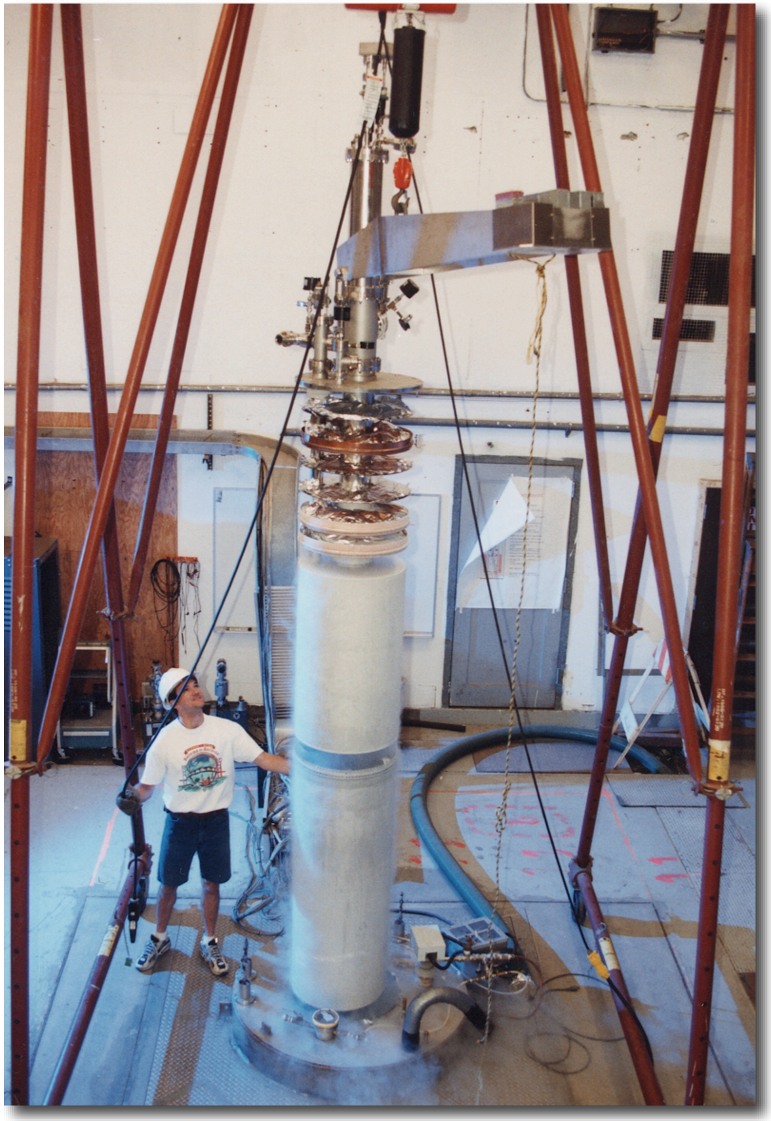


UC Davis High Energy Seminar

Ultrasensitive Searches for the Axion

Karl van Bibber, LLNL

January 23, 2007

AXION

Outline

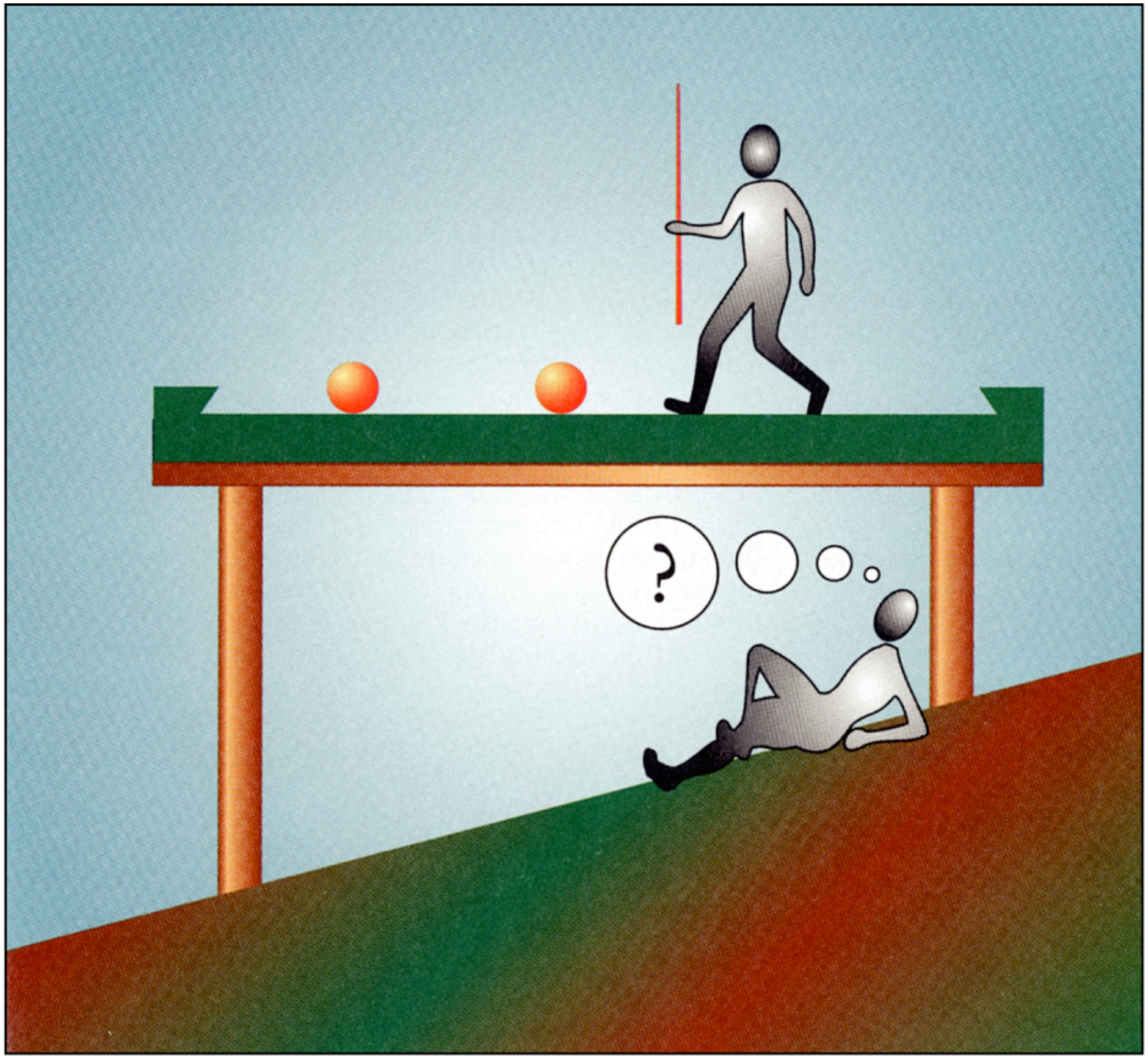
Some basics about the axion

Three experimental fronts:

- **Searches for halo dark matter**
- **Searches for solar axions**
- **Purely laboratory experiments**

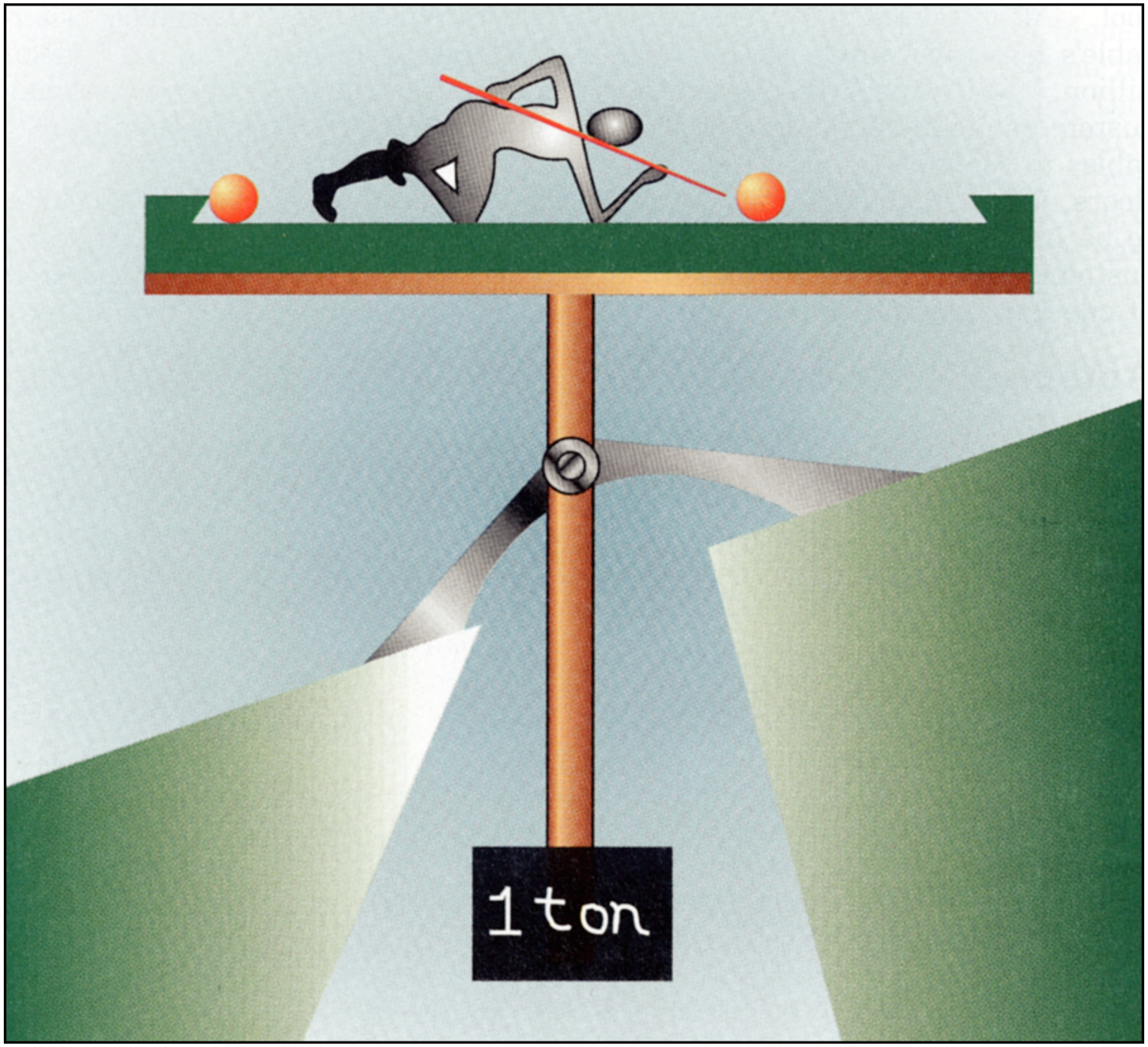
Final remarks

TSP's* fine-tuning problem

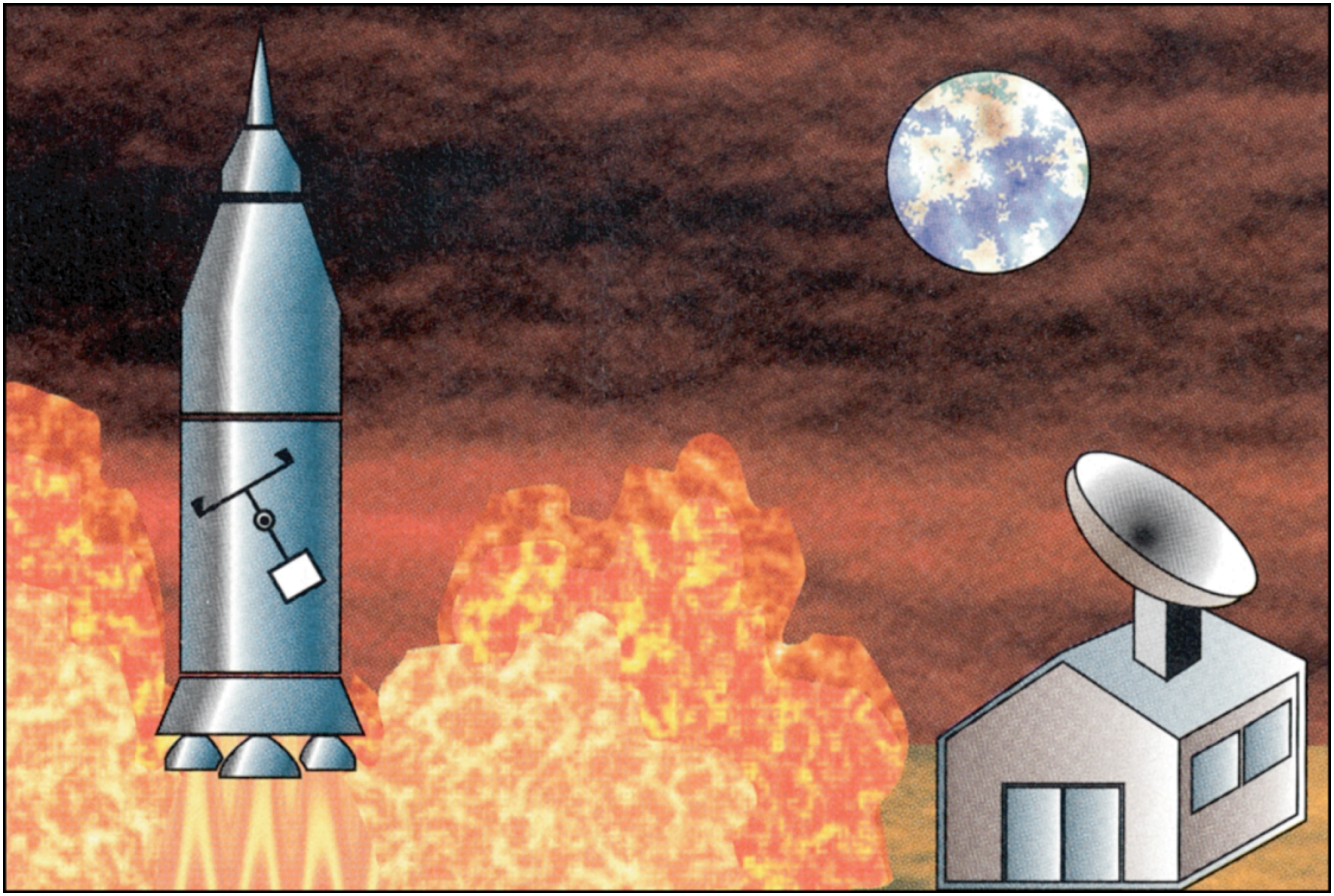


*Thinking Snookers Player (Pierre Sikivie, Physics Today 49 (1996)22)

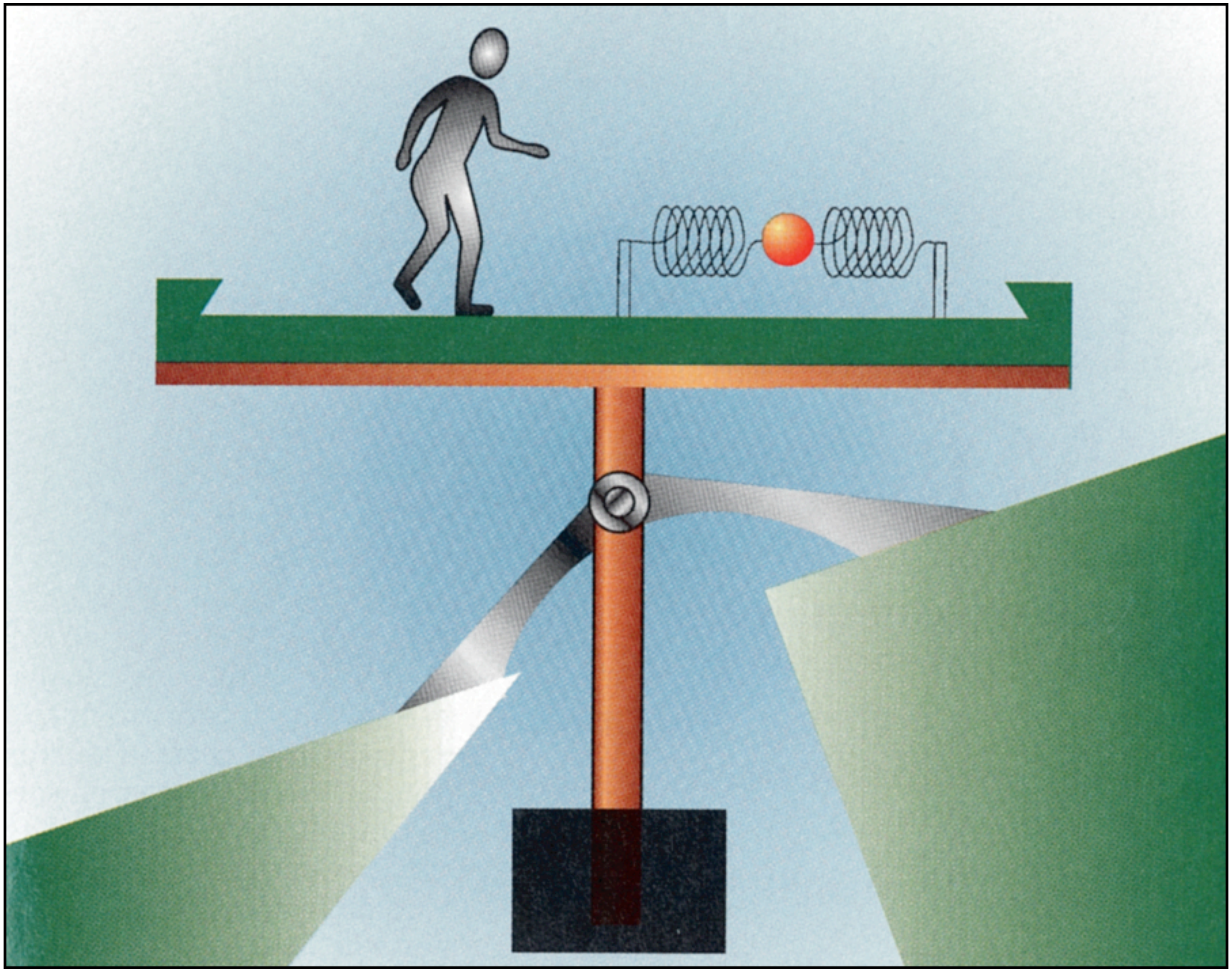
TSP's hypothesis, and first unsuccessful experiment



The key insight



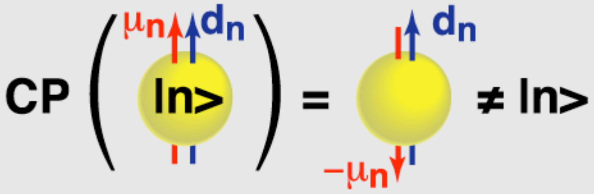
A high-Q search for relic oscillations



The Axion

The Strong-CP Problem

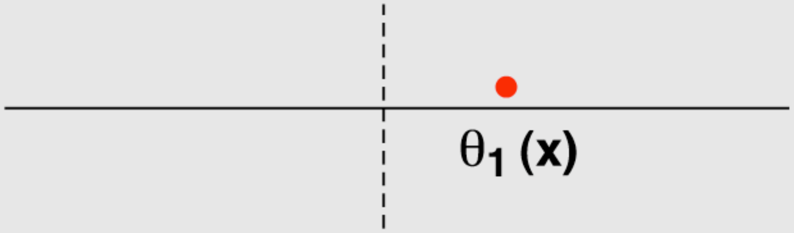
- $\mathscr{L}_{QCD} = ... + \frac{\theta}{32\pi^2} G\tilde{G}$
  - Explicitly CP-violating
- But neutron e.d.m.
  $|d_n| < 10^{-25}$ e · cm
  - $\bar{\theta} < 10^{-10}$
  - Strong-CP preserving



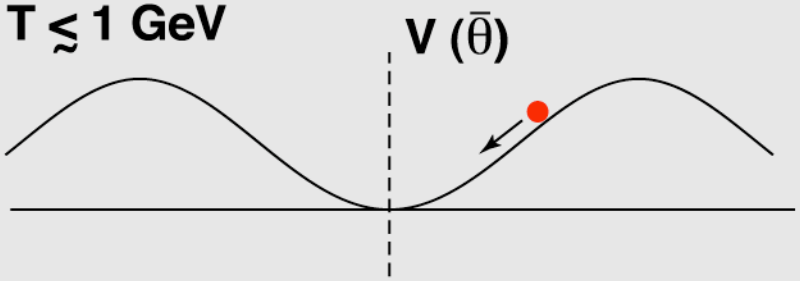
- Why?

Peccei-Quinn / Weinberg-Wilczek

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



- T $\lesssim$ 1 GeV



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

Completing the analogy $f \longleftrightarrow l$

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

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

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

Generically, all couplings

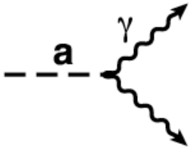
$$g_{aii} \propto \frac{1}{f_a}$$

Cosmological Abundance

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

(Vacuum misalignment mechanism)

Coupling to Photons



$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a};\ g_\gamma = \left\{\begin{array}{l}0.97\text{ KSVZ}\\ -0.36\text{ DFSZ}\end{array}\right.$$

Axion Mass 'Window'

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

(Overclosure) (SN1987a)

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

Microwave cavity searches for axionic dark matter

Some basics about dark matter

Principle of the Sikivie experiment

The first generation experiments (RBF, UF) c. 1990

Axion Dark Matter eXperiment (ADMX) @ LLNL

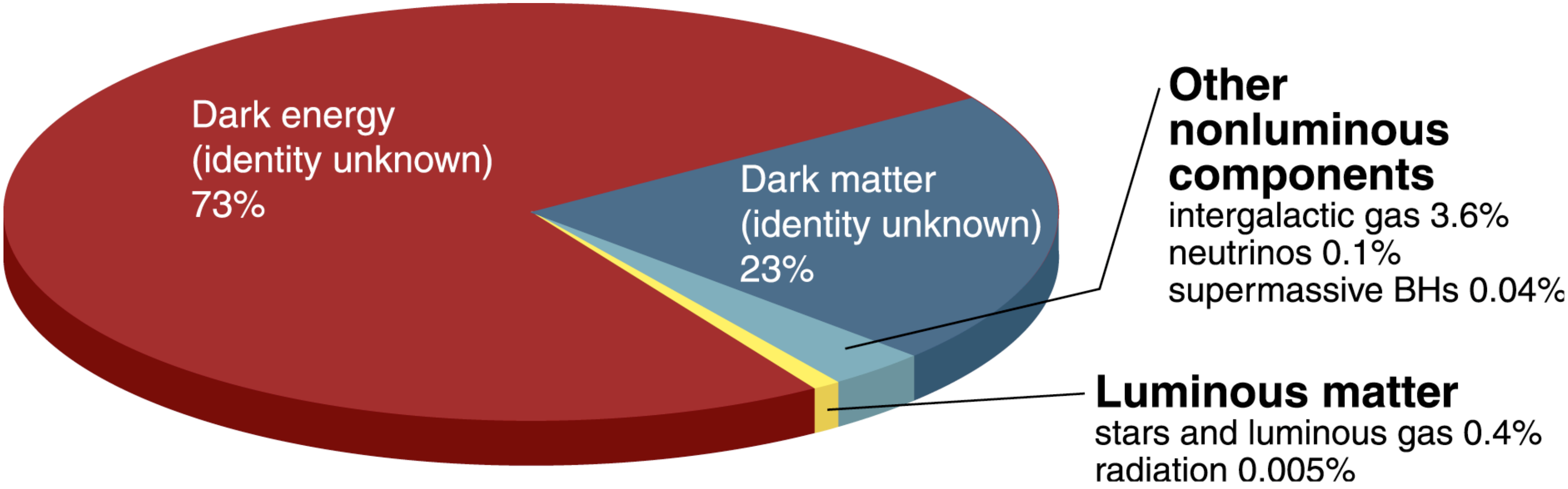
Upgrade based on quantum-limited SQUID amplifiers

The Rydberg-atom single-quantum detector @ Kyoto

The cosmological inventory is now well-delineated

- But we know neither what the “dark energy” or the “dark matter” is

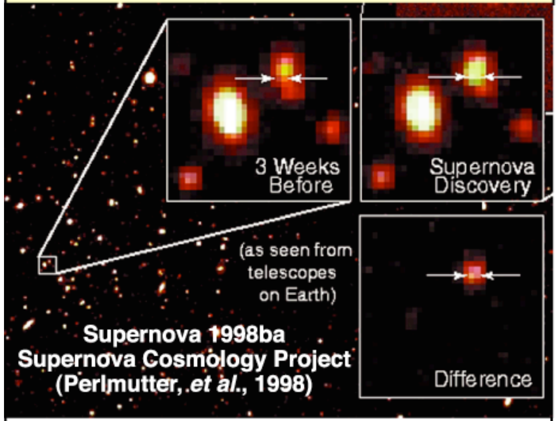
- A particle relic from the Big Bang is strongly implied for DM
  - — WIMPs ?
  - — Axions ?

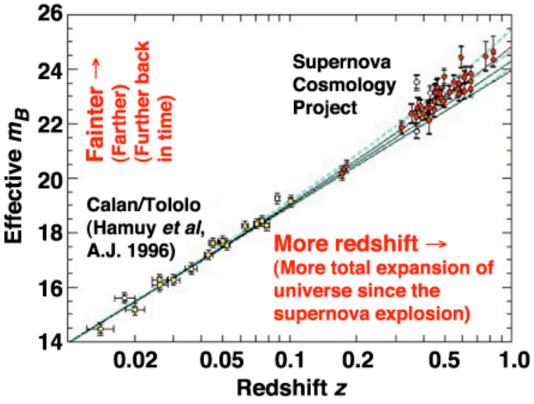


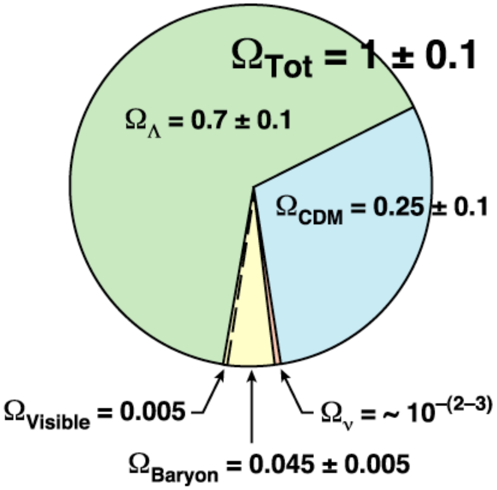
The advent of "precision cosmology"

AXION

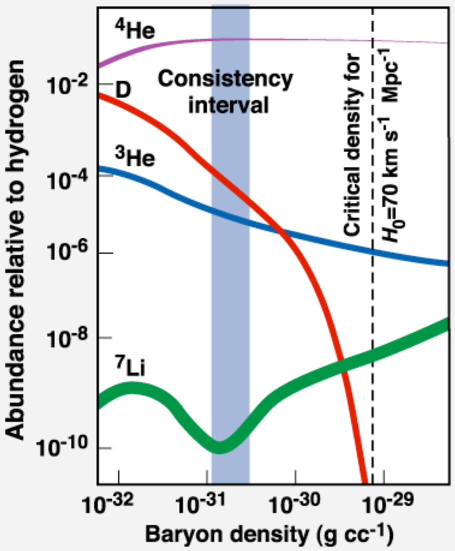
Sn-Ia: $\Omega_\Lambda - \Omega_M$



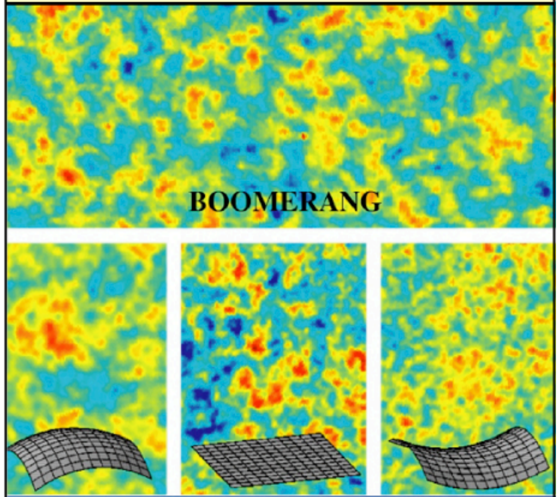




Primordial Nucleosynthesis

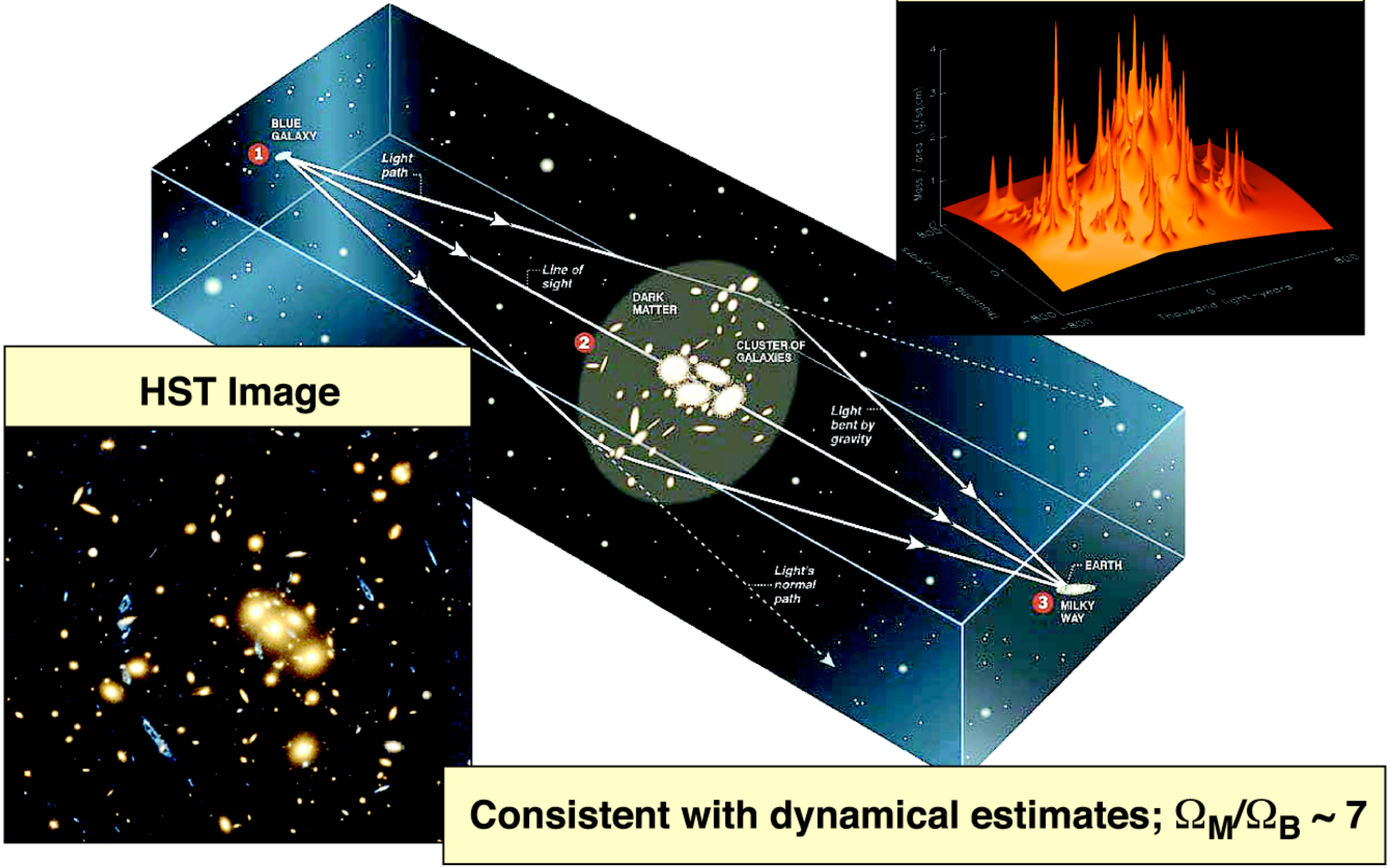


CMBR: $\Omega_\Lambda + \Omega_M$



Cluster lensing of background galaxy

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



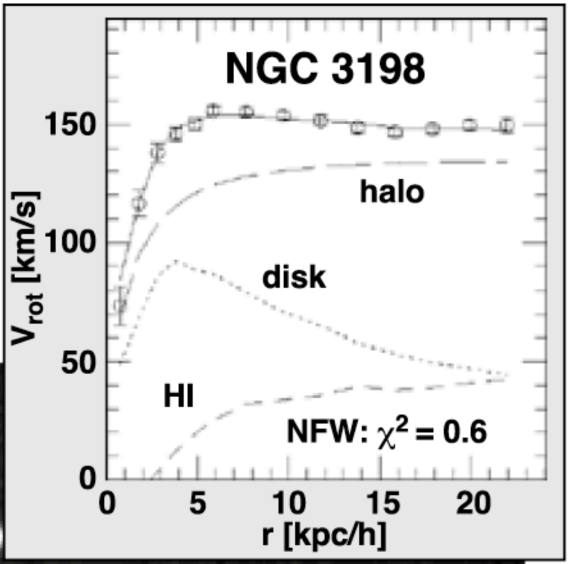
Reconstructed Cluster Mass Distribution

HST Image

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

Rotation Curves — Galactic Dark Matter

- Galaxies have constant rotation curves

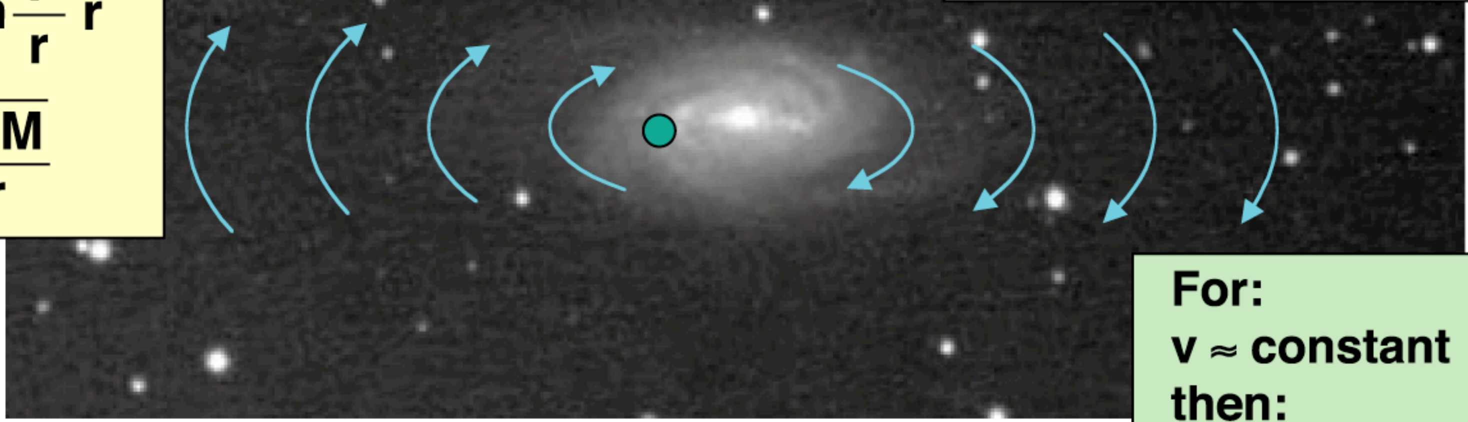


If mass were localised

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

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

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



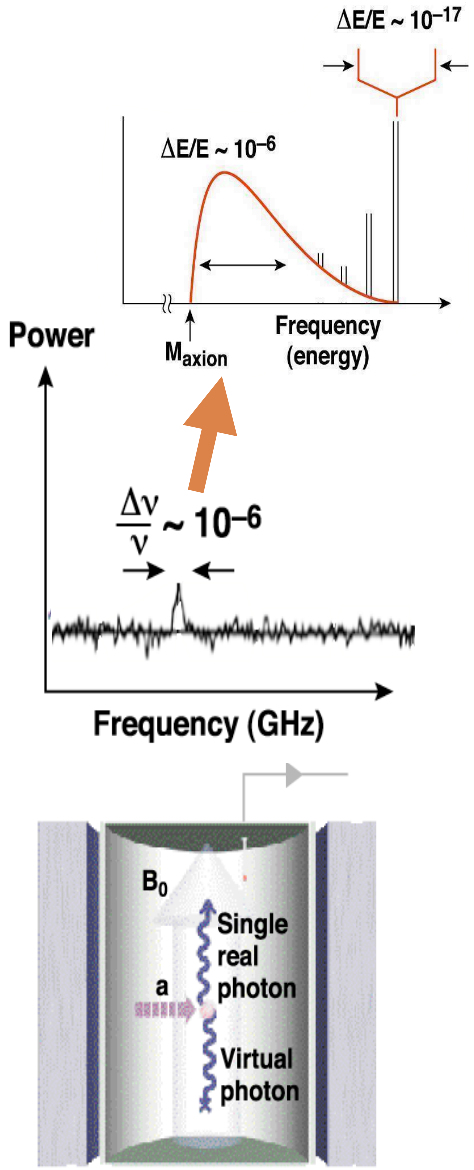
For:
$v \approx$ constant
then:

$M(r) \propto r$

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

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

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



Axionic dark matter is very dense

Milky Way density: $\rho_{halo} \approx 450\ MeV \cdot cm^{-3}$

Thus if m_a~10μeV: $\rho_{\#} \approx 10^{14}\ cm^{-3}$

Axionic dark matter is highly coherent

$\beta_{virial} \approx 10^{-3}$ → $\lambda_{De\ Broglie} \approx 100\ m$

$\Delta\beta_{flow} \approx 10^{-7}$ → $\lambda_{Coherence} \approx 1000\ km$

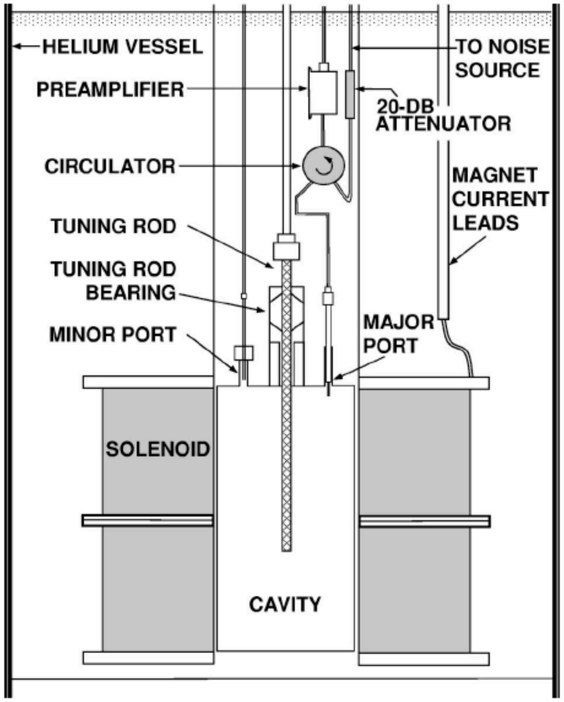
Resonance condition: $hn = m_a c^2[1 + O(b^2 \sim 10^{-6})]$

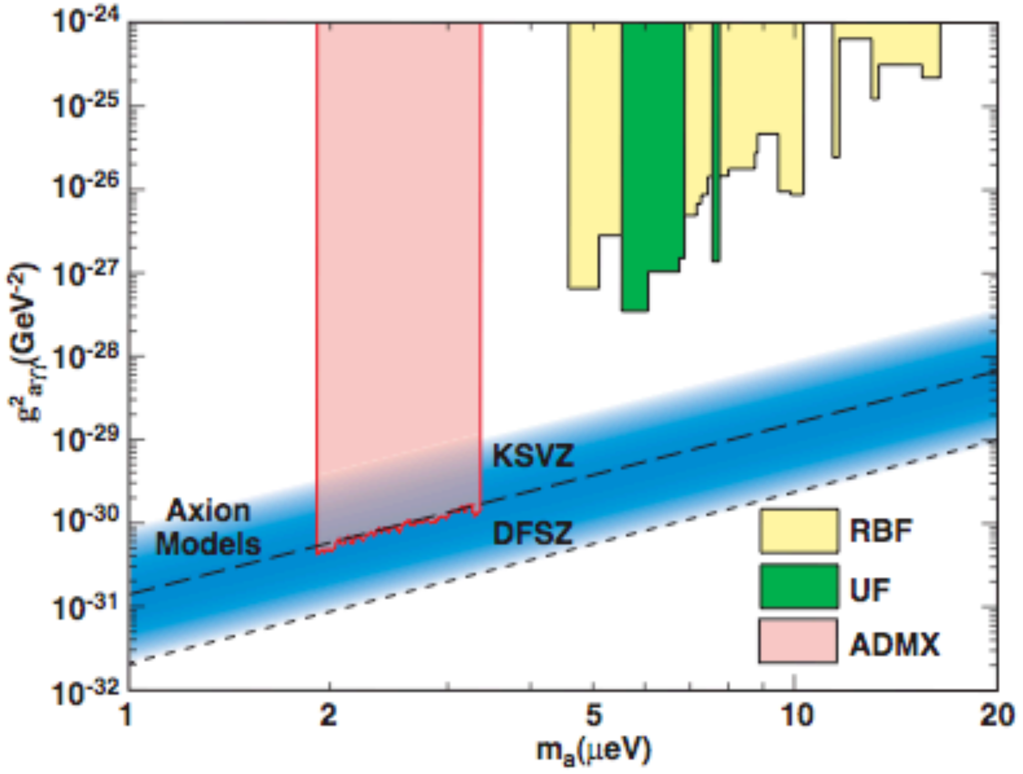
Signal power: $P \propto (B^2 V Q_{cav})(g^2 m_a r_a) \sim 10^{-23} W$

The microwave cavity experiment measures the *total energy* of the axion, thus revealing both Doppler motion and coherence of the axion fluid

The first-generation experiments RBF, UF – 1980's

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





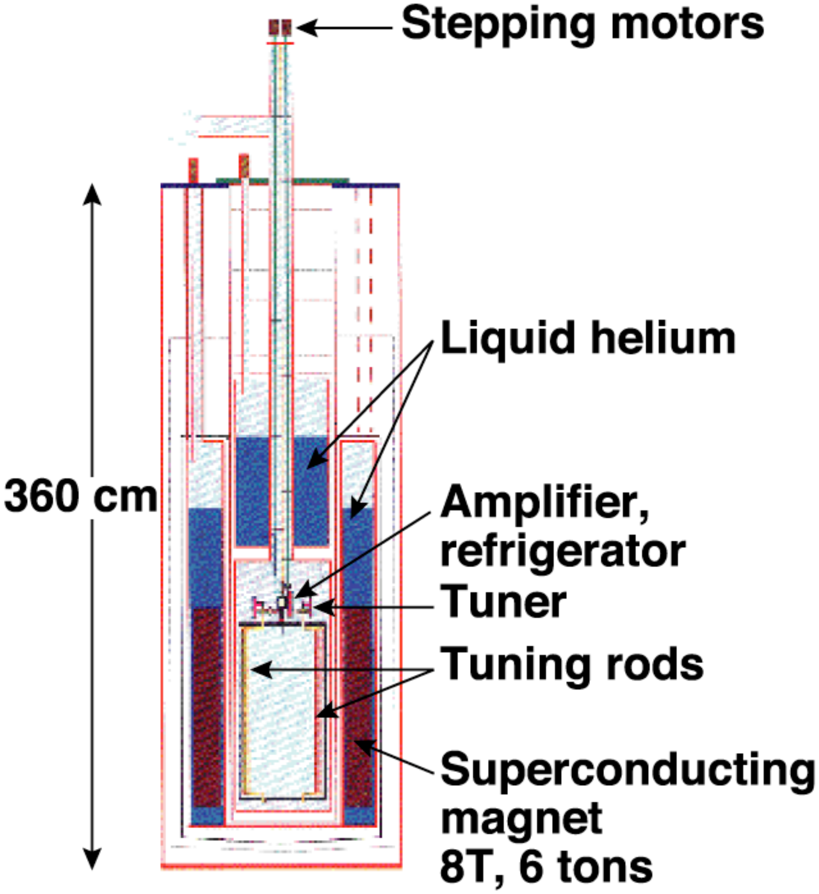
The first-generation experiments already came within a factor of 100-1000 of the desired sensitivity – a stunning achievement

Axion hardware

ADMX LLNL-Florida-Berkeley-NRAO

AXION

Magnet with Insert (side view)



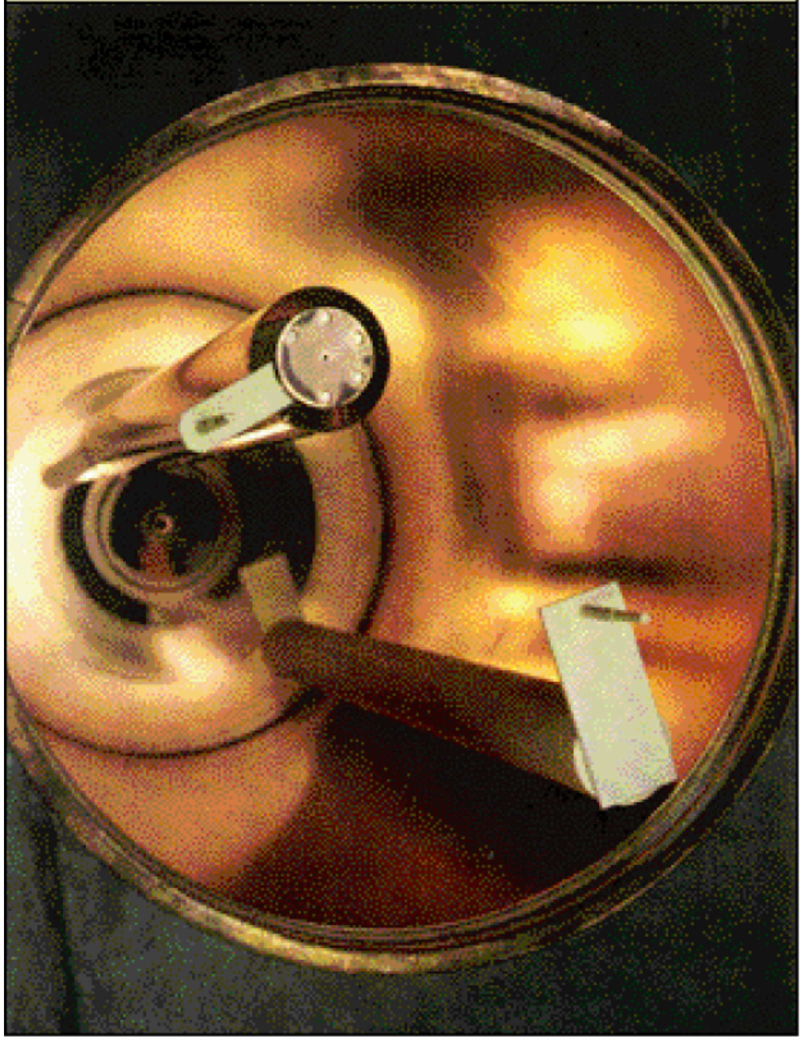
Pumped LHe → T ~ 1.5 k

Magnet (Wang NMR Inc.)

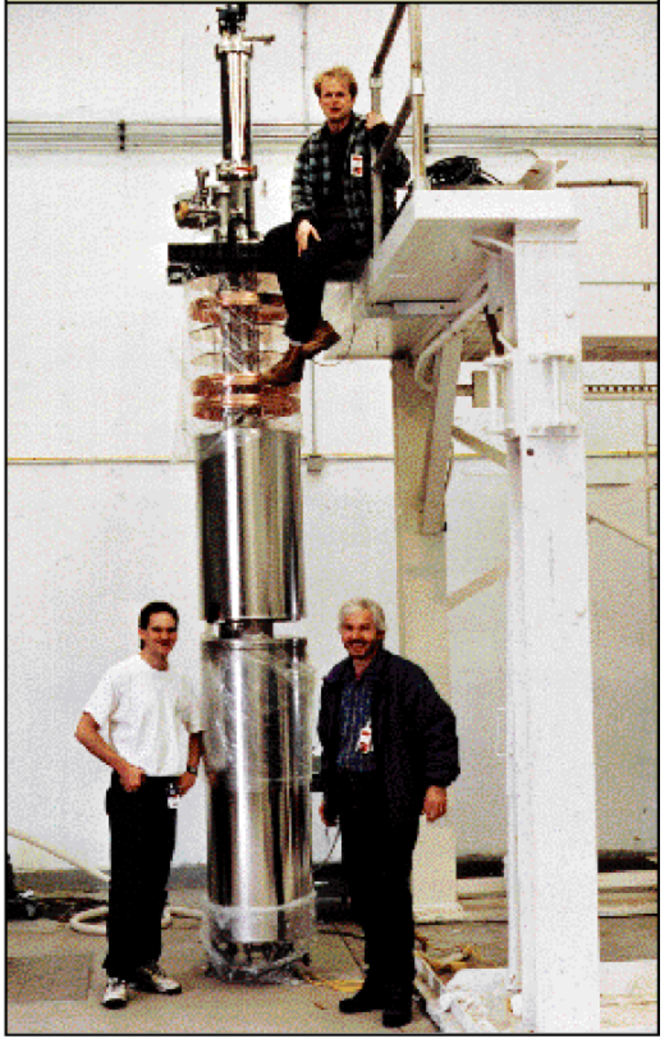
8 T, 1 m × 60 cm ∅

Axion hardware (cont'd)

High-Q Cavity (~200,000)

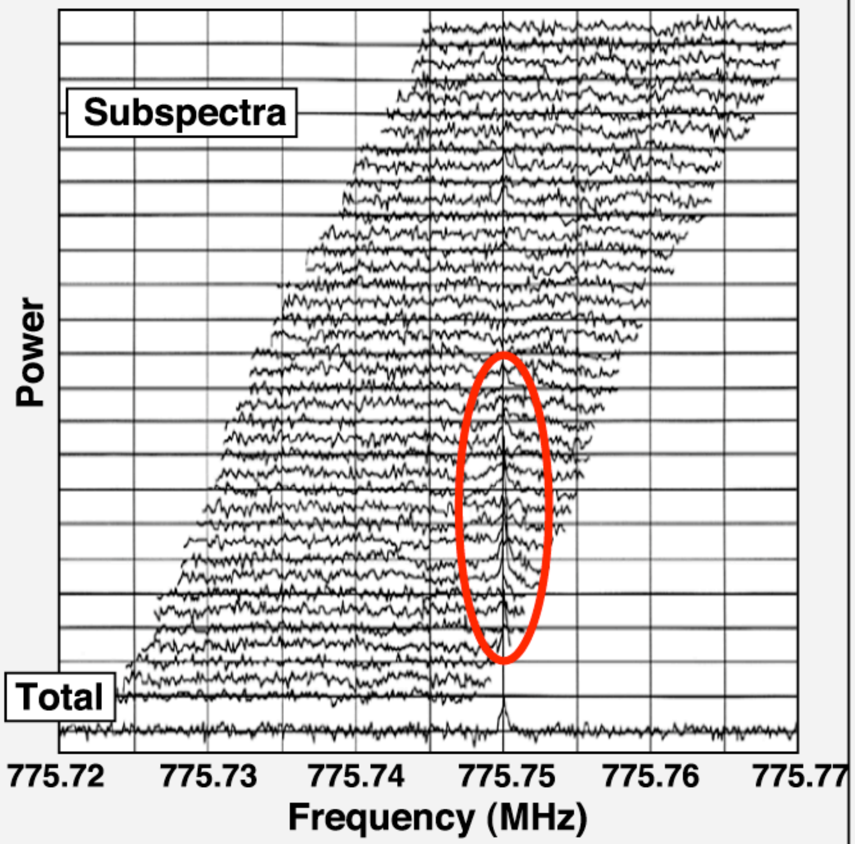


Experimental Insert



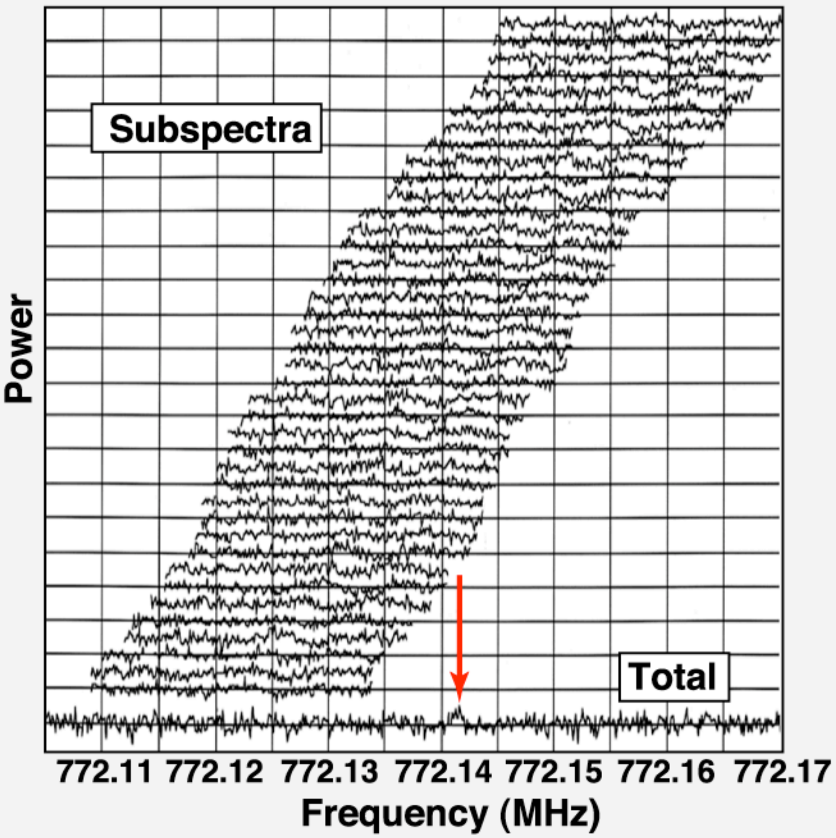
Sample data and candidates

Environmental



Signal maximizes off-resonance: Radio peak

Statistical



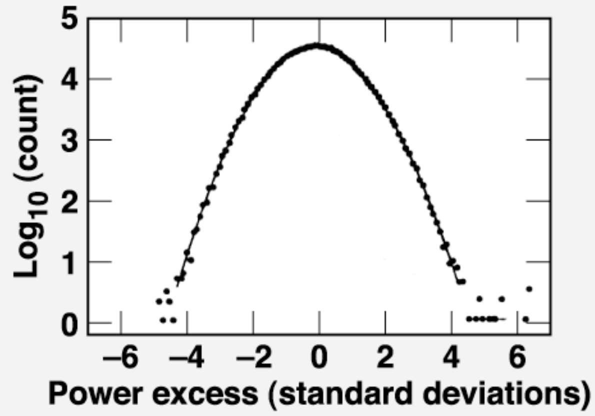
Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)

Brief outline of analysis — 100 MHz of data

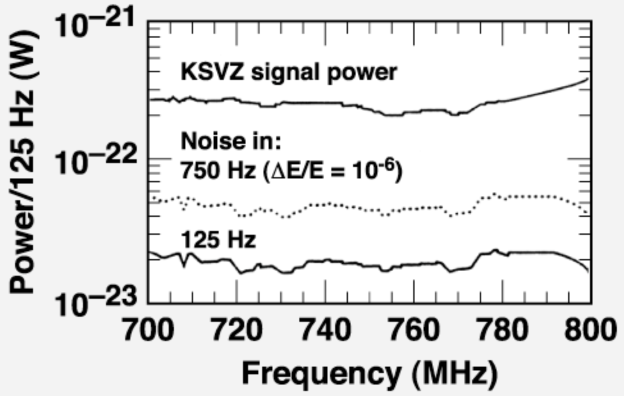
AXION

Data, with Theoretical Curve

(Gaussian noise through receiver and analysis)



S/N > 4 for Thermalized KSVZ Axion

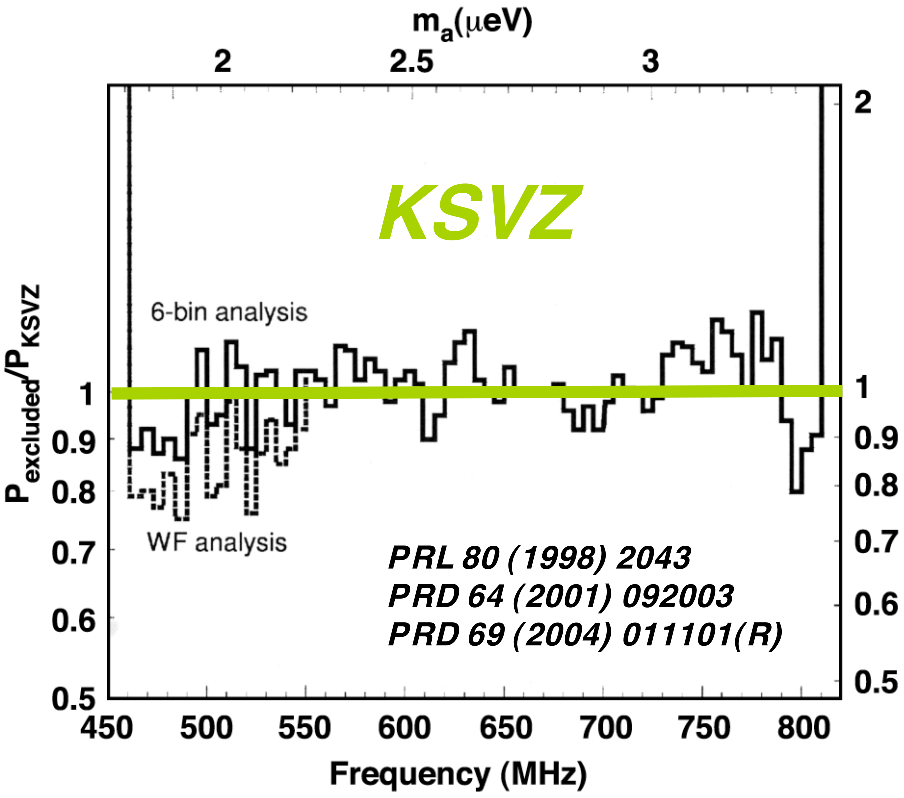


- Each frequency appears in >45 subspectra
- Weighted and co-added to produce spectrum
- 800,000 bins (125 Hz)/100 MHz

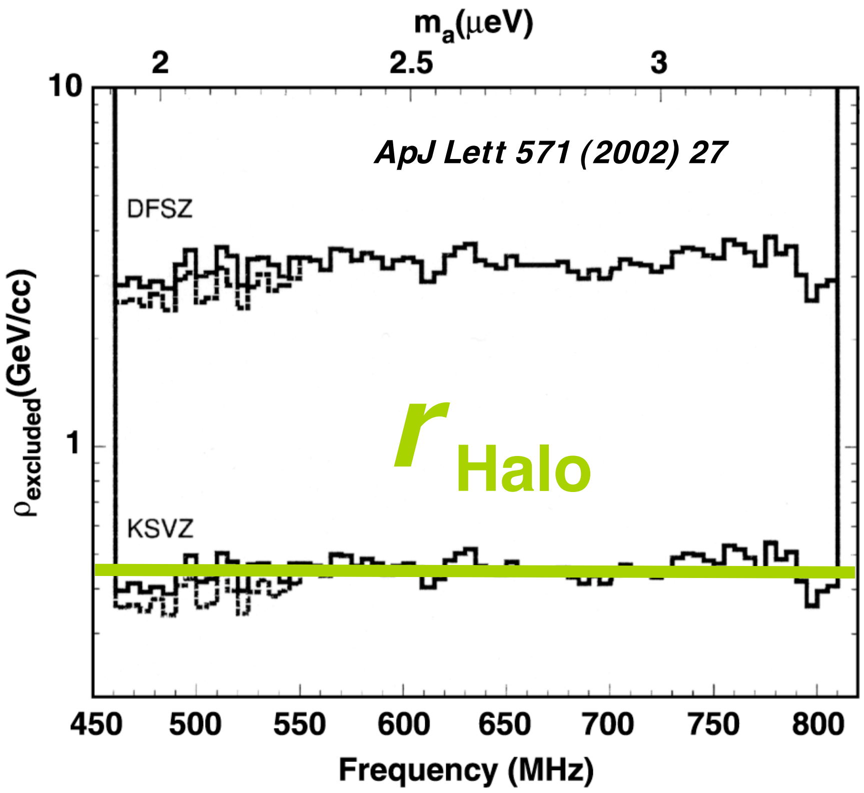
→ 6535 candidates $> 2.25\sqrt{6}\,\overline{\sigma}$ (95% C.L.)
→ Rescan all to same sensitivity
→ 23 candidates (Net 90% C.L.)
→ Each examined: radio peaks

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

Limits on axion models and local axion halo density



PRL 80 (1998) 2043
PRD 64 (2001) 092003
PRD 69 (2004) 011101(R)

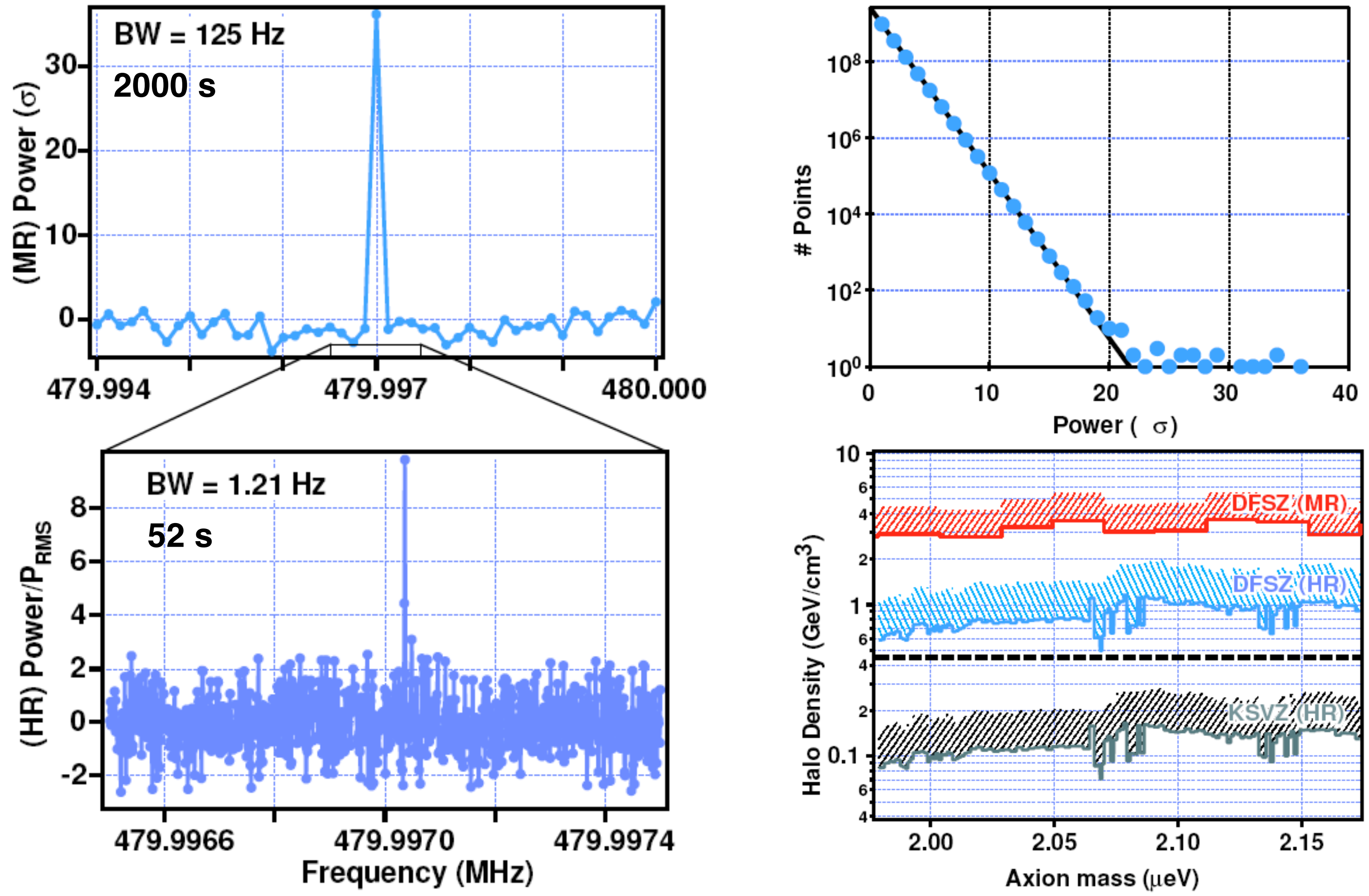


ApJ Lett 571 (2002) 27

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

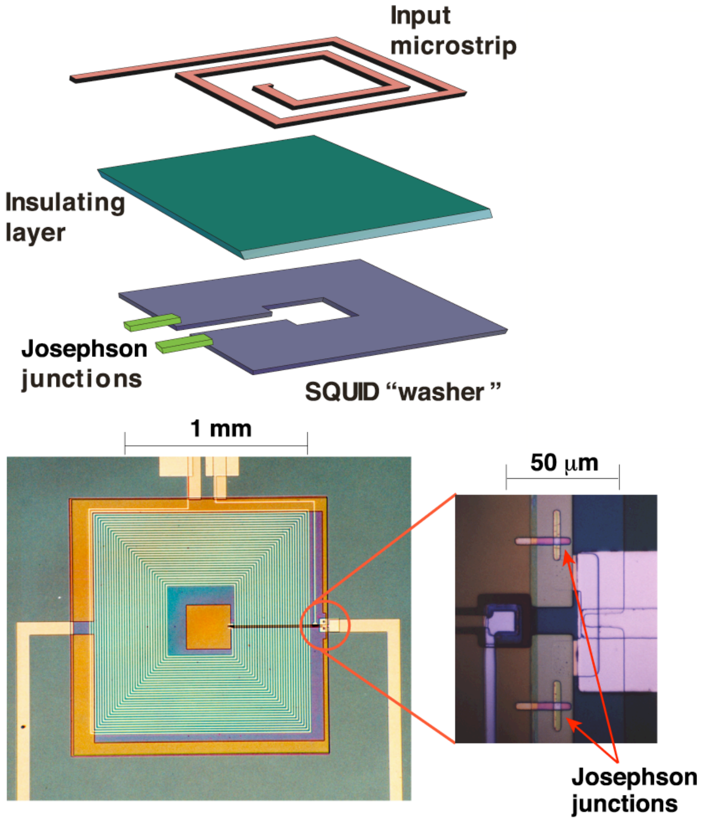
Results of a high-resolution analysis

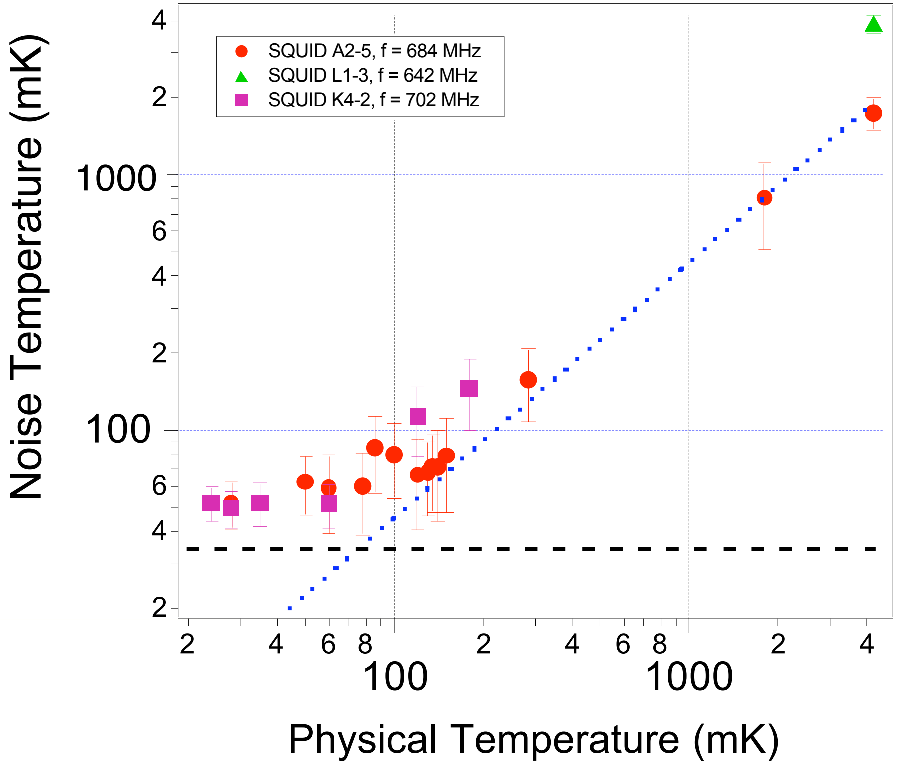
PRL 95 (9) 091304 (2005)



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

Upgrade well underway to GHz SQUID amplifiers





Latest SQUIDs are now within 30% of the Standard Quantum Limit

Rydberg-atom single-quantum detectors

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

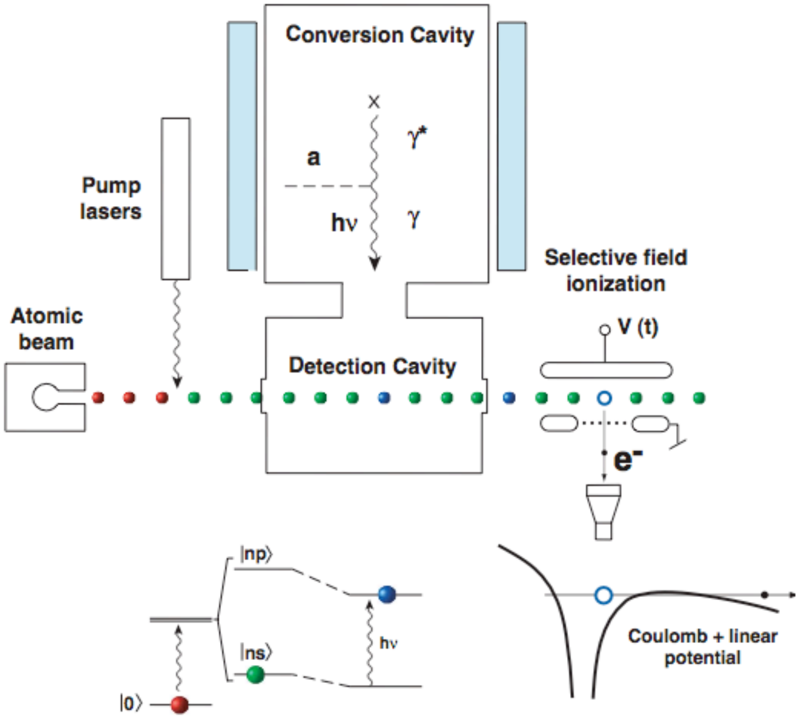
Potential for highly sensitive microwave photon detectors ("RF photo-multiplier tubes") realized by Kleppner and others in the1970's. The axion experiment is an ideal application for Rydberg atoms:

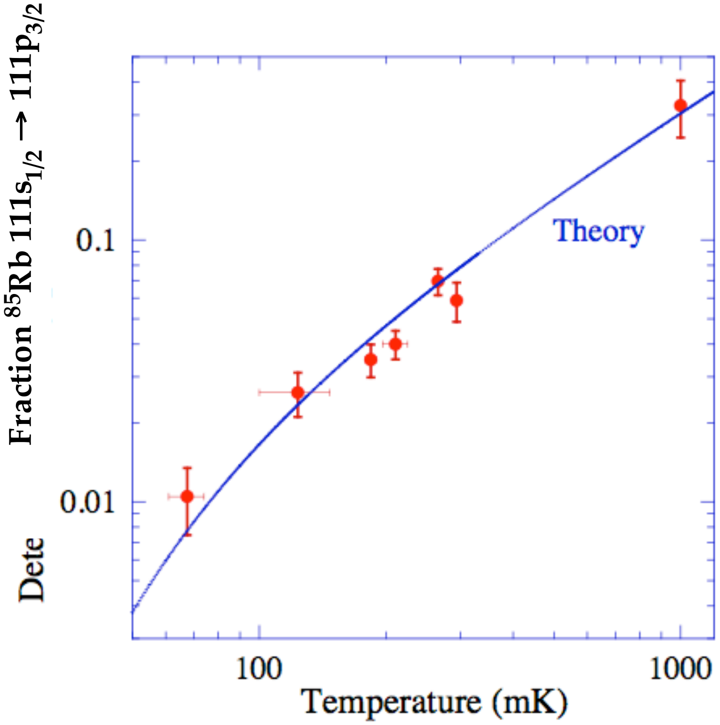
- *Large transition dipole moments* $\langle n \pm 1 | er | n \rangle \propto n^2 a_0$
- *Long liftetimes* $\tau_n \propto n^3 \quad (l \ll n); \quad \tau_{100} \approx 1\, m\,\mathrm{sec}$
- *Transitions span microwave range* $\Delta E_n = E_{n+1} - E_n \approx 2R/n^2\,; \quad \Delta E_{100} \approx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

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

$$h\nu = kT$$

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

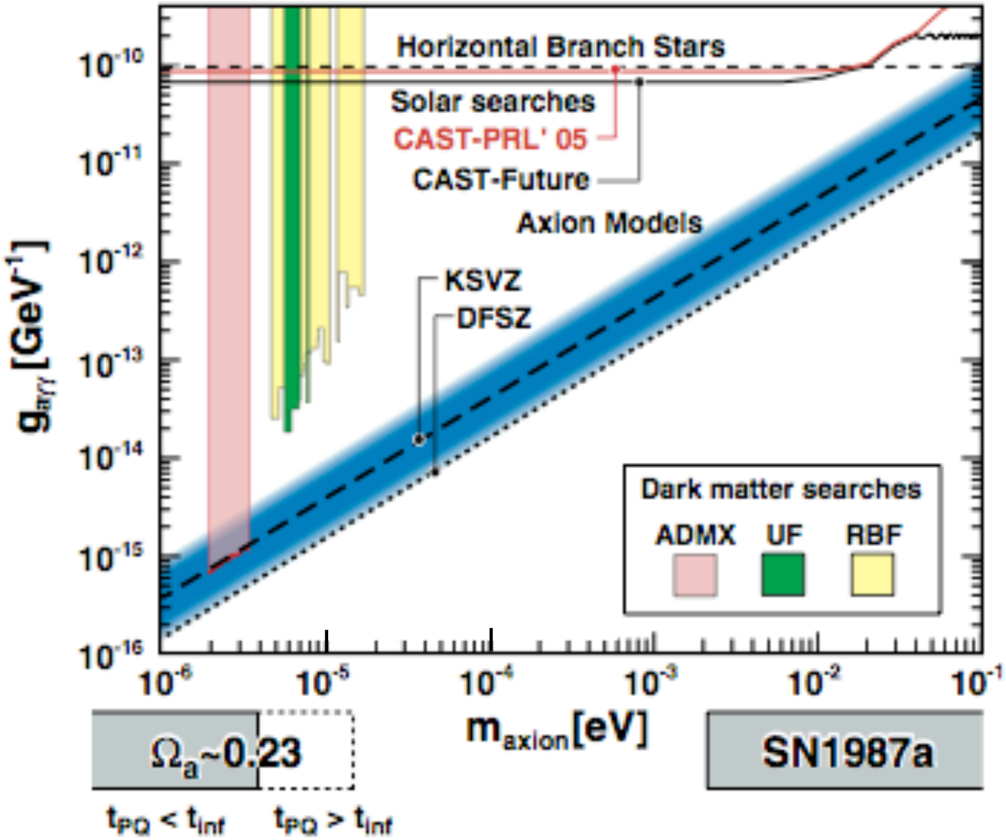




M. Tada et al., Phys. Lett. A (accepted)

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

Summary of axionic dark matter & microwave cavity searches



Cosmology bounds $m_a > 1\ \mu\text{eV}$

- *$\Omega_a \propto m_a^{-7/6}$, ~ O(1) for 1-10 μeV*
- *Why it's a good DM candidate*

Astrophysics bounds $m_a < 1$ meV

- *Sn1987a, stellar evolution & lab*

Model $g_{a\gamma\gamma}$ banded within ~10

- *From limited exploration by Kim*

ADMX already in region of interest

- *SQUIDs enable definitive exp't*

The ADMX upgrade is almost complete and will resume operation in 2007

Solar axion searches

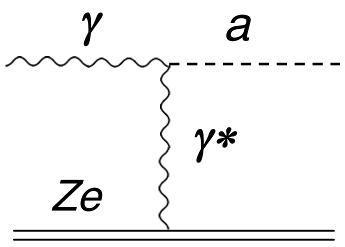
Solar axion spectrum

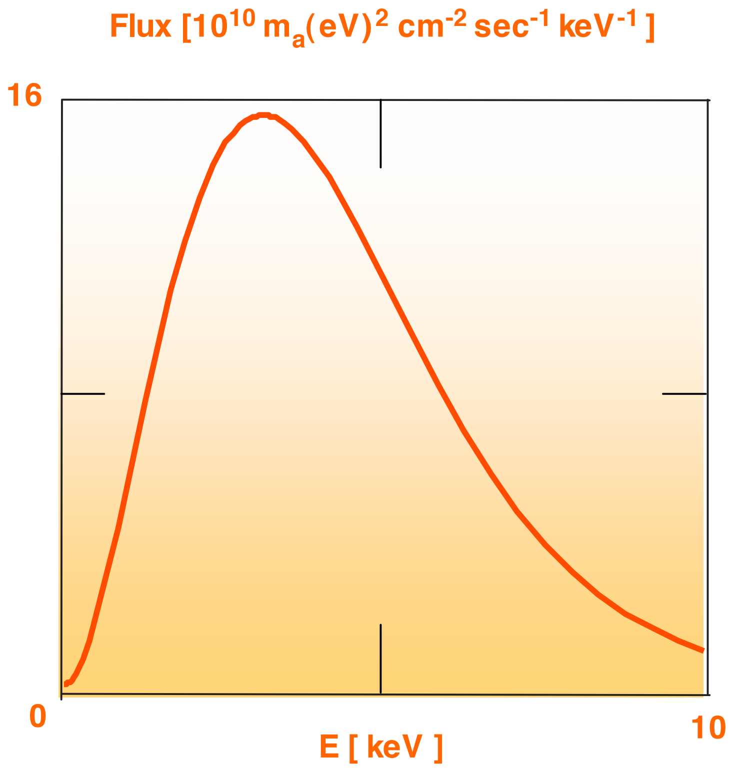
Axion-photon mixing & principle of the experiment

The CERN Axion Search Telescope (CAST)

Results, future plans

The solar axion spectrum





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

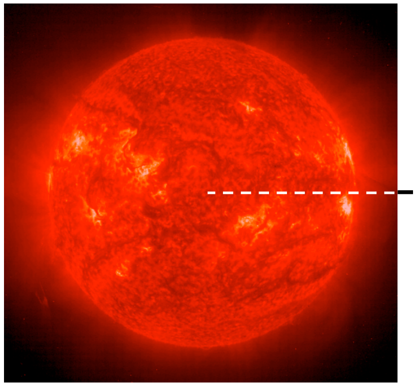
$T_{central}$ = 1.3 keV, but plasma screening suppresses low energy part of spectrum

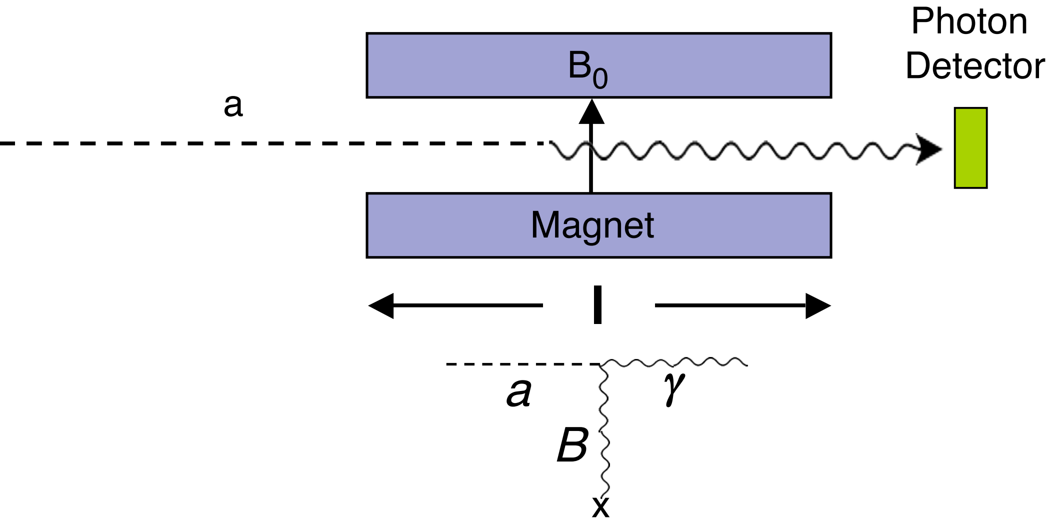
The total flux (for KSVZ axions) at the Earth is given by

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

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

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

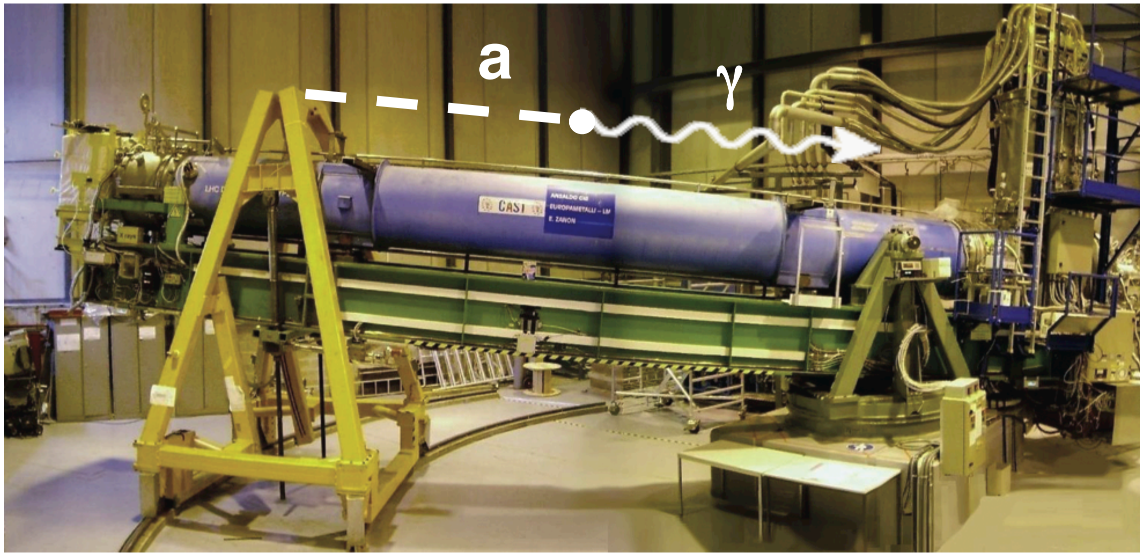




$$L_{a\gamma\gamma} = a g_{a\gamma\gamma} E \cdot B \quad \Longrightarrow \quad \Pi(a \leftrightarrow \gamma) = \frac{1}{4}\left(g_{a\gamma\gamma} B_0 L\right)^2 \left|F(q)\right|^2$$

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

The CERN Axion Solar Telescope (CAST)

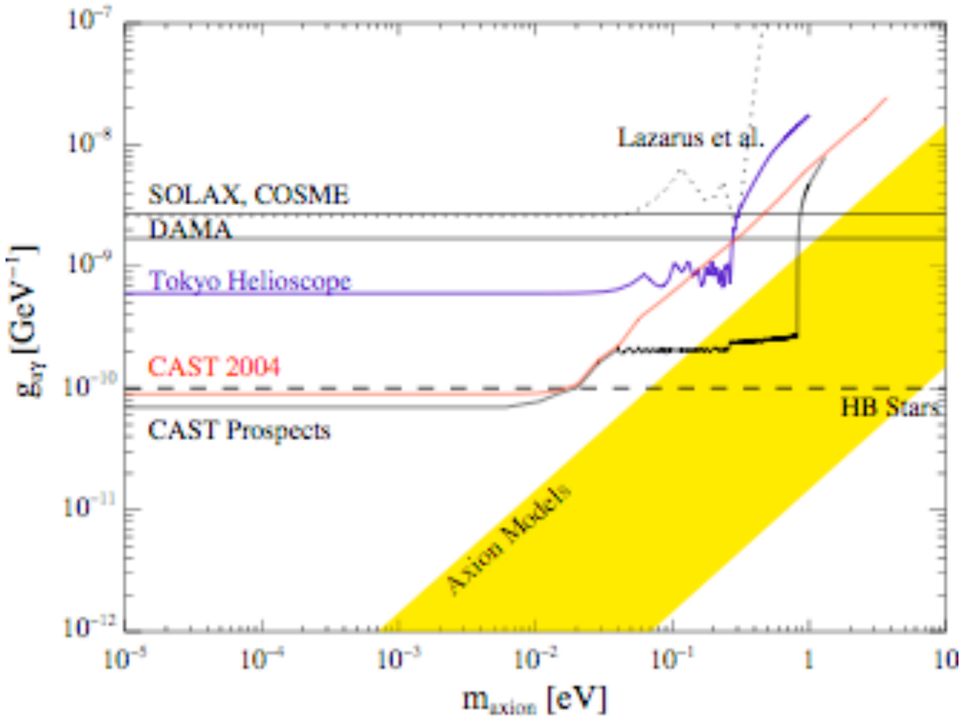


Prototype LHC dipole magnet, double bore, 50 tons, L~10m, B~10T

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

LLNL is providing ^{3}He for the Phase II run, and fabricating a second x-ray optic

Purely laboratory experiments

Photon regeneration

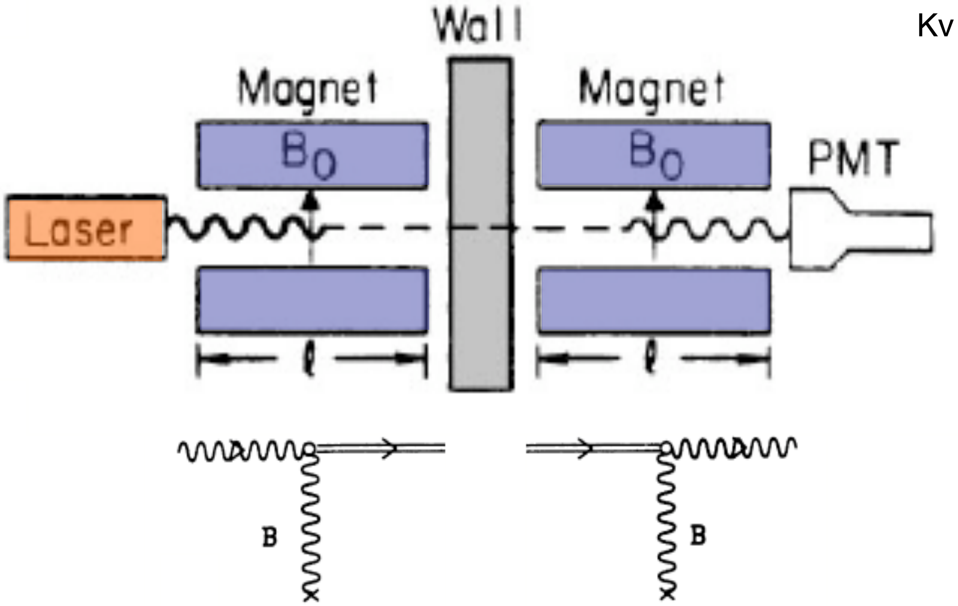
Optical activity of the vacuum

Magnetically-induced vacuum birefringence & dichroism

The PVLAS results

Photon regeneration *(a.k.a. "shining light through walls")*

KvB et al. PRL 59, 759 (1987)



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

Difficult to push down to competitive values of the axion-photon coupling

Only measurement to date $g < 7.7 \times 10^{-7}$ GeV^{-1} for $m_a < 1$ meV @ BNL

[G. Ruoso et al., Z. Phys. C. 56, 505 (1992)] – but several in preparation now

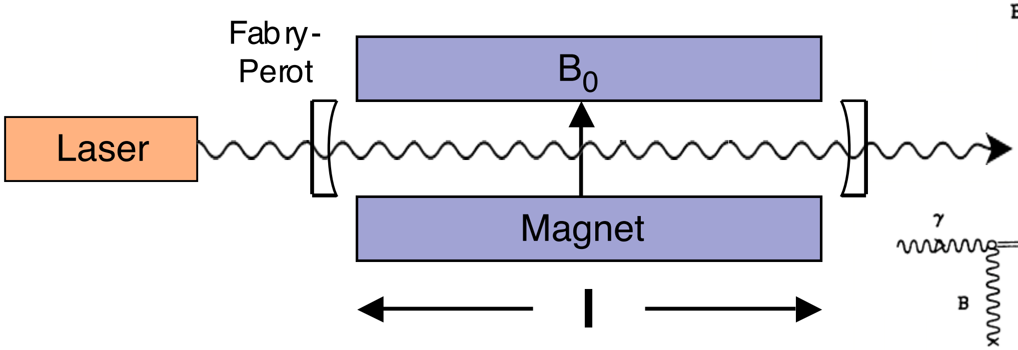
Vacuum birefringence & dichroism

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

Vacuum dichroism

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

(N = number of passes)



Vacuum birefringence

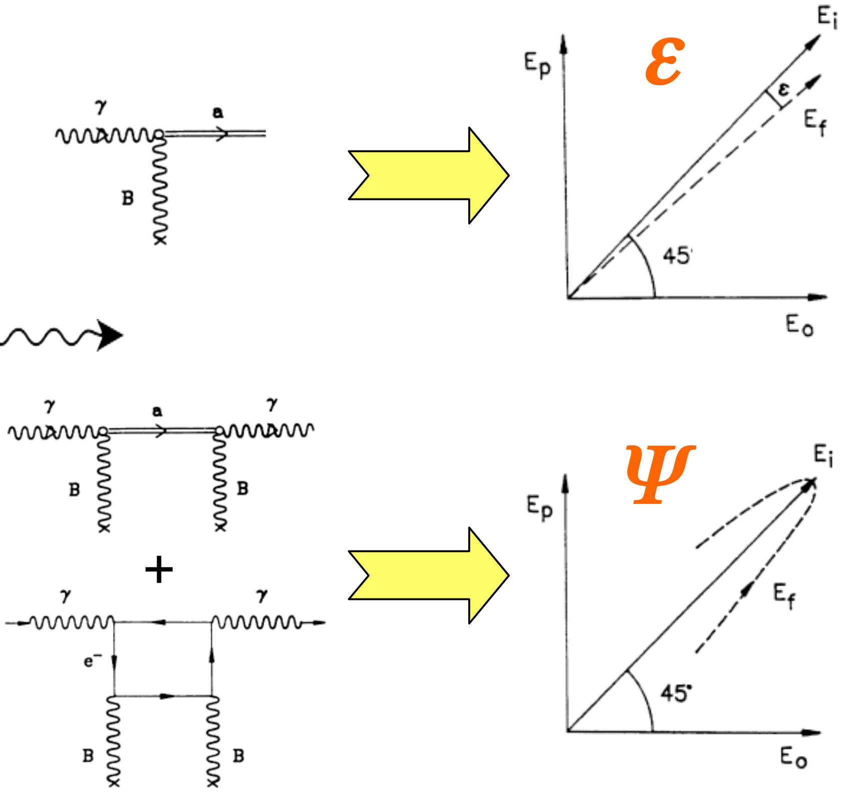
QED:

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

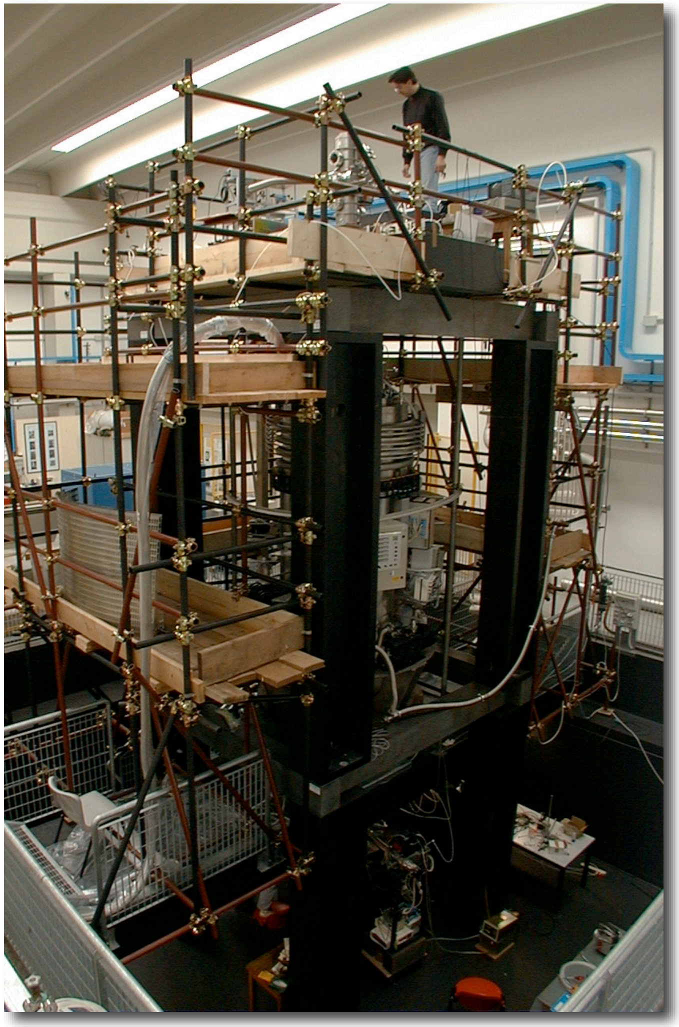
$\xi = \alpha/45\pi\, (B/B_{crit})^2$, $B_{crit} = m_e^2/e \sim 4.41 \times 10^{13}$ G

Axion:

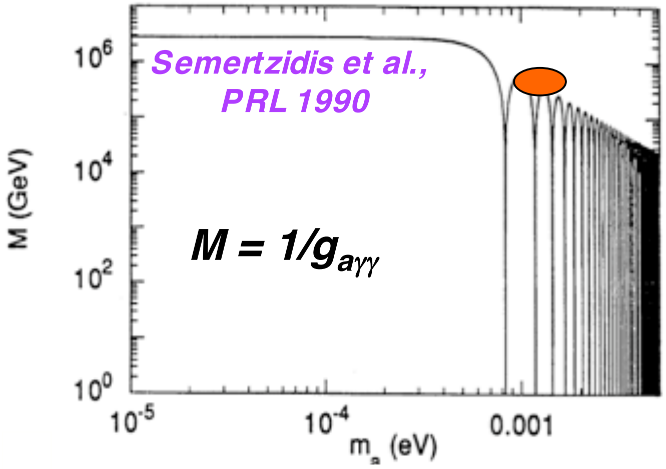
$\Psi = N \cdot (1/96) \cdot (g\, B_0 m_a)^2 \cdot L^3/\omega$

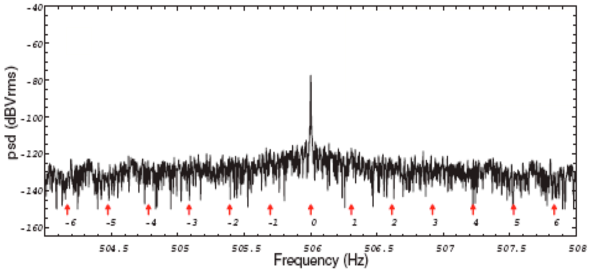


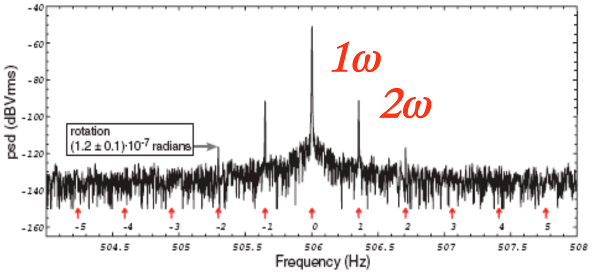
The PVLAS experiment (INFN Legnaro)



Zavattini et al., PRL 2006



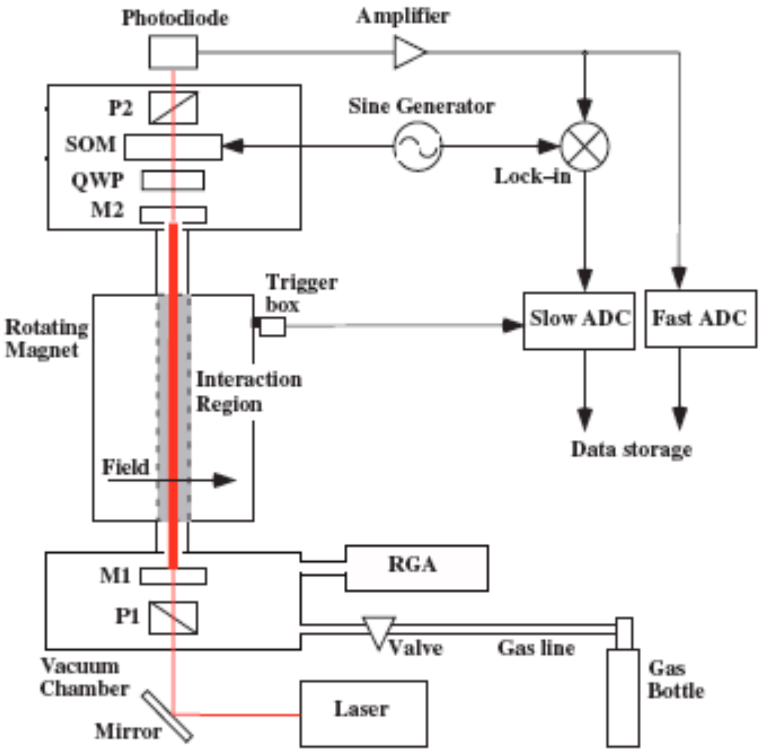




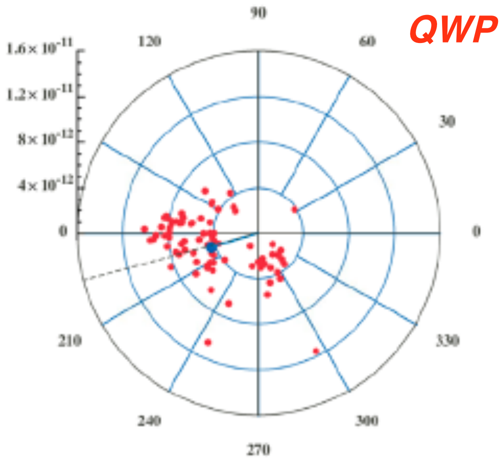
rotation
$(1.2 \pm 0.1)\cdot 10^{-7}$ radians

PVLAS details & data

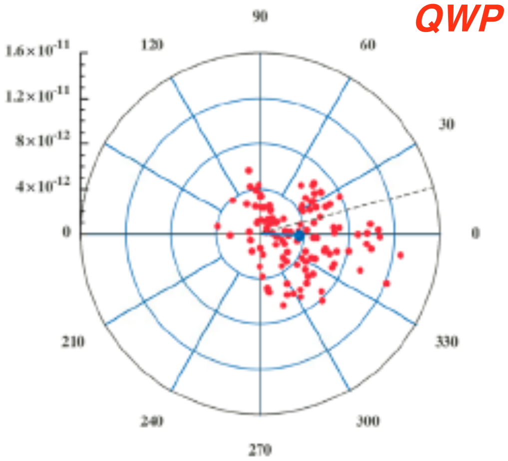
PVLAS Schematic



Phase-Amplitude Plot



QWP = 0 °



QWP = 90 °

The PVLAS results are intriguing but very odd

The experimenters had hoped to see the QED effect (“light-by-light” scattering), but their sensitivity was not good enough by many orders of magnitude

Their value of $g_{a\gamma\gamma}$ *is 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

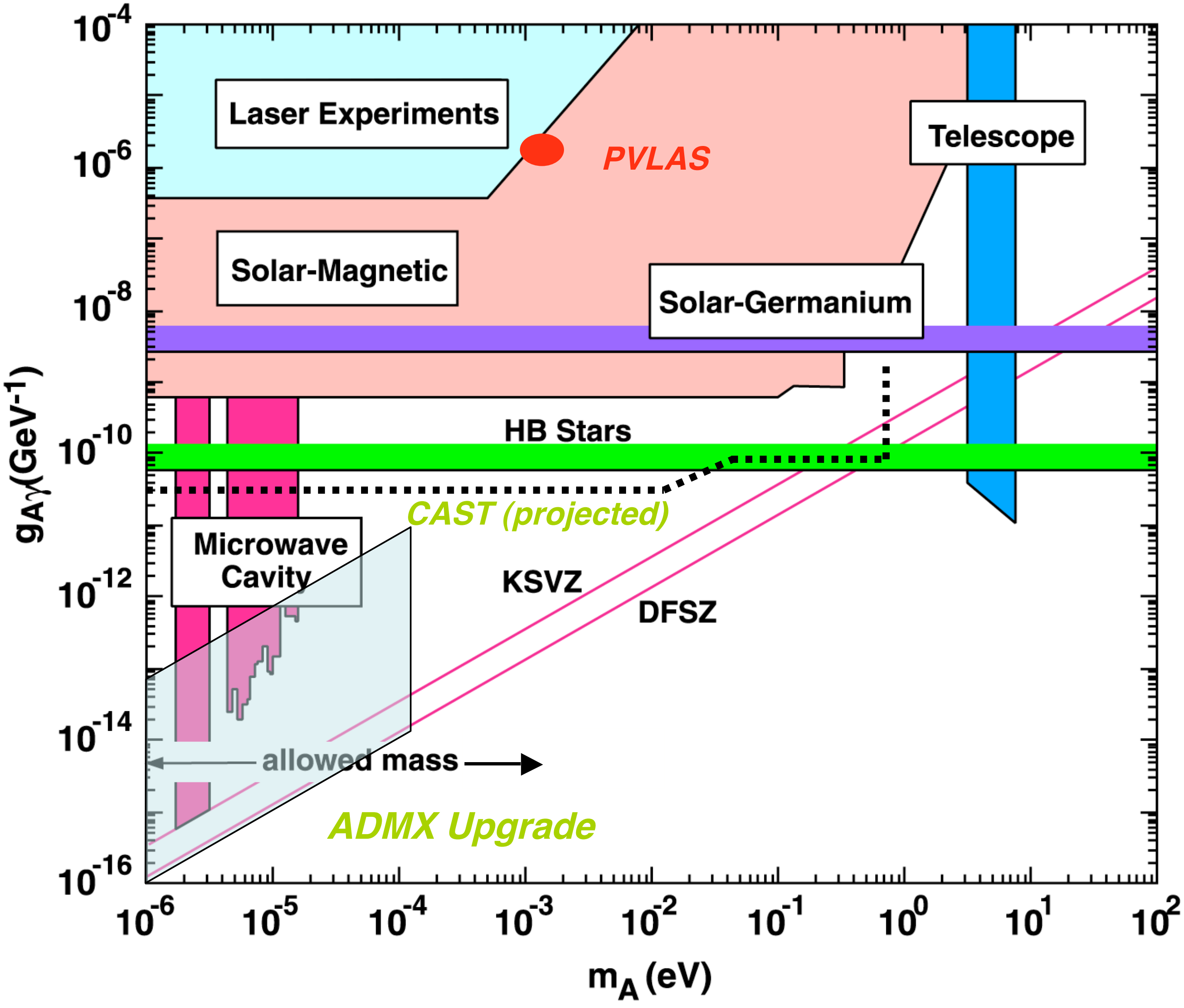
The signal is extremely small: 3.9 x 10^{-12} *rad/pass – the angular width of a pencil lead on the Moon viewed from Earth*

There are evident systematic issues with the experiment: large run-to-run variations in the data, many times the estimated error per point; the unexplained 1ω *peak; anomalous dichroism with gases at low pressure, etc.*

The effect of stray magnetic fields on the optics, particularly on the Fabry-Perot mirrors may be suspected; this was problematic for the earlier RBF experiment

Nevertheless, this result has launched half a dozen polarization-rotatation experiments around the world, and much theoretical work!

Excluded g_{Agg} vs. m_A with all experimental and observational constraints



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Summary & final remarks

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)*

Experiments are making excellent progress, and discovery would teach us a lot

- *Discovery of dark-matter axions could reveal the detailed history of our galactic evolution*
- *Discovery of solar axions would give us an unprecented picture of the nuclear-burning core*
- *Discovery of axions in the laboratory would have imponderable consequences*

Experiments have challenges

– *Cavity experiments:*	*With SQUID amps, sensitivity is not an issue, but mass may be*
– *Solar helioscope:*	*The sensitivity will beat the HB limit, but not by much*
– *Lab experiments:*	*While independent of astrophysics/cosmology, the limits are weak*

But remember – Physics is where you find it!