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Axions

Recent Searches and New Limits

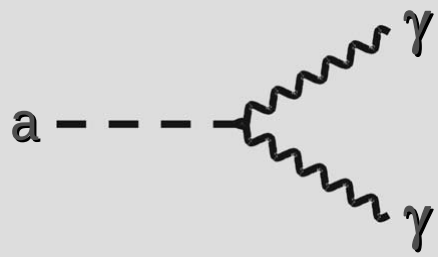
Axion Physics in a Nut Shell

Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism

→ Axions $a \sim \pi^0$

$m_\pi f_\pi \approx m_a f_a$



For $f_a \gg f_\pi$ axions are "invisible" and very light

Solar and Stellar Axions

Axions thermally produced in stars, e.g. by Primakoff production

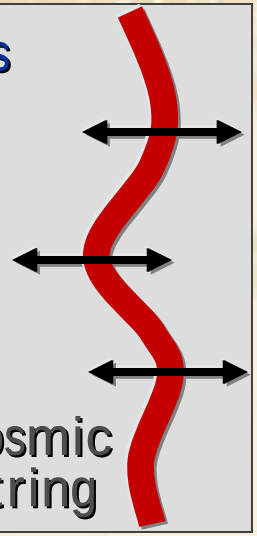
- Limits from avoiding excessive energy drain
- Search for solar axions (CAST)

Cosmology

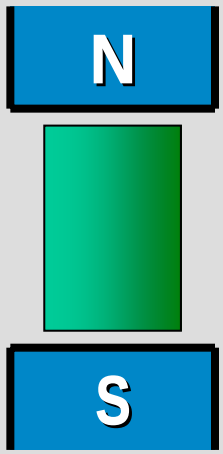
In spite of small mass, axions are born non-relativistically ("non-thermal relics")

→ Cold dark matter candidate

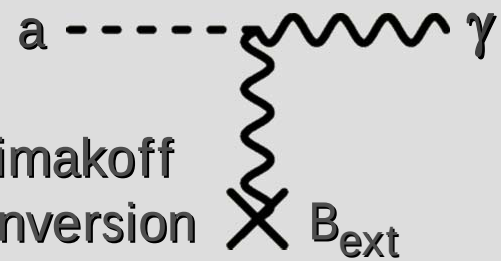
$m_a \sim 1\text{-}1000\ \mu eV$



Search for Axion Dark Matter



Microwave resonator (1 GHz = 4 μeV)



The CP Problem of Strong Interactions

Characterizes degenerate QCD ground state (Θ vacuum)

Phase of Quark Mass Matrix

Standard QCD Lagrangian contains a CP violating term

$$L_{CP} = -\frac{\alpha_s}{8\pi}\underbrace{(\Theta - \arg\det M_q)}_{0\leq\bar{\Theta}\leq 2\pi}\,\mathrm{Tr}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$$

Induces a neutron electric dipole moment (EDM) much in excess of experimental limits

$$d_n \approx \bar{\Theta}\,10^{-16}\,e\,\mathrm{cm} \approx \frac{\bar{\Theta}}{10^2}\mu_n < 3\times 10^{-26}\,e\,\mathrm{cm}$$

$\bar{\Theta} \lesssim 10^{-10}$ **Why so small?**

Dynamical Solution

Peccei & Quinn 1977 - Wilczek 1978 - Weinberg 1978

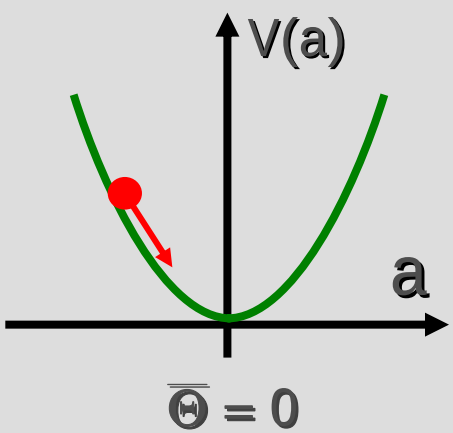
Re-interpret $\overline{\Theta}$ as a dynamical variable (scalar field)

$$\overline{\Theta} \rightarrow \frac{a(x)}{f_a}$$

Pseudo-scalar axion field

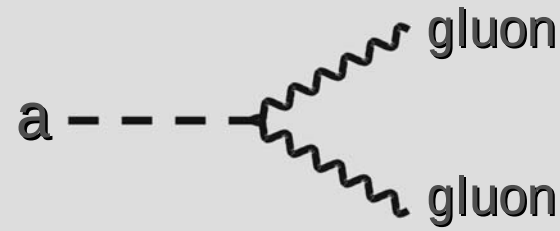
Peccei-Quinn scale, Axion decay constant

$$L_{CP} = -\frac{\alpha_S}{8\pi}\overline{\Theta}\,\mathrm{Tr}(G\tilde{G}) \quad \Rightarrow \quad L_{CP} = -\frac{\alpha_S}{8\pi}\frac{a(x)}{f_a}\,\mathrm{Tr}(G\tilde{G})$$



Potential (mass term) induced by L_{CP} drives a(x) to CP-conserving minimum

CP-symmetry dynamically restored

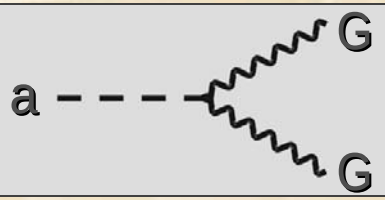
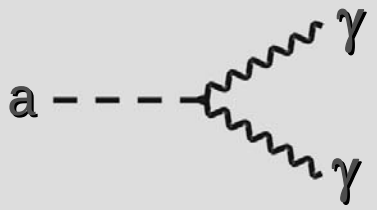
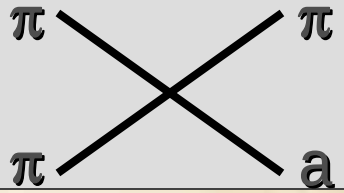
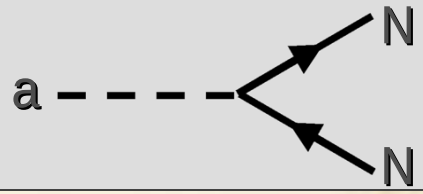
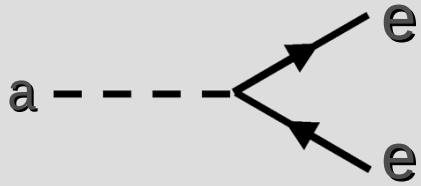


Axions generically couple to gluons and mix with π^0

$$\begin{pmatrix}\text{Axion mass}\\ \text{\& couplings}\end{pmatrix} \sim \begin{pmatrix}\text{Pion mass}\\ \text{\& couplings}\end{pmatrix} \times \frac{f_\pi}{f_a}$$

$f_\pi \approx 93$ MeV
Pion decay constant

Axion Properties

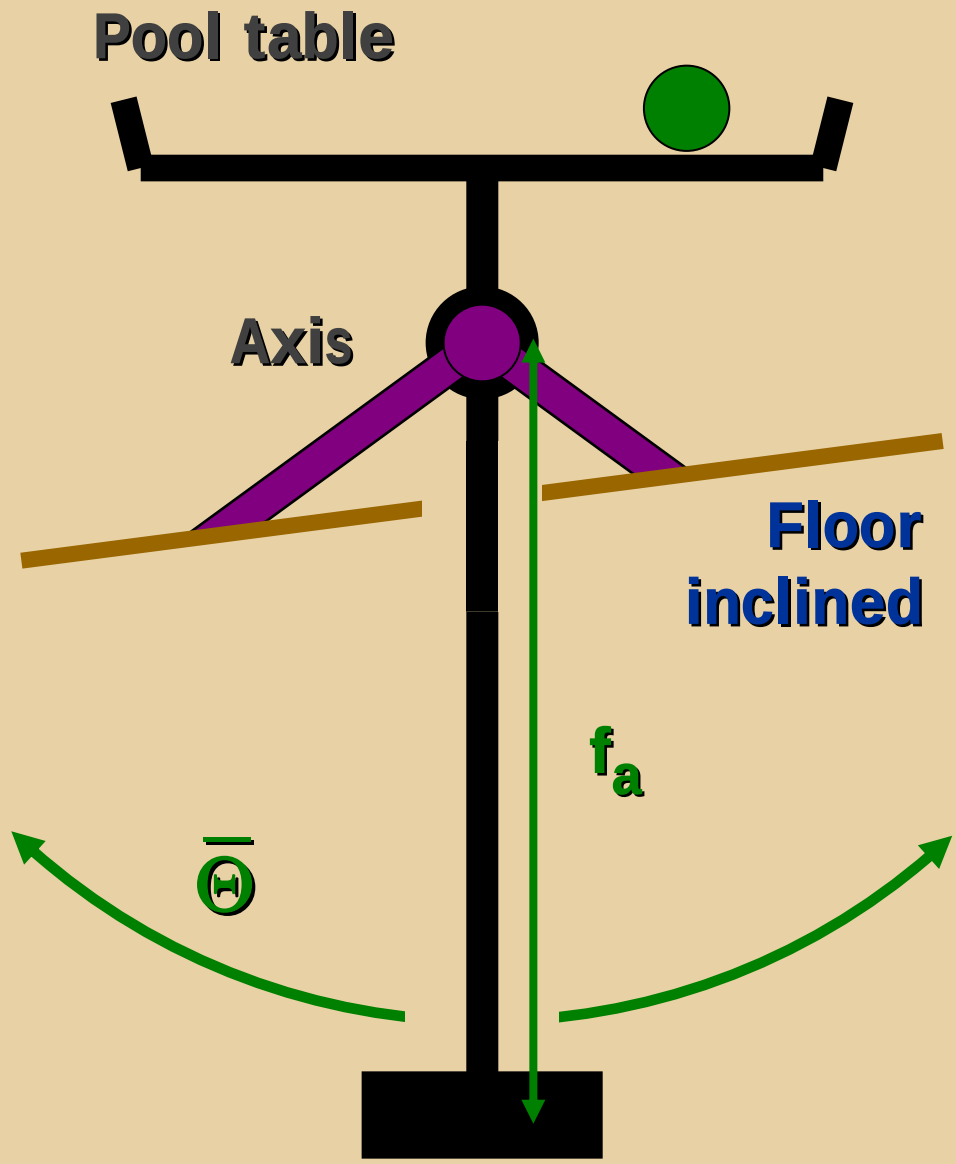
Gluon coupling (Generic property)	$L_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$	
Mass	$m_a = \frac{0.6\,\text{eV}}{f_a / 10^7\,\text{GeV}} \approx \frac{m_\pi f_\pi}{f_a}$	
Photon coupling	$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\vec{E}\cdot\vec{B}a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	
Pion coupling	$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}(\pi^0\pi^+\partial_\mu\pi^- + \ldots)\partial^\mu a$	
Nucleon coupling (axial vector)	$L_{aN} = \frac{C_N}{2f_a}\overline{\Psi}_N\gamma^\mu\gamma_5\Psi_N\,\partial_\mu a$	
Electron coupling (optional)	$L_{ae} = \frac{C_e}{2f_a}\overline{\Psi}_e\gamma^\mu\gamma_5\Psi_e\,\partial_\mu a$	

The Pool Table Analogy

P.Sikivie, Physics Today, Dec. 1996, pg. 22

Gravity

New degree of freedom
➔ Axion



Symmetric relative to gravity

Floor inclined

Symmetry broken

Symmetry dynamically restored

Windows of Opportunity

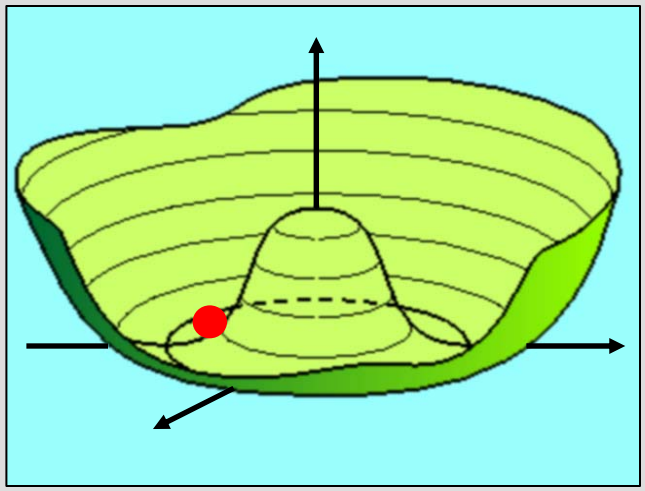
Axions	Alternatives
Solve strong CP problem by Peccei-Quinn dynamical symmetry restoration	• Massless up-quark • Spontaneous CP violation • $\overline{\Theta} = 0$ set at some high energy scale (no radiative corrections)
• Cosmic cold dark matter candidate • Direct detection possible	• Supersymmetric particles • Superheavy particles • Sterile Neutrinos • Many others … (but usually not experimentally accessible)
Search for new physics at E $\gg$ TeV in low-energy experiments (Axions Nambu-Goldstone boson of spontaneously broken symmetry)	• Neutrino masses (see-saw) • Proton decay • Neutron electric dipole moment • Deviation from Newton's law (e.g. large extra dimensions)

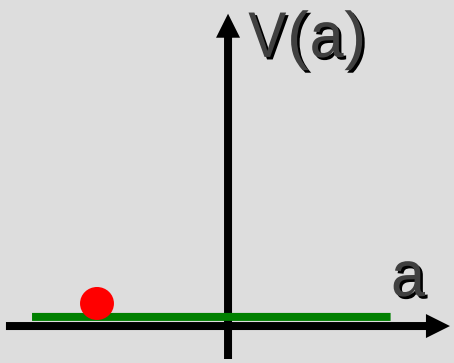
Axions as Pseudo Nambu-Goldstone Bosons

- The realization of the Peccei-Quinn mechanism involves a new chiral U(1) symmetry, spontaneously broken at a scale f_a
- Axions are the corresponding Nambu-Goldstone mode

$E \approx f_a$

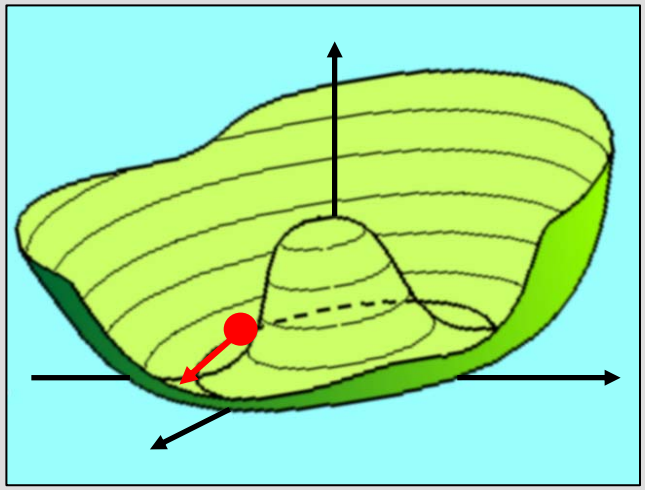
- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"

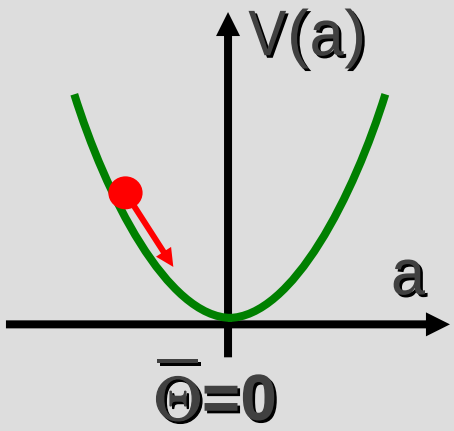




$E \approx \Lambda_{QCD} \ll f_a$

- $U_{PQ}(1)$ explicitly broken by instanton effects
- Mexican hat tilts
- Axions acquire a mass





Production of Cold Axion Population in the Early Universe

Approximate axion cold dark matter density

$$\Omega_a \approx 0.5 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{7/6} \approx 4 \left(\frac{1\,\mu\mathrm{eV}}{m_a} \right)^{7/6}$$

Inflation after PQ symmetry breaking

Homogeneous mode oscillates after

$$T \lesssim \Lambda_{QCD}$$

Dependence on initial misalignment angle

$$\Omega_a \propto \overline{\Theta}_i$$

- Isocurvature fluctuations from large quantum fluctuations of massless axion field created during inflation
- Strong CMBR bounds on isocurvature fluctuations
- Scale of inflation required to be very small $\Lambda_I \lesssim 10^{13}$ GeV

[Beltrán, García-Bellido & Lesgourgues hep-ph/0606107]

Reheating restores PQ symmetry

- Cosmic strings of broken $U_{PQ}(1)$ form by Kibble mechanism
- Radiate long-wavelength axions
- Ω_a independent of initial conditions

Inhomogeneities of axion field large, self-couplings lead to formation of mini-clusters

Typical properties

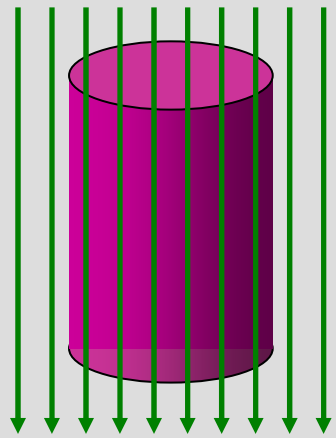
- Mass ~ 10^{-12} M_{sun}
- Radius ~ 10^{10} cm
- Mass fraction up to several 10%

Search for Galactic Axions (Cold Dark Matter)

DM axions	m_a = 10-3000 μeV
Velocities in galaxy	$v_a \approx 10^{-3}$ c
Energies therefore	$E_a \approx (1 \pm 10^{-6})\, m_a$

→ Microwave Energies (1 GHz ≈ 4 μeV)

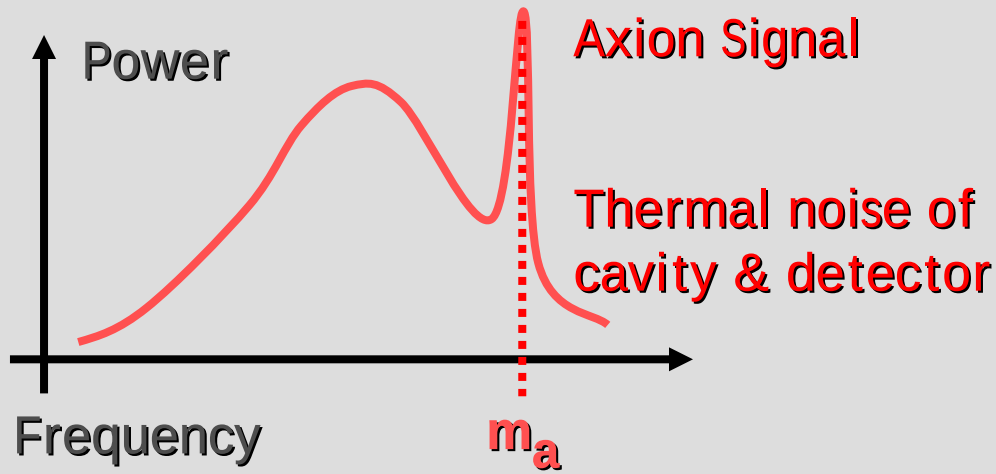
Axion Haloscope (Sikivie 1983)



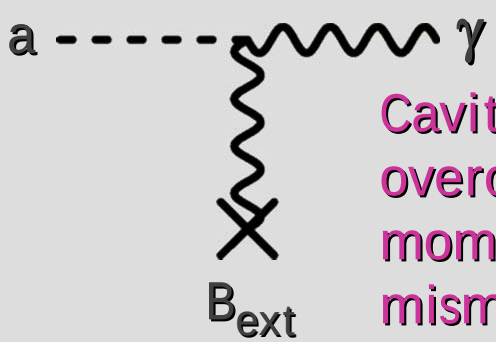
$B_{ext} \approx 8$ Tesla

Microwave Resonator

$Q \approx 10^5$



Primakoff Conversion



Cavity overcomes momentum mismatch

Power of galactic axion signal

$$4\times10^{-21}\,\mathrm{W}\,\frac{V}{0.22\,\mathrm{m}^3}\left(\frac{B}{8.5\,\mathrm{T}}\right)^2\frac{Q}{10^5}\times\left(\frac{m_a}{2\pi\,\mathrm{GHz}}\right)\left(\frac{\rho_a}{5\times10^{-25}\,\mathrm{g/cm}^3}\right)$$

Axion Dark Matter Experi t (ADMX)

Present am:

, D. Kinion,

N.S. Sullivan,

R. Bradley

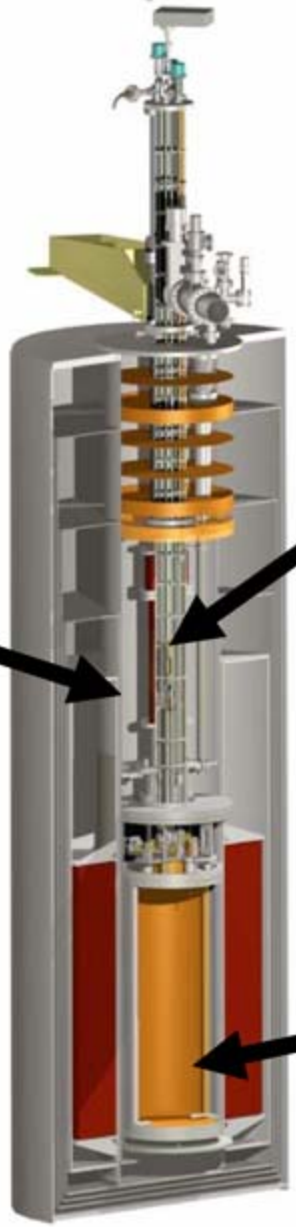
ch and vacuum.

sis techniques.

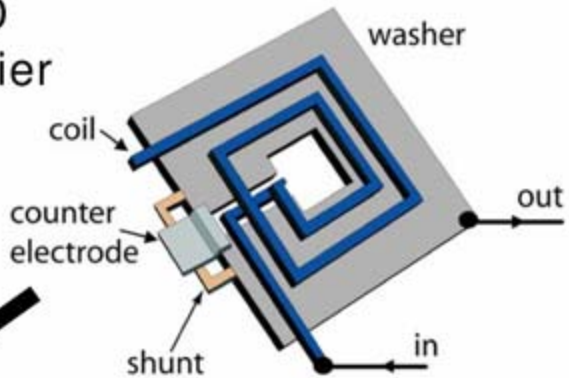
See parallel talk at
the workshop here
by
Gianpaolo Carosi

Phase I upgrade under construction

Field compensation magnet for SQUIDs



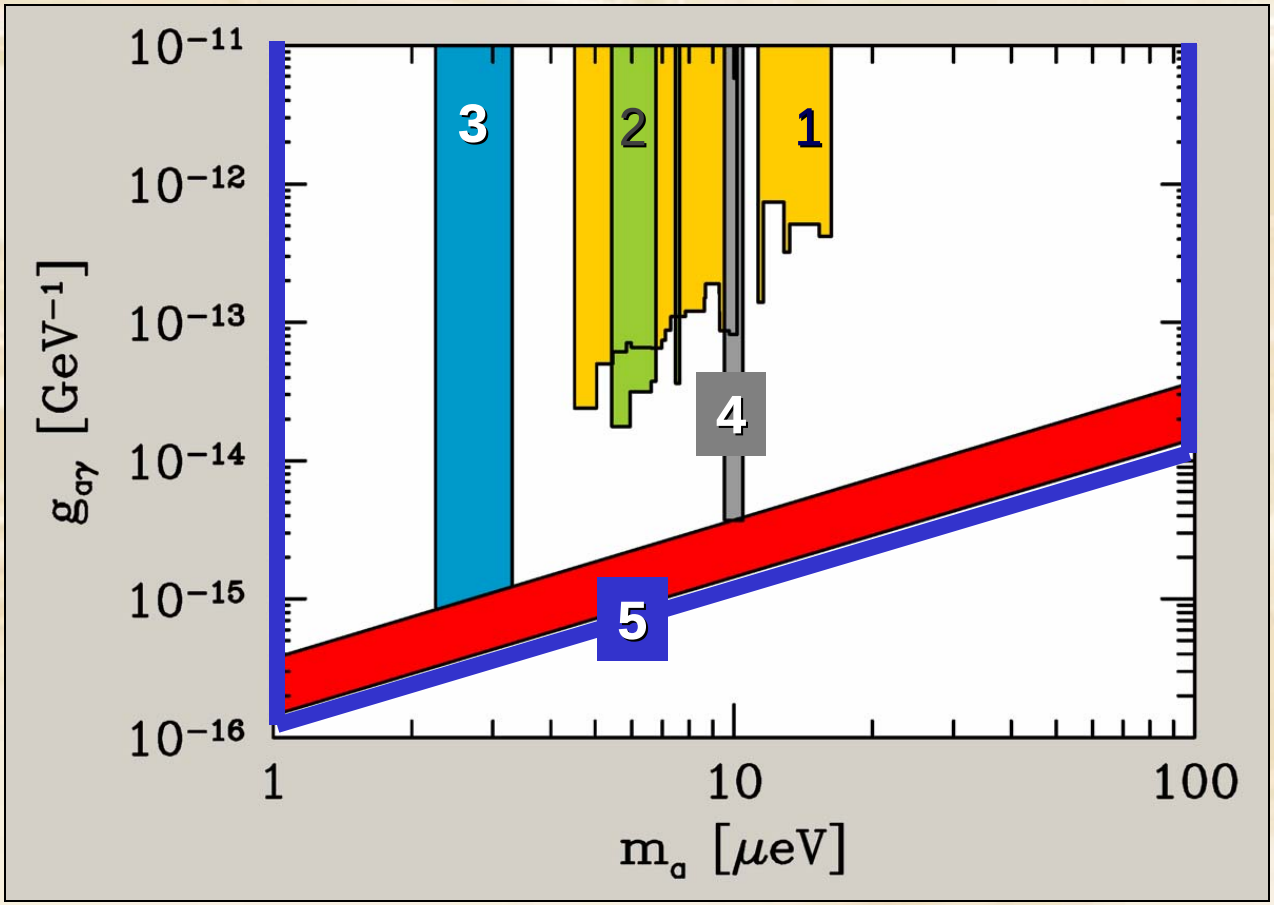
SQUID amplifier



New microwave cavity

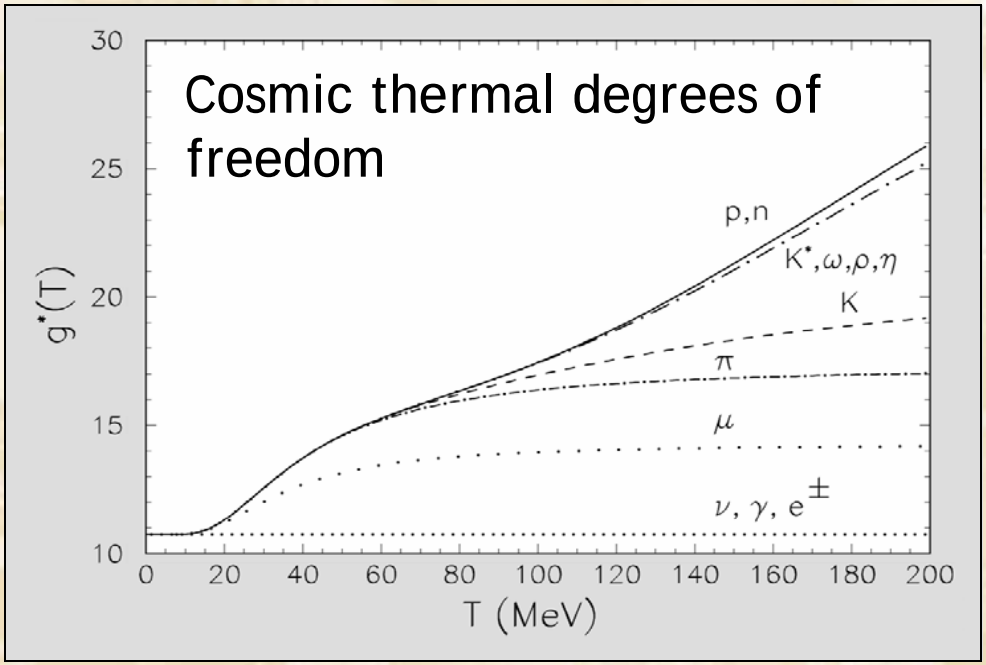
Axion Dark Matter Searches

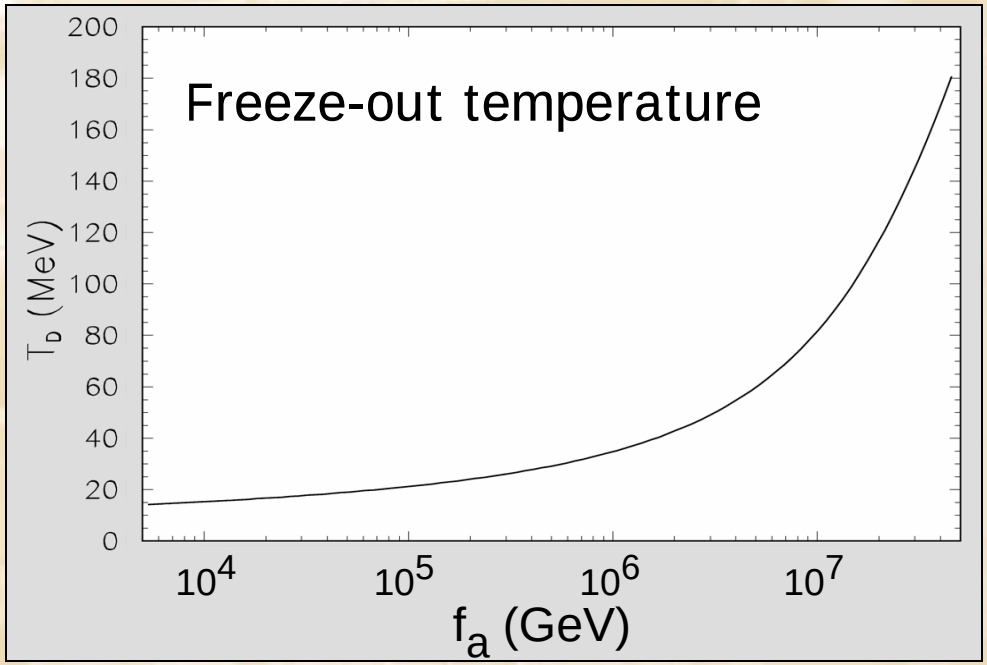
Limits/sensitivities, assuming axions are the galactic dark matter



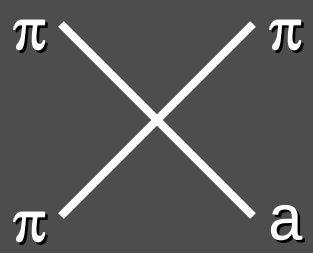
1. Rochester-Brookhaven-Fermilab
   PRD 40 (1989) 3153
2. University of Florida
   PRD 42 (1990) 1297
3. US Axion Search (Livermore)
   ApJL 571 (2002) L27
4. CARRACK I (Kyoto) preliminary
   hep-ph/0101200
5. ADMX (Livermore) foreseen
   e.g. Rev. Mod. Phys. 75 (2003) 777

Axion Hot Dark Matter from Thermalization after Λ_{QCD}



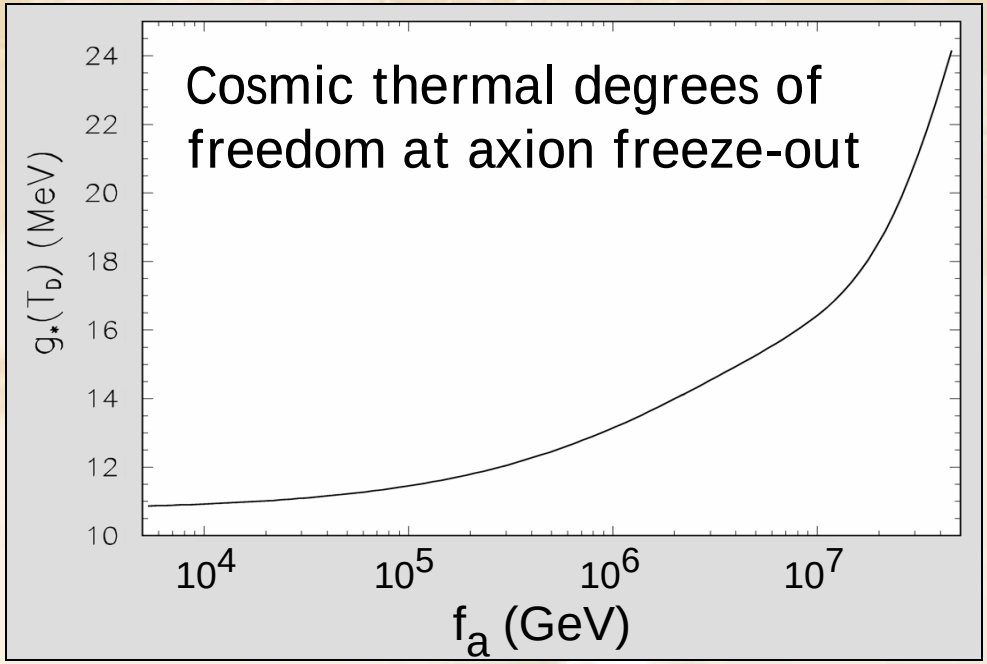


$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0)\partial^\mu a$$



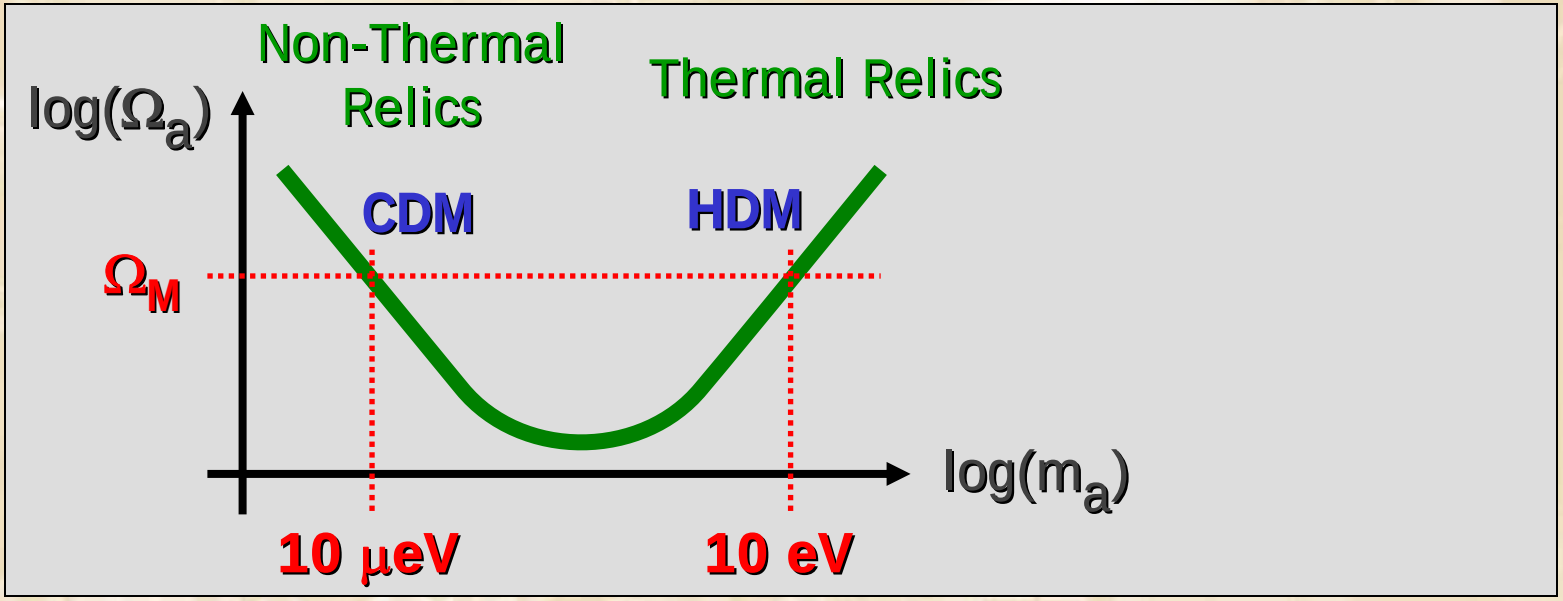
$$C_{a\pi} = \frac{1-z}{3(1+z)} \approx 0.094$$

Chang & Choi, PLB 316 (1993) 51

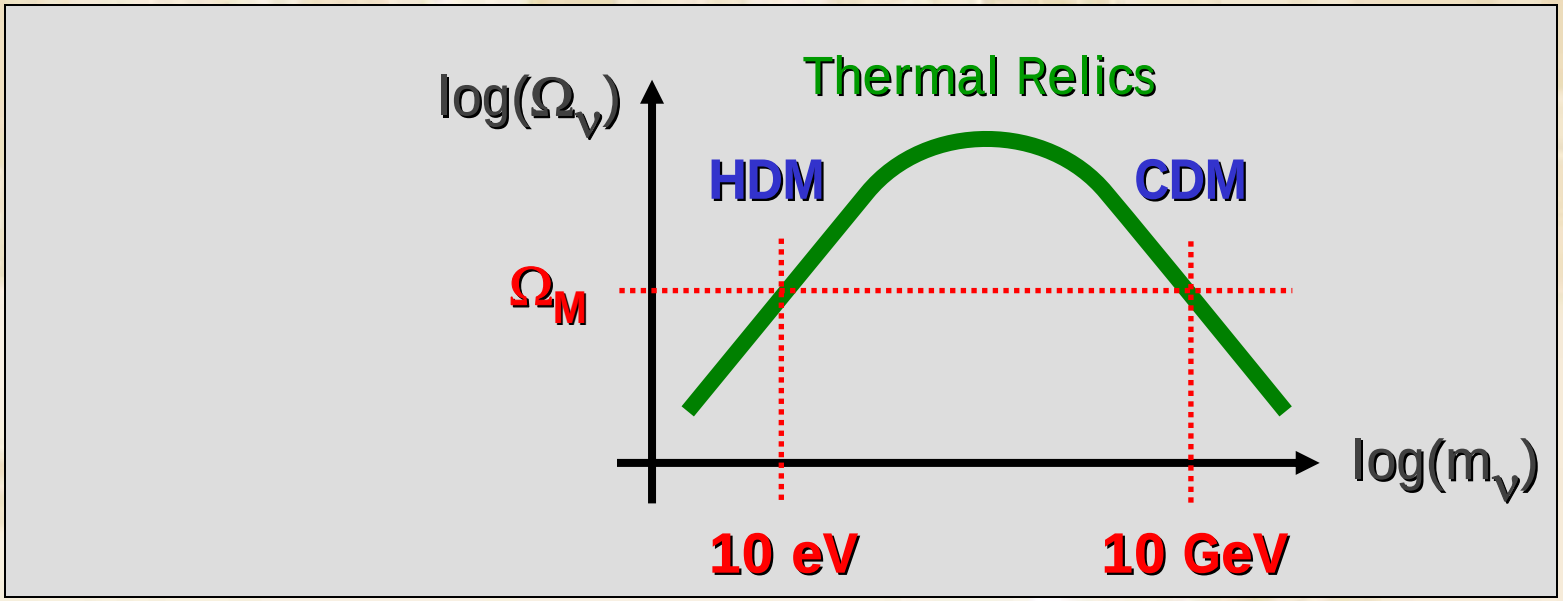


Lee-Weinberg Curve for Neutrinos and Axions

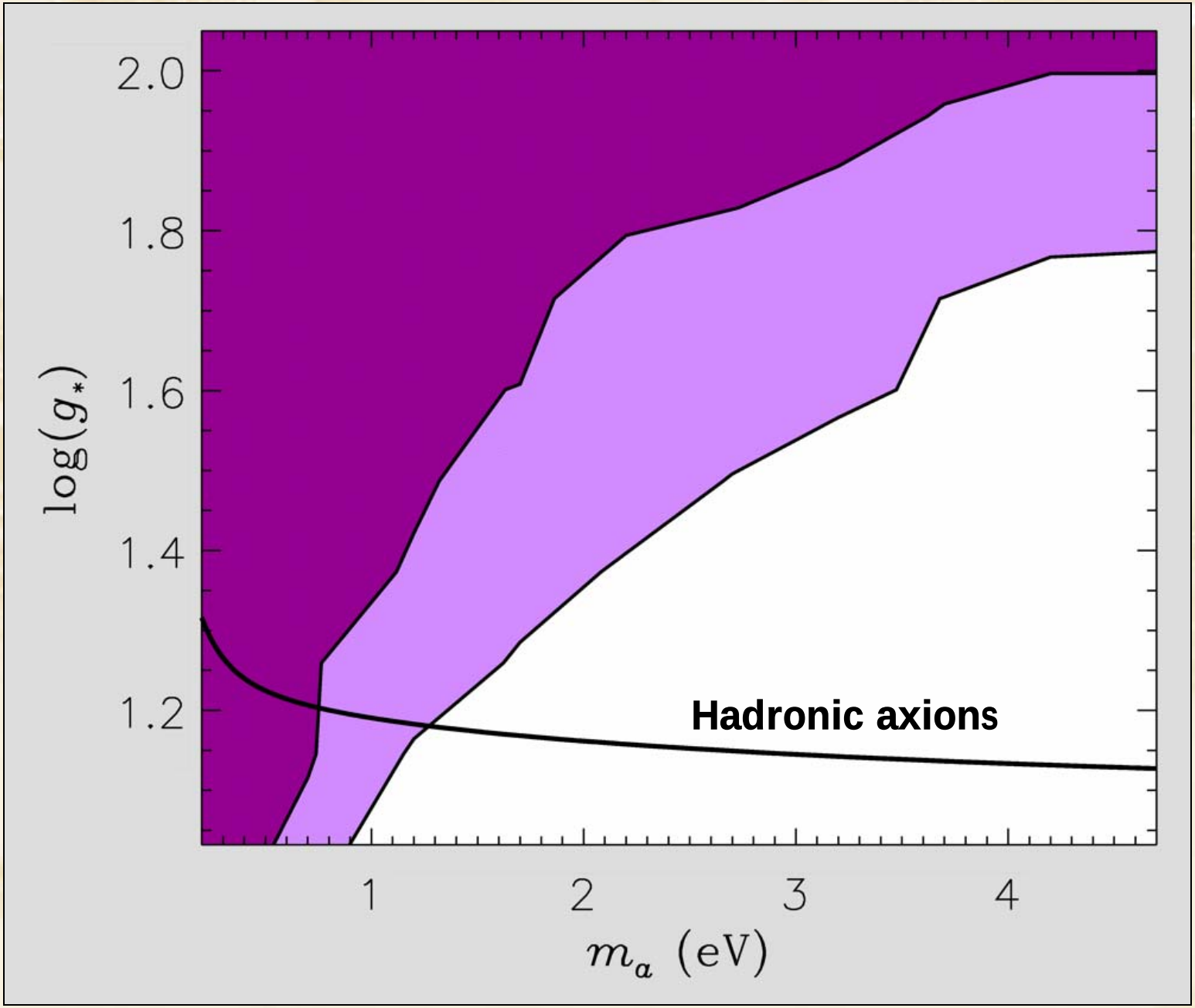
Axions



Neutrinos



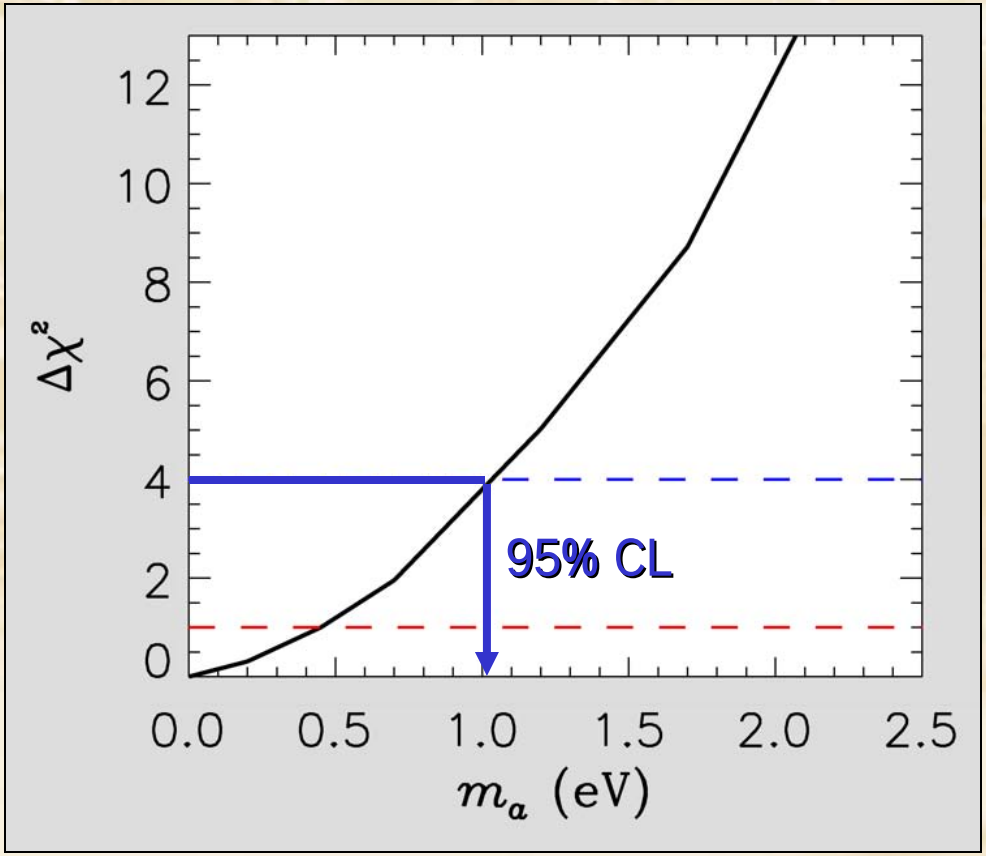
Structure-Formation Exclusion Range for Axions



Hannestad, Mirizzi & Raffelt, hep-ph/0504059

Mass Limits on Hot Dark Matter Axions and Neutrinos

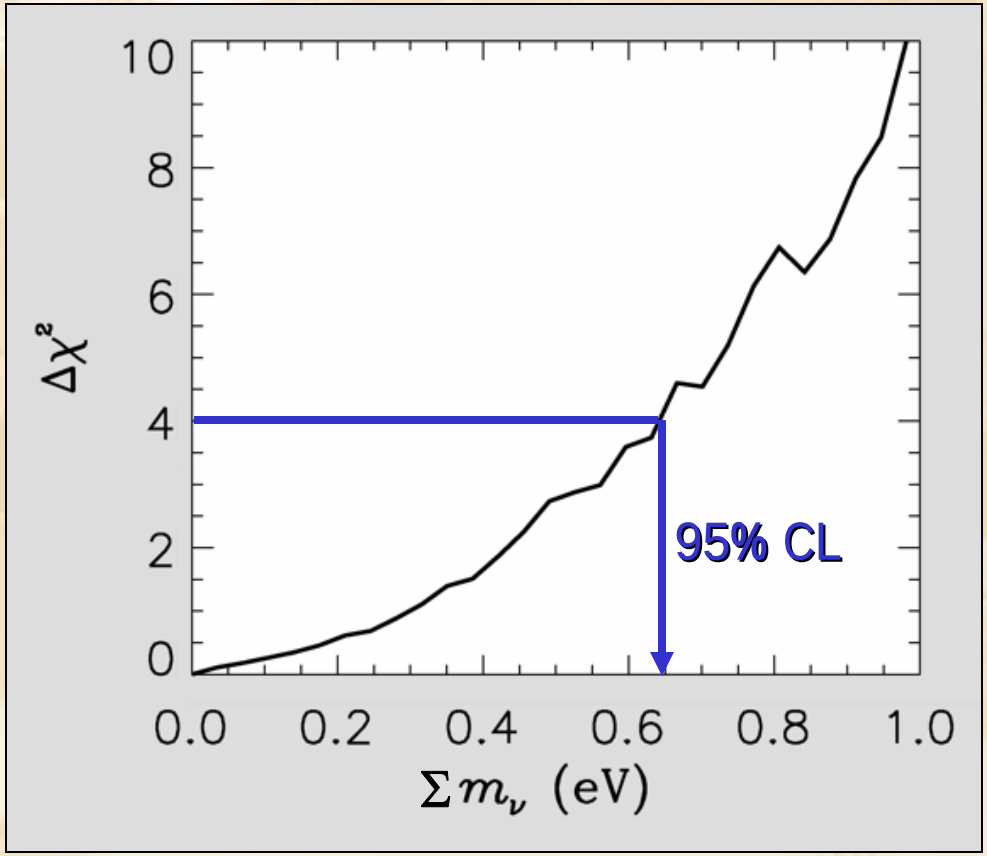
Hannestad, Mirizzi & Raffelt
hep-ph/0504059



Axions

$m_a < 1.05$ eV (95% CL)

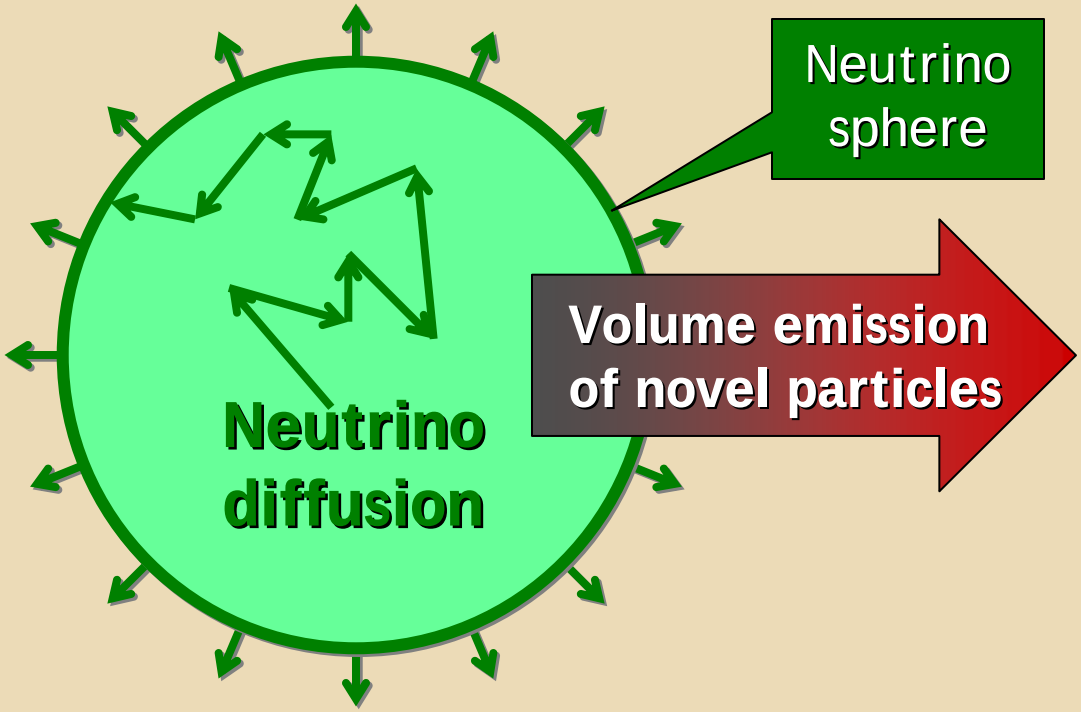
Hannestad, astro-ph/0409108
(Seesaw proceedings, Paris, 2004)



Neutrinos

$\Sigma m_\nu < 0.65$ eV (95% CL)

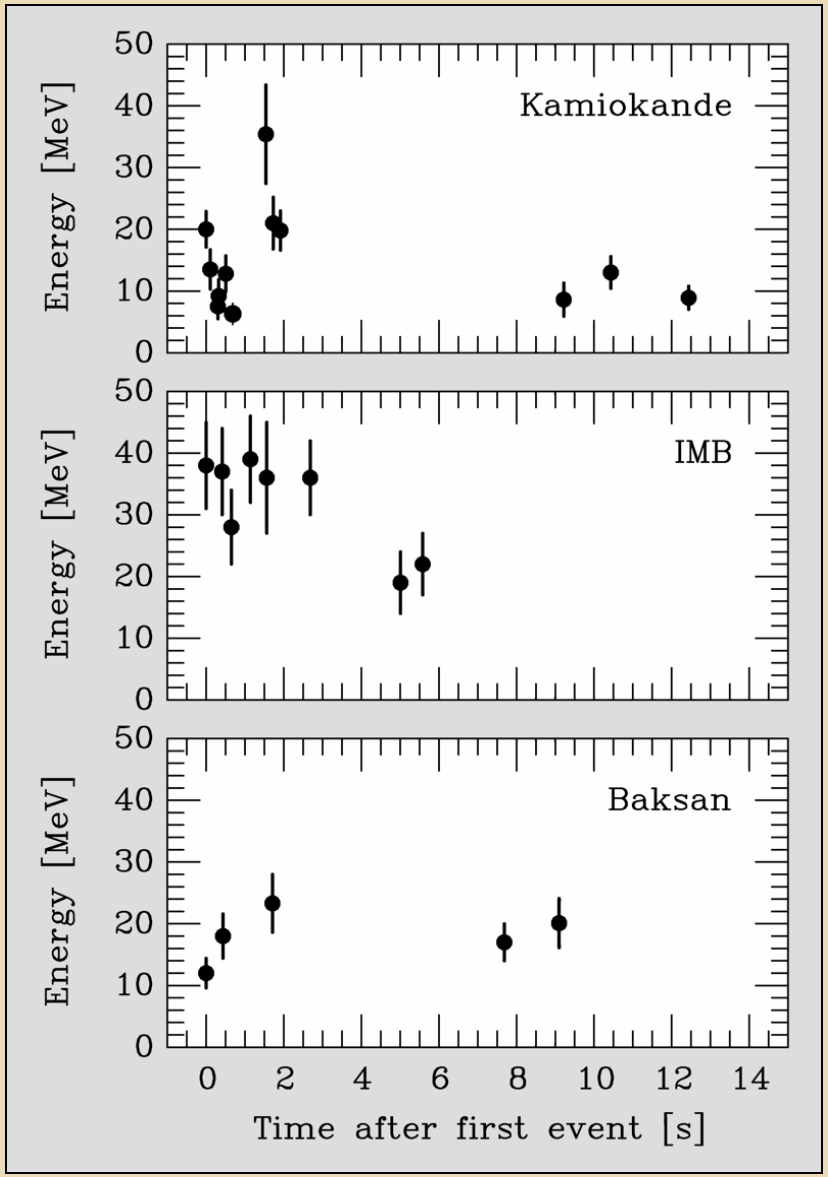
Supernova 1987A Energy-Loss Argument



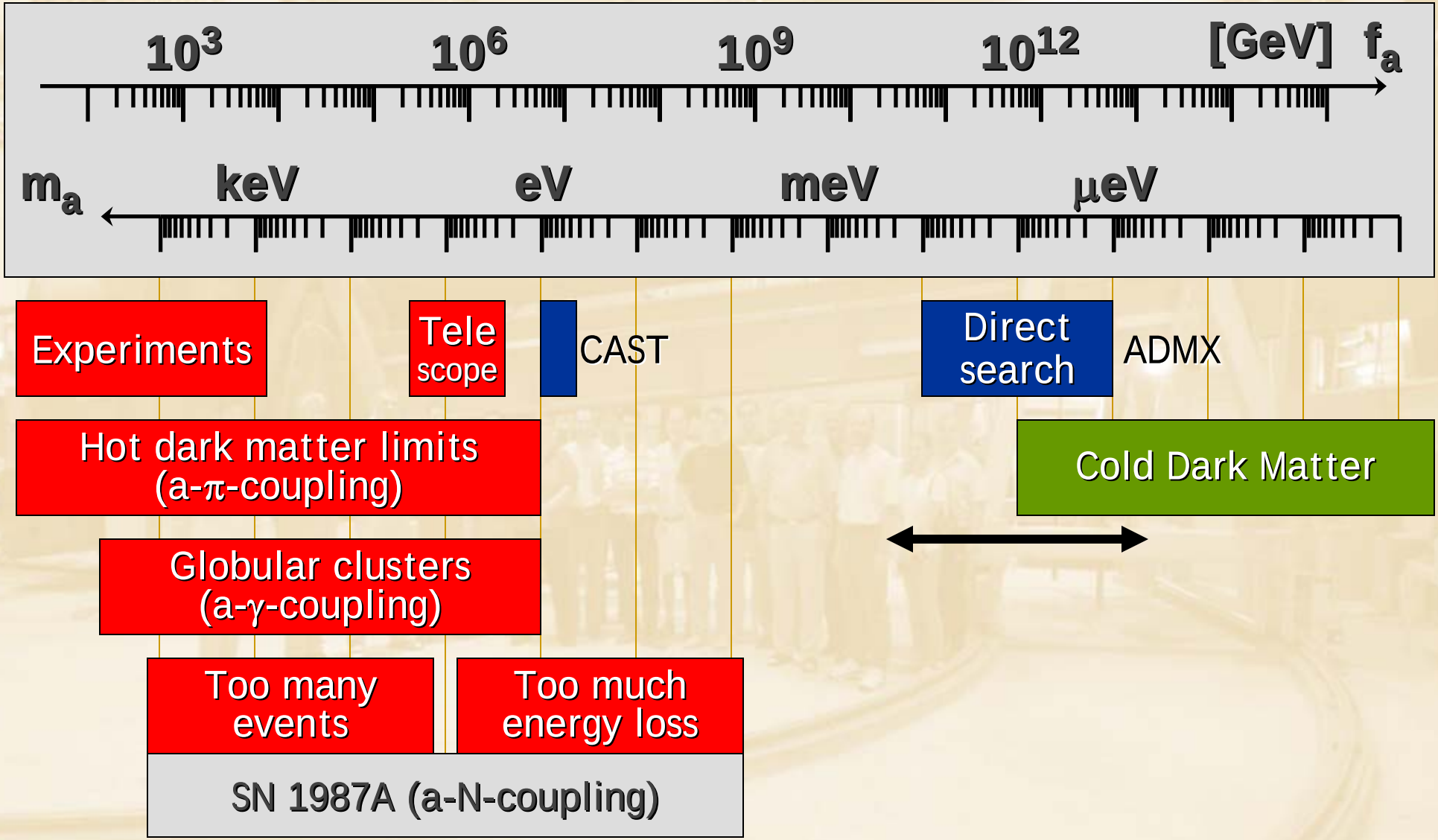
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

SN 1987A neutrino signal

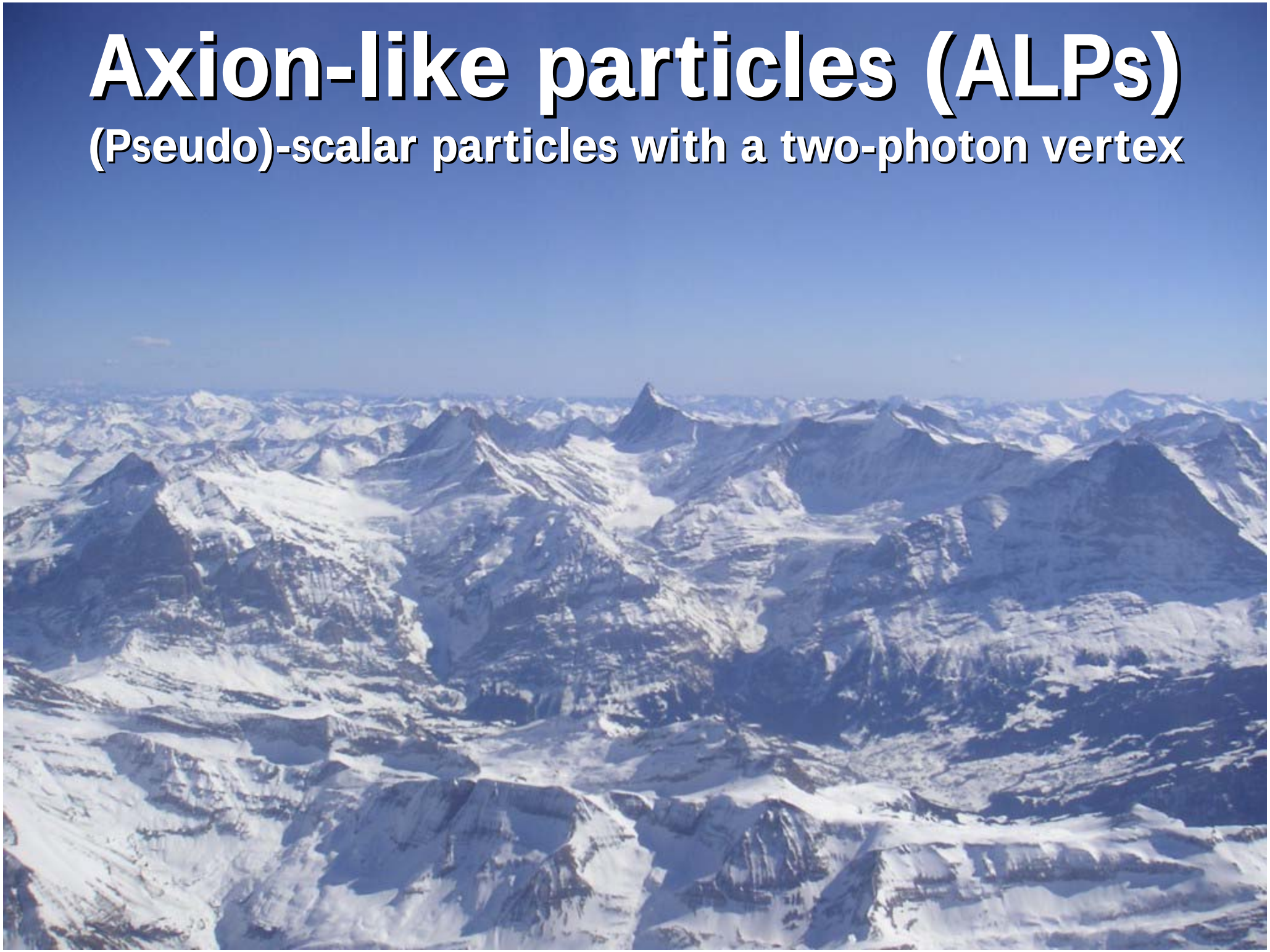


Astrophysical Axion Bounds



Axion-like particles (ALPs)

(Pseudo)-scalar particles with a two-photon vertex

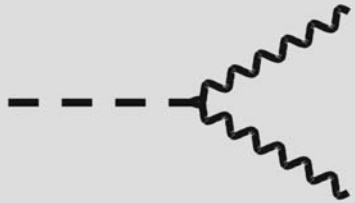


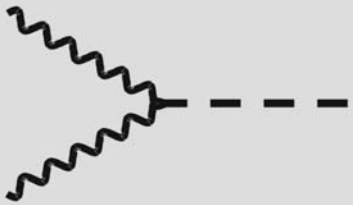
Particles with Two-Photon Coupling

Particles with two-photon vertex:

- Neutral pions (π^0), Gravitons
- Axions (a) and similar hypothetical particles

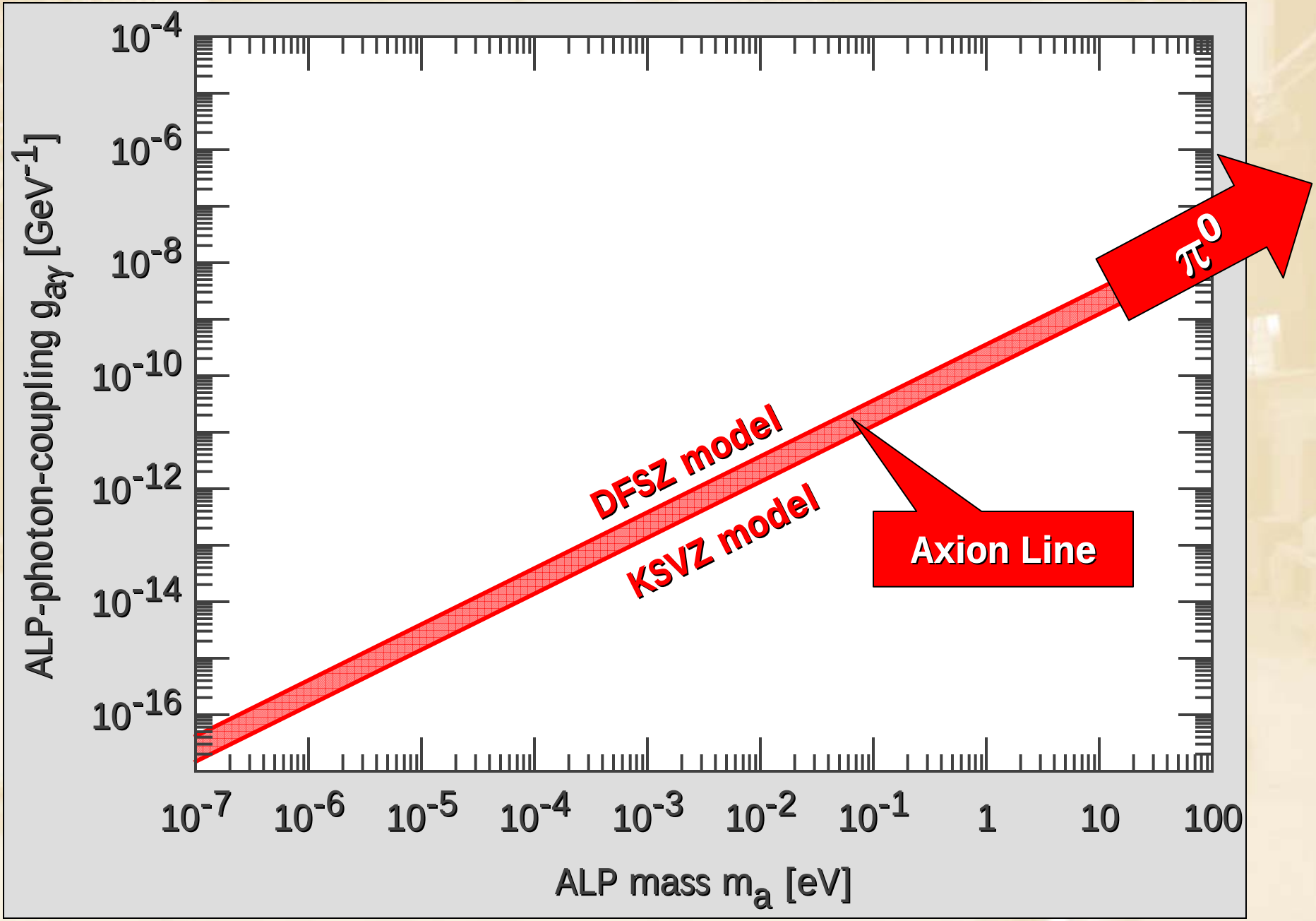
$$L_{a\gamma} = g_{a\gamma}\vec{E}\cdot\vec{B}a$$



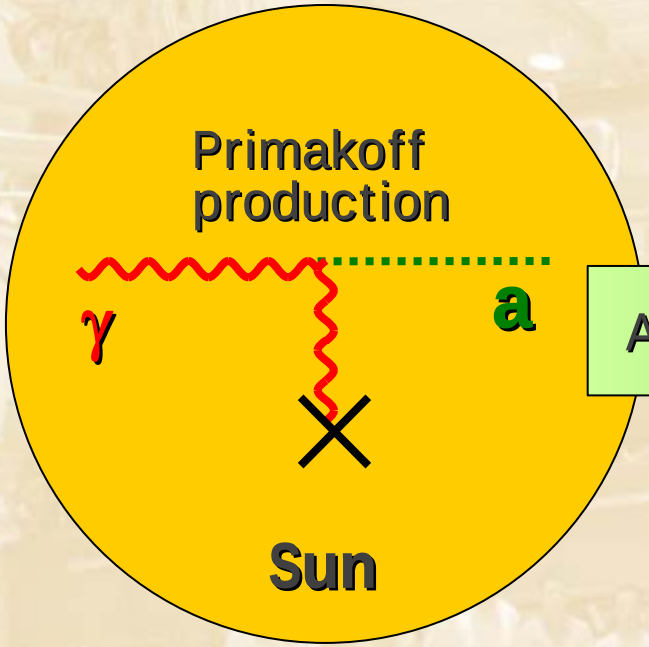
Two-photon decay	$\Gamma_{a\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi}$	Photon Coalescence	
Primakoff Effect	Conversion of photons into pions, gravitons or axions, or the reverse		
Magnetically induced vacuum birefringence	In addition to QED Cotton-Mouton-effect		

PVLAS experiment currently measures an effect ~ 10^4 larger than QED expectation

ALP-Photon-Coupling vs. Mass



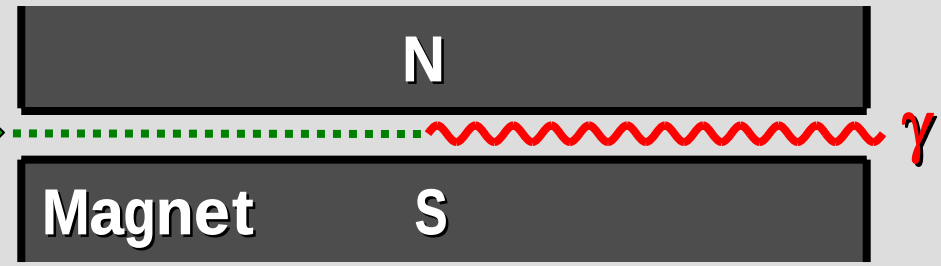
Search for Solar Axions

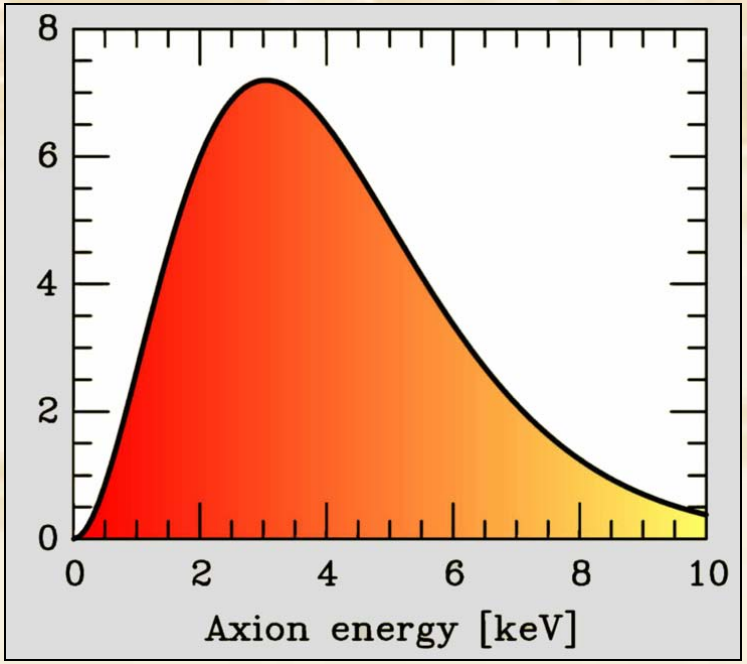


Axion flux

Axion Helioscope (Sikivie 1983)

Axion-Photon-Oscillation

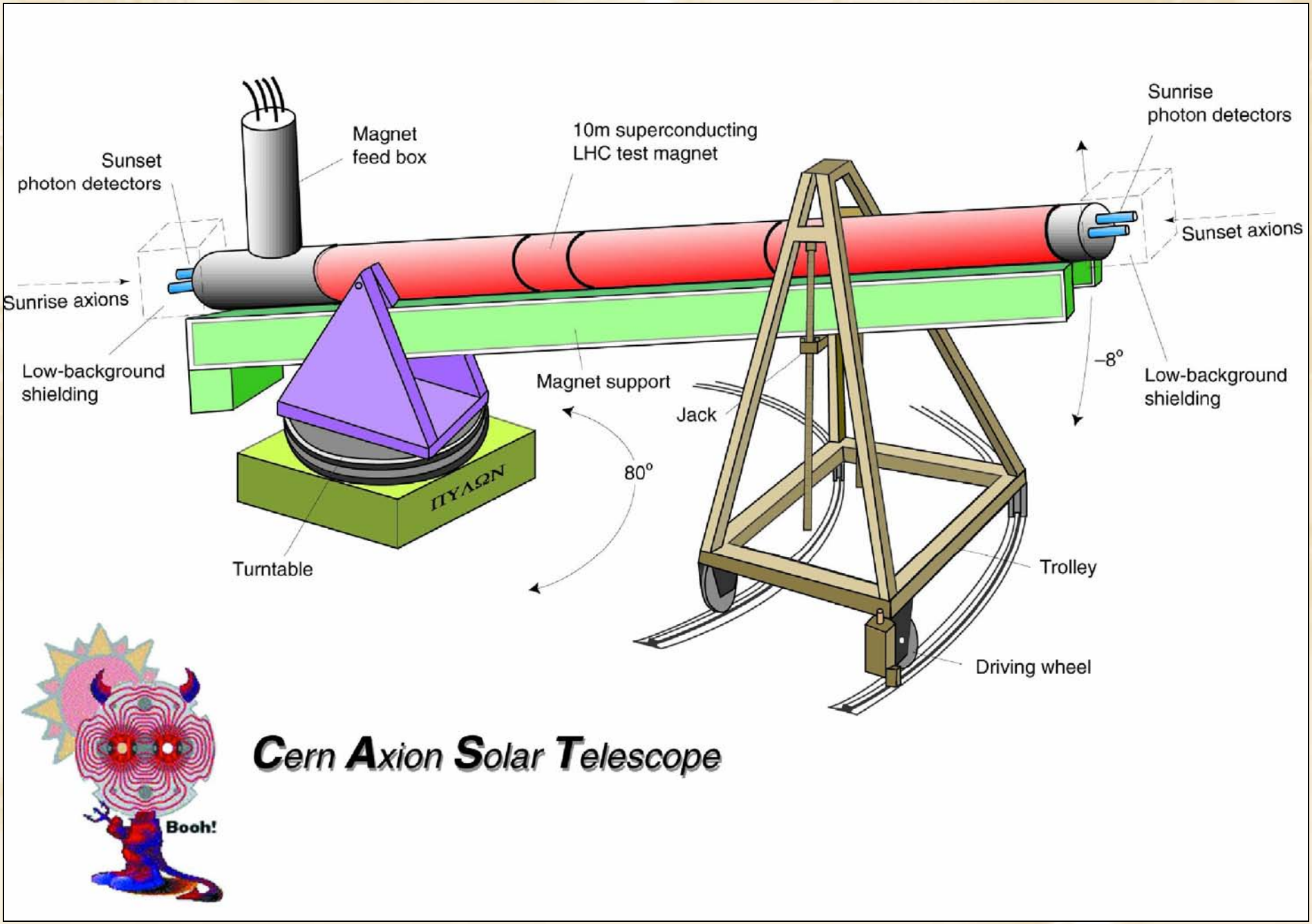




- ➔ Tokyo Axion Helioscope (Results since 1998)
- ➔ CERN Axion Solar Telescope (CAST) (Data since 2003)

Alternative technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments (SOLAX, COSME, DAMA, …)

LHC Magnet Mounted as a Telescope to Follow the Sun



CAST Movies (1)

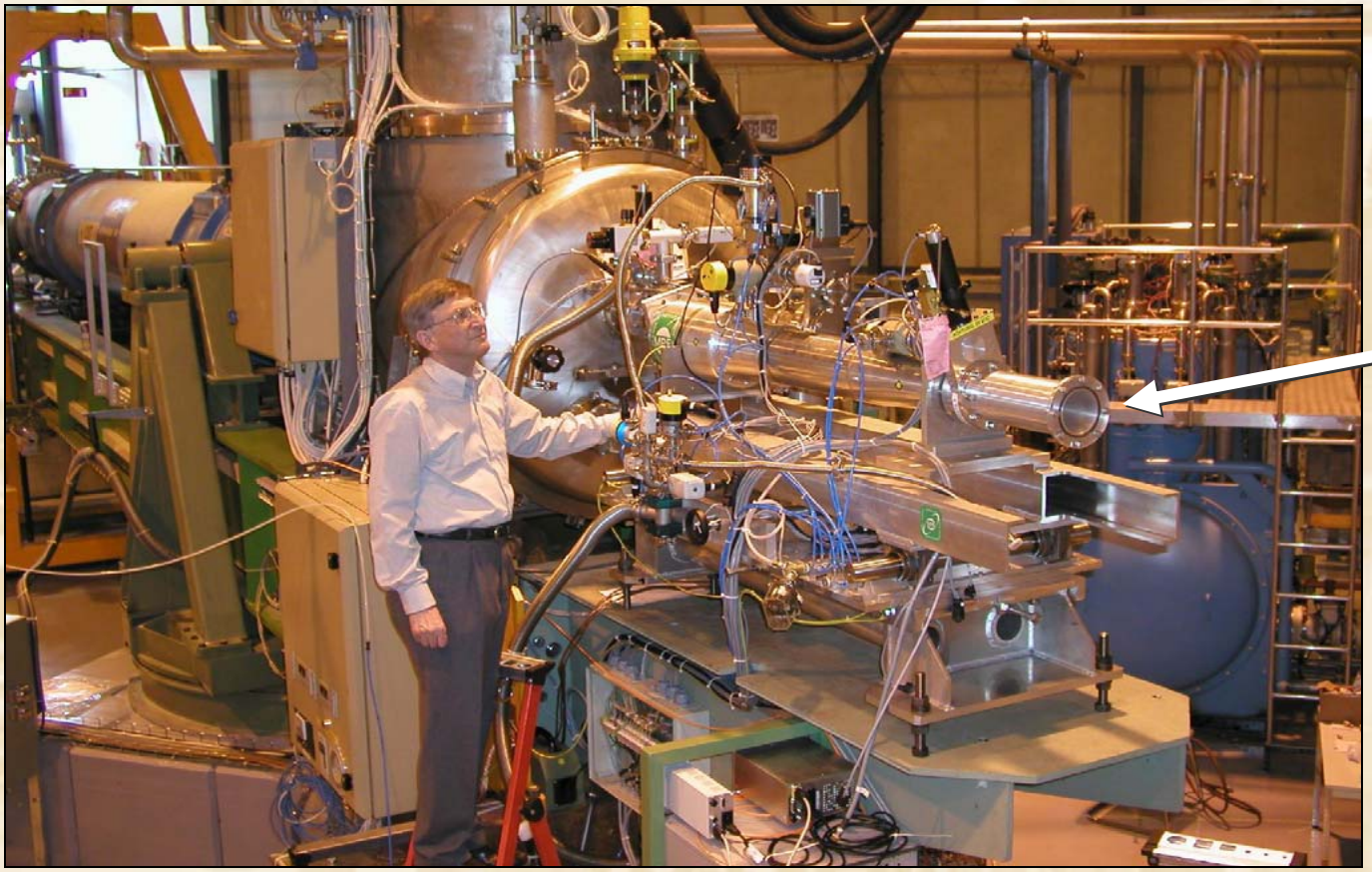
CAST Moving

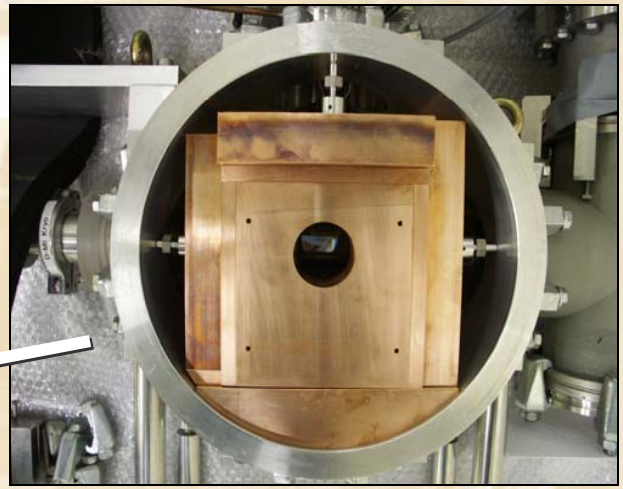
Expected X-Ray Flux at CAST

Axion-photon coupling	$g_{10} = g_{a\gamma} / 10^{-10}\,\mathrm{GeV}^{-1}$
Solar axion flux at Earth	$\Phi_a = 3.5 \times 10^{11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} g_{10}^2$
Conversion probability $a \to \gamma$ at CAST for low-mass axions	$1.8 \times 10^{-17} g_{10}^2 \left(\frac{B}{9.0\mathrm{T}}\right)^2 \left(\frac{L}{9.26\mathrm{m}}\right)^2$
X-ray events at CAST per exposure time (Cross section 2×14 cm^2)	$\Phi_\gamma = 15\,\mathrm{d}^{-1} g_{10}^4$
Integrated exposure time (±40º horizontal and ±5º vertical tracking)	33 days per year

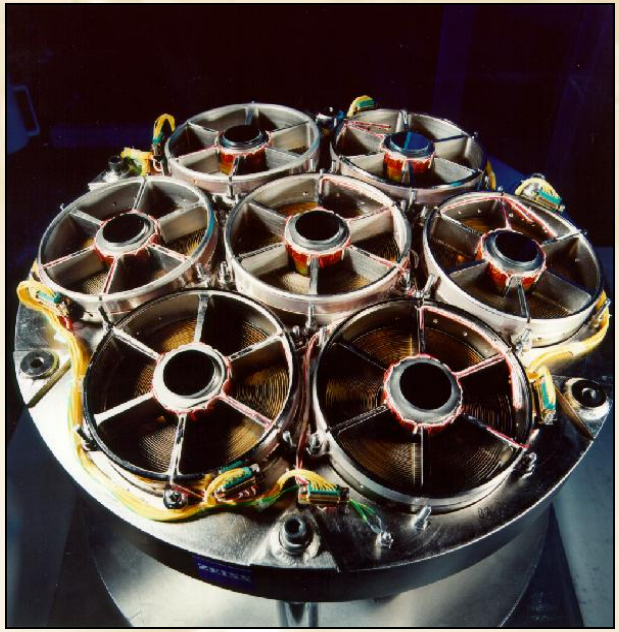
Fourth-power dependence:
Weak sensitivity gain with exposure time

CAST Focussing X-Ray Telescope





- From 43 mm ∅ (LHC magnet aperture) to ~3 mm ∅
- Signal/background improvement > 100
- Signal and background simultaneously measured



One spare mirror system from the failed Abrixas x-ray satellite

Sun Spot on CCD with X-Ray Telescope

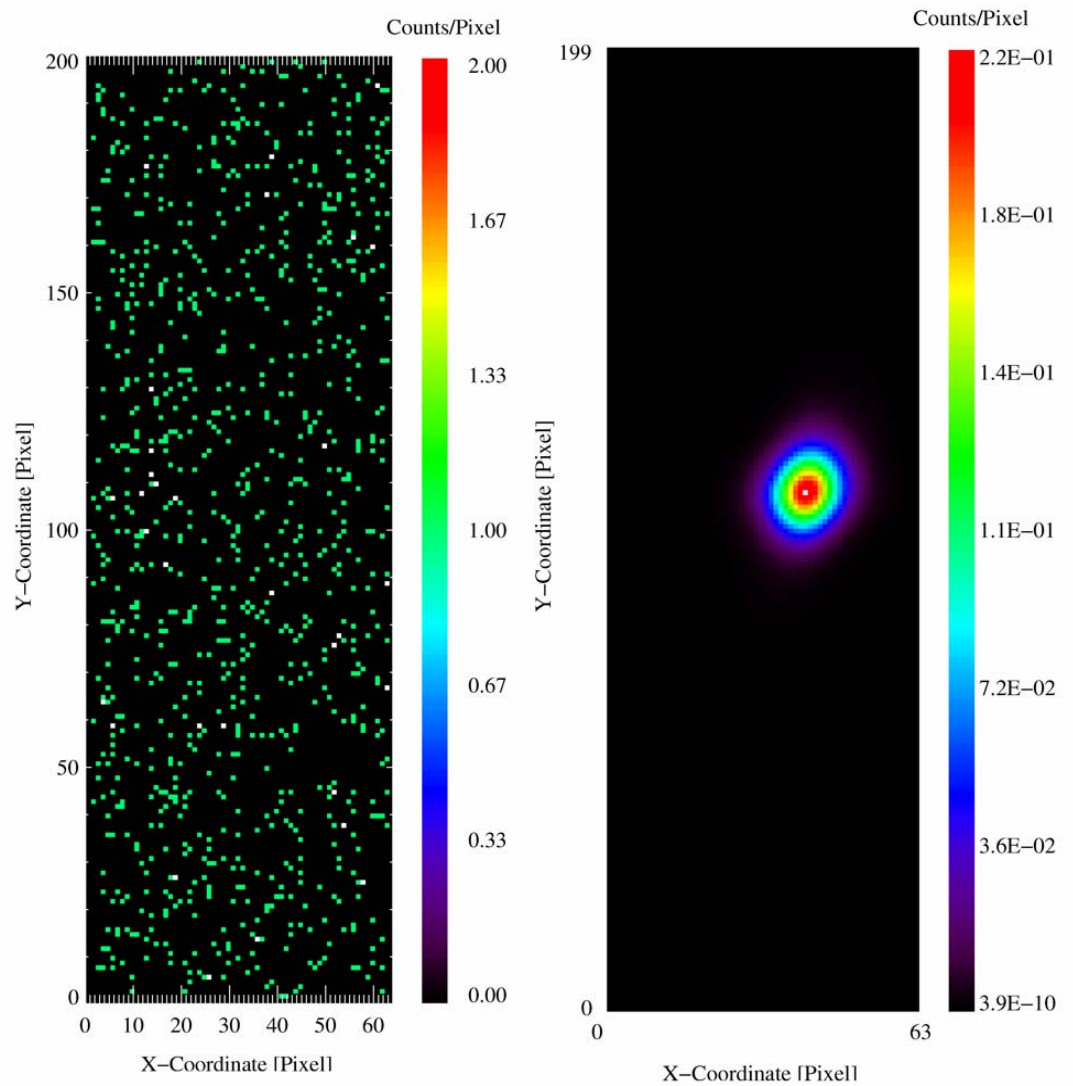
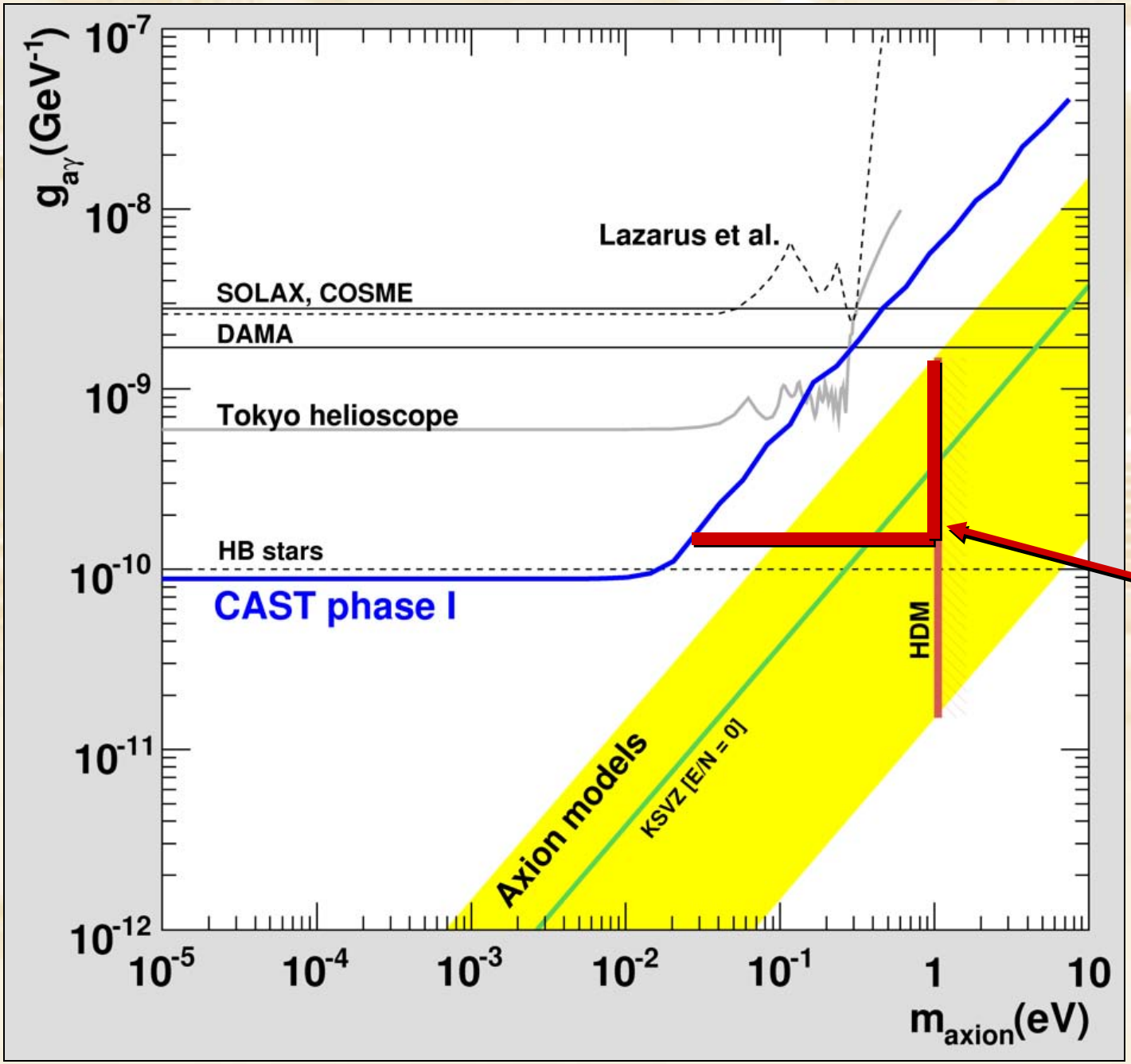


Figure 6: Left: Spatial distribution of events observed under axion sensitive conditions by the CAST X-ray telescope during the 2004 data taking period. The intensity is given in counts per pixel and is integrated over the full observation period of $t_{\mathrm{obs}} = 707$ ksec. Right: Expected "axion" image of the sun as it would be observed by the pn-CCD detector. To determine the axion spot on the pn-CCD, the PSF of the mirror system and the total effective area of the X-ray telescope was taken into account. The count rate integrated over the region of the spot is normalized to unity.

CAST Exclusion Range (2003-2004 Data)



CAST Results:

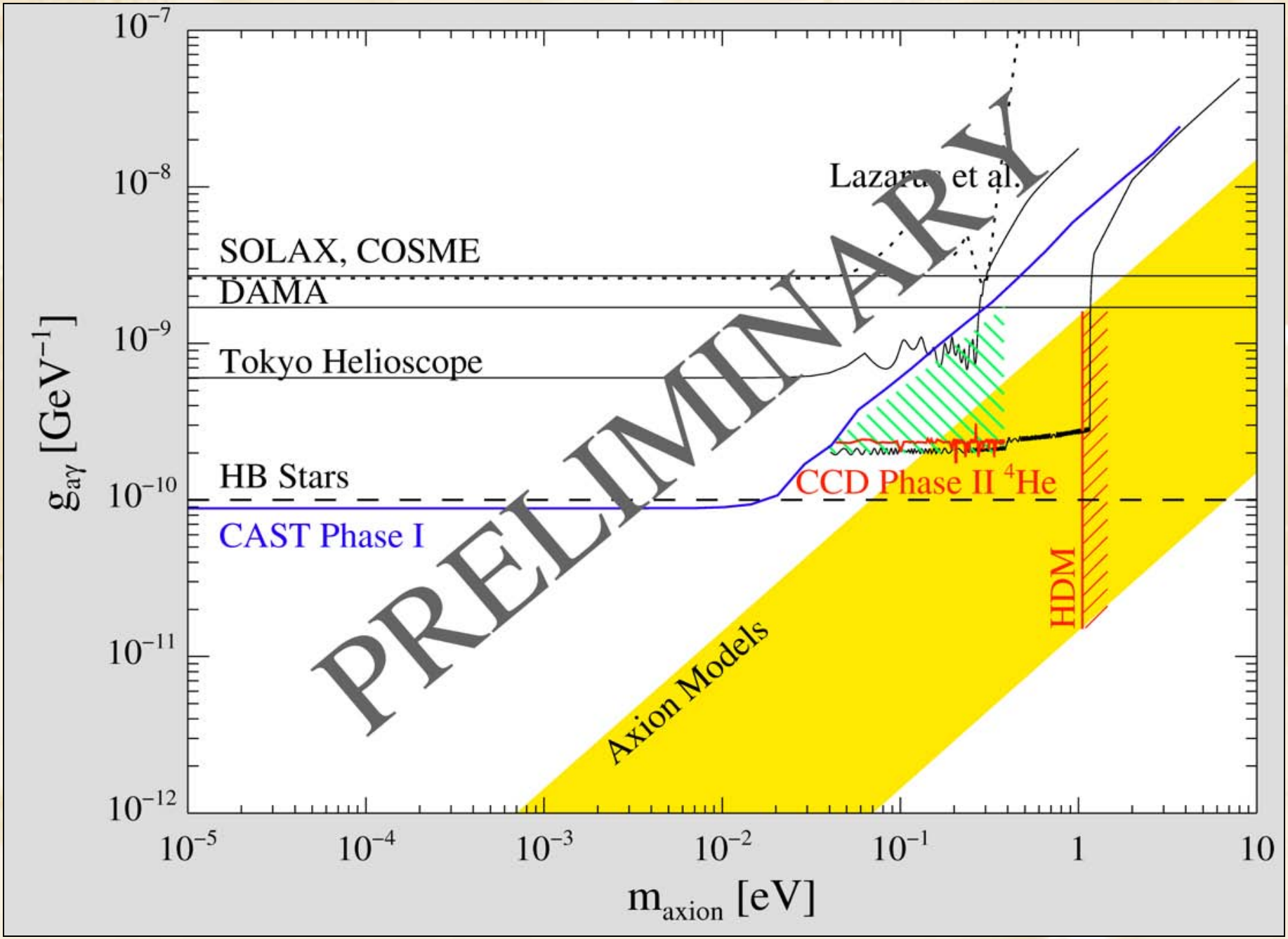
PRL 94:121301 (2005) (hep-ex/0411033)

JCAP, in press hep-ex/0702006

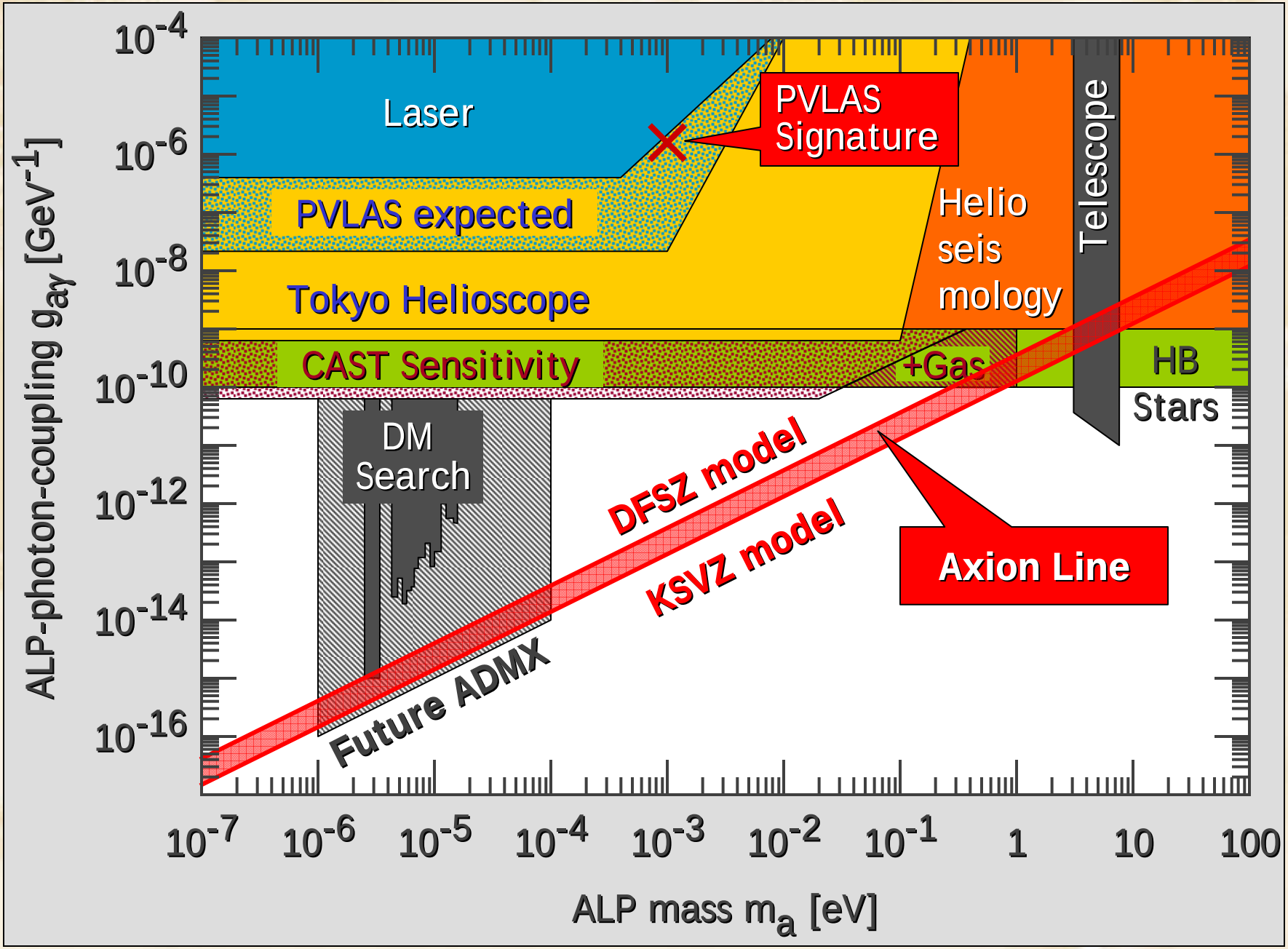
Anticipated sensitivity with variable-pressure helium filling

For the first time covers QCD axion parameters

Preliminary Limits from He-4 Filling Phase (CAST II)



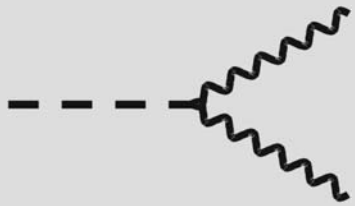
Limits on ALP-Photon-Coupling

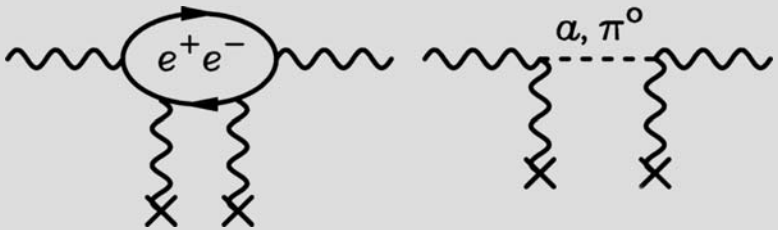


ALP Signatures in Laser Experiments

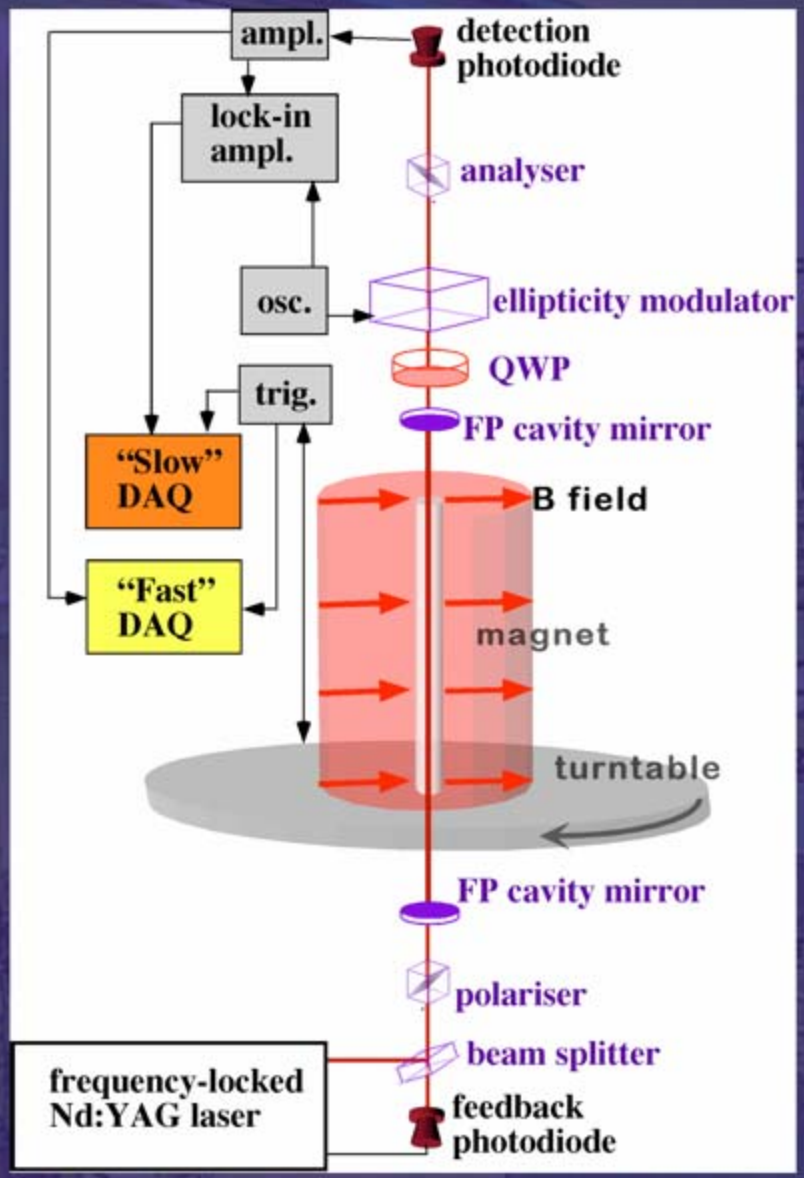
Particles with two-photon vertex:
- Neutral pions (π^0), Gravitons
- Axions (a) and similar hypothetical particles

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



Primakoff effect		Dichroism (Rotation of plane of polarization by loss of one component into ALP channel)
Magnetically induced vacuum birefringence (Cotton-Mouton effect, also caused by QED)		Ellipticity of beam that was originally linearly polarized

PVLAS - Schematic



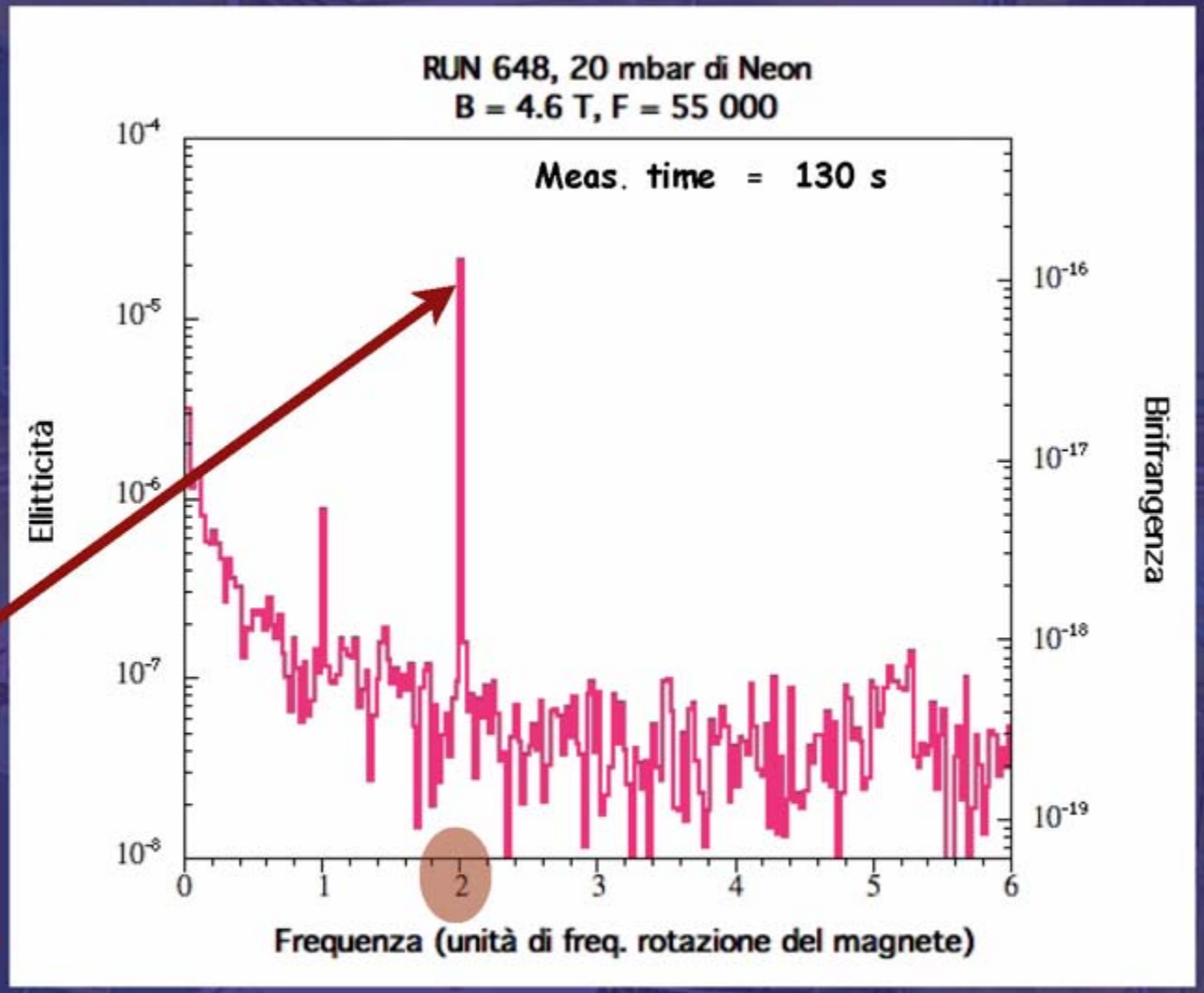
- Main parameters of the apparatus
  - magnet
    - dipole, 6 T, temp. 4.2 K, 1 m field zone
  - cryostat
    - rotation frequency ~300 mHz, sliding contacts, warm bore to allow light propagation in the interaction zone
  - laser
    - 1064 nm, 100 mW, frequency-locked to the F.-P. cavity
  - Fabry-Perot optical cavity
    - 6.4 m length, finesse ~100000, optical path in the interaction region ~ 60 km
  - heterodyne ellipsometer
    - ellipticity modulator (SOM) and high extinction (~10^{-7}) crossed polarisers + Quarter Wave Plate (QWP)
    - time-modulation of the effect
  - detection chain
    - photodiode with low-noise amplifier
  - DAQ
    - Slow: demodulated at low frequency and phase-locked to the magnetic field instantaneous direction
    - Fast: high sampling frequency direct acquisition

Performance tests with gases

Measurements of the Cotton-Mouton effect in gases (done without the QWP)

The slow DAQ gives an amplitude spectrum demodulated at the carrier frequency of the ellipticity modulator (506 Hz)

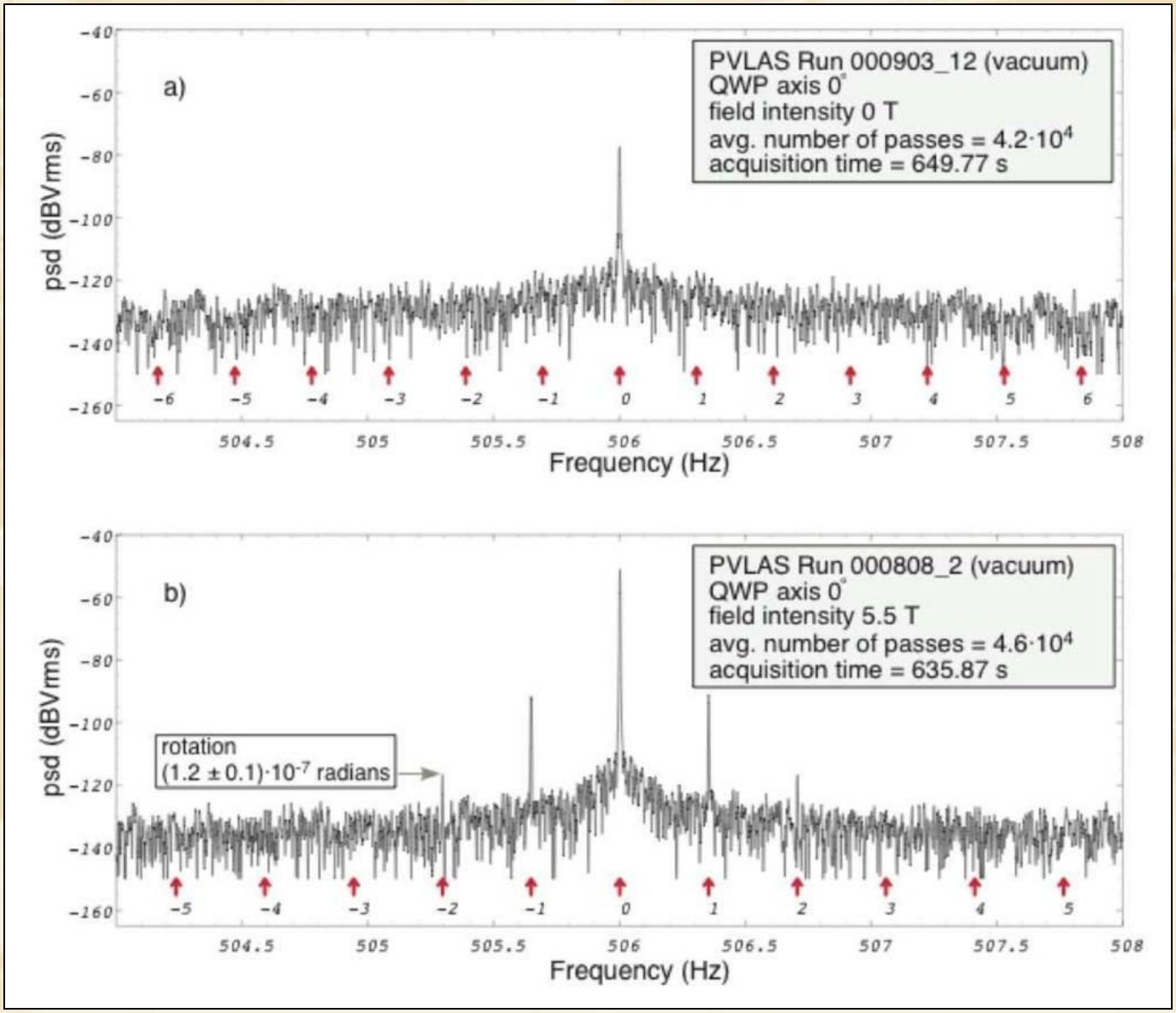
The expected signal (magnetic birefringence of a gas in this case) appears at twice the magnet rotation frequency (here 0.6 Hz)



Sensitivity

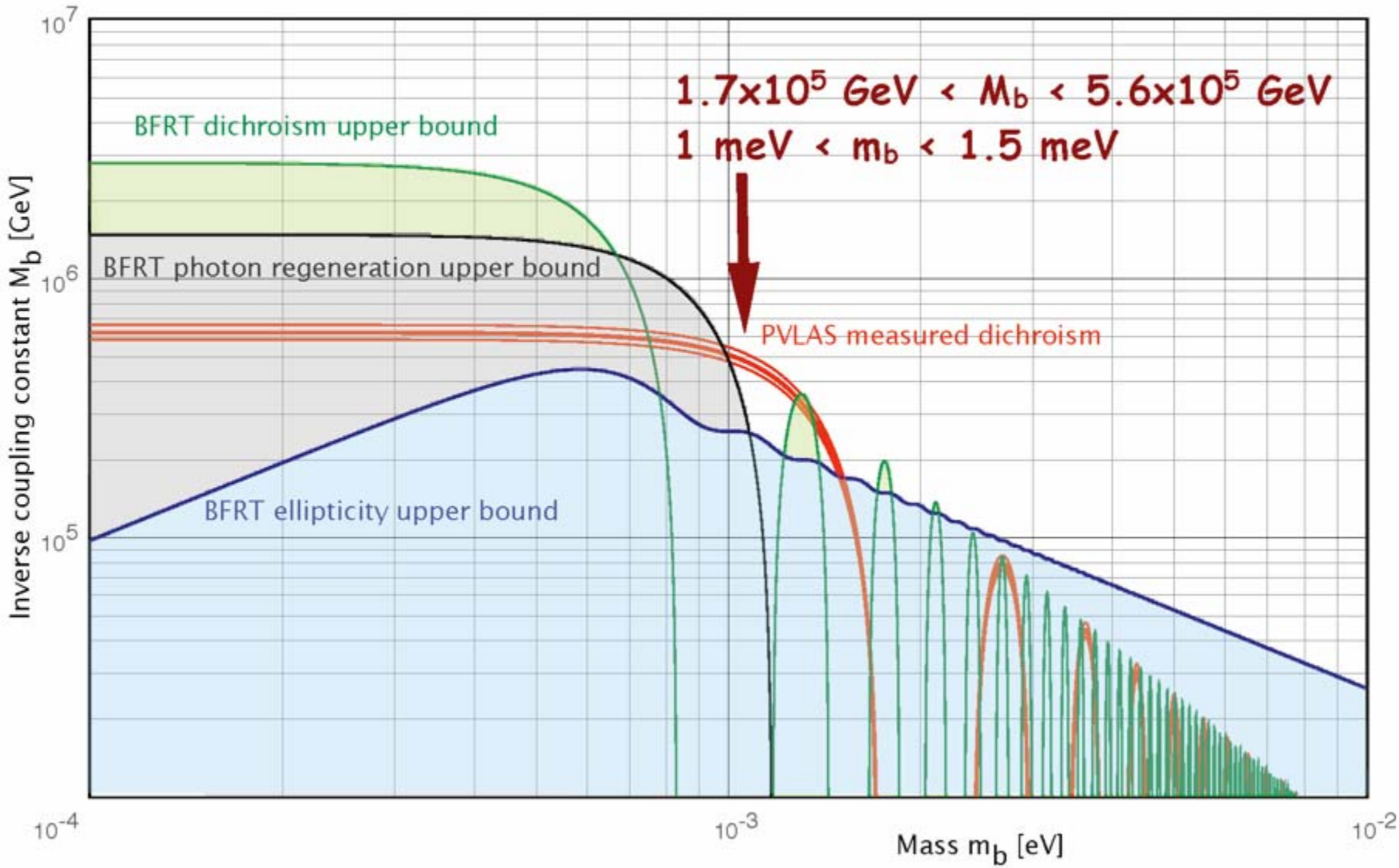
$$\psi^s \approx 6 \cdot 10^{-7} \quad 1/\sqrt{Hz};$$
$$\Delta n^s \approx 2 \cdot 10^{-18} \quad 1/\sqrt{Hz};$$

The PVLAS Dichroism Signal



PVLAS, PRL 96:110406 (2006), hep-ex/0507107

BFRT and PVLAS results on the m_b-M_b plane



Do Axions Escape from the Sun?

Primakoff conversion rate in the static limit (no recoil, screening included)

$$\Gamma_{\gamma\to a} = \frac{g_{a\gamma}^2 T k_S^2}{32\pi}\left[\left(1+\frac{k_S^2}{4E^2}\right)\ln\left(1+\frac{4E^2}{k_S^2}\right)-1\right]$$

Conversion rate $\gamma \to a$ for given energy identical to reverse rate $a \to \gamma$

$$\lambda_a = \Gamma_{a\to\gamma}^{-1} = \Gamma_{\gamma\to a}^{-1}$$

Example of Sun for E_a = 4 keV, near center of Sun (k_S = 9 keV)

$$\lambda_a \approx g_{10}^{-2}\, 10^{25}\,\mathrm{cm} \approx g_{10}^{-2}\, 10^{14} R_{sun} \approx g_{10}^{-2}\, 10^{-3} H_0^{-1}$$

Even for PVLAS particle interpretation with $g_{10} \approx 5\times10^4$ several orders of magnitude to spare

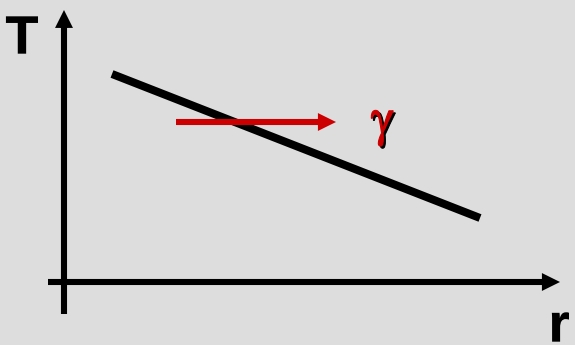
$$L_a(\mathrm{PVLAS}) \approx 5\times10^6 L_{sun}$$

Sun would burn out in about 1000 years!

What if axion-like particles are "trapped"?

Radiative energy transfer

Photons transport energy over a distance ~ 1 mean free path (mfp)



To be harmless, a "trapped" low-mass particle species, e.g., axion-like particles, must have a mfp approximately less than photons (in the Sun ~ 10 cm)

A new low-mass particle has the strongest effect on a star when its mfp is of order the geometric dimensions of the star!

Raffelt & Starkman, "Stellar energy transfer by keV-mass scalars", Phys. Rev. D 40, 942 (1989)

PVLAS-Inspired ALPs Industry

- PVLAS paper (PRL 96:110406,2006, hep-ex/0507107) has 102 citations as of April 2007
- Numerous theory papers to reconcile PVLAS particle interpretation with stellar energy-loss limits and with CAST limits
- About half a dozen experimental projects to test PVLAS particle interpretation by photon regeneration (DESY, CERN, Jefferson Lab, Toulouse, PVLAS, Fermilab ...)
- Astrophysical consequences for photon propagation in ubiquitous B-fields

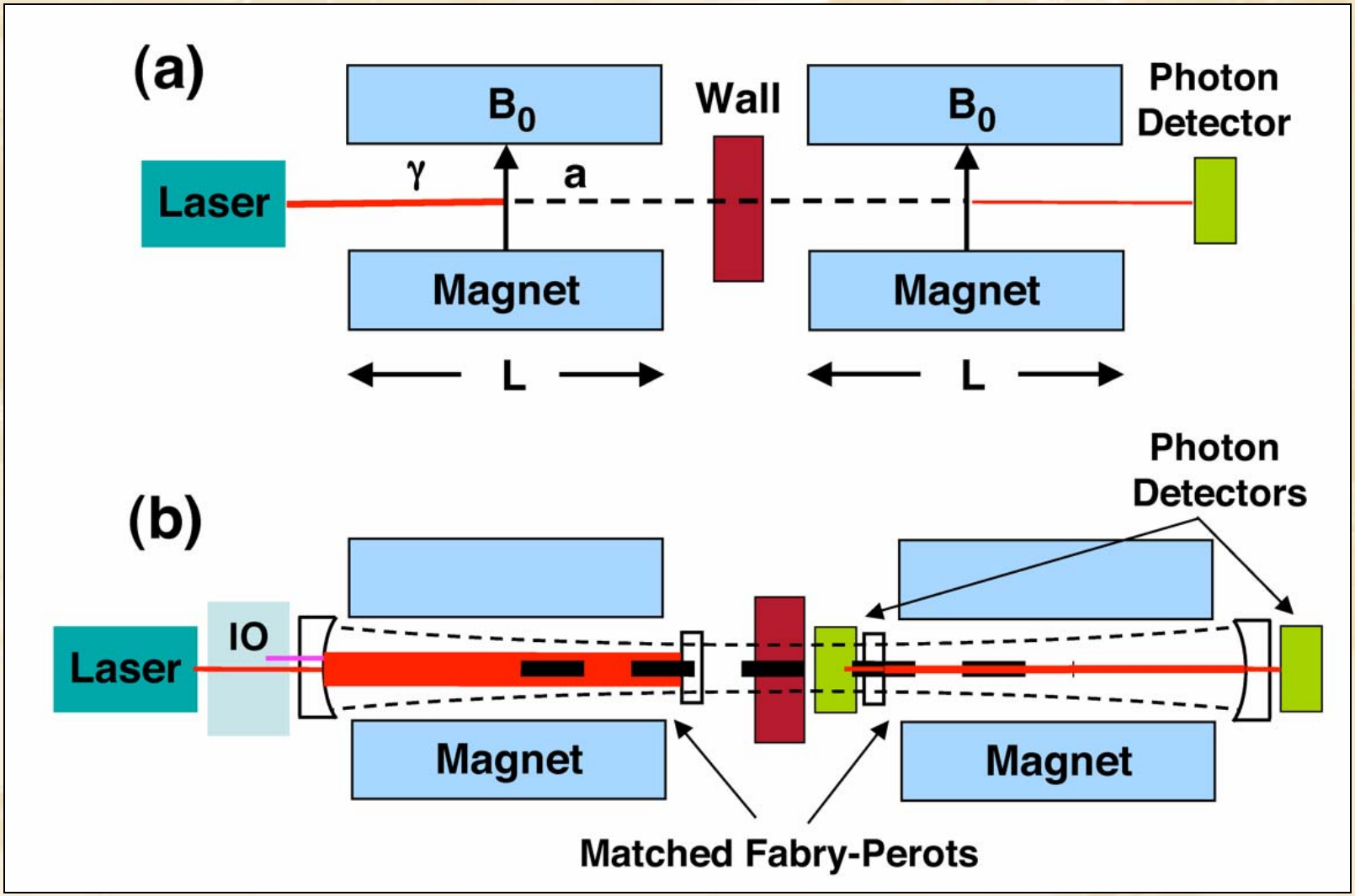
Photon Regeneration Experiments

"Shining light through a wall"

Single pass

Resonant cavities on generation & regeneration side

hep-ph/0701198



Depletion of TeV Gammas from Galactic Center

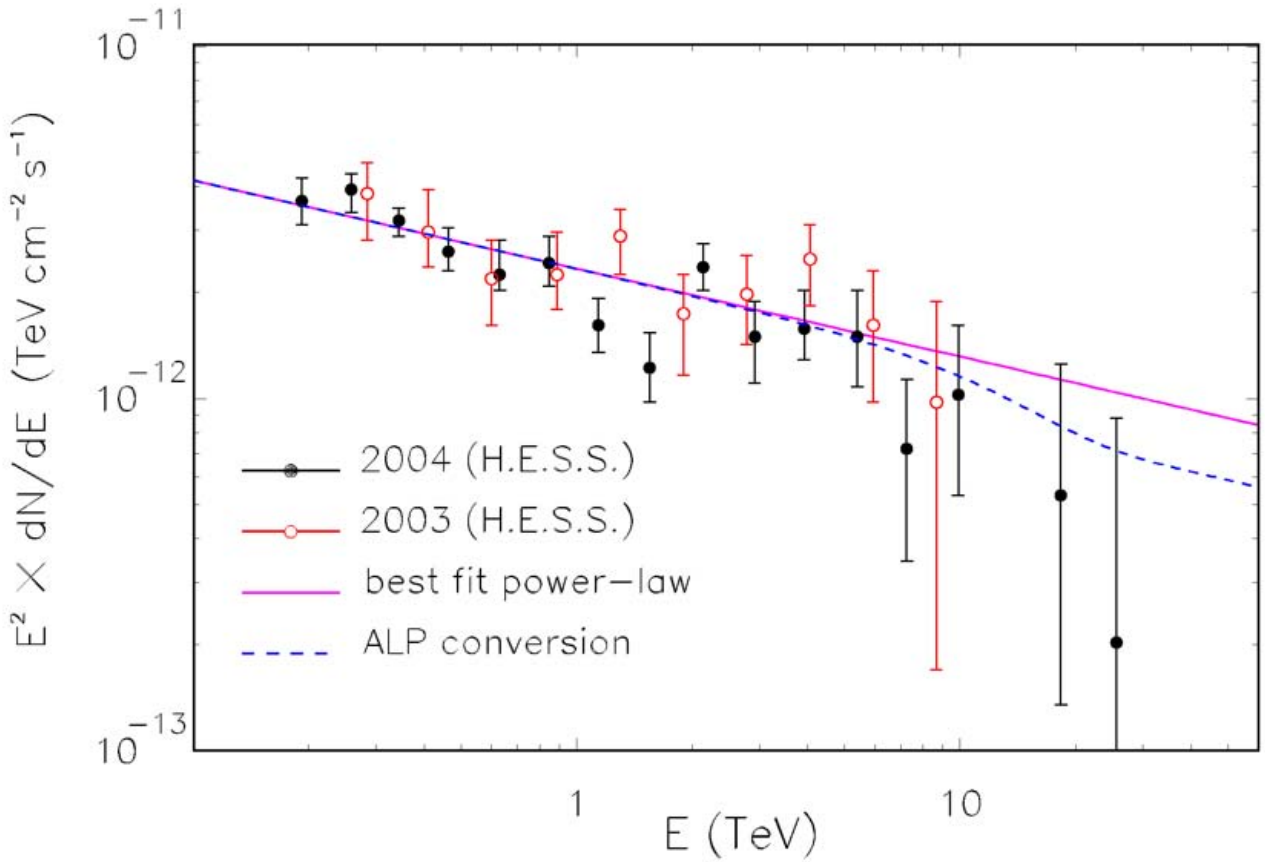


FIG. 1: Spectral energy density $E^2 \times \mathrm{d}N/\mathrm{d}E$ of photons from the galactic center source, for the 2004 data (full points) and 2003 data (open points) of H.E.S.S. [35]. Error bars represent 95% CL. The continuous line shows the best-fit power-law $\mathrm{d}N/\mathrm{d}E \sim E^{-\Gamma}$ with $\Gamma = 2.25$ [35]. The dashed line shows the effect of photon-ALP conversion with coupling and mass suggested by PVLAS.

Mirizzi, Raffelt & Serpico, Signatures of axion-like particles in TeV gamma-ray sources, arXiv:0704.3044

Technological Applications of PVLAS Particles

Long Distance Signaling Using Axion-like Particles

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Abstract

The possible existence of axions or axion-like particles could lead to a new type of long distance communication. In this letter, basic antenna concepts are defined and a Friis-like equation is derived to facilitate long-distance link calculations. An example calculation is presented showing that world-wide signaling may be possible if the axion interpretation of the recent PVLAS experiment is confirmed.

arXiv:0704.0490v1 [hep-ph]