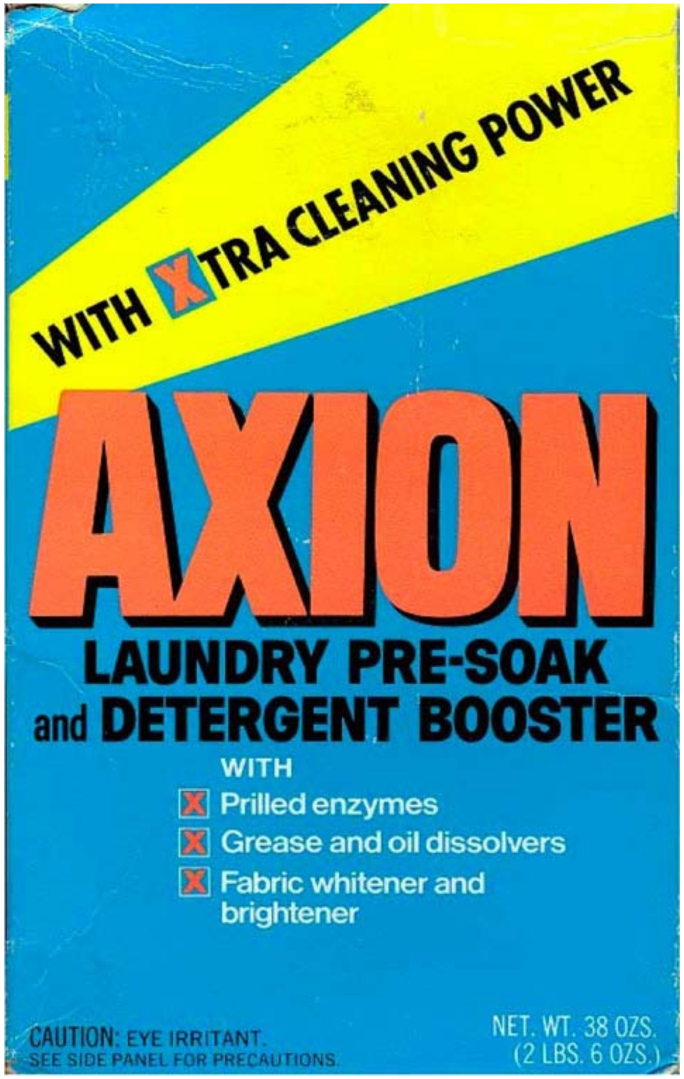
Axions:

A Clean Solution to Strong CP and Dark Matter?

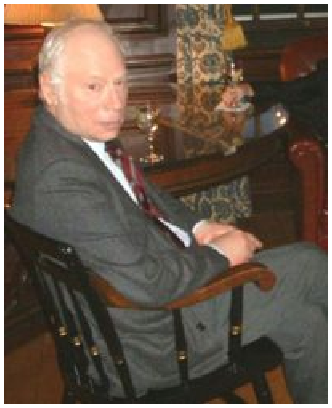


History:

- Strong CP problem
  - Naively, the QCD Lagrangian has CP violating terms
  - So why is the neutron EDM so small?
    - Current limits: $\theta_{\text{eff}} \leq 10^{-10}$
- Could there be a new symmetry?
  - Peccei-Quinn suggested new U(1) symmetry
  - Assumed symmetry breaking scale to be the electroweak scale

History:

- Weinberg and Wilczek realized PQ solution requires existence of a pseudoscalar
  - Mass, couplings are inversely proportional to symmetry breaking scale
  - Electroweak scale implies $m_\mathrm{a} \approx 100$ keV
    - Coupling would be large enough that the axion would be observable in accelerators
    - Quickly excluded by experiment



Steven Weinberg

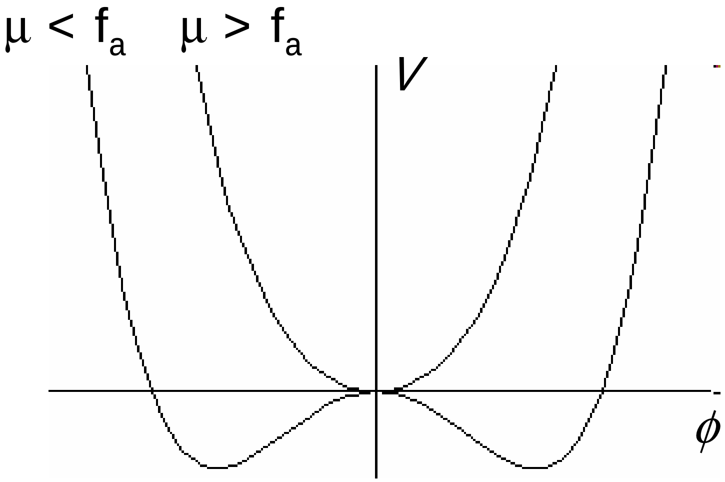
Frank Wilczek

Symmetry Breaking

- Consider the Lagrangian:

$$\mathcal{L} = \frac{1}{2}[(\partial\phi)^2 - (\mu^2 - f_a^2)\phi^2] - \frac{\lambda}{4}\phi^4$$

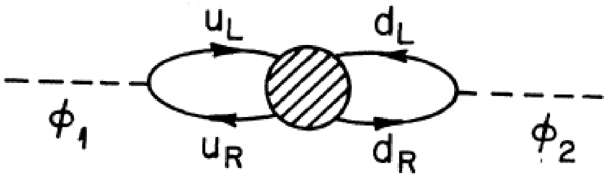
- Choice of vacuum breaks symmetry



$$V(\phi) = \frac{1}{2}(\mu^2 - f_a^2)\phi^2 + \frac{\lambda}{4}\phi^4$$

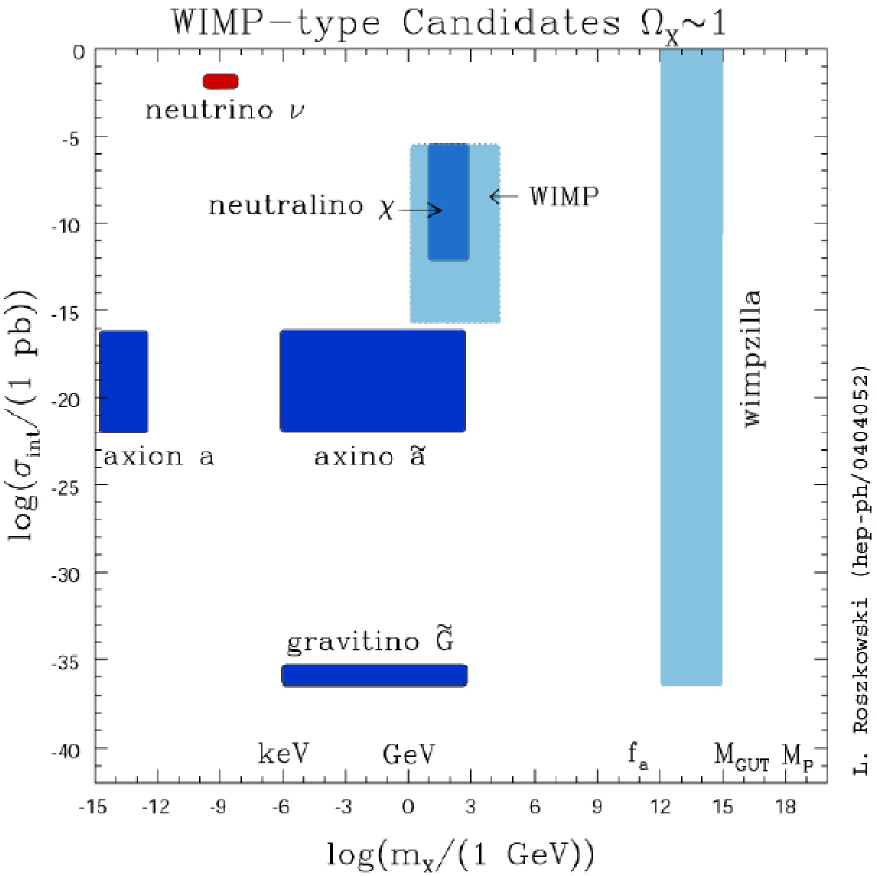
- For U(1) symmetry, the potential is minimized when $|\phi|^2 = v$
- Massless boson corresponding to excitations around the circle of minima

Axion acquires mass through interactions



History:

- What if PQ symmetry breaking scale (f_a) is much larger than the electroweak scale?
  - “Invisible axion” models

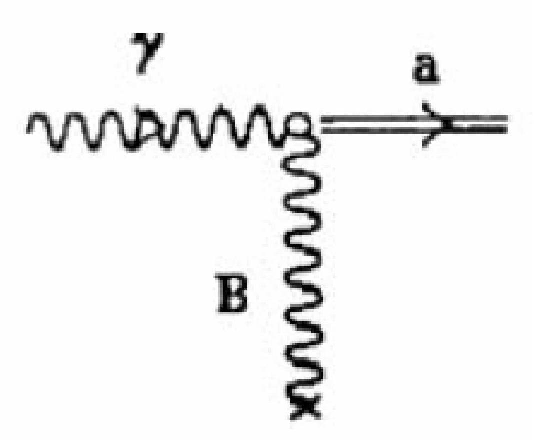


- Cosmological abundance increases!
  - $\Omega_a \propto f_a^{7/6}$
  - Well-motivated candidate for Cold Dark Matter

Primakoff Effect

- Laboratory searches use the axion-photon coupling:

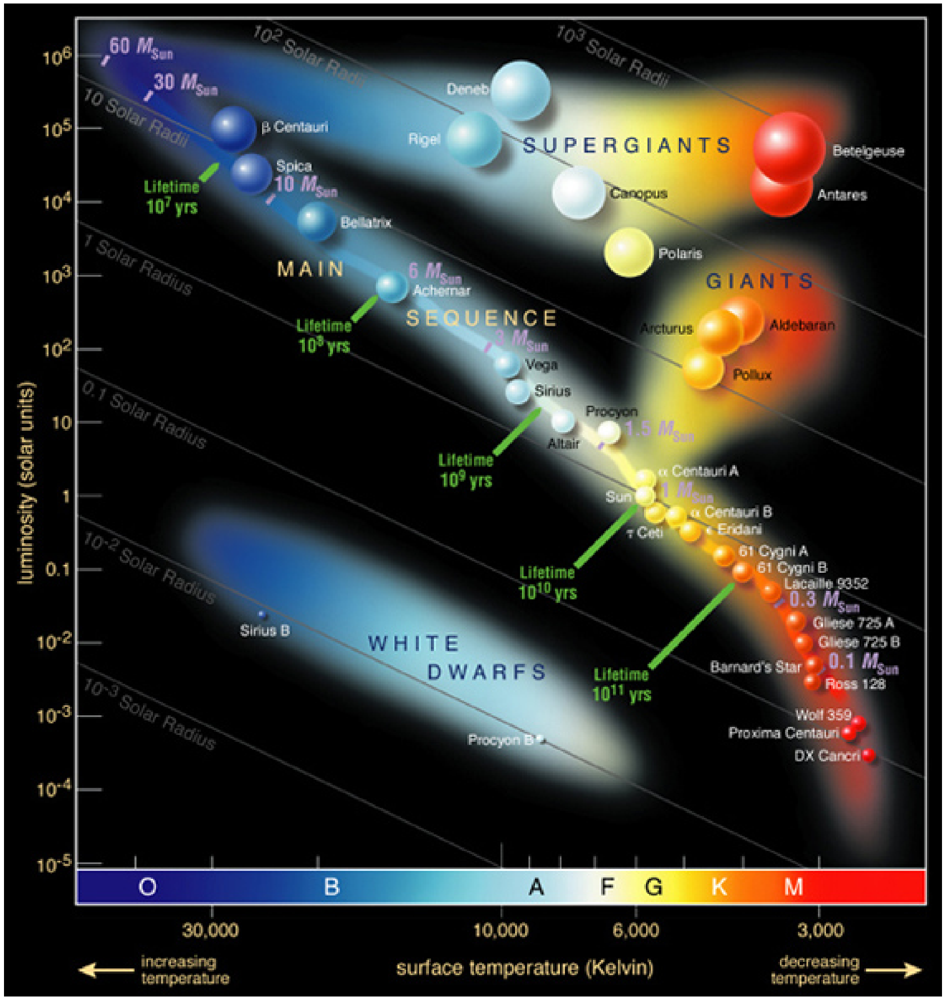
$$\mathcal{L}_{A\gamma\gamma} = -g_{\gamma}\frac{\alpha}{\pi}\frac{A(x)}{f_A}\vec{E}\cdot\vec{B}$$



- This can lead to the conversion of an axion to a photon in a magnetic field, or vice versa

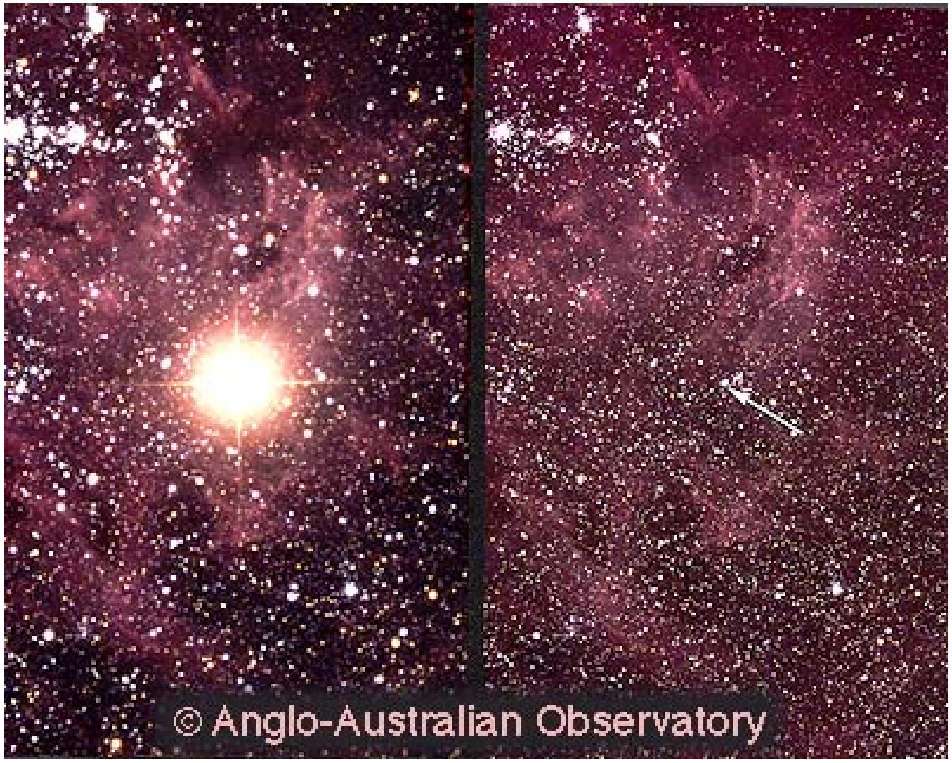
Looking for “Invisible Axions”

- Astrophysical constraints:
  - Stellar evolution in globular clusters
  - Limits energy loss by axion emission
  - Most accurate limits come from ratio of HB stars



Astrophysical Constraints

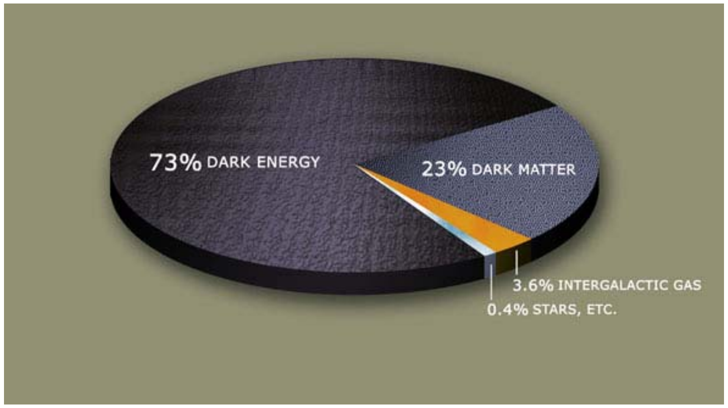
- Neutrino flux from Supernova 1987 A observed by Kamiokande, IMB, BNO



- Duration of a few seconds
- Indicates cooling primarily by neutrinos
- Limits axion coupling, mass

Cosmological Constraints

- Astrophysical observations give upper limits on mass, coupling
- Inflation and string models give lower limits
  - $\Omega_{\mathrm{CDM}} \approx 0.22$
  - $\Omega_a \propto f_a^{7/6}$ (independent of exact mechanism)



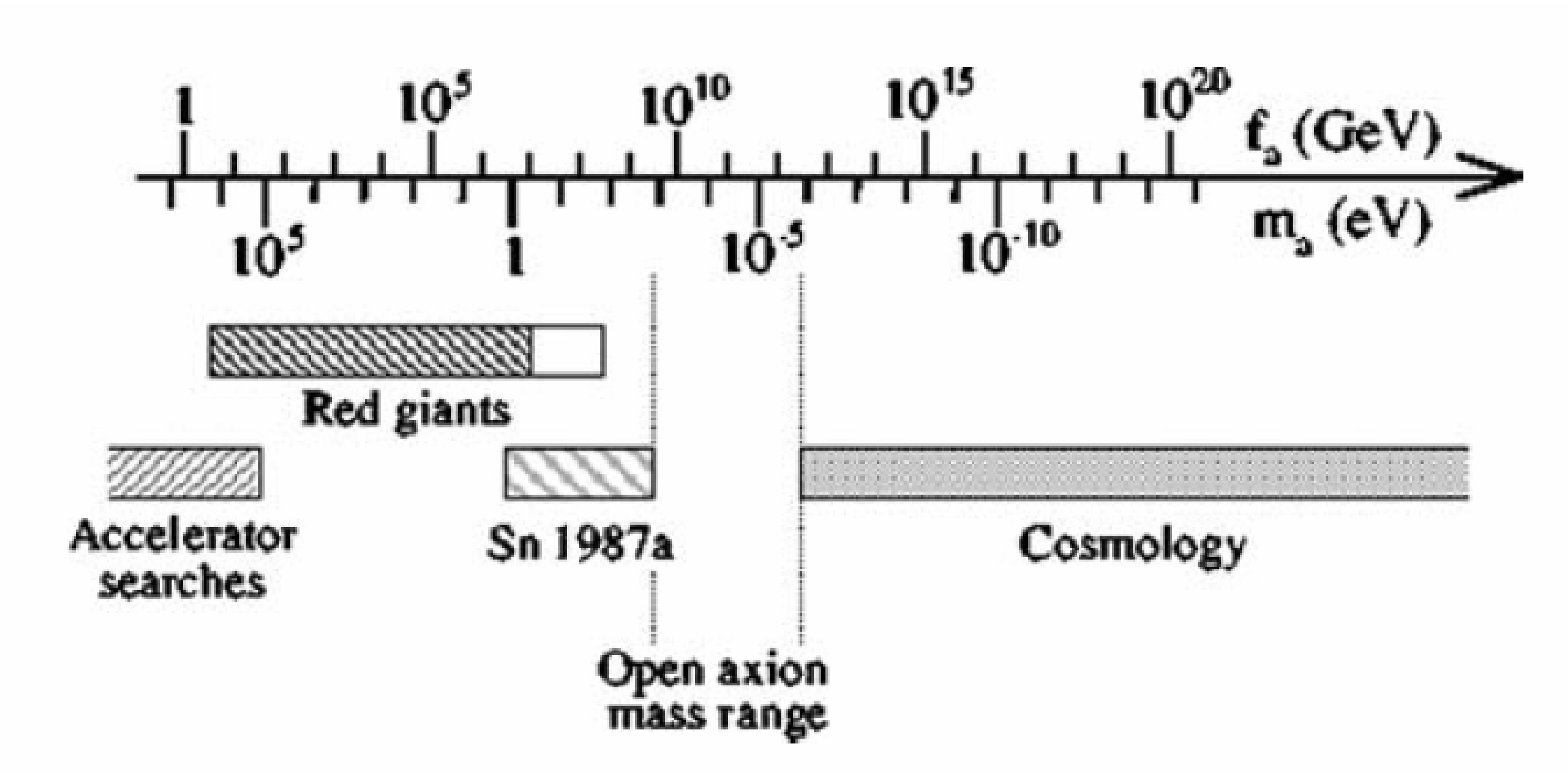
- This leaves a range $10^{-6} < m_a < 10^{-3}$ eV
  - Axion with $m_a \approx 10^{-5}$ is a candidate for CDM

How Can Axions be “Cold”?

- Dark matter should be non-relativistic before structure formation
  - For $m_A = 10^{-5}$ eV at 2.7 K = 2×10^{-4} eV
  - These “thermal” axions would be relativistic

- Also have axions produced at QCD phase transition
  - “Non-thermal” axions are cold and form BE condensate

Summary of Astrophysical Constraints



Laboratory Searches

- Using the Primakoff Effect, several types of experiments have been performed:

  - Microwave Cavity Experiments
  - Axion Helioscopes

Rely on
astrophysical
sources of axions

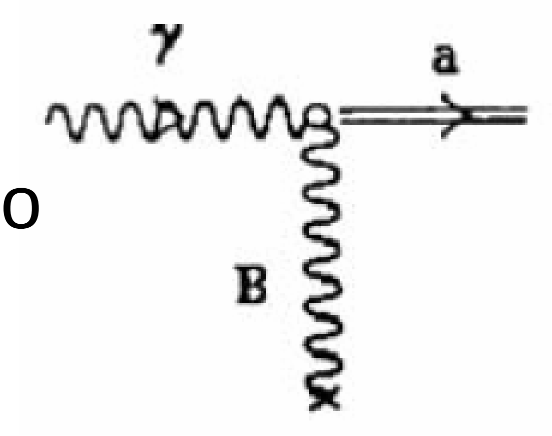
  - Polarization Effects
  - Photon Regeneration

Produce axions
directly in the lab

Microwave Cavity Experiments

- High-Q cavity placed in large magnetic field
  - Stimulated conversion of axions to microwave photons:

    $f = E / h \approx m_A / h$



  - For $m_\text{A} = 10^{-5}$ eV then f = 2.4 GHz

- Need to be able to tune cavity since m_A unknown

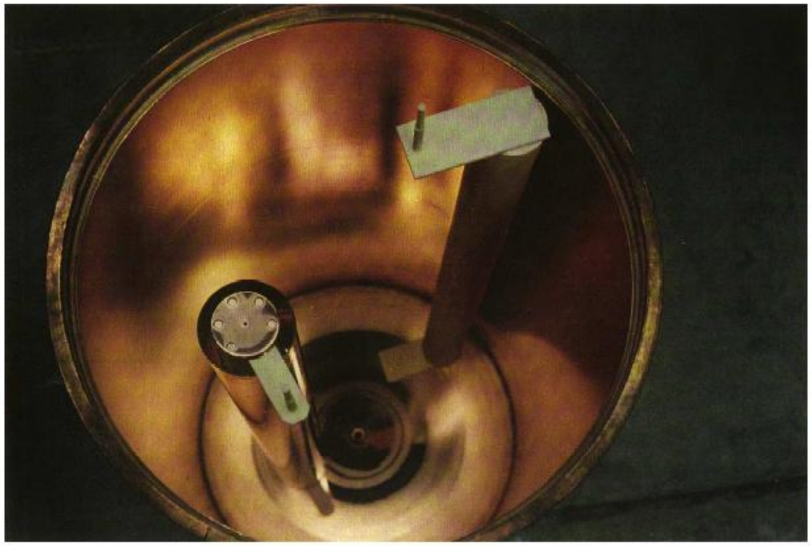
Microwave Cavity Experiments

- Proof of concept: University of Florida and Rochester-Brookhaven-Fermilab (late 80s)
  - Sensitivity several orders of magnitude lower than needed for realistic axion models

- Second generation experiments:
  - Axion Dark Matter Experiment (ADMX)
  - Cosmic Axion Research using Rydberg Atoms in a Resonant Cavity in Kyoto (CARRACK)

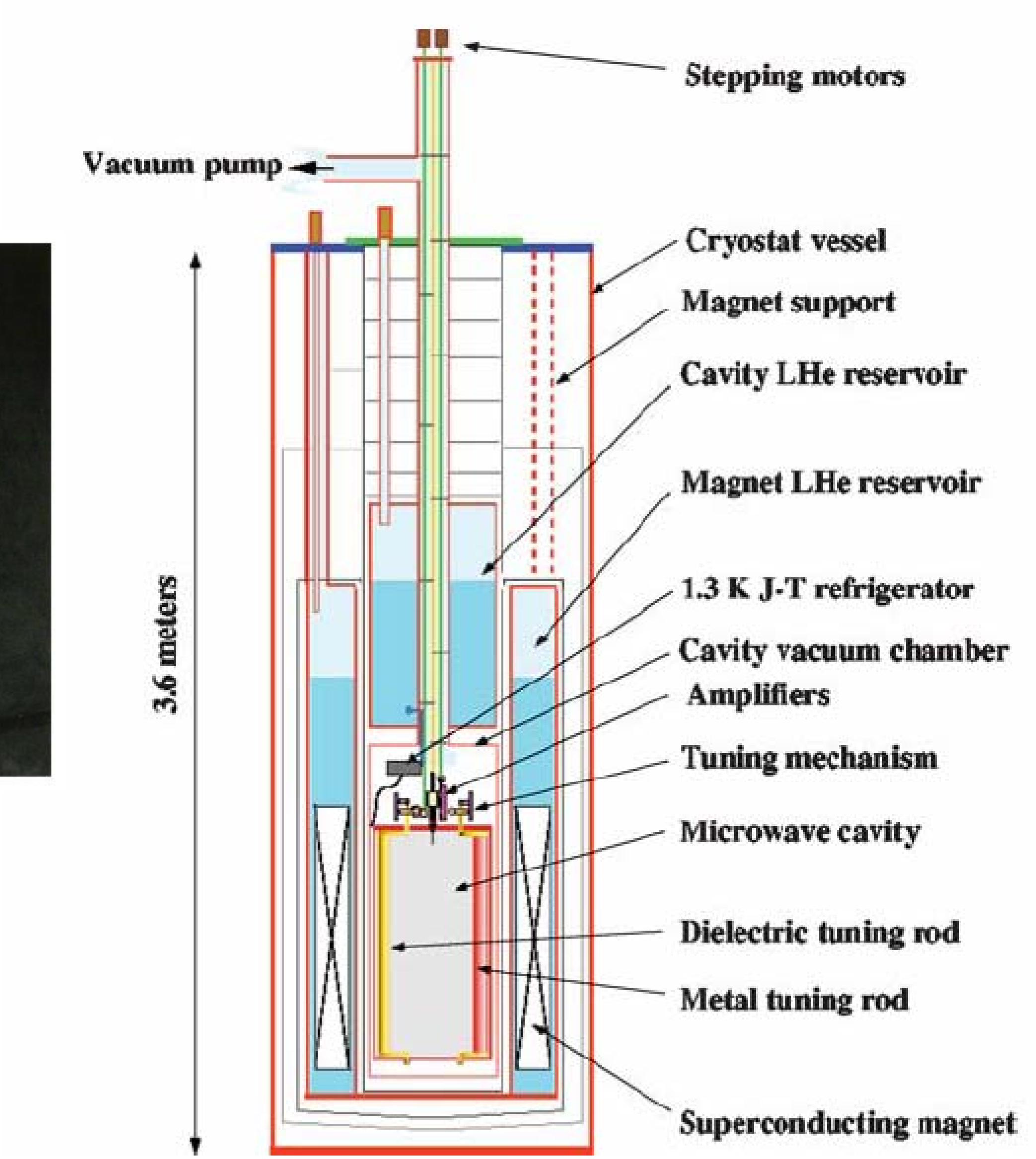
ADMX

Resonant Cavity:



h = 1.0 m
D = 0.5 m
B = 8.5 T

Q $\approx$ 10^5



ADMX

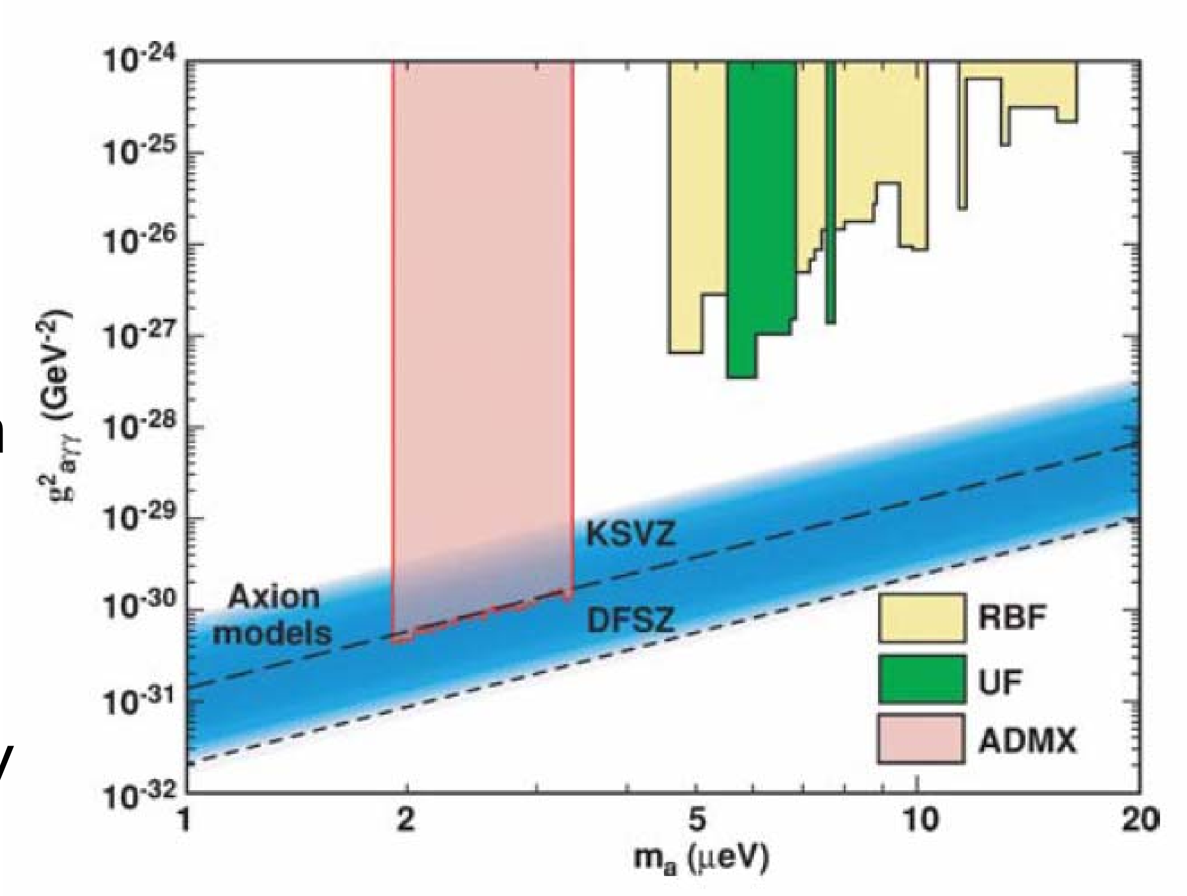
- Axion signal would show up as excess power above background
  - $E_a = m_a + m_a \beta^2 / 2$
  - For halo axions, $\beta = 10^{-3}$
    - $\Delta f / f \sim 10^{-6}$
- Diurnal, annual modulation
  - $\beta_{\mathrm{rot}} \sim 10^{-6}$, $\beta_{\mathrm{rev}} \sim 10^{-4}$
- Late infalls could show up as narrow peaks with much higher signal to noise
  - Intrinsic widths ~ 10^{-17}

ADMX

- Ran from 1996 – 2004
  - Excluded KSVZ axions for $1.86 < m_A < 3.36\ \mu\text{eV}$

- Currently being upgraded
  - GHz SQUID amplifiers, dilution refrigerator
  - Goal: DFSZ axions for

    $1 < m_A < 10\ \mu\text{eV}$

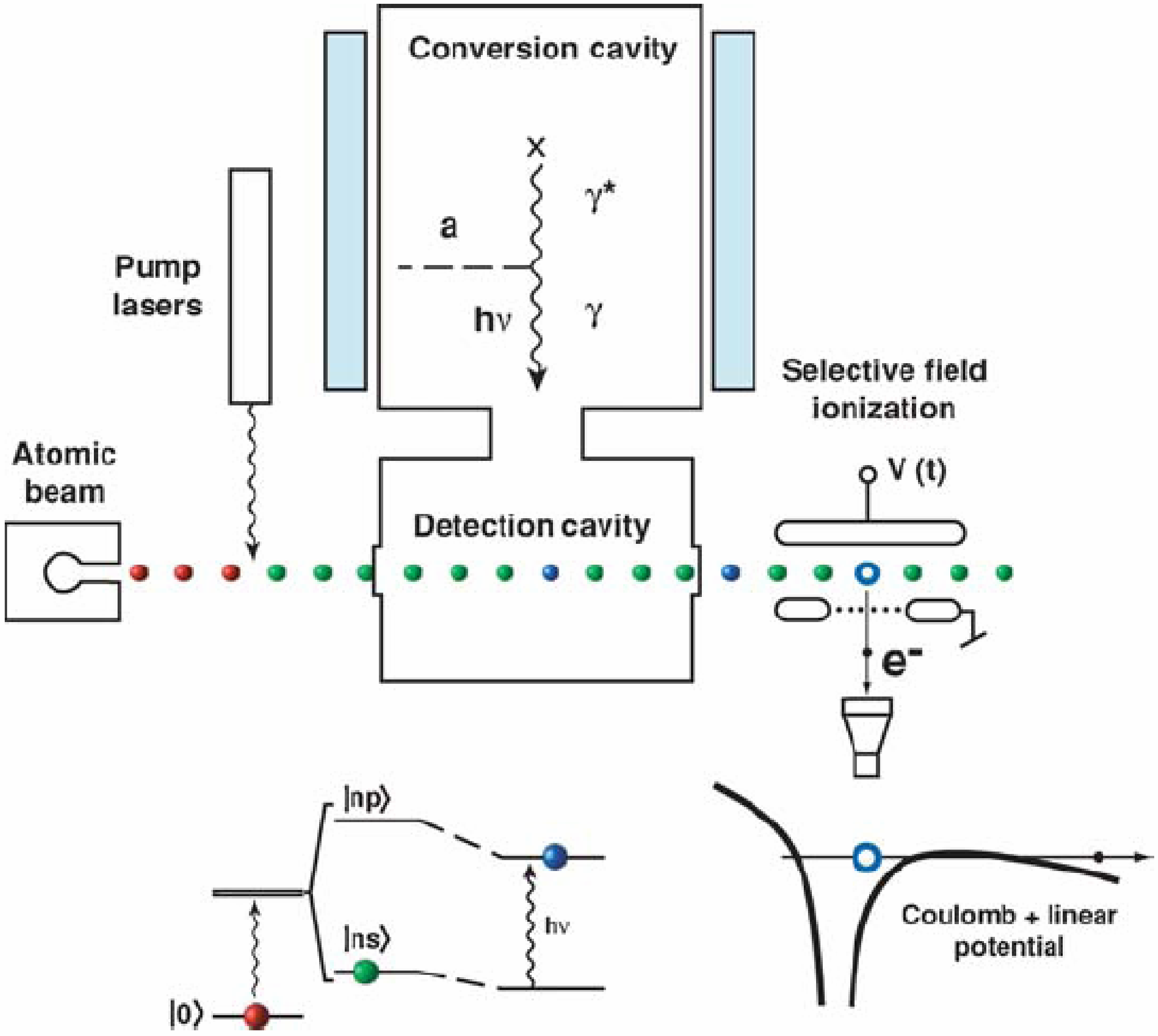


CARRACK

- Same front end as ADMX, but photon detection done with Rydberg atoms
  - Atoms with single electron with n >> 1
  - Transitions in microwave range:

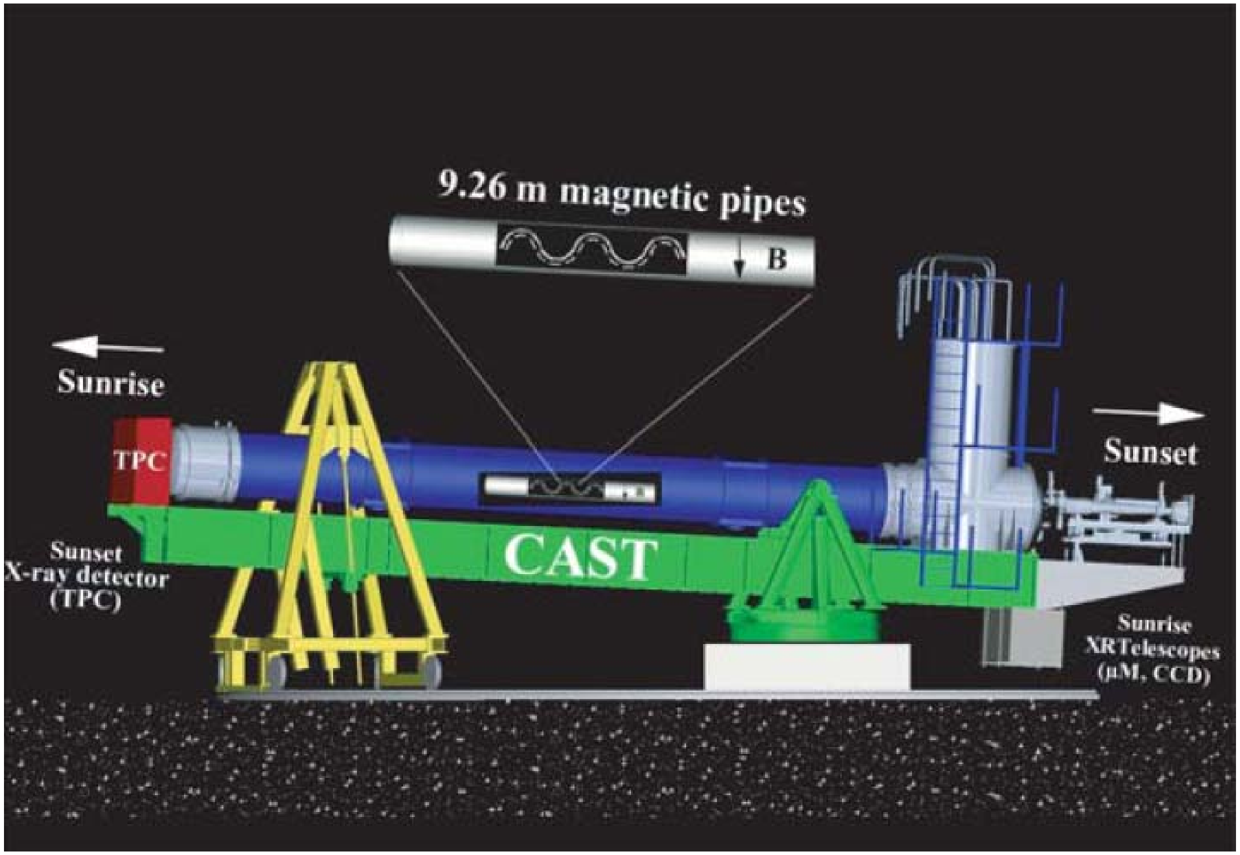
    e.g. $E_{100} - E_{99} \approx 7$ GHz
  - Long lifetimes: $\tau_{100} \approx 1$ msec
- ^{85}Kr optically pumped into $|111\ s_{1/2}\rangle$
- Use Stark effect to tune splitting with $|111\ p_{3/2}\rangle$ to the cavity frequency
- Selectively ionize excited atoms

Rydberg Atom Detection



Axion Helioscopes

- BNL (1992), Tokyo Axion Helioscope (2002)
- 3rd Generation: CERN Axion Telescope (CAST)
  - Refurbished LHC test magnet



L = 9.26 m

D = 6 cm

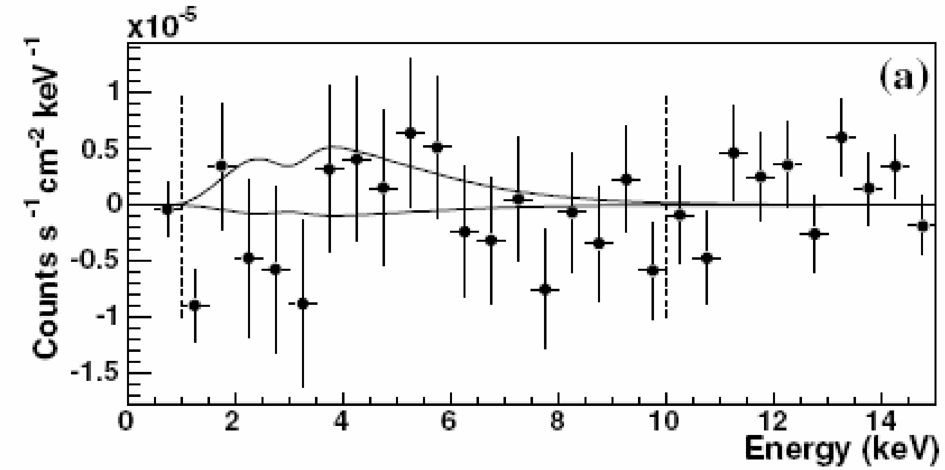
B = 9.0 T

CAST

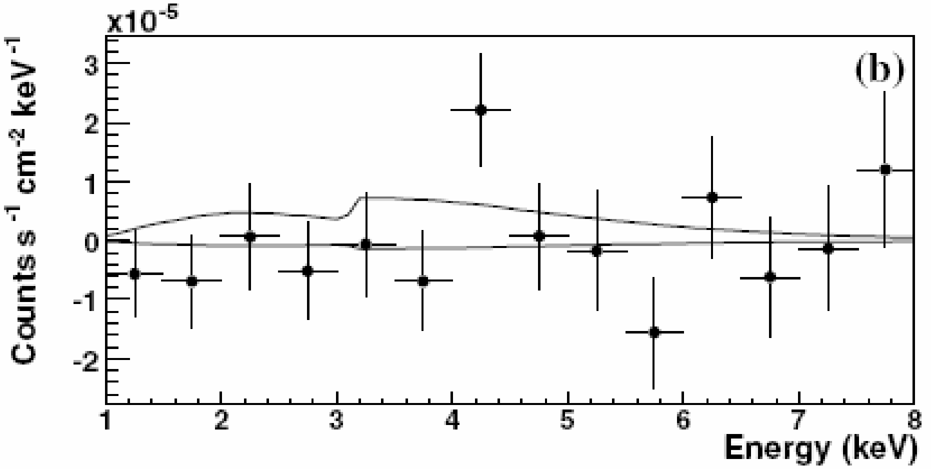
- Points at sun 1.5 h during sunrise and sunset nearly all year
  - Detector backgrounds measured at other times
  - Roughly 10 times longer exposure during nonalignment
- Operated ~6 months (May – Nov 2003)

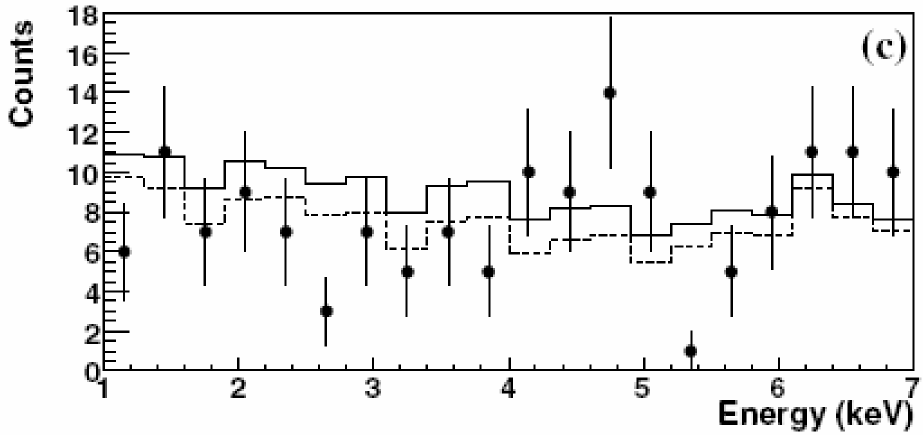
CAST

Time Projection Chamber (TPC)



Smaller MICROMEGAS gaseous chamber



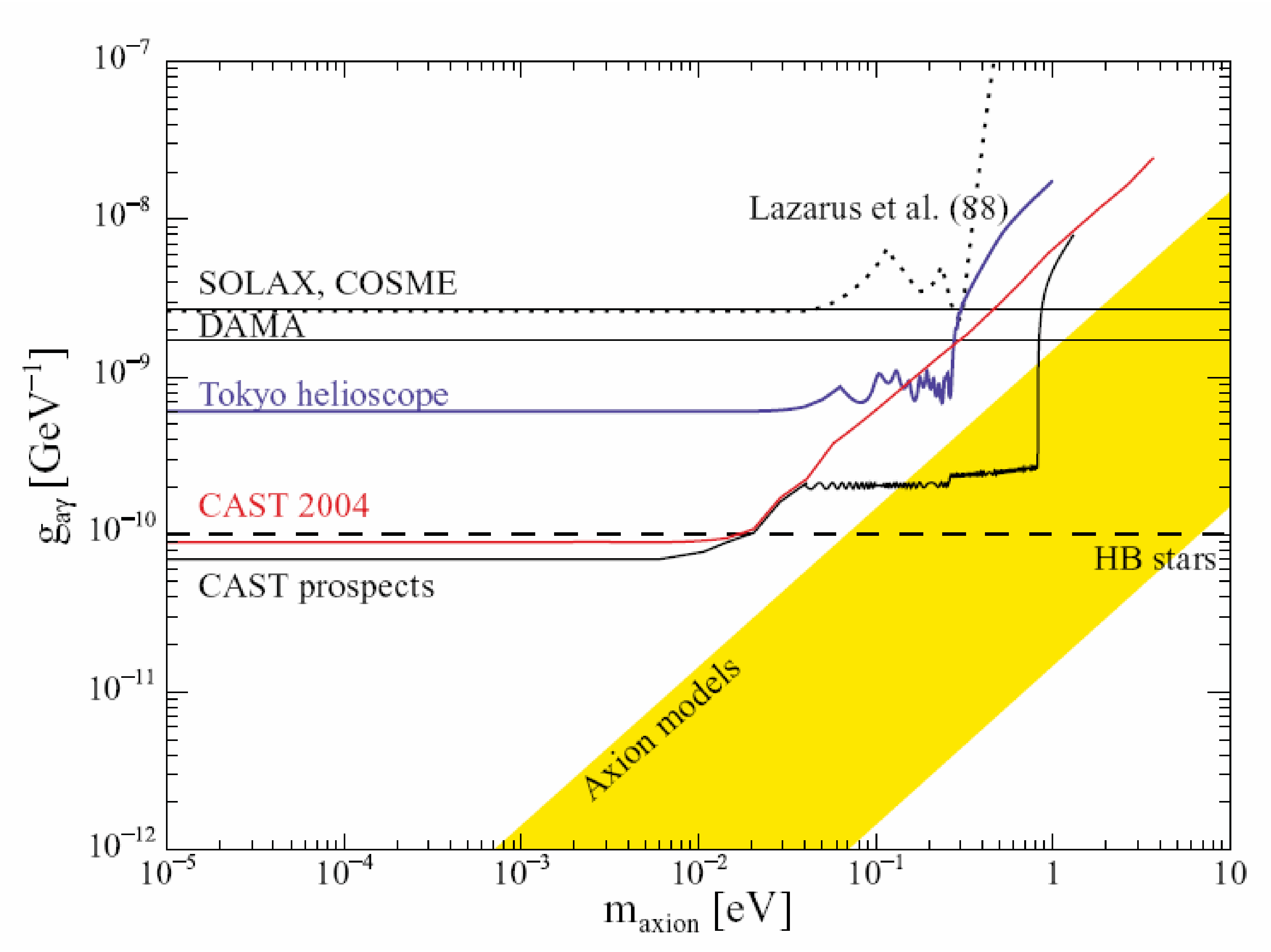


X-ray mirror system with CCD

Higher Masses

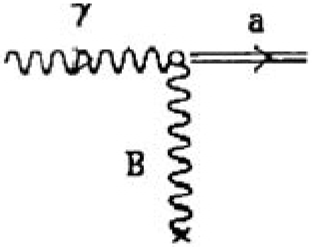
- Upgrade underway:
  - Fill with refractive gas ^{4}He or ^{3}He to modify photon dispersion relation and probe higher masses
- For best conversion probability, $qL \leq 1$
  - $q = k_\gamma - k_a = \omega - (E_a^2 - m_a^2)^{1/2} \approx m_a^2 / 2E_a$
- Refractive gas slows propagation
  - Adds effective mass term to photon dispersion relation
  - $q \rightarrow |m_\gamma^2 - m_a^2| / 2E_a$

CAST

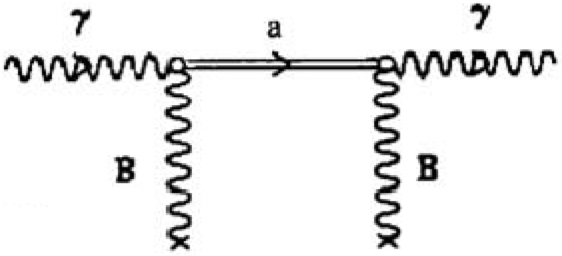

10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$g_{a\gamma}$ [GeV^{-1}]
Lazarus et al. (88)
SOLAX, COSME
DAMA
Tokyo helioscope
CAST 2004
HB stars
CAST prospects
Axion models
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
m_{axion} [eV]

Polarization Effects

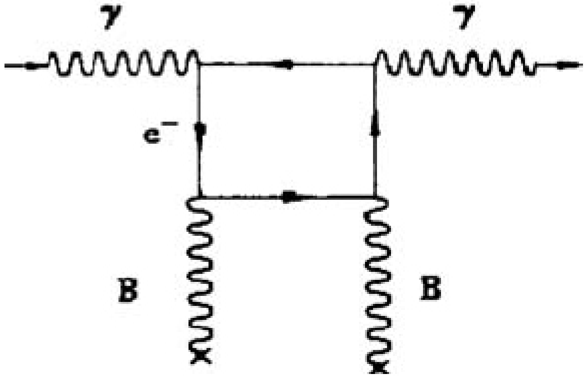
- Linearly polarized light passing through magnetic field



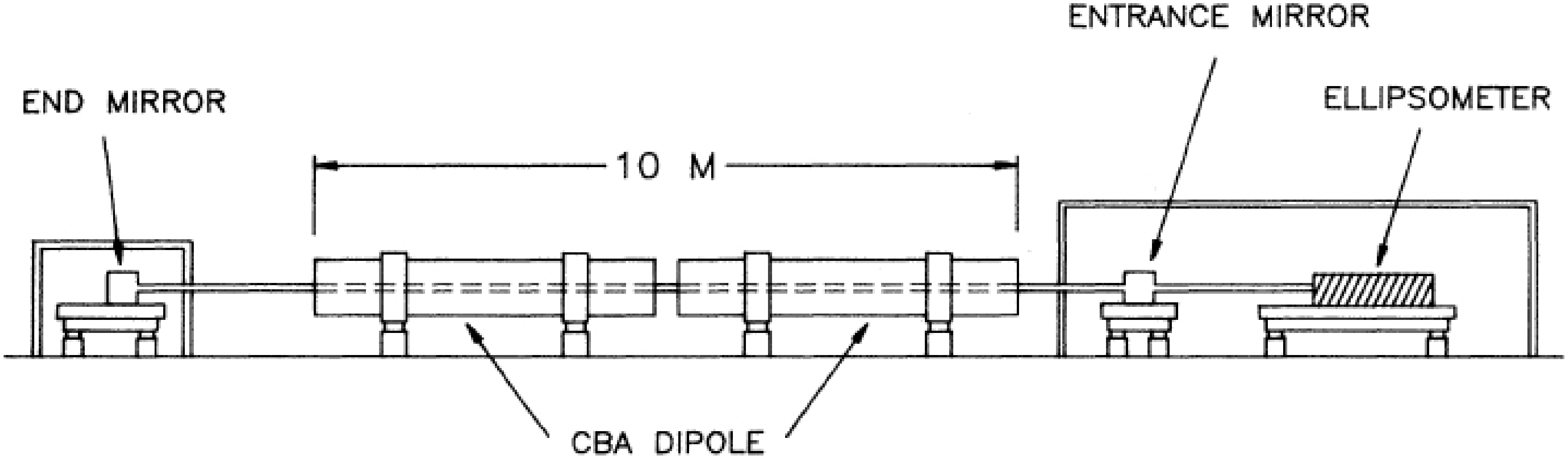
- Primakoff effect reduces parallel component, perpendicular component unchanged
  - Rotates the plane of polarization



- Bottom two diagrams give vacuum birefringence
  - Changes linear polarization to elliptical polarization

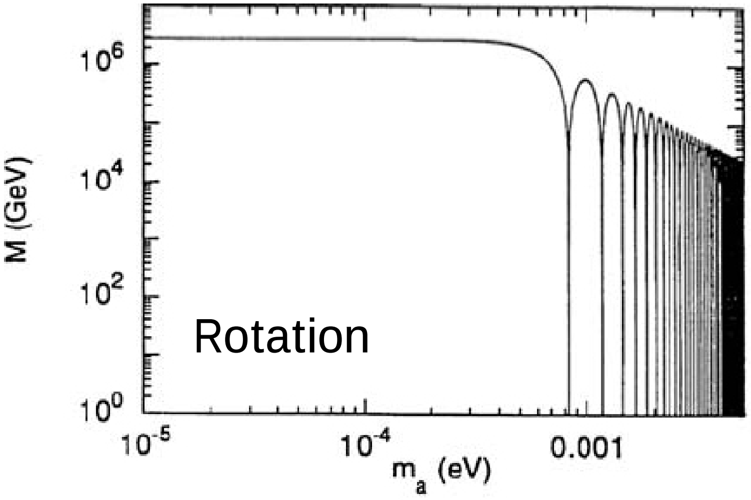


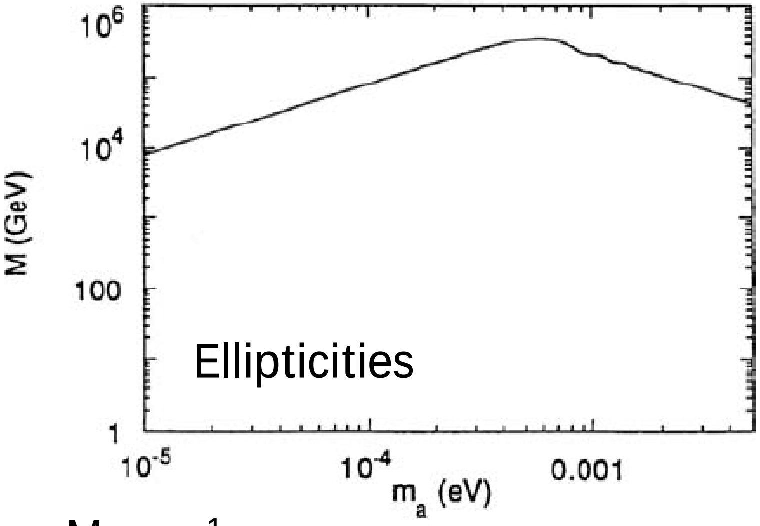
RBF



RBF

Exclusions:





$M = g^{-1}$

- Two superconducting dipoles end to end
  - 8.8 m, $\langle B^2 \rangle = 4.5\ T^2$
- Optical cavity allowed laser ~500 passes
- Sensitivity to rotation, ellipticity:

  $\theta = 0.38 \times 10^{-9}$, $\varepsilon = 2 \times 10^{-9}$
- Predicted ellipticities:

  $\varepsilon^{\text{QED}} = 4.7 \times 10^{-13}$

  $\varepsilon^{A} \approx 3 \times 10^{-22}$

PVLAS

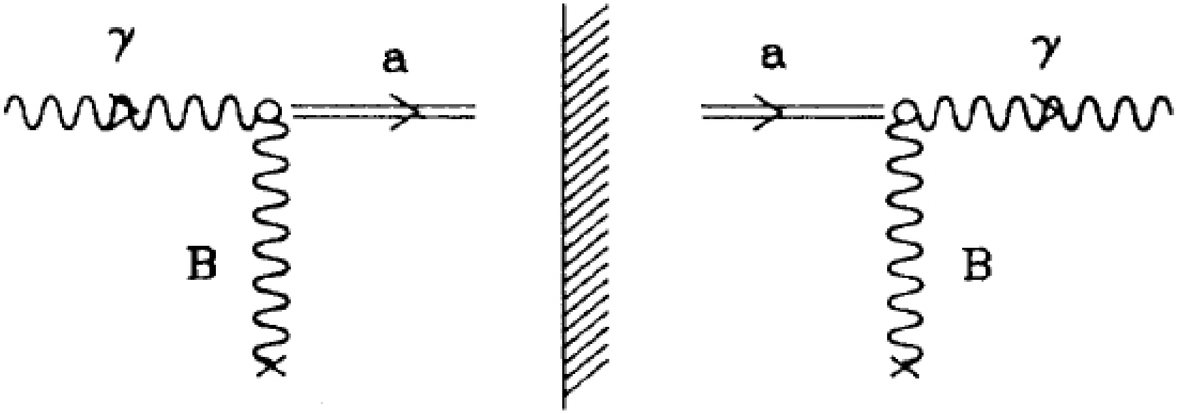
- Linearly polarized light in high finesse Fabry-Perot cavity
  - $F \sim 7\times10^{4}$ for PVLAS
  - Optical path length increased by $N = 2\ F/\pi = 4.5\times10^{4}$
- Dipole with $B = 5.5$ T over 1 m interaction region

- Report signal corresponding to rotation of:

  $(3.0 \pm 0.5)\times 10^{-12}$ rad per pass
- To agree with RBF:
  - m_A: 1-1.5 meV $g^{-1} = M$: $(2 – 6)\times10^{-5}$ GeV
  - This would seem to contradict astrophysical limits

Photon Regeneration

- "Shining light through walls"

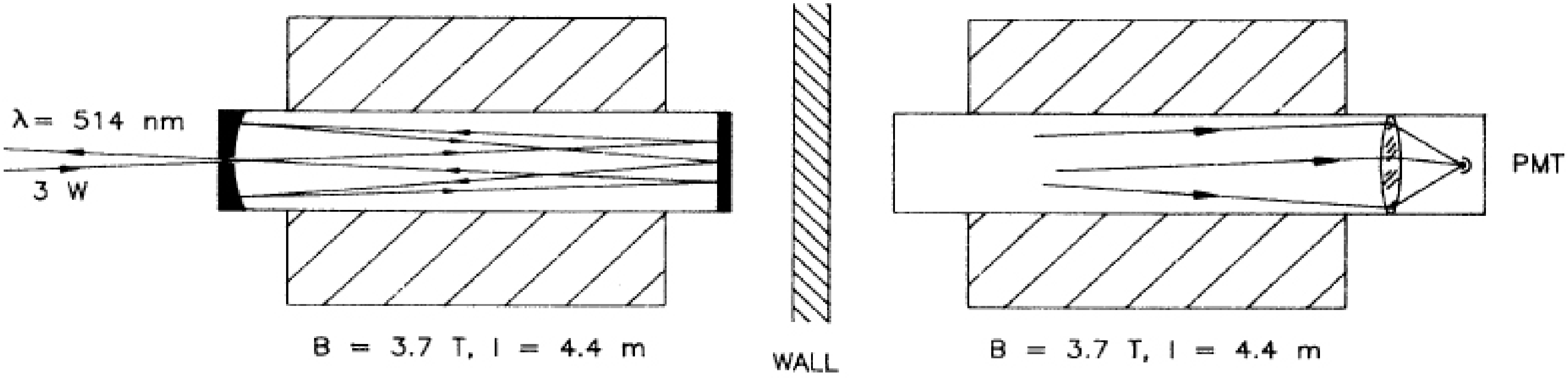


- $P(\gamma \rightarrow A \rightarrow \gamma) \propto (g\, B_0\, l)^4$

- Need large magnetic fields over long distances

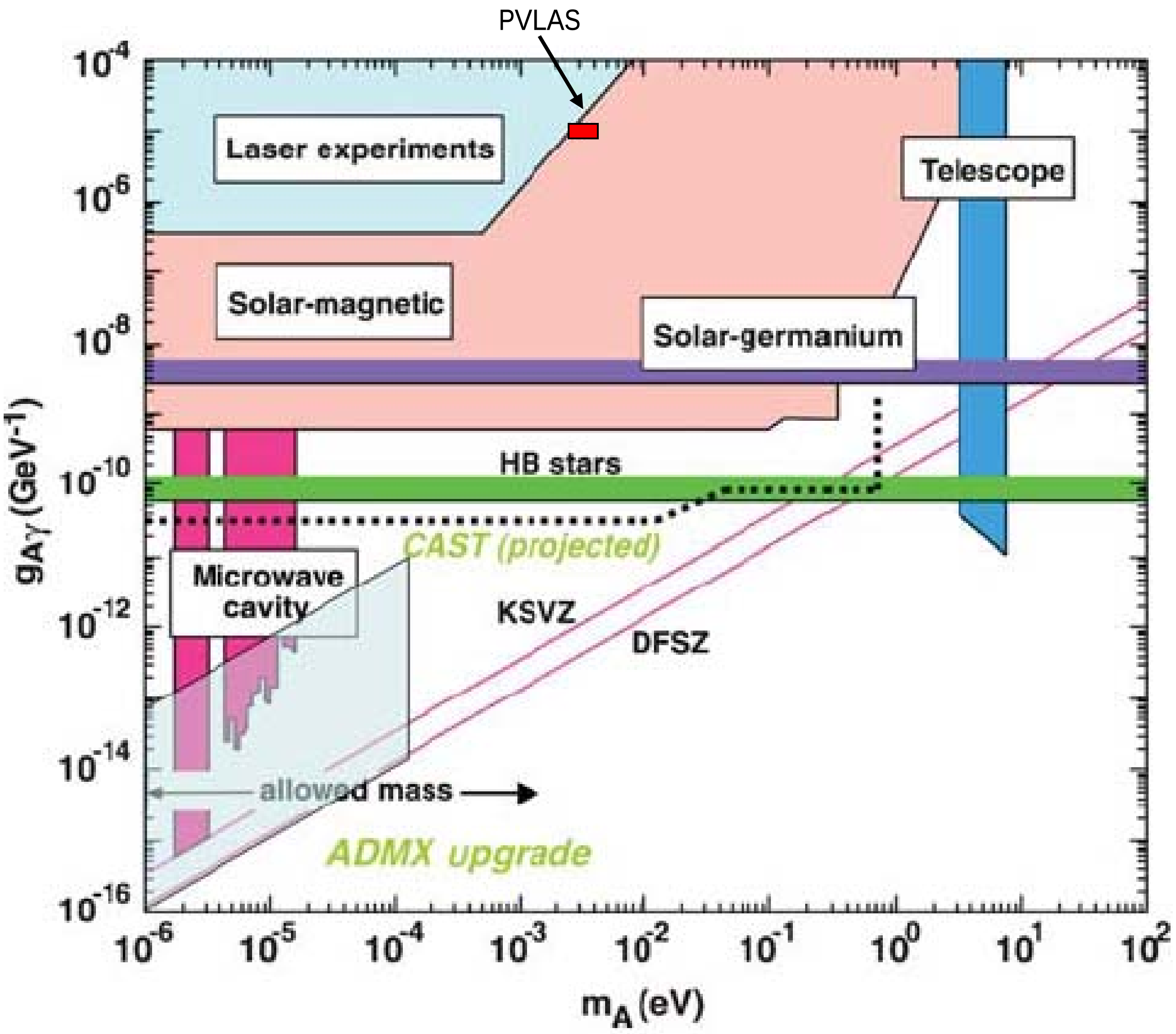
RBF

- 4.4 m, 3.7 T dipoles, 200 traversals in an optical cavity



- Limit $g < 7.7 \times 10^{-7}$ GeV for $m_A < 1$meV

Summary


PVLAS
Laser experiments
Telescope
Solar-magnetic
Solar-germanium
HB stars
CAST (projected)
Microwave cavity
KSVZ
DFSZ
allowed mass
ADMX upgrade
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$g_{A\gamma}$ (GeV^{-1})
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
m_A (eV)

Conclusions

- Axions remain to be a promising solution to Strong CP but have proven difficult to detect
- They additionally provide a well-motivated candidate for CDM
- Realistic axion models will soon be probed:
  - 10^{-6} – 10^{-4} eV range by microwave cavity experiments
  - 0.1 – 1 eV range by axion helioscopes
- Laser experiments are being pursued after a reported signal by PVLAS