united nations educational, scientific and cultural organization
international atomic energy agency

the **abdus salam** international centre for theoretical physics

ICTP 40th Anniversary

H4.SMR/1574-29

"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Axion Searches

K. Zioutas

University of Thessaloniki,
University of Patras & CERN

Axion Searches

K. Zioutas

U. of Thessaloniki – U. of Patras & CERN

VII School on Non-Accelerator Astroparticle Physics

ICTP / TRIESTE

5th and 6th August 2004

Further reading :

1)

Stars as Laboratories for Fundamental Physics:
The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles (Theoretical Astrophysics)

by

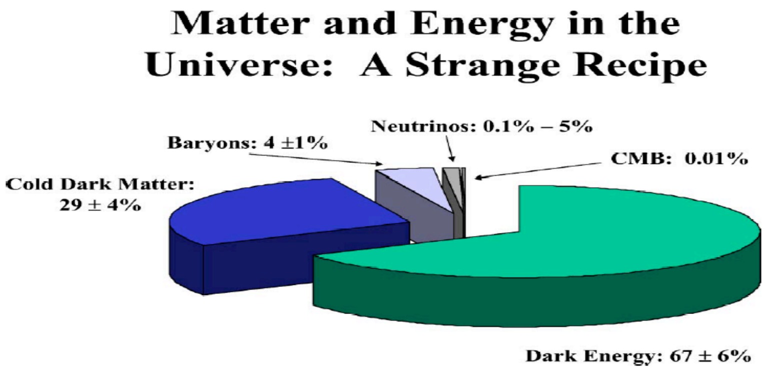
Georg G. Raffelt

2)

Bradley, Clarke, Kinion, Rosenberg, v.Bibber, Matsuki, Mück, Sikivie
Microwave-cavity searches for dark-matter axions
Rev. Mod. Phys. 75 (**2003**) 777.

3)

e.g.: ***http://physicsweb.org/article/world/13/1/9/1***



Freedman, M.S. Turner
*REV. MOD. PHYS. 75 (**2003**) 1433*

The light-emitting components of the universe comprise about 0.4% of the total energy. The remaining components are dark. Of those, ~3.7% are identified: cold gas and dust, neutrinos, and black holes. ~23% is dark matter, and ~73% is some type of gravitationally self-repulsive dark energy.

➔ Repulsive DM, consisting of a **condensate** of massive bosons with short-range repulsive potential

➔ **Decaying DM** … into relativistic particles … without altering large-scale structure.

*J.P. Ostriker, P. Steinhardt, SCIENCE 300 (**2003**)1909*

➔ **WMAP** Constraints on **Decaying Cold DM** : _ > 123 Gyr *Ichiki, Oguri, Takahashi astro-ph/**04**03164*

⇓

s. also ref. [5,9]

"… affects **S-Z** fluctuations significantly … and the early ***reionization*** of the universe."

"… explain the ***large optical depth*** observed by WMAP without contradicting other astrophysical and cosmological constraints"

"… ***we simply assume the particles decay to 2_***"

➔ "… if reionization occurs at z_{re}~20...
A decaying DM particle :

➔ ionization of the **IGM**

➔ cosmological parameters"

Chen, Kamionkowski
astro-ph/0310473 (**2004**)

Dark matter = a mystery ⊕ *other mysteries* in astrophysics?

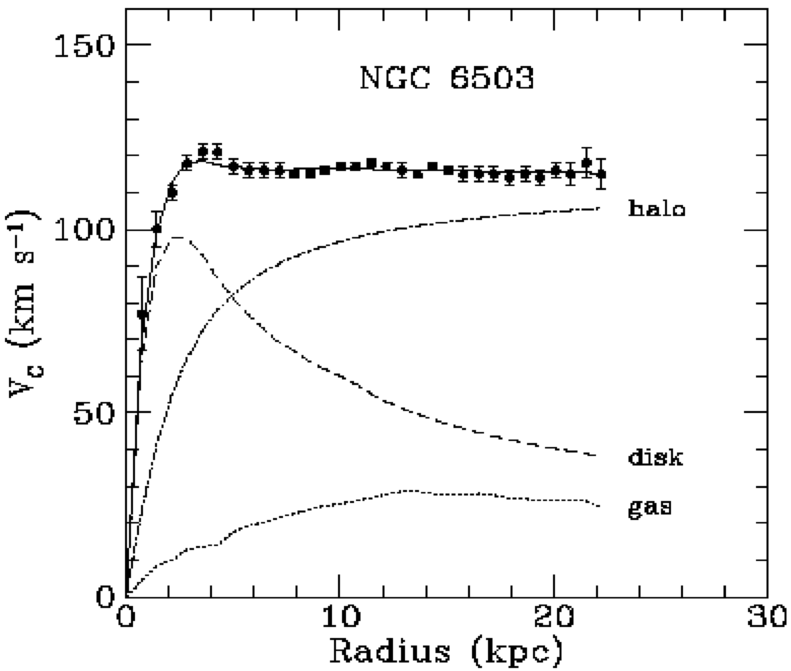
				Components	Totals
1	dark sector				0.954 ± 0.003
1.1	energy			0.72 ± 0.03	
1.2	dark matter			0.23 ± 0.03	
1.3	primeval gravitational waves			$\lesssim 10^{-10}$	
2	primeval thermal remnants				0.0010 ± 0.0005
2.1	electromagnetic radiation			$10^{-4.3}$	
2.2	neutrinos			$10^{-2.9\pm0.1}$	
2.3	prestellar nuclear binding energy			$-10^{-4.1}$	
3	baryon rest mass				0.045 ± 0.003
3.1	warm intergalactic plasma			0.040 ± 0.003	
3.1a	virialized regions of galaxies		0.024 ± 0.005		
3.1b	intergalactic		0.016 ± 0.005		
3.2	intracluster plasma			0.0018 ± 0.0007	
3.3	main sequence stars	spheroids and bulges		0.0015 ± 0.0004	
3.4		disks and irregulars		0.00055 ± 0.00014	
3.5	white dwarfs			0.00036 ± 0.00008	
3.6	neutron stars			0.00005 ± 0.00002	
3.7	black holes			0.00007 ± 0.00002	
3.8	substellar objects			0.00014 ± 0.00007	
3.9	HI + HeI			0.00062 ± 0.00010	
3.10	molecular gas			0.00016 ± 0.00006	
3.11	planets			10^{-6}	
3.12	condensed matter			$10^{-5.6}$	
3.13	sequestered in massive black holes			$10^{-5.4}(1+\epsilon_n)$	
4	primeval gravitational binding energy				$-10^{-6.1\pm0.1}$
4.1	virialized halos of galaxies			$-10^{-7.2}$	
4.2	clusters			$-10^{-6.9}$	
4.3	large-scale structure			$-10^{-6.2}$	
5	binding energy from dissipative gravitational settling				$-10^{-4.9}$
5.1	baryon-dominated parts of galaxies			$-10^{-8.8}$	
5.2	main sequence stars and substellar objects			$-10^{-8.1}$	
5.3	white dwarfs			$-10^{-7.4}$	
5.4	neutron stars			$-10^{-5.2}$	
5.5	stellar mass black holes			$-10^{-4.2}\epsilon_s$	
5.6	galactic nuclei	early type		$-10^{-5.6}\epsilon_n$	
5.7		late type		$-10^{-5.8}\epsilon_n$	
6.	poststellar nuclear binding energy				$-10^{-5.2}$
6.1	main sequence stars and substellar objects			$-10^{-5.8}$	
6.2	diffuse material in galaxies			$-10^{-6.5}$	
6.3	white dwarfs			$-10^{-5.6}$	
6.4	clusters			$-10^{-6.5}$	
6.5	intergalactic			$-10^{-6.2\pm0.5}$	
7	poststellar radiation				$10^{-5.7\pm0.1}$
7.1	resolved radio-microwave			$10^{-10.3}$	
7.2	far infrared			$10^{-6.1}$	
7.3	optical			$10^{-5.8\pm0.2}$	
7.4	X-γ ray			$10^{-7.9}$	
7.5	gravitational waves			10^{-12}	
8	stellar neutrinos				$10^{-5.5}$
8.1	nuclear burning			$10^{-6.8}$	
8.2	white dwarf formation			$10^{-7.7}$	
8.3	core collapse			$10^{-5.5}$	
9	cosmic rays and magnetic fields				$10^{-8.4^{+0.6}_{-0.3}}$
10	kinetic energy in the intergalactic medium				$10^{-8.0}$

The Cosmic Energy Inventory

M. Fukugita & P.J.E. Peebles

astro-ph/0406095

X-_ rays → ~10^{-8}



Rotation curve of a spiral galaxy. The dashed and dotted curves are the contribution to the circular rotational velocity due to the observed disk and gas, respectively. The dot-dash curve is the contribution from **the dark halo**:

➔ ***Most of the mass of the Milky Way is contributed by its halo, presumably in the form of non-interacting cold dark matter.***

➔ $_{DM}$ ~ 0.3 GeV/cm^3

well-motivated dark matter candidates beyond the SM :

WIMPs (SS) & *Axions* (CP @ QCD)

⇓

spin-parity ⇒ **0^-** ⇒ **~** π– **,** _ (M1)

AXION PHYSICS

The QCD Lagrangian is :

$$\mathcal{L}_{QCD} = \mathcal{L}_{\rm pert} + \theta \frac{g^2}{32\pi^2} G\widetilde{G}$$

➔ $L_{\rm pert}$ ⇒ numerous phenomenological successes of QCD.

➔ **_-term** (G is the gluon field-strength tensor) is a consequence of non-perturbative effects, ***violates CP***.

Experimentally ➔ CP is not violated in the strong interactions, or if it is, the level of violation is tiny. From the neutron electric-dipole moment $d_n \sim 10^{-25}$ *e cm* ⇒ _ $< 10^{-10}$

⇒ ***why is _ so small?***

➔ ***the strong-CP problem.***

To solve the strong-CP problem, i.e., to suppress strong charge-parity (**CP**) violation, the ***axion*** was invented, which still seems to be the most promising solution. **Peccei-Quinn** introduced a global $U(1)_{PQ}$ symmetry broken at a scale f_a, and non-perturbative quantum effects drive **_ _ 0**

➔**“ CP-conserving value ”**

and also generate a mass for the axion :

$$m_a = \frac{f_\pi m_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} = 0.6 \text{ eV} \frac{10^7 \text{ GeV}}{f_a}$$

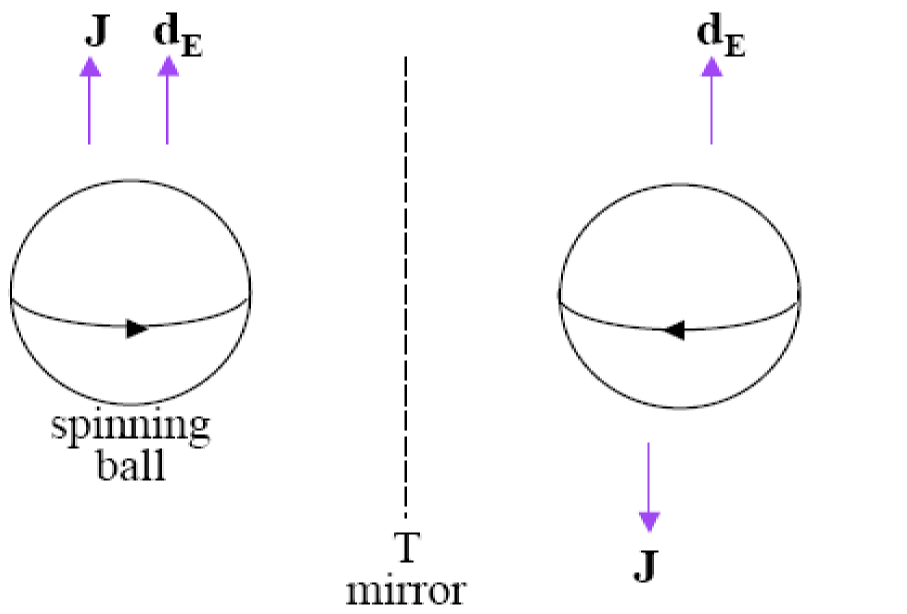
All the axion couplings are inversely proportional to f_a .

The discrete symmetry "mirrors"

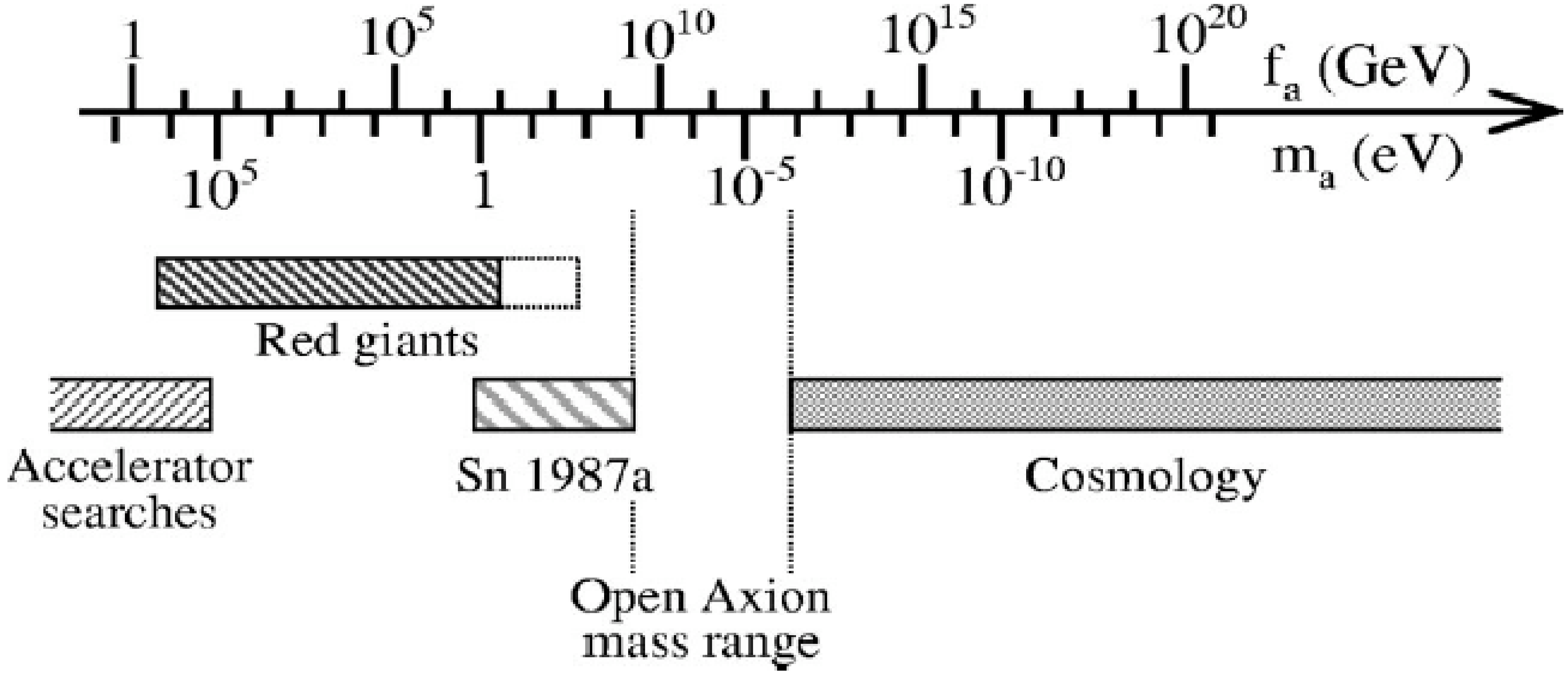
T ≡ time reversal

C ≡ changing particles to antiparticles

P ≡ space inversion

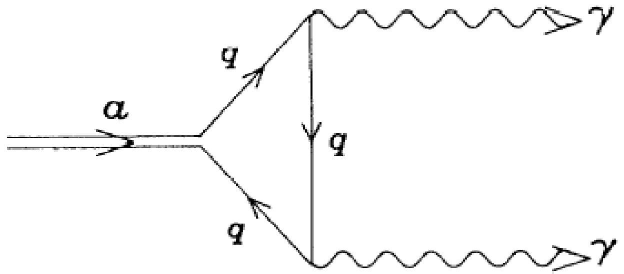


If you see an EDM: $\not{T}$ + CPT = $\not{CP}$

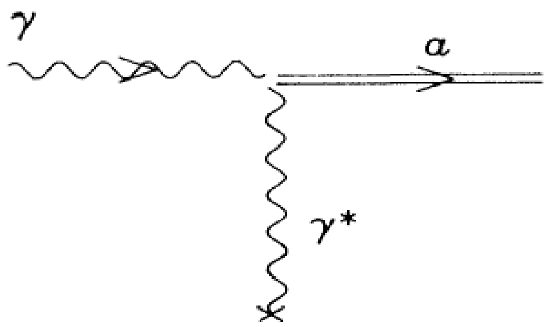


1
10^5
10^10
10^15
10^20
f_a (GeV)
m_a (eV)
10^5
1
10^-5
10^-10
Red giants
Accelerator searches
Sn 1987a
Cosmology
Open Axion mass range

Of particular interest ➔ ***axion coupling to two photons*** (in all models)



(a)

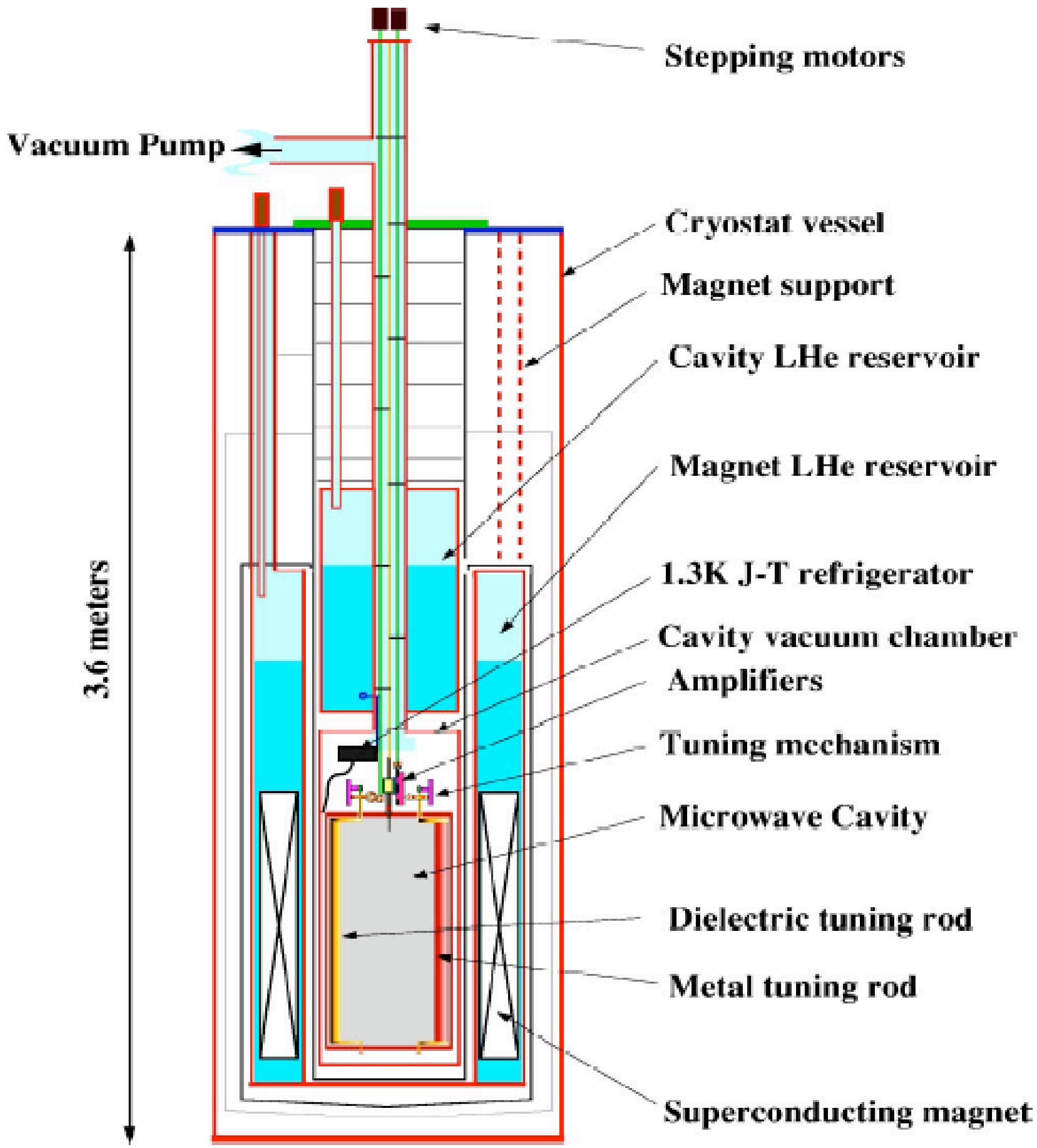


(b)

(a) Axion coupling to two photons through a triangle graph.

(b) Axion production by photon propagating in a static magnetic field (**Primakoff effect**). *R.Cameron et al.,PRD47(1993)3707*

THE SIKIVIE MW CAVITY EXPERIMENT



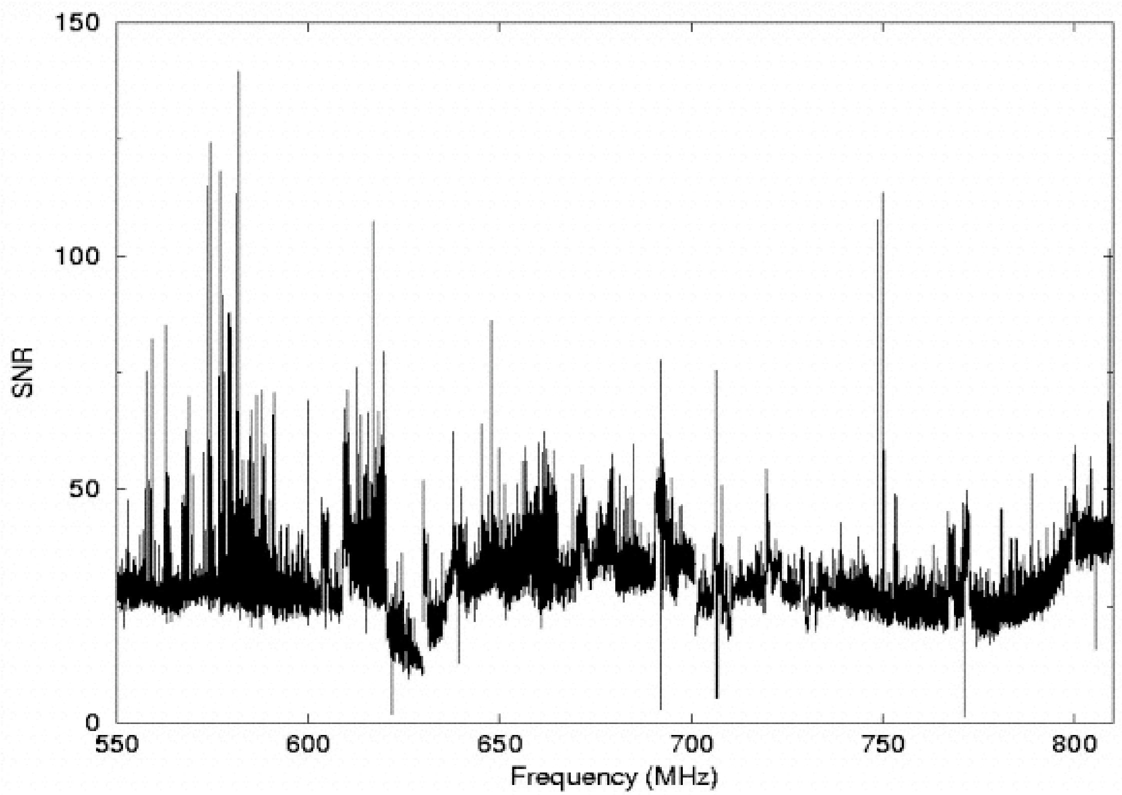
Axions can be detected by stimulating their conversion to photons in a strong magnetic field. An electromagnetic cavity permeated by a strong static magnetic field can detect **galactic halo axions**, provided ➔

cavity size << $_{DB}$

These halo axions have velocities of order 10^{-3}c and a spread of ~10^{-6} above the axion mass. When the frequency of a cavity mode is = m_a, galactic halo axions convert resonantly into quanta of excitation (*photons*) of that cavity mode :

m_a=4.14 _eV ↔ _ = 1 GHz

S/N for the complete six-bin combined data set. The minimum target S/N ratio for these data is 10.

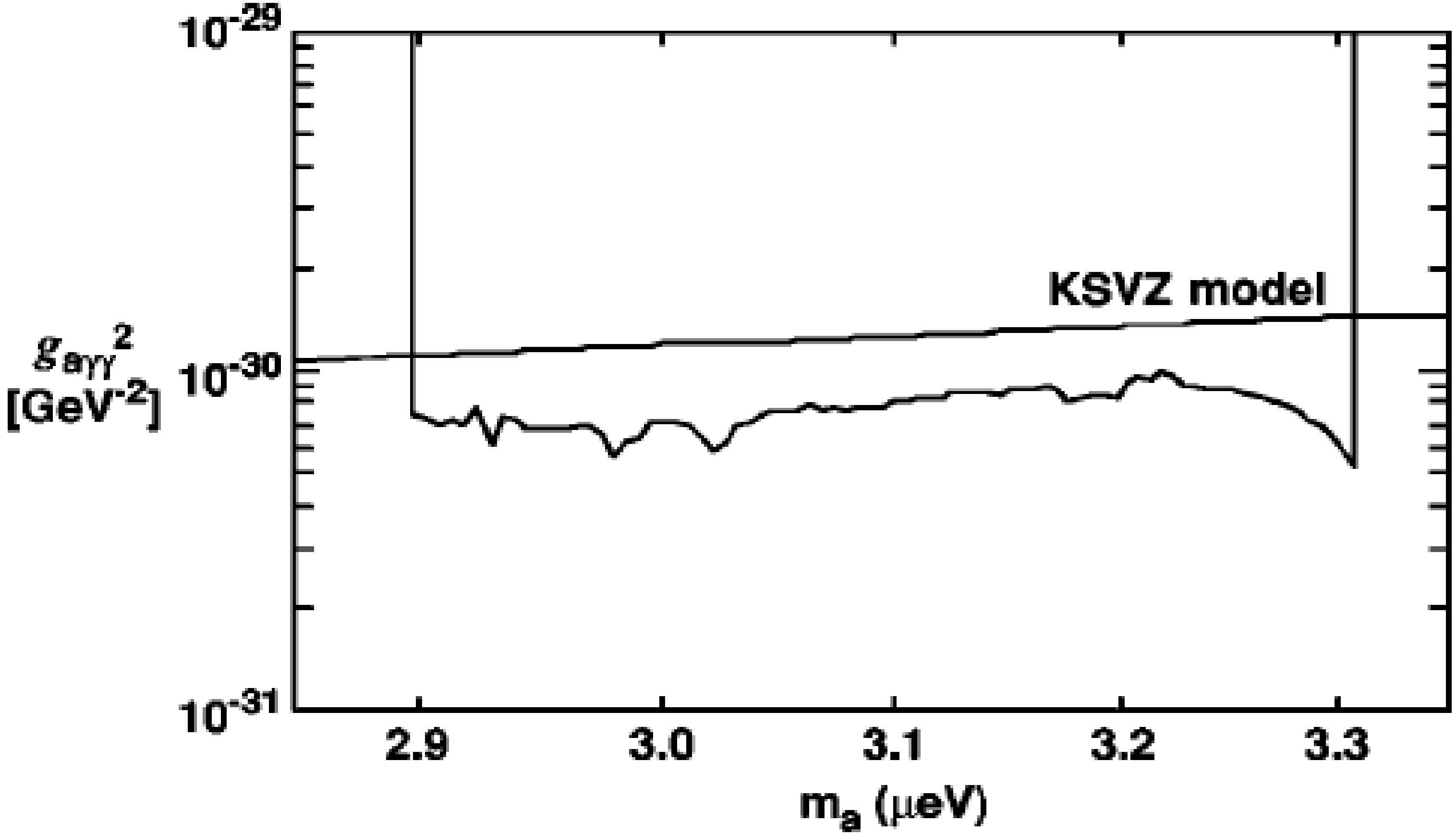


ApJ. 571(2002) L27, S.J. Asztalos et al.

Since 1995 using a single resonant cavity to search for axions that may constitute the local dark matter halo over the frequency interval 550 MHz *f* 810 MHz. The lack of a persistent signal allows to exclude the axion from contributing more than 0.45 GeV cm^{-3} to the halo dark matter mass density over the mass range of 2.3 _ 10 eV^{-6} m_a 3.4 _ 10^{-6} eV.

…. 34 candidates survived ….

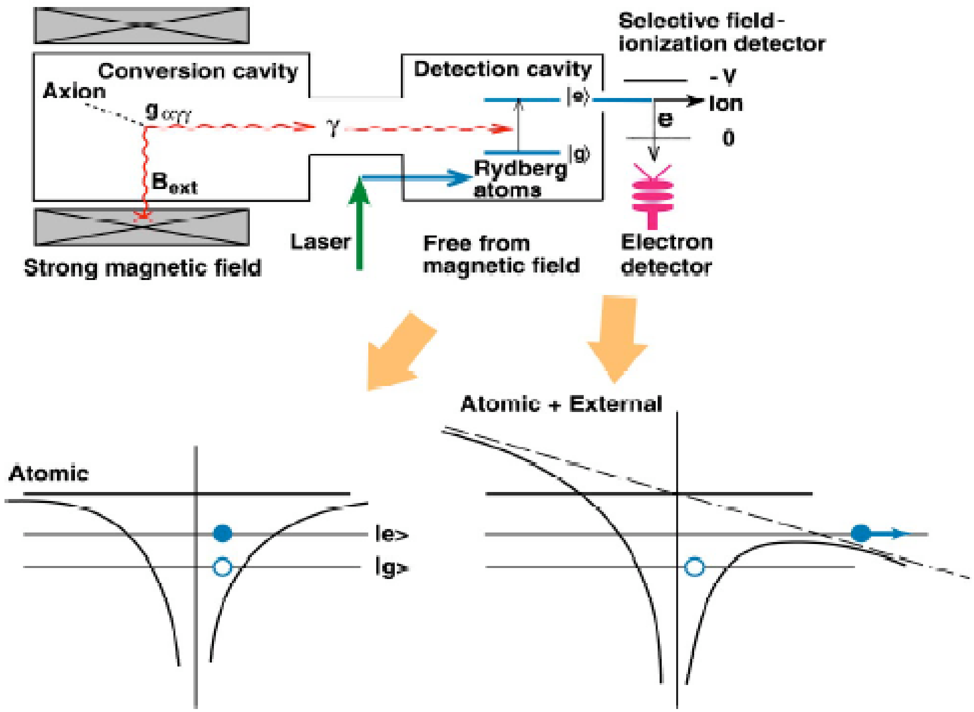
All candidates have been identified with strong external radio peaks.



Axion-photon couplings excluded at 90% confidence level, assuming the axion spectral line is significantly narrower than 125 Hz.

From Asztalos *et al.*, 2001.

THE RYDBERG-ATOM SINGLE-QUANTUM DETECTOR



Experimental principle of the Kyoto axion detector with the Rydberg-atom cavity detector (Tada *et al.*, 2001).

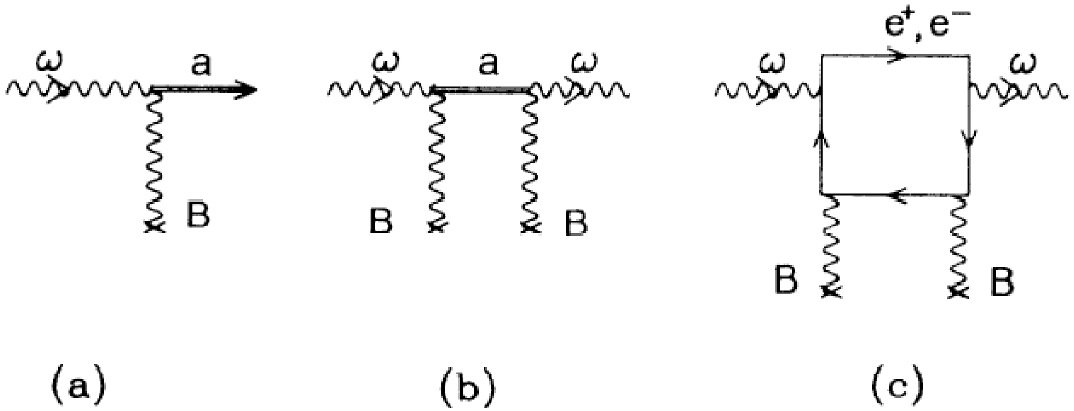
10 mK !

hep-ph/0101200 18 Jan **2001**

The Rydberg-Atom-Cavity Axion Search, *K. Yamamoto, et al.*

Experimentally, we have searched for the dark matter axions in the mass range **2350MHz - 2550MHz** around 10 _eV with the prototype detector CARRACK I. The experimental parameters are taken as Tc = 12mK - 15mK,… The theoretical calculations indicate that the sensitivity with these parameter values exceeds the limit of KSVZ axion. The actual limit will be placed soon after making some more detailed calculations and checks.

Y. Semertzidis et al., PRL 64 (1990) 2998



Possible coherent interactions of a photon in a static magnetic field. (a) Primakoff production; (b) virtual production; (c) QED vacuum-polarization loop.

Optical production & detection of dark matter candidates

F.Brandi etal., *N.I.M.**A**461(**2001**) 329*

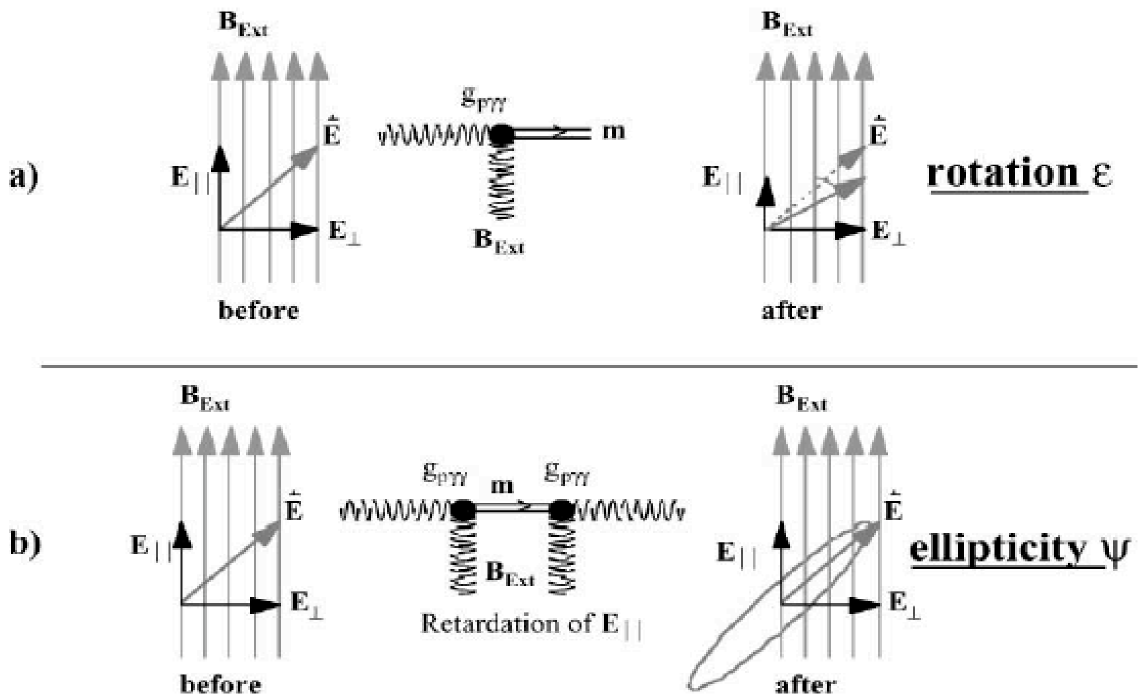
Previous works:

K.Van Bibber etal., PRL59(1987)759

Y.Semertzidis etal., PRL64(1990)2988

G.Ruoso etal., Z.Phys. C56(1992)505

R.Cameron etal., PRD47(1993)3707



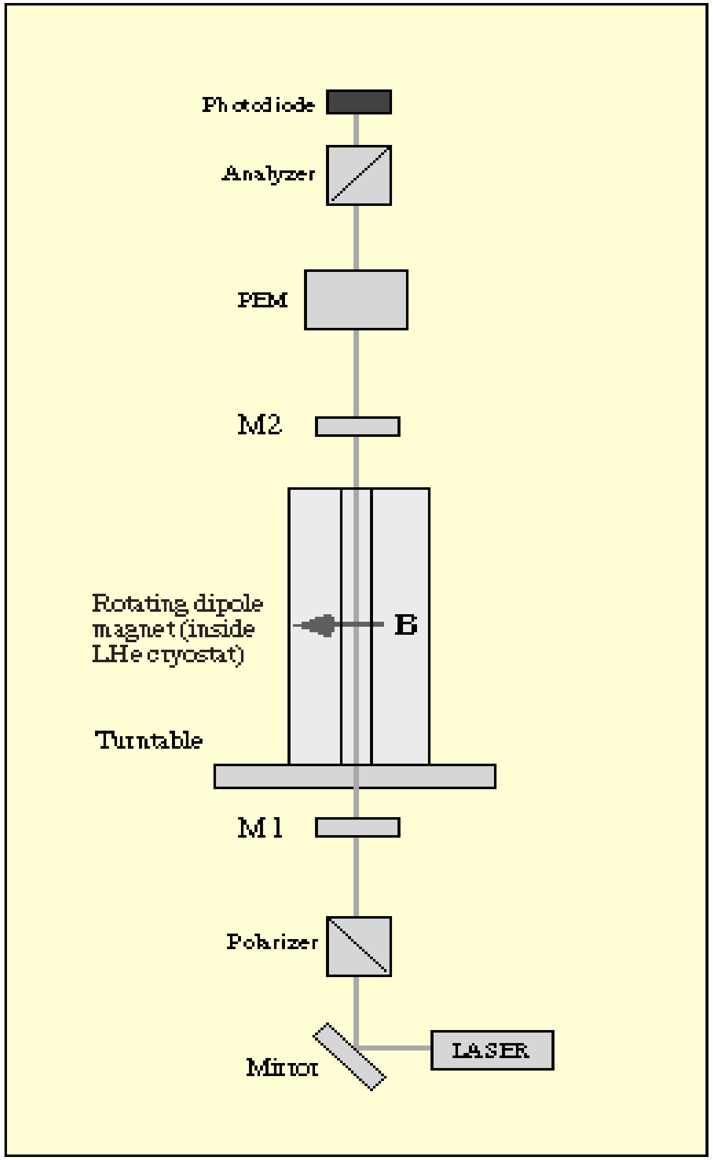
a) ***Dichroism*** induced by the production of a massive particle coupling to two photons ➔ ***rotation of the polarization plane.***

b) ***Ellipticity*** induced by the ***retardation*** between the two components of the electric field of the laser beam by the virtual production of a massive particle coupling to two photons.

B rotates normal to the light propagation direction

➔ ***a time-modulation of the effect.***

PVLAS-experiment



M1 & M2

→ very high reflectivity dielectric mirrors

→ Fabry-Perot optical resonator

→ 1 msec

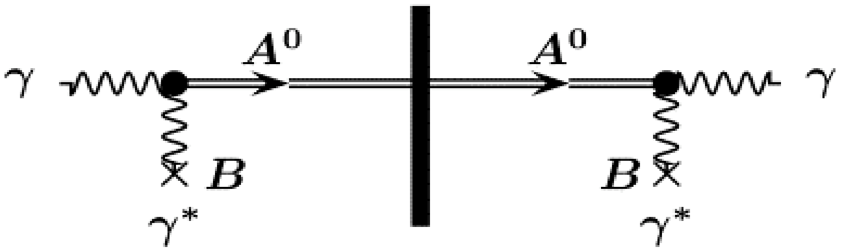
LASER

→ linearly polarized light

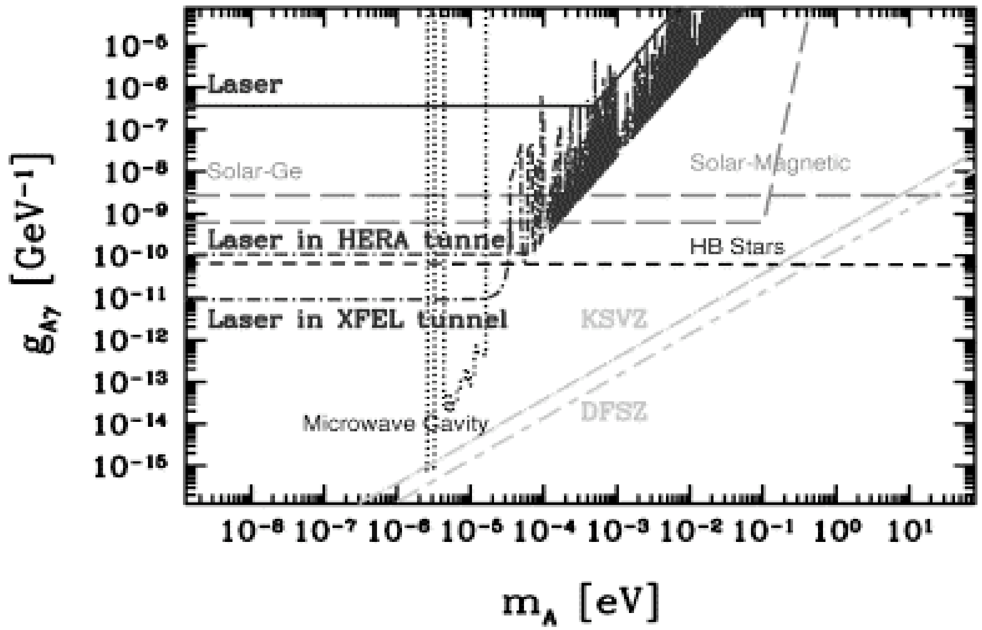
→ elliptical polarized

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

A. Ringwald, Phys. Lett. B569 (2003)51.



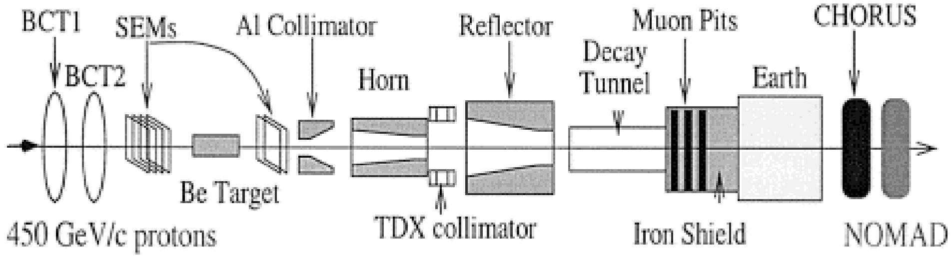
Schematic view of axion production through photon conversion in a magnetic field (left), subsequent travel through a wall, and final detection through photon regeneration (right).

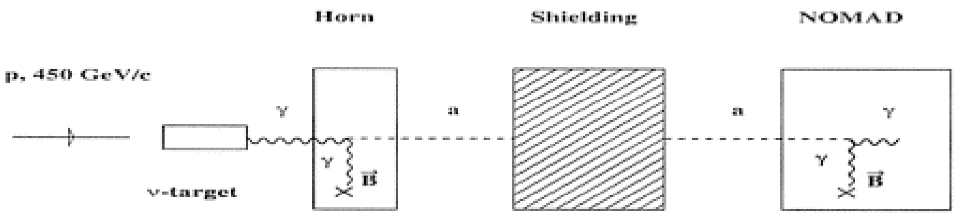


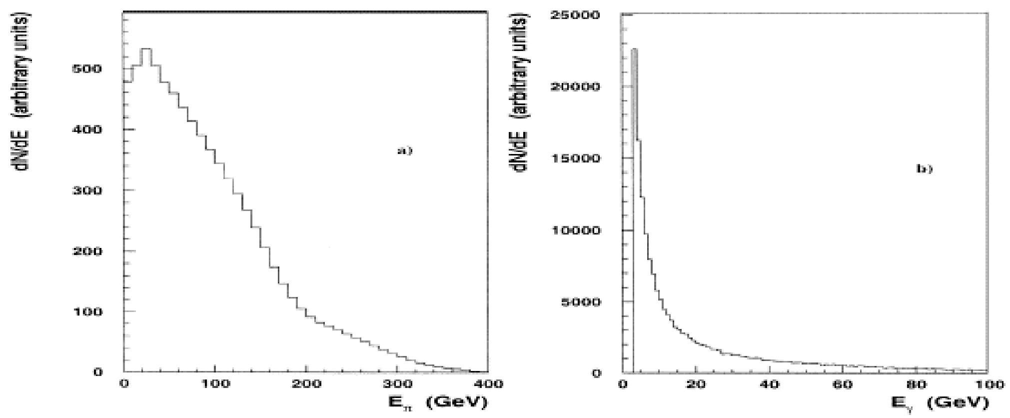
Exclusion region in mass m_A vs. axion–photon coupling g_A for various current experiments and for the ones proposed in this Letter (labelled as "Laser in HERA tunnel" and "Laser in XFEL tunnel"). The laser experiments aim at both, *axion production and detection* in the laboratory. The microwave cavity experiments aim at axion detection under the assumption that axions are the galactic dark matter, the telescope search looks for axions thermally produced in galaxy clusters, and the solar-magnetic and solar-germanium experiments search for axions from the sun. The constraint from helium burning (HB) stars arises from a consideration of the energy losses associated with axion production and the corresponding influence on stellar evolution .

Search for eV (pseudo)scalar penetrating particles in the SPS neutrino beam

NOMAD Collaboration *Phys. Lett.* ***B**479 (**2000**) 371*



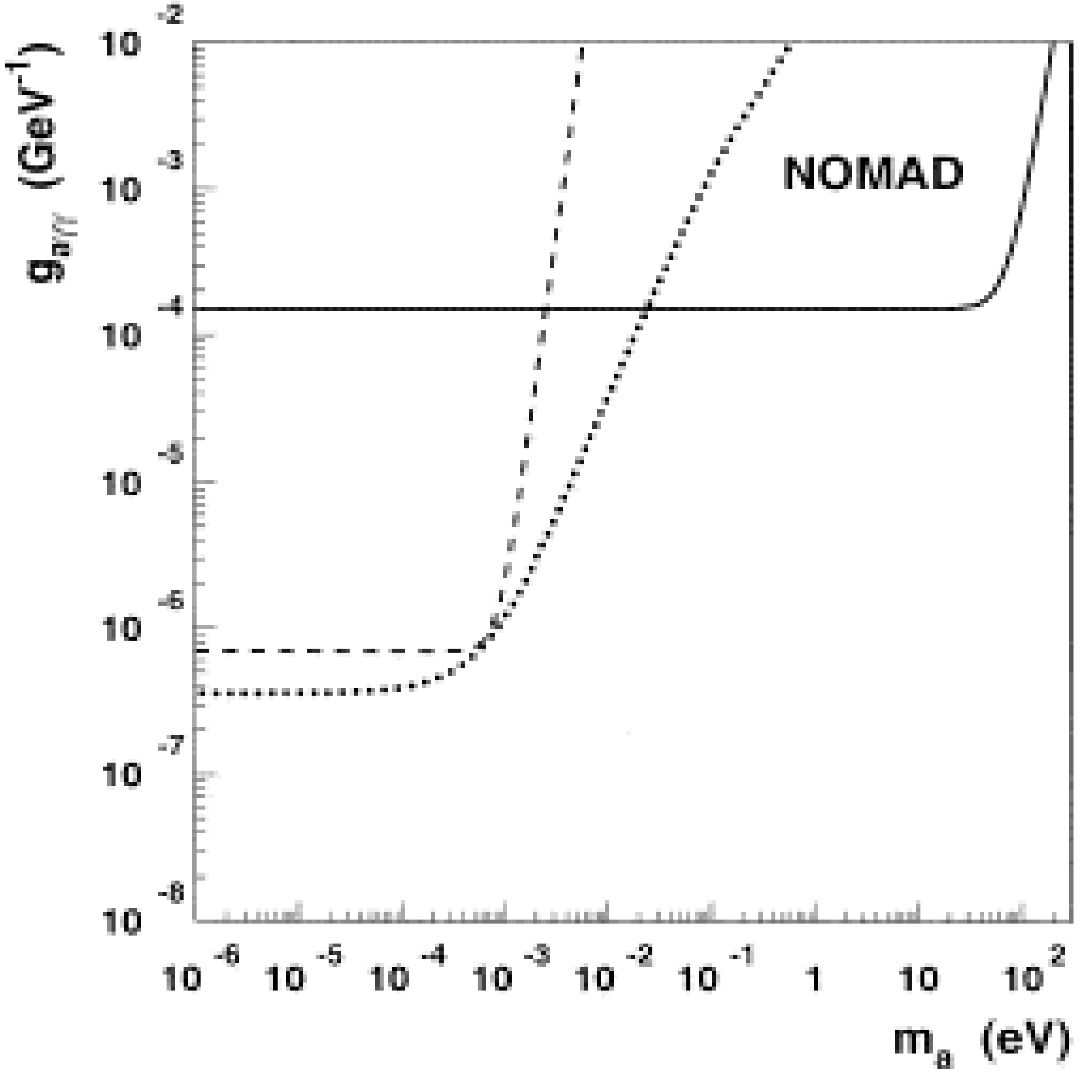




Schematic layout of the WANF beam line and an illustration of the principle of the WANF-NOMAD high energy photon-regeneration exp. @ **CERN** ➔

_ - REGENERATION

The energy spectrum of _'s produced in 450 GeV proton collisions with the neutrino target in a cone of ~2 mrad. b) Energy spectrum of the photons crossing the horn magnetic field and momenta pointing towards the NOMAD fiducial volume.



Upper limit on the coupling $\boldsymbol{g_a}$_ as a function of the (pseudo)scalar mass $\boldsymbol{m_a}$ derived from the present analysis and from the direct searches of light (pseudo)scalars performed by using the polarization rotation of a laser beam in a magnetic field (dotted line) and using the laser photon regeneration method (dashed line).

Axion searches in particle decays

The most sensitive channel: $K^+ \rightarrow \pi^+$ + nothing visible

Expectation for axions with $f_a \approx 247$ GeV: BR ($K^+ \rightarrow \pi^+ + a$) $\approx 10^{-5}$

<u>BNL-787 experiment</u>: search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Study K^+ decay at rest in a magnetic detector with full acceptance to identify $K^+ \rightarrow \pi^+ \pi^0$.

Separate $K^+ \rightarrow \pi^+$ + nothing visible from $K^+ \rightarrow \mu^+ \nu_\mu$ by range and dE/dx measurement.

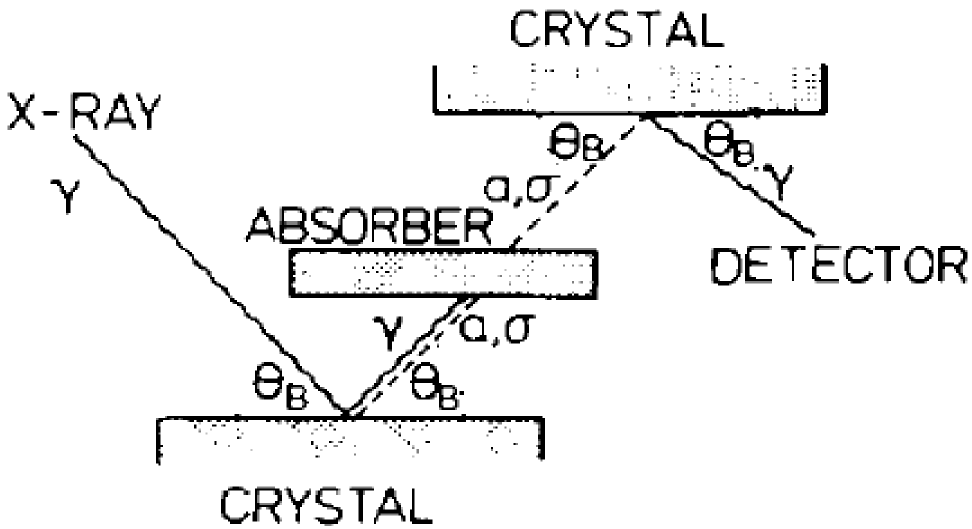
Two events, consistent with expectations for $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$:

$$\mathrm{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.6^{+1.8}_{-0.8} \times 10^{-10}$$

➡ **NO EVIDENCE FOR AXIONS**

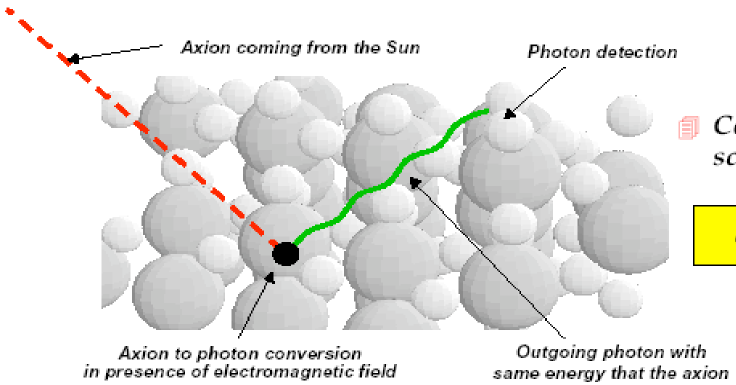
Axion-BRAGG scattering

Buchmueller , Hoogveen, Phys. Lett. ***B****237 (***1990***) 278*



➔➔ **CREATION + DETECTION**

- *The Primakoff conversion in a periodic lattice is a coherent process. Analogous to Bragg scattering of X-rays.*



- *Condition for Bragg scattering:*

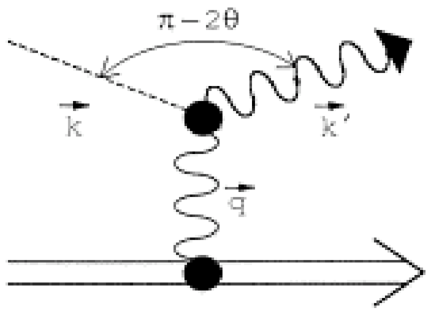
$$q_{axion} \sim d^{-1}_{lattice}$$

➔***Experimental setup to search for light scalar particles in Bragg scattering***

*Paschos, Z. , Phys. Lett. B323 (**1994**) 367*

➔ **CREATION @ *Sun***

➔ **Axion-to-photon conversion**
in the nuclear Coulomb field by the Primakoff effect.



The peak of the reflected/converted X-rays is also very narrow and has an angular width

$$\Delta = \frac{1}{\pi}\frac{\lambda}{L}\frac{1}{\sin 2\Theta_{\mathrm{Bragg}}}$$

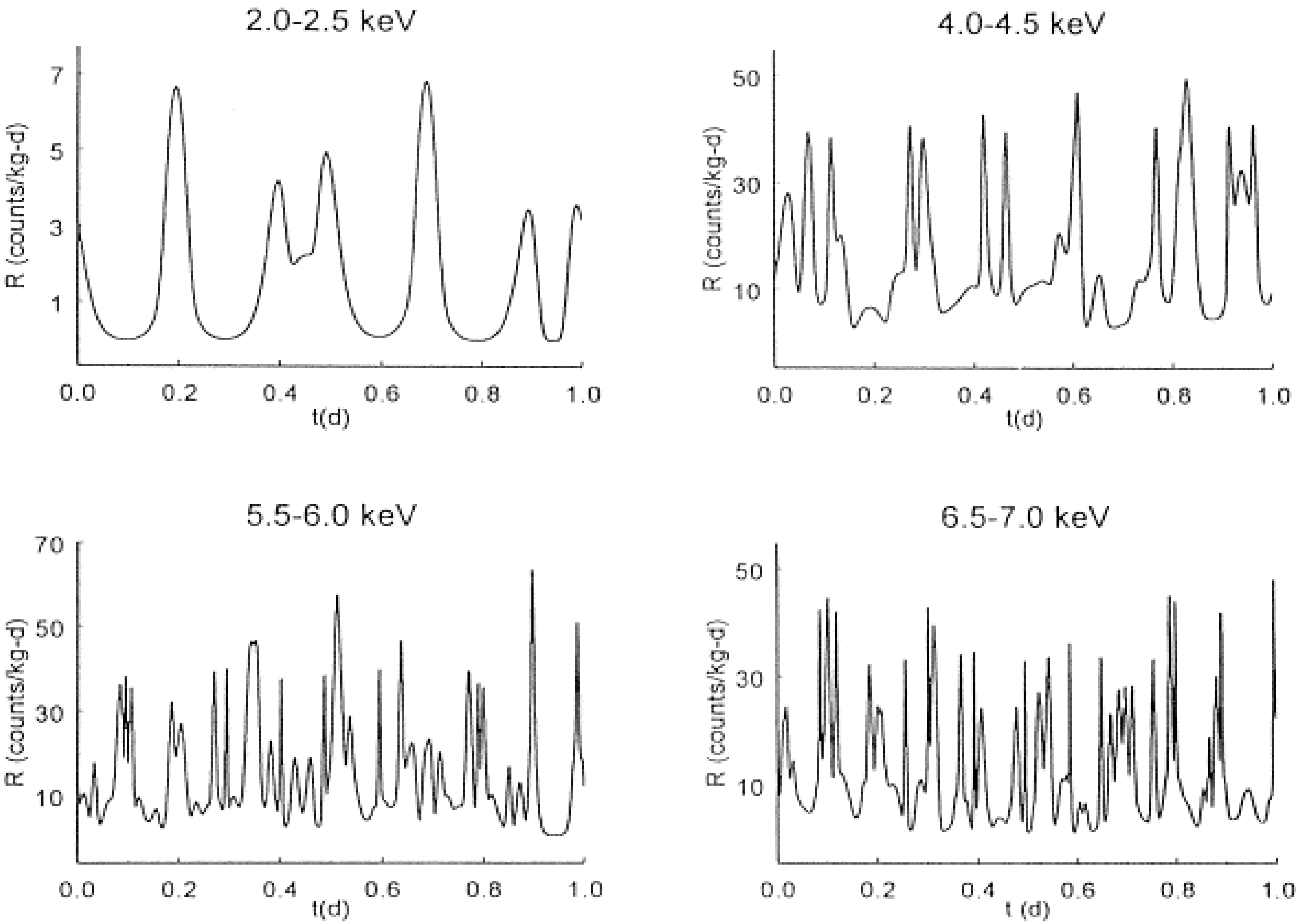
$$2d \sin \Theta_{\mathrm{Bragg}}\left(1 - \frac{1-n}{\sin^2\Theta_{\mathrm{Bragg}}}\right) = m\lambda$$

$$m = 1, 2, \dots ,$$

_ = photon wavelength

L = thickness of the crystal which contributes to the coherent scattering.

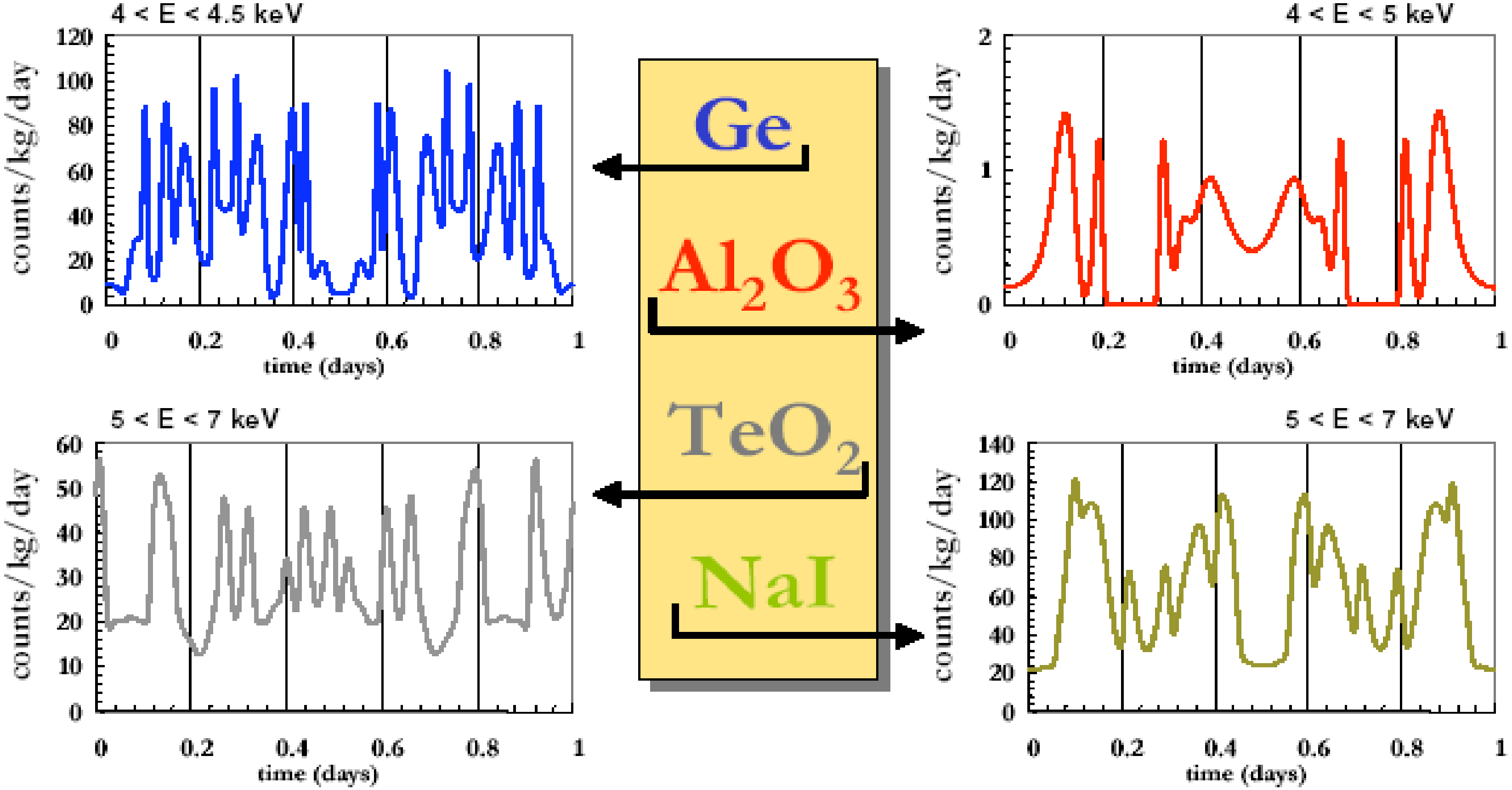
WIMP detectors ➔ axion detectors



Theoretical prediction of the count rate of photons converted from axions incident at a Bragg angle, for a detector located at Sierra Grande, Argentina (41°41' S, 65°22' W). The rate was calculated for $1/M=g_{a\_\_}=10^{-8}$ GeV^{-1}. The location that was chosen is where the pilot experiment is being performed.

R.J. Creswick et al., Phys. Lett. B427 (1998) 235.

Typical axion-photon conversion rates



Other axion searches :

1) **Axioelectric effect**

→ **"photoelectric effect" with axions**

_axion ~ E^{-4} → **suppressed (pseudoscalar)**

No result !

2) **M_ssbauer effect**

→ **axion replaces an M1 _-transition**

→ ***resonant beam-dump experiment***

No result ?

→ **solar 14.4 keV**

limits → **CAST ?**

3) **Spontaneous decay a _ __ :**

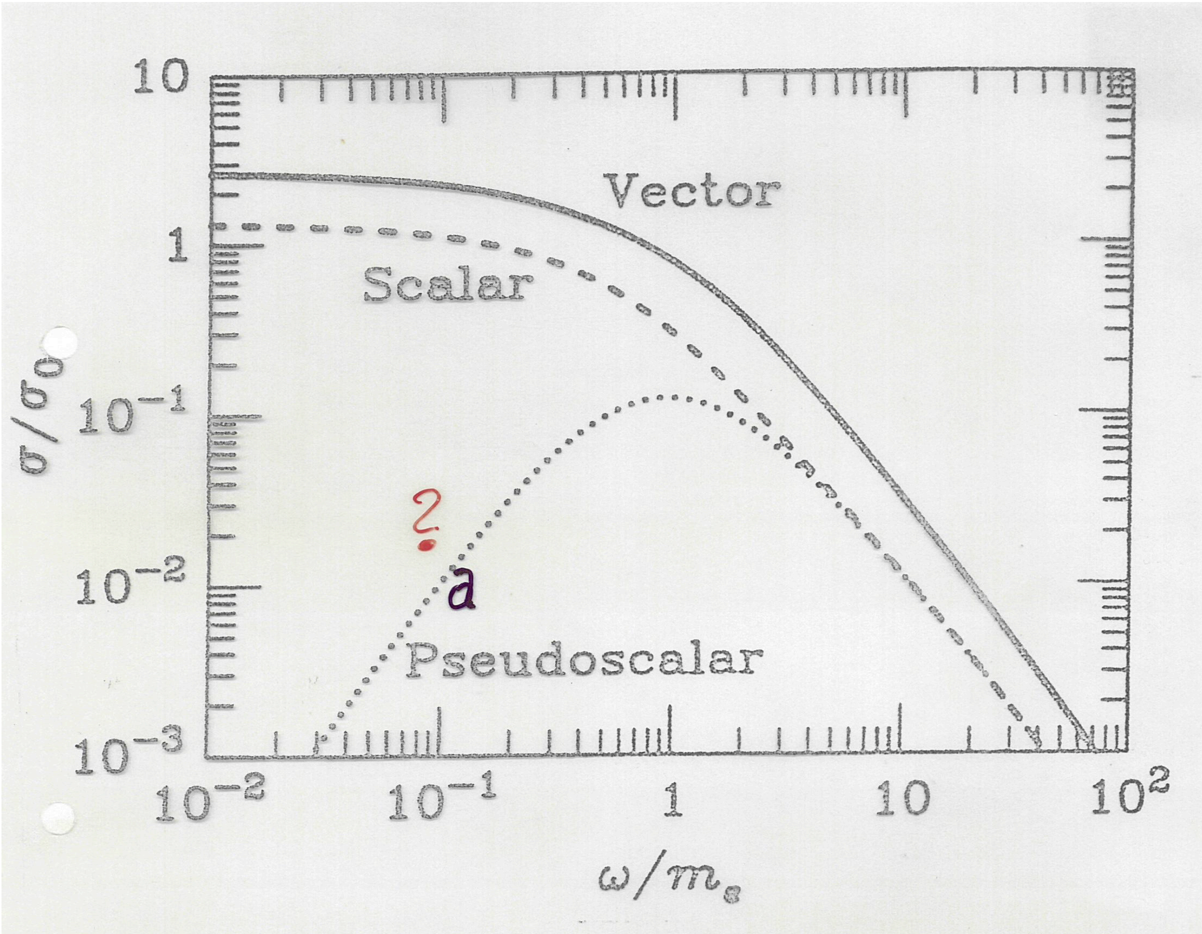
→ ***a few eV cosmic axions***

excluded

→ **~200 eV – 100 GeV → ??**

G. G. Raffelt

Stars as Laboratories for Fundamental Physics 1996



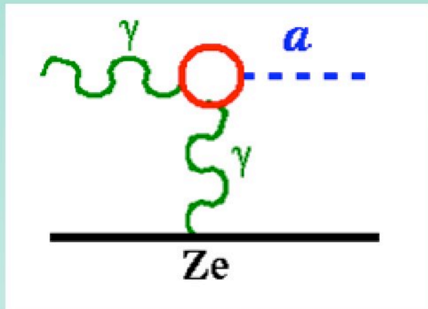
Total cross section for the Compton process with final-state verctor, scalar or pseudoscalar boson.

Axions from the Sun

Solar axion production

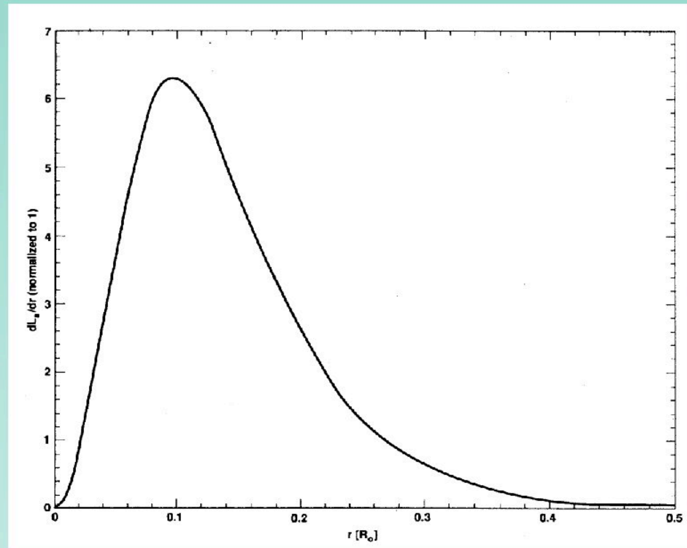
Conversion of thermal photons which couple to the Coulomb field of the plasma in the core of the sun by

Primakoff effect



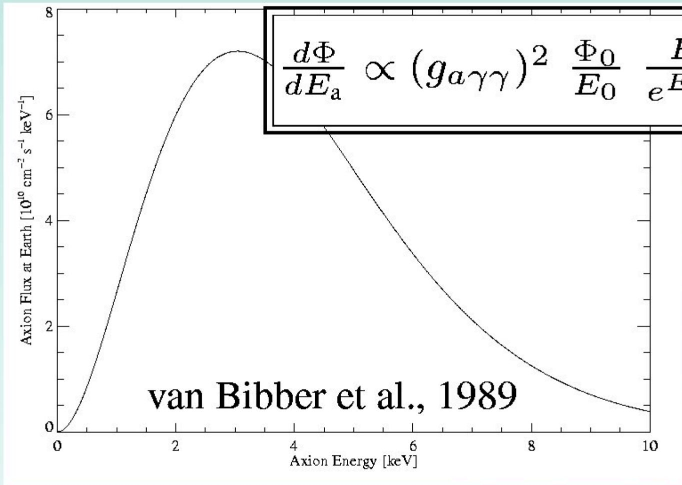
- Process is most efficient for $R < 0.2R_\odot$
- Mean axion energy $< E_\mathrm{a} >= 4.2\,\mathrm{keV}$
- Expected total axion Luminosity: $L_a = 7.3 \times 10^{23}\,\mathrm{W}$ $(L_\odot = 3.8 \times 10^{26}\,\mathrm{W})$

Radial Distribution $\mathrm{dL_a/dr}$

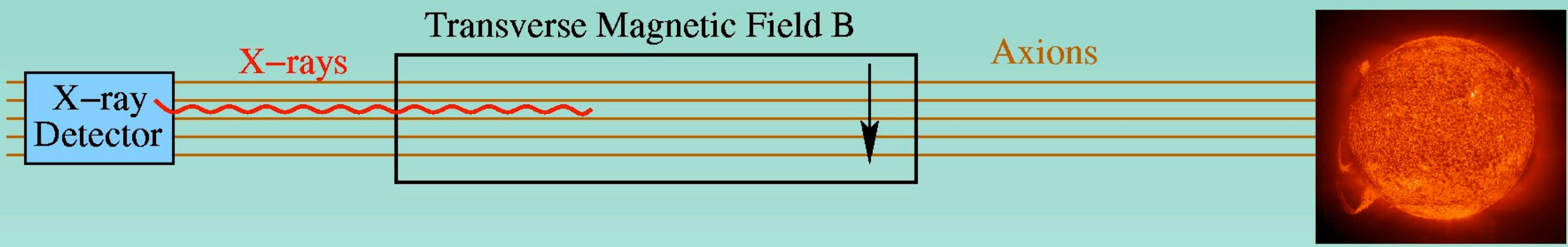


Predicted solar axion spectrum

$$\frac{d\Phi}{dE_\mathrm{a}} \propto (g_{a\gamma\gamma})^2 \; \frac{\Phi_0}{E_0} \; \frac{E_a/E_0}{e^{E/E_0} - 1}$$



How to Detect Axions I



- Use a strong magnetic field (decommissioned LHC dipole)
- Point magnet to the Sun, follow the Sun as long as possible
- Use X-ray detectors at the end of the magnet to measure X-rays

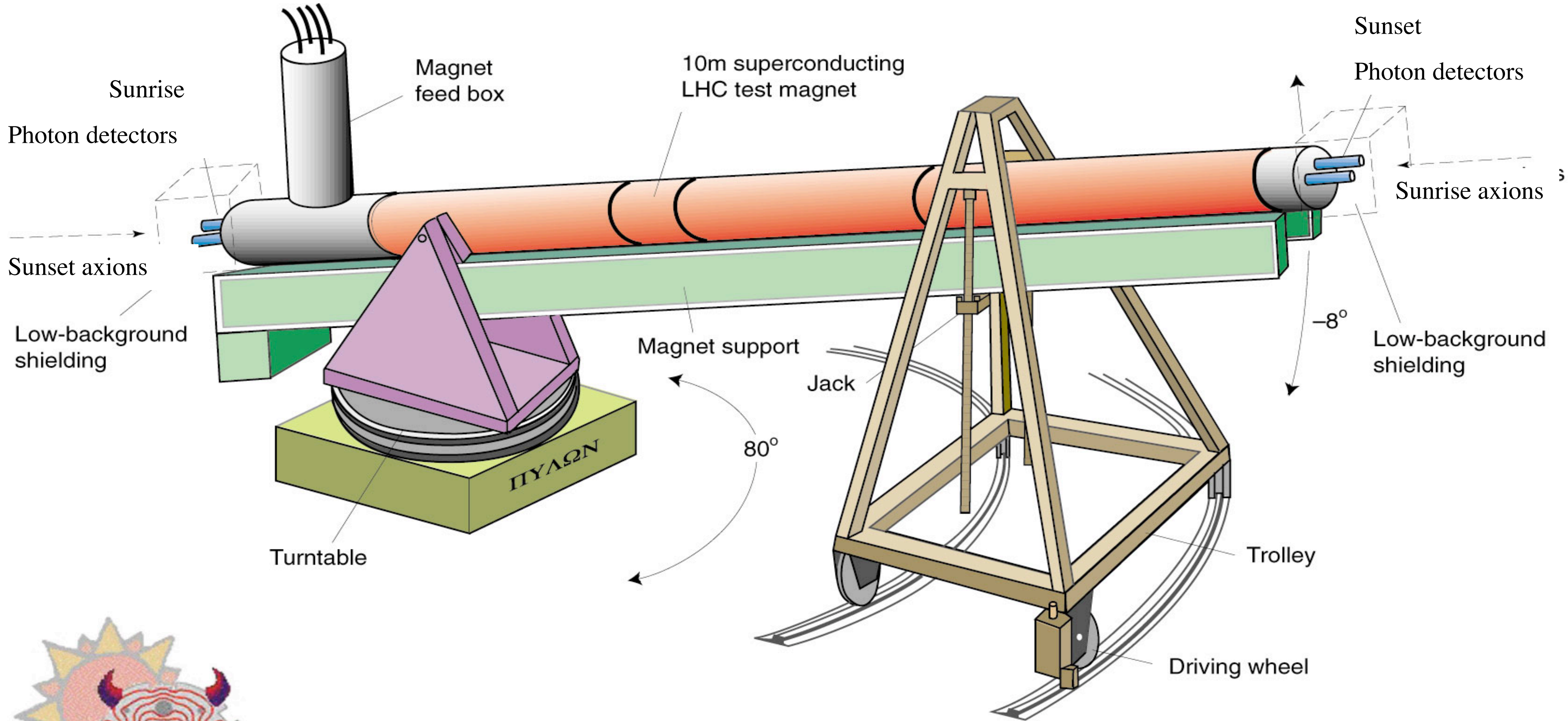
Theoretical axion $\Longrightarrow$ photon conversion probability (assuming full coherence):

$$P_{a\gamma} = 2.3 \times 10^{-17} \left(\frac{B \cdot L}{9.6\,\mathrm{T} \cdot 10\,\mathrm{m}}\right)^2 \left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^2$$

Coherence condition holds as long as momentum transfer to the photon is negligible $qL \ll 1$ ($m_a < 10^{-2}\,\mathrm{eV}/c^2$)

For higher axion masses coherence is lost !

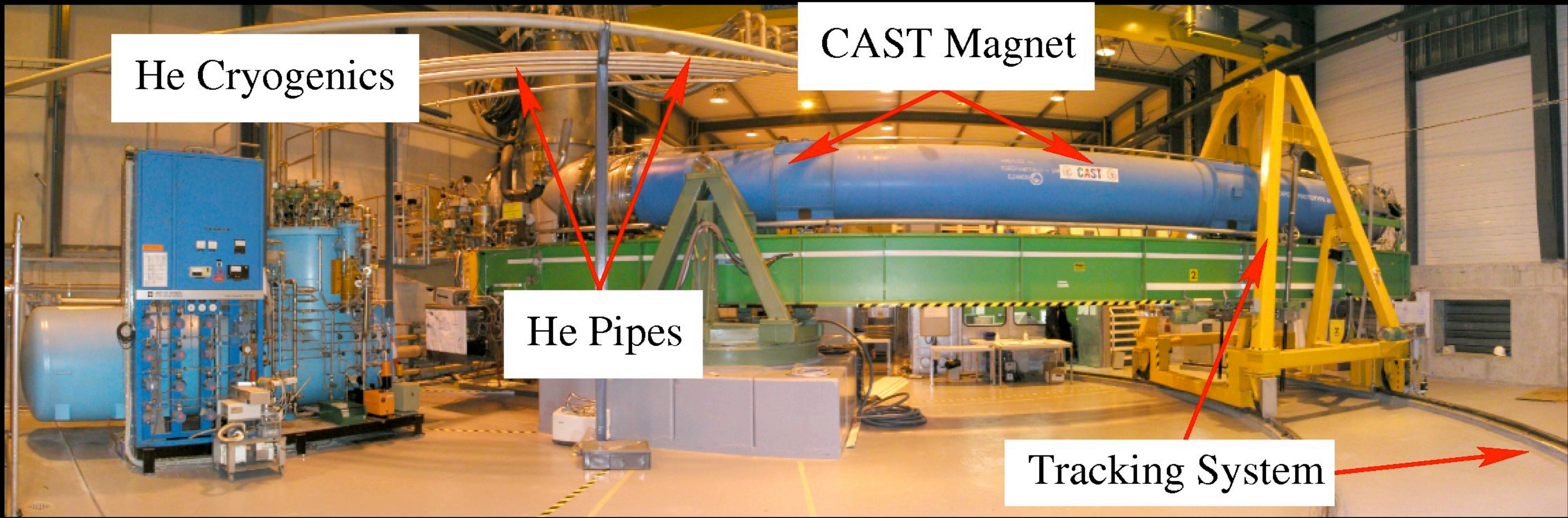
Cern Axion Solar Telescope



Cern Axion Solar Telescope

- Decomissioned LCH test magnet
- Rotating platform
- 3 X-ray detectors
- X-ray Focusing Device

The CAST Superconducting Magnet at *CERN*



Prototype LHC magnet:

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

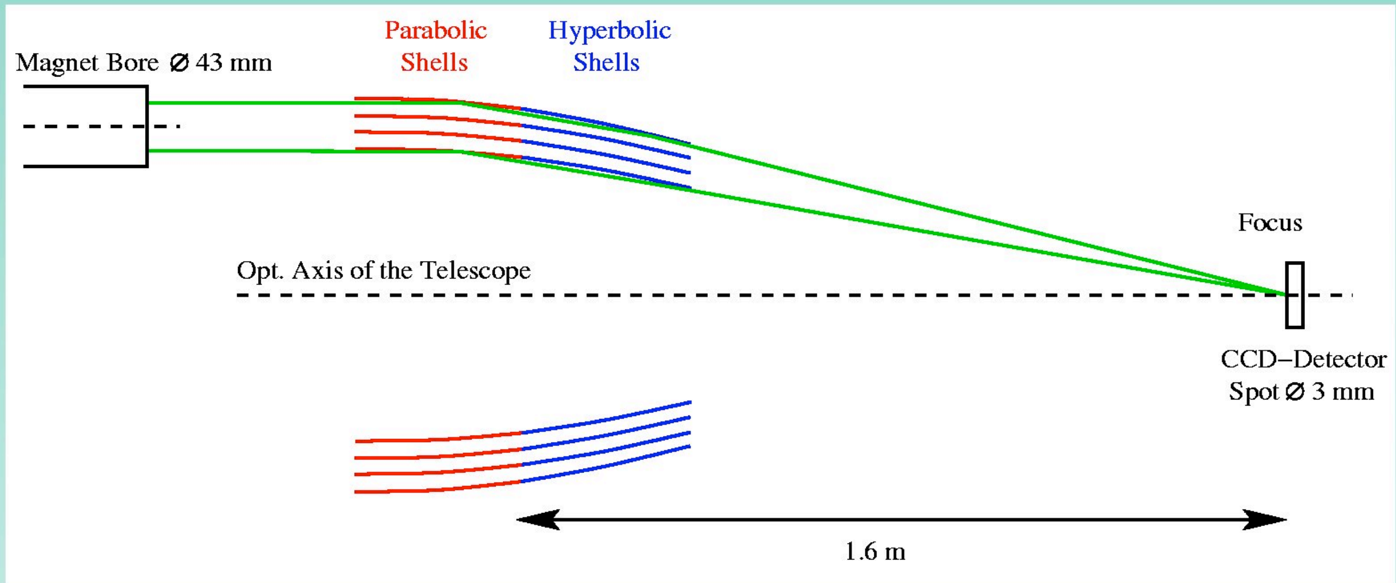
$$T = 1.8\,\mathrm{K} \quad m \approx 30\,\mathrm{t}$$

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 ($\approx$ 46 days/year)

The X-ray Telescope



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

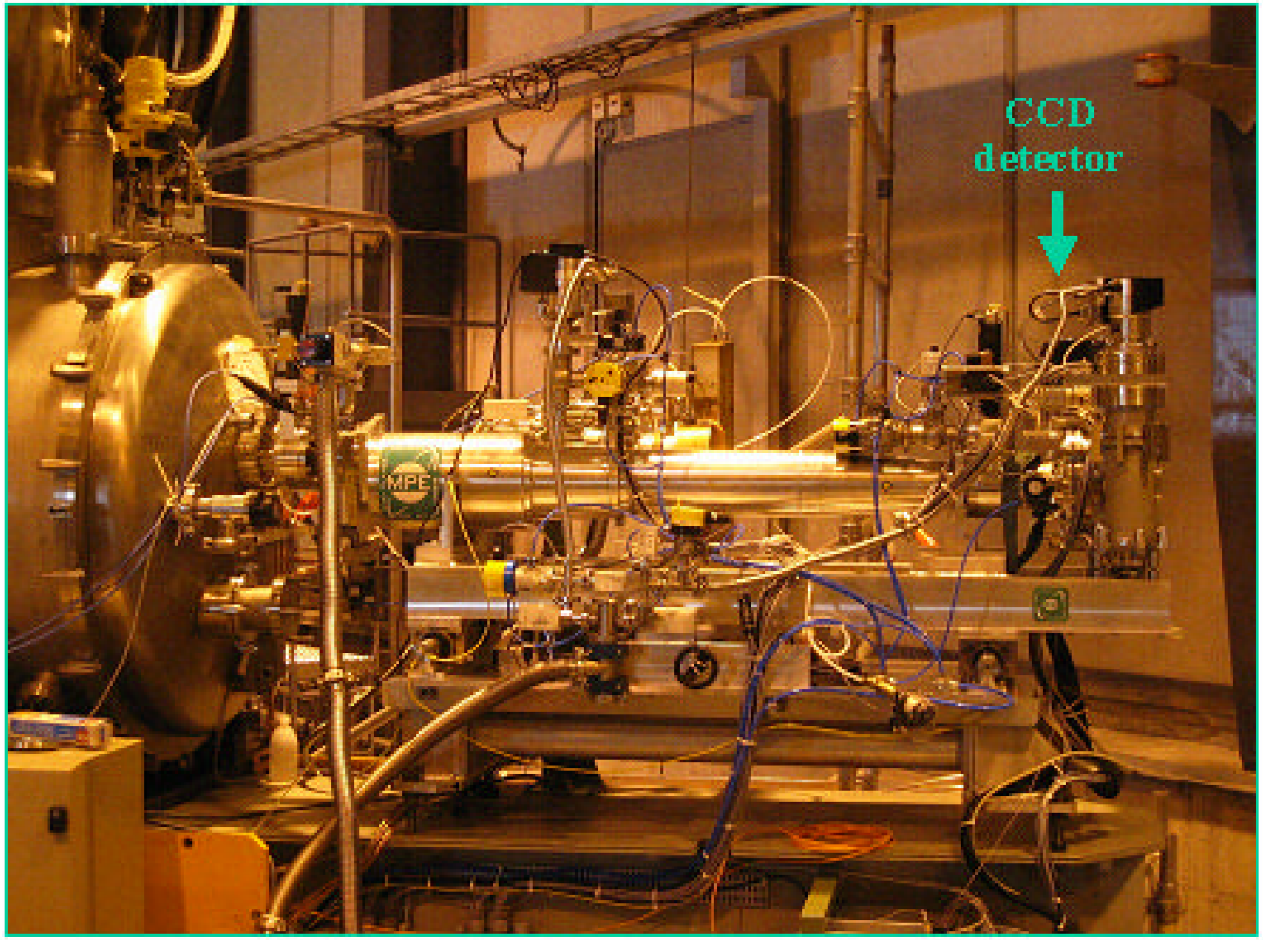
- 27 nested gold coated nickel shells, on-axis resolution $\approx$ 43 arcsec (HEW)
- Telescope aperture 16 cm, used for *CAST* 43 mm
- Only one sector of the full aperture is used for *CAST*

$\varnothing$43 mm (LHC Magnet aperture) $\Longrightarrow$ $\varnothing$3 mm (spot of the sun)
Signal to background improves by a factor $\approx$ 200

THE CAST X-ray telescope

A spare unit from the ABRIXAS Space Mission

- 27 nested shells
- Focal length 1.7 m
- Transmission 35%



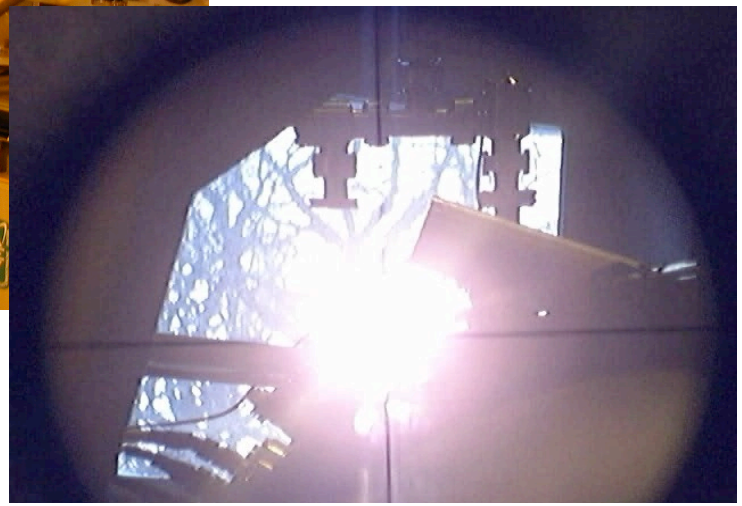
Magnet,platform,cryogenics

Looking at sunrise

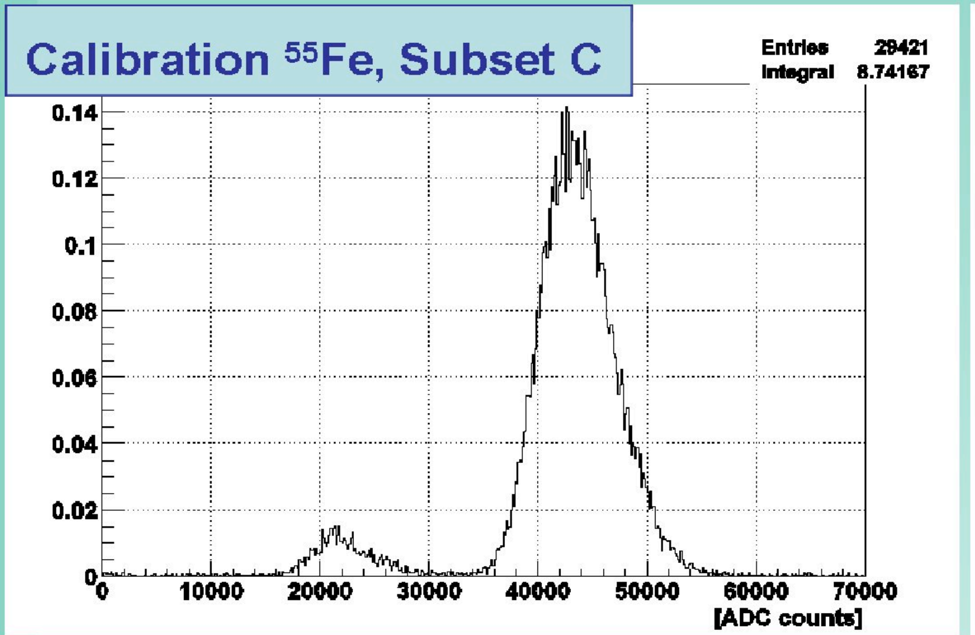
Tracking System:

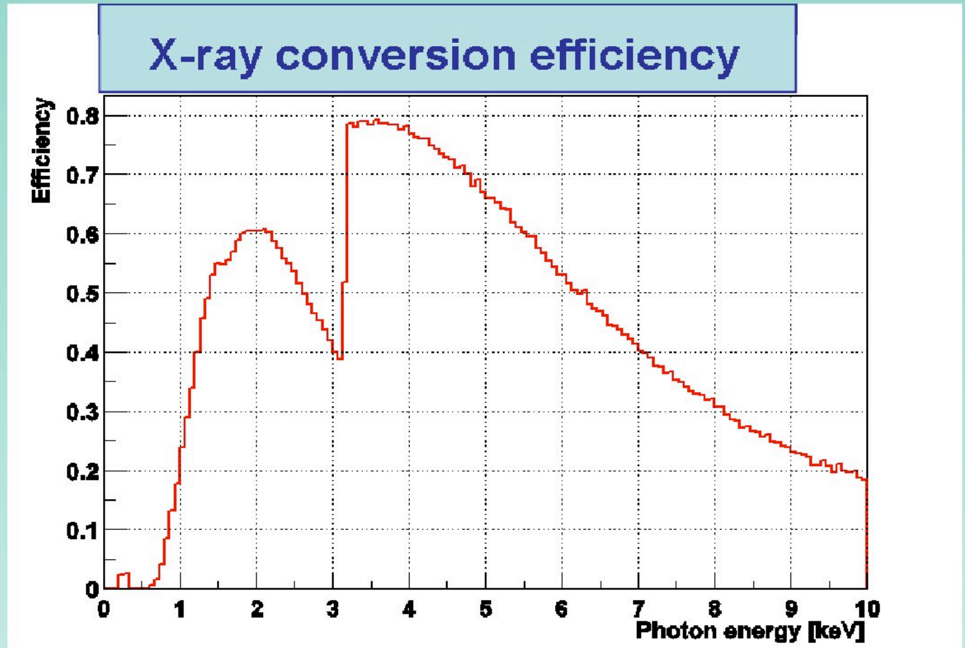
Calibrated and correlated with celestial coordinates

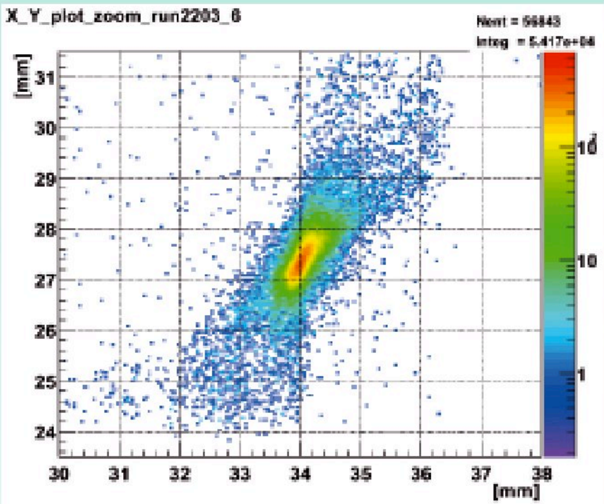
Twice a year (September&March) we can film the Sun through the window



Micromegas–Performance







Detector Dead time: 5 %

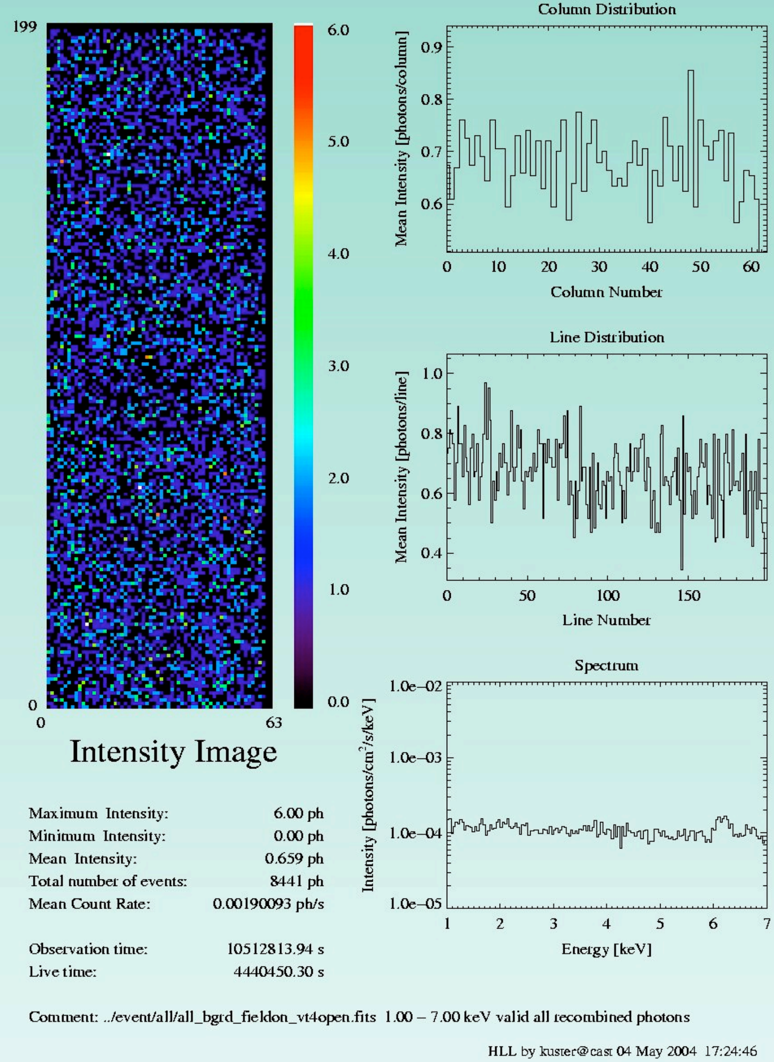
Software efficiency

77%@3 keV 87%@6 keV

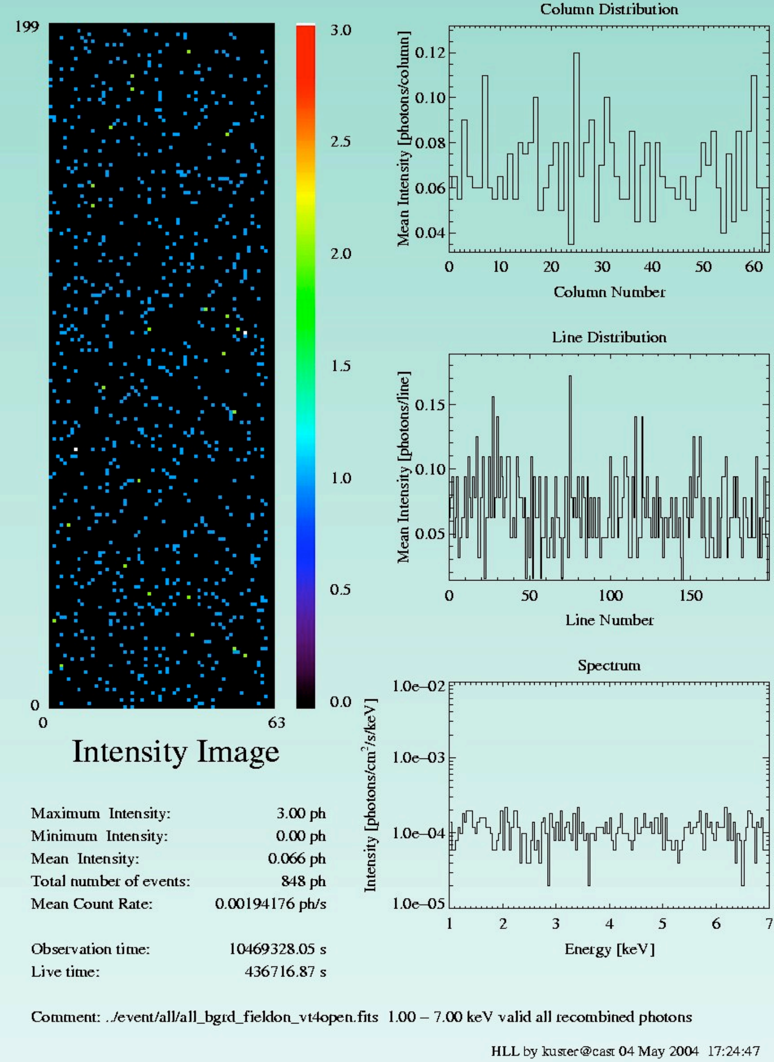
> 2003 detector is replaced by a new detector with better performance for 2004 !

CCD – Preliminary Results

CCD Background Data

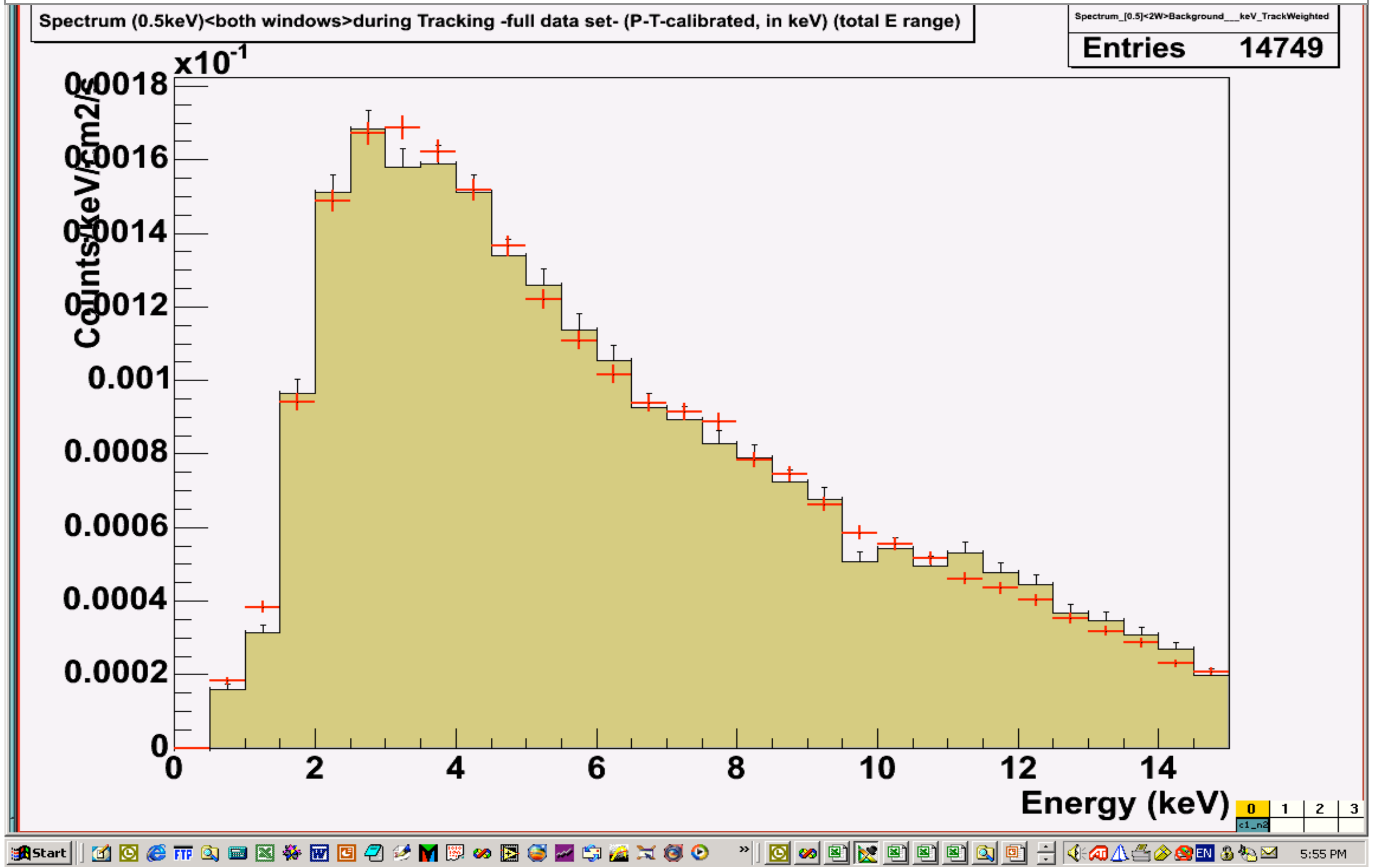


CCD Tracking Data



TPC data analysis

Sun tracking (red) & background spectra



How to Detect Axions II

Conversion probability

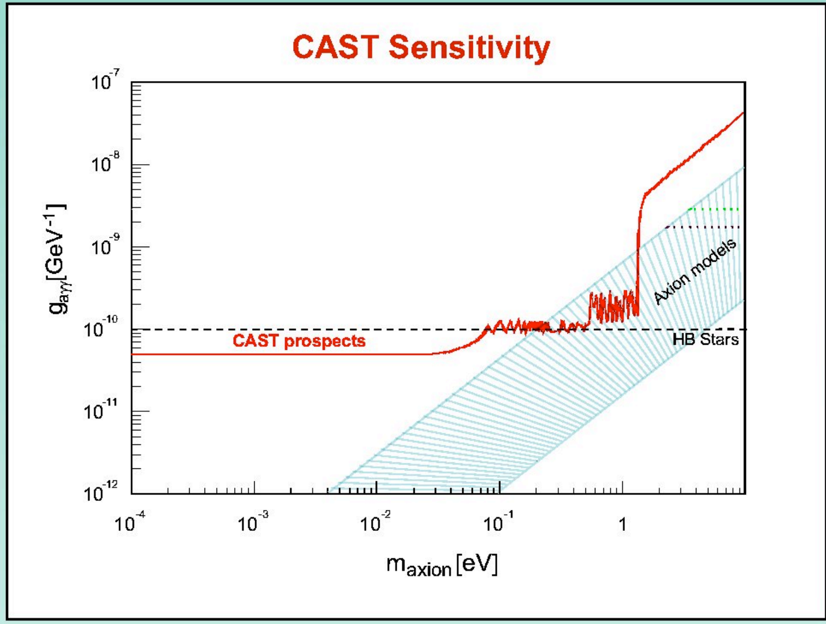
$$P_{a\gamma} = P_{a\gamma} \cdot |M|^2$$

with $M = \int_0^L \Psi_\gamma^*(x)\Psi_a(x)\,dx$

$$|M|^2 = \frac{2(1-\cos(qL))}{(qL)^2} \quad |\vec{q}| = \frac{m_a^2 - m_\gamma^2}{2E}$$

Extension to higher masses

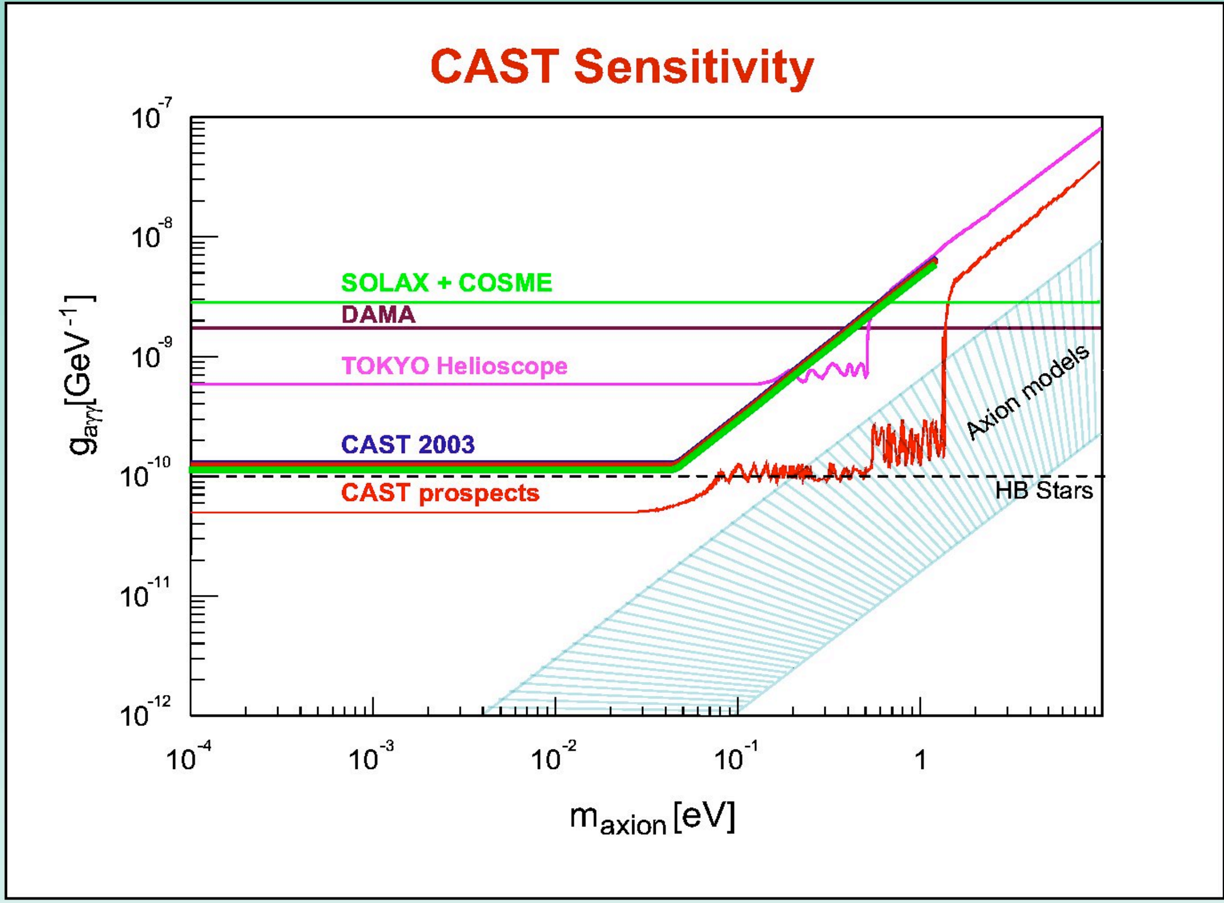
(Planned for 2005–2006)



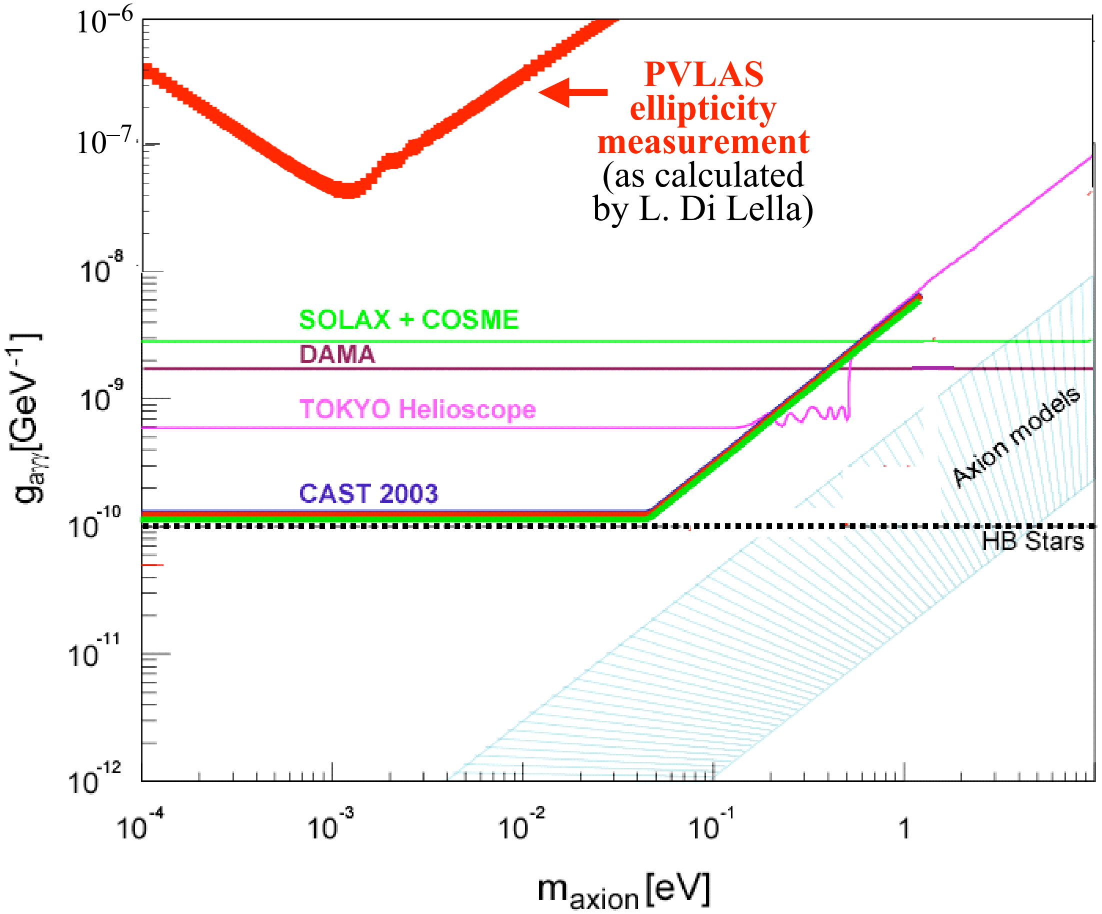
- Fill magnet bore with buffer gas, e.g. ^{3}He or ^{4}He $\Longrightarrow$ photon has an effective mass $m_\gamma \neq 0$ with $m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}}$ or $m_\gamma \approx \sqrt{20.34\frac{P(\text{atm})}{T}}$
  $\Longrightarrow$ coherence is given for a narrow mass range
- Change pressure to change effective mass

$\Longrightarrow$ Allows to scan masses $m_a > 10^{-2}\,\text{eV}/c^2$

CAST Preliminary Results



Limits derived for all detectors independently from data taken in 2003



Region of axion parameters consistent with PVLAS ellipticity excluded by CAST results

- **PVLAS ellipticity is not an axion effect ; or**
- **For $g_{a\gamma\gamma}$ > few x 10^{-8} GeV^{-1} solar axions are reabsorbed by the Sun**

CAST PLANS AND PROSPECTS

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

Fill the magnetic channels with Helium gas → $_{\gamma} > 0$

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

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

$$|\vec{\mathbf{q}}| = \frac{|\mathbf{m}_a^2 - \mathbf{m}_\gamma^2|}{2\mathbf{E}}$$

(qL <<1 for coherence)

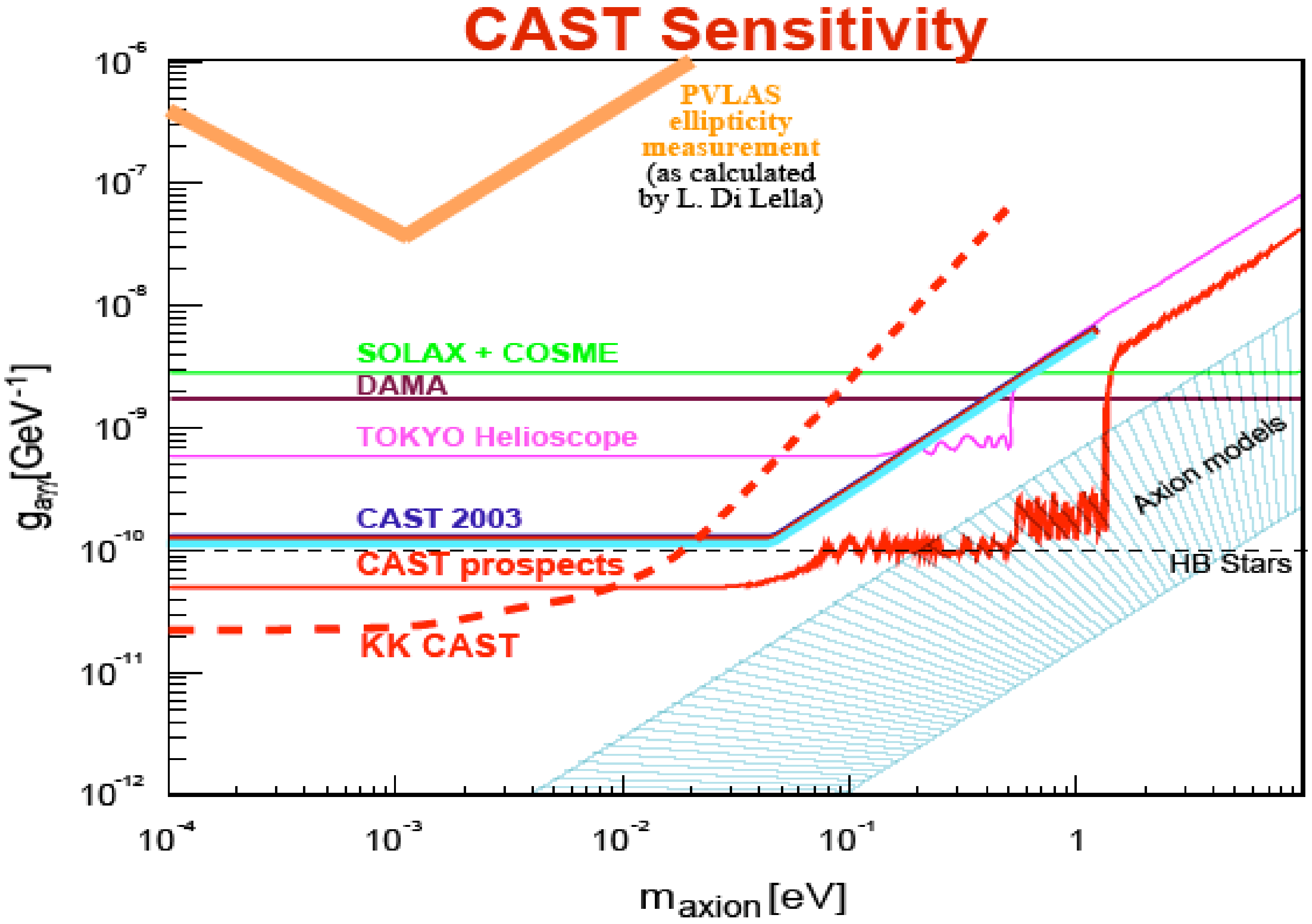
Data taking plans:

2004: take data with vacuum in the magnetic channels

2006 - 2007: take data with Helium at different density values

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

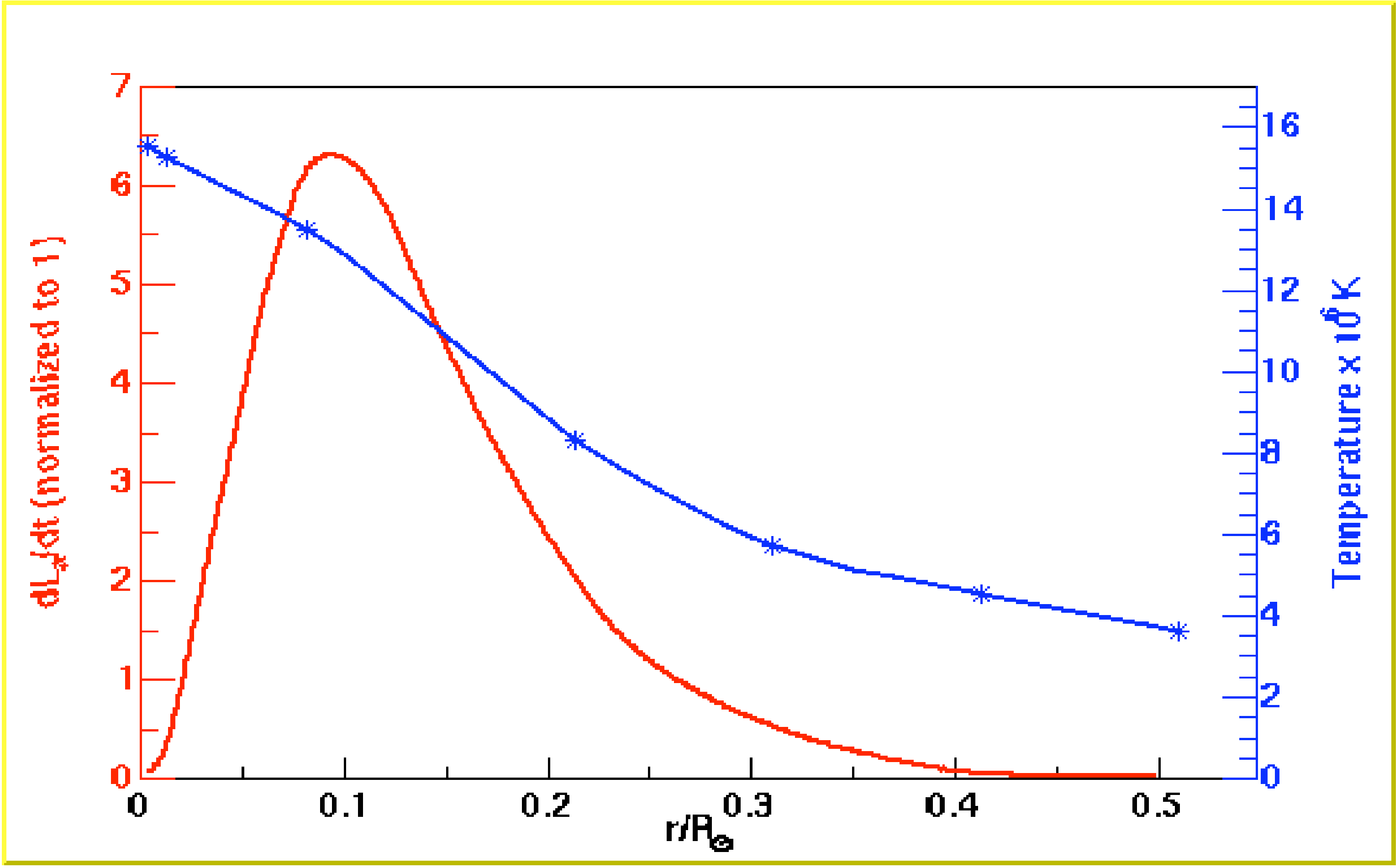
To reach higher m_γ values need He^3



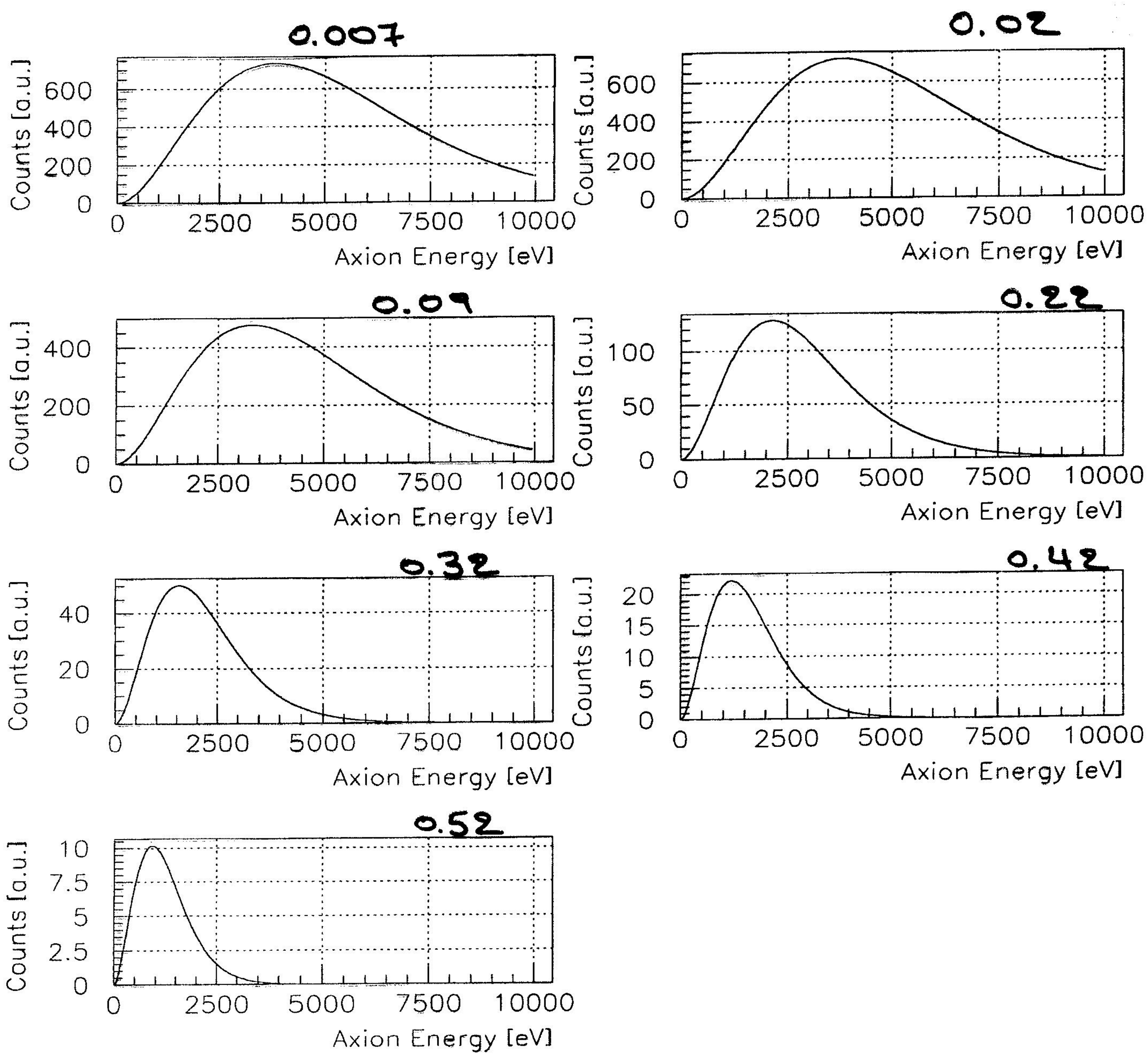
KK CAST … *Krcmar, Lakic PRD* (**2004**) [astro-ph/0312030]

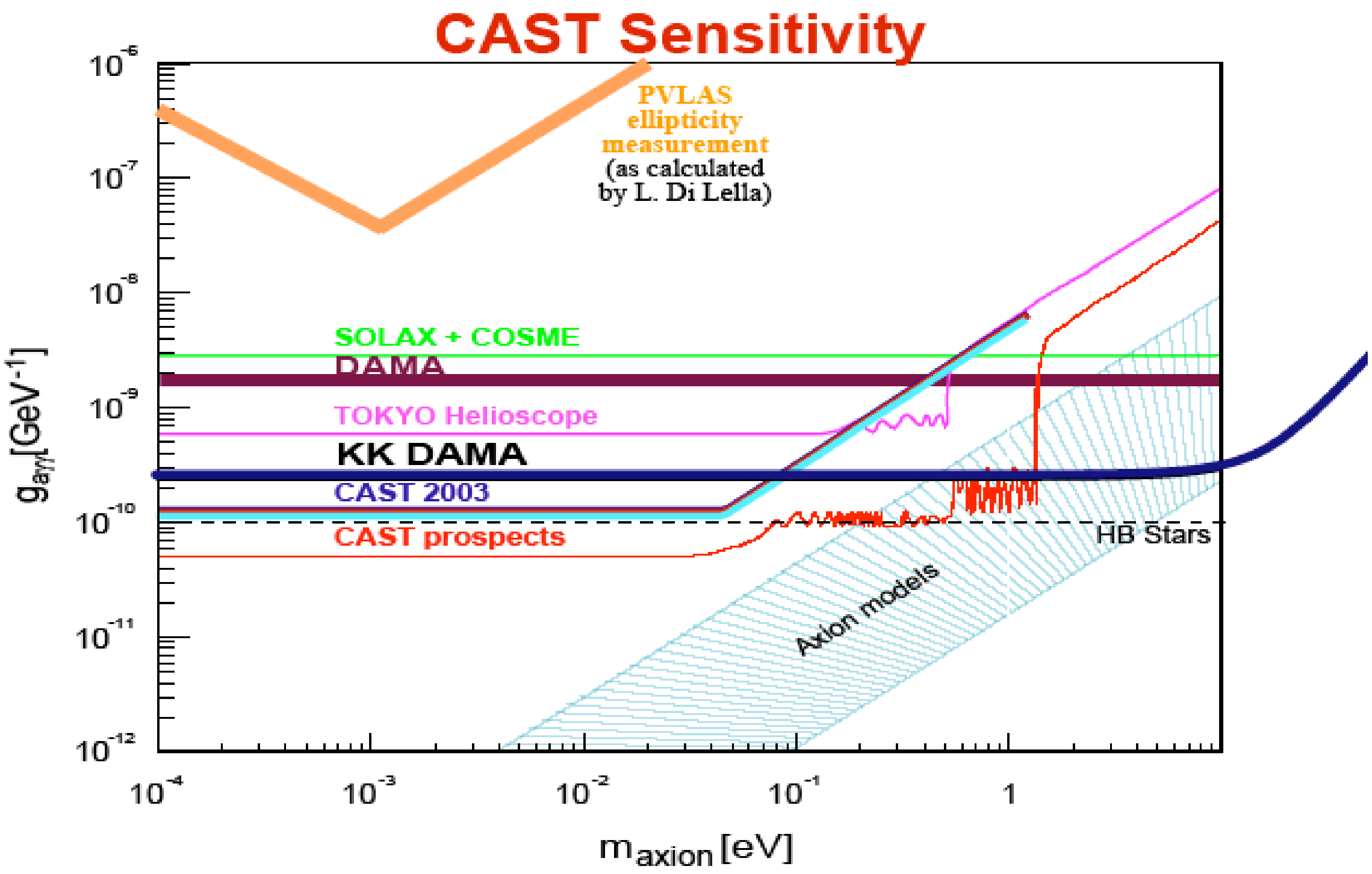
N=2, _=1, R=758 eV^{-1} (0.15 mm)

Improvements



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





KK DAMA , Krcmar, Lakic *to be published*

N=2, _=1, R=1eV^{-1}

Beyond CAST :

- *Axions* from Bremsstrahlung @ Sun core

  → $E_a \sim 0.8$ keV

- *Axions* from nuclear reactions @ Sun

  → d+p → ^{3}He + _ (5.5 MeV, ~$2 \cdot 10^{38}$/sec)

  → n+p → d + _ (2.2 MeV)

- (Solar) *axions* of Kaluza-Klein type

  → extra dimensions

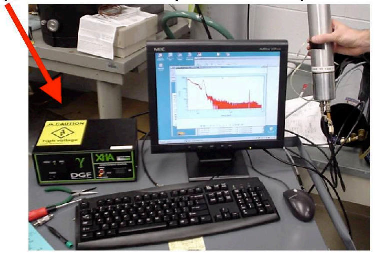
- Non-solar *axions* ??

  → G.C., Sco X-1, Crab pulsar, …

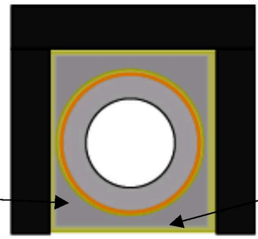
Minimalist detector and DAQ

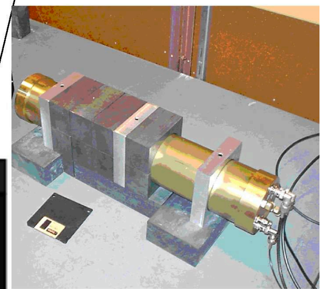
(space between μMs and CCD very limited, also must not add to platform burden. Must be sturdy to withstand frequent activity in its vicinity)

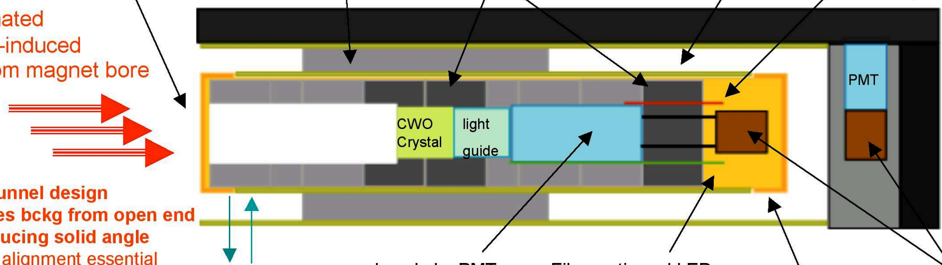
DAQ: XIA Polaris DSPEC digital spectrometer (shoebox-sized package offers event-by-event waveform capture for pulse-shape discrimination (PSD), muon veto input and all power supplies)



Front View







4π Plastic Muon Veto **(doubles as protection)**

thermal-neutron absorber (2mm)

Pb shielding

Thin brass endcap (Tedlar seals against Rn)

Ultra-low bckg Pb (<0.02 Bq ^{210}Pb/kg)

thermocouple (gain monitoring)

collimated axion-induced γ's from magnet bore

long tunnel design reduces bckg from open end by reducing solid angle
(good alignment essential to accept 100% of signal)

Rn displacement (N2 purge gas)

Low-bckg PMT

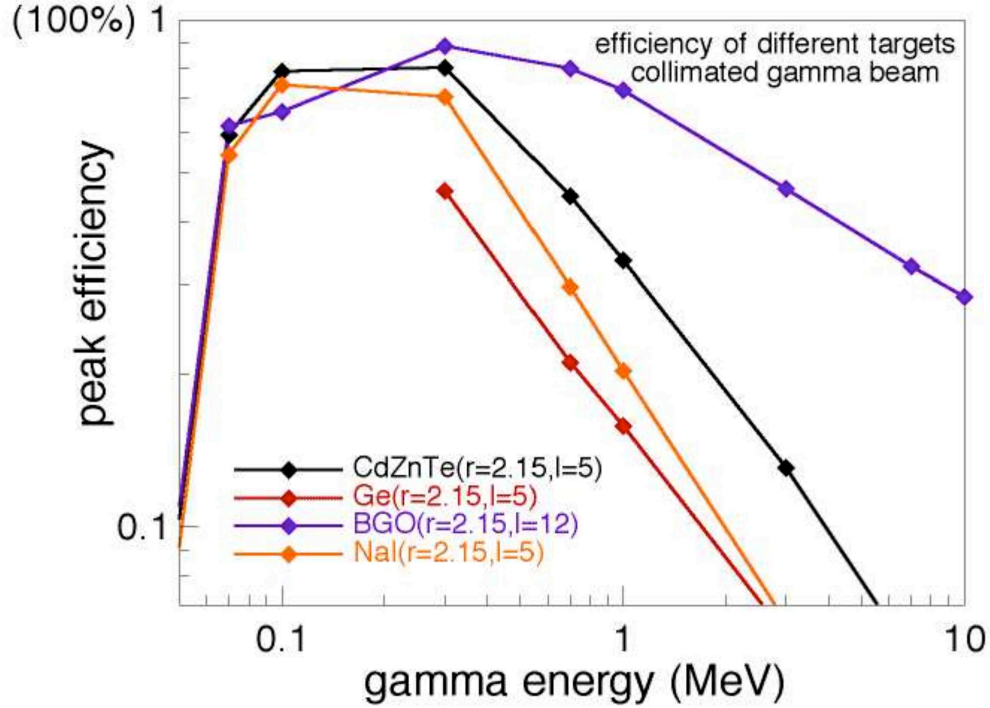
(Electron tubes, < 20 ^{40}K gamma / day)

Fiber optic and LED (to pulser, for dead time monitoring)

brass support canister

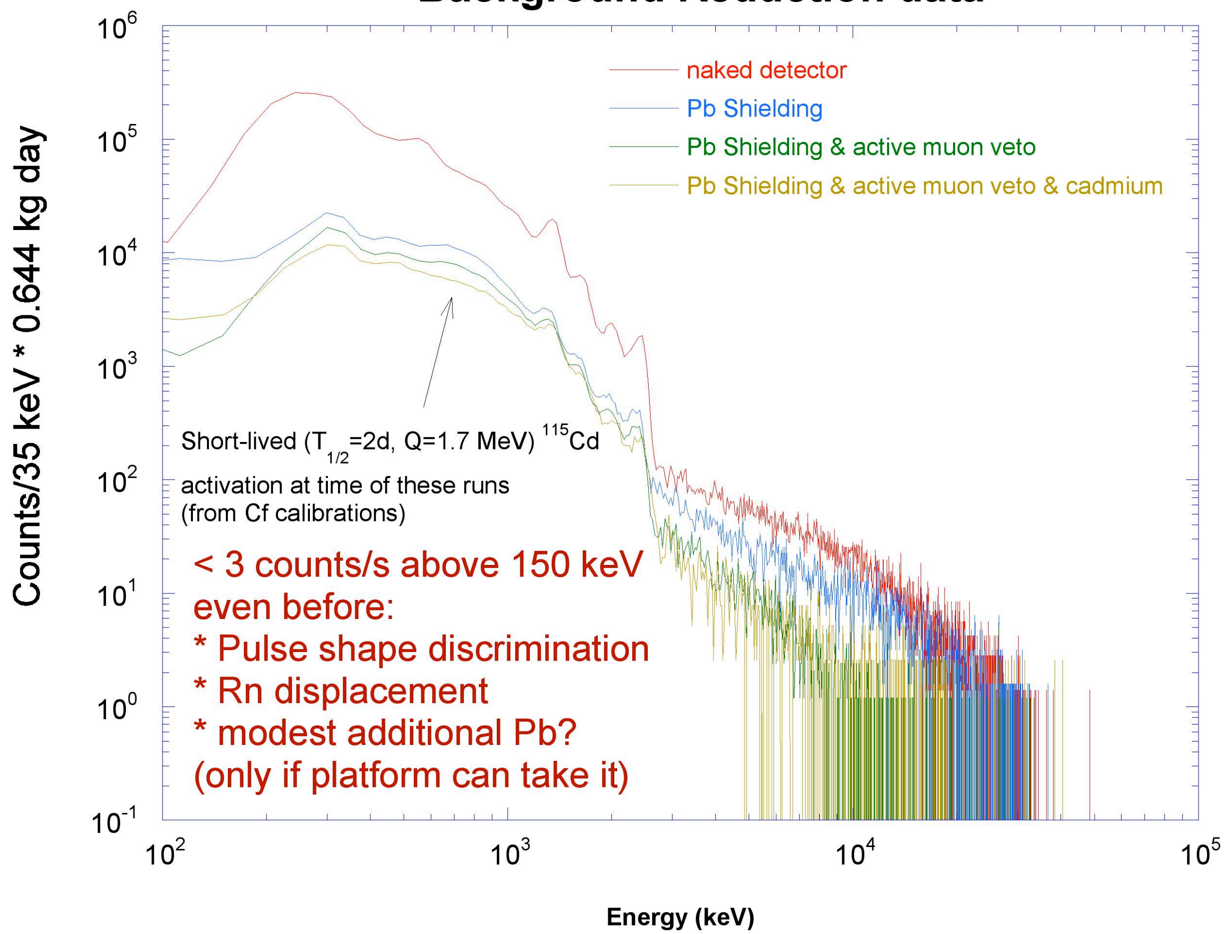
protected PMT low-voltage (5V) power bases

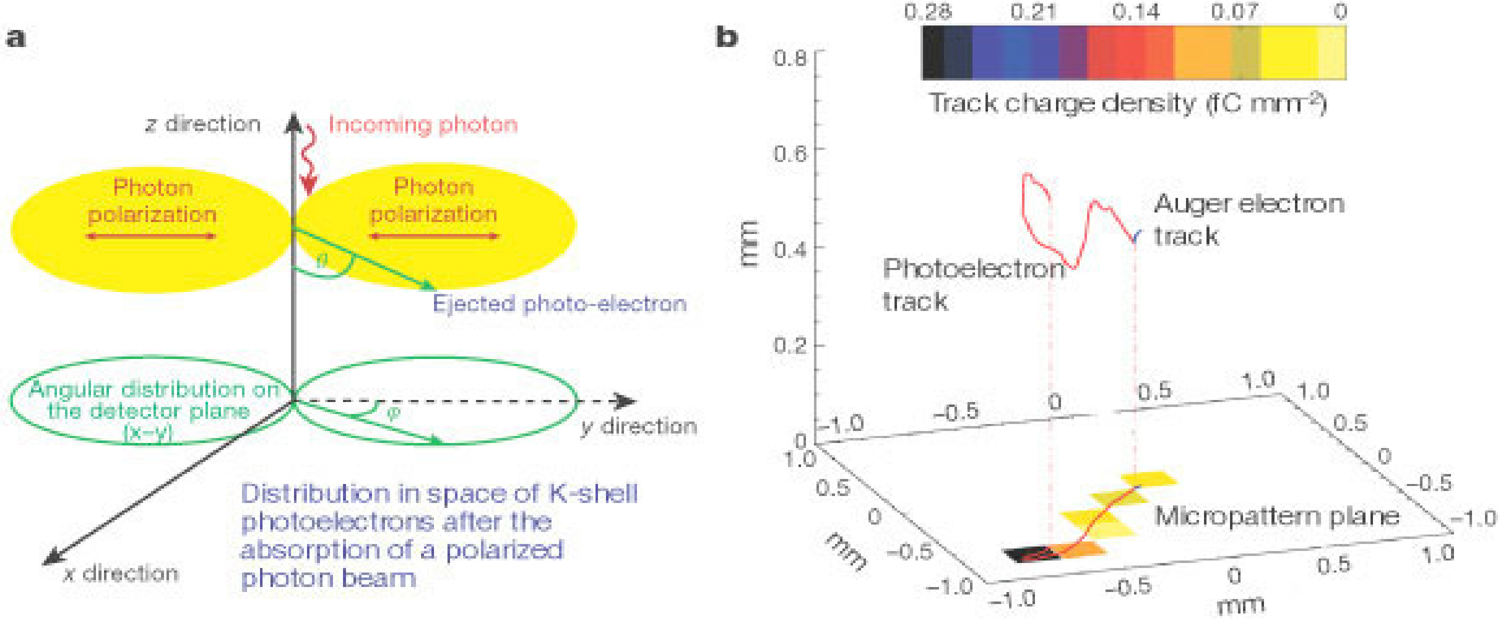
Side View (total length 60 cm, weight ~ 25 kg)



efficiency of different targets
collimated gamma beam
(100%) 1
0.1
peak efficiency
0.1
1
10
gamma energy (MeV)
CdZnTe(r=2.15,l=5)
Ge(r=2.15,l=5)
BGO(r=2.15,l=12)
NaI(r=2.15,l=5)

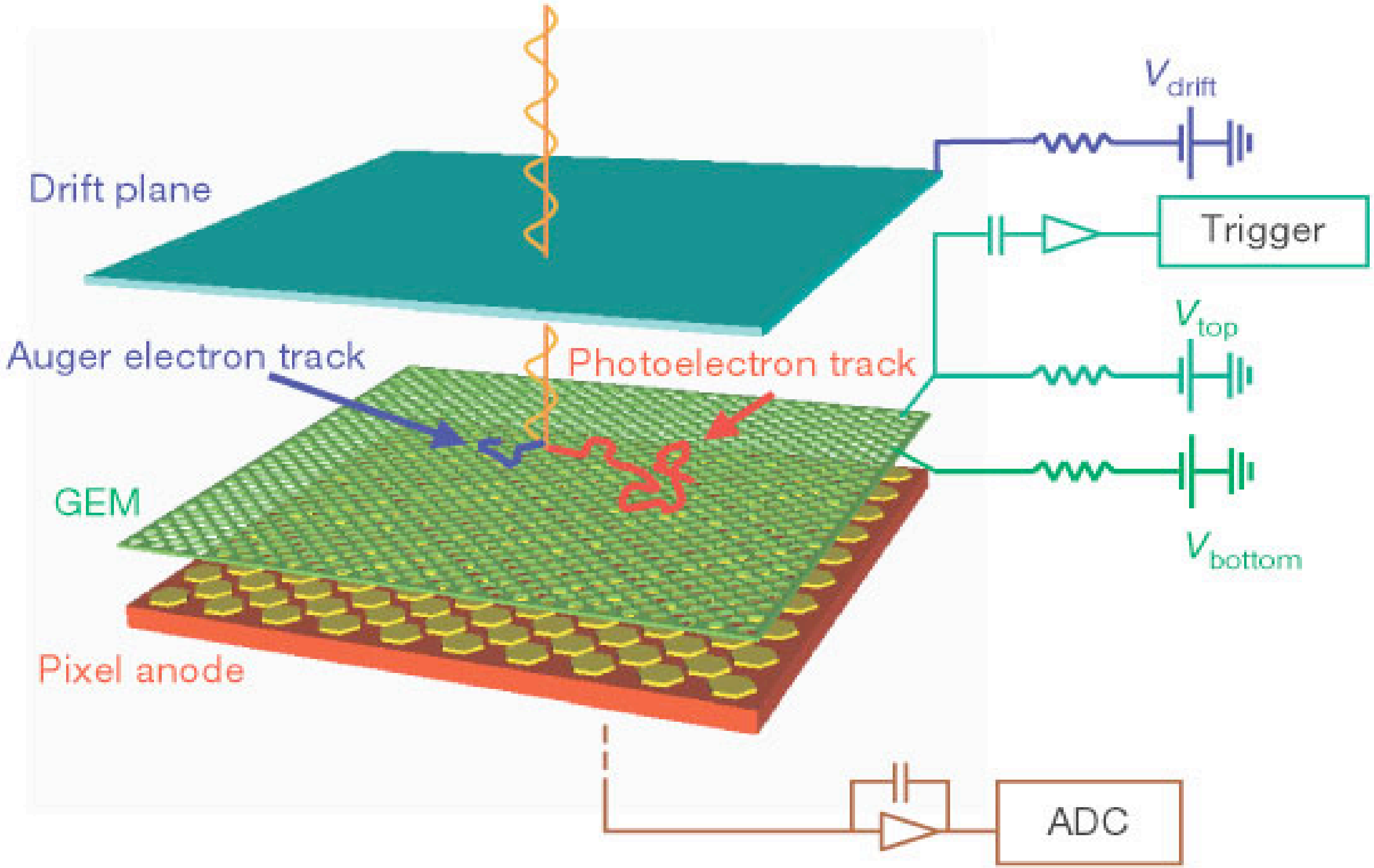
PRELIMINARY:
Background Reduction data





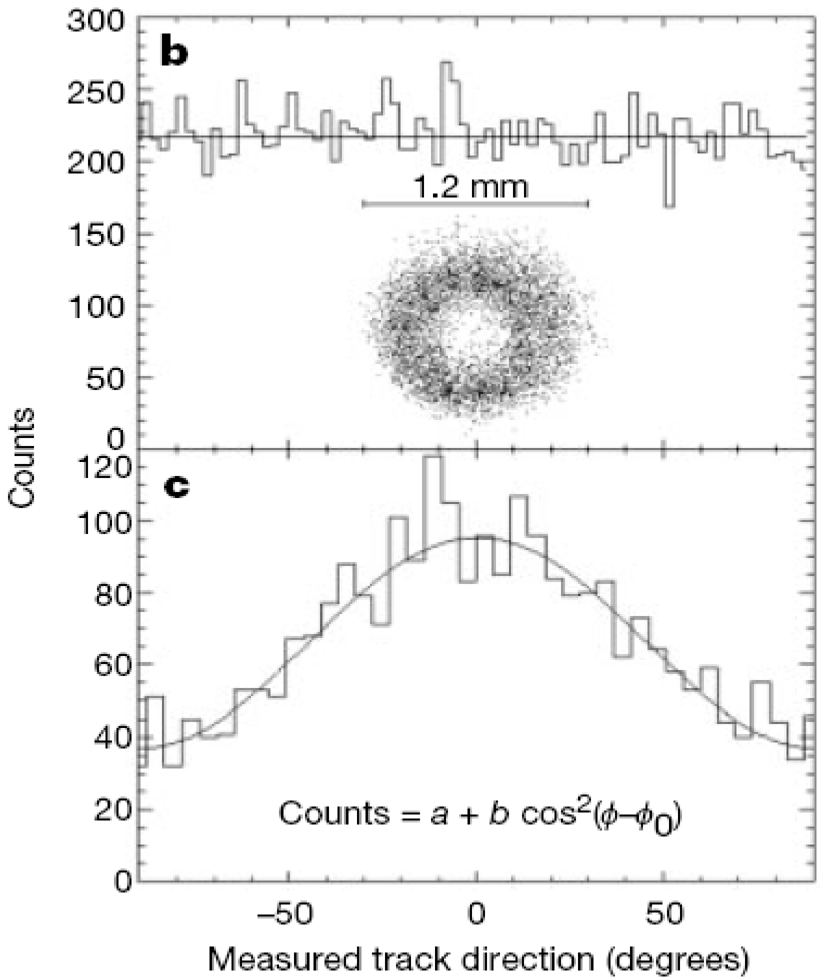
Basic physics of the ***photoelectric effect*** in a gas. **a**, Following the photon conversion in the gas, the photoelectron is ejected in directions that carry a significant ***memory*** of the electric field of the photon. When the beam is linearly polarized the electrons are ejected preferentially around the electric field.

E. Costa et al., **Nature** 411 (**2001**) 662



The micro-pattern gas detector. The photon is absorbed at some point in the drift gap. The photoelectron track is drifted by the electric field to the gas electron multiplier (GEM).

E. Costa et al., **Nature** 411 (**2001**) 662



b Unpolarized photons from a ^{55}Fe. No preference in track direction. Histogram is consistent with a flat curve.

c ~100% polarized photons from a 5.4 keV extended source. The amplitude of the cos^2_ to the histogram of counts is directly related to the sensitivity of a real ***polarimeter***. The angular phase is the direction of polarization of the incoming photons.

E. Costa et al., **Nature** 411 (**2001**) 662

Related References :

Dienes, Dudas, Gherghetta *PRD 62 (2000) 105023*
Invisible Axions and Large-radius Compactifications

DiLella, Pilaftsis, Raffelt, Z. *PRD 62 (2000) 12501*
Search for solar Kaluza-Klein axions in theories of low-scale quantum gravity

DiLella, Z., *Phys. Lett. B531 (2002) 175 & Astropart. Phys. 19 (2003) 145*
Observational evidence for gravitationally trapped massive axion(-like) particles

Z., Dennerl, DiLella, Hoffmann, Jacoby, Papaevangelou *ApJ. 607 (2004) 575*
Quiet Sun X-Rays as Signature for New Particles

Hoffmann, Jacoby, Z. *Astropart. Phys. 20 (2003) 73*
Gravitational lensing by the Sun of non-relativistic penetrating particles

Dafni, Hoffmann, Jacoby, Z. *Proc. 10th MG Meeting, Rio de Janeiro (2003)*
Novel approaches in DM research due to (self)gravitating effects

Hoffmann, **Z**., *(2004)* *in preparation*
On the Correlation between Solar X-rays and Magnetic Fields

Z. (2004)
Solar X-rays as Signature for New Particles
Results and Perspectives in Particle Physics, La Thuile / Aoste
(http://www.pi.infn.it/lathuile/2004/talks/contributi/zioutas.pdf)

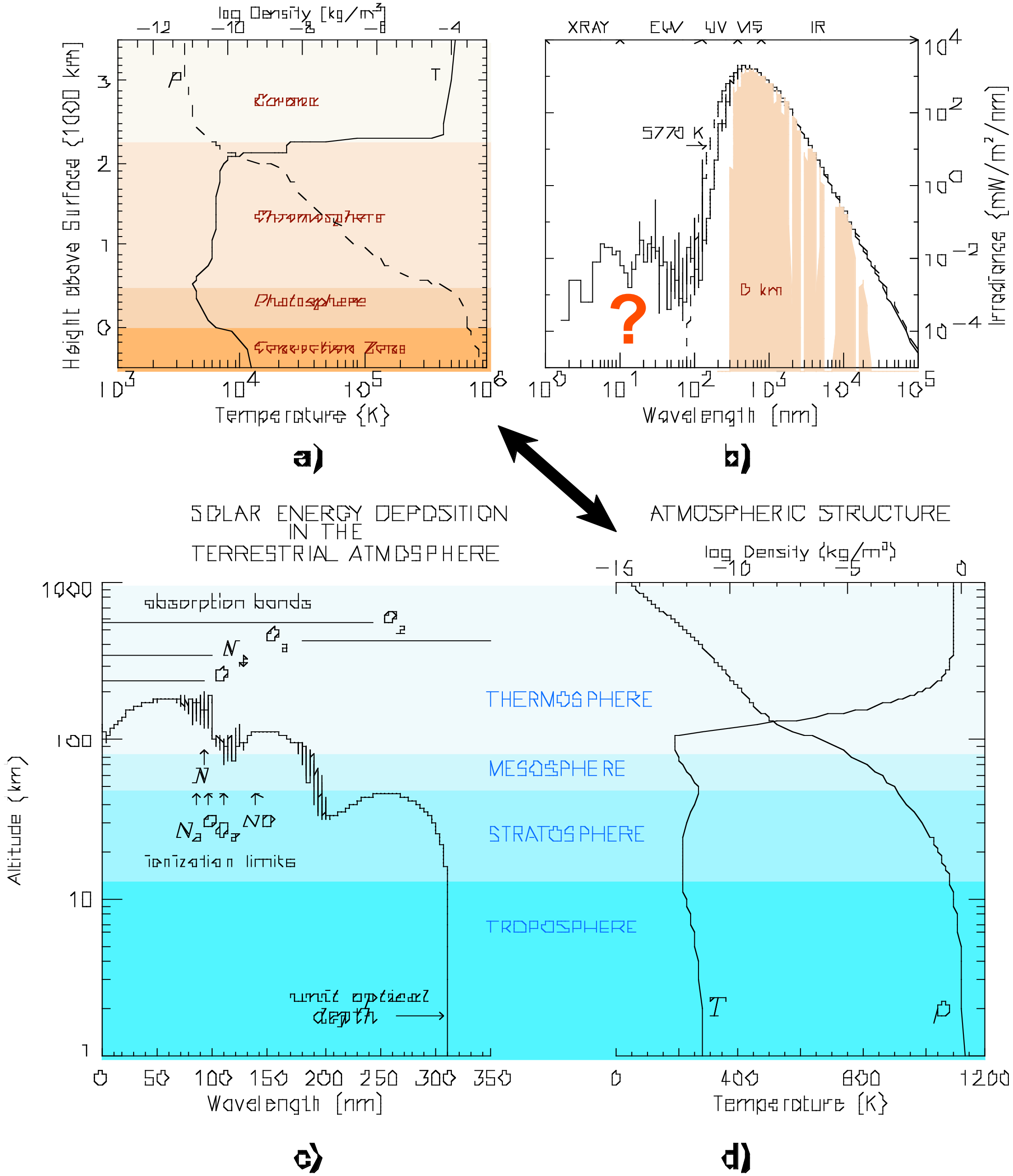
Dennerl (2004)
Axion Constraints from the solar quiet X-rays
(http://library.mppmu.mpg.de/webdocs/conf/DMMconference04.html)

Z. (2004)
Search for exotic particles from the sun and beyond
(http://library.mppmu.mpg.de/webdocs/conf/DMMconference04.html)

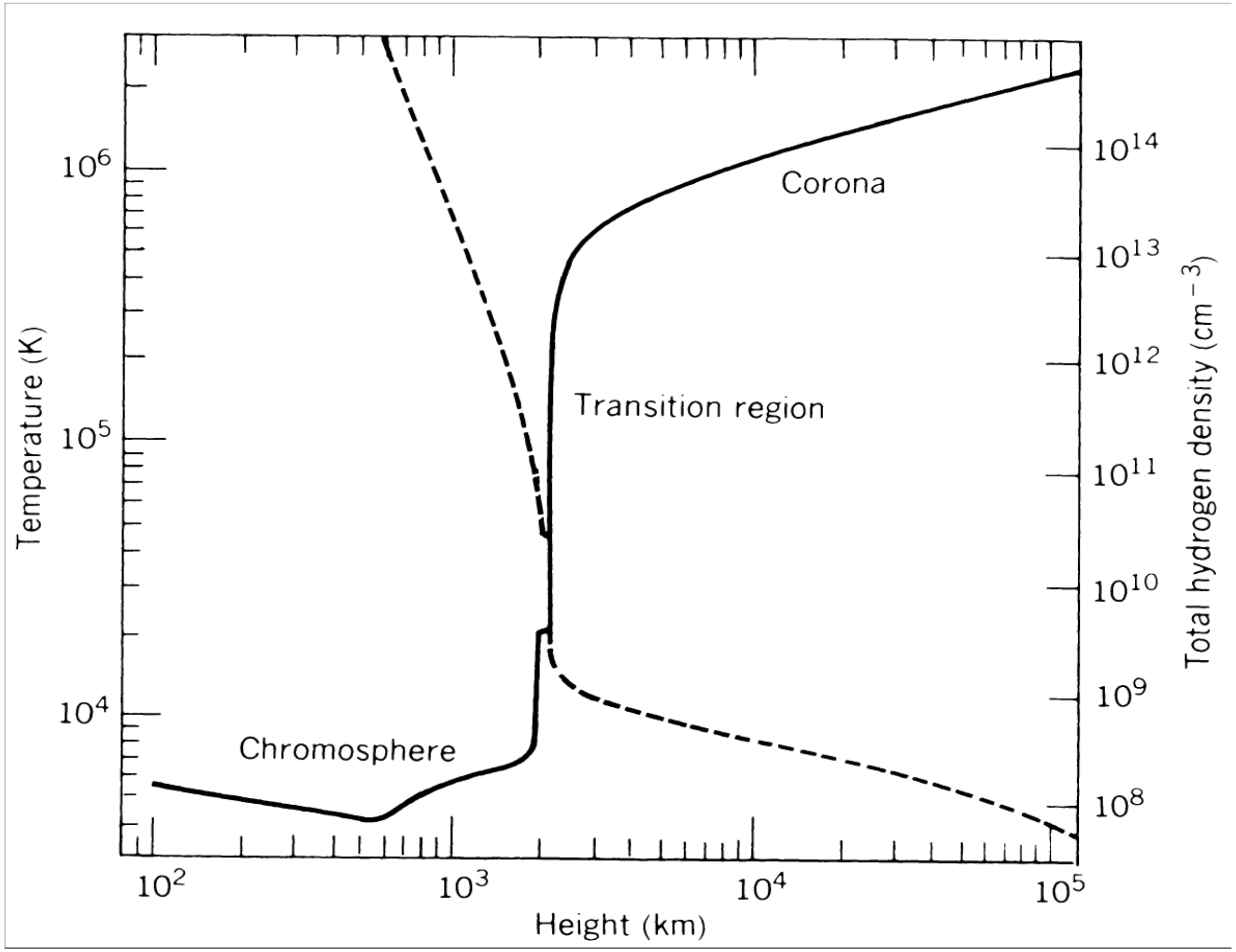
Kuster (2004)
The CERN Solar Axion Telescope
(http://library.mppmu.mpg.de/webdocs/conf/DMMconference04.html)

➔ **solar X-ray self-irradiation**

? how ?

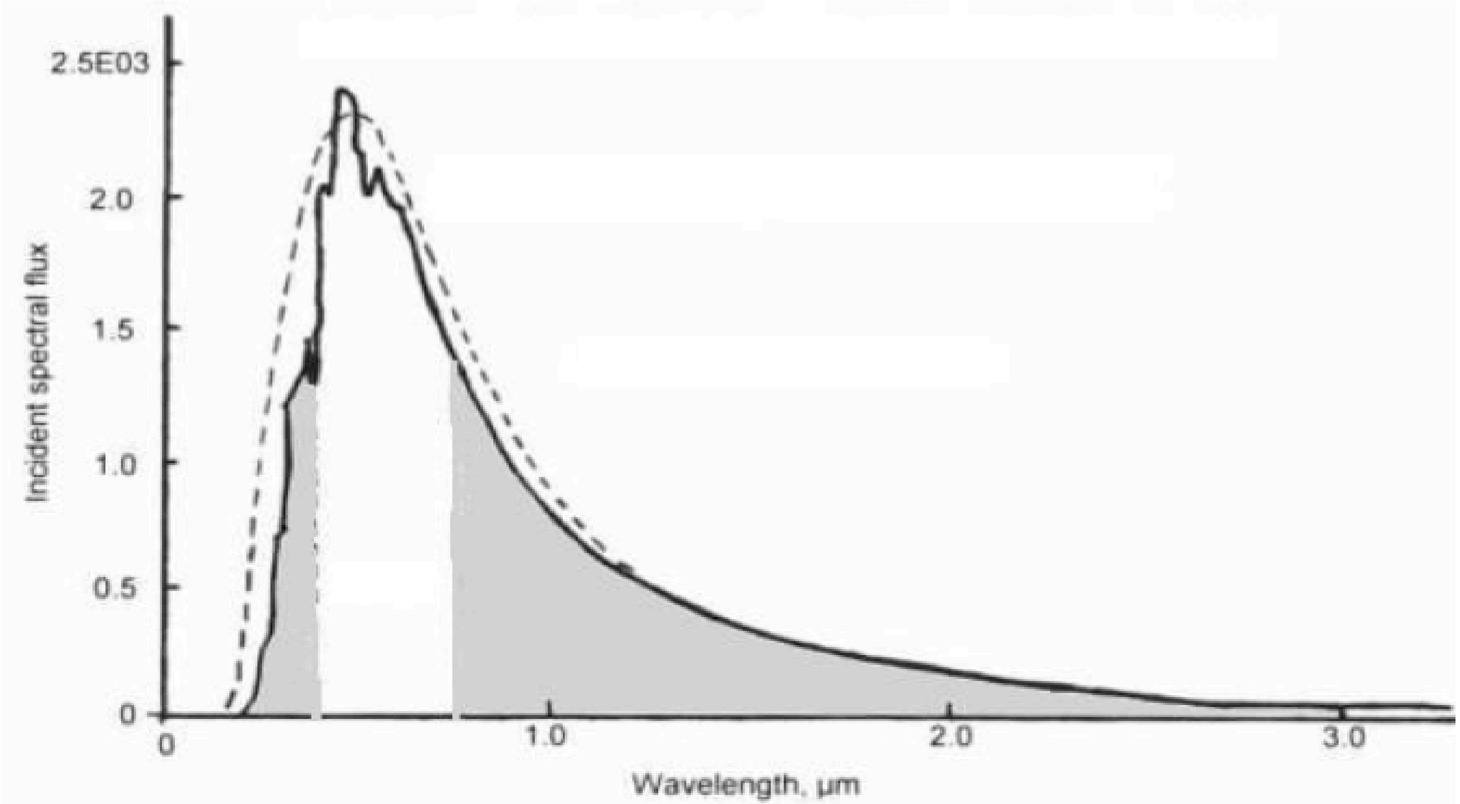


DiLella, Z. Astropart. Phys. 19 (**2003**) 145



"Average" temperature and electron number density of the solar atmosphere as a function of height above the photosphere.

http://www.sp.ph.ic.ac.uk/~mkd/AndreHandout.pdf



The electromagnetic radiation emitted from sun. The white area shows the radiation in the visible. The dotted line represents the radiation from a blackbody.

A. Ekenbäck andreas.ekenback@irf.se **11th February 2004**
http://www.irf.se/gsst/SpaceEnvironment/Space_Environment_Andreas_Ekenback.pdf

Solar corona problem

→ ***Grotrian*** *1939*
Naturwissenschaften 27 (1939) 214

The physics of coronal heating remains one of the most fundamental problems in stellar (and solar) astrophysics.
→ Güdel, Audard , Kashyap, Drake, Guinan **ApJ. 582 (2003) 423**

How are coronae heated **?** → *it remains* ***unanswered*** **!** Güdel, **A.&A. Rev.** (27.5.2004)
(astro-ph/0406661)

The identification of chromospheric and coronal heating mechanisms remains one of the major unsolved problems in solar and stellar physics.
→ Judge, Saar, Carlsson, Ayres **ApJ. 609** (1.7.2004) **392**

Transition region ***dynamics*** … *significant developments…*
UK Solar Physics *meeting Dublin from 7–11 April 2003* ***Erdélyi, Fletcher, Doyle***
http://star.arm.ac.uk/preprints/AAG44313.pdf

…the coronal plasma is somehow being heated continuously. … our results have made the coronal heating process even more of a mystery.
Antiochos, Karpen, DeLuca, Golub, Hamilton **ApJ. 590 (10.6.2003) 547**

A substantial amount of hidden magnetic energy in the quiet Sun.

… should help to solve many of the key problems of solar & stellar physics, such as …. ***the coronal heating***.

J. Trujillo Bueno, N. Shchukina, A. Asensio Ramos

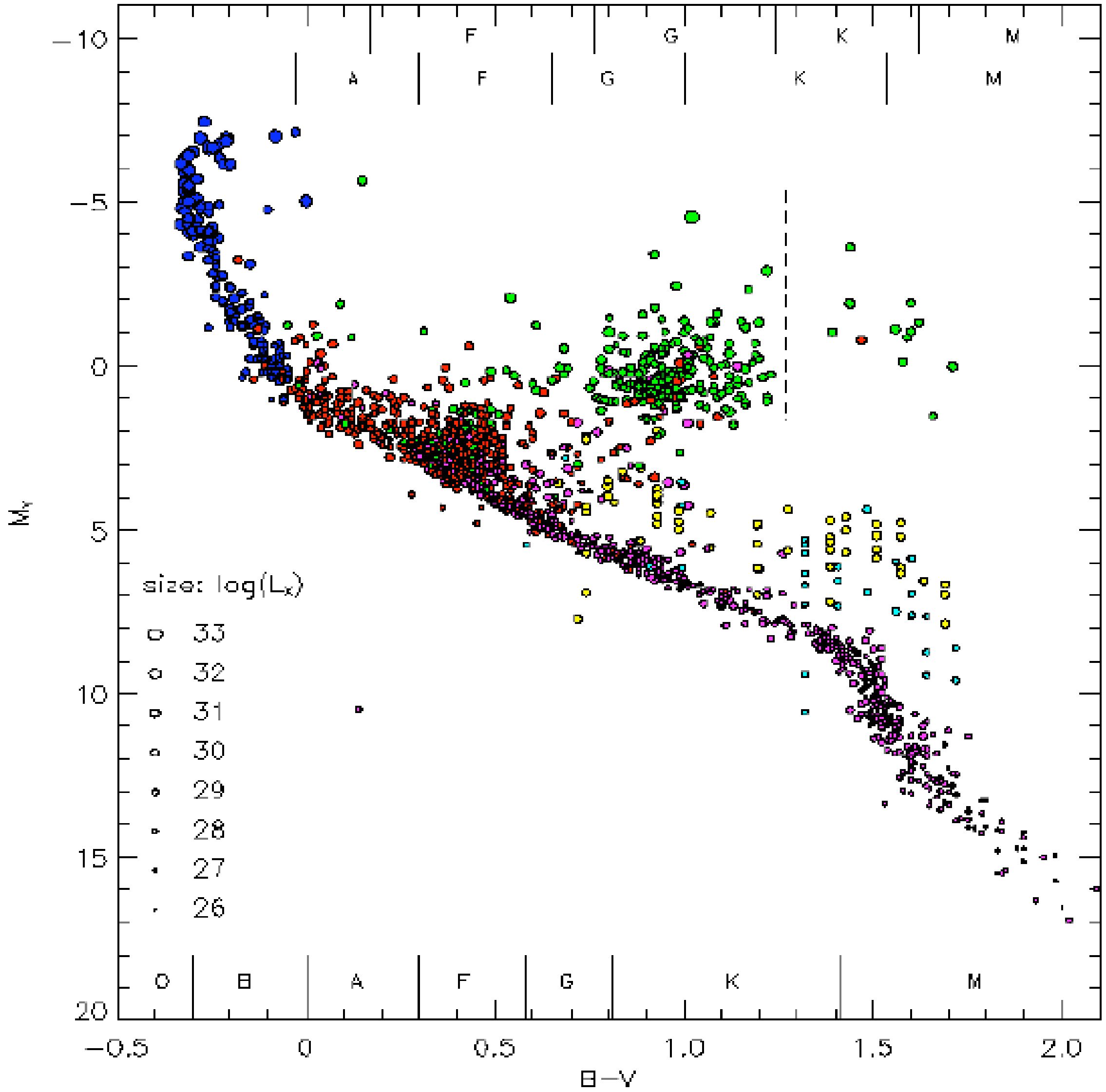
NATURE 430 (**15 JULY 2004**) 326

Bondi, Hoyle & Lyttleton, *M.N.R.A.S. 107* (**1947**) *184*

→ ***capture of interstellar material by the Sun*** ←

⇓

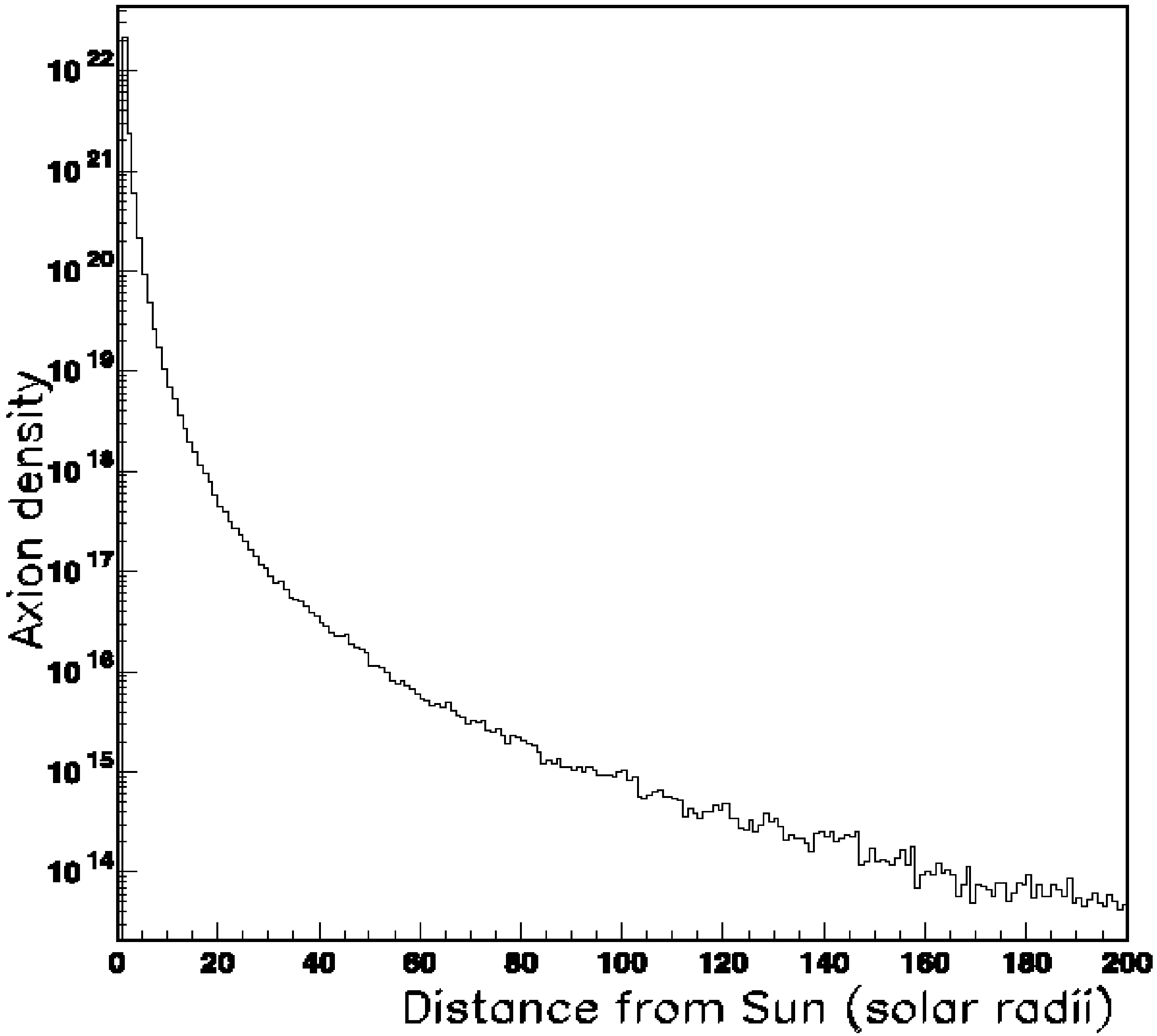
"These results accord well with the theory of the present paper."



Hertzsprung-Russell diagram based on about 2000 X-ray detected stars

(from *Berghöfer et al*., *Hünsch et al*.)

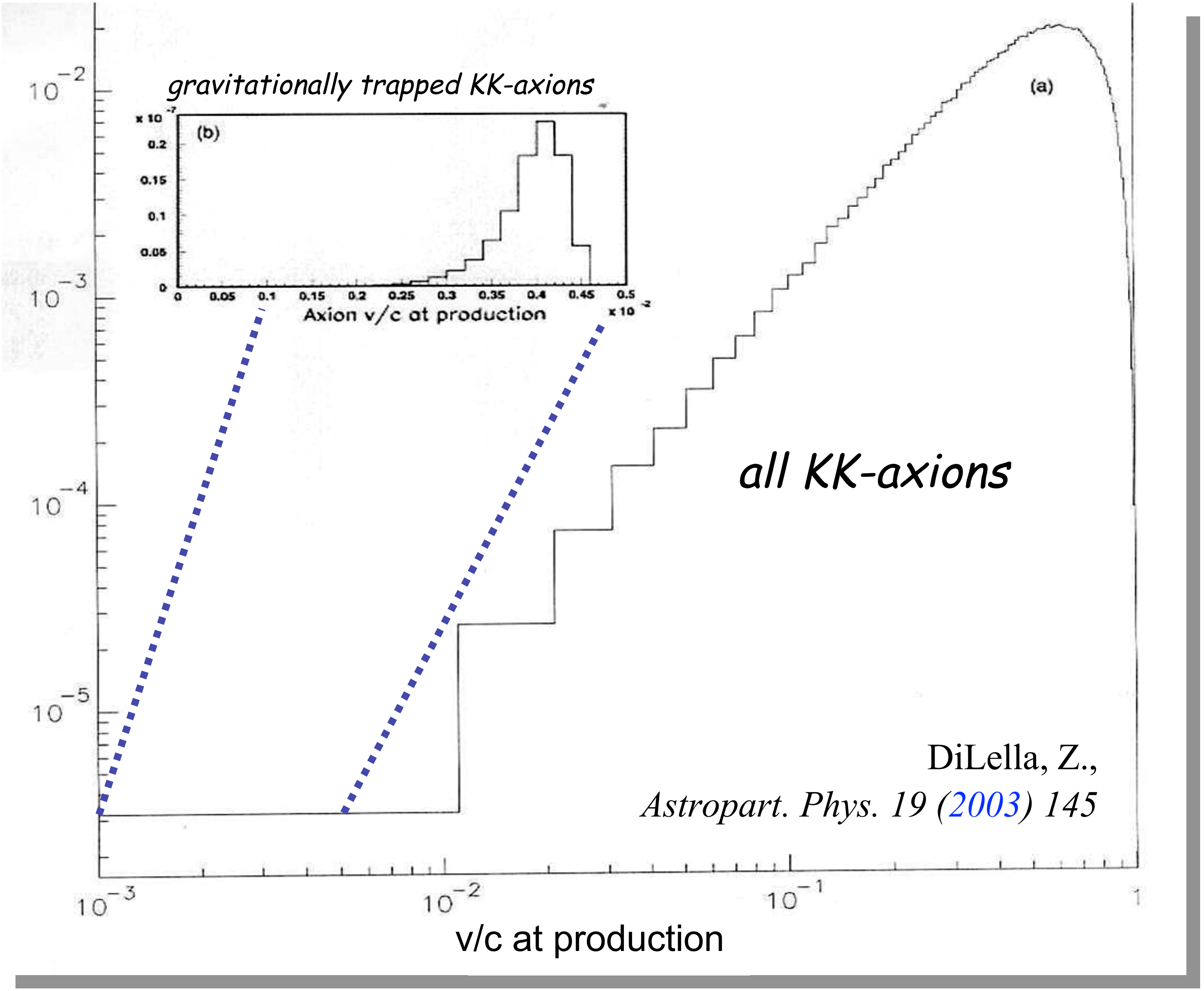
Güdel, A.&A. Rev. (**2004**), astro-ph/0406661



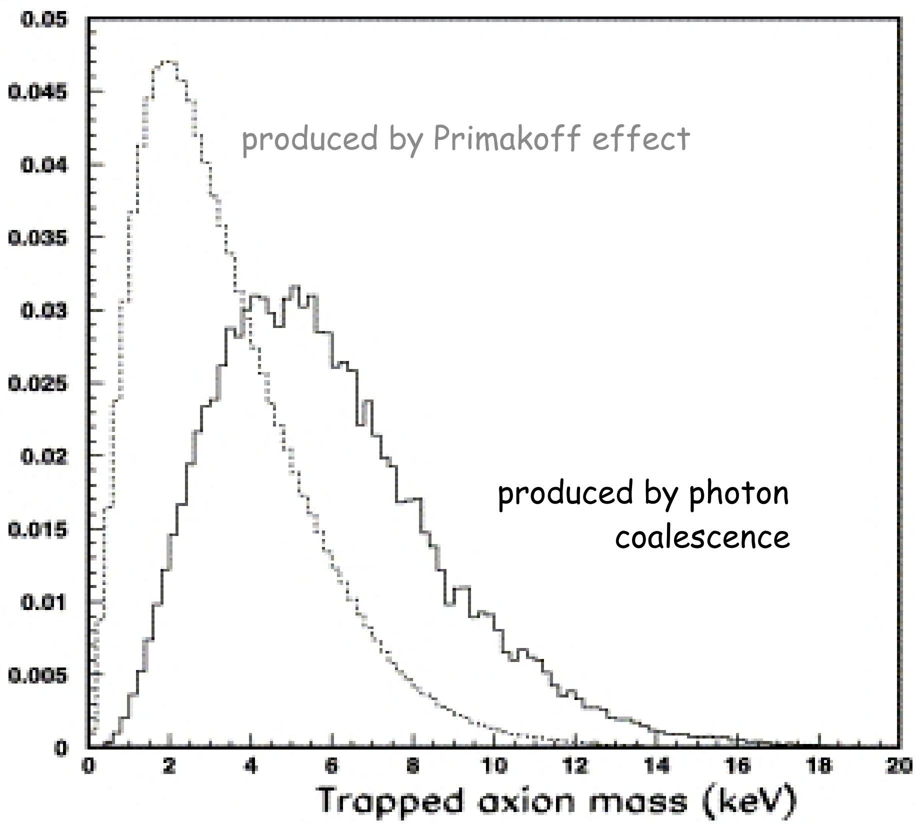
Present density (axions per m³) of gravitationally trapped axions in the region around the Sun, as a function of the distance from the Sun centre.

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

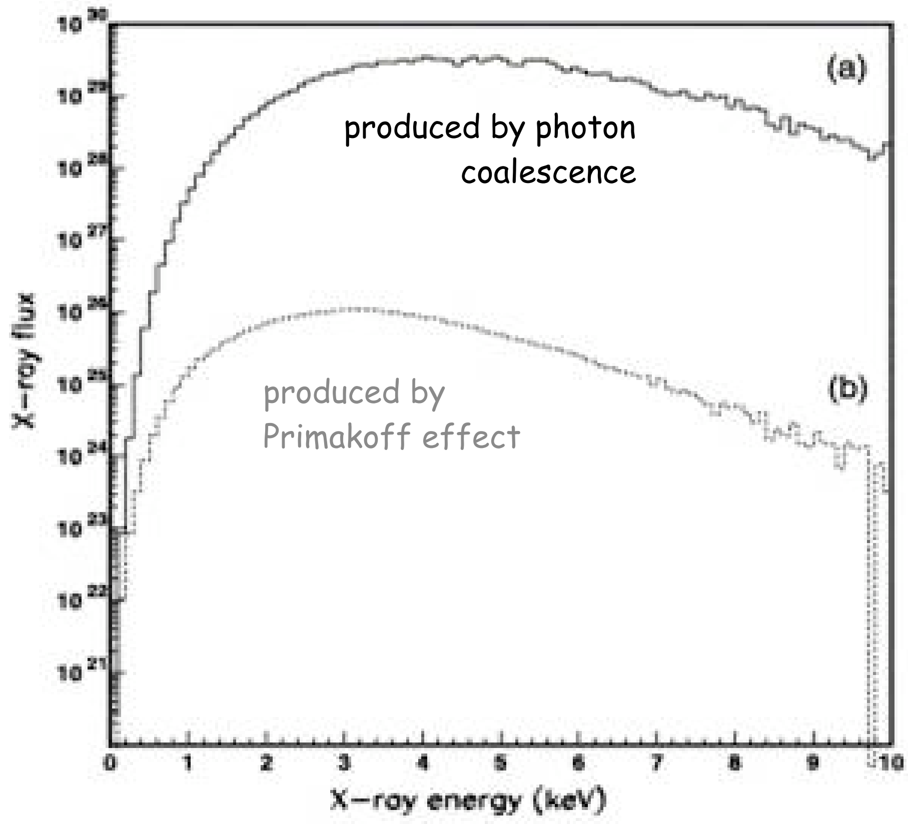
Velocity distribution for solar KK-axions



Mass distribution of gravitationally trapped solar axions, and expected energy spectrum



Mass distribution (normalized to unit area)



expected X-ray spectrum

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

Possible solution :

Whole Sun irradiation by the radiative decay/interaction of gravitationally trapped massive ***axion-like*** *particles around the Sun.*

Generic candidates :

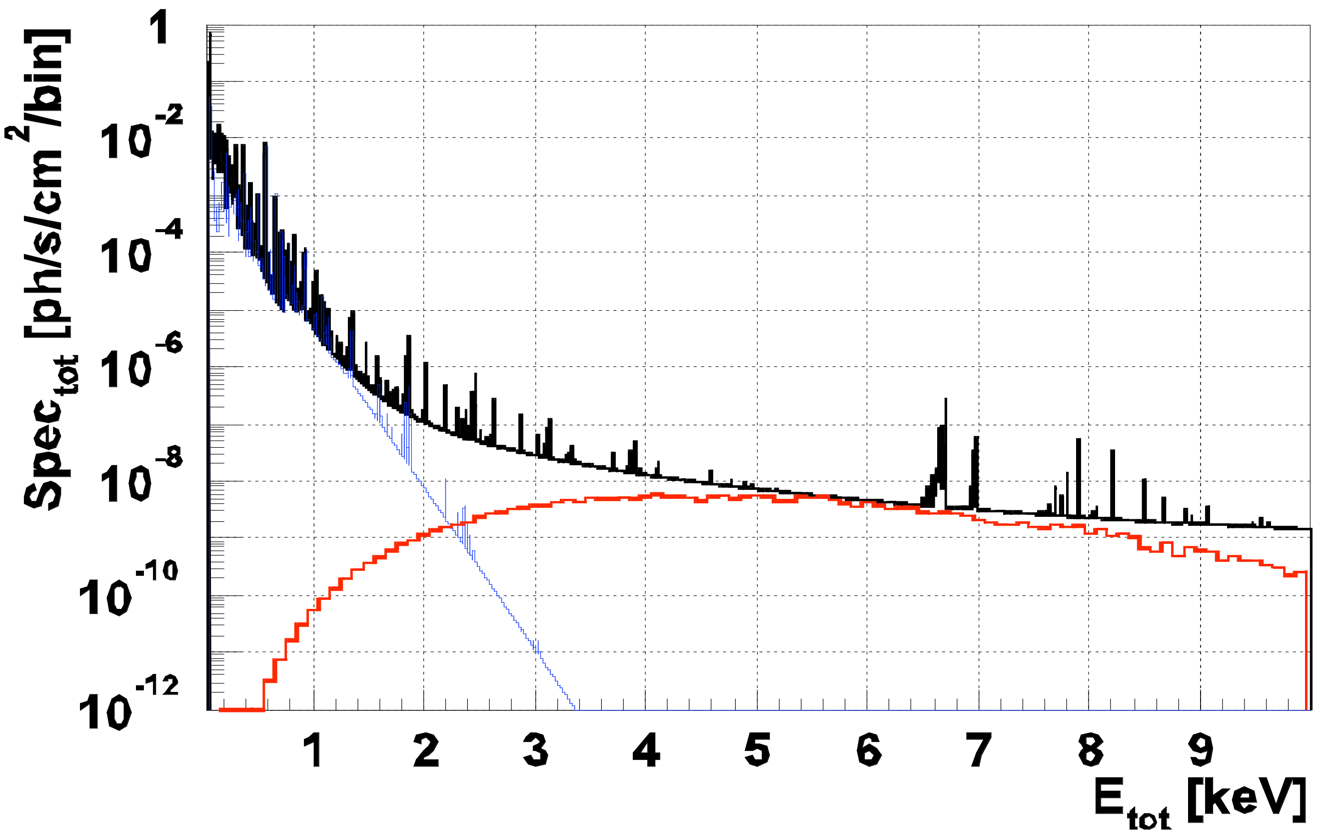
Solar KK-axions gravitationally trapped by the Sun

$$I(v^{KK} \leq v^{escape} \approx 600 - 1200 \text{ km/s}) \approx \mathbf{10^{-7}}$$

- PQ-axions → NO (*superrelativistic*)
- KK-axions → YES (_ ~ *0.6 c*)

➔ ***accumulate over cosmic times*** ➔

➔ $g_{a\_} = 9.2\times10^{-14}$ GeV^{-1} & $\tau^{KK} \cong 10^{20}$ s



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 (thin line in **blue**). Bin size =6.1 eV. (EM(T) is approximately the product of the square of the electron density with the emitting volume V(T) as a function of temperature).

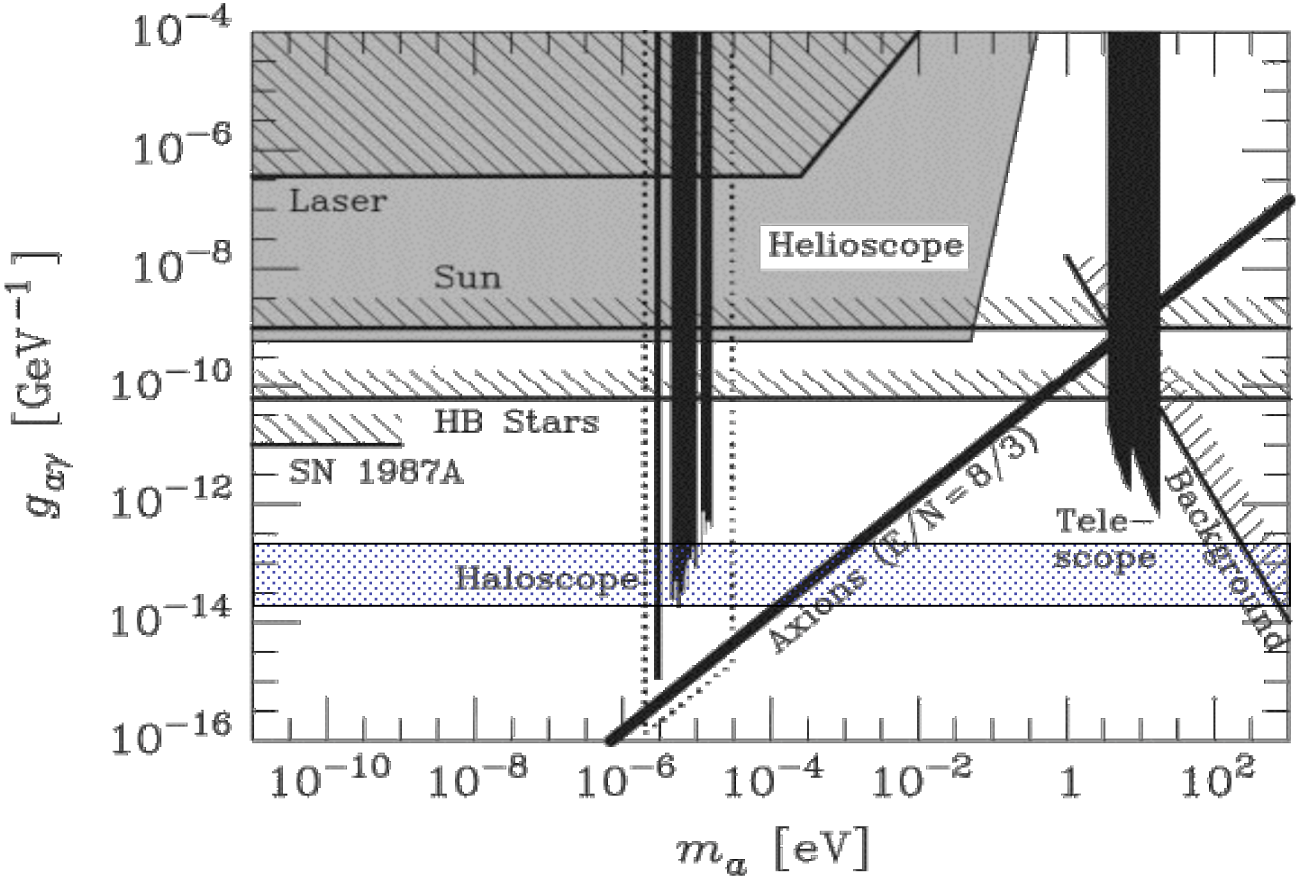
Red line : solar KK-axion model →

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

[16] G.Peres, S.Orlando, F.Reale, R.Rosner,H.Hudson ***ApJ. 528 (2000) 537***

The axion-photon coupling constant $g_{a\_\_}$

G.G. Raffelt / Physics Reports 333–334 (2000) 593–618



$L_x \sim (g_{a\_\_})^4$

Quiet Sun X-rays as Signature for New Particles

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

ApJ. 607 (2004) 575

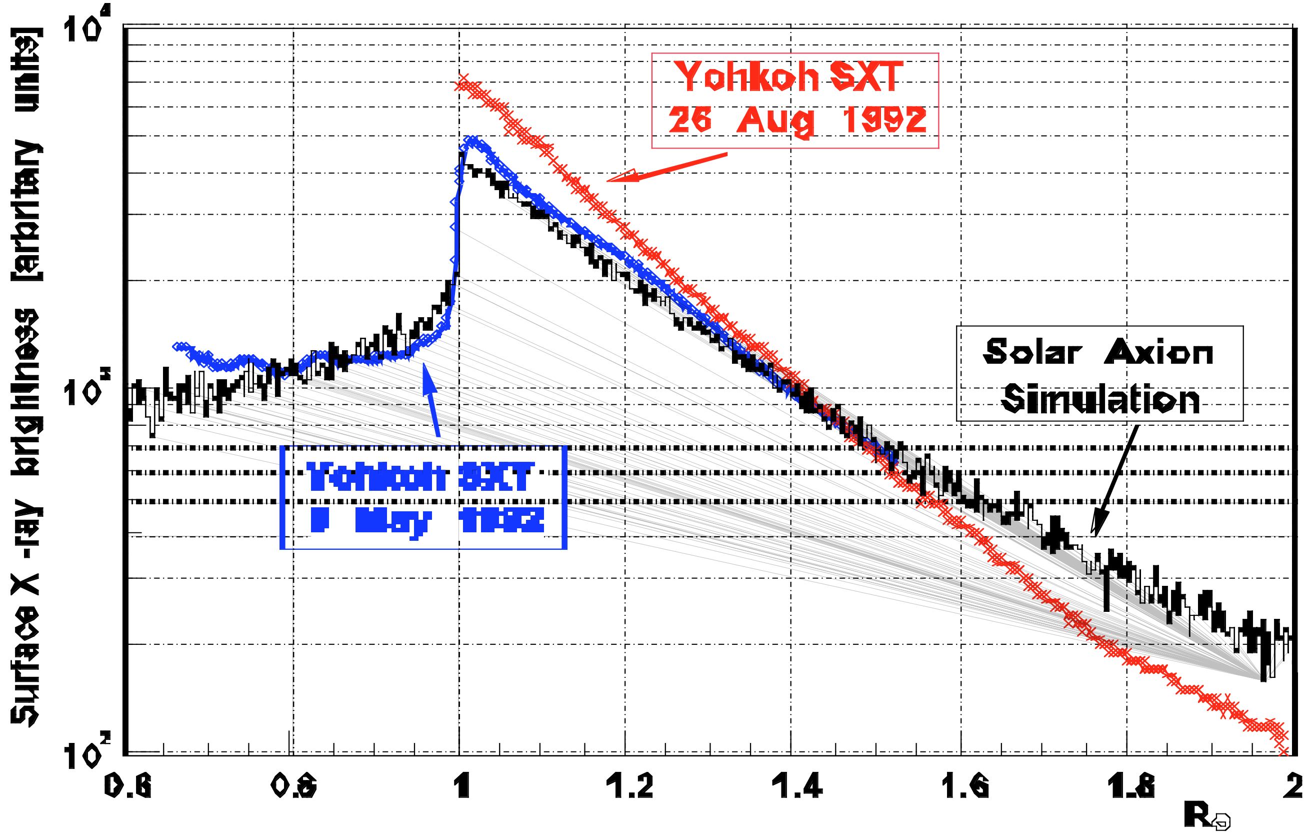


Fig. 1.— Theoretical (DZ03) and experimental (Sturrock et al. 1996; Wheatland et al. 1997) soft X–ray surface flux distributions from the quiet Sun. The simulated curve has been shifted relative to the experimental points of both observations, which implies $g_{a\gamma\gamma} \leq 40 \cdot 10^{-14}$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

Yohkoh-SXT 1992 observations :

The standard view : the deposition of nonthermal energy occurs low in the "inner corona," and that this region in turn supplies heat to the upper corona and to the "solar wind," a term used to represent the continuous expansion of the corona into interplanetary space.

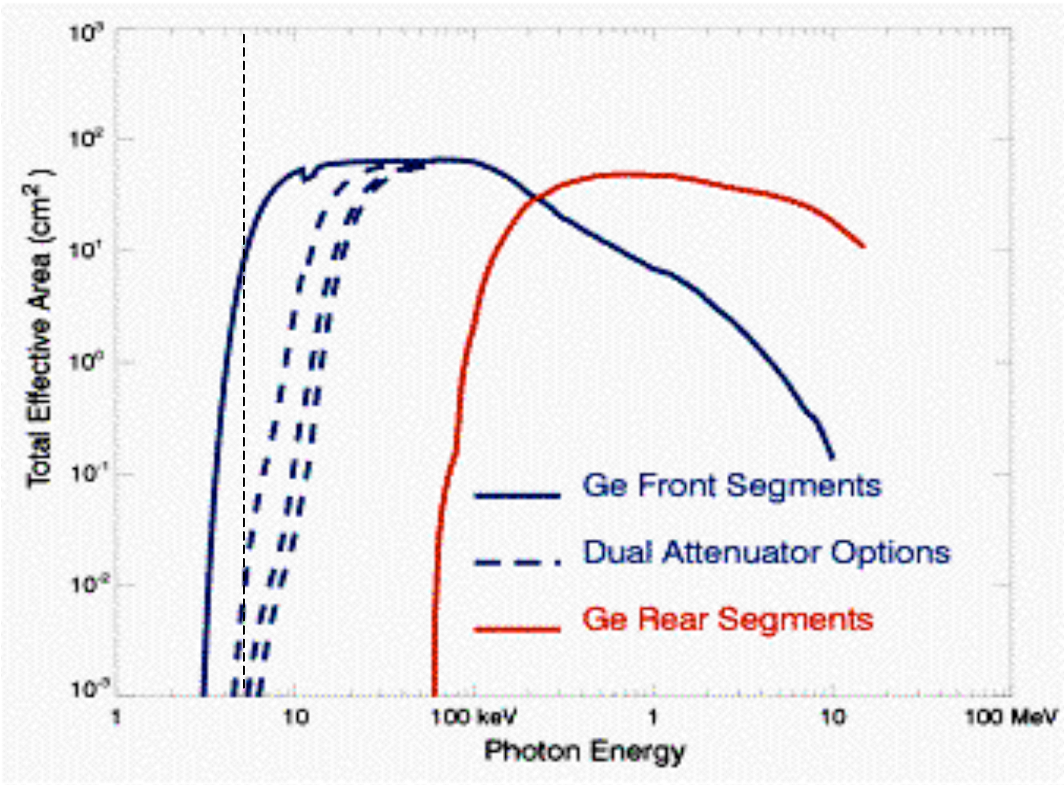
The standard view may need revision … ***the solar wind may supply heat to the inner corona rather than the other way around.***

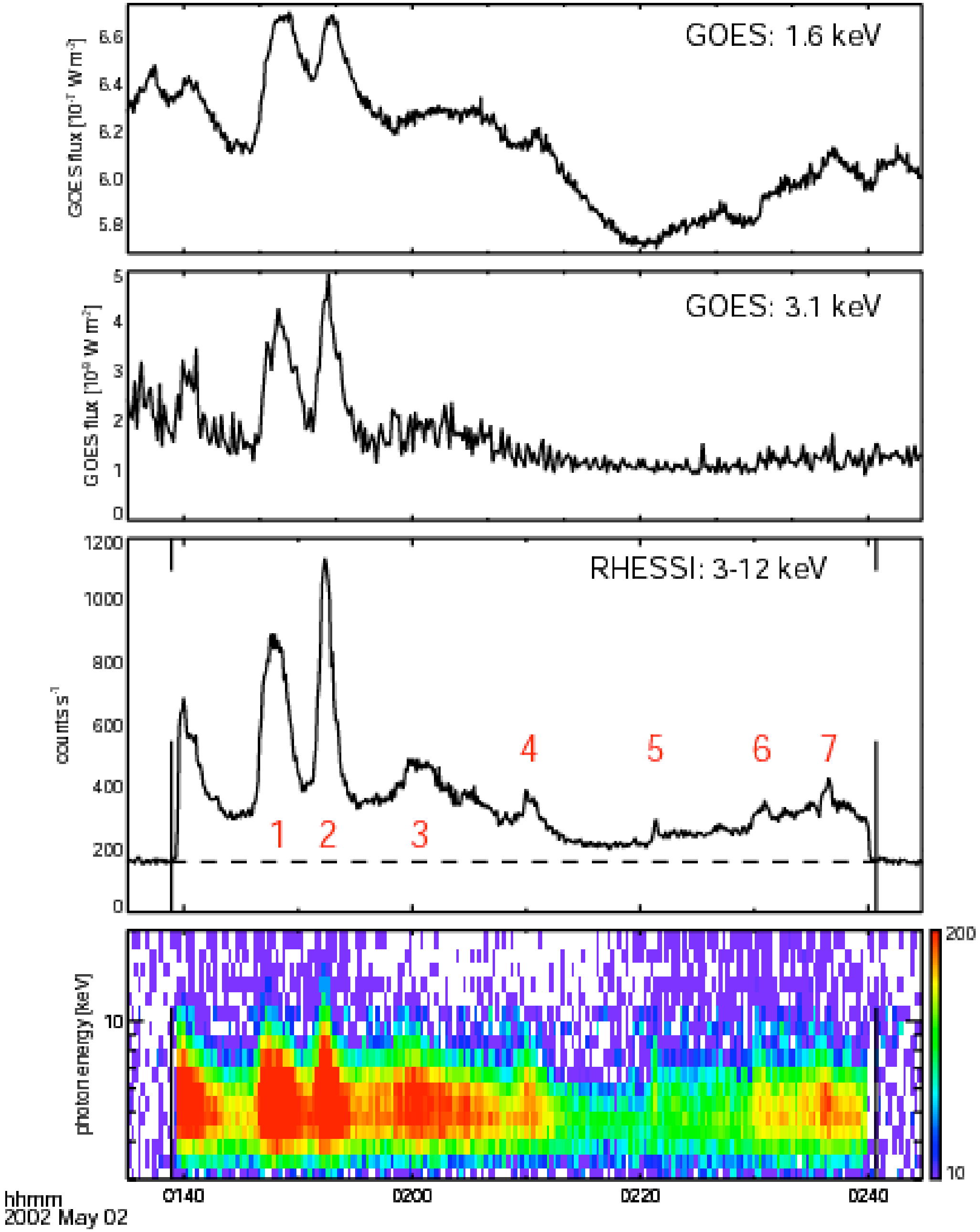
…. There is no evidence of nonthermal heating in either the observed regions or in the inner corona.

➔ …re-think the standard picture of the corona-solar-wind system

http://www.stanford.edu/dept/physics/newsletter/96/corona.html

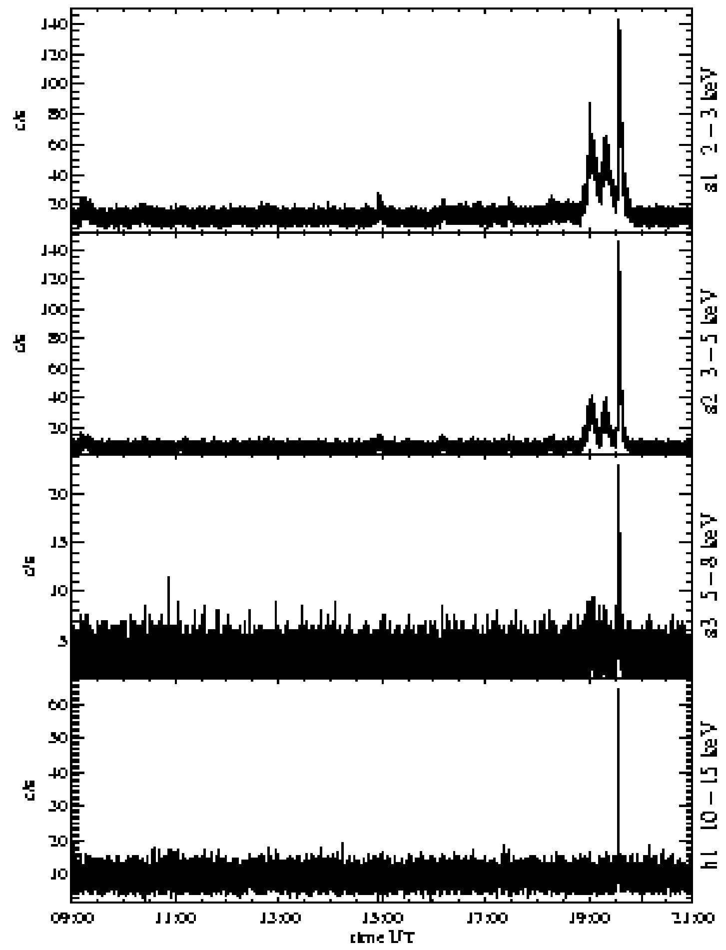
RHESSI effective area





The GOES and RHESSI (from top to bottom) X-ray observations during 1h of low solar activity. The vertical lines define the spacecraft day. The RHESSI detector background level is measured before and after the daylight part of the orbit (dashed line). The RHESSI count spectrogram plot (bottom) is background subtracted.

Z., Dennerl, DiLella, Hoffmann, Jacoby, Papaevangelou, ***ApJ. 607 (2004) 575***



RHESSI 11th Febr. 2004,

http://www.spectrumastro.com/SAI_PressReleases/PR_details.cfm?PRID=147

...the first detection of continuous glow from the sun at 3-15 keV

INTERBALL: "We have found it *very unexpected* that there is present quiet-Sun emission in the 10-15 keV band in the period of the lowest solar activity (1995)"

ESA SP-448 (1999) p.176, ed. A. Wilson

M.Siarkowski, J.Sylwester, S.Gburek, Z.Kordylewski

(s. also J. Sywester et al., ***Solar Phys. 197 (2000) 337, Fig.3***)

COSPAR, 18-25 July 2004

E2.3 List of Accepted Contributions ➔ *submitted abstracts*

(http://www.cosis.net/abstracts/COSPAR04/03164/COSPAR04-A-03164.pdf)

THE MICROFLARE FREQUENCY DISTRIBUTION OBSERVED BY RHESSI

S. Christe, S. Krucker , R.P. Lin

RHESSI provides uniquely high sensitivity in the 3-15 keV energy range with an effective area from 14 to 130 times larger then previous solar instruments. We present a microflare frequency distribution derived from RHESSI observations. Times were chosen such that activity is very low (GOES B Class background) and includes ***a 24 hour period when no active regions were present on the Sun***. Microflares were found through searching for 5 σ increases in count rate, summing over all detectors, between two adjacent time bins in the 3-10 keV energy band. Count rates were binned from 4 seconds to 3 minutes, increasing by 4 seconds increments, and the search repeated in order to detect flares of various time scales. Each microflare was individually checked in order to reject nonsolar events. Few microflares are seen to occur below the time scale of minutes.

The observed occurence rate is ***one microflare every ~ 8 minutes****) above **a threshold flux of ~ 0.4 /(cm^2 s keV)****) over the 5-10 keV energy range. Microflares were also found when no active regions were present on the Solar disk.

= =

*) with a time resolution of ~ 10 msec !

) ➔ **L_X(<10 keV) > 1.5 10^{20} erg/s (assuming 100% efficiency) ???

Stars as Suns: Activity, Evolution, and Planets, IAU Symposium 219 (**2004**) 461.
A. K. Dupree and A. O. Benz, Eds.

Nanoflares and the Heating of the Solar Corona

A.O. Benz

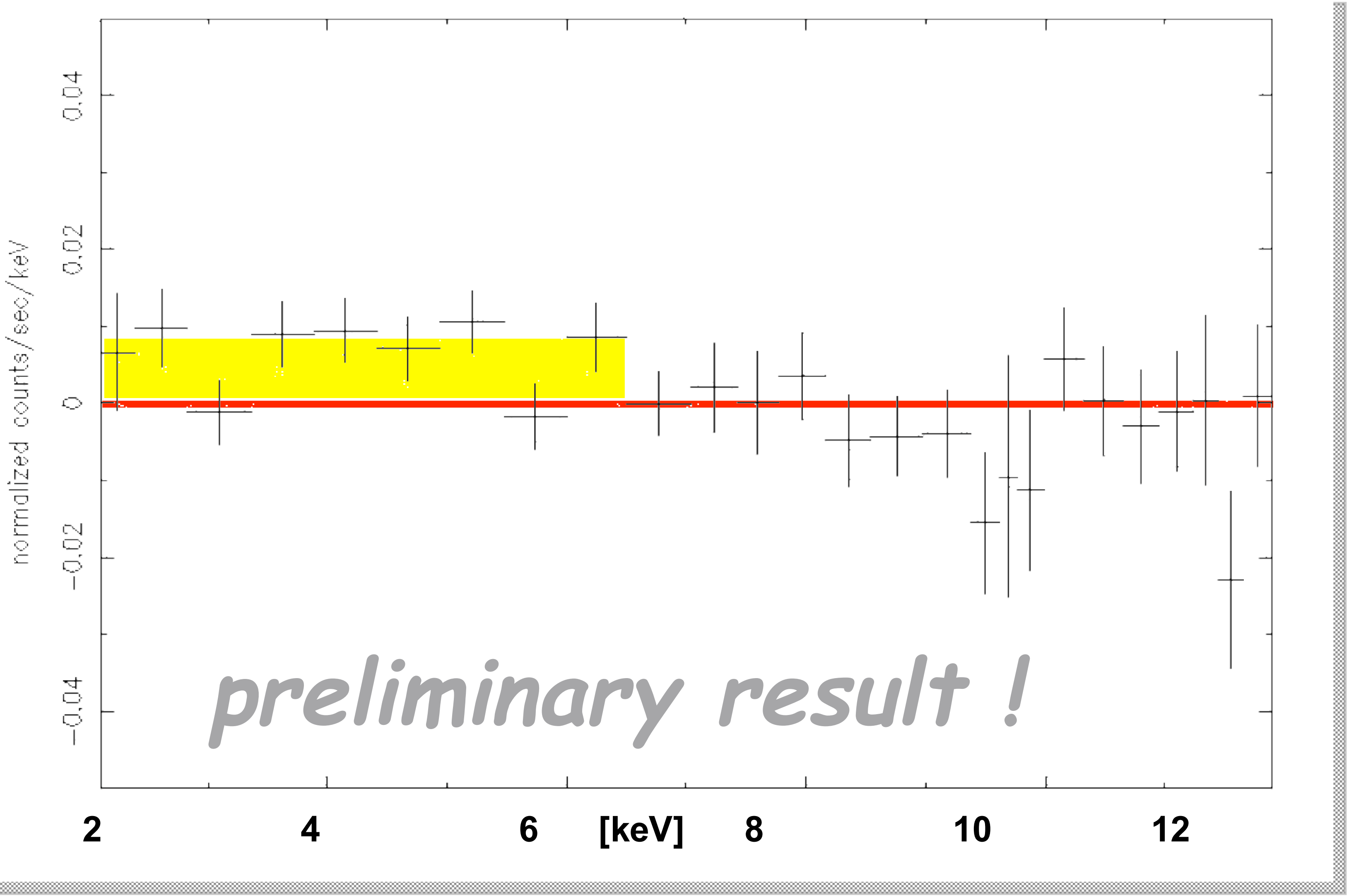
The heating of the solar corona has been a challenge to theory since the discovery of the MK temperature in the late 1930s.

…. the heating process must be able to account for the coronae of more active stars showing coronal emissions at levels of more than 3 orders of magnitude higher than the Sun.

The popularity of **nanoflare heating of the corona** comes in waves. It reached a first peak in the 1980s with microflares discovered in active regions, a second peak was reached with nanoflares discovered in the quiet corona. In both cases it was later realized that **the observed energy was too low to account for all of the heating**, luring some people to conclude that nanoflares cannot heat the corona. It is argued in this review that ***this conclusion is premature***.

It is clear from the experience of regular flares that soft X-ray and EUV brightenings are not direct evidence of the heating process, but represent secondary reactions of the chromosphere resulting from a primary energy input possibly at a different site. The conversion of the primary energy, possibly precipitating energetic particles, into thermal plasma at high temperature is just one of several possible channels of coronal energy input. Nevertheless ***the observed impulsive energy content manifest in nanoflares of the quiet corona amounts to more than 10% of the energy required for the observed coronal radiation.*** **The rest of the energy input appears in the form of a quasi-constant base. Its origin is unclear** and may have several reasons: Unresolved nanoflares at lower energy may mimic a smooth input. Energy released directly into the corona by the observed microevents in the form of waves may distribute energy in a non-impulsive way. ***More information on flare energy partition is necessary to decide whether there is room for*** ***some entirely different process to release additional energy.***

Chandra difference spectrum:
„Venus background – Mars background“ *K. Dennerl*



Bose Einstein Condensation

of a boson field as Dark Energy & the bose gas as Dark Matter

BEC occurs when the de Broglie length _$_{dB}$ exceeds the mean separation length of the particles.

When the energy density of the BEC exceeds some critical value, the condensate rapidly **collapses** into compact boson stars and black holes, which work as the standard CDM and also become the seeds of galaxies.

The collapse of the condensate proceeds in the smallest scale … of density fluctuations.
➔ the collapsing object can easily fragment into many pieces, because the pressure is always negative.
➔ many collapsing objects are expected.

For bosons, only the Heisenberg uncertainty principle can support the boson star against the collapse into a black hole. The size R of the object is ~ the compton wave length _$_{compton}$ = 2π_/(mc) ≈ 2R.
This size must be larger than the Schwarzschild radius R = 2GM/c^2 of this object.

➔ the critical mass for the boson star below which a structure can exist is:

$M_{critical} \approx m^2_{pl}/m$ _ M_{KAUP}

➔ For m ≈ 5 keV ➔ $M_{critical} \approx 10^{-14}$ M_ and _$_{compton}$ ≈ 2 Å ›› R ≈ 0.2 Å

The bounces of the condensate need not to be isotropic, especially when total angular momentum **L ∴ 0**
➔ bounce preferably in the direction of **L**
➔ we expect for each bounce a pair of blobs of the condensate ejected parallel to **L,**
which can take place repeatedly many times ➔ **2 jets** emanating from the GC.

*Nishiyama, Morita, Morikawa astro-ph/**04**03571*

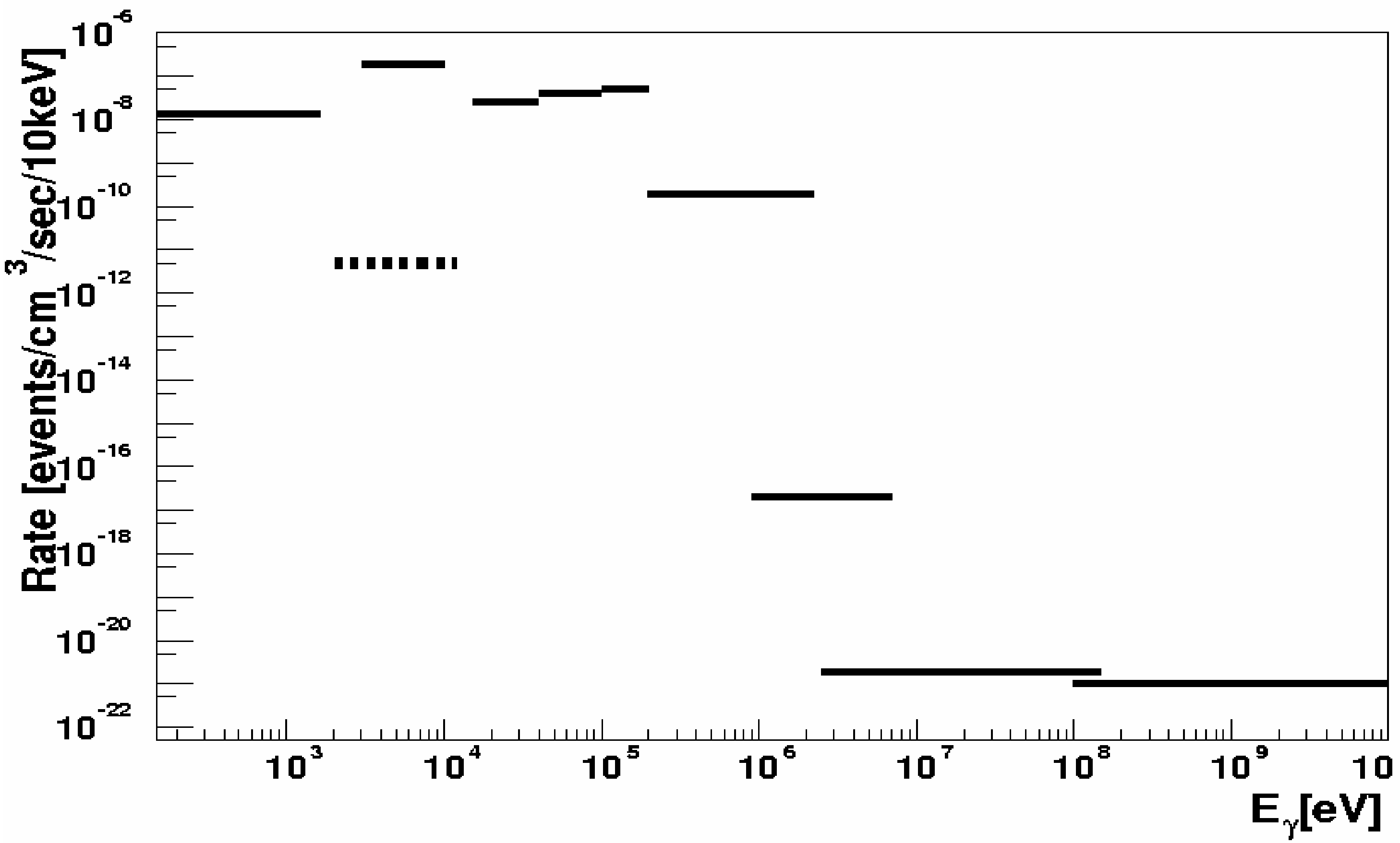
<u>**Solar KK-axions**</u> ➔ _$_{dB}$ = 0.2 μm (m=3 keV/c^2, v = 600 km/s & _=10^{16} a's/cm^3)

➔ _ > 100 KK-axions / (_$_{dB}$)^3 ➔ **??**

ROSAT, Ge, Solar X-rays, KamLAND, SuperKamiokande, EGRET

→ **Search for 1- or 2-prong events**

→ ***First exclusion plot***



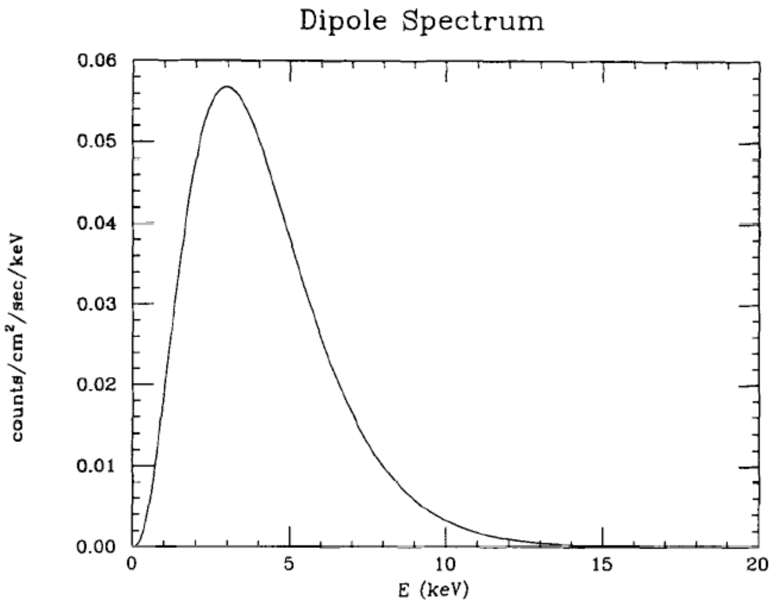
Dafni, Hoffmann, Jacoby, Z.

*Proc. MG-10, Rio De Janeiro (**2003**)*

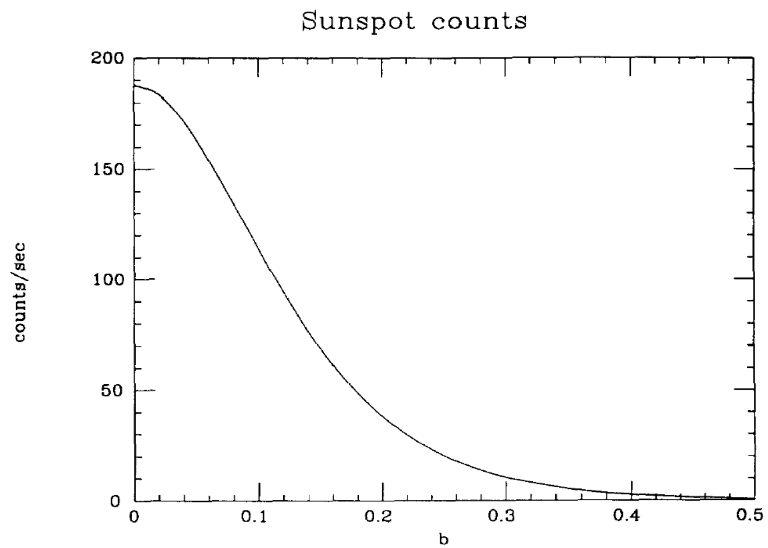
Pseudoscalar conversion and X-rays from the sun

Carlson & Tseng , Phys. Lett. B 365 (1996) 193

… on the conversion of pseudoscalars produced in the sun's interior in the presence of the sun's external magnetic dipole field and sunspot-related magnetic fields. We find that the sunspot approach is superior. Measurements by the **SXT/Yohkoh** can measure the coupling constant down to $g_{a\_\_}$ = 0.5-1x10^{-10} GeV^{-1}, provided m < 7x10^{-6} eV.



The expected X-ray signal due to pseudoscalar-photon conversion in the sun's general dipole field, taking $g_{a\_\_}$ = 10^{-10} GeV^{-1} and B_P = 1 Gauss.



The expected X-ray count rate detected by Yohkoh's unfiltered SXT due to pseudoscalar-photon conversion in the magnetic field of a sunspot ($g_{a\_\_}$ = 10^{-10} GeV^{-1} & _=10^{23} maxwells). The sunspot's center defines the impact parameter bR_{solar}.

Unfortunately, the signal is dominated by background, which for such a large sunspot would be of the order of 4100 counts/s.

Search for ~ massless solar axions ⊗ $\mathbf{B}_{sun}$

➔ limits for $g_{a\_\_}$ & m_{axion}

"**Magnetic fields** play a crucial role in heating the outer atmospheres of the Sun and Sun-like stars, but ***the mechanisms by which magnetic energy in the photosphere is converted to thermal energy in the corona remain unclear."***

- ➔ **Magnetic reconnection**
- ➔ **mixed-polarity regions**

Schrijver et al., Nature 394 (**1998**) *152*

"The corona is a magnetically dominated environment. … Our findings favour turbulent breaking and reconnection of magnetic field lines as the ***heating mechanism*** of the diffuse solar corona."

Priest et al., Nature 393 (**1998**) *545*

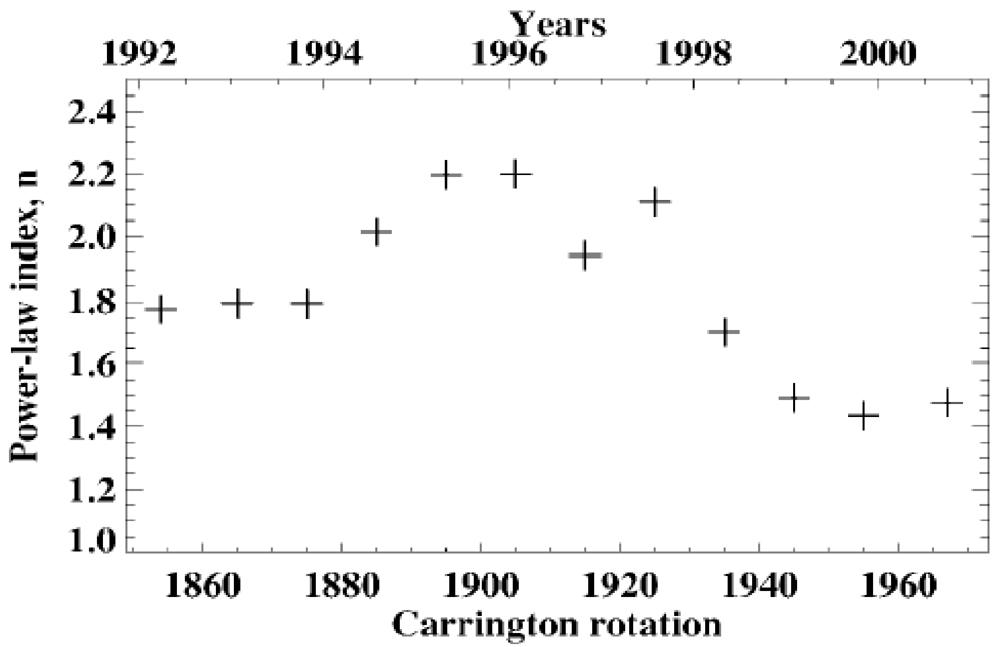
"Theoretical arguments suggest that are magnetic structures on scales < ***km*** in the Sun's photosphere."

Thomas, Nature 420 (**2002**) *134*

Flares and X-ray jets on the Sun arise in active regions … The interactions are believed to occur in ***electric current sheets*** separating regions of ***opposite magnetic polarity*** … (?) act as an important ***source of coronal heating*** … a complex magnetic field structure ….

Solanki, Lagg, Woch, Krupp, Collados Nature 425 (**2003**) *692*

➔ input for $\mathbf{P}_{a\rightarrow\_}$ **?**



Power-law index, ***n***, of the $\mathbf{I_{AlMg}} \sim \mathbf{B}^{n}$ 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*

➔ **Coherent axion-to-photon conversion ~ $(\mathbf{LB})^2$** ➔ Hoffmann & Z. *in preparation.*

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

2) interaction with $\mathbf{B}_{SOLAR}$ ➔ also local effects

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

➔ **?** 11-years solar cycle **?**

RHESSI

April 16 to 18, 2004

pointing was offset toward a fictitious target near the Sun.
***Solar data should not be used*, …** may be usable for some purposes, ….
potential users should communicate with the instrument team

June 16 2003 ➔ **Off-pointing to the Crab Nebula successful !**
Sun at least partially visible to RHESSI's grids

May 8th & 23rd **Off-pointing tests … up to 3^0 from the Sun.**
Data should not be used for solar studies.

RHESSI Characteristics

Energy Range :	3 keV - 15 MeV
Energy Resolution (FWHM) :	< 1 keV @ 3 keV, 5 keV @ 15 MeV
Angular Resolution :	2 arcsec to 100 keV, 7 arcsec to 400 keV, 36 arcsec to 15 MeV
Temporal Resolution :	Tens of ms for basic image, 2 s for detailed image
Field of View :	Full Sun
Effective Area [cm^2]:	10^{-3} @ 3 keV, 50 @ 10 keV (attenuators out), 60 @ 100 keV, 20 @ 10 MeV

Radiative decay of solar massive particles

➔ e.g. KK-axions (*generic example*)

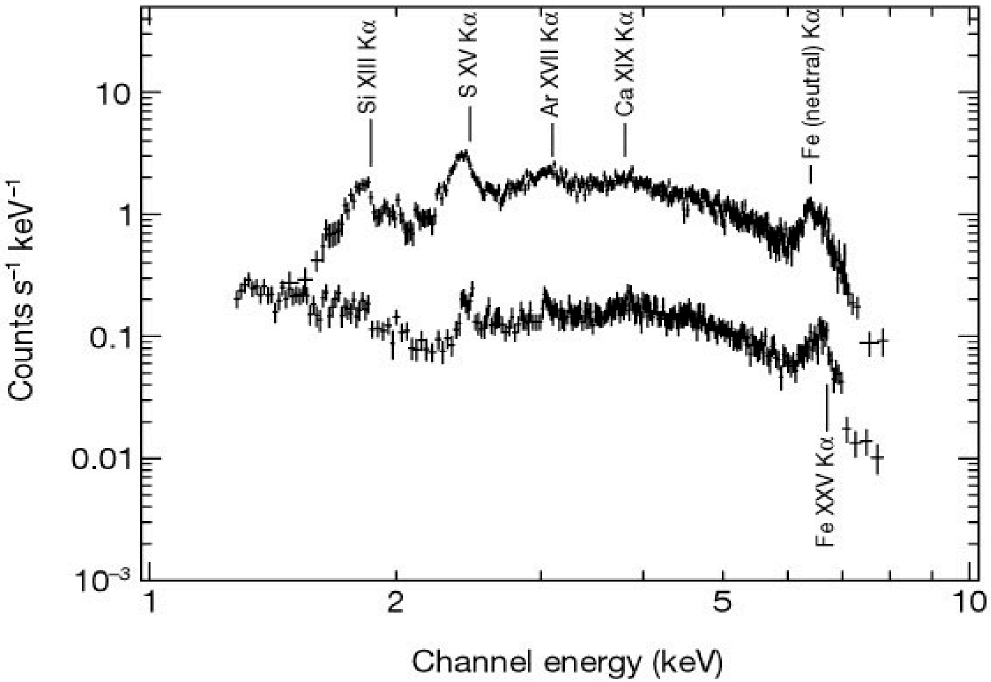
Search for contradictions - implications **beyond the Sun**, e.g.:

Galactic Center
Clusters of Galaxies ➔ S-Z effect
XRB radiation

Decaying KK-axions mimic a not existent plasma component
➔ + a permanent heating source ➔ manipulate the real plasma

Galactic Centre,

*Wang, Gotthelf, Lang Nature **415** (2002)148*



Point-source (lower) and ***diffuse emission*** (**upper**).

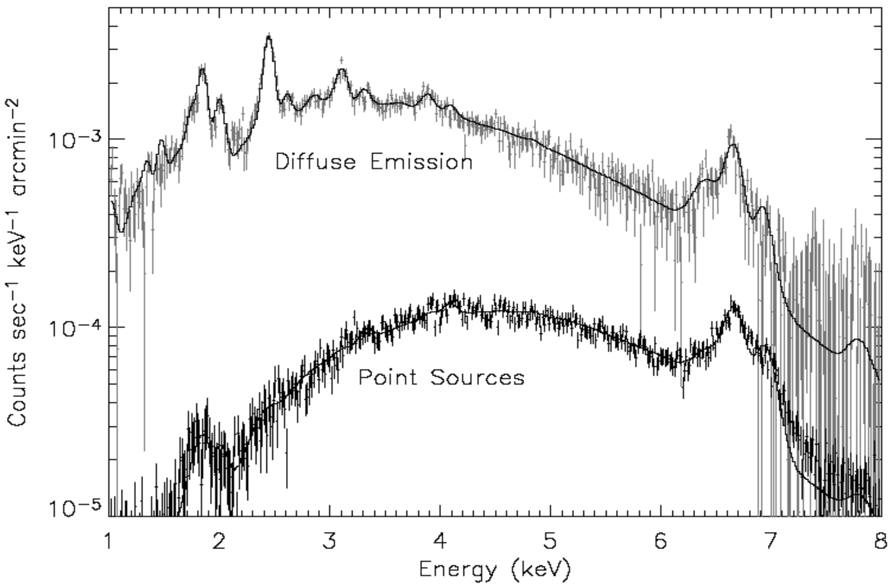
➔ The origin of the X-ray emission … a **mystery**

Also ➔ Hands et al. (**2004**): in the 2–10 keV band, 80% of the ridge emission is probably ***diffuse***, and only 9% can be accounted for by Galactic sources.

*Strong, Diehl, Halloin, Schönfelder, Bouchet, Mandrou, Teegarden, Lebrun, Terrier astro-ph/**04**05023*

"***The temperature*** (>7 keV) is much higher than that from supernova shocks
➔ **too high** for the plasma **to be gravitationally bound** to the Galactic disk.

*Ebisawa, Maeda, Kaneda, Yamauchi SCIENCE 293 (**2001**)1633*



DIFFUSE X-RAY EMISSION IN A DEEP Chandra IMAGE OF THE GALACTIC CENTER

Muno et al., ApJ. (20.9.**2004**) *(astro-ph/0402087)*

…this soft plasma is probably heated by supernovae, along with a small contribution from the winds of massive Wolf-Rayet and O stars.

The hotter, kT ~ 8 keV component is more spatially uniform…

Neither supernova remnants nor WR/O stars are observed to produce thermal plasma hotter than ~3 keV. Moreover, a kT ~ 8 keV plasma would be too hot to be bound to the Galactic center, and therefore would form a slow wind or fountain of plasma.

...alternative explanations for the ~8 keV diffuse emission are equally unsatisfying. The hard X-rays are unlikely to result from undetected point sources, because no known population of stellar object is numerous enough to the observed surface brightness. There is also no evidence that non-thermal mechanisms for producing the hard emission are operating, as the expected shifts in the line energies and ratios from their collisional equilibrium values are not observed. We are left to conclude that either there is a significant shortcoming in our understanding of the mechanisms that heat the interstellar medium, or that a population of faint (< 10^{31} erg s_1), hard X-ray sources that are a factor of 10 more numerous than CVs remains to be discovered.

1) For **massive clusters**, **self similar** models (gravity and shock heating of the gas) predict :

$$L_x \sim T_x^2$$

The observed relation is much steeper :

$$L_x \sim T_x^{2.6\text{-}3.0}$$

➔ *"additional" gas physics ?*

2) The source(s) of the **"excess" entropy** is still not known.

S-Z effect is extremely sensitive to the presence of an entropy floor of the ICM.

➔ analysis indicates that the entropy of the ICM has been significantly raised by some ***non-gravitational process(es).*** This corresponds to a thermal energy of a few keV per particle for massive clusters. This means that SNe explosions probably cannot the sole contributor to the entropy floor, since they are expected to impact ≤0.3 keV per particle.

3) "X-ray Observations Deepen **Mystery** of What Happens in the Cores of Galaxy Clusters". Huge amounts of gas in cluster cores should cool and collapse @ 100-1000 M_o / year. Cold material and enhanced star formation ➔ is by an order of magnitude too low, i.e., large amounts of gas are not cooling completely.

➔ **a universal feedback mechanism ?**

Something stops most of the plasma from cooling beyond 1/3 of the initial temperature

C. Day, Physics Today (March **2003***) 16*
s. also S. Peng Oh, astro-ph/0404345

The bulk of the mass in clusters is in the form of non-baryonic DM

➔ only 20-30% of the total mass is in the form of visible matter.

Observations of the **S-Z** effect are becoming increasingly accurate.

The S-Z effect is dominated by the Compton parameter

$$y = \_{T} \int \_{e} kT_e \, dl$$

"*X-ray observed temperatures should be used with great caution in the study of* **S-Z** *observations*"

*Hansen, astro-ph/***04***01391*

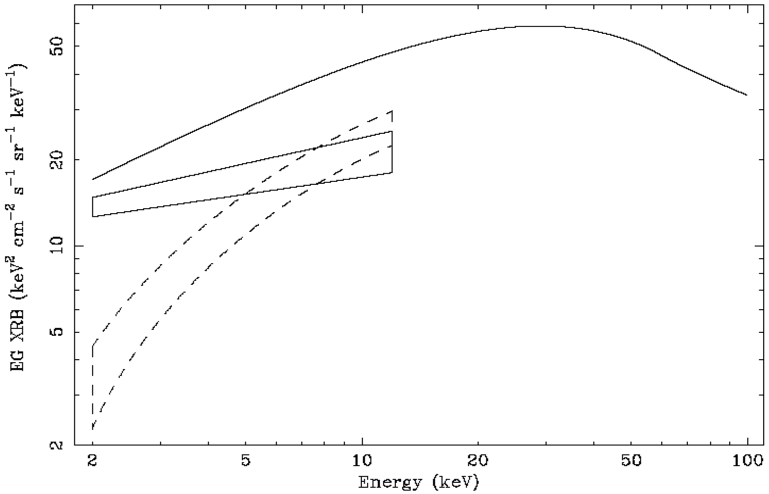
This work ➔ T_e and $\_{e}$!

S-Z effect ⊗ X-rays ➔ *new information*

- ***Sunyaev-Zeldovich* = *f(z)* ➔** *the entropy history of the gas.*
- *Estimates of cluster masses from gravitational lensing very often differ from those determined from X-ray data (sometimes by up to a factor of 2).*

McCarthy, Babul, Holder, Balogh ApJ. 591 (**2003**) *515, 526*

*Worsley, Fabian, Barcons, Mateos, Hasinger, Brunner, astro-ph/***04***04273*



The total extragalactic **XRB** (HEAO-1, 1999).

Solid region = resolved spectrum.
Dashed region = residual unresolved component.

➔ " *... only ~50% above 7 keV is resolved and we are* ***missing*** *a considerable population of faint, hard ... heavily absorbed AGN.*"

XRB spectrum fits remarkably well thermal Bremsstrahlung at a temperature of ~30 keV.
➔ Isotropic @ a true cosmological origin.

The lack of spectral distortions of the CMB ruled out the presence of substantial amounts of intergalactic gas at this very high temperature needed to produce the CXRB through thermal Bremsstrahlung.

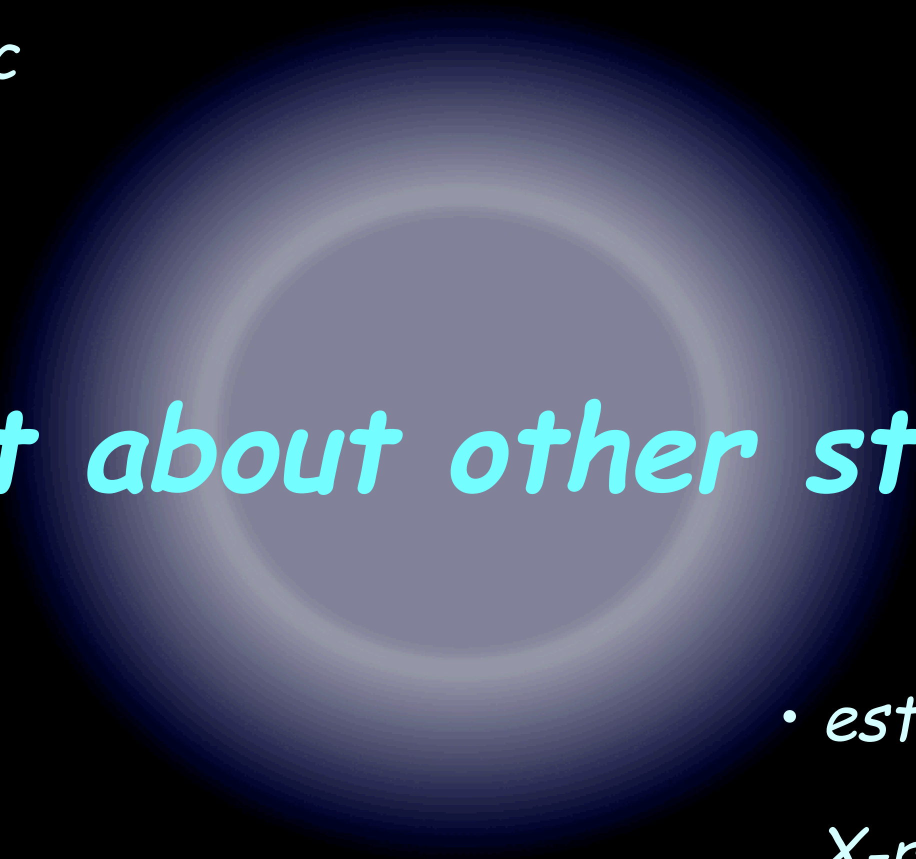
Barcons, astro-ph/0306411

➔ **?** ***diffuse component from decaying massive particles*** **?**

Predicted observable properties of an axion induced X-ray halo around the Sun

K. Dennerl

- *characteristic morphology*
- *temporally constant*

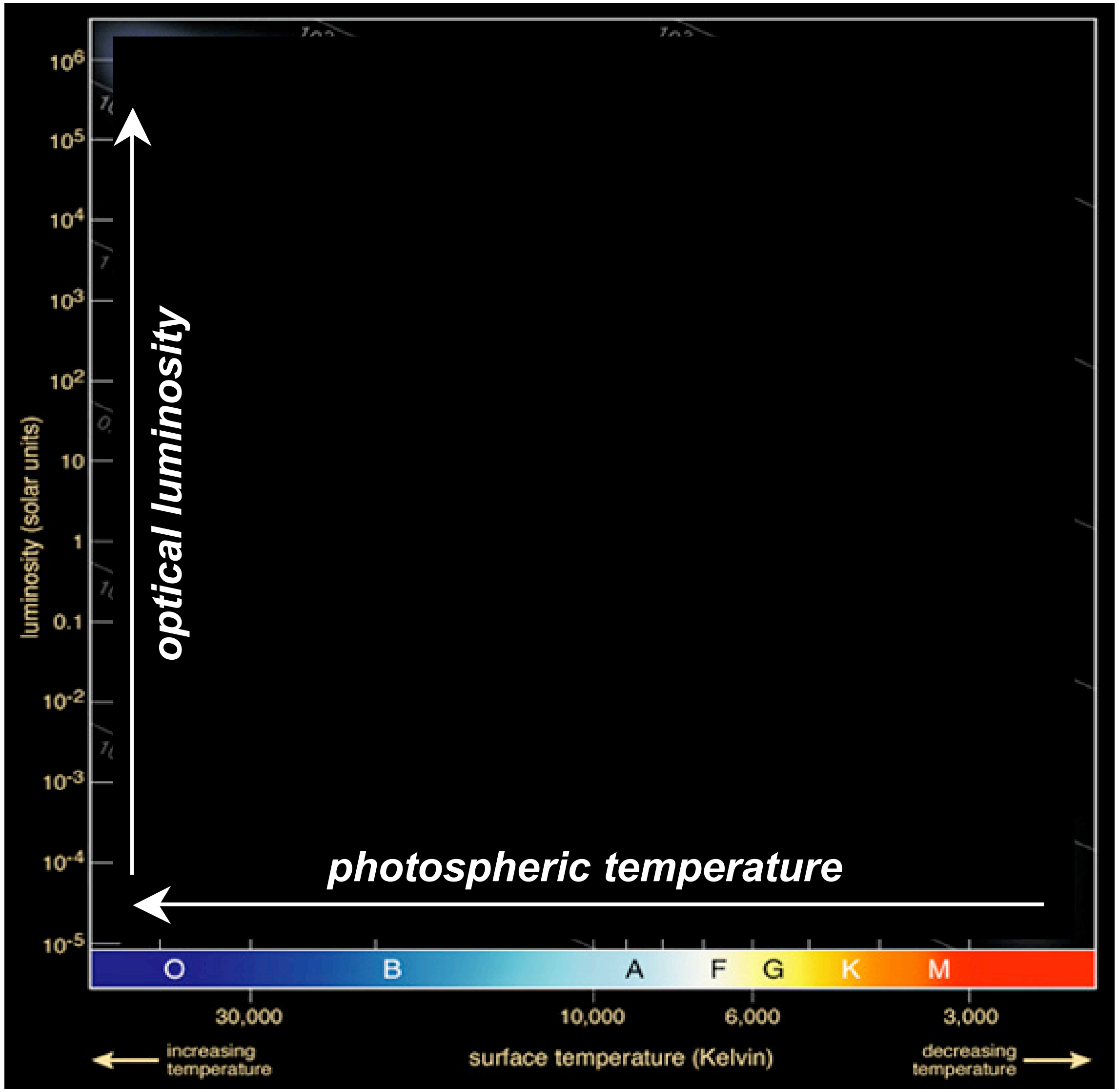


What about other stars ?

- *hard X-ray spectrum*
- *estimated total X-ray luminosity:*

$L_x \sim 4 \cdot 10^{25}$ erg/s

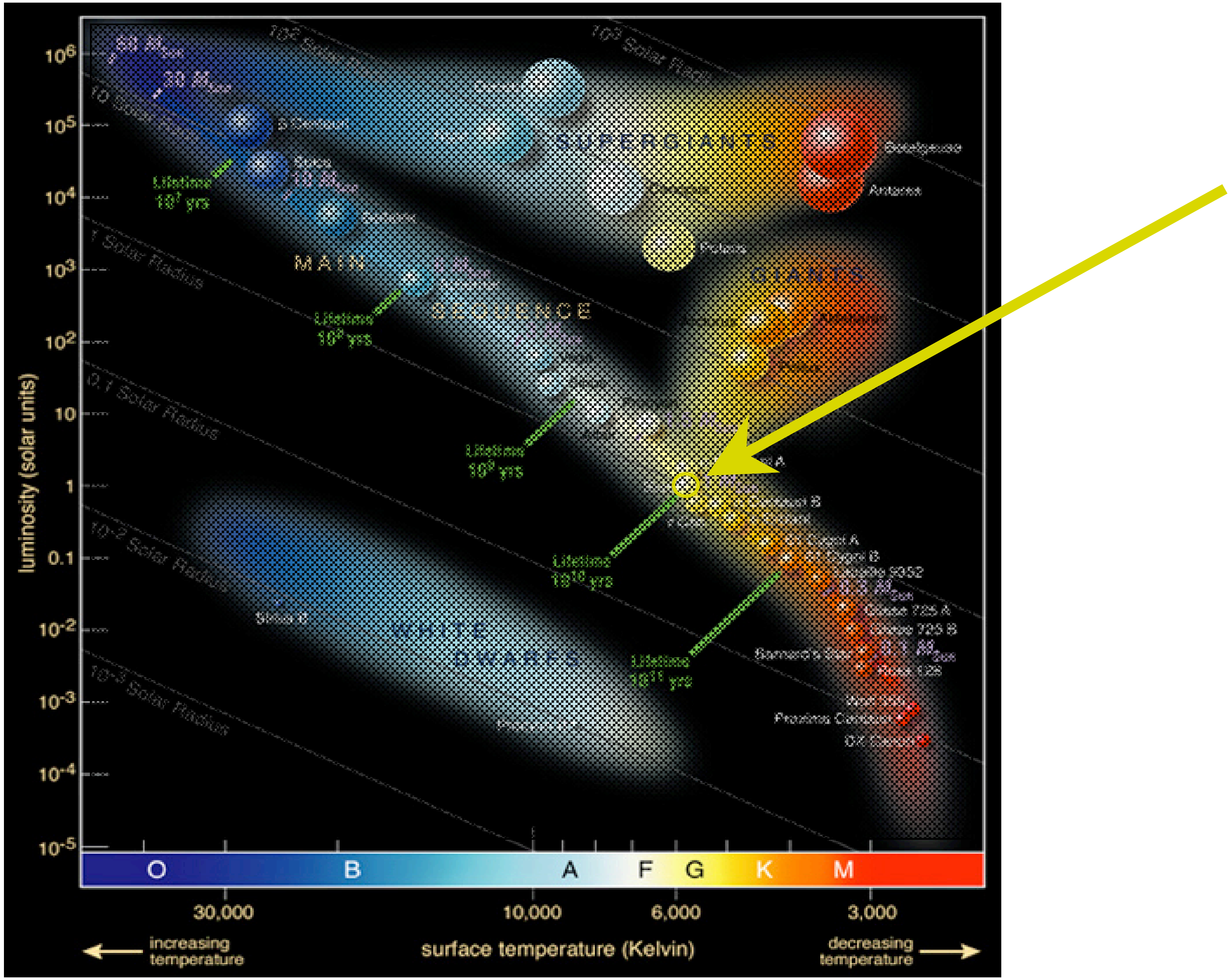
Axion halos around other stars ?



Hertzsprung Russell Diagram

http://physics.njit.edu/~dgary/202/Lecture17.html

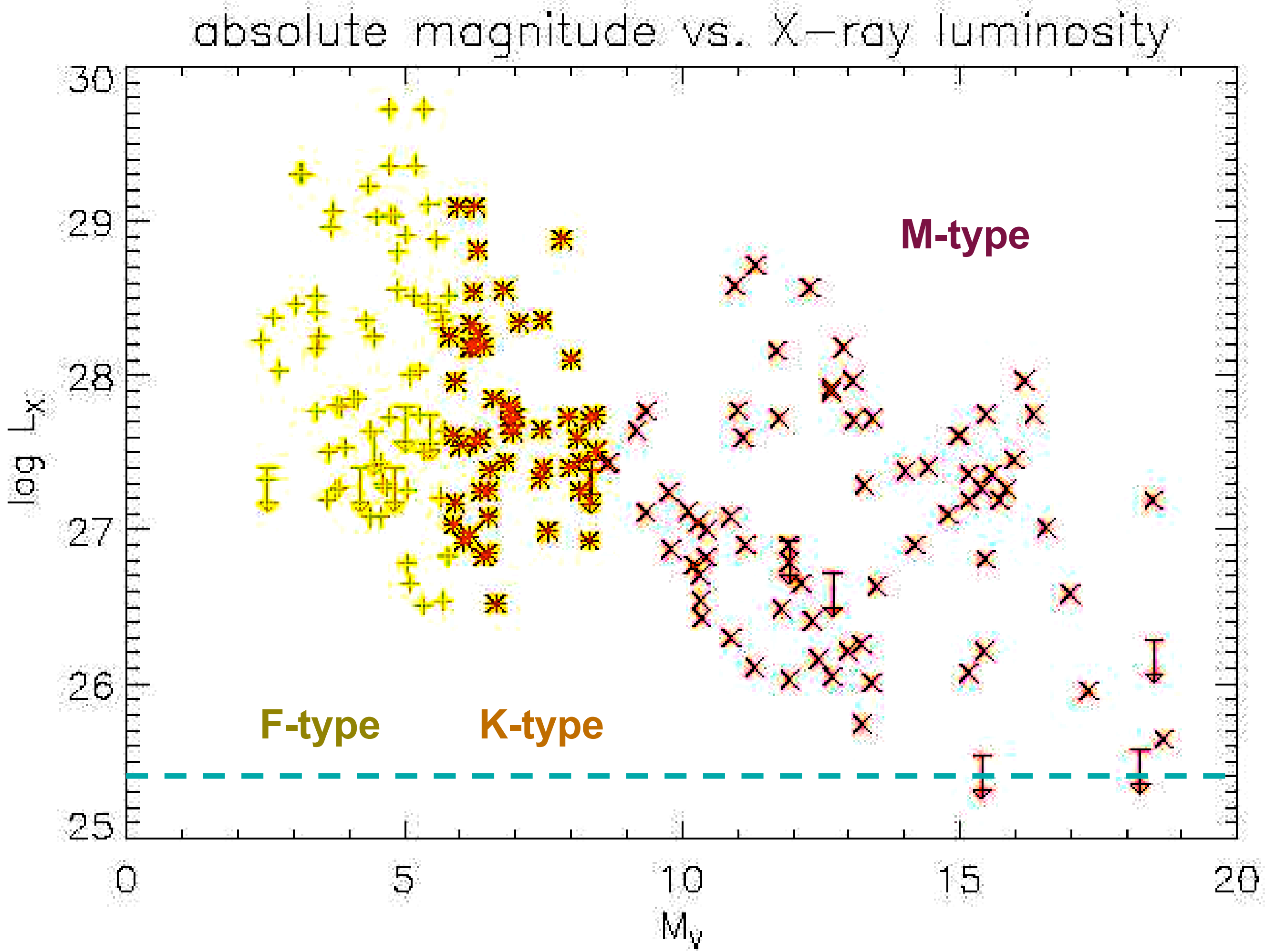
Axion halos around other stars ?



Sun

http://physics.njit.edu/~dgary/202/Lecture17.html

Axion halos around other stars ?

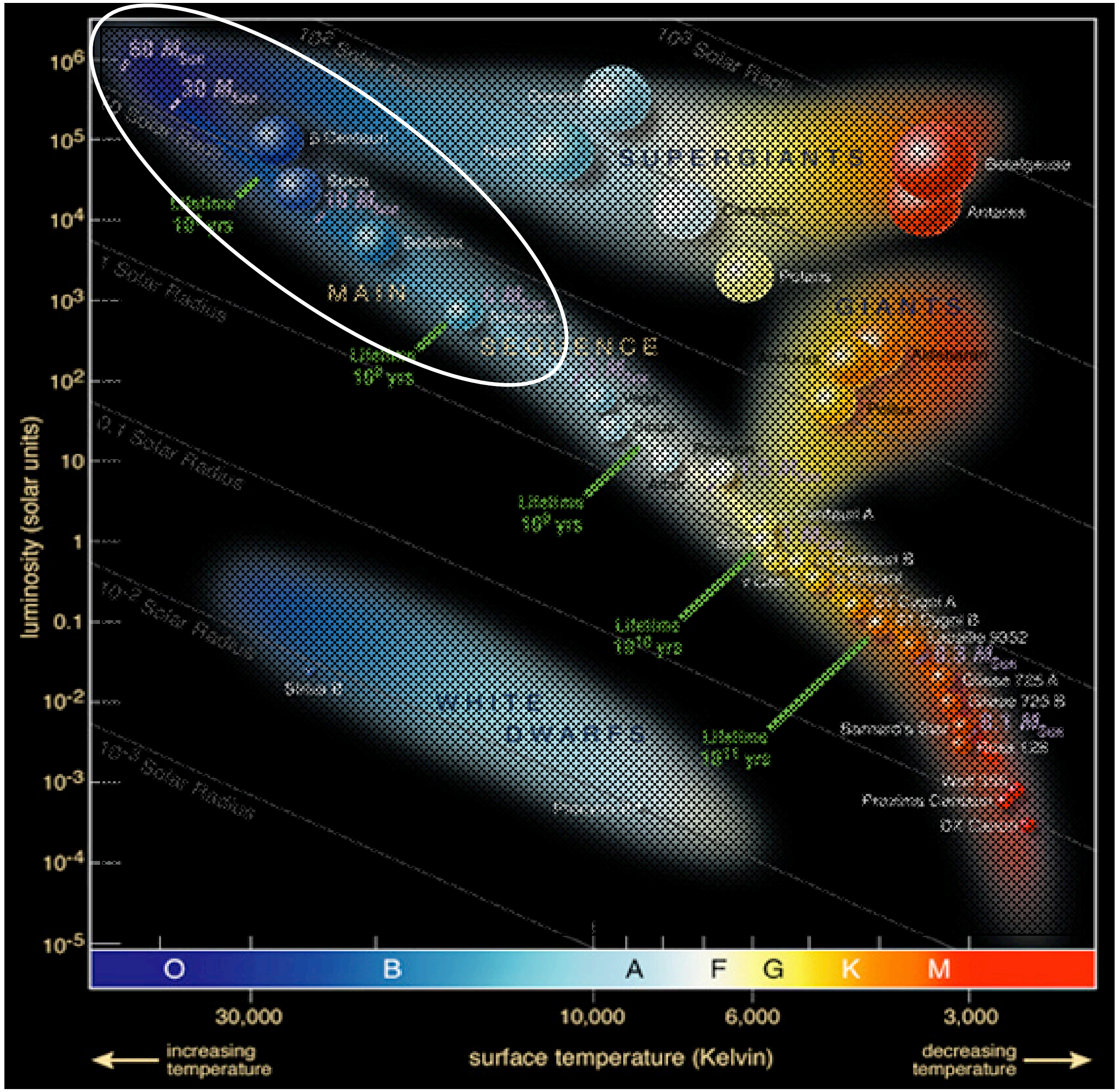


X-ray luminosities for nearby cool stars

„X-ray dark solar-like stars do not exist (at least within the immediate solar environment)"

Schmitt, IAU Symp 219 *(2004) 187-198*

Axion halos around other stars ?



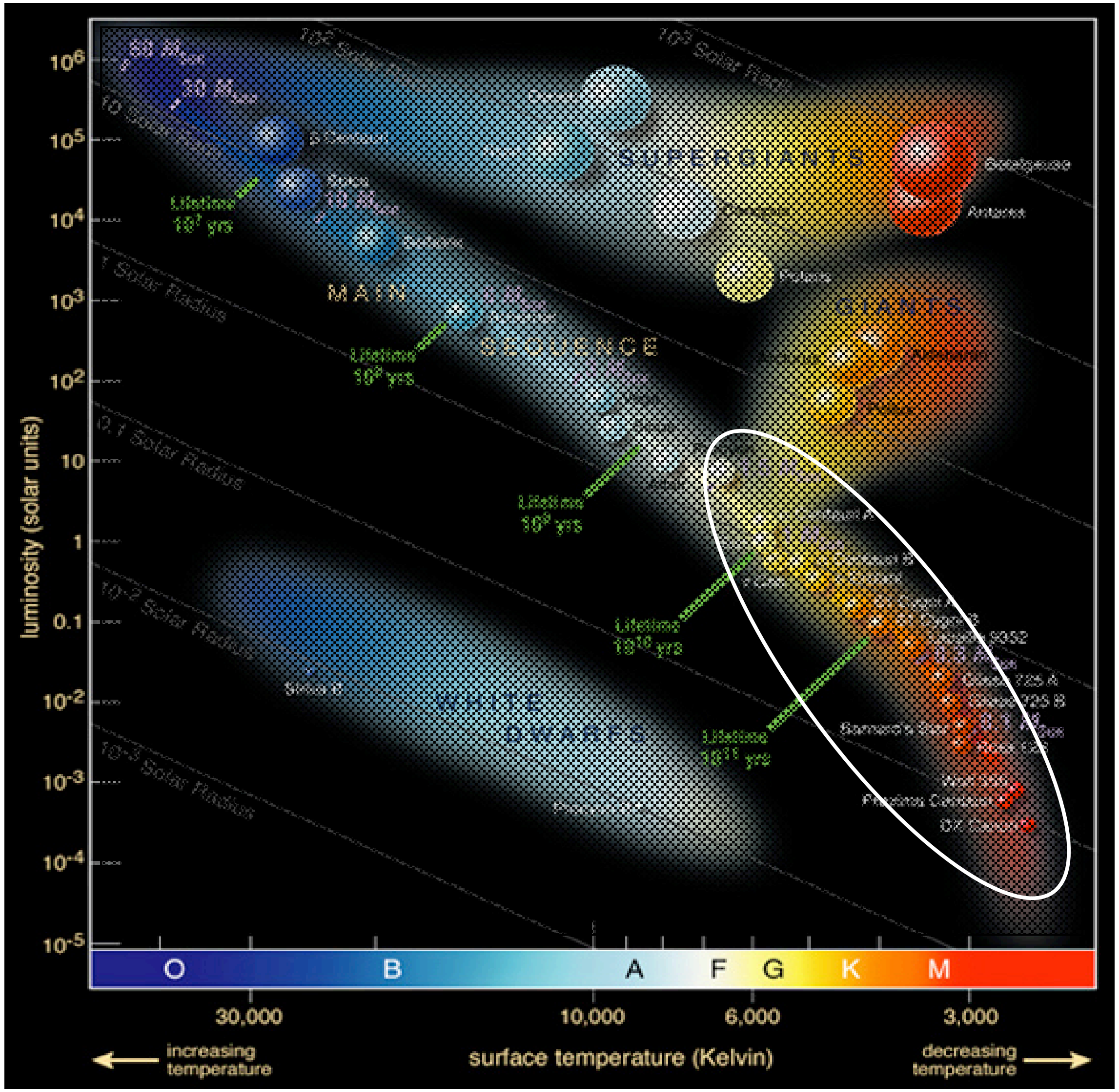
http://physics.njit.edu/~dgary/202/Lecture17.html

K. Dennerl / MPE

„X-ray emission is very common from early-type stars of spectral type O and B. The X-ray emission from these stars is thought to originate from instabilities in their radiatively driven winds.“

Schmitt, IAU Symp 219
(2004) 187-198

Axion halos around other stars ?



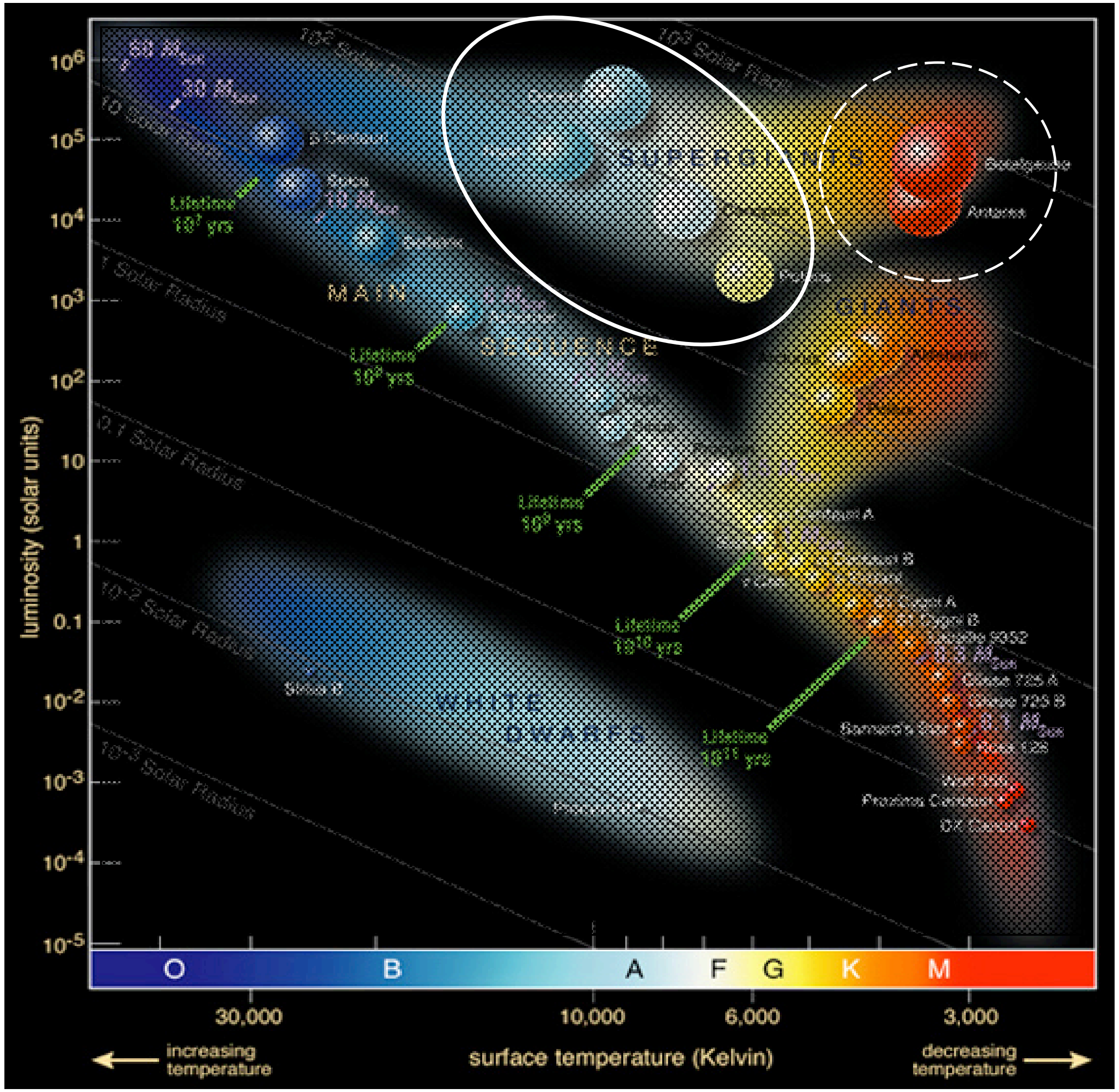
http://physics.njit.edu/~dgary/202/Lecture17.html

K. Dennerl / MPE

„X-ray emission is likely to occur for all stars down to the bottom of the main sequence.“

Schmitt, IAU Symp 219
(2004) 187-198

Axion halos around other stars ?



http://physics.njit.edu/~dgary/202/Lecture17.html

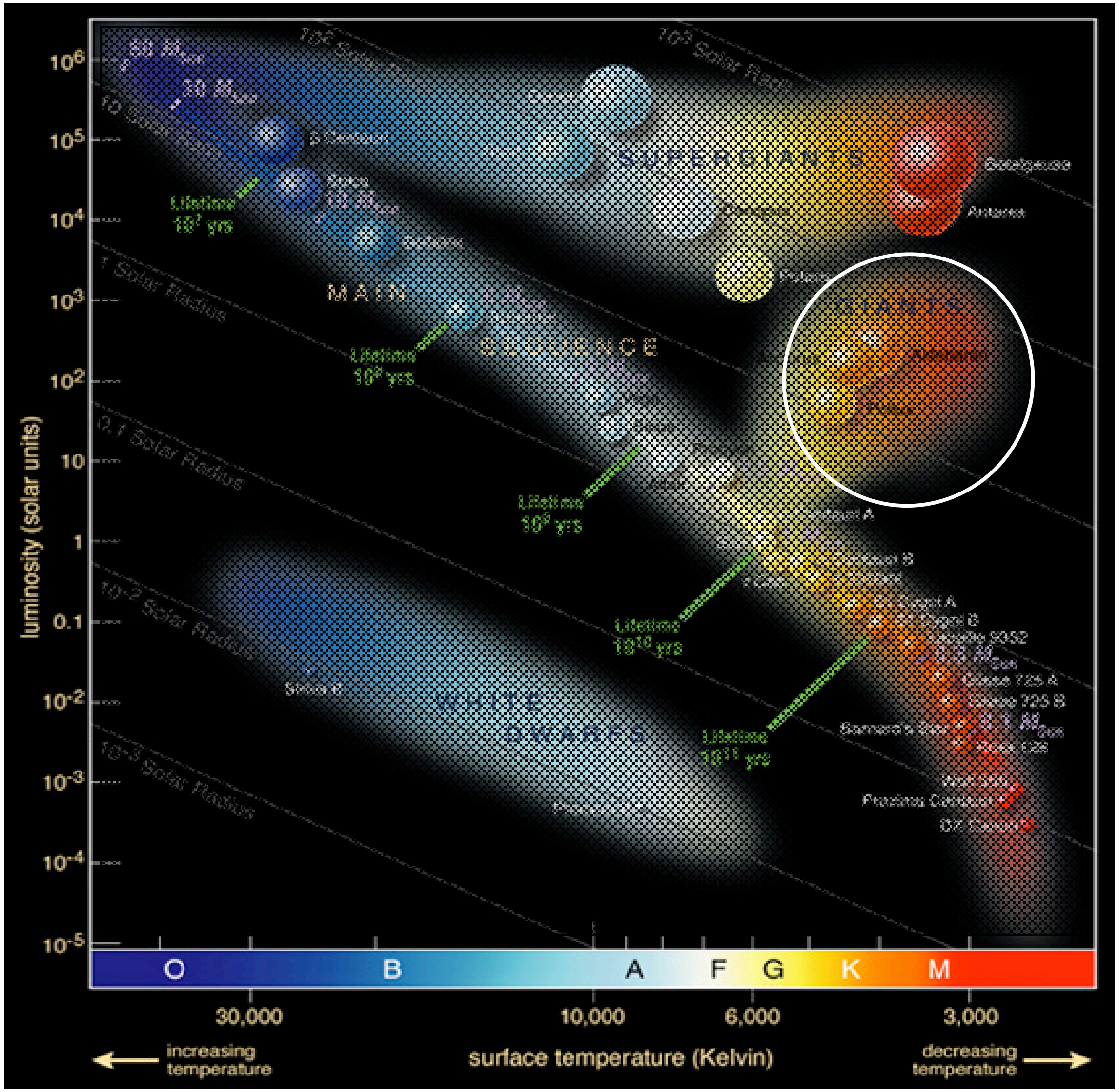
K. Dennerl / MPE

„X-ray emission for giants to the left of the dividing line seems to be ubiquitous.“

„The concept of a dividing line seems to disappear, however, among the brighter giants and supergiants.“

Schmitt, IAU Symp 219 ***(2004) 187-198***

Axion halos around other stars ?



http://physics.njit.edu/~dgary/202/Lecture17.html

K. Dennerl / MPE

„X-ray emission from M giants is extremely rare.“

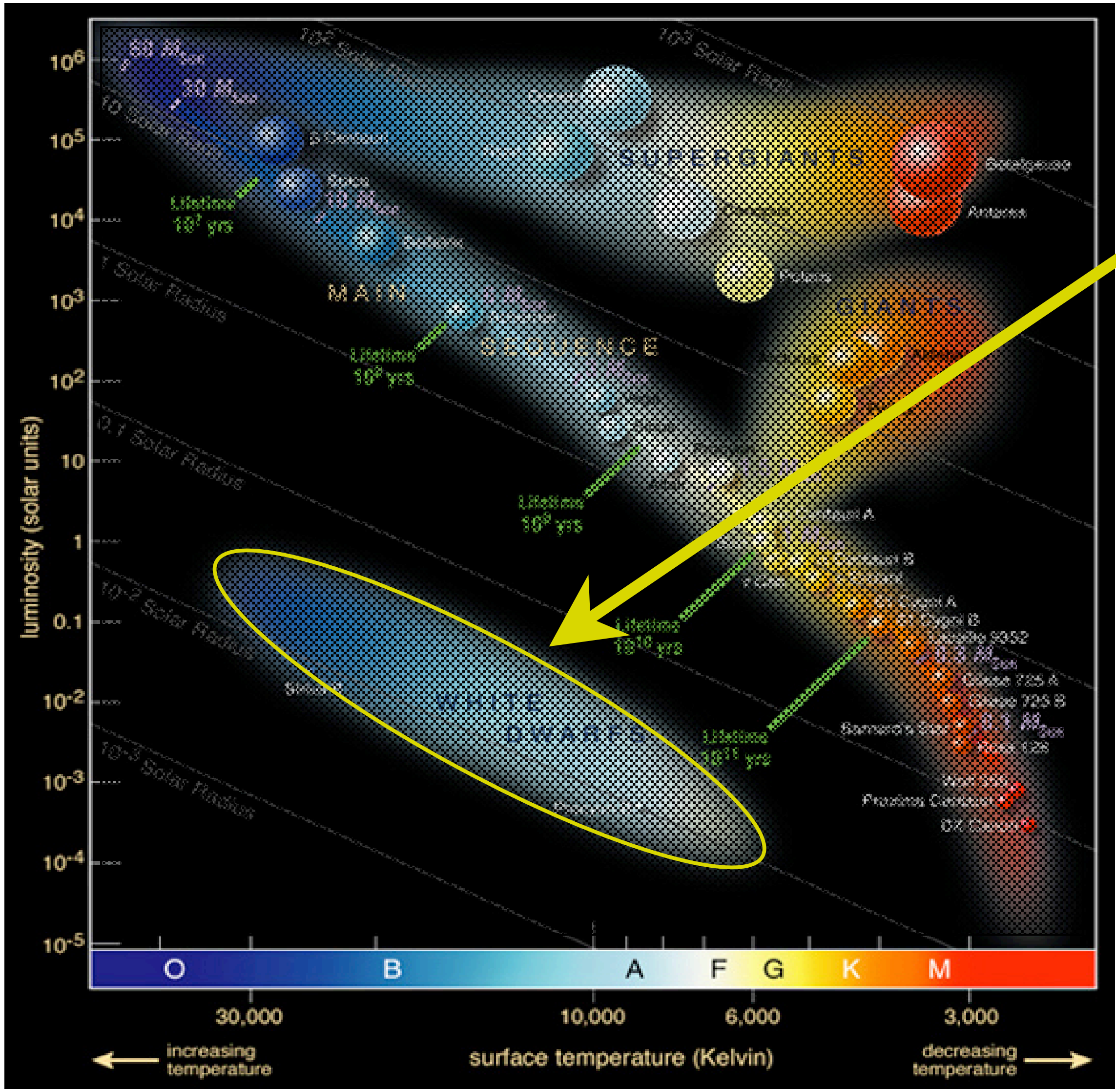
But extremely large luminosities in excess of 10^{30} erg / s have also been observed.

Lowest upper limit for Aldebaran.

Schmitt, IAU Symp 219 *(2004) 187-198*

Axion halos around other stars ?

K. Dennerl / MPE



http://physics.njit.edu/~dgary/202/Lecture17.html

White Dwarfs

X-ray luminosities:

$L_x \sim 10^{27} - 10^{34}$ erg s^{-1}

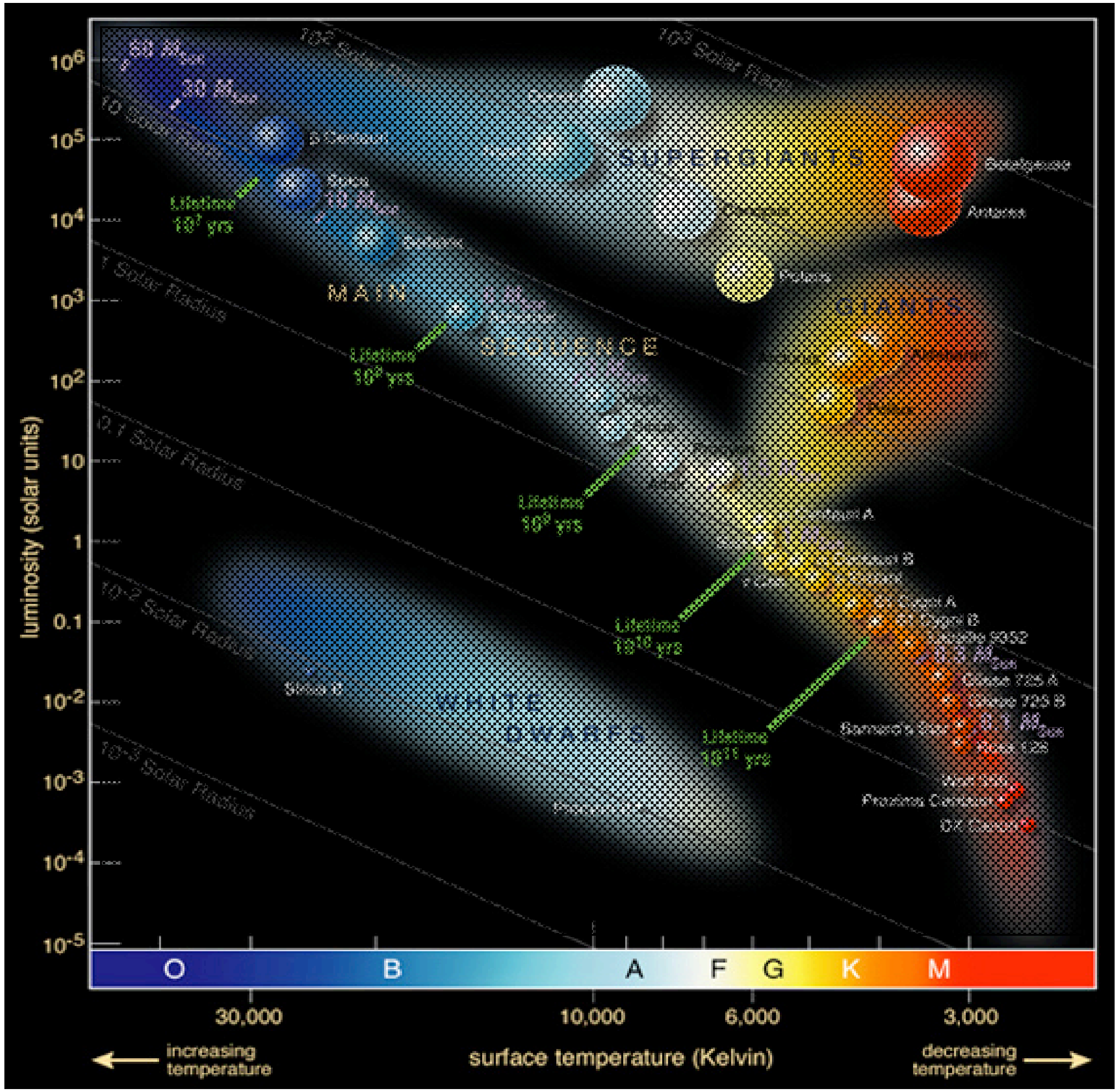
(sensitivity limit ?)

"White dwarfs are not expected to emit X-rays at energies greater than 0.5 keV, but numerous white dwarfs appear to be associated with hard X-ray emission. A small number of them appear to be single."

Chu et al. (2004), ApJ 127, 477-480

Axion halos around other stars ?

K. Dennerl / MPE



http://physics.njit.edu/~dgary/202/Lecture17.html

Neutron

stars

X-ray luminosities:

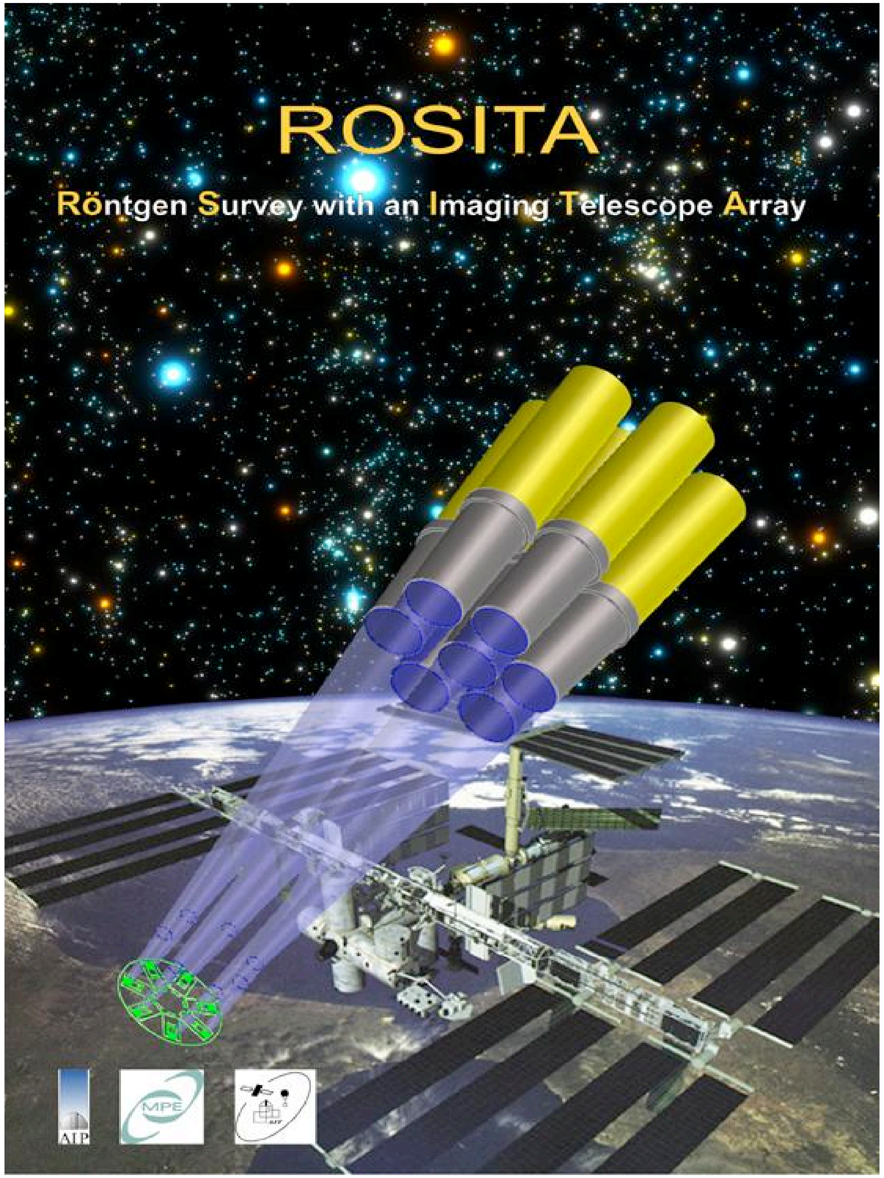
$L_x > 10^{27}$ erg s^{-1}

(sensitivity limit ?)

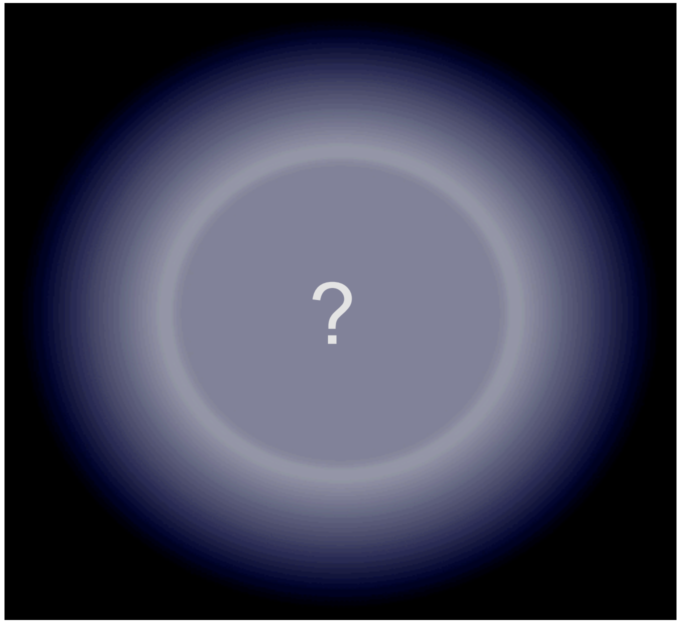
The quiet Sun in hard X-rays:

K. Dennerl / MPE

a target for ROSITA ?

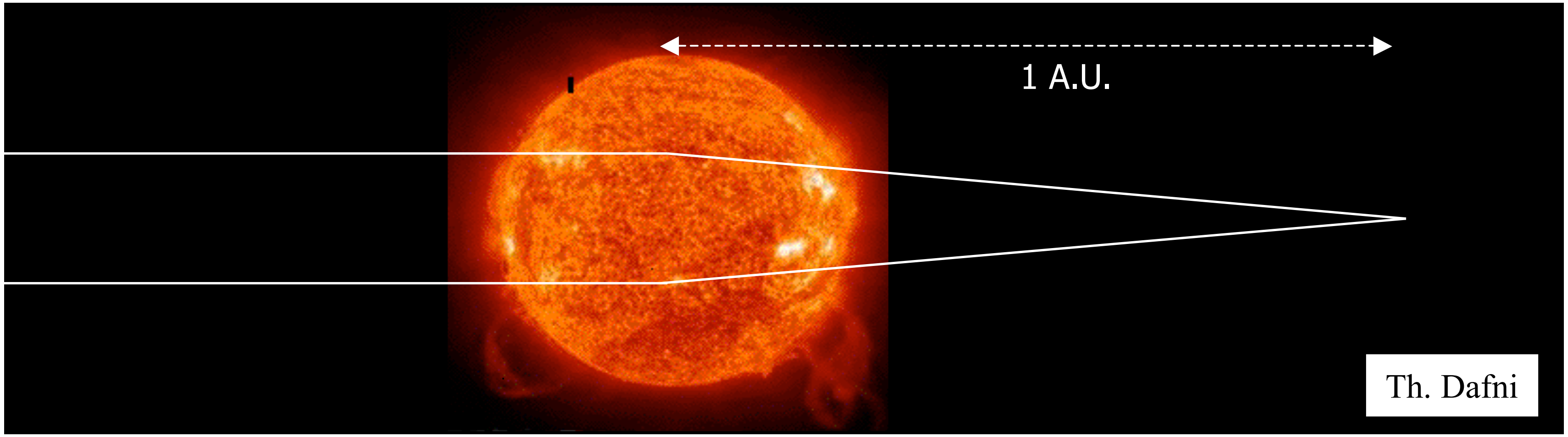


- energy range: ~0.5 – 11 keV
- inividual field of view: 43' x 43'
- telescope resolution: < 1 arcmin
- optical filter between the baffle and the mirror module (!)



Gravitational lensing by the Sun of non-relativistic penetrating particles (of cosmic origin)

Hoffmann, Jacoby, Z. Astropart. Phys. 20 (**2003**) 73



No lack of data in dark matter research

➔ they do not fit the ***recoil spectrum*** and/or ***time modulation*** picture

➔ useless so far **!**

Single events ➔ not 2-prong events

_ ≈ 10^{-3} c - - - - ? ? ? - - - - - - _ _ ≈ c ✔

➔ **_ ≈ 0.25 c** ➔ **solar core = gravitational lens @ Earth** ➔ **x$10^{3\pm1}$**

New algorithm & energy range in dark matter experiments :

Search for burst-like events repeating each year ➔ **dark matter telescopes** ➔

Observations can be reconciled with gravitationally bound massive axions of the KK-type (*generic example*)

➔ suggestive for new searches in DM, Astrophysics & Cosmology :

- ➔ **solar X-rays** + correlations **?**
- ➔ 2-prong ⊗ volume ➔ TPC ➔ DRIFT
  + astrophysical shadows (Moon, Sun,…)
- ➔ 1-prong ⊗ volume ⊕ **B** ➔ TPCs @ LHC
- ➔ up-coming precise **S-Z** observations
- ➔ **burst like events** in DM (un)related observations
  repeating each year (beyond Fourier-analysis)
  ……………………………………………
- ➔ *missing, unknown origin, excess, mystery*

Sun's halo linked to dark matter particle

A MYSTERIOUS X-ray glow that surrounds the sun may be evidence for the existence of an exotic particle that physicists have been hunting for decades.

Astronomers have been puzzled by the sun's X-ray halo since it was first detected in the 1940s. Curiosity deepened when the Japanese satellite Yohkoh, launched in 1991, sent back X-ray pictures showing spectacular flares streaming from sunspots and a gentle glow emanating from the sun's outer atmosphere.

But the surface of the sun is not hot enough to produce such a bright X-ray glow. So where are the X-rays coming from? Konstantin Zioutas and his colleagues think that heavyweight particles called axions could be the source.

Zioutas, a theorist who works at the University of Thessaloniki in Greece and the CERN particle physics laboratory in Geneva, Switzerland, suggests that the X-rays are produced by the decay of axions. According to his team's model, axions are created in the hot core of the sun and expelled, only to become trapped by the sun's gravity. The physicists have calculated the rate at which axions might accumulate around the sun and combined it with an estimate of how quickly they might decay. This predicts how the brightness of the X-ray halo should change with increasing distance from the centre of the sun.

"Axions were dreamed up in the 1970s to explain anomalies in the way nuclear forces behave in experiments"

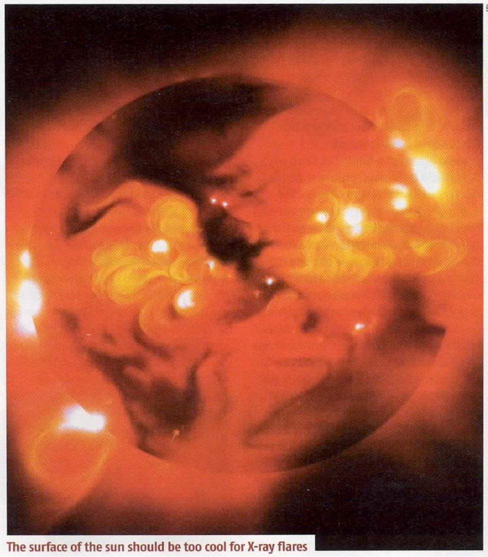
In a paper to be published in *The Astrophysical Journal* next month, Zioutas and his colleagues report that the predictions match brightness measurements made by the Yohkoh satellite.

The catch is that no one is sure axions even exist. Axions were dreamed up in the 1970s to explain differences between the way nuclear forces behave in experiments, and the way theories predict they should. The search for them intensified in the 1980s when cosmologists realised that axions could be the missing dark matter that holds the universe together. But they are predicted to interact with other matter only weakly and no axions have ever been detected.

Have Zioutas and his colleagues finally managed to pin them down? "It's exciting," says Pierre Sikivie, a theorist in the physics department at the University of Florida in Gainesville, "but I don't think the evidence presented can, at this point, be considered proof that axions exist." There may be a simpler explanation for the origin of the solar X-rays.

Until all the alternatives have been ruled out, says Leslie Rosenberg, head of an axion-hunting experiment at Lawrence Livermore National Laboratory in California, assuming that axions are responsible for the sun's X-ray glow is "like coming home, seeing the door to your house open and saying, 'Oh my God, Martians must have been here'". It's not wrong, but it is wildly speculative.

Rosenberg also cautions that Zioutas's model relies on a type of axion that can only exist in a universe with more than four dimensions – and so far we have no evidence for extra dimensions in ours. **Jenny Hogan** ●



The surface of the sun should be too cool for X-ray flares

SOUNDBITES

"This case represents an extraordinary decision by a woman in labour."

A doctor at Dr Manuel Velasco Suarez Hospital in San Pablo, Mexico, on a patient's decision to perform a Caesarean on herself (BBC Online, 7 April)

"We all have a need to decorate Mother Nature because it belongs to us all."

Marco Evaristti, Danish artist, after painting an iceberg red in Greenland (Associated Press, 26 March)

"Animals are more tactile and supportive. The workplace is seeing less of that these days."

Psychologist Cary Cooper on a Zoological Society of London plan to ask volunteers to mimic chimp behaviour at work (BBC Online, 7 April)

"It is as likely to happen next week as in a randomly selected week a thousand years from now."

Lindley Johnson of NASA tells the US Senate why it is important to search for objects that could hit the Earth (7 April)

"Our science has been in such a poor condition that it is simply unable to produce anything that can represent state secrets."

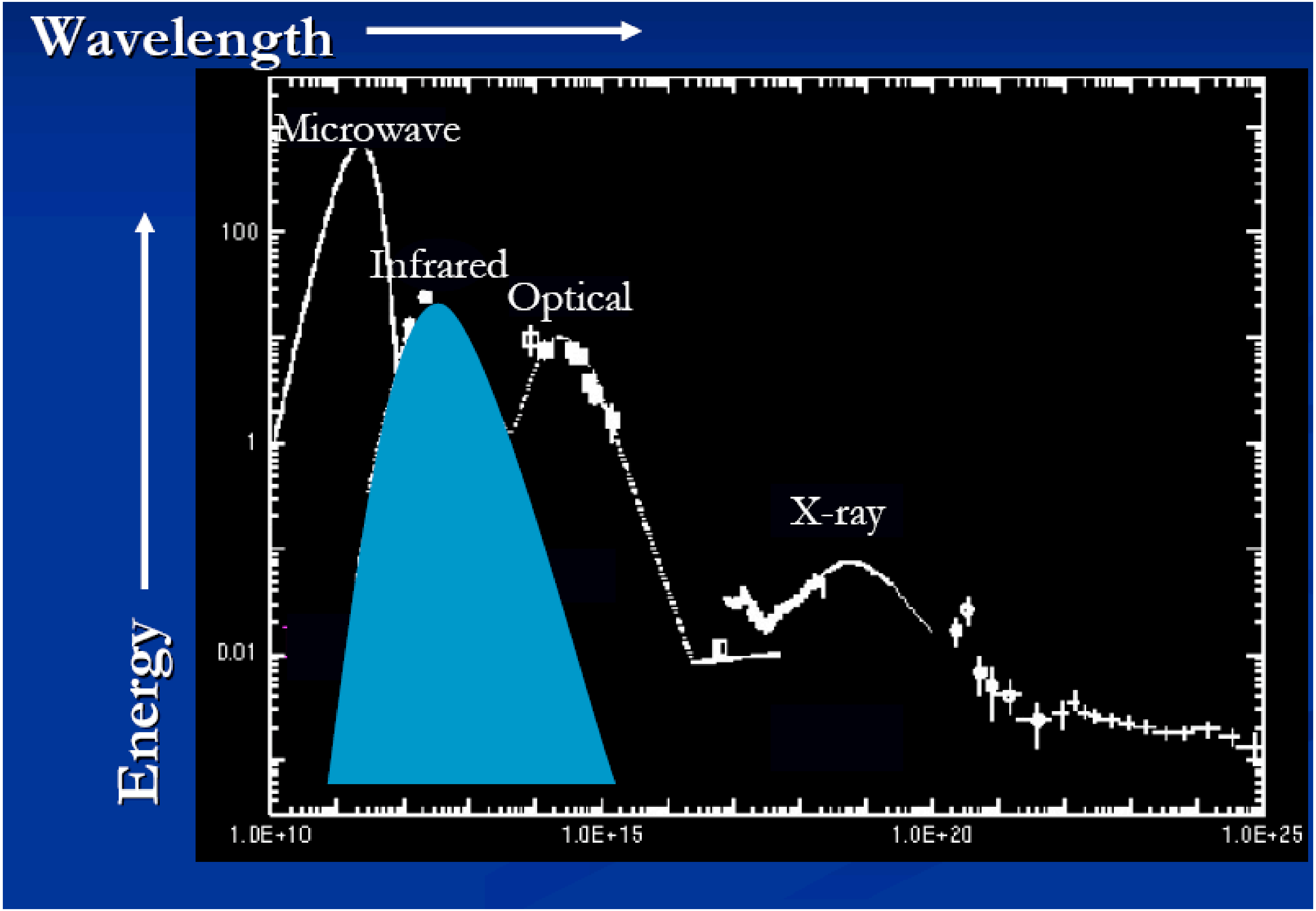
Physicist Valentin Danilov, who was cleared of spying last December, on the jailing of Russian nuclear weapons expert Igor Sutyagin for espionage (*The Moscow Times*, 7 April)

"Peter has been very clever at keeping undercover. They thought they would never see him again."

Natalie Pritchard of the Earthwatch Institute, after a celebrated penguin was found alive and well in South Africa. Peter rose to fame after being rescued from an oil spill in June 2000 (*The Guardian*, London, 7 April)

New Scientist,

17 April 2004



Wavelength
Energy
Microwave
Infrared
Optical
X-ray
100
1
0.01
1.0E+10
1.0E+15
1.0E+20
1.0E+25