Axion Experiments Lecture 2

Symmetry Magazine/ Sandbox Studio

Andrew Sonnenschein, Fermilab

ICTP-SAIFR

São Paulo, Brazil, August 2, 2018

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

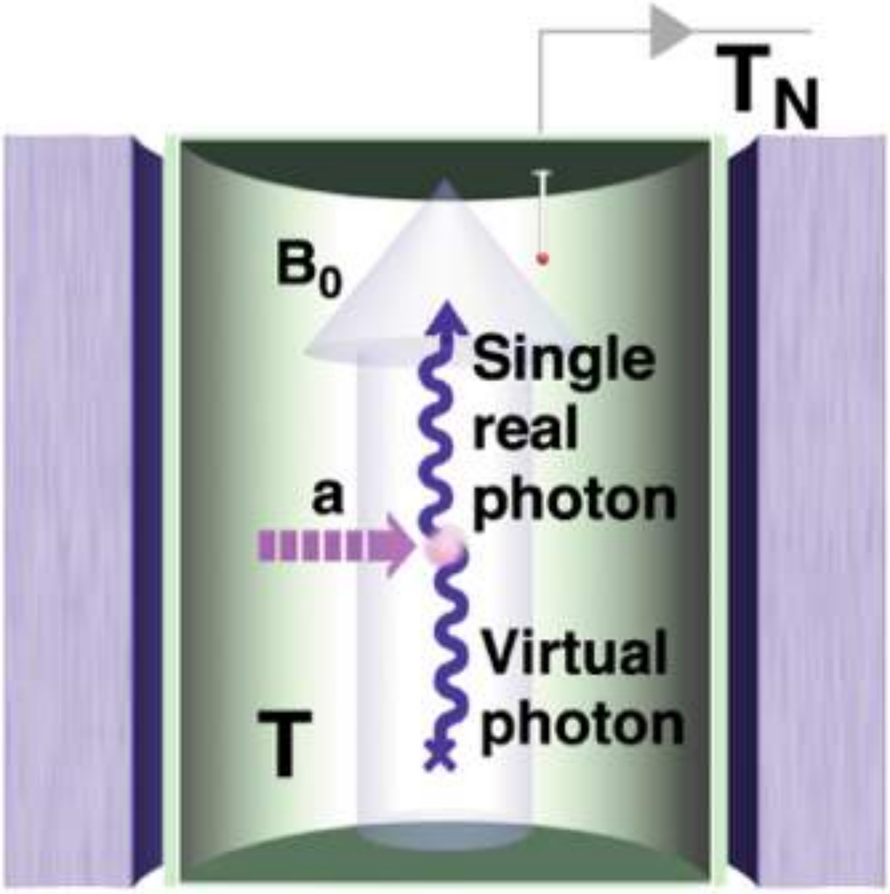
- Axion lecture #2: Future experiments, R&D
  - Higher frequency and mass
    - High frequency R&D- Magnets, Cavities & Electronics
    - Broadband detectors- dish antenna
    - Open resonators- Madmax, Orpheus
  - Lower frequency
    - LC circuits
    - ABRACADABRA, DM Radio

Haloscope Technique

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

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

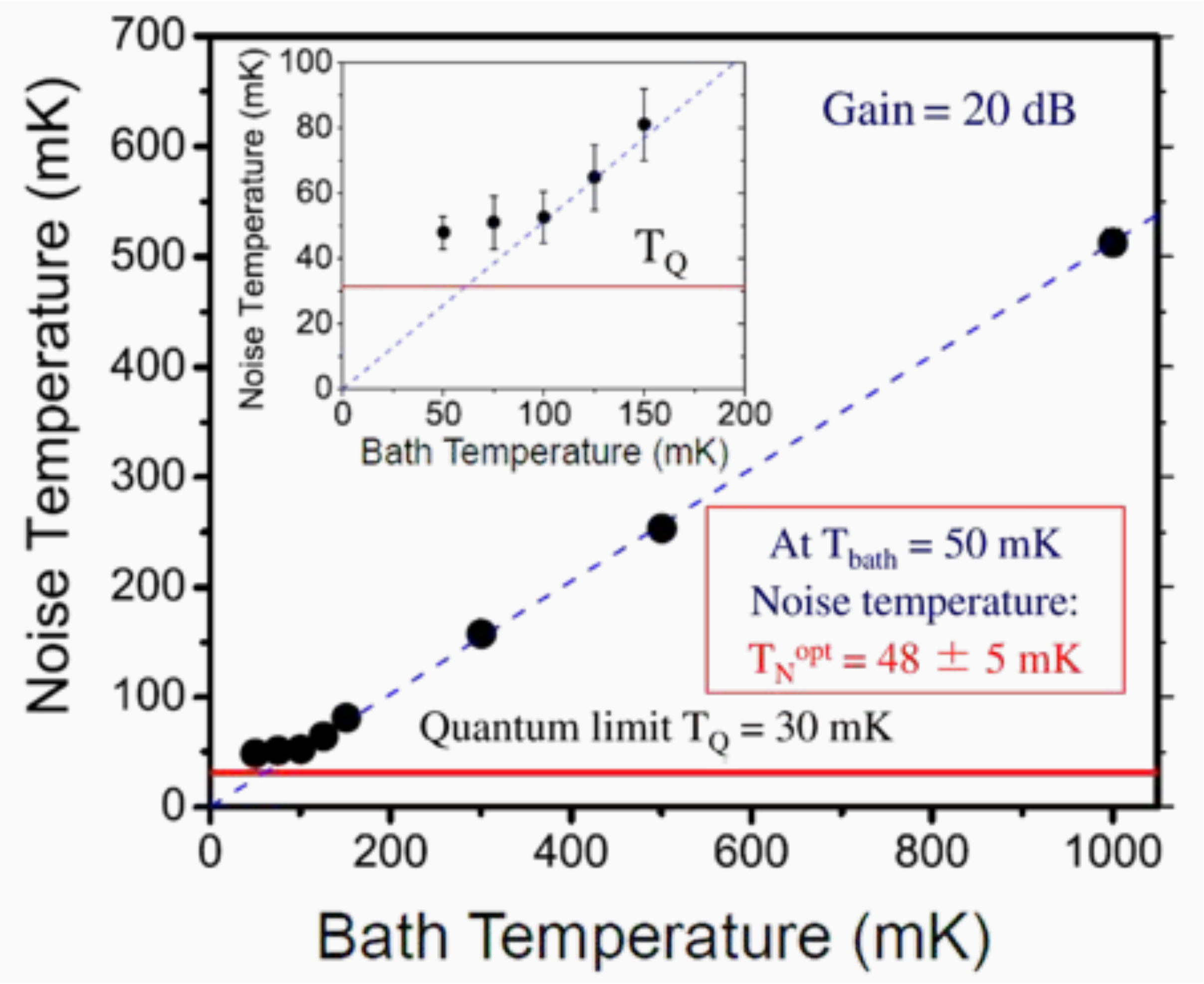
Form Factor C_{nl} *overlap of cavity mode* $\boldsymbol{E} \cdot \boldsymbol{B}_0$
Dark Matter Density ρ_a
Axion Mass m_a
Resonator Quality Factor $Q_L \sim 10^5$
Axion Q from velocity dispersion $Q_a \sim 10^6$
Couplings to Photon $g_\gamma \sim 0.97$ for KSVZ model
$g_\gamma \sim 0.36$ for DFSZ



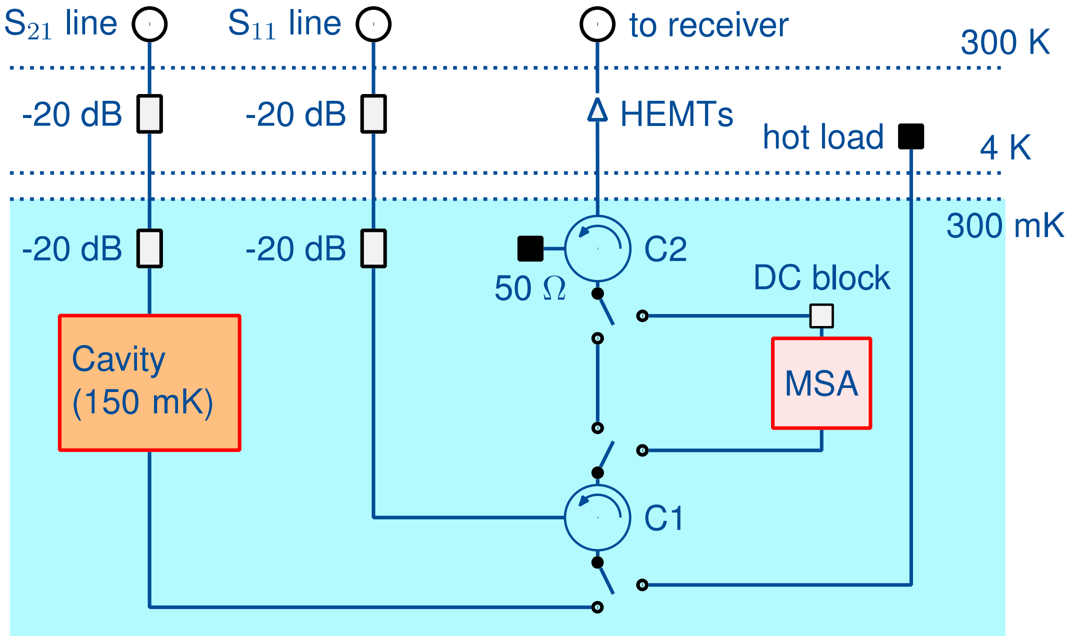
See Pierre Sikivie, “Experimental Tests of the Invisible Axion” 1983 PRL

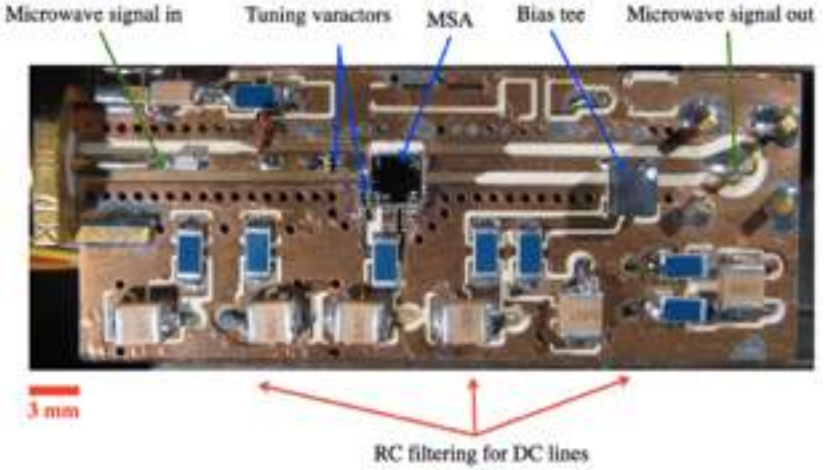
Noise Performance of Microstrip Squid Amplifiers

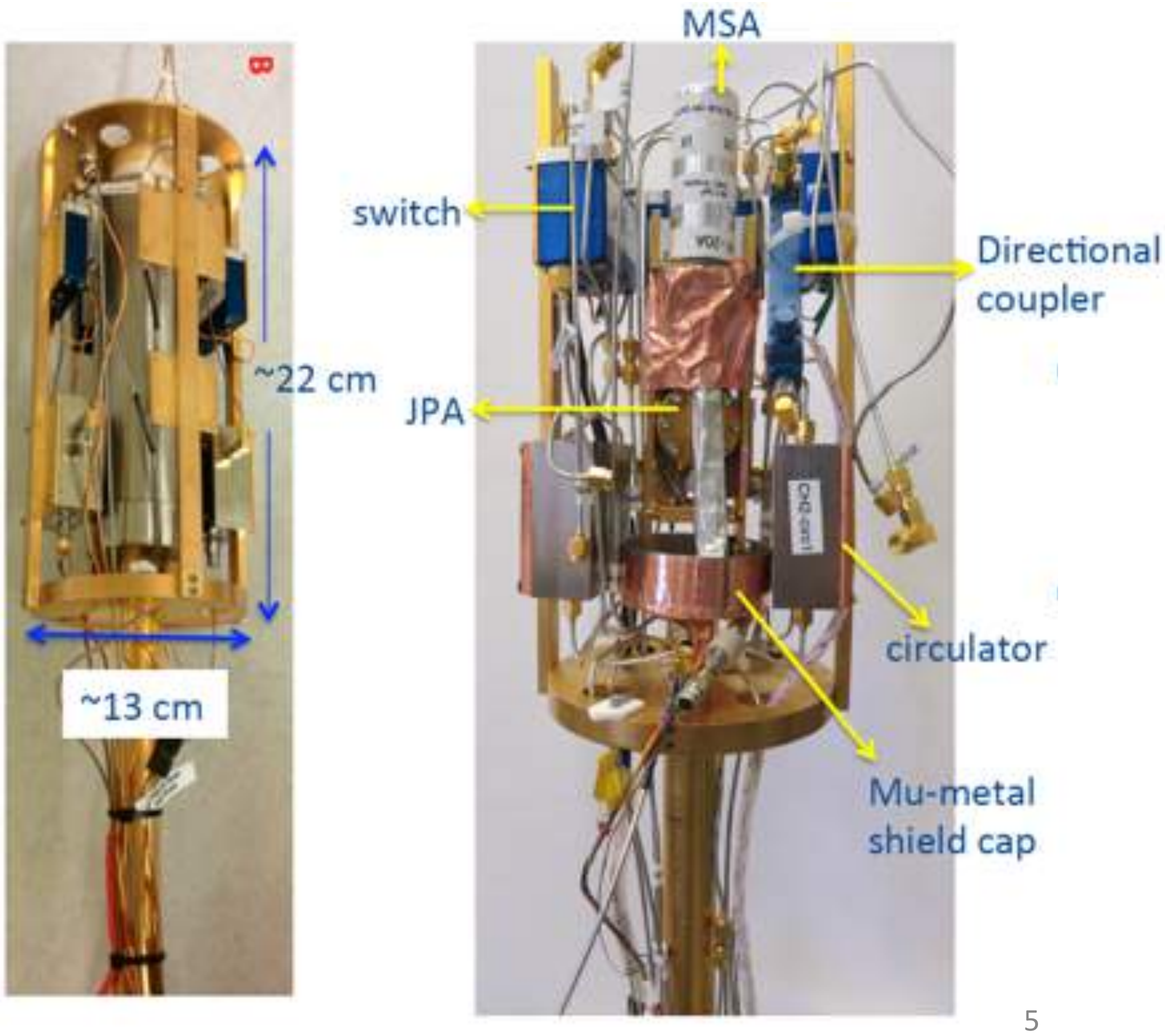
- $T_{Noise} = \frac{1}{k_B} \frac{Noise\ Power}{Bandwidth}$
- Achieved T_N= 48 mK at 600 MHz during testing at UC Berkeley
- 1.7 x quantum limit.
- In ADMX operation, *system* noise temperatures has additional contributions from:
  - Black body radiation in cavity
  - Attenuation
  - Post amplification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



Cryogenic Electronics System Package- 2017/2018

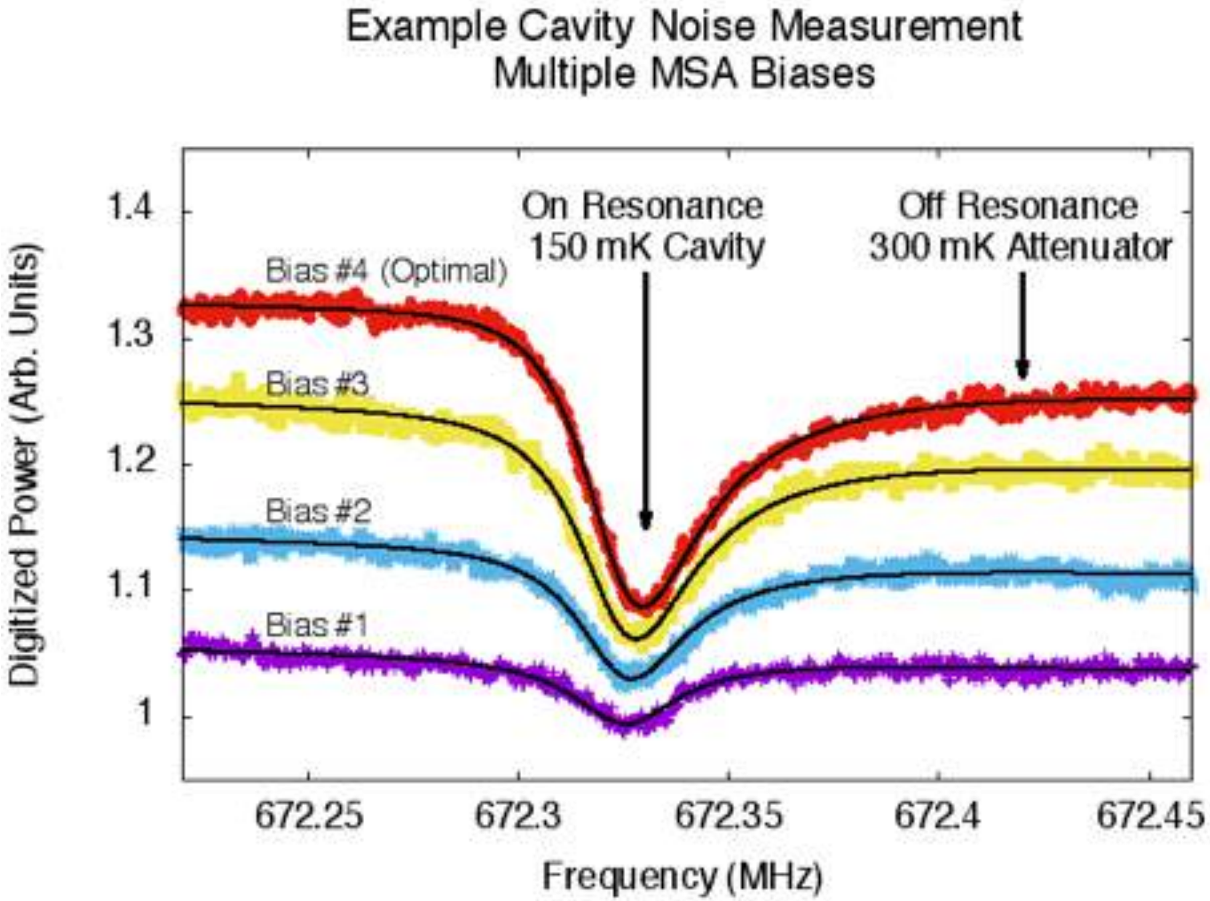


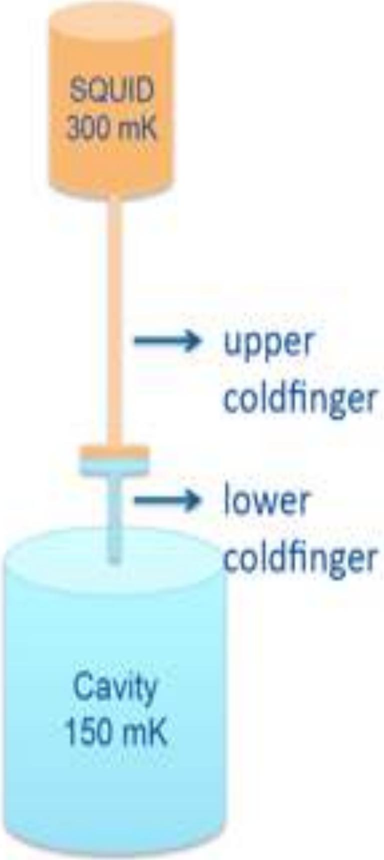




MSA Operation in ADMX 2017/ 2018 Runs

- 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.

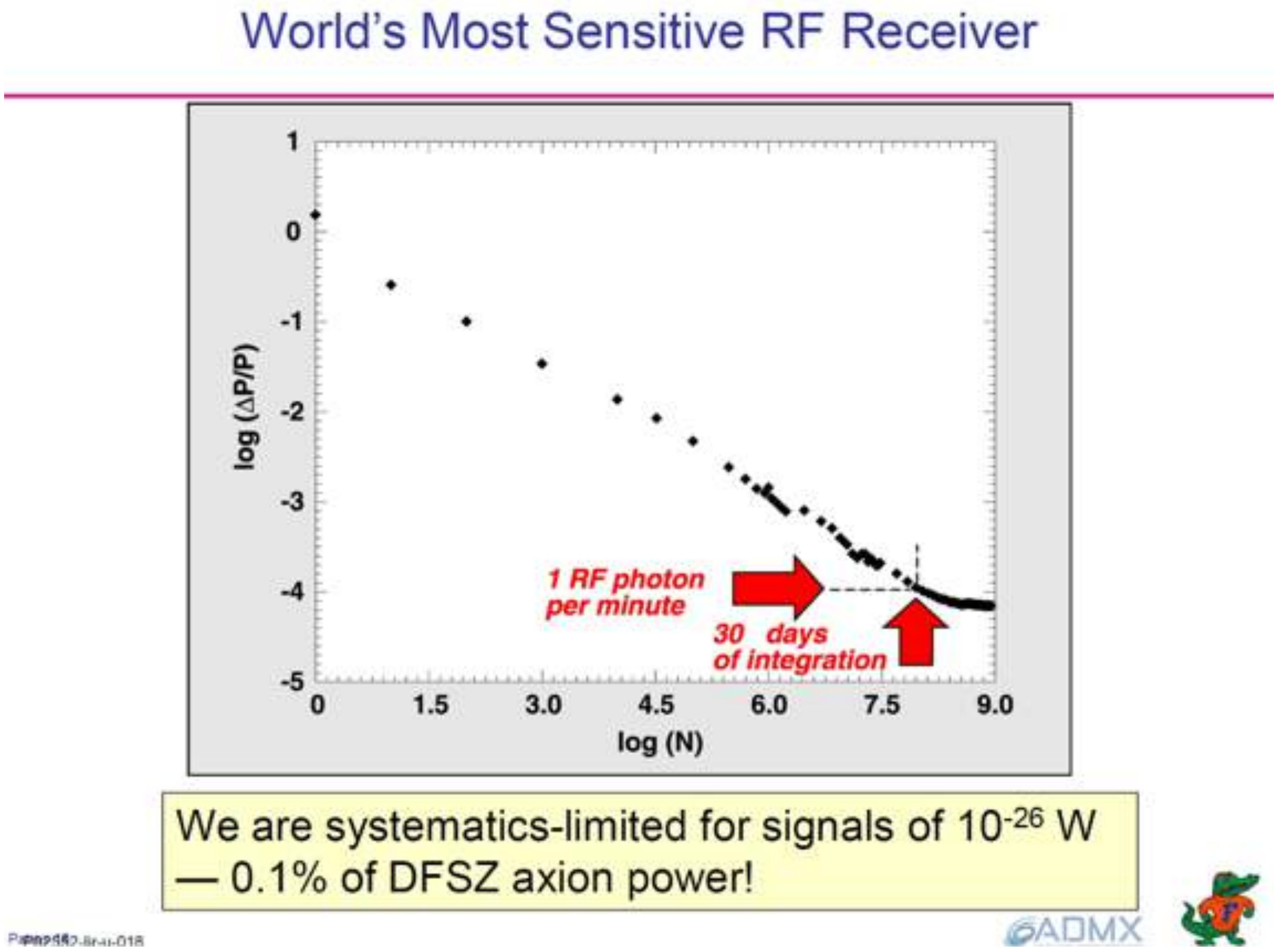




Signal to Noise

- $T_{Noise} = \frac{1}{k_B} \frac{Noise\ Power}{Bandwidth}$
- Suppose we have $T_{Noise} = 0.5\ Kelvin$
- $P_{noise} = k_B T_{Noise} * Bandwidth = 0.5 \cdot 1.4 \times 10^{-23} W/Hz \cdot Bandwidth$
- Bandwidth of axion is due to halo velocity dispersion $\frac{\Delta f}{f} \sim 10^{-6}$
- ~ 1 kHz at 1 GHz axion frequency
- So $P_{noise} \sim 10^3 Hz \cdot \frac{10^{-23} W}{Hz} = 10^{-20} W$
- Still about three orders of magnitude larger than the signal!

Noise reduction by averaging



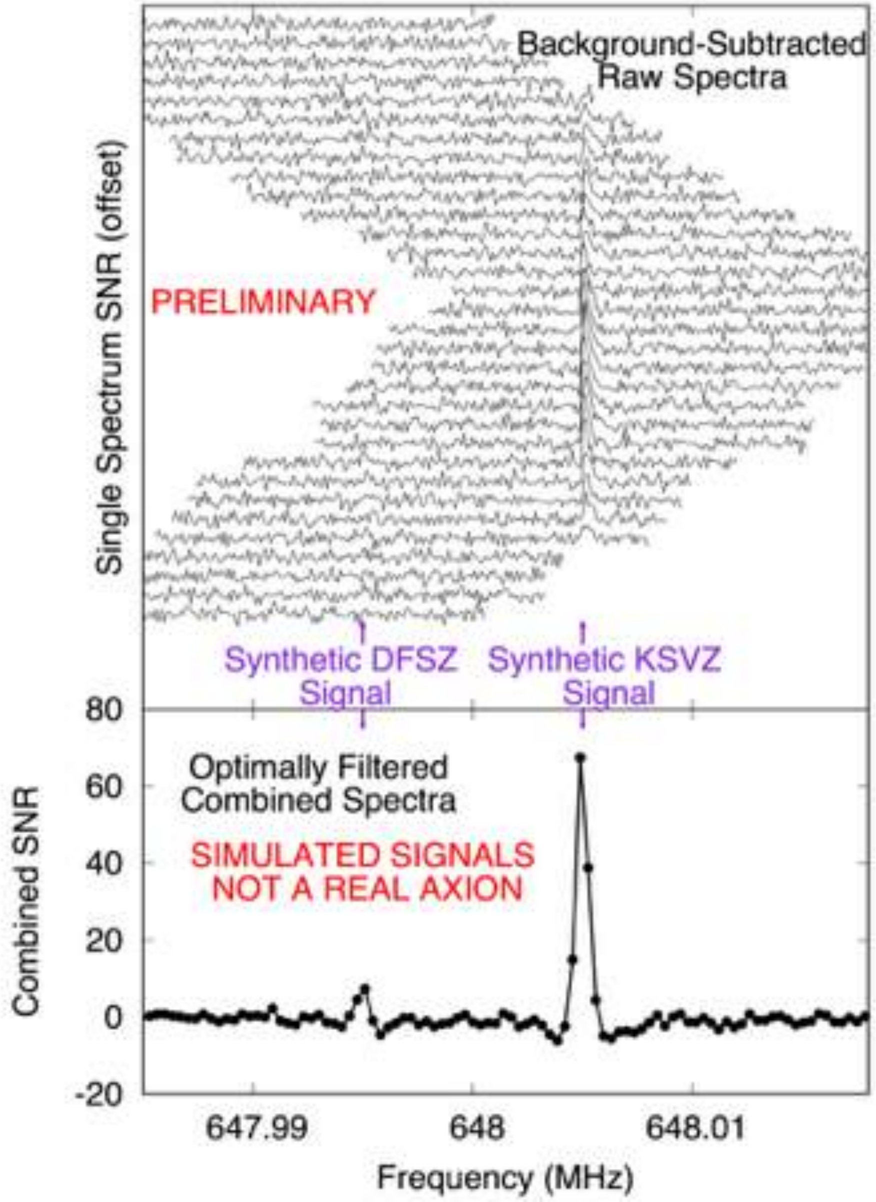
World’s Most Sensitive RF Receiver

We are systematics-limited for signals of 10^{-26} W — 0.1% of DFSZ axion power!

Dave Tanner, Patras 2018

Experiment Operation Procedure

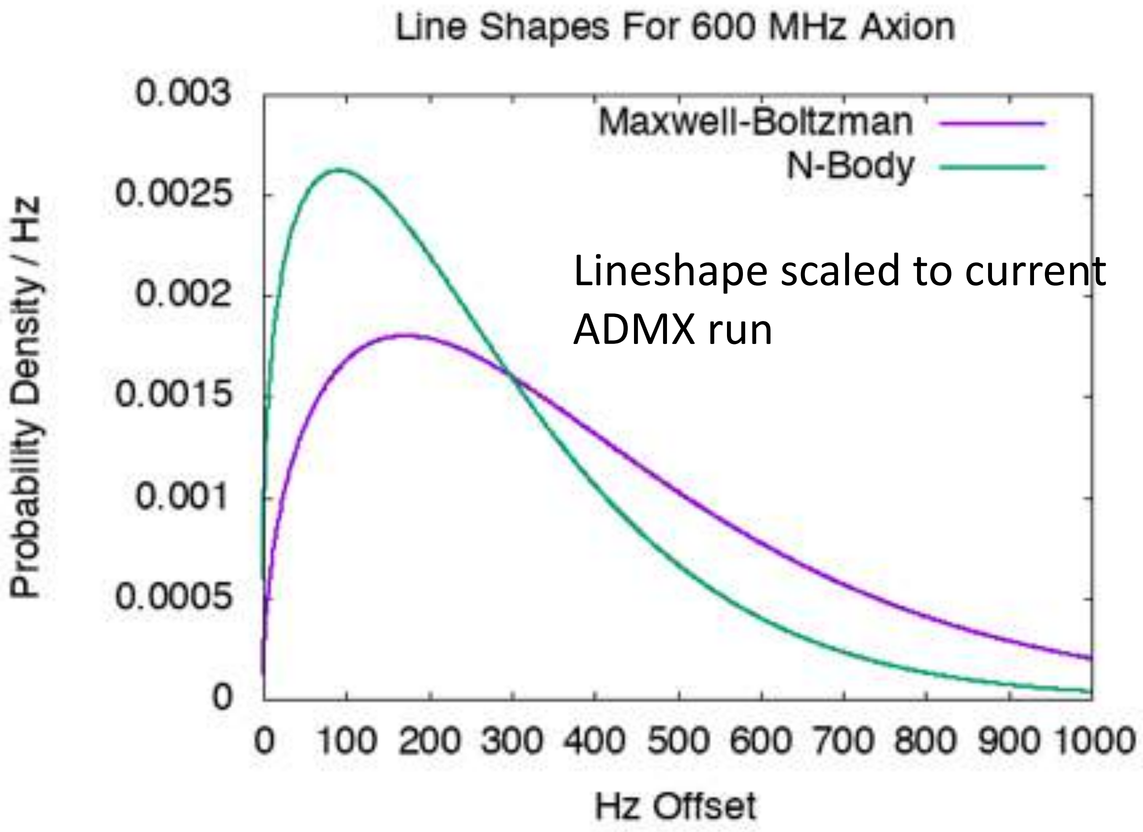
- The cavity frequency is scanned over a region until the desired SNR is achieved.
- Convolution with filter matched to expected axion line shape.
- Typically we have ~10^6 independent measurements on each axion linewidth, averaged to reduce noise by $\sqrt{10^6}$
- We then examine the combined power 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)

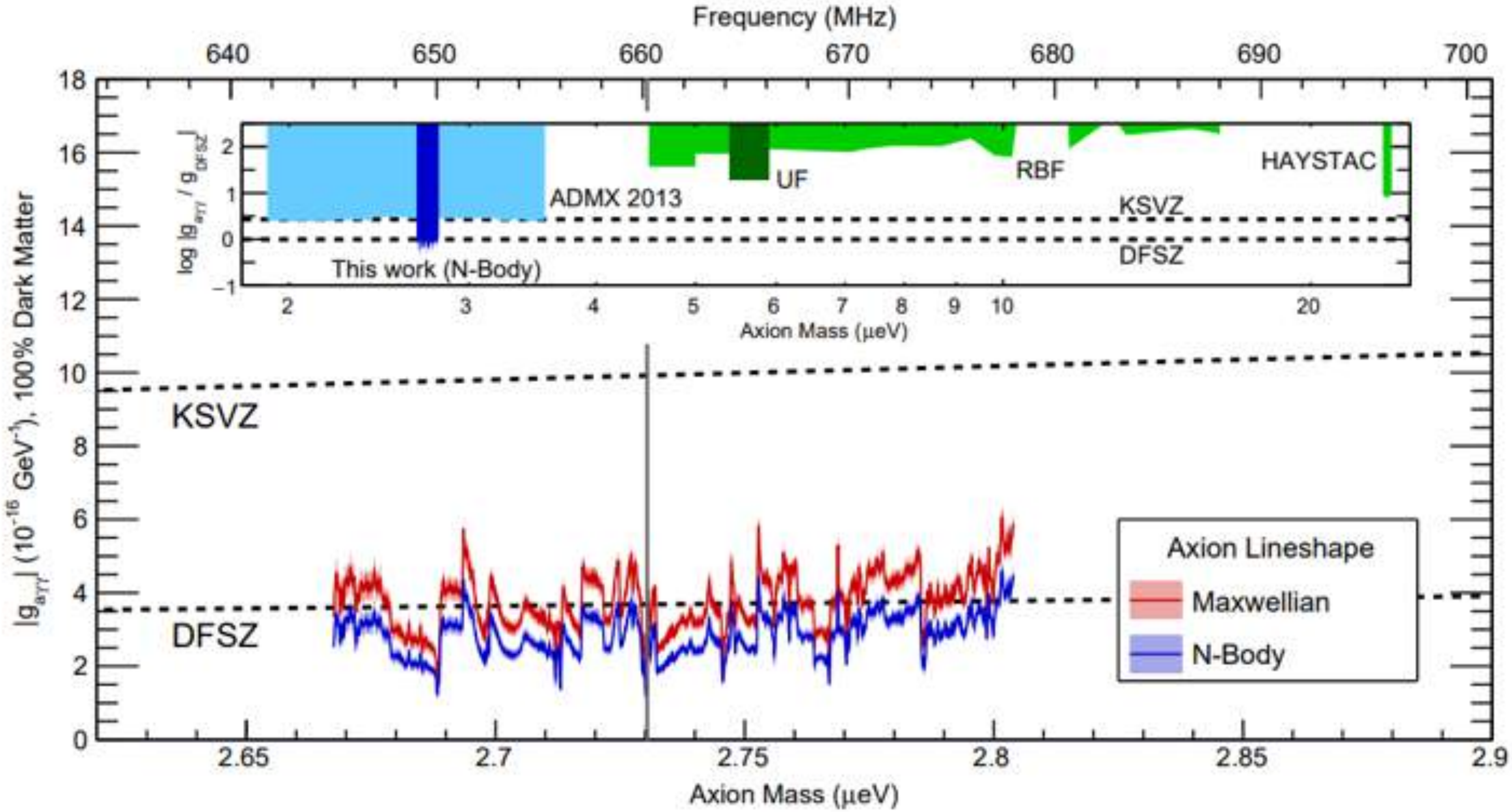
You might have an axion if the signal…

- 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)

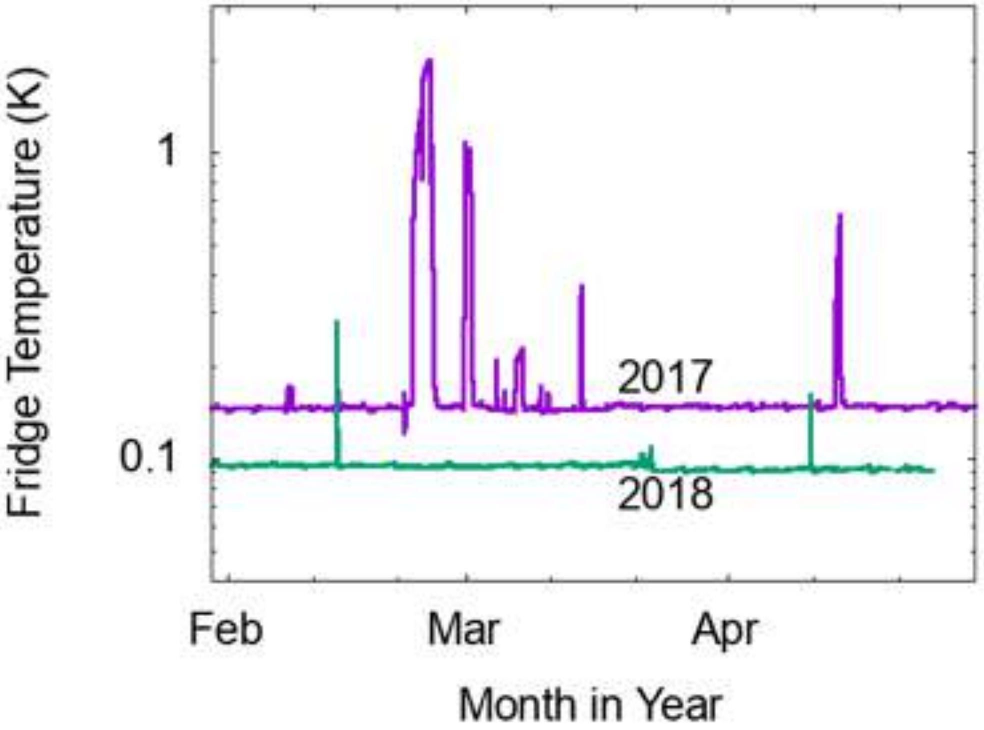
- Exclude DFSZ models at 90% CL from 2.66-2.82 μeV.

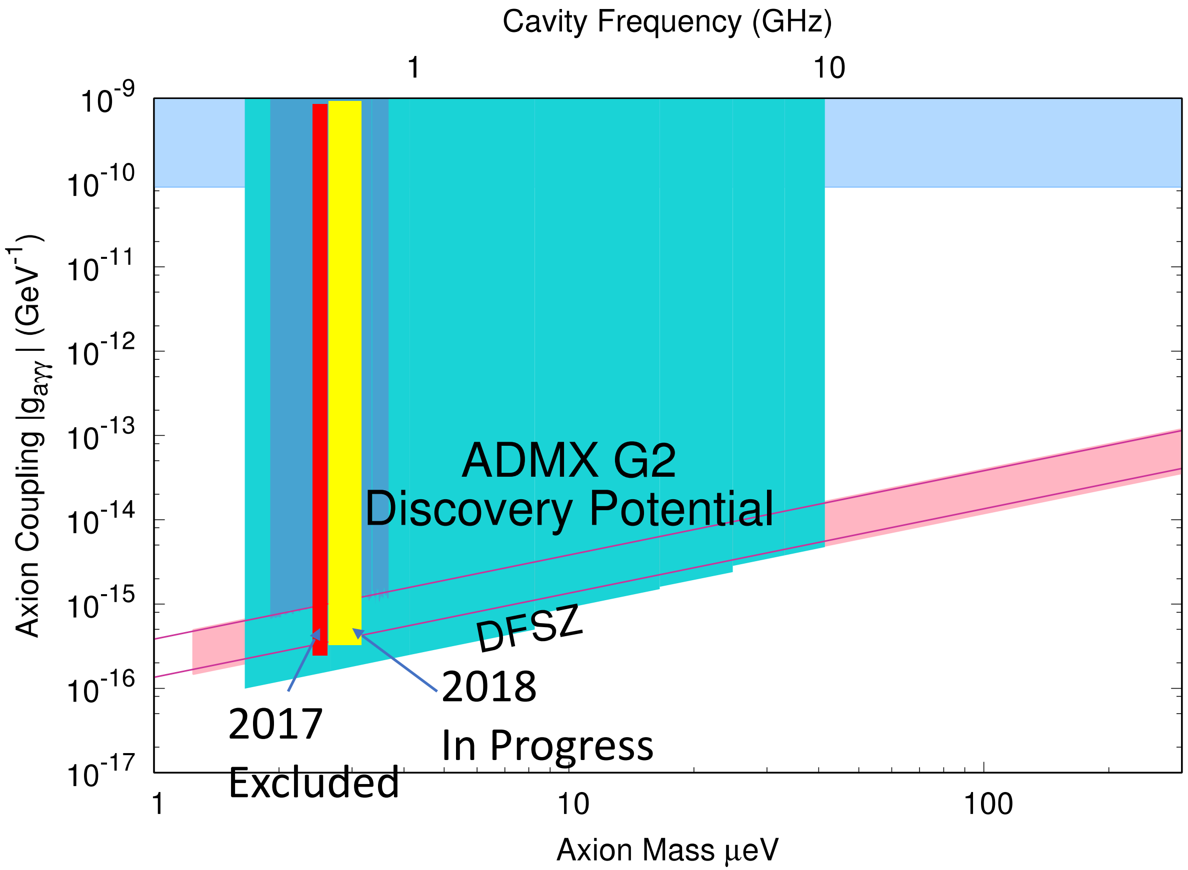


ArXiv 1804.05750 & PRL April 2018

2018 Operations

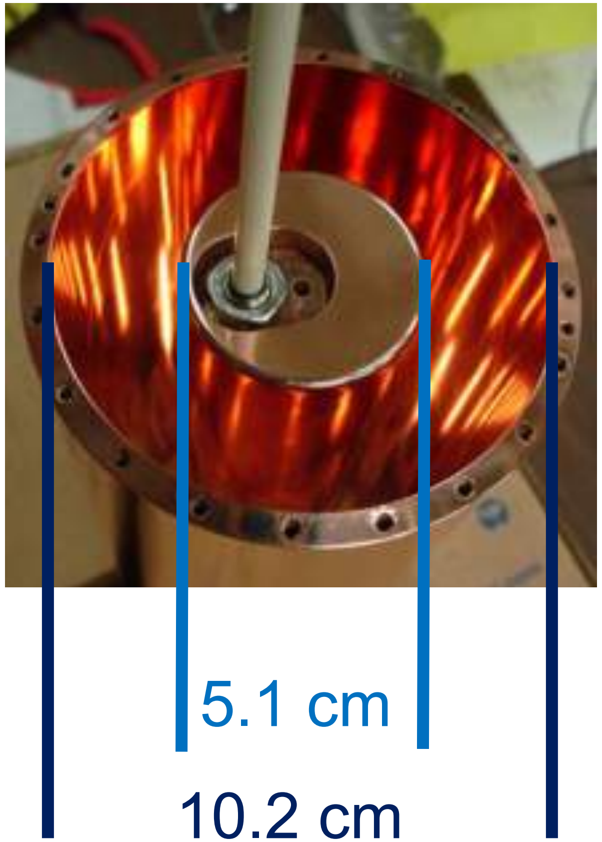
- Improved performance in 2018 running– lower temperatures and more efficient data collection.



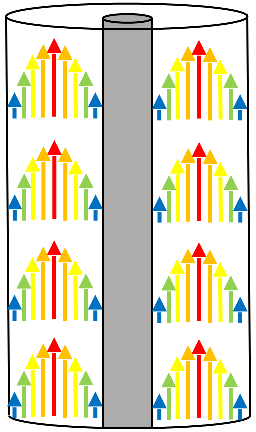


Setup: Cavity

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

HAYSTAC

He^3/He^4 dilution refrigerator

Josephson Parametric Amplifiers

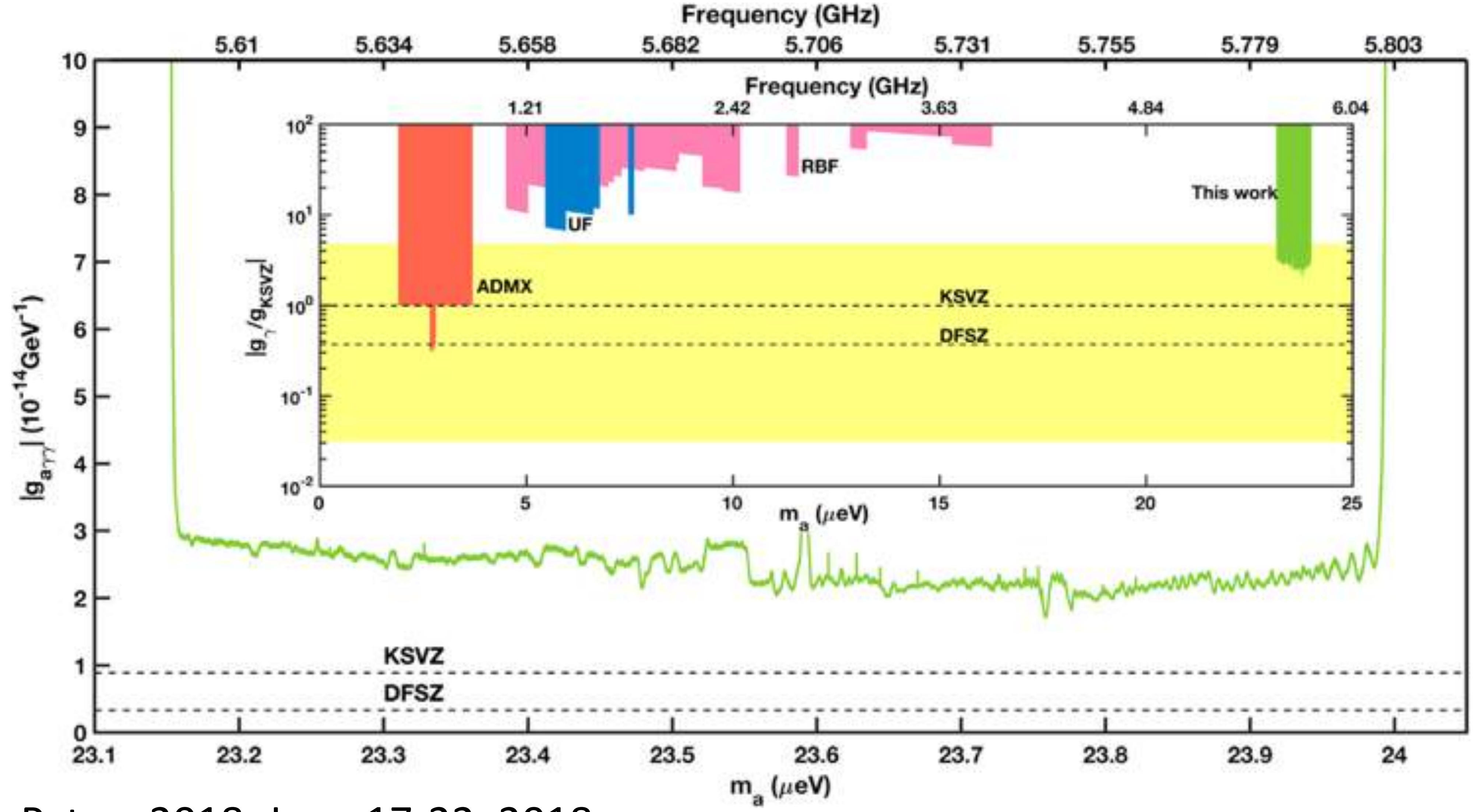
Final phase at 127 mK

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)

How to Speed up Axion Searches

- Effective scan rate of ADMX in 2018 was ≈ 1 MHz/ day
- As we move up in frequency,
  - Expected axion coupling increases
  - Cavity volume decreases, decreasing signal
  - Cavity Q decreases, decreasing signal
  - Quantum limit increases, increasing noise

Scan Rate Vs Frequency & other parameters

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

Higher Magnetic Field Increases Signal

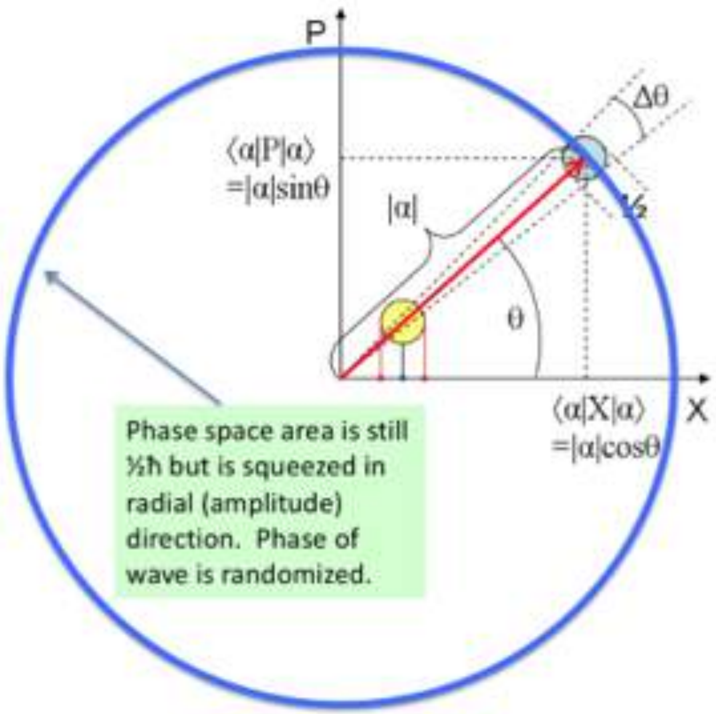
Arrays of Cryogenic RF Resonators Increase Volume

Quantum Sensors Reduce Noise (qubits, etc.)

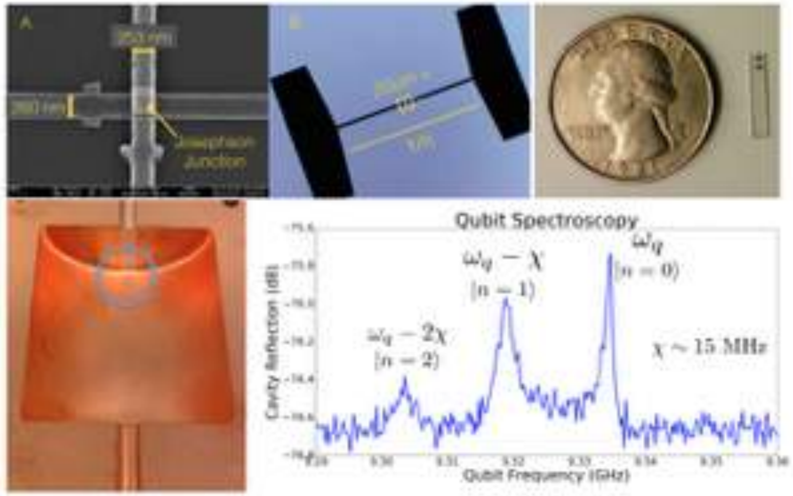
Beyond the Quantum Limit

- Quantum limit comes from trying to measure both amplitude and phase of a harmonic oscillator (mode of E field)
- Can we avoid measuring both amplitude and phase?

- Various proposals
  - “Squeezing the vacuum” using Josephson Parametric Amplifiers (Haystac)
  - Qubit single microwave photon detectors (R&D at Lawrence Livermore National Lab and Fermilab)
  - Single microwave photon counting using Rydberg atoms (R&D at Yale)

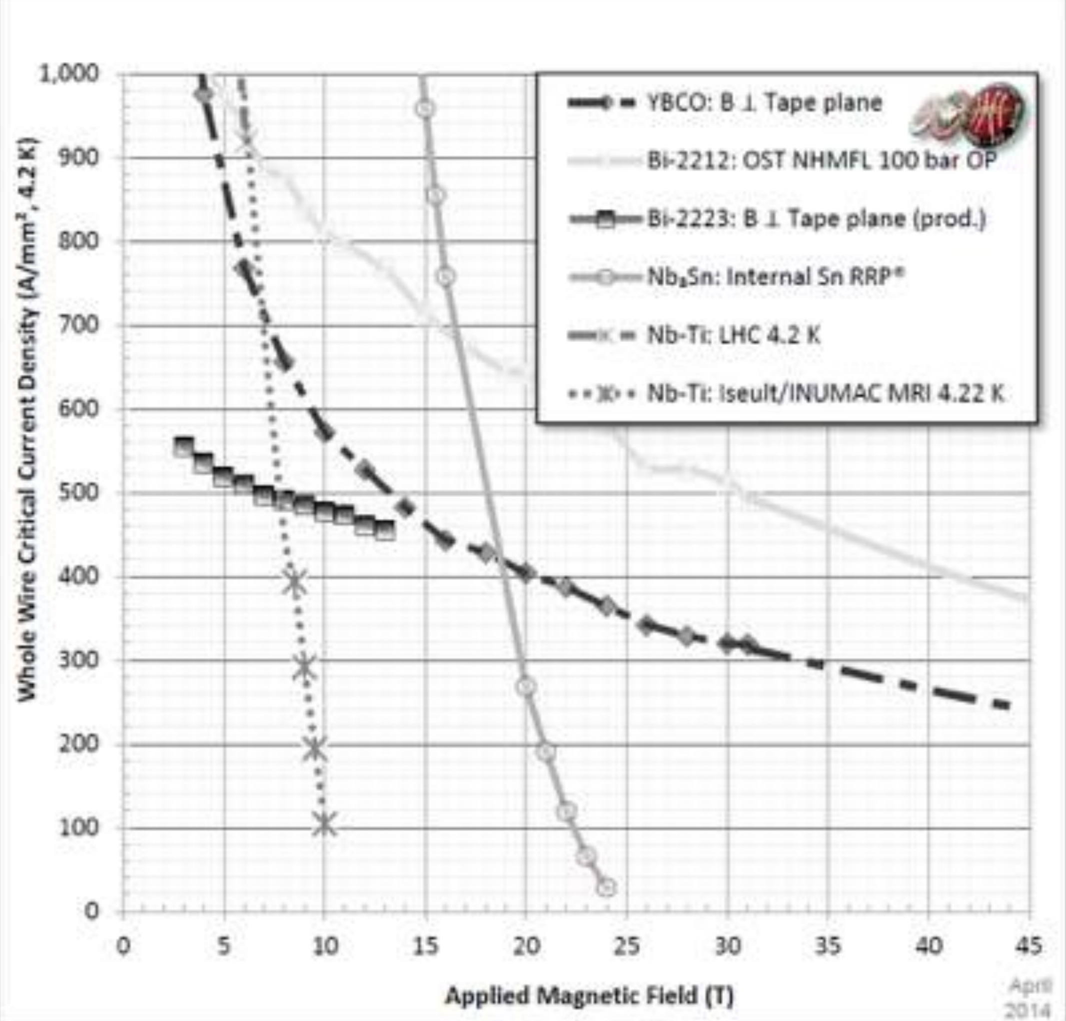


Phase space area is still ½ħ but is squeezed in radial (amplitude) direction. Phase of wave is randomized.



Qubit (FNAL/ Chicago)

Superconducting Materials for Magnets

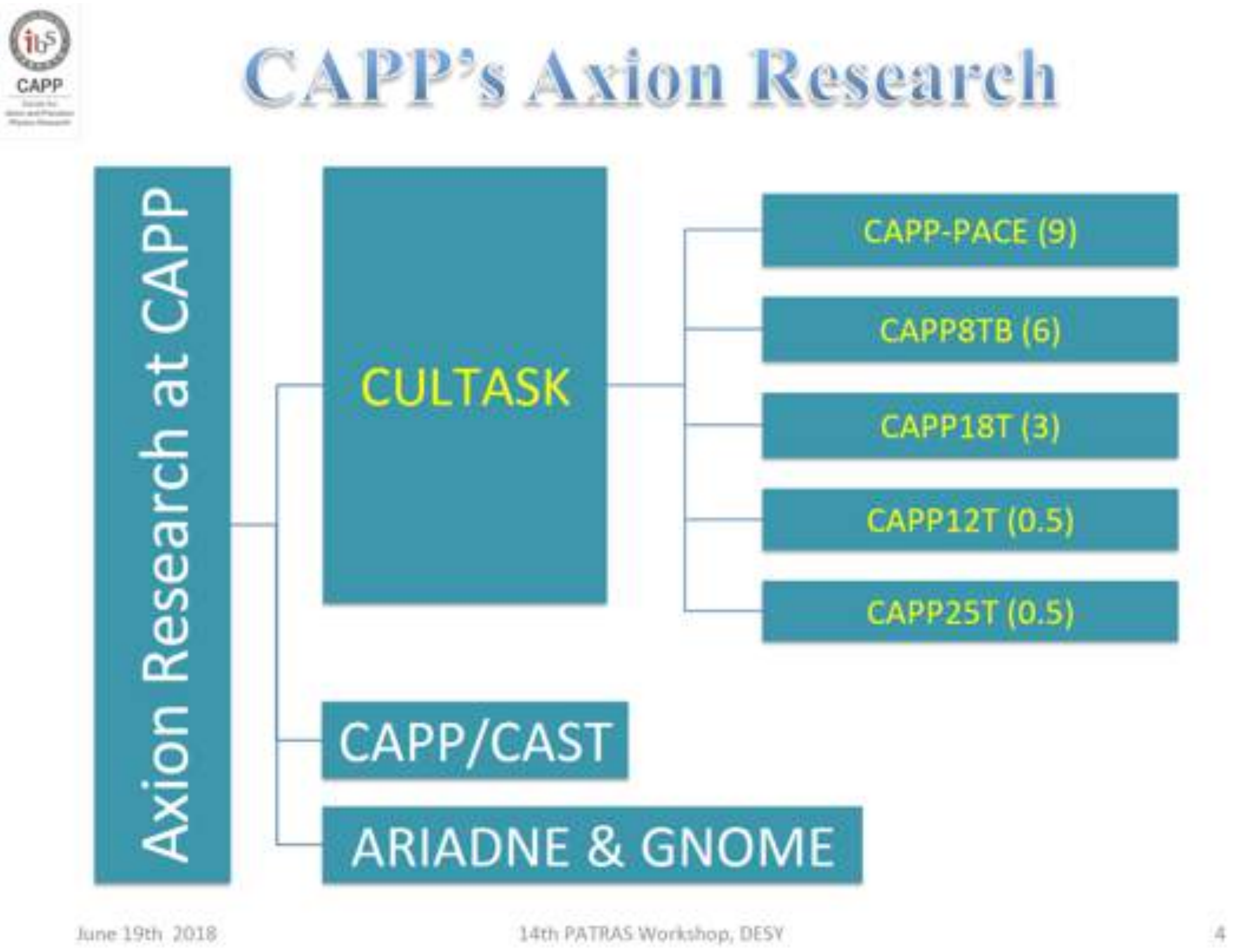


- The High-Temperature Superconductors (HTS) REBCO, Bi2212, Bi2223 will superconduct at fields >100T.
- For >25 T Solenoids, HTS is required.
- At 4 K, extremely high combinations of field and current-density attained!
- (BI2212, Bi2223, & REBCO superconduct at > 100 T!)

J_e of wire maintained by P. Lee (http://magnet.fsu.edu/~lee/plot/plot.htm)

Korean Institute for Basic Sciences Axion Institute research program

- New institute dedicated to axion research.
- 5 separate haloscope projects.



CAPP's Axion Research

Axion Research at CAPP

CULTASK

CAPP-PACE (9)

CAPP8TB (6)

CAPP18T (3)

CAPP12T (0.5)

CAPP25T (0.5)

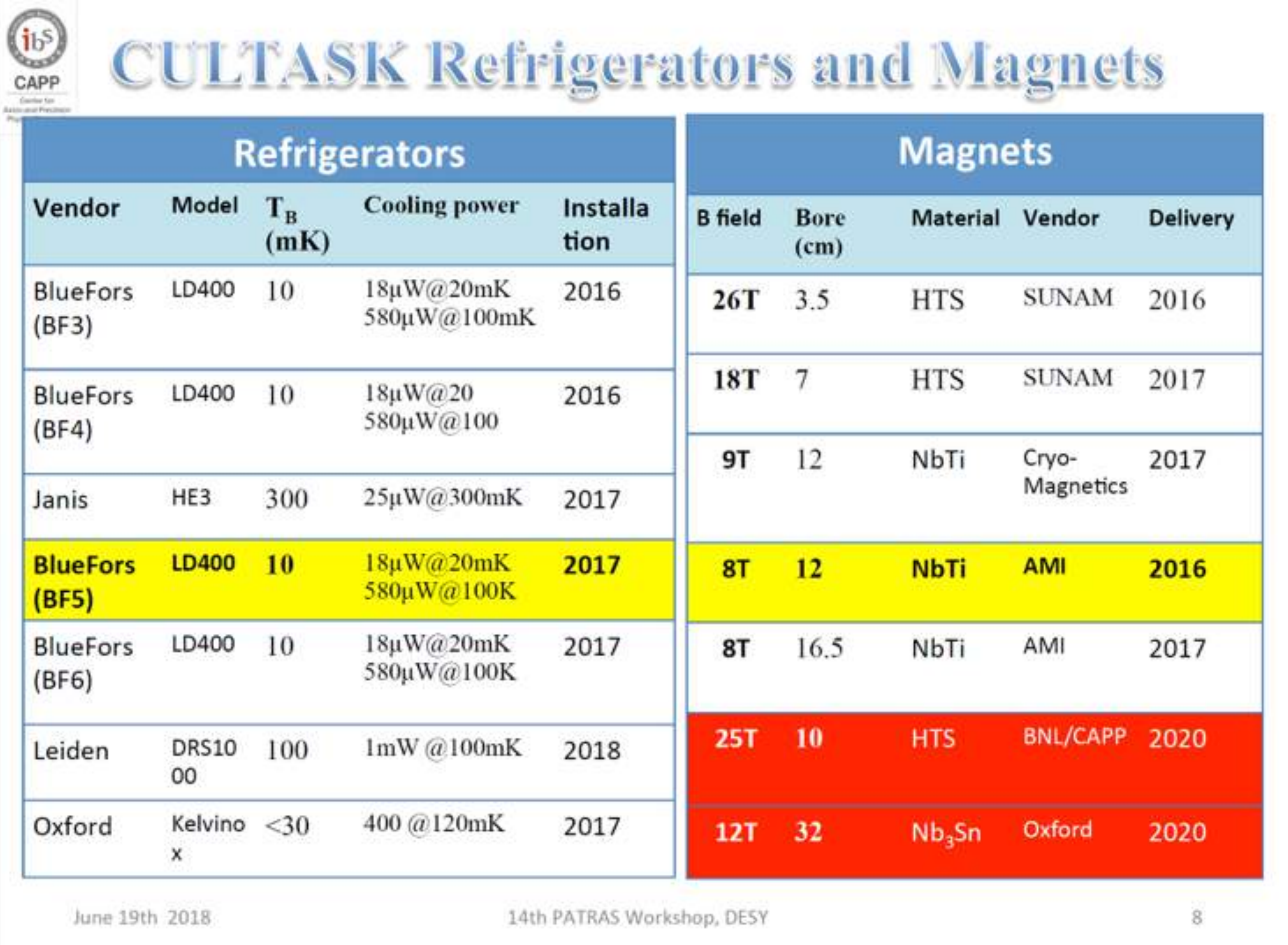
CAPP/CAST

ARIADNE & GNOME

June 19th 2018 14th PATRAS Workshop, DESY 4

Multiple experiments planned for CAPP Center for Axion and Precision Physics Research, Korea.

Two high field HTS magnets already received.



CULTASK Refrigerators and Magnets

Refrigerators

Vendor	Model	T_B (mK)	Cooling power	Installation
BlueFors (BF3)	LD400	10	18μW@20mK 580μW@100mK	2016
BlueFors (BF4)	LD400	10	18μW@20 580μW@100	2016
Janis	HE3	300	25μW@300mK	2017
BlueFors (BF5)	**LD400**	**10**	18μW@20mK 580μW@100K	**2017**
BlueFors (BF6)	LD400	10	18μW@20mK 580μW@100K	2017
Leiden	DRS1000	100	1mW @100mK	2018
Oxford	Kelvinox	<30	400 @120mK	2017

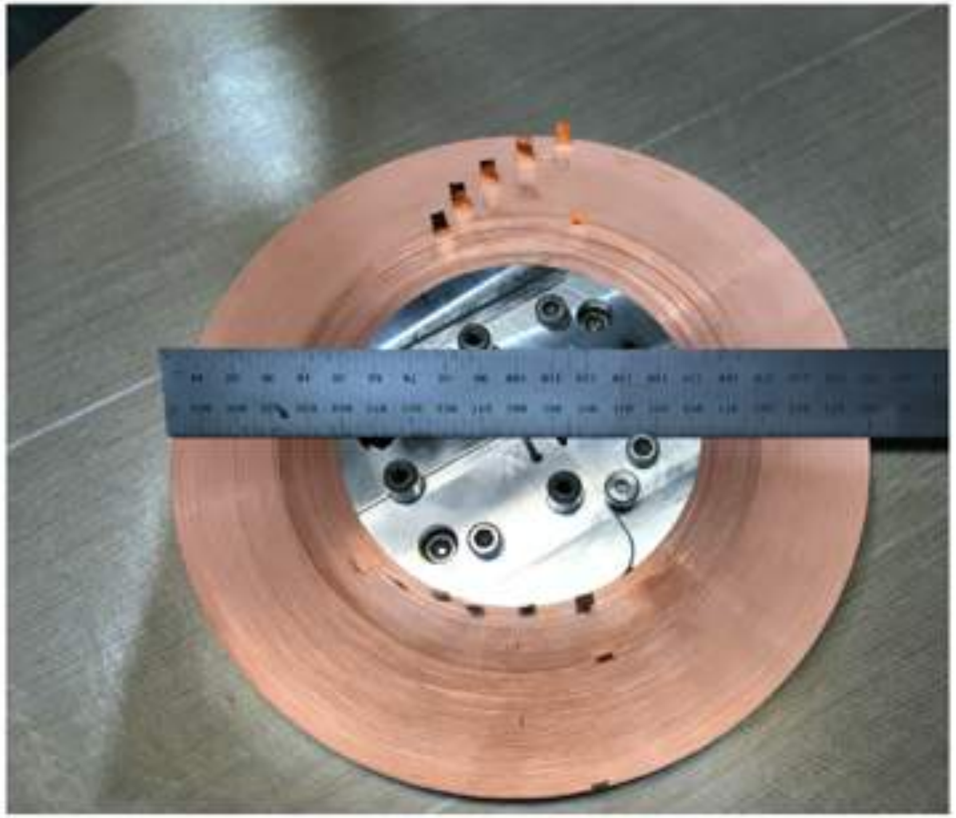
Magnets

B field	Bore (cm)	Material	Vendor	Delivery
26T	3.5	HTS	SUNAM	2016
18T	7	HTS	SUNAM	2017
9T	12	NbTi	Cryo-Magnetics	2017
8T	**12**	**NbTi**	**AMI**	**2016**
8T	16.5	NbTi	AMI	2017
25T	**10**	**HTS**	**BNL/CAPP**	**2020**
12T	**32**	**Nb_3Sn**	**Oxford**	**2020**

CAPP-PACE R&D

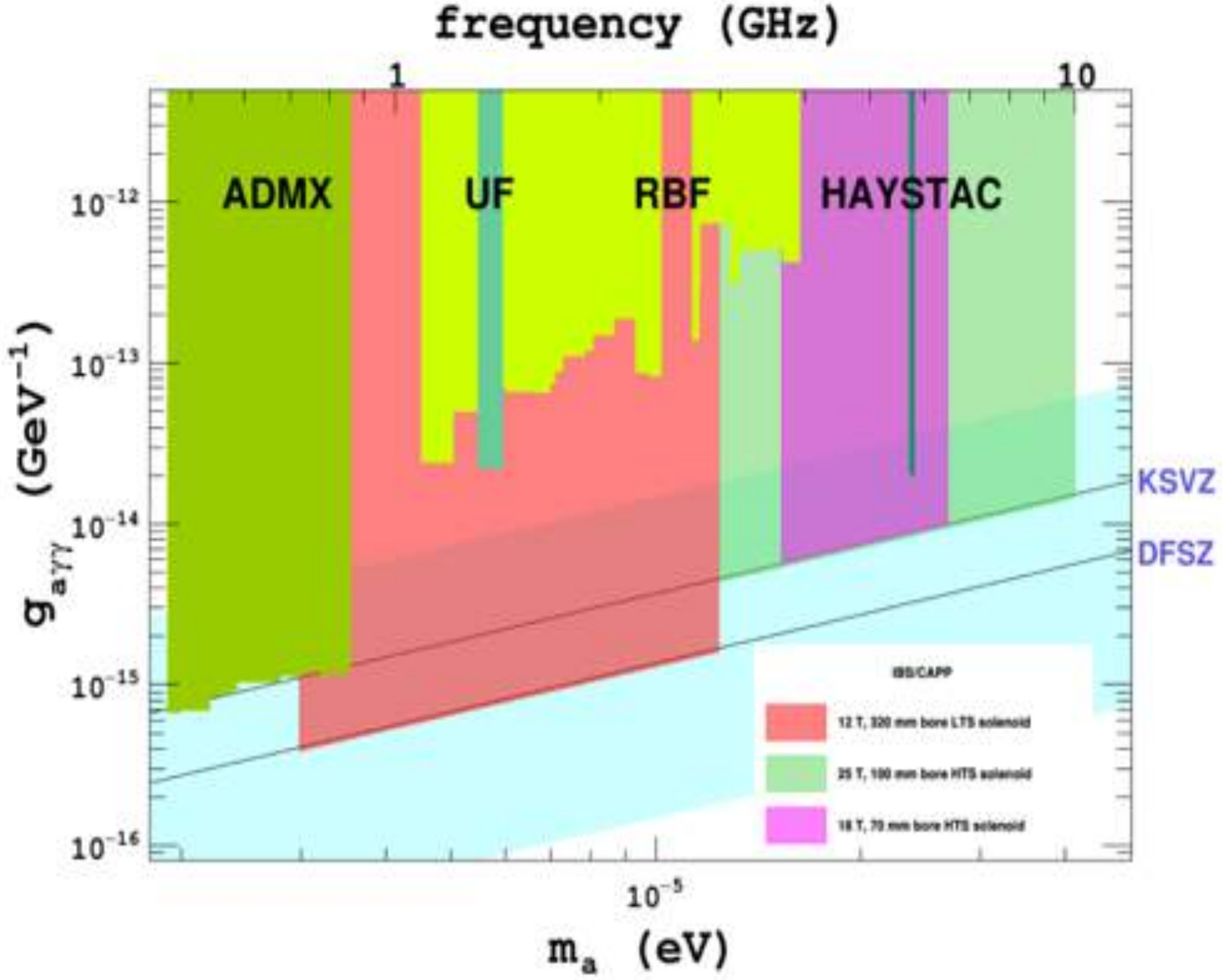
25T 10cm bore HTS magnet by BNL

- The first (of 24) pancake wound! - test will follow
- 5 km of SC tape will be delivered next 5 months

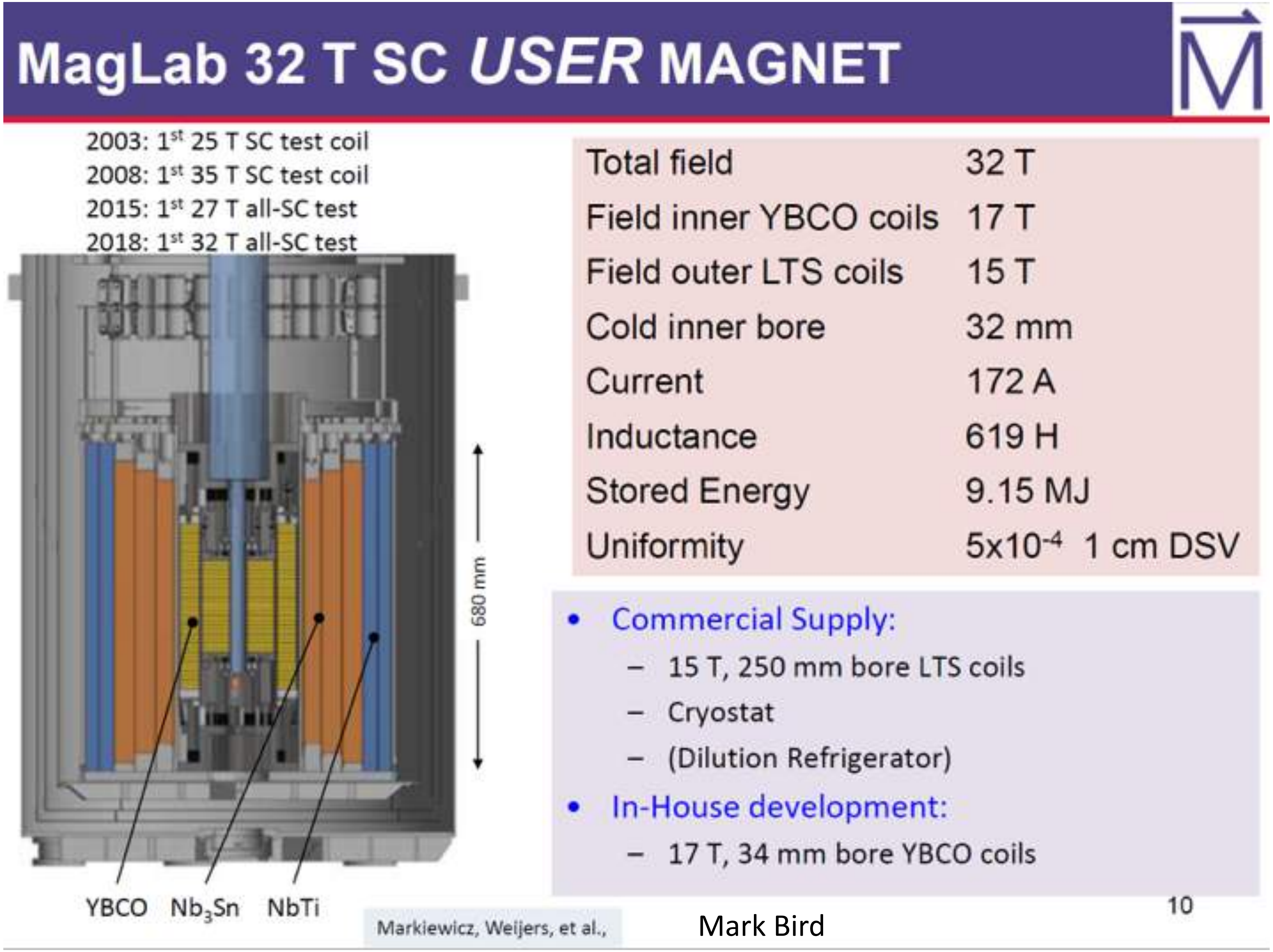


CAPP

CULTASK Sensitivity



- World’s highest field “user” magnet- 32 Tesla with 32 mm bore.
- National High Magnetic Field Lab, Florida.



MagLab 32 T SC *USER* MAGNET

2003: 1st 25 T SC test coil
2008: 1st 35 T SC test coil
2015: 1st 27 T all-SC test
2018: 1st 32 T all-SC test

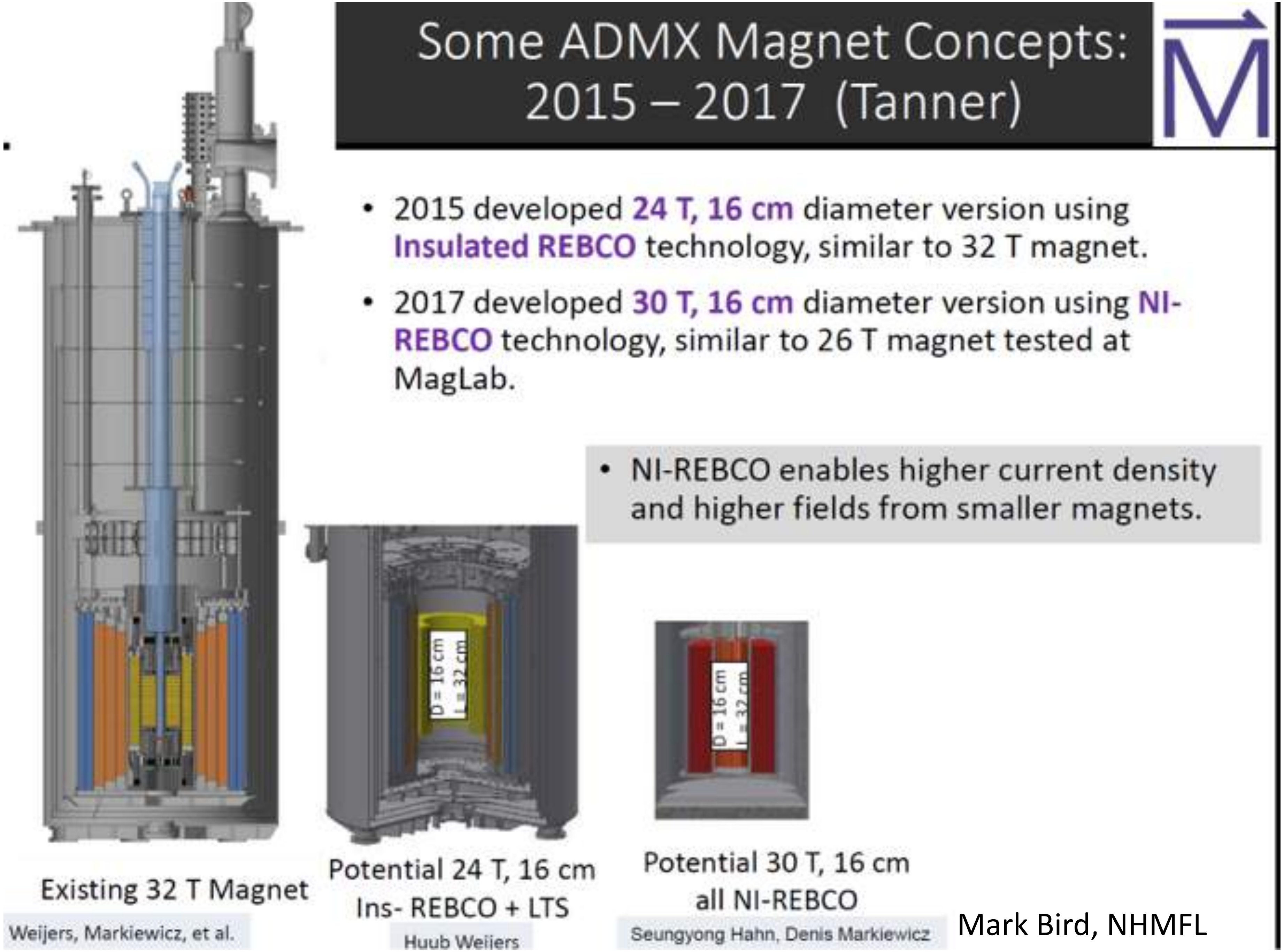
Total field	32 T
Field inner YBCO coils	17 T
Field outer LTS coils	15 T
Cold inner bore	32 mm
Current	172 A
Inductance	619 H
Stored Energy	9.15 MJ
Uniformity	5×10^{-4} 1 cm DSV

- Commercial Supply:
  - 15 T, 250 mm bore LTS coils
  - Cryostat
  - (Dilution Refrigerator)
- In-House development:
  - 17 T, 34 mm bore YBCO coils

Markiewicz, Weijers, et al.,

Mark Bird

- ADMX magnet conceptual design studies at NHMFL



Some ADMX Magnet Concepts: 2015 – 2017 (Tanner)

- 2015 developed **24 T, 16 cm** diameter version using **Insulated REBCO** technology, similar to 32 T magnet.
- 2017 developed **30 T, 16 cm** diameter version using **NI-REBCO** technology, similar to 26 T magnet tested at MagLab.

- NI-REBCO enables higher current density and higher fields from smaller magnets.

Existing 32 T Magnet

Weijers, Markiewicz, et al.

Potential 24 T, 16 cm
Ins- REBCO + LTS

Huub Weijers

Potential 30 T, 16 cm
all NI-REBCO

Seungyong Hahn, Denis Markiewicz

Mark Bird, NHMFL

Challenge of higher frequency axion searches

ADMX AXION DARK MATTER EXPERIMENT

- Scaling single cavity to higher frequencies (f) – Volume ~ $(f)^{-3}$!
- Quality factor also goes down as frequency increases ($Q_L \sim 10^5 \cdot (f)^{-2/3}$)
- Need to move to multi-cavity array's.

Frequency ~ 540 MHz
Q_L – 100,000
Axion Mass ~ 2 μeV
Volume – 135 liters

16" diameter

Frequency ~ 2.4 GHz
Axion Mass ~ 9 μeV
Q_L – 60,000
Volume ~ 2.6 liters

5" diameter

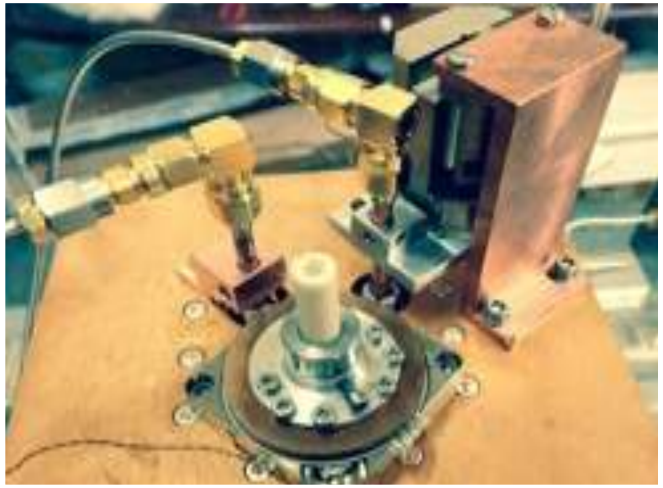
Frequency ~ 10 GHz
Axion Mass ~ 36 μeV
Q_L – 25,000
Volume – 0.025 liters

1" diameter

Tuning Cavities with Miniature Cryogenic Piezoelectric Actuators

Cryogenic Piezo Actuators (Attocube)- tested to 31 Tesla and 10 mK

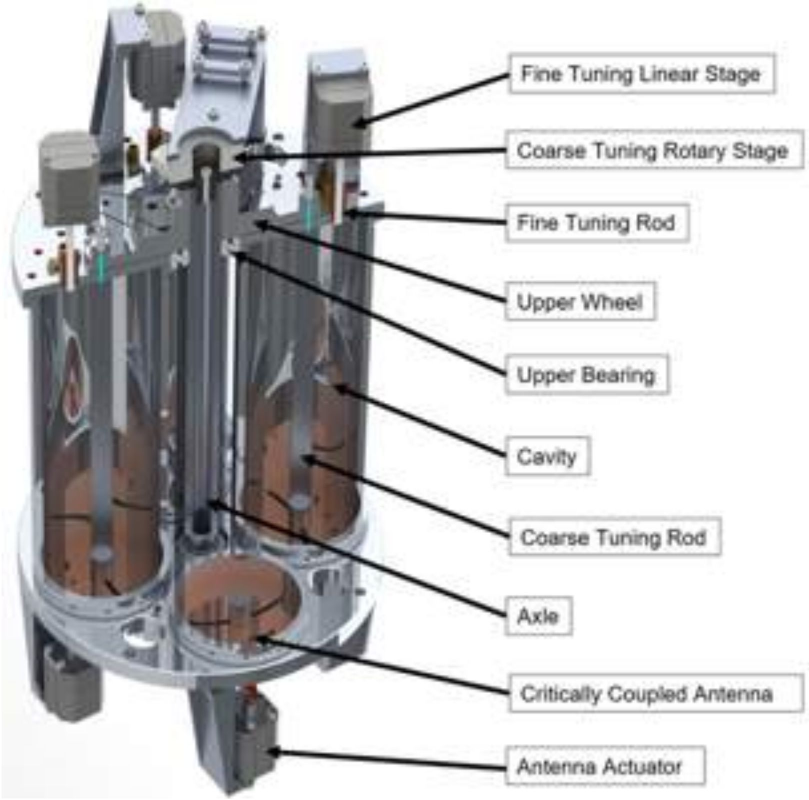
4-6 GHz Test Cavity with piezo actuators at U. Washington



ADMX 1-2 and 2-4 GHz Cavity Arrays

- Near term plan is to build arrays of power-combined higher frequency cavities
  - 4- Cavity array for 1.5- 2.5 GHz
  - 14- Cavity array for ~2.5-5 GHz

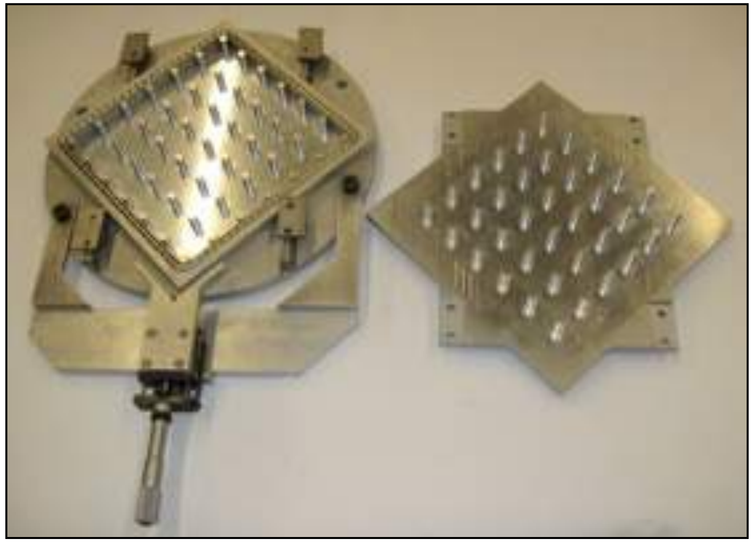
4- Cavity Array



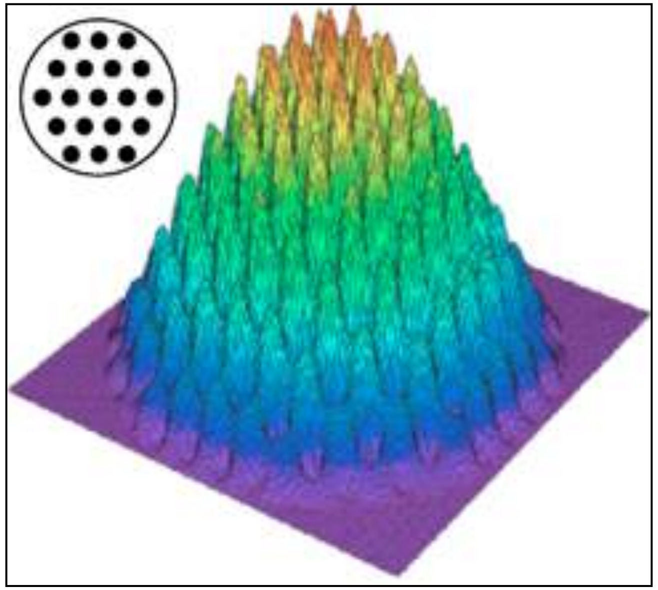
14- Cavity
(2x7) Array

R&D Towards Large Volume, High Frequency Resonators

- Challenging to fill a large volume with small tunable structures ("Swiss Watch" problem)
- Number of elements goes as f^3
- Explore systems that allow simultaneous tuning of many elements with only a few mechanical motions.
  - Photonic bandgap cavity
  - "Comb Cavity"
  - Electronic fine tuning using nonlinear dielectrics

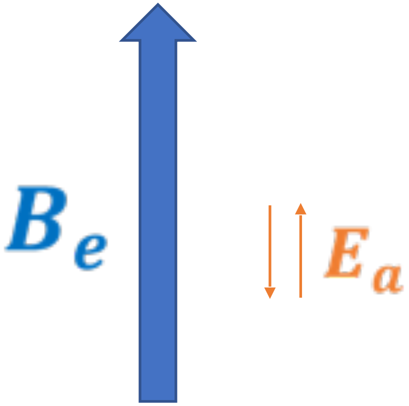


241 cell Comb Cavity (4-8 GHz)



Maxwell's Equations With an Axion

$$\begin{aligned}
\nabla\cdot\mathbf{E} &= \rho_Q - g_{a\gamma}\mathbf{B}\cdot\nabla a\\
\nabla\times\mathbf{B}-\dot{\mathbf{E}} &= \mathbf{J}+\boxed{g_{a\gamma}(\mathbf{B}\dot{a}}-\mathbf{E}\times\nabla a)\\
\nabla\cdot\mathbf{B} &= 0\\
\nabla\times\mathbf{E}+\dot{\mathbf{B}} &= 0
\end{aligned}$$



- The a field is now a classical field oscillating with a frequency corresponding to the axion mass ($f = m_a c^2/h$).
- In the presence of a uniform background **magnetic field $\boldsymbol{B_e}$**, a small oscillating parallel electric field $\boldsymbol{E_a}$ field appears:

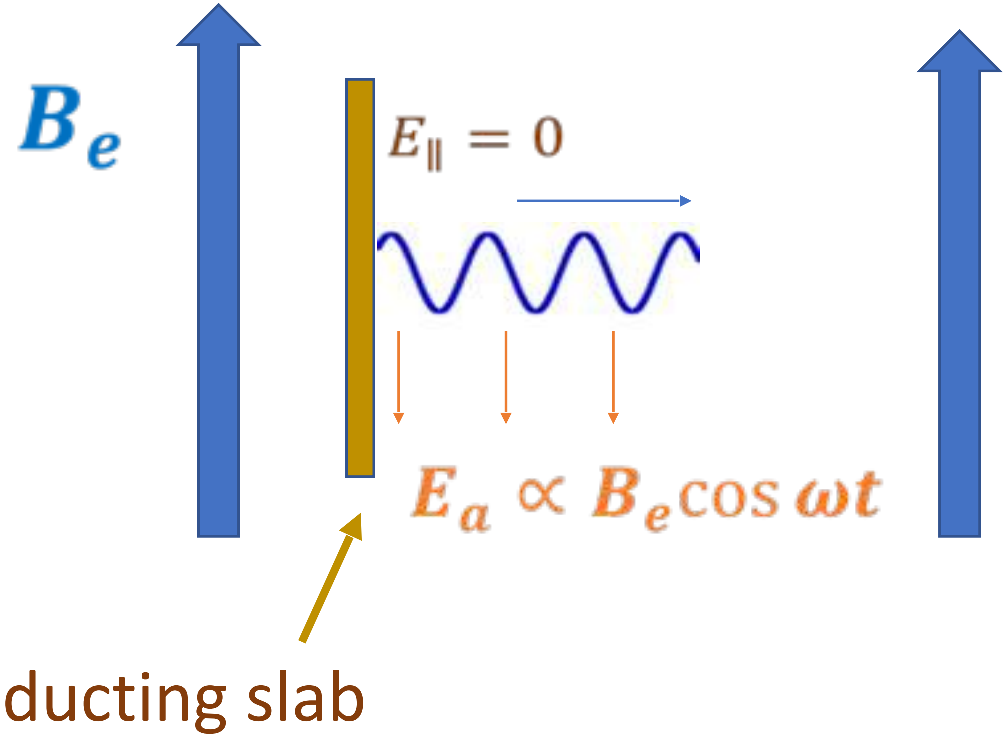
$$\mathbf{E}_a(t) = -g_{a\gamma}\mathbf{B}_e a(t)$$

Irastorza & Redondo 2006

Radiation from a Conducting Surface in a Magnetic Field

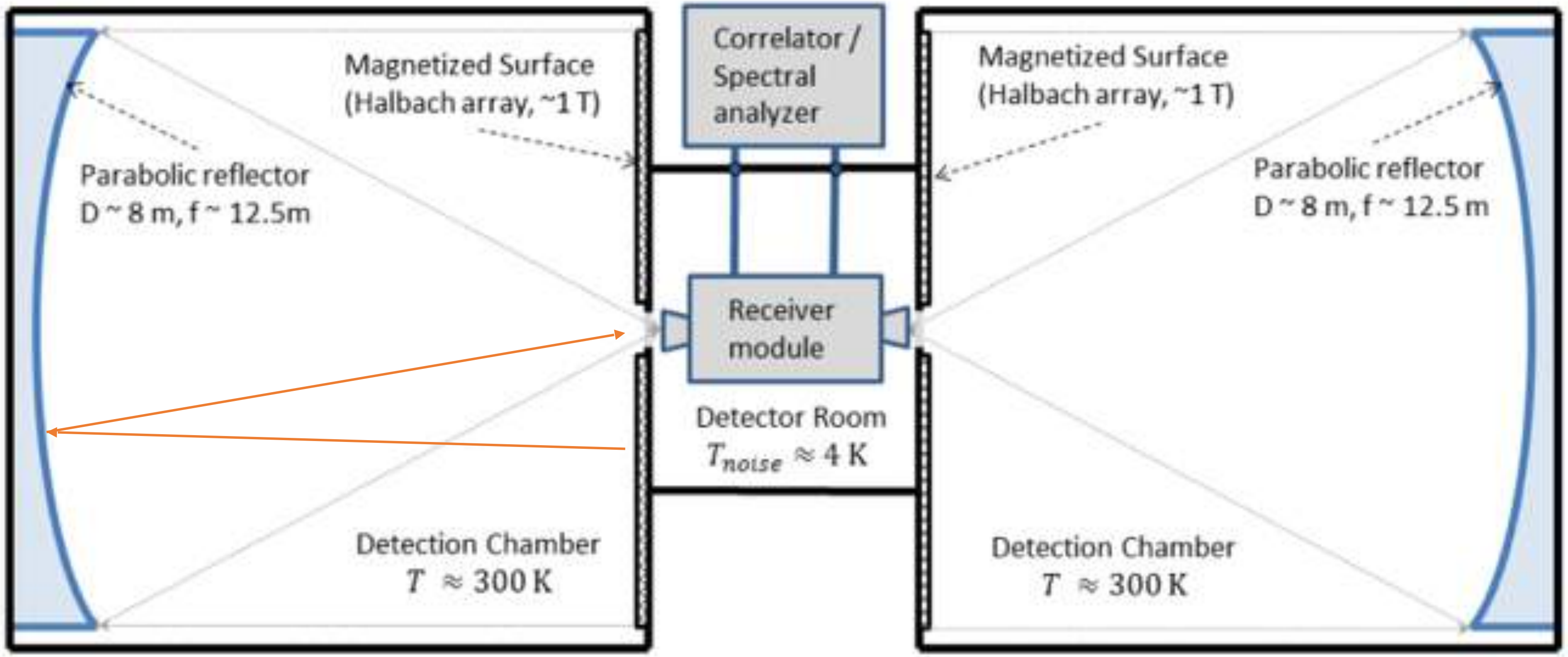
- A conducting surface must have no parallel E field at boundary.
- An outgoing wave cancels parallel component of axion-induced E field.

- Power of emitted wave $$P_a/\mathcal{A} = \frac{1}{2}E_a^2 = 3.3\times 10^{-27}\,\frac{W}{\mathrm{m}^2}\left(\frac{g_{a\gamma}}{2\times 10^{-14}\mathrm{GeV}^{-1}}\right)^2\left(\frac{10^{-4}\,\mathrm{eV}}{m_a}\right)^2\frac{|\mathbf{B}_e|^2}{10\,\mathrm{T}},$$



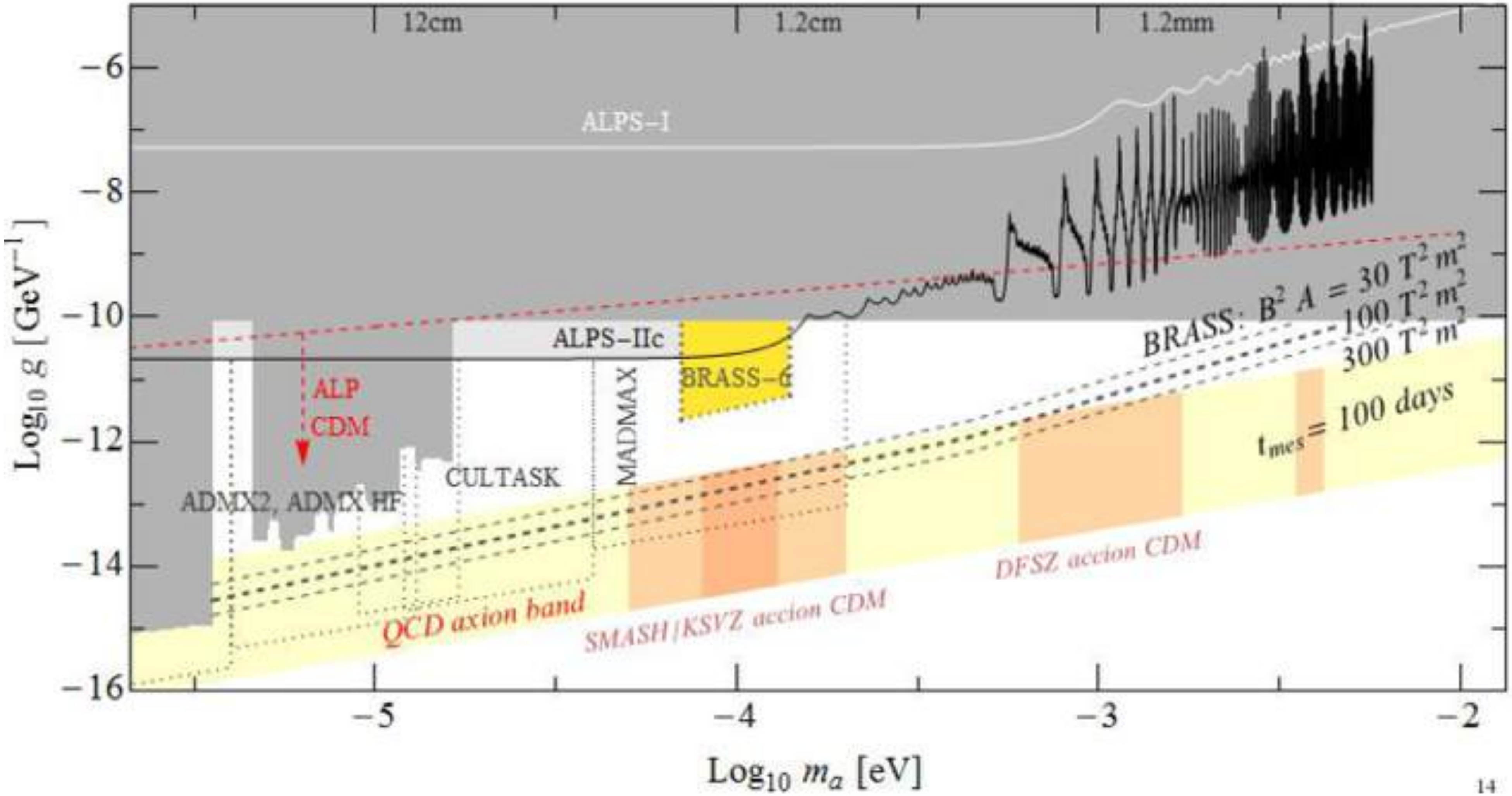
Conceptual Design for BRASS

- ❑ Broadband Radiometric Axion/ALP SearcheS:
  - -- Flat, permanently magnetized surface (Halbach array; 100 m^2, B~1T)
  - -- Focusing the signal with a parabolic reflector
  - -- Broadband recording (16+ GHz bandwidth, spectral resolution of 10^{-7}).
  - -- Correlating signals from multiple modules
  - -- Natural synergy with VLBI and ALMA/APEX developments at MPIfR



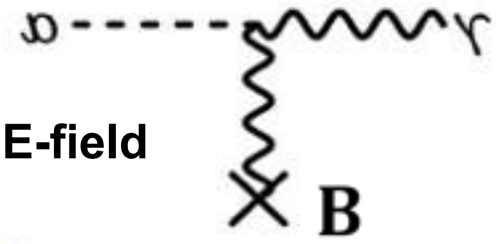
BRASS on Axion/ALP Dark Matter

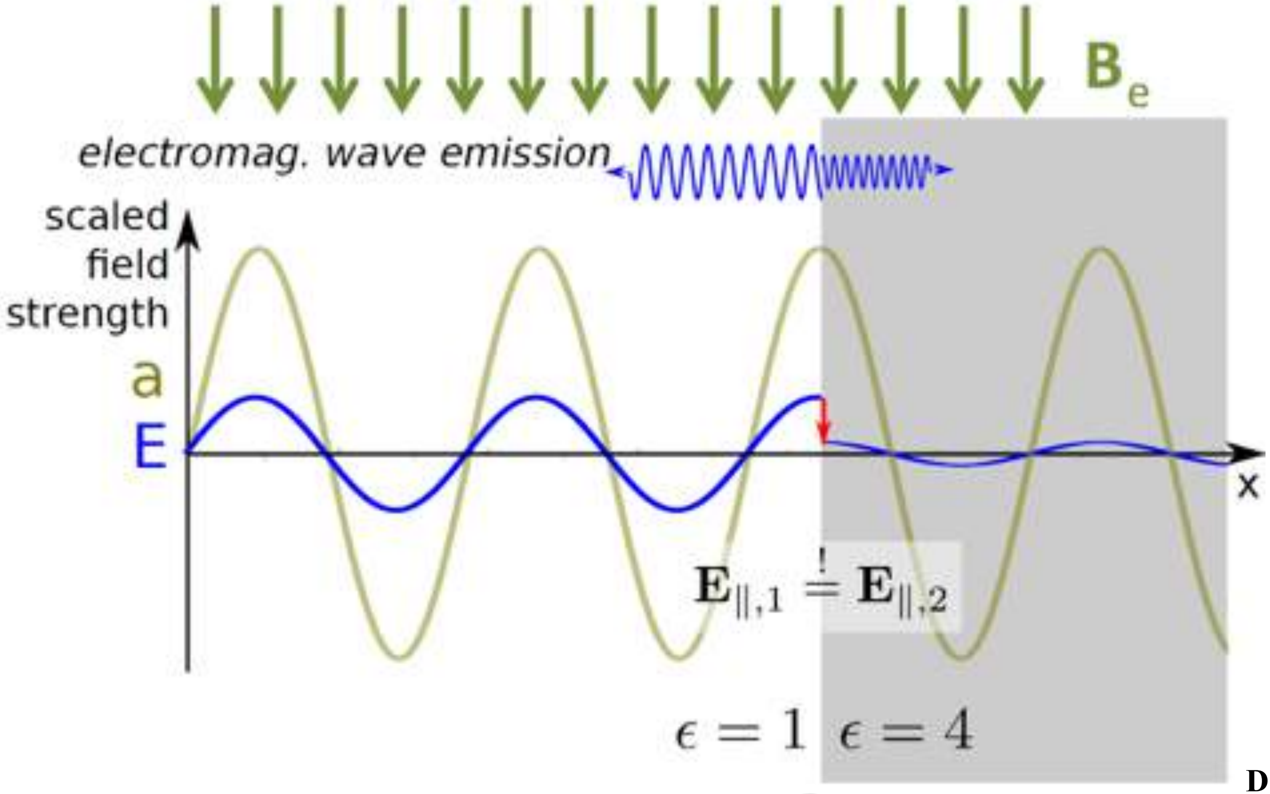
- ☐ BRASS: Assuming 4K and 5$h\nu$ detection sensitivity.
  BRASS-6: T_{sys} = 40 K, Band 1: 18 – 32 GHz.



Experimental approaches: Effect of Dielectric

Mixing of axion with photon in extrenal B-field
→ Sources oscillating E-field
At surfaces with transition of ε: Discontinuity of E-field
→ Emission of photons

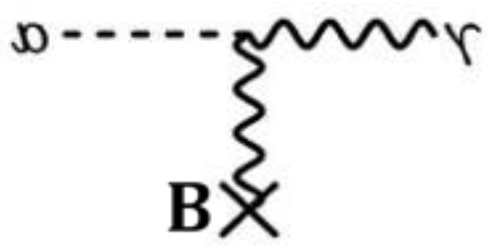




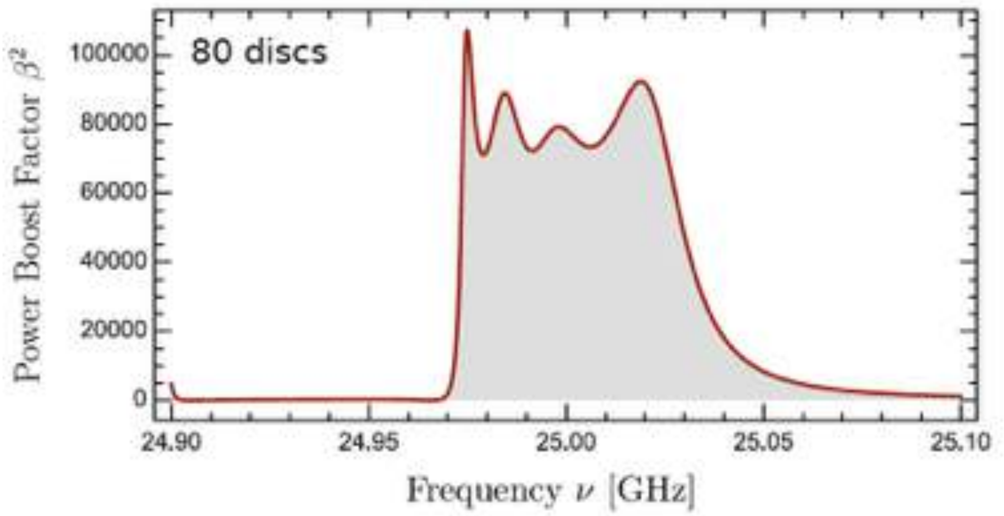
$$\left(\frac{P}{A}\right)_{mirror} \sim 2 \cdot 10^{-27} \frac{W}{m^2} \left(\frac{B_{||}}{10\,T}\right)^2 \left(g_{a\gamma\gamma} m_a\right)^2$$

D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo and A. Ringwald JCAP 1304 (2013) 016 [arXiv: 1212.2970].

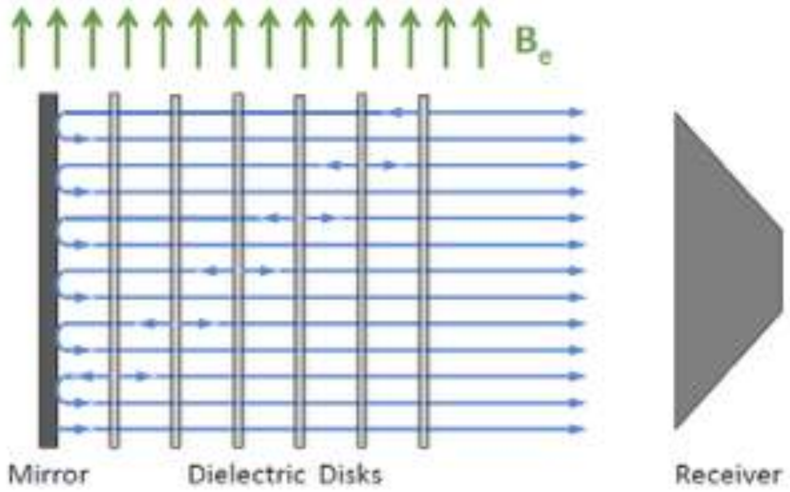
Experimental approaches
Dielectric haloscopes:



- **Mixing of axion with photon in extrenal B-field → Sources oscillating E-field**
- **Many surfaces with transition of ε:**
- **→ Coherent emission of photons from each surface**
- **Interference effects can be exploited**



A. Caldwell et al, Phys. Rev. Lett. 118, 091801 (2017)



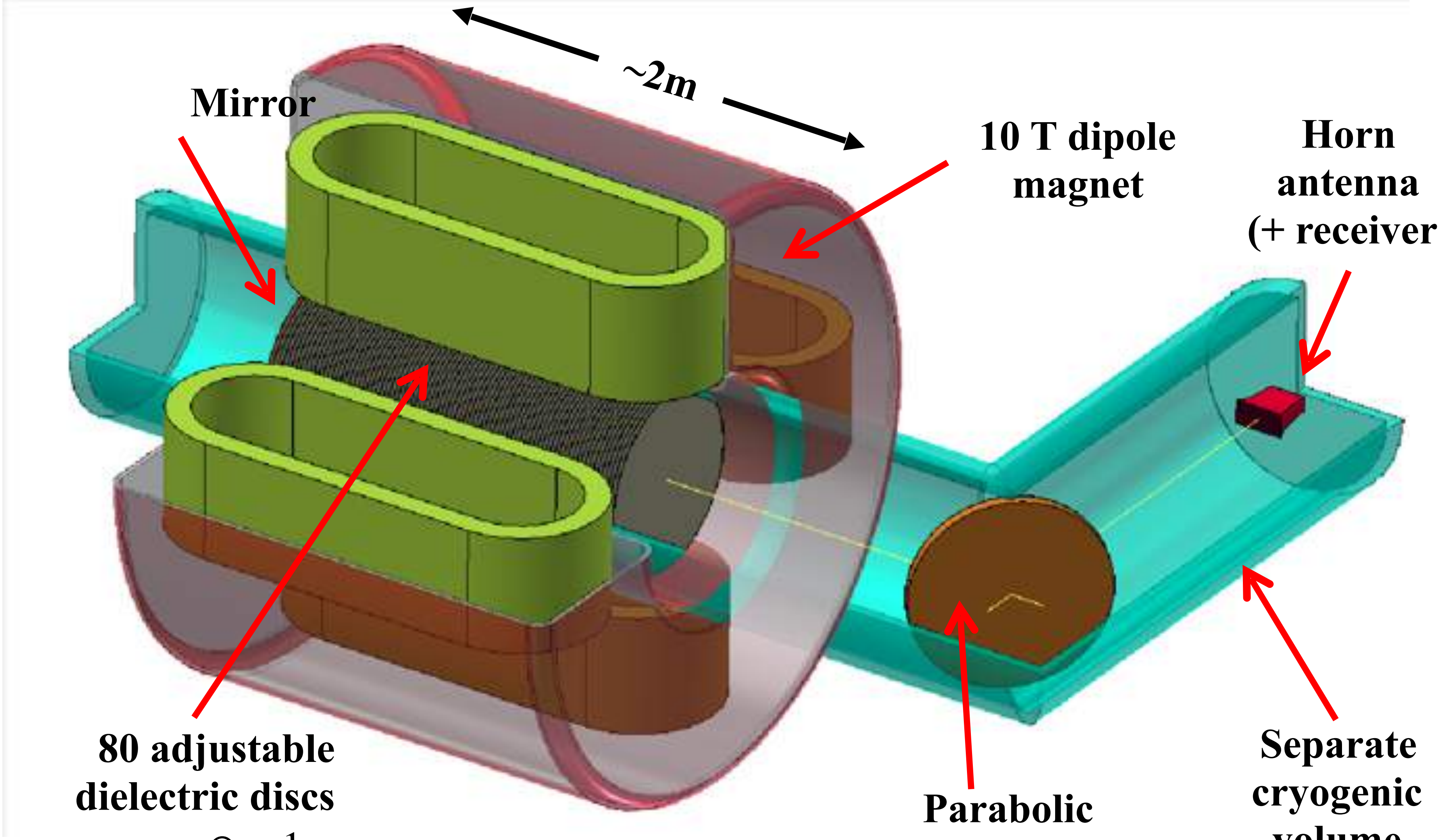
$$\left(\frac{P}{A}\right)_{cavity} \sim 2\cdot 10^{-27}\frac{W}{m^2}\left(\frac{B_{||}}{10\,T}\right)^2 \left(g_{a\gamma\gamma} m_a\right)^2 \beta^2$$

"Quasi broadband" approach

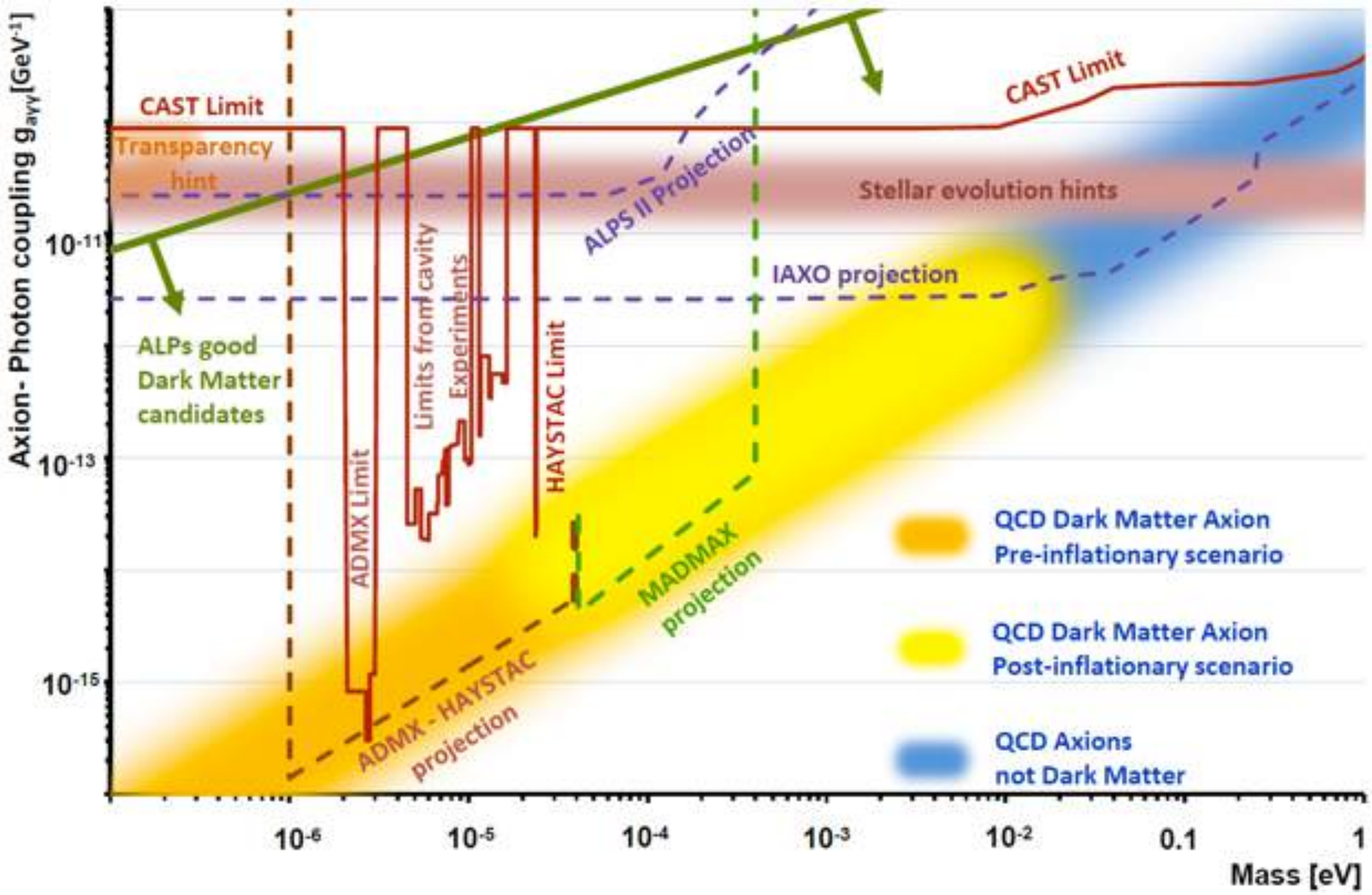
Also works for kinetic mixing

à Sensitive to hidden photon, no B-field needed

MAgnetized Disc and Mirror Axion eXperiment



MADMAX sensitivity projection

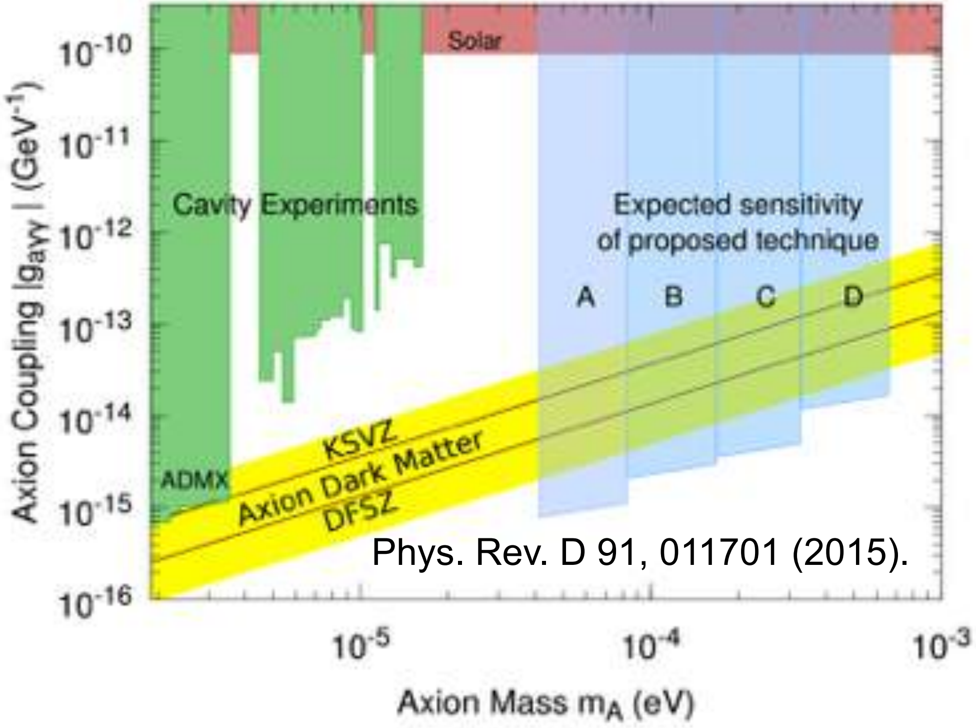


Open resonator design with dipole magnet

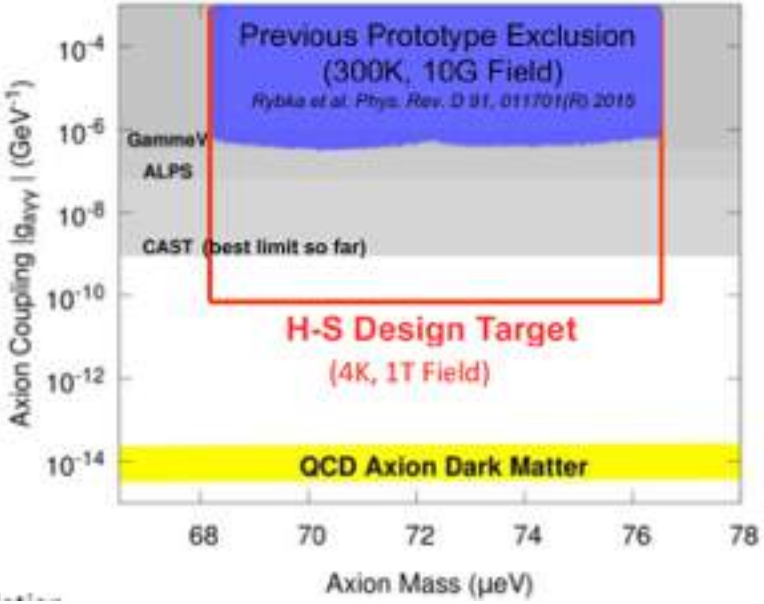
Orpheus Project (UW)

Open resonator would usually not couple to axion field (positive and negative E-fields cancel).

Manipulating modes with dielectrics or alternating the magnetic field leads to a net axion coupling.



Phys. Rev. D 91, 011701 (2015).



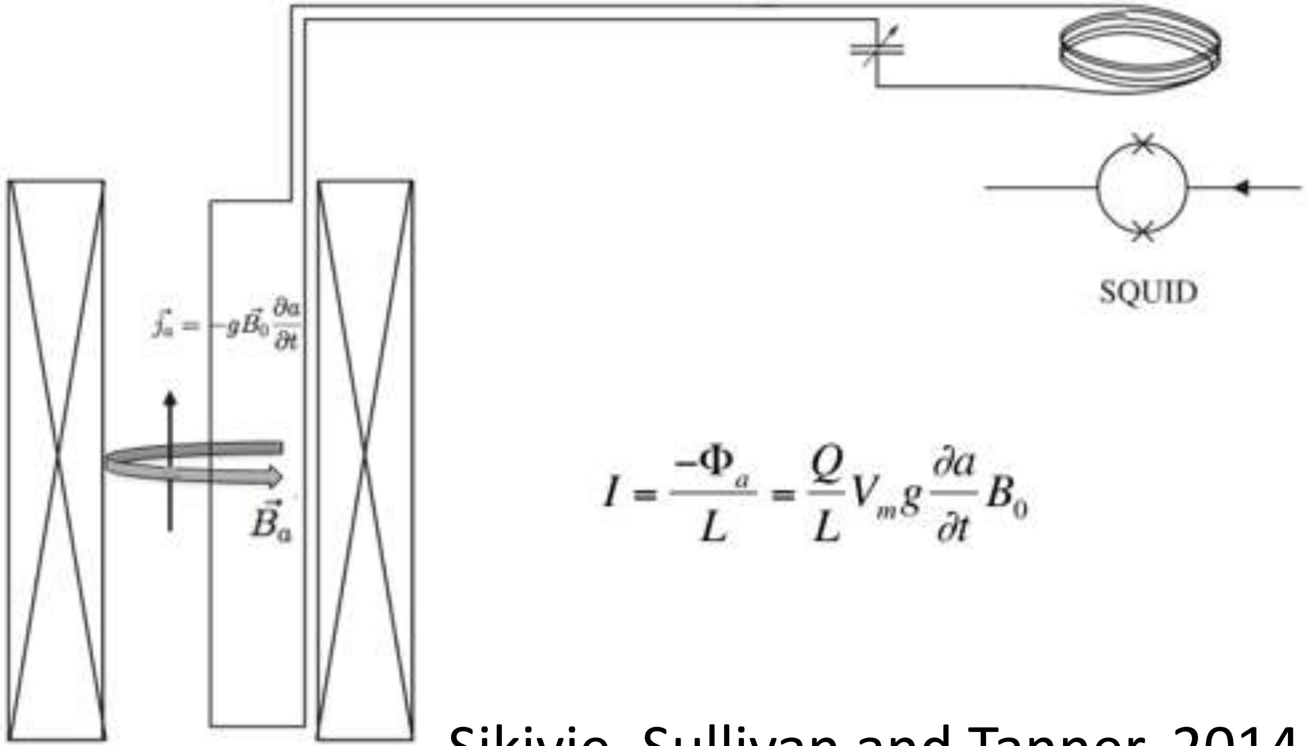
Low Frequency Experiments with LC Circuits

- "Axion Current" $J_a = g_{a\gamma}\boldsymbol{B}\dot{a}$ can source an oscillating magnetic field.

$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J} + \boxed{g_{a\gamma}(\mathbf{B}\dot{a}} - \mathbf{E} \times \nabla a)$$

- Collect the magnetic flux with a transformer coil and measure with a SQUID.

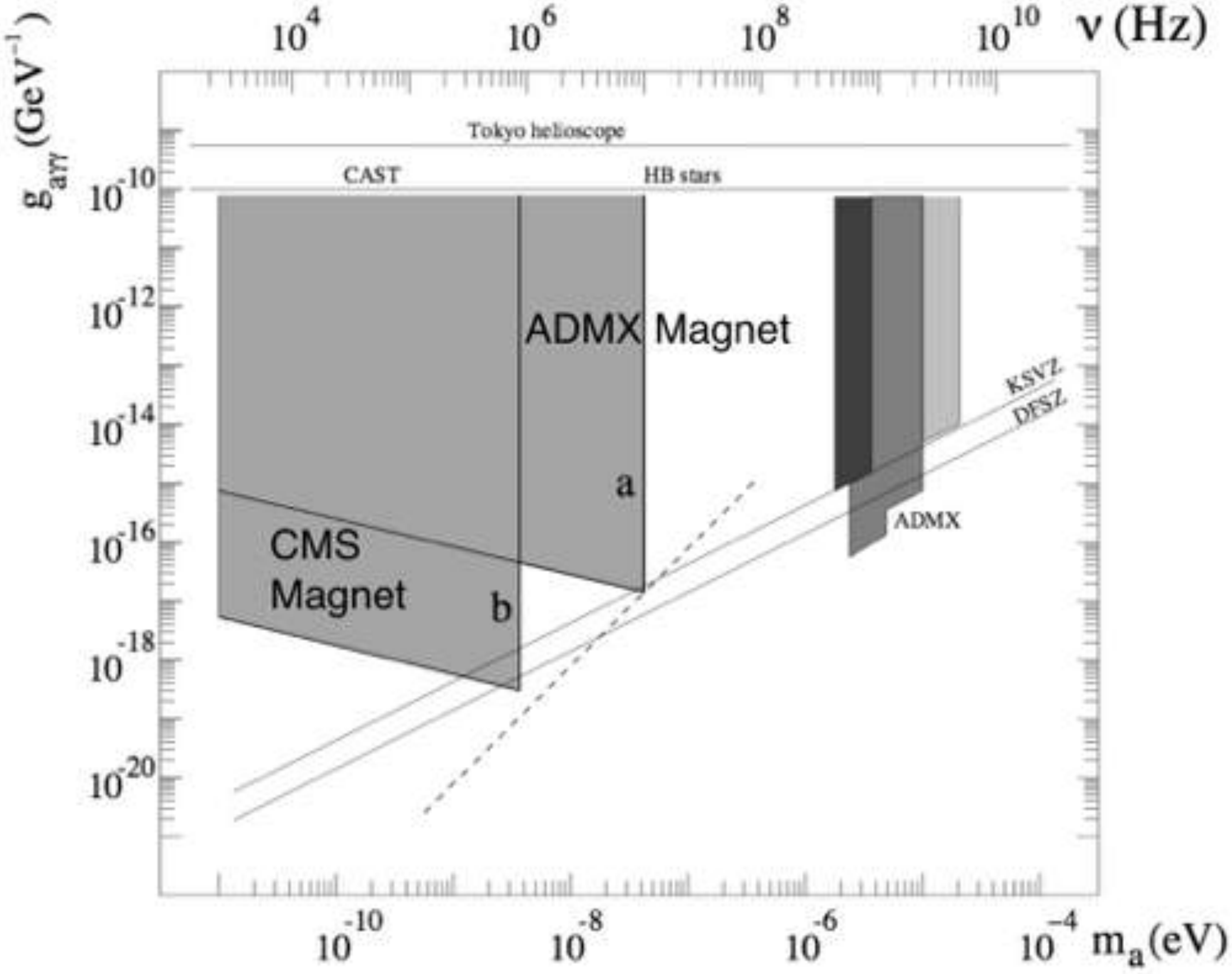
- Can be resonant or non resonant.



$$I = \frac{-\Phi_a}{L} = \frac{Q}{L} V_m g \frac{\partial a}{\partial t} B_0$$

Sikivie, Sullivan and Tanner, 2014

LC Circuit projections using various magnets

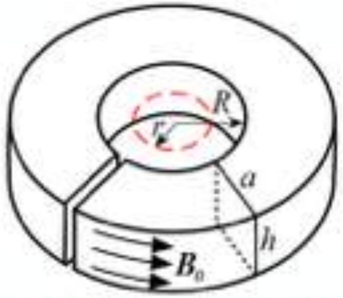


Proposal for Axion Dark Matter Detection Using an LC Circuit
PRL 112, 131301 (2014)

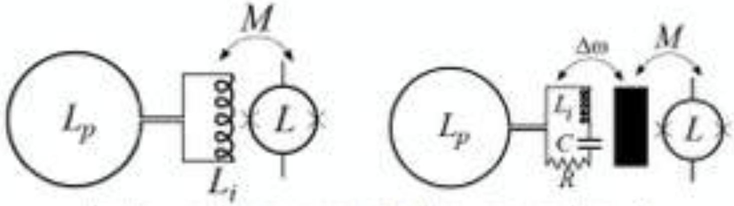
ABRACADABRA Experiment

A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus

Theory:



Toroidal geometry for zero-field detection



Interchangeable readout: broadband (low freq.) or resonant (high freq.)

YK, Safdi, Thaler, Phys. Rev. Lett. 2016

Experiment:

Prototype specs:

$R_{\text{in}} = 3$ cm, $R_{\text{out}} = 6$ cm, $h = 12$ cm,
$V = 680$ cm^3, $B_{\text{max}} = 1$ T, $G = 0.085$

ABRA-10cm @ MIT

*figures from Yoni Kahn

Thank you!

Extra Slides

Axion modifies Maxwell's Equations

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

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

which couples to EM via Faraday's law:

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

- In the presence of a constant background magnetic field, the response of the electric