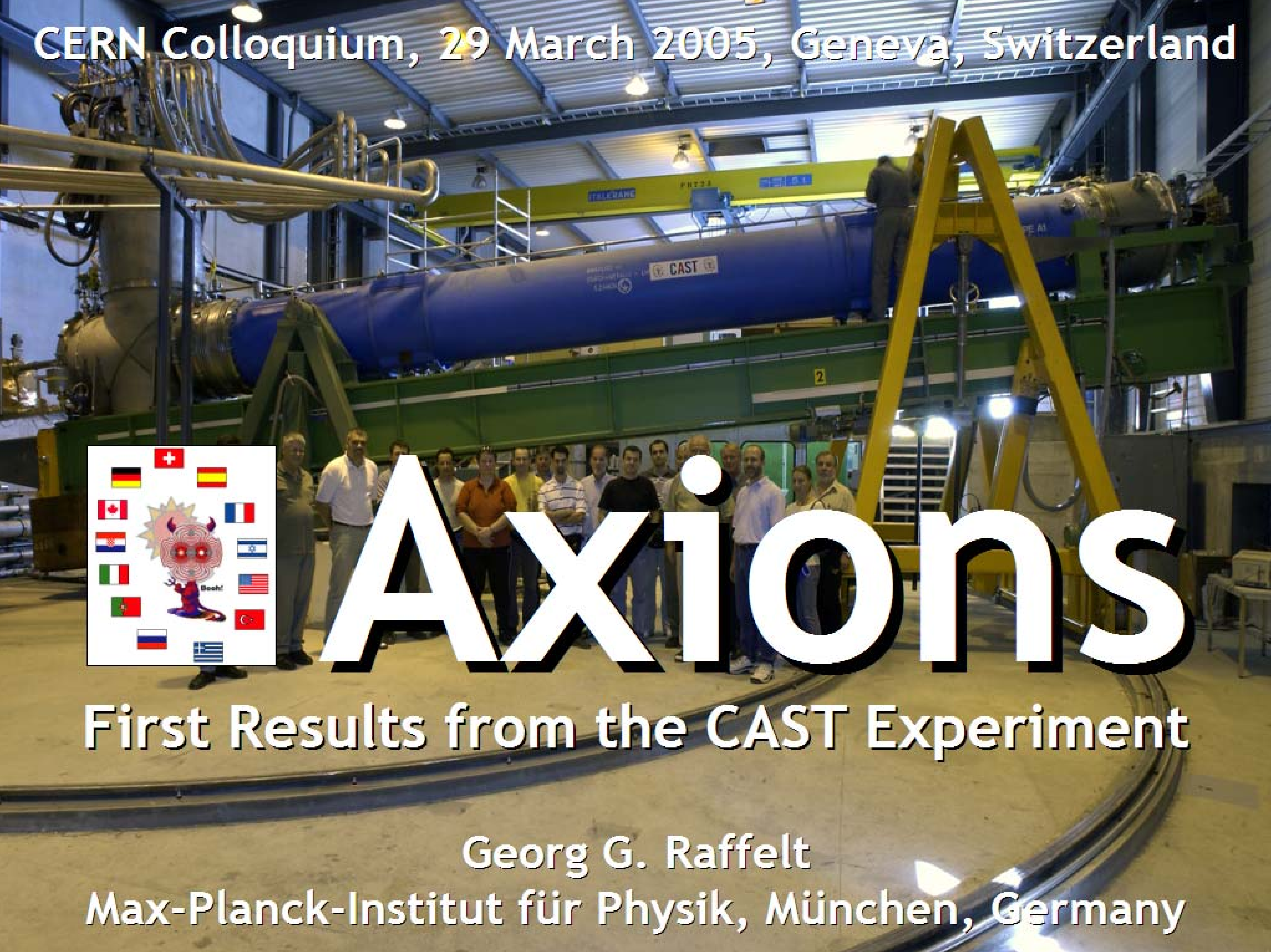
CERN Colloquium, 29 March 2005, Geneva, Switzerland



Axions

First Results from the CAST Experiment

Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany

The CAST Collaboration

arXiv:hep-ex/0411033 v2 1 Mar 2005

PRL, in press (2005)

First results from the CERN Axion Solar Telescope (CAST)

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(CAST Collaboration)

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[9] *National Center for Scientific Research "Demokritos", Athens, Greece*
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[14] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Munich, Germany*
[15] *Rudjer Bošković Institute, Zagreb, Croatia*

(Dated: March 1, 2005)

Axion Software

ax·ion (ăk'shən) *n.*
1.The process of acting or doing.
2.Makers of sport specific footwear.
see logo

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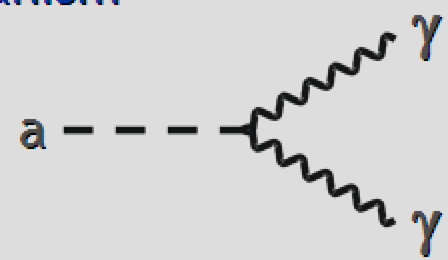
Axion Physics in a Nut Shell

Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism

→ Axions $a \sim \pi^0$

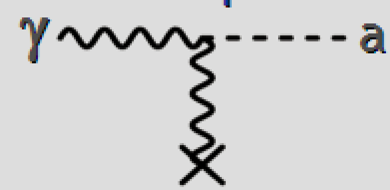
$m_\pi f_\pi \approx m_a f_a$



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

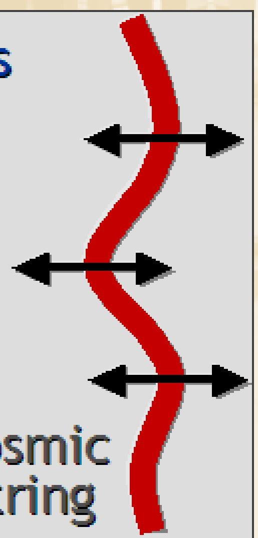


- Limits from avoiding excessive energy drain
- Search for solar axions (CAST)

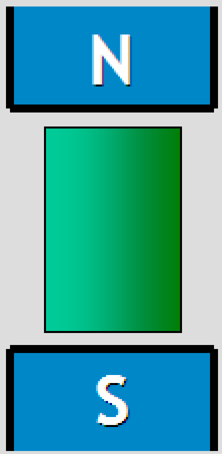
Cosmology

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

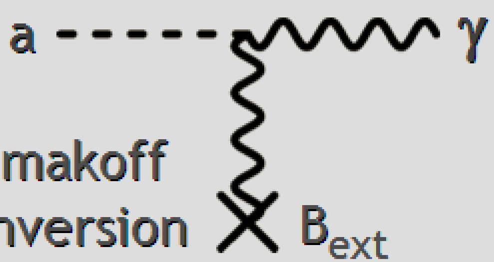
→ "Cold dark matter" candidate
$m_a \sim$ 1-1000 μeV



Search for Axion Dark Matter



Microwave resonator (1 GHz = 4 μeV)



Primakoff conversion

Axion Physics in a Nut Shell

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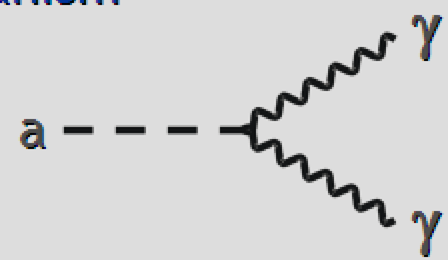

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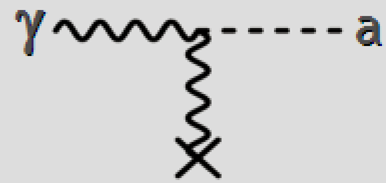

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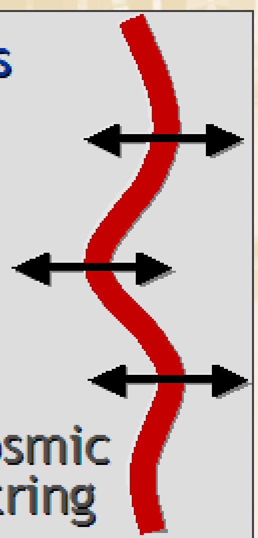
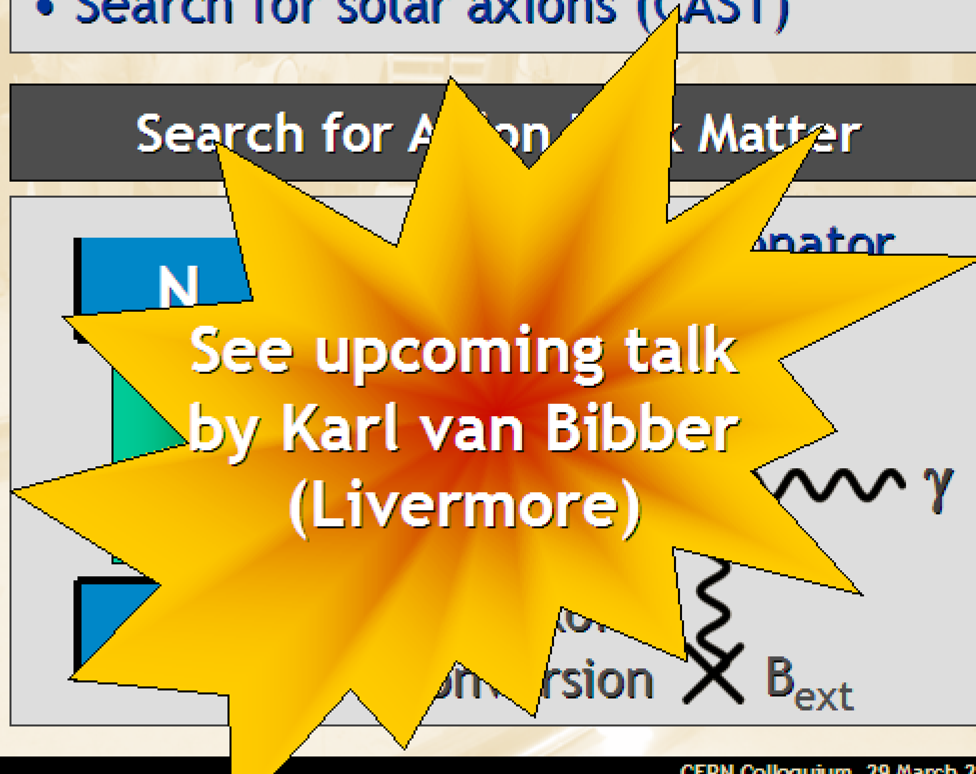


Cosmic String

Search for A…on …k Matter



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

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

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

$$d_n \approx \overline{\Theta}\, 10^{-16}\, e\,\mathrm{cm} \approx \frac{\overline{\Theta}}{10^2} \mu_n < 10^{-25}\, e\,\mathrm{cm}$$

$\overline{\Theta} < 10^{-9}$ **Why so small?**

Dynamical Solution

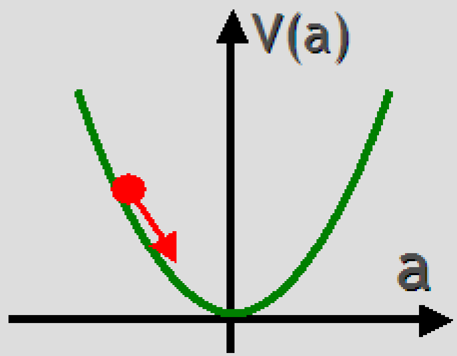
Peccei & Quinn 1977 - Wilczek 1978 - Weinberg 1978

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

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

- $a(x)$: Pseudo-scalar axion field
- f_a: Peccei-Quinn scale, Axion decay constant

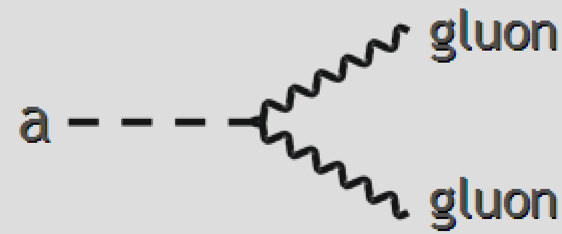
$$L_{CP} = -\frac{\alpha_s}{8\pi}\,\overline{\Theta}\,\mathrm{Tr}(G\tilde{G}) \quad \Longrightarrow \quad L_{CP} = -\frac{\alpha_s}{8\pi}\,\frac{a(x)}{f_a}\,\mathrm{Tr}(G\tilde{G})$$



$\overline{\Theta} = 0$

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

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

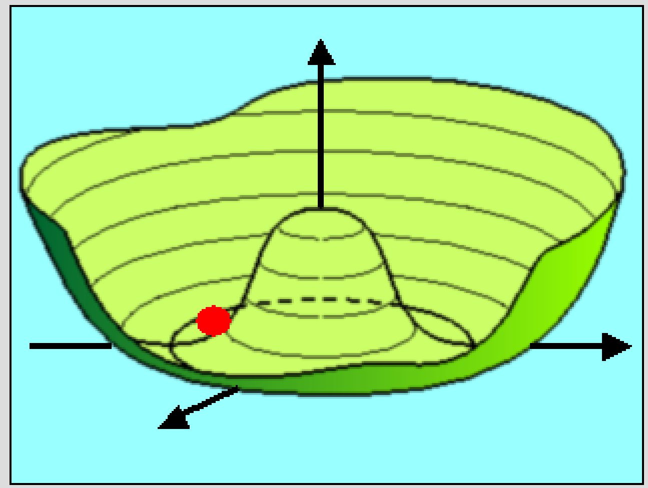
$f_\pi \approx 93$ MeV
Pion decay constant

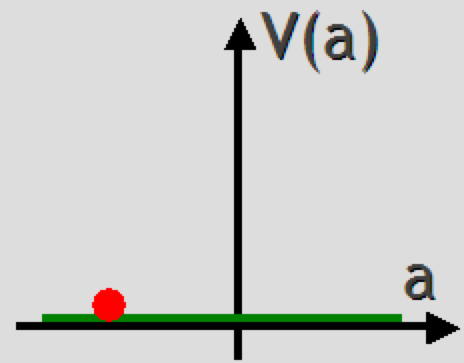
Axions as Pseudo Nambu-Goldstone Bosons

- 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

$E \approx f_a$

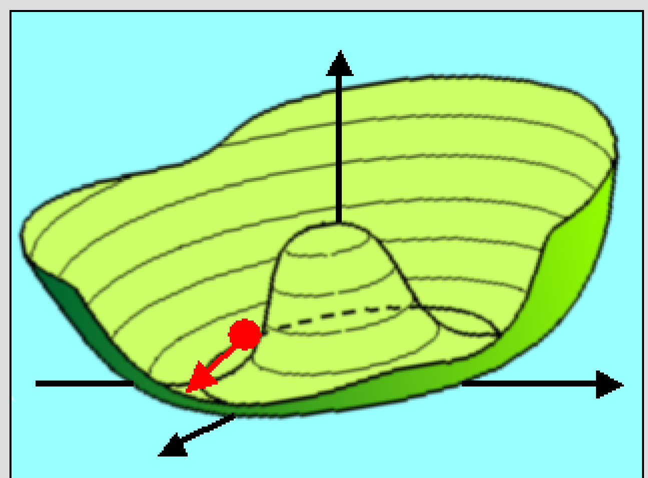
- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"

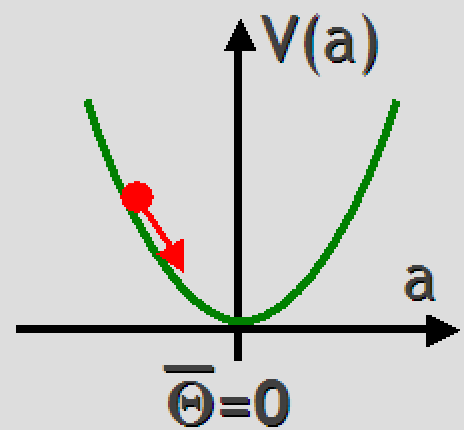




$E \approx \Lambda_{QCD} \ll f_a$

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

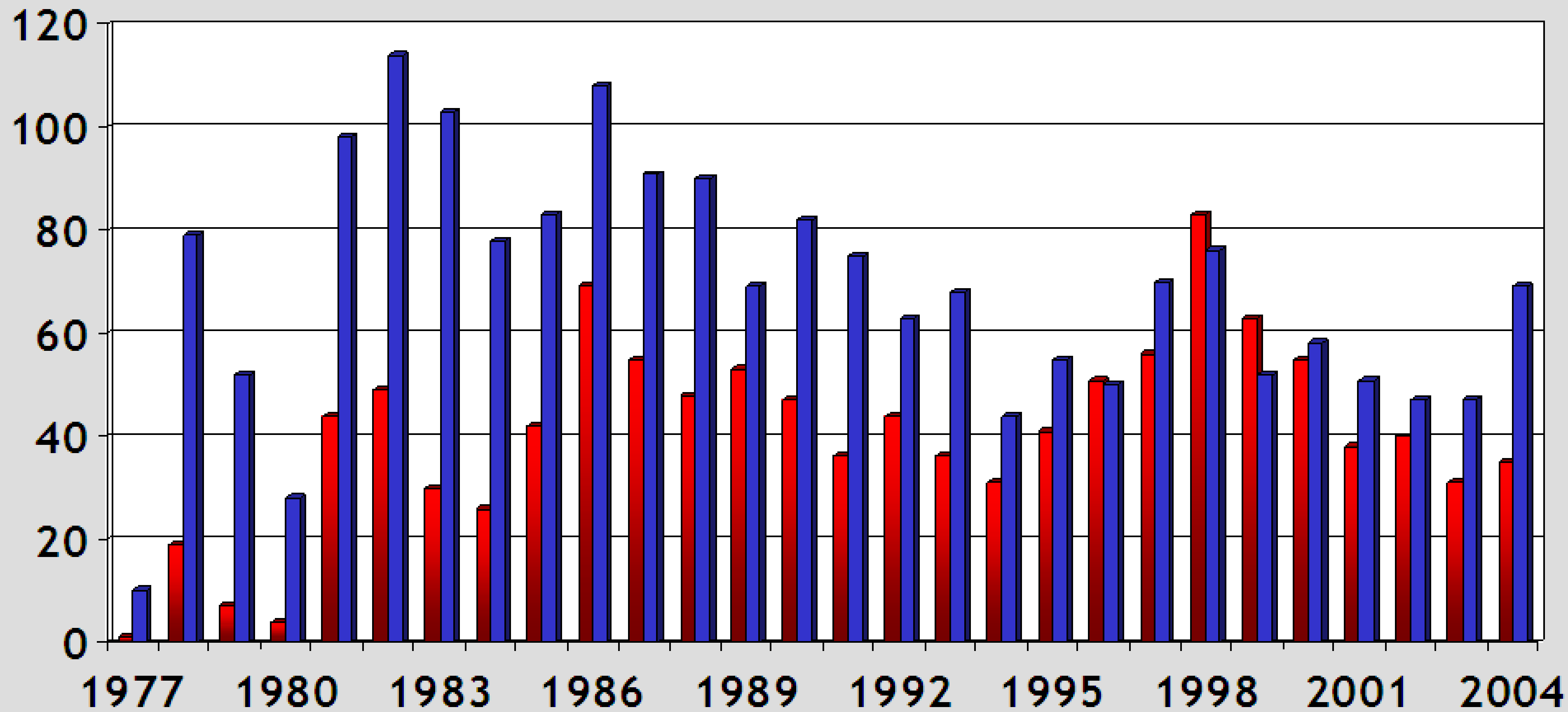




Windows of Opportunity

Axions	Alternatives
Solve strong CP problem by Peccei-Quinn dynamical symmetry restoration	• Massless up-quark • Spontaneous CP violation • Fine tuning
• 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 • Monopoles • Deviation from Newton's Law (e.g. large extra dimensions)

Axions as a Research Topic

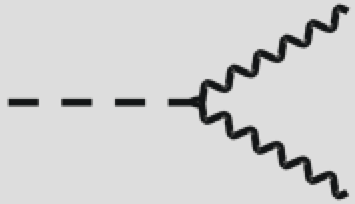


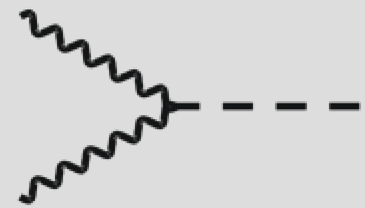
- Papers in SPIRES that cite one of the two original Peccei and Quinn papers or Weinberg's or Wilczek's paper (total of 1926 papers)
- Papers in SPIRES with "axion" or "axino" in their title (total of 1141 papers)

Particles with Two-Photon Coupling

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

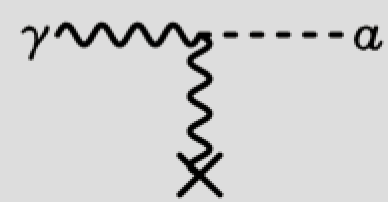
$$L_{a\gamma} = g_{a\gamma}\vec{E}\cdot\vec{B}\,a$$



Two-photon decay	$\Gamma_{a\gamma} = \dfrac{g_{a\gamma}^2 m_a^3}{64\pi}$	Photon Coalescence	

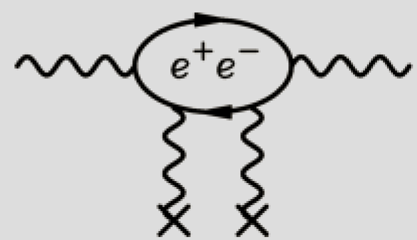
Primakoff Effect

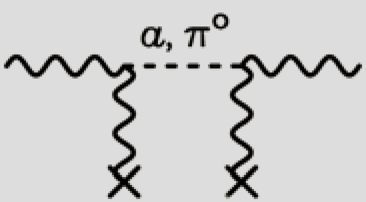
Conversion of photons into pions, gravitons or axions, or the reverse



Magnetically induced vacuum birefringence

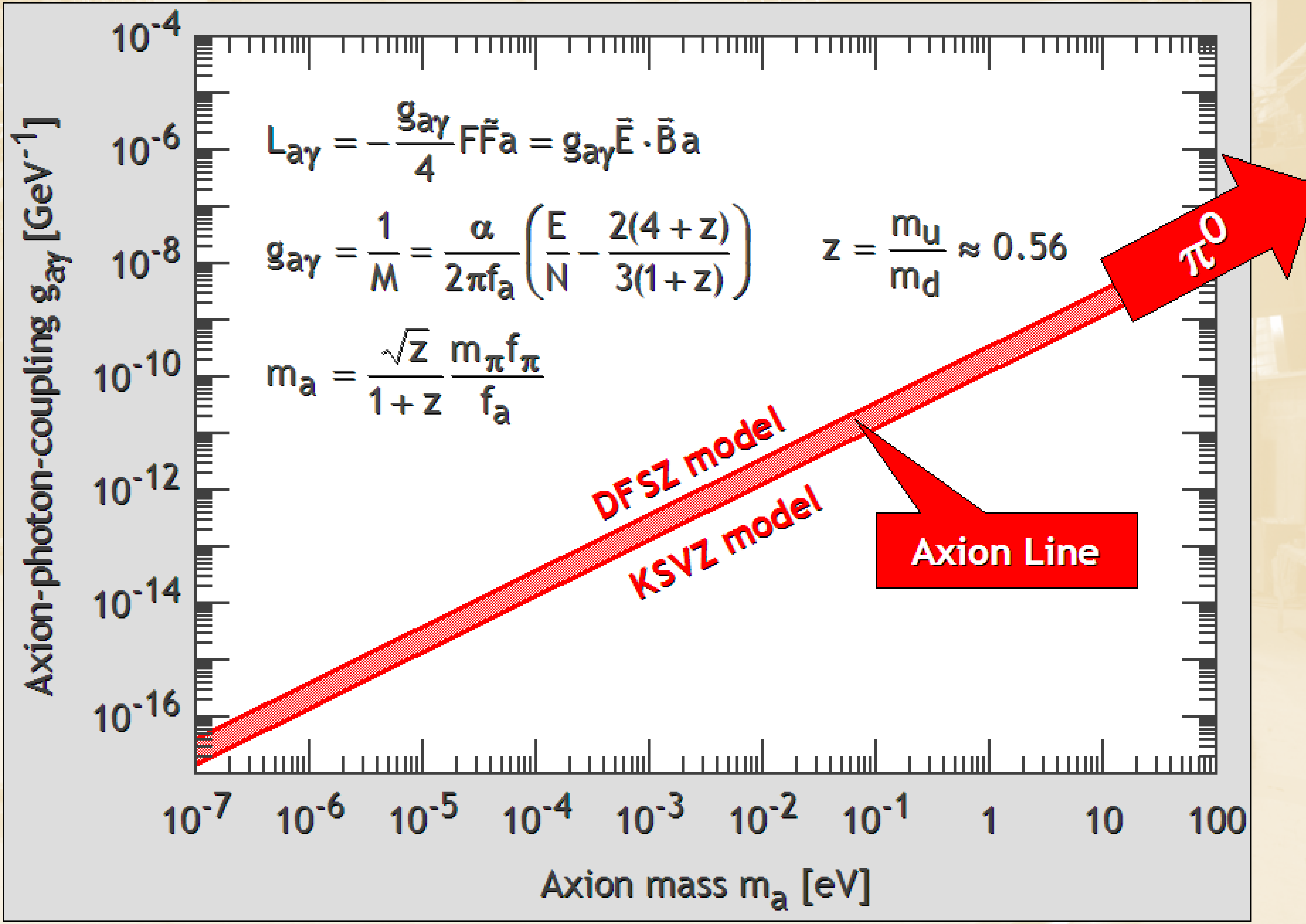
In addition to QED Cotton-Mouton-effect





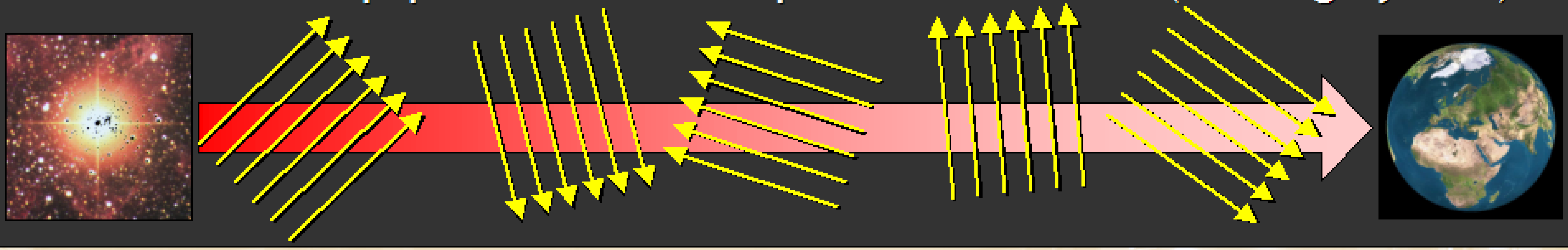
PVLAS experiment currently measures an effect ~ 10^4 larger than QED expectation

Axion-Photon-Coupling vs. Mass



Dimming of Supernovae without Cosmic Acceleration

Axion-photon-oscillations in intergalactic B-field domains dim photon flux
- Effect grows linearly with distance
- Saturates at equipartition between photons and axions (unlike grey dust)



Mixing matrix

$$\frac{1}{2\omega}\begin{pmatrix}\omega_{pl}^2 & g_{a\gamma}B\omega \\ g_{a\gamma}B\omega & m_a^2\end{pmatrix} = \begin{pmatrix}10.8\,n_e\omega^{-1} & 0.15\,g_{a\gamma}^2 B \\ 0.15\,g_{a\gamma}^2 B & 7.8\times10^{-4}\,m_a^2\omega^{-1}\end{pmatrix}\mathrm{Mpc}^{-1}$$

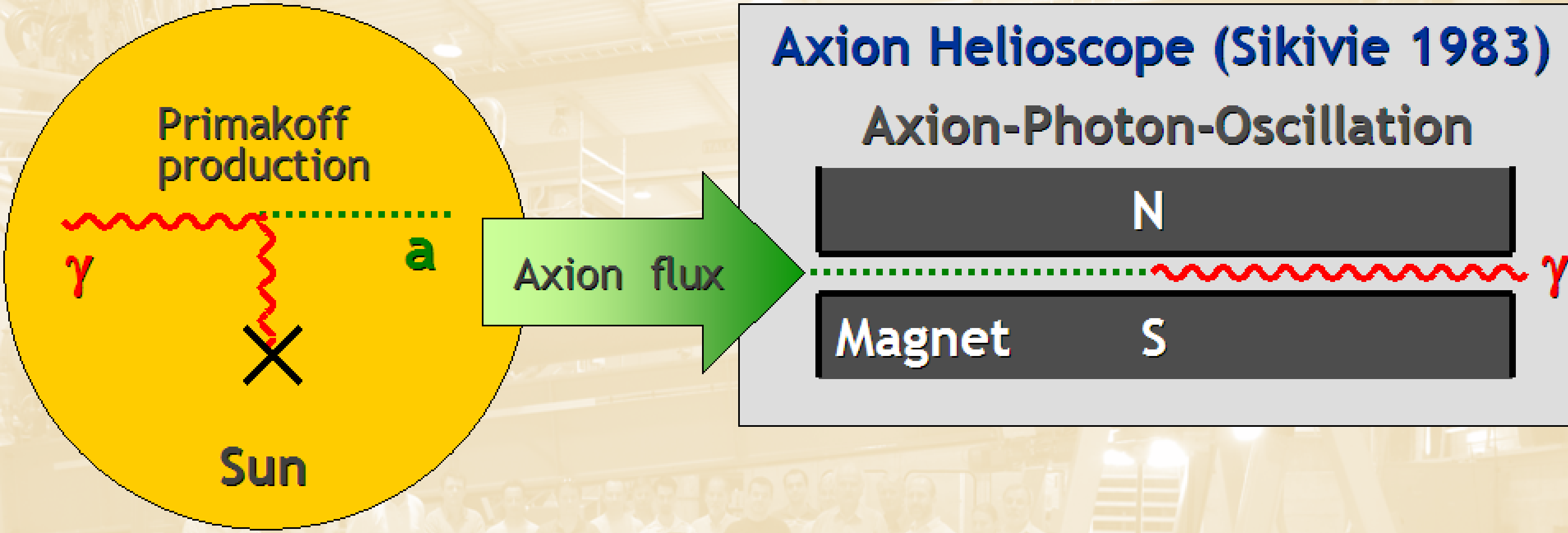
Domain size ~ 1 Mpc
Field strength ~ 1 nG
a-γ-coupling ~ 10^{-10} GeV^{-1}
Axion mass < 10^{-16} eV

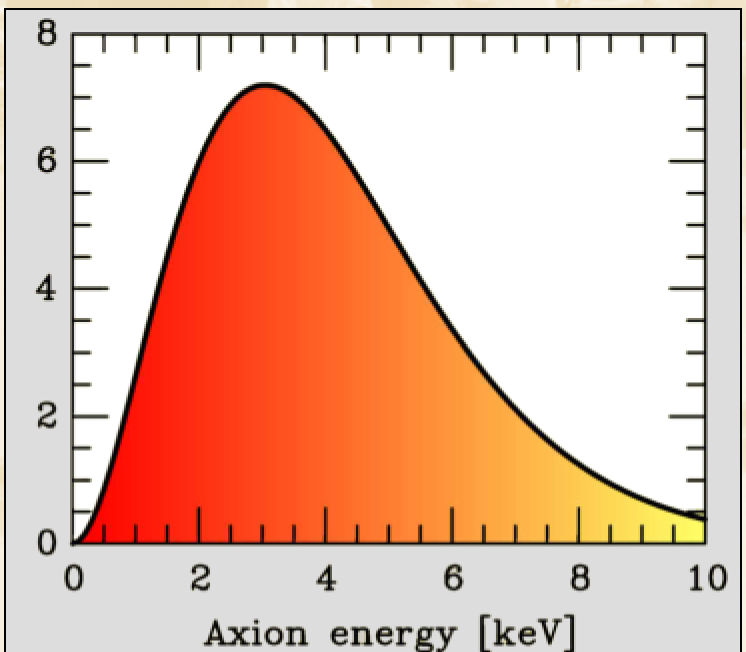
Photon energy ~ 1 eV
Electron density ~ 10^{-7} cm^{-3}
(average baryon density)

Chromaticity depends sensitively on assumed values and distribution of n_e and B

Csáki, Kaloper & Terning (hep-ph/0111311, hep-ph/0112212, astro-ph/0409596). Erlich & Grojean (hep-ph/0111335). Deffayet, et al. (hep-ph/0112118). Christensson & Fairbairn (astro-ph/0207525). Mörtsell et al. (astro-ph/0202153). Mörtsell & Goobar (astro-ph/0303081). Bassett (astro-ph/0311495). Ostman & Mörtsell (astro-ph/0410501).

Search for Solar Axions





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

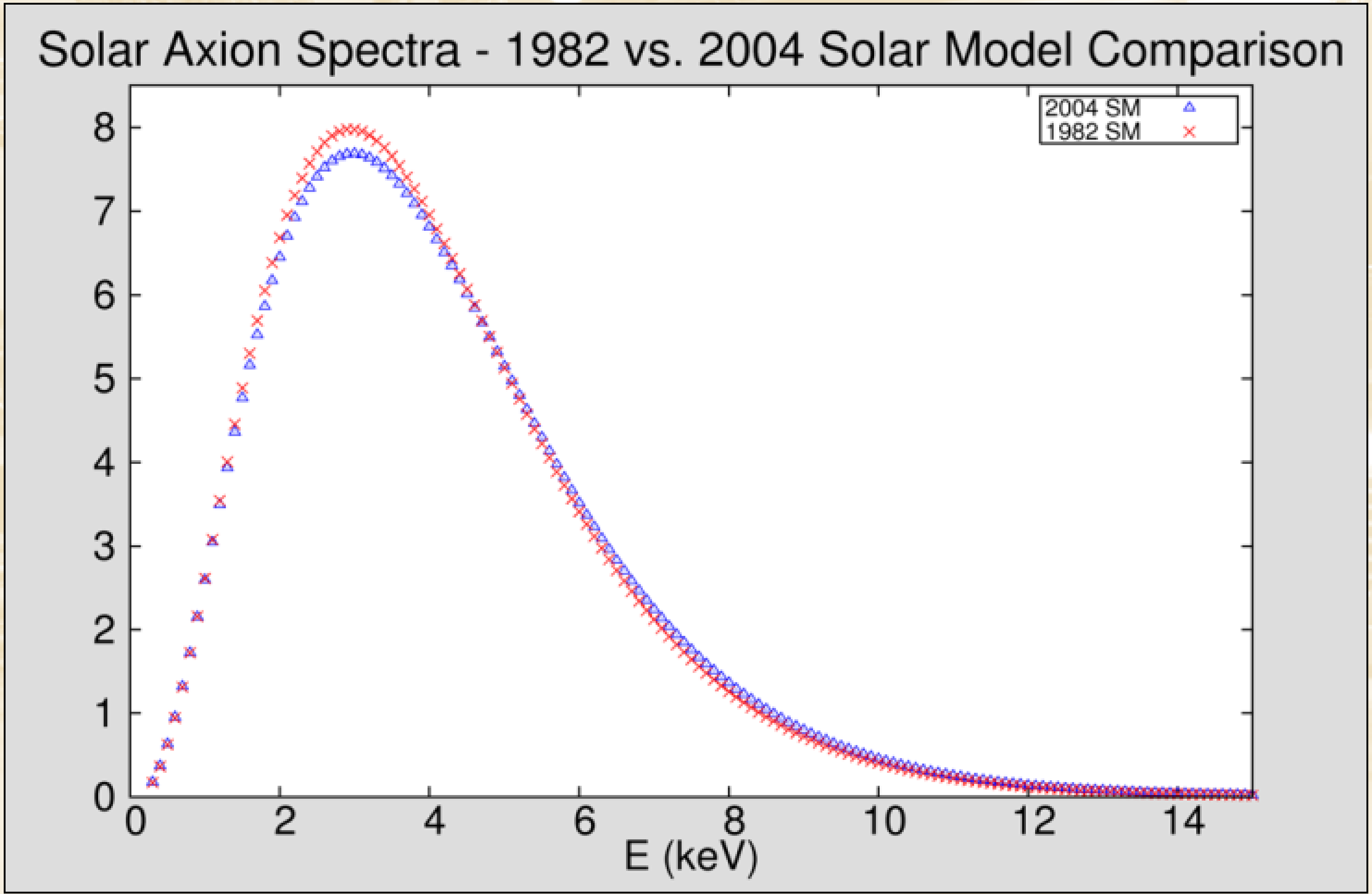
Alternative technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments (SOLAX, COSME, DAMA, ...)

Primakoff Process in the Sun

Interaction Lagrangian	$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \vec{E} \cdot \vec{B} a$
Primakoff cross section	$\frac{d\sigma_{\gamma\to a}}{d\Omega} = \frac{g_{a\gamma}^2 Z^2 \alpha}{8\pi} \frac{\left\lvert \vec{k}_a \times \vec{k}_\gamma \right\rvert^2}{\left\lvert \vec{k}_a - \vec{k}_\gamma \right\rvert^4}$ 
Conversion rate (screening effects, no nuclear recoil)	$\Gamma_{\gamma\to a} = \frac{g_{a\gamma}^2 T k_S^2}{32\pi} \left[\left(1 + \frac{k_S^2}{4E^2} \right) \ln\left(1 + \frac{4E^2}{k_S^2} \right) - 1 \right]$
Screening scale (non-relativistic non-degenerate)	$k_S^2 = \frac{4\pi\alpha}{T} n_B \left(Y_e + \sum_j Z_j^2 Y_j \right)$

- G. Raffelt, "Astrophysical axion bounds diminished by screening effects", Phys. Rev. D 33 (1986) 897 (Part of GR's Ph.D. Thesis)
- Consistent with results from FTD methods, see Altherr, Petitgirard & del Rio Gaztelurrutia, Astropart. Phys. 2 (1994) 175

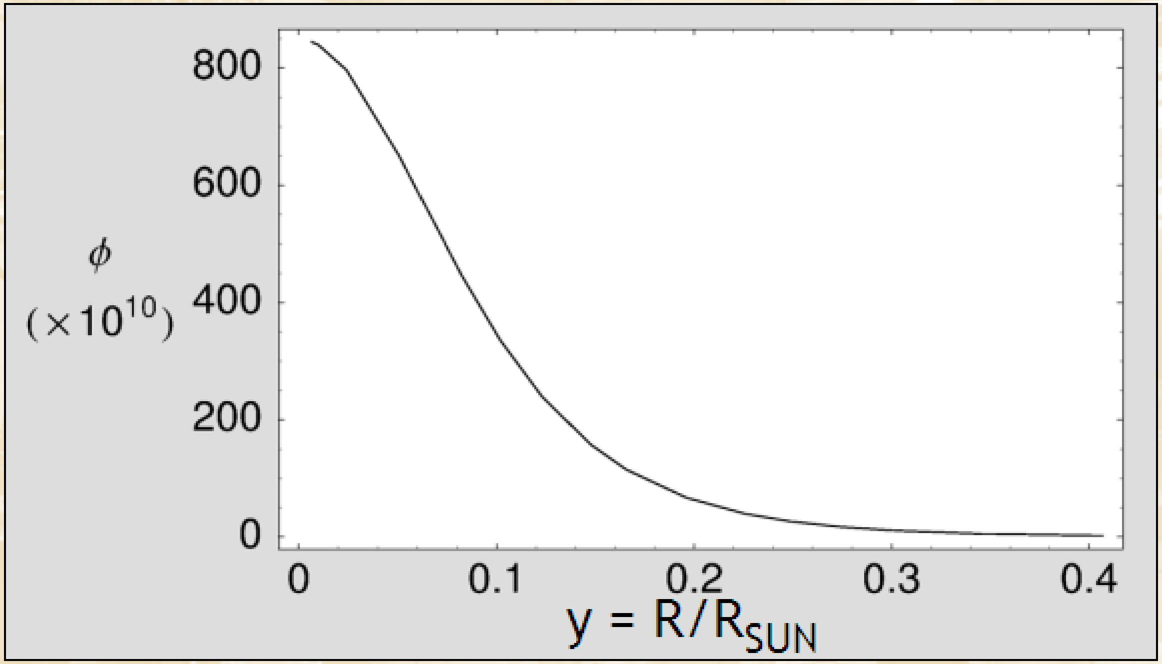
Axion Flux from1982 vs. 2004 Solar Model

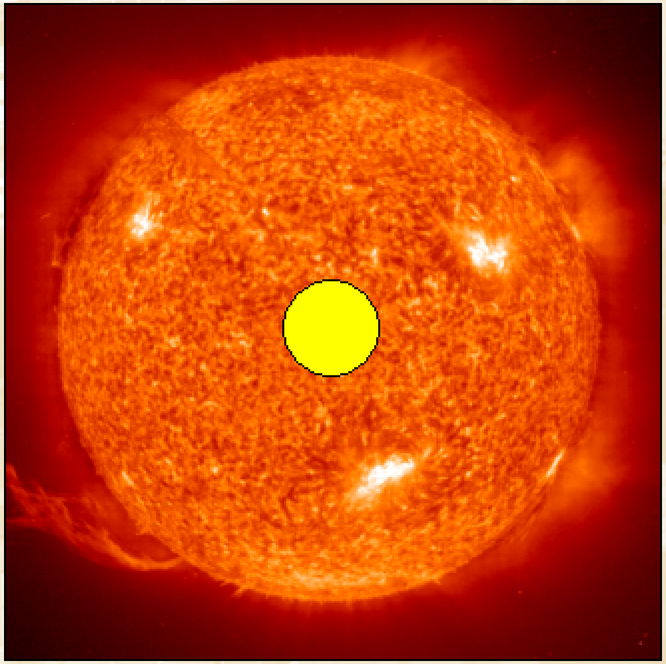


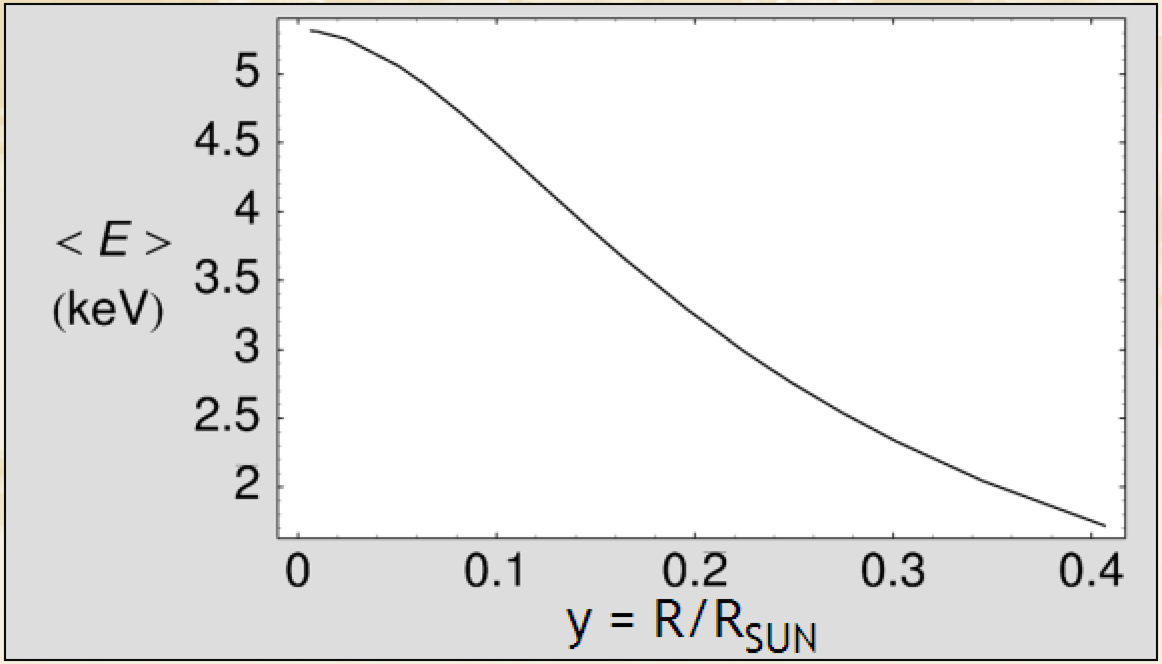
New calculation by Pasquale Serpico (MPI Physik)

[1] Bahcall et al., Rev. Mod. Phys. 54 (1982) 767
[2] Bahcall & Pinsonneault, PRL 92 (2004) 121301

Axion "Surface Luminosity" on Solar Disk

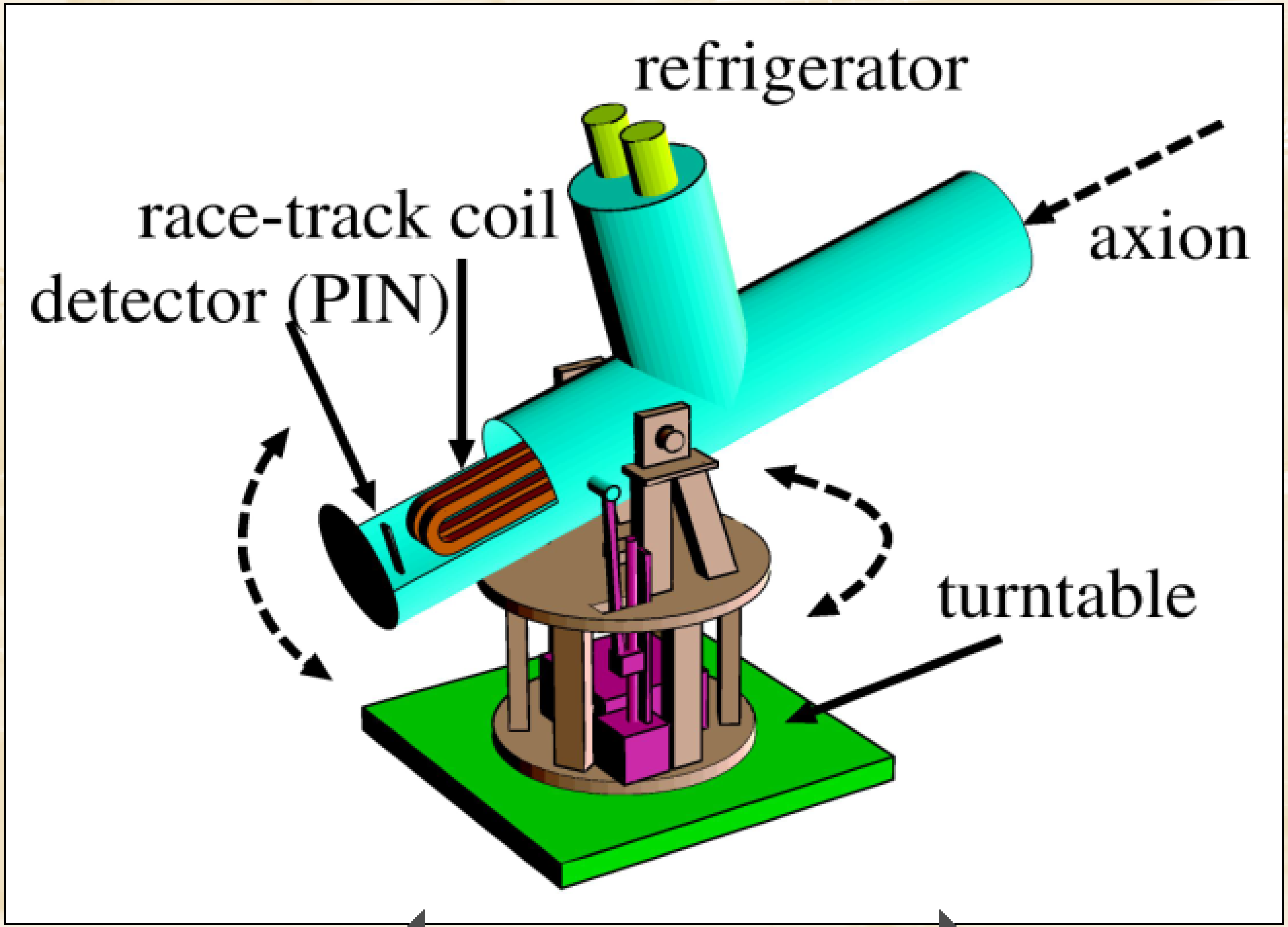






"Surface luminosity" is axion luminosity per unit square on solar disk (solar disk radius = 1 unit)

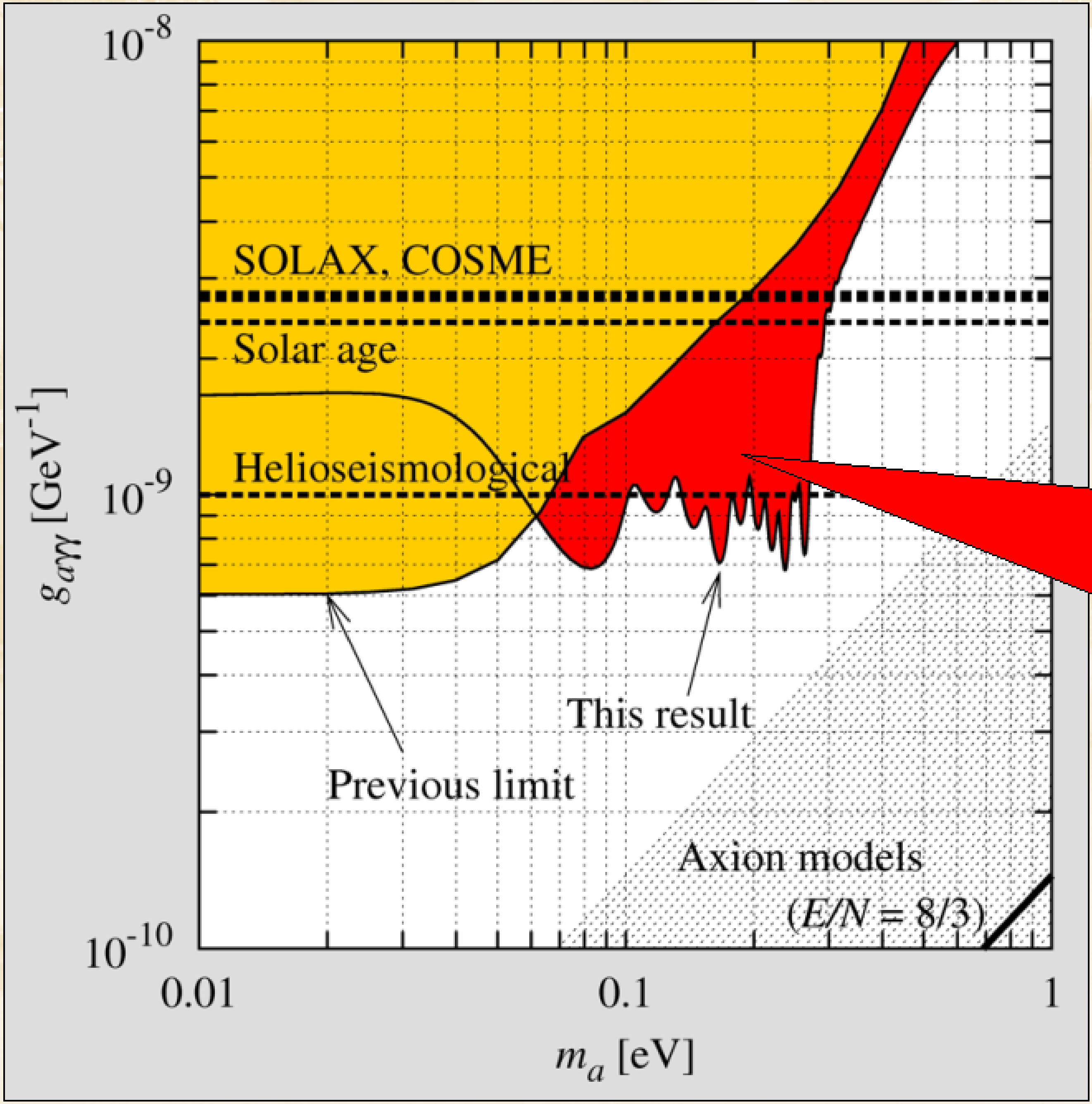
Tokyo Axion Helioscope



~ 3 m

S.Moriyama, M.Minowa, T.Namba, Y.Inoue, Y.Takasu & A.Yamamoto, PLB 434 (1998) 147

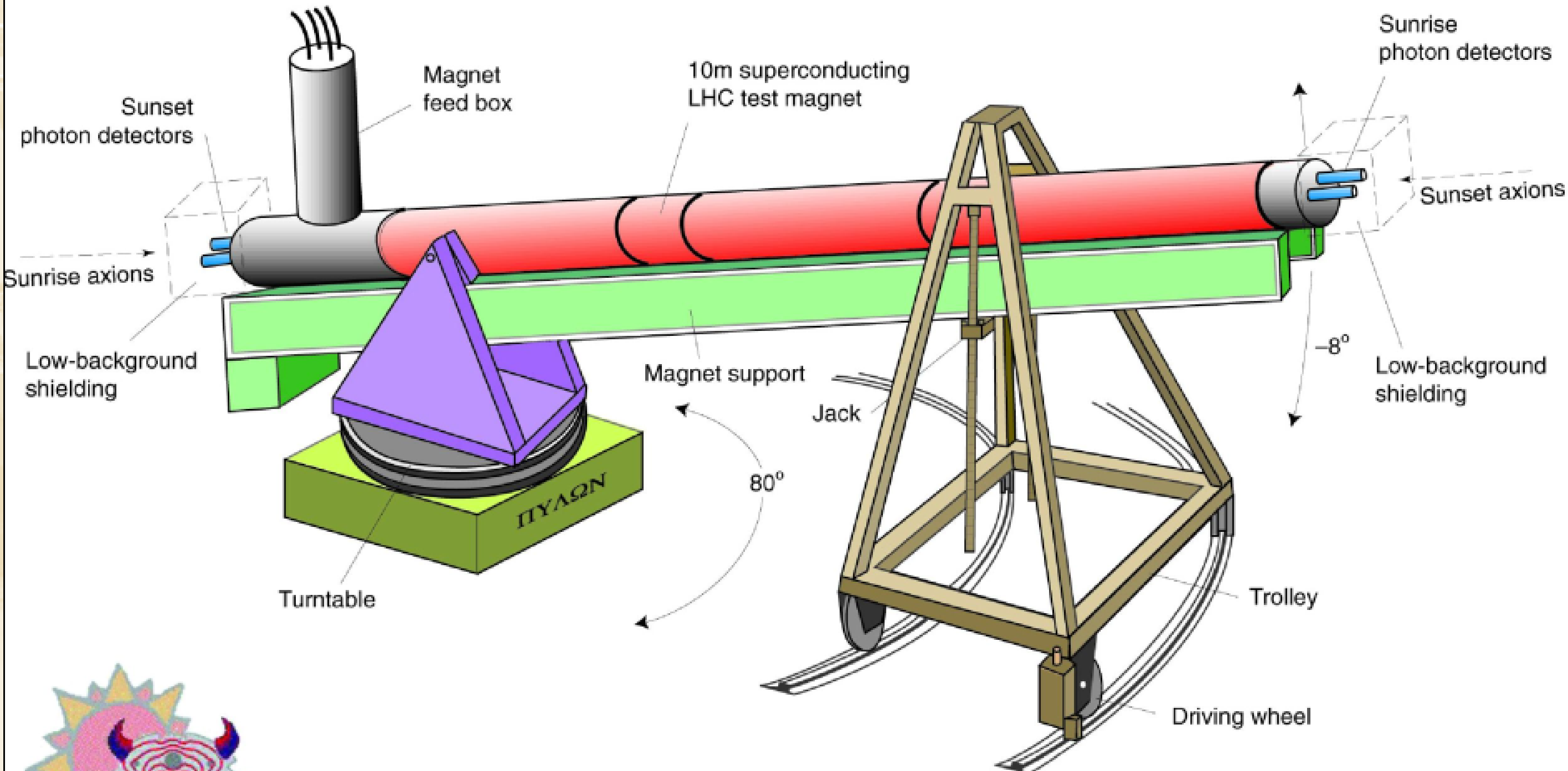
Limits from Tokyo Axion Helioscope

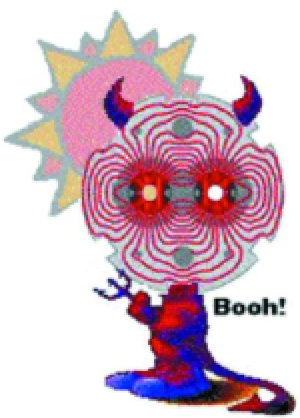


Y. Inoue et al., PLB 536 (2002) 18 [astro-ph/0204388]

Axion-photon transition region filled with pressurized gas to give photons an effective mass (avoid momentum mismatch)

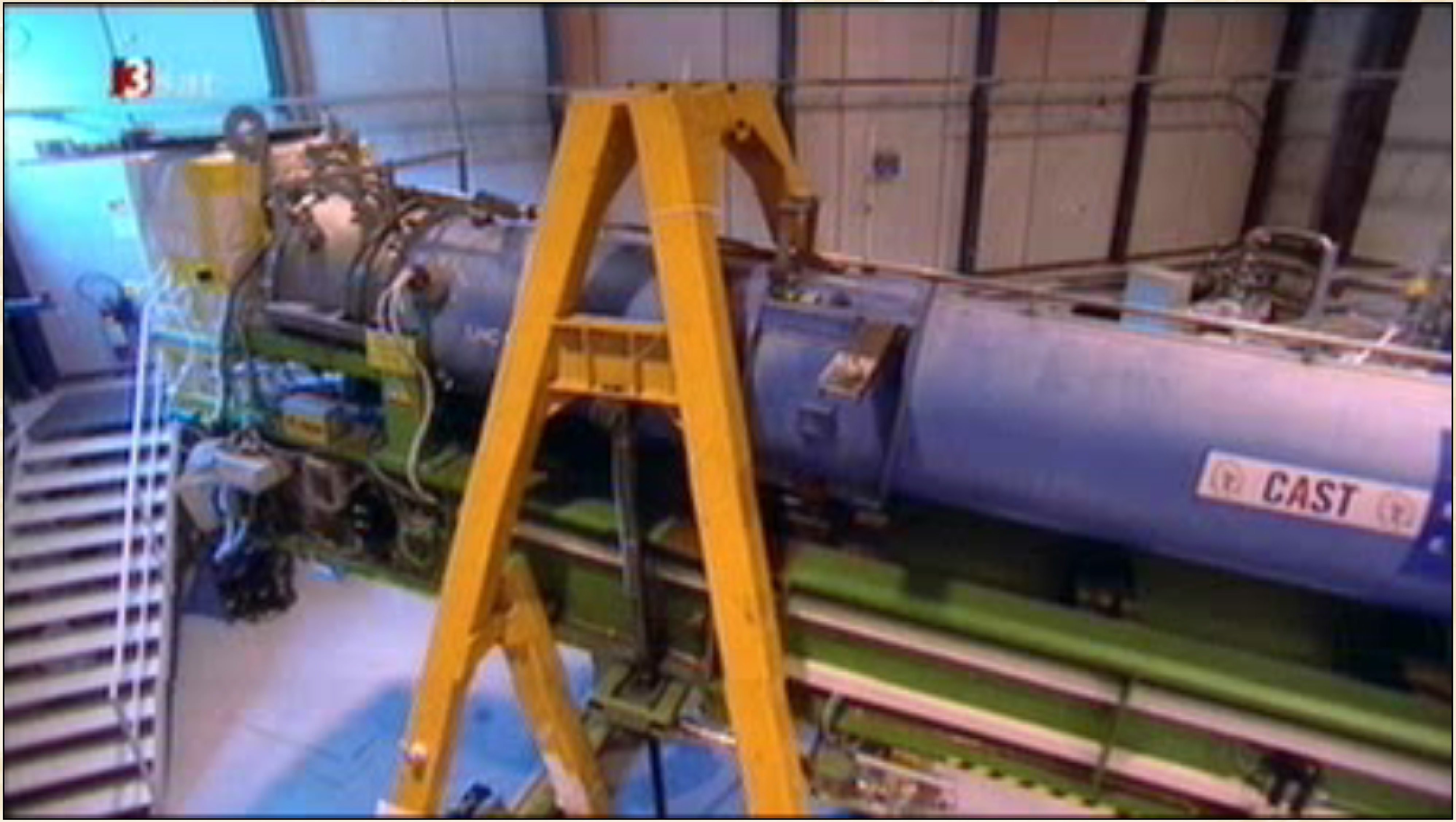
LHC Magnet Mounted as a Telescope to Follow the Sun





Cern **A**xion **S**olar **T**elescope

CAST Movies (1)



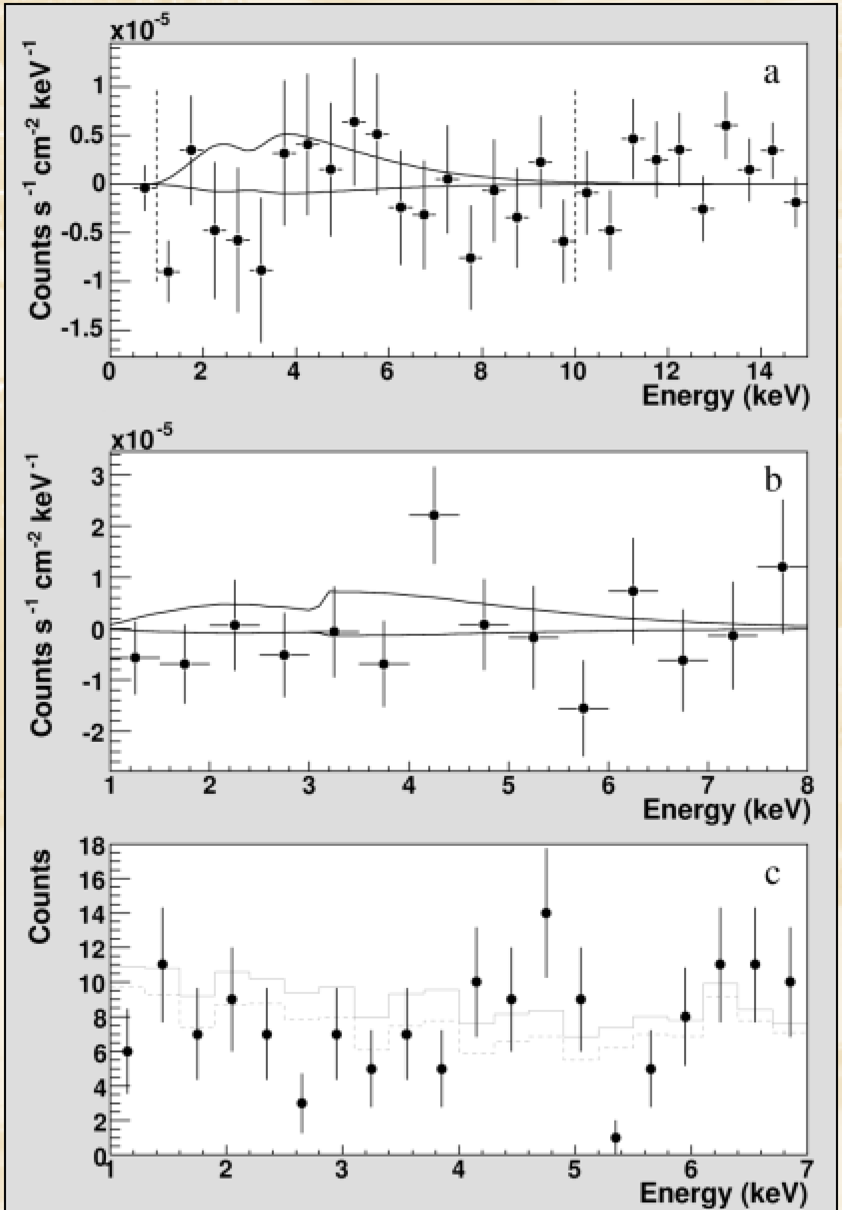
CAST Movies (2)

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 2x14 cm^2)	$\Phi_\gamma = 15\, \mathrm{d}^{-1} g_{10}^4$
Integrated exposure time (±40° horizontal and ±5° vertical tracking)	33 days per year

Fourth-power dependence:
Weak sensitivity gain with exposure time

Measurements from all Three Detectors (2003 Data)



Conventional TPC

Two magnet bores (sunset direction)
Tracking 62.7 h, Background 719.9 h

$g_{10}^4 = -1.1 \pm 3.3$ $\quad g_{10} < 1.55$ (95% CL)

Micromegas (Data set A)

One bore (sunrise)
Tracking 43.8 h, Background 431.4 h

$g_{10}^4 = -1.4 \pm 4.5$ $\quad g_{10} < 1.67$ (95% CL)

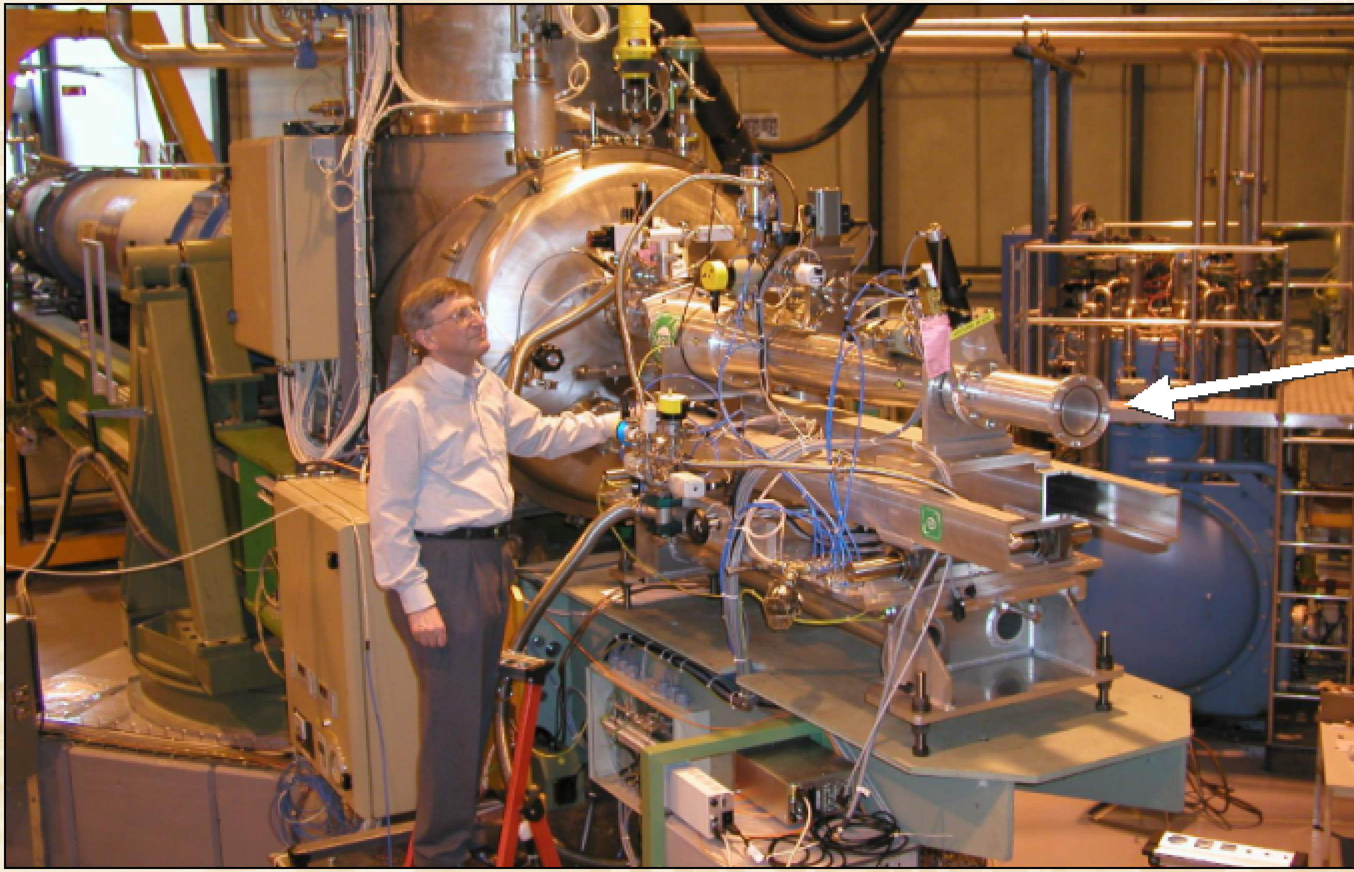
CCD with focussing x-ray telescope

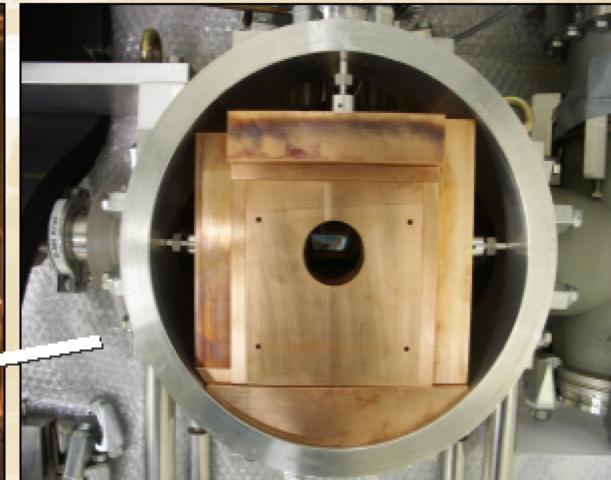
One bore (sunrise)
Tracking 121.3 h, Background 1233.5 h

$g_{10}^4 = 0.4 \pm 1.0$ $\quad g_{10} < 1.23$ (95% CL)

Combined limit $\quad g_{10} < 1.16$ (95% CL)

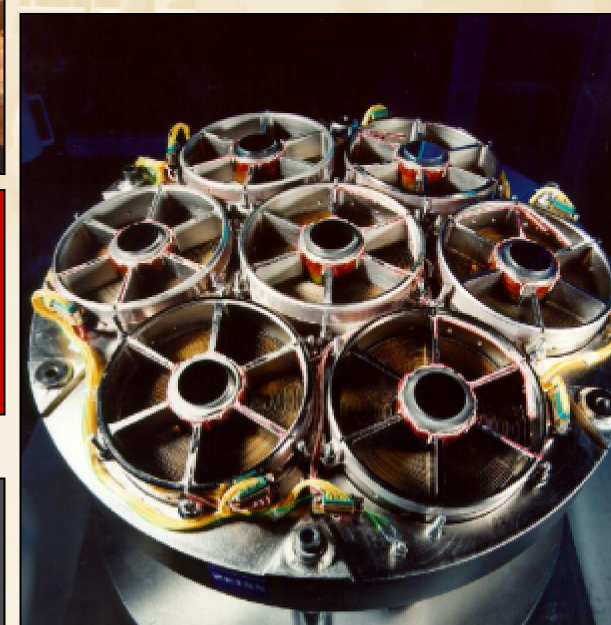
CAST Focussing X-Ray Telescope



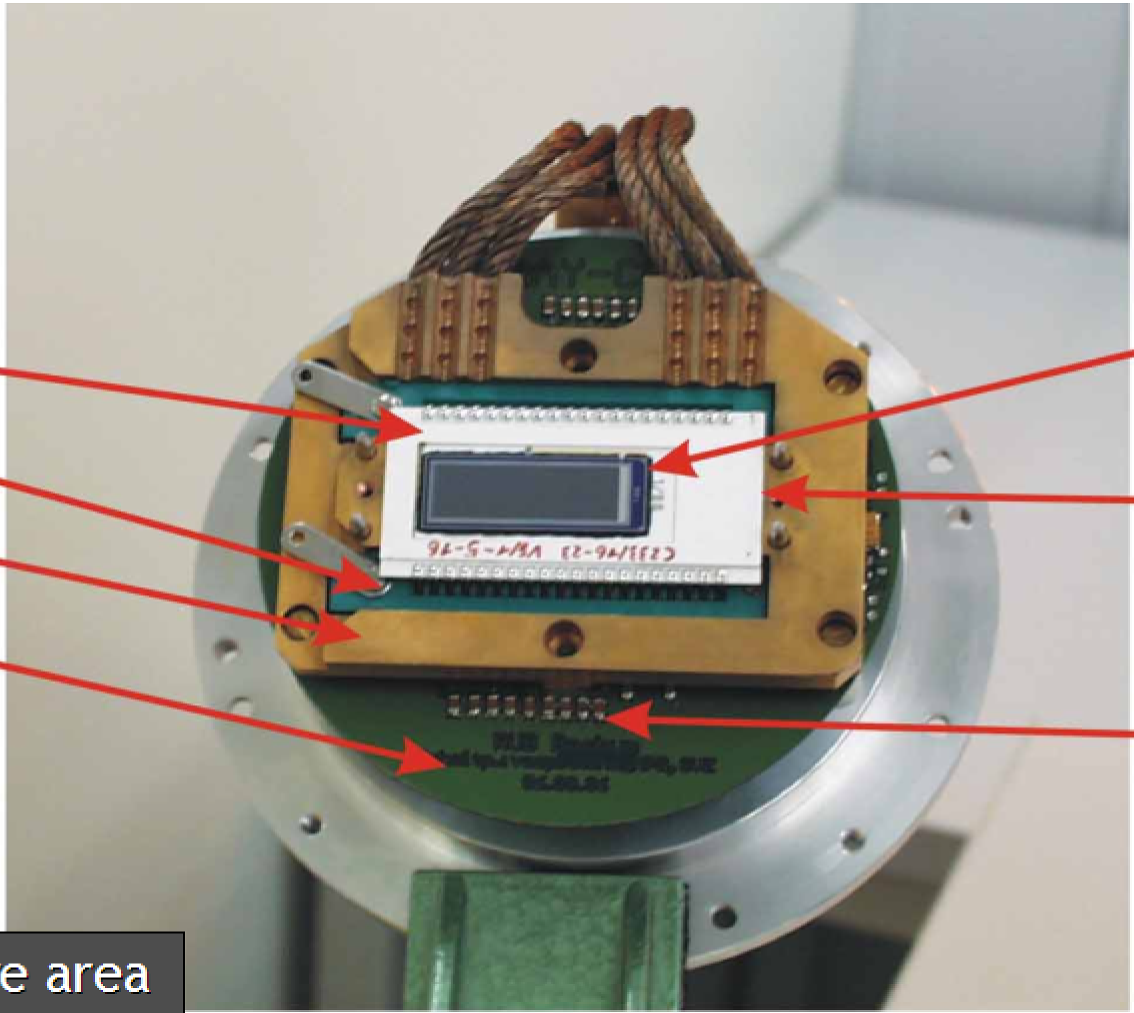


- From 43 mm ∅ (LHC magnet aperture) to ~3 mm ∅
- Signal/background improvement > 100
- Signal and background simultaneously measured

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



CAST pn-CCD Detector

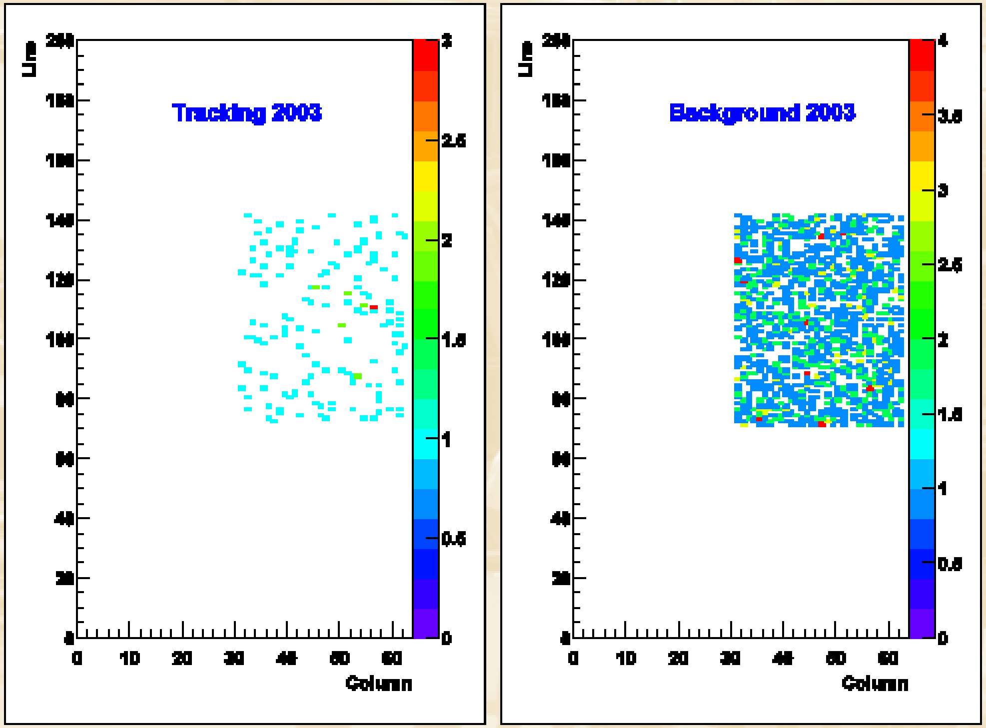


1×3 cm^2 sensitive area
64×200 pixels
150×150 μm^2
280 μm thick
14 frames/sec

MPI Halbleiterlabor
Robert Hartmann
05.07.2001

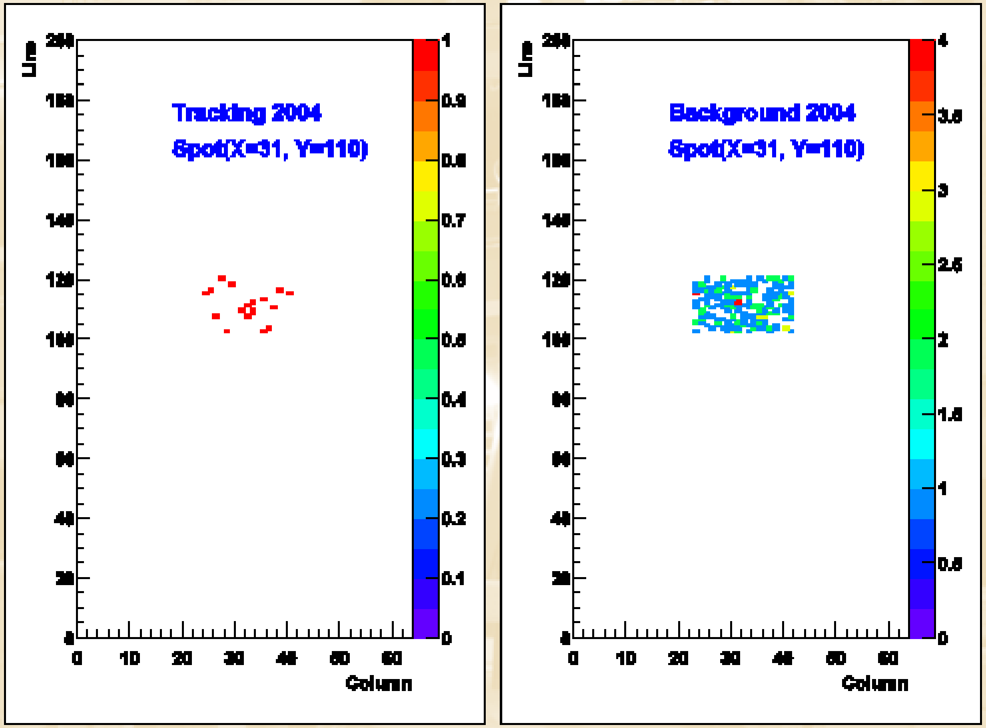
CCD Analysis

2003 Data



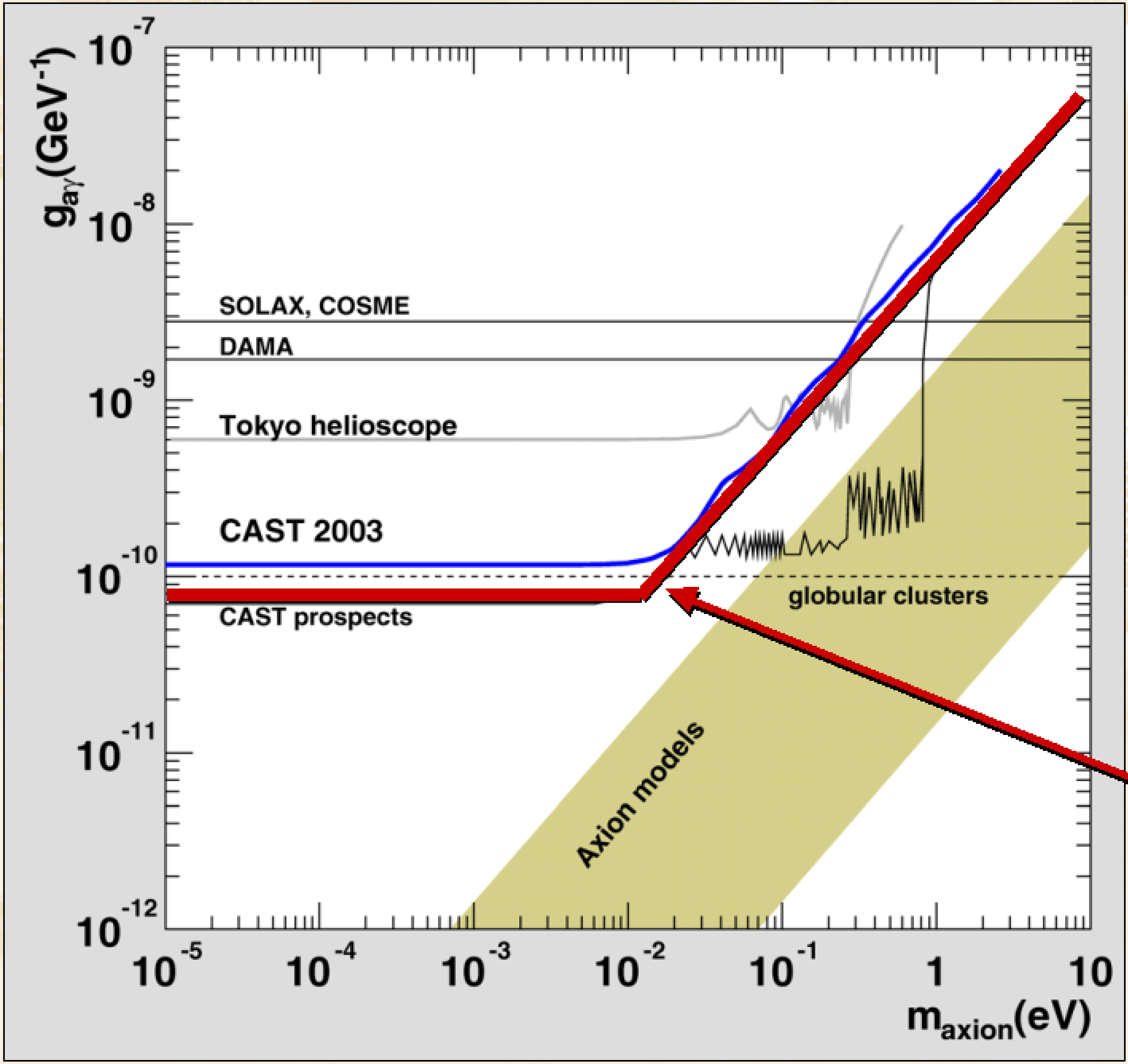
Signal area 34 × 71 pixels = 54.3 mm^2
Solar tracking time 121.3 h
155 counts

2004 Data (preliminary)



Signal area 19 × 19 pixels = 8.1 mm^2
Tracking 18 counts (80% of data)
Background 237 counts

CAST Exclusion Range (2003 Data)



CAST Collaboration:

First results from the CERN Axion Solar Telescope (CAST)
PRL, in press (2005)
(hep-ex/0411033)

Anticipated sensitivity with 2004 data
- Additional exposure
- Solar image of x-ray telescope better known and stability control:
  Use smaller spot on CCD

Phase II: Extending to higher mass values with gas filling

Axion-photon transition probability

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma}B}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right)$$

Axion-photon momentum transfer

$$q = \left|\frac{m_a^2 - m_\gamma^2}{2E}\right|$$

Transition suppressed for $qL \gtrsim 1$

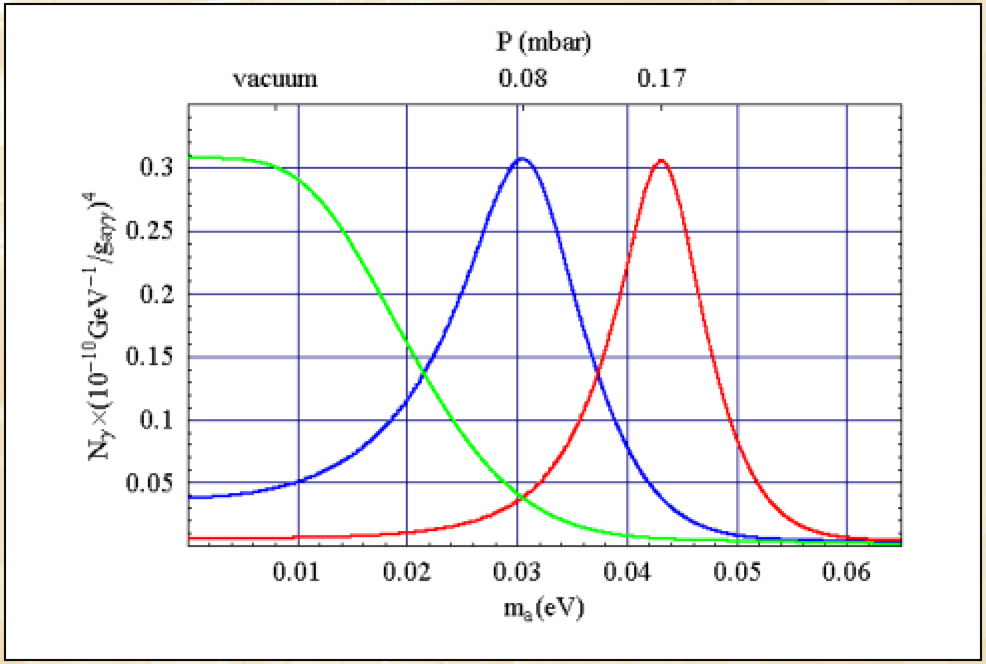
Gas filling: Give photons a refractive mass to restore full transition strength (~ MSW effect)

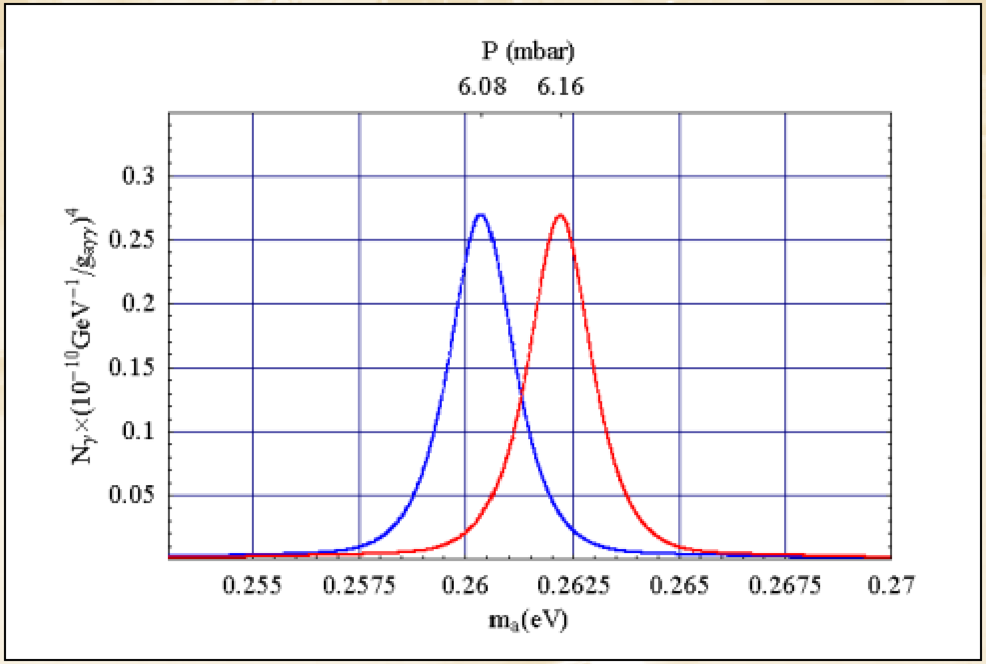
$$m_\gamma^2 = \frac{4\pi\alpha}{m_e} n_e \qquad (n_e \text{ electron density})$$

$$m_\gamma = 28.9\ \text{eV}\sqrt{\frac{Z}{A}\rho_{Gas}}$$

He^4 vapour pressure at 1.8 K

$$\rho \approx 0.2\times10^{-3}\,\text{g cm}^{-3} \qquad m_\gamma = 0.26\ \text{eV}$$



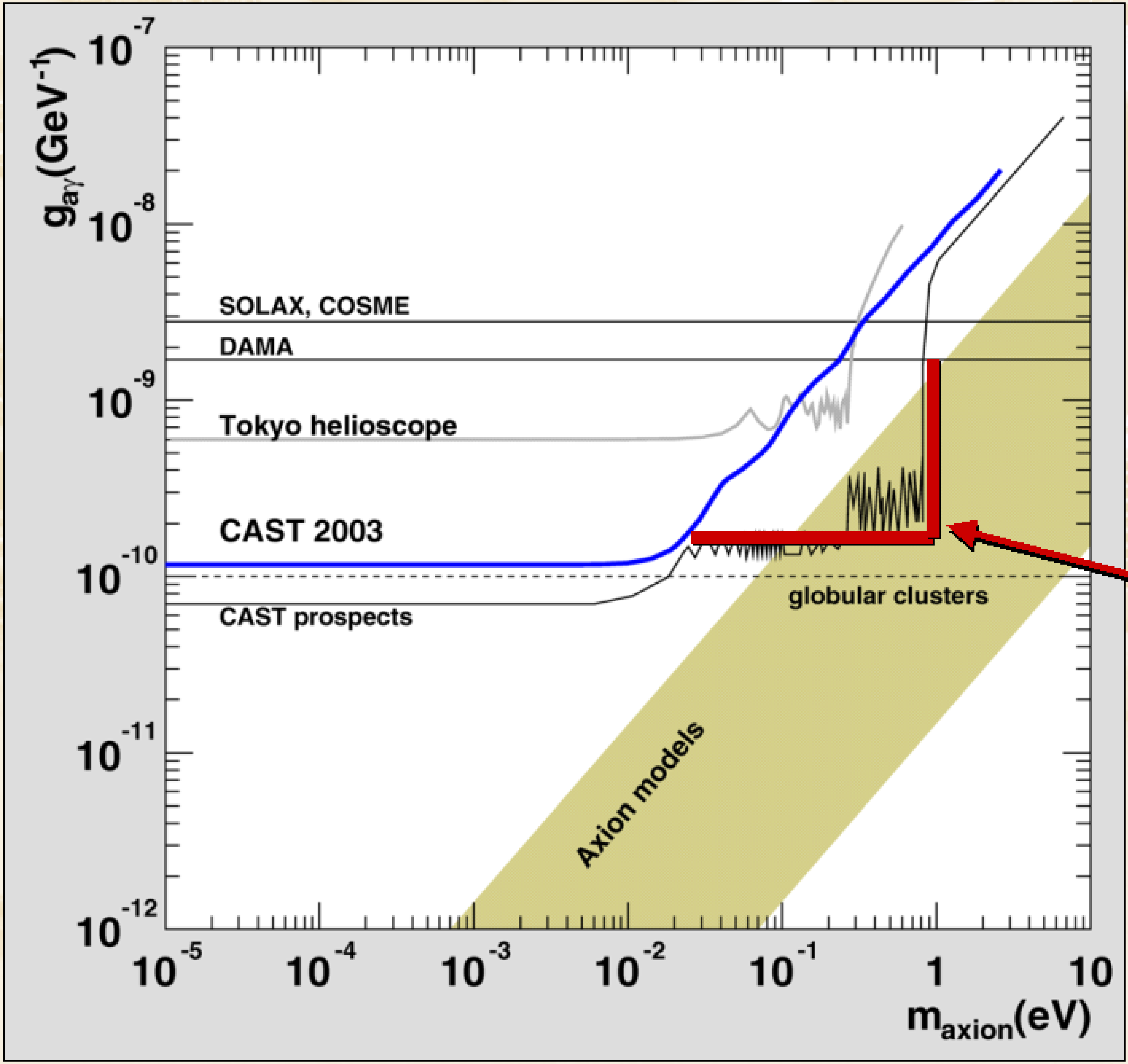


CAST Phase II (Variable pressure helium filling)

Step 1		He^4 at $T = 1.8$ K, $p < 6$ mbar $0.02 < m_a < 0.26$ eV 70 pressure settings ($\Delta p = 0.08$ mbar) 1.5 h Sun tracking each setting
Step 2	Option A	He^3 at $T = 1.8$ K, $p < 60$ mbar $m_a < 0.8$ eV
	Option B	He^4 at $T = 5.4$ K, $p < 180$ mbar Gas cell inside cold bore $m_a < 1.4$ eV

- CAST Phase II approved by CERN Research Board on 2 Dec 2004 for 2005-2007 (3 years)
- MoU of collaborating institutions in preparation
- Lawrence Livermore National Lab (California) intends to join (second x-ray telescope, helium-3 for gas-filling)

CAST Phase II Sensitivity Forecast (2005-2007)



CAST Collaboration:

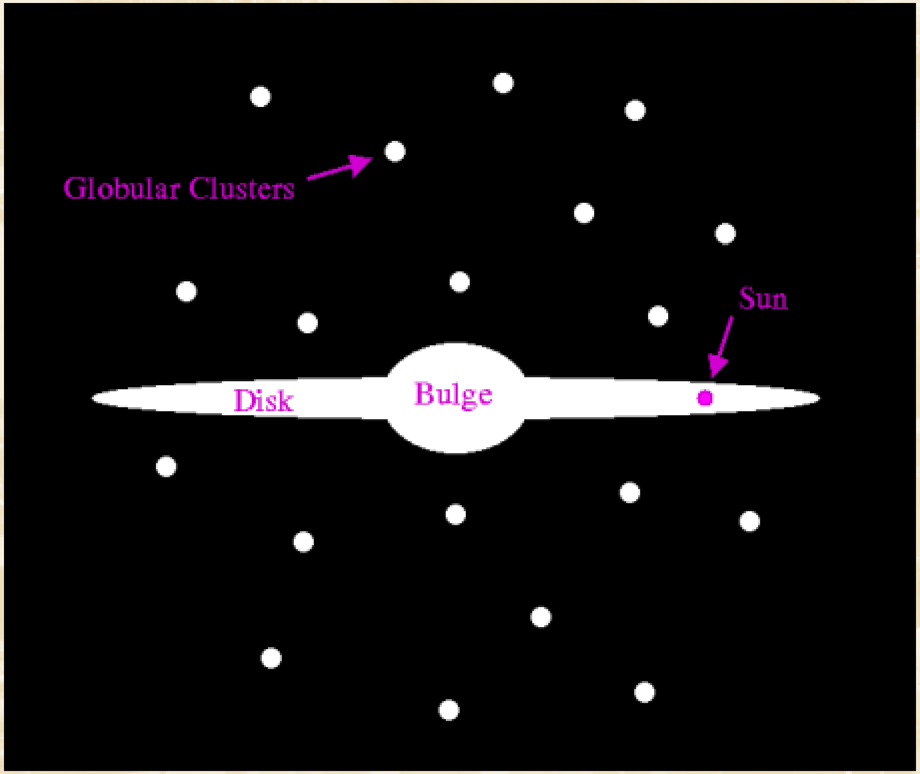
First results from the CERN Axion Solar Telescope (CAST)

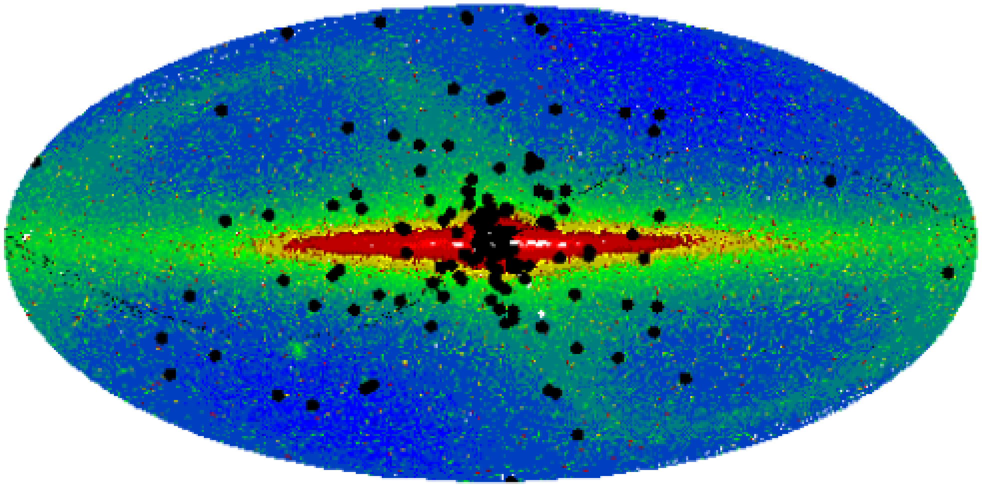
PRL, in press (2005) (hep-ex/0411033)

Anticipated sensitivity with variable-pressure helium filling

For the first time covers QCD axion parameters

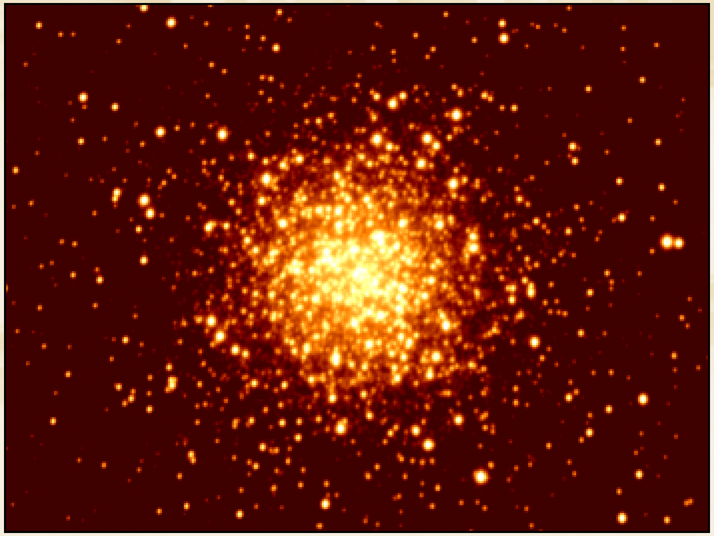
Globular Clusters of the Milky Way





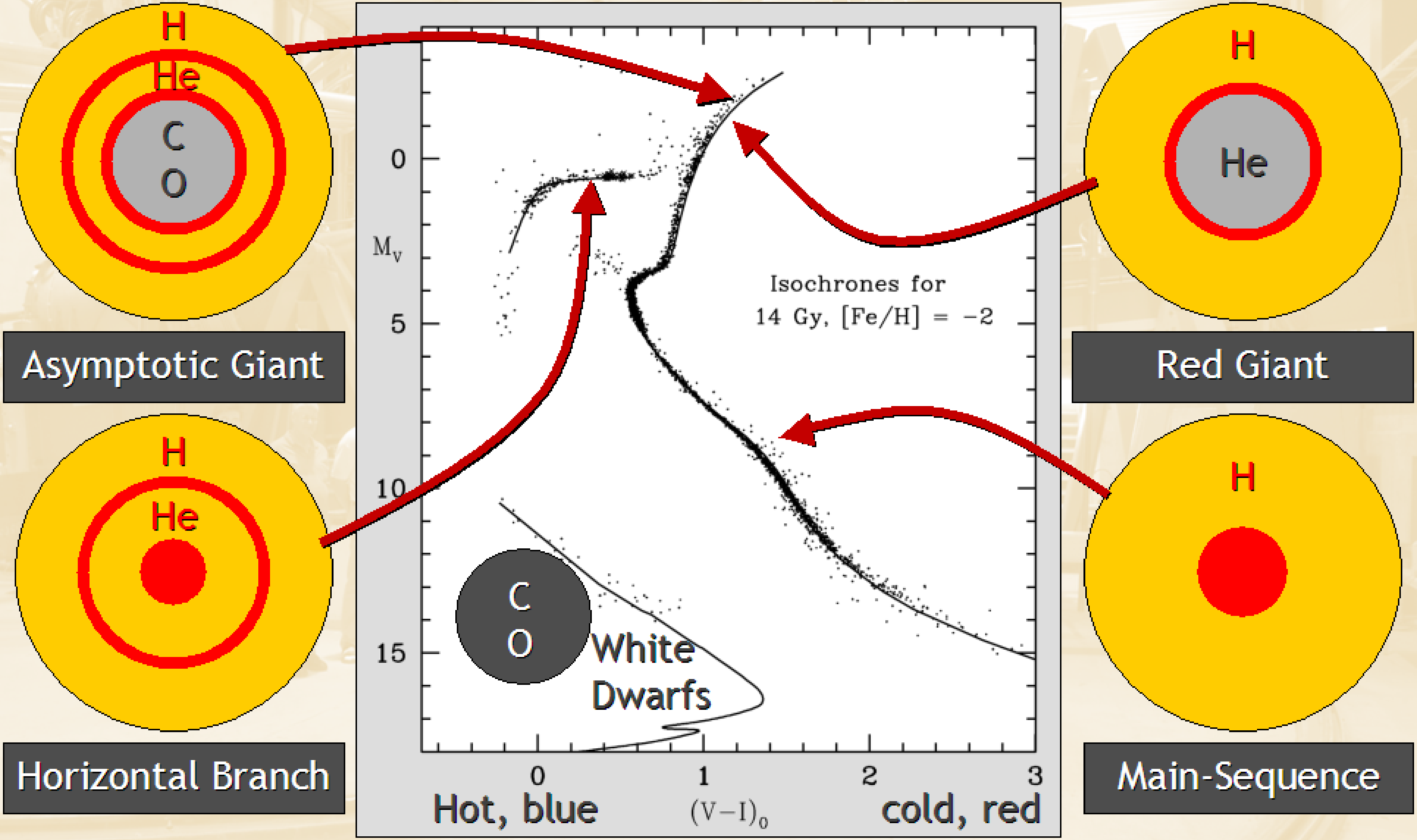
http://www.dartmouth.edu/~chaboyer/mwgc.html

Globular clusters on top of the FIRAS 2.2 micron map of the Galaxy



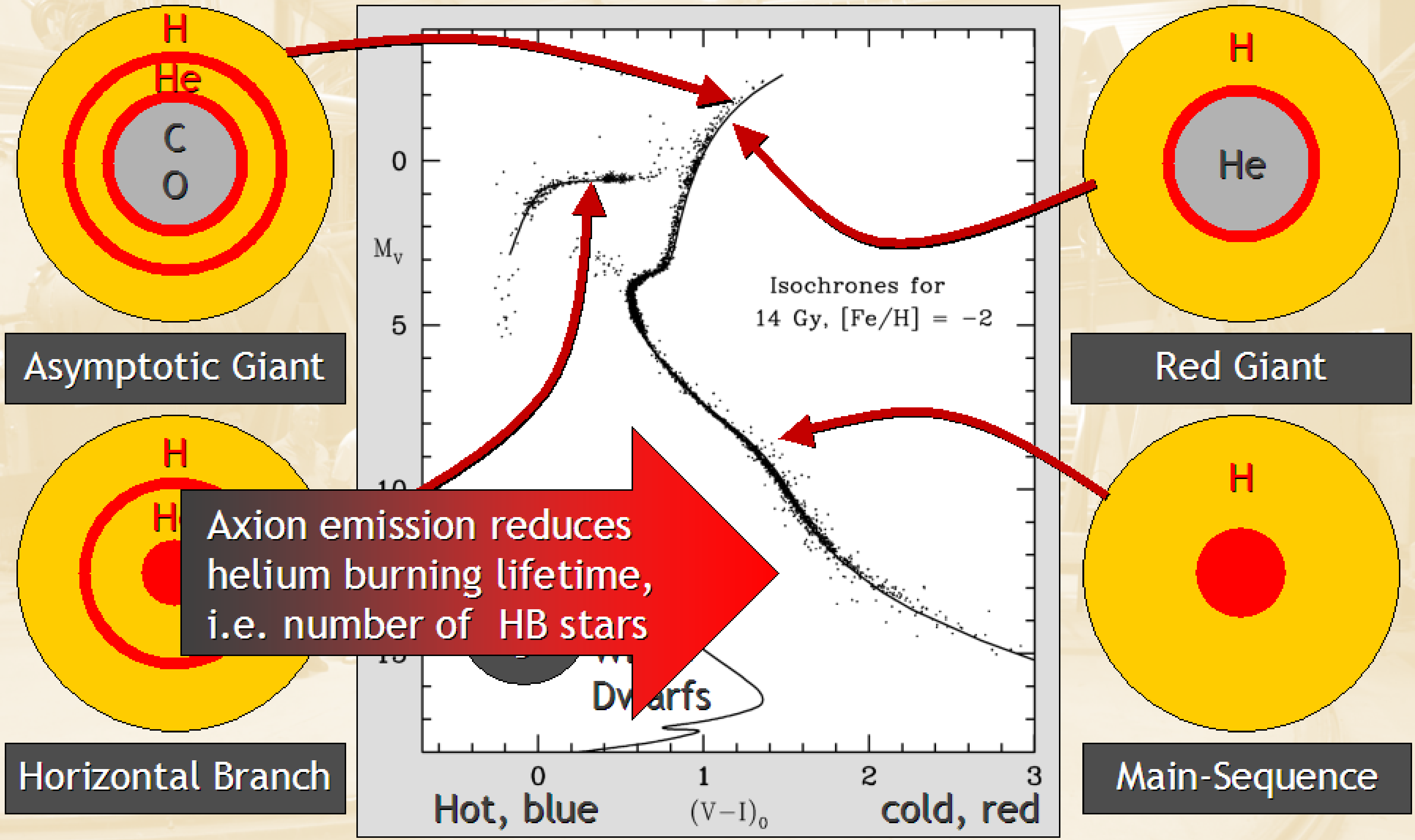
The galactic globular cluster M3

Color-Magnitude Diagram for Globular Clusters



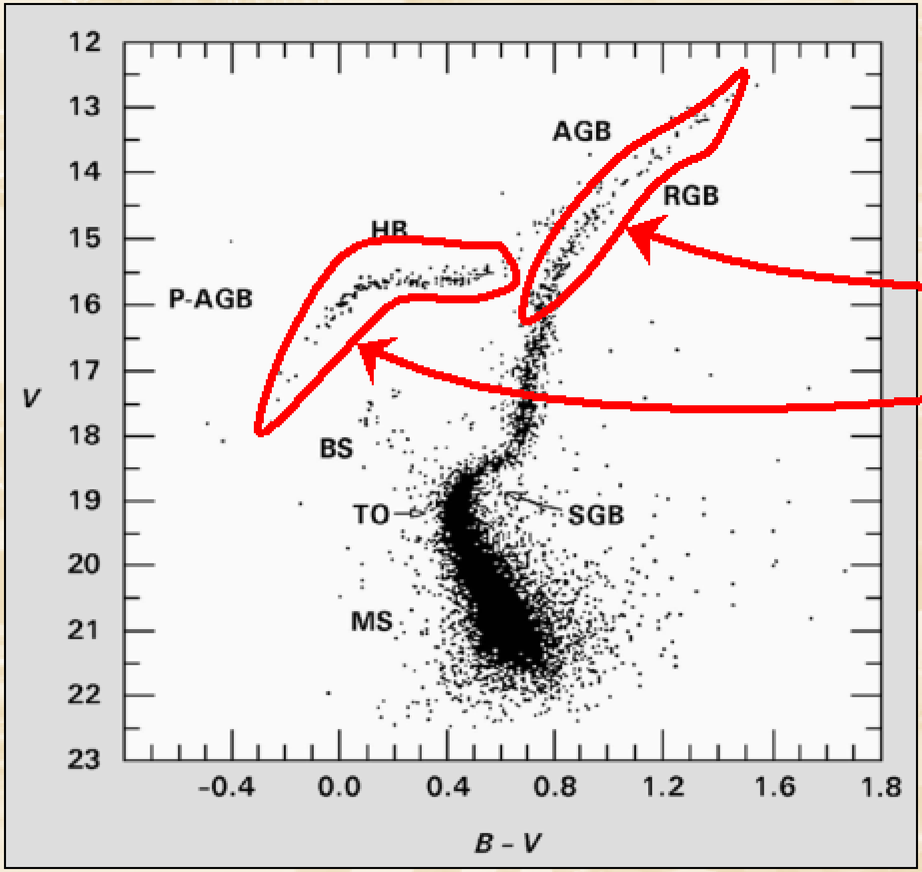
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

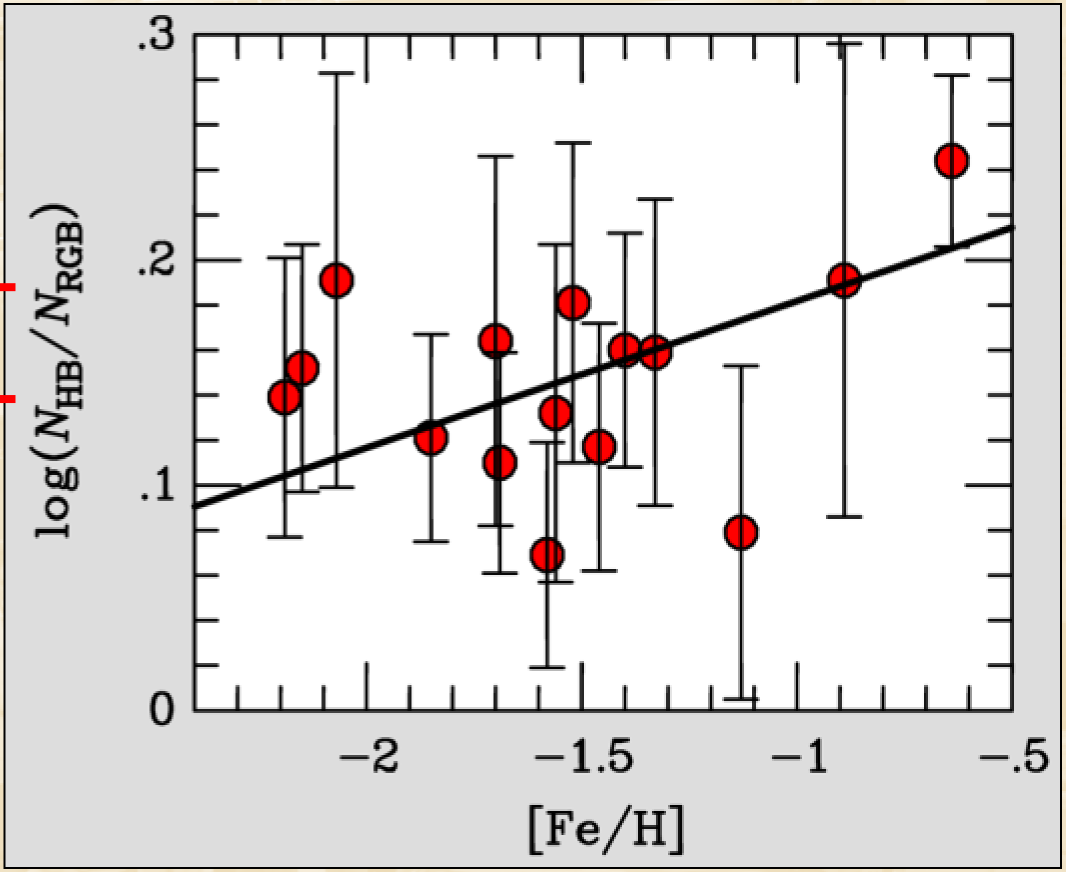
Color-Magnitude Diagram for Globular Clusters



Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Helium-Burning Lifetime of Globular Cluster Stars

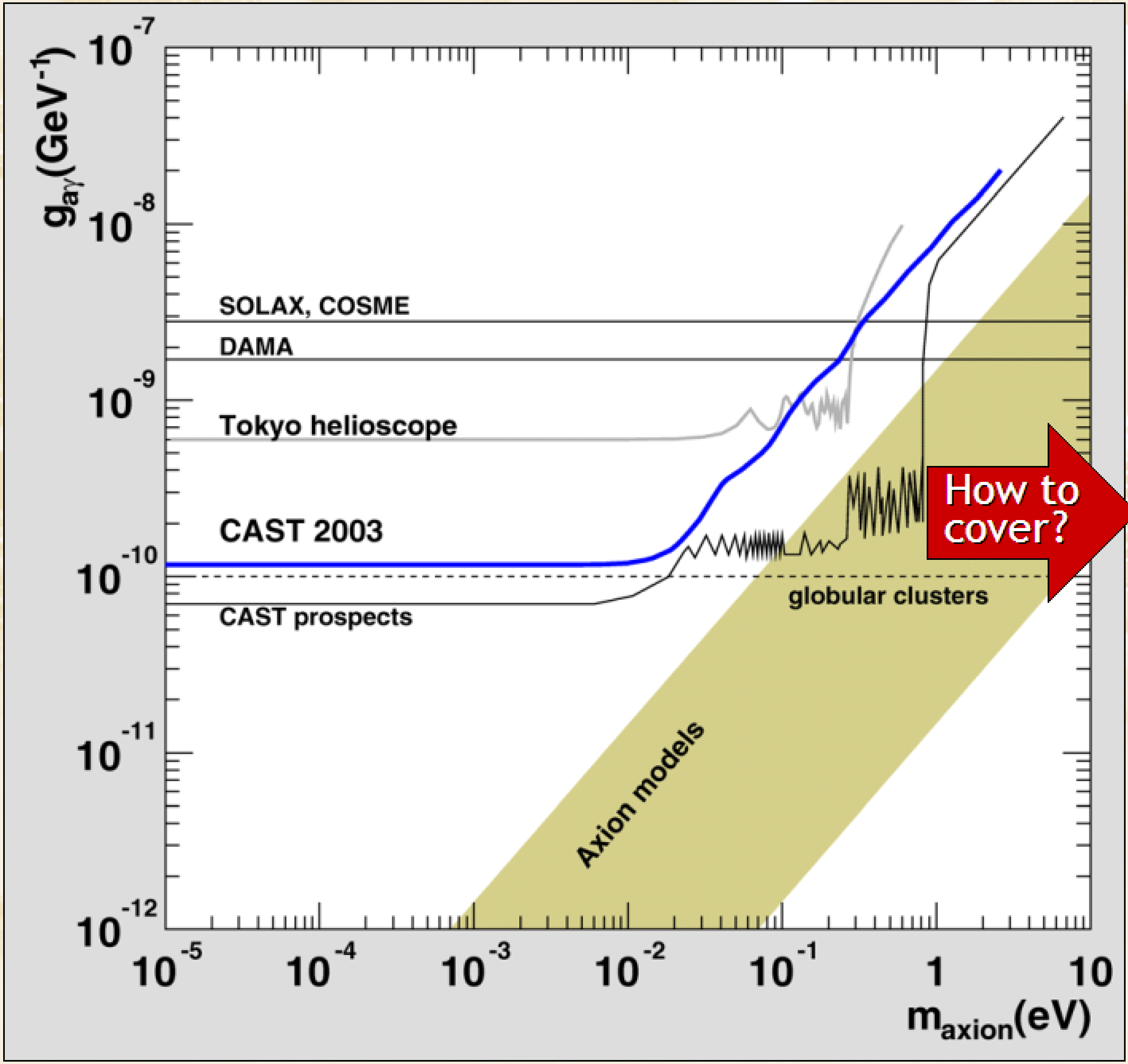




Number ratio of HB-Stars/Red Giants in 15 galactic globular clusters (Buzzoni et al. 1983)

Helium-burning lifetime established within ±10%

Mass Range Beyond CAST Phase II



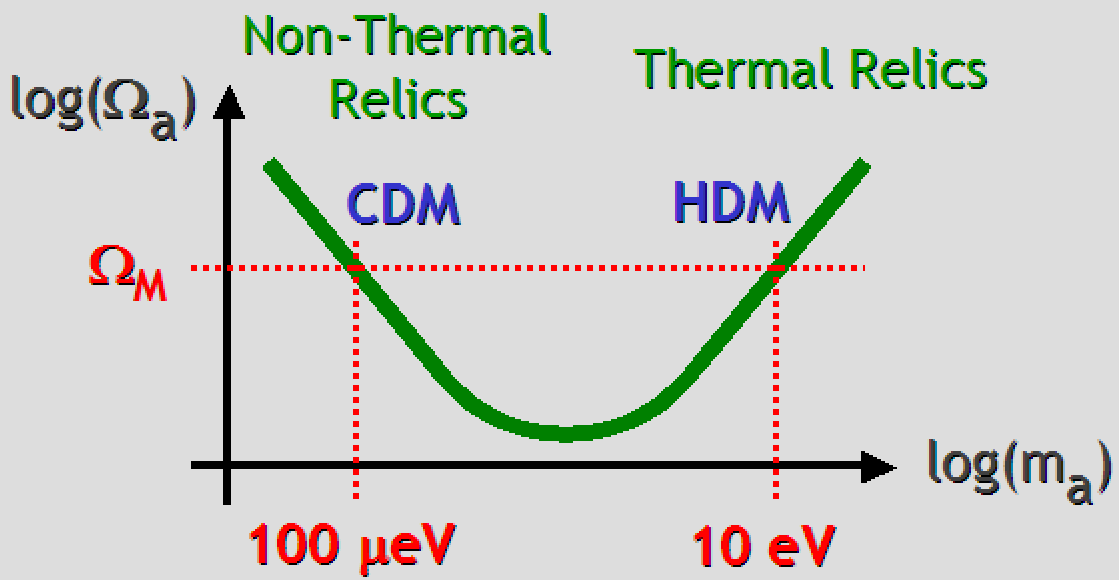
CAST Collaboration:

First results from the CERN Axion Solar Telescope (CAST)

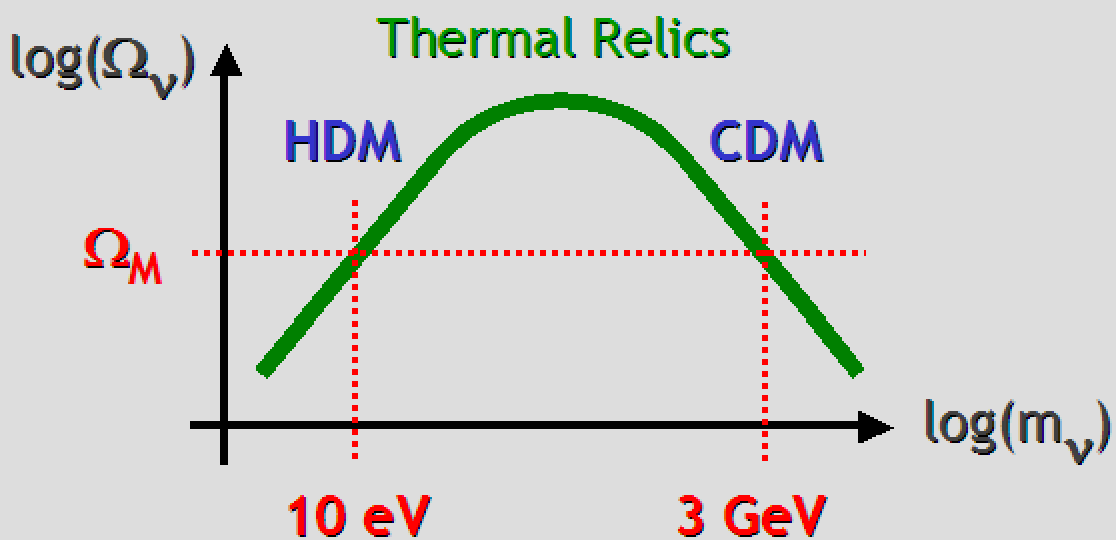
PRL, in press (2005) (hep-ex/0411033)

Lee-Weinberg Curve for Neutrinos and Axions

Axions



Neutrinos

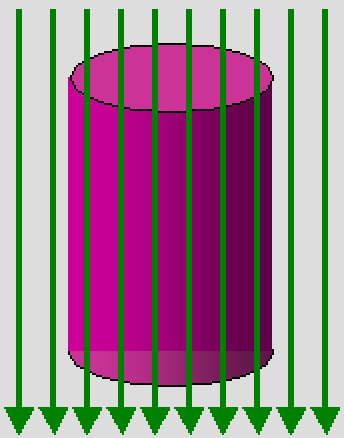


Search for Galactic Axions (Cold Dark Matter)

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

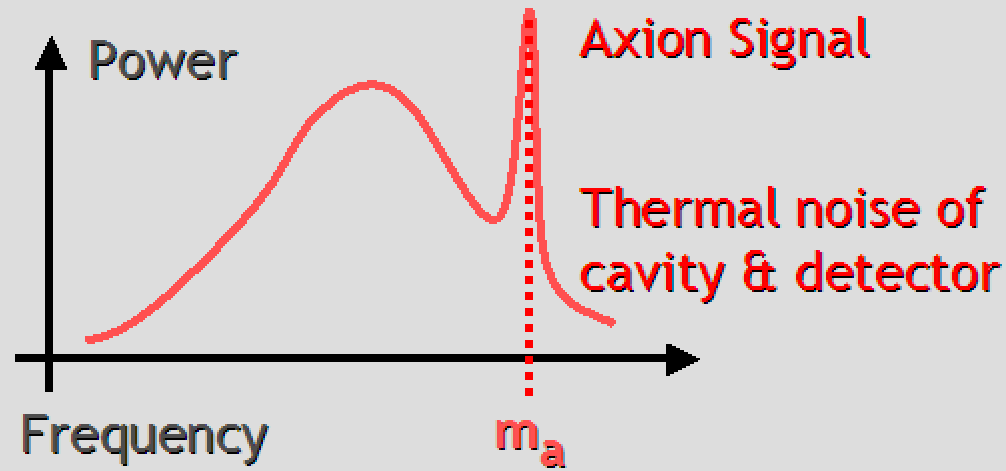
→ Microwave Energies (1 GHz ≈ 4 μeV)

Axion Haloscope (Sikivie 1983)

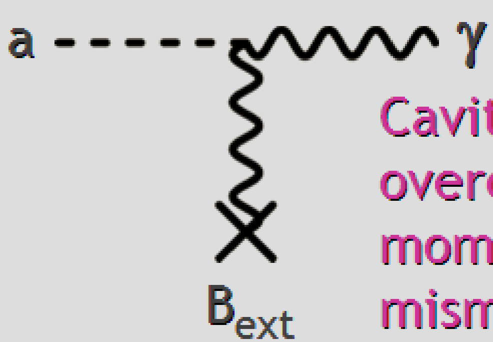


$B_{ext} \approx 8$ Tesla

Microwave Resonator $Q \approx 10^5$



Primakoff Conversion



Cavity overcomes momentum mismatch

Power of galactic axion signal

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

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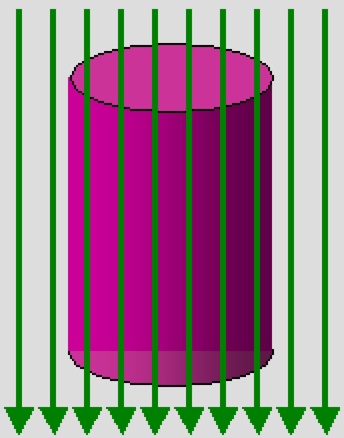

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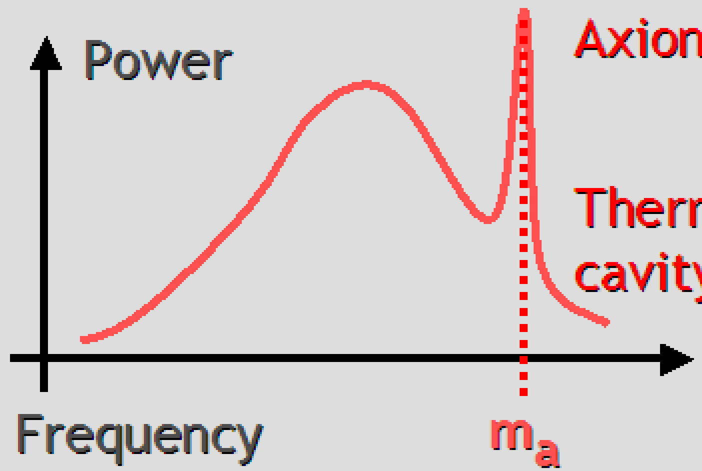
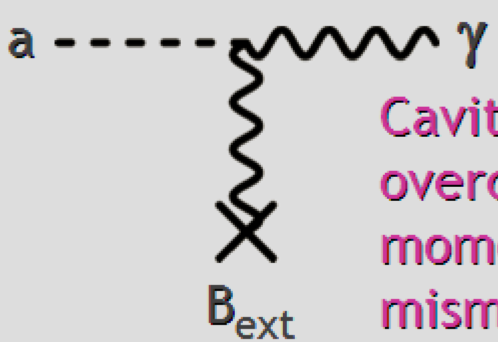


Primakoff Conversion



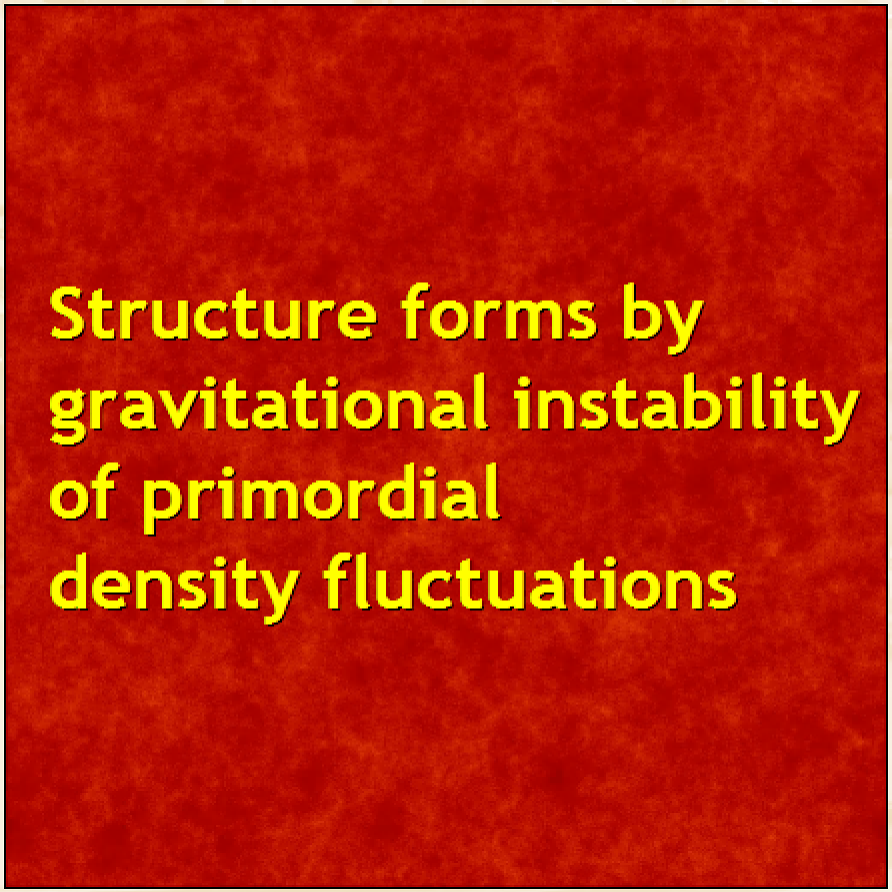
Cavity overcomes momentum mismatch

2 Large-Scale Experiments

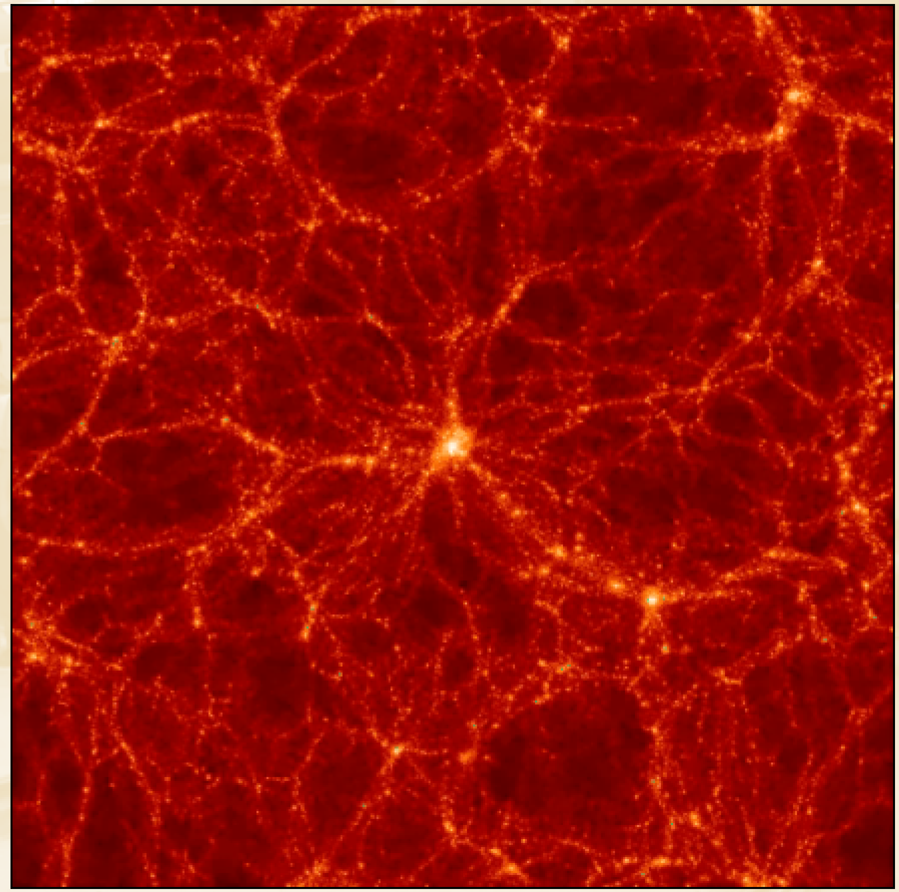
- Axion Dark Matter Experiment (ADMX), Livermore, US
- CARRACK II, Kyoto, Japan

Formation of Structure

Smooth	Structured

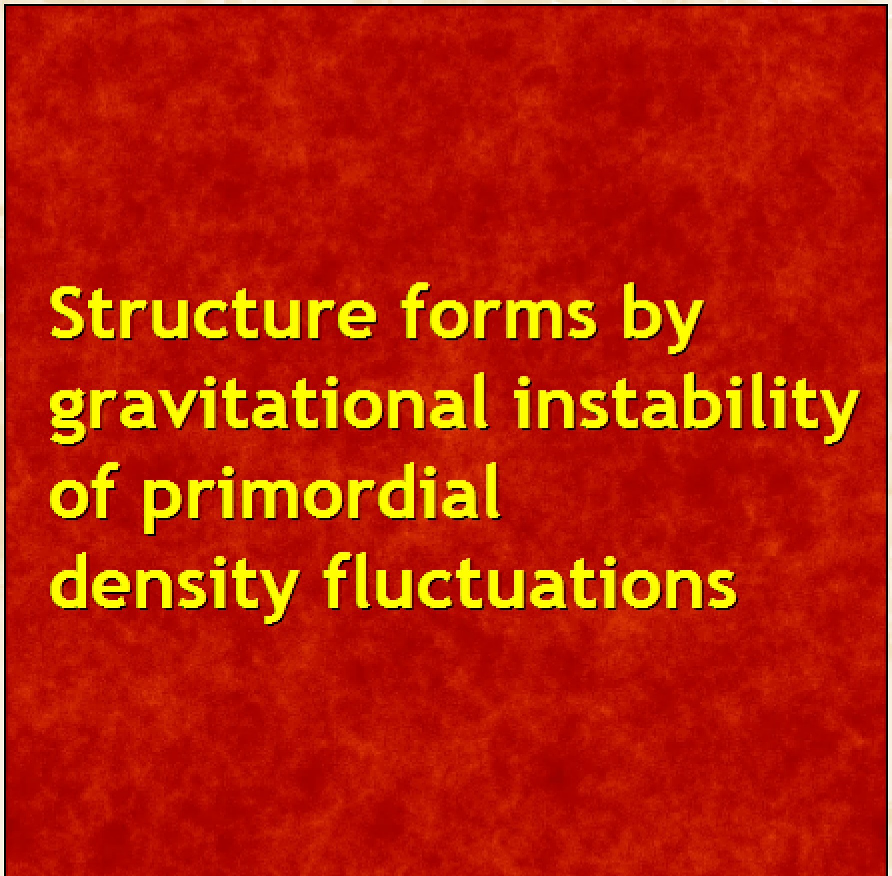


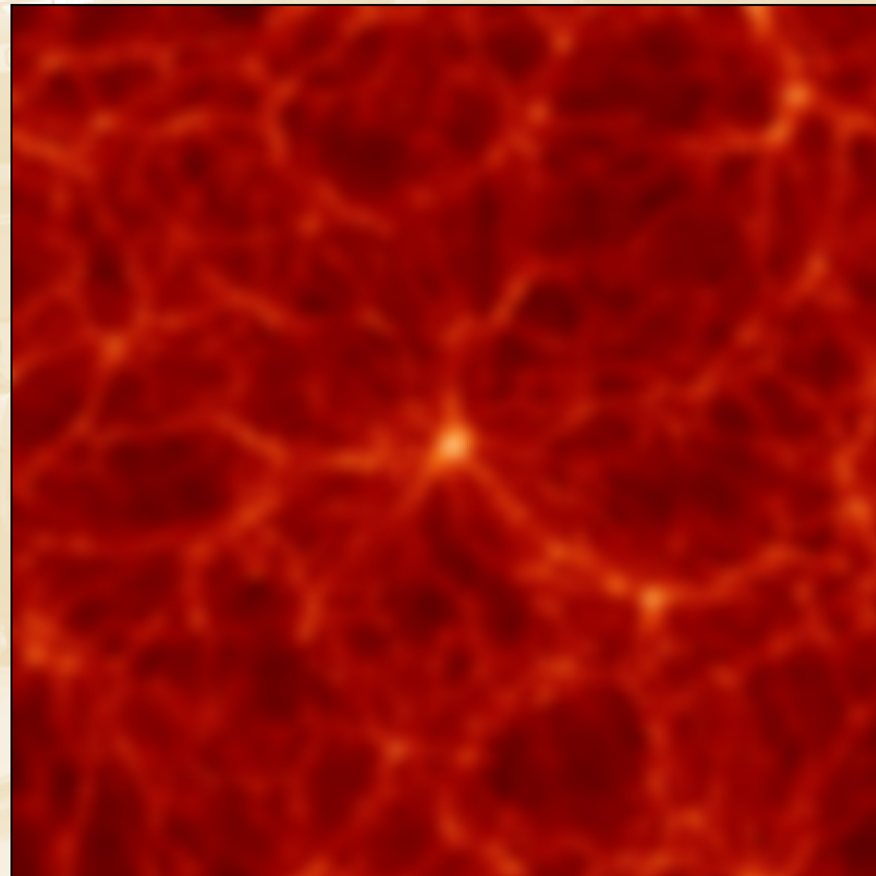
Structure forms by gravitational instability of primordial density fluctuations



Formation of Structure

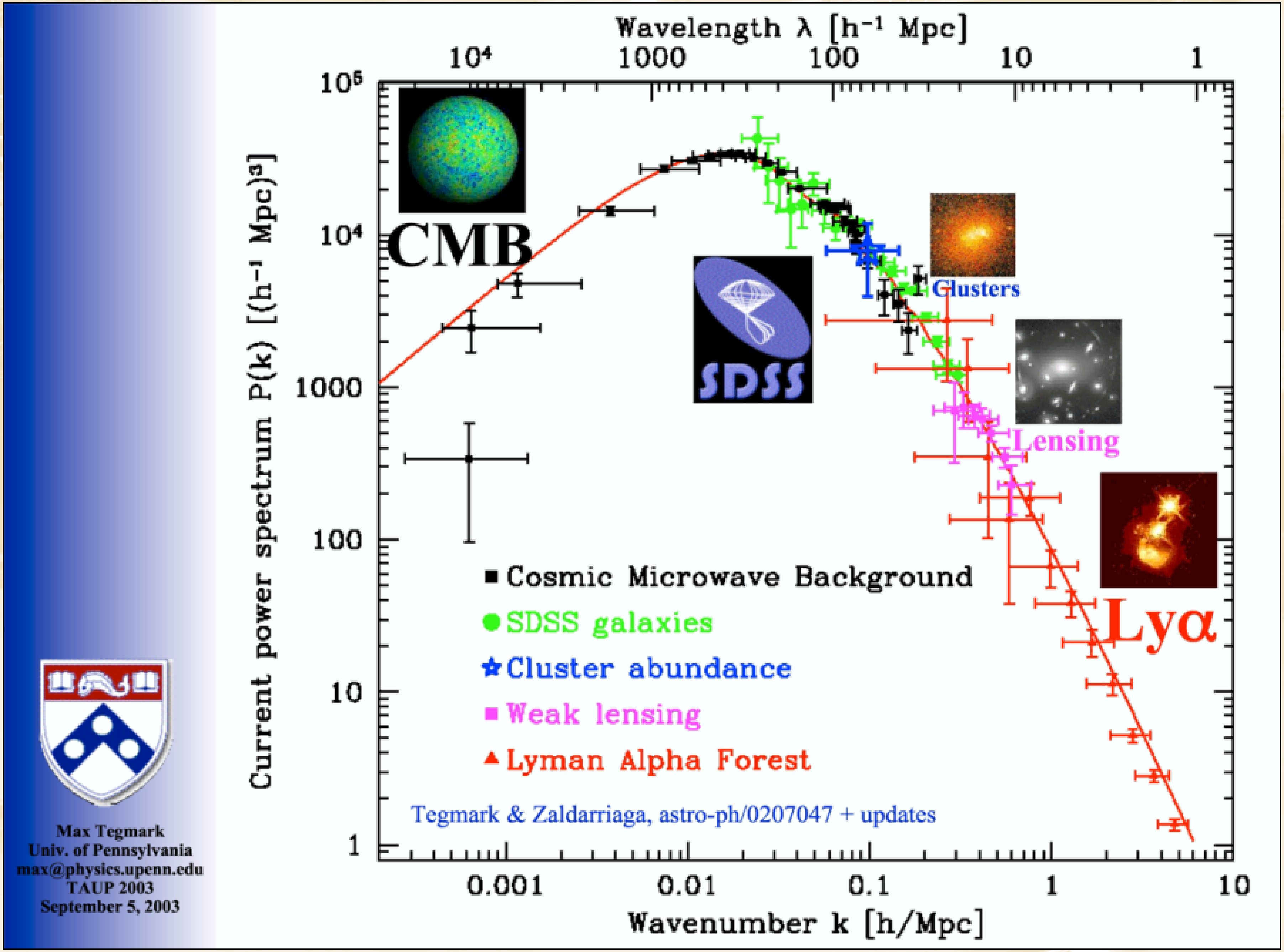
Smooth → **Structured**





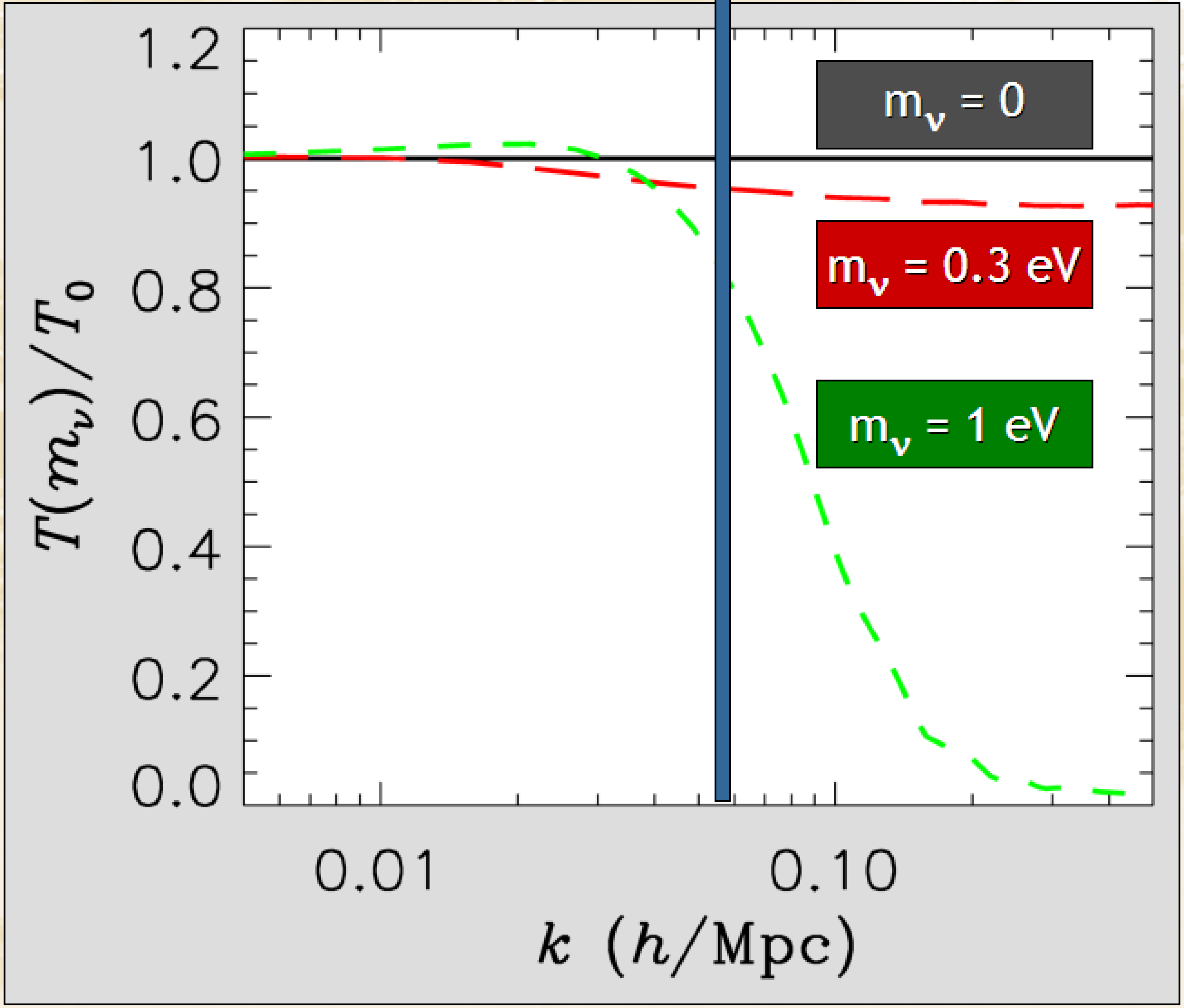
A fraction of hot dark matter suppresses small-scale structure

Power Spectrum of Cosmic Density Fluctuations



Neutrino Free Streaming – Transfer Function

Power suppression for $\lambda_{FS} \lesssim 100$ Mpc/h



Transfer function

$P(k) = T(k)\,P_0(k)$

Effect of neutrino free streaming on small scales

$T(k) = 1 - 8\Omega_\nu/\Omega_M$

valid for

$8\Omega_\nu/\Omega_M \ll 1$

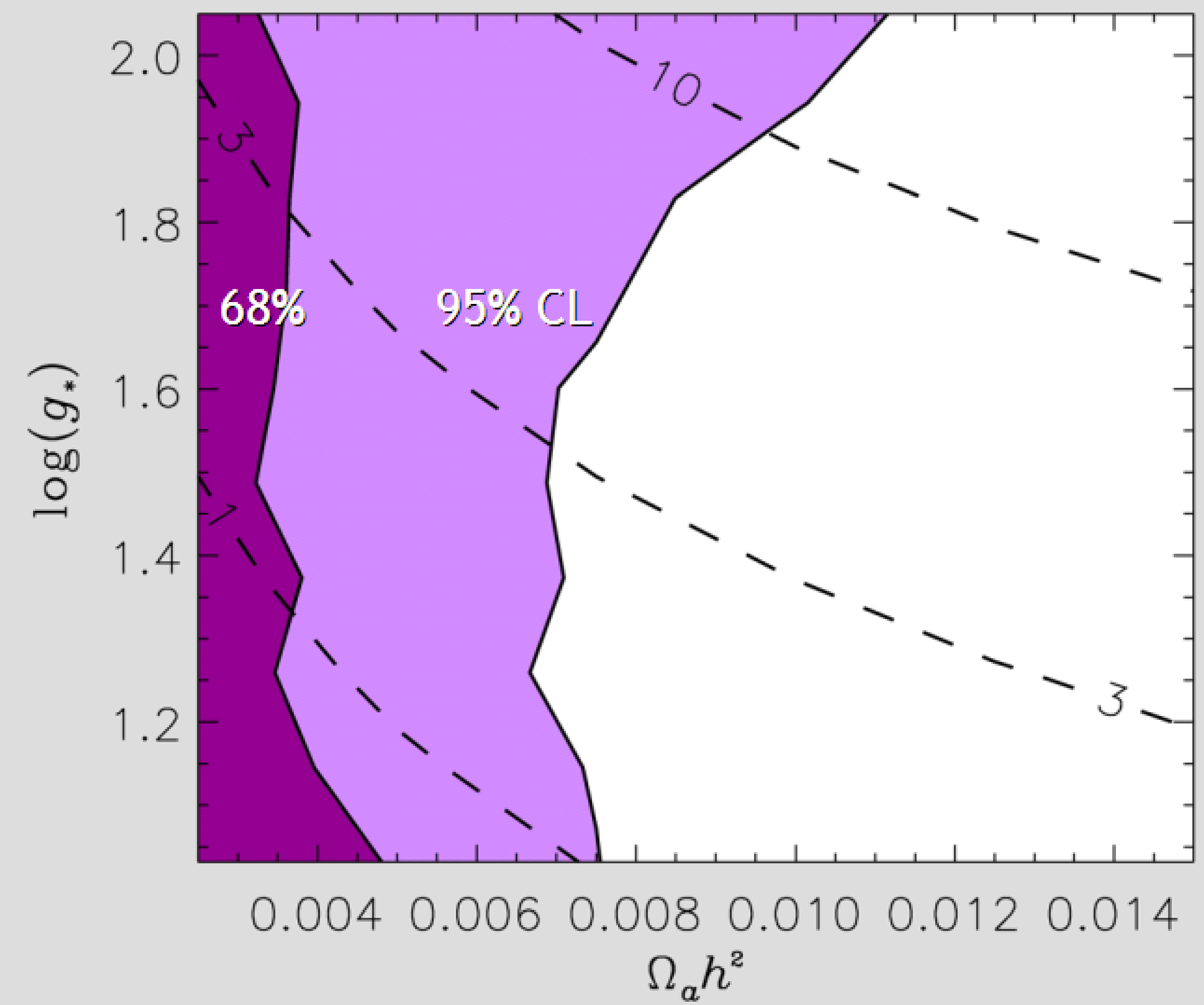
Hannestad, Neutrinos in Cosmology, hep-ph/0404239

Recent Cosmological Limits on Neutrino Masses

Authors	Σm_ν/eV (limit 95%CL)	Data / Priors
Spergel et al. (WMAP) 2003	0.69	WMAP, CMB, 2dF, σ_8, H_0
Hannestad 2003	1.01	WMAP, CMB, 2dF, H_0
Tegmark et al. 2003	1.8	WMAP, SDSS
Barger et al. 2003	0.65	WMAP, CMB, 2dF, SDSS, H_0
Crotty et al. 2004	1.0	WMAP, CMB, 2dF, SDSS, H_0
Hannestad 2004	0.65	WMAP, SDSS, SN Ia gold sample, Ly-α data from Keck sample
Seljak et al. 2004	0.42	WMAP, SDSS, Bias, Ly-α data from SDSS sample

Structure-Formation Exclusion Range of a Scalar Boson

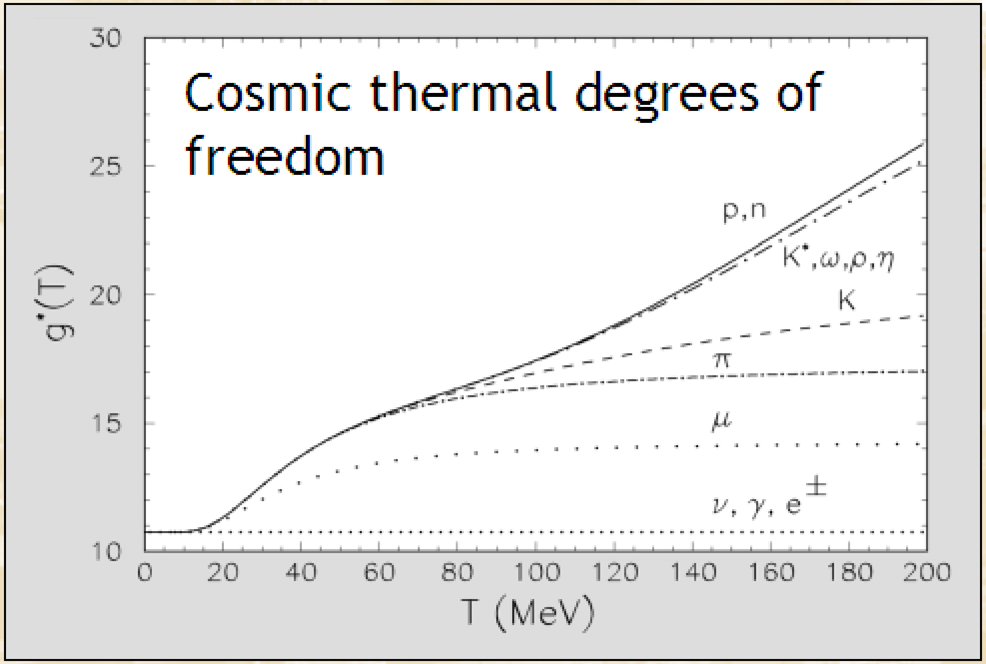
- Effective number of cosmic thermal degrees of freedom when scalar bosons freeze out
- Determines number density and velocity distribution

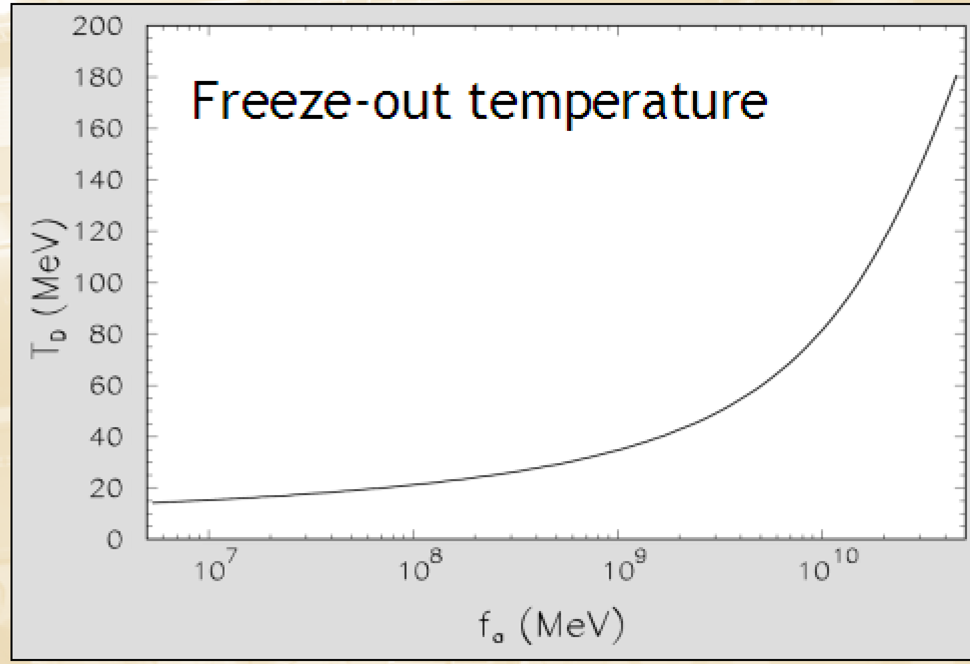


Hannestad, Mirizzi & Raffelt, Work in progress (2005)

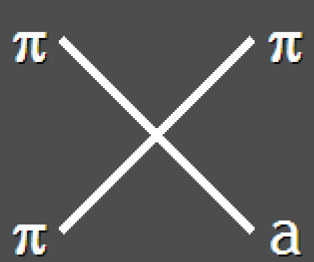
Hot dark matter fraction in a scalar boson

Axion Freeze-Out



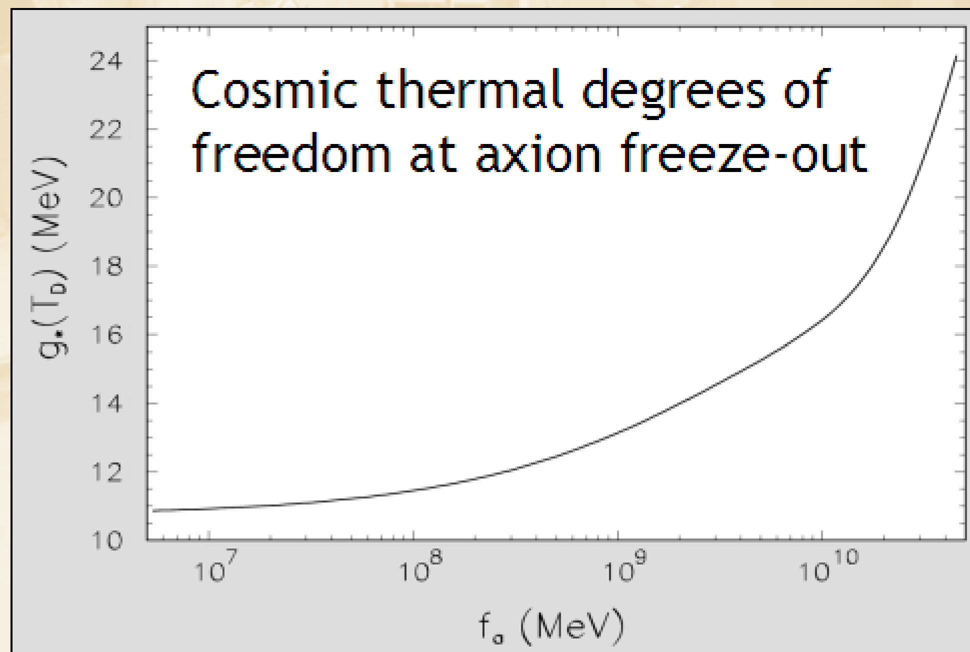


$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0)\partial^\mu a$$

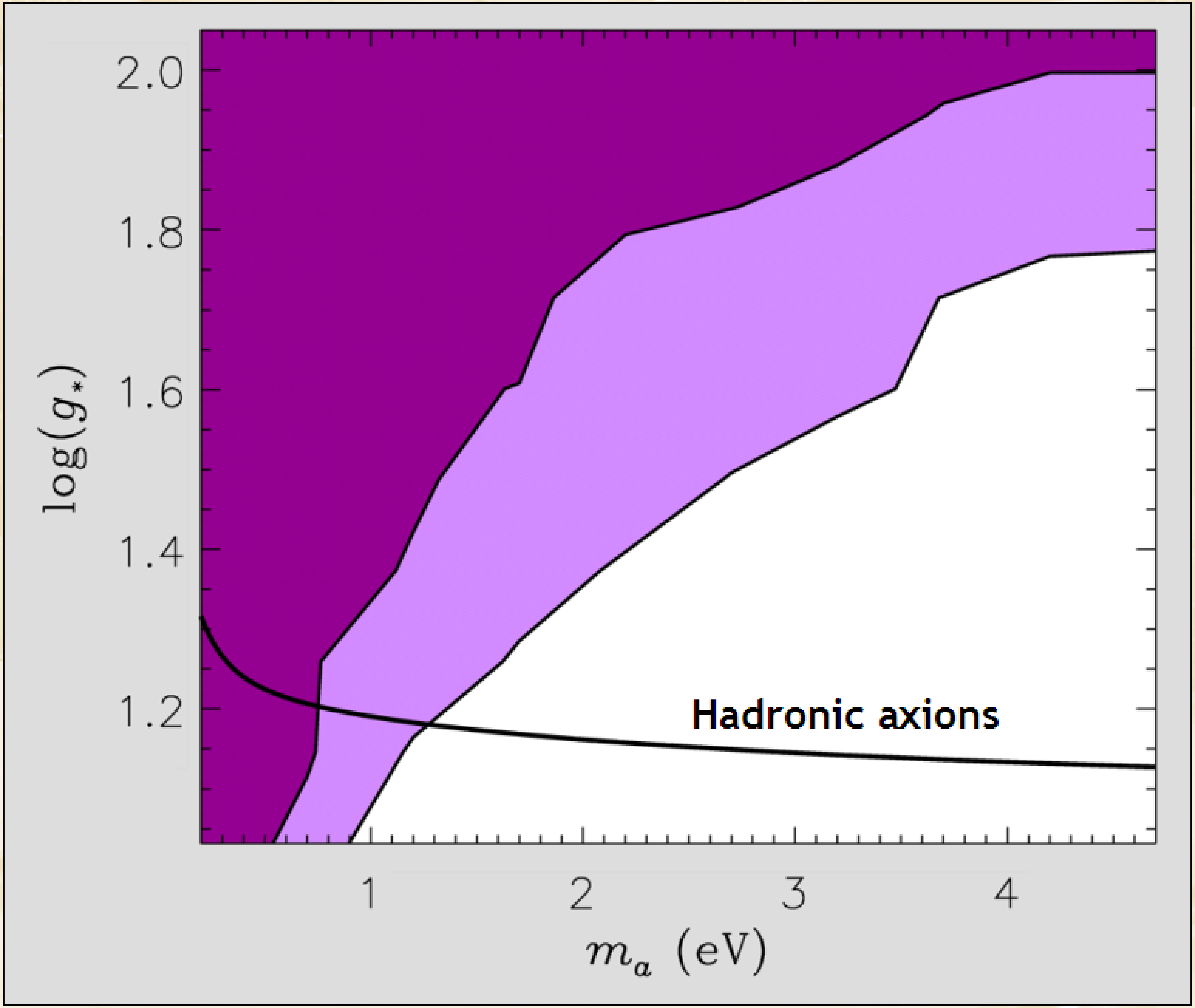


$$C_{a\pi} = \frac{1-z}{3(1+z)} \approx 0.094$$

Chang & Choi, PLB 316 (1993) 51

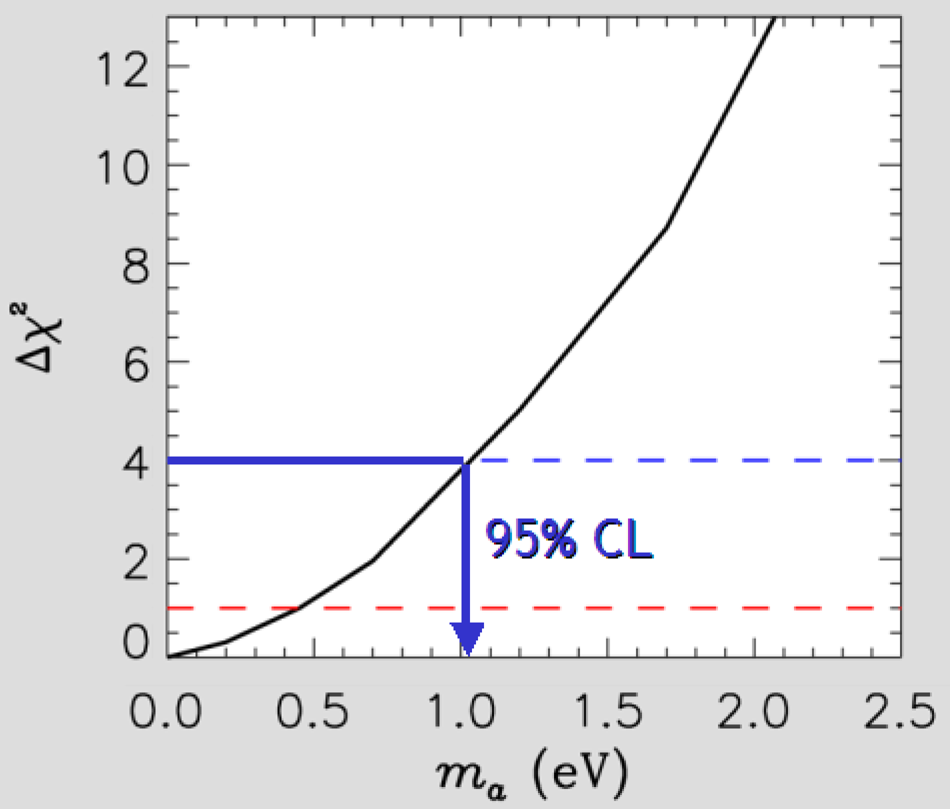


Structure-Formation Exclusion Range for Axions



Mass Limits on Hot Dark Matter Axions and Neutrinos

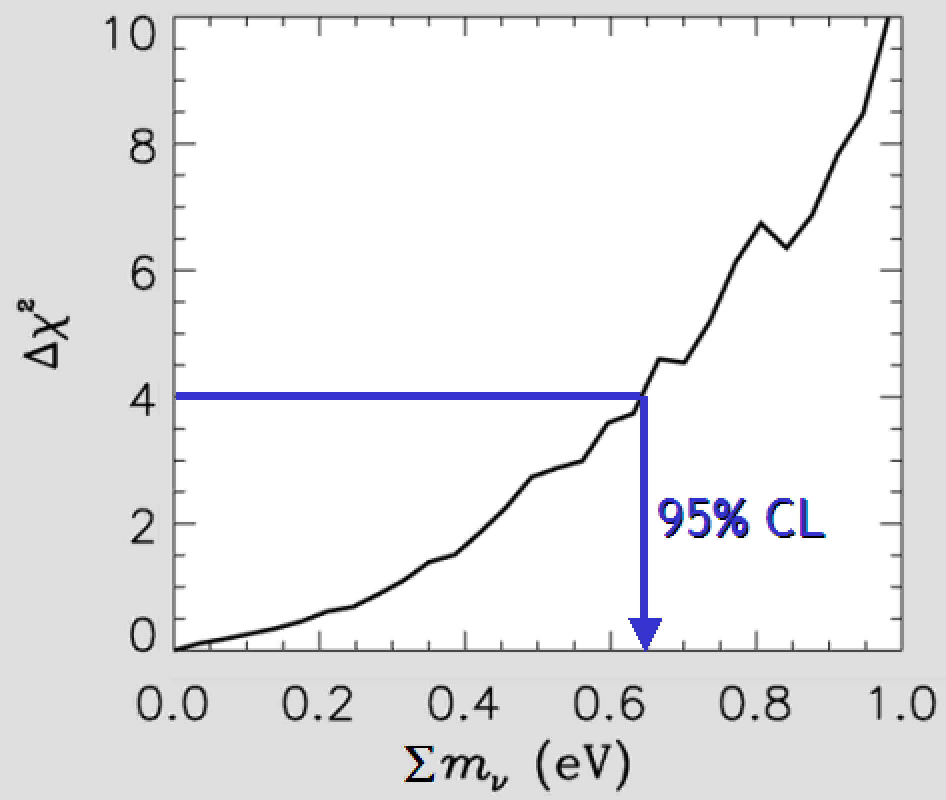
Hannestad, Mirizzi & Raffelt
Work in progress (2005)



Axions

$m_a < 1.05$ eV (95% CL)

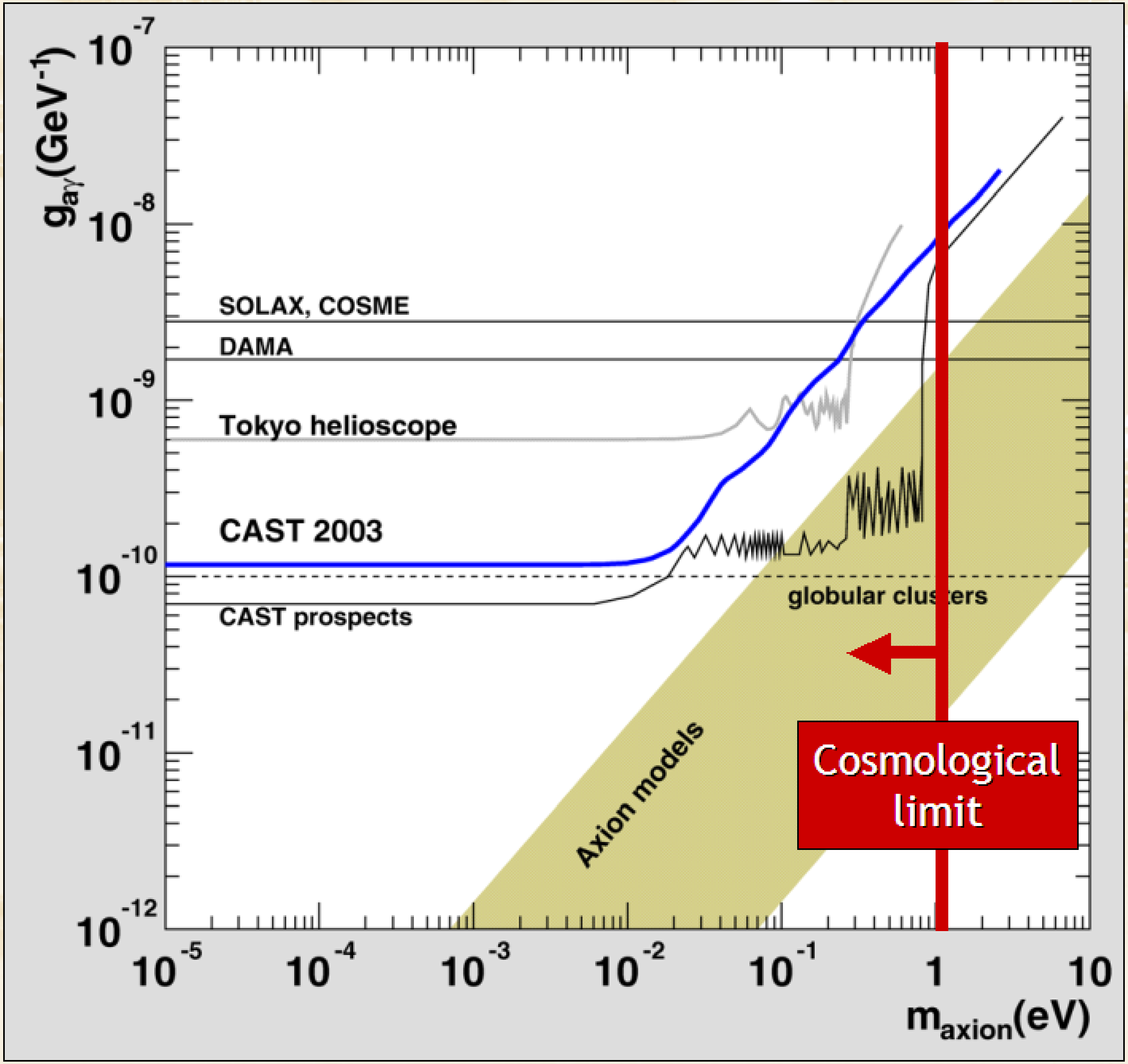
Hannestad, astro-ph/0409108
(Seesaw proceedings, Paris, 2004)



Neutrinos

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

Mind the Gap



CAST Collaboration:

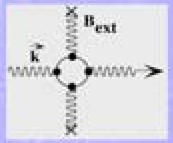
First results from the CERN Axion Solar Telescope (CAST)

PRL, in press (2005) (hep-ex/0411033)

CAST Phase II and future cosmological sensitivity probably connect

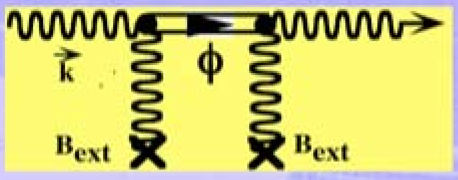
"Theme" of the PVLAS experiment

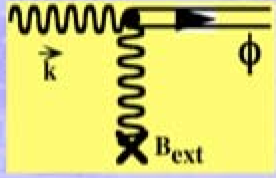
- Measure the magnetically induced birefringence and optical activity of the vacuum element (in practice a gas in the zero-pressure limit)
  - possible contributions to macroscopic properties
    - treat vacuum as a "target": photon-photon collider
      - QED interactions



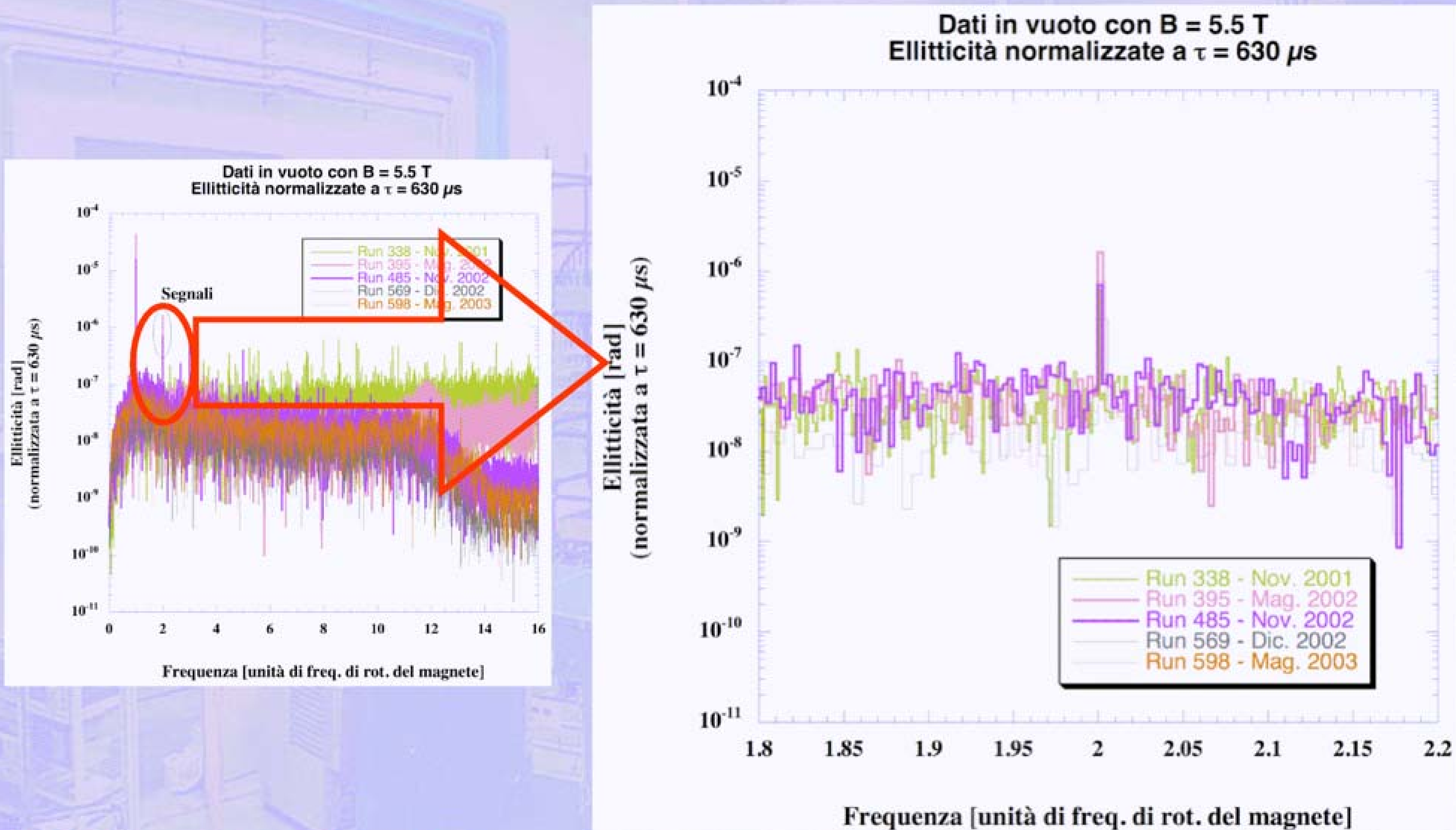
+ diagrams of order higher than α^2

      - QCD (quark loops)?
    - production of:
      - dark matter particles
      - ...





Vacuum observed signals



Ellipticity signals are shown here

Dichroism signals have the same appearance

Speculations (I)

- Believing in the PVLAS observed vacuum ellipticity signal (averaged at 6.1×10^{-7} rad with B = 5.5 T, and finesse = 97000) one finds
  - $\Delta n_{exp} = 3.4\times10^{-18}$
- QED calculations give, for B = 5.5 T,
  - $\Delta n_{QED} = 1.21\times10^{-22}$
- It follows
  - $\Delta n_{exp}/\Delta n_{QED} \sim 2.8\times10^{4}$
  - "Pure QED" is not then the sole contribution to the vacuum magnetic birefringence:
    - particle production?
    - QCD contribution?
    - ....

$\sigma_{\gamma\gamma} = 7.3\times10^{-43}$ pb

$\sigma_{\gamma\gamma}(\text{pred}) = 1.8\times10^{-51}$ pb

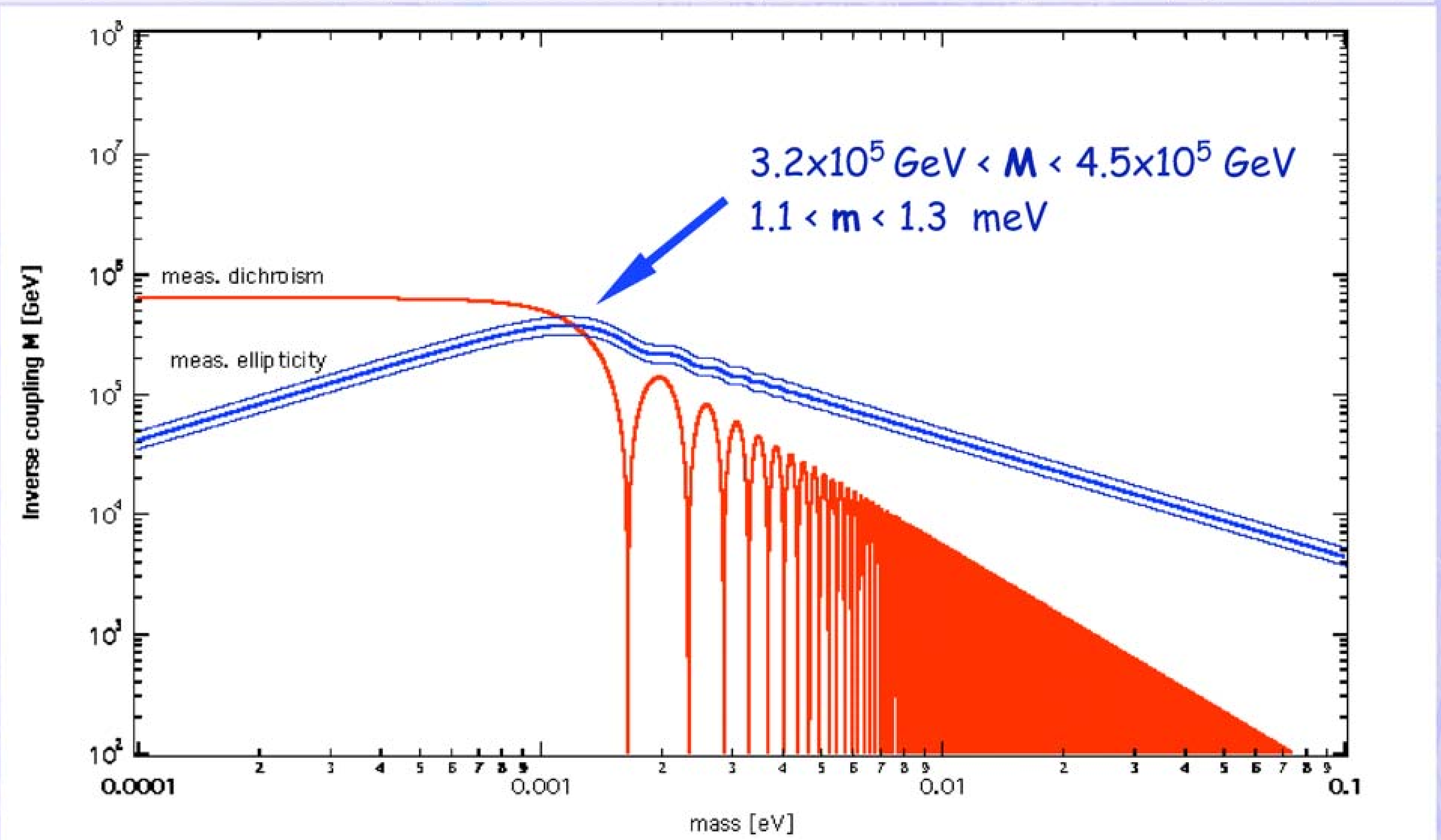
$\sigma_{\gamma\gamma}(\text{direct}) = 1.5\times10^{-34}$ pb

Speculations (II)

Believing in both the PVLAS observed signals in vacuum at B = 5.5 T, finesse = 97000)

$(6.1\pm2)\times10^{-7}$ rad ellipticity $(3.4\pm0.2)\times10^{-7}$ rad dichroism

and linking them to virtual and real particle production one can fix particle mass **m** and **M** (inverse coupling to two photons)



Limits on Axion-Photon-Coupling