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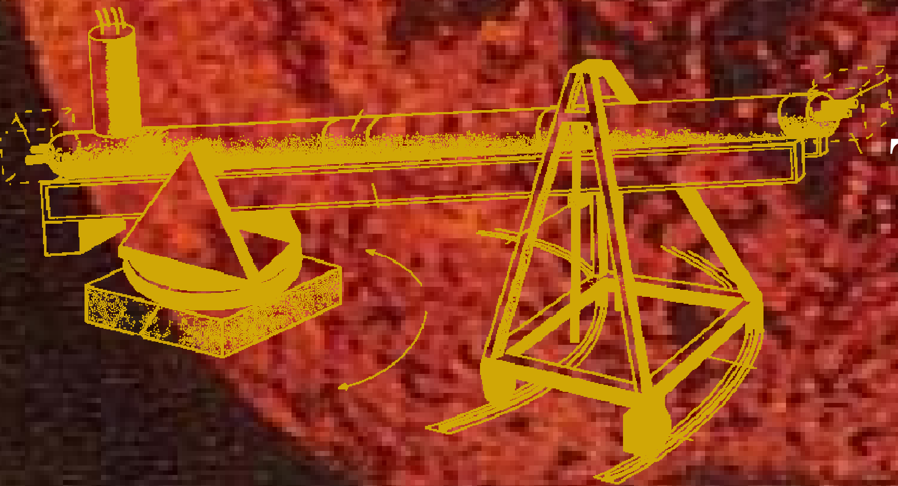
CERN AXION SOLAR TELESCOPE

CAST and the search for solar axions

Representing the CAST collaboration:

Dieter H.H. Hoffmann

TU-Darmstadt & GSI- Darmstadt



Thessaloniki 23.04.2005

GSI

planned

today

CERN and CAST

Outline

-Solar Axions

-CAST :

- Status

    Magnet, sun tracking

-Detectors:

    TPC
    Micromegas
    X-ray Telescope and CCD

-Outlook

DNA sequencing

Different dyes for clear-cut colours

Proc. Natl Acad. Sci. USA 102, 5346–5351 (2005)

Since its introduction almost 20 years ago, four-colour DNA sequencing has largely relied on the same, somewhat error-prone, method. Now Ernest K. Lewis *et al.* have built a prototype sequencing machine that could improve accuracy.

In conventional colour sequencing, the chemical bases that make up DNA are tagged with fluorescent dyes — a different colour for each of the four bases. A machine shines a laser onto the DNA molecules, and detects the wavelength of light emitted from each base to determine their sequence. But mistakes happen, partly because the spectra produced by the dyes overlap, and hence the glow from one dye can be mistaken for that from another.

For the new method, called pulsed multi-line excitation, the researchers developed a different set of four fluorescent dyes, each of which is excited by a separate wavelength. Their machine fires a series of four laser beams at the dye, but only the appropriate laser triggers a signal. The method could greatly improve the ease with which one base can be distinguished from another. **Helen Pearson**

Cancer

Remote control

Curr. Biol. 15, 561–565 (2005)

BRCA1 is notorious as the first gene to be linked with inherited susceptibility to breast and ovarian cancer. It has been thought of as a classic 'tumour suppressor', but Rajas Chodankar *et al.* suggest that it may have another, more subtle, effect.

Granulosa cells in the ovary produce the sex hormones that regulate the ovulatory cycle — and the growth of ovarian tumours. Given that repeated ovulations (that is, fewer pregnancies or reduced oral contraceptive use) are known to increase the risk of non-hereditary ovarian cancer, the researchers wondered whether decreased levels of BRCA1 protein in granulosa cells are involved. Using mice, they inactivated the gene specifically in these cells. The animals developed tumours in the ovaries and uterine horns. But the tumour cells looked like epithelial cells and had normal copies of the gene, implying that they had not developed from granulosa cells.

Inactivating *BRCA1* seems, therefore, to be controlling some intermediary produced by the granulosa cells. It is this unidentified factor that appears to promote tumours in the ovary epithelium, so providing a lead for further investigation. **Helen Dell**

CAST COLLABORATION

Particle physics

The elusive axion

Phys. Rev. Lett. 94, 121301 (2005)

An effect known as charge–parity violation is linked to the fact that the Universe contains far more matter than antimatter, and it is well documented in processes involving the so-called weak nuclear force, one of the four fundamental forces of nature. But it seems to be suppressed by the strong force, and this can be explained by postulating a hitherto undiscovered particle, the axion. Axions interact hardly at all with radiation or other matter, making them hot candidates to be the 'cold dark matter' that is thought to pervade the Universe.

The CAST (CERN Axion Solar Telescope) collaboration has adopted an innovative approach to the search for axions. They are pointing a powerful test magnet (pictured), decommissioned from CERN's Large Hadron Collider, at the Sun. Axions might be produced in the solar plasma when photons are scattered in strong electromagnetic fields. CAST has put the scattering effect into reverse by producing X-ray photons from solar–axion interactions on Earth.

The magnet can be tilted at either end to an angle that allows the Sun to be observed at sunrise and sunset, both ends being fitted with X-ray detectors and an X-ray telescope recycled from the German space programme. The results, assuming a very small axion mass, show no signal above background, and constrain the axion–photon coupling strength by a factor of five compared with results from previous lab experiments. Future measurements should deliver still better sensitivity, and also test the axion hypothesis for higher masses. **Richard Webb**

Neurobiology

Illuminating behaviour

Cell 121, 141–152 (2005)

Through genetic engineering, researchers have developed a new technique for exciting neurons and influencing fruitfly behaviour. Whereas scientists typically excite these cells with electricity, the effect here was achieved with laser light.

Susana Q. Lima and Gero Miesenböck designed fruitflies to express particular ion channels in neurons that control escape mechanisms — such as jumping and wing beating — or in the dopamine-producing cells that influence movement. The next step involved injecting the flies with ATP (energy-storing molecules) held in chemical cages.

A 200-millisecond pulse of laser light — directed at the flies — removed the cage from the ATP molecules, allowing them to stimulate the channels and depolarize the neurons. When the authors targeted the neurons linked to escape mechanisms, the light set off jumping and wing flapping in the fruitflies. Similarly, targeting dopamine-producing cells altered the insects' walking behaviour. The authors speculate that this ability to direct animal behaviour by remote control will enable them to study how specific behaviours are related to specific neurons. **Roxanne Khamsi**

Spintronics

How electrons relax

Phys. Rev. Lett. 94, 116601 (2005)

In the burgeoning field of spintronics, binary bits of data are stored in the spins of electrons, rather than in their charge, with a '1' equating to spin up and a '0' to spin down. But one problem facing the development of spintronic devices is that, although electron spin can be manipulated, it tends not to stay so — an induced spin decays as the electron interacts with the magnetic field of nearby nuclei.

P.-F. Braun and colleagues have now directly observed this 'spin relaxation' in quantum dots — clusters of atoms just nanometres across — made of the semiconductor materials indium arsenide and gallium arsenide. The authors found that the initial spin polarization of such dots decays with a half-life of just 0.5 nanoseconds — half a millionth of a millisecond — before remaining stable at about a third of its initial value for at least a further 10 nanoseconds.

However, they also report that this relaxation process can be suppressed by an externally applied static magnetic field of just 100 mT, which can be provided by small permanent magnets. Such a field increases the characteristic decay half-life to around 4 nanoseconds, and could prove useful in future practical devices, they suggest. **Mark Peplow**

budget is "a very challenging target," Gardini said. "We are trying very hard to get support from NASA to reduce the cost and risk of the mission." Canada, Japan, and Russia might also take part in the mission, he added.

European researchers see the 2011 mission as preparation for a much more ambitious round trip to return samples of Mars rock, soil, and atmosphere. Space scientist John Zarnecki of The Open University in the United Kingdom, a participant in the workshop, said the group recommended working toward such a mission in 2016, which would fit with NASA's timing for such a mission. "I think everyone hopes and expects that this is going to be a big international push with ESA, NASA, and possibly other agencies," Zarnecki says.

This work is designed to prepare for possible international crewed missions to Mars, which ESA hopes will begin around 2030. Gardini said the sample-return mission would be valuable practice in making the round trip. Aurora faces a big test in December, when ESA's governing council will vote on funding.

—Mason Inman

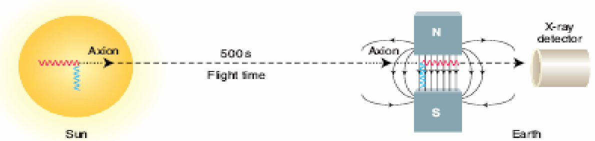
PARTICLE PHYSICS

Magnetic Scope Angles for Axions

After 2 years of staring at the sun, an unconventional "telescope" made from a leftover magnet has returned its first results. Although it hasn't yet found the quarry it was designed to spot—a particle that might or might not exist—physicists say the CERN Axion Solar Telescope (CAST) is beginning to glimpse uncharted territory. "This is a beautiful experiment," says Karl van Bibber, a physicist at Lawrence Livermore National Laboratory in California. "It is a very exciting result."

CAST is essentially a decommissioned, 10-meter-long magnet that had been used to design the Large Hadron Collider, the big atom smasher due to come on line in 2007 at the particles exist (*Science*, 11 April 1997, p. 200). If axions do exist, however, oodles of them must be born every second in the core of the sun and fly away in every direction.

That's where CAST comes in. "When an axion comes into your magnet, it couples with a virtual photon, which is then transformed into a real photon" if the axion has the correct mass and interaction properties, says Konstantin Zioutas, a spokesperson for the project. "The magnetic field works as a catalyst, and a real photon comes out in the same direction and with the same energy of the incoming axion." An x-ray detector at the bottom of the telescope is poised to count those photons.



X-files. CAST "telescope" hopes to detect hypothesized particles from the sun by counting the x-rays they should produce on passing through an intense magnetic field.

CERN, the European high-energy physics lab near Geneva. When CERN scientists turn on the magnet, it creates a whopping 9-tesla magnetic field—about five times higher than the field in a typical magnetic resonance imaging machine. From a particle physicist's point of view, magnetic fields are carried by undetectable "virtual" photons flitting from particle to particle. The flurry of virtual photons seething around CAST should act as a trap for particles known as axions.

Axions, which were hypothesized in the 1970s to plug a gap in the Standard Model of particle physics, are possible candidates for the exotic dark matter that makes up most of the mass in the cosmos. Decades of experiments have failed to detect axions from the depths of space, and many physicists doubt

The first half-year's worth of data, analyzed in the 1 April *Physical Review Letters*, showed no signs of axions. But CAST scientists say the experiment is narrowing the possible properties of the particle in a way that only astronomical observations could do before. "It's comparable to the best limits inferred from the stellar evolution of red giants," van Bibber says, and he notes that plans to improve the sensitivity of the telescope will push the limits further. Even an improved CAST would be lucky to spot axions, van Bibber acknowledges, because most of the theoretically possible combinations of the particle's properties would slip through the telescope's magnetic net. Still, he's hoping for the best. "Maybe Nature will deal a pleasant surprise," he says.

—Charles Seife

ScienceScope

Lockheed Boosts Los Alamos Bid

U.S. aerospace giant Lockheed Martin strengthened its bid to run Los Alamos National Laboratory in New Mexico this week by recruiting a key senior scientist. Sandia National Laboratories Director C. Paul Robinson, who spent 18 years at Los Alamos before moving to Sandia in 1990, has joined the proposal team for the Bethesda, Maryland–based company.

Lockheed officials want Robinson, 63, to head Los Alamos if they beat out the lab's current contractor, the University of California. Final competition details are expected soon, with bids in the summer. Meanwhile, former weapons chief Thomas Hunter has been promoted to director of Sandia, which has facilities in California and New Mexico.

—Eli Kintisch

Pig Flu Scare—Case Closed?

The World Health Organization (WHO) hopes that the results of a new study will put to rest suspicions that pigs in South Korea have become infected with a potentially dangerous flu strain.

Last fall, Sang Heui Seo of Chungnam National University in Daejeon, Korea, deposited flu sequences in GenBank that suggested that Korean pigs carried WSN/33, a flu strain widely used in labs but not known to occur in nature. Several experts and WHO dismissed the findings as the result of lab contamination (*Science*, 4 March, p. 1392); now, Yoshi Kawaoka of the University of Wisconsin, Madison, and his colleagues have tested 400 samples from two Korean pig farms, WHO says, and found no trace of WSN/33.

Seo declined to comment. Henry Niman, a business owner in Philadelphia who backs Seo's claim, says Kawaoka's study wasn't broad enough to refute the theory. But, says WHO flu expert Klaus Stöhr, "we've spent too much time on these speculations already."

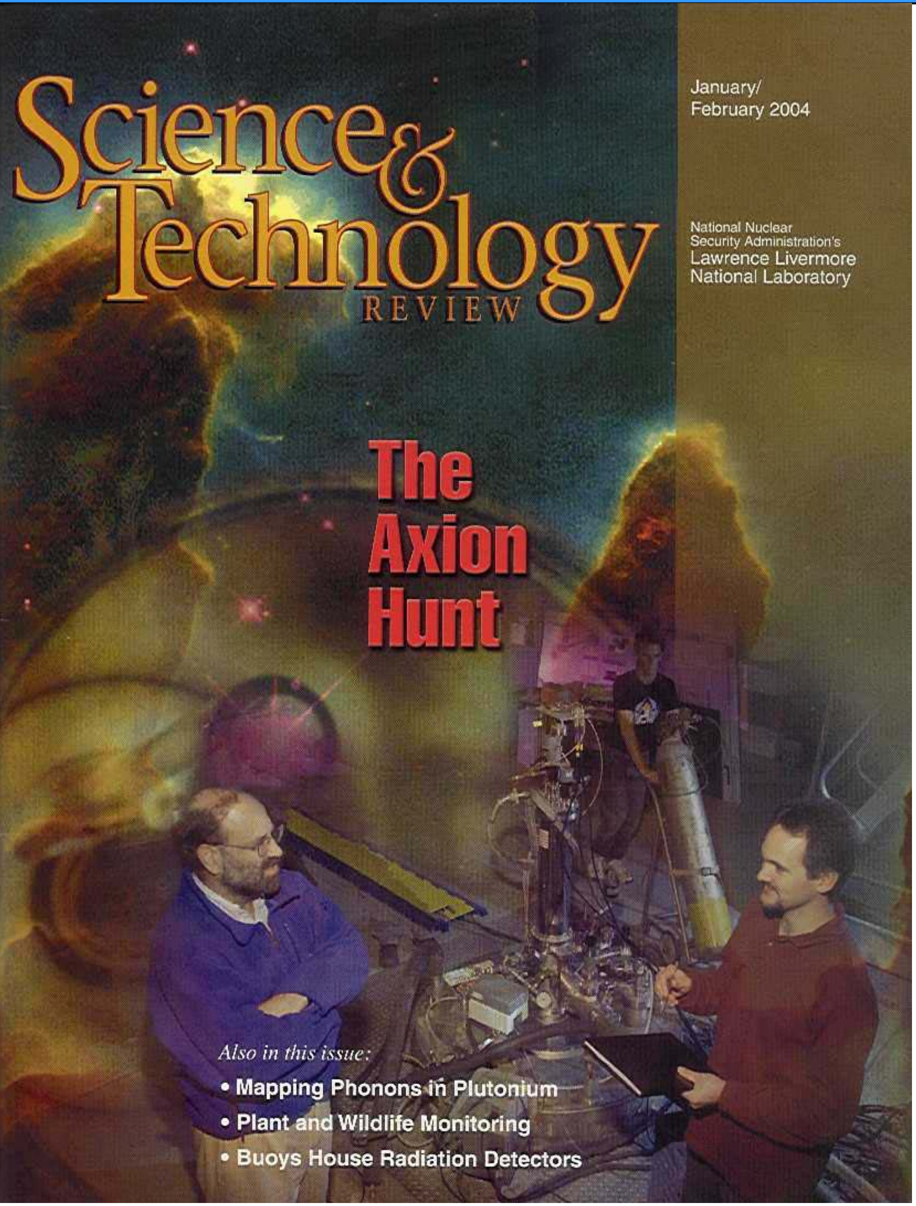
—Martin Enserink

Plant Center to Cut Jobs

The John Innes Centre in Norwich, U.K., one of Europe's top plant science institutions, plans to cut up to 35 researchers from its 800-person staff. Director Christopher Lamb announced on the center's Web site last week that the center began losing money 18 months ago when two funders—the European Union and private industry—became "less reliable sources." Income to the center, which has a $40 million annual budget, has dropped by $5.7 million.

This is "a big blow," says plant geneticist Michael Wilkinson of the University of Reading, U.K., adding that the institution produces an "astonishing number" of widely cited basic science papers. —Eliot Marshall

The Axion Hunt



January/February 2004

National Nuclear
Security Administration´s
Lawrence Livermore
National Laboratory

What are Axions good for (1)

Plasma Physics

CP-problem in strong Interaction

Axions were proposed as an extension to the Standard Model of particle physics to explain why CP violation - a phenomenon linked to the dominance of matter over antimatter in the universe - is observed in weak but not strong interactions - the so-called strong-CP problem.

The STRONG CP PROBLEM

Possible CP-violating term in QCD lagrangian:

$$\mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G\tilde{G}$$

$$\left(\tilde{G}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{\rho\sigma} \right)$$

Two different contributions here: QCD vacuum and EW quark mixing

Experimental consecuence: ***prediction of electric dipole moment for the neutron:***

$$|d_n| = A|\theta| \times 10^{-15} e \times cm$$

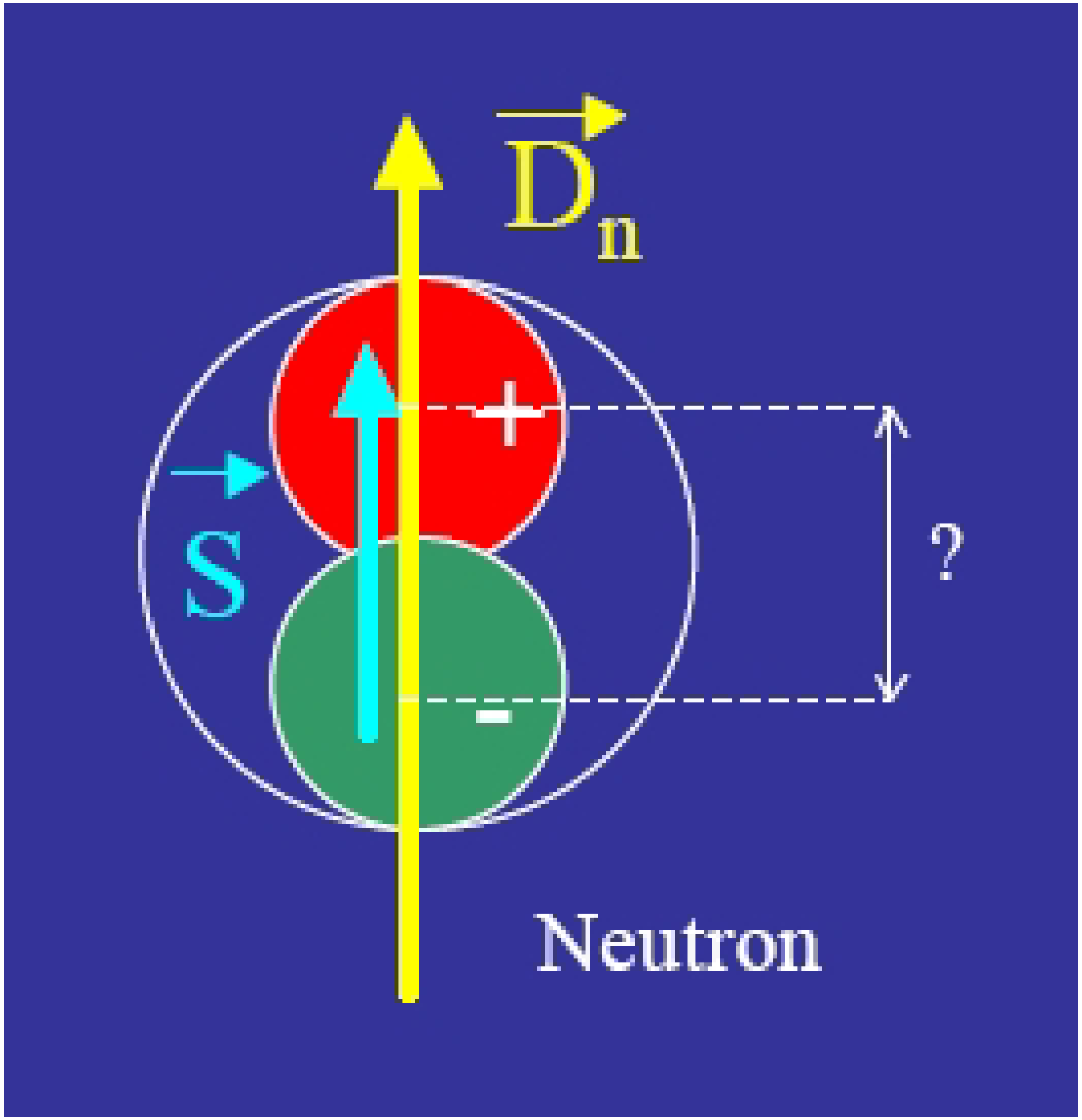
(A = 0.04 – 2.0)

is the stat. el. dipolmoment of the neutron = 0 ?

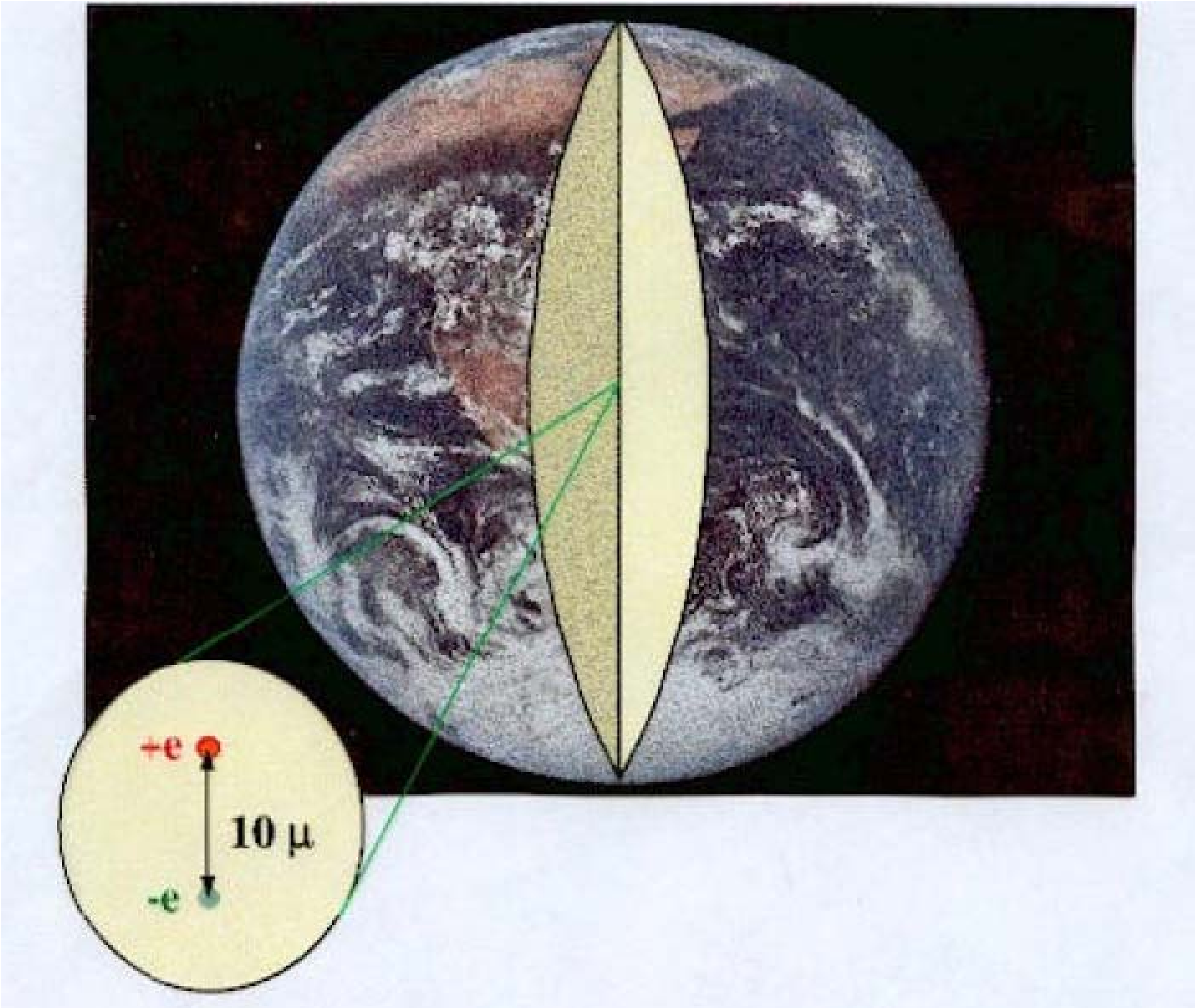
One of the most striking consequences of this is the neutron electric dipole moment, which, due to a CP-violating term in the standard equations of QCD, is calculated to be 10 orders of magnitude larger than its measured upper limit.

Best experimental value $d_n < 10^{-26}$ e·cm

What are Axions good for (2)



Static electric dipolmoment of the neutron



The STRONG CP PROBLEM

BUT experiment says...

$$|d_n| < 0.63 \times 10^{-25} e \times cm$$

So,

$$|\theta| < 10^{-9}$$

- *Why so small?*
- *Hight fine-tunning of two different contributions required*

Peccei-Quinn (1977) propose an elegant solution to this problem.
θ not anymore a constant, but a field → the axion a(x).
Fine-tunning reached naturally, dynamically.

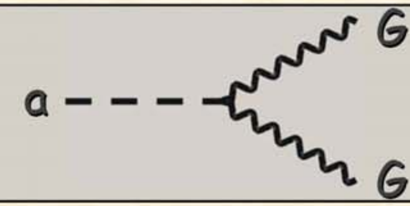
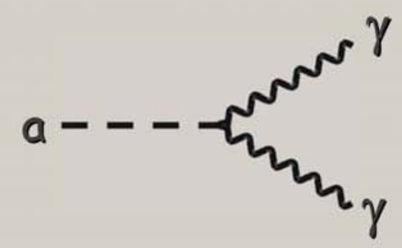
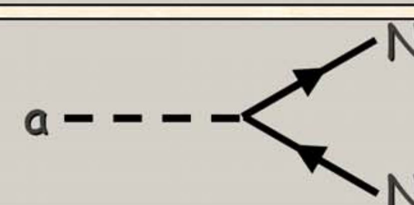
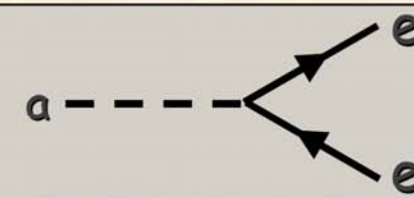
What are Axions good for (3)

This can be overcome by introducing a further symmetry, the spontaneous breaking of which yields the axion - a neutral pion-like particle that interacts very feebly. Owing to their potential abundance in the early universe, axions are also leading candidates for the dark matter of the universe.

Axion : O^- **Pseudoscalar**

Plasma Physics GSI

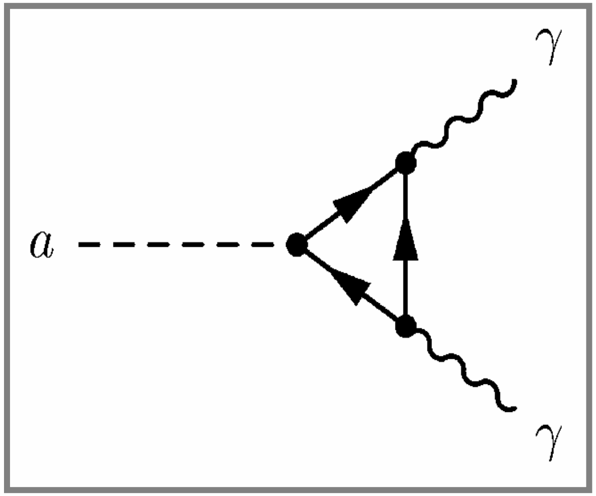
Axion Properties

Coupling to gluons (Most generic axion property)	$L_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G} a$	
Mass	$m_a = \frac{0.6\,\mathrm{eV}}{f_a/10^7\,\mathrm{GeV}} \approx \frac{m_\pi f_\pi}{f_a}$	
Photon coupling	$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F} a = g_{a\gamma} \vec{E}\cdot\vec{B}\, a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{B} - 1.92\right)$	
Nucleon coupling (axial vector)	$L_{aN} = \frac{C_N}{2f_a} \overline{\Psi}_N \gamma^\mu \gamma_5 \Psi_N \partial_\mu a$	
Electron coupling (optional)	$L_{ae} = \frac{C_e}{2f_a} \overline{\Psi}_e \gamma^\mu \gamma_5 \Psi_e \partial_\mu a$	

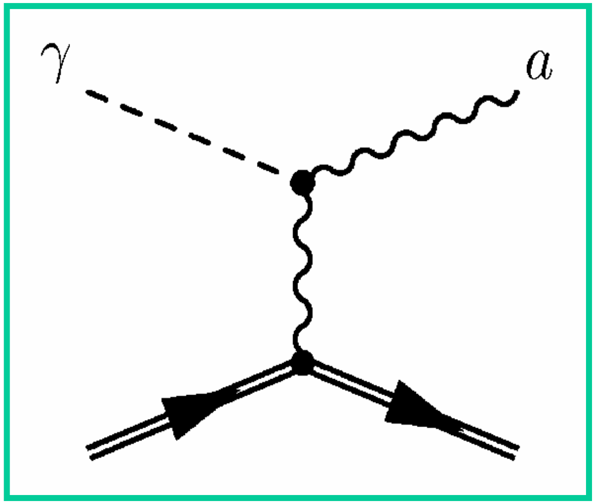
G. Raffelt

Axions

- pseudoscalar
- neutral
- practically stable
- phenomenology driven by the breaking scale f_a and the specific axion model
- Couples to photon



$$\mathscr{L}_{\alpha\gamma} = g_{\alpha\gamma}\,(\mathbf{E}\bullet\mathbf{B})\; a$$



Primakoff (1951) [$\pi^\circ \rightarrow \gamma\gamma$]

PRIMAKOFF EFFECT

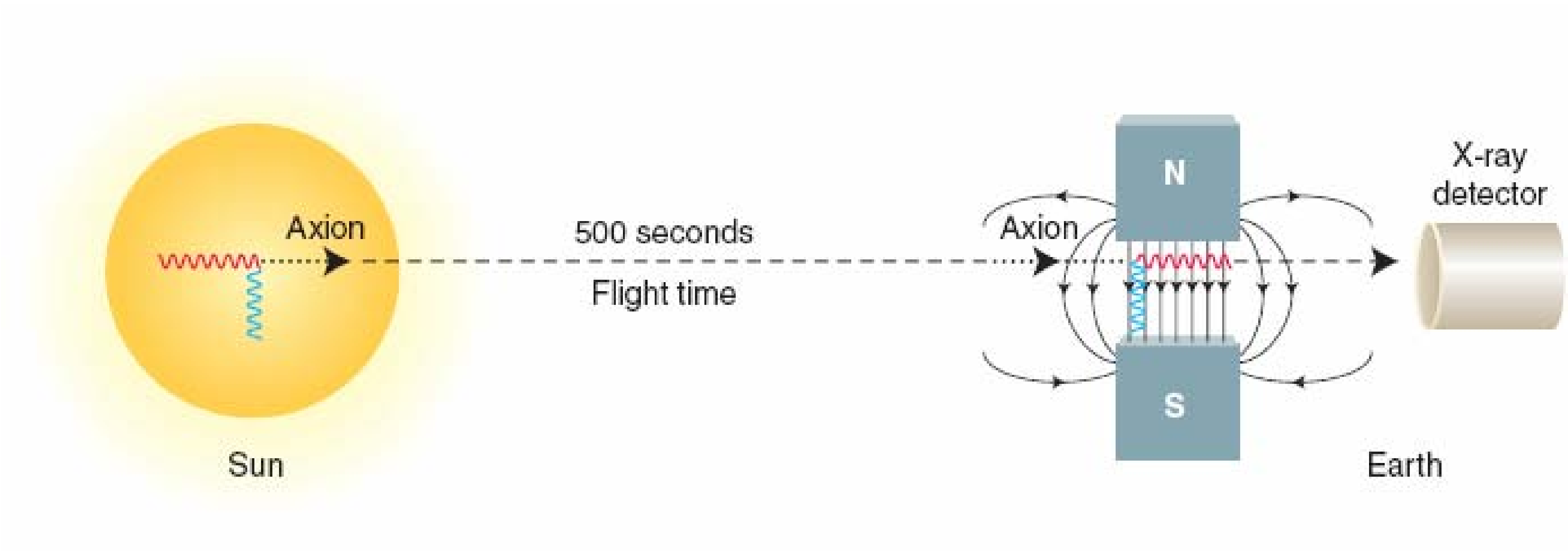
Any scalar or pseudoscalar particles:

axion-like particles

Prinzipieller Aufbau von CAST

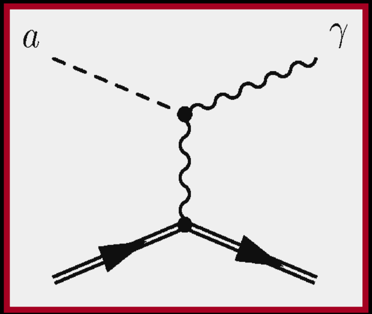
Axion - Quelle ↓

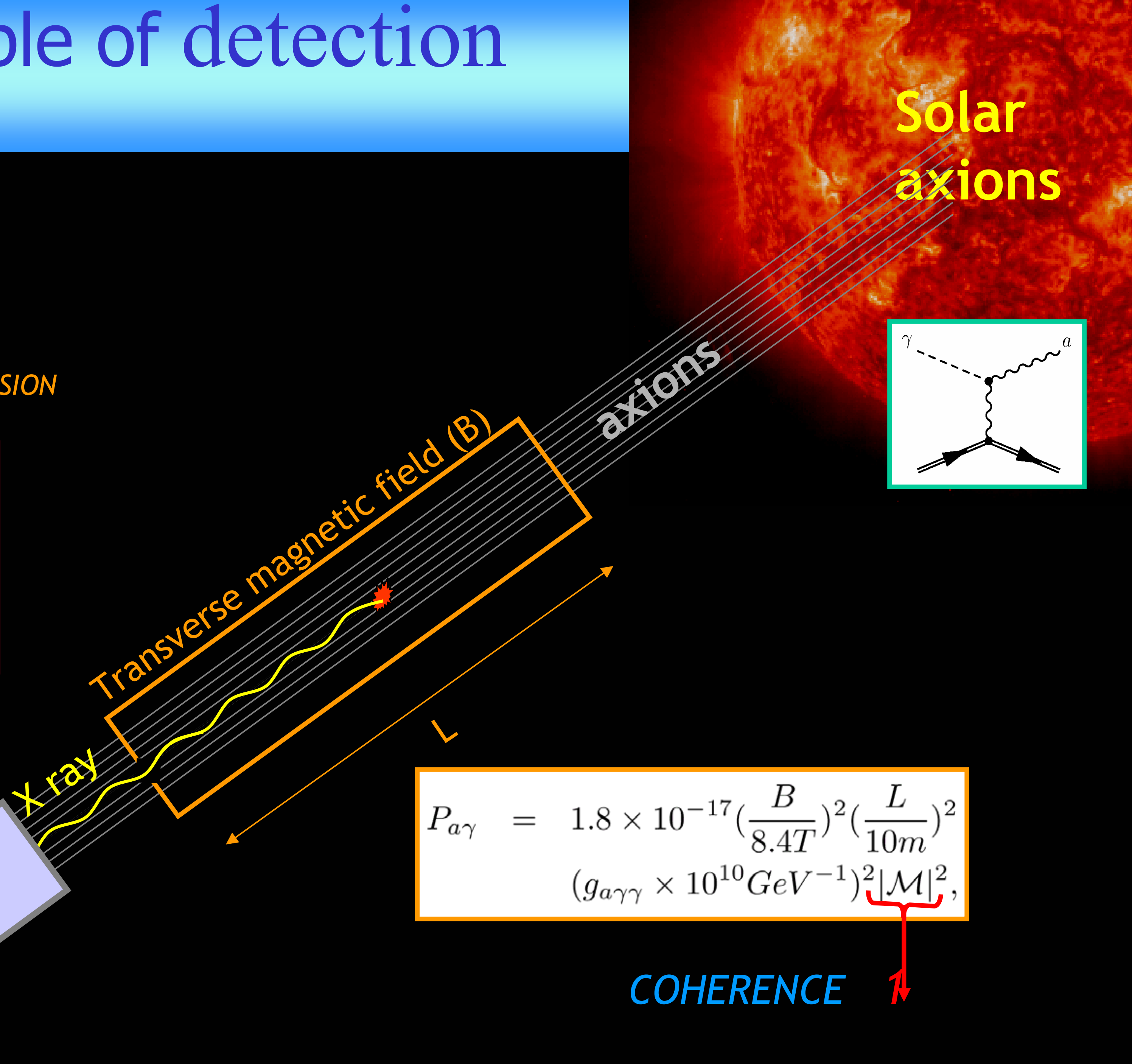
Axion - Nachweis ↓



Principle of detection

AXION PHOTON CONVERSION





$$P_{a\gamma} = 1.8 \times 10^{-17} \left(\frac{B}{8.4T}\right)^2 \left(\frac{L}{10m}\right)^2 (g_{a\gamma\gamma} \times 10^{10} GeV^{-1})^2 |\mathcal{M}|^2,$$

COHERENCE

Solar Axion Spectrum

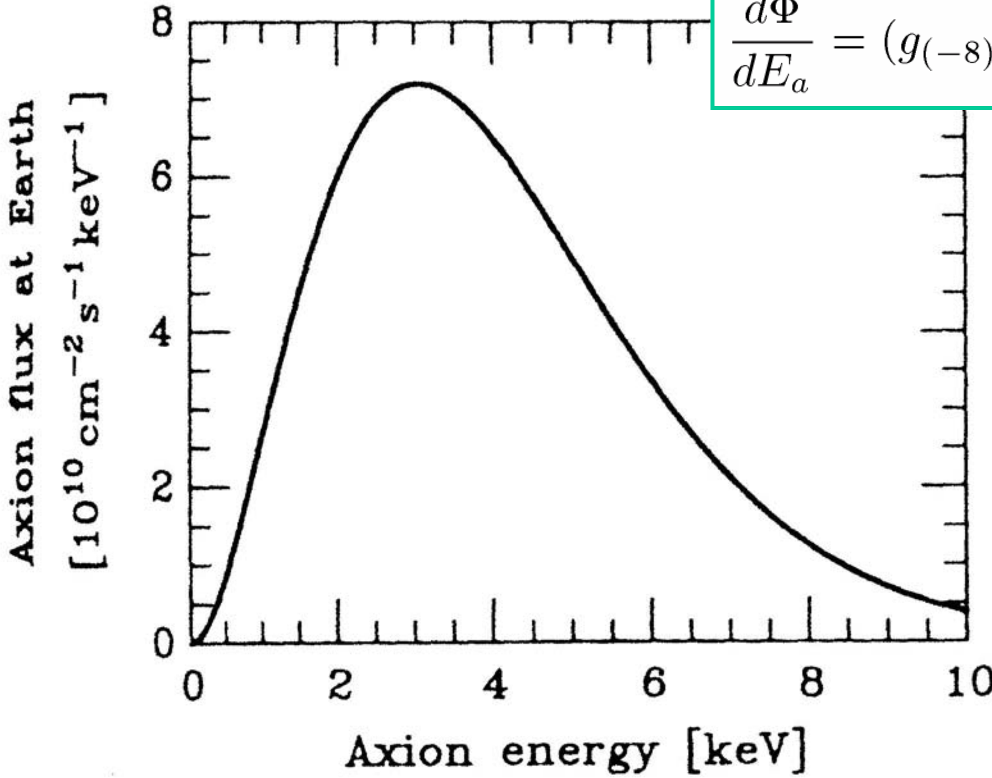
PRIMAKOFF EFFECT

Stellar interior → the Sun!! → *Solar Axions*

Flux at the Earth

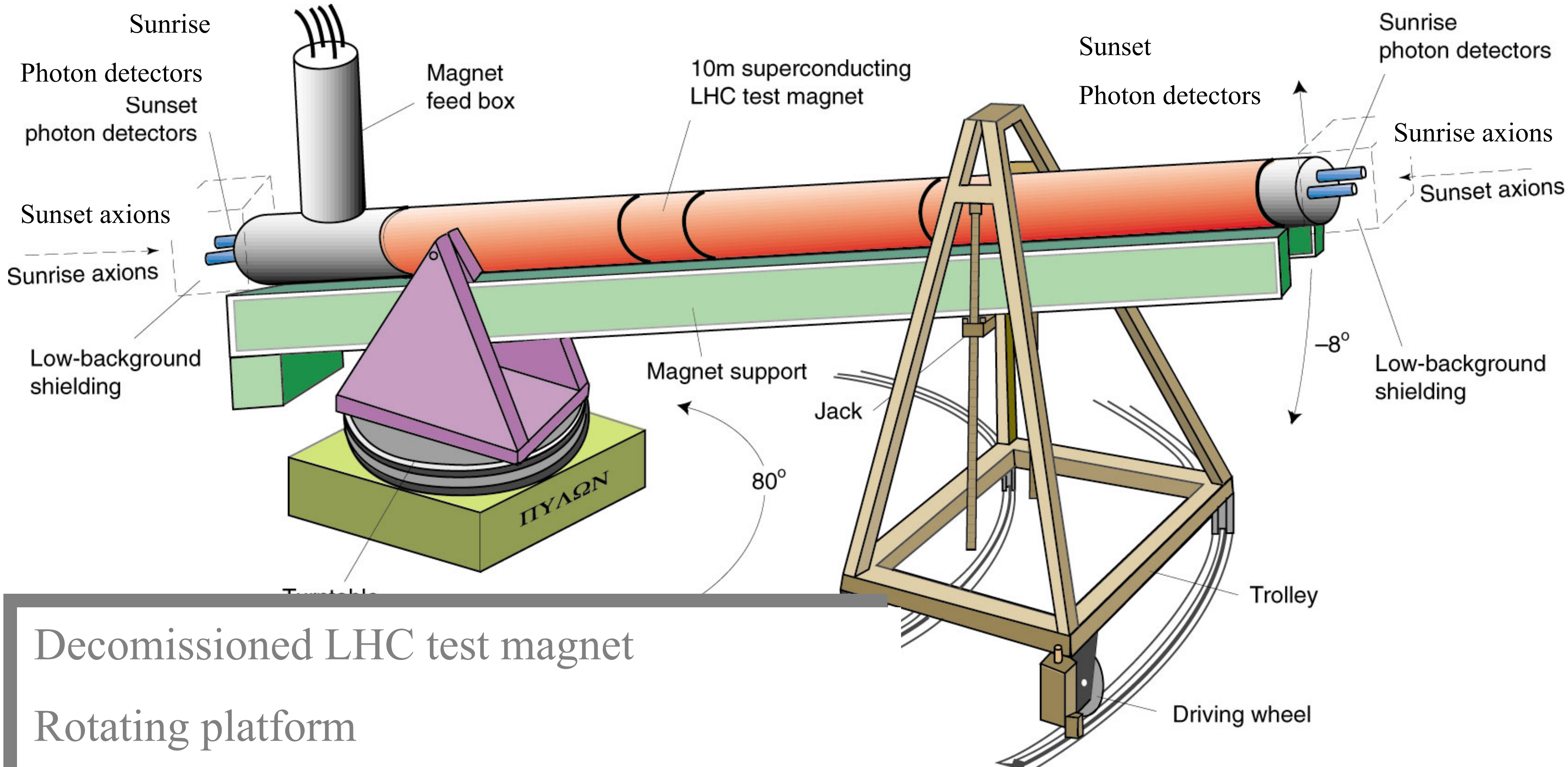
$$\frac{d\Phi}{dE_a} = (g_{(-8)})^2 \frac{\Phi_0}{E_0} \frac{(E_a/E_0)^3}{e^{E_a/E_0} - 1}$$

$$g_{(-8)} = g_{a\gamma\gamma} \times 10^8/\mathrm{GeV}^{-1}$$



[K.van Bibber et al.,1989]

Cern Axion Solar Telescope



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

CAST : Magnet

Plasma Physics

L= 10 m, B=9 T

→100 times better than previous exp.

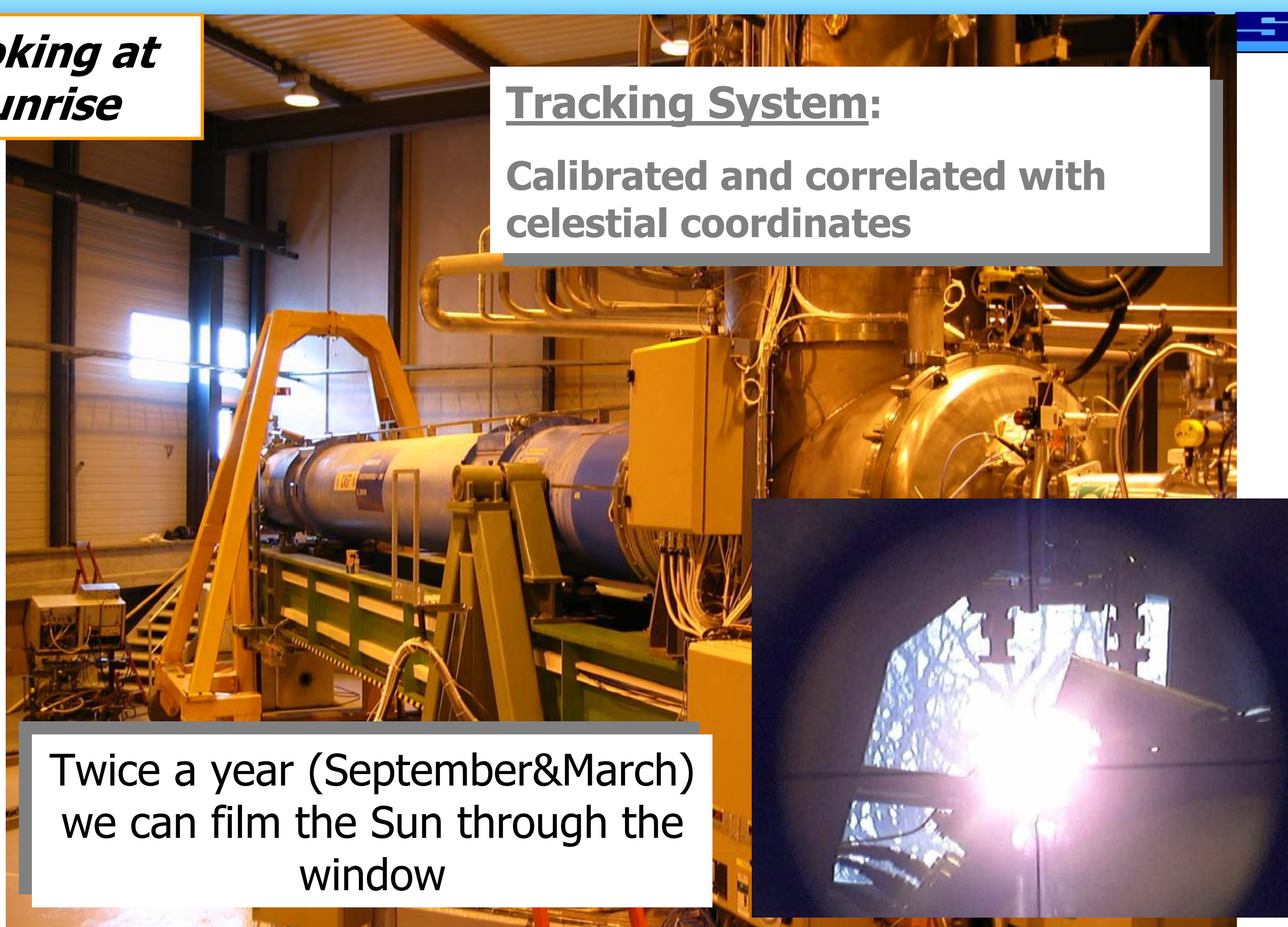
3sat-hitec-CAST.avi

Angular encoders

Magnet, sun tracking

Plasma Physics

Looking at sunrise



Tracking System:

Calibrated and correlated with celestial coordinates

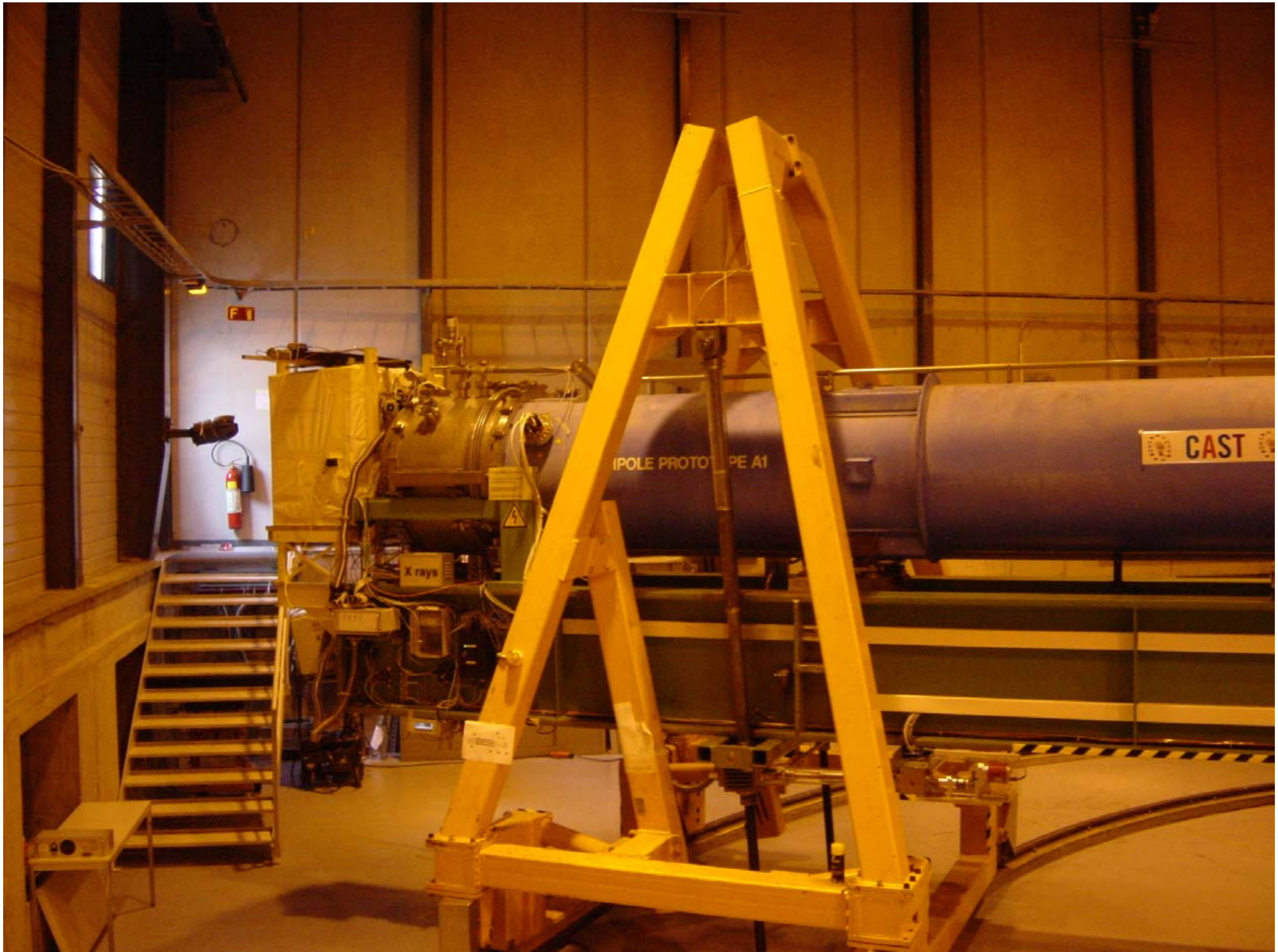
Twice a year (September&March) we can film the Sun through the window

Optical sun tracking

Magnet Quenching

8 events in 2003
3 events in 2004

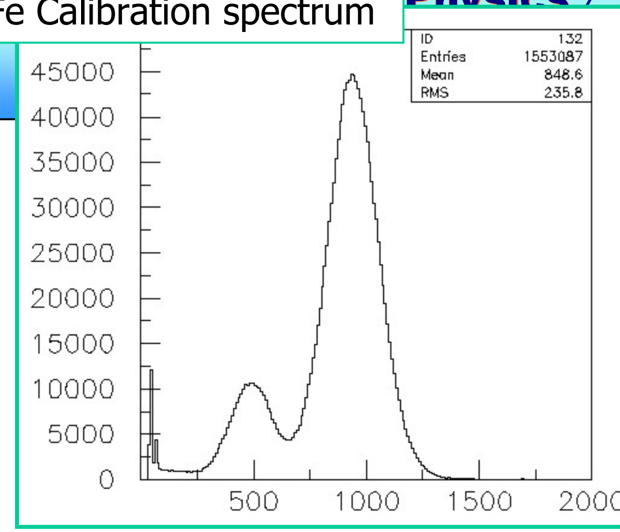
TPC

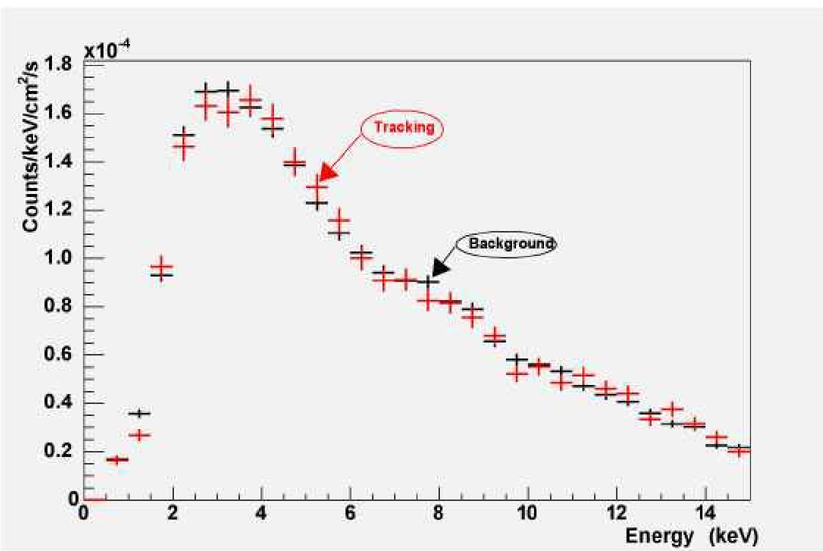


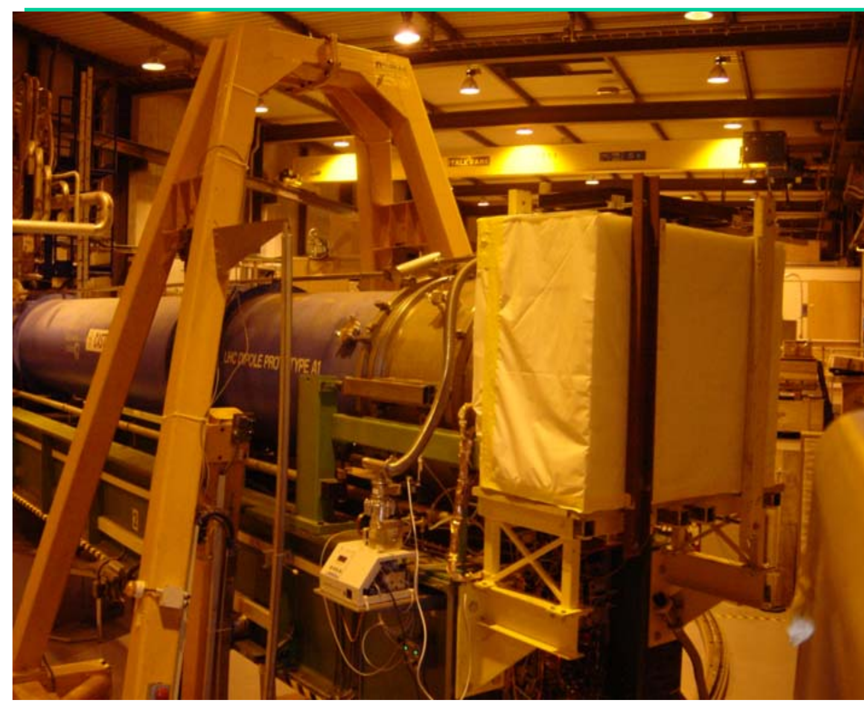
TPC spectra of 2003

Clean materials + shielding (polyethylene+copper+*ancient* lead)

^{55}Fe Calibration spectrum



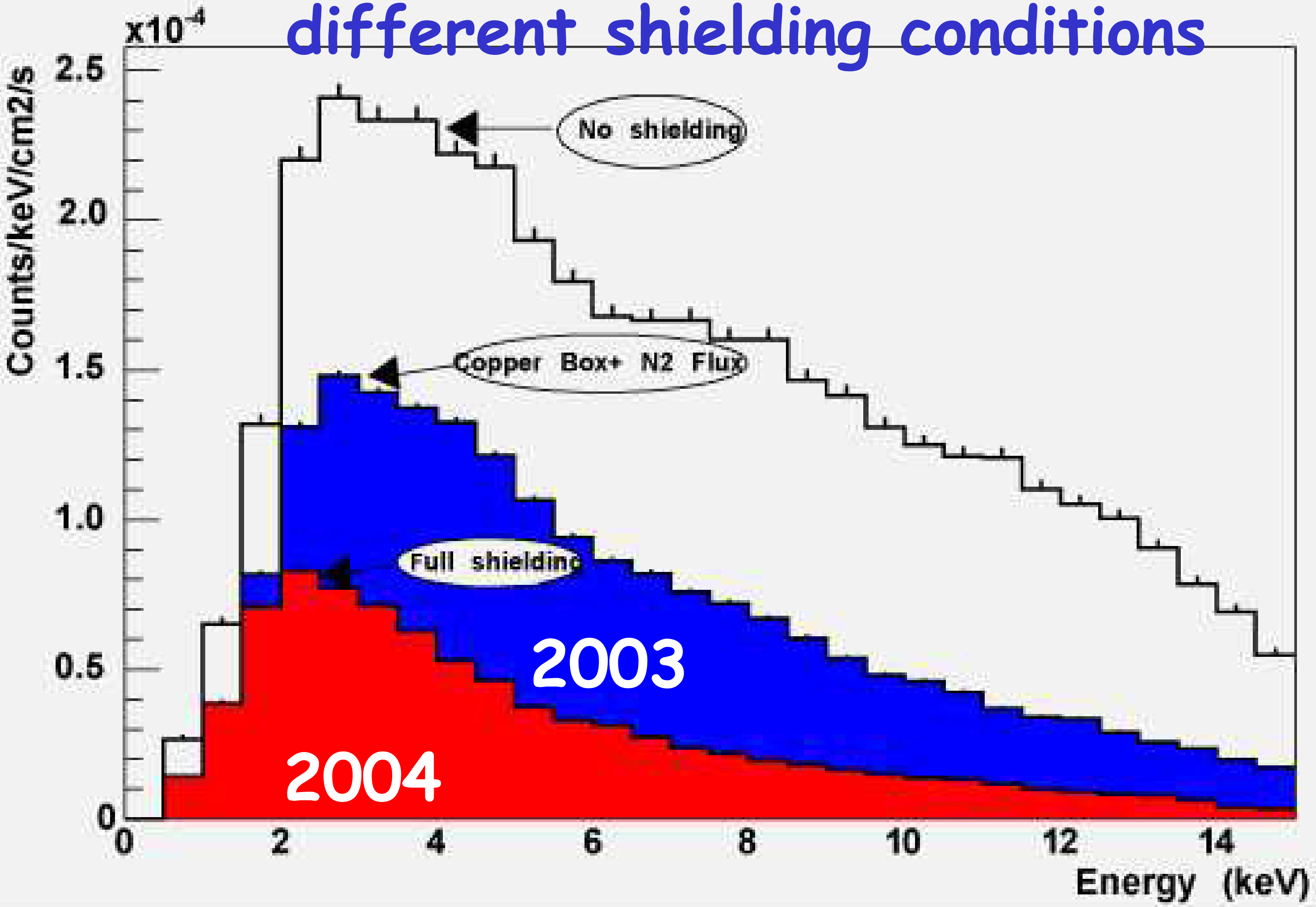




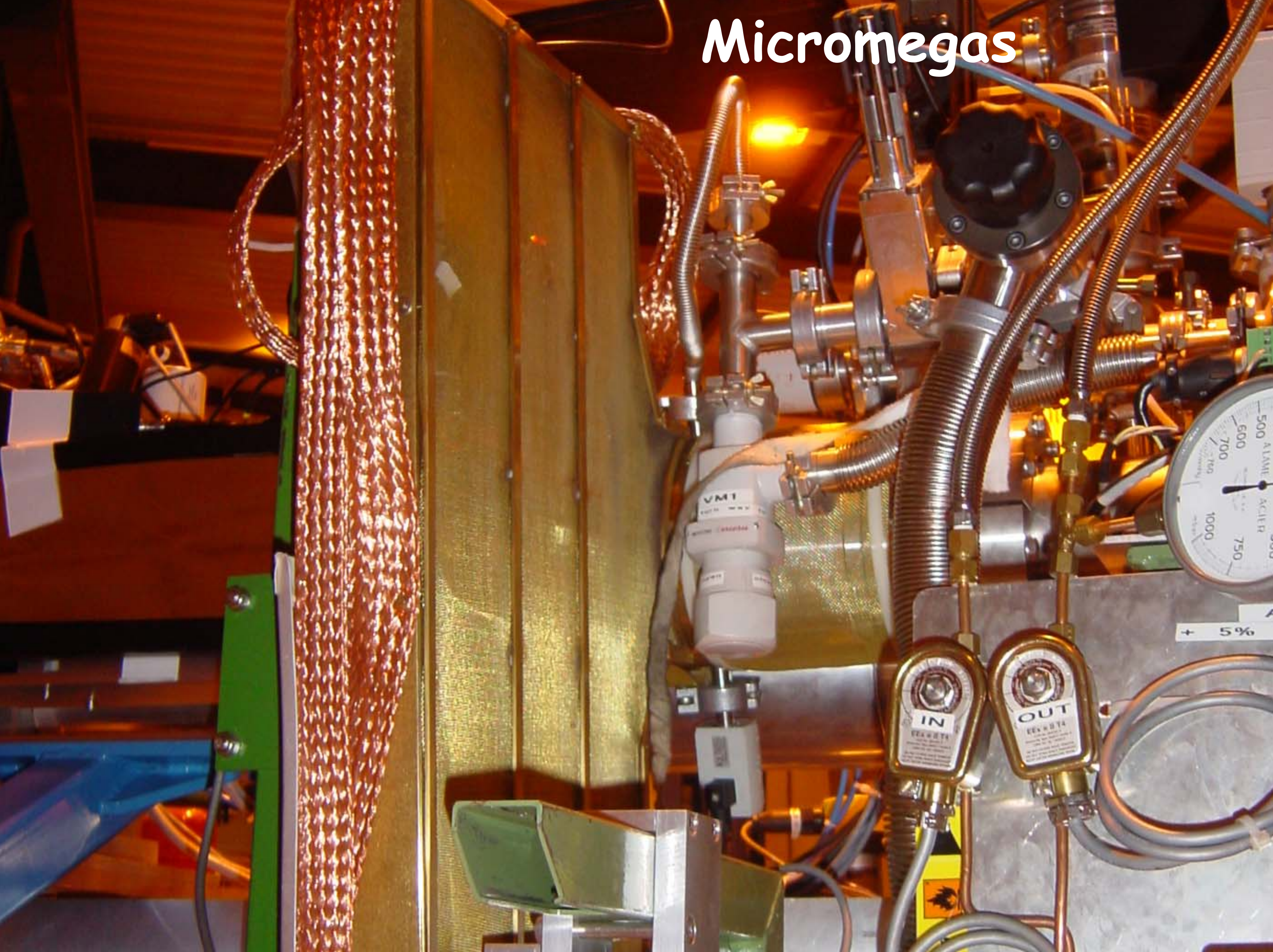
Low Background

TPC spectra in 2003 and 2004

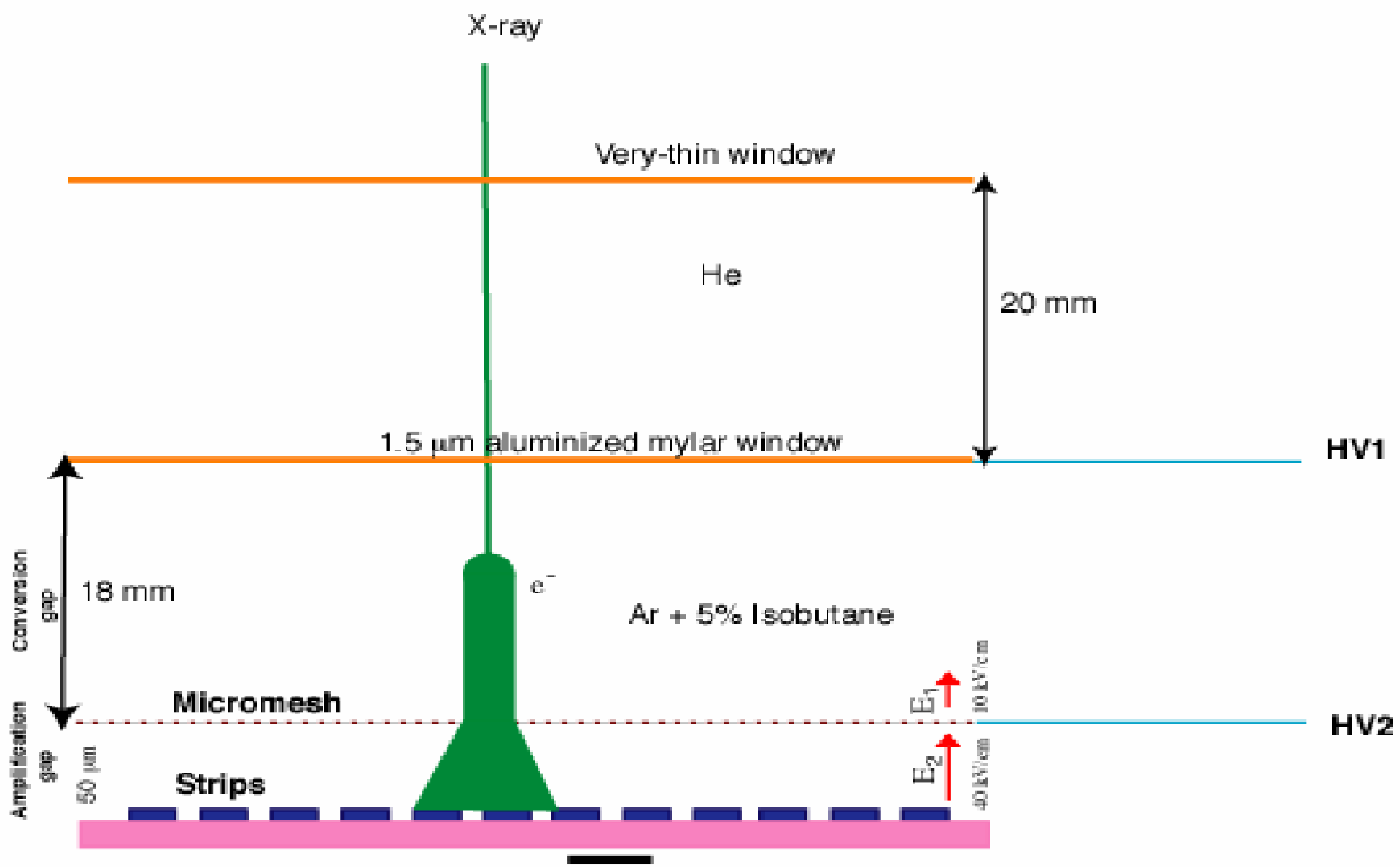
different shielding conditions



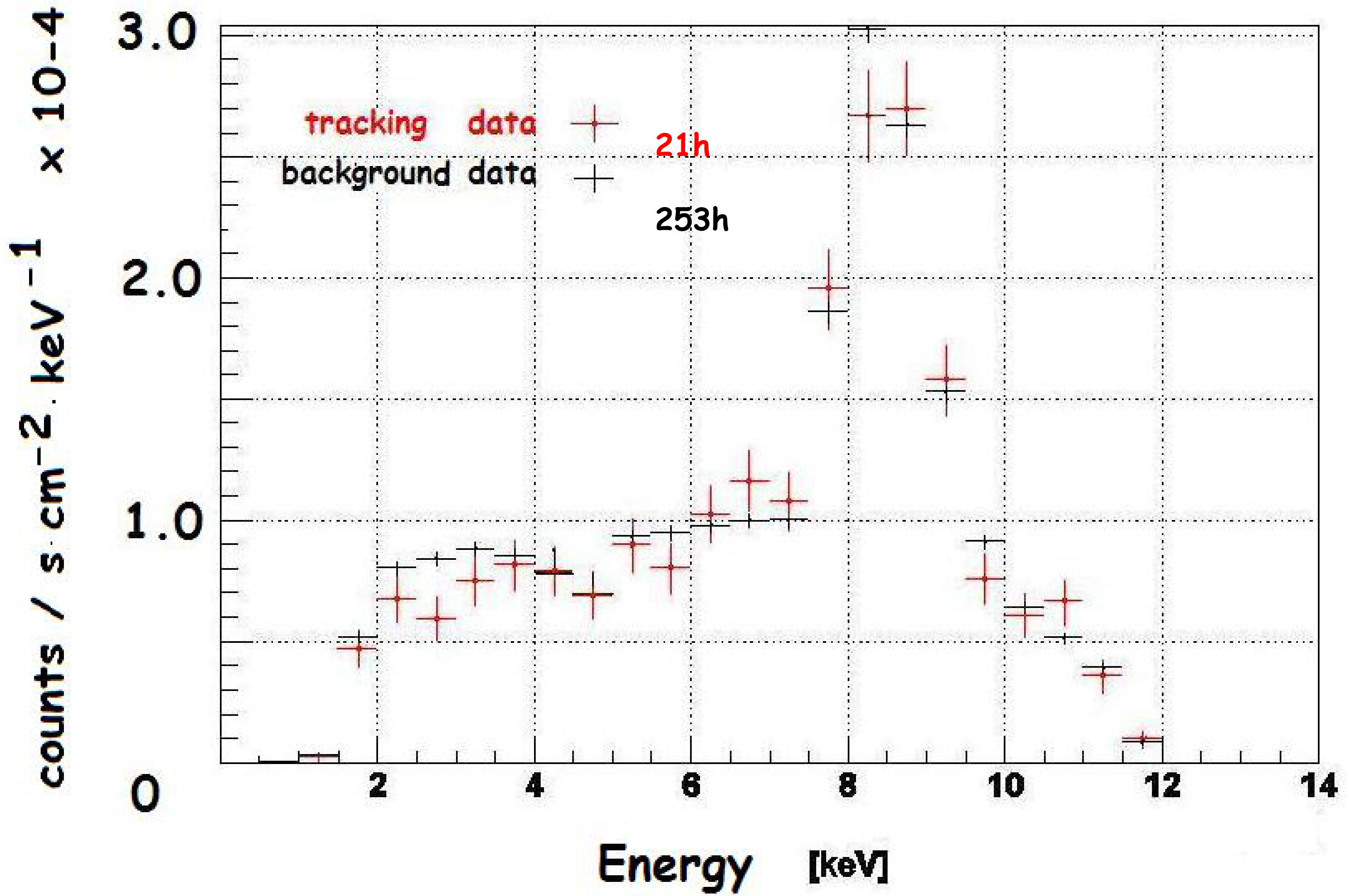
Micromegas



Micromegas Priciple



Micromegas detector (2003)



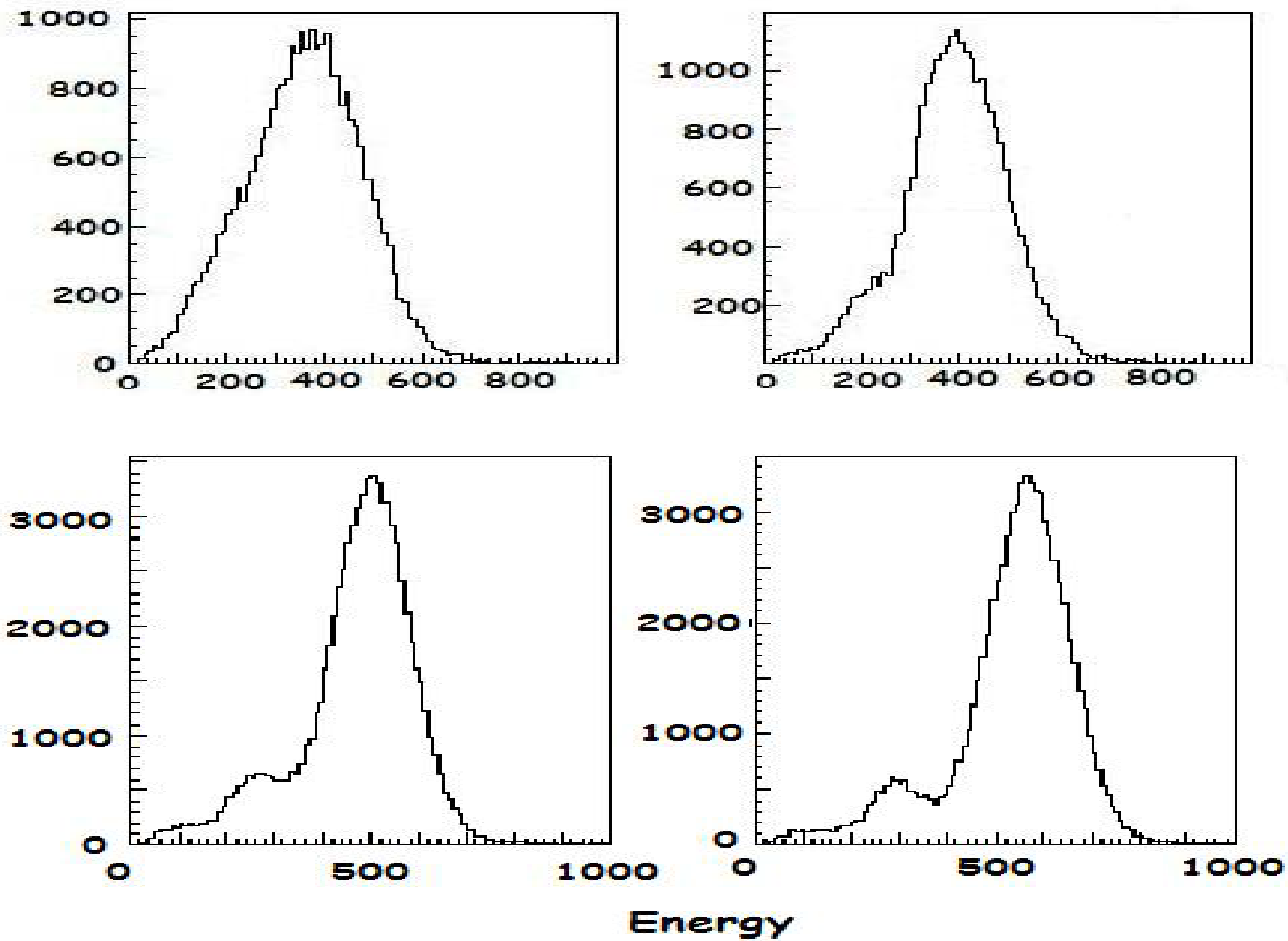
$g_{\alpha\gamma\gamma} < 1.39\times10^{-10}\ GeV^{-1}$ (95% CL)

Strip Energy Resolution

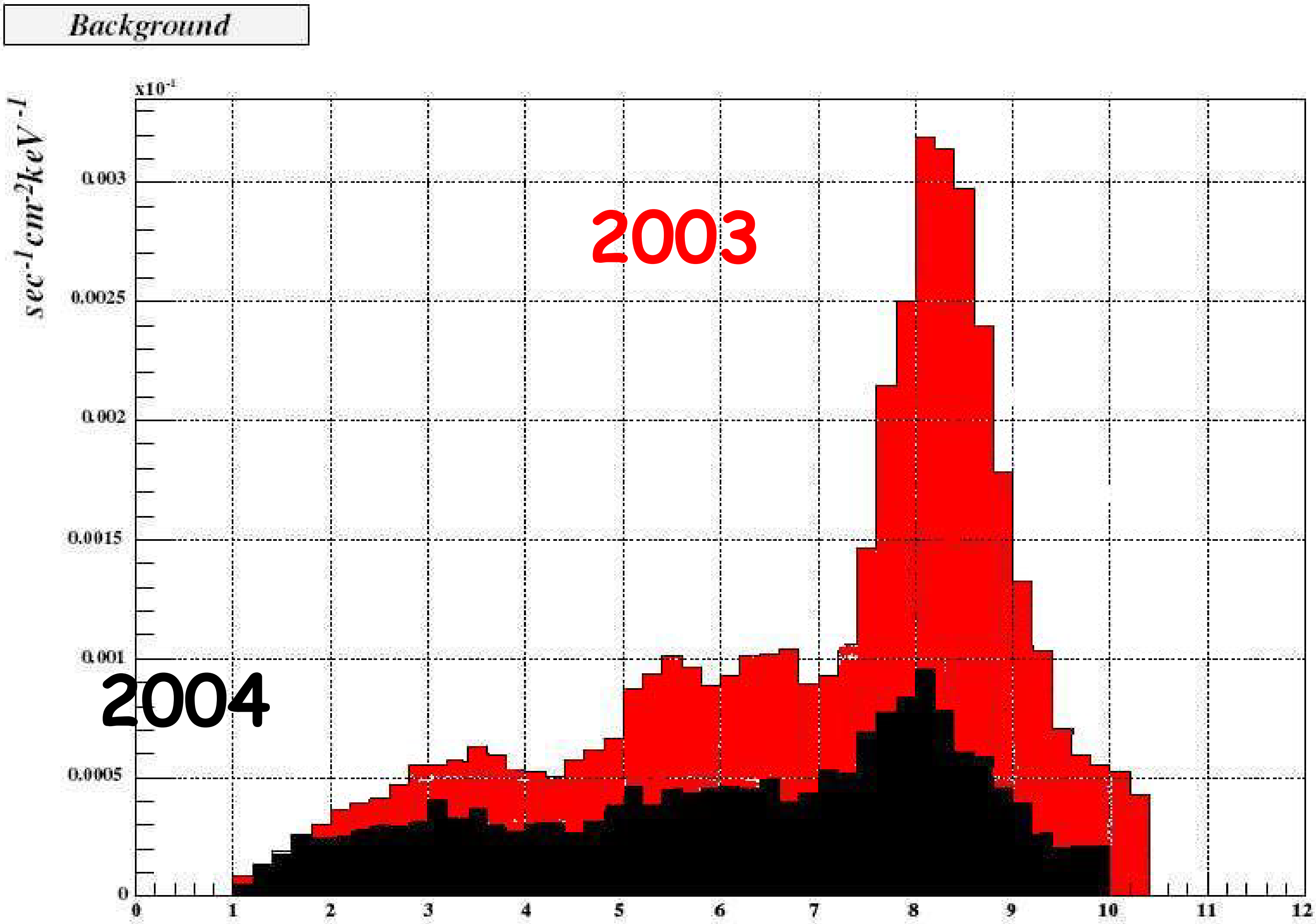
Plasma Physics

2003

2004



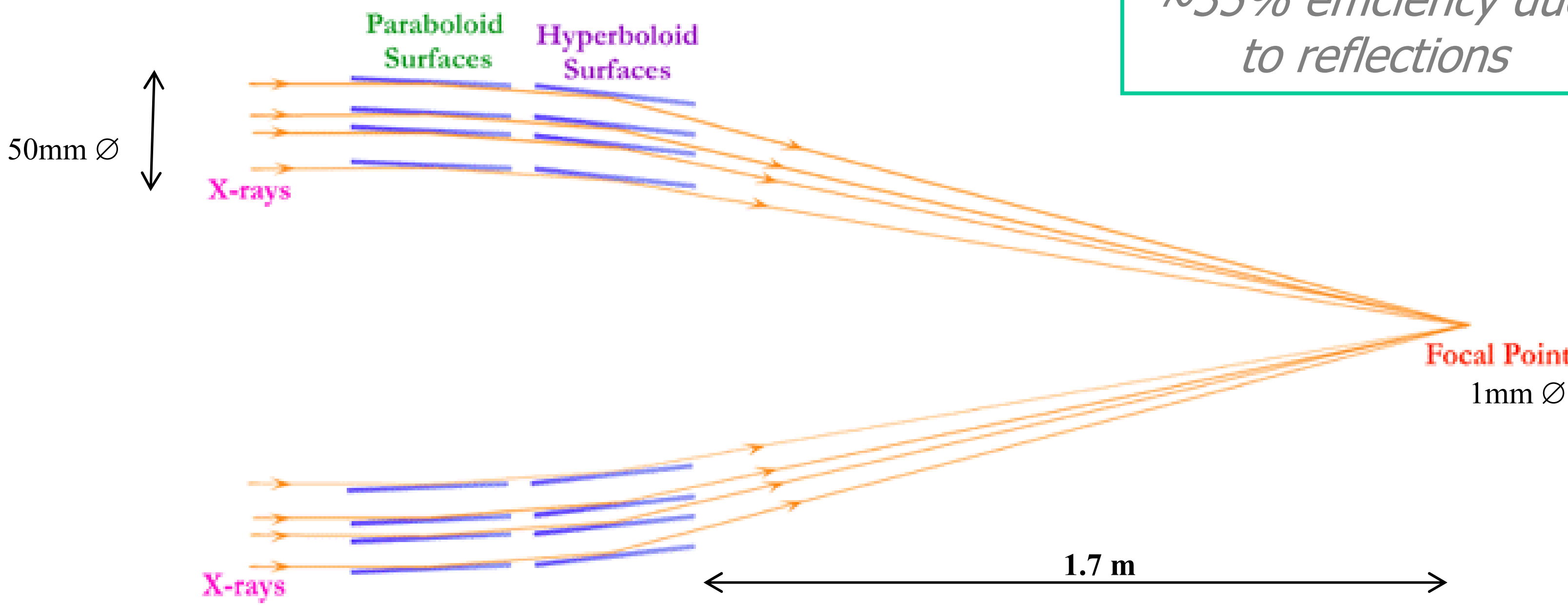
Micromegas background improvement



Energy /keV

The X-Ray Telescope

~35% efficiency due to reflections



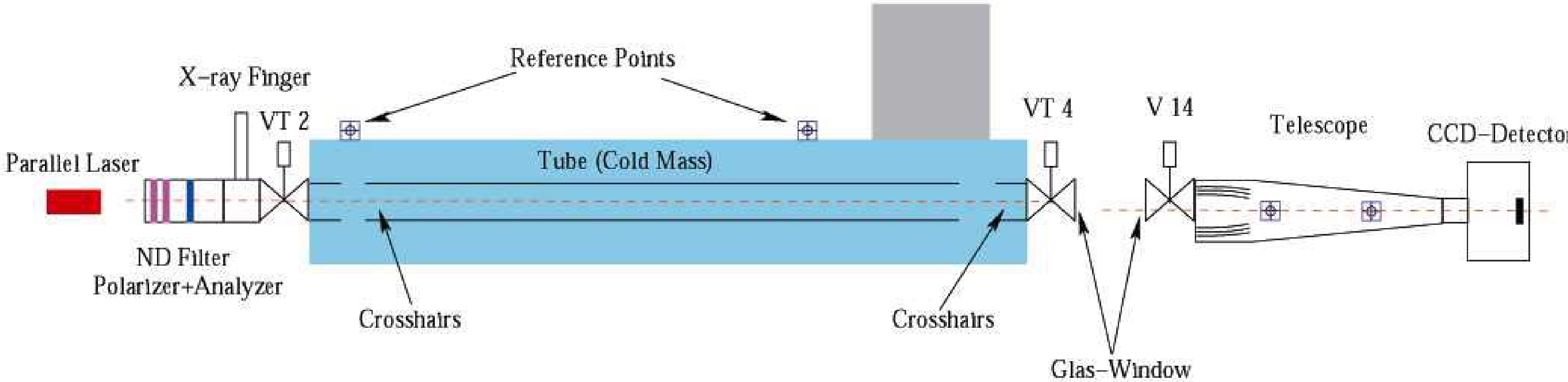
- 27 nested pairs of mirrors
- From 43 mm ∅ (LHC magnet aperture) to ~1mm ∅

signal and background simultaneously

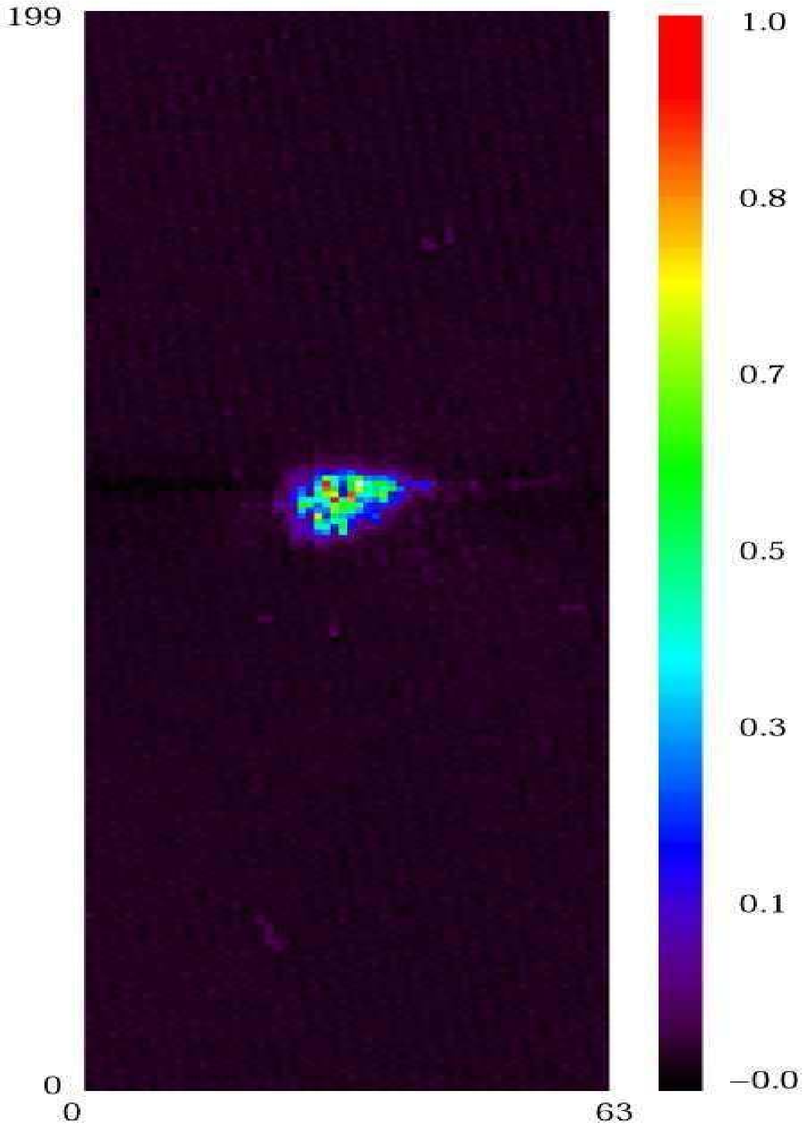
signal-to-noise improvement

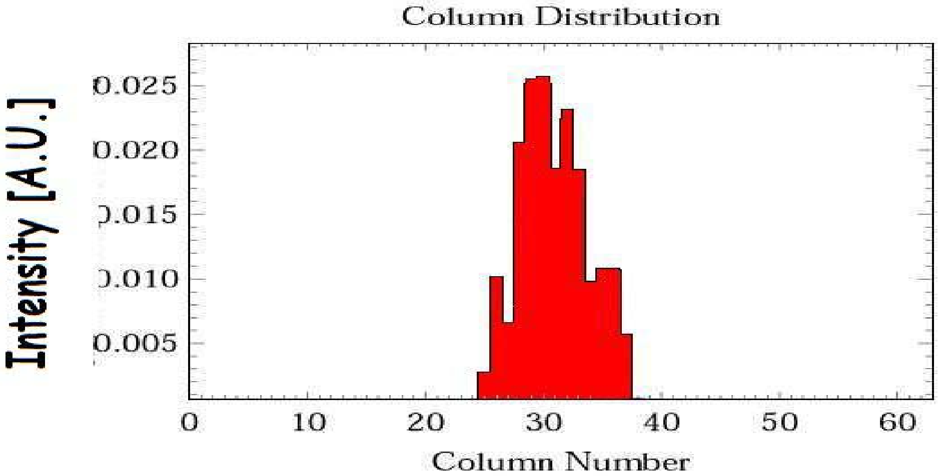
X-ray telescope

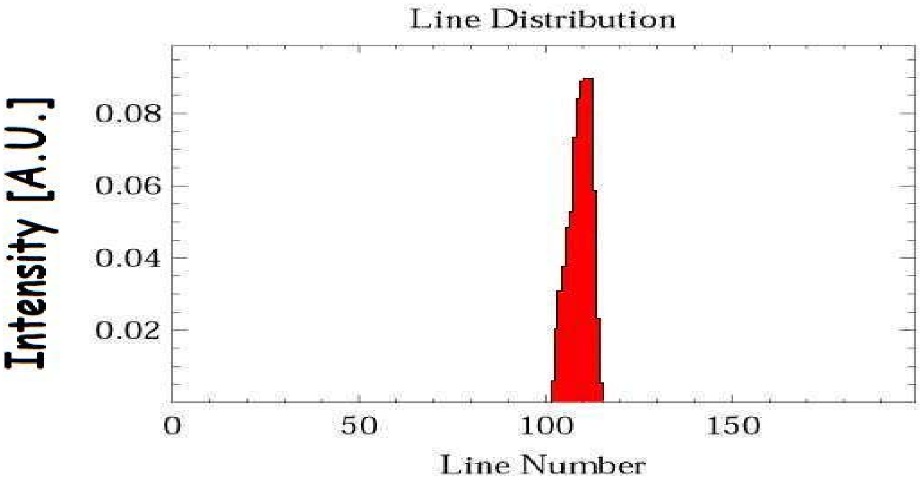
X-ray telescope alignment



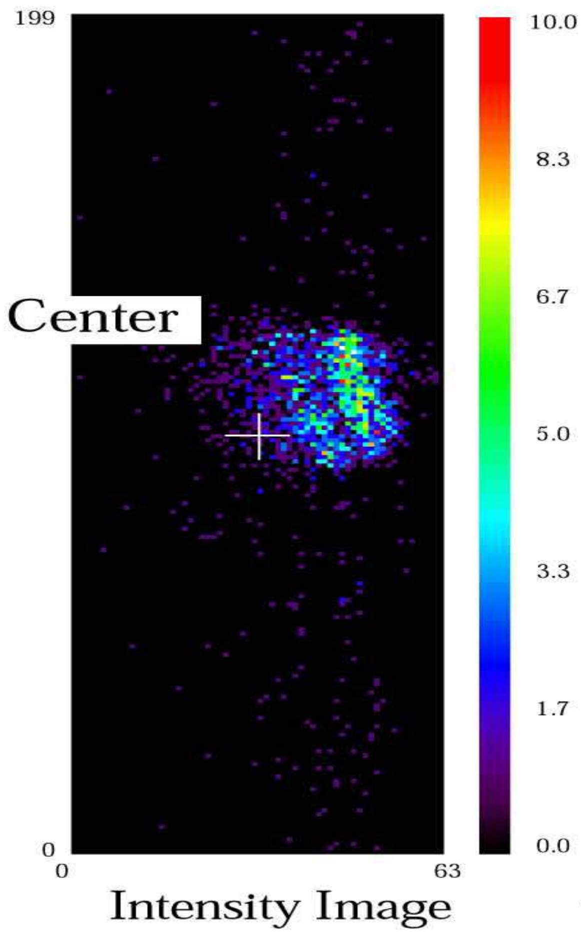
pn-CCD detector: laser spot

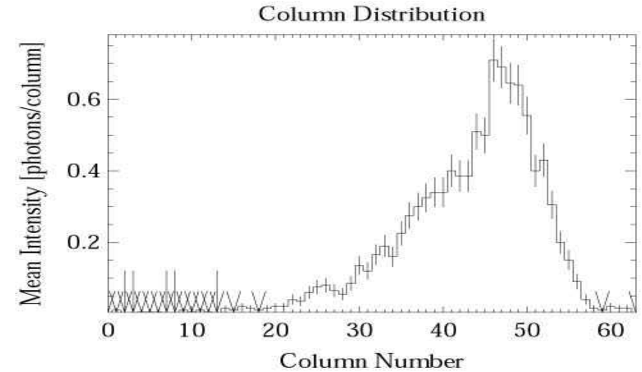


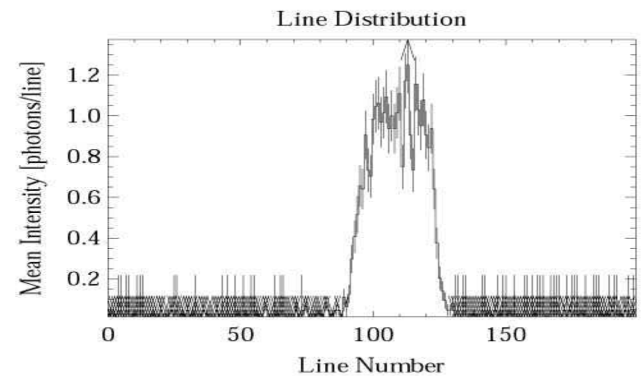


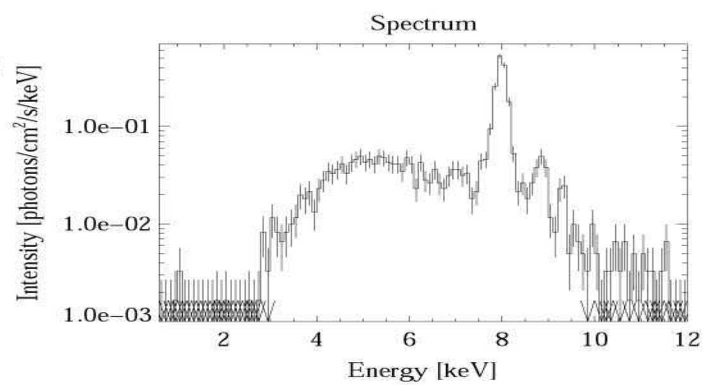


X-ray image of near parallel x-ray beam



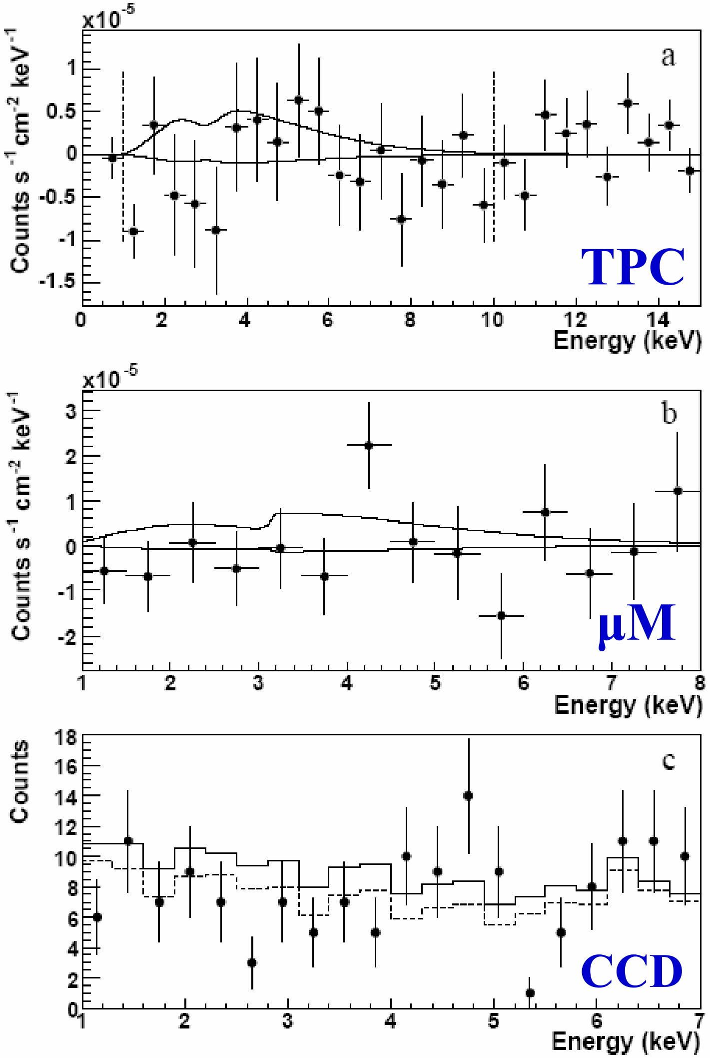






2003 Plasma Physics

[x10^{-10}GeV $^{-1}$]



1.55

1.51

1.23

FIG. 1: Panels (a) and (b) show respectively the experimental subtracted spectrum of the TPC data set and MM data set A, together with the expectation for the best fit $g_{a\gamma}$ (lower curve) and for the 95% CL limit on $g_{a\gamma}$. For (a) the vertical dashed lines indicate the fitting window. Panel (c) shows both the tracking (dots) and background (dashed line) spectra of the CCD data set, together with the expectation (background plus signal) for $g_{a\gamma}$ at its 95% CL limit, in units of total counts in the restricted CCD area (54.3 mm^2) in the tracking exposure time (121.3 h).

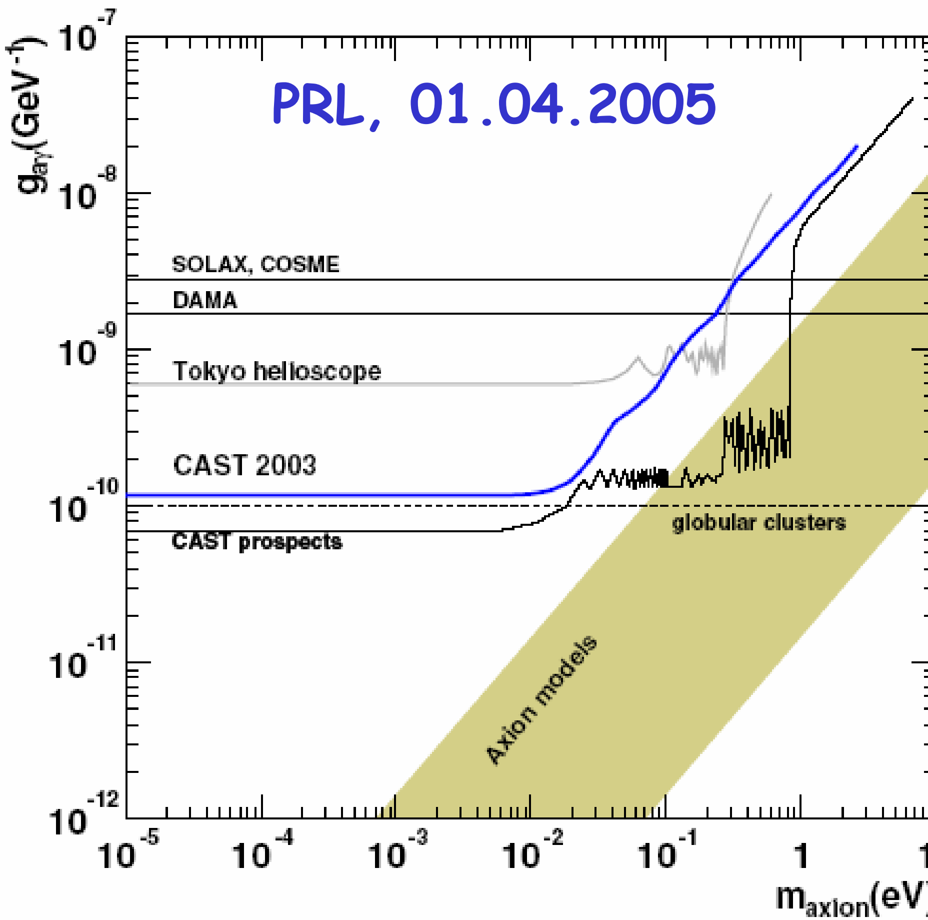
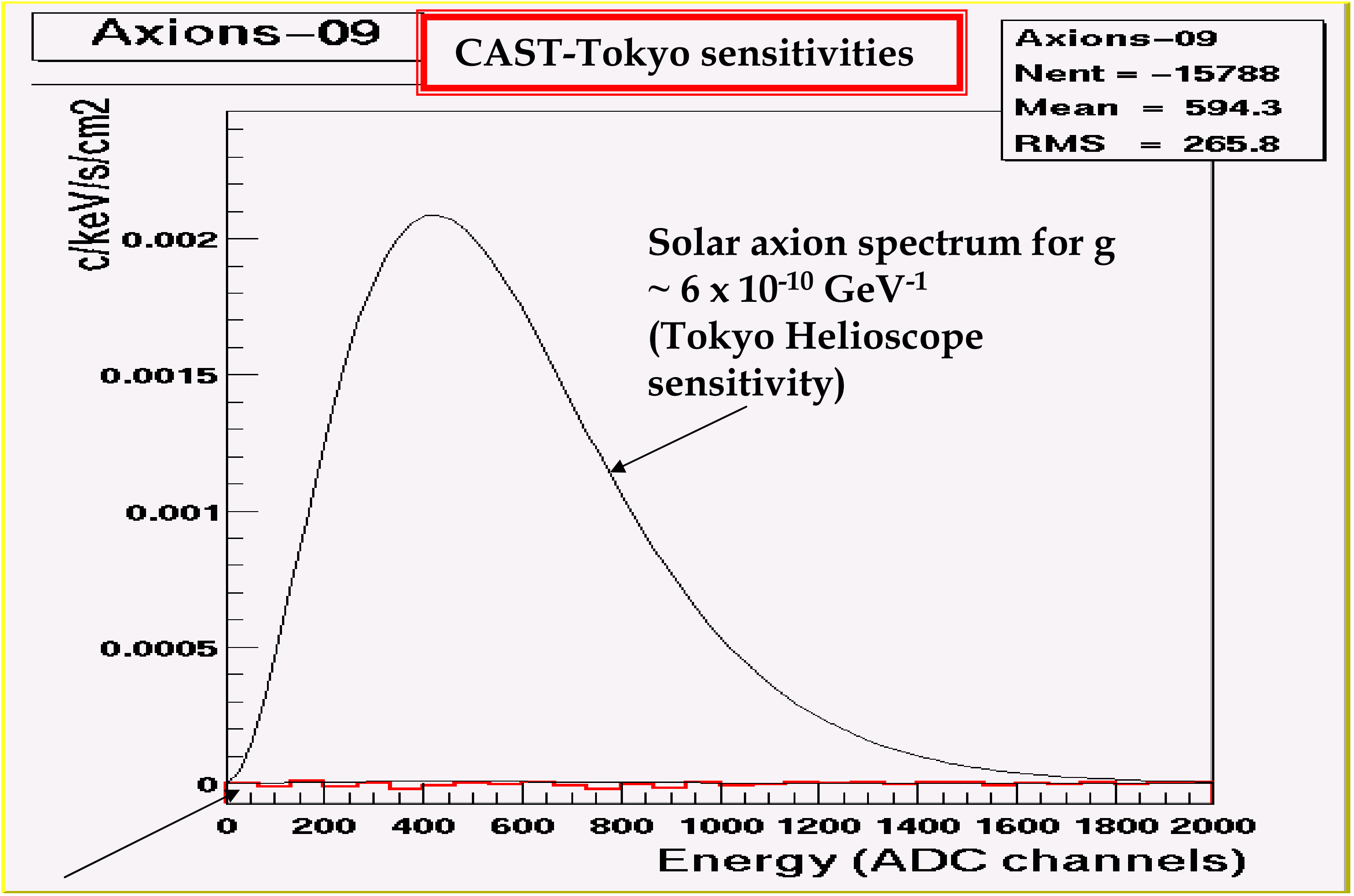


FIG. 2: Exclusion limit (95% CL) from the CAST 2003 data compared with other constraints discussed in the introduction. The shaded band represents typical theoretical models. Also shown is the future CAST sensitivity as foreseen in the experiment proposal.

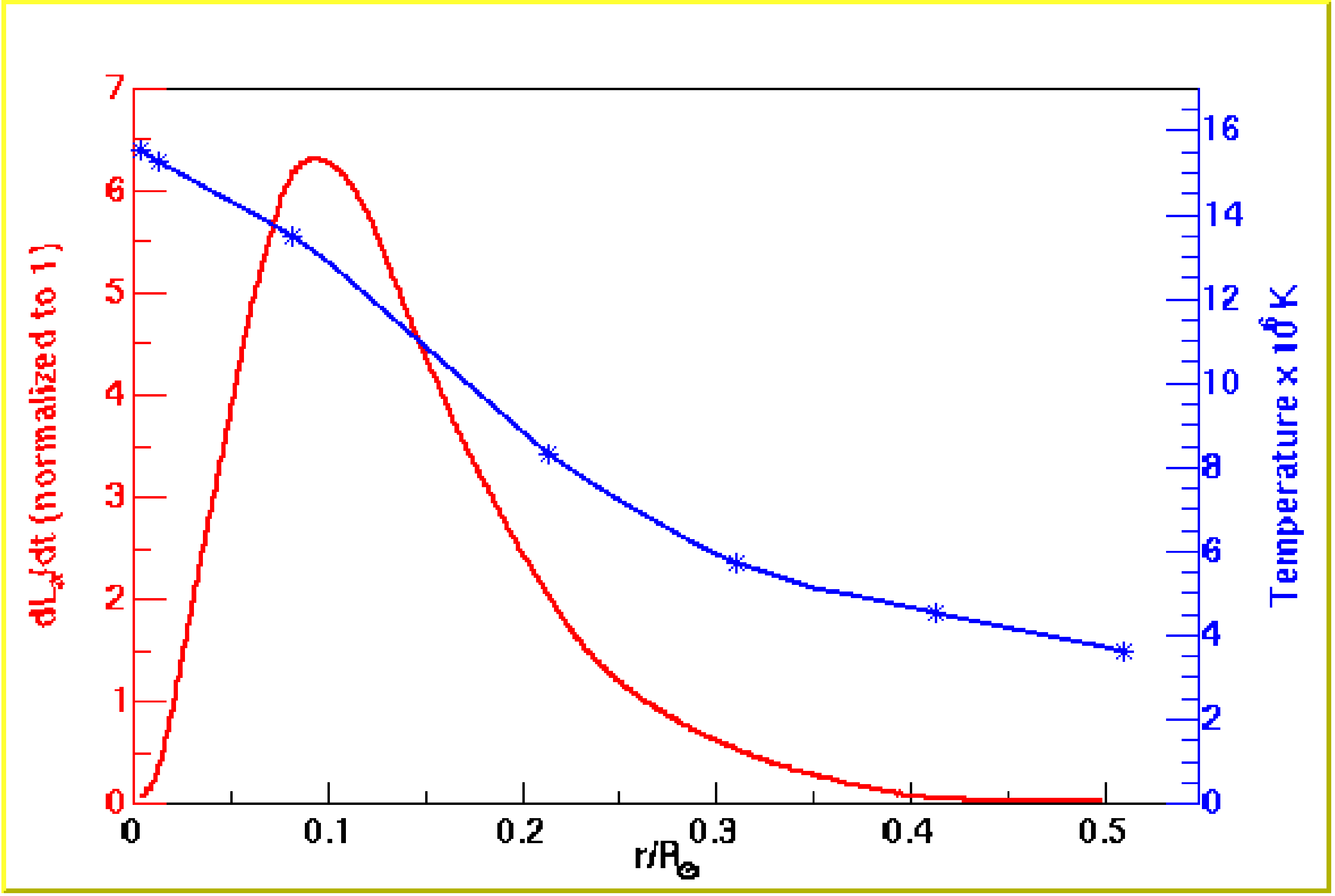
$g_{a\gamma\gamma}$(95% CL)<1.16×10^{-10} GeV^{-1} (m_a< .02eV)

Comparison of CAST to other experiments



CAST TPC
4.7 h spectrum
(bck subtracted)

Improvements

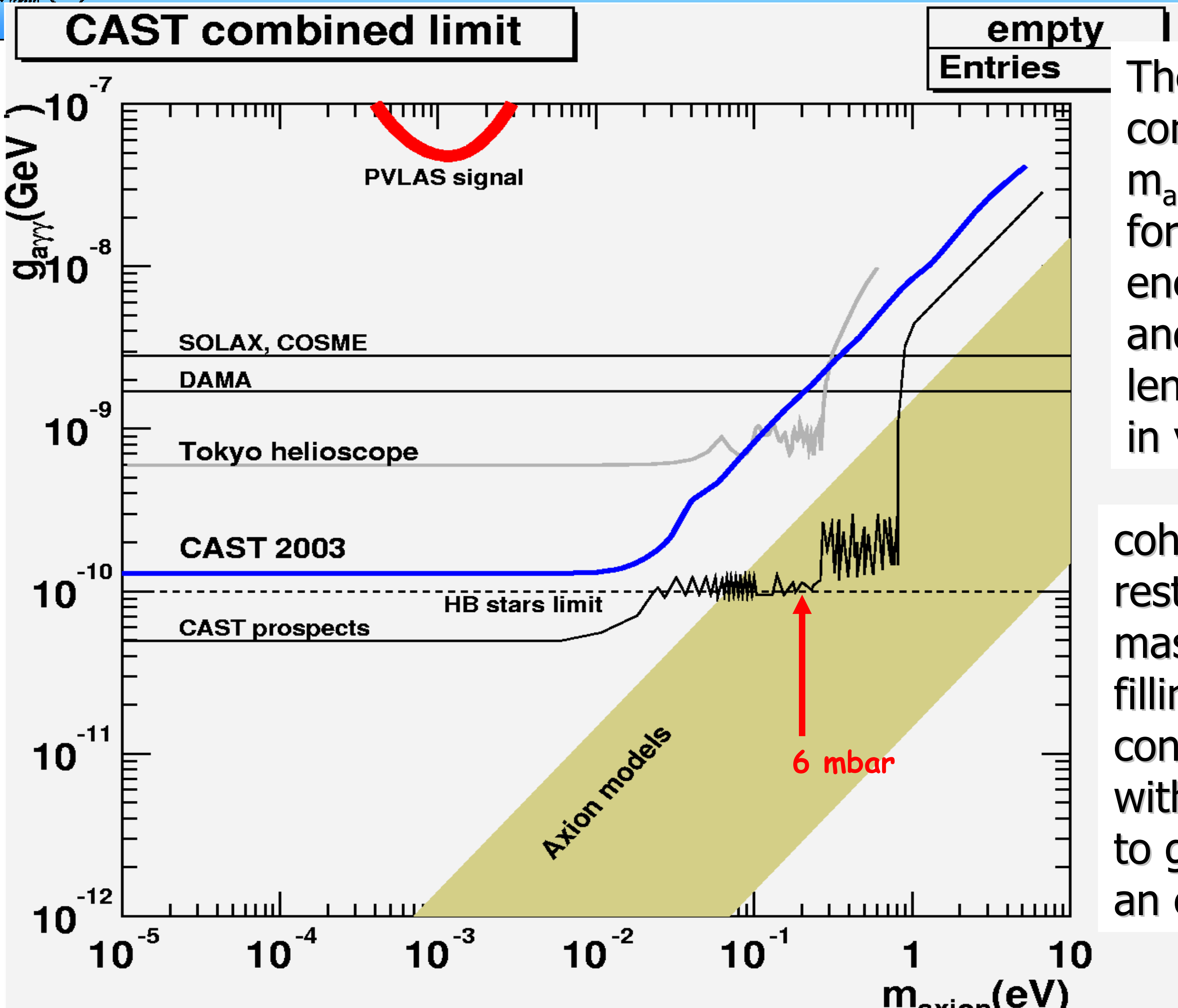


Cosmological Mass Limits on General Light Particles

Hannestad & Raffelt, Cosmological mass limits on neutrinos, axions, and other light particles, JCAP 04(2004)008 Hep-ph/0312154

Neutrinos (3 active degenerate)	$m_\nu < 0.34\,eV$
Neutrinos 3+1 (3 active massless and 1 sterile with mass)	$m_\nu < 1.0\,eV$
QCD axions	$m_a < 2-3\,eV$
Axion-like particles that couple only to photons	No limit

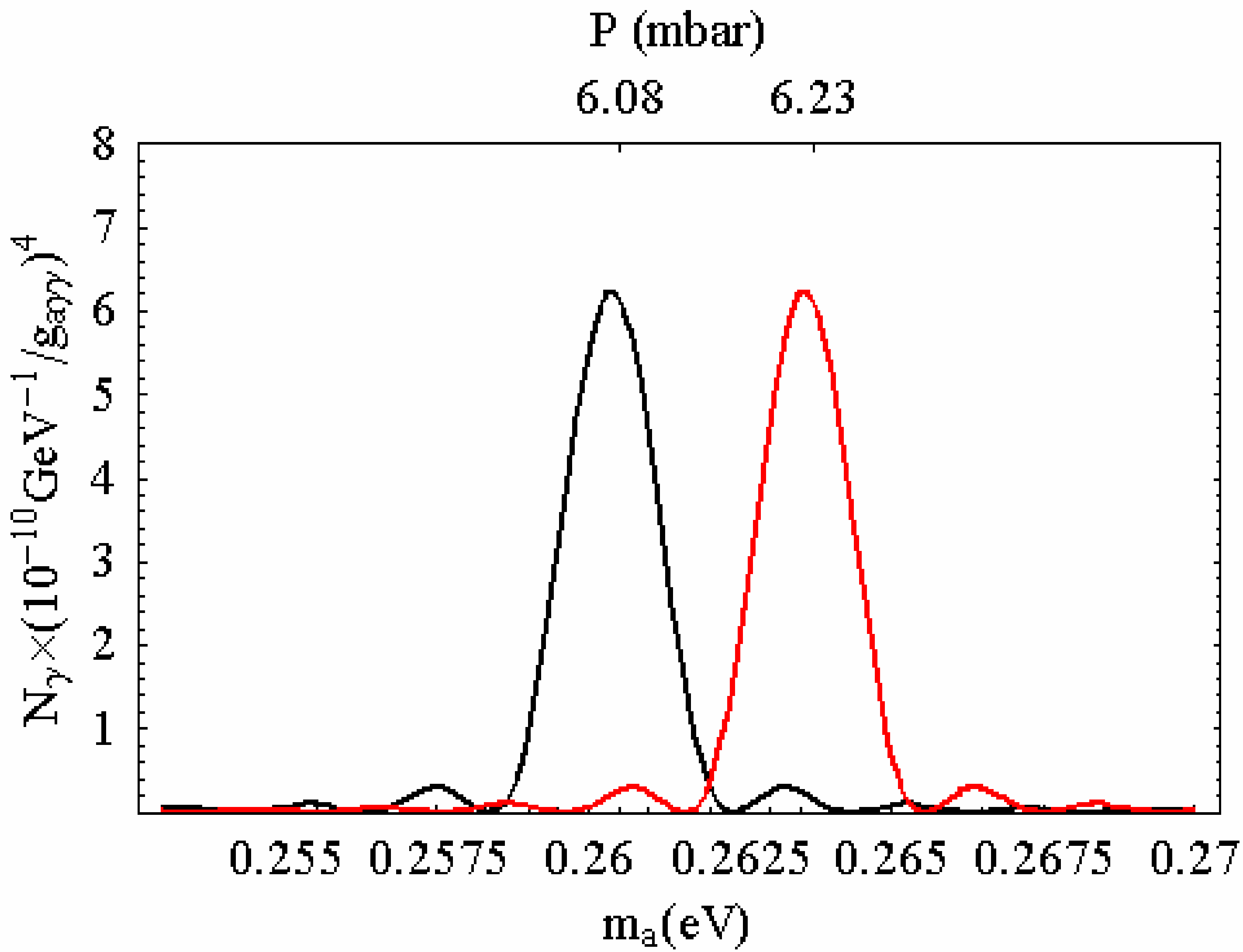
CAST : 2nd phase



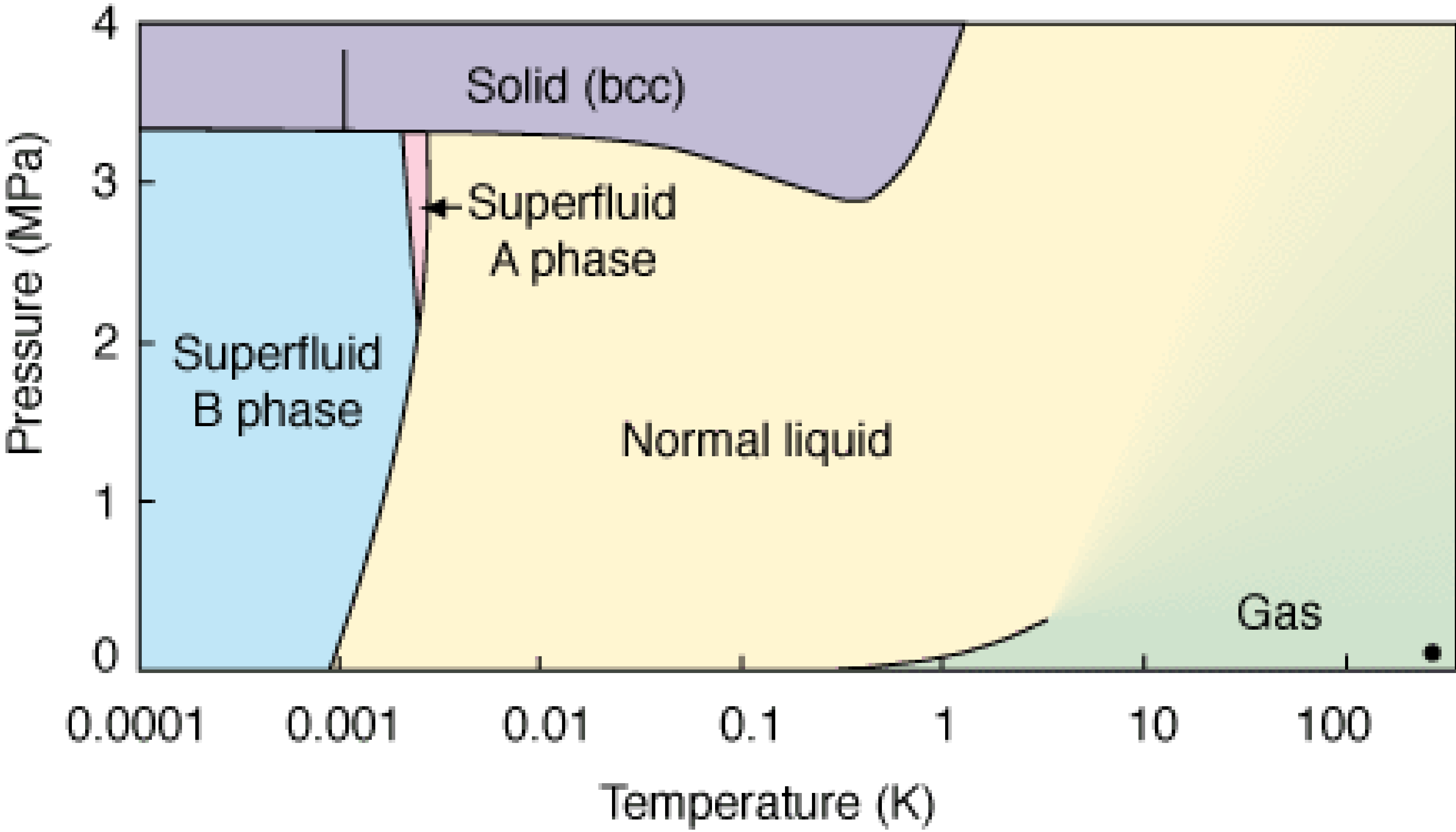
The coherence condition: m_a<0.023 eV/c^2 for a photon energy of 4.2 keV and a coherence length of 10 m in vacuum.

coherence can be restored for more massive axions by filling the magnetic conversion region with a low Z gas to give the photons an effective mass

Pressure increments

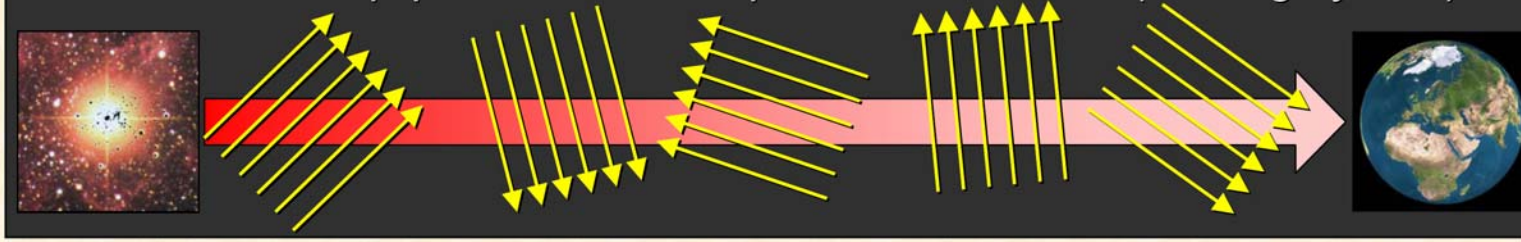


^{3}He Phase Diagram



Dimming of Supernovae without Cosmic Acceleration

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



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

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

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

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

Csáki, Kaloper & Terning, hep-ph/0111311, hep-ph/0112212. Erlich & Grojean, hep-ph/0111335.
Deffayet, Harari, Uzan, & Zaldarriaga, hep-ph/0112118. Christensson & Fairbairn, astro-ph/0207525.
Mörtsell et al. astro-ph/0202153. Bassett, astro-ph/0311495.

Axions may occur in two flavors:

- Standard (Peccei-Quinn) Axion:
  - similar to very light neutral pion (π^0)
  - rest mass ~ 10^{-6}.. 10^{-1} eV/c^2
  - lifetime much longer than the age of the Universe

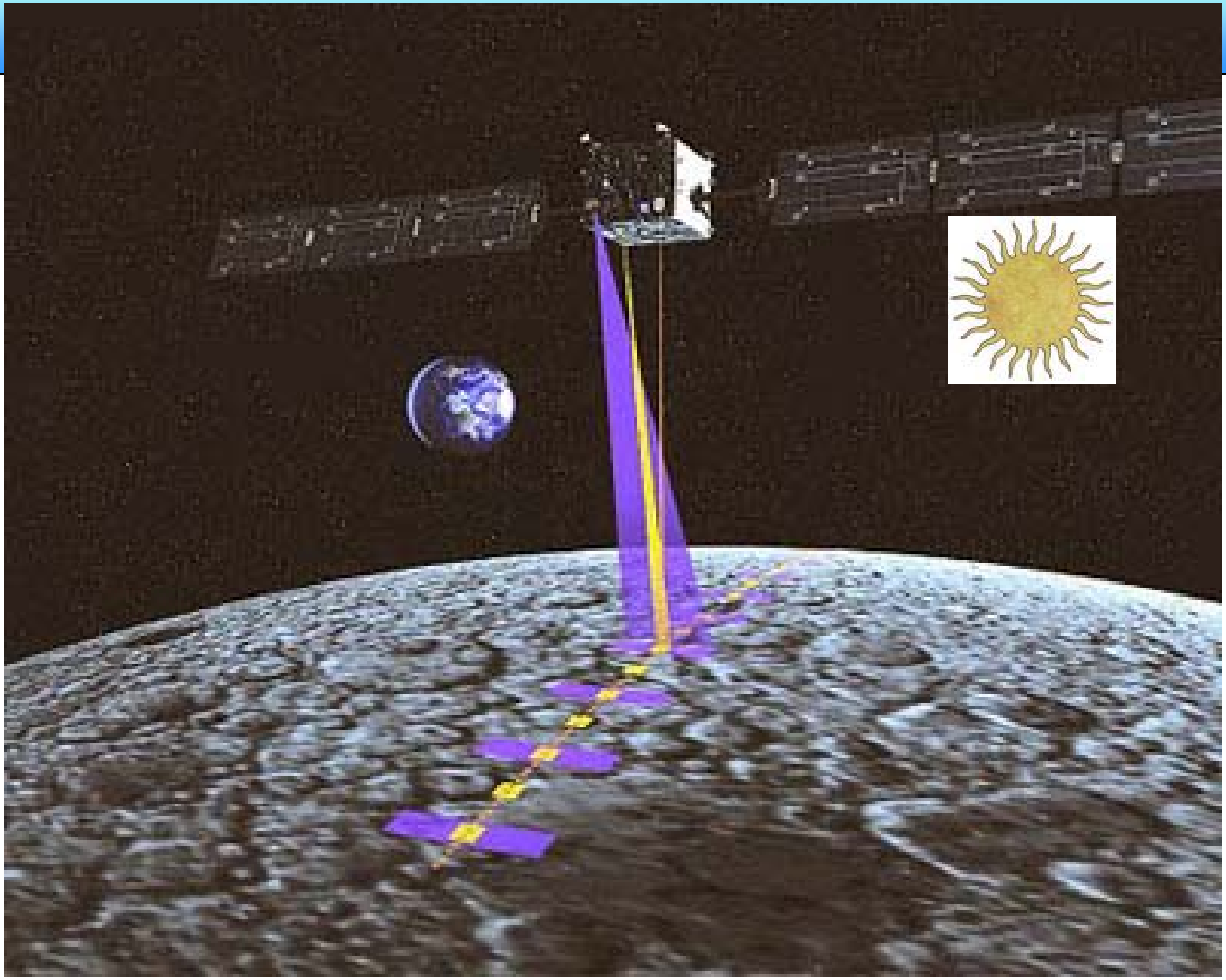
- Kaluza-Klein (KK) Axions:
  - predicted by recent theories of extra-dimensions, proposed as extensions of the Standard Model
  - mass spectrum of all the excited Kaluza-Klein states extends up to ~ 10 keV / c^2
  - relative shorter lifetime: $\tau \sim m^{-3}$

K. Dennerl

The axion-photon-photon coupling constant $g_{a\gamma\gamma}$ is the same for both types

SMART mission: *orbiting X-ray detectors* → Moon → Sun

Plasma Physics GSI



➔ *planned collaboration with Observator University/Helsi*
S. Tzamarias, K. Zioutas, M. Kuster DHHH
23.05. first meetin

Search for ***massive axions*** ➔ spontaneous radiative decays **a** → γγ

Benefits of Axions

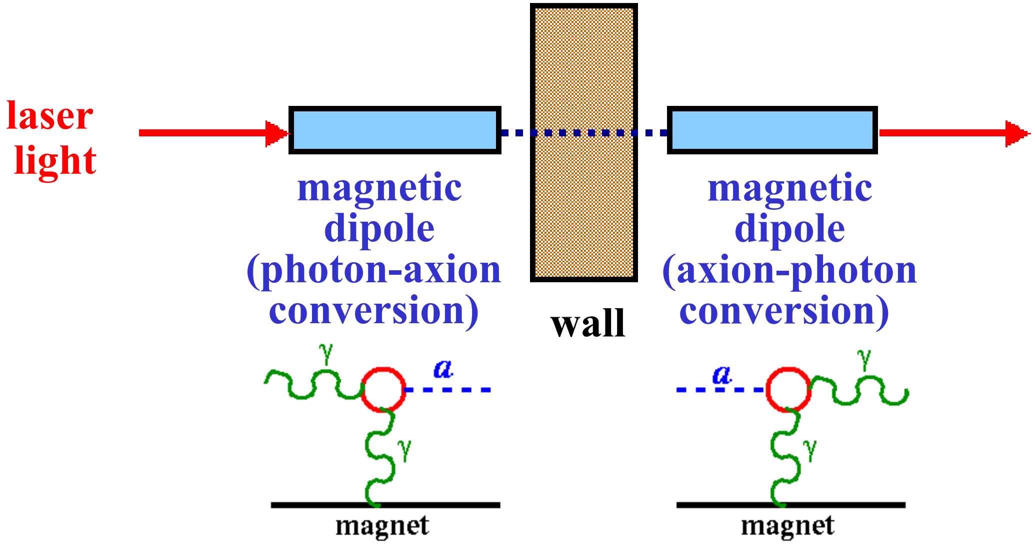
Axions may contribute to

- solve symmetry problem
- solve dark matter problem
- solve ... ?

K. Dennerl

And yet...

"Light shining through walls"



Magnetic field direction at 90° to laser light beam

Polarization experiments

Polarized laser light propagating through a magnetic dipole (field B)

Only the component of $\vec{E}$ parallel to $\vec{B}$ can produce axions ⟶ small rotation of the polarization vector (use mirrors at the end of the dipole for multiple traversals)

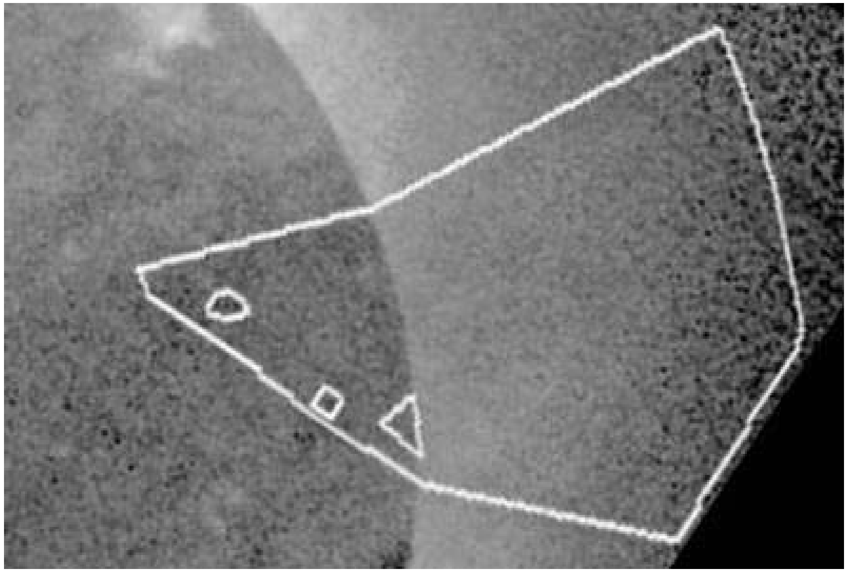
X-ray surface brightness as a function of the solar elongation

Plasma Physics

surface brightness for the thin Al filter

estimated scattering component for the thin Al filter

Sturrock, Wheatland, Acton, ApJ 461 (1996) L115



Yohkoh SXT, 8 May 1992