The enigmatic sun: laboratory for new physics.

K. Zioutas

University of Patras & CERN

→ **follow-up of axions → CAST motivated!**

+ V. Anastassopoulos, Th. Papaevangelou, Y. Semertzidis, M. Tsagri.

Further reading: http://axion-wimp.desy.de/e30/e252/talk-21-zioutas.pdf

ICPP
Bogazici University,
Istanbul, Turkey

27th October 2008

Probing eV-scale axions with CAST.
By CAST Collaboration (: E. Arik *et al.*). Oct 2008. 17pp.

e-Print: **arXiv:0810.4482** [hep-ex]

E. Arik[18*], S. Aune[2], D. Autiero[1†], K. Barth[1], A. Belov[11], B. Beltrán[6‡], S. Borghi[1], F. S. Boydag[18], H. Bräuninger[5], G. Cantatore[19],J. M. Carmona[6], S. Cebrián[6], S. A. Cetin[18], J. I. Collar[7], T. Dafni[2], M. Davenport[1], L. Di Lella[1§], O. B. Dogan[18¶], C. Eleftheriadis[8], N. Elias[1], G. Fanourakis[9], E. Ferrer-Ribas[2], H. Fischer[10], J. Franz[10], J. Galán[6], E. Gazis[21], T. Geralis[9], I. Giomataris[2], S. Gninenko[11], H. Gómez[6], M. Hasinoff[12], F. H. Heinsius[10], I. Hikmet[18], D. H. H. Hoffmann[3,4], I. G. Irastorza[2,6], J. Jacoby[13], K. Jakovčić[15], D. Kang[10], T. Karageorgopoulou[21], M. Karuza[19], K. Königsmann[10], R. Kotthaus[14], M. Krčmar[15], K. Kousouris[9], M. Kuster[3,5], B. Lakić[15], C. Lasseur[1], A. Liolios[8], A. Ljubičić[15], V. Lozza[19], G. Lutz[14], G. Luzón[6], D. Miller[7], A. Morales[6‖], J. Morales[6], T. Niinikoski[1], A. Nordt[3,5], A. Ortiz[6], T. Papaevangelou[1], M. Pivovaroff[17], A. Placci[1], G. Raiteri[19], G. Raffelt[14], H. Riege[1], A. Rodríguez[6], J. Ruz[6], I. Savvidis[8], Y. Semertzidis[16], P. Serpico[14], S. Solanki[20], R. Soufli[17], L. Stewart[1],M. Tsagri[16], K. van Bibber[17], J. Villar[6], J. Vogel[10], L. Walckiers[1], K. Zioutas[16]

The CAST Collaboration

1. European Organization for Nuclear Research (CERN), Genève, Switzerland
2. DAPNIA, Centre d'Études Nucléaires de Saclay (CEA-Saclay), Gif-sur-Yvette, France
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20. Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, Germany
21. National Technical University of Athens, Athens, Greece

Why axions?

Physics motivation for axions:

to solve the strong CP problem →

why nEDM $\longrightarrow$ 0

spin-parity $\Rightarrow$ 0^- $\Rightarrow \approx \pi^o$, γ (M1)

Axions → cosmology ← dark matter

\+ Sun, ...

→ solve solar problems?!

→ This work

(solar) ~axions in the spotlight!

➔ Several exp's …

Searching for ~axions with space missions!

e.g., Yohkoh, RHESSI, HINODE, ...

SUN:

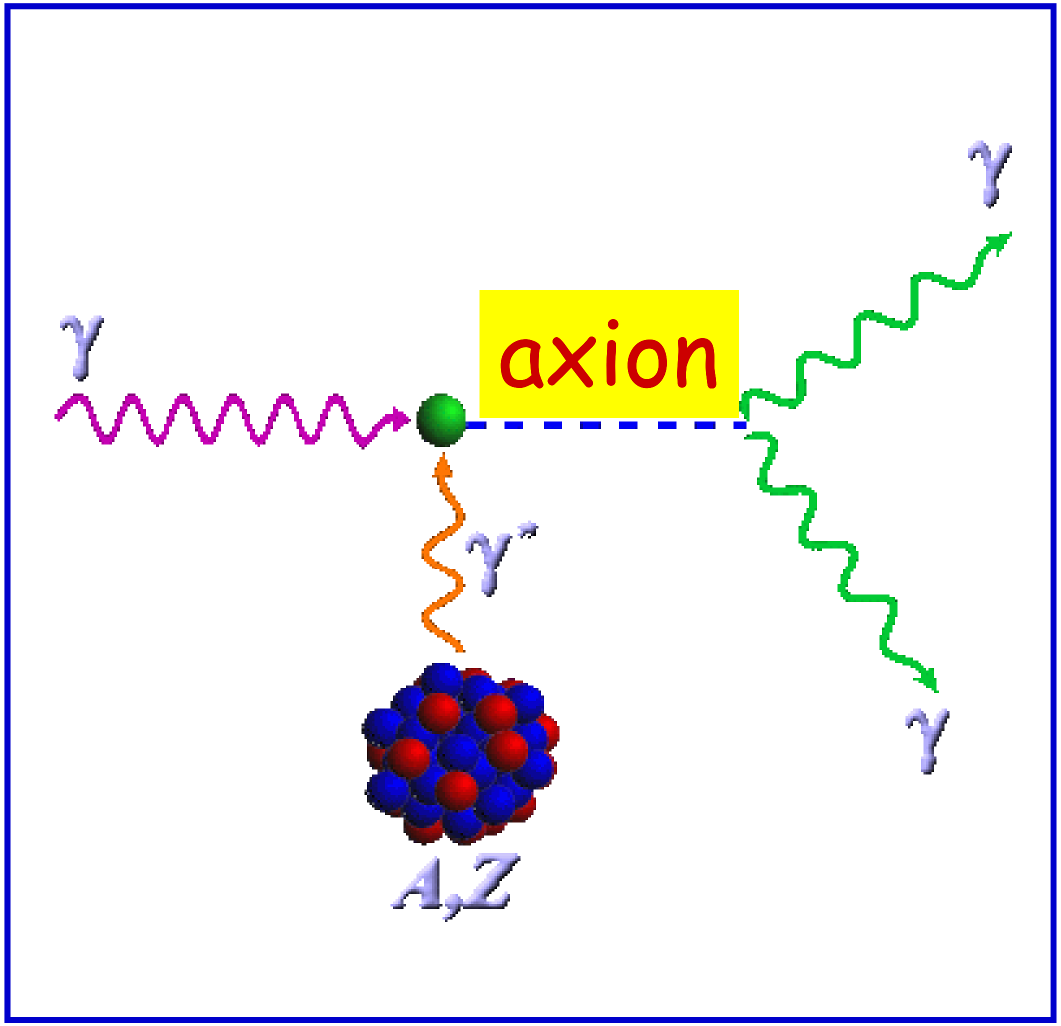
➔ 5 Mtons / s of energy is released

~100 ktons ~axions / s …

… overlooked?!

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

The Primakoff Effect 1951



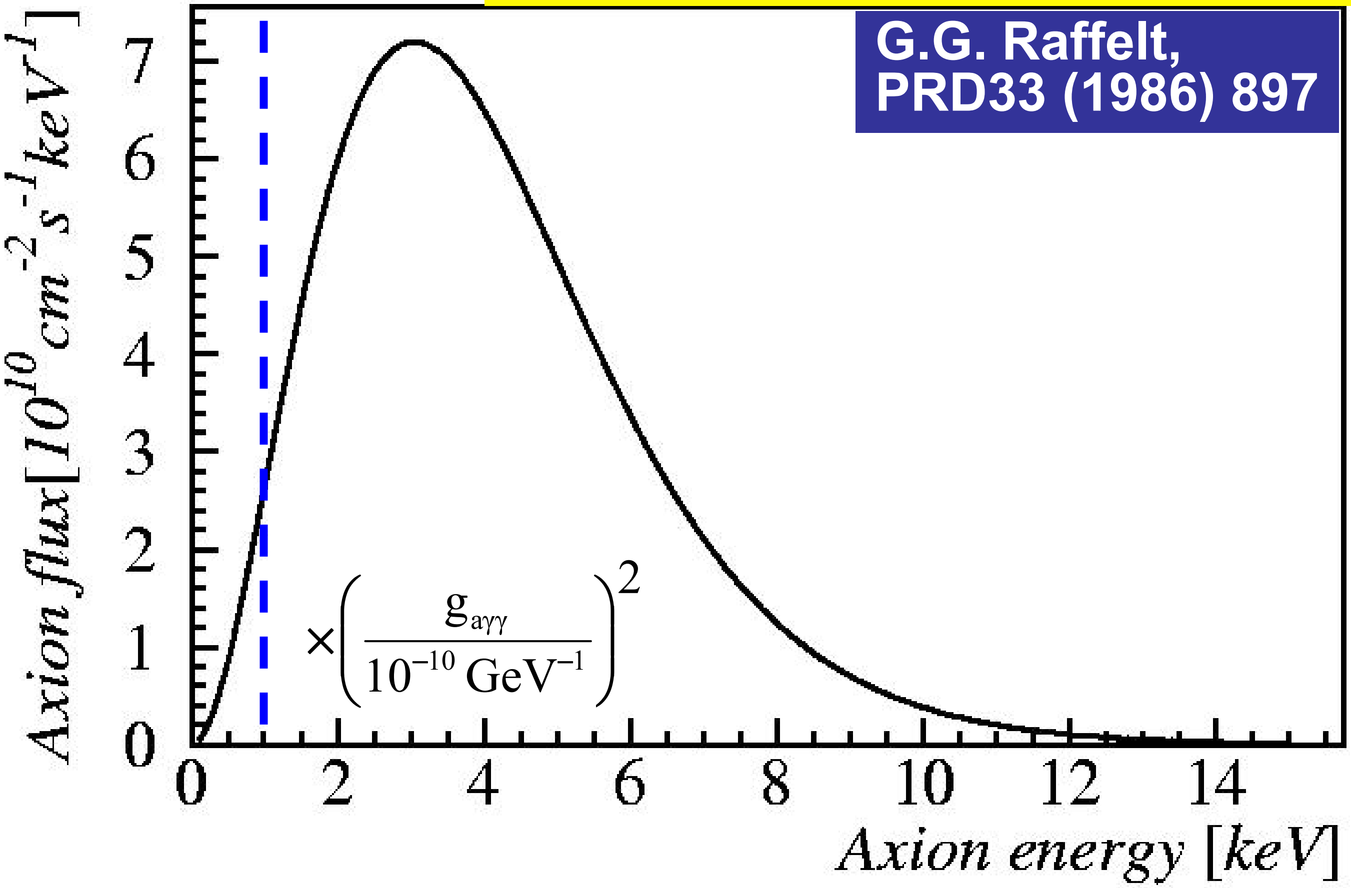
Behind all present axion work! ➔ solar axions

➔ B

➔ aQED

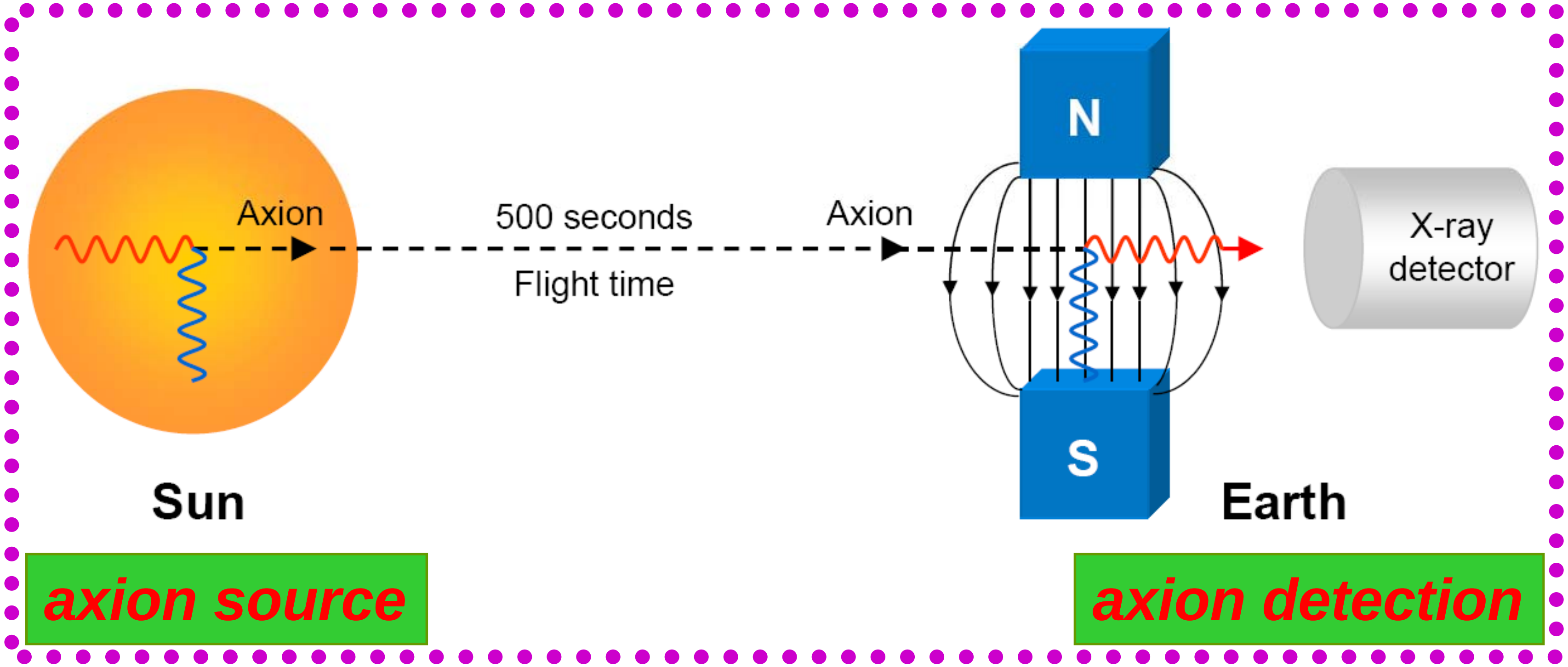
Solar axion spectrum

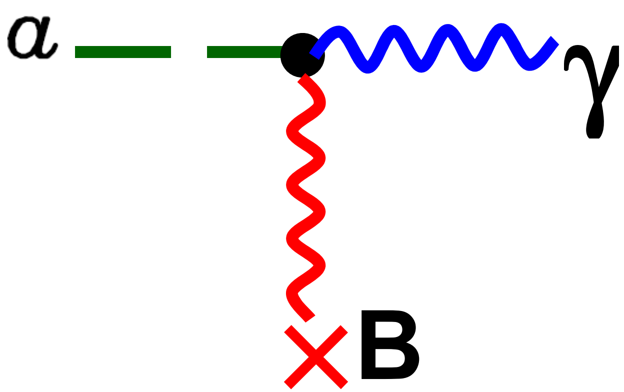
screening effects ➔ 25x suppression, or?



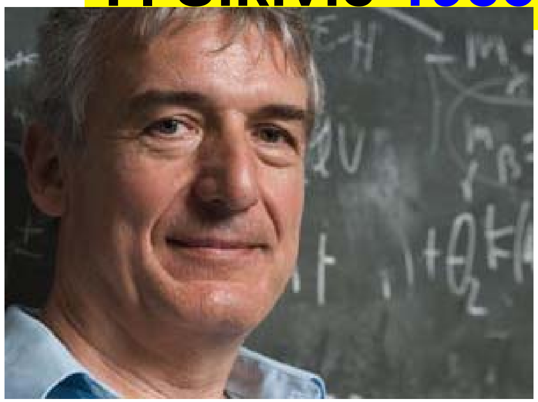
↛ Theoretically + experimentally ➔ new territory!

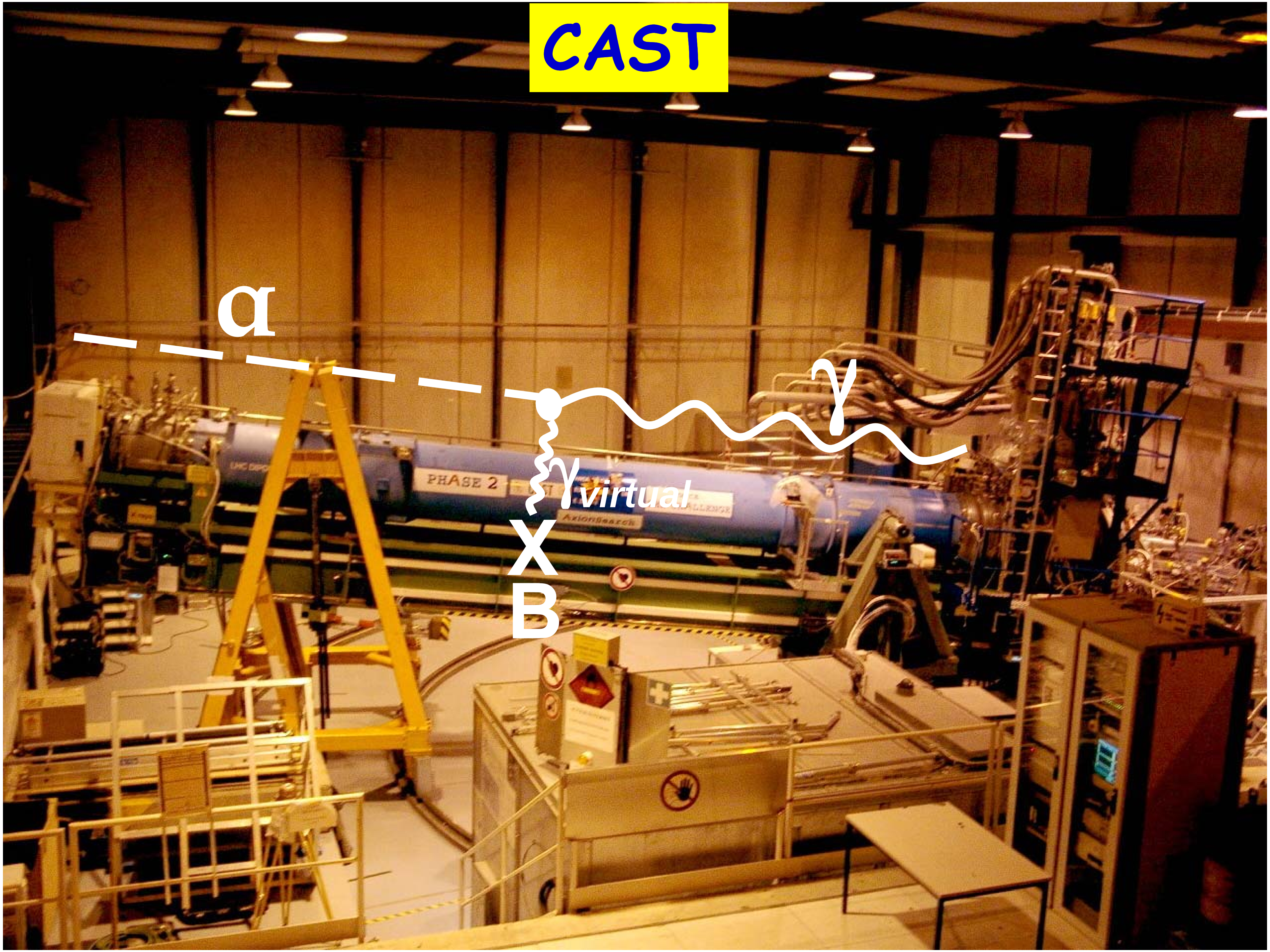
CAST



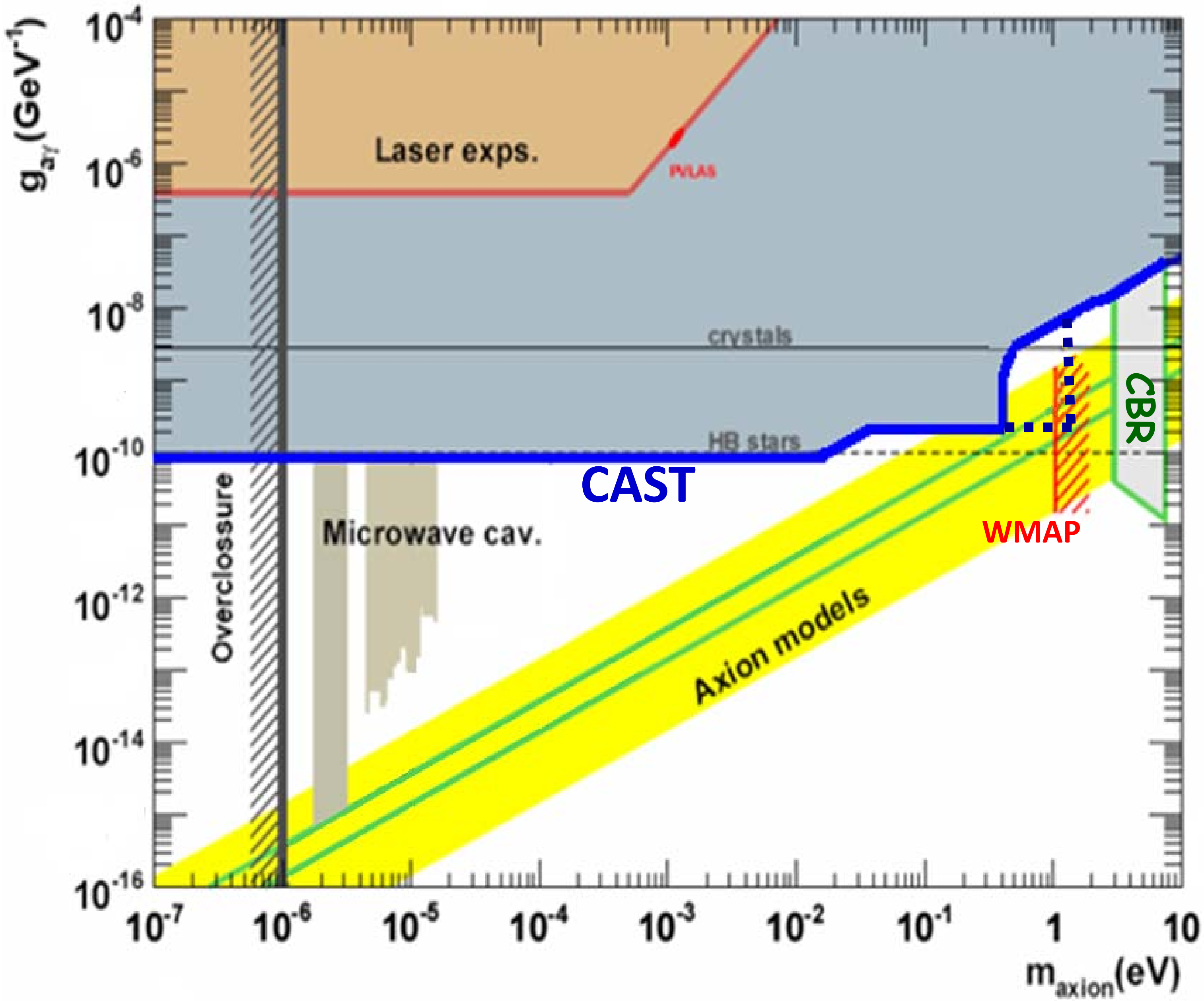


P. Sikivie 1983

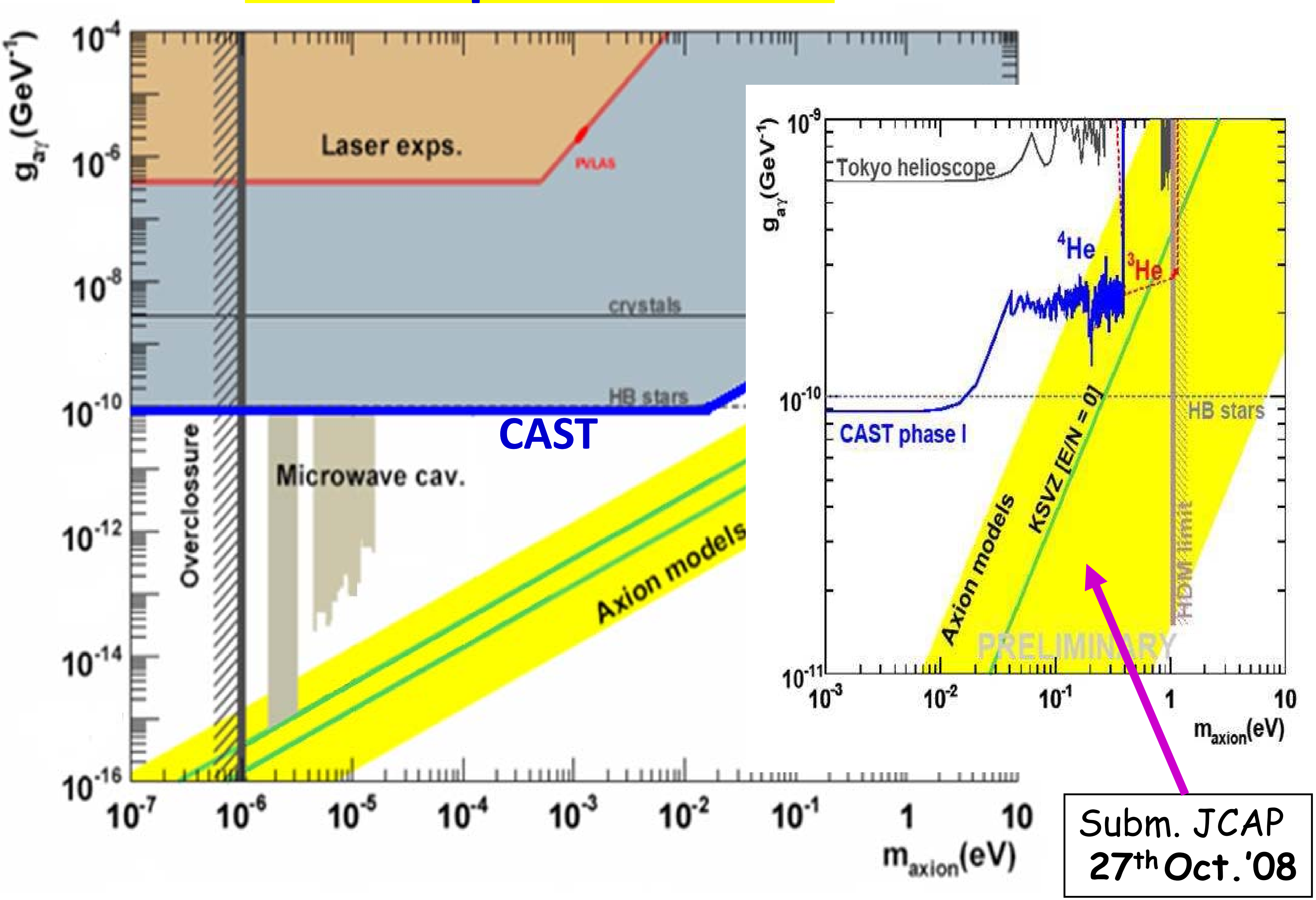



CAST
α
γ
$\gamma_{virtual}$
X
B
PHASE 2

CAST performance



CAST performance



Subm. JCAP
27th Oct.'08

This work:

CAST @ the Sun?

→ hidden ~axions in published OR archived data!!?

Is the Sun enigmatic?

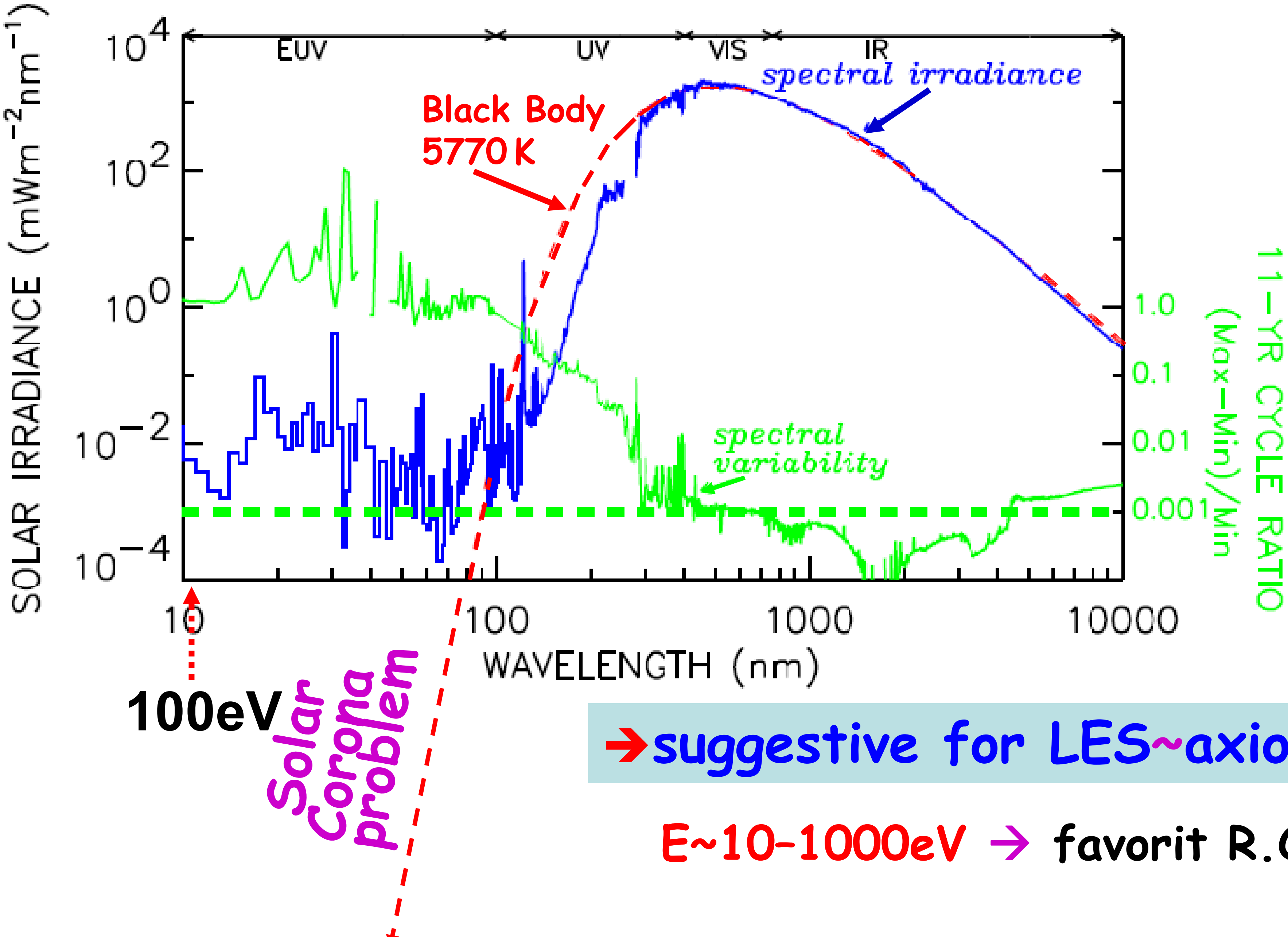
→ YES!

> a few eV

- Heating of the chromosphere + corona:
  → a long-standing puzzle in solar physics
- Mystery: Corona + TR are highly dynamic

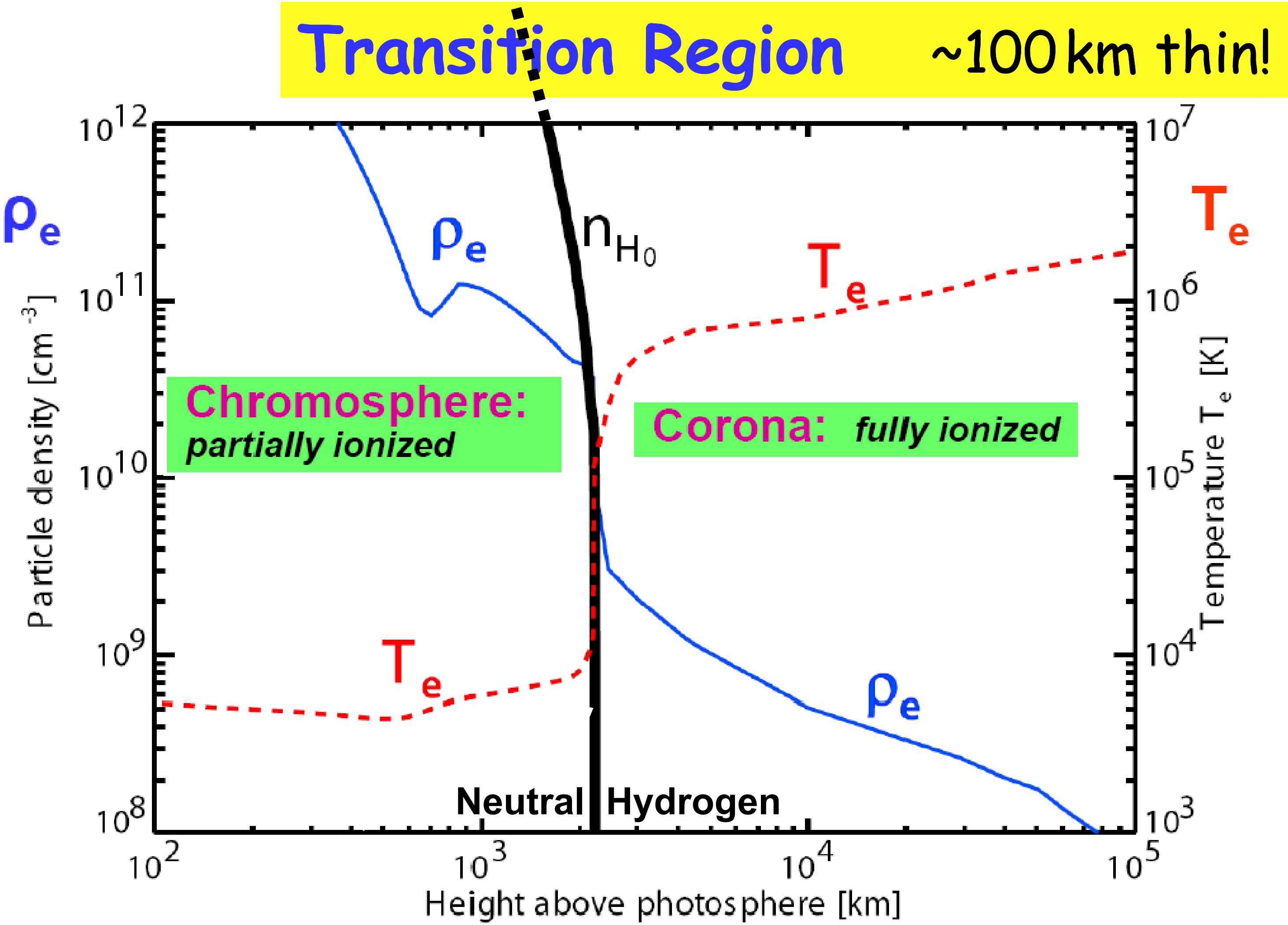
K. Shibata et al., astro-ph/0810.3974 (22/10/2008)

Solar e/m spectrum



→suggestive for LES~axions!

E~10–1000eV → favorit R.O.I.



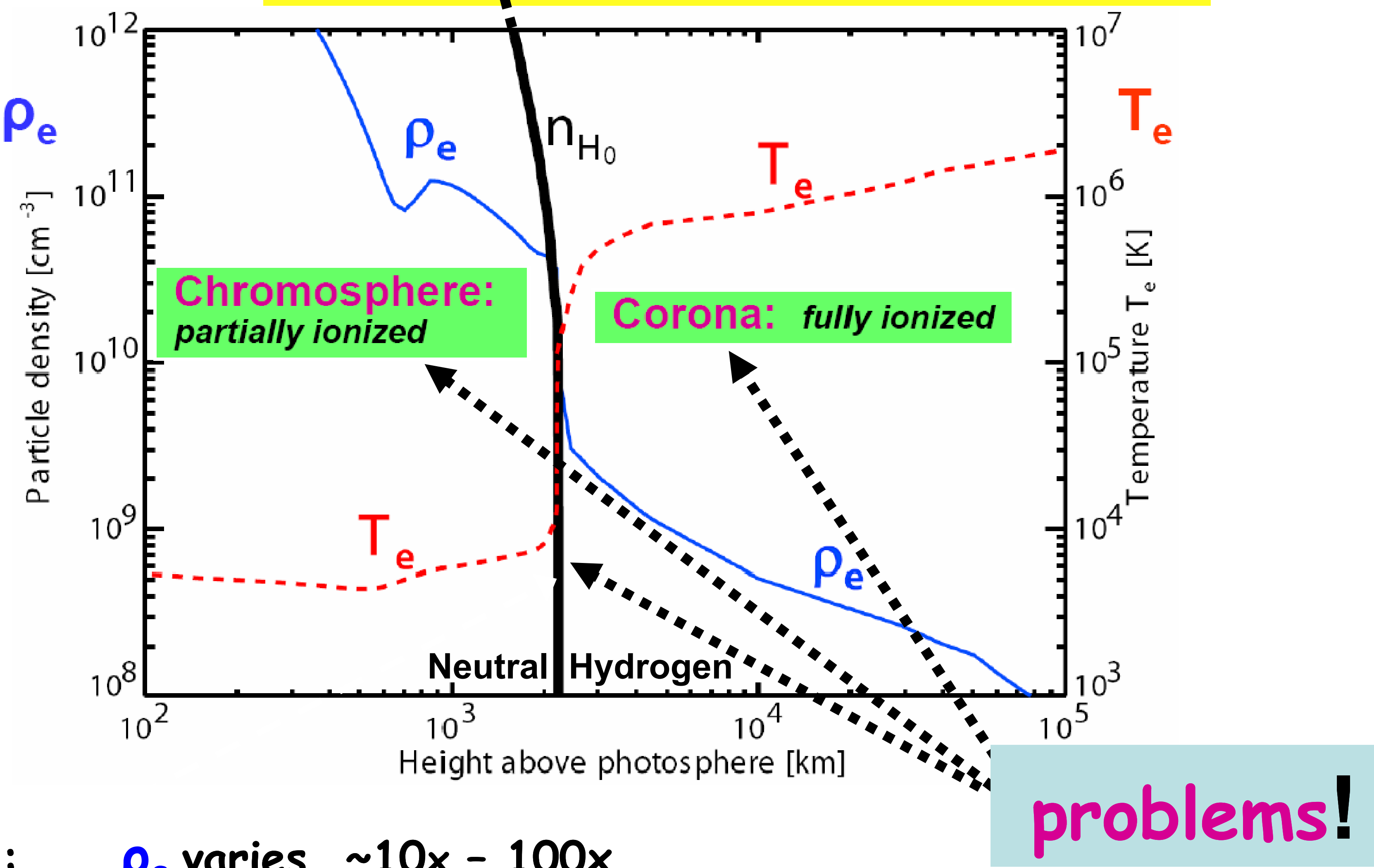
Corona: ρ_e **varies ~10x – 100x**

Photosphere: ~1‰ of the gas is ionized (= plasma).

S Patsourakos *et al*, ApJ. 522 (1999) 540; M Aschwanden, Physics of the Solar Corona (2004) 24-26

http://www.windows.ucar.edu/tour/link=/sun/atmosphere/photosphere.html

Transition Region ~100 km thin!



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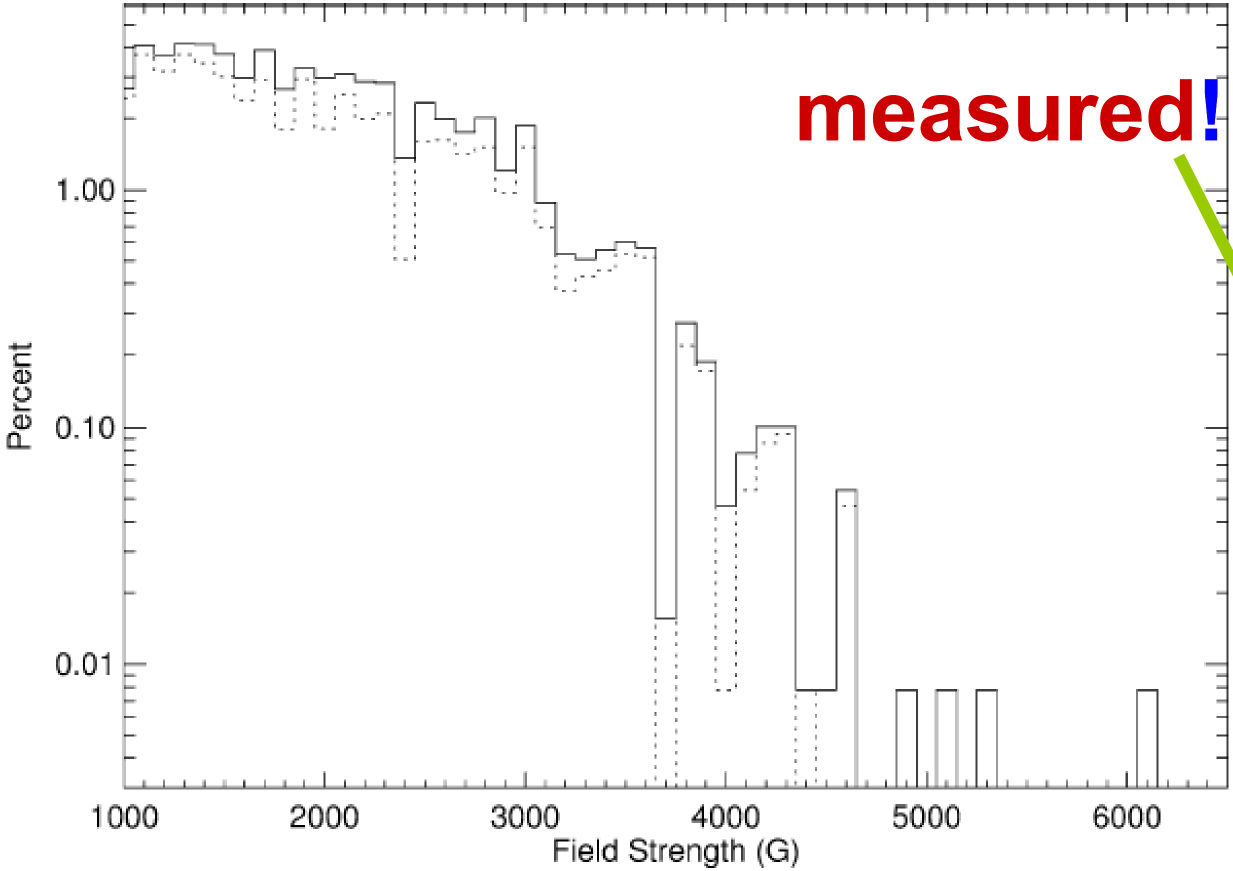
http://www.windows.ucar.edu/tour/link=/sun/atmosphere/photosphere.html

behind a mystery
→ a hidden unknown physics!

B_{solar} ← ignored

Note: axion <--> photon = $f(B^2)$

Magnetic field in sunspots



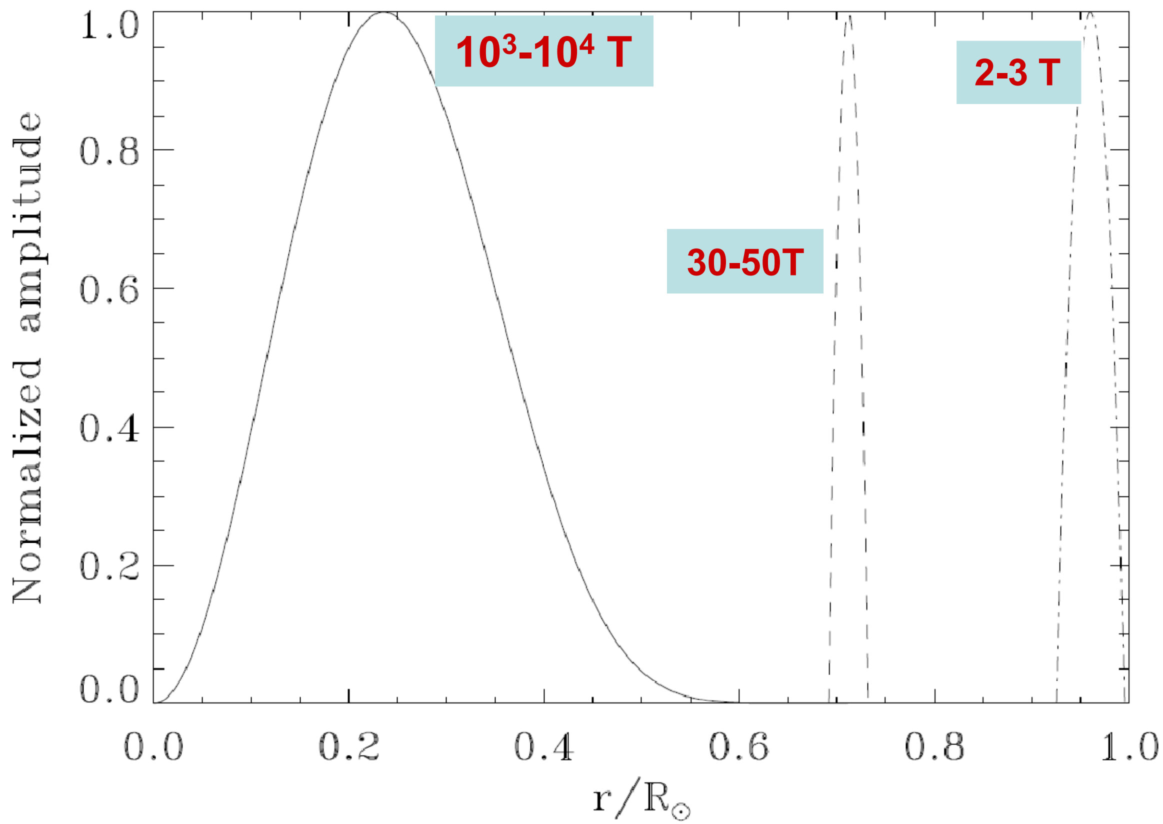
measured!

locally?

Distribution of maximum field strengths in **12804 sunspot groups** measured at Mt.Wilson (1917–1964) and Rome (1965–1974). The *dashed histogram* is only Mt. Wilson measurements.

W. Livingston, J. W. Harvey, O. V. Malanushenko, L. Webster, Sol. Phys. 239 (**2006**) 41

Solar seismic models + the ν-predictions



Solar magnetic fields simulated. .

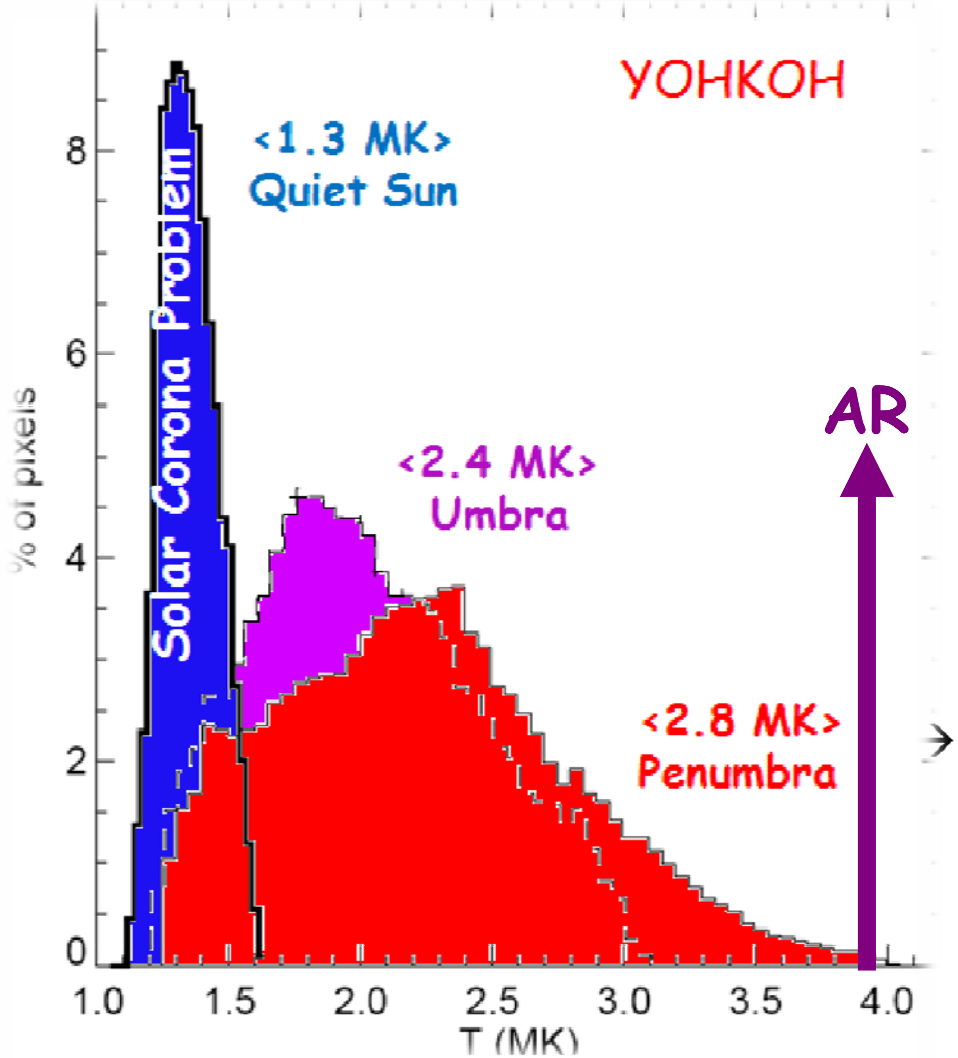
> 10^5 T *change solar ν-fluxes*

the internal rotation profile is not included in the study → new surprises may appear

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

Origin of **Sunspots** → one of the great puzzles of astrophysics

Zhao, et al., ApJ. 557 (**2001**) 384



Temperature distributions

Photosphere: T ⇩ ~4500K

Corona: T ⇧

Transition Region ⇧ (!?)

B ~2kGauss above most sunspots!

→heat flux problem @ umbra / penumbra

Spruit, Scharmer, A.&A. 447 (2006) 343

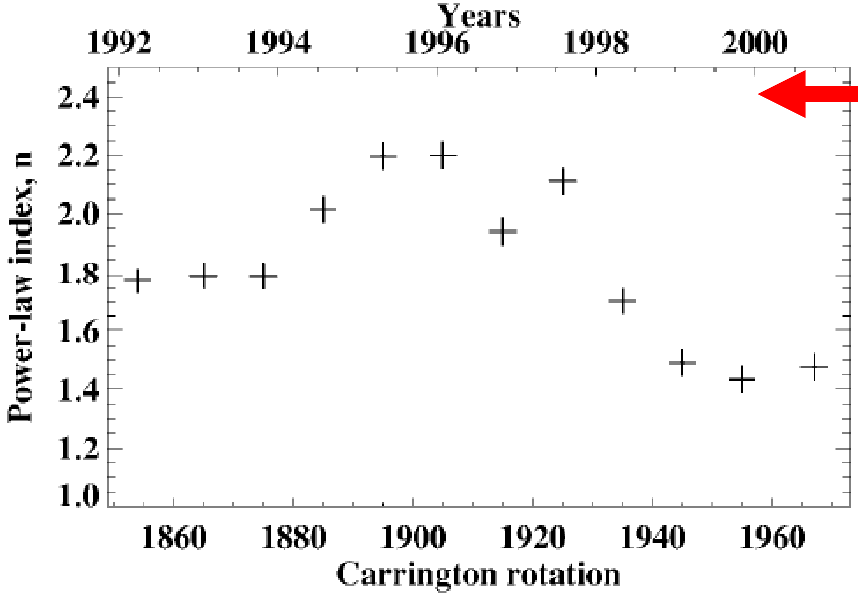
Some ARs are more productive

→ productivity ⊗ B-configuration, as in the case of large flares.

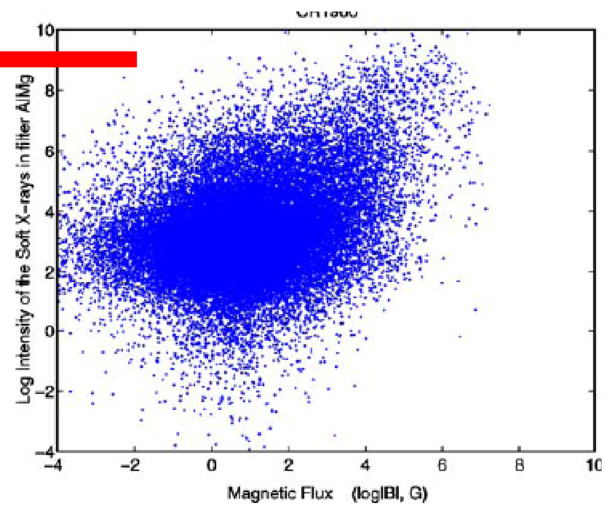
Qiu et al., ApJ. 612 (**2004**) 530

Nindos, et al., ApJ. SUPPL. 130 (**2000**) 485

L_x vs. B



E.E. Benevolenskaya,
Adv. Space Res. 39 (2007) 1491



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 <index> ≈ 2.

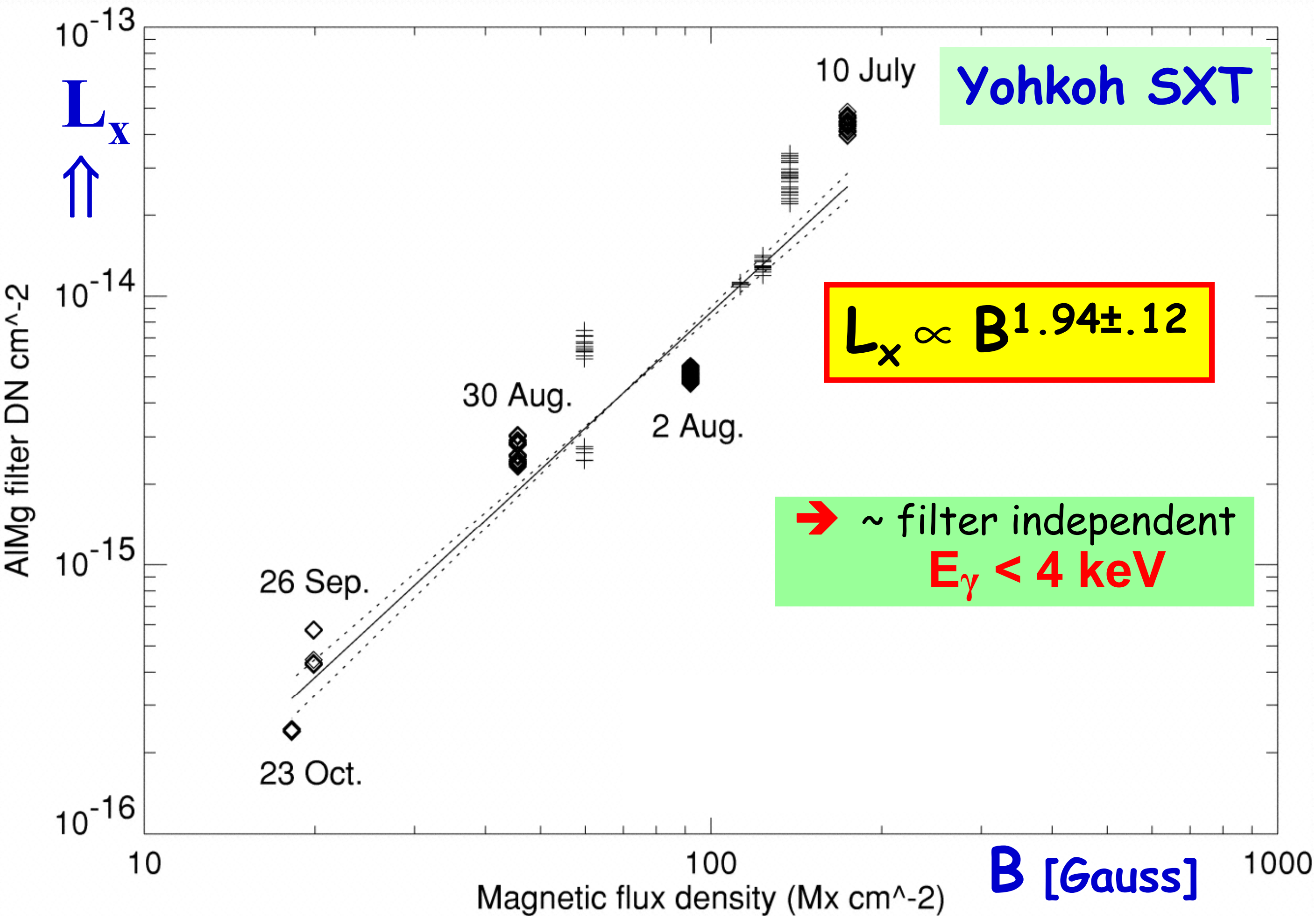
E.E. Benevolenskaya, Kosovichev, Lemen, Scherrer, Slater ApJ. 571 (2002) L181

➔ the soft X-ray flux depends not only on the amount of the photospheric magnetic flux but also on some magnetic field structural properties that vary with the solar cycle (2007).

➔ axion-to-photon oscillation $\propto B^2$ Hoffmann, Z., Nucl. Phys. B S151 (2006) 359

⊗ **11 years solar cycle?**

The long-term evolution of AR7978



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, Démoulin, Mandrini, Harra, 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

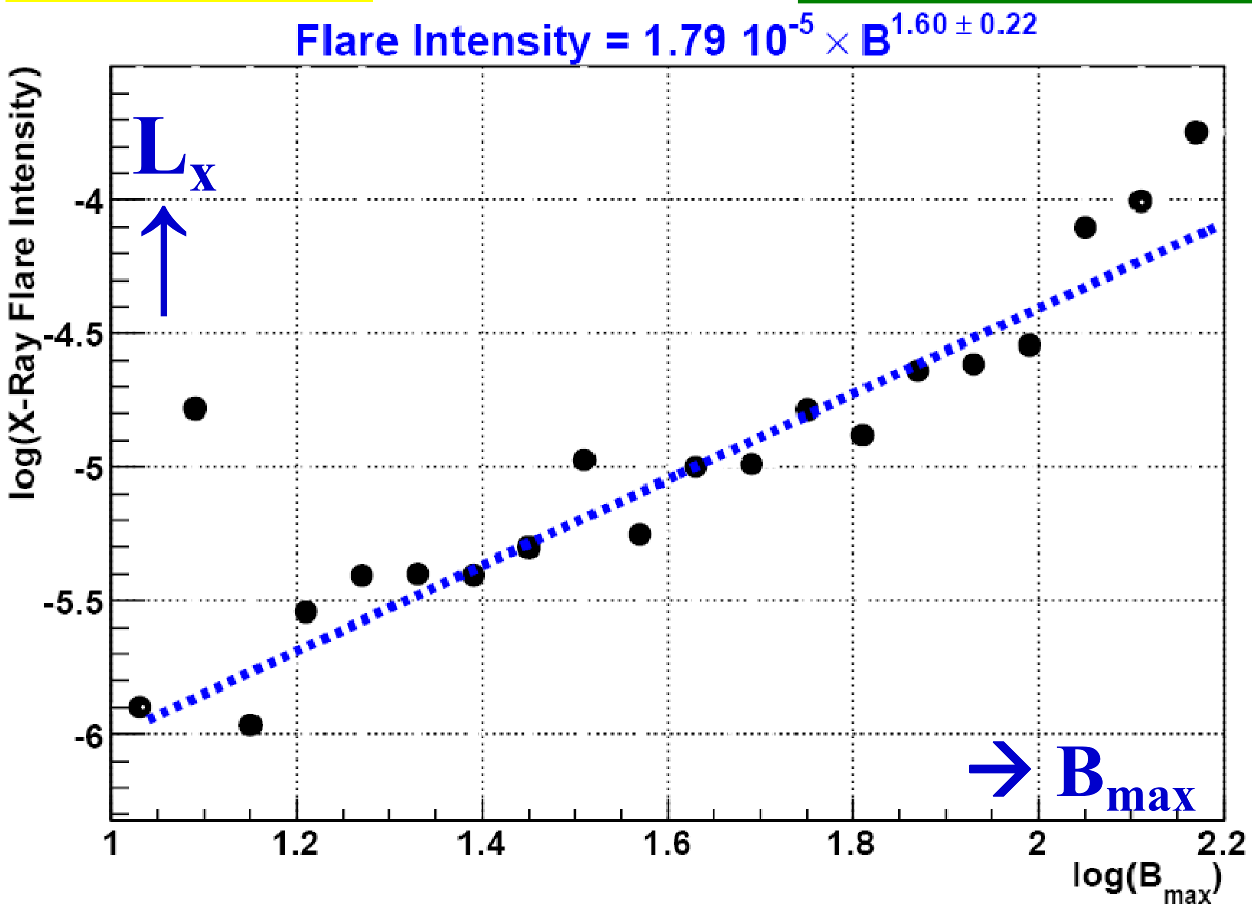
FLARES

1st surface brightness < max. L_{axion}

2nd <T> ~ 15-20MK

3rd $L_x \propto B^2$

4th ~axion



Rebinned peak flare X-ray intensity → B_{max}

Mason et al., ApJ. 645 (2006) 1543 → B^2 correlation

The Electron "Problem"

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

G. Emslie (2005)

http://www.astro.auth.gr/%7Evlahos/ascona/memberstalks/energeticsEmslie.ppt#366,8

Flares must be E/M in origin.

JJ Sudol, JW Harvey, ApJ. 635 (10.12.2005) 647

FLARES: unpredictable **magnetic "explosions"**

B-reconnection (~annihilation)

→ is widely (but not universally) accepted to be essential

→ is reconnection the flare trigger?

OR,

is reconnection a consequence of the "explosion"?

RL Moore, AC Sterling, HS Hudson, JR Lemen, ApJ. 552 (2001) 833

The dynamical energy balance of ARs presents challenges.

… the source of the flare energy is not well understood.

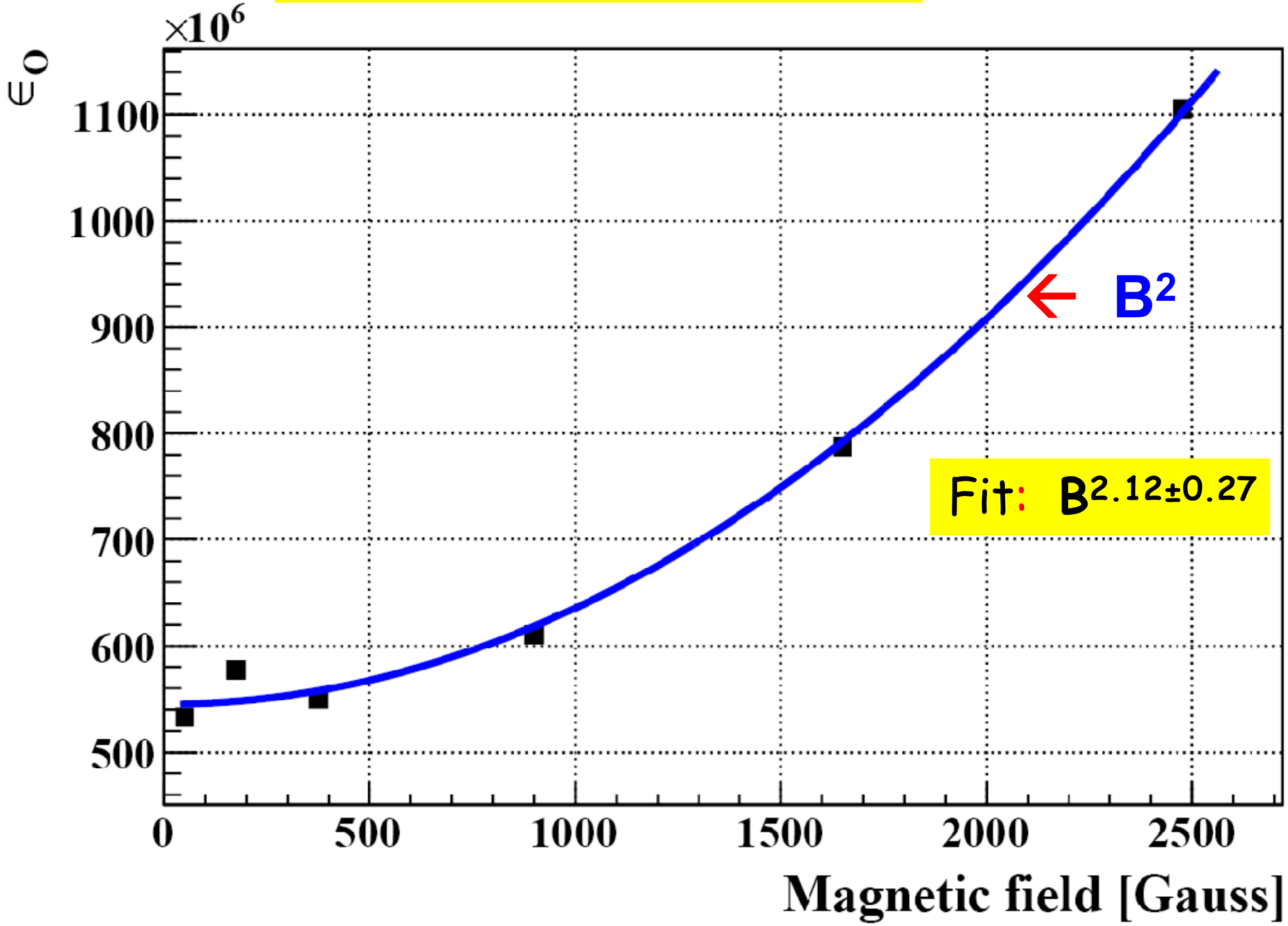
MS Wheatland, ApJ. 679 (June 2008) 1621

The solar "reconnection flare" concept is deceptive …

… many unknowns.

HS Hudson, SPD, May 27th 2008

Oxygen abundance



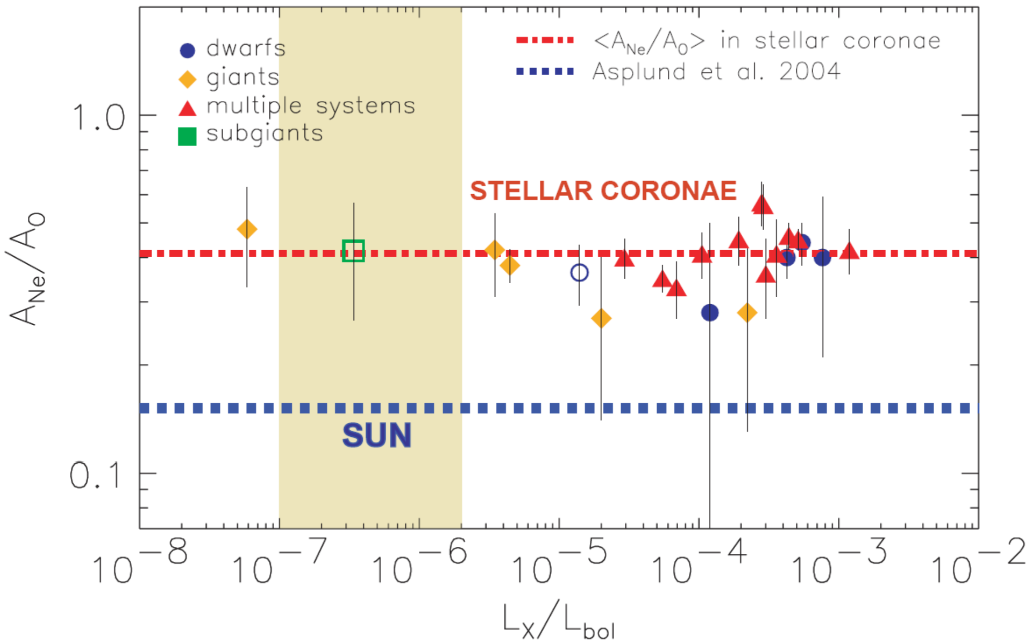
Solar oxygen abundance → **B** **at the base of the photosphere near a pore**. The blue line: B^2-dependence + constant component

→ Private communication, H. Socas-Navarro.

Z., Tsagri, Semertzidis, Papaevangelou, Nordt, Anastassopoulos, astro-ph/200701627

M. Asplund et al., astro-ph/200410214 :

measured photospheric abundances of C, N, O, Ne ~30% below prediction!



Ne/O abundance ratios vs. coronal activity.

Quiet ARs:
Ne / O ~ 0.15
Flares:
enhanced Ne detection (~2x)

+ solar TR dynamical behaviour:

2 ~axion components?!

- Outwards (B)
  ➔ >Ne
- Inwards(self-irradiation)
  ➔ <Ne

Note: $\sigma_{pe(Ne\text{-}to\text{-}O)} > 2\times$ @ Eγ~1 keV

→ models incorrectly predict

- the depth of the convection zone
- the depth profiles of sound speed and density
- the helium abundance

➔ why the Sun is so special?

C.Liefke, JHMM. Schmitt, A&A L. (2006)

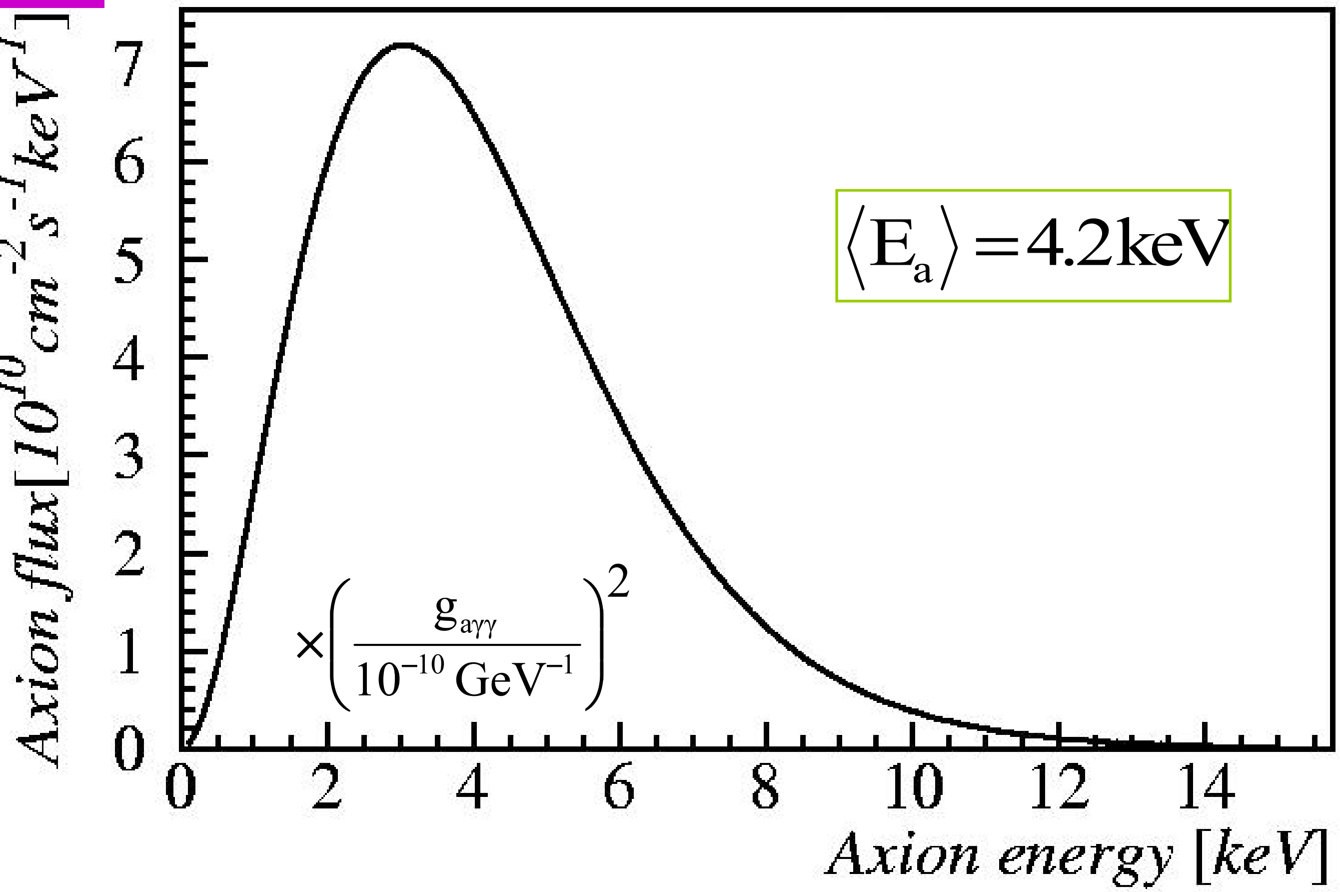
So far:

IF solar X-rays come from axions

➔

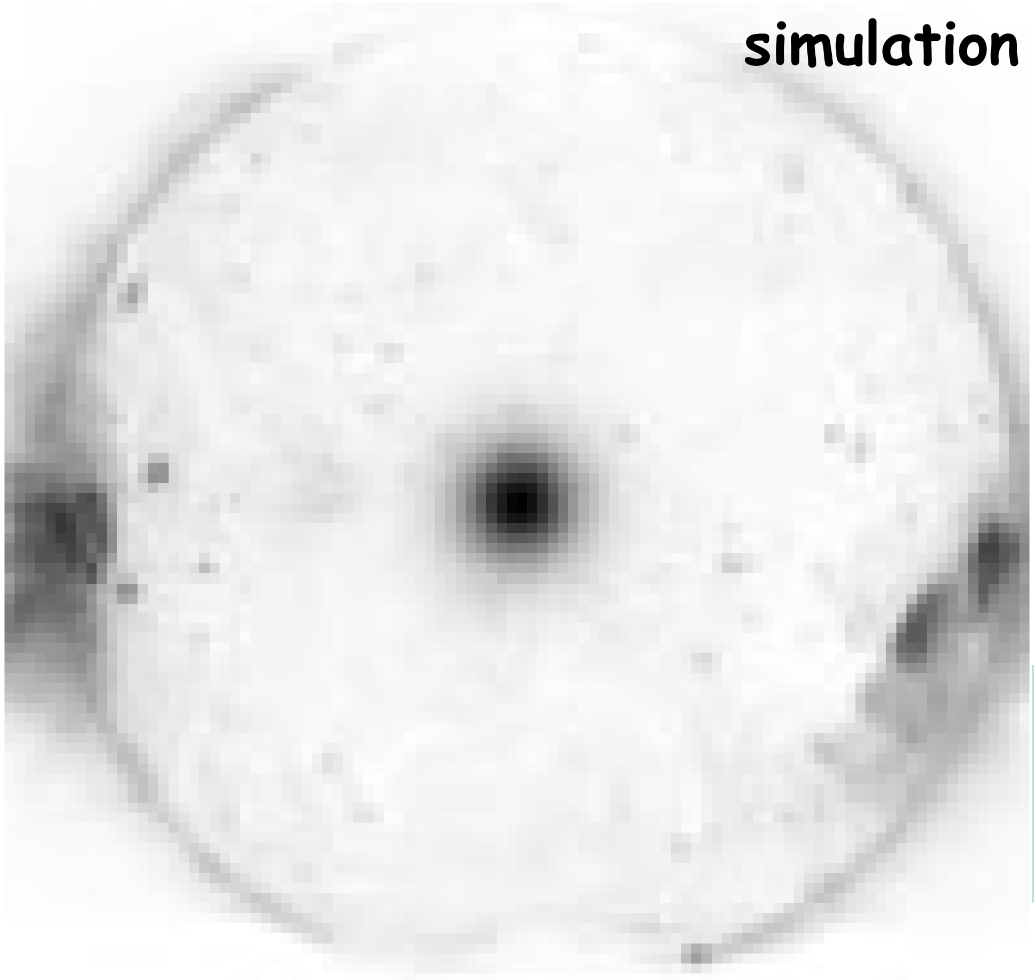
1st

Solar axion / X-ray spectrum



2nd

Search for solar X-rays from axions



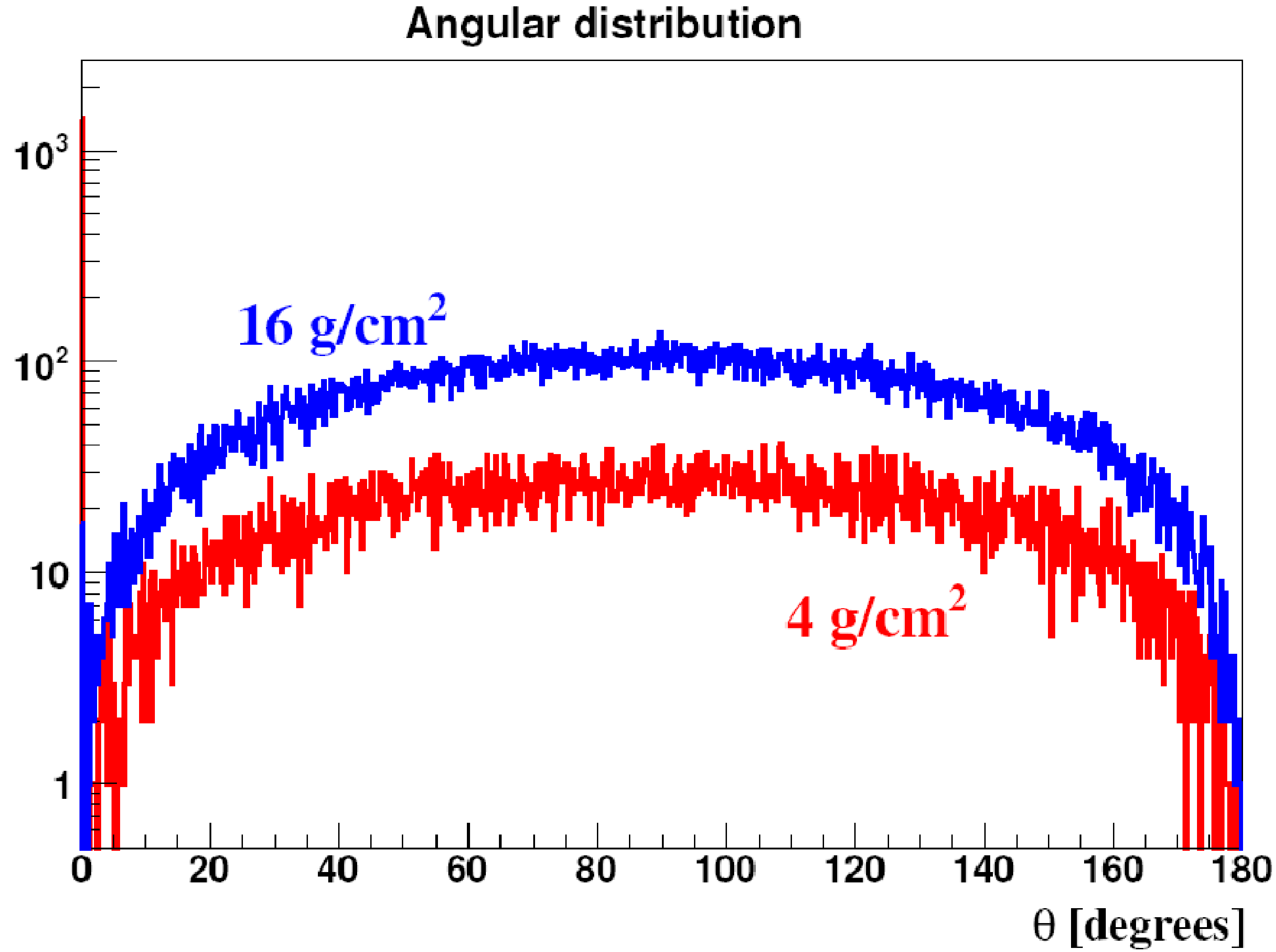
RHESSI
science nugget
H. Hudson,
30.4.**2007**

Soft X-rays from **Hinode/Yohkoh** showing an axion signal. The axions, for
uniform coronal magnetic field,would give an **image of the solar cor**

Hinode/Yohkoh → axion-like, RHESSI → QCD axion

However, ...

... **this work** ➔



Simulation of the angular distribution of the converted solar axions inside the magnetized solar surface for two different column densities of the solar atmosphere above the initial place of birth. The photoelectric effect has been inactivated resembling thus plasma.

Z., Tsagri, Semertzidis, Papaevangelou, astro-ph/0808.1545V4

M. Tsagri, Diploma Thesis, Patras, 2008

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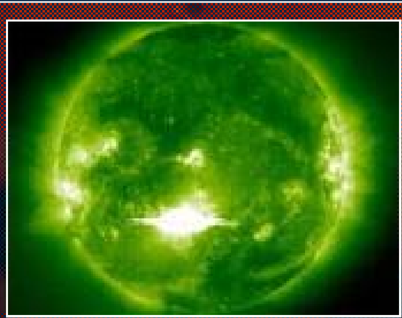

Some solar flares may be caused by dark matter

Theoretical dark matter particles called axions could account for some bright X-ray explosions on the Sun, new calculations suggest

more...

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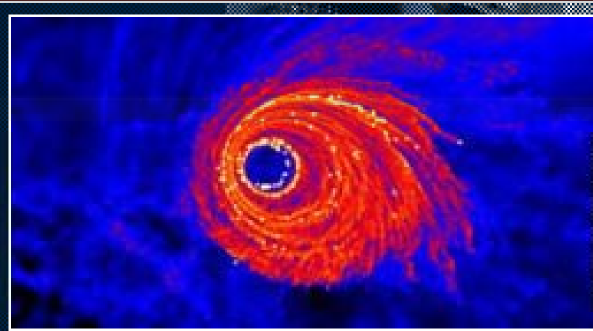

Simulation shows stars form

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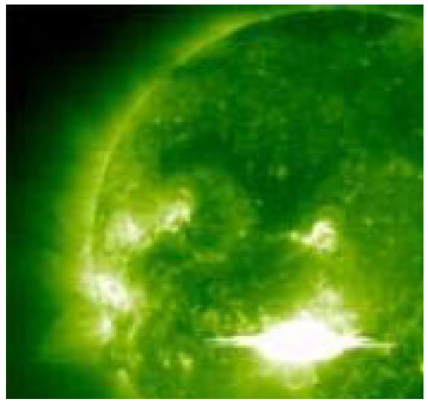
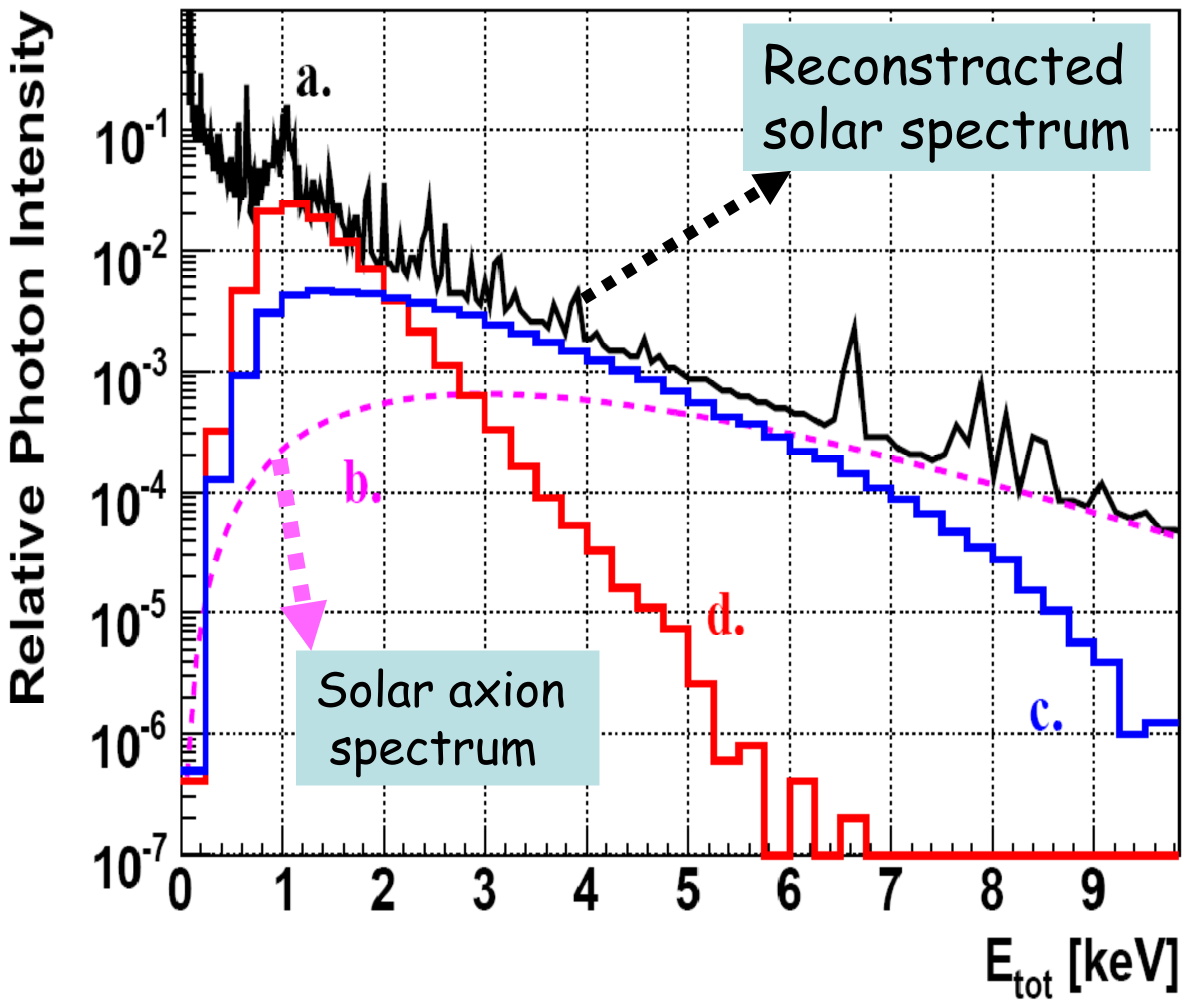
NewScientist.com news service
Anil Ananthaswamy



Some solar flares may be caused by dark matter particles called axions spewing out from the centre of the Sun, new calculations suggest.

Solar flares are sudden changes in the Sun's brightness thought to be caused when twisted magnetic fields on the Sun snap and reconnect explosively.

But they could also be caused by dark matter, the mysterious entity that makes up most of the universe's mass – if it is made up of theoretical particles called axions.



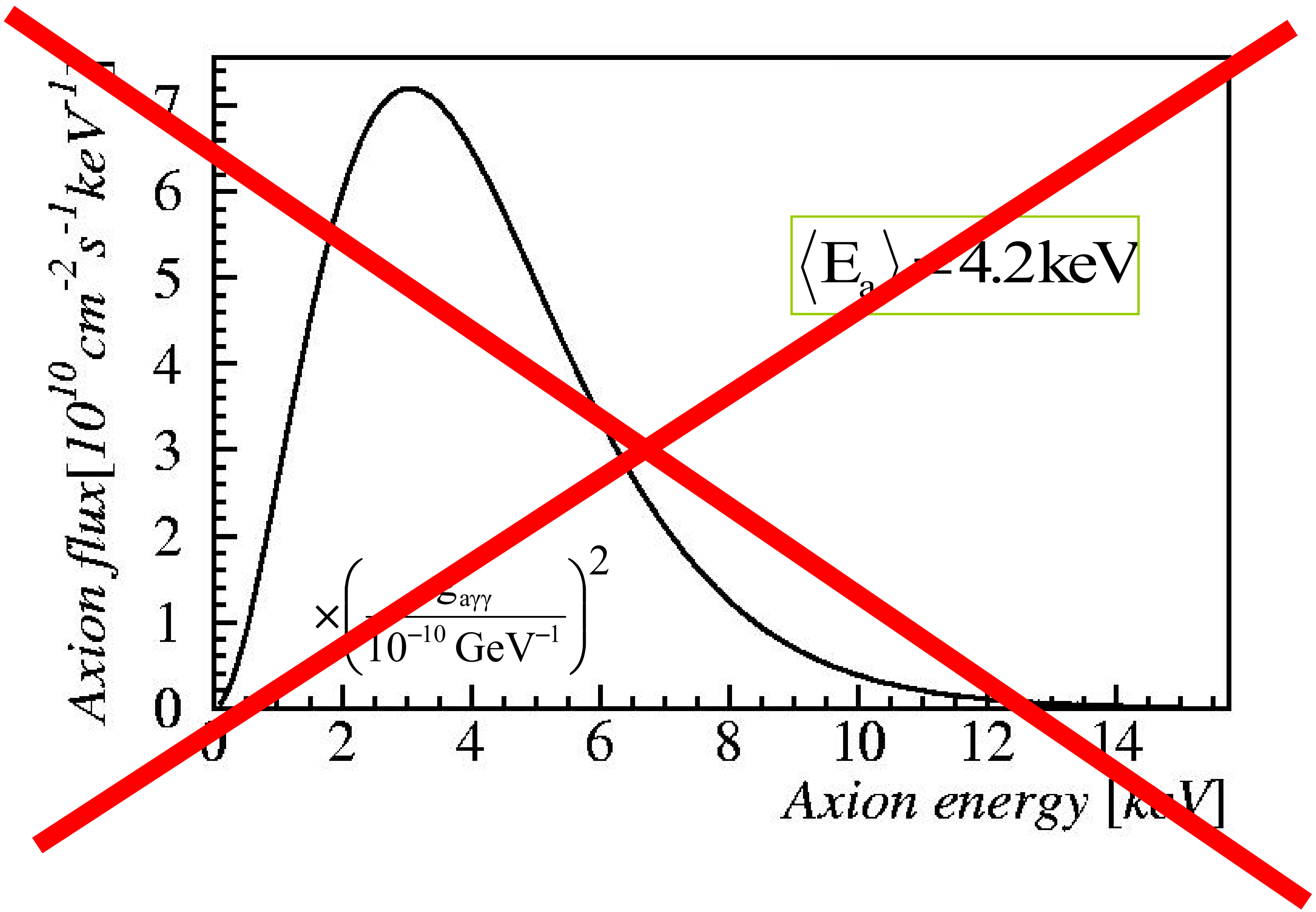
Flaring Sun: interpretation of a reconstructed solar photon spectrum (**a.**) below 10 keV derived from Figure 6 of ref. [25]. The dashed line (**b.**) is the converted solar axion spectrum assuming zero column density. Two degraded spectra due to multiple Compton scattering are also shown for comparison reasons: (**c.**) 16 g/cm2 and (**d.**) 64 g/cm2. All this fits also the observed B2-dependence in [5-7] for X-rays below ~3 keV, where the initial axion spectrum is negligible compared to the observed one.

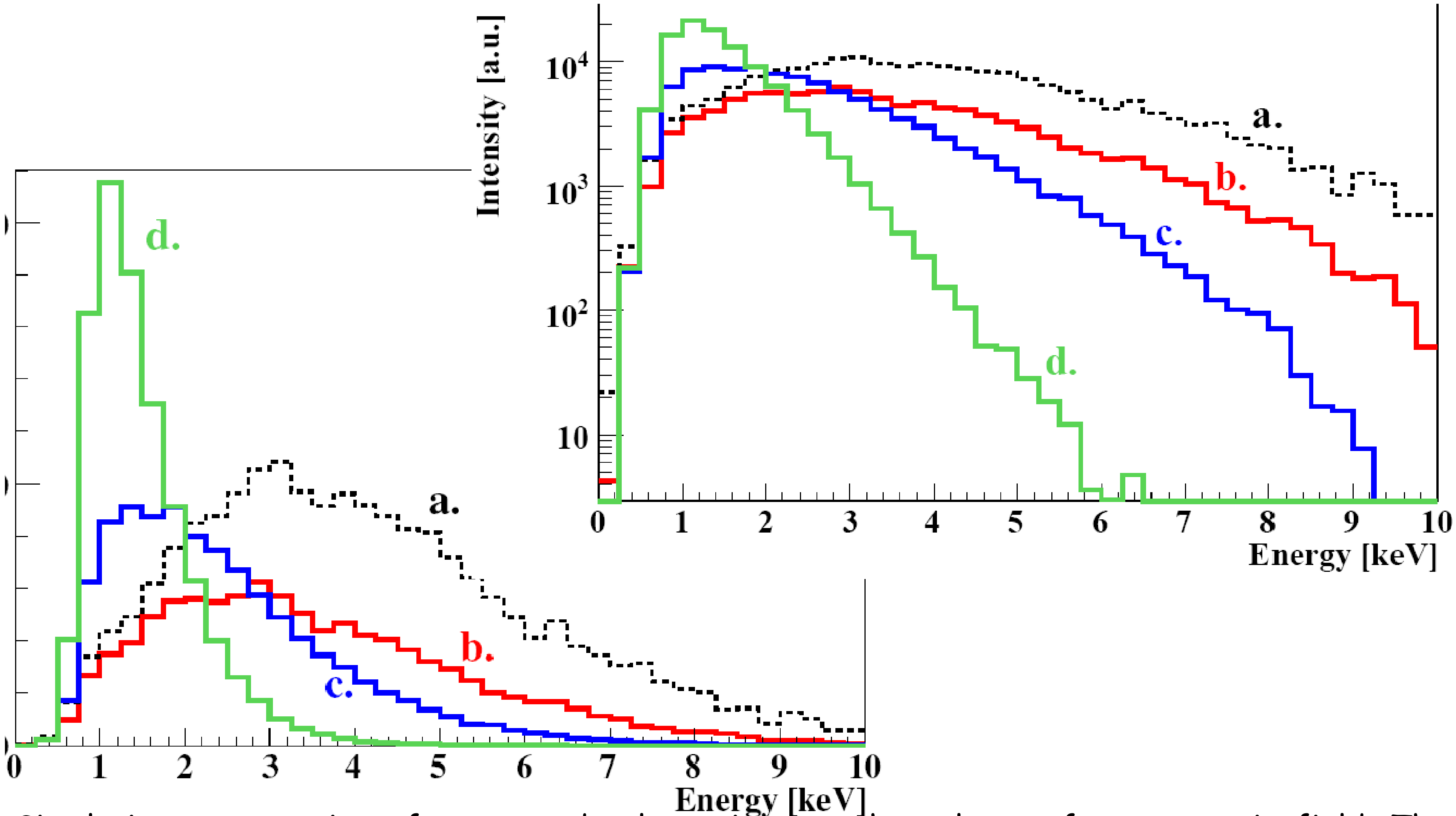
Z., Tsagri, Semertzidis, Papaevangelou, astro-ph/0808.1545V4

Then,

… converted solar axion are expected …

Solar axion / X-ray spectrum



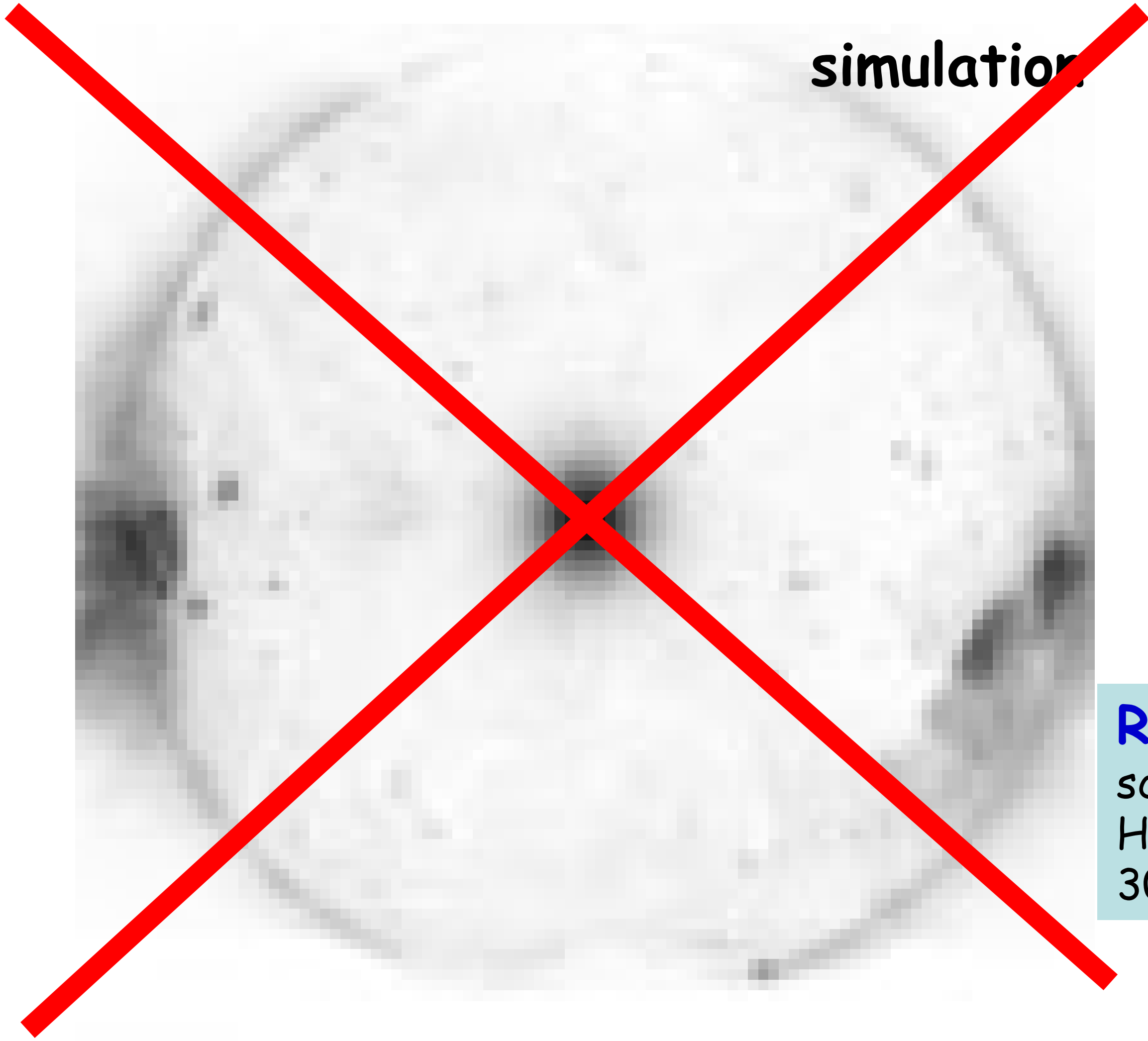


Simulation: propagation of converted solar axions at the solar surface magnetic field. The converted axions can photoionize the atmosphere above the initial place of birth of the X-ray spectrum (**a**) emitted radially from magnetically induced axion "decays" according to the inverse Primakoff – effect ➔ mean photon energy degradation with increasing column density: (**b**) 4 g/cm2, (**c**) 16 g /cm2, (**d**) 49 g/cm2.

Z., Tsagri, Semertzidis, Papaevangelou, astro-ph/0808.1545V4

M. Tsagri, Diploma Thesis, Patras, **2008**

Search for solar X-rays from axions



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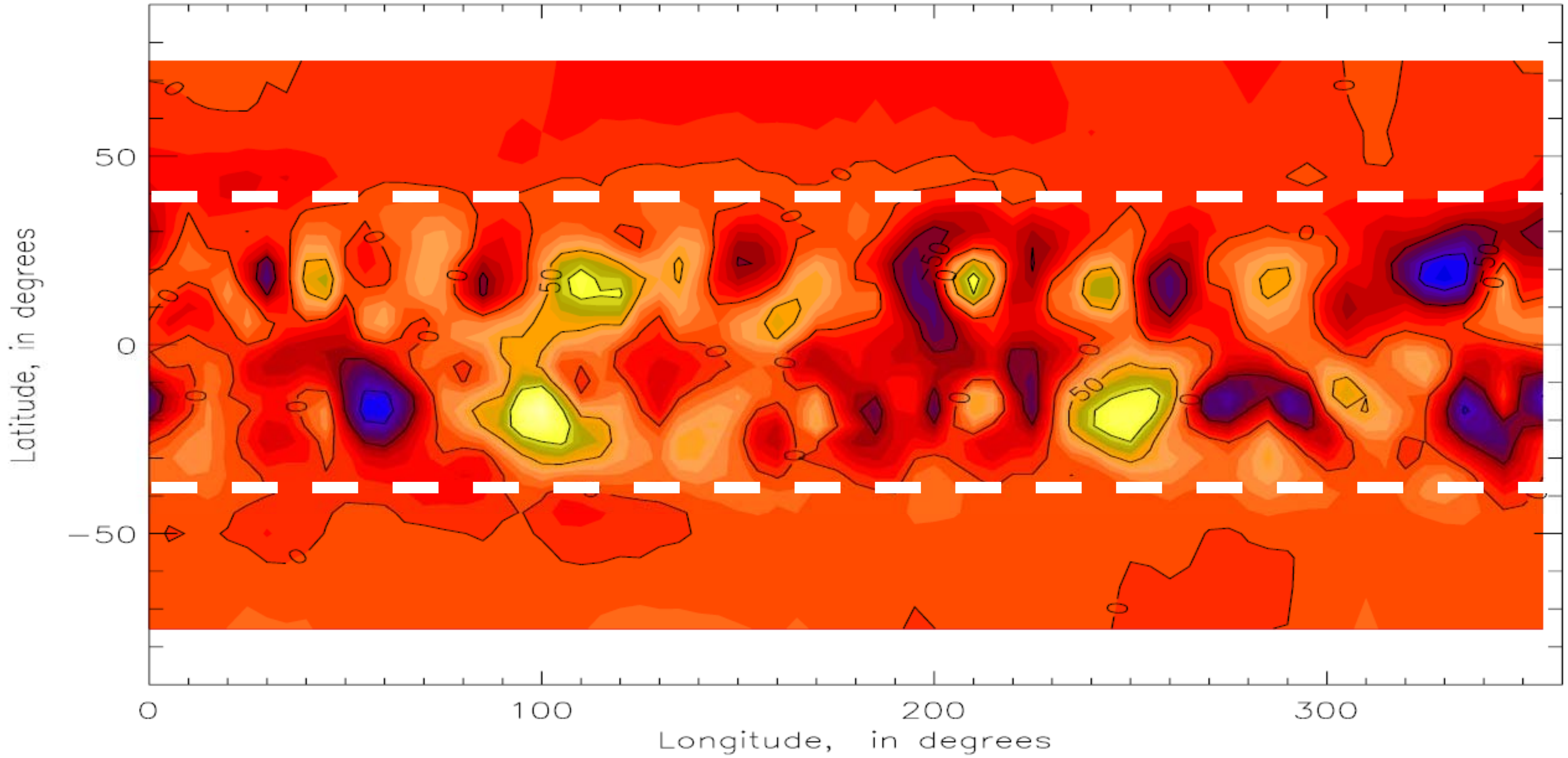


Distribution in longitude and in latitude of the mean over 260 Carrington rotations magnetic field on the solar surface.

E. Gavryuseva, Solar Activity and its Magnetic Origin, Proc. IAU Symposium No. 233, **2006**, V. Bothmer & A. A. Hady, eds., p.61

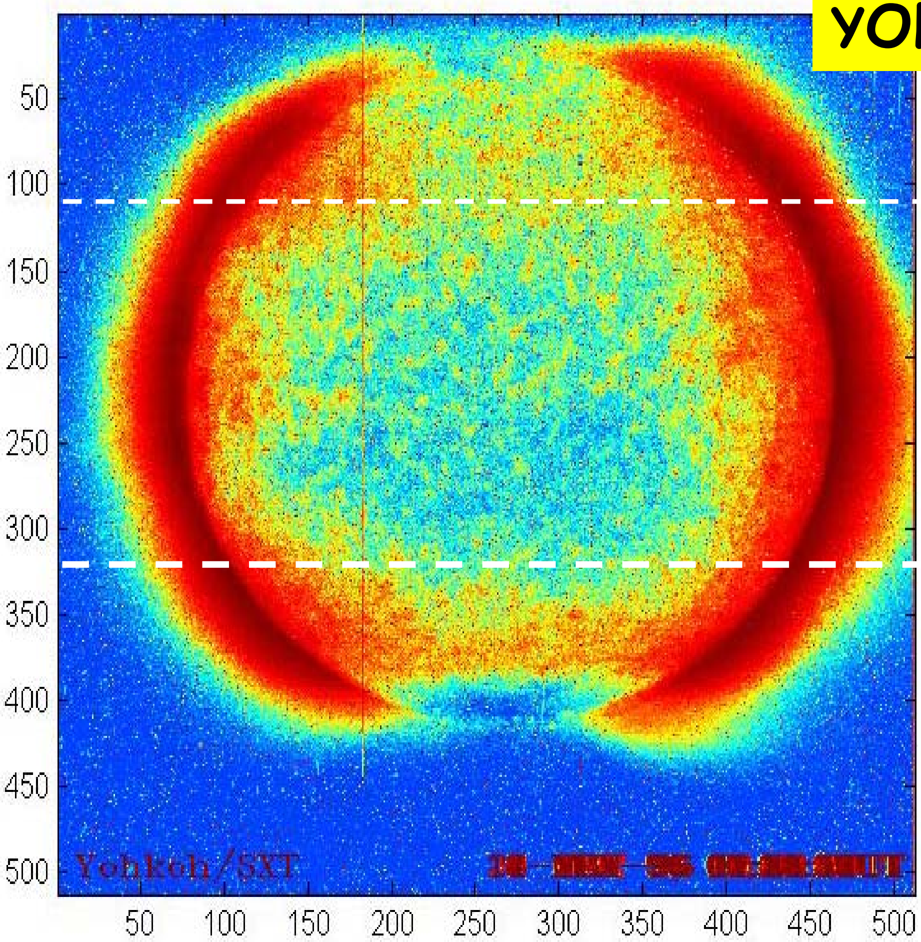
Flux ~95% for the range ±40°

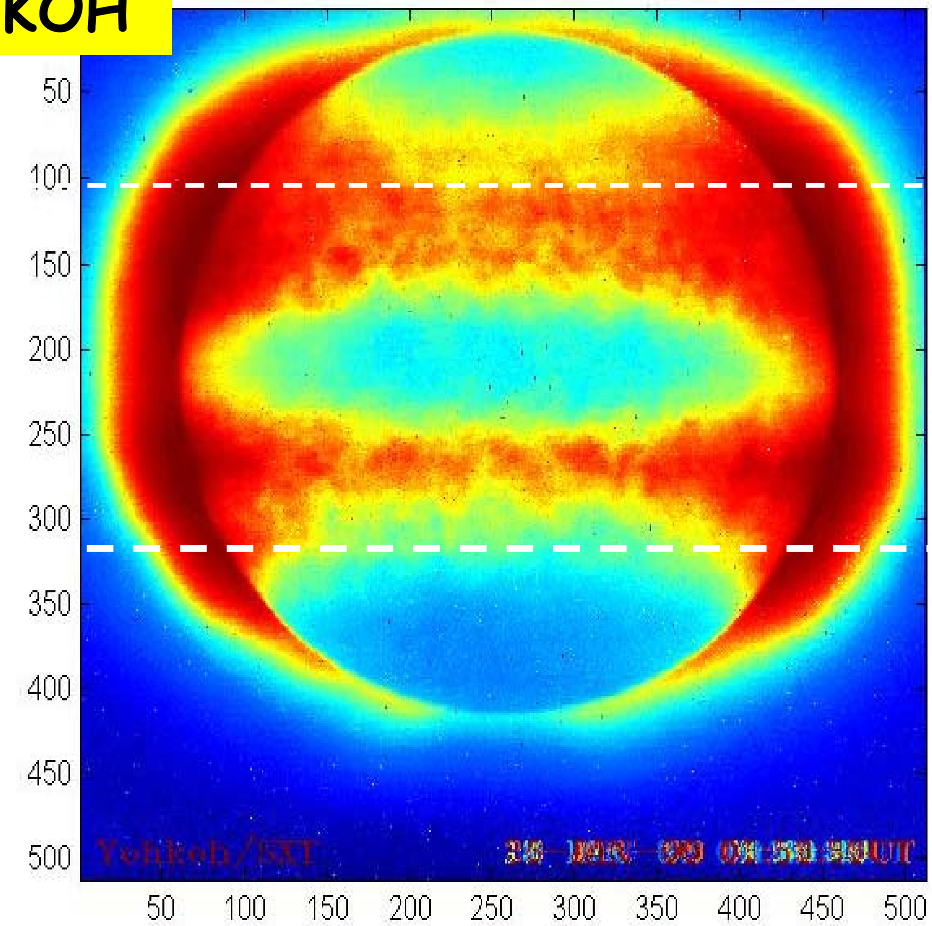
R.Howard, Solar Phys. 38 (1974) 59

Solar Minimum

Solar Maximum

YOHKOH





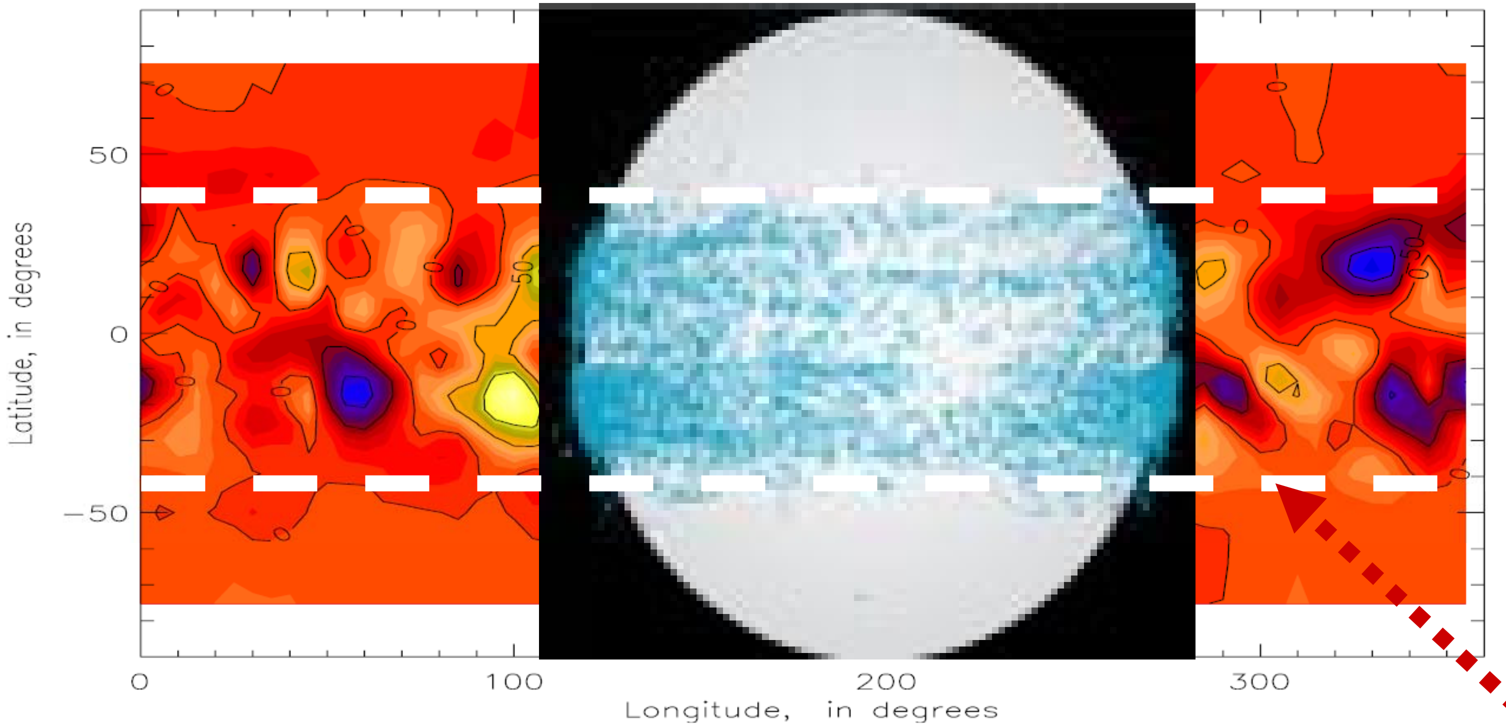
V. Anastassopoulos + M. Tsagri

< 2-4 keV ➔ low energy tail of solar axion spectrum!

Other published work, which has NOT

been related to axions so far!

➔

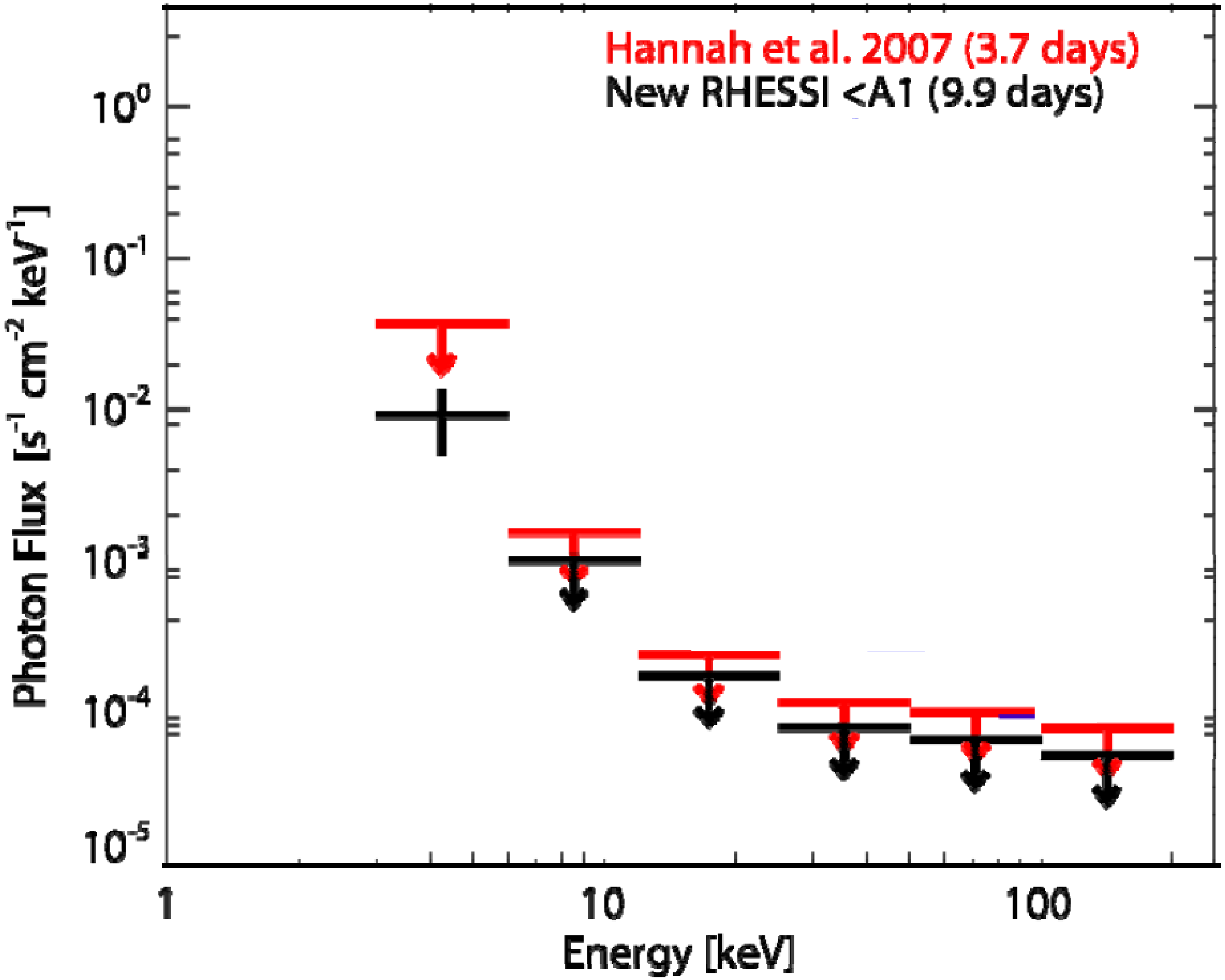


Longitude + latitude
positions of ~24000 μflares

Magnetic flux ~95% in ±40°
R. Howard, Sol Phys 38(1974)59

20/5/2007, RHESSI nugget, I.G. Hannah + Christe

http://sprg.ssl.berkeley.edu/~tohban/nuggets/?page=article&article_id=52



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This 3-6 keV QS excess can be from

1) B_{solar}-converted ~axions

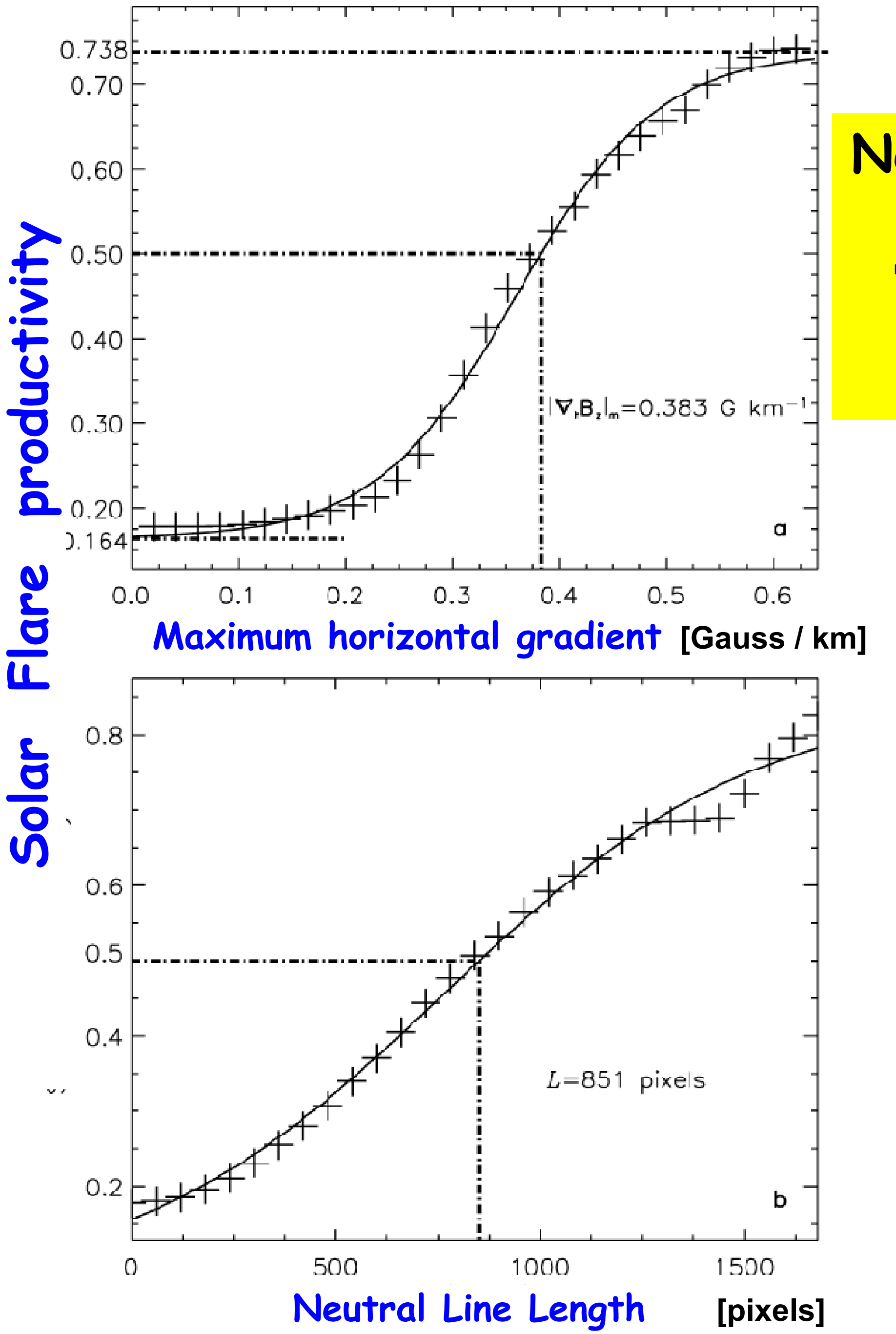
and/or

2) Decaying massive ~axions

Di Lella, Z. (2002)

Note:
Hannah *et al* (sept. 2008) argue as being one or two thermal high energy tails,

➔ its origin remains elusive!



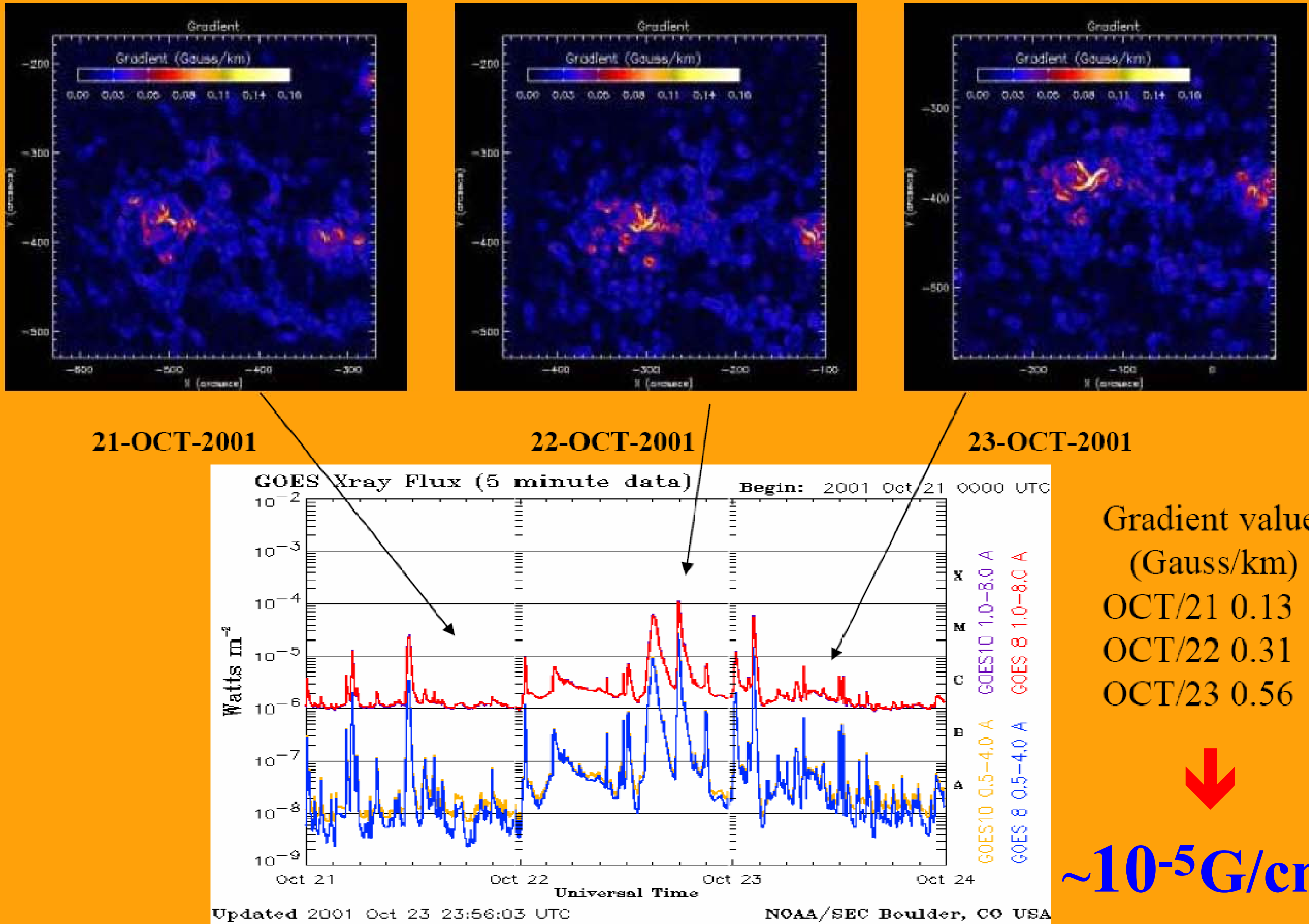
Neutral line in ARs: opposite B-polarities

➔ **High magnetic field gradient**

➔ **solar activity & flares + CME**

Y. Cui et al., Sol. Phys. 237 (**2006**) 45 &
242 (**2007**) 1

Evolution of AR 9672



Gradient values (Gauss/km)

OCT/21 0.13

OCT/22 0.31

OCT/23 0.56

~10^{-5}G/cm

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Physics Letters B 662 (2008) 445–448

www.elsevier.com/locate/physletb

Photon and axion splitting in an inhomogeneous magnetic field

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Available online 1 April 2008

Editor: T. Yanagida

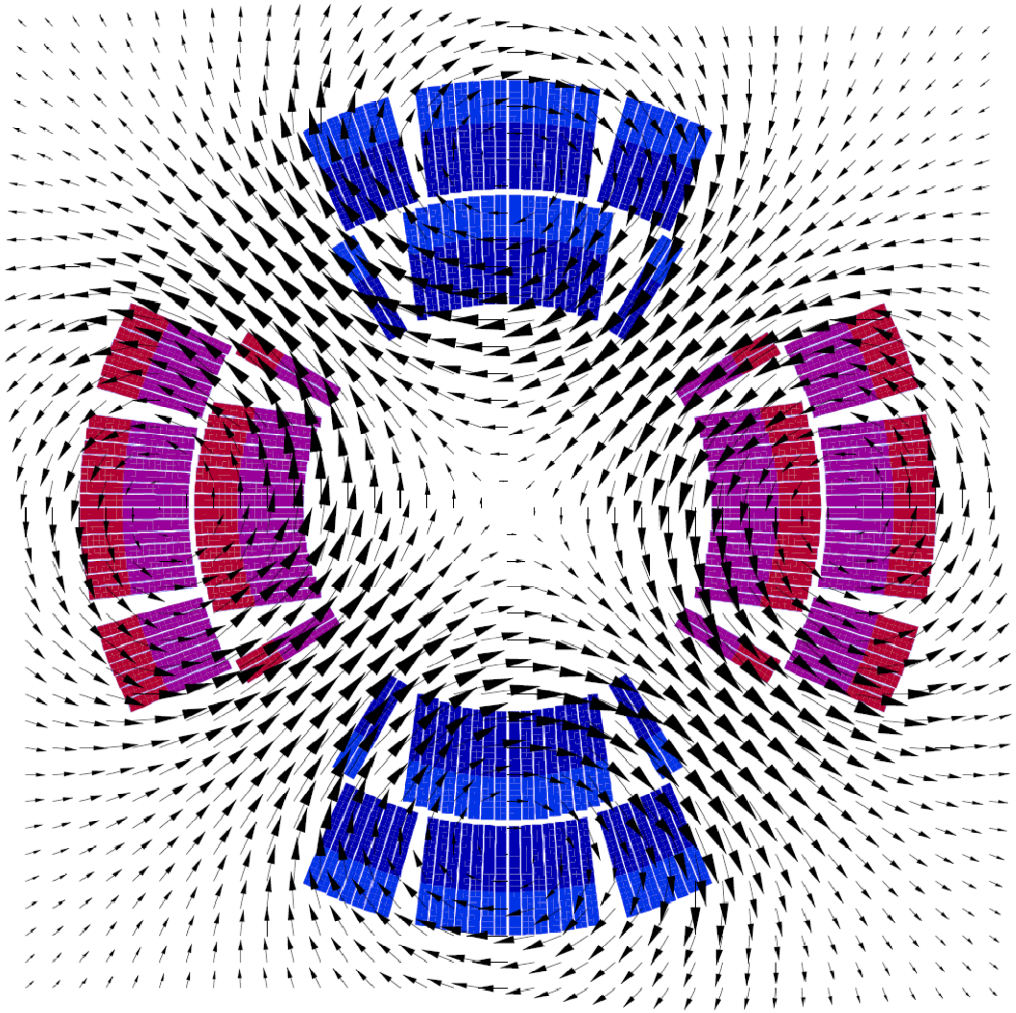
New axion↔photon interaction?

➔ **Novel experimental approaches** ←

Feedback?!

➔ CAST, OSQAR,…?!

Quadrupole magnet



Stephan Russenschuck

SUN	aQuadrupoles
~10^{-8} Tesla / m	>100 Tesla / m
$10^{7\pm1}$ m	~10 m

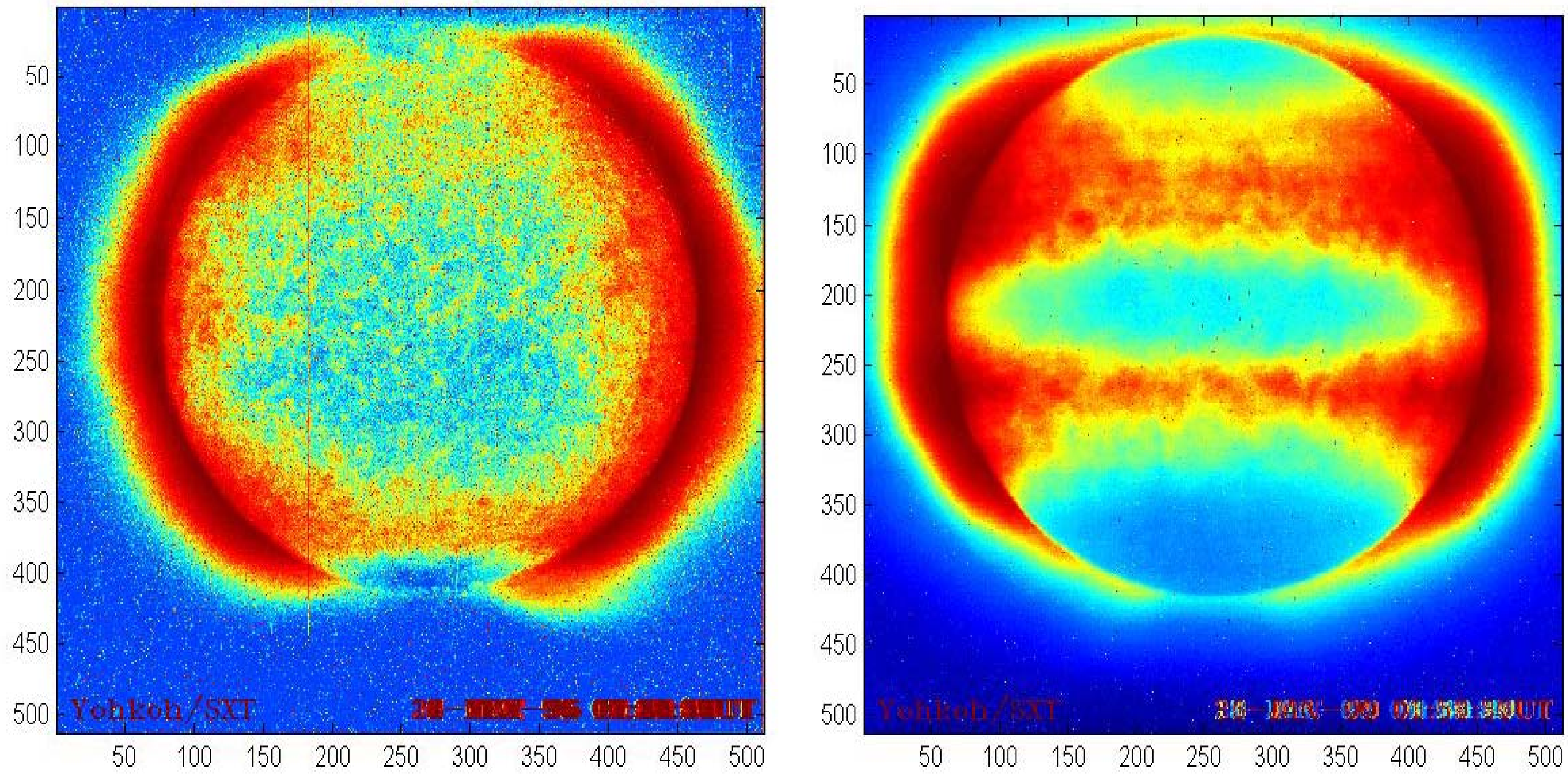
Length x gradient

< 1	>1000

X-rays reveal Van Gogh's hidden face

http://www.guardian.co.uk/artanddesign/2008/jul/31/2

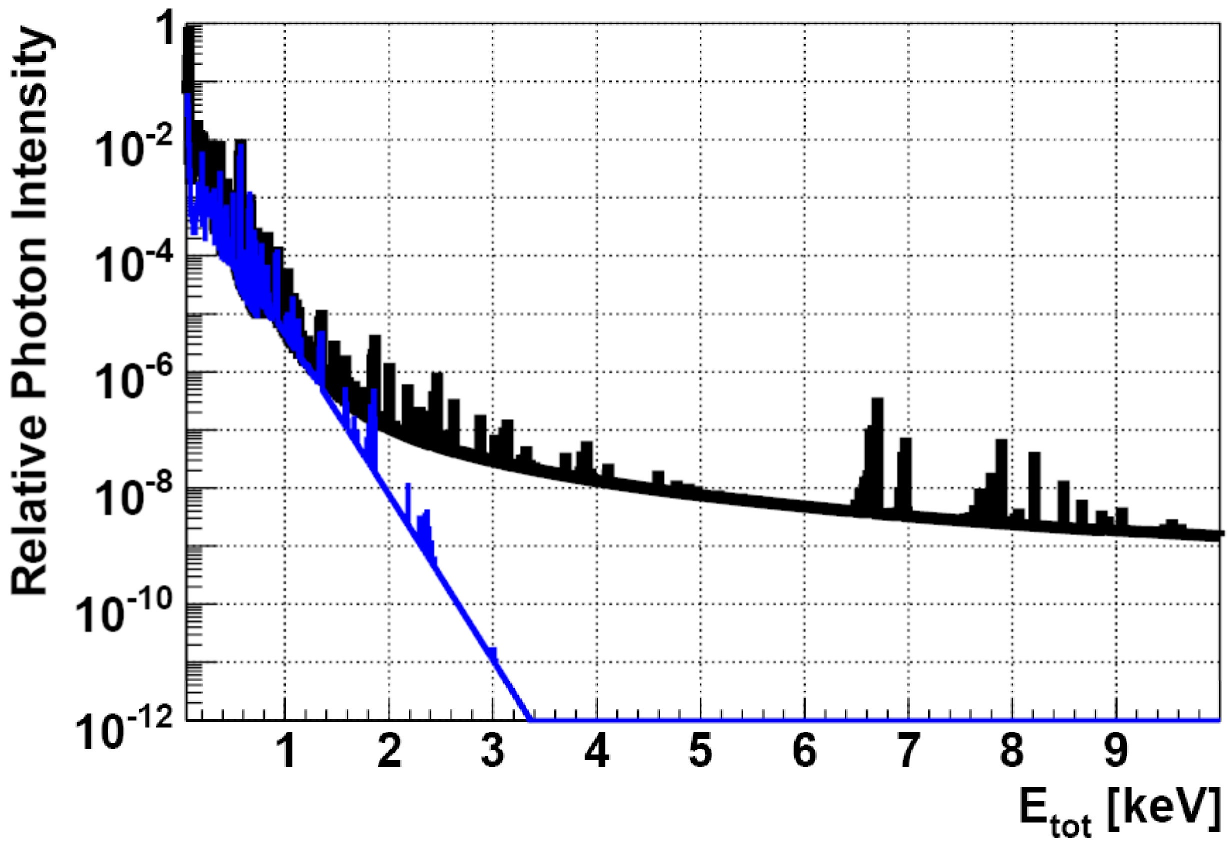
X-rays reveal Sun's hidden face



Additional slides

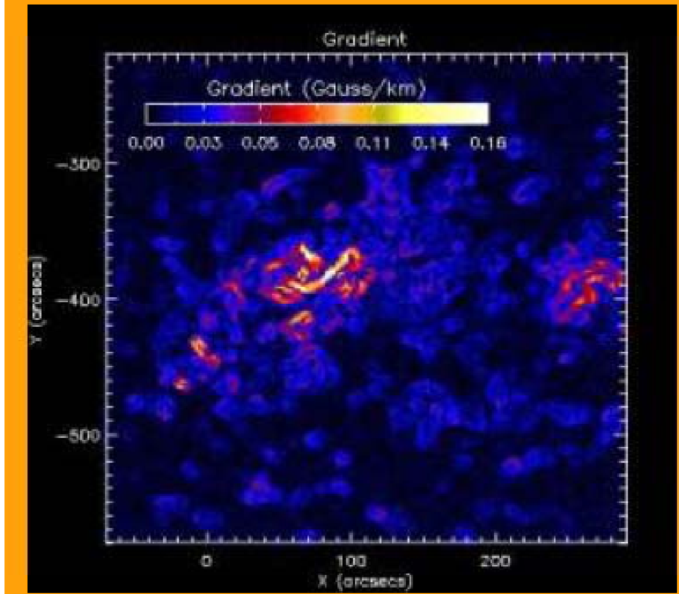
… quiet Sun ➔

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

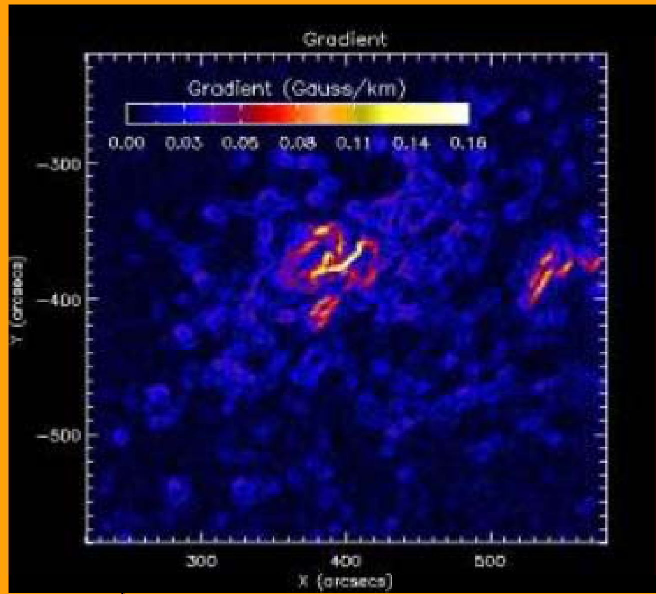


[X] Peres, Orlando, Reale, Rosner, Hudson, ApJ. 528 (2000) 537

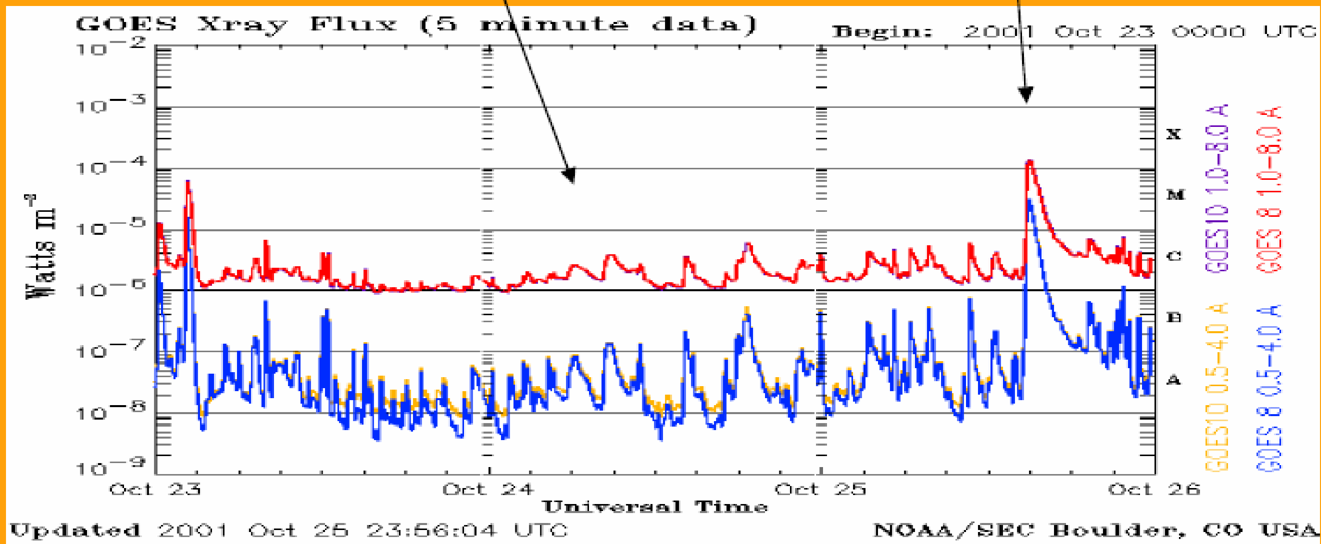
Evolution of AR 9672 cont…



24-OCT-2001



25-OCT-2001



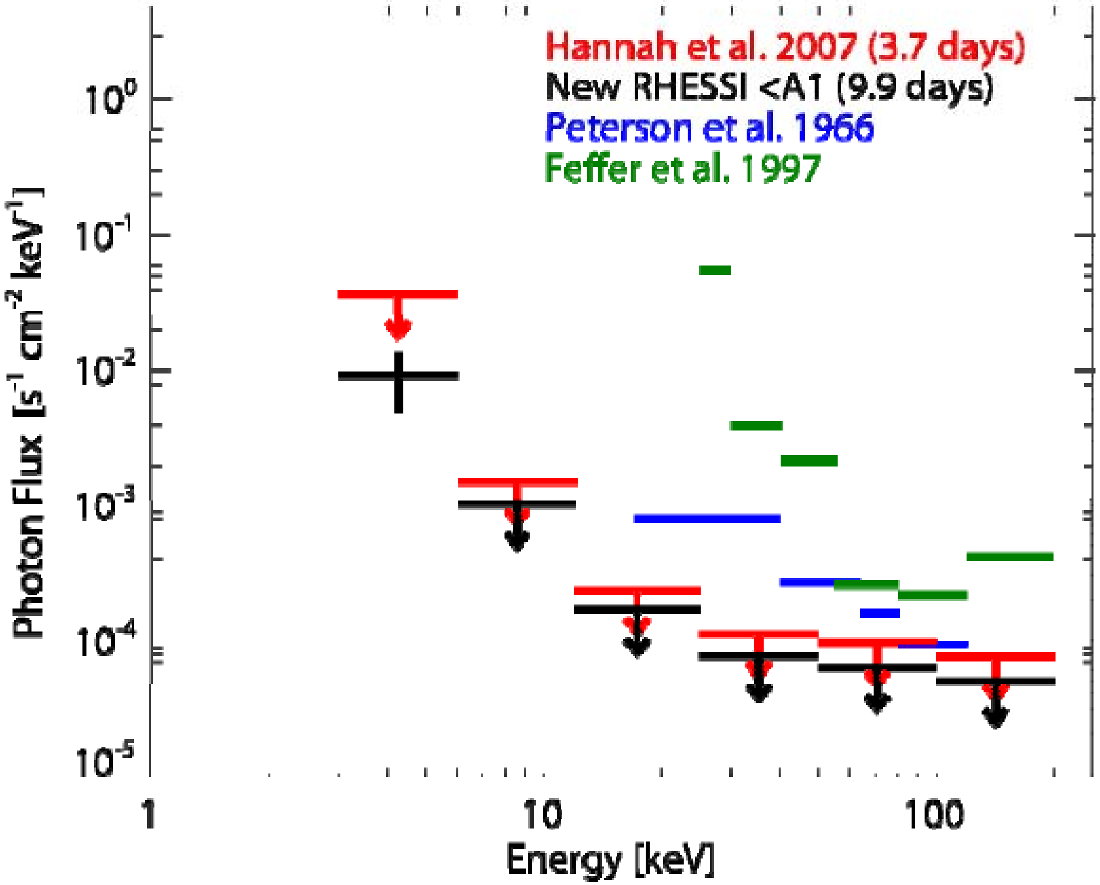
Gradient values
(Gauss/km)
OCT/24 0.18
OCT/25 0.29

➔ relationship between B-gradients + Solar Flare Activity

RHESSI Quiet Sun Spectrum

- Previous work and first analysis of RHESSI QS data between October 2005 and October 2006, when GOES <A1.

- New RHESSI QS analysis covers all useful offpointing data from October 2005 to August 2008, with GOES<A1.
- 3-6 keV now >3σ, not upper limits.
- What thermal or non-thermal emission is consistent with these limits?



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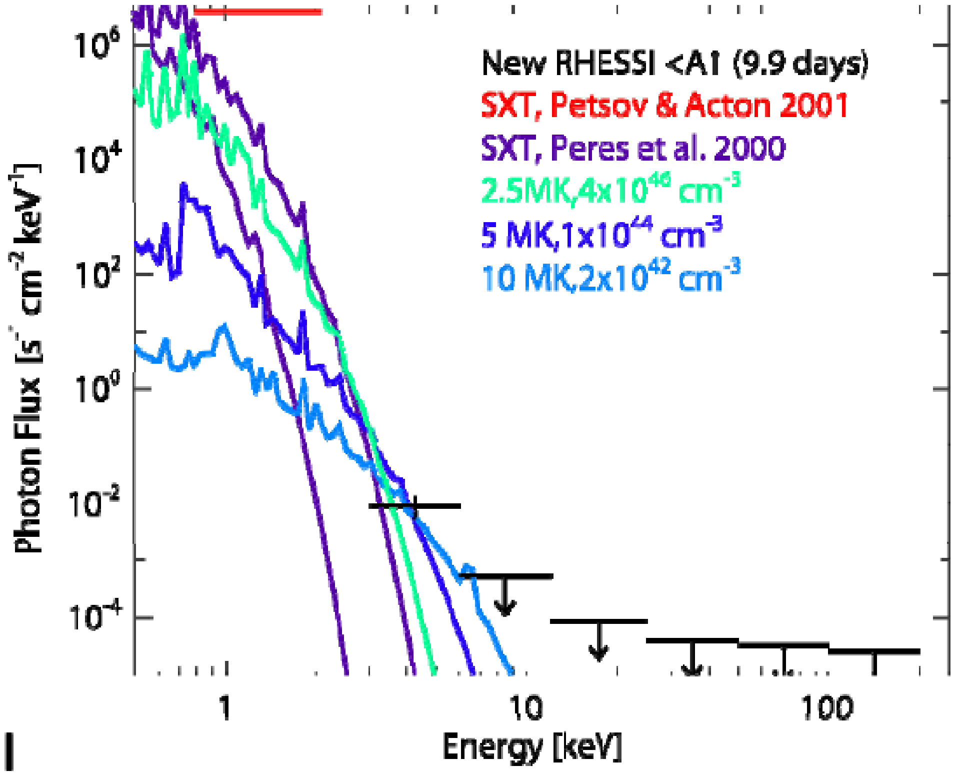
Quiet Sun Thermal Emission ?

- Pevtsov & Action 2001 Yohkoh/SXT solar min AlMg $5x10^6$ ph/cm^2/s
- Peres et al. 2000 thermal fit to SXT solar min 0.97MK $1.3x10^{49}$ cm^{-3} and 1.78MK, $2.8x10^{48}$ cm^{-3}
- Find considerably lower EM than DEM(T) of Peres et al. 2000
- Other isothermal fits with higher T, lower EM fit RHESSI 3-6 keV but do not match SXT values.



Not isothermal? Two Maxwellians?

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