Title: Using quantum computing techniques to detect dark matter axions

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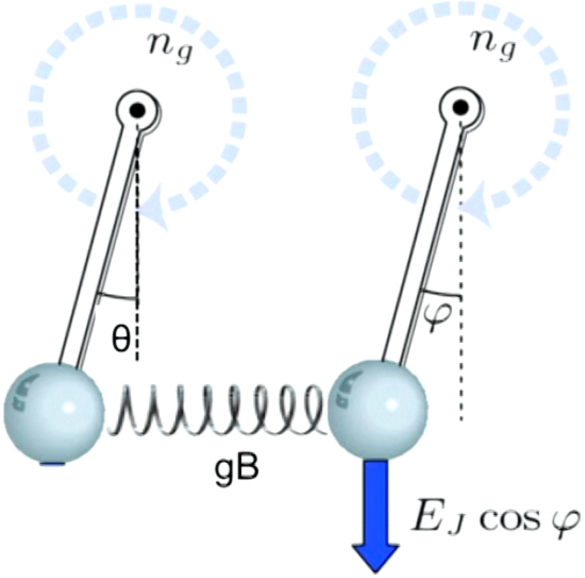
Abstract: <p>Quantum non-demolition measurements performed using qubit-based artificial atoms may enable the next generation of higher mass dark matter axion search experiments. These QND measurements can precisely determine the amplitude of the photon wave sourced by the dark matter axions while placing the back reaction noise into the phase quadrature. By evading the standard quantum limit of phase-preserving amplifiers, the QND photon can potentially reduce readout noise by orders of magnitude. Combined with the radio frequency quantum buses to extract the signals, the next generation axion dark matter detector may closely resemble or actually be a multi-qubit quantum computer.</p>

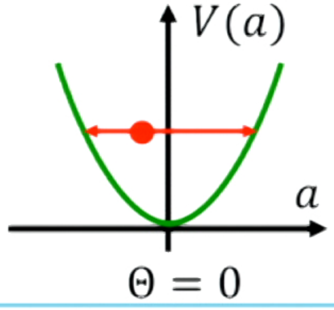
Perimeter Institute Seminar

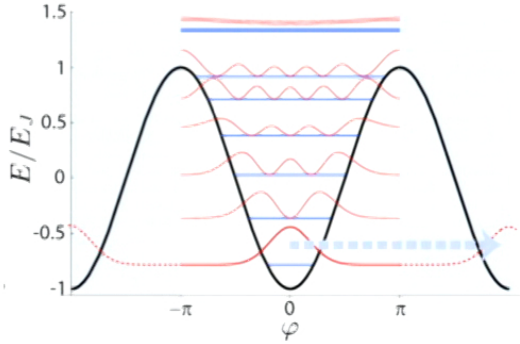
Using Quantum Computers to Detect Dark Matter Axions

Aaron S. Chou
FNAL

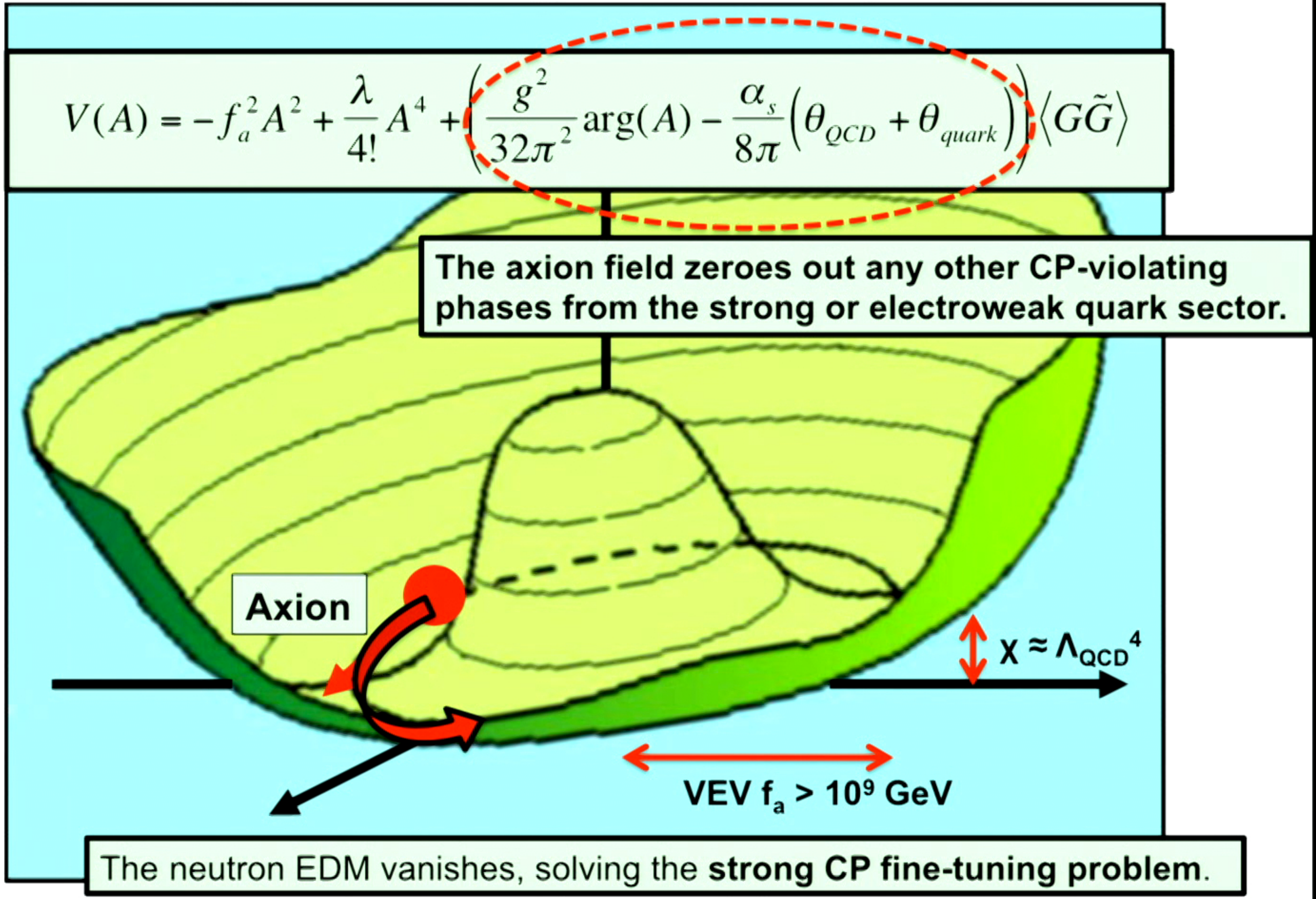
May 30, 2017







Explaining the vanishing neutron EDM (Peccei,Quinn 1977)



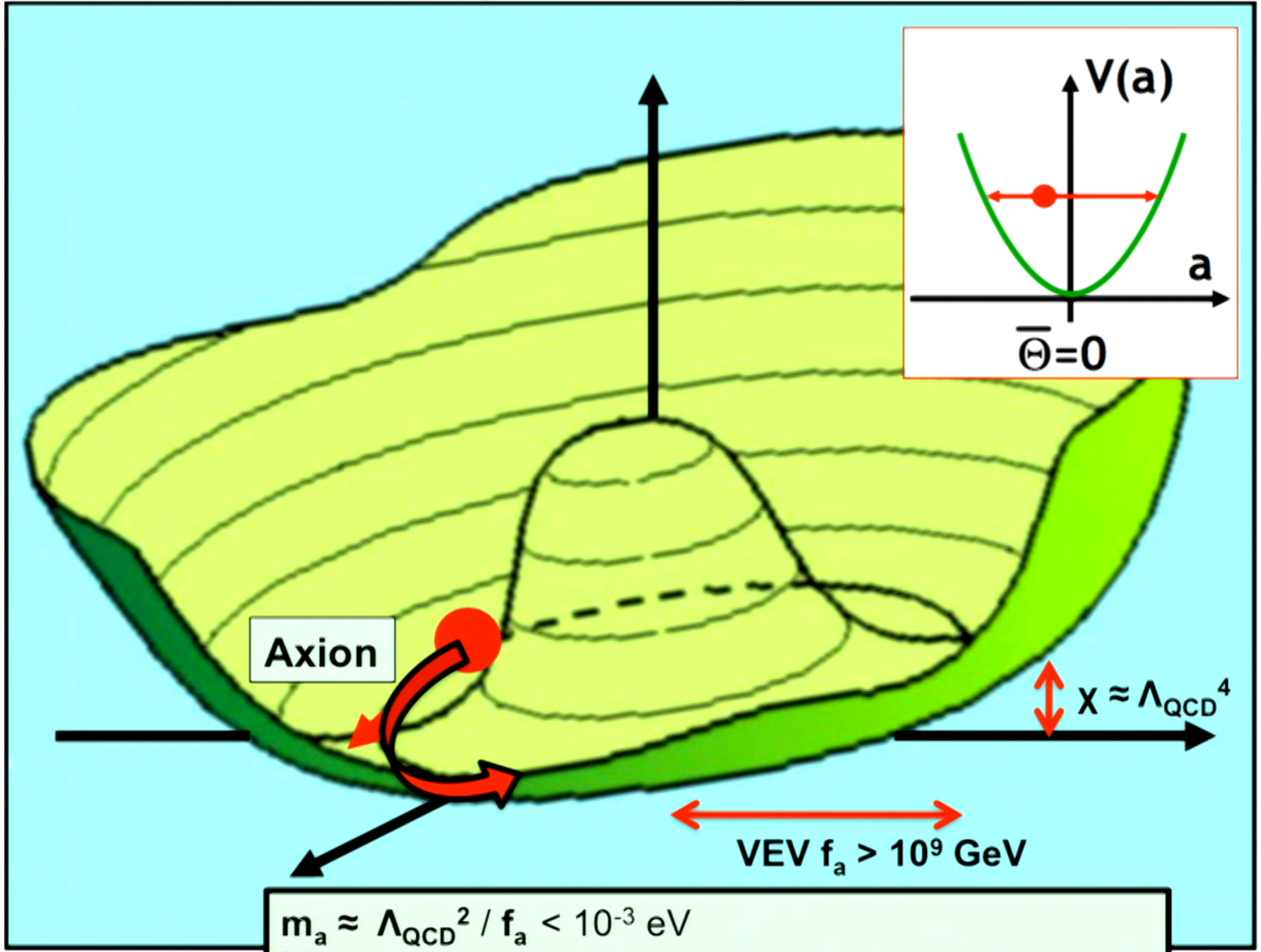
$$V(A) = -f_a^2 A^2 + \frac{\lambda}{4!} A^4 + \left(\frac{g^2}{32\pi^2} \arg(A) - \frac{\alpha_s}{8\pi} \left(\theta_{QCD} + \theta_{quark} \right) \right) \langle G \tilde{G} \rangle$$

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**.

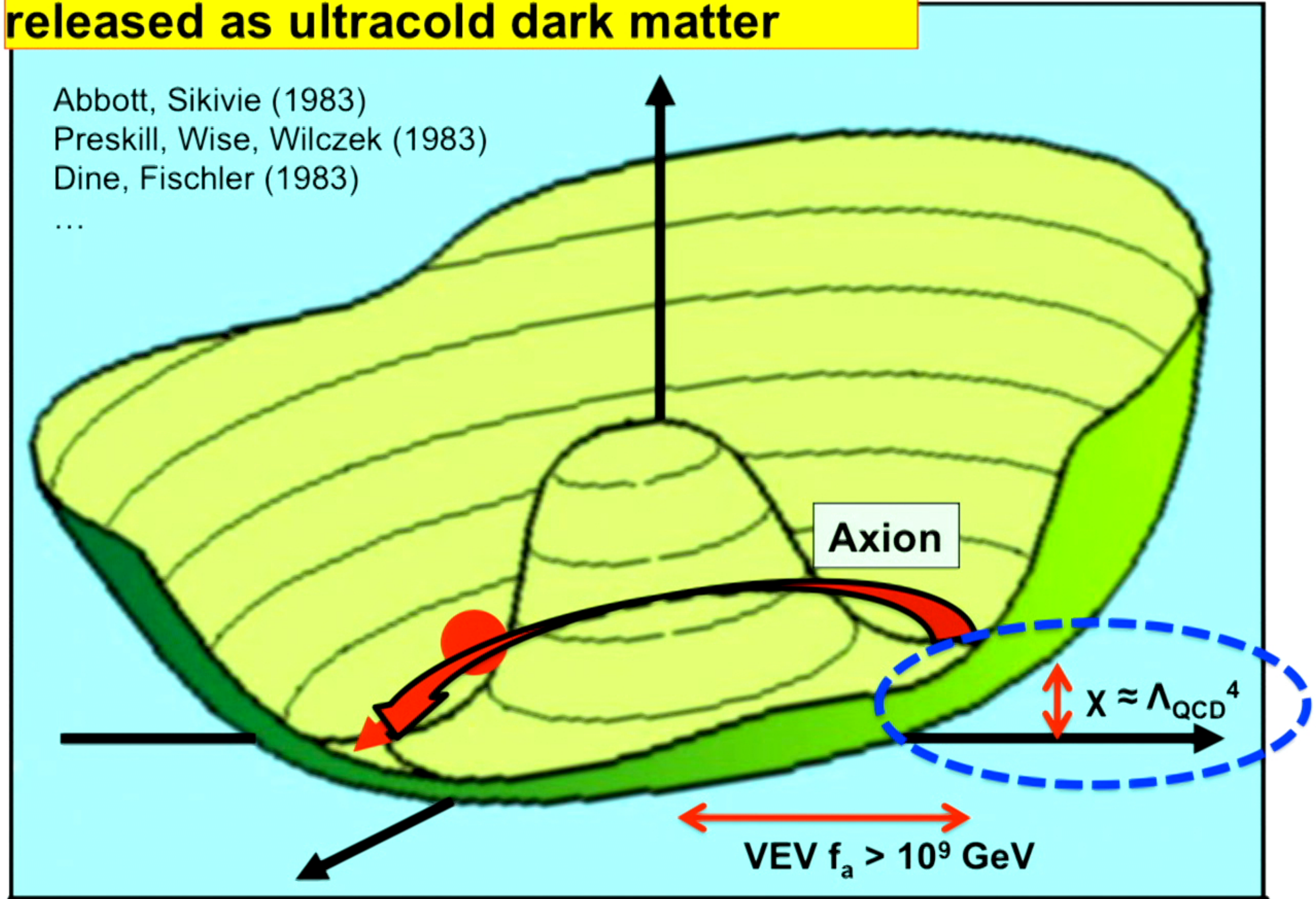
Aaron S. Chou, PI Seminar 5/30/17

See-saw mechanism gives a single-parameter axion model



$m_a \approx \Lambda_{QCD}^2 / f_a < 10^{-3}$ eV
Mass is determined by coupling scale and vice-versa

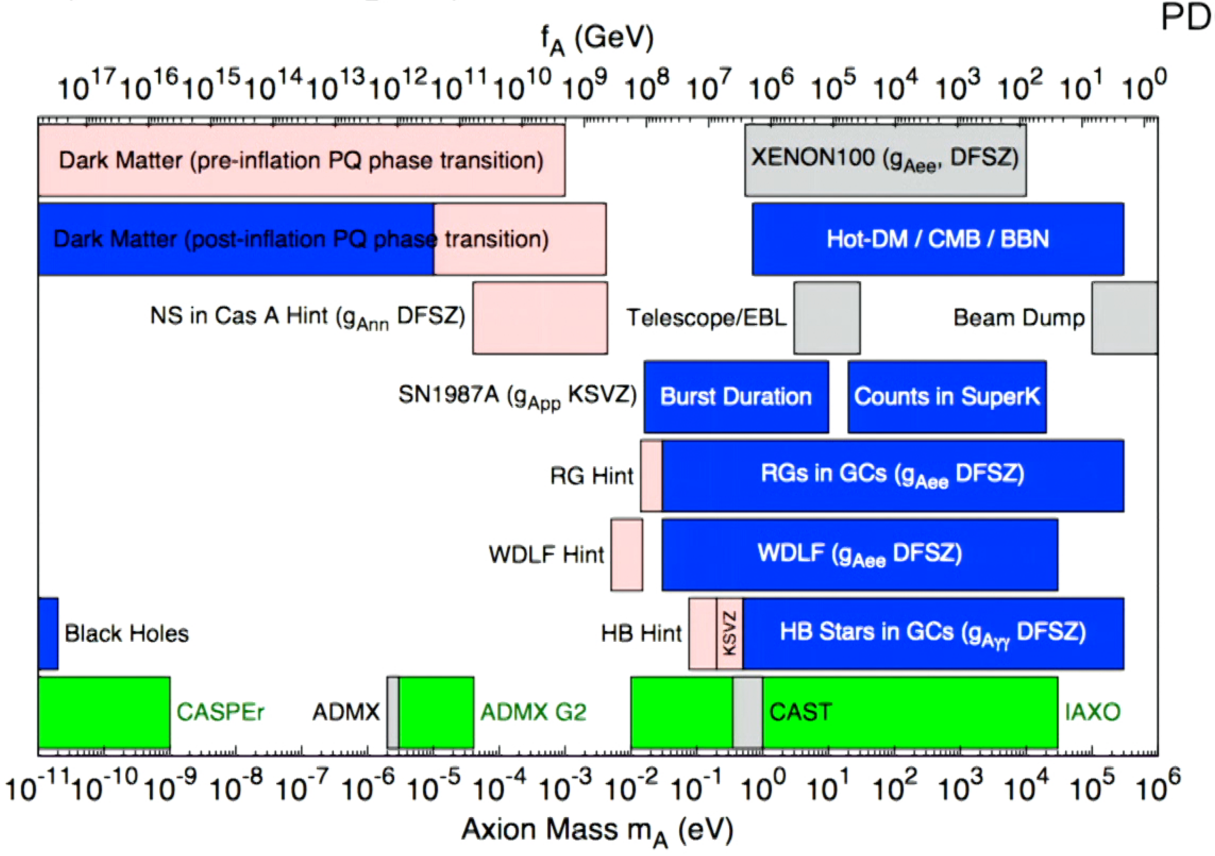
The initial potential energy density is released as ultracold dark matter



Abbott, Sikivie (1983)
Preskill, Wise, Wilczek (1983)
Dine, Fischler (1983)
…

The random initial axial **theta angle θ_0** $=a_0/f_a$ determines the available potential energy to be converted into axion dark matter.

Roadmap for the single-parameter QCD axion model

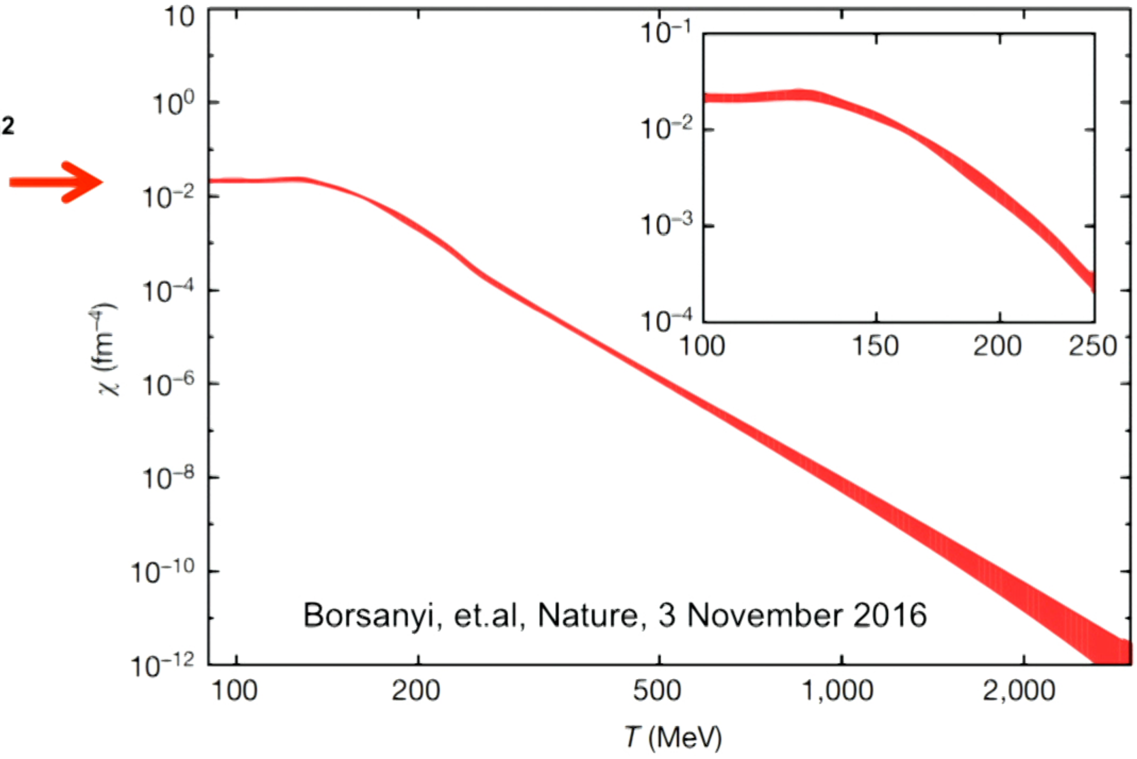


PDG 2016

Blue = astrophysical constraints, Pink = astro hints,
Grey = experimental results, Green = planned or ongoing experiments

Latest lattice result for QCD topological susceptibility agrees with naïve estimate

$\chi = d^2V/d\theta^2$
$\approx \Lambda_{QCD}^4$



Borsanyi, et.al, Nature, 3 November 2016

This gives the QCD potential energy density available to convert into DM axions.

Bucket of dark matter is dumped into the red-shifting photon bath at time $1/H \approx 3/m_a$

Non-DM density redshifting away →

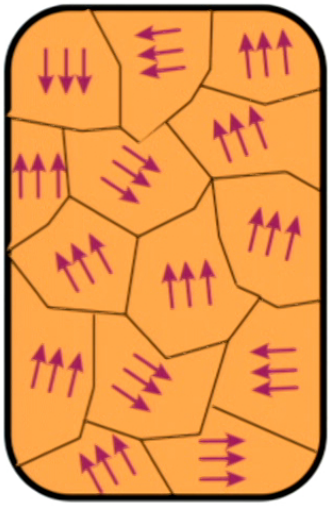
River drying up

For a bucket filled to the level $\langle \sin^2 \theta_0 \rangle \times \chi$ of fish, dumping it too late creates an improper balance of fish/water.

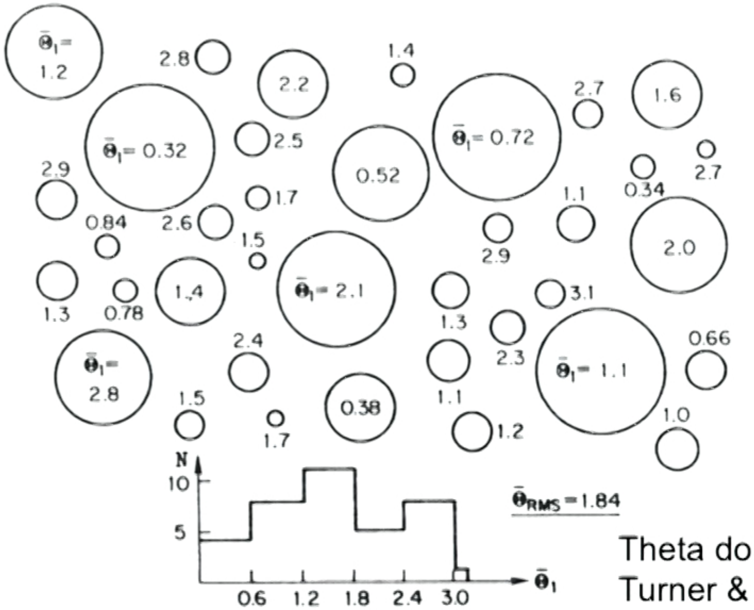
If you are going to procrastinate and dump it late, you better not have too many fish in that bucket since there is not a lot of water left!

→ **Small m_a requires small $\langle \sin^2 \theta_0 \rangle$ to avoid overproducing dark matter.**

Fullness of bucket depends on whether the axion phase transition happens before or after inflation



Ferromagnetic spin domains

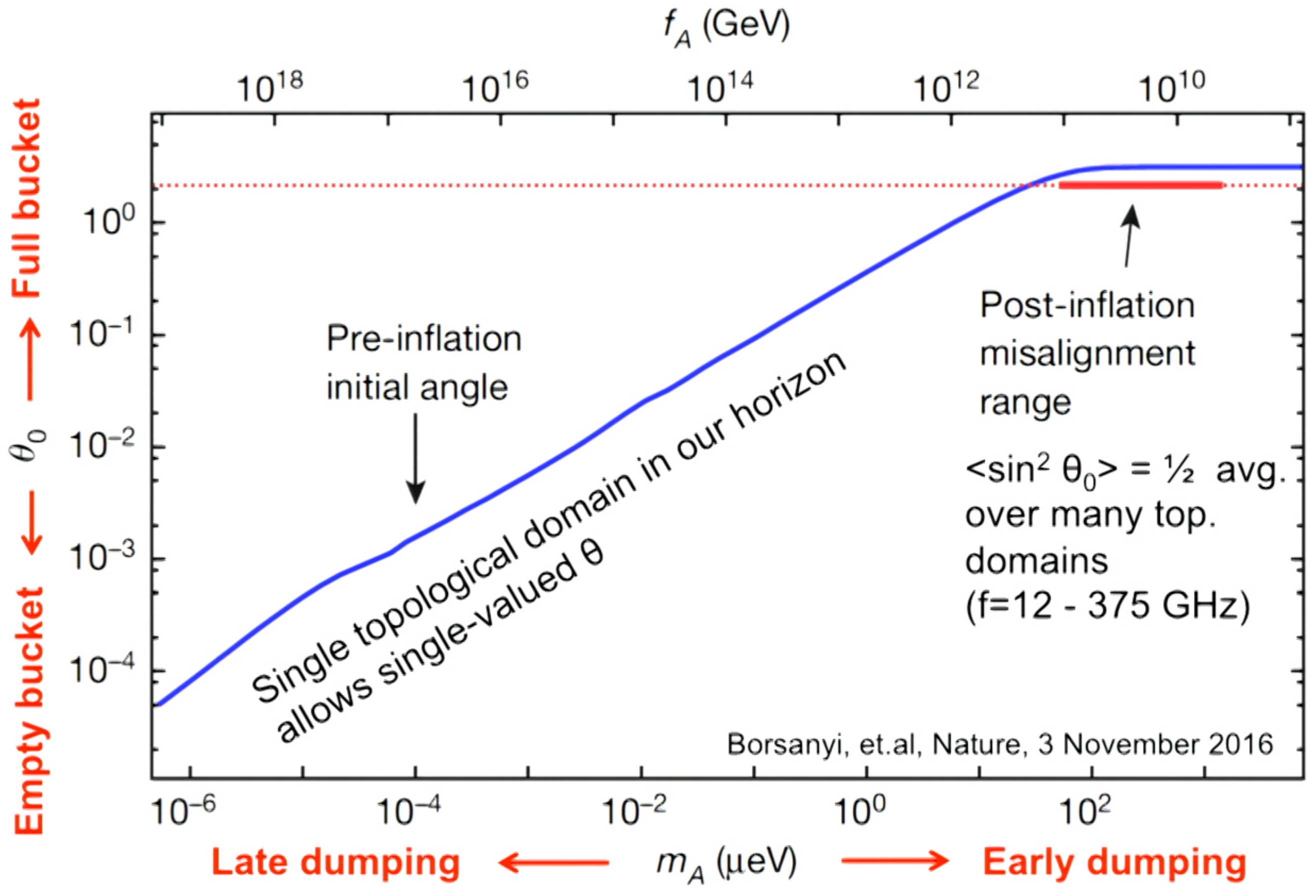


Theta domains,
Turner & Kolb
The Early Universe

Fig. 10.9: Distribution of $|\bar{\Theta}_1|$ in an inflationary Universe.

- If axion phase transition occurs **pre-inflation**, bubbles are inflated, and we live in one which by chance can have $\theta<1$.
- If axion phase transition occurs **post-inflation**, many bubbles are contained within our horizon, and so we get average value $\langle \sin^2\theta \rangle \times \Lambda_{QCD}^4$ of dark matter.

New lattice result gives dividing line at $m_a \approx 50$ μeV between pre- vs post-inflationary axion phase transition



Pre-inflation initial angle

Single topological domain in our horizon allows single-valued θ

Post-inflation misalignment range

$\langle \sin^2 \theta_0 \rangle = \frac{1}{2}$ avg. over many top. domains (f=12 - 375 GHz)

Borsanyi, et.al, Nature, 3 November 2016

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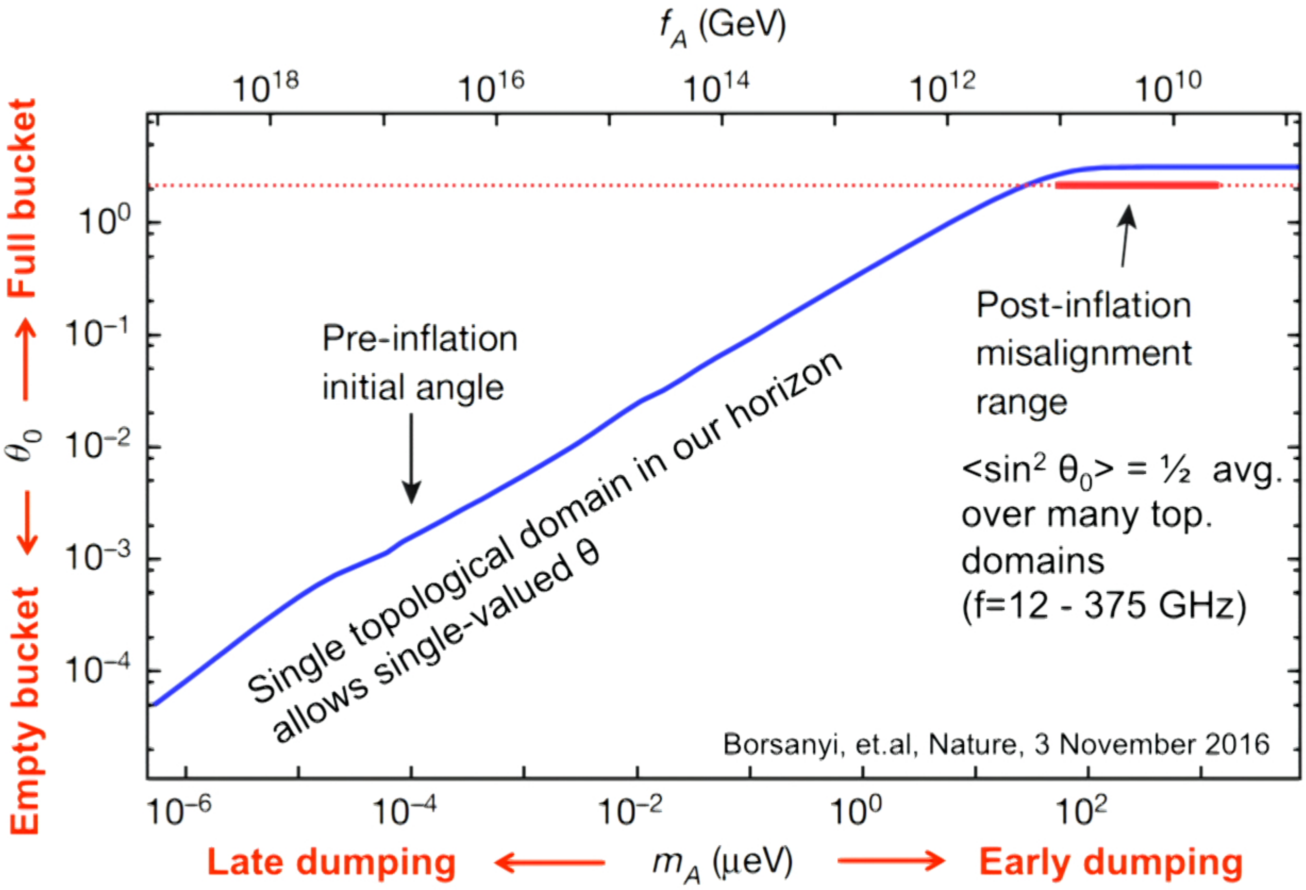

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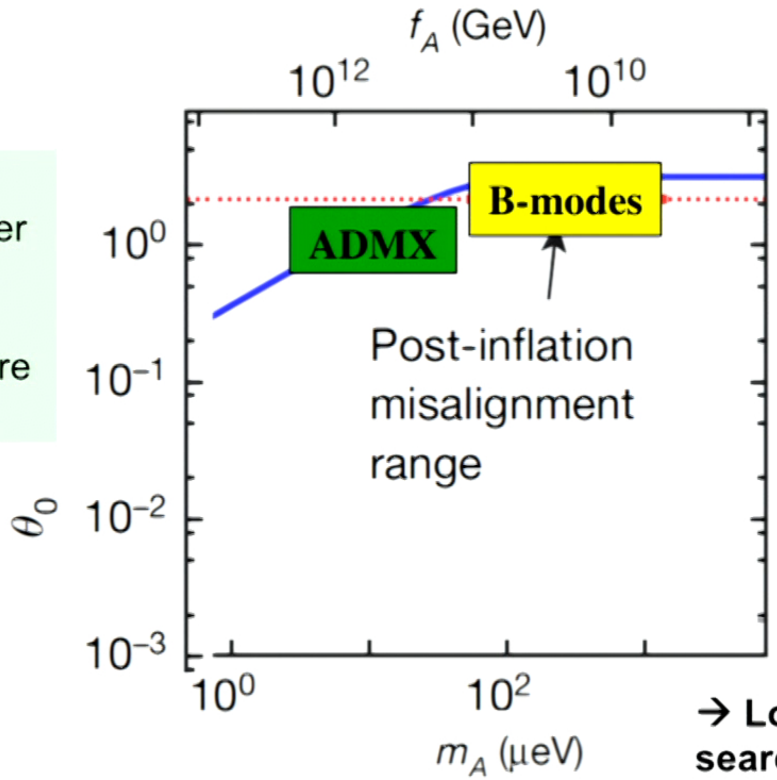
ADMX and CMB B-modes are complementary probes of cosmic inflation

B-modes are observable only if the scale of inflation $E_{inf} > 10^{16}$ GeV:

$$V^{1/4} \sim (r/0.01)^{1/4} \times 10^{16}\ \mathrm{GeV}$$

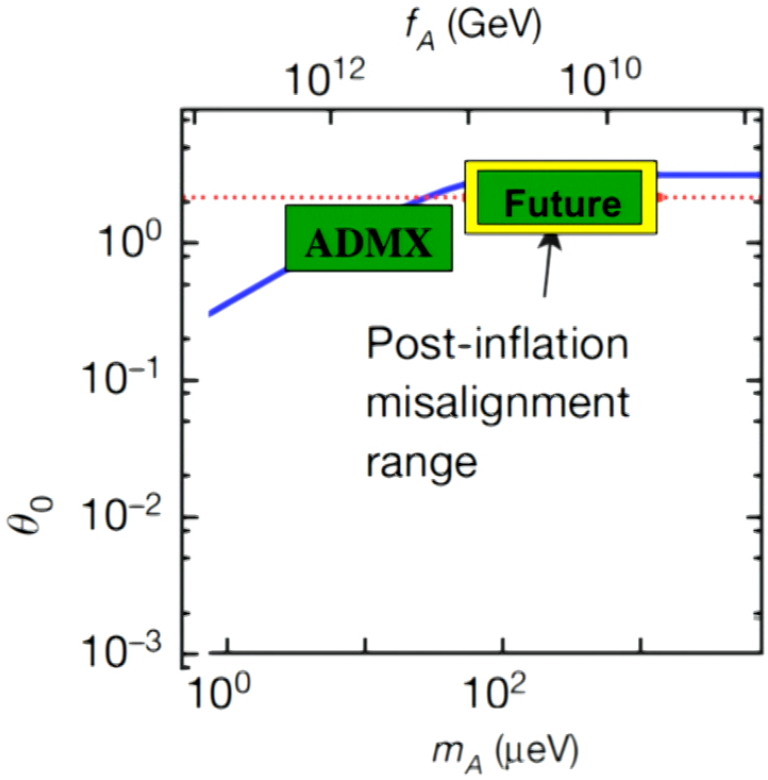
If ADMX-G2 observes a lower mass axion, $E_{inf} < 10^{12}$ GeV, and B-modes are not detectable.



If CMB inflationary B-modes are seen, then $E_{inf} > 10^{16}$ GeV and dark matter axion masses are too high to be seen by ADMX-G2.

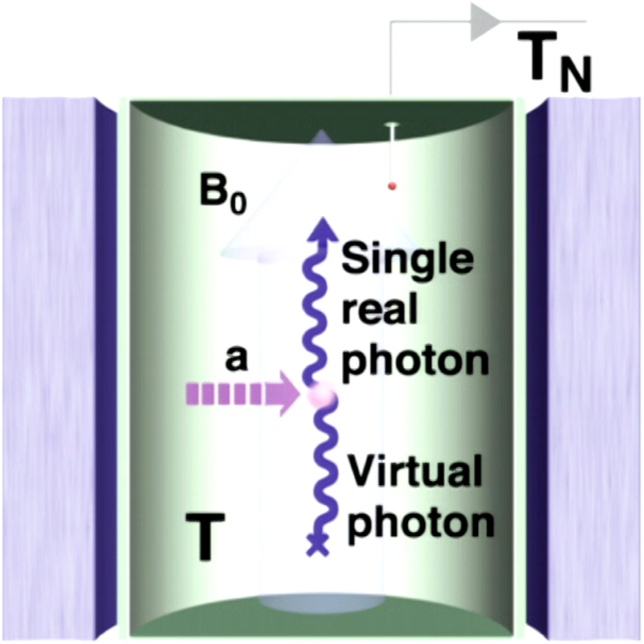
→ **Lower mass axion searches can probe low scale inflation!**

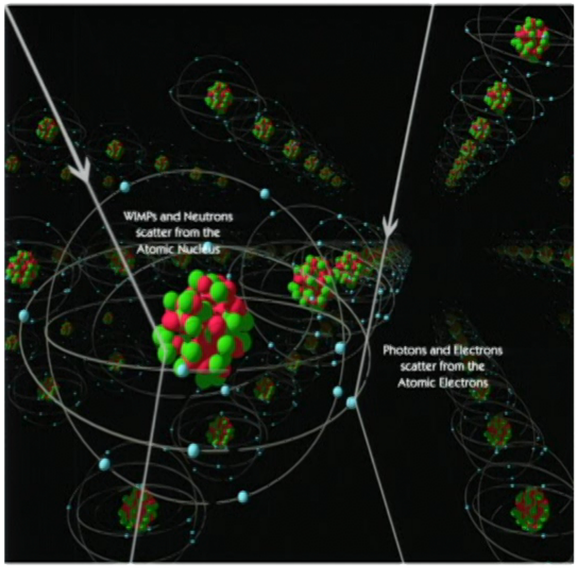
A future axion experiment should focus on higher mass to study the same class of "simple" inflationary models using an independent probe



What prevents us from immediately going to higher frequencies?

Axions vs WIMPs 1 :
Axions are wimpier than WIMPS





Axion scattering rate suppressed by **10^{12} GeV** scale

WIMP-nucleon scattering rate suppressed by **10^{3} GeV** scale.

Axions vs WIMPs 2 :
Mass and number density

Axion mass ≈ 10^{-5} eV

→ density = 10^{16}/liter

WIMP mass ≈ 100 GeV

→ density = 1/liter

Axions vs WIMPs 3 :

As bosonic DM, axions can be described as a classical wave defined by the number density and linewidth

Axion scattering
(classical sine wave)

$$|\ \alpha = \sqrt{10^{26}\ \text{quanta}}\ \rangle$$

This is how you beat the ultraweak coupling!

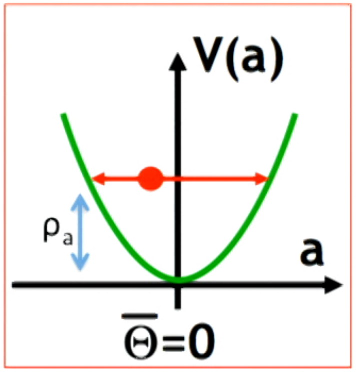
WIMP scattering
(individual quanta)

The correct way to think about the axion DM

Locally coherent oscillation of the QCD θ angle about its CP-conserving minimum:

$$\theta(x,t) = \theta_{\max} e^{i(kx - m_a t)}$$

where
$$\theta_{\max} = \sqrt{\frac{2\rho_a}{\Lambda_{\mathrm{QCD}}^4}} \approx 3.7 \times 10^{-19} \mathrm{radians}$$



Local DM oscillations partially undo the Peccei-Quinn mechanism

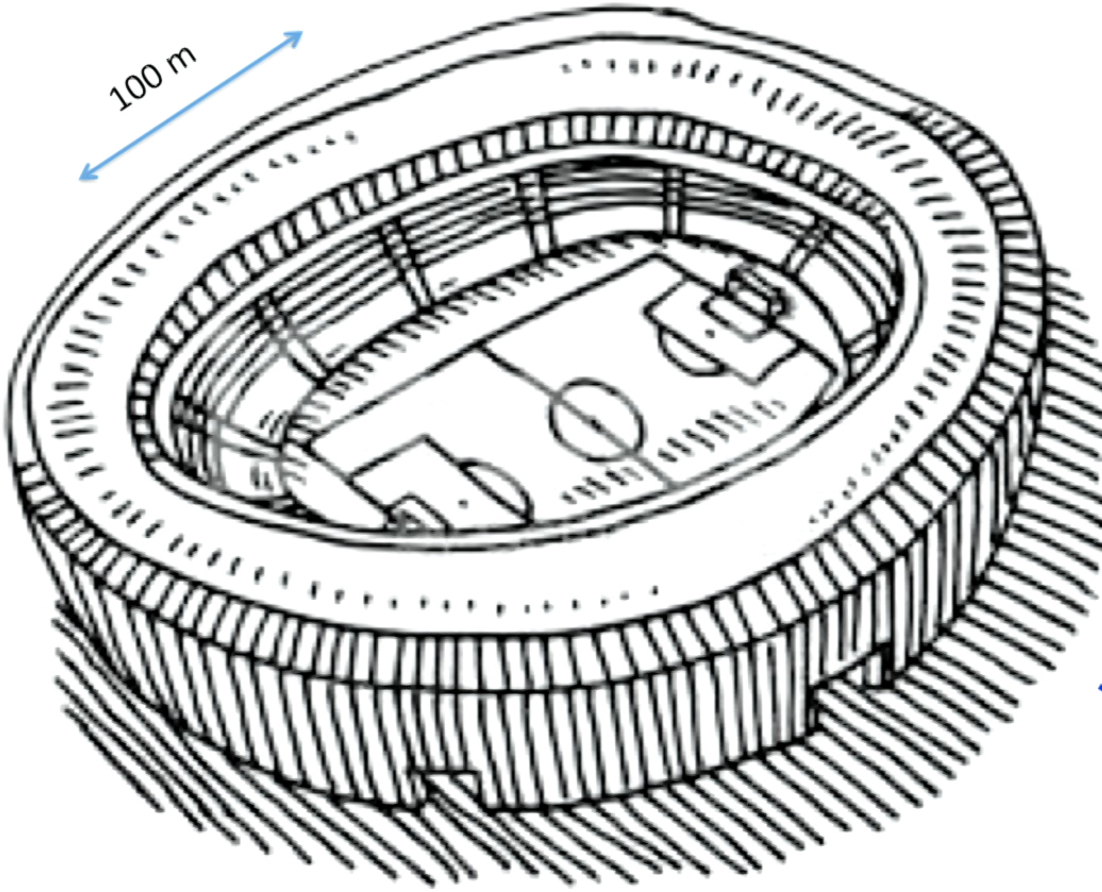
Phenomenology:

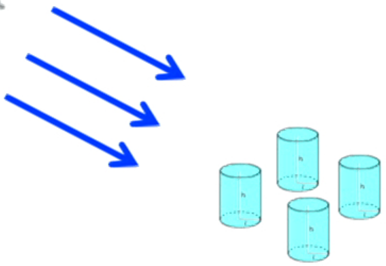
1. Axion-gluon coupling → Oscillating electric dipole moments **(CASPEr-Electric)**
2. Axion-fermion coupling → Axion field gradient gives oscillating local magnetic dipole force **(CASPEr-Wind, QUAX)**
3. Axion-photon coupling + laboratory B field → Oscillating current source

   Use to drive cavity resonator **(ADMX-G2*, HAYSTAC, ORPHEUS)**
   Use to drive LC resonator **(DM Radio, ABRACADABRA, LC Experiment)**
   Use spatial Bragg focusing of radiated power **(MADMAX)**

*Currently operating and taking data with DFSZ coupling sensitivity.

Axions DM is like a stream of gigantic, slow laser pulses



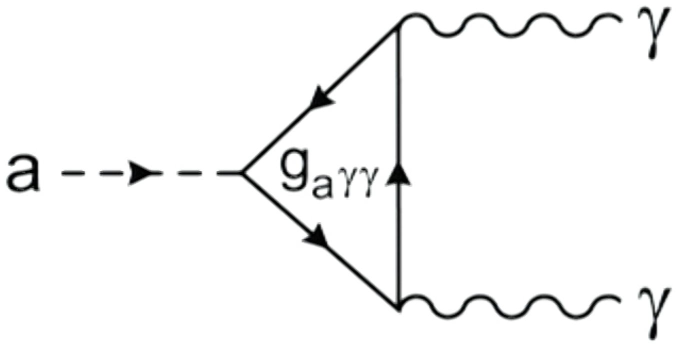


→ Phase coherent signals over 10^{-3} s.

Football stadium-sized clumps of coherently oscillating axions drifting through detectors.

$$\Delta x = 1/\Delta p = 1/m_a \Delta v \approx 100 \text{ m}$$

Search for dark matter via axion-photon coupling induced by loop



$g_{a\gamma\gamma} \approx g\alpha/\pi f_a$ where g is an O(1) model-dependent factor.

Experiments usually designed to reach the more pessimistic Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) axion coupling with g≈1/3

The Sikivie Haloscope technique (1983)

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

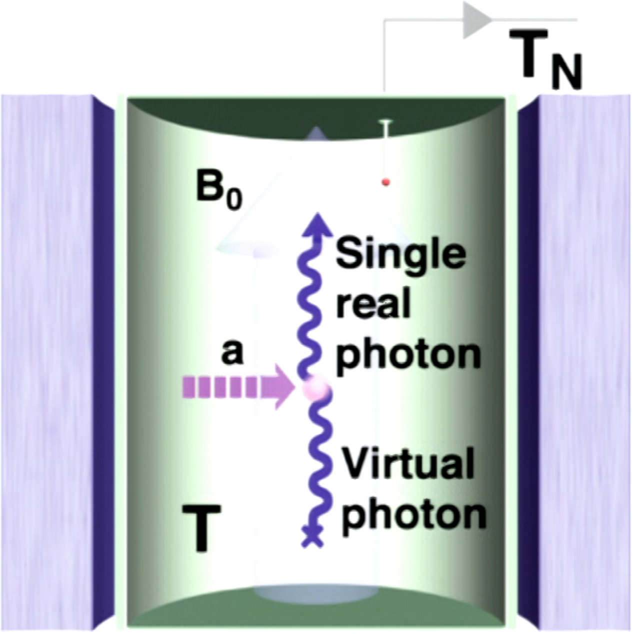
$$\vec{J}_a(t) = -\frac{g\alpha}{\pi}\left(\frac{\sqrt{2\rho_a}}{\Lambda^2_{\mathrm{QCD}}}\right)\vec{B}_0 m_a e^{i m_a t}$$

which drives E&M 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.

*Amplitude is **independent** of f_a



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

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

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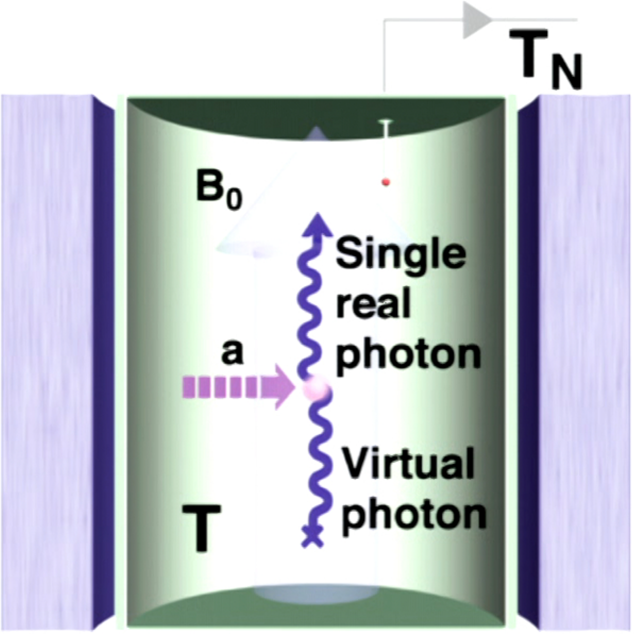

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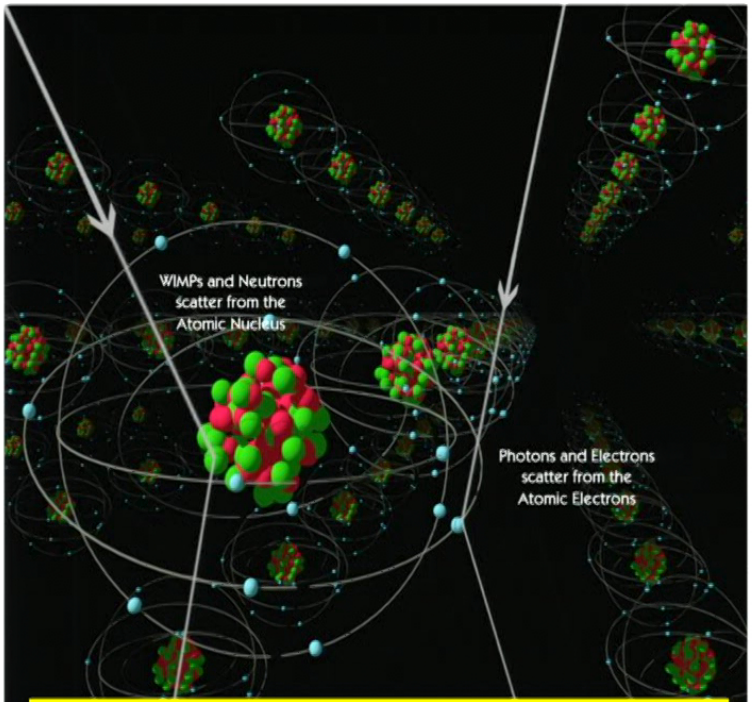
Axions vs WIMPs 4: Resonant power transfer

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

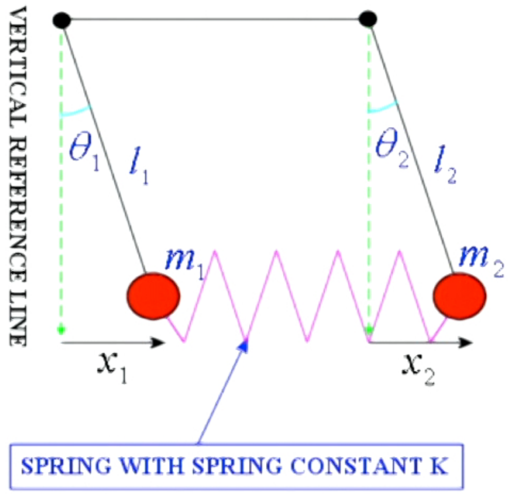
4 μeV mass axions scatter on 50cm size microwave cavities.



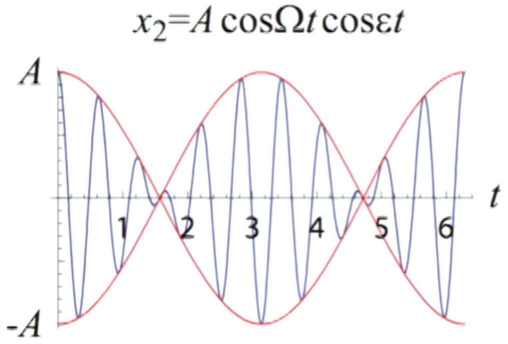
WIMPS scatter on 10 Fermi size atoms

Tune the cavity frequency to match the axion mass.

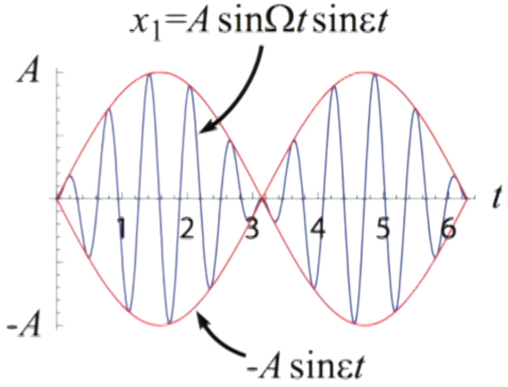
Transfer of energy from the axion DM to the RF cavity is the same as that of a system of two pendula coupled by a weak spring



Axions



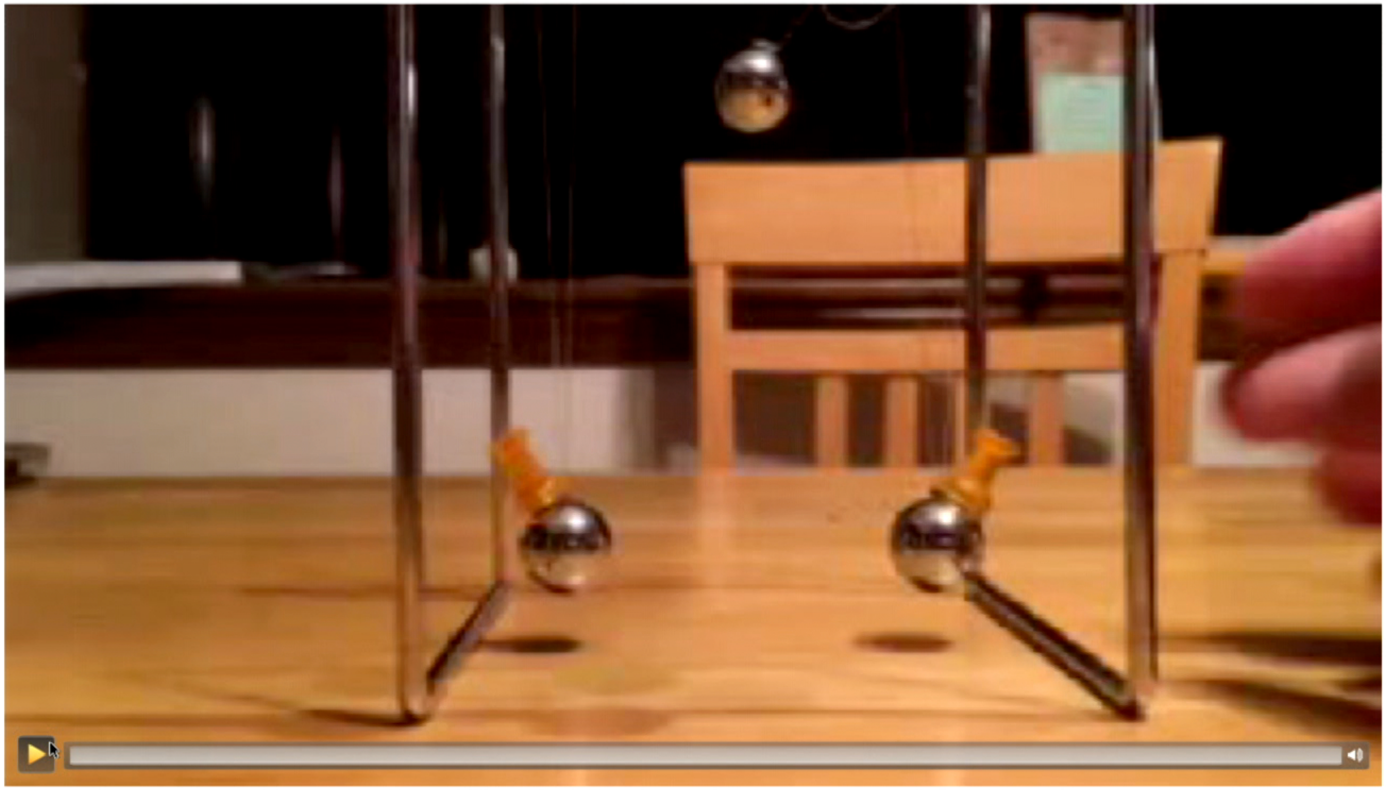
Standing wave photons



Mixing angle=45° on resonance:

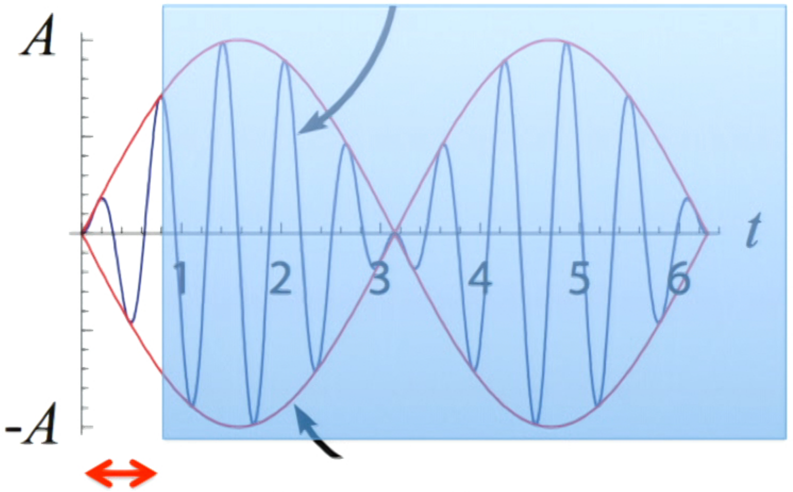
In the limit of infinite coherence time, **all** of the dark matter would be converted into photons. In finite coherence time, only get a few signal photons.

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



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

Achievable $Q_{cav} \approx 10^5$ is smaller than the axion DM $Q_a \approx 10^6$. Neither is large enough to have any significant power transfer.

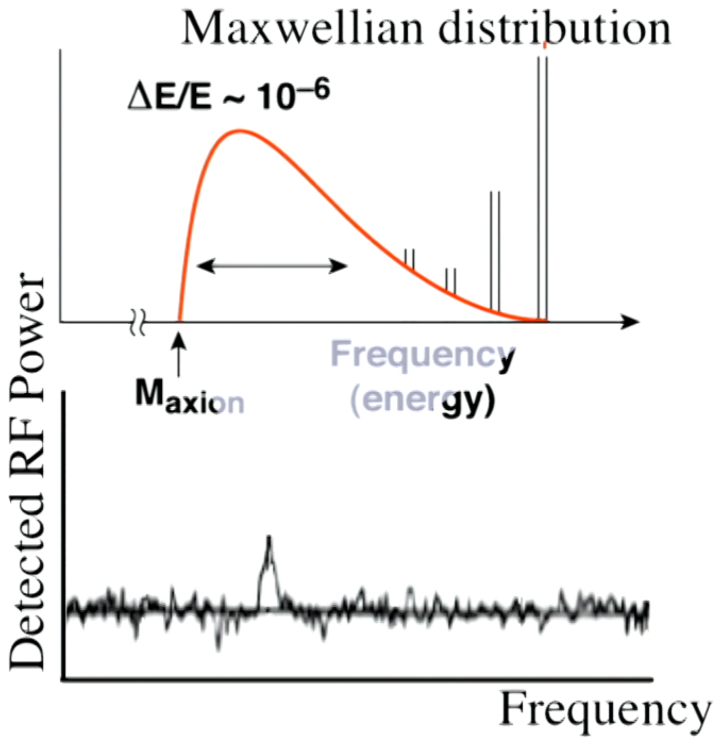
Square the wavefunction → **the accumulated energy scales as $(t_{cav})^2 = Q_{cav}^2 / f^2$.**
This energy is dissipated over lifetime t_{cav}, including into the readout channel
→ **the instantaneous extracted power is linear in Q_{cav}**

The axion wave also has finite coherence time because its linewidth is kinetically broadened by virial velocity

Non-relativistic DM:

Kinetic energy $= \frac{1}{2} m_a v^2$
$\Delta E = m_a v \Delta v$
$E_{rest} = m_a c^2$

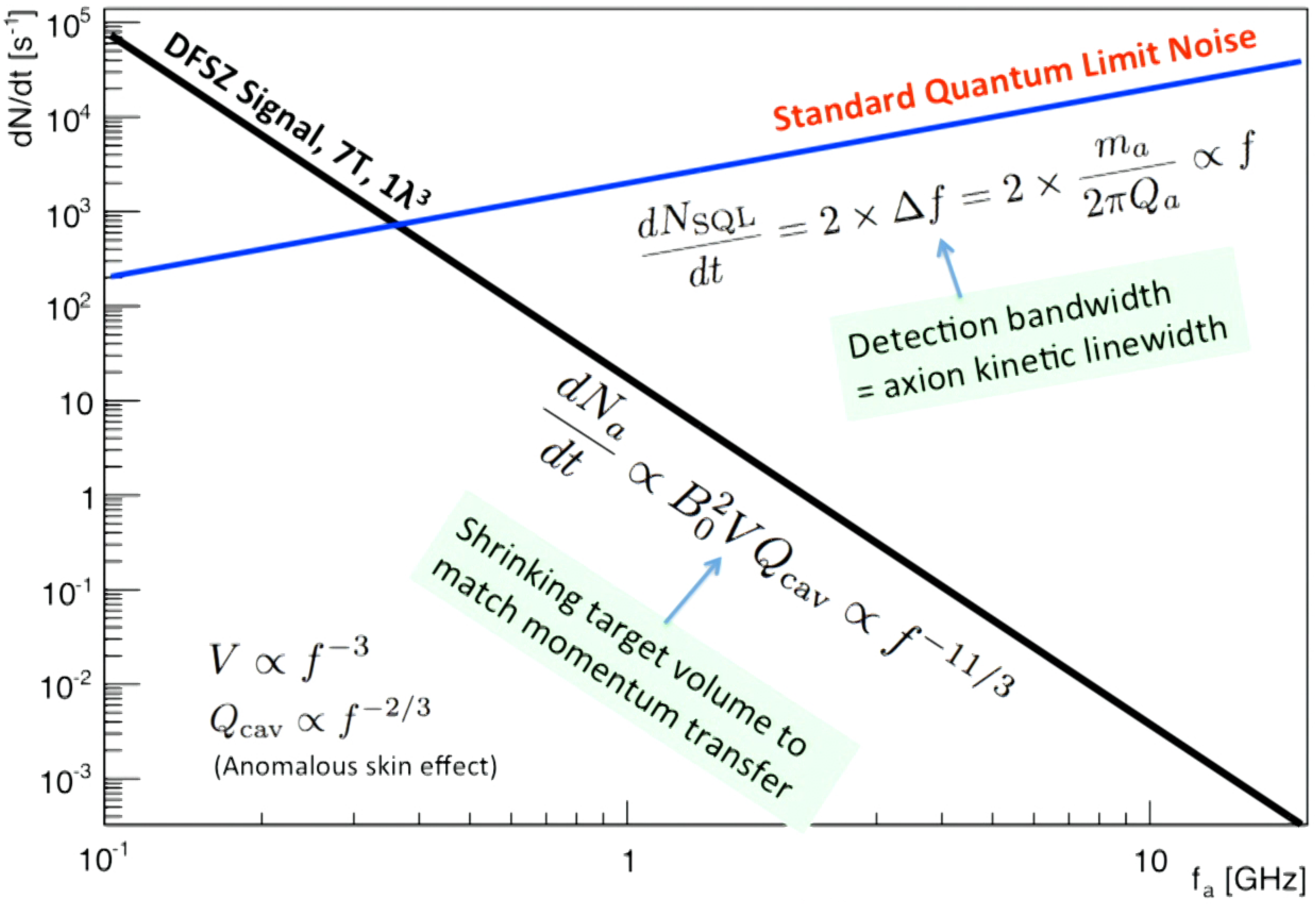
$\Delta E/E = v \Delta v / c^2 \sim 10^{-6}$



Very narrowband line, but can reconfirm signal in minutes once found.

Like J/Ψ scan: most of search time spent slowly stepping through frequency space, one frequency tuning at a time.

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



$$\frac{dN_{\mathrm{SQL}}}{dt} = 2 \times \Delta f = 2 \times \frac{m_a}{2\pi Q_a} \propto f$$

Detection bandwidth = axion kinetic linewidth

$$\frac{dN_a}{dt} \propto B_0^2 V Q_{\mathrm{cav}} \propto f^{-11/3}$$

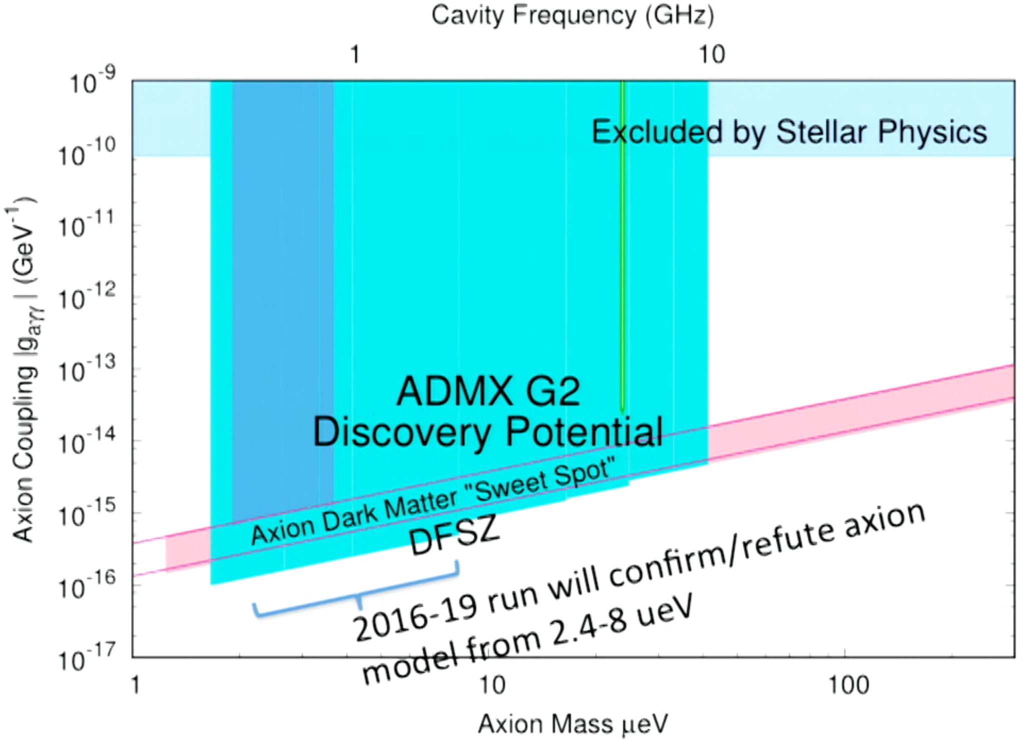
Shrinking target volume to match momentum transfer

$$V \propto f^{-3}$$

$$Q_{\mathrm{cav}} \propto f^{-2/3}$$

(Anomalous skin effect)

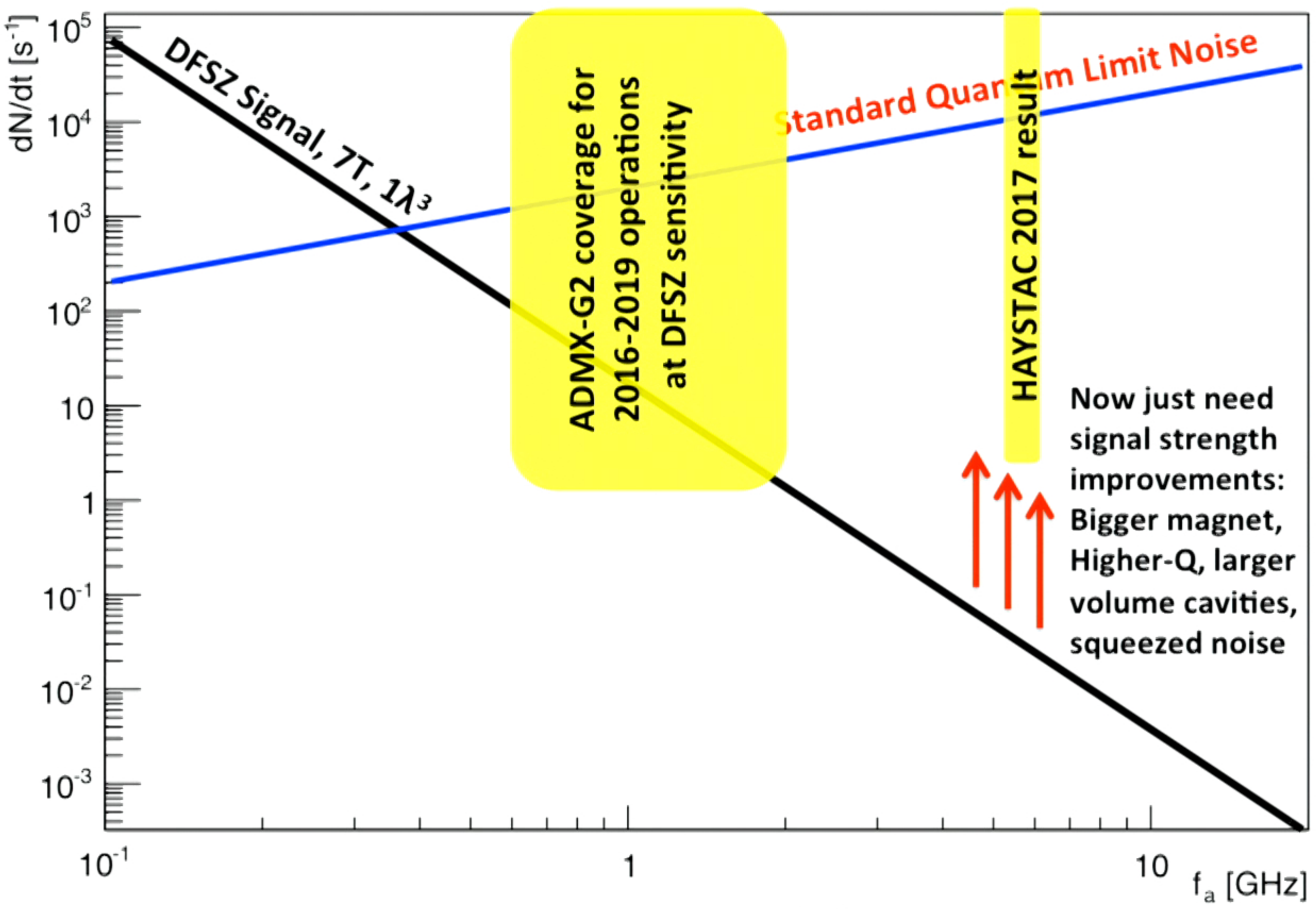
ADMX-G2 – the world's lowest noise radio: 90%CL sensitivity projection using new quantum-limited SQUID amplifiers



Signal Power=10^{-23} W

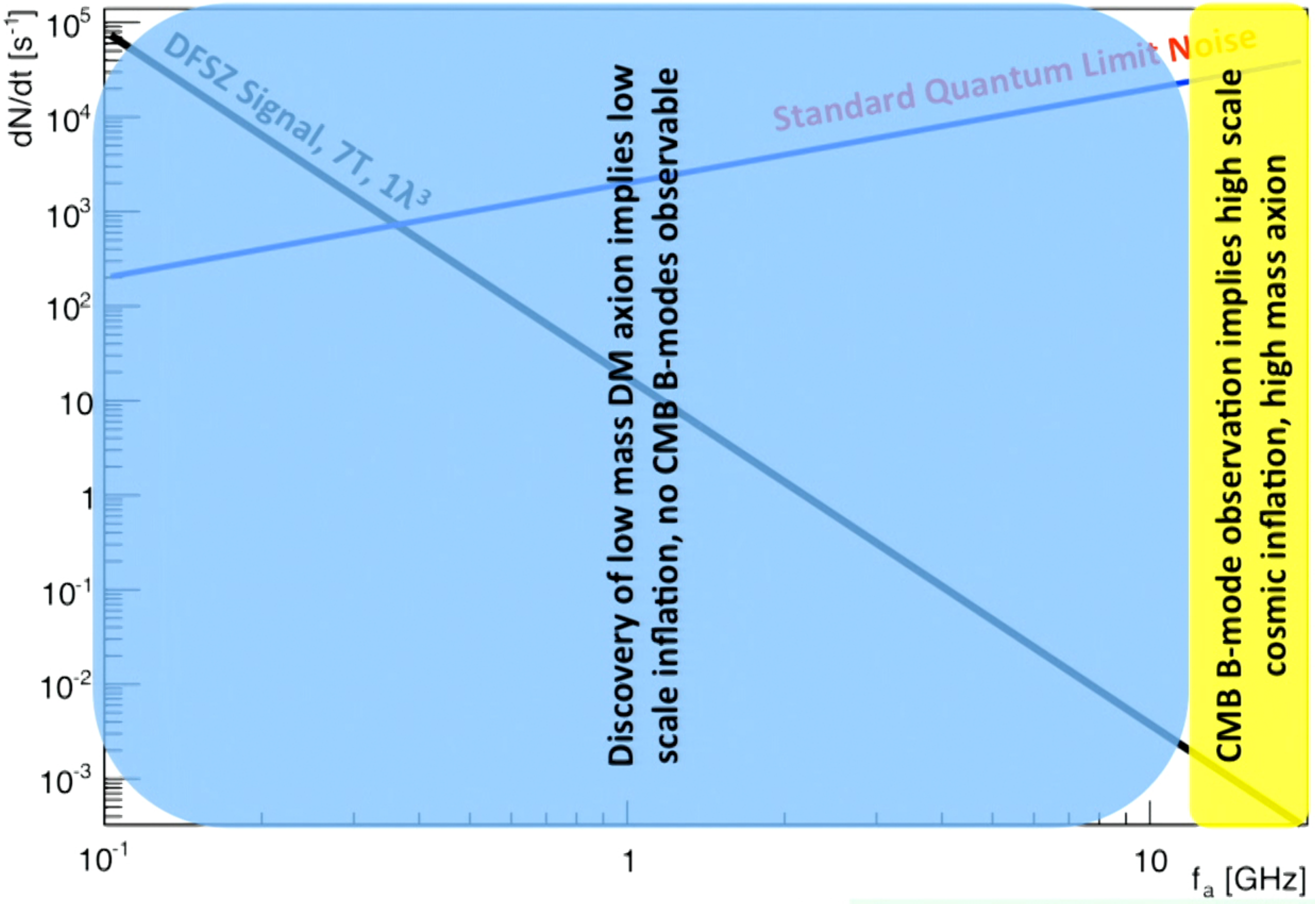
U.S. DEPARTMENT OF ENERGY | Office of Science

Microwave cavity experiments with nearly **quantum-limited** readout



Now just need signal strength improvements: Bigger magnet, Higher-Q, larger volume cavities, squeezed noise

Current DM Axion searches and CMB B-modes can falsify each other



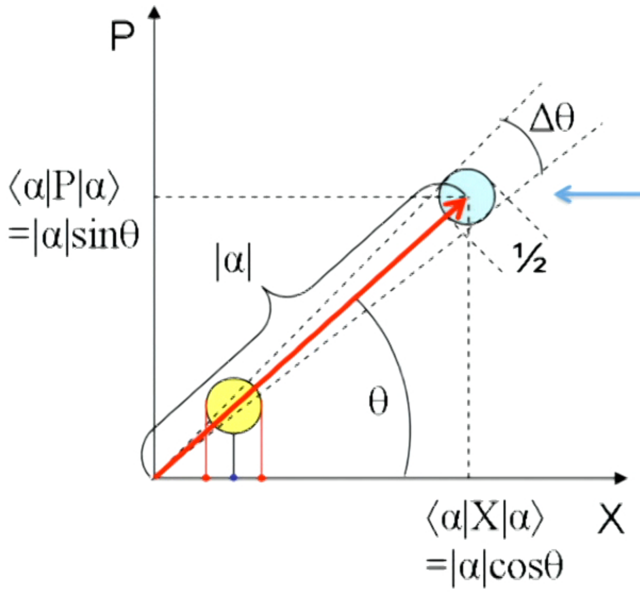
Discovery of low mass DM axion implies low scale inflation, no CMB B-modes observable

CMB B-mode observation implies high scale cosmic inflation, high mass axion

Aaron S. Chou, PI Seminar 5/30/1

How to reach higher axion mass???

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)

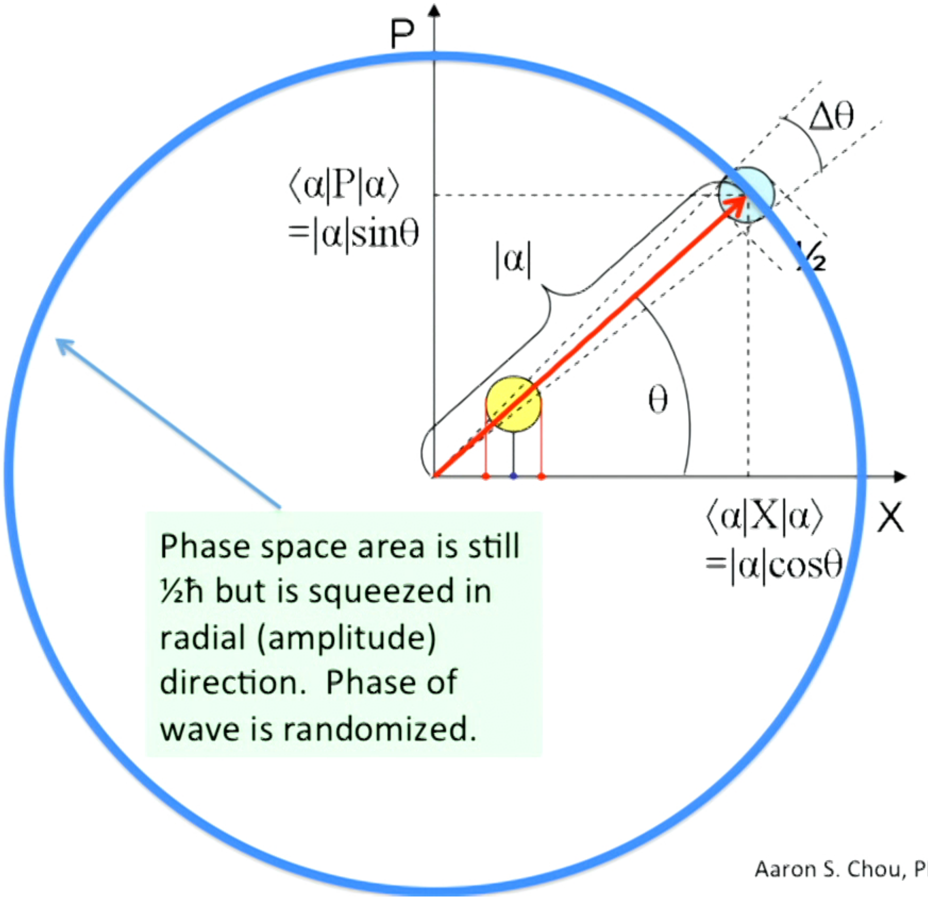
Thermal noise = kT of energy per resolved mode

→ **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.



Phase space area is still ½ħ but is squeezed in radial (amplitude) direction. Phase of wave is randomized.

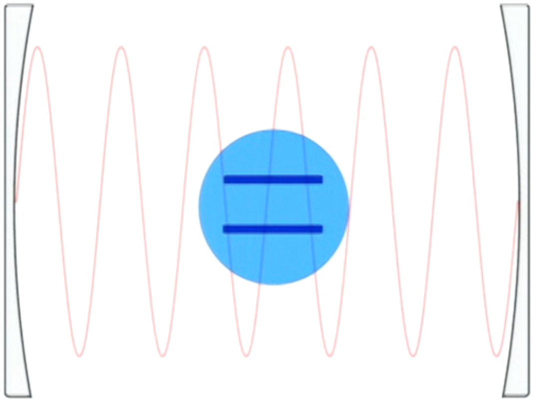
Demonstrated with Rydberg atoms, (Haroche/Wineland Nobel Prize 2012)

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

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

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

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

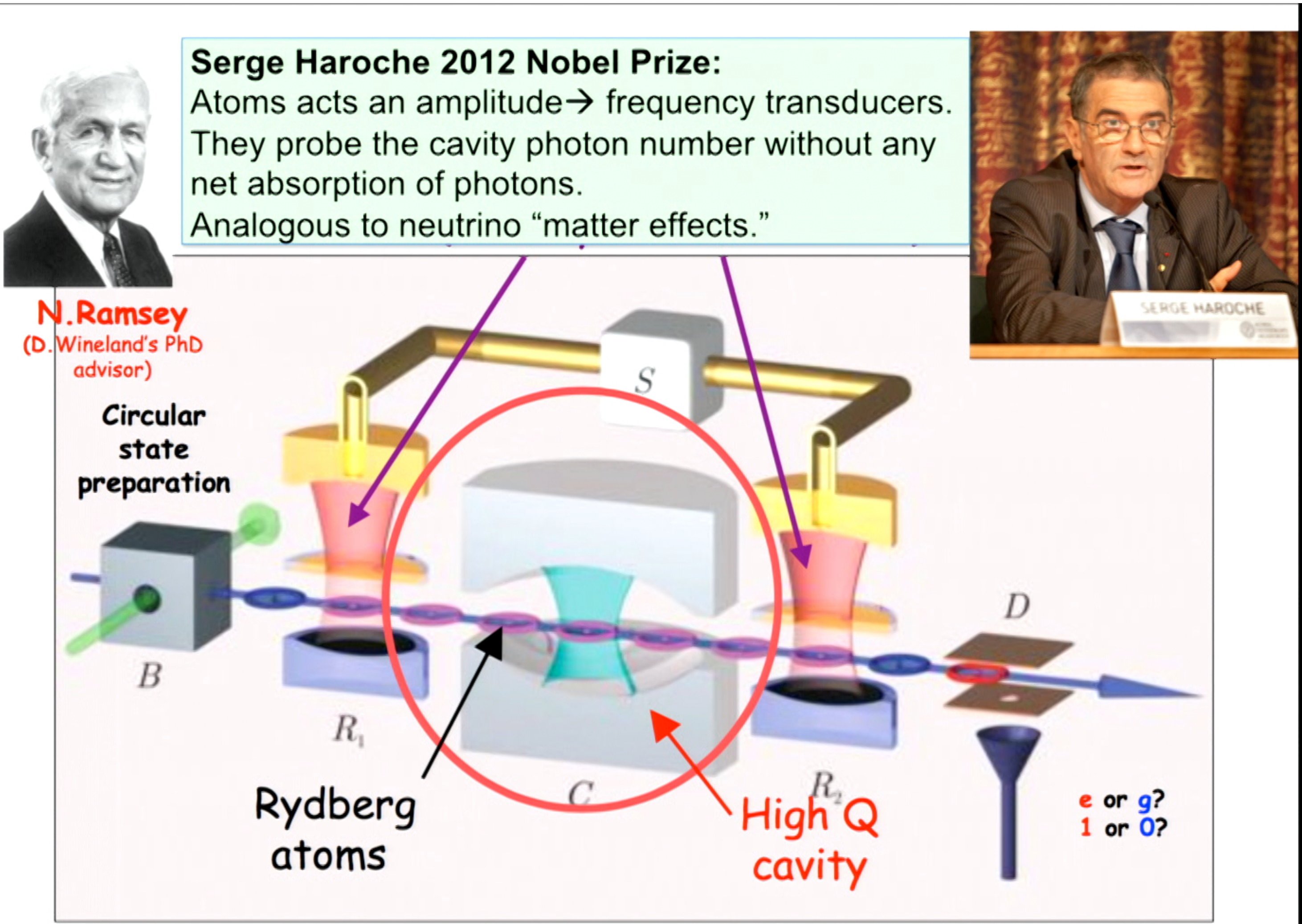


2-level atom
Fermionic oscillator,
Number operator = σ_z

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

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

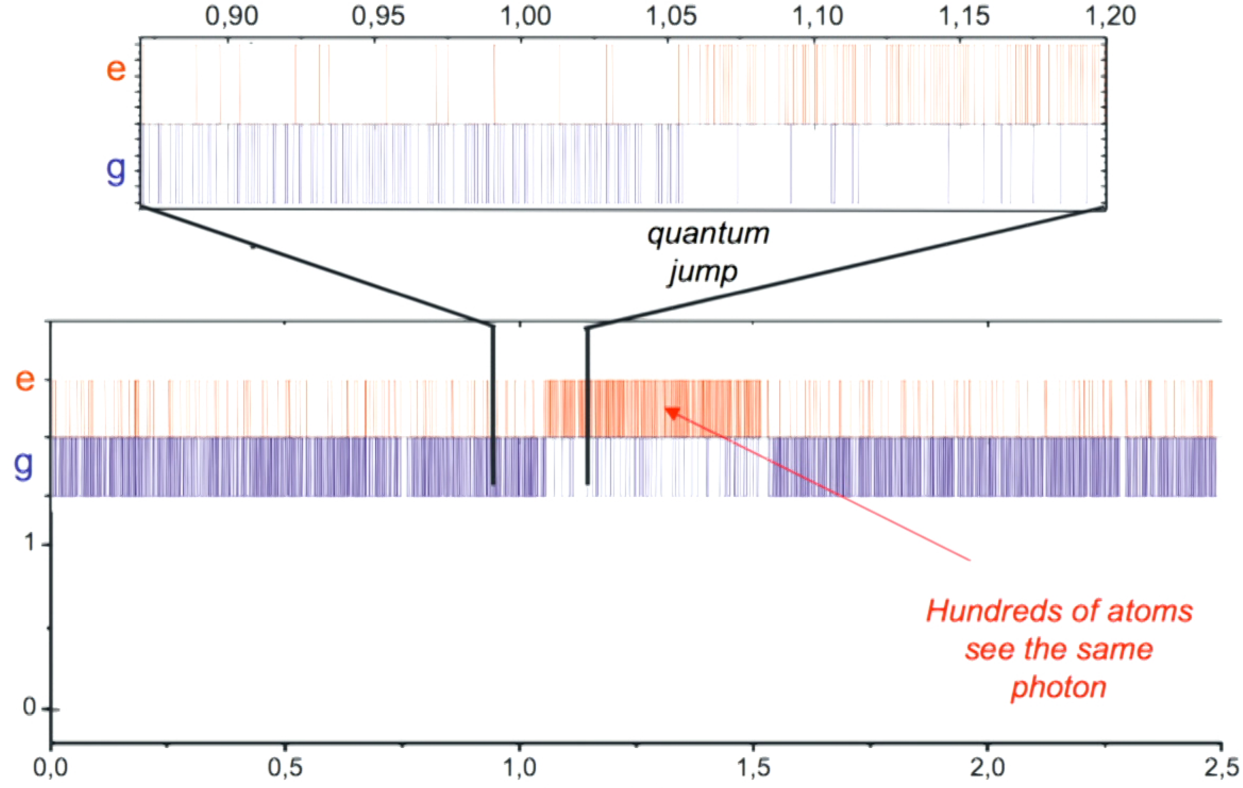
The atom frequency depends on the cavity resonator's occupation number!
This product of number operators commutes with H and allows QND measurement.



Serge Haroche 2012 Nobel Prize:
Atoms acts an amplitude→ frequency transducers.
They probe the cavity photon number without any net absorption of photons.
Analogous to neutrino “matter effects.”

An atomic clock delayed by photons trapped inside

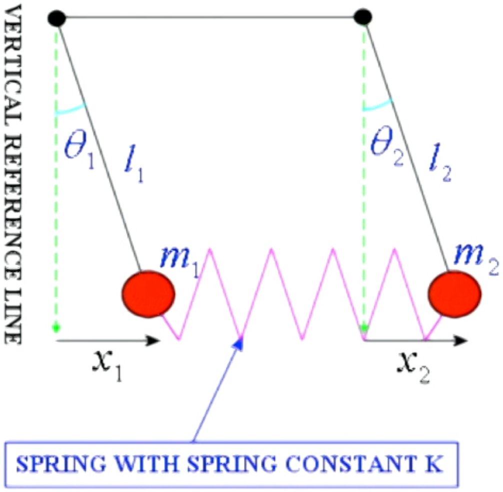
Birth, life and death of a photon



Hundreds of atoms see the same photon

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

Coupled oscillators



Energy stored in the spring

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

Mixing angle to diagonalize:

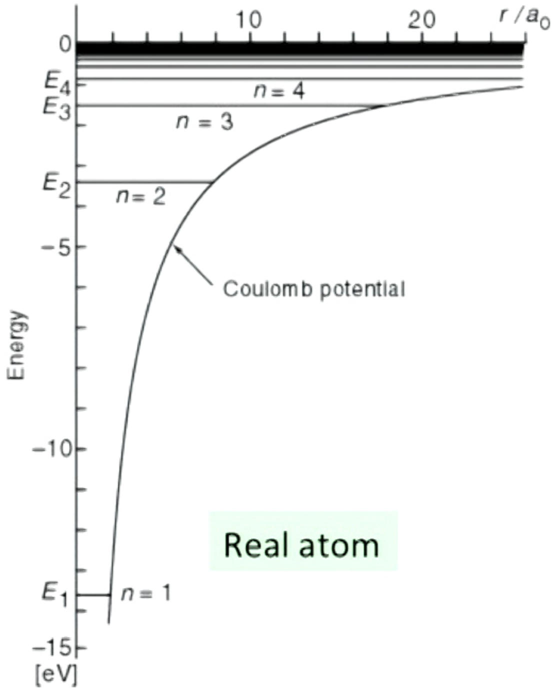
$$\tan 2\theta = 2g/(\omega_1 - \omega_2)$$

Normal mode frequencies for small g

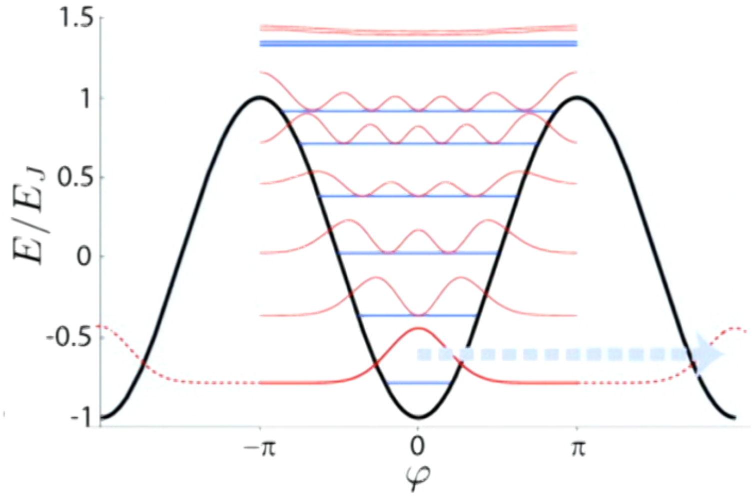
$$\tilde{\omega}_1 = \omega_1 + \frac{2g^2}{\omega_1 - \omega_2}$$

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

Any anharmonic oscillator exhibits 2-level system behavior and acts as an artificial atom



Real atom



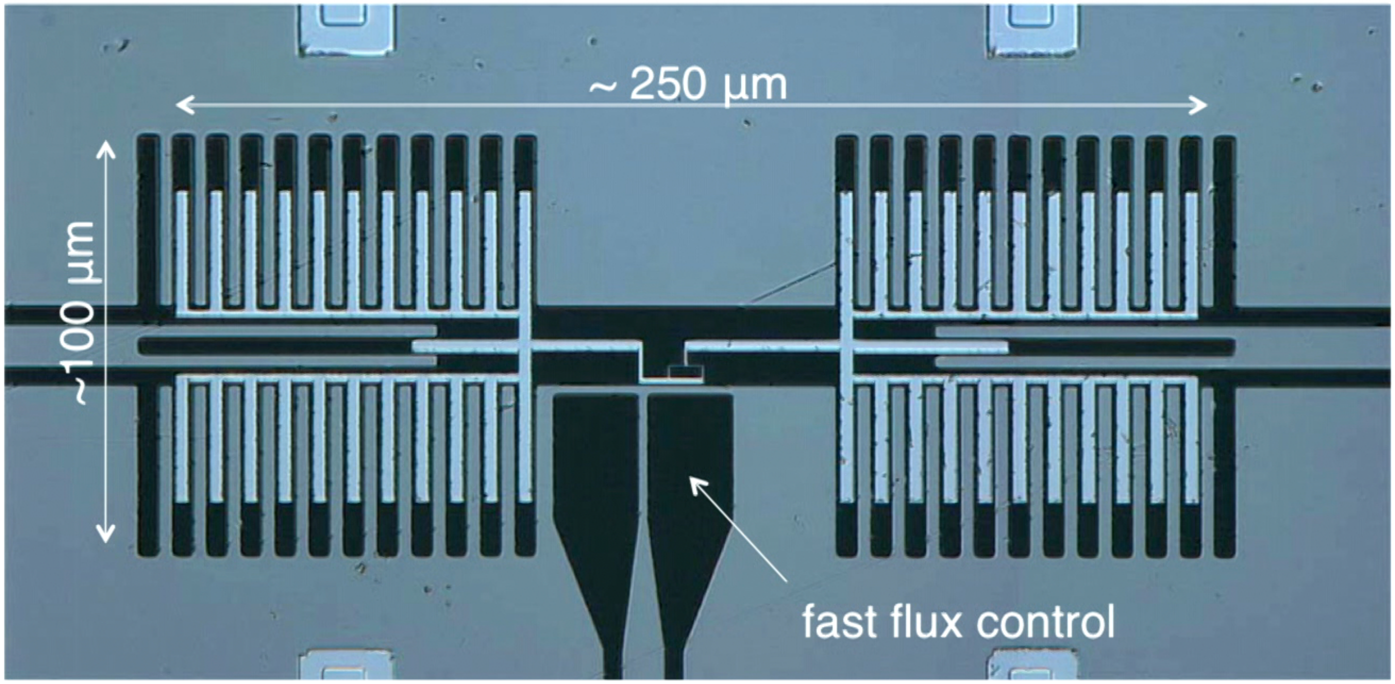
Artificial atom (Josephson junction oscillator)

Both have non-degenerate energy level spacings.
When restricting probes to a constrained range of frequencies, each acts as a 2-level system with anti-commuting, fermionic creation/annihilation operators.

Use solid-state superconducting qubits as "artificial atom" photon detectors

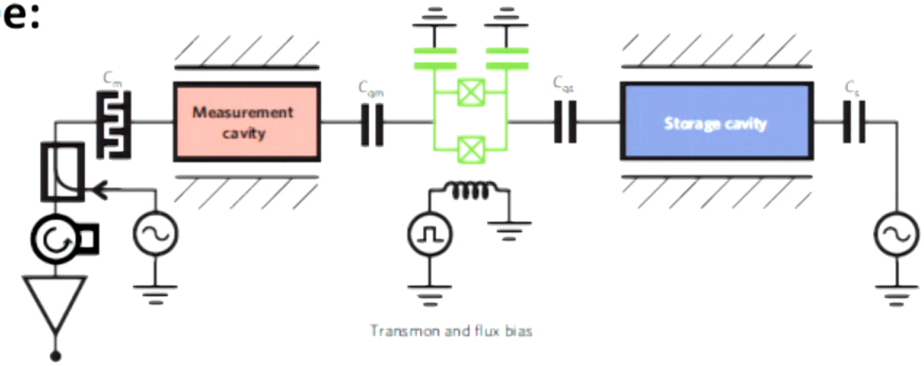
Just like real atoms, qubits are 2-level systems storing either 0 or 1.
These anharmonic oscillators are implemented using various techniques.

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

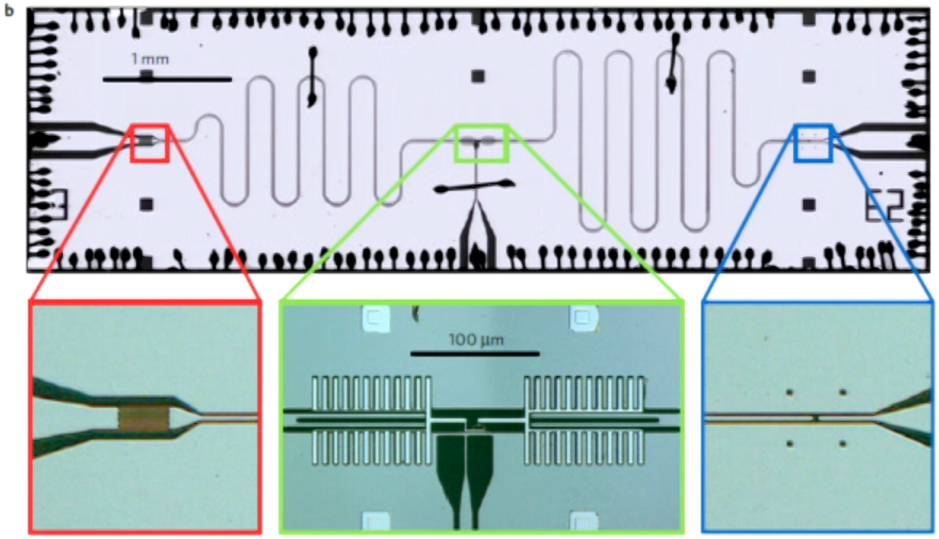


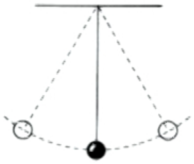
Couple non-linear qubit oscillator to linear cavity oscillator

2D example:



Qubit frequency shifts in response to cavity oscillator amplitude.

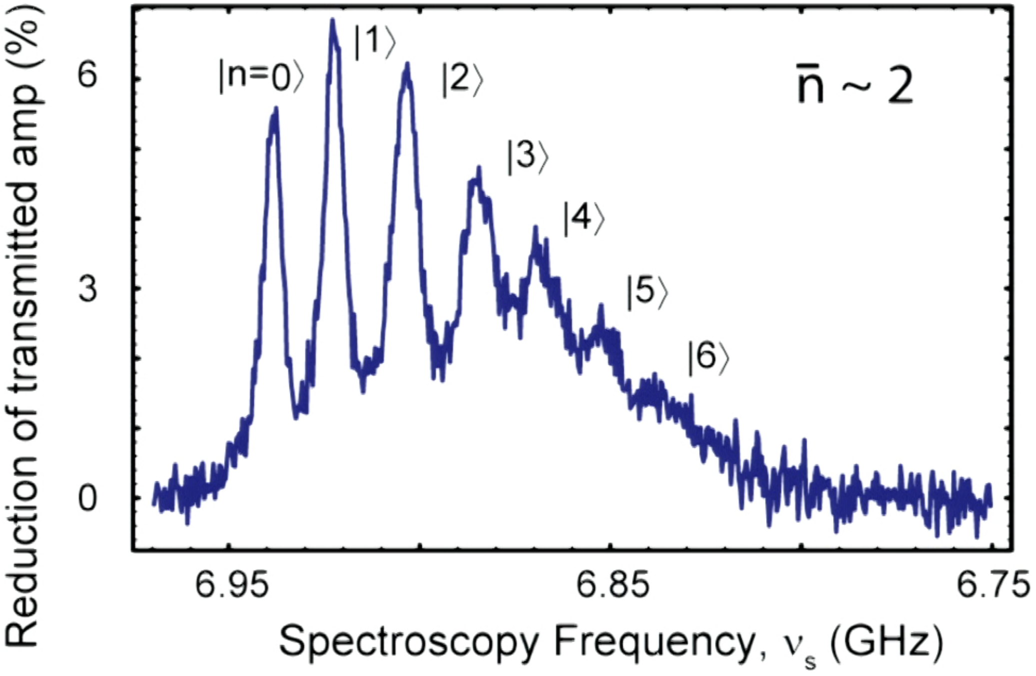




Axion DM

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

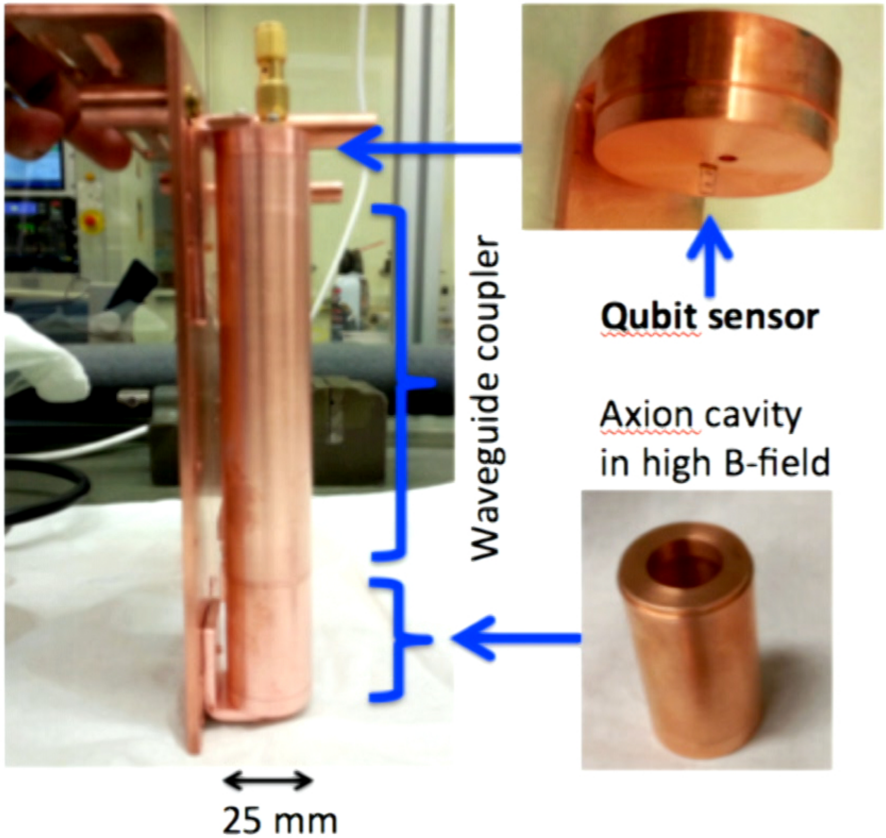
- Just like matter-effects in neutrino oscillations, large detuning from qubit resonance prevents destructive absorption of photons.

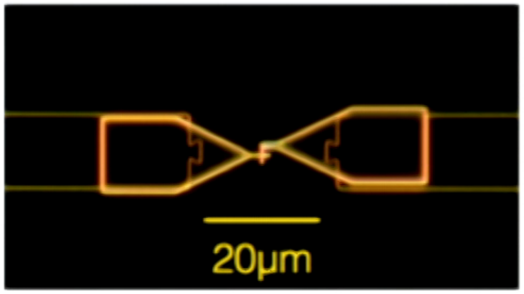
Theory: J. Gambetta, A. Blais, …, S. Girvin, and R. J. Schoelkopf, *PRA 94 123602 (2005)*

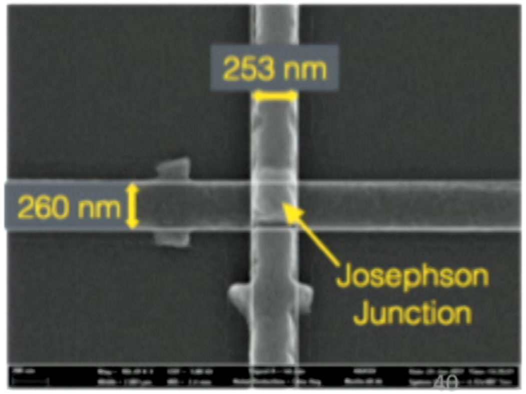
Experiment: D. I. Schuster, … , S. M. Girvin, R. J. Schoelkopf, Nature (London) **445** 515 (2007)

3D Qubit-based detector prototype

AC, Akash Dixit, D.Schuster (U.Chicago)

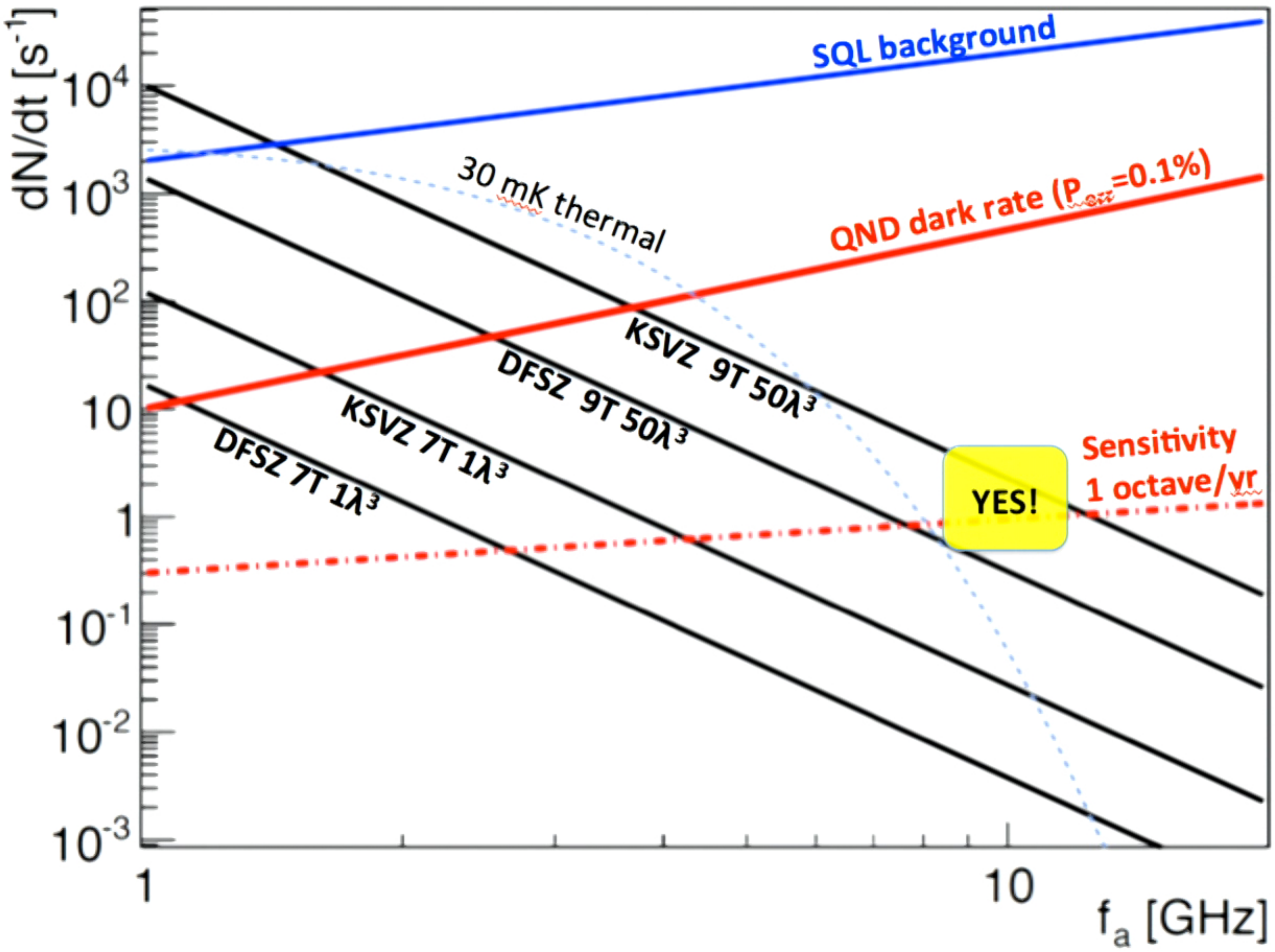




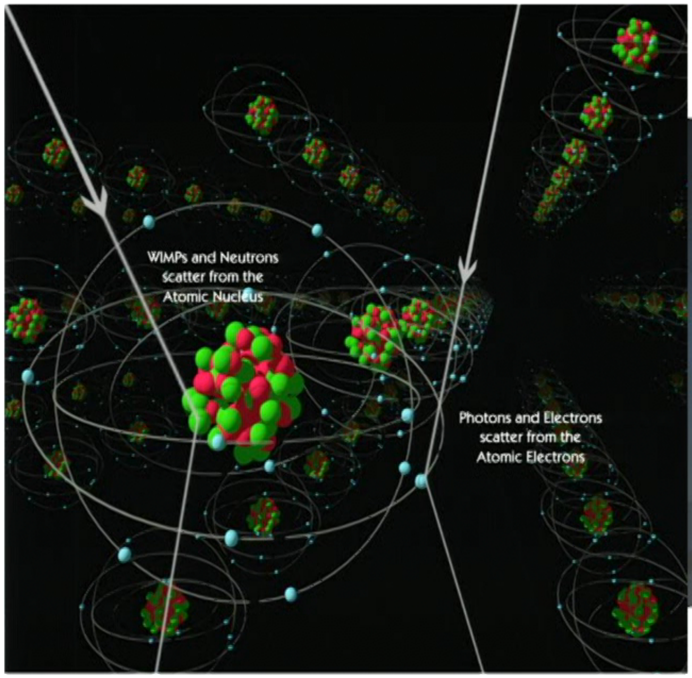


R&D supported by Heising-Simons Foundation.

Projected improvements from qubit QND sensor, higher B field, larger combined cavity volume



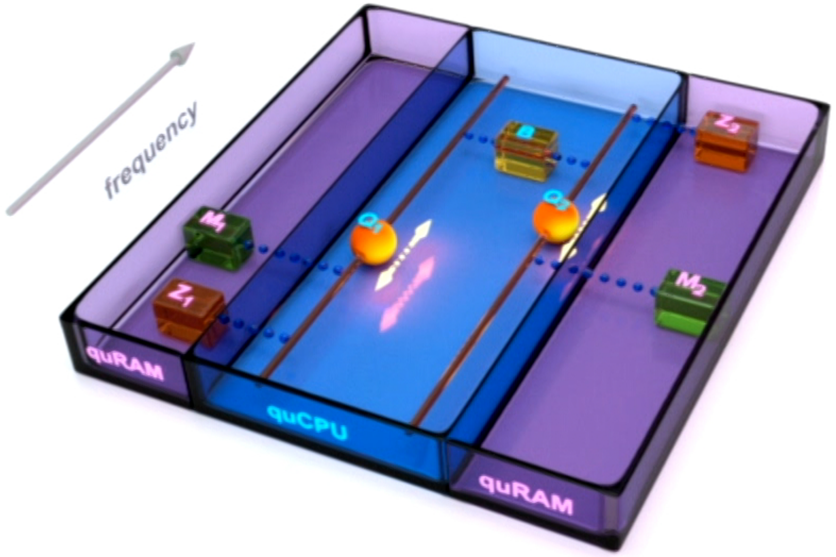
Ideally we would like our axion detector to be a highly multiplexed array of scattering targets just like the semiconductor crystals used in WIMP experiments



Need large volume but also high frequency
→ multi-cell array of resonators

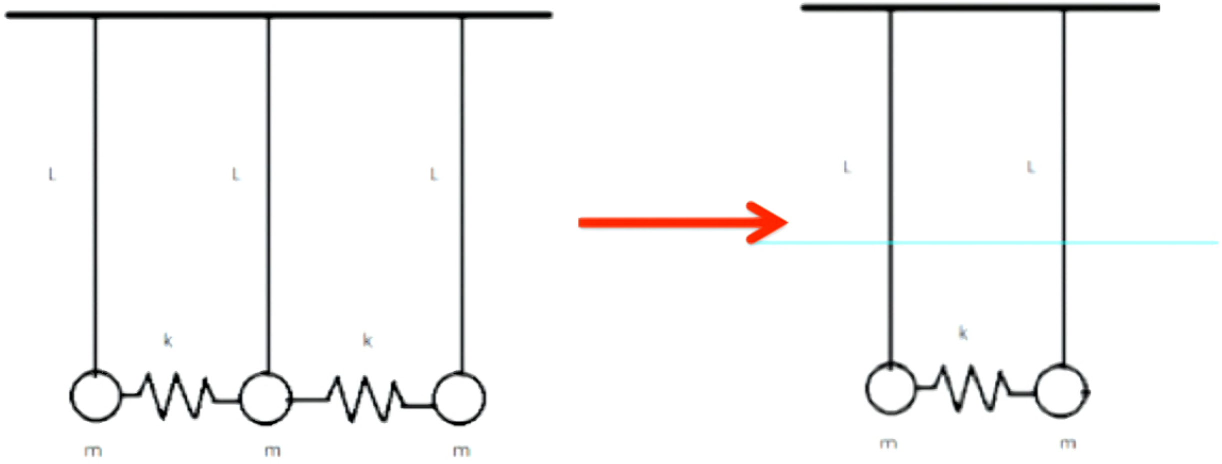
How do we make such a 3-dimensional metamaterial for use in axion detection?

A quantum computer needs a qubits, a quantum bus, and readout plumbing … just like an axion detector



Mariantoni, Martinis, Cleland (2011)
quRAM made of cavities,
Qubits extract information by adiabatic level crossing

Can we make an axion detector directly from qubits and skip the microwave cavity?



Axion
$\alpha=10^{13}$

Cavity
$\alpha=1$

Qubit
$\alpha=0$

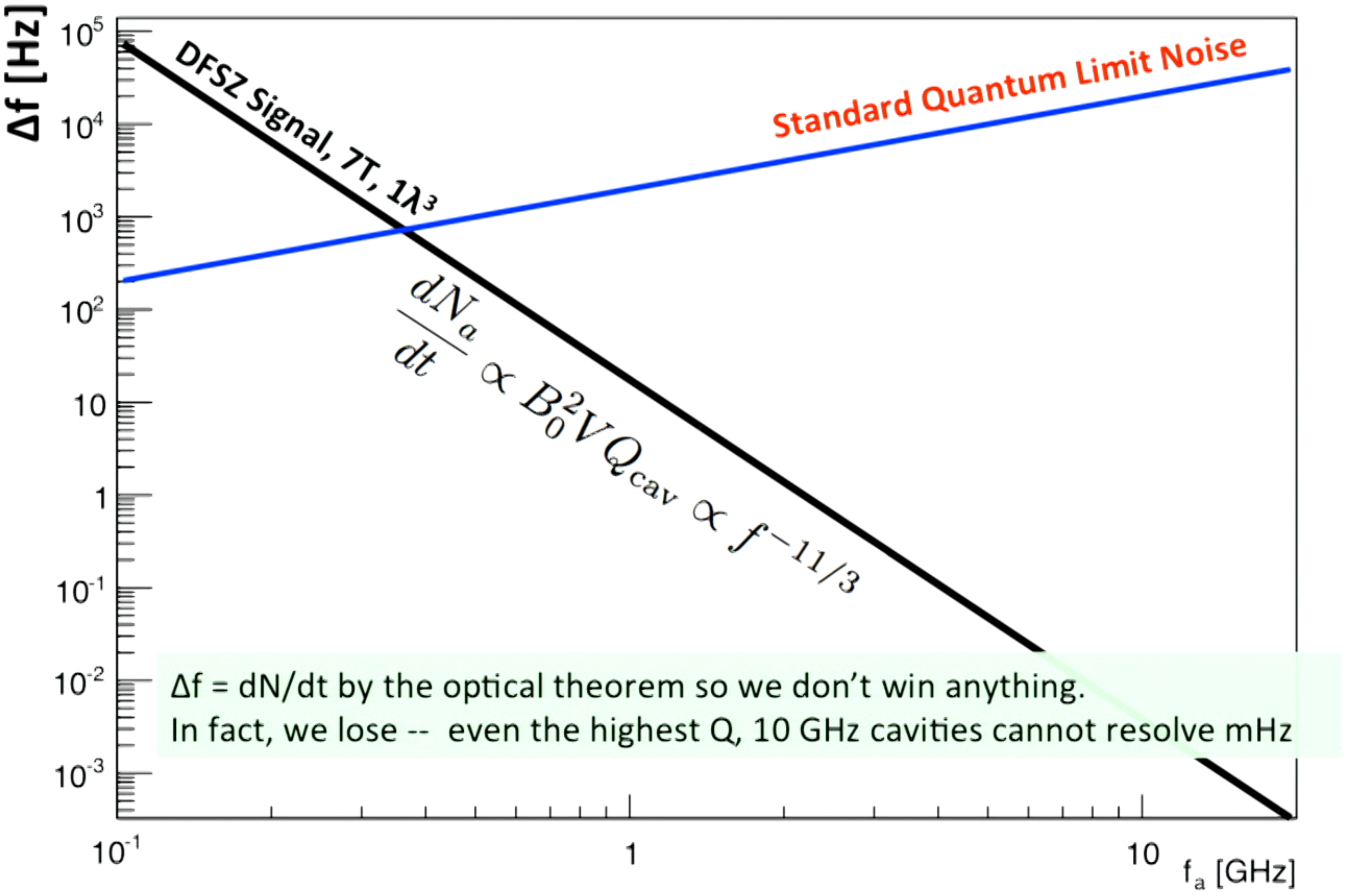
Axion
$\alpha=10^{13}$

Qubit
$\alpha=0$, **$\Delta f \neq 0$**

Qubit is capacitively coupled to the high occupation number θ-oscillation*.
Can we see the frequency shift of a frequency-detuned qubit, thus performing a QND measurement of the axion wave?

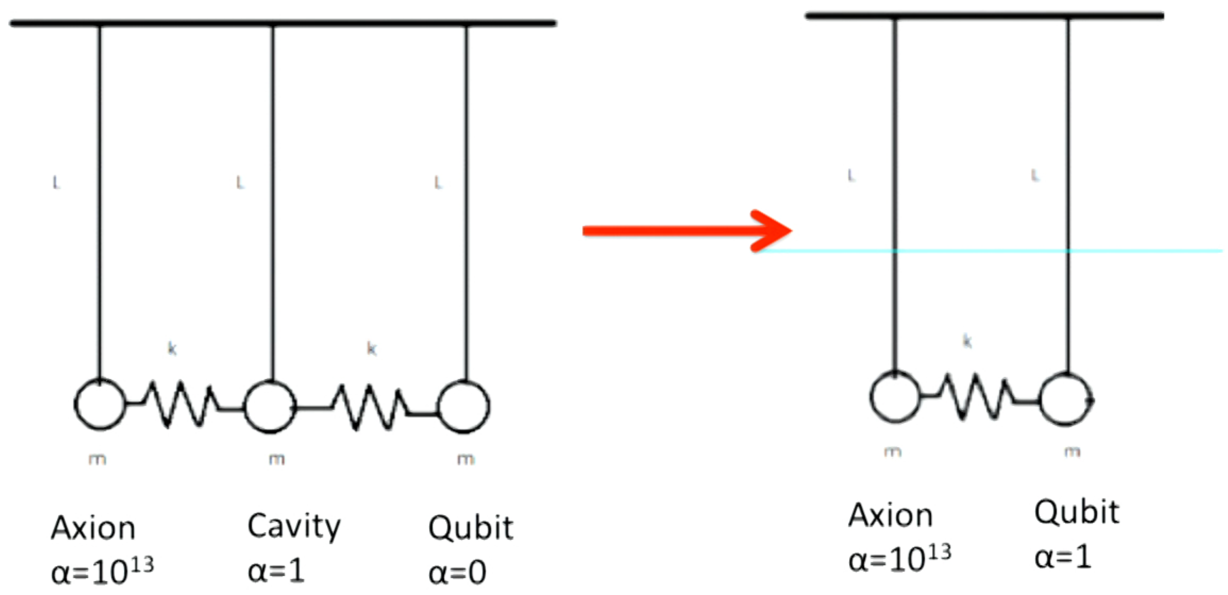
***Not** Christian Beck's model which assumes an (unrealistic) infinitely stiff spring.

DFSZ axion-induced frequency shift for single volume≈λ^3 qubit, detuned by 1 linewidth



Δf = dN/dt by the optical theorem so we don't win anything.
In fact, we lose -- even the highest Q, 10 GHz cavities cannot resolve mHz

Instead, tune qubit frequency to axion mass and look for resonant conversion



If qubit absorbs a quantum, then its readout frequencies will shift.
Could this be the source of mysterious athermal qubit errors
– qubits inexplicably found to be spontaneously in the e state rather than the g state?

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By Magdalena Petrova

Video Correspondent, IDG News Service | FEB 17, 2017 10:17 AM PT

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Can the Internet Survive A Cosmic Ray?

Stephen Liu - January 27, 2012 - 3 Comments

Aaron S. Chou, PI Seminar 5/30/17

Take-aways

- Axion physics is fun!
- ADMX-G2 is the first haloscope experiment to reach DFSZ sensitivity and will definitively confirm or refute the QCD axion model from 600 MHz-2 GHz in the next 3 years -- Plans underway to go to 10 GHz
- Axion scientists are using state-of-the-art quantum electronics:
  - ADMX-G2 and HAYSTAC have both demonstrated near quantum-limited readout with SQUID, Josephson parametric amplifier
  - Just need more cavity volume, higher field magnet for f<10 GHz.
  - Quantum zero-point noise is still too high for higher mass axion search
- **Qubit-based single photon sensor can reduce readout noise by orders of magnitude**
- **The technical requirements for quantum computers are nearly identical to those for future high mass axion searches.**