Quantum Computers as Dark Matter Detectors

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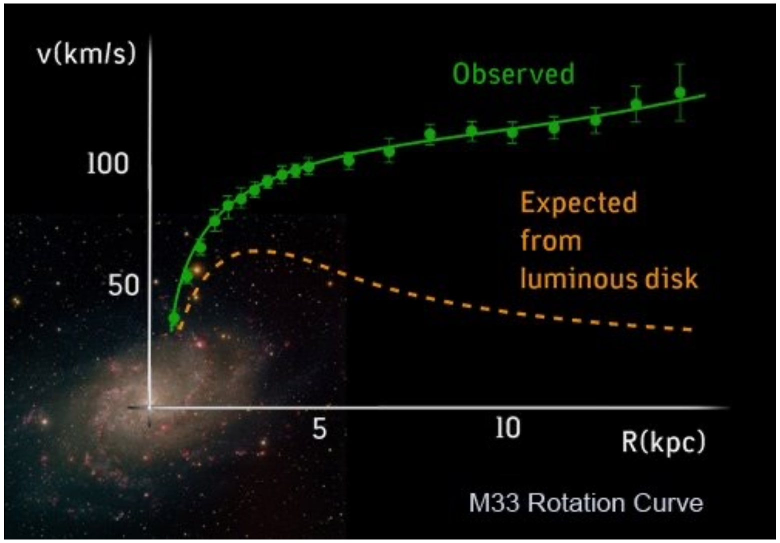
Yale Physics Club
August 29, 2022

Outline:
1) Dark matter overview
2) Measuring tiny forces using qubits as clocks – GHz dark matter
3) Qubits vs broken Cooper pairs – THz dark matter
4) Qubits vs THz dark radiation from a rolling dark energy field
5) Qubits vs Milli-charged dark particles
6) Quantum computers for quantum sensor arrays

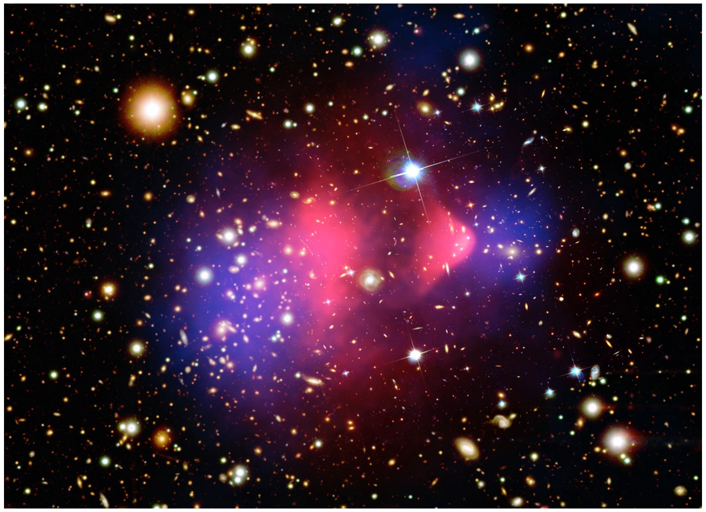
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Most of the matter in the universe is dark matter (Not protons or electrons)

Measured velocity of stars orbiting center of galaxy indicate significant amounts of invisible gravitational mass that **does not have usual electromagnetic interactions**



Size: 1,000,000 light years

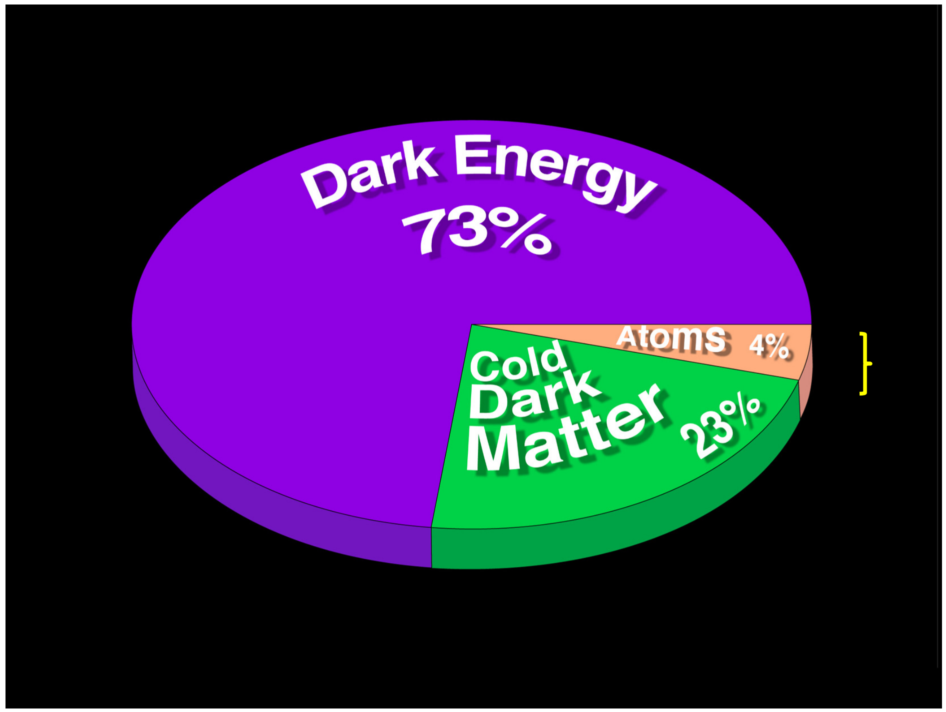


Bullet cluster: Collision of 2 galaxy clusters.

Red = hot X-ray signal from charged particles colliding and stopping

Blue = inferred dark matter mass distribution from gravitational lensing of background galaxies

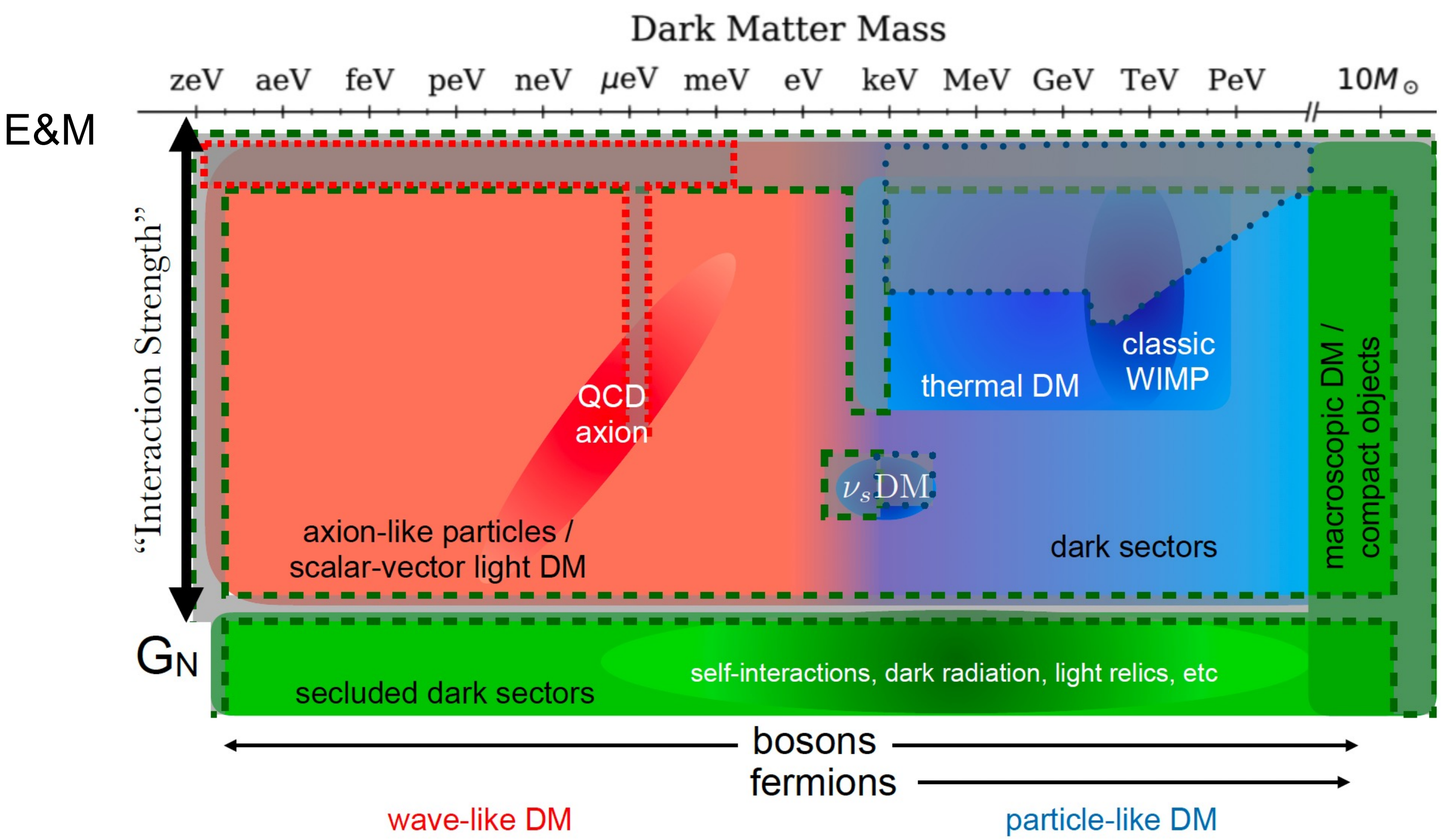
Energy budget of the universe
(from various experimental probes)



Things we design our shielding for

We have *no* idea what is all of this other dark stuff around us.
It has so far been undetectable other than via its gravitational effects.
Prime experimental target for QUANTUM SENSING!

Our current understanding of the dark matter landscape (APS-DPF Snowmass Study, July 2022)



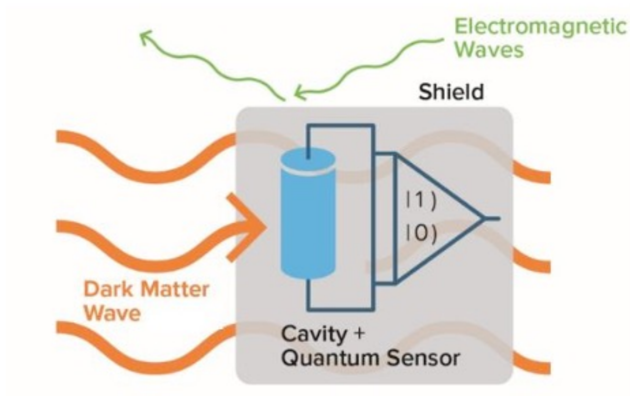
A diverse variety of experimental techniques are proposed to cover every decade of possible dark matter mass.

Dark matter of some sort is probably flying through your lab.

Does it have interactions stronger than gravity???

Hmmm… quantum computing platforms look just like dark matter searches:

DOE-OHEP Basic Research Needs white paper, 2018

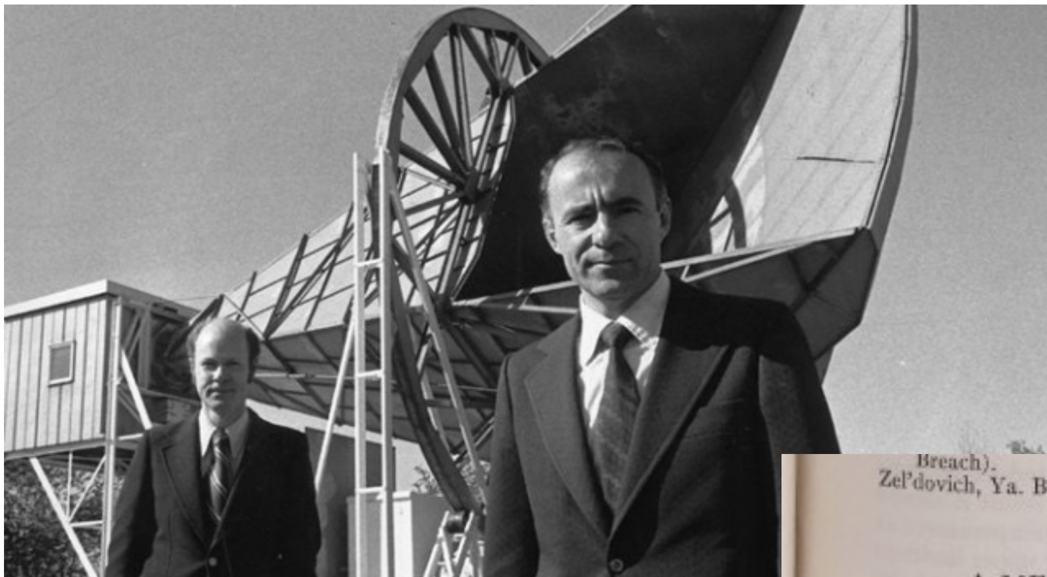


Sensitive single-quantum devices are operated in a cryostat and/or vacuum system and well-shielded from external disturbances (heat, light, sound) in order to maximize their coherence time.

Impossible to shield from the dark matter – the DM interacts so weakly that it flies right through the walls.

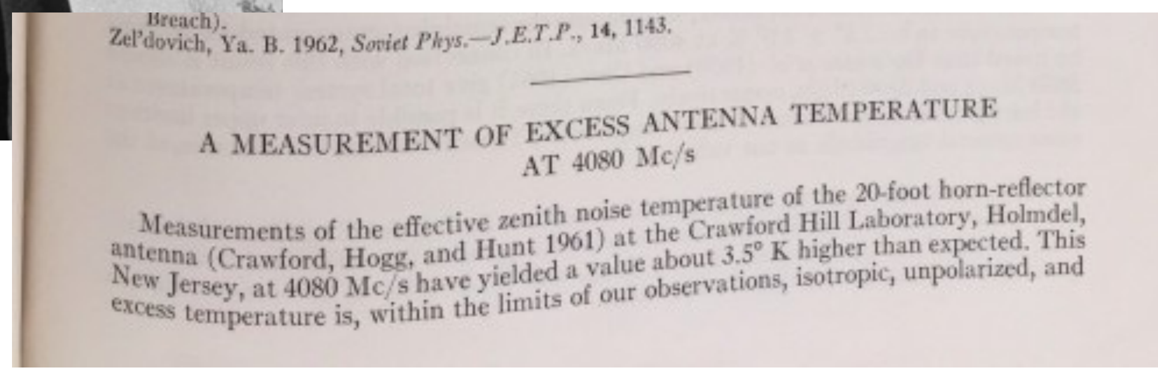
If your quantum computer crashes, it could be due to dark matter!
… but as consolation, you'll get a Nobel prize anyway for the discovery.

Mystery noise in your experimental apparatus is not necessarily mundane



Penzias and Wilson, 1965:
After chasing away nesting birds with a shotgun, discovered the cosmic microwave background

– They had no idea that this was first evidence for the big bang theory
– Nobel Prize, 1978



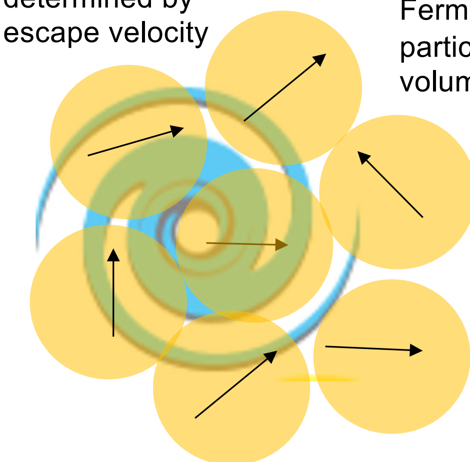
Breach).
Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, 14, 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

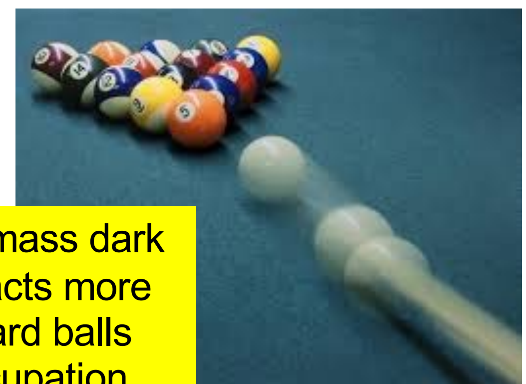
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

Low mass dark matter generically takes the form of classical bosonic sine waves

The smaller the particle mass, the more particles you need to account for the inferred mass density.
For **mass < 70 eV**, Pauli exclusion principle would cause dark matter clumps to swell up to be larger than the size of the smallest dwarf galaxies. (Randall, Scholtz, Unwin 2017)



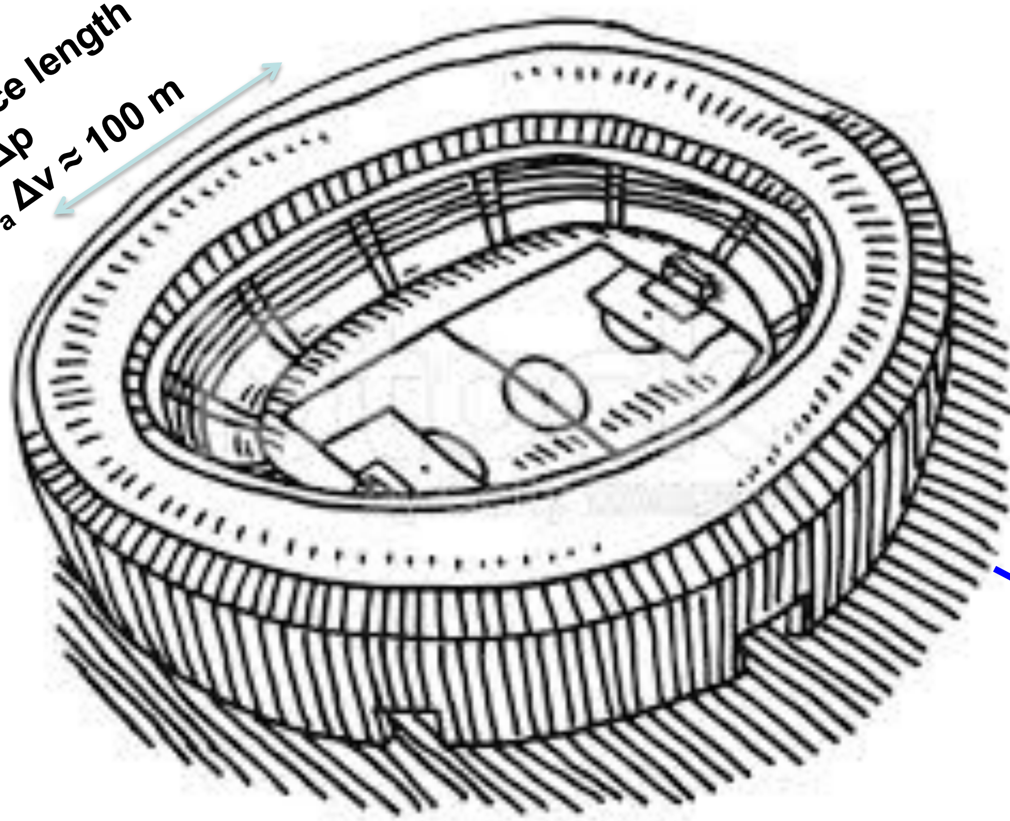
→ If lower mass, dark matter must be coherent bosonic sine waves with **macroscopic mode occupation number >>1**



Higher mass dark matter acts more like billiard balls with occupation number <<1

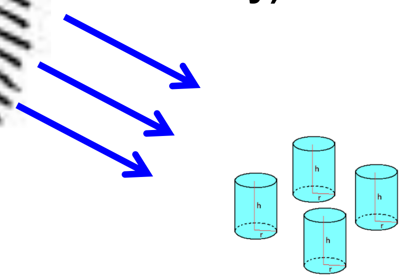
Example: 10^{-5} eV = GHz dark matter

Coherence length
$\Delta x = 1/\Delta p$
$= 1/m_a \Delta v \approx 100$ m



Non-relativistic bosonic DM is like a slow CW laser with oscillation frequency $f=m_a/2\pi$

$v \approx \Delta v \approx 300$ km/s (galactic escape velocity)

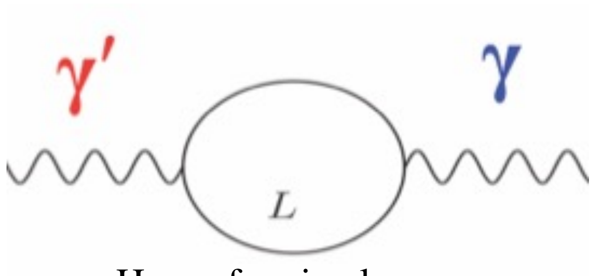


Football stadium-sized regions of coherently oscillating **classical sine waves** slowly drifting through detectors. Mean DM occupation number **$N>10^{22}$ per mode.**

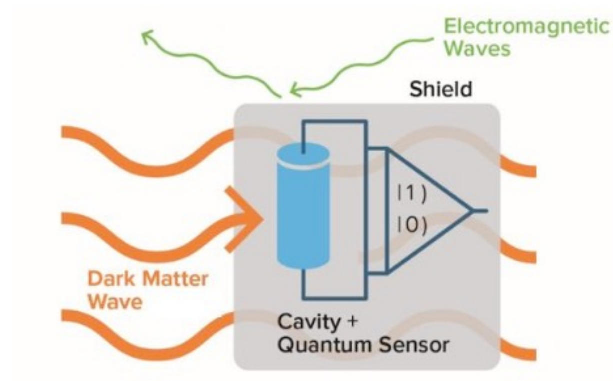
Accumulate oscillatory signals in various kinds of laboratory oscillators which are weakly coupled to the DM wave

Examples: dark photons, spin-0 particles like the QCD axion

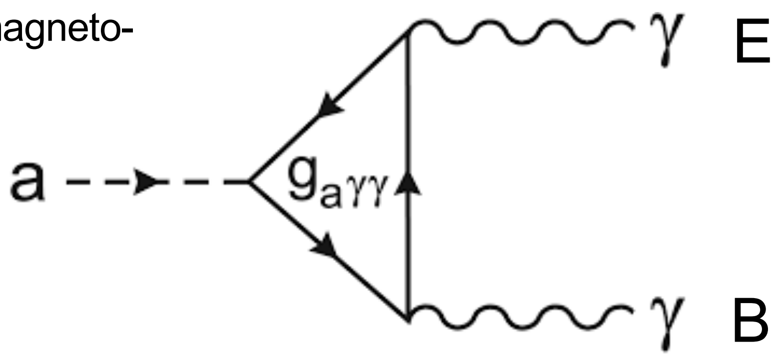
Flavor mixing



Heavy fermion loop



Topological magneto-electric effect



Forces from dark matter waves can deliver energy/momentum in the form of single photons that mysteriously appear in your well-shielded apparatus.

The Dark Matter Haloscope: Classical axion wave drives RF cavity mode

Pierre Sikivie, Phys.Rev.Lett. 51, 1415 (1983)

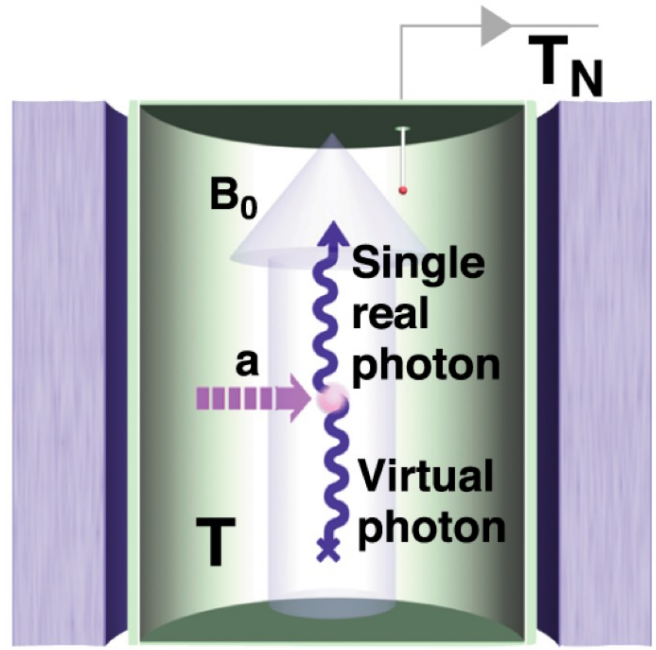
- In a constant background B_0 field, the oscillating axion field acts as an exotic, space-filling current source

$$\vec{J}_a(t) = -g\theta\vec{B}_0 m_a e^{i m_a t}$$

which drives E&M via Faraday's law:

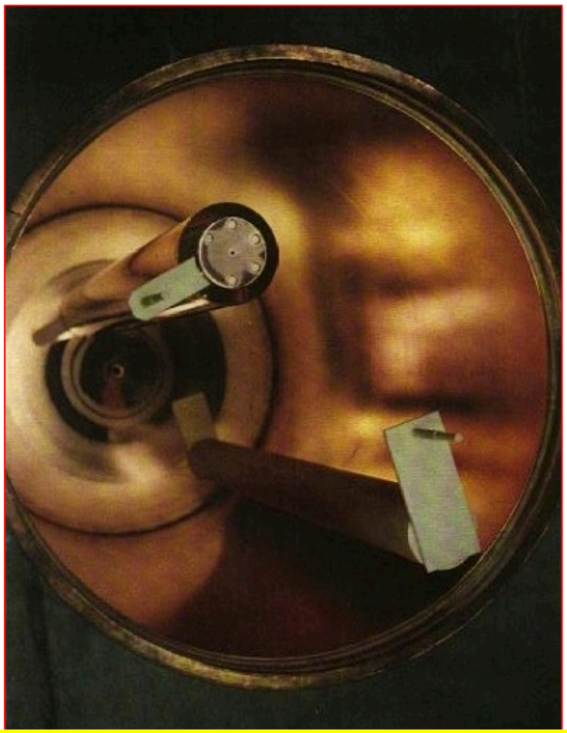
$$\vec{\nabla} \times \vec{H}_r - \frac{d\vec{D}_r}{dt} = \vec{J}_a$$

- Periodic cavity boundary conditions extend the coherent interaction time **(cavity size ≈ 1/m_a)** → the exotic current excites standing-wave RF fields.

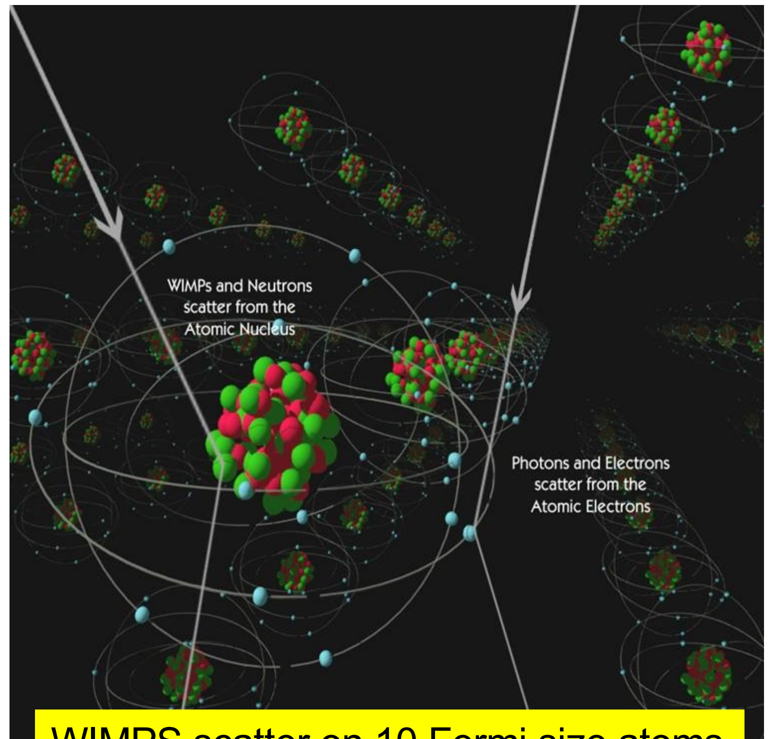


Axions vs heavy WIMPs:

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



4 μeV mass axions scatter on 50cm size microwave cavities

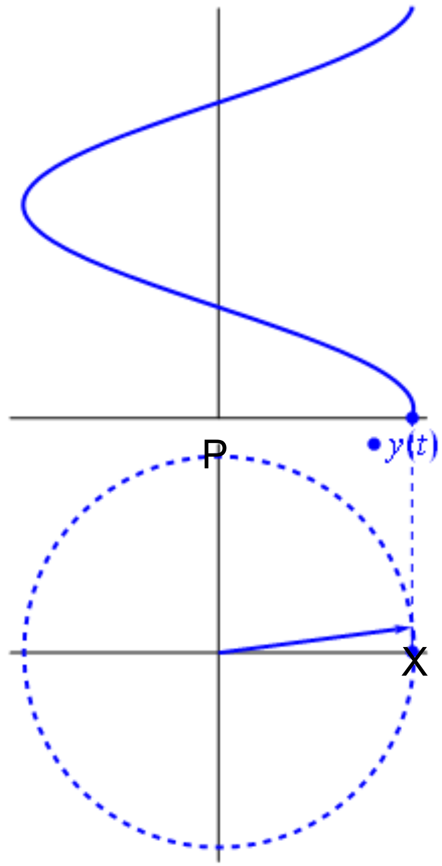


WIMPS scatter on 10 Fermi size atoms

The laboratory oscillator is a classical sine wave, described by a rotating phasor:

The energy oscillates between potential energy and kinetic energy, as parameterized by the **position X** and **momentum P**.

$$H = \frac{p^2}{2m} + \frac{1}{2} m\omega^2 x^2$$
$$= \hbar\omega(a^\dagger a + 1/2)$$

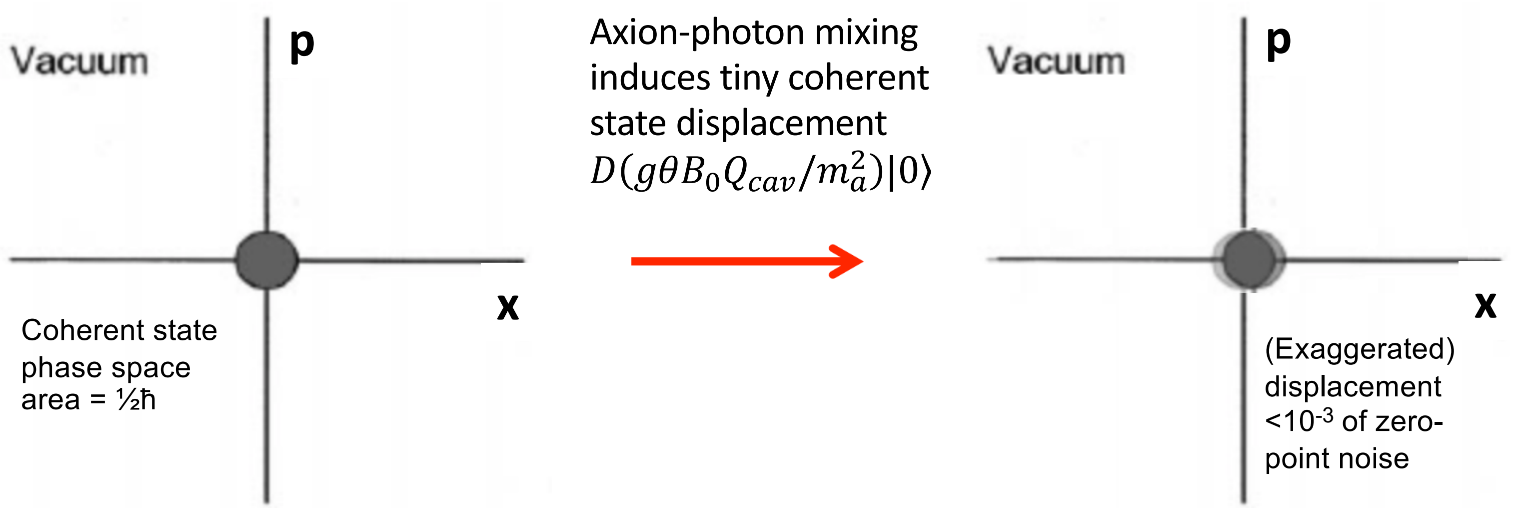


For photons, “X” and “P” are the cosine and sine quadratures of the electric field oscillation.

2nd quantization: [X,P]=i even for internal field quadratures (since these can drive mechanical oscillators.)

Heisenberg uncertainty principle
→ Phase space is quantized in units of area= ½ħ

Force from dark matter wave displaces the cavity vacuum state by an amount much smaller than the zero-point vacuum noise (If larger, we would have discovered it already!)



Standard quantum limit: As T→0, even the best phase-preserving amplifiers have an irreducible zero-point noise floor of +/-1 photon/mode (Carlton Caves, 1982)

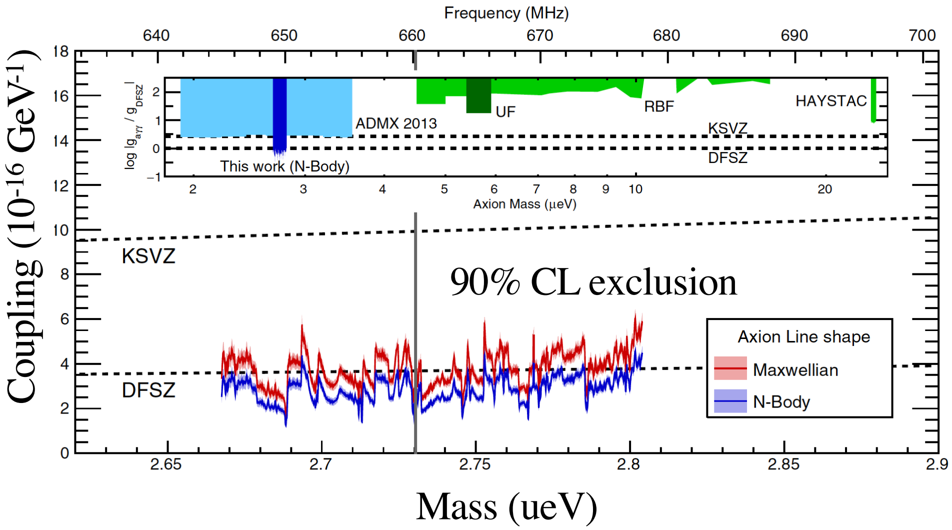
For measurements of amplitude and phase of an amplified sine wave (i.e. in the coherent state basis), the Gaussian blob describes the quantum-limited probe resolution.

Need millions of power spectrum measurements to average away the zero-point noise.

2018: 30-year axion R&D program results in first sensitivity to DFSZ axions

PRL 120, 151301 (2018)

Operate an ultrasensitive radio in a cold, RF-shielded box infused with dc magnetic field. Read out with nearly quantum-limited amplifier.

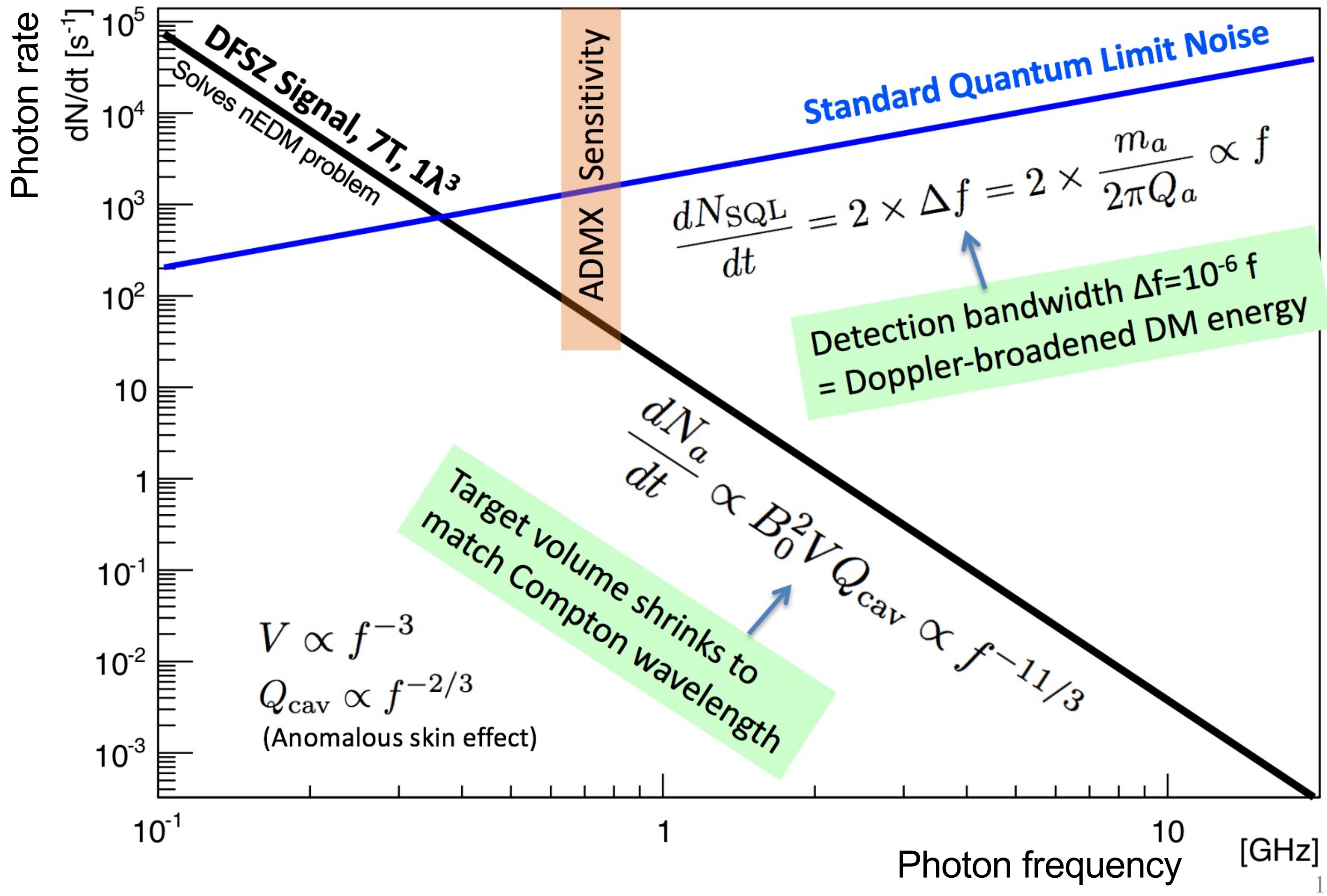


Look for "spontaneous" emission from local axion dark matter wave into the empty cavity mode.

Signal power level = 10^{-23} W
Need 15 minutes integration per radio tuning to average away the thermal noise power at 500 mK.

Also see Yale's HAYSTAC result using squeezed-state receiver! Talk to Steve Lamoreaux and Reina Maruyama.

The predicted axion DM signal/noise ratio plummets as the axion mass increases → SQL readout is not scalable.

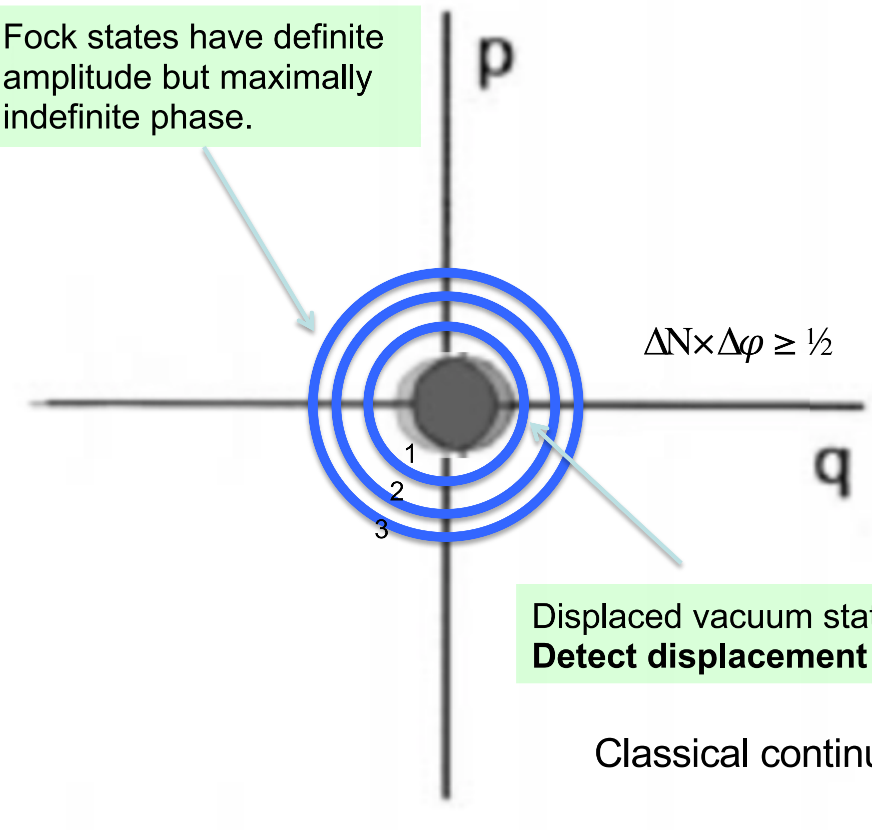


Part 2:
Measuring tiny forces with qubits instead of amplifiers

To further reduce readout noise, use photon counting to measure displacement using the Fock basis, i.e. number eigenstates

Previously we measured *both amplitude and phase*, but this is dumb since the axion phase is randomized every coherence time. Useless information obtained at high cost!

Fock states have definite amplitude but maximally indefinite phase.



$\Delta N \times \Delta \varphi \geq ½$

Instead, measure only displacement amplitude

→ no zero-point noise since we are not simultaneously measuring non-commuting observables

→ ***Measurement noise, i.e. dark count rates can be arbitrarily low***

Displaced vacuum state exponentially leaks into non-zero Fock number.
Detect displacement by counting the occasional single photon.

Classical continuous force delivers a digitized impulse!

Use artificial atoms made of superconducting “transmon” qubits to nondestructively sense microwave photons

A.S. Chou, Dave Schuster, Akash Dixit, Ankur Agrawal, …

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

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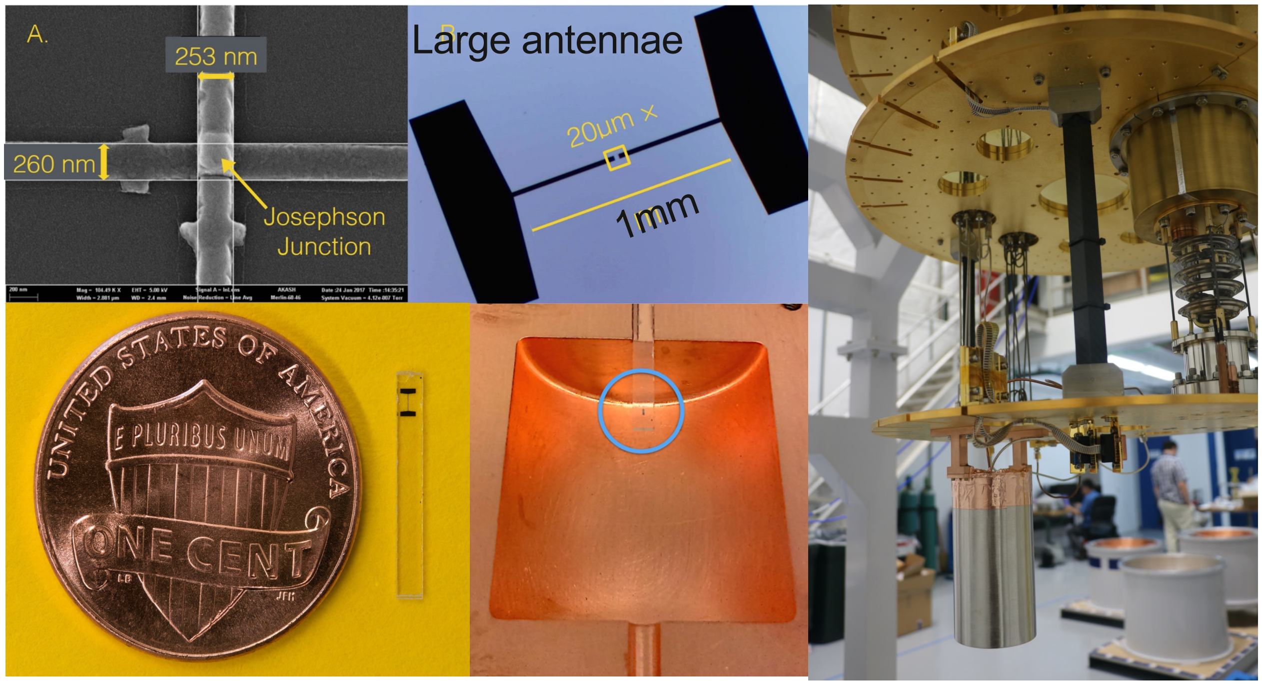
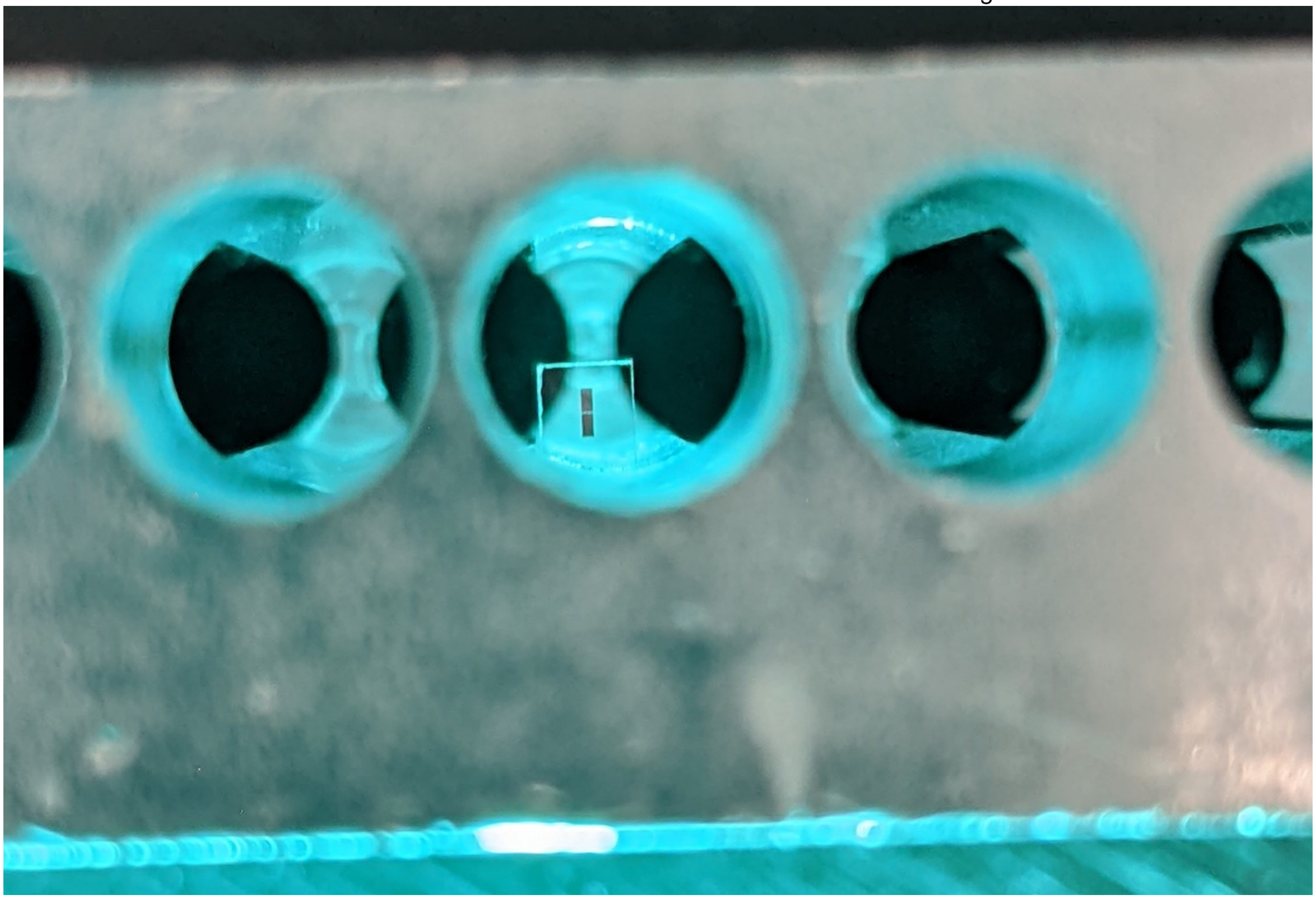


The electric field of individual photons drives a tiny current which exercises the nonlinear inductance of the Josephson junction. **Photon number is transduced into frequency shifts of this single quantum LC oscillator.** Same as Lamb shift, but for finite photon number.

Transmon qubit in dark matter cavity

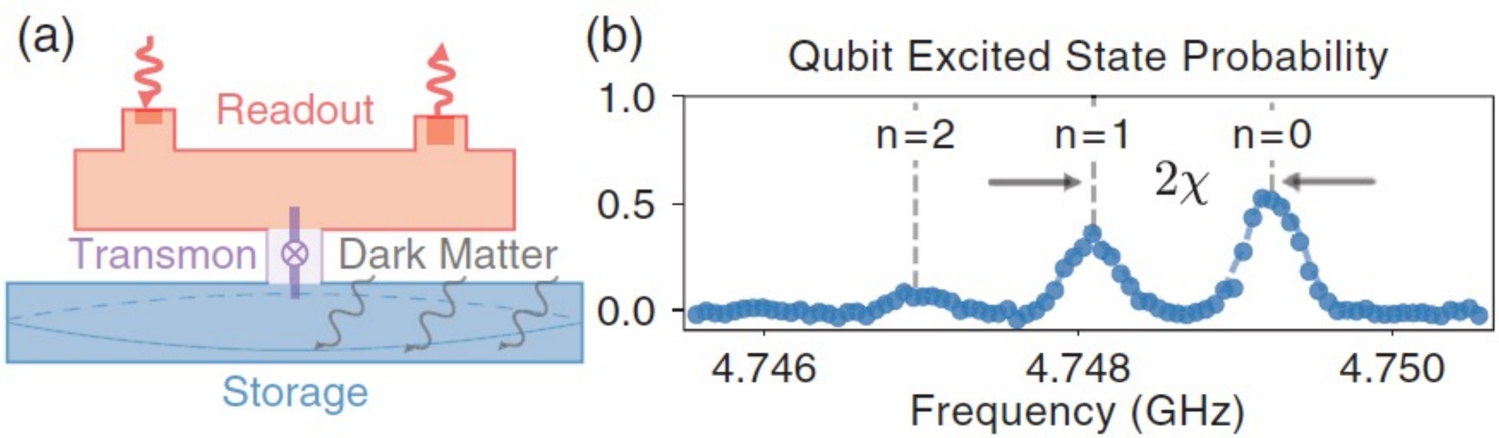
Image credit: Akash Dixit



Single photon resolution:

Measure qubit $|g\rangle \rightarrow |e\rangle$ transition frequencies after weakly driving the primary cavity mode into a coherent state with <n>=1

First demonstrated by Blake Johnson, 2011 Yale PhD thesis

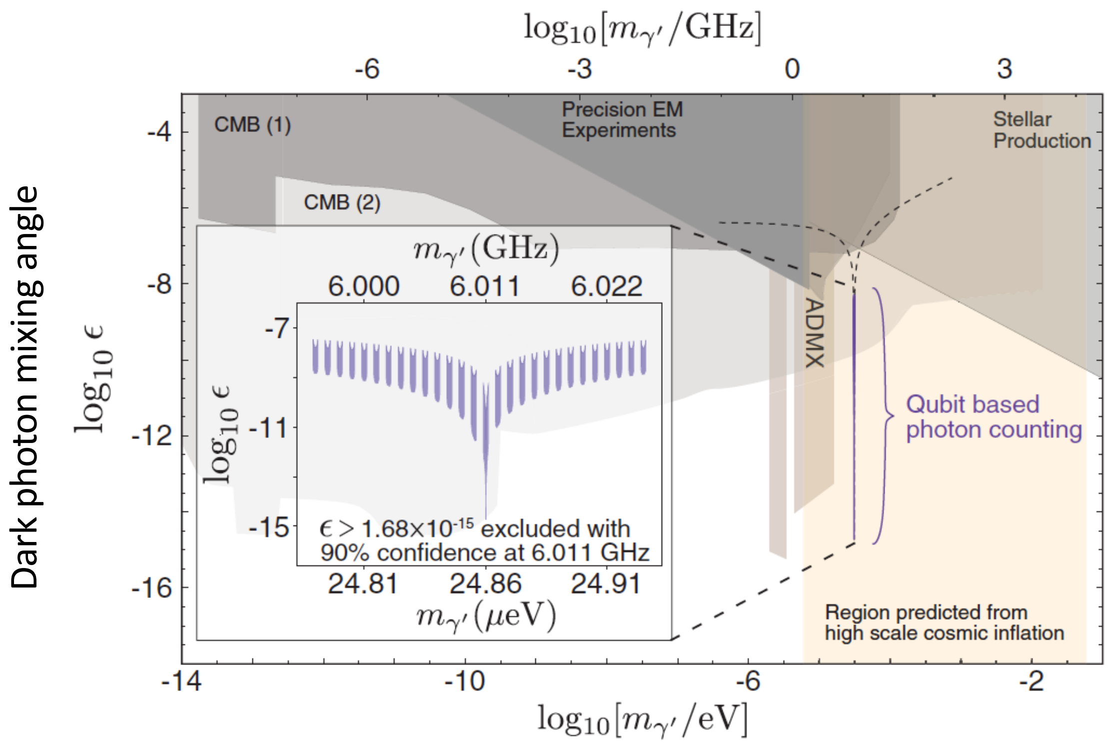


The measured qubit response spectrum exhibits a distribution of resonances which are in 1-1 correspondence with the Poisson distribution of the cavity's coherent state.

- **Non-destructively count photons by measuring the qubit's quantized frequency shift via this "quantum non-demolition" measurement.**
- **Repeat many times for high fidelity single photon detection.**

Single frequency dark photon sensitivity:

Akash Dixit

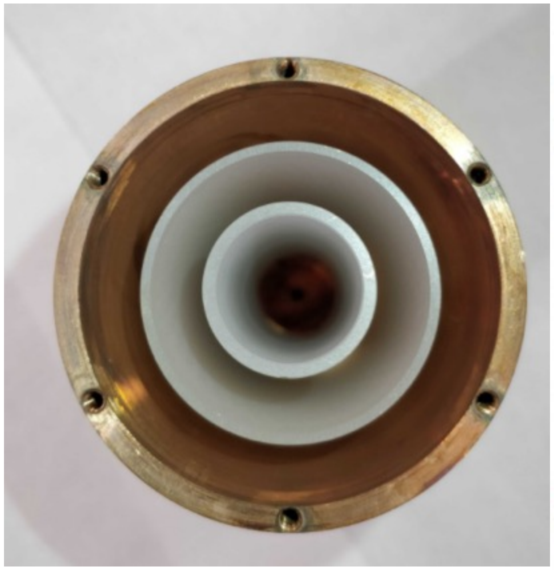


A. V. Dixit, et.al, Phys.Rev.Lett. 126, 141302 (2021)

15,141 cavity population measurements over **12.81 s** run time with superconducting Al cavity.

Now to add magnetic field! But s-wave superconductors cannot tolerate high B field. What to do?

Bragg fiber cavity made with low loss sapphire



6 cm

Lambda/4 spacing coherently reflects microwaves away from the lossy copper enclosure. **Q>10⁶** for 12 GHz cavity in high B=1-10 T magnetic field!

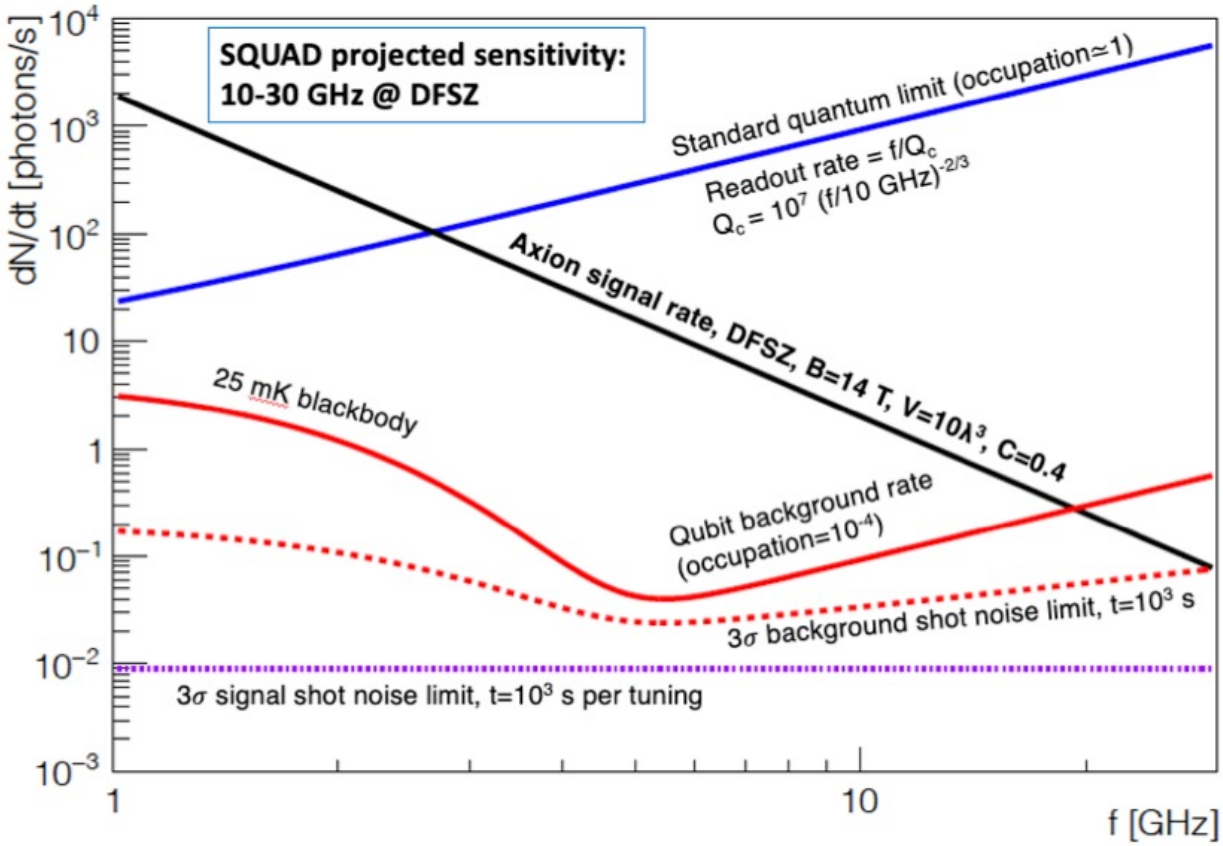
1K still shield

Let signal photons slowly leak out of this magnetized cavity and into a remote cavity located well outside of the B field. Then measure with qubit.

Superconducting Qubit Advantage for Axion Detection (SQuAD)

Photon rates from a single cavity

Ankur Agrawal



Reduced noise 100x below SQL with qubit-based photon counting

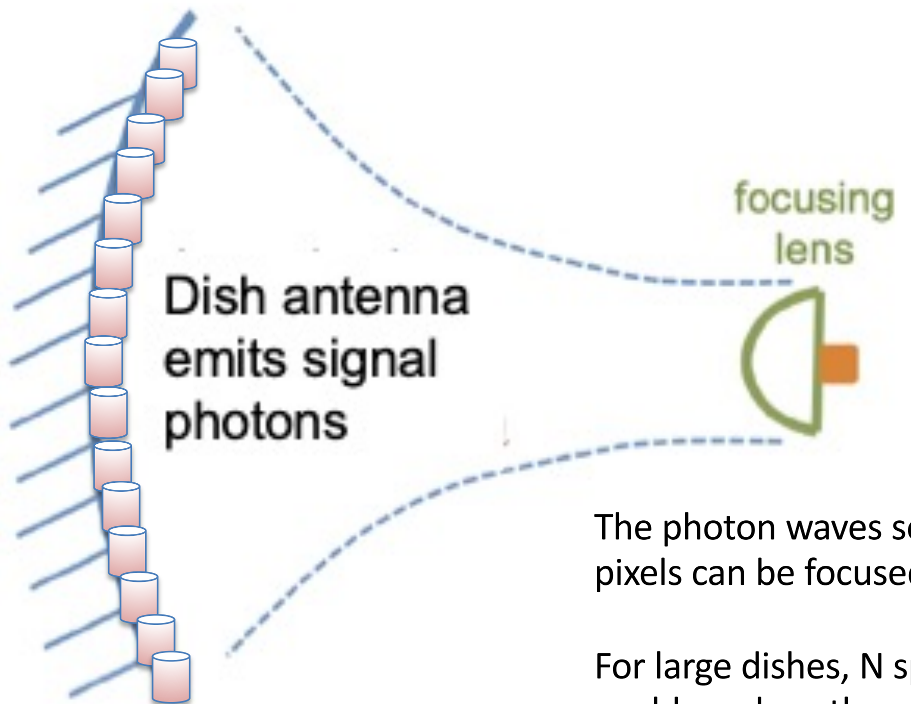
Boosted signal 100x with high-Q dielectric cavity

Cavity-based photon counting (qubits, Rydberg atoms) should reach 30 GHz before running out of signal photons.
What about higher frequencies? Qubits become lossy and cavities become tiny and unmanageable….

One can instead use a huge dish antenna whose area contains many wavelength-squared pixels

D. Horns, et.al, JCAP 1304, 016 (2013)

This is like having an array of N cavities, where each cavity only gets 1 bounce.



Dark matter emits transition radiation upon seeing the impedance mismatch between metal and vacuum.

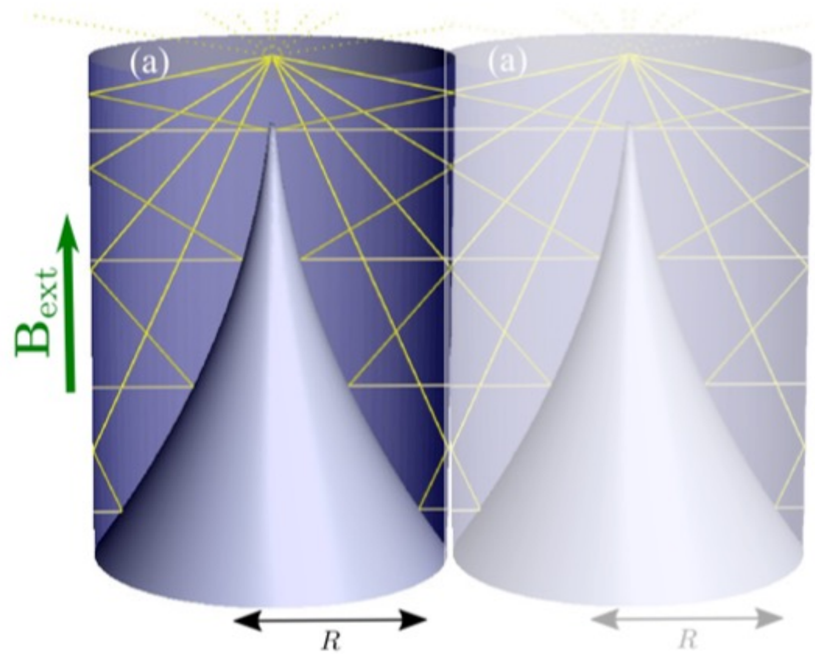
The photon waves sourced from the individual pixels can be focused using geometric optics.

For large dishes, N spatially distinct emitters could produce the same total signal rate as that of Q bounces inside a resonant cavity.

BREAD: Broadband Reflector Experiment for Axion Detection

Phys. Rev. Lett. 128 (2022) 13, 131801

Cylindrically symmetric reflector geometry optimized for inexpensive solenoid magnets



Rotate parabolic dish antenna geometry through 360 degrees and place it in a mirrored cylinder. This creates a ”coaxial” focal point where **single photon detectors** can be placed.

Insert assembly into solenoid magnet bore for an inexpensive dark matter axion search!

Part 3:
Qubits sense larger energy deposits which break Cooper pairs

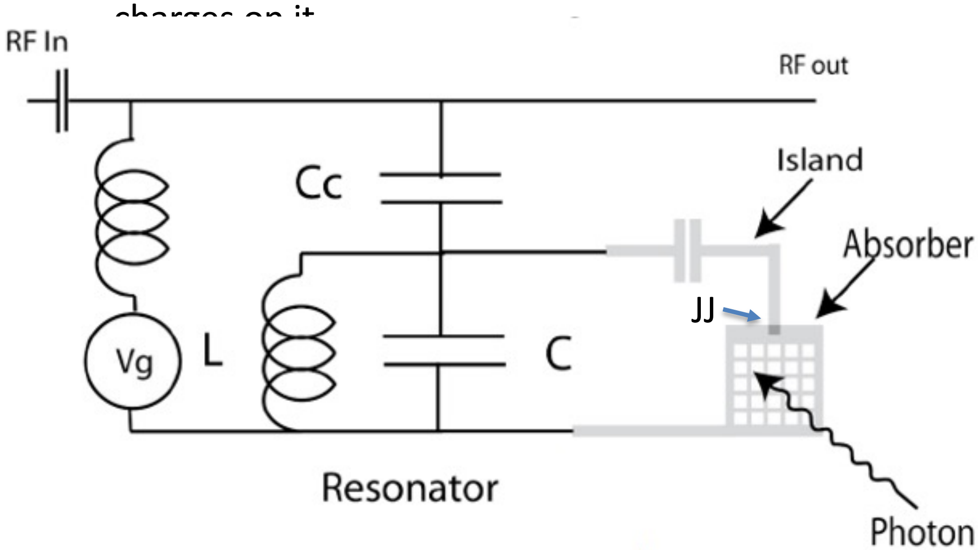
Instead of just perturbing the atomic clock, high energy photons completely break it!

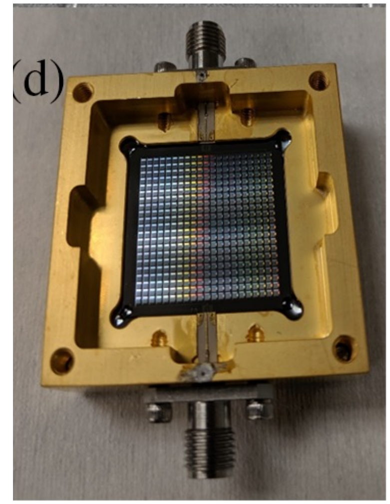
Quantum Capacitance Detector: Sensing photons via large qubit errors

Based on the Cooper pair box, a.k.a. a charge qubit.

Senses single THz (10^{-3} eV) photons which break 10's of Cooper pairs with 10^{-4} eV binding energy.

A Josephson oscillator's capacitance has a large discrete change depending on whether the superconducting island has an even or odd number of charges on it.





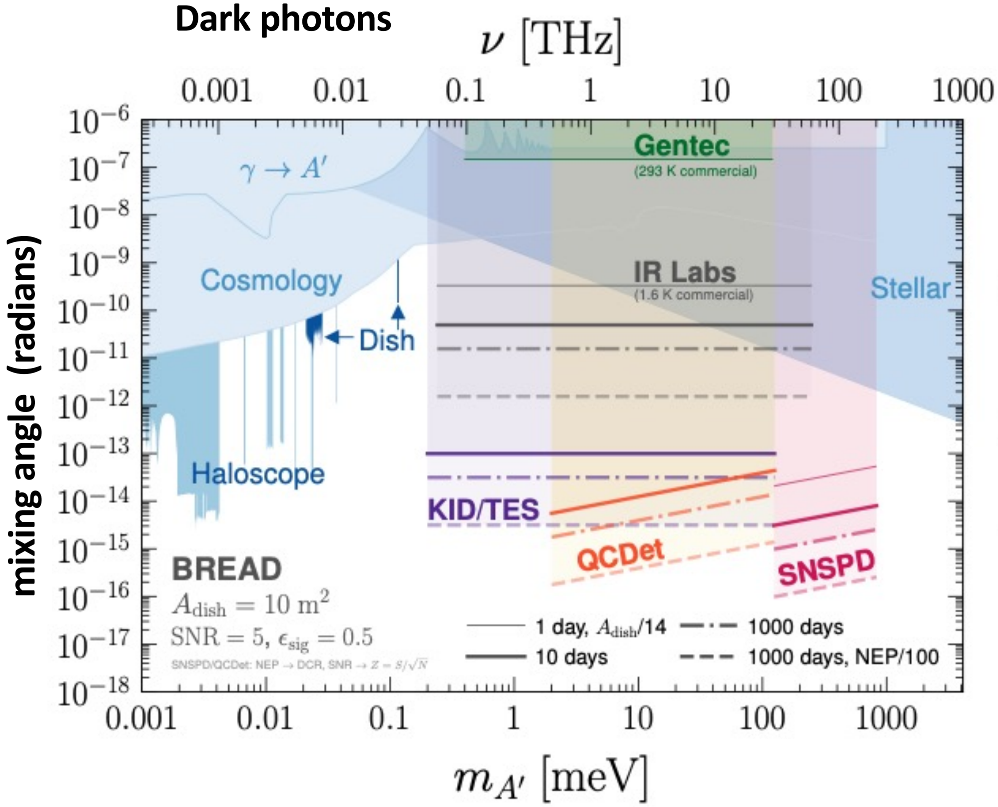
21x21 pixel array from Jet Propulsion Lab.
P. Echternach, A. Beyer, and C. Bradford (2021)
https://doi.org/10.1117/1.JATIS.7.1.011003

After photon is absorbed, qubit exhibits a long dead time with a sequence of repeated frequency errors as the excess charged particles tunnel onto the island and repeatedly change the LC oscillator frequency.

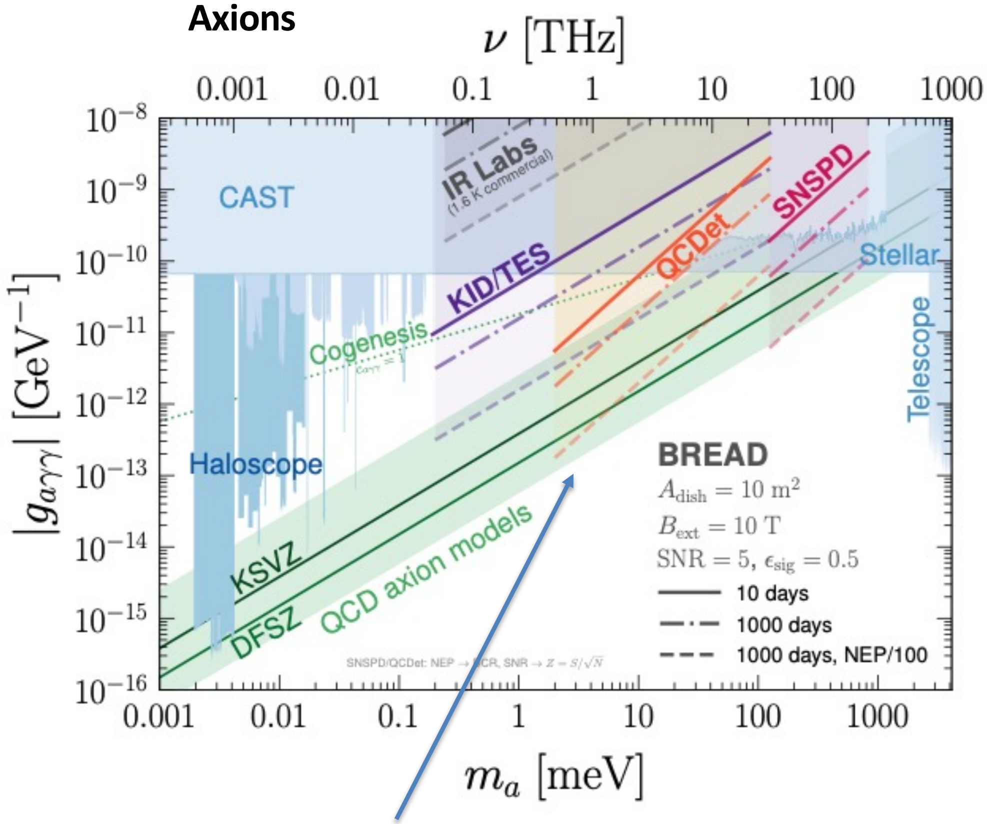
BREAD projections with different photon detector technologies

Phys. Rev. Lett. 128 (2022) 13, 131801

Dark photons

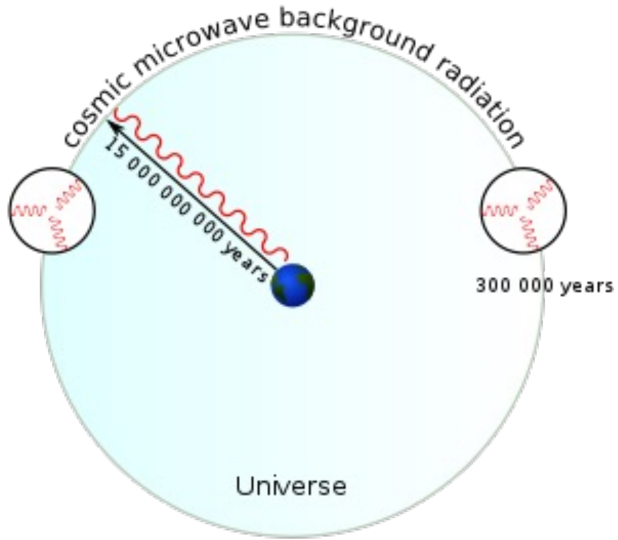


Axions



QCDet currently has 100 Hz dark count rate, need to push to 0.01 Hz to see QCD axions.

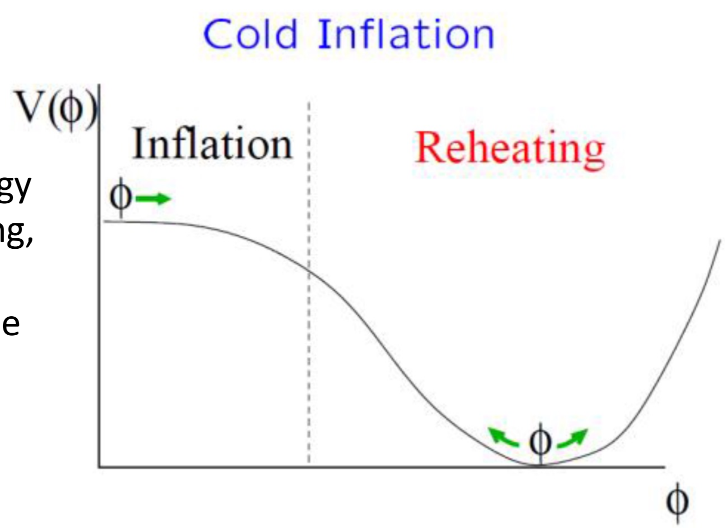
Part 4:
Search for dark radiation from cosmic dark energy evolution

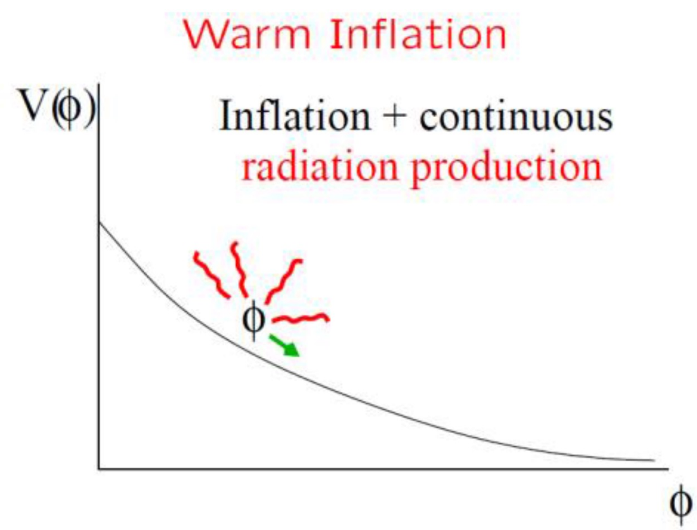


13.7 billion years ago…
Cosmic inflation model provides 60 e-foldings of the expanding universe to explain homogeneity and isotropy of the CMB temperature

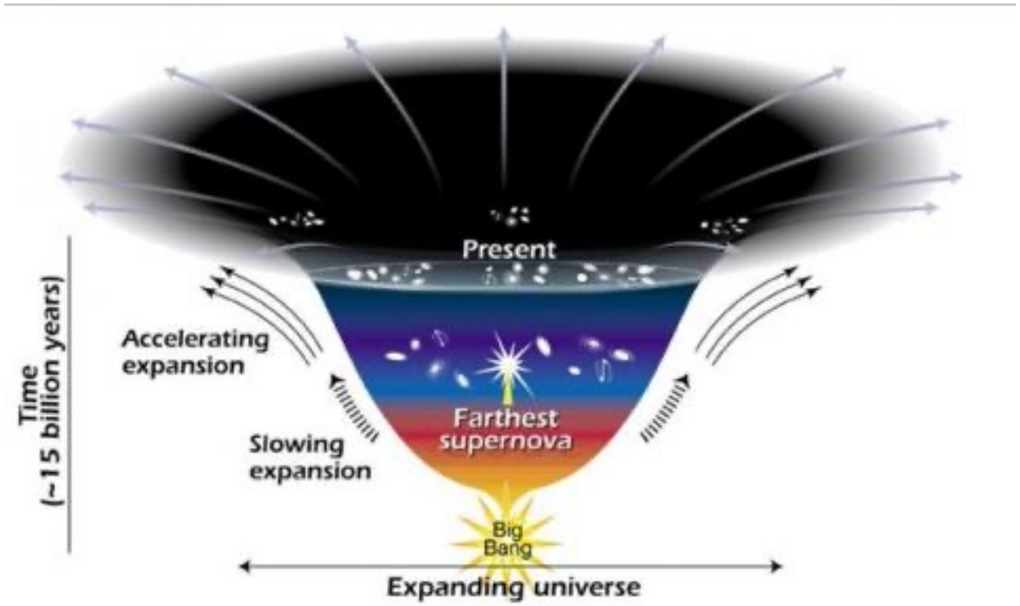
Postulated phase transition at ultra high energy scale < 10^{16} GeV

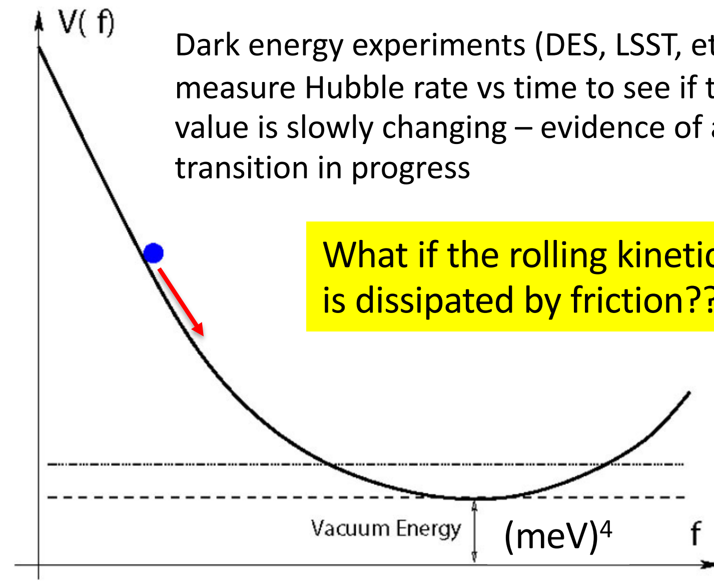
Vacuum potential energy density is self-replicating, sources accelerated expansion of space-time





Dark energy: we are currently entering another inflationary epoch



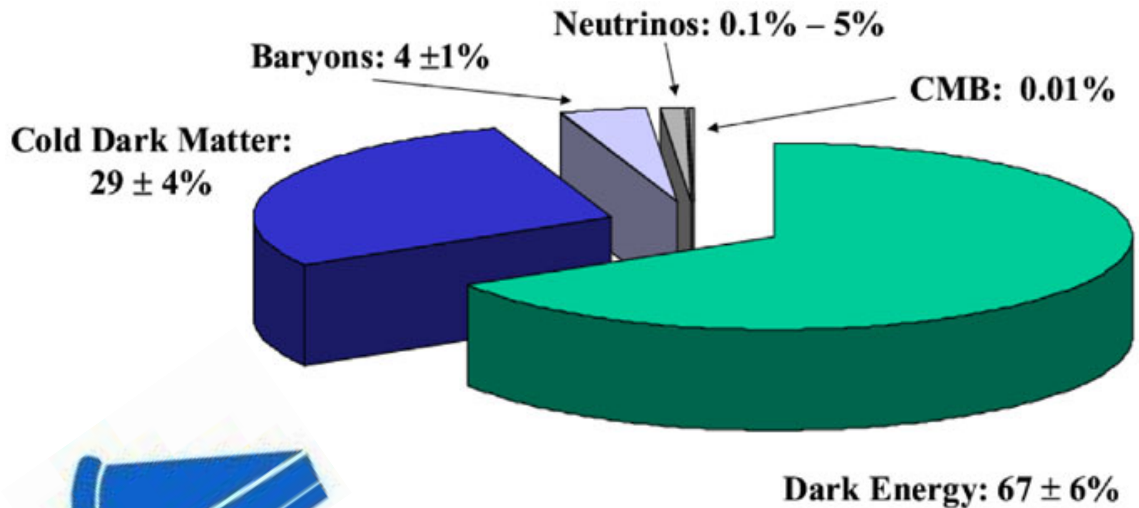


Dark energy experiments (DES, LSST, etc) measure Hubble rate vs time to see if the field value is slowly changing – evidence of a phase transition in progress

What if the rolling kinetic energy is dissipated by friction???

If this is warm inflation, can we see the relativistic bath of 10 K radiation at a fraction of the dark energy potential energy density (meV)^4 ? K.V. Berghaus et al., Phys Rev D 104, 083520 (2021)

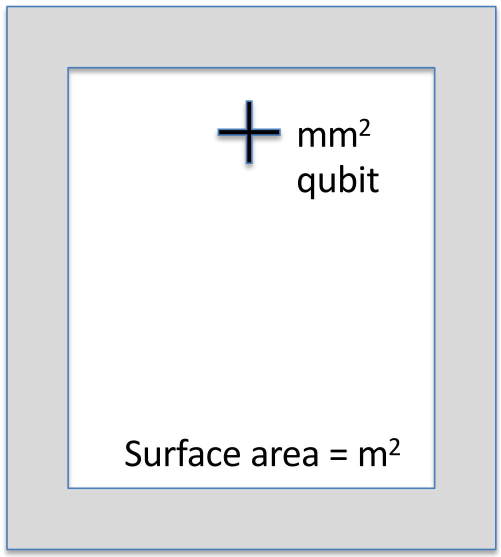
Cosmological energy density of 10K dark background could be comparable to that of dark matter



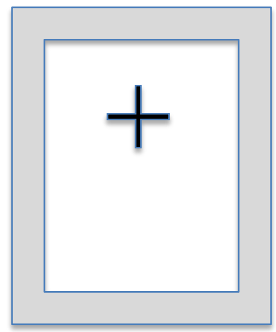
+ 10% in 10 K dark photons???

Experimental concept with high-Q cavities and black painted box

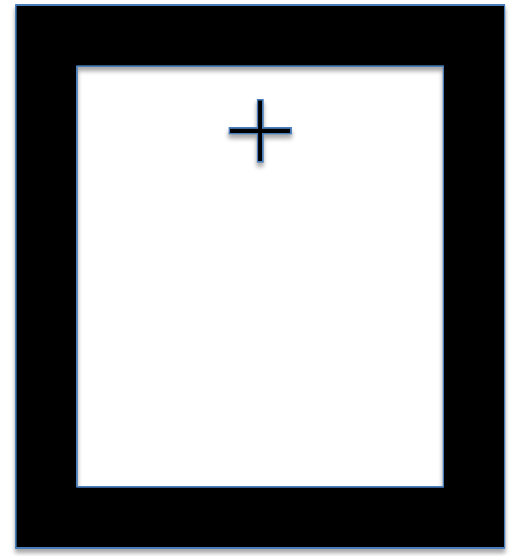
Detect non-directional transition radiation from dark photons scattering on walls of enclosure



Mirrored walls:
Qubit absorbs all transition radiation from surface area of walls.



Does the qubit error rate scale with the surface area of the enclosure?



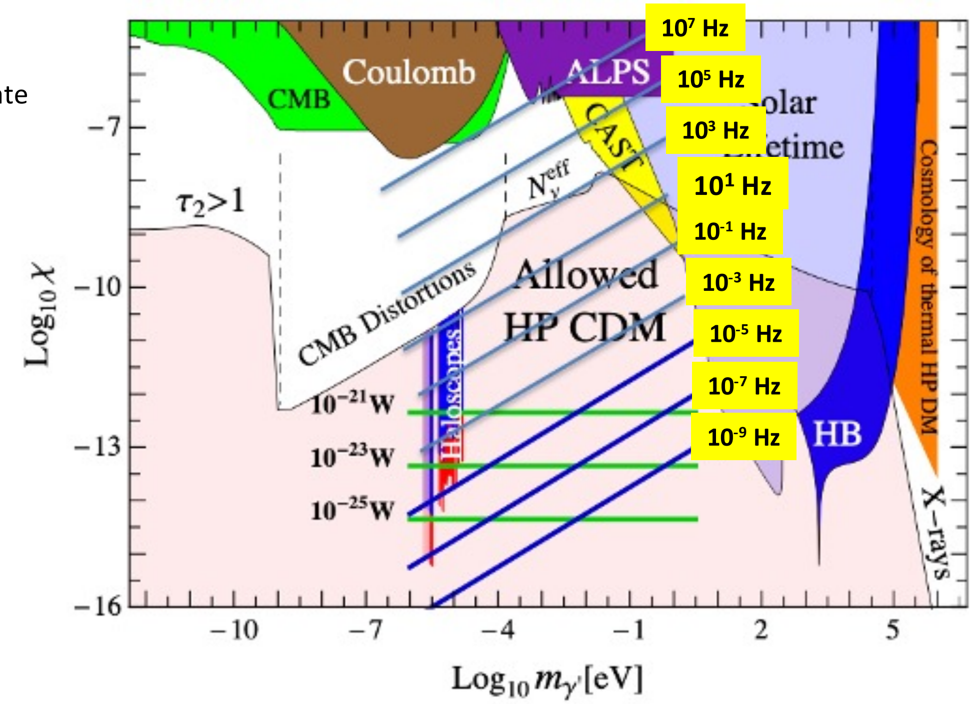
Black walls:
Control experiment.
Qubit absorbs only its area fraction of emitted photons.

Compare quasiparticle density via measured qubit error rates in these cases.

Predicted signal photon rates from 10K dark blackbody for 1 m^2 enclosure, integrated across blackbody spectrum.

Figure adapted from Horns et.al JCAP 04 (2013) 016

NB: CMB constraints from don't apply to late (z<5) production of relativistic particles

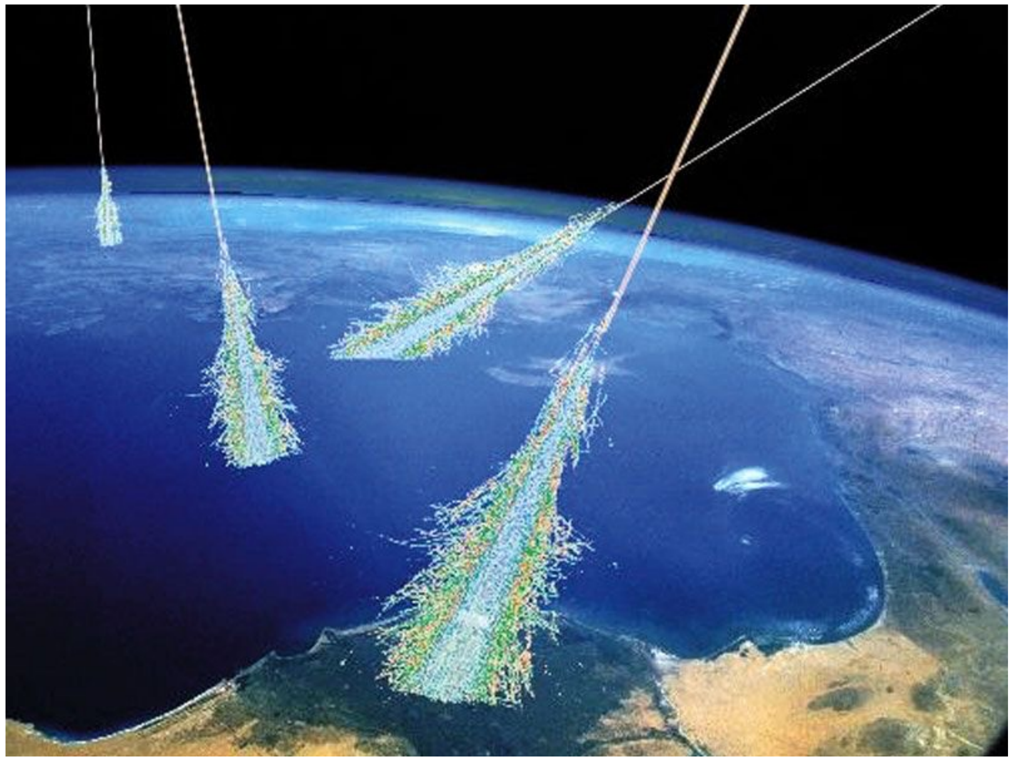


Dark photons could be both the dark matter and the dark radiation!

Here, I've just reduced the predicted rates for dark matter events by factor 10^5 since relativistic dark radiation does not clump in galaxies.

Quantum Computers vs Ionizing Radiation

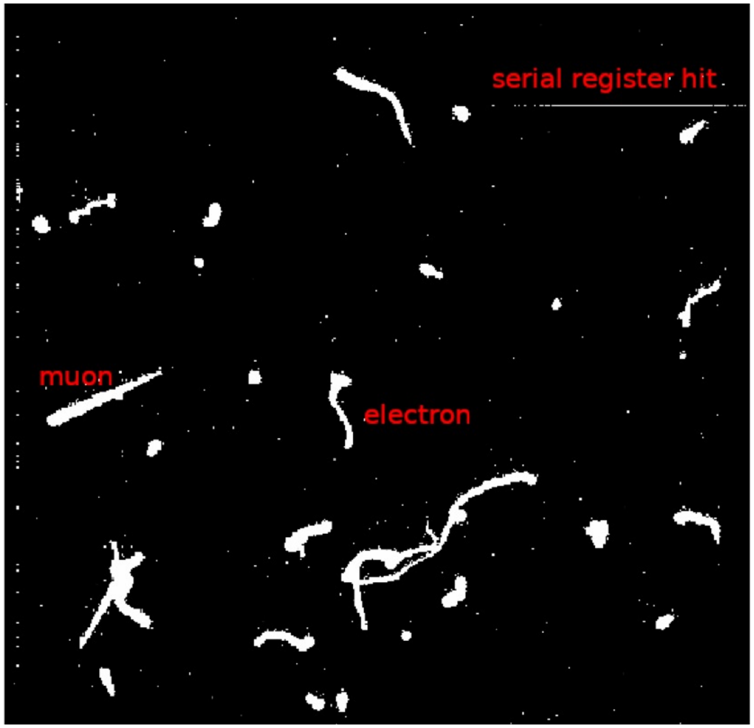
Cosmic ray events are caused by energetic protons and charged nuclei smashing into the earth's atmosphere and creating a cascade of particles



Initial energies up to 10^{20} eV

Arrays of silicon cosmic ray shower detectors are based on cell phone apps.

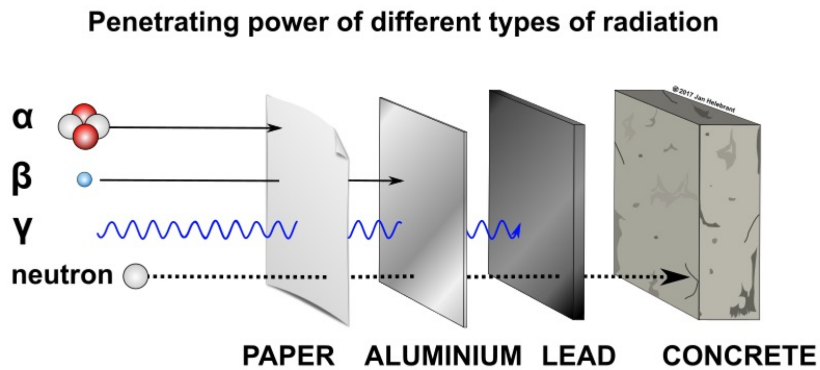
Patterns of ionizing radiation hits in a silicon CCD (SENSEI DM experiment)



In silicon-based computers, Single Event Upsets (SEU) due to cosmic rays are well-known, and are believed to have given a candidate 4096 extra votes in a 2003 election in Belgium.

They can also give you super powers!

Probably only muons and high energy gamma rays can penetrate the walls of the cryostat to hit the qubit substrates



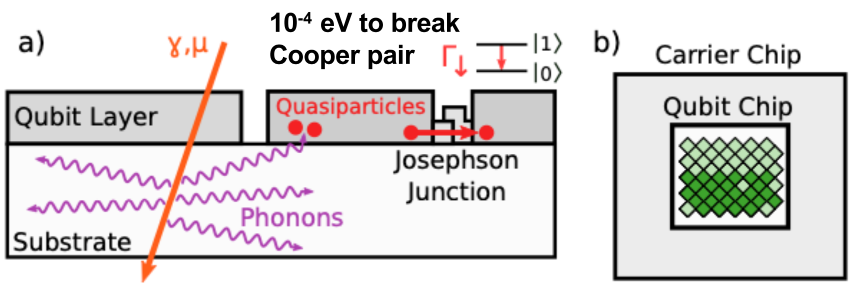
Can mitigate with extra lead or heavy copper shielding.

Qubit installed in
dilution refrigerator

Ionizing radiation produces 10^{-2} Hz rate in superconducting qubit CPUs

Google Sycamore chip functions as a phonon detector with **100% chip-wide failure** in response to ionizing radiation events which can be localized in both space and time

M. McEwen, et al., Nature Physics 18 (2022)



100 keV energy deposit breaks a billion Cooper pairs

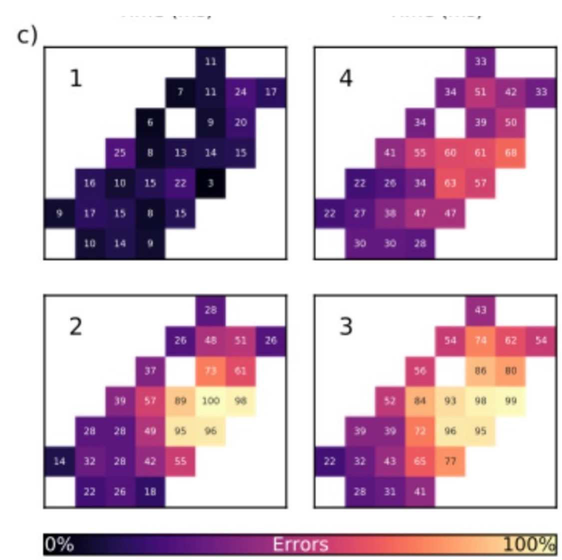
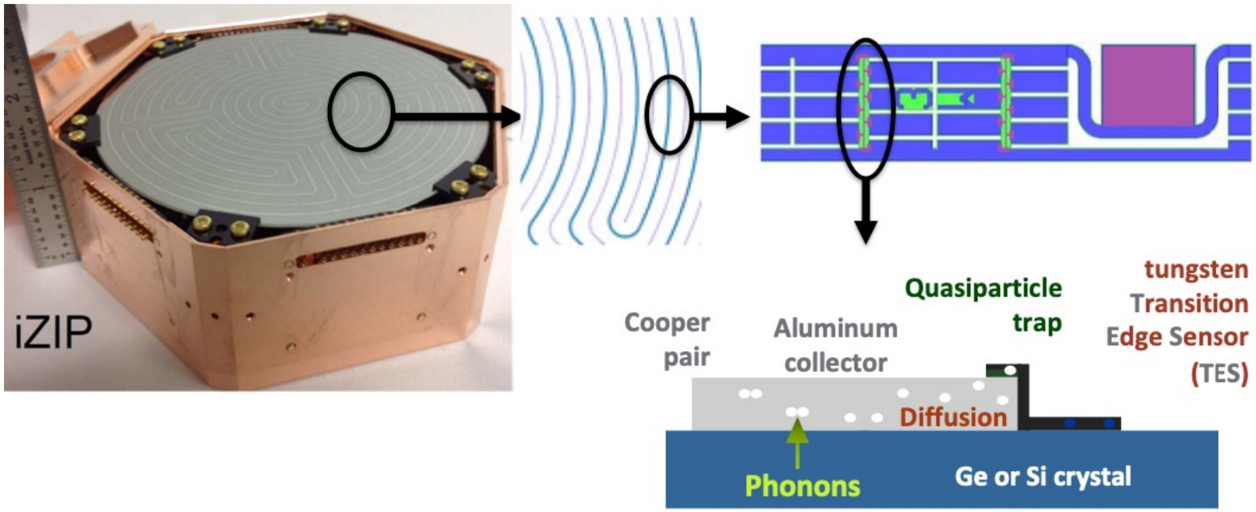


Figure 3. **Localization and spread of error.** (a-b) Time-

Just like in a dark matter detector, the ionizing radiation deposits energy primarily in the bulk substrate of the qubit chip. Electrons and holes recombine and the resulting emitted phonons bounce around and break Cooper pairs in the thin film superconductors on the surface.

Compare to the SuperCDMS Dark Matter Detector

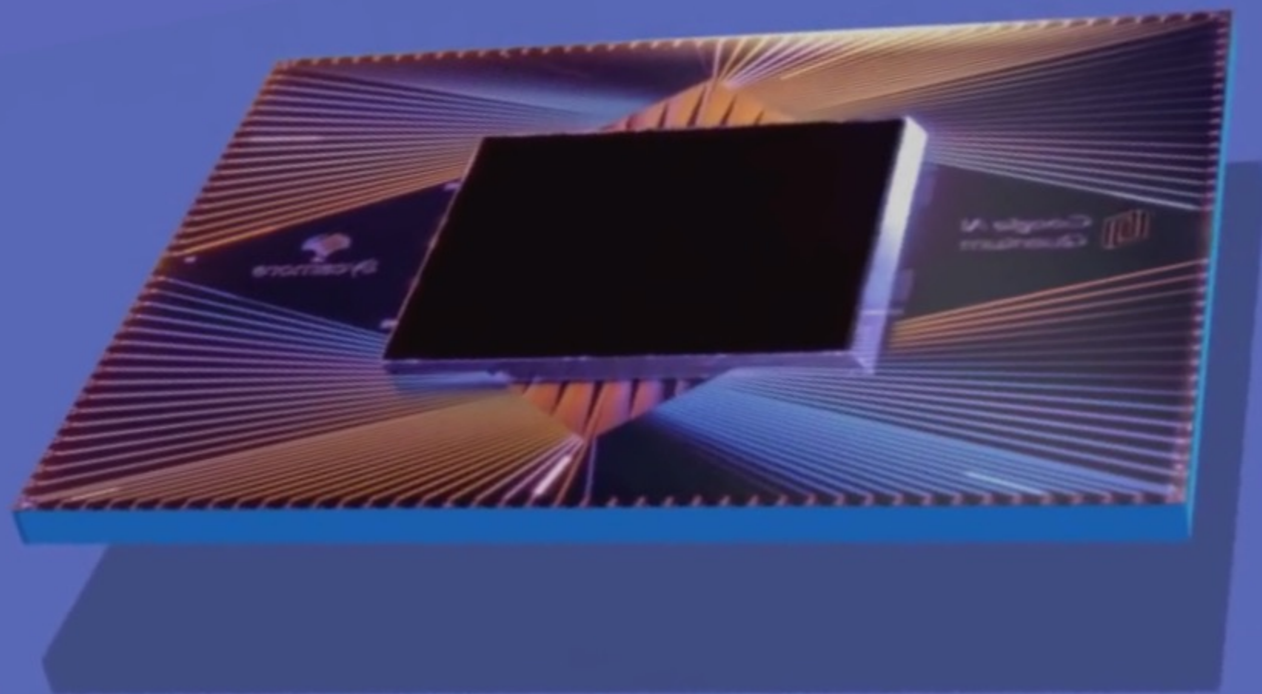


Transition edge sensors sense change in superconductor's resistance due to ~10^5 broken Cooper pairs.

Qubits much more sensitive, can be screwed up by even 1 broken Cooper pair!

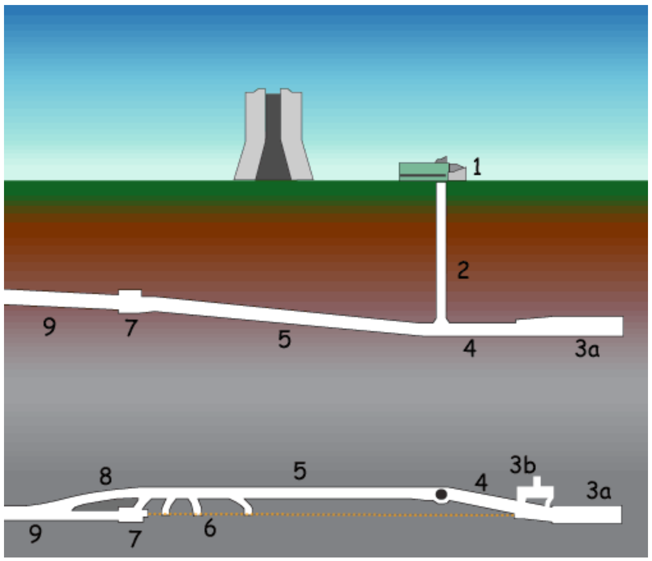
Google claims to be working on quantum computing, but secretly they are building a dark matter detector!

Quantum cpu = versatile sensor?

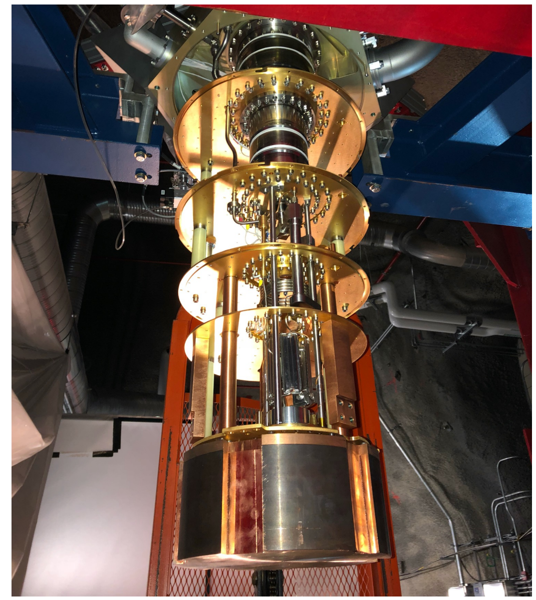


To reduce ionizing radiation on quantum devices, the Quantum Science Center is setting up underground dilution refrigerators in Fermilab's neutrino beamline

Based on existing NEXUS test stand for prototyping dark matter experiments



>100m

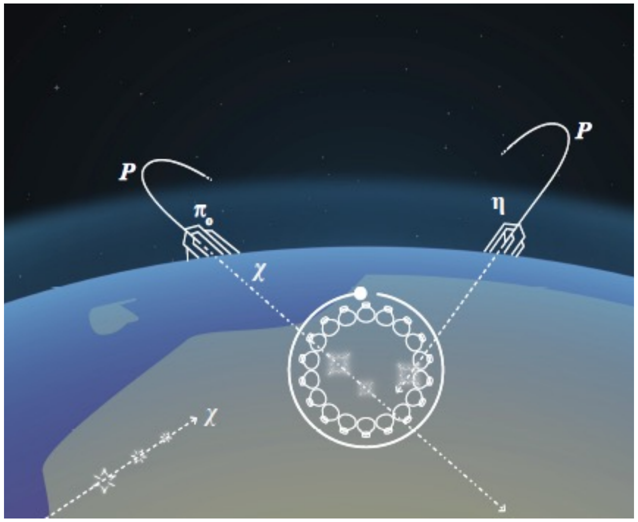


Lead sarcophagus shields against natural radioactivity

QUANTUM SCIENCE CENTER

Qubits vs milli-charged dark matter Q<10^{-3} e

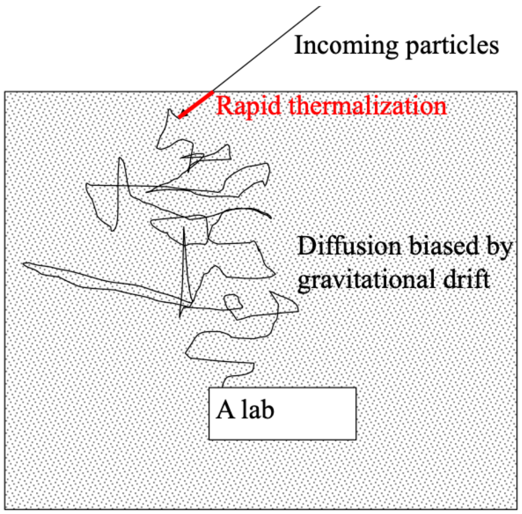
Due to weakly ionizing interactions, the earth scoops up millicharged particles floating around in the galaxy or created in cosmic ray air showers



Artwork: C. Arguelles, K. Kelly, V. Munoz, 2104.13924

Low mass particles evaporate back into space while high mass ones are captured and sink towards the center of the earth.

M.Pospelov, H.Ramani, Phys Rev D103, 115031 (2021)



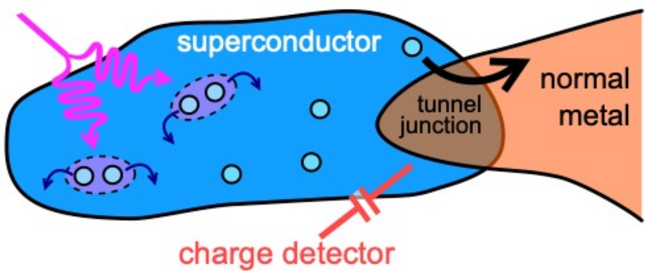
Benchmark: 10^3 ambient mQ particles/cc in lab, thermalized to 300 K → 10^8/cm^2/s flying through your cryostat shields!

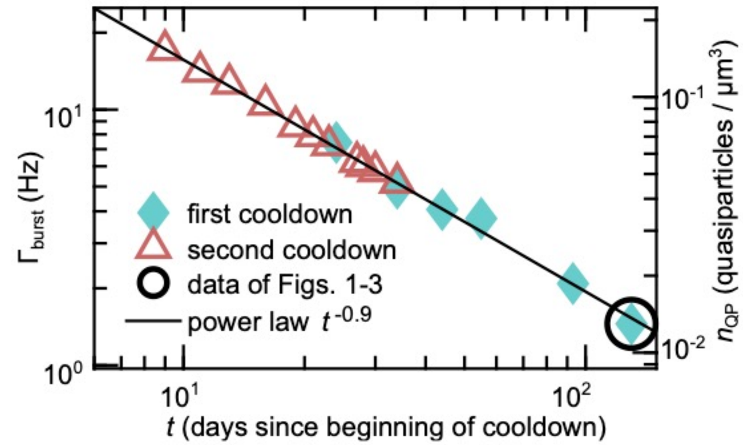
Upon hitting qubit substrate, **kinetic energy = 0.03 eV is enough to break many Cooper pairs** (0.0001 eV).

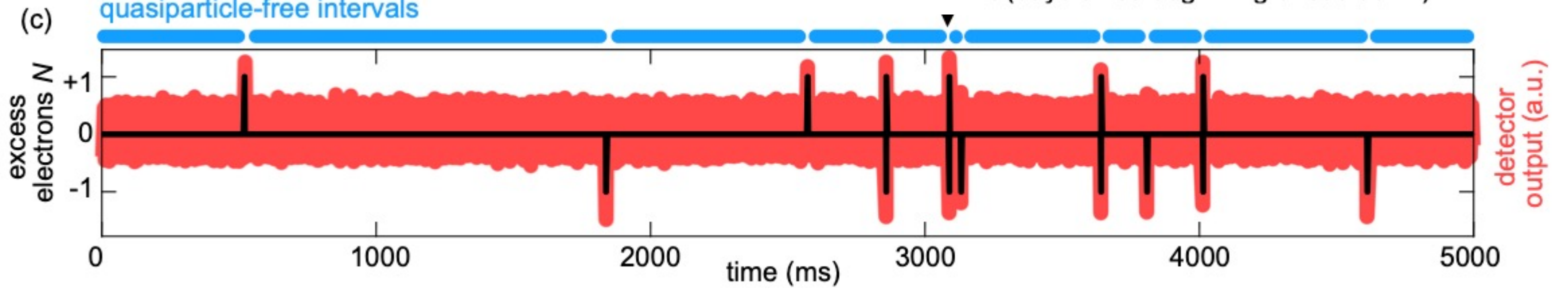
Superconducting devices all suffer from mysterious non-equilibrium quasiparticle population: Boltzmann suppression $e^{-1.2K/0.01K} = 10^{-52}$

These now appear to be created in discrete, time-resolved events with much higher rate than cosmic rays.

E.T. Mannila, et al., Nature Physics 18 (2022)







Origins of events still a 20-year-old mystery … have we discovered $q=10^{-9}$ e dark matter?
Will increasing the thickness of the 10 mK shield help thermalize to sub-gap energies?

Part 6:
Quantum computers to read out sensor arrays

Windchime concept:

Phys.Rev.D 102 (2020) 7, 072003

Proposal for gravitational direct detection of dark matter

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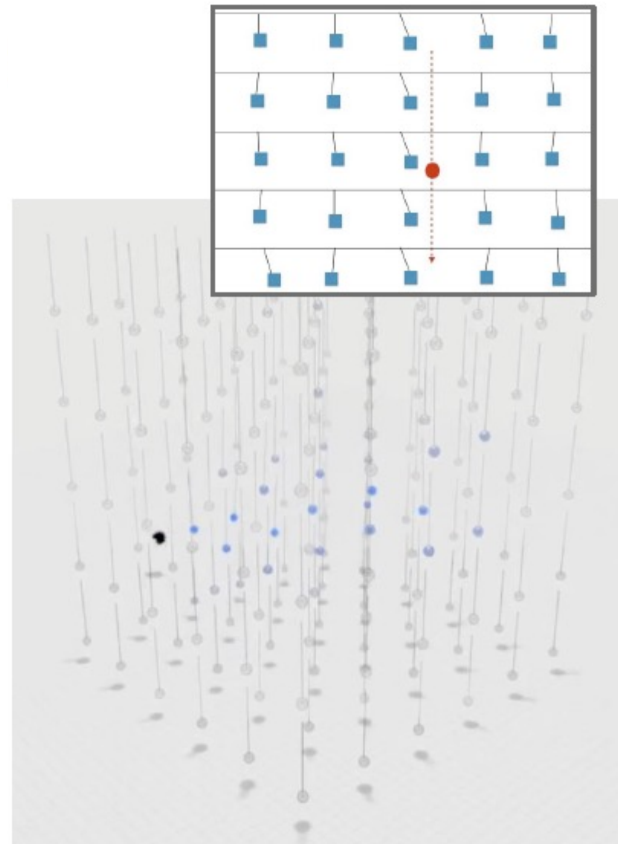
[1]*Joint Quantum Institute/Joint Center for Quantum Information and Computer Science, University of Maryland, College Park, Maryland 20742/National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA*
[2]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*



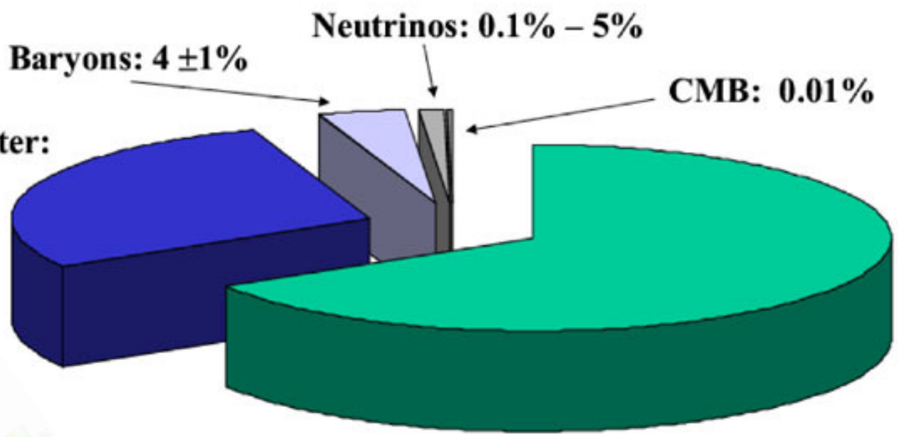
Cubic meter array of **10^9 accelerometers** with millimeter spacing to detect force from passing dark matter.

How to affordably read out sensor array and reconstruct track of 1000 excitations in real-time???

- Probably impossible with classical computers.
  - cf. LHC = 400M channels
  - Heat load = 5 dedicated nuclear power plants
- Diffraction of light? Quantum annealing?
- **If Dark matter detector = Quantum Computer**
  → Should provide in-situ processing of tracks
- Co-located trapped ion computer seems well-suited to detect long correlation length excitations.

Summary

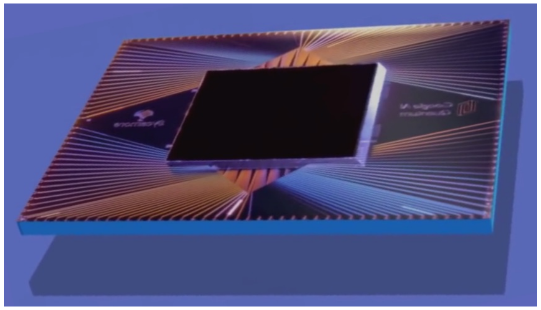
- Okay, so the mystery noise you are seeing is probably because your apparatus is crap and you should really try to do better….
- But, it is **not unlikely** that it is due to dark matter or dark radiation flying through your lab.



+ 10% in 10 K dark photons???

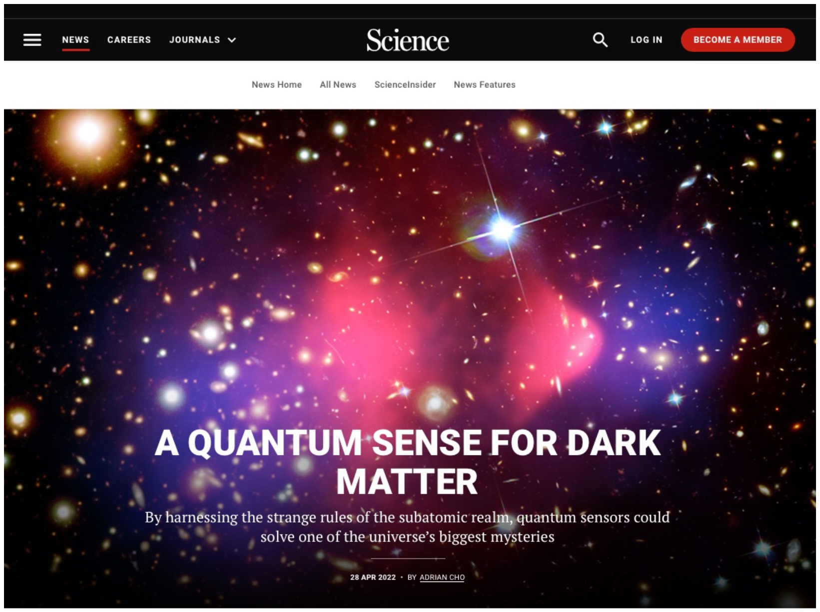
Most of this unknown dark stuff is invisible to conventional detector technologies.

Need to use something that is crazy sensitive to disturbances and shield the heck out of it ... Oh but we are already doing that!



Backup slides

Related news articles:



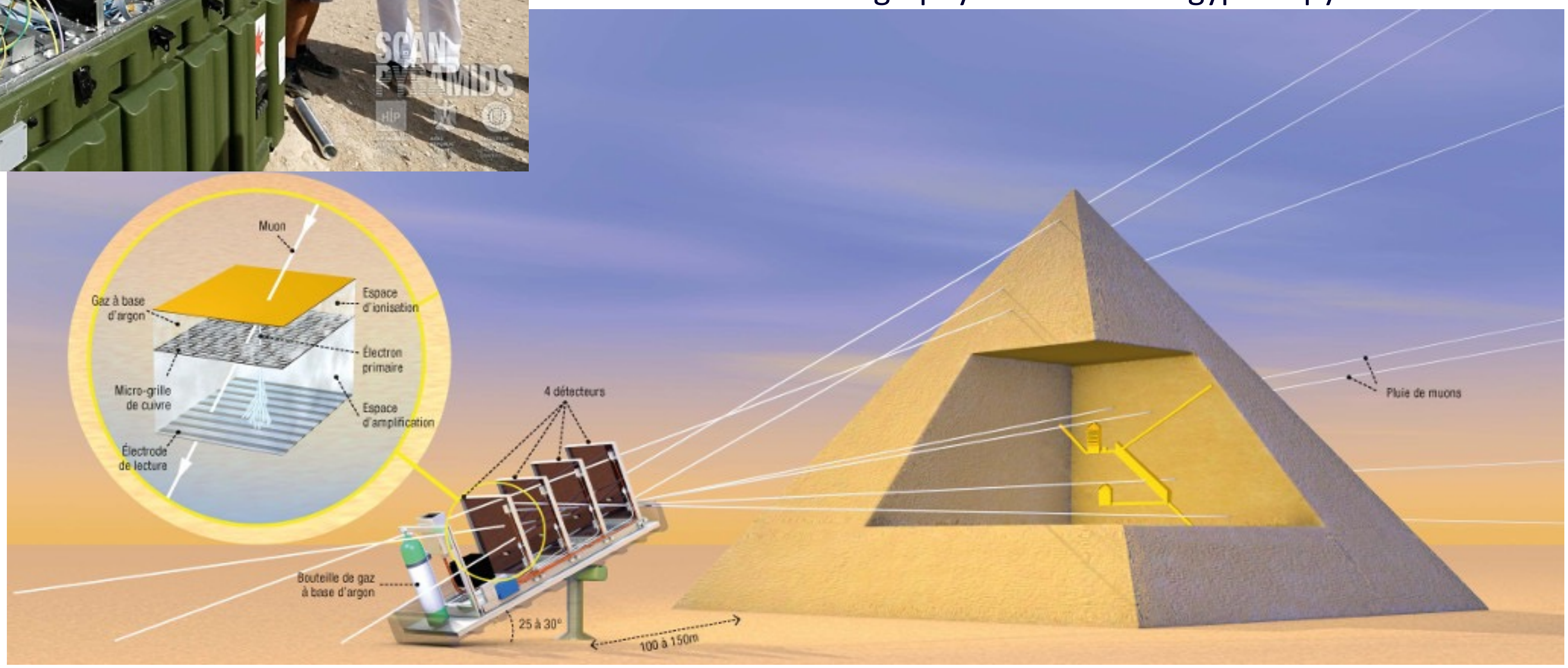
Science, April 28, 2022

Physics Today, June 2019

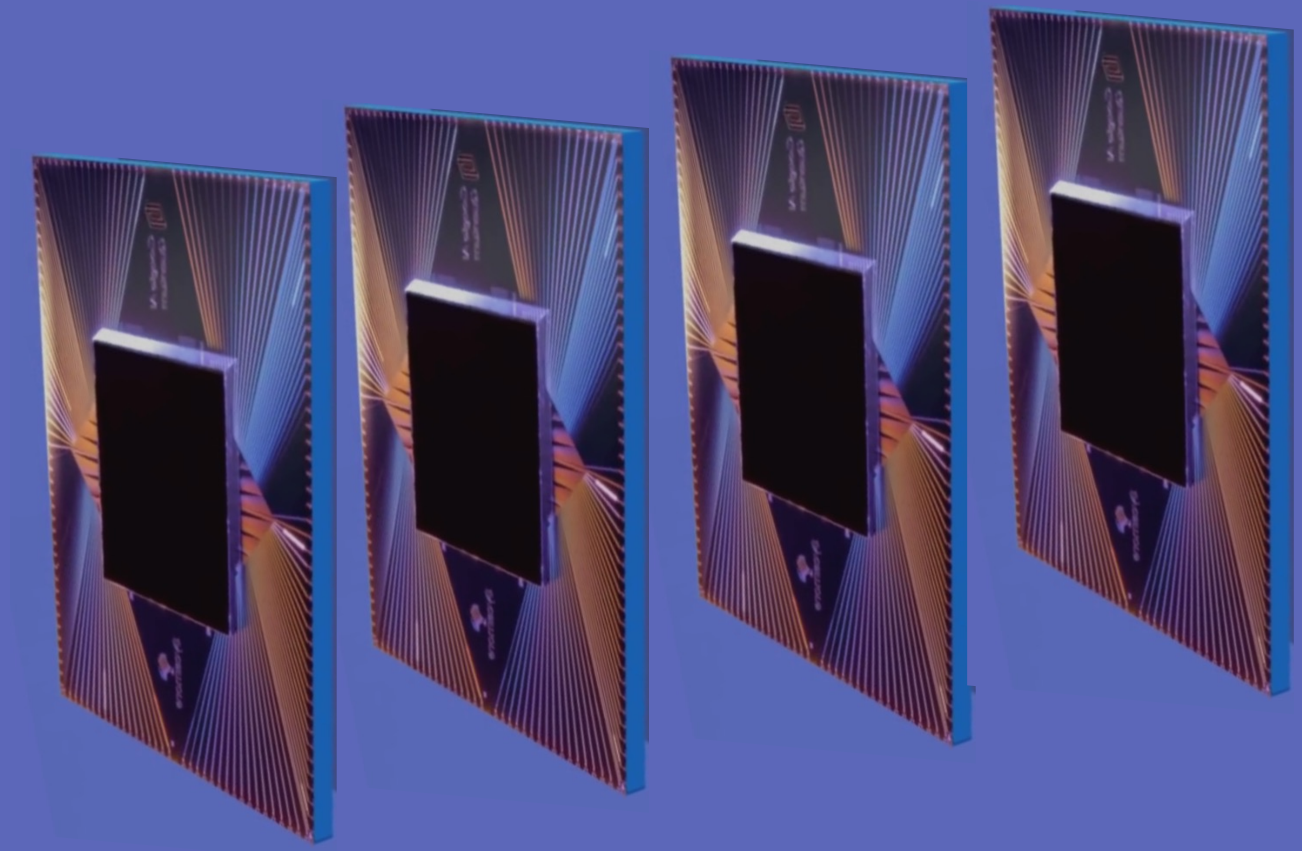
Analogy – plastic scintillators are used as cosmic muon detectors

CEA Muon Telescope

Muon tomography of interior of Egyptian pyramids

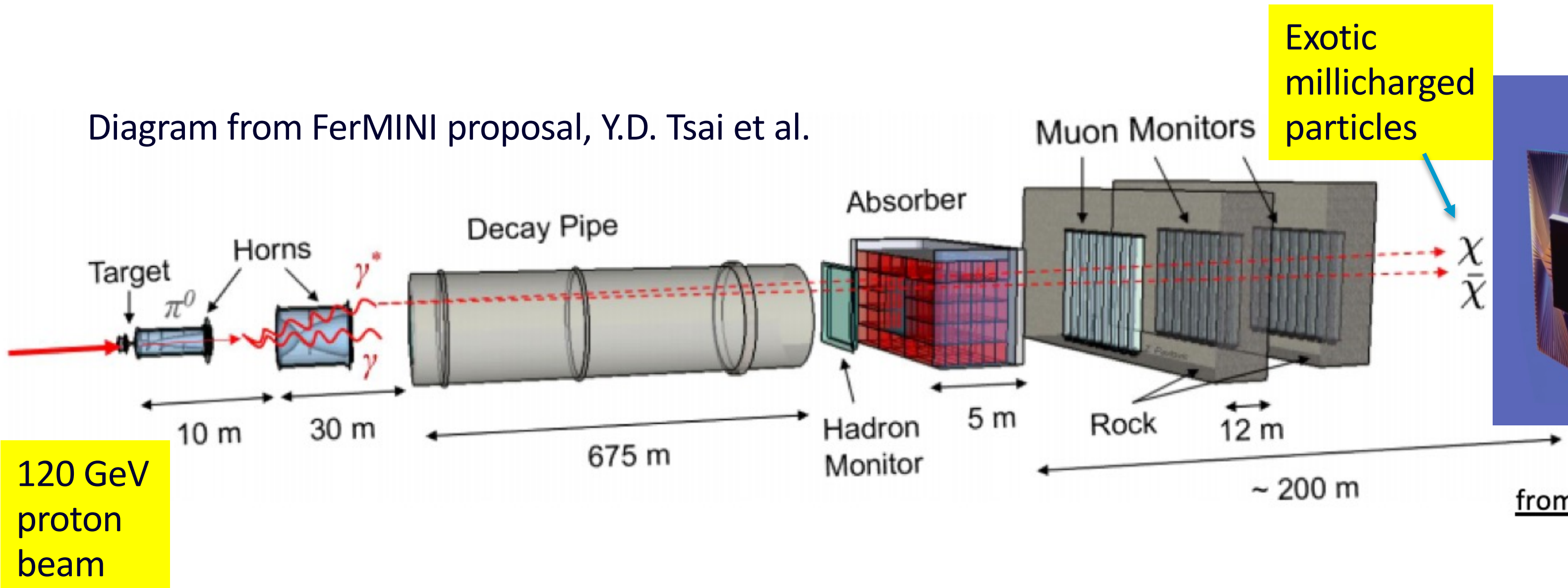


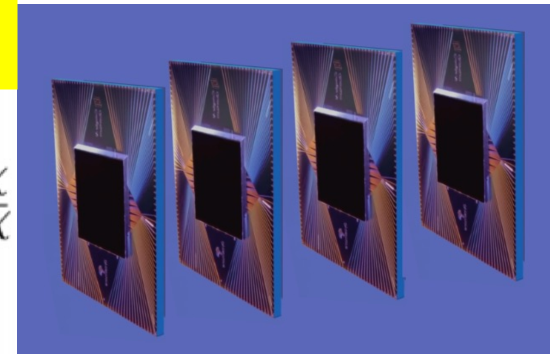
A lower threshold tracking detector?



The secret reason we've put qubits underground in Fermilab's neutrino beamline (Shh!)

Diagram from FerMINI proposal, Y.D. Tsai et al.





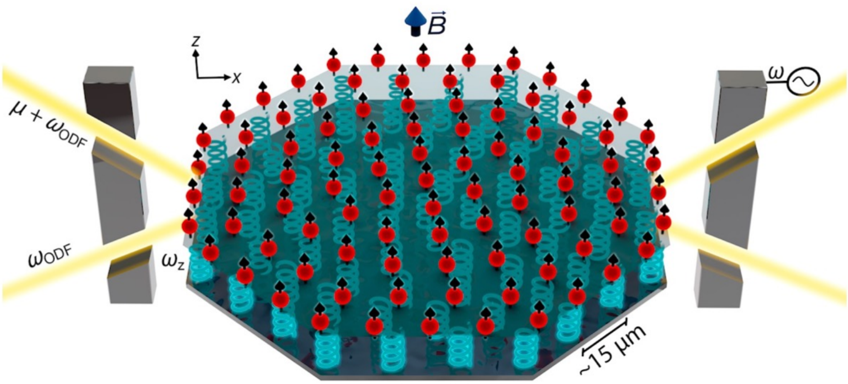
from 1812.03998, ***PRD version***

Not really the right tool for the job though.

Qubit chips only have small cm^2 cross-sectional collecting area.
Also no need for low threshold detector for high energy particles coming out of a beamline.

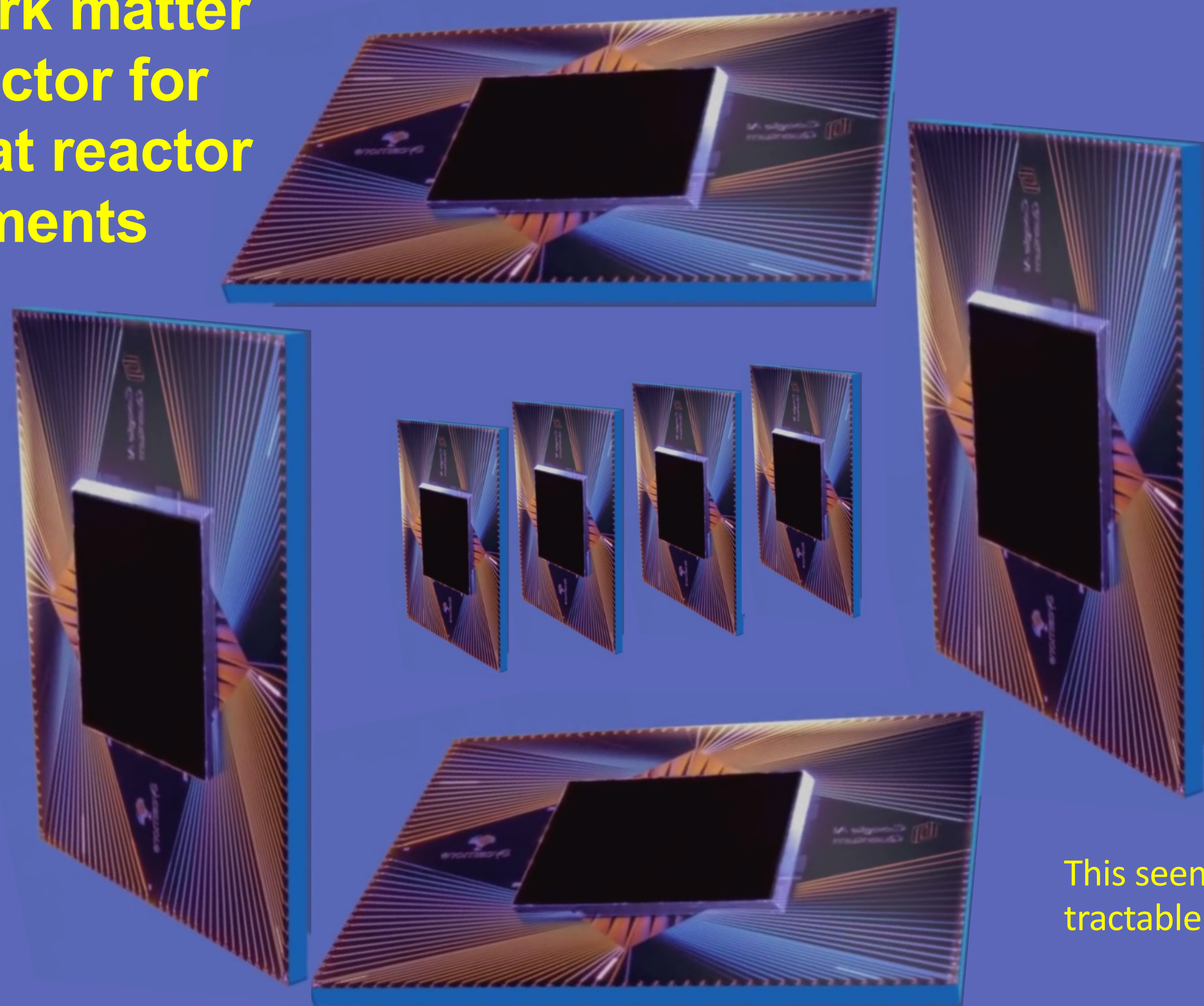
NIST trapped ion displacement sensor

Gilmore, et.al, Science 373, 6555, (2021)



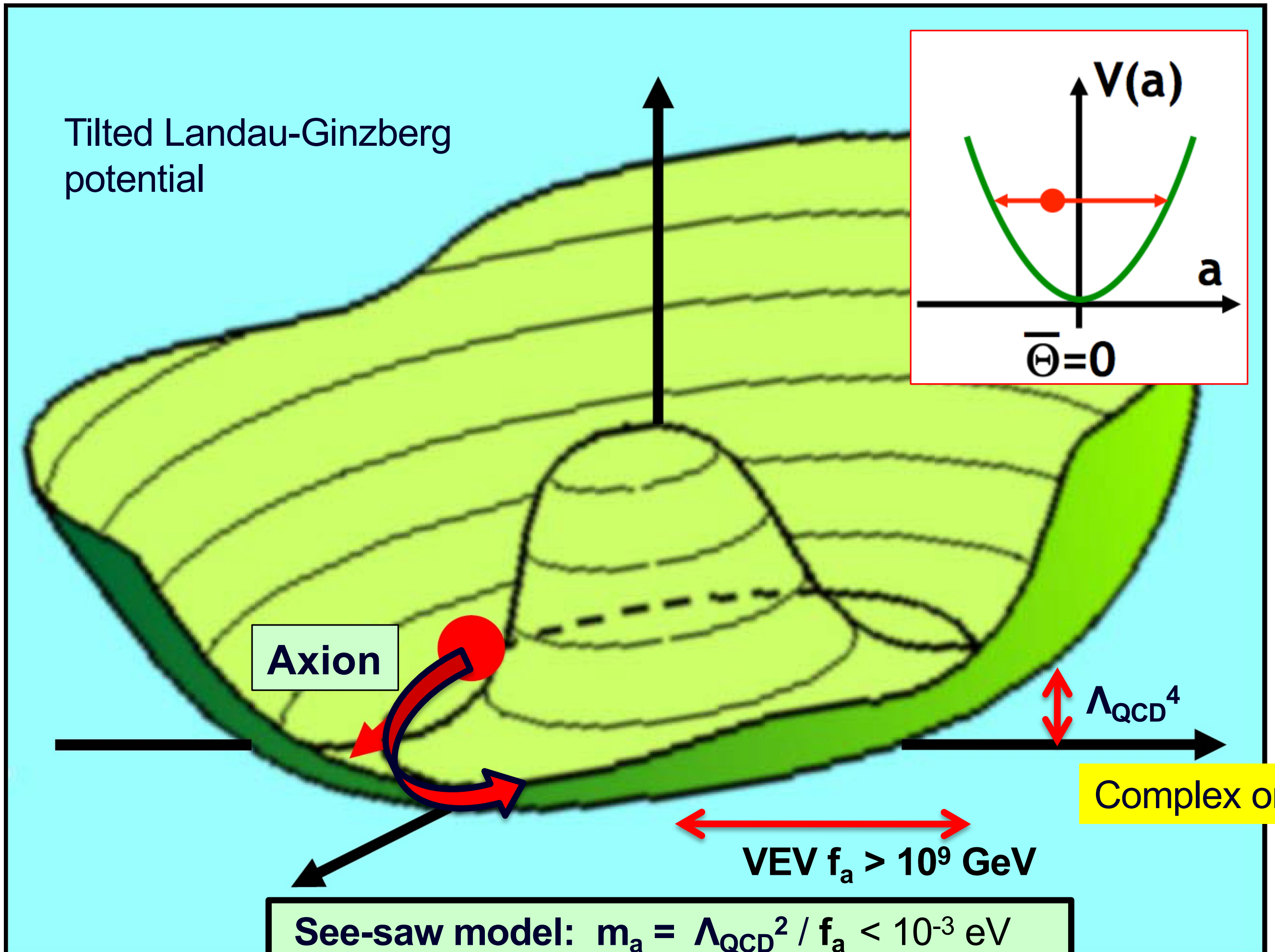
Co-locate accelerometer array with trapped ion system to efficiently transduce analog data prior to quantum template fitting?

Cosmic dark matter veto detector for CW beam at reactor experiments



This seems like a more tractable problem

Ex. QCD axions are oscillations of the CP-violating angle of the strong force



Neutron EDM zero'ed out at potential minimum

Complex order parameter field

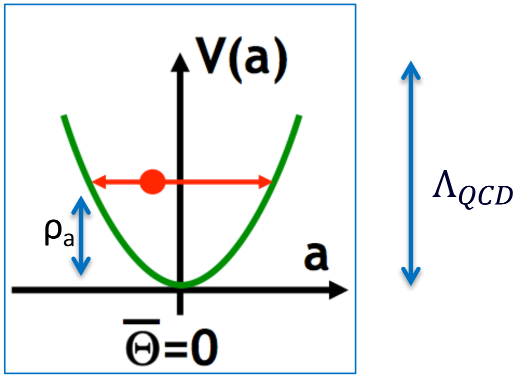
See-saw model: $m_a = \Lambda_{QCD}^2 / f_a < 10^{-3}$ eV
→ Coupling scale is dependent on mass.

Local dark matter density determines the amplitude of the coherent oscillation

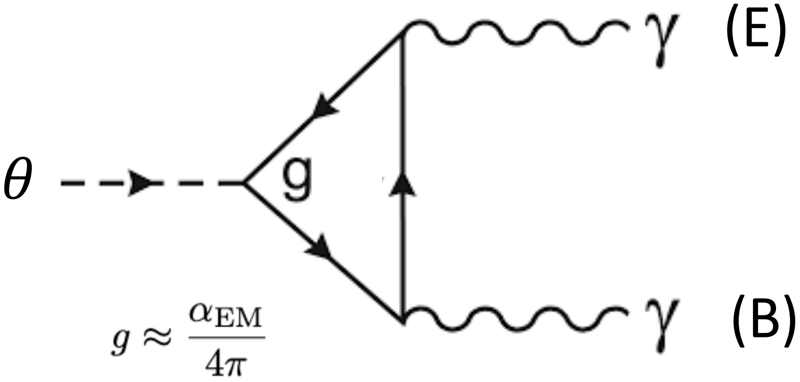
Locally coherent oscillation of the QCD $\boldsymbol{\theta}$ angle about its CP-conserving minimum:

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

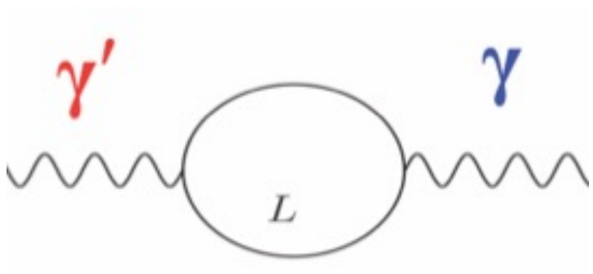
where $\theta_{\max} = \sqrt{\frac{2\rho_a}{\Lambda^4_{\rm QCD}}} \approx 3.7 \times 10^{-19} \text{radians}$



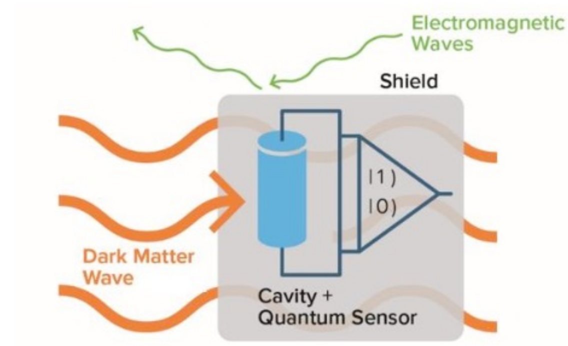
Topological magneto-electric effect:
Classically oscillating angle $\boldsymbol{\theta}$:
- **Rotates B-fields into E-fields**
- Creates ac nucleon EDMs
- Creates ac torques on fermion spins



Example 2: Exotic dark photons can mix with the visible photon

X_μ  A_μ

Heavy fermion loop



Interaction basis: $\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{m_{\gamma'}^2}{2}(X_\mu X^\mu - 2\chi A_\mu X^\mu + \chi^2 A_\mu A^\mu) + J^\mu A_\mu$

Tiny mixing angle χ so dark photons do not have much conventional photon component

→ Effective charge of electrons for coupling to dark photon = χe.

→ Dark photons fly right through your shielding and weakly interact with what's inside