Quantum Sensors

Daniel Bowring

HCPSS 2018

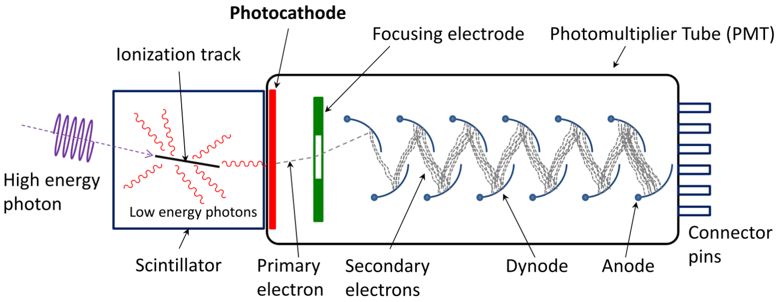
August 28, 2018

Talk outline

1. Approaches to photon detection
2. Motivation: axion dark matter
3. Qubits and quantum nondemolition
4. Proposed work (2018 DOE ECA)

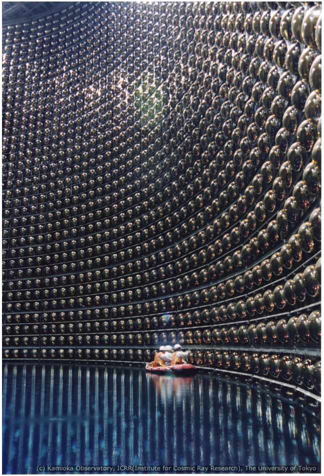
This is very interdisciplinary work. Links/references are included where possible in the event you want more depth.

Start with (probably familiar) PMTs



https://commons.wikimedia.org/wiki/File:PhotoMultiplierTubeAndScintillator.svg

PMTs for Super-Kamiokande



http://www-sk.icrr.u-tokyo.ac.jp/sk/gallery/index-e.html

PMT wavelengths are in the hundreds of nm.

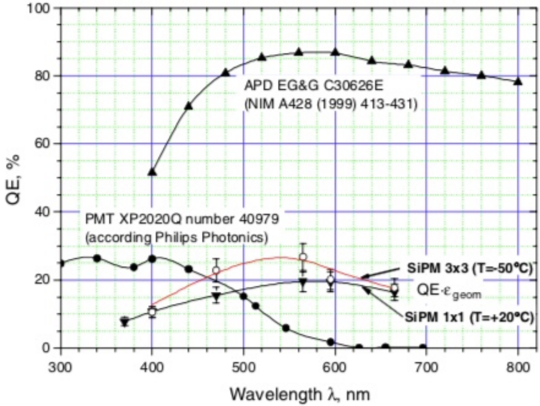


Fig. 1. Comparison of the photon detection efficiency for SiPM, APD and PMT.

B. Dolgoshein *et al.*, NIM-A **563** (2006) 368-376.

Silicon Photomultipliers (SiPMs)

Available online at www.sciencedirect.com

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ELSEVIER

Nuclear Instruments and Methods in Physics Research A 518 (2004) 560–564

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

Novel type of avalanche photodetector with Geiger mode operation

V. Golovin[a], V. Saveliev[b,*]

[a] Center of Perspective Technology and Apparatus, Moscow, Russia
[b] Obninsk State University of Nuclear Engineering, Obninsk, Russia

- Robust against B-fields
- Timing resolution ∼10s of ps
- ∼10s of kHz dark rate
- c.f. CMS HCAL upgrades, `http://cds.cern.ch/record/1481837/files/CMS-TDR-010.pdf`

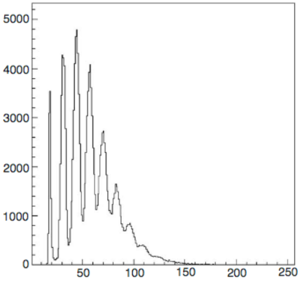
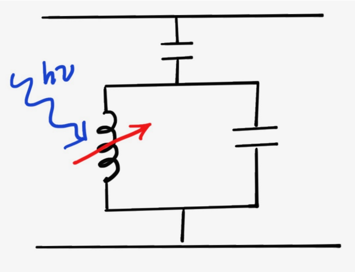


Fig 3. Low photons flux detected by SiPM.

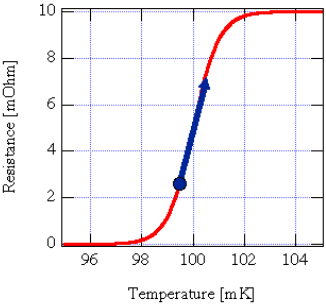
Low-flux spectrum, $\bar{n} = 12.93$. (This type of spectrum will come up again.)

Microwave Kinetic Inductance Detectors (MKIDs)



- `https://www.nature.com/articles/nature02037`
- "High"-Q superconducting resonator
- Incident photons generate quasiparticles, change surface impedance
- Look for phase shift in resonator
- Demonstrated for keV x-rays

Transition edge sensors



http://web.mit.edu/figueroagroup/ucal/ucal_tes/

- Near the superconducting gap, dR_s/dT is quite large.
- $\sim$ mK transition widths
- Near-IR detection efficiency $\sim$95%: https://ws680.nist.gov/publication/get_pdf.cfm?pub_id=32855

Skipper CCD

Javier Tiffenberg, 2018 DOE ECA

Single-electron and single-photon sensitivity with a silicon Skipper CCD

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Yann Guardincerri,[1,†] Steve Holland,[4] Tomer Volansky,[5] and Tien-Tien Yu[6]
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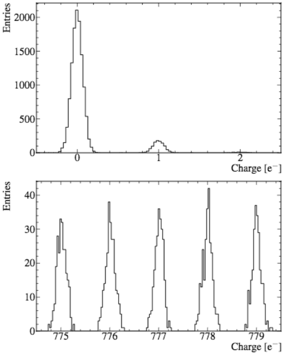
[6]*Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*
(Dated: June 2, 2017)

`arxiv.org/pdf/1706.00028.pdf`



- Multiple measurements of each pixel's charge
- Error prob. $\sim 10^{-13}$
- $10\ \mu s/\text{pix}/\text{amp}$

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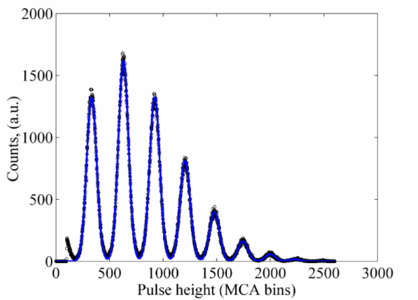
A quantum mechanics interlude



Lita *et al.*, 2008,
`https://ws680.nist.gov/publication/get_pdf.cfm?pub_id=32855`

Q: Why should we expect a photon spectrum that looks like this?

A: This is a feature of coherent photon states.

Coherent states are not eigenstates of the Hamiltonian. Consider eigenstate of a:

$$a|\alpha\rangle = \alpha|\alpha\rangle$$
$$|\alpha\rangle = \sum_n |n\rangle\langle n|\alpha\rangle$$
$$a|\alpha\rangle = \sum_n \alpha c_n|n\rangle$$

We can write a coherent state as a superposition of Fock states $|n\rangle$:

$$|\alpha\rangle = e^{-|\alpha|^2/2}\sum_n \frac{\alpha^n}{\sqrt{n!}}|n\rangle.$$

$|\alpha\rangle$ can be interpreted as the amplitude of n photons in a coherent state.

A: This is a feature of coherent photon states.

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_n \frac{\alpha^n}{\sqrt{n!}} |n\rangle.$$

So what is the probability of finding n photons in your state?

$$P_n = e^{-|\alpha|^2} \frac{|\alpha|^{2n}}{n!}$$

and this is a Poissonian distribution.

Editorial Interlude

- All these devices exploit important physical principles that cannot be described without quantum mechanics.
- (Does this make them quantum sensors? What is a quantum sensor?)
- These devices address photon energies > 1 eV. What if we need to go lower?
- It turns out we do need to go lower to look for...

Axion dark matter

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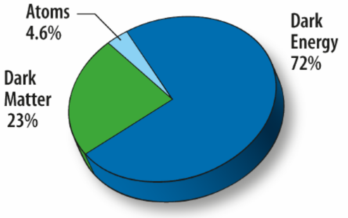
There's good evidence that baryonic matter is only 5% of the matter in our universe.

1. Velocity distributions of galaxies and clusters are unexpected.
2. Anomalous gravitational lensing.
3. There's too much mass in galactic clusters.



M. Hotz, PhD Thesis, U. Washington, Seattle, 2013.
https://arxiv.org/pdf/0803.0586.pdf
http://pdg.lbl.gov/2006/reviews/darkmatrpp.pdf
http://bustard.phys.nd.edu/Phys171/lectures/dm.html

The "Strong CP Problem" of QCD in one slide:

- Non-Abelian nature of QCD gauge transformations $\rightarrow$ infinite, degenerate potential energy minima (vacua) $|n\rangle$!
- Continuous transformations $|n\rangle \rightarrow |n+q\rangle$ are not possible, but tunneling is allowed.
- $|\theta\rangle = \sum e^{\imath n\theta}|n\rangle$ for $0 \leq \theta \leq 2\pi$.
- QCD Lagrangian gets a term $\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G^{\mu\nu a}\tilde{G}^a_{\mu\nu}$ that violates CP symmetry.
- $\bar{\theta} = \theta + \arg\det\mathcal{M}$ is *measurable*, *nonzero*, and *small*: $\bar{\theta} < 10^{-10}$.
- **The strong CP problem:** Why does $\bar{\theta}$ "just happen" to be so small?

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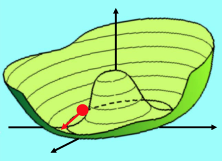
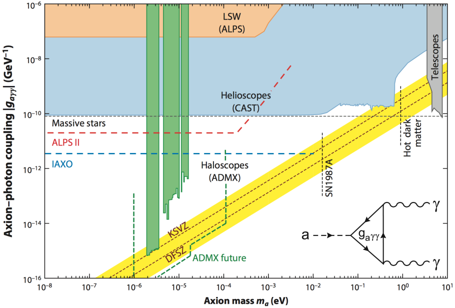
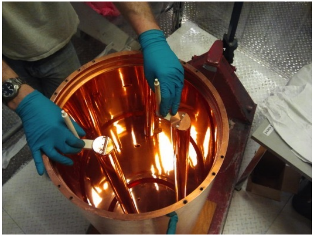
The axion is a proposed solution to the strong CP problem.



- Peccei & Quinn, Phys. Rev. Lett **38**, 1440, 1977.
- Spontaneously broken symmetry $\rightarrow$ new boson
- Axion field “tilts” the degenerate QCD vacuum, resulting in a CP-conserving minimum.
- Primordial universe cools below some threshold, PQ symmetry is broken. Resultant particles are “light dark matter”.

QCD axions: well-motivated, but the mass is not well-constrained





ADMX 500 MHz - 1 GHz "haloscope"

- $\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}$
- $P_{a\gamma\gamma} = g^2_{a\gamma\gamma}\frac{\rho_0}{m_a}B_0^2 V C_{nm\ell} Q_L \sim 10^{-23}$ W
- SN1987A give us an upper limit $m_a \sim 250$ GHz...
- μeV $< m_a <$ meV.

How to detect axions?

Maxwell's equations (theorist units):

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = \mathbf{J}_{\mathrm{EM}}$$

$$\nabla \cdot \mathbf{E} = \rho_{\mathrm{EM}}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0$$

Axions represent an extra source term in Maxwell's equations:

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = g \left(\mathbf{E} \times \nabla a - \mathbf{B} \frac{\partial a}{\partial t} \right) + \mathbf{J}_{\mathrm{EM}}$$

$$\nabla \cdot \mathbf{E} = \rho_{\mathrm{EM}} + g \mathbf{B} \cdot \nabla a$$

`http://arxiv.org/pdf/1310.8545.pdf`

How do you detect axions?

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = g\left(\mathbf{E} \times \nabla a - \mathbf{B}\frac{\partial a}{\partial t}\right) + \mathbf{J}_{\mathrm{EM}}$$

$$\nabla \cdot \mathbf{E} = \rho_{\mathrm{EM}} + g\mathbf{B} \cdot \nabla a$$

In the presence of a strong magnetic field B_0, axions give us an exotic current density $J_a = -gB_0\dot{a}$. Then we have a detection strategy:

1. Use a multi-Tesla B-field to convert axions into virtual photons.
2. Use a resonator to accumulate/detect the faint signal ($< 10^{-21}$ W) from photons.
3. Make the cavity *tunable*.

$a \to \gamma$ signal power

$$P_{\text{sig}} \approx 3 \times 10^{-25}\ \mathrm{W} \times \left(\frac{\rho_a}{0.3\ \mathrm{GeV/cm^3}}\right)\left(\frac{f}{10\ \mathrm{GHz}}\right) \times \left(\frac{B}{14\ \mathrm{T}}\right)^2 \left(\frac{V}{0.23\ \mathrm{L}}\right)\left(\frac{C_{nm\ell}}{0.4}\right)\left(\frac{Q}{10^4}\right)$$

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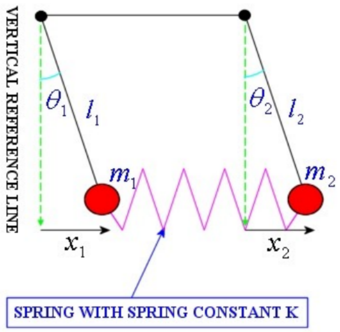
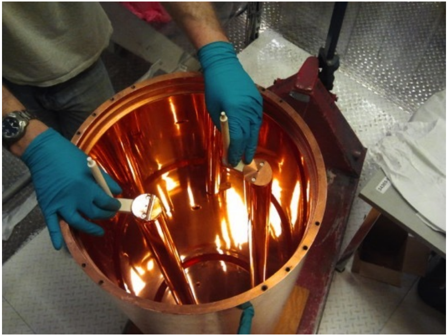
Resonant axion detection: an analogy

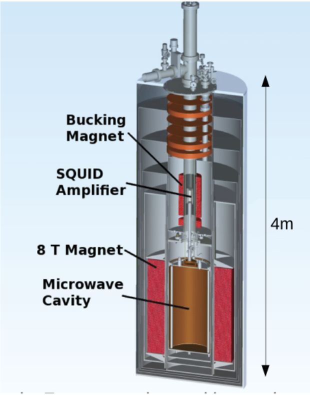
Accelerators use RF cavities to impart energy to particle beams. This is just the inverse problem: using RF cavities to extract energy from weak sources.



The Axion Dark Matter eXperiment (ADMX)



http://depts.washington.edu/admx/index.shtml



http://www.pnas.org/content/112/40/12278.full.pdf

Problem: $\mu\text{eV} < m_a < \text{meV}$

This is why the ADMX cavity is tunable. $Q_a \approx 10^6$. Recall

$$Q = \frac{\omega_0}{\delta\omega}$$

and the signal power $P_a \sim Q$.

- The axion mass must fall within the ADMX cavity bandwidth or we'll miss it! (And the cavity bandwidth can't be too low or we'll lose signal power.)
- We tune the cavity like a radio dial to "receive" the axion signal.

This is a major design challenge.

- How can you mechanically tune a large resonator over a wide frequency range without destroying the Q?
- Magnets are expensive. At higher frequencies, we need to pack more cavities into the same volume. Tuning problems compound. ("Swiss watch problem").
- Physics & EE challenges associated with detecting and amplifying a $< 10^{-23}$ W signal.

ADMX is the only axion search with DFSZ-compatible “discovery potential”.

PHYSICAL REVIEW LETTERS **120,** 151301 (2018)

Editors' Suggestion | Featured in Physics

Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment

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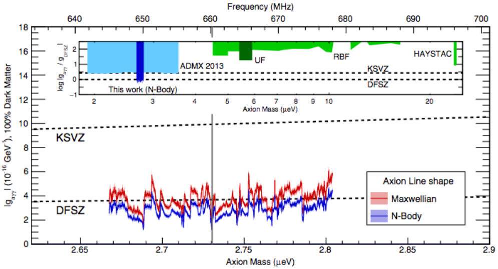
https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.120.151301



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To sum up:

- Axion searches require sub-eV photon detection.
- Axion signal is low-power, and noise is a concern.
- The next few slides will explain why we can't just scale the current experiment. We need a new kind of detector.

Let’s pause to check in.

Lower noise limit of one photon per resolved mode.

From Clerk *et al.*, `https://arxiv.org/abs/0810.4729`:

- Apply a gain G to a bosonic input mode a: $b = \sqrt{G}a + F$, for added noise $\mathcal{F}$.
- $[b, b^\dagger] = G[a, a^\dagger] + [F, F^\dagger]$
- Apply the generalized uncertainty principle: $(\Delta b)^2 \geq G(\Delta a)^2 + \frac{1}{2}|G - 1|$
- In the large-gain limit,

$$\frac{(\Delta b)^2}{G} \geq (\Delta a)^2 + \frac{1}{2}$$

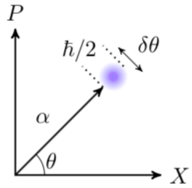
Linear amplifiers suffer from irreducible QM noise.

- **Standard Quantum Limit (SQL):** one photon per resolved mode
- Expressed as a rate:

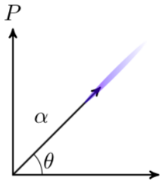
$$\frac{dN_{\mathrm{SQL}}}{dt} = 1 \times \Delta f = \frac{2f}{Q_a}$$

- The axion width means $Q_a \sim 10^6$.
- This is just a consequence of the Heisenberg uncertainty principle.

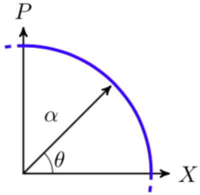
“Squeezed states” can help solve this problem.



(a) Coherent state, $\Delta P \Delta X \gtrsim \hbar/2$

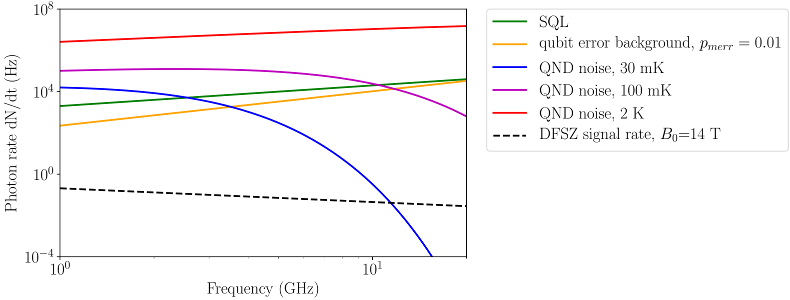


(b) Squeeze in phase, θ



(c) Quantum nondemolition

Quantum nondemolition



- We can circumvent the SQL using a technique called *quantum nondemolition*.
- If we are successful, the dominant noise source will be the system's blackbody photons.

Stark Effect in quantum mechanics

Hydrogen atom perturbed by an electric field $\vec{E} = E\hat{z}$:

$$H = \frac{p^2}{2m_e} - \frac{e^2}{4\pi\epsilon r} + e|\vec{E}|z.$$

Solve using perturbation theory to find

$$\Delta E = -\frac{1}{2}\alpha|\vec{E}|^2$$

where

$$\alpha = 2e^2 \sum \frac{|\langle n\ell m|z|n'\ell' m\rangle|^2}{E_{n'\ell' m'} - E_{n\ell m}}$$

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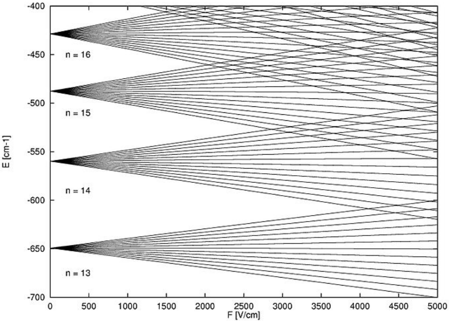
The consequence of this is a field-dependent level-splitting.



M. Courtney, `commons.wikimedia.org/wiki/File:Hfspec1.jpg`

Similar problem: two-level "atom" weakly coupled to a harmonic oscillator

$$H = \hbar\omega_r(a^\dagger a + 1/2) + \hbar\omega_q\sigma_z/2 + \frac{\hbar g^2}{\Delta}(a^\dagger a + 1/2)\sigma_z$$

with $\Delta = \omega_q - \omega_r$. We'll assume weak coupling $g \ll \Delta$.

- Weak coupling $\rightarrow$ photon not absorbed by "atom".
- Note that the final term commutes with the others.
- This is the *Jaynes-Cummings Hamiltonian*.

Rewrite JC Hamiltonian suggestively.

$$H = \hbar\omega_r(a^\dagger a + 1/2) + \hbar\omega_q\sigma_z/2 + \frac{\hbar g^2}{\Delta}(a^\dagger a + 1/2)\sigma_z$$

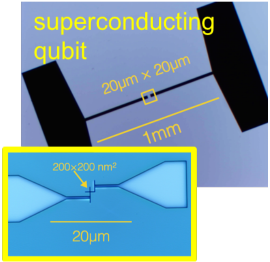
$$H = \hbar\left(\omega_r + \frac{g^2\sigma_z}{\Delta}\right)(a^\dagger a + 1/2) + \hbar\omega_q\sigma_z/2$$

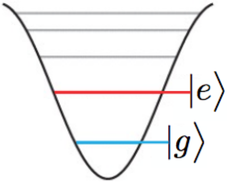
so $\omega_r \to \omega_r \pm g^2/\Delta$. Or, similarly,

$$H = \hbar\omega_r(a^\dagger a + 1/2) + \frac{\hbar}{2}\left(\omega_q + 2\frac{\hbar g^2}{\Delta}a^\dagger a + \frac{g^2}{\Delta}\right)\sigma_z.$$

This is effectively an AC Stark shift in the atom transition frequency $\omega_q \to \omega_q + 2\bar{n}g^2/\Delta$.

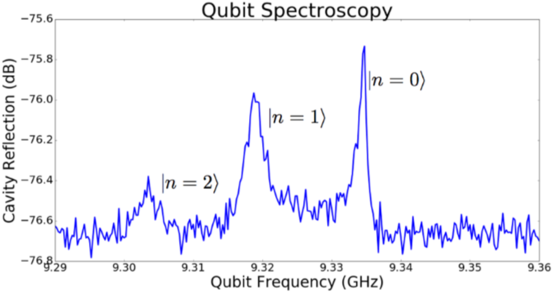
Choice of “atoms” not limited to atoms.





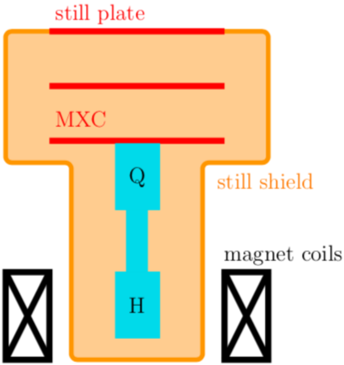
$$\omega_q = E_1 - E_0$$

Probing the qubit state $|n\rangle$ by observing a frequency shift in the cavity



Observation of $|n\rangle$ through 15 MHz dispersive frequency shift.

Measurement cartoon



Thermal background Boltzmann-suppressed via 10 mK He dilution refrigerator, funded through Fermilab LDRD.

Our current challenge: mitigate dark rates

- Our qubits show false positives w/ $p_{\mathrm{err}} \sim 0.01$.
- To improve, require N-qubit concordance: $p_{\mathrm{err}} \to (p_{\mathrm{err}})^N$.
- N-qubit readout is an R&D challenge we'll tackle in the coming years.

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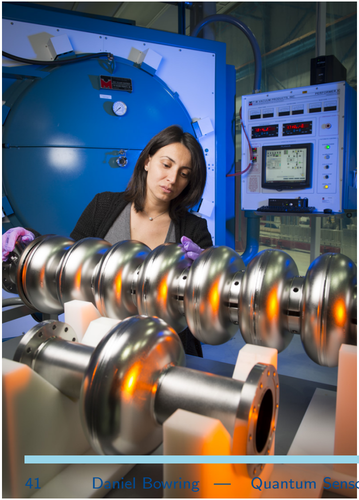
Other interesting QIS work happening at Fermilab, too.



- A. Grassellino and A. Romanenko apply high-Q SRF cavity technology to the problem of qubit coherence.
- Atom interferometric probes of spacetime curvature: https://arxiv.org/pdf/1610.03832.pdf.

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Acknowledgements

Much of the qubit development work shown here is by Akash Dixit, a U. Chicago grad student in the Schuster Lab (`http://schusterlab.uchicago.edu/`).

- Collaborators: Ankur Argawal, Aaron Chou, Konrad Lehnert, Reina Murayama, David Schuster.
- ADMX Collaboration
- You, for listening!