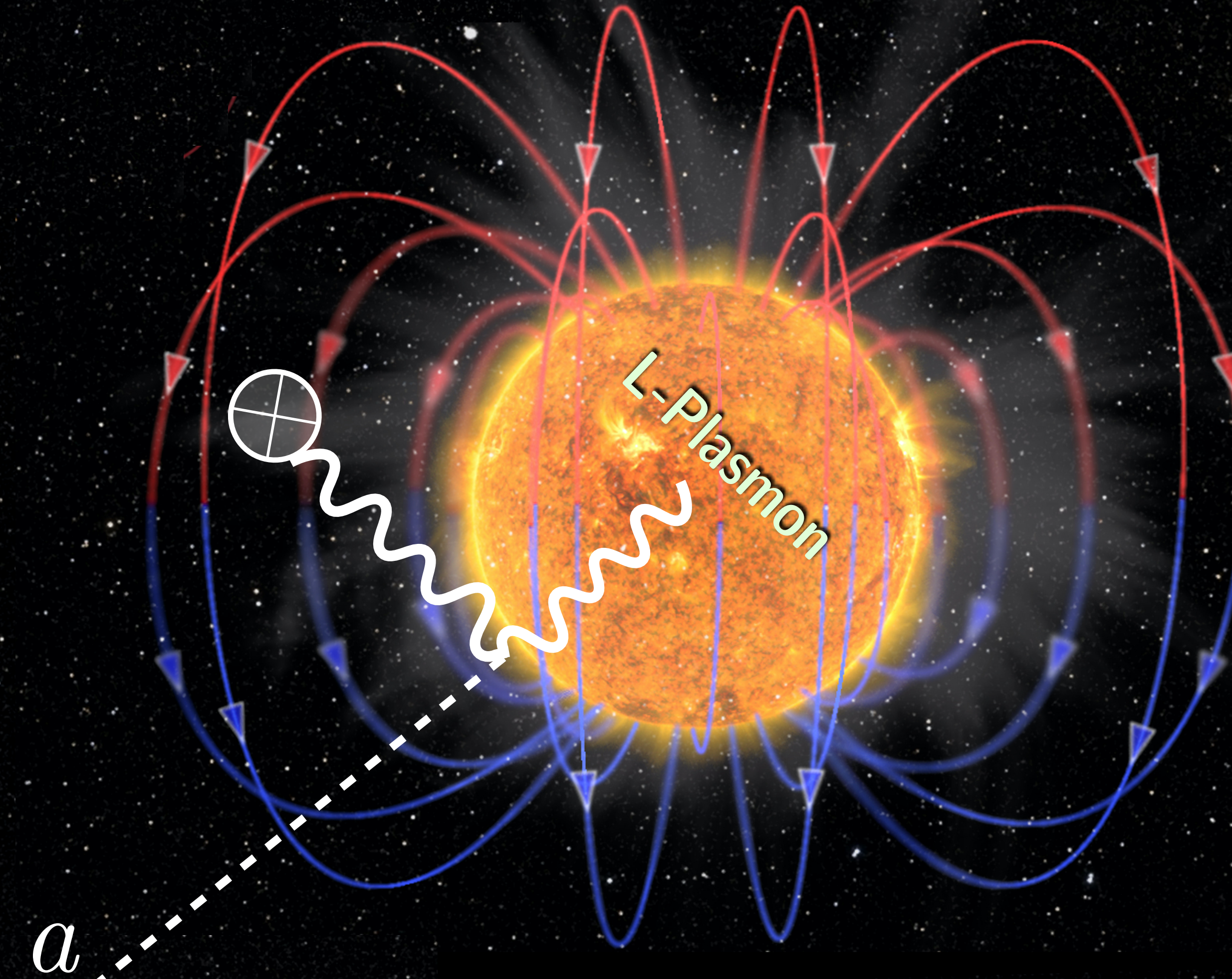
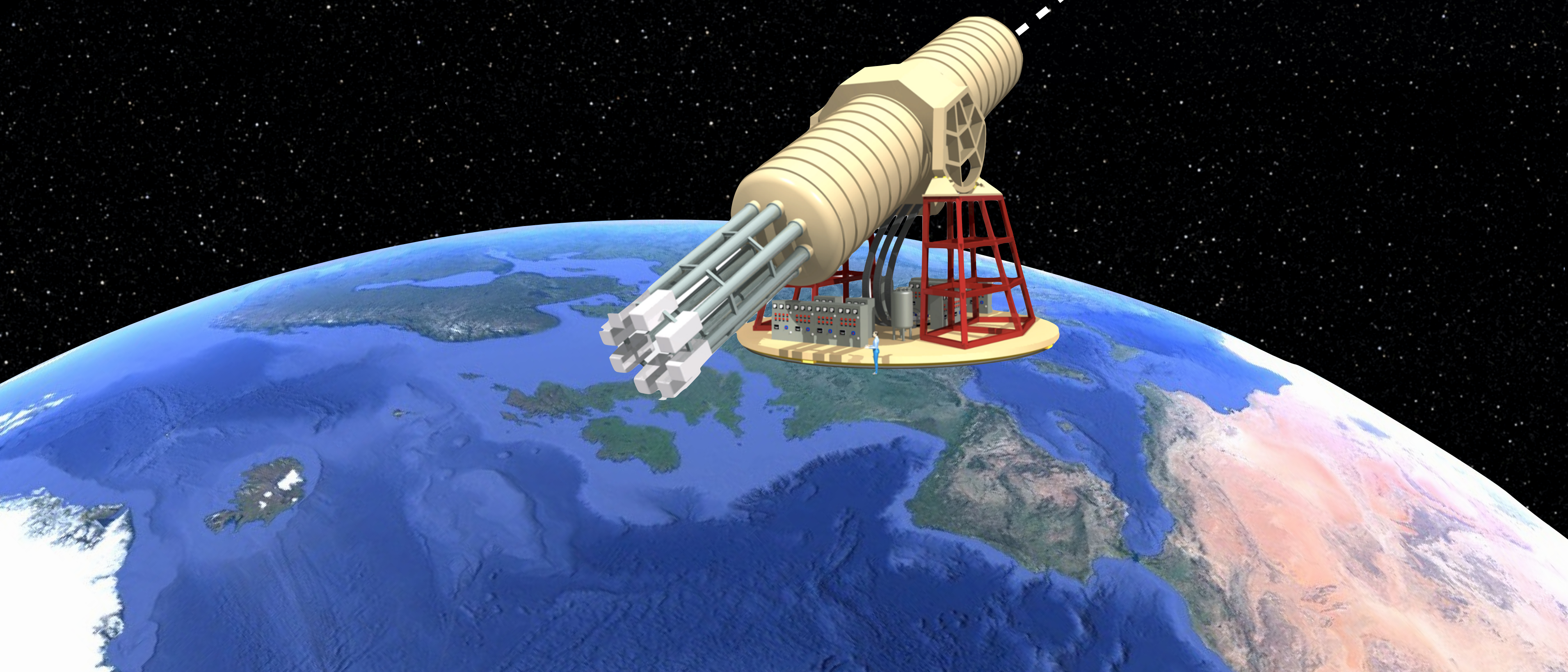
IAXO as a solar magnetometer

Ciaran O'Hare, U. Sydney

[2005.00078], [2006.10415]





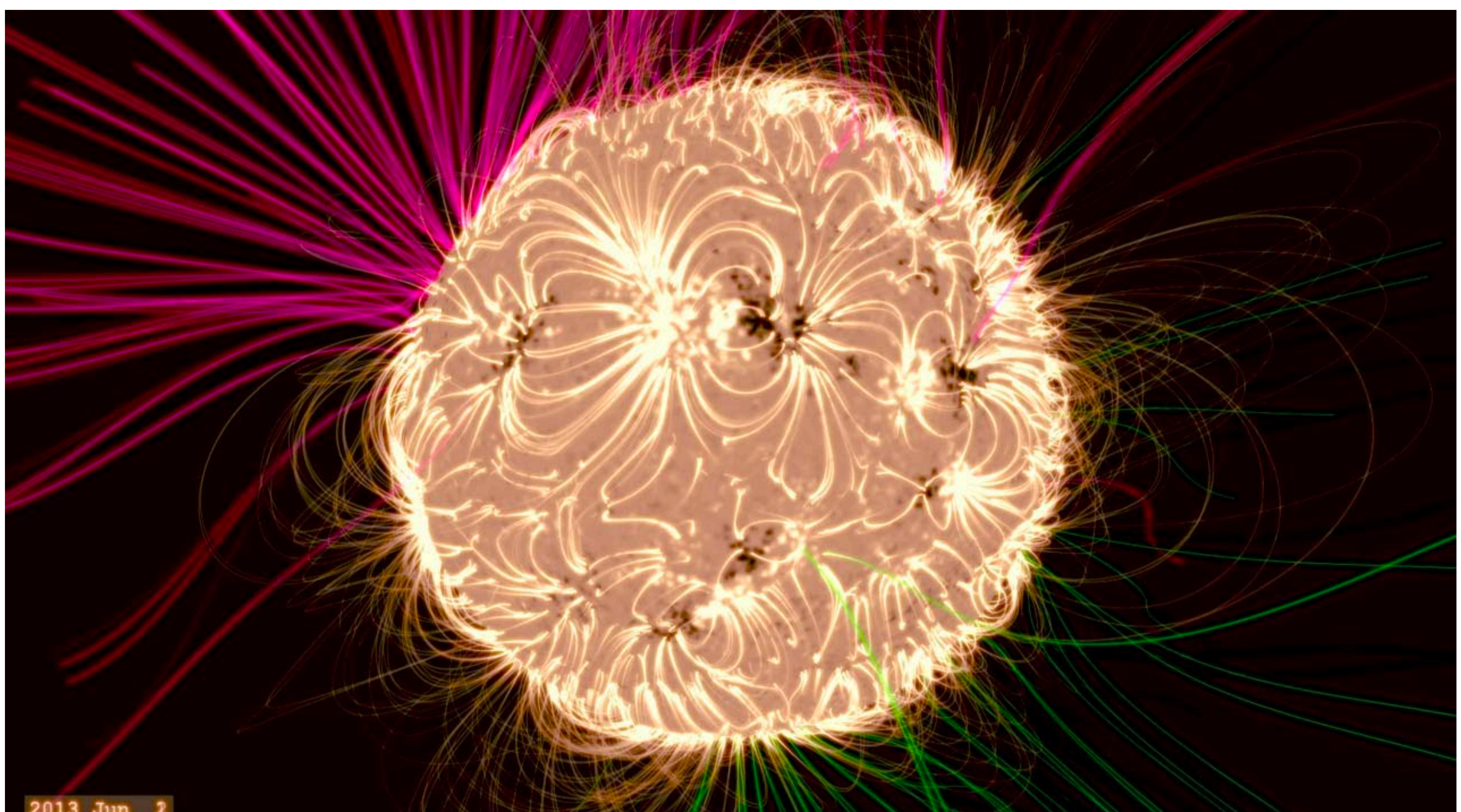
with Andrea Caputo
Edoardo Vitagliano
Alexander Millar

- Can we measure the Sun’s magnetic field using solar axions?

The Sun's magnetic field: why do we care?

Improving our understanding of the Sun has far-reaching consequences for astronomy

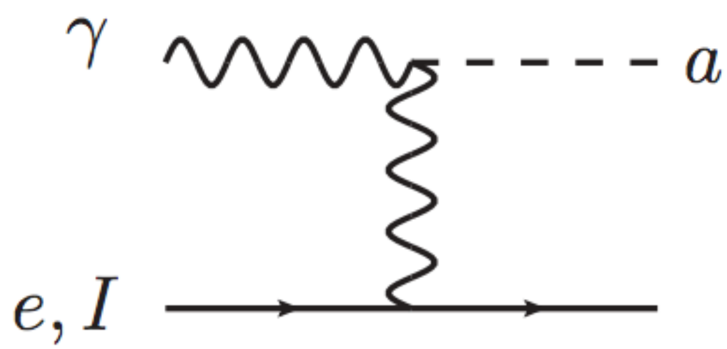
- The Sun is our prototypical cool main sequence star
- Our understanding of all similar stars is normalised on our Sun
- Understanding solar B-field→ solar wind, solar cycle, prominences etc.
- Has the sun trapped an ancient interstellar fossil field?
- Measuring solar B-field is **hard**



Usual axion fluxes

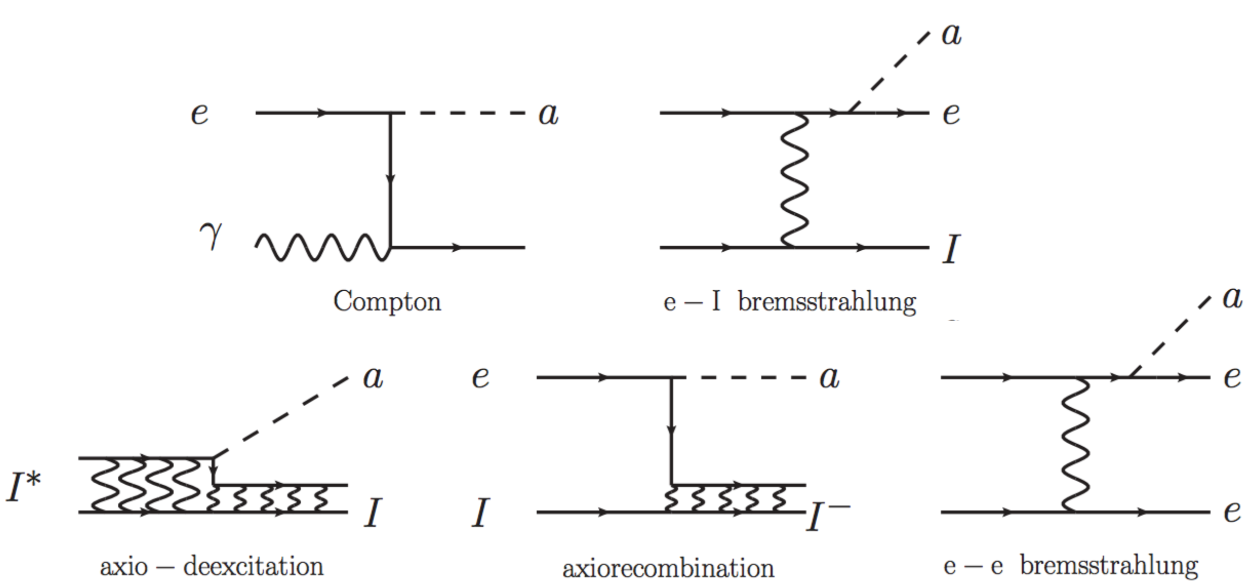
No B-field dependence

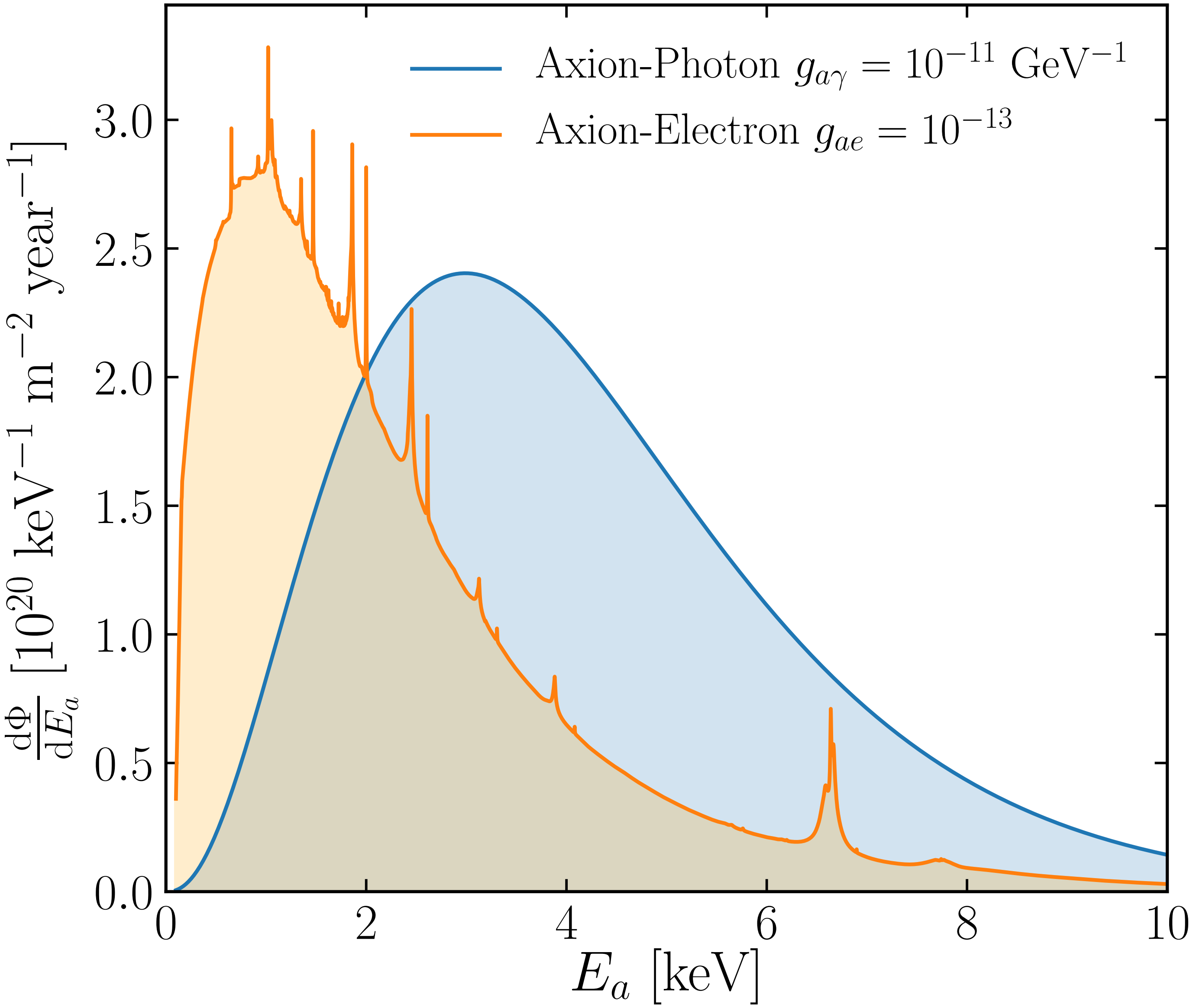
Primakoff (Axion-photon)



ABC fluxes (Axion-electron)

Redondo [1310.0823]

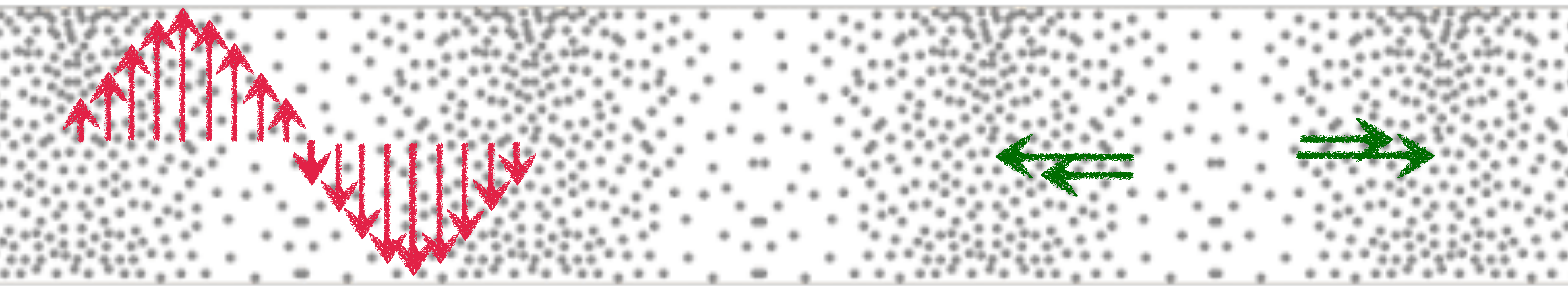




Oscillations in ionised medium (e.g. the Sun)

Plasma frequency: $$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e}$$

At low temperatures relative to m_e



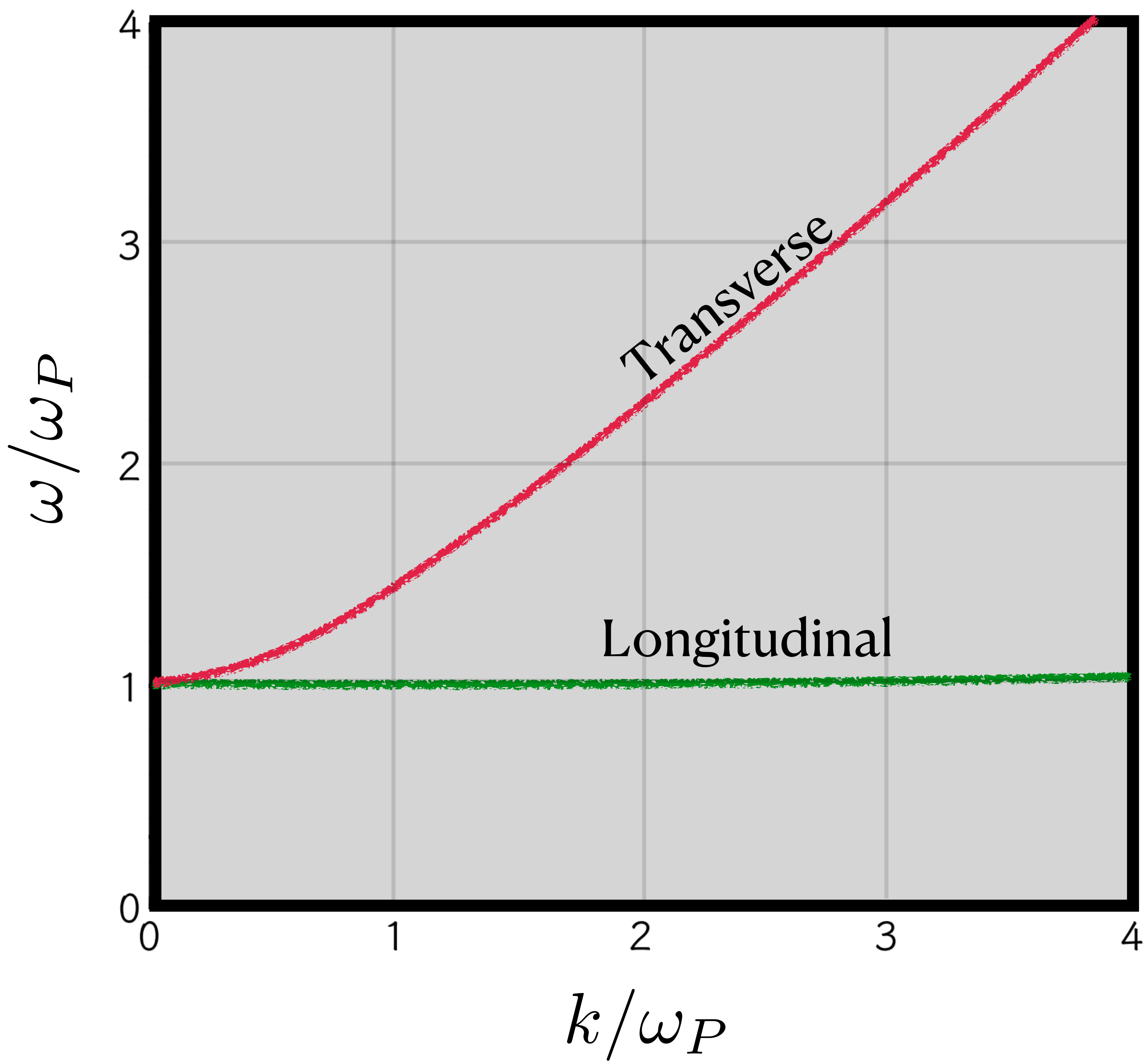
Transverse plasmons
~ free massive particles with mass ω_p

$$\omega^2 - k^2 = \omega_p^2$$

Longitudinal plasmons
Oscillations at ~plasma frequency

$$\omega^2 = \omega_p^2$$

Non-rel. plasmons in medium at temperature *T*:
longitudinal & transverse



Transverse modes ~
behave like free massive particles

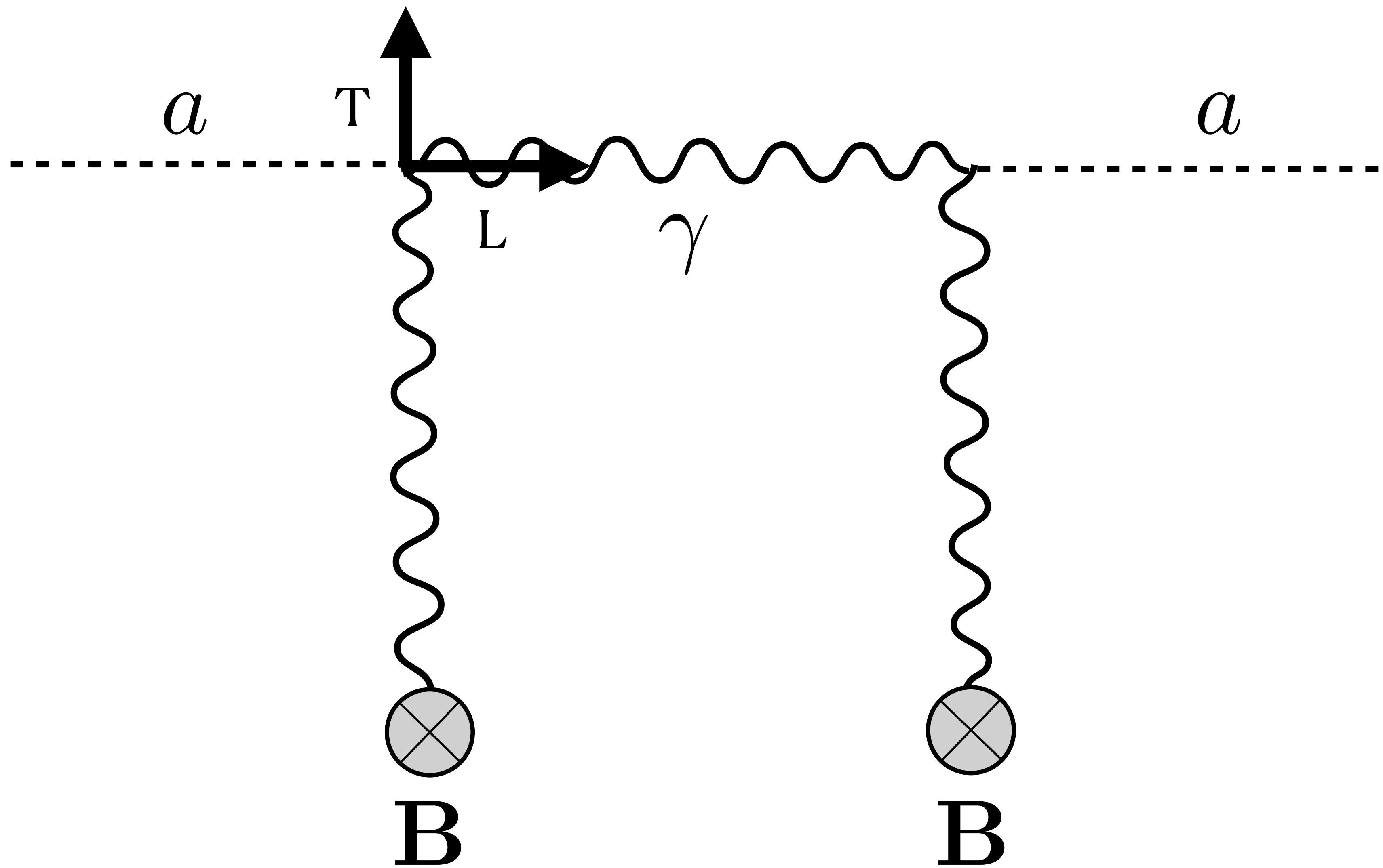
$$\omega^2 = k^2 + \omega_{\mathrm{P}}^2\left(1 + \frac{k^2}{\omega^2}\frac{T}{m_e}\right)$$

Longitudinal mode
oscillate ~const freq.

$$\omega^2 = \omega_{\mathrm{P}}^2\left(1 + 3\frac{k^2}{\omega^2}\frac{T}{m_e}\right)$$

Axion-photon oscillations

[2005.00078]



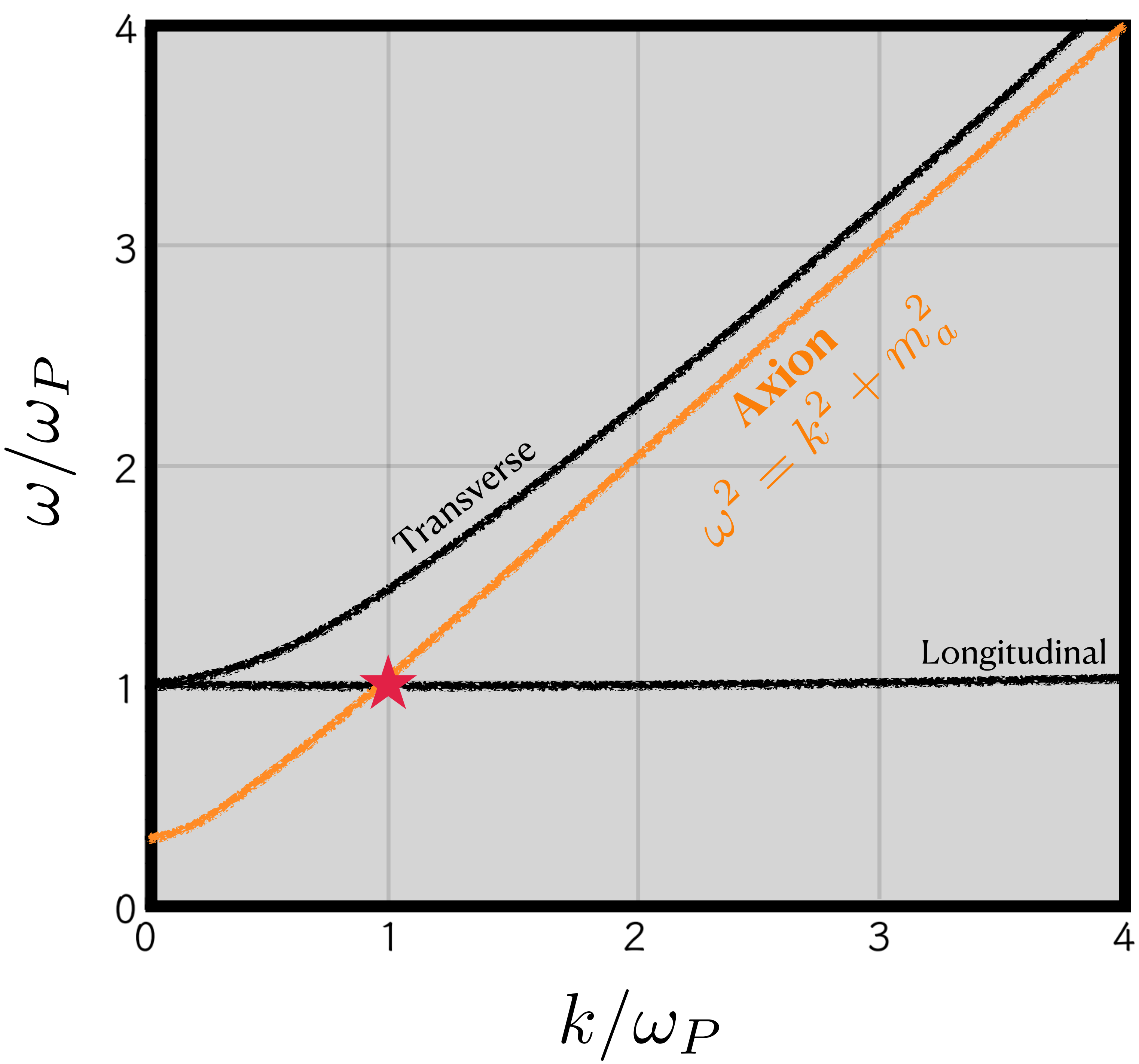
Axion's self-energy in a magnetic field

$$K = (\omega, \mathbf{k})$$

$$\Pi_{\rm axion} = m_a^2 + m_a^2 g_{a\gamma}^2 B_\parallel^2 \frac{1}{K^2 - \Pi_{\gamma,L}(K)} + m_a^2 g_{a\gamma}^2 B_\perp^2 \frac{1}{K^2 - \Pi_{\gamma,T}(K)}$$

Mass — Longitudinal — Transverse

Coupling axion to longitudinal plasmon



Longitudinal mode
oscillate ~const freq.

$$\omega^2 = \omega_{\rm P}^2 \left(1 + 3\frac{k^2}{\omega^2}\frac{T}{m_e}\right)$$

Longitudinal plasmon always crosses free axion dispersion relation at some momentum
★ → **resonant conversion**

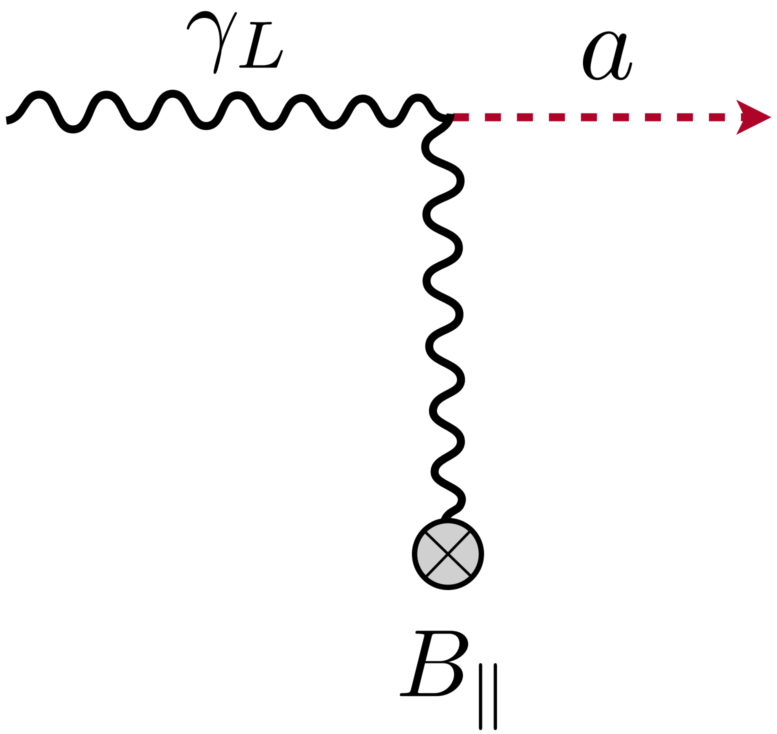
The new flux

See 1996 paper by Mikheev *et al.* [hep-ph/9803486] revisited in [2005.00078]

Axion emission rate from LPlasmons

$$\Gamma_{\mathrm{LP}\to a}(\omega) = \frac{g_{a\gamma}^2 B_\parallel^2}{e^{\omega/T}-1}\frac{\omega^2\Gamma_L}{\left(\omega^2-\omega_p^2\right)^2+\left(\omega\Gamma_L\right)^2}$$

$$\simeq \frac{g_{a\gamma}^2 B_\parallel^2}{e^{\omega/T}-1}\frac{\pi}{2}\delta\left(\omega-\omega_p\right)$$



→ resonance at plasma frequency

→ Proportional to the **transverse** magnetic field squared

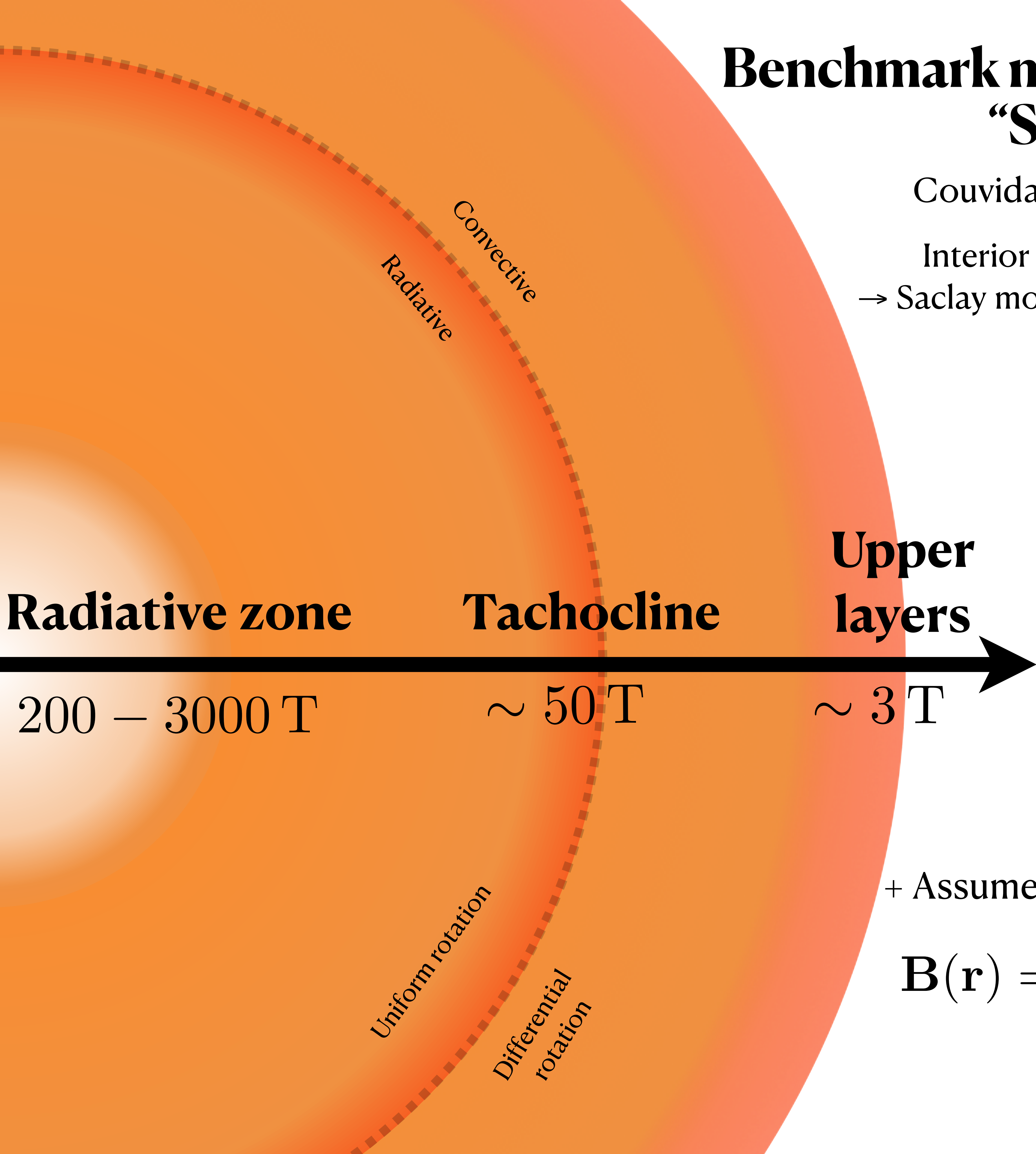
Integrate over phase space and Sun → Axion luminosity

$$L_{\mathrm{LP}\to a} = \int_\odot \mathrm{d}^3\mathbf{r}\int\frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3}\omega\frac{g_{a\gamma}^2 B_\parallel^2}{\left(e^{\omega/T}-1\right)}\frac{\pi}{2}\delta\left(\omega-\omega_p\right)$$

Benchmark model of solar B-field: "Saclay seismic model"

Couvidat *et al.* (2002) astro-ph/0203107

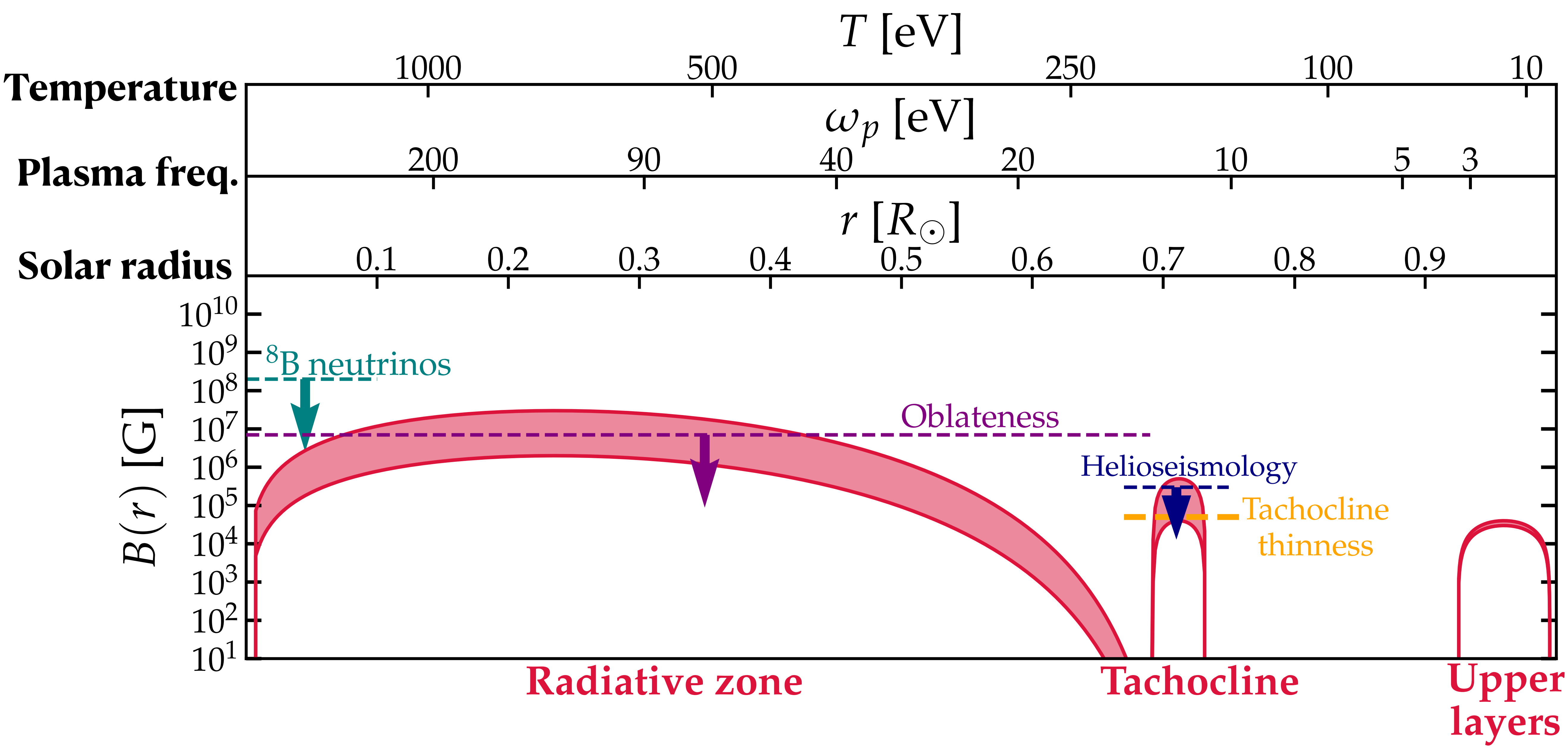
Interior Solar B-field still highly uncertain
→ Saclay model is just a solid benchmark that satisfies observational bounds



+ Assume toroidal angular dependence

$$\mathbf{B}(\mathbf{r}) = B(r)\frac{\mathrm{d}}{\mathrm{d}\theta}P_k(\cos\theta)\hat{\mathbf{e}}_\phi$$

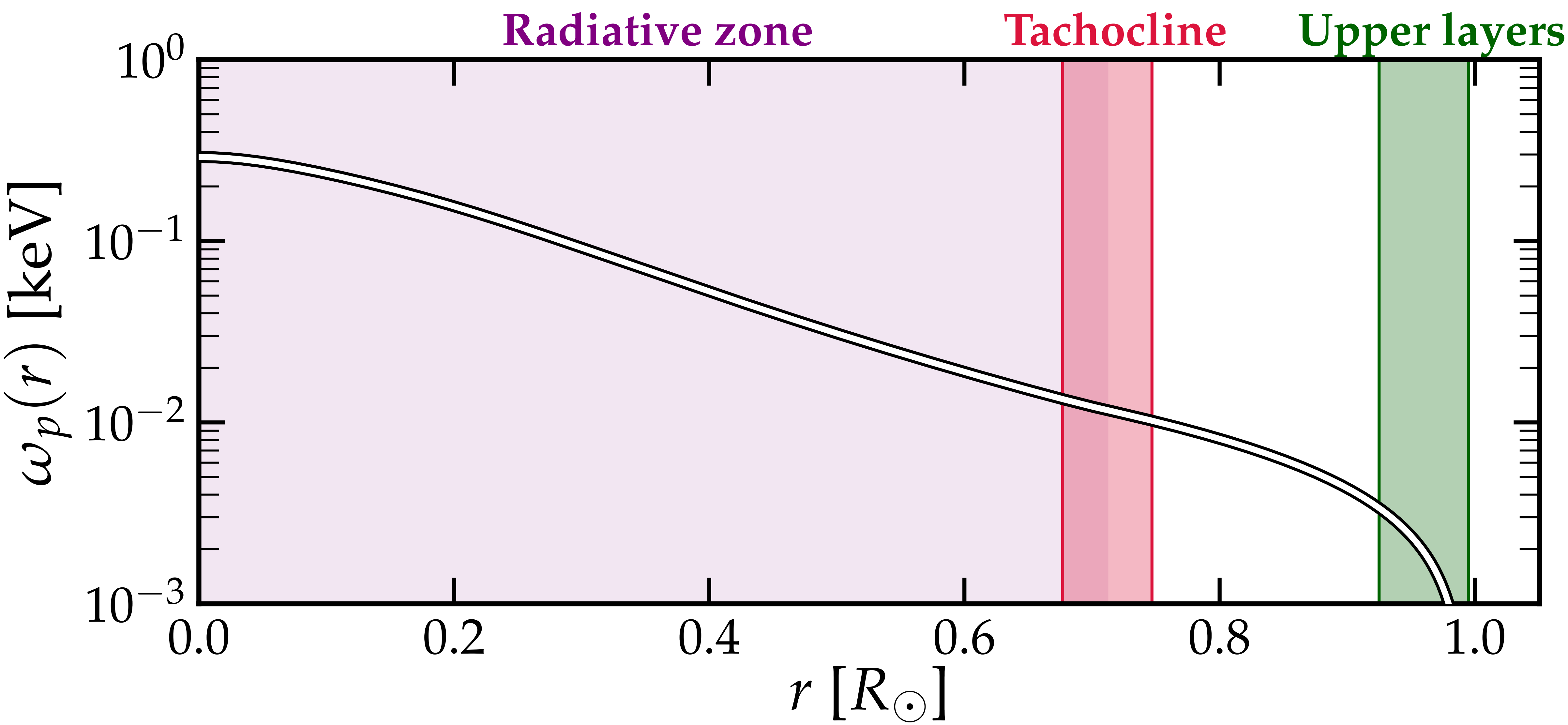
Solar B-field profile: “Saclay seismic model”



Typical energies

- Plasma frequency ~ 300 eV at r=0, then decreasing outwards

→ Highest energy axions from core



→ need sub-keV energy resolutions for detection

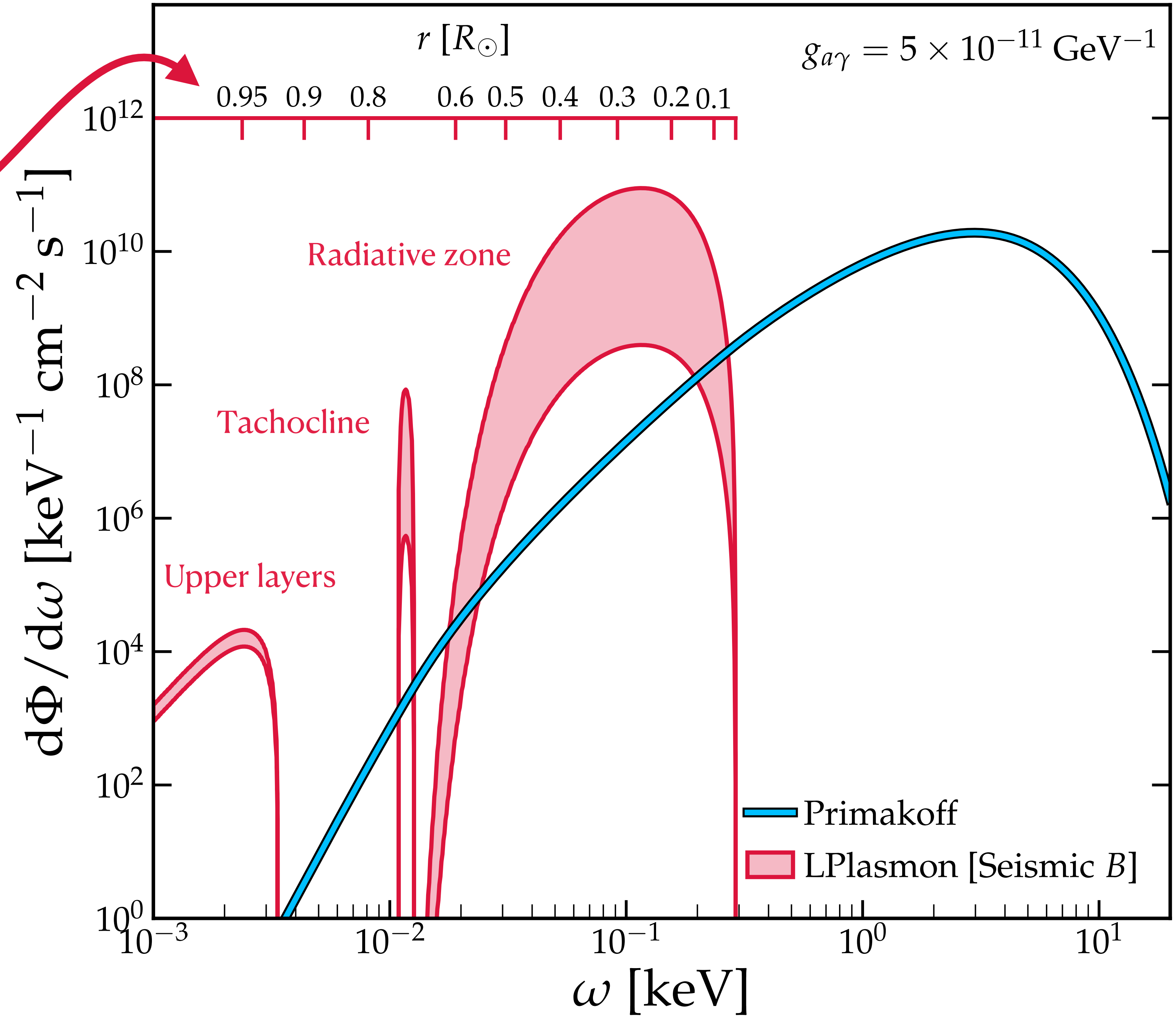
The new flux

- Resonance at plasma frequency means that an axion's energy can be mapped to the radius it came from!

- Lower energies → larger radii

- Seeing **smaller** radii is **less** demanding of detector energy resolution!

→ **highly novel** compared to conventional probes e.g. helioseismology which can't access smaller radii



Download .txt file with the new flux: [cajohare/solax/master/data/solar/LPlasmonFlux_SeismicB.txt]

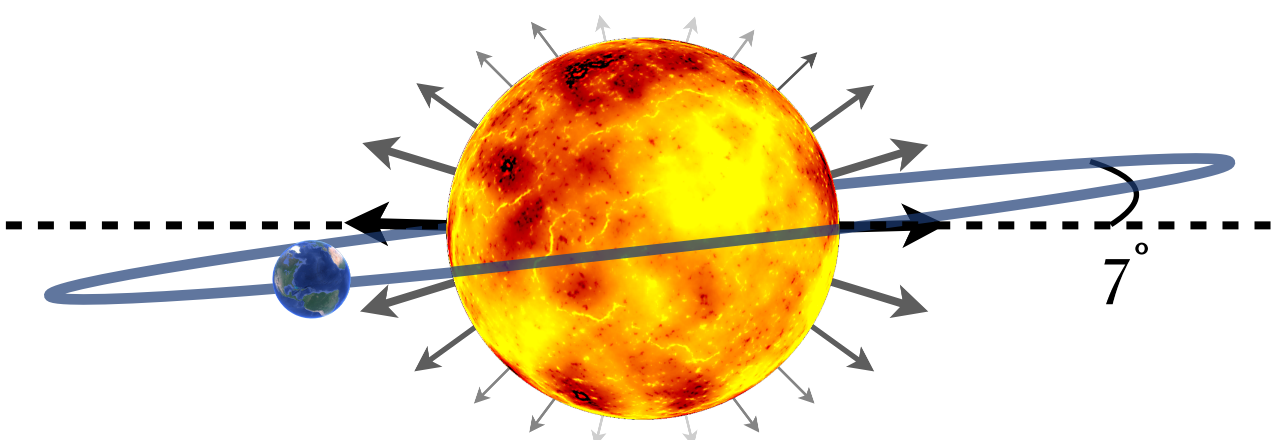
A brief aside…

Side note: two sources of annual modulation

1.

Toroidal field = flux strongest at equator
→ biannual modulation

$$\mathbf{B}(\mathbf{r}) = B(r)\frac{\mathrm{d}}{\mathrm{d}\theta}P_k(\cos\theta)\hat{\mathbf{e}}_\phi$$

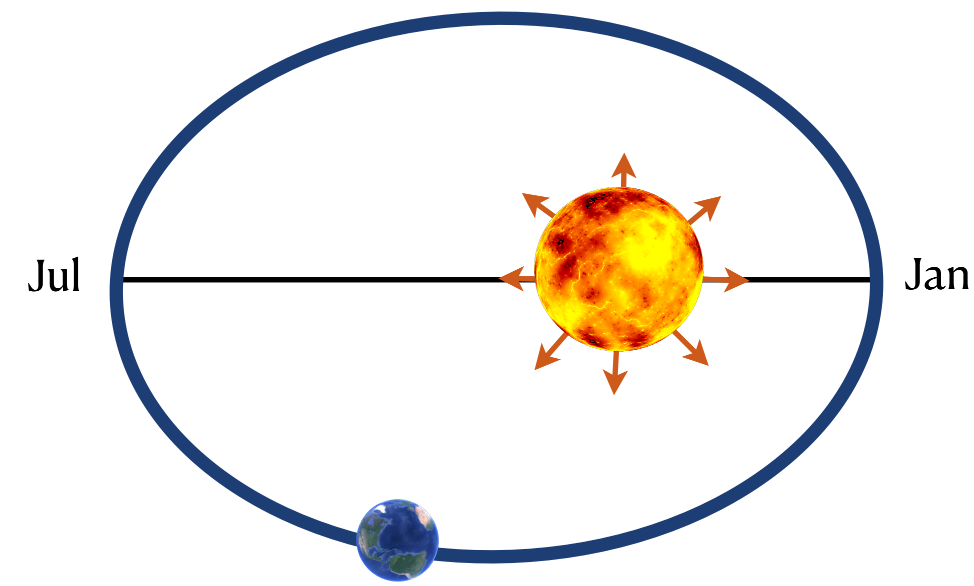


Ecliptic plane inclined by 7°
= **1.5%** biannual modulation peaking in December and June

2.

Flux is stronger when we're closer to the Sun
→ annual modulation from our orbital eccentricity

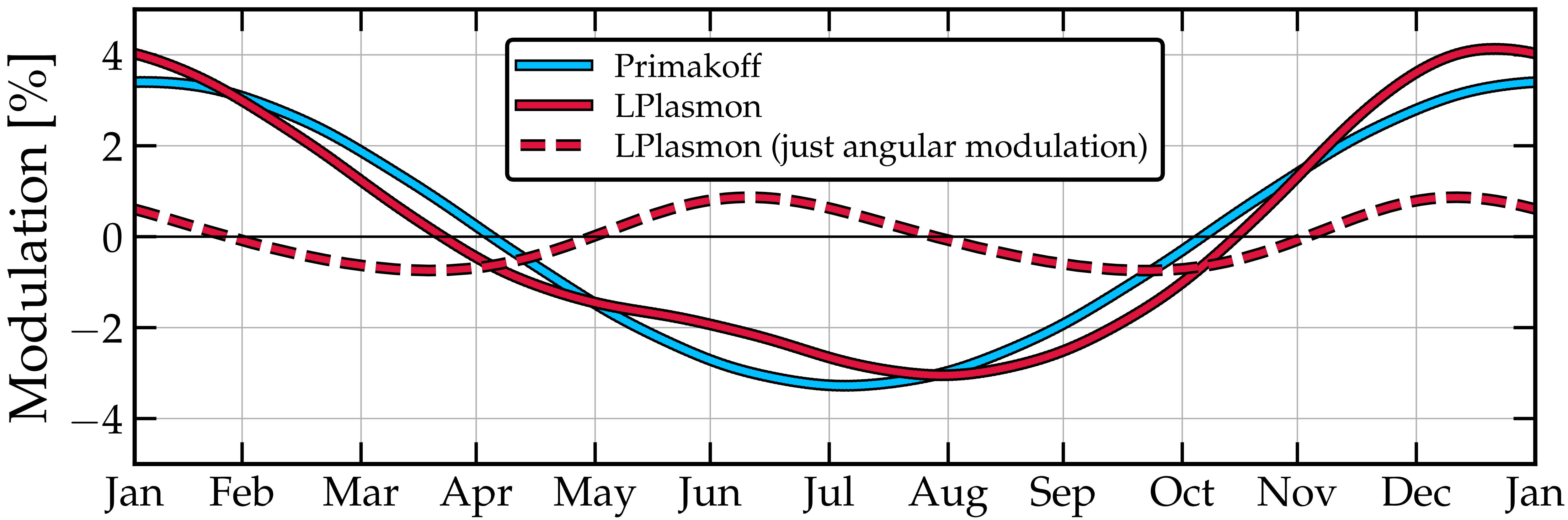
$$\frac{1}{r_\oplus^2(t)} = \frac{1}{(1\mathrm{AU})^2}\left[1 + 2e\cos\left(\frac{2\pi\,(t-t_e)}{T}\right)\right]$$



Earth's orbital eccentricity e=0.0167
= **7%** annual modulation peaking in January

Annual modulations

Primakoff flux → doesn't depend on B-field, so only has the annual modulation
LPlasmon flux → has annual modulation + biannual modulation



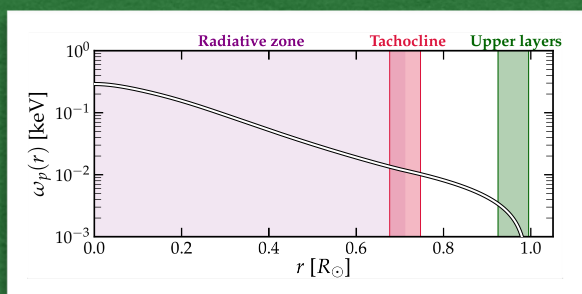
Too small to be important for now, but post-discovery, could be a very interesting signal to study if the B-field is toroidal down into the radiative zone

Back to the main topic…

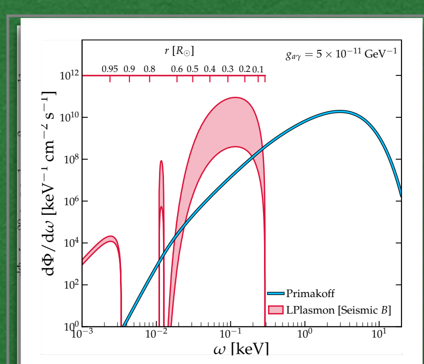
The signal in a helioscope: ingredients

Axion flux

Solar model



Axion fluxes



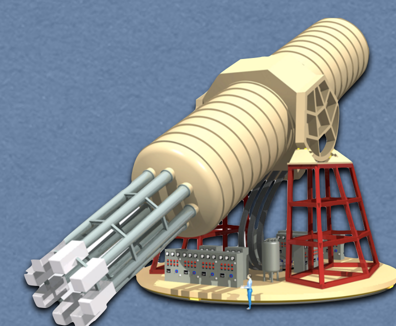
Axion coupling and mass

$$(g_{a\gamma},\, m_a)$$

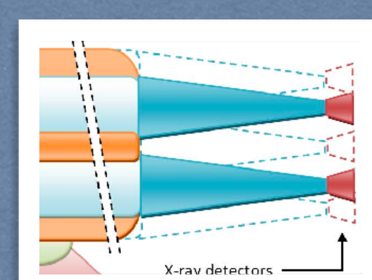
+

Helioscope

B-field, Length Aperture



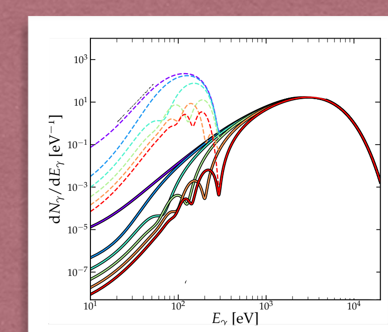
Detector: efficiency + energy res.



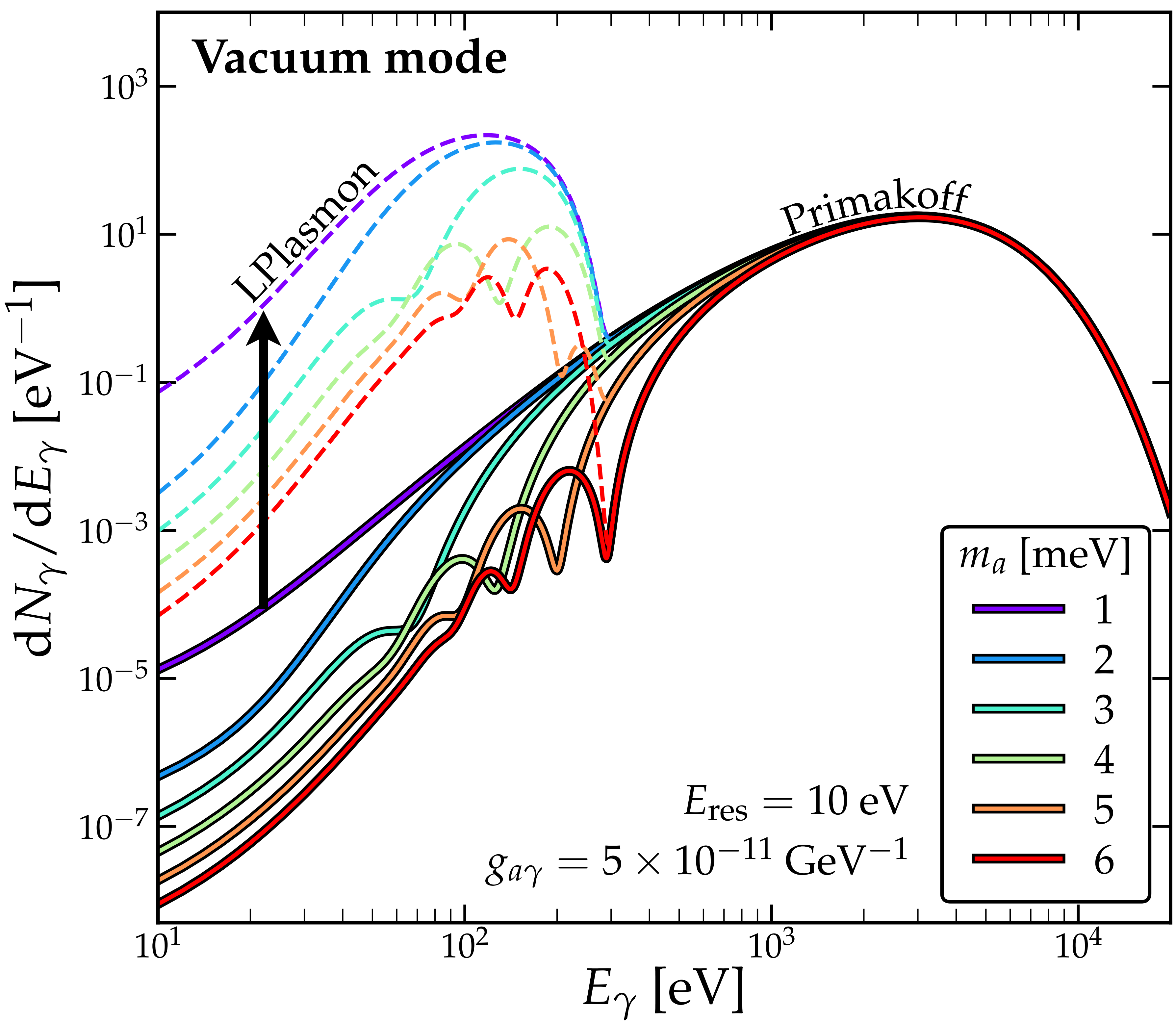
→

X-ray spectrum

dN/dE



The signal in IAXO: low masses (vacuum mode)

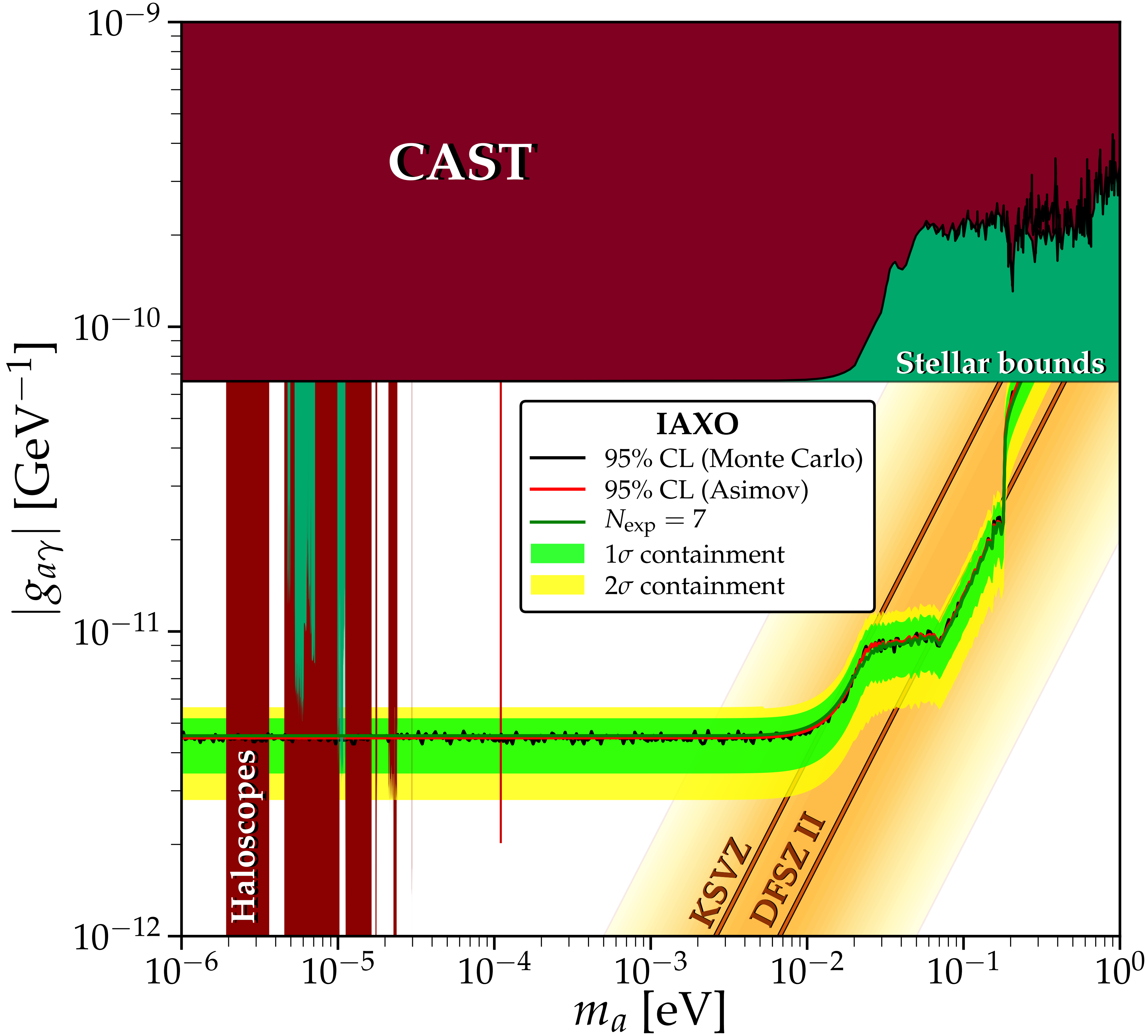


Stronger solar B-field = more events at low energies

For masses above ~1 meV axion-photon decoherence destroys the signal

Run strategy:

We attempted to reproduce projection from IAXO physics potential paper [1904.09155]



1.5 years in vacuum mode

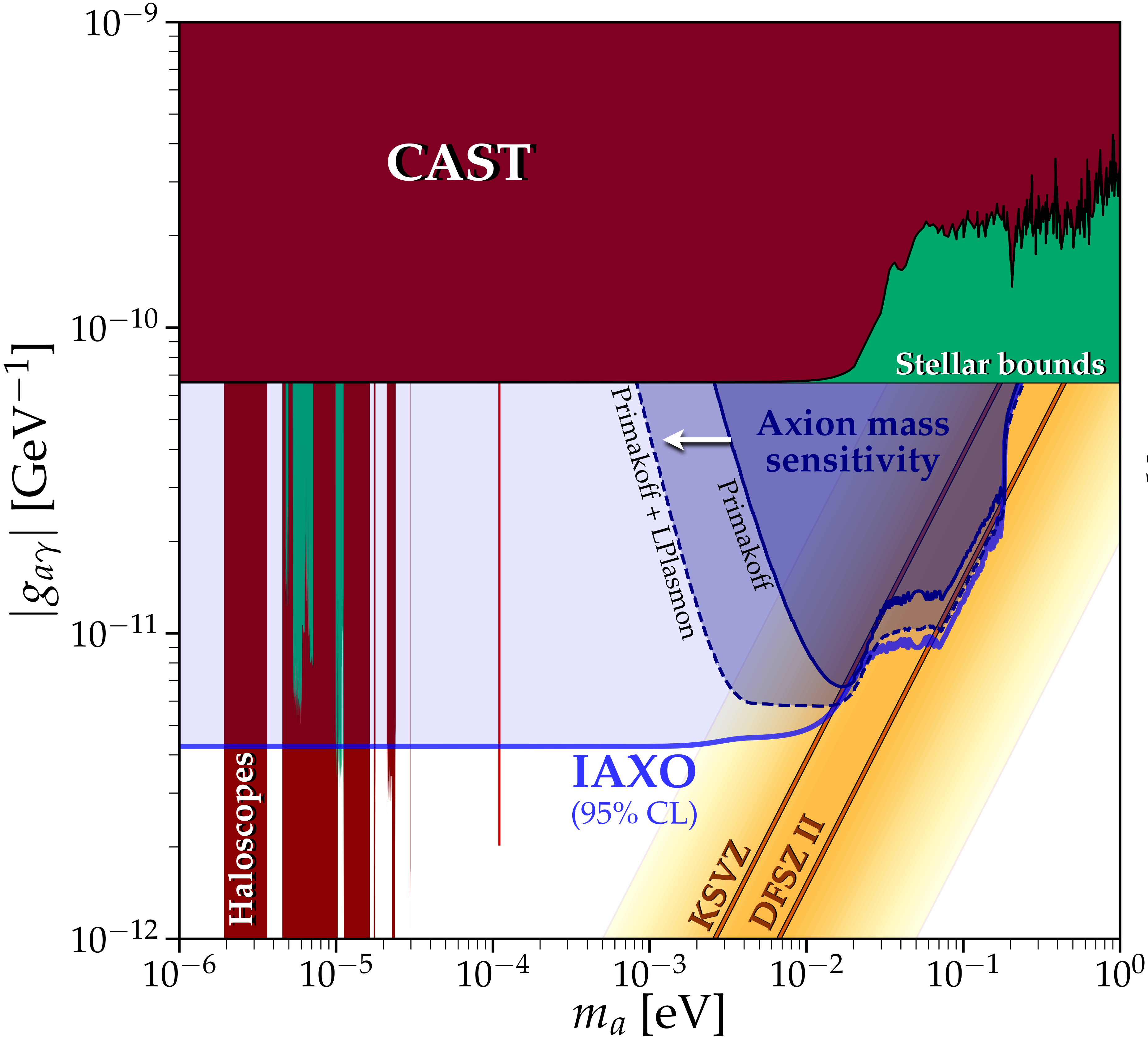
+

1.5 years He buffer gas scan

→ reach DFSZ

(Some post-discovery optimisation of gas pressure is possible to target certain stellar radii of flux, however the benefit was very minor)

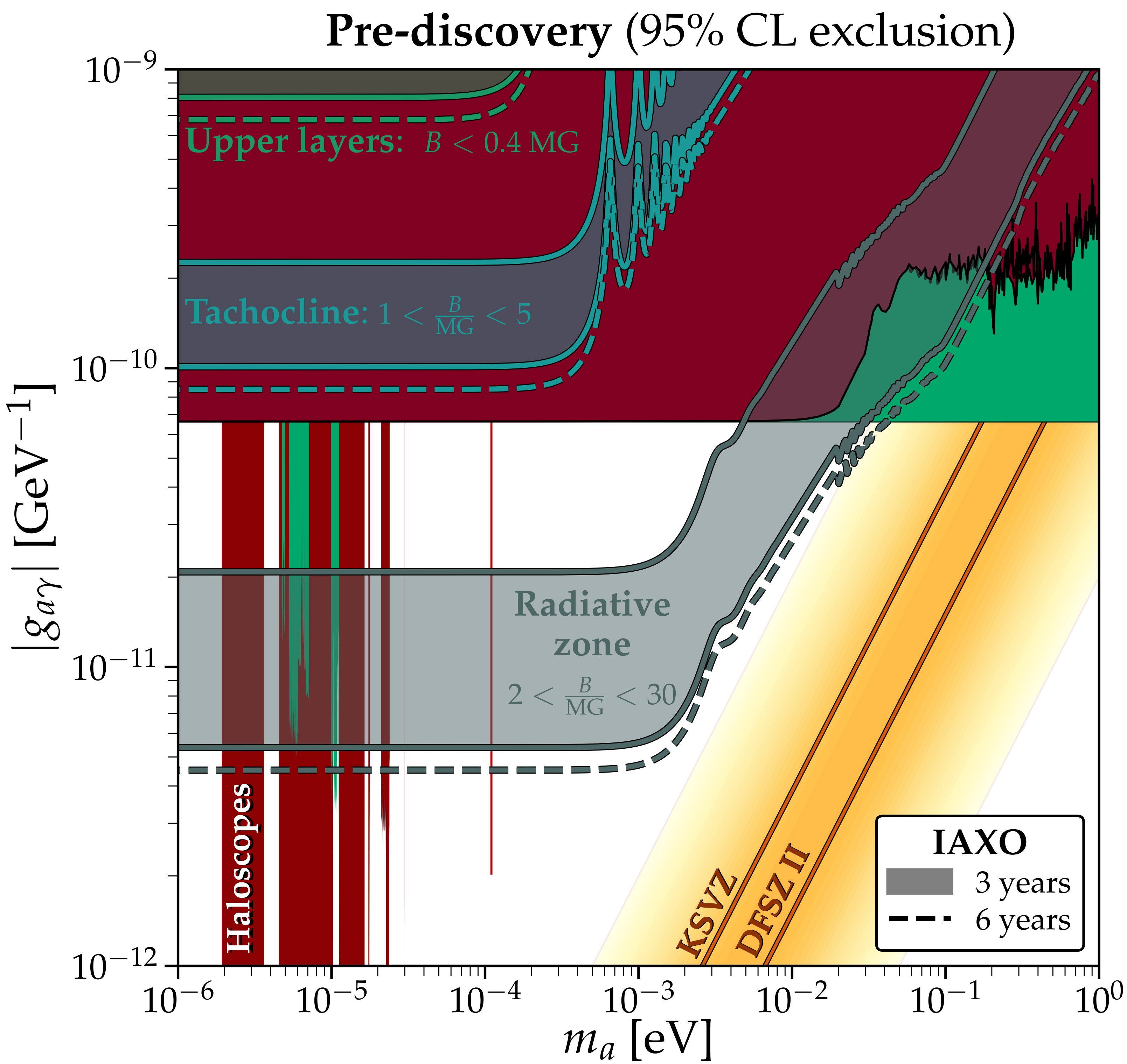
Additional benefit of new source of flux at low energies
Better measurement of the axion mass



More flux at lower energies → extends mass sensitivity down to meV axions

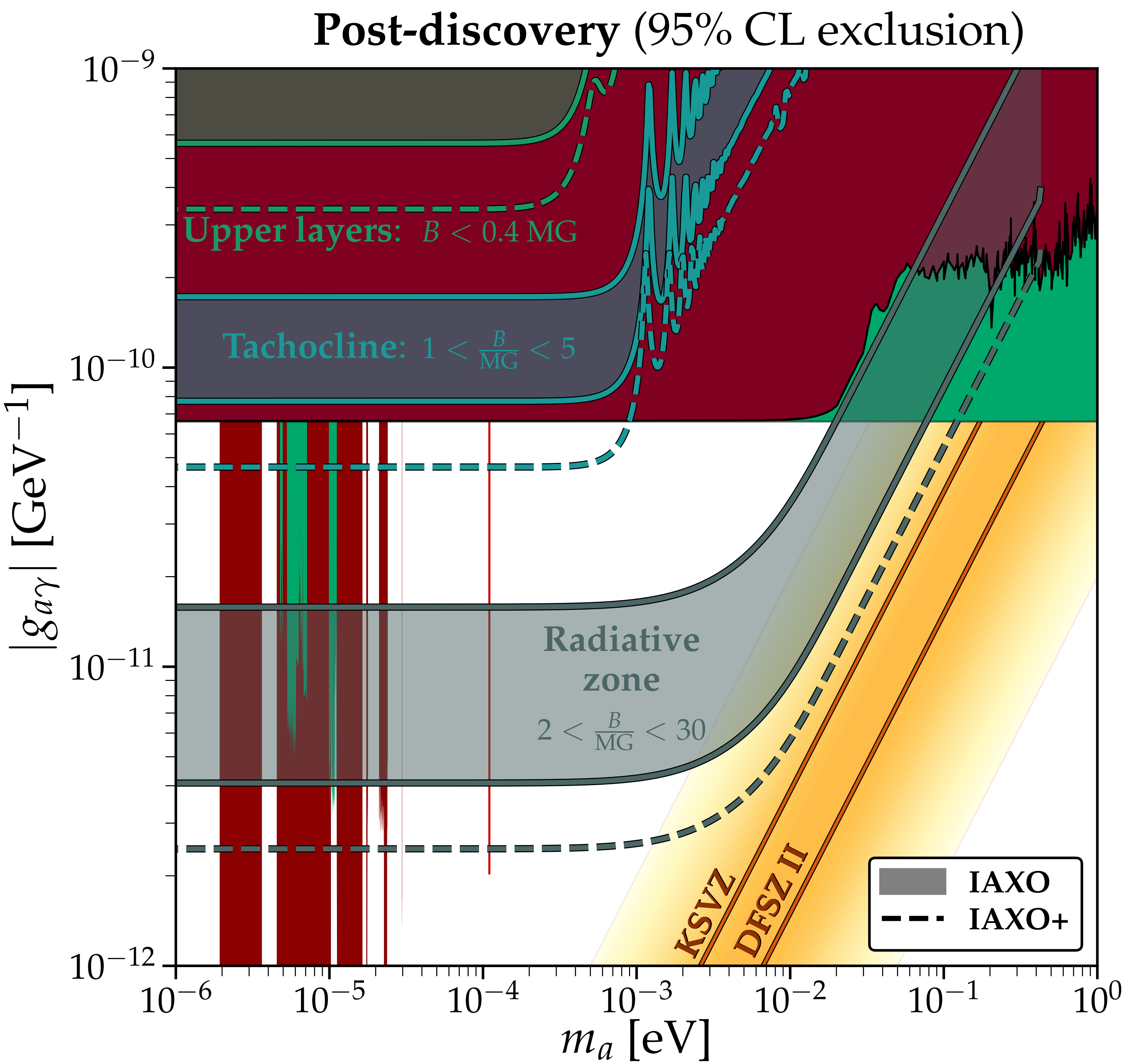
See Dafni, O'Hare *et al.* [1811.09290]
For details of this type of analysis

How well can IAXO measure the Sun's magnetic field?



Range of axion mass and couplings where the magnetic field can be excluded from 0 at 95% CL **within** the 3 (or 6) year exposure of IAXO

How well can IAXO measure the Sun's magnetic field?

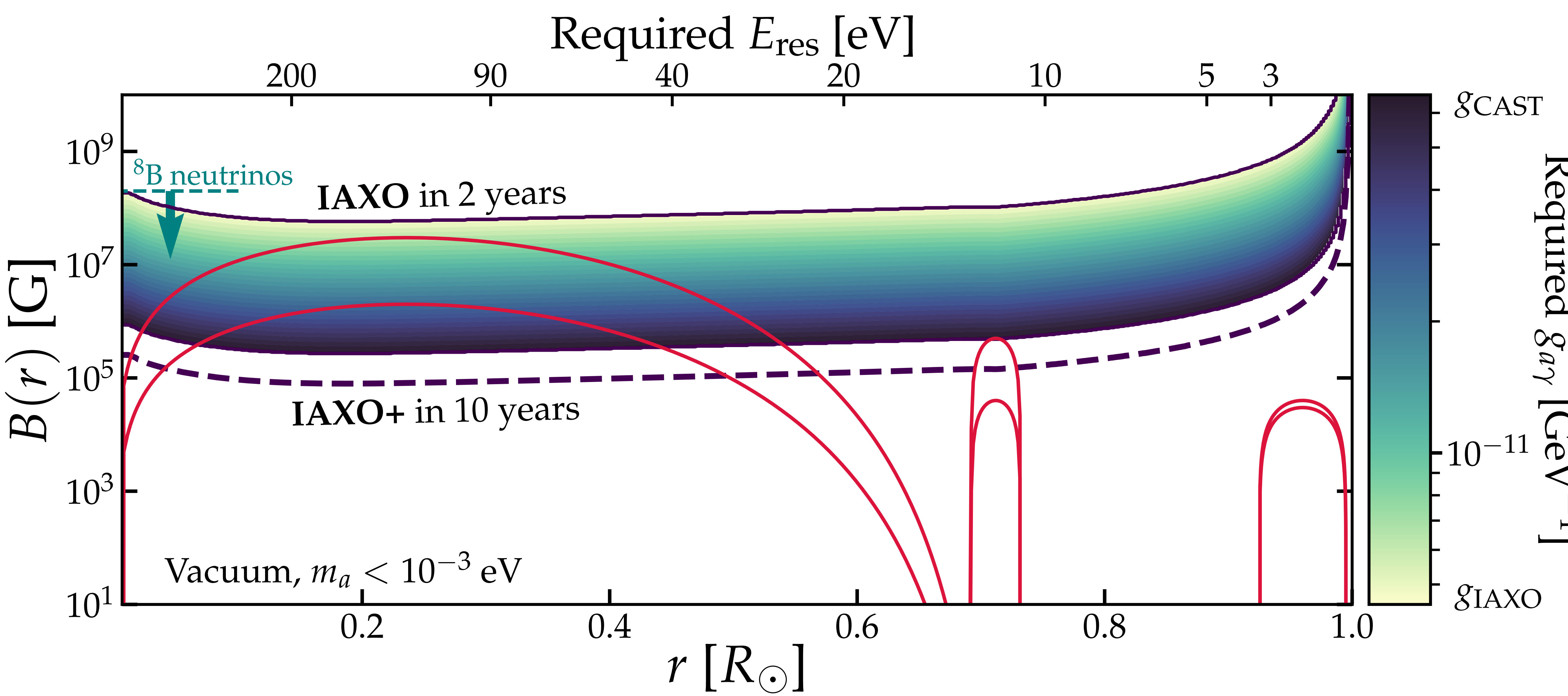


Range of axion mass and couplings where the LPlasmon flux can be excluded from 0 at 95% CL for a 6 year exposure at optimised pressure setting

Ultimate sensitivity (summary)

Probing larger radii requires better energy resolution

- Energy resolution better than 0.2 keV → IAXO will have better sensitivity to core's magnetic field than neutrinos
- Energy resolution better than 20 eV → Saturate uncertainty on Saclay solar model
- Energy resolution better than 10 eV → Probe tachocline with IAXO+
- Upper layers probably out of reach for IAXO and IAXO+



- Can we measure the Sun's magnetic field using solar axions?

- Yes: with a new flux of axions from resonant longitudinal plasmon conversion

Summary

- New source of axions from the sun: resonant conversion of longitudinal plasmons
- Spectrum of new flux maps the Sun’s magnetic field
- With X-ray detector energy resolution <0.2 keV this flux is measurable, and even dominates at low energies
- IAXO could use this flux to constrain the Sun’s magnetic field → Particularly novel for the B-field in the inner parts, exactly where other measures fail.

For more

→ arxiv.org/abs/2005.00078 for calculation of flux
→ arxiv.org/abs/2006.10415 for IAXO sensitivity
→ GitHub.com/cajohare/solax to see the code for both

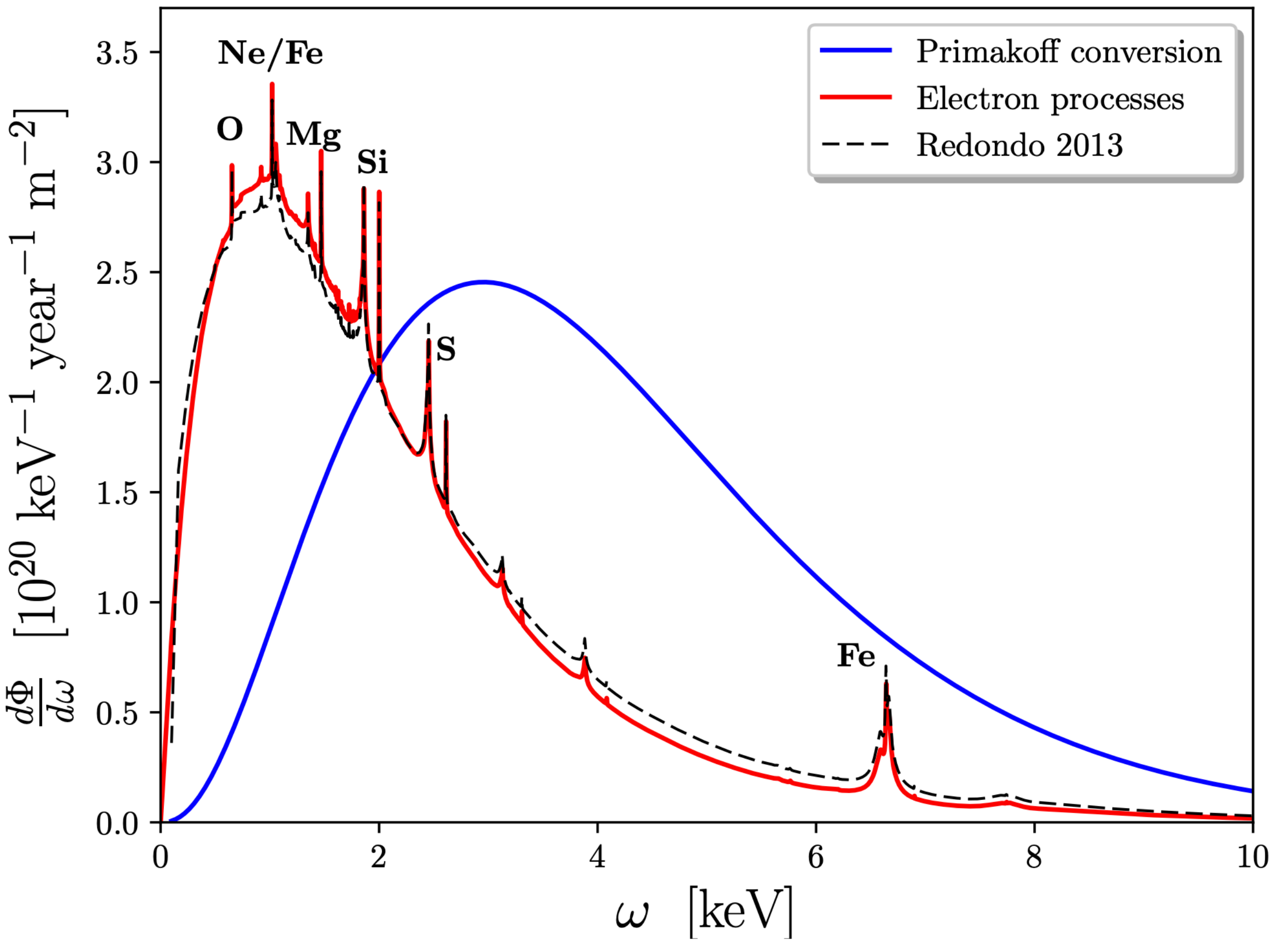
Extra slides

Other physics with helioscopes beyond axions

Axions as a probe of solar metals

Joerg Jaeckel[a] and Lennert J. Thormaehlen[b]
Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany

[1908.10878]



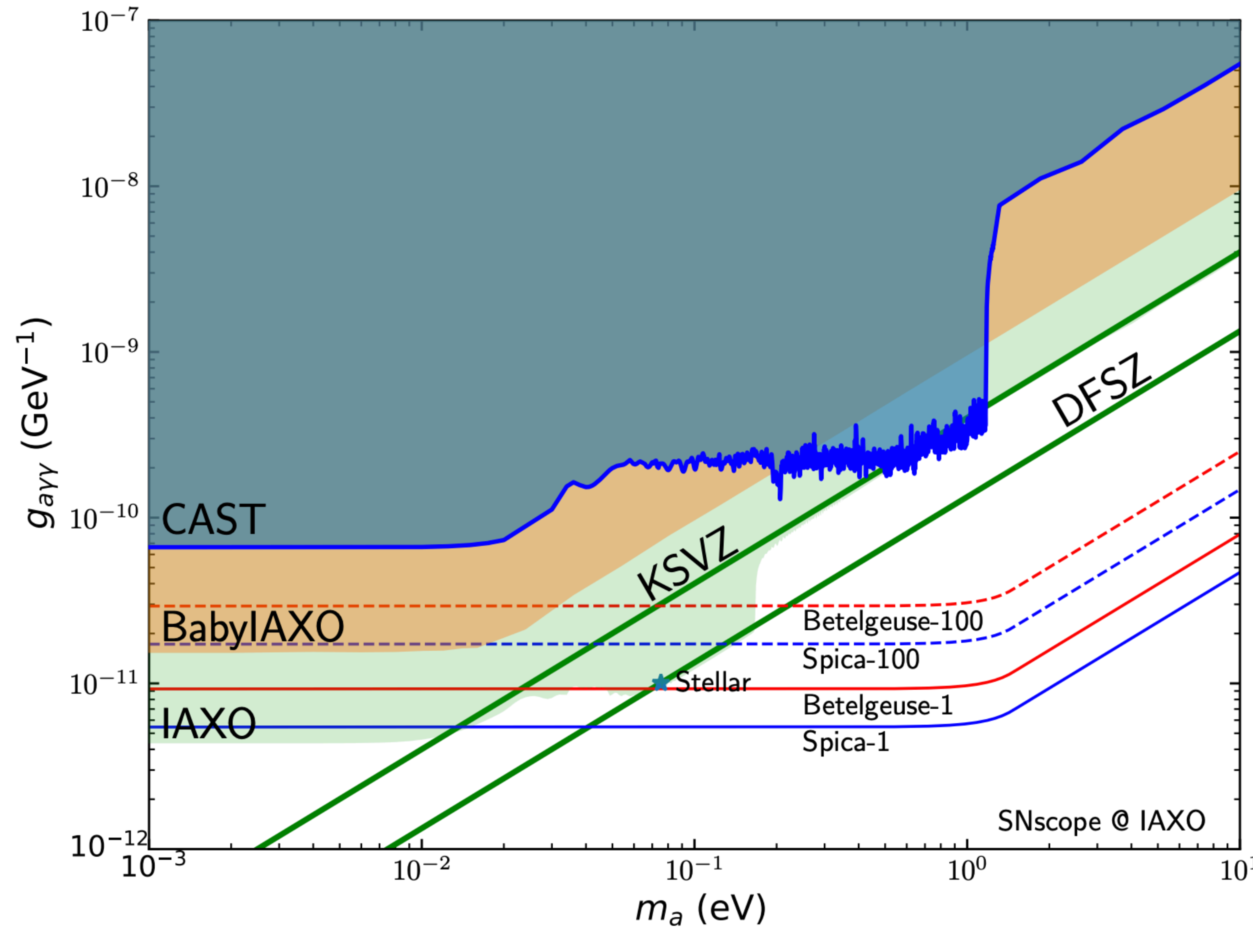
Measure solar abundances

Supernova-scope for the Direct Search of Supernova Axions

Shao-Feng Ge[a,b,c], Koichi Hamaguchi[d,e], Koichi Ichimura[f,e] Koji Ishidoshiro[f], Yoshiki Kanazawa[d], Yasuhiro Kishimoto[f,e], Natsumi Nagata[d], Jiaming Zheng[a,b]

[a] *Tsung-Dao Lee Institute, Shanghai 200240, Shanghai Jiao Tong University, China*
[b] *School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*

[2008.03924]



Detect galactic SN

Note: Take care with the Primakoff flux

- At low energies Primakoff flux suppressed by non-zero plasma freq.
- This is not accounted for in the usual empirical formula

→ when looking at the LPlasmon flux, use full Primakoff calculation

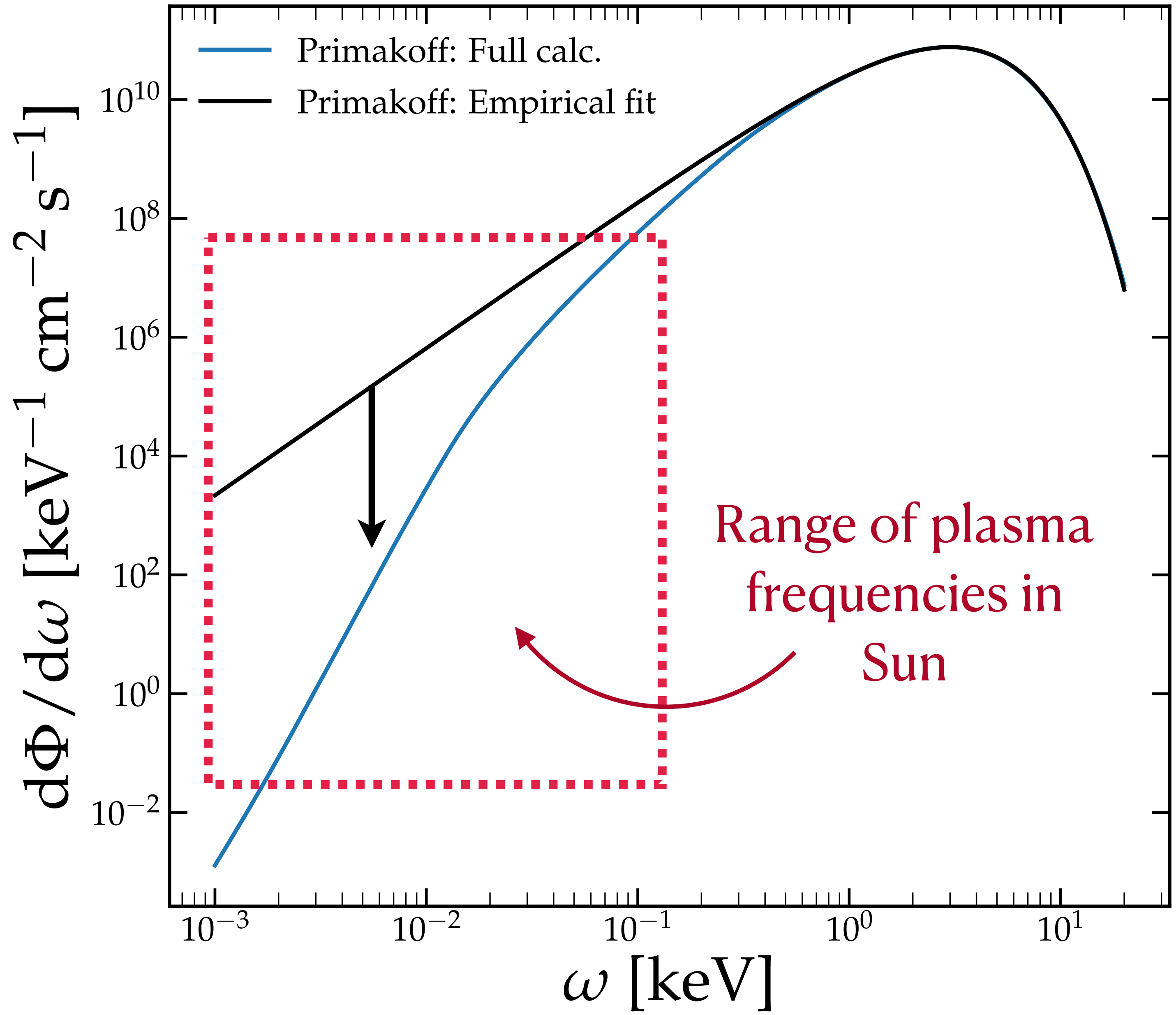
- See paper by Jaeckel *et al.* hep-ph/0610203 (or ours 2005.00078)

Use this:

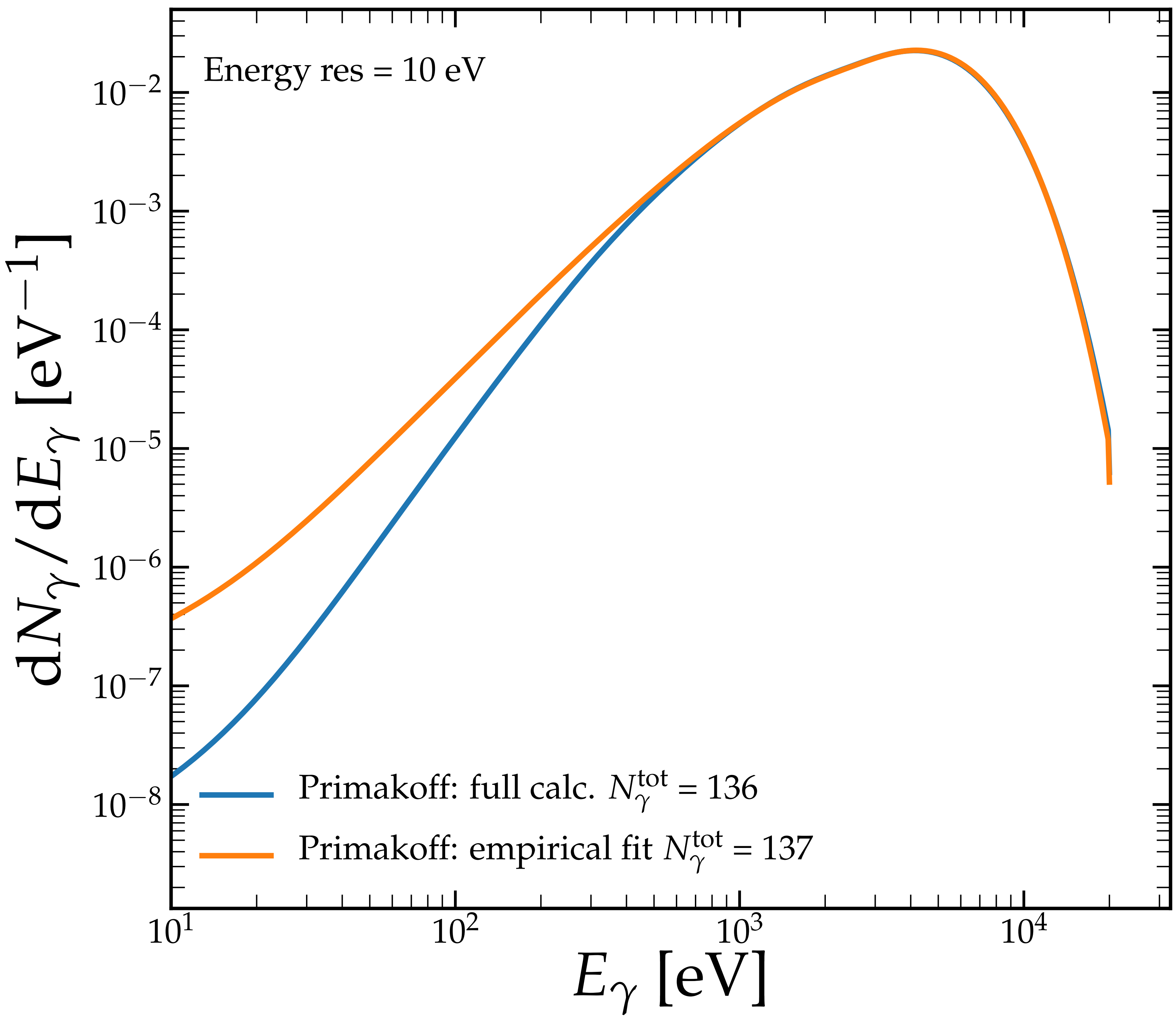
$$\frac{\mathrm{d}\Phi_P}{\mathrm{d}\omega} = \frac{1}{(1\mathrm{AU})^2}\int_0^{R_\odot} r^2\mathrm{d}r\,\frac{\omega^2}{\pi^2}\,\frac{\Gamma_{\gamma\to a}(\omega,r)}{\mathrm{e}^{\omega/T(r)}-1}$$

Not this:

$$\frac{\mathrm{d}\Phi_P}{\mathrm{d}\omega} = \Phi_{P10}\left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2\frac{\omega^{2.481}}{e^{\omega/1.205}}$$

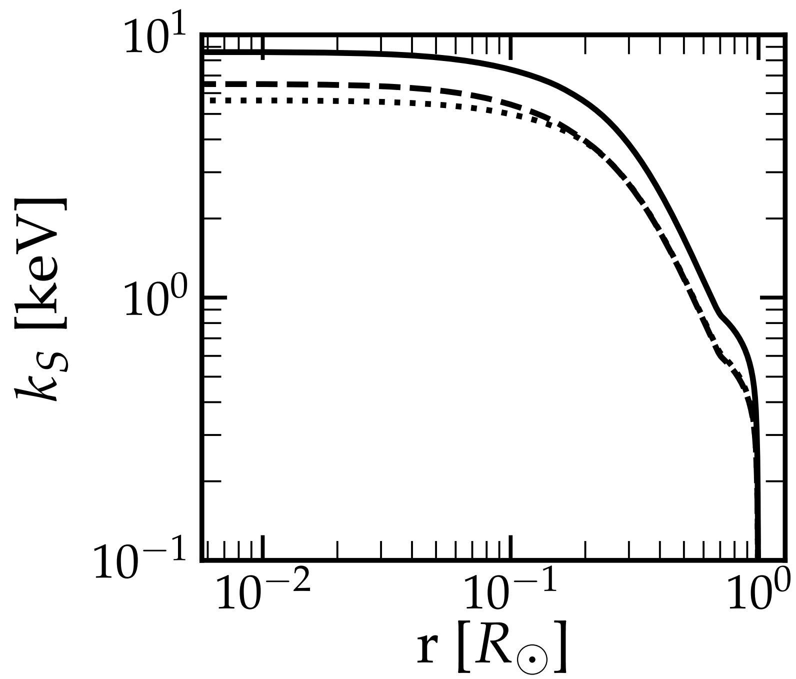


Note: Take care with the Primakoff flux

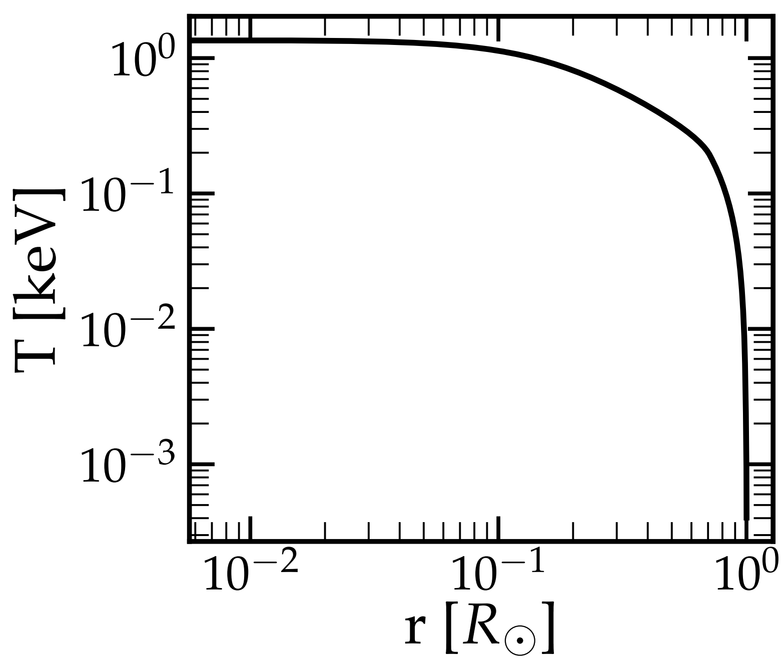


Saclay model

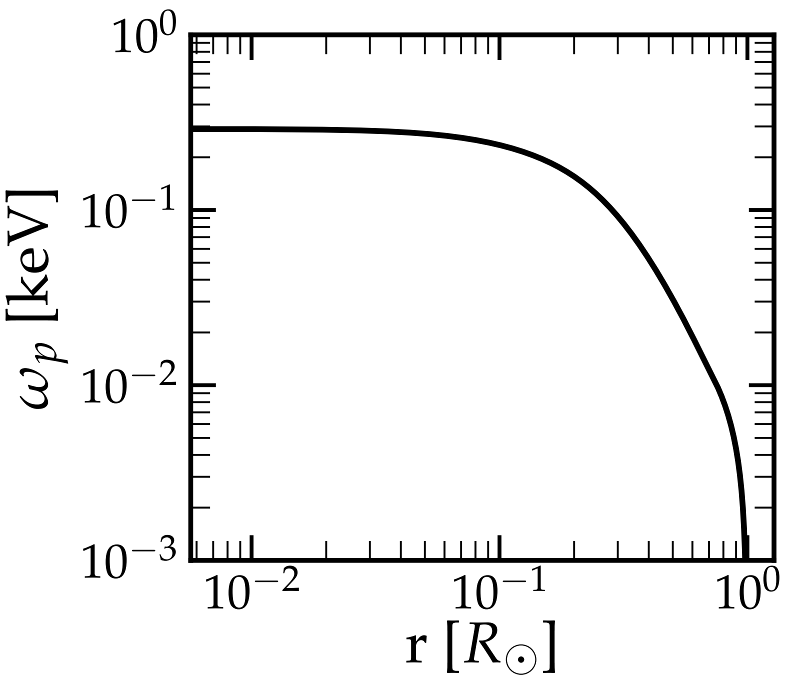
Debye screening scale



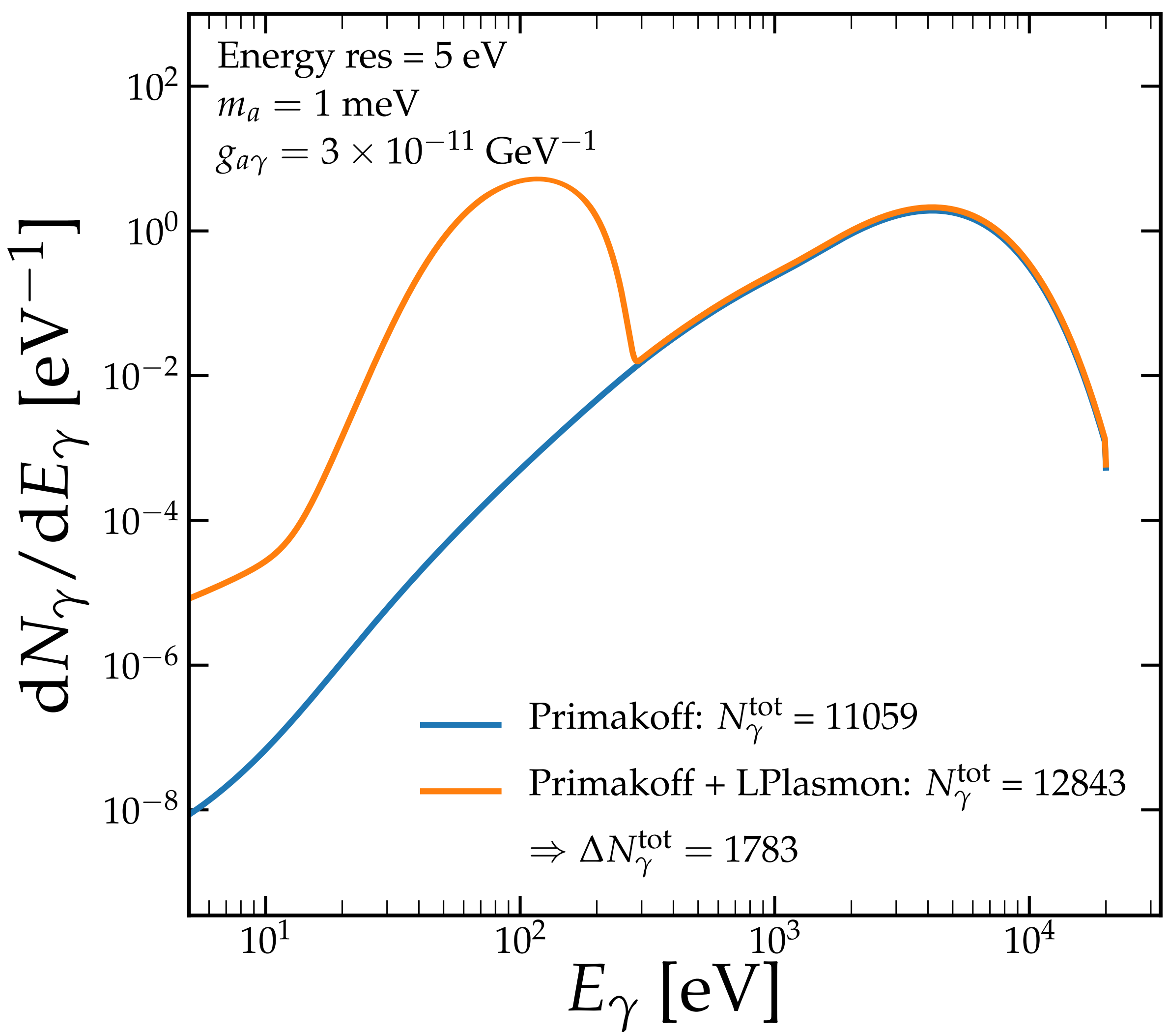
Temperature



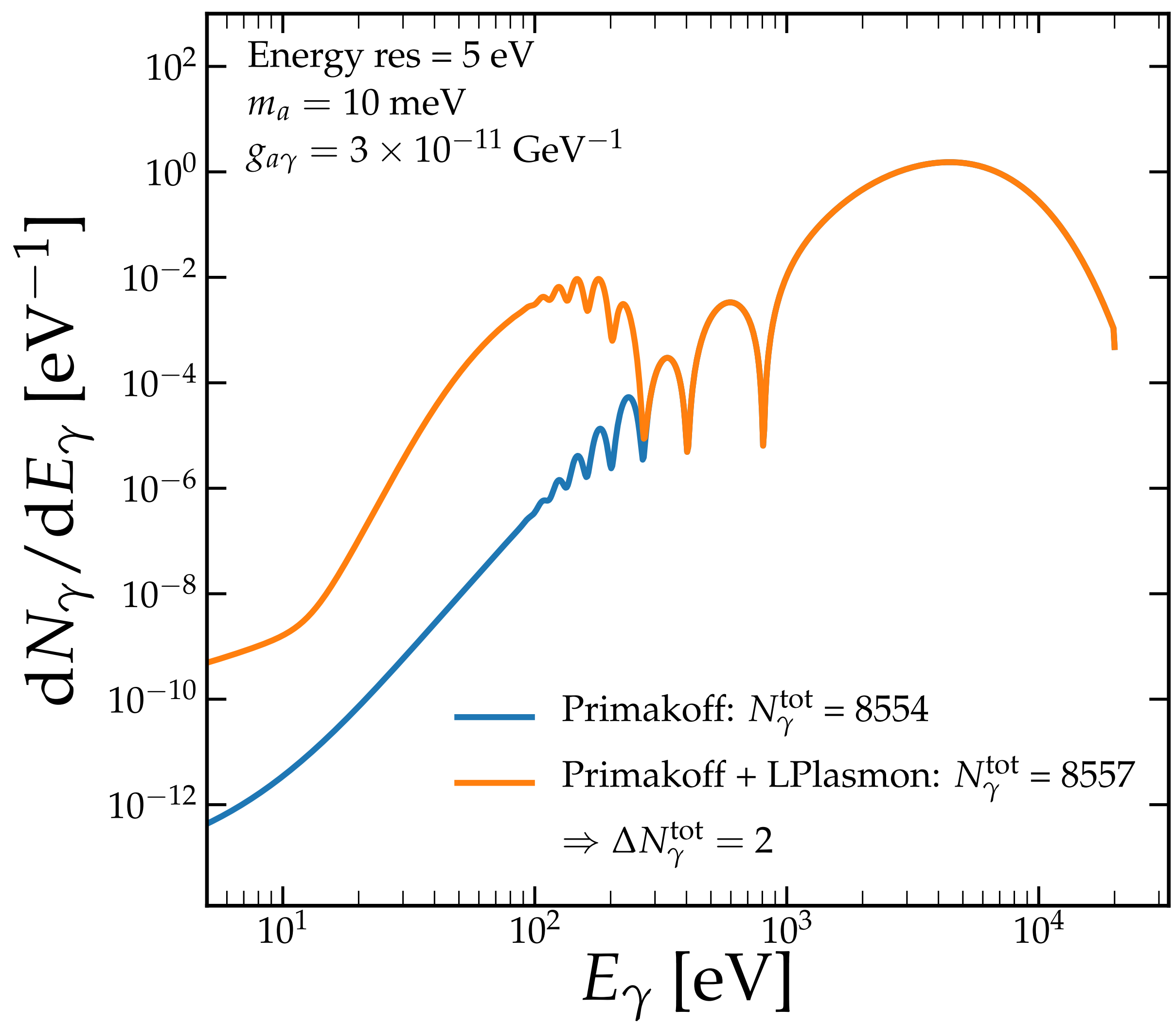
Plasma frequency

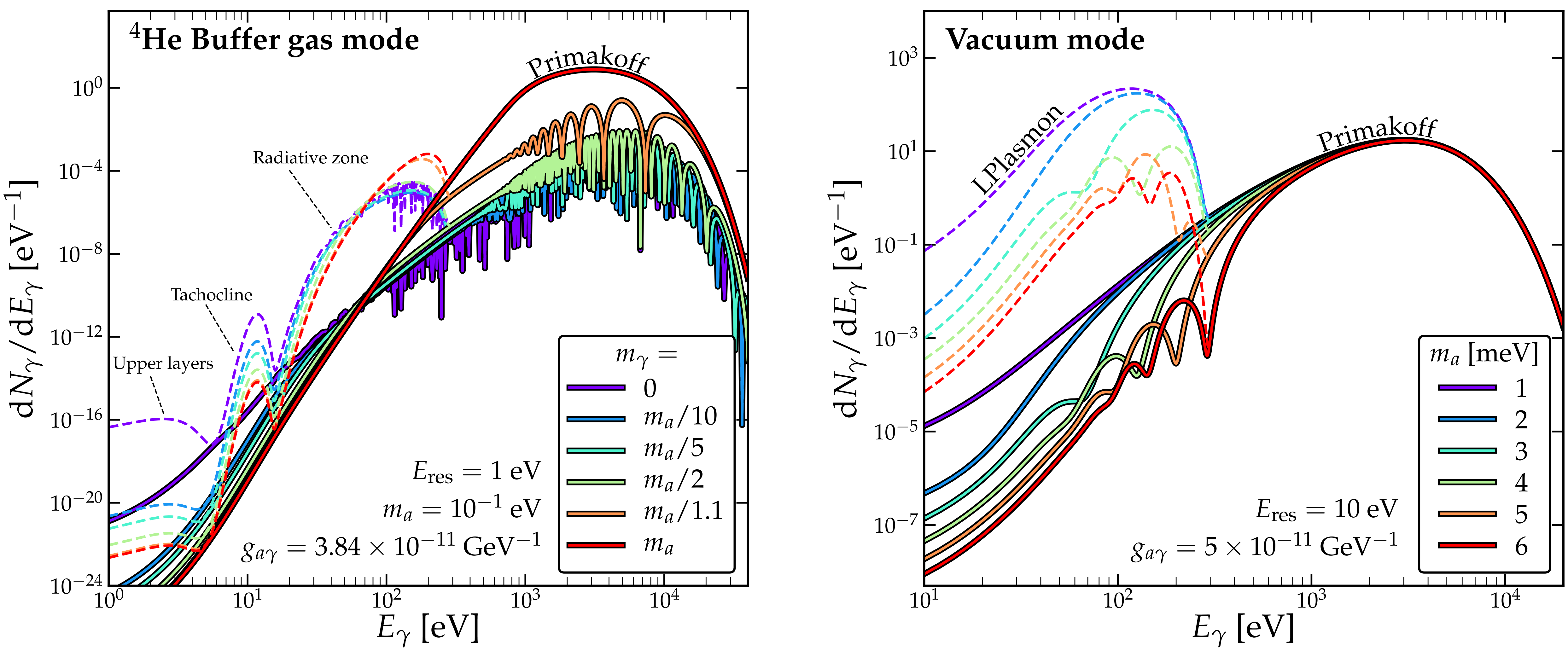


1 meV axion



10 meV axion





^{4}He Buffer gas mode
Primakoff
Radiative zone
Tachocline
Upper layers
$m_\gamma =$
0
$m_a/10$
$m_a/5$
$m_a/2$
$m_a/1.1$
m_a
$E_{\rm res} = 1$ eV
$m_a = 10^{-1}$ eV
$g_{a\gamma} = 3.84 \times 10^{-11}$ GeV^{-1}
dN_γ/dE_γ [eV^{-1}]
E_γ [eV]
Vacuum mode
LPlasmon
Primakoff
m_a [meV]
1
2
3
4
5
6
$E_{\rm res} = 10$ eV
$g_{a\gamma} = 5 \times 10^{-11}$ GeV^{-1}