Signatures for Low Energy Solar ~axions

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Collaboration work with:
E. Arik, M. Davenport, E. Gazis, B. Lakic, A. Nordt, Th. Papaevangelou, Y. Semertzidis, S. Solanki, M. Tsagri, Y. Unruh

➔ **EU-ILIAS AXIONS wg**
➔ **CERN UPatras' libraries**
➔ **Open Access!**

3rd Joint ILIAS–CERN–DESY Axion–WIMPs Training Workshop

University of Patras / Greece
19-25 June 2007

CAST motivated work

→ CAST feedback?

SUN:

➔ **5 Mtons / s of energy is released**

~100 ktons ~axions / s …

… overlooked?

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

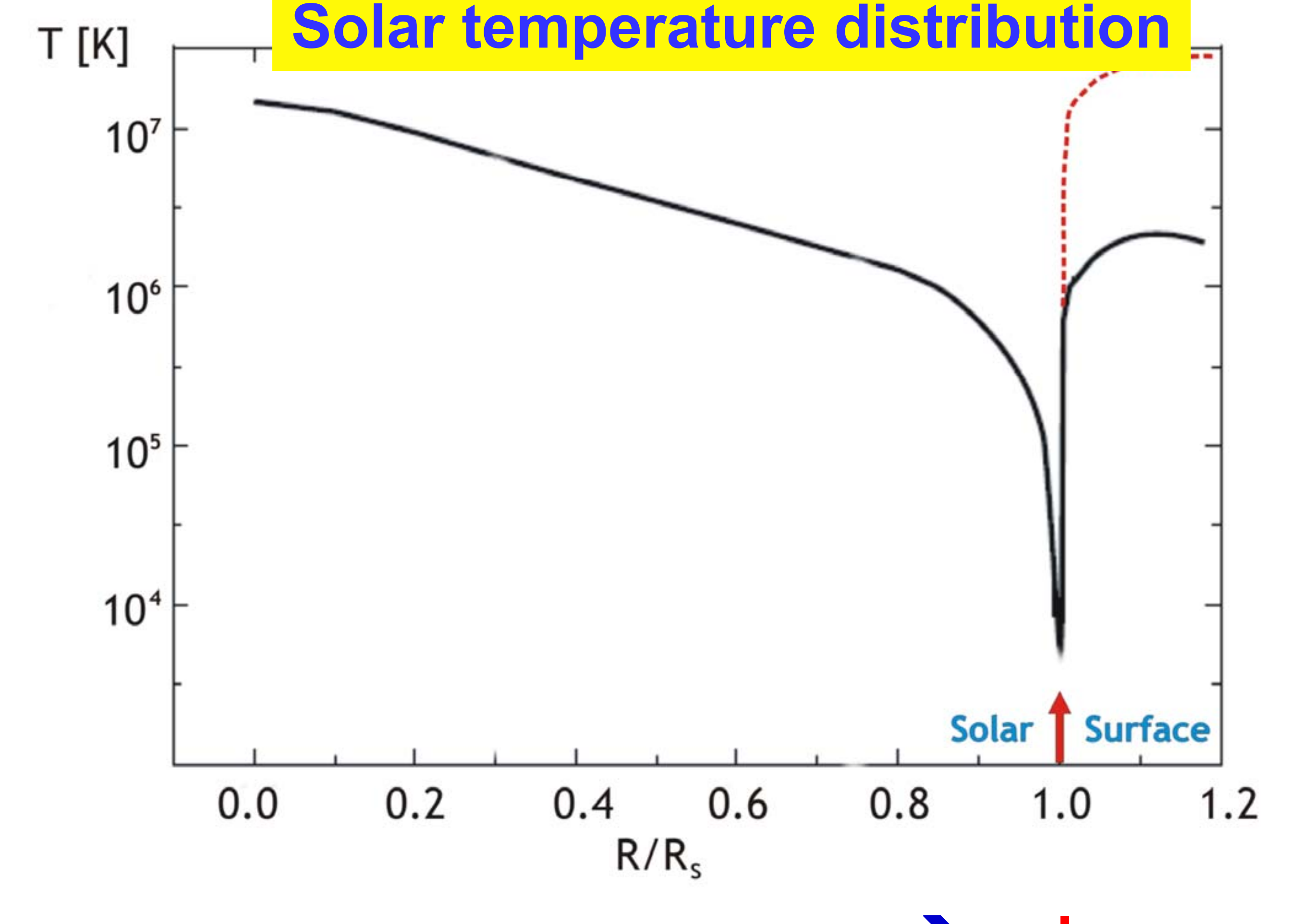
Open solar questions

- 11 years cycle!?
- Solar corona heating
- Flares → instantaneous particle acceleration
- Dynamo(s) → $B_\odot$
- Sunspots heating
- Ne composition ← "Solar Model problem"!

→ » *smoking-gun signatures for new physics?*

e.g.: *~axions* ?

Solar temperature distribution



➔ **solar corona problem**

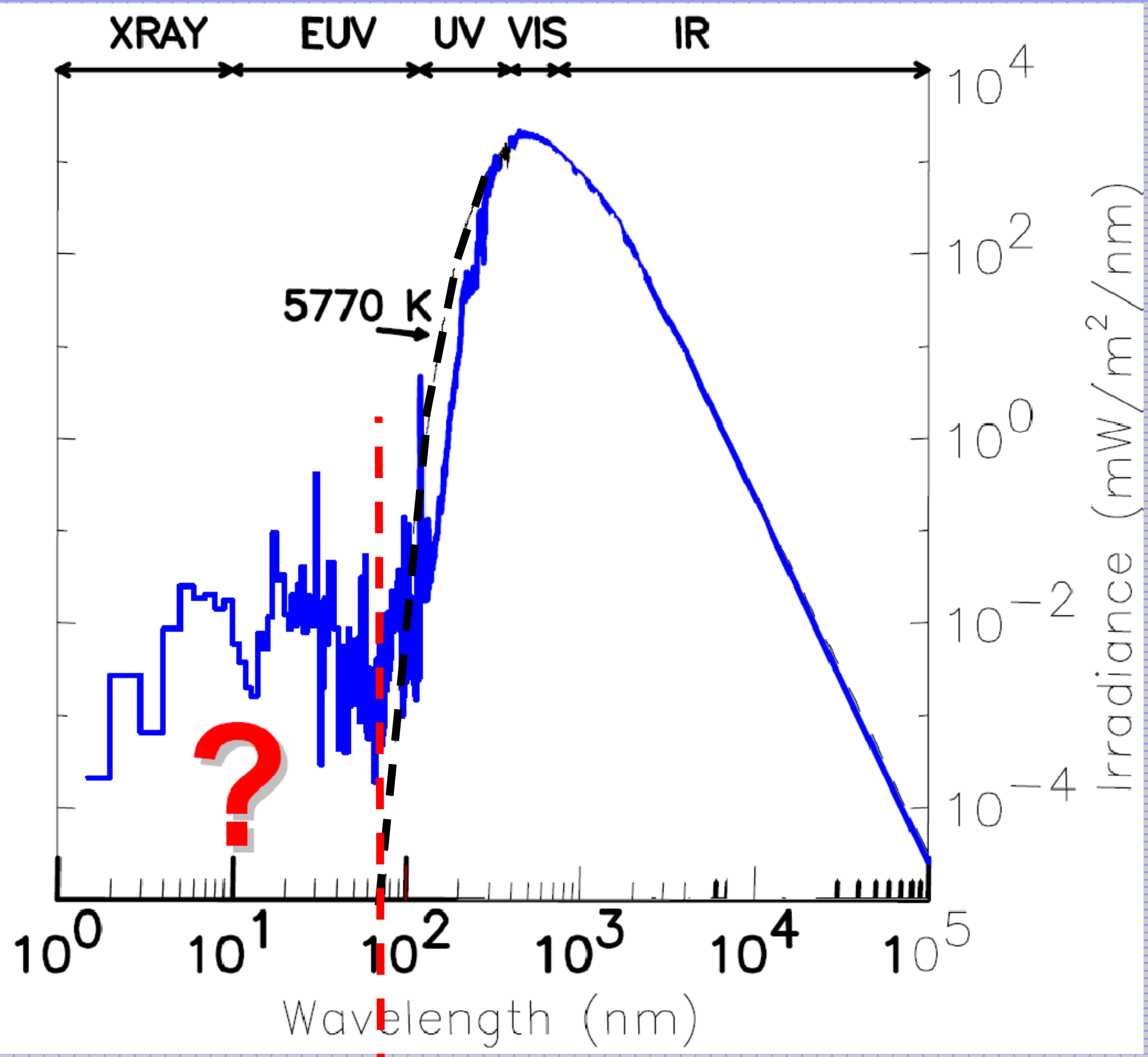
Grotrian (**1939**)

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 (**2006**) 151

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

Solar spectrum



← >20 eV

… 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*

"For reasons no one understands, the solar corona is much hotter than the sun's surface, another mystery"
Hinode may help solve.

http://science.nasa.gov/headlines/y2006/02nov_firstlight.htm?list68112

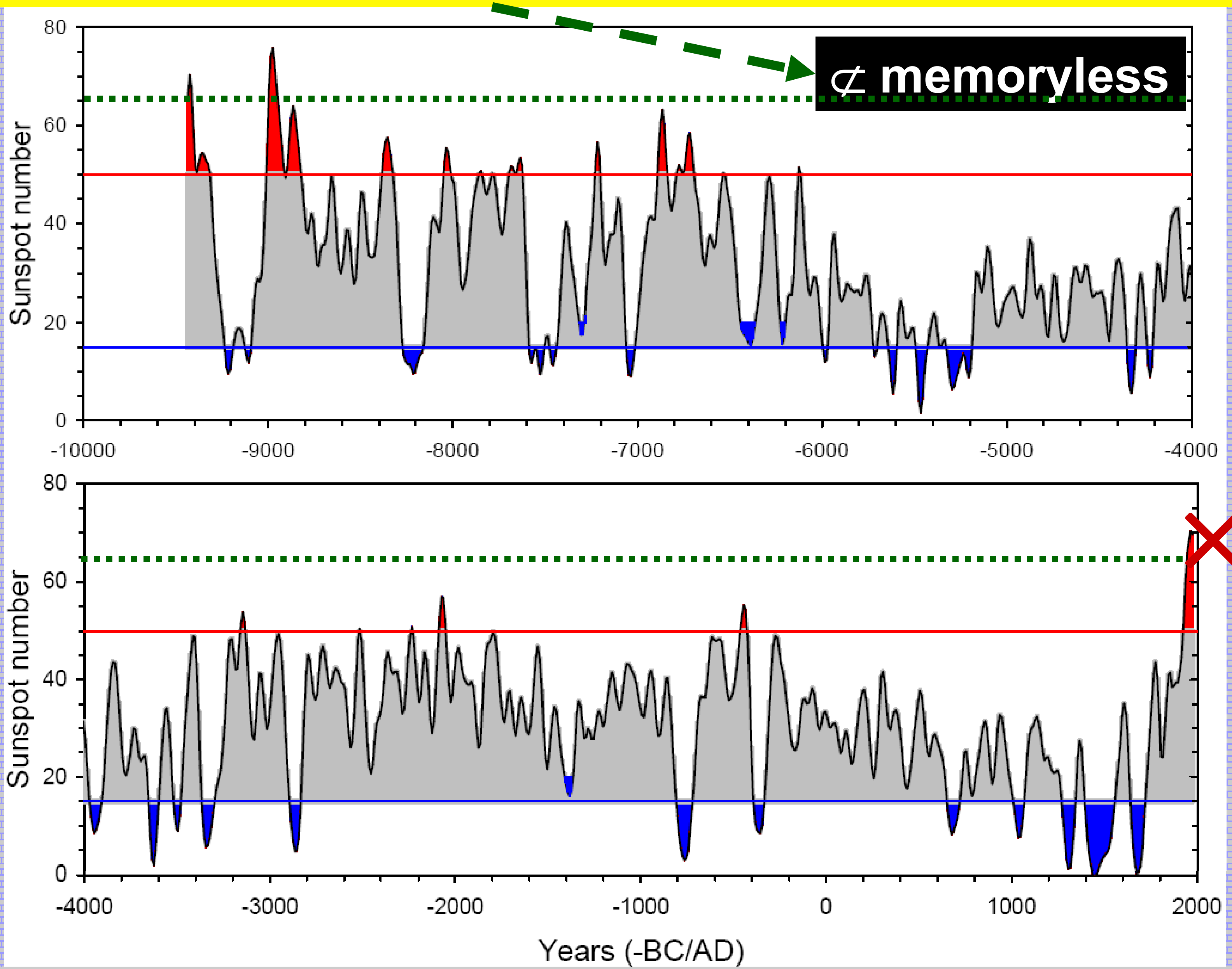
The Coronal Heating Paradox

… over 60 years →

100s of theoretical models have been proposed *without an obvious solution in sight.*

M.J. Aschwanden, A. Winebarger, D. Tsiklauri, H. Peter,
ApJ. 659 (20.4.2007) 1673

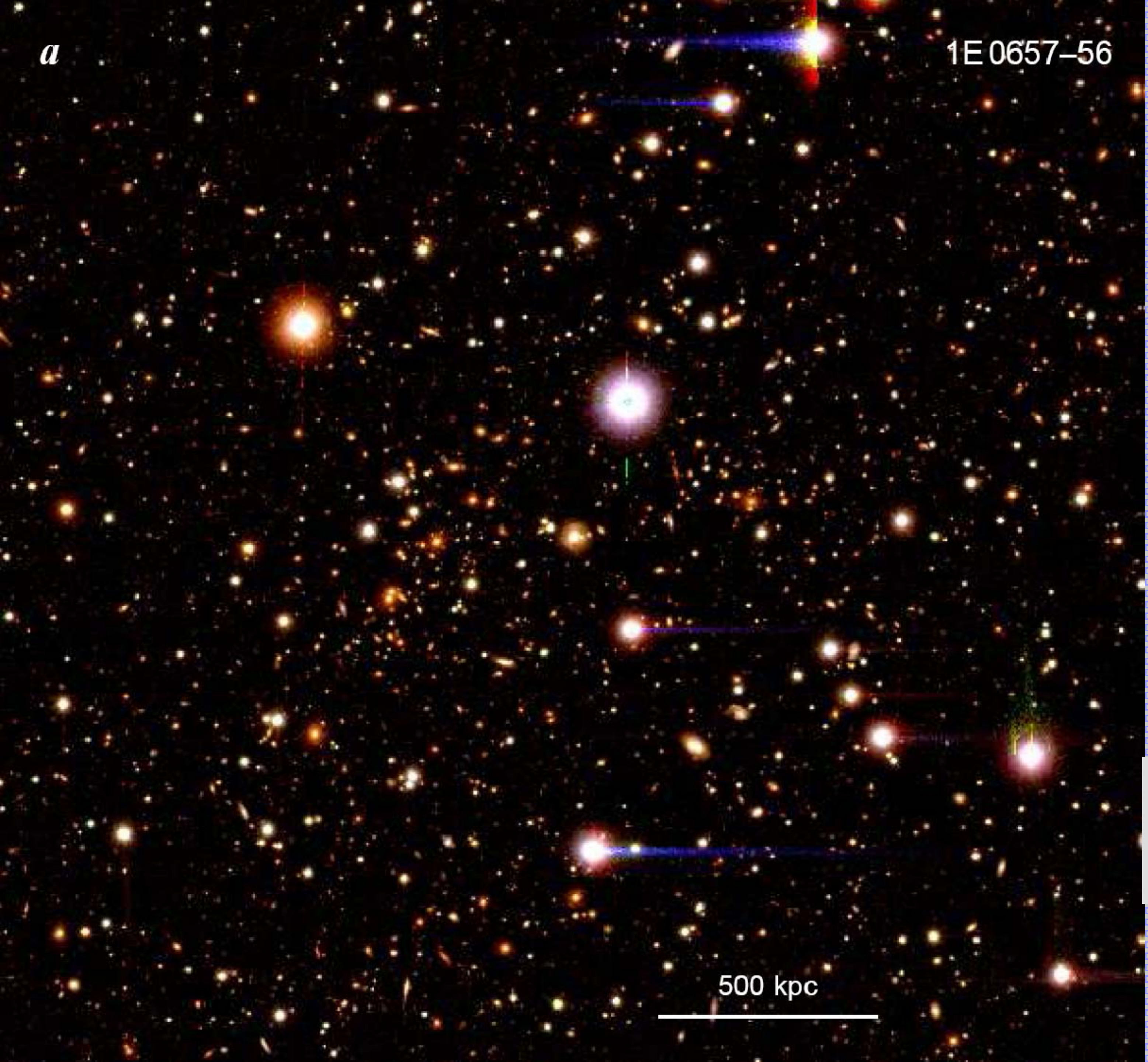
Grand minima / maxima of solar activity



I.G. Usoskin, S.K. Solanki, G.A. Kovaltsov, Astron. & Astrophys. (2007) *in press.*

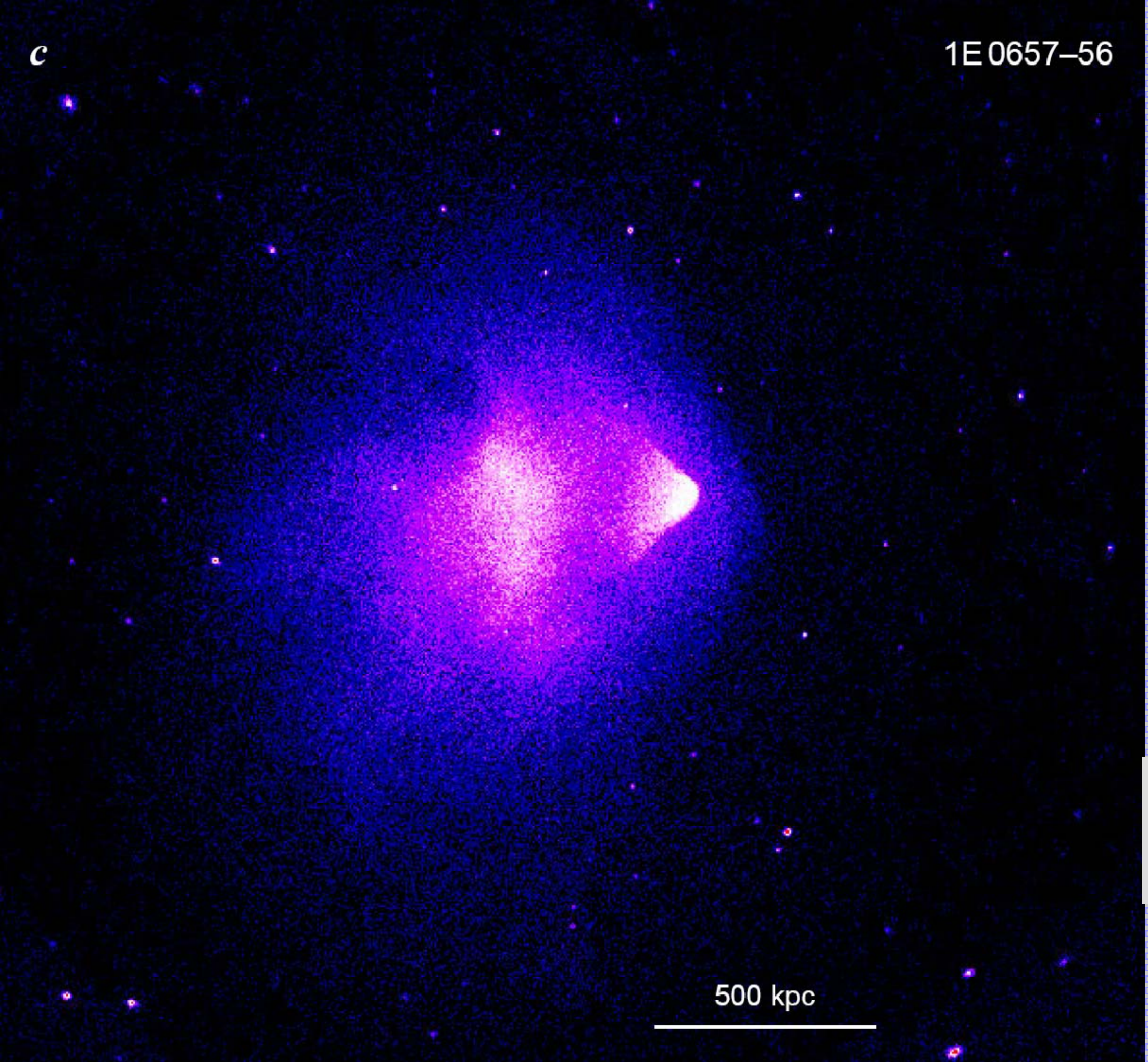
Sun = source + target of

→ neutrinos
→ axions
→ MCP's
→ ...?



Optical 10’x10’

M.Markevitch,
A.Vikhlinin,
astro-ph/0701821



X-rays 10’x10’

M.Markevitch,
A.Vikhlinin,
astro-ph/0701821

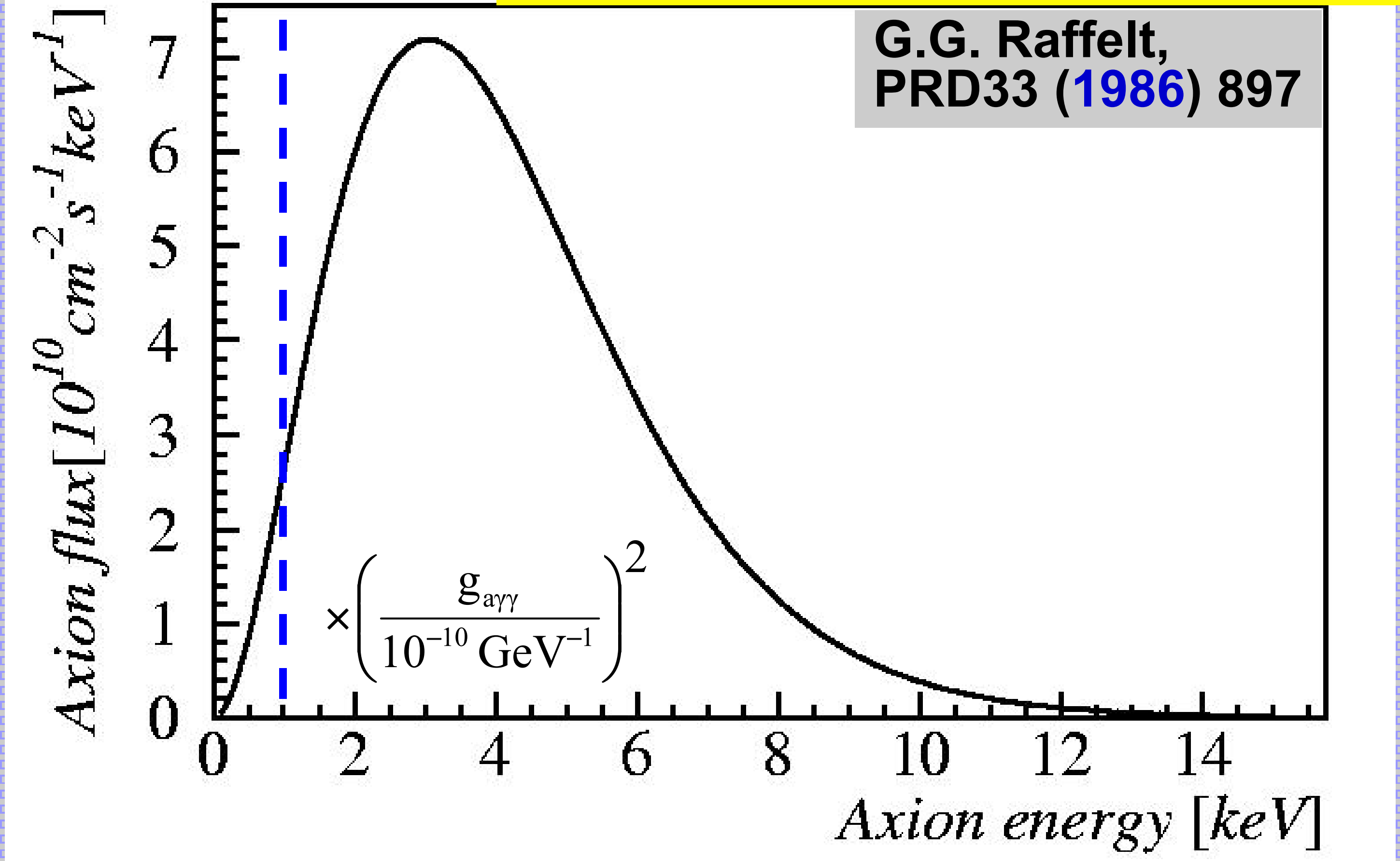
Motivation?

So far **<0.5 – 1 keV** solar axions ignored

→ why?

Solar axion spectrum

screening effects ➔ 25x suppression, or?



↛ Theoretically + experimentally

➔ new territory!

→ ...lower CAST threshold!

- 0.5 – 1 keV
- 0.3 – 0.5 keV
- 0.1 – 0.3keV
- EUV
- UV
- visible

→ see talks by:
Y. Giomataris, G. Lutz

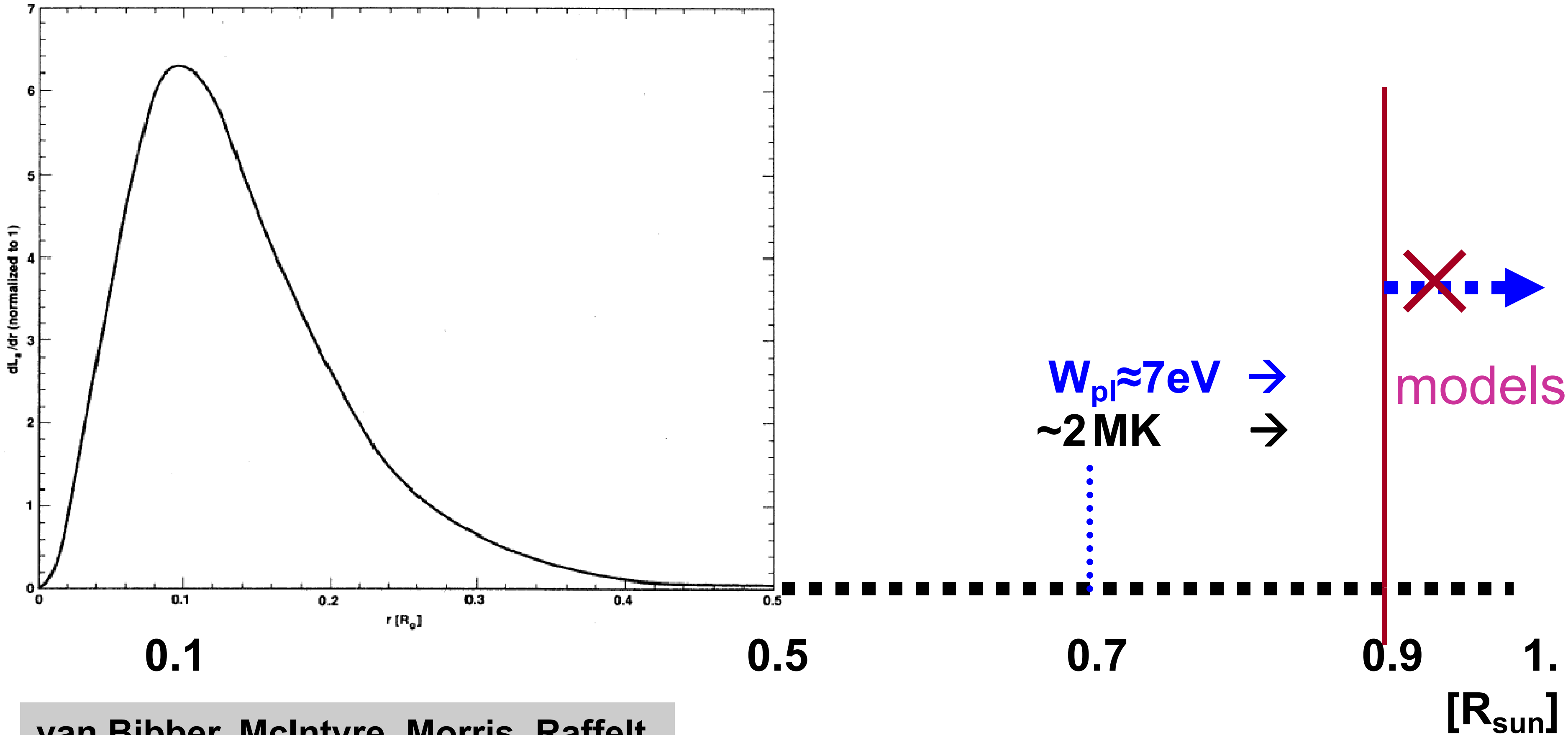
→ Direct axion signal ←

...soon?

B_{sun} ← ignored in **ALL** models

→ **New axion source + axion conversion @ Sun**

Radial axion energy loss by the Sun



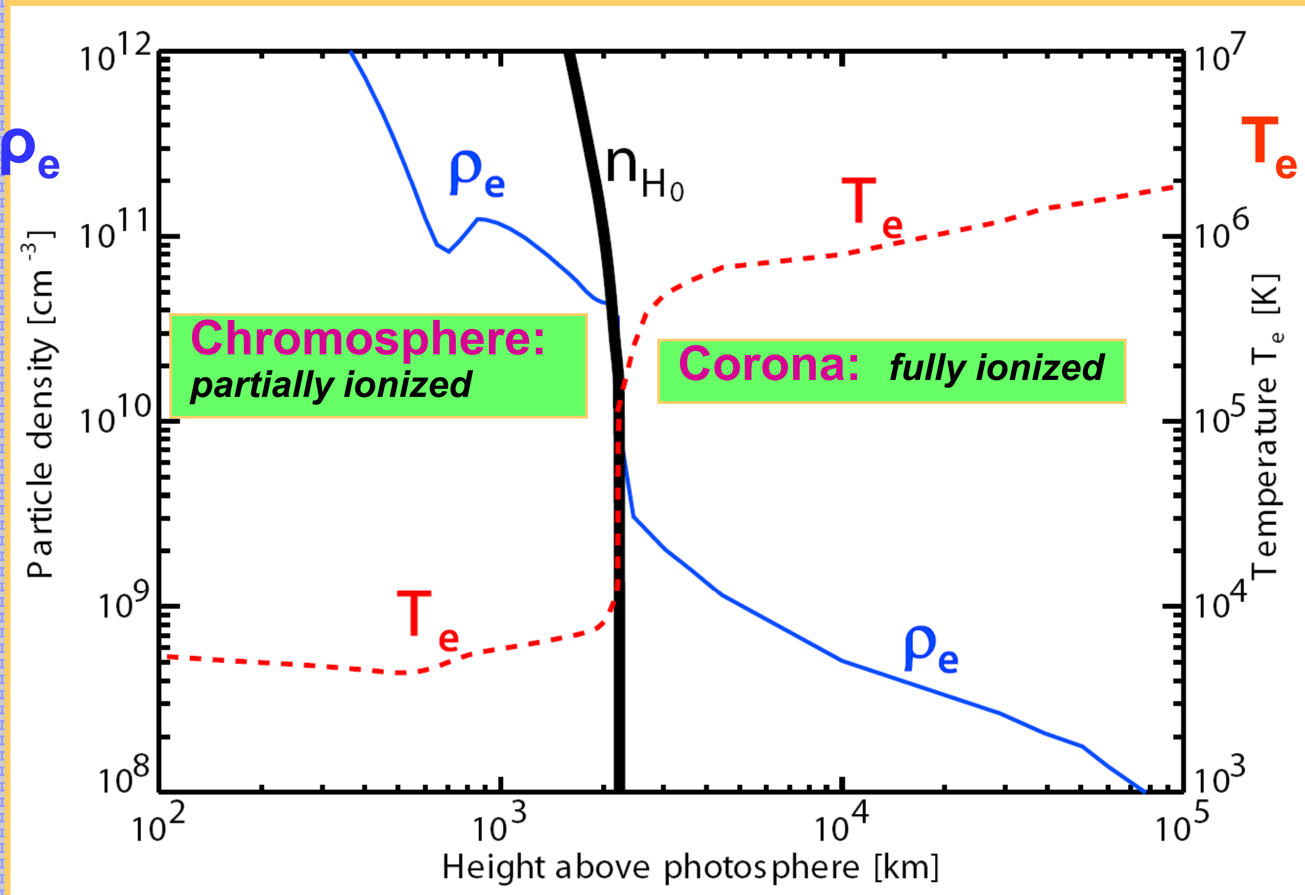
van Bibber, McIntyre, Morris, Raffelt,
Phys. Rev. D39 (**1989**) 2089

kT < a few 100 eV

➔ **LES~axions!**

.... $m_a \approx w_{plasma}$

➔ resonance crossing ← little Phase Space ➔ ~KK axions → large PS



Electron density (ρ_e) and temperature (T_e) model of the chromosphere and the corona. The plasma becomes fully ionized at the ***sharp transition***: *)

Chromosphere → Corona

n_{H_0} = neutral hydrogen density.

***) ~100 km thick (vertical)**
(S. Patsourakos et al., ApJ. 522 (1999) 540)

"At any given height, ρ_e varies by a factor of 10 - 100 over the entire corona." …

"The physical understanding of this high temperature in the solar corona is still a **fundamental problem in astrophysics**, because it seems to violate the **second thermodynamic law**, given the photospheric temperature T≈5785K (and drops to T~4500K in **sunspots**)." M. Aschwanden, *Physics of the Solar Corona* (**2004**) p.24-26

Photosphere: **only ~0.1% of the gas is ionized** (= plasma).

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

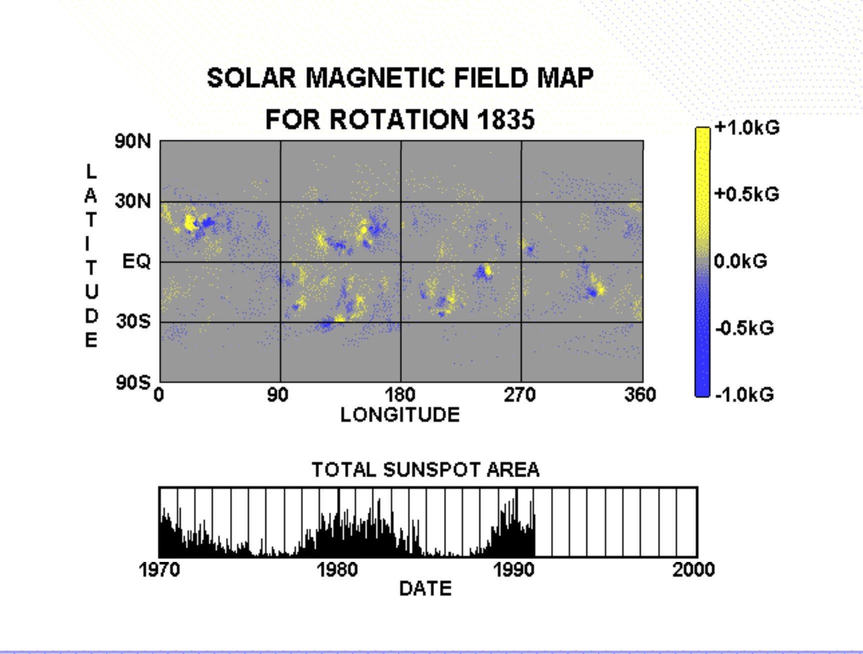
Magnetic fields are at the root of virtually all of the features we see on+above the Sun.

Without magnetic fields → Sun would be a rather boring star

http://solarscience.msfc.nasa.gov/the_key.shtml

Magnetic fields are pervasive in astrophysics + create many important physical effects, yet they remain one of the more poorly understood aspects of astrophysical objects. **Much of what is interesting about the Sun** …follows directly from its production of fields, but even on such a nearby object many **mysteries** remain. This is even more true of stars that are not like the Sun.

A. Reiners, G. Basri ApJ. 656 (**20.2.2007**)1121



B_{solar}^{In+out} ⊗ **axions ignored!**

!*new*!

http://solarscience.msfc.nasa.gov/maghstry.shtml

“Unfortunately, the signal is dominated by background…

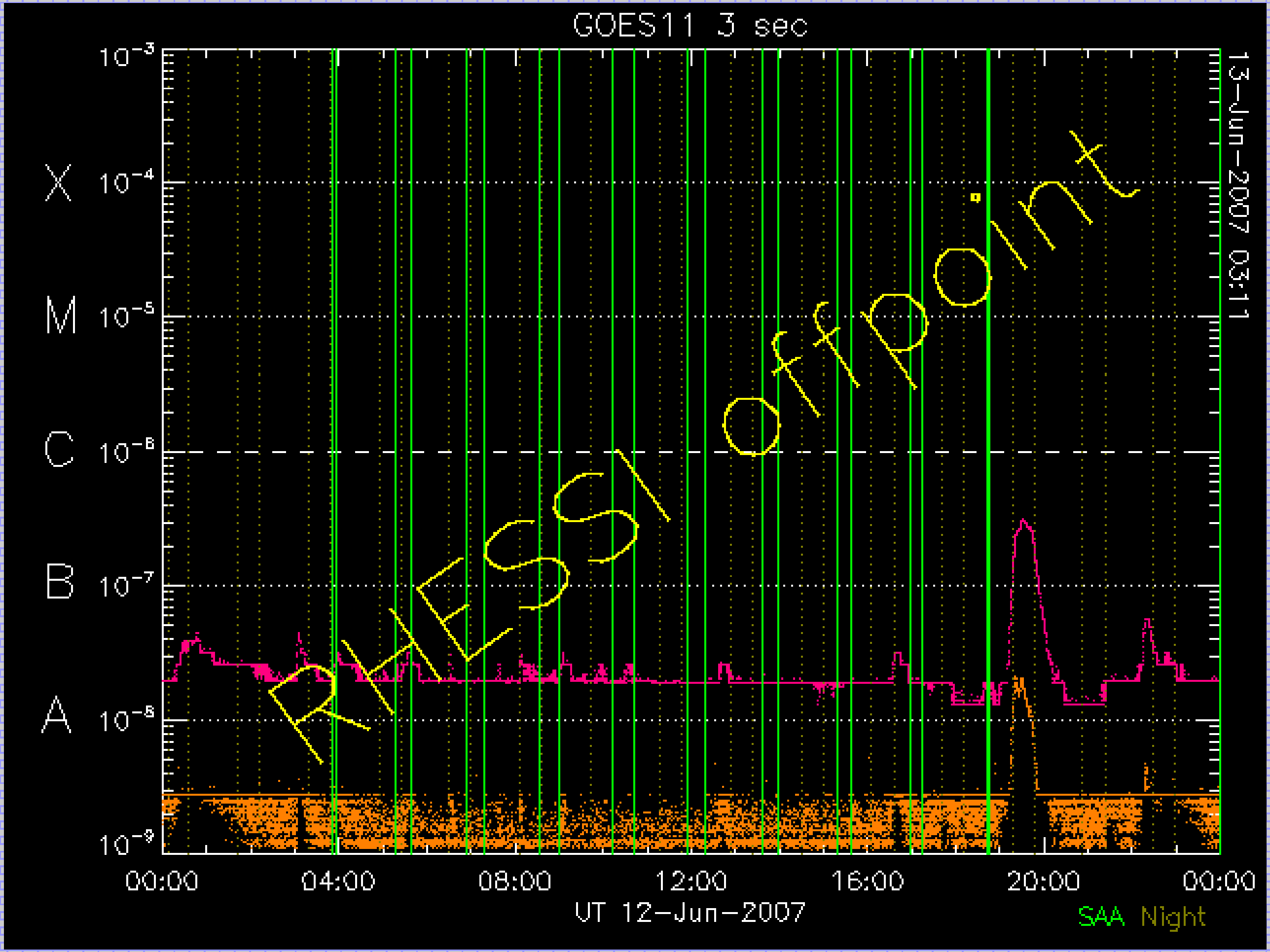
Sunspots: ***the X-ray background is relatively small …”***

Carlson & Tseng , Phys. Lett. B365 (1996) 193

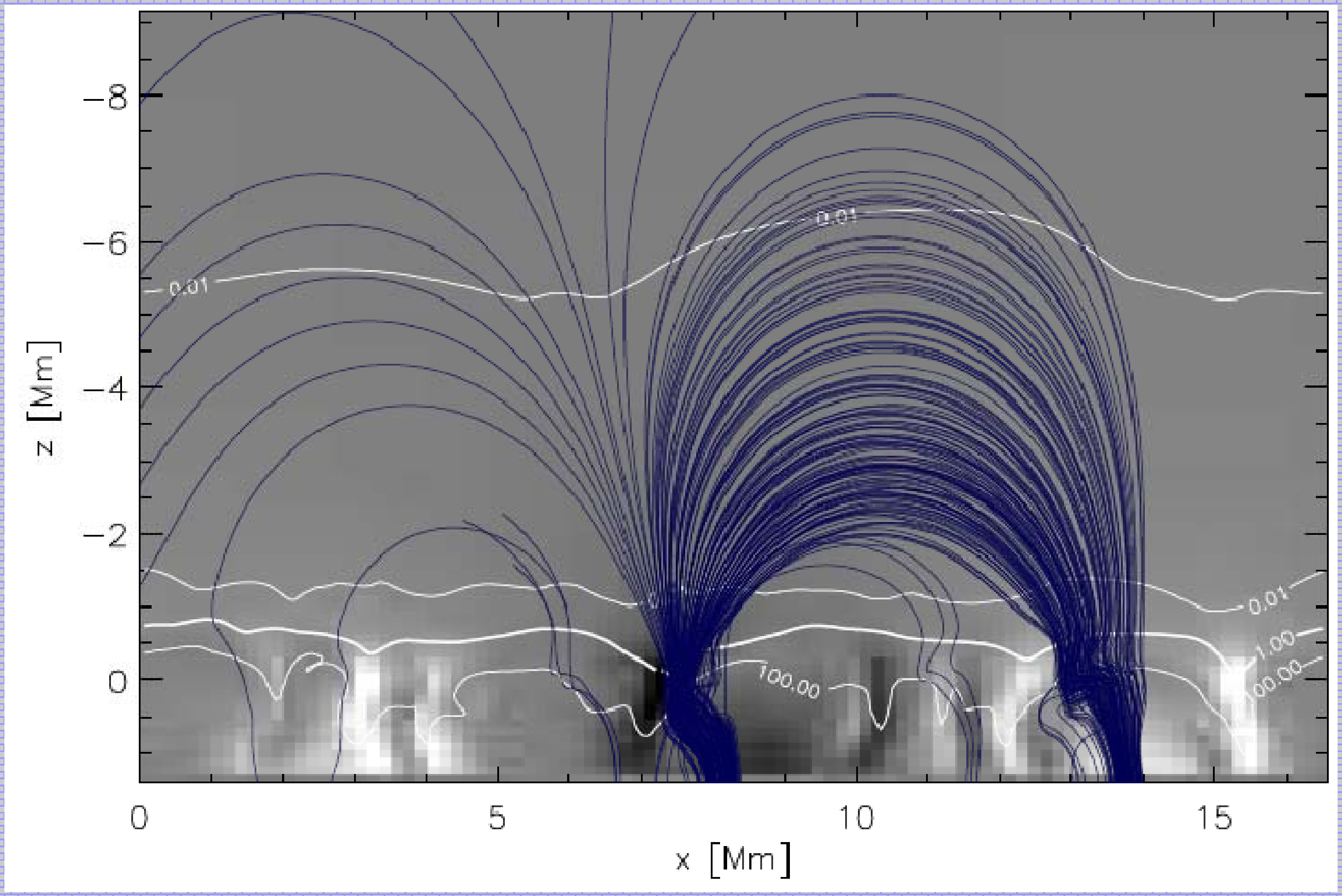
→ RHESSI, Hinode search for axions

→ This work

RHESSI last off-pointing: 12/6/2007- 21/6/2007



→ ~10-20% → sensitivity?



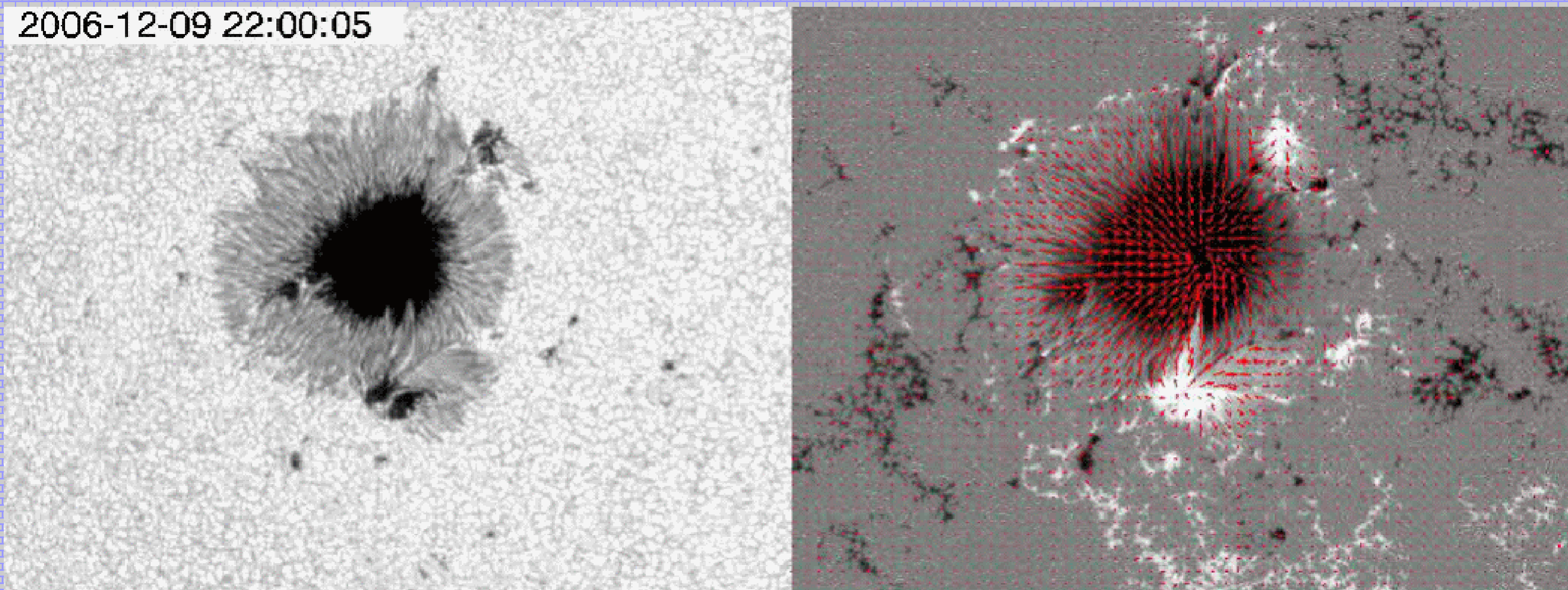
The B_z component of the magnetic field in the photosphere.

V.H. Hansteen, M. Carlsson, B. Gudiksen, astro-ph/0704.1511

Magnetic fields are at the root of virtually all of the features we see on+above the Sun.

Without magnetic fields the Sun would be a rather boring star.

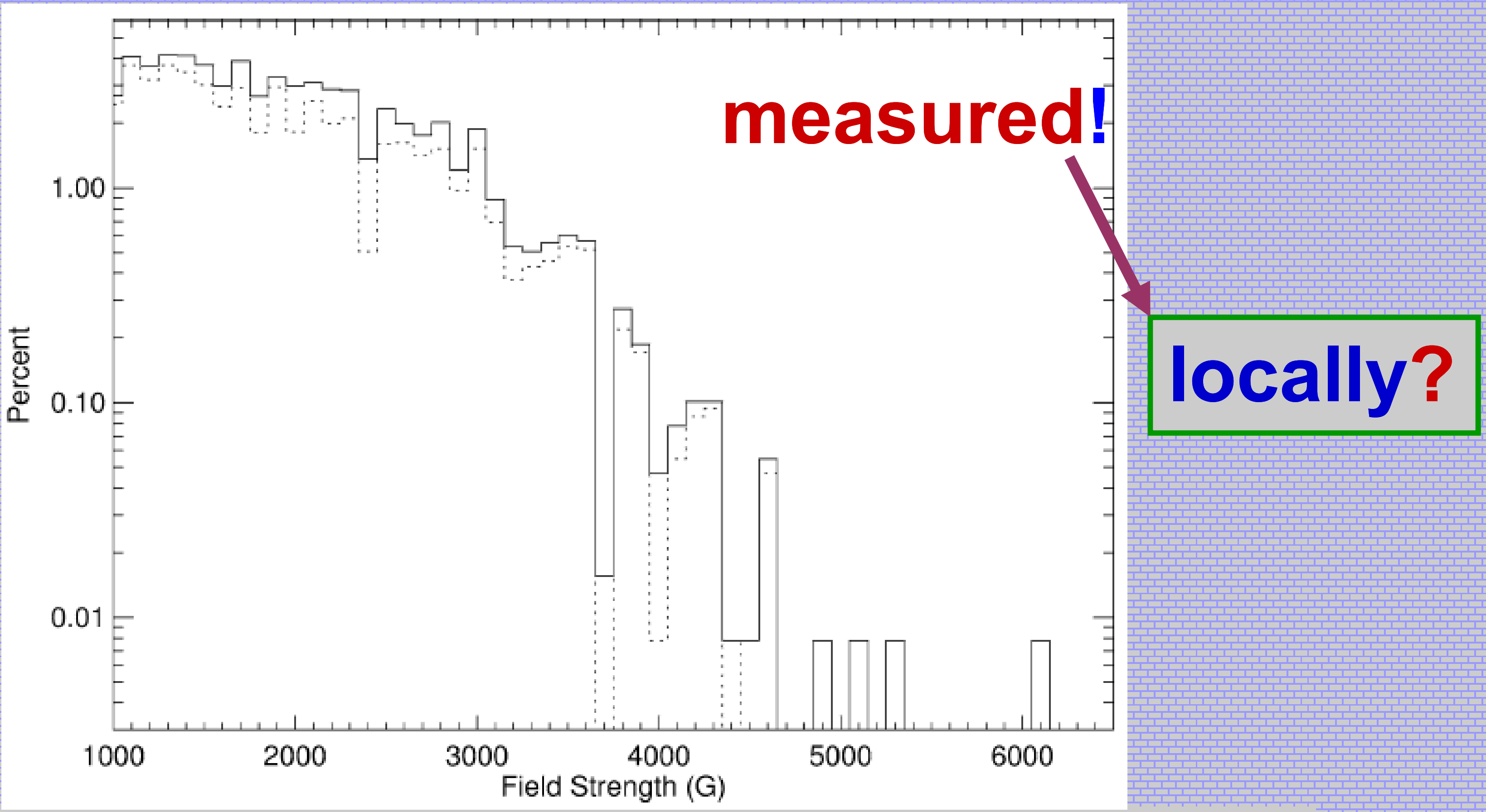
http://solarscience.msfc.nasa.gov/the_key.shtml



Japan's Hinode spacecraft made the movie on Dec. 13, 2006. It shows magnetic fields swirling around sunspot 930. The storm system was two Earth-diameters wide. This solar storm exploded, producing an X3-class solar flare

http://science.nasa.gov/headlines/y2007/images/hubble4sun/hurricane_huge.gif

Magnetic field in sunspots

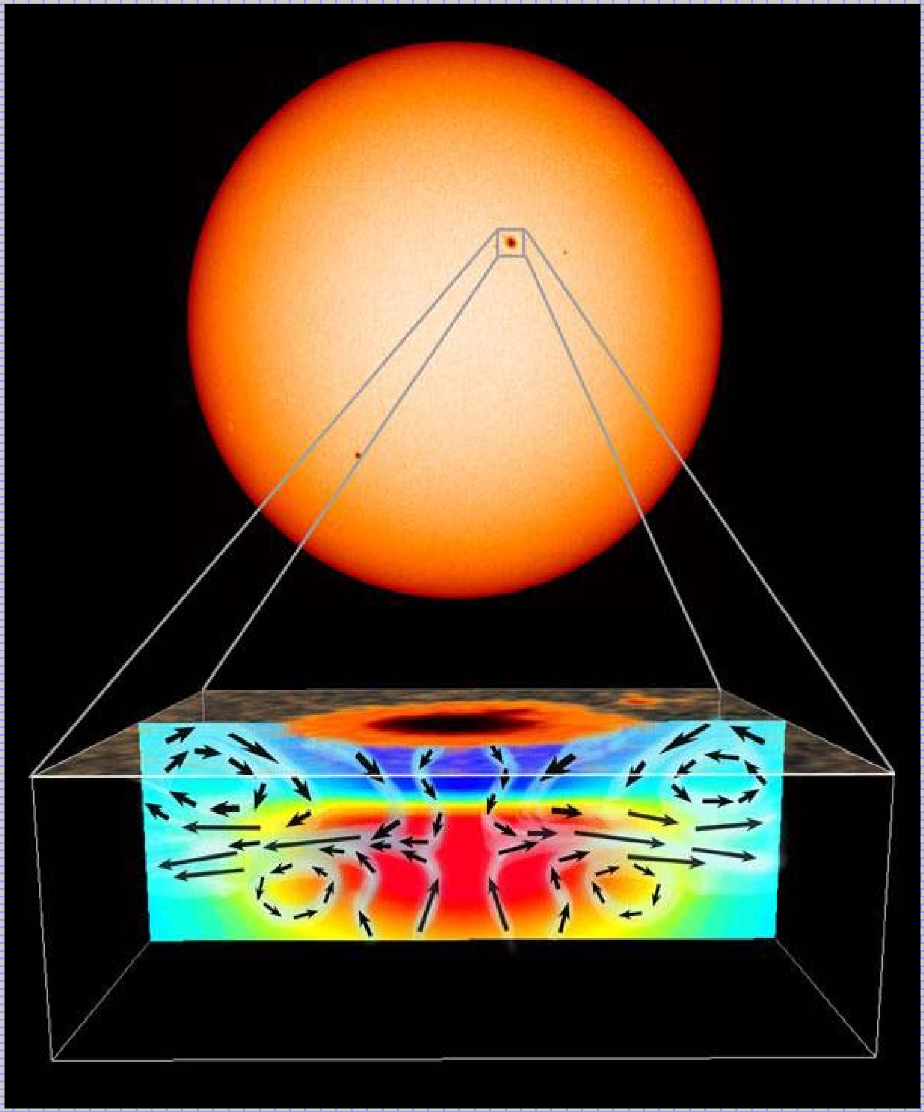


Distribution of maximum field strengths in **12804 sunspot groups** measured at Mt.Wilson (1917–1964) and Rome (1965–1974). The *dashed histogram* is only Mt. Wilson measurements.

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

The origin of sunspots is not understood.

Junwei Zhao, Dissertation, March **2004**, p.58
http://soi.stanford.edu/papers/dissertations/junwei/thesis/PDF/thesis_double_page.pdf



… not clear whether or how the downward flow of plasma might trigger solar flares.

http://www.space.com/news/sunspot_inside_011106.html

The roots of the "tree" are still a mystery.

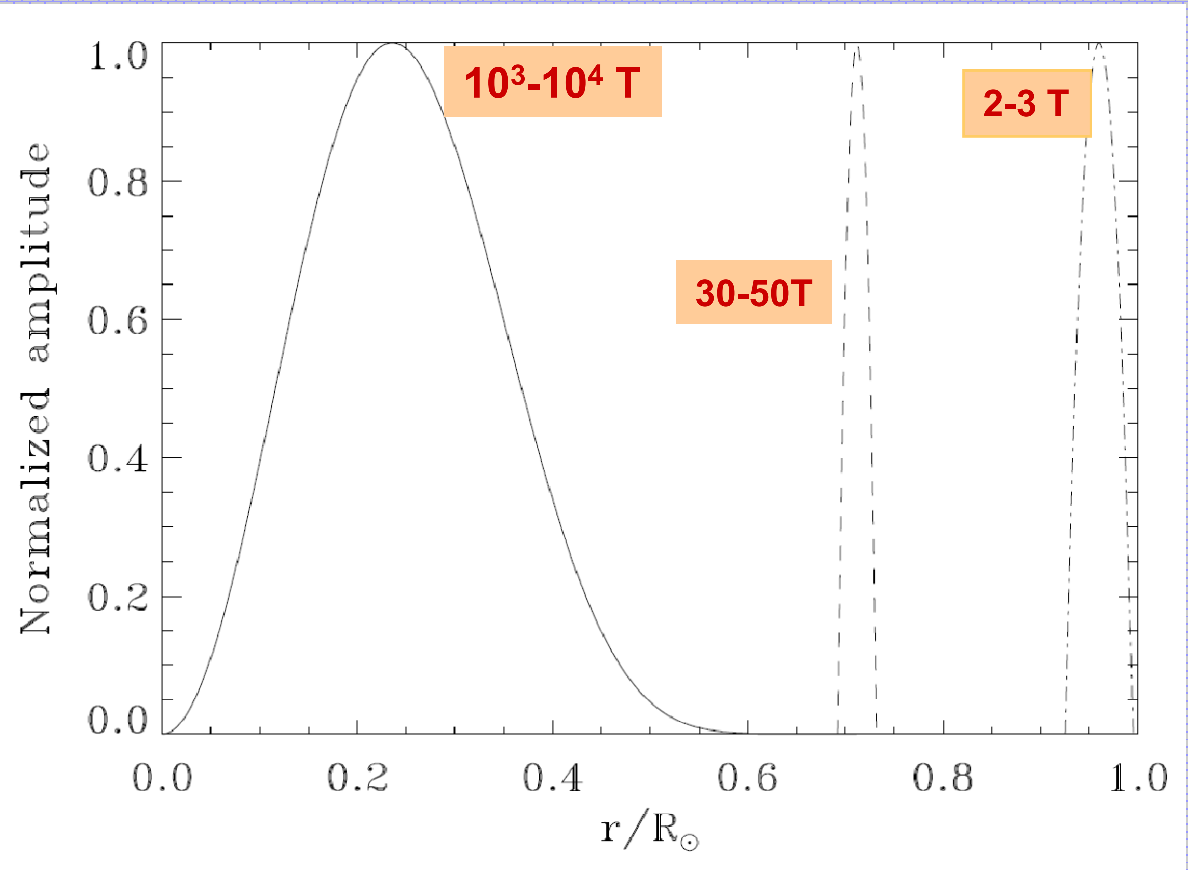
"… surprised how shallow sunspots are [Kosovichev]. Below **4800 km** … ***the roots of the sunspots were hotter than their surroundings, just the opposite of the surface*** (**rot** = hot temperature)

An artist's concept of what lies beneath sunspots, *enigmatic*, planet-sized dark areas on the surface of the Sun. Bottom: a close-up revealing the hidden structure of a sunspot.

Click here for images and movies from Stanford.

http://science.nasa.gov/headlines/y2001/ast07nov_1.htm

Solar seismic models + the ν-predictions



> 10^5 T *change solar ν-fluxes*

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

Solar magnetic fields simulated. .

?(Primakoff)$_B$ » (Primakoff)$_E$? ⟶ Solar X-rays??

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

mimic CAST at the Sun?

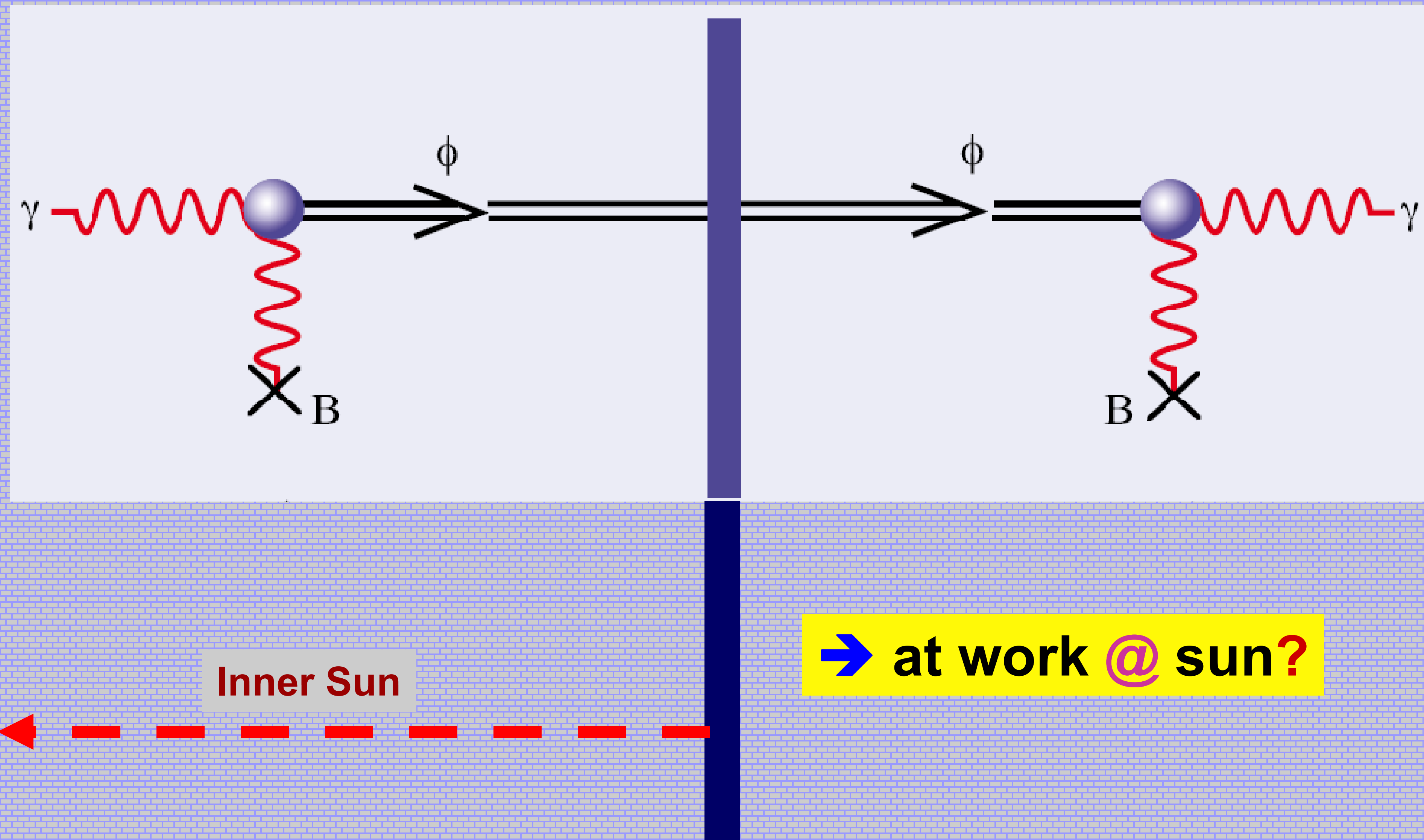
⇓

→ indirect axion-signals?

→ **WIMPs**

OR even ….

“light shining through a wall”



➔ at work @ sun?

B plays a crucial role in heating the corona …

the exact energy storage & 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, CE Parnell, A.& A. 439 (**2005**) 335
RB Dahlburg, JA Klimchuk, SK Antiochos, ApJ. 622 (**2005**)1191
S Regnier, RC Canfield, Proc. SOHO 15 Workshop - Coronal Heating, St. Andrews, Scotland, 6-9 September 2004, ESA SP-575 (**2004**) 255

➔ **axions** $\otimes$ B^2

Observations suggest:

magnetic energy = main energy source for solar active phenomena.

open question:

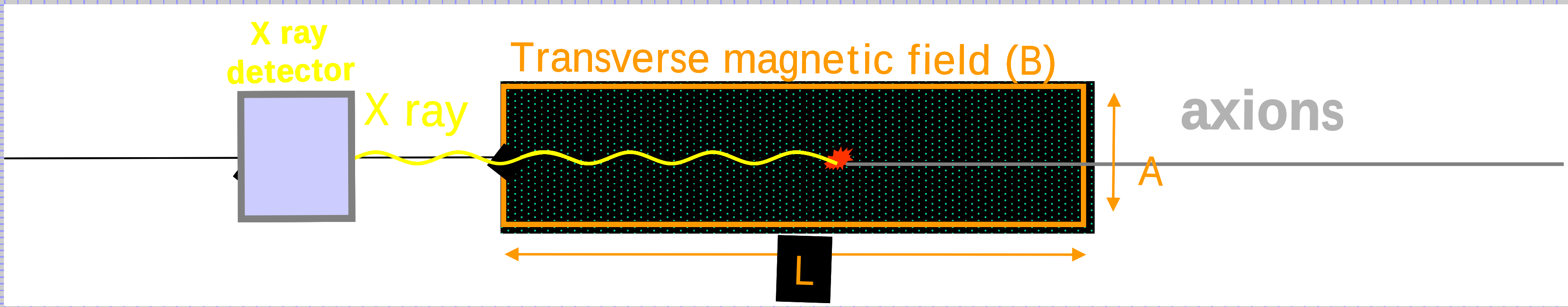
how magnetic energy is rapidly released in the solar corona so as to create solar explosions such as flares + CMEs …. catastrophic events.

….

Y. Chen, Y. Q. Hu, L. D. Xia, astro-ph/0705.3886, Adv. Space Res. (2007) *in press*

Y. Chen, Y.Q. Hu, S.J. Sun, astro-ph/0705.3885, ApJ. 666 (Sept. 2007) *in press*

CAST phase II – principle of detection



Extending the coherence to higher axion masses…

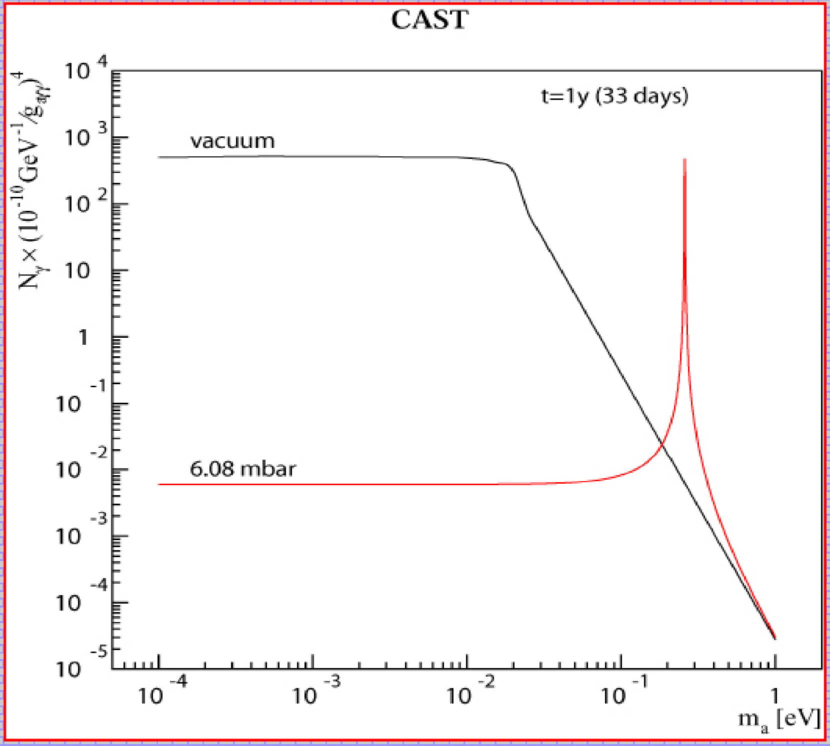
Coherence condition (qL << 1) is recovered for a narrow mass range around m_γ

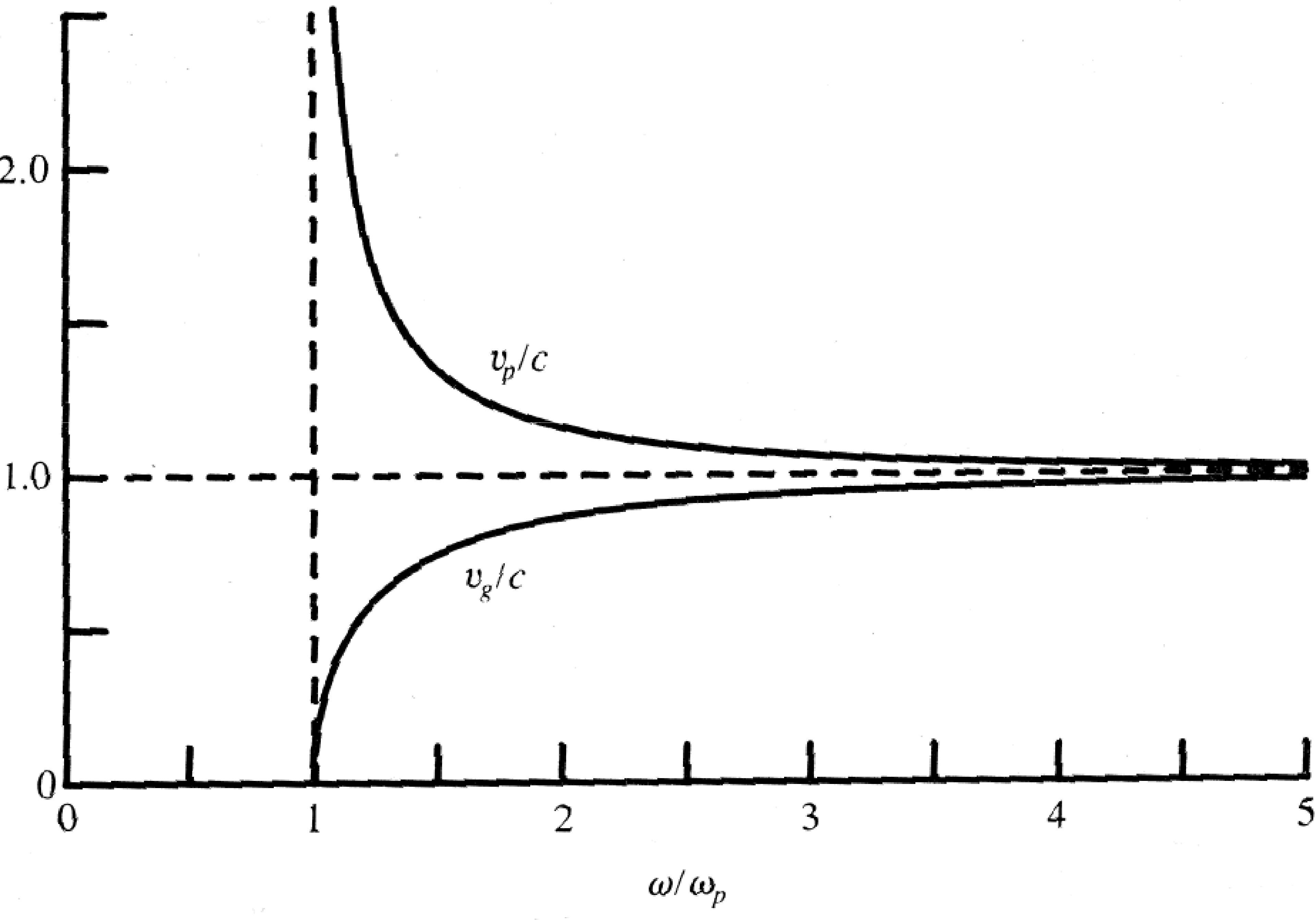
$$|q| = \frac{m_a^2 - m_\gamma^2}{2E}$$

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

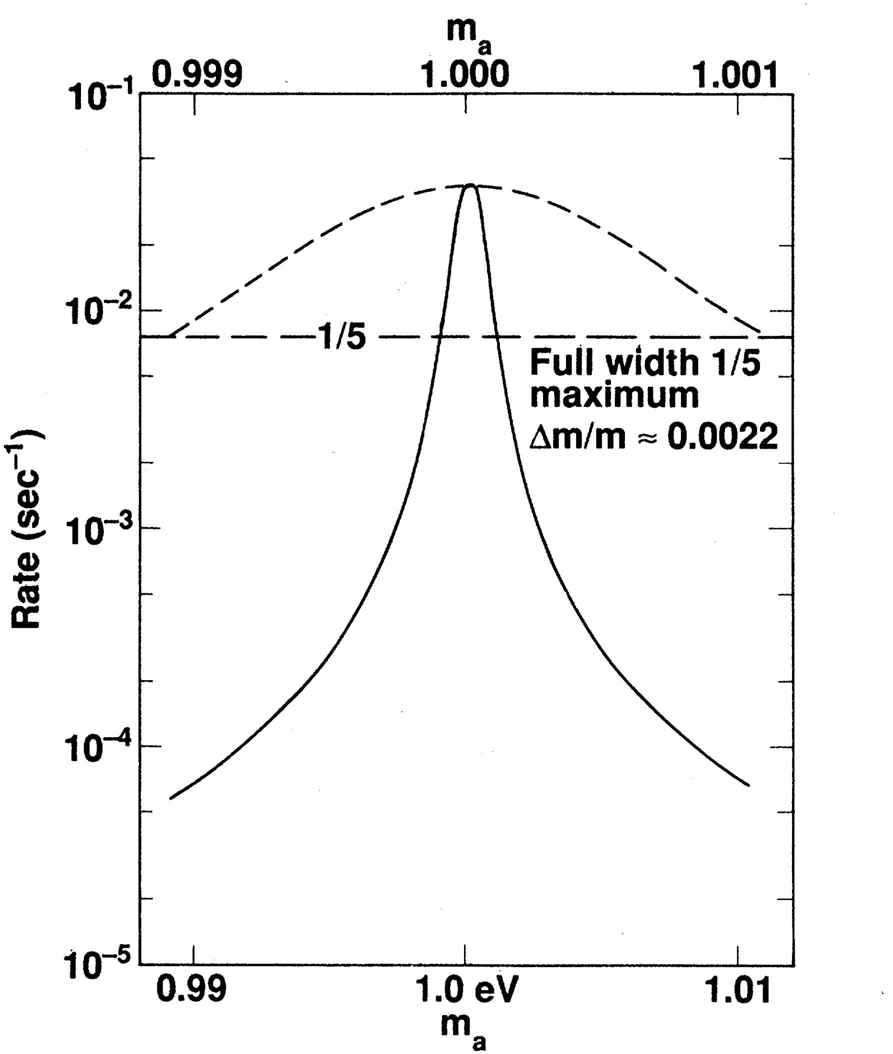
N_e: number of electrons/cm^3

ρ: gas density (g/cm^3)





Phase (v_p) and group (v_g) velocities of an em wave in a plasma.



➔ narrow!?

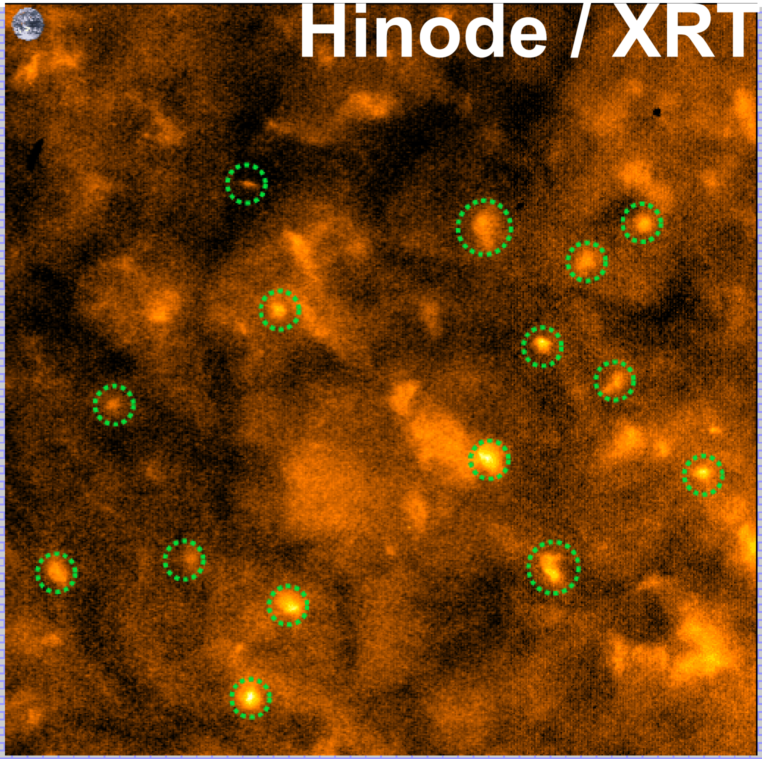
+ steep!?

➔ strong transient events!

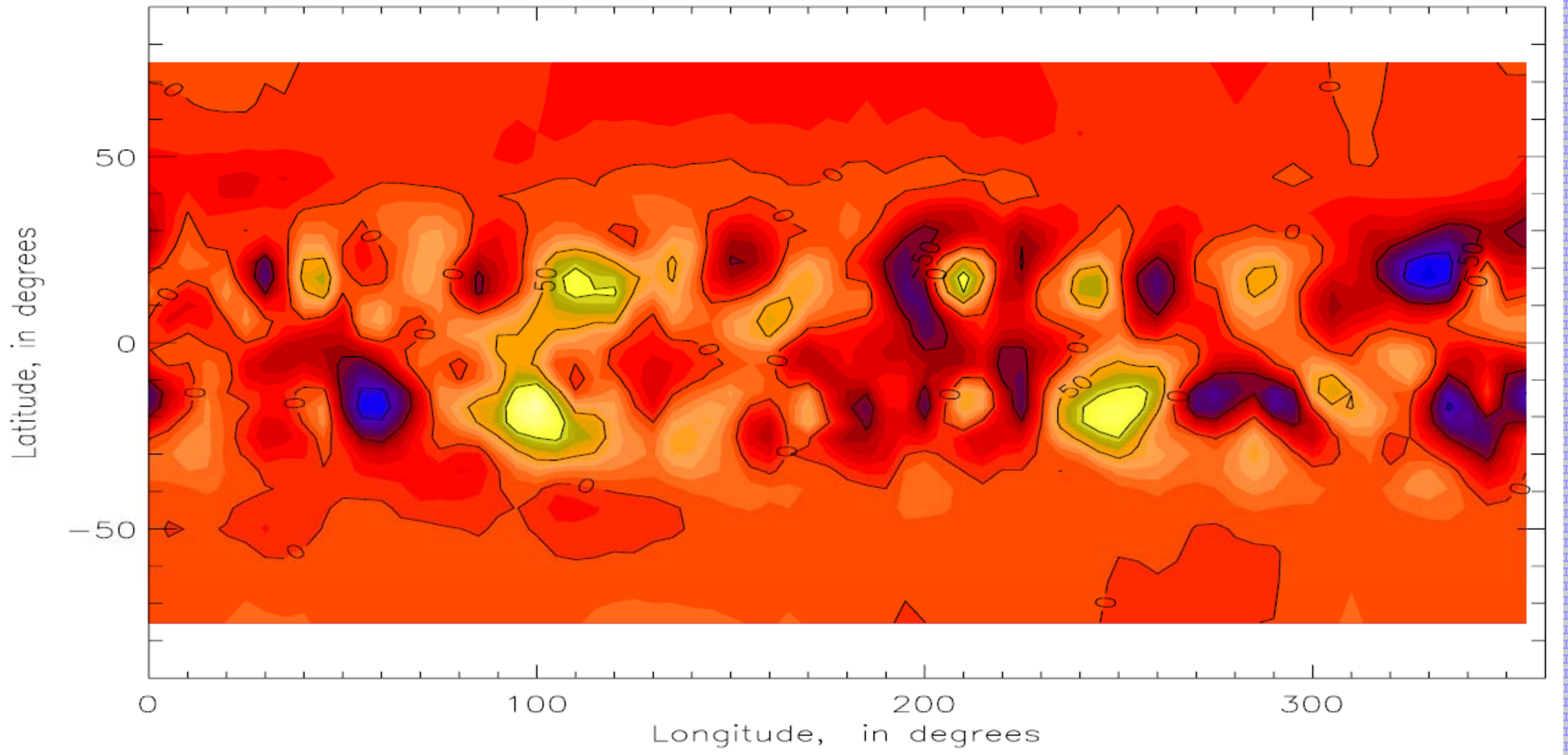
X-ray bright points in quiet region

Many X-ray bright points have been found in close-up movie of quiet region. Thanks to high resolution of XRT, it has become evident that X-ray bright points are actually loop structures ➔ *ubiquitous activities of X-ray bright points, even in the quiet region.* Definition of "quiet region" might be changed by *Hinode* observations.

March 2007



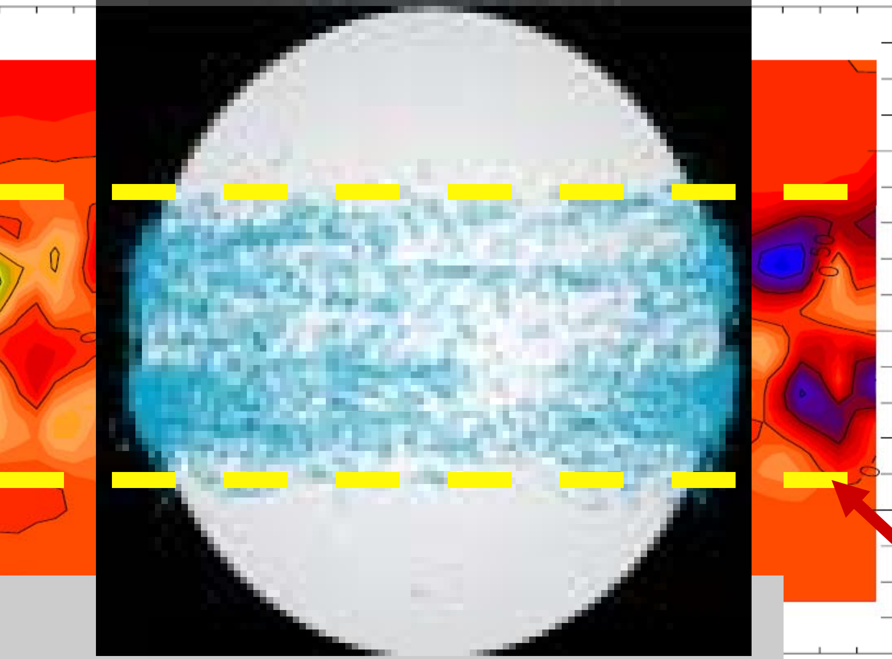
http://solar-b.nao.ac.jp/news_e/20070527_xrt_e.shtml



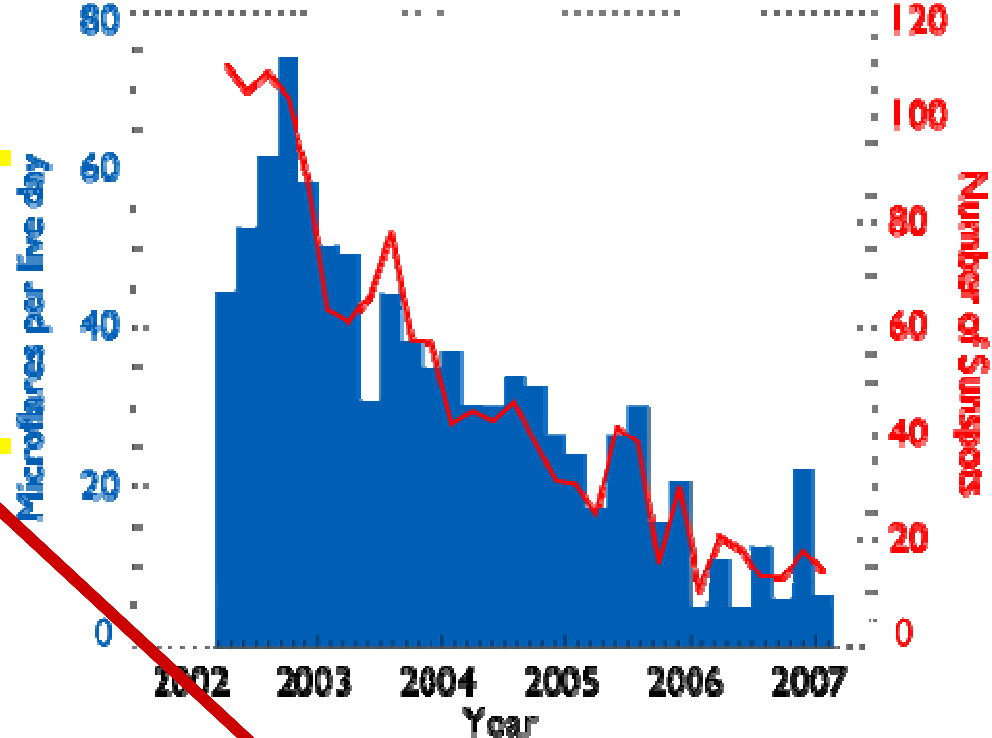
Distribution in longitude and in latitude of the mean over 260 Carrington rotations magnetic field on the solar surface.

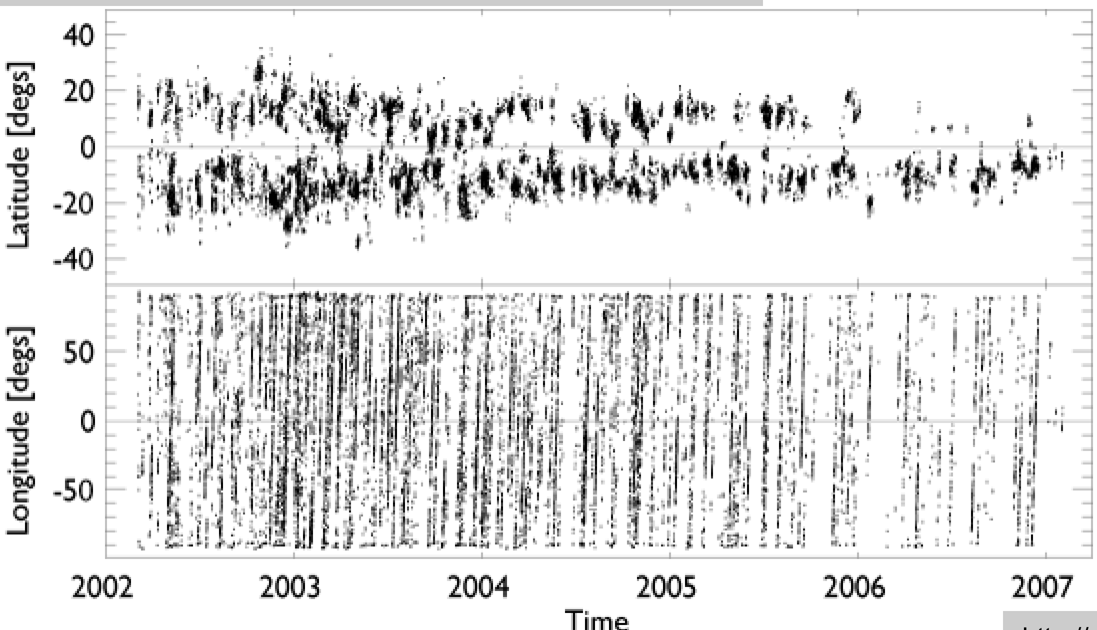
E. Gavryuseva, Solar Activity and its Magnetic Origin, Proc. IAU Symposium No. 233, 2006, V. Bothmer & A. A. Hady, eds., p.61

Flux ~95% for the range ±40°   R.Howard, Solar Phys. 38 (1974) 59



Longitude + latitude positions of ~24000 μflares



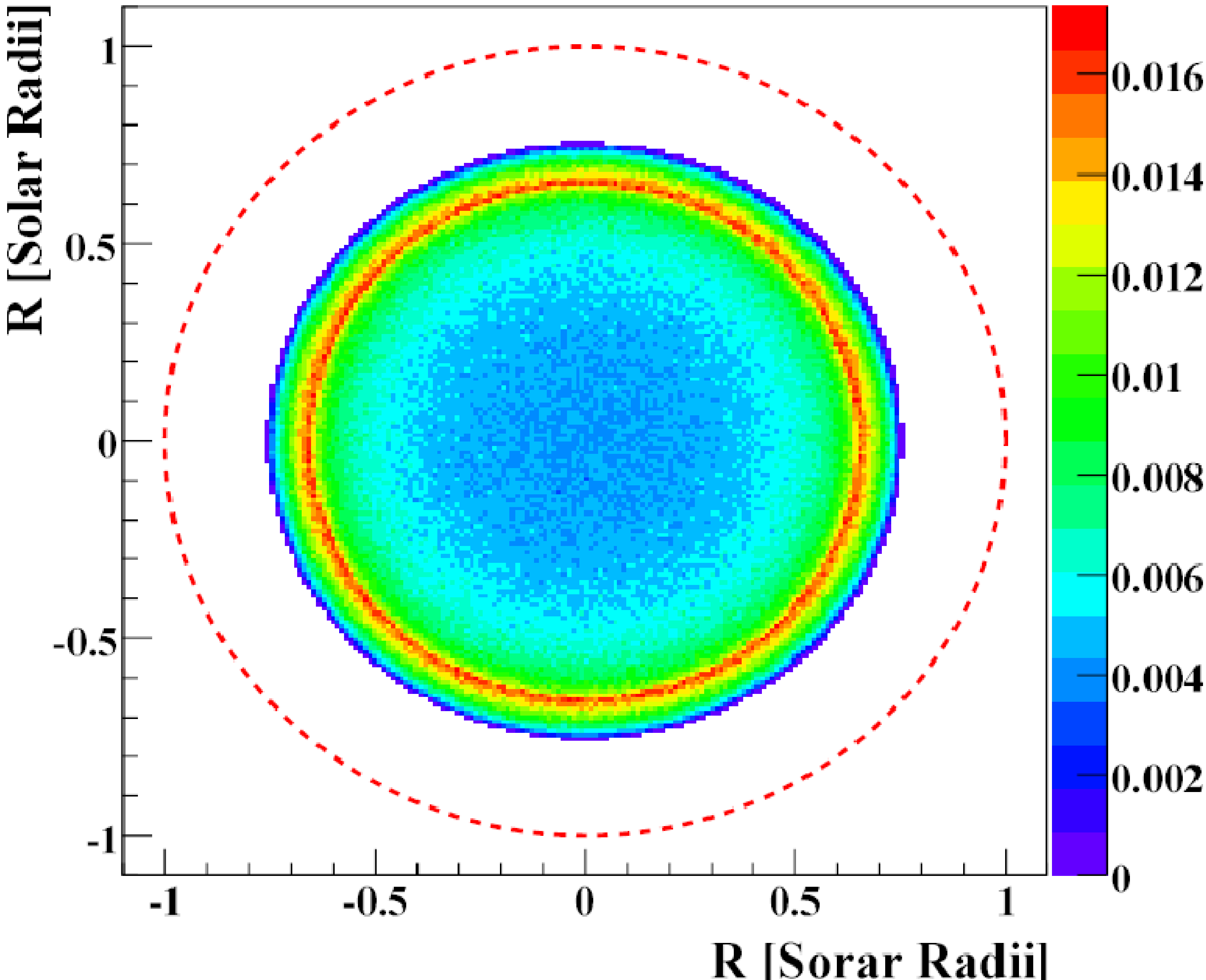


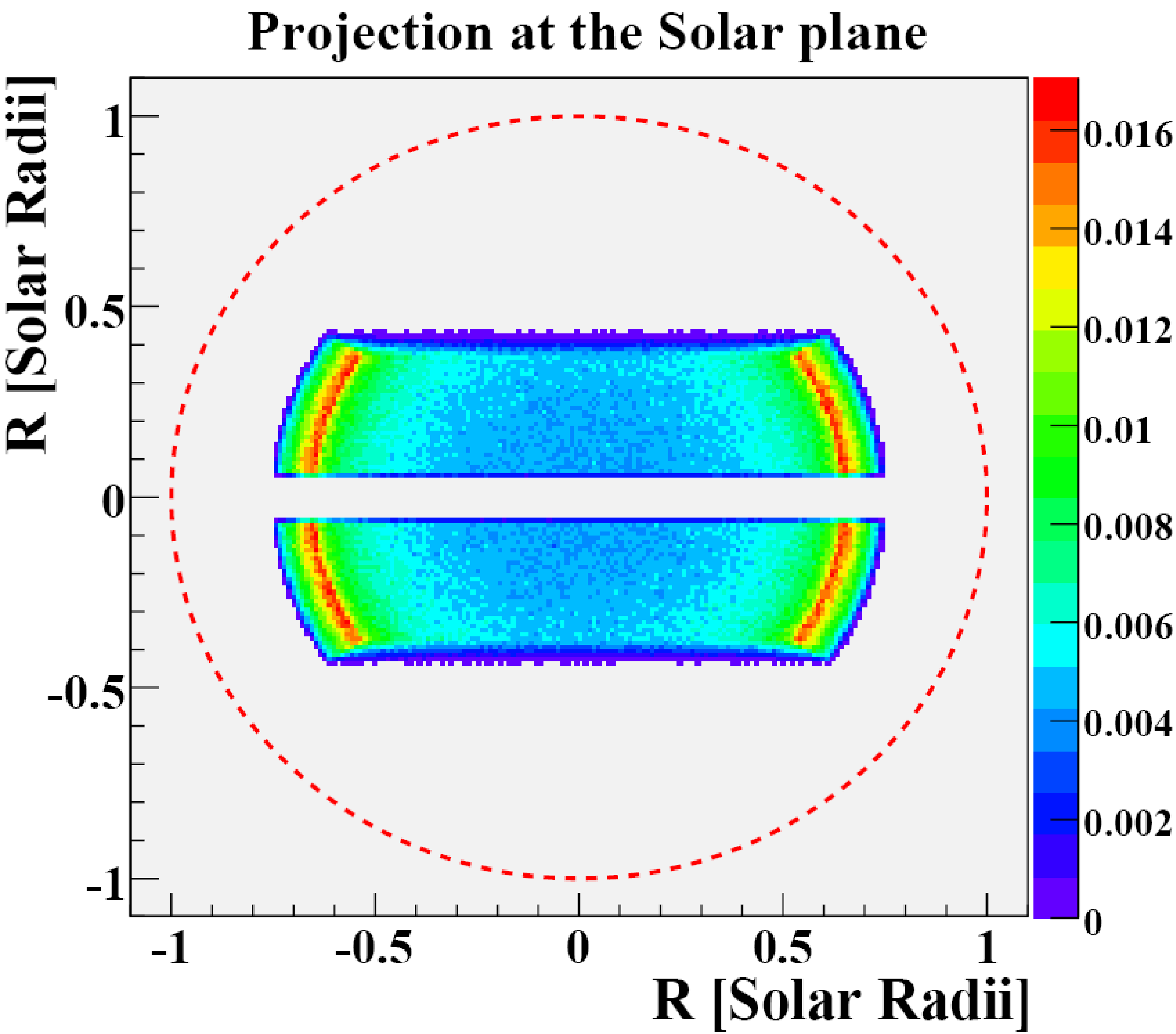
Magnetic flux ~95% in ±40°
R. Howard, Sol Phys 38(1974)59

20/5/2007, RHESSI nugget
I. Hannah, Steven Christe

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

Projection at the Solar plane




Projection at the Solar plane
R [Solar Radii]
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
R [Solar Radii]
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0

Low energy solar axion signals?

1. **axion ⇄ photon**

→ X-rays, visible, …

Unexpected (dis)appearance of photons

L_x ~ B^2

~ ρ

dynamical behaviour

→ **transient effects** ← ubiquitous @ Sun, …

2. **axion ⟶ 2γ** → decay of gravitationally trapped massive ~axions, e.g. KK-type → **generic**

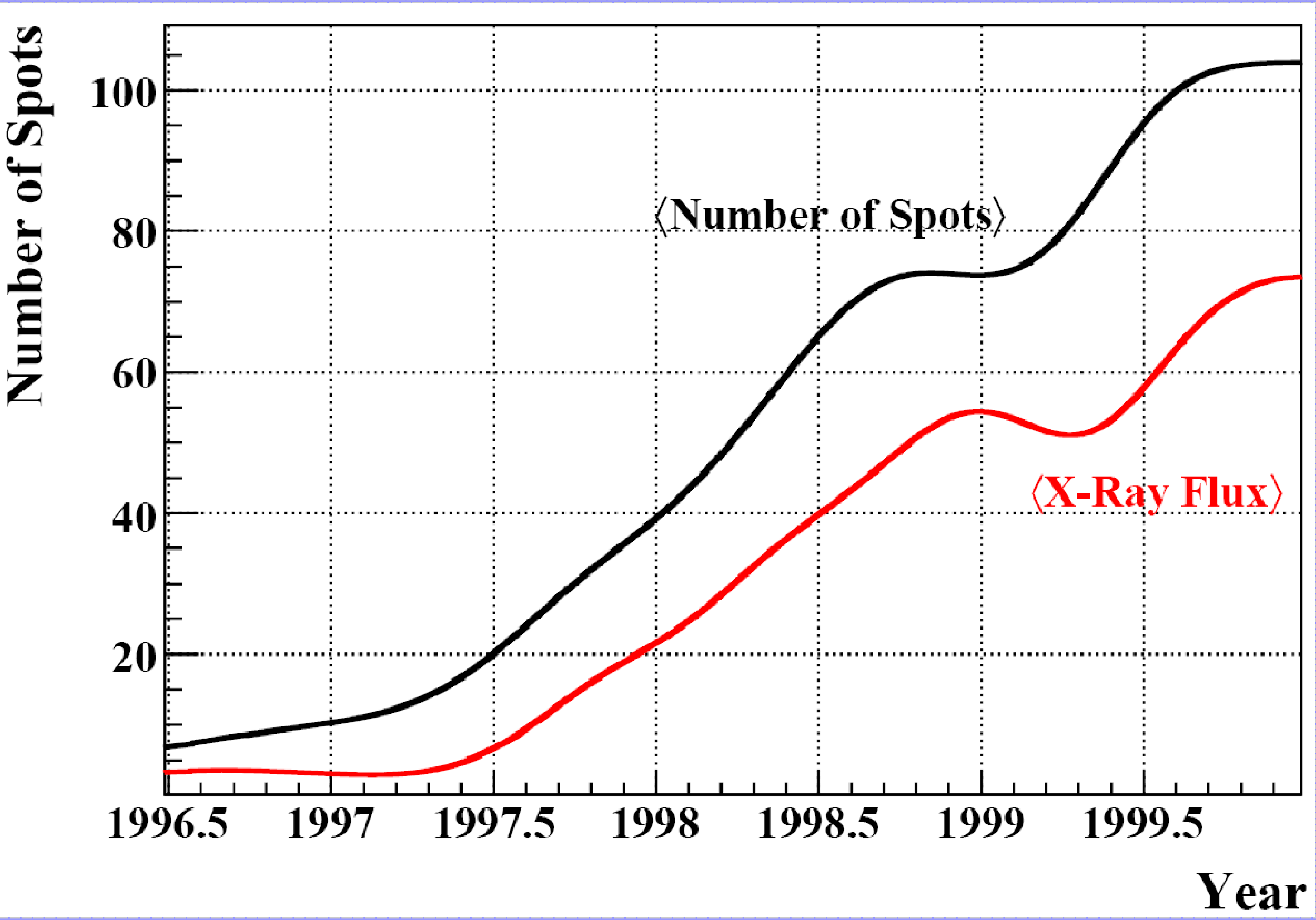
▼

ghost "plasma"

▼

$L_x \approx$ **constant**

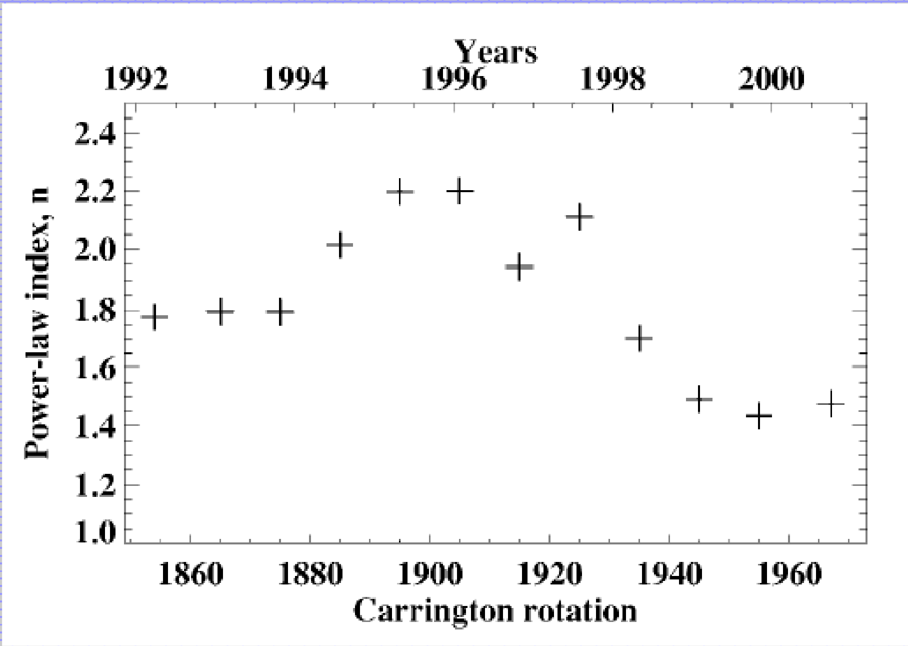
solar observations require both components



Number of Spots
100
80
60
40
20
⟨Number of Spots⟩
⟨X-Ray Flux⟩
1996.5
1997
1997.5
1998
1998.5
1999
1999.5
Year

L_x vs. B

1st



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.

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

Note: axion-to-photon oscillation ∝ B^2

Hoffmann, Z., Nucl. Phys. B S151 (2006) 359

⊗ 11 years solar cycle?

TOTAL SOLAR IRRADIANCE

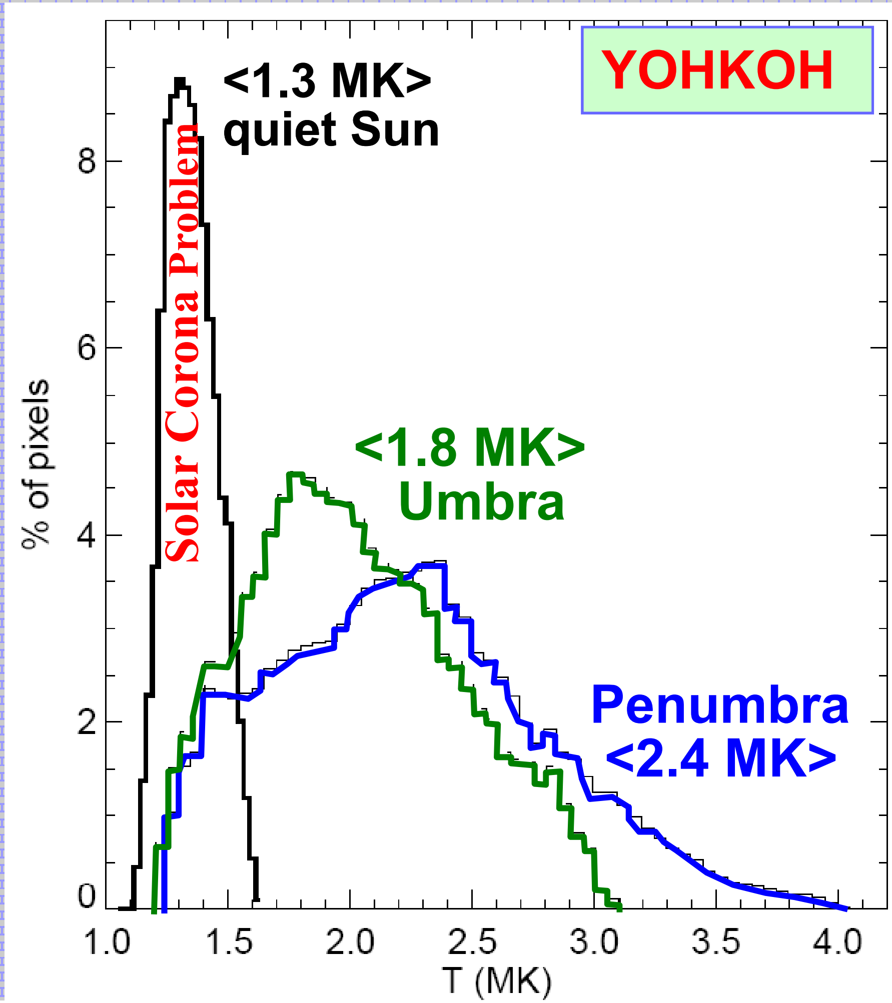
→ **visible light**

→ ***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

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

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



Temperature distributions

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

Photosphere → T ⇩

→ ~4500K

Corona → T ⇧

B ~2 kG above most sunspots!

→ ***heat flux problem @ umbra / penumbra***

HC Spruit, GB Scharmer, A.&A. 447 (**2006**) 343

See also: Y-K. Ko etal., ApJ. 578 (2002) 979:

Above **ARs** 8194,8194,8198 → **T_e~3MK**

Above **quiet Sun** → **T_e ~1.5MK**

T. Shimizu, S. Tsuneta, ApJ. 486 (1997) 1045:

QS → **~1.6 – 2.7 MK, stable**

Above **ARs** → **~3 – 5 MK,variable**

→ gives ref. from 1970!

Some ARs are more productive than others, and the productivity of a certain AR is associated with its B-configuration, as in the case of large flares.

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

Large solar flares ➔ 10^{32} erg in ~10^{3}s ~ 10^{29} erg/s

Solar wind ➔ $3\cdot10^{27}$ erg/s

P. C. Grigis, A. O. Benz, A. & A. (**2006**) *in press*

R.L. Moore ApJ. 324 (**1988**) 1132

if solar axions are their cause & $L_{axion} \sim L_{solar}$

➔ derived Primakoff conversion $[a\rightarrow\gamma]_B$:

$P_{a\rightarrow\gamma} \sim 10^{-6}$ ← **solar wind**

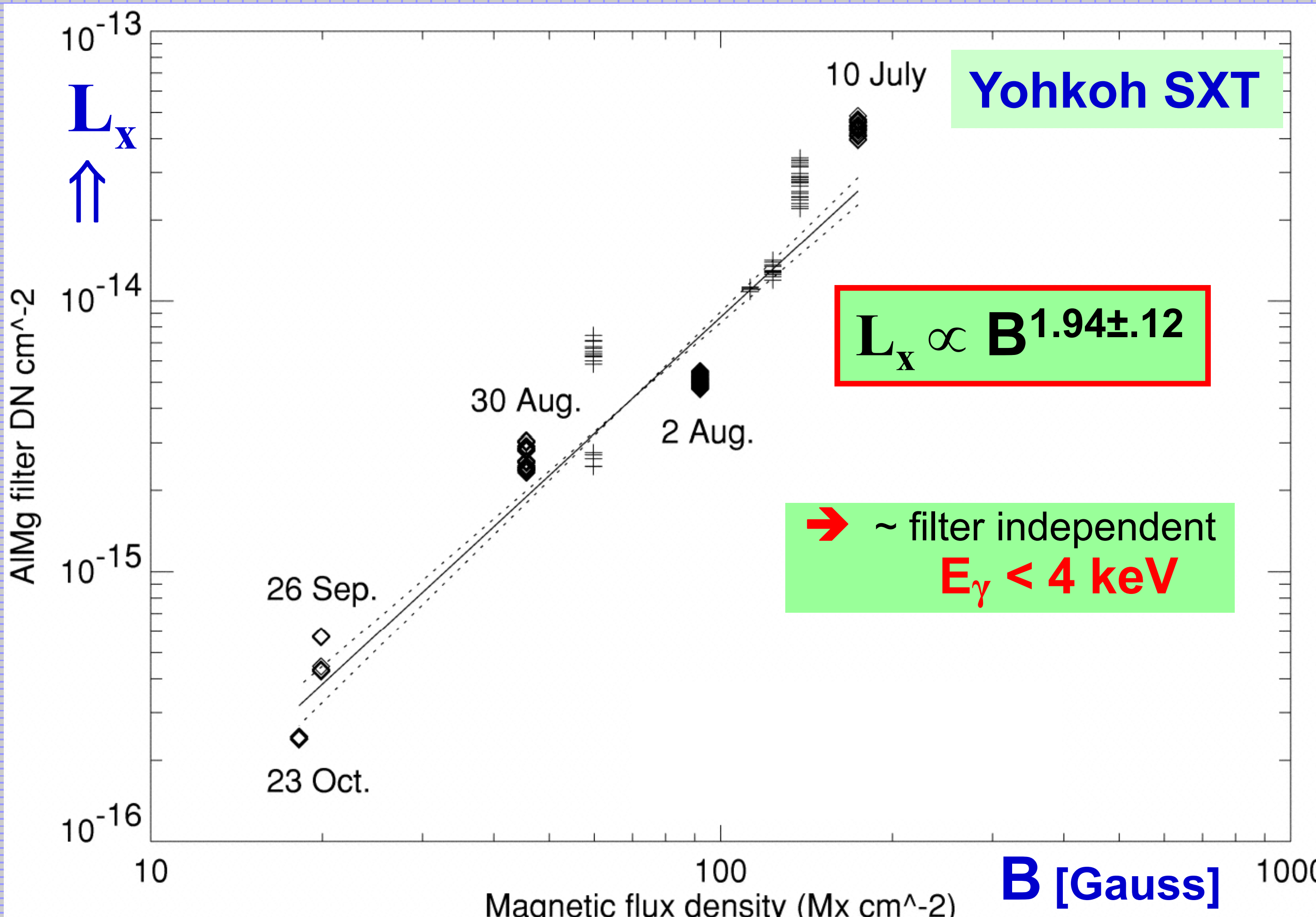
$P_{a\rightarrow\gamma} < 10^{-1}$ ← **flares**

▼

reasonable!

The long-term evolution of AR7978

2nd



<X-ray flux> / cm^2 vs. <B> **July-Nov. 1996**

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

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

What produces solar flares? → µflares, nanoflares,..

➔ The precise causes of solar flares & CMEs is one of the great solar mysteries. (2003)

➔ flare-quiet ≈ flare-imminent regions

↓

… storage and release of the energy that powers solar flares is generally believed to be in the coronal *magnetic field* …

\+ magnetic reconnection necessary for solar flares to occur.

G. Barnes, K.D. Leka, ApJ. 646 (August 2006) 1303,
ibid. 595 (2003) 1277

DH Hathaway, http://science.msfc.nasa.gov/ssl/pad/solar/quests.html (2003)

“One of the most amazing things about solar flares," says Brian Dennis of NASA's Goddard Space Flight Center, "is the efficient way they accelerate subatomic particles to energies exceeding 10^9 eV." As much as 50% of the total explosion energy emerges as electrons and atomic nuclei traveling at nearly the speed of light. "Flares operate much more efficiently than any particle accelerator we've been able to build here on Earth.“

"How do flares do that?" he asks. We don't know.

What ignites solar flares?

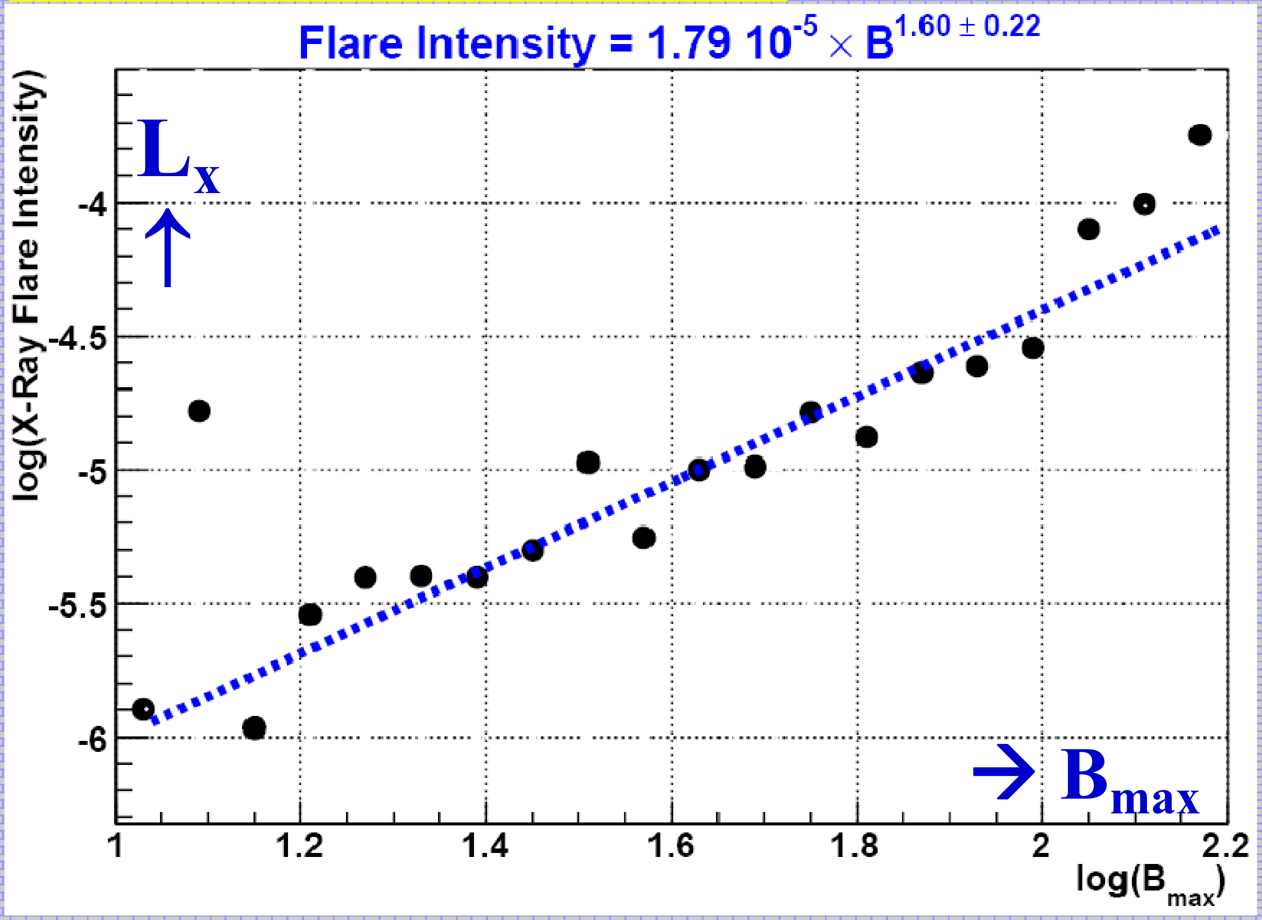
- ➔ How do they unleash so much energy so quickly?
- ➔ And is it possible to predict when they will happen?

Such questions have vexed astronomers **since 1859** when Lord Carrington spotted a solar flare for the first time.

http://science.nasa.gov/headlines/y2002/06feb_hessi.htm

FLARES → origin?

3rd



The Electron "Problem"

e^- ≈ 10^5× hard X-rays from Bremsstrahlung!

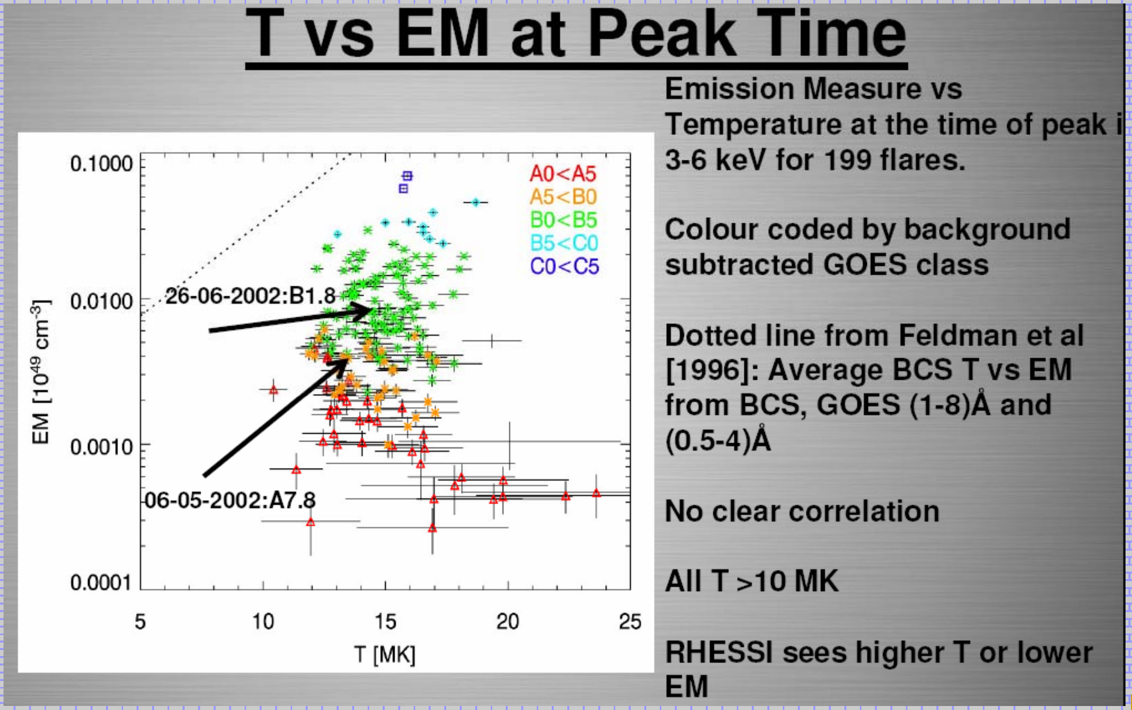
Rebinned peak flare X-ray intensity → B_{max}

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

G. Emslie (2005)

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

Flares:



μflares are small flares that occur in active regions.

They are hot (>10 MK)

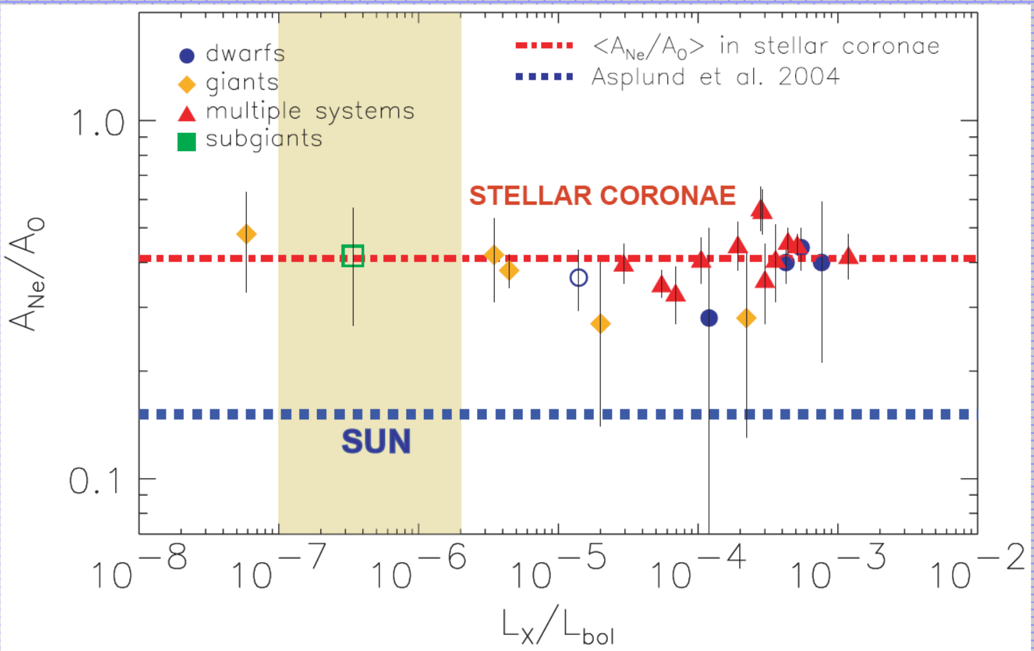
http://www.soho15.org/PDF/hannah.pdf

- <T> ~ 15-20MK
- surface brightness < maximum L_{axion}
- $\sim B^2$

- **solar metalicity**

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

measured photospheric abundances of C, N, O, Ne 25-35% below prediction!



Ne/O abundance ratios vs. coronal activity.

Quiet ARs:
Ne / O at ~0.15.

Flares:
enhanced Ne detection (~2x)

➔ **Why the Sun is so special?**

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

models incorrectly predict

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

Serious disagreement between the predictions of the solar model and the observations obtained by helioseismology.

M Asplund, N Grevesse, M Guedel, AJ Sauval, Nature 436 (**2005**) 525

- **some element differentiation process operates @ ~10000K**
  ➔ chromosphere
- **Flares show an enhanced abundance of Ne**

JLR Saba, KT Strong, Proc. Kofu Symp., NRO Report No 360(**1994**)305

X

Martin ASPLUND, private communication, **11/9/2006**

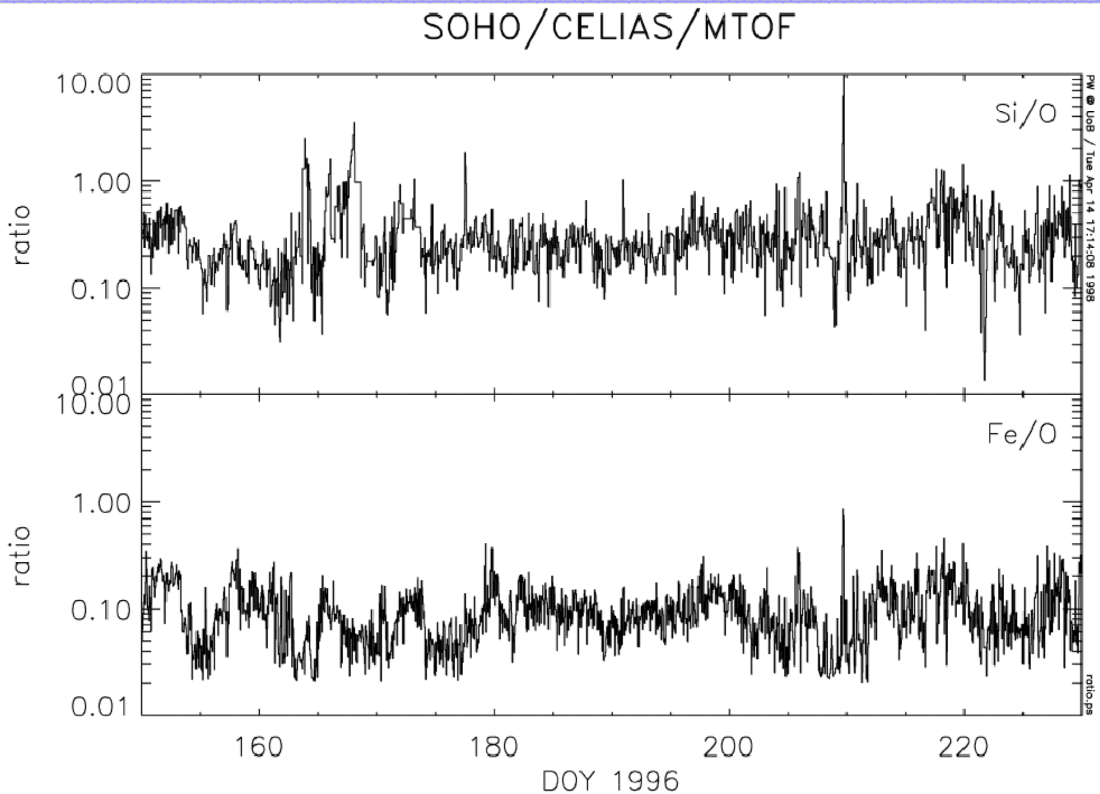
"the most promising aspect in my opinion is not the increase in radiation pressure, but rather the extra heating from absorption of axions in the atmosphere which might increase the temperature in the spectral line formation region of the Sun."

▼

Solar axion surface effects at work?

… changing diffusion locally.

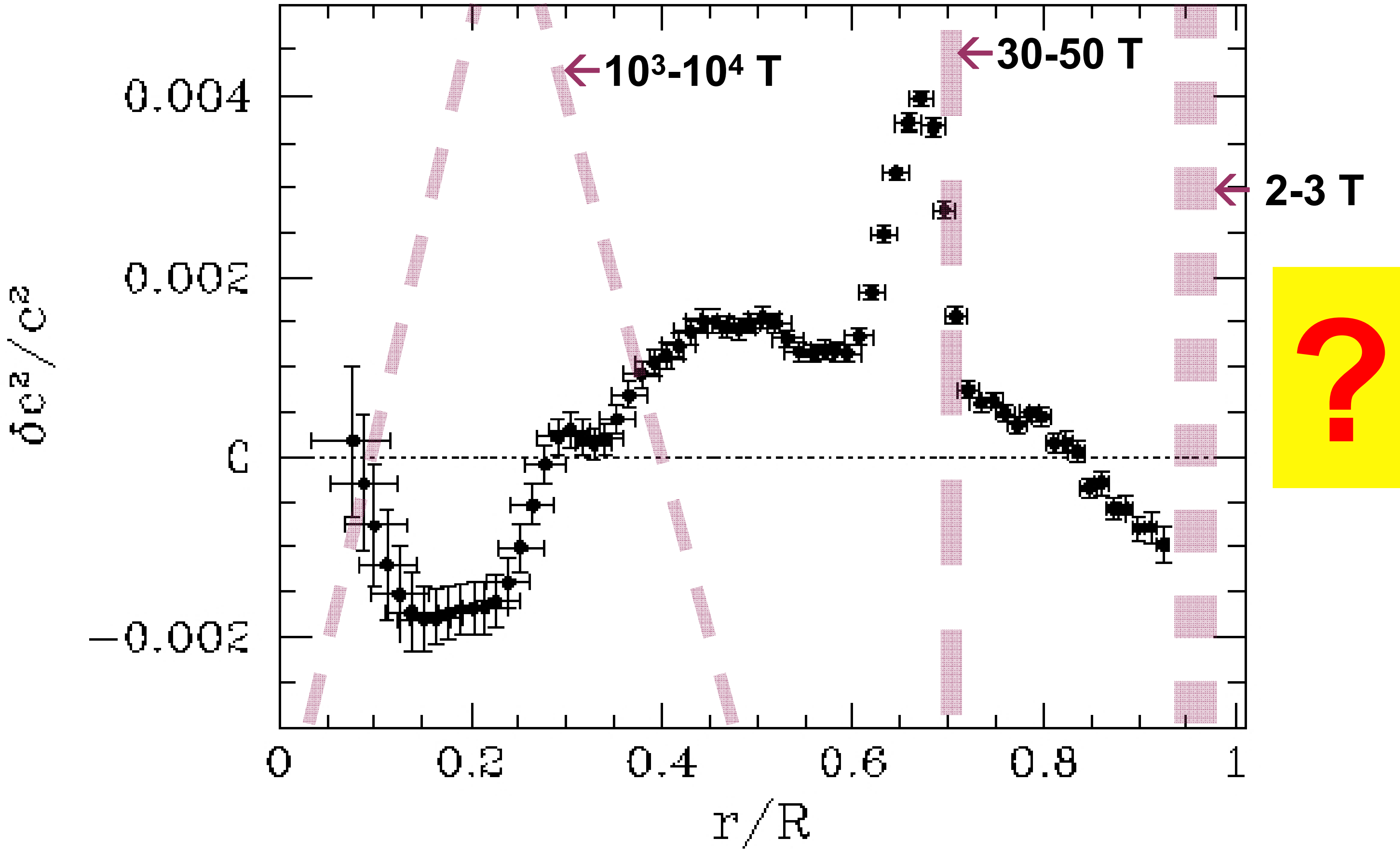
➔ No problem with the Solar Model



Elemental abundances in the solar corona are the basis of comparison for investigations of the coronae of other stars and for abundances measured in the solar wind. They differ from solar photospheric abundances by as much as an order of magnitude, and they vary from place to place and time to time.

Abundance ratios of Si and Fe to O. 30 min running averages of 5 min data from CELIAS/MTOF - SOHO.

J.C. Raymond et al.,
CP598, Solar and Galactic Composition, ed. R. F. Wimmer-Schweingruber A I P (2001) 49



Difference between observed and model sound speed as a function of depth in the Sun. **The "bump" just below 0.7 R indicates the possible location of excess turbulence.** → **Simulated inner solar magnetic fields**

http://sohowww.nascom.nasa.gov/gallery/Helioseismology/mdi012.html

X

Conclusion towards ➔

X

Conclusion towards ➔

In the footsteps of solar ~axions!