The running CERN axion helioscope CAST

TDR

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University of Patras / Greece

BNL seminar

19th October 2006

ON THE STATUS OF CAST
Motivation, first results, upgrades and inspiring concept.

TDR

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➔ **EU-ILIAS AXIONS**

Axion workshop
Princeton / IAS

19^{th} - 22^{nd} October 2006

Birth of solar axion astrophysics in BNL

Search for Solar Axions

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We have searched for a flux of axions produced in the Sun by exploiting their conversion to x rays in a static magnetic field. The signature of a solar axion flux would be an increase in the rate of x rays detected in a magnetic telescope when the Sun passes within its acceptance. From the absence of such a signal we set a 3σ limit on the axion coupling to two photons $g_{a\gamma\gamma} \equiv 1/M < 3.6\times10^{-9}$ GeV^{-1}, provided the axion mass $m_a < 0.03$ eV, and $< 7.7\times10^{-9}$ GeV^{-1} for $0.03 < m_a < 0.11$ eV.

PACS numbers: 14.80.Gt, 95.85.Qx, 96.60.Vg

ent theories of elementary particles predict the ex- of low mass scalar or pseudoscalar particles. rise naturally when a global symmetry is spon-

Axions that couple directly to electrons through an *eea* vertex provide a very efficient energy-loss mechanism and their relative coupling is excluded by many orders of

PRL 94, 121301 (2005) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2005

First Results from the CERN Axion Solar Telescope

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The CAST Collaboration **+ LLNL**

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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

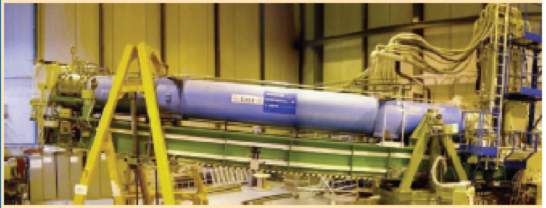
Remote control

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**



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 Hadro Collider, at the Sun. Axions might be produc the solar plasma when photons are scatter strong electromagnetic fields. CAST has pu scattering effect into reverse by producing photons from solar–axion interactions on E

The magnet can be tilted at either end an angle that allows the Sun to be observe sunrise and sunset, both ends being fitted X-ray detectors and an X-ray telescope rec from the German space programme. The re assuming a very small axion mass, show n above background, and constrain the axion coupling strength by a factor of five compa with results from previous lab experiments Future measurements should deliver still b sensitivity, and also test the axion hypothes higher masses. **Rich**

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

P.-F. Braun and colleagues have n directly observed this 'spin relaxatio in quantum dots — clusters of atoms just nanometres across — made of t semiconductor materials indium ars and gallium arsenide. The authors fo that the initial spin polarization of su decays with a half-life of just 0.5 nano — half a millionth of a millisecond — remaining stable at about a third of i value for at least a further 10 nanose

However, they also report that thi relaxation process can be suppressed an externally applied static magnetic of just 100 mT, which can be provide small permanent magnets. Such a fie increases the characteristic decay hal to around 4 nanoseconds, and could prove useful in future practical devic they suggest. **M**

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 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

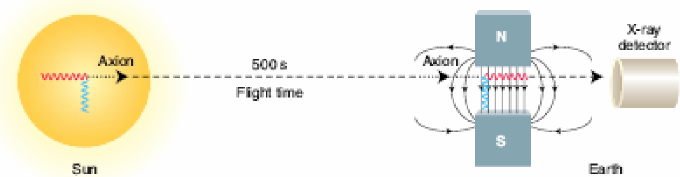
PARTICLE PHYSICS

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

Lockheed Boosts Los Alar

U.S. aerospace giant Lockheed Ma strengthened its bid to run Los Ala National Laboratory in New Mexi week by recruiting a key senior sci Sandia National Laboratories Dire C. Paul Robinson, who spent 18 ye Alamos before moving to Sandia i has joined the proposal team for t Bethesda, Maryland–based compa

Lockheed officials want Robins head Los Alamos if they beat out t current contractor, the University nia. Final competition details are e soon, with bids in the summer. Me former weapons chief Thomas Hu been promoted to director of San has facilities in California and New

—E

Pig Flu Scare—Case Clo

The World Health Organization (W hopes that the results of a new stu put to rest suspicions that pigs in S Korea have become infected with a tially dangerous flu strain.

Last fall, Sang Heui Seo of Chung National University in Daejeon, Kor deposited flu sequences in GenBan gested that Korean pigs carried WS strain widely used in labs but not kn occur in nature. Several experts and missed the findings as the result of tamination (*Science*, 4 March, p. 13 Yoshi Kawaoka of the University of Madison, and his colleagues have te 400 samples from two Korean pig f WHO says, and found no trace of W

Seo declined to comment. Hen a business owner in Philadelphia w Seo's claim, says Kawaoka's study broad enough to refute the theory WHO flu expert Klaus Stöhr, "we'v too much time on these speculatio already."

—Marti

Plant Center to Cut Jobs

The John Innes Centre in Norwich, of Europe's top plant science instit plans to cut up to 35 researchers f 800-person staff. Director Christop announced on the center's Web sit week that the center began losing 18 months ago when two funders— European Union and private indust became "less reliable sources." Inc center, which has a $40 million an budget, has dropped by $5.7 millio

This is "a big blow," says plant g Michael Wilkinson of the Universit ing, U.K., adding that the institutio duces an "astonishing number" of c cited basic science papers. —Eliot

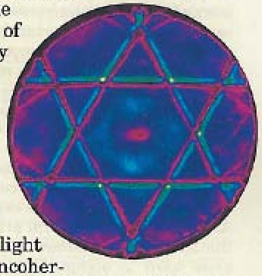
Physics Update

A new mode for desorption has been uncovered. The detachment of atoms and molecules from a surface is one of the fundamental processes of surface science. One of two mechanisms is generally invoked. Thermal desorption calls for the material to be heated, which can stretch and eventually break the bonds of adsorbed atoms and molecules through the action of phonons. In contrast, electronic desorption calls for an external stimulus—say, from an incident electron or photon—to induce an electronic transition of sufficient energy to promote the adsorbed atom or molecule from a bound to an unbound state. The two mechanisms operate on vastly different time scales, with electronic transitions being faster. Studying bromine adsorbed on silicon, John Weaver and his colleagues at the University of Illinois at Urbana-Champaign have found a third mode, one that has elements of both of the others. The researchers examined bromine's desorption kinetics as a function of silicon doping and of temperature. A detailed analysis revealed the rare but crucial event of 10–20 phonons simultaneously interacting with a single electron. Rather than directly breaking a bond as in the thermal case, the phonons induce an electronic transition that promotes the adsorbate to an unbound state. Thus, the Illinois group found the surprising result that electronic desorption prevails in this system without needing any external excitation. Multiphonon processes are common during a system's relaxation, but the Illinois work may show that they can also play an important role in surface chemistry. (B. R. Trenhaile et al., *Surface Science*, in press.) —SGB

A search for the hypothetical axion has produced a new limit on the axion–photon interaction strength. The putative axion, a leading candidate for cosmological dark matter, could be produced in a two-photon interaction with an electric or magnetic field. Now, the CERN Axial Solar Telescope (CAST) collaboration has investigated how axions produced at the Sun interact with a laboratory magnetic field to back-convert into x rays. In the CAST experiment, which ran for about six months in 2003, a 10-m-long, 9-T magnet refurbished from the Large Hadron Collider followed the Sun like a telescope. It was outfitted with x-ray detectors and an x-ray telescope recovered from the German space program. No axions were seen, but for lightweight axions of 0.02 eV or less, the data analysis improved the previous state-of-the-art laboratory limit on the axion–photon interaction strength by a factor of five. The CAST group expects further improvement after analyzing their 2004 data. (K. Zioutas et al., *Phys. Rev. Lett.* **94**, 121301, 2005.) —SKB

Direct detection of extrasolar planets has been achieved. Previously, the existence of planets around other suns has been inferred from subtle modulation of the starlight, either as a planet gravitationally tugged its star or as a star's light decreased when a planet eclipsed it. Now, two groups have used the *Spitzer Space Telescope* to directly record infrared light from eclipsing planets. The planets—with the prosaic names of HD 209458b (153 light years away) and TrES-1 (489 light years away)—have circular orbits a tenth the size of Mercury's, which makes the Jupiter-sized planets hot enough to be viewed by *Spitzer*. Unlike observations of other eclipsing systems, these detections relied on the planet being hidden *behind* the star. When the starlight was subtracted from the light of the complete system, only the planet's IR emission remained. (D. Deming et al., *Nature* 434, 740, 2005; D. Charbonneau et al., *Astrophys. J.*, in press.) —PFS

Seeing the Brillouin zones of photonic lattices. The properties of periodic photonic systems depend on fundamental features of periodic structures, as described in standard condensed-matter physics texts. Periodic photonic structures and their defects (for example, the hollow core of a photonic-crystal fiber) have been directly imaged routinely for some time, but their characterization is incomplete without knowledge of the momentum-space (reciprocal-lattice) structure of the system—its Brillouin-zone (BZ) structure. Researchers from the Technion–Israel Institute of Technology, the University of Zagreb in Croatia, and Princeton University in the US, have now directly imaged the extended BZs of two-dimensional square and trigonal photonic lattices. Their technique relies on Bragg diffraction of laser light that was made spatially incoherent with a rotating diffuser, and on an optical Fourier transform. The result is textbooklike pictures previously obtainable only by computer calculations. Shown here is a typical image of the first, second, and third BZs of a trigonal lattice with an embedded defect. According to the group's leader, Moti Segev, the BZ characterization technique is general and may be used to map the momentum space of any periodic photonic structure, as well as of periodic systems beyond optics. (G. Bartal et al., *Phys. Rev. Lett.*, in press.) —SGB



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

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

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.

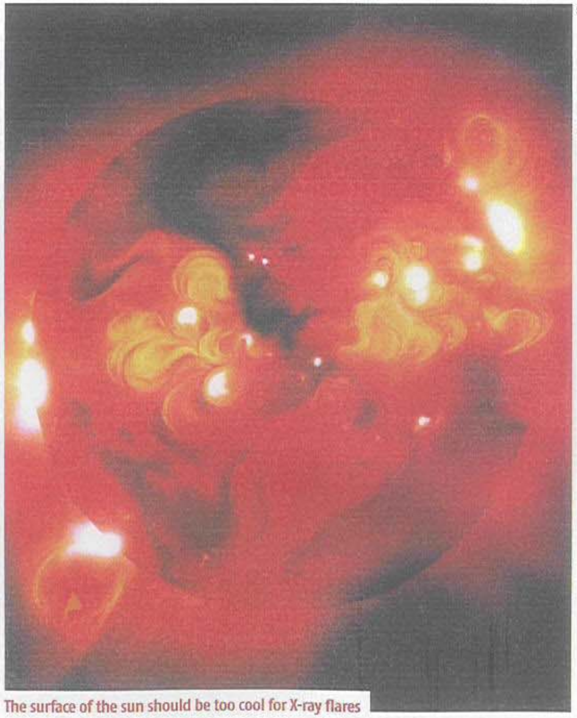
In a paper to be published in *The Astrophysical Journal* next month, Zioutas and his colleagues report that the predictions match brightness measurements made by the Yohkoh satellite.

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

"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

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

Axion searches in the spotlight

Journal of Cosmology and Astroparticle Physics
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Evading astrophysical constraints on axion-like particles

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Abstract. Stellar energy loss arguments lead to strong constraints on the coupling $\phi\gamma\gamma$ of a light axion-like particle to two photons. Helioscopes, like CAST, are able to impose competitive bounds. The PVLAS experiment has recently observed a rotation of the polarization of a laser propagating in a magnetic field that can be interpreted as the effect of a quite strong $\phi\gamma\gamma$ coupling. We present scenarios where the astrophysical and CAST bounds can be evaded, and we show that the PVLAS result can be accommodated in one of the models, provided that the new physics scale is at very low energies.

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Axion alternatives

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June 30, 2006

And others...

Axion searches in the spotlight

- **The interest on axions reaches also string theorists…**

arXiv:hep-th/0605206 v2 9 Jun 2006

Axions In String Theory

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In the context of string theory, axions appear to provide the most plausible solution of the strong CP problem. However, as has been known for a long time, in many string-based models, the axion coupling parameter F_a is several orders of magnitude higher than the standard cosmological bounds. We re-examine this problem in a variety of models, showing that F_a is close to the GUT scale or above in many models that have GUT-like phenomenology, as well as some that do not. On the other hand, in some models with Standard Model gauge fields supported on vanishing cycles, it is possible for F_a to be well below the GUT scale.

UMD-PP-06-054
UFIFT-HEP-06-15

Reconciling the CAST and PVLAS Results

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The PVLAS experiment has recently claimed evidence for an axion-like particle in the milli-electron-Volt mass range with a coupling to two photons that appears to be in contradiction with the negative results of the CAST experiment searching for solar axions. The simple axion interpretation of these two experimental results is therefore untenable and it has posed a challenge for theory. We propose a possible way to reconcile these two results by postulating the existence of an ultralight pseudo-scalar particle interacting with two photons and a scalar boson and the existence of a low scale phase transition in the theory.

PACS numbers: 12.20.Fv,14.80.Mz,95.35.+d

hep-ph/0610068, 6 Oct. 2006

I. INTRODUCTION

Two recent experiments, CAST[1] and PVLAS[2] searching for an ultralight axion-like pseudoscalar particle (denoted by a) with coupling of the form

the same in the laboratory. Our basic idea is to avoid this problem by introducing an interaction of the form $\phi a F\tilde{F}/M^2$ rather than a direct $aF\tilde{F}$ interaction and assuming the field ϕ to have the following properties: (i) it has a non-zero vev, which is induced by a field σ such

A model solving the PVLAS-CAST puzzle

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08193 Bellaterra, Barcelona, Spain

Axion physics has received a boost with the recent claim of the PVLAS collaboration. Their results can be interpreted as due to a new axionlike particle but the CAST collaboration has not found trace of it. While the axionlike particle interpretation of the PVLAS signal is going to be probed by dedicated laboratory experiments, it is mandatory to find either alternatives to it or models in which the astrophysical bounds could be evaded. In this communication one of such models is presented. The new physics involved appears at a low energy scale $<$ eV.

PACS numbers: 12.20.Fv,14.80.Mz,95.35.+d,96.60.Vg

hep-ph/0610213, 17 Oct 2006

I. THE PVLAS & CAST PUZZLE

The PVLAS collaboration has recently claimed a rotation of the polarization of laser light propagating through a transverse magnetic field [1]. This can be interpreted

Inspired by this ideas we have suggested in [6] that the value of M could decrease with the momentum transfer q^2 at which the interaction (1) is probed. Note that in PVLAS $\sqrt{q^2} \sim 10^{-6}$ eV while in the Primakoff conversion in stars $\sqrt{q^2} \sim$ keV. This idea has been generalized

Motivation?

AXION PHYSICS

The QCD Lagrangian :

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

L_{pert} ⇒ numerous phenomenological successes of QCD.

G is the gluon field-strength tensor

➔ **θ-term** → a consequence of non-perturbative effects

→ implies ***violation of CP symmetry***

→ would induce EDMs of strongly interacting particles

Experimentally ➔ CP is **not** violated in QCD → the neutron EDM $d_n < 10^{-25}\ e\ cm$ ⇒ $\theta < 10^{-10}$

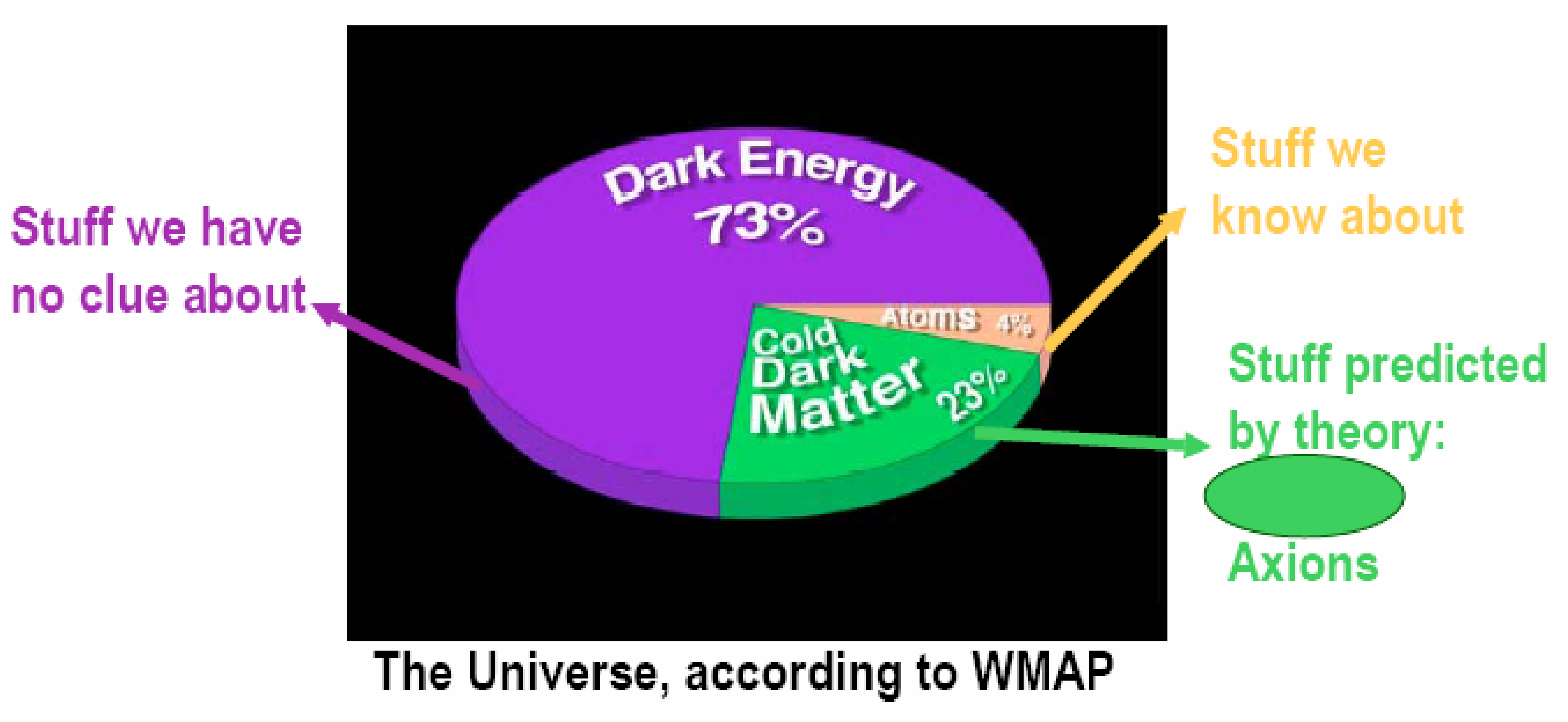
⇒ ***why is θ so small?*** ➔ ***the strong-CP problem***

➔ ***the only outstanding flaw in QCD***

➔ To solve the strong-CP problem, **Peccei-Quinn** introduced a global $U(1)_{PQ}$ symmetry broken at a scale f_{PQ}, and non-perturbative quantum effects drive **θ → 0** ➔ **"CP-conserving value"** and also generate a mass for the axion :

$$m_{\rm PQ} = 6\ {\rm eV} \frac{10^6}{f_{\rm PQ}/1\ {\rm GeV}}$$

➔ All the axion couplings are inversely proportional to f_{PQ} .



Axion ➔ **Dark Matter particle *candidate*** ➔ **new physics**

➔ **also solar axions!**

http://www.fnal.gov/directorate/Longrange/PartAstro1003_Talks/Bauer.pdf

Solar energy is created within the core of the Sun.

→ **Nuclear reactions:** **4p = 1α**

→ **The one He is about .7 % less massive than the 4p.**

→ **Energy generated in the Sun's core takes ~10^6 years to reach its surface.**

→ **700 million tons H / s are converted into He.**

➔ **5 million tons of pure energy is released** ➔

➔ ***~10^5 tons of axions / sec*** ➔

➔ ***overlooked?***

http://www.solarviews.com/eng/sun.htm

< 1998

AXION SEARCHES

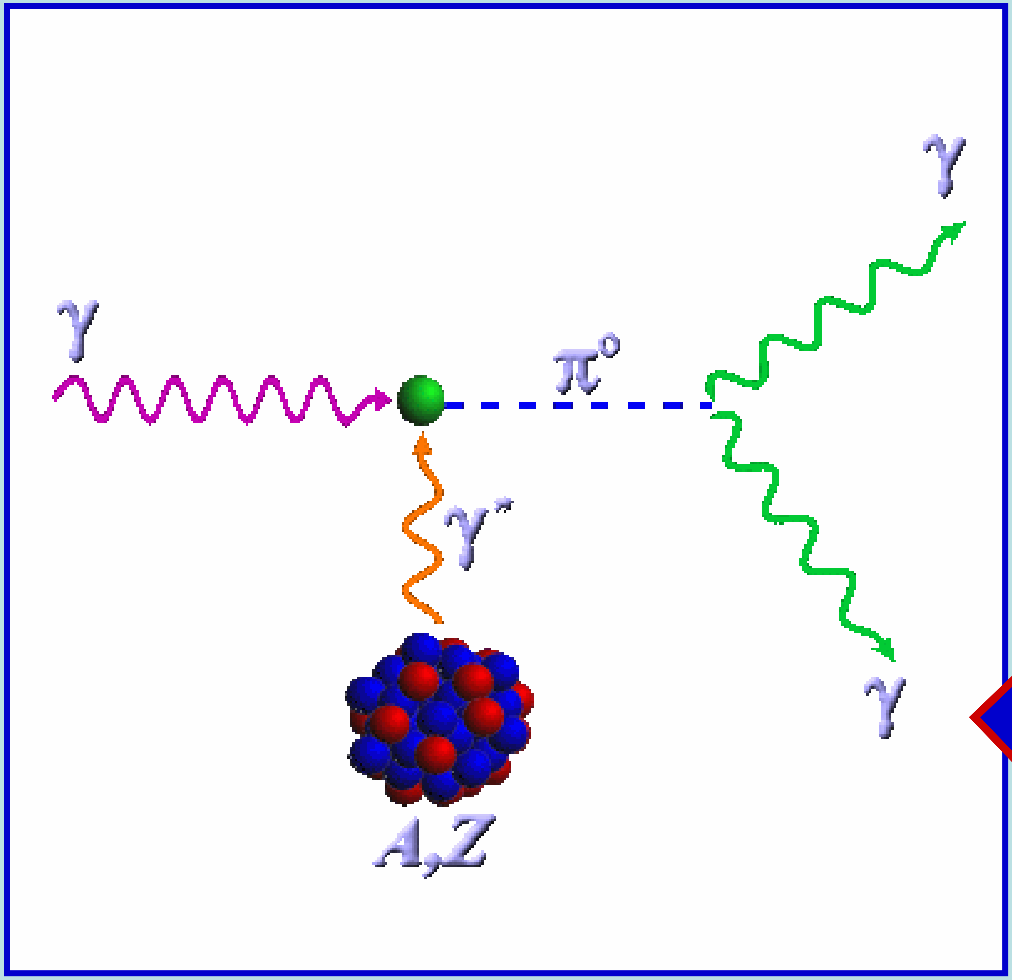
are

○ MANDATORY

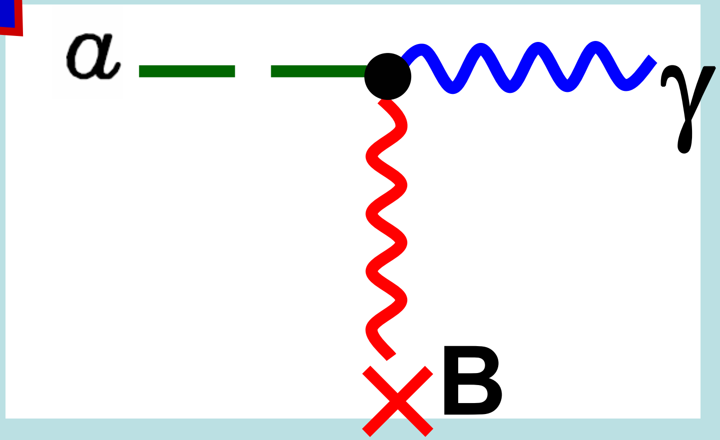
○ FUN, CREATIVE

○ PROCEEDING

The Primakoff Effect 1951



H. Primakoff



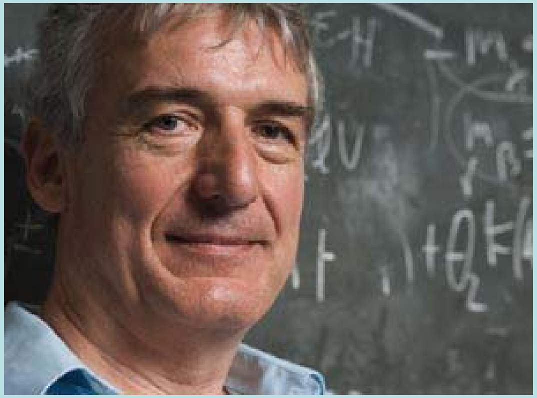
Behind all present axion work

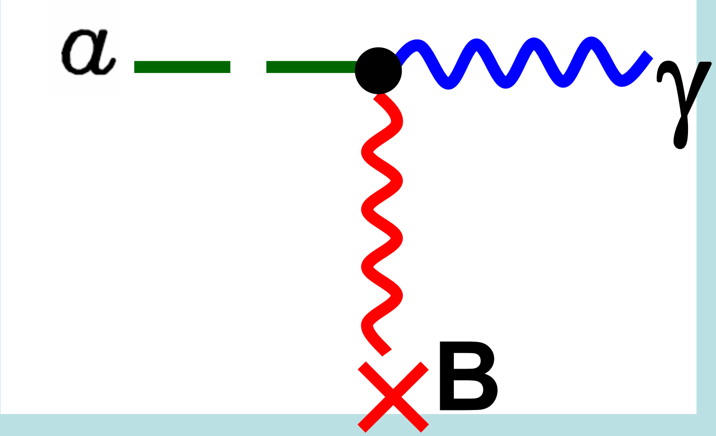
before CAST:

- ➔ BNL & Tokyo
- ➔ axion-Bragg @ Ge, NaI, …

CAST

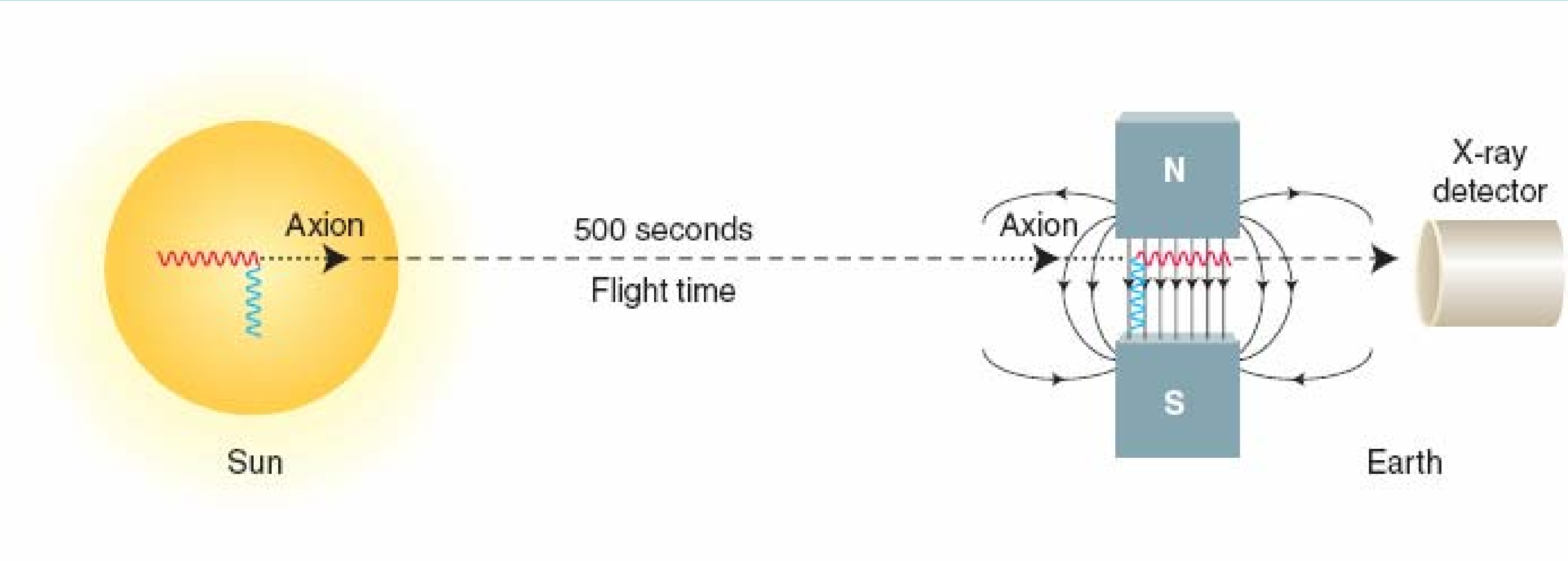
P. Sikivie



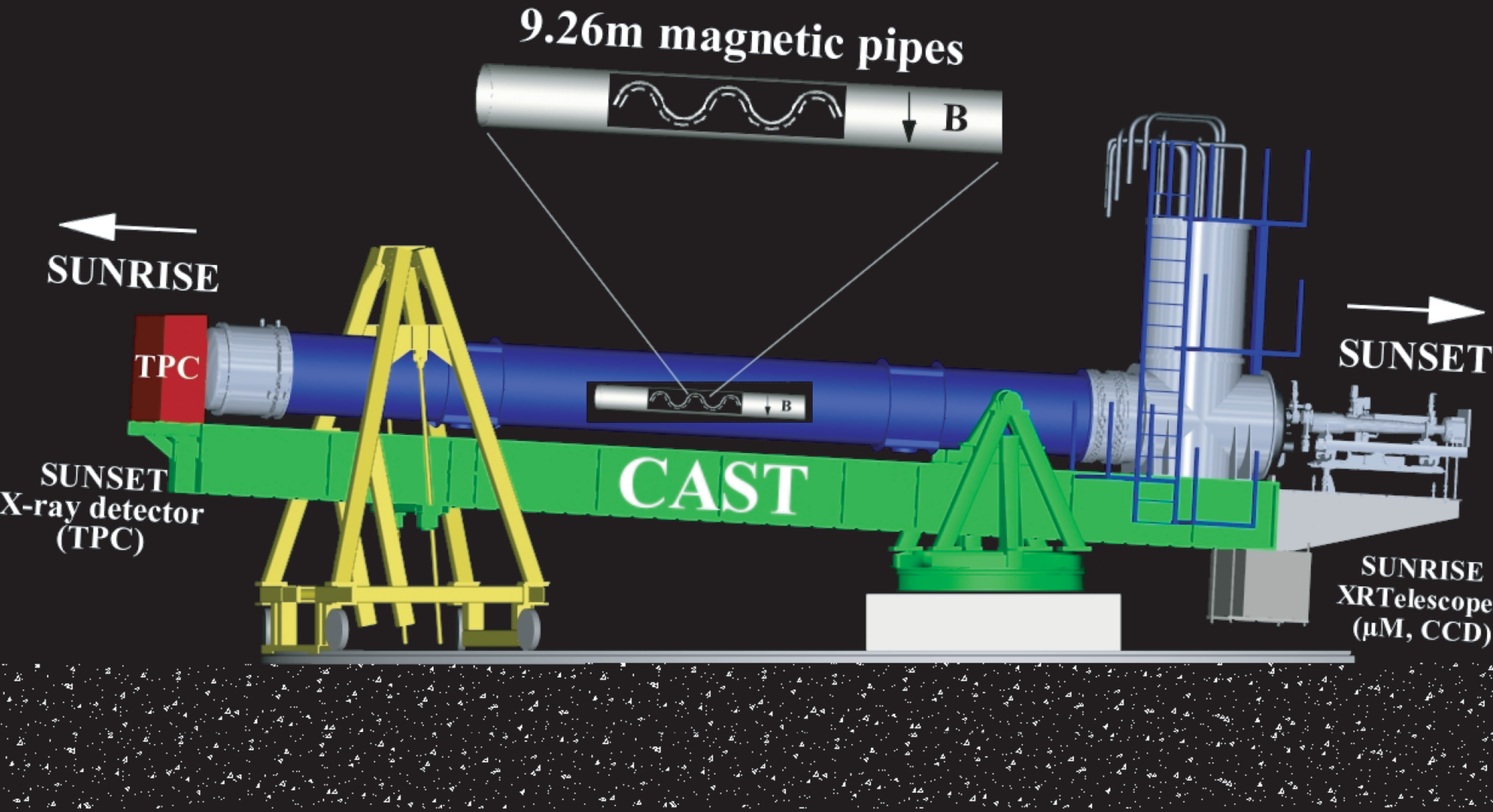


Axion - source ↓

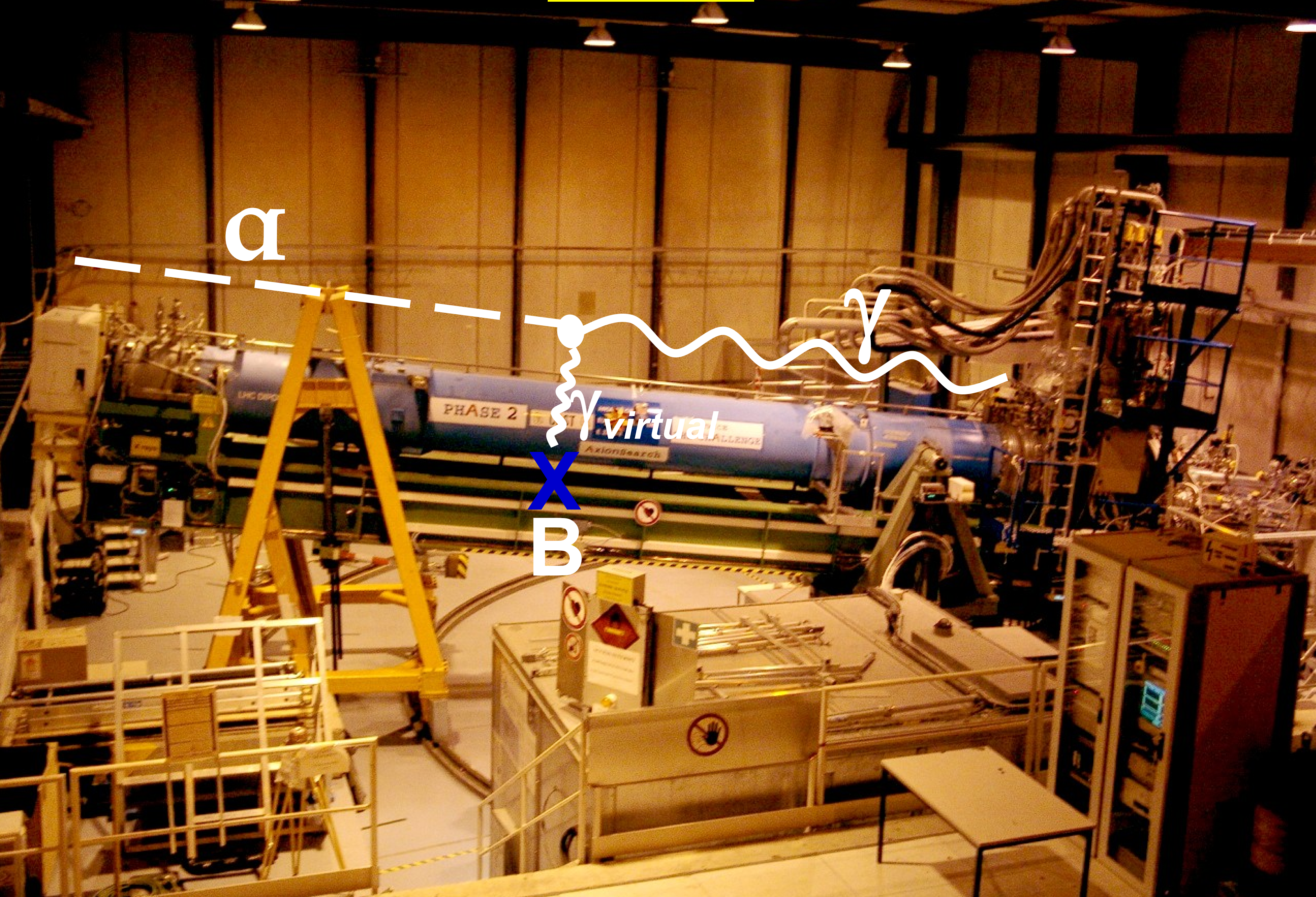
Axion - detection ↓

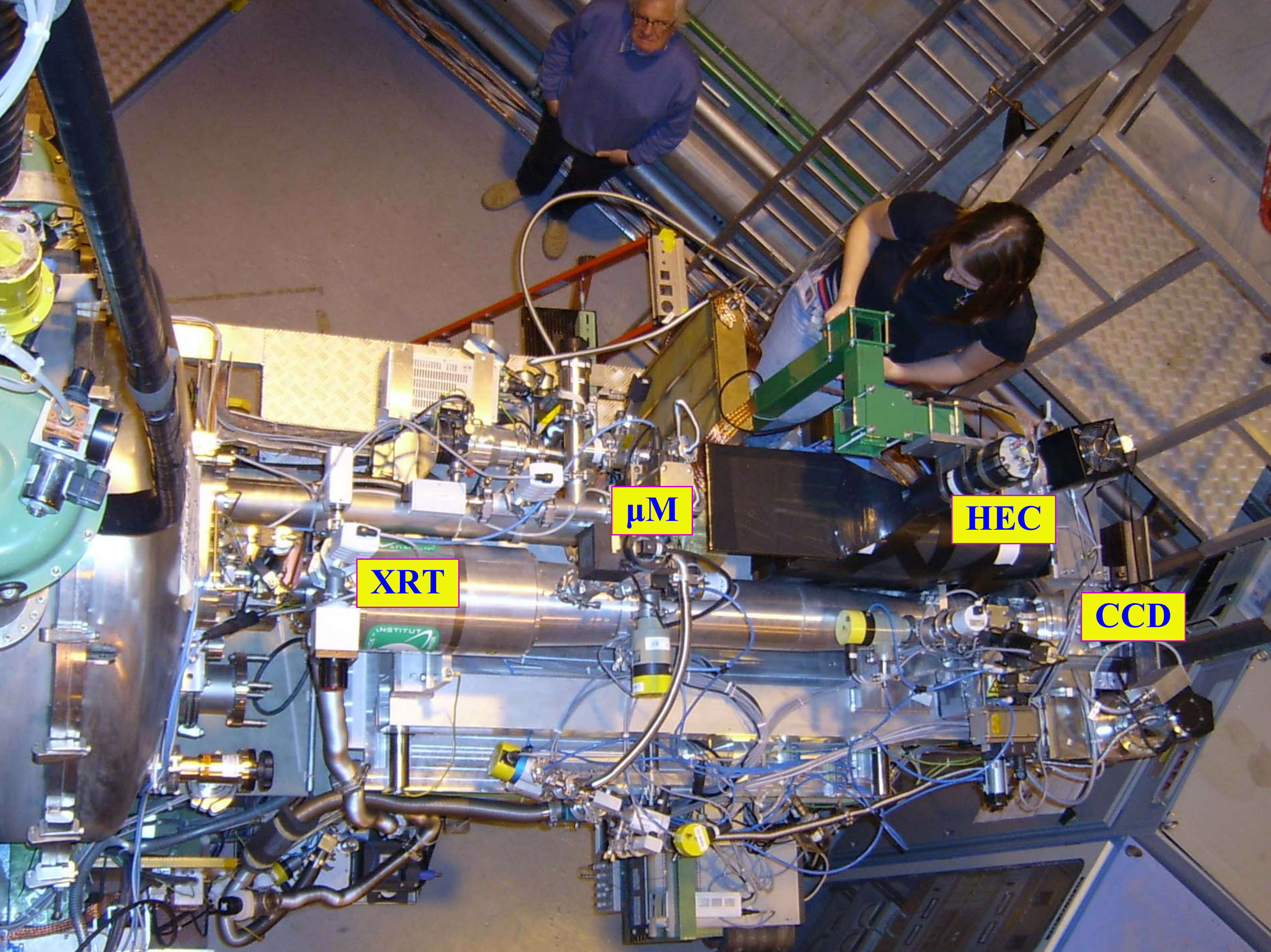


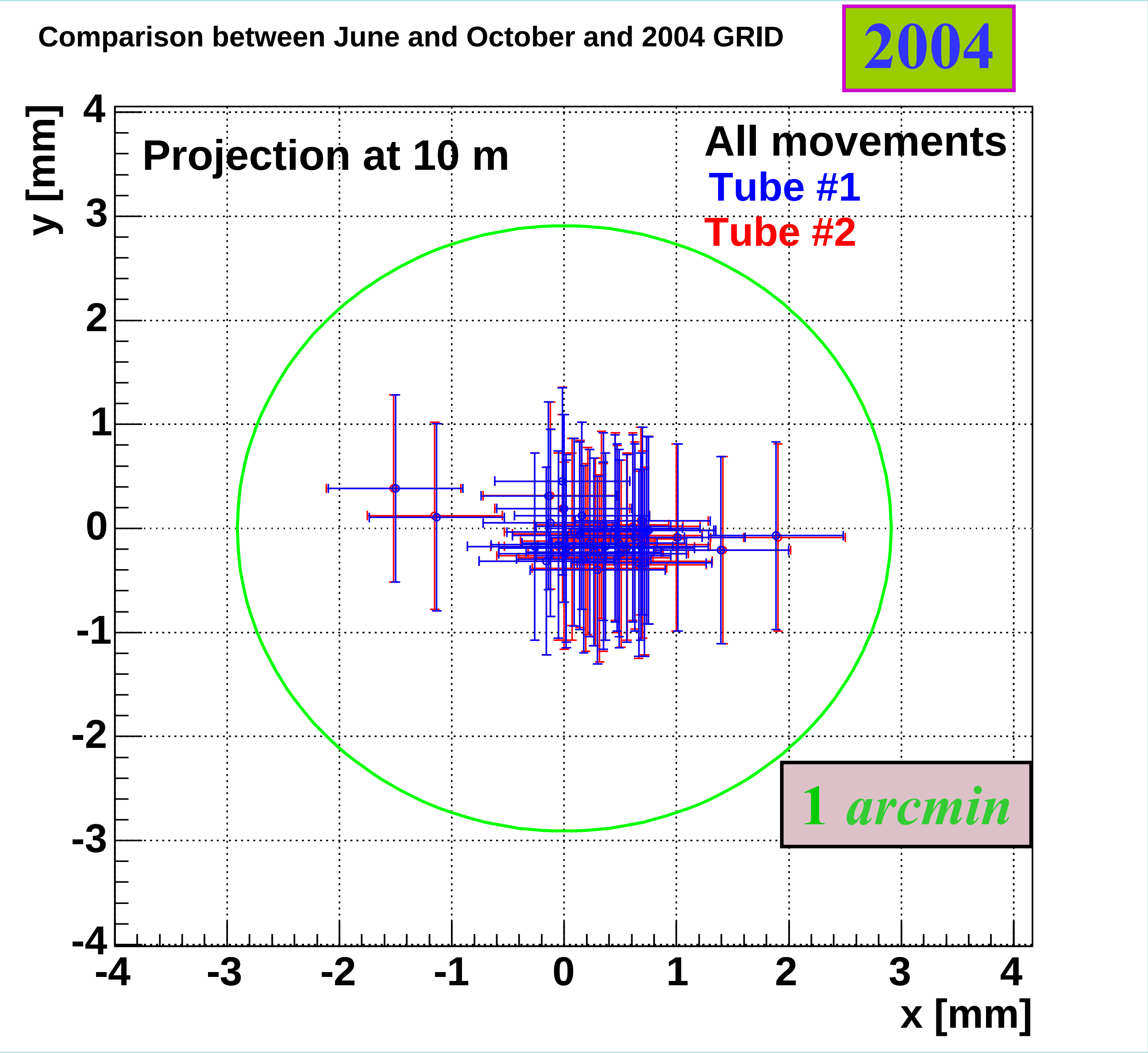
Cern Axion Solar Telescope



CAST




µM
HEC
XRT
CCD



Comparison between June and October and 2004 GRID
2004
Projection at 10 m
All movements
Tube #1
Tube #2
1 arcmin
y [mm]
x [mm]
4
3
2
1
0
-1
-2
-3
-4
-4
-3
-2
-1
0
1
2
3
4

GRID measurements:

➔ with the surveyors of CERN

➔ define pointing of the magnet + XRTelescope

➔ at ~ 100 positions

→ cold & warm

➔ **Tracking System**:

→ Calibrated and correlated with celestial coordinates

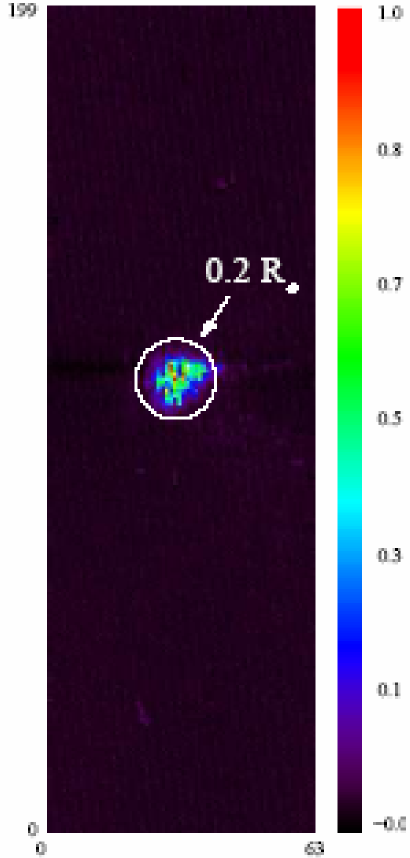
Filming of the Sun:

→ March & September

➔ alignment cross check

Telescope Alignment – Improvement

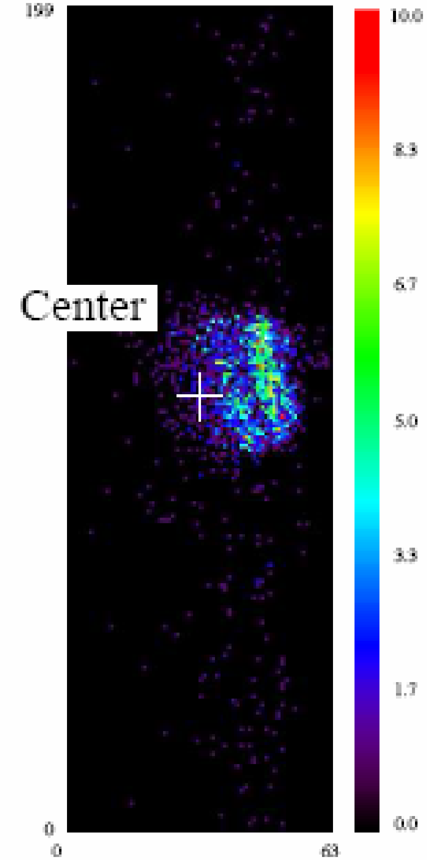
Laser Spot



Defines the location of the Axion signal !

$$X = 30.8 \quad Y = 109.6$$

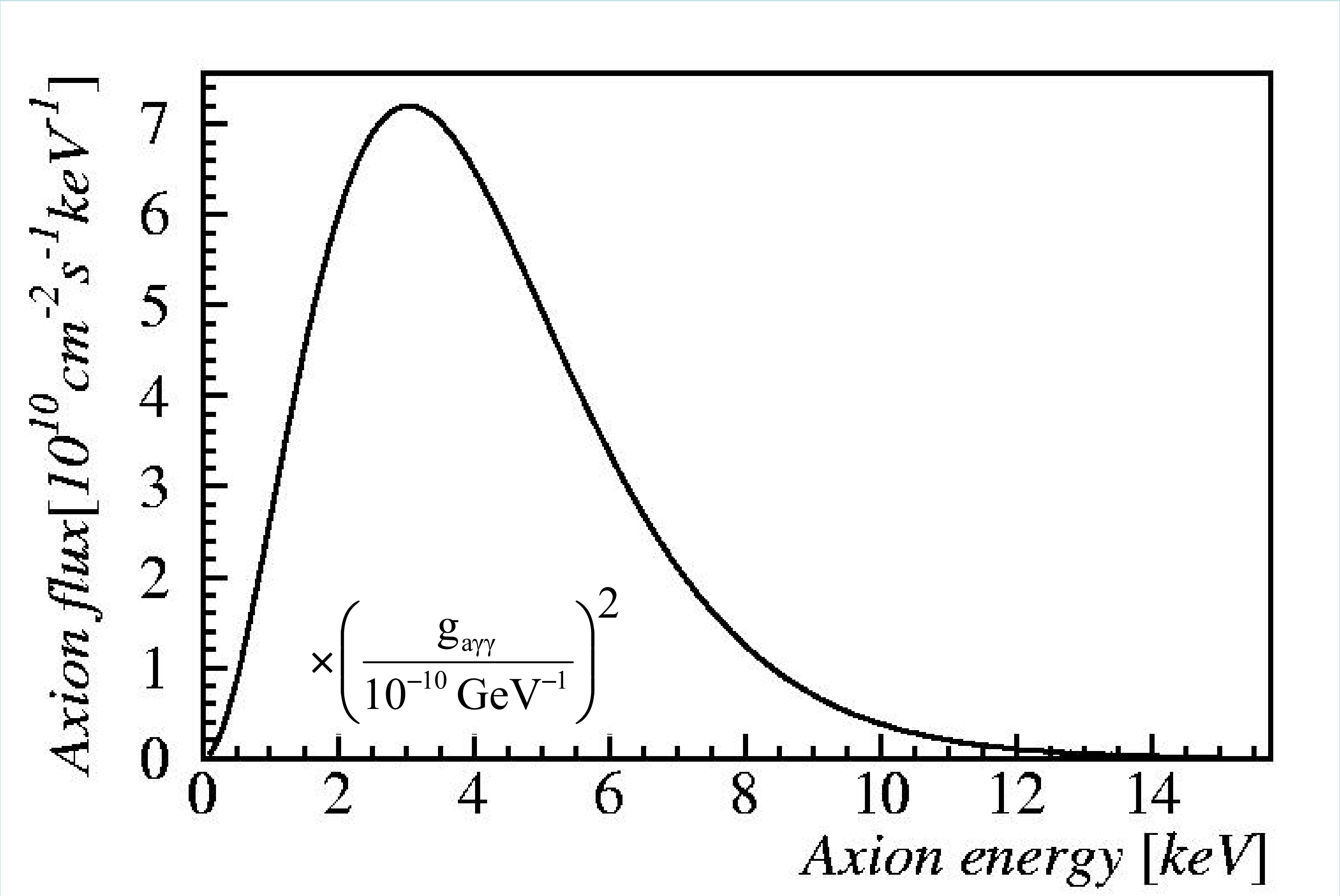
X-ray Finger Spot



Defines the reference position to verify the alignment !

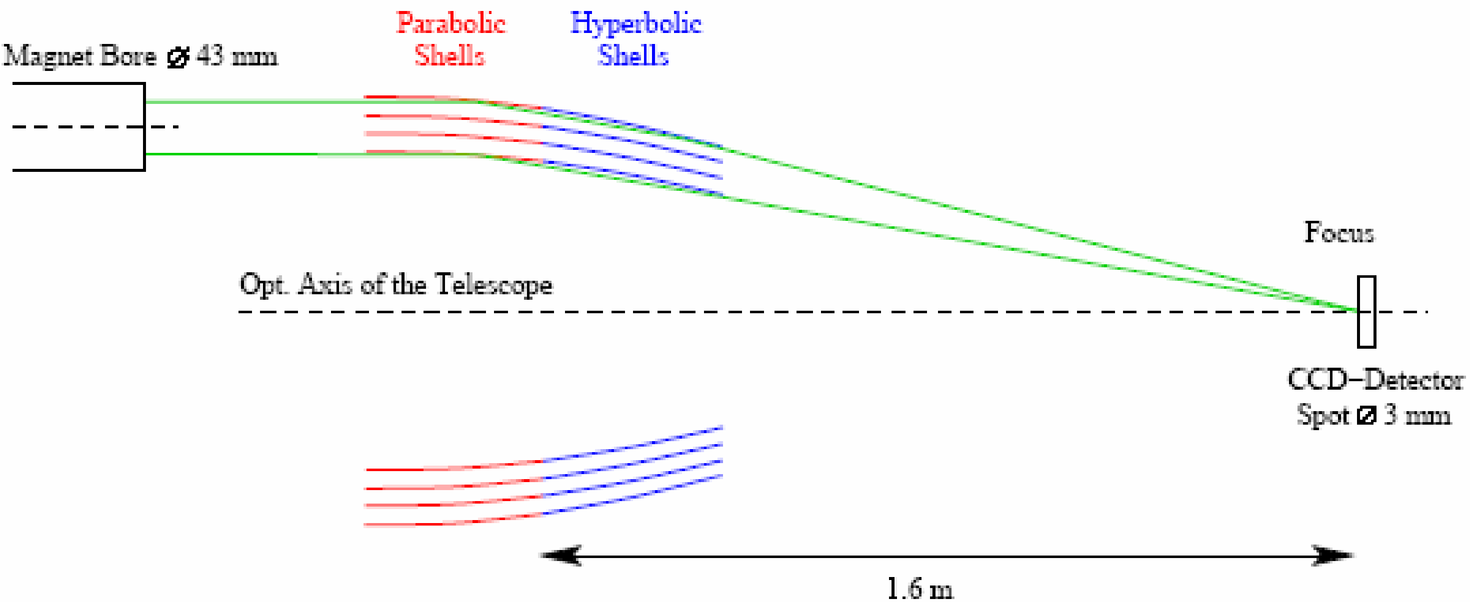
$$X = 43.5 \quad Y = 108.0$$

Solar axion spectrum



$P_{a\rightarrow\gamma} \approx 1.7\times10^{-17}$ ➔ $\Phi_\gamma = 0.51\ \mathrm{cm}^{-2}\ \mathrm{d}^{-1}\ g_{10}^4 \left(\frac{L}{9.26\ \mathrm{m}}\right)^2 \left(\frac{B}{9.0\ \mathrm{T}}\right)^2$

The X-ray Telescope of CAST



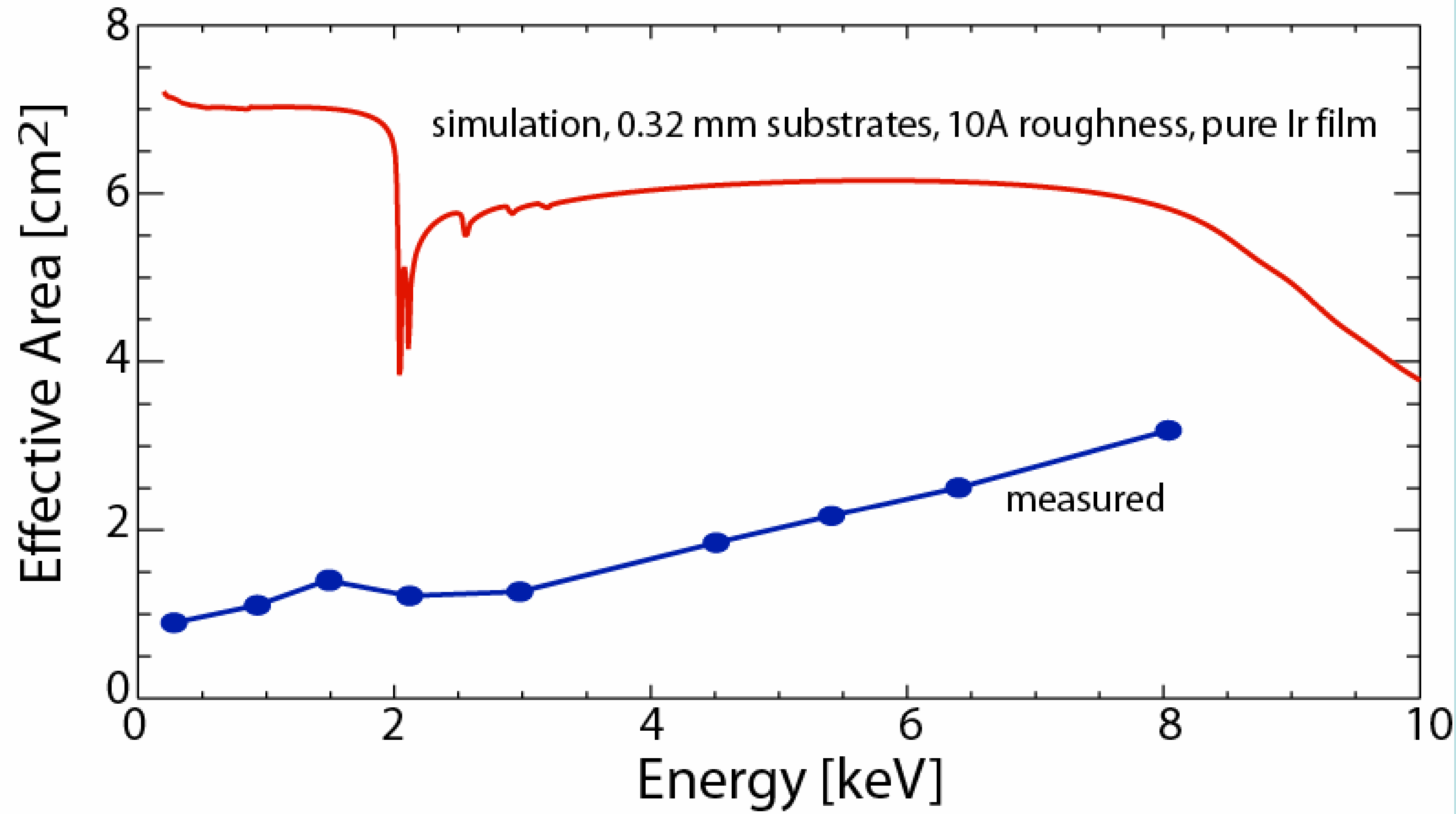
Wolter I type grazing incident optics (Prototype for *ABRIXAS* space mission):

- 27 nested gold coated nickel shells, on-axis resolution $\approx$ 43 arcsec
- 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)
Significantly improves the signal to background ratio !

2nd X-ray optic

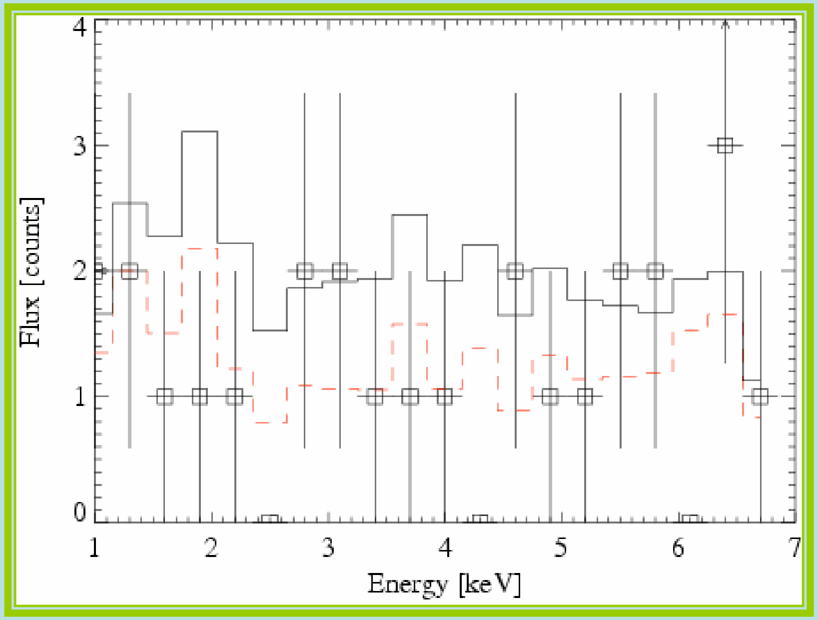
- Measured effective area (throughput) very different than simulations
- Several factors at play

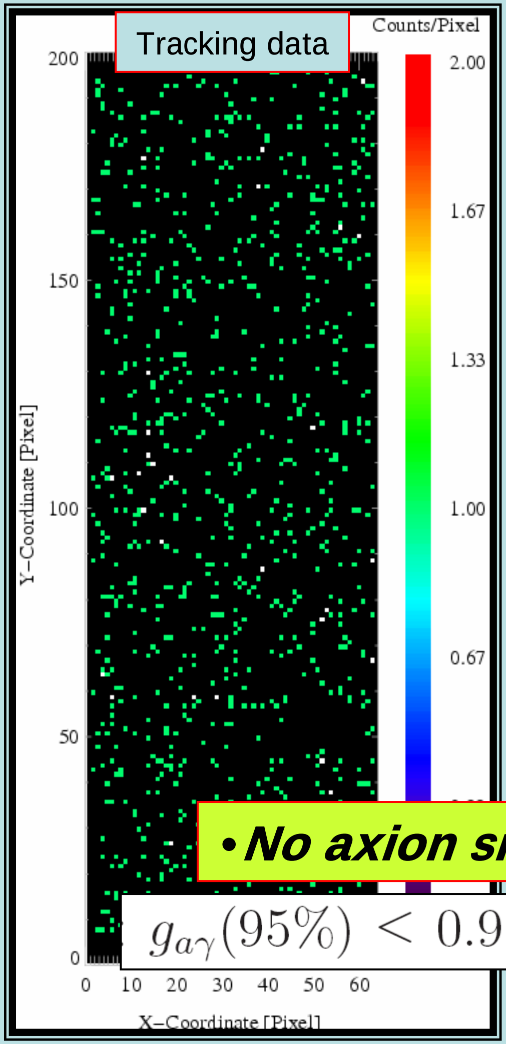


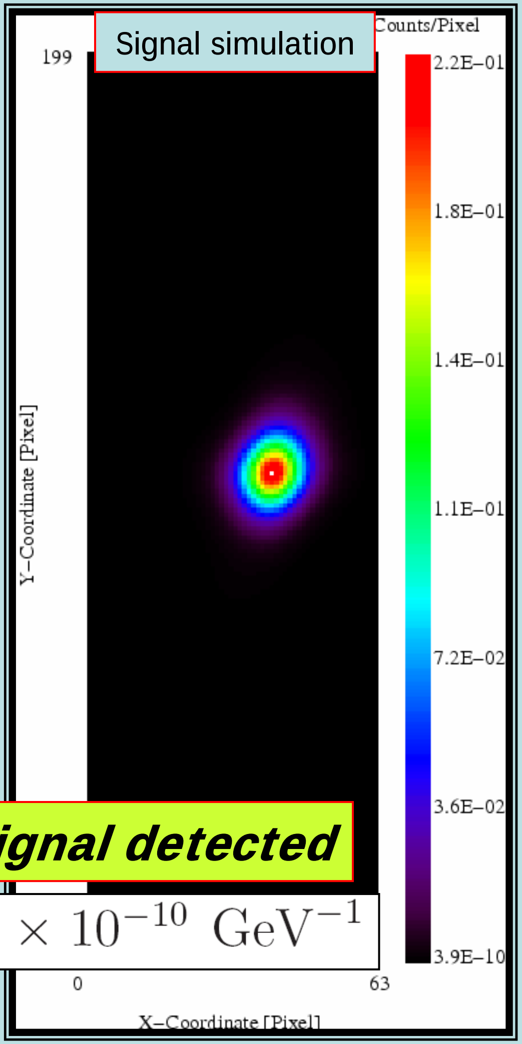
2004 data analysis

CCD / Telescope

- Spot position well determined
- Full sensitivity of telescope exploited
- Counts inside the spot compatible with background level







- ***No axion signal detected***

$$g_{a\gamma}(95\%) < 0.9 \times 10^{-10}\ \mathrm{GeV}^{-1}$$

2004 result

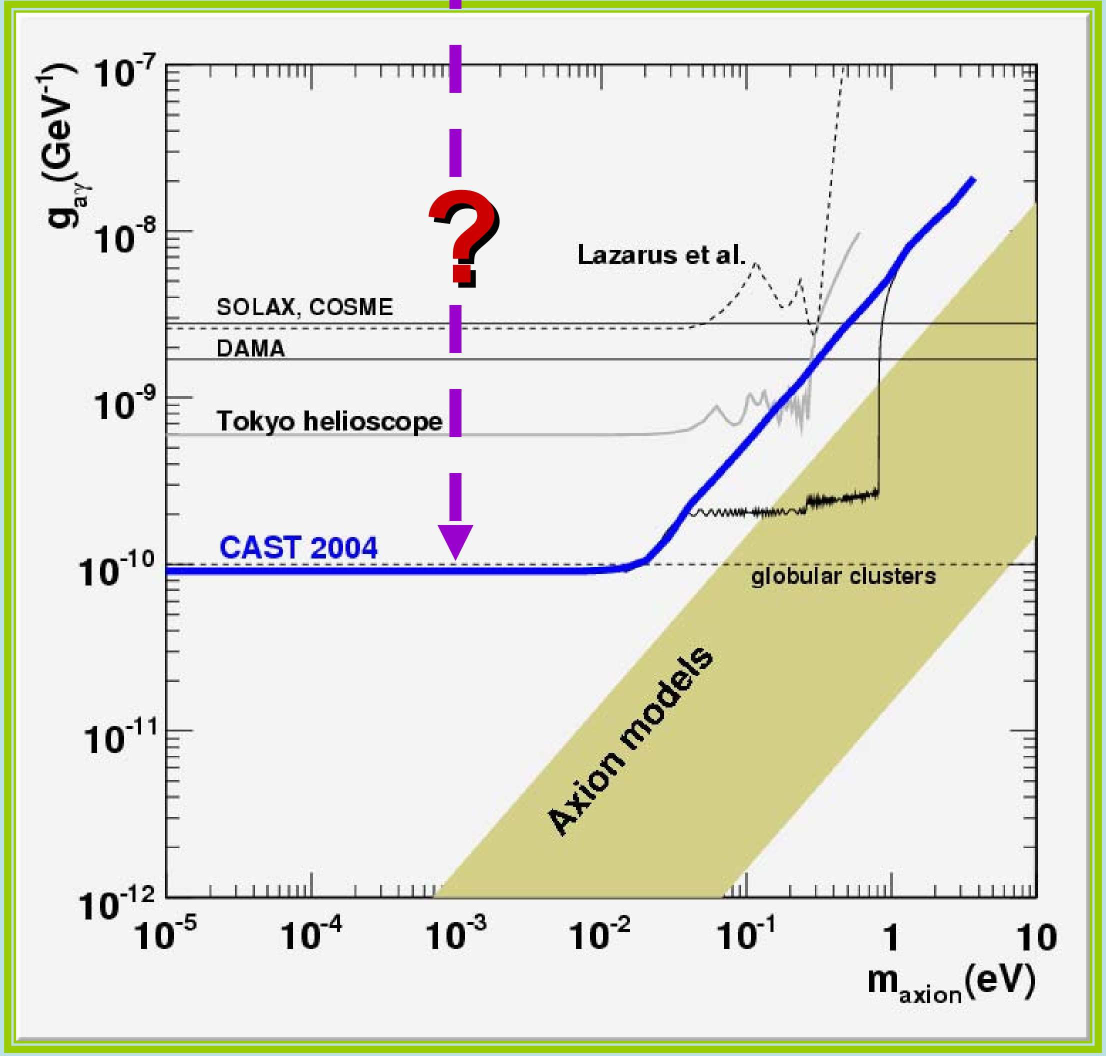
X ⟵ **PVLAS**

➔ e.g. KK-axions ≠ QCD axions

- New exclusion plot, improving 2003 result
- Factor of 7 improvement beyond previous experimental searches.
- It goes beyond astrophysical limit of globular clusters for coherence masses
- **Publication now under preparation**

$$g_{a\gamma}(95\%) \leq 0.9 \times 10^{-10}\ \mathrm{GeV}^{-1}$$

for $m_a < 0.02$ eV.



***bridge the gap* PVLAS ↔ CAST**

➔ ***demanding + inspiring new experiments***

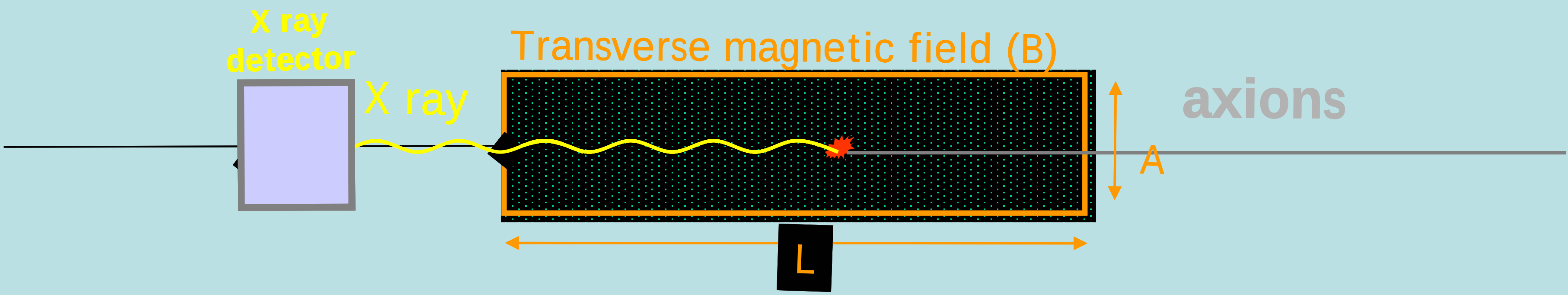
CAST Phase II → 2005 - 2007

→ ***why*?**

→ ***how*?**

CAST Phase II' → 2008-2009?

CAST phase II – principle of detection



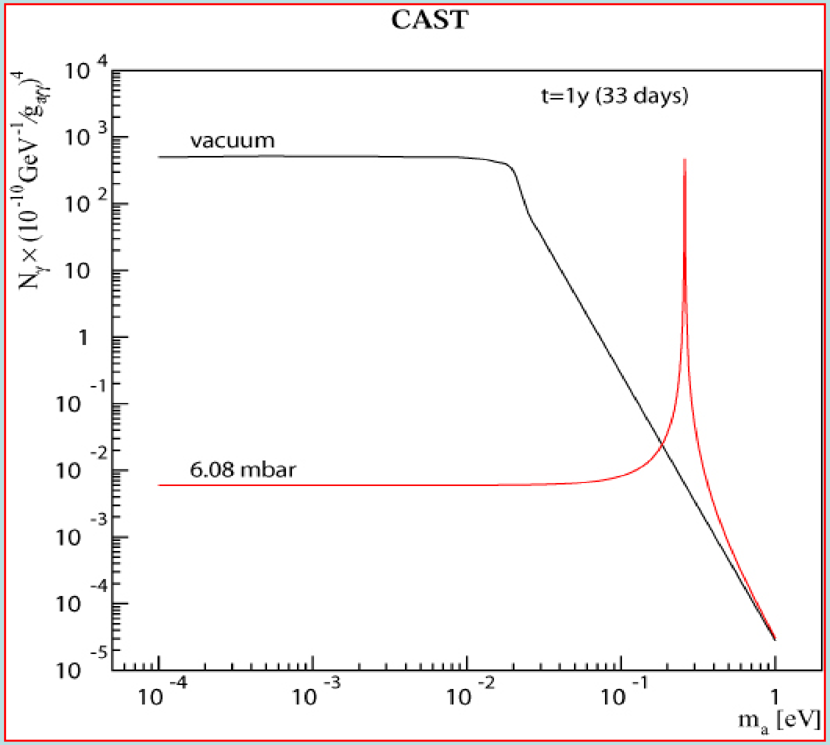
Extending the coherence to higher axion masses...

•Coherence condition (qL << 1) is recovered for a narrow mass range around m_γ

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

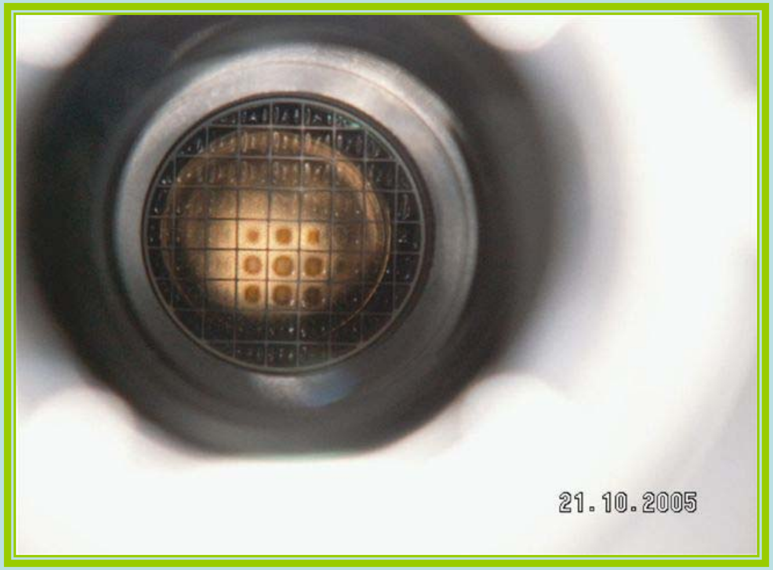
$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \quad \text{eV}$$

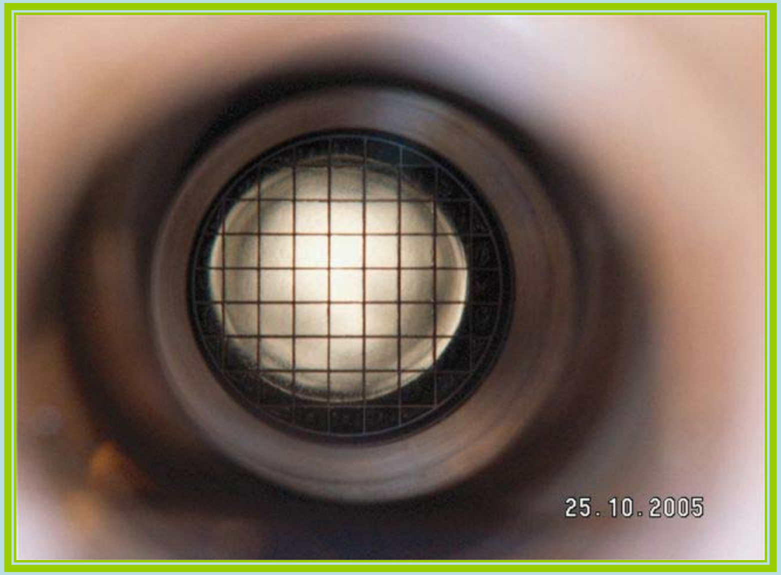
N_e: number of electrons/cm³
ρ: gas density (g/cm³)



Cold Windows

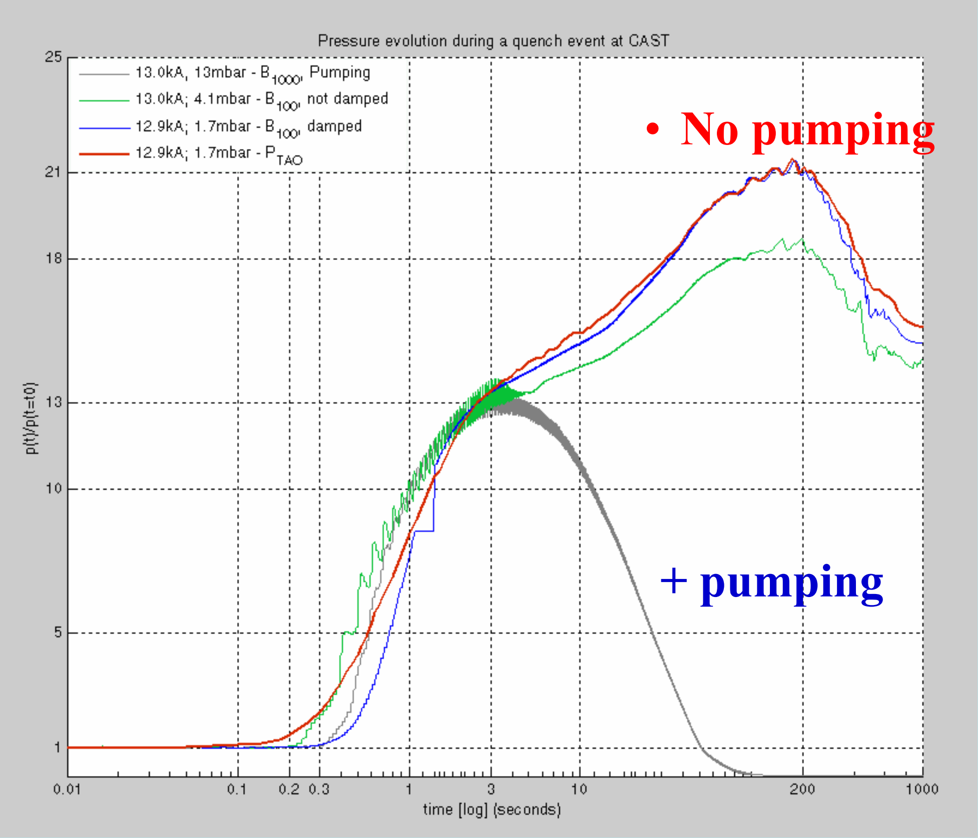
- New effect observed: “Dark spots” on the windows
  - Condensation of water from residual vacuum (outgassing) of the “warm” side
  - Vacuum better controlled (pumped)
  - Periodic bake out of windows





CONSTRAINTS

TAOs



- **Fast Increase - ~13x, in about 3 seconds,**
- **Maximum increase < 20x, in about 200 seconds.**

CAST Phase II

Fill magnet bore with buffer gas

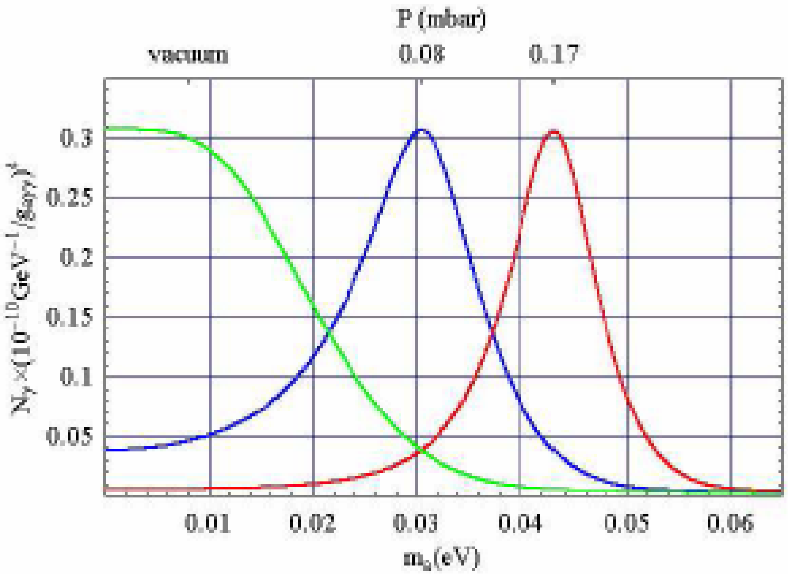
^{4}He or ^{3}He

$(p_{\text{vap}} = 16/140\,\text{mbar}@1.8\,\text{K})$

$\Longrightarrow$ photon acquires an effective mass

$$m_{\gamma,\text{eff}} \approx \sqrt{0.02\frac{P[\text{mbar}]}{T[K]}}[\text{eV}/c^2]$$

Different Pressure Settings



Systematically change pressure $\Longrightarrow$ scan mass range $m_a > 0.02\,\text{eV}/c^2$

- ^{4}He: ≈ 74 pressure steps $0 \leq p \leq 6\,\text{mbar}$, $m_a \leq 0.26\,\text{eV}/c^2$
- ^{3}He: ≈ 590 pressure steps $6 < p \leq 60\,\text{mbar}$, $m_a \leq 0.8\,\text{eV}/c^2$

$\Longrightarrow$ Allows to scan axion masses $0.02\,\text{eV}/c^2 \leq m_a \leq 0.8\,\text{eV}/c^2$

Coherence as a function of axion energy and 0.2 eV axion mass

Yannis Semertzidis-BNL
June 2006

The axion/photon oscillation length in vacuum is given by [1,2]

$$qL = 2\pi \Rightarrow L = \frac{4\pi\omega}{m_a^2}$$

Where ω is the axion energy and the converted photon energy as well. In order to improve the axion mass coverage one can "slow down" the photons by effectively givin them mass [3]. Right at the resonance condition the oscillation length is infinite. The axion mass range covered at one pressure setting is limited and it depends on the axion mass, the length of the magnetic field and the energy of the axion. The plasma angular velocity frequency is given by [2]

$$\omega_p = \omega\left(\frac{m_a}{\hbar\omega}\right)\left[1 \pm \frac{\pi}{kL}\left(\frac{\hbar\omega}{m_a}\right)^2\right] = \left(\frac{m_a}{\hbar}\right)\left[1 \pm \frac{\pi}{L}\frac{\hbar^2\omega c}{m_a^2}\right]$$

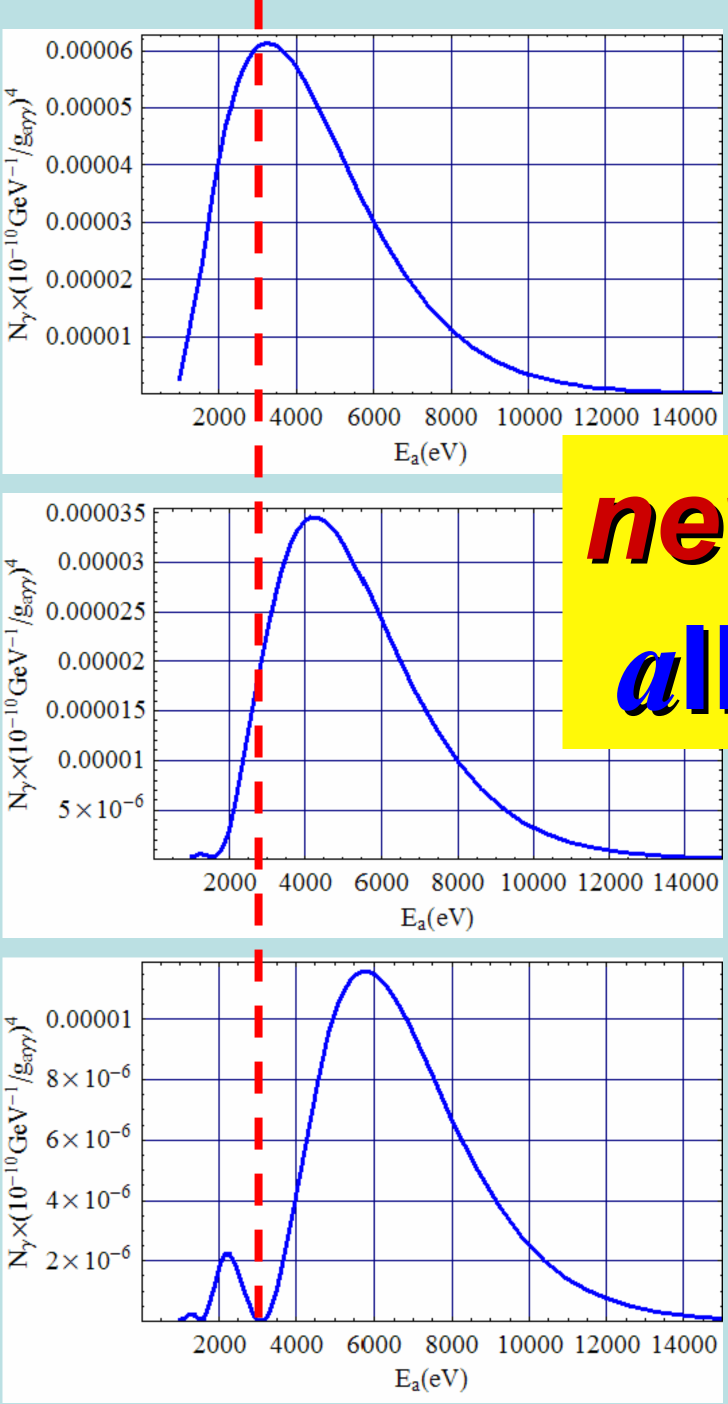
It is clear that the plasma frequency that corresponds to one axion mass is independent o the axion energy. The axion energy influences linearly the width of the pressure setting that is valid to a specific axion mass. As an example for 3 KeV axion energy, L=10 m and 0.2 eV axion mass, the equation becomes:

$$\omega_p = 0.3\times 10^{15}\,\mathrm{s}^{-1}\left[1 \pm 0.005\right]$$

For 6 KeV axion energy the equation becomes:

converted axion spectrum

- $\Delta m=0, \Delta P=0$ → **@ *resonance***
  $\langle E \rangle = 4.48$ keV
- $\Delta m=0.001, \Delta P=0.037$;
  $\langle E \rangle = 5.36$ keV → **off-resonance**
- $\Delta m=0.002, \Delta P=0.074$;
  $\langle E \rangle = 6.69$ keV → **off-resonance**

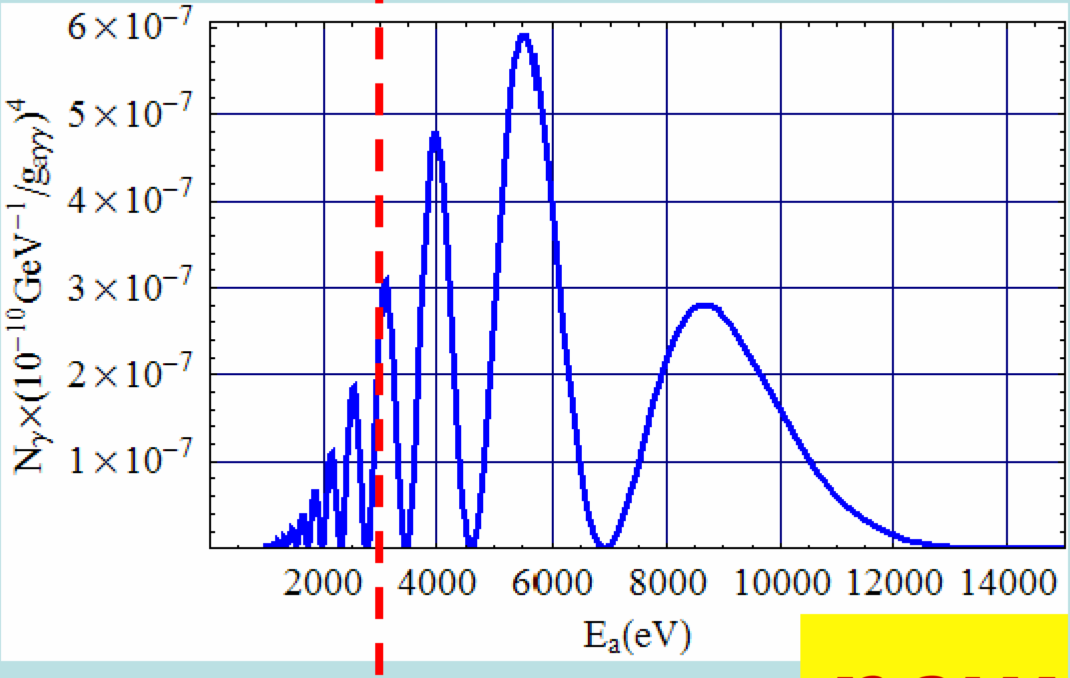


new *a*ID

converted axion spectrum

Δm=0.0088, ΔP=0.332 (***4 steps***)

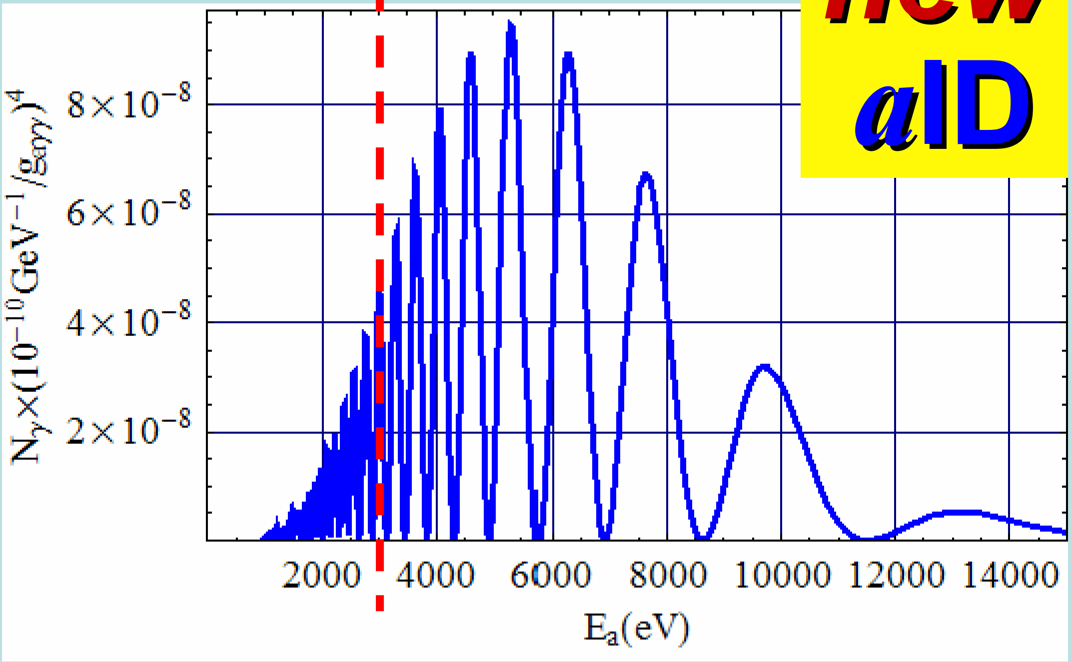
⟨E⟩=6.48 keV → off-resonance



new *a*ID

Δm=0.0214, ΔP=0.83 (***10 steps***)

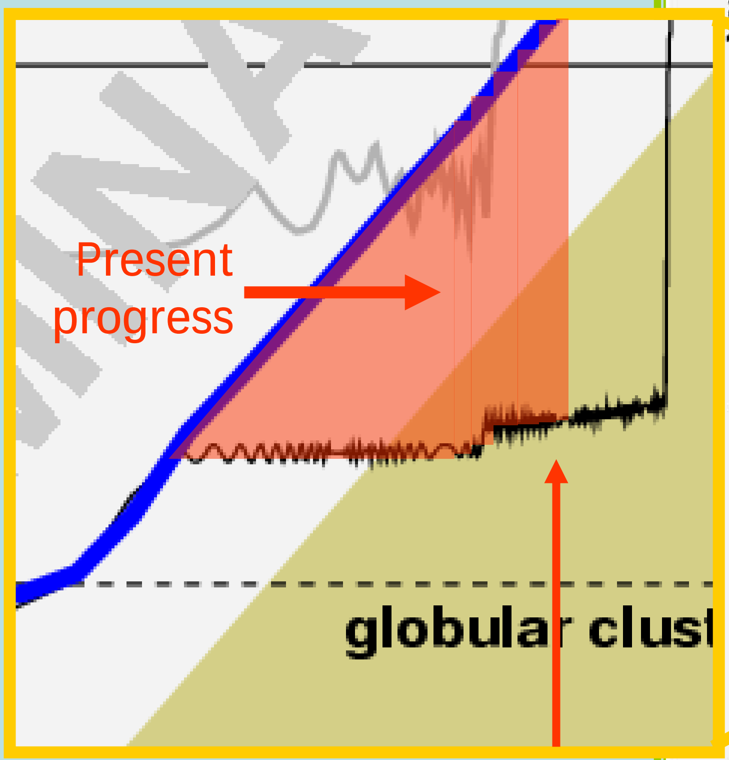
⟨E⟩=6.46 keV → off-resonance



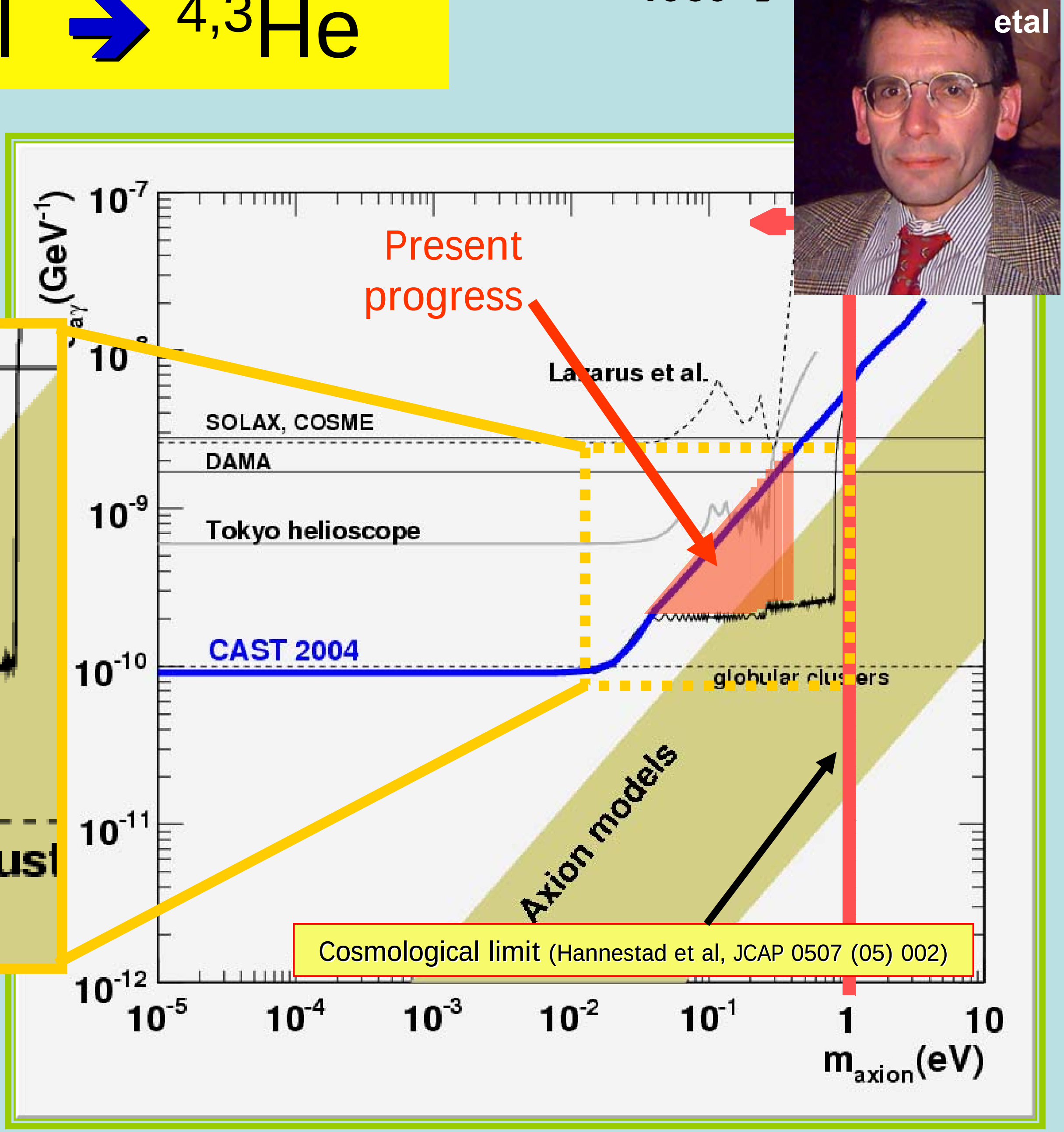
CAST Phase II ➔ $^{4,3}He$

1989 ➔ K. van Bibber etal

Scanning progress:

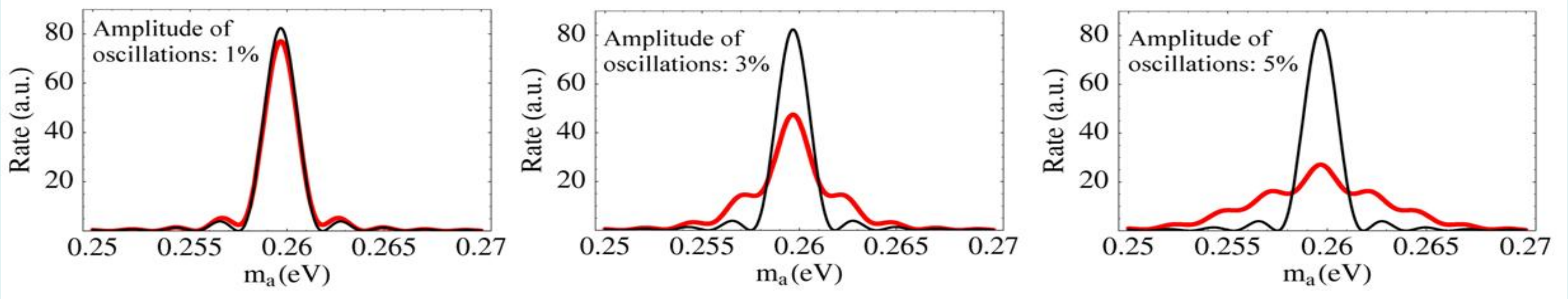


~10 mbar
~0.340 eV



THERMO ACOUSTIC OSCILLATIONS

unpredicted



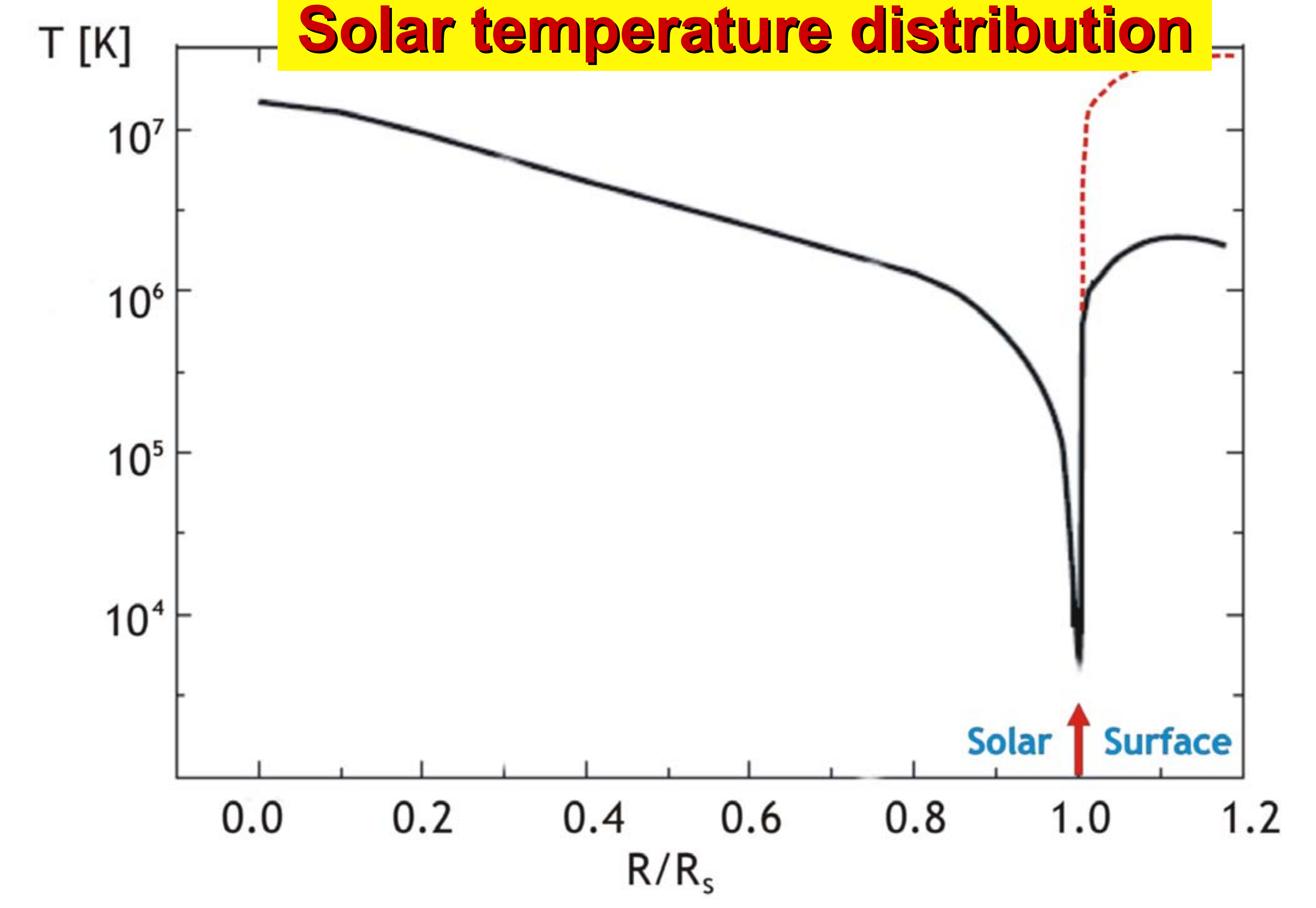
- **Thermoacoustic oscillations were observed with ^{4}He gas filling for p > 2mbar with f=3.7Hz and ~6% amplitude ($\delta p/p$); Isentropic model gives 3.5% density fluctuation ($\delta\rho/\rho$).**
- **Phenomenon was studied and solutions designed; Damping plugs installed on the linking pipes**

mimic CAST

$\Downarrow$

(in)direct axion-signals ?

Solar temperature distribution



➔ **solar corona problem**
Grotrian (**1939**)

➔ **The enigma of coronal heating represents… one of the outstanding puzzles of stellar astronomy + one of the most challenging problems in astrophysics.**

S.M. Jefferies, McIntosh, Armstrong, Bogdan, Cacciani, Fleck, ApJL. 648 (10.9.**2006**)151

E R Priest, D W Longcope, J Heyvaerts, ApJ. 624 **(2005)** 1057

On solving the Coronal Heating Problem

▼

"*one of the most important problems in astrophysics*"

"There are many different heating mechanisms operating in the corona "

J.A. Klimchuk, Solar Physics 234 (2006) 41

→ *invited review*

➔ **The mechanism that heats the solar corona remains elusive.**

➔ **Everything above the photosphere …would not be there at all.**

M.J. Aschwanden, A.I. Poland, D.M. Rabin, A.R.A.A. 39 (**2001**) 75

C.J. Schrijver, A.A. van Ballegooijen, ApJ. 630 (**2005**) 552

Stellar observations + theory on stellar evolution

↛ stars might possess atmospheres … that produce X-rays.

L.W. Acton, Magnetodynamic Phenomena in the Solar Atm. (**1996**) 3

➔ **The magnetic field plays a crucial role in heating the solar corona** (this has been known for many years) ➔ ***the exact energy release mechanism(s) is(are) still unknown*.**

➔ **the process by which it is converted into heat and other forms remains *a nagging unsolved problem*.**

K. Galsgaard, C.E. Parnell, A.& A. 439 (August **2005**) 335

R.B. Dahlburg, J.A. Klimchuk, S.K. Antiochos, ApJ. 622 (**2005**) 1191

One key issue to understand the coronal heating problem is to know:

S Regnier, RC Canfield, Proc. SOHO 15 Workshop - Coronal Heating, St. Andrews, Scotland, 6-9 September 2004, ESA SP-575 (2004) 255

***how* magnetic energy can be stored and then released in a solar magnetic configuration.**

In the axion scenario →

B = catalyst ⊗ $\rho_{local,\Delta t} \sim \omega_{plasma} = m_{axion}$

the magnetic field can transform out streaming

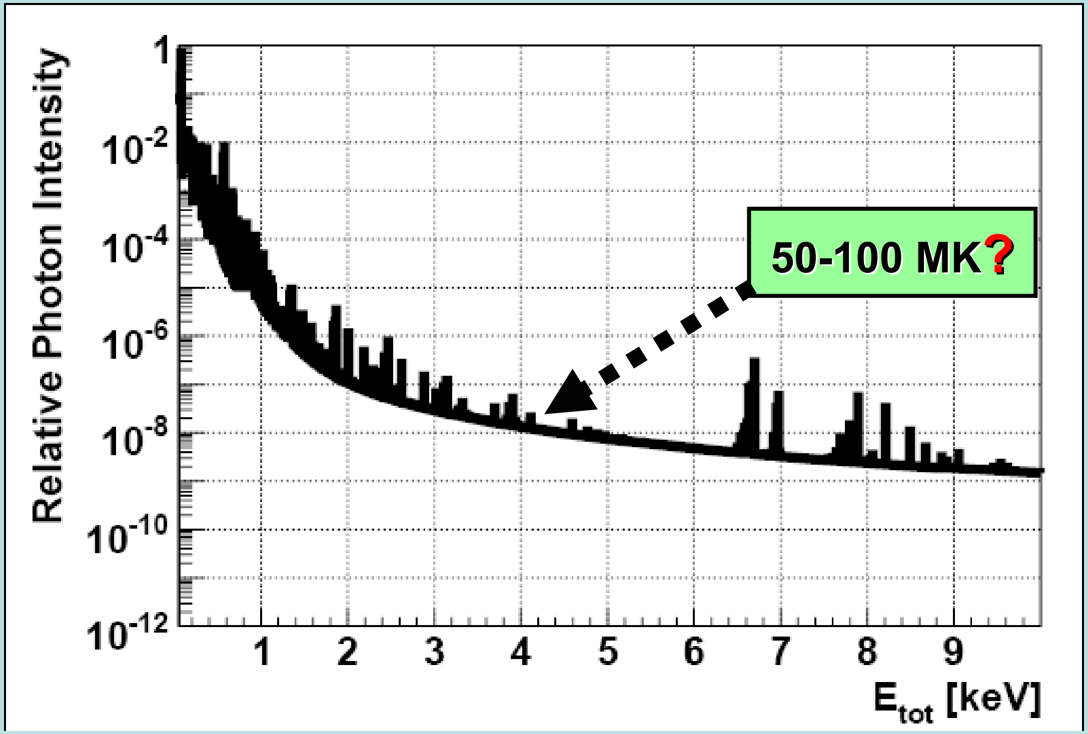
~axions-to-photons + *vice versa*

+

→ transient brightenings!

→ CAST @ Sun

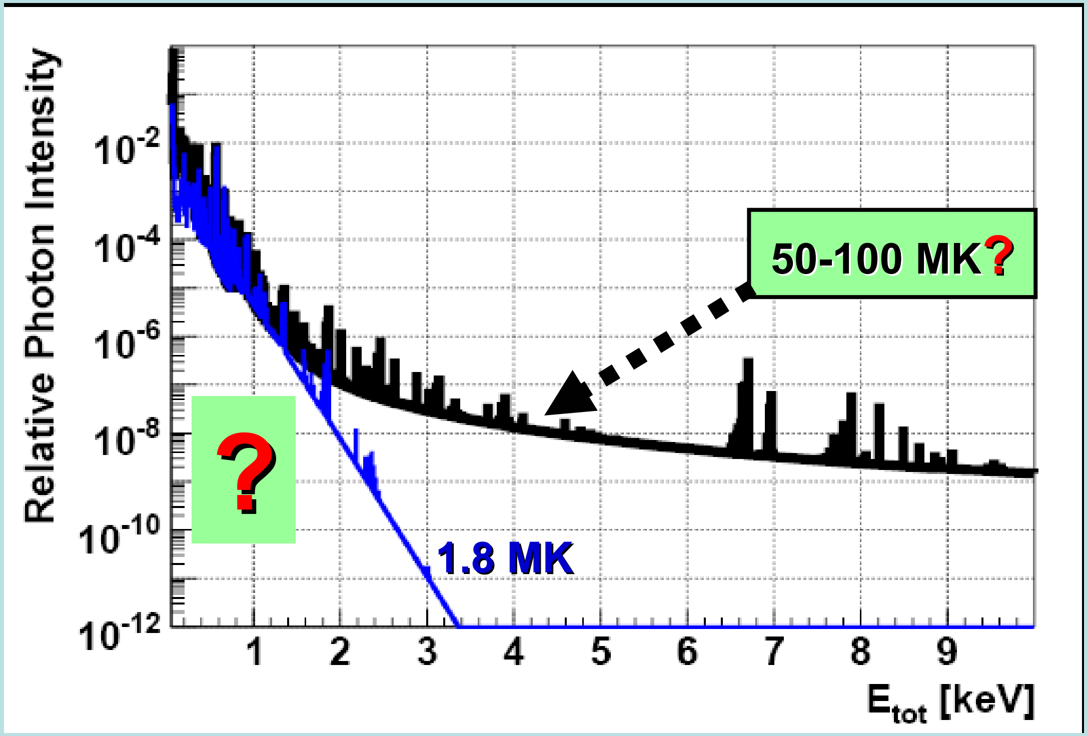
Reconstructed X-ray spectrum
➔ non-flaring Sun @ solar minimum [X]



$\bar{T}_{flare}$ < 20MK

[X] G. Peres, S. Orlando, F. reale, R. Rosner, H. Hudson, ApJ. 528 (2000) 537

Reconstructed X-ray spectrum
➔ non-flaring Sun @ solar minimum [X]

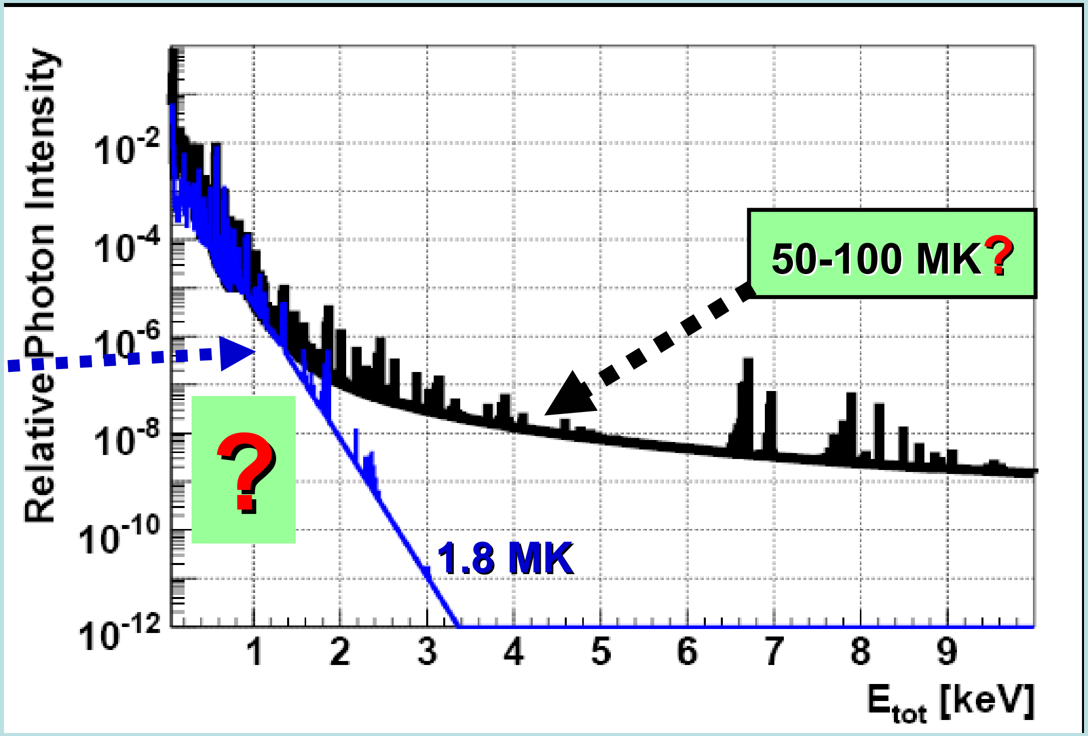


[X] G. Peres, S. Orlando, F. reale, R. Rosner, H. Hudson, ApJ. 528 (2000) 537

Reconstructed X-ray spectrum
➔ non-flaring Sun @ solar minimum [X]

B-modified solar axion spectrum?

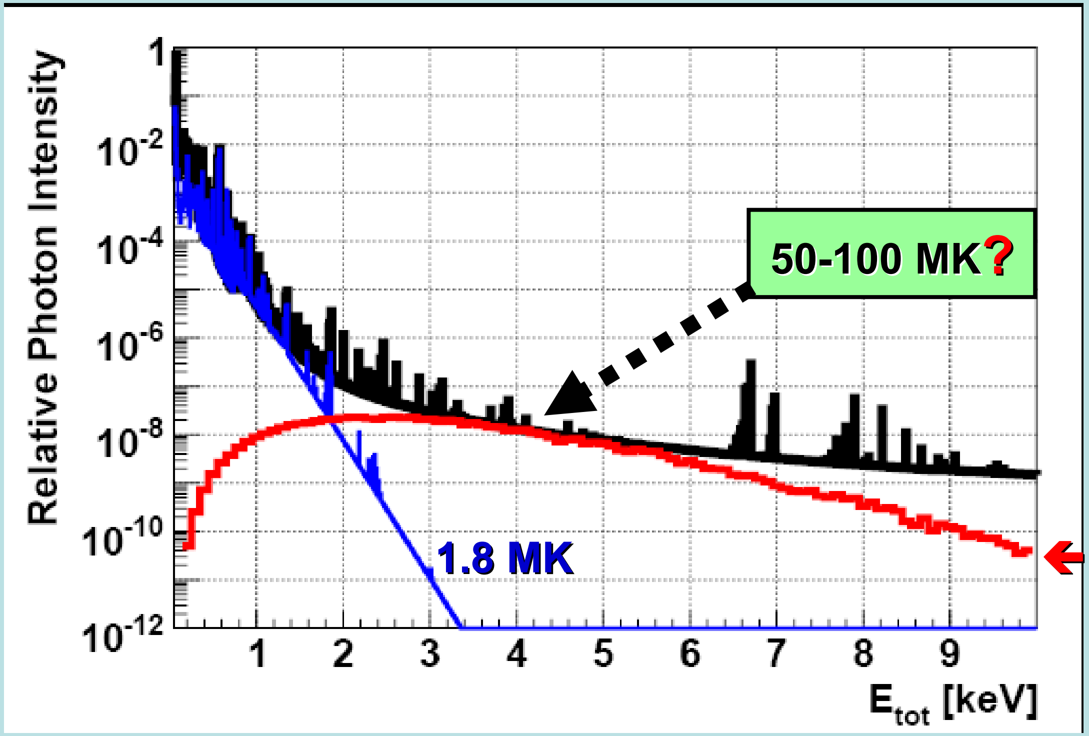
→ inner/outer Sun



? ➔ feedback to CAST, …

[X] G. Peres, S. Orlando, F. reale, R. Rosner, H. Hudson, ApJ. 528 (2000) 537

Reconstructed X-ray spectrum
➔ non-flaring Sun @ solar minimum [X]



➔ KK-axion model

➔ **generic**

➔ $g_{a\gamma\gamma} \approx 10^{-13}$GeV^{-1}

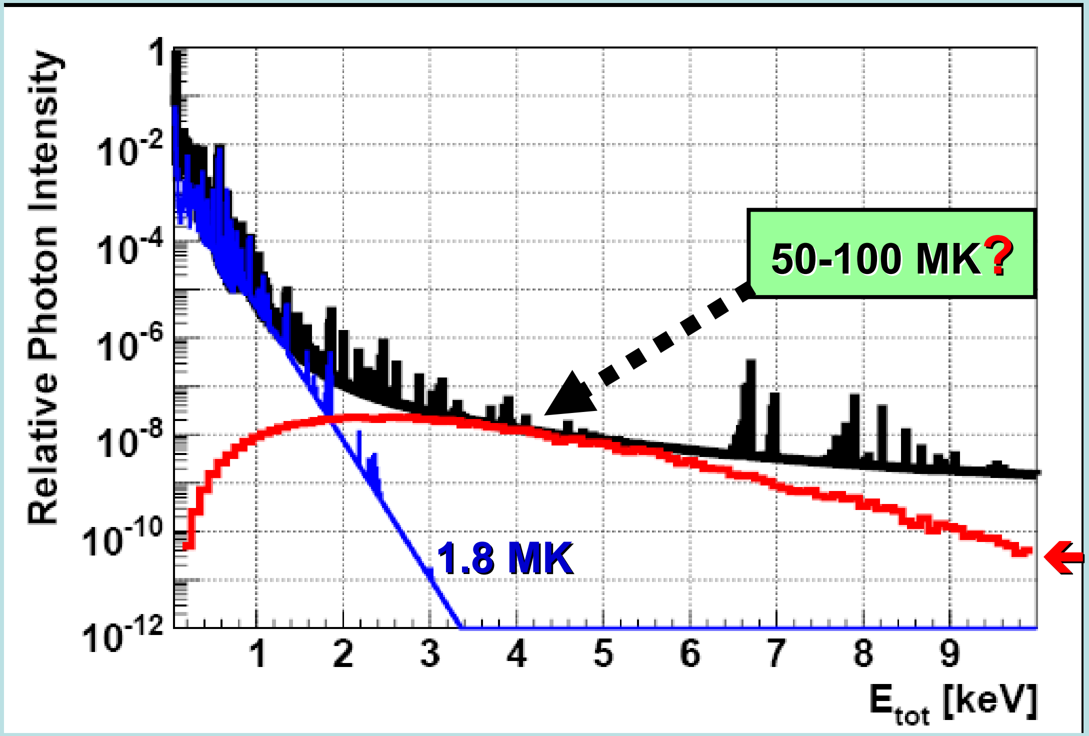
$m_{KK} \approx 10^{-3}$ eV

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

[X] G. Peres, S. Orlando, F. reale, R. Rosner, H. Hudson, ApJ. 528 (2000) 537

2005- → RHESSI
SMART_1

Reconstructed X-ray spectrum
→ non-flaring Sun @ solar minimum [X]



← KK-axion model

→ generic

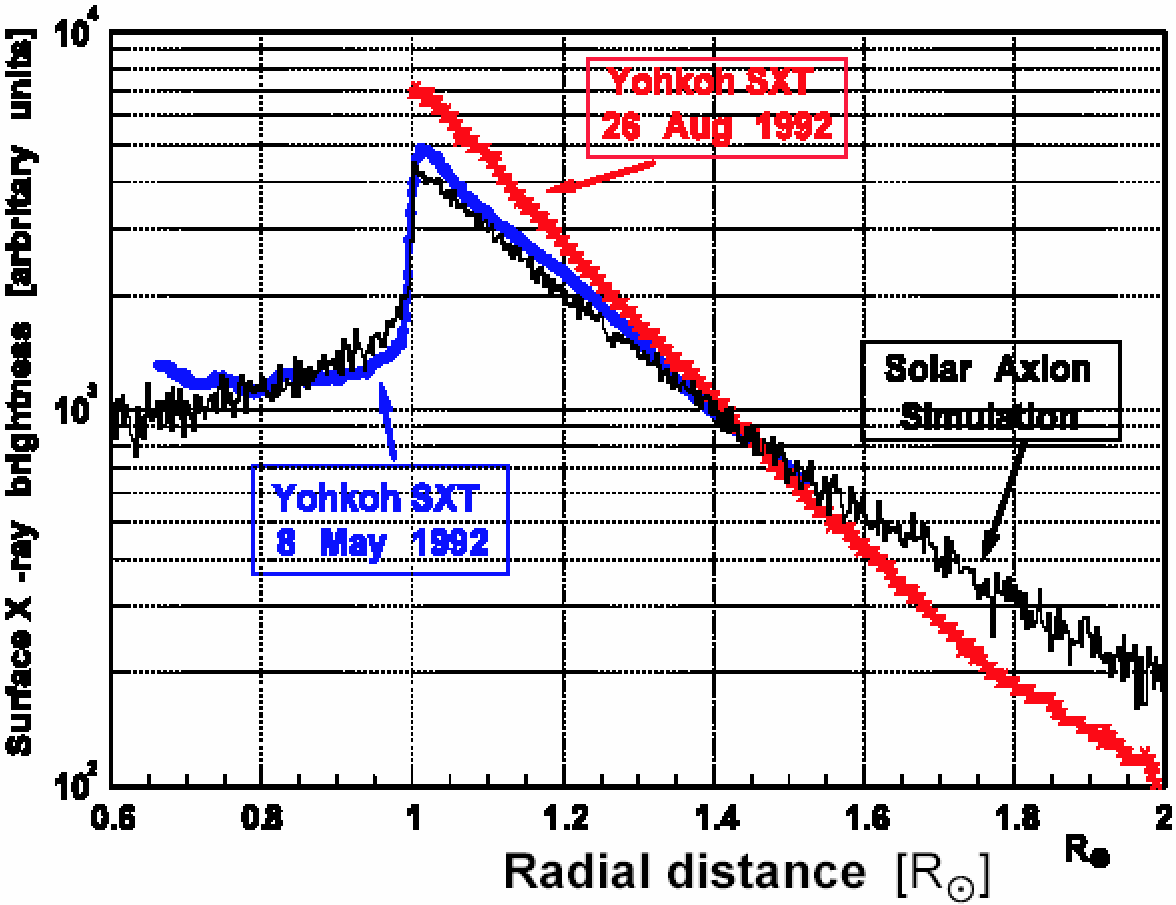
$L_a \approx 0.16 L_{solar} \approx 10^6$ t/s → $L_{trapped} \approx 200$ kg/s → 10^{22} g ← now

→ $g_{a\gamma\gamma} \approx 10^{-13} GeV^{-1}$
$m_{KK} \approx 10^{-3}$ eV

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

[X] G. Peres, S. Orlando, F. reale, R. Rosner, H. Hudson, ApJ. 528 (2000) 537

Quiet Sun X-rays as Signature for New Particles



Soft X-ray surface brightness from the quiet Sun.

Simulation with trapped solar KK-axions ⇒ $g_{a\gamma\gamma}$<40•10^{-14}GeV^{-1}.

26 August: off-pointing

(JL Culhane, Adv. Space Res. 19 (1997) 1839)

- **Diffuse emission.**
- **Hydrostatic equilibrium doesn't fit observations**

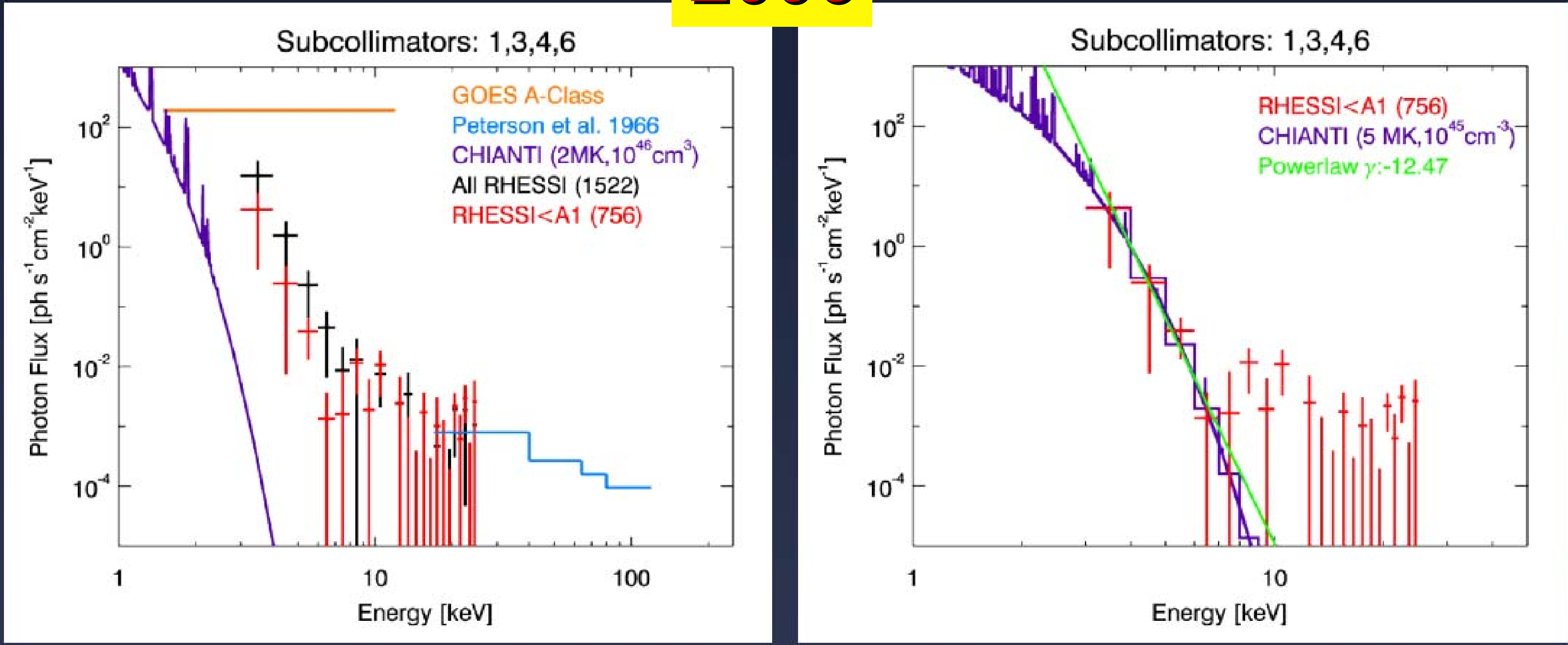
OFFPOINTING:

1992 → YOHKOH
2005- → RHESSI
→ 33 days

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

RHESSI QS Spectrum: 1keV bins

2006



Values in 3-12 keV correlate with GOES implying signal?

How is this energetic e⁻ population created in the Quiet Corona ?

➔ more offpointing 2006 thru 2007

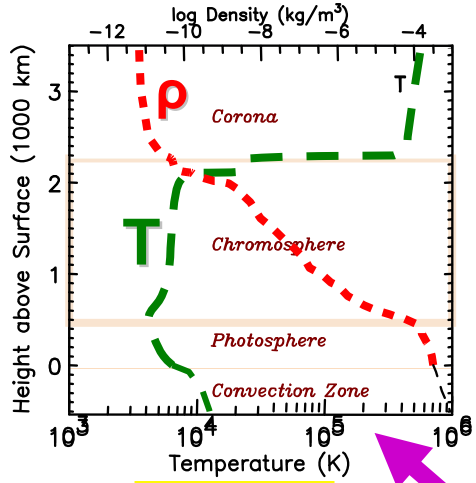
http://sprg.ssl.berkeley.edu/~hannah/presentations/pdf_spd_06.pdf

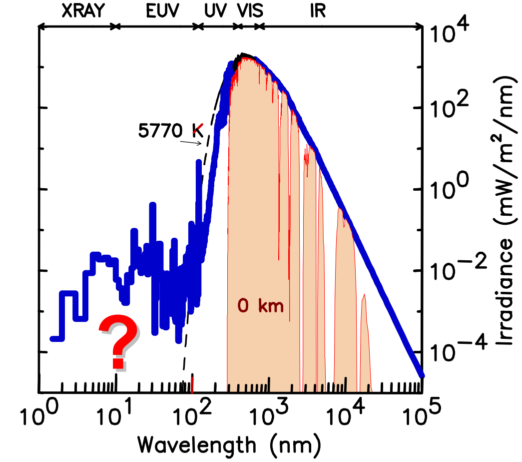
not ≠ reconstructed solar X-ray spectrum

see DiLella **+** Z. (**2003**)

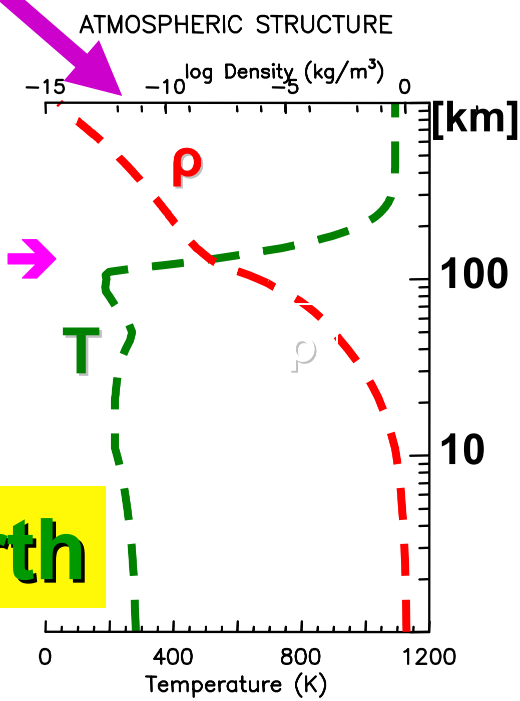
↷ 2nd Law of Thermodynamics ➔

Heat transfer → hotter-to-cooler





Sun



<u>**Suggestion:**</u>

↷ 2nd Law of Thermodynamics ➔

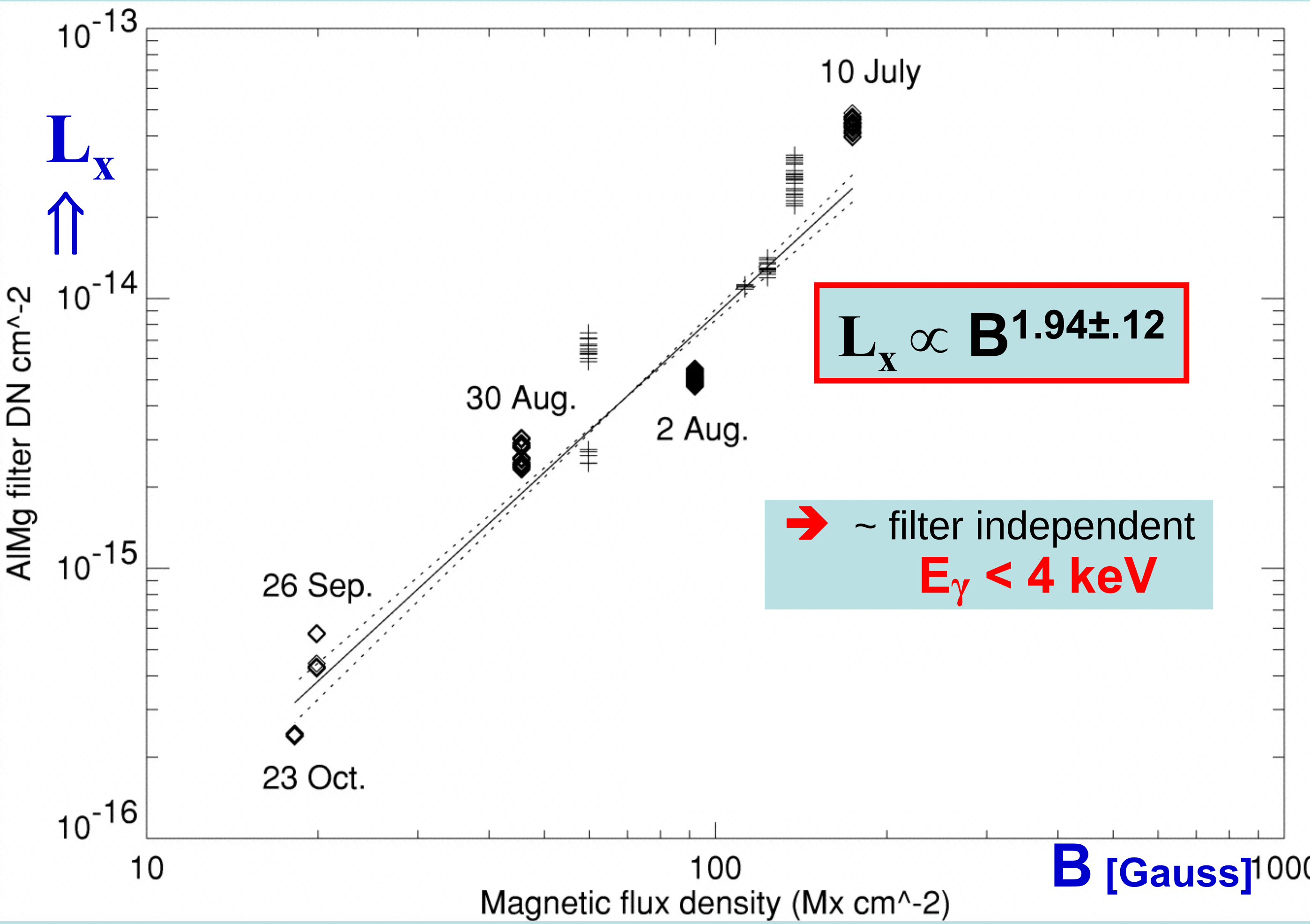
➔ solar X-ray
self-irradiation

Earth

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

The long-term evolution of AR 7978 (S10º) ➔ Yohkoh / SXT

1st



RHESSI :
often hard X-ray emission from non-flaring ARs.

➔ $\gtrsim$ **5 keV**

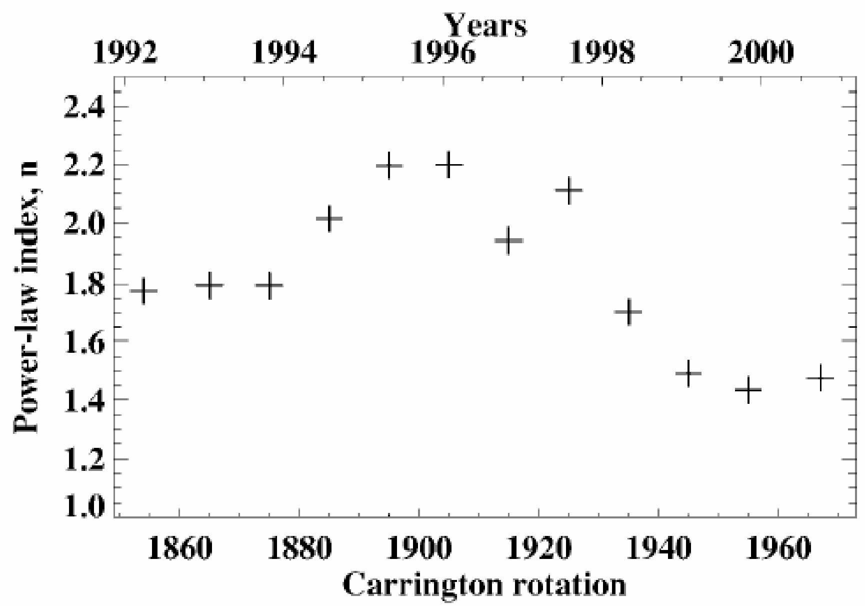
Hannah, Hurford, Hudson, Abstract: 2005AGUFMSH11A0242H AGU Fall meeting, 5-9/12/2005

<X-ray flux> / cm² vs. <B> **July-Nov. 1996**

L van Driel-Gesztelyi, P Démoulin, CH Mandrini, L Harra, JA Klimchuk, ApJ. 586(**2003**)579

K. Zioutas, K. Dennerl, M. Grande, D.H.H. Hoffmann, J. Huovelin, B. Lakic, S. Orlando, A.Ortiz, Th. Papaevangelou, Y. Semertzidis, Sp. Tzamarias, O. Vilhu J. Phys. Conf. Ser. 39 (2006) 103

2^{nd}



Power-law index **n** of $L_x \sim B^n = f(\text{time})$ ➔ **YOHKOH** / XRT

The relation between the solar soft X-ray flux (below ~4.4keV) …and B can be approximated by a power law with an averaged index close to 2.

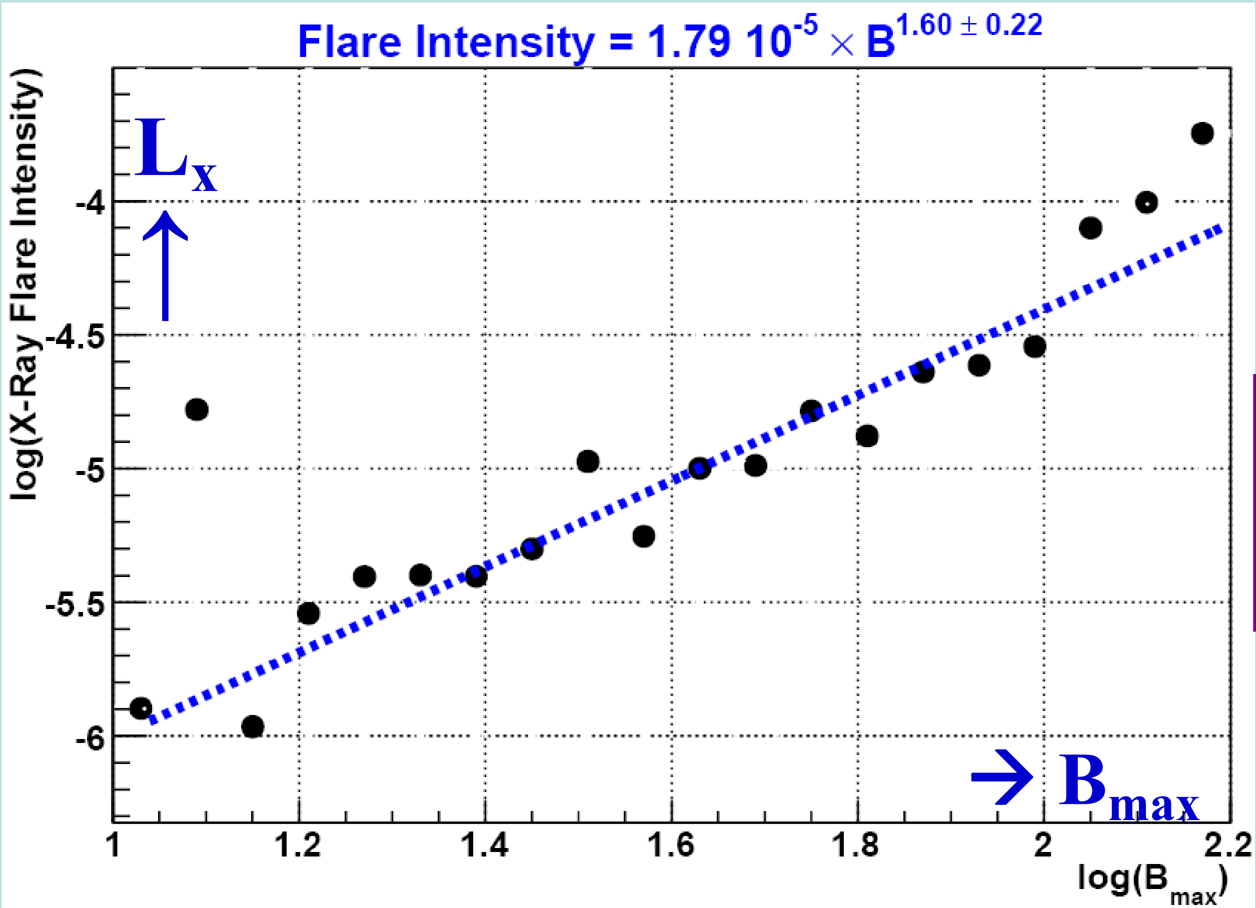
Benevolenskaya, Kosovichev, Lemen, Scherrer, Slater ApJ. 571 (**2002**) L181

Note: axion-to-photon oscillation $\propto$ $\mathbf{B}^2$ ➔ e.g., in **CAST**

DHH Hoffmann, K. Z., Nucl. Phys. B Suppl. 151 (2006) 359

➔ **11 years solar cycle?** ➔

FLARES → origin?



3rd

The Electron "Problem"

e^- flux~$10^5\times$ hard X-rays from Bremsstrahlung!

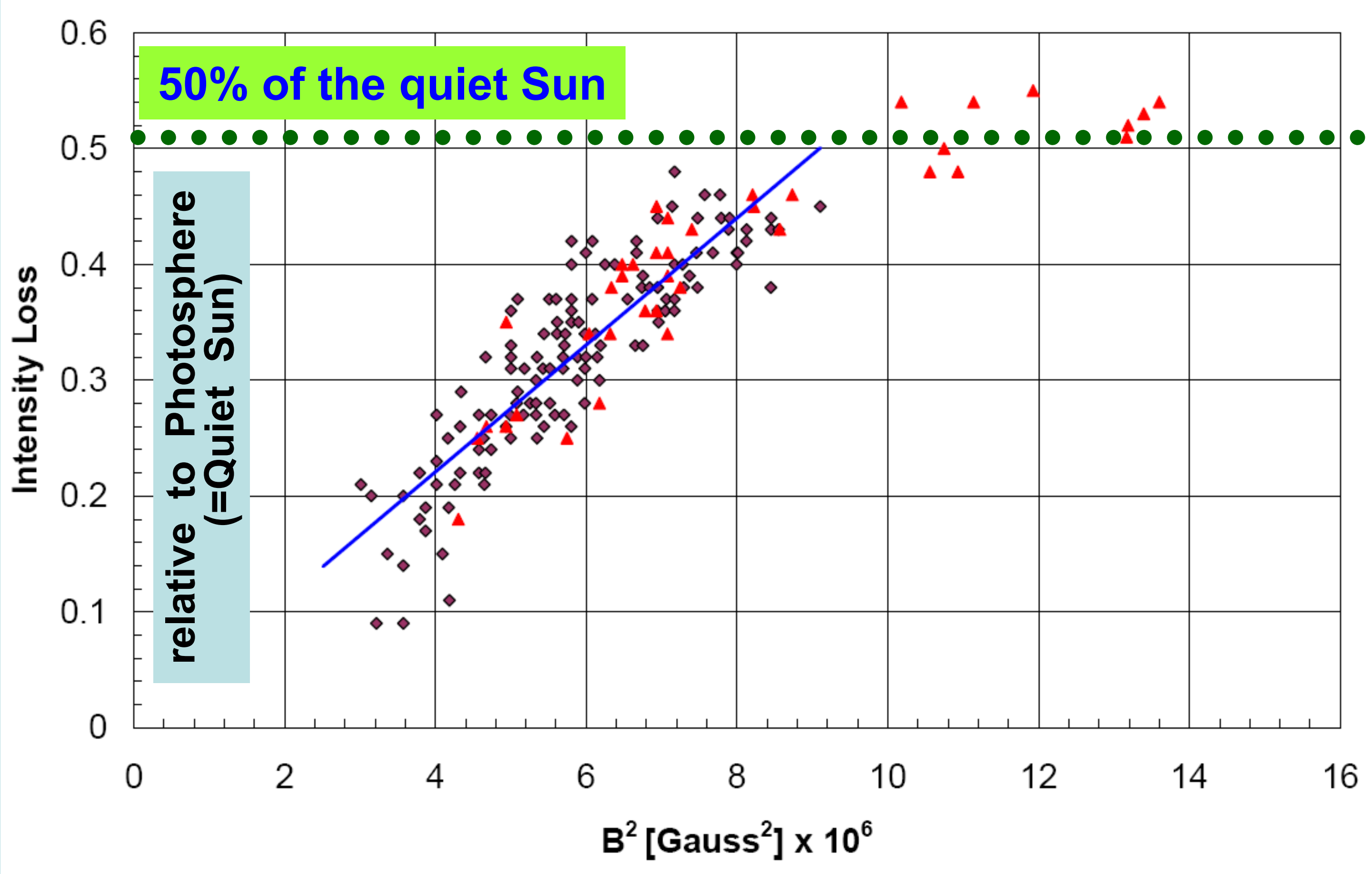
Rebinned peak flare X-ray intensity vs. B_{max}

D. Mason et al., ApJ. 645 (10.7.2006)1543 → B^2 correlation

G. Emslie (2005)
http://www.astro.auth.gr/%7Evlahos/ascona/memberstalks/energeticsEmslie.ppt#366,8

SUNSPOTS ← *origin?*

4th



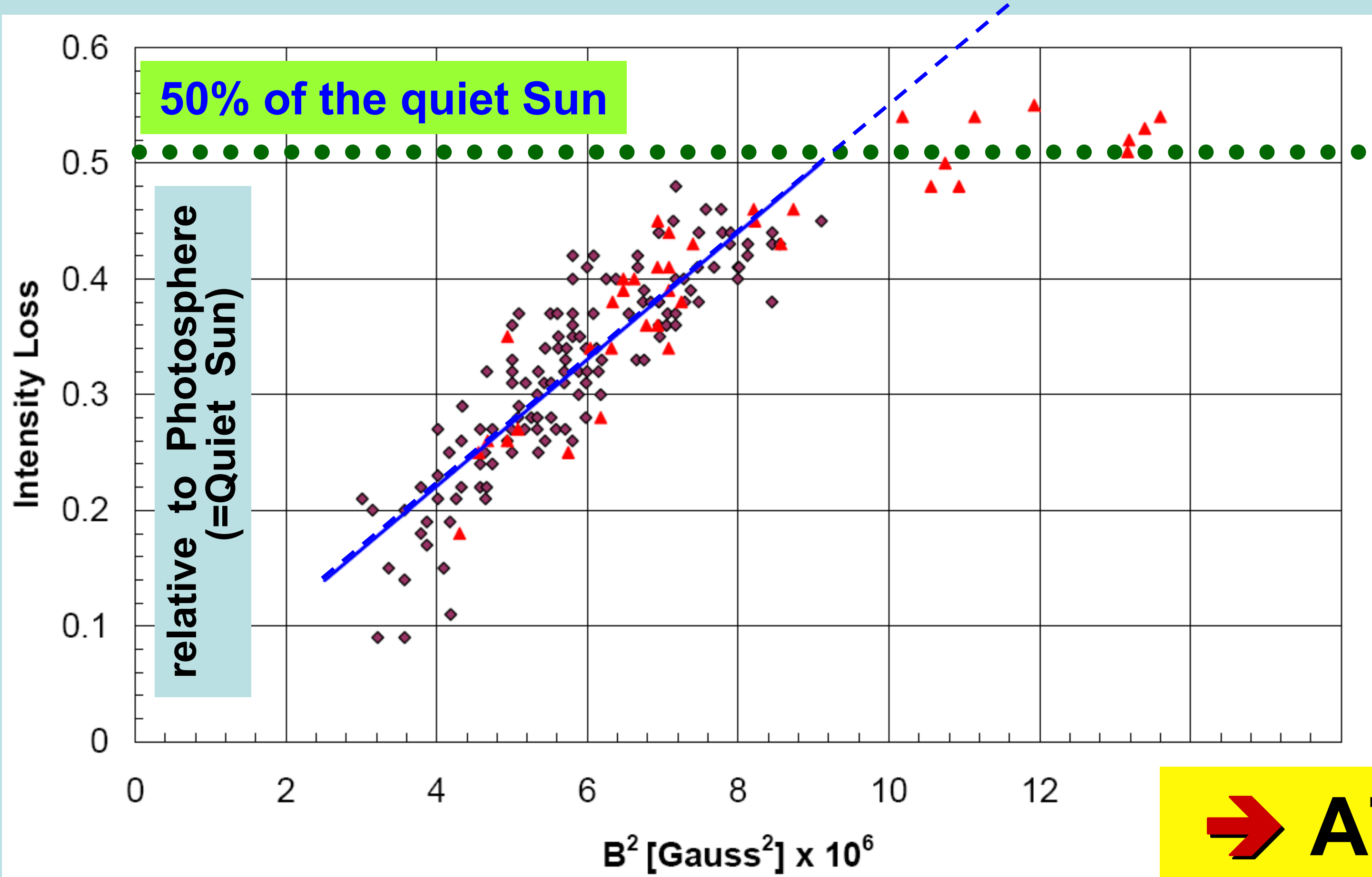
K. Zioutas, K. Dennerl, M. Grande, D.H.H. Hoffmann, J. Huovelin, B. Lakic, S. Orlando, A.Ortiz, Th. Papaevangelou, Y. Semertzidis, Sp. Tzamarias, O. Vilhu **J. Phys. Conf. Ser. 39(2006)103**

Plot reconstructed from **: SK Solanki A.&A. Rev.11 (2003) 153** →

- **fundamental questions remain unanswered.**
- ***is an additional mechanism needed*?**

SUNSPOTS ← *origin?*

4th



→ ATLAS?

K. Zioutas, K. Dennerl, M. Grande, D.H.H. Hoffmann, J. Huovelin, B. Lakic, S. Orlando, A.Ortiz, Th. Papaevangelou, Y. Semertzidis, Sp. Tzamarias, O. Vilhu **J. Phys. Conf. Ser. 39(2006)103**

Plot reconstructed from **: SK Solanki A.&A. Rev.11 (2003) 153 →**

- **fundamental questions remain unanswered.**
- ***is an additional mechanism needed?***

Conclusion

CAST insists

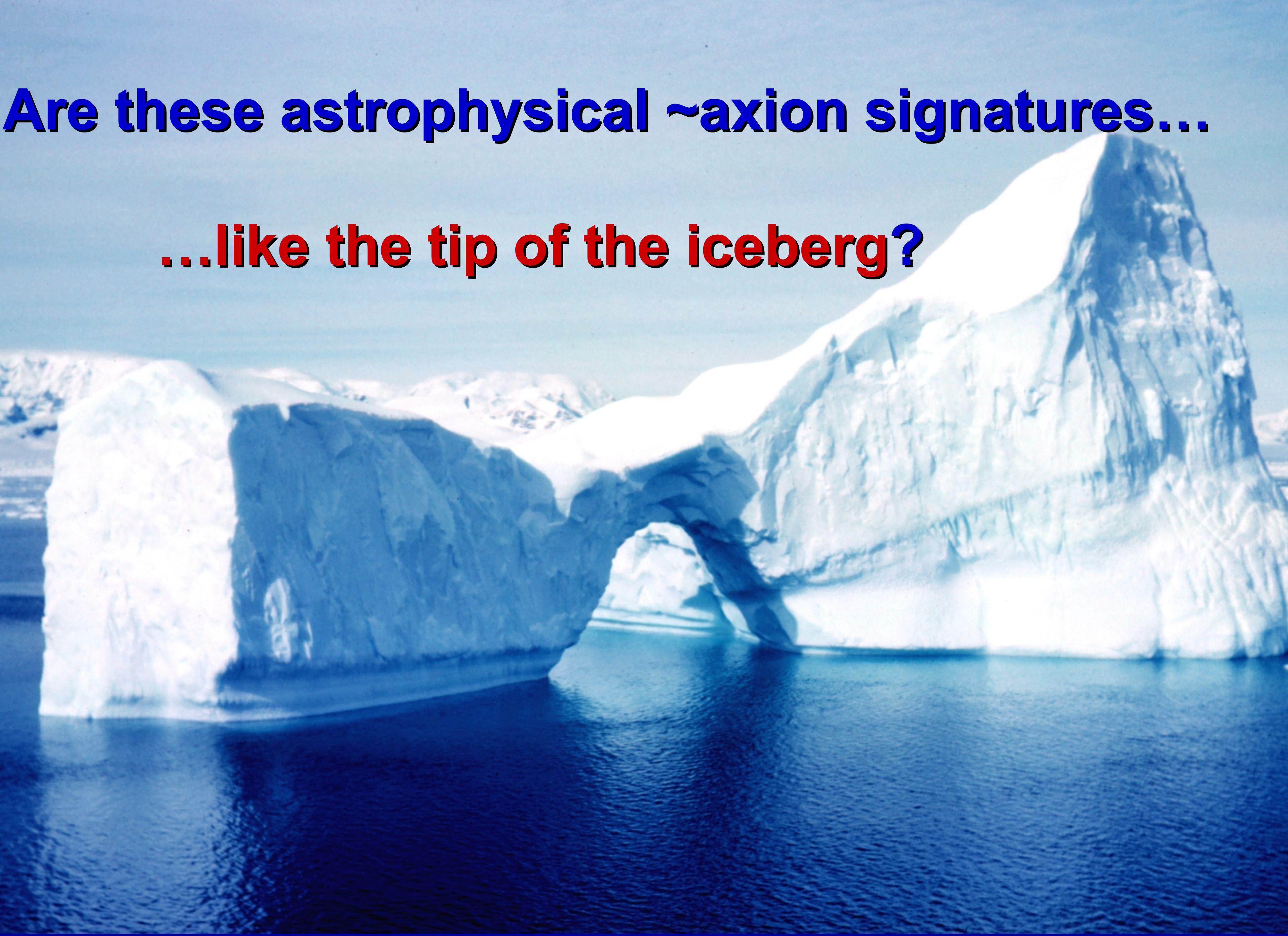
➔ welcome

... and beyond CAST?

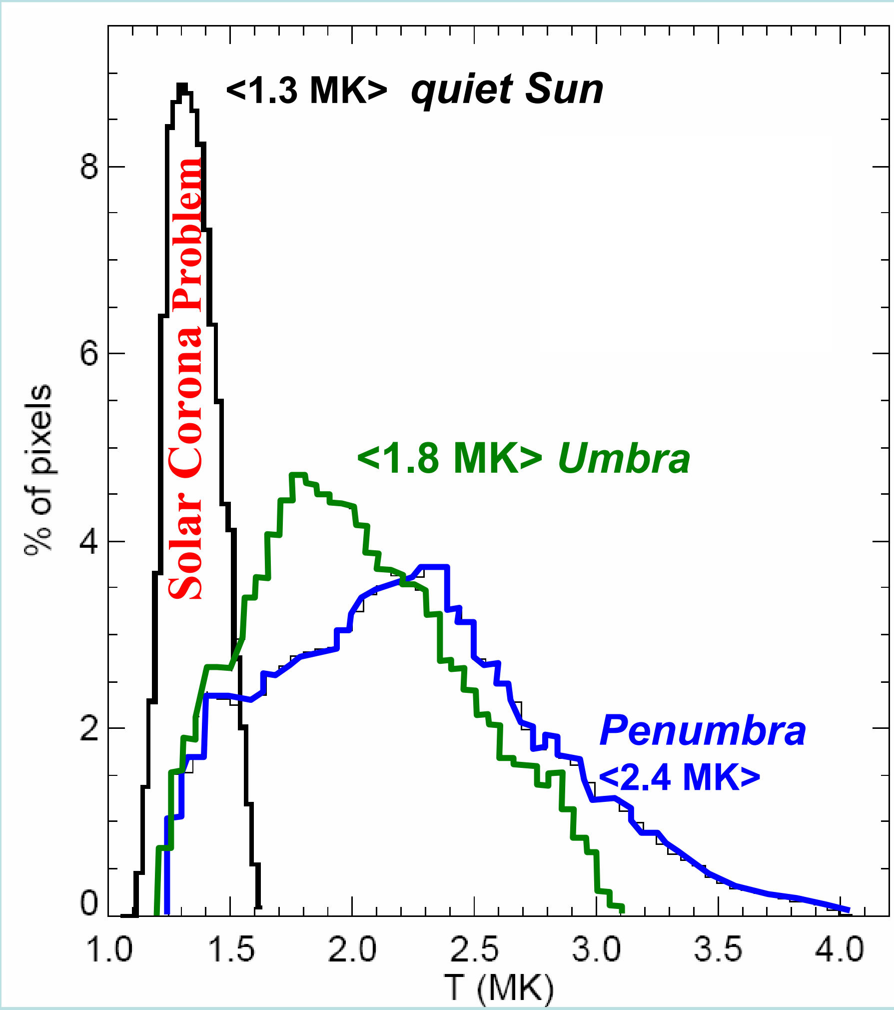
Conclusion towards ➔

Conclusion towards ➔

Every solar puzzle is due to ~axions!


Are these astrophysical ~axion signatures…
…like the tip of the iceberg?

SUNSPOTS



Temperature distributions

→ **Yohkoh - XRTelescope**

→ **TAUP2005**

Sunspots = "*dark spots*" → **T** ⇩

→ **photosphere**

~ 4500K → ***heat flux problem***

in ***umbra*** **+** ***penumbra***

Spruit, Scharmer, A.&A. (2005), astro-ph/0508504

→ **Corona**

Soft X-ray fluxes **T** ⇧

Sunspots:	~ 50 - 190	DN/s
Quiet Sun:	~ 10 - 50	DN/s
(**AR**s:	~ 500 - 4000	DN/s)

→ ***sunspot plasma parameters***

are higher than @ quiet-Sun

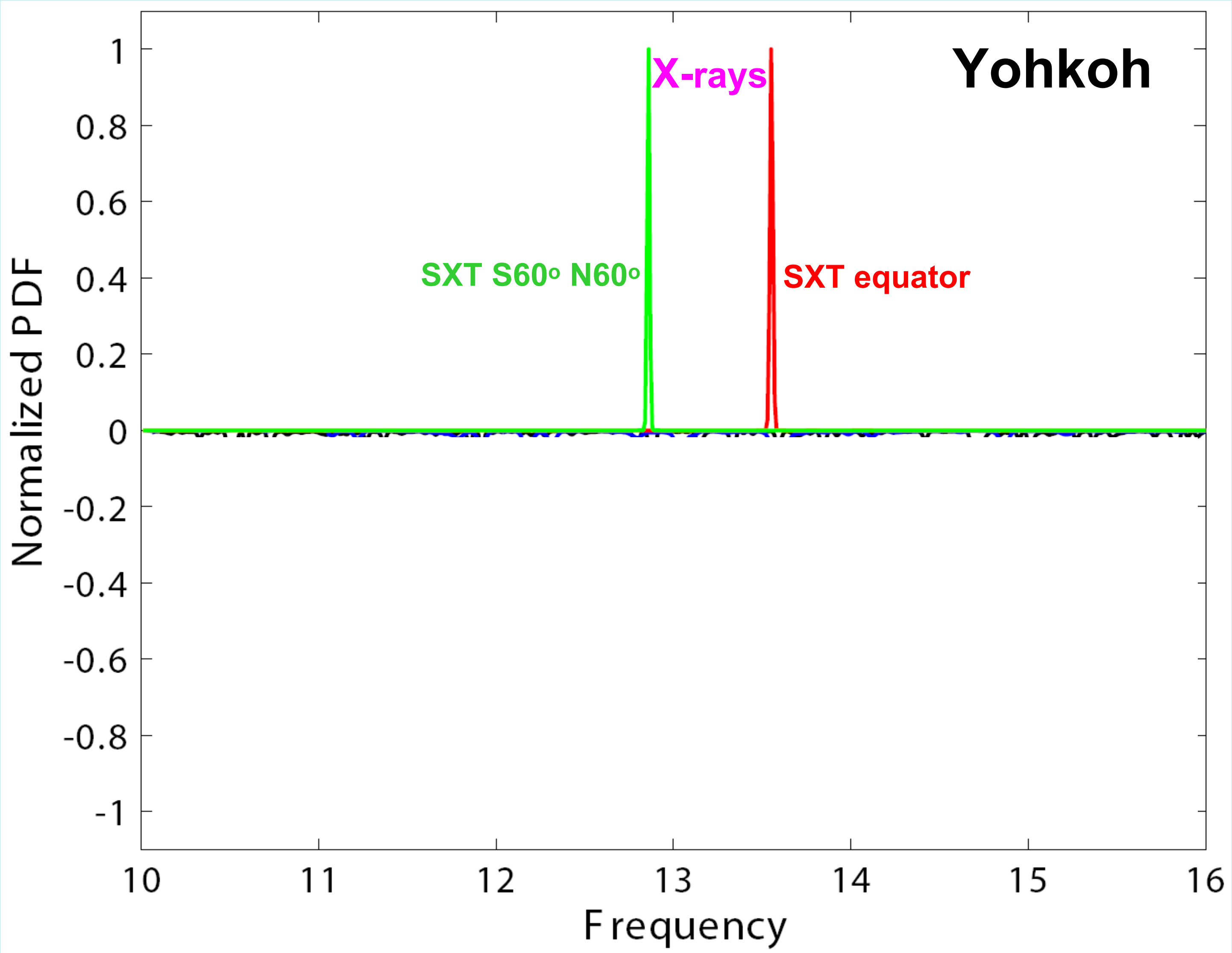
→ **B ~ 2 kG above most sunspots !**

A.Nindos, M.R.Kundu, S.M.White, K.Shibasaki, N.Gopalswamy,
ApJ. SUPPL. 130 (2000) 485

→ **"… sunspots remain mysterious".**

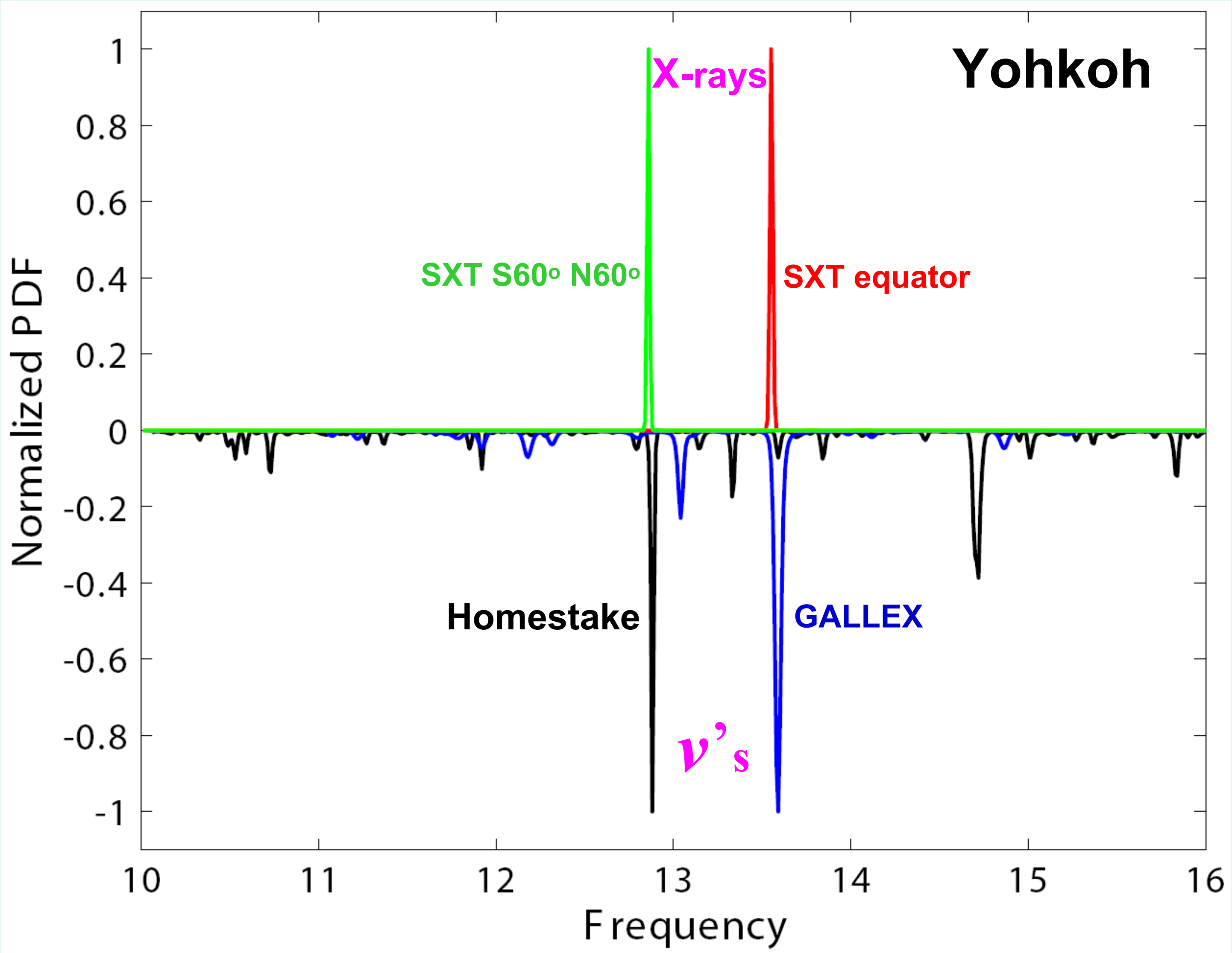
→ **The penumbral mystery … the very reason for its existence unknown.**

http://www.solarphysics.kva.se/NatureNov2002/background.html



Comparison of normalized probability distribution functions formed from power spectra of data from SXT equator (***red***), SXT N60-S60 (***green***), Homestake (***black***), and GALLEX (***blue***). Note that the SXT (***red***) and GALLEX data are equatorial, and the other two are not. Frequencies are given in cycles per year.

D.O. Caldwell, P.A. Sturrock, Astroparticle Phys. 23 (**2005**) 543



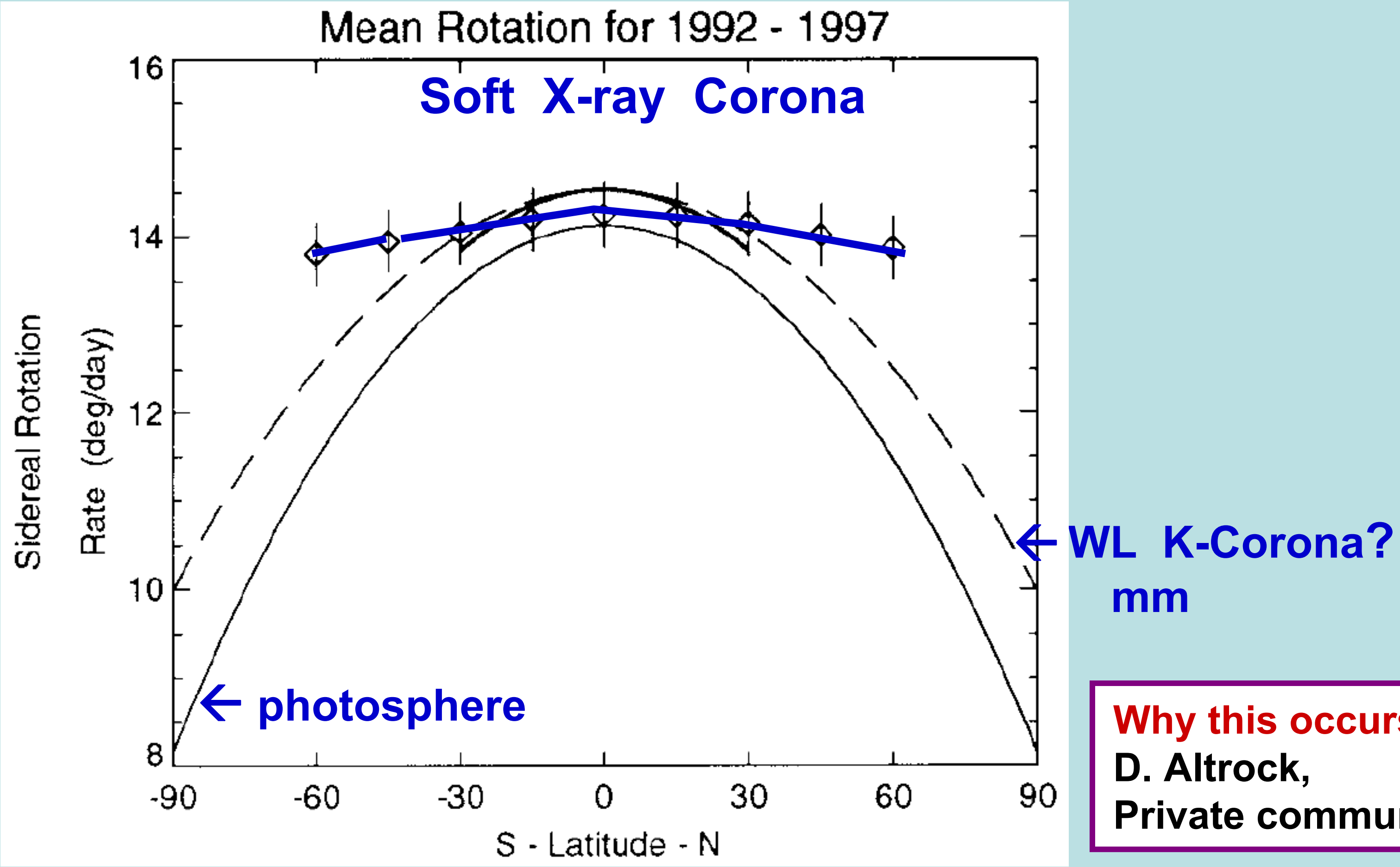
Comparison of normalized probability distribution functions formed from power spectra of data from SXT equator (***red***), SXT N60-S60 (***green***), Homestake (***black***), and GALLEX (***blue***). Note that the SXT (***red***) and GALLEX data are equatorial, and the other two are not. Frequencies are given in cycles per year.

D.O. Caldwell, P.A. Sturrock, Astroparticle Phys. 23 (**2005**) 543

Standard Solar Model problem with:

Solar metallicity

→ manifestation of 2 opposite effects?



Why this occurs is unclear!
D. Altrock,
Private communication

The rotation profile across latitude for all years averaged.
<u>Short solid line:</u> sunspot groups; <u>thin solid line:</u> Mt. Wilson Doppler measurements of the photosphere; <u>dashed line:</u> the WL K-corona.

M.A. Weber, L.W. Acton, D. Alexander, S. Kubo, H. Hara, Sol. Phys. 189 (1999) 271

X-ray mysteries:

- **Class 0 protostar** (10-100 kyears) → **origin of X-rays (<10 keV): matter is falling 10x faster?**
  K. Hamaguchi *et al.*, ApJ. 623 (**2005**) 291

  → **Similar-to-Sun logic = wrong** ←

Galactic Center → **origin of diffuse X-rays?**
too hot (~ 90MK) to be a gravitationally bound plasma!
→ ***how to produce it?***

Clusters of Galaxies → **"strong evidence of some thing wrong"**
"physical mechanism for the energy (or the entropy) excess? "
"some homogeneous process heats the gas"
P. Tozzi, astro-ph/0602072
[see also B.A. Reid, D.N. Spergel, astro-ph/0601133 v2 (**23.7.2006**)] pp. 4-6,27,30

XRB*radiation* ← **origin?**

TOTAL SOLAR IRRADIANCE

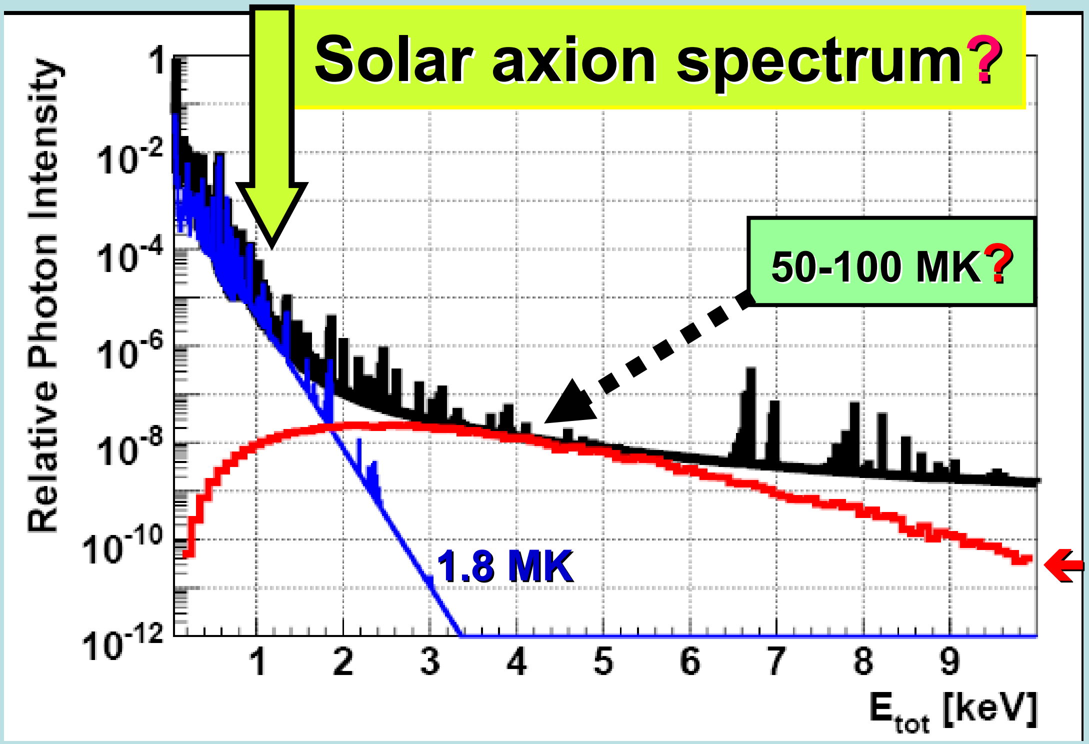
→ visible light

→ ***strong evidence that the magnetic elements with higher flux are less bright.***

N.A. Krivova, S.K. Solanki,M. Fligge, Y.C. Unruh, A.&A. 399 (2003) L1

2005- → RHESSI
SMART_1

Reconstructed X-ray spectrum
→ non-flaring Sun @ solar minimum [X]



← **KK-axion model**

→ **generic**

→ $g_{a\gamma\gamma} \approx 10^{-13}$ GeV^{-1}

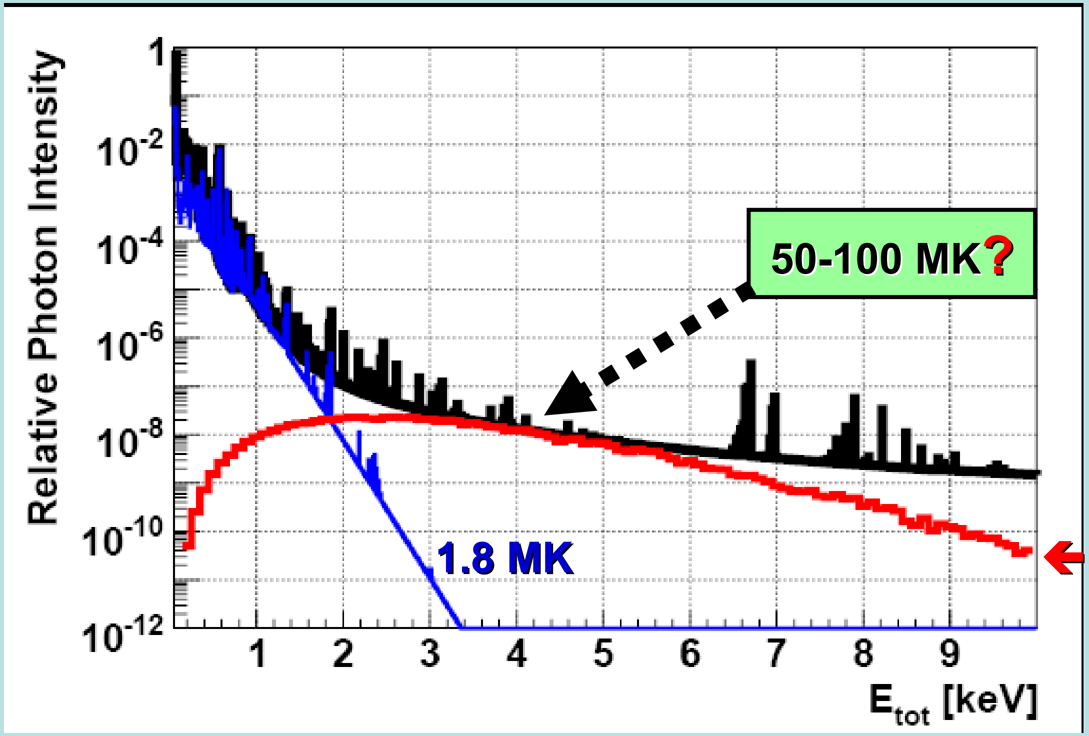
$m_{KK} \approx 10^{-3}$ eV

$L_a \approx 0.16 L_{solar} \approx 10^6$ t/s → $L_{trapped} \approx 200$ kg/s → 10^{22} g ← now

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

[X] G. Peres, S. Orlando, F. reale, R. Rosner, H. Hudson, ApJ. 528 (2000) 537

Reconstructed X-ray spectrum
➔ non-flaring Sun @ solar minimum [X]



➔ KK-axion model

➔ generic

➔ $g_{a\gamma\gamma} \approx 10^{-13} GeV^{-1}$

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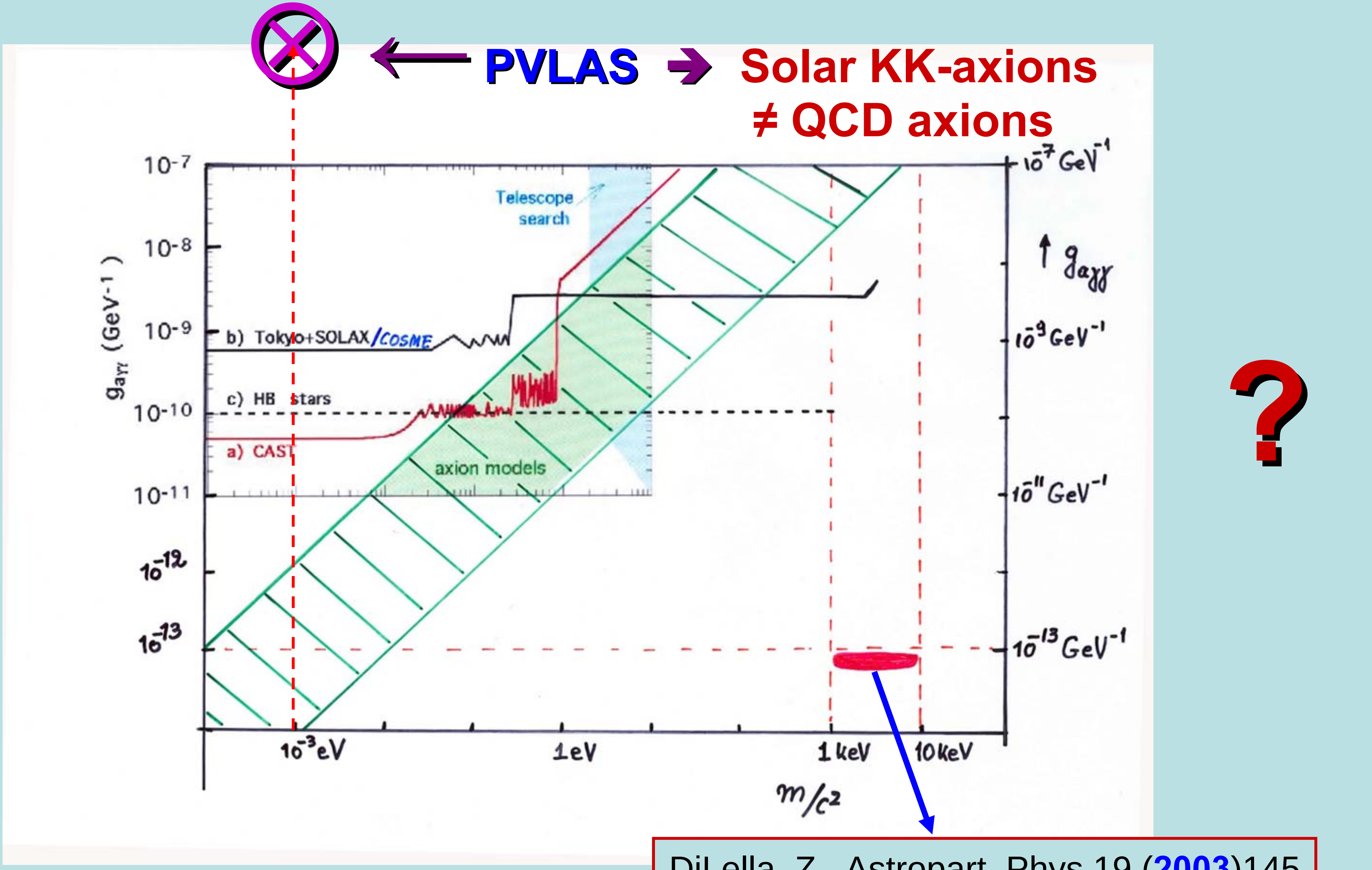
$L_a \approx 0.16 L_{solar} \approx 10^6$ t/s ➔ $L_{trapped} \approx 200$ kg/s ➔ 10^{22} g ➔ now

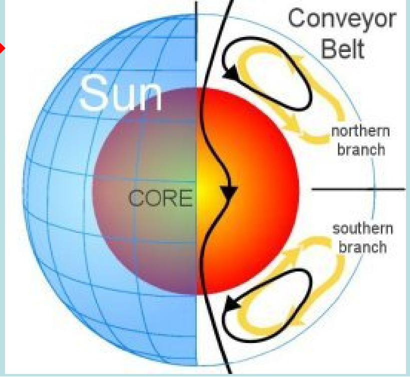
L. DiLella, K.Z., Astropart. Phys. 19 (2003) 145

[X] G. Peres, S. Orlando, F. reale, R. Rosner, H. Hudson, ApJ. 528 (2000) 537

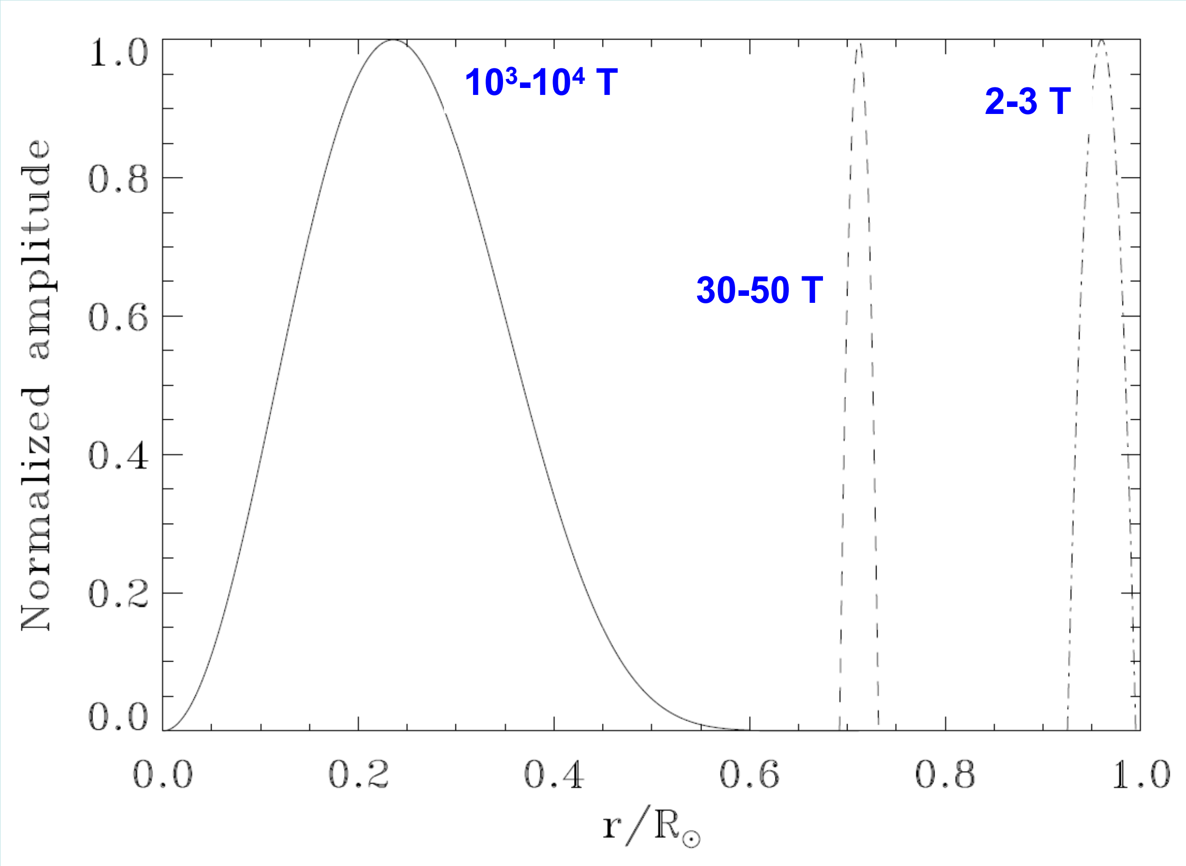


DiLella, Z., Astropart. Phys.19 (**2003**)145

http://www.unine.ch/phys/corpus/tpc2002/zioutas.ppt http://science.nasa.gov/headlines/y2006/10may_longrange.htm →



Solar seismic models + the ν-predictions



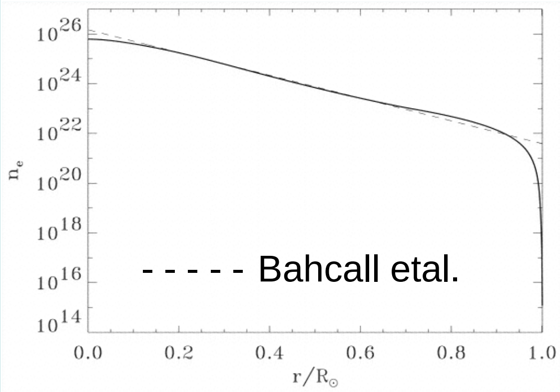
Magnetic fields simulated. Normalized amplitudes by their maximum intensity.

S Couvidat, S Turck-Chieze, AG Kosovichev. ApJ. 599 (**2003**) 1434

...seismic models are very close to the real Sun in the regions of concern.

But →

… as far as the internal rotation profile is not included in the study, new surprises may appear …



~10^5 Tesla

→ *change significantly solar ν-fluxes*