Brief Overview of the Axion Dark Matter Experiment

New Perspectives

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LLNL-PRES-XXXX
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Outline of Today's Talk

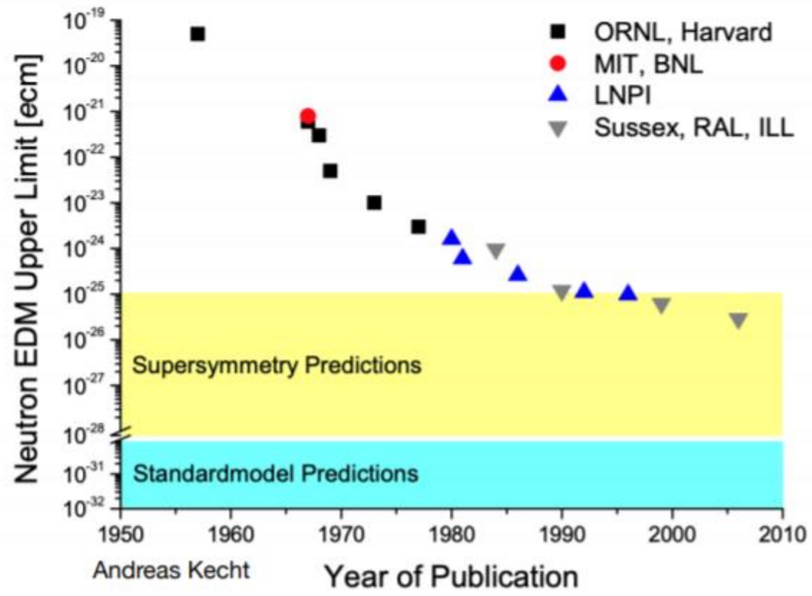
- What are axions?
  - Strong CP Problem
  - Dark Matter
  - Coupling to photons
- How the ADMX currently operates
  - Haloscopes
  - Scanning Cadence
  - Current Limits
- Future ADMX run plans
  - Multi-Cavity Systems
  - SRF cavities (My work)

ADMX Run 1B pullout procedure at CENPA

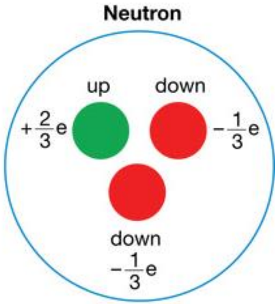
Run 2A 4-Cavity System assembly at LLNL

What are axions?:
The Strong CP problem in experiment

- CP violation in strong force → measurable neutron electric dipole moment (EDM). Theory predicted to be ~ 10^{-18}e m.
- Experiments constrain the neutron EDM close to zero implying CP conservation ($\theta_{QCD} = 0$)
- Fine-tuning problem "Everything not mandatory, is compulsory" –Murray Gell-Mann (1956?)[1]



$$L_\theta = \frac{g^2}{32\pi^2}\theta_{QCD} F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$$



$$d_n \approx \theta_{QCD}\, e \frac{m_q}{m_n^2}$$

$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26} e{\cdot}cm$$

[1]Helge, Kragh. https://arxiv.org/ftp/arxiv/papers/1907/1907.04623.pdf
[2] C. Abel et al. Phys. Rev. Lett. 124, 081803 — Published 28 February 2020

What are axions?:
Peccei-Quinn Symmetry and the Axion

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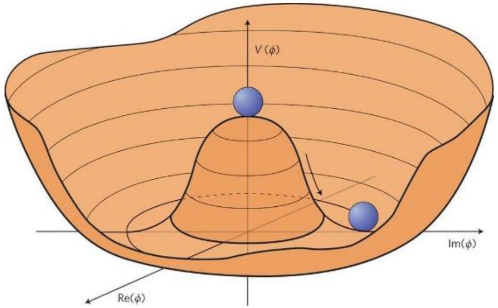
- Peccei-Quinn Solution to Strong CP Problem
  - New global U(1) chiral symmetry spontaneously broken in the early universe
  - θ_{QCD} is a dynamical variable which relaxes to zero when the wine bottle potential tips
- Weinberg and Wilczek:
  - PQ Symmetry produced a pseudo scalar boson which is the **axion!**
  - f_a , the symmetry breaking energy scale, was assumed at the electroweak level (250 GeV)
  - Quickly ruled out by reactor experiments and f_a became an open parameter

$$\mathcal{L}_a := -\frac{1}{2}\partial_\mu a \partial^\mu a - \mathcal{L}_{int}(\partial_\mu a;\psi) + (\frac{a}{F_a}\xi + \bar{\theta})\frac{g^2}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

$$\bar{\theta} = \frac{a}{F_a}\xi$$



Wine Bottle/ Sombrero potential.

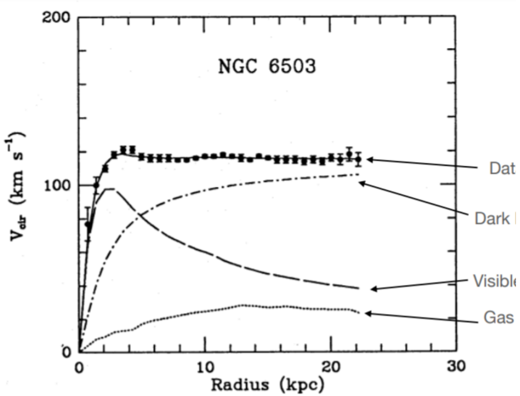
$$m_a \cong 57\mu eV\left(\frac{10^{11}\ GeV}{f_a}\right)$$

Roberto Peccei 1942-2020

Helen Quinn

What are axions?:
The Dark Matter Problem and Axions

Dark Matter	Axions
Feebly-interacting with Photons	✓
Gravitationally interacting	✓
Non-baryonic	✓
Very stable	✓
Cold (non-relativistic)	✓



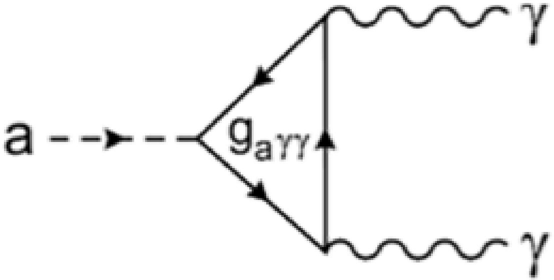
[3] K. G. Begeman, et all, Extended rotation curves of spiral galaxies: dark haloes and modified dynamics (1991) https:// doi.org/10.1093/mnras/249.3.523


[4] Bullet Cluster. Blue-Dark Matter. Pink-Matter
X-RAY: NASA/CXC/CFA/M.MARKEVITCH ET AL.

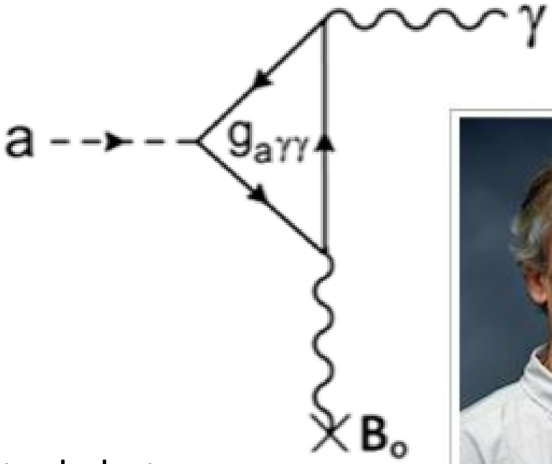
- The Dark Matter hypothesis is now well accepted, and its density can been mapped (GAIA satellite[5]). The question remains for a direct EM detection of one of the DM candidates.
- Axions can constitute the entirety of dark matter: $m_{axion} \sim 1 - 100\ \mu\mathrm{eV}$
- A particle created to solve a discrepancy in physics **theory**, solves an **experimental** discrepancy as well.

[5] https://iopscience.iop.org/article/10.1088/1475-7516/2019/04/026

What are axions?
Coupling to photons and detection schemes



$$\mathcal{L}_{A\gamma\gamma} = -g_{A\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B}\phi_A$$

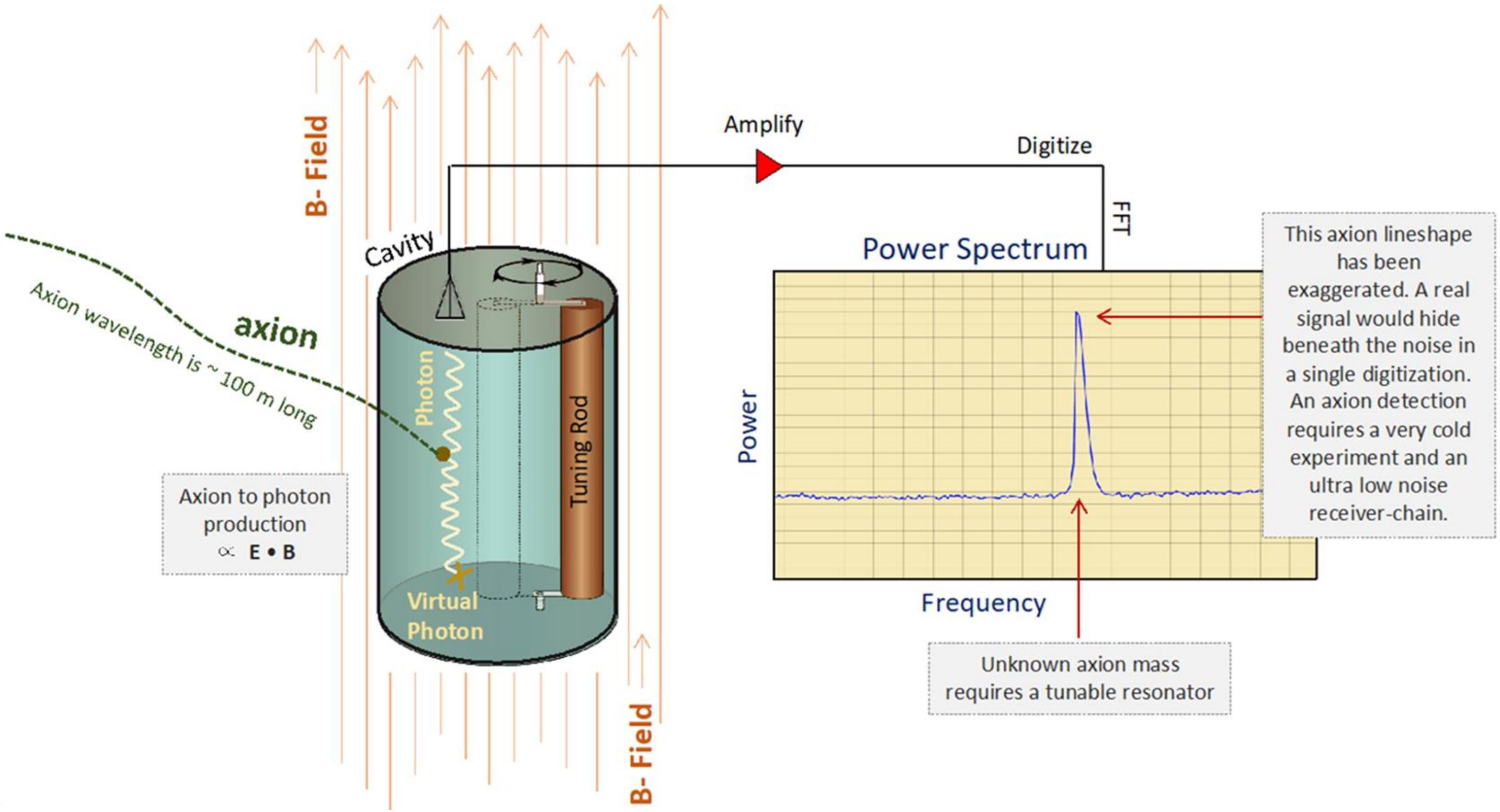


Pierre Sikivie

- Axions decay to photons via **inverse Primakoff effect**

- 1983 Pierre Sikivie: using a high static magnetic field as a virtual photon:
  - Axion 'Halo'-scopes would look for cold axions in the dark matter halo (velocity with respect the speed of light , $\beta{\sim}10^{-3}$) from RF photons
  - Axion 'Helio'-scopes could look for solar axions but resultant photons would be X-rays (β is larger)

How does ADMX currently operate?
The Axion Haloscope



How does ADMX currently operate?
Axion Power Equation

$$P_{axion} = 2.2 \cdot 10^{-23} W \cdot \{(\frac{g_\gamma}{0.36})^2 \cdot \frac{\rho_0}{0.45\ GeV\ cm^{-3}} \cdot \frac{f}{740\ MHz}\} \cdot \{\frac{V}{136\ L} \cdot \left(\frac{B_0}{7.6\ T}\right)^2 \cdot \frac{Q_L}{30000} \cdot \frac{C_{lmn}}{0.4}\}$$

$$SNR = \frac{P_{axion}}{kT_{sys}} \sqrt{\frac{t}{\Delta f}}$$

Model- Dependent Parameters

- g_γ – Coupling Constant
- f – Axion frequency
- ρ_0 – Dark matter halo density

Experimental Parameters

- B_0 – External magnetic Field
- V – Cavity volume
- Q_L – Cavity quality factor
- C_{lmn} – Cavity form factor
- SNR – Signal-to-noise
- T_{sys} – System noise temperature
- t – Integration time of FFT
- Δf – Bandwidth of FFT

How does ADMX currently operate?
Axion Scan Rate Equation

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$$\frac{df}{dt} \approx 1.98\frac{GHz}{year}\boxed{\left(\frac{g_\gamma}{0.36}\right)^4\left(\frac{f}{1\ GHz}\right)\left(\frac{\rho_0}{0.45\frac{GeV}{cc}}\right)^2}\cdot\boxed{\left(\frac{5}{SNR}\right)^2\left(\frac{B_0}{7.6T}\right)^4\left(\frac{V}{136l}\right)^2\left(\frac{Q_L}{30{,}000}\right)\left(\frac{C_{lmn}}{0.4}\right)^2\left(\frac{0.35K}{T_{sys}}\right)^2 *}$$

Combining signal power with SNR we can arrive at **the instantaneous scan rate** for a haloscope

*Does not include deadtime (Candidate rescans, engineering studies, COVID-19, etc.)

Experimental Parameters
- B_0 – External magnetic Field
- V – Cavity volume
- **Q_L – Cavity quality factor**
- C_{lmn} – Cavity form factor
- SNR – Signal-to-noise
- T_{sys} – System noise temperature
- t – Integration time of FFT
- Δf – Bandwidth of FFT

Model- Dependent Parameters
- g_γ – Coupling Constant
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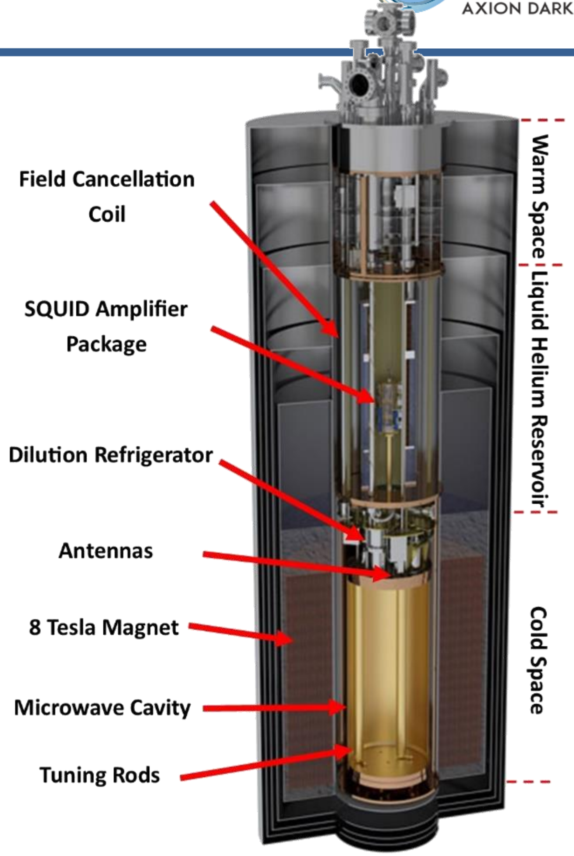
How does ADMX currently operate?
ADMX Insert

- ADMX insert has many systems to optimize scan rate
  - 8T magnet with 0.5 M bore→ maximize B^2V
  - Helium Dilution Refrigerator → minimize T_{sys}
  - Quantum Amplifiers→ amplify signal
  - Copper cavity resonator→ High Q in field
  - Cavity tuning rod system→ maximize run length
- These systems are then supported by more systems
  - Bucking Coil
  - RF layout to digitization
  - Helium Liquefaction plant
  - Great Science Operators!

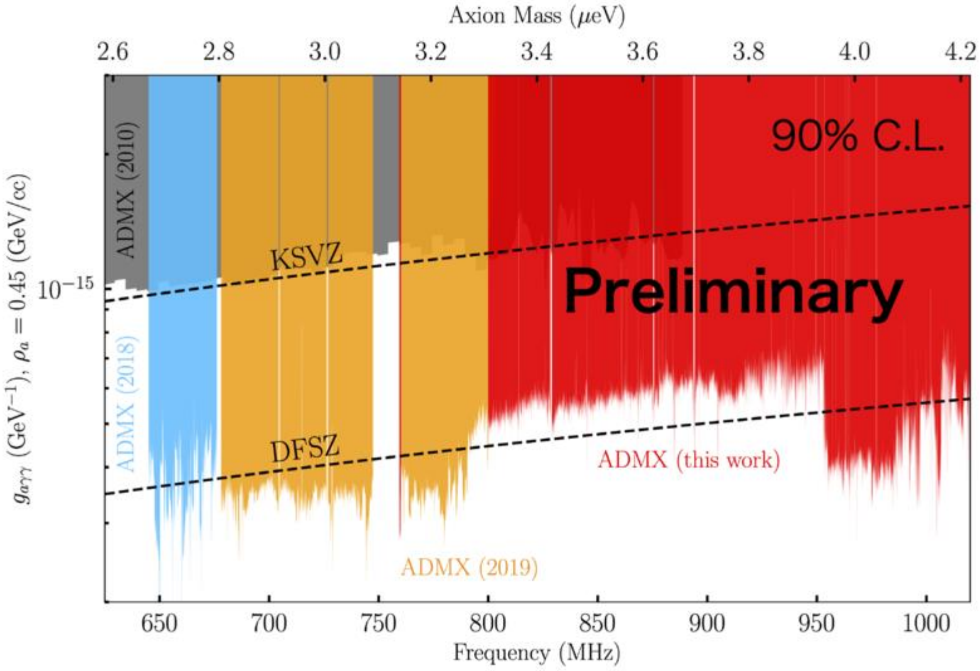


How Does ADMX Operate?
Experimental Cadence

1. The cavity frequency is scanned over a region until the desired SNR is achieved
2. We then examine the combined power spectrum for signs of excess
3. Excess power regions can be statistical fluctuations, synthetically injected signals, RF interference, or axions
4. Excess power regions are rescanned to see if they persist
5. Persistent candidates are subjected to confirmation tests (Ex: scan outside cavity or ramp magnet)

How does ADMX currently operate?
Current and Future Limits

- No Axions detected yet! We set exclusion limits
- ADMX G2 has excluded axions at DFSZ sensitivity for first two runs(~2.7- 3.3 μeV)
- Run 1C just concluded (June 2021), and due to COVID operating constraints, we only excluded to DFSZ for some of the range
- Gaps are due to cavity mode crossings
- The current cavity will retire after the next run, 1D!



Current Axion Limits set by ADMX G2

Future of ADMX

Challenges at Higher Frequencies

- Combine multiple smaller cavities with a higher $f_{\mathrm{TM}_{010}}$ to maintain volume (scaling issue for RF layout however)
  - Side benefit: $\sqrt{N}$ improvement to SNR from coherently adding N cavities in phase (PNNL cavity combining electronics)

- Bigger and stronger magnets are expensive (Fermilab acquiring 9T MRI magnet)

- Limited ability to cool further (Possibility of squeezing quantum states to circumvent standard Quantum limit)

- Quality factor goes down for ordinary metals
  - Volume to surface ratio
  - Anomalous skin depth

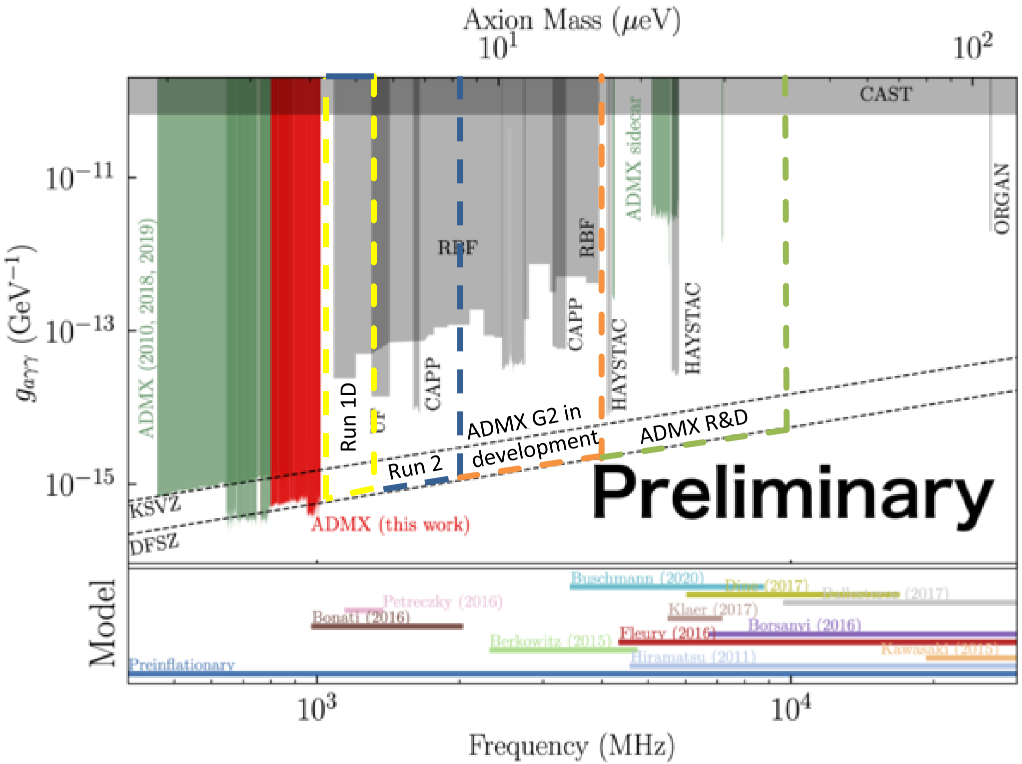
- My graduate work is looking at Superconducting cavities to improve Quality factor. This is tricky in high magnetic fields!

Run 2A 4-cavity system @ LLNL

The Future of ADMX

<u>Top Left</u>: Run 1 Single Copper Cavity, in operation to 1.2GHz

<u>Top Right</u>: Proposed 14 cavity array in development, potentially **Superconducting (SRF)**, covering 2-4 GHz.



Planned coverage of Axion parameter space

Thank You! Questions?

ADMX
AXION DARK MATTER EXPERIMENT

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