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Axion emissivity from photon conversions in the solar magnetic fields

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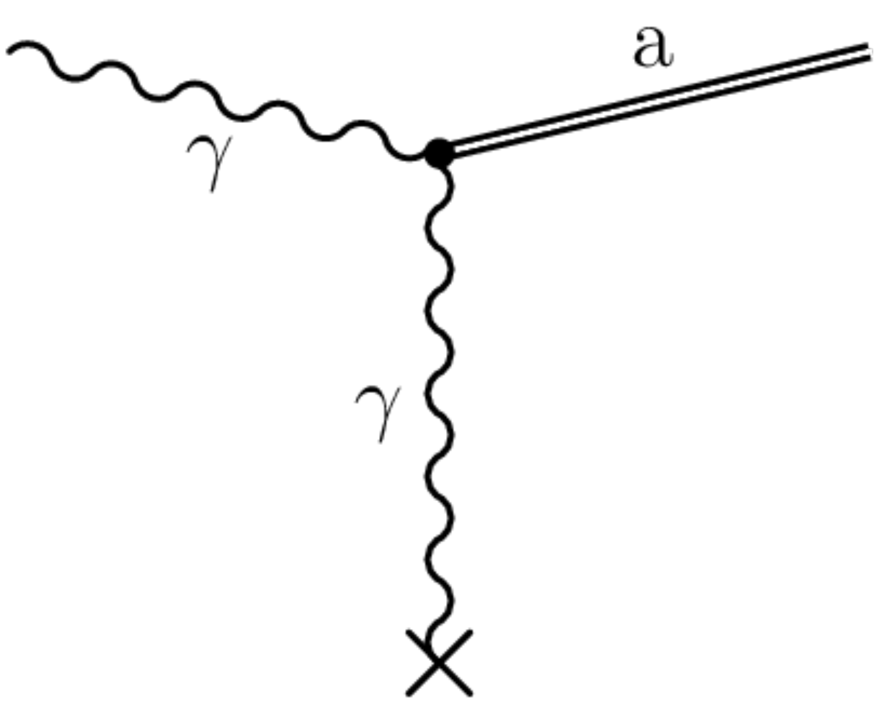
ALP PRODUCTION IN SUN

The two-photons coupling axion Lagrangian

$$\mathscr{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} a \tilde{F}^{\mu\nu} F_{\mu\nu} = g_{a\gamma} a \overrightarrow{E} \cdot \overrightarrow{B}$$

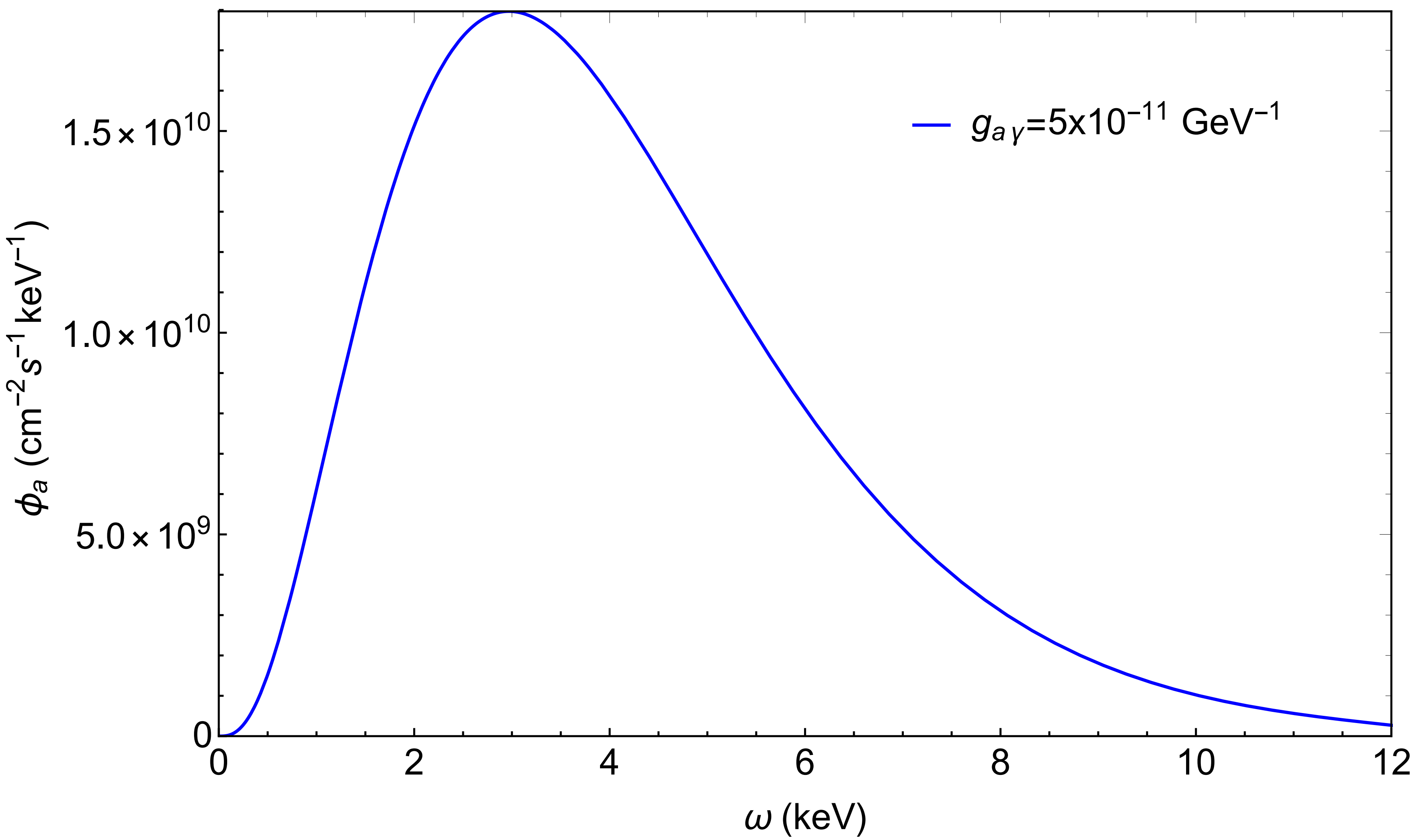
This allows for two photon-ALP conversion processes.

- Primakoff effect: photon-ALP transition in external static **E** or **B** field.
- Solar magnetic fields can provide a large coherent transition rate over the solar interior.



SOLAR ALP FLUX FROM PRIMAKOFF PRODUCTION

CAST Collaboration [hep-ex/0702006]



ALP-photon coupling

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

Average ALP energy

$$\langle\omega\rangle = 4.15\ \mathrm{keV}$$

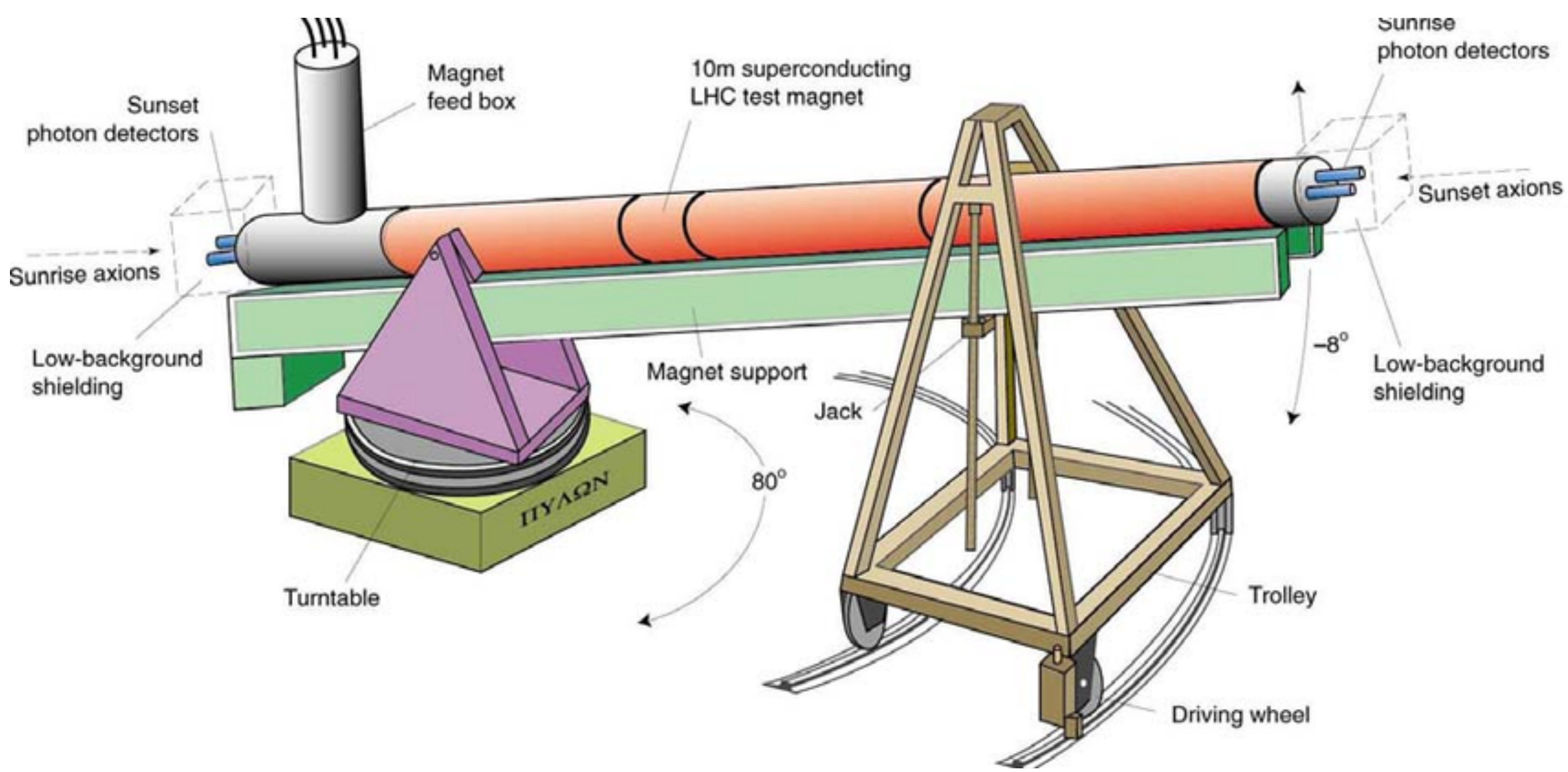
Solar ALP luminosity

$$L_a = 1.72 \times 10^{-3}\ g_{10}^2\ L_\odot$$

Solar ALP flux

$$\Phi_a = 3.43 \times 10^{11}\ g_{10}^2\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

The CAST experiment at CERN



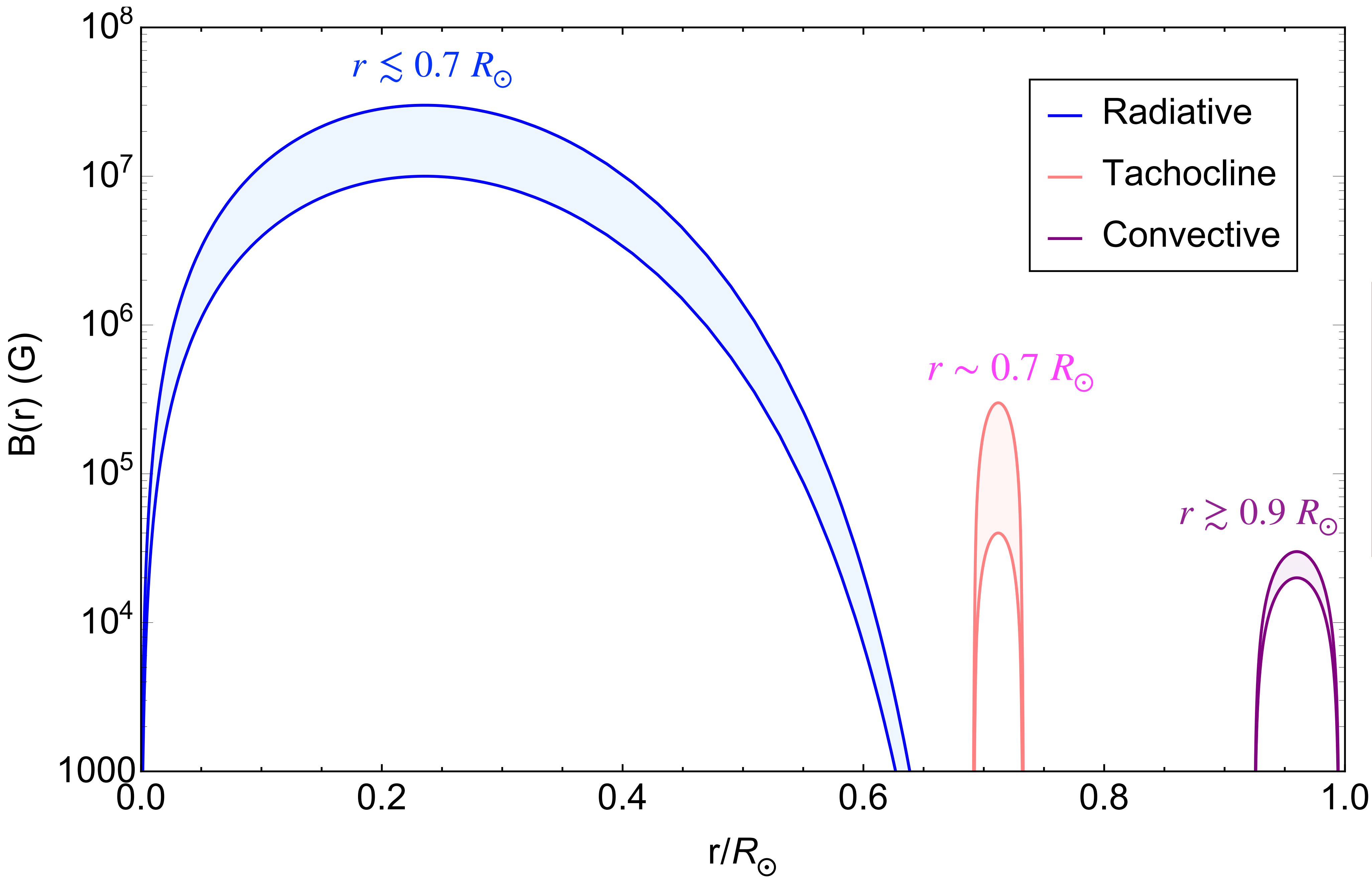
- CERN Axion Solar Telescope (CAST) is a third generation helioscope.
- The magnet tracks the Sun about 3 hours per day.
- Solar ALPs are converted into a beam of photons in the cavity filled with a magnetic field and then detected at one X-ray detectors.

- CAST set the bound for $m_a < 0.02$ eV [Anastassopoulos *et al.* (CAST), Nature Phys. **13** (2017),584]:

$$g_{a\gamma} < 0.66 \times 10^{-10}\ \mathrm{GeV}^{-1}$$

SOLAR MAGNETIC FIELDS

Large-scale coherent magnetic fields in the Sun are predicted by the Seismic solar models. These are generated by the electric currents in the solar plasma. [Antia *et al.*, Astron. Astrophys. **360** (2000), 335-344, Couvidat *et al.*, Astrophys. J. **599** (2003), 1434, Dzitko *et al.*, Astrophys. J. **447** (1995), 428-442, Gough and Thompson, MNRAS vol. **242** (1990), 25-55]



$B_{\rm rad} \in [1;3] \times 10^7$ G

$B_{\rm tach} \in [3;5] \times 10^5$ G

$B_{\rm conv} \in [2;3] \times 10^4$ G

PHOTON-ALP CONVERSIONS IN SOLAR MAGNETIC FIELDS

ALPs can be produced in the Sun also through photon conversions in large-scale coherent B-fields.

Photon transverse modes [Raffelt and Stodolsky, Phys. Rev. D, **37**, 1237 (1988)]

For transverse photons (TP) the TP-ALP conversion probability after the beam has traveled a distance z in the B-field is:

$$P(\gamma_T \to a) = (\Delta_{a\gamma}^T)^2 \frac{\sin^2(\Delta_{\mathrm{osc}}^T z/2)}{(\Delta_{\mathrm{osc}}^T z/2)^2}$$

where

$$\Delta_{a\gamma}^T = \frac{g_{a\gamma} B_T}{2} \quad , \quad \Delta_{\mathrm{osc}}^T = \sqrt{4 {\Delta_{a\gamma}^T}^2 + (\Delta_{\mathrm{p}} - \Delta_a)^2}$$

$$\Delta_{\mathrm{p}} = -\frac{\omega_{\mathrm{p}}^2}{2\omega} \quad , \quad \Delta_a = -\frac{m_a^2}{2\omega}$$

Photon longitudinal modes [Terças et al., Phys. Rev. Lett. **120**, no.18, 181803 (2018)]

For longitudinal photons (LP) the LP-ALP conversion probability is:

$$P(\gamma_T \to a) = (\Delta_{a\gamma}^L)^2 \frac{\sin^2(\Delta_{\mathrm{osc}}^L z/2)}{(\Delta_{\mathrm{osc}}^L z/2)^2}$$

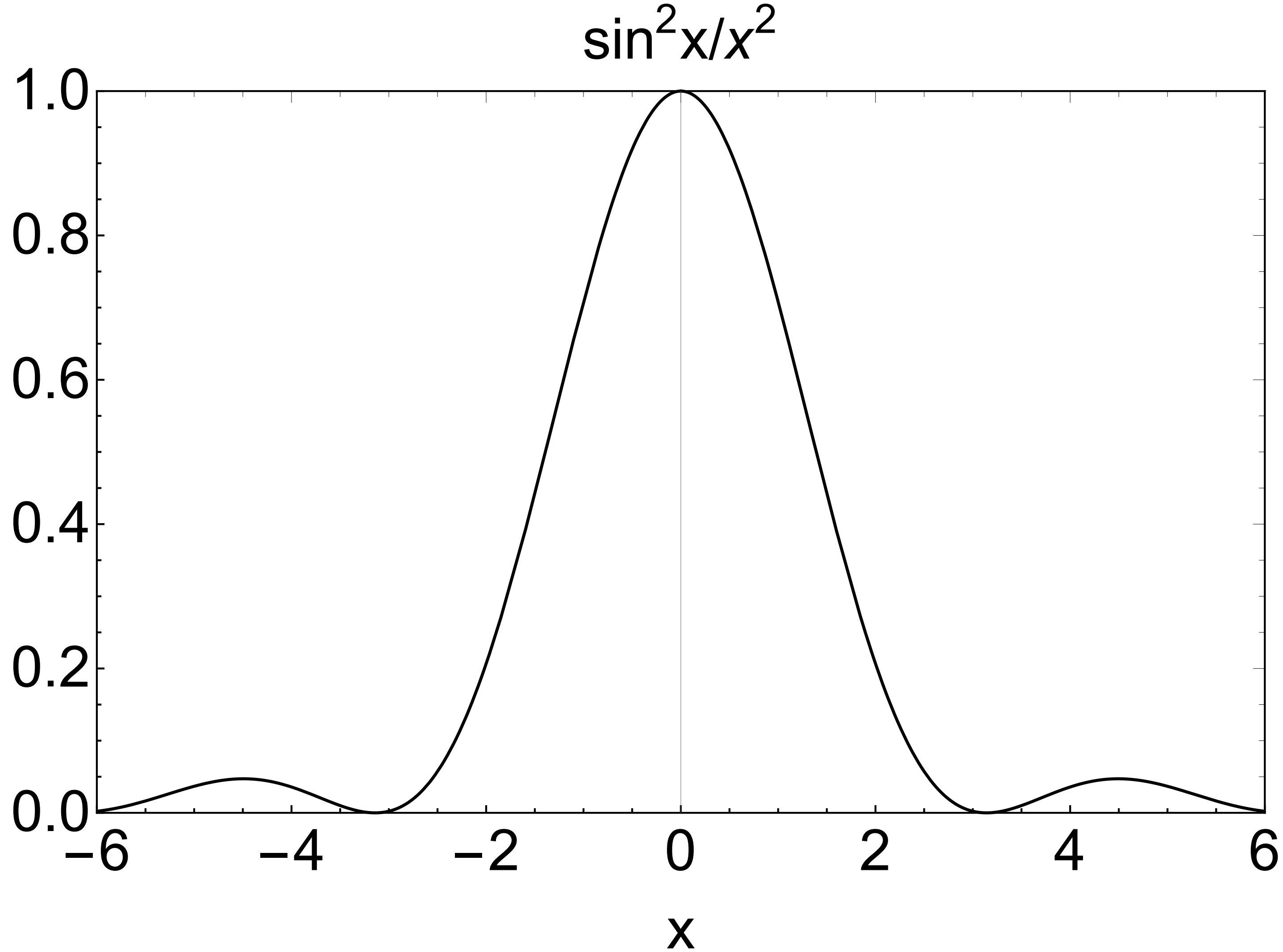
where

$$\Delta_{a\gamma}^L = \frac{g_{a\gamma} B_L}{2} \quad , \quad \Delta_{\mathrm{osc}}^L = \sqrt{4 {\Delta_{a\gamma}^L}^2 + (\omega_p - \omega_a)^2}$$

We have defined the **plasma frequency** :

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

Resonant conversions

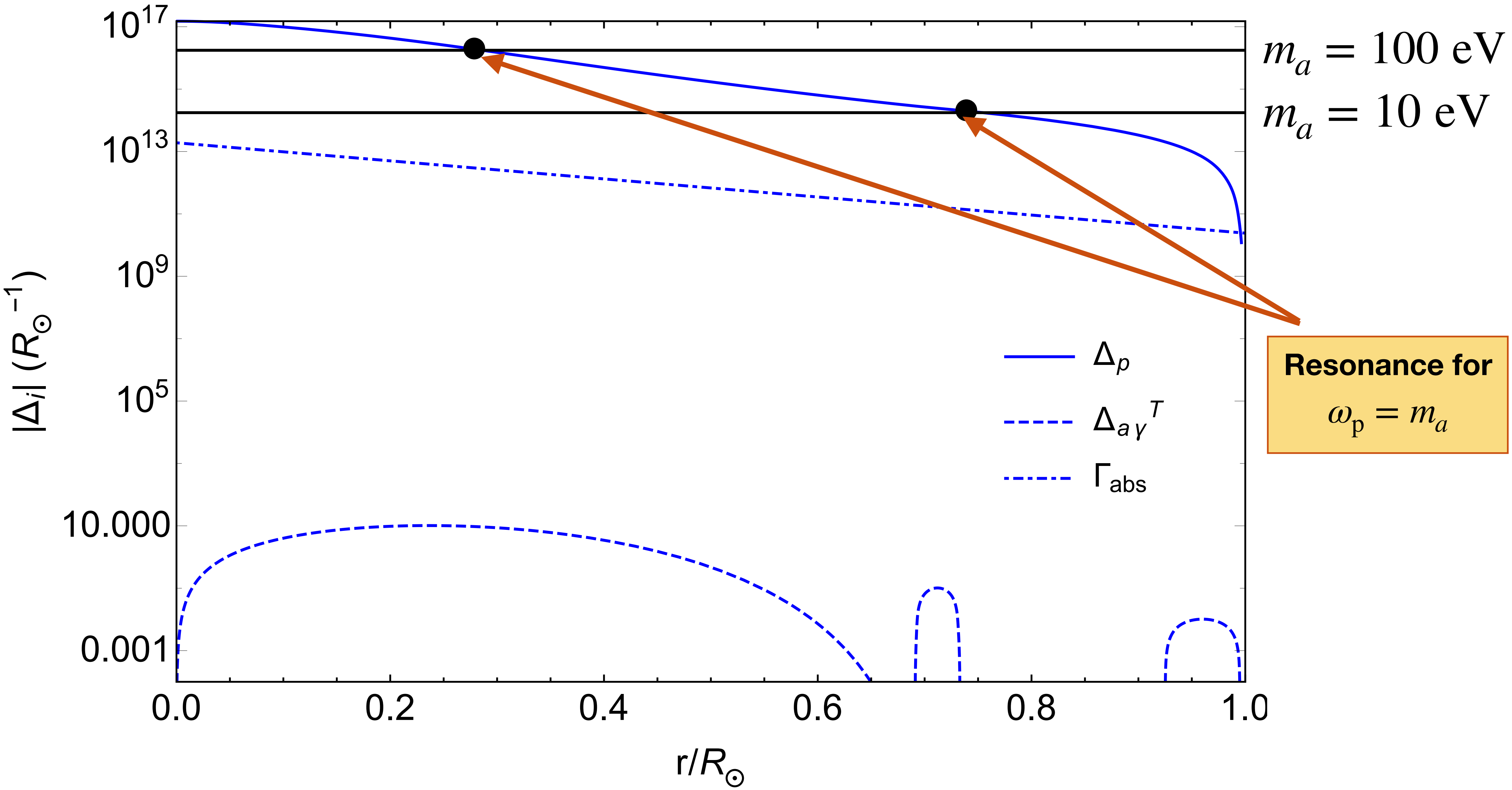


$$x = \frac{\Delta_{\rm osc}\, z}{2}$$

Both the TP-ALP and LP-ALP conversion probability becomes maximal when the oscillatory term $\sin^2 x/x^2 = 1$, i.e. when where a **resonance occurs**.

- TP-ALP conversions: the resonance occurs for $\omega_{\rm p} = m_a$.
- LP-ALP conversions: the resonance occurs for $\omega_{\rm p} = \omega_a$.

OSCILLATION PARAMETERS FOR TP-ALP CONVERSIONS



In the solar plasma there is both photon absorption and photon-ALP mixing.

If Γ_{abs} is the absorption rate of photons in the solar plasma, the total collisional rate is:

$$\Gamma = \Gamma_{abs}(1 - e^{-\omega/T})$$

SOLAR ALPs FROM B-FIELD CONVERSIONS

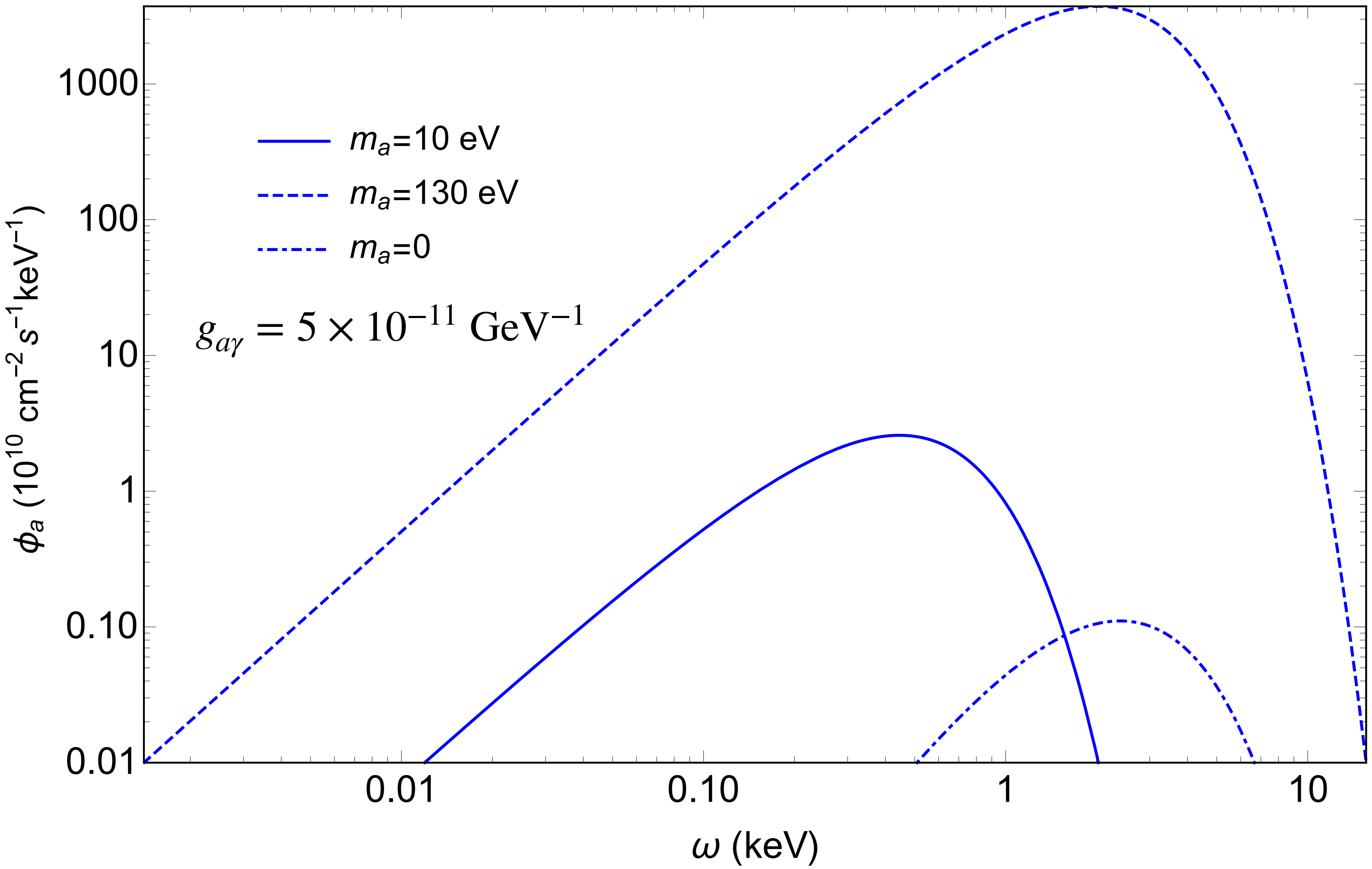
ALPs can be produced in the Sun also through photon conversions in large-scale coherent B-fields. We used the kinetic approach to compute the ALP production rate [Sigl and Raffelt, Nucl. Phys. B **406** (1993), 423-451, Redondo and Raffelt, JCAP **08** (2013), 034].

Photon transverse modes

For transverse photons (TP), the TP-ALP conversion process exhibits a resonance for $\omega_{\rm p} = m_a$. The ALPs production process is narrowly concentrated around this condition and the ALP production rate reads:

$$\Gamma_a^{\rm prod} = \frac{\Gamma {\Delta_{a\gamma}^T}^2}{\left(\frac{\omega_{\rm p}^2 - m_a^2}{2\omega}\right)^2 + \frac{\Gamma^2}{4}} \frac{1}{e^{\omega/T} - 1} \approx \frac{\pi}{2}(g_{a\gamma}B_T)^2 \delta\left(\frac{\omega_{\rm p}^2 - m_a^2}{2\omega}\right)\frac{1}{e^{\omega/T} - 1}$$

ALP FLUX AT EARTH FROM TP-ALP CONVERSIONS IN THE SOLAR B-FIELD



The computed flux parameters for different ALP masses are:

	Φ_a (g_{10}^2 cm^{-2} s^{-1})	L_a (g_{10}^2 $L_\odot$)	$\langle\omega\rangle$ (keV)
m_a = 10 eV	7.44×10^{10}	4.52×10^{-5}	0.6
m_a = 130 eV	4.88×10^{14}	0.6	2.76
m_a = 0	1.56×10^{10}	5.76×10^{-8}	3.24

SOLAR ALPs FROM B-FIELD CONVERSIONS

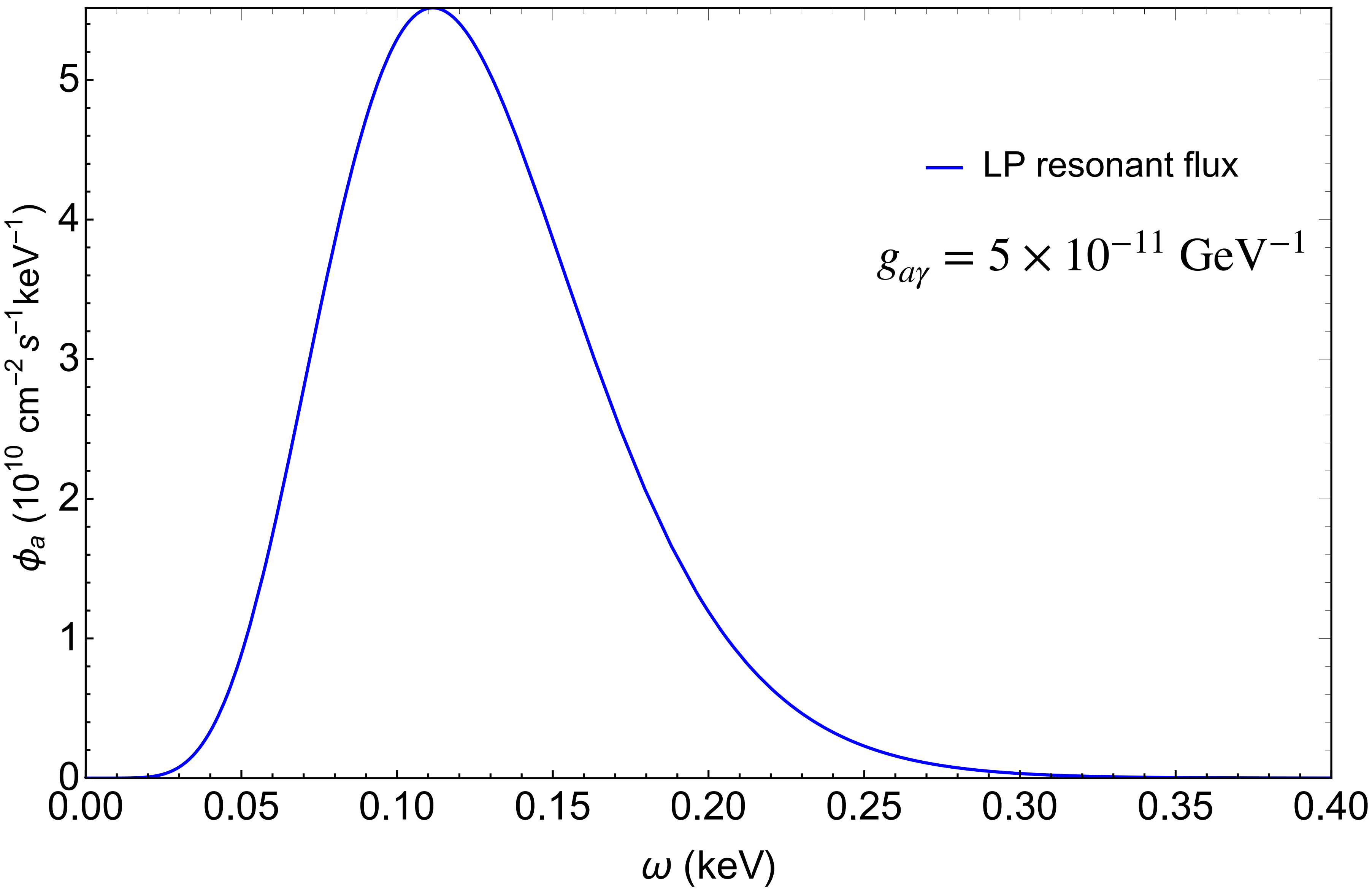
Photon longitudinal modes [Caputo et al., Physical Review D 101, 123004 (2020), O'Hare *et al.*, arXiv: 2006.10415]

For longitudinal photons (LP), the LP-ALP conversion exhibits a resonance for $\omega_a = \omega_{\rm p}$, where the ALP **production rate** is:

$$\Gamma_a^{\rm prod} = \frac{\Gamma \Delta_{a\gamma}^L}{(\omega_{\rm p} - \omega_a)^2 + \Gamma^2/4} \frac{1}{e^{\omega/T} - 1} \approx 2\pi {\Delta_{a\gamma}^L}^2 \delta(\omega_a - \omega_{\rm p})$$

! Note that for both TP-ALP and LP-ALP conversion we neglect the non-resonant production, since its contribution is negligible.

ALP FLUX AT EARTH FROM LP-ALP CONVERSIONS IN THE SOLAR B-FIELD



Solar ALP flux

$$\Phi_a = 2.18 \times 10^{10}\, g_{10}^2 \text{ cm}^{-2}\text{ s}^{-1}$$

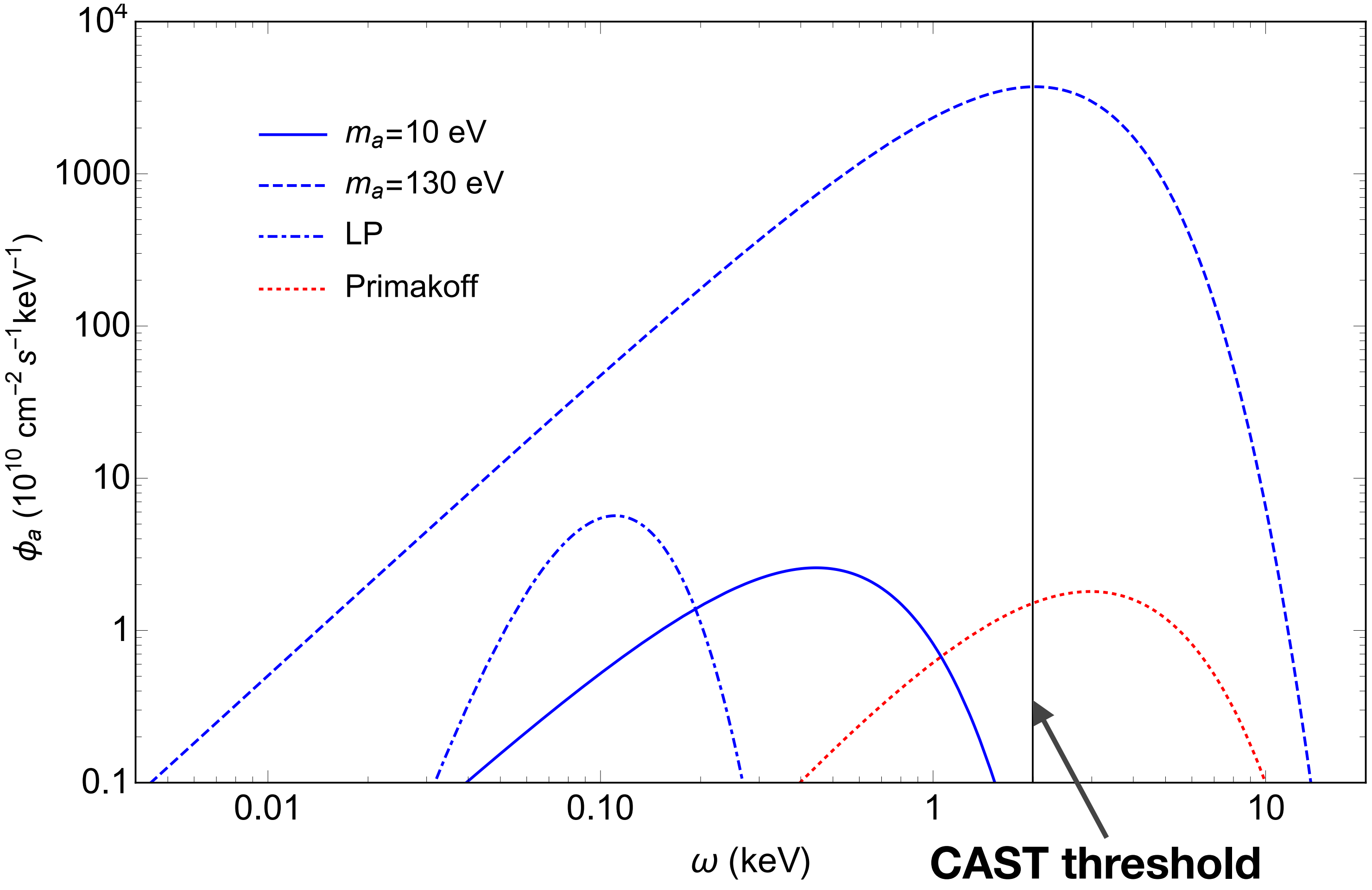
Solar ALP luminosity

$$L_a = 3.34 \times 10^{-6}\, g_{10}^2\, L_\odot$$

ALP average energy

$$\langle \omega \rangle = 0.13 \text{ keV}$$

DETECTION PERSPECTIVES



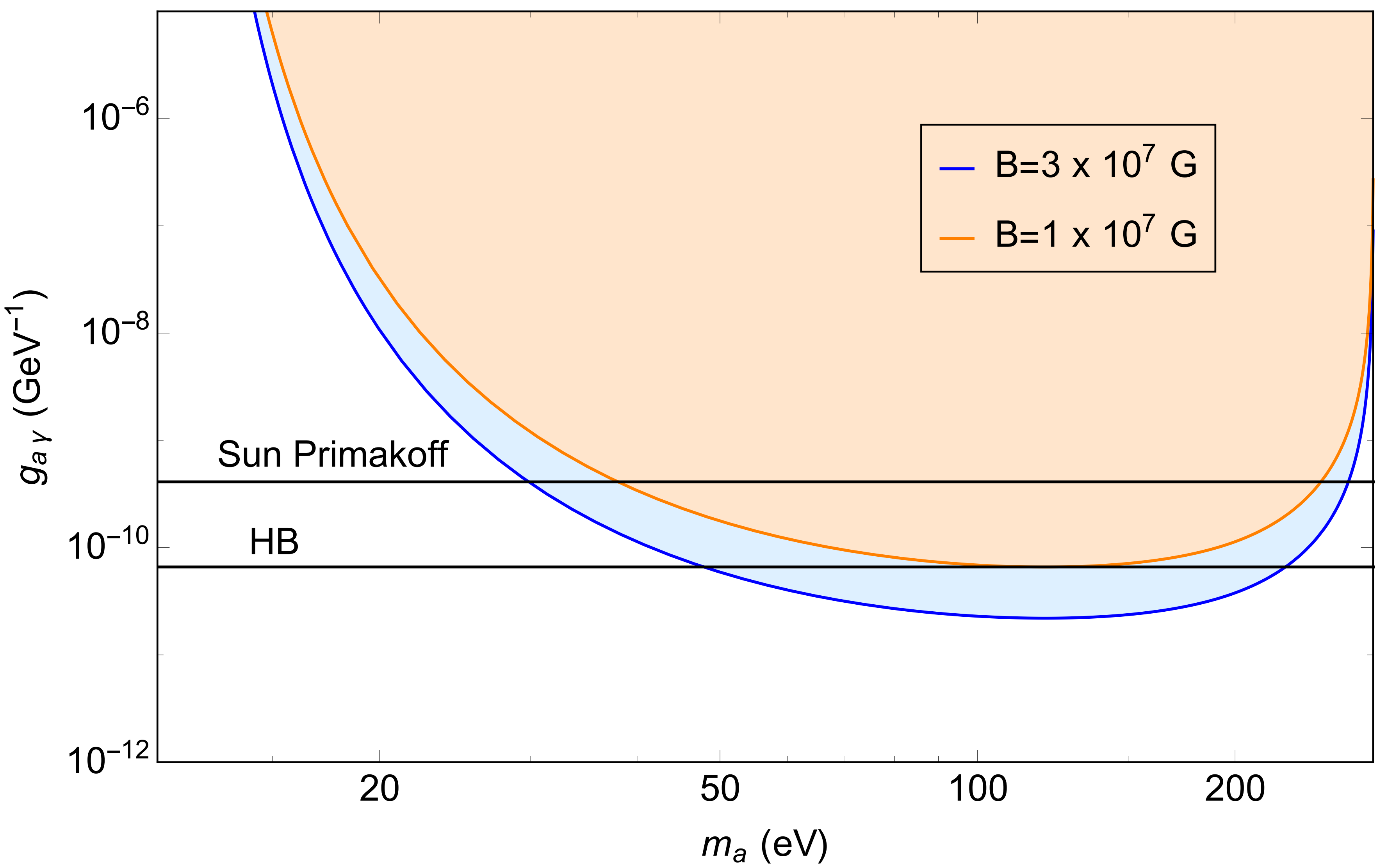
ALP flux from LP-ALP conversions

- In the recent work by O'Hare *et al.* [arXiv: 2006.10415 [astro-ph.CO]] they suggest the possibility of detecting these kind of ALPs through an upgraded version of IAXO.
- Energy range 10^{-2} keV $\lesssim \omega \lesssim 10^{-1}$ keV.
- Sensitivity down to $m_a \simeq 10^{-2}$ eV.

ALP flux from TP conversions

- $m_a \sim 10$ eV : it is dominant at energies $\omega <$ keV, below the CAST threshold [CAST collaboration, JCAP **04** (2007), 010]
- IAXO could have the threshold in the sub-keV region, but the coherence in the magnetic field of the helioscope for masses larger than $m_a \sim 1$ eV is lost.
- AMELIE could be sensitive to ALPs with masses from fews meV to several eV [Galàn *et al.*, JCAP **12** (2015), 012]
- $m_a \sim 130$ eV: the flux would be much larger than the Primakoff one.
- A dark matter detector such as CUORE could cover the range $m_a \lesssim 100$ eV [Li *et al.*, JCAP **10** (2015), 065].
- The bound set by primordial hydrogen ionization (x_{ion}) $g_{a\gamma} \lesssim 5 \times 10^{-13}$ GeV^{-1} seems to prevent the possibility of detecting axions with mass $m_a \sim 100$ eV [Cadamuro and Redondo, JCAP **02** (2012), 146].

ENERGY-LOSS BOUNDS



- From the combination of helioseismology and solar neutrino observations [Vinyoles *et al.*, JCAP 10 (2015), 015]:

$$L_a \lesssim 0.03\ L_\odot$$

- Using the luminosity associated with the ALP flux for $m_a \sim \mathcal{O}(100)$ eV we set the new bound:

$$g_{a\gamma} \lesssim (2.2 - 6.3) \times 10^{-11}\ \mathrm{GeV}^{-1}$$
$$\text{for } 100\ \mathrm{eV} \lesssim \mathrm{m_a} \lesssim 140\ \mathrm{eV}$$

- Our new bound is comparable or even better than the bound from Helium burning stars in GCs ($g_{a\gamma} < 6.6 \times 10^{-11}\ \mathrm{GeV}^{-1}$).

- If we consider smaller values of m_a we obtain smaller luminosities, then less stringent constraints.

CONCLUSIONS

- We considered realistic models for the solar B-field in the radiative zone and in the tachocline of the Sun.
- We have characterized the resonant production of ALPs both from transverse and longitudinal photon conversions in the solar magnetic field.
- We have discussed the perspectives of ALPs detection at helioscope experiments and dark matter detectors.
- We have set a new bound on $g_{a\gamma}$ from energy-loss arguments in the Sun.

We are waiting for the axions to join our…CAST of particles!

Thanks for the attention