Searching for Axions

Fermilab Particle Astrophysics Seminar

May 12, 2014

Leslie J Rosenberg

University of Washington

Searching for Axions

Outline

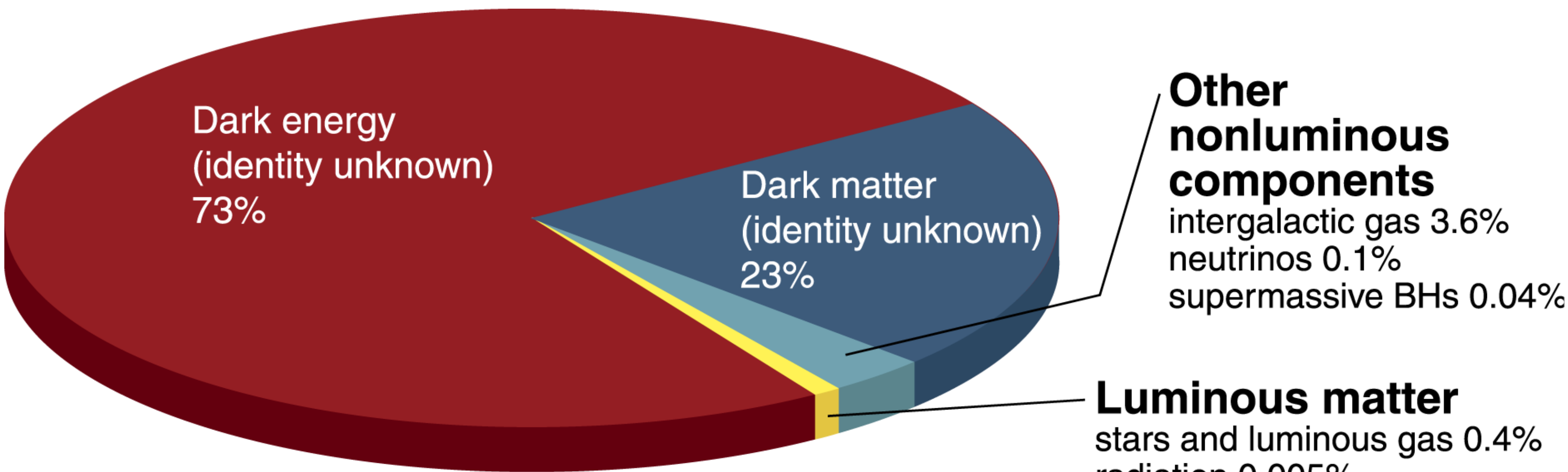
Basic axion properties

Selected searches:

- Photon regeneration and optical rotation
- Solar axion searches
- RF cavity (dark-matter axions)

Overall status of axion searches

We’ve inventoried the cosmos …

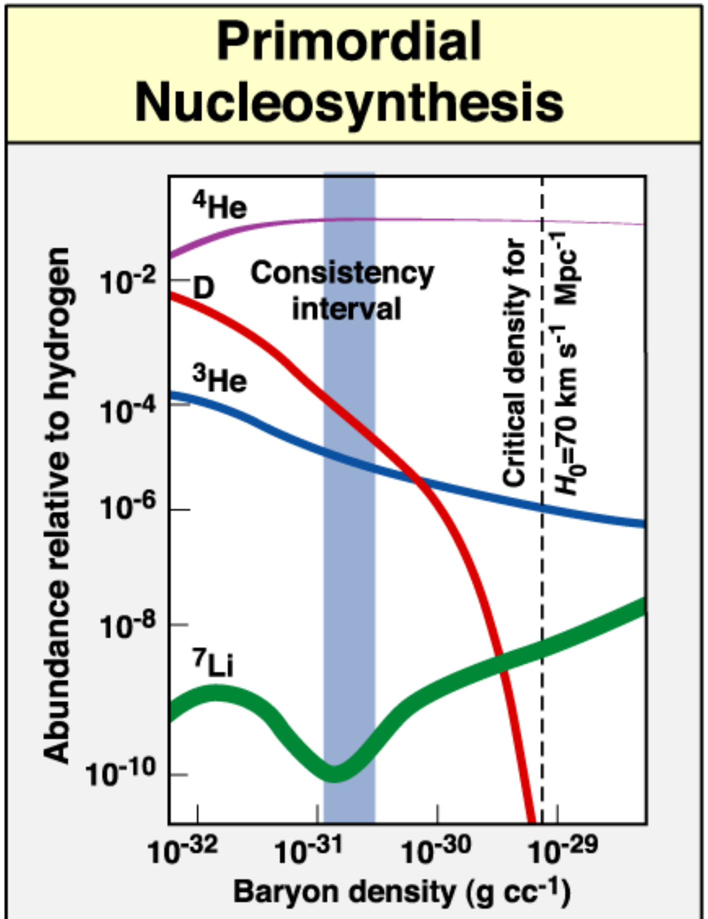


Science (20 June 2003)

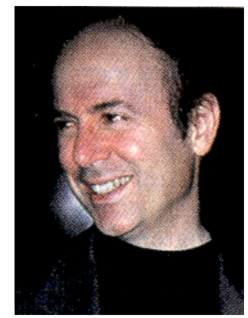
… but we know neither what the “dark energy” or the “dark matter” is. These are two of the very big questions.

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…"

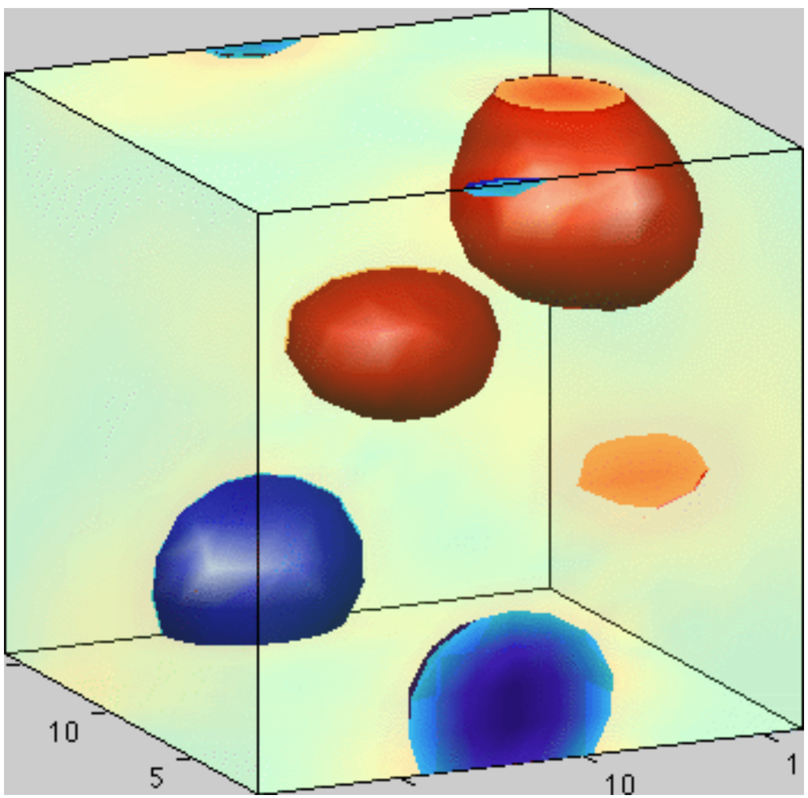
Frank Wilczek in Physics Today

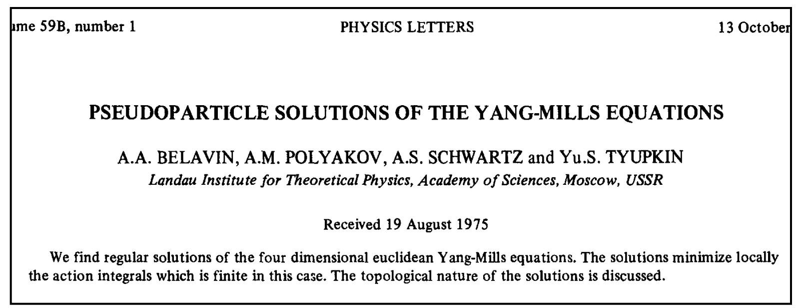
Frank's referring to WIMPS and Axions

New thread: 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

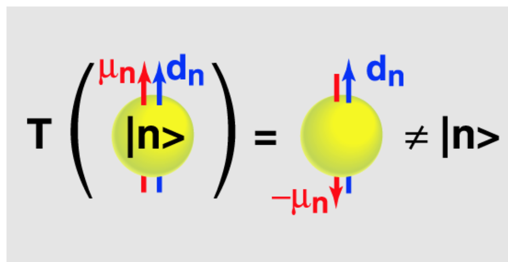
Received 19 August 1975

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 ($\not{T}$ + CPT = $\not{CP}$); none is unobserved.
(9 orders-of-magnitude discrepancy)



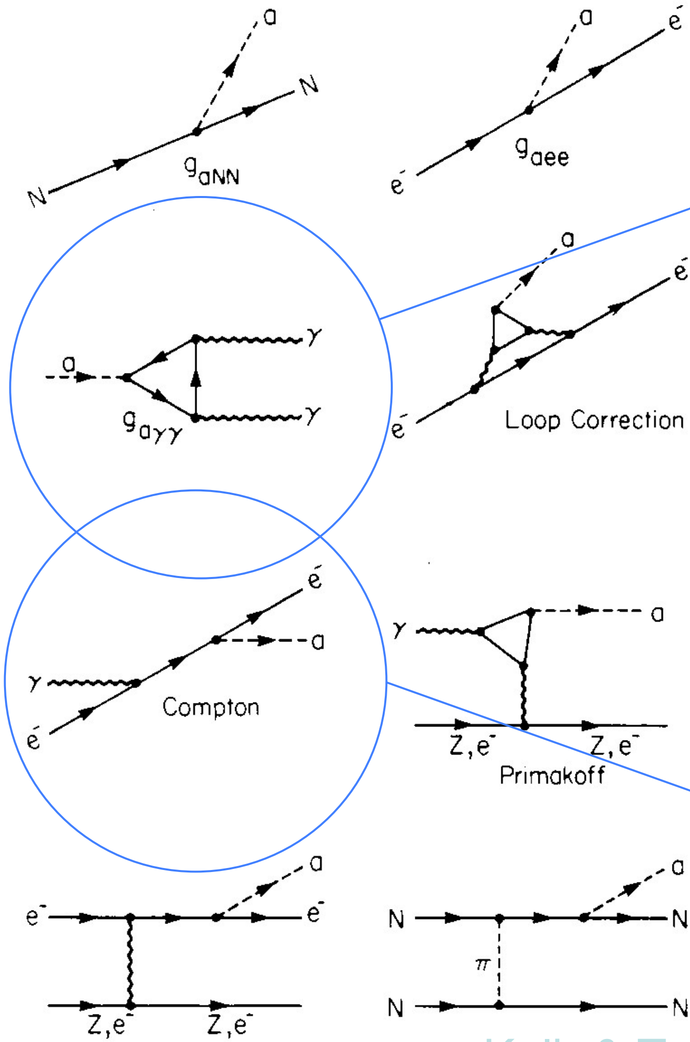
Why doesn't the neutron have an electric dipole moment?

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

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

What's an axion?

Selected axion couplings
& the important two-photon coupling



Bremsstrahlung

Kolb & Turner

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 large model uncertainty
Can occur, e.g., in the Sun
Contains unknown $U(1)_{PQ}$ charge of electron

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

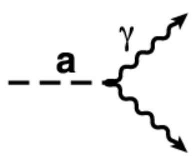
$$g_{aii} \propto \frac{1}{f_a}$$

Cosmological Abundance

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

(Vacuum misalignment mechanism)

Coupling to Photons



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

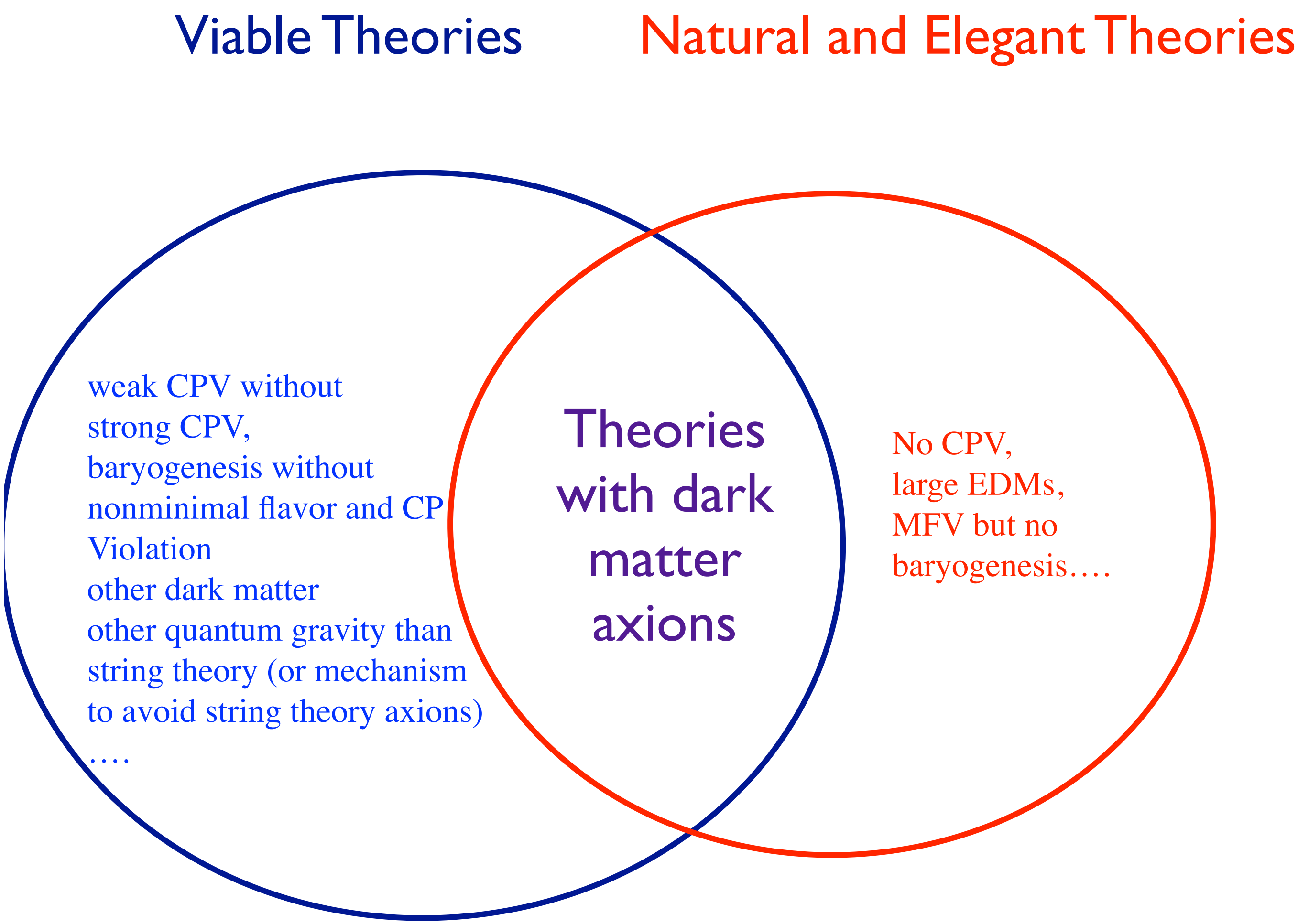
Axion Mass 'Window'

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

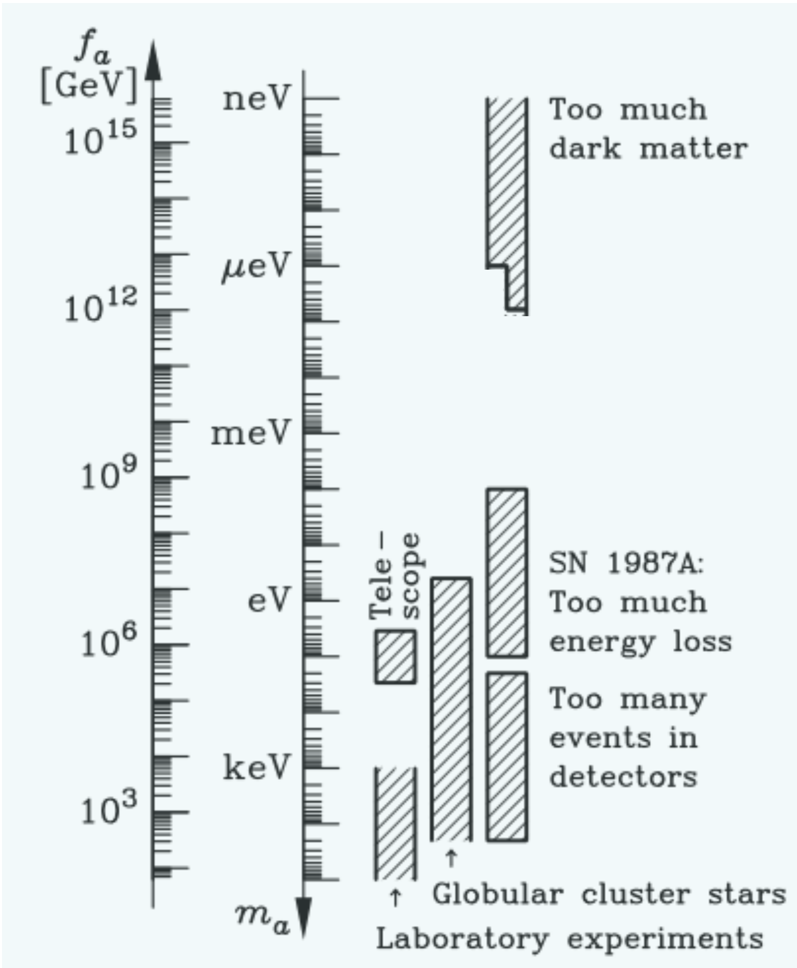
(Overclosure) (SN1987a)

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

From A. Nelson



Present bounded window of allowed 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

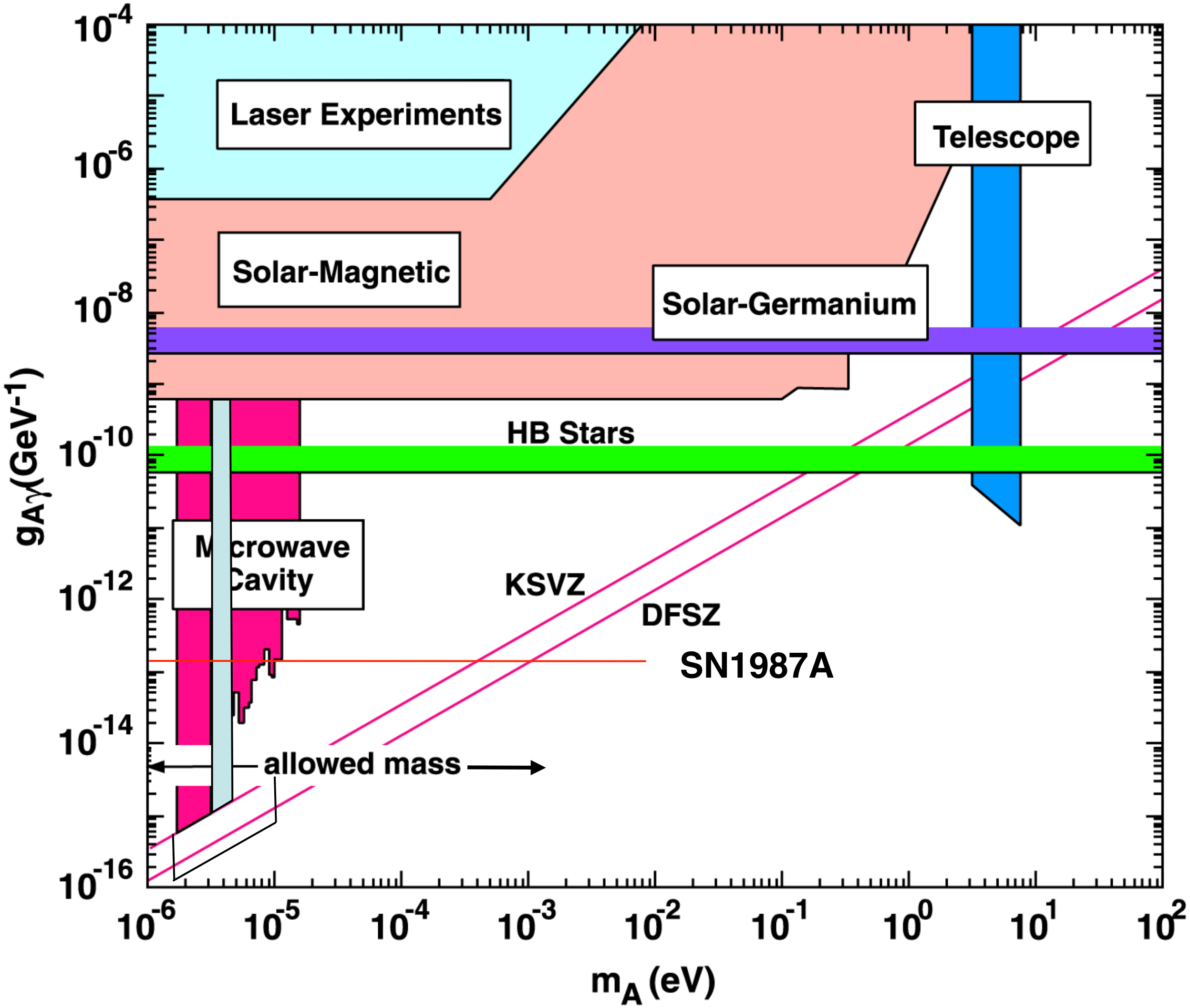
Recap: Axions and dark matter

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).

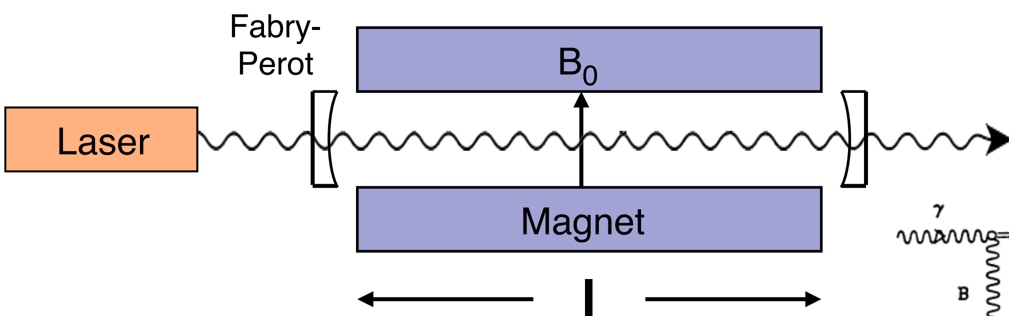
Various limits on QCD axion masses and couplings

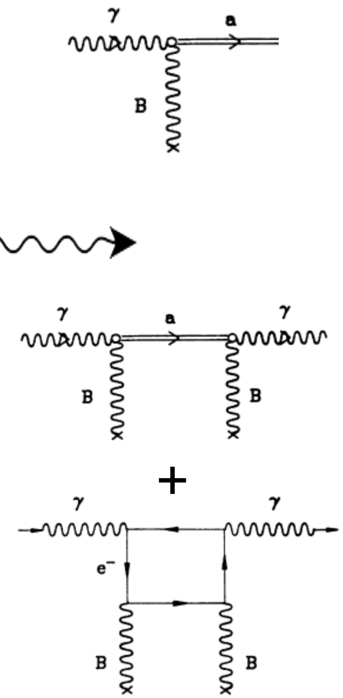


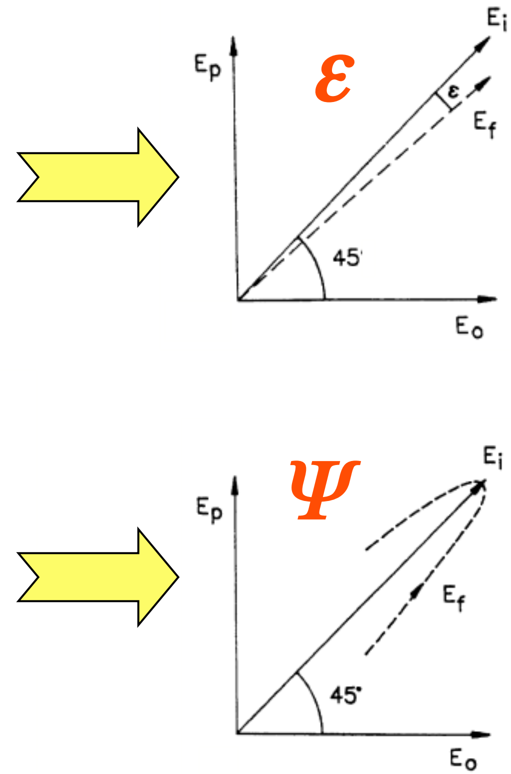
Search 1: Vacuum birefringence & dichroism

Vacuum dichroism

$\varepsilon \sim N \cdot (1/4\, gB_0L)^2$ *(N = number of passes)*







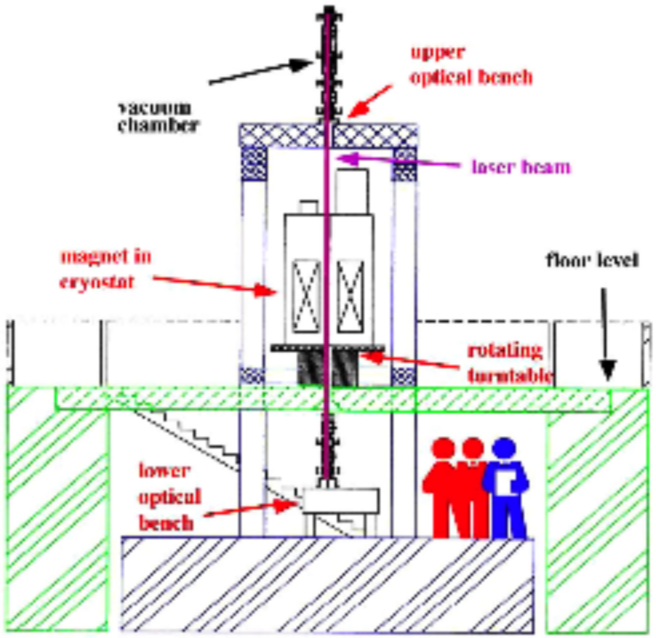
Vacuum birefringence

$\Psi = N \cdot (1/96) \cdot (g\, B_0 m_a)^2 \cdot L^3/\omega$

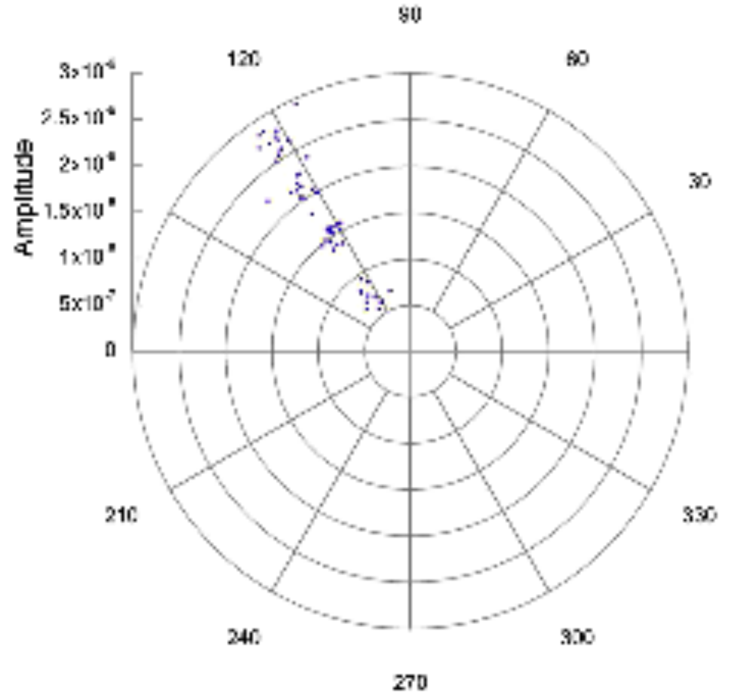
Maiani, Zavattini, Petronzio, Phys. Lett. B 175 (1986) 359

Spurious PVLAS signal

PVLAS Schematic



Phase-Amplitude Plot



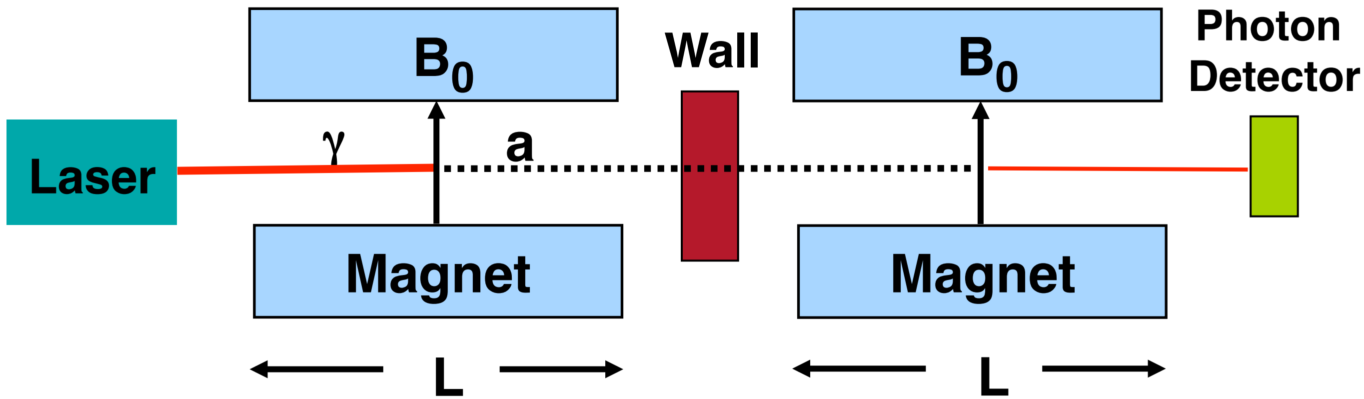
Rebuilt detector doesn't find signal.

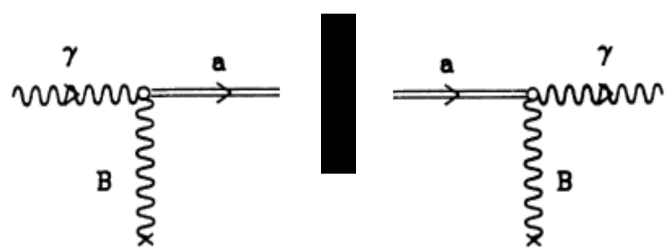
Their early value of $g_{a\gamma\gamma}$ was ostensibly excluded already by 4 orders of magnitude, by CAST, and stellar evolution (stars would live only a few thousand years)

The allowed region is on the very fringe of the exclusion region of the earlier RBF polarization experiment, plus the photon regeneration experiment

Nevertheless, this renewed polarization-rotatation experiments around the world, and much theoretical work

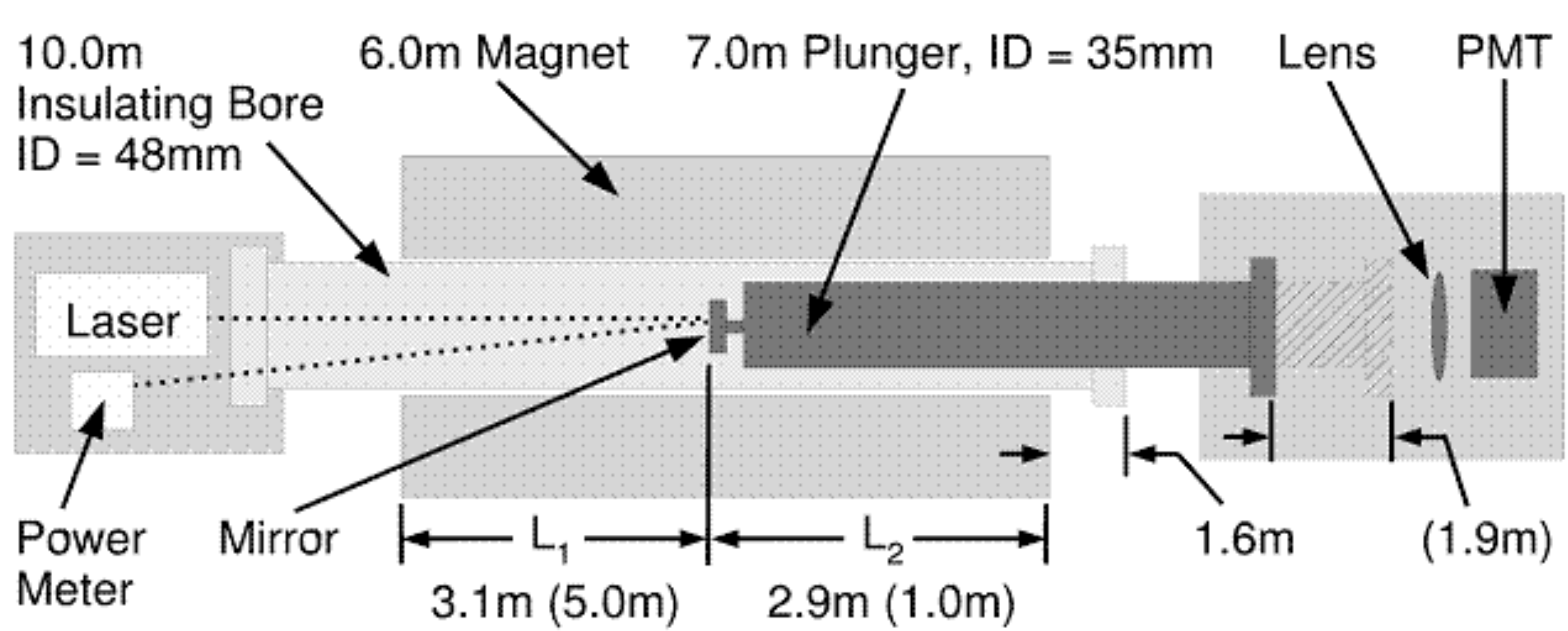
Search 2: Photon regeneration
("shining light through walls")





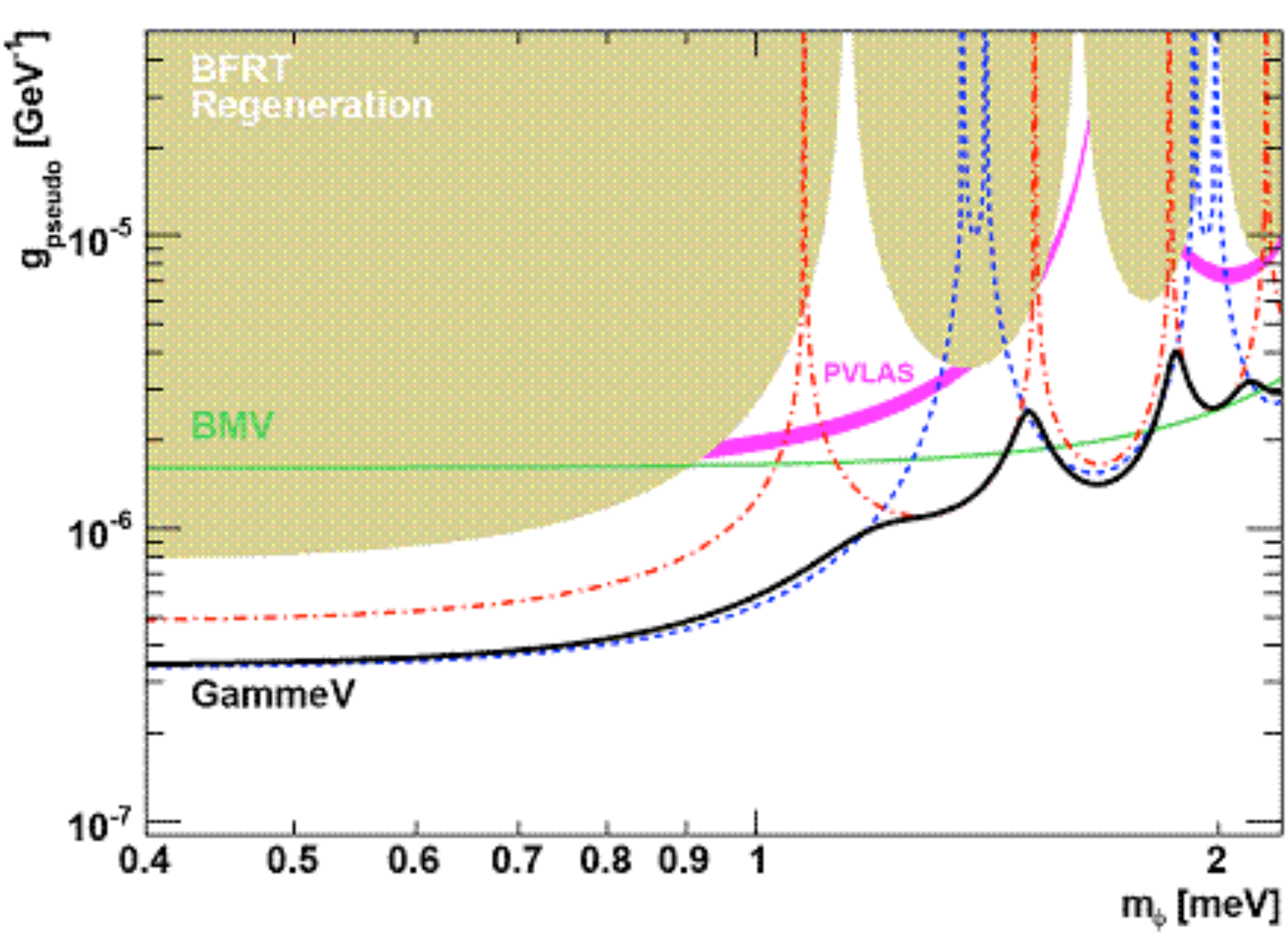
$$P(\gamma \rightarrow a \rightarrow \gamma) \sim 1/16\ (gB_0L)^4$$

Current most sensitive: GammeV at FNAL



Laser Axion Searches: Sensitivity

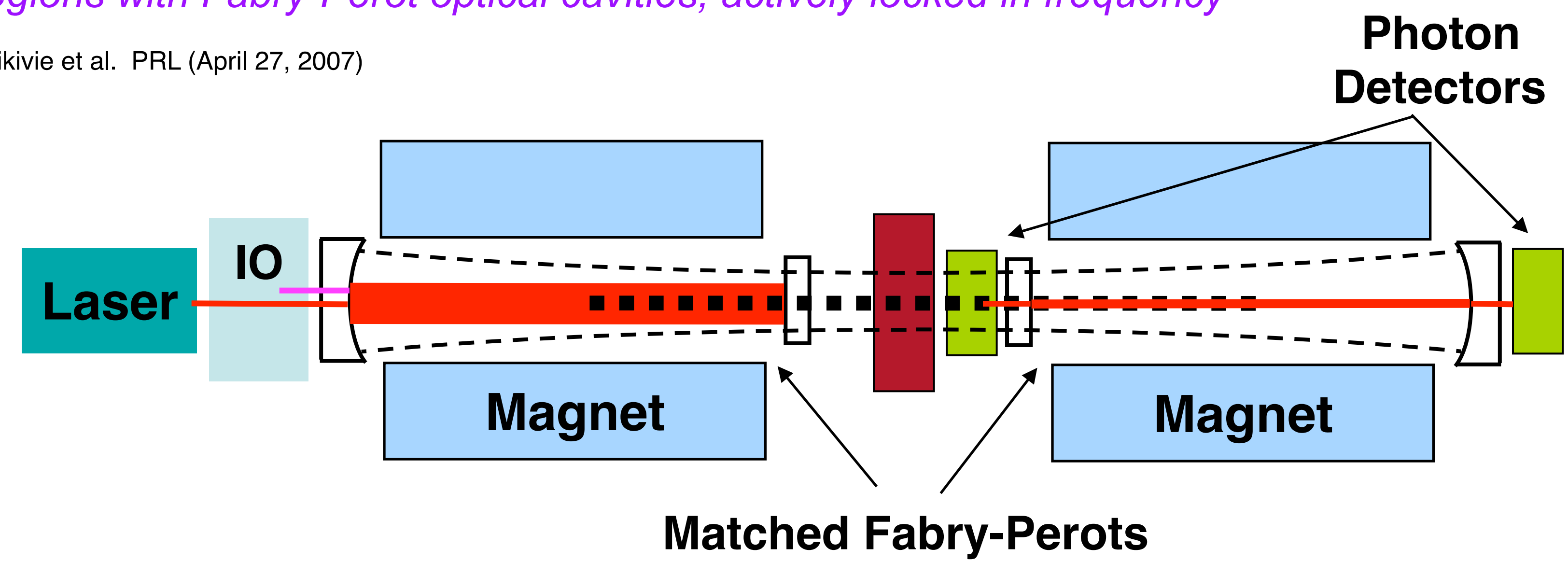
GammeV at FNAL



Future: resonantly enhanced photon regeneration

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

Sikivie et al. PRL (April 27, 2007)



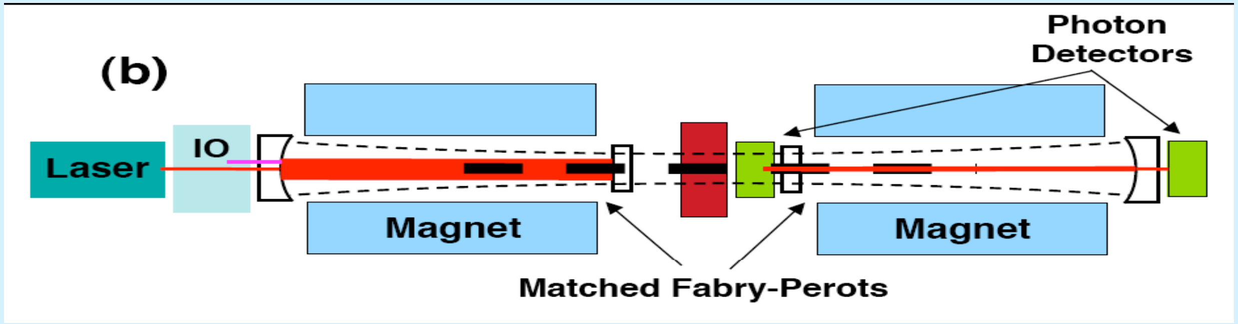
$$P^{\mathrm{Resonant}}(\gamma \to a \to \gamma) = \frac{2}{\eta \eta'} \cdot P^{\mathit{Simple}}(\gamma \to a \to \gamma) = \frac{2}{\pi^2} F F' \cdot P^{\mathit{Simple}}(\gamma \to a \to \gamma)$$

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 $10^{(2.5\text{–}3)}$

Laser futurism (1): REAPR at FNAL

REAPR Requirements



- Optimize magnetic field length — Talk by P. Mazur
- High finesse cavities — Talk by D. Tanner
- Cavities locked to each other with no leakage from the generation cavity
- Need sensitive photon detection

4/24/12 W. Wester, Fermilab, Vistas in Axions

Laser futurism (2): ALPS-II at DESY

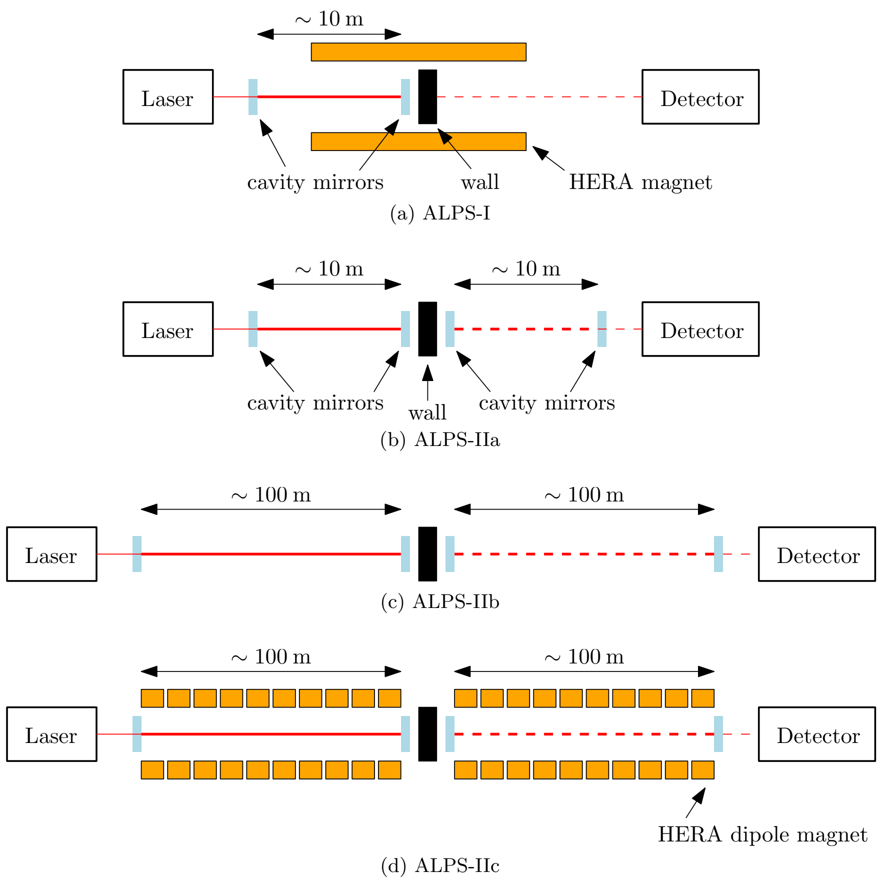
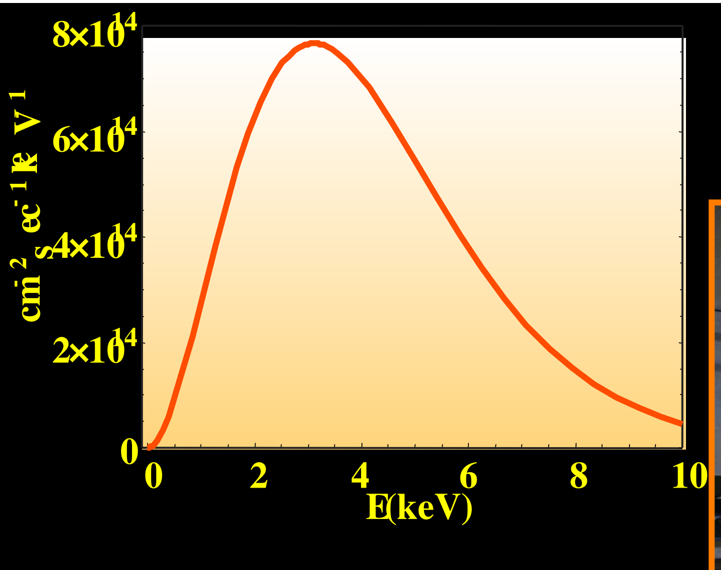
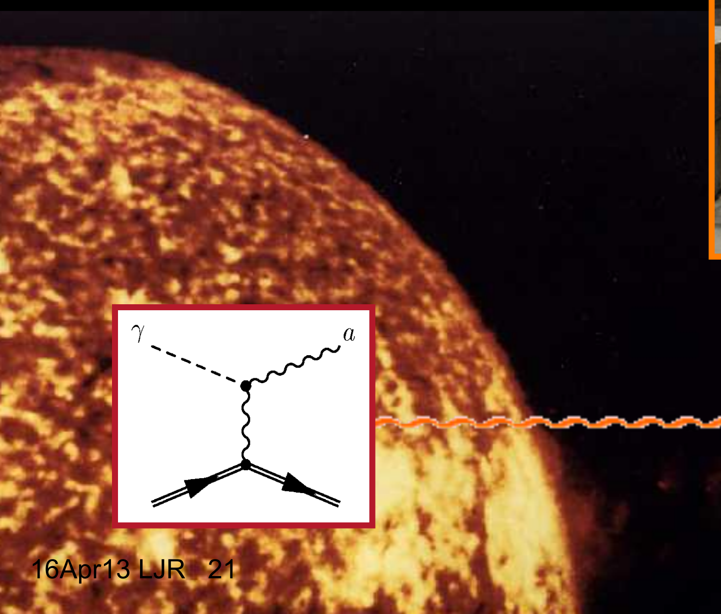


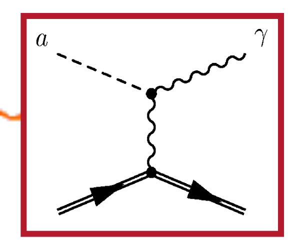
Figure 3.1: Schematic view of the different phases of ALPS-II and of ALPS-I. (a) ALPS-I with a ~10 m long production cavity and cavity end mirror and wall inside of a HERA superconducting dipole magnet. (b) ALPS-IIa: prototype with two 10 m long cavities. (c) ALPS-IIb: prototype with two 100 m long cavities. (d) ALPS-IIc: prototype with two 100 m long cavities using the HERA superconducting dipole magnets.

Search 3: CERN Axion Solar Telescope (CAST). Searching for axions produced in the Sun.



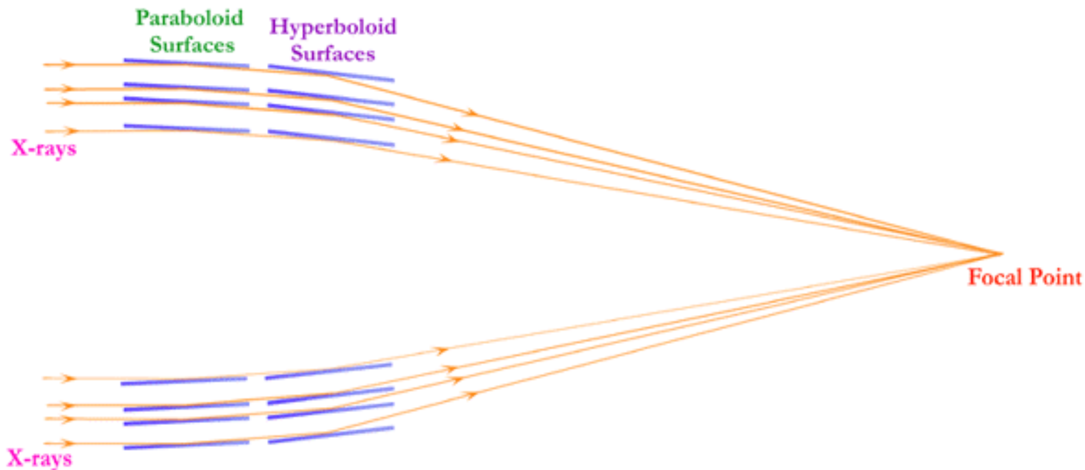
Axions from the sun become x-rays inside a spare LHC dipole magnet



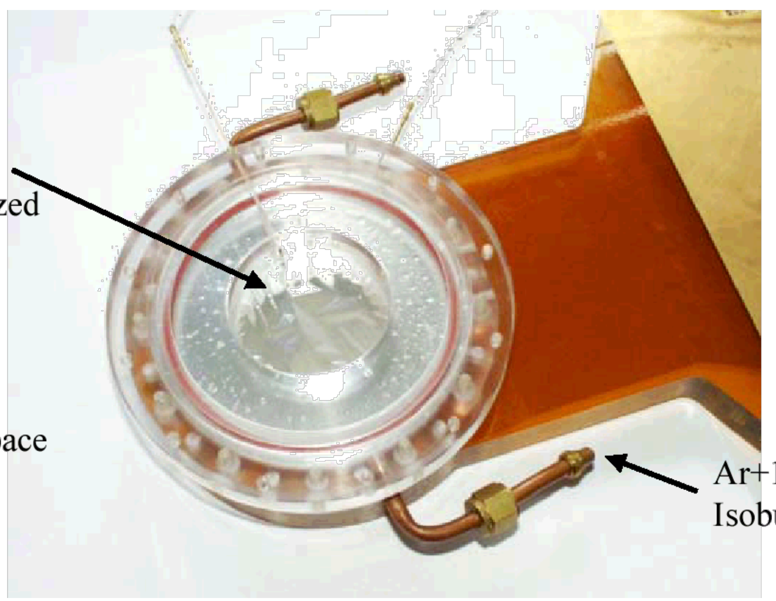


CAST Technology

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

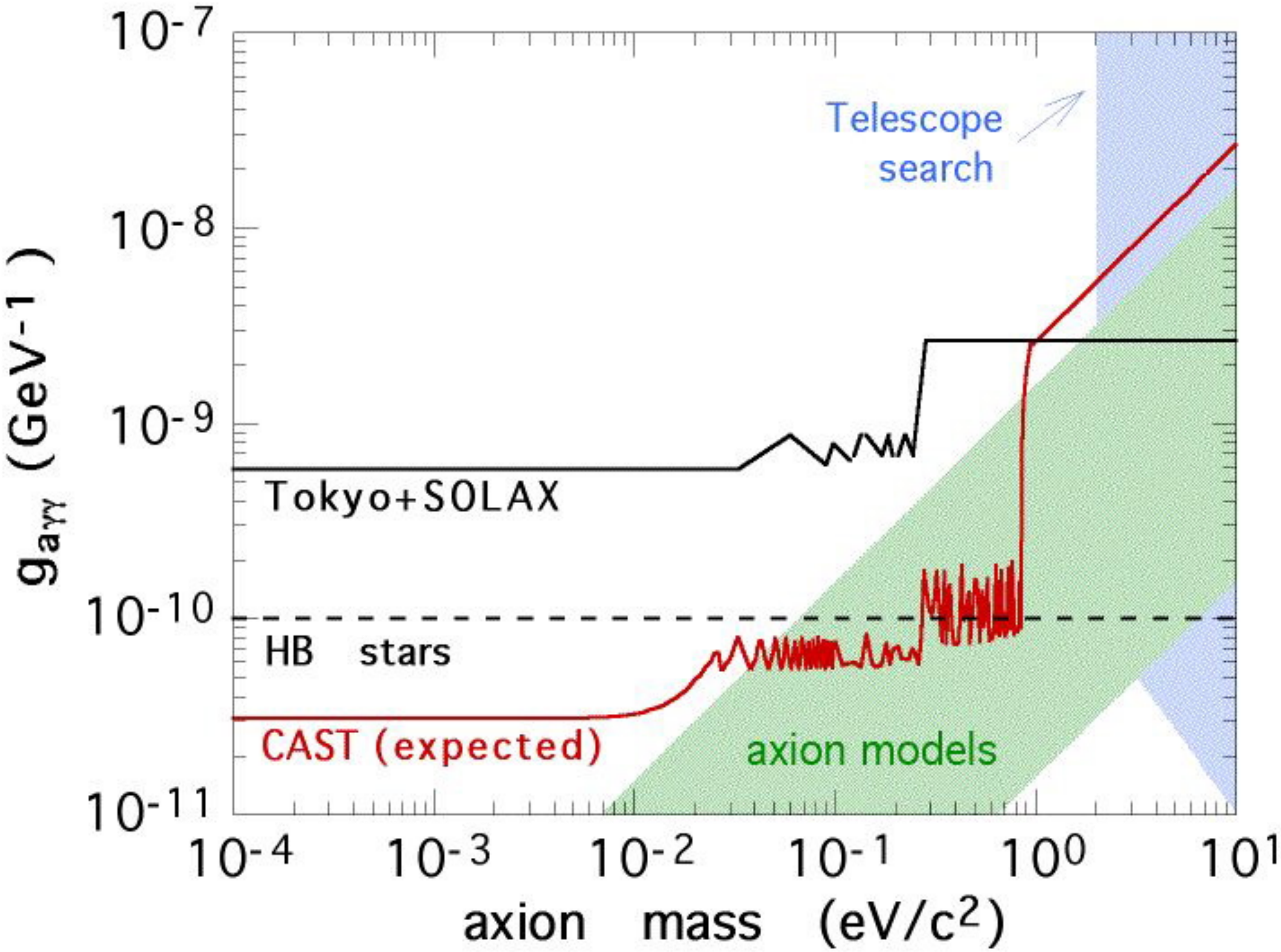


Grazing-incidence x-ray optics



Micromegas x-ray camera

CAST Search Range



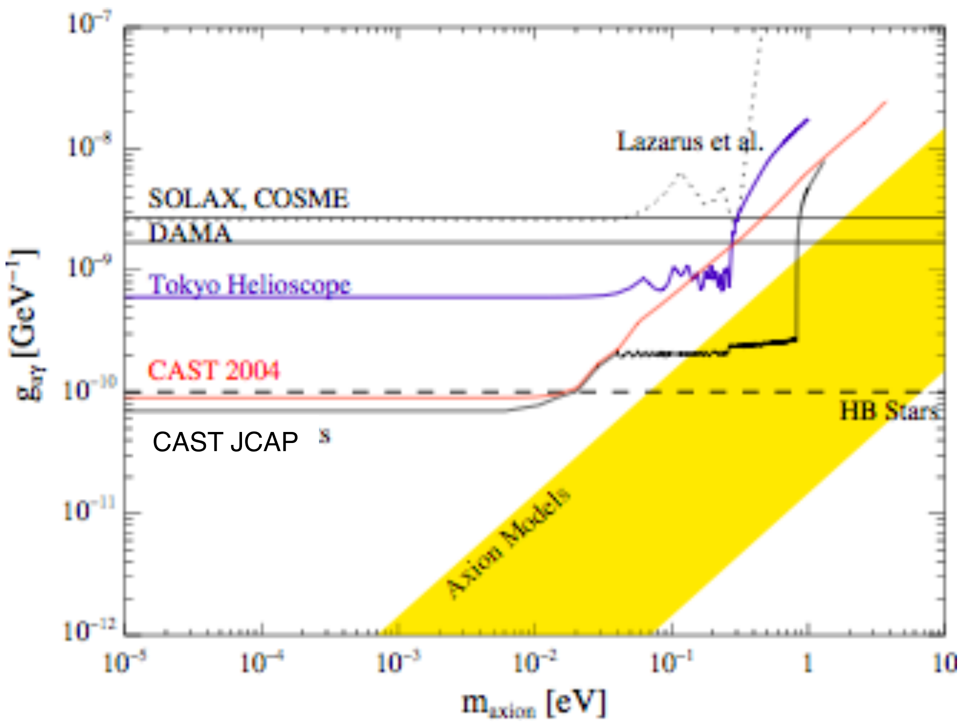
They are conceptualizing IAXO: a next-generation helioscope.

Larger magnetic field volume

Better x-ray optics.

Lower backgrounds.

CAST results and future



K. Zioutas et al., Phys. Rev. Lett. **94**, 121301 (2005)

CAST has published results equaling the Horizontal Branch Star limit (Red Giant evolution)

They are pushing the mass limit up into the region of axion models, 0.1-1 eV

Plan: Fill the magnet bore with gas (e.g. helium), and tune the pressure

When the plasma frequency equals the axion mass, full coherence and conversion probability are restored:

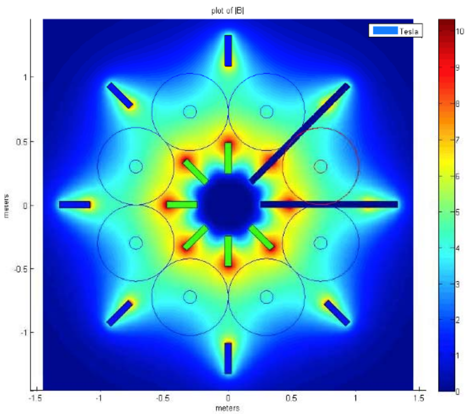
$$\omega_p = (4\pi\alpha N_e / m_e)^{1/2} \equiv m_\gamma$$

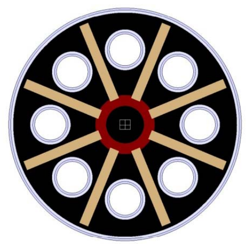
KvB, P. McIntyre, D. Morris, G. Raffelt PRD 39 (1989) 2085

They went to higher m_a with ^{3}He, and a second x-ray optic

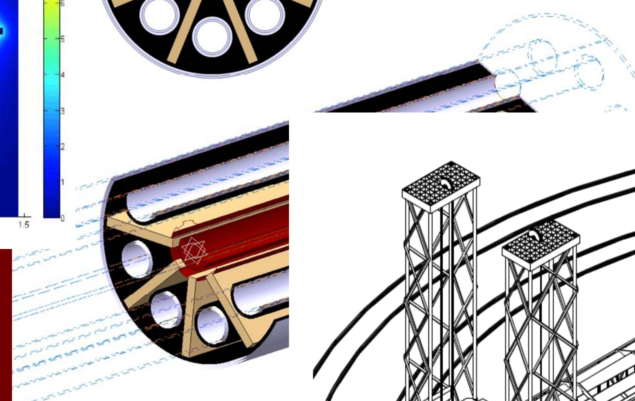
Helioscope Futurism: IAXO

IAXO magnet: 1st concept



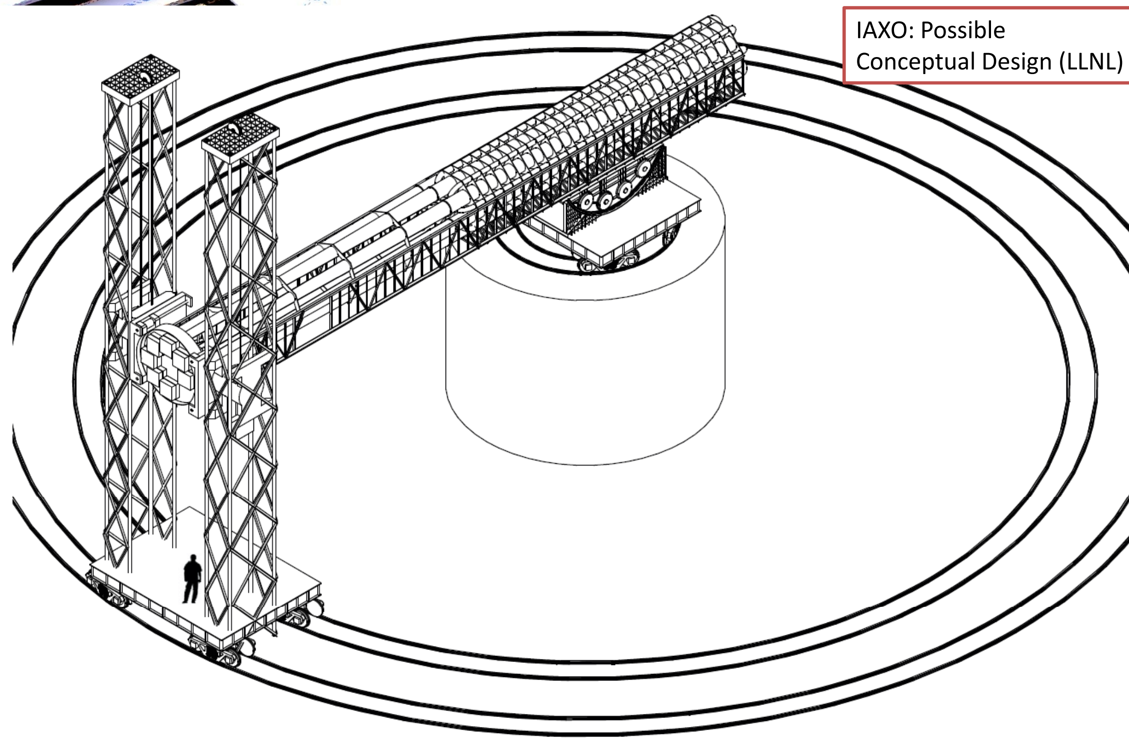


Total R = 2 m
Bore diameter = 600 mm
N bores = 8
Average B in bore = 4 T
(in critical surface)
MFOM = 770



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

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



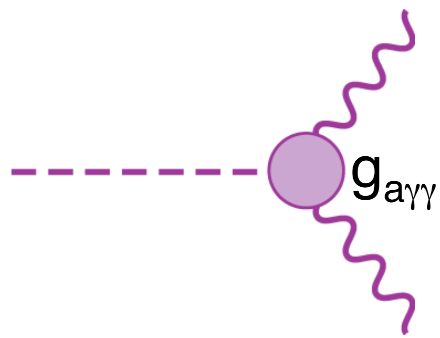
IAXO: Possible Conceptual Design (LLNL)

Search 4: RF cavity experiments

Recall:

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

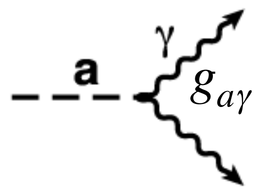
But it happens that the axion 2γ coupling has relatively little axion-model dependence



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

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

The axion-photon coupling…



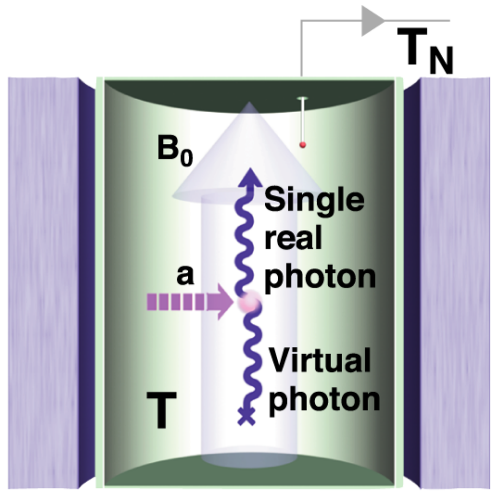
…is a source term in Maxwell's Equations

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

So imposing a strong external magnetic field B transfers axion field energy into cavity electromagnetic energy.

Some experimental details of the RF-cavity technique

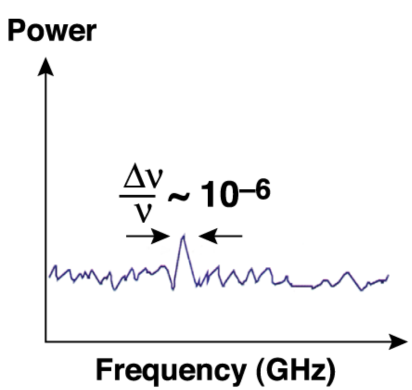
Primakoff Conversion



- 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

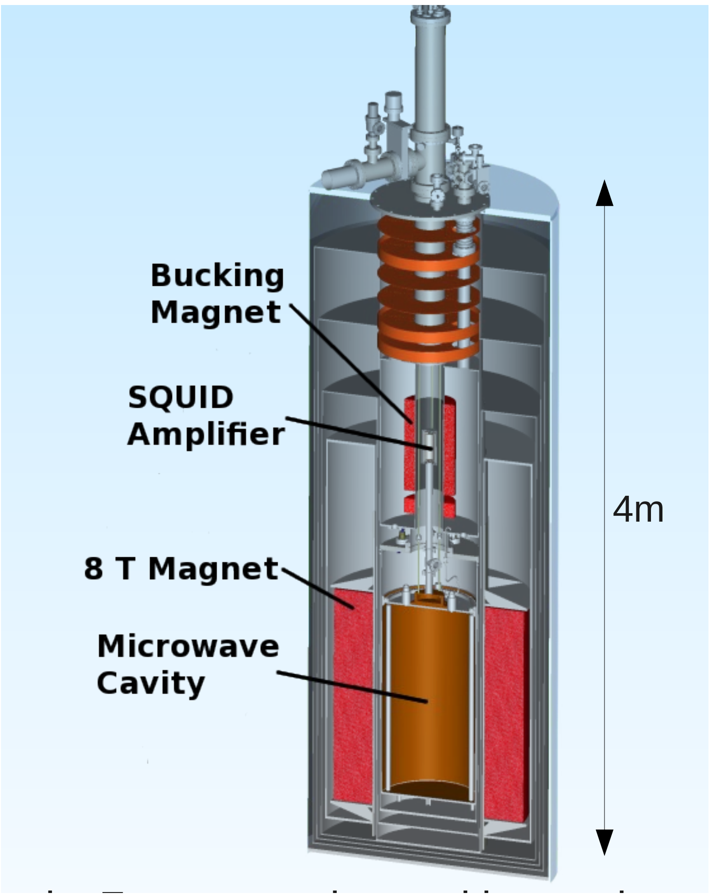


Scaling Laws	
$\frac{d\nu}{dt} \propto B^4 V^2 \cdot \frac{1}{T_S^2}$	$g_\gamma^2 \propto \left(B^2 V \cdot \frac{1}{T_S}\right)^{-1}$
For fixed model g^2	For fixed scan rate $\frac{d\nu}{dt}$

ADMX: Axion Dark-Matter eXperiment

U. Washington, LLNL, U. Florida, U.C. Berkeley, National Radio Astronomy Observatory, Sheffield U., Yale U.

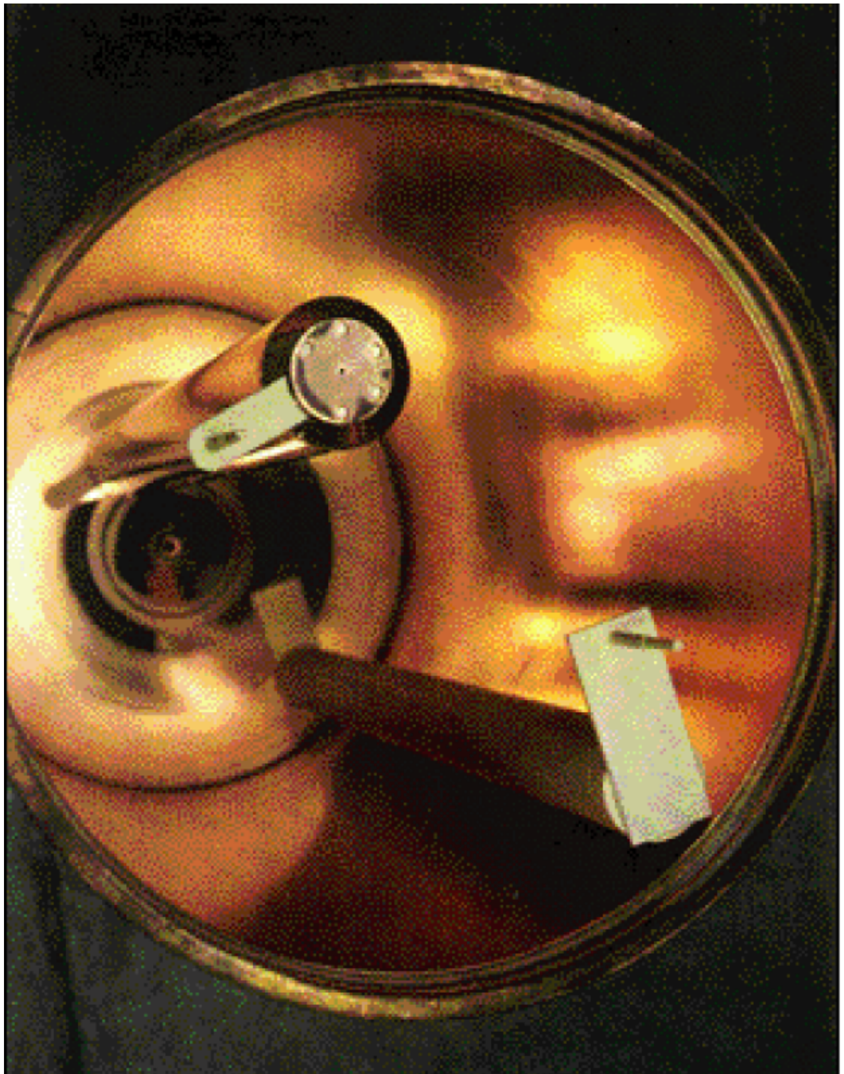
Magnet with insert



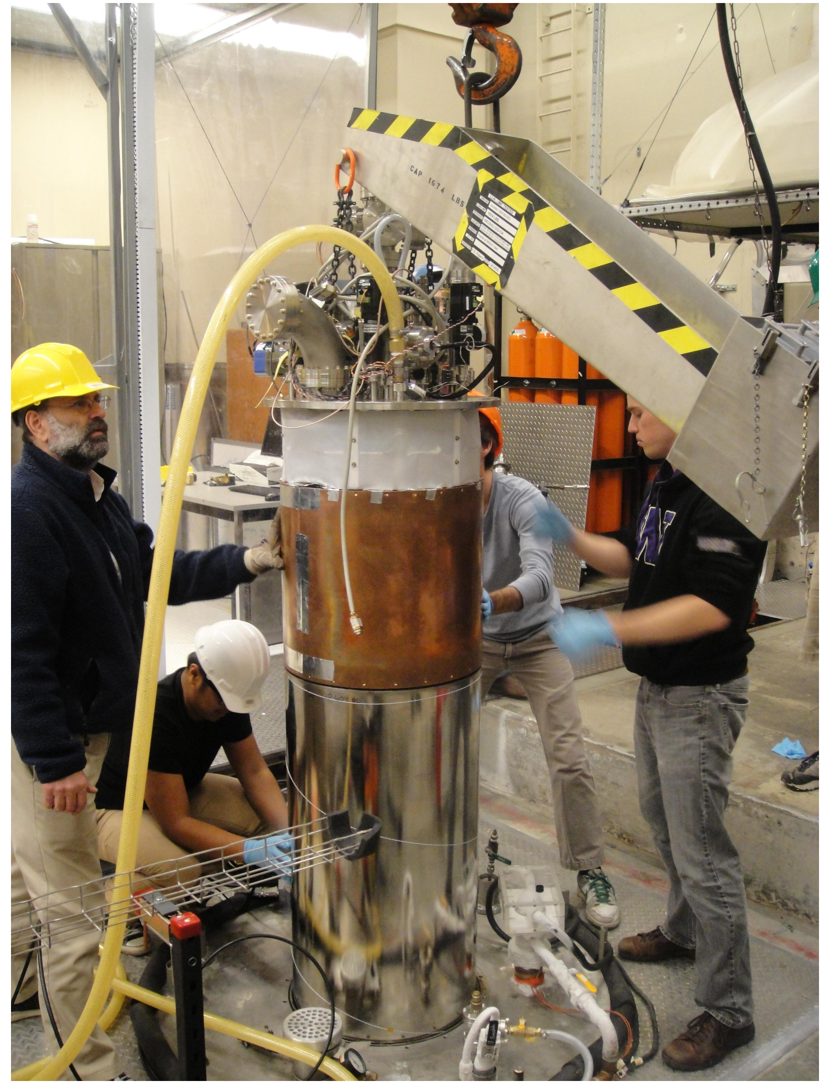
Magnet cryostat

ADMX key hardware 1

high-Q microwave cavity

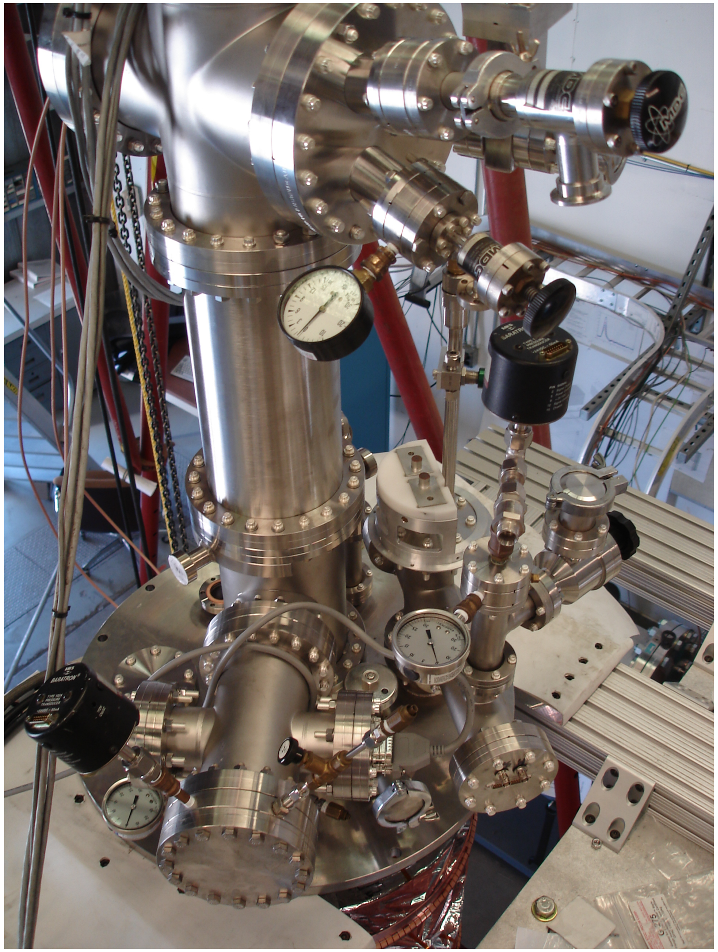


Experiment insert



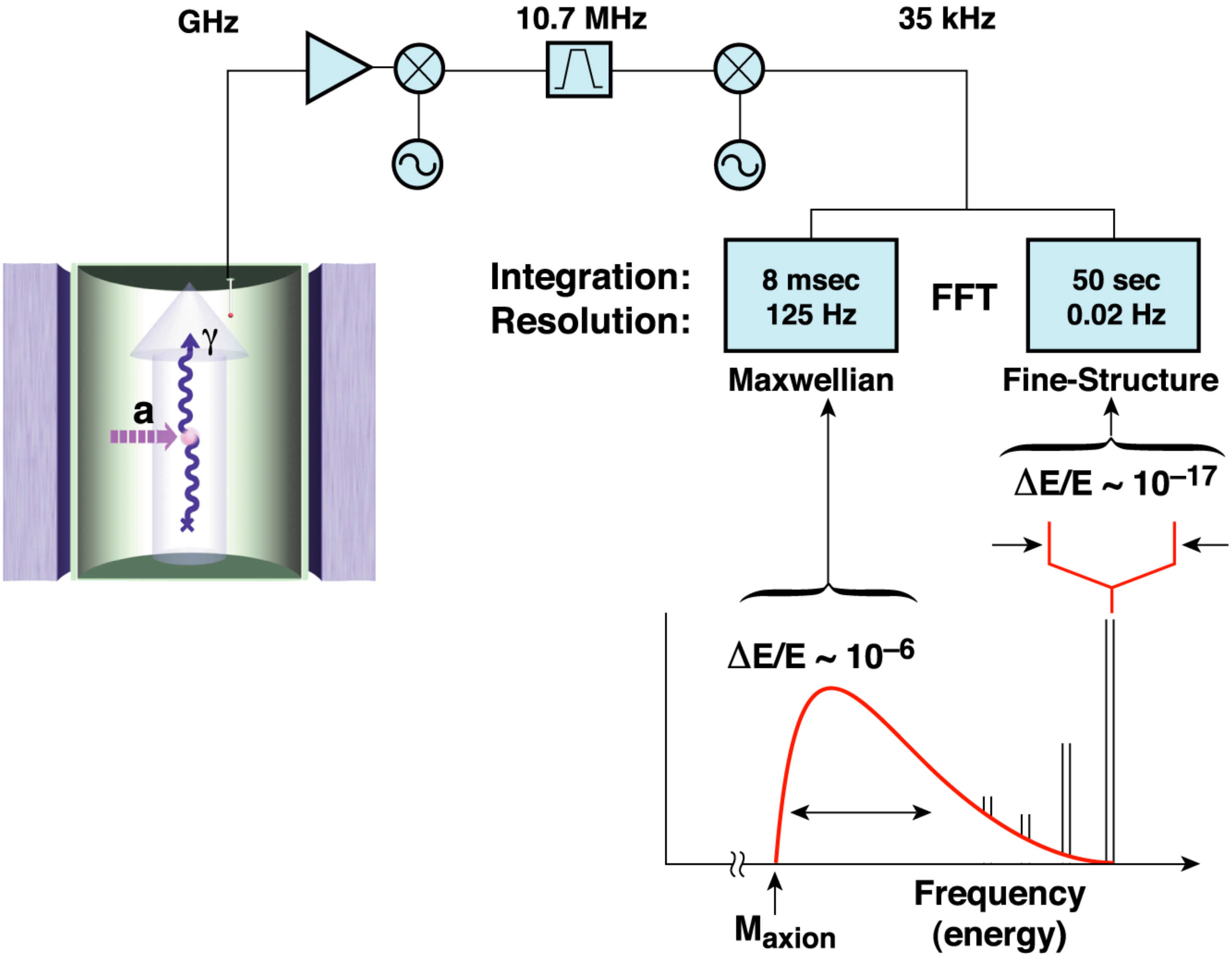
ADMX key hardware 2

Vacuum and cryo

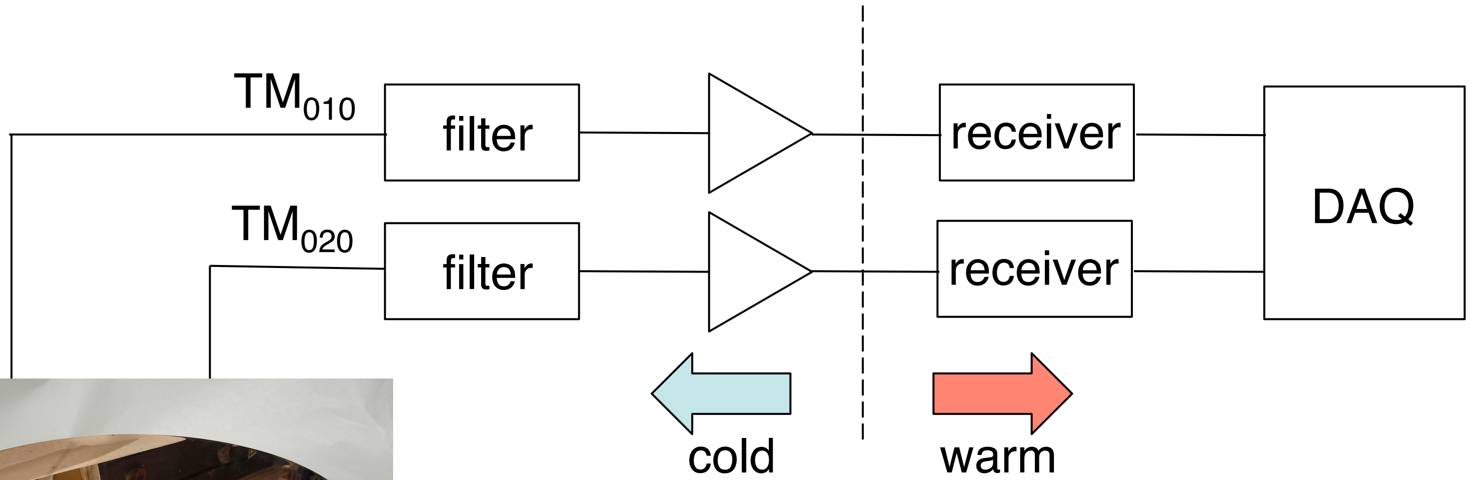


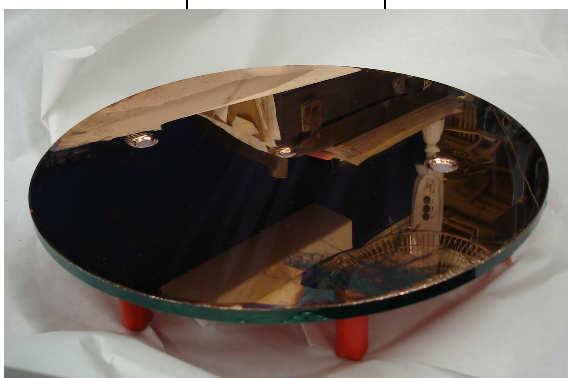
Quantum electronics

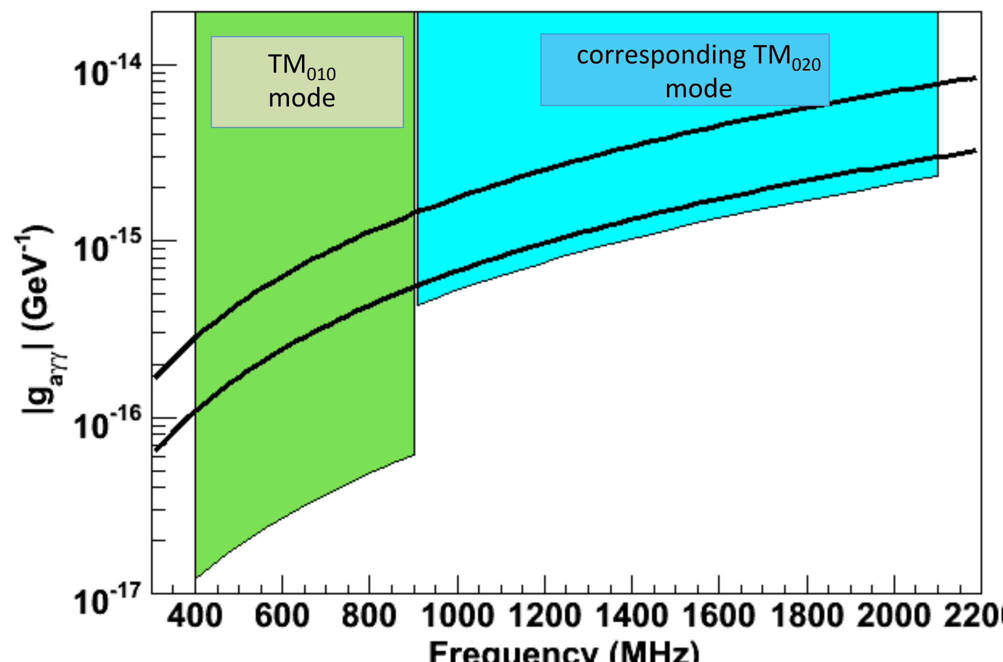
ADMX key hardware 3: axion receiver



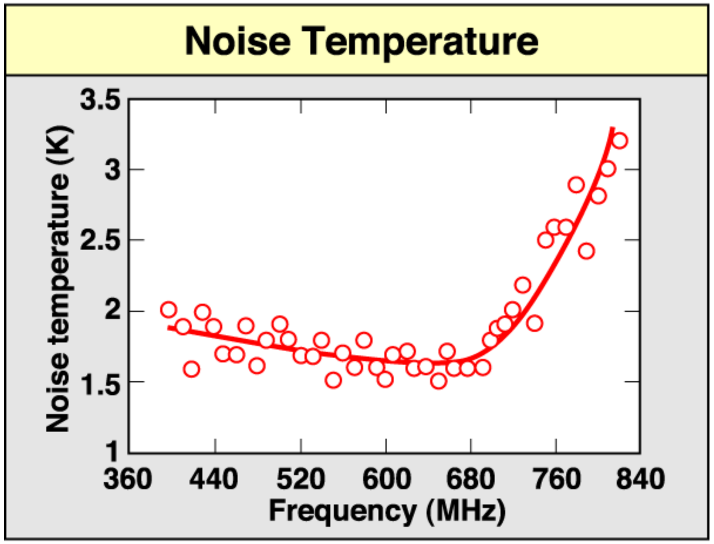
ADMX Phase IIa: Multi-mode readout

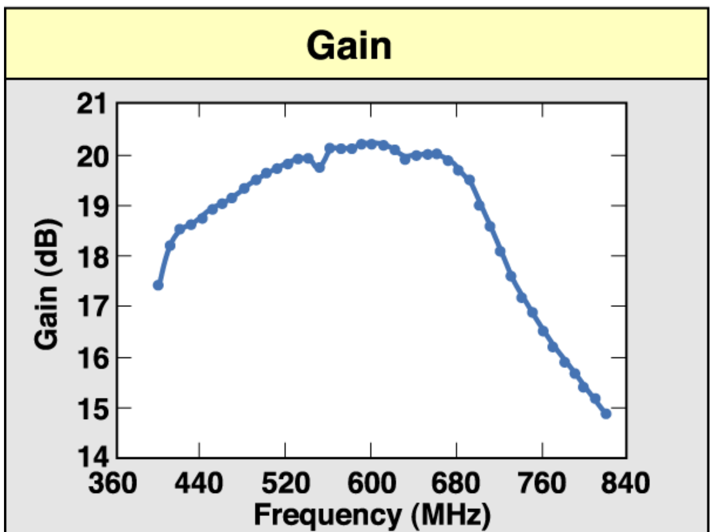






A brief digression on microwave amplifiers





HFET amplifiers
(Heterojunction Field-Effect Transistor)

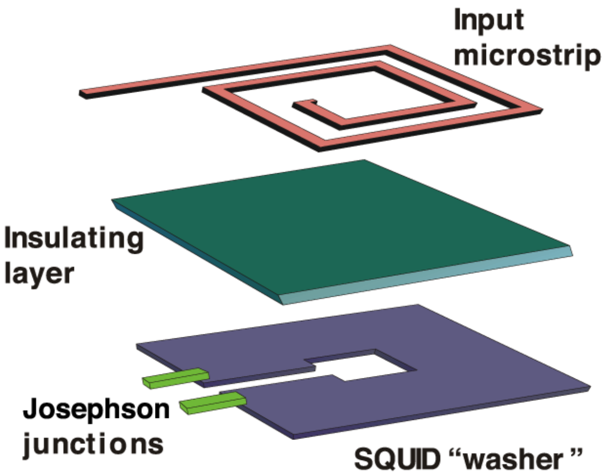
- A.k.a. HEMT™ (High Electron Mobility Transistor)
- Workhorse of radio astronomy, military communications, etc.

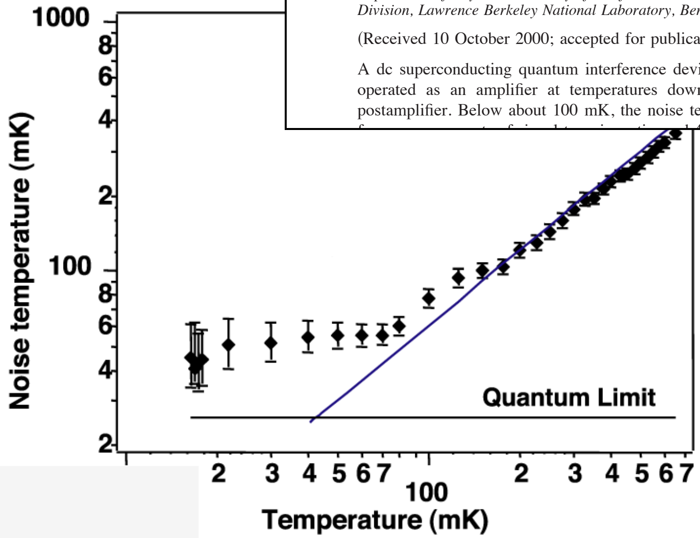
- Best to date $T_N \gtrsim 1$ K

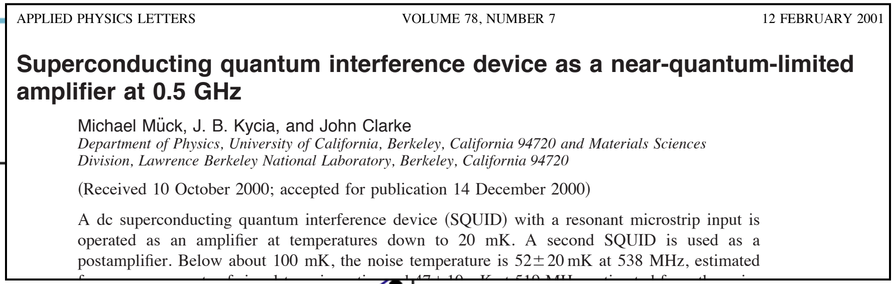
But the quantum limit $T_Q \sim h\nu/k$ at 500 MHz is only ~ 25 mK!

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

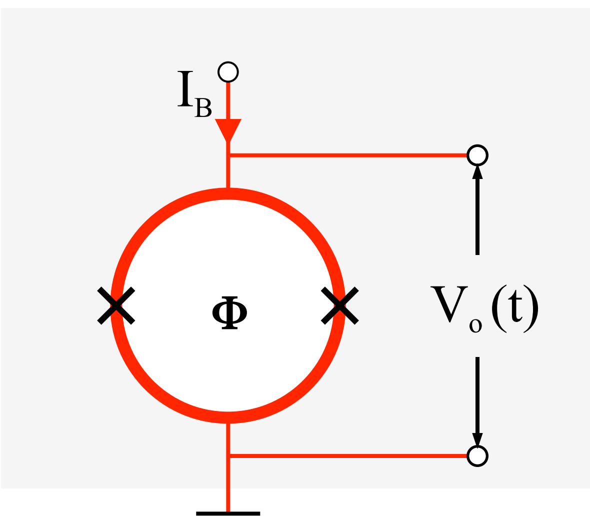
Superconducting quantum interference device as a near-quantum-limited amplifier at 0.5 GHz

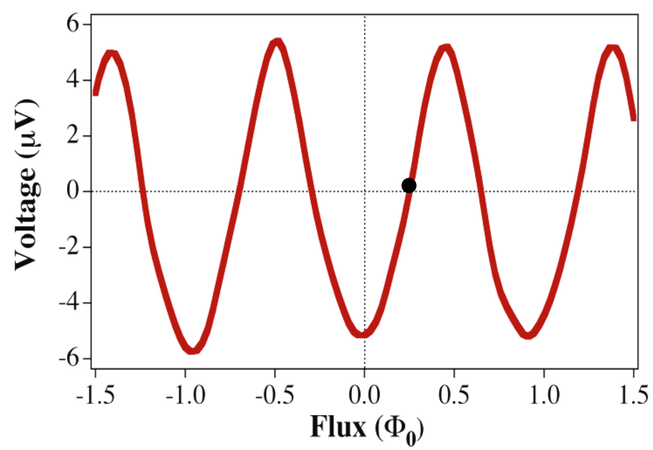
Michael Mück, J. B. Kycia, and John Clarke
Department of Physics, University of California, Berkeley, California 94720 and Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

(Received 10 October 2000; accepted for publication 14 December 2000)

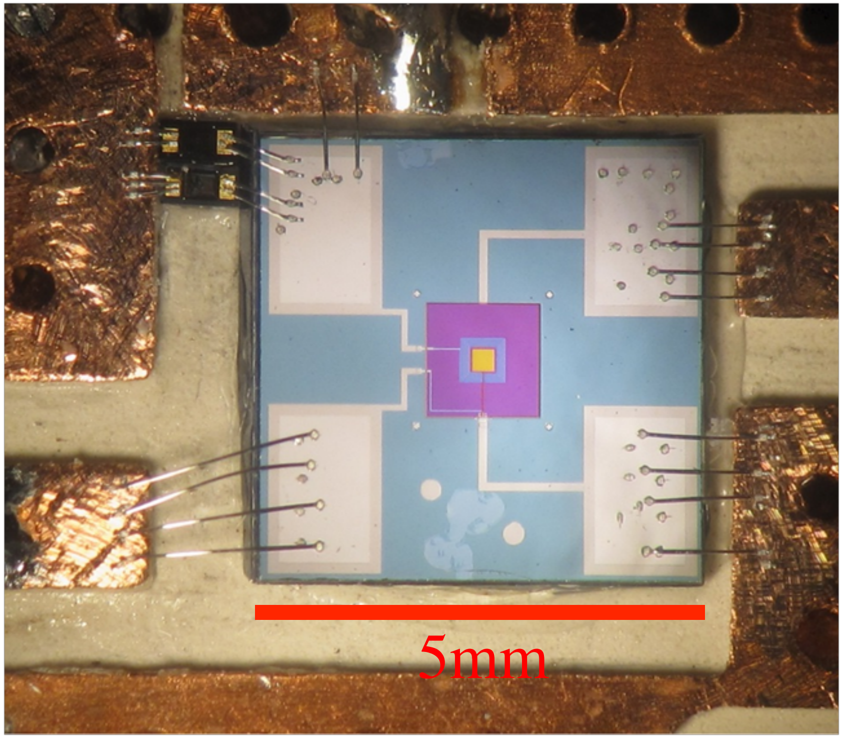
A dc superconducting quantum interference device (SQUID) with a resonant microstrip input is operated as an amplifier at temperatures down to 20 mK. A second SQUID is used as a postamplifier. Below about 100 mK, the noise temperature is 52±20 mK at 538 MHz, estimated

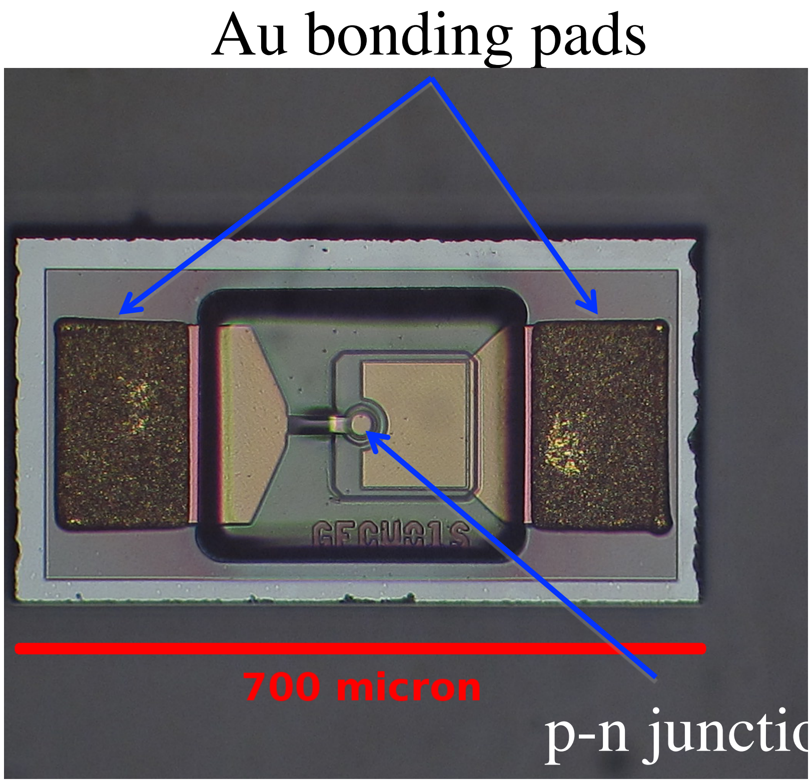
- GHz SQUIDs have been measured with T_N ~50 mK
- Near quantum–limited noise
- This provides an enormous increase in ADMX sensitivity



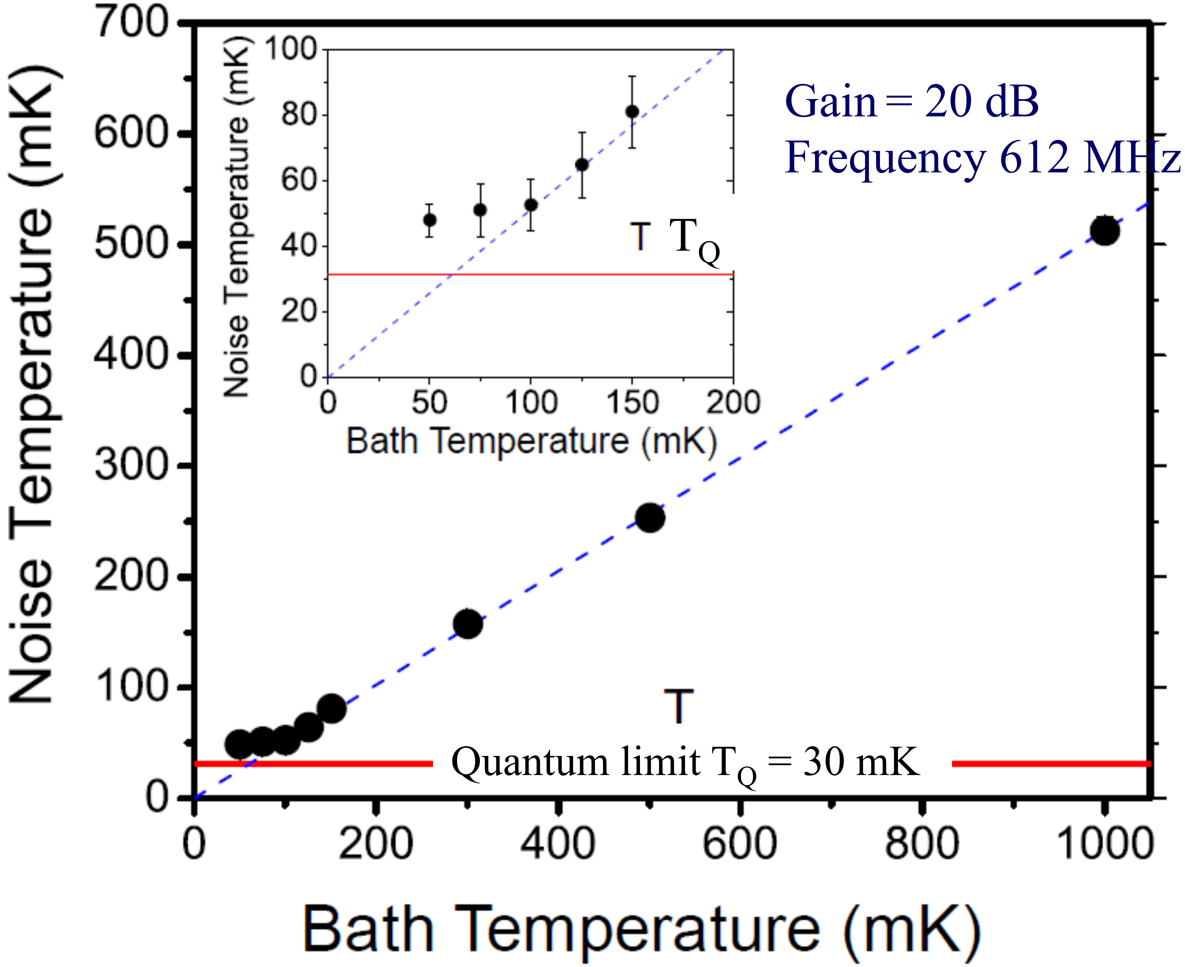


Microstrip SQUID amplifiers with varactor tuning

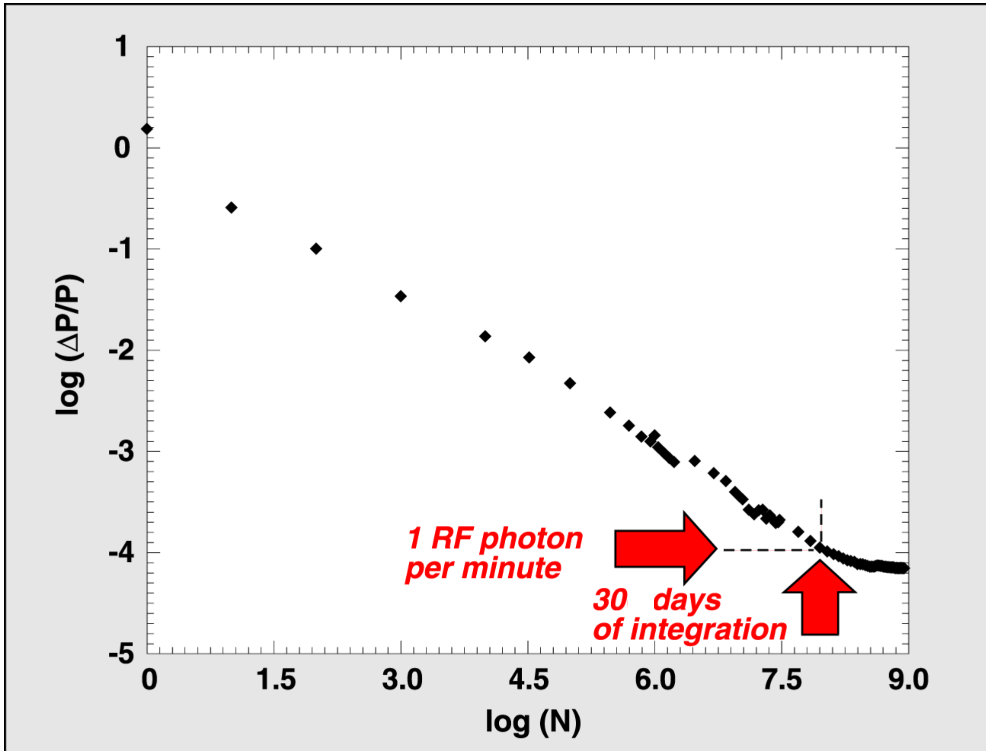




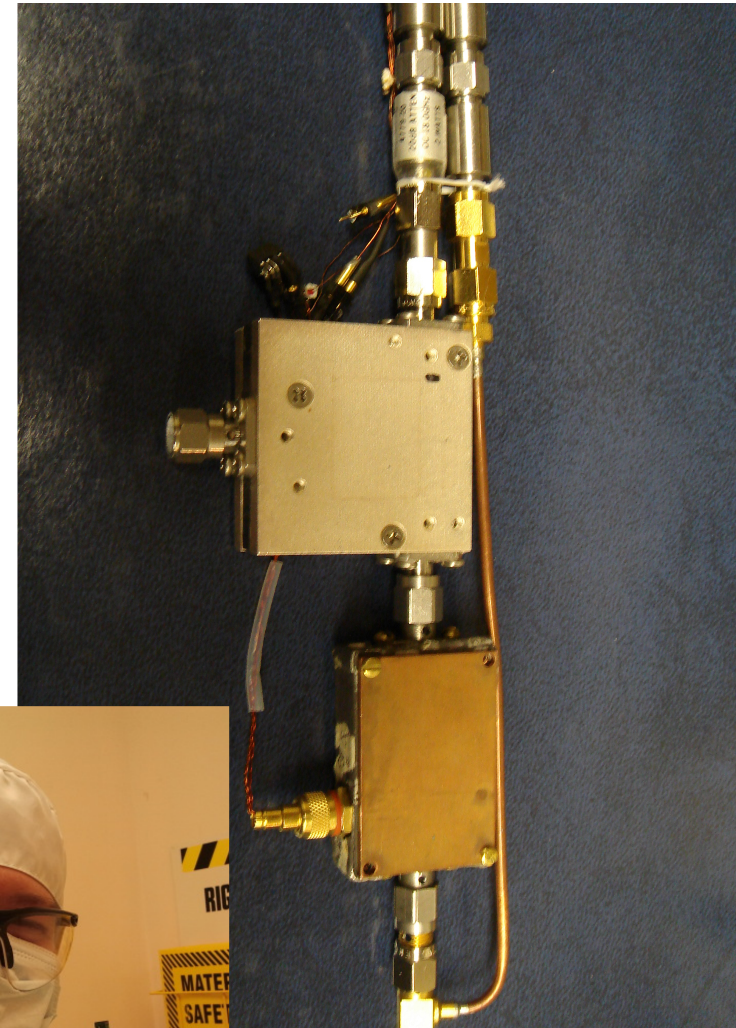
SQUID Amplifier Noise Temperature

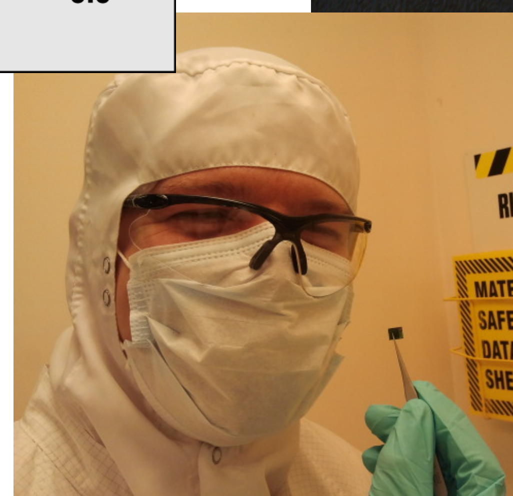


Phase I introduced SQUIDs and lower system noise

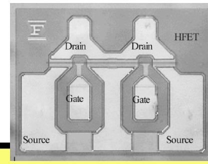


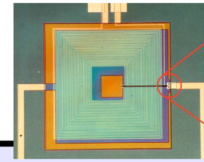
Systematics-limited for signals < 10^{-26} W ~10^{-3} of "DFSZ" axion power (< 1/100 yoctoWatt).

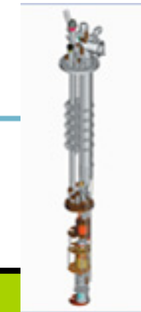




ADMX: Upgrade phases nomenclature

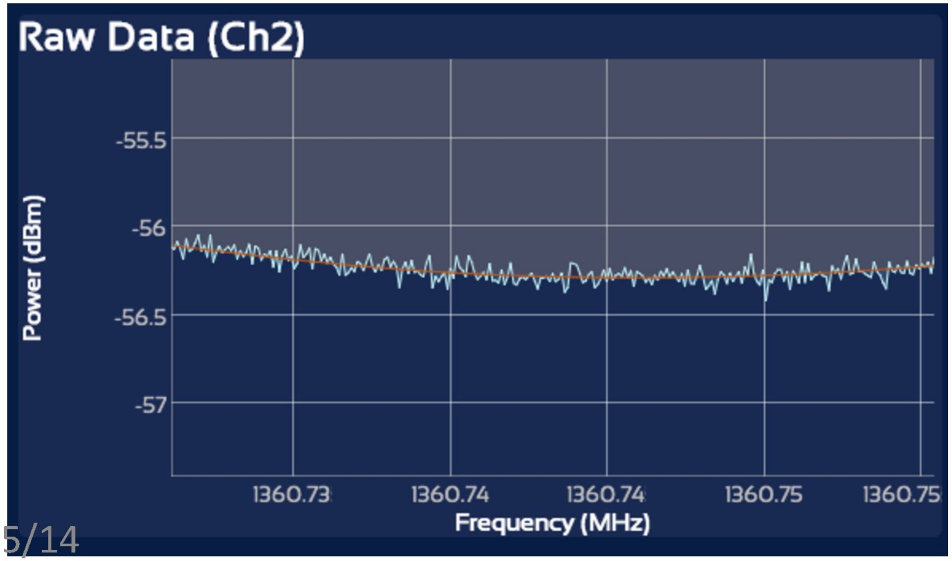


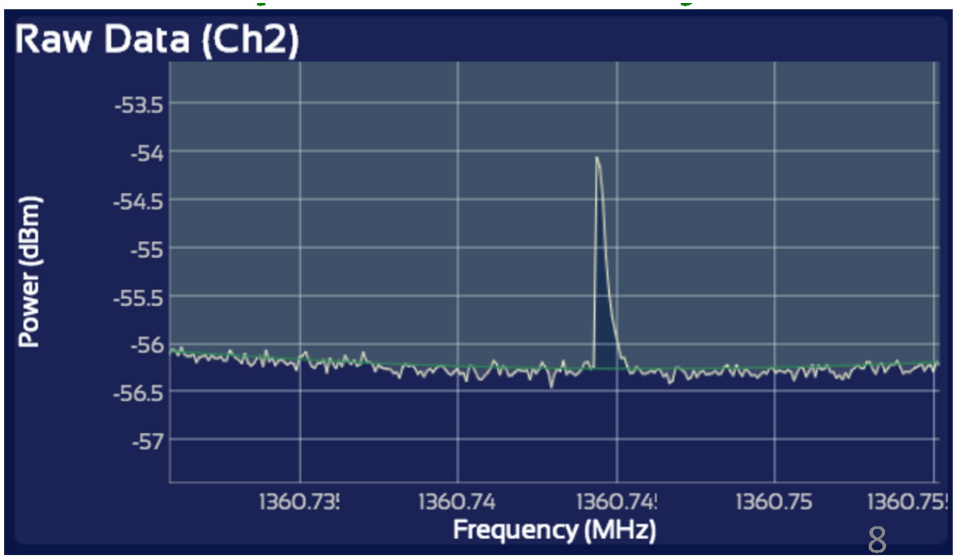




phase	**Original ADMX**	**Phase I**	**Phase IIa**	**Gen 2**
technology	HFET; pumped ^4He	SQUID; pumped ^4He	SQUID; pumped ^3He	SQUID; dilution refrigerator
construction & operation	1995-2001	2002-2009	operating	In construction
T_{phys}	2. K	2. K	0.4 K	0.1 K
T_{amp}	4. K	1. K	0.2 K	0.05 K
scan rate $\propto (T_{sys})^{-2}$	1 @ KSVZ	4 @ KSVZ	100 @ KSVZ	1600 @ KSVZ

Raw data and hardware synthetic axion (×100)

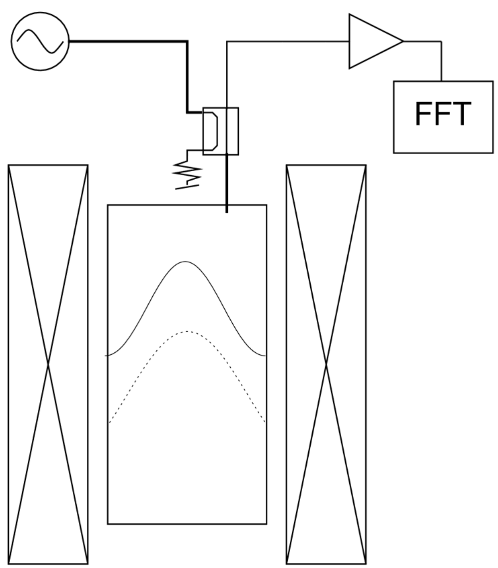




Operations include searches for exotics: "Chameleons" & hidden-sector photons

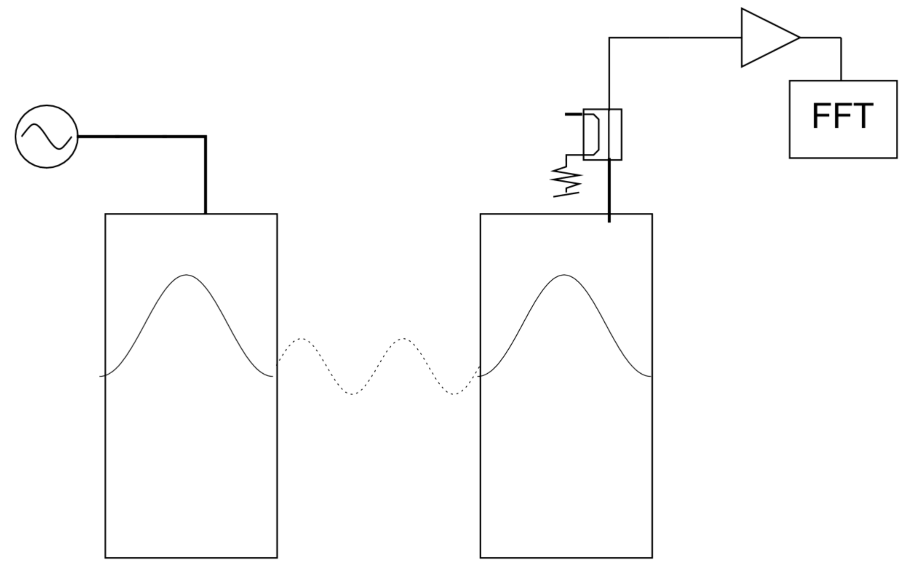
Chameleons

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



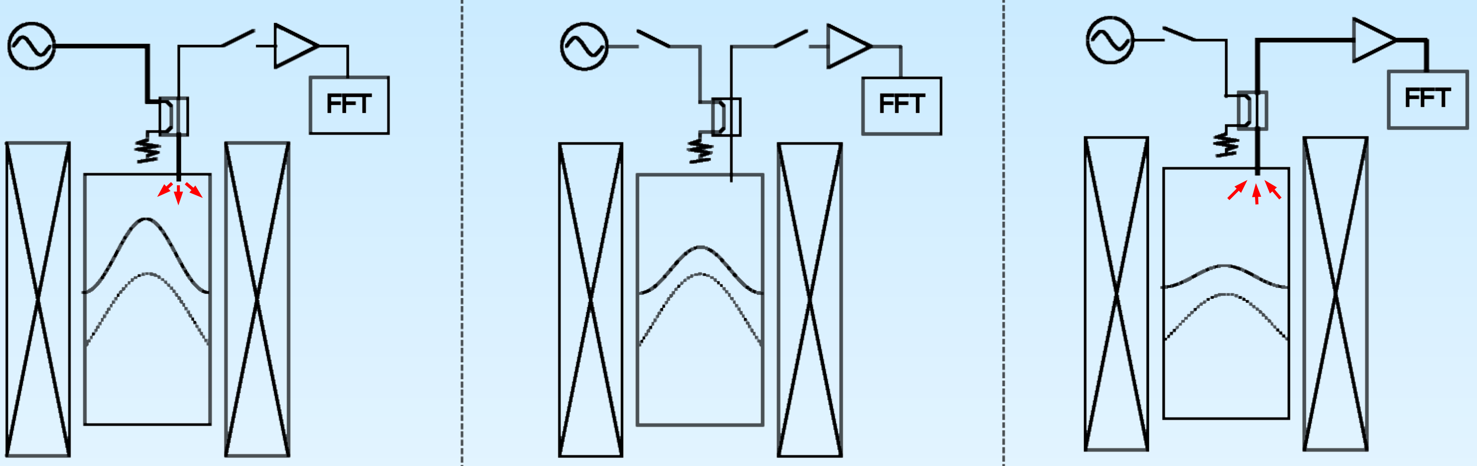
Hidden-sector photons

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

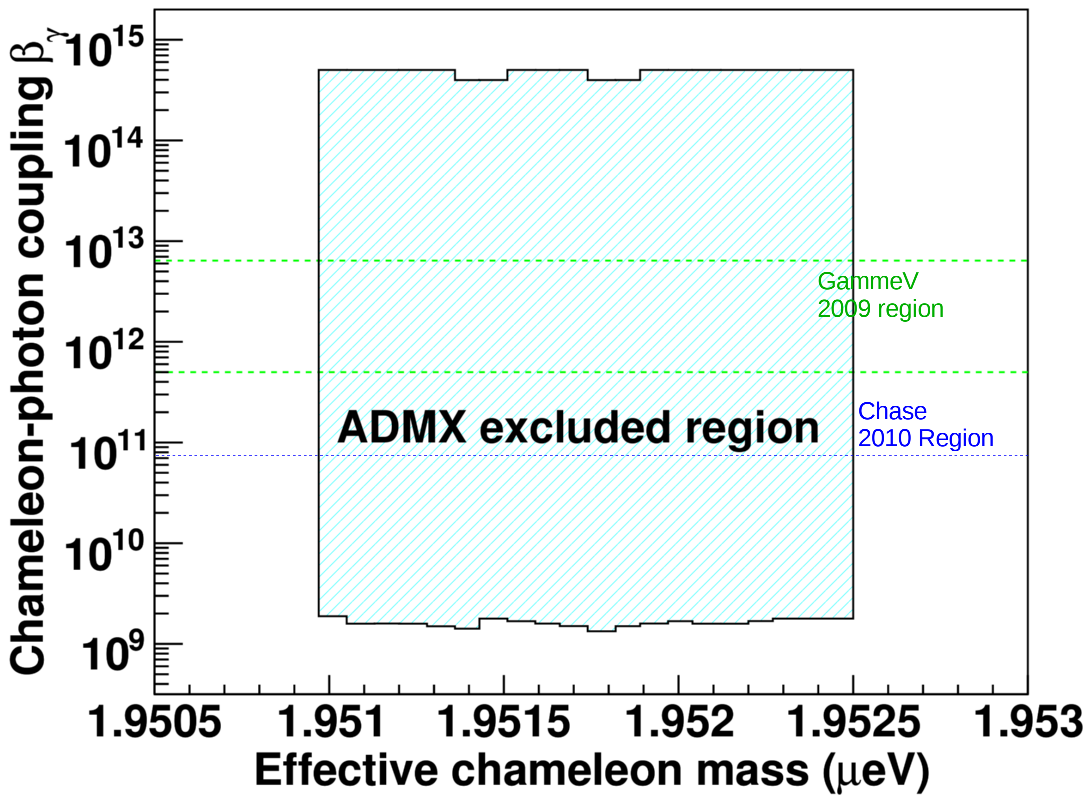
Timescale: 10 minutes

Sensitivity ~10^{-22} W

Bandwidth ~20 kHz

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

Chameleons

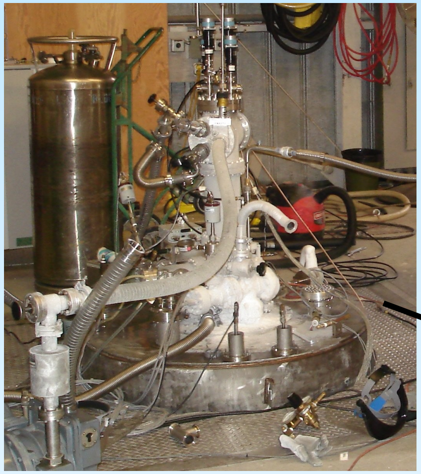


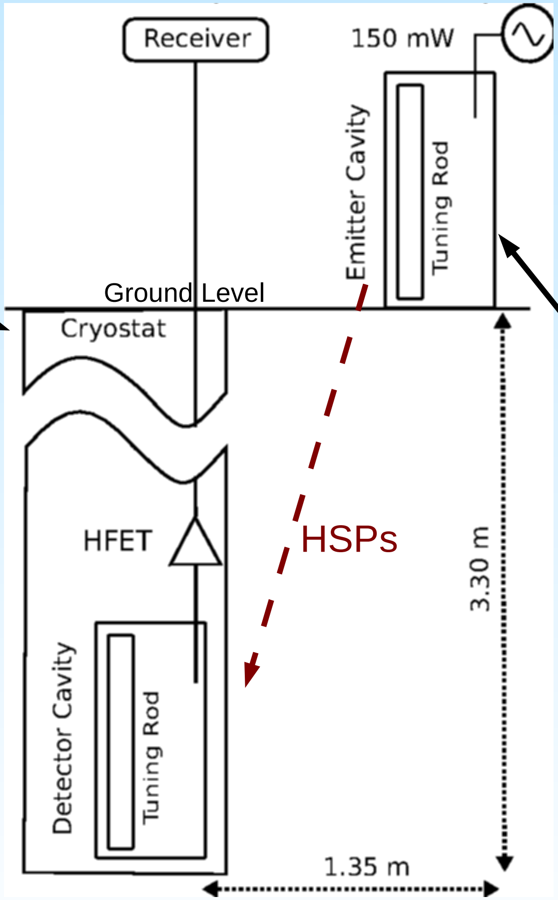
Laboratory Dark Energy Search

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





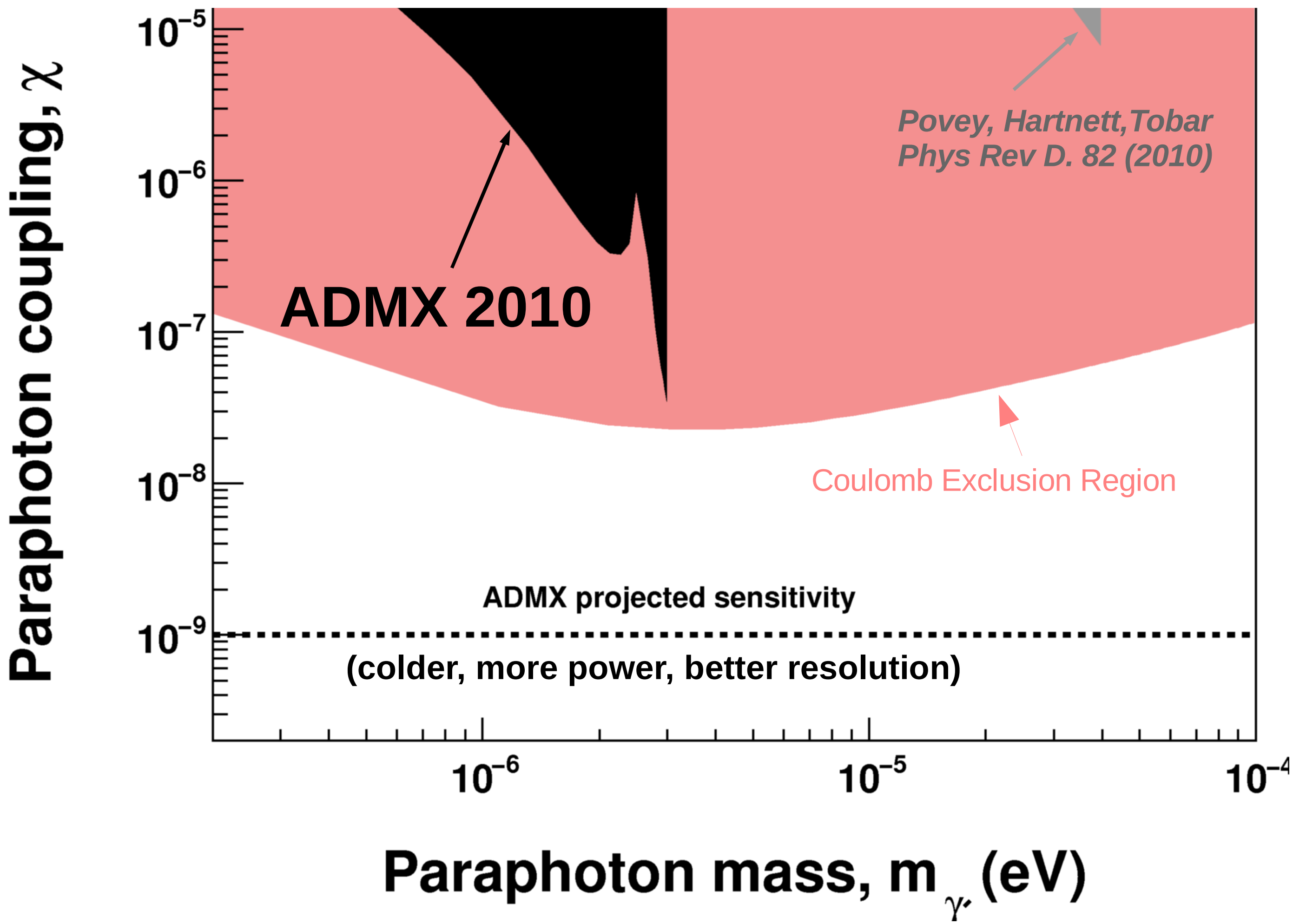
1

Photons in this driven cavity mix with HSPs and escape

2

HSPs mix with photons and are detected in the ADMX cavity

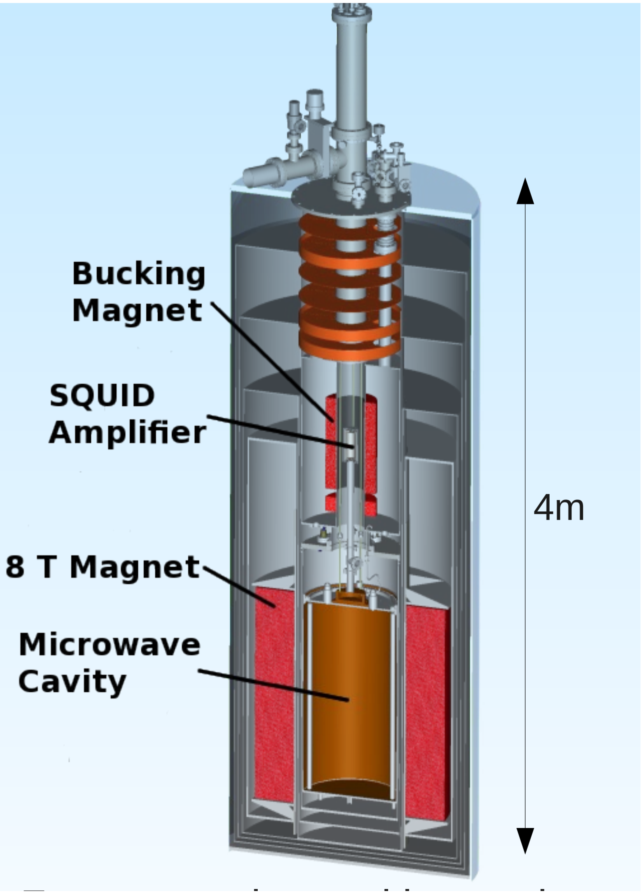
Hidden Sector Photons: Results



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

ADMX: Overview of Phase IIa (operating now)

Phase IIa major new components:
He liquefier (we consume 100 liter/day)
[Hedges cost & delivery upsets (including magnet risk)]
Pumped ^{3}He refrigerator (goes from 2K to 400mK)
[then the pumped ^{3}He fridge goes into dilution fridge)]
Multi-mode readout (more than doubles data set;
a sensitive search into next decade).



Building the ADMX infrastructure

July 2011

September 2011

June 2012

September 2012

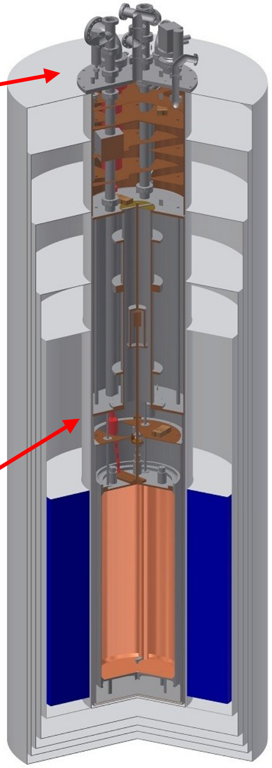
April 2013

April 2014

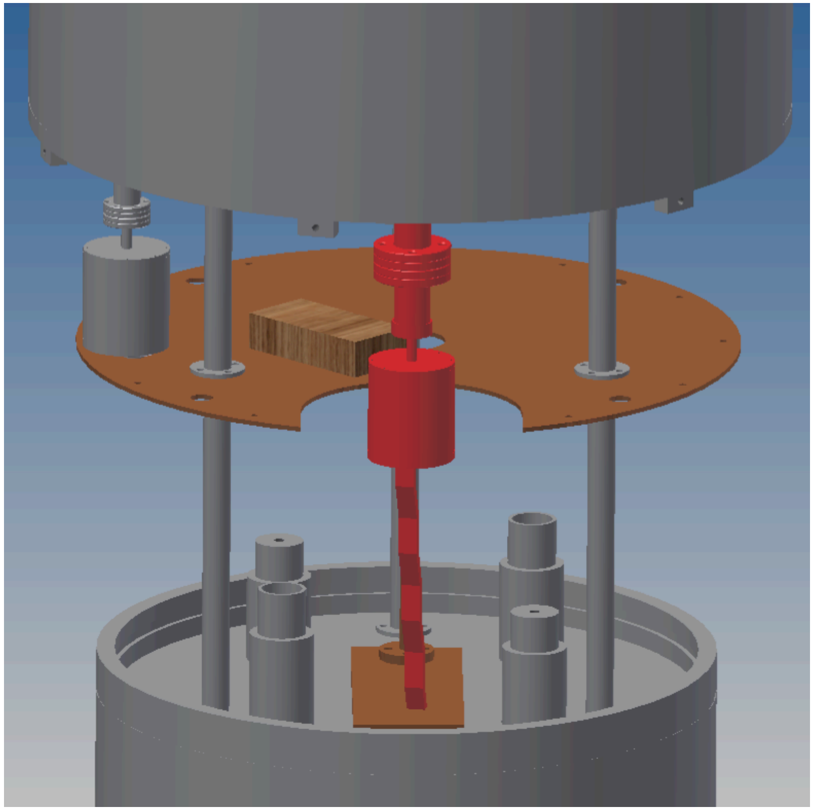
Assembling the Phase IIa experiment insert

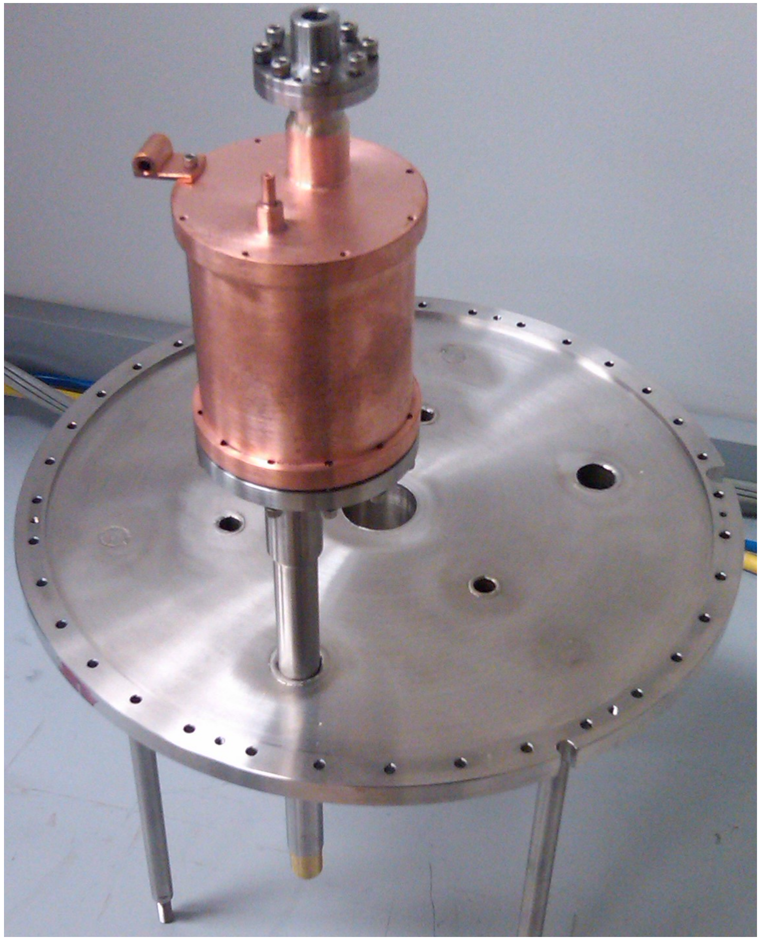
Installation of bucking coil

Assembly of top half of insert

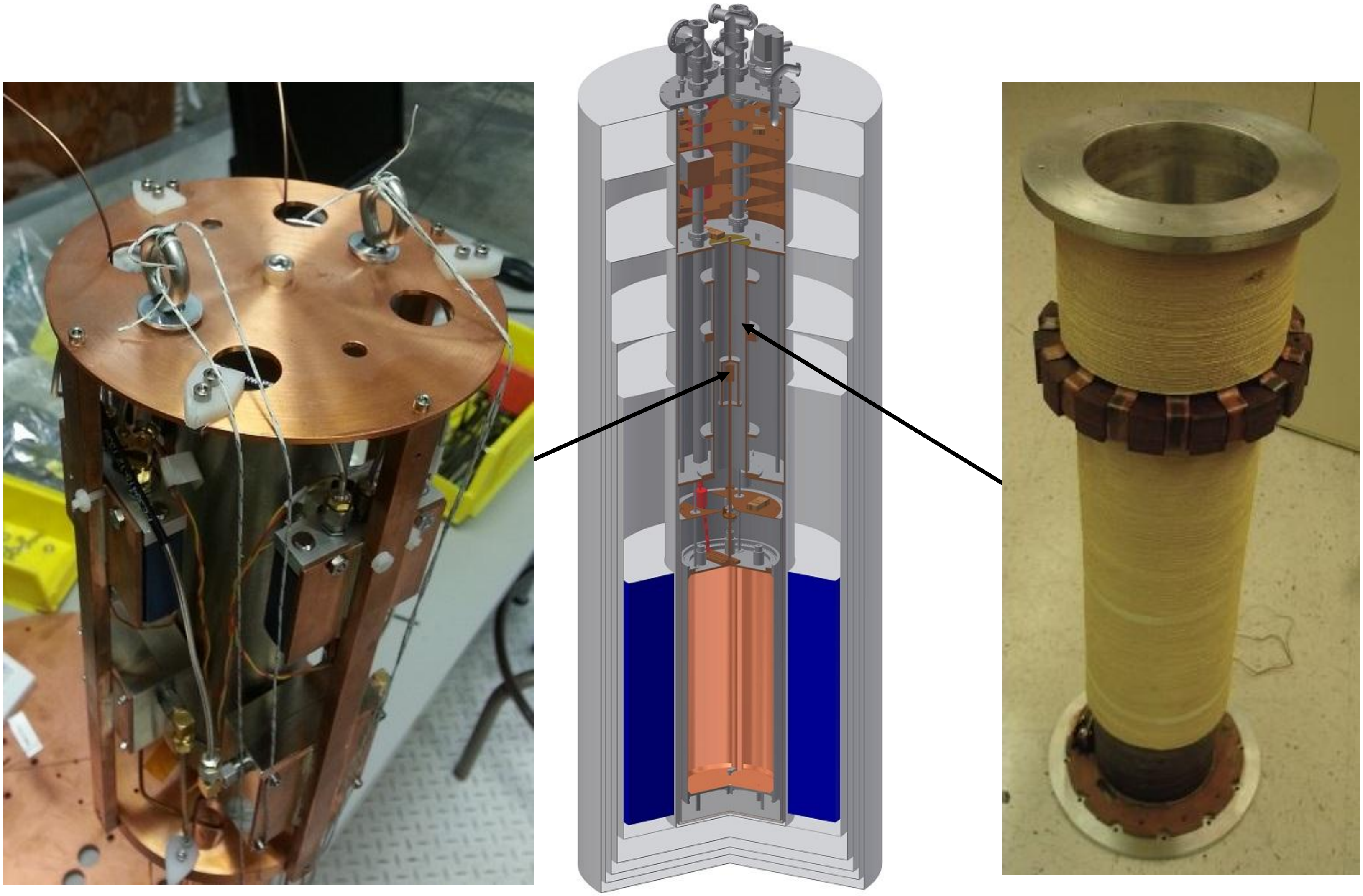


ADMX Phase IIa: Pumped ^{3}He and lower system noise

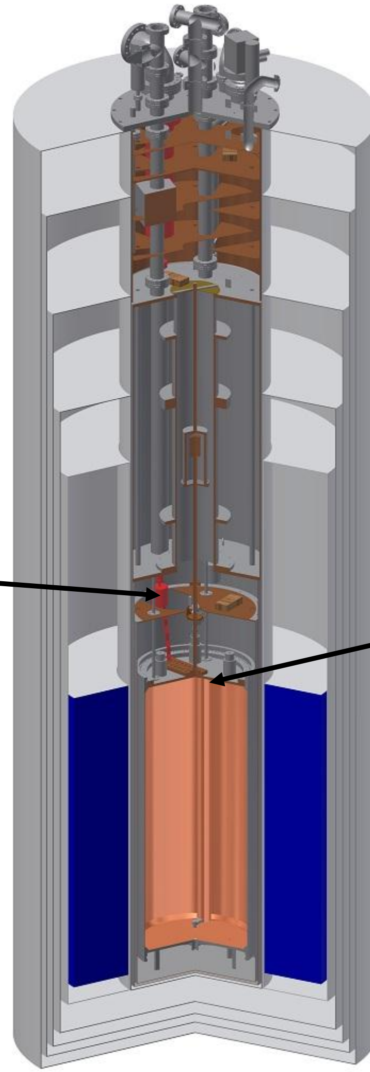




Quantum-electronics and bucking coil

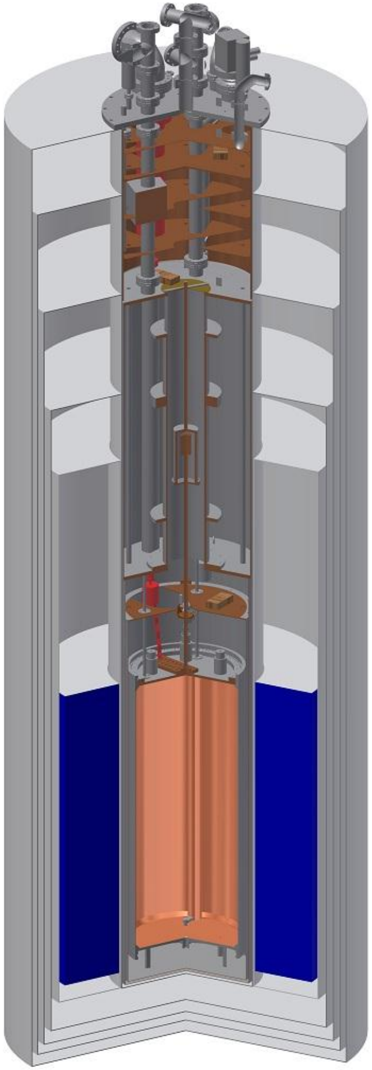


Cavity, tuning and coupling



ADMX insert going into and out the magnet bore

Science, Nov. 2013, 552 - 555



Typical Phase IIa Run Cadence

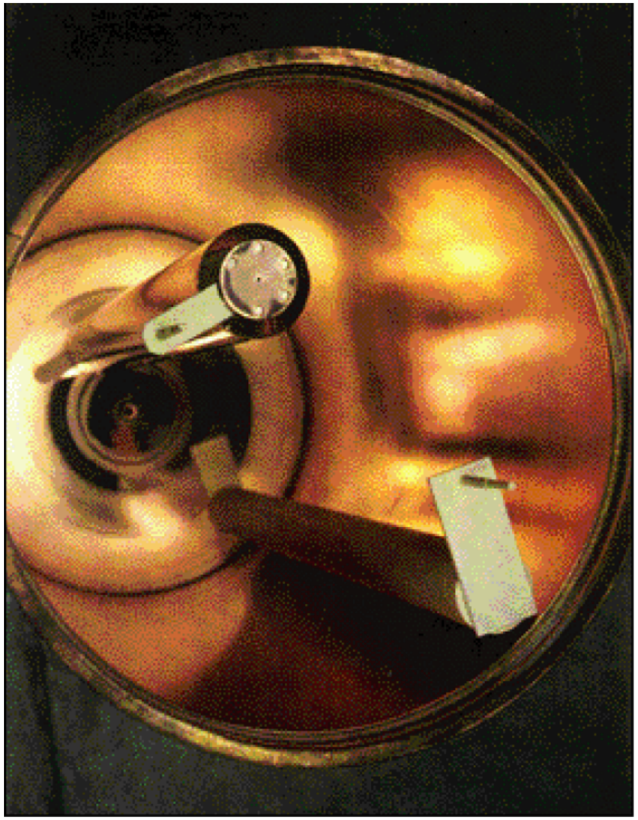
- Inject broad swept RF signal to record cavity response. Record state data (temperature sensors, hall sensors, pressure, etc.).

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

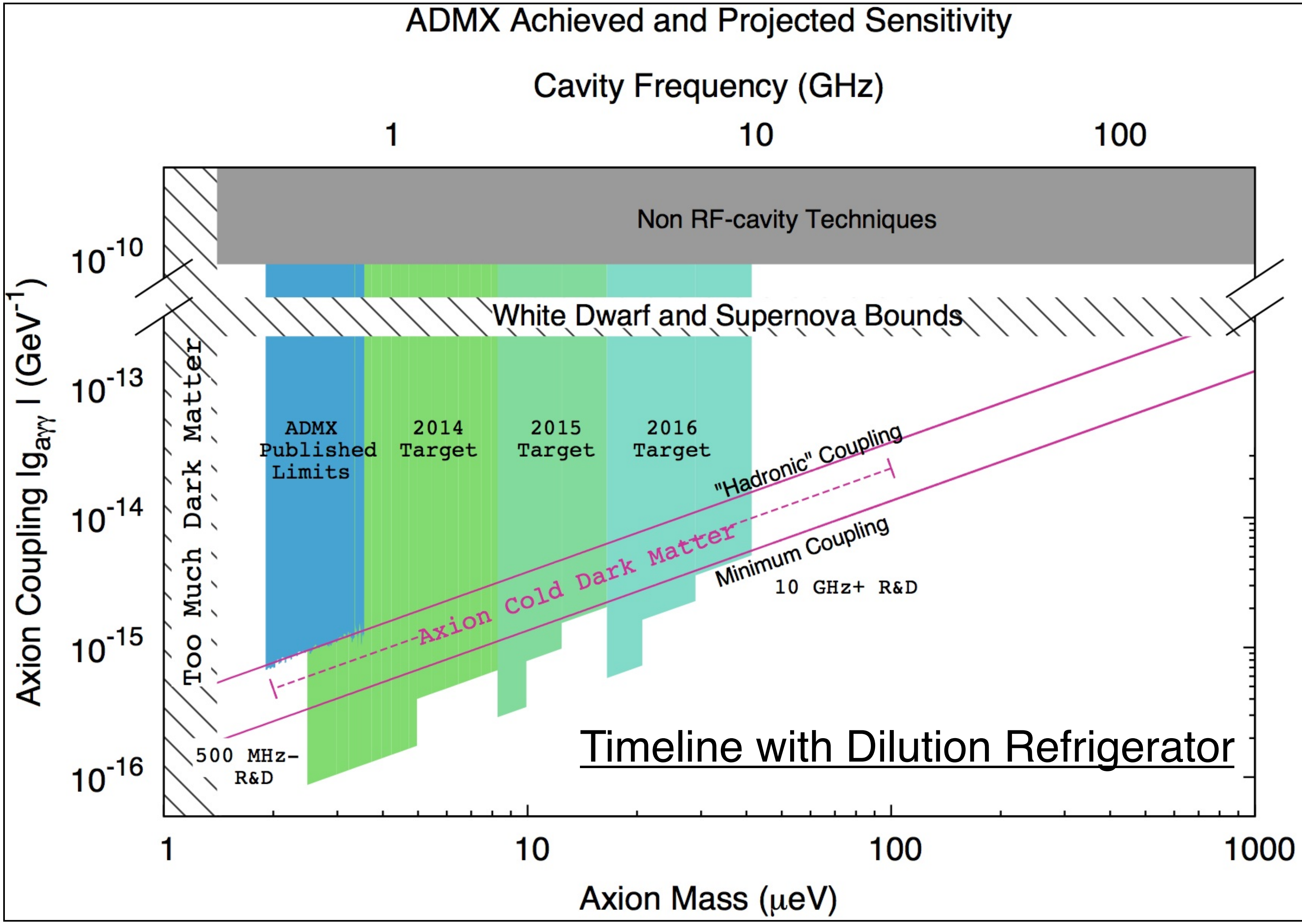
- Move tuning rod to shift TM_{010} & TM_{020} modes (~ 1 kHz at a time).

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

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

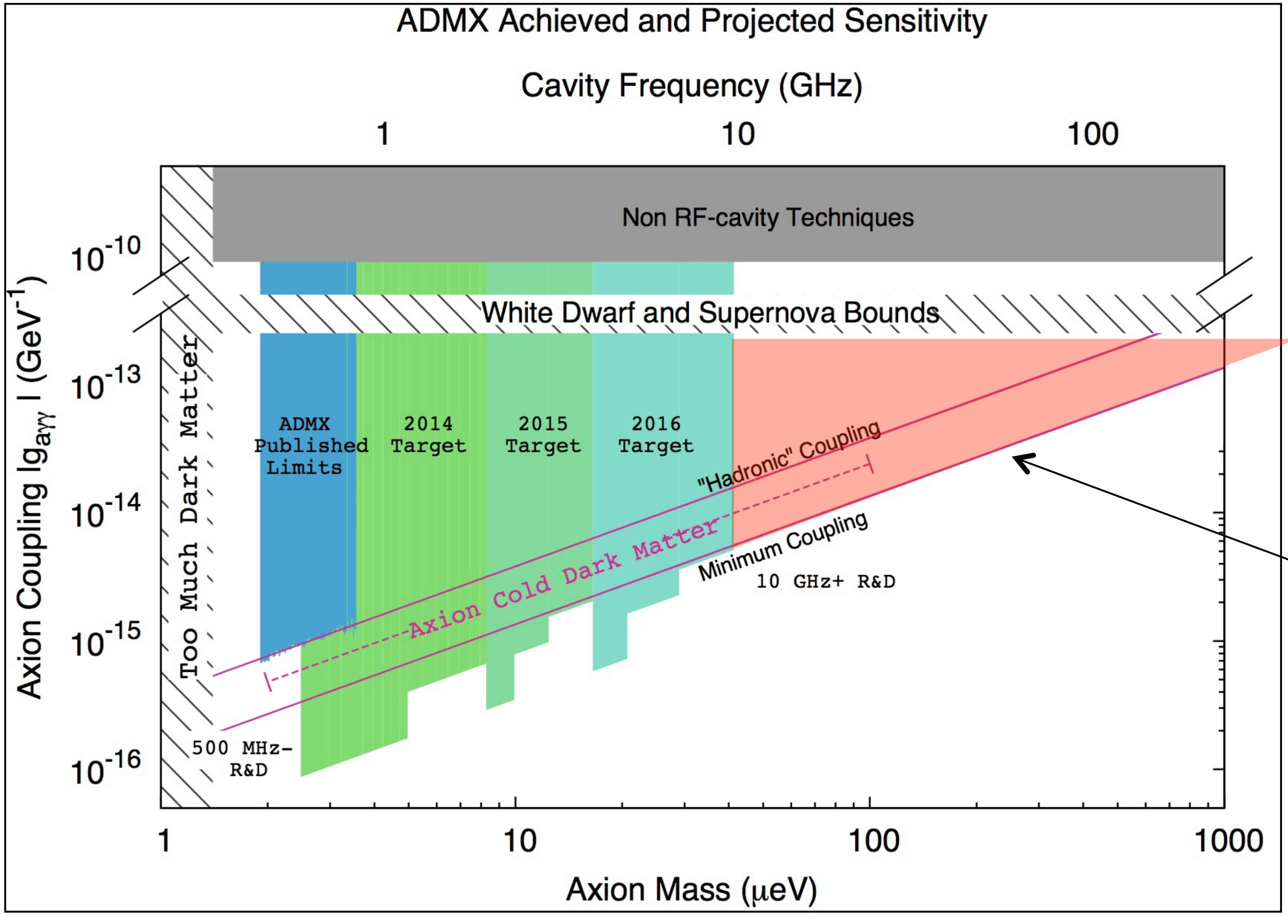


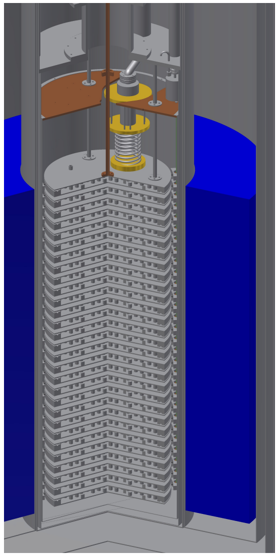
ADMX Gen 2: Science Prospects



Thoughts on ADMX Gen 3

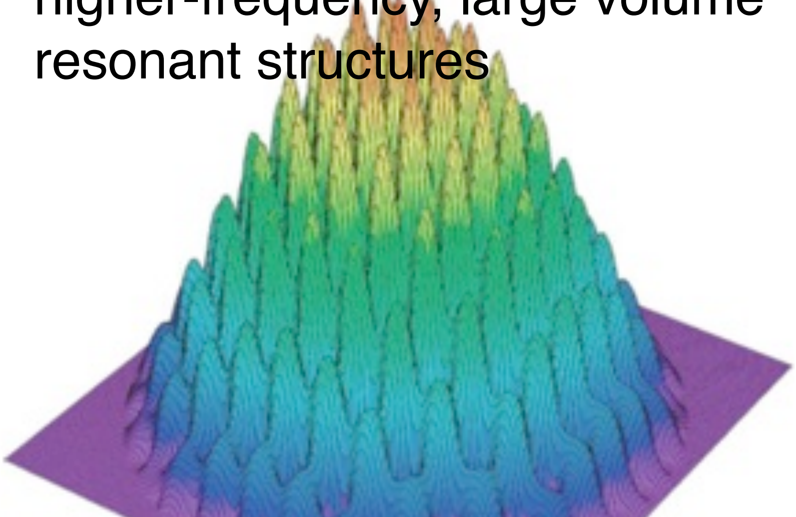
Well beyond this talk but we are looking at how to search for axions > 10 GHz
May be advantageous to switch to bolometers or other technology

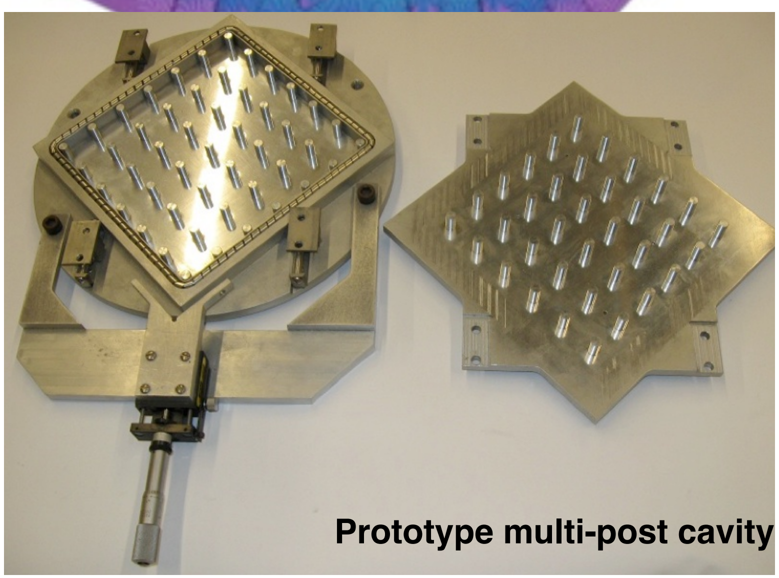




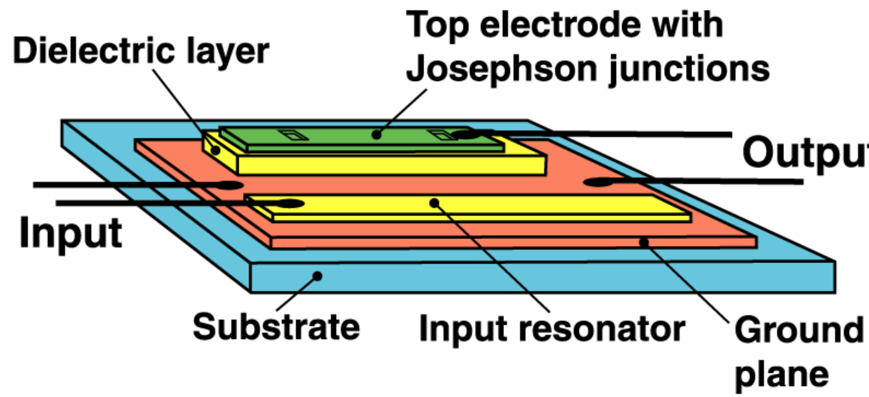
Gen 3: Can the RF-cavity experiments do better? Higher frequencies, higher Q, etc. ?

higher-frequency, large volume resonant structures



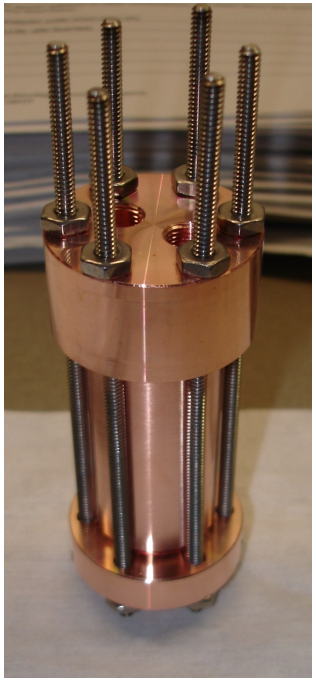


Prototype multi-post cavity

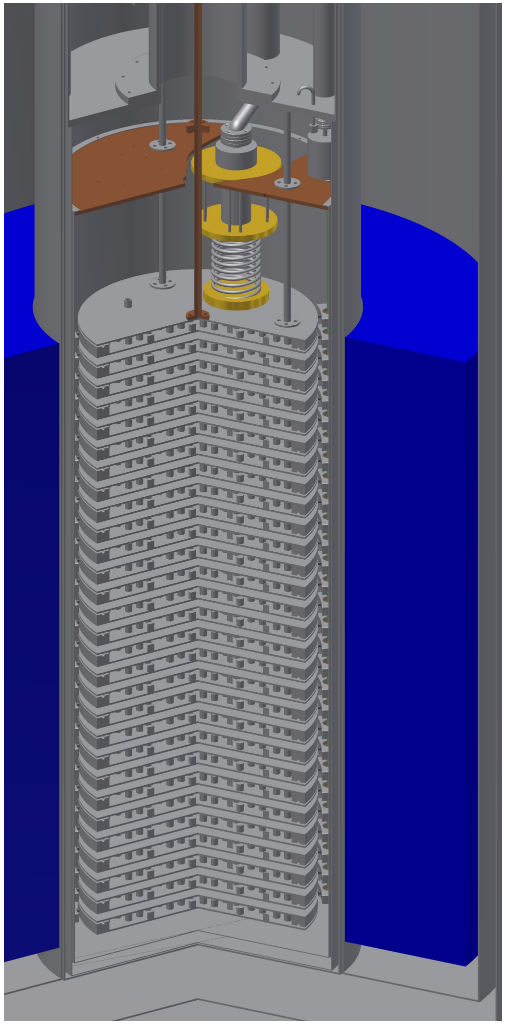


higher-frequency quantum-limited SQUIDs (or maybe other quantum devices)

Gen 3: High-frequency R&D

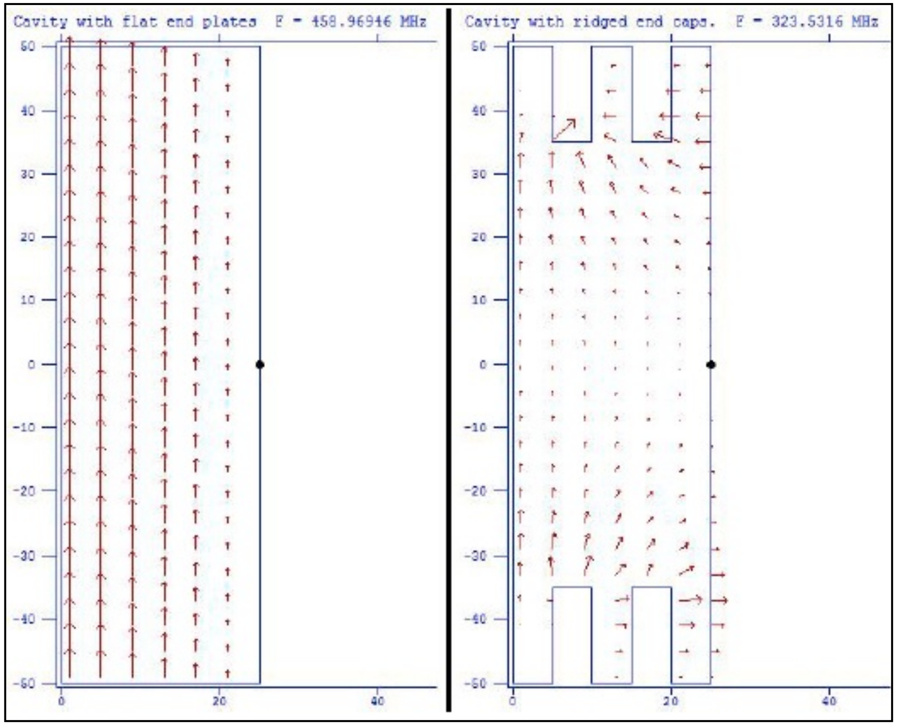


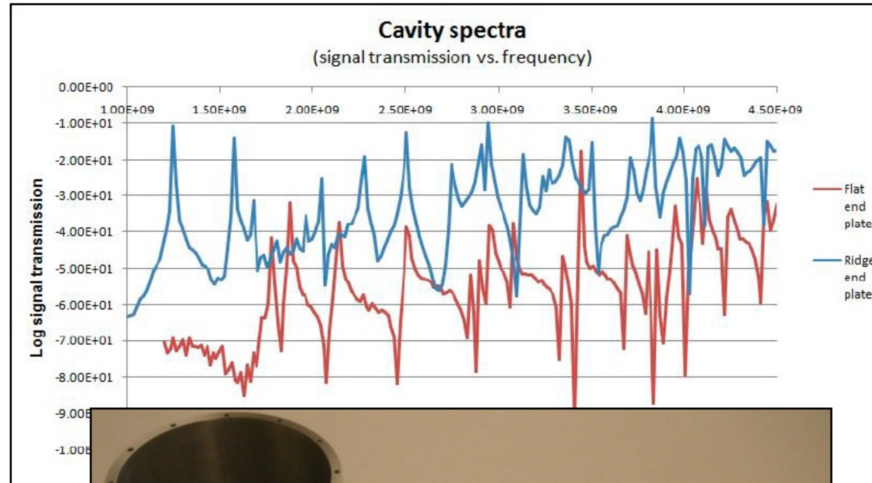
“Hybrid” superconducting cavities (Yale group)

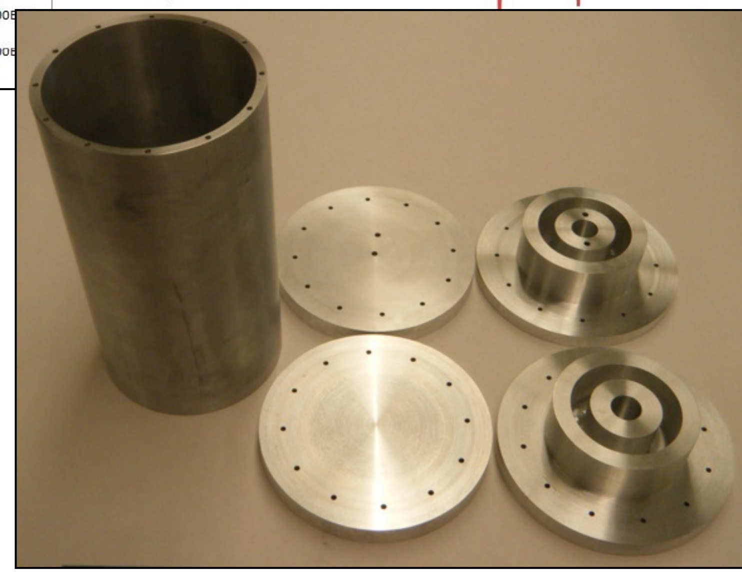


Gen 3 cavity concepts

Gen 3: Low-frequency R&D







***work from H. Swan (UW)**

Can the RF-cavity experiments do better?
Non-classical photon states: Bolometers

Single microwave-photon detection: a RF-photon phototube

For any detector of electromagnetic radiation, there's a number-of-quanta, phase-of-radiation uncertainty relation:

$$\Delta n \cdot \Delta\phi \geq 1$$

Evading the "Standard Quantum Limit":
If you don't measure the electromagnetic phase ϕ,
you can measure the number of quanta n to arbitrarily high precision.
(We do this all the time in the optical with photomultiplier tubes.)

This is a "phototube" for microwave photons.

Two realizations for axion detection: Rydberg atom & microcavity

RF Phototube: Rydberg-atom microwave-photon detection

Rydberg atoms are alkali metals in high states of excitation

Small energy difference between n and n+1 levels

$\Delta W_n \sim 1/n^3$

$\Delta W_{100} \approx 7$ GHz

Large E1 transition between n and n+1 levels

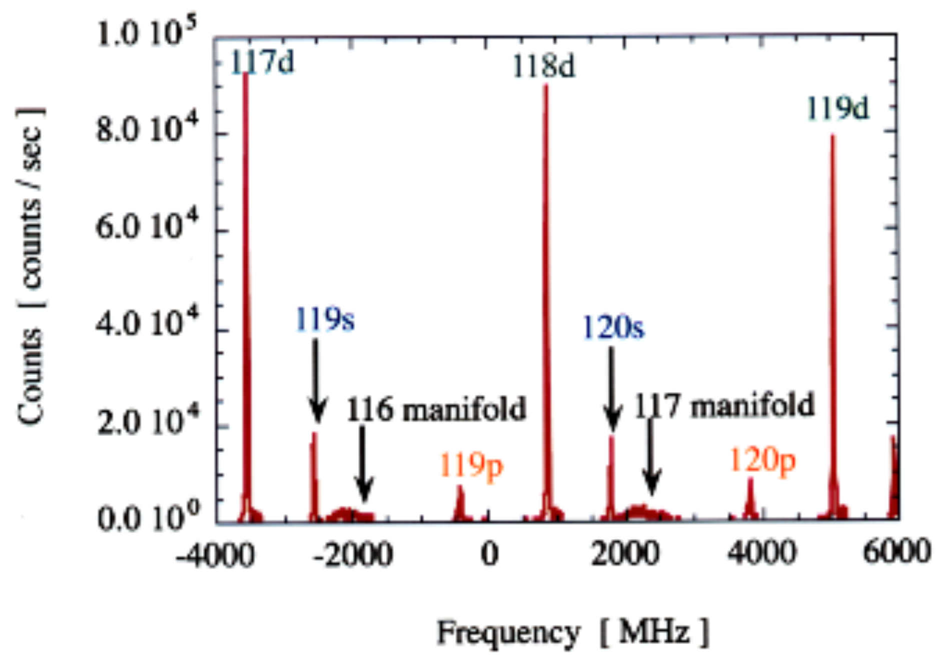
$\langle n+1|er|n\rangle \sim n^2$, $\Gamma_n \sim n^4$

$\Gamma_{100} \approx 3\times10^4$/sec

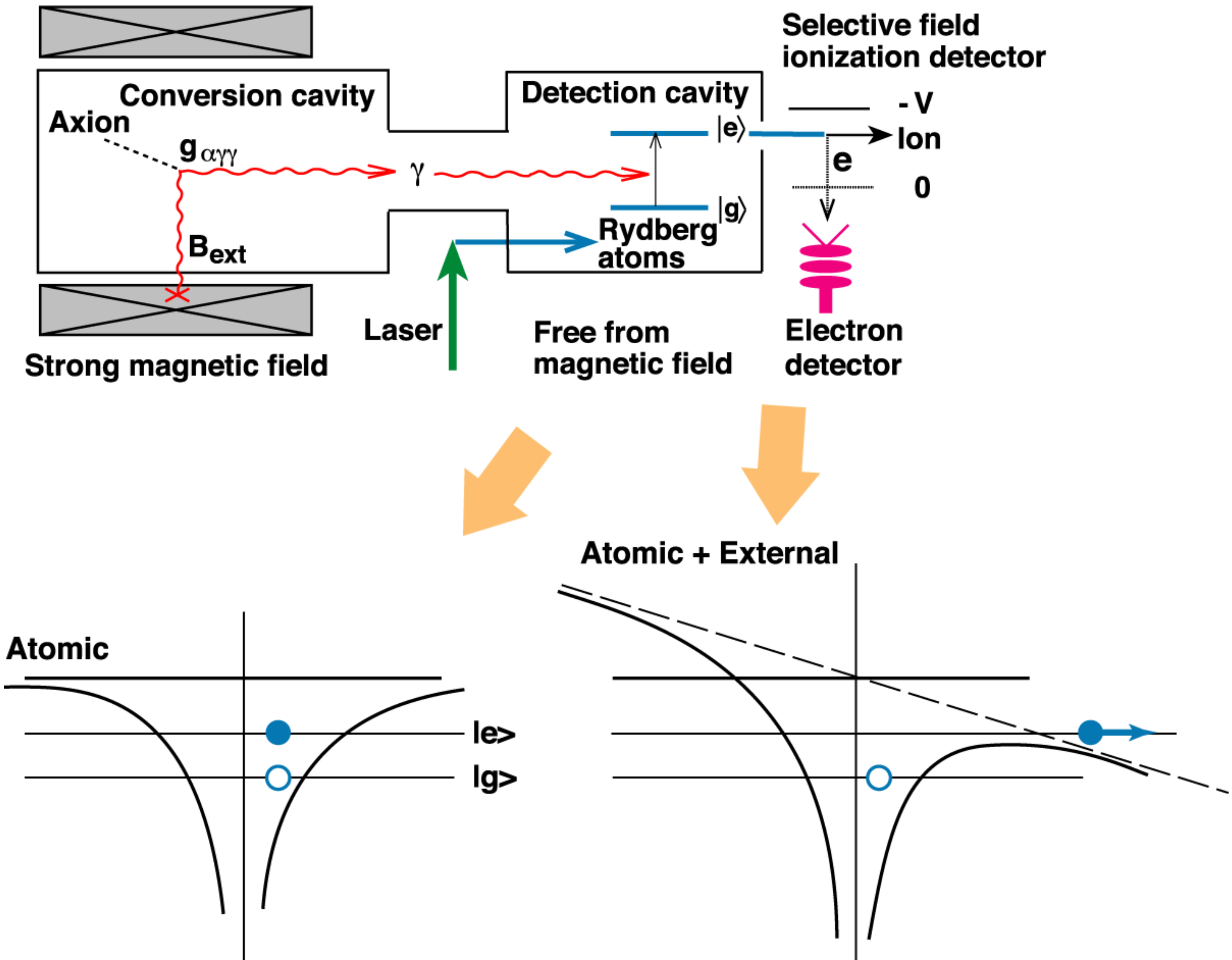
Long life time

$\tau_n \sim n^3$

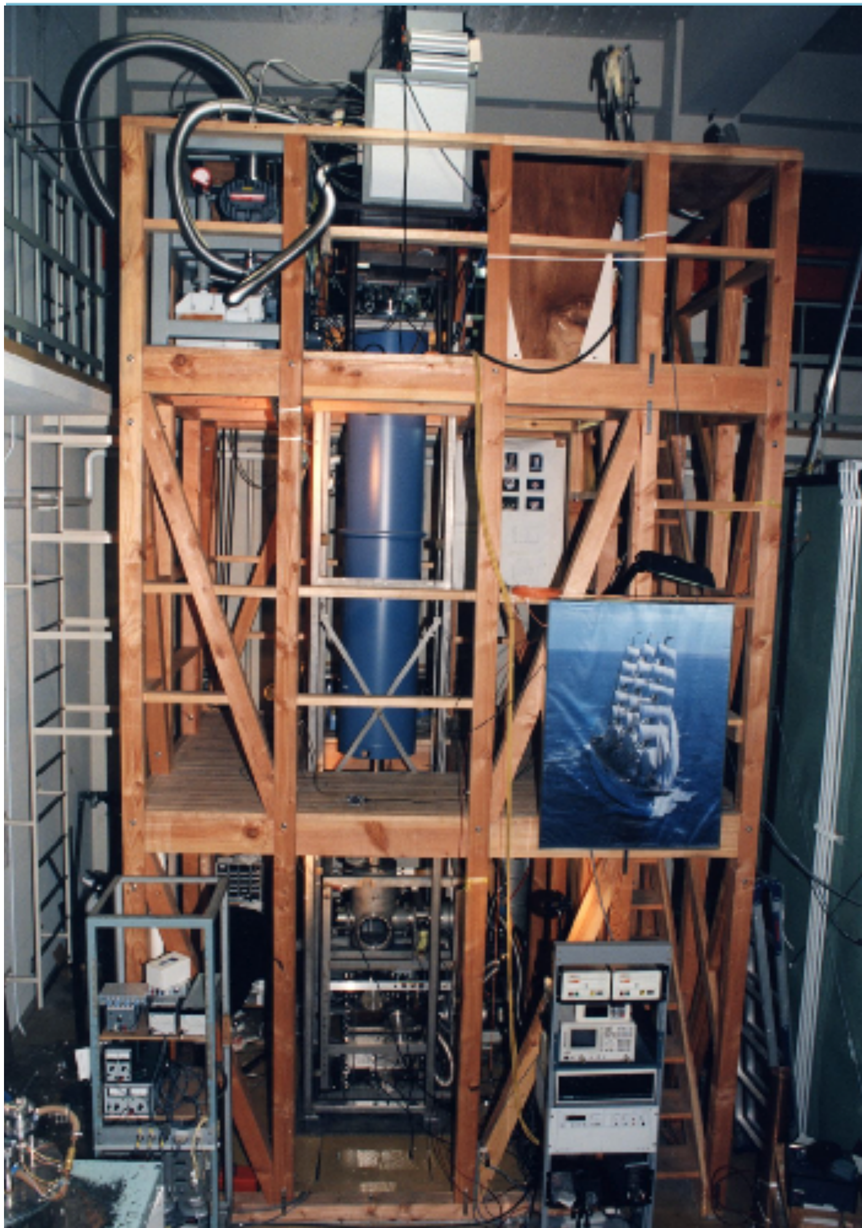
$\tau_{100} \approx 1$ msec

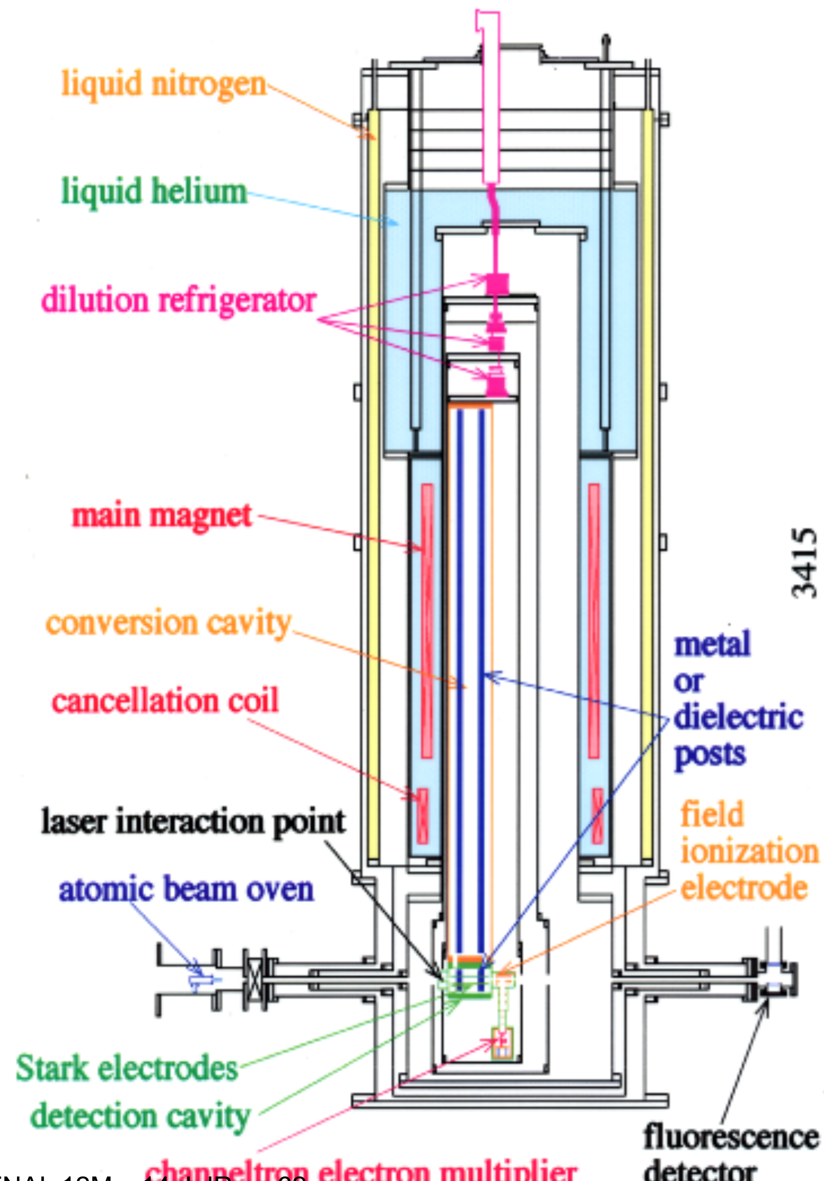


Principle of Rydberg-atom-based axion detector



CARRACK: Cosmic Axion Research with Rydberg Atoms in resonant Cavities in Kyoto





Microcavity for single-photon detection

Quantum Non-demolition Detection of Single Microwave Photons in a Circuit

B. R. Johnson,[1] M. D. Reed,[1] A. A. Houck,[2] D. I. Schuster,[1] Lev S. Bishop,[1] E. Ginossar,[1]
J. M. Gambetta,[3] L. DiCarlo,[1] L. Frunzio,[1] S. M. Girvin,[1] and R. J. Schoelkopf[1]

[1]*Departments of Physics and Applied Physics, Yale University, New Haven, CT 06511, USA*
[2]*Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA*
[3]*Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Waterloo, ON, Canada, N2L 3G1*

(Dated: March 12, 2010)

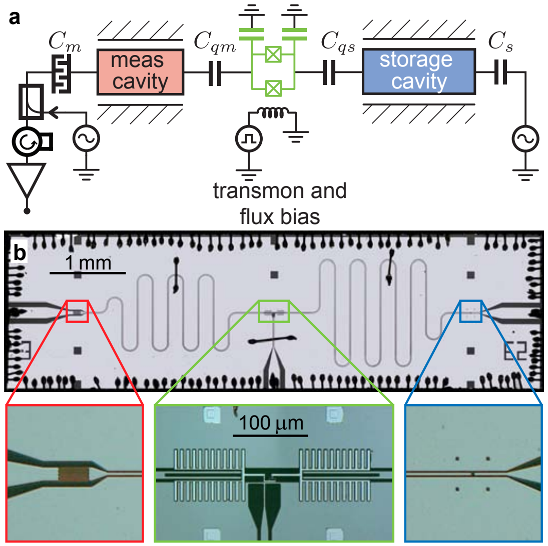


FIG. 1. Circuit schematic and device. **a**, Circuit schematic showing two cavities coupled to a single transmon qubit. The measurement cavity is probed in reflection by sending microwave signals through the weakly coupled port of a directional coupler. A flux bias line allows for tuning of the qubit frequency on nanosecond timescales. **b**, Implementation on a chip, with $\omega_m/2\pi = 6.65\,\text{GHz}$ measurement cavity on the left and its large coupling capacitor (red), and $\omega_s/2\pi = 5.07\,\text{GHz}$ storage cavity on the right with a much smaller coupling capacitor (blue). A transmon qubit (green) is strongly coupled to each cavity, with $g_s/2\pi = 70\,\text{MHz}$ and $g_m/2\pi = 83\,\text{MHz}$. It has a charging energy $E_C/2\pi = 290\,\text{MHz}$ and maximal Josephson energy $E_J/2\pi \approx 23\,\text{GHz}$. At large detunings from both cavities, the qubit coherence times are $T_1 \approx T_2 \approx 0.7\,\mu\text{s}$.

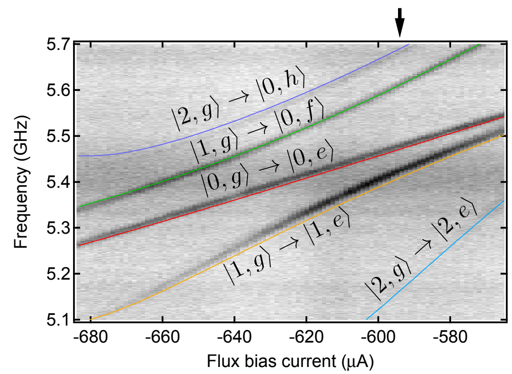
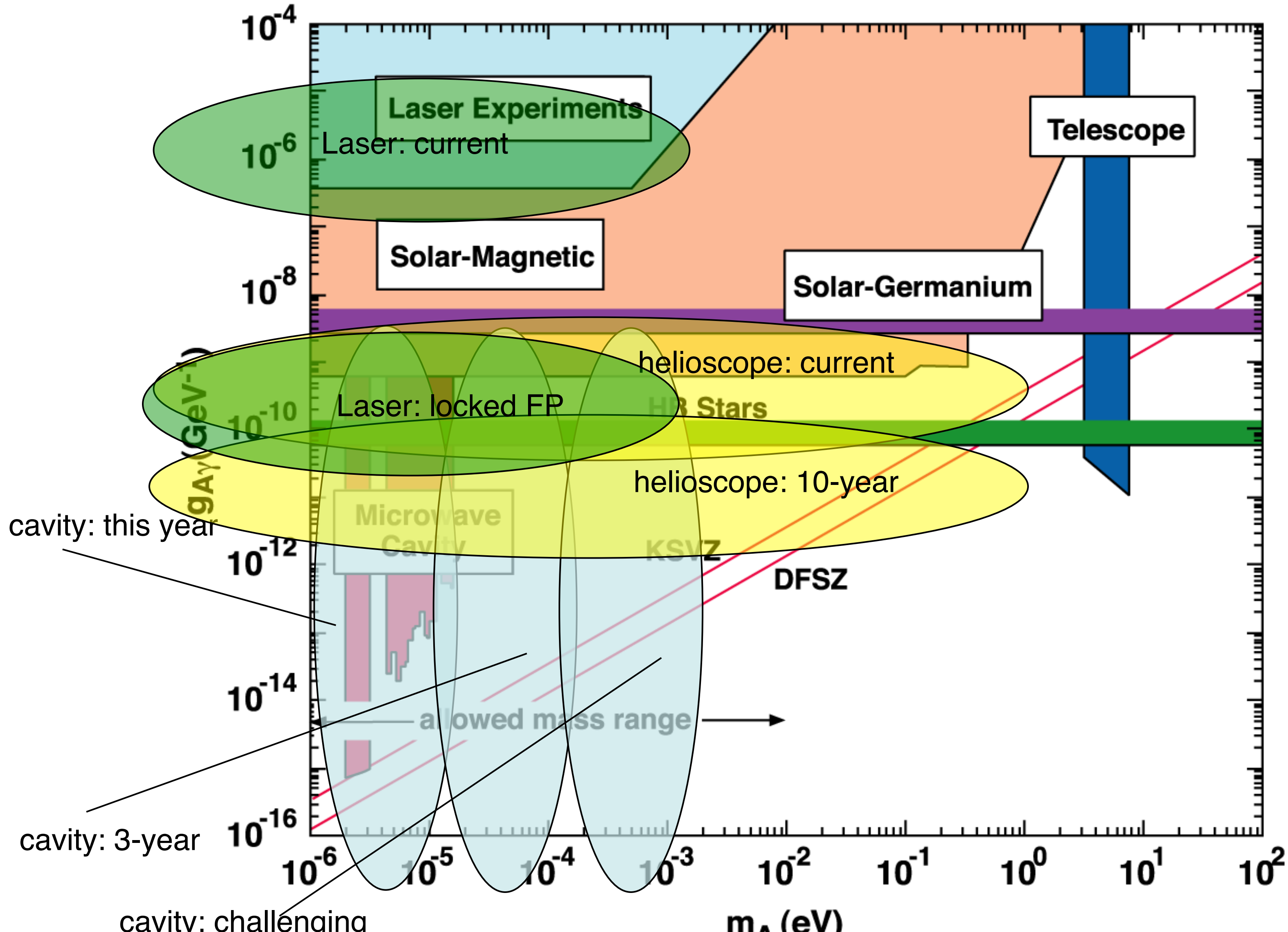


FIG. 2. Pulsed spectroscopy with coherent state in storage cavity ($\langle n\rangle \approx 1$) vs. qubit-cavity detuning $\Delta_s = \omega_{g,e} - \omega_s$. Calculated transition frequencies are overlaid in color. Red and orange lines are the $|g\rangle \leftrightarrow |e\rangle$ transitions of the qubit when $n = 0$ and 1, respectively. Transitions to higher transmon levels ($|f\rangle$ and $|h\rangle$) are visible because of the small detuning. The arrow indicates the flux bias current used during the CNOT operations.

number-dependent transition frequency $|n,g\rangle \to |n,e\rangle$. Other transitions, such as $|2,g\rangle \to |0,h\rangle$, are allowed due to the small detuning. Fortunately, we also see that the separation between $\omega^0_{g,e}$ and $\omega^1_{g,e}$ grows rapidly to order $\sim 2g = 140\,\text{MHz}$ as the qubit approaches the storage cavity.

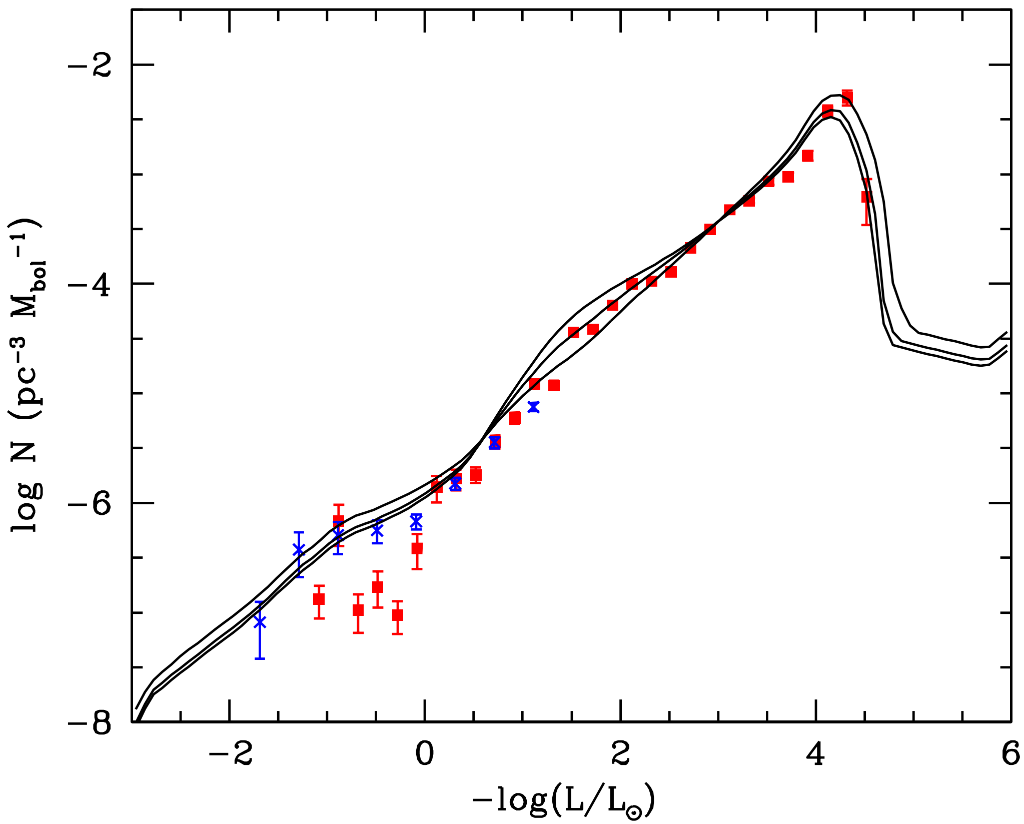
To test the photon meter, we generate single photons in the storage cavity with an adiabatic protocol. Our method uses the avoided crossing between the $|0,e\rangle$ and $|1,g\rangle$ levels to convert a qubit excitation into a photon.

An Experimental Scenario: Focus on Three Key Technologies



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) $g_{aee}/10^{-13} = 0, 2.2, 4.5$ respectively.

Theory challenges going forward (2) include

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

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?

F. Tavecchio[1⋆], M. Roncadelli[2], G. Galanti[3], G. Bonnoli[1]
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[2] *INFN, Sezione di Pavia, Via A. Bassi 6, I–27100, Pavia, Italy*
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1 March 2012

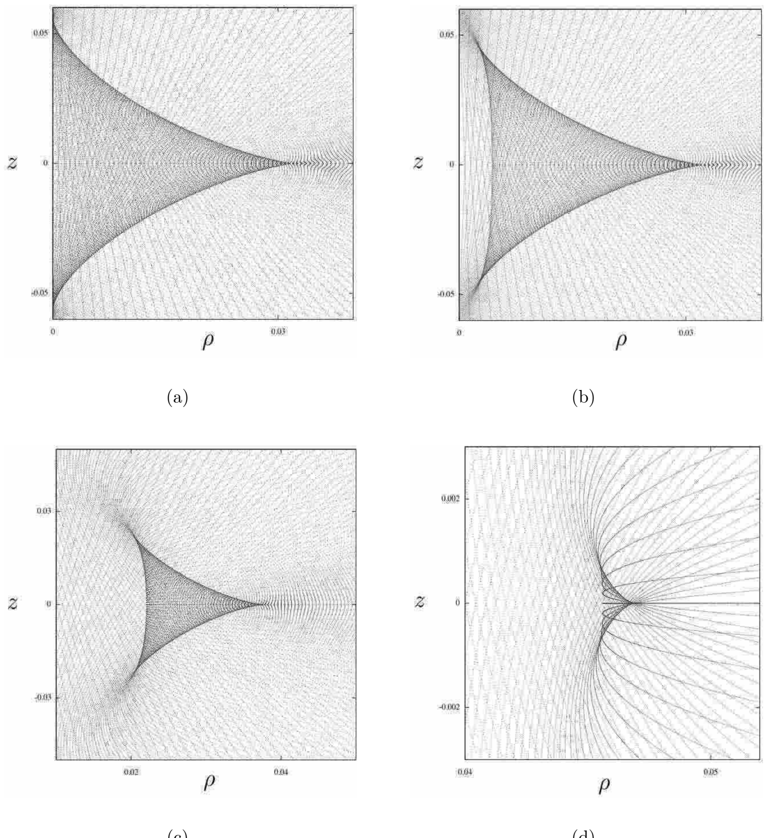
ABSTRACT
The surprising discovery by MAGIC of an intense, rapidly varying very high energy ($E > 50$ GeV) emission from the flat spectrum radio quasar PKS 1222+216 represents a challenge for all interpretative scenarios. Indeed, in order to avoid absorption of γ rays in the dense ultraviolet radiation 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

Theory challenges going forward (3) include

Axion Bose-condensates & structure

Is the dark matter a Bose condensate? Does it matter?



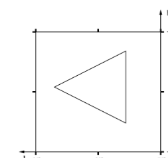
Nararajan & Sikivie, 2005

FIG. 13: Cross sections of the inner caustics produced by the axially symmetric initial velocity field of Eq. (27) with $g_1 = -0.033$, and (a) $c_1 = 0$, (b) $c_2 = 0.01$, (c) $c_3 = 0.05$, (d) $c_3 = 0.1$. Increasing the rotational component of the initial velocity field causes the tent caustic (a) to transform into a tricusp ring (d).

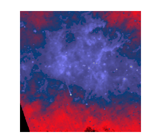
E.g.,
look where a ring would be in our galaxy
Skyview virtual observatory

10° x 10°

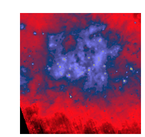
Triangular Feature Locator



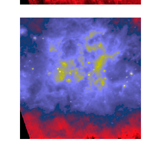
12 µm



25 µm



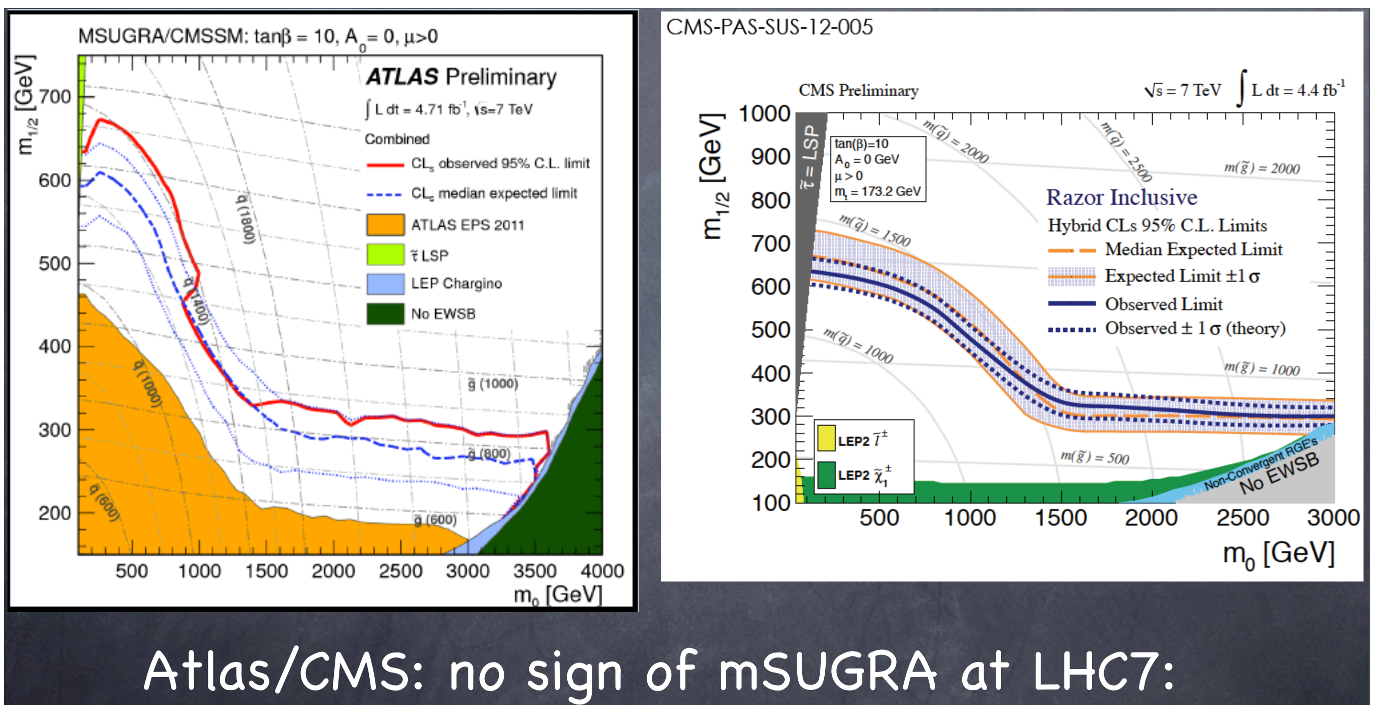
60 µm



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.



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

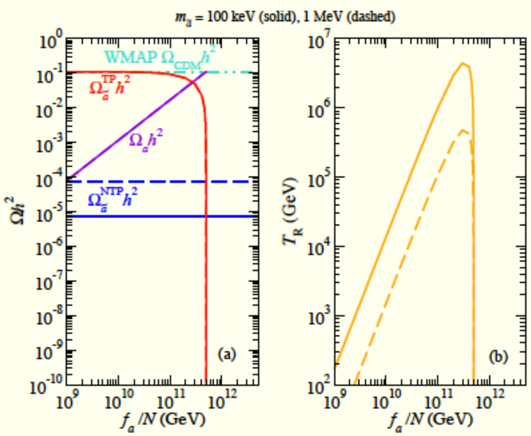
H. Baer

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.