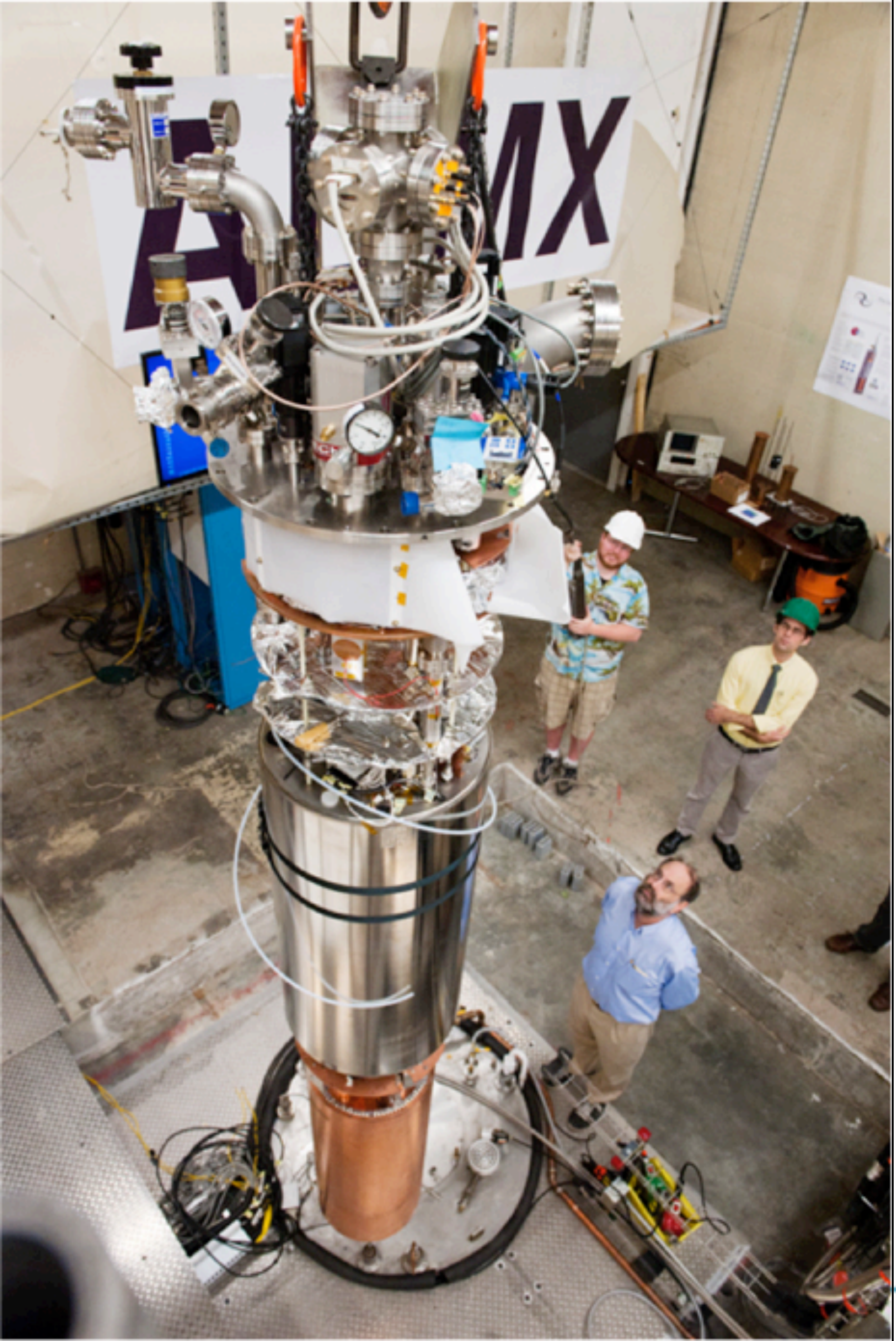


Overview of Axion Searches

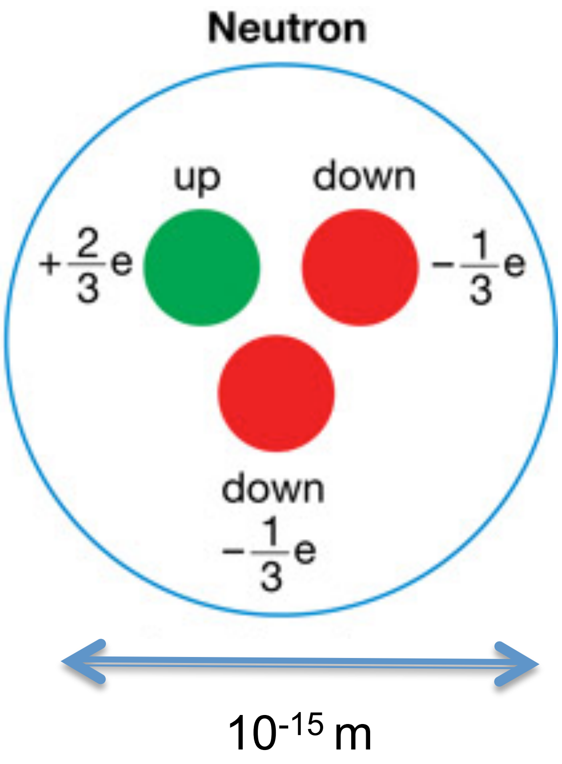
Gianpaolo Carosi
LLNL

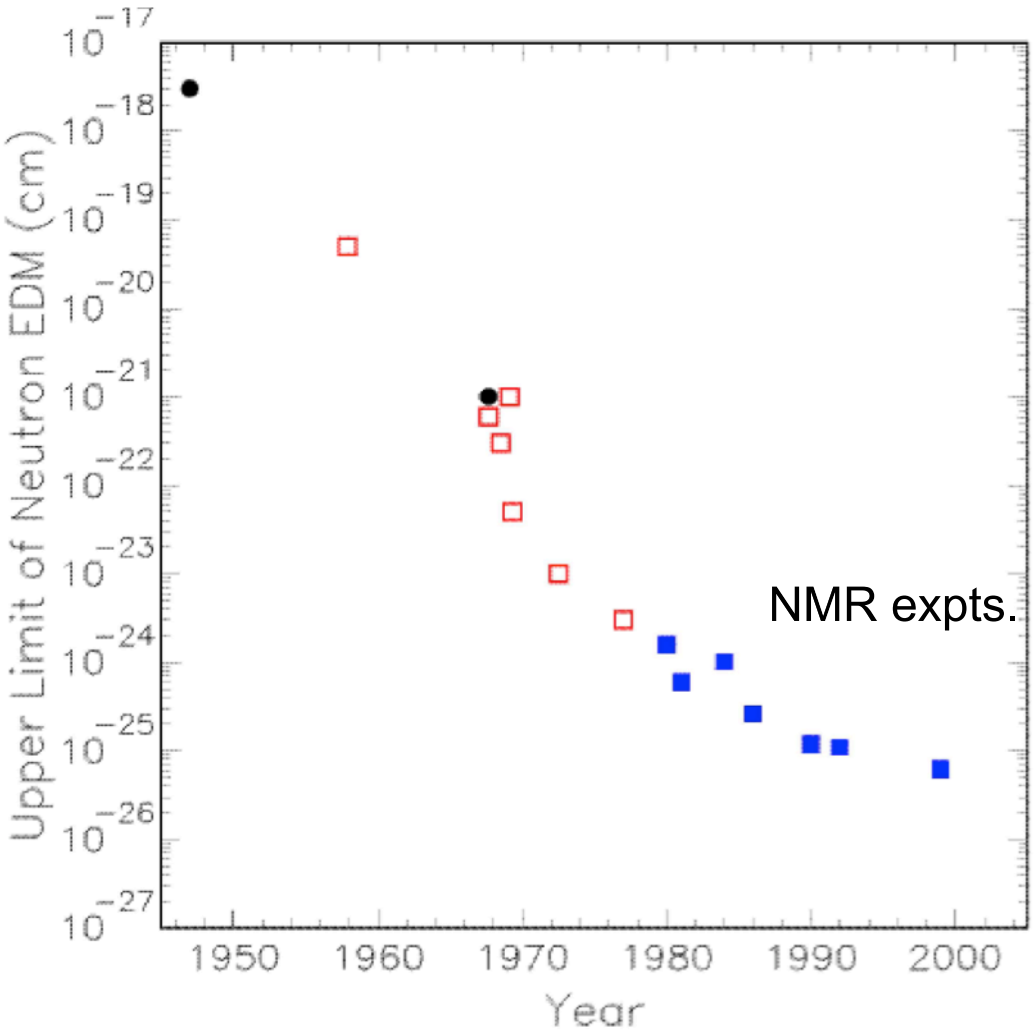
TAUP

July 25th, 2017

Why is the neutron electric dipole moment so small?

Naive estimate gives
$d_n \approx 10^{-16}$ e-cm





*from Aaron Chou (FNAL)

Peccei-Quinn solution to the strong-CP problem


Roberto Peccei


Helen Quinn

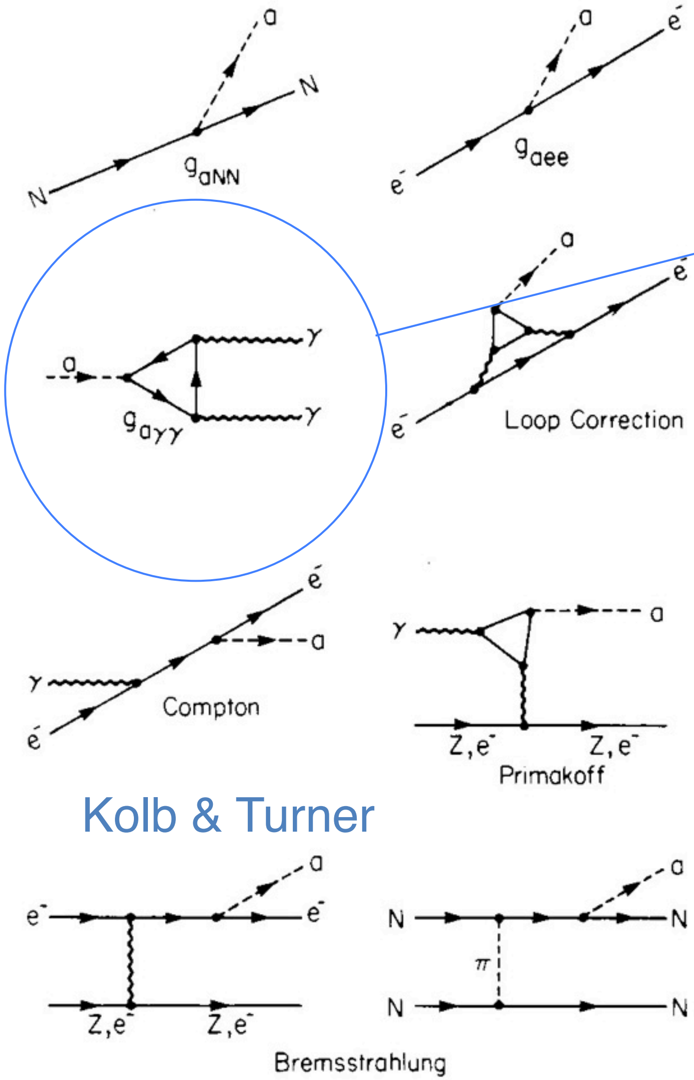

Steven Wienberg


Frank Wilczek

- Peccei & Quinn: Postulate new U(1) symmetry that would be spontaneously broken.
- Weinberg & Wilczek: A new Goldstone boson (the axion)
- Remnant axion VEV nulls QCD CP violation.
- Only free parameter: Symmetry breaking scale (f_a).
- “Invisble Axion”: $f_a >>$ Weak Scale
- Two general classes of models
  - **KSVZ** [Kim (1979), Shifman, Vainshtein, Sakharov (1980)]: “QCD axion” or “hadronic axion”
  - **DFSZ** [Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)]

“clean up” the Strong-CP problem

Axion couplings



Kolb & Turner

General classes of couplings

Axion – Nucleon
Axion – Electron
Axion – Photon

$g_{a\gamma\gamma}$ is a process with small model uncertainty
Easily calculable
Coupling used for haloscopes

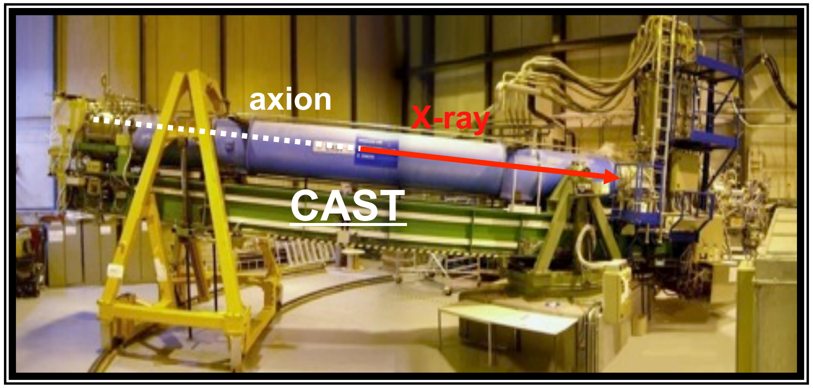
Rate depends on "unification group" (that is, the particles in the loops), ratio of u/d quark masses, and mostly f_{PQ}

$$g_{a\gamma\gamma} \sim \frac{\alpha}{f_{PQ}}\left(\frac{E}{N} - 1.95\right)$$

Variety of experiments

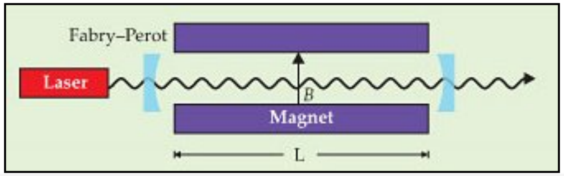
Pierre Sikivie

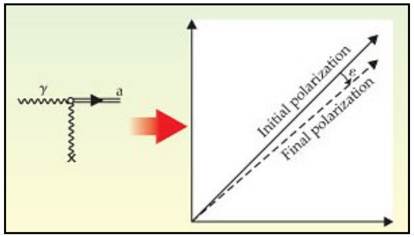
- **Axions as Dark Matter**
  - Haloscopes: Microwave cavities in solenoid magnet
  - Look for dark matter axions (low mass) converting to photons in B-Field
    - — Sikivie PRL 51:1415 (1983)
  - **New techniques being explored: NMR, LC-circuit, Axion Wind**



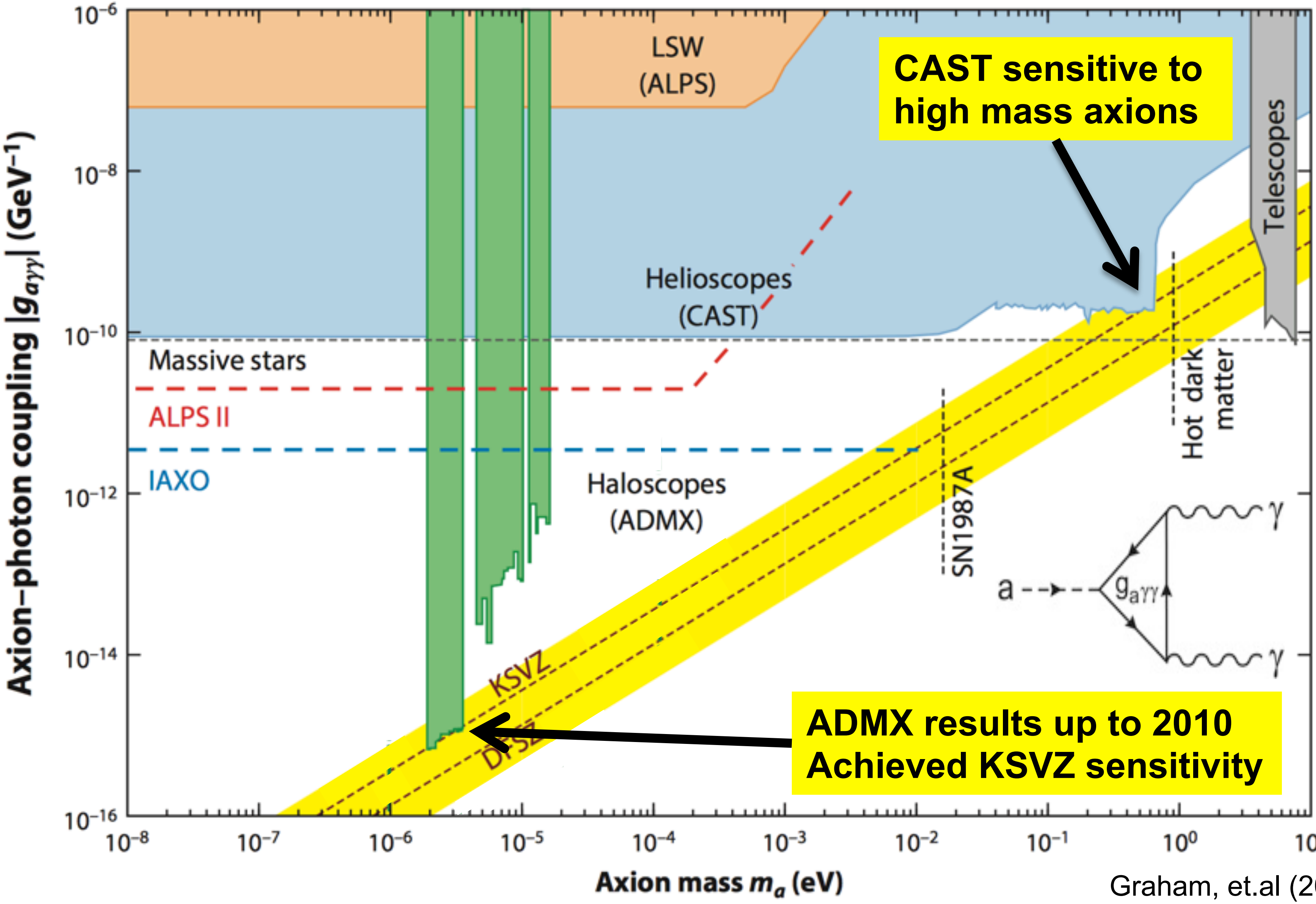
- Axions from the Sun
  - Helioscopes: Axions generated from the sun
    - — Sikivie PRL 51:1415 (1983)
    - — Van Bibber et al. PhysRevD 39:2089 (1989)
    - — **CAST, IAXO**
  - Bragg scattering, noble liquids (g_{ae})

- Axions in the Lab
  - Photon regeneration and polarization changes
    - — **PVLAS, ALPS**
  - Modifications to short range forces
    - — **ARIADNE, Torsion-balance**





Axion parameter space



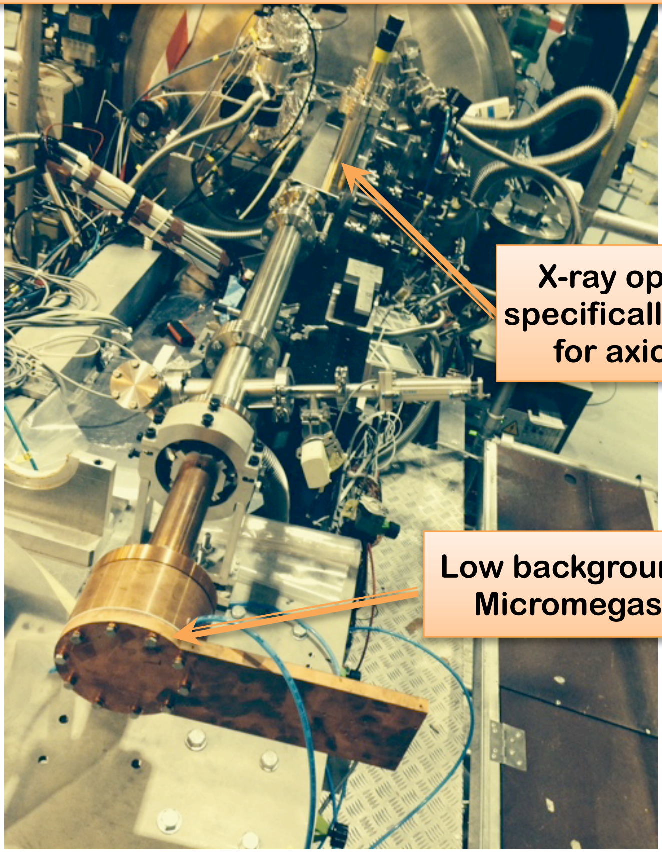
CAST sensitive to high mass axions

ADMX results up to 2010 Achieved KSVZ sensitivity

Graham, et.al (2016)

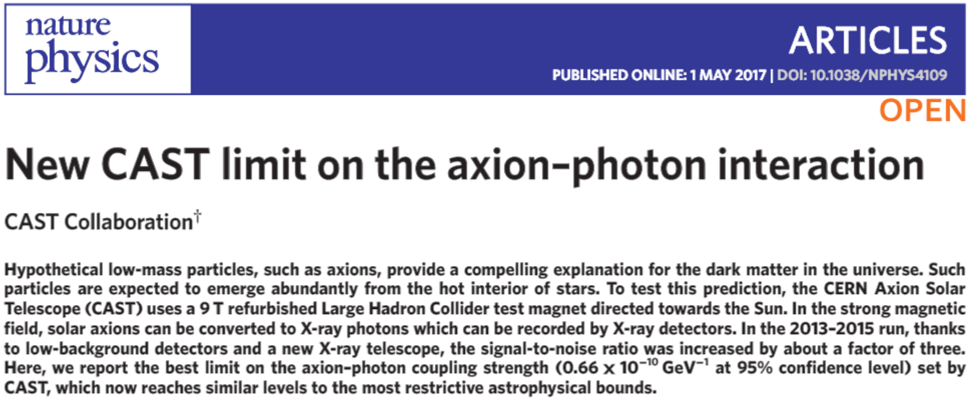
New CAST Limit

Enabled by the IAXO pathfinder system



X-ray optics specifically built for axions

Low background Micromegas



nature physics

ARTICLES

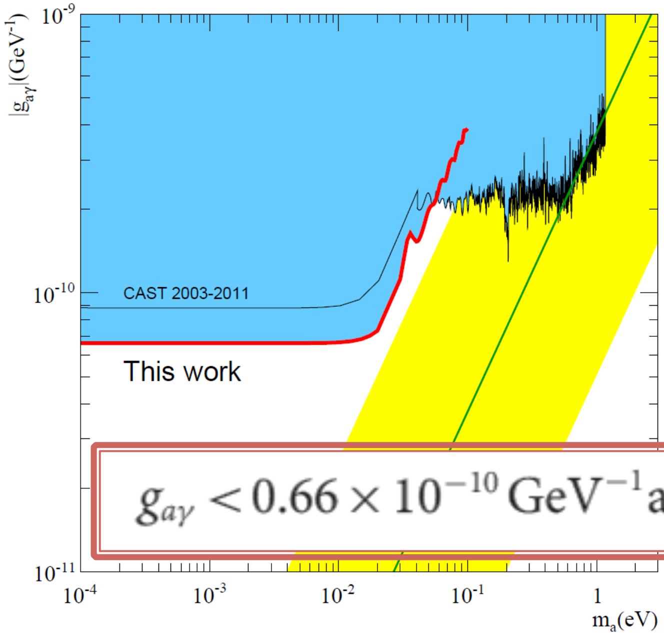
PUBLISHED ONLINE: 1 MAY 2017 | DOI: 10.1038/NPHYS4109

OPEN

New CAST limit on the axion–photon interaction

CAST Collaboration†

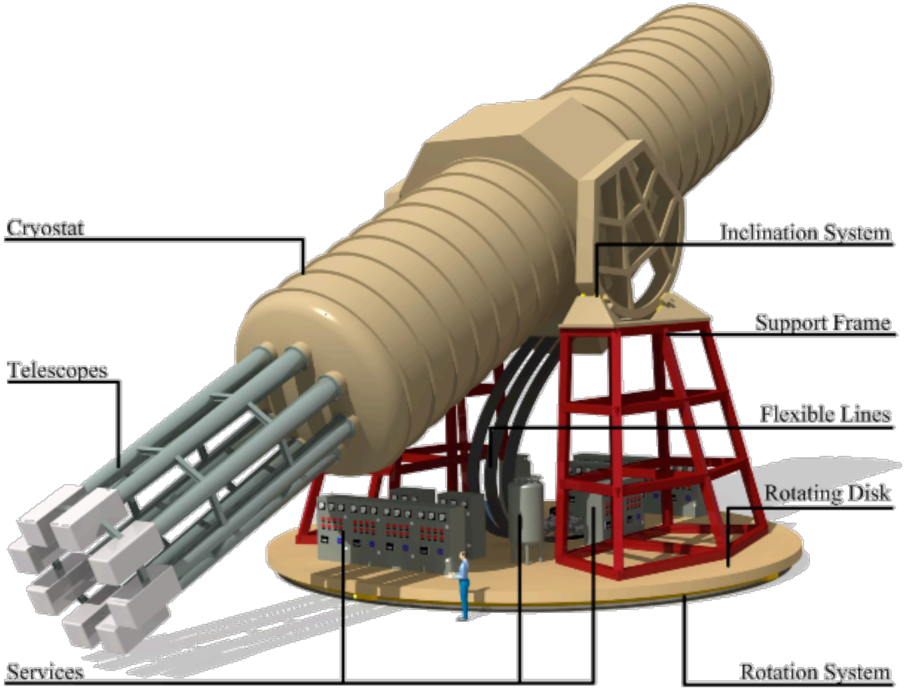
Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such particles are expected to emerge abundantly from the hot interior of stars. To test this prediction, the CERN Axion Solar Telescope (CAST) uses a 9 T refurbished Large Hadron Collider test magnet directed towards the Sun. In the strong magnetic field, solar axions can be converted to X-ray photons which can be recorded by X-ray detectors. In the 2013–2015 run, thanks to low-background detectors and a new X-ray telescope, the signal-to-noise ratio was increased by about a factor of three. Here, we report the best limit on the axion–photon coupling strength (0.66 x 10^{-10} GeV^{-1} at 95% confidence level) set by CAST, which now reaches similar levels to the most restrictive astrophysical bounds.

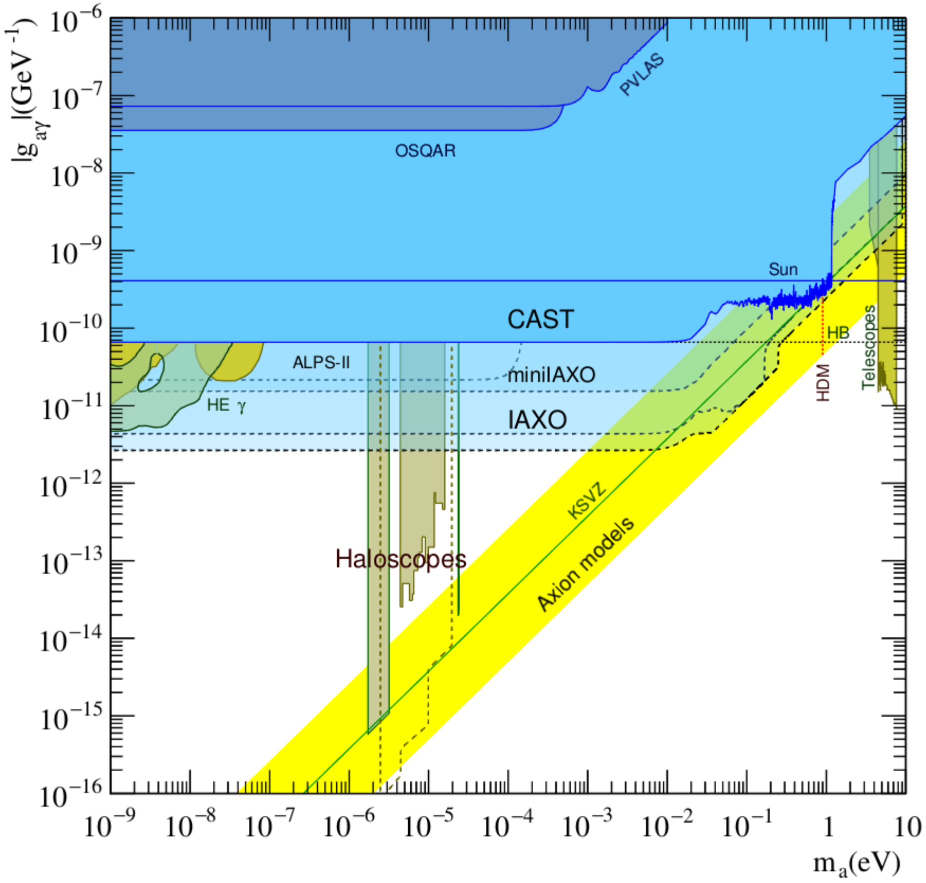


$$g_{a\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1} \text{at } 95\%\ \mathrm{CL}$$

IAXO: the next Helioscope generation

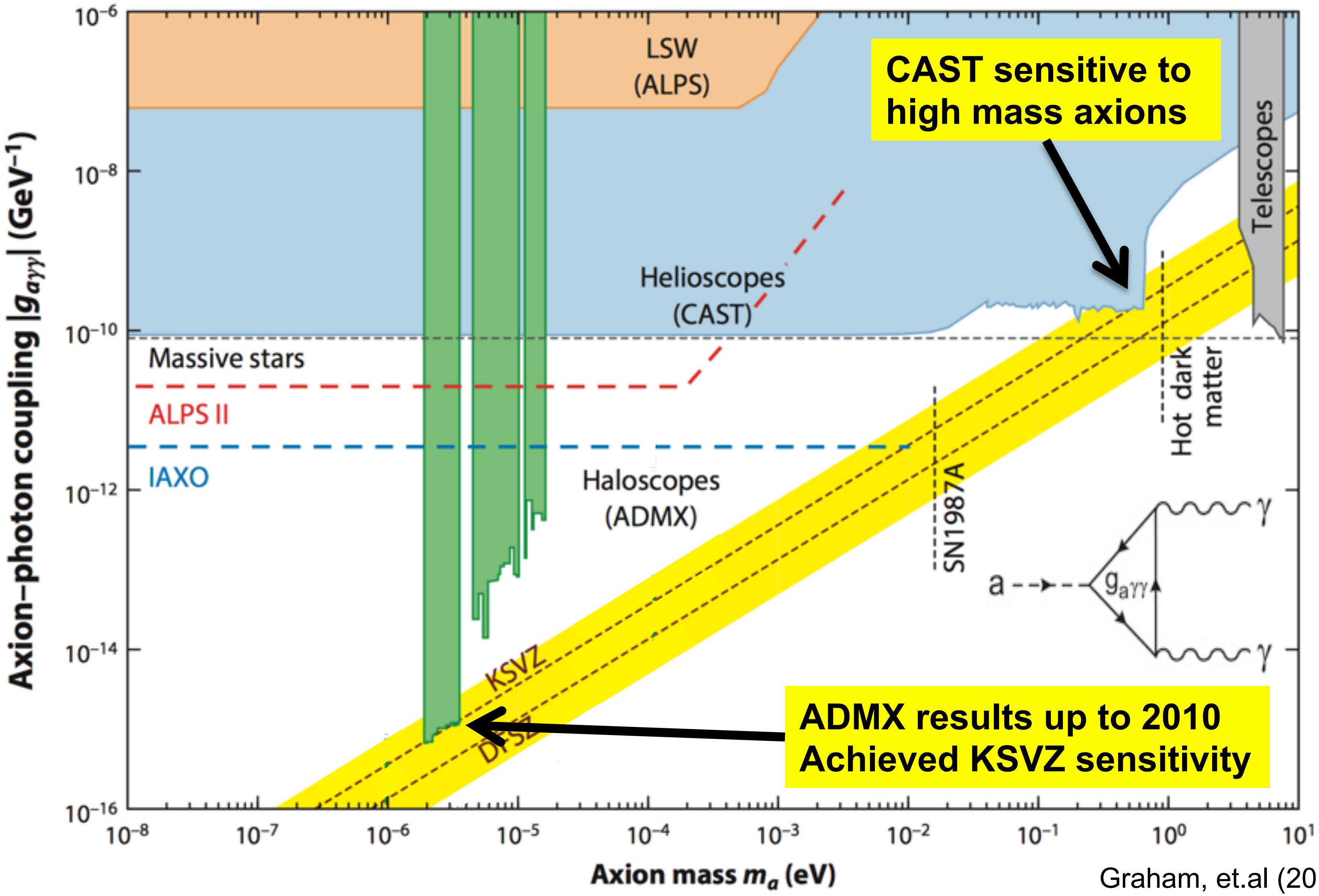
- Large toroidal 8-coil magnet *L* = ~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection system
- Rotating platform with services





*Please see Beljana Lakic’s talk tomorrow in the DM parallel session

Axion parameter space



CAST sensitive to high mass axions

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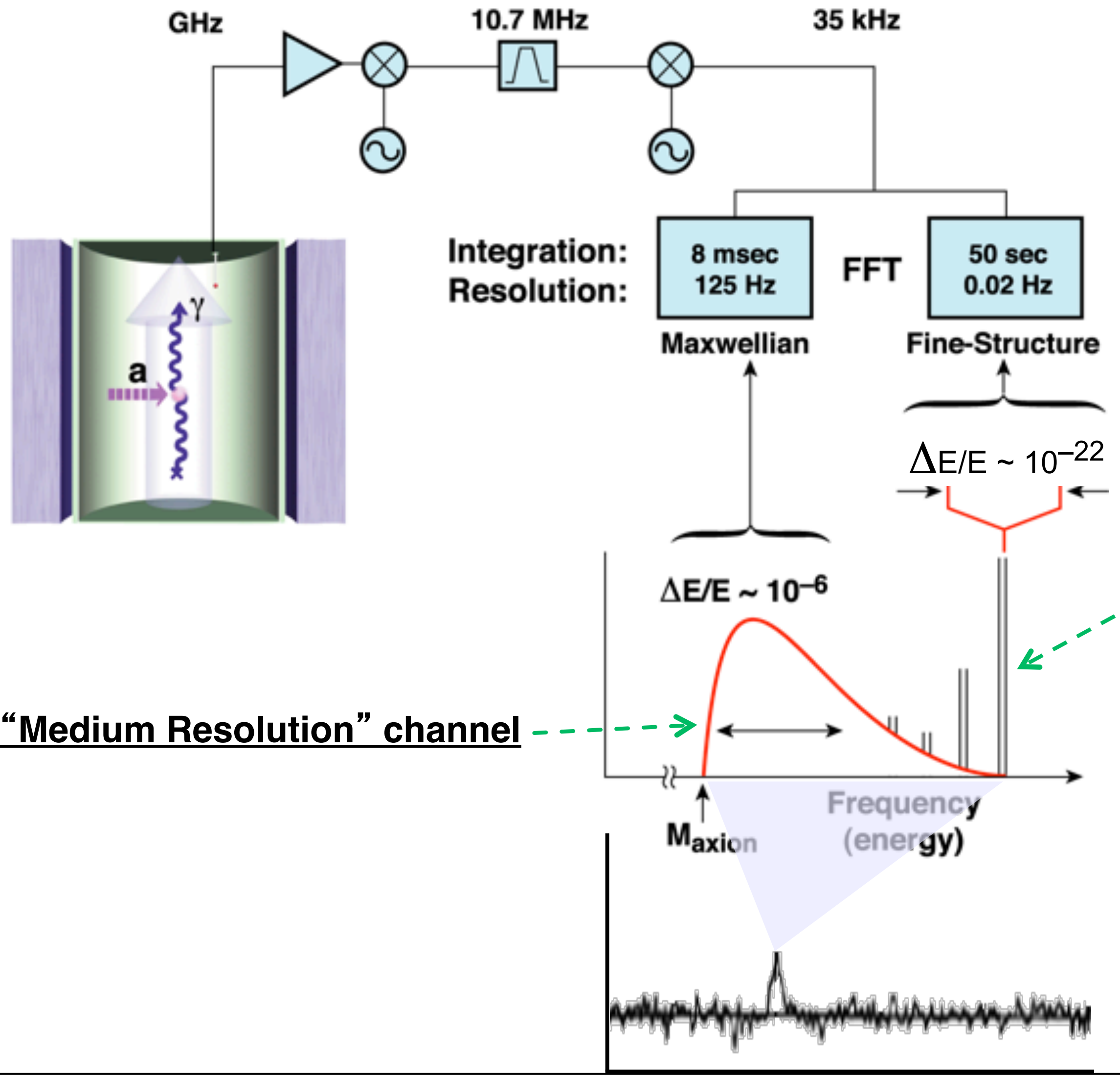
The ADMX experimental layout



“Medium Resolution” channel

“High Resolution” channel

Local Milky Way density:

ρ_{halo} ~ *450 MeV/cm³*

Thus for $m_a \sim 10\ \mu eV$:

$\rho_{halo} \sim 10^{14}\ cm^{-3}$

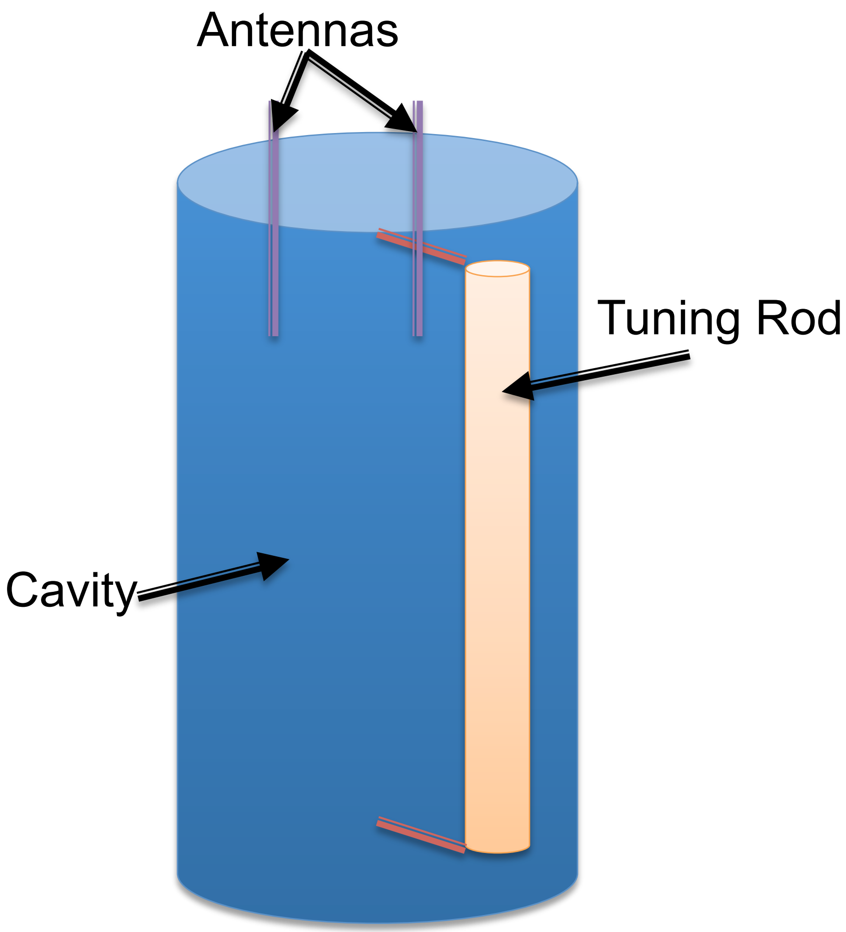
$\beta_{virial} \sim 10^{-3}$:

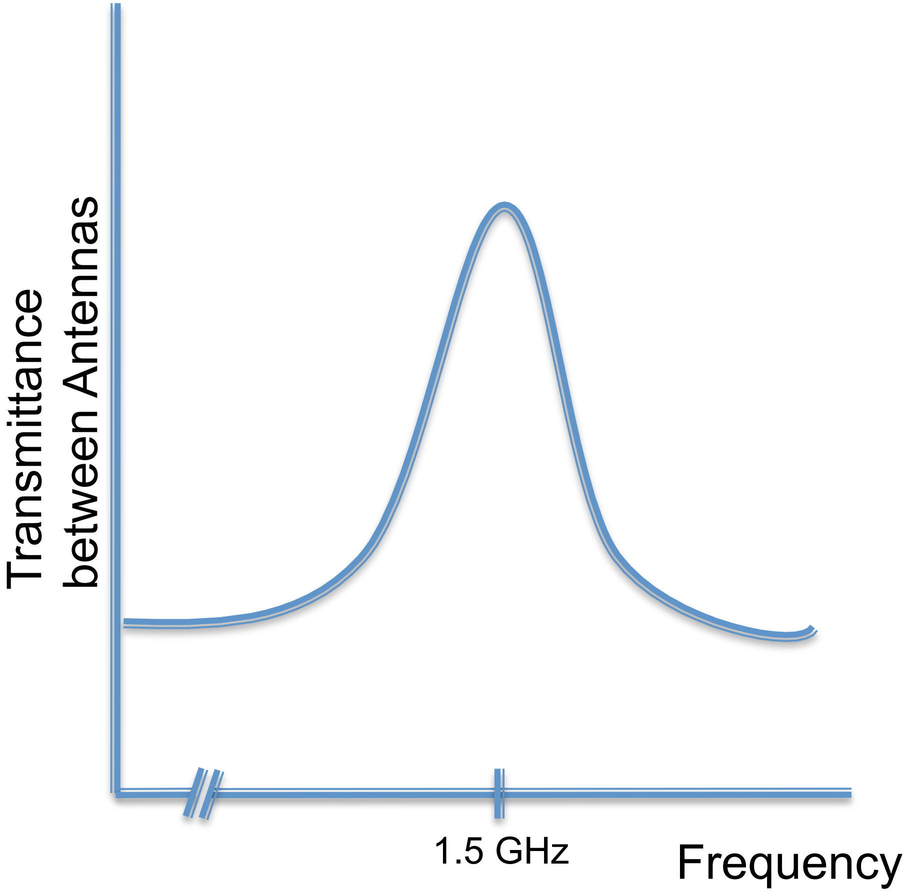
$\lambda_{De\ Broglie} \sim 100\ m$

$\Delta\beta_{flow} \sim 10^{-11}$:

$\lambda_{Coherence} \sim 1000\ km$

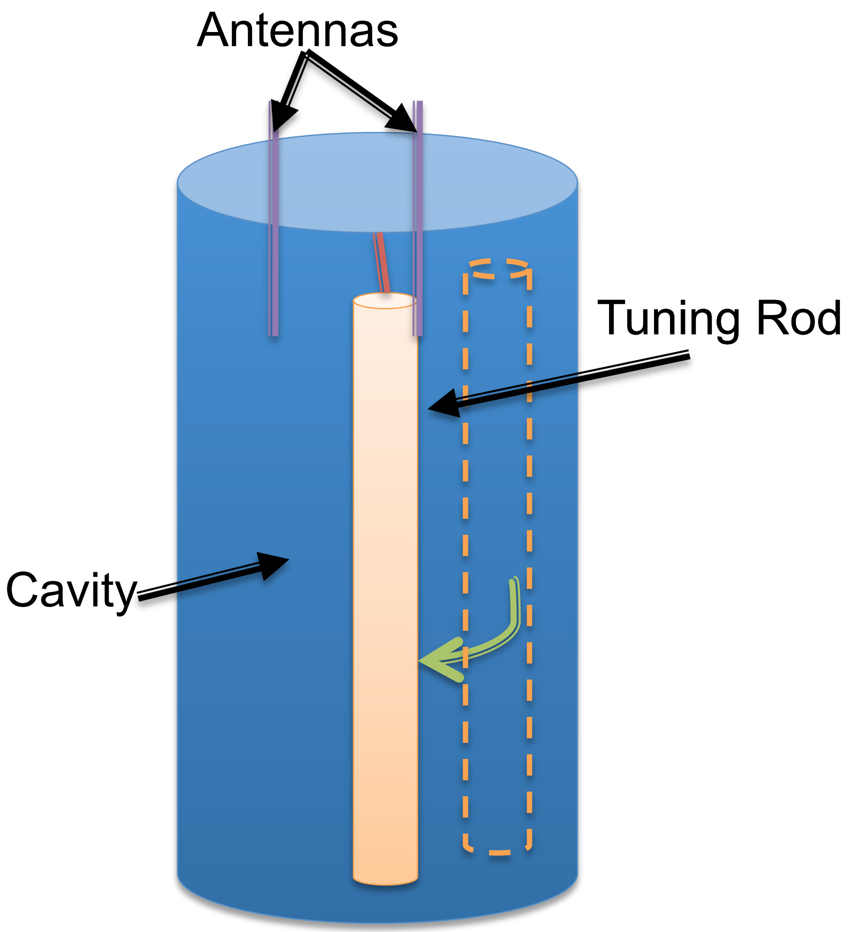
Microwave Cavity needs tunable resonance

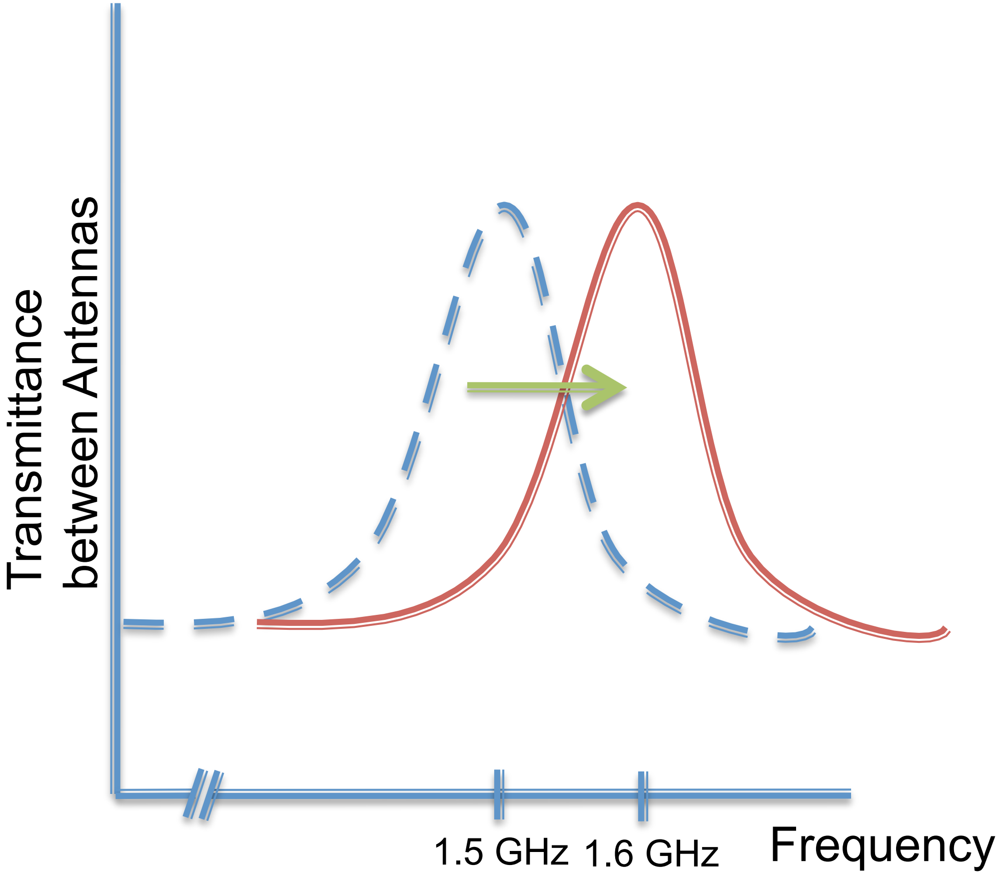




* LLNL sponsored HMC Clinic Final Presentation – 2010

Microwave Cavity needs tunable resonance





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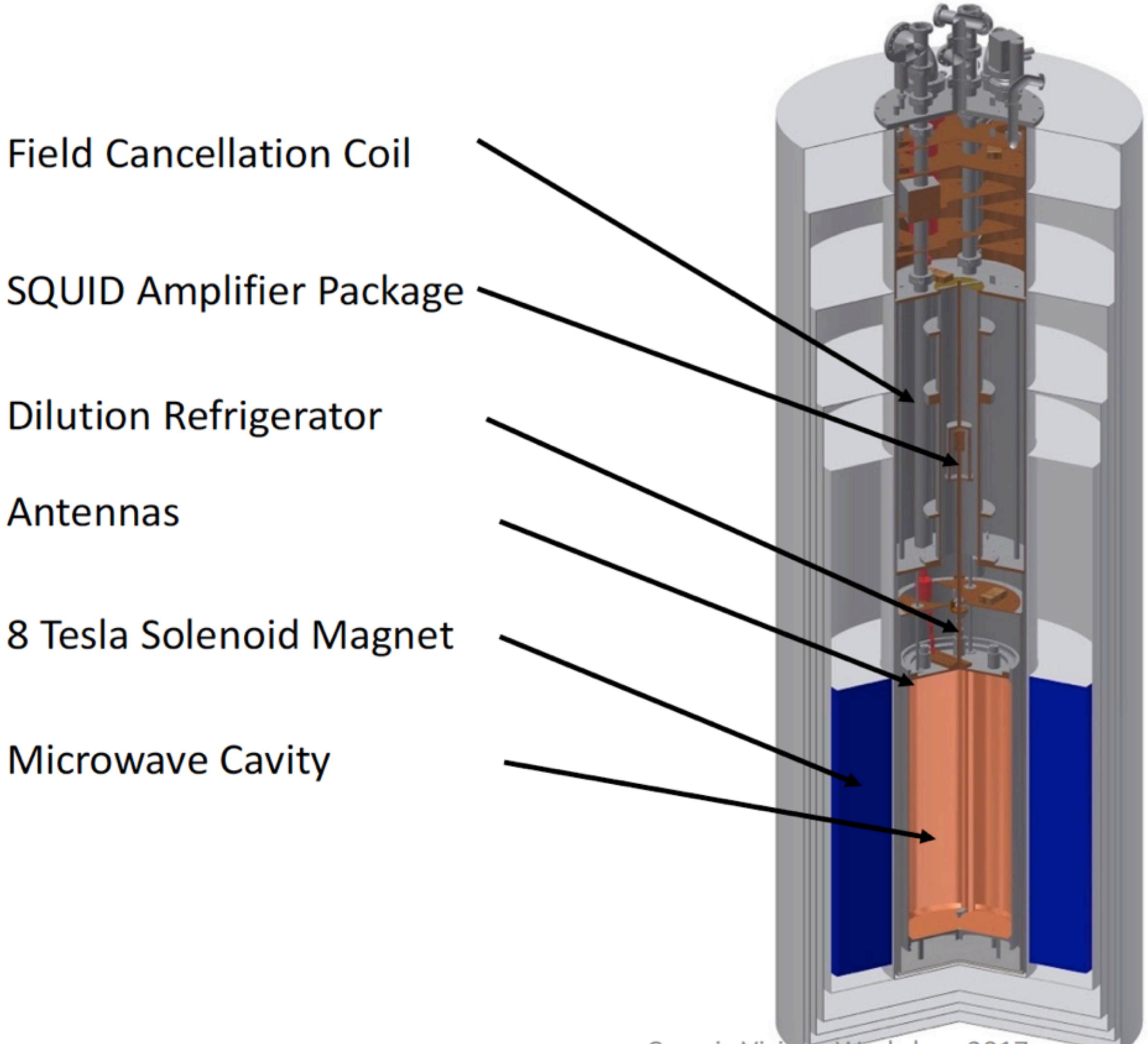
ADMX experimental layout



Field Cancellation Coil

SQUID Amplifier Package

Dilution Refrigerator

Antennas

8 Tesla Solenoid Magnet

Microwave Cavity

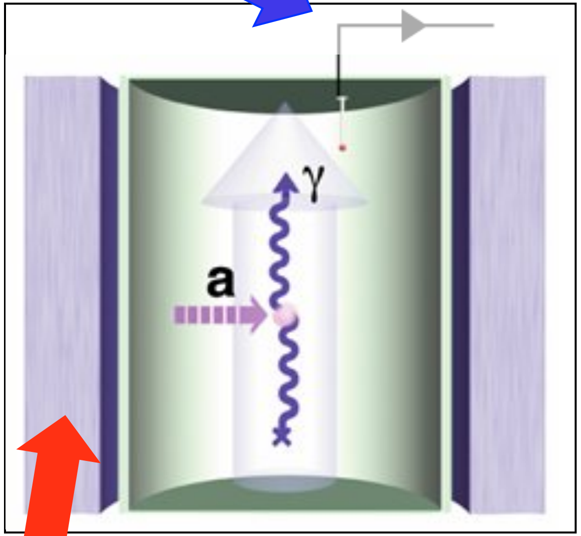
Cosmic Visions Workshop 2017

The Radiometer equation dictates strategy

$$\frac{s}{n} = \frac{P_{sig}}{kT_S} \cdot \sqrt{\frac{t}{\Delta\nu}}$$

Integration time limited to ~ 100 sec

** Dicke, 1946*



System noise temp.

$$T_S = T_{phys} + T_N$$

T_{Quant} ~ 48 mK @ 1 GHz

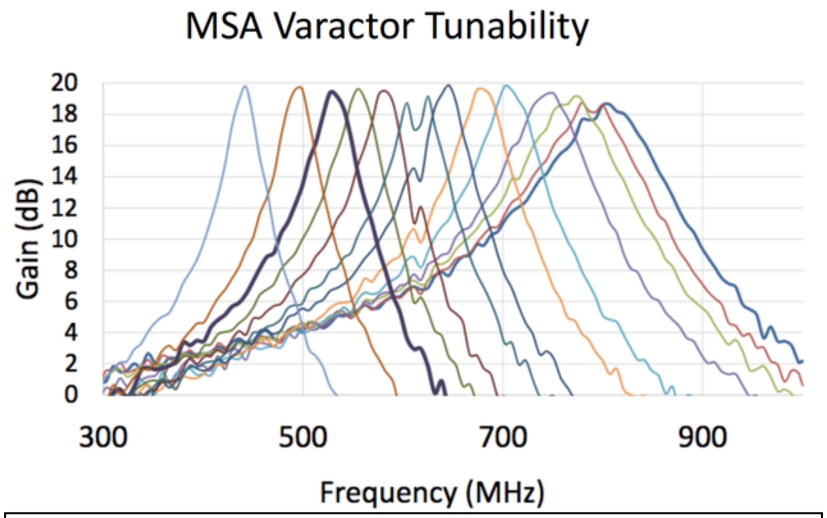
Gen2: Dilution Fridge + Quantum-limited amps

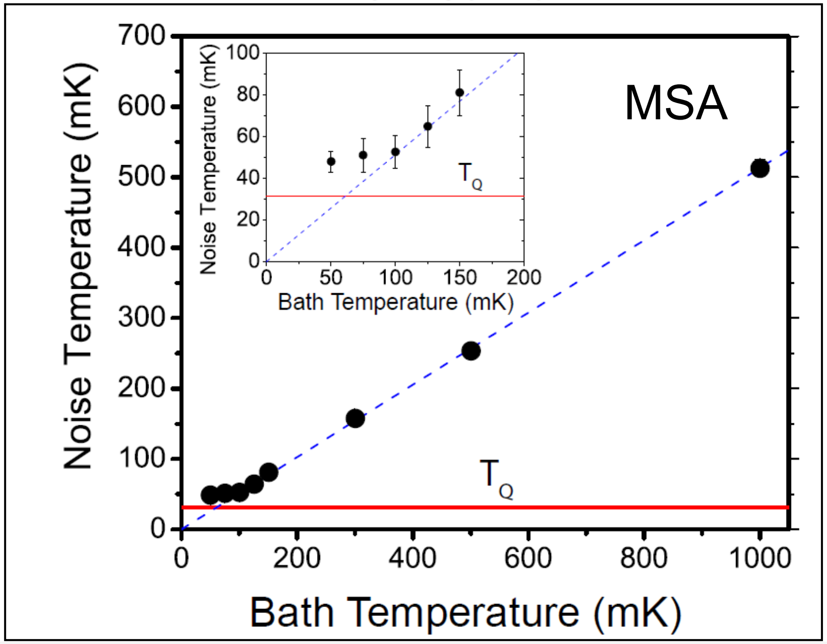
$$P_{sig} \sim (B^2V\,Q_{cav}C_{010})(g^2 m_a \rho_a)$$

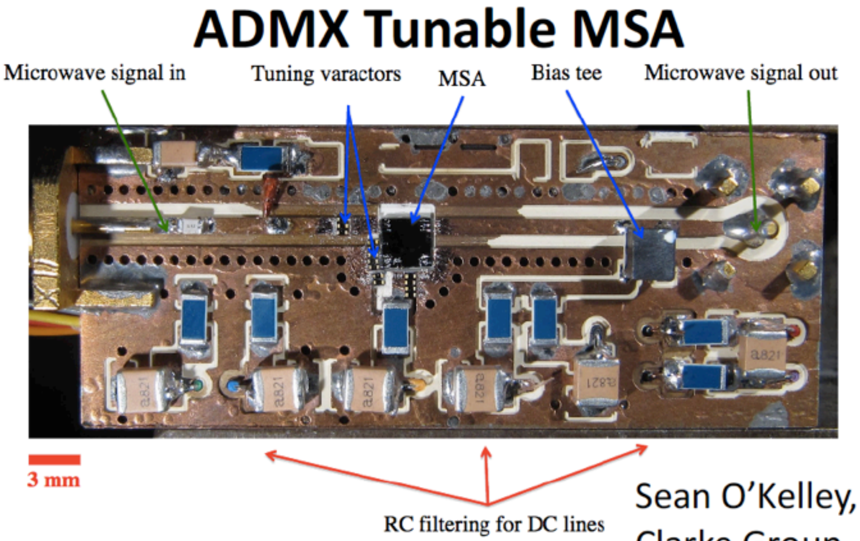
$$\sim 10^{-23}\ \text{Watts for ADMX}$$

Magnet size, strength B^2V ~ \$

Quantum-limited amplifiers







Sean O'Kelley, Clarke Group, UC Berkeley

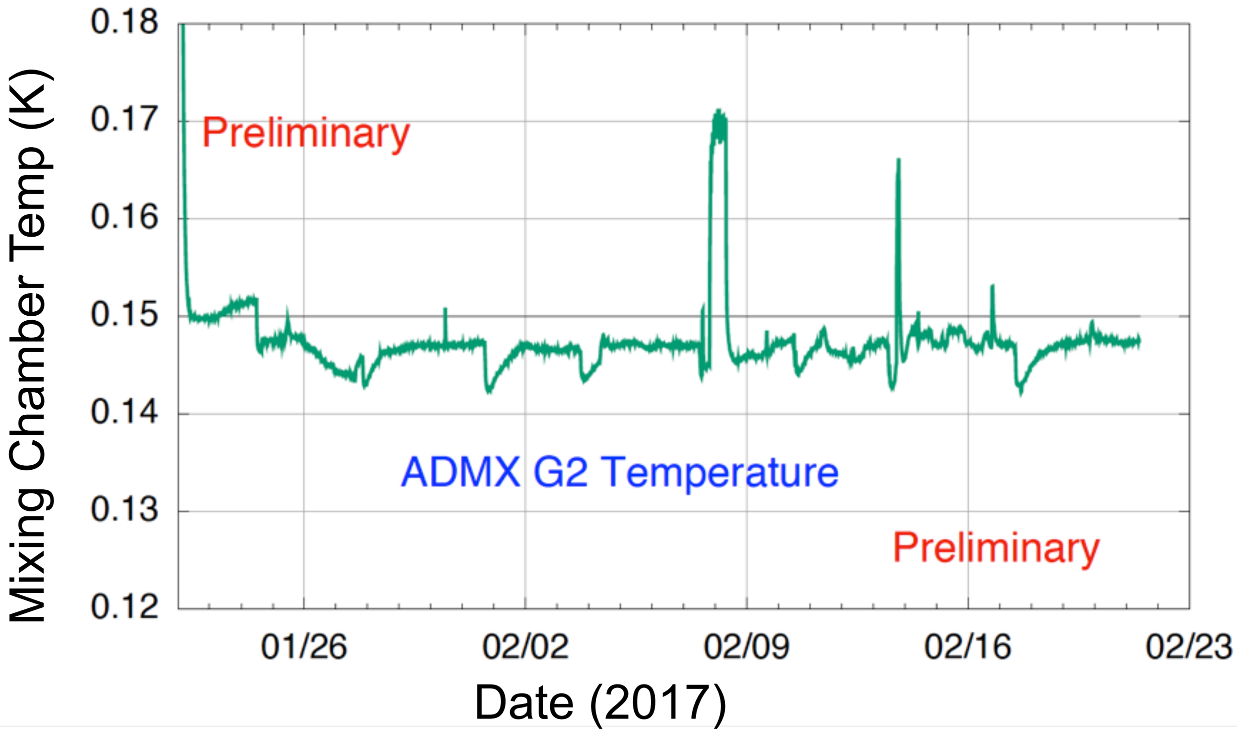
< 1 GHz

Yanjie Qiu, Siddiqi Group, UC Berkeley

> 1 GHz

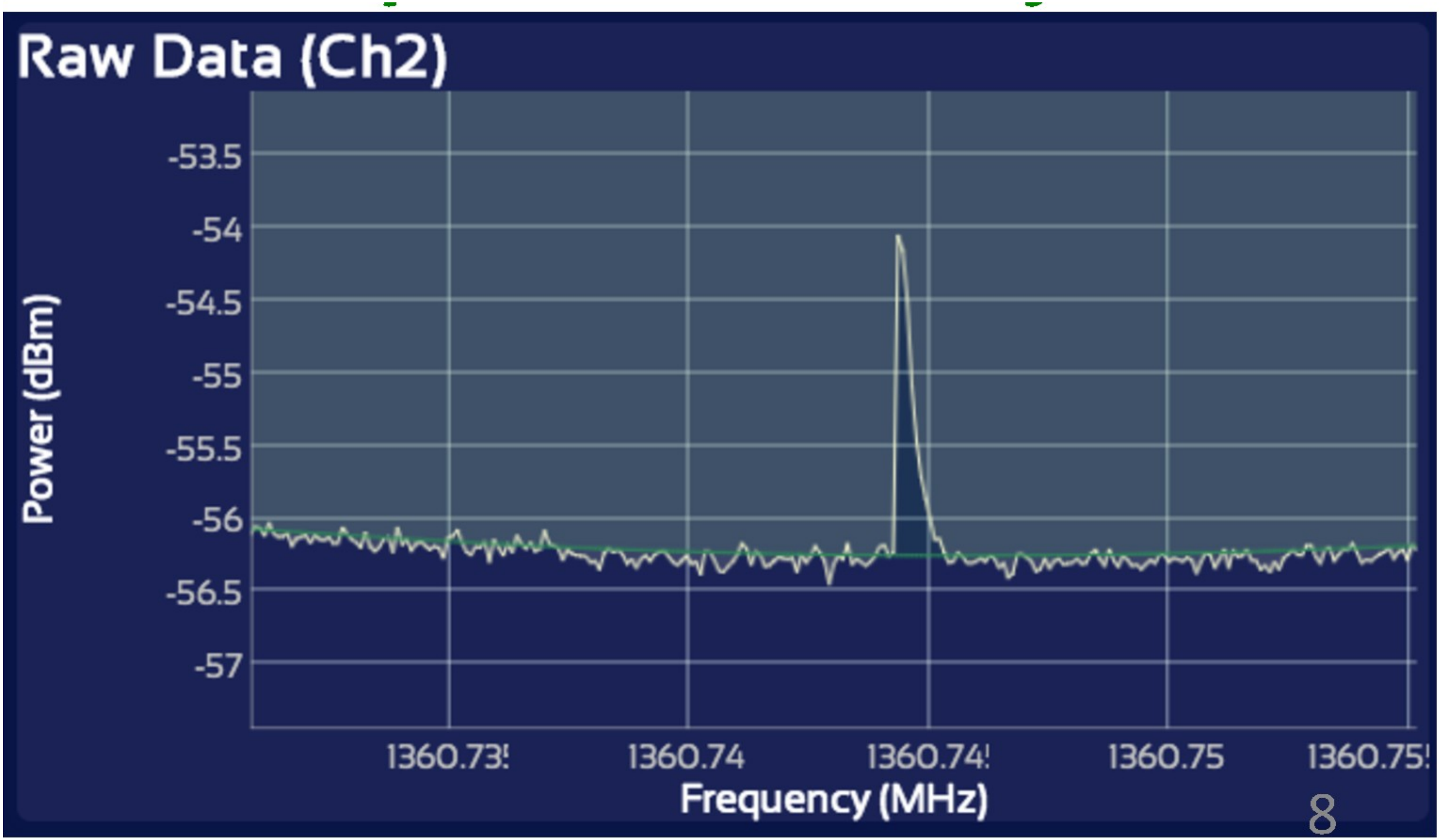
ADMX recently operations

- **Initial commissioning run Aug 9th – Oct 3rd, 2016 (T_{phys} ~ 200 mK and B ~ 2 T)**
- **Oct – Dec, 2016**
  - Upgrades to RF chain and heat sinking
- **First science data run: January - June, 2017**



Raw data and hardware synthetic axion

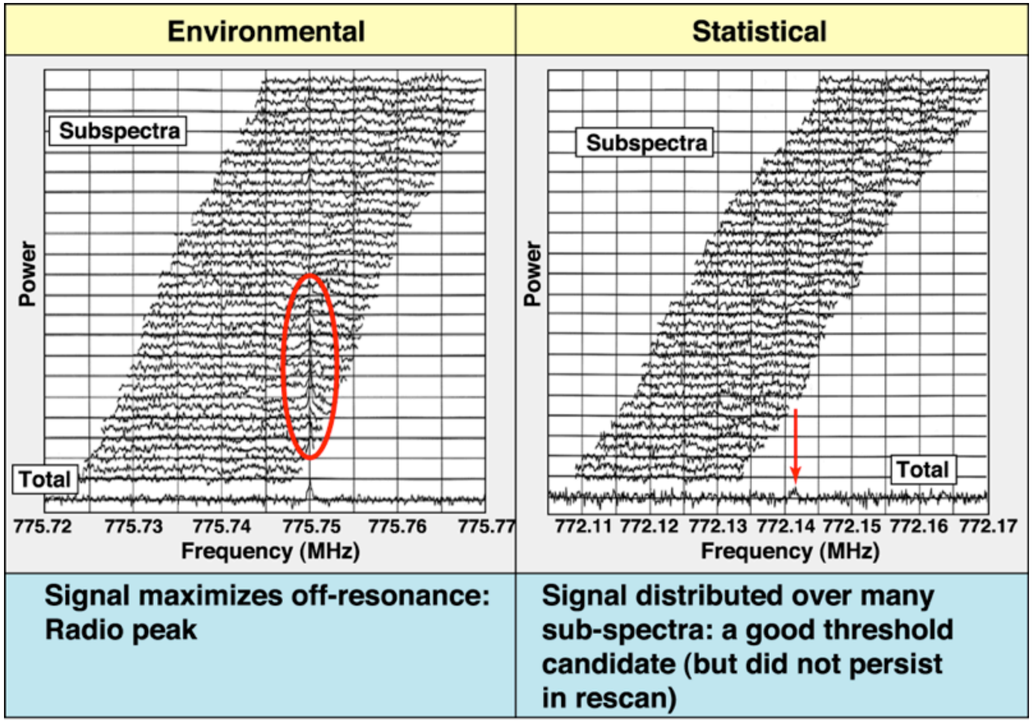
Able to inject custom line-shape through weak port (blinded)



ADMX operations

Live Analysis

1. Cavity frequency scanned until a desired signal-to-noise level is reached.
2. Regions with power above trigger threshold are flagged as potential candidates
   a. Statistical anomalies, external RF leakage, synthetic injected axions, or AXIONS
3. Rescan candidates; do they persist.
4. If they persist they are transferred to the detection committee
   a. Several immediate checks…
   b. Switch to resonant mode that couple to axions (TEM mode).
   c. Turn B-Field down (power as B^2).



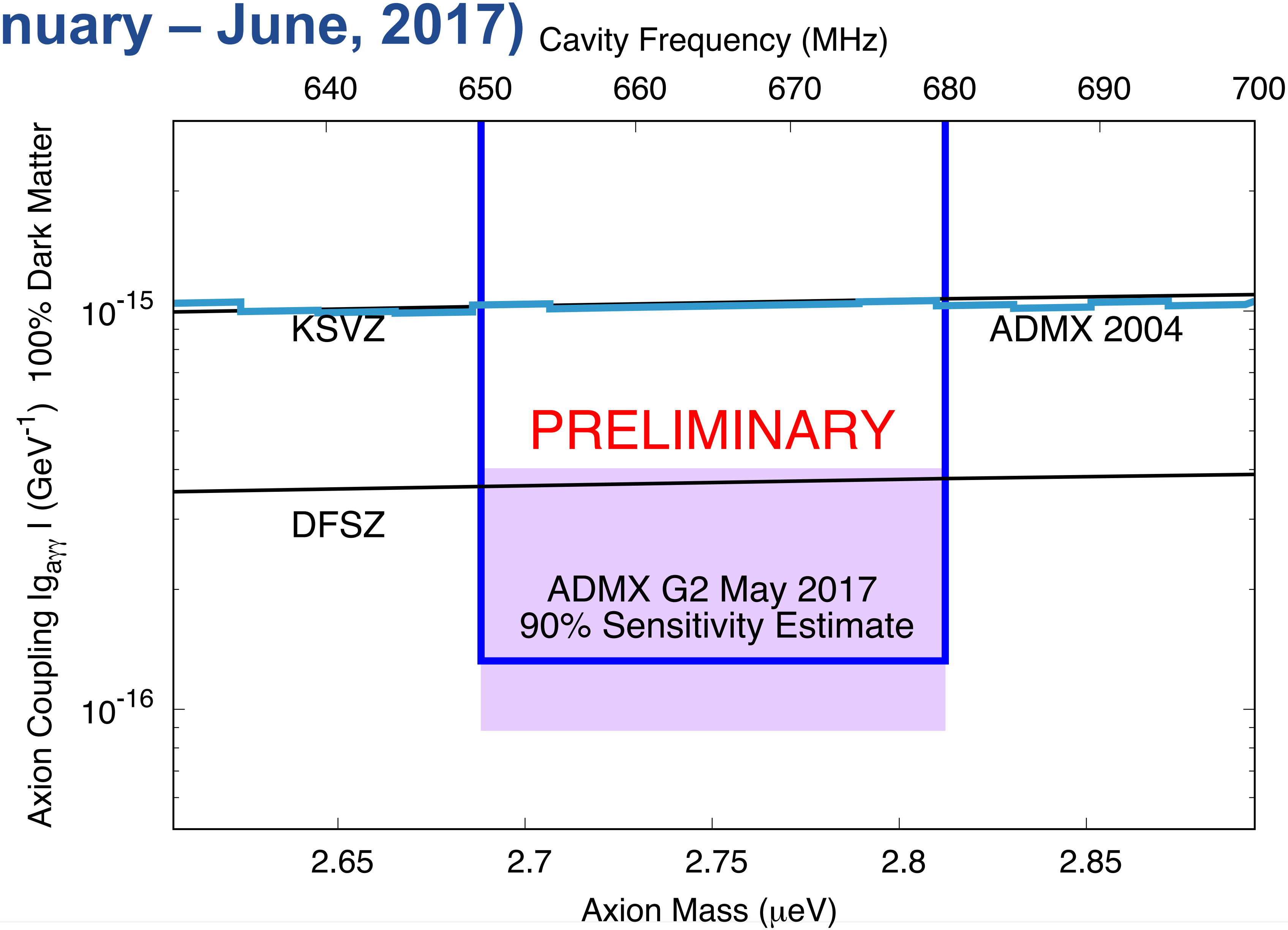
Signal maximizes off-resonance: Radio peak

Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)

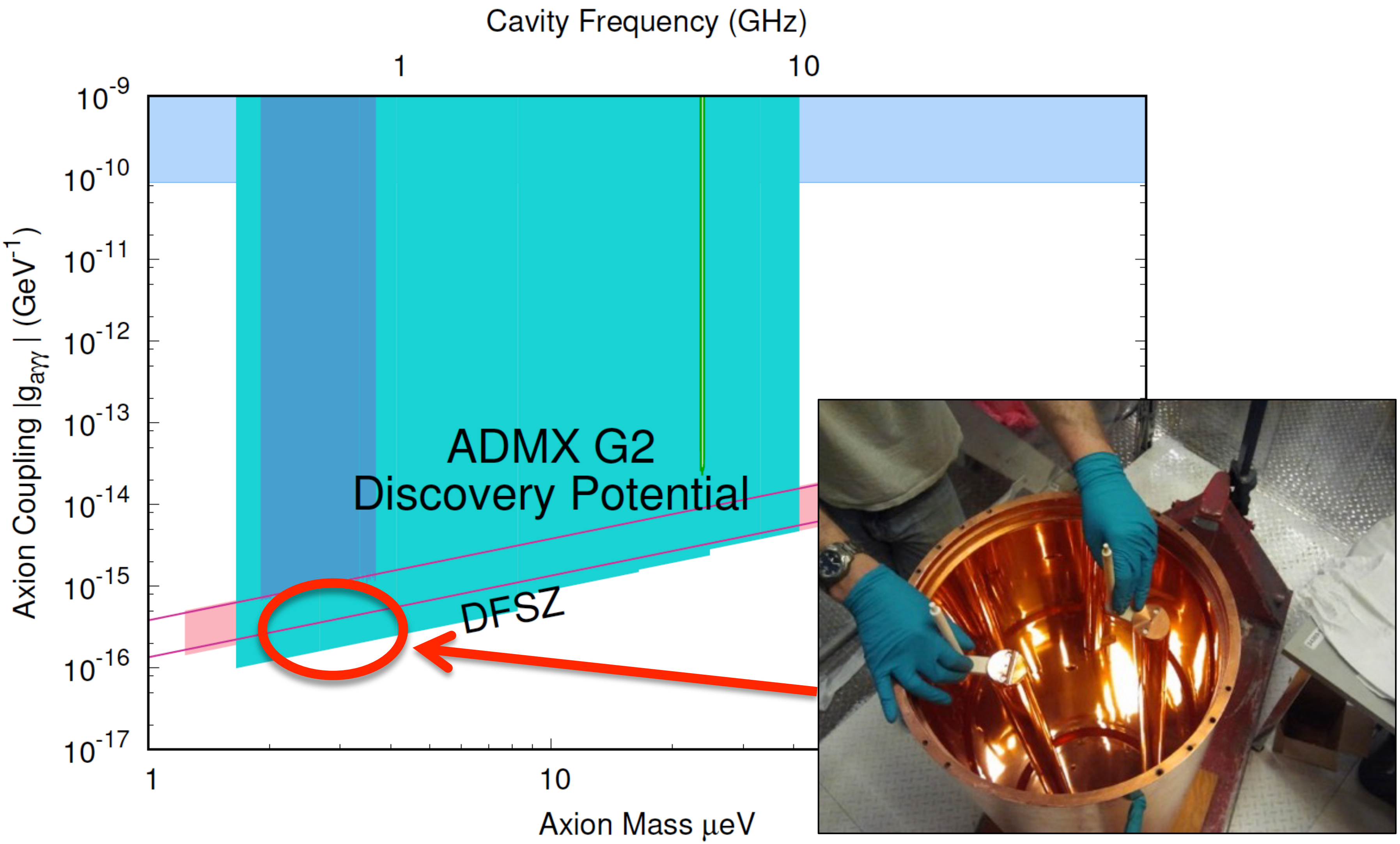
Further Offline Analysis

- Vary the bin size from time-series data.
- High Res analysis for ultra-sharp lines.

Sensitivity of recent data run (January – June, 2017)

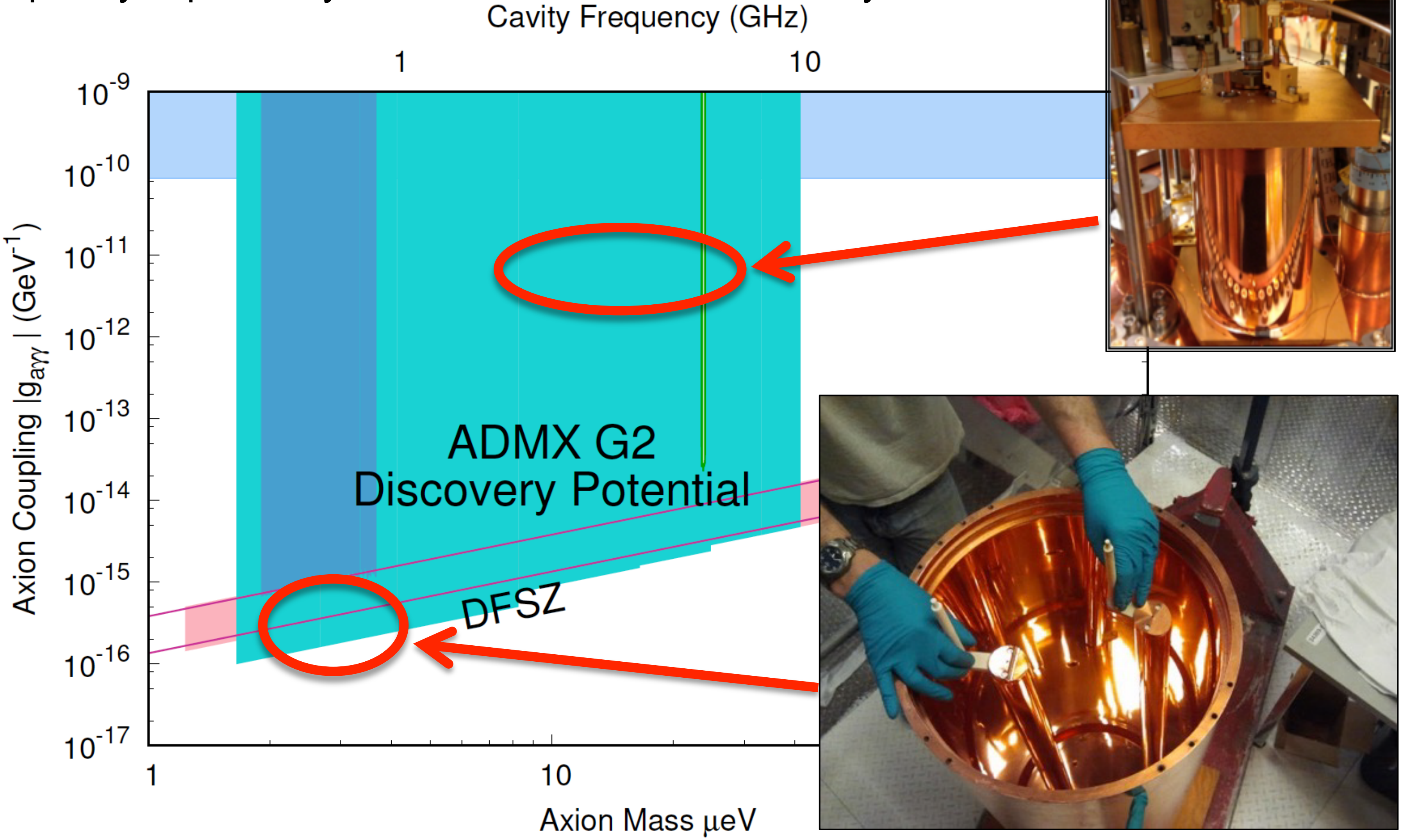


ADMX Main Cavity: Initial run 0.65-1 GHz



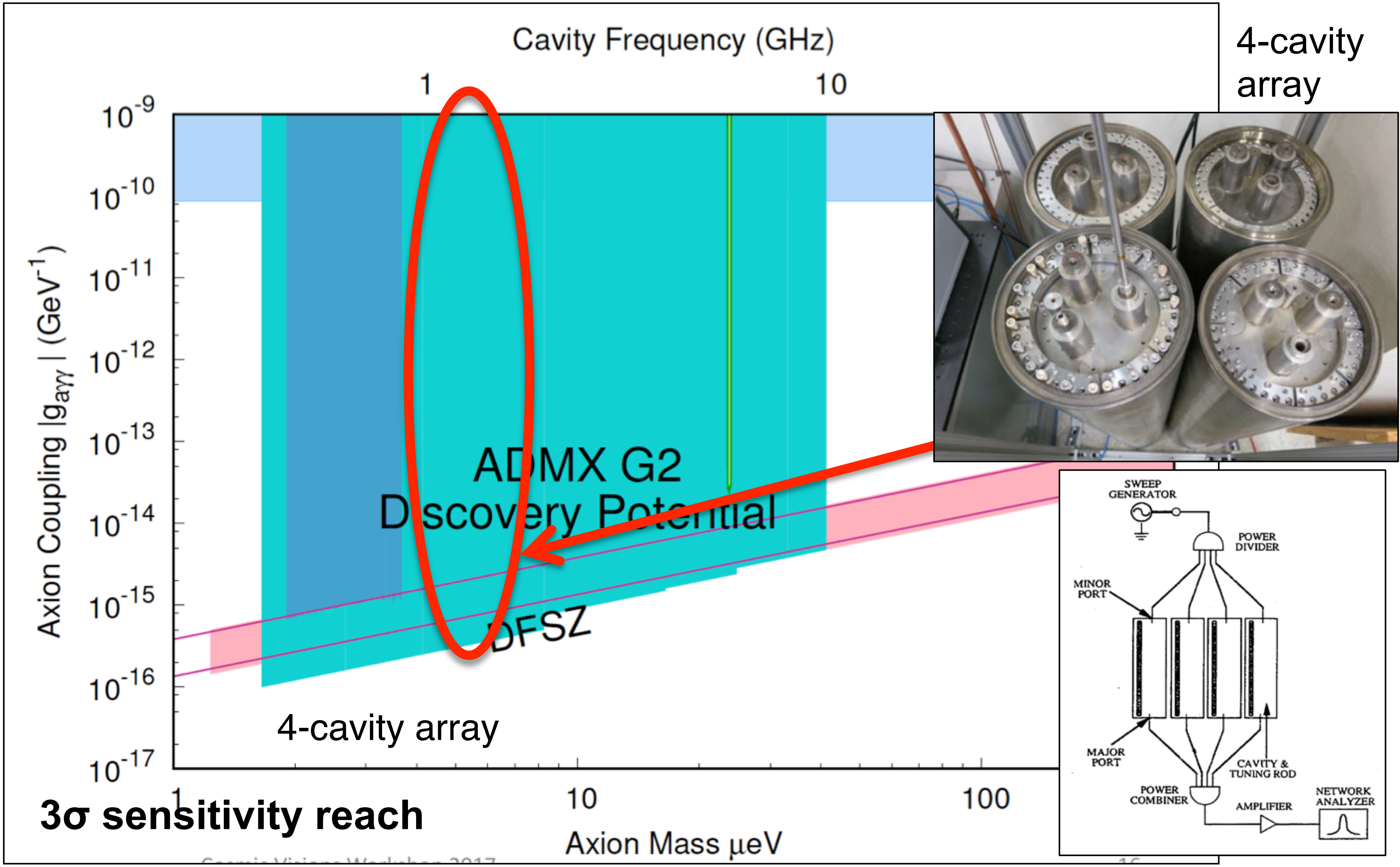
ADMX Sidecar Cavity
4-6 GHz TM_{010} & 6-7 GHz TM_{020}

Completely separate system installed above main cavity



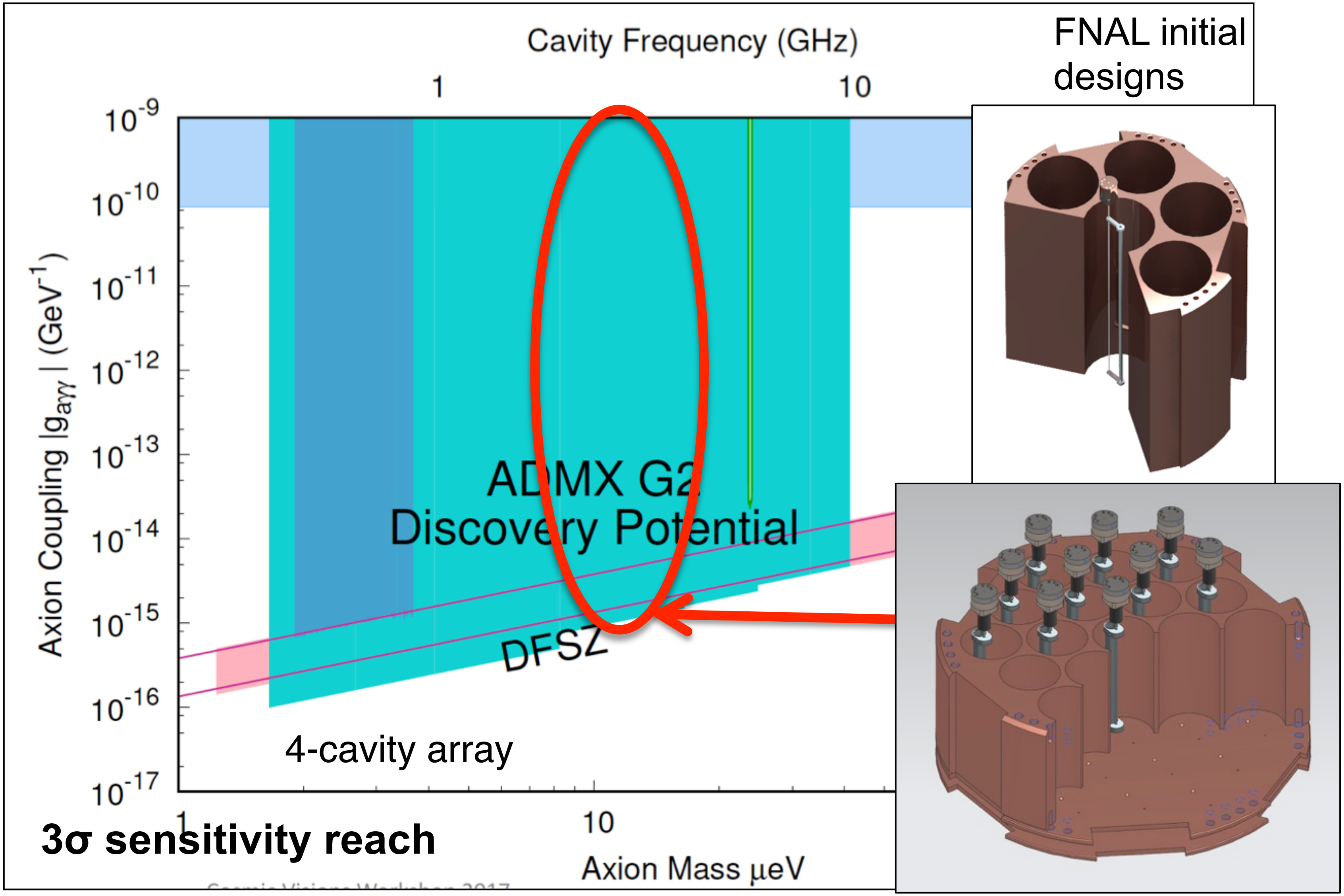
ADMX Science Prospects (1-2 GHz)

4-cavity array



3σ sensitivity reach

ADMX Science Prospects (2-6 GHz)



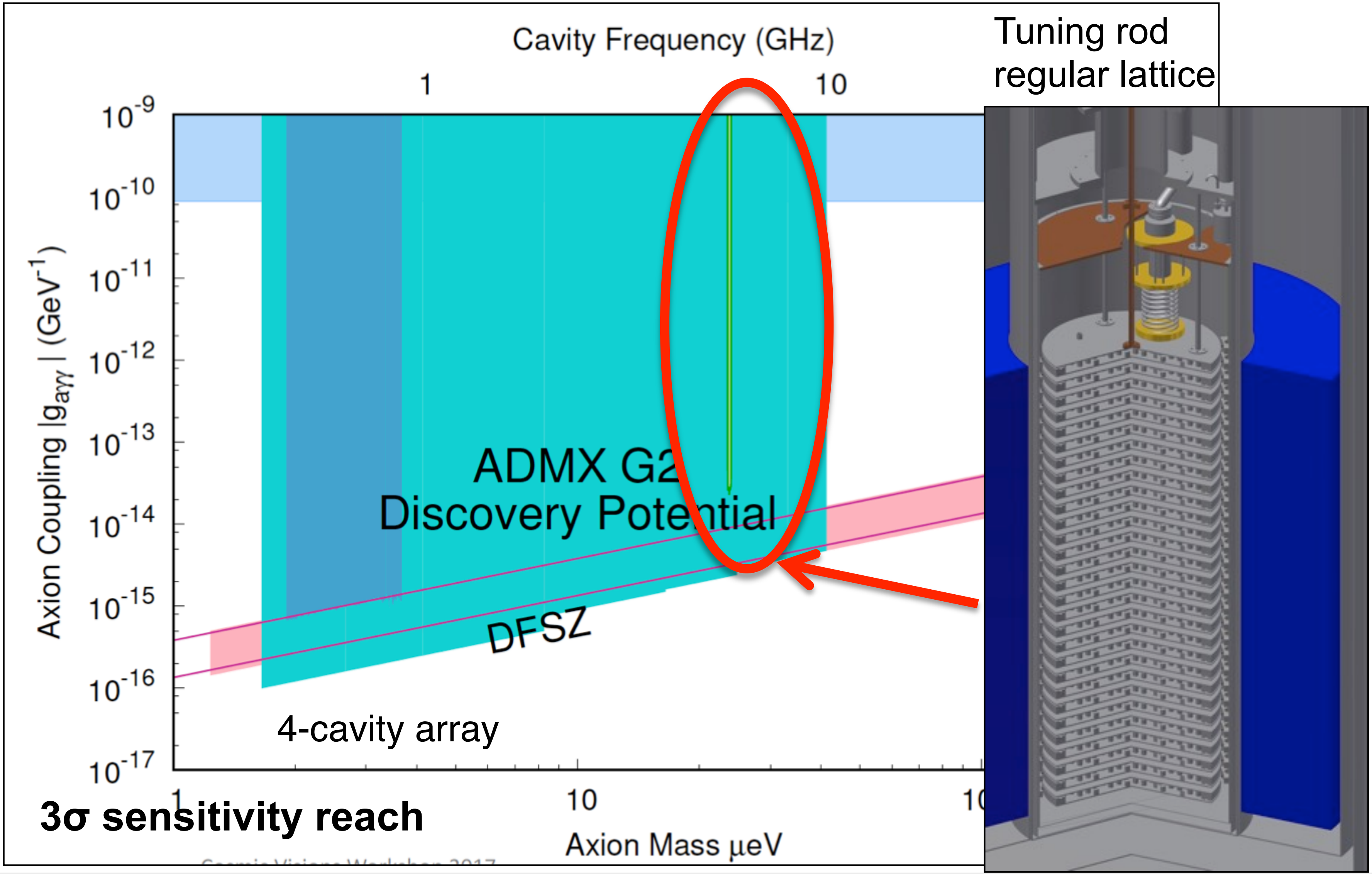
FNAL initial designs

4-cavity array

3σ sensitivity reach

Cosmic Visions Workshop 2017

ADMX Science Prospects (6-10 GHz)



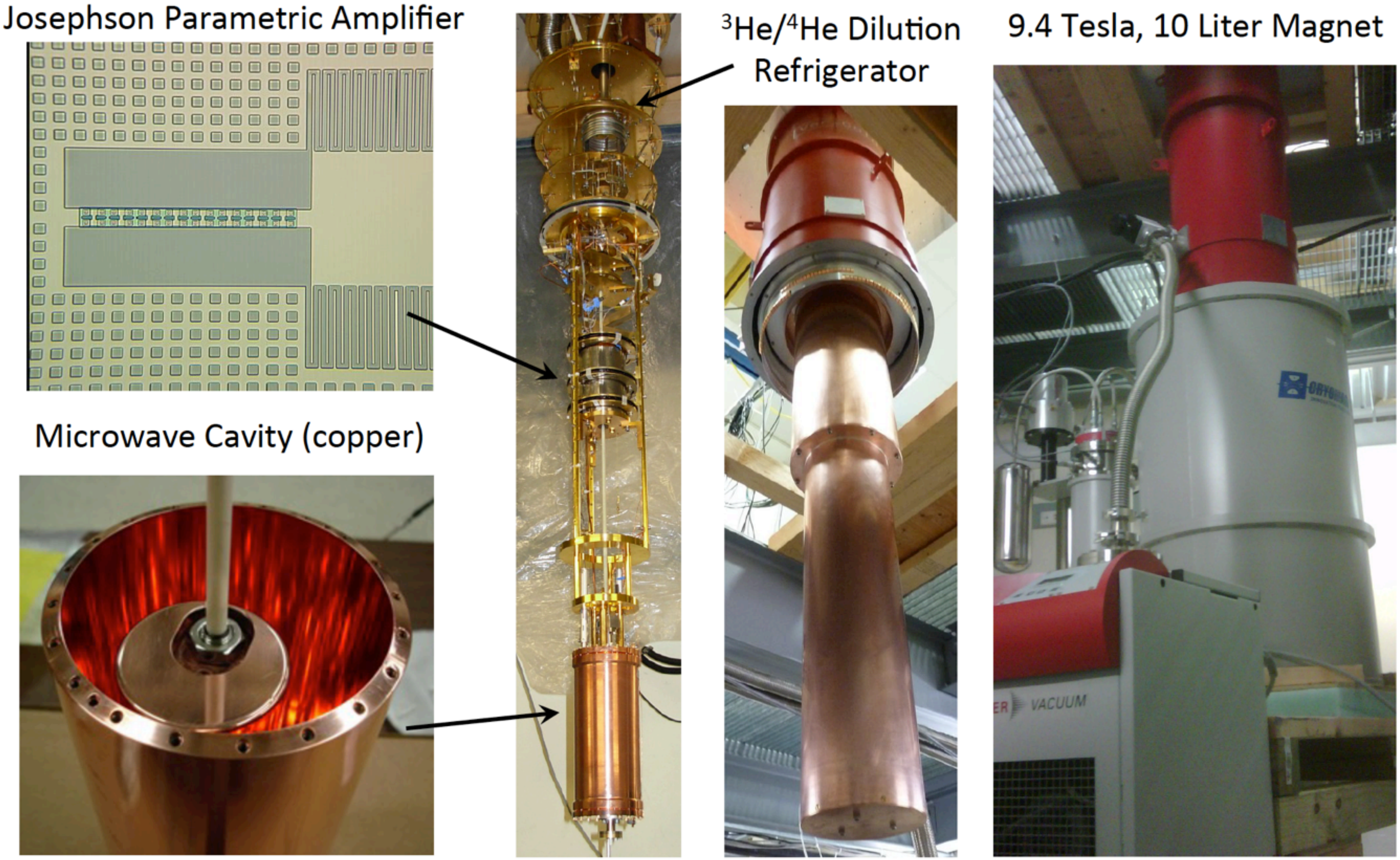
Tuning rod regular lattice

4-cavity array

3σ sensitivity reach

Cosmic Visions Workshop 2017

Other groups: HAYSTAC (formally ADMX-High Frequency)
9.4 Tesla magnet and 1.5 liter cavity at Yale U.



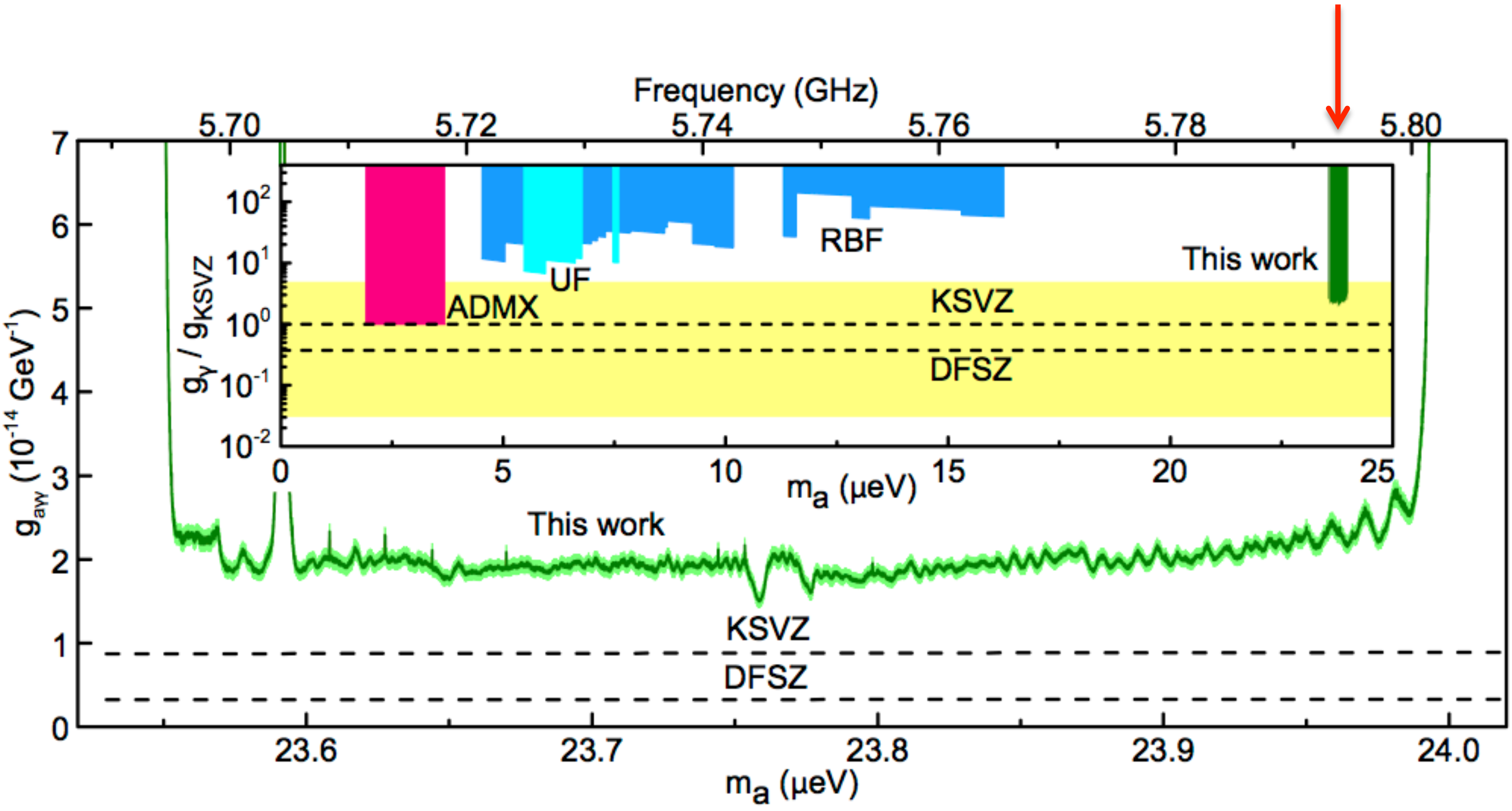
Josephson Parametric Amplifier

Microwave Cavity (copper)

^{3}He/^{4}He Dilution Refrigerator

9.4 Tesla, 10 Liter Magnet

HAYSTAC recent results



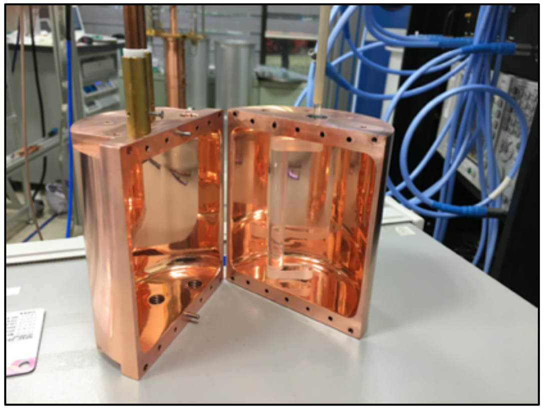
Results: B.M. Brubaker et al., Phys. Rev. Lett. 118 (2017) 061302.
Design details: S. Al Kenany et al., Nucl. Instrum. Methods A 854 (2017) 11-24.

Other Haloscopes coming online

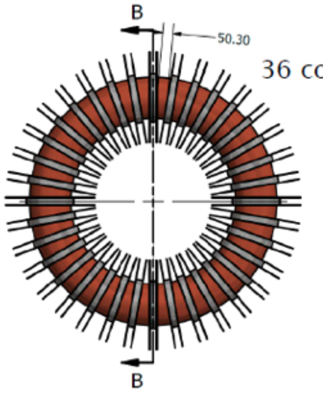
CAPP
Center for
Axion and Precision
Physics Research

Center for Axion and Precision Physics (CAPP) in South Korea

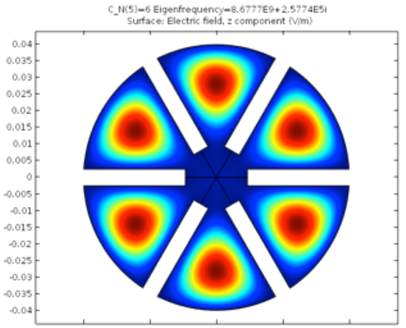
Bring online multiple experimental efforts over the next few years including microwave cavity searches (CULTASK, Toroid & multi-cell cavities)



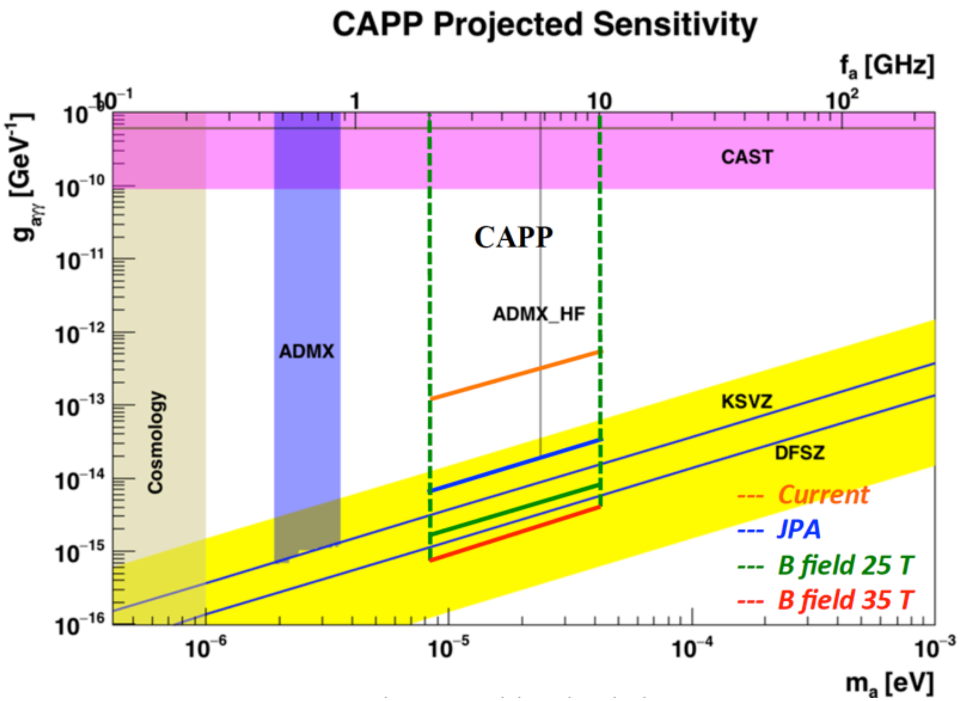
Prototype copper cavity



Toroid cavity



Multi-cell cavities

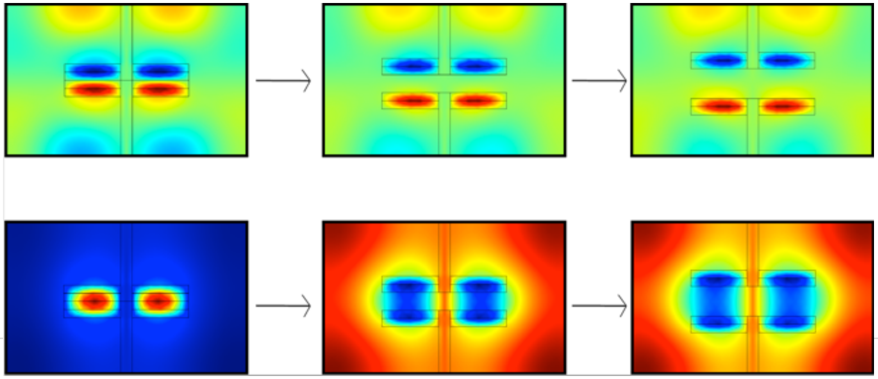


Figures from CAPP Patras 2017

Other Haloscopes coming online

ORGAN experiment

Oscillating Resonant Group AxioN Experiment
(U. of Western Australia)

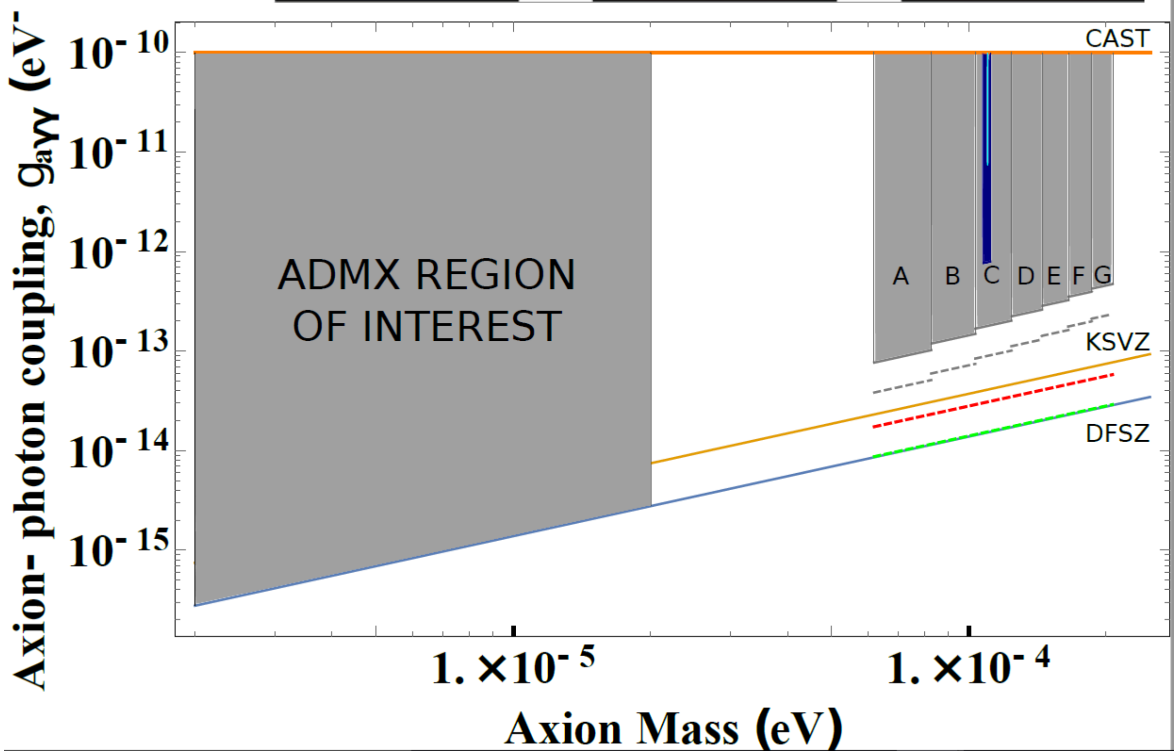


Exploring new cavity geometries and modes with sapphire disks.

Initial experiments aimed at 26-27 GHz.

Runs A→G are the 2018-2025 runs, with 14 T magnet and SQL Amps

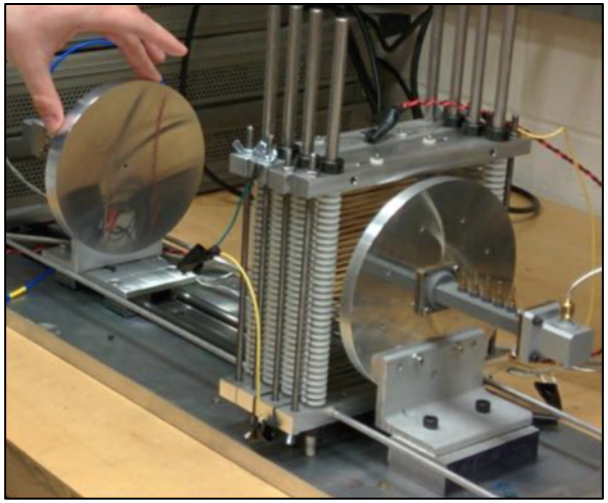
Dashed lines rely on success of squeezed state amplifiers and magnet upgraded to 28 T



Figures from CAPP Patras 2017

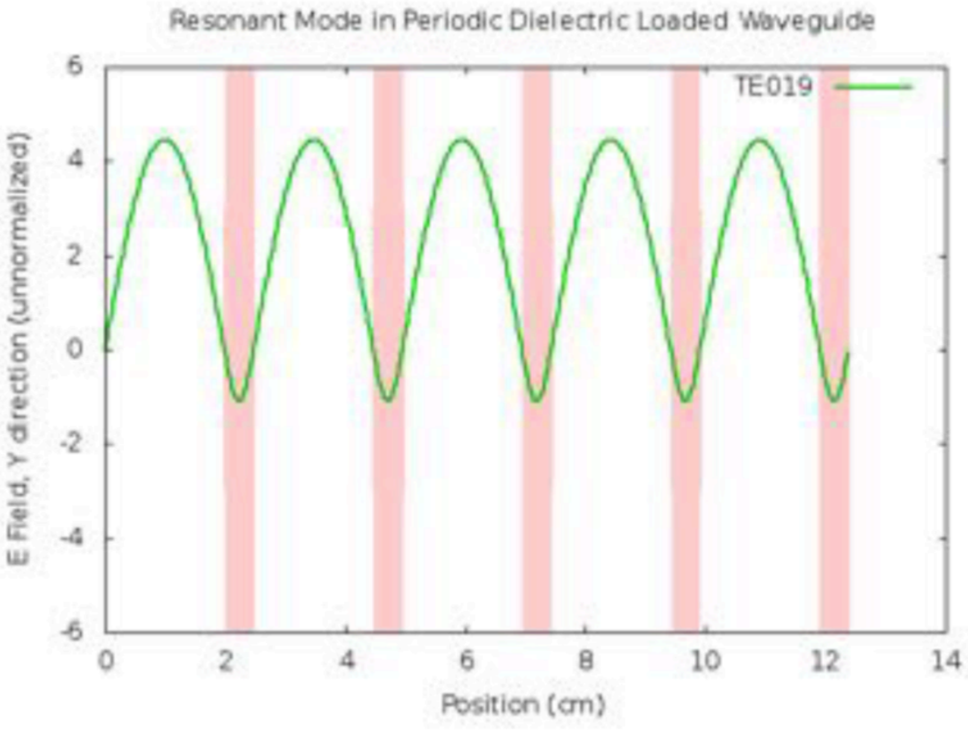
Open resonator design with dipole magnet

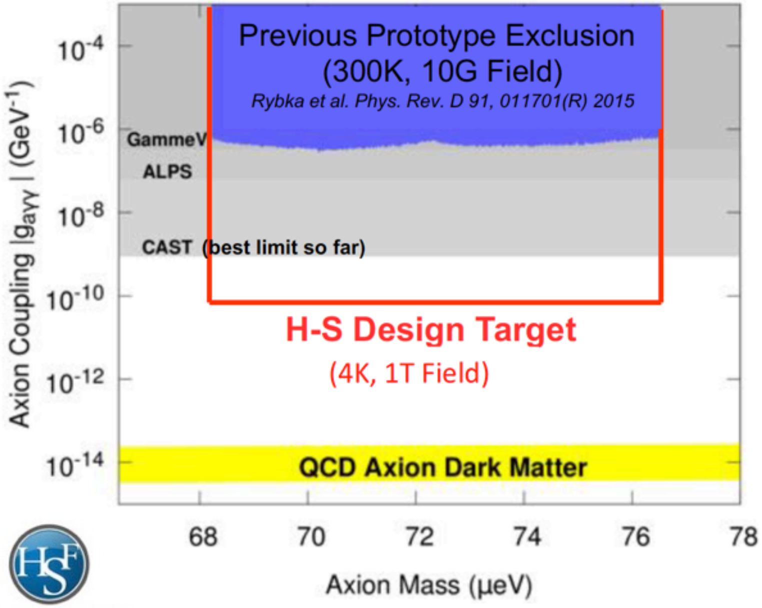
Orpheus Project (UW)



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.





HEISING - SIMONS
FOUNDATION

Open resonator design with dipole magnet

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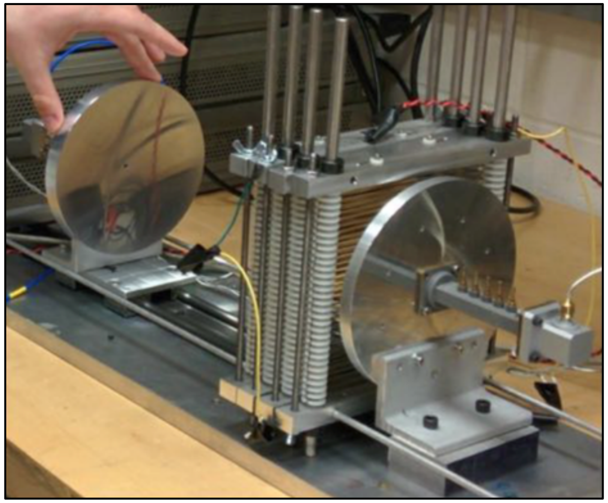
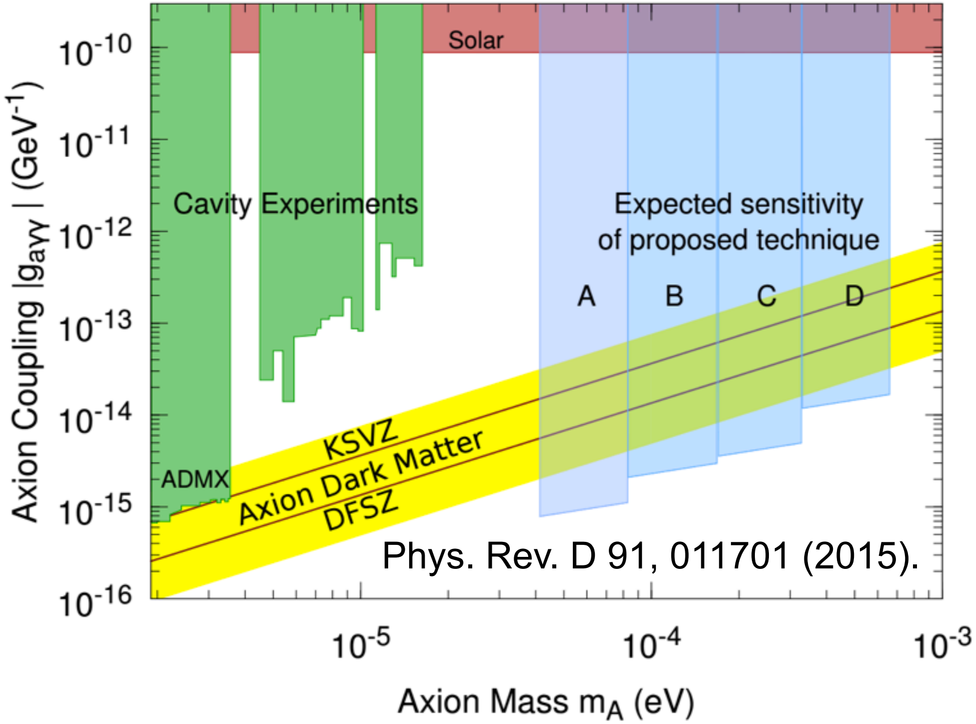
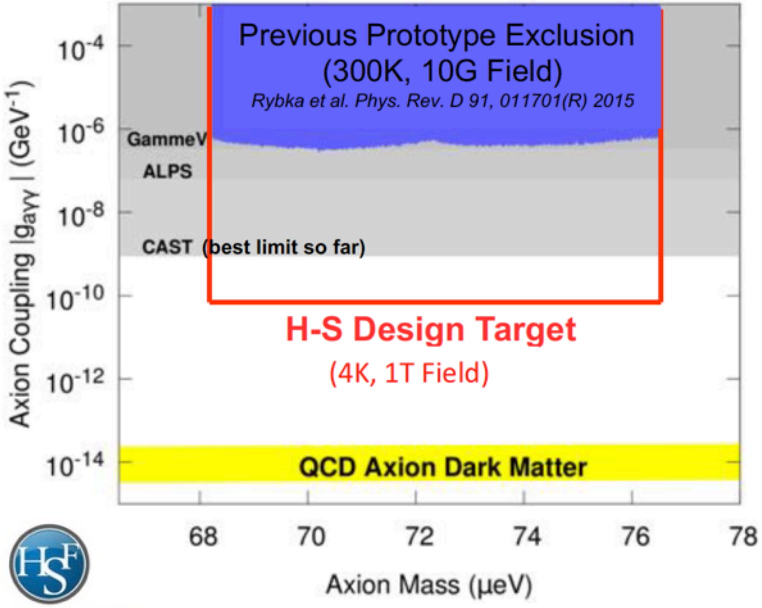


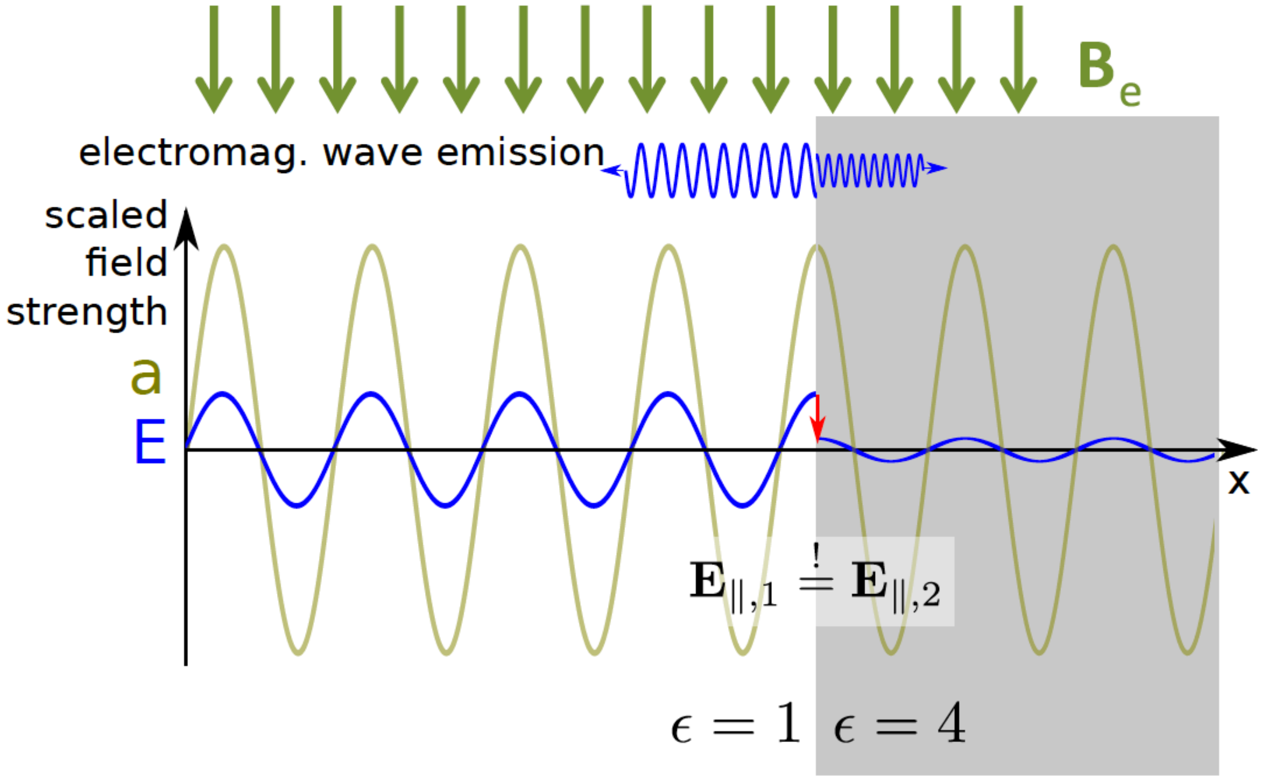


Phys. Rev. D 91, 011701 (2015).



HEISING - SIMONS FOUNDATION

Broadband design with dipole magnet: MADMAX



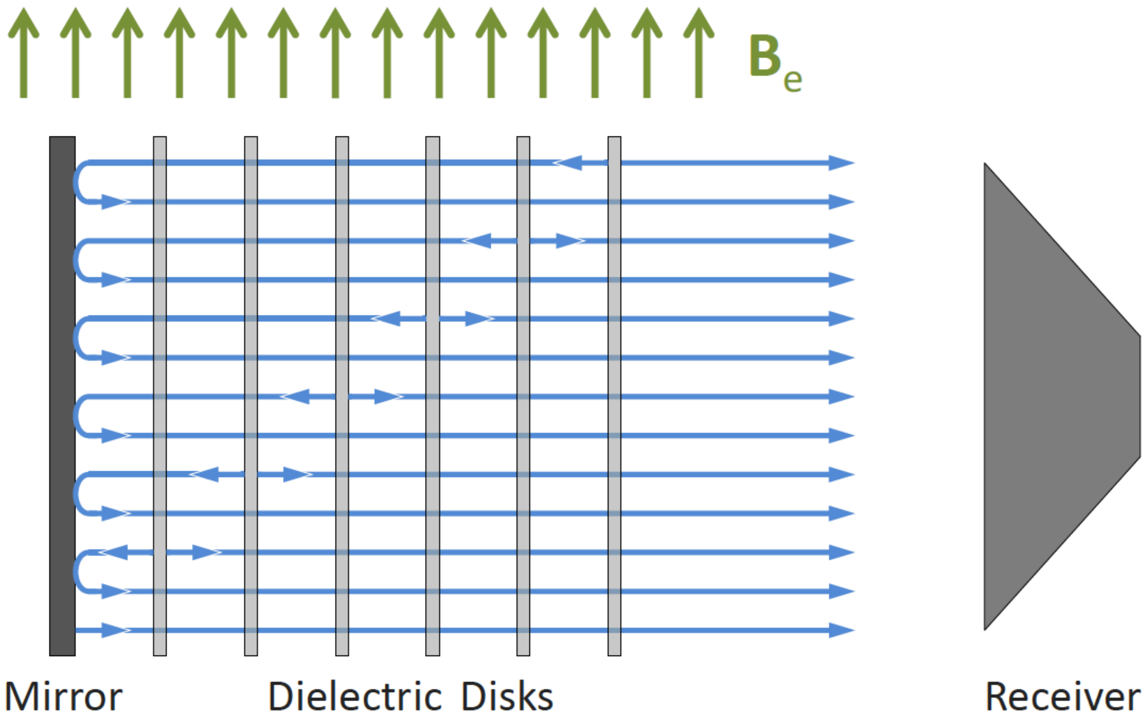
$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a$$

$$P/A = 2.2 \times 10^{-27}\,\mathrm{W\,m}^{-2}\left(\frac{B_e}{10\,\mathrm{T}}\right)C_{a\gamma}{}^2 \cdot f(\epsilon_1, \epsilon_2)$$

Slide from Stefan Knirck Patras 2017
PRL 118, 091801 (2017)

Broadband design with dipole magnet: MADMAX

- Multiple dielectrics can constructively interfere

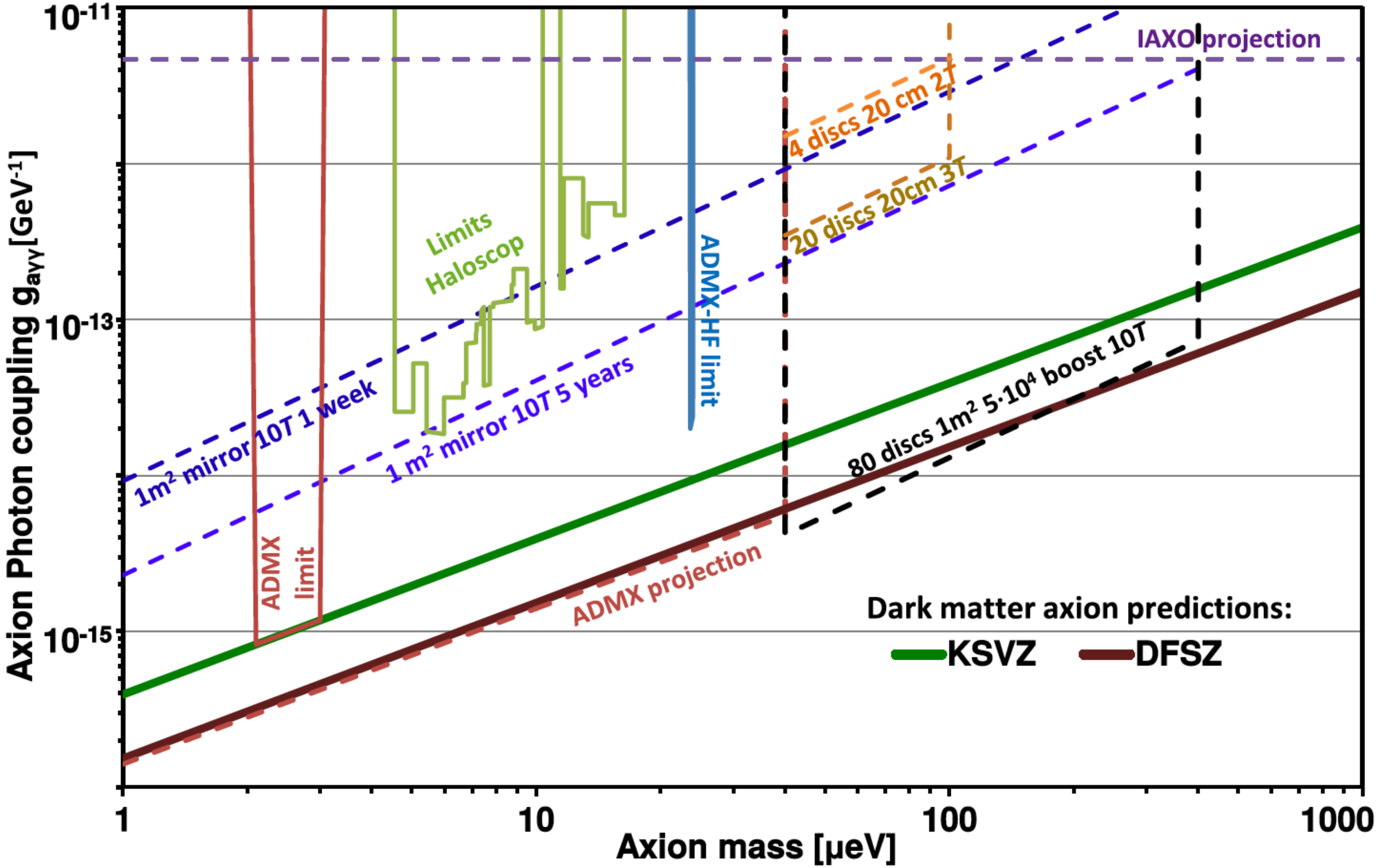


$$P/A = 2.2 \times 10^{-27}\,\mathrm{W\,m^{-2}} \left(\frac{B_e}{10\,\mathrm{T}}\right) C_{a\gamma}{}^2 \cdot \beta^2$$

β^2: power emitted by booster / power emitted by single mirror ($\epsilon = \infty$)

Slide from Stefan Knirck: Patras 2017
PRL 118, 091801 (2017)

MADMAX sensitivity projections



Bela Majorovit and Stefan Knirck gave more detailed talks yesterday (July 24th)

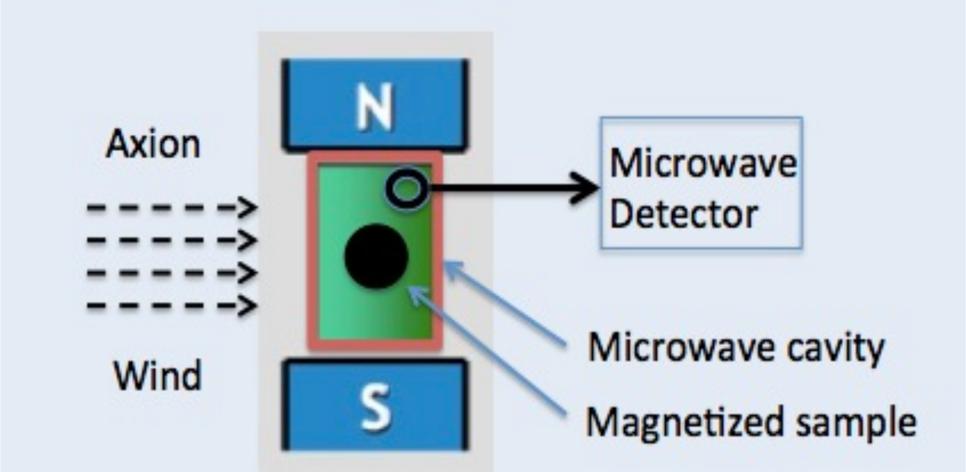
Slide from Stefan Knirck: Patras 2017

Alternative strategy for high mass axions

- **Look for an axion "wind"** which acts as an **effective RF magnetic field on electron spin** via **electron-axion coupling**

- This axion induced RF excites **magnetic transition in a magnetized sample** (Larmor frequency) and produces a detectable signal

- The **QUAX** (QUest for AXion) experiment



- R. Barbieri et al., *Searching for galactic axions through magnetized media: The QUAX proposal* Phys. Dark Univ. **15,** 135 - 141 (2017)

The effective magnetic field associated with the axion wind

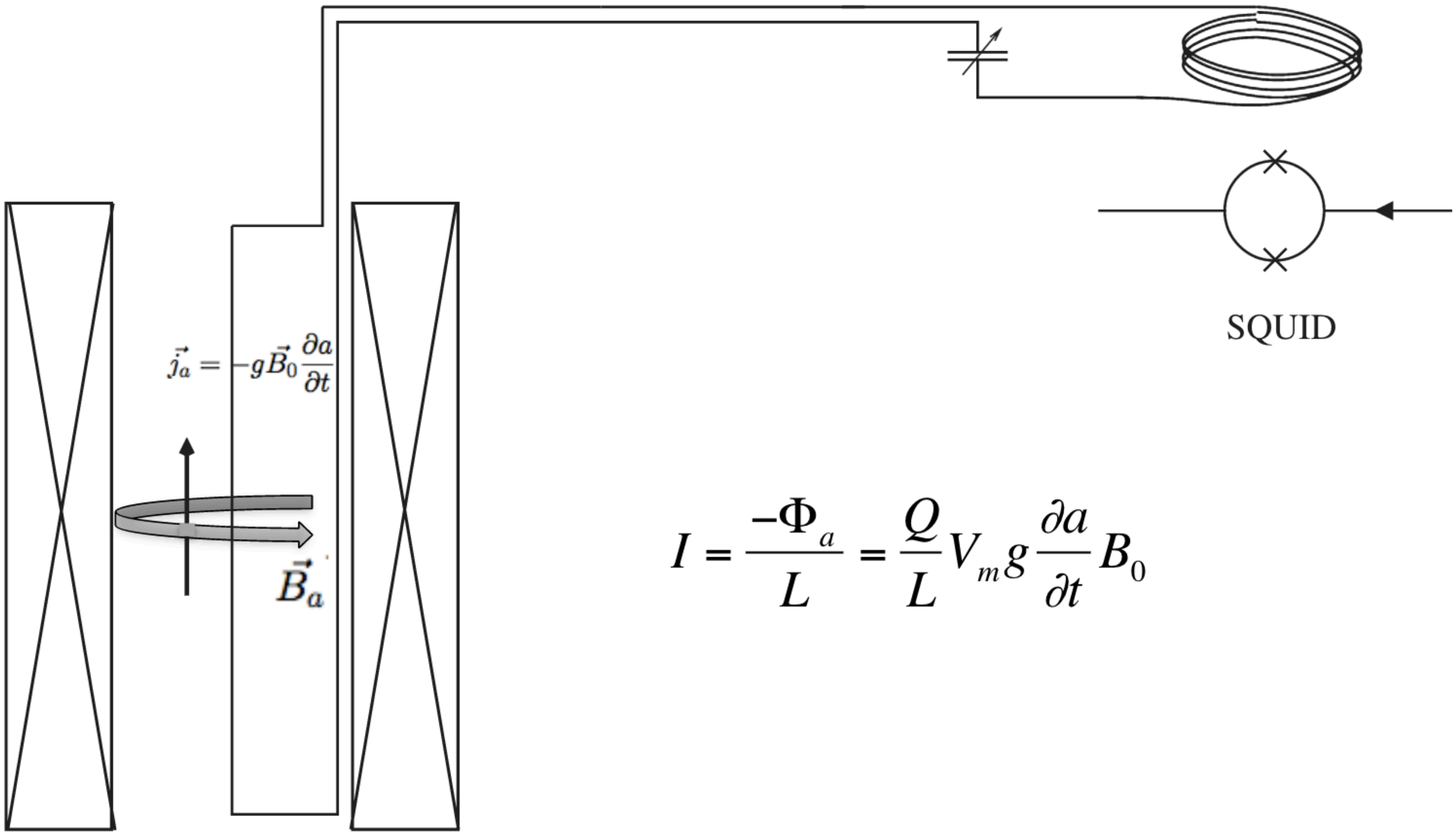
$$B_a = \frac{g_p}{2e}\left(\frac{n_a h}{m_a c}\right)^{1/2} m_a v_E$$

$$B_a = 2.0 \cdot 10^{-22} \left(\frac{m_a}{200\ \mu\text{eV}}\right) \quad \text{T},$$

$$\frac{\omega_a}{2\pi} = 48 \left(\frac{m_a}{200\ \mu\text{eV}}\right) \quad \text{GHz},$$

Slide from Giuseppe Ruoso

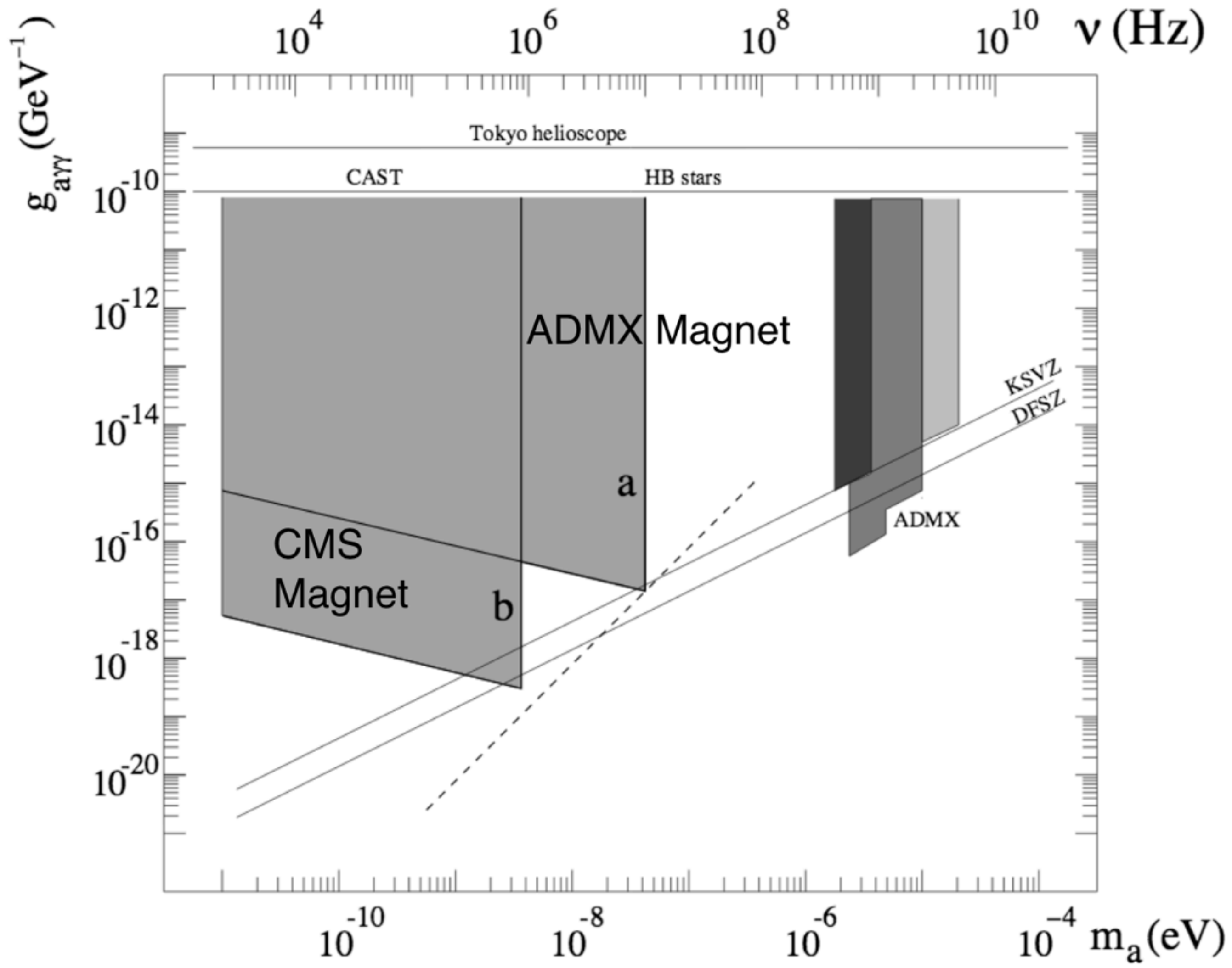
Going to lower masses (< 1 μeV): LC Circuit



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

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

LC Circuit projections using various magnets

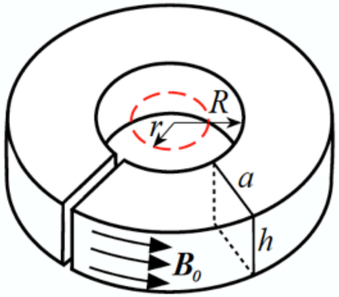


Proposal for Axion Dark Matter Detection Using an LC Circuit
PRL 112, 131301 (2014)

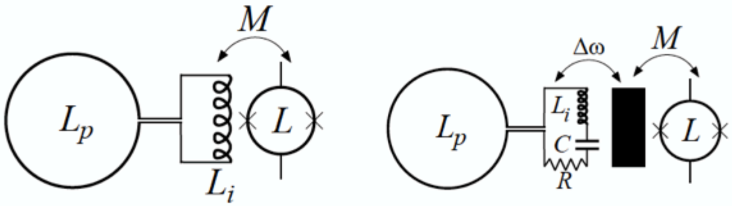
ABRACADABRA Experiment

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

Theory:



Toroidal geometry for zero-field detection

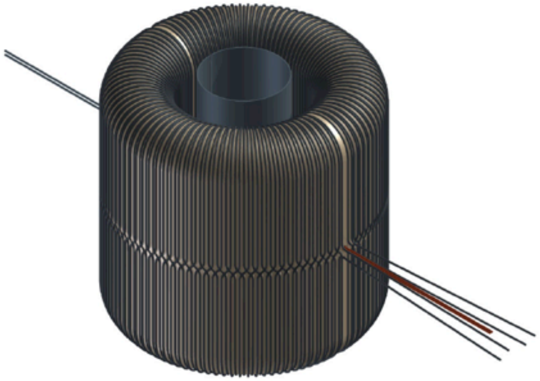


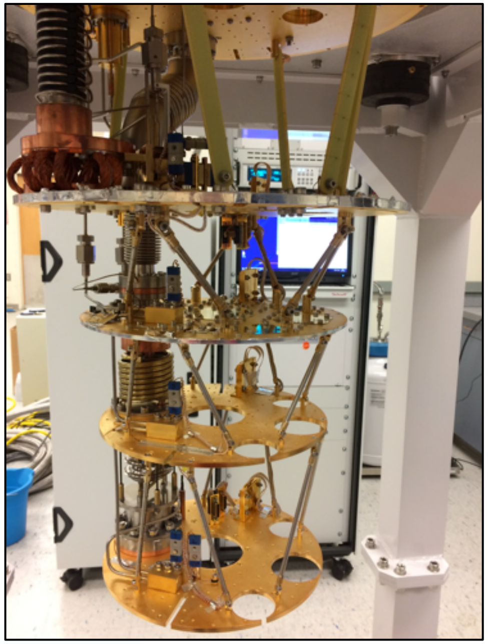
Interchangeable readout: broadband (low freq.) or resonant (high freq.)

Experiment:

Prototype specs:

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





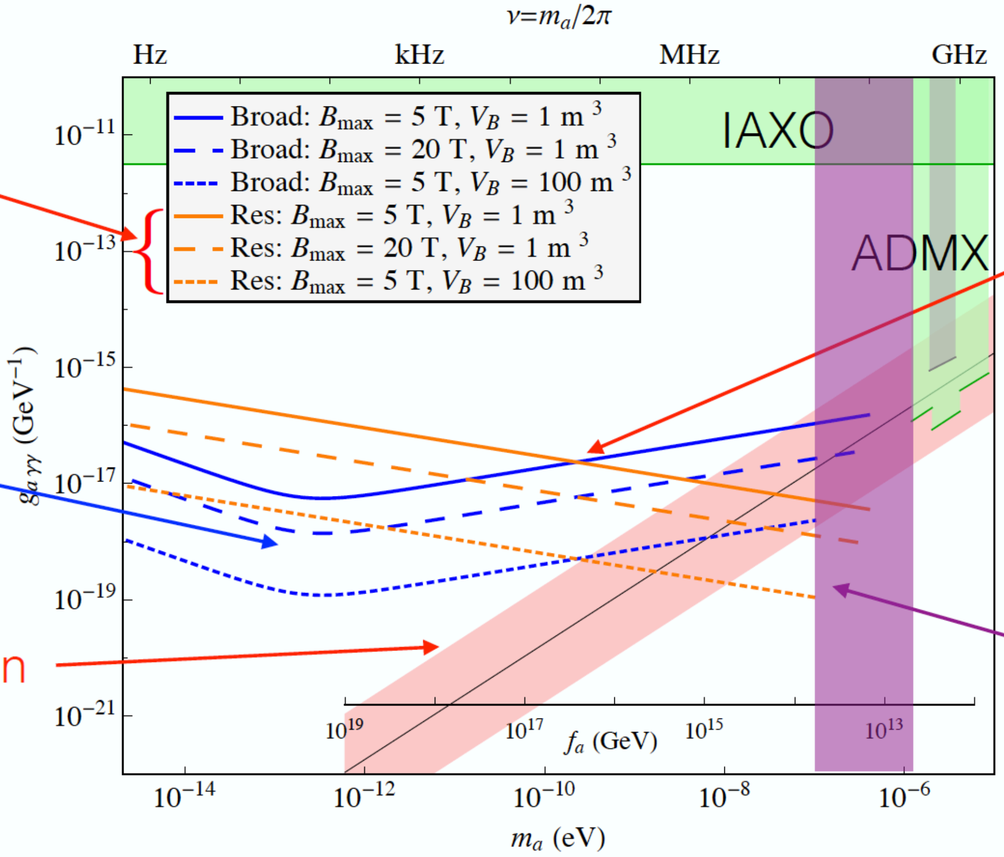
ABRA-10cm @ MIT

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

*figures from Yoni Kahn

ABRACADABRA sensitivity projections

1 year **total** measurement time



$Q = 10^6$
$T = 0.1$ K

1/f noise

QCD axion

~50 kHz crossover, scales as T

MQS breaks down (detailed sim. needed)

With same experimental parameters,
broadband for low frequencies, resonant for high frequencies

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

*figures from Yoni Kahn

Very low mass axions (neV)
NMR based experiment: CASPEr

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

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

CASPEr Electric

Budker D, et al. Phys. Rev. X4:021030 (2014)

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

CASPEr Wind

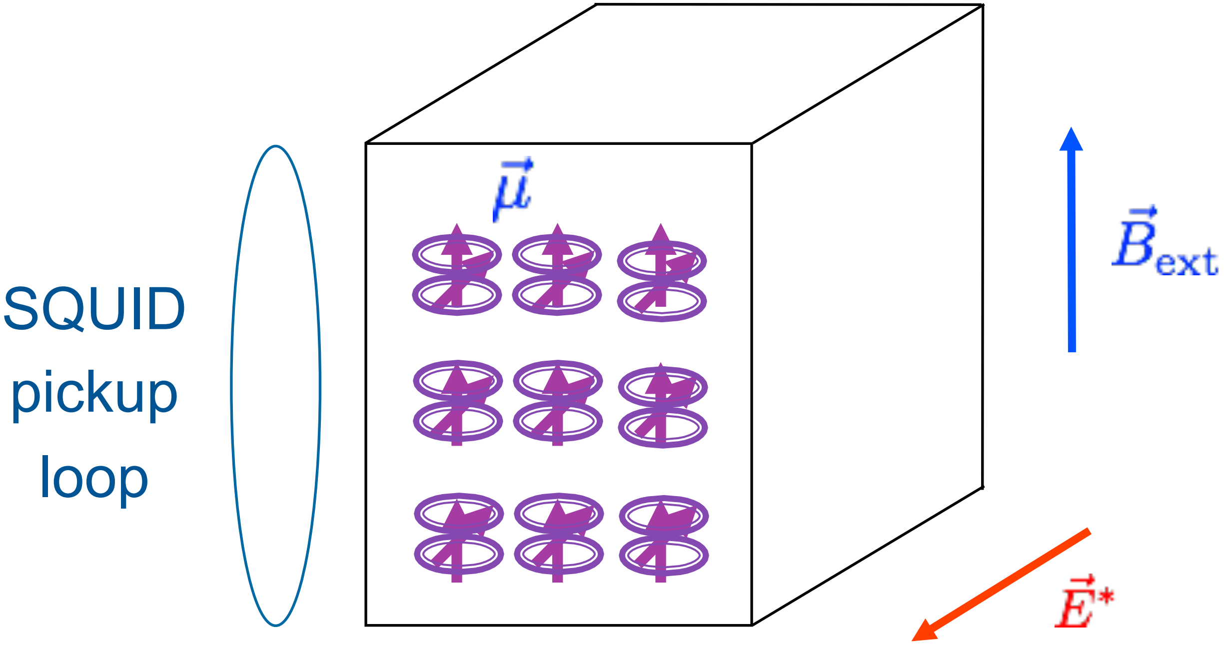
Graham PW, Rajendran S. Phys. Rev. D88:035023 (2013)

*slides from Derek Kimball

CASPEr-Electric Experiment

EDM coupling to axion plays role of oscillating transverse B-field

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



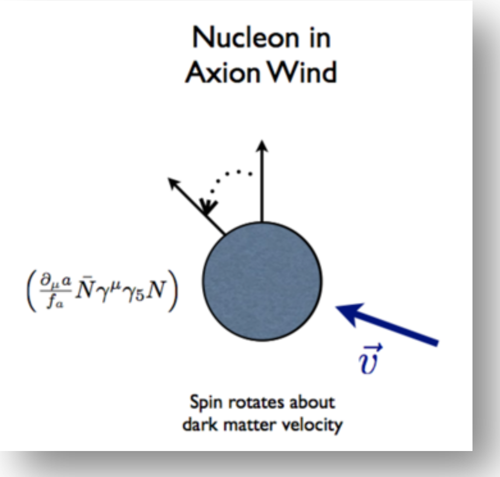
Larmor frequency = axion Compton frequency
➔ resonant enhancement.

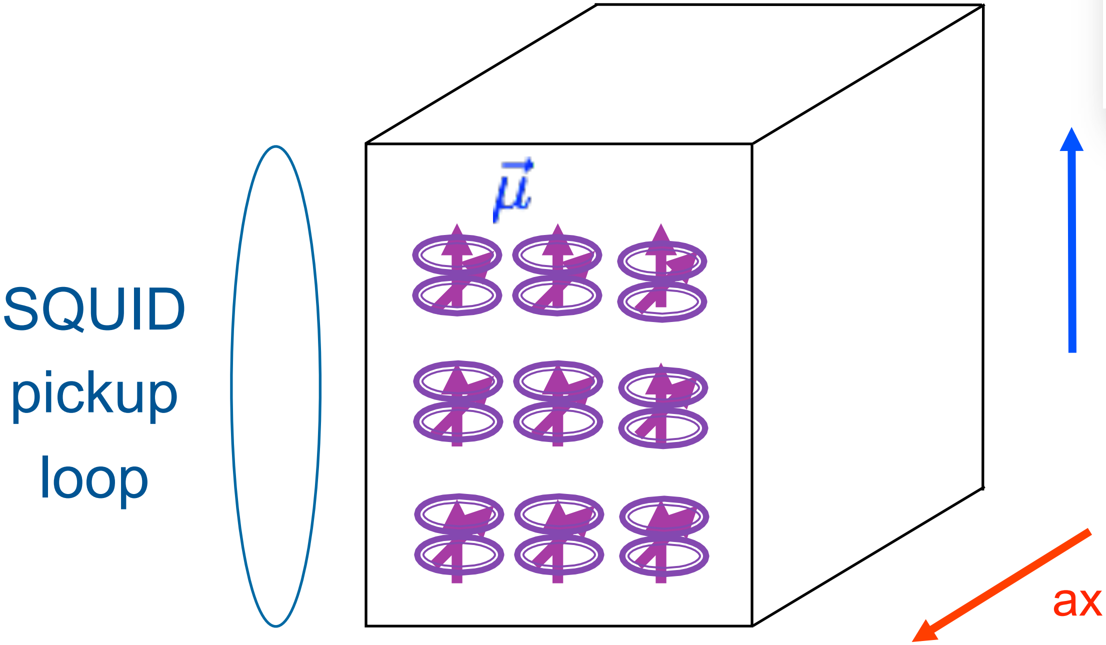
*slides from Derek Kimball

Axion/ALP-induced spin precession (axion wind)
CASPEr-Wind

Nonrelativistic limit of the axion-fermion coupling yields a Hamiltonian:

$$H_{\text{wind}} \approx g_{aNN} \nabla a \cdot \boldsymbol{\sigma}_N \ .$$

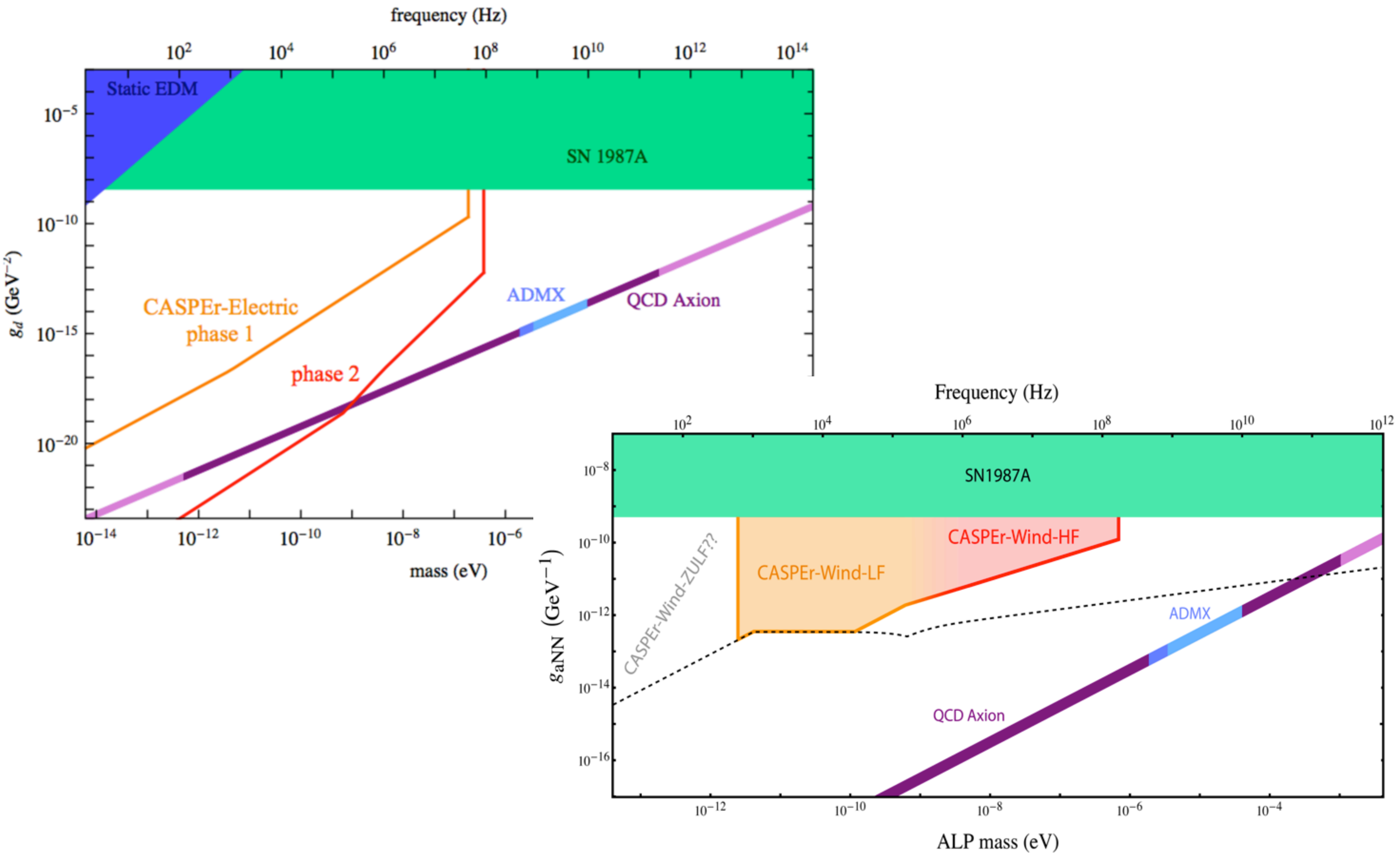




Larmor frequency = axion Compton frequency
➔ resonant enhancement.

*slides from Derek Kimball

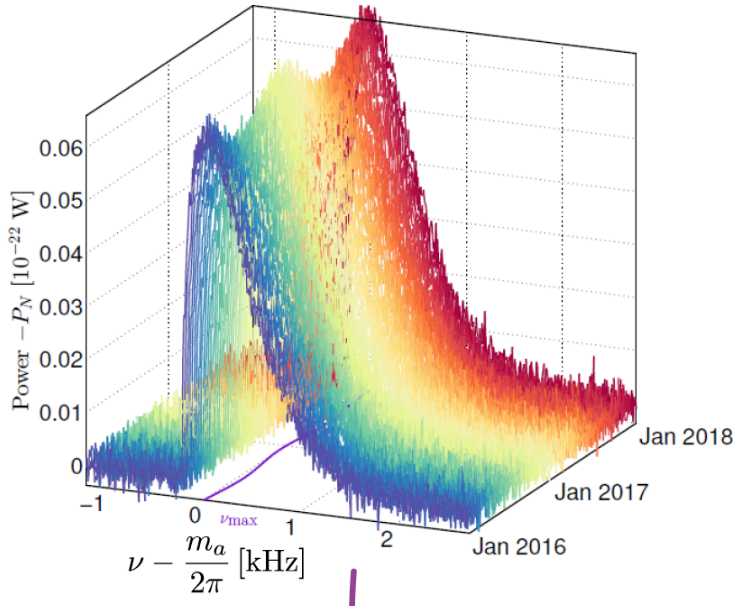
CASPEr Anticipated Sensitivities



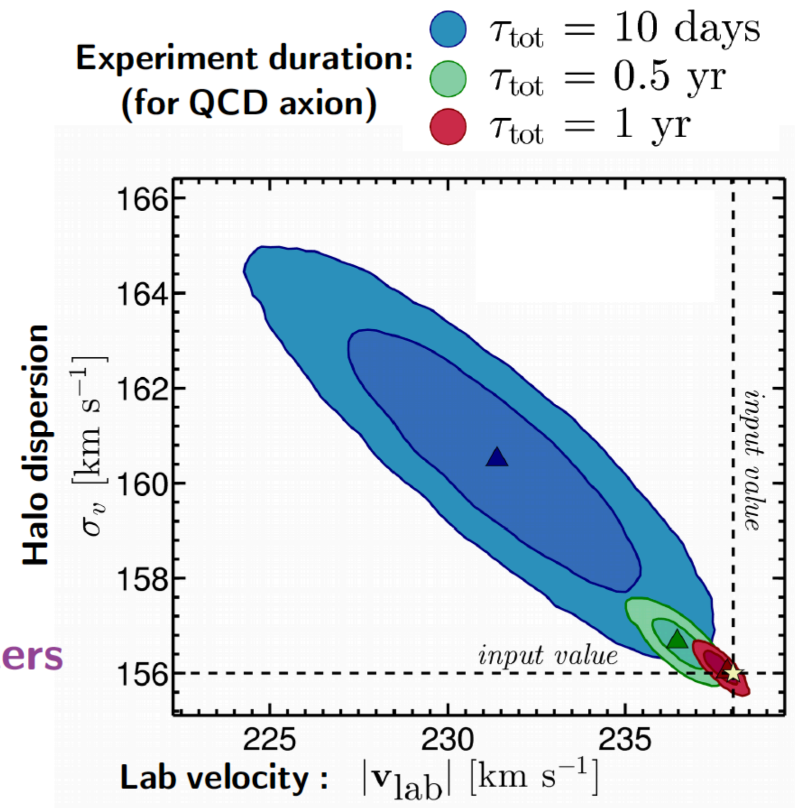
*slides from Derek Kimball

Studying the axion!

Studying the axion is studying the halo!



O'Hare & Green [1701.03118]



Max likelihood fit:
→ Extract astrophysical parameters

Accuracy <1 km/s
Better than astronomical determinations!

Slide from Ciaran O'Hare: Patras 2017

Summary

Axions: solve the Strong-CP problem and are a compelling DM candidate

Haloscopes such as ADMX have sensitivity to DM axions:

- **ADMX Gen 2**: Taking science data since Jan 2017
- **First experiment to reach sensitivity to DFSZ axions!**
- Anticipate continuous data taking up to 10 GHz

A number of other haloscopes taking data, coming online

HAYSTAC, CULTASK, ORGAN

New ideas for both high and low mass axion searches already in R&D phases

Orpheus, MADMAX, QUAX, LC-circuit, ABRACADABRA, CASPEr, etc

Information on galaxy dynamics to be learned from studying axion signal.

Discovery of the dark matter axion may be just around the corner!

Supported by DOE Grants DOE grant DE-SC00098000, DOE grant DE-SC0011665, DE-AC52-07NA27344, DE-AC03-76SF00098, the Heising-Simons Foundation, and the Lawrence Livermore National Laboratory, Fermilab and Pacific Northwest National Laboratory LDRD programs. SQUID development was supported by DOE grant DE-AC02-05CH11231.

Backup slides

The CP Problem of Strong Interactions

Characterizes degenerate QCD ground state (Θ vacuum)

Phase of Quark Mass Matrix

Standard
QCD Lagrangian
contains
a CP violating term

$$L_{CP} = -\frac{\alpha_s}{8\pi}\underbrace{(\Theta - \arg\det M_q)}_{0 \leq \overline{\Theta} \leq 2\pi} \mathrm{Tr}\, \tilde{G}_{\mu\nu} G^{\mu\nu}$$

Induces a neutron
electric dipole moment
(EDM) much in excess
of experimental limits

$$d_n \approx \overline{\Theta}\, 10^{-16}\, e\,\mathrm{cm} \approx \frac{\overline{\Theta}}{10^2}\, \mu_n < 3 \times 10^{-26}\, e\,\mathrm{cm}$$

$\overline{\Theta} \lesssim 10^{-10}$ **Why so small?**

*from George Raffelt (DESY)

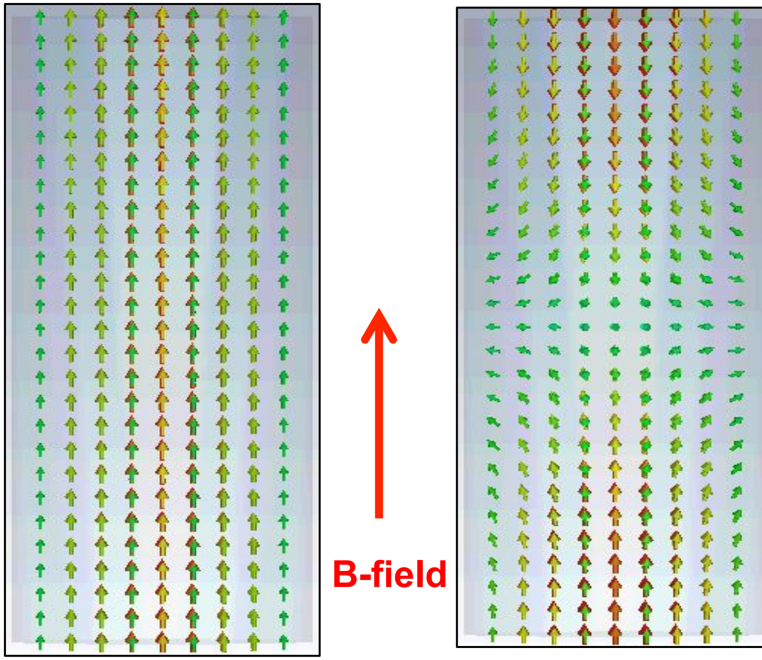
Key Microwave Cavity Design Constraints

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

- 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: $(8\mathrm{T})^2 \cdot (\sim 100$ liters)
- Loaded Quality factor Q_L = frequency/bandwidth

($Q_L \sim 10^5$ 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%)



TM_{010} mode
$C_{010} \sim 0.69$

TM_{011} mode
$C_{011} \sim 0.0$

Main Cavity Properties

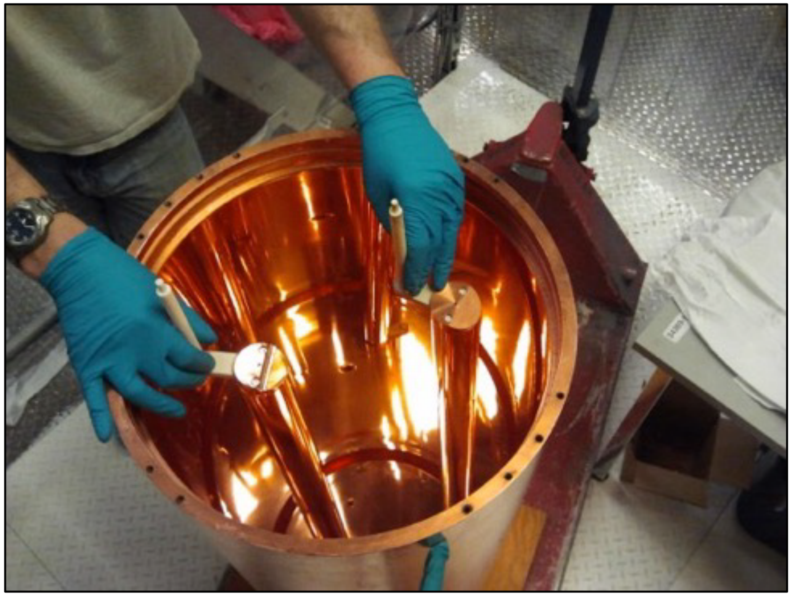
Volume: 133 liters

Q_{loaded}: 60,000

580 – 890 MHz

(with current rods)

Dilution Refrigerator directly attached to top



Receiver Chain

Injection of swept power & fake axions

Reflection to look at antenna coupling

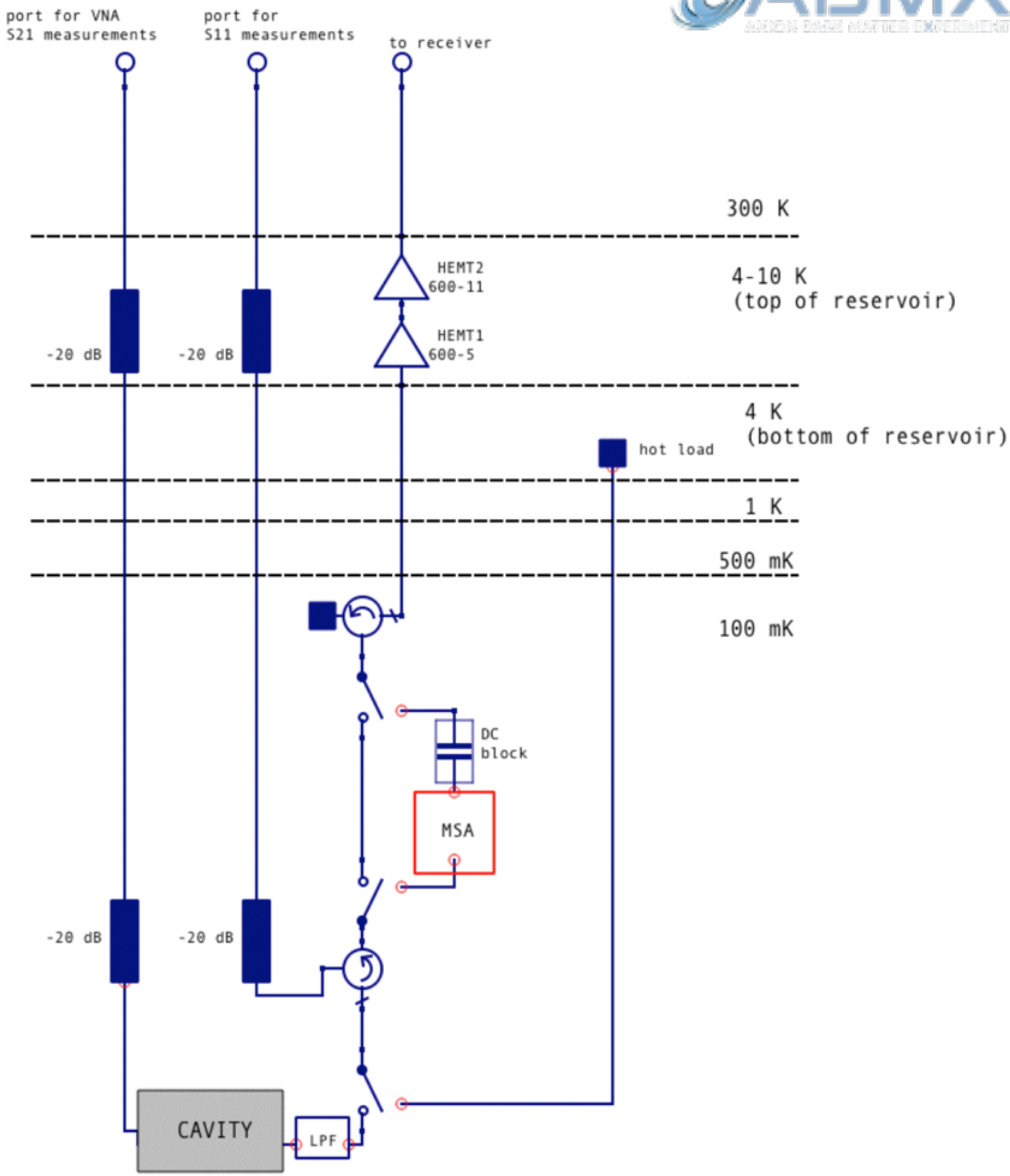
Hot / Cold load:
Measure system noise temperature

SQUID at $T_{physical}$~ 300 mK
Cavity at $T_{physical}$~ 150 mK

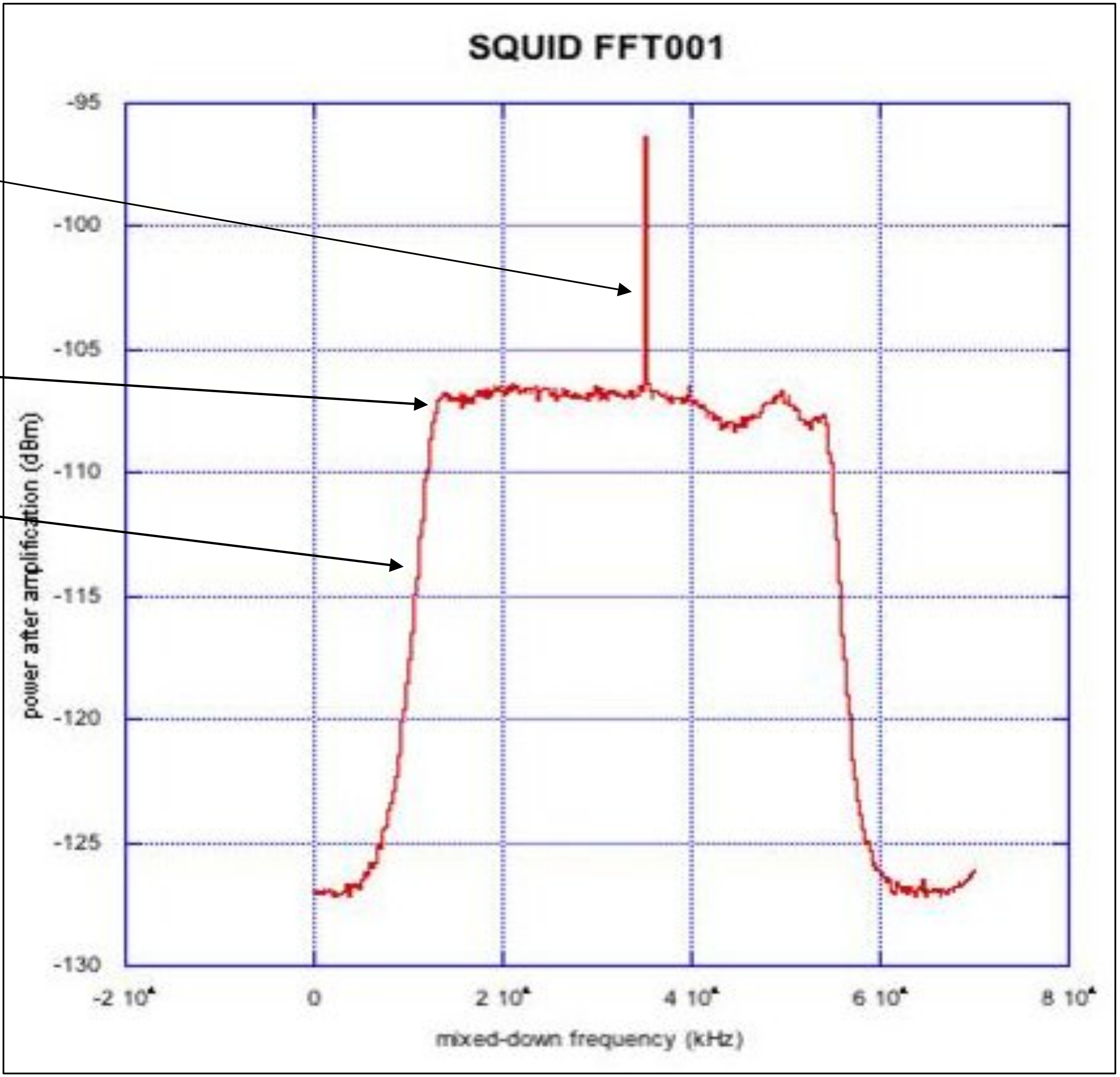
Total system noise ~ 0.5 K*

*includes attenuation + post-amplifier contributions.

ADMX Cryogenic RF Layout for
Channel 1 Electronics @100mK



Example of injected tone (fake axion) (Phase I with SQUID amplifiers)

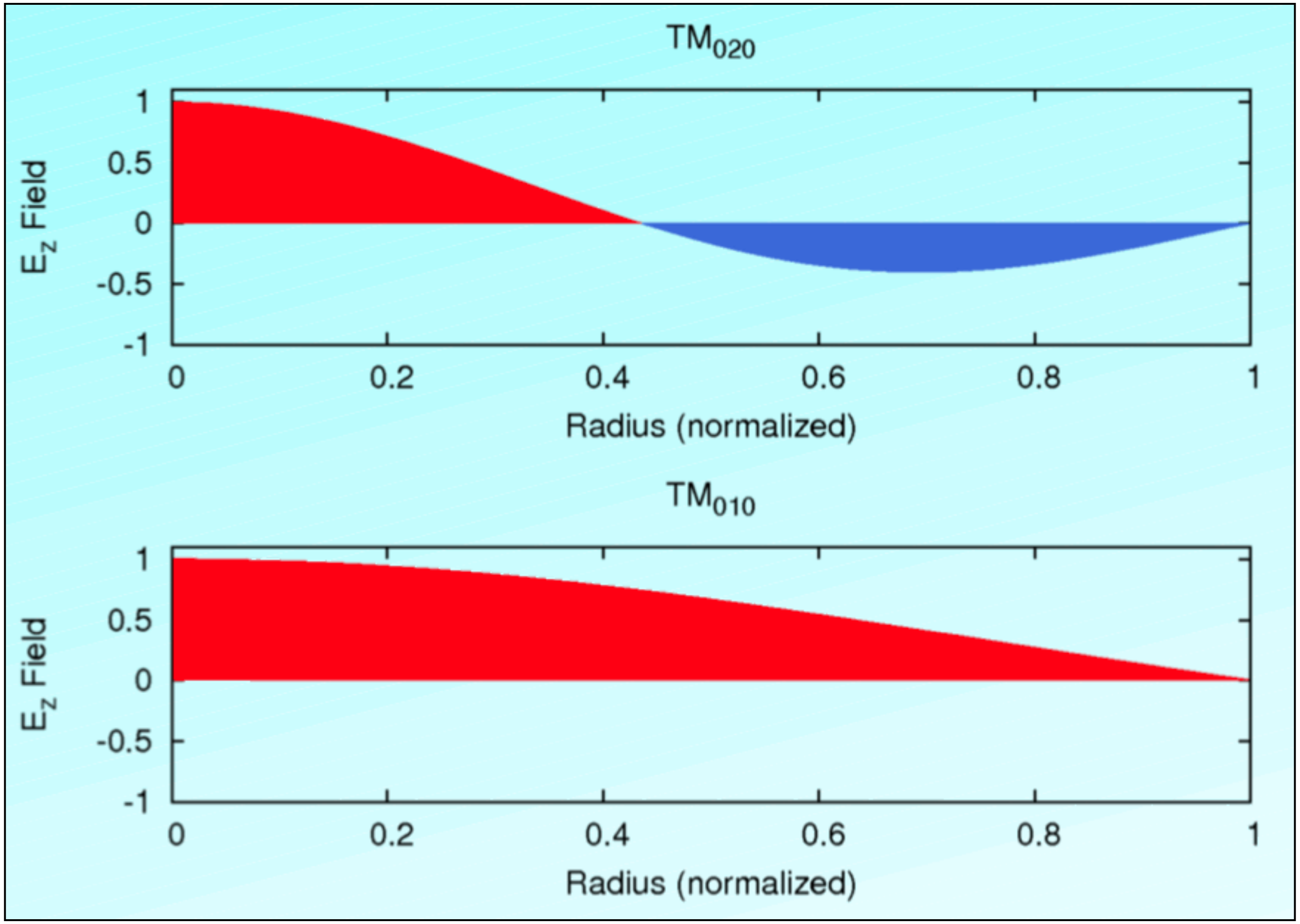


- Injected Power

x100-1000 axion power

- Noise floor
- Bandpass filter

Possible to instrument higher order modes



TM_{020} Mode

Relative Frequency
2.3

Tuning Range
920-2,100 MHz

Relative Power
0.41

TM_{010} Mode

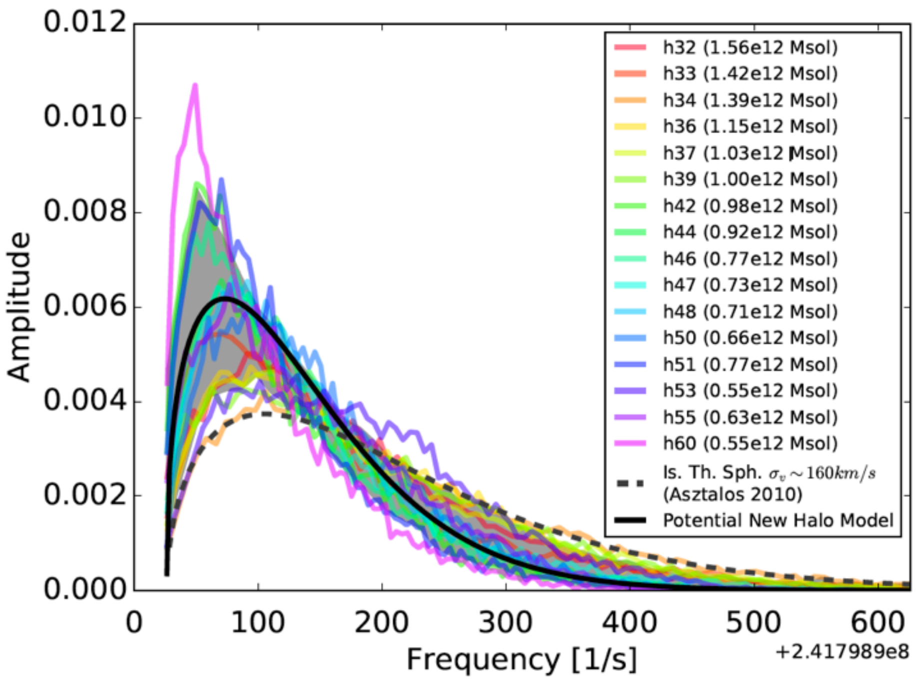
Relative Frequency
1.0

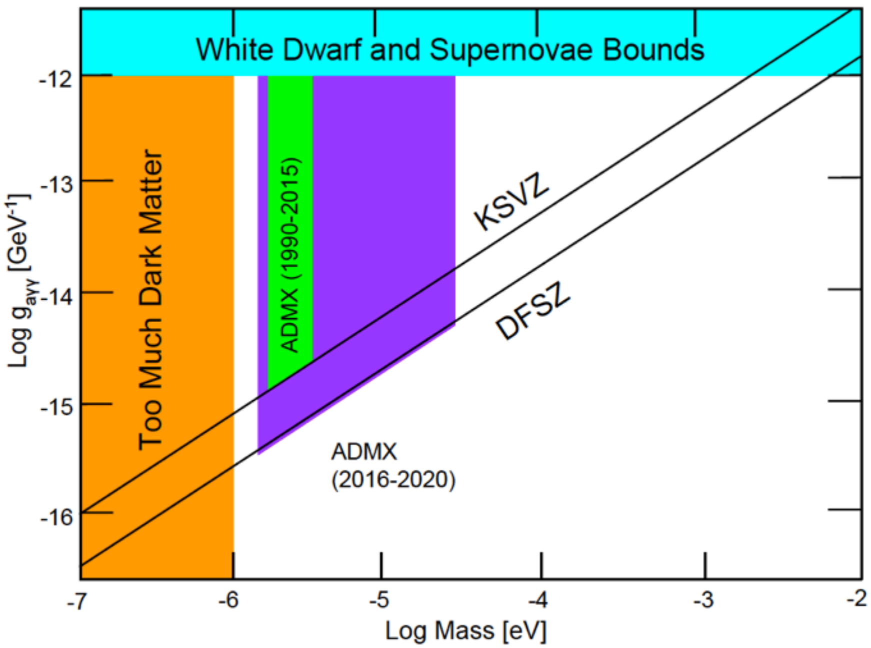
Tuning Range
400-900 MHz

N-body simulations point to sharper line-shape

If true than haloscope experiments would naturally be even more sensitive

Currently we continue to operate with conservative isothermal halo





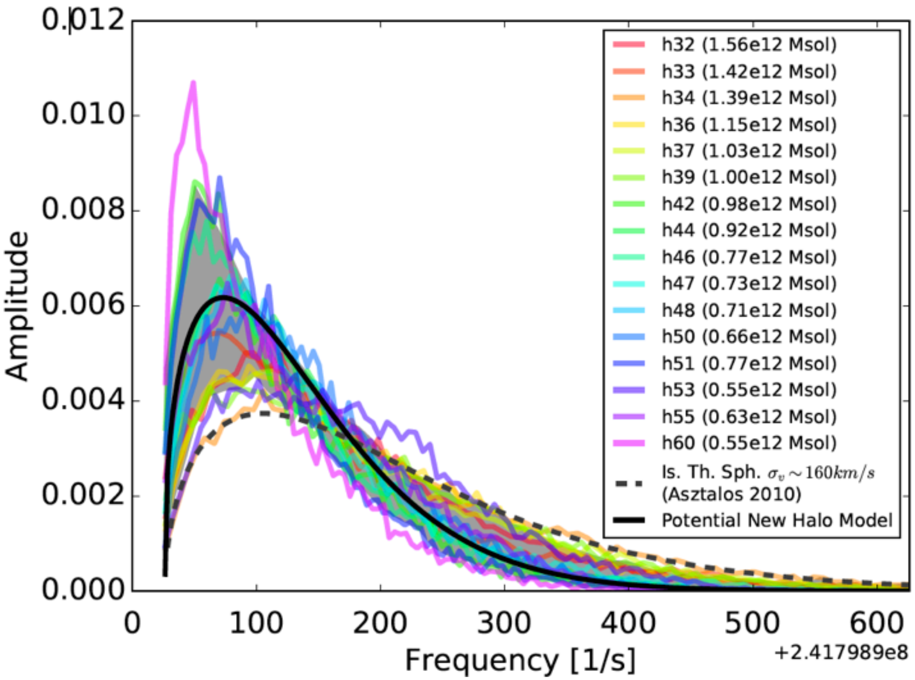
*Slide from Aaron Chou (FNAL)

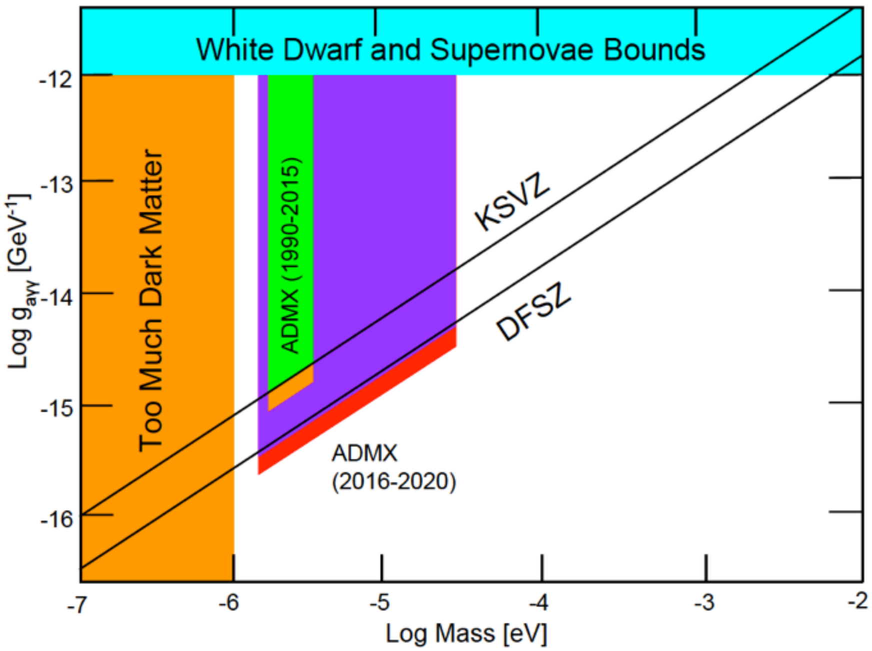
N-body simulations point to sharper line-shape

If true than haloscope experiments would naturally be even more sensitive

Currently we continue to operate with conservative isothermal halo

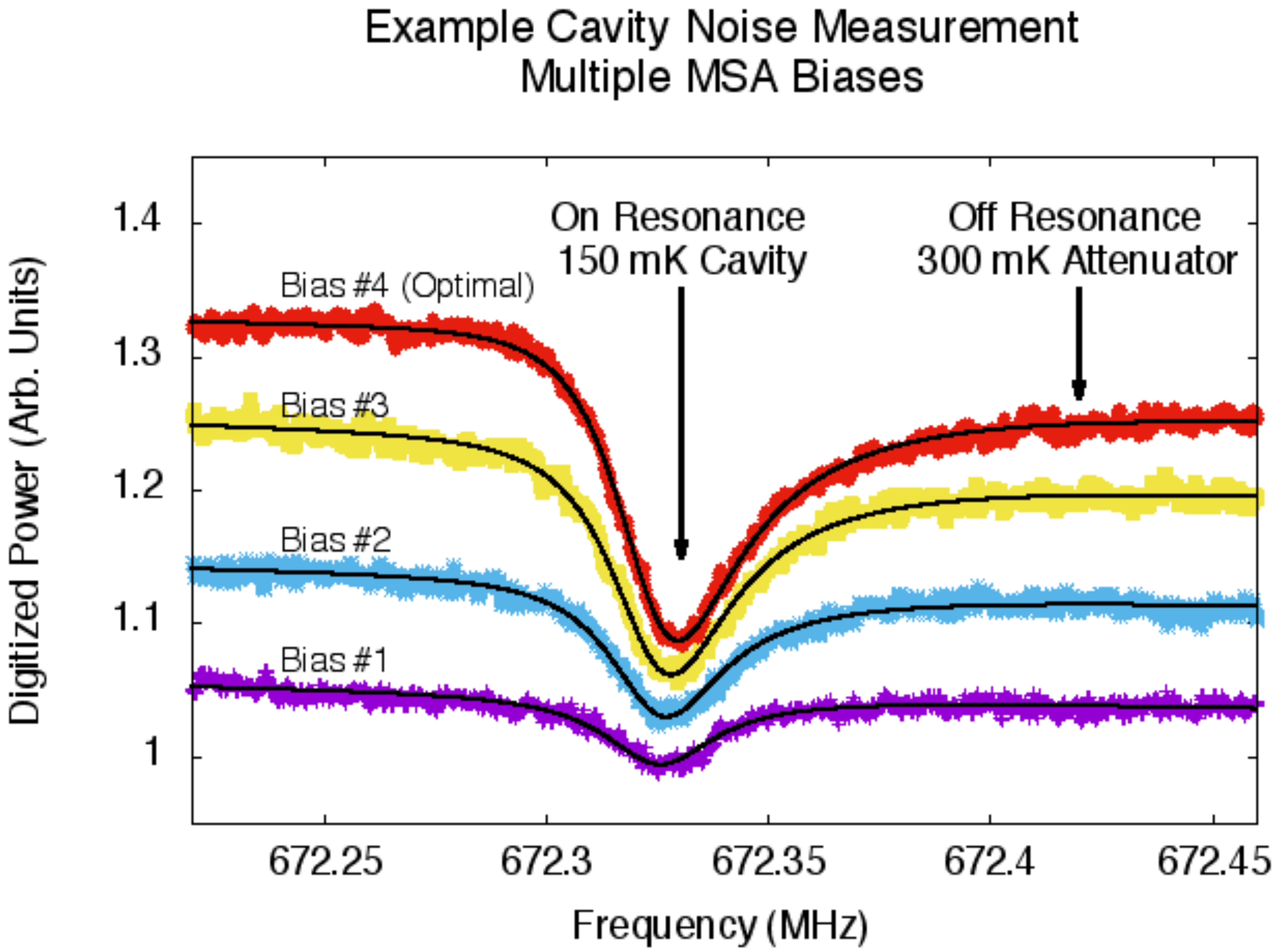
If the simulations from the UW “N-body shop” are correct limits can be extended.





*Slide from Aaron Chou (FNAL)

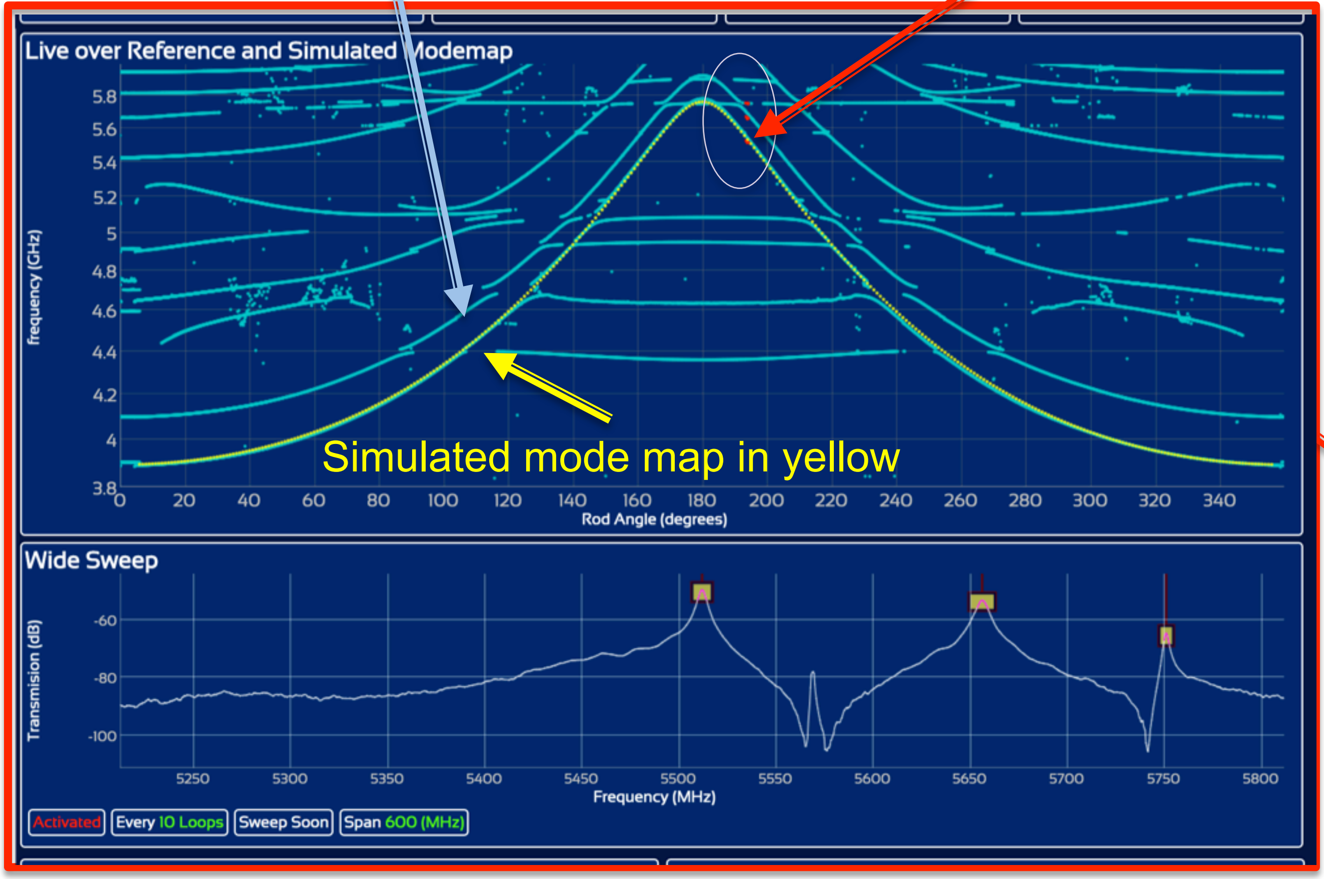
Fit receiver chain to determine system noise



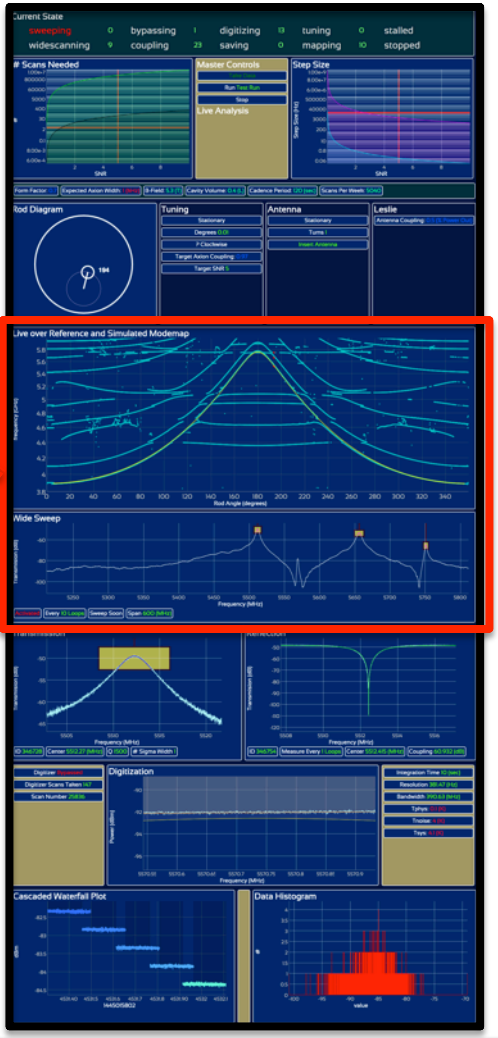
Sidecar DAQ: Mode Map

Reference mode map in blue

Red Dots are live data taken from wide scan



Simulated mode map in yellow



*Recent Ph.D thesis of Christian Boutan (now at PNNL)

ADMX: Collaboration

ADMX
AXION DARK MATTER EXPERIMENT

University of Washington · 1861

UF University of Florida

Lawrence Livermore National Laboratory

Berkeley
University of California

NRAO

The University Of Sheffield.

Fermilab

Pacific Northwest
NATIONAL LABORATORY

Washington University in St. Louis · 1853 · *

Los Alamos
NATIONAL LABORATORY

Sponsors

ADMX now DOE Gen 2 project

Department of Energy · United States of America

NSF

HSF
HEISING - SIMONS
FOUNDATION

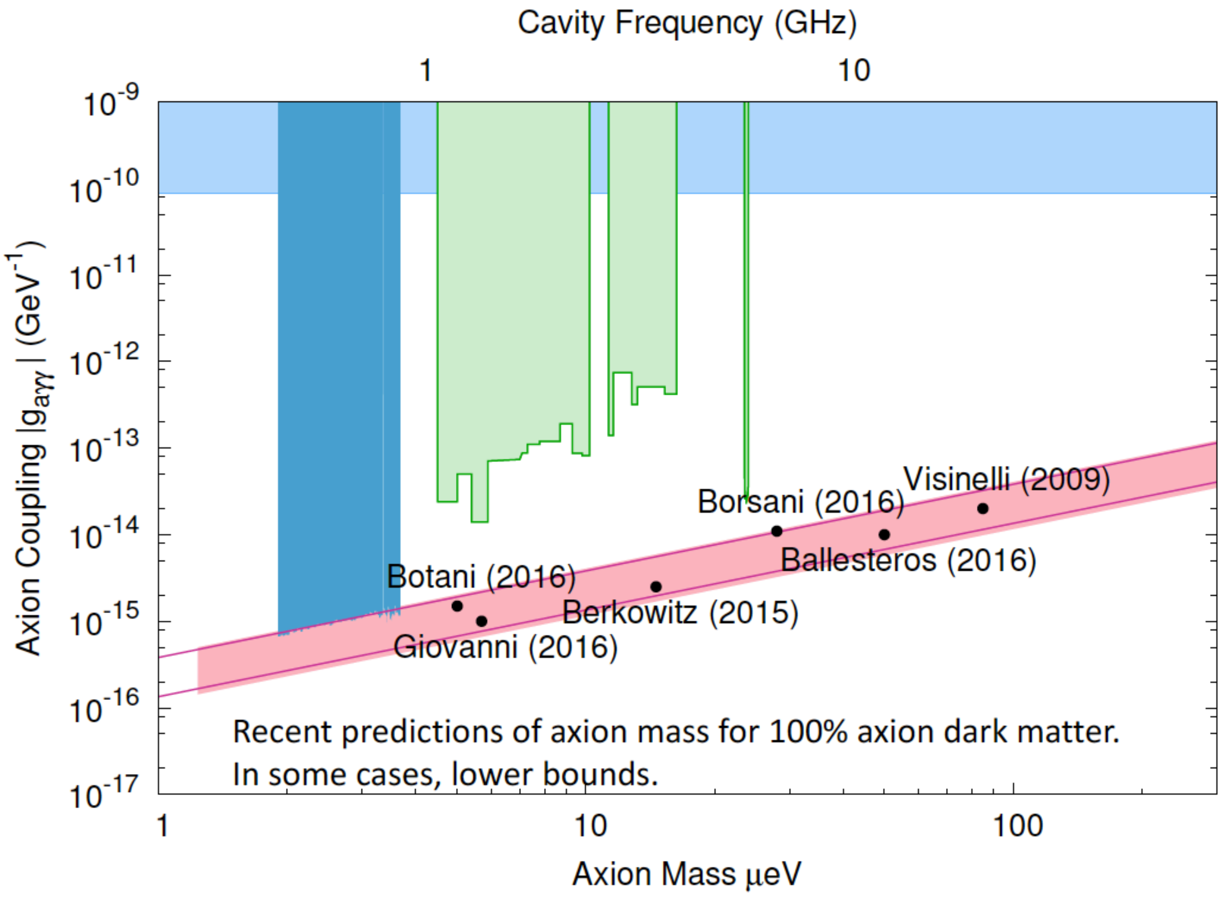
Primary sponsor

R&D support

Where to look in mass?

For PQ symmetry breaking **after** inflation analytical and lattice results point to 1-100 μeV masses.

For PQ symmetry breaking **before** inflation less constrained
(could be << μeV masses)



Plot from Gray Rybka (UW)

ADMX site: University of Washington

Center for Experimental Nuclear Physics and Astrophysics (CENPA)

ADMX DAQ & Controls

Cleanroom
(with insert hanging)

ADMX Magnet

Helium liquefier

Scan Rate from Dicke Radiometer equation

- Rate determined from SNR

$$\frac{df}{dt} \approx 750\ MHz/year\ \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{5}{SNR}\right)^2 \left(\frac{f}{1\ GHz}\right)^2 \cdot \left(\frac{B_0}{8\ T}\right)^4 \left(\frac{V}{100l}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2\ K}{T_{sys}}\right)^2$$

- *SNR* is the Signal-to-Noise for detection (usually set to 5),
- *f* is the frequency being searched (where 1 GHz ~ m_a = 4.1 ueV)
- T_{sys} is the total system temperature ($T_{sys} = T_{cavity} + T_{amps}$)
- To scan at this sensitivity would take > 100 years with original ADMX

Managing mode-crossings

- Transverse Magnetic (TM) modes move up in frequency as tuning rods are rotated

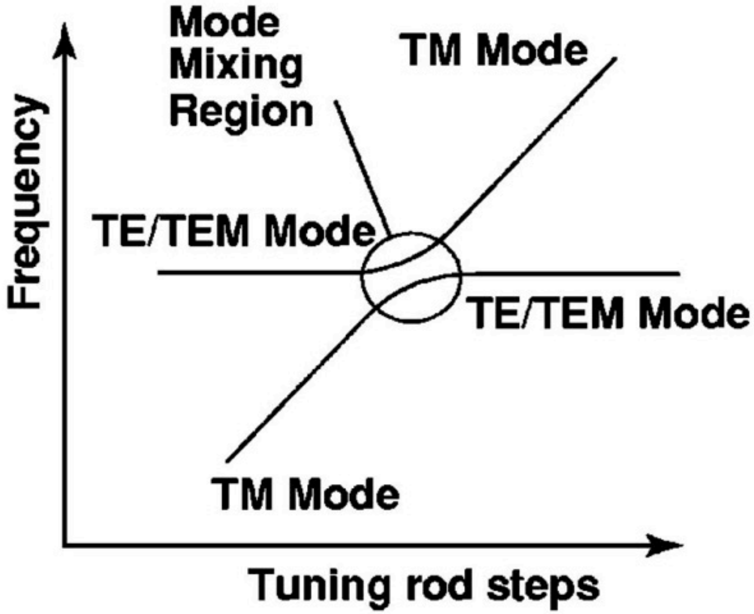
- Transverse Electric (TE) modes remain relatively static in frequency.

- When both mode’s frequencies are degenerate there’s a “mode crossing” in which the two modes “mix” and the resonant peak can disappear.

- The longer the cavity, the more TE modes there a in the tuning range.

  Keep aspect ratios: *Length / radius* ~ 5.

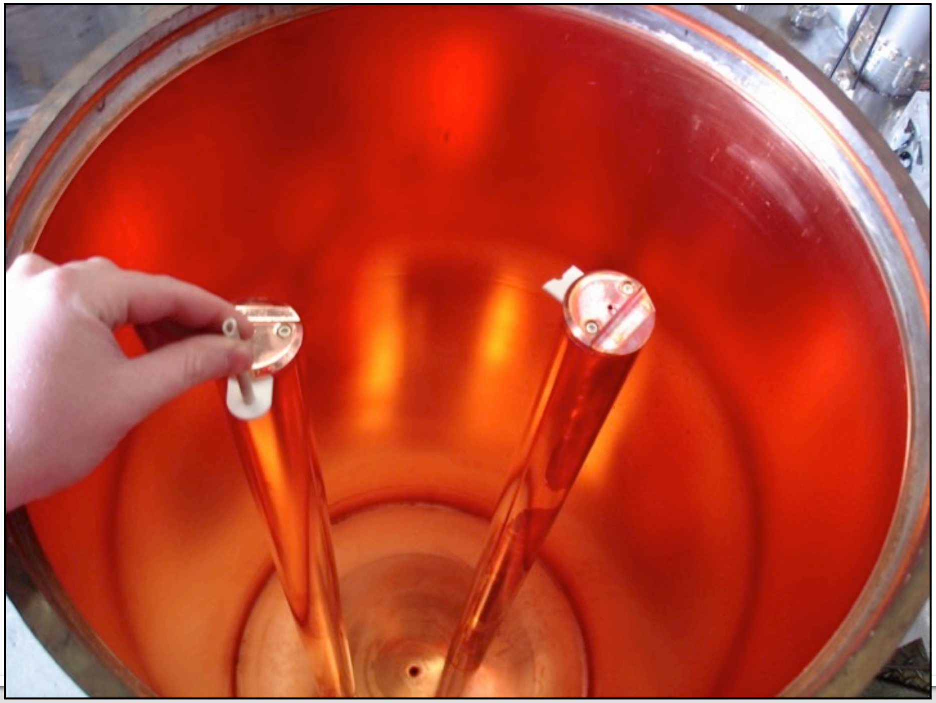
- We step around mode crossings by using multiple tuning rods (metal and dielectric).



Challenge of moving to higher axion mass (frequency)

- 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

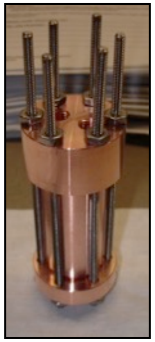


16” diameter

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

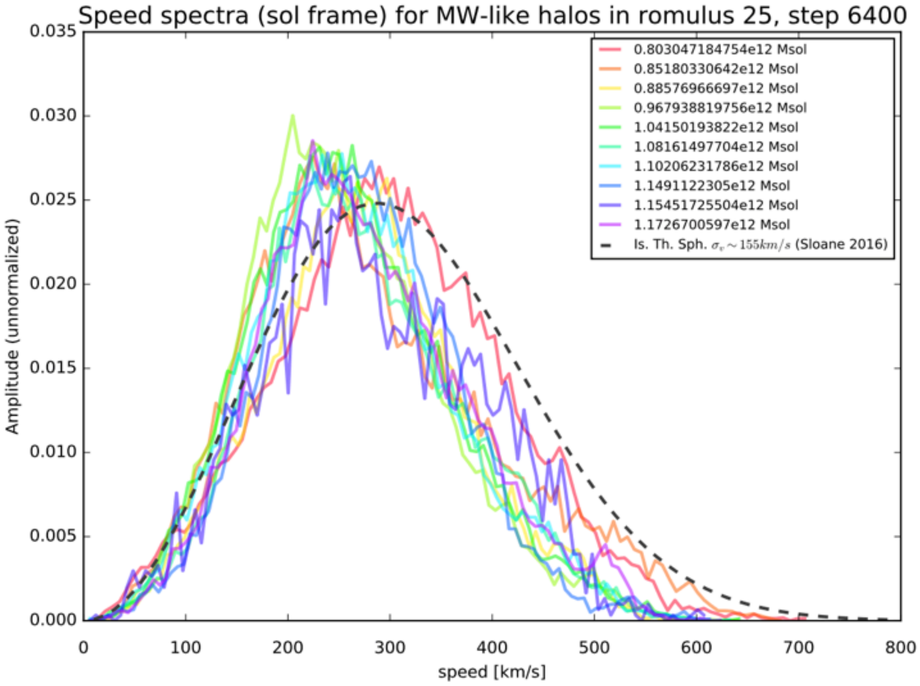
5” diameter

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

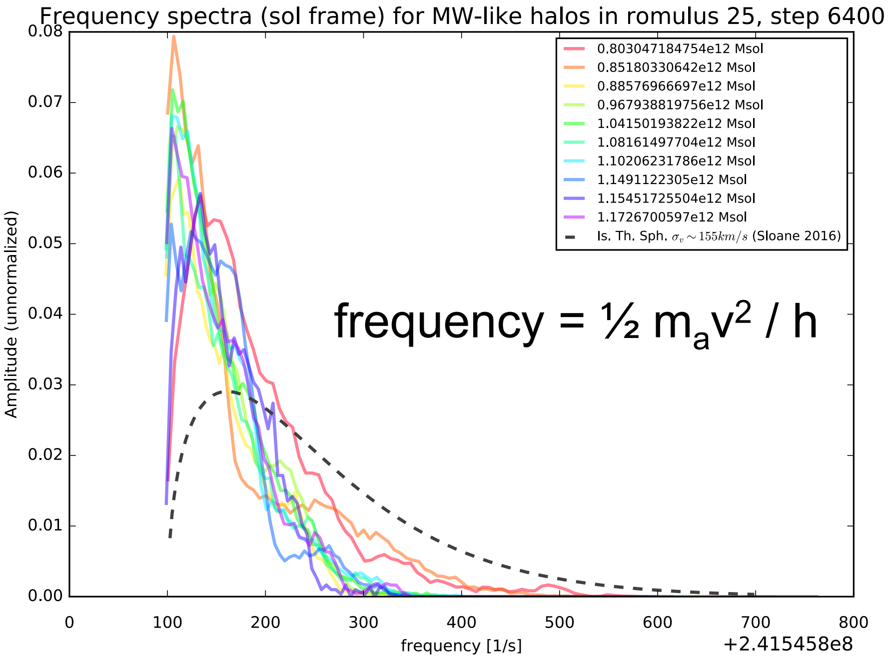


1” diameter

Can obtain axion phase space distribution immediately after discovery + reconfirmation



For example:
Test N-body simulations from T. Quinn predicting long-suspected co-rotating galactic DM → Softer spectrum?
Narrower line = better Signal/Noise?



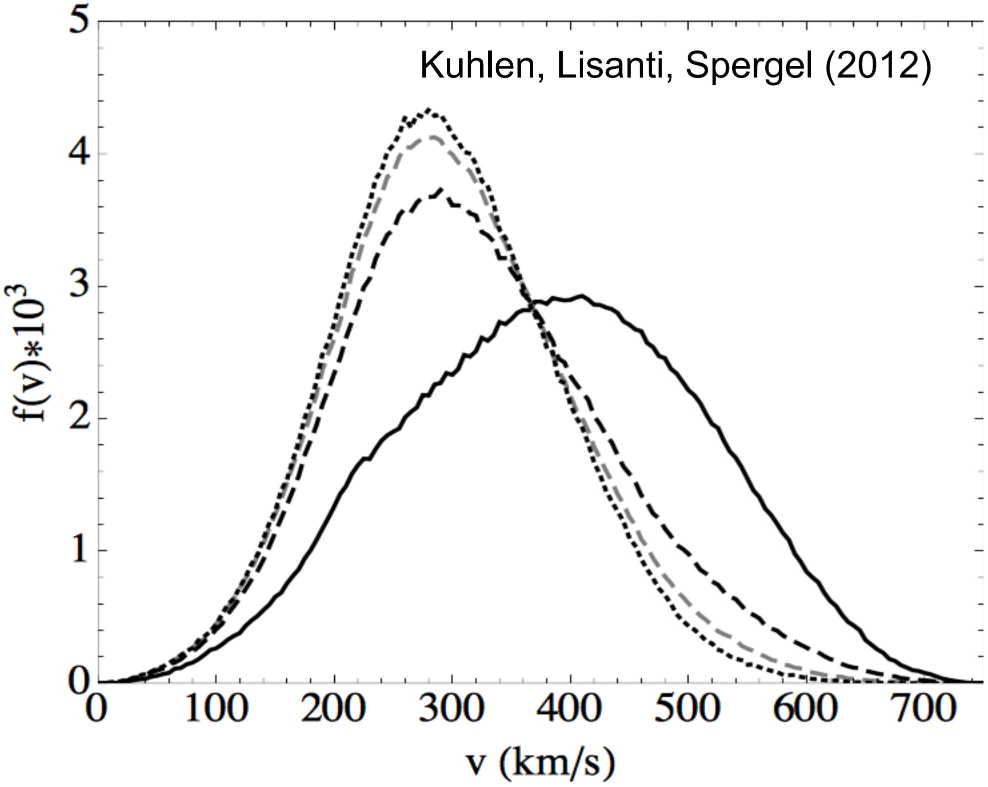
frequency = $\frac{1}{2} m_a v^2 / h$

For 2x frequency resolution, need 2x sample time. Half-power in each bin requires 4x samples. Total 8x integration time is easy!

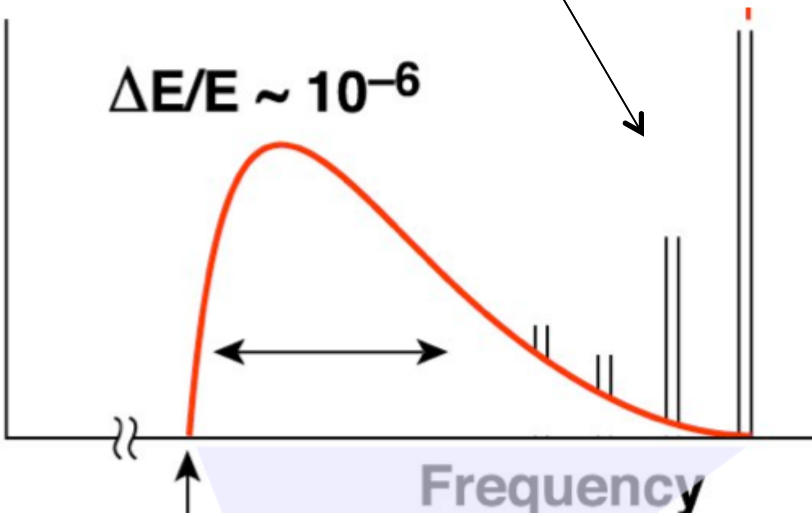
*Slide from Aaron Chou (FNAL)

Test models of debris flow, narrowband caustic structure from recent infalls, etc.

Via Lactea 2 simulation,



Caustics (Sikivie)



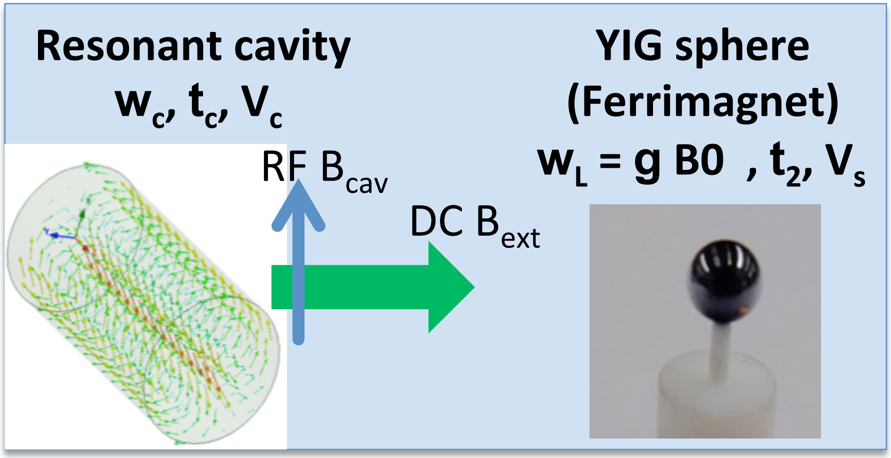
If dark matter is multicomponent, these measurements could also provide valuable input to WIMP detection experiments.

*Slide from Aaron Chou (FNAL)

QUAX: Axion induced RF emission

A **volume V_s of magnetized material, strong coupled in a microwave resonant cavity,** will absorb energy from the axion wind and **re-emit as rf power**

With magnetizing field
B0 = 1.7 T => 48 GHz



$$P_{\text{out}} = \frac{P_{\text{in}}}{2} = 3.8 \times 10^{-26} \left(\frac{m_a}{200\ \mu\text{eV}}\right)^3 \left(\frac{V_s}{100\ \text{cm}^3}\right) \left(\frac{n_S}{2 \cdot 10^{28}/\text{m}^3}\right) \left(\frac{\tau_{\min}}{2\ \mu s}\right) \text{W}$$

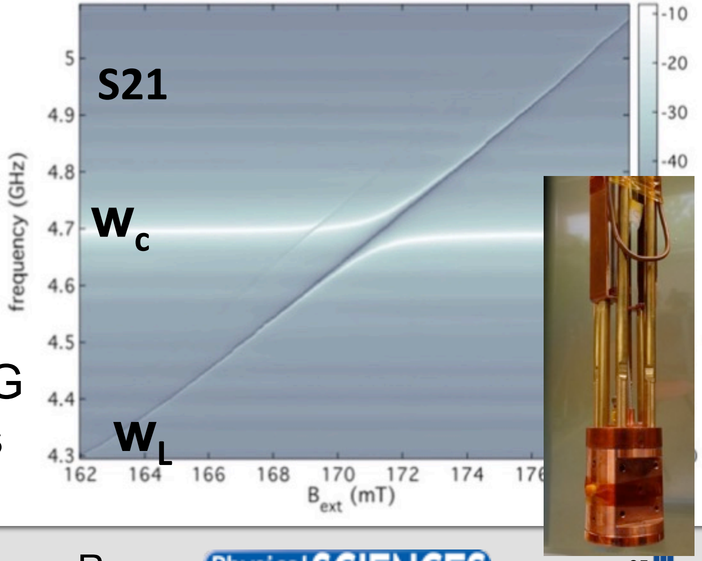
R & D in progress

Niobium Cavity

T = 300K
f_c = 13.964 GHz
Q_0 = 5.0*10^3

T = 4.2K
f_c = 13.960 GHz
Q_0 = 5.0*10^5

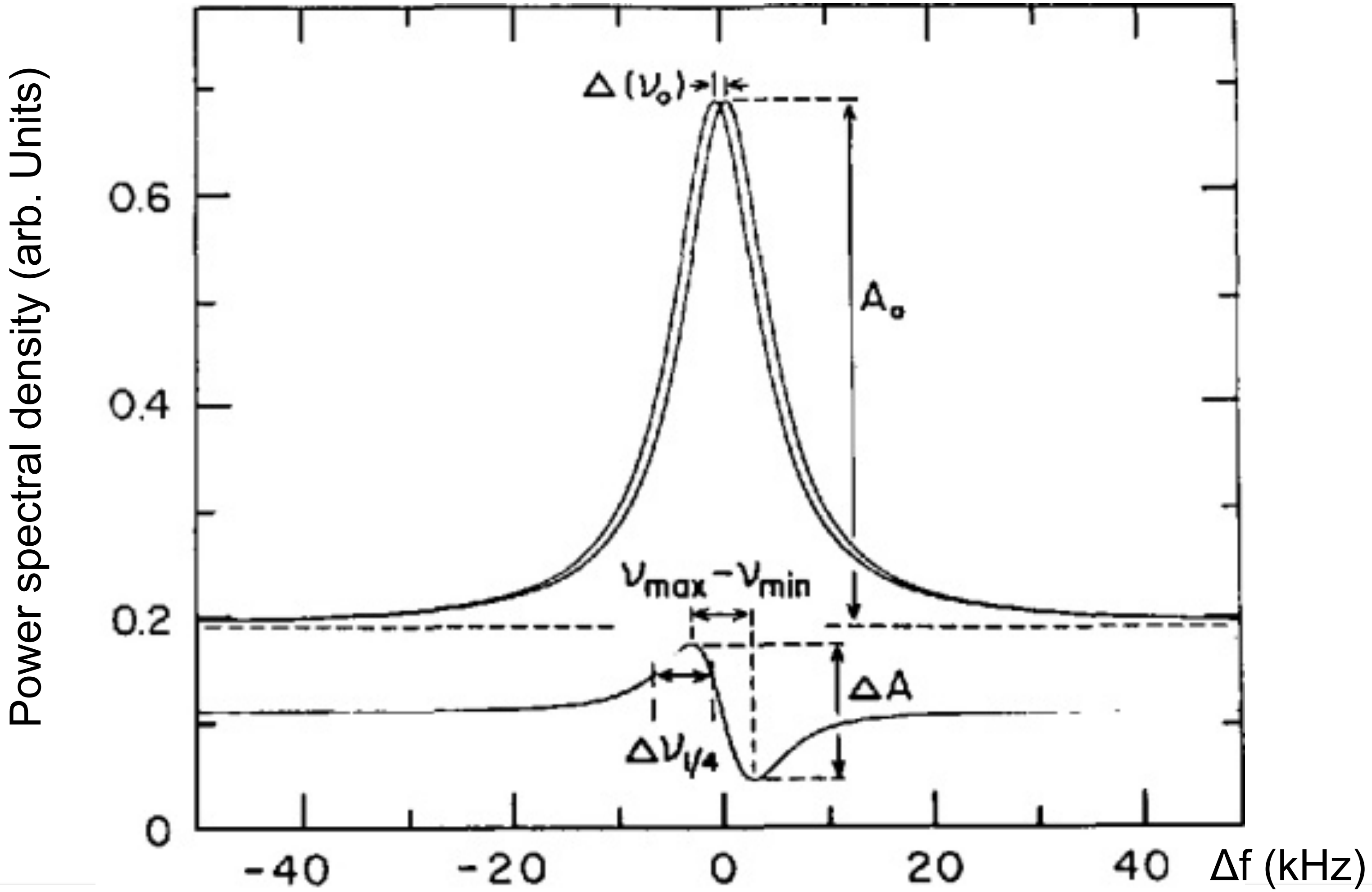
Cavity – YIG resonances



Slide from Giuseppe Ruoso

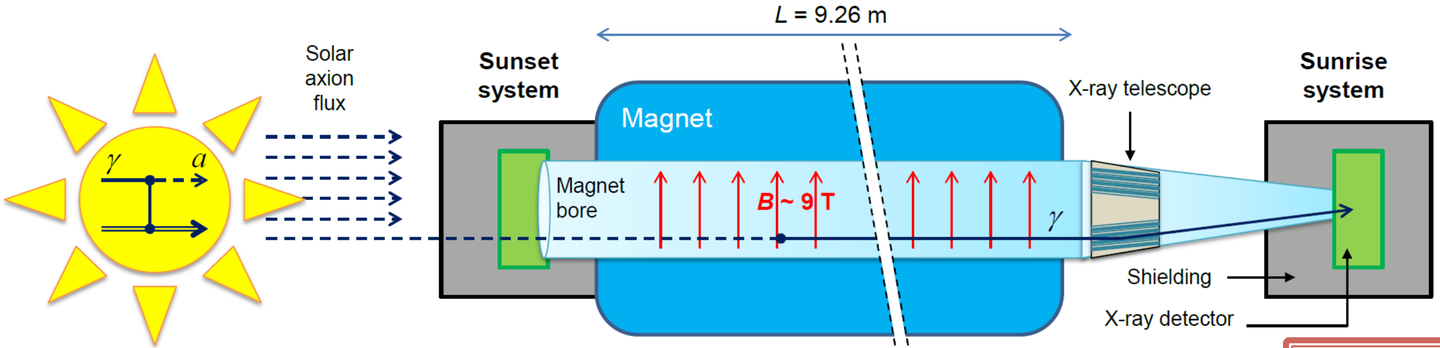
Annual modulation is also easy

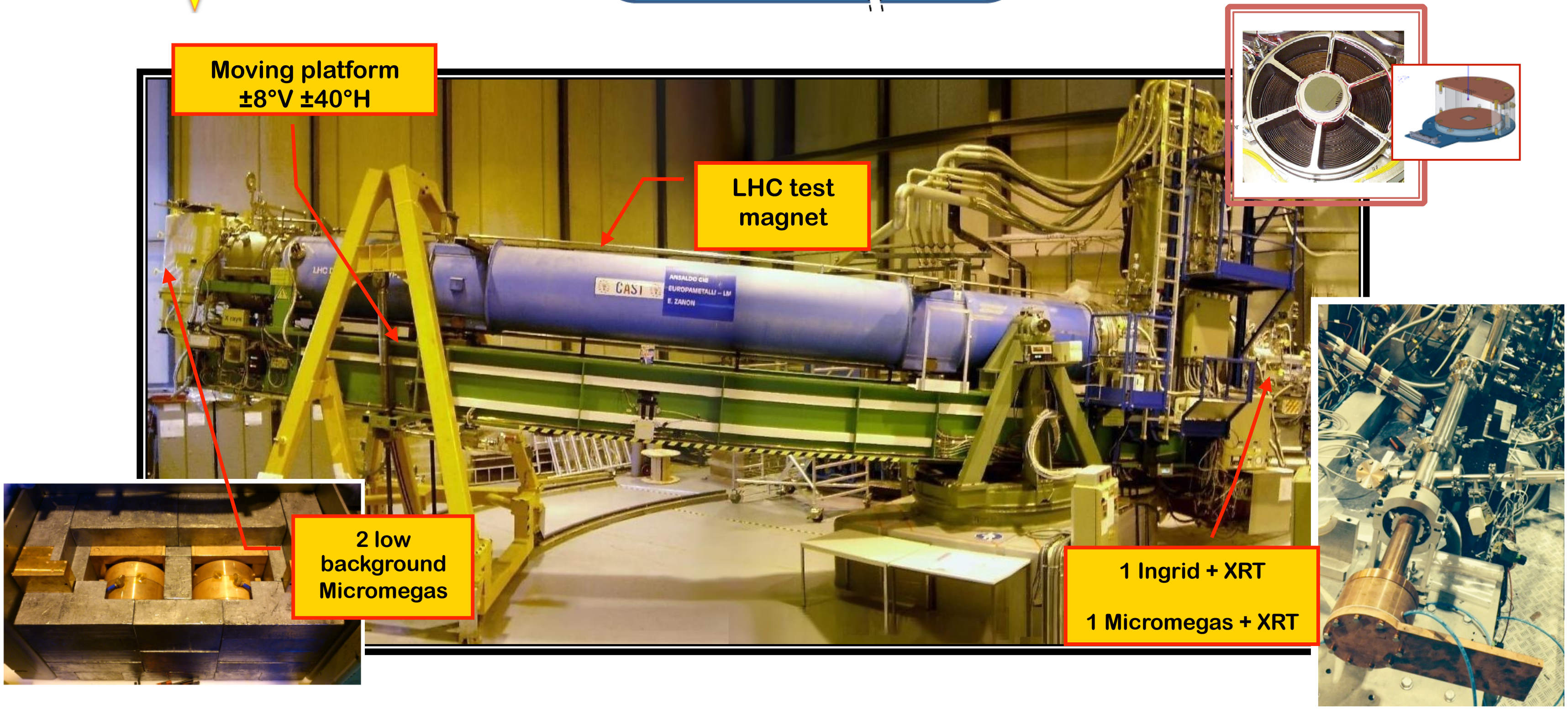
Annual modulation δv/Δv = (60 km/s) / (300 km/s) = 20% of linewidth.
Resolve frequency shift with 5x integration time = few 10's minutes.



*Slide from Aaron Chou (FNAL)

CAST experiment @ CERN





Moving platform ±8°V ±40°H

LHC test magnet

2 low background Micromegas

1 Ingrid + XRT

1 Micromegas + XRT

*slides provided by J. Ruz Armendariz