\,e\,\mathrm{cm} \approx \frac{\bar{\Theta}}{10^2}\mu_n < 3\times 10^{-26}\,e\,\mathrm{cm}$$

$\bar{\Theta} \lesssim 10^{-10}$ **Why so small?**

Slide from G. Raffelt

The 1977 Peccei-Quinn solution to the strong-CP problem

Isidor Isaac Rabi
Columbia

Julian Schwinger

Kenneth Alan Johnson
MIT

Roberto Daniele Peccei
UCLA

J. Robert Oppenheimer
UC Berkeley

Sidney M. Dancoff
UIUC

Sidney D. Drell
Stanford

James Daniel Bjorken
Stanford

Helen R. Quinn
Stanford

Isidor Isaac Rabi
Columbia

Julian Schwinger

Charles M. Sommerfield
Yale

Howard M. Georgi
Harvard
(Options)

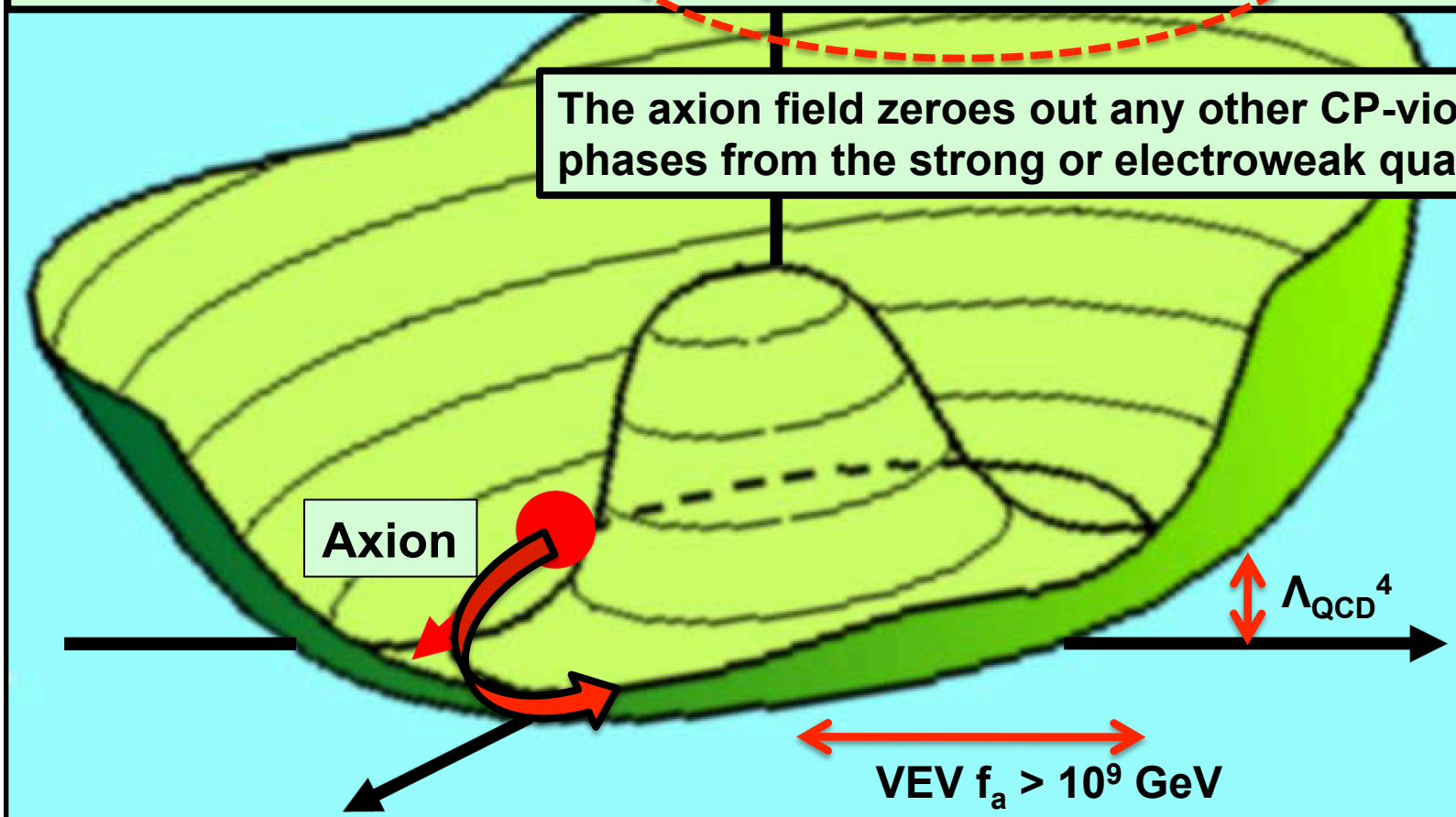
- Postulate a new dynamical scalar field which has a two-gluon coupling.
- Think like an electrical engineer*: Use this field in a cosmological feedback loop to dynamically zero out any pre-existing CP-violating phase angles.

*cf. Dirac, Schwinger, Treiman …

Natural potential energy function

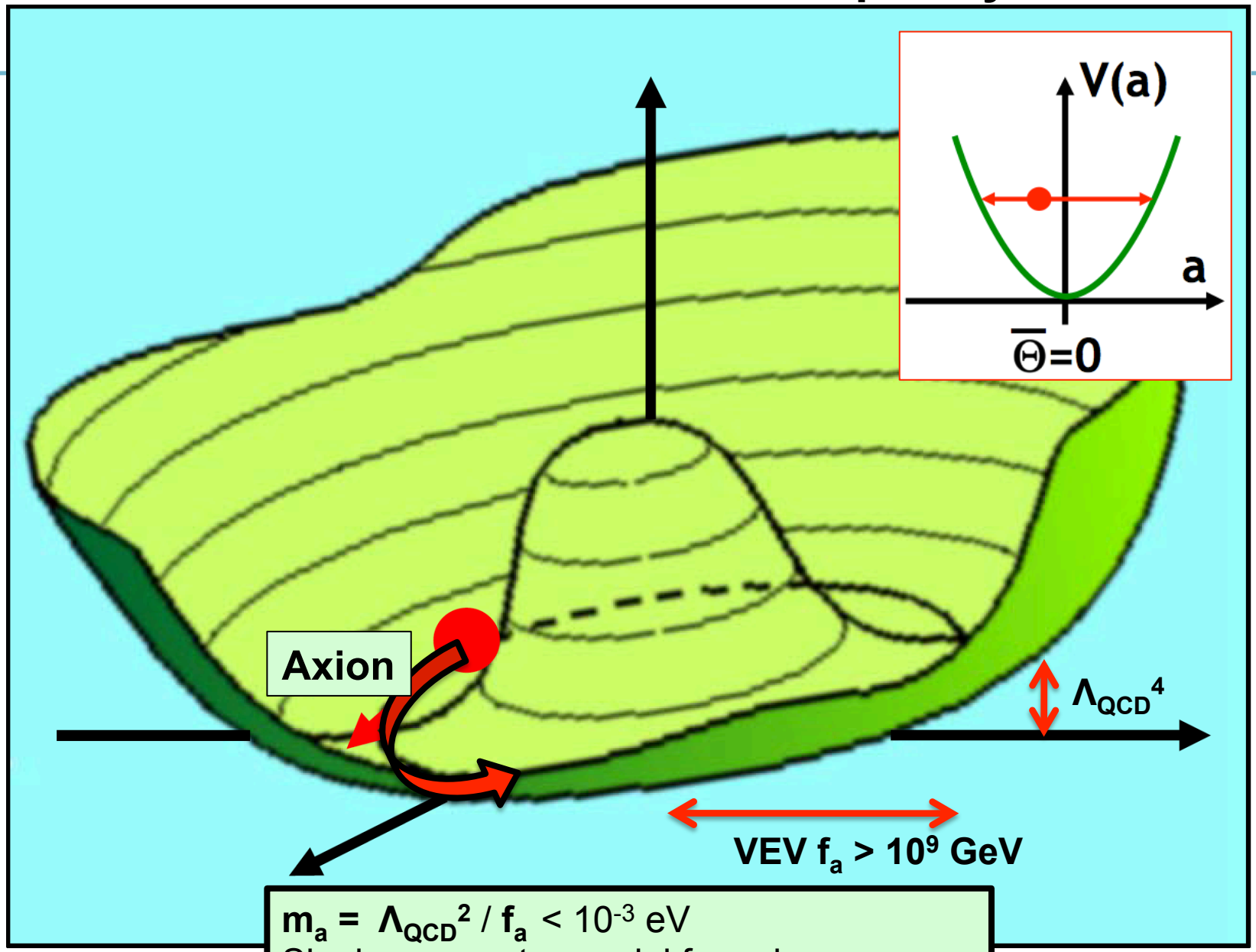
$$V(A) = -f_a^2 A^2 + \frac{\lambda}{4!} A^4 + \left(\frac{g^2}{32\pi^2} \arg(A) - \frac{\alpha_s}{8\pi} \left(\theta_{QCD} + \theta_{quark} \right) \right) \langle G\tilde{G} \rangle$$

The axion field zeroes out any other CP-violating phases from the strong or electroweak quark sector.



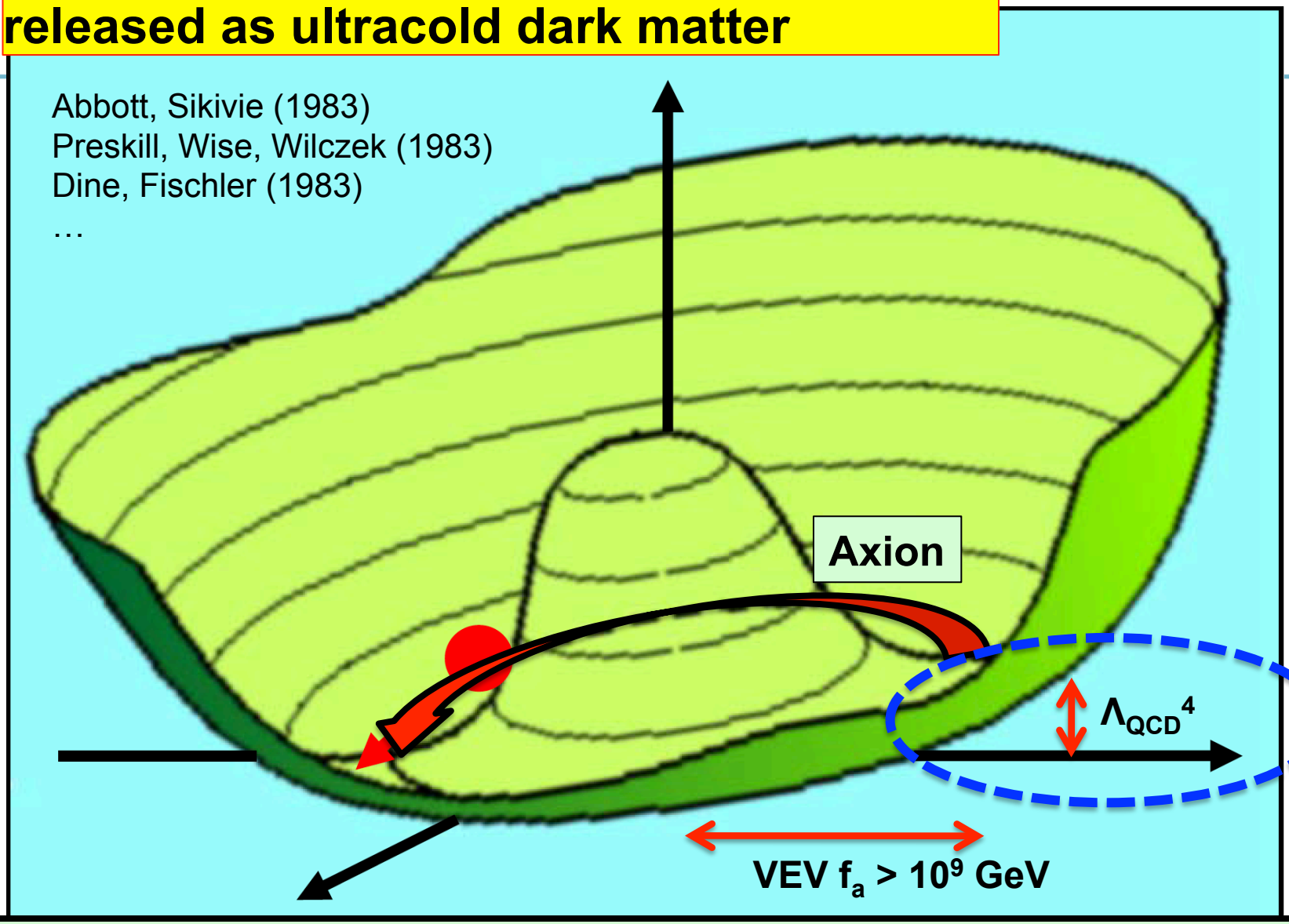
The neutron EDM vanishes, solving the **strong CP fine-tuning problem**.

Axion mass = harmonic oscillator frequency



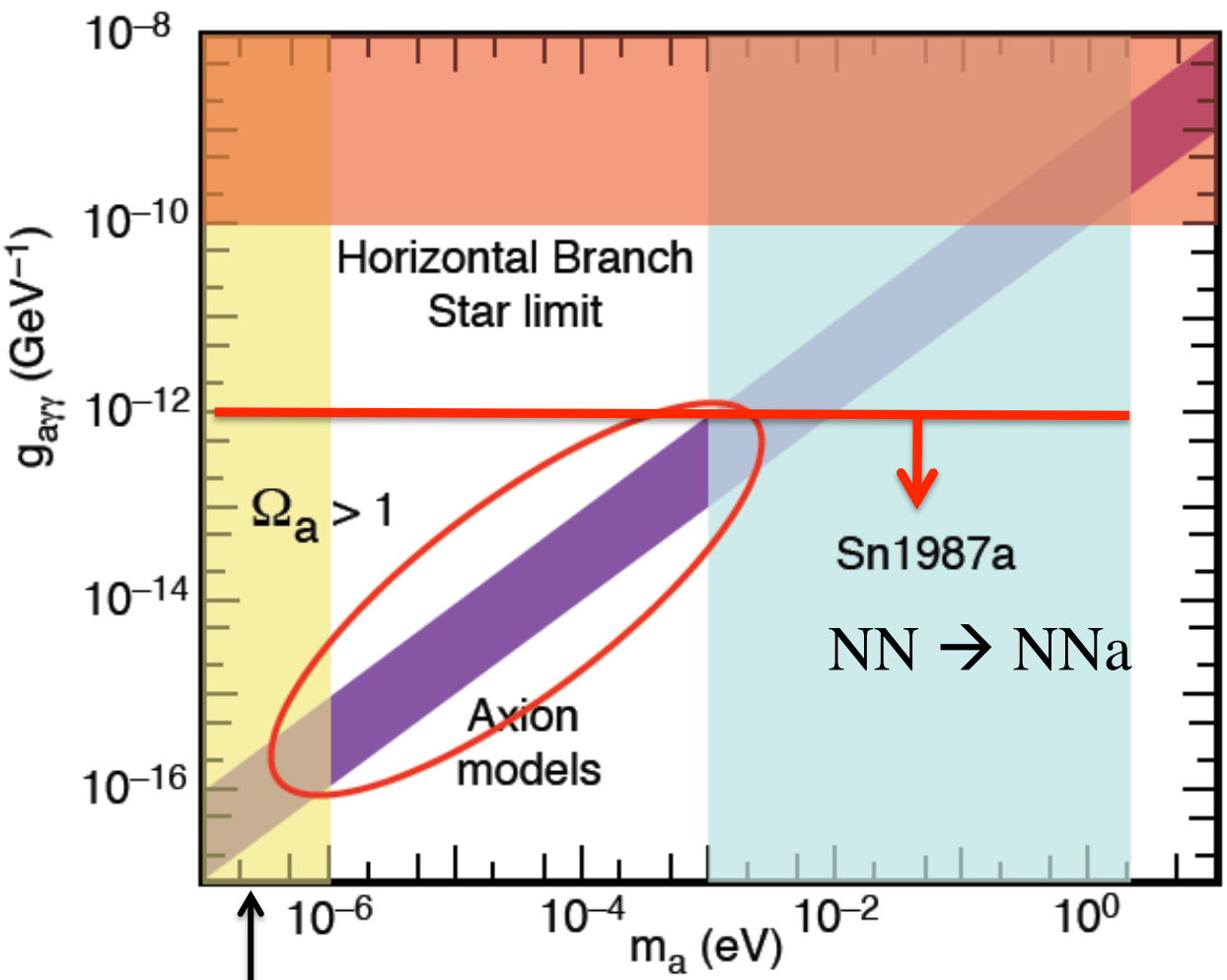
$m_a = \Lambda_{QCD}^2 / f_a < 10^{-3}$ eV
Single parameter model for axions

The initial potential energy density is released as ultracold dark matter



The initial axial **theta angle θ**, determines the available potential energy to be released. **$O(1)\times\Lambda_{QCD}^4$** of potential energy density is converted into **dark matter**.

Dark matter is the smoking gun for the PQ model



$$\Omega_a \approx \left(\frac{6\,\mu\mathrm{eV}}{m_a}\right)^{\frac{7}{6}}$$

or even more due to cosmic string decay.

PQ model + local energy conservation **guarantees** the existence of dark matter axions in the last place we haven't looked!

Excluded by "naturalness." Requires small initial θ to avoid DM overproduction.

Axion DM vs WIMP DM

Low mass bosonic axions:

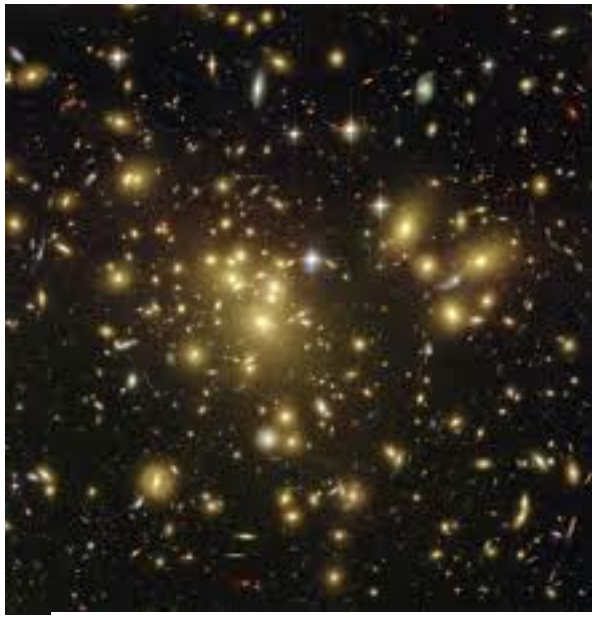
1) Scatter as narrowband classical wave with $N=10^{17}$/liter
2) Rate suppressed by QCD scale
3) **Quantum-limited noise due to measurement back-reaction**

Fermionic WIMPs:

1) Scatter as individual quanta, N=1/liter
2) Rate suppressed by electroweak scale
3) Radiogenic backgrounds

Ultracold low mass dark = classical wave

Described by a **Glauber** coherent state with properties similar to a modern laser.

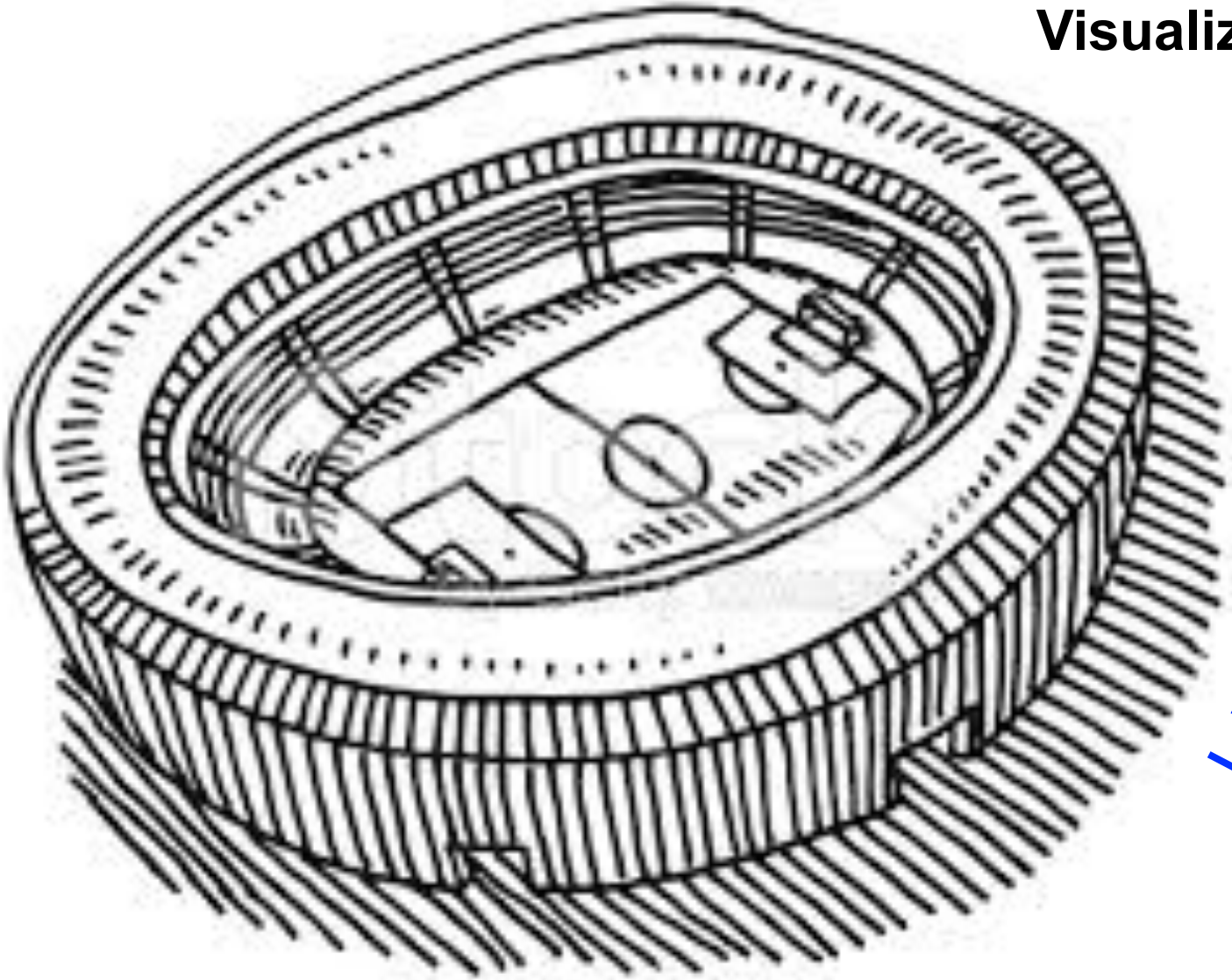


Huge number density 10^{14}/cc,
Linewidth ≈ kHz

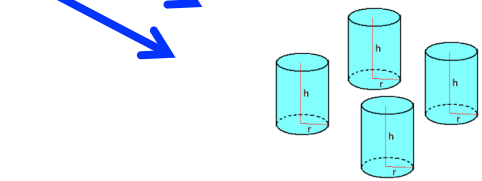
$$a \approx \frac{\sqrt{2\rho_a}}{m_a} e^{i(\vec{k}\cdot\vec{x} - m_a t + \phi)}$$

$$|\vec{A}| \approx \frac{\sqrt{Z_0 P_{\text{laser}}/\text{Area}}}{\omega} e^{i(\vec{k}\cdot\vec{x} - \omega t + \phi)}$$

Visualizing Axion DM



300 km/s



Football stadium-sized clumps of coherently oscillating axions drifting through detectors.
Macroscopic occupation number 10^{20} axions/m^3.

→ Phase coherent signals over 10^{-3} s.

The Sikivie Haloscope technique (1983)

- In a constant background B_0 field, the oscillating axion field acts as an exotic, space-filling current source

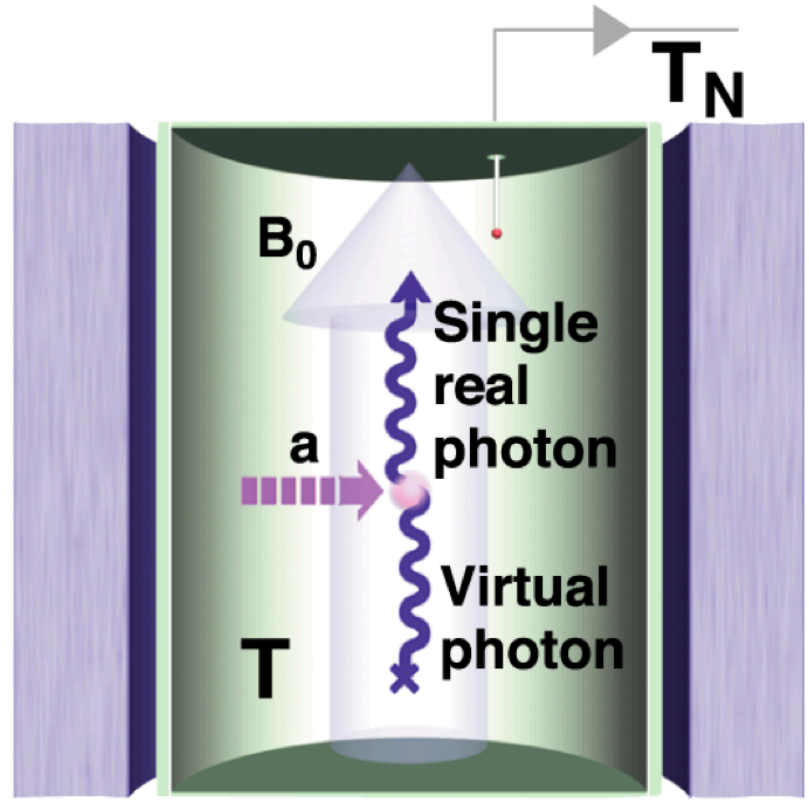
$$\vec{J}_a(t) = -\frac{g_\gamma \alpha}{\pi}\left(\frac{\sqrt{2\rho_a}}{\Lambda^2_{\mathrm{QCD}}}\right)\vec{B}_0 m_a e^{i m_a t}$$

which couples to EM via Faraday's law:

$$\vec{\nabla} \times \vec{B}_r - \frac{d\vec{E}_r}{dt} = \vec{J}_a$$

- In the presence of matched cavity boundary conditions to absorb momentum, the exotic source current excites standing-wave RF photons.

- **RF photon frequency = axion mass**
  - Classic window range: 250 MHz – 250 GHz

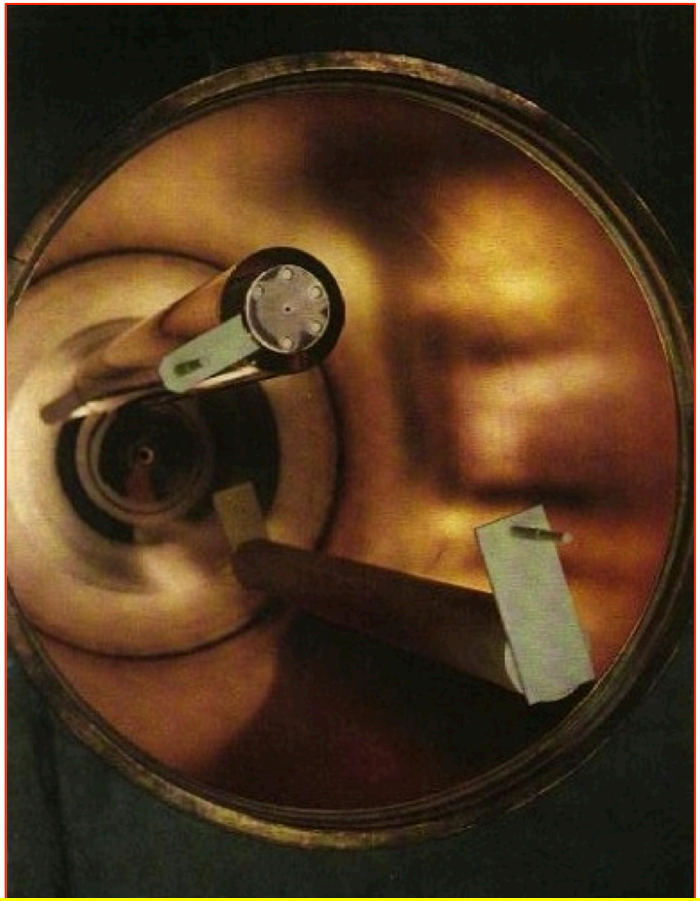


The Haloscope **optimally** extracts power from the potential energy of interaction:

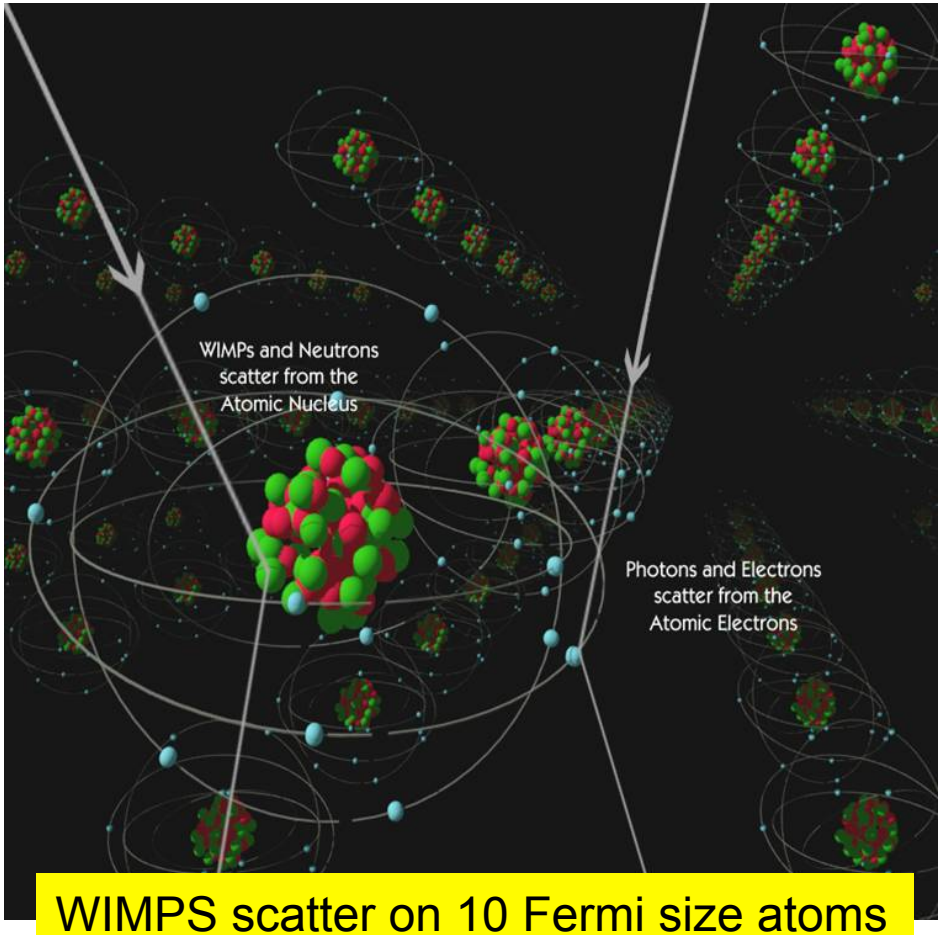
$$P_a = \int \vec{J}_a \cdot \vec{E}_r \, dV$$

Axions vs WIMPs:

Resonant scattering requires size of scattering target = 1/(momentum transfer)



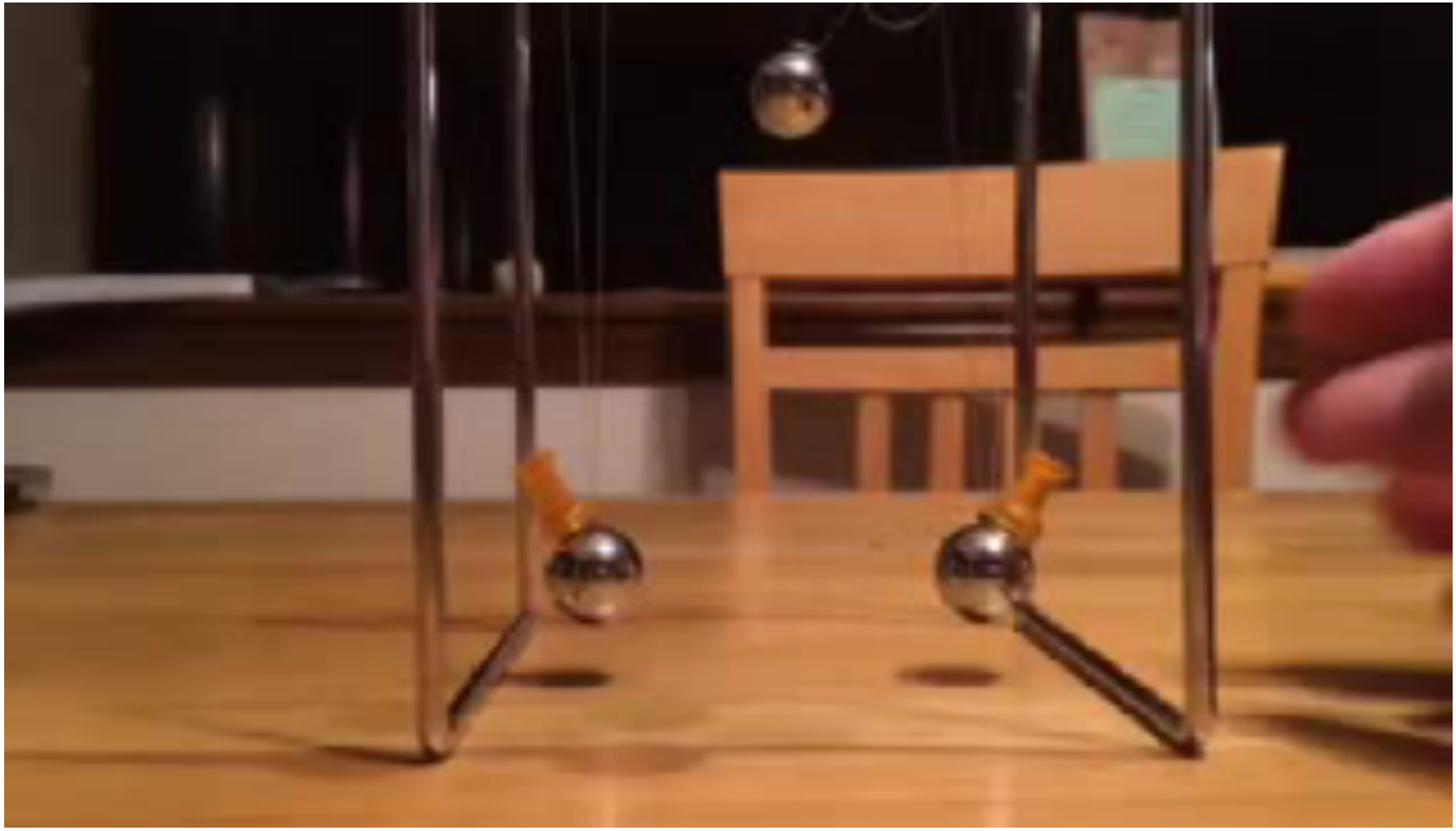
4 μeV mass axions scatter on 50cm size microwave cavities



WIMPS scatter on 10 Fermi size atoms

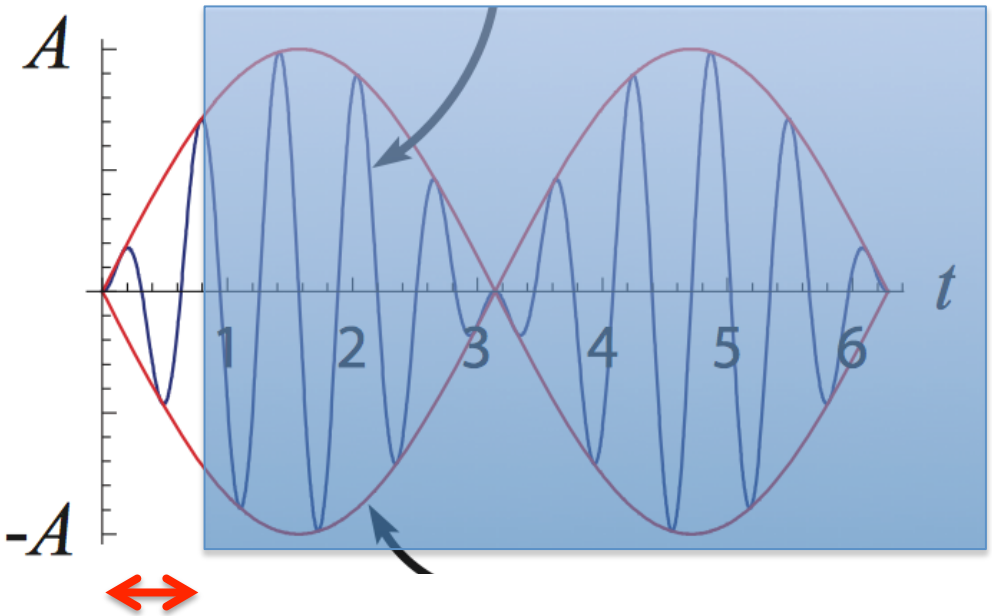
Higher frequency searches will require many smaller cavities.

Power transfer increased by time coherence between cavity E field and axion field



Weak coupling -- takes many swings to fully transfer the wave amplitude.
Number of swings = cavity Quality factor.
Narrowband cavity response → iterative scan through frequency space.

The quality factor Q_{cav} determines the cavity coherence time t_{cav} over which the axion signal can be coherently accumulated as cavity E field



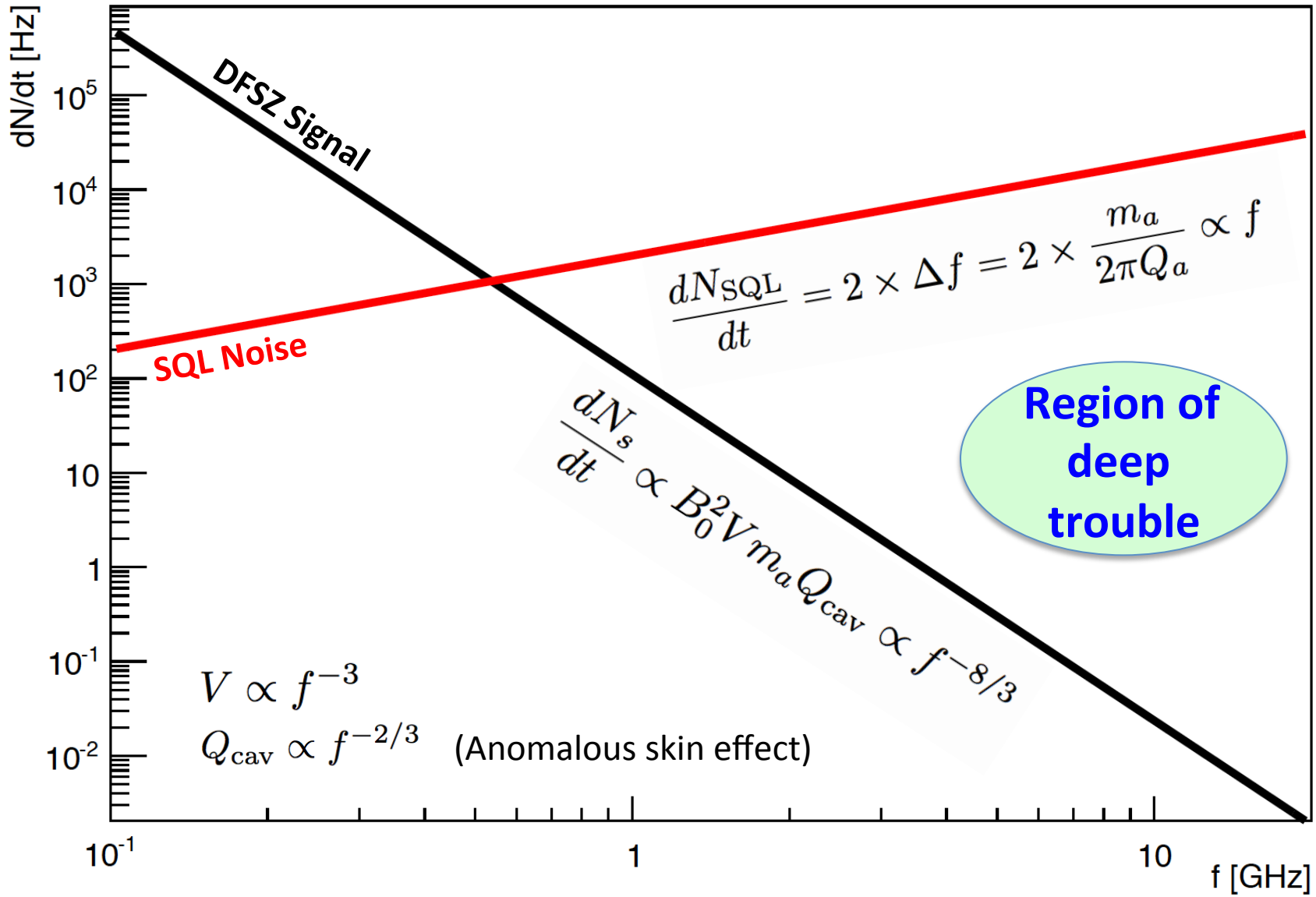
$t_{cav} = 1/df_{cav} = Q_{cav}/f$

Oscillation period = 1/(Interaction Energy)

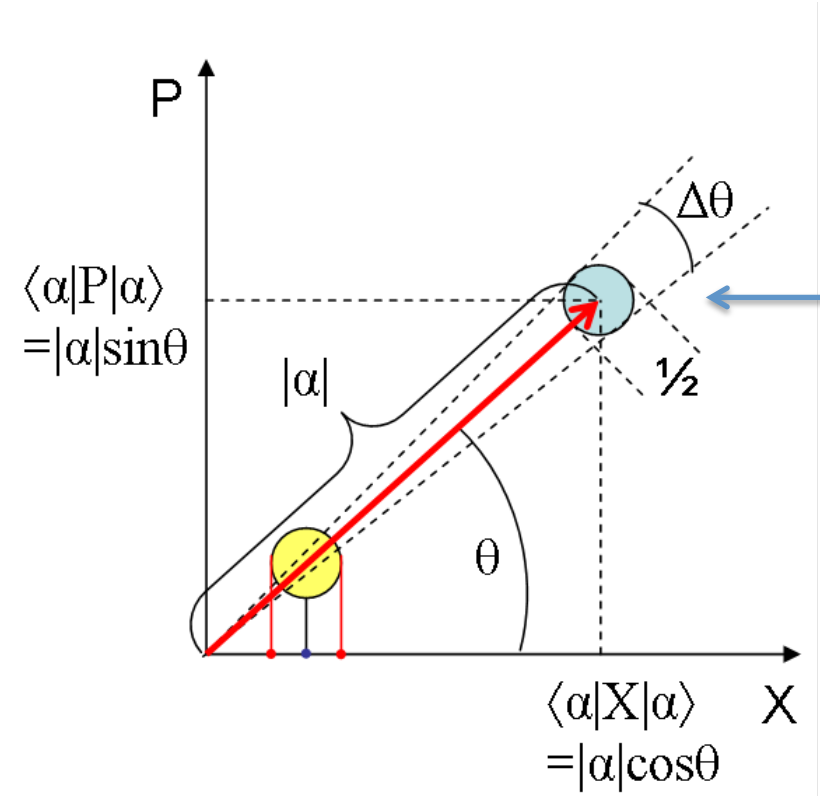
>> coherence time

Square the wavefunction → **the accumulated energy scales as $(t_{cav})^2 = Q_{cav}^2 / f^2$**

DFSZ signal photon rate for single volume=λ³ cavity vs. Standard Quantum Limit readout noise



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)

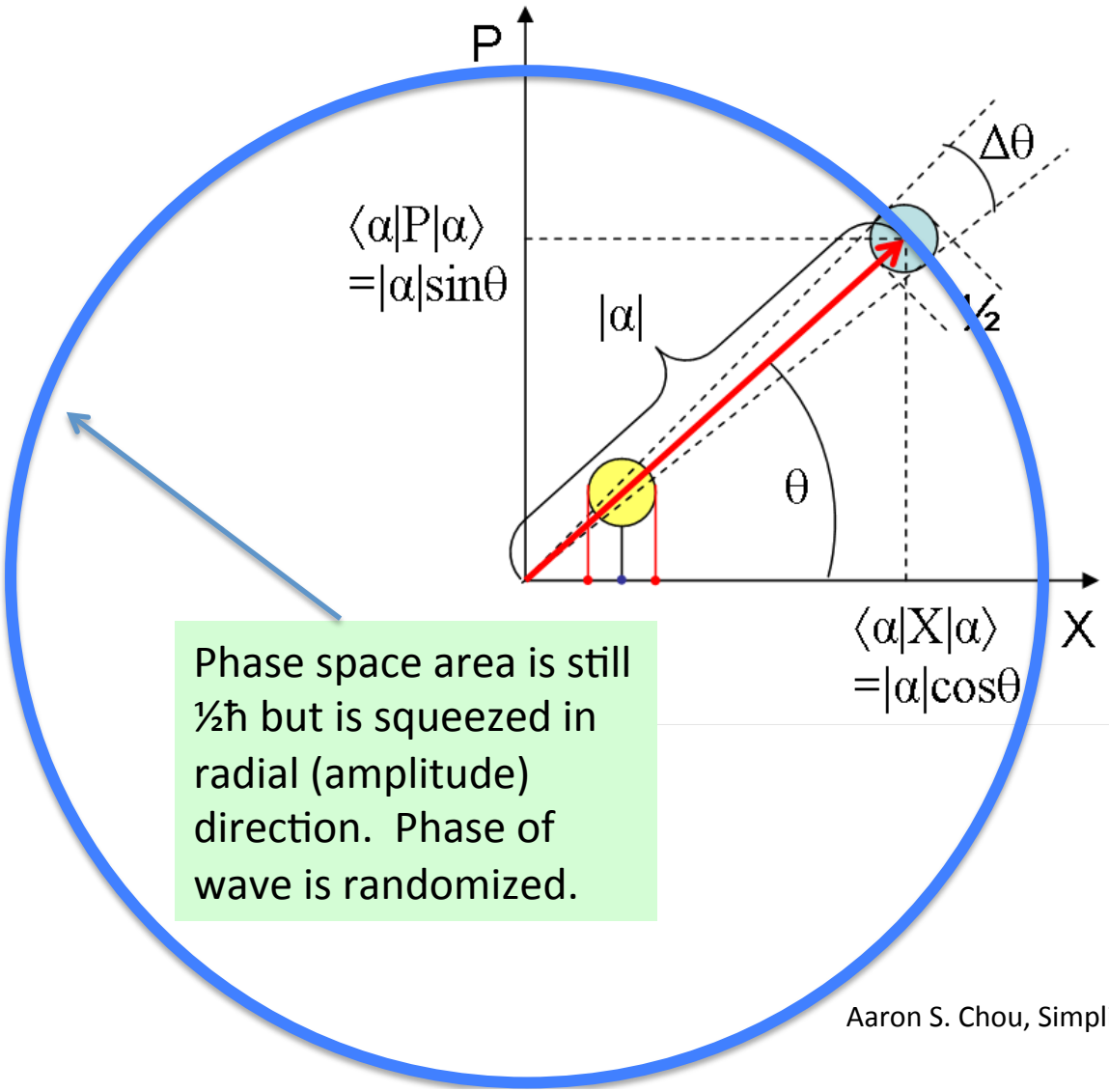
Casimir effect does not imply existence of zero point energy.
-- Bob Jaffe (2005)

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.



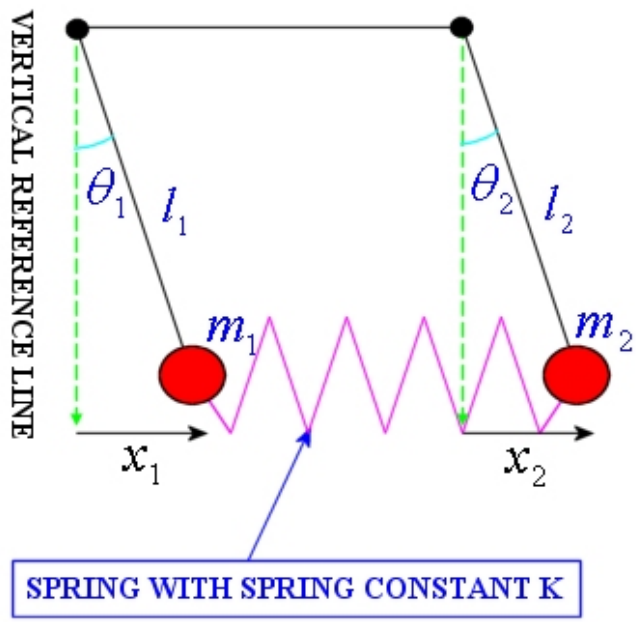
Demonstrated with Rydberg atoms, (Haroche/Wineland Nobel Prize 2012)

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

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

What does a QND single microwave photon detector look like and what are the interesting physics?

Coupled oscillators



Energy stored in the spring

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

Mixing angle to diagonalize:

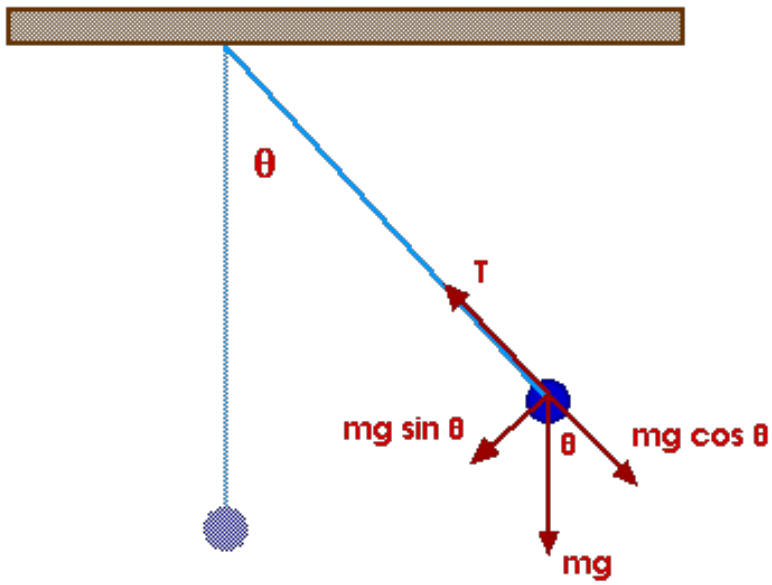
$$\tan 2\theta = 2g/(\omega_1 - \omega_2)$$

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
$\omega_2 = \omega_2(A_2)$

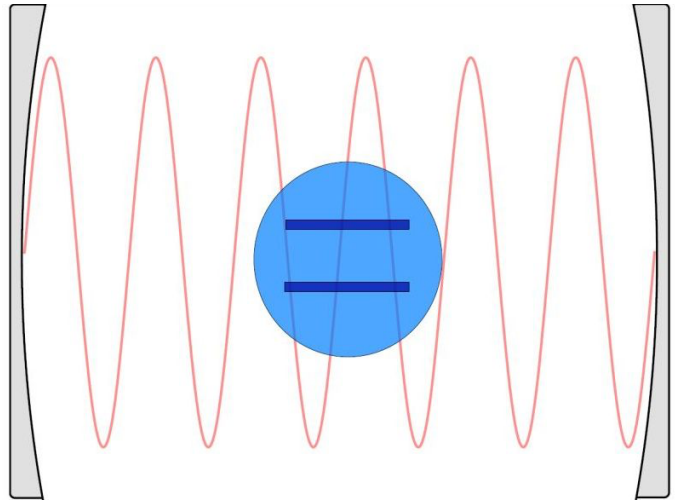
Then the instantaneous resonant frequency of **linear** oscillator 1 depends weakly on the amplitude or occupation number of **nonlinear** oscillator 2

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

Measuring the frequency of oscillator 1 performs a 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:

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

$\Delta = \omega_r - \omega_a$

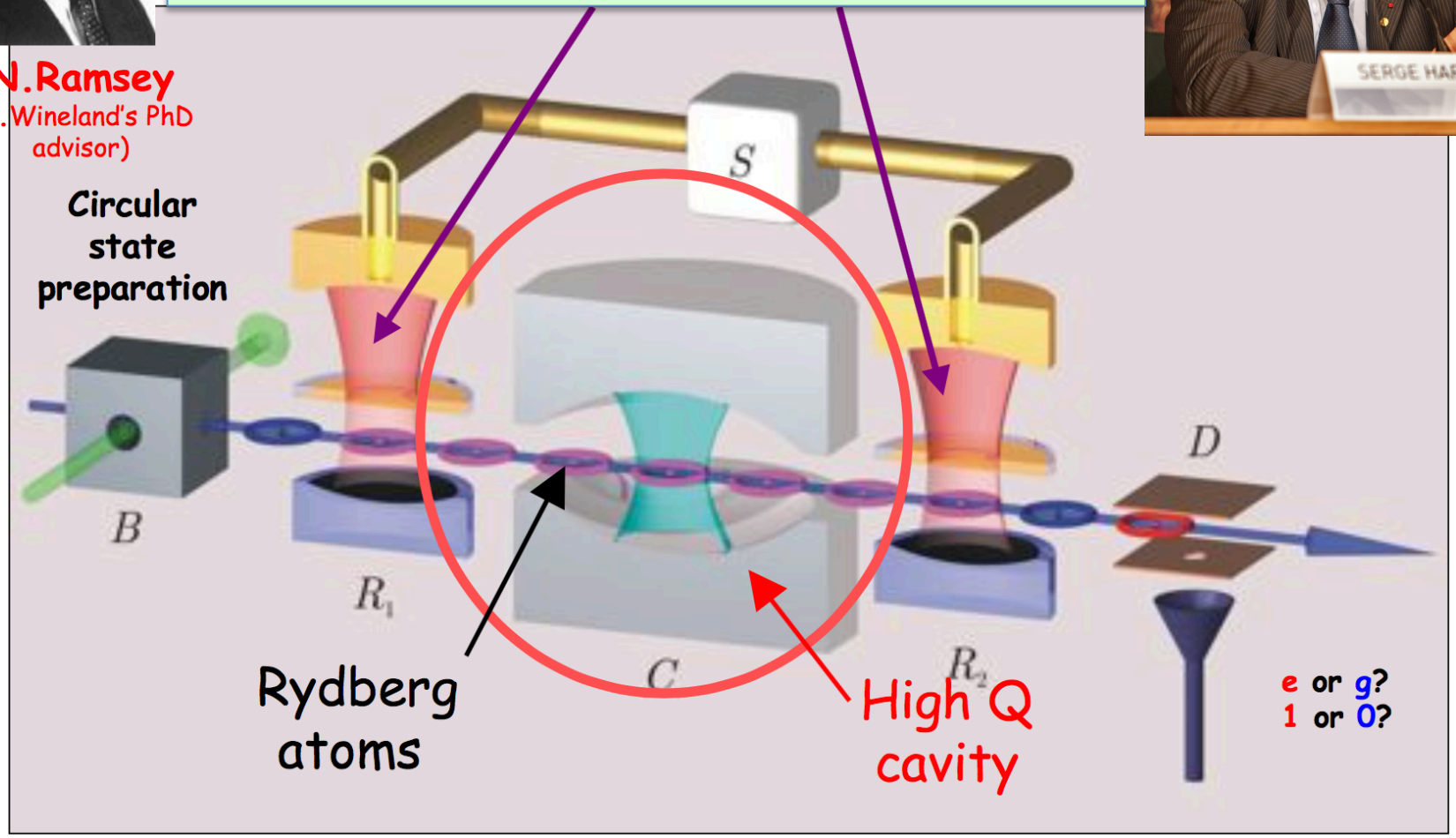
The atom frequency depends on the cavity resonator's occupation number!

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

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

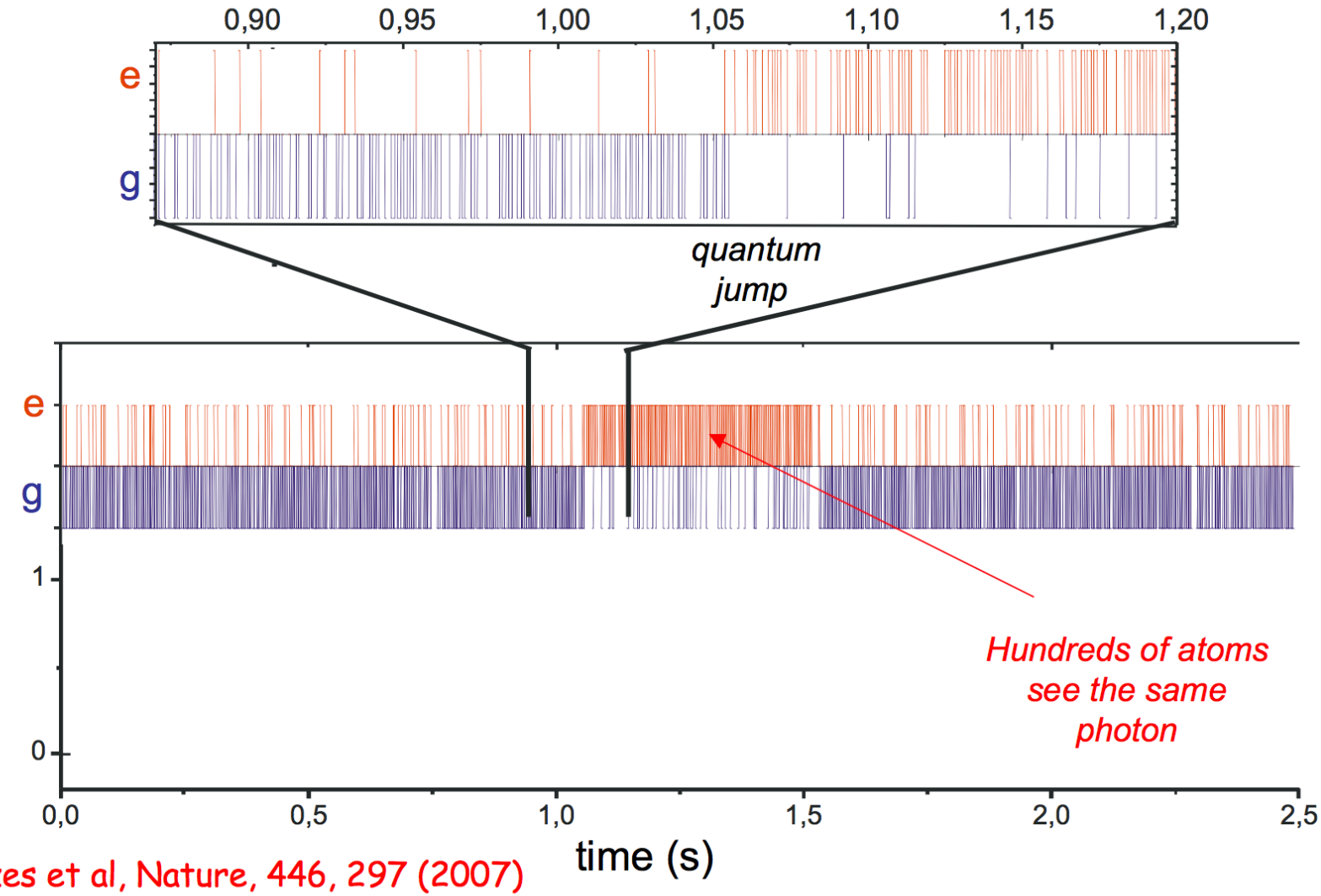
Serge Haroche 2012 Nobel Prize:

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

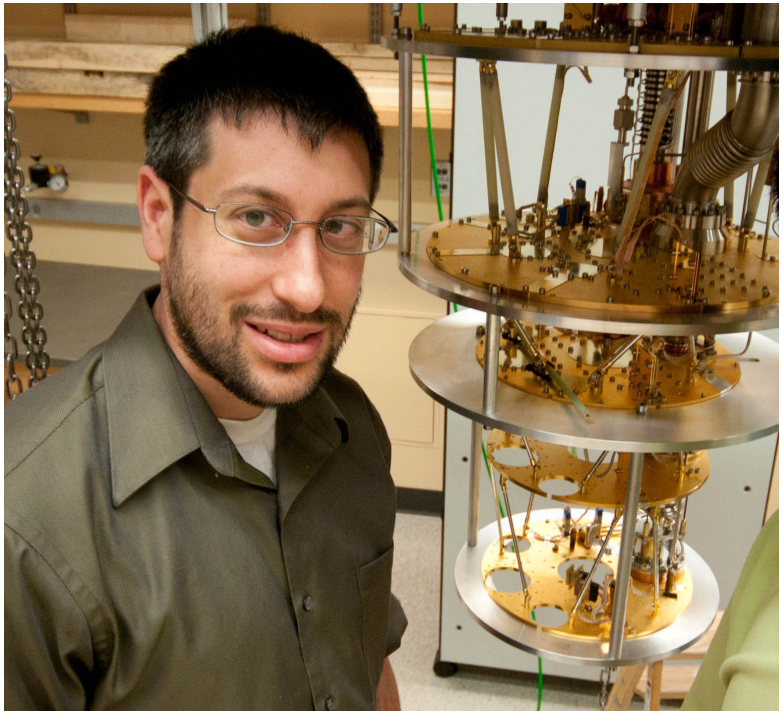
Birth, life and death of a photon



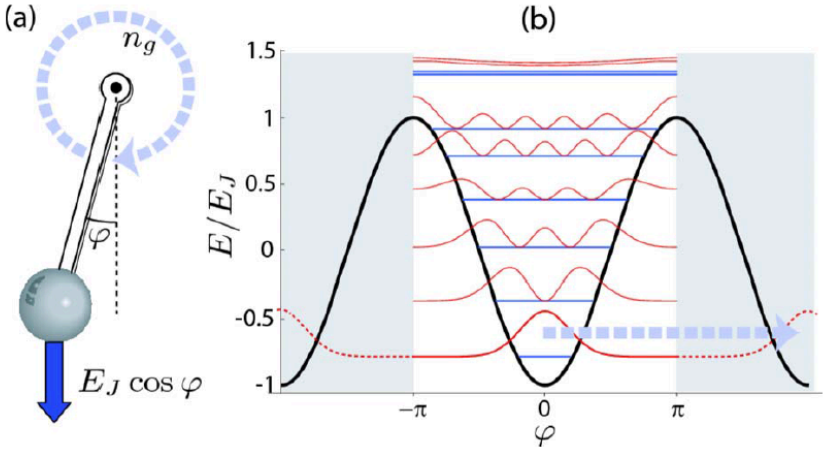
S.Gleyzes et al, Nature, 446, 297 (2007)

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

Cf. Randall-Sundrum graviton tower



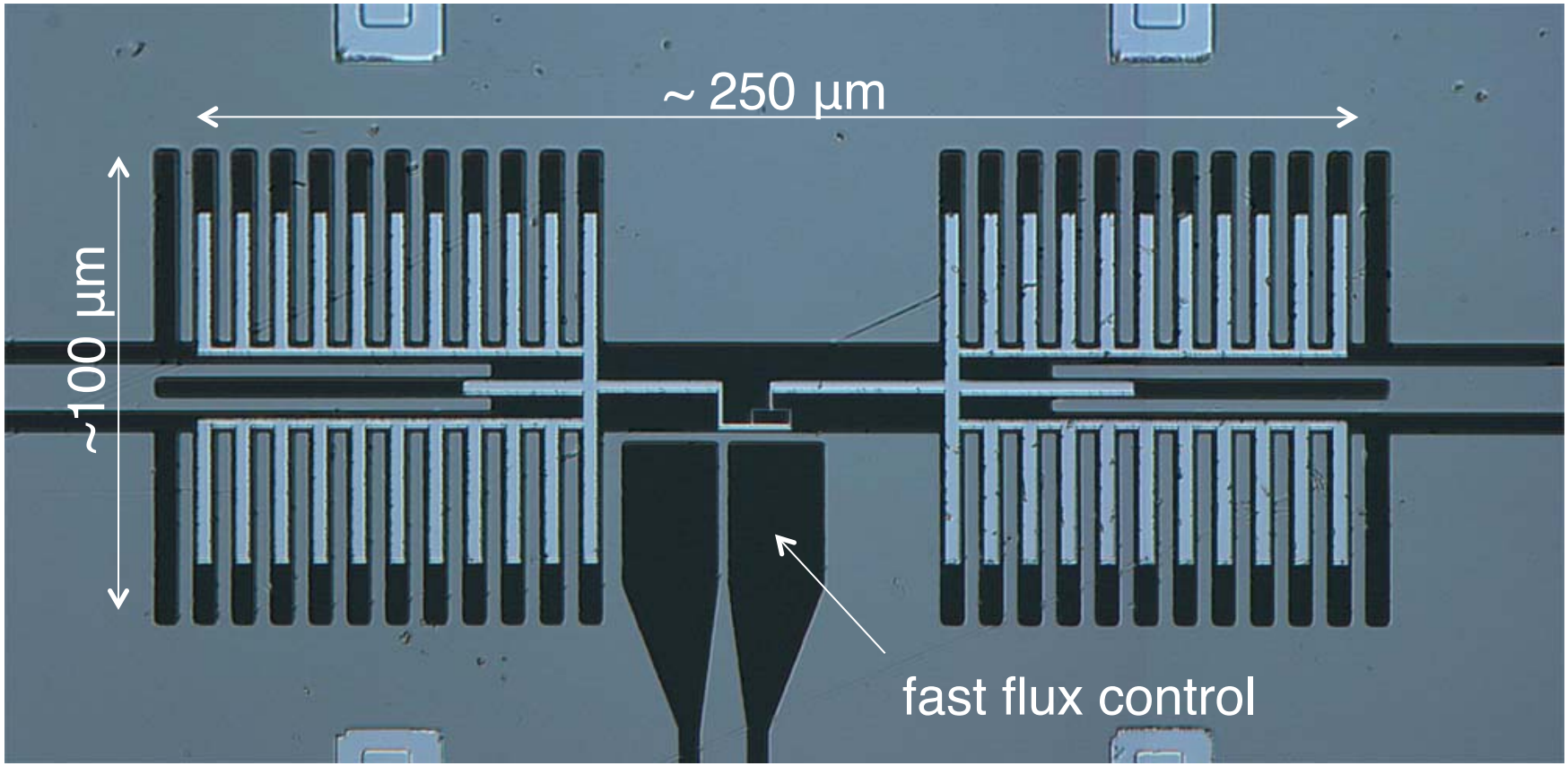
Slides from Dave Schuster (U.Chicago)



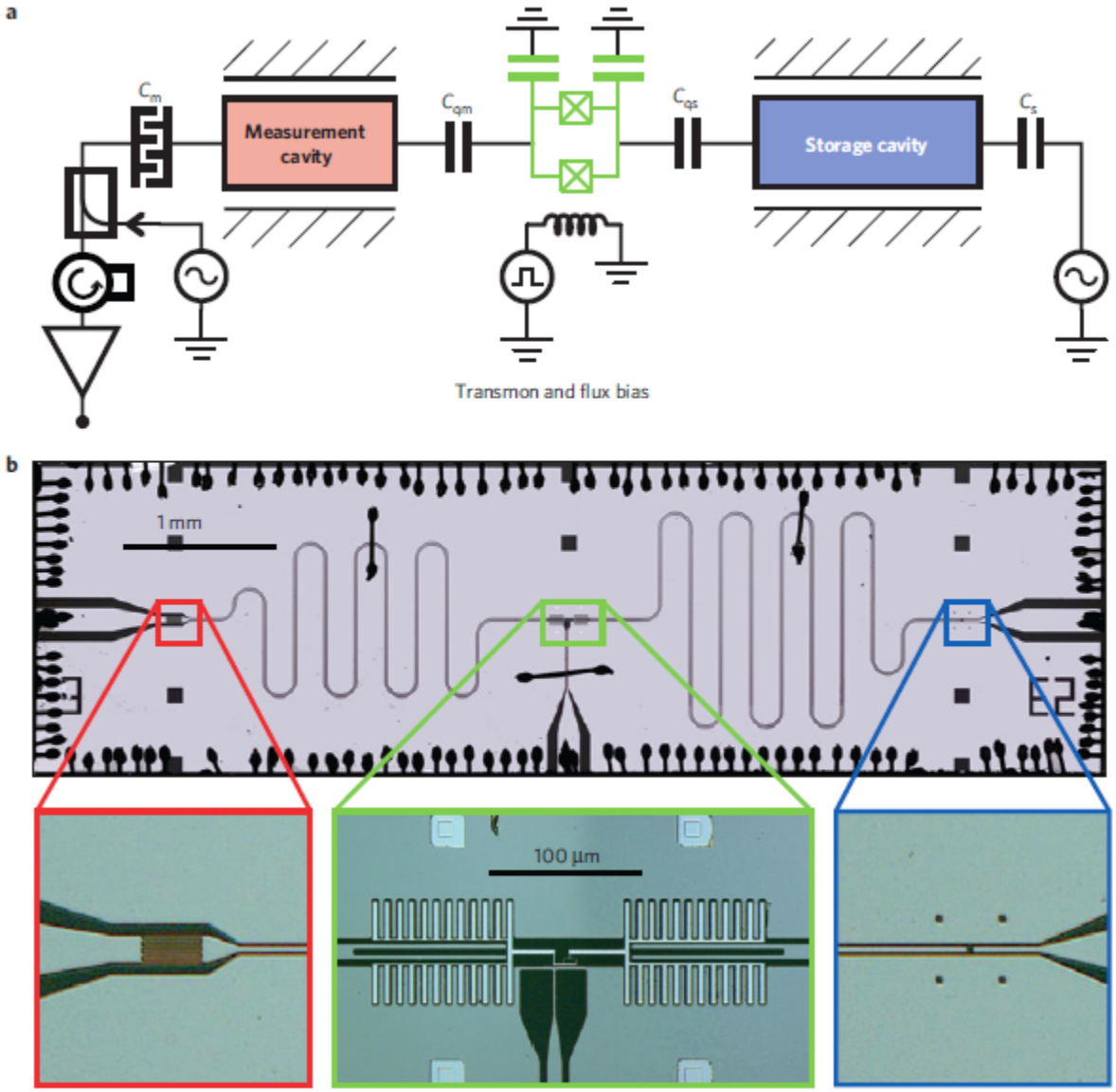
J.Koch, e.al, Phys.Rev.A76, 042319 (2007)
B.R. Johnson, et.al, Nature Physics 6, 663-667 (2010)

The sarantapede

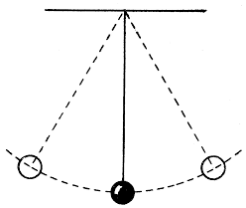
- An end-coupled “transmon” qubit with ~40 legs



QND Detector = qubit + fast cavity



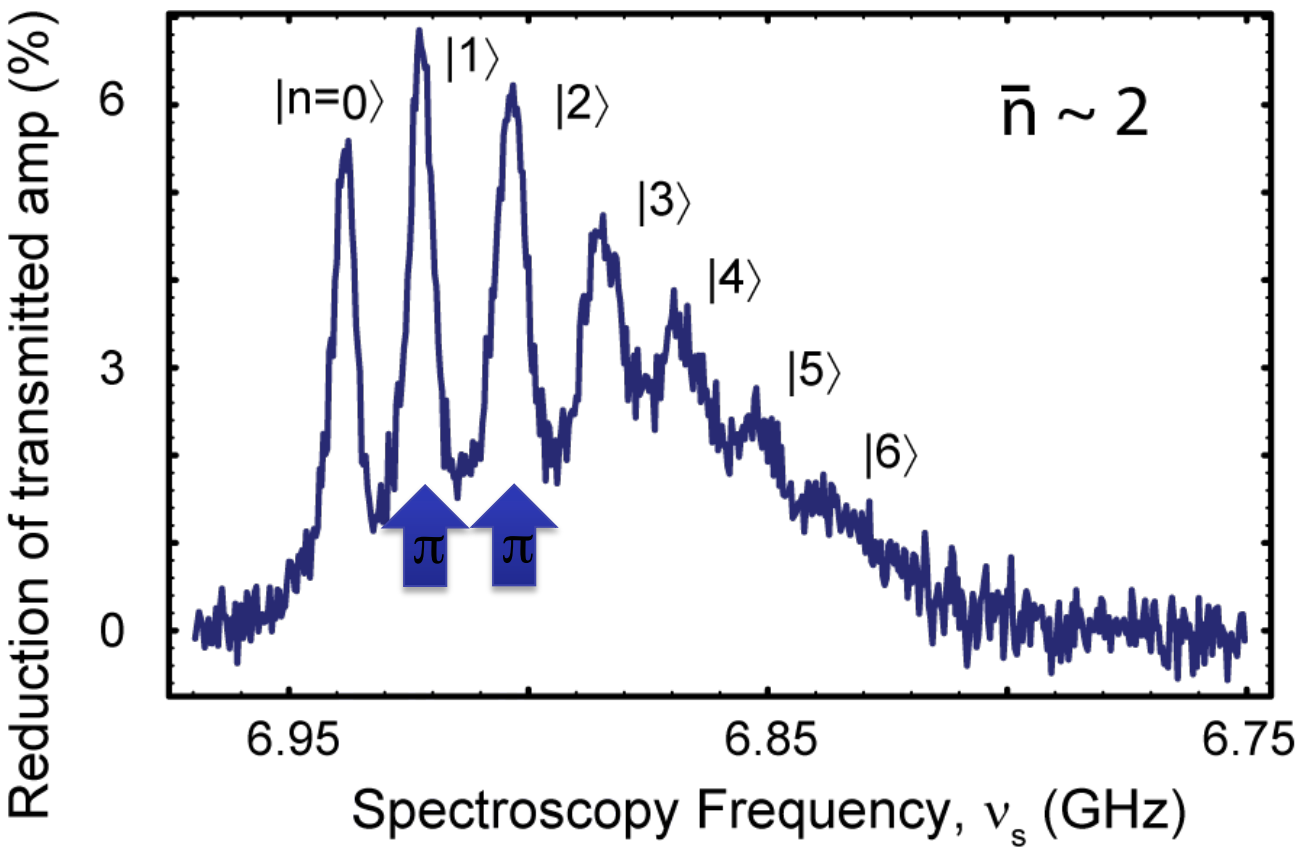
Readout freq. shift



Axion DM

Sensing photon number with a qubit

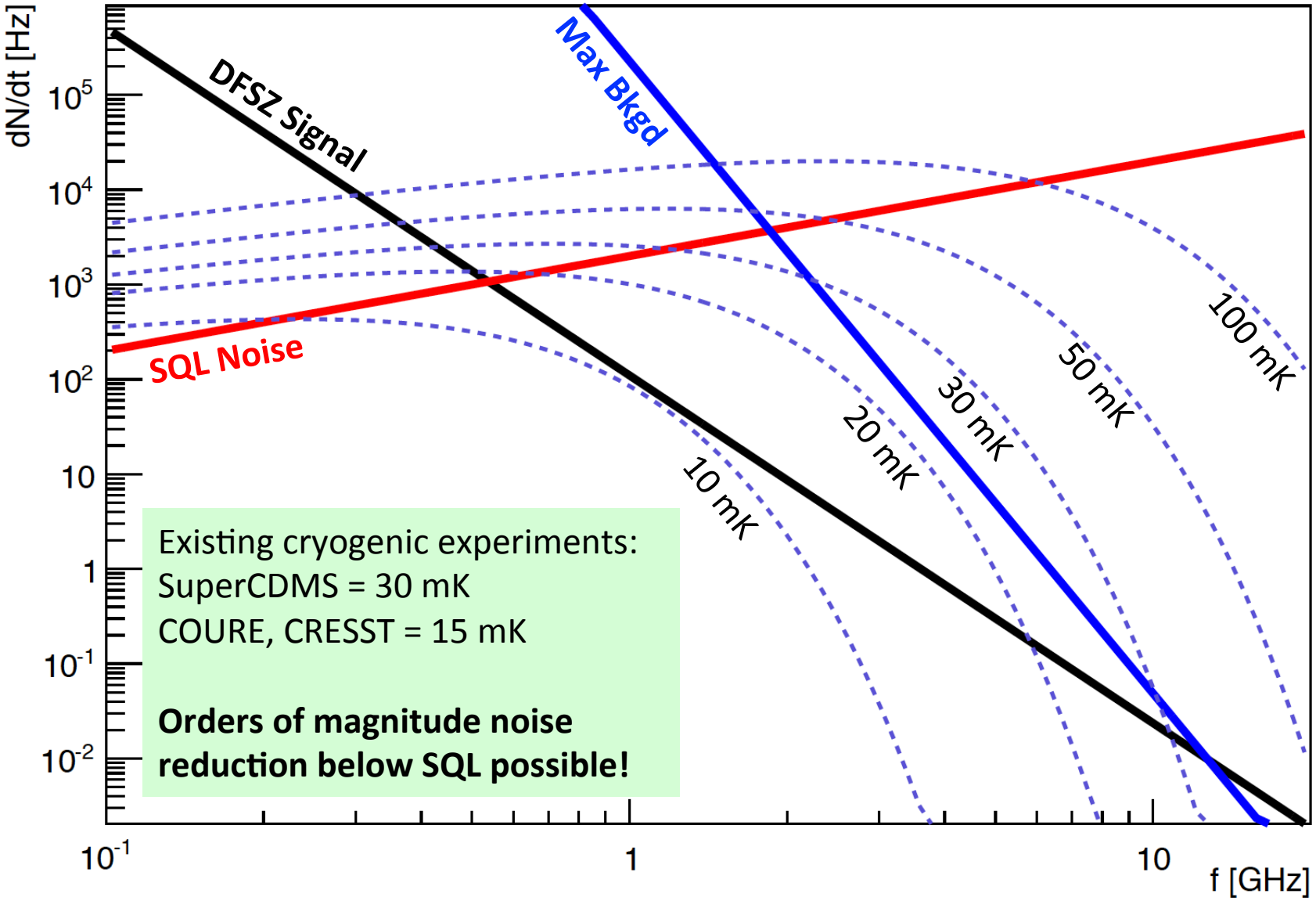
$$H \approx \hbar\omega_r a^\dagger a + \frac{\hbar}{2}(\omega_a' + 2\chi a^\dagger a)\sigma_z$$



- 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)

Blackbody background rates in QND-based experiments are Boltzmann-suppressed



Existing cryogenic experiments:
SuperCDMS = 30 mK
COURE, CRESST = 15 mK

Orders of magnitude noise reduction below SQL possible!

Possible take-aways from this "case study"

- Gravitationally-observed dark matter is the smoking gun for the Peccei-Quinn axion model.

- Zero-point energy may be just an artifact of the quantum measurement process. This backreaction can be avoided.

- For constrained probe energy, anharmonic oscillators can be modeled as fermionic 2-level systems.
  - 1st order perturbation theory then transfers the anharmonicity to the probe.
  - Is this useful for HEP phenomenology?

- Lot's of well-developed theoretical and experimental techniques exist outside of HEP. (They even get Nobel prizes.)
  - The physics community was not always this silo-ed

How do we engage the other communities?

Can we get the funding agencies to agree to this?