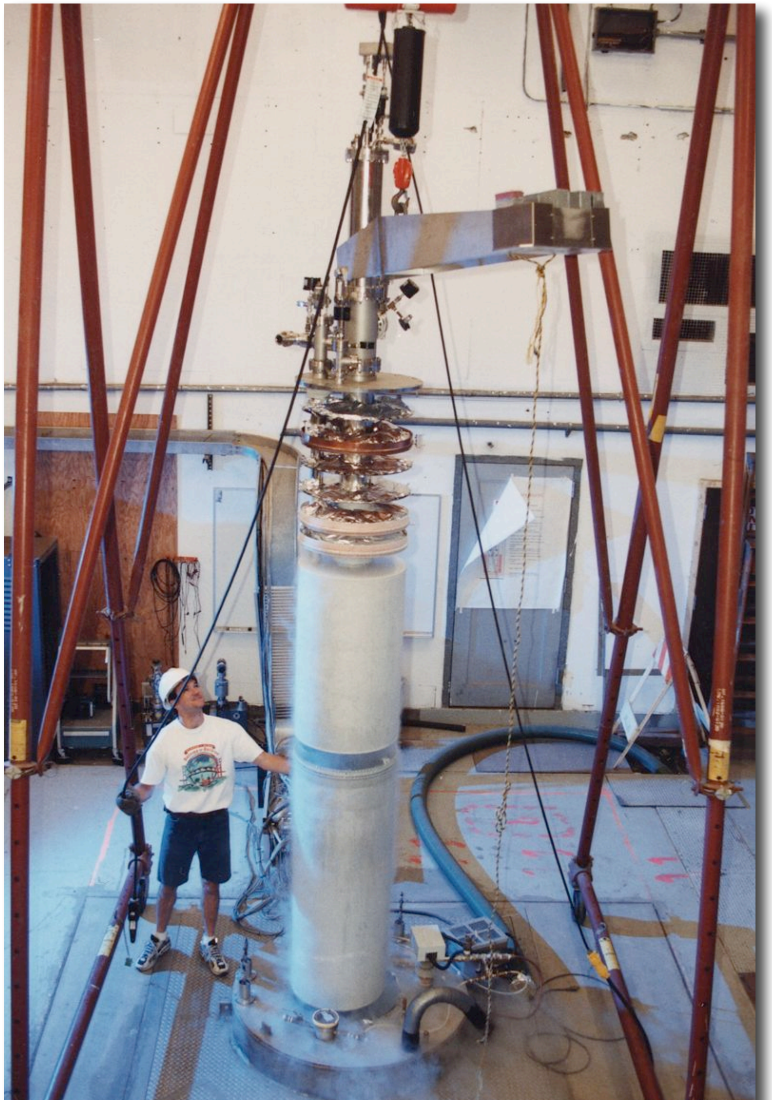


Fermilab Seminar

Ultrasensitive Searches for the Axion

Karl van Bibber, LLNL

January 30, 2008

AXION

A disproportionate number of axion-hunters are Red Sox fans. It prepares you for life.

But everyone deserves a pleasant surprise, once a century!

Two cosmic events took place simultaneously on October 27, 2004

Outline

Some basics about the axion

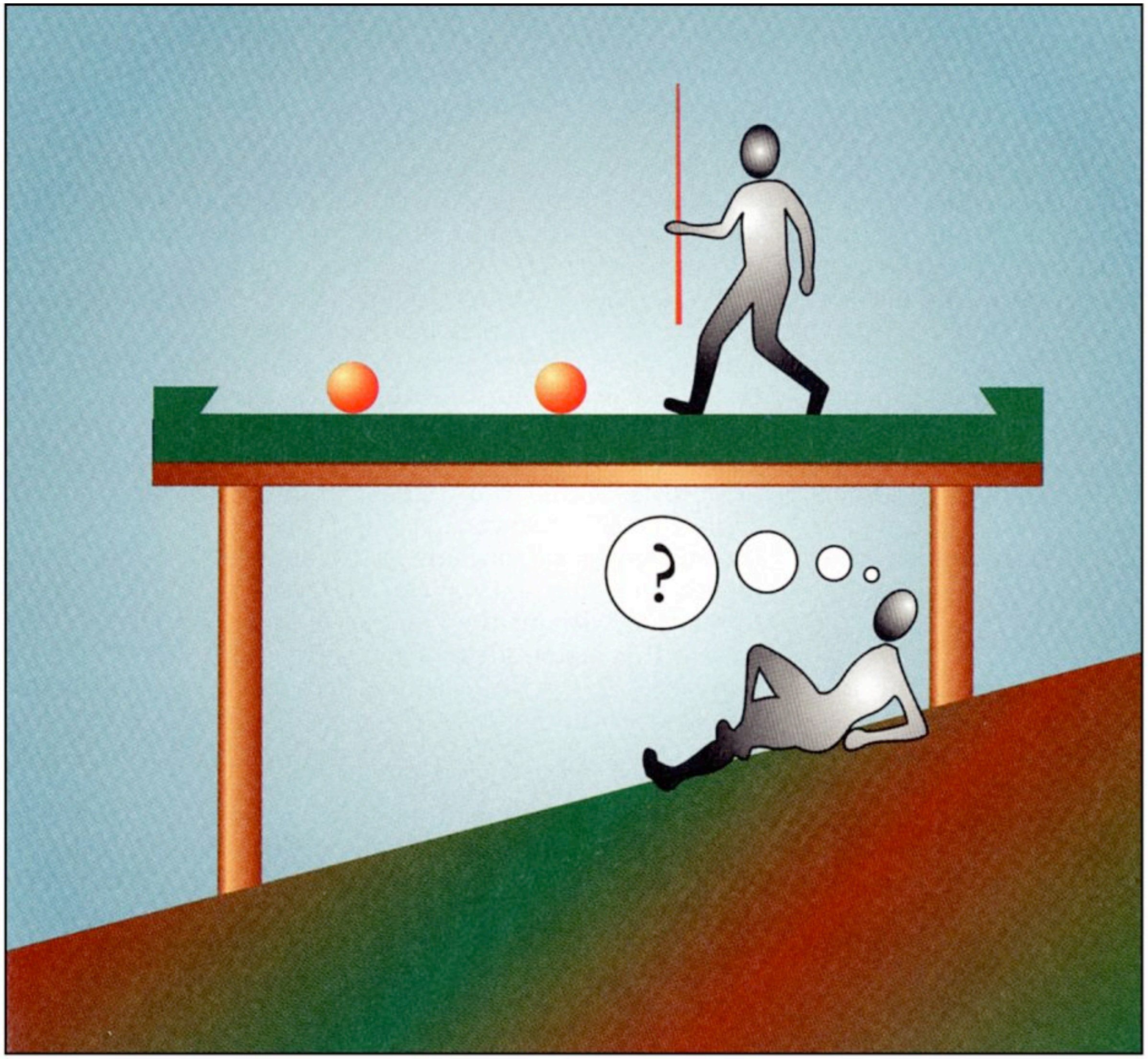
Microwave-cavity searches for dark matter axions

Other axion searches

What if the axion be found?

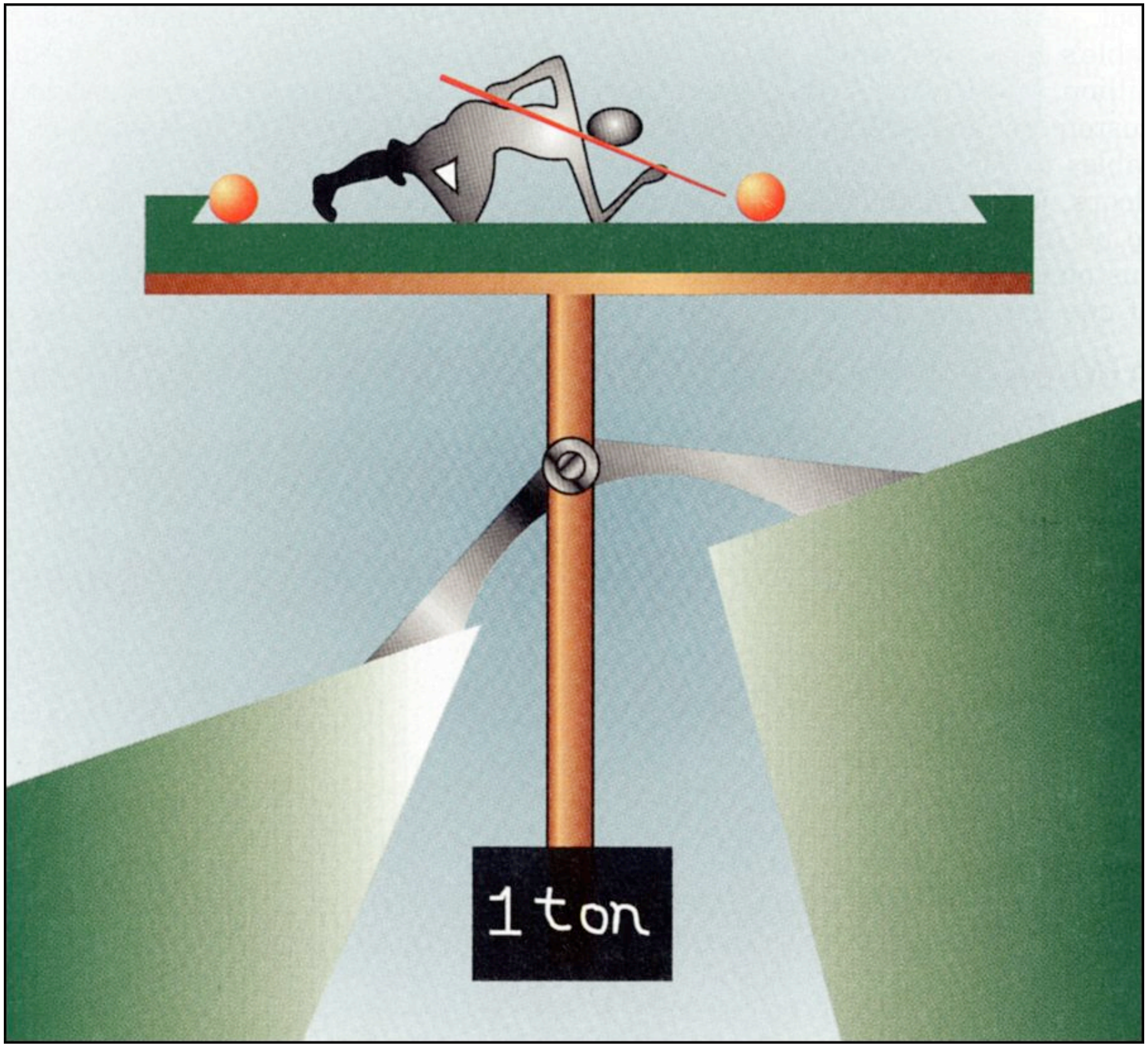
(See *Physics Today*, August 2006, KvB & Les Rosenberg)

TSP's* fine-tuning problem

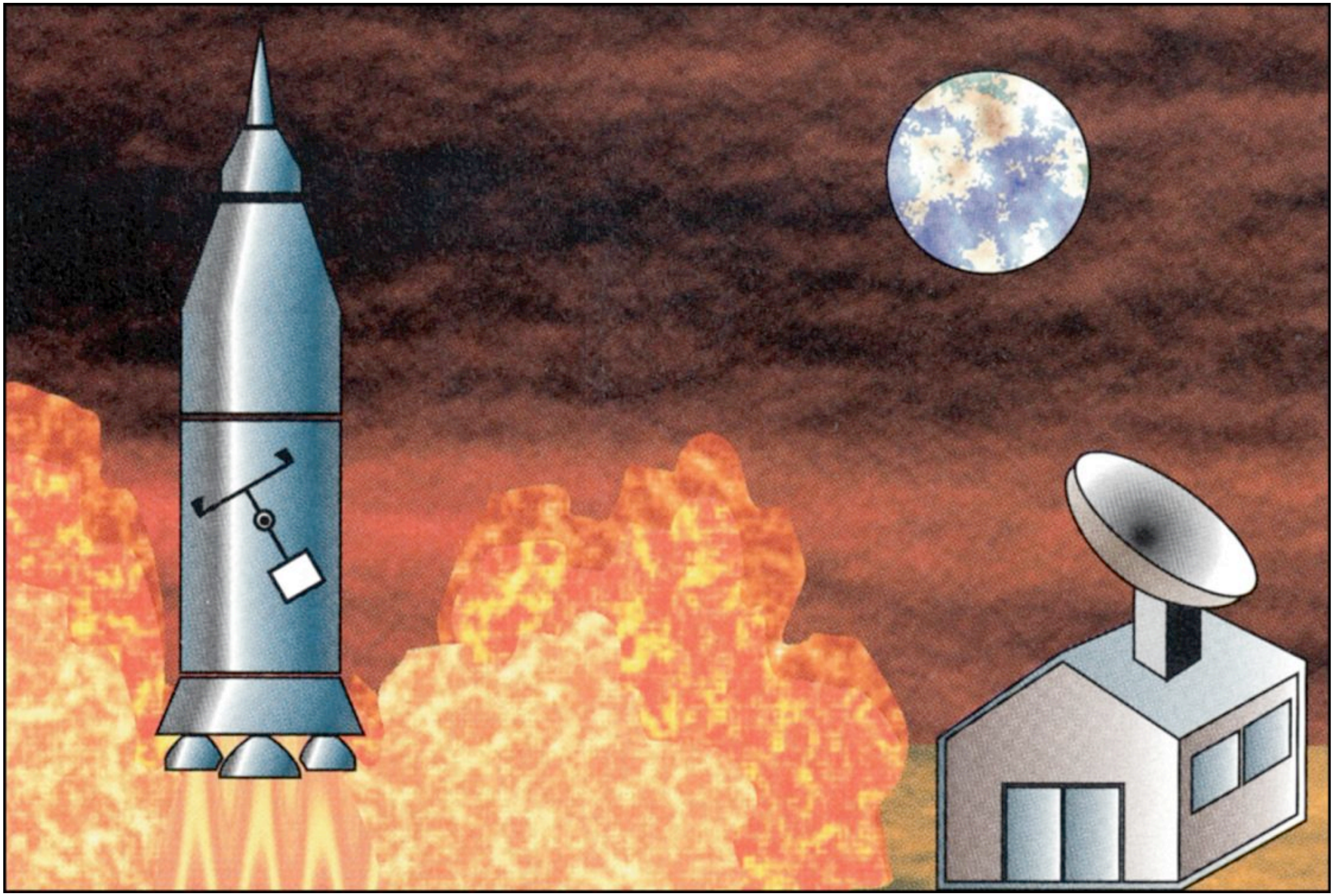


*Thinking Snookers Player (Pierre Sikivie, Physics Today 49 (1996)22)

TSP's hypothesis, and first unsuccessful experiment

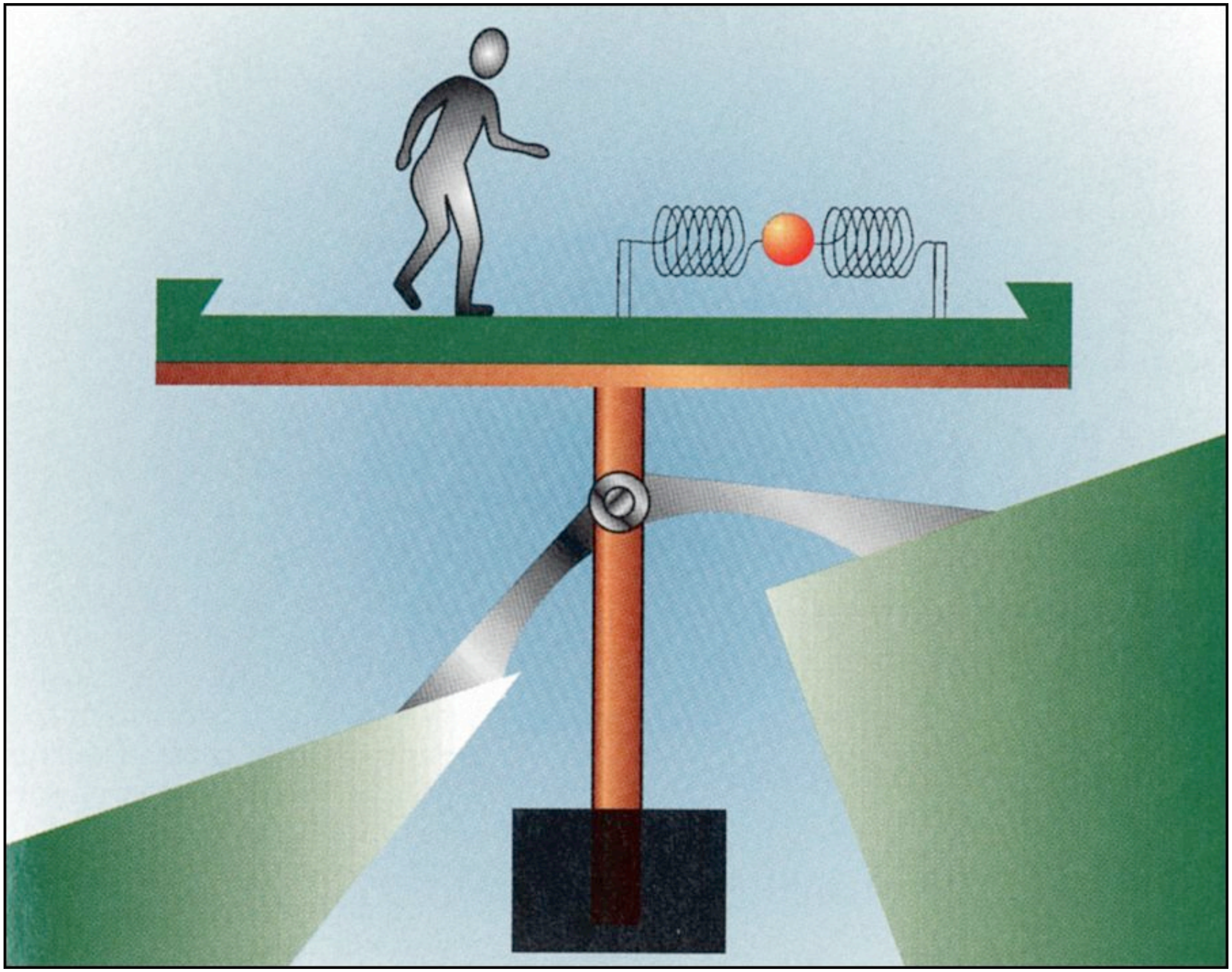


The key insight



A high-Q search for relic oscillations

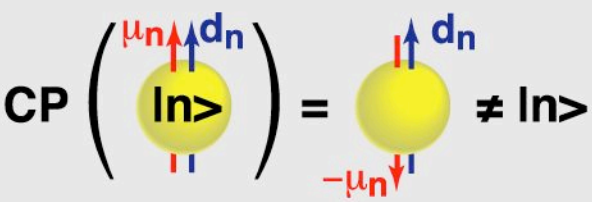
AXION



The Axion

The Strong-CP Problem

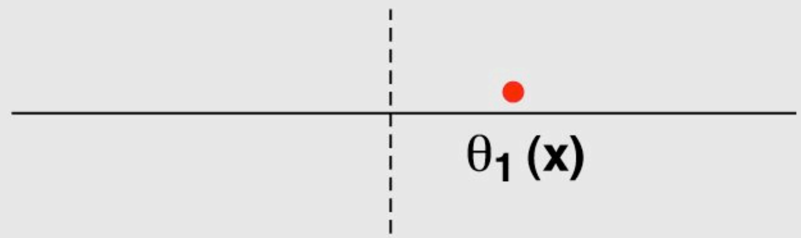
- $\mathscr{L}_{QCD} = \ .... + \dfrac{\theta}{32\pi^2}\ G\tilde{G}$
  - Explicitly CP-violating
- But neutron e.d.m. $|d_n| < 10^{-25}$ e · cm
  - $\bar{\theta} < 10^{-10}$
  - Strong-CP preserving



- Why?

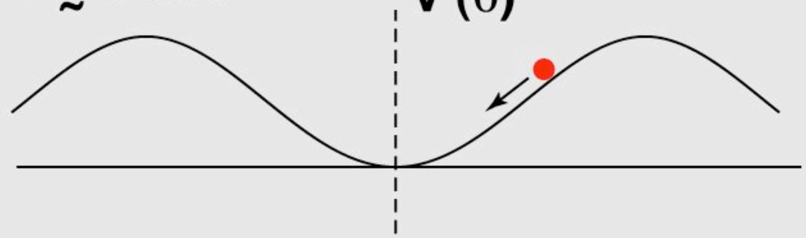
Peccei-Quinn / Weinberg-Wilczek

- θ a dynamical variable
- $T = f_a$ spontaneous symmetry breaking



- $T \lesssim 1$ GeV

V ($\bar{\theta}$)



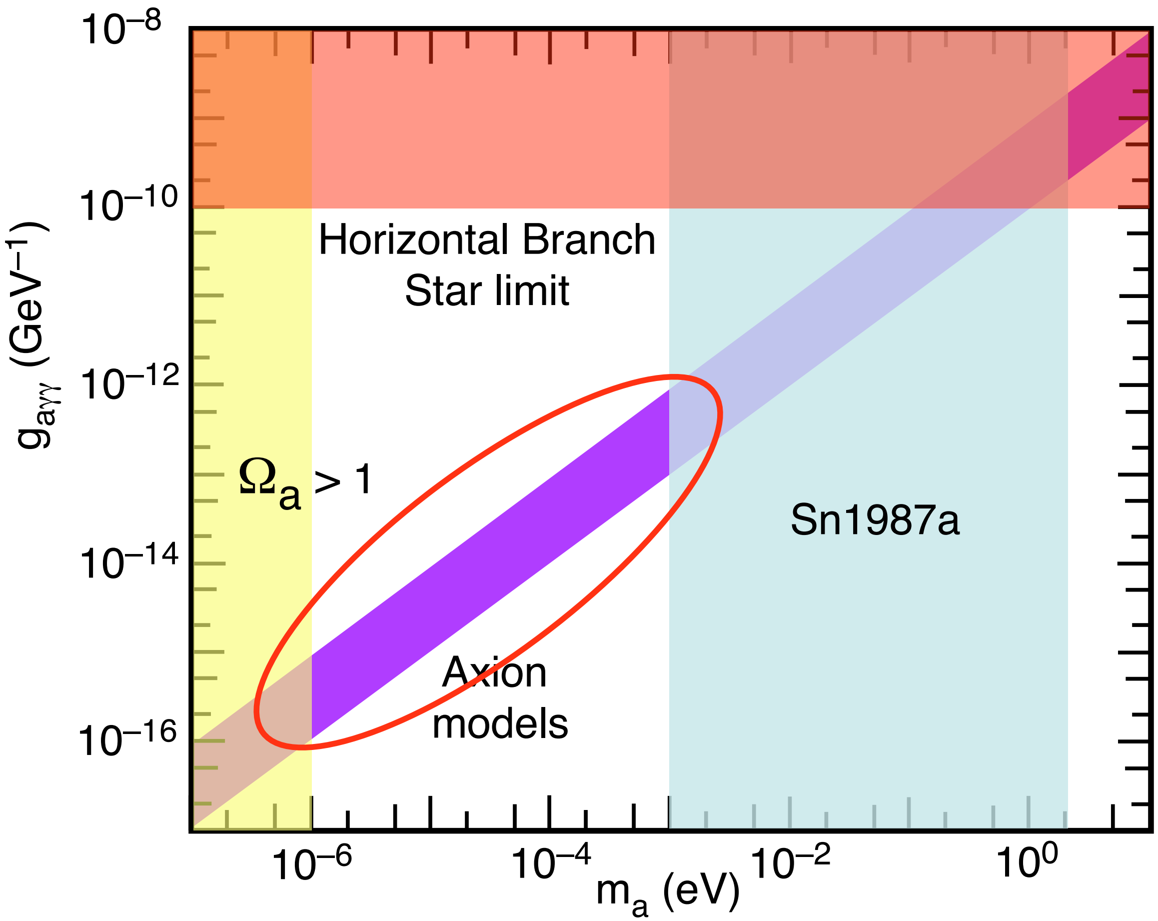
  - $\bar{\theta}$ dynamically → 0
  - Remnant oscillation = Axion

Completing the analogy $f \longleftrightarrow l$

AXION

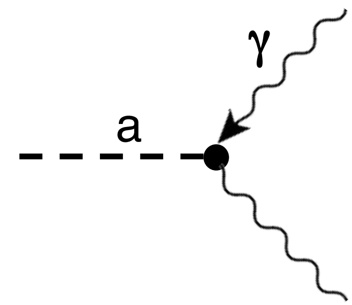
	PQ-symmetry breaking scale	Pendulum length
Quanta m_a (ω)	$\sim f^{-1}$	$\sim l^{-1/2}$
Couplings g_{aii}	$\sim f^{-1}$	$\sim l^{-1}$
Total energy Ω_a (E)	$\sim f^{7/6}$	$\sim l$

Axion basics



Good news – Parameter space is bounded
Bad news – All couplings are *extraordinarily* weak

Light cousin of π^0: $J^{\pi} = 0^-$



m_a , $g_{aii} \propto f_a^{-1}$ ∴ $g_{a\gamma\gamma} \propto m_a$

$\Omega_a \propto f_a^{7/6} \rightarrow m_a > 1\ \mu eV$

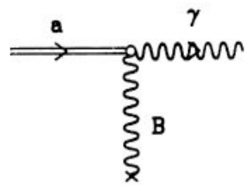
Sn1987a ν pulse precludes
$NN \rightarrow NNa$ for $m_a \sim 10^{-(3-0)}$ eV

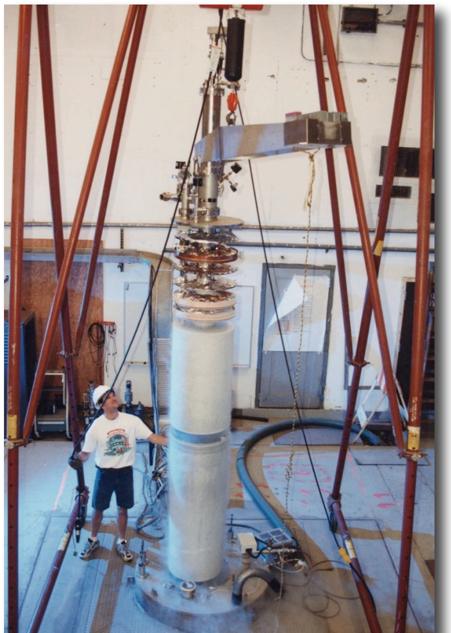
Red giant evolution precludes
$g_{a\gamma\gamma} > 10^{-10}\ GeV^{-1}$

G.G. Raffelt *"Stars as Laboratories for Fundamental Physics"* U. Chicago Press (1996)

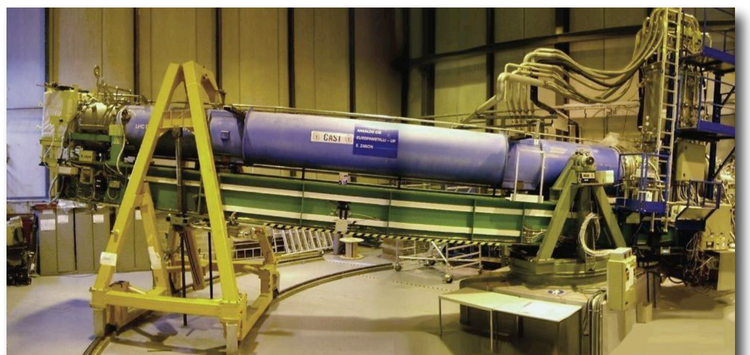
Axion-photon mixing provides the key [P. Sikivie, PRL 51, 1415 (1983)]

$$L_{\text{int}} = a g_{a\gamma\gamma} E \cdot B$$

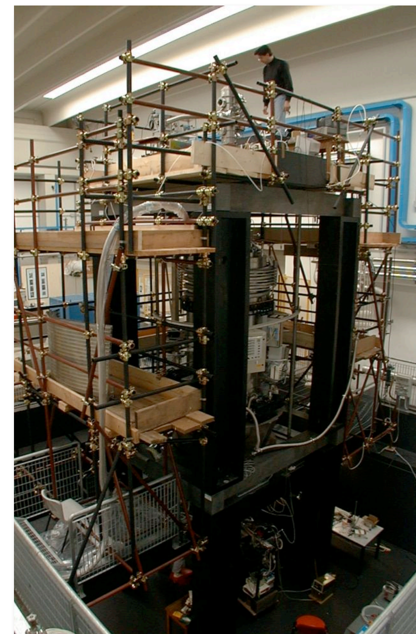




Dark matter



Solar

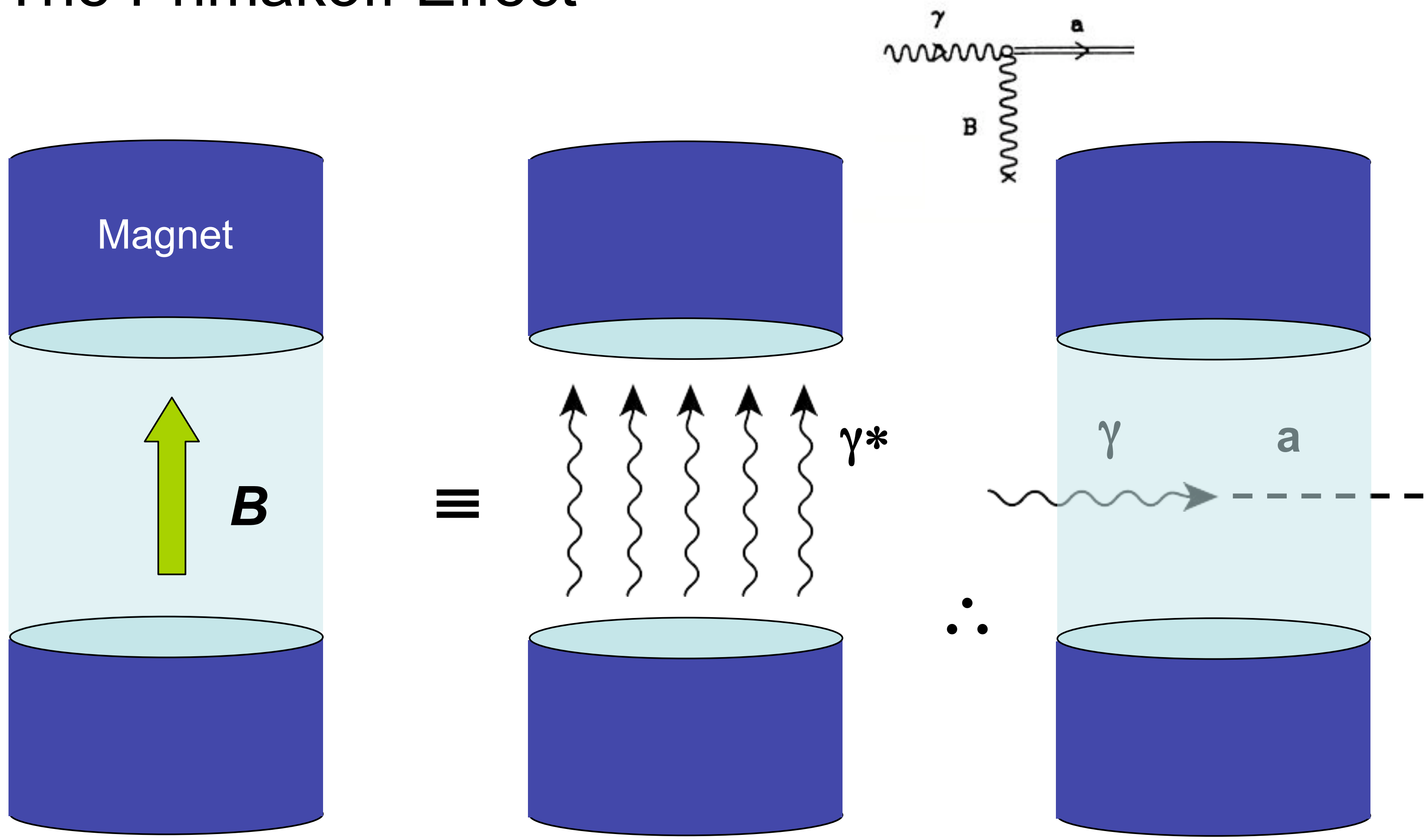


Laboratory

Coherent mixing of axions and photons over large spatial regions of strong magnetic fields (a sea of virtual photons) compensates for the extraordinarily small value of $g_{a\gamma\gamma}$

See Raffelt & Stodolsky for general treatment of axion-photon mixing – PRD 37, 1237 (1988)

The Primakoff Effect

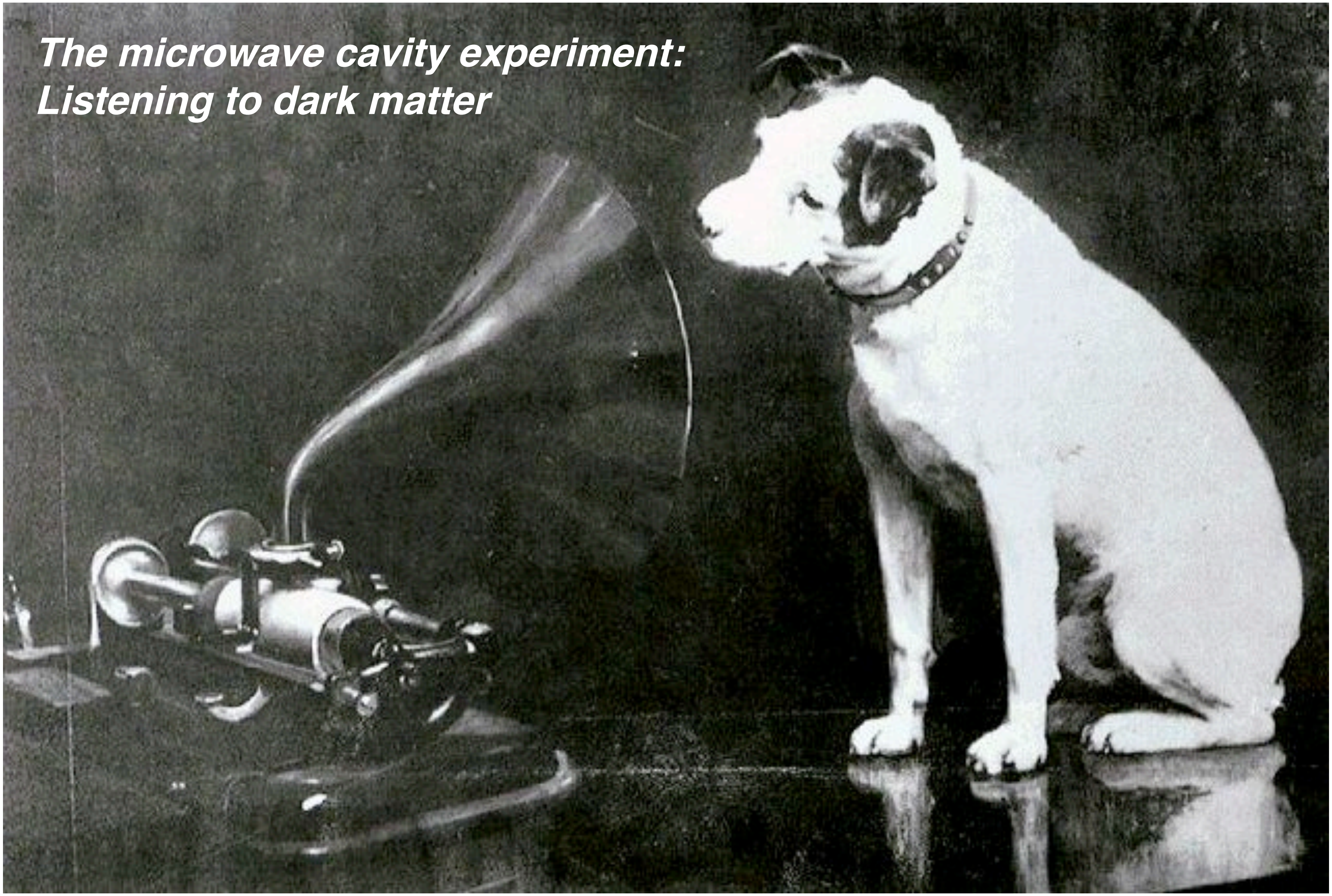


Classical EM field

Sea of virtual photons

Primakoff Effect

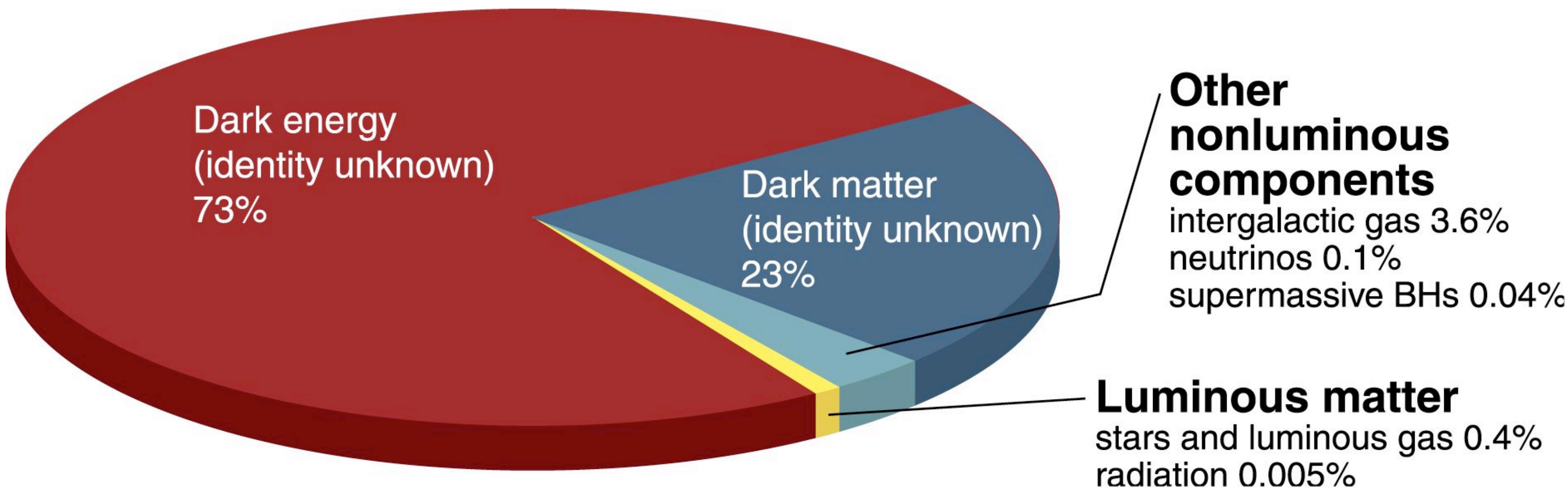
The microwave cavity experiment: Listening to dark matter



The cosmological inventory is now well-delineated

AXION

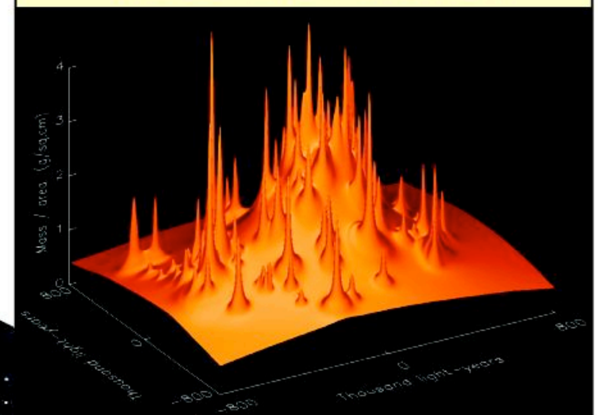
- **But we know neither what the "dark energy" or the "dark matter" is**
- **A particle relic from the Big Bang is strongly implied for DM**
  - **— WIMPs ?**
  - **— Axions ?**

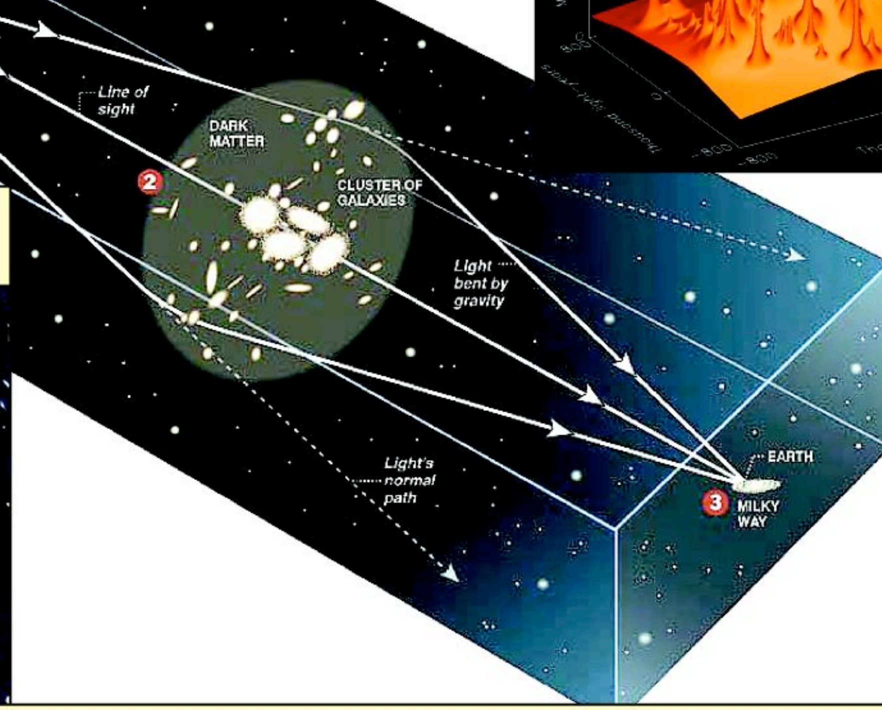


Evidence for dark matter: Gravitational lensing by clusters of galaxies

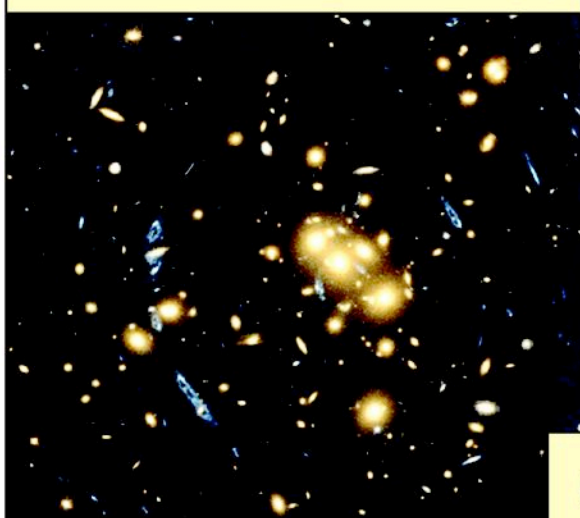
- **Cluster mass reconstruction from multiple gravitational lensing of background galaxy**

Reconstructed Cluster Mass Distribution





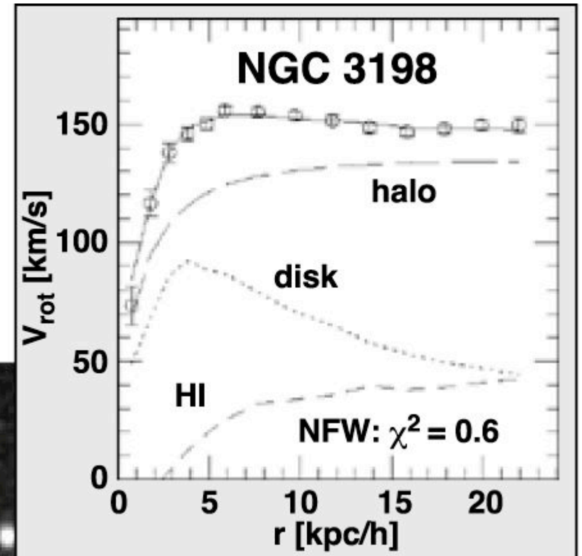
HST Image



Consistent with dynamical estimates; $\Omega_M/\Omega_B \sim 7$

Evidence for dark matter:
Rotation curves of spiral galaxies

- **Galaxies have constant rotation curves**

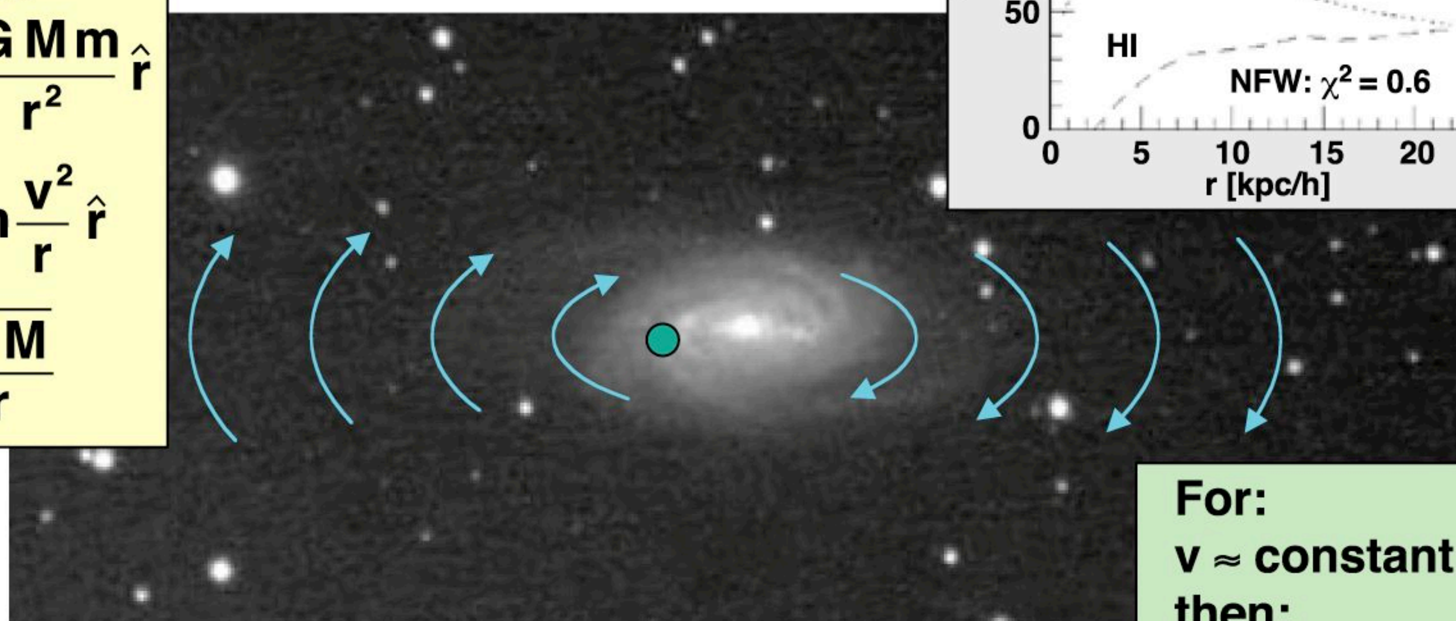


If mass were localised

$$F = -\frac{G\,M\,m}{r^2}\,\hat{r}$$

$$= -m\frac{v^2}{r}\,\hat{r}$$

$$v = \sqrt{\frac{G\,M}{r}}$$



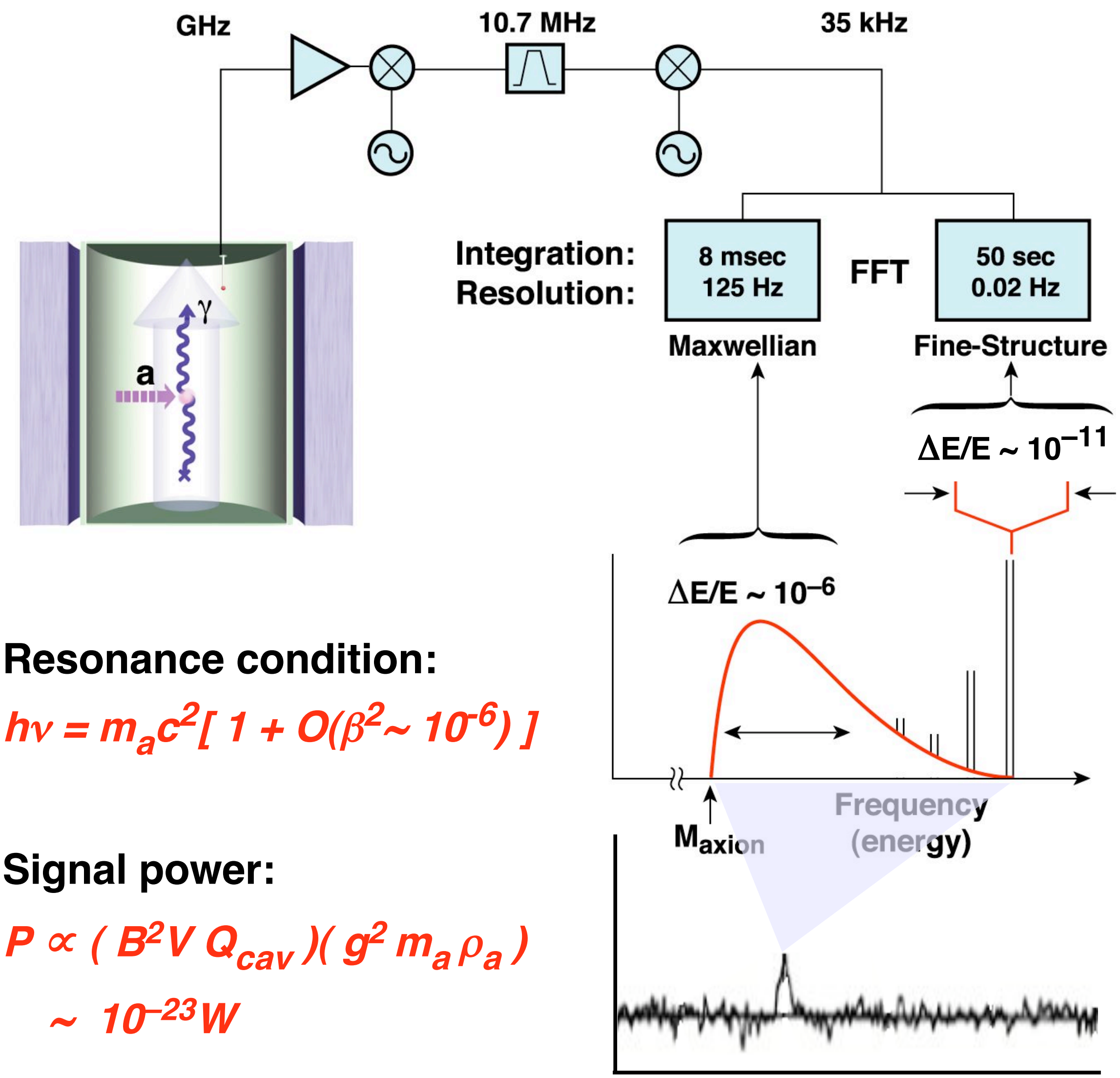
For:
$v \approx$ constant
then:

$$M(r) \propto r$$

$$M_{dark} \geq 10 M_{lum}$$

- **Dark Matter is right in our own Milky Way!**
- **Maximum likelihood local density $\rho \sim 450\ \mathrm{MeV/cm^3}$**

Nature of axionic dark matter, and principle of the microwave cavity experiment *[Pierre Sikivie, PRL 51, 1415 (1983)]*



Local Milky Way density:

$\rho_{halo} \sim 450\ MeV/cm^3$

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

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

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

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

$\Delta\beta_{flow} \sim 10^{-3}$:

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

Resonance condition:

$h\nu = m_a c^2 [\ 1 + O(\beta^2 \sim 10^{-6})\ ]$

Signal power:

$P \propto (\ B^2 V\ Q_{cav})(\ g^2\ m_a\ \rho_a\ )$

$\sim\ 10^{-23} W$

Key point !
The signal is the
Total Energy
(= Mass + Kinetic)
of the axion

Axion Dark Matter eXperiment (ADMX)

University of California, Berkeley
John Clarke

University of Florida
Pierre Sikivie, Neil Sullivan, David Tanner

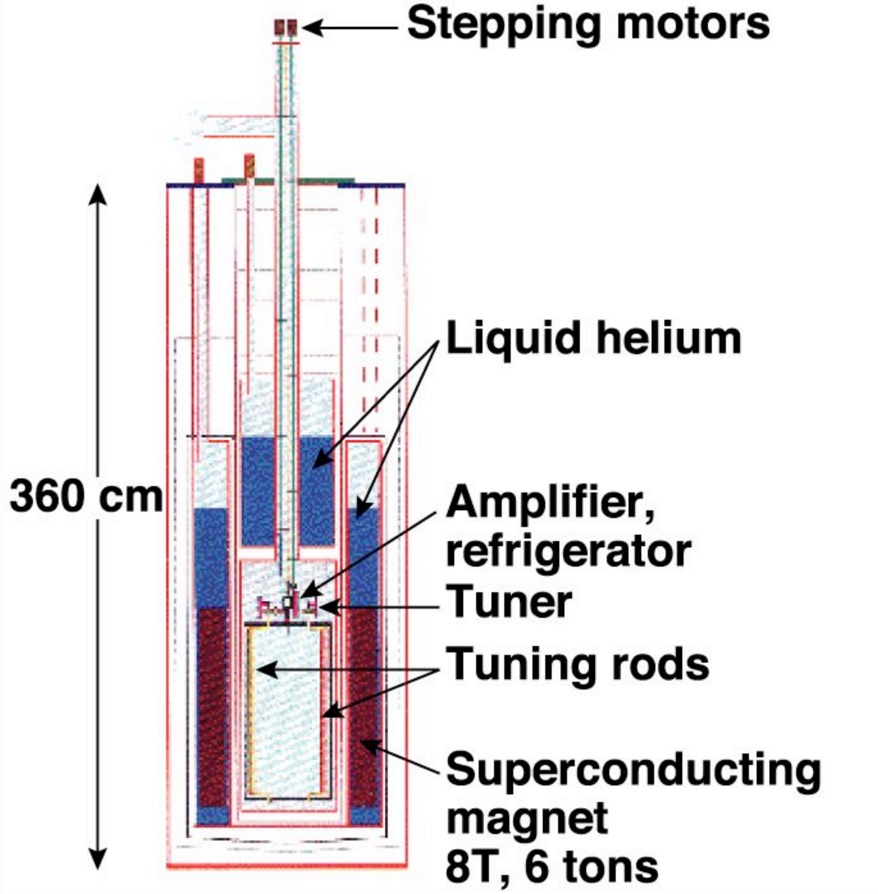
Lawrence Livermore National Laboratory
Stephen Asztalos, Gianpaolo Carosi, Christian Hagmann, Darin Kinion, Karl van Bibber

National Radio Astronomical Observatory
Richard Bradley

University of Washington
Michael Hotz, Leslie Rosenberg, Gray Rybka

Axion hardware *ADMX LLNL-UW-Florida-Berkeley-NRAO*

Magnet with Insert (side view)



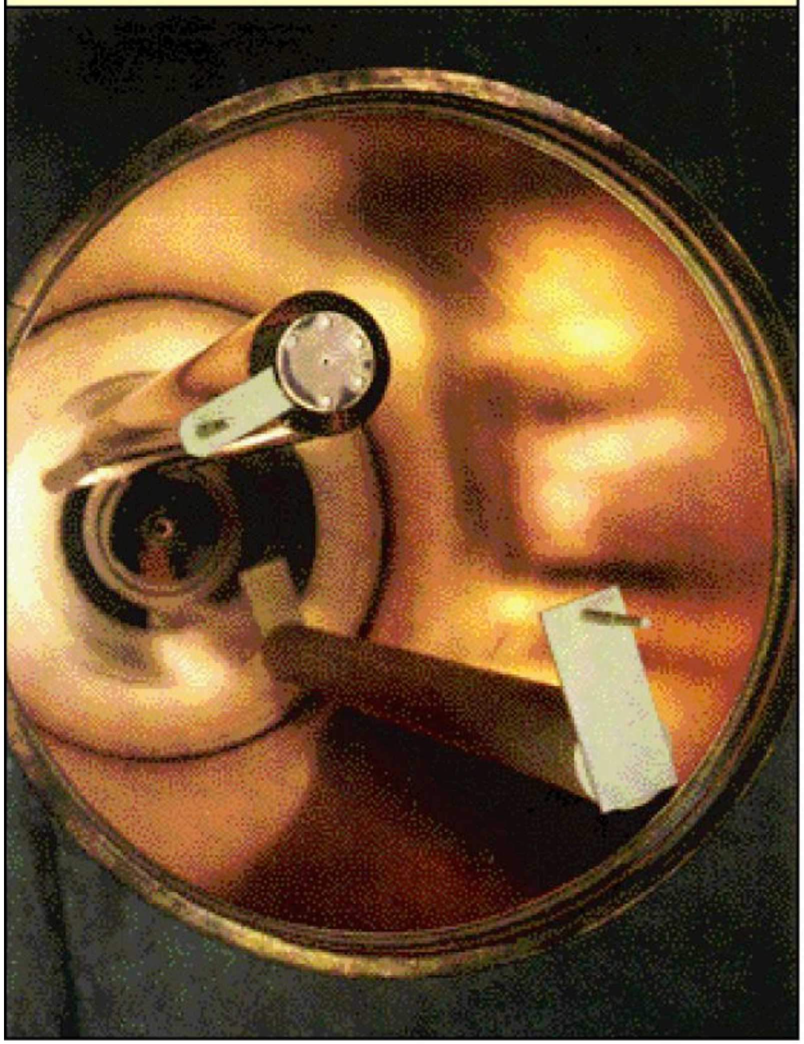
Pumped LHe → T ~ 1.5 k

Magnet (Wang NMR Inc.)

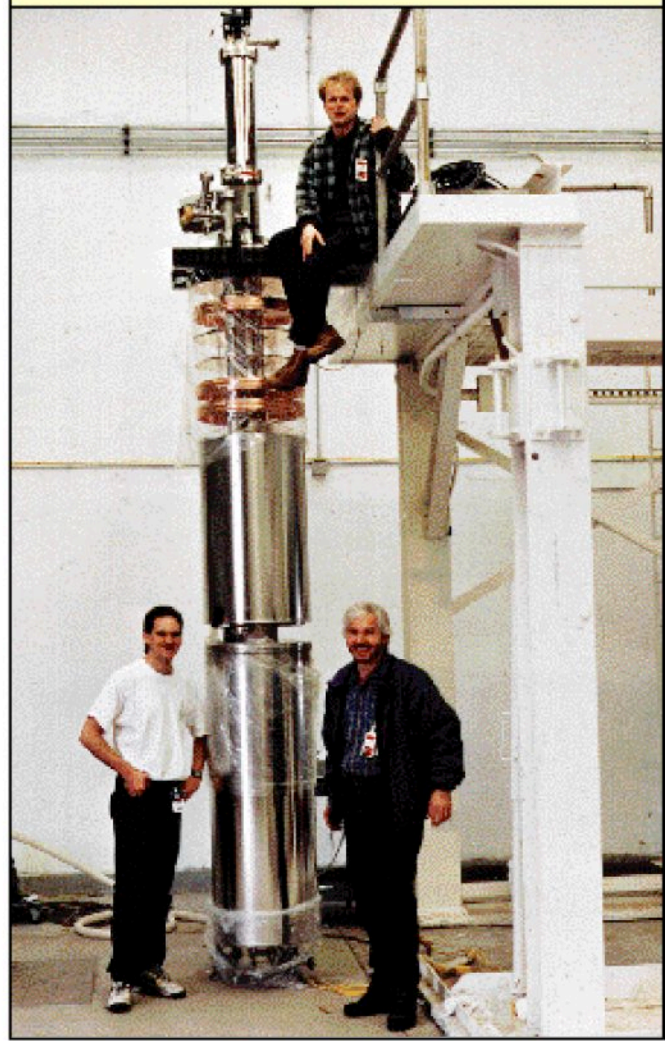
8 T, 1 m × 60 cm ∅

Axion hardware (cont'd)

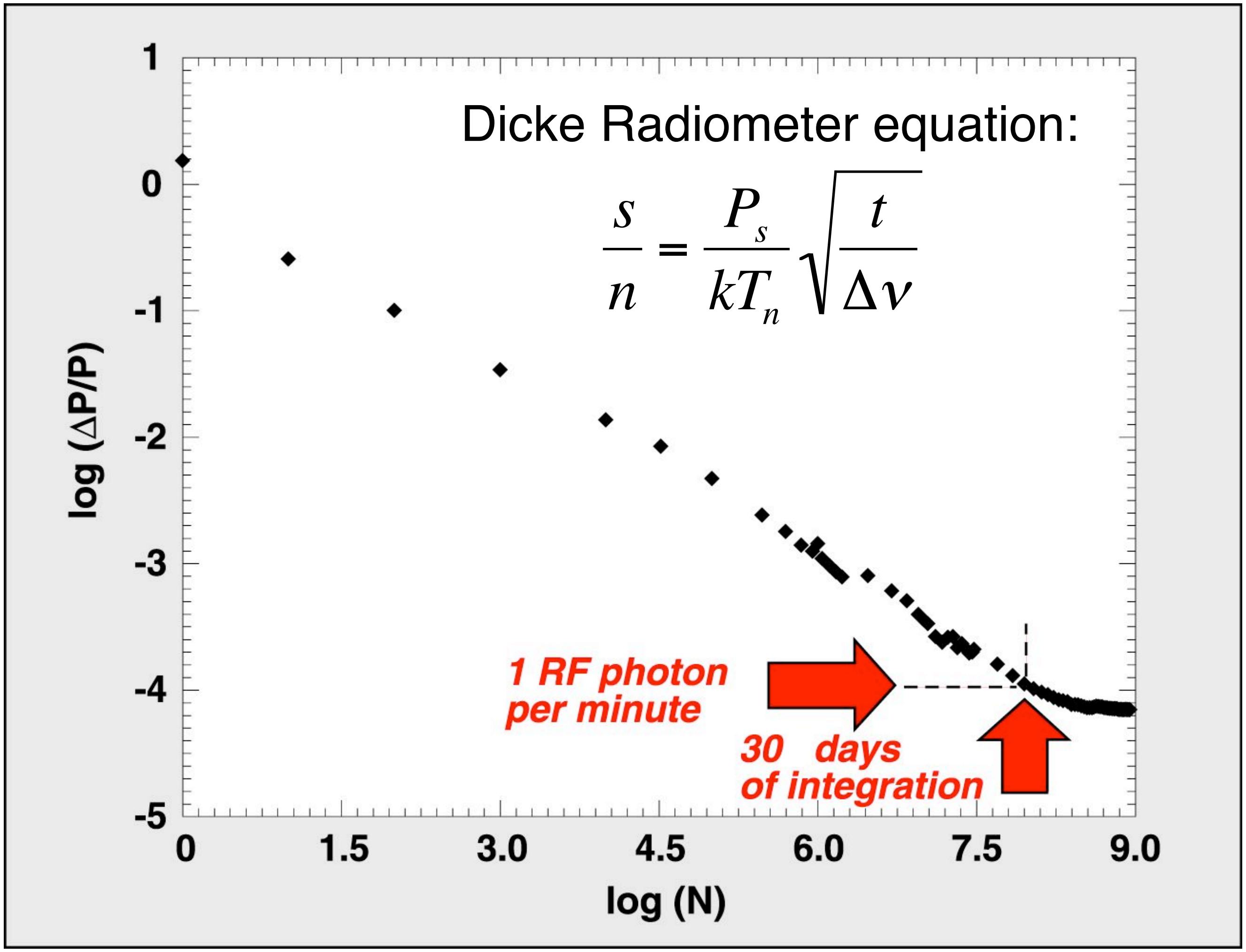
High-Q Cavity (~200,000)



Experimental Insert

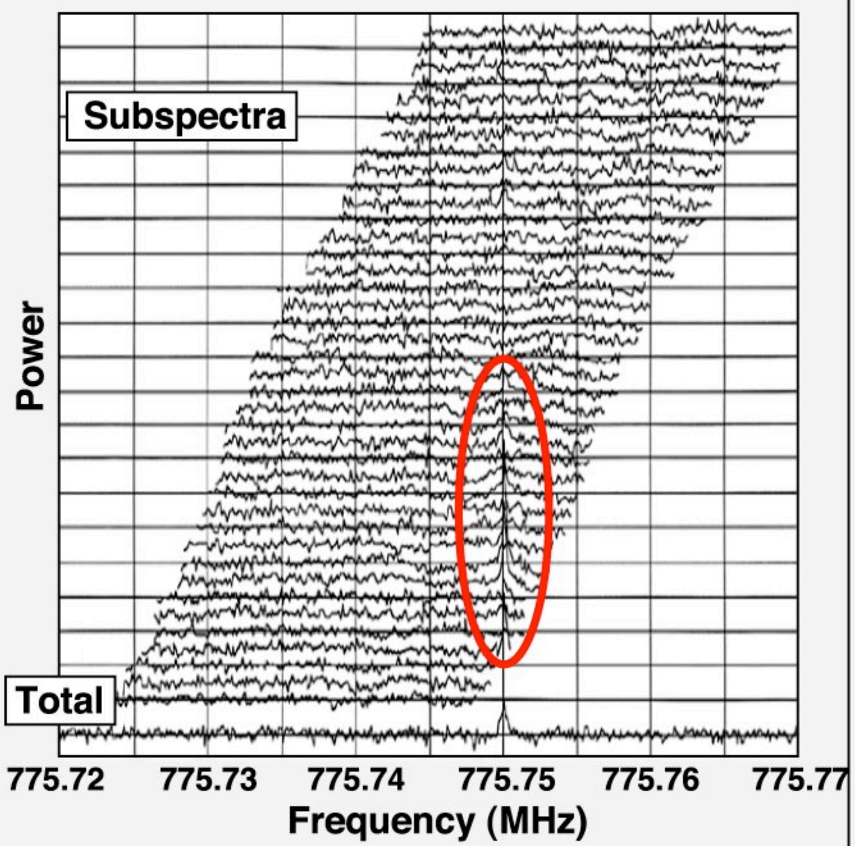
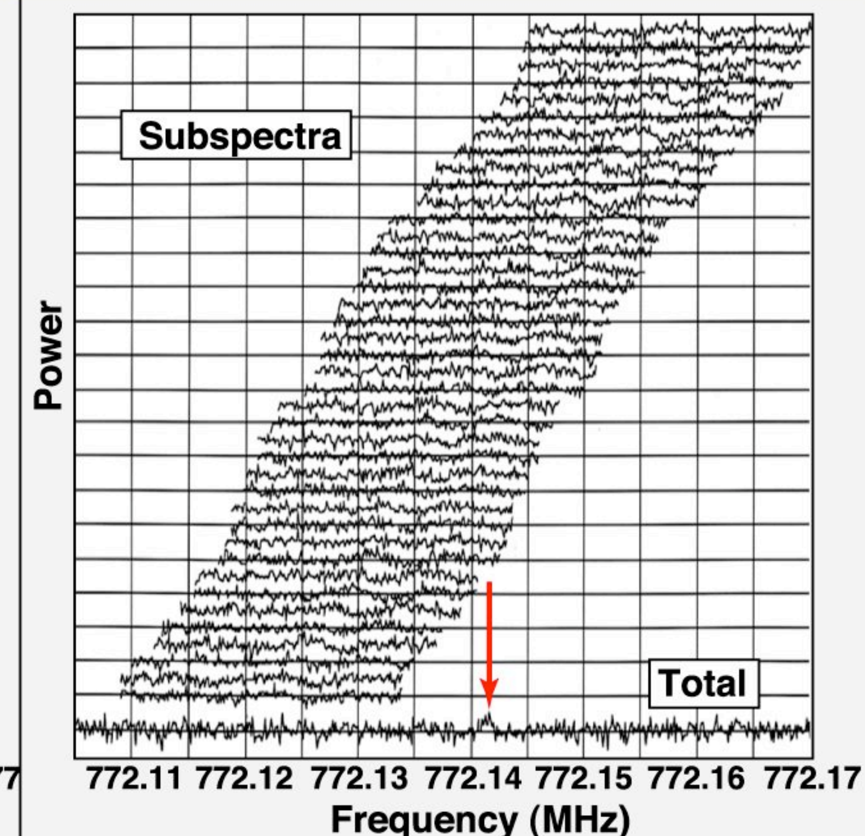


ADMX may be the world's quietest spectral receiver



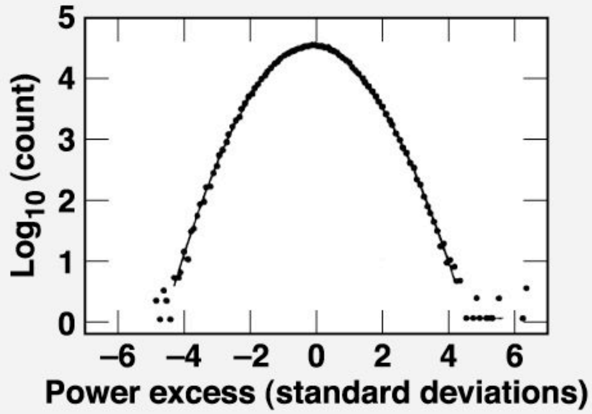
Systematics-limited for signals of 10^{-26} W – 10^{-3} of DFSZ axion power.
Last signal received from Pioneer 10 (6 billion miles away) ~ 10^{-21} W.

Sample data and candidates

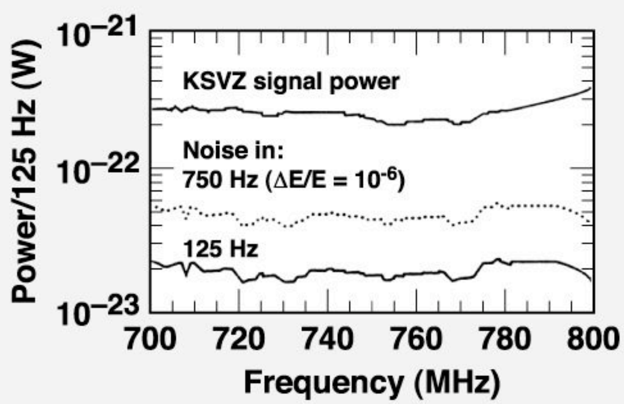
Environmental	Statistical
	
Signal maximizes off-resonance: Radio peak	**Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)**

Brief outline of analysis — 100 MHz of data

Data, with Theoretical Curve
(Gaussian noise through receiver and analysis)



S/N > 4 for Thermalized KSVZ Axion

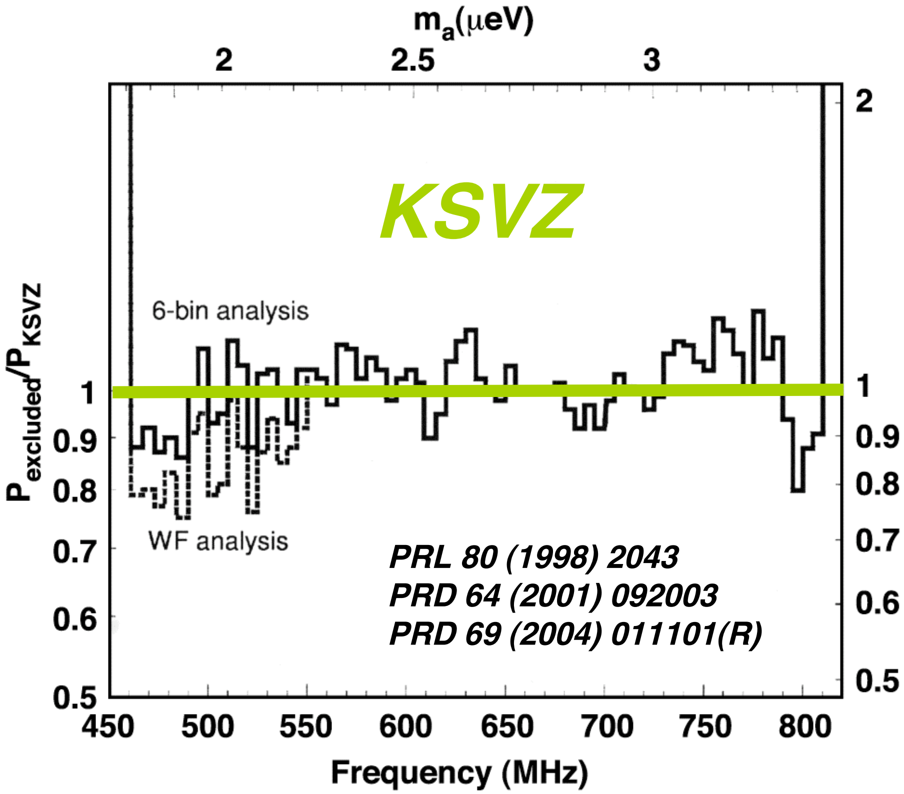


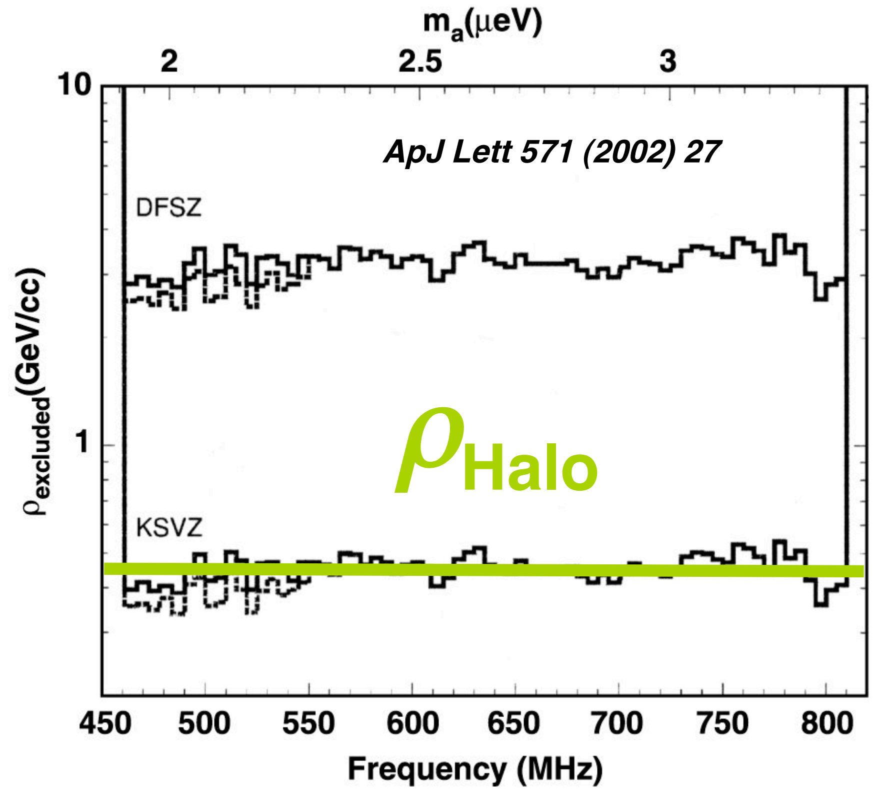
- **Each frequency appears in >45 subspectra**
- **Weighted and co-added to produce spectrum**
- **800,000 bins (125 Hz)/100 MHz**

→ **6535 candidates > 2.25 $\sqrt{6}\,\overline{\sigma}$ (95% C.L.)**
→ **Rescan all to same sensitivity**
→ **23 candidates (Net 90% C.L.)**
→ **Each examined: radio peaks**

For a persistent peak, the ultimate test is to turn off the magnet!

Limits on axion models and local axion halo density



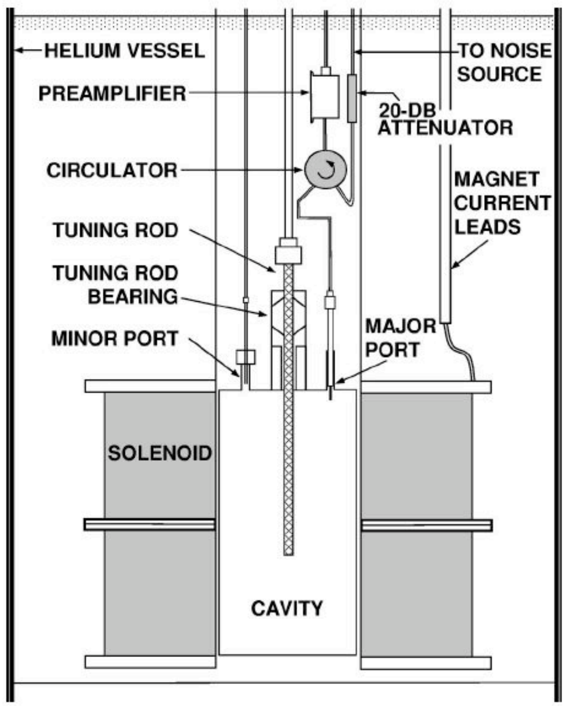


Plausible models have been excluded at the halo density over an octave in mass range

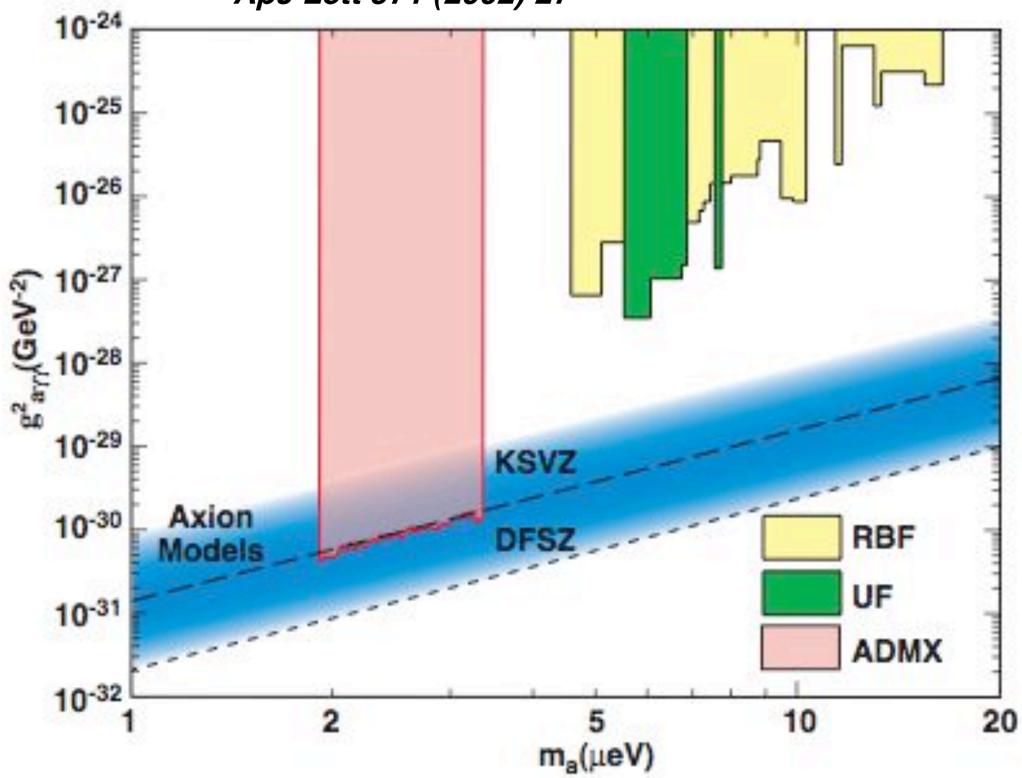
P02589-ljr-u-022

ADMX performed as designed – scanned in the model band

From W. Wuensch *et al.*,
Phys. Rev. D40 (1989) 3153

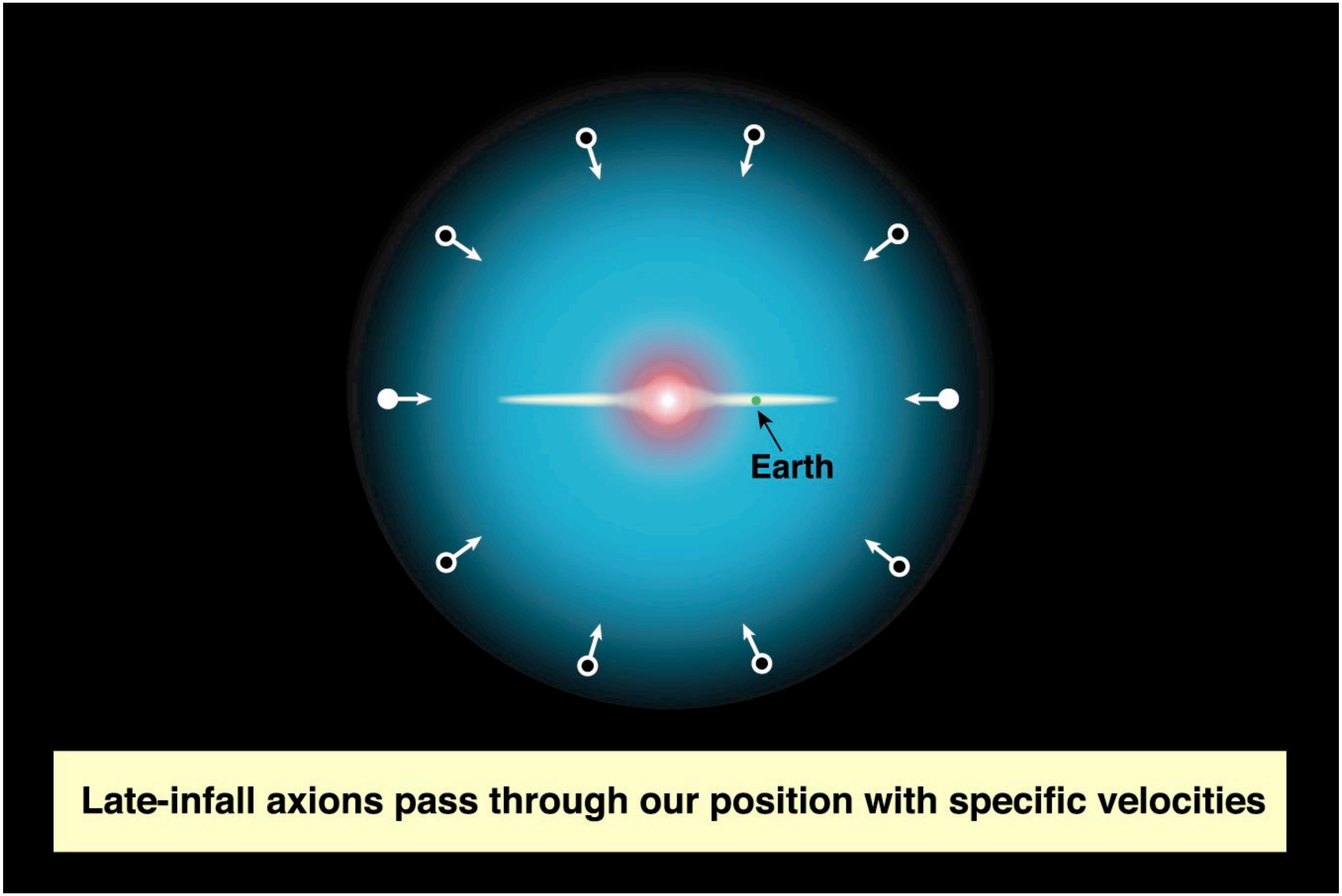


PRL 80 (1998) 2043
PRD 64 (2001) 092003
PRD 69 (2004) 011101(R)
ApJ Lett 571 (2002) 27

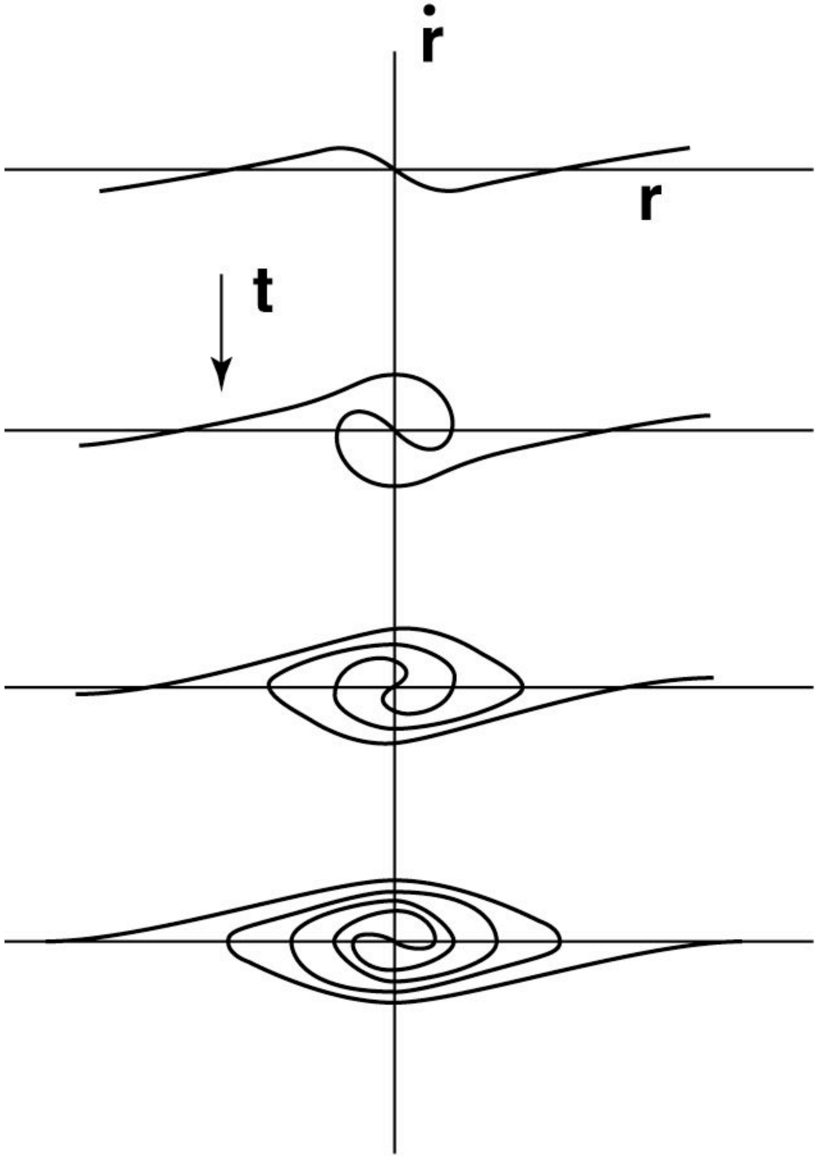


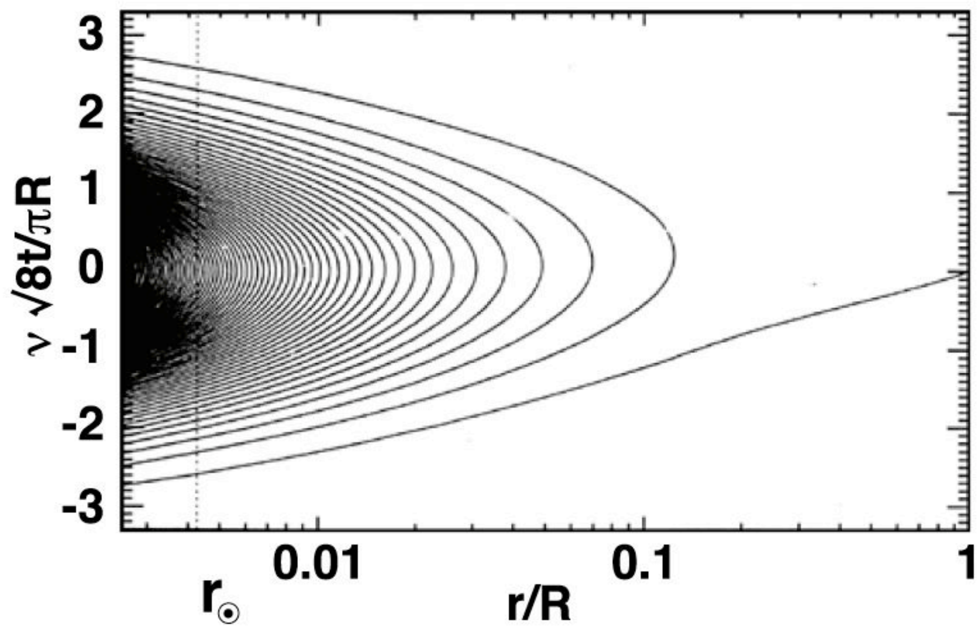
We learned much from the first-generation exp'ts (~ liter volume)
Already came within a factor of 100-1000 of the desired sensitivity

Origin of the non-thermalized component



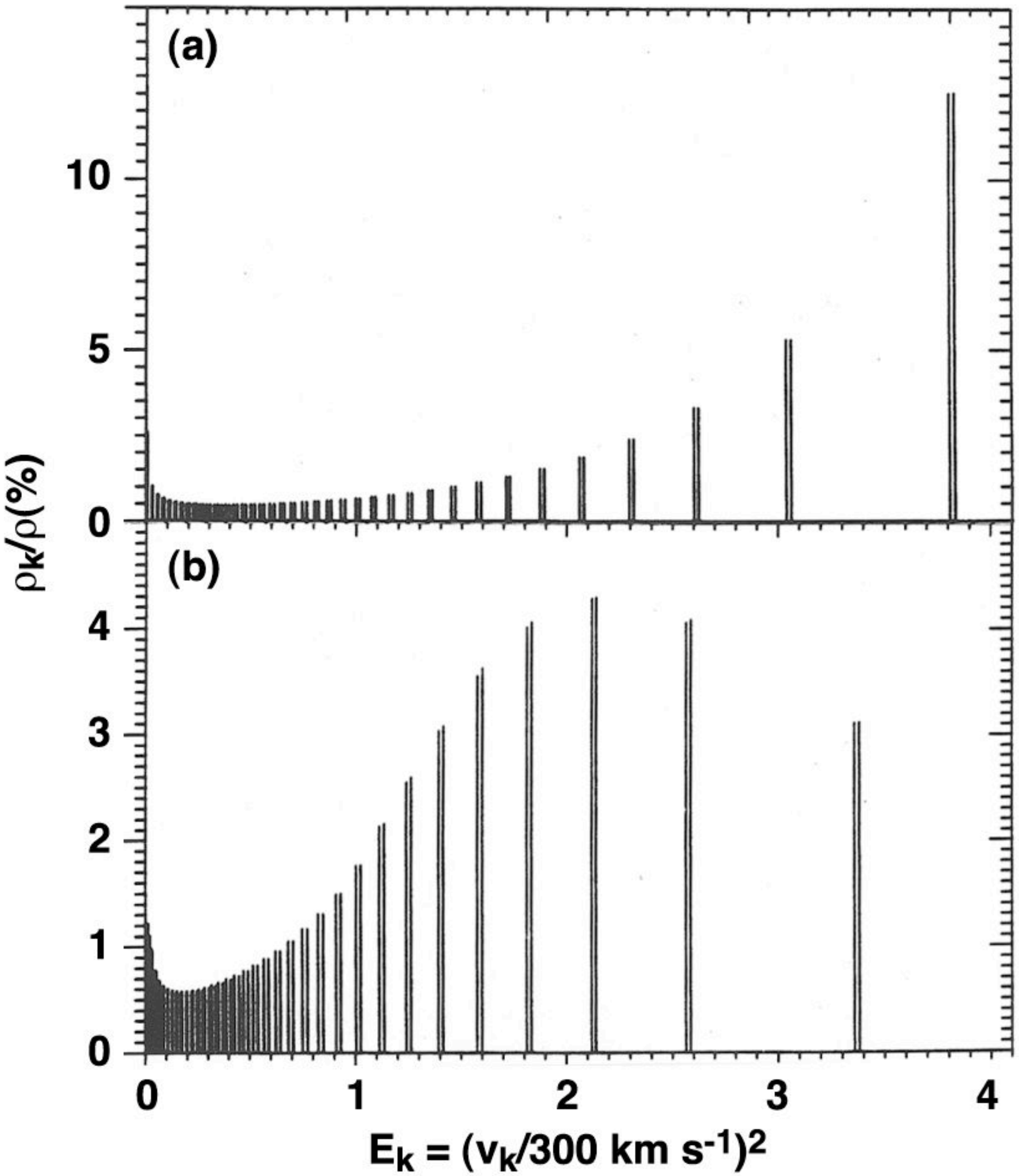
1-D infall, and the "folding" of phase space





- Model begins with
  - Zero Temperature CDM
  - Hubble expansion
  - Initial density perturbation r = o
- Grows self-consistent potential

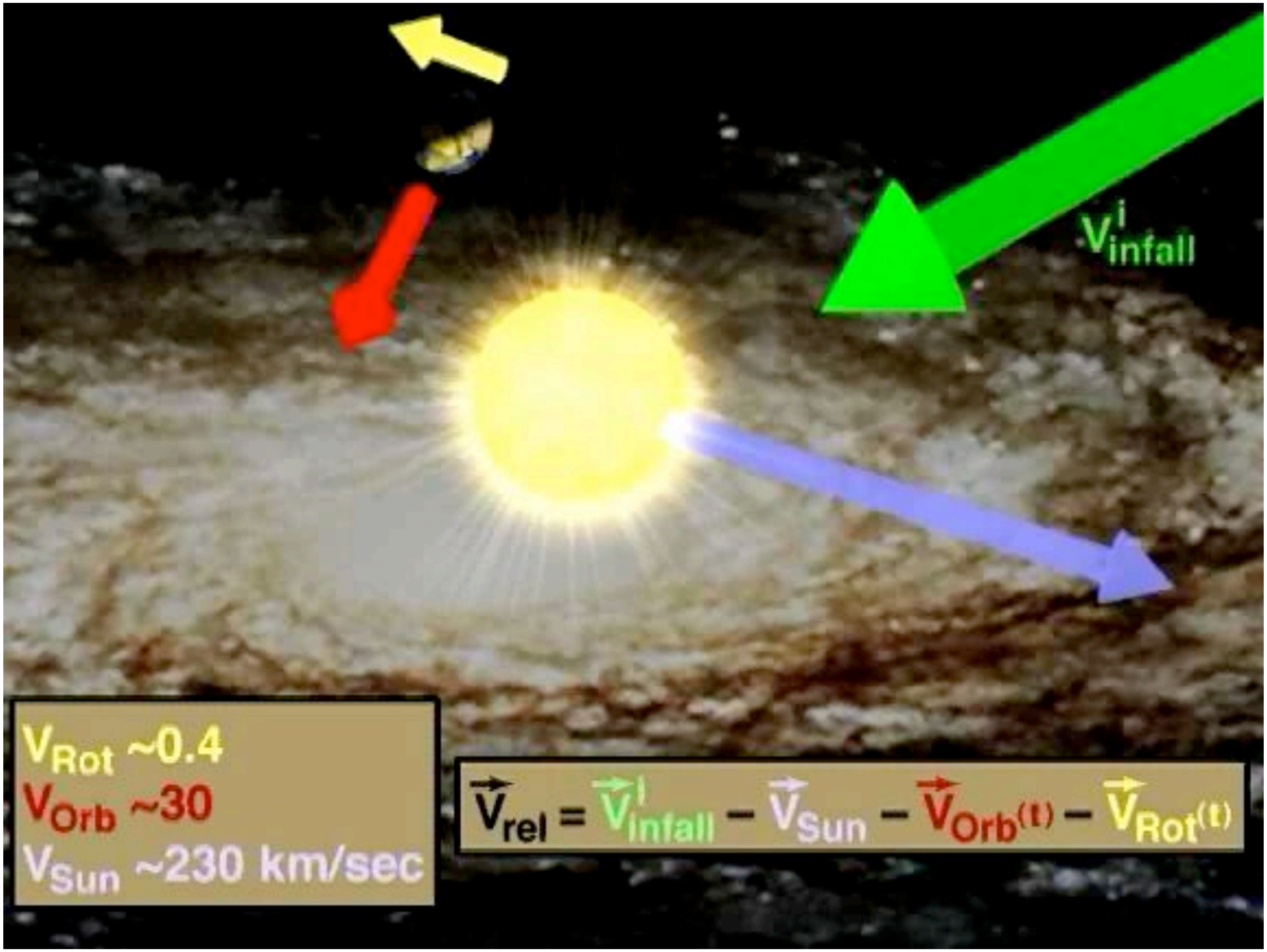
Velocity spectrum of axions at our solar system



(a) No angular momentum

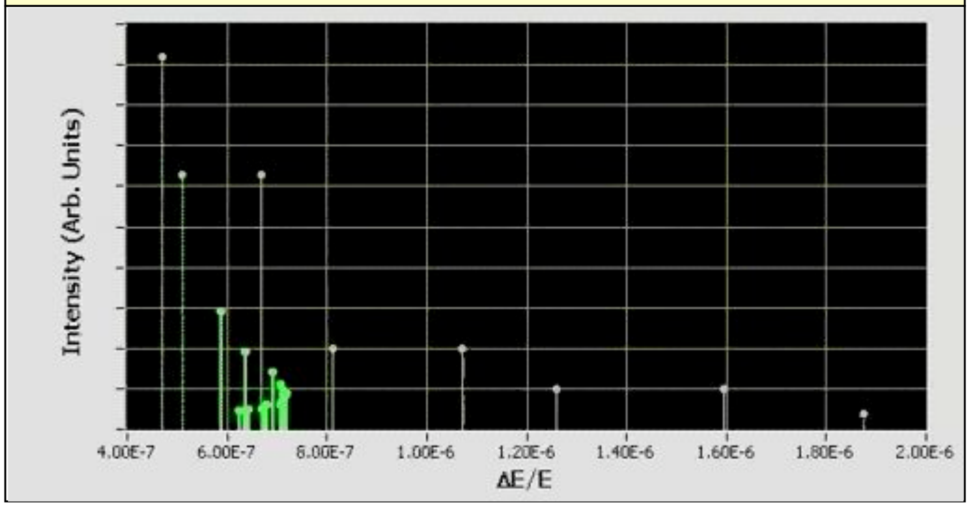
(b) Finite angular momentum

Diurnal and sidereal oscillation of the fine-structure

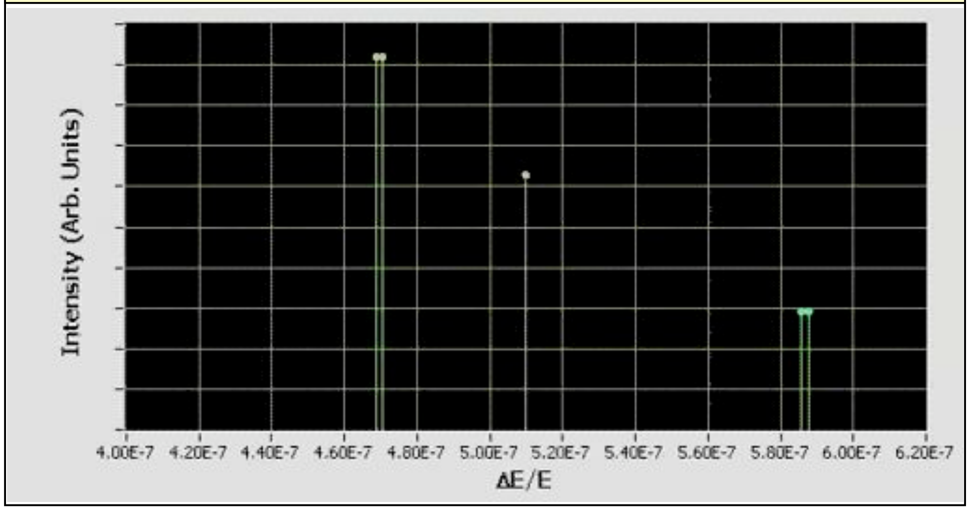


Simulation of one infall model

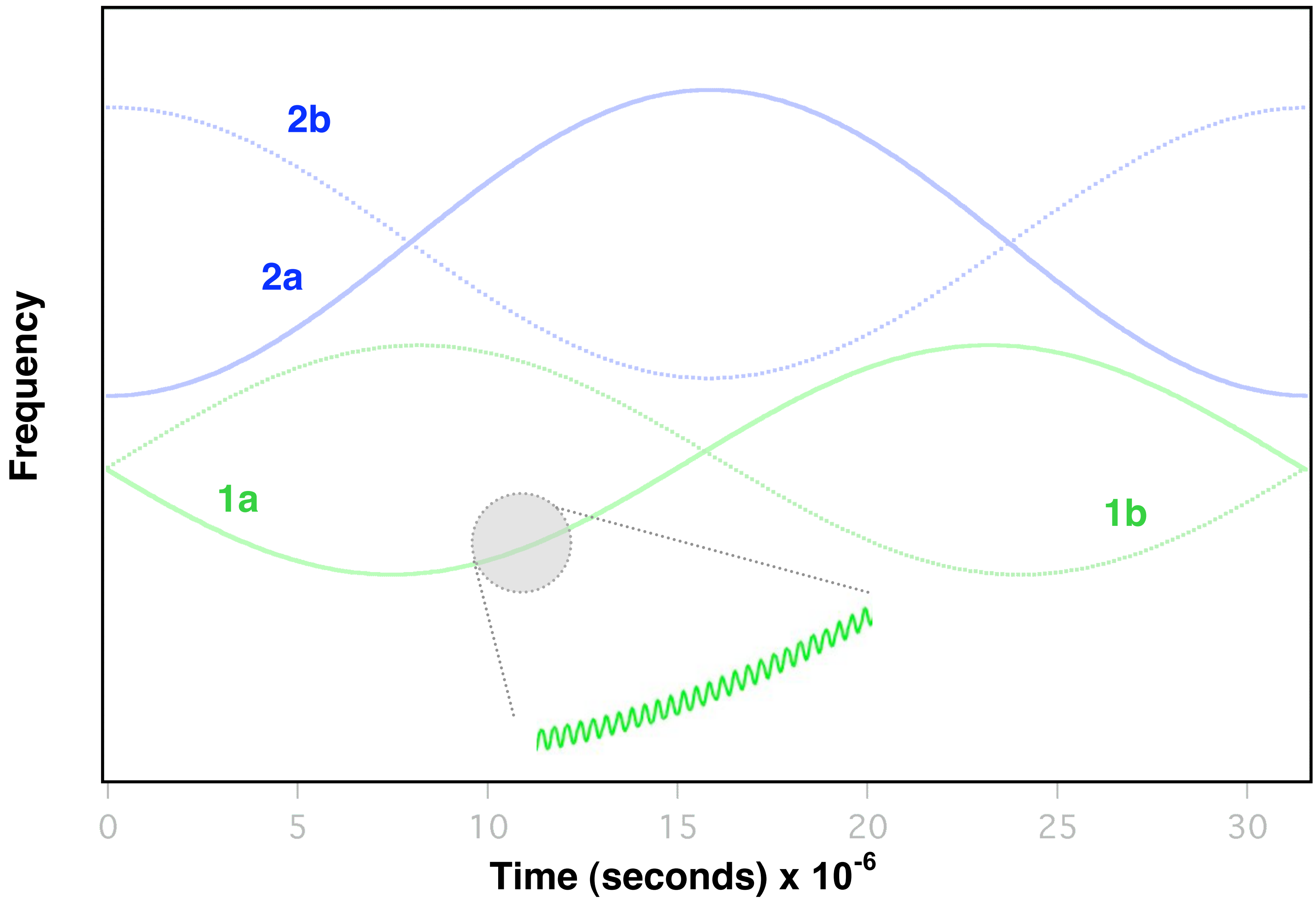
Annual



Daily

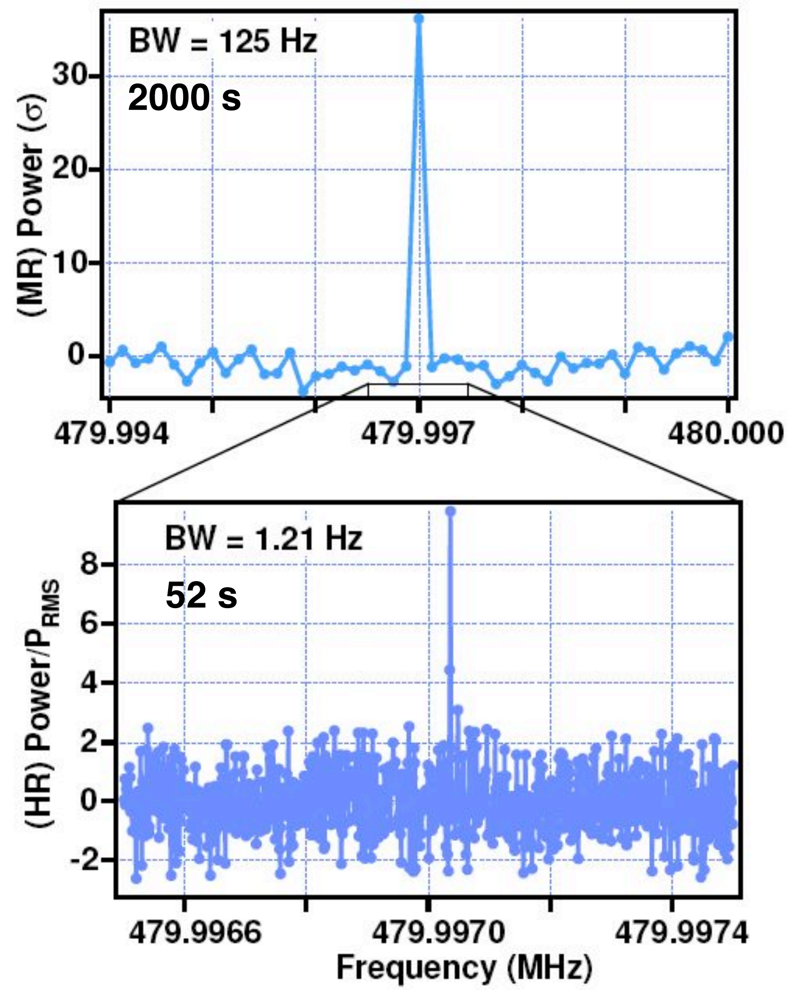


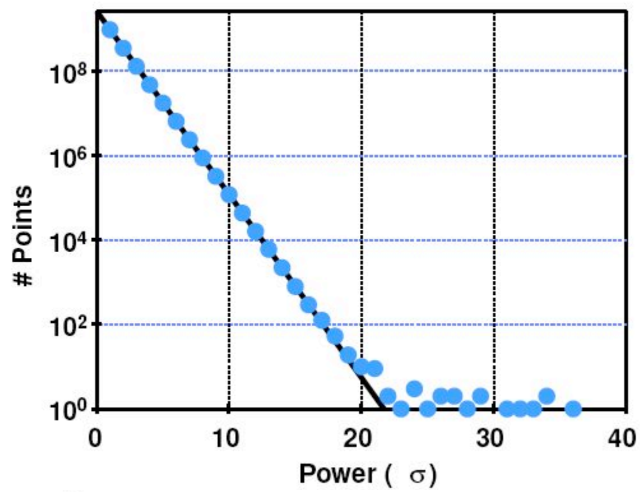
Diurnal and sidereal oscillation of late-infall axion peaks

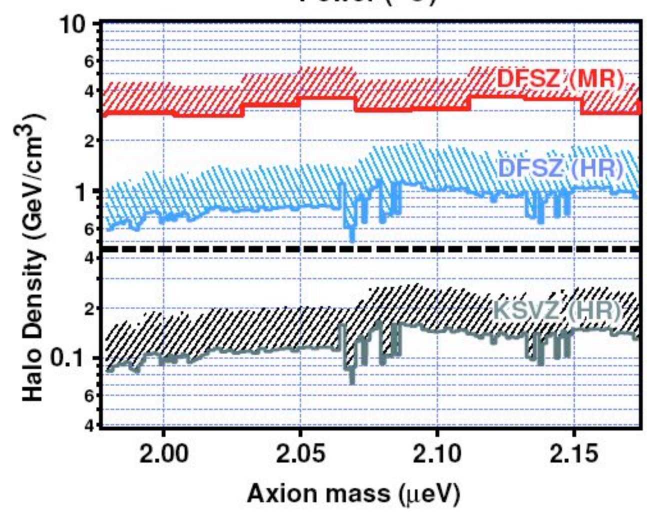


Results of a high-resolution analysis

PRL 95 (9) 091304 (2005)

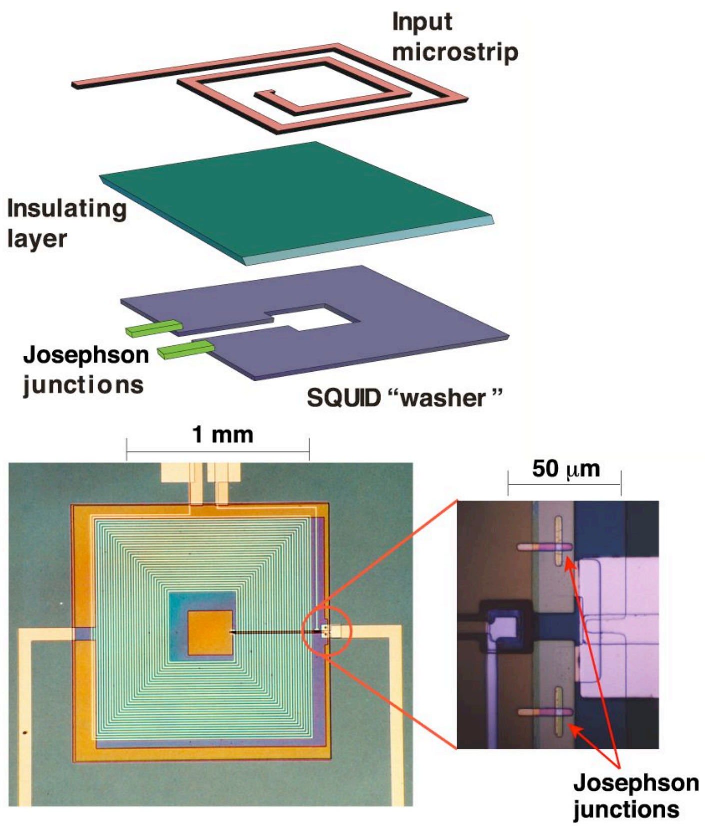


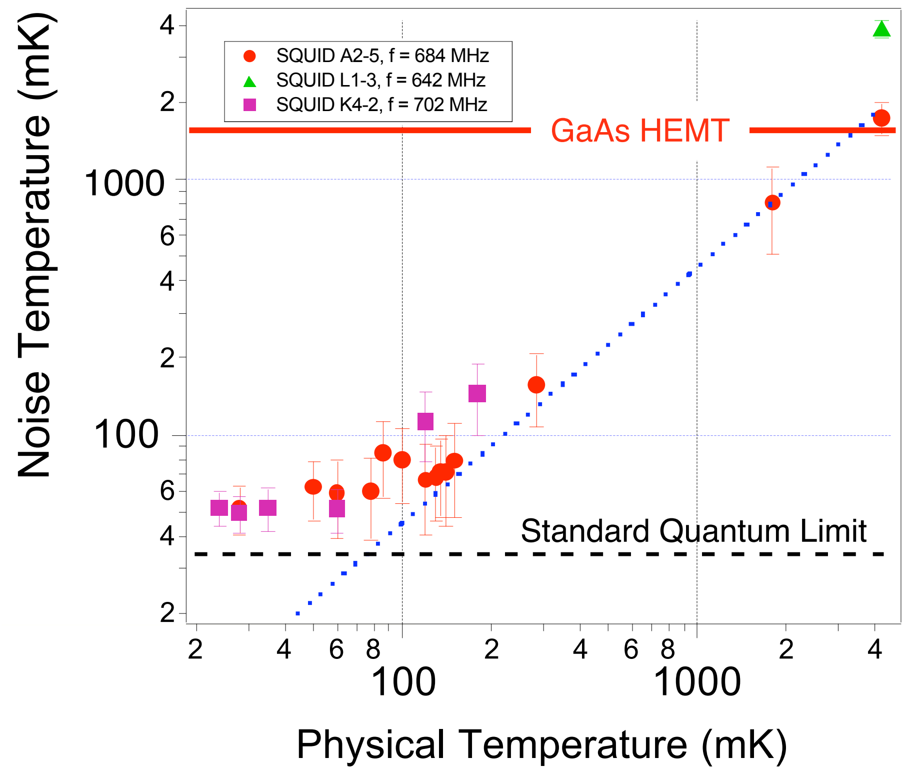




Measured power in environmental (radio) peak same in Med- & Hi-Res

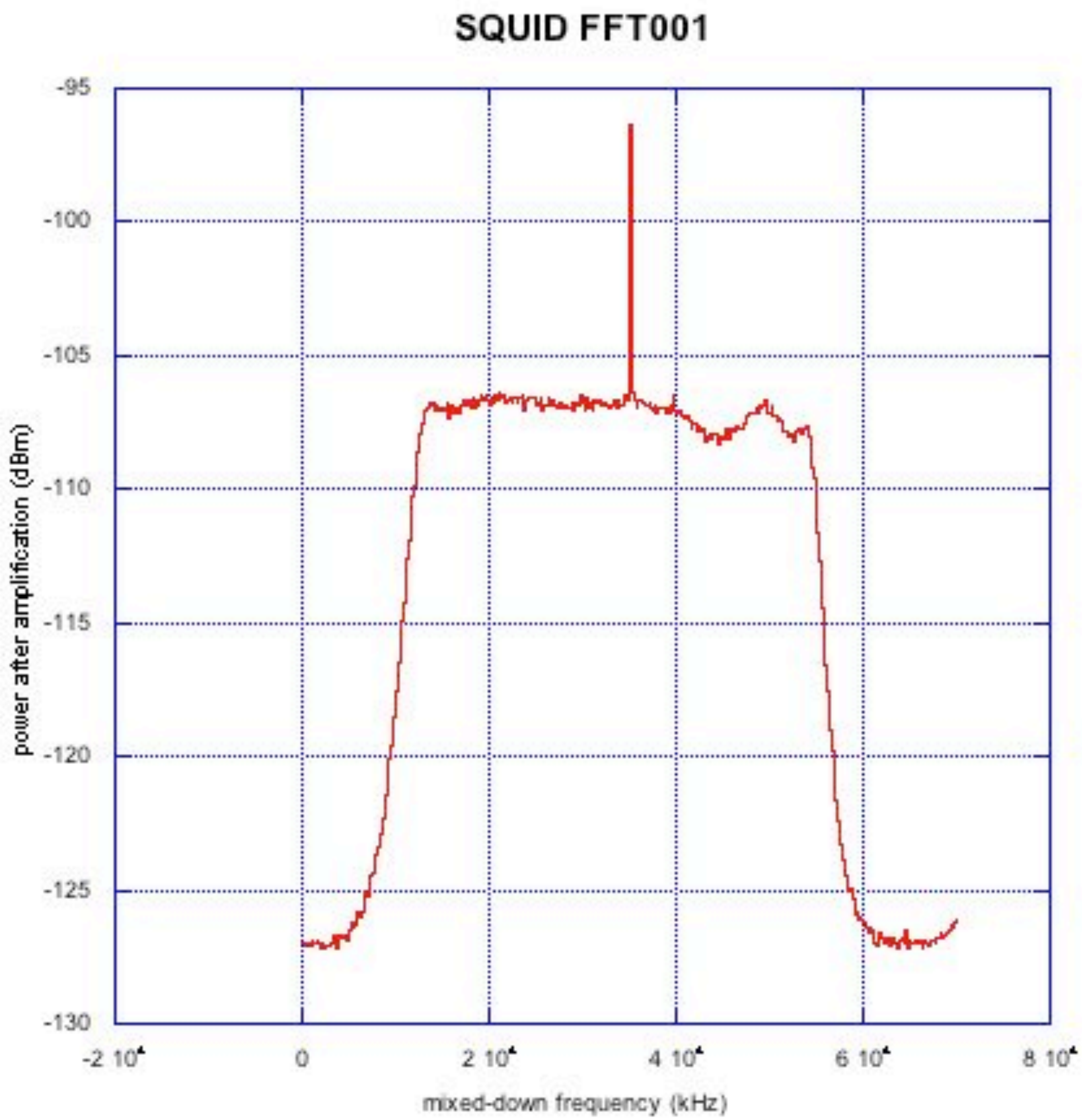
Upgrade (Phase I) to GHz SQUID amplifiers commissioning!



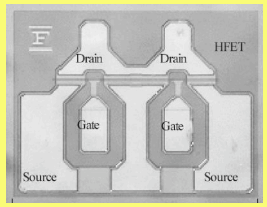
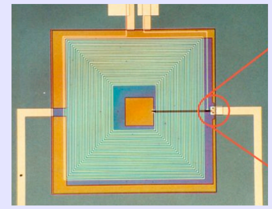


Latest SQUIDs are now within 15% of the Standard Quantum Limit

Calibration peak injected into the upgraded experiment with the SQUID amplifier (just received last night!)

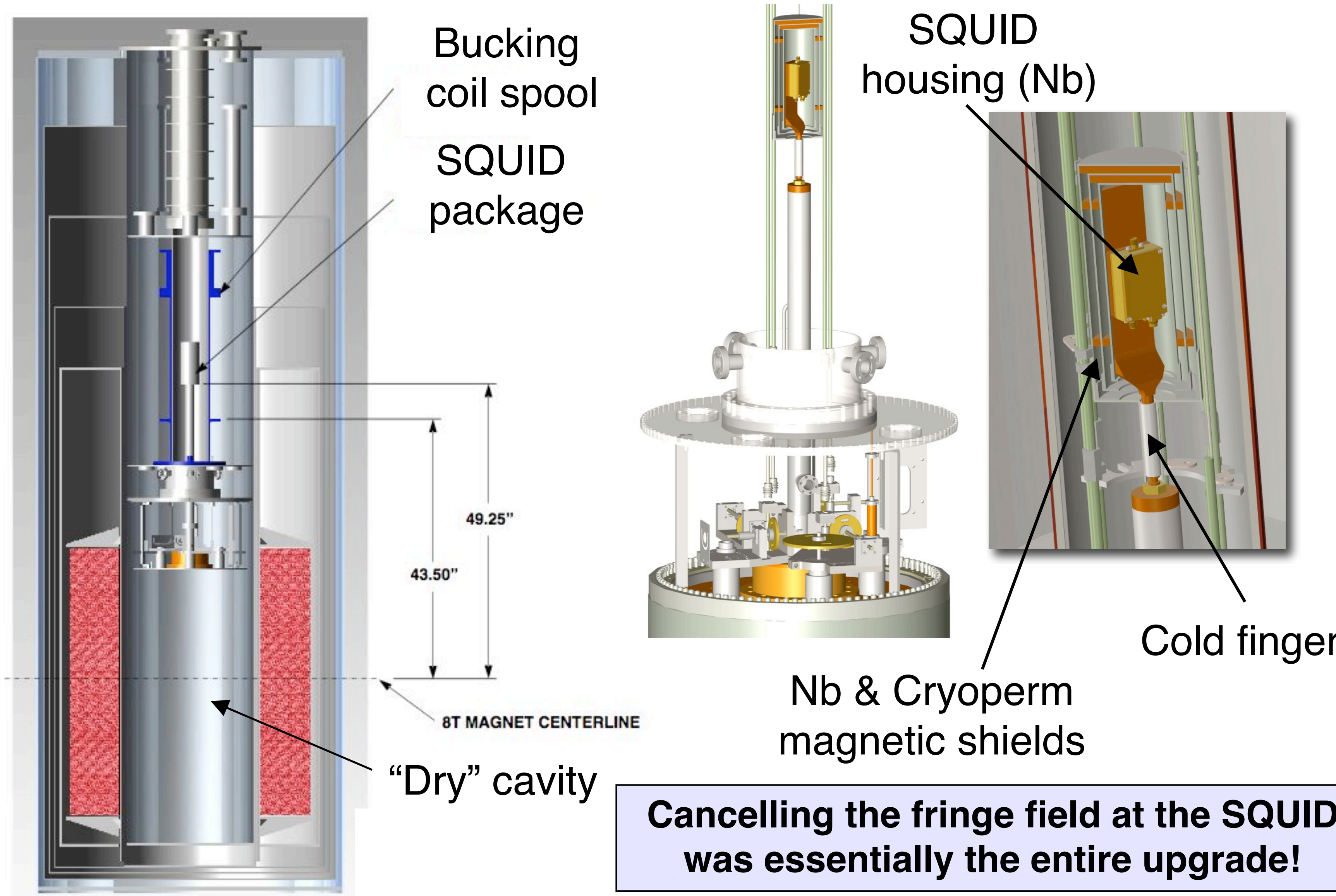


Phase I / Phase II Upgrades in detail

Stage	**ADMX Now**	**Phase I**	**Phase II**
Technology	HEMT; Pumped LHe 	Replace w. SQUID 	Add Fridge 
T_{phys}	1.3 K	1.3 K	100 mK
T_{amp}	2	0.4	100
$T_{sys} = T_{phys} + T_{amp}$	3.3	1.7	200
Scan Rate $\propto (T_{sys})^{-2}$	1 @ KSVZ	4 @ KSVZ ***OR***	5 @ DFSZ ***AND !***
Sensitivity Reach $g^2 \propto T_{sys}$	KSVZ	0.5 x KSVZ	DFSZ

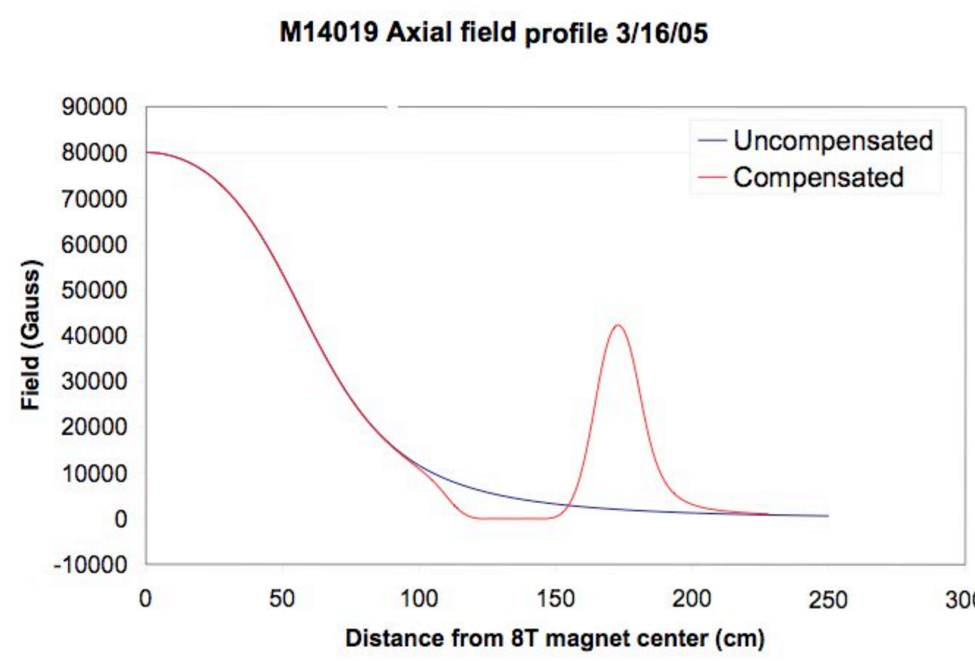
Unlike HEMTs, the SQUIDs require a B-field-free environment

AXION



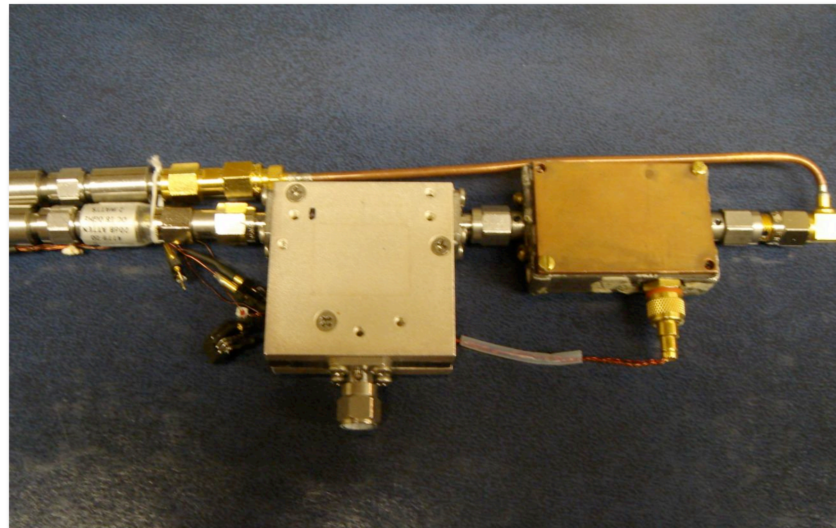
Cancelling the fringe field at the SQUID was essentially the entire upgrade!

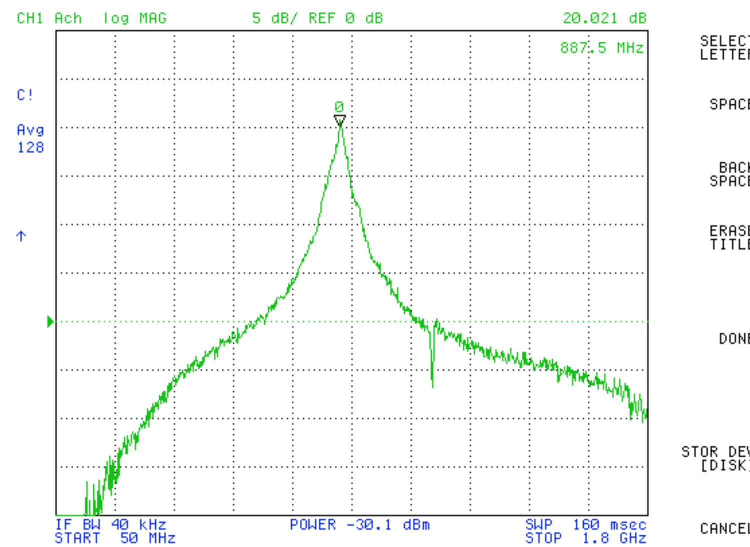
The field compensation coil



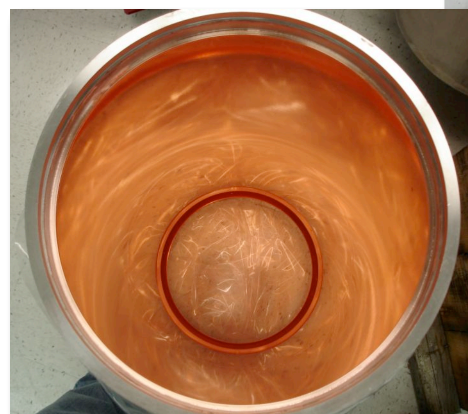
A clever design allows the bucking coil to experience no net force for any value of the main magnet

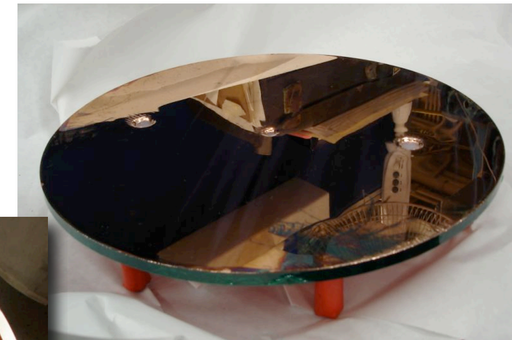
The SQUID amplifier + receiver

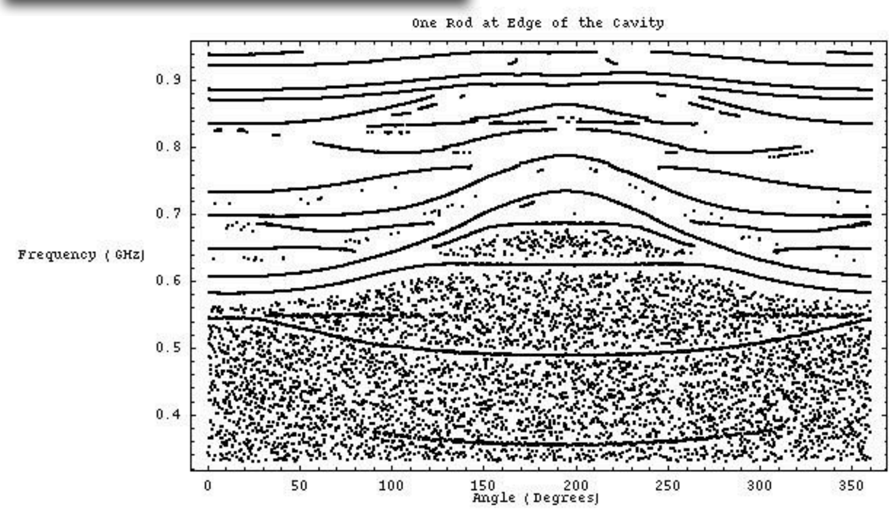




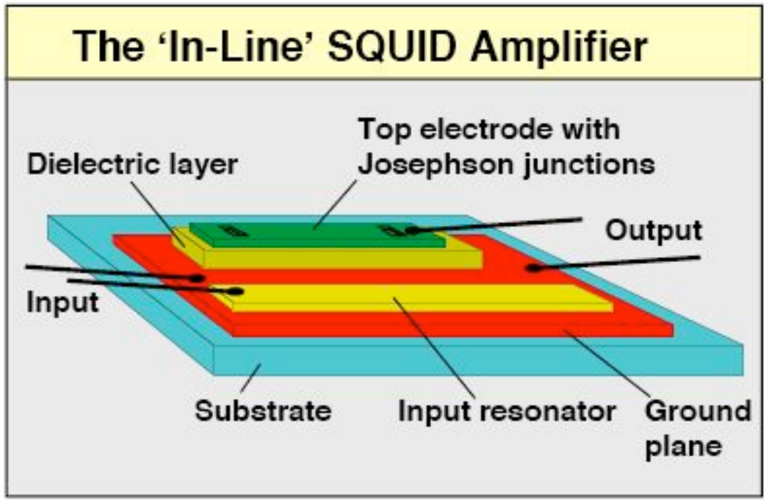
The cavity






One Rod at Edge of the Cavity
Frequency (GHz)
0.9
0.8
0.7
0.6
0.5
0.4
0
50
100
150
200
250
300
350
Angle (Degrees)

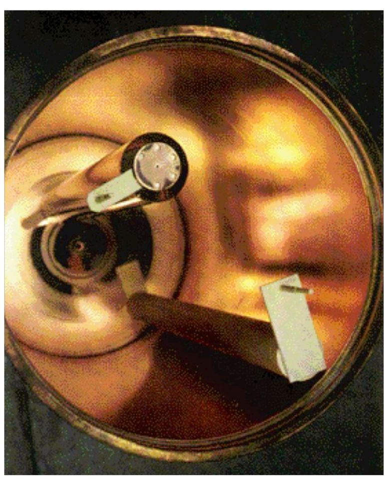
For the long term, ADMX needs concurrent R&D



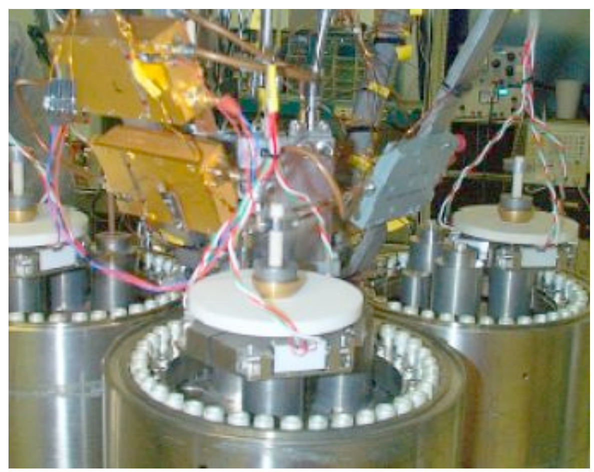
To get to 10 GHz (40 μeV), and ultimately 100 GHz (0.4 meV), we need to:

- **Develop new RF cavity geometries**
- **Develop new SQUID geometries**

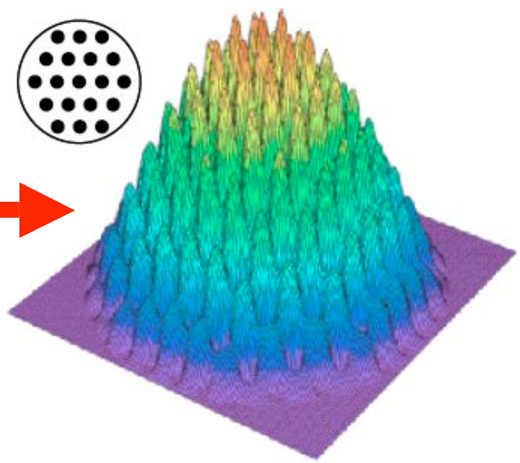
1 GHz



10 GHz



100 GHz



Rydberg-atom single-quantum detectors

AXION

Atoms with a single electron promoted to a large principal quantum number, n >> 1. Superposition of Rydberg states yields "classical atoms" with macroscopic dimensions (e.g. ~ 1 mm).

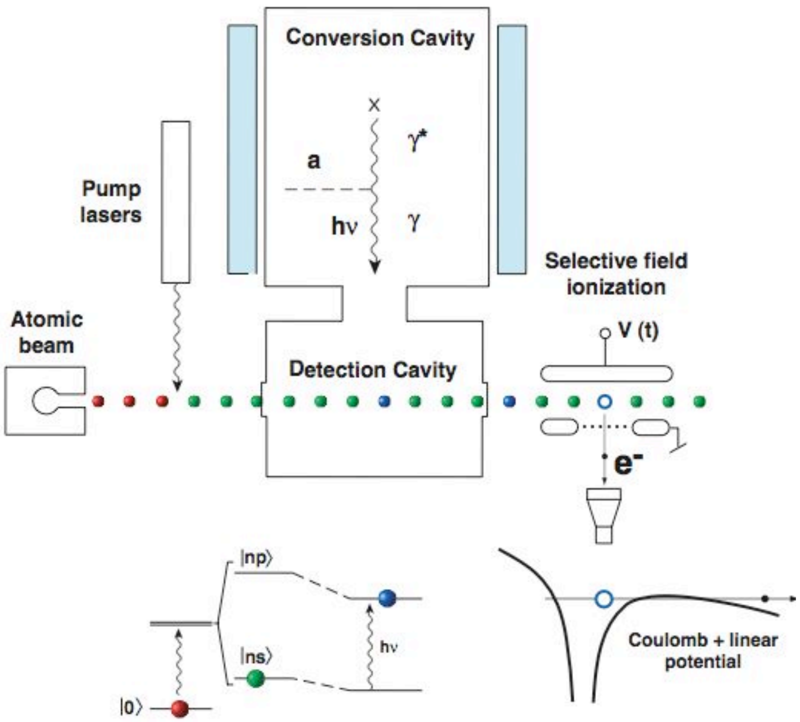
Potential for highly sensitive microwave photon detectors ("RF photo-multiplier tubes") realized by Kleppner and others in the 1970's. The axion experiment is an ideal application for Rydberg atoms:

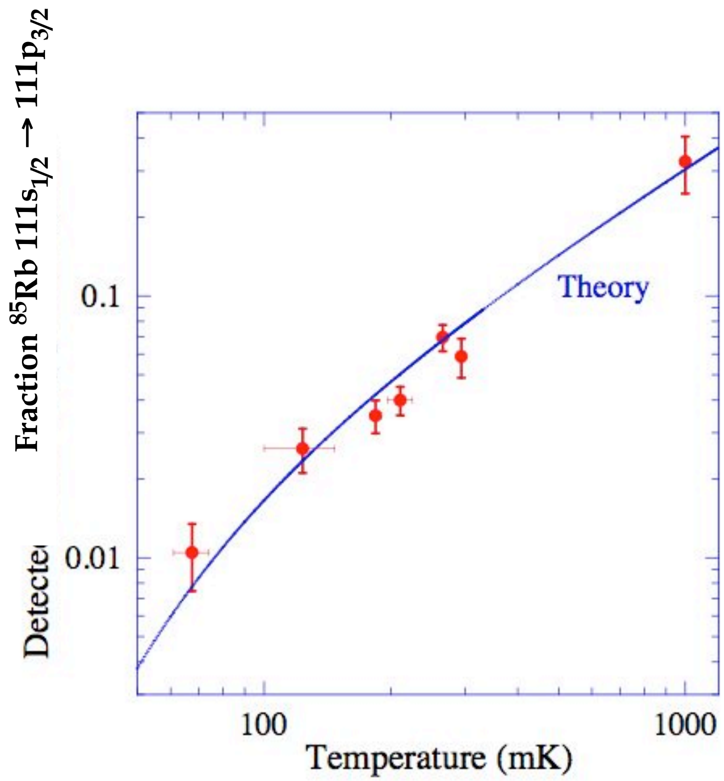
- *Large transition dipole moments* $\langle n \pm 1 | er | n \rangle \propto n^2 a_0$
- *Long liftetimes* $\tau_n \propto n^3 \quad (l << n); \quad \tau_{100} \approx 1\, m\sec$
- *Transitions span microwave range* $\Delta E_n = E_{n+1} - E_n \approx 2R/n^2\,; \quad \Delta E_{100} \approx 7\ GHz$

Most importantly, being a phaseless detector (photons-as-particles), the Rydberg-atom detector can evade the standard quantum limit:

hν = kT

Rydberg single-quantum detection *(S. Matsuki et al., Kyoto)*

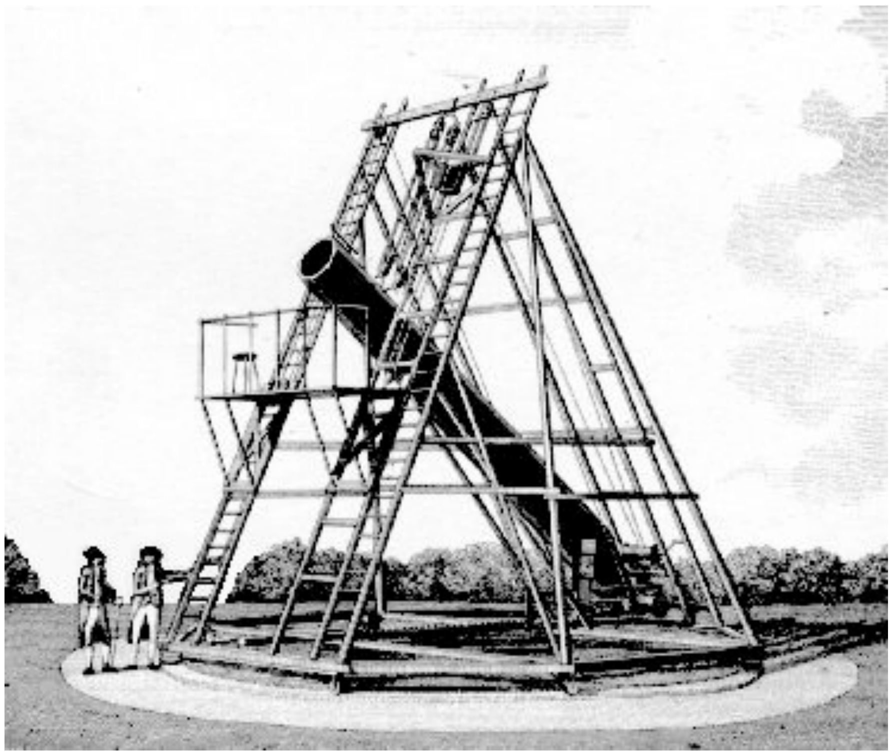




M. Tada et al., Phys. Lett. A (accepted)

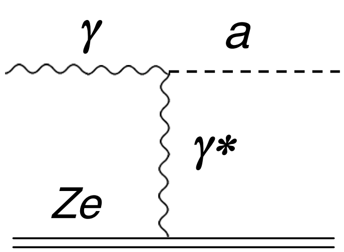
The blackbody spectrum has been measured at 2527 MHz a factor of ~2 below the standard quantum limit (~120mK)

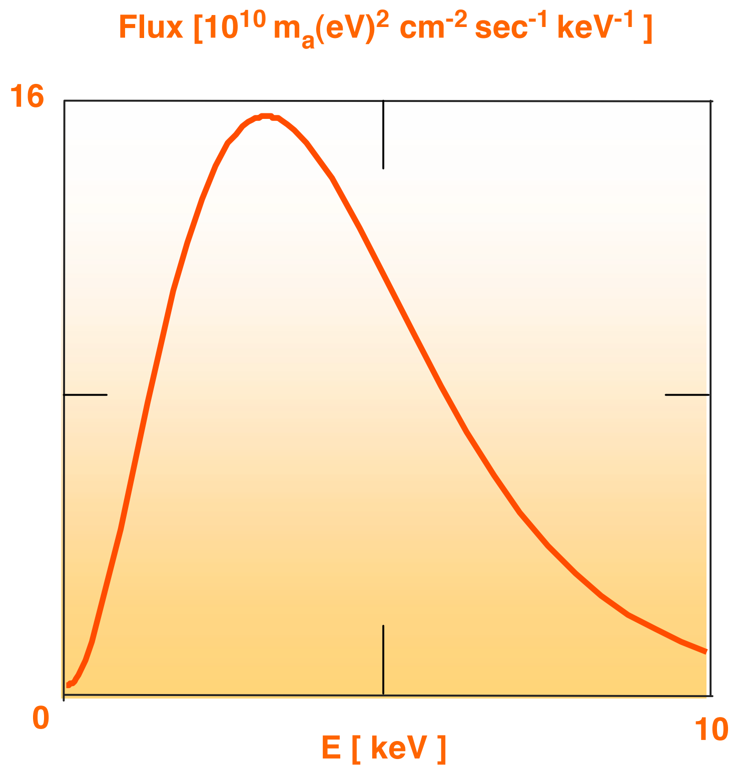
Searches for Solar Axions



AXION

The solar axion spectrum





Produced by a Primakoff interaction, with a mean energy of 4.2 keV

$T_{central}$ = 1.3 keV, but plasma screening suppresses low energy part of spectrum

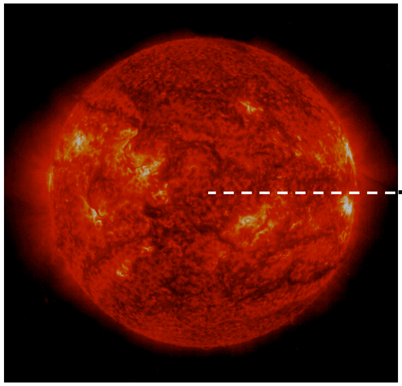
The total flux (for KSVZ axions) at the Earth is given by

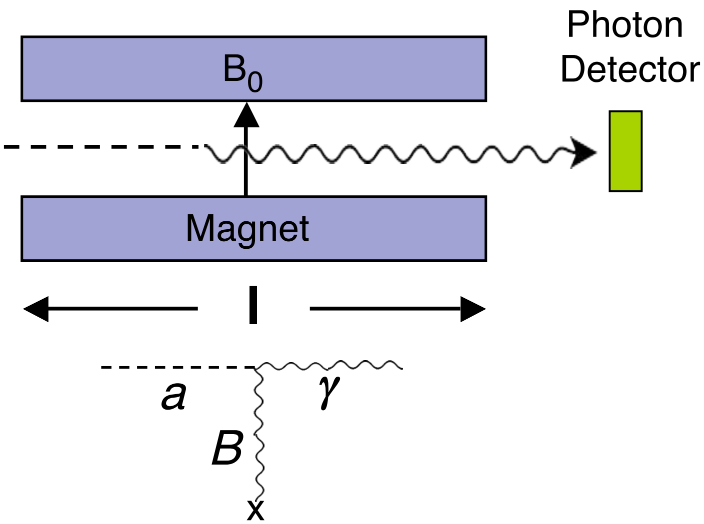
$$\Phi_a = 7.44 \times 10^{11} cm^{-2} \sec^{-1} (m_a / 1eV)^2$$

The dominant contribution is confined to the central 20% of the Sun's radius

Principle of the experiment *(Sikivie's PRL 1983 again!)*

AXION

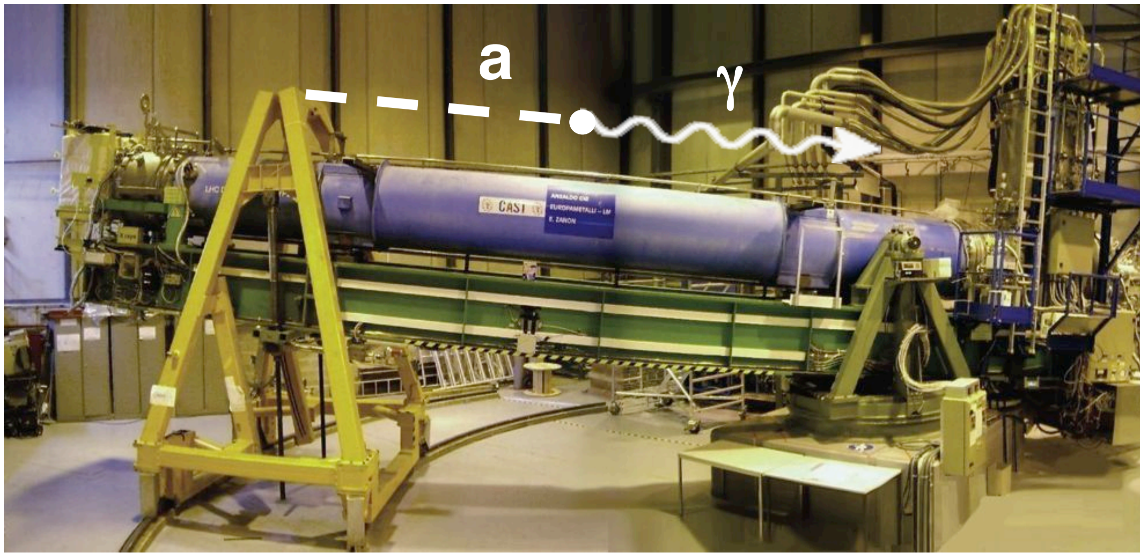




$$L_{a\gamma\gamma} = a g_{a\gamma\gamma} E \cdot B \quad \Rightarrow \quad \Pi(a \leftrightarrow \gamma) = \frac{1}{4}(g_{a\gamma\gamma} B_0 L)^2 |F(q)|^2$$

where $F(q) = \frac{Sin(qL/2)}{(qL/2)}$, $F(0) = 1$ and $q = k_\gamma - k_a \approx m_a{}^2 / 2\omega$

The CERN Axion Solar Telescope (CAST)

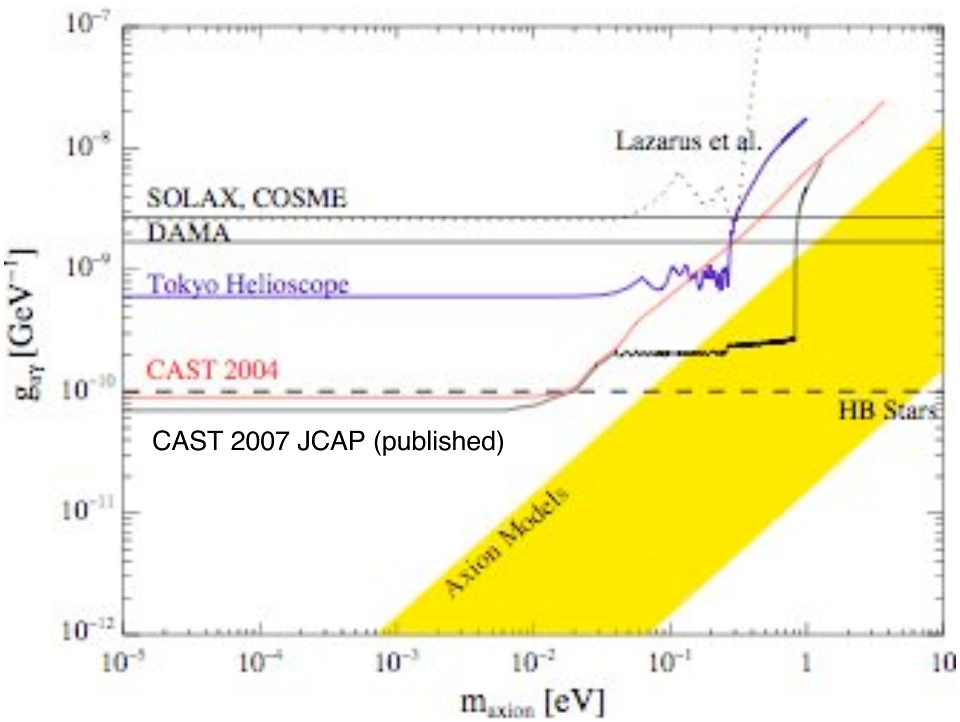


Prototype LHC dipole magnet, double bore, 50 tons, L~10m, B~10T

Tracks the Sun for 1.5 hours at dawn & 1.5 hours at dusk

Instrumented w. 3 technologies: CCD w. x-ray lens; Micromegas; TPC

CAST results and future prospects



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

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

The Phase II run underway is pushing the mass limit up into the region of axion models, 0.1-1 eV

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:

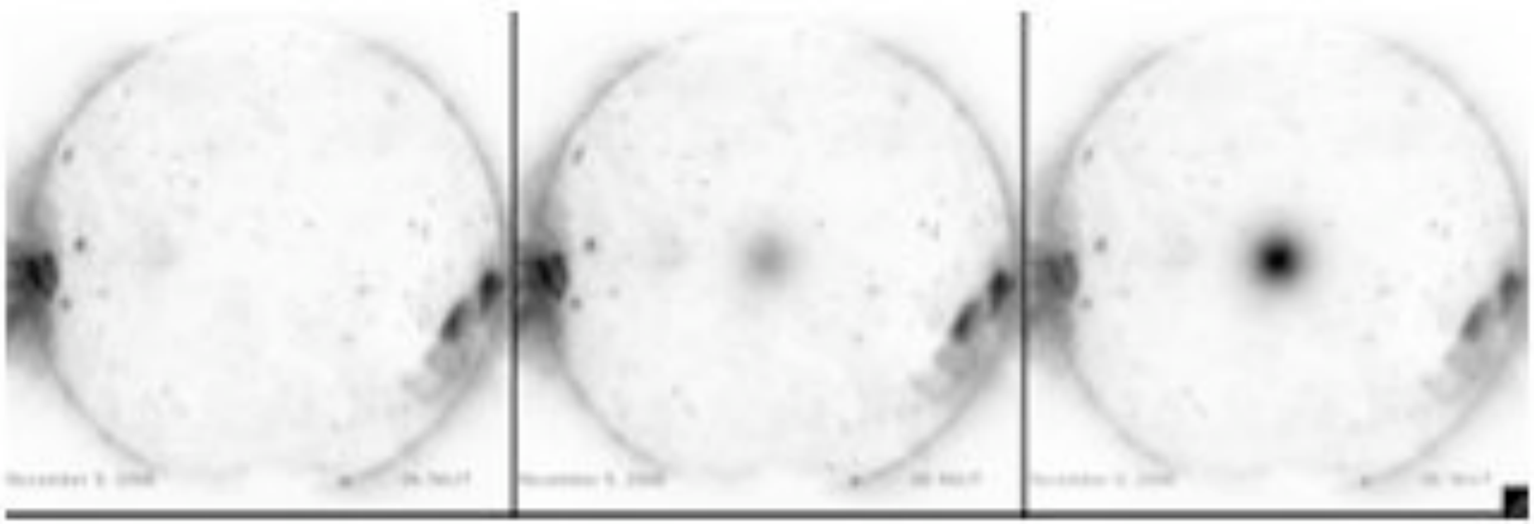
$$\omega_p = (4\pi\alpha N_e / m_e)^{1/2} \equiv m_\gamma$$

KvB et al. PRD 1989

The Phase II run will go to yet higher m_a with ^{3}He, and add a second x-ray optic

The Sun's photosphere has its own magnetic field, and ongoing analyses of RHESSI, Yohkoh & Hinode x-ray satellite data may yield a competitive limit on solar axions (or - who knows - see something)

Synthetic axion signal superimposed onto Hinode 'quiet sun' image



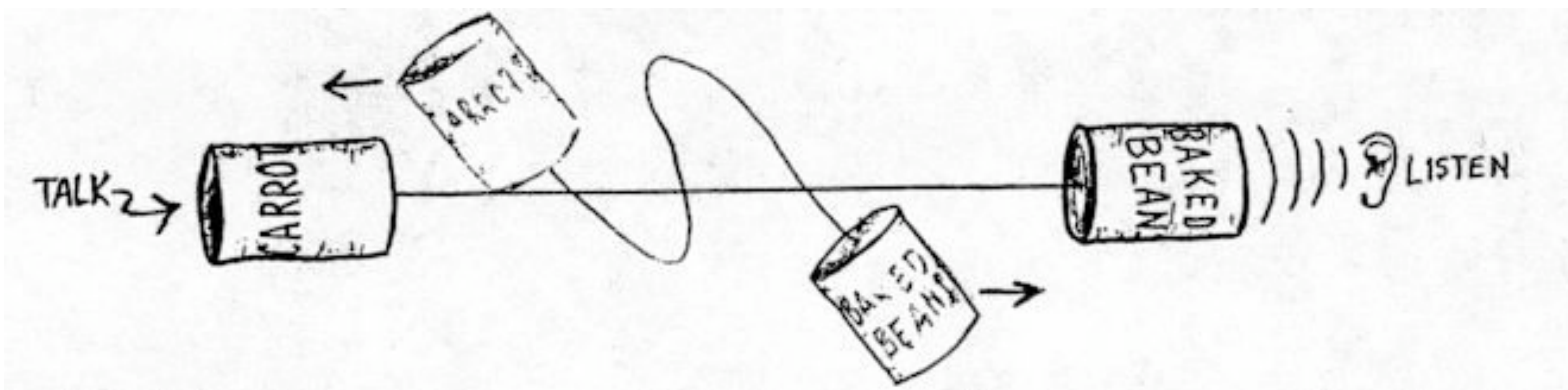
Increasing $g_{a\gamma\gamma}$ →

Google "RHESSI Science Nuggets" for April 30, 2007

"First limits on the 3-200 keV X-Ray Spectrum of the Quiet Sun Using RHESSI", I. G. Hannah, G.J. Hurford, H.S. Hudson, R.P. Lin, K. van Bibber, Astrophysical Journal, 659:L77-L80, 2007, 9 March 2007

AXION

Purely laboratory experiments



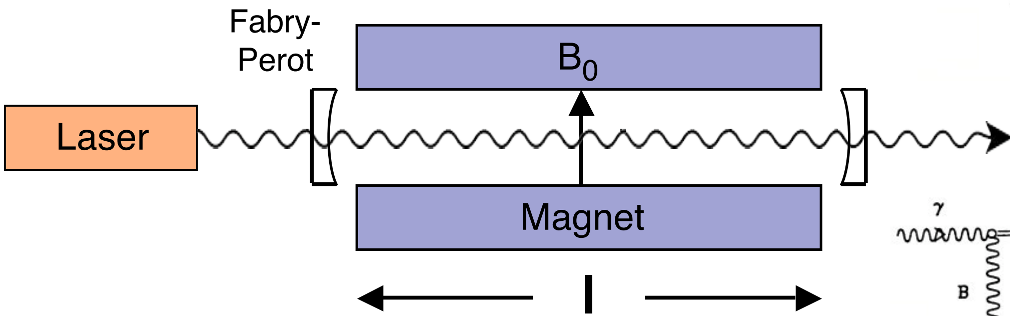
Vacuum birefringence & dichroism

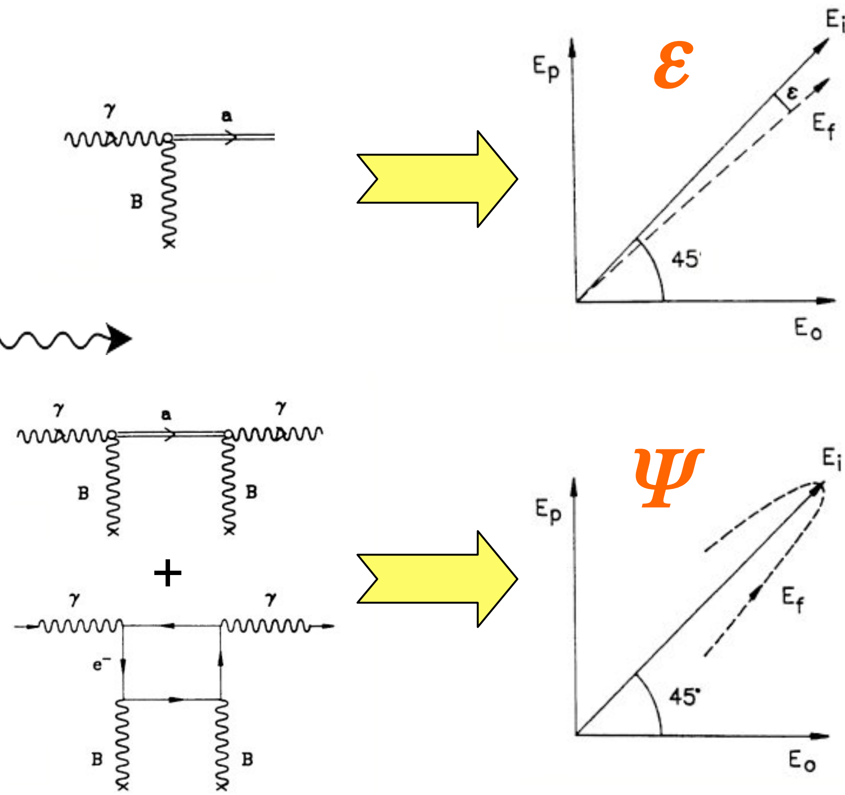
(Maiani, Zavattini, Petronzio, Phys. Lett. 1986)

Vacuum dichroism

$$\varepsilon = N \cdot (1/4\ gB_0L)^2 \cdot |F(q)|^2$$

(N = number of passes)





Vacuum birefringence

QED:

$n_{\perp} = 1 + 4/2 \cdot \xi$, $n_{||} = 1 + 7/2 \cdot \xi$

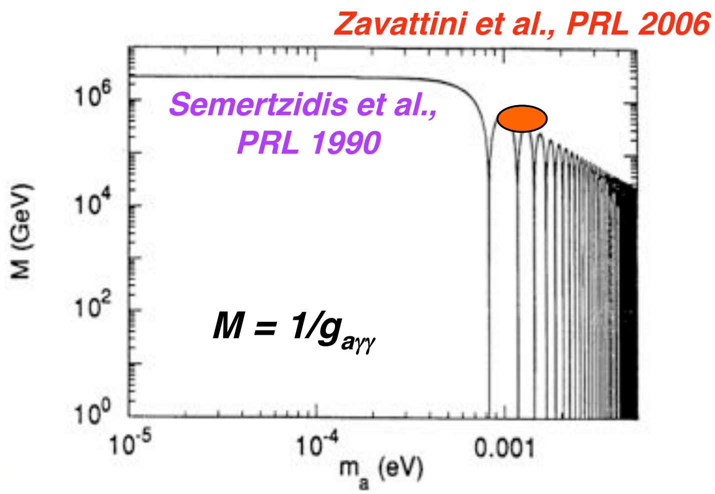
$\xi = \alpha/45\pi\ (B/B_{crit})^2$, $B_{crit} = m_e^2/e \sim 4.41 \times 10^{13}$ G

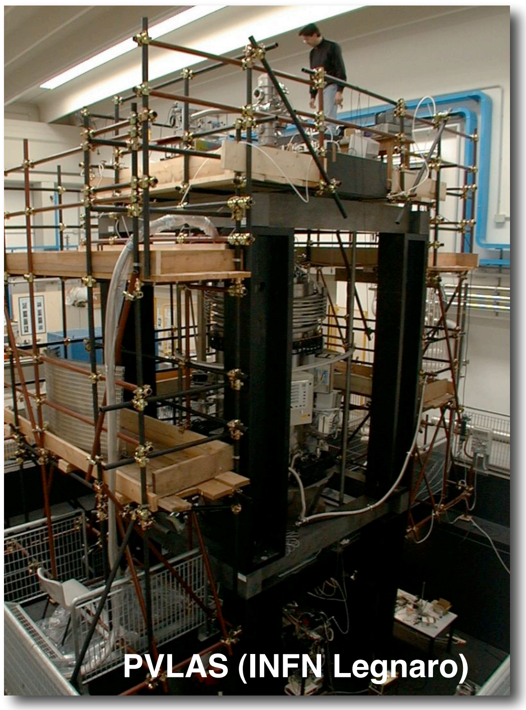
Axion:

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

The Rochester-BNL-FNAL-Trieste (1990) & PVLAS (2006) exp'ts

AXION





Brief summary of the PVLAS episode

Neither RBFT nor PVLAS experiments came within orders of magnitude of measuring the higher-order QED effect

Nevertheless PVLAS published a positive vacuum dichroism result at the very fringe of the RBFT exclusion region

PVLAS was always problematic from many viewpoints

The PVLAS effect is tiny – rotation of 3.9×10^{-12} *rad/pass: width of mechanical pencil lead at the distance of the Moon!*

There were evident unexplained systematic errors in their data

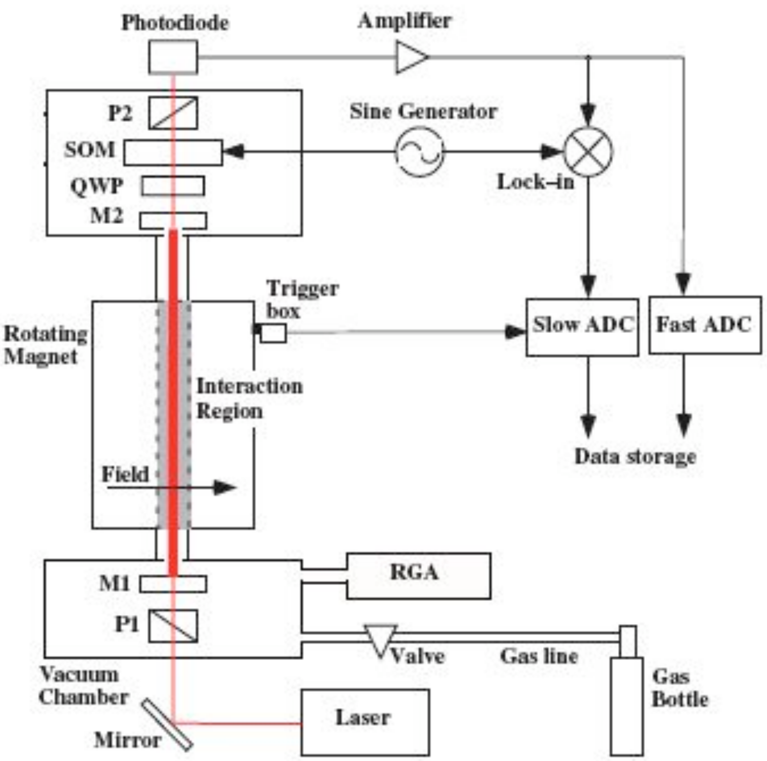
If interpreted as a pseudoscalar, it should have been excluded by CAST & HBS limits, 4 orders of magnitude stronger

Finally, PVLAS concluded it was an instrumental artifact, and not new physics at all *(hep-ex:0706.3419v1)*

Nevertheless, this result launched several new photon-regeneration experiments around the world, and much theoretical work!

PVLAS details & data

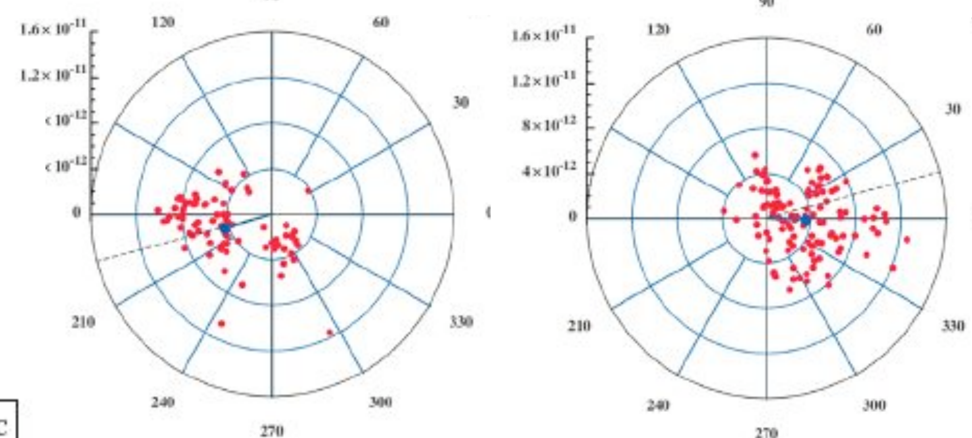
PVLAS Schematic

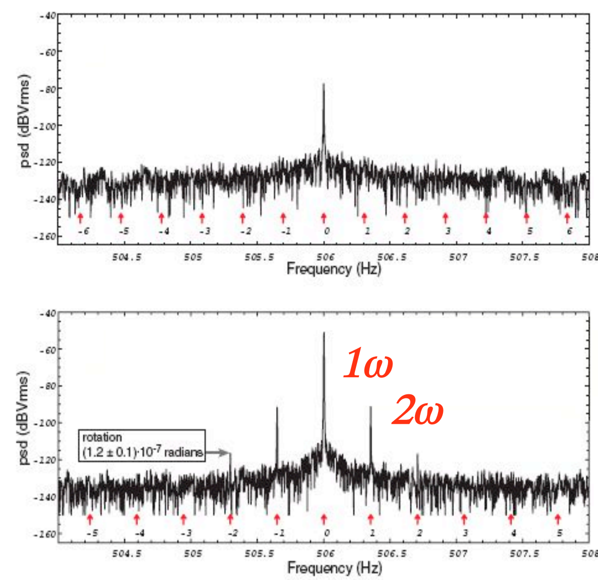


Phase-Amplitude Plot & Spectrum

QWP = 0 º

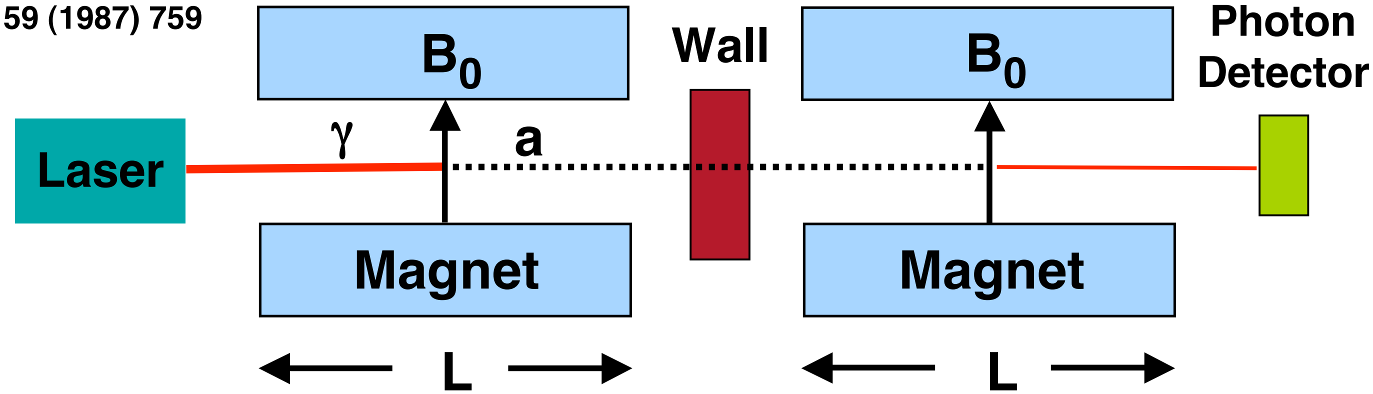
QWP = 90 º

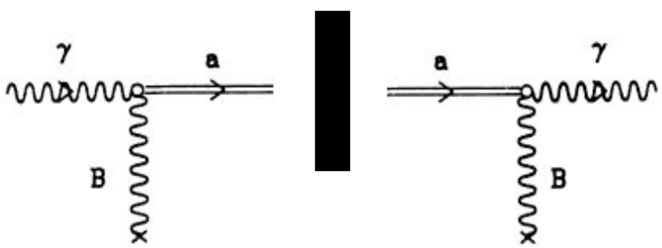




Photon regeneration – simple *("shining light through walls")*

KvB et al., PRL 59 (1987) 759



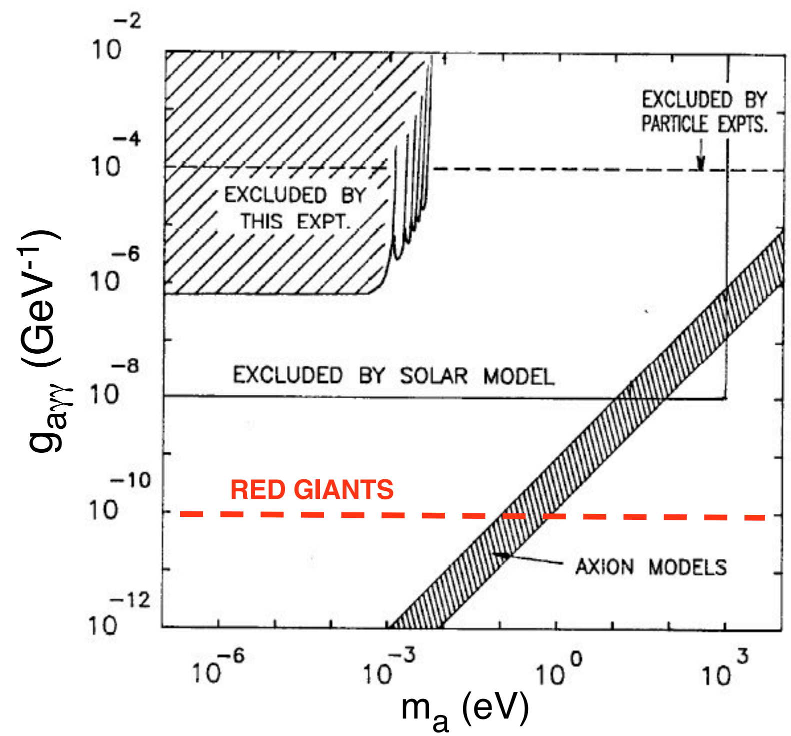


$$P(\gamma \rightarrow a \rightarrow \gamma) = \Pi^2 = 1/16\ (gB_0L)^4\ |F(q)|^4$$

Only two published measurements to date:

$g < 6.7 \times 10^{-7}\ GeV^{-1}$ for $m_a < 1$ meV

G. Ruoso et al., Z. Phys. C. 56, 505 (1992) &
R. Cameron et al., Phys. Rev. D47, 3707 (1993)
LULI collaboration (2007)



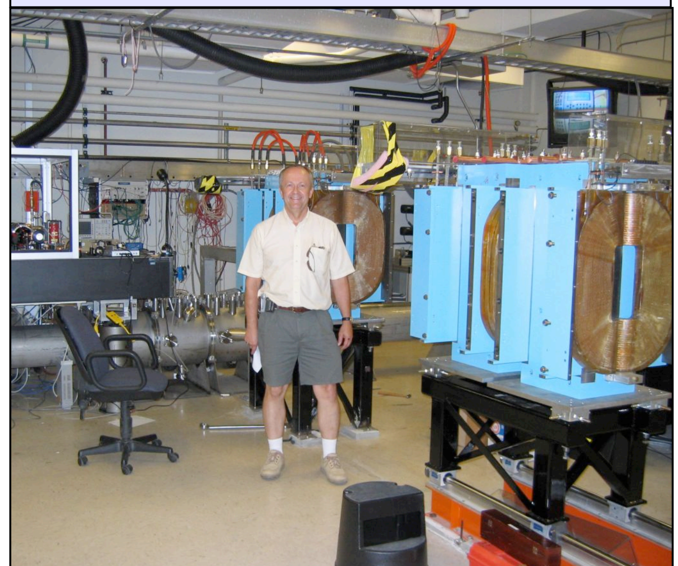
Several photon regeneration efforts launched around the world

Experiments in various phases of prepation or operation

name	place	magnet (field length)	laser wavelength power	P_{PVLAS}	photon flux at detector
ALPS	DESY	5 T 4.21 m	1064 nm 200 W cw	$= 10^{-19}$	10/s
BMV	LULI	11 T 0.25 m	1053 nm 500 W 4 pulses/day	$= 10^{-21}$	10/pulse
LIPSS	Jefferson Laboratory	1.7 T 1.0 m	900 nm 10 kW cw	$= 10^{-23.5}$	0.1/s
OSQAR (preliminary phase)	CERN	9.5 T 1.0 m 9.5 T 3.3 m	540 nm 1 kW cw	$= 10^{-20}$	10/s
PVLAS (regeneration)	INFN Legnaro	5 T 1 m 2.2 T 0.5 m	1064 nm 0.8 W cw Npass $= 5 \times 10^5$	$= 10^{-23}$	10/s

CERN Courier, Vol. 47 No. 2 (March 2007)

LIPSS, GammeV & BMV took data



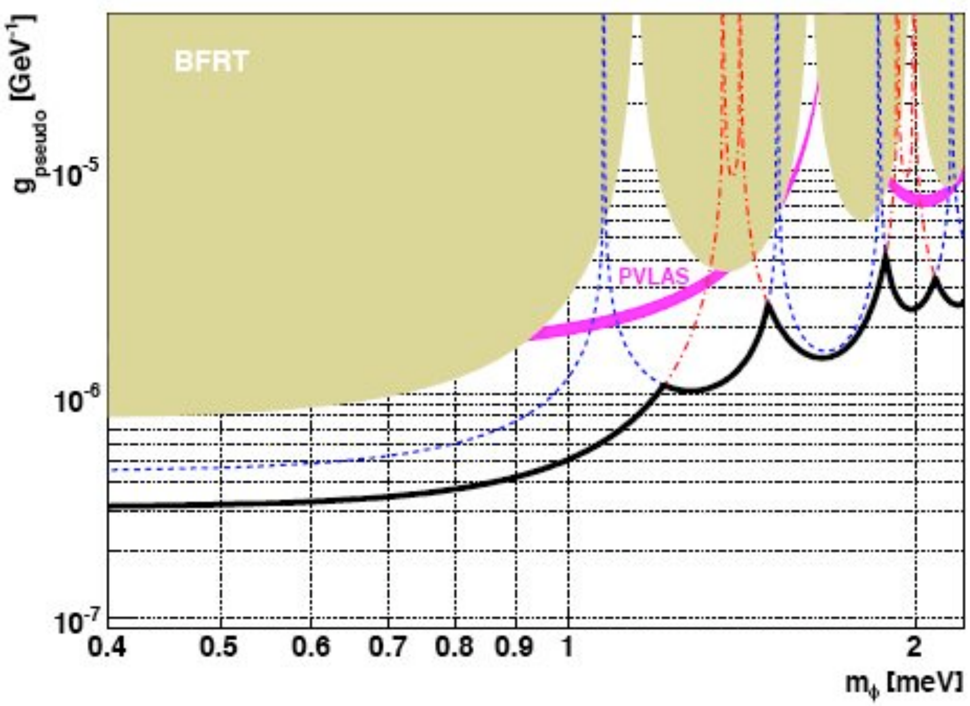
LIPSS (Yale-Hampton-Jlab)

But all of them would still be orders of magnitude away from CAST/HBS limits

One of the early ones to be late to the funeral … “GammeV”

Search for axion-like particles using a variable baseline photon regeneration technique

A. S. Chou[1,2], W. Wester[1], A. Baumbaugh[1], H. R. Gustafson[3], Y. Irizarry-Valle[1], P. O. Mazur[1], J. H. Steffen[1], R. Tomlin[1], X. Yang[1], and J. Yoo[1]
[1] *Fermi National Accelerator Laboratory, PO Box 500, Batavia, IL 60510*
[2] *Center for Cosmology and Particle Physics, New York University, 4 Washington Place, New York, NY 10003*
[3] *Department of Physics, University of Michigan, 450 Church St, Ann Arbor, MI 48109*
(Dated: November 16, 2007)



One FNAL Tev dipole (used in two halves)

3m + 3m , 5 Tesla

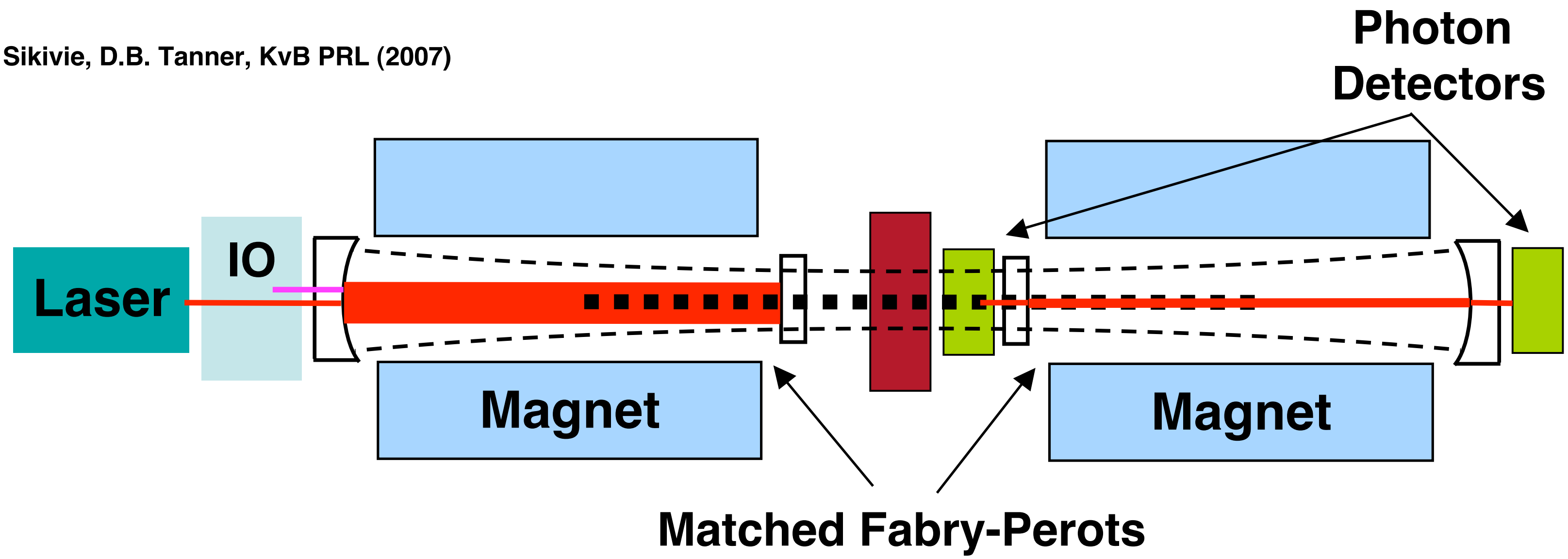
Nd:YAG 2ω (532 nm)

PMT detector

Resonantly-Enhanced Photon Regeneration

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

P. Sikivie, D.B. Tanner, KvB PRL (2007)

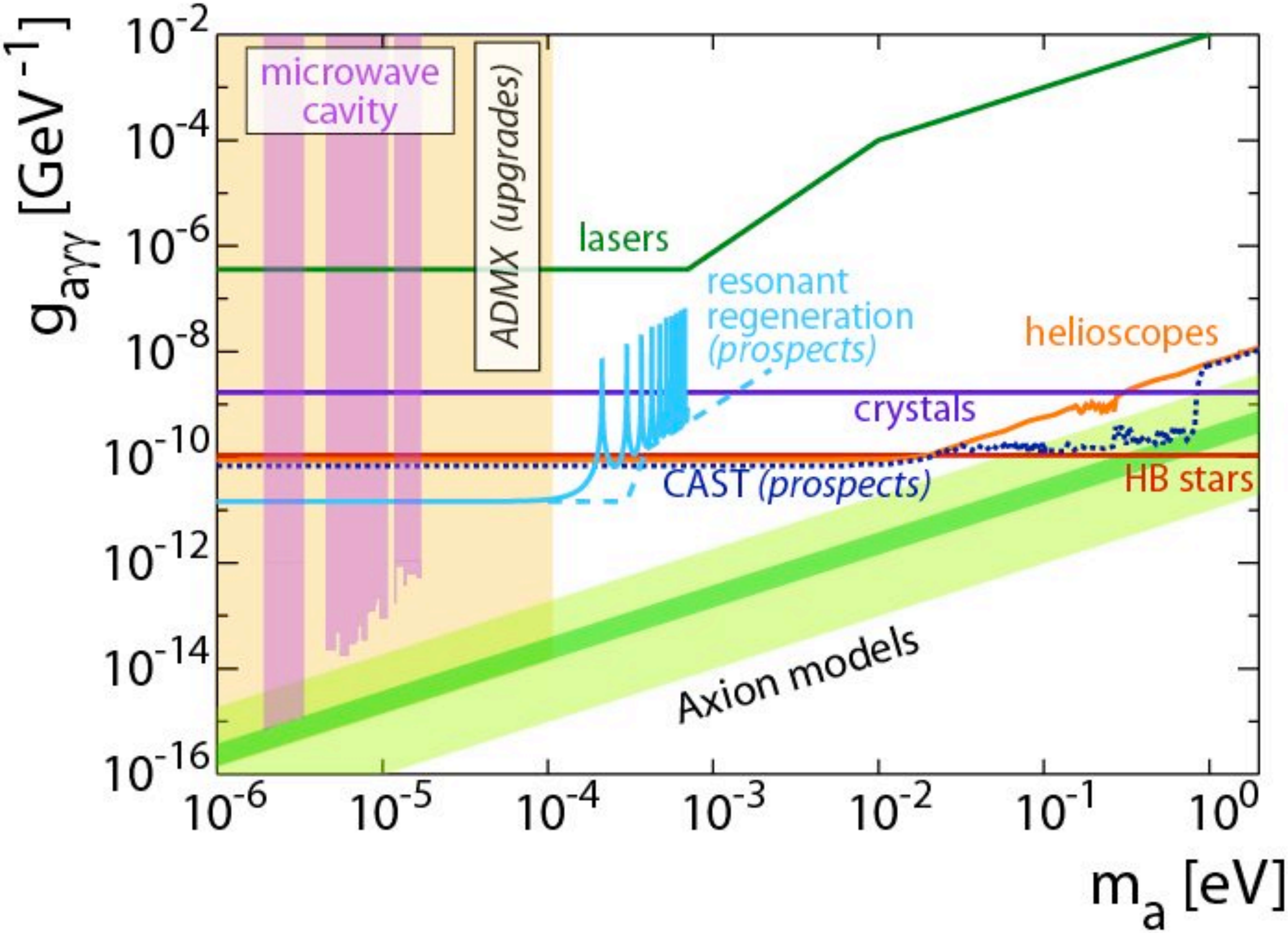


$$P^{\mathrm{Re}\,sonant}(\gamma \to a \to \gamma) = \frac{2}{\eta\eta'} \cdot P^{Simple}(\gamma \to a \to \gamma) = \frac{2}{\pi^2} FF' \cdot P^{Simple}(\gamma \to a \to \gamma)$$

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 $10^{(2.5\text{–}3)}$

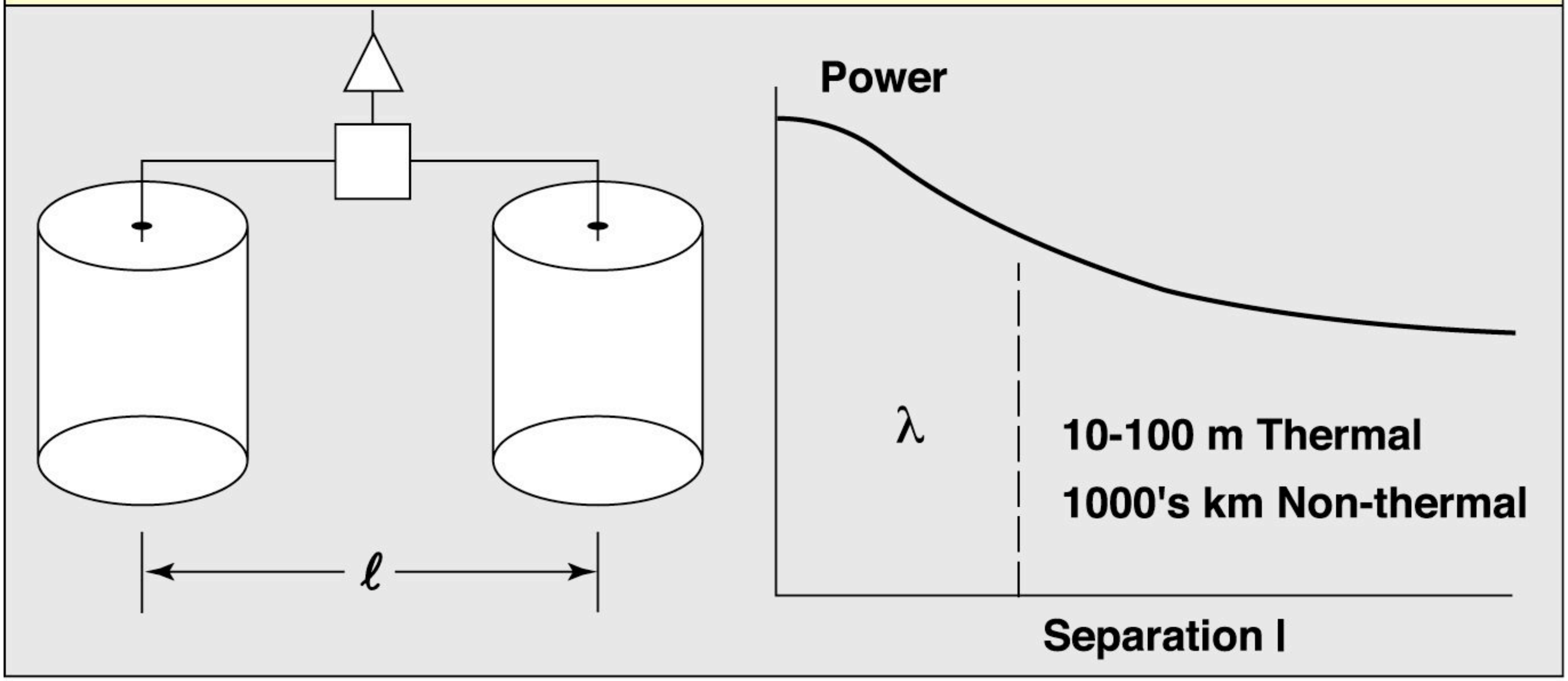
Excluded $g_{A\gamma\gamma}$ vs. m_A with all experimental and observational constraints



And if the axion be found?

AXION

The Study of Unique Quantum System

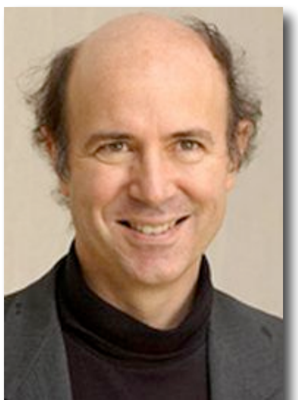


And should the axion posses fine-structure, it would constitute a "movie" of the formation of our Milky Way galaxy

Wilczek on axions *(Physics Today, Oct. '03)*

"…I'm much more optimistic about the dark matter problem. Here we have the unusual situation that two good ideas exist – which, according to William of Occam (the razor guy), is one too many.

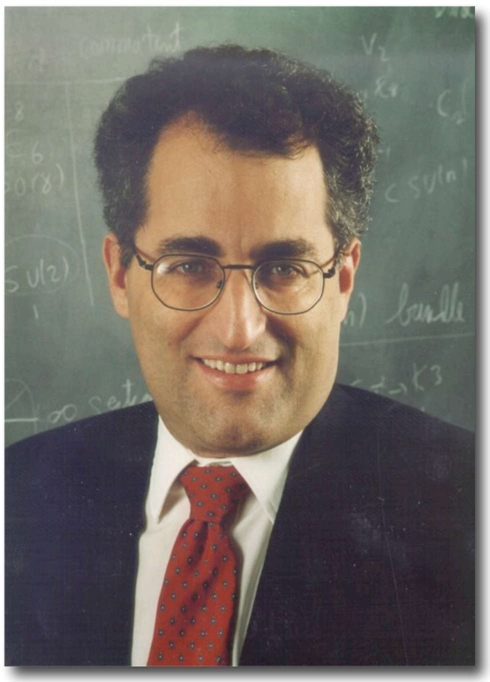
"The symmetry of the standard model can be enhanced, and some of its aesthetic shortcomings can be overcome, if we extend it to a larger theory. Two proposed extensions, logically independent of one another, are particularly specific and compelling.



"One incorporates a symmetry suggested by Roberto Peccei and Helen Quinn in 1977. Peccei-Quinn symmetry rounds out the logical structure of quantum chromodynamics by removing QCD's potential to support strong violation of time-reversal symmetry, which is not observed. This extension predicts the existence of a remarkable new kind of very light, feebly interacting particle: the axion. …

"The properties of the particles, axion or LSP, are just right for dark matter. Moreover, you can calculate how abundantly each would be produced in the Big Bang. For both particles, the predicted abundance is also quite promising. Vigorous, heroic experimental searches are under way to observe dark matter in either of those forms. We will also get crucial information about supersymmetry once the Large Hadron Collider starts running in 2007. I will be disappointed – and surprised – if, a decade from now, we don't have a much more personalized portrait of the dark matter. …"

Witten on axions *(priv. comm., July 2006)*



"The axion is the most plausible known solution of the strong CP problem, so axion searches are very important. Axions are also one of the most plausible known dark matter candidates. So it is doubly important to search for axions as dark matter.

"In particular, it is important to look for axionic dark matter in the range of F_a suggested by cosmological arguments. It is true that if axions are found in that range, this will cause problems for some theories (including many string-based models), but that is what experiments do sometimes.

"If it turns out that axionic dark matter doesn't exist in the range that is suggested by cosmology, and which is the focus of current searches, it is important – though difficult – to continue to search for axionic dark matter at higher values of F_a, as suggested by some grand unified and string-based models. Again, if axions are eventually found at these higher values of F_a, this will challenge our understanding of cosmology at very high energy scales, and this will be part of the importance of the discovery."

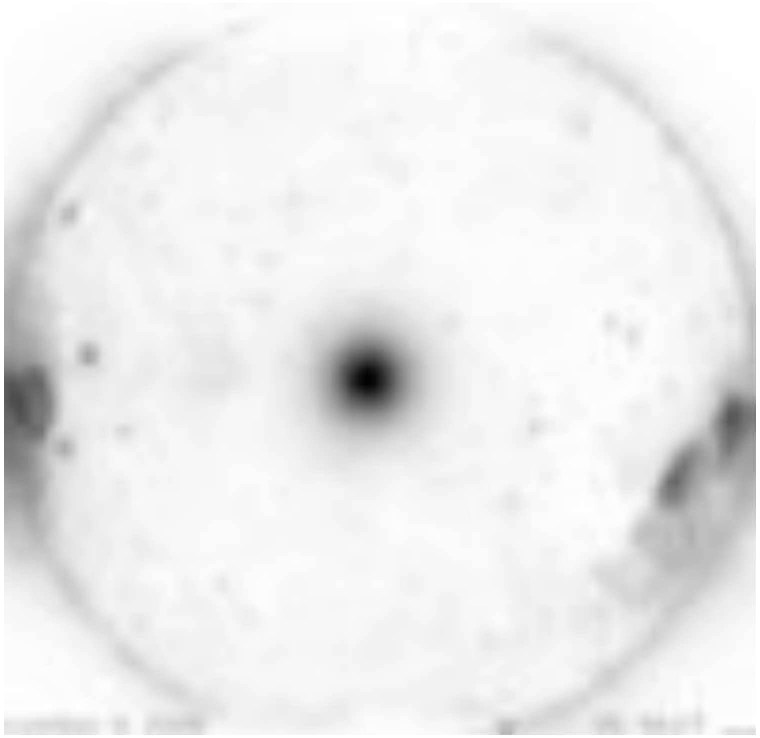
Summary & final remarks

AXION

The theoretical case is better than ever

"If the axion doesn't exist, please tell me how to solve the Strong-CP problem" (Wilczek)

"Axions may be intrinsic to the structure of string theory" (Witten)



Experimental progress is excellent & discovery would teach us a lot

Be prepared for the unexpected

The really unexpected …