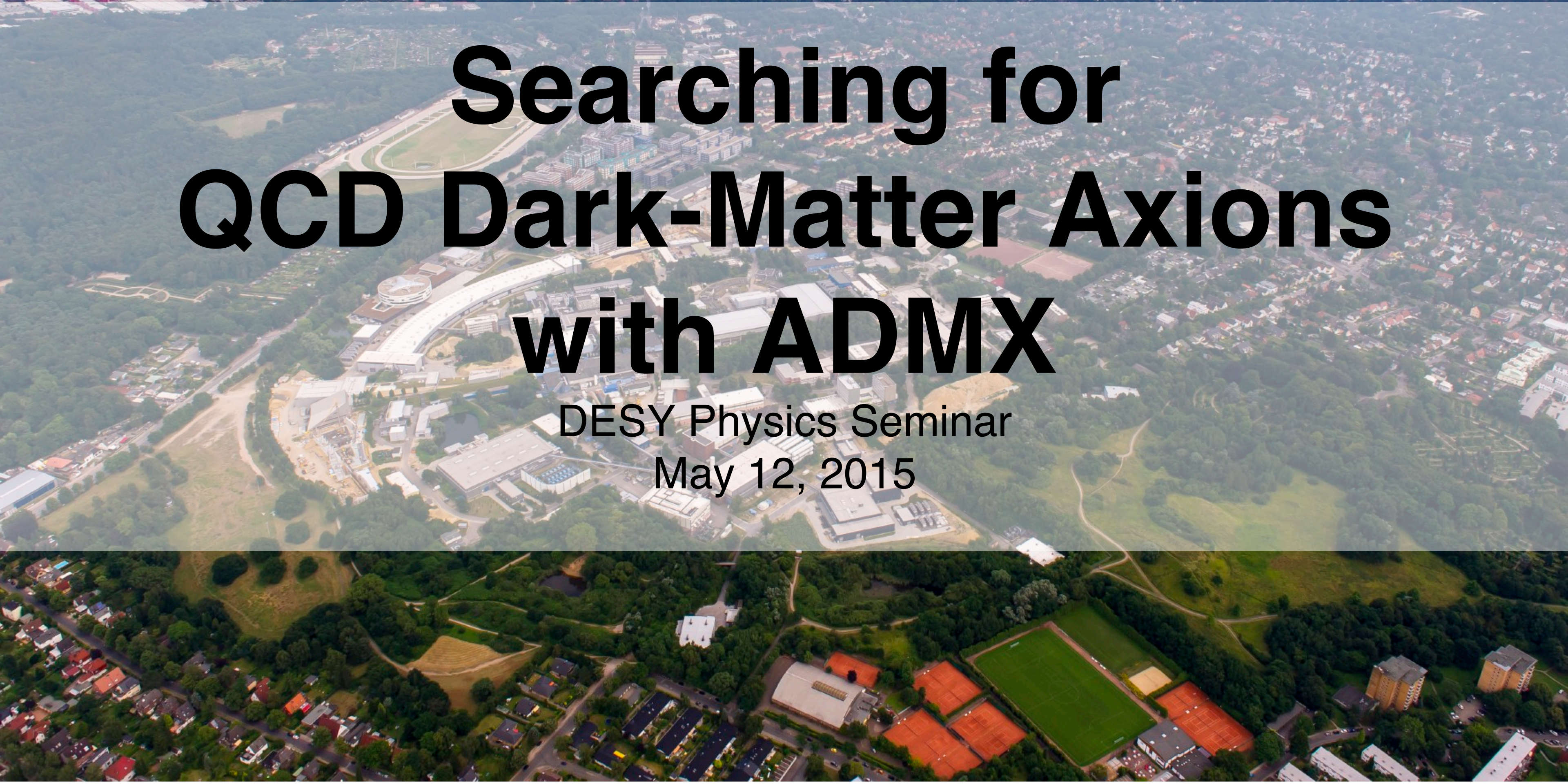

Searching for QCD Dark-Matter Axions with ADMX

DESY Physics Seminar
May 12, 2015

Leslie J Rosenberg
University of Washington

Searching for Axions

Outline

Basic axion properties

"Flagship" searches:

ALPS (laser)

CAST/IAXO (solar)

*** ADMX (RF cavity)

Overall status of axion searches

The longstanding problem of dark matter

FIRST ATTEMPT AT A THEORY OF THE ARRANGEMENT AND MOTION OF THE SIDEREAL SYSTEM[1]

By J. C. KAPTEYN[2]

ABSTRACT

First attempt at a general theory of the distribution of masses, forces, and velocities in the stellar system.—(1) *Distribution of stars.* Observations are fairly well represented, at least up to galactic lat. 70°, if we *assume that the equidensity surfaces are similar ellipsoids of revolution*, with axial ratio 5.1, and this enables us to compute quite readily (2) *the gravitational acceleration at various points due to such a system*, by summing up the effects of each of ten ellipsoidal shells, in terms of the acceleration due to the average star at a distance of a parsec. The *total number of stars* is taken as 47.4×10^9. (3) *Random and rotational velocities.* The nature of the equidensity surfaces is such that the stellar system cannot be in a steady state unless there is a general rotational motion around the galactic polar axis, in addition to a random motion analogous to the thermal agitation of a gas. In the neighborhood of the axis, however, there is no rotation, and the behavior is assumed to be like that of a gas at uniform temperature, but with a gravitational acceleration ($G\eta$) decreasing with the distance ρ. Therefore the density Δ is assumed to obey the barometric law: $G\eta = -\bar{u}^2(\delta\Delta/\delta\rho)/\Delta$; and taking the mean random velocity $\bar{u}$ as 10.3 km/sec., the author finds that (4) *the mean mass of the stars* decreases from 2.2 (sun = 1) for shell II to 1.4 for shell X (the outer shell), the average being close to 1.6, which is the value independently found for the average mass of both components of visual binaries. In the galactic plane the resultant acceleration—gravitational minus centrifugal—is again put equal to $-\bar{u}^2(\delta\Delta/\delta\rho)/\Delta$, $\bar{u}$ is taken to be constant and the average mass is assumed to decrease from shell to shell as in the direction of the pole. The angular velocities then come out such as to make the linear rotational velocities about constant and equal to 19.5 km/sec. beyond the third shell. If now we suppose that part of the stars are rotating one way and part the other, the relative velocity being 39 km/sec., we have a quantitative explanation of the phenomenon of star-streaming, where the relative velocity is also in the plane of the Milky Way and about 40 km/sec. It is incidentally suggested that when the theory is perfected it may be possible to determine *the amount of dark matter* from its gravitational effect. (5) The *chief defects of the theory* are: That the equidensity surfaces assumed do not agree with the actual surfaces, which tend to become spherical for the shorter distances; that the *position of the center of the system* is not the sun, as assumed, but is probably located at a point some 650 parsecs away in the direction galactic long. 77°, lat. −3°; that the average mass of the stars was assumed to be the same in all shells in deriving the formula for the variation of $G\eta$ with ρ on the basis of which the variation of average mass from shell to shell and the constancy of the rotational velocity were derived—hence either the assumption or the conclusions are wrong; and that no distinction has been made between stars of different types.

1. *Equidensity surfaces supposed to be similar ellipsoids.*—In *Mount Wilson Contribution* No. 188[3] a provisional derivation was given of the star-density in the stellar system. The question was there raised whether the inflection appearing near the pole in the

[1] *Contributions from the Mount Wilson Observatory*, No. 230.

[2] Research Associate of the Mount Wilson Observatory.

[3] *Astrophysical Journal*, **52**, 23, 1920.

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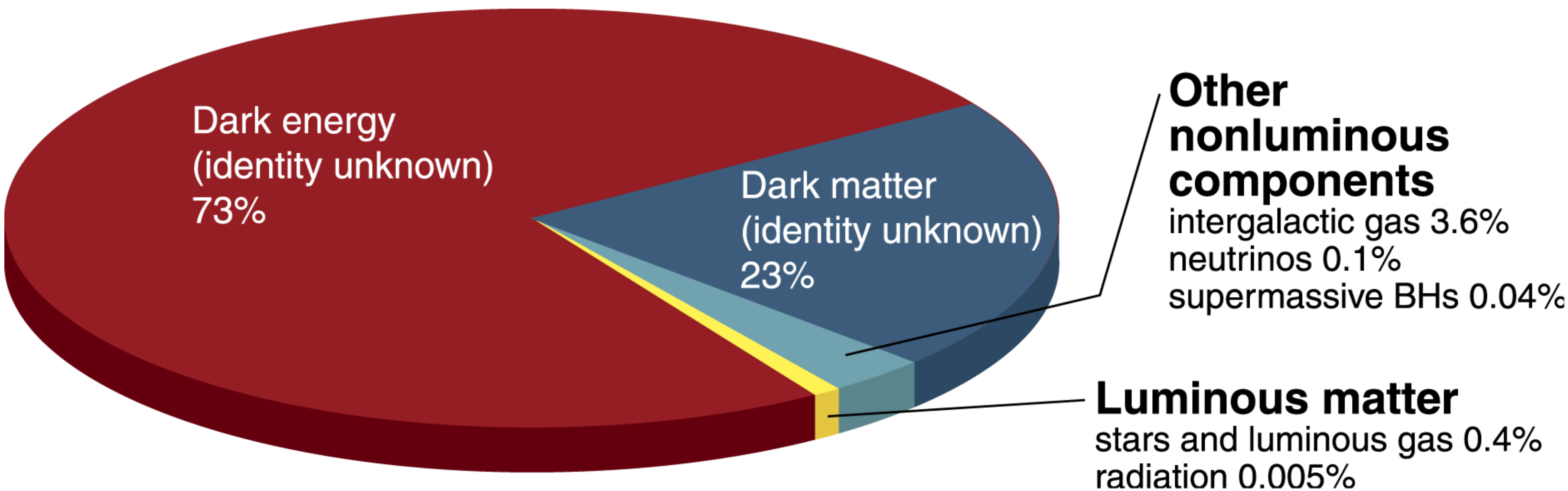
Kapetyn 1922

as to the distribution of dark matter. It would appear from the comparison that the dark mass must be relatively more frequent near the galactic plane than far from it, but the data are too uncertain to derive numerical results. A similar conclusion was reached by KAPTEYN in the investigation quoted above.

Recognized by Oort 1932

… then Zwicky, Smith …

Now: We've inventoried the cosmos …



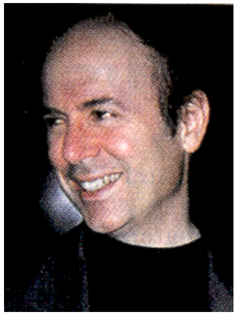
Science (20 June 2003)

… but we know neither what the "dark energy" or the "dark matter" is. These are two of the very big questions.

What do we know about the nature of dark matter? Its not normal matter or radiation and it's "cold"

(1) From light element abundance:
Dark matter probably isn't bowling balls or anything else made of baryons.

(2) Is dark matter made of, e.g., light neutrinos?
Probably not: fast moving neutrinos would have washed-out structure.
Dark matter is substantially "cold".



(3) "Dark matter: I'm much more optimistic about the dark matter problem. Here we have the unusual situation that two good ideas exist…"

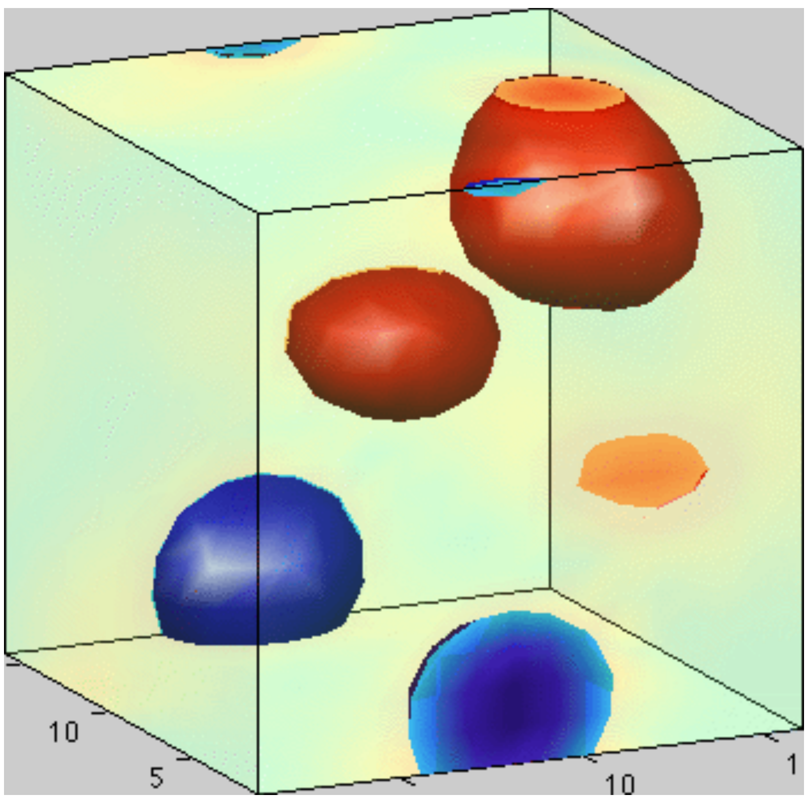
Frank Wilczek in Physics Today

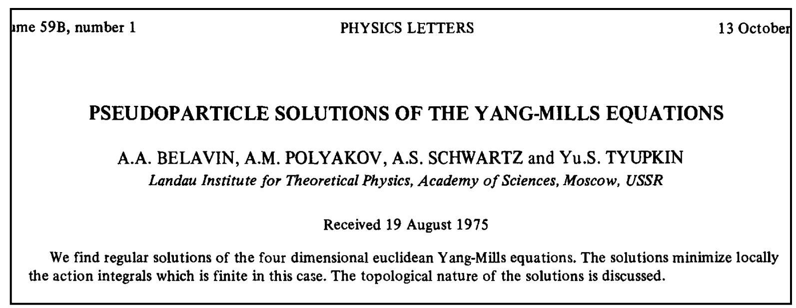
Frank's referring to WIMPS and Axions

New idea: Why does QCD conserve the symmetry CP?

1973: QCD…a gauge theory of color.
QCD theory embedded the observed conservation of C, P and CP.

1975: QCD + “instantons” ⇒ QCD is expected to be hugely CP-violating.




ıme 59B, number 1 PHYSICS LETTERS 13 October

PSEUDOPARTICLE SOLUTIONS OF THE YANG-MILLS EQUATIONS

A.A. BELAVIN, A.M. POLYAKOV, A.S. SCHWARTZ and Yu.S. TYUPKIN
Landau Institute for Theoretical Physics, Academy of Sciences, Moscow, USSR

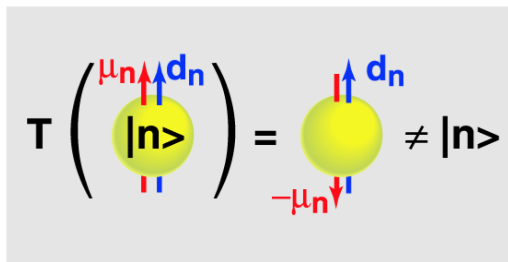
Received 19 August 1975

We find regular solutions of the four dimensional euclidean Yang-Mills equations. The solutions minimize locally the action integrals which is finite in this case. The topological nature of the solutions is discussed.

QCD on the lattice:
CP-violating instantons in 3D
(sort of)

Peccei and Quinn:
CP conserved through a hidden symmetry

QCD CP violation should, e.g., give a large neutron electric dipole moment (~~T~~ + CPT = ~~CP~~); none is unobserved.
(9 orders-of-magnitude discrepancy)



Why doesn't the neutron have an electric dipole moment?

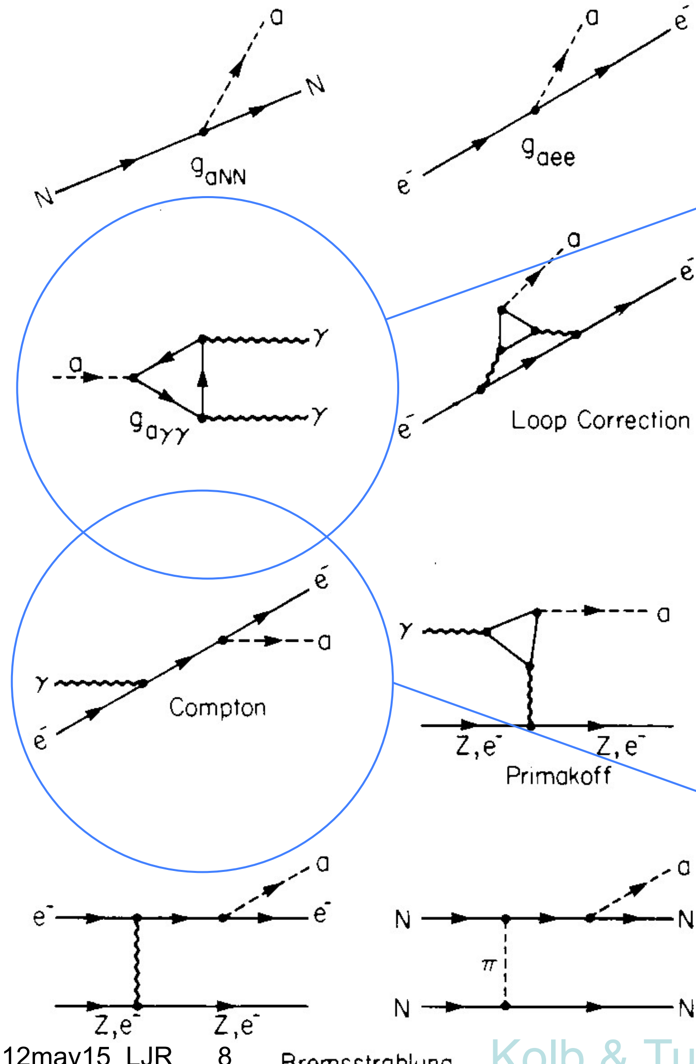
$d_e < 3 \cdot 10^{-26}$ e-cm
Baker et al. 2006

This leads to the "Strong CP Problem": Where did QCD CP violation go?

1977: Peccei and Quinn: Posit a hidden broken U(1) symmetry ⇒
1) A new Goldstone boson (the axion);
2) Remnant axion VEV nulls QCD CP violation.

What's a QCD axion?

Selected axion couplings
& the important two-photon coupling



A process with small model uncertainty
Exploited in certain terrestrial searches
Easily calculable

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

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

A process with larger model uncertainty
Can occur, e.g., in the Sun
Contains unknown $U(1)_{PQ}$ charge of electron
(e.g., white-dwarf cooling)

Kolb & Turner

Summary properties of the axion

- The Axion is a light pseudoscalar resulting from the Peccei-Quinn mechanism to enforce strong-CP conservation

- f_a, the SSB scale of PQ-symmetry, is the one important parameter in the theory

Mass and Couplings

$$m_a \sim 6\ \mu eV \cdot \left(\frac{10^{12}\ GeV}{f_a}\right)$$

Generically, all couplings

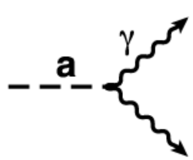
$$g_{aii} \propto \frac{1}{f_a}$$

Cosmological Abundance

$$\Omega_a \sim \left(\frac{5\ \mu eV}{m_a}\right)^{7/6}$$

(Vacuum misalignment mechanism)

Coupling to Photons



$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a};\ g_\gamma = \begin{cases} 0.97\ \text{KSVZ} \\ -0.36\ \text{DFSZ} \end{cases}$$

Axion Mass 'Window'

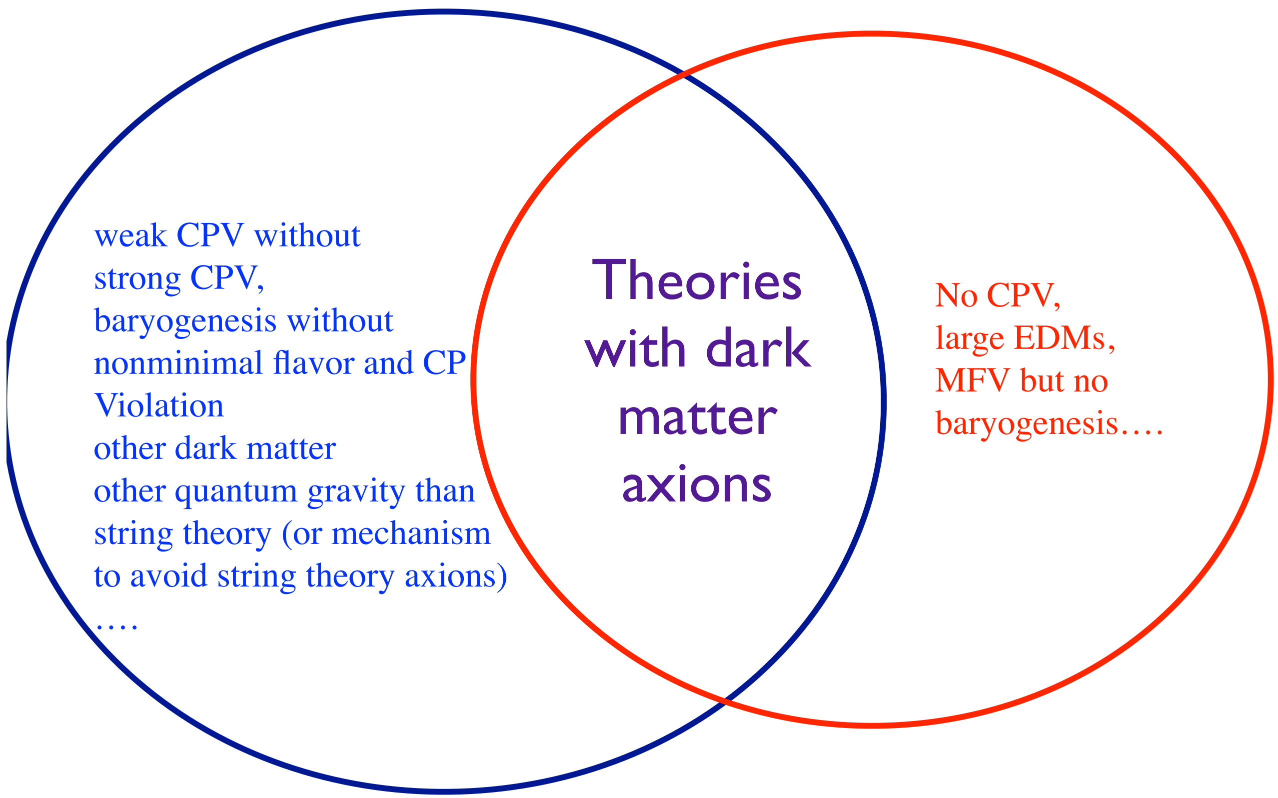
$$10^{-(5\ \text{to}\ 6)}\ eV < m_a < 10^{-(2\ \text{to}\ 3)}\ eV$$

(Overclosure) (SN1987a)

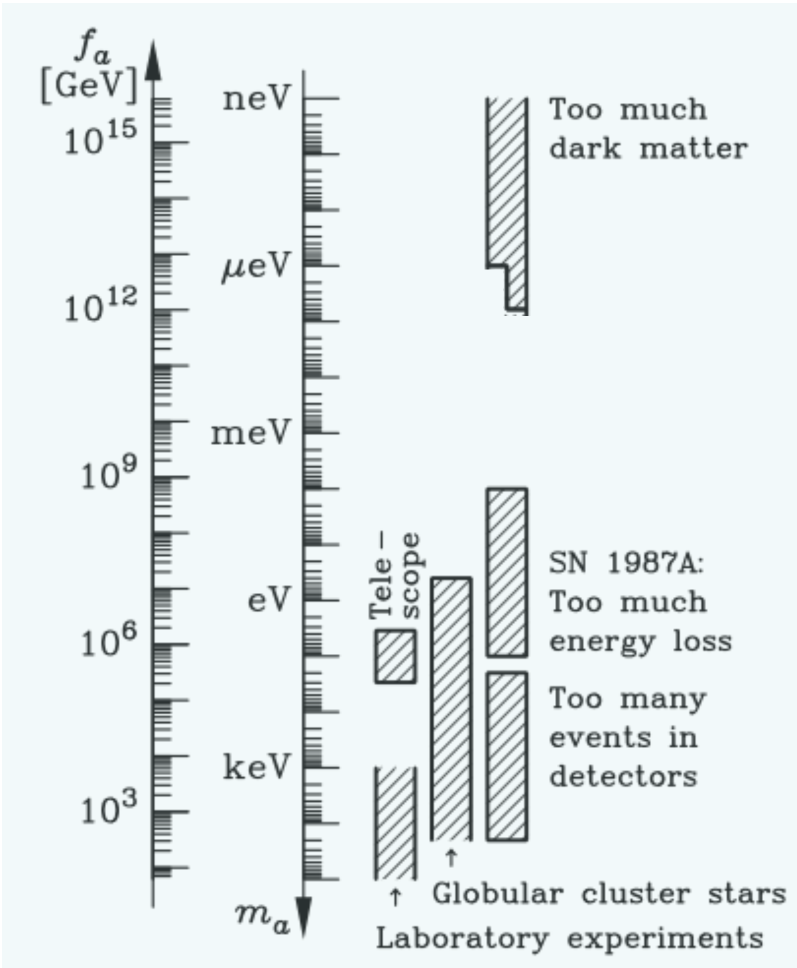
With lower end of window preferred if $\Omega_{CDM} \sim 1$

Axions in particle physics: From A. Nelson

Viable Theories   Natural and Elegant Theories



Present bounded window of allowed "QCD" axion masses



Very light axions forbidden: else too much dark matter

⇐Dark matter range:"axion window"

very hard to detect "invisible axions"

Heavy axions forbidden: else new pion-like particle

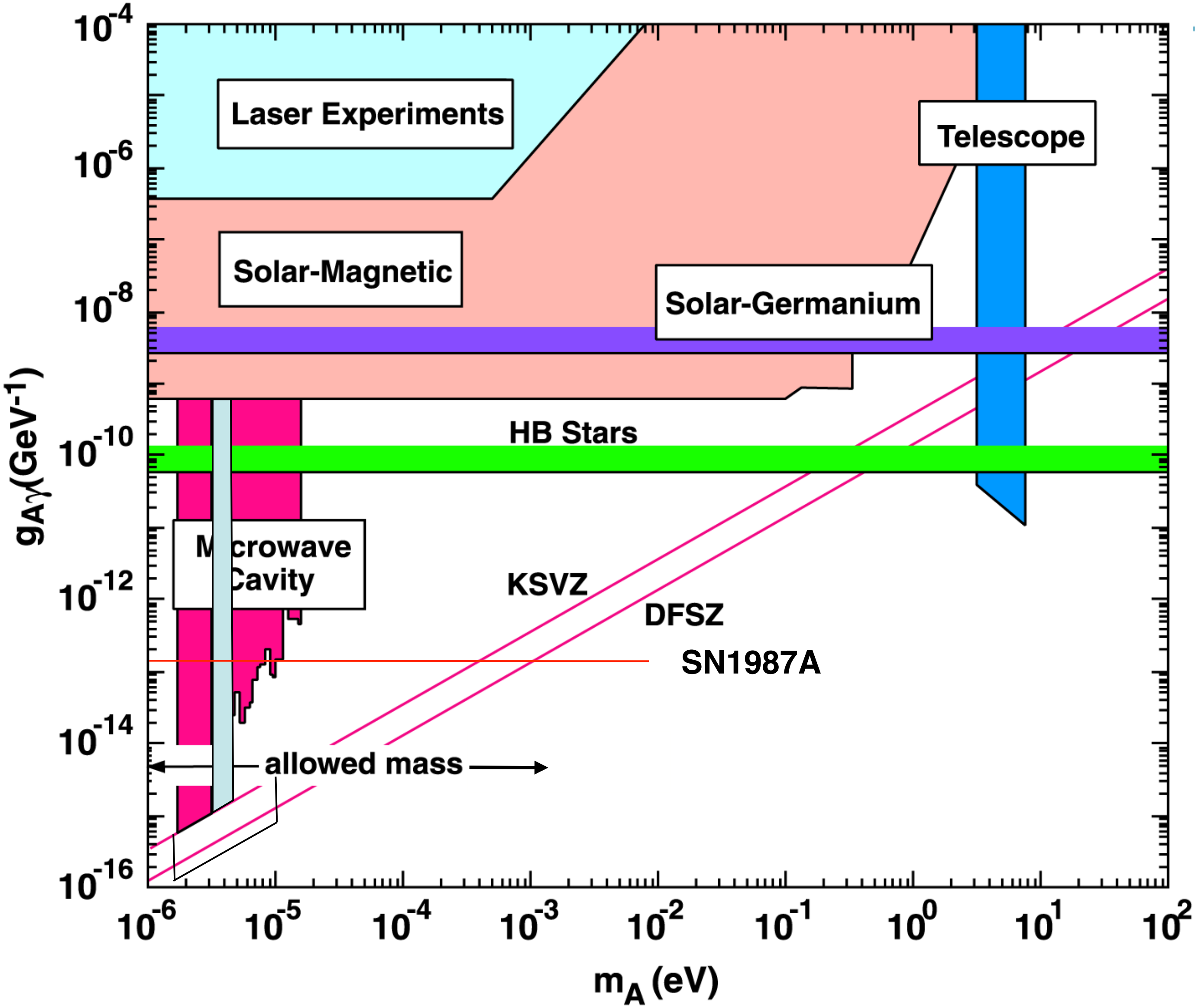
Recap: Axions and dark matter (the QCD dark-matter axion)

Some properties of dark matter:
Almost no interactions with normal matter and radiation ("dark…");
Gravitational interactions ("…matter");
Cold (slow-moving in the early universe);

Dark matter properties are those of a low-mass axion:
Low mass axions are an ideal dark matter candidate:
"Axions: the thinking persons dark-matter candidate", Michael Turner.

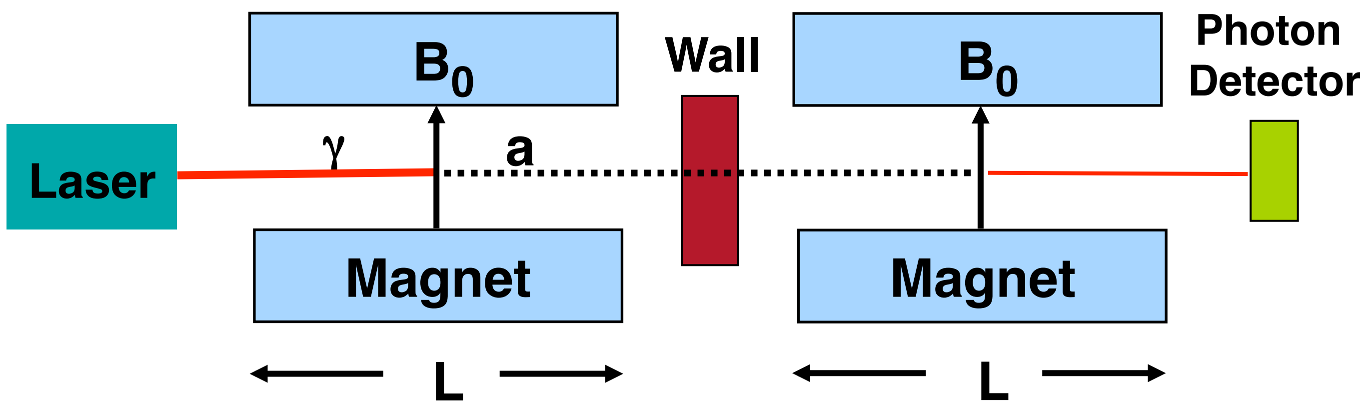
Plus…
The axion mass is constrained to 1 or 2 orders-of-magnitude;
Some axion couplings are constrained to 1 order-of-magnitude;
The axion is doubly-well motivated…it solves 2 problems (Occam's razor).

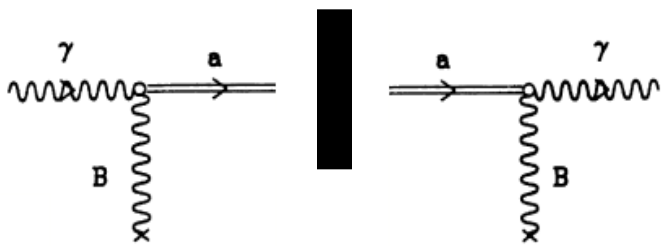
Selected limits on QCD axion masses and couplings



"Despite a lot of effort that has gone into understanding the axion emission rate, these limits remain fairly rough estimates." Georg Raffelt

Search 1: Photon regeneration
("shining light through walls")

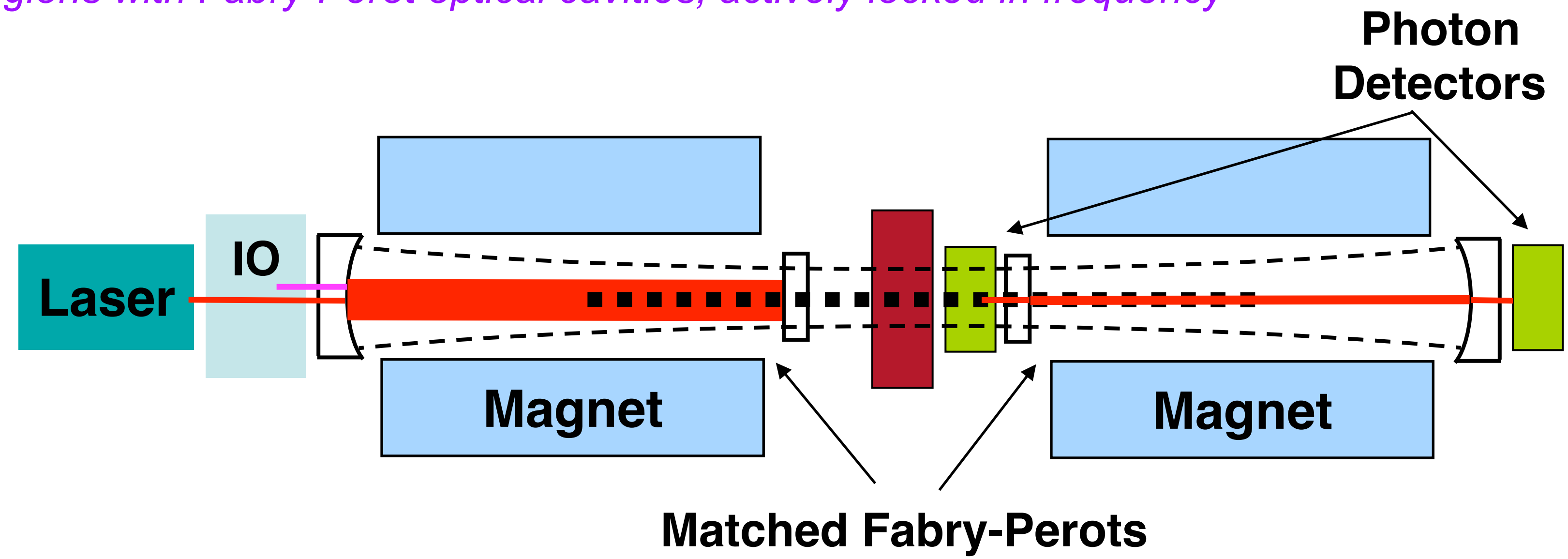




$$P(\gamma \rightarrow a \rightarrow \gamma) \sim 1/16\ (gB_0L)^4$$

Search 1: resonantly enhanced photon regeneration

Basic concept – encompass the production and regeneration magnet regions with Fabry-Perot optical cavities, actively locked in frequency

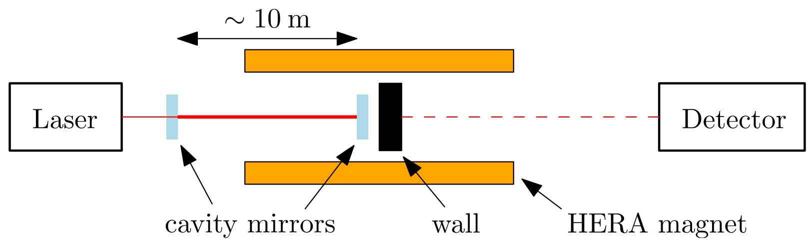


$$P^{\mathrm{Re}\,sonant}(\gamma \to a \to \gamma) = \frac{2}{\eta\eta'} \cdot P^{Simple}(\gamma \to a \to \gamma) = \frac{2}{\pi^2} FF' \cdot P^{Simple}(\gamma \to a \to \gamma)$$

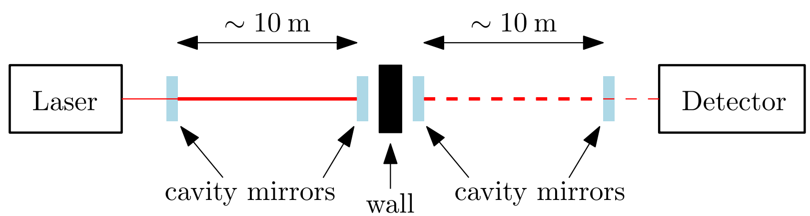
where η, η' are the mirror transmissivities & F, F' are the finesses of the cavities

For $\eta \sim 10^{(5\text{-}6)}$, the gain in rate is of order $10^{(10\text{-}12)}$ and the limit in $g_{a\gamma\gamma}$ improves by $10^{(2.5\text{–}3)}$

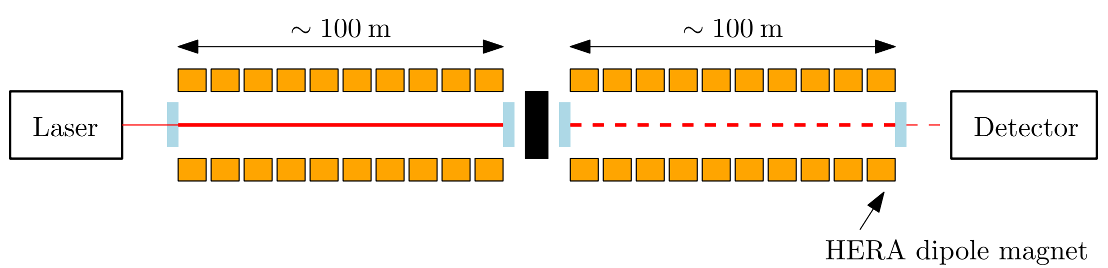
Flagship Search 1: ALPS-II at DESY



(a) ALPS-I

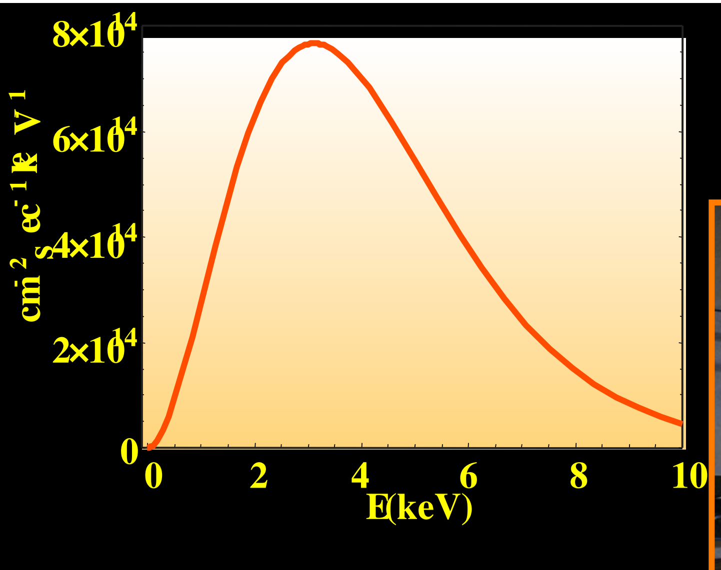


(b) ALPS-IIa

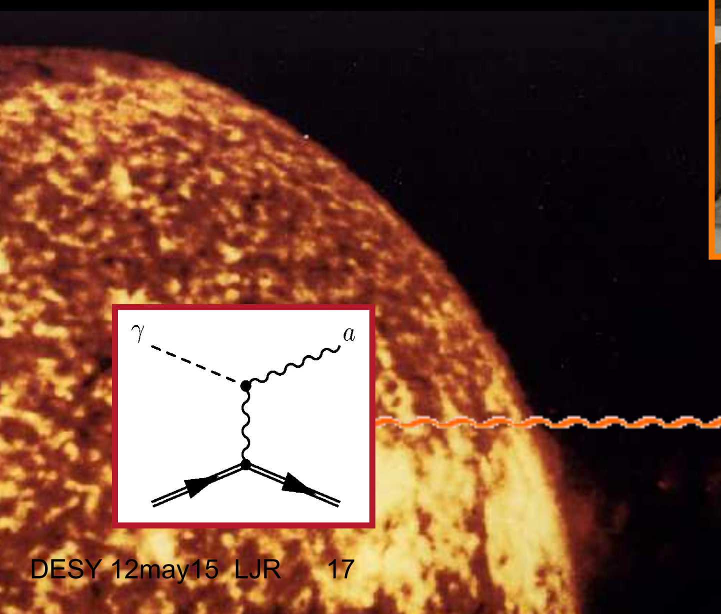


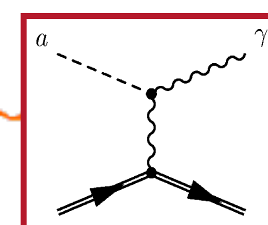
(d) ALPS-IIc

Flagship Search 2: CERN Axion Solar Telescope (CAST). Searching for axions produced in the Sun.



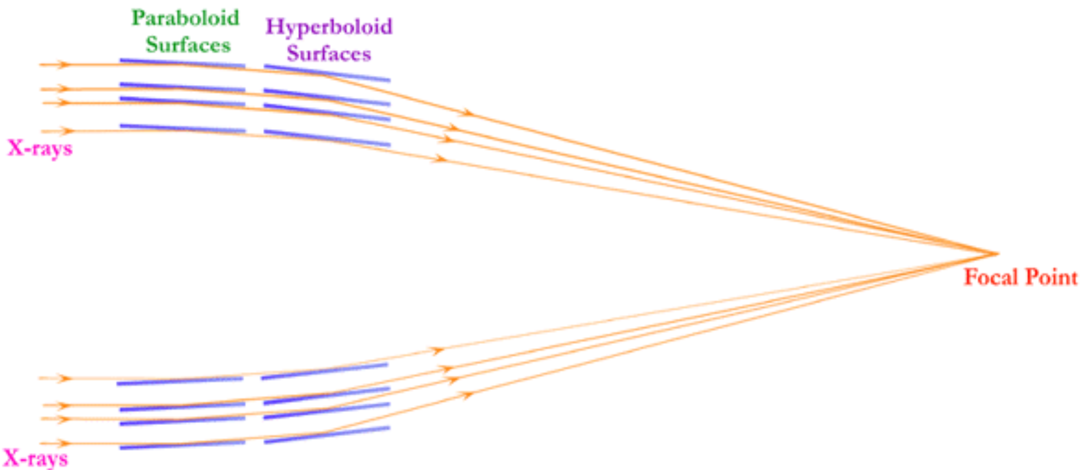
Axions from the sun become x-rays inside a spare LHC dipole magnet



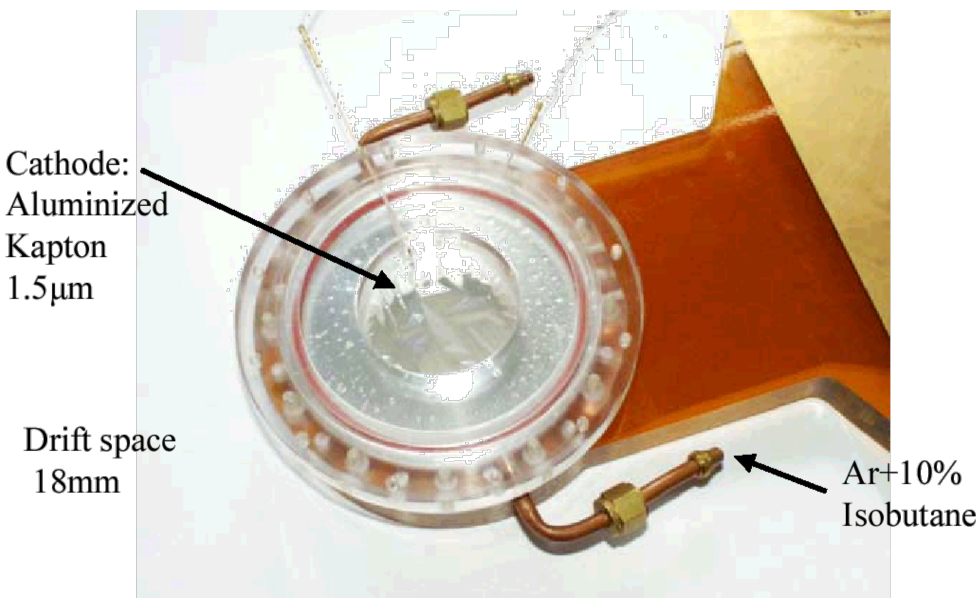


Search 2: CAST Technology

State-of-the-art x-ray detection borrowed from astrophysics



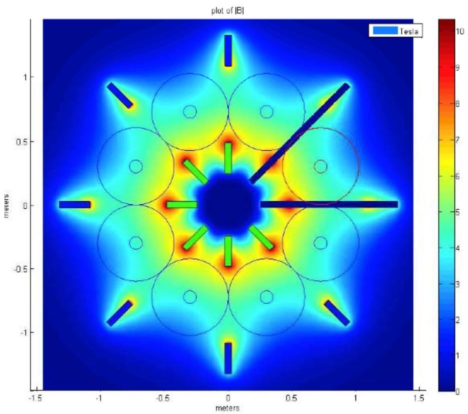
Grazing-incidence x-ray optics

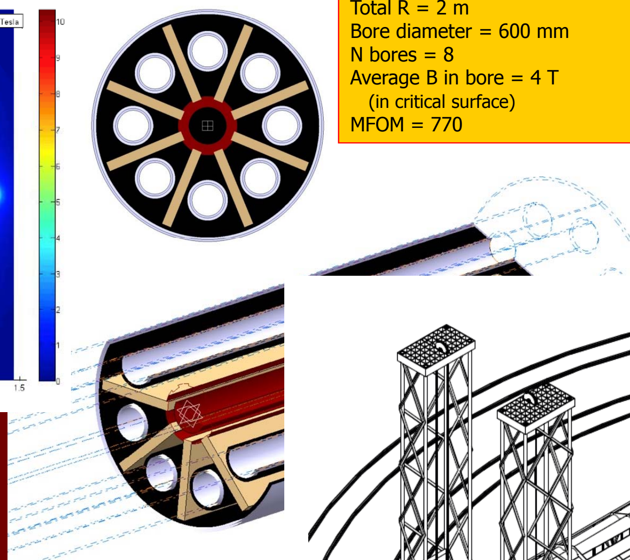


Micromegas x-ray camera & Si drift sensors.

Search 2: Helioscope Futurism IAXO

IAXO magnet: 1st concept

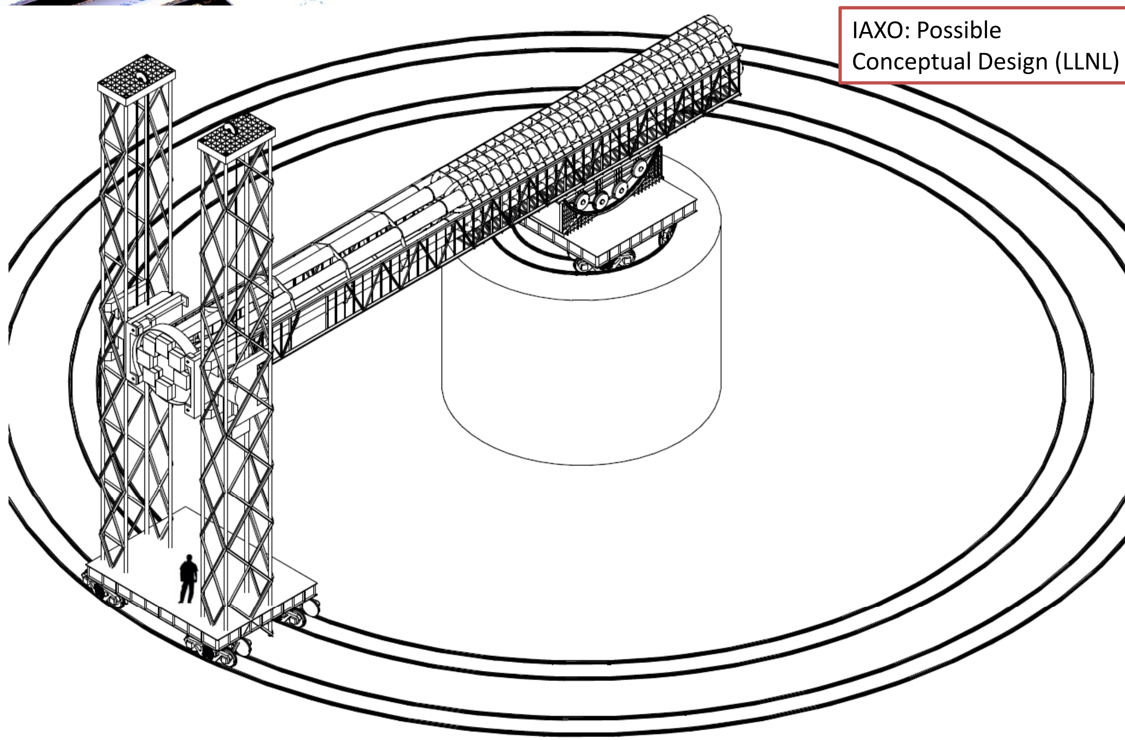




Total R = 2 m
Bore diameter = 600 mm
N bores = 8
Average B in bore = 4 T
(in critical surface)
MFOM = 770

IAXO scenario 2 conservative
Surpass IAXO scenario 3 is possible
Further optimization ongoing

INT Washington, April 2012 Igor G. Irastorza / Universidad de Zaragoza



IAXO: Possible Conceptual Design (LLNL)

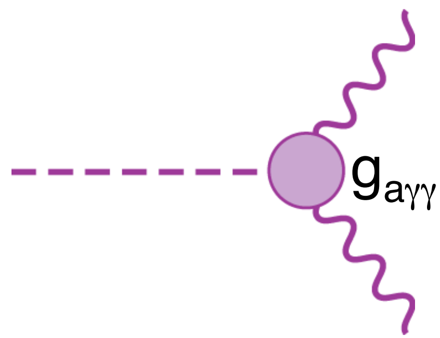
INT Washington, April 2012 Igor G. Irastorza / Universidad de Zaragoza

Search 3: RF cavity experiments

Recall:

The axion couples (very weakly, indeed) to normal particles.

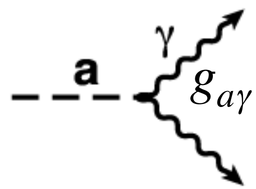
But it happens that the axion 2γ coupling has relatively little axion-model dependence



Axions constituting our local galactic halo would have huge number density ~10^{14} cm^{-3}

Pierre Sikivie's RF-cavity idea (1983): Axion and electromagnetic fields exchange energy

The axion-photon coupling…



…is a source term in Maxwell's Equations

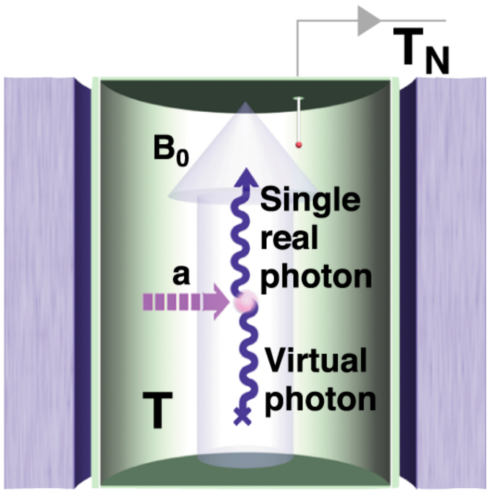
$$\frac{\partial\left(\mathbf{E}^2/2\right)}{\partial t} - \mathbf{E}\cdot\left(\nabla\times\mathbf{B}\right) = g_{a\gamma}\dot{a}\left(\mathbf{E}\cdot\mathbf{B}\right)$$

This leads to many possible experimental approaches.

One approach is to impose a strong external magnetic field B; this transfers axion field energy into cavity electromagnetic fields E.

Some experimental details of the RF-cavity technique

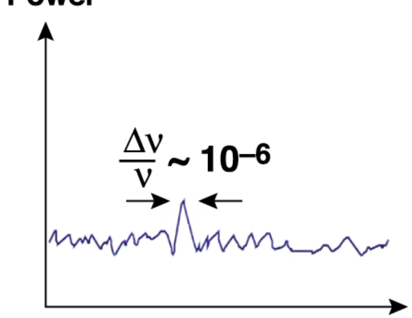
Primakoff Conversion



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

The search speed is quadratic in 1/Ts

Signal

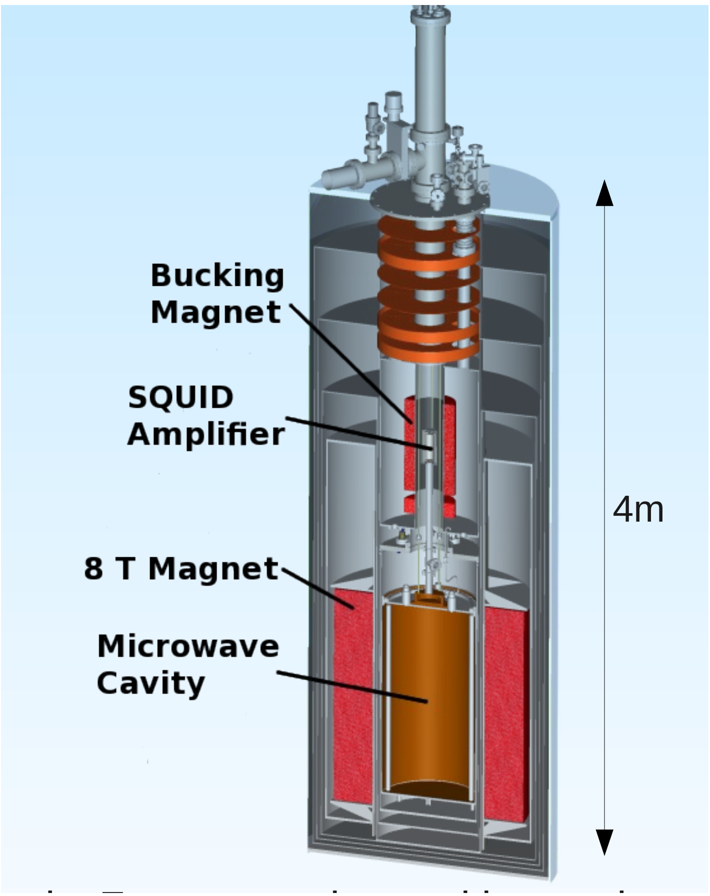


Scaling Laws	
$\frac{d\nu}{dt} \propto B^4 V^2 \cdot \frac{1}{T_S^2}$	$g_\gamma^2 \propto \left(B^2 V \cdot \frac{1}{T_S}\right)^{-1}$
For fixed model g^2	For fixed scan rate $\frac{d\nu}{dt}$

Flagship Search 3:
Axion Dark-Matter eXperiment (ADMX)

U. Washington, LLNL, U. Florida, U.C. Berkeley, National Radio Astronomy Observatory, Sheffield U., Yale U. + … (recently expanded)

Magnet with insert



Magnet cryostat

ADMX is Generation 2 Dark-Matter Detector

Courtesy of NASA

breaking

July 11, 2014

US reveals its next generation of dark matter experiments

Together, the three experiments will search for a variety of types of dark matter particles.

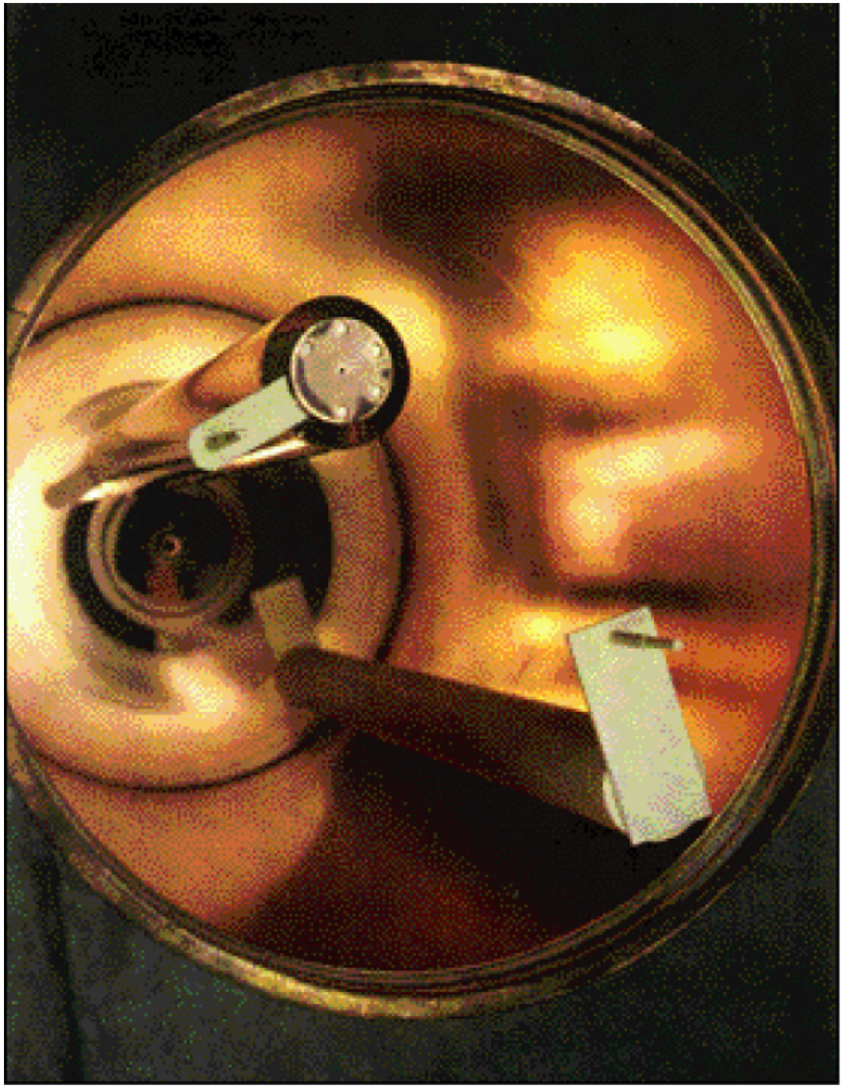
By Kathryn Jepsen

Two US federal funding agencies announced today which experiments they will support in the next generation of the search for dark matter.

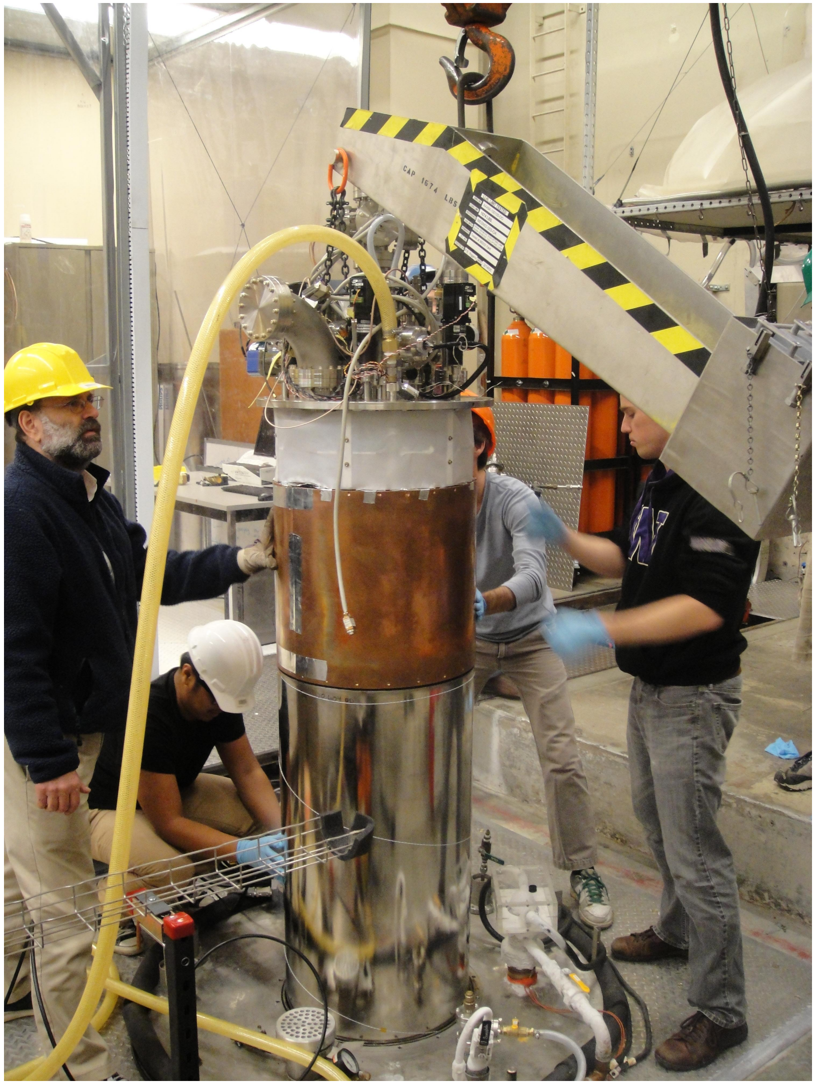
Symmetry Magazine

ADMX key hardware 1

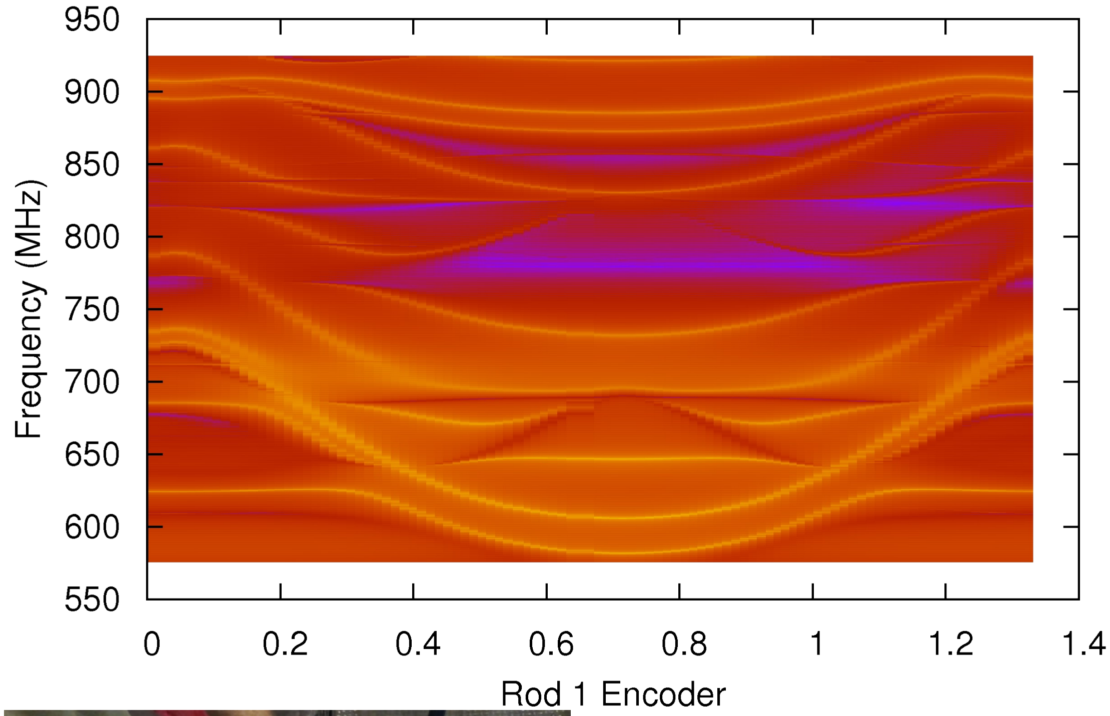
high-Q microwave cavity

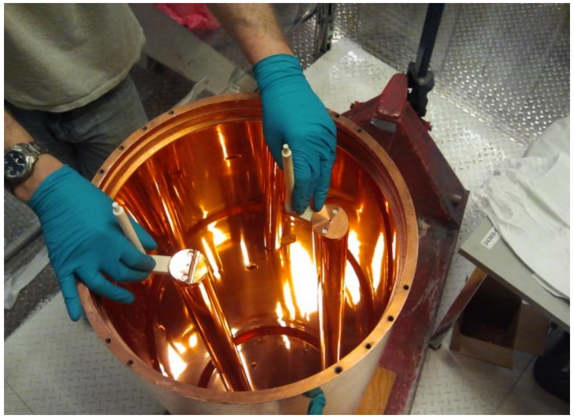


Experiment insert

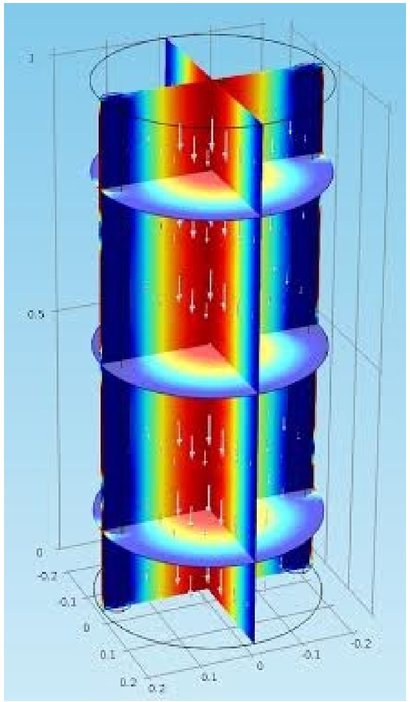


ADMX key hardware 2: Tuning





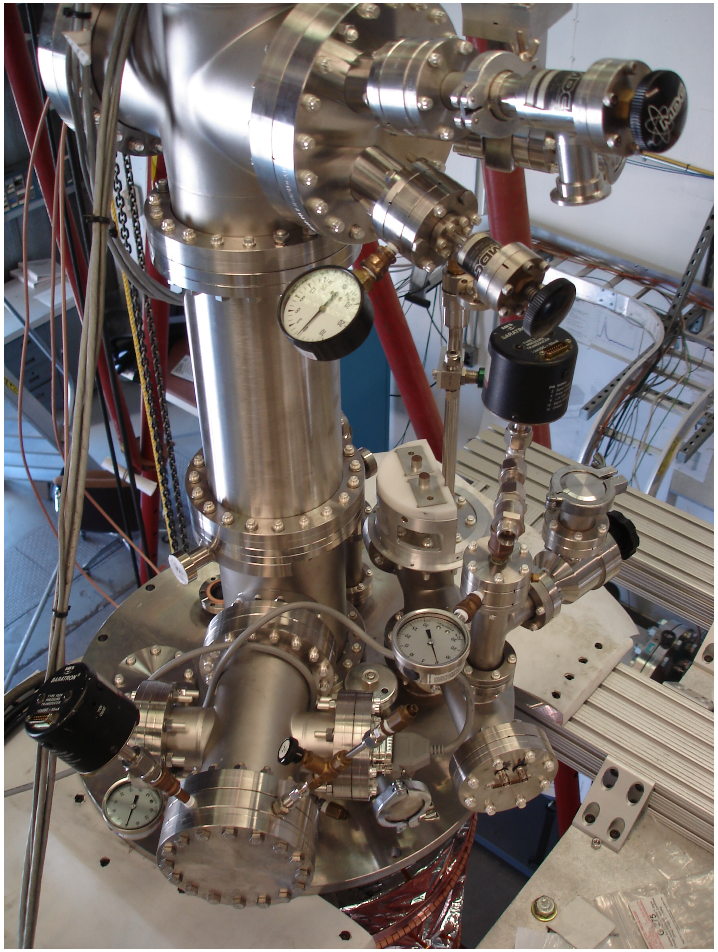
Cavity with lid off, showing tuning rods



Field simulation of TM010 mode, no rods

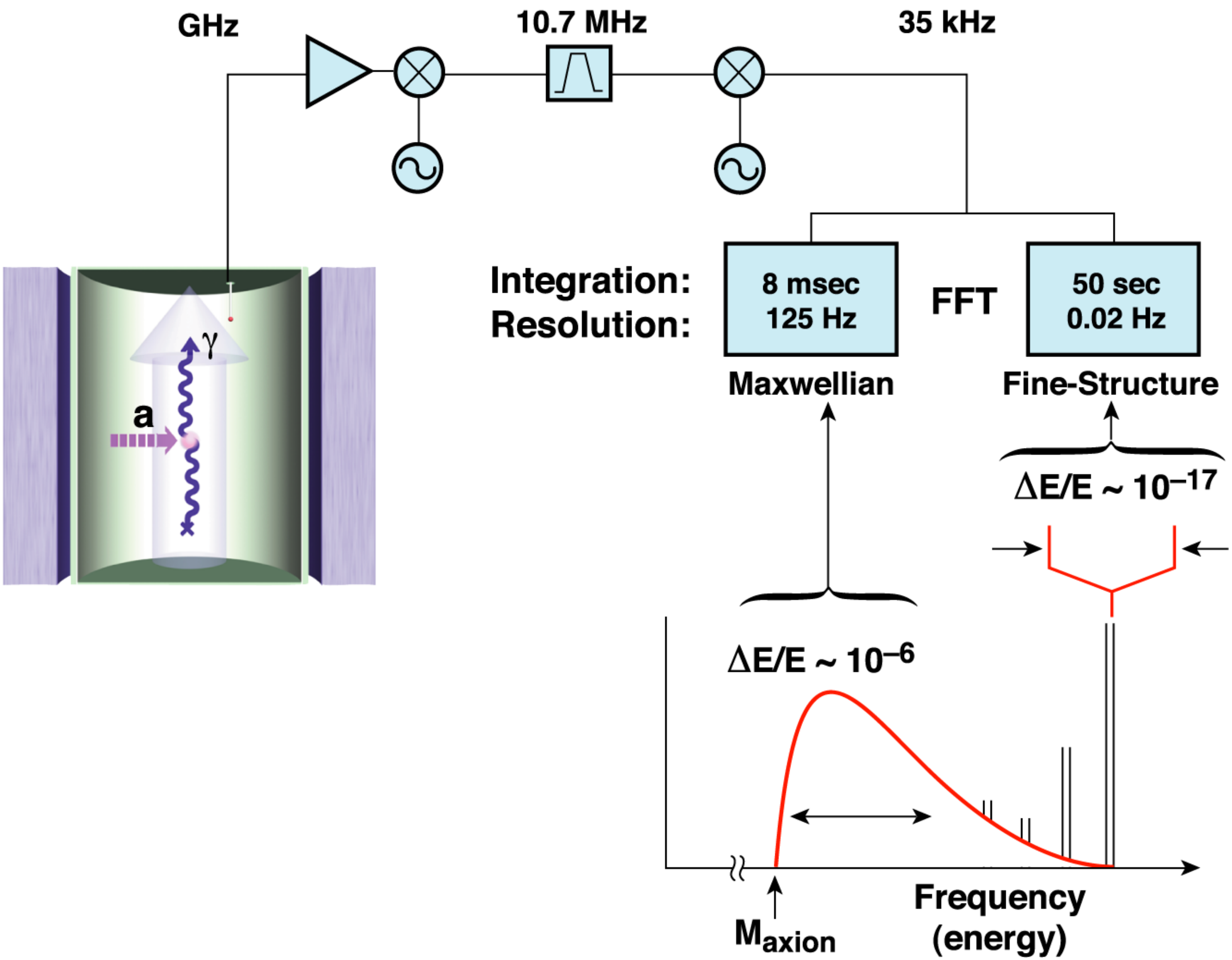
ADMX key hardware 3

Vacuum and cryo

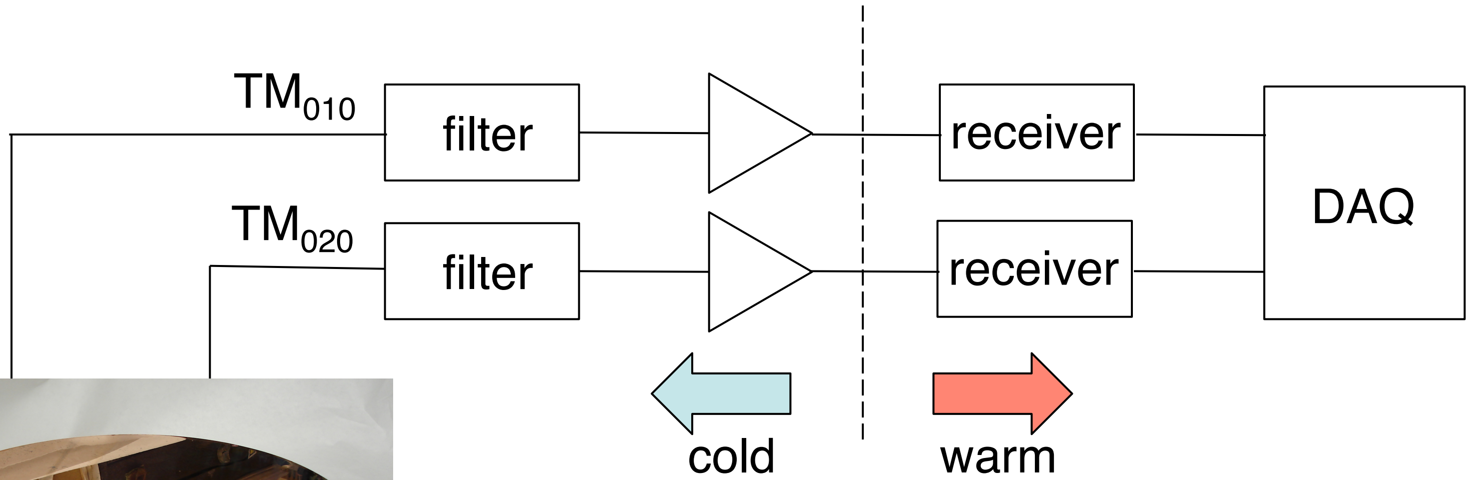


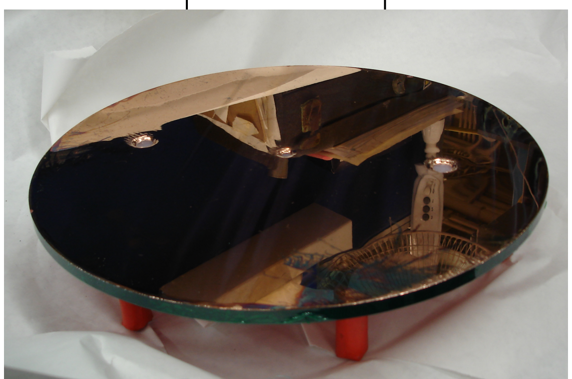
Quantum electronics

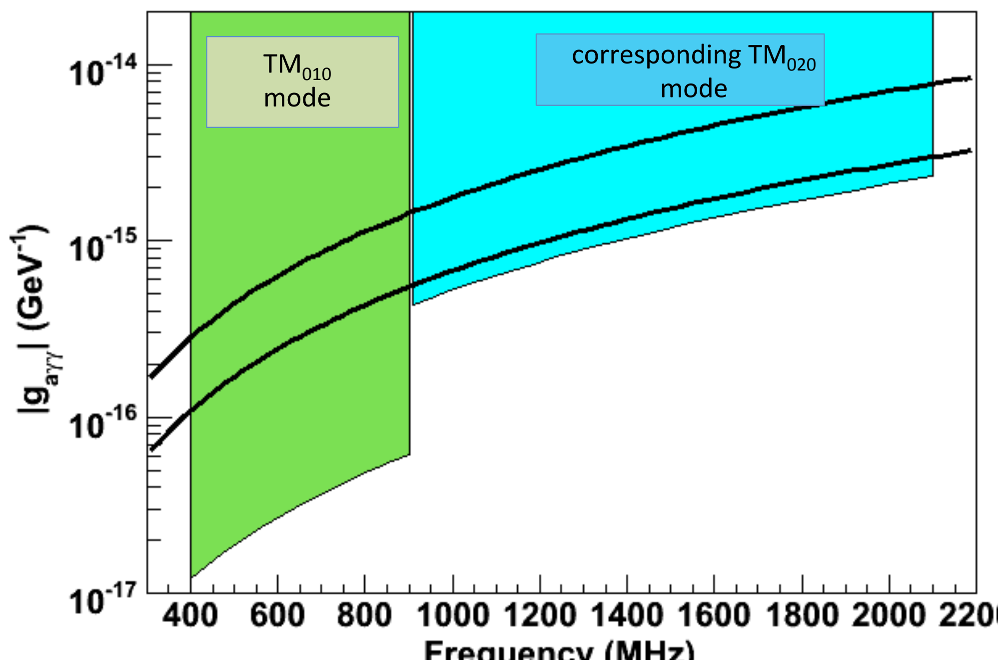
ADMX key hardware 4: axion receiver



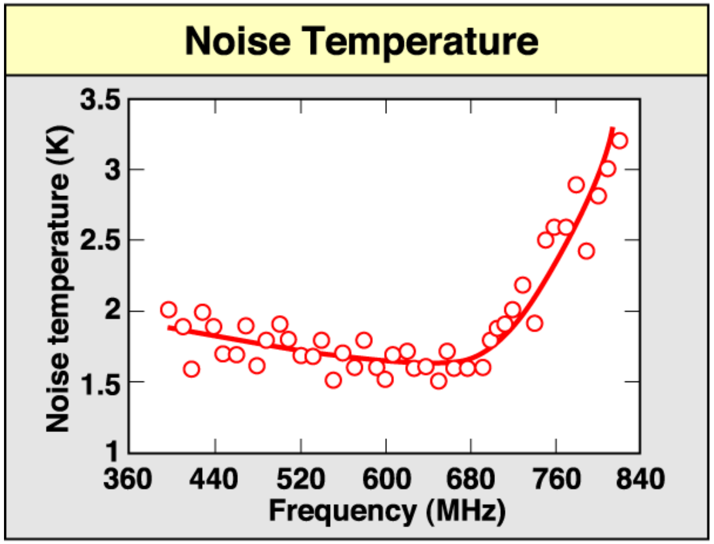
ADMX: Multi-mode readout

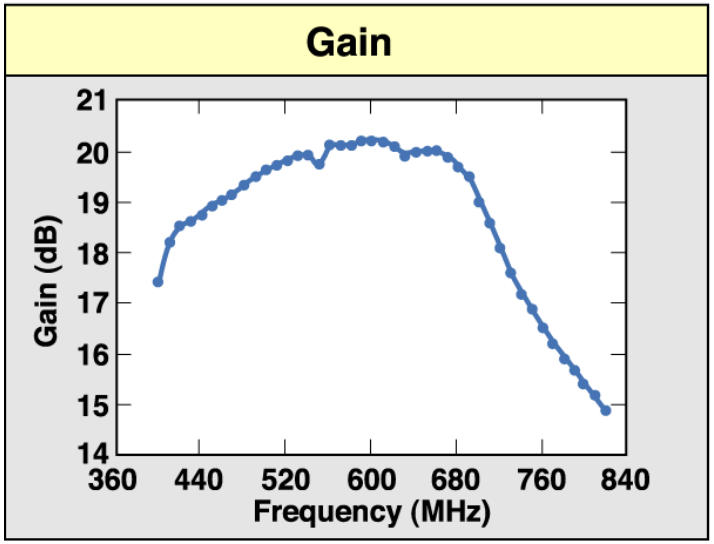






A brief digression on microwave amplifiers





HFET amplifiers
(Heterojunction Field-Effect Transistor)

- **A.k.a. HEMT™ (High Electron Mobility Transistor)**
- **Workhorse of radio astronomy, military communications, etc.**

- **Best to date $T_N \gtrsim 1$ K**

But the quantum limit $T_Q \sim h\nu/k$ at 500 MHz is only ~ 25 mK!

A quantum-limited amplifier would both give us definitive sensitivity, *and* dramatically speed up the search!

Quantum-limited SQUID-based amplification

APPLIED PHYSICS LETTERS VOLUME 78, NUMBER 7 12 FEBRUARY 2001

Superconducting quantum interference device as a near-quantum-limited amplifier at 0.5 GHz

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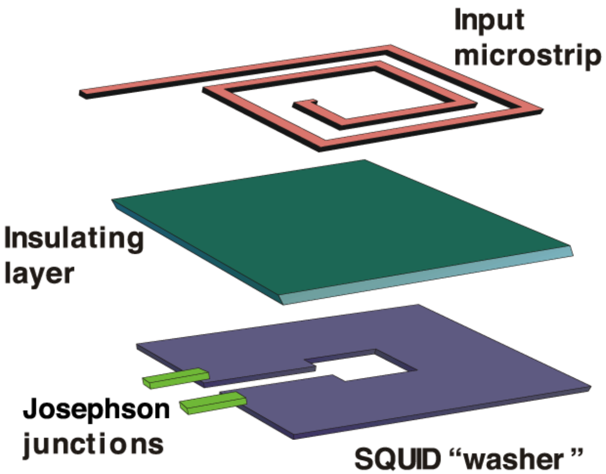
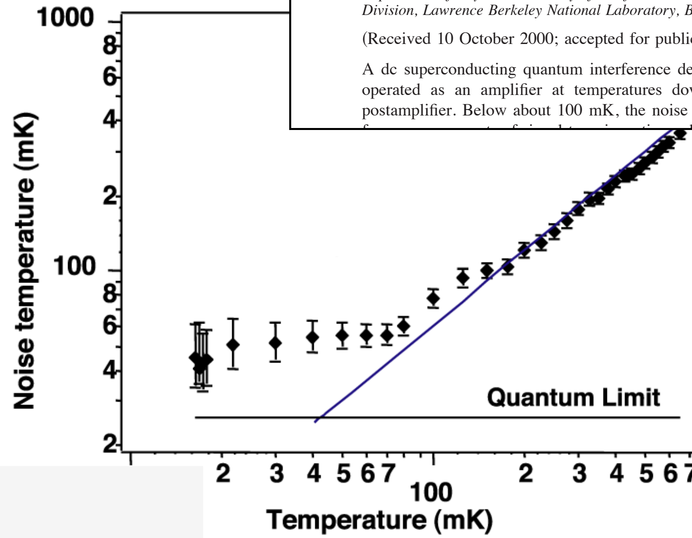
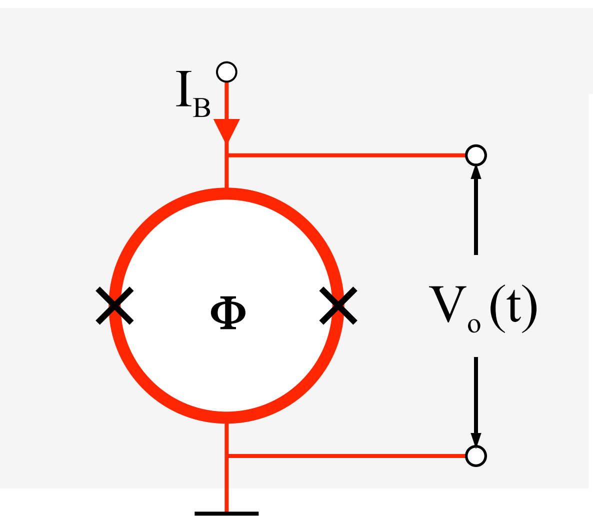
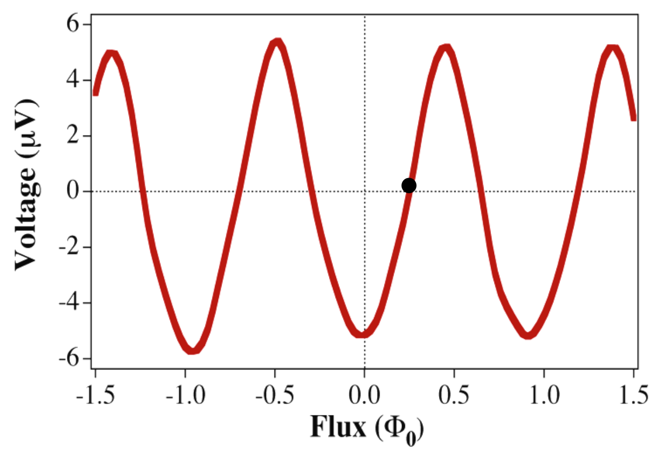
A dc superconducting quantum interference device (SQUID) with a resonant microstrip input is operated as an amplifier at temperatures down to 20 mK. A second SQUID is used as a postamplifier. Below about 100 mK, the noise temperature is 52±20 mK at 538 MHz, estimated



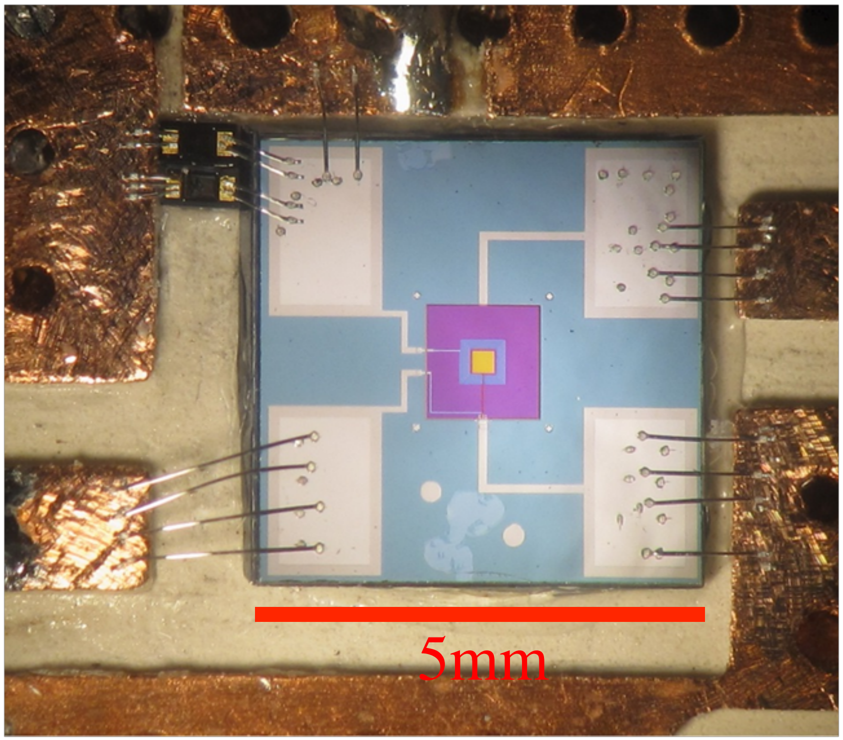




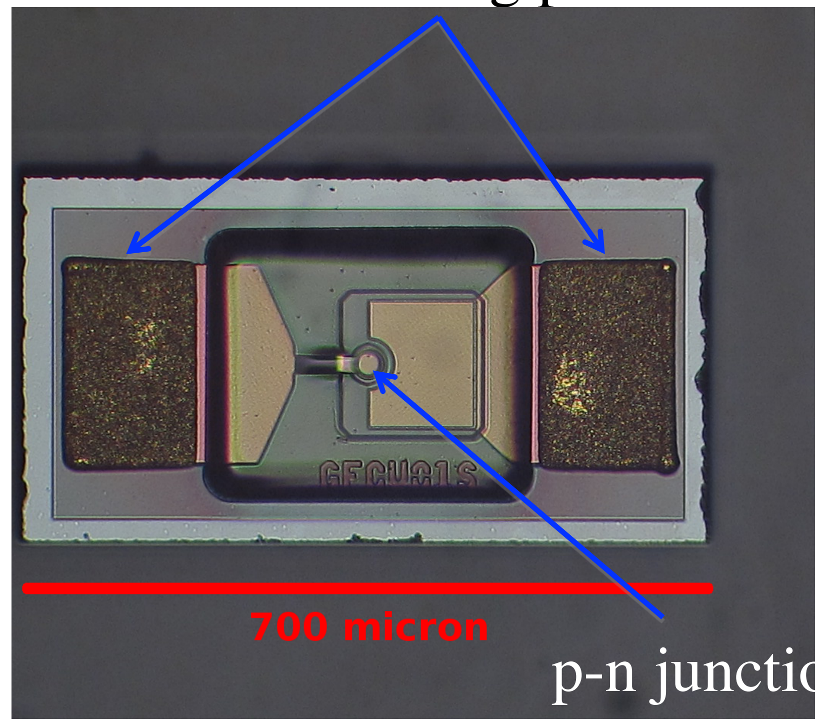


- GHz SQUIDs have been measured with T_N ~50 mK
- Near quantum–limited noise
- This provides an enormous increase in ADMX sensitivity

Microstrip SQUID amplifiers with varactor tuning

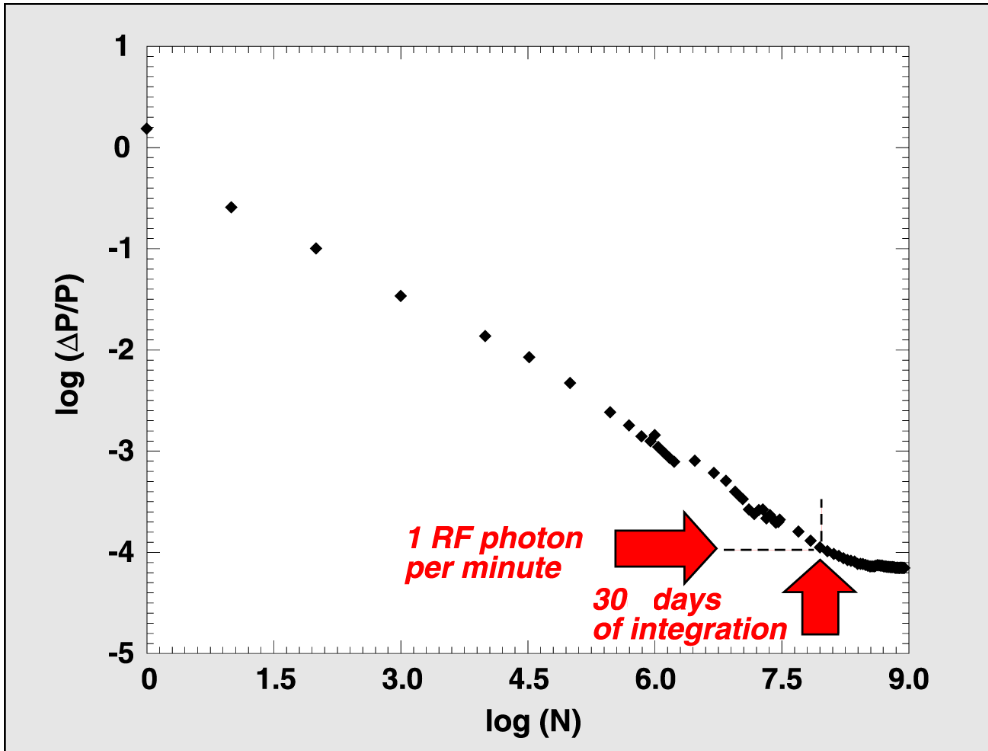


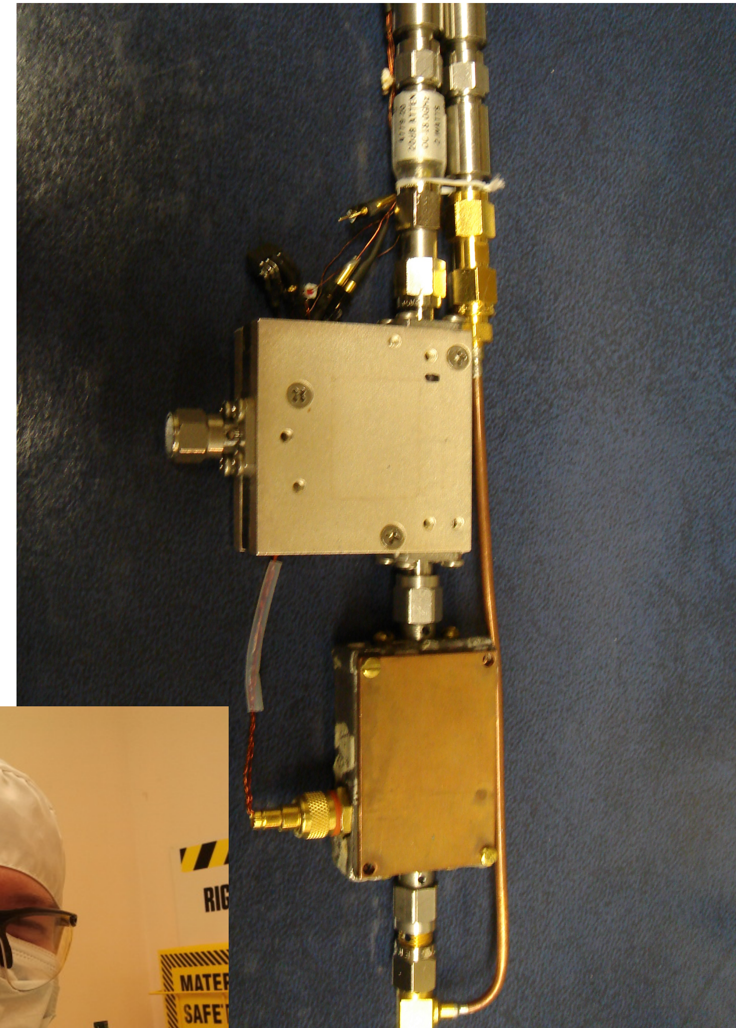
SQUID washer

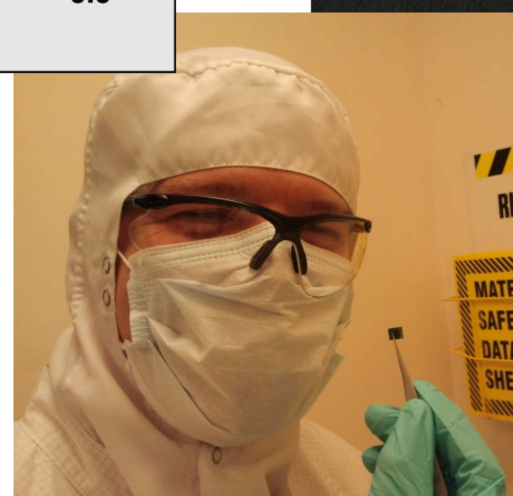


varactor tuning

SQUIDs and lower system noise

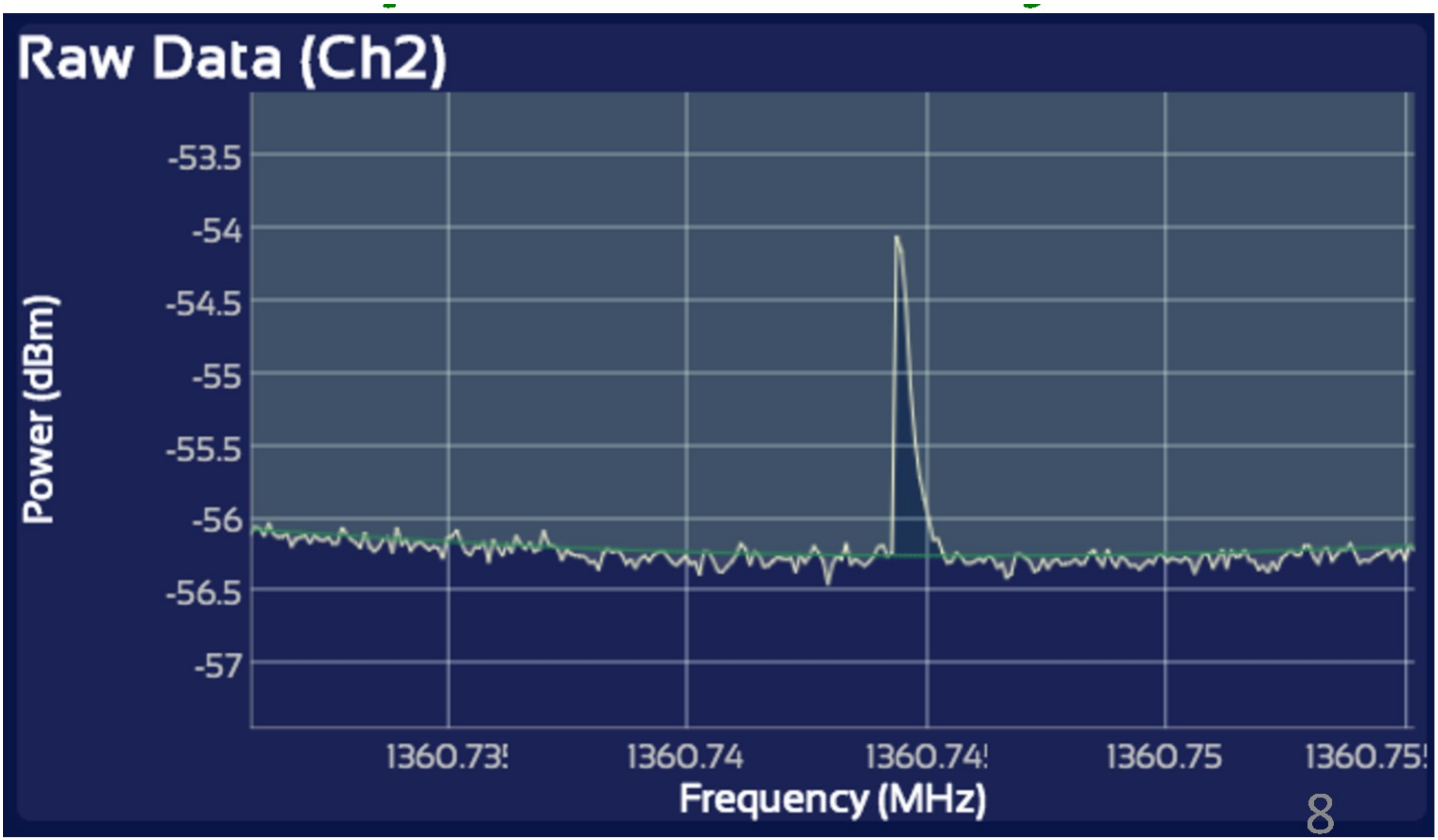






Systematics-limited for signals < 10^{-26} W ~10^{-3} of "DFSZ" axion power (< 1/100 yoctoWatt).

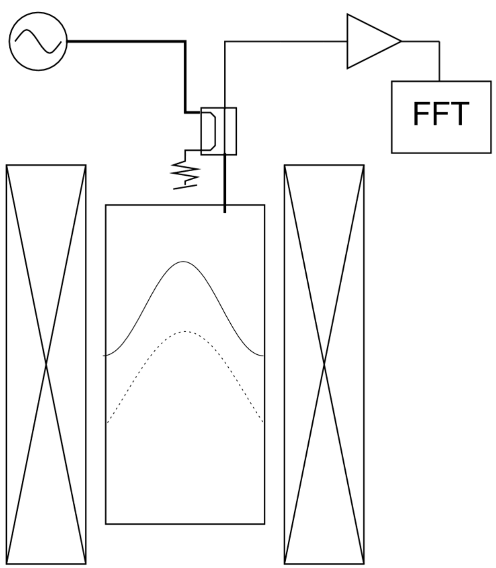
Raw data and hardware synthetic axion (×100)



Operations include searches for exotics: "Chameleons" & hidden-sector photons

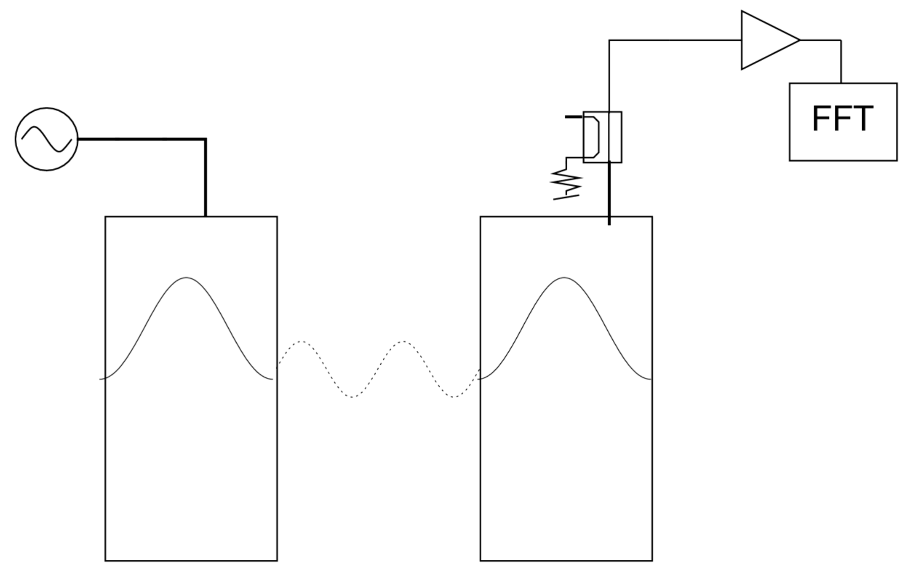
Chameleons

Scalars/pseudoscalars that mix with photons, and are trapped by cavity walls. Arise in some dark energy theories. Detectable by slow decay back into photons in cavity



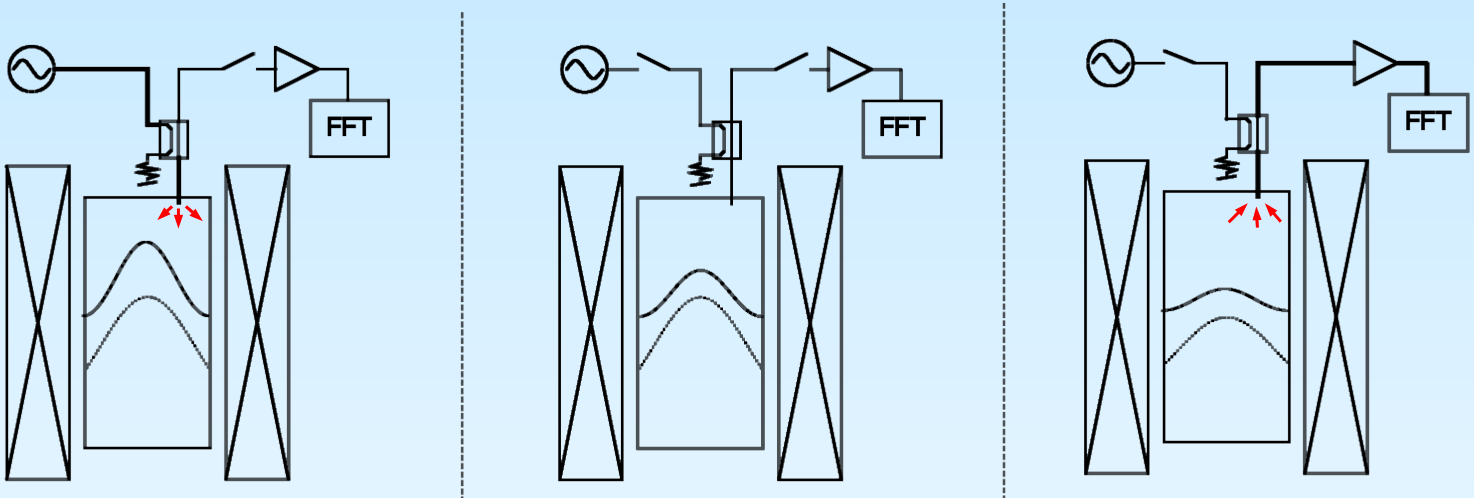
Hidden-sector photons

Vector bosons with photon quantum numbers and very weak interactions. Detectable by reconverting HSPs back into photons in ADMX cavity



Chameleons: How experiment worked

ADMX as a chameleon-photon regenerator



Step 1: Injected RF power excites E&M and chameleon modes

Timescale: 10 minutes

Power in ~25 dBm

Step 2: Power is turned off, E&M modes decay

Timescale: 100 milliseconds

Step 3: Chameleon modes slowly decay into E&M modes which are detected through antenna

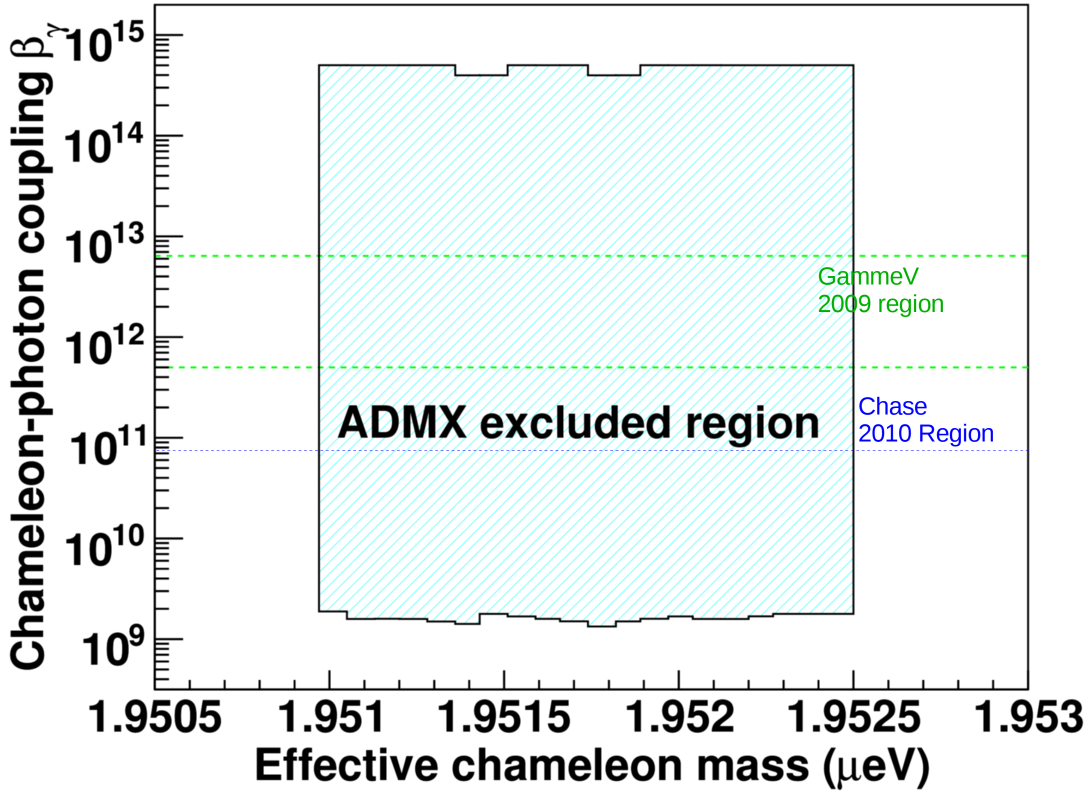
Timescale: 10 minutes

Sensitivity ~10^{-22} W

Bandwidth ~20 kHz

(Step 4: tune rods ~10 kHz and repeat)

Chameleons

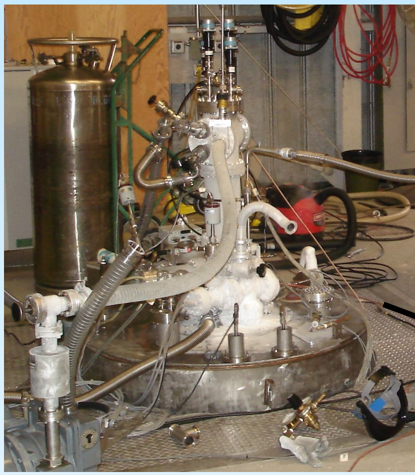


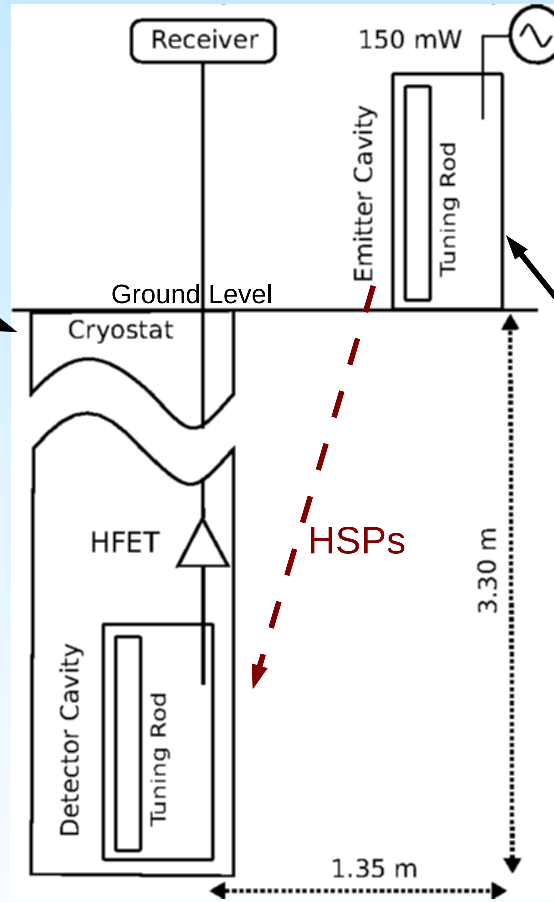
Laboratory Dark Energy Search

One day of running set limits 100 times more sensitive than that from FNAL.

Hidden-Sector Photons: Another dark-matter candidate

ADMX as a HSP receiver





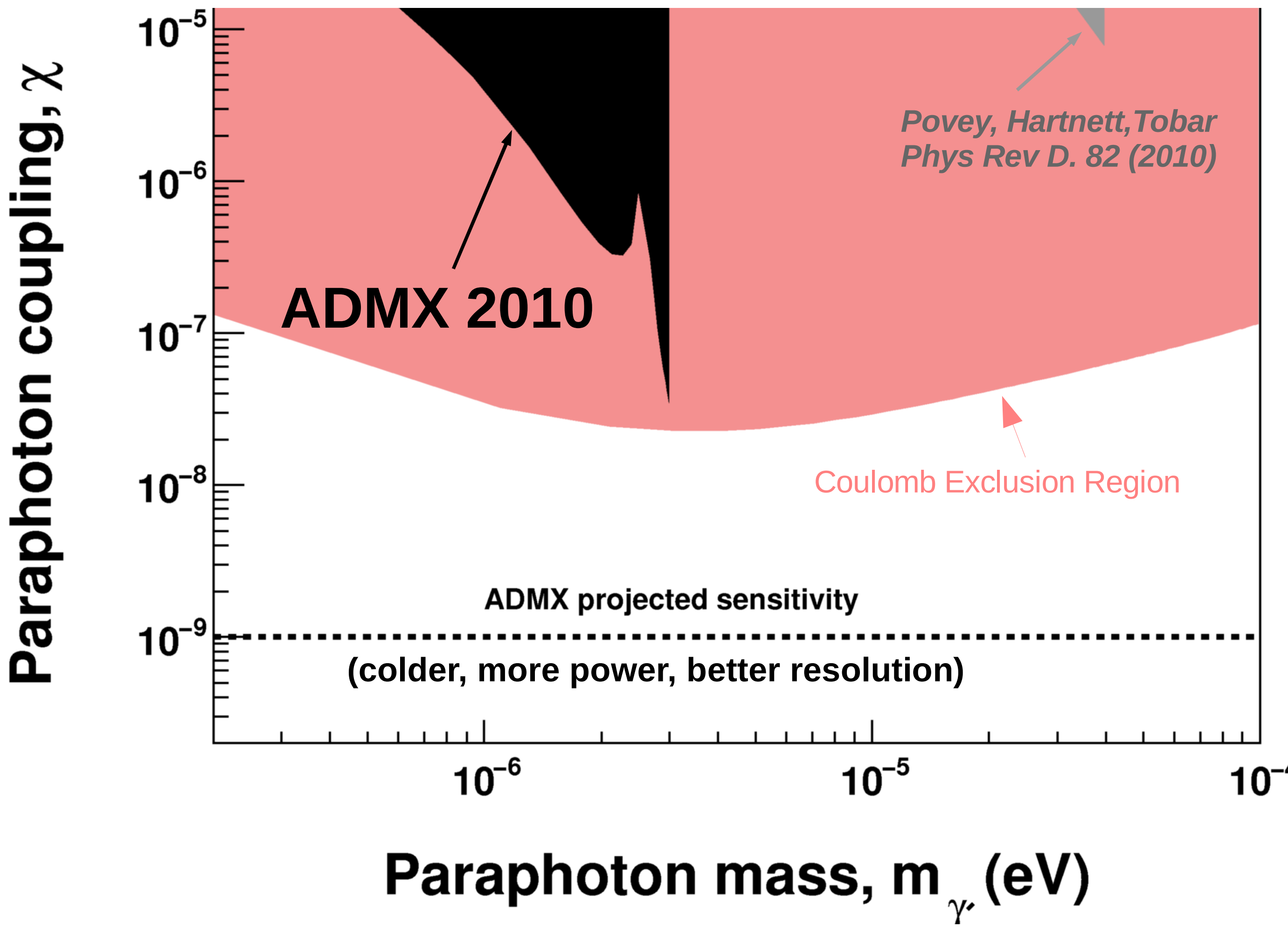
1

Photons in this driven cavity mix with HSPs and escape

2

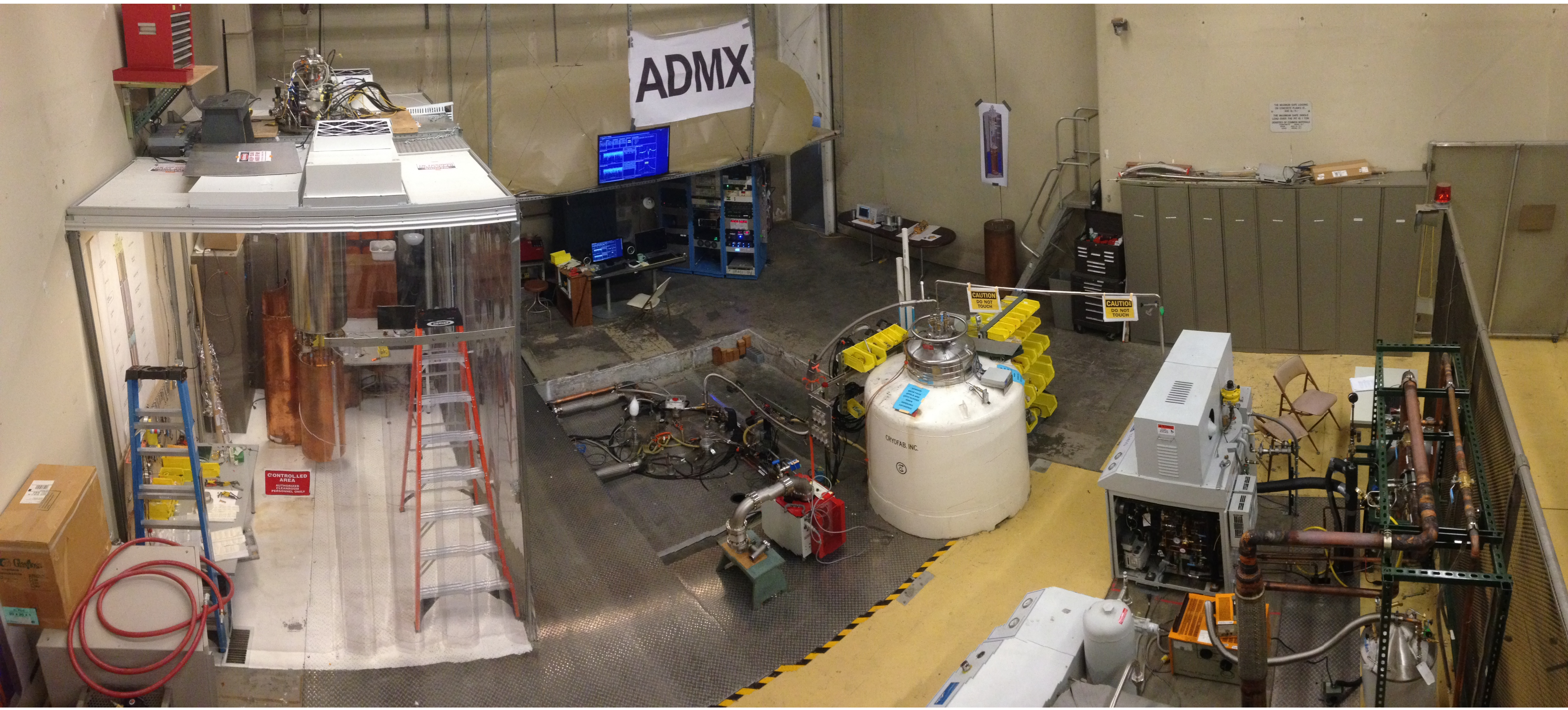
HSPs mix with photons and are detected in the ADMX cavity

Hidden Sector Photons: Results



Next phase projected to extend limits by more than a factor of 10.

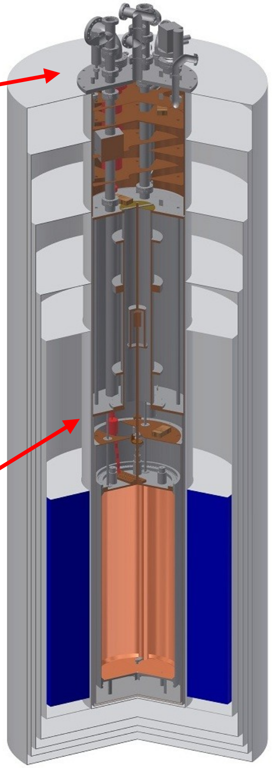
ADMX infrastructure



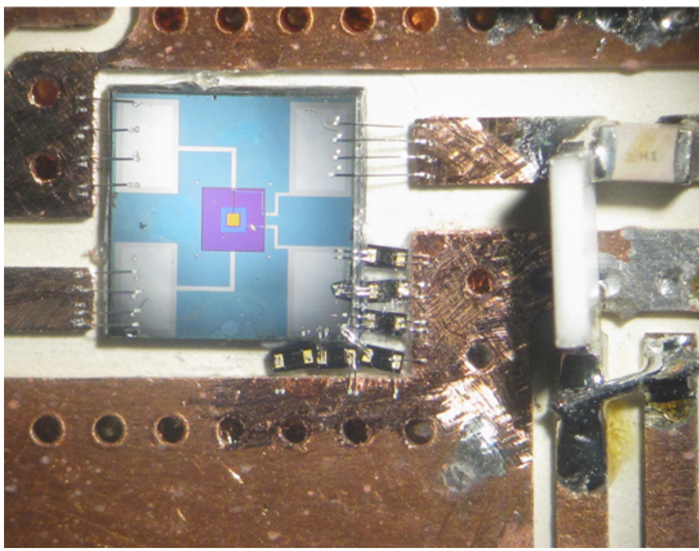
Assembling the experiment insert

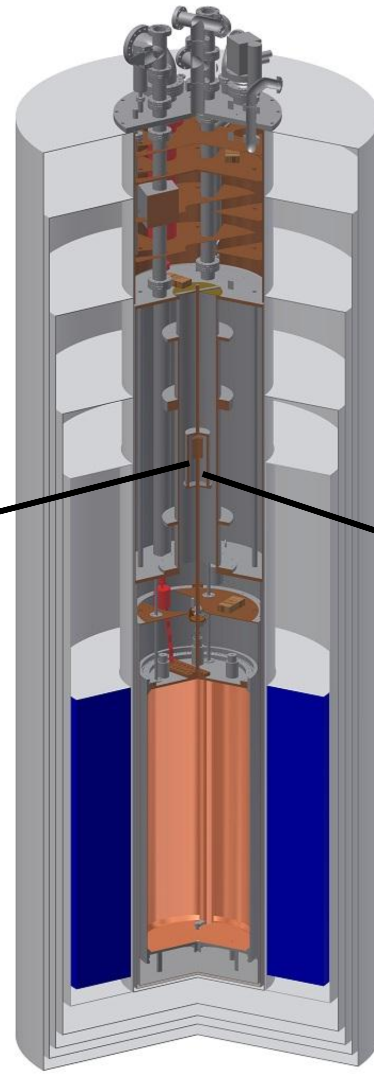
Installation of bucking coil

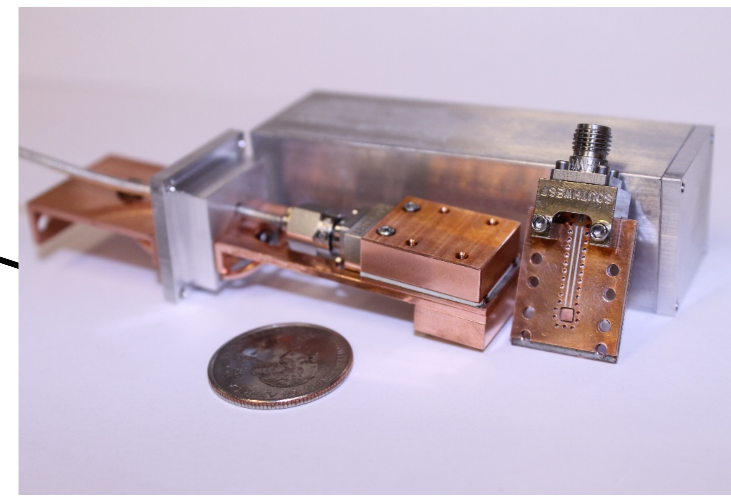
Assembly of top half of insert



Quantum-electronics



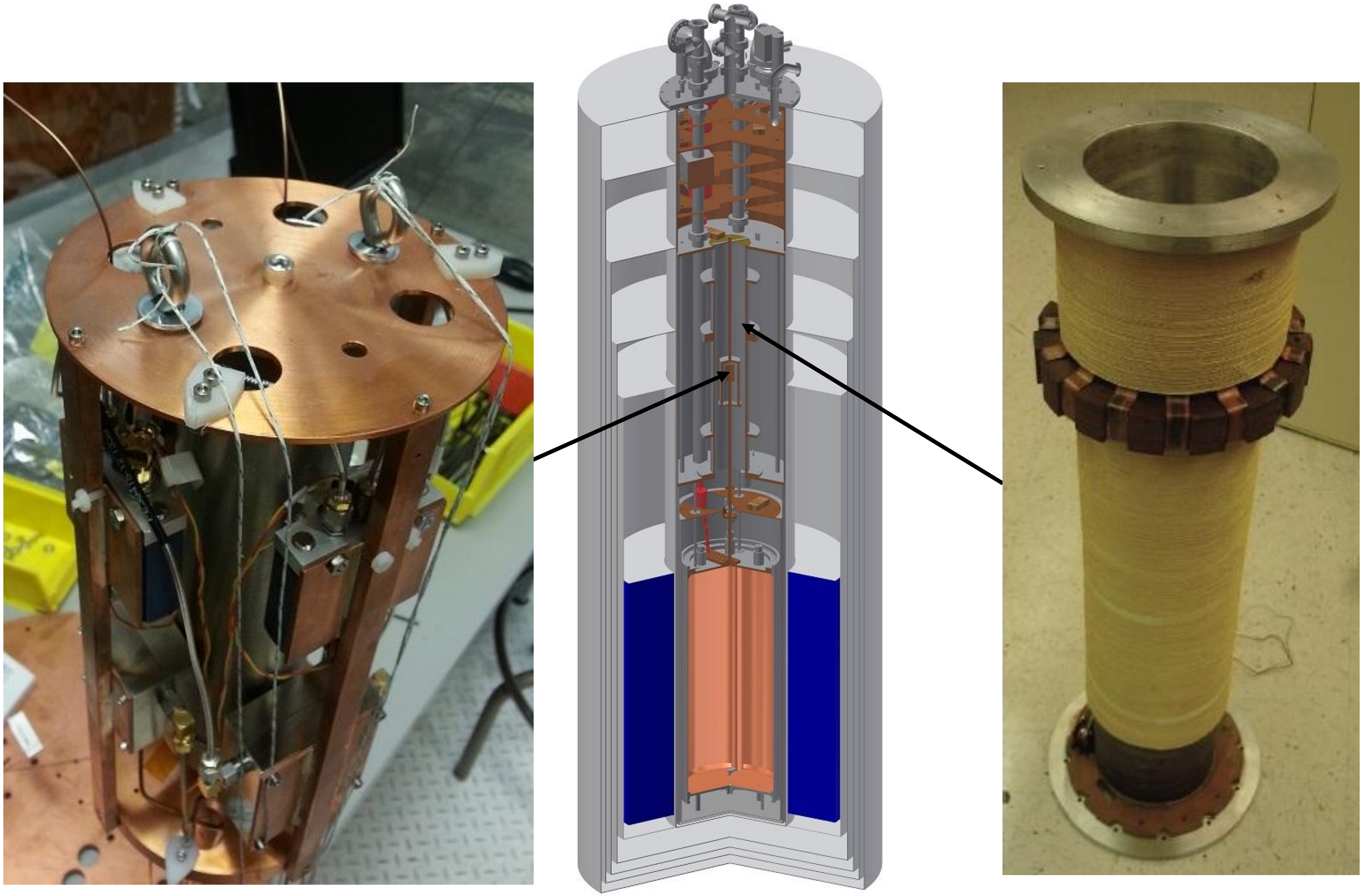




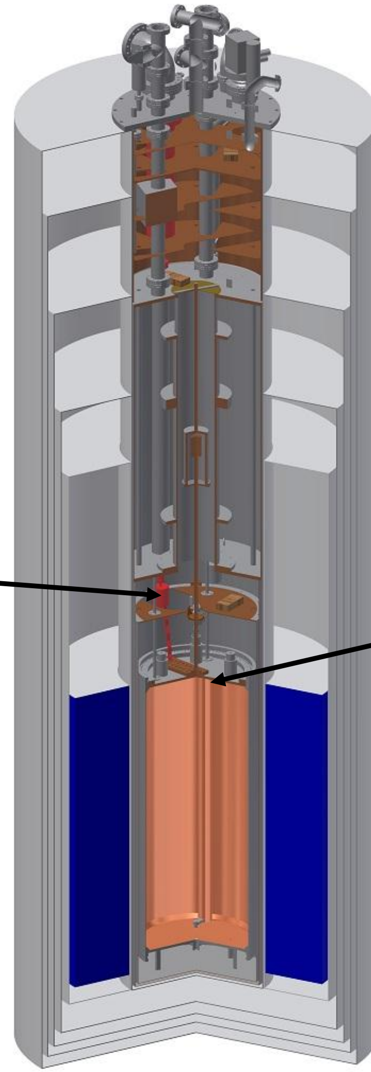
SQUIDs
(at lower frequencies)

"JPAs"
(at higher frequencies)

bucking coil and “squidadel”



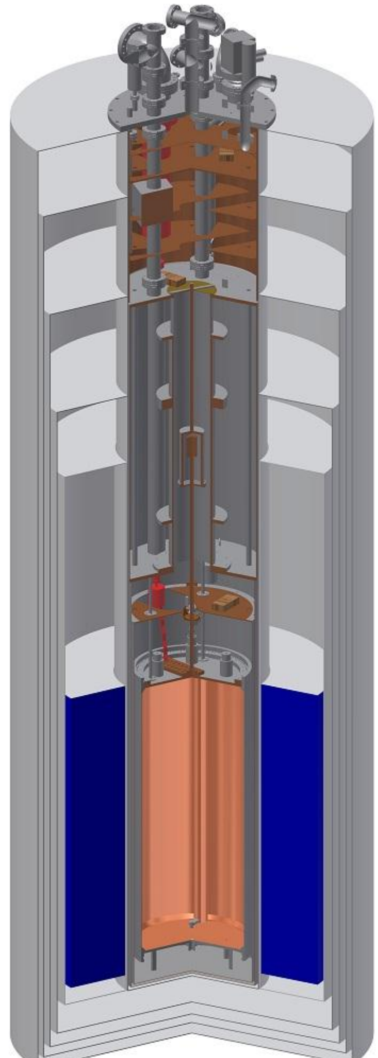
Cavity, tuning and coupling



High-frequency (high axion mass) “side car” cavity

ADMX insert going into and out the magnet bore

Science, Nov. 2013, 552 - 555



Typical ADMX Run Cadence

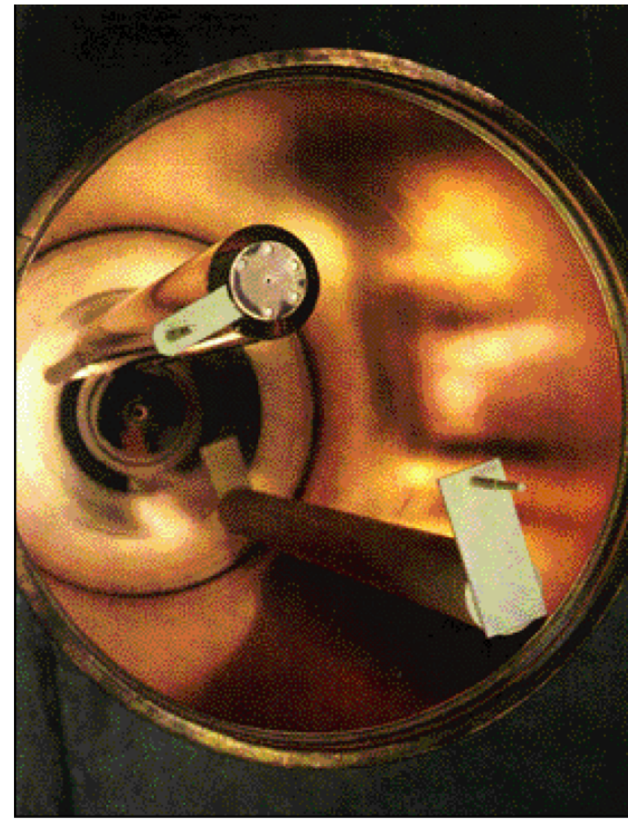
- Inject broad swept RF signal to record cavity response. Record state data (temperature sensors, hall sensors, pressure, etc.).

- Integrate for ~ 80 seconds (final integration time based on results from cold commissioning).

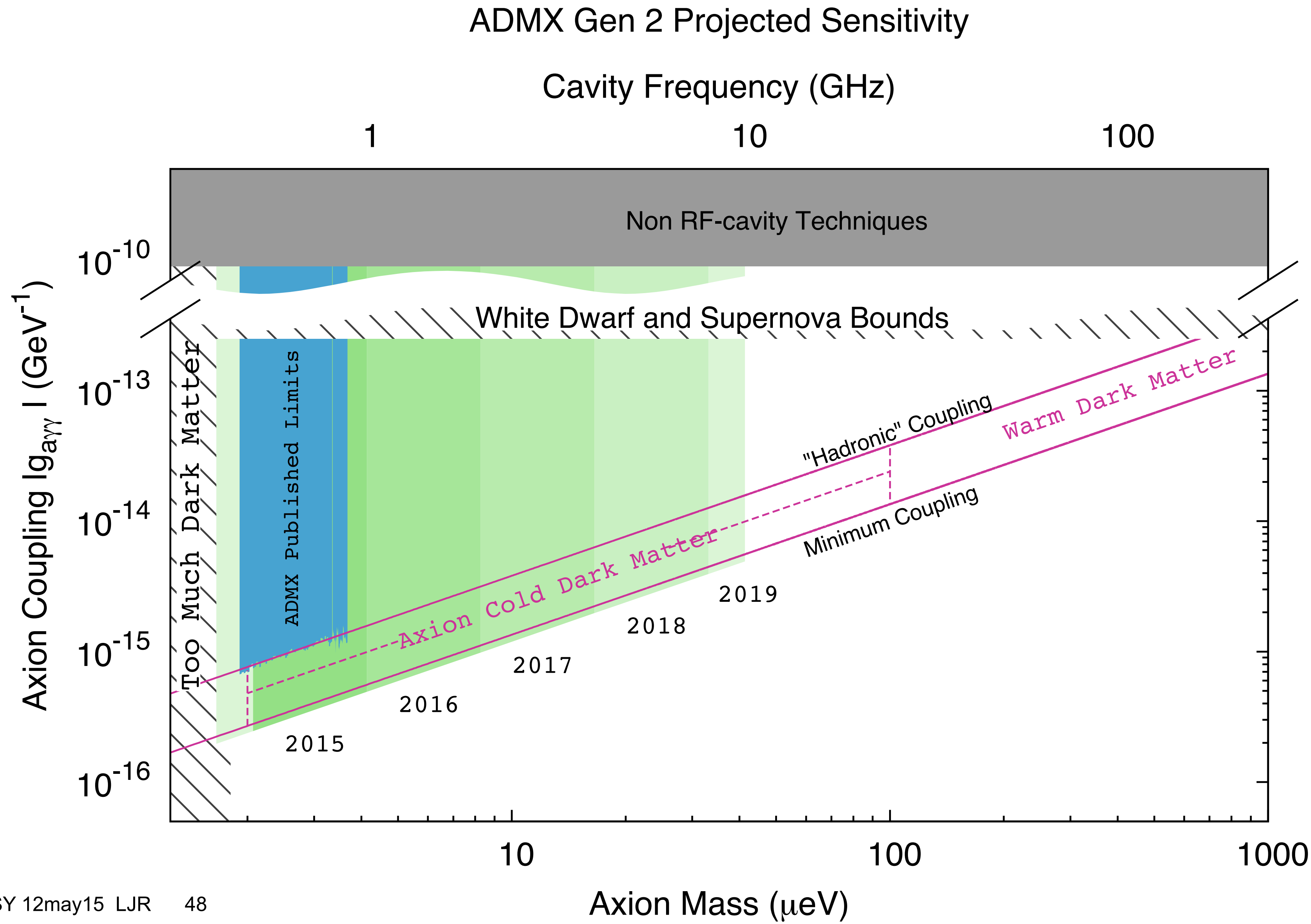
- Move tuning rod to shift TM_{010} & TM_{020} modes (~ 1 kHz at a time).

- Every few days adjust critical coupling of TM_{010} & TM_{020} antennas.

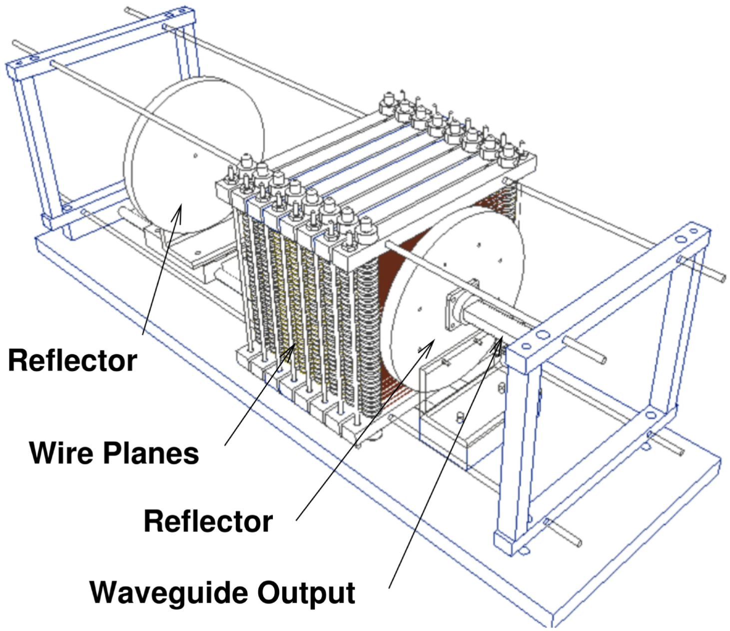
- Anticipated scan rate ~100 MHz (0.5 µeV) every 3 months

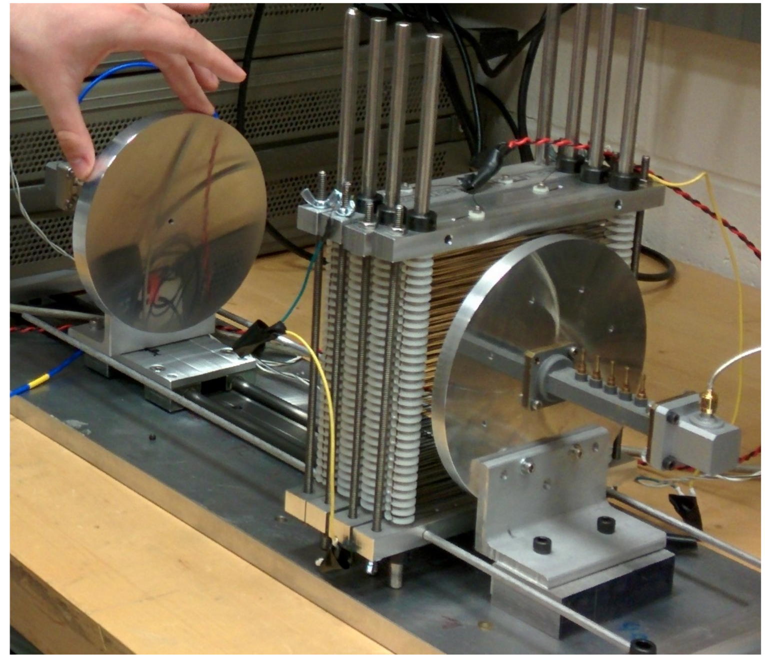


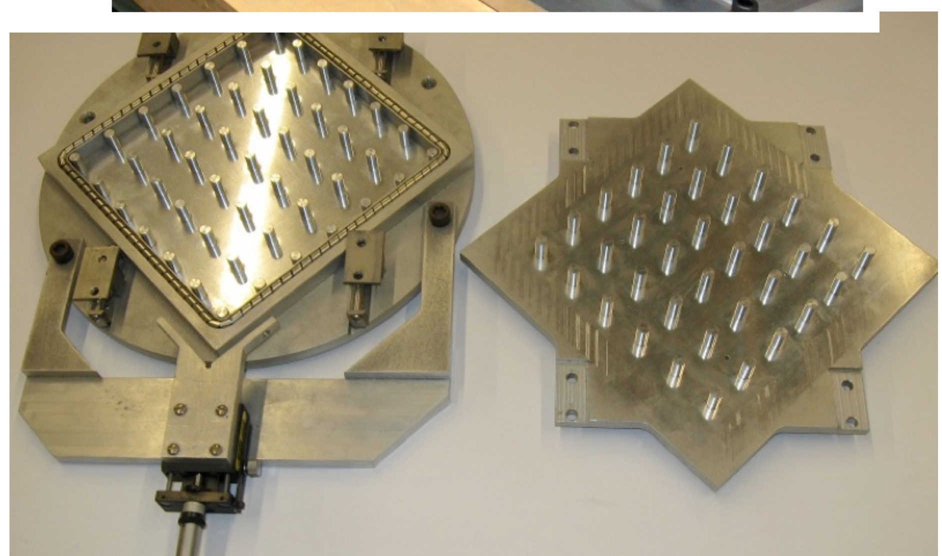
ADMX Gen 2: Science Prospects



Gen 3 and beyond: Can the RF-cavity experiments do better? Very high frequencies, higher Q, etc. ?

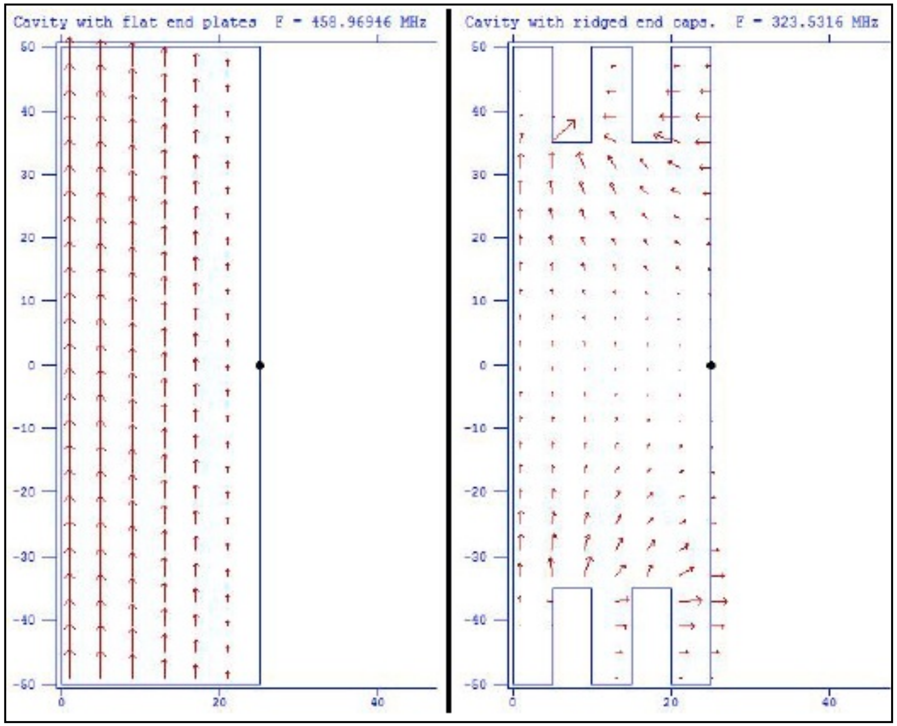


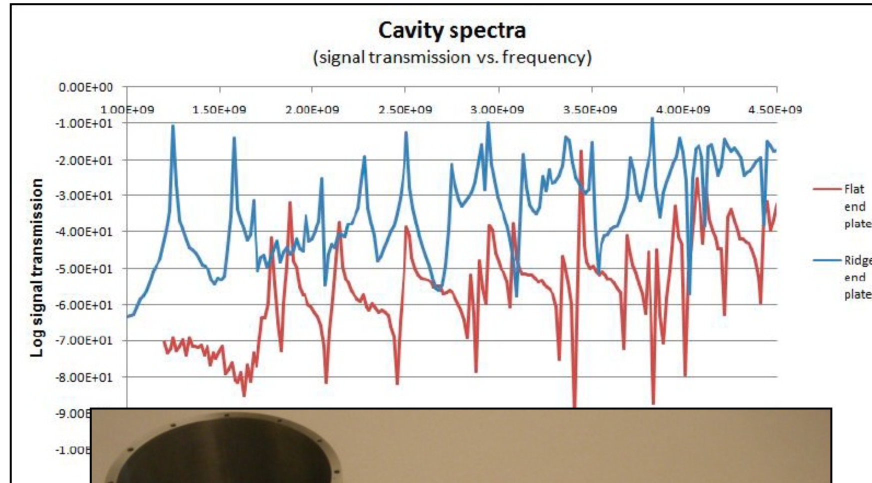




higher-frequency, large volume resonant structures

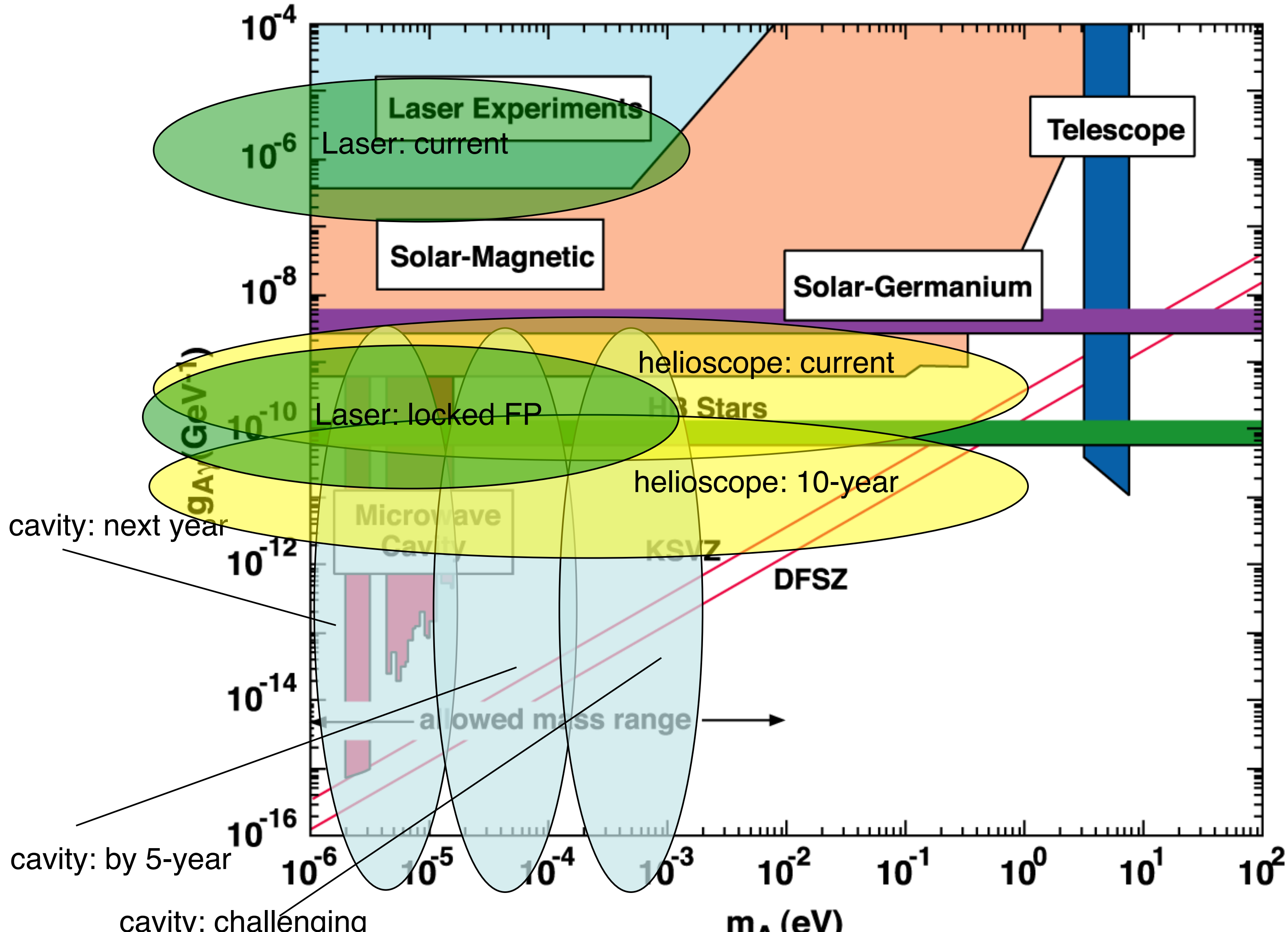
Gen 3: Low-frequency R&D





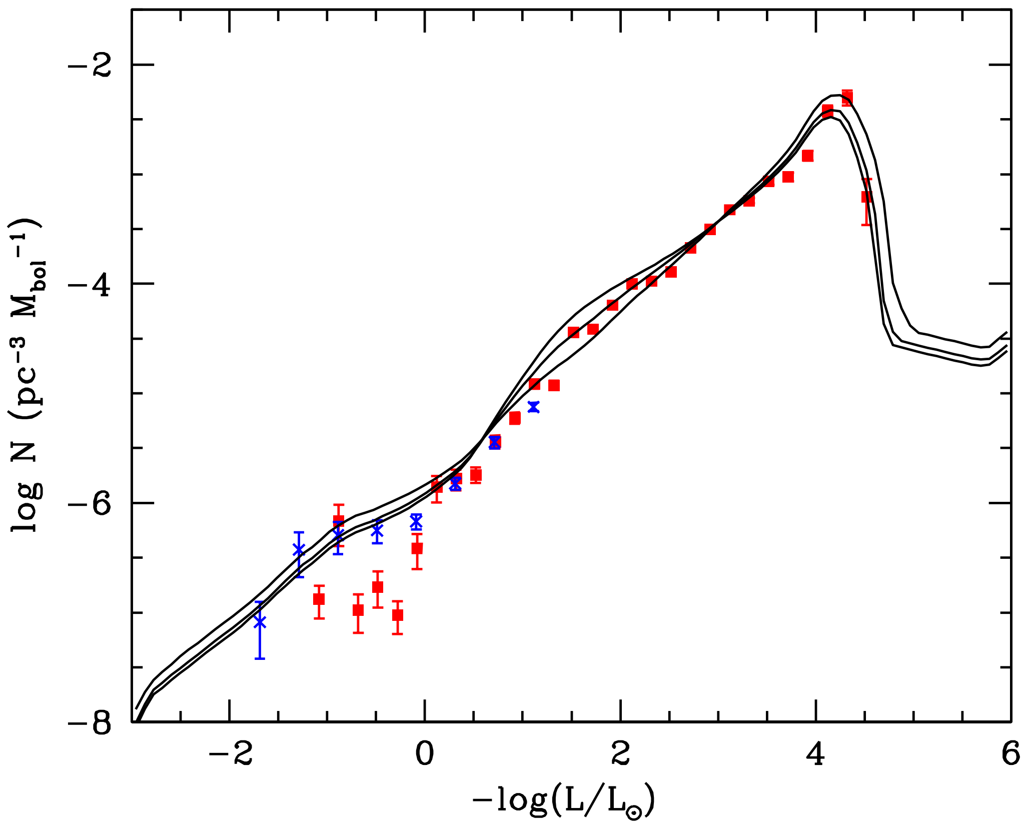
*work from H. Swan (UW)

An experimental scenario for QCD dark-matter axions: Focus on three "flagship" technologies in the near term



Theory challenges going forward (1) include

e.g, White dwarfs:
Can we better understand their cooling?



Isern et al., 2012

Figure 1: White dwarf luminosity function. The solid lines represent the models obtained with (up to down) $g_{\rm aee}/10^{-13} = 0, 2.2, 4.5$ respectively.

Theory challenges going forward (2) include

Gamma ray propagation:
e.g., Can we better understand gamma-ray propagation?

Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 1 March 2012 (MN LaTeX style file v2.2)

Evidence for an axion-like particle from PKS 1222+216?

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1 March 2012

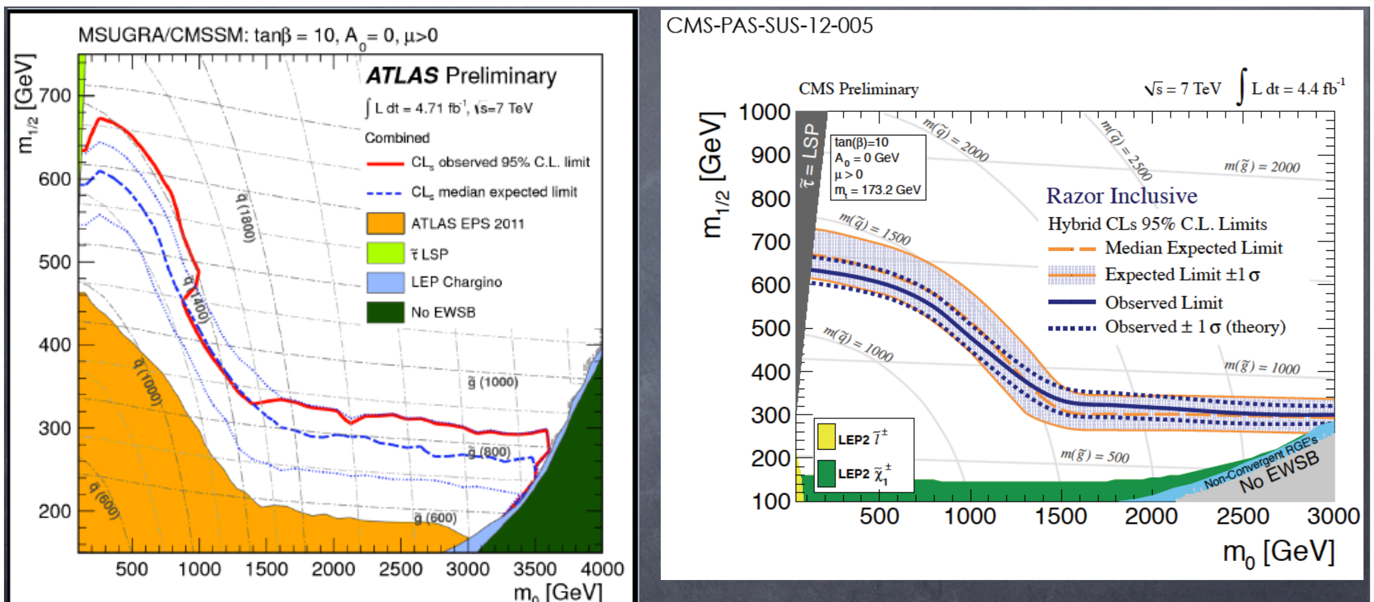
ABSTRACT
The surprising discovery by MAGIC of an intense, rapidly varying very high energy ($E > 50$ GeV) emission from the flat spectrum radio quasar PKS 1222+216 represents a challenge for all interpretative scenarios. Indeed, in order to avoid absorption of γ rays in the dense ultraviolet radiation field of the broad line region (BLR), one is forced to invoke the existence of a very compact ($r \sim 10^{14}$ cm) emitting region at a large distance ($R > 10^{18}$ cm) from the jet base. We present a scenario based on the standard blazar model for PKS 1222+216 where γ rays are produced close to the central engine, but we add the new assumption that inside the source photons can oscillate into axion-like particles, which are a generic prediction of many extensions of the Standard Model of elementary particle interactions. As a result, a considerable fraction of photons can escape absorption from the BLR much in the same way as they largely avoid absorption from extragalactic background light when propagating over cosmic distances. We show that observations can be explained in this way for reasonable values of the model parameters, and in particular we find it quite remarkable that the most favourable value of photon-ALP coupling happens to be the same in both situations. An independent laboratory check of our proposal can be performed by the planned upgrade of the ALPS experiment at DESY.

Key words: radiation mechanisms: non-thermal — γ–rays: theory — galaxies: individual: PKS 1222+216

Conclusions (1)

Listen to Nature:
We’re keeping our eye on the LHC and WIMP detectors.

The jury is certainly still out, but if SUSY-WIMPs remain undetected, you might want to look harder at axions.



Atlas/CMS: no sign of mSUGRA at LHC7:

Conclusions (2)

On the other hand, some say, LHC finding SUSY may strongly suggest axion dark matter.

Why thermally-produced neutralino-only DM is not the answer (in spite of the hype):

- Generates too much or too little DM; only rarely is $\Omega_\chi^{std} h^2 \sim 0.11$: fine-tuned!
- gravitino problem and BBN constraints
- neglects the strong CP problem and its solution

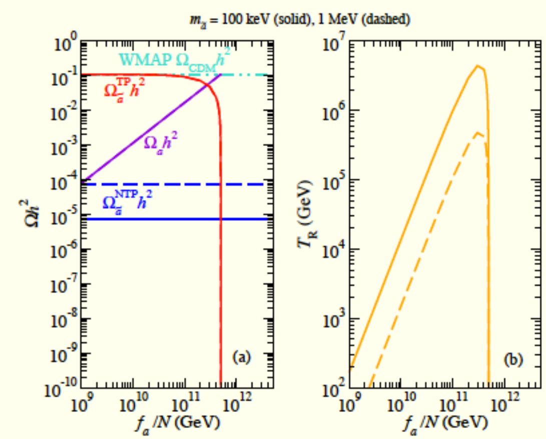
H. Baer

mSUGRA model with mixed axion/axino CDM: $m_{\tilde{a}}$ fixed

$(m_0, m_{1/2}, A_0, \tan\beta, sgn(\mu)) = (1000\text{ GeV}, 300\text{ GeV}, 0, 10, +1)$

$\Omega_a h^2 + \Omega_{\tilde{a}}^{TP} h^2 + \Omega_{\tilde{a}}^{NTP} h^2 = 0.11$

model with *mainly* axion CDM favored for large T_R!



Overall Conclusions

Axions: A very compelling dark-matter candidate.
- The QCD dark-matter axion is well bounded in mass and couplings.
- The dark-matter axion focus is 1-100 μeV axion masses.

There are many search techniques, but the RF-cavity one is most sensitive.
- ADMX is largest and most mature; several others are on the horizon.
- The next several years will either see a discovery or reject the QCD dark-matter axion hypothesis.

The space of variant axion (non "QCD") models is wide open.
- Large efforts are underway for solar axions and laser experiments.
- And ideas are out there for searching for very low-mass & high-mass axions

Quite starkly: These experiments have the sensitivity and mass reach to either detect or rule out QCD dark-matter axions at high confidence.

We gratefully acknowledge the generous support of the U.S. Department of Energy, Office of High Energy Physics