3rd Joint ILIAS-CERN-DESY AXION-WIMPS TRAINING WORKSHOP

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LOW ENERGY SOLAR AXIONS

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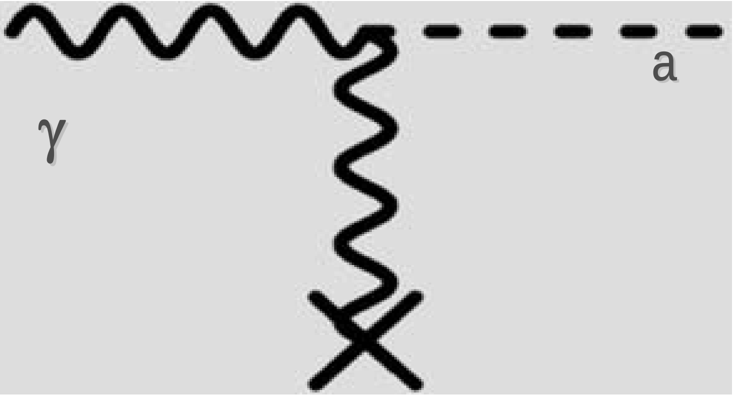
OUTILINE

- Primakoff axion production in the Sun
- CAST limit on ~ keV axion flux
- PVLAS inspired models and solar axion flux
- Low energy solar axion flux
- Production of solar axions in B-fields
- Conclusions

AXION PRODUCTION IN SUN

In the Sun, axions are produced by Primakoff photon-axion conversions in the microscopic fluctuating E-fields of the charged particles of the plasma



$$L_{a\gamma} = g_{a\gamma} \vec{E} \cdot \vec{B} a$$

PRIMAKOFF PROCESS IN THE SUN

[G.Raffelt, PRD 33, 897 (1986)]

Conversion rate

$$\Gamma_{\gamma\to a} = \frac{g^2_{a\gamma} T\, k_s^2}{32\pi}\left[\left(1+\frac{k_s^2}{4\omega^2}\right)\ln\left(1+\frac{4\omega^2}{k_s^2}\right)-1\right]$$

Screening scale

$$k_s^2 = \frac{4\pi\alpha}{T} n_B \left(Y_e + \sum_j Z_j^2 Y_j\right)$$

Plasma frequency

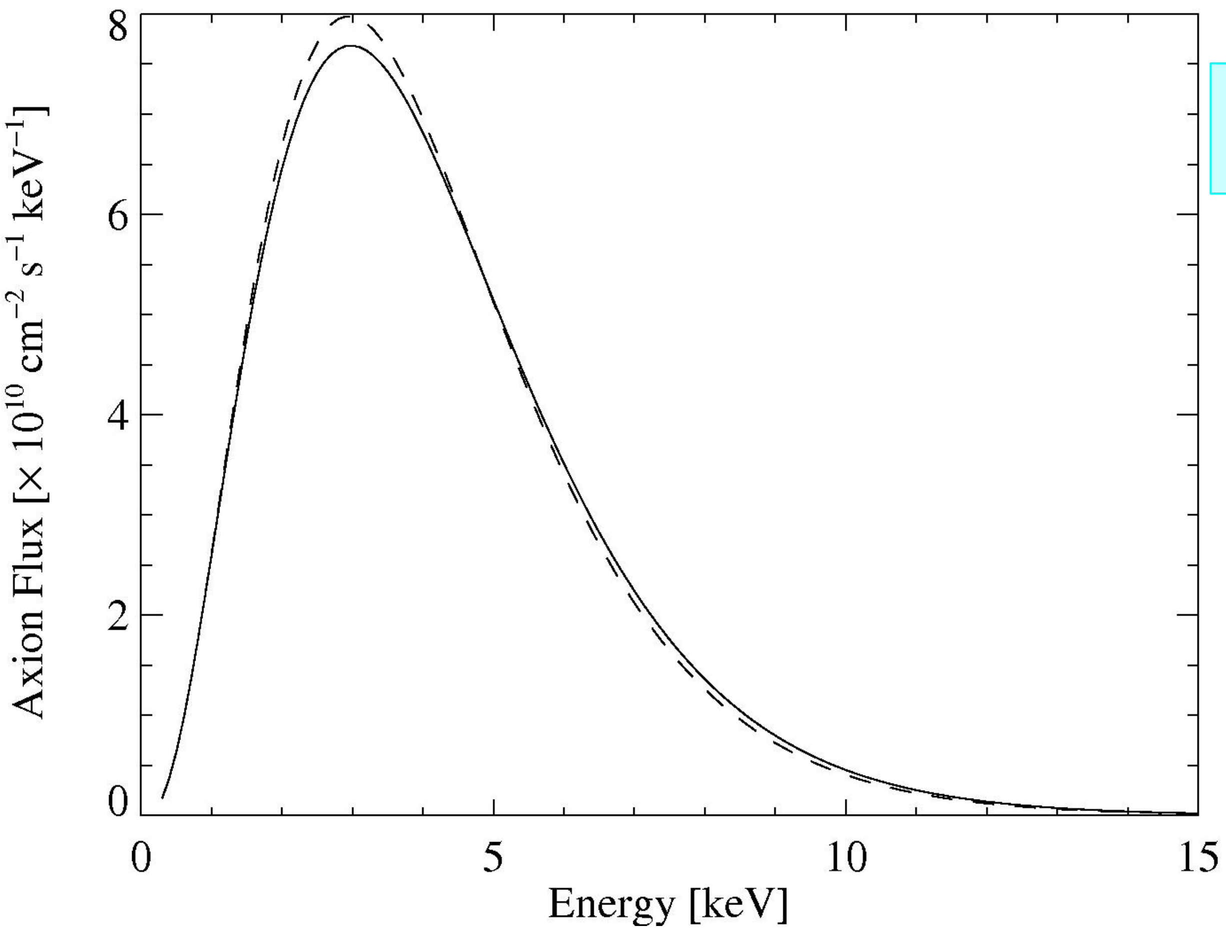
$$\omega_{pl}^2 = \frac{4\pi\alpha n_e}{m_e}$$

Axion luminosity

$$L_a = \int_0^{R_\odot} dr\, 4\pi r^2 \int \frac{2d^3k}{(2\pi)^3} \frac{\omega}{e^{\omega/T}-1} \Gamma_{\gamma\to a}$$

SOLAR AXION FLUX

CAST Collaboration: (hep-ex/0702006)



Axion-photon coupling

$$g_{10} = g_{a\gamma} / 10^{-10}\ GeV^{-1}$$

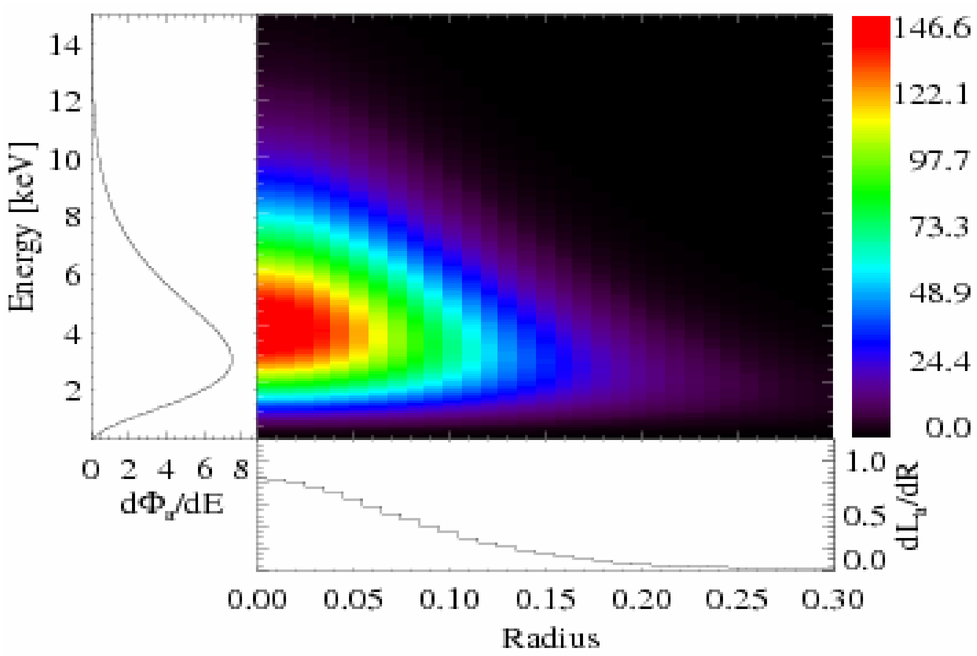
Solar axion flux

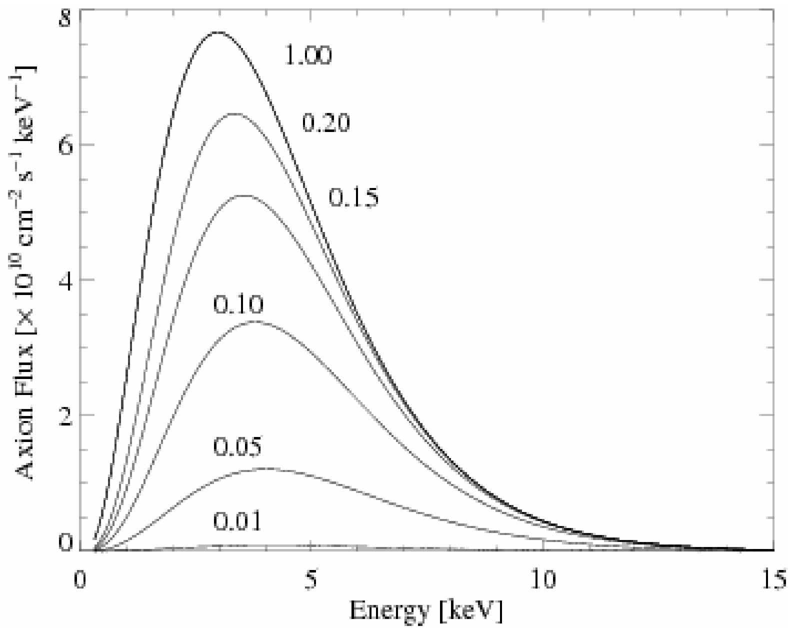
$$\phi_a = 3.75 \times 10^{11}\ cm^{-2} s^{-1} g_{10}^2$$

Solar axion luminosity

$$L_a = g_{10}^2 1.85 \times 10^{-3} L_{\odot}$$

SOLAR AXION RADIAL DISTRIBUTION



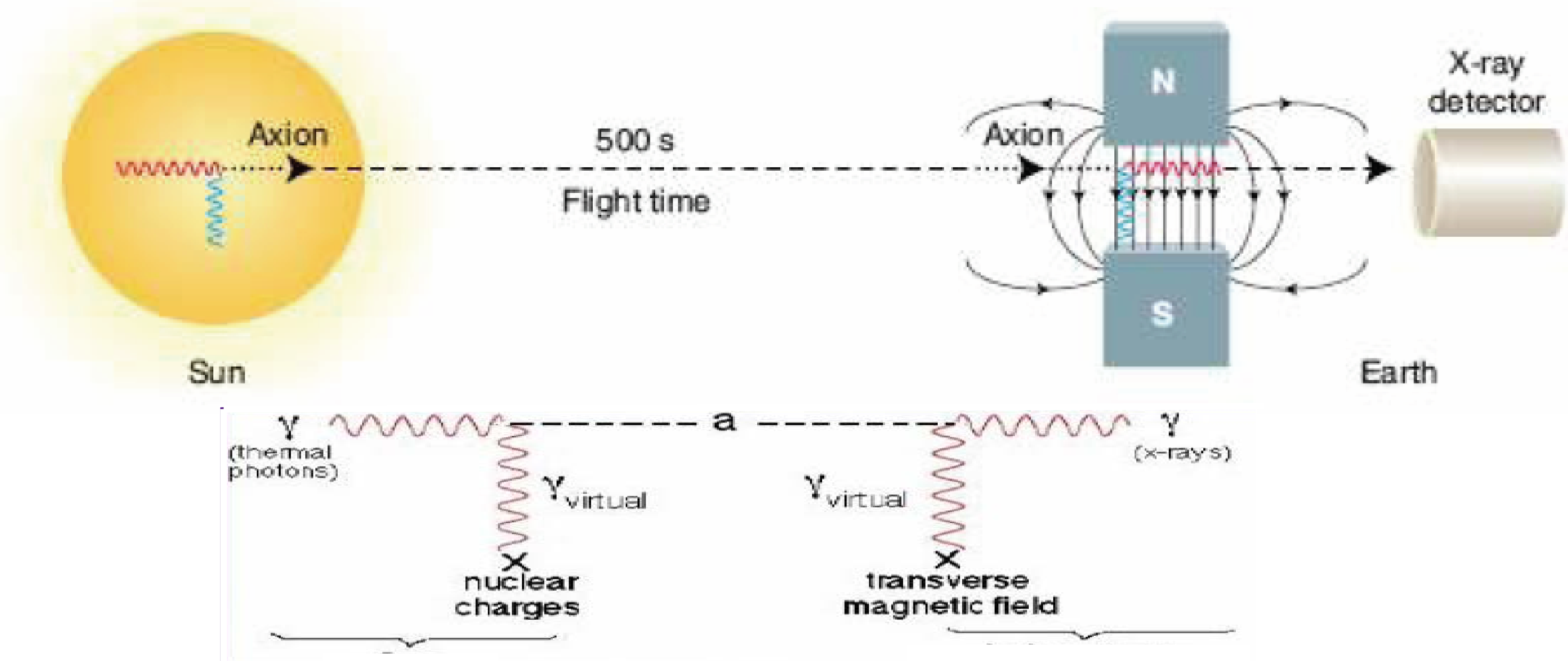


Most of the axion flux emerge from the inner 20% of the solar disk

SOLAR AXION SEARCHES

Searches for solar axions: Axion helioscopes

Primakoff process **Axion-photon oscillation**



Sun **Laboratory**

- **Tokyo axion helioscope ⟶ Results since 1998**
- **CERN Axion Solar Telescope (CAST) ⟶ Data since 2003**

Conversion probability axion-photon

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma}B}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right) \approx \left(\frac{g_{a\gamma}B}{2}L\right)^2 \quad \text{for } qL \ll 1$$

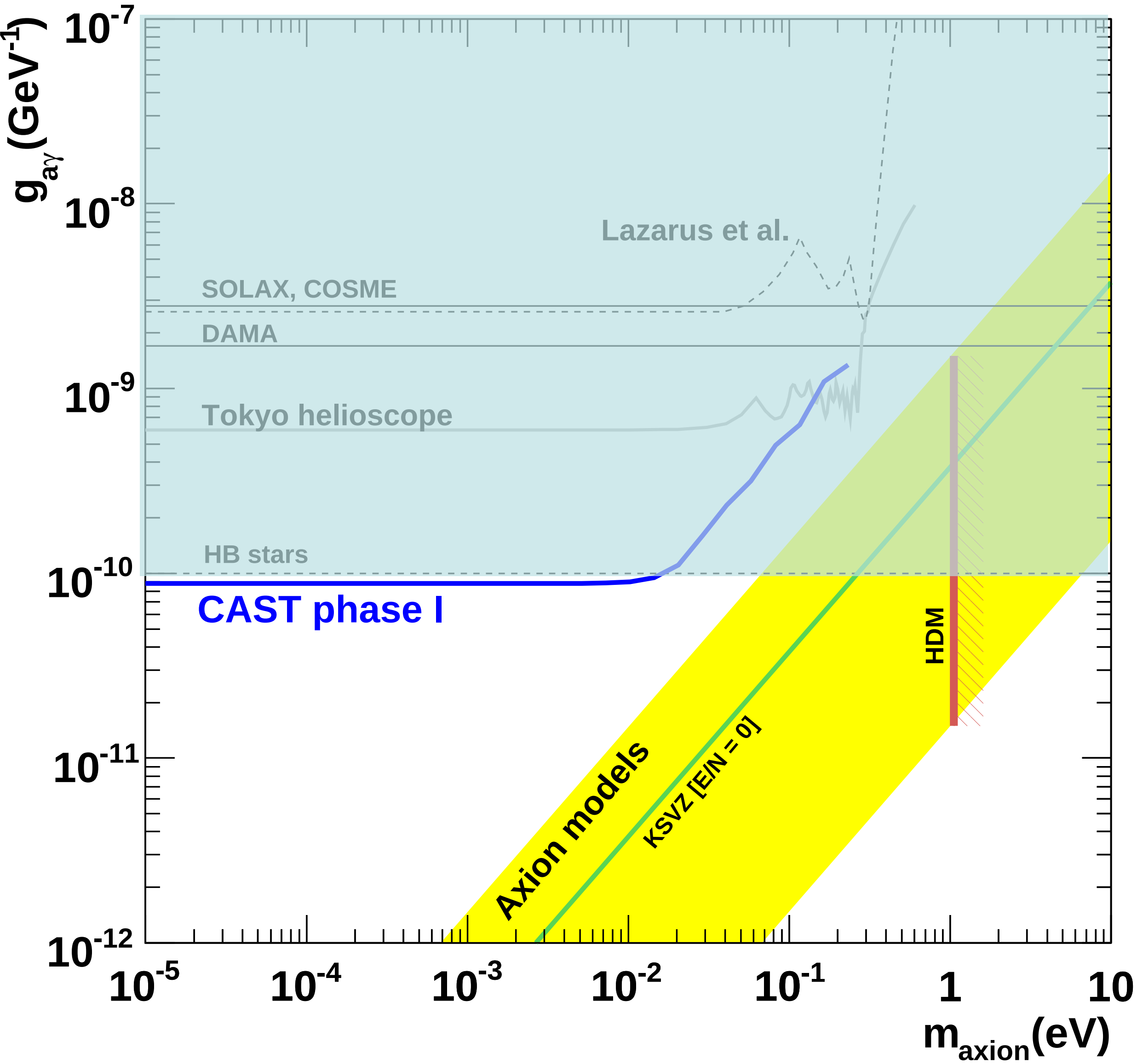
$$\simeq 1.7\times 10^{-17}\left(\frac{BL}{9T\times 9.26m}\right)^2 g_{10}^2$$

$$q = m_a^2 / 2E$$

X-rays flux at CAST

$$\phi_\gamma = 0.51\ cm^{-2} day^{-1} g_{10}^4 \left(\frac{L}{9.26\ m}\right)^2 \left(\frac{B}{9.0\ T}\right)^2$$

CAST EXCLUSION RANGE (2004 DATA)



CAST Collaboration: (hep-ex/0702006)

$g_{a\gamma} < 8.8 \times 10^{-11}$ GeV^{-1} at 95% CL for $m_a < 0.02$ eV

It supersedes the limit from the Globular cluster stars

PVLAS AXION-LIKE PARTICLE (ALP)

In 2006 the PVLAS collaboration has reported the observation of a rotation of a polarization plane of a laser propagating through a transverse magnetic field. This signal could be explained by the existence of a new axion-like particle (ALP) with

$$m_a \approx 10^{-3} eV$$

$$g_{a\gamma} \approx 2.5 \times 10^{-6} GeV^{-1}$$

[*Zavattini et al., Phys.Rev.Lett. 96, 110406 (2006)*]

In serious conflict with astrophysical constraints and CAST result !

Solar axion luminosity by Primakoff process

$$L_a = g_{10}^2 1.85 \times 10^{-3} L_{\odot}$$

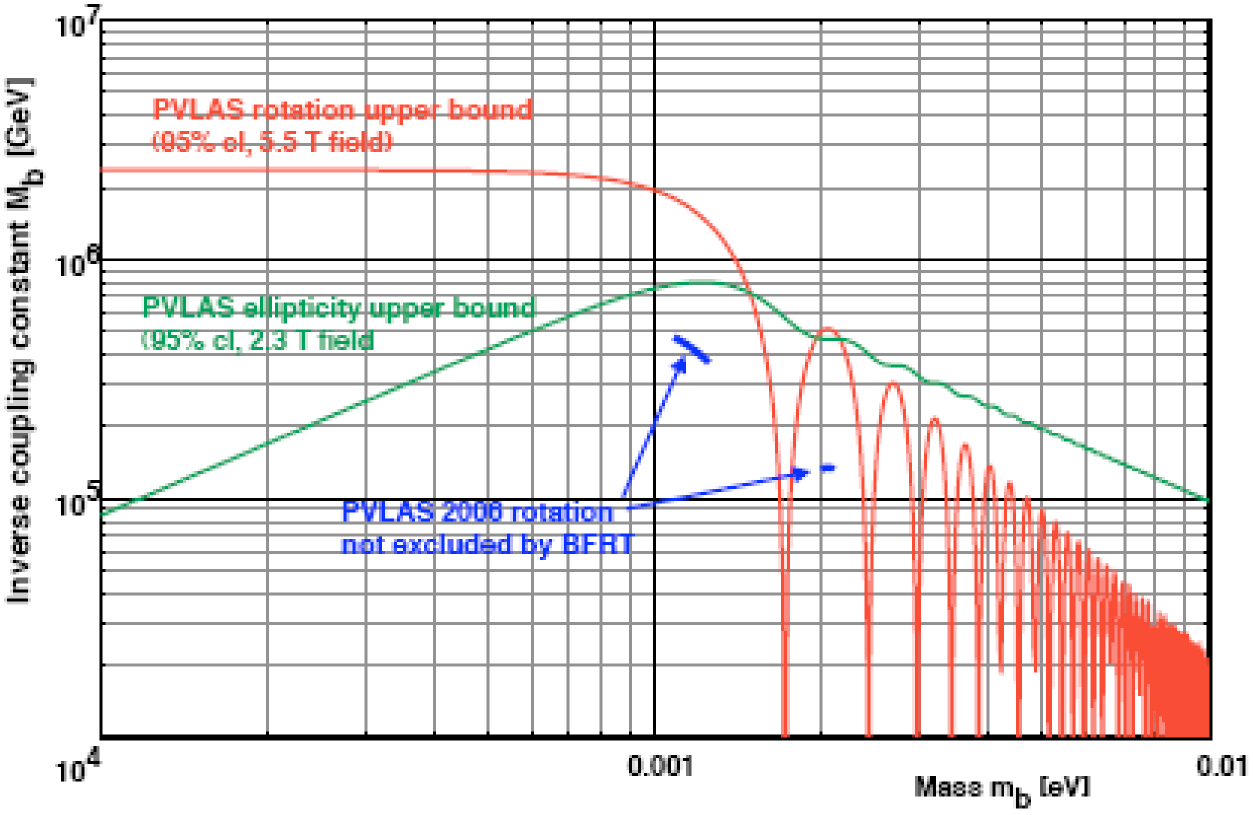
For $g_{a\gamma} = 2.5 \times 10^{-6}\ \mathrm{GeV}^{-1}$

$$L_a(PVLAS) \approx 10^6 L_{\odot}$$

It can not be accomodated in a self-consistent solar model

NEW PVLAS RESULTS

[E. Zavattini et al., 07063419 (hep-ex)]



Different new models have been proposed to evade astrophysical constraints

See, e.g.,

- E. Masso, and J. Redondo, hep-ph/0504202, hep-ph/0606063
- R. Mohapatra, S. Nashri, hep-ph/0610068
- I. Antoniadis, A. Boyarsky, O. Ruchayskiy, hep-ph/0606306
- ……………………………………..

Beyond PVLAS, could these models have some possible signature?

DYNAMICAL SUPPRESSION FROM MACROSCOPIC ENVIROMENTAL PARAMETERS

[*Jaeckel, Masso, Redondo, Ringwald, Takahashi, hep-ph/0610202*]

A possibility is to assume that axion-photon coupling can depend on an enviromental parameter η [*E. Masso, and J. Redondo, hep-ph/0606063; R. Mohapatra, S. Nashri, hep-ph/0610068*]

$$g_{a\gamma} \to g_{a\gamma}(\eta)$$

$$\eta = \omega_{pl}, T, k_s^2, \rho, q^2, \ldots\ldots$$

such that the production of ALPs is suppressed in stellar enviroment.

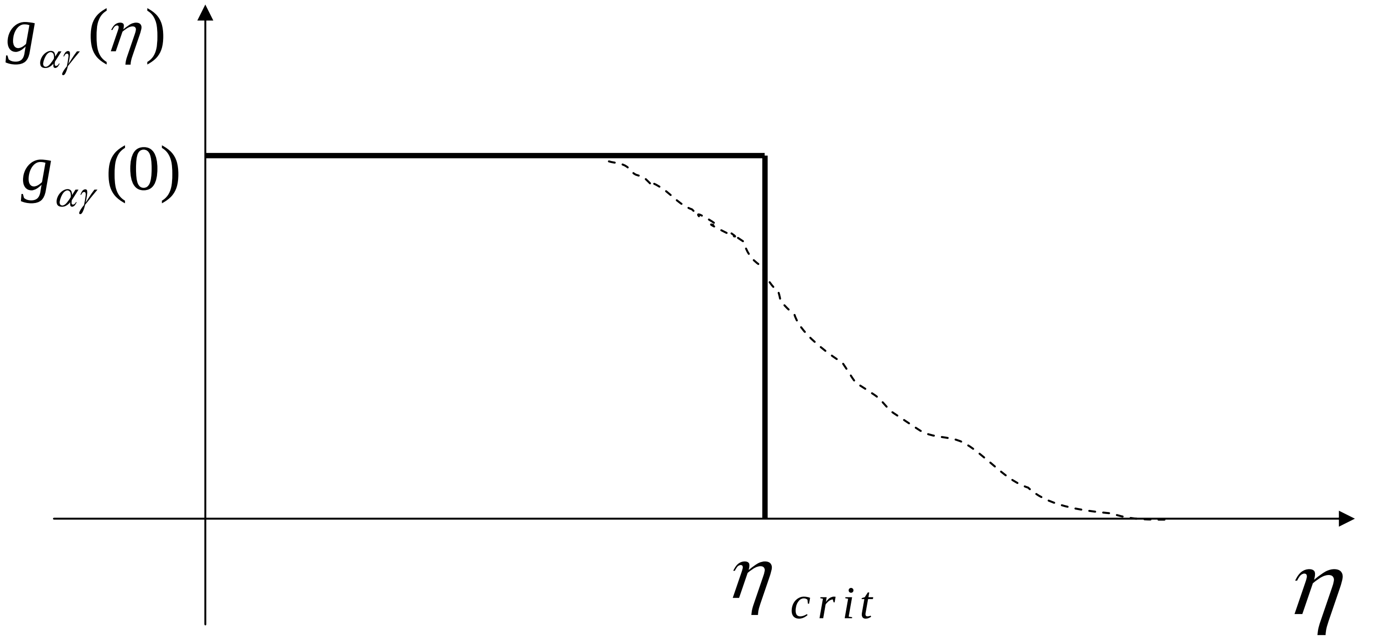
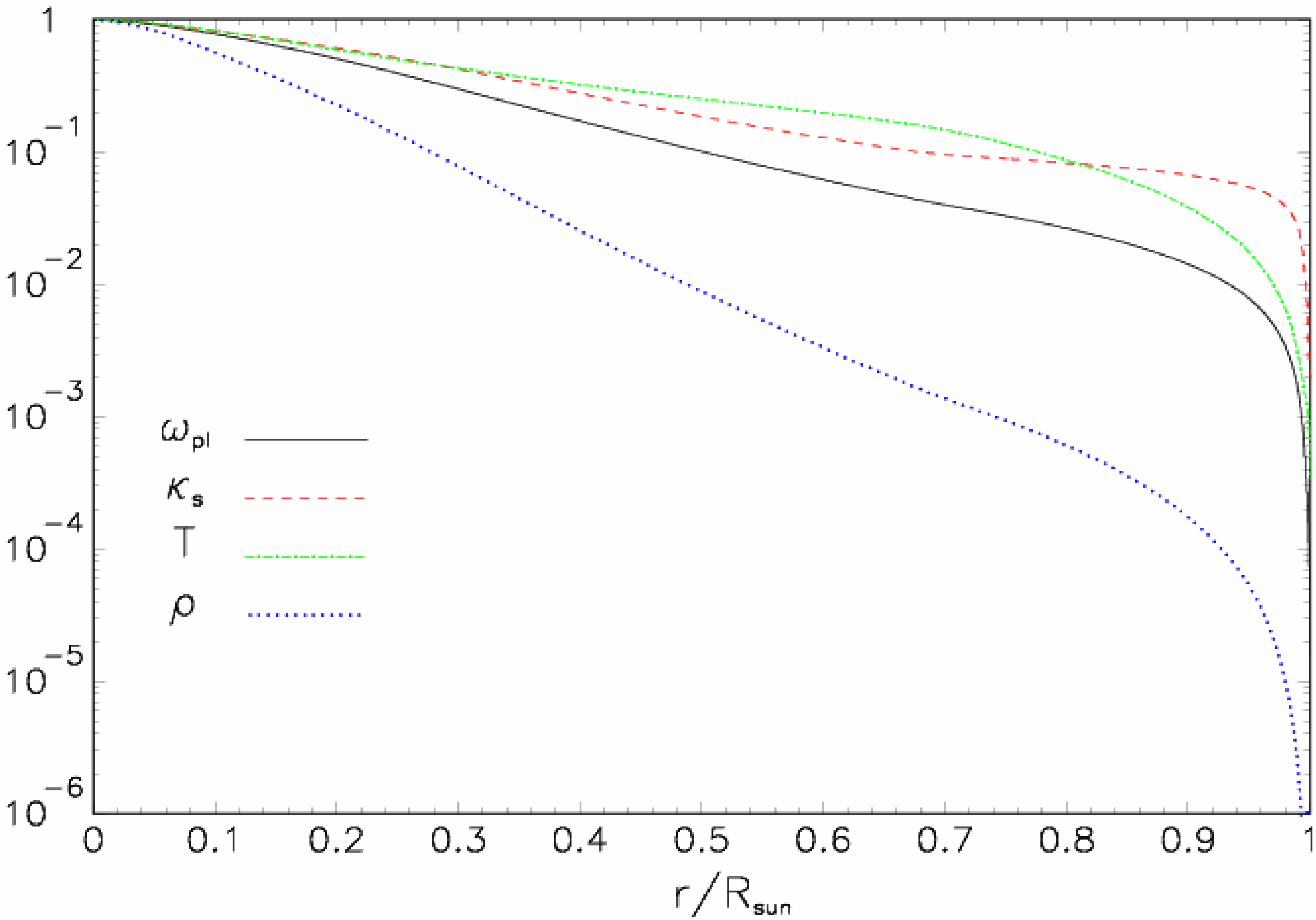


TABLE I. Comparison between the values of environmental parameters, such as the temperature T, typical momentum transfer q, plasma frequency ω_p, and matter energy density ρ, in the stellar plasma and in the PVLAS experiment. Other parameters to consider could be the Debye screening scale k_s, or, to name something more exotic, the neutrino flux, or the average electromagnetic field.

Env. param.	Solar core	HB core	PVLAS
T [keV]	1.3	8.6	~ 0
q^2 [keV^2]	~ 1	~ 1	$\sim 10^{-18}$
ω_p [keV]	0.3	2	0
ρ [g cm^{-3}]	1.5×10^2	10^4	$< 10^{-5}$



Saclay Solar Seismic model, Turck-Chieze et al., ApJ, 555:L69-L73, 2001

Referring to definiteness to PVLAS, if a flux of ALPs from a stellar plasma is suppressed by a factor S, to have a consistent scenario

$$\left(S\, g^2_{PVLAS}\right) g^2_{PVLAS} < g^2_{CAST}\, g^2_{CAST}$$

$$S < \left(\frac{g_{CAST}}{g_{PVLAS}}\right)^4 \sim 10^{-20}$$

In [*Jaeckel, Masso, Redondo, Ringwald, Takahashi, hep-ph/0610202*] the suppression factor S has been evaluated as function of R_{crit}

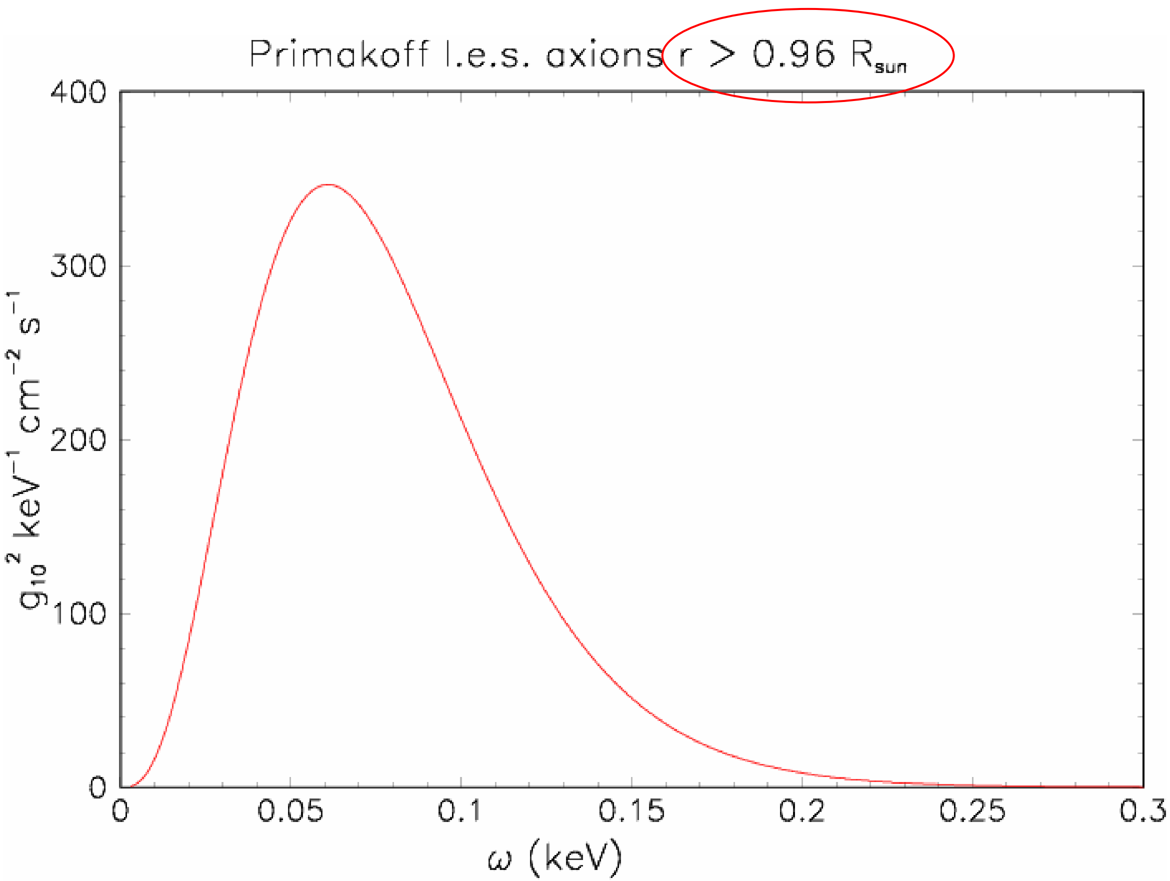
TABLE II. Several values of $S(\omega_0 = 1\text{ keV}, R_{crit})$ with their respective values of the suppression scales η_{crit}.

$R_{crit}/R_\odot$	T_{crit} [keV]	ρ_{crit} [g cm^{-3}]	$\omega_{P,crit}$ [keV]	S
0	1.35	150	0.3	1
0.2	0.81	35	0.16	0.67
0.5	0.34	1.3	0.03	0.08
0.7	0.2	0.2	0.01	2×10^{-3}
0.8	0.12	0.09	0.008	2×10^{-5}
0.85	0.08	0.05	0.006	2×10^{-7}
0.9	0.05	0.03	0.004	4×10^{-11}
0.95	0.025	0.009	0.0025	$\sim 10^{-20}$

Critical enviromental parameters are quite small, and R_{crit} is in the region close to Sun surface.

LOW ENERGY SOLAR AXION FLUX

If $g_{a\gamma}$ switches to the a larger value in outer regions of Sun, a low energy axion flux could result



$$L_a = 2\times10^{-15} g_{10}^2 L_\odot$$

$$\phi_a \approx 30 g_{10}^2 \text{ cm}^{-2} s^{-1}$$

For $g_{a\gamma} = 2.5\times10^{-6}$ GeV^{-1}

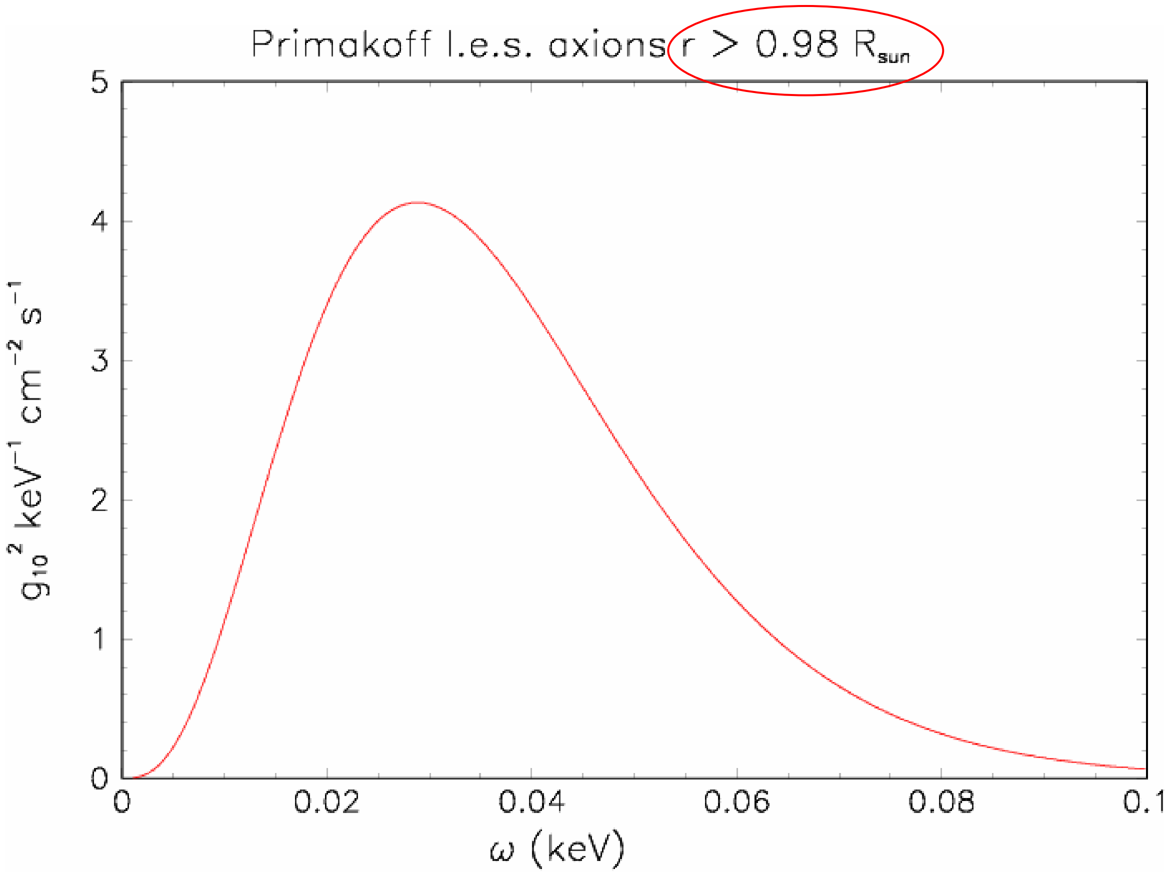
$$L_a \simeq 1.7\times10^{-6} L_\odot$$

$$\phi_a = 1.8\times10^{10} cm^{-2} s^{-1}$$

$$\phi_\gamma \approx 190 cm^{-2} s^{-1}$$

@ CAST

~90-95 % ionization



~only H ionized

$$L_a = 7 \times 10^{-18} g_{10}^2 L_\odot$$

$$\phi_a \approx 0.17 g_{10}^2 cm^{-2} s^{-1}$$

For $g_{a\gamma} = 2.5 \times 10^{-6}$ GeV^{-1}

$$L_a \simeq 4 \times 10^{-9} L_\odot$$

$$\phi_a \simeq 10^8 cm^{-2} s^{-1}$$

$$\phi_\gamma \simeq 1\, cm^{-2} s^{-1}$$

@ CAST

SOLAR AXIONS FROM B-FIELD CONVERSION

[*Calculation by G.Raffelt*]

In addition to the Primakoff process, axion can be produced by photon conversions in large-scale coherent B-fields.

Photon-axion conversion probability

$$P_{a\to\gamma} = \left(\Delta_{a\gamma} L\right)^2 \frac{\sin^2(\Delta_{osc} L/2)}{\left(\Delta_{osc} L/2\right)^2}$$

$$\Delta_{a\gamma} = \frac{g_{a\gamma} B}{2}$$

$$\Delta_{osc} = \left[4\Delta_{a\gamma}^2 + \left(\frac{\omega_{pl}^2 - m_a^2}{2\omega}\right)^2\right]^{1/2}$$

At resonance, $m_a \approx \omega_{pl}$ the resonant oscillation length is

$$L_{res} = \frac{2\pi}{\Delta_{osc}} = \frac{2\pi}{g_{a\gamma} B} = \frac{6.3\times 10^{12}\, cm}{g_{10} B_4}$$

$$B_4 = \frac{B}{10^4 G}$$

which is greater than the photon mean free path in the Sun (cm): photons scatter before an oscillation cycle is complete

Conversion rate

$$\Gamma_{\gamma \to a} = P_{a \to \gamma} L^{-1}$$

L is the photon mean-path in Sun

SOLAR AXION FLUX

Even slightly off resonance the transition rate is very much smaller than the on-resonance rate. For a given axion mass only a small fraction of solar volume is close to the resonance condition

$$L_a = 96\varsigma_5 \left(\frac{g_{a\gamma} B}{m_a} \right)^2 R_{res}^2 R_e T_{res}^5$$

$$\phi_a = 4 \left(\frac{g_{a\gamma} B}{m_a} \right)^2 R_{res}^2 R_e \frac{\omega^3}{e^{\omega / T_{res}} - 1}$$

where $R_e = \left| \frac{d \ln n_e}{dr} \right|_{res}^{-1}$

For a simplified (exponential) solar axion model one obtains

$$\frac{L_{a,B}}{L_{a,P}} = 5\times 10^{-4} B_4^2 \left(\frac{m_a}{451\ \mathrm{eV}}\right)^{4/3} \log_{10}^2\left(\frac{m_a}{451\ \mathrm{eV}}\right)$$

After the integration over the entire Sun, the Primakoff effect dominates. However, in the region where the resonance condition is satisfied there could be a significant magnetic conversion effect.

SOLAR MAGNETIC FIELD

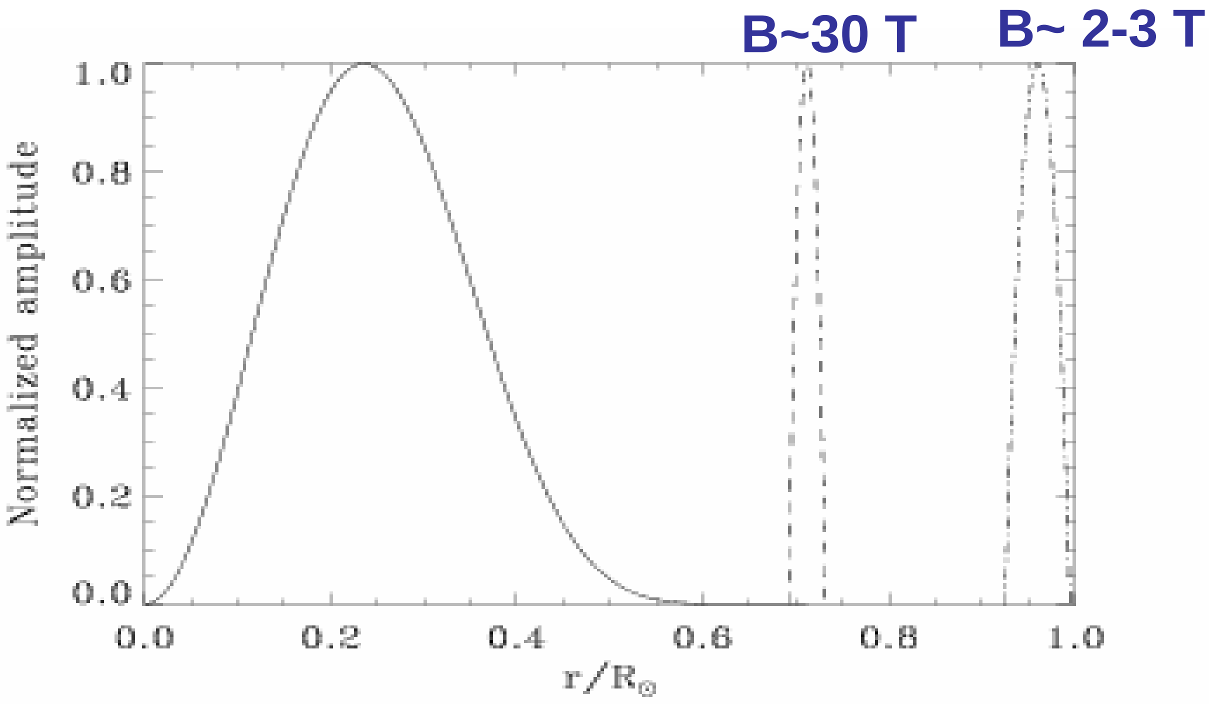
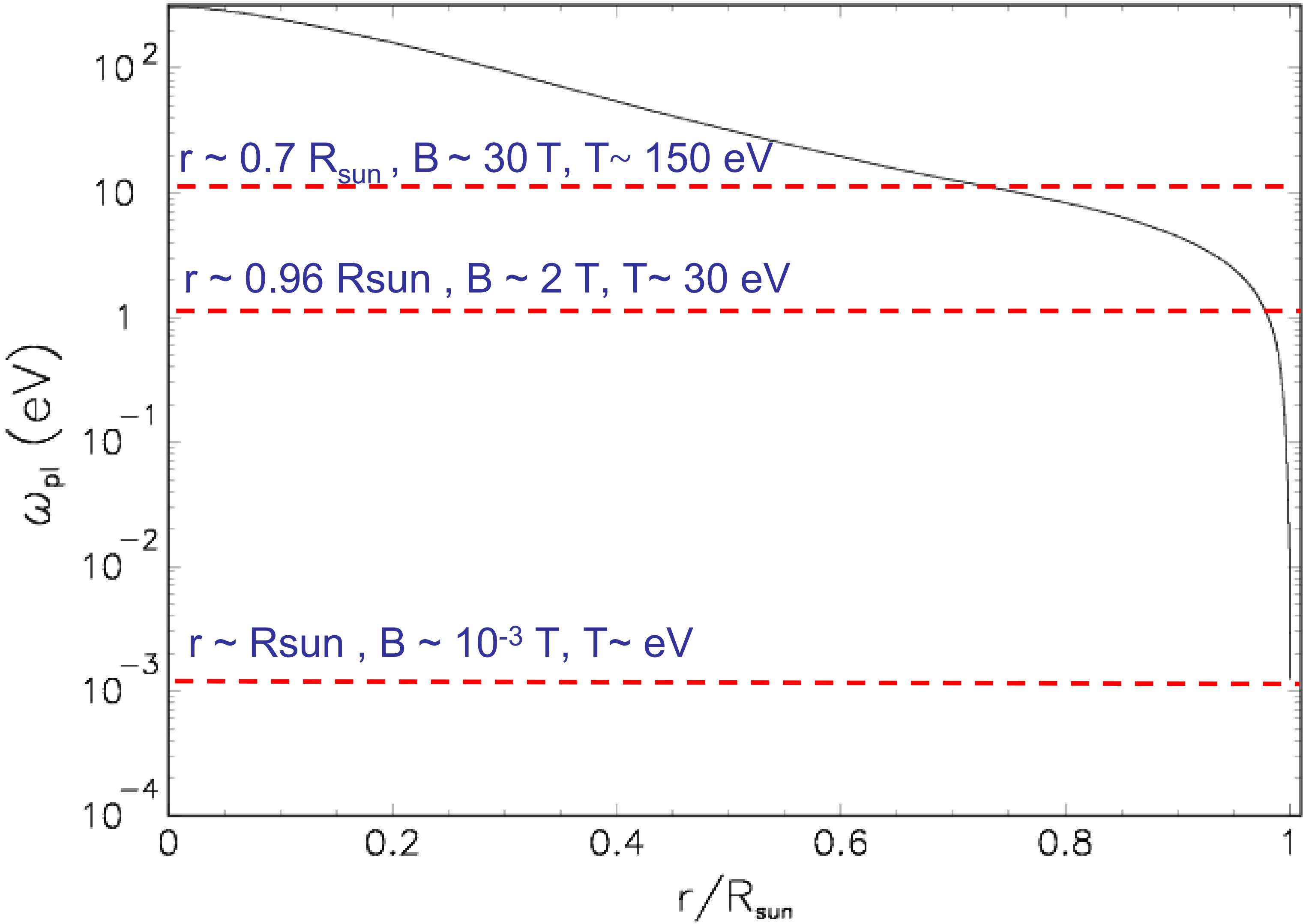
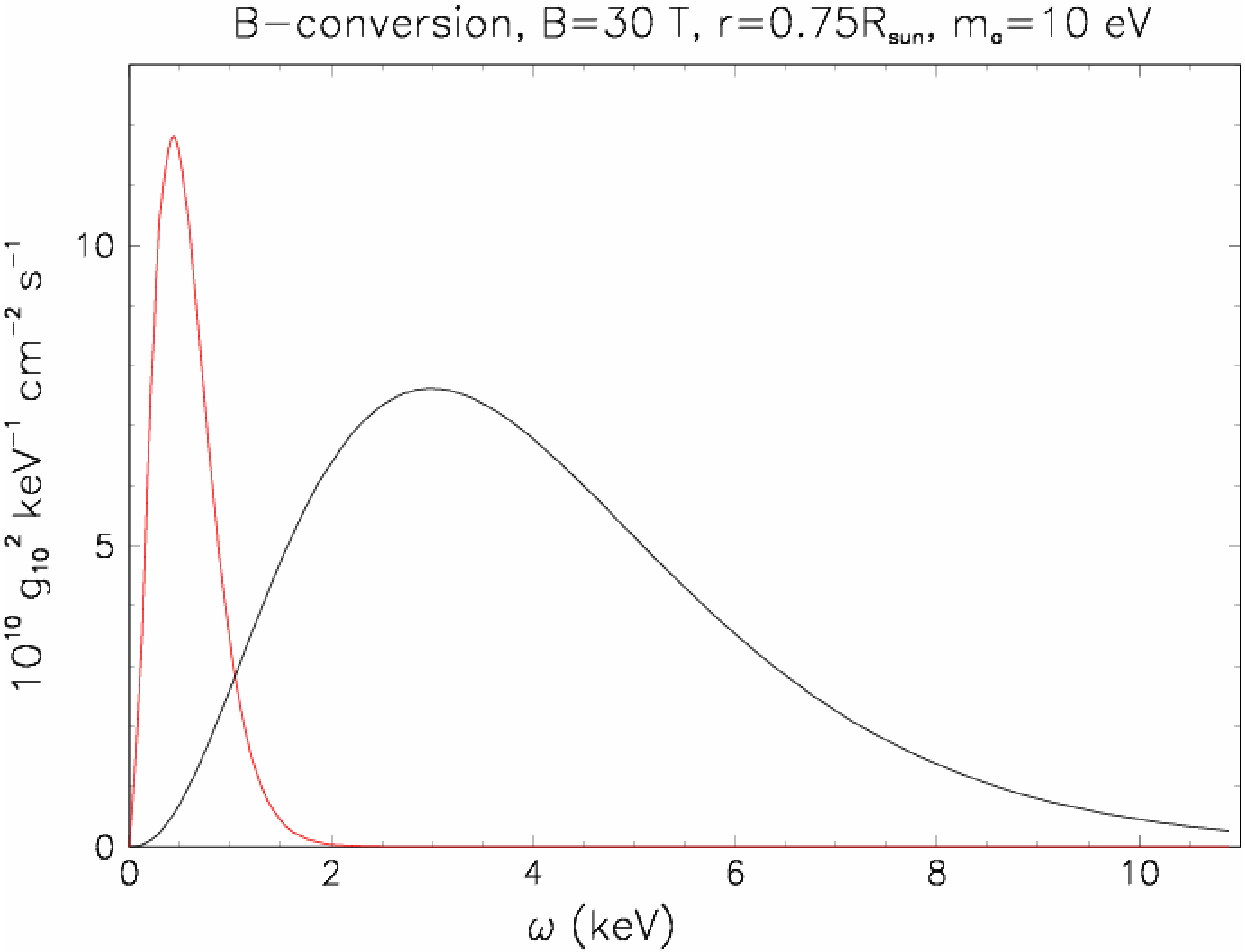


FIG. 7.—Magnetic fields simulated: in the radiative interior (*solid curve*), in the tachocline (*dashed curve*), in the upper layers (*dot-dashed curve*). The amplitudes of the fields have been normalized by their maximum intensity.

[*S.Couvidat, S. Turck-Chieze, A. Kosovichev, APJ 599, 1434 (2003)*]

RESONANCE CONDITION ($\omega_{pl}=m_a$)



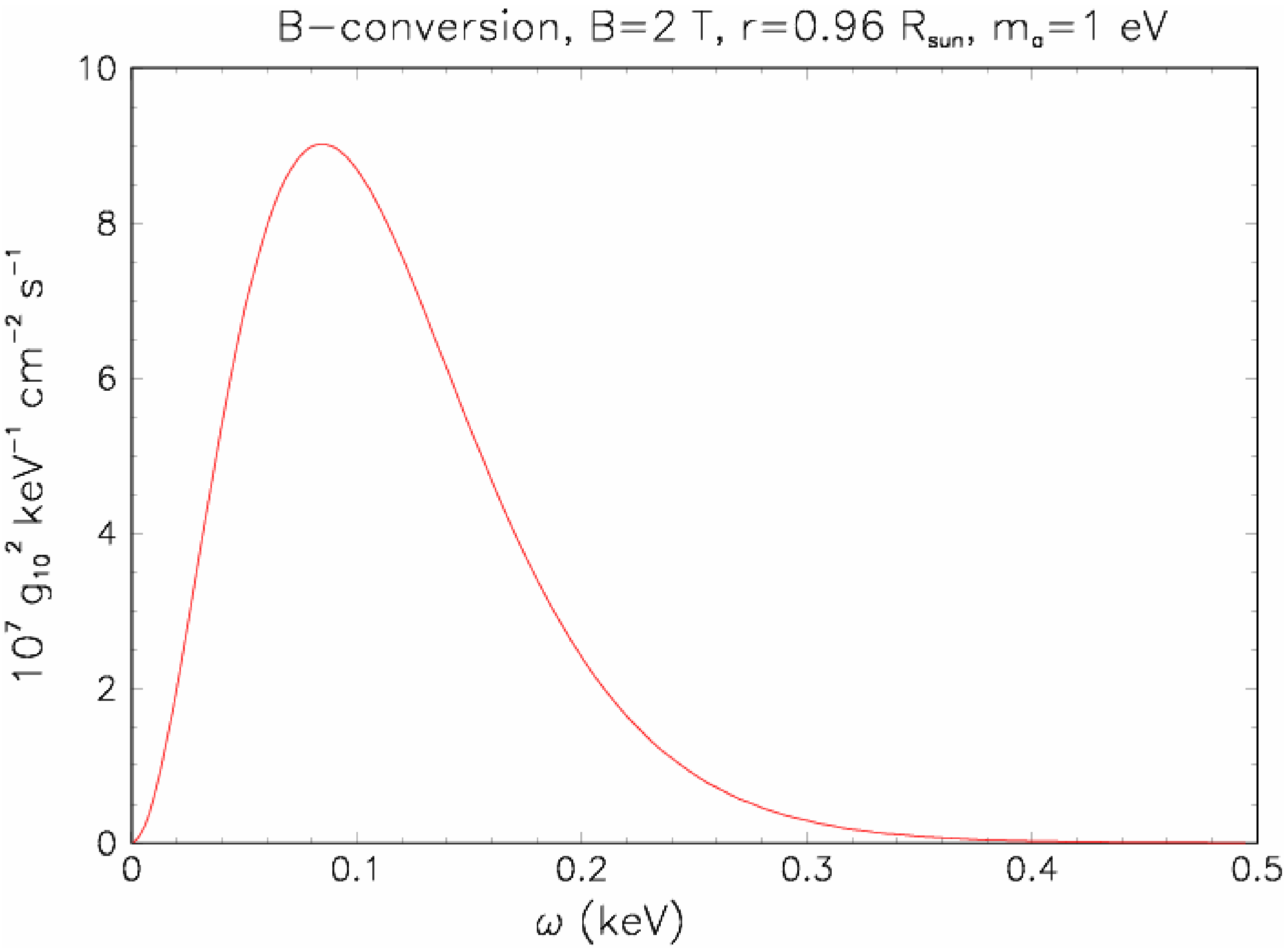


$$L_B \approx 6\times10^{-5} g_{10}^2 L_\odot$$

$$\phi_a \approx 8\times10^{10} g_{10}^2 \ cm^{-2} s^{-1}$$

$$\phi_\gamma \approx 1.3\times10^{-6} \ g_{10}^4 cm^{-2} s^{-1}$$

2 ev/day vs. 8 ev/day Primakoff in CAST

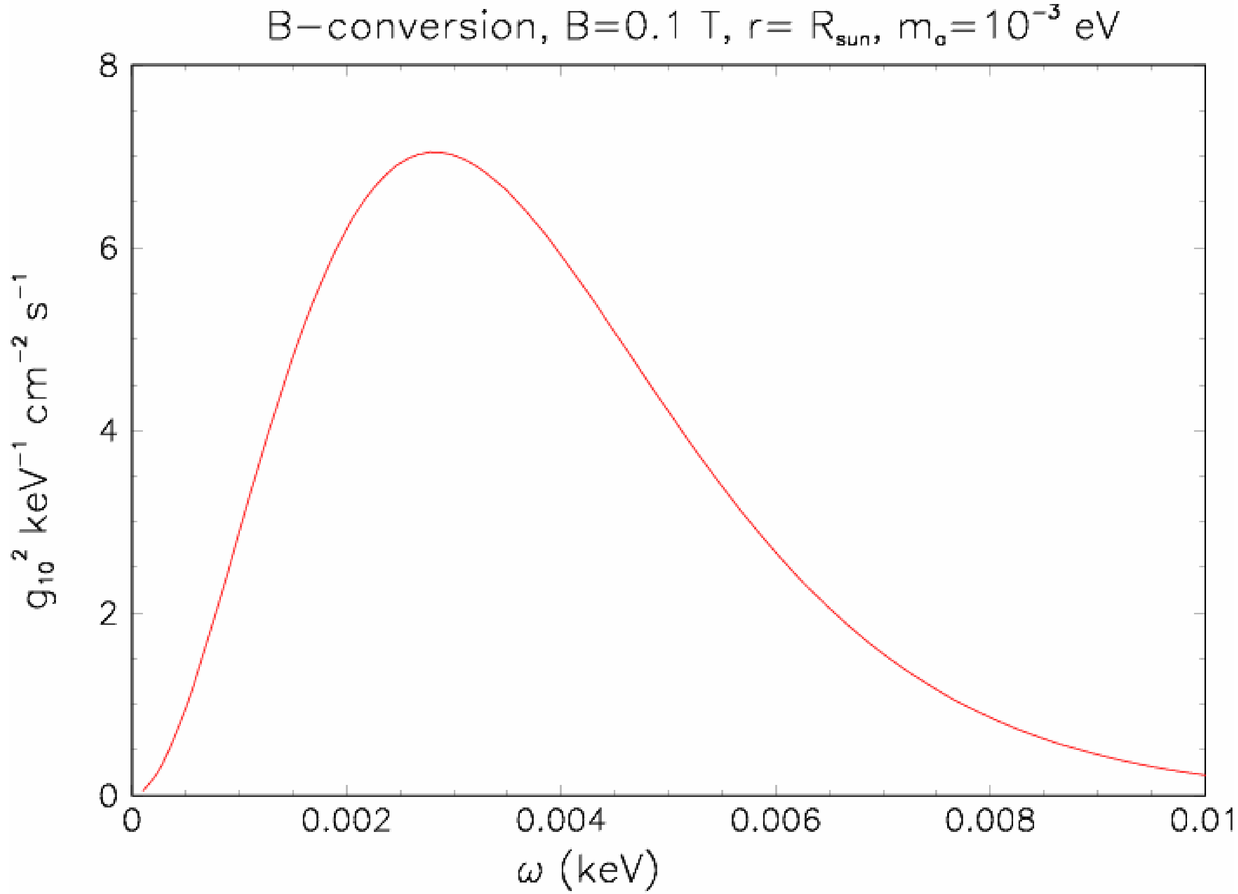


$$L_B \approx 1.6\times10^{-9}\, g_{10}^2 L_\odot$$

$$\phi_a \approx 1.2\times10^{7}\, g_{10}^2 \ \mathrm{cm}^{-2} s^{-1}$$

$$\phi_\gamma = 2\times10^{-10}\, g_{10}^4 \ \mathrm{cm}^{-2} s^{-1}$$

For $g_{a\gamma}=10^{-8}$ GeV^{-1} : 0.3 ev/s in CAST



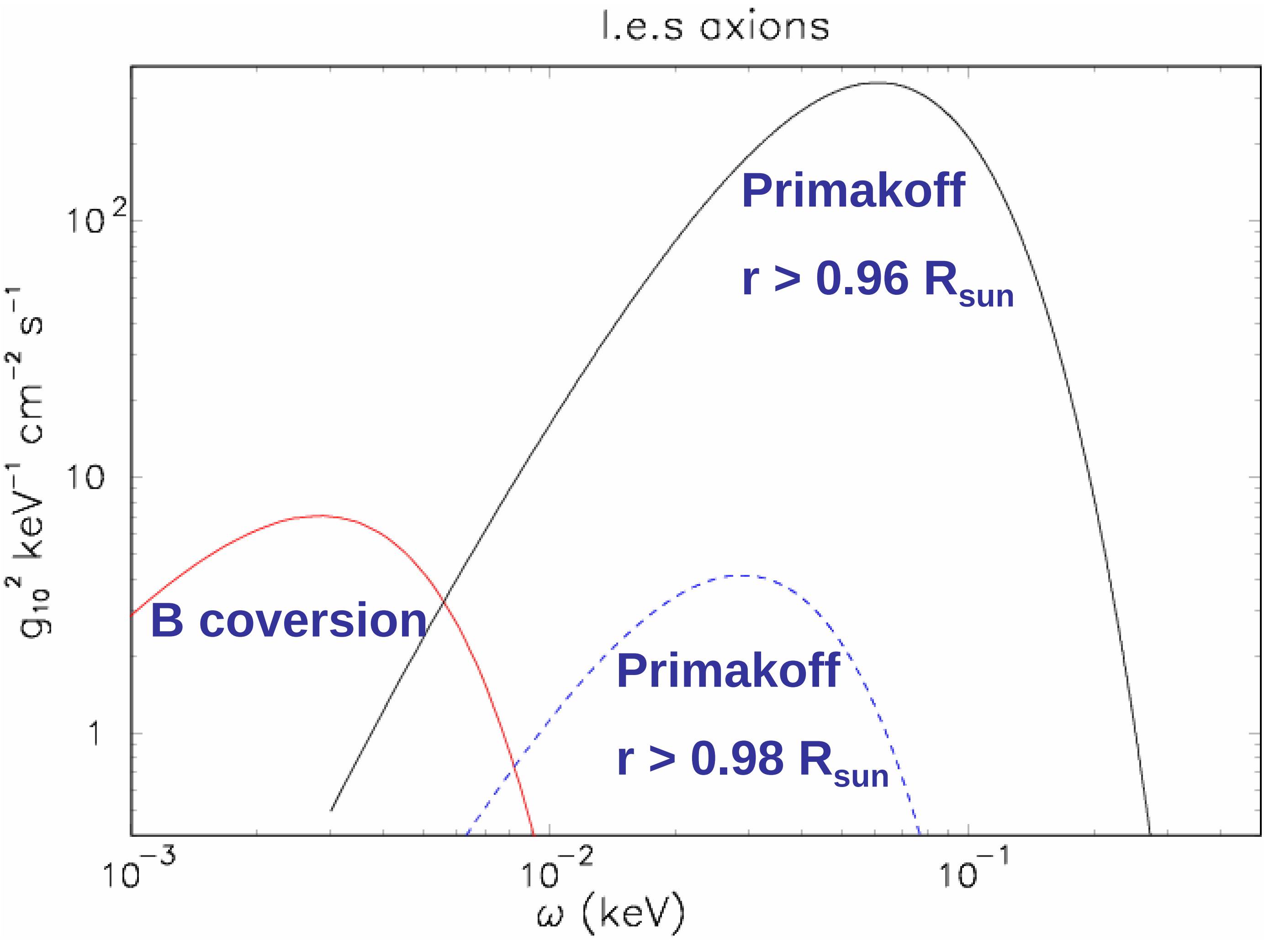
$$L_B = 1.4\times10^{-19}\, g_{10}^2 L_\odot$$

$$\phi_a = 3.2\times10^{-2}\, g_{10}^2 \ \mathrm{cm}^{-2} s^{-1}$$

$$\phi_\gamma = 5\times10^{-19}\, g_{10}^4 \ \mathrm{cm}^{-2} s^{-1}$$

For $g_{a\gamma}$= 2.5 ×10^{-6} GeV^{-1} : 3 ev/s in CAST

LOW ENERGY SOLAR AXIONS



CONCLUSIONS

We presented a first estimation of low-energy solar axion flux, considering both Primakoff production and B-field photon-axion conversions.

An observable axion flux could be produced below 100 eV, if some running of the axion-photon constant would happen in outer regions of the Sun.

Looking at low energy axions could show signatures of some of the PVLAS-inspired models

We wait diligently for l.e.s. axions!