Axion Experiments Lecture 1

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Outline

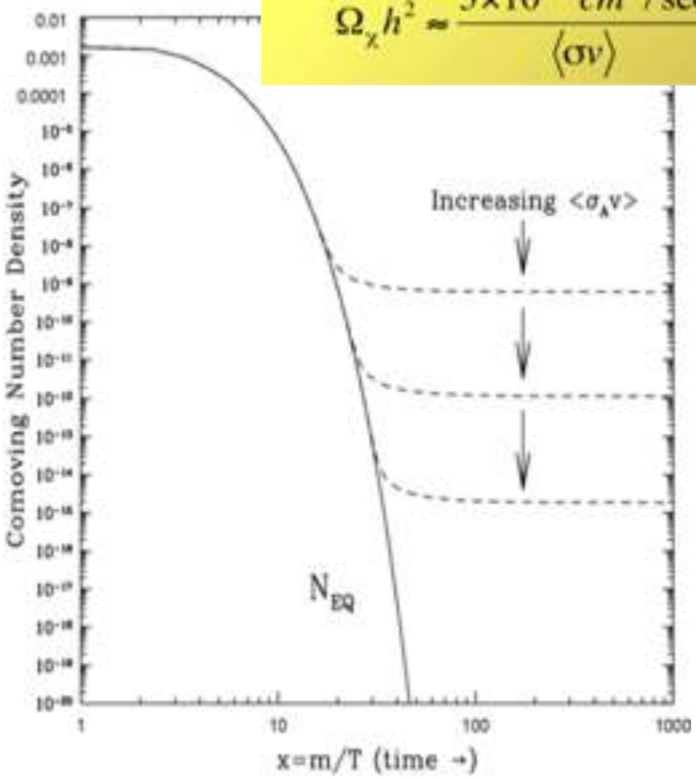
- Axion lecture #1: Current/ Past generation axion experiments
  - Theory motivation
  - "Light Shining Through Walls"
  - Solar axions
  - Sikivie haloscope (resonant cavity) technique and current results
    - ADMX, HAYSTAC

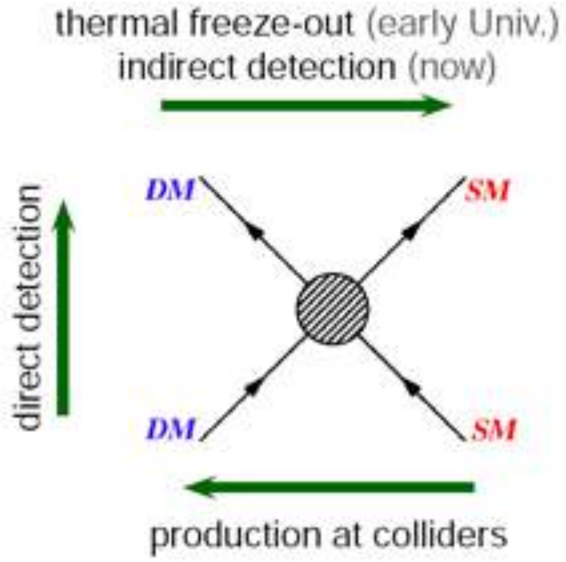
- Axion lecture #2: Future experiments, R&D
  - Higher frequency and mass
    - High frequency R&D- Magnets, Cavities & Electronics
    - Broadband detectors- dish antenna
    - Open resonators- Madmax, Orpheus
  - Lower frequency
    - LC circuits
    - ABRACADABRA, DM Radio
    - CASPER

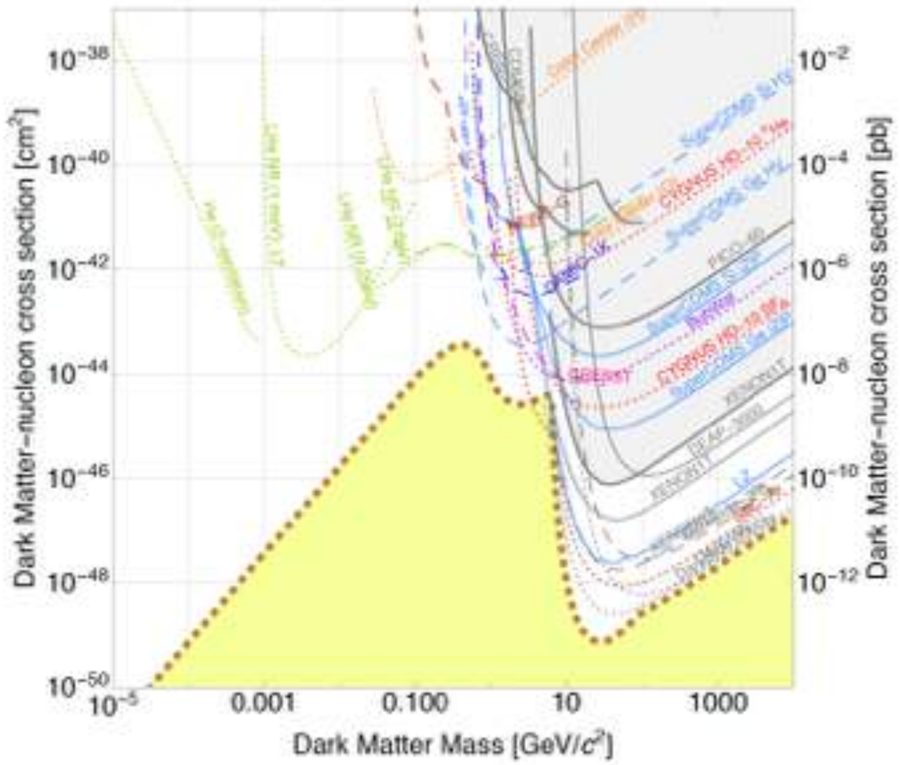
"WIMP Miracle": Current Status

- "WIMP Miracle" argument: Weakly interacting particles $M_{wimp/boson}$~100 GeV produce the right abundance of dark matter .
- Many discussions motivated by supersymmetry: Lightest Supersymmetric Particle may be neutral and stable.
- But by 2018 has the most promising part of parameter space already been explored?

$$\Omega_\chi h^2 \approx \frac{3\times10^{-27}\,cm^3/\sec}{\langle\sigma v\rangle}$$







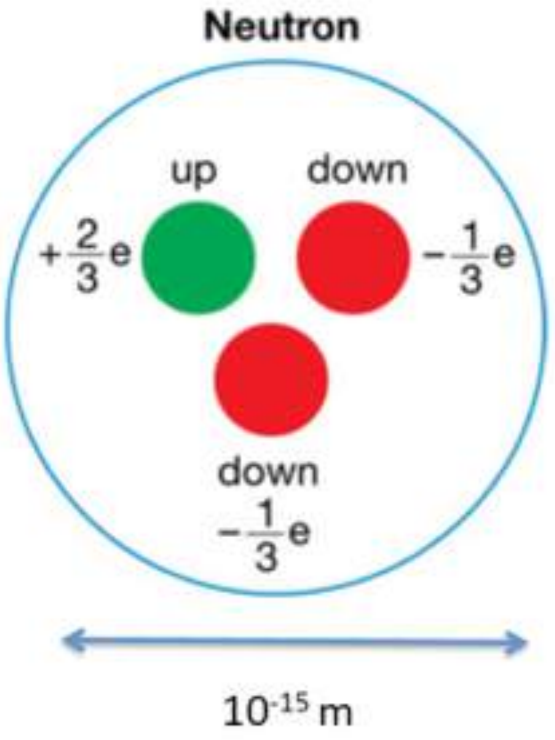
WIMPS vs. Axions

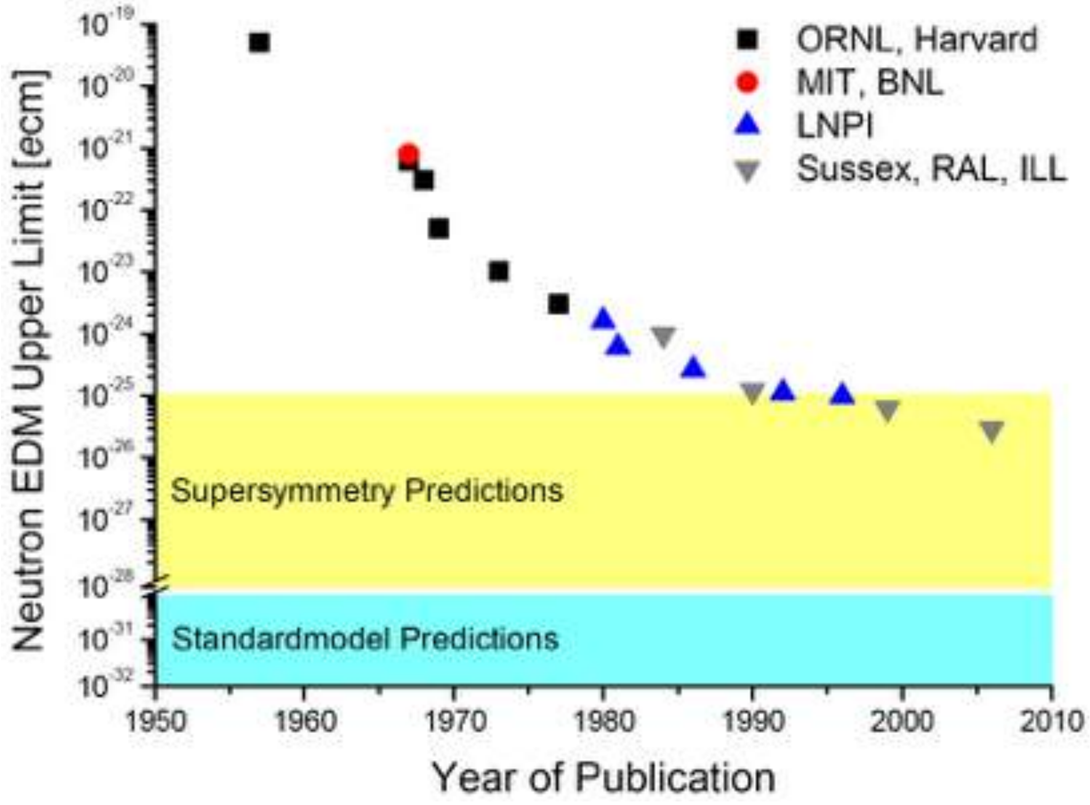
- Both are assumed to be cold dark matter with density ~0.3 GeV/cm^3 and velocity determined by depth of Milky Way gravitational potential (escape velocity ~300 km/s or v/c~0.001).
- Axions are much lighter and colder. They are not in thermal equilibrium.
- Small energy and long wavelength imply different detection techniques.

	WIMPs (typical)	Axions
Mass M	~100 GeV	~2- 200 μeV post inflation PQ breaking
Velocity in galaxy	<0.001 c	<0.001 c (escape velocity)
Kinetic energy ½ M V^2	<100 keV	<10^{-10} eV
De Broglie Wavelength (h/MV)	~10^{-15} m	~10- m

Axions-- Motivation

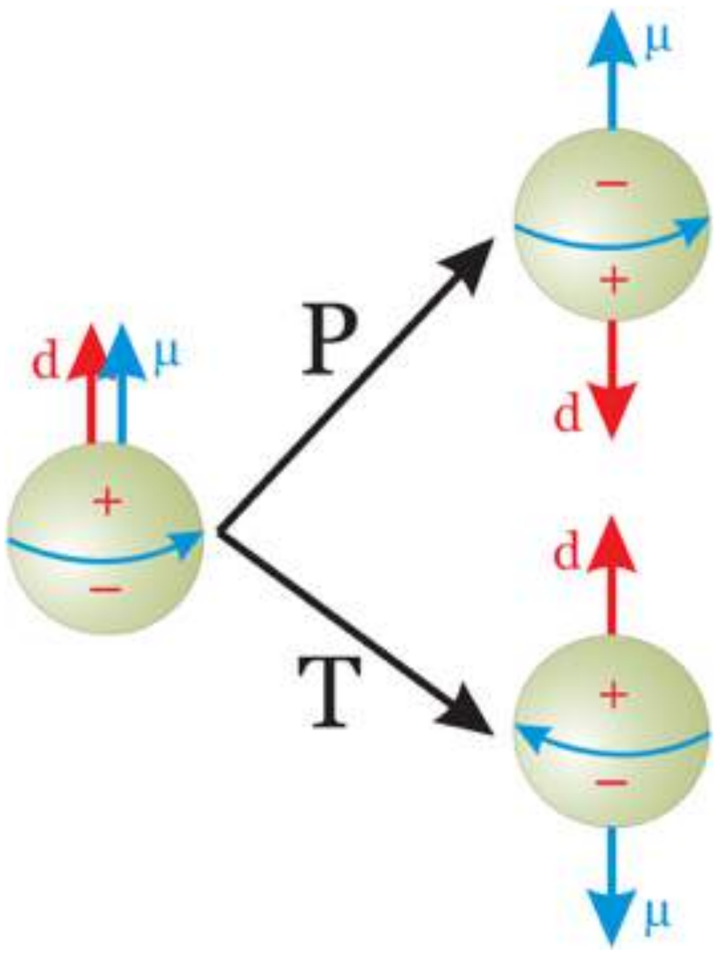
- Protons and neutrons have a charged substructure (quarks)
- Naïve expectation: they should have electric dipole moment of order 10^{-16} e-m ?





Electric Dipole Moments Violate CP (or T) Symmetry

- Small electric dipole moment of neutron could be explained by approximate CP symmetry of strong interaction.
- But the strong interaction Lagrangian appears to have CP- violating terms that don't need to be small.



CP Violation in QCD

- The QCD Lagrangian contains a term that changes sign under Parity or Time reversal

Strong coupling constant

Gluon field strengths

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

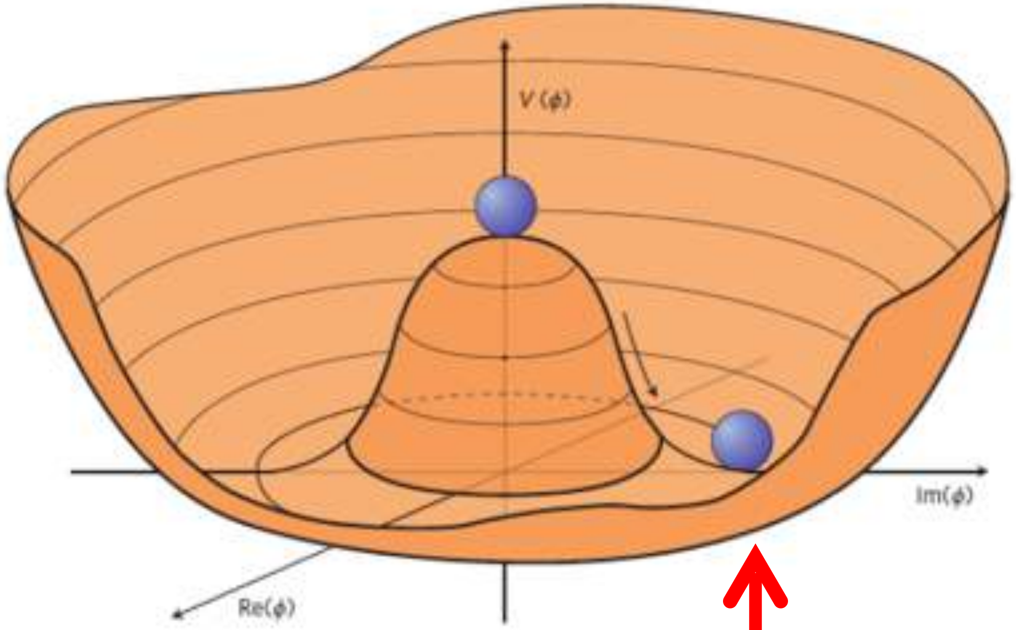
- Limits on the neutron electric dipole moment ($< 3 \times 10^{-26}$ e cm) constrain the CP violation parameter $\Theta < 10^{-9}$

R.D. Peccei, Hep-ph/0607268

Peccei Quinn Solution

- Introduce a new field ϕ coupled to GG with a spontaneously broken symmetry.
- To minimize vacuum energy, radial part of ϕ takes on a vacuum expectation value (VEV).
- CP violating term in QCD Lagrangian is cancelled out by the VEV of ϕ.
- ϕ can still move in the axial direction– the axion!

$$\mathcal{L} = \underbrace{\left(\frac{\phi_A}{f_A} - \bar{\Theta}\right)}_{\text{0 in vacuum state}} \frac{\alpha_s}{8\pi} G^{\mu\nu a} \tilde{G}^a_{\mu\nu}$$

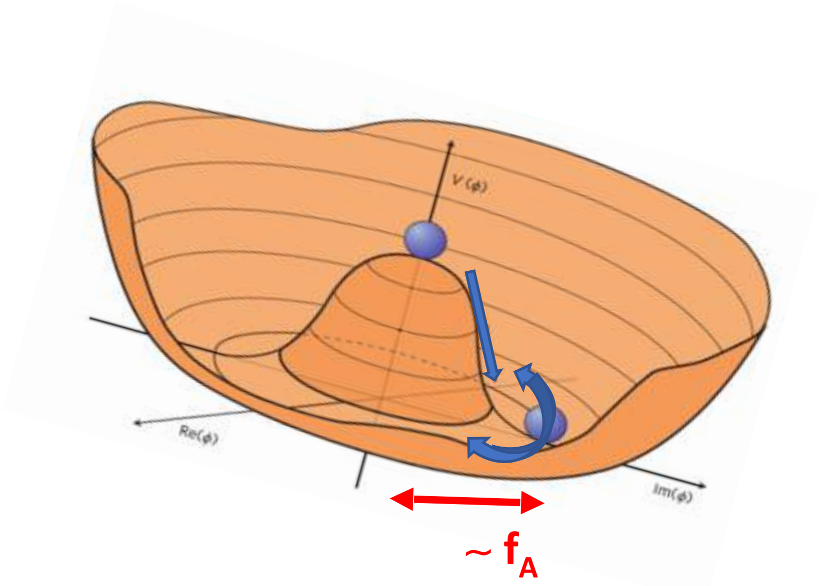


$$\phi_A = \bar{\Theta} f_A$$

Axion Mass

- QCD effects at the time of the QCD phase transition (quark- gluon plasma -> free particles) cause a small tilt in the Peccei Quinn potential producing an axion mass.
- Axion mass is determined by curvature of potential around minimum.

$$m_A = 5.70(7) \left(\frac{10^9 \text{ GeV}}{f_A} \right) \text{meV}$$



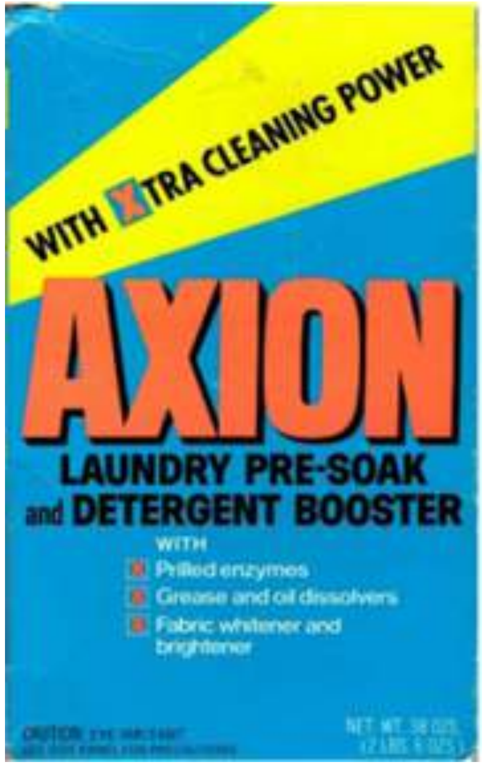
Axion Inventors

Roberto Peccei

Helen Quinn

Steven Wienberg

Frank Wilczek

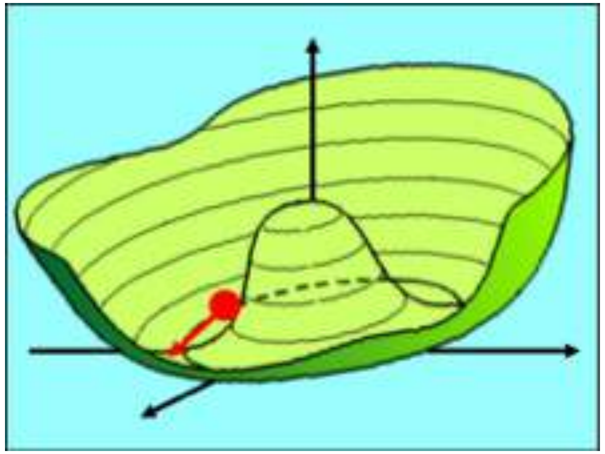


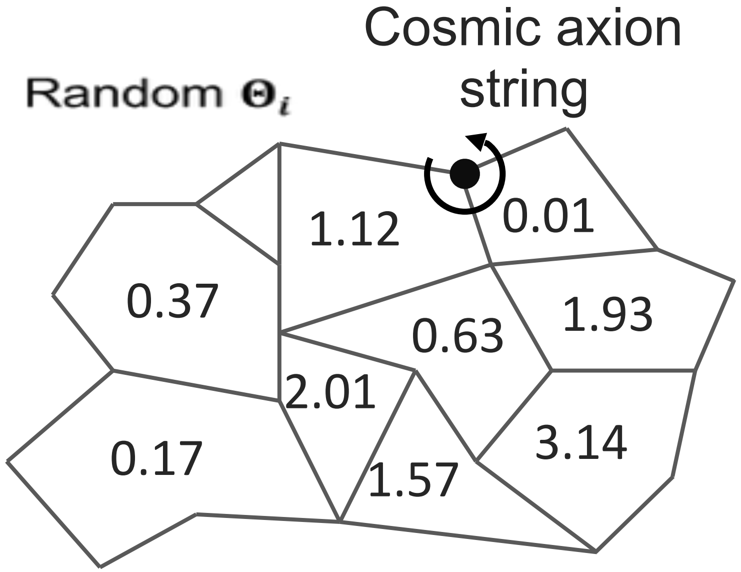
"Clean up" the Strong-CP problem

- <u>Peccei & Quinn</u>: Postulate new field that dynamically zeros out CP violation.
- <u>Weinberg & Wilczek</u>: Implies a new Goldstone boson (the axion)

Production of Dark Matter by Vacuum Realignment

- After PQ symmetry breaking the Θ angle is a random number.
- Tilting of PQ potential below QCD phase transition causes the field to roll to its minimum, converting vacuum energy to axion particles.
- Axion dark matter density today determined by random initial value of Θ.
- Can assume different values in causally disconnected regions of space-> domain walls.

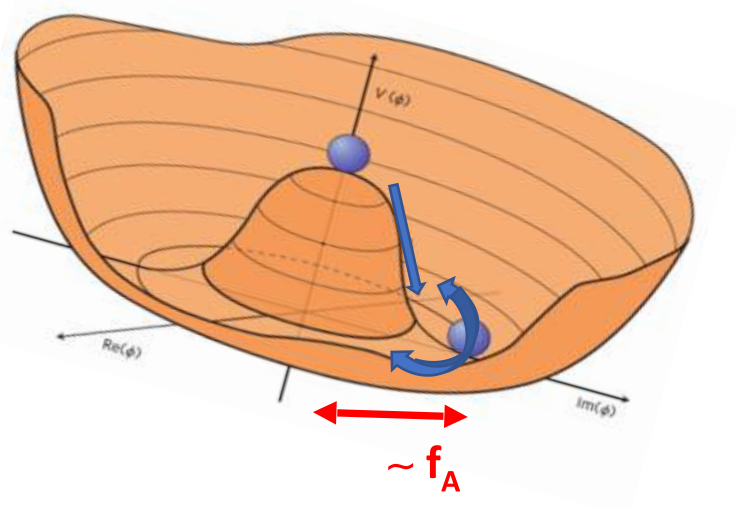




The QCD Axion- A Very Predictive Model

- Everything depends on just one unknown parameter– the axion decay constant f_a
  - The axion mass.

$$m_A = 5.70(7)\left(\frac{10^9\,\mathrm{GeV}}{f_A}\right)\mathrm{meV}$$



  - Coupling to gluons and photons.

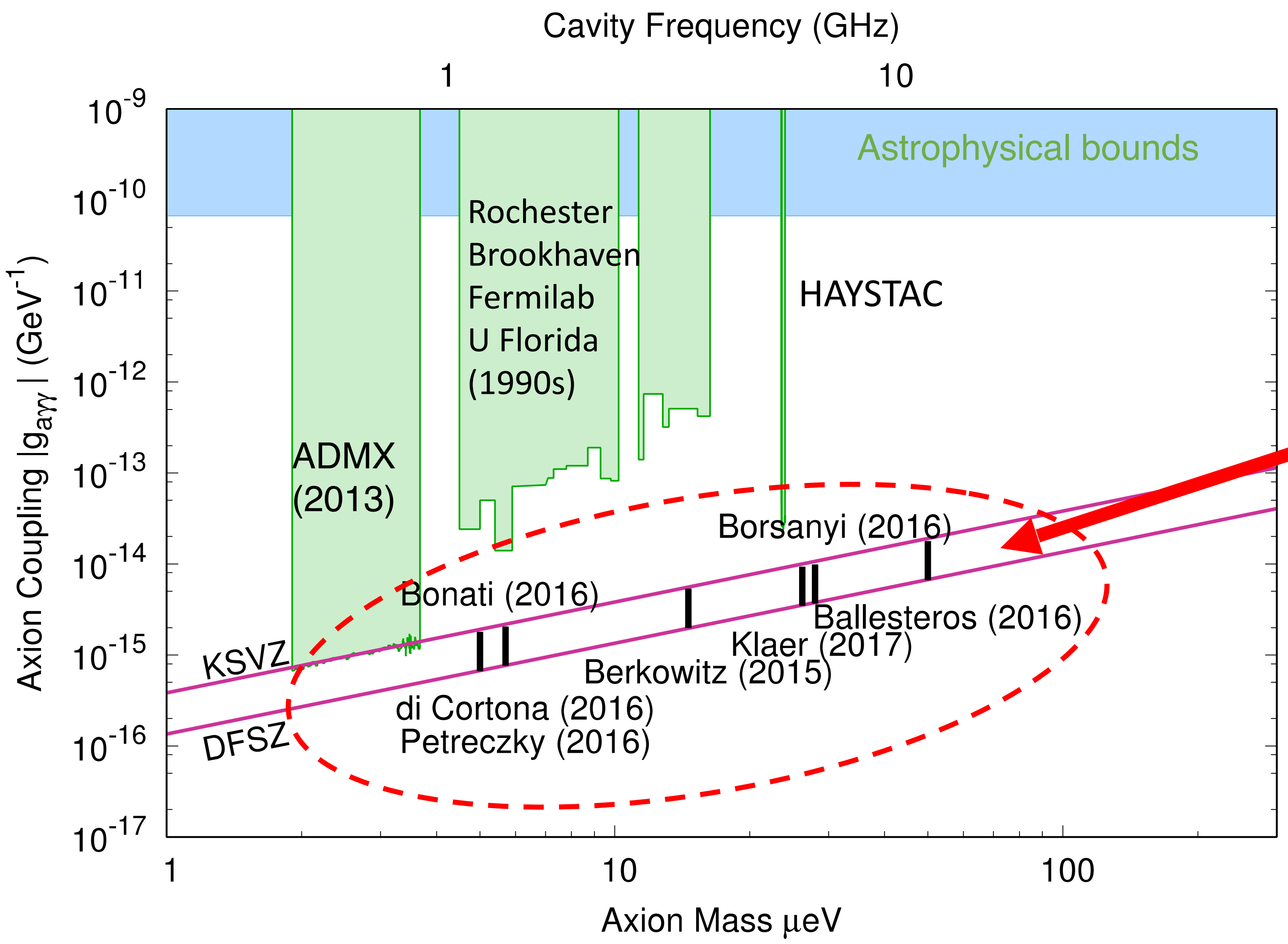
$$\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad G_{A\gamma\gamma}\mathbf{E}\cdot\mathbf{B}\,\phi_A \qquad G_{A\gamma\gamma} = \frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - 1.92(4)\right)$$

  - The cosmological abundance*

$$\Omega_A^{\mathrm{vr}}h^2 \approx 0.12\left(\frac{30\ \mu\mathrm{eV}}{m_A}\right)^{1.165}$$

*Vacuum realignment contribution for post inflation scenario, not including cosmic strings & domain walls…

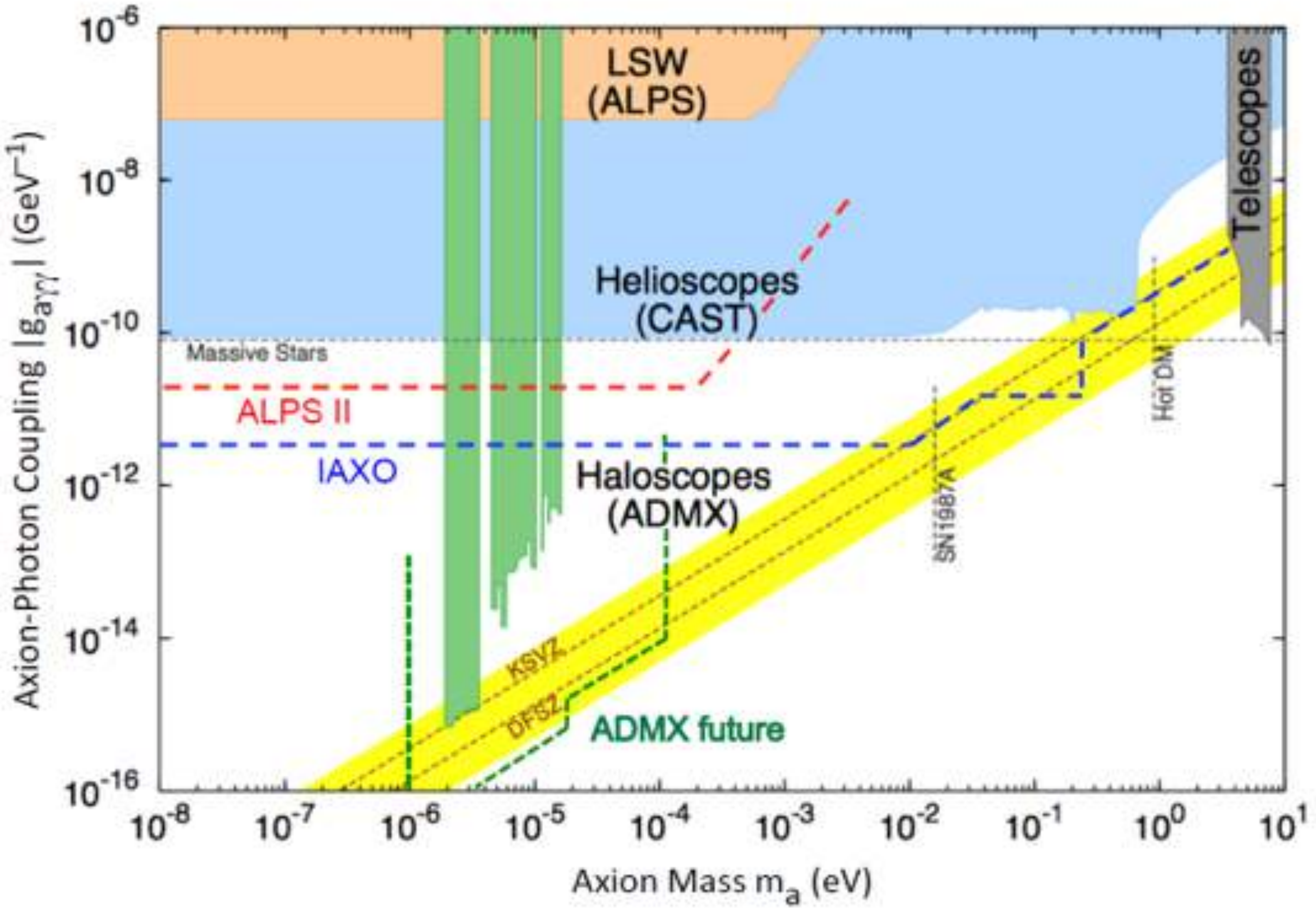
Predictions Vs. Previous Experiment Constraints



Classical "post inflation" axion window: fine tuning of Θ not required for axions to make up 100% of observed dark matter

Axion 2d Sensitivity Plot: Photon Coupling vs Mass

- Constructed to resemble standard WIMP sensitivity plot.
- Allows for a more general parameter space of "axion like particles" or ALPS with independent mass & cross section.
- QCD axion appears along diagonal band.



Graham, Irastrorza, Lamoreaux, Linder and Van Bibber, arXiv: 1602.00039

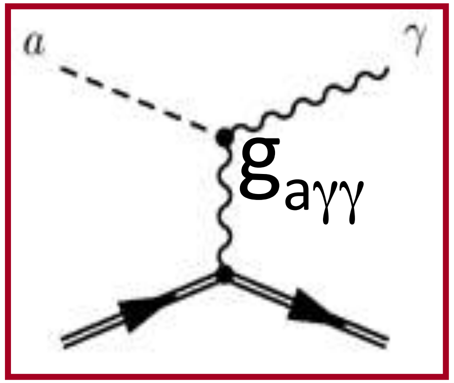
"Light Shining Through Walls" Experiments

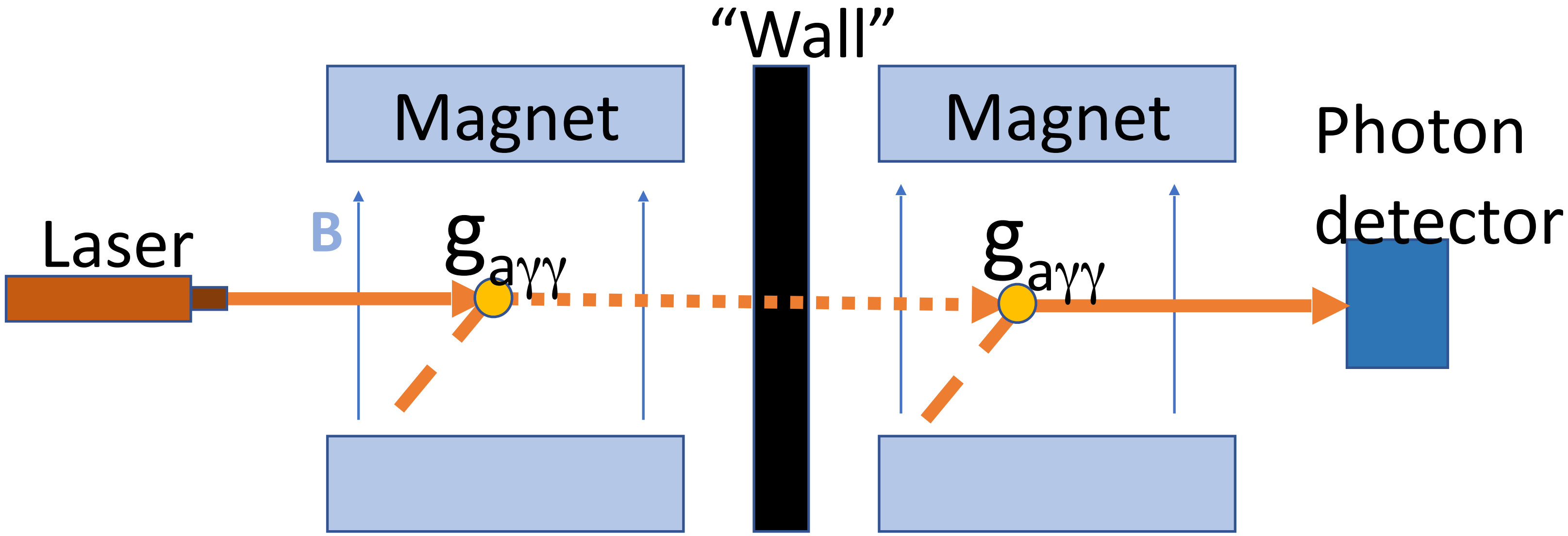
- Photons convert into axions in magnetic field, then pass through a wall.
- Convert back into photons so they can be detected.
- Probability of gamma->axion-> gamma round trip goes as $g_{a\gamma\gamma}^4$

$$P(\gamma \to axion) = 4\frac{g_{a\gamma\gamma}^2 B_{ext}^2 E_\gamma^2}{m_a^4} sin^2\left(\frac{m_a^2 L}{4E_\gamma}\right)$$

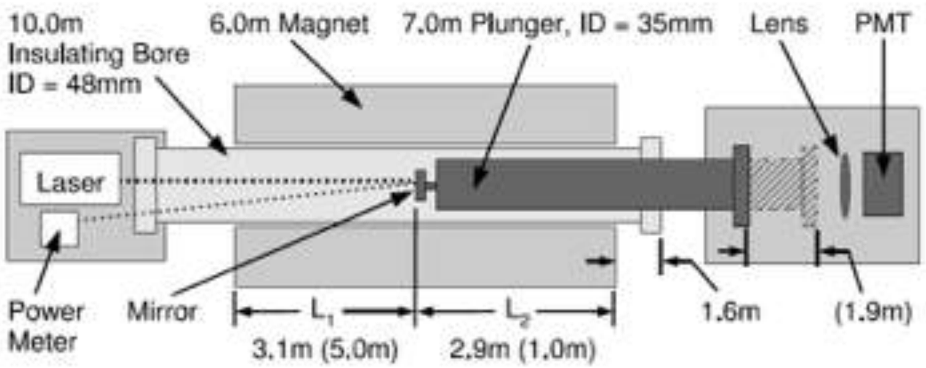
$$P(\gamma \to axion \to \gamma) \propto \frac{g_{a\gamma\gamma}^4 B_{ext}^4 E_\gamma^4}{m_a^8}$$

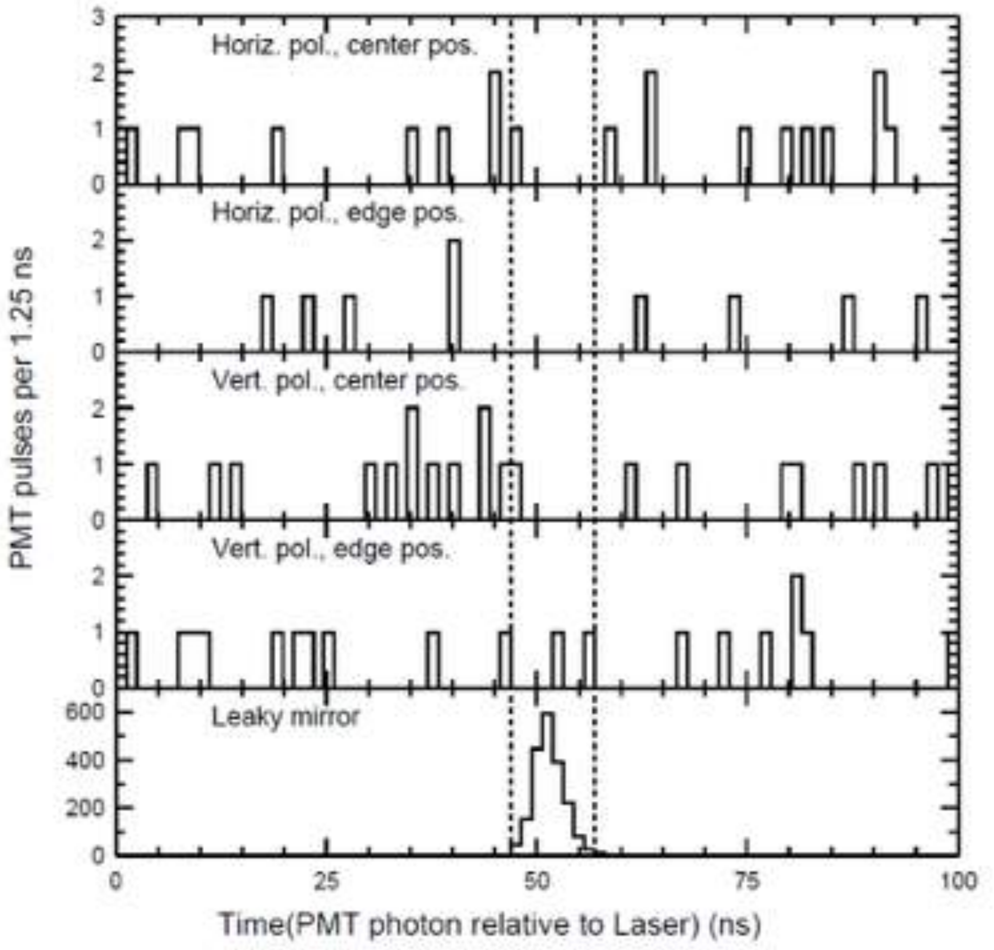
Primakoff Process





GammeV at Fermilab





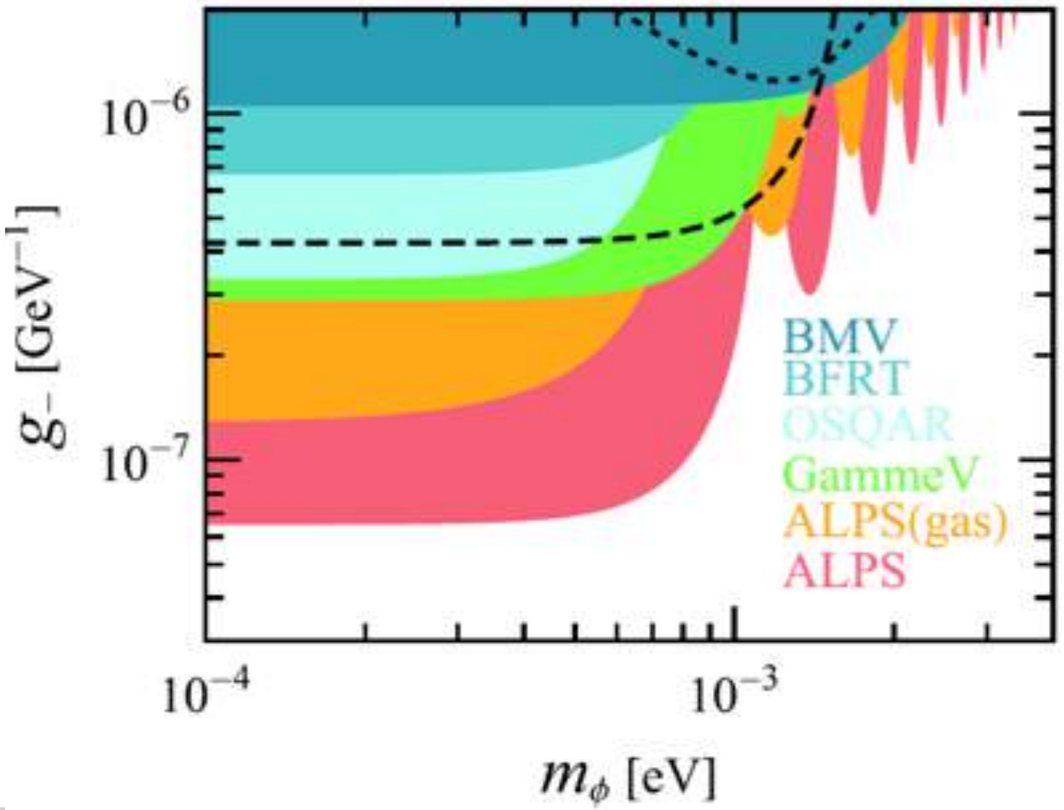
- 5 ns wide pulses from Nd: YAG laser

A. S. Chou, W. Wester et al., 2008

Constraints on $g_{a\gamma\gamma}$ from Completed LSW Experiments

Experiment	ω	P_g	β_g	Magnets
ALPS (DESY) [61,62]	2.33 eV	4 W	300	$B_g = B_r = 5$ T $L_g = L_r = 4.21$ m
BFRT (Brookhaven) [64,65]	2.47 eV	3 W	100	$B_g = B_r = 3.7$ T $L_g = L_r = 4.4$ m
BMV (LULI) [66,67]	1.17 eV	$8 \times 10^{21} \frac{\gamma}{\text{pulse}}$ (14 pulses)	1	$B_g = B_r = 12.3$ T $L_g = L_r = 0.4$ m
GammeV (Fermilab) [68]	2.33 eV	$4 \times 10^{17} \frac{\gamma}{\text{pulse}}$ (3600 pulses)	1	$B_g = B_r = 5$ T $L_g = L_r = 3$ m
LIPSS (JLab) [69,70]	1.03 eV	180 W	1	$B_g = B_r = 1.7$ T $L_g = L_r = 1$ m
OSQAR (CERN) [71,72]	2.5 eV	15 W	1	$B_g = B_r = 9$ T $L_g = L_r = 7$ m
BMV (ESRF) [73]	50/90 keV	10/0.5 mW	1	$B_g = B_r = 3$ T $L_g = 1.5, L_r \sim 1$ m

Table 1. Some experimental parameters of the past and current generation of LSW experiments.



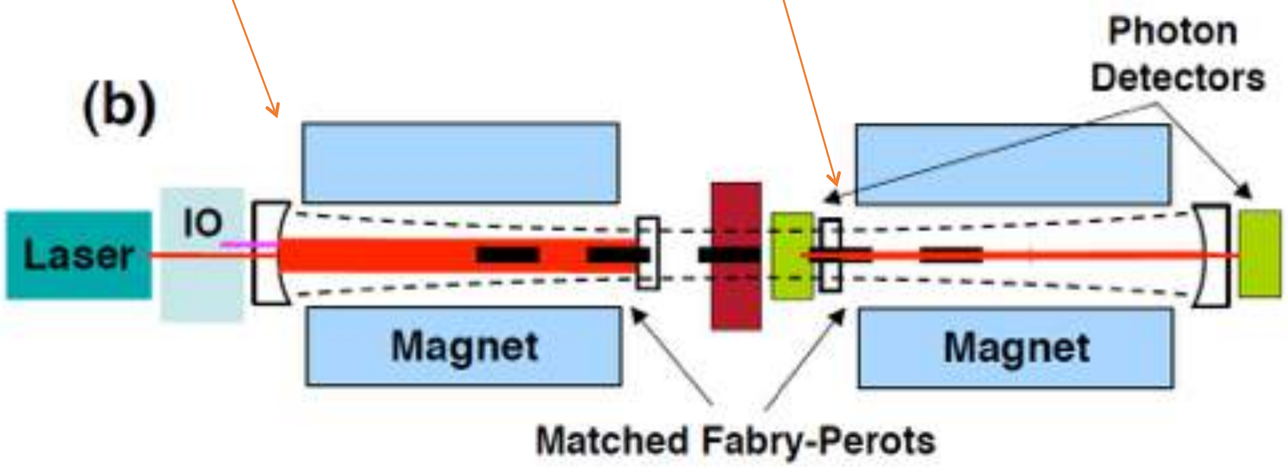
Redondo & Ringwald 2010

Resonant Regeneration of Axion Signal

- Optical resonators are placed on both the source and receiver side of the wall.
- Resonators are phase locked to each other;
- Receiver power is enhanced by the product of the finesse of the two optical resonators.
  - Enhancement factor in signal power can be $\sim 10^5 \times 10^4 = \sim 10^9$ at optical frequencies
  - But coupling sensitivity scales only as $power^{1/4}$...

Resonator on source side recycles photons from laser

Resonator on receiver side amplifies signal



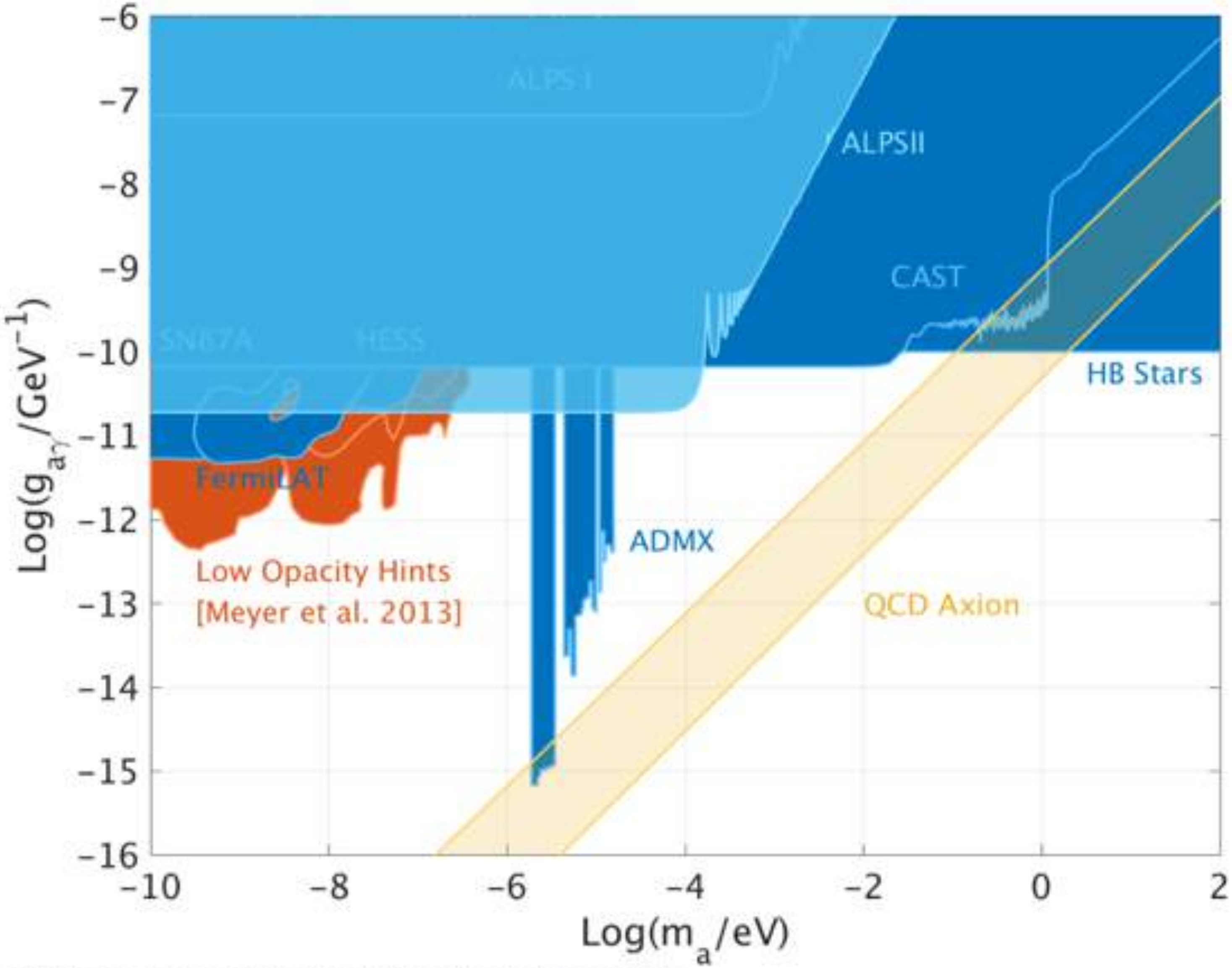
Sikivie, Tanner & Van Bibber 2007

ALPS I and ALPS II at DESY: Any Light Particle Search

parameter	scaling	ALPS I	ALPS IIc	sens. gain
BL (total)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
PC built up ($P_{\text{laser,eff.}}$)	$g_{a\gamma} \propto \beta_{PC}^{-1/4}$	1 (kW)	150 (kW)	3.5
rel. photon flux $\dot{n}_{\text{prod}}$	$g_{a\gamma} \propto \dot{n}_{\text{prod}}^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
RC built up β_{RC}	$g_{a\gamma} \propto \beta_{RC}^{-1/4}$	1	40,000	14
detector eff. DE	$g_{a\gamma} \propto DE^{-1/4}$	0.9	0.75	0.96
detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	$1.8 \cdot 10^{-3}\,\text{s}^{-1}$	$10^{-6}\,\text{s}^{-1}$	2.6
combined				3082

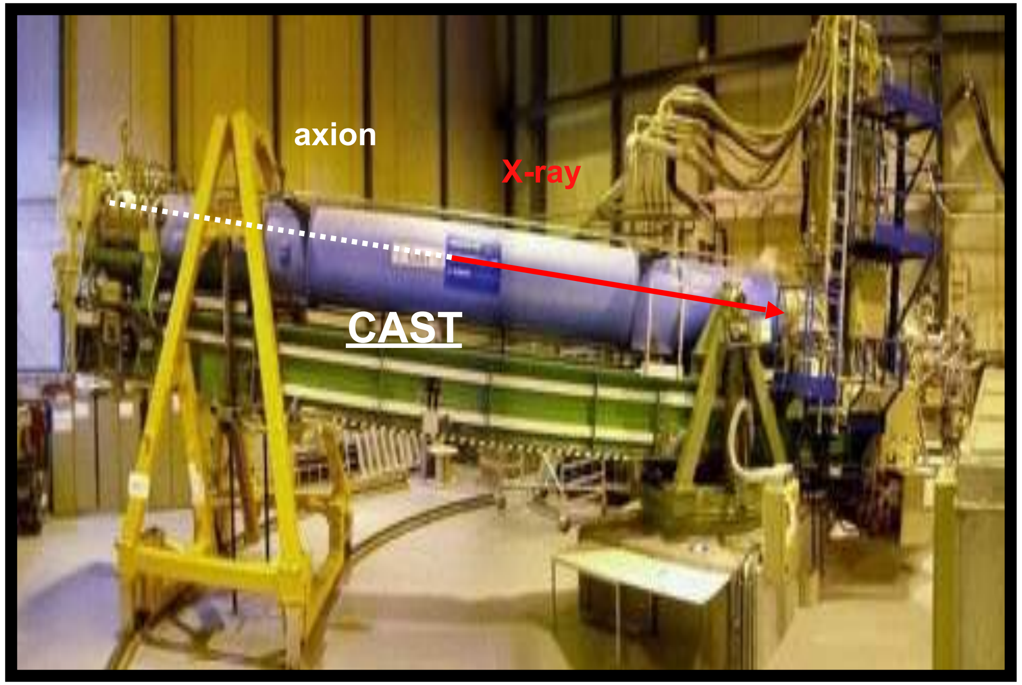
Aaron Spector, Patras 2018

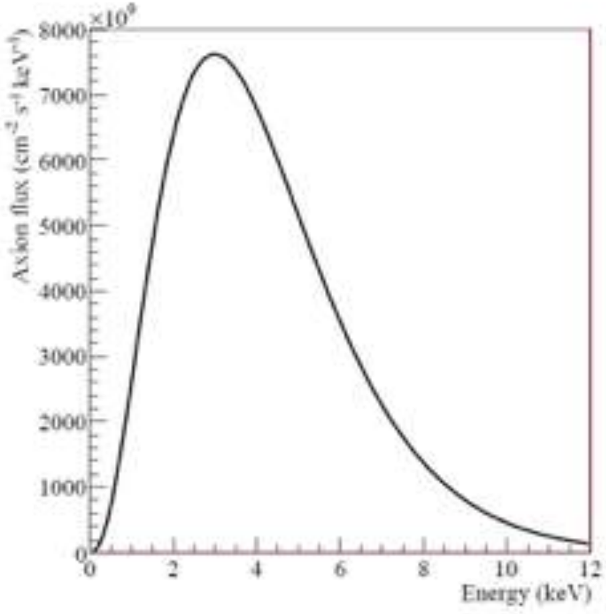
ALPS II Sensitivity

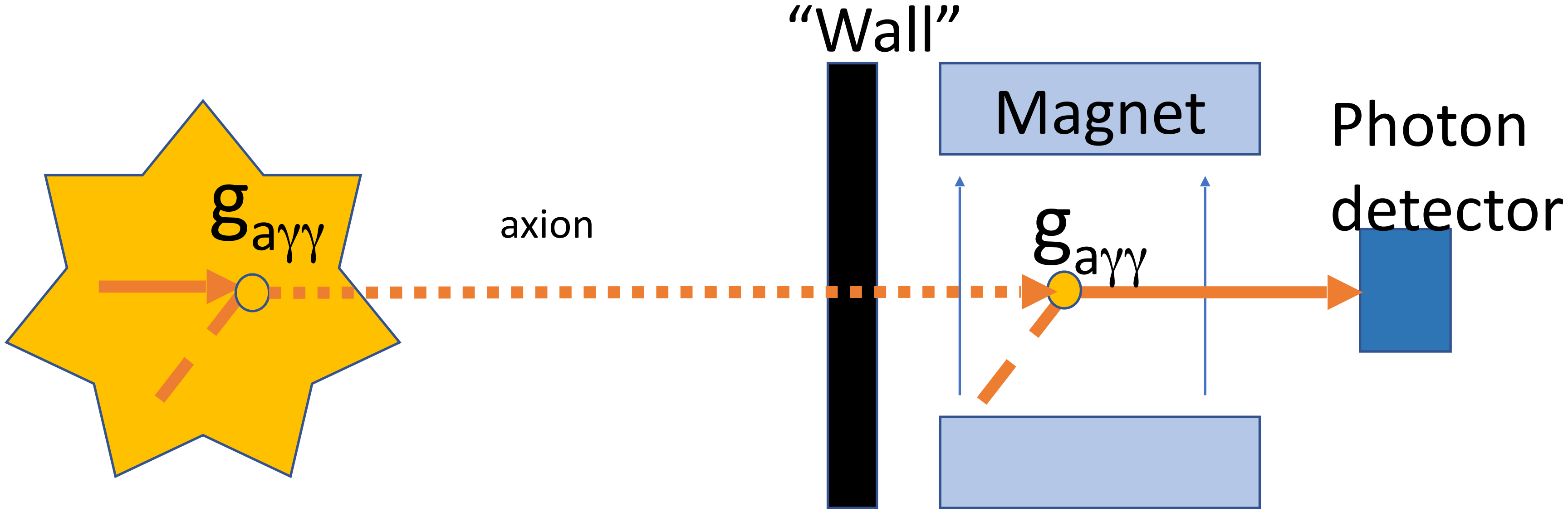


Solar Axions

- Similar to “light shining through walls”, but replace laser with the Sun.
- Electromagnetic fields in solar plasma convert X- ray photons to axions.
- Solar axion flux: 0.2% L_{solar} or 3.75 x 10^{11} cm^{-2} s^{-1} for $g_{a\gamma\gamma} = 10^{-10} GeV^{-1}$ (Raffelt, 2006)

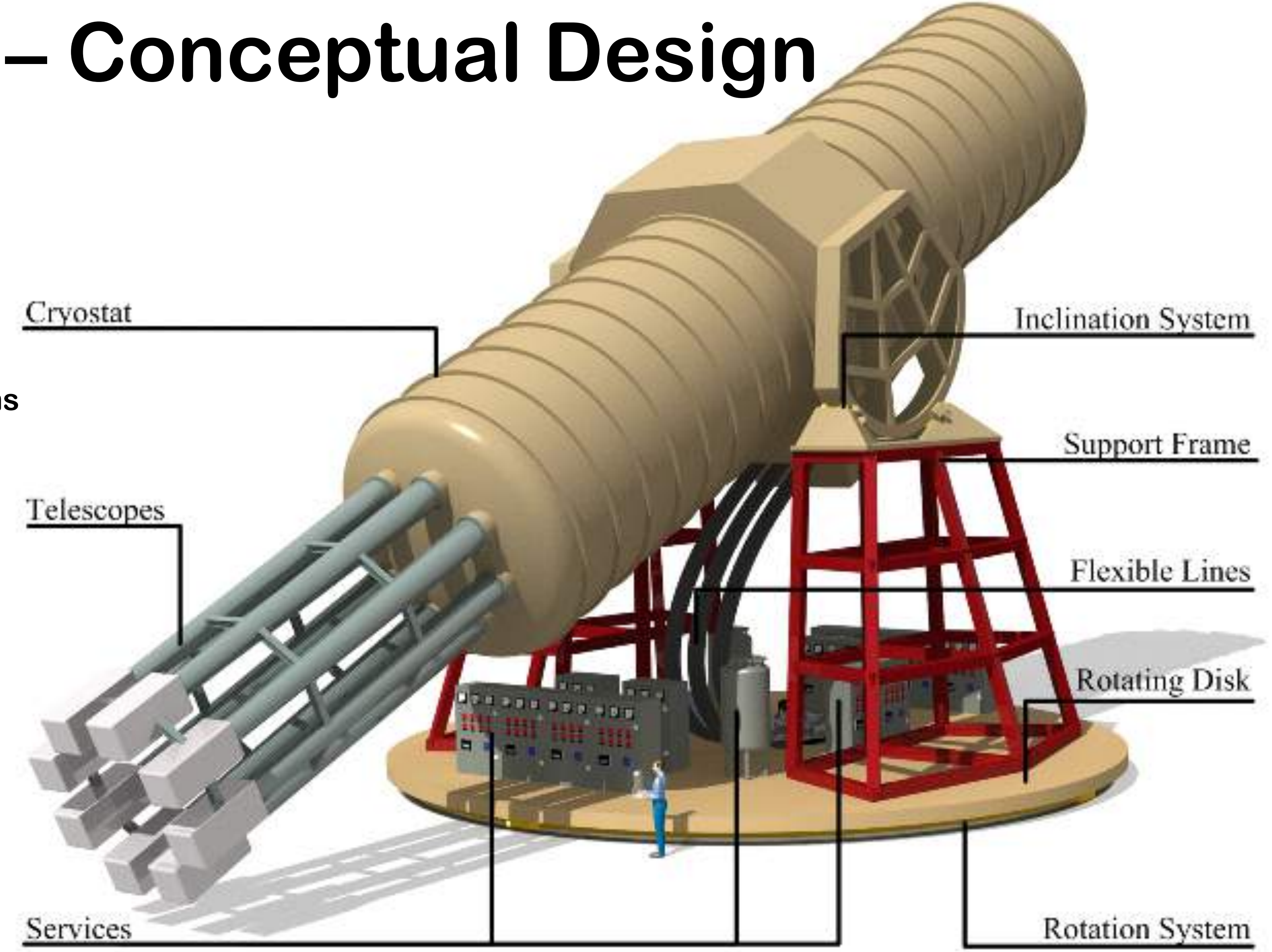




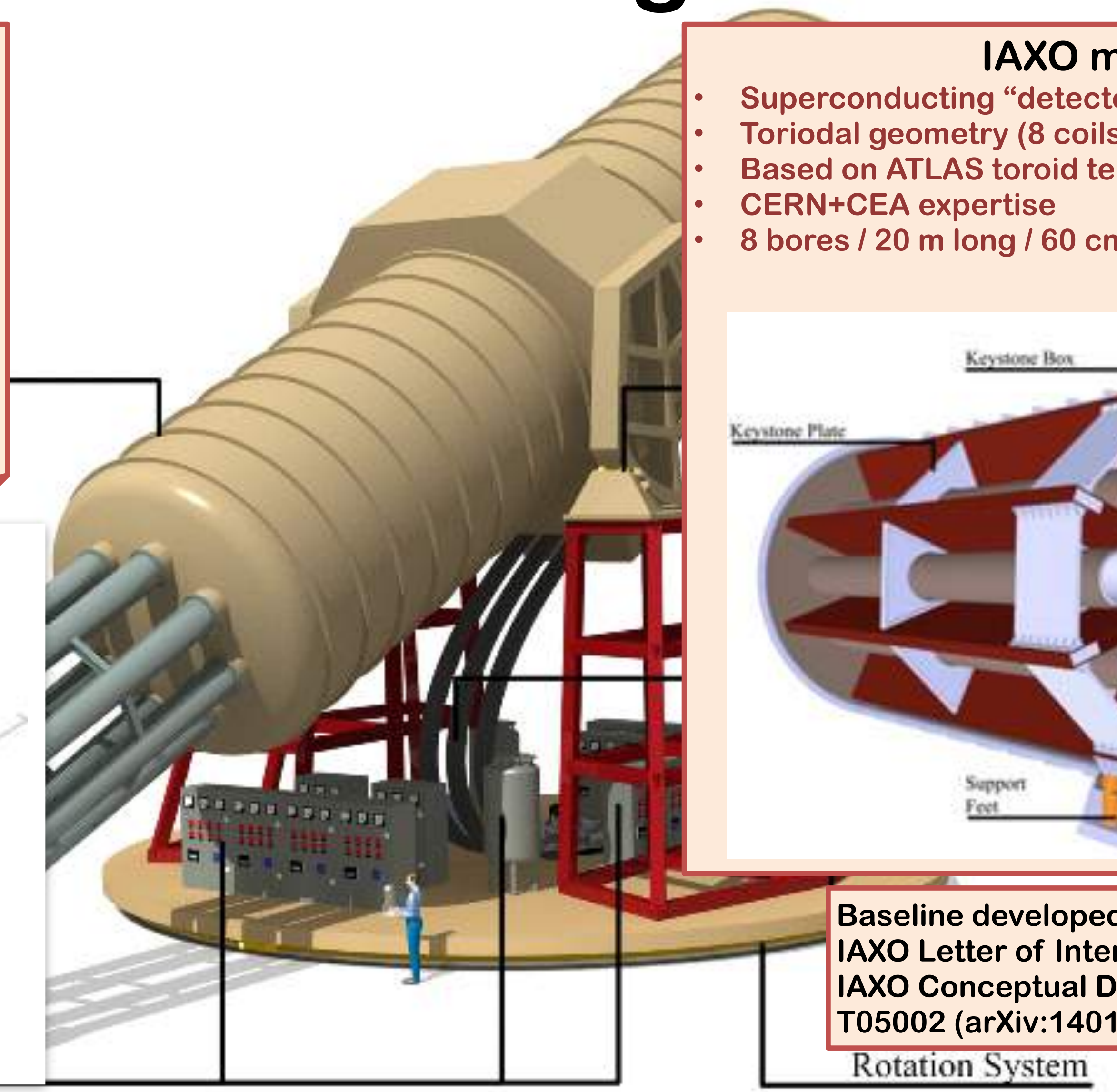


IAXO – Conceptual Design

- Large toroidal 8-coil magnet L = ~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services

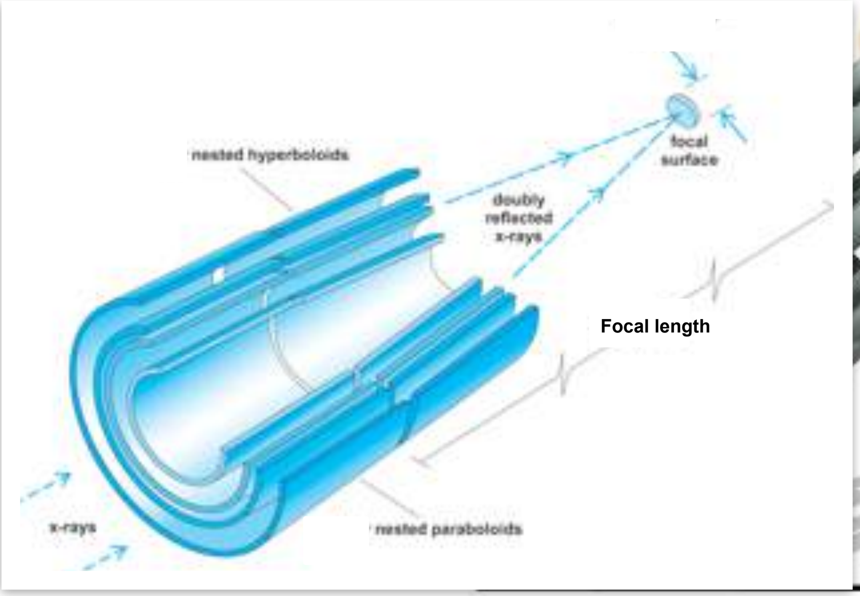


IAXO technologies



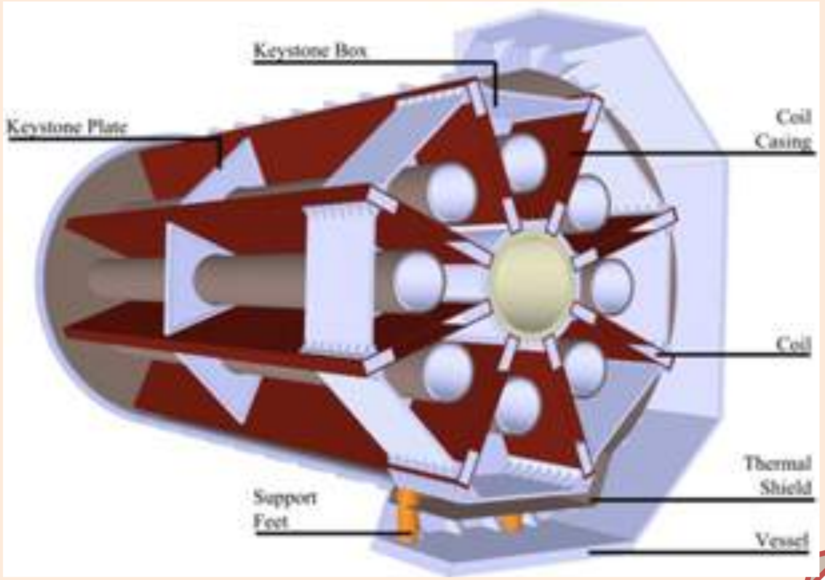
IAXO telescopes

- Slumped glass technology with multilayers
- Cost-effective to cover large areas
- Similar to NuSTAR optics
- Focal length ~5 m
- 60-70% efficiency
- LLNL+UC+DTU
  + MIT + INAF



IAXO magnet

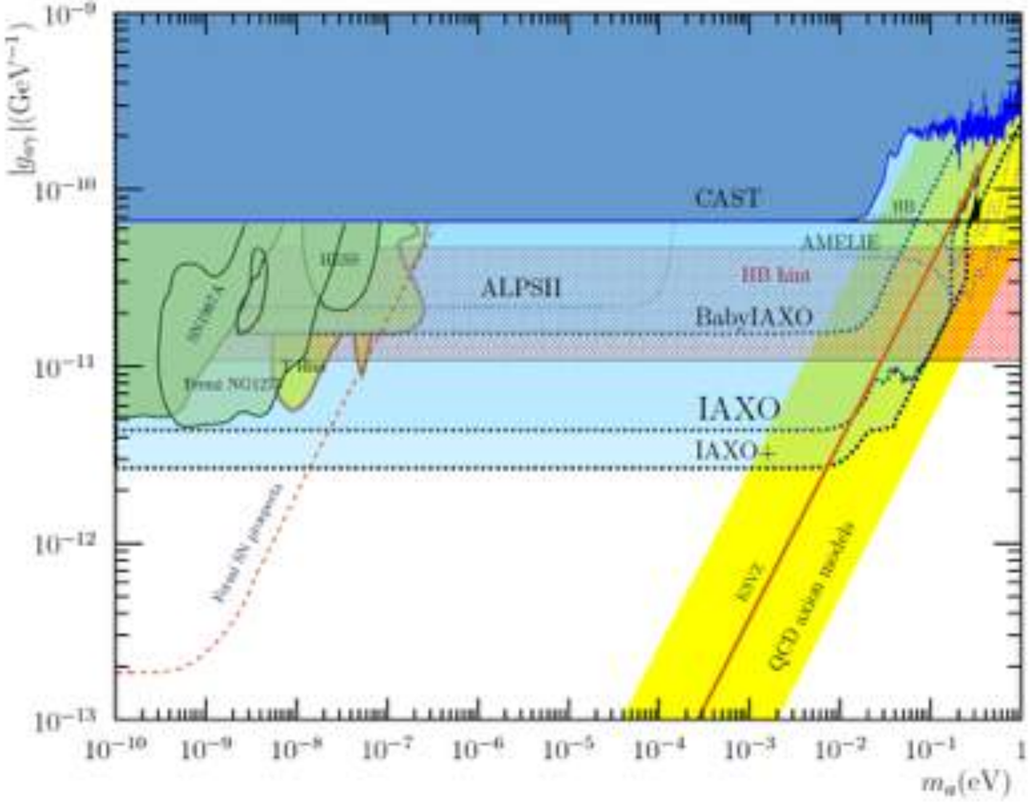
- Superconducting “detector” magnet.
- Toriodal geometry (8 coils)
- Based on ATLAS toroid technical solutions.
- CERN+CEA expertise
- 8 bores / 20 m long / 60 cm Ø per bore



Baseline developed at:
IAXO Letter of Intent: CERN-SPSC-2013-022
IAXO Conceptual Design: JINST 9 (2014) T05002 (arXiv:1401.3233)

Solar Axion Telescopes- Summary

Experiment	references	status	B (T)	L (m)	$\mathcal{A}$ (cm^2)	focusing	g_{10}
Brookhaven	[38]	past	2.2	1.8	130	no	36
SUMICO	[46, 486]	past	4	2.5	18	no	6
CAST	[481, 483, 488, 491, 492]	ongoing	9	9.3	30	partially	0.66
TASTE	[499]	concept	3.5	12	2.8×10^3	yes	0.2
BabyIAXO	[500]	in design	~2.5	10	2.8×10^3	yes	0.15
IAXO	[487, 501]	in design	~2.5	22	2.3×10^4	yes	0.04



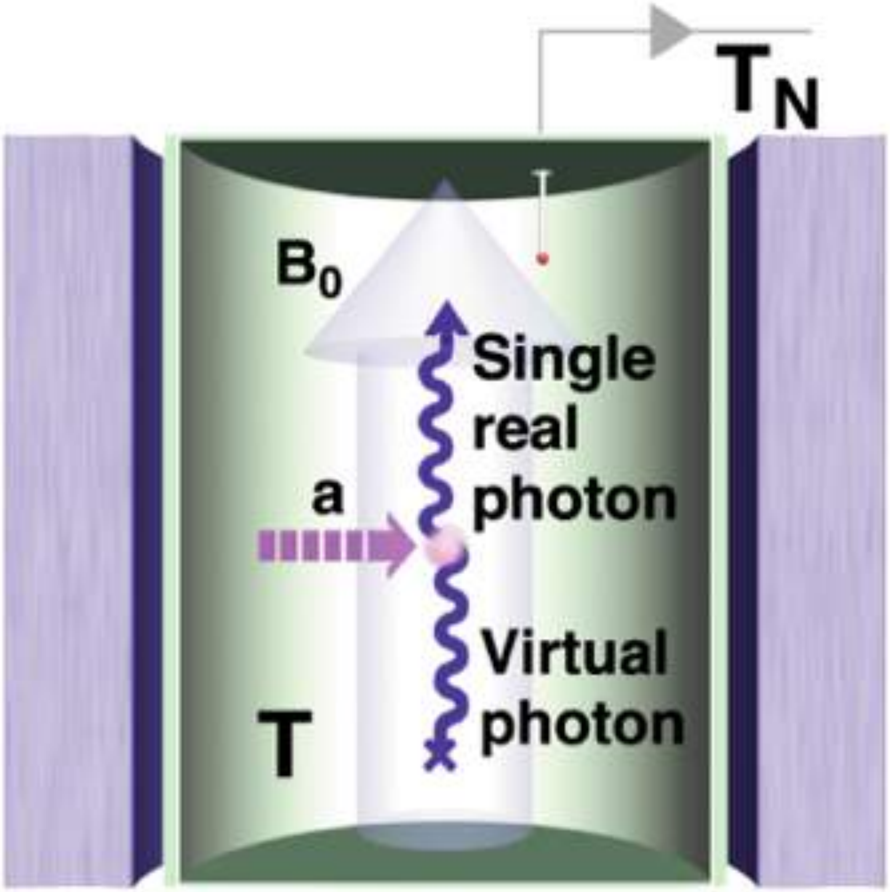
Irastorza and Redondo, 2018

Haloscope Technique

- Axions from galaxy halo convert to microwave photons in a magnetic field.
- Signal power:

$$P = 4 \cdot 10^{-22}\,\mathrm{W} \left(\frac{V}{200\ \ell}\right)\left(\frac{B_0}{8\ \mathrm{Tesla}}\right)^2 C_{nl}\left(\frac{g_\gamma}{0.97}\right)^2 \cdot \left(\frac{\rho_a}{0.5 \cdot 10^{-24}\ \mathrm{g/cm^3}}\right)\left(\frac{m_a}{1\ \mathrm{GHz}}\right)\left(\frac{\min(Q_L, Q_a)}{1 \times 10^5}\right)$$

Form Factor C_{nl} *overlap of cavity mode* $\boldsymbol{E} \cdot \boldsymbol{B_0}$
Dark Matter Density ρ_a
Axion Mass m_a
Resonator Quality Factor $Q_L \sim 10^5$
Axion Q from velocity dispersion $Q_a \sim 10^6$
Couplings to Photon $g_\gamma \sim 0.97$ for KSVZ model
$g_\gamma \sim 0.36$ for DFSZ



See Pierre Sikivie, "Experimental Tests of the Invisible Axion" 1983 PRL

History

First and second generation haloscope experiments (1980s-90s) :

Cooled to 4 K w/FET transistor amplifiers, noise temperature range 3 - 20 K.

- BNL
- University of Florida
- Rochester/ Brookhaven/ Fermilab (RBF)
- ADMX- achieved KFVZ sensitivity

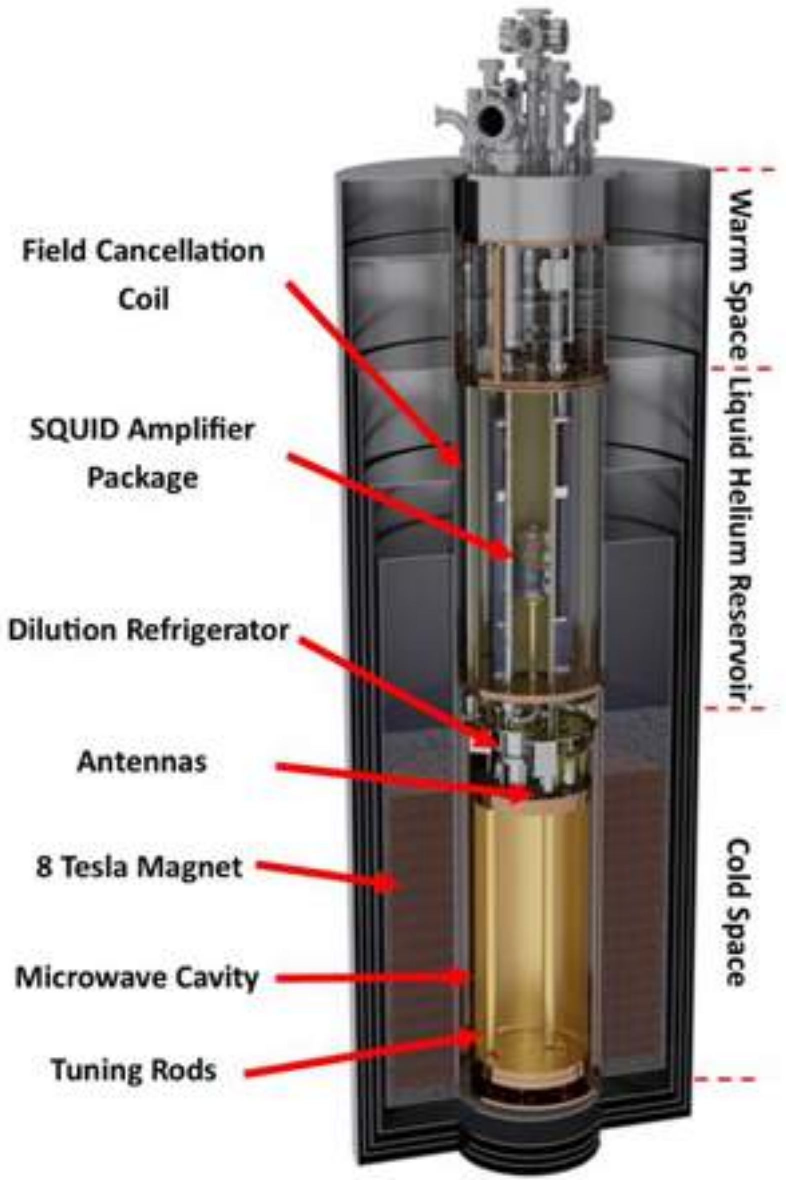
3rd generation (current):

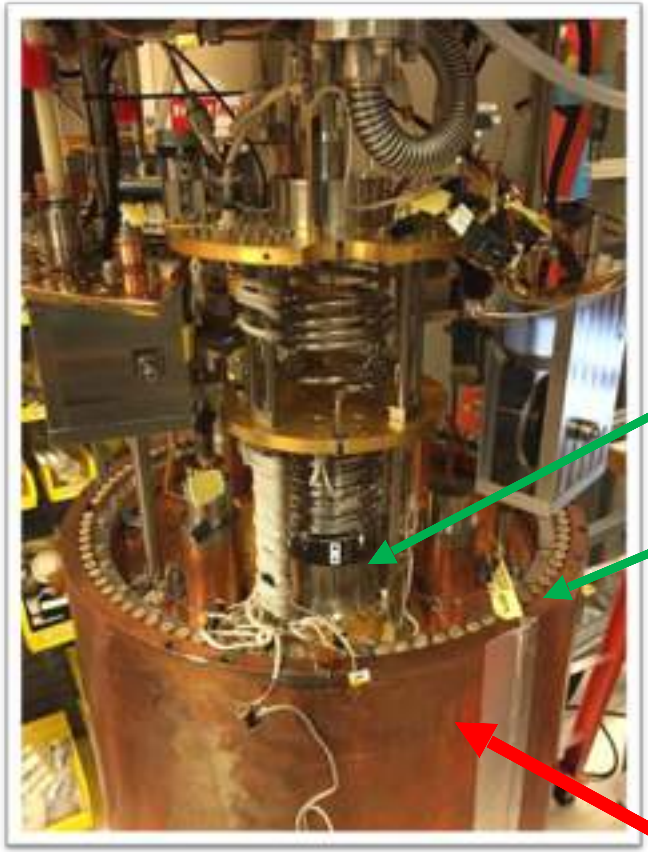
Superconducting amplifiers <100 mK approaching standard quantum limit of noise.
Microstrip Squid Amplifiers & Josephson Parametric Amplifiers.

- ADMX-G2.
- Haystac
- CAPP

4th Generation? Beyond standard quantum limit?

ADMX Experiment Design





Dilution refrigerator $^3He/^4He$ mixing chamber

Microwave Cavity

2017 Run: 150 mK
2018 Run: 90 mK

ADMX site: University of Washington

Center for Experimental Nuclear Physics and Astrophysics (CENPA)

ADMX DAQ & Controls

Cleanroom
(with insert hanging)

ADMX Magnet

Helium liquefier

ADMX Magnets

field cancellation coil

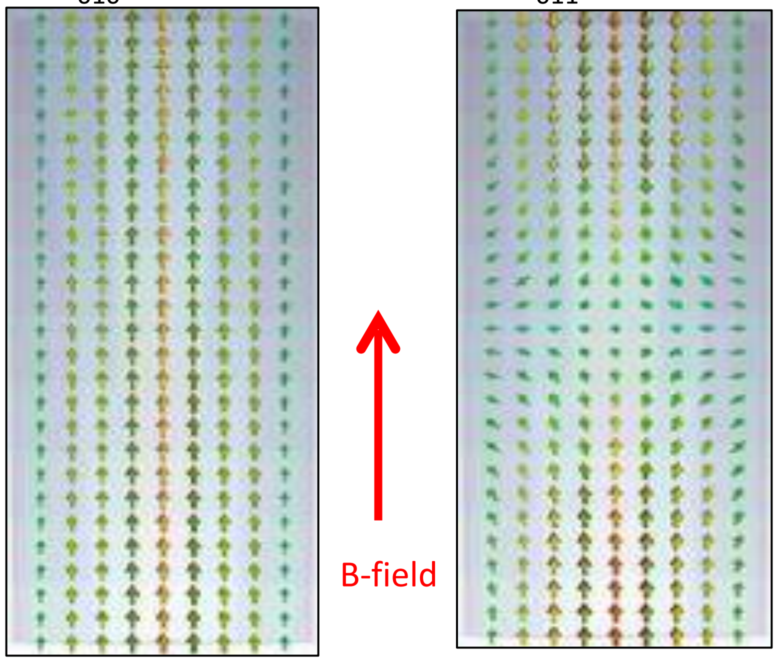
ADMX 8-Tesla x 50 cm solenoid

Key Microwave Cavity Design Constraints

$$\frac{df}{dt} \approx 1.68\ \text{GHz/year} \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \text{GHz}}\right)^2 \left(\frac{\rho_0}{0.45\ \text{GeV/cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{8\ \text{T}}\right)^4 \left(\frac{V}{100\text{l}}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2\ K}{T_{sys}}\right)^2$$

TM_{010} mode
C_{010} ~ 0.69

TM_{011} mode
C_{011} ~ 0.0

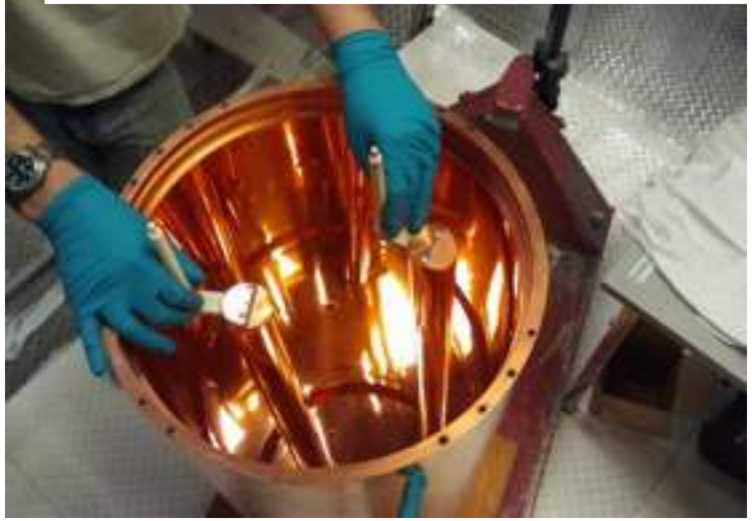


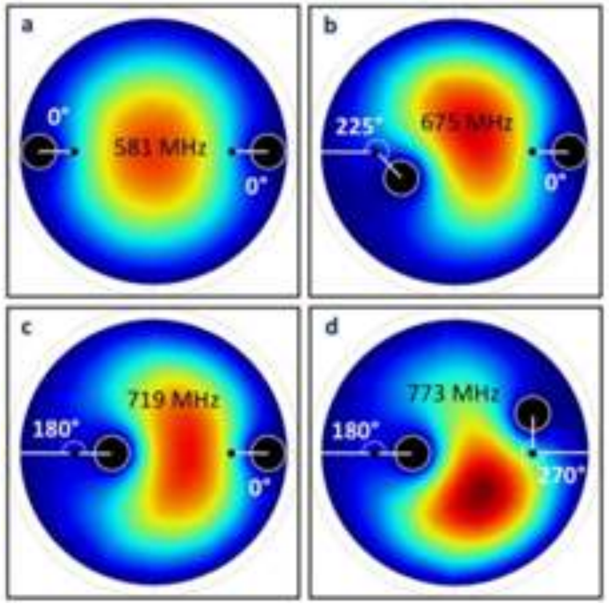
- Maximize product of $B^2 \cdot V \cdot Q_L \cdot C_{lmn}$ to maximize axion-to-photon conversion power
  - B^2V set by the magnet bore: $(8\text{T})^2 \cdot$(~100 liters)
- Loaded Quality factor Q_L = frequency/bandwidth

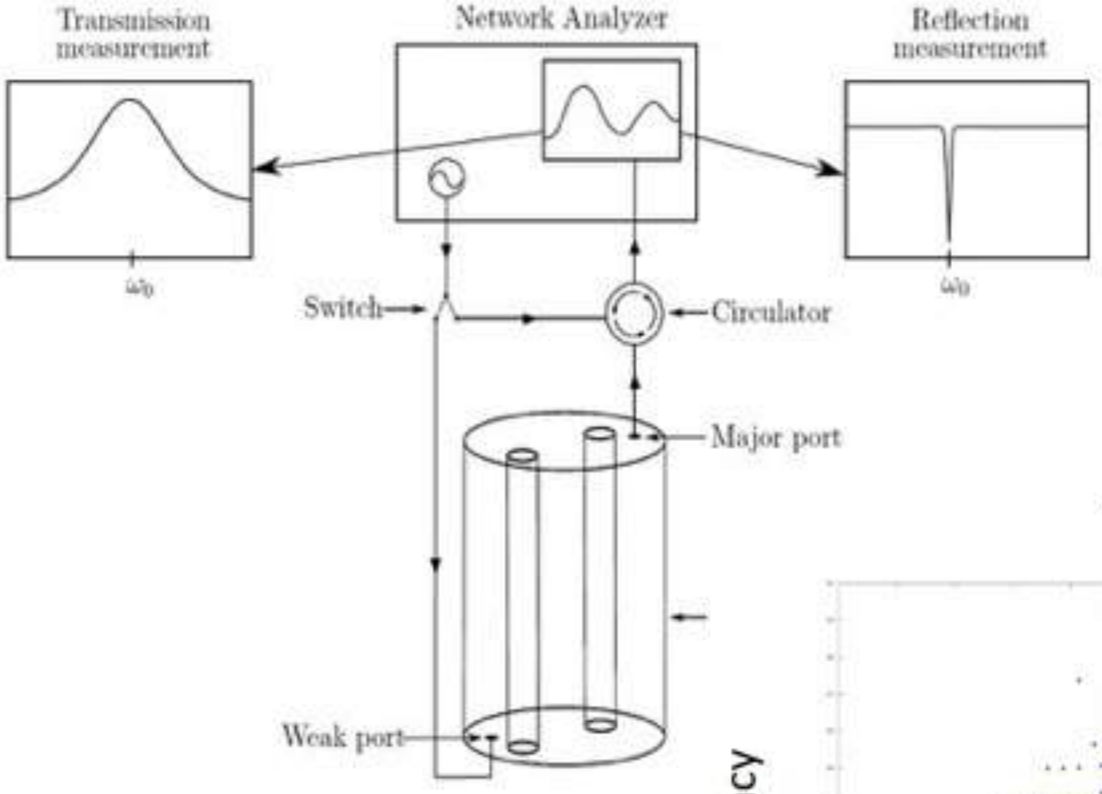
  (Q_L ~ 10^5 for copper cavity ~1 GHz)
- Mode Form Factor C_{lmn}
- Tunability: must be able to shift resonant frequency over an appreciable range (typically 30-50%)

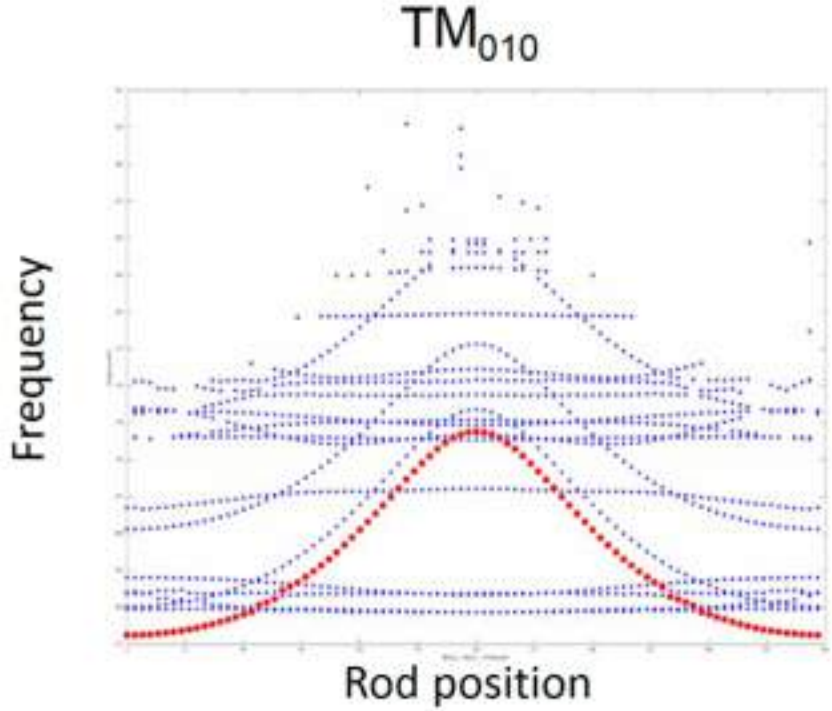
The Resonator

Tuning Rods





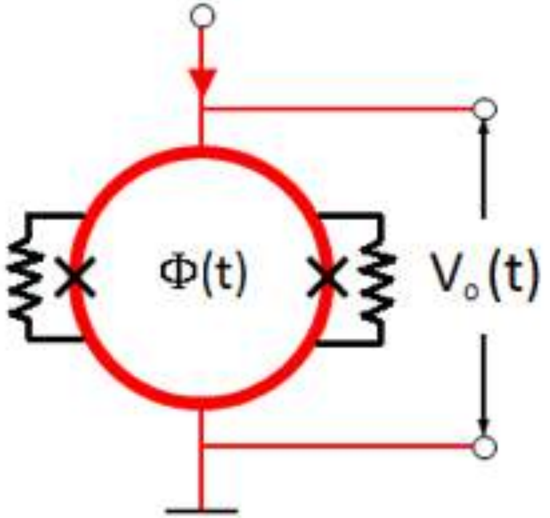


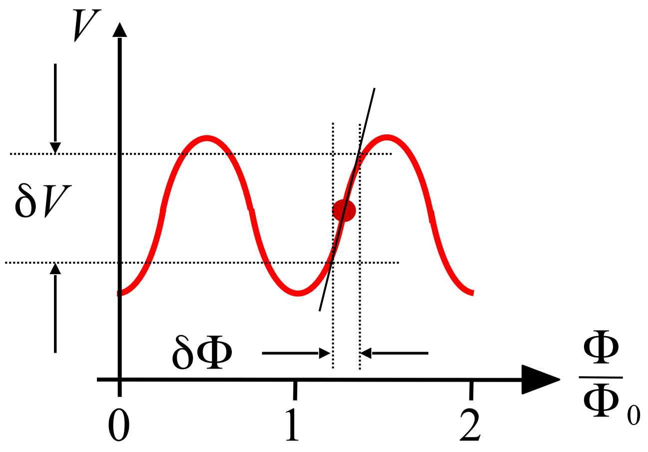


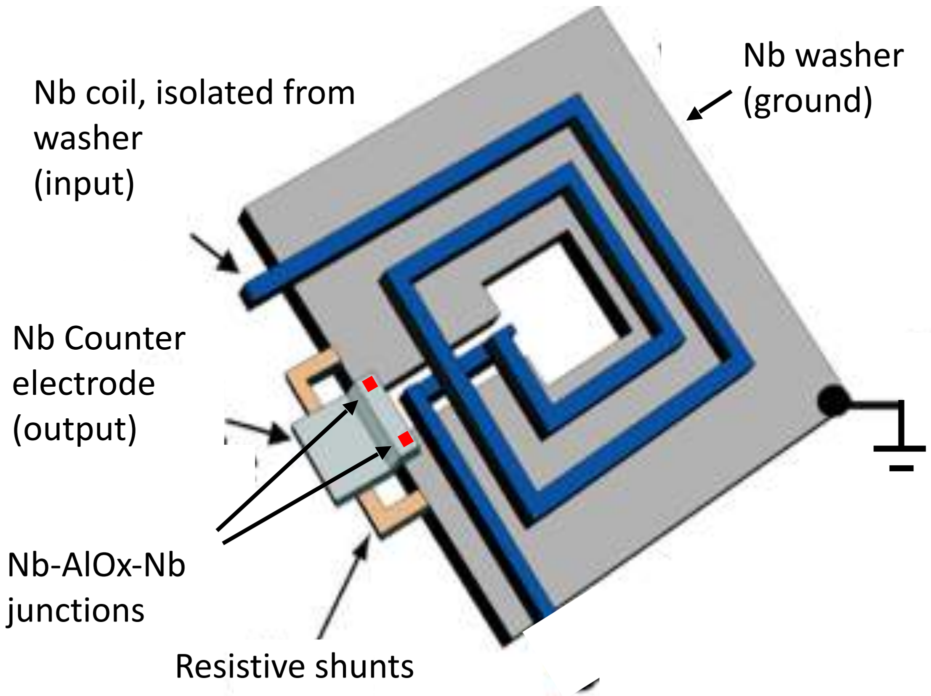
- Frequency steps typically 1/10 cavity line width ~ 2 KHz

Microstrip Squid Amplifier (MSA)

- Very similar to conventional DC Squid.
- Flux to voltage converter sensitive to a fraction of a flux quantum.
- Adapted for high frequency use.
- Supplied to ADMX by Clarke group at UC Berkeley.

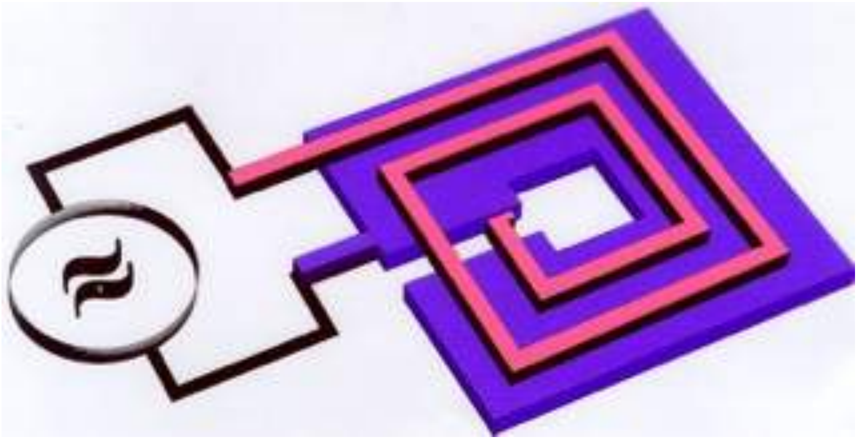


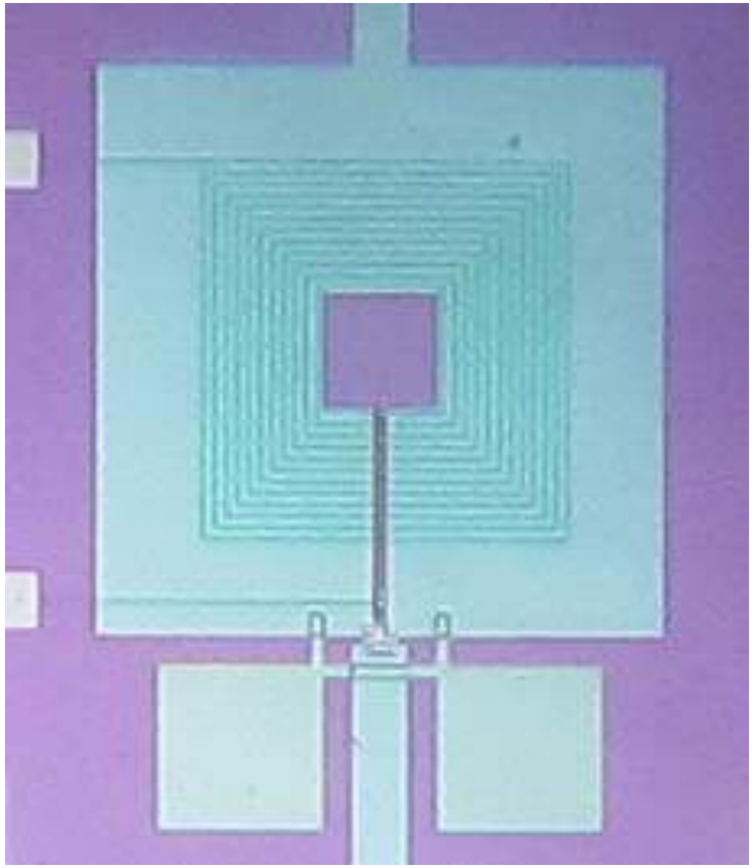




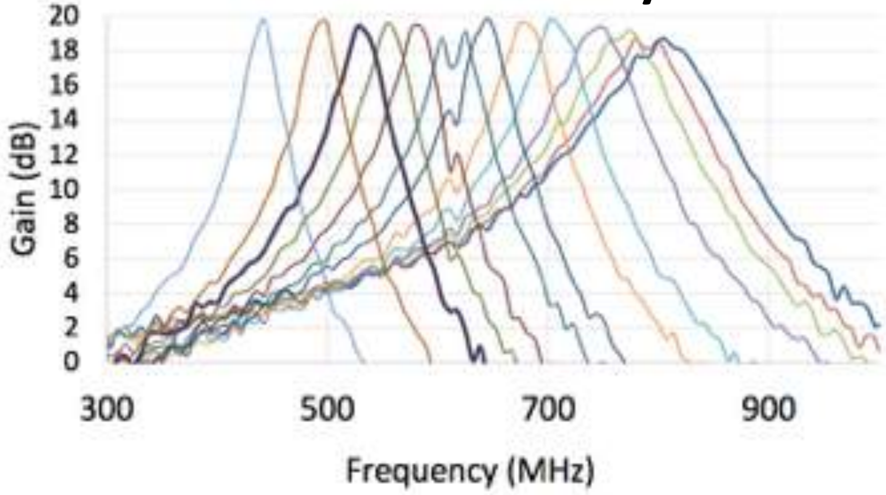
Microstrip Squid Amplifier (MSA)

- To couple a microwave signal into the SQUID:
  - Cover the washer with an insulating layer (350nm of SiO_2)
  - Add a spiral path of conductor around central hole
  - This creates a **microstrip** transmission line resonator between the input coil and SQUID washer.
- GaAs varactor used to tune the microstrip resonator.

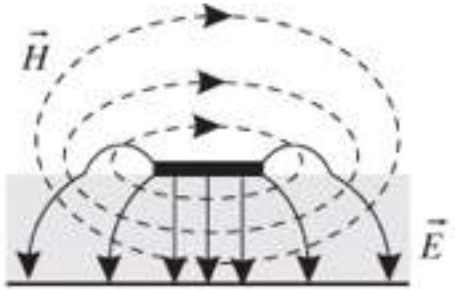




MSA Varactor Tunability

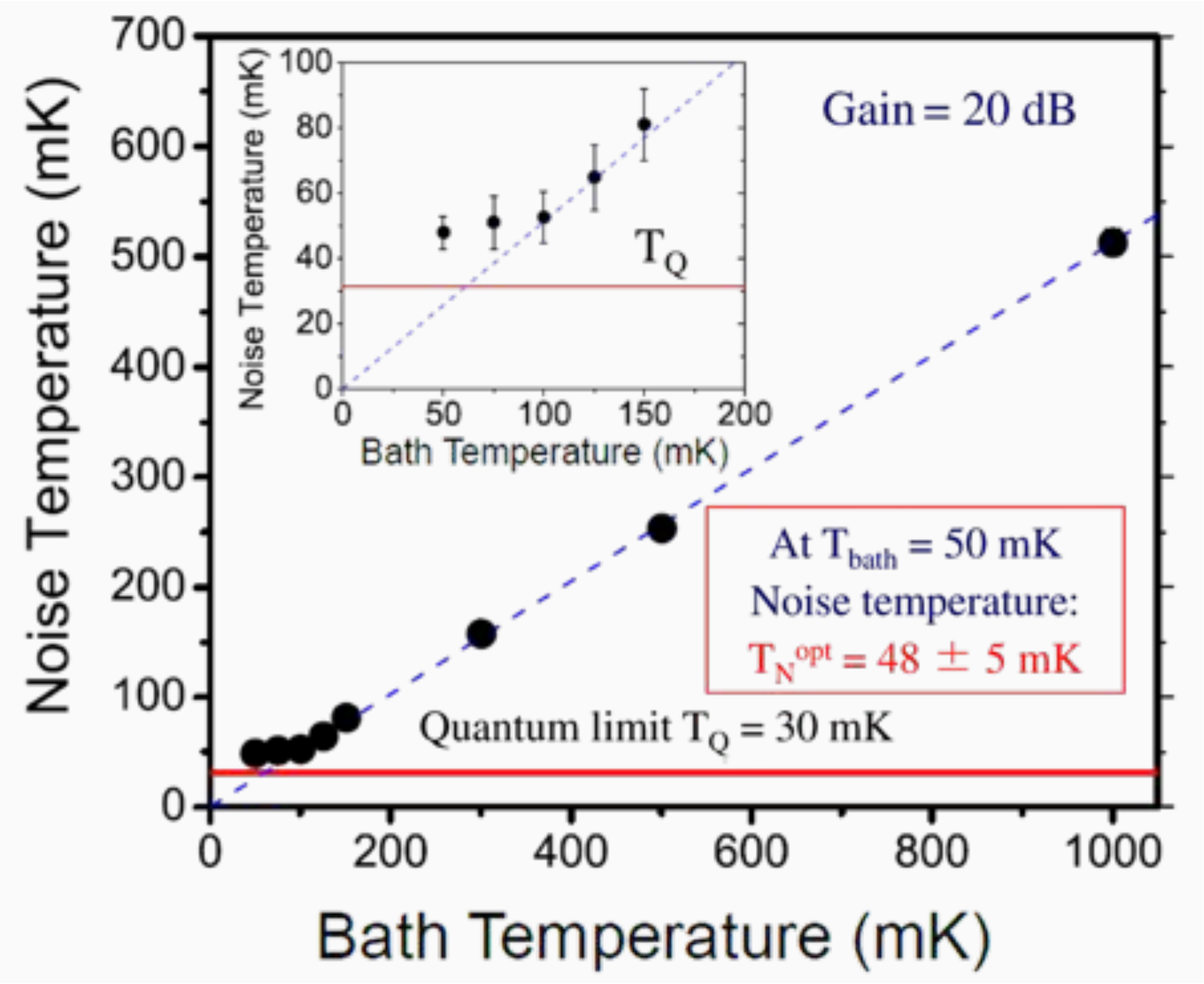


Stripline Field Geometry

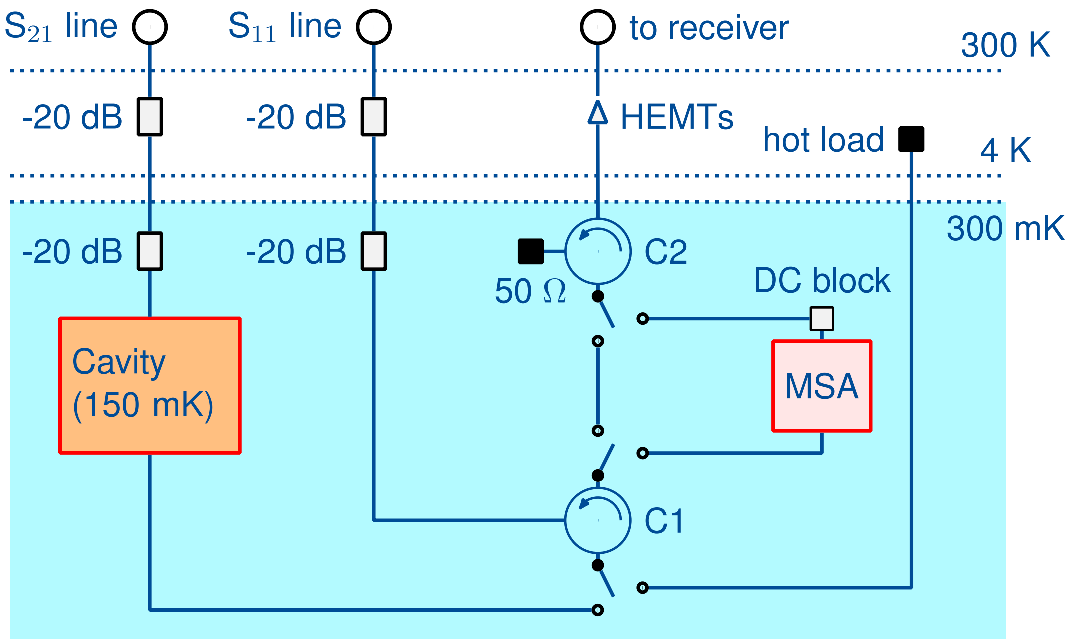


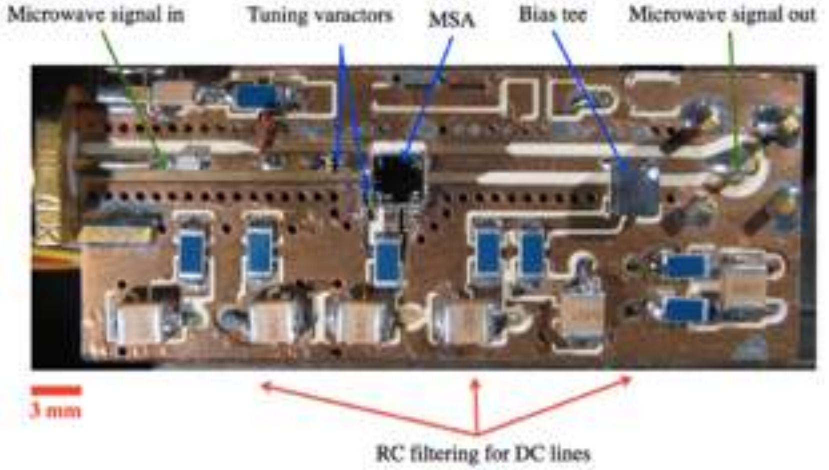
Noise Performance of Microstrip Squid Amplifiers

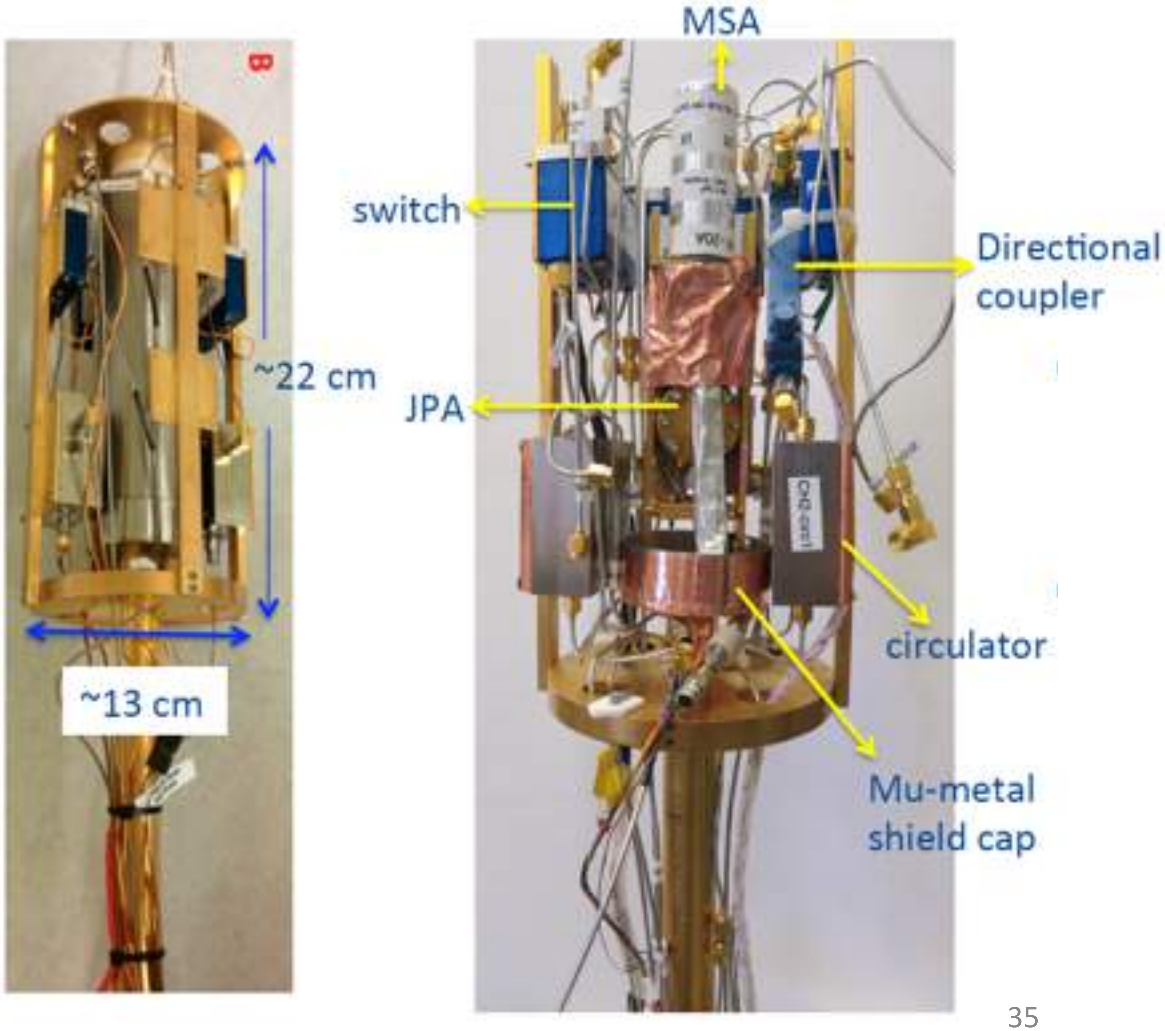
- $$T_{Noise} = \frac{1}{k_B}\frac{Noise\ Power}{Bandwidth}$$
- Achieved T_N= 48 mK at 600 MHz during testing at UC Berkeley
- 1.7 x quantum limit.
- In ADMX operation, *system* noise temperatures has additional contributions from:
    - Black body radiation in cavity
    - Attenuation
    - Post amplification stages



Cryogenic Electronics System Package- 2017/2018

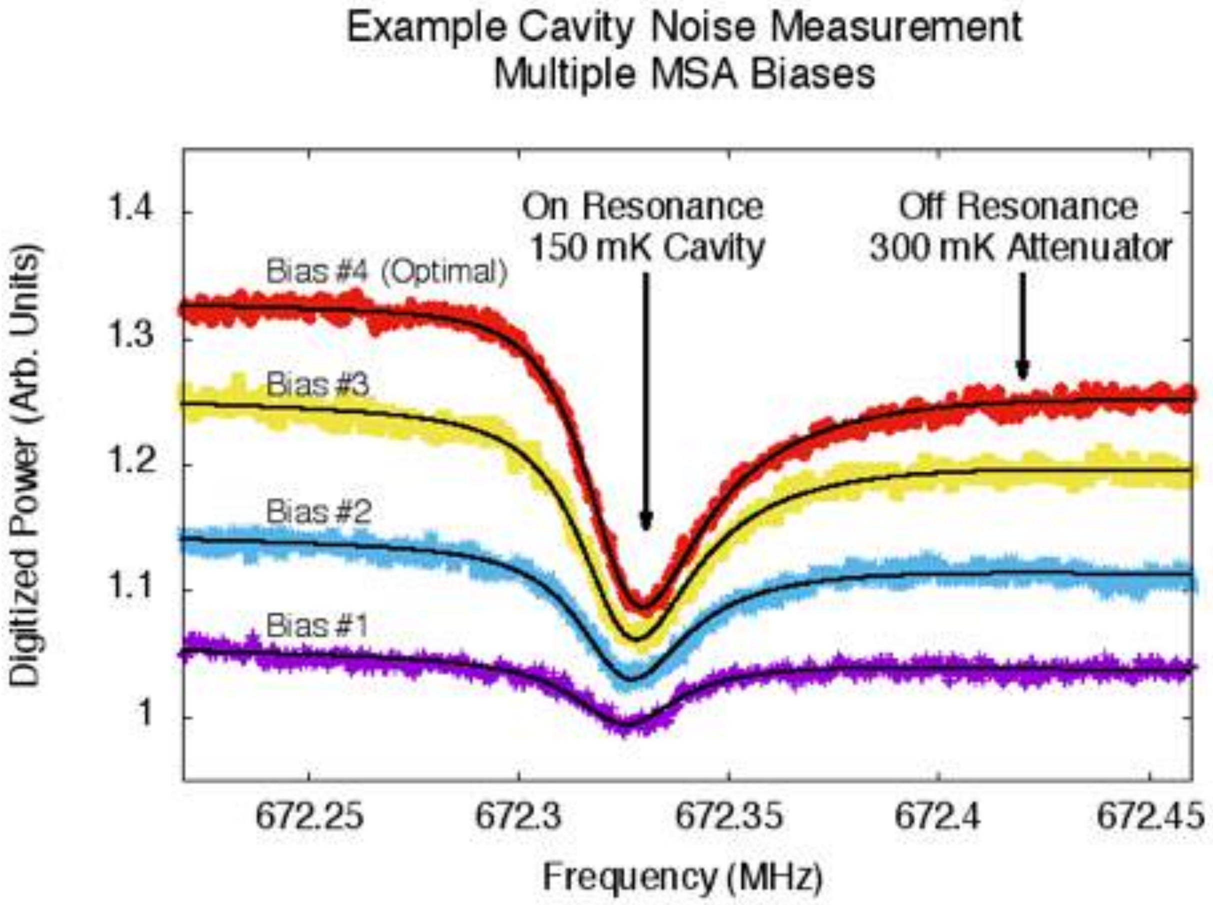


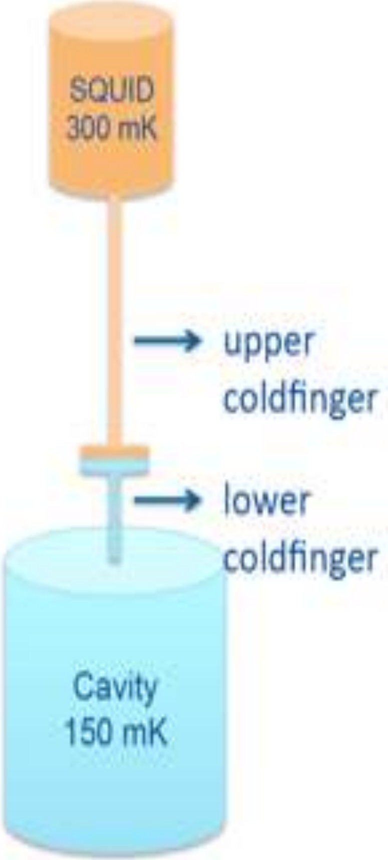




MSA Operation in ADMX 2017/ 2018 Runs

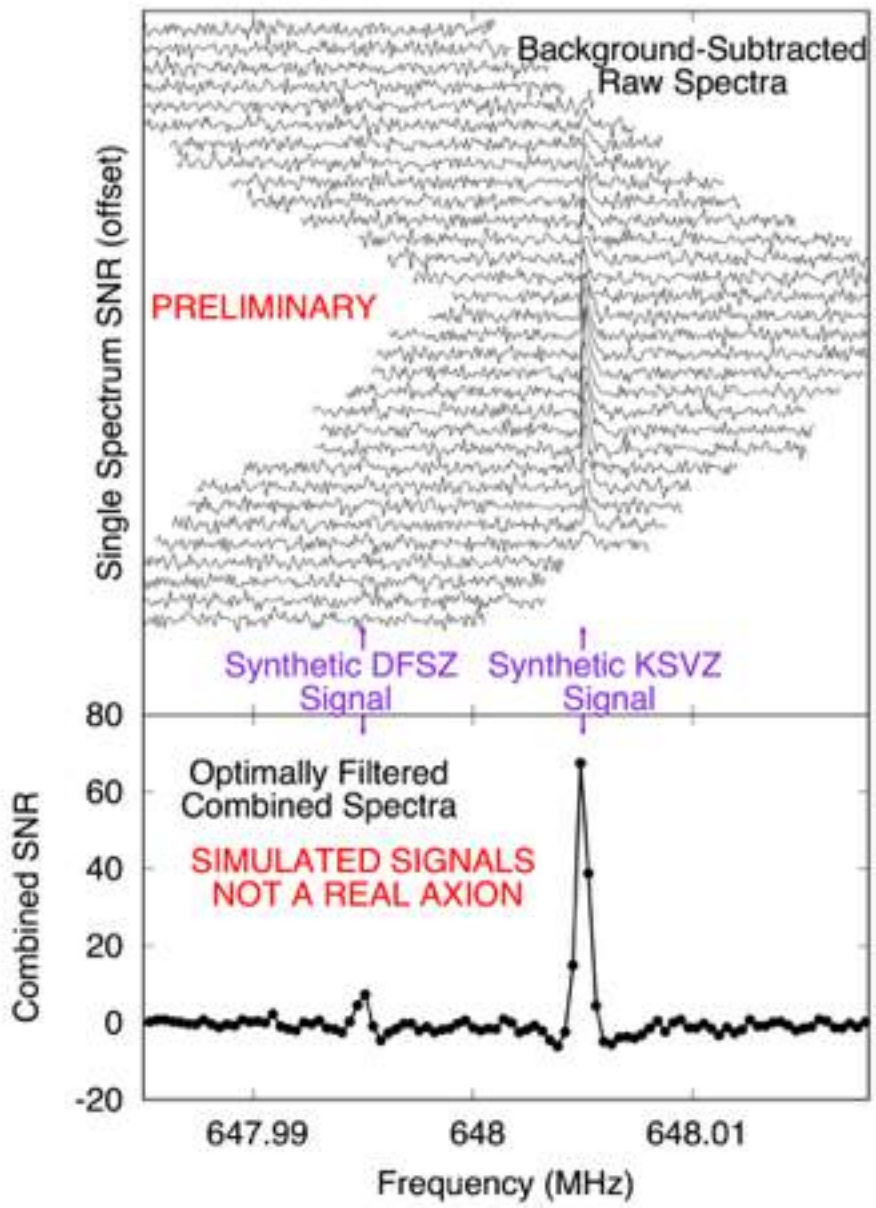
- Amplifier package at higher temperature than resonator due to thermal short.
- Causes distinctive "dip" in noise power at cavity resonance.
- Typical system noise temperature was ~500 mK.





Experiment Operation Procedure

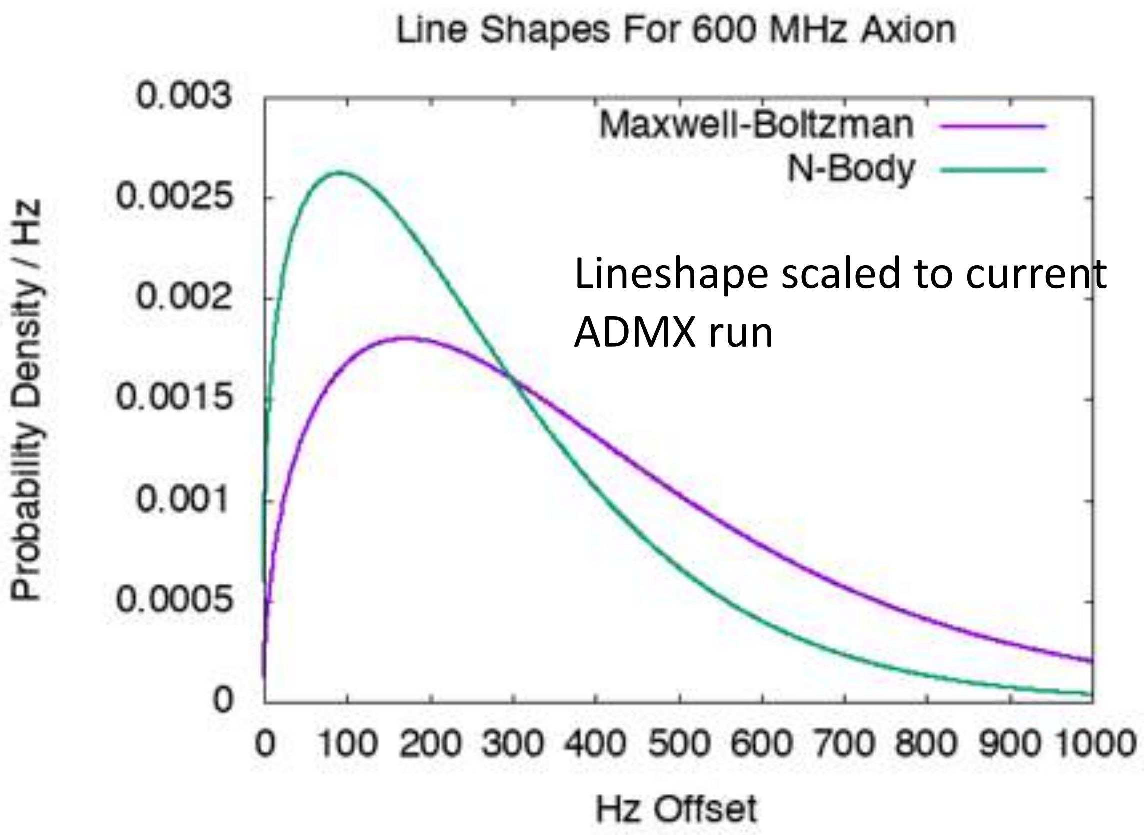
- The cavity frequency is scanned over a region until the desired SNR is achieved.
- Convolution with filter matched to expected axion linewidth.
- Typically we have ~10^6 independent measurements on each axion linewidth, averaged to reduce noise by $\sqrt{10^6}$
- We then examine the combined power spectrum for signs of excess
- Excess power regions can be statistical fluctuations, synthetically injected signals, RF interference, or axions
- Excess power regions are rescanned to see if they persist
- Persistent candidates are subjected to a variety of confirmation tests: for example: magnet field changes or probing with other cavity modes.
- We do blind signal injection, so we always have candidates



Predicted Axion Signal Shape

Recent N-Body models actually suggest the axion lineshape is narrower than the standard virialized model.

Our analysis searches for both.



Lineshape scaled to current ADMX run

Adapted from: Lentz et al. Ap.J. 845 (2017)

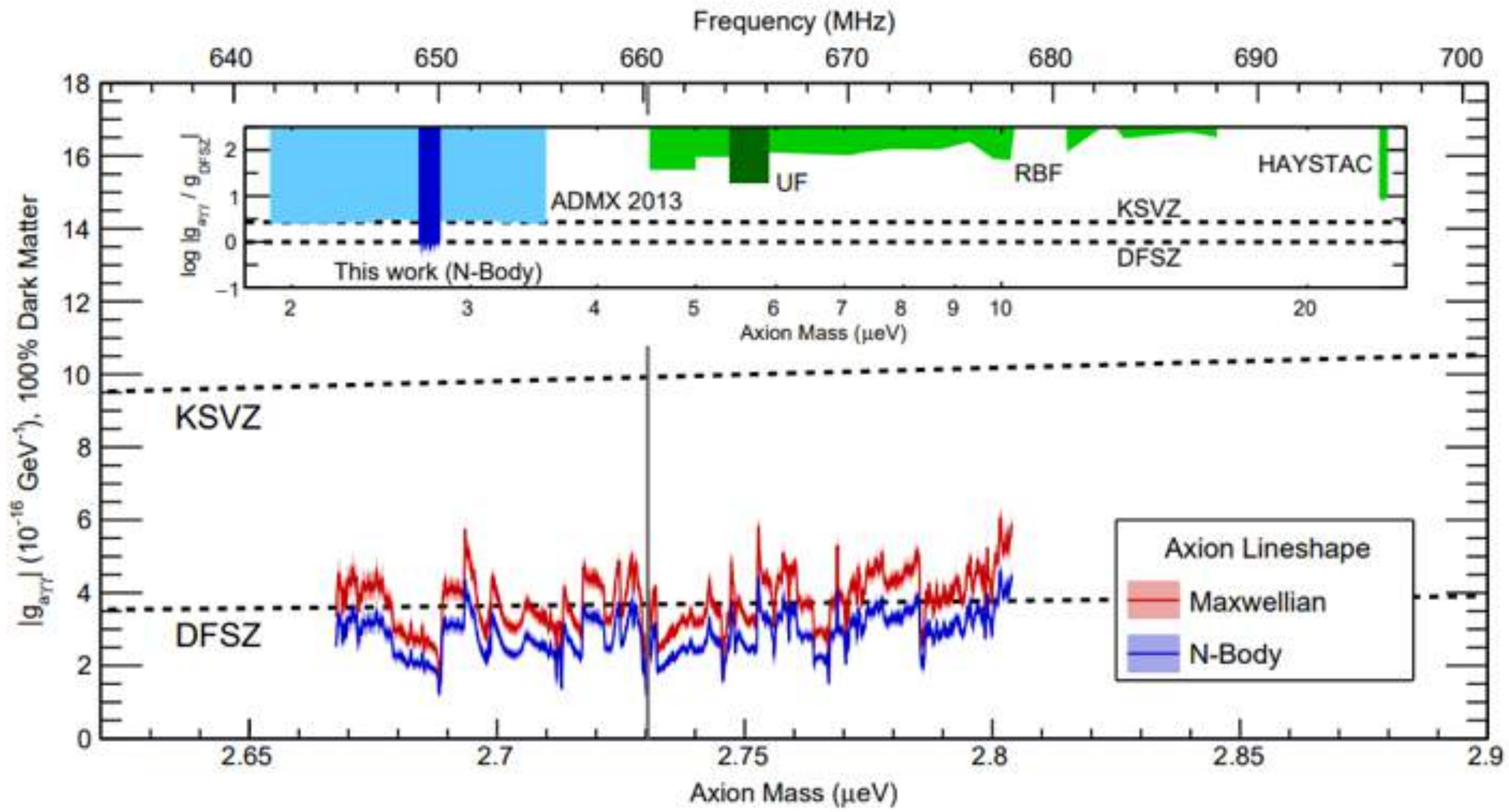
You might have an axion if the signal…

- Can’t be seen in the room outside of the magnetic field
- Persists all the time
- Follows the Lorentzian lineshape of the cavity
- Is suppressed in non TM010 modes
- Scales with the B^2 of the magnet
- Has a tiny daily and annual frequency modulation

No candidates passed tests in 2017 run.

First ADMX-G2 Result (Data from 2017 Run)

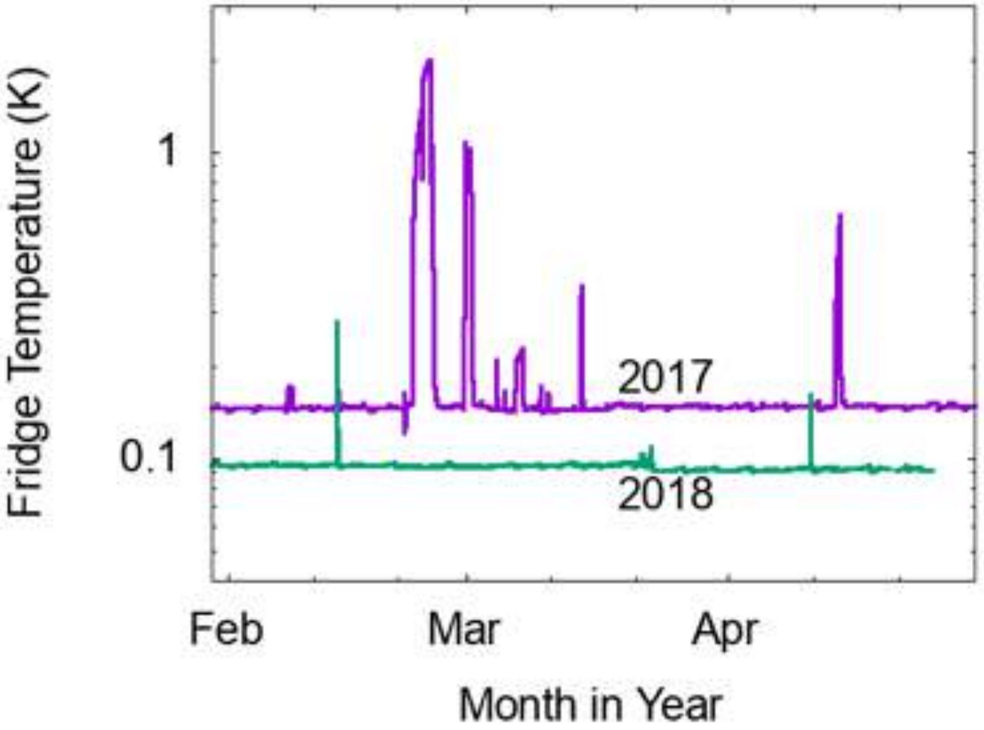
- Exclude DFSZ models at 90% CL from 2.66-2.82 μeV.

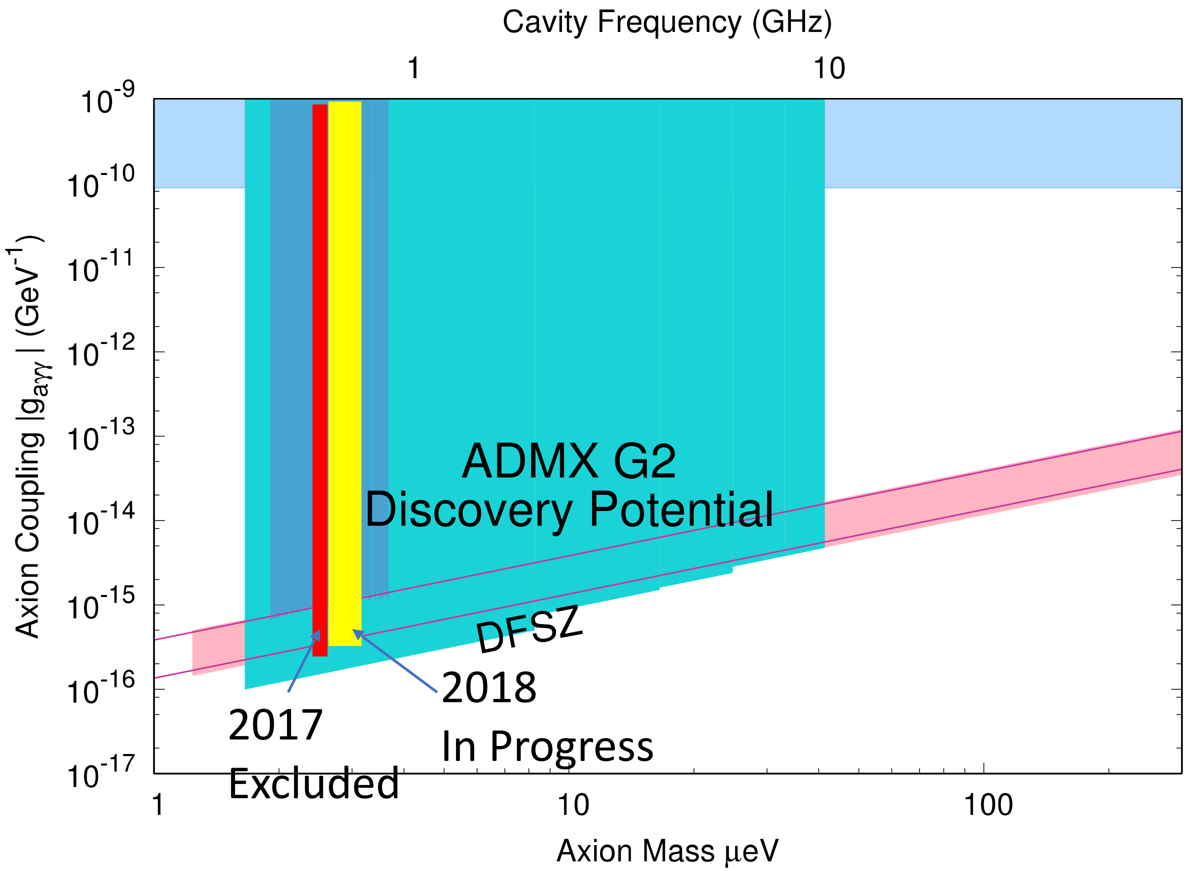


ArXiv 1804.05750 & PRL April 2018

2018 Operations

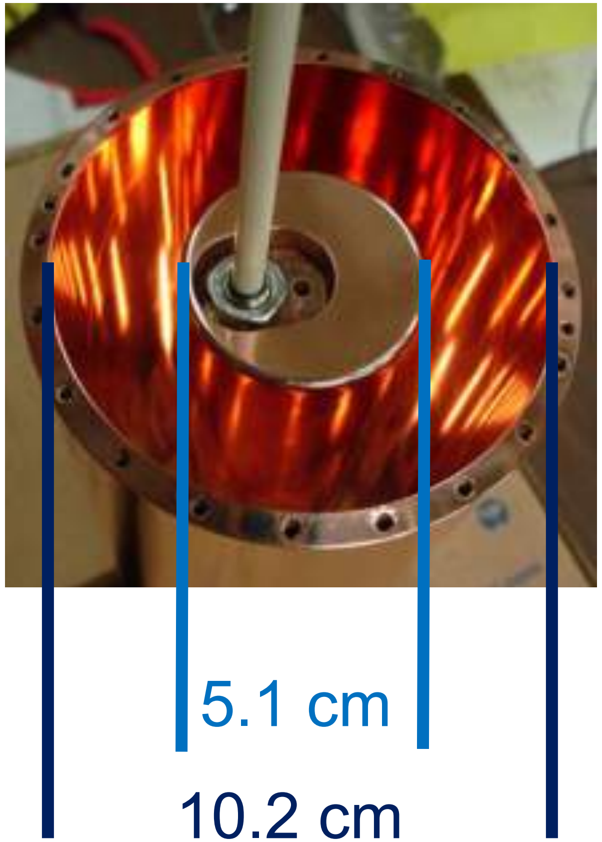
- Improved performance in 2018 running– lower temperatures and more efficient data collection.



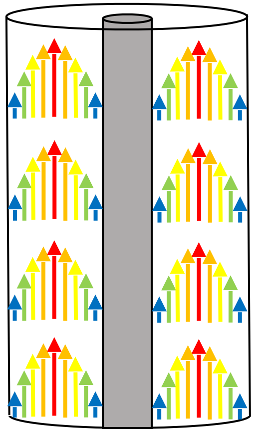


Setup: Cavity

Resonant Microwave Cavity



TM_{010}-like mode:
3.6-5.8 GHz



Piezo electric motor controls position of rod

S. Al Kenany, *et al*, NIM A**854**, (2017) 11-24.

Setup: Magnet & Cryogenics

He^3/He^4 dilution refrigerator

Josephson Parametric Amplifiers

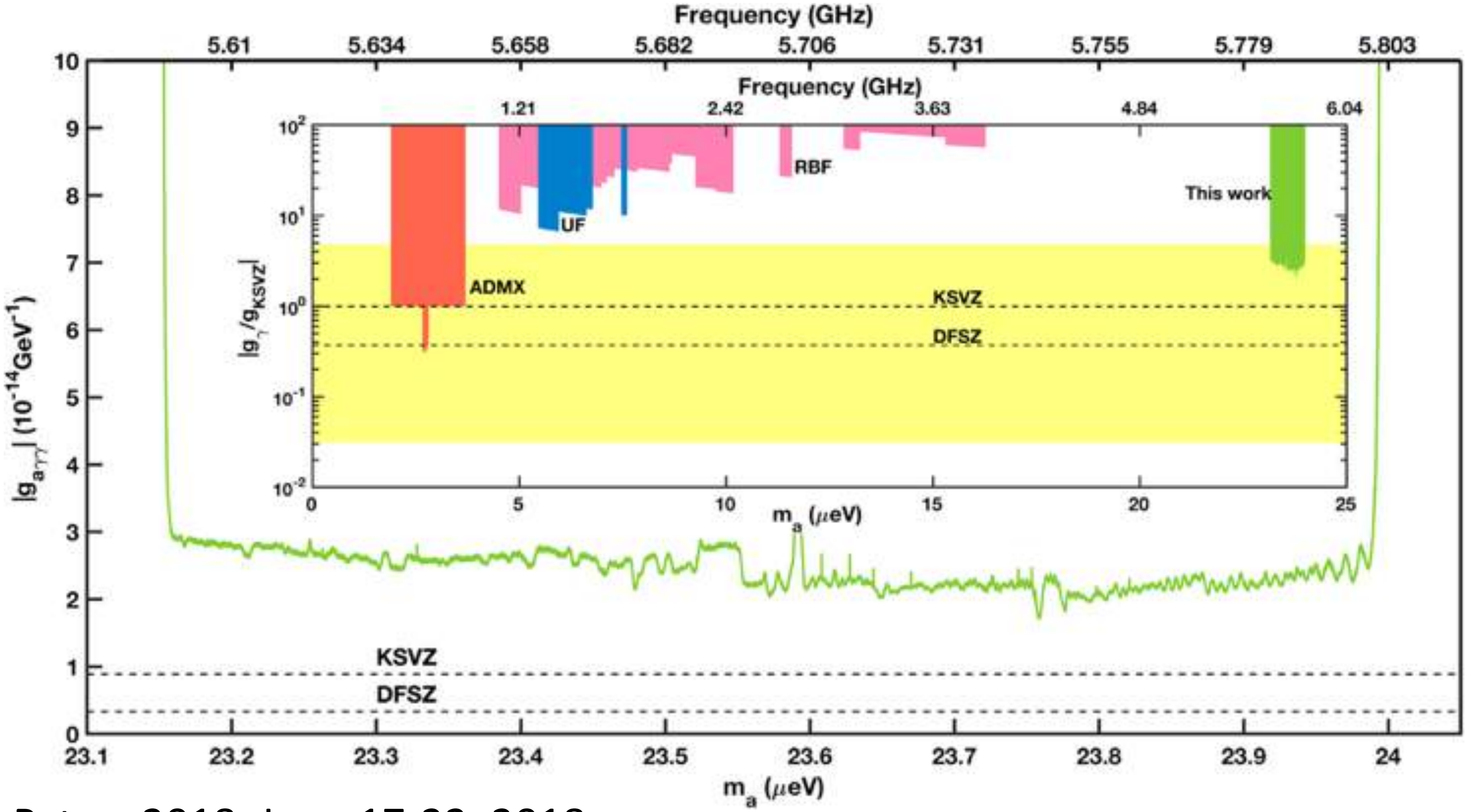
Final phase at 127 mK

9.4 Tesla Magnet

10L Magnet

Results of Phase I

HAYSTAC



Rapidis, Patras 2018, June 17-22, 2018

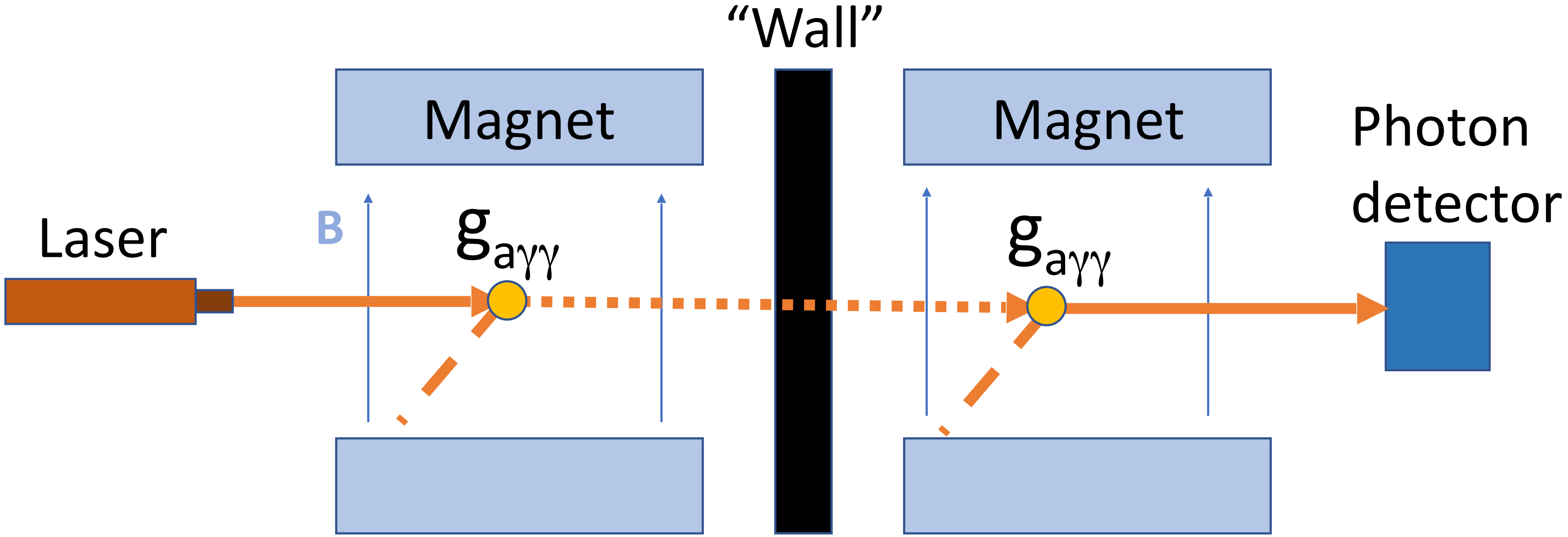
L. Zhong, et al, Phys. Rev. D **97**, 092001, (2018)

Moving forward to higher frequencies

As search frequency increases:

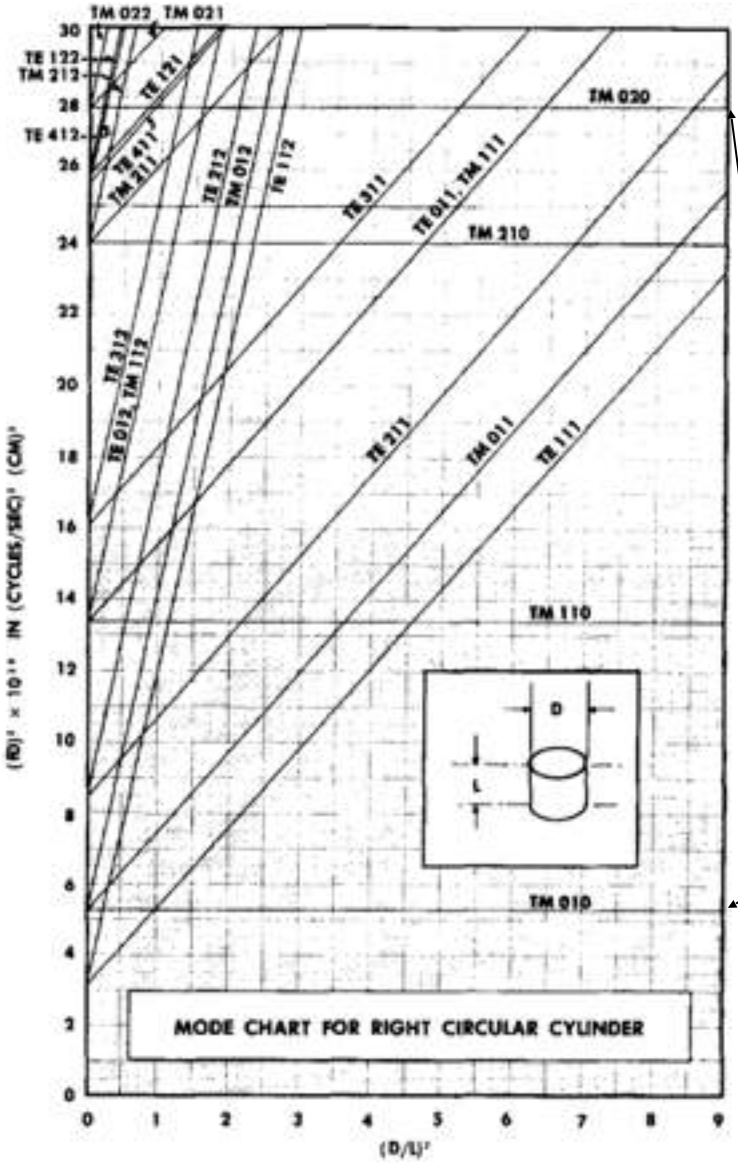
- Expected axion coupling increases
- Cavity volume decreases, decreasing signal
- Cavity Q decreases, decreasing signal
- Quantum limit increases, increasing noise

Extra Slides



"Wall"
Magnet
Magnet
Photon detector
Laser
B
$g_{a\gamma\gamma}$
$g_{a\gamma\gamma}$

Why TM ?



The TM_{010} and TM_{020} modes tune together: data from both modes are taken in parallel.

The TM_{020} mode has acceptable "form factor."

Complementary frequency coverage.

For open cylinder

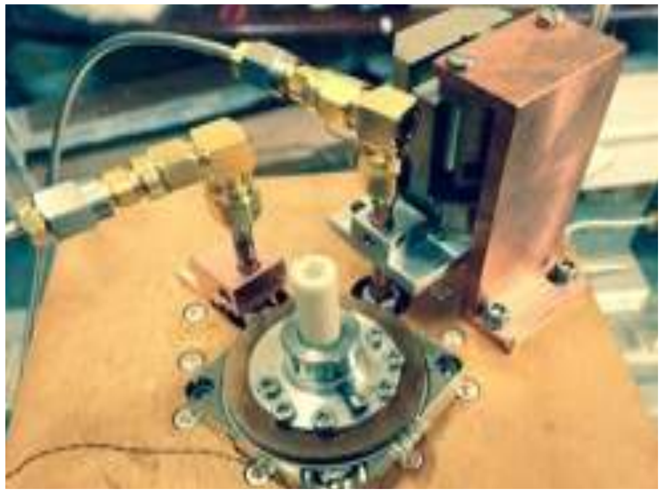
mode	Relative frequency	Tuning range (MHz)	relative power
TM_{010}	1	400-900	1
TM_{020}	2.3	920-2,100	0.41

Concurrent “Sidecar” High-Frequency Prototype

Smaller cavity = higher-mass axion search

Characteristic Frequency:
TM010: 4-6 GHz
TM020: 7 GHz

Prototype: not yet sensitive to QCD axions



The signals are very weak

- Power from the cavity is

$$P = 2.3 \cdot 10^{-26}\text{Watt}\left(\frac{V}{200\ell}\right)\left(\frac{B_0}{8\text{Tesla}}\right)^2 C_{nl}\left(\frac{g_\gamma}{0.97}\right)^2 \cdot \left(\frac{\rho_\text{a}}{0.5\cdot 10^{24}\text{g/cm}^3}\right)\left(\frac{m_\text{a}}{2\pi\text{GHz}}\right)\min(Q_\text{L}, Q_\text{a})$$

- Q_L ~ 70000 $(\text{GHz}/f)^{2/3}$ (ASE) and Q_a ~10^6

- g_γ ~ 0.97 (KSVZ)
- g_γ ~ 0.36 (DFSZ)

f_A : One Parameter Controls Everything

- f_A is the "axion decay constant", an unknown energy scale in the theory.
- Determines axion mass and all couplings

$$m_A = 5.70(7)\left(\frac{10^9\,\mathrm{GeV}}{f_A}\right)\mathrm{meV}$$

Coupling to gluon field $\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu}$

Coupling to electromagnetic field $\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$

Coupling to fermions $\frac{\partial_\mu a}{f_a}\bar{\Psi}_f\gamma^\mu\gamma_5\Psi_f$

- f_A Originally identified with the electroweak symmetry breaking scale by Peccei and Quinn (~100 GeV), predicting axion mass to be ~ 100 keV.