fERMILAB-SLIDES-20-049-E

AXION DARK MATTER EXPERIMENT

Tuning the axion radio with Axion dark matter experiment (ADMX)

Fermilab, New Perspectives

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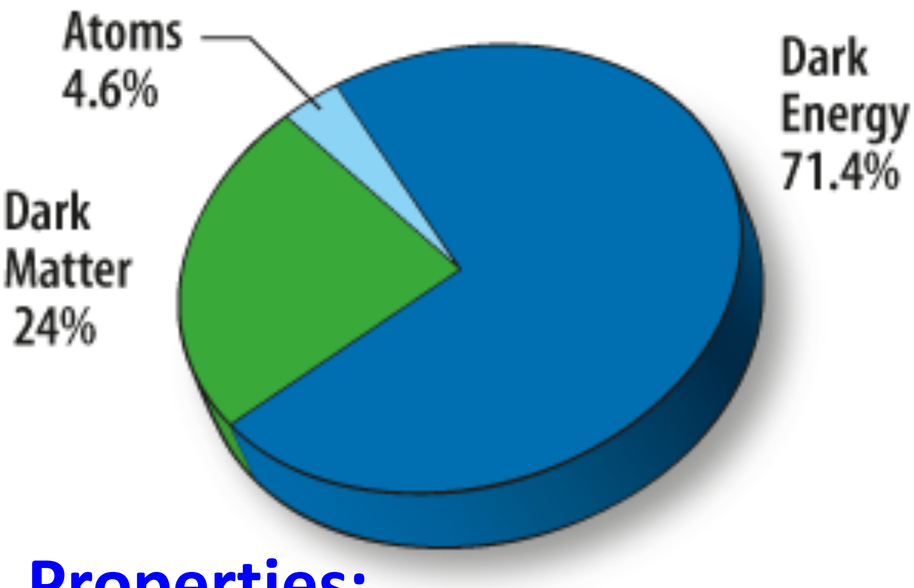
ADMX
AXION DARK MATTER EXPERIMENT

Dark Matter



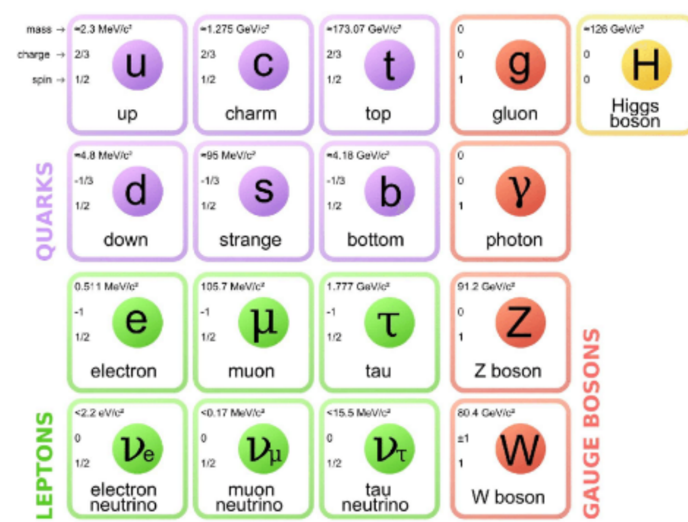
*Makes up large structures of the universe – **forms clumps – cold dark matter**

*Axions will be the lightest particle

Properties:

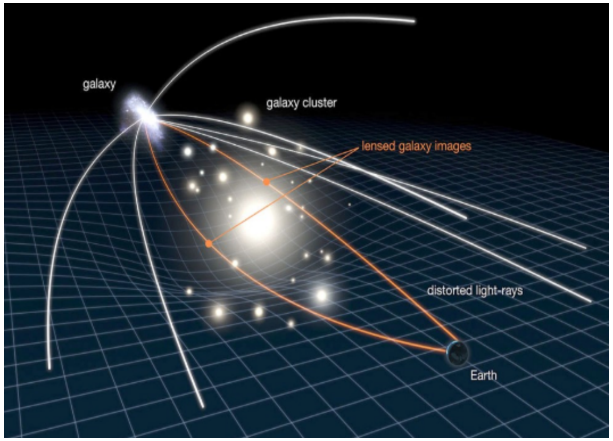
*Non-standard model particle

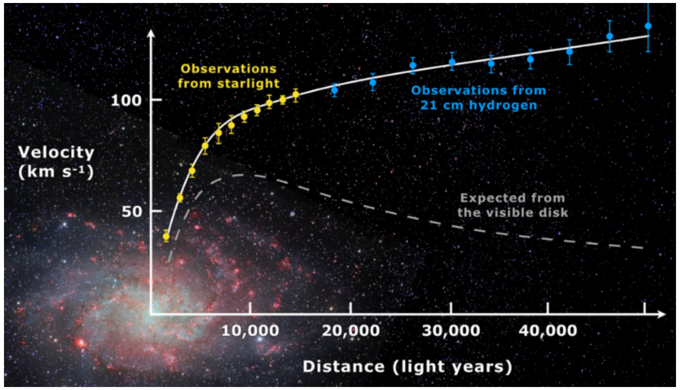
***Weakly interacting** – can't be detected with traditional observational astronomy tools – doesn't reflect, absorb or emit light



Evidence of dark matter

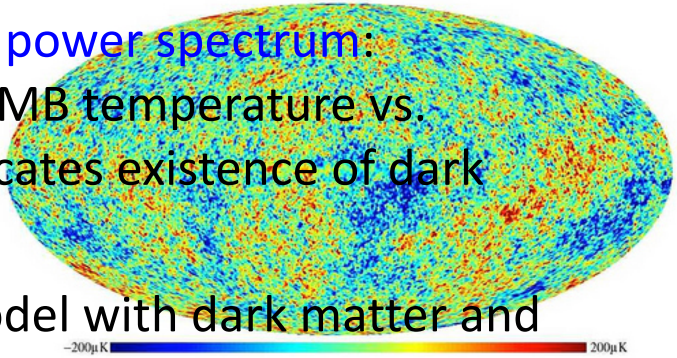
*Gravitational lensing: Light bent by galaxies

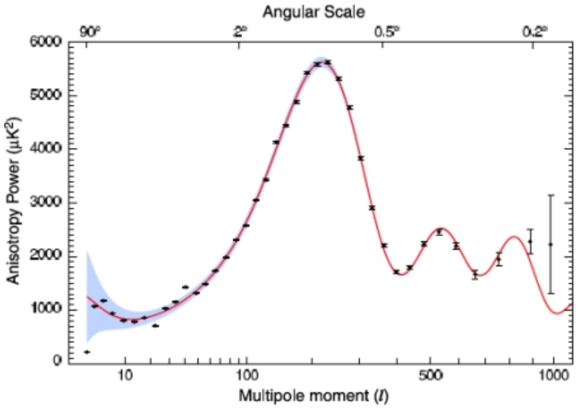




*Galaxy clusters/rotation curve: Orbital speed of galaxy and stars vs. distance from the center

*Shape of the CMB power spectrum: fluctuation of the CMB temperature vs. angular scale – indicates existence of dark matter

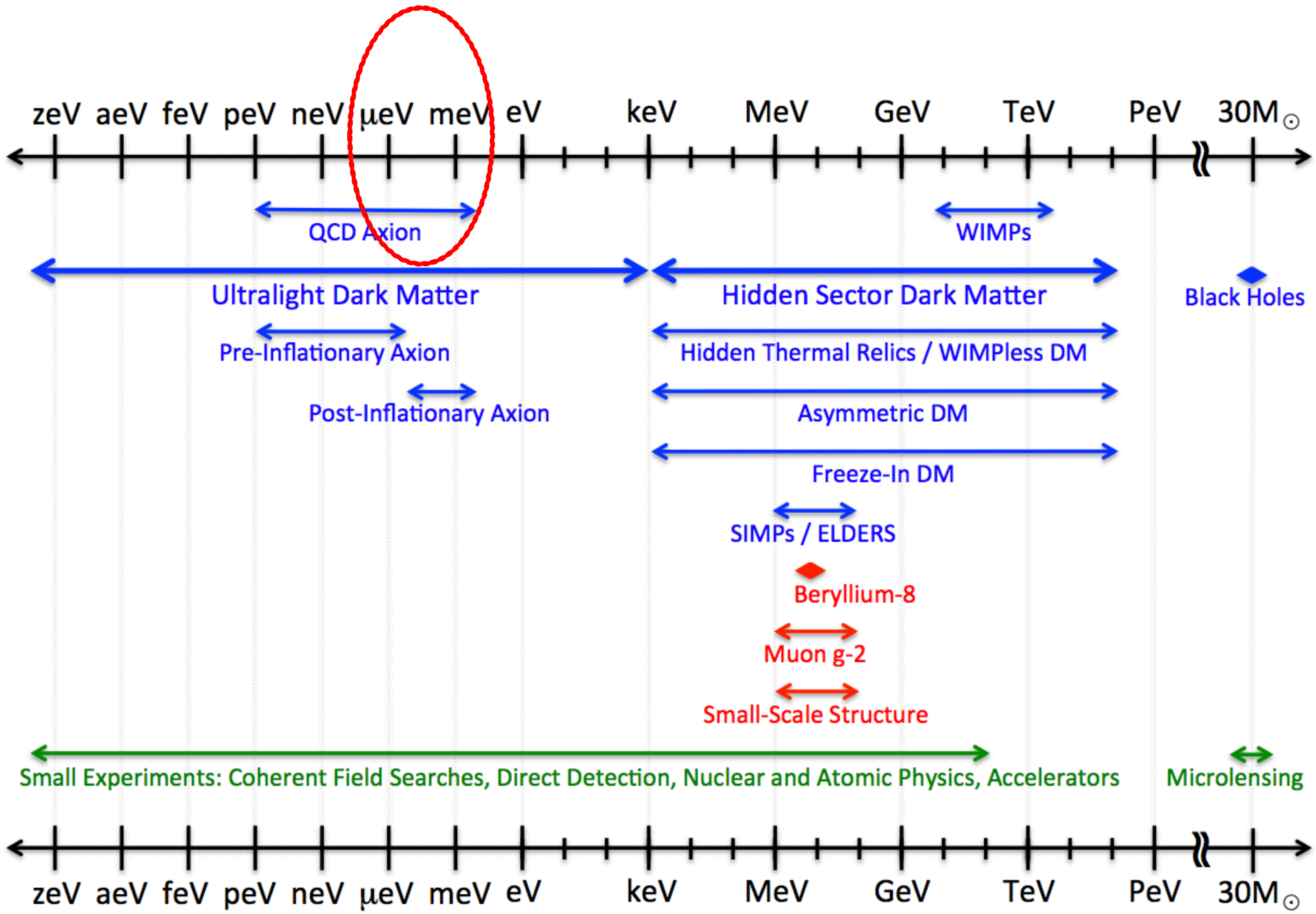




*Comparison of model with dark matter and observation matches

NASA, Bosma, A (1987), Corbelli, E. Salucci, P. (2000)

Dark Matter parameter space



US Cosmic vision

Axion

Frank Wilczek

Big Bang

→Axion produced ~ inflation

→Theoretically motivated

-- Strong CP problem

→Standard Model QCD -- CP violating parameter θ (0-2π)

→θ≠ 0 => CP violation in Strong Int. => neutron's electric dipole moment $d_n \neq 0$

→Experimental upper limit on d_n very small

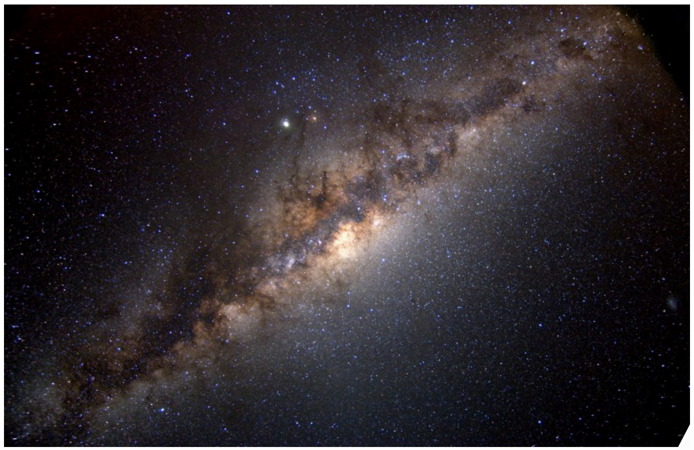
=> θ really really small ! => Strong CP problem

Θ promoted to a field (Peccei-Quinn theory)

--adding new U(1) global symmetry to the SM--that gets spontaneously broken

→ Axion associated particle

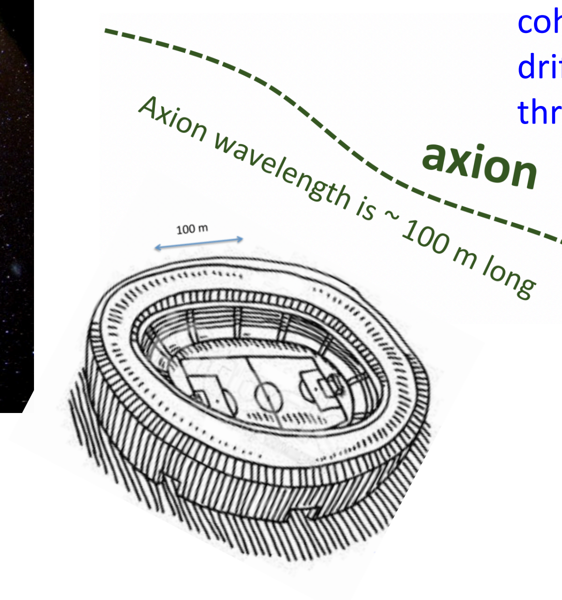
Axion in the galactic halo



- *Produced around inflation*
- *Big bang-> Milkyway halo-> gravitational potential-> Maxwell Boltzmann distribution of v (**mean 10^{-3}c ~ local virial velocity)***
- *# density local galactic halo ≈ 10^{14} cm^{-3}*

-- (ρ= 450 MeV/cm^3)

- ❑ *Lifetime 10^{42} years!*



β_{virial} (local galactic) ~ 10^{-3}c :

$\lambda_{\text{De Broglie}}$ *(coherent) ~ 100 m,*

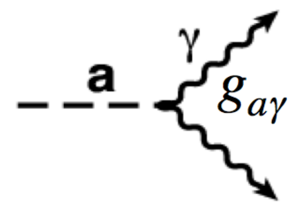
Football stadium sized clumps of coherently oscillating axions drifting
through the detector

Oscillating electric current
In external **B**

$$\boldsymbol{J_a}(t) = g_{a\gamma}\boldsymbol{B_0}a_0e^{-i\omega t}$$

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

$m_a c^2 = h\nu$



$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma}a\vec{E}\cdot\vec{B},$$

Serge Brunier@NASA

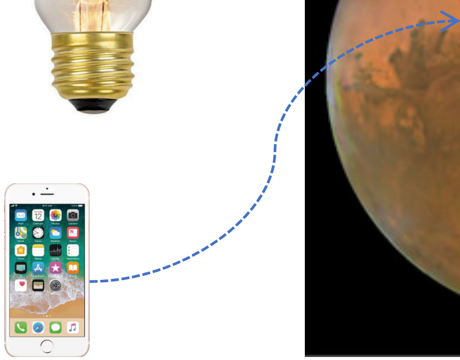
A good axion detector

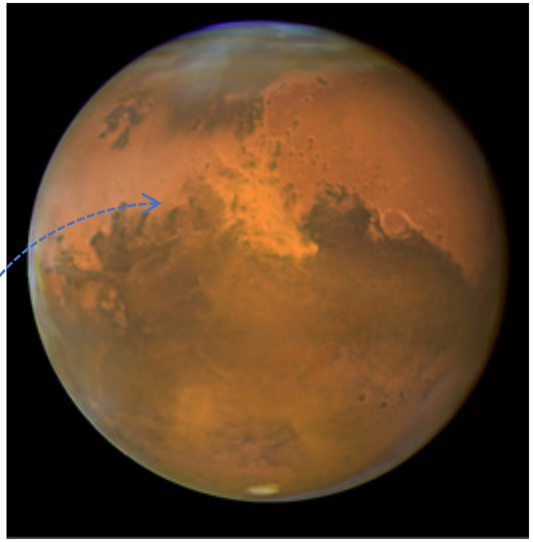
- ❑ Tunable in frequency (compton) ~ mass of axion unknown
- ❑ Low thermal photon background => very cold
- ❑ Low added electronics noise => quantum technology

ADMX => World's most sensitive RF receiver

60 W

*Sensitivity: 10^{-26} Watts
*A cellphone with similar
 capability: 4 bars on Mars!!





NASA

How to detect axion?

- Analogous to radio tuning.

Radio station

Radio frequency waves

When you radio's (electronics) frequency matches to that of the broadcasted FM's frequency, you can hear the music

classicfm.com Dailymail.com

How to detect axion?

- Analogous to radio tuning.

Local galactic halo containing axions

Radio station

Radio frequency waves

axion wave

electronics

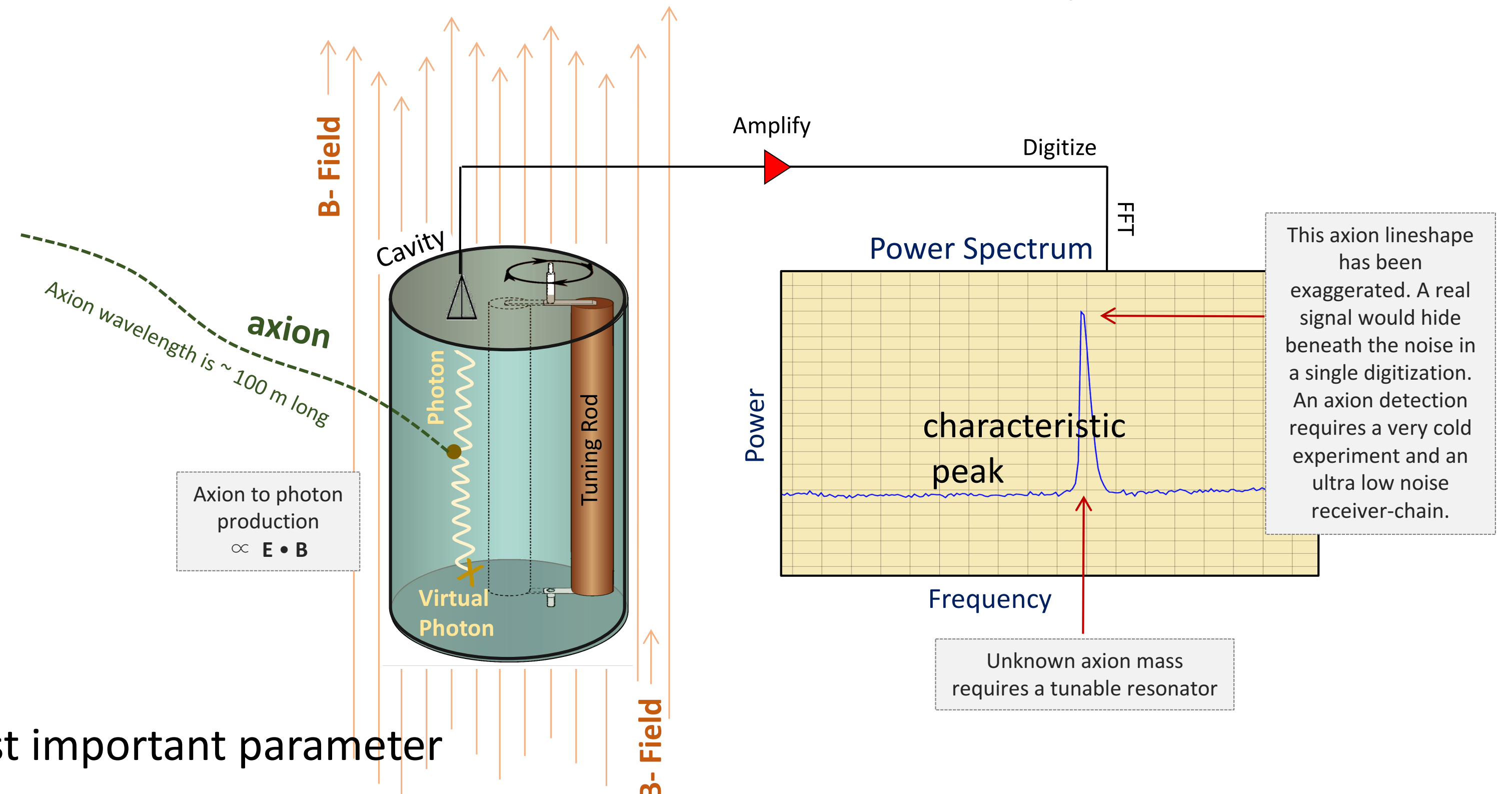
Haloscope experiment

When your haloscope's frequency matches to that of the axion's frequency, you can detect the axion (if it exists)

classicfm.com Dailymail.com

Axion dark matter radio

The Axion Haloscope



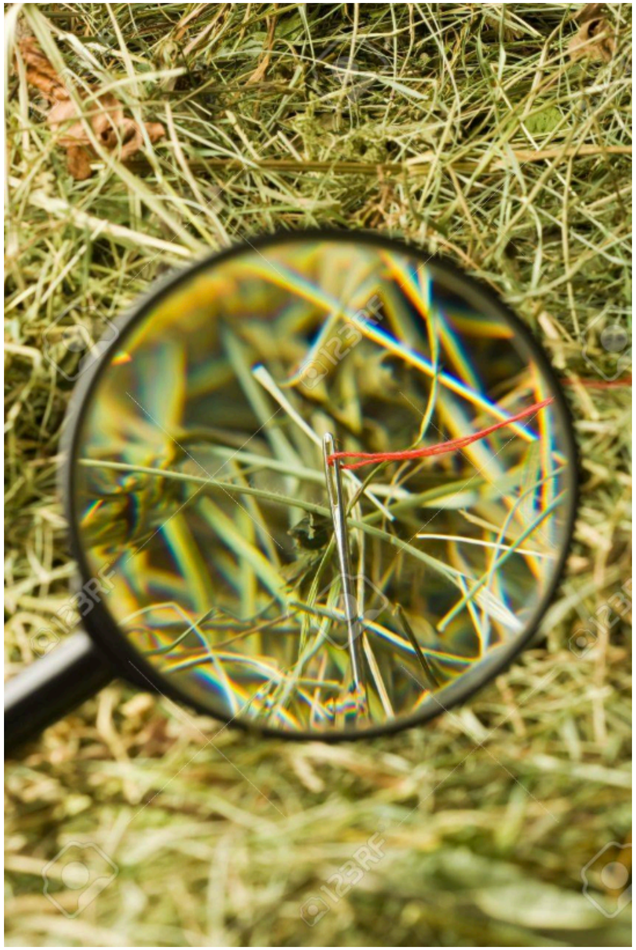
Most important parameter

$$SNR \propto \frac{P_{out}}{k_B T_{system}} \sqrt{\frac{t}{b}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{b^{\frac{1}{2}} T_{system}}$$

C. Boutan

Searching for a tiny signal

Needle in a haystack!

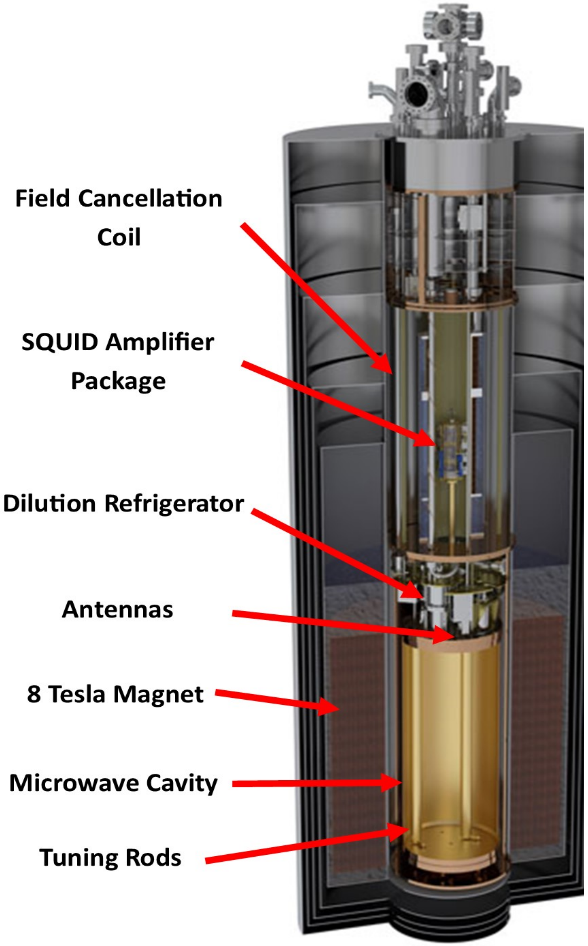


Shrink the haystack!
(Reduce the thermal noise)

=> cool with a refrigerator
=> use low noise electronics

feature.fm

ADMX detector



Field cancellation coil: cancels the residual magnetic field around the SQUID electronics

Superconducting QUantum Interference Device (SQUID) amplifiers: amplifies the signal while being quantum noise limited

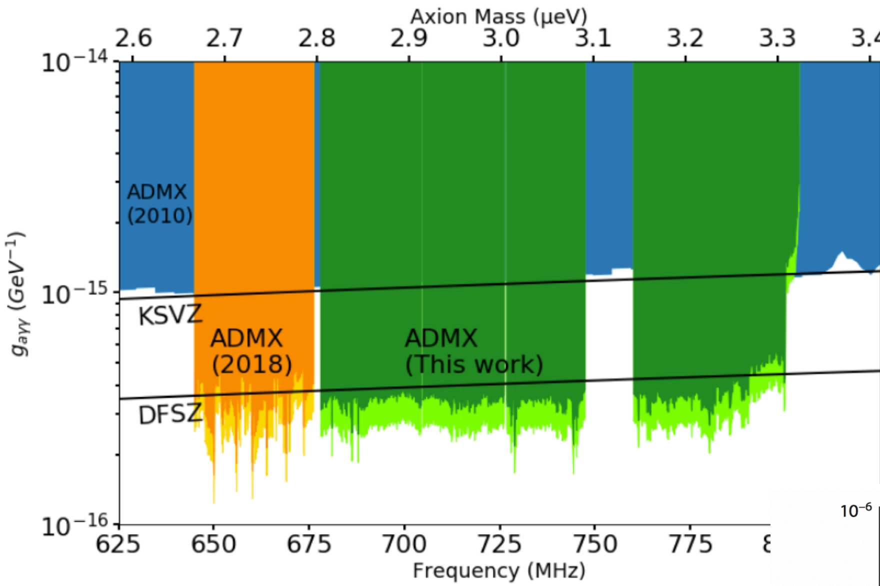
Dilution refrigerator: cools the insert to ~ 90mK

Antennas: pick up signal

Magnet: facilitates the axion conversion to photons, 8T

Microwave Cavity: converts axions into photons, tunable

ADMX results 2018-2020

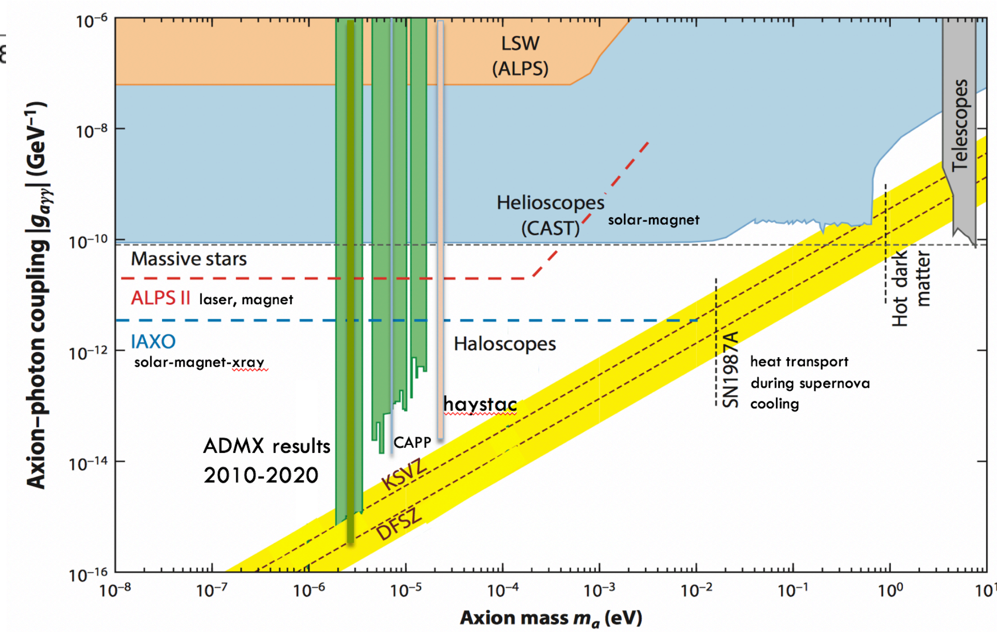


*Axion mass covered to this date: 2.66 to 3.3 μeV (645 to 800 MHz)

*Phys. Rev. Lett. **124**, 101303 (2020)

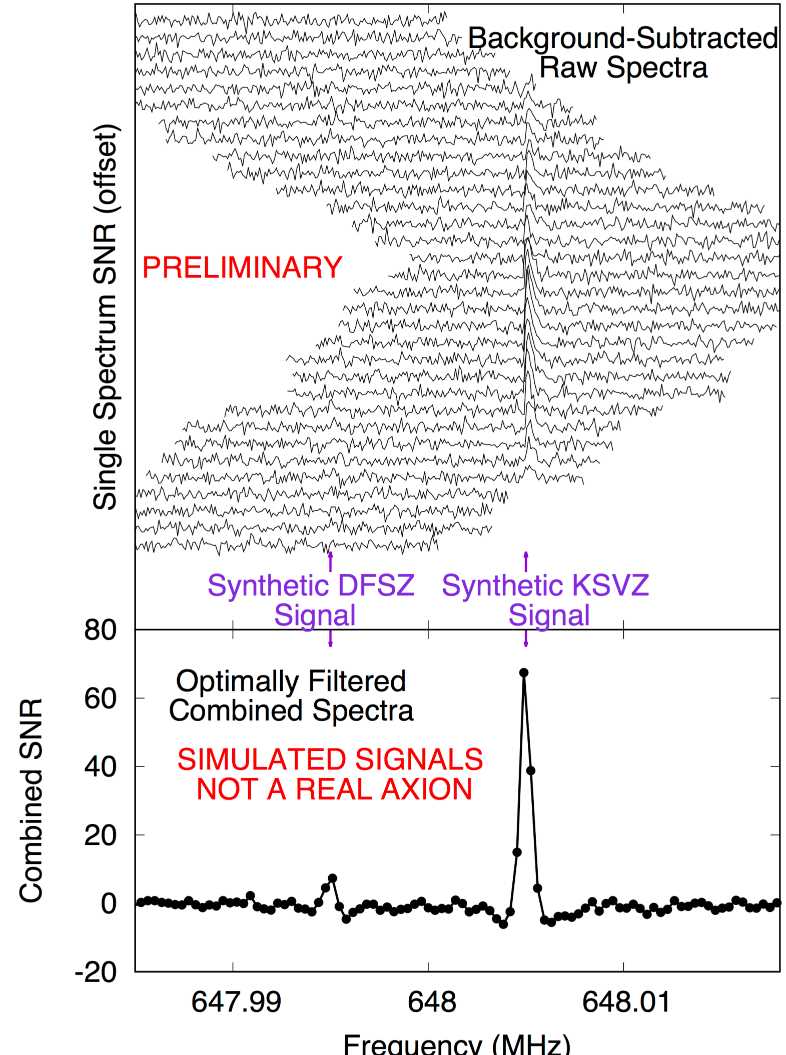
*Only axion experiment with DFSZ sensitivity in the world

*Currently taking data > 4 μeV (985 MHz)



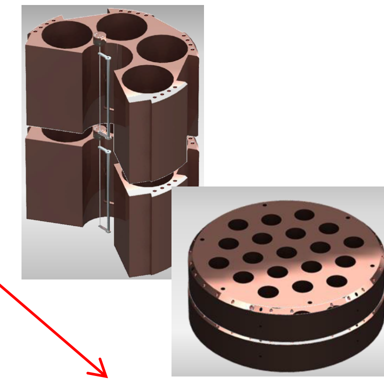
What would an Axion signal look like?

- Synthetic Axion Generator (SAG)--software simulated axion signal added to real data
- -weighted signal by Lorentzian line shape
- Combined added spectra



Future direction: key parameters

$$SNR \propto \frac{P_{out}}{k_B T_{system}}\sqrt{\frac{t}{b}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{b^{\frac{1}{2}} T_{system}}$$



$$T_{system} \propto T_{amps.} \propto \frac{h\omega}{k_B}$$

*48 mK at 1 GHz
n x 48 mK at n GHz

*other techniques
that add < QL

*single-photon
detection

*Squeezed quantum
vacuum JPAs -- < Quantum
Limit noise

*high quality factor (Q) cavity

*powerful magnet

$$f_{cav.} \propto \frac{1}{r_{cav.}}$$

*multi-cavity array
-- power combine

*too many cavities

*photonic band-gap,
open resonators,
cavity-qubit

Axion search summary

- ADMX DFSZ sensitivity -- forefront of Axion Dark Matter search
- **If discovered, axions will:**

  -- tell us about early universe

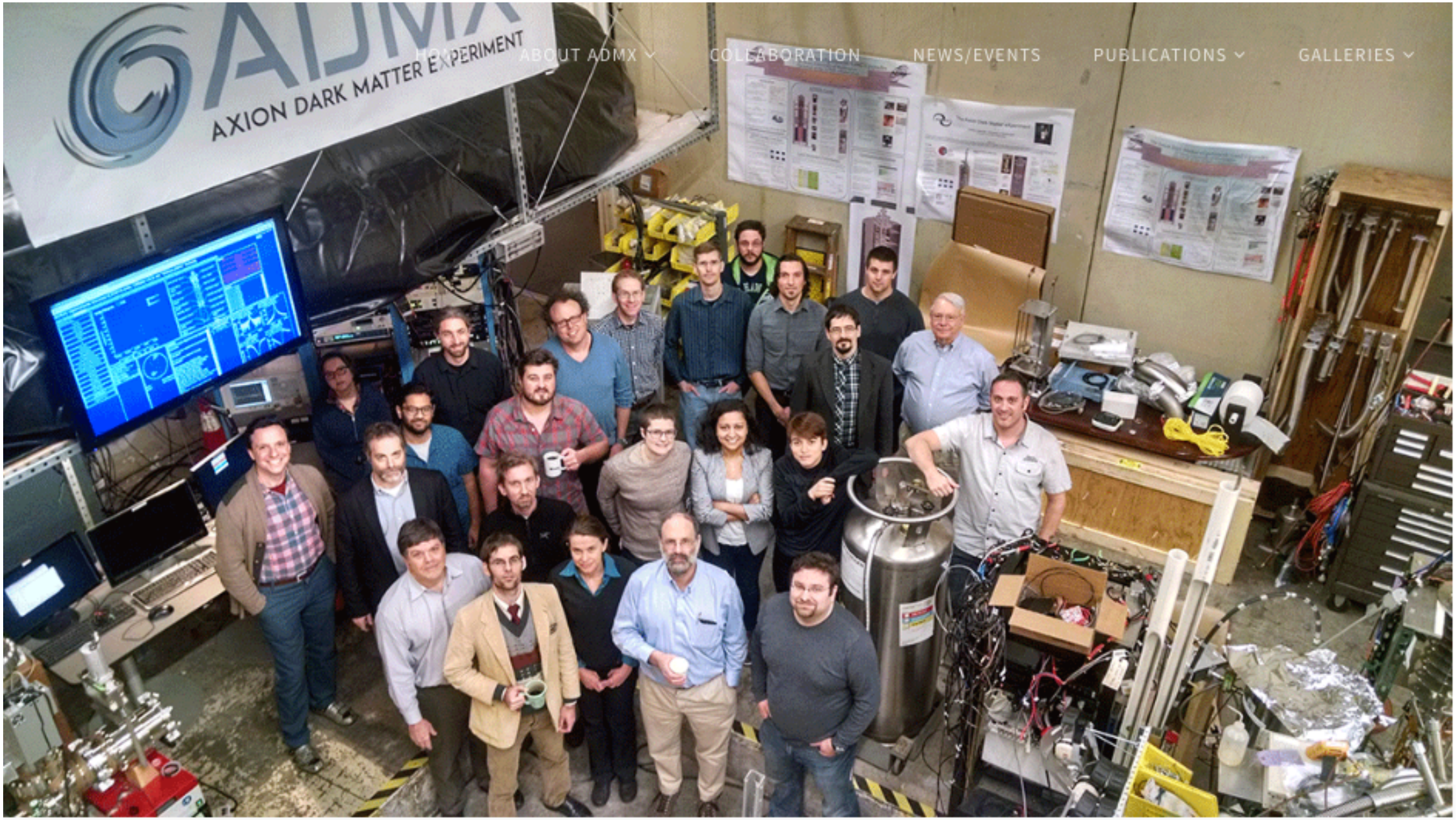
  -- solve the strong CP problem

  -- solve the Dark Matter puzzle
- **Future direction:**

  -- quantum science based novel methods and technology

  -- without these, axion search impossible in reasonable amount of time
- DISCOVERY CAN HAPPEN ANYTIME DURING DATA TAKING! – **2020 run ongoing! (>4 μeV axion) – Stay tuned!!**

Collaboration



Acknowledgement

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Heising-Simons Foundation

University of Washington, Dept. of Physics

Additional slides

Axion

where the amplitude of the axion wave

$$\theta_0 = \sqrt{\frac{2\rho_a}{\Lambda_{\rm QCD}^4}} \approx 3.7 \times 10^{-19} \text{ radians}$$

$$P_{\rm axion} = 1.9 \times 10^{-22}\text{W} \left(\frac{V}{136\ l}\right)\left(\frac{B}{6.8\ \text{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_{\rm a}}{0.45\ \text{GeV}\,\text{cm}^{-3}}\right)\left(\frac{f}{650\ \text{MHz}}\right)\left(\frac{Q}{50,000}\right).$$

Axion production

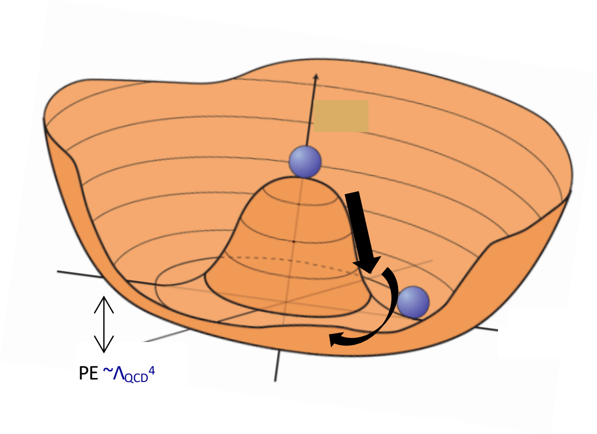
- Global symmetry broken at scale f_a
  -- axion produced through misalignment mechanism
  -- during QCD phase transition, trough tilted by Λ_{QCD}^4
- PE $\sim\Lambda_{QCD}^4$ released, makes up dark matter

-- oscillation of the QCD θ angle about its minimum--vacuum energy to axions

- QCD axion mass $m_a \sim \Lambda_{QCD}^2/f_a$
  $\sim (200\ \text{MeV})^2/f_a$

--- f_a unknown

⇒**GHz frequencies at $f_a \sim 10^{13}$ GeV scale**



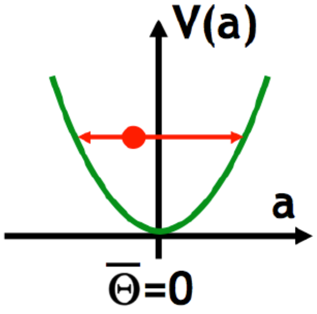


Fig 1:J. Ellis et al; arxiv:1201.6045v1

SAG

- Blind injection – input fake axion signal (python script) to arbitrary function generator mixed with local oscillator to axion like frequencies

Noise temp.

$$T_{N,MSA} = T_{sys.} - T_{HFET}$$

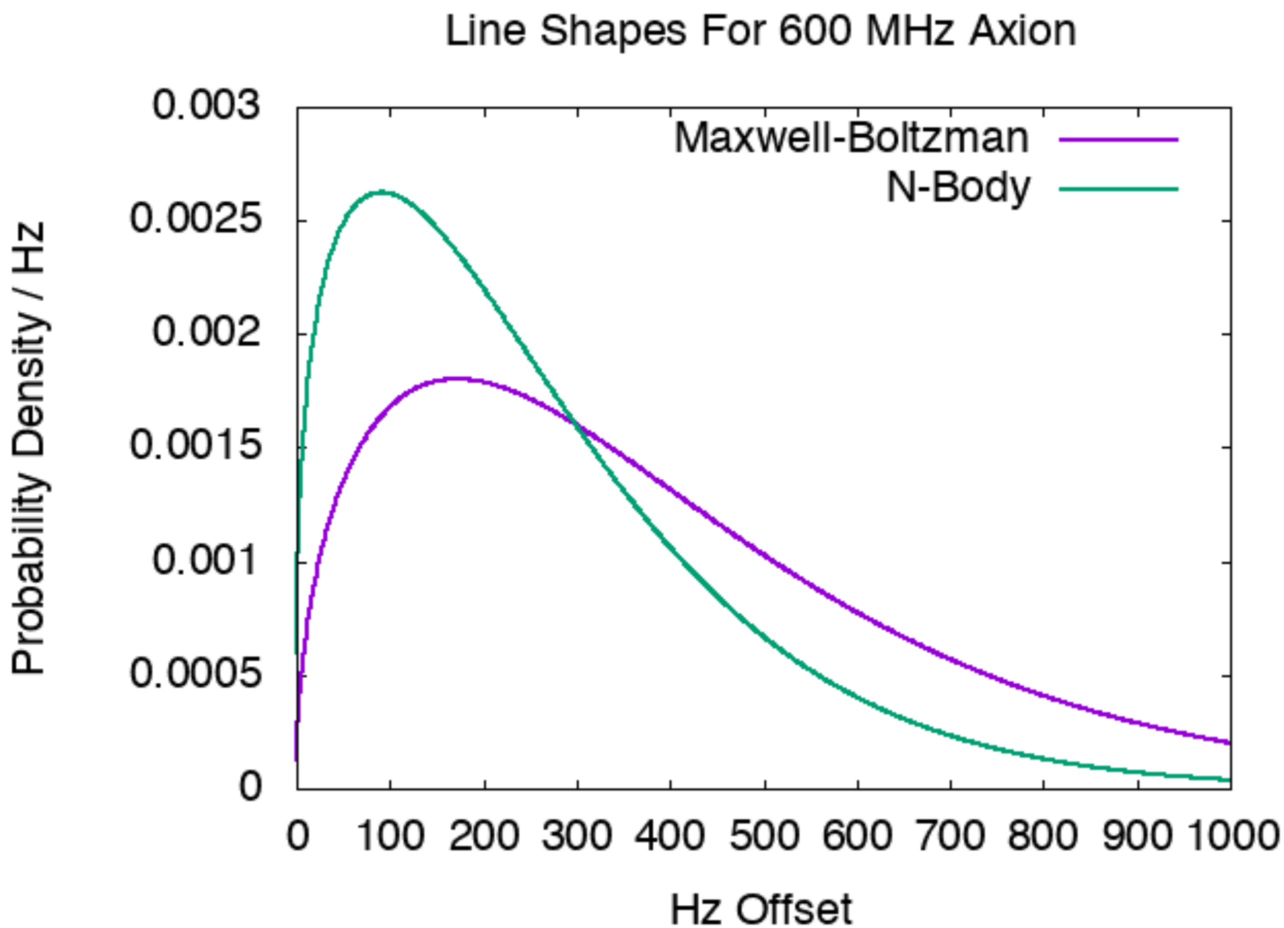
$$T_{HFET} = T_{N,HFET}/G_{MSA}$$

$$T_{syst.} = T_{N,HFET}/SNR$$

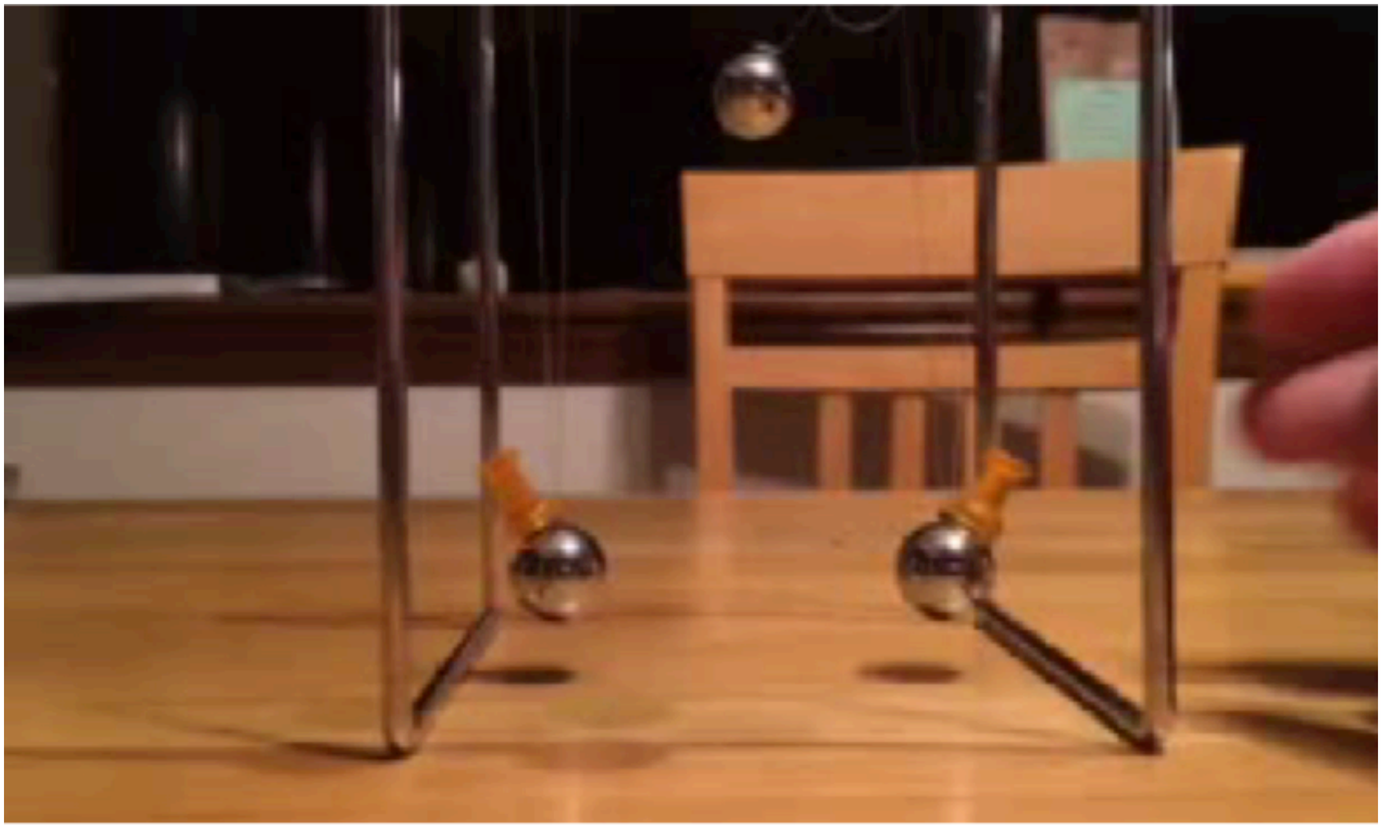
Data Taking/Analysis steps

- Tune the cavity resonance TM_{010} to the desired mass of Axion (photon frequency), tune the SQUID amps. to match this.
- NA checks at this frequency: antenna coupling, Q_{cav}
- SA (Digitize): Record noise power spectra data for 100s in a BW of 25kHz centered at TM_{010}
- For one bin with this BW (25kHz), use at least 20 overlapping noise power spectra
- Background receiver transfer function shapes were removed to 95% of least-deviant power bins using Savitsky Golay filter shapes (length 121, polynomial order 4) – removes signal much broader than axions.
- Power scaled to known T_{sys} and weighted by Q_L to produce excess power in each bin for Axion signal
- This excess power is then convolved using two astrophysical signal shapes—Maxwellean predicted by Standard Halo Model and N-body shape.
- When the data were statistically consistent with no Axion signal, the Power equation is used to put the limits on the coupling.
- Frequencies with >3σ above the mean power were flagged candidates for rescan/analysis
- If persists, individually checked for RF interference

N-body line-shape



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

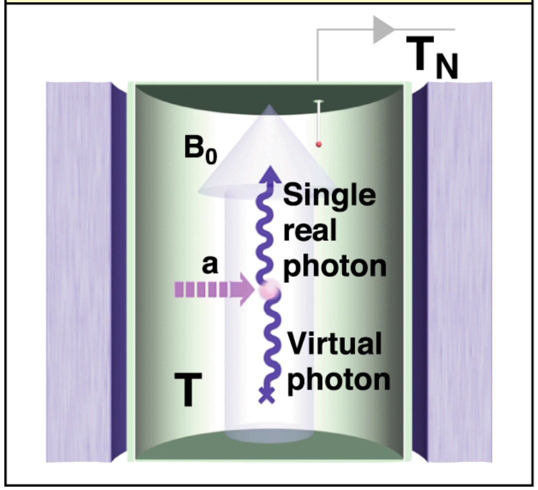


Weak coupling -- takes many swings to fully transfer the wave amplitude.
Number of swings = cavity Quality factor.
Narrowband cavity response → iterative scan through frequency space.

Slide from Aaron Chou (FNAL)

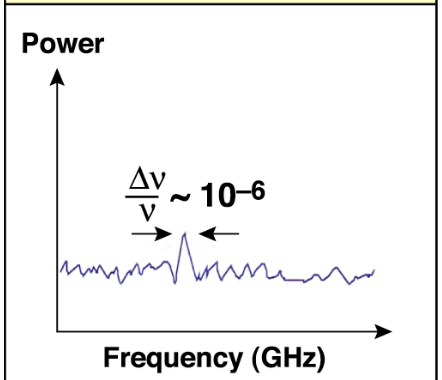
Scaling laws

Primakoff Conversion



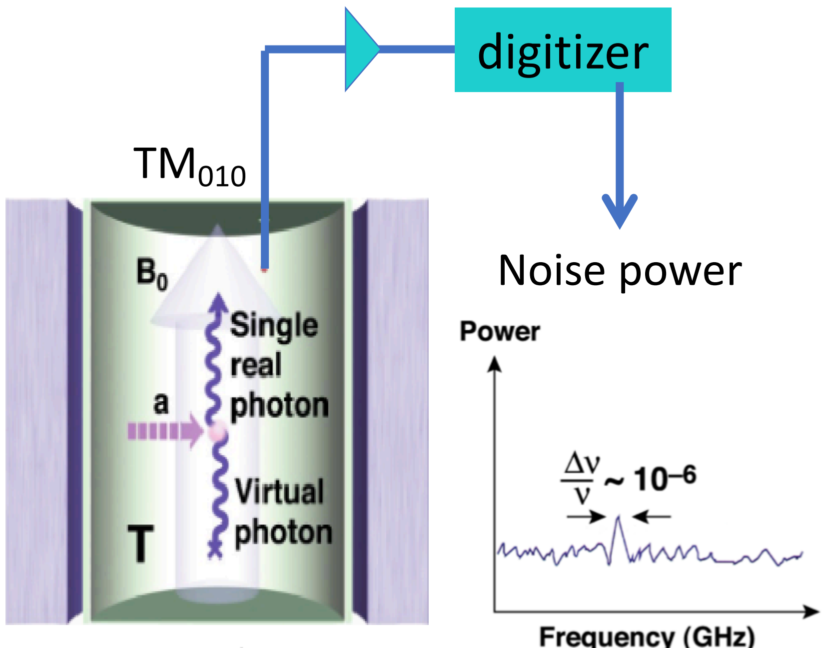
- **The conversion is resonant, i.e. the frequency must equal the mass + K. E.**
- **The total system noise temperature $T_S = T + T_N$ is the critical factor**

Signal



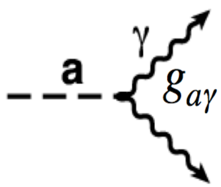
Scaling Laws	
$\frac{d\nu}{dt} \propto B^4 V^2 \cdot \frac{1}{T_S^2}$	$g_\gamma^2 \propto \left(B^2 V \cdot \frac{1}{T_S}\right)^{-1}$
For fixed model g^2	For fixed scan rate $\frac{d\nu}{dt}$

Axion current



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

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



$$\mathcal{L}_{\text{int}} = g_\gamma \theta \vec{B}_0 \cdot \vec{E}$$
$$= g_\gamma \partial_t \theta \vec{B}_0 \cdot \vec{A} + \ldots$$
$$\vec{J}_a(t)$$
$$\vec{\nabla} \times \vec{B}_r - \frac{d\vec{E}_r}{dt} = \vec{J}_a$$

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

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

Cavity array

- **Higher frequency search:**

$$f = \frac{c}{2.61 * R} or \frac{R}{1cm} = \frac{11.5GHz}{f}$$

$$f = 550MHz \Rightarrow R = 21cm, L = 100cm$$

$$f = 4.5GHz \Rightarrow R = 2.6cm, L = 5.6cm$$

❑Cavities get smaller -- use many cavities

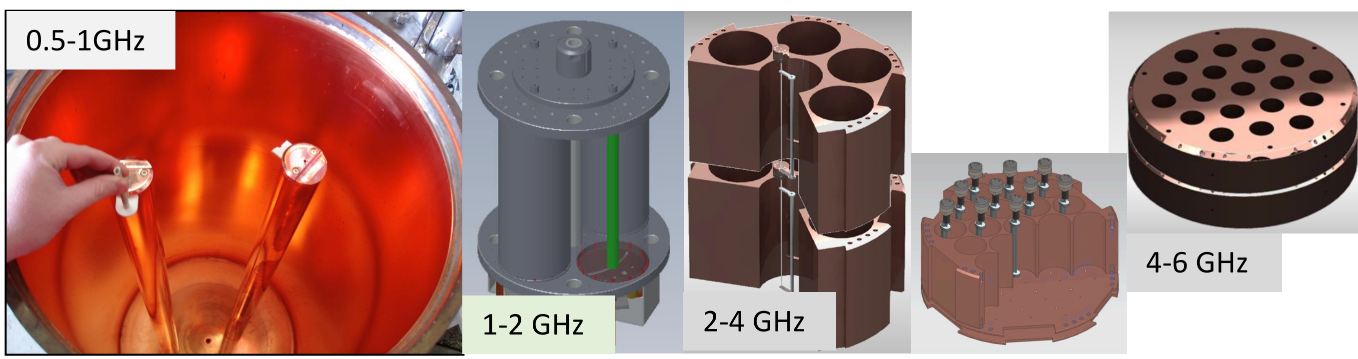
❑Need to be in phase/identical resonance
-- frequency lock system

❑Power combiner and divider R &D

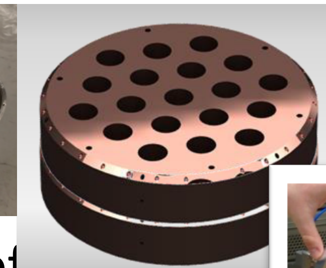
❑>1 GHz in production/development

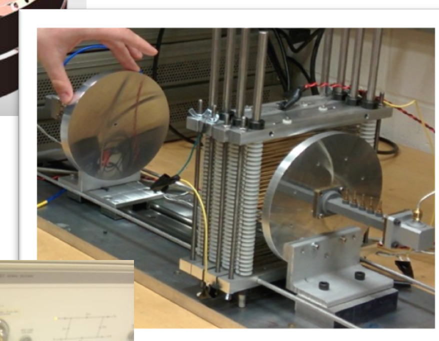
Cavities #	Res freq. MHz	Tuning range MHz	Tuning range μeV
1	575	402-575	1.7-2.4
1	575	575-908	2.4-3.8
2	897	897-1417	3.7-5.9
4	1207	1207-1907	5-7.9
8	1899	1899-3001	7.8-12
16	2959	2959-4675	12-19
32	3983	3983-6293	16-26

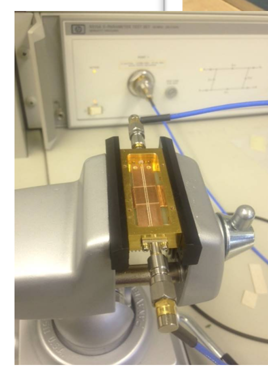
Cavities etc.:
multi-array,
photonic band-gap,
open resonators,
photon counting



Future technology for axion search



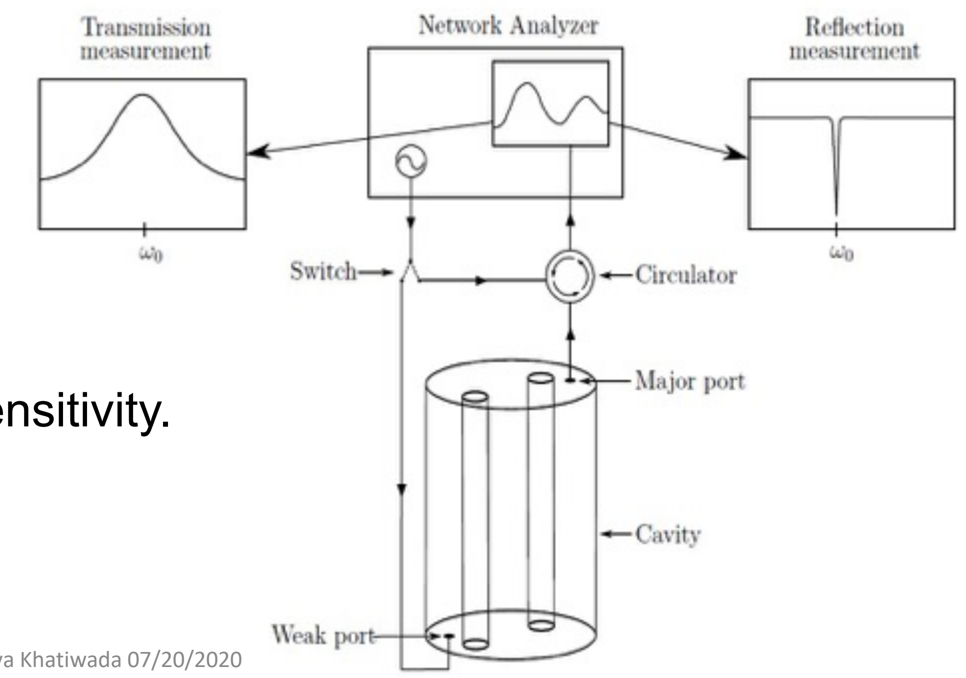




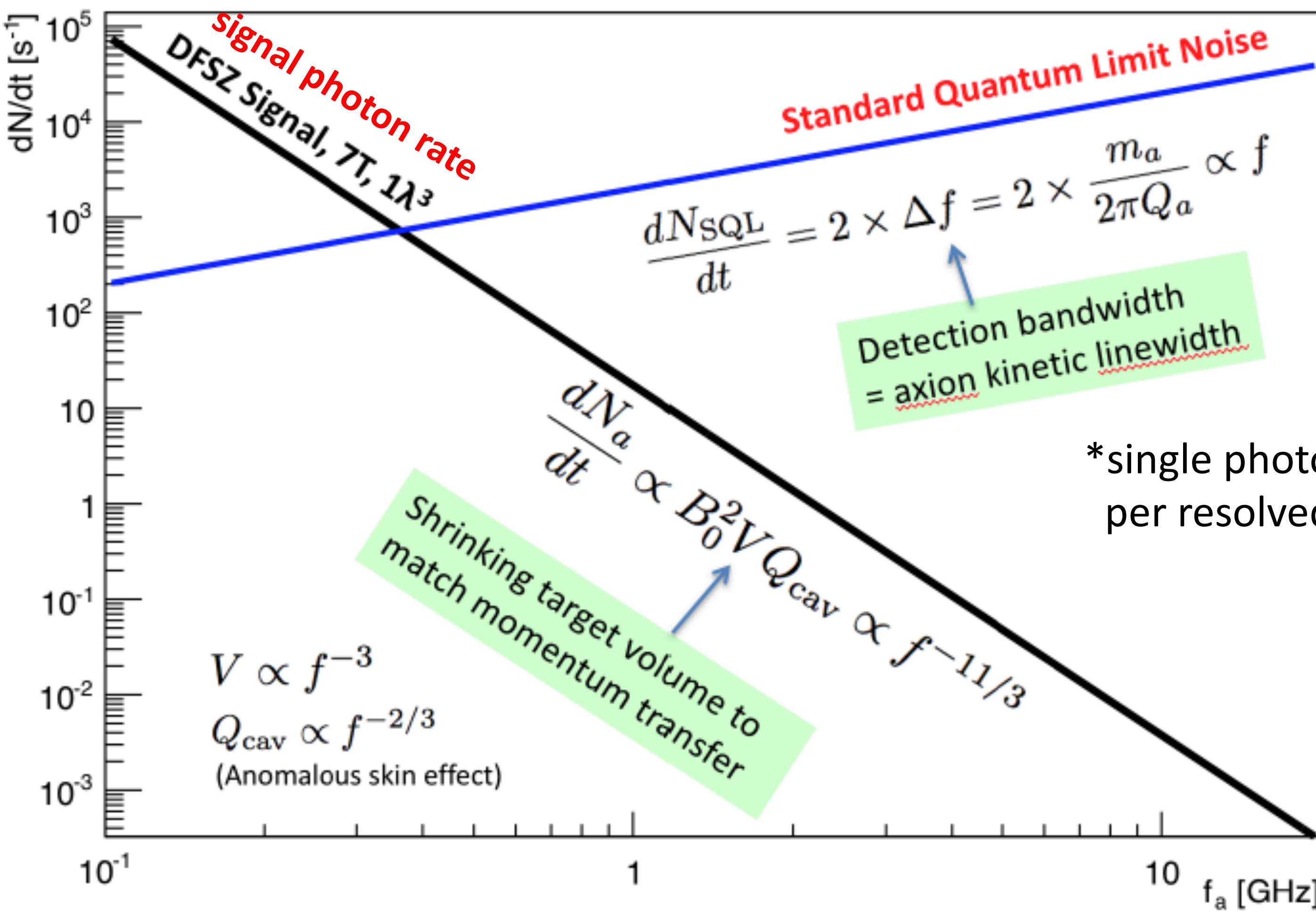
- **Multi-cavity array:** power combine
- **Open resonators:** resonators and series of current carrying wires (Orpheus etc.)
- **Photonic bandgap cavities:** Isolate a single mode using a defect in an open periodic lattice of metal and/or dielectric rods. High volume, defined mode
- **Dielectric tuned cavity:** lower loss/higher Q and form factor, B field compatible
- **Quantum Non-Demolition (QND) photon counting**
- **Squeezed parametric amplifier for < QNL**

Typical ADMX Run Cadence

- Start by injecting a broad, swept RF signal to record cavity response. Record state data (temperatures, hall sensors, pressures, etc)
- Integrate for ~ 100 sec to 10s of minutes (final integration time dependent experimental parameters).
- Every few days adjust the critical coupling of the antennas
- Scan rate is trade off in sensitivity vs frequency (mass) coverage
- The scan rate uses a threshold sensitivity.
- Any candidate above threshold is flagged for further study.



Limitation of quantum amplifiers

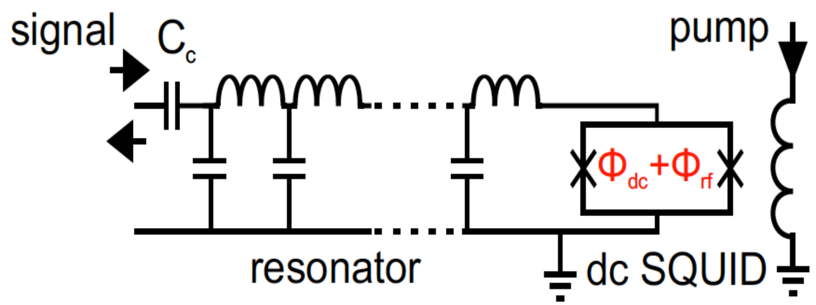


*single photon of noise per resolved mode

Josephson Parametric amplifier (JPA)

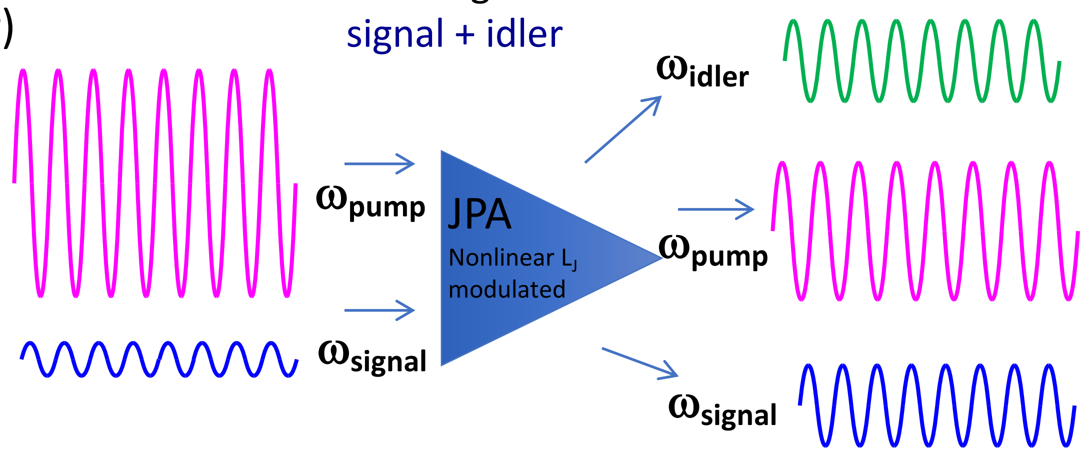
- Parametric amplifier: Oscillator whose resonance frequency is modulated

$$\omega_0 = \frac{1}{2\pi\sqrt{(C(L_{stray} + L_{SQUID}))}}$$



- Oscillating system a λ/4 resonator
- Inductance varied with SQUID (flux dependent nonlinear inductor)
- Energy transfer from pump to two normal modes of swing
- Noise – Quantum Limit

two normal modes of swing:
signal + idler



Paramp schematic: L. Zhong et al., "Squeezing with a fluxdriven Josephson parametric amplifier," New J. Phys. 15, 125013 (2013).

Tuning the dark matter radio

1. Tune the cavity and SQUID amps. to the desired frequency -- m_a
2. Achieve lowest system noise temp.
3. Record noise power spectra
4. Digitize (100s)
5. Repeat until desired SNR

   Repeat the above for different m_a

6. Analyze data -- filter, convolve with axion lineshape
7. Excess power signals rescanned
8. If candidate persist, Individually probe
9. Put limits or discover Axion!