SEARCH FOR AXIONS AT CERN

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SPSC Villars meeting, 22-28/9/2004

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Contents

CAST → – 2004 ✓ → 1^{st} phase → m_{axion} < .03 eV/c^2 +upgrade

→ **PRL** *to be submitted*

CAST → 2005 – 2007 → 2^{nd} phase → m_{axion} < .8 eV/c^2

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CAST → 2008 – → H_2-anticryostat → m_{axion} < 1.5 eV/c^2

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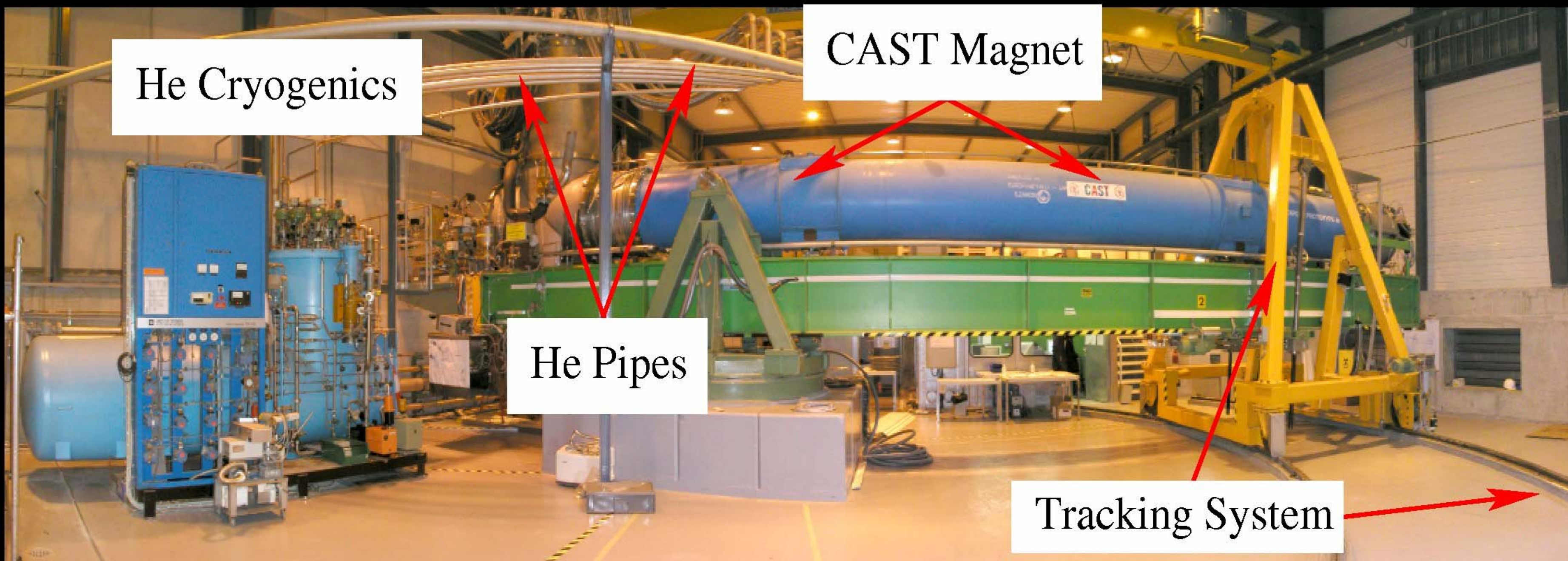
Beyond CAST-baseline:

Axion(-like) particles:

- ***Light***
  - → PVLAS-claim
    - → test PVLAS @ CERN ?
- ***Massive***
  - → Kaluza-Klein axions
    - → direct detection → with CAST
      - → with a large TPC
    - → indirect signature → solar X-rays

The CAST Superconducting Magnet at *CERN*



Prototype LHC magnet:

$$B = 9.2\,\mathrm{T} \quad l = 10\,\mathrm{m}$$

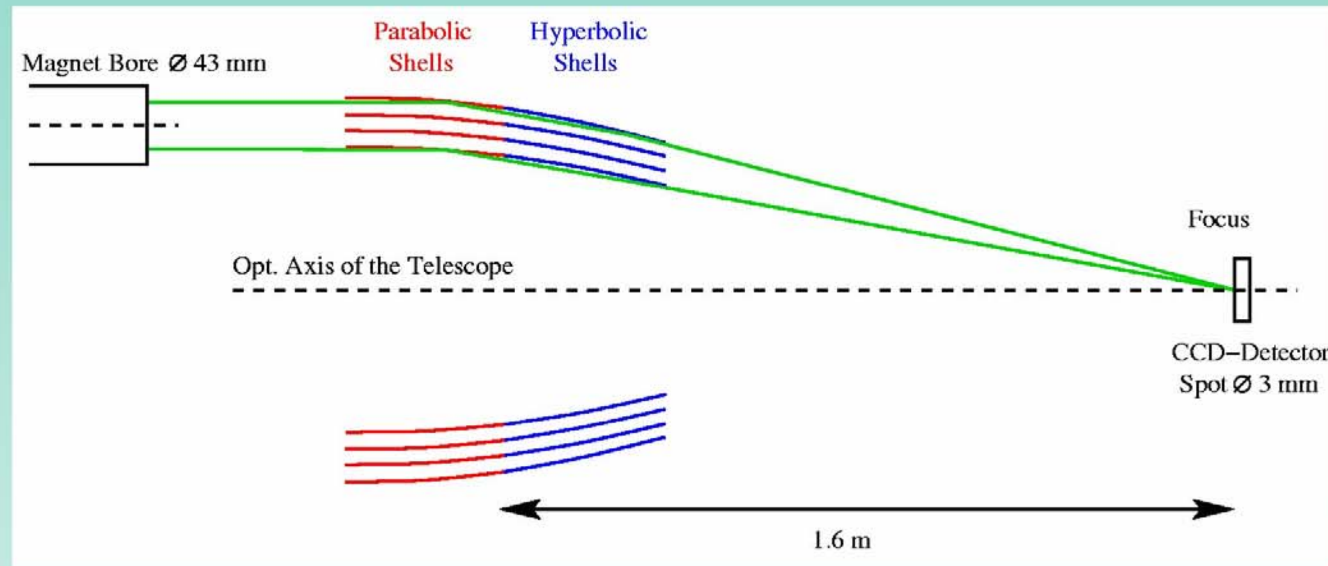
$$T = 1.8\,\mathrm{K} \quad m \approx 30\,\mathrm{t}$$

Tracking system:

$$H = -8^\circ \ldots 8^\circ \quad Az = 40^\circ \ldots 140^\circ$$

$\Longrightarrow$ 1.5 h observation time during sun rise and sun set (≈ 46 days/year)

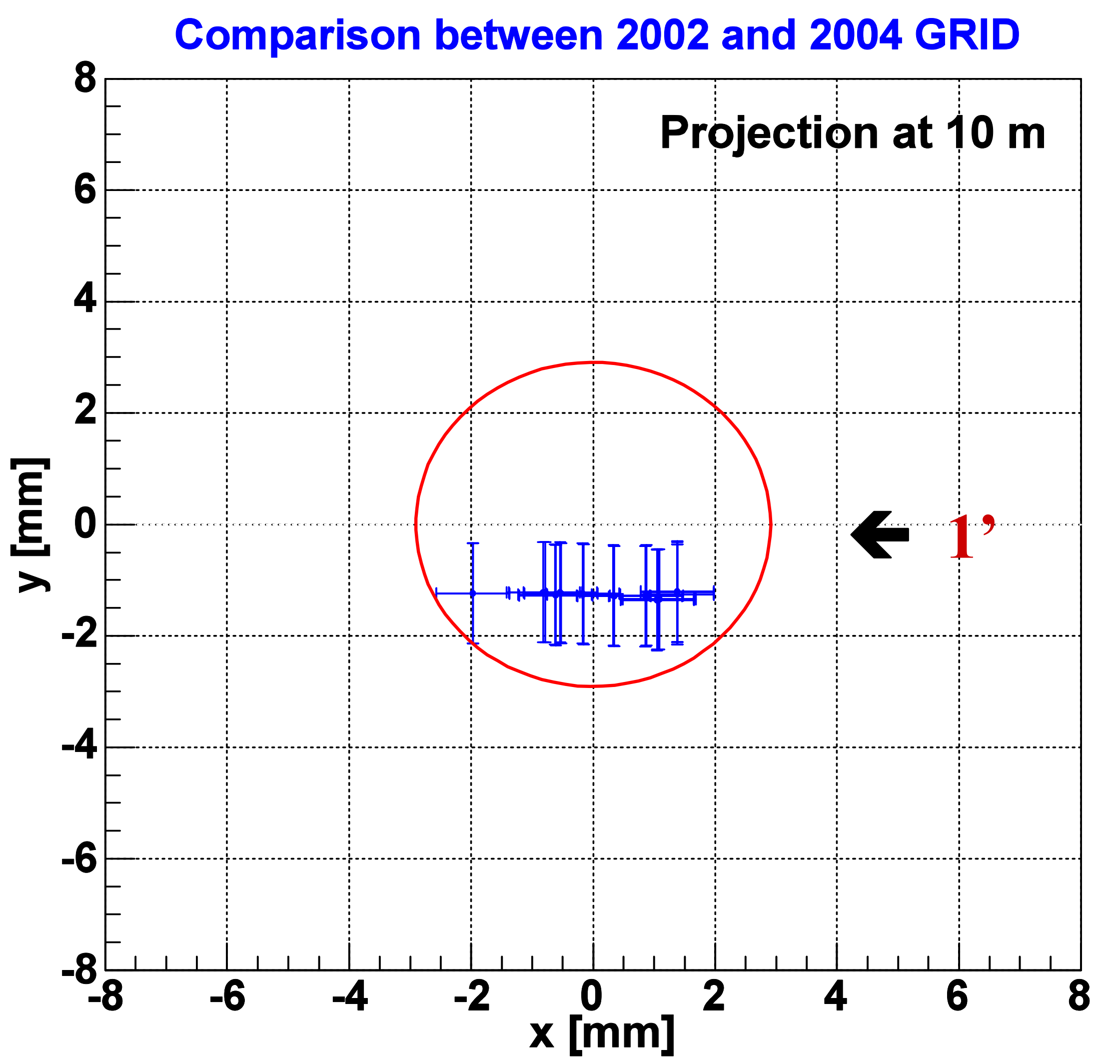
The X-ray Telescope



Wolter I type grazing incident optics (Prototype for *ABRIXAS* space mission):

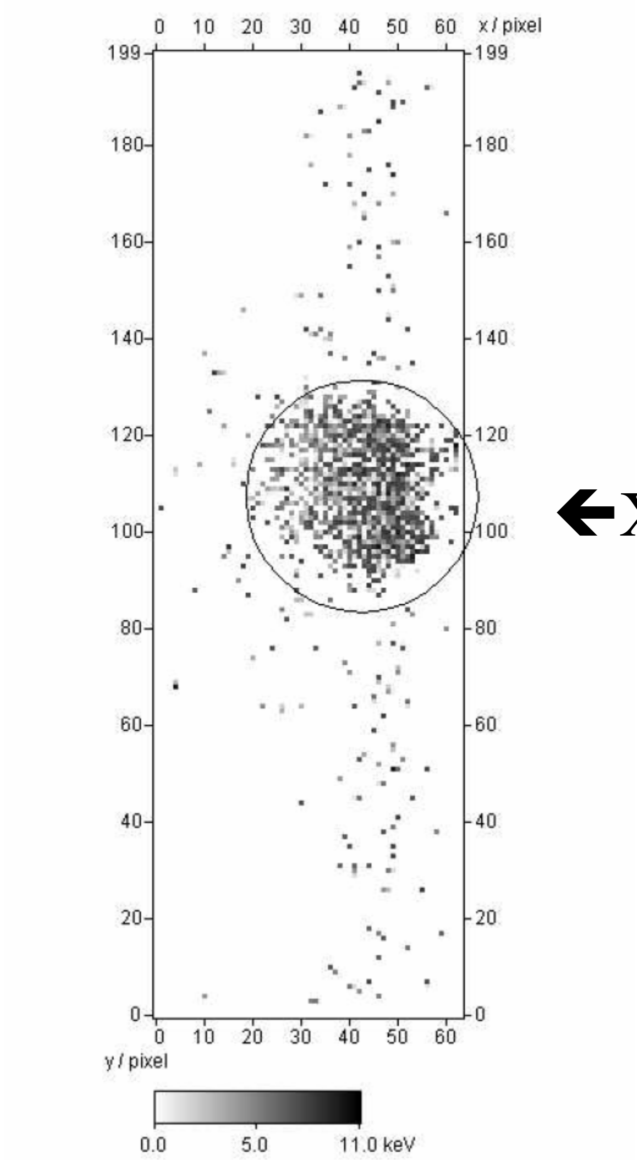
- 27 nested gold coated nickel shells, on-axis resolution ≈ 43 arcsec (HEW)
- Telescope aperture 16 cm, used for *CAST* 43 mm
- Only one sector of the full aperture is used for *CAST*

> ∅43 mm (LHC Magnet aperture) ⟹ ∅3 mm (spot of the sun)
> Signal to background improves by a factor ≈ 200



Comparison between 2002 and 2004 GRID
Projection at 10 m
y [mm]
x [mm]
8
6
4
2
0
-2
-4
-6
-8
-8
-6
-4
-2
0
2
4
6
8
1'

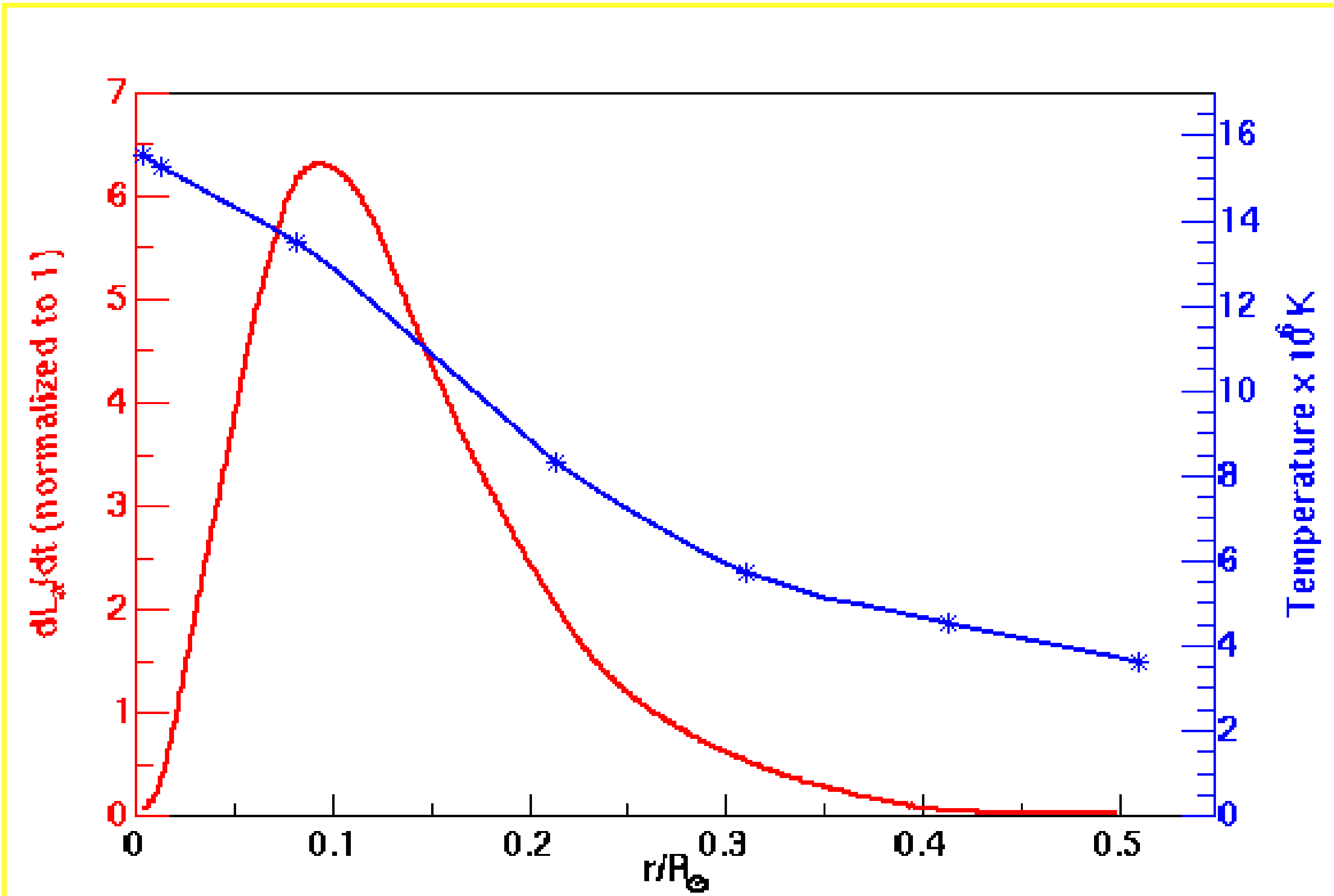
CAST X-ray Alignment



← X-ray spot on CCD. Vertical = +8°

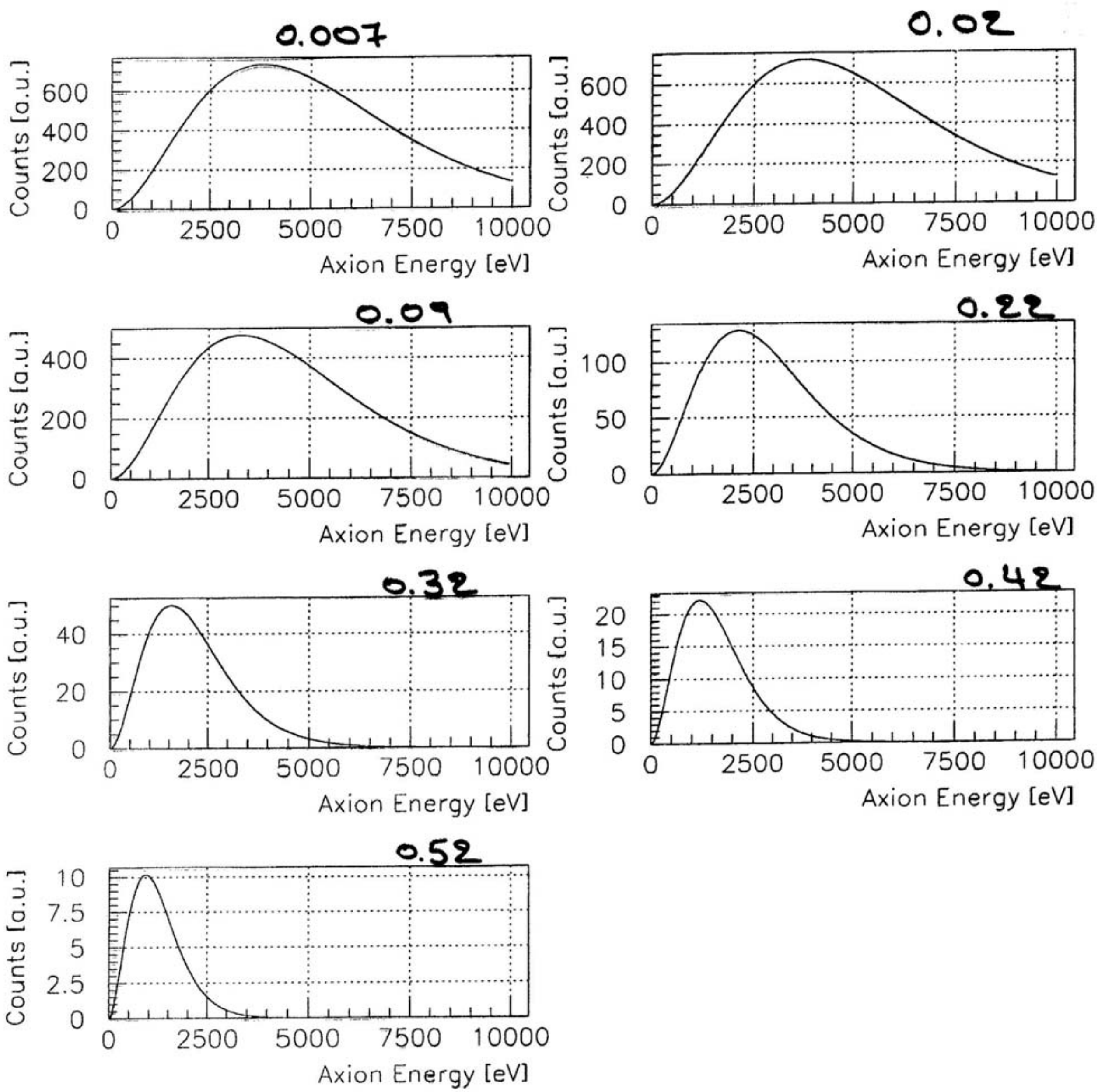
2004 → *stable*

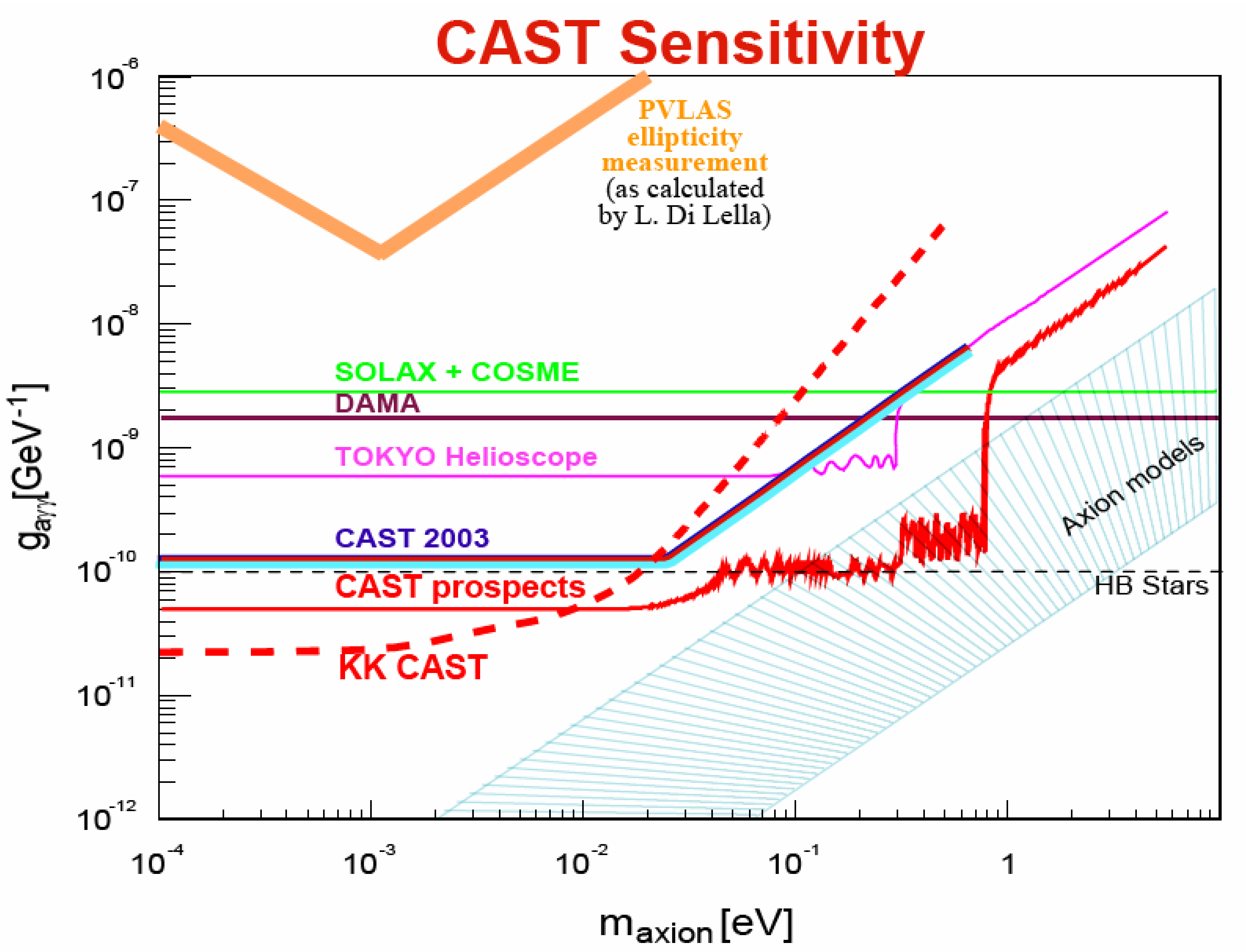
Improvements: solar core temperature gradient



Y. Semertzidis / TU-Darmstadt

Solar axion spectra = $f(r/R_{sun})$





Kaluza-Klein (KK) axions → Horvart, Krcmar, Lakic PRD 69 (**2004**) 125011

Search for solar nuclear M1-transitions

→ The Sun is the strongest source of M1 transitions, e.g.
14.4 keV
2.2 MeV
5.5 MeV

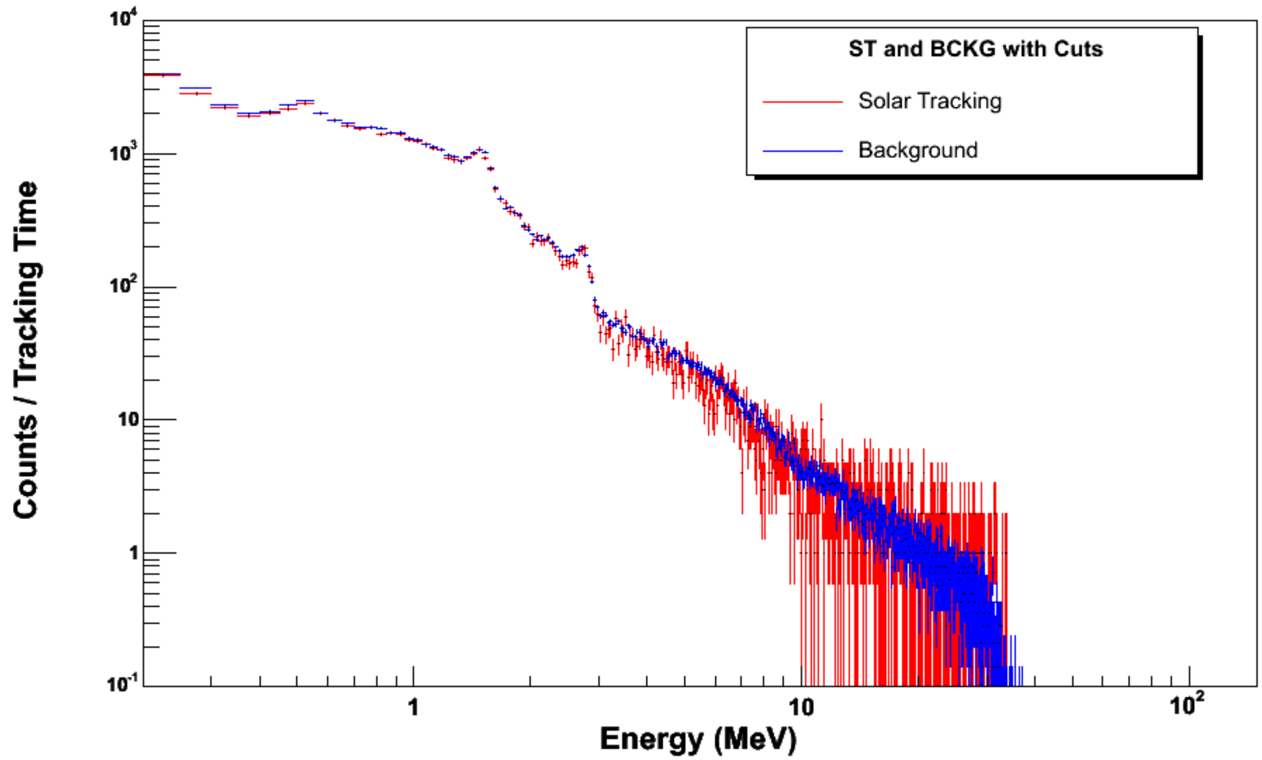
→ High Energy Calorimeter

Motivation:

- Broad band axion search with the high axion-to-photon conversion efficiency inside the CAST magnetic pipes.
- Axion coupling to nuclear magnetic dipole (M1) transitions.

First measurements with the CAST H.E. Calorimeter.

➔ detector: $CdWO_4$ crystal 0.6 kg (Ø45mm x 50 mm)



Comparison of energy spectra acquired during ***solar tracking*** (9.28 h) and normalized ***background*** measurements (130.5 h) with very moderate software cuts. Counting rate over full energy spectrum above 200 keV after cuts ~1.65 Hz. Correction to local back-ground conditions in different magnet positions is not included yet.

CAST 2^{nd} phase with buffer gas

→ ^4He 2005 / 2006 → below $m_a \sim$ 0.35 eV
→ ^3He 2006, 2007 → below $m_a \sim$ 0.8 eV

……………………………………………………

→ H_2 / anticryostat
beyond 2007 → below $m_a \sim 1.5$ eV

Improvements:

- Upgrade of the detectors & shielding
- Additional more efficient X-ray telescopes
- Accurate solar tracking → utilize solar temperature gradient

MOTIVATION:

- crossing of the theoretical line ($g_{a\gamma\gamma} \rightarrow m_a$) with the best astrophysical limit (see exclusion plot), while the cosmologically allowed axion rest mass region from evaluated WMAP data is below 2-3 eV/c^2.
- search for massive axions (also of the Kaluza-Klein type).

CAST's 2nd PHASE: relevant relations

Extend coherence for $a \rightarrow \gamma$ transitions to higher m_a values.

Fill the magnetic pipes with Helium gas ➡ $m_\gamma > 0$.

$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho}\ \text{eV}$$

N_e: electron density
ρ : gas density (g/cm^3)

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

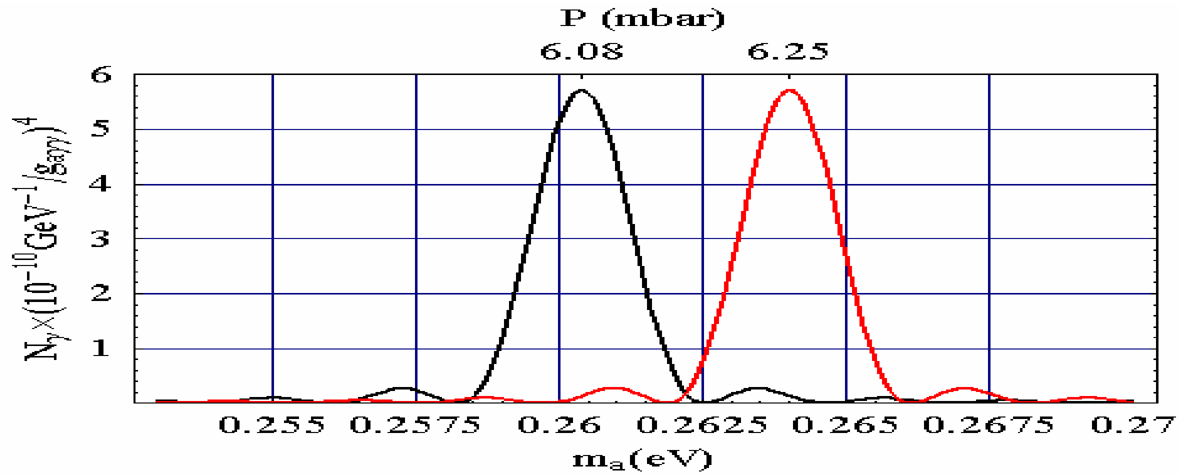
(qL <<1 for coherence)

Max. density ~ $0.3\text{x}10^{-3}$ g/cm^3 limited by ^{4}He saturated vapour pressure at 1.8°K ➡ $m_\gamma \sim 0.35$ eV.

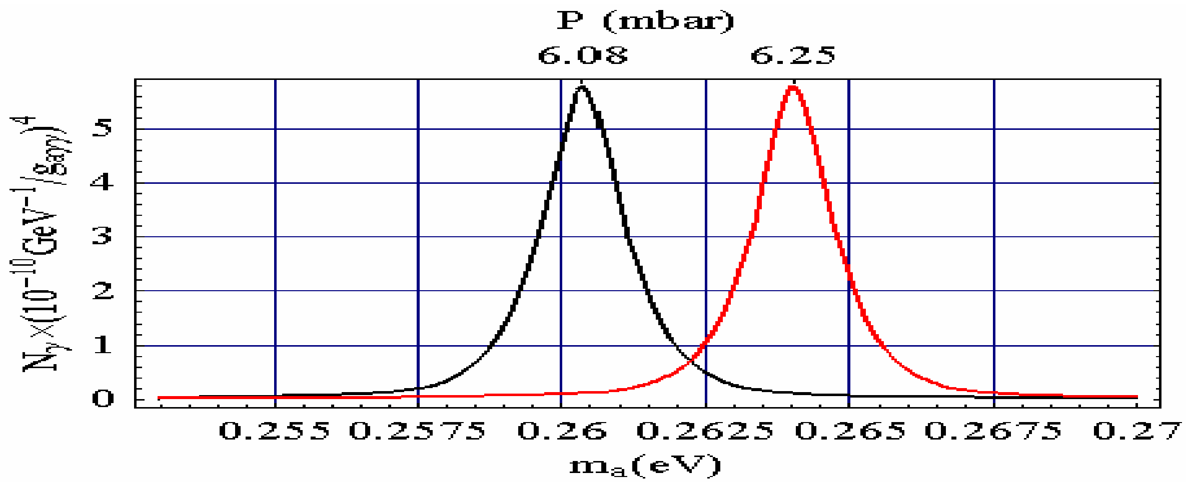
To reach higher m_γ values we need ^{3}He as buffer gas.

Plots without absorption

4.2 keV



All energies



Cryowindows for 2nd phase of CAST

Tapio Niniikoski

Two Ø8 mm windows (Metorex) tested at the cryolab of CERN.

→ ***leak rate at 4 K < $3 \cdot 10^{-9}$ mbar·litre/s***

→ ***compatible with the requirements of 2nd phase of CAST.***

→ see Cryolab Note 03-04

this rate is likely due to back diffusion of helium from the atmosphere of the lab, or due to contamination of the vacuum system by helium. The lack of any correlation between the helium pressure and leak signal enables to conclude that the window leak rate was «10^{-9} mbar·litre/s. The leak rate at room temperature had a similar upper limit and pressure variation. The two windows tested showed identical behaviour, but one was prematurely broken because of the Taconis effect, which made the window fail. This effect was avoided in the subsequent tests.

The yield of the hermetic 8 mm windows is less than 0.9 basing on rejection rate due to leaks. Depending on the character of the leaks, the yield may then become less than 1.6% for perfectly hermetic 50 mm windows, and we may have to accept a diffusion leak, which vanishes at low temperatures. Pin holes with visible leak rate at RT cannot be accepted for LT use. The yield becomes a problem in this case.

In addition:

Design study in preparation → T. Niniikoski & N.A. Elias
Ongoing **simulation** → CAST

→ At present, the plan for the ***2nd phase of CAST seems feasible***.

→ While preparing for VILLARS **&** looking to the future of CAST, we identified →

(Alternative) solution (~2007 -):

T.Niniikoski

1) ^4He/ H_2 inside anticryostat ➔ ~ 2x axion rest mass

A warmer gas cell solution (5.5K for ^4He or 30K for H_2) avoids the window problems. It also avoids the need for high stability of the temperature and pressure, because the filling is almost constant for a closed system. The physics potential is better, because of the higher axion rest mass reach.

The cost of the system is likely to be much lower than that of the ^3He.

➔ ***design study*** **→ 2005**

2) Si-diodes as cryo-windows & X-ray detectors 2007-

Cold silicon detectors have been operated successfully in S134 first time in 1974, with Ø1.5cm. They would be compatible with CAST ~1 keV threshold requirements, if a modern low-noise preamplifier with long integration time would be used. Background, noise & threshold measurements can be made by **RD-39** at short notice.

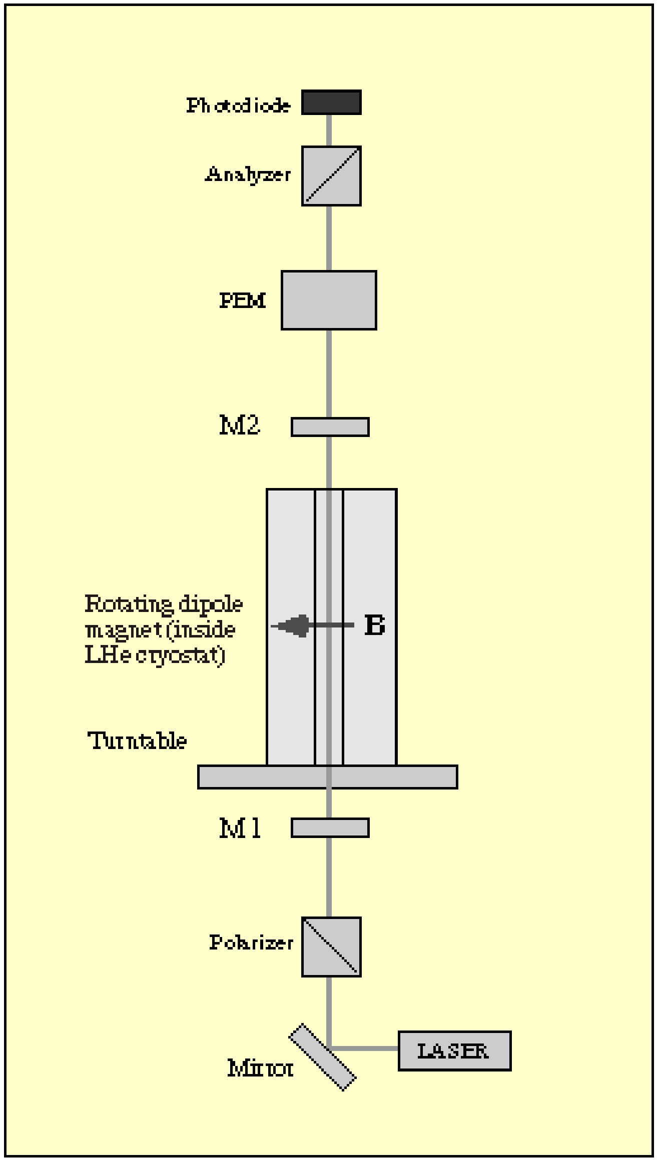
➔ **necessary for $m_a > 0.8\ eV/c^2$**

Sofar:

this is the maximum CAST performance we think we can achieve with X-rays.

➔ **PVLAS claim !**

PVLAS-experiment



M1 & M2

→ very high reflectivity dielectric mirrors

→ Fabry-Perot optical resonator

→ 1 msec

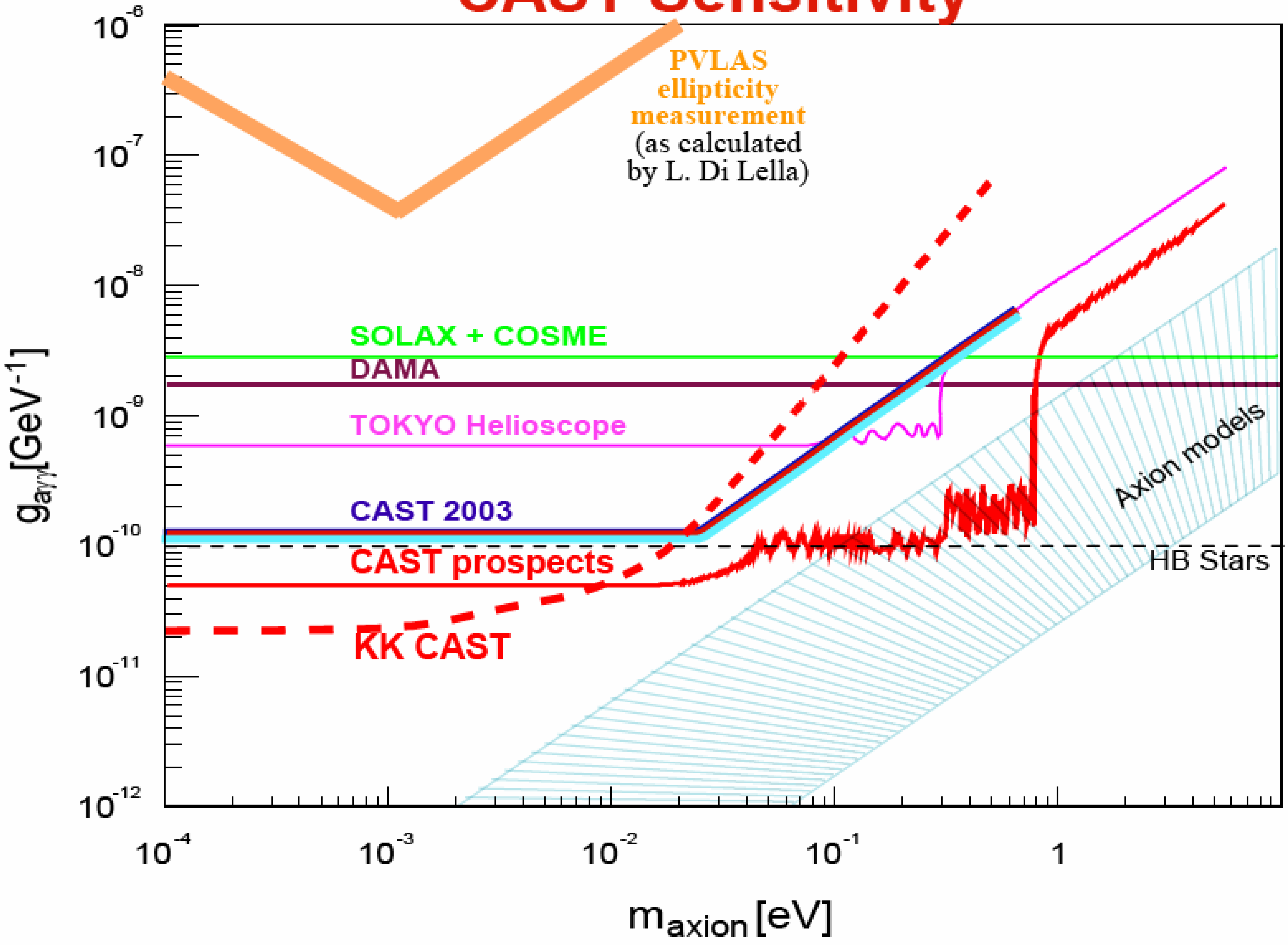
LASER

→ linearly polarized light

→ elliptical polarized

Magnet: http://www.ts.infn.it/experiments/pvlas/magnet/pict-magnet/cryogen.jpg

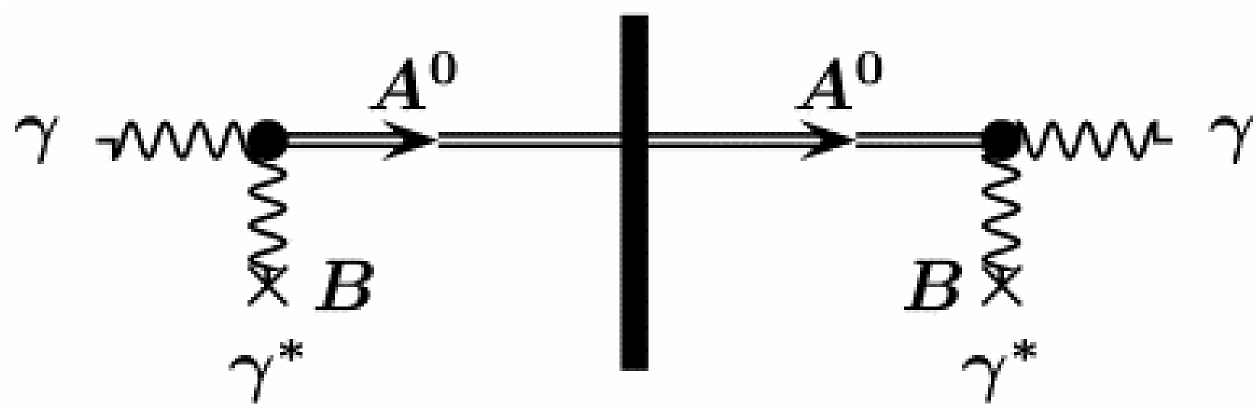
x CAST Sensitivity



NOTE: KK- axions ⏲ PQ-axions

Test PVLAS @ CERN

"Light shining through a wall experiment"



➔ **Possible options:**

- CAST + 1 LHC magnet
- CAST/2
- 2 LHC magnets @ SM18
- lowest energy solar axions ⊗ CAST

Light shining through a wall

An experiment to verify the interpretation of the PVLAS results as an axion effect.

L. DiLella

The **PVLAS** Collaboration has recently measured ***abnormally large elipticity and polarization rotation of laser light*** undergoing multiple reflections in a dipole magnet, being consistent with the effects expected from an axion with a mass $\boldsymbol{m_a \approx 10^{-3}}$ **eV/c²** and a coupling constant $\mathbf{g_{a\gamma\gamma} = (2\text{-}3)\cdot 10^{-6}}$ **GeV⁻¹**. If these results are confirmed, and assuming -as a working hypothesis- that all other experiments that have already excluded the PVLAS region of axion parameters are wrong for some reason, it is important to ***verify the PVLAS*** results using an independent experiment. This could be an experiment of the type called "Light shining through a wall" :
A laser beam traverses a first dipole magnet where photon-axion transitions occur. The axion then traverses a wall and is converted back to the original photon in another dipole magnet. Obviously, the amount of light shining through the wall is proportional to $(g_{a\gamma\gamma})^4$, while the magnitude of the effects measured by PVLAS is proportional to $(g_{a\gamma\gamma})^2$. Nevertheless, with the use of two decommissioned LHC magnets,it is possible to ***reach a sensitivity to*** $\boldsymbol{g_{a\gamma\gamma}}$ ***values as low as*** $\boldsymbol{10^{-7}\ GeV^{-1}}$ by multiple reflections of the laser beam in the first magnet.

The rate of photons “shining through the wall”, R_γ, is given by

$$R_\gamma = (P_{a\to\gamma})^2 \frac{W}{E_\gamma}\frac{n}{2}\eta \qquad (1)$$

where W is the power of the laser beam, E_γ is the photon energy, n is the number of reflections in the first magnet (only the photon paths pointing to the wall are useful), and η is the photon detection efficiency.
The axion-to-photon conversion probability is given by:

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma\gamma}}{2}BL\right)^2 \frac{\sin^2(qL/2)}{(qL/2)^2} \qquad (2)$$

where $g_{a\gamma\gamma}$ is in GeV^{-1}, B is the magnetic field (in Tesla), L is the magnet effective length (in metres) and q is the momentum transfer to the magnet. For $g_{a\gamma\gamma}=10^{-7}$ GeV^{-1}, B = 9 T, L = 9.26 m, and assuming that q = 0 (see below), $\boldsymbol{P_{a\to\gamma} \approx 1.7\cdot10^{-11}}$.
We use a green laser (λ= 514.5 nm, E_γ = 2.41 eV) with an average power W = 2 mW. The value $n = 2\cdot10^5$ can be obtained using commercially available mirrors to create a Fabri-Perot resonance cavity in the space

between them (this requires that the distance between the two mirrors be adjusted to correspond to a multiple of the wave-length λ). Finally, we assume a photon detection efficiency η=0.5, which can be obtained using Visible Light Photon Counters (VLPC).
Using these values, we find:

$$\boldsymbol{R_\gamma \approx 0.08\ /\ \mathrm{s}}$$

which corresponds to ~5 counts per minute above noise. Hence the VLPC noise should be reduced to much less than this value, if possible. The laser should be pulsed and the VLPC should be gated for ~0.01 s after the laser pulse to allow for the multiple light reflections.This will reduce the VLPC noise contribution to R_γ. The laser light should be linearly polarized and data should be taken by alternating the polarization between a direction parallel to the magnetic field and a direction orthogonal to it. No signal is expected in the latter case, giving further evidence for an axion effect if an excess of counts above noise is observed.

The momentum transfer to the magnet has been assumed so far to be zero. In the presence of gas in the magnet gap, it is given by the expression:

$$q = \frac{m_a^2 - m_\gamma^2}{2E_\gamma}$$

where m_γ is an effective photon mass. For optical photons:

$$\frac{v}{c} = \frac{1}{n} = \frac{\sqrt{E_\gamma^2 - m_\gamma^2}}{E_\gamma} \approx 1 - \frac{m_\gamma^2}{2E_\gamma^2} \qquad (3)$$

where n is the refraction index. For gases $n=1+\alpha\rho$, where ρ is the density in g cm^{-3}. Using ^{4}He ($\alpha = 0.1954$) and setting $m_\gamma=10^{-3}$ eV/c^2 in Eq. (3), we find $\rho = 4.4 \cdot 10^{-7}$ g cm^{-3}, which is well below the density corresponding to the ^{4}He saturated vapour pressure at 1.8° K ($\rho_{sat} \approx 3 \cdot 10^{-4}$ g cm^{-3}).
In vacuum ($m_\gamma = 0$), for $m_a = 10^{-3}$ eV/c^2 the momentum transfer to the magnet is $q = 2.07 \cdot 10^{-7}$ eV/c, corresponding to a wavelength of **~6 m**, giving $qL/2 = 4.86$. Using this value in Eq. (2) squared reduces the photon rate R_γ by about three orders of magnitude.

Since the axion mass is not precisely known, the ^4He density should be varied in small steps, or varied continuously during data taking. A relative variation $\Delta\rho/\rho \approx 2\cdot10^{-4}$ near $\rho = 4.4\cdot10^{-7}$ g cm^{-3} changes the axion mass for which $q = 0$ by 10^{-4} eV/c^2. Obviously, a scan of R_γ as a function of the gas density is expected to show the oscillatory behaviour predicted by Eq. (2), thus providing additional evidence for an axion effect.

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Alternative suggestions:

- ***M. Davenport***

2x15 m LHC-magnets in SM18 → ~ 2007 - ?

- ***R. Kotthaus***

CAST magnet only

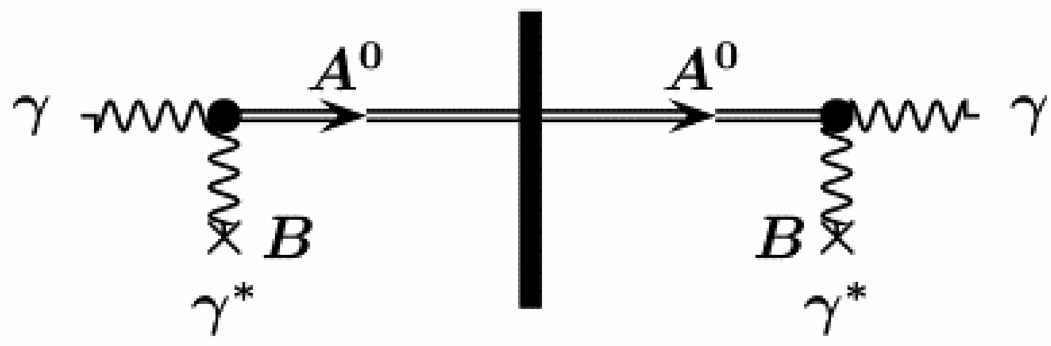
A high power UV-LASER (~10 W, λ=200 nm)

→ without optical cavity **&** buffer gas

A wall at the center of the magnet

→ Rate ~ a few Hz

CAST operation in the visible: *continuous & discret lines*



- ***visible photon*** → ***axion*** inside $\mathbf{B}_{solar}$ near the photosphere
- axion coupling to forbidden ***atomic M1 transitions***,
  e.g. the ***green*** (Fe-XIV) and ***red*** (Fe-X) lines in solar atmosphere
  → ***outer Sun = source of ~ eV axions*** ?

→ **Needed: CAST** + ***single photon sensitive detectors*** in the visible

→ film, APDs (IR to vacuum UV), PMTs → **noise = ?**

→ ***first test run already in 2004*** ?

→ MOTIVATION:

a) lowest threshold solar axion search with CAST

b) ***test PVLAS with CAST*** ?

CAST *performance in the visible* with PVLAS *results & solar input*

➔ **PVLAS:** $g_{a\gamma\gamma} \approx 2.5 \cdot 10^{-6}$ **GeV**$^{-1}$ & $m_{axion} \approx 10^{-3}$ **eV/c**^{2}**.**

Above the solar photosphere, we take:

- $B_{solar} \approx 9$ **Gauss.**
- solar oscillation length **L ≈ 1 km**.

  ➔ at the solar surface the density ($\rho \sim 10^{-4}$ bar) is decreasing exponentially outwards. In order to have $m_{axion} \approx m_\gamma$ inside the solar atmosphere (as for CAST 2nd phase), a $\rho \approx 10^{-5}$ bar is needed. Therefore, above the solar surface the photon-to-axion conversion can be enhanced in the axion rest mass range $\sim 10^{-2}$ to $\sim 10^{-5}$ eV/c^2. I.e., for a distance of ~1 km the local density is the required one to restore coherence.
- $L_{solar} \approx 4 \cdot 10^{33}$ erg/s.

➔ $P_{\gamma \to a} \approx 6 \cdot 10^{-13}$ ➔ $\Phi \approx 10^6$ **axions / sec·CAST-exit**

In CAST:

➔ $P_{a \to \gamma} \approx 10^{-9}$ (assuming ~5 m oscillation length)

➔ Rate = $P_{a \to \gamma} \cdot \Phi \approx 10^{-3}$ photons / sec·CAST-exit

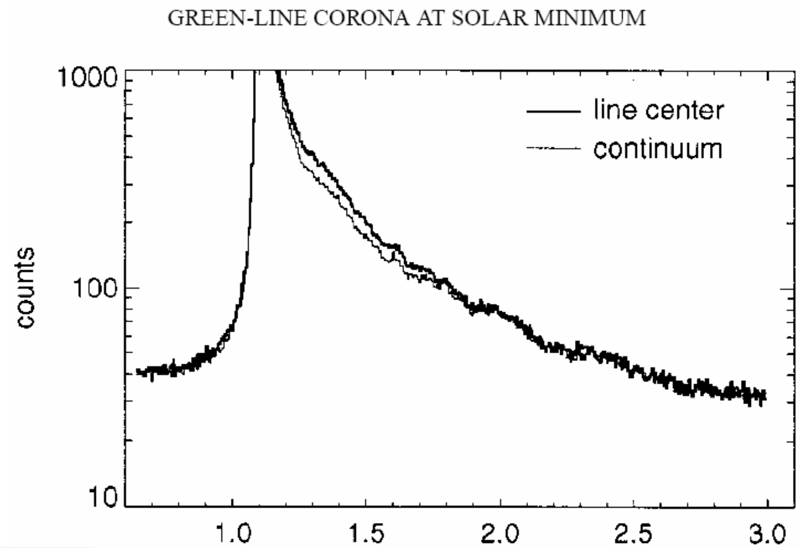
Note:
this is probably a conservative estimate. The solar oscillation length may be taken ~10 km, since the opacity in the visible seems to be reasonable for some 1000 km above the photosphere. Also, the local (quiet) $\mathbf{B}_{solar}$ might be even larger with peaks at ~1.5 kGauss.

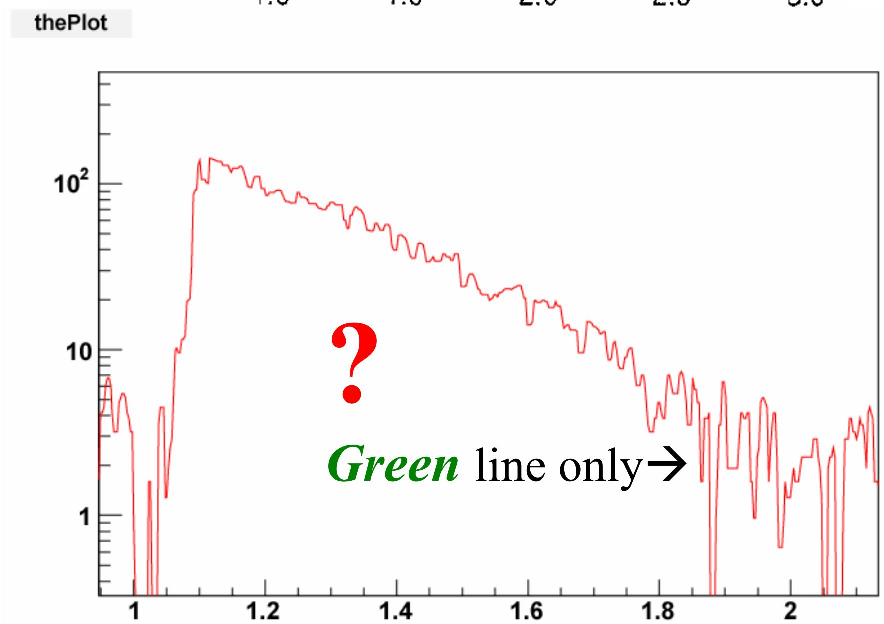
[see F. Cataaneo, ApJ. 515 (**1999**) L39; S.R. Cranmer, astro-ph/**04**09260; R.M. Sainz et al., ApJL. 614 (10.10.**2004**)].

Thus, the photon rate during solar tracking with CAST can be

➔ **Rate ~ $10^{-3} \to 1$ visible phot. / sec·CAST-exit**

R. Schwenn et al.,
Sol. Phys. 175 (**1997**) 667. ➔





R_{solar}

➔ ***Green*** Fe-XIV M1 line
@ 530.3 nm

Axion ⊗ atomic M1 transitions
Z., Semertzidis, PLA130 (**1988**) 94.

Note the different radial shapes.

Beyond CAST

➔ **Direct search** for solar **massive axion**(-like) particles, e.g. of the Kaluza-Klein type with a large volume chamber:

➔ **ALICE-TPC** → → ***'trigger'*** **?** ***noise*** **?**

→ $g_{a\gamma\gamma}$ ✓

→ $\tau \sim (m_{axion})^{-3}$ ➔ "*short lived*" ($\sim 10^{20}$ s)

➔ ***Signal*** due to spontaneous / **B-**induced decay of axions:

a) ***2-prong*** events → $E_{\gamma 1} \approx E_{\gamma 2} \approx$ 1-10 keV **&** **Rate ~ 1/m³day**

b) ***1-prong*** events inside **B** → single X-ray photon below ~10 keV

→ rate = **?**

➔ ***Present indirect limit:*** ~ 20000 / m^3day

preferred place: underground + shielding ➔ ***"a first"***

Motivation: ➔

***Solar corona heating problem* 1939-**

… one of the longest unsolved mysteries in all of astrophysics

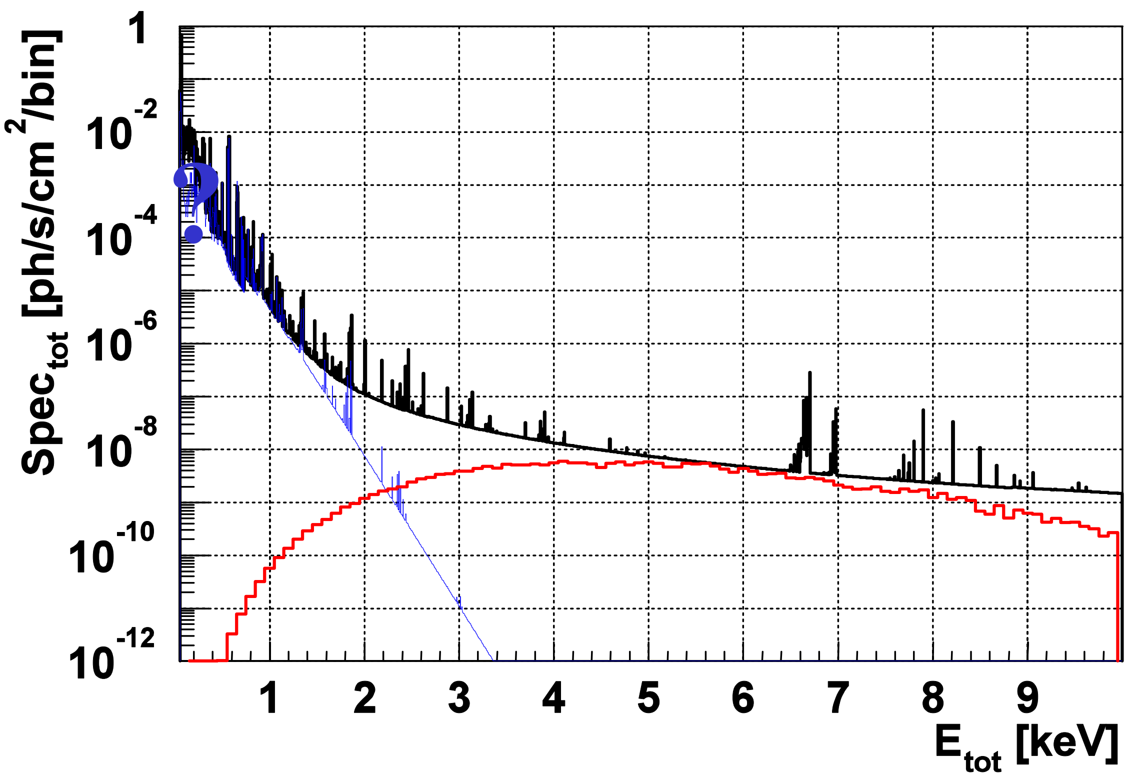
Schmelz,
Adv. Space Res. 32 (**2003**) 895

➔ ***Suggested solution within astroparticle physics*:**

- decay X-rays from accumulated solar massive axions of the Kaluza-Klein type, gravitationally trapped by the Sun over 4.6 Gyears.

Observational evidence for gravitational trapped massive axion(-like) particles

DiLella, Z., Astropart. Phys. 19 (**2003**) 145



The solar X-ray spectrum reconstructed from the emission measure distribution (EM(T)) for the **non-flaring Sun at the solar minimum** **[16]**. A thermal component of ~1.8 MK is also shown (**blue** line). (EM(T) is approximately the product of the square of the electron density with the emitting volume V(T) as a function of temperature). **Red** line : solar KK-axion model

[16] Peres, Orlando, Reale, Rosner, Hudson, ApJ. 528 (2000) 537

Quiet Sun X-rays as Signature for New Particles

Z., Dennerl, DiLella, Hoffmann, Jacoby, Papaevangelou

ApJ. 607 (**2004**) 575

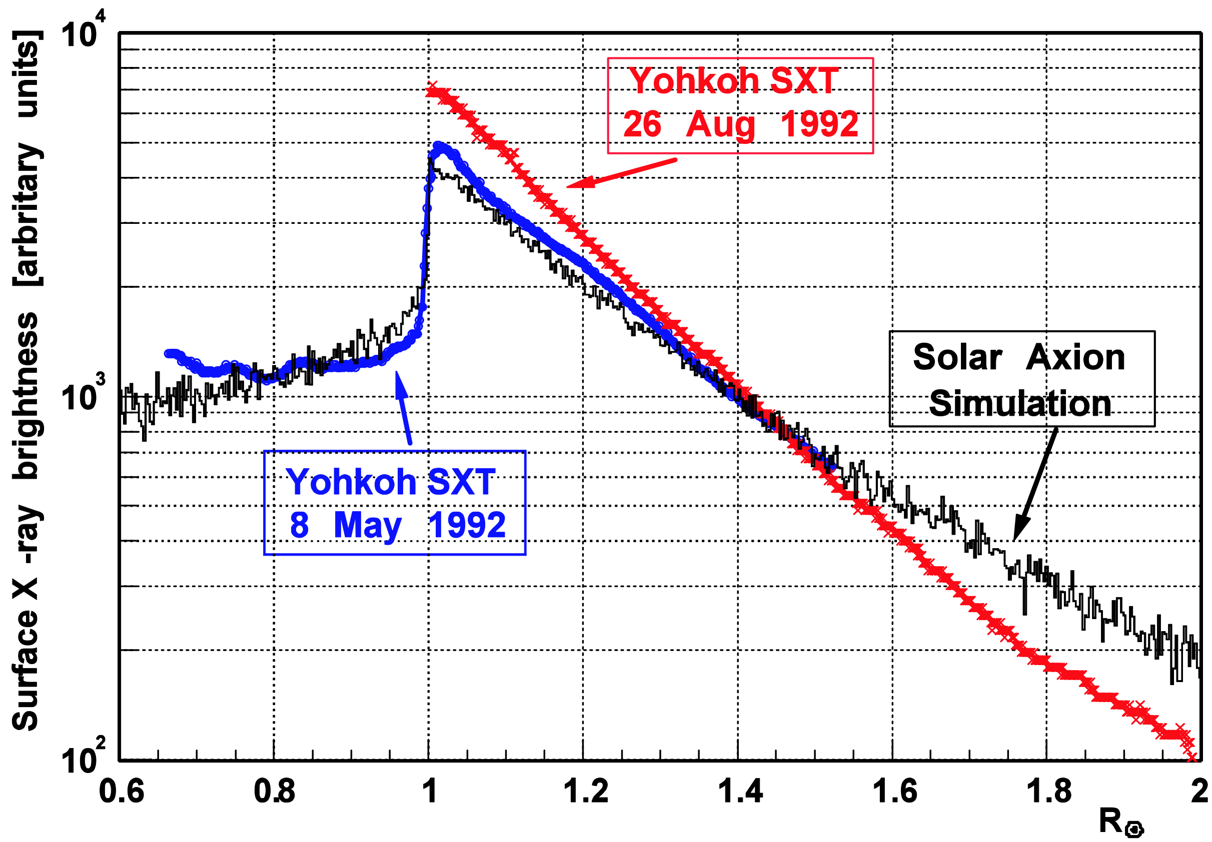


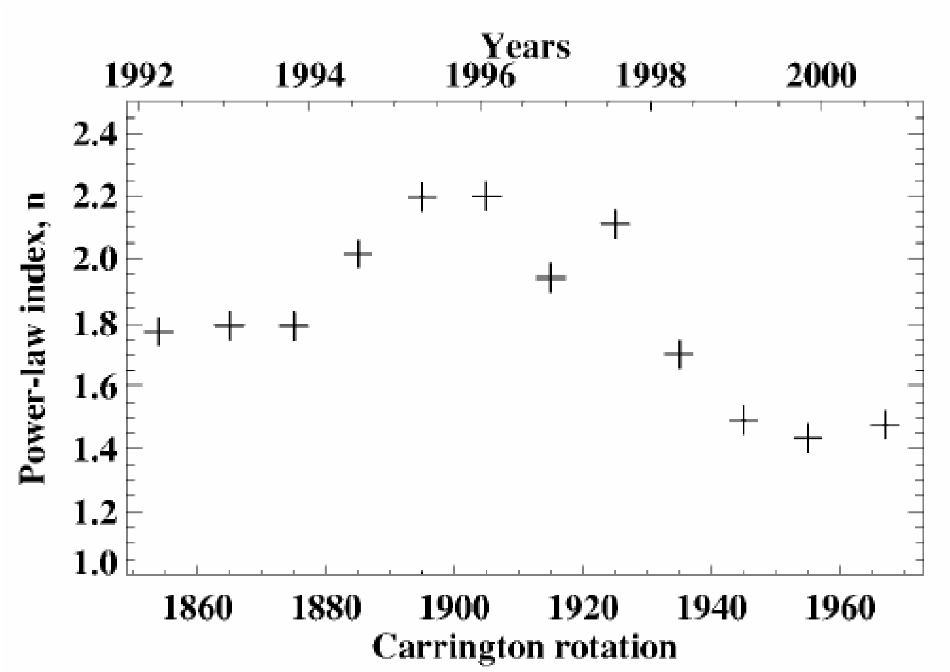
Fig. 1.— Theoretical (DZ03) and experimental (Sturrock et al. 1996; Wheatland et al. 1997) soft X–ray surface flux distributions from the quiet Sun. The simulated curve has been shifted relative to the experimental points of both observations, which implies $g_{a\gamma\gamma} \leq 40 \cdot 10^{-14}$ GeV^{-1}. The effective exposure time was 136.5 s and 121.3 s for the May and August observation, respectively.

X-ray activity is connected to strong $B_\odot$

e.g. J. Qiu et al., ApJ. 612 (**2004**) 530

➔ solar axions ⊗ $B_\odot$?

➔ ***search 1-prong events***



YOHKOH: I_{AlMg} **(<4keV) ~** B^n dependence as a function of time.

"The relation between the soft X-ray flux … and … the magnetic flux can be approximated by a power law with an averaged index close to 2."

*Benevolenskaya, Kosovichev, Lemen, Scherrer, Slater ApJ. 571 (**2002**) L181*

➔ **axion-to-photon conversion ∝ B^2** ➔ **Hoffmann, Z.** *in preparation*

Then : **1) radiative decay** ➔ constant term

2) interaction with B_{SOLAR} ➔ also local effects

3) ***axion - condensate(s)*** ?

➔ ? 11-years solar cycle ?

Summary:

- CAST proposal 9.8.1999
- Improvements/extensions:
  X-ray telescope
  → ~ arcmin space resolution
  Point to other celestial sources (parasitic runs) → background
  High energy calorimeter
- 2003 data → 5 times better limit for $g_{a\gamma\gamma}$ → PRL paper
- 2004 data → upgraded performance → high quality data
- 2005-2007 → 2^{nd} phase of CAST → m_{axion} below ~ 0.8 eV/c^2
- 2008 -- → with H_2 → m_{axion} below ~ 1.5 eV/c^2
- PVLAS claim & spontaneous axion decays (e.g. of the Kaluza-Klein type) were not in sight in 1999.
- Motivation for further work: test PVLAS, search for massive axion(-like) particles & theoretical/observational studies.

Table 1.1: The plasma-β parameter in the solar atmosphere.

Parameter	Photosphere	Cool corona	Hot corona	Outer corona
Electron density n_e (cm^{-3})	2×10^{17}	1×10^9	1×10^9	1×10^7
Temperature T (K)	5×10^3	1×10^6	3×10^6	1×10^6
Pressure p (dyne cm^{-2})	1.4×10^5	0.3	0.9	0.02
Magnetic field B (G)	500	10	10	0.1
Plasma-β parameter	14	0.07	0.2	7

M.J. Aschwanden,
Physics of the Solar Corona (**2004**)