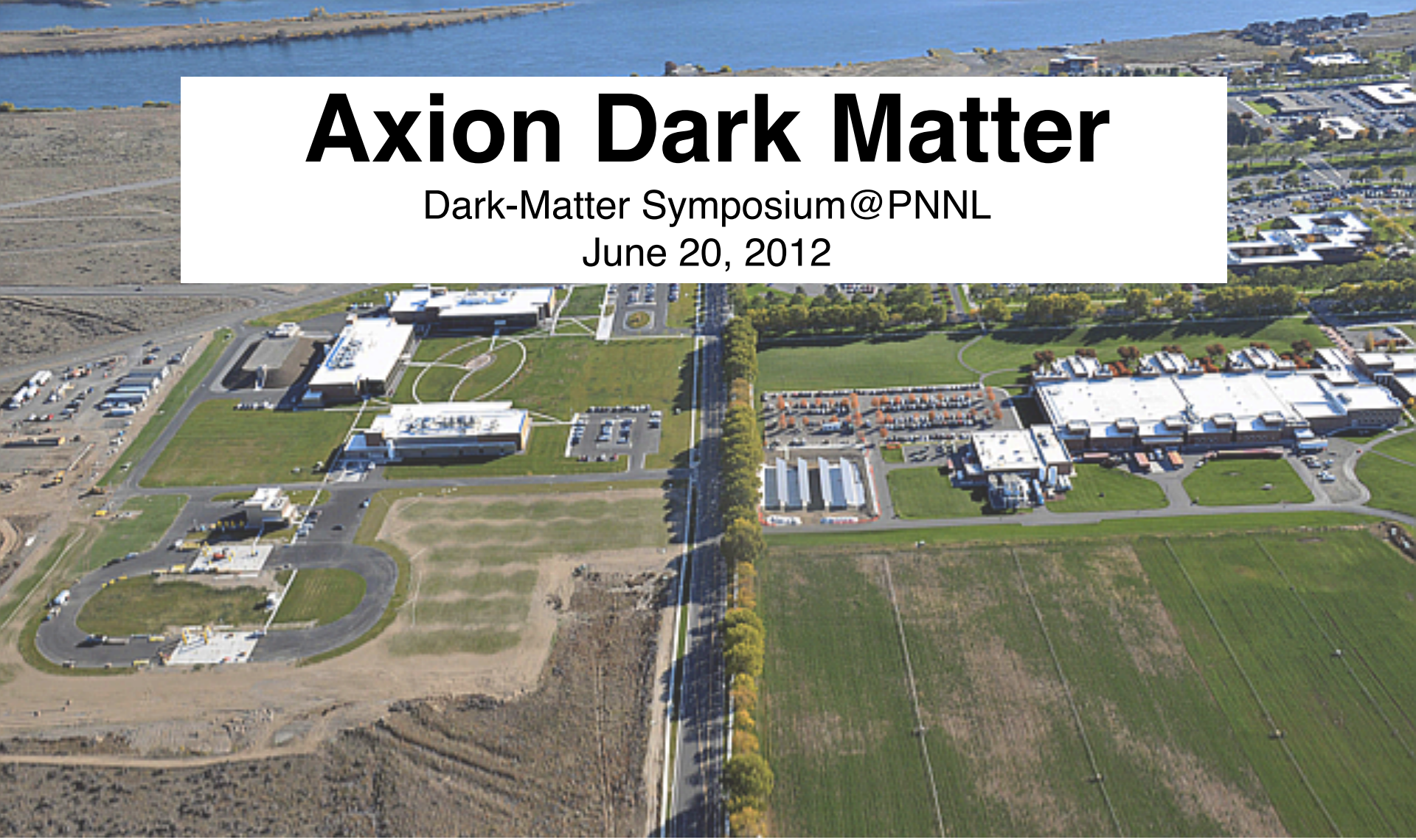
Axion Dark Matter

Dark-Matter Symposium@PNNL

June 20, 2012



Leslie J Rosenberg

University of Washington

All of axion dark matter in 45 minutes from an experimenter's perspective. Talk outline:

What's an axion? Where did it come from? What does it have to do with dark matter? (Briefly, covered earlier.)

Axion mass and couplings. (Where to look.)
- Why the emphasis on the two-photon coupling?
- Theory (constrains low mass) and experiment (high mass).

Searches: Overview of current limits.

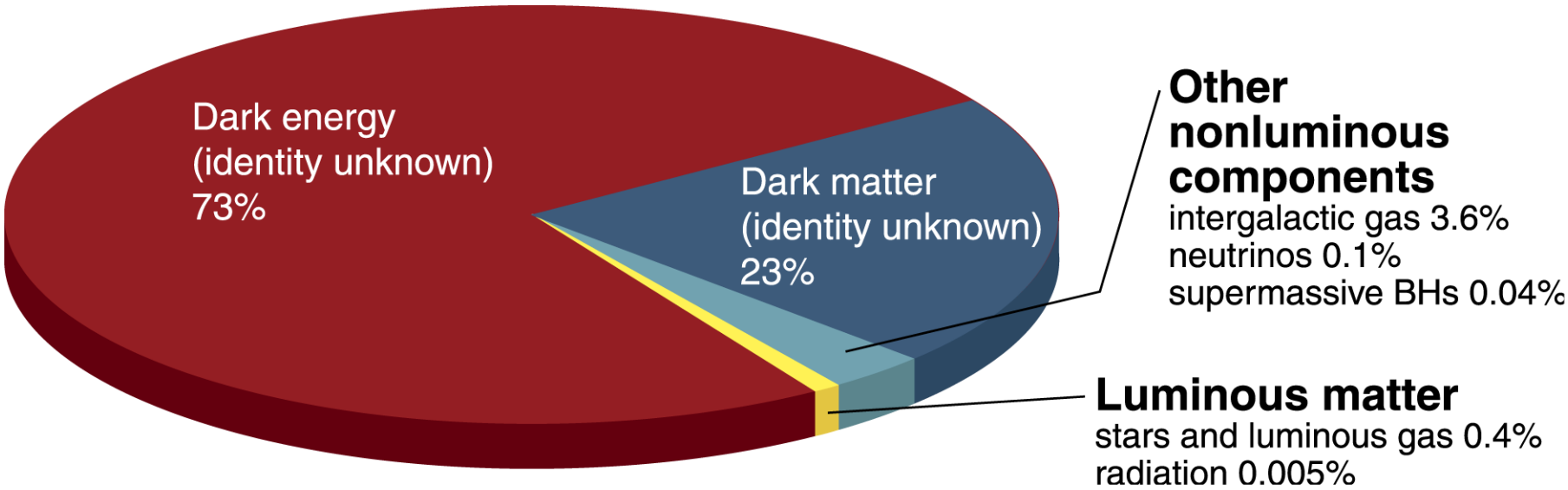
Current initiatives (not complete): Cavities, Lasers, Solar.

1. The RF-cavity technique
   - Device technology: Quantum electronics, squeezed states
2. Laser techniques ("shining light through walls")
3. Solar-axion searches

Futurism: Experiment & theory challenges.

Summary and prospects

Dark-matter axions address the big question: We've inventoried the cosmos (the famous pie chart) …



Science (20 June 2003)

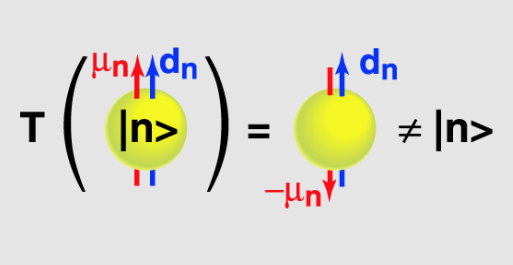
… but we know neither what the "dark energy" or the "dark matter" is. These are two of the very big questions.

What's an axion? (1)
Covered in earlier talks (c.f., Sandick & Gondolo)

Where did it come from? The "QCD Axion"

There's something disturbing about the Standard Model:
The Standard Model violates P and CP, we expect QCD to violate P and CP, yet QCD does not.

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



$\theta_{QCD} < 10^{-9}$

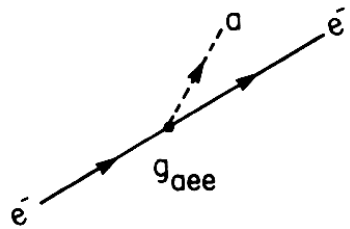
Leads to the "Strong CP Problem": Where did QCD CP violation go?

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

Simple & Elegant

The a→γγ coupling is special

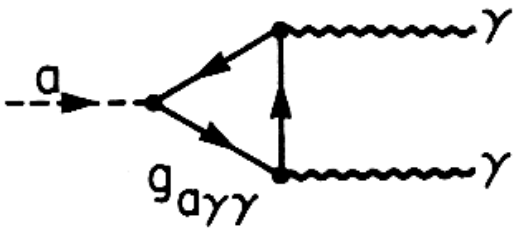
Compare, e.g., axion bremstrahlung off an electron to the axion decay into photons



bremstrahlung

???

$$g_{aee} = \left[\frac{X_e}{N} + \frac{3\alpha^2}{4\pi}\left(\frac{E_{PQ}}{N}\ln(f_{PQ}/m_e) - 1.95\ln(\Lambda_{QCD}/m_e)\right)\right] \times \frac{m_e}{f_{PQ}/N}$$



decay

$(3/8)^{-1}$ "GUT" axion

$$g_{a\gamma\gamma} = \frac{\alpha/2\pi}{f_{PQ}/N}(E_{PQ}/N - 1.95)$$

Few parameters, small residual model dependence: Experimenters and funding agencies like this.

Axions in string theory

Peter Svrček

Department of Physics and SLAC, Stanford University
Stanford CA 94305/94309 U.S.A.
E-mail: svrcek@stanford.edu

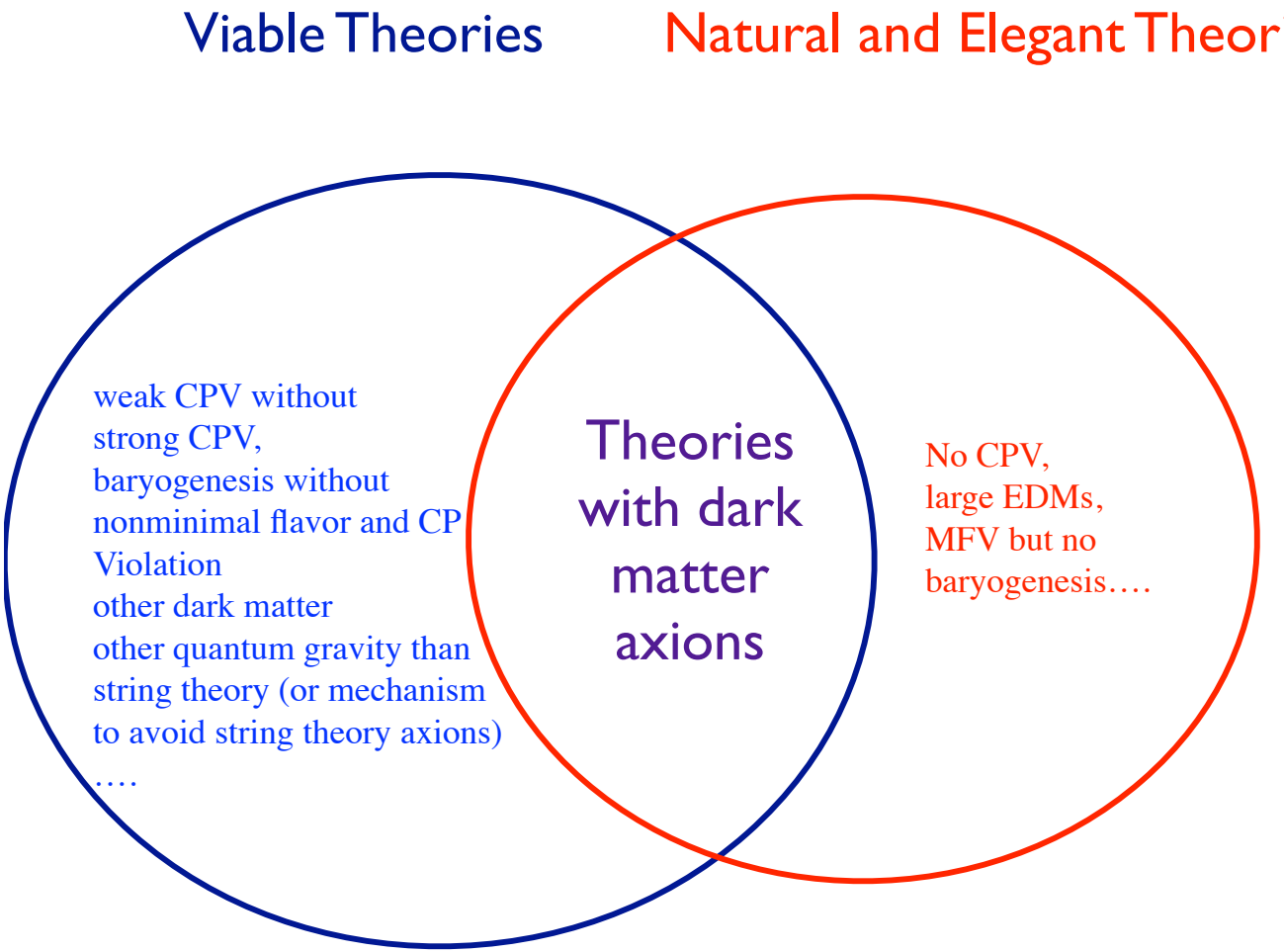
Edward Witten

Institute For Advanced Study
Princeton NJ 08540 U.S.A.
E-mail: witten@ias.edu

It's true in string theory as well.

Abstract: In the context of string theory, axions appear to provide the most plausible solution of the strong CP problem. However, as has been known for a long time, in many

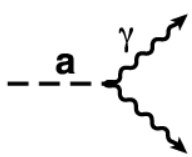
What's an axion? (2): "Cut to the chase"



A. Nelson

What's an axion? Summary properties

- 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	Cosmological Abundance
$m_a \sim 6\ \mu\text{eV} \cdot \left(\frac{10^{12}\ \text{GeV}}{f_a}\right)$ Generically, all couplings $g_{aii} \propto \frac{1}{f_a}$	$\Omega_a \sim \left(\frac{5\ \mu\text{eV}}{m_a}\right)^{7/6}$ (Vacuum misalignment mechanism)
Coupling to Photons	**Axion Mass 'Window'**
 $g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$; $g_\gamma = \begin{cases} 0.97 \text{ KSVZ} \\ -0.36 \text{ DFSZ} \end{cases}$	$10^{-(5\text{ to }6)}\ \text{eV} < m_a < 10^{-(2\text{ to }3)}\ \text{eV}$ (Overclosure) (SN1987a) With lower end of window preferred if $\Omega_{CDM} \sim 1$

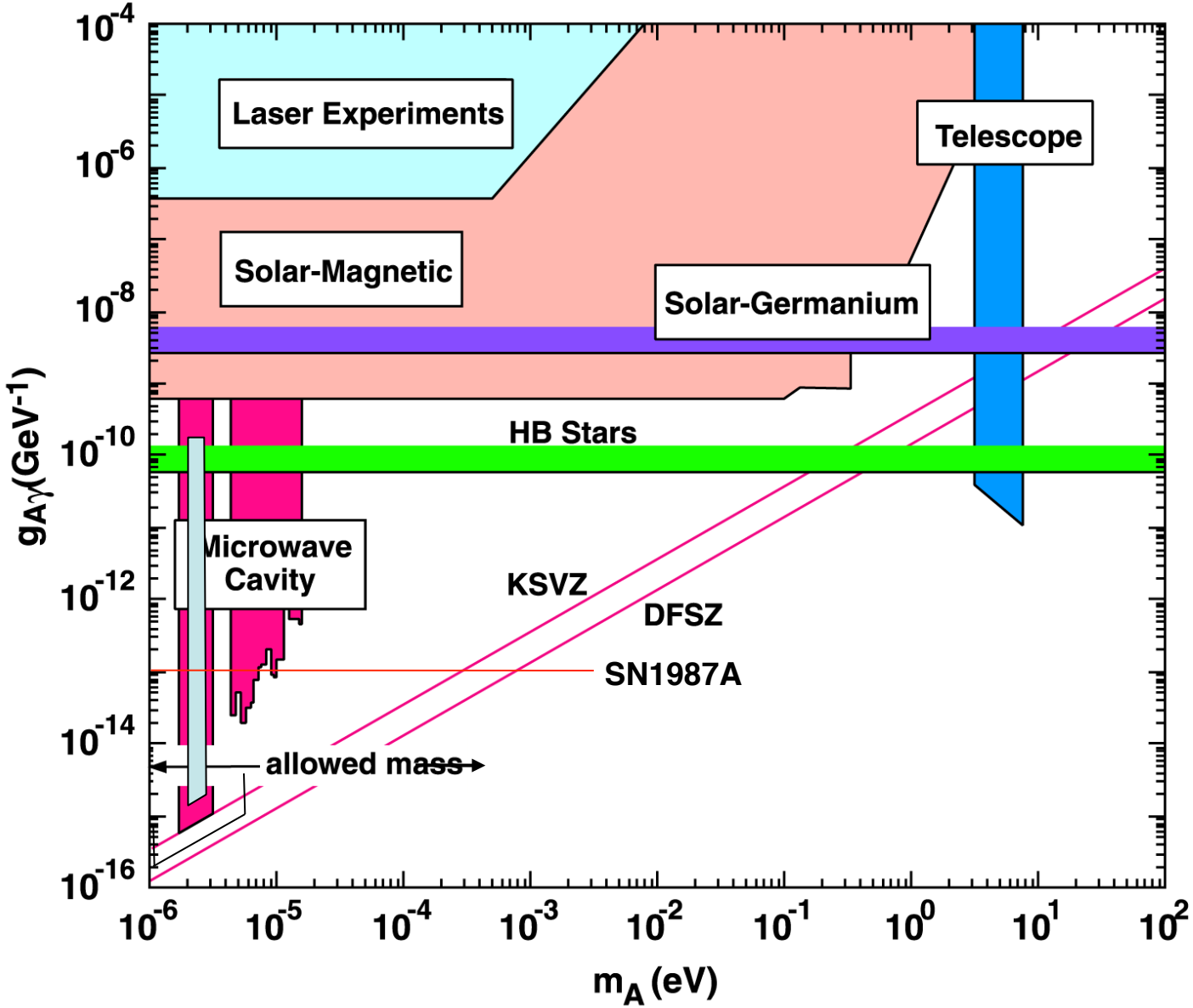
Recap: Axions and dark matter

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

Low mass axions are an ideal dark matter candidate:
"Axions: the thinking persons DM 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 dark-matter axion masses and couplings



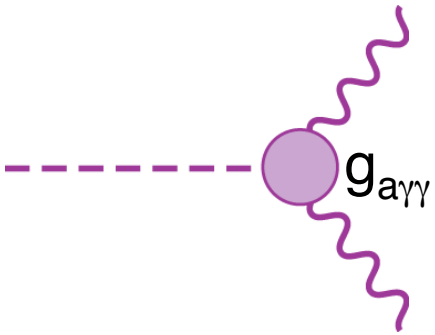
Focus on:

RF-cavity
Solar
Laser

RF-cavity experiments.
RF-cavity experiments exploit the axion's 2-photon coupling

The axion couples (very weakly, indeed) to normal particles.
(μeV mass axions would live around 10^{50} seconds.)

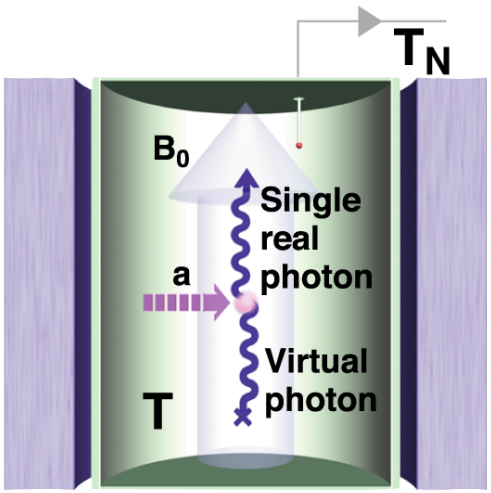
But it recall the axion 2γ coupling has relatively little axion-model dependence



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

RF-cavity axion search: Dark-matter axions and electromagnetic fields exchange energy

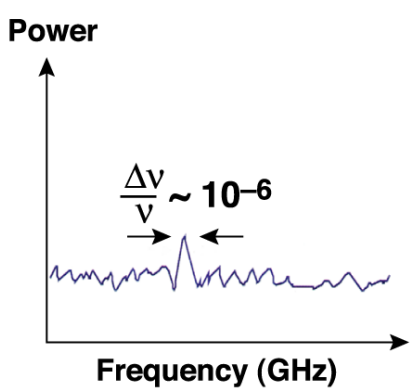
Primakoff Conversion



- 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



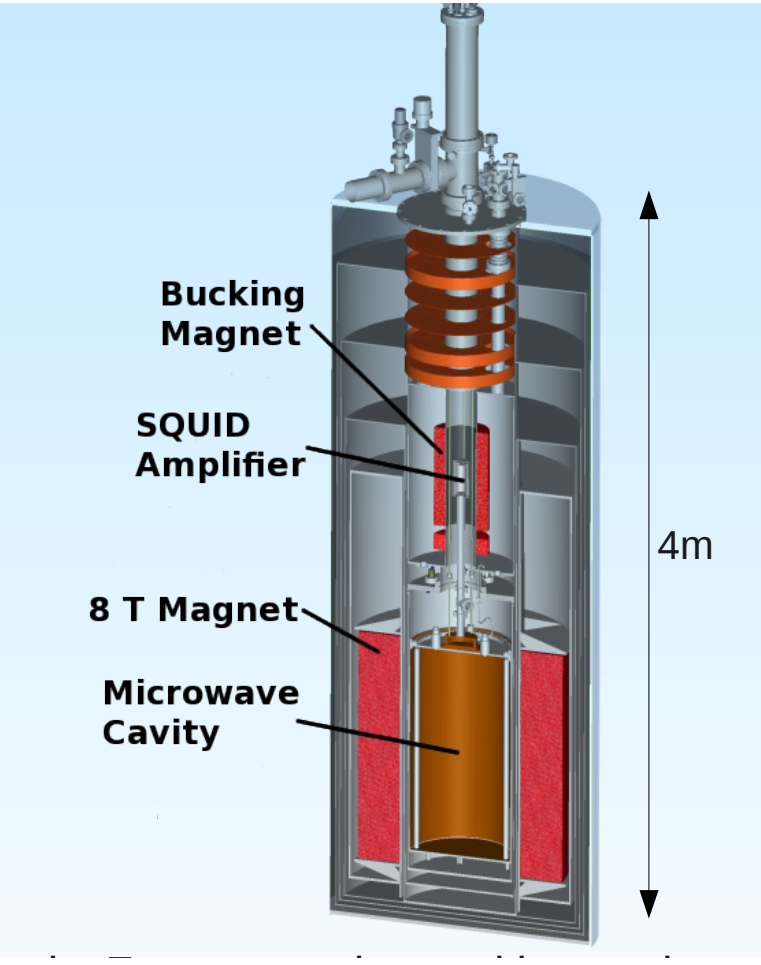
Scaling Laws

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

ADMX: Axion Dark-Matter eXperiment

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

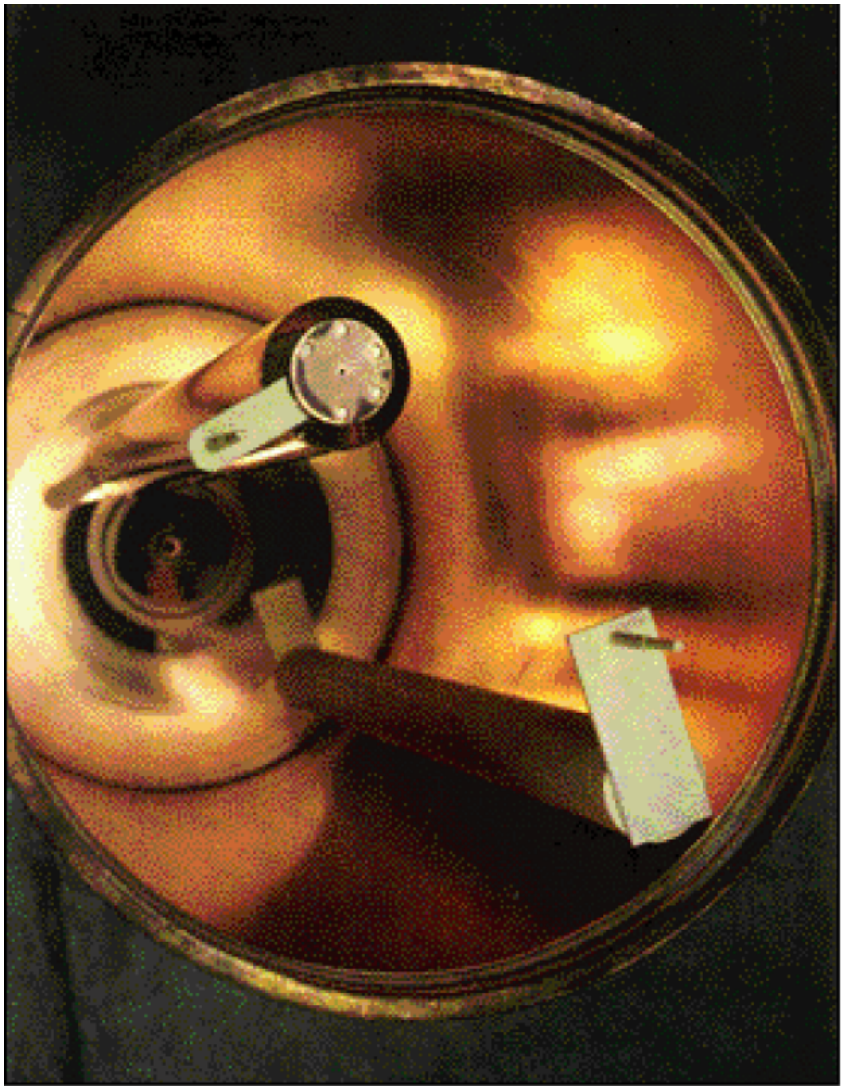
Magnet with insert



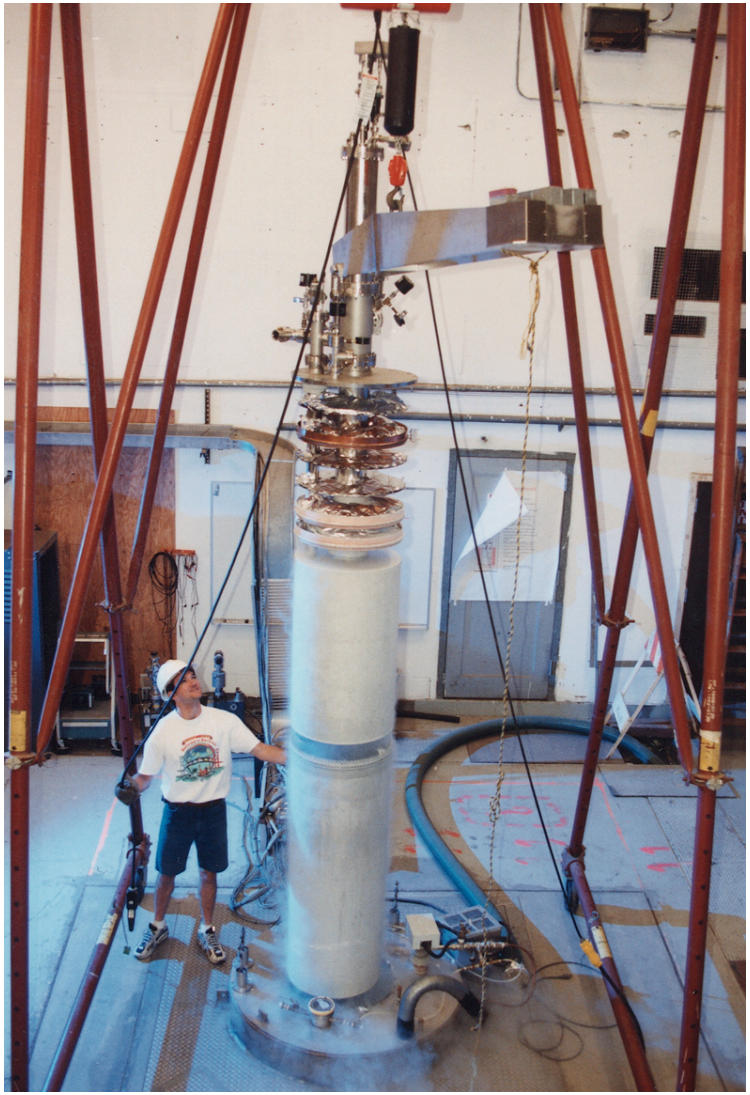
Magnet cryostat

ADMX hardware (1)

High-Q microwave cavity

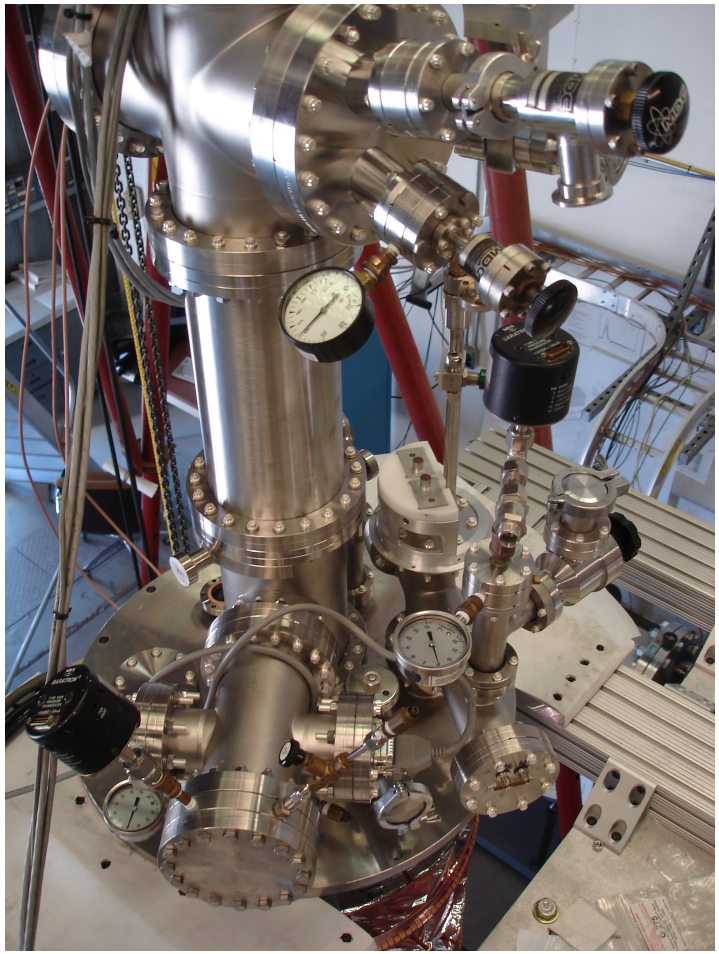


Experiment insert



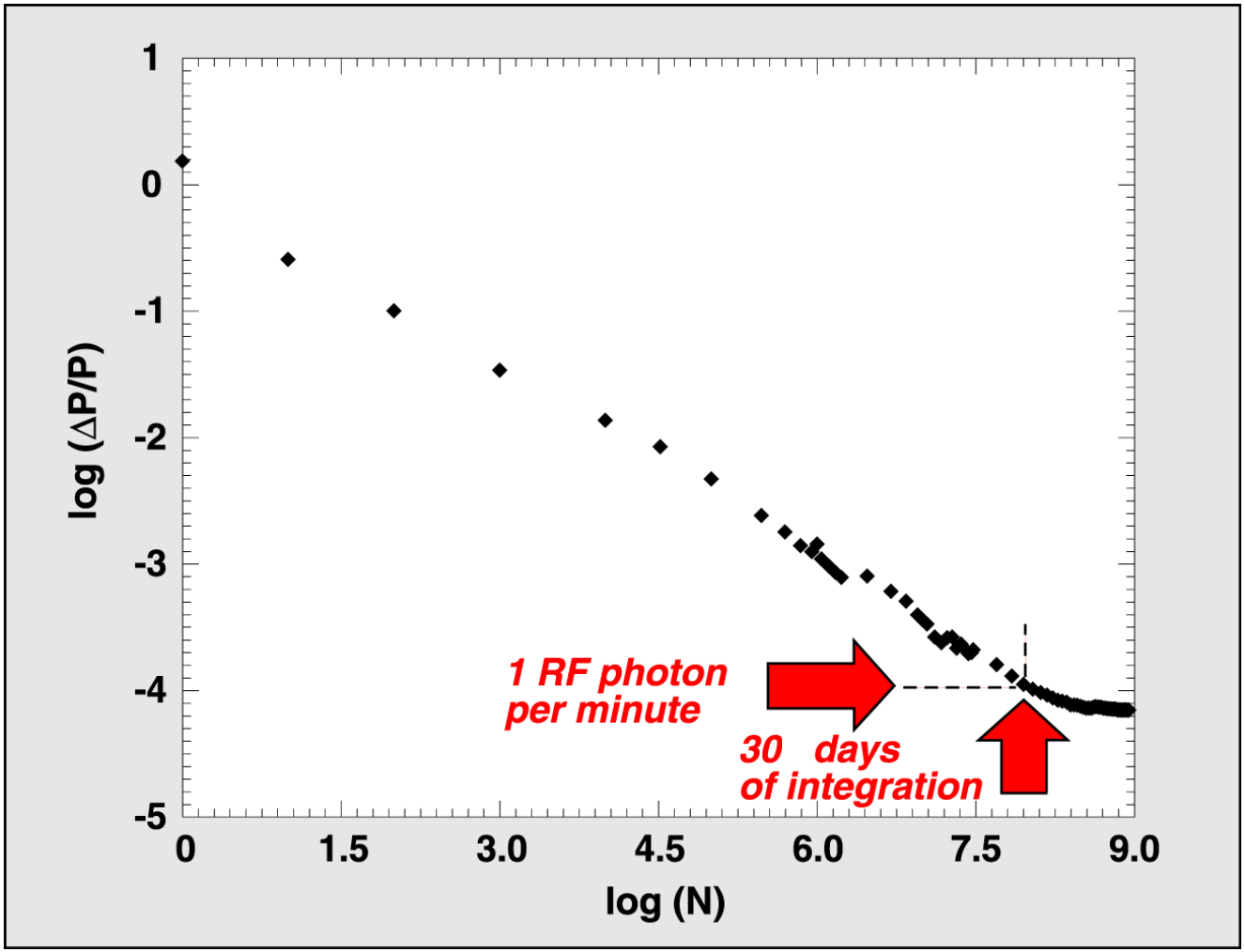
ADMX hardware (2)

Vacuum and cryo



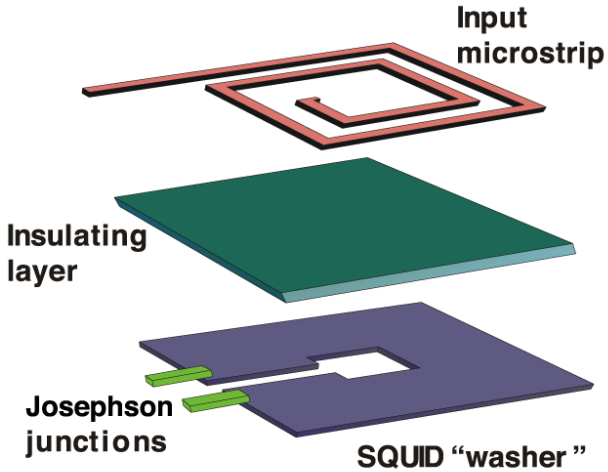
Cryostat lowered at the U. of Washington

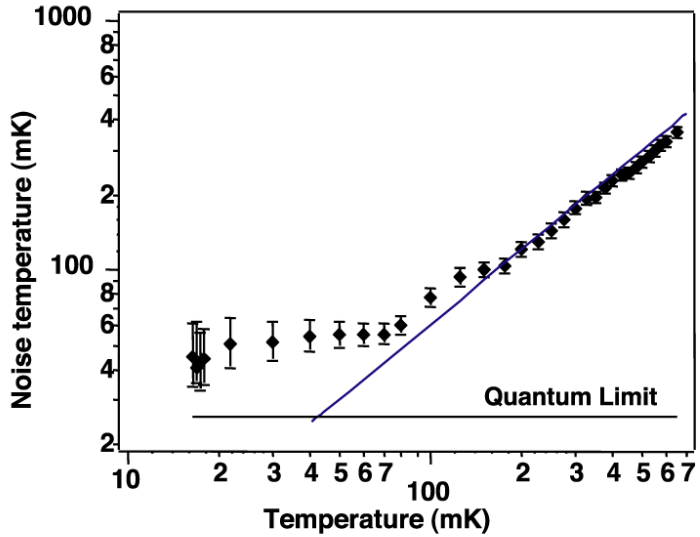
Converted microwave photons are detected by the world's quietest radio receiver



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

Breakthrough: (J. Clarke/UCBerkeley) Quantum-limited SQUID-based microwave amplification

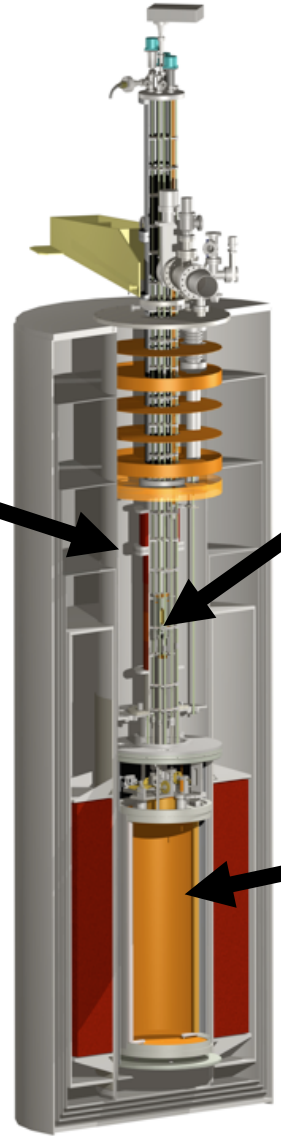




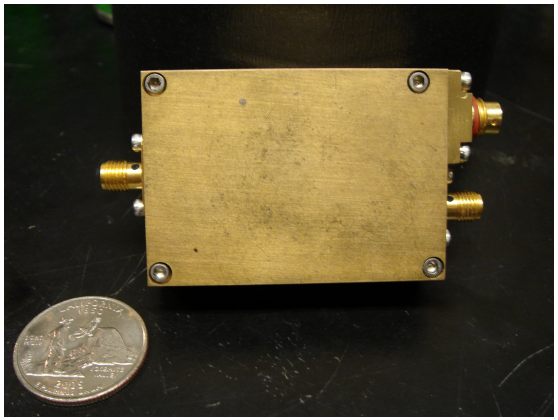
- SQUIDs have been measured with $T_N \sim 50$ mK
- Near quantum–limited noise
- This provides the enormous increase in ADMX sensitivity

ADMX SQUID-based detector

Field compensation magnet for SQUIDs

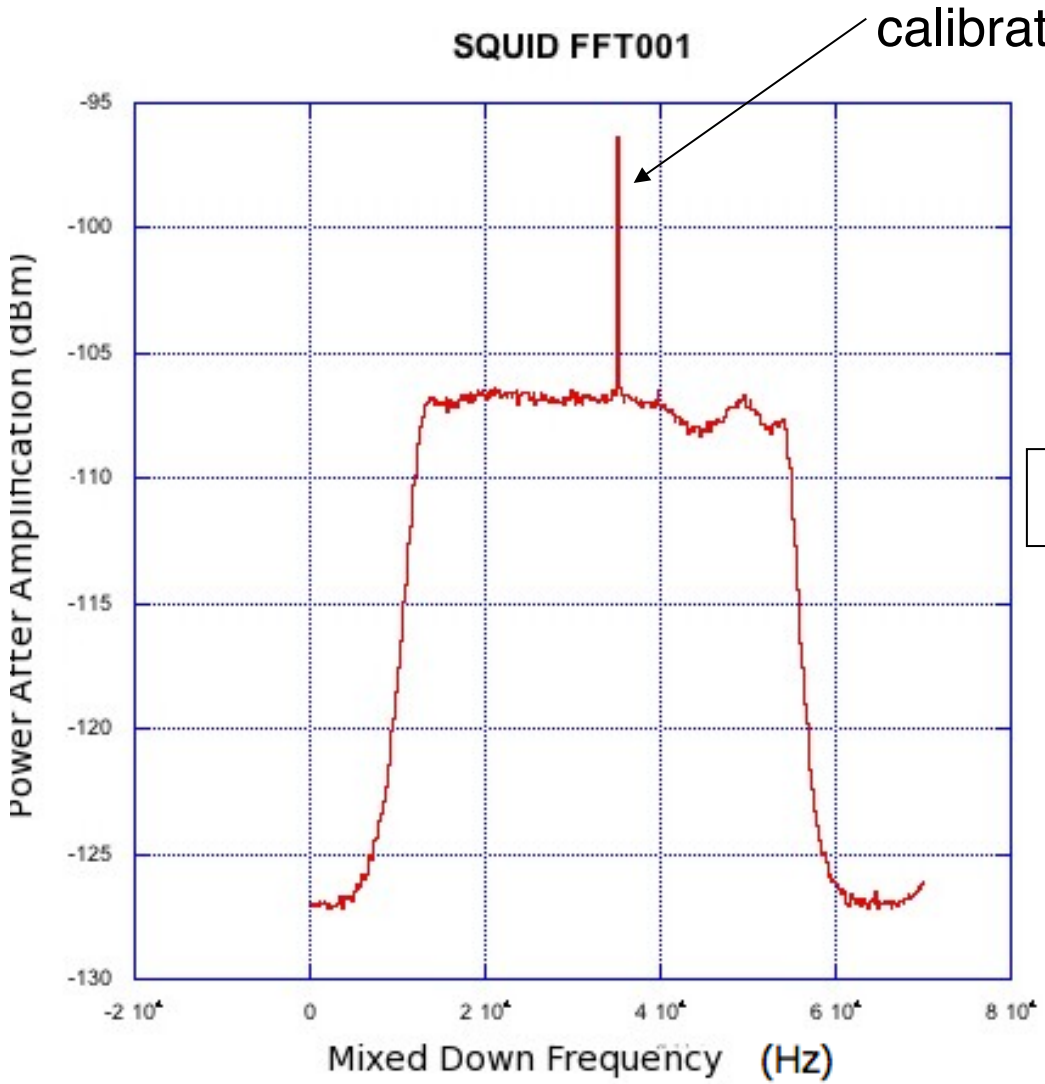


SQUID amplifier



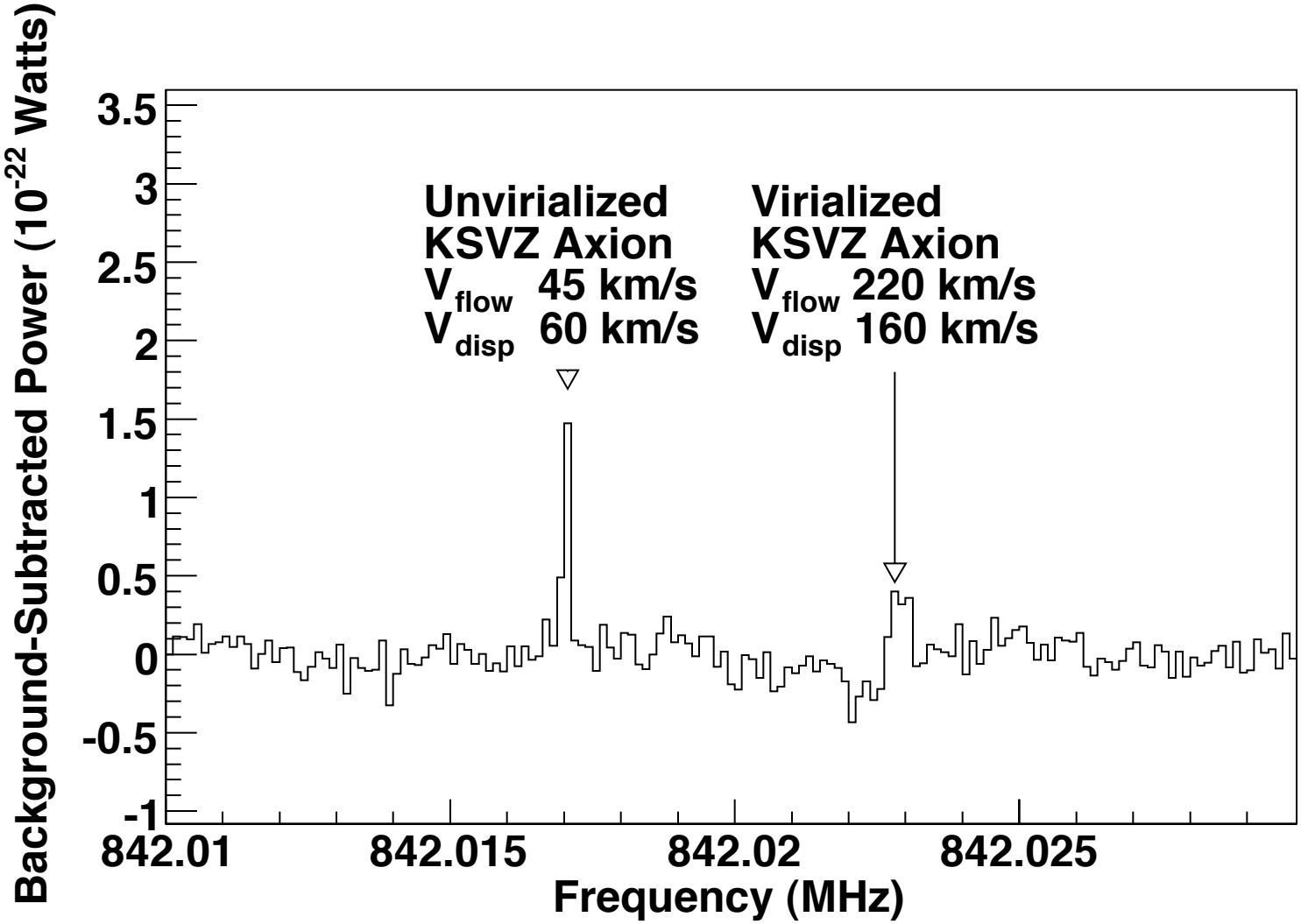
All new experiment package

ADMX: SQUID amplifier

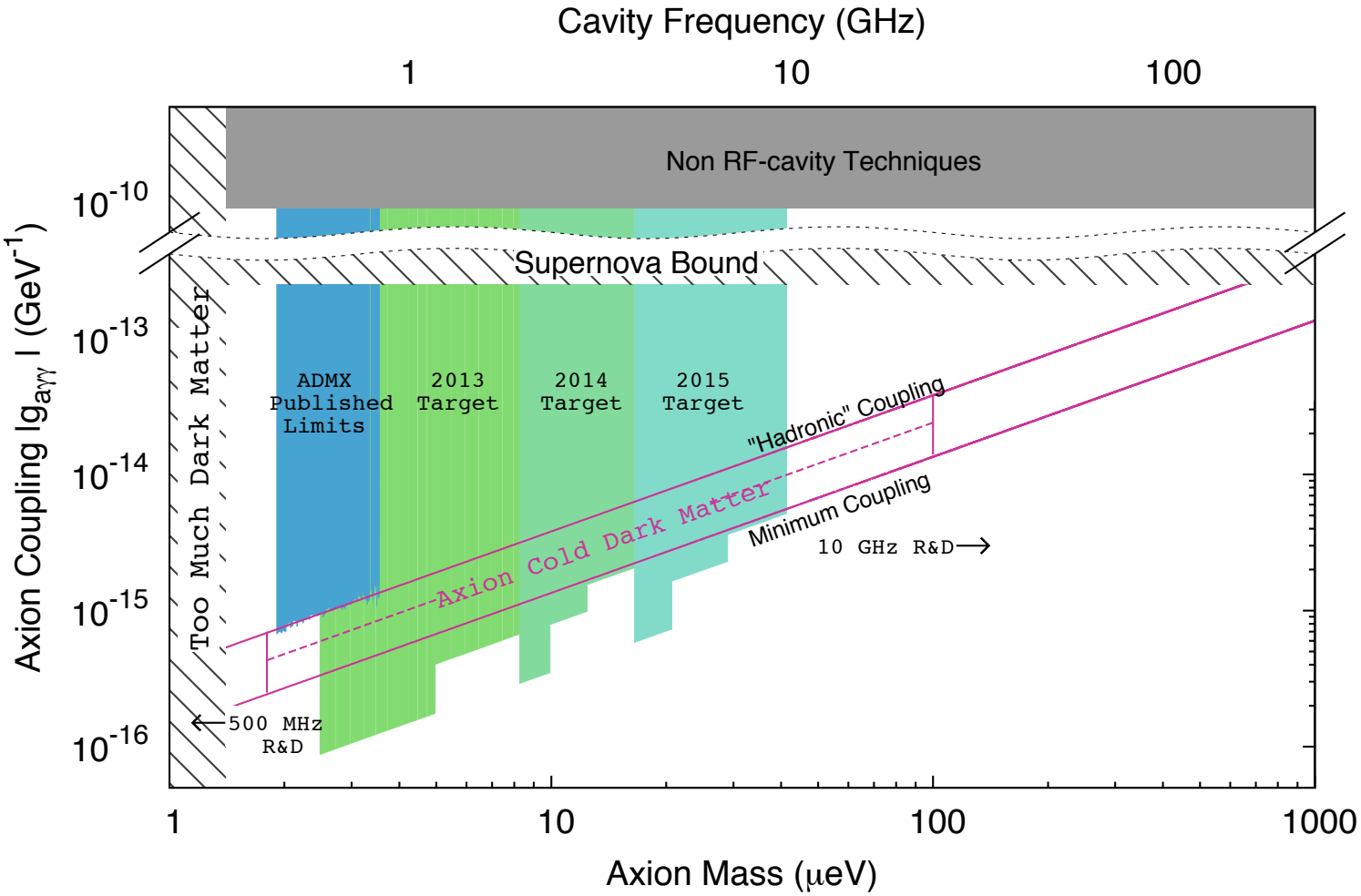


SQUID microwave amplifier

What would a signal look like in ADMX?

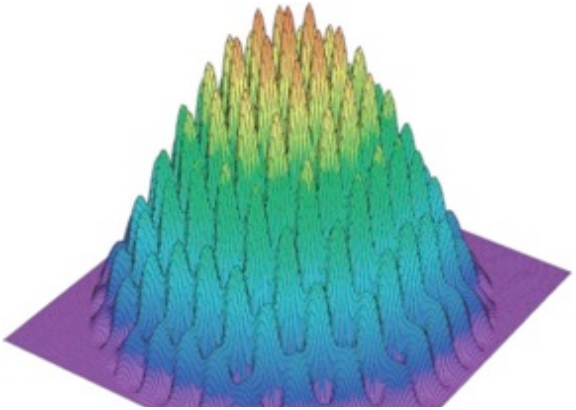


Possible ADMX Sensitivity with dilution-refrigerator cooling

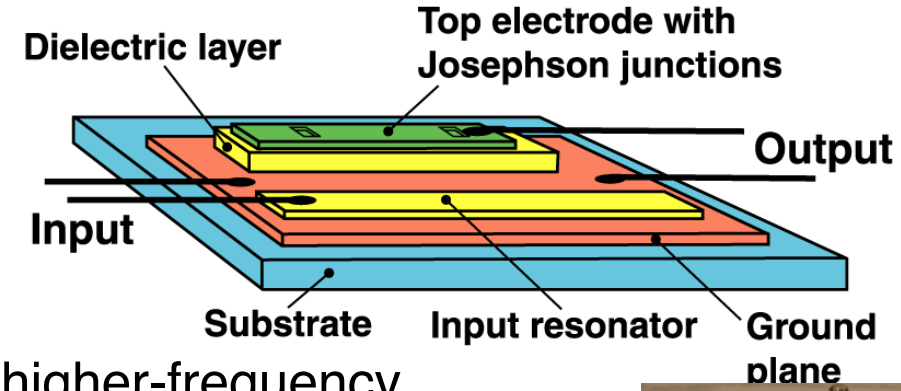


Dilution refrigerator cooled detectors allow scanning at or below DFSZ sensitivity at fractional dark-matter halo density.
This defines a "definitive" QCD dark-matter axion search

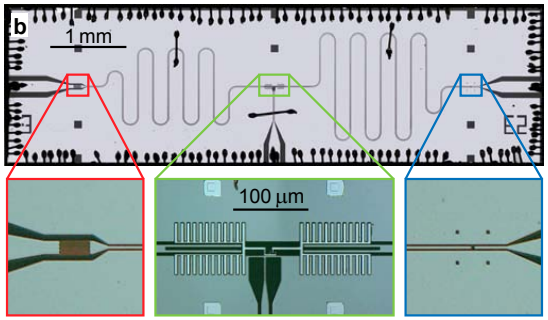
Can the RF-cavity experiments do better? Higher frequencies, higher Q, squeezed states? Active R&D paths.



higher-frequency, large volume resonant structures



higher-frequency quantum-limited SQUIDs



RF-Driven Josephson Bifurcation Amplifier for Quantum Measurement

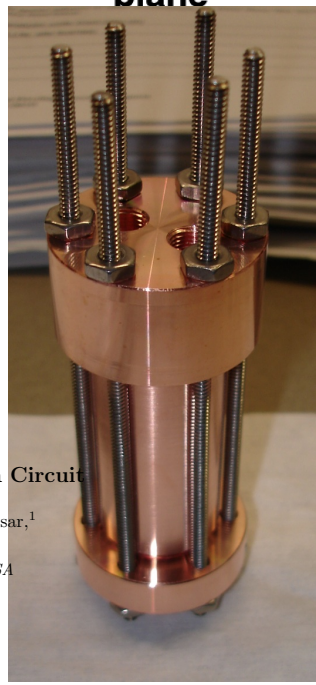
I. Siddiqi, R. Vijay, F. Pierre, C. M. Wilson, M. Metcalfe, C. Rigetti, L. Frunzio, and M. H. Devoret
Departments of Applied Physics and Physics, Yale University, New Haven, Connecticut 06520-8284, USA
(Received 11 February 2004; published 10 November 2004)

We have constructed a new type of amplifier whose primary purpose is the readout of superconducting quantum bits. It is based on the transition of a rf-driven Josephson junction between two distinct oscillation states near a dynamical bifurcation point. The main advantages of this new amplifier are speed, high sensitivity, low backaction, and the absence of on-chip dissipation. Pulsed microwave reflection measurements on nanofabricated Al junctions show that actual devices attain the performance predicted by theory.

new amplifier technologies

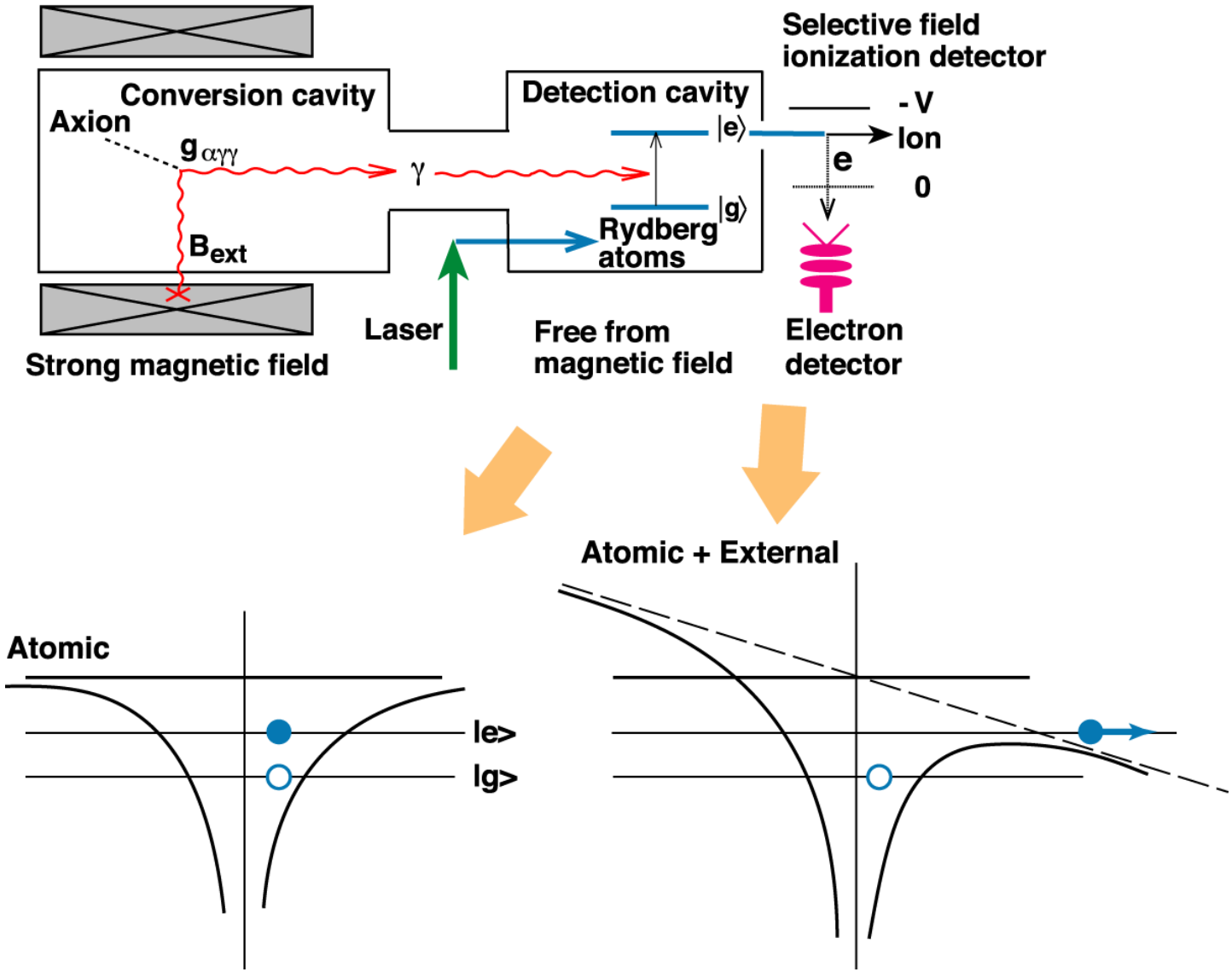
Quantum Non-demolition Detection of Single Microwave Photons in a Circuit

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)

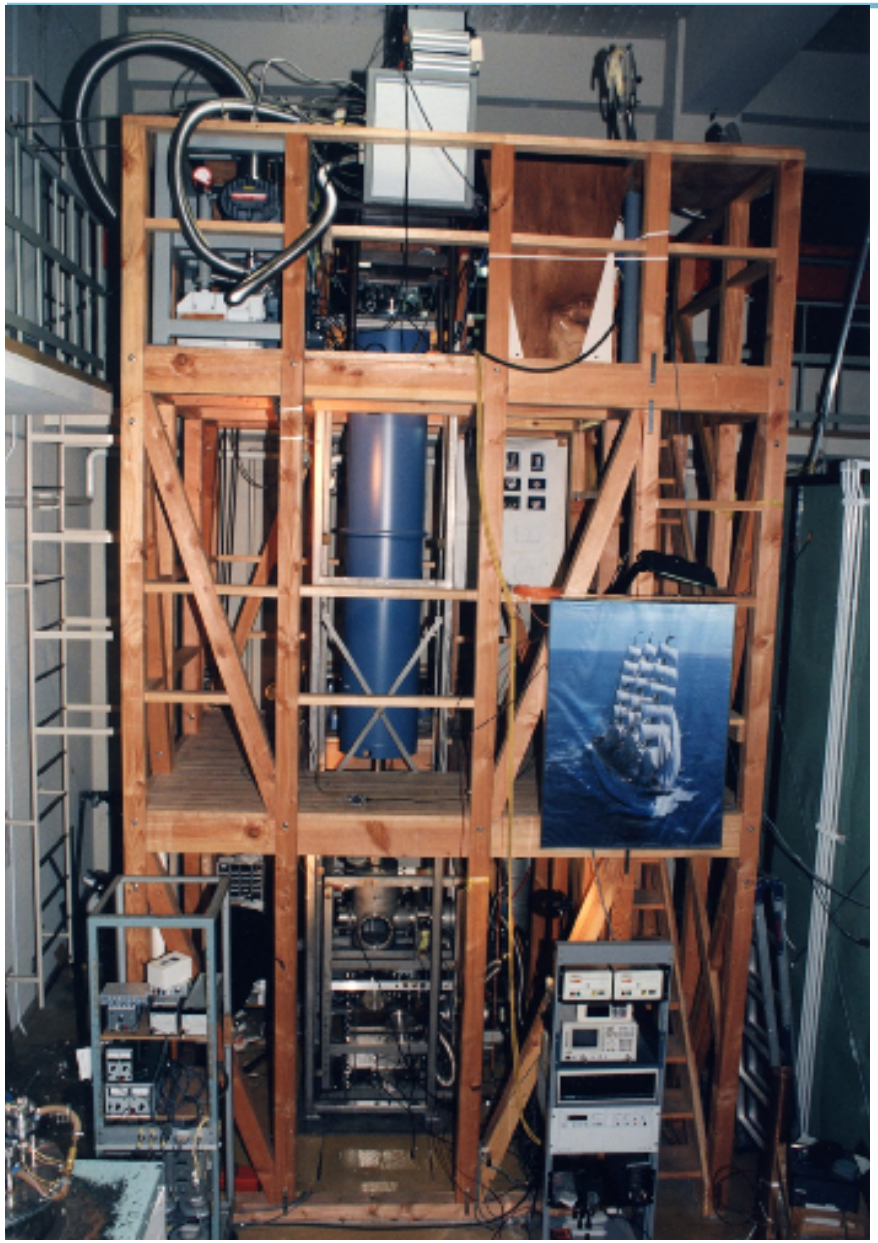


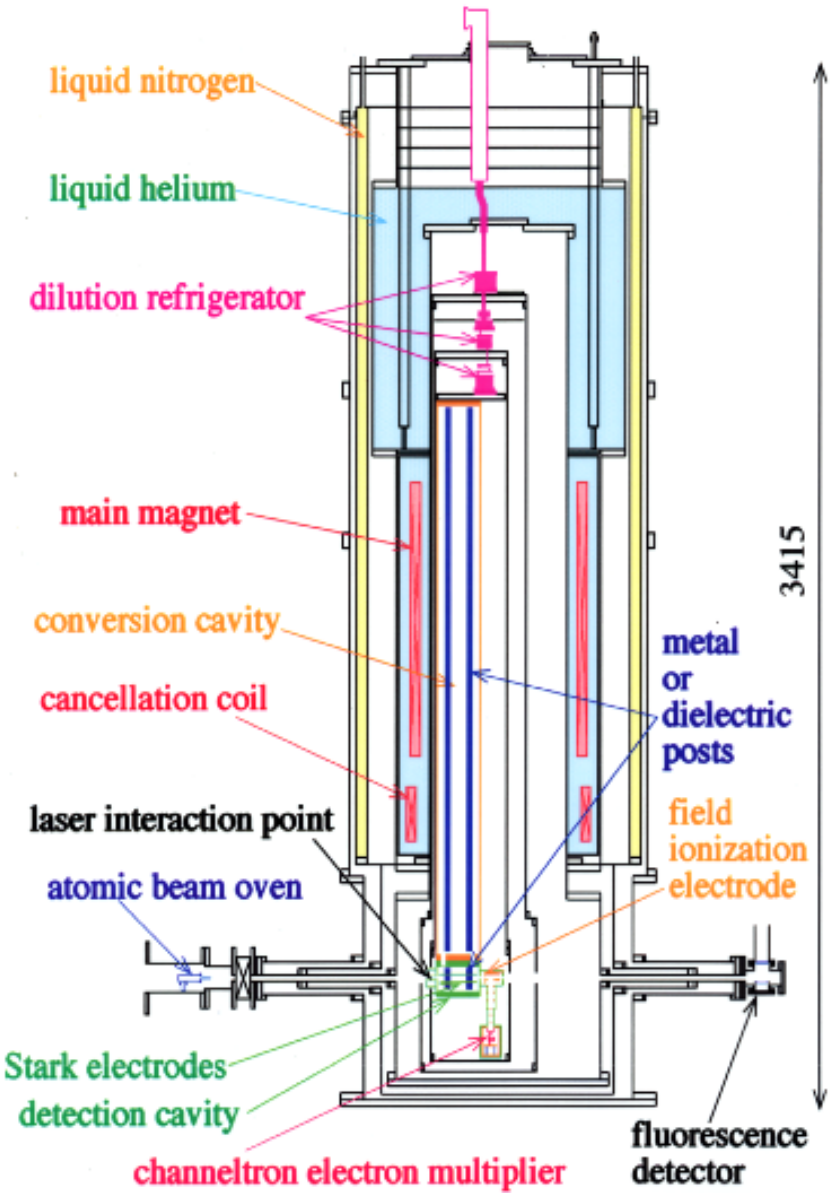
“hybrid” superconducting cavities (Yale group)

Better receivers? Rydberg-atom-based axion detector



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





RF-Cavity Futurism

ADMX "Phase IIa": microwave amplification via SQUID amplifiers.
In process of installing ^{3}He & dilution refrigerator:
"Definitive" search in 1st mass decade.

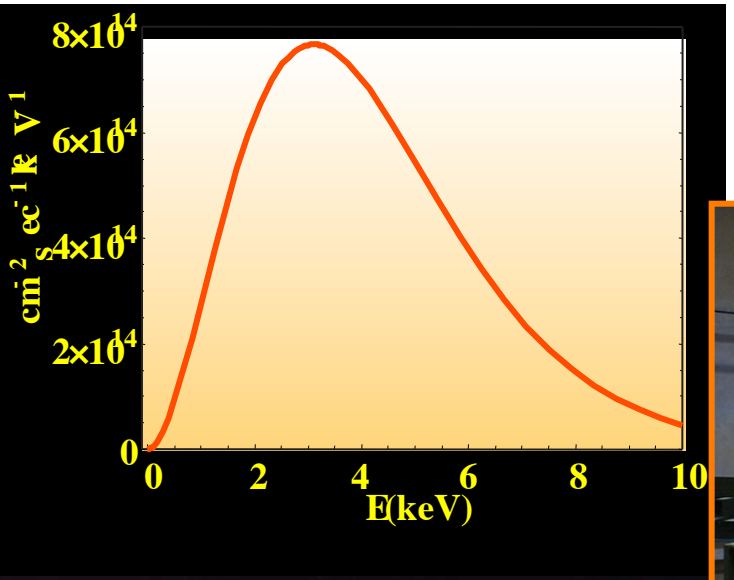
ADMX "Gen 2":
Higher masses via, e.g., microwave "photonic bandgap" cavities.
"Definitive" search in 2nd mass decade.

Kyoto: Rydberg-atom photon detector.

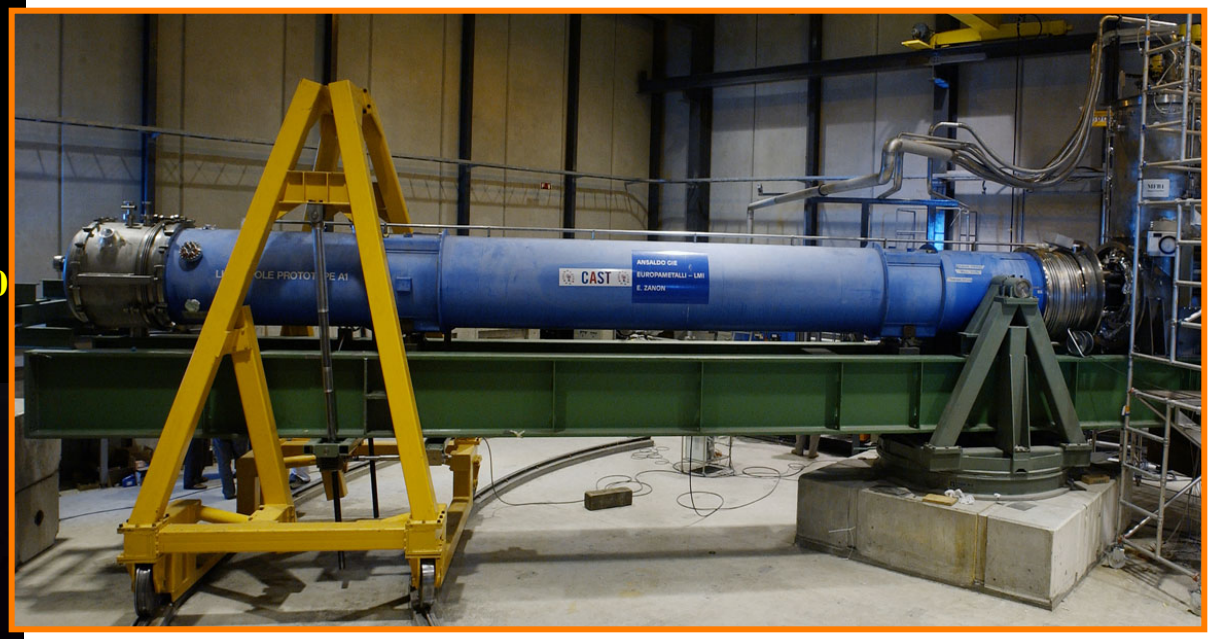
Yale: R&D on higher frequency structures & single-photon microcavities.

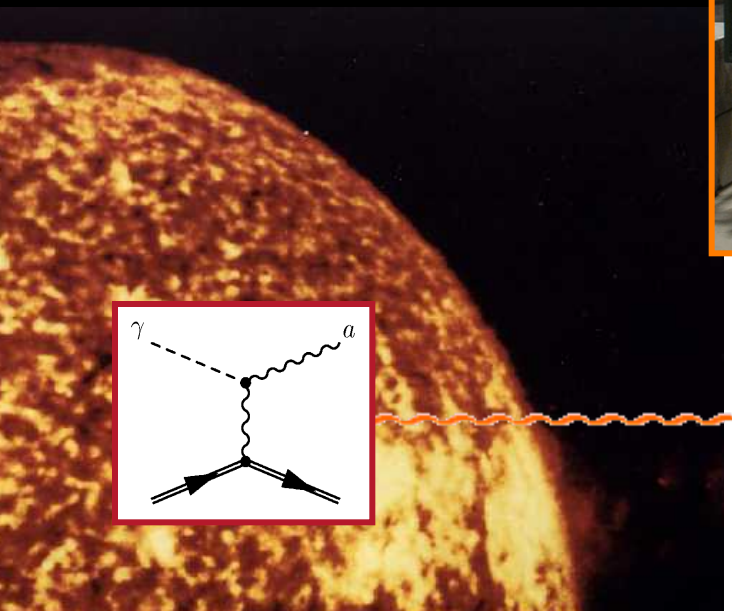
Korea: Possible large RF-cavity system as part of their dark-matter center.

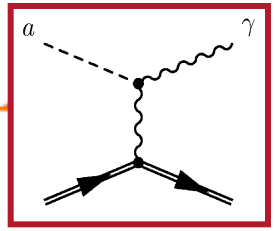
CAST: CERN Axion Solar Telescope.
Searching for axions produced in the Sun.



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

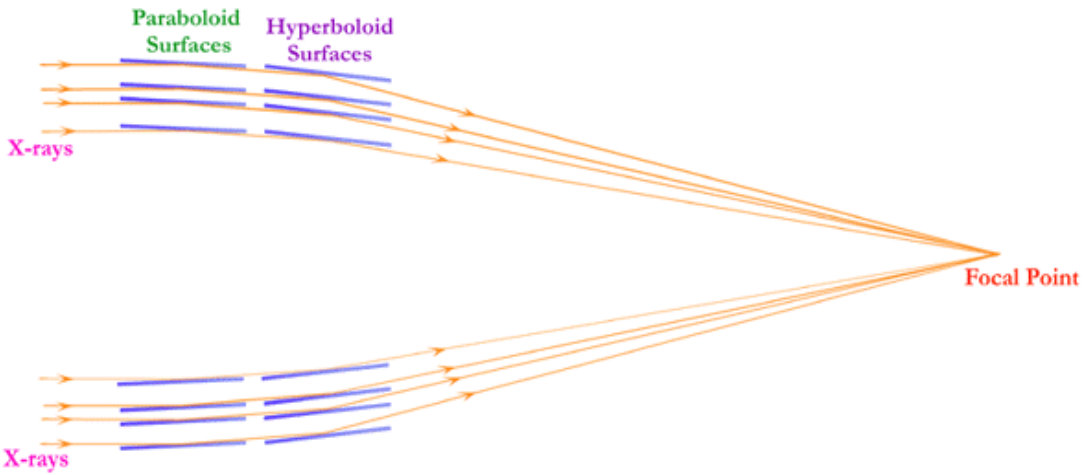




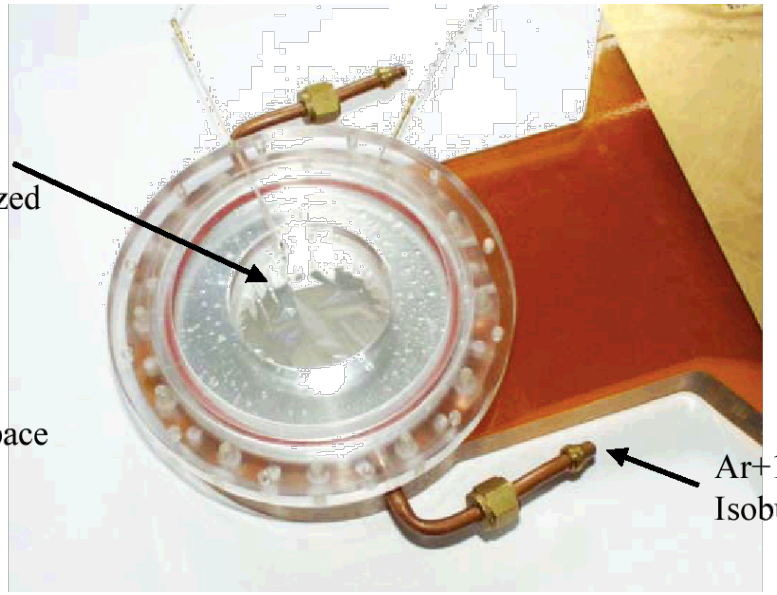


CAST Technology

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

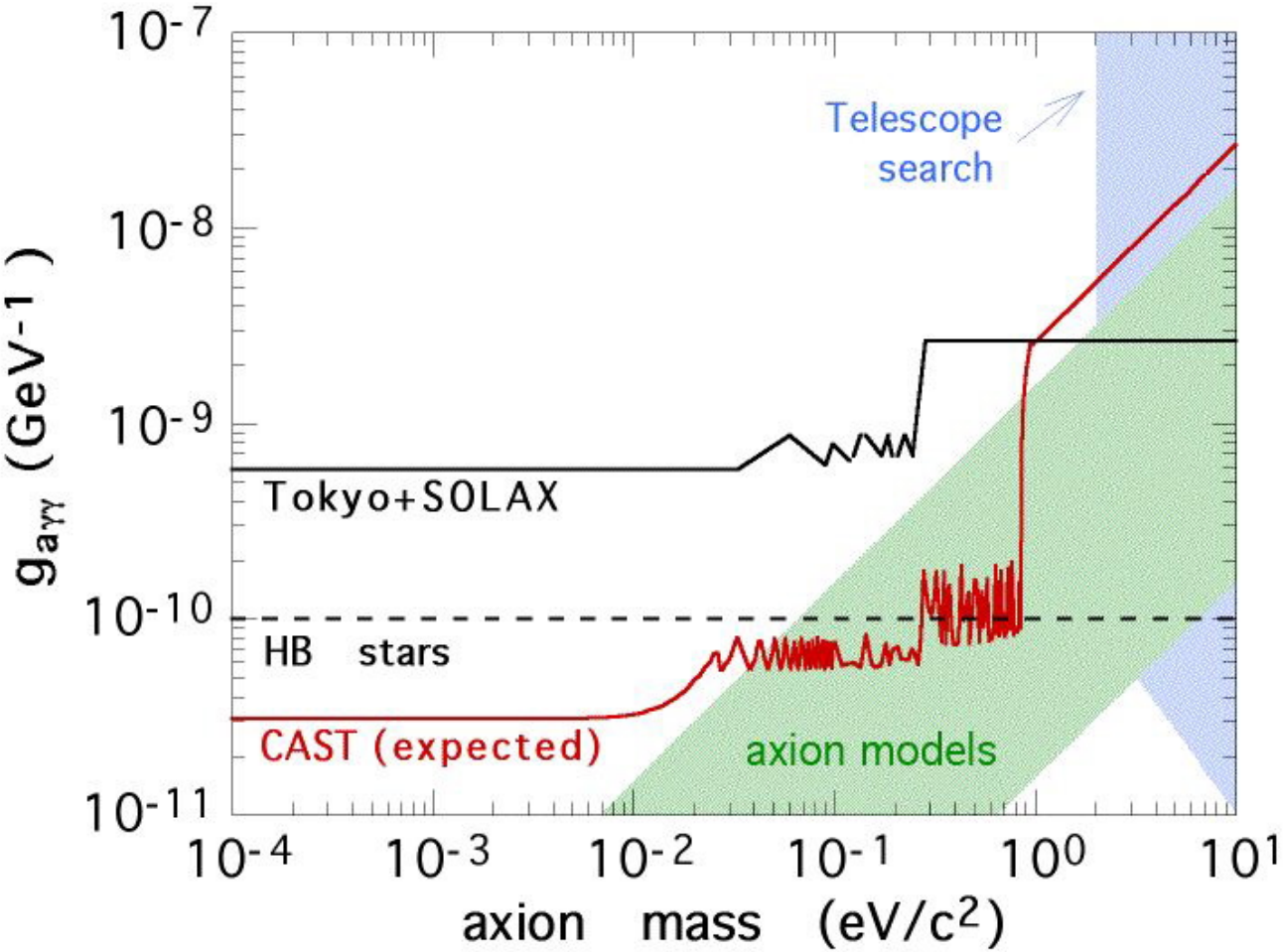


Grazing-incidence x-ray optics



Micromegas x-ray camera

CAST Search Range

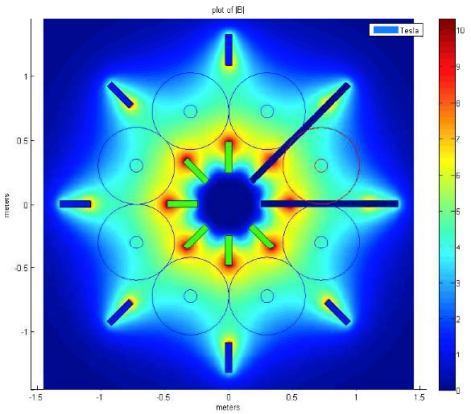


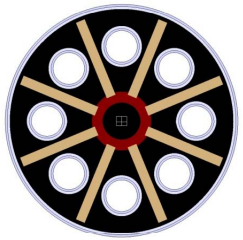
They are conceptualizing IAXO: a next-generation helioscope.

- Larger magnetic field volume
- Better x-ray optics.
- Lower backgrounds.

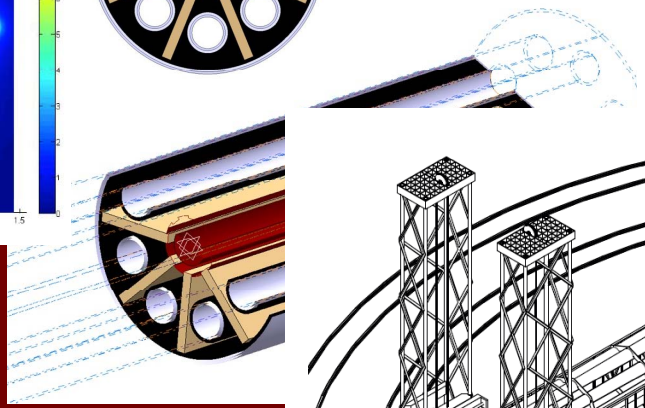
Helioscope Futurism

IAXO magnet: 1st concept



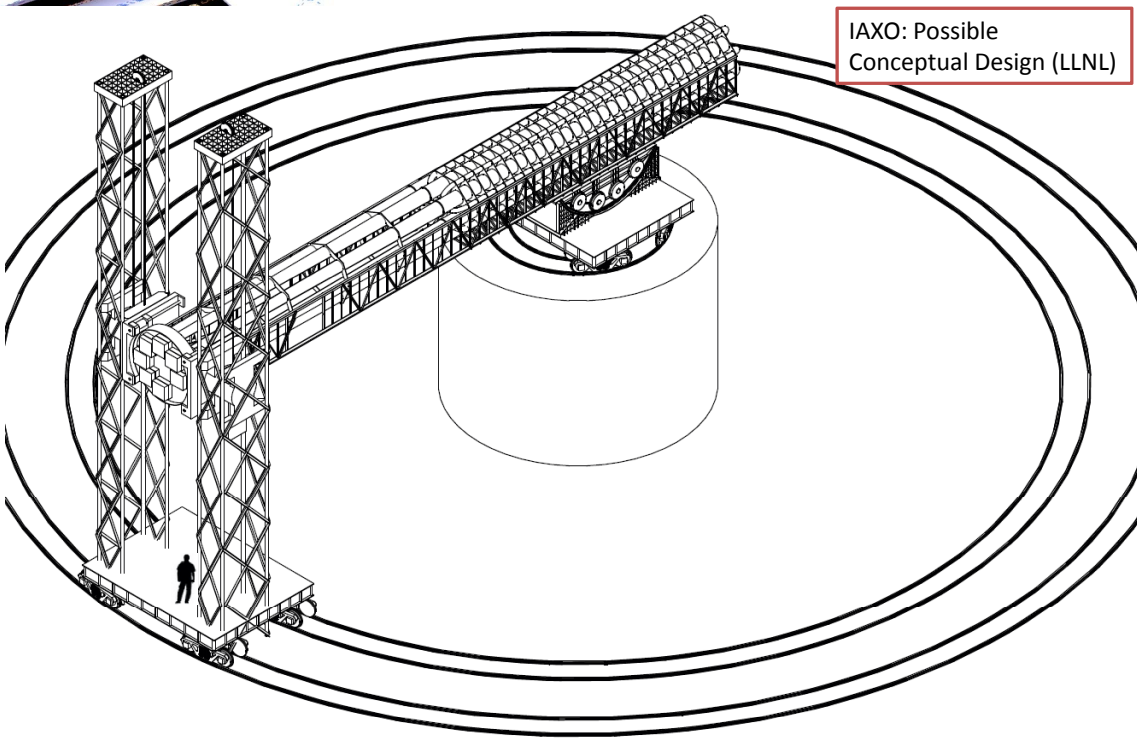


Total R = 2 m
Bore diameter = 600 mm
N bores = 8
Average B in bore = 4 T
(in critical surface)
MFOM = 770



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

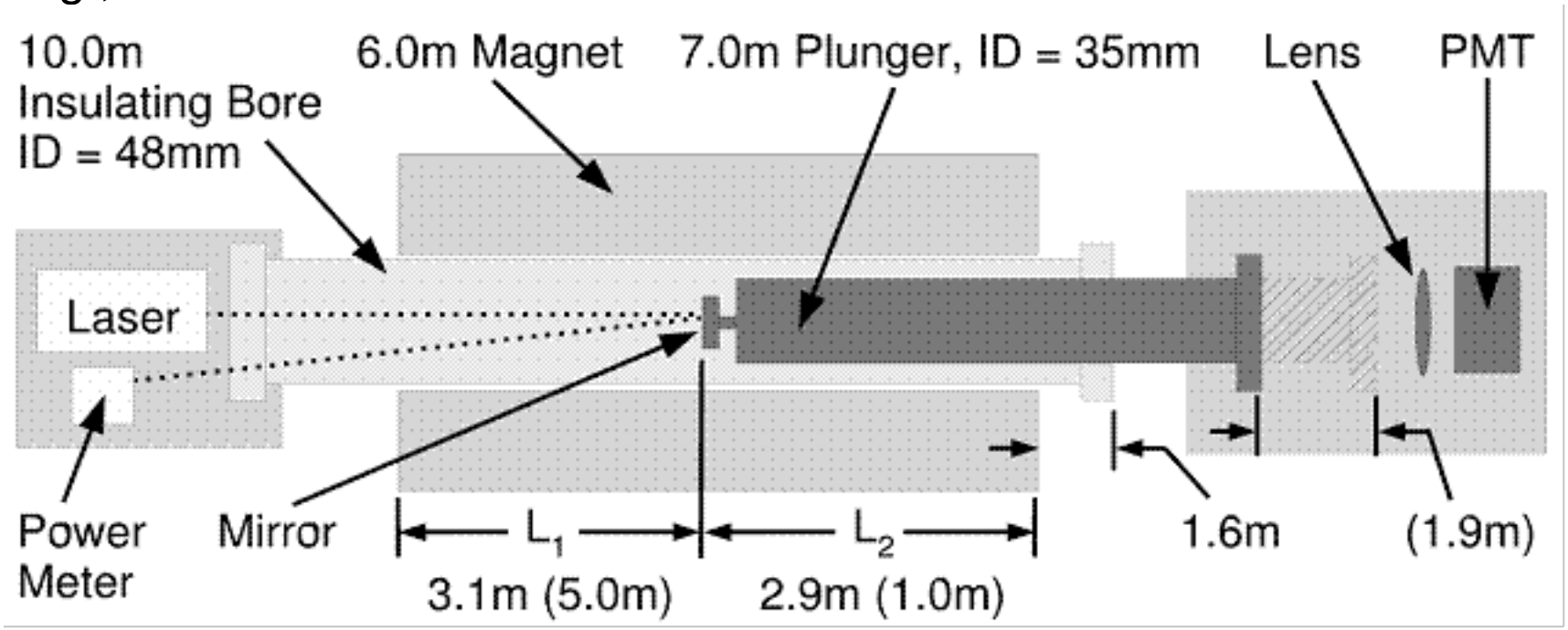
INT Washington, April 2012 Igor G. Irastorza / Universidad de Zaragoza



IAXO: Possible Conceptual Design (LLNL)

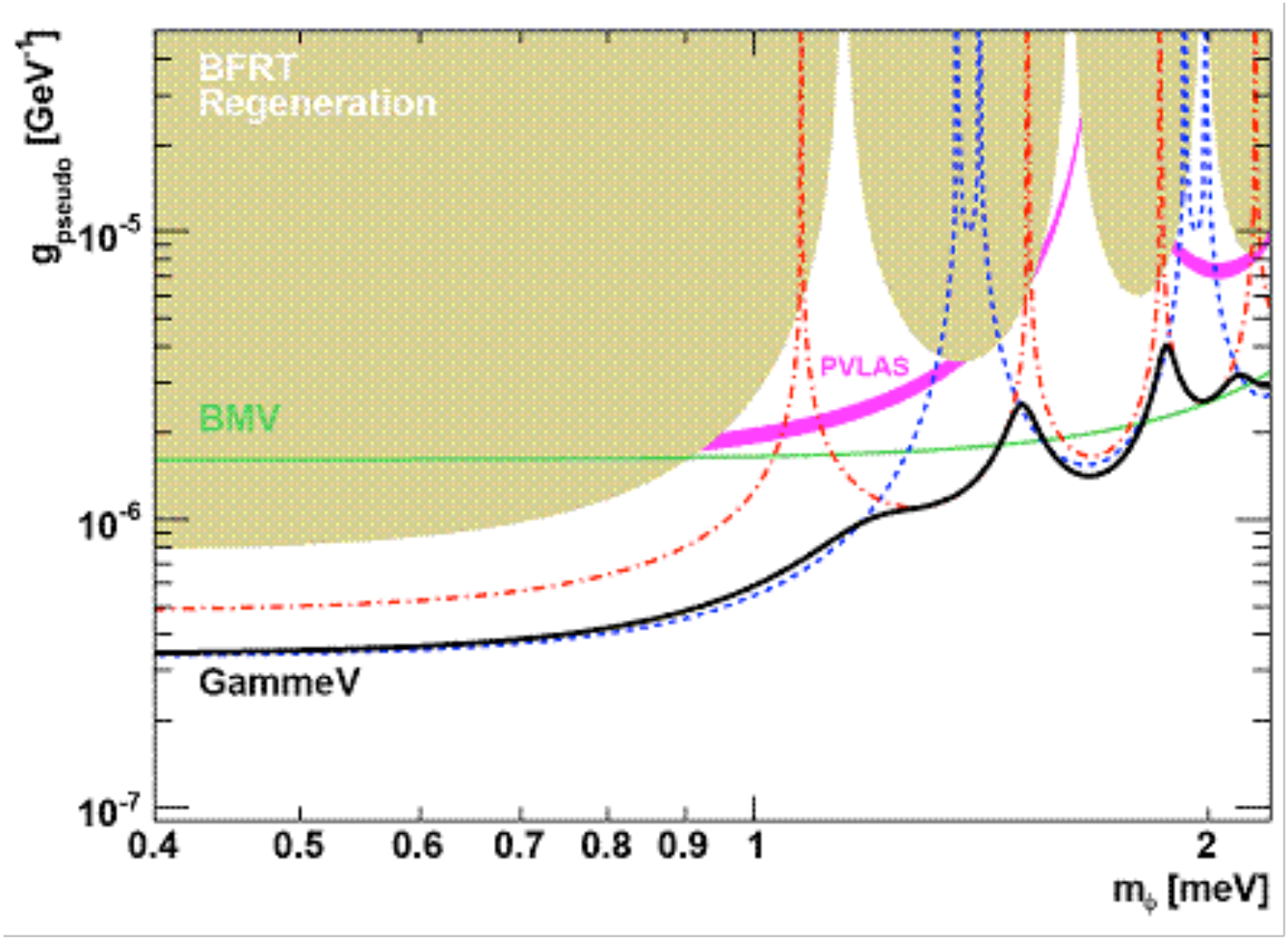
Laser Axion Searches

e.g., GammeV at FNAL



Laser Axion Searches: Sensitivity

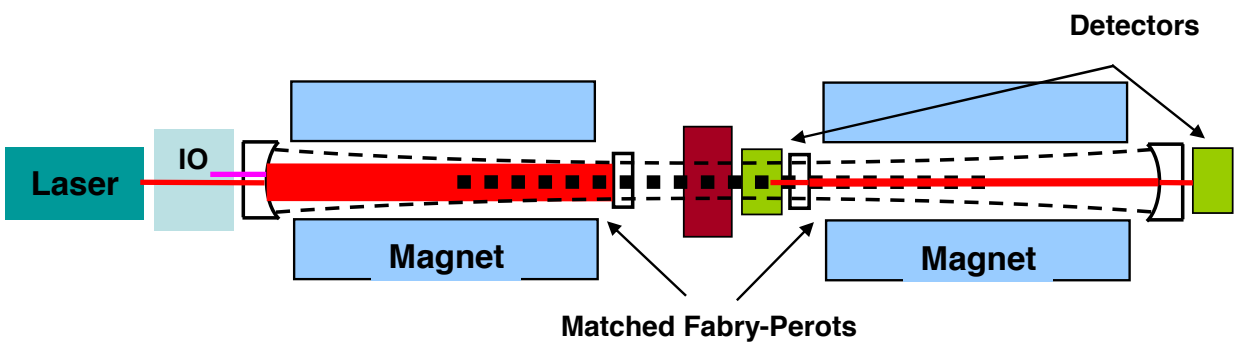
e.g., GammeV at FNAL



Laser axion search: future experiments

Add pair of phase-locked, high finesse optical cavities

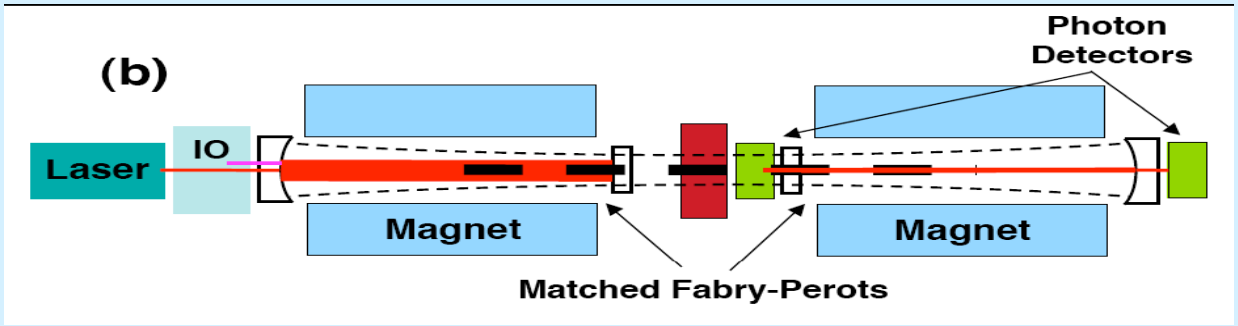
- Laser must be “locked” to production cavity.
- Regeneration cavity must be locked to resonance of production cavity *without filling it with light at the laser wavelength.*
- Cavities must be aligned on mirror image modes (as if inner mirrors and wall were not present).
- Need sensitive readout of weak emission from regeneration cavity.



Sensitivity would be about that from astrophysical bounds (red giant, white dwarf, solar)

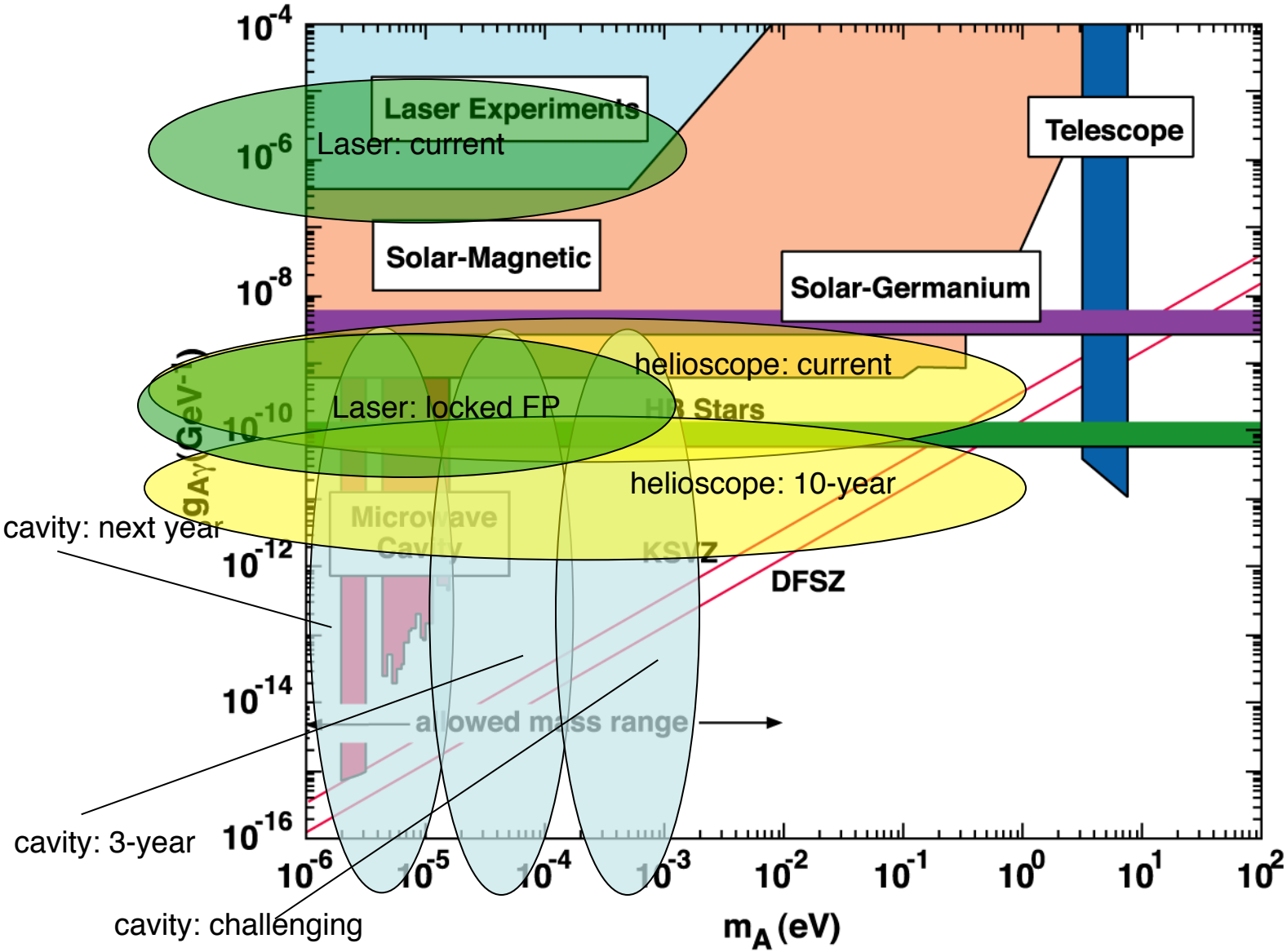
Laser futurism

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

An Experimental Scenario: Focus on Three Key Technologies



Ideas to broaden the mass reach include …

The meV mass frontier of axion physics

Georg G. Raffelt,[1] Javier Redondo,[1] and Nicolas Viaux Maira[2]

ıck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 Münc
[2] *Departamento de Astronomía y Astrofísica, Pontificia Universidad Católica de Cl*
Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile.
(Dated: 19 August 2011)

For $f_a \sim 10^{17}$ GeV: $\theta_i \simeq 10^{-3} \Longrightarrow$ $\delta v = 10^{-4}$ sensitive to $r = 10^7$!

We could detect an axion string 10,000,000 times horizon lengths away (6 x 10^{16} light-years)

It isn't crazy to think about detecting neV axion

Peter Graham &
Surjeet Rajendran

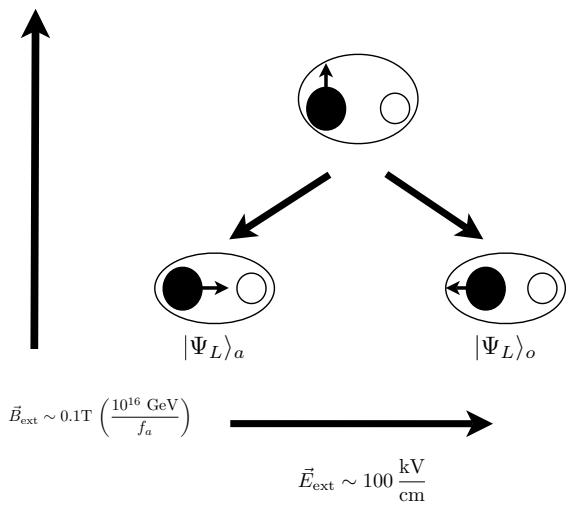


FIG. 2: The molecules are polarized by an external electric field $\vec{E}_{\rm ext} \sim 100\,\frac{\rm kV}{\rm cm}$. They are then placed in a linear superposition of the two states $|\Psi_L\rangle_a$ and $|\Psi_L\rangle_o$, where the nuclear spin is either aligned or anti-aligned with the molecular axis respectively, leading to a phase difference between them in the presence of the axion induced nuclear dipole moment d_n. The external magnetic field $\vec{B}_{\rm ext} \sim 0.1$ T $\left(\frac{f_a}{M_{\rm GUT}}\right)$ causes the spins to precess, so that the phase difference can be coherently accrued over several axion oscillations. The frequency can be scanned by dialing this magnetic field $\vec{B}_{\rm ext}$ until it is resonant with the axion frequency.

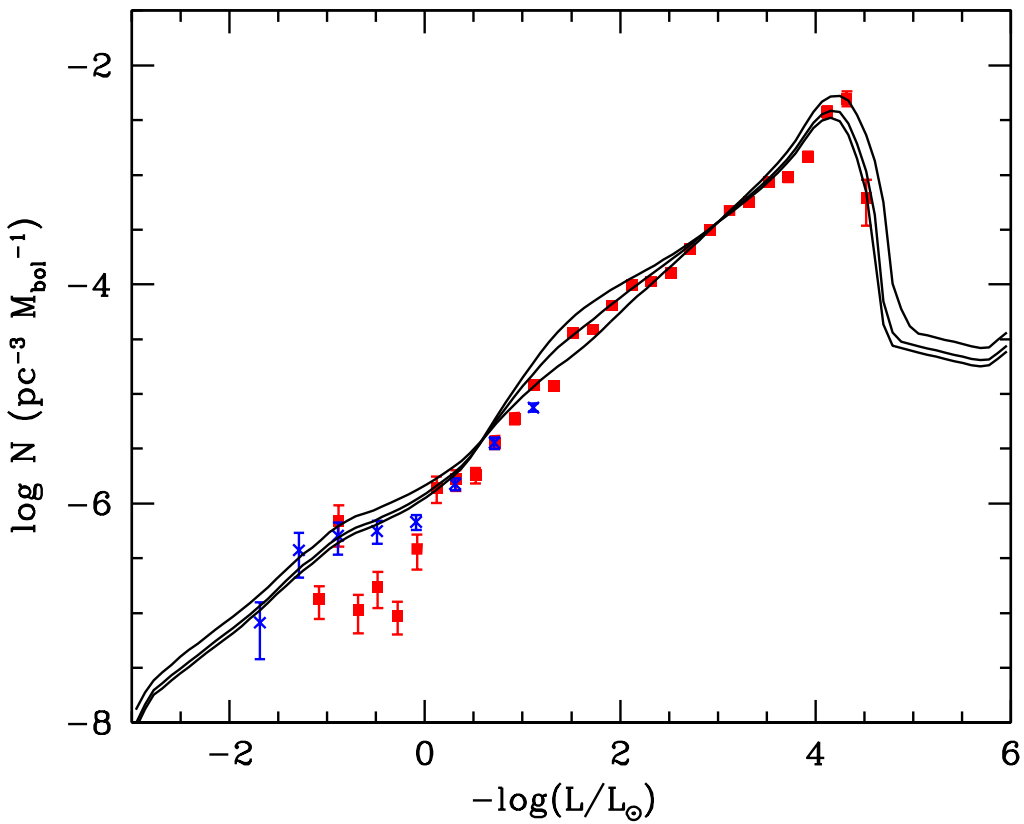
field. When the precession frequency matches the axion frequency, a phase shift will be continually accrued over several axion oscillations. After interrogation for a time T, the phase shift in the experiment (using the energy shift δE from (11)) is

$$\delta\phi = \delta E\, T \sim 10^{-10}\left(\frac{T}{1\ {\rm s}}\right)\left(\frac{\delta E}{10^{-25}\ {\rm eV}}\right) \tag{13}$$

This relative phase between the two spin states $|\Psi_L\rangle_a$ and $|\Psi_L\rangle_o$ can then be measured.

Theory challenges going forward (1) include

e.g, White dwarfs:
Can we 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 understand gamma-ray absorption?

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

F. Tavecchio[1⋆], M. Roncadelli[2], G. Galanti[3], G. Bonnoli[1]
[1]*INAF – Osservatorio Astronomico di Brera, Via E. Bianchi 46, I–23807 Merate, Italy*
[2]*INFN, Sezione di Pavia, Via A. Bassi 6, I–27100, Pavia, Italy*
[3]*Dipartimento di Fisica, Università dell'Insubria, Via Valleggio 11, I–22100, Como, Italy*

1 March 2012

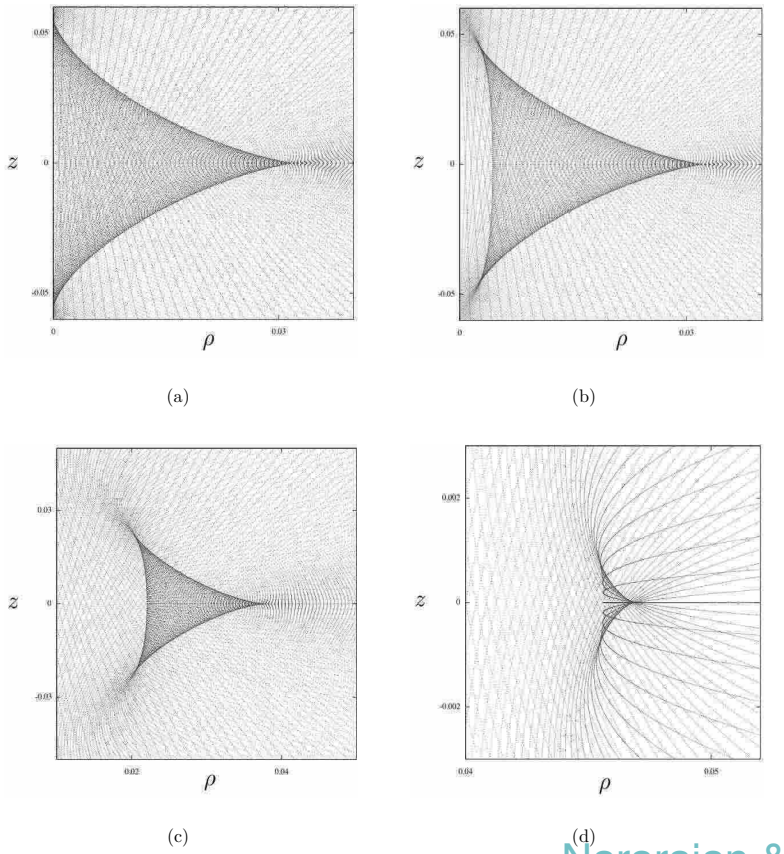
ABSTRACT
The surprising discovery by MAGIC of an intense, rapidly varying very high energy ($E > 50$ GeV) emission from the flat spectrum radio quasar PKS 1222+216 represents a challenge for all interpretative scenarios. Indeed, in order to avoid absorption of γ rays in the dense ultraviolet radiation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

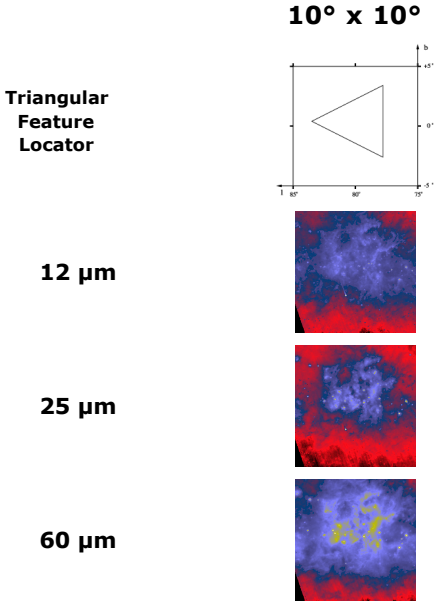
Is the dark matter a Bose condensate?



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).

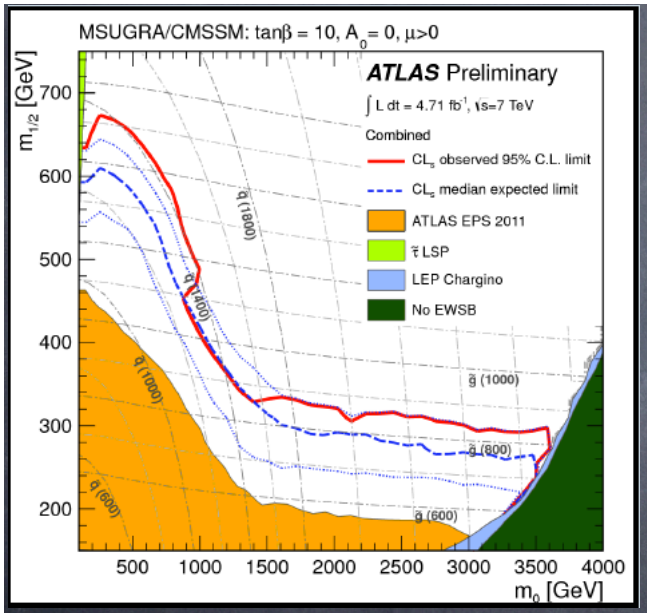
E.g.,
look where a ring would be in our galaxy
Skyview virtual observatory

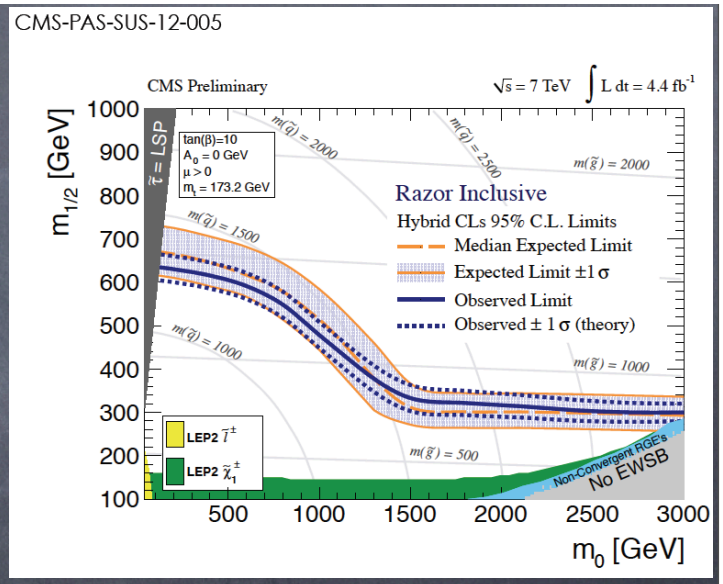


Conclusions (1)

We need to keep our eye on the LHC (and WIMP detectors).

The longer SUSY remains undetected, the more compelling axions become.





Atlas/CMS: no sign of mSUGRA at LHC7:

Conclusions (2)

On the other hand, LHC finding SUSY would 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

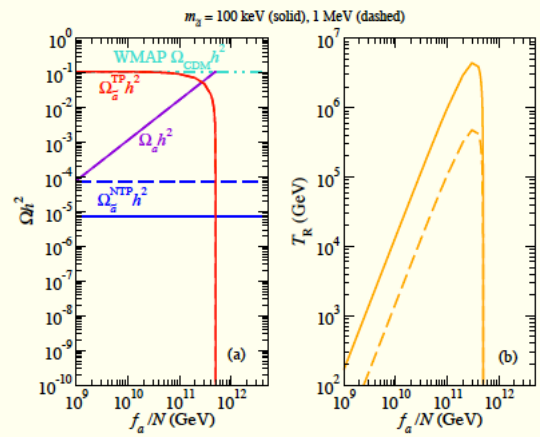
H. Baer

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 axion is well bounded in mass and couplings.
Dark-matter 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 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 models is still wide open.
Major efforts for solar axions and laser experiments.
Ideas are out there for very low-mass axions (inspired by string theory and anthropic principle).

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