Axion Conversion in the Solar Magnetic Field

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2nd General COSMIC WISPers Meeting, Istanbul, 06.09.2024

Outline

- **Axion-photon conversion**
- **The Sun**
- **Conversion of axion dark matter in the solar atmosphere**

E.T., M. Regis, M. Taoso, M. Giannotti, J. Ruz, J. K. Vogel

"*The Sun as a target for axion dark matter detection*"

Phys. Lett. B 854 (2024) 138752

- **Conversion of solar axions in the solar atmosphere**

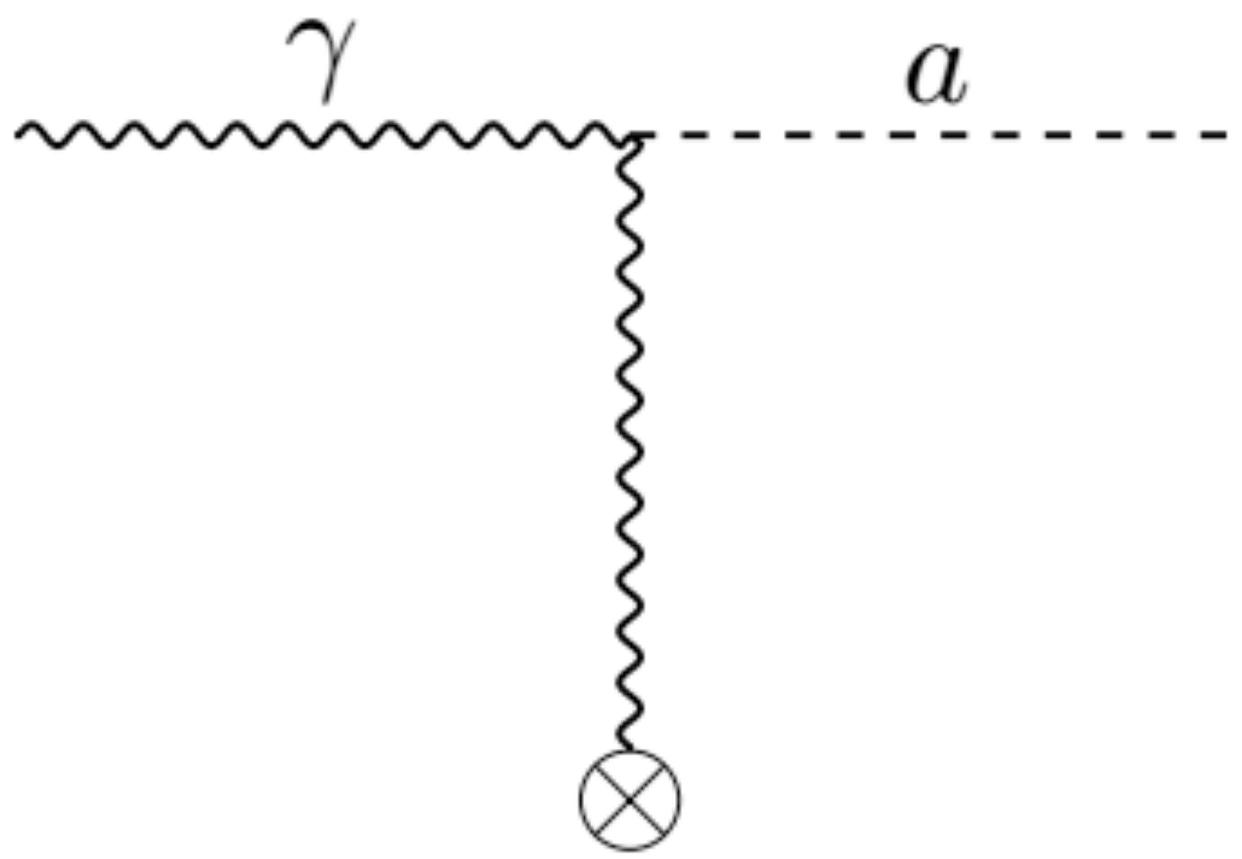
J. Ruz, **E. T.**, J. K. Vogel, M. Giannotti, B. Grefenstette, H. S. Hudson, I. G. Hannah, I. G. Irastorza, C. S. Kim, T. O'Shea, M. Regis, D. M. Smith, M. Taoso, J. Trujillo Bueno

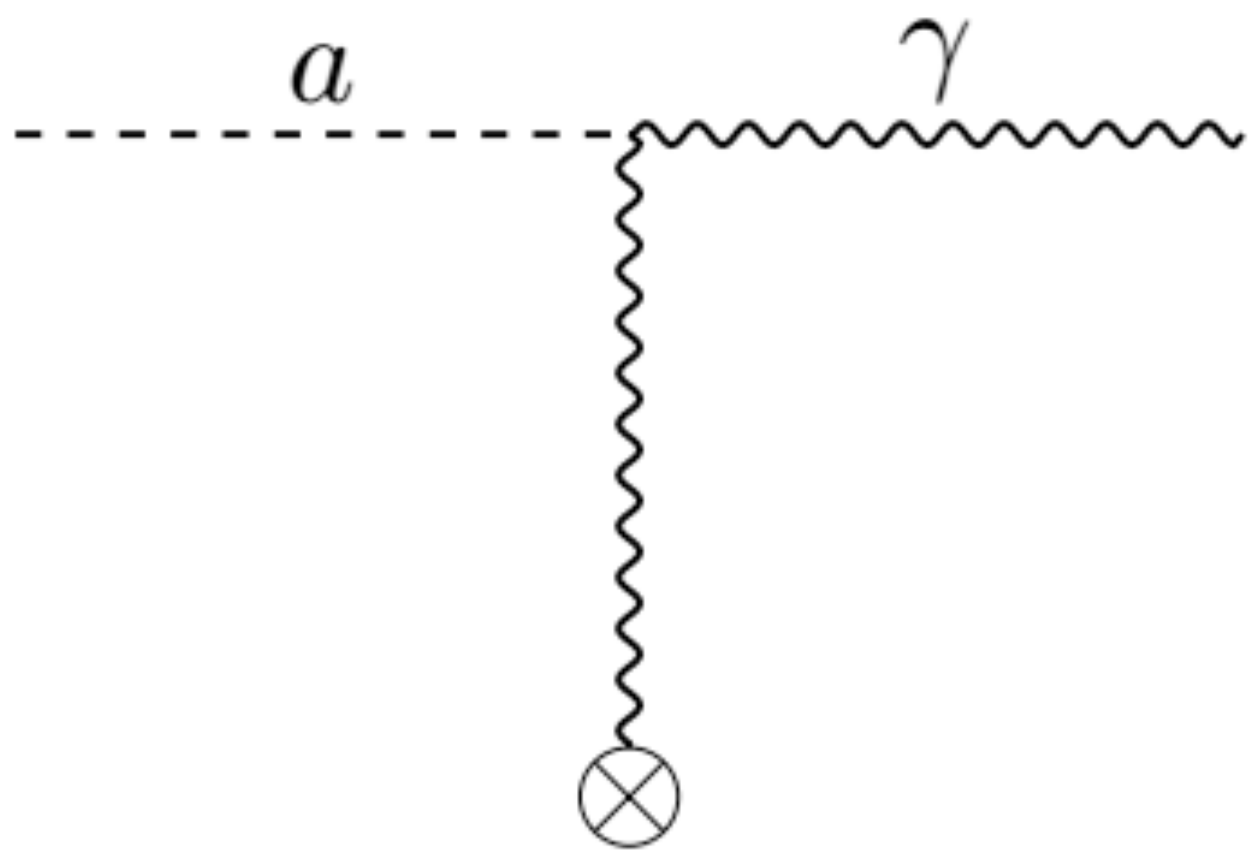
"*NuSTAR as an Axion Helioscope*"

arXiv:2407.03828 [astro-ph.CO]

Axion-Photon Conversion

$$\mathcal{L}_{a\gamma\gamma} = \frac{1}{4} g a F_{\mu\nu} \tilde{F}^{\mu\nu}$$





Axion-Photon Conversion

In a static background $\omega = \omega_a$

$$(n^2\omega^2 + \nabla^2)\vec{A} = ig\omega\vec{B}_0 a_0 \ e^{i\vec{k}_a\cdot\vec{x}}$$

Index of refraction in a weakly magnetized plasma

$$n = \frac{k}{\omega} = \frac{\sqrt{\omega^2 - \omega_p^2}}{\omega}$$

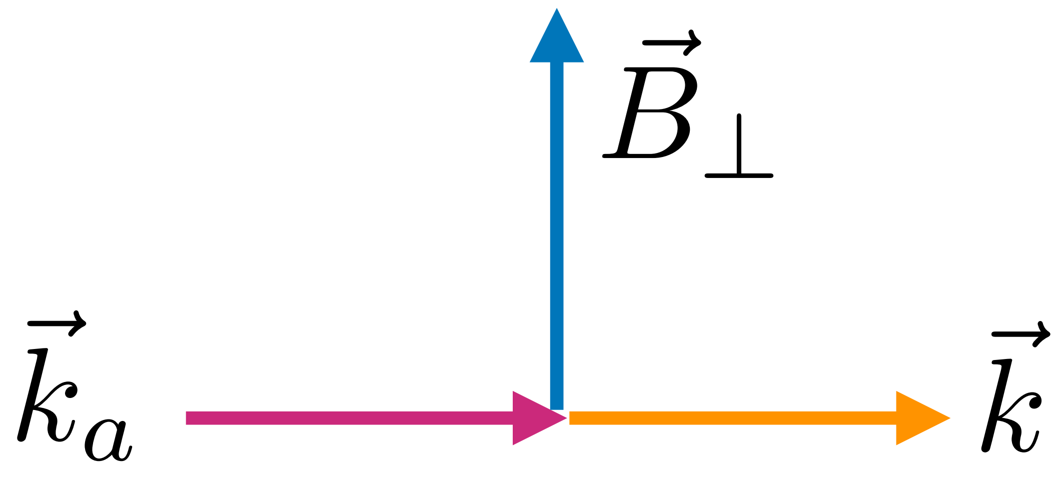
← The photon gets an effective mass

Axion-Photon Conversion

If fields propagating along a given direction

$$P_{a\to\gamma}(h) = \frac{1}{4} g^2 \frac{1}{v_a} \left| \int_0^h dh' \frac{1}{\sqrt{n}} B_\perp(h') \; e^{i \int_0^{h'} dh'' q(h'')} \right|^2$$

$$q = k - k_a = n\omega - \sqrt{\omega^2 - m_a^2}$$



Sikivie, Rev.Mod.Phys. 93 (2021)
Leroy et al., PRD 101 (2020) 12

Resonant Conversion

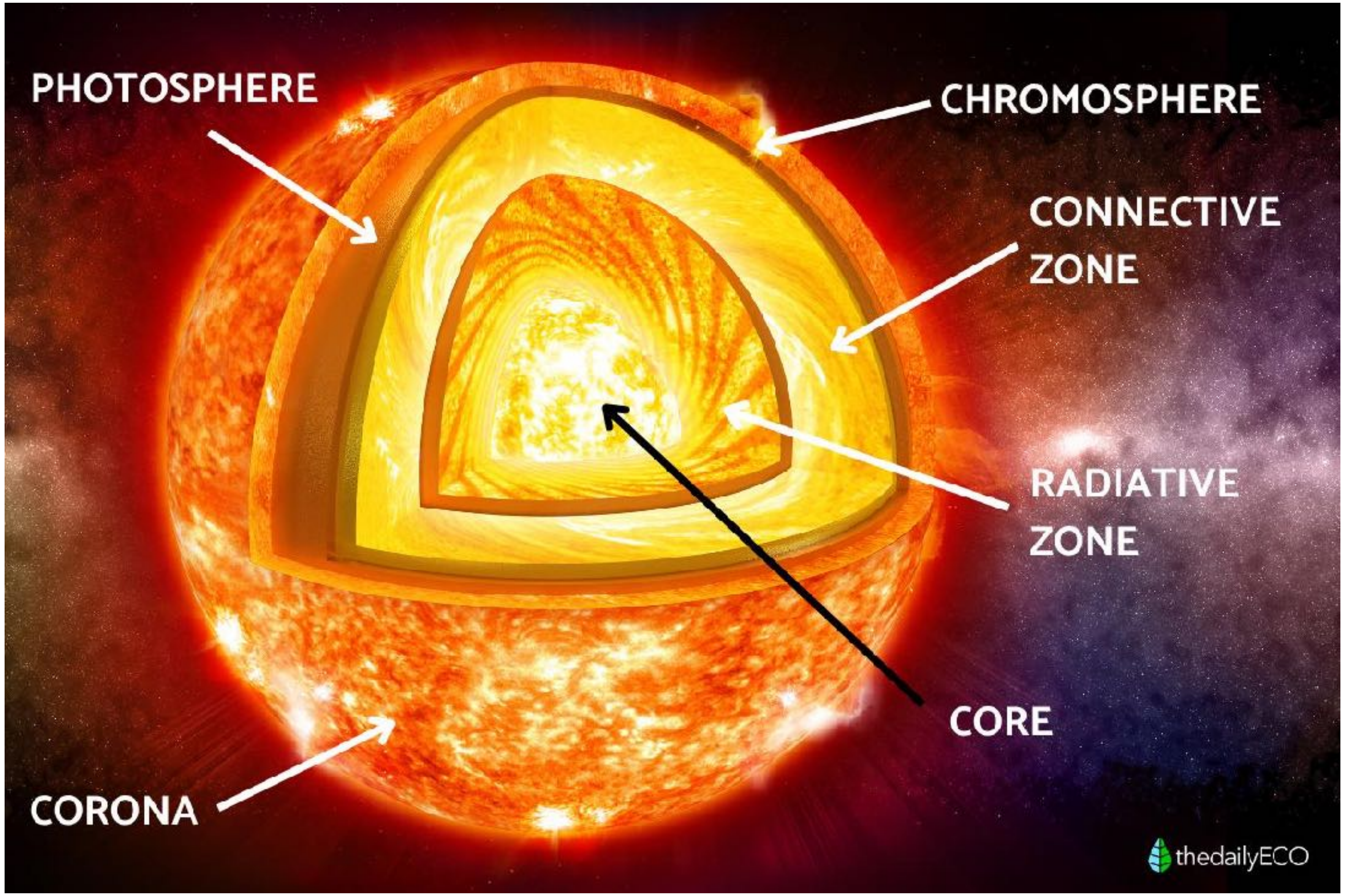
$$P_{a\to\gamma}(h) = \frac{1}{4} g^2 \frac{1}{v_a} \left| \int_0^h dh' \frac{1}{\sqrt{n}} B_\perp(h')\, e^{i \int_0^{h'} dh'' q(h'')} \right|^2$$

$$q = 0 \;\longrightarrow\; q = k - k_a = \sqrt{\omega^2 - \omega_p^2} - \sqrt{\omega^2 - m_a^2} = 0 \;\longrightarrow\; m_a = \omega_p$$

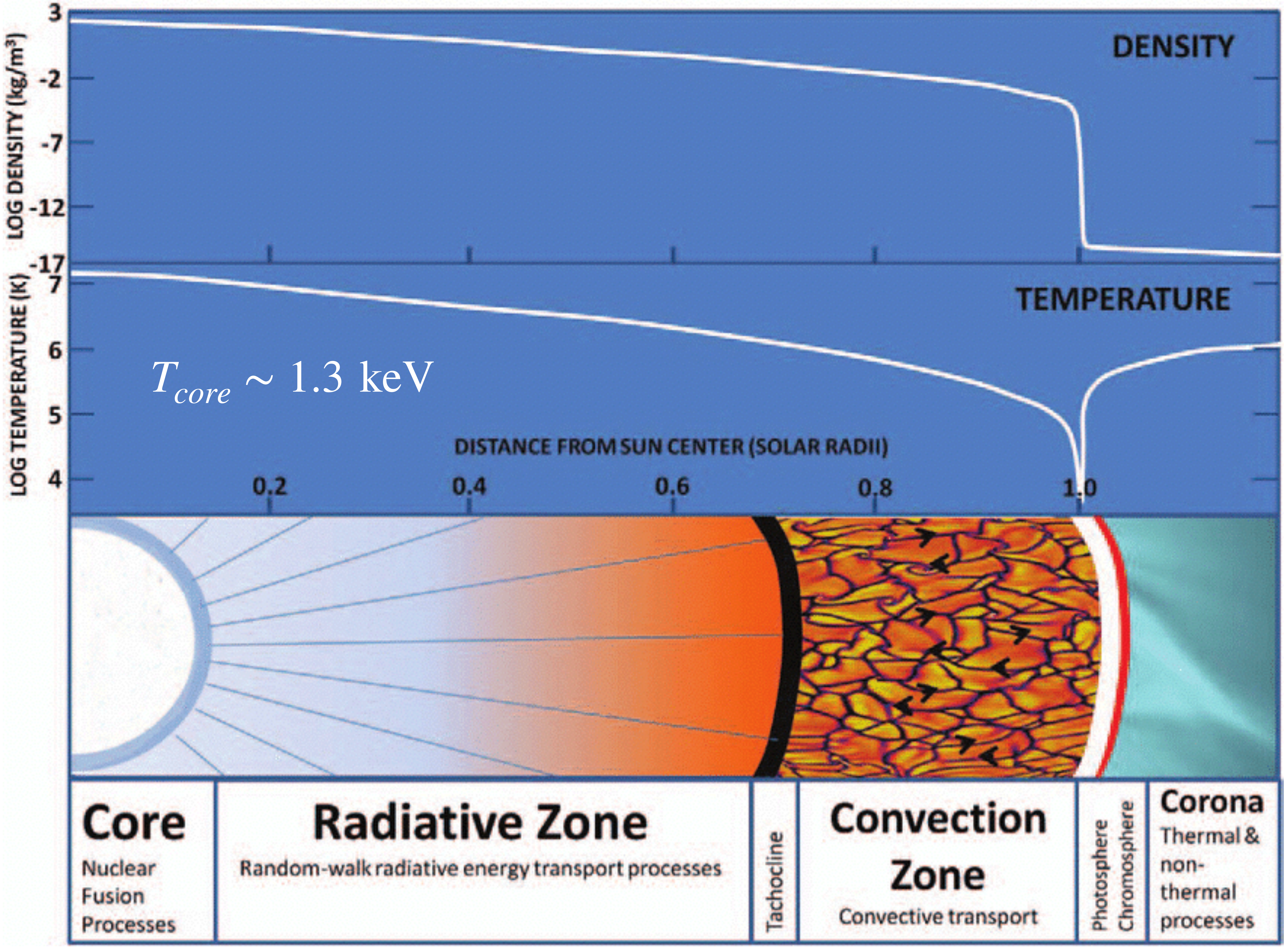
Stationary phase approximation

$$P_{a\to\gamma} \simeq \frac{\pi}{2} \frac{g^2 B_\perp^2}{v_a\, \omega_p'} \Big|_{h=h_c}$$

The Sun

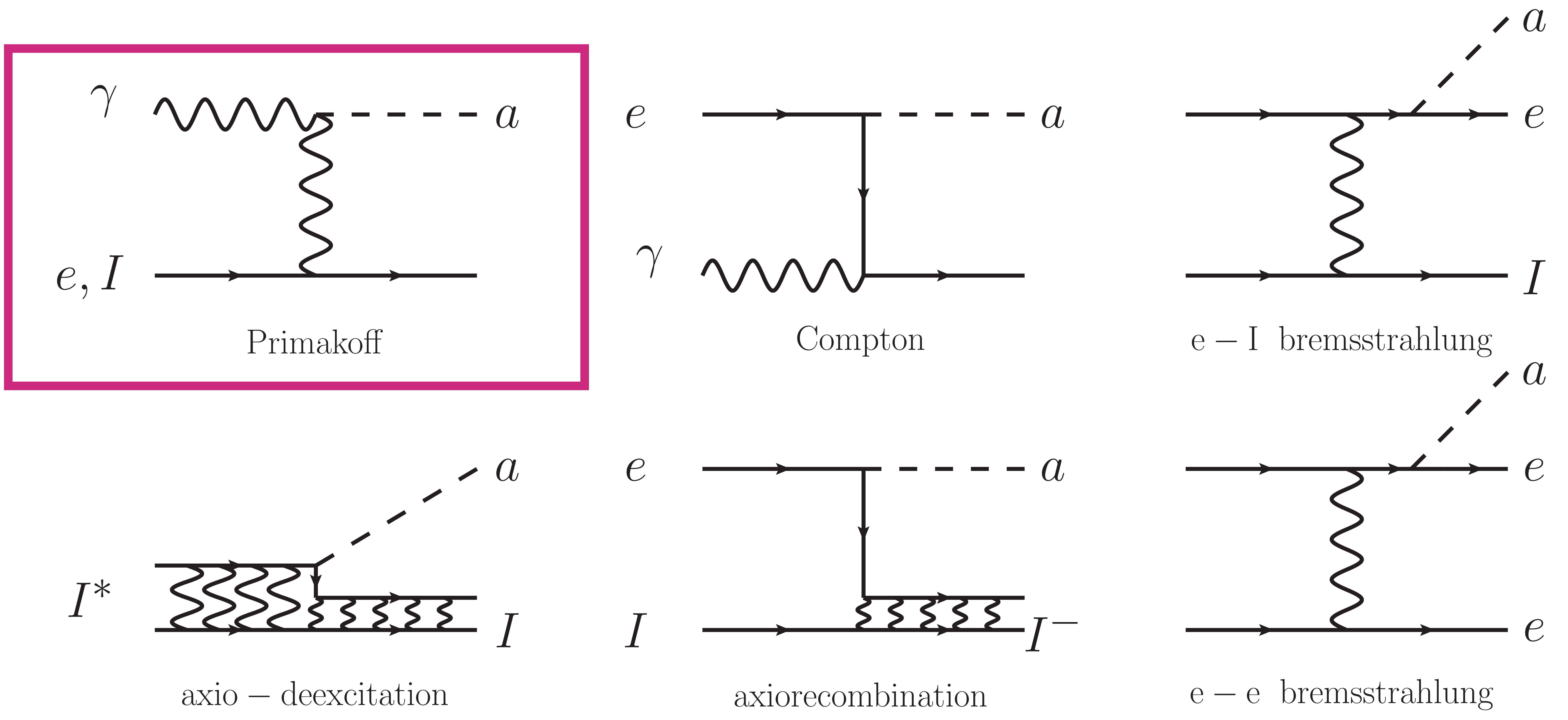

PHOTOSPHERE
CHROMOSPHERE
CONNECTIVE ZONE
RADIATIVE ZONE
CORE
CORONA
thedailyECO

The Sun's Layers



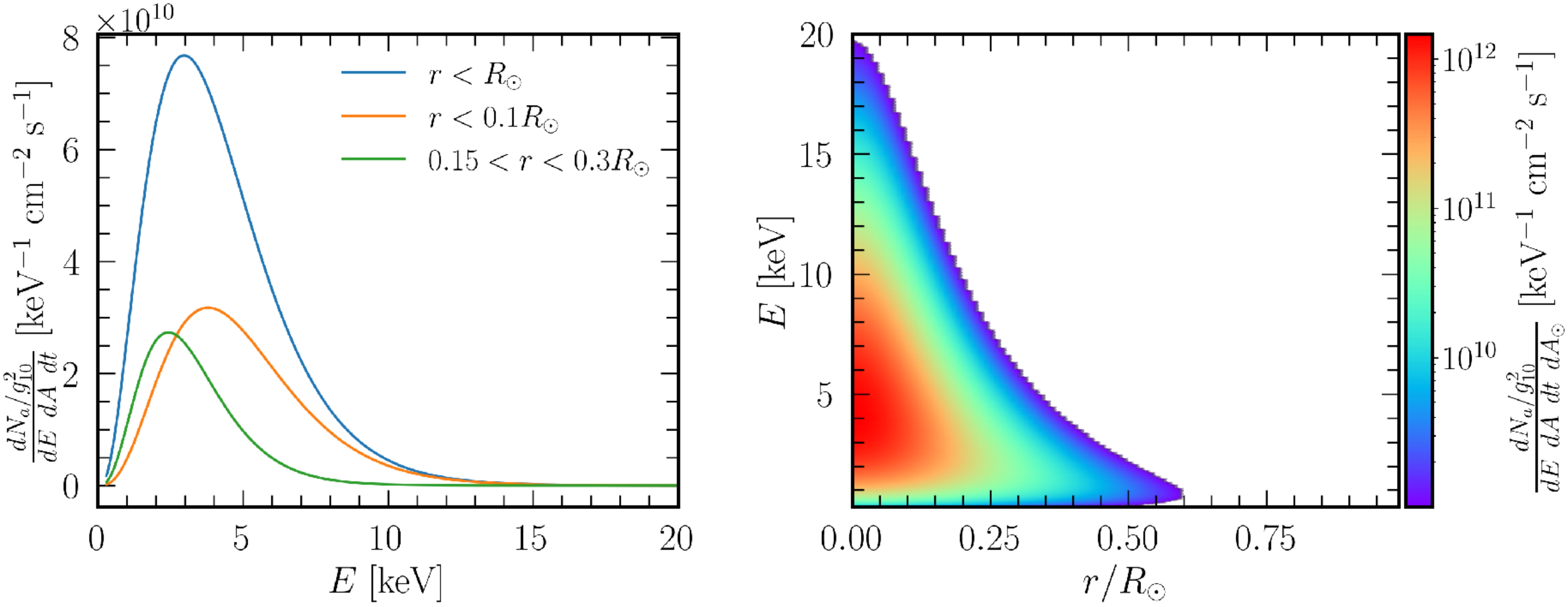
K. Strong et al., Bulletin of the American Meteorological Society, vol. 93, issue 9, pp. 1327-1335

Axions from the Solar Core



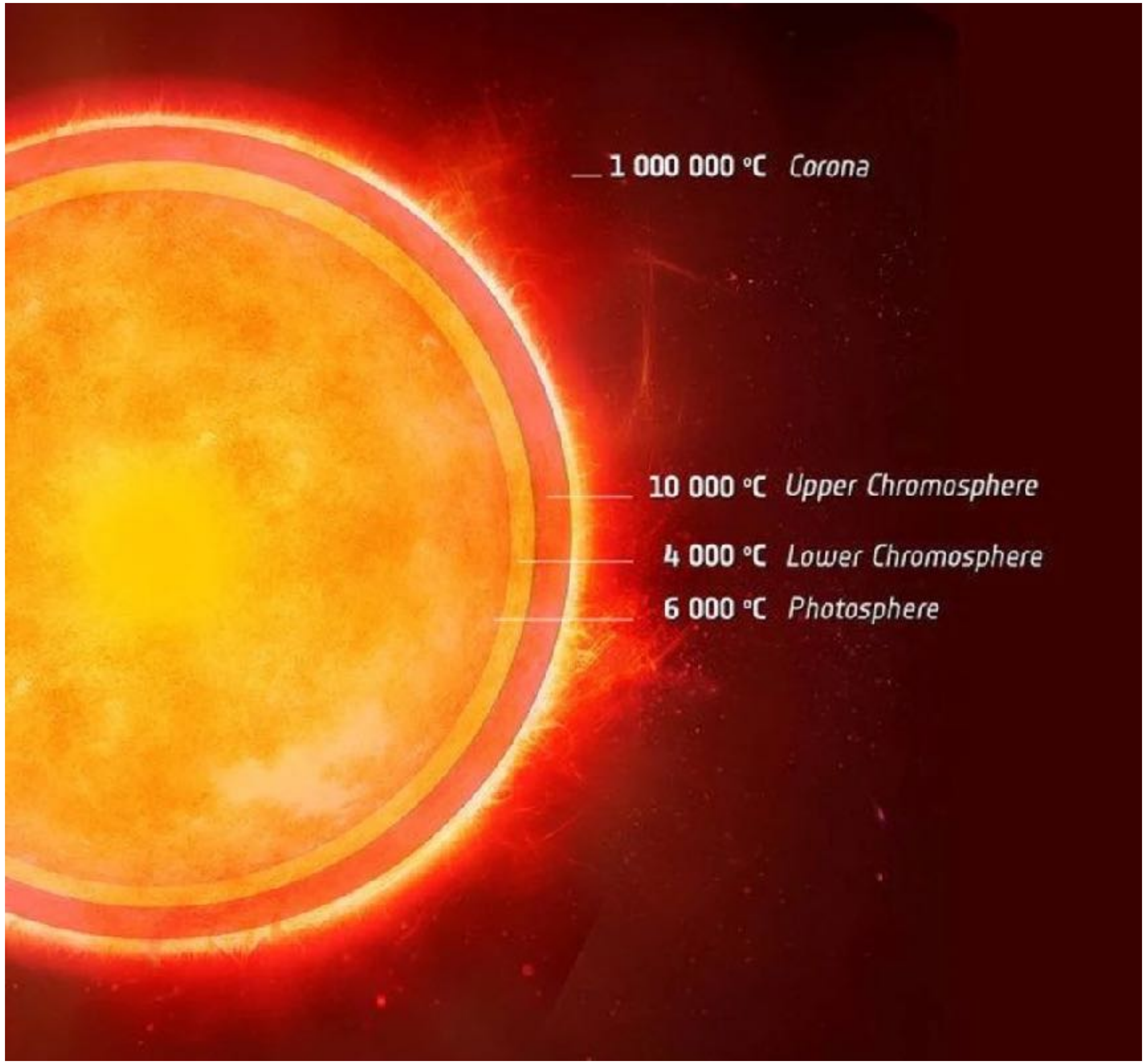
J. Redondo, JCAP 12 (2013) 008

Axion Flux at Earth

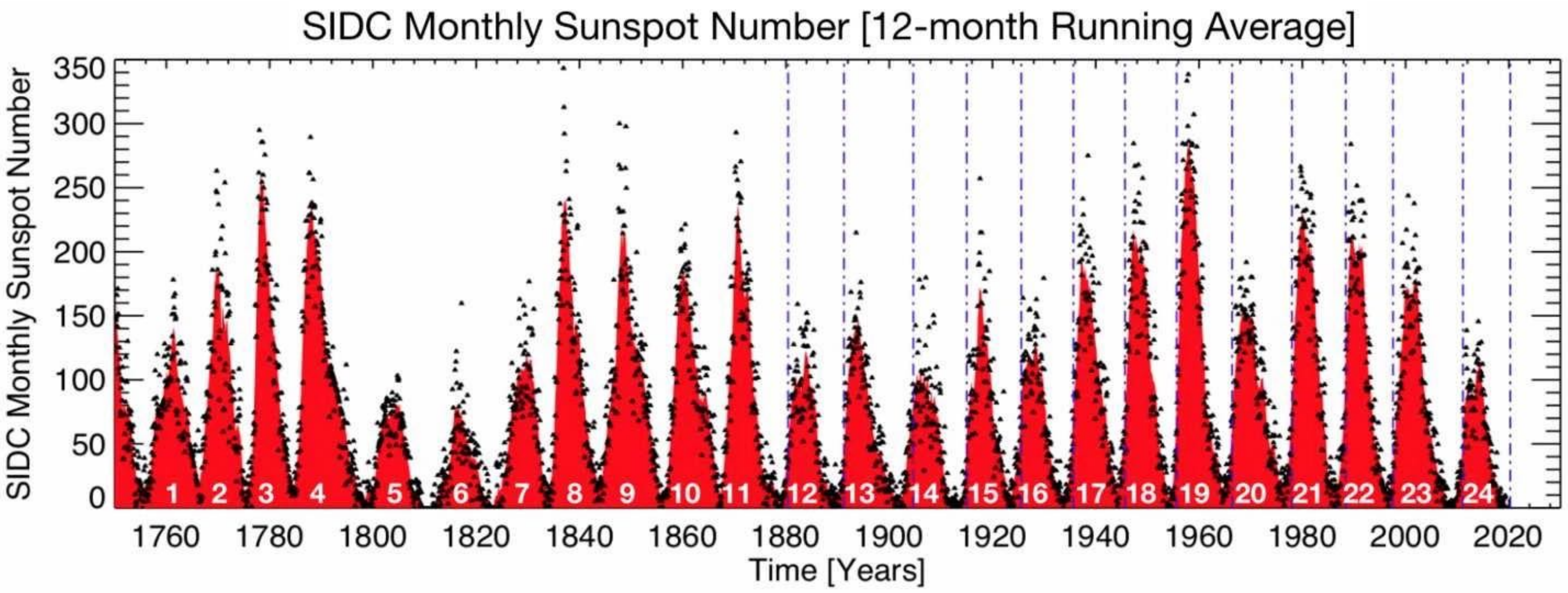


Solar composition from Bahcall, Pinsonneault, Phys.Rev.Lett. 92 (2004) 121301

The Solar Atmosphere



Solar Cycles



S. W. McIntosh et al., Sol Phys 295, 163 (2020). Data from www.sidc.be/silso

Quiet Sun's Magnetic Field

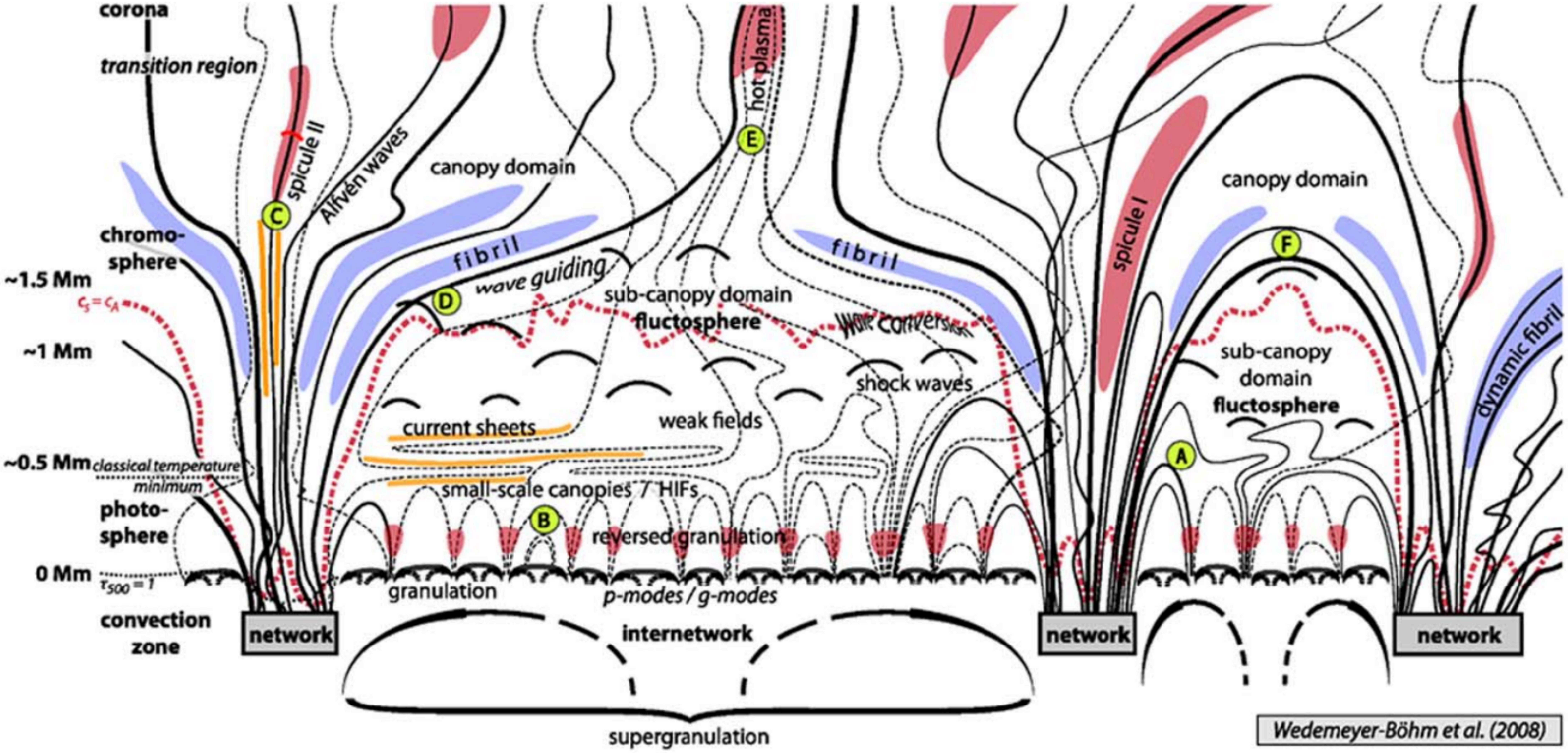
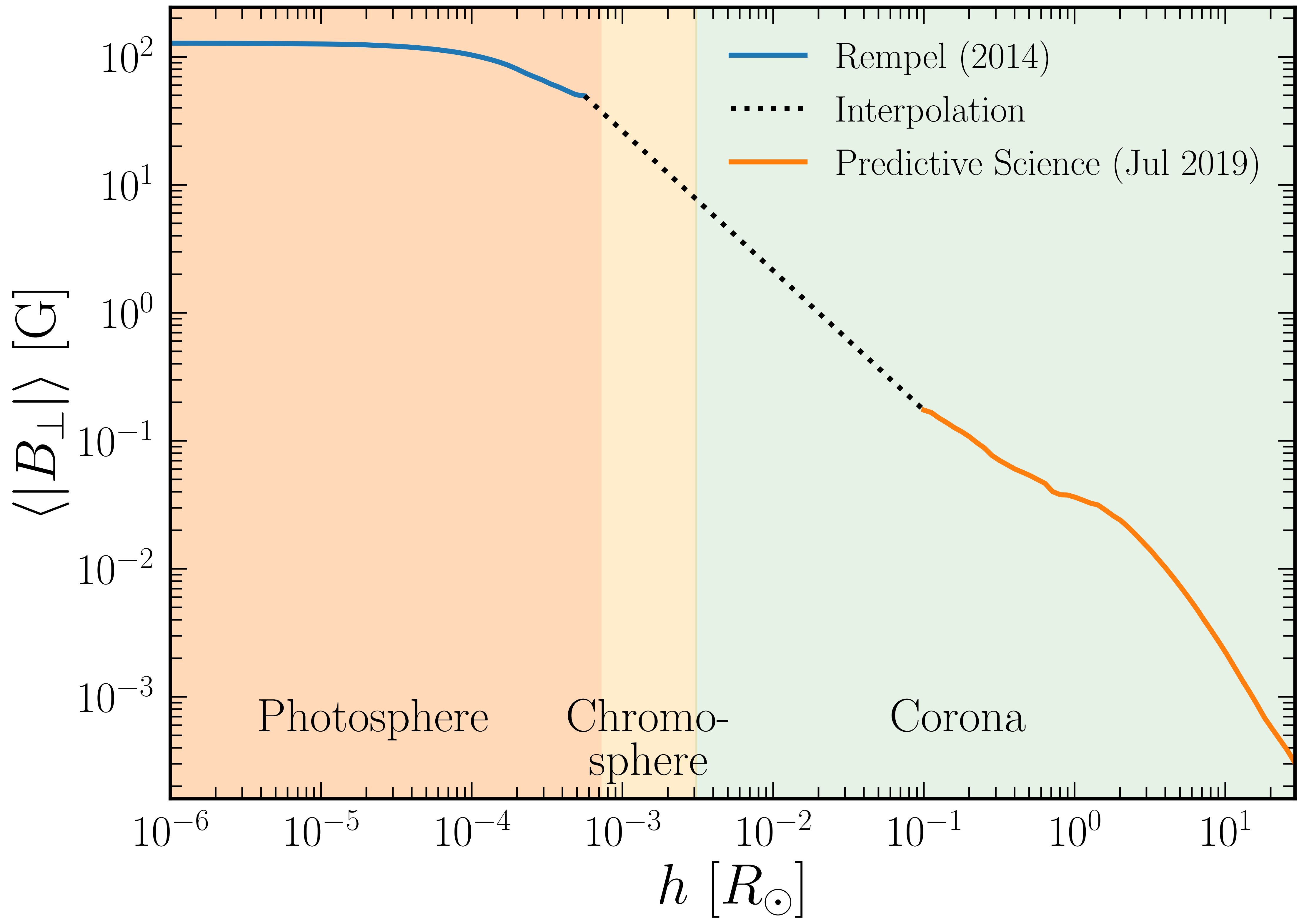


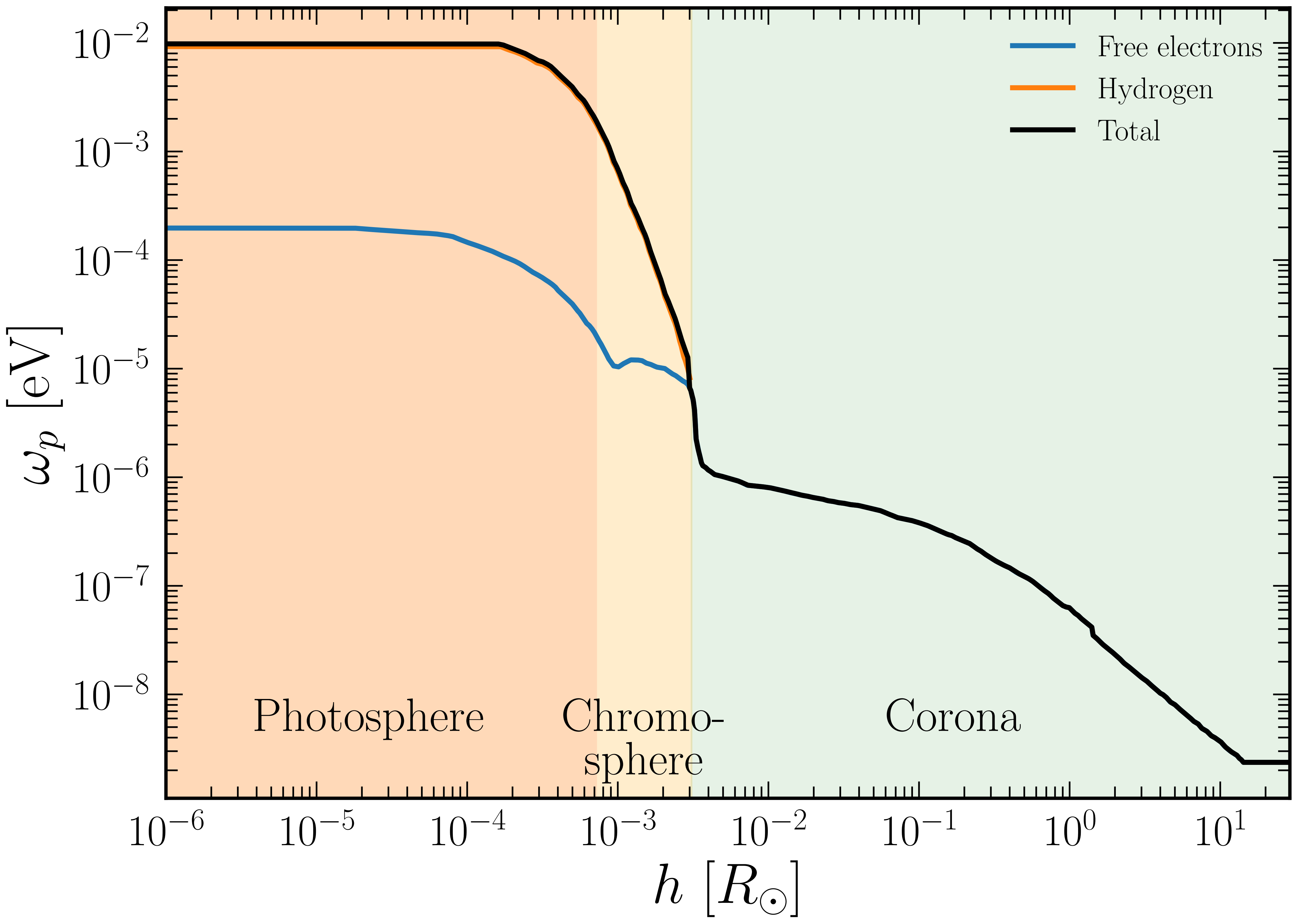
Fig. 16 Schematic, simplified structure of the lower quiet Sun atmosphere (dimensions not to scale): The *solid lines* represent magnetic field lines that form the magnetic

Our Model of Quiet Sun's Atmosphere

Perpendicular magnetic field

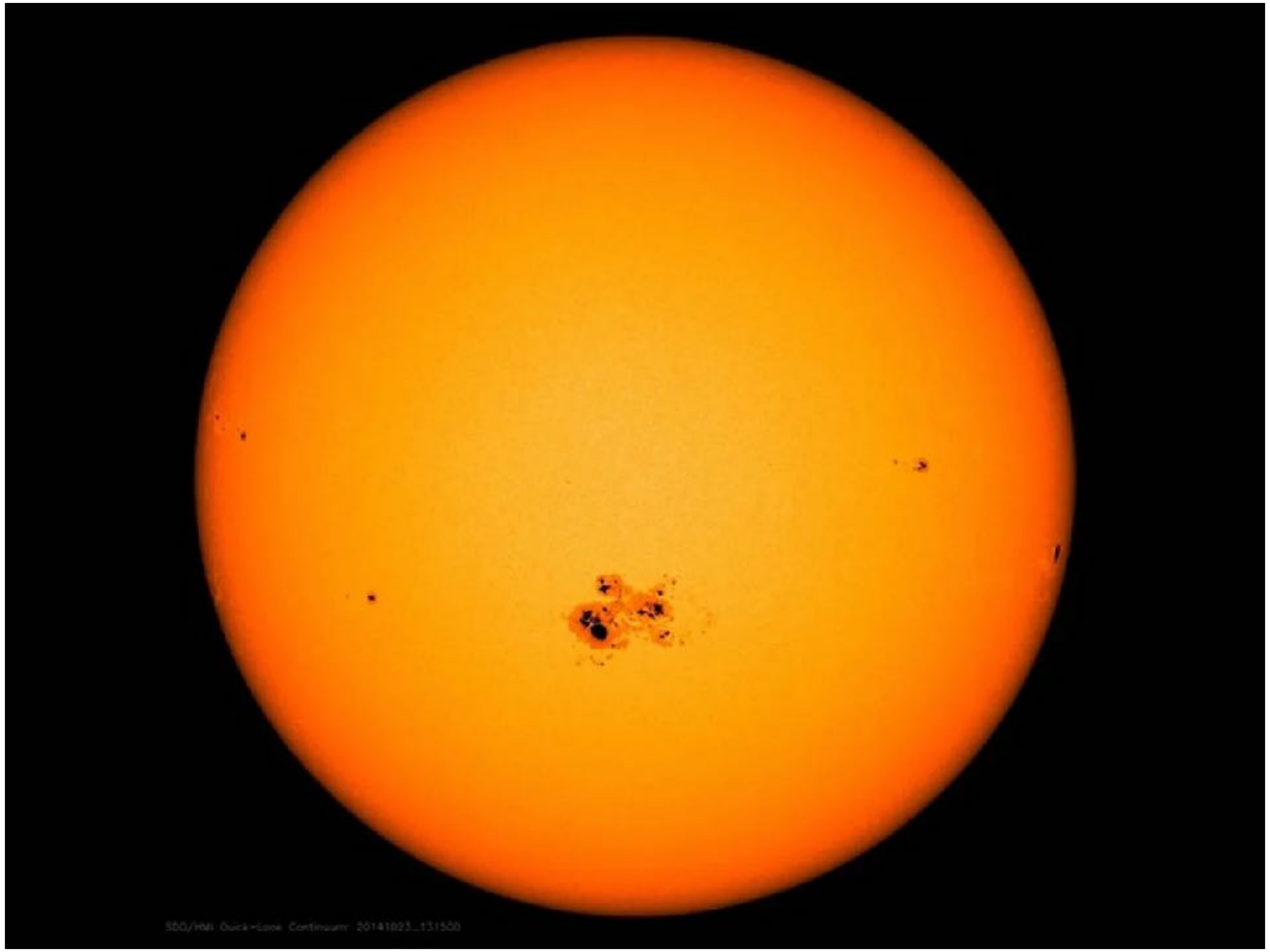


Plasma frequency

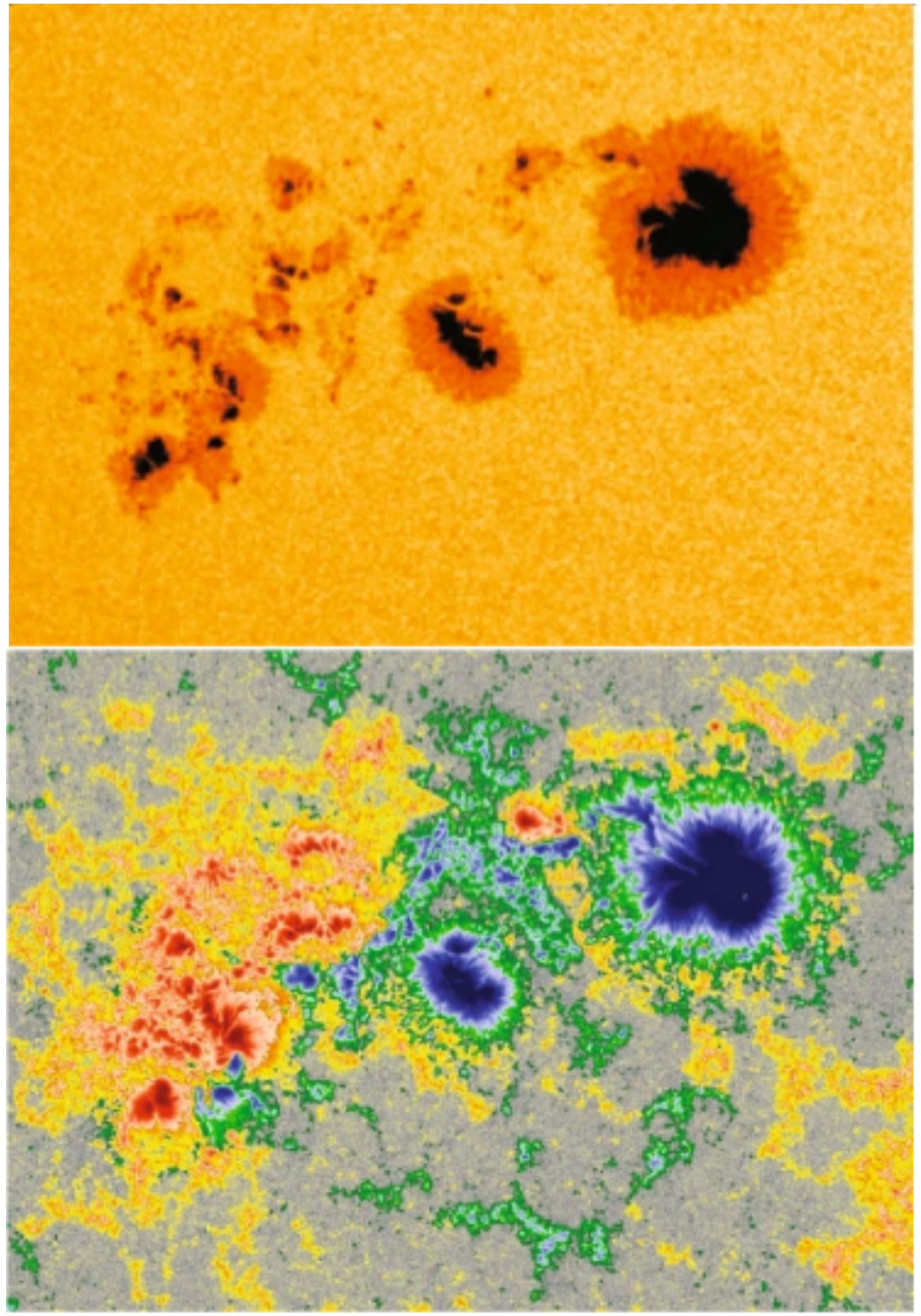


More on this later

Sunspots



The magnetic field above a sunspot can reach thousands of Gauss!



Muñoz-Jaramillo et al., *Nat Astron* **3**, 205–211 (2019)

Conversion of Axion Dark Matter

Conversion of Axion DM: whole Sun

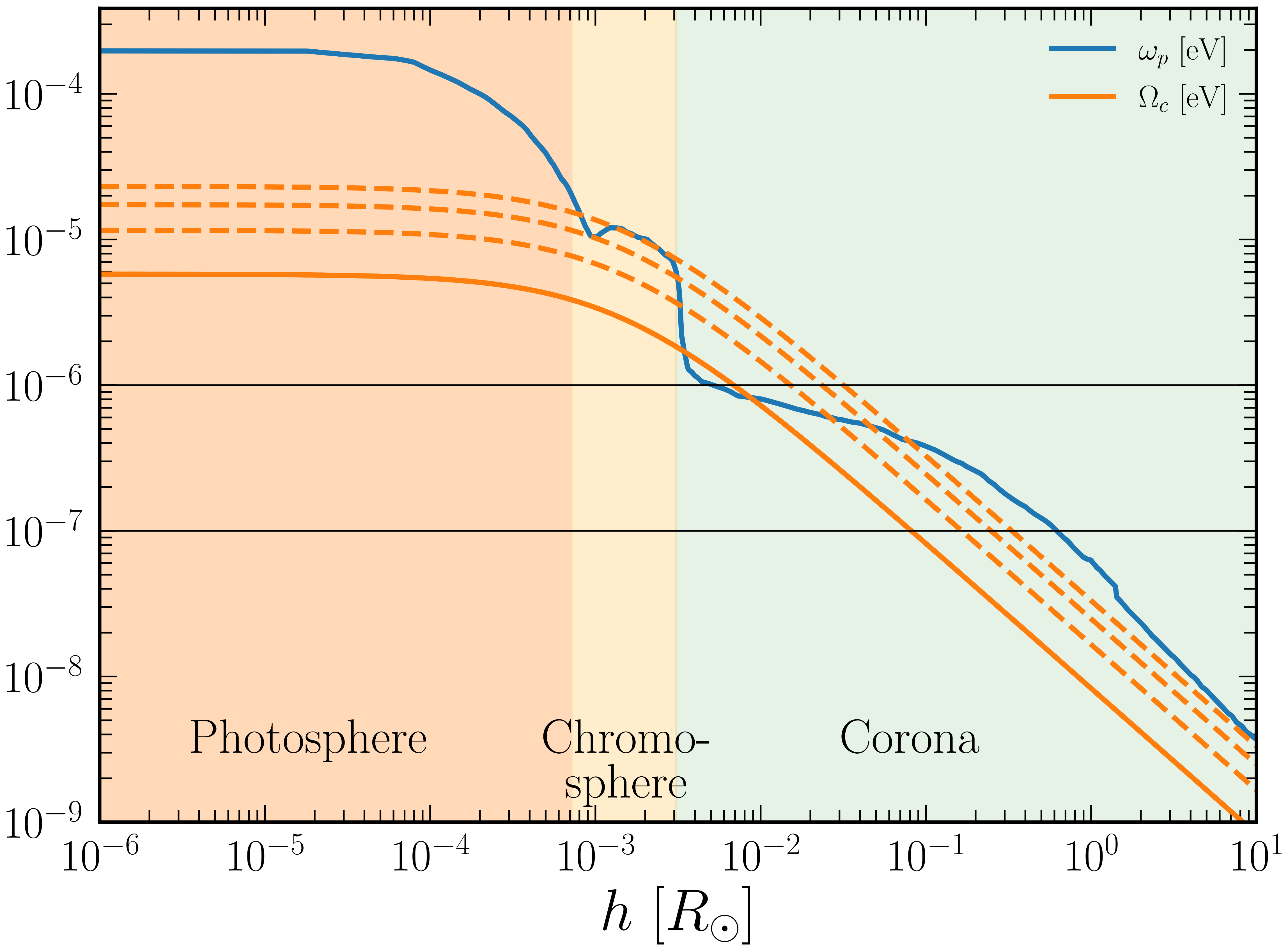
Assuming $\omega_p \propto h^{-\alpha}$

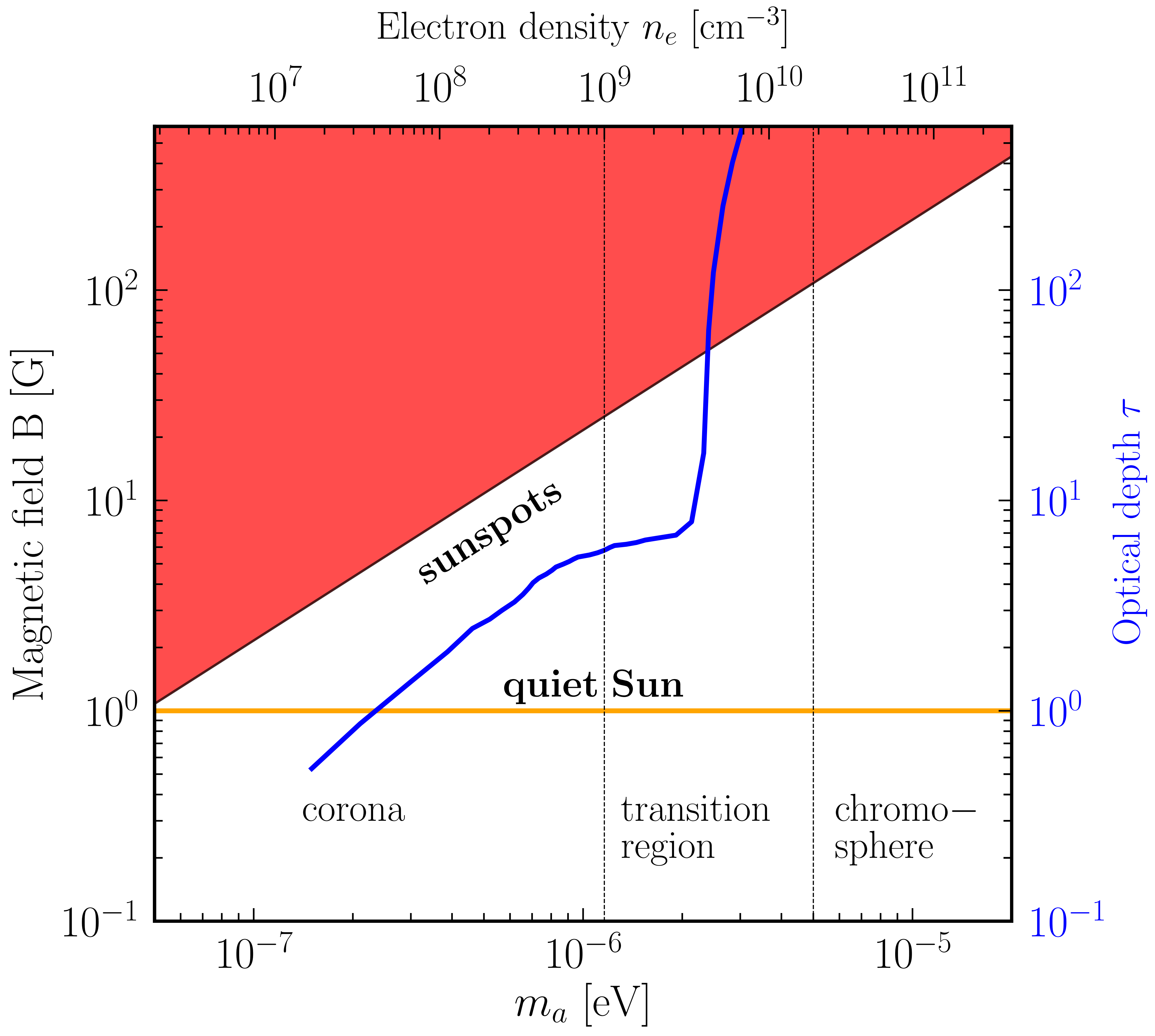
$$P_{a\to\gamma} \simeq \frac{\pi}{2}\,\frac{g^2\,B_\perp^2}{v_a\,\omega_p'}\bigg|_{h=h_c}$$

$$\begin{aligned} S &= \frac{\Delta A}{8\ \Delta\nu\, d^2}\,\rho_a\,\frac{g^2\,B_\perp^2}{\omega_p'}\,e^{-\tau}\bigg|_{h=h_c} \\ &= 2.1\,\mathrm{mJy}\left(\frac{10^{-6}}{\Delta\nu/\nu}\right)\left(\frac{R_\odot}{7\times 10^5\mathrm{km}}\right)^2\left(\frac{\rho_a}{1.0\,\mathrm{GeV/cm^3}}\right)\left(\frac{g}{10^{-12}\mathrm{GeV}^{-1}}\right)^2 \\ &\times \left(\frac{B_\perp}{1\,\mathrm{G}}\right)^2\left(\frac{\mu\mathrm{eV}}{m_a}\right)^2\left(\frac{0.5}{\alpha}\right)\left(\frac{h_c}{3\times 10^3\mathrm{km}}\right)e^{-\tau} \end{aligned}$$

Absorption

- Gyro-resonance absorption for $\omega = n\Omega_B$ $\quad n \leq 4$ $\quad \Omega_B = \frac{eB}{m_e}$
- Free-free absorption





Observational Prospects with SKA

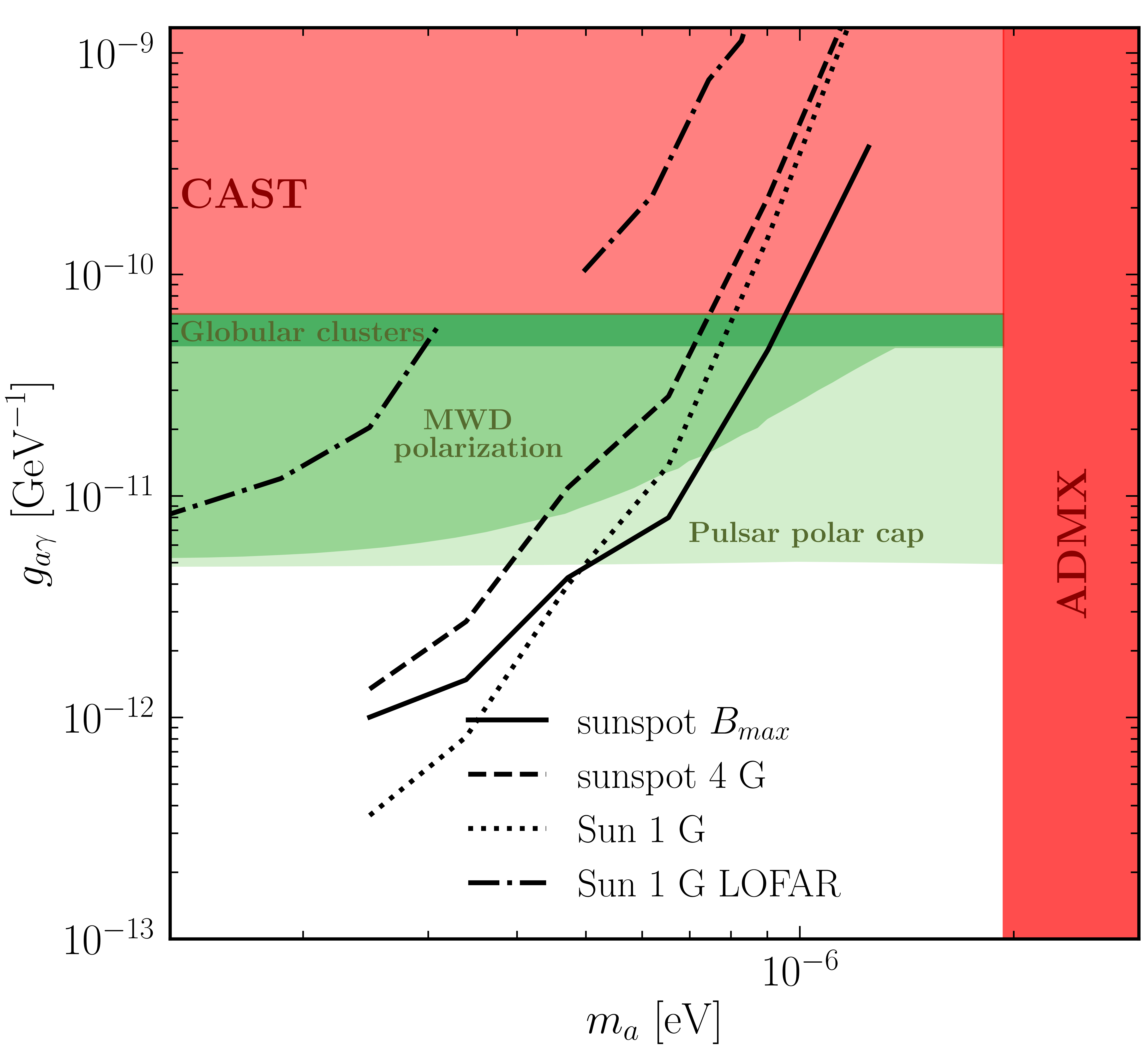
Sunspots are seen as point sources, even after broadening due to scattering off inhomogeneities

The whole Sun is not a point source

Account for degradation in sensitivity due to background from Sun

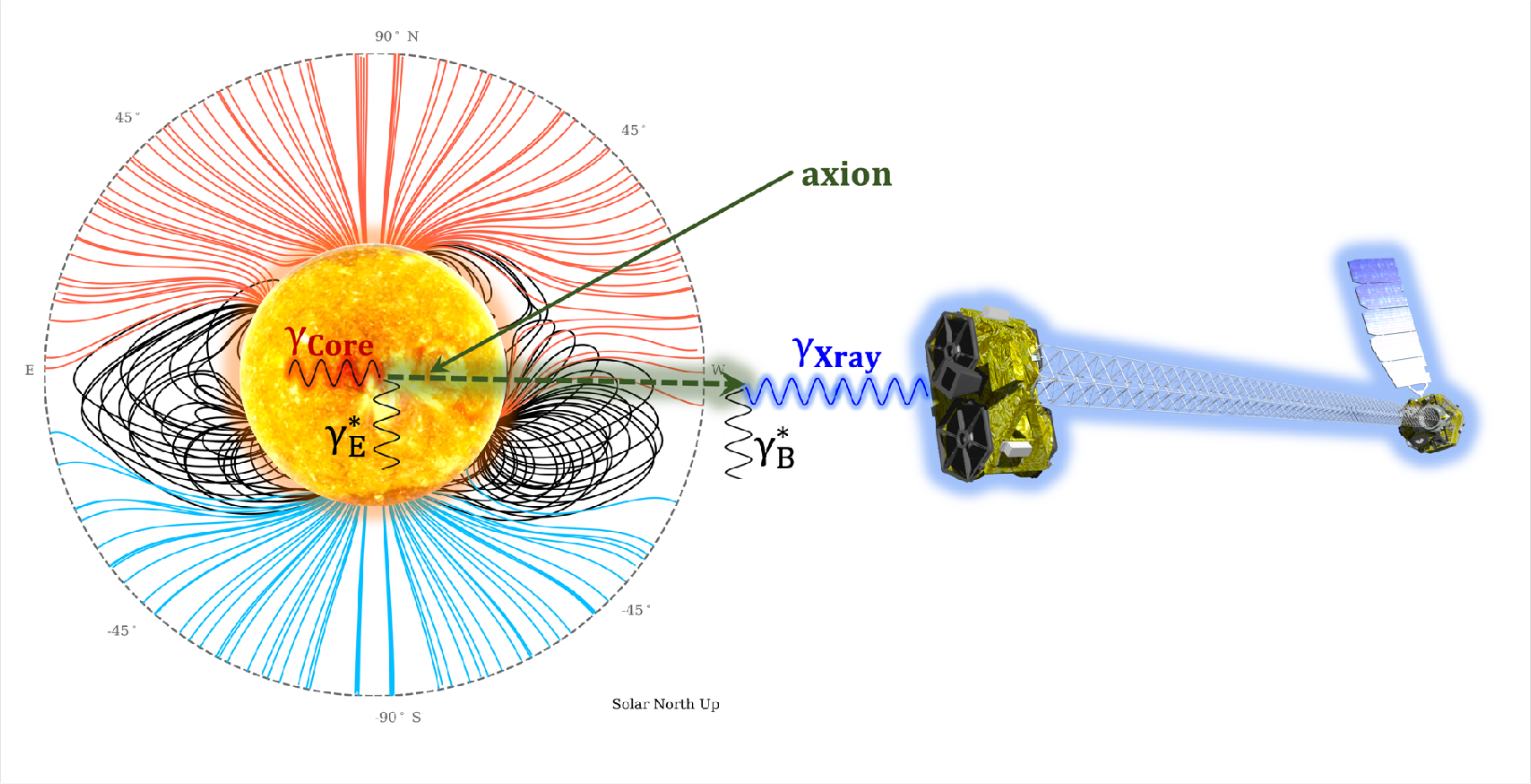
Large dynamical range. Difficult but achievable

See also
An et al., Nature Commun. 15 (2024) 915
An et al., PRL 126 (2021) 18



Conversion of Solar Axions

NuSTAR as an Helioscope



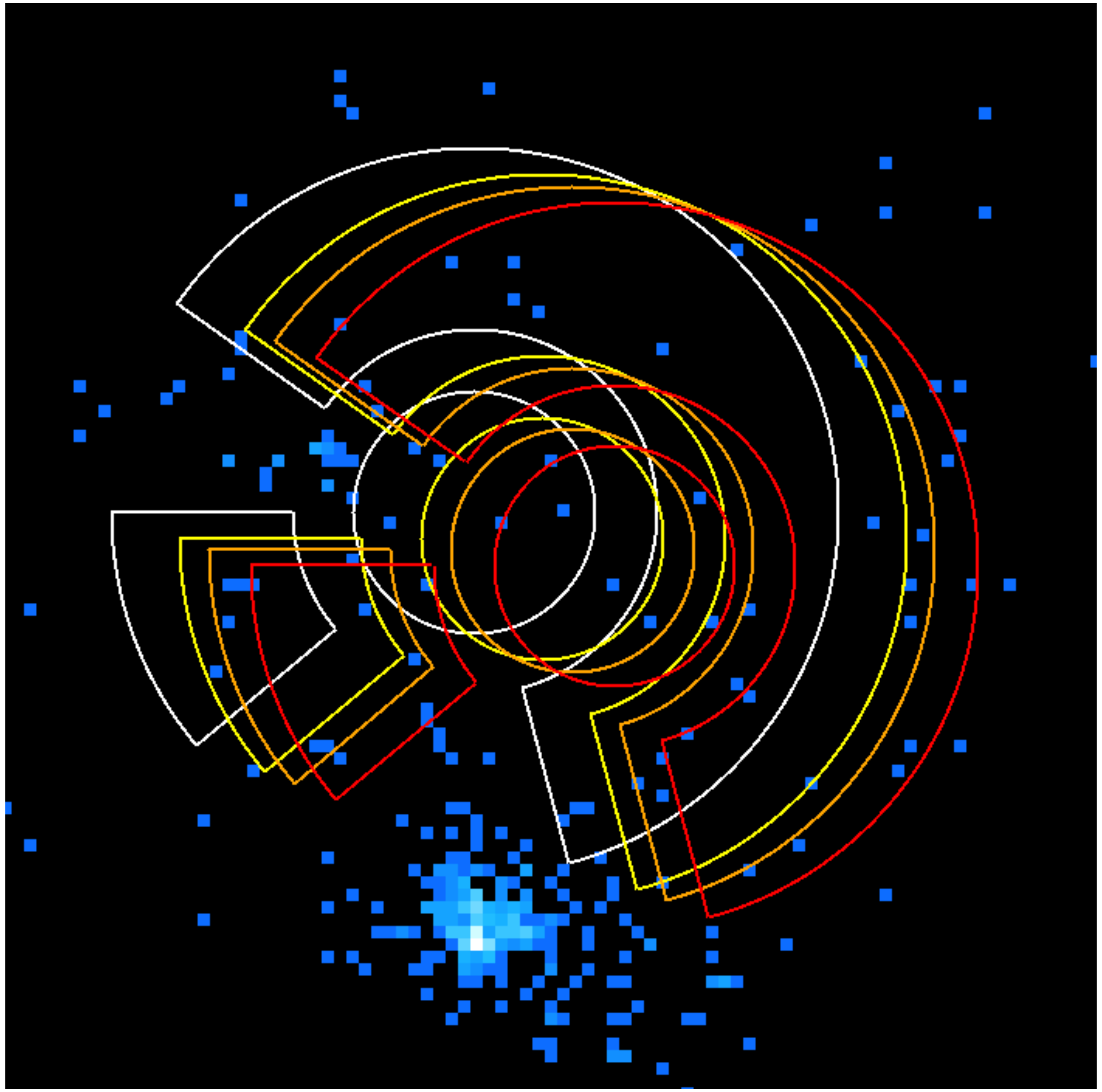
NuSTAR as an Helioscope

Observed the center of the solar disk for 23,000 seconds during solar minimum in 2020

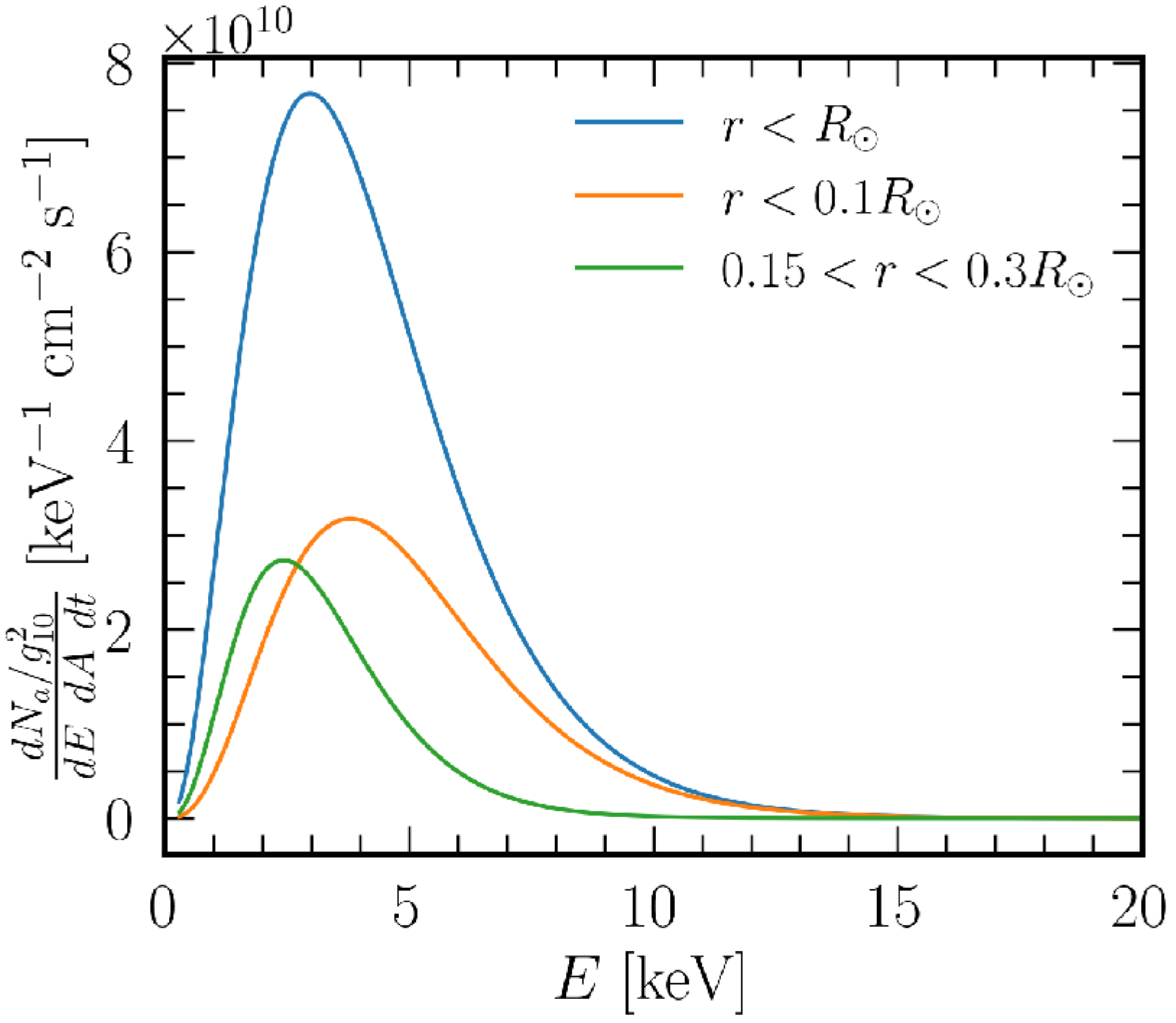
Signal region $r < 0.1R_\odot$

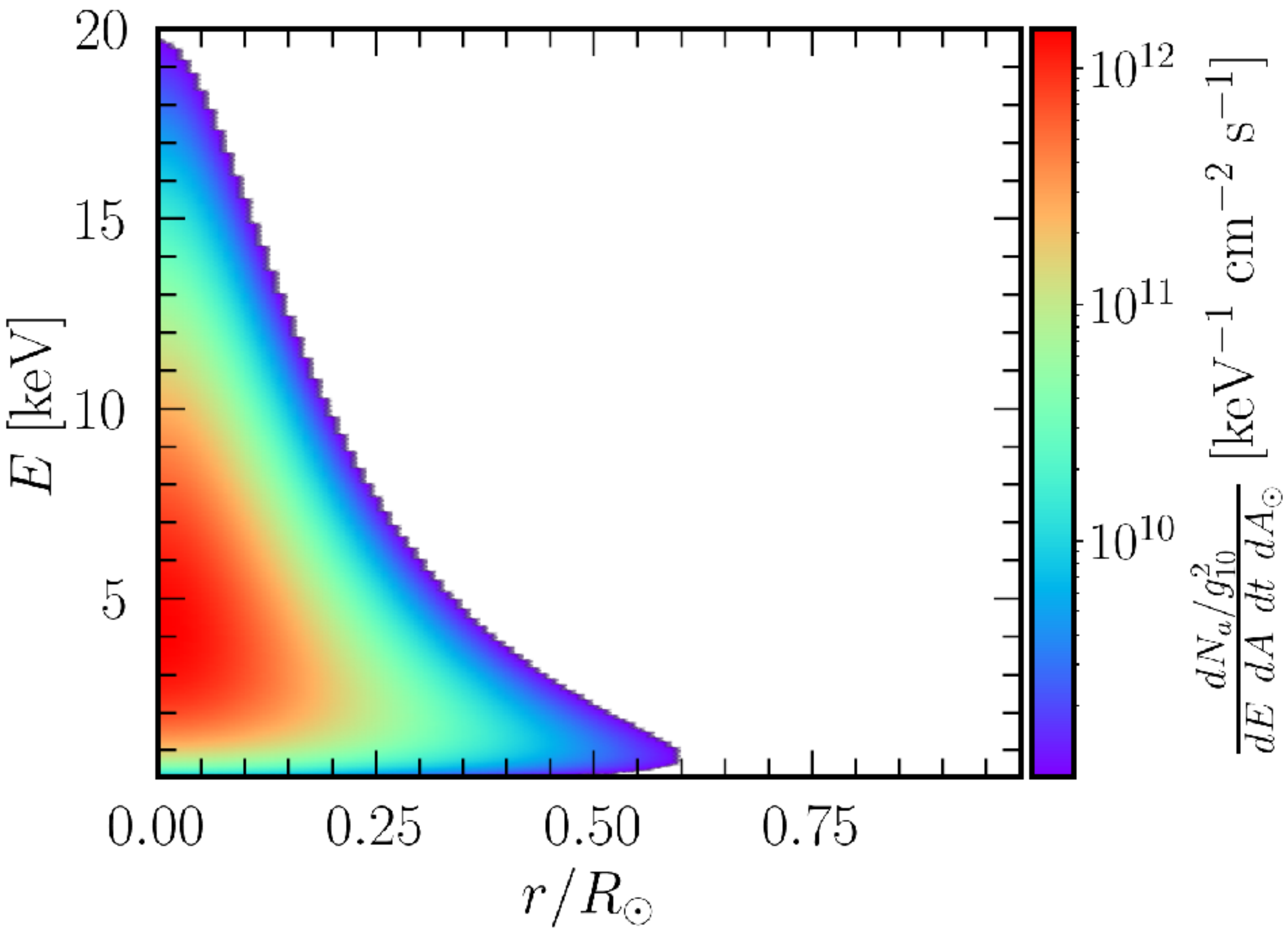
Background region $0.15R_\odot < r < 0.3R_\odot$

Remove wedges containing X-ray bright points



Axion Flux at Earth





Solar composition from Bahcall, Pinsonneault, Phys.Rev.Lett. 92 (2004) 121301

Conversion of Ultra-relativistic Axions

In the limit $E \gg \omega_p$

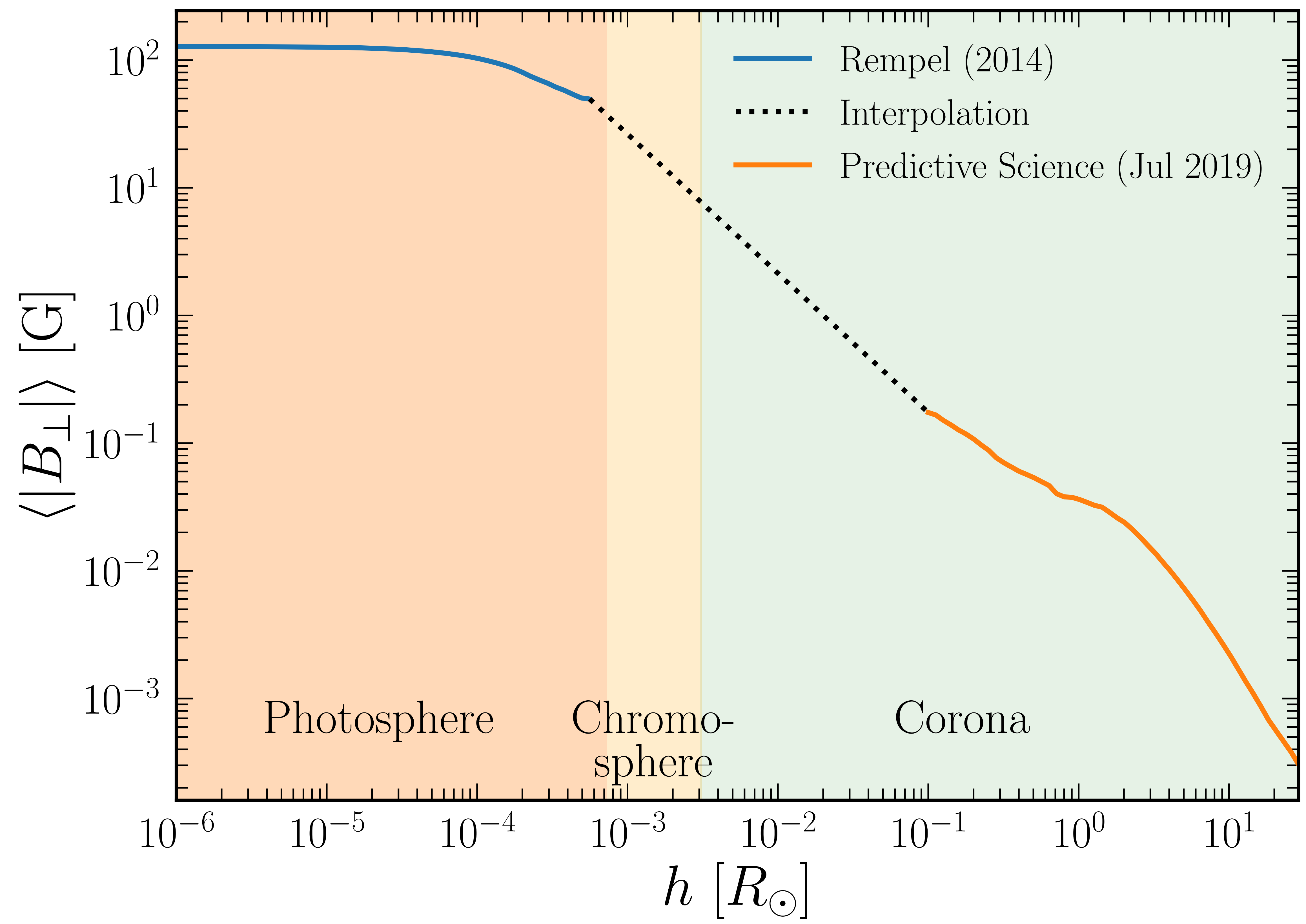
$$P_{a\to\gamma}(h) = \frac{1}{4}g^2 \left| \int_0^h dh' B_\perp(h')\ e^{i\int_0^{h'} dh'' q(h'')}\ e^{-\frac{1}{2}\int_{h'}^{h} dh'' \Gamma(h'')} \right|^2$$

$$q = k - k_a \approx \frac{\omega_p^2 - m_a^2}{2E}$$

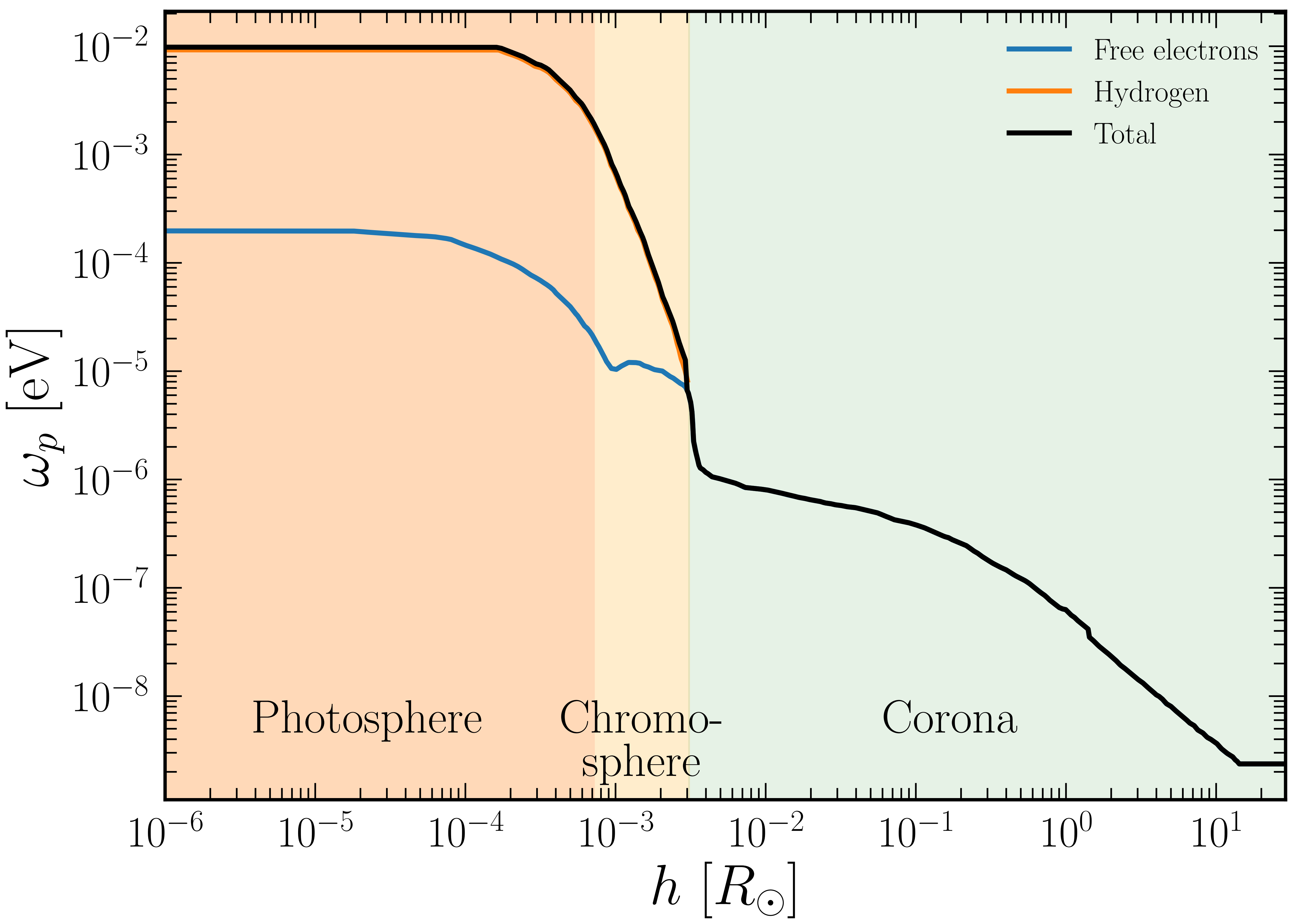
$$\Gamma = \sum_i n_i \sigma_i$$

Our Model of Quiet Sun's Atmosphere

Perpendicular magnetic field

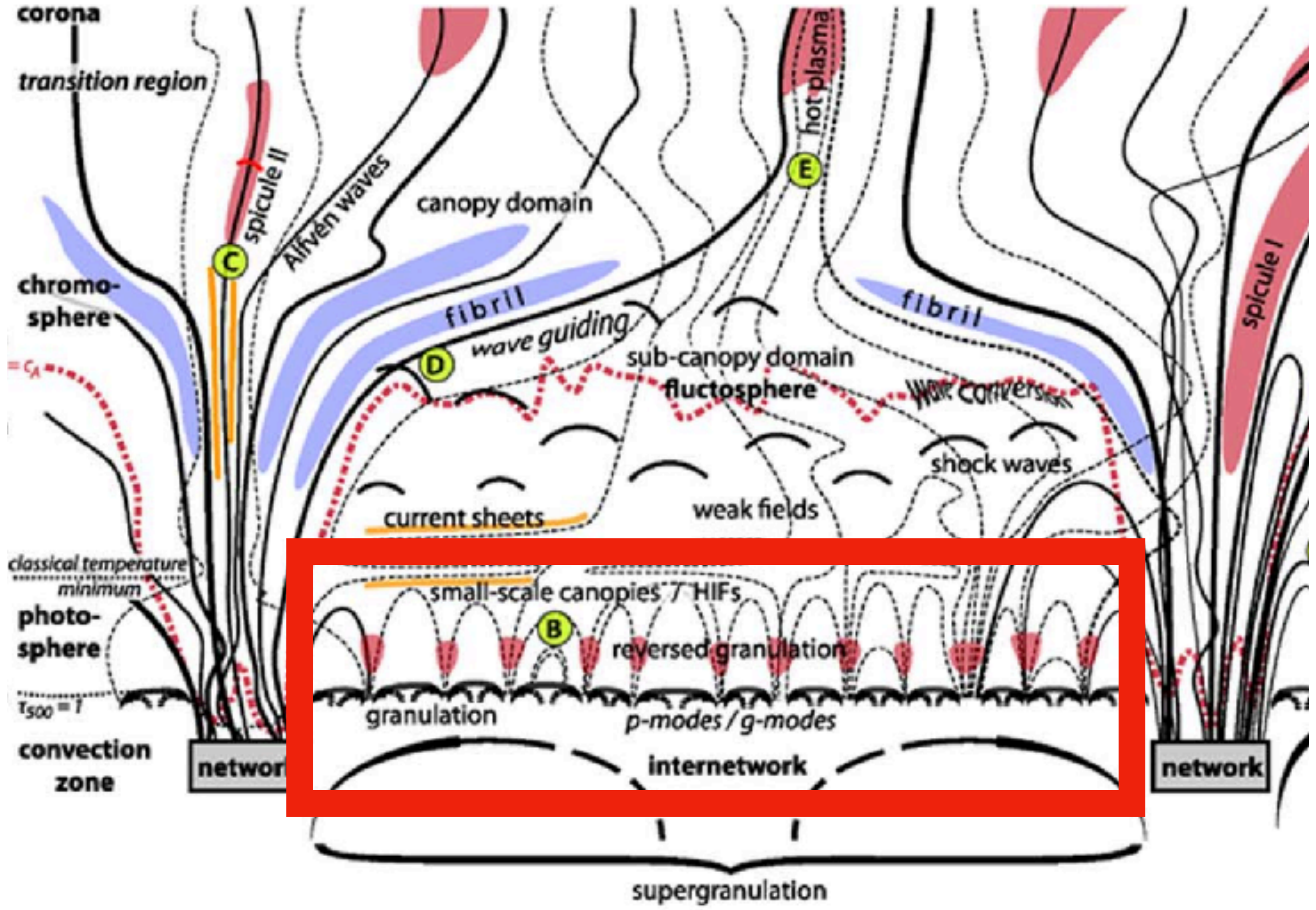


Plasma frequency



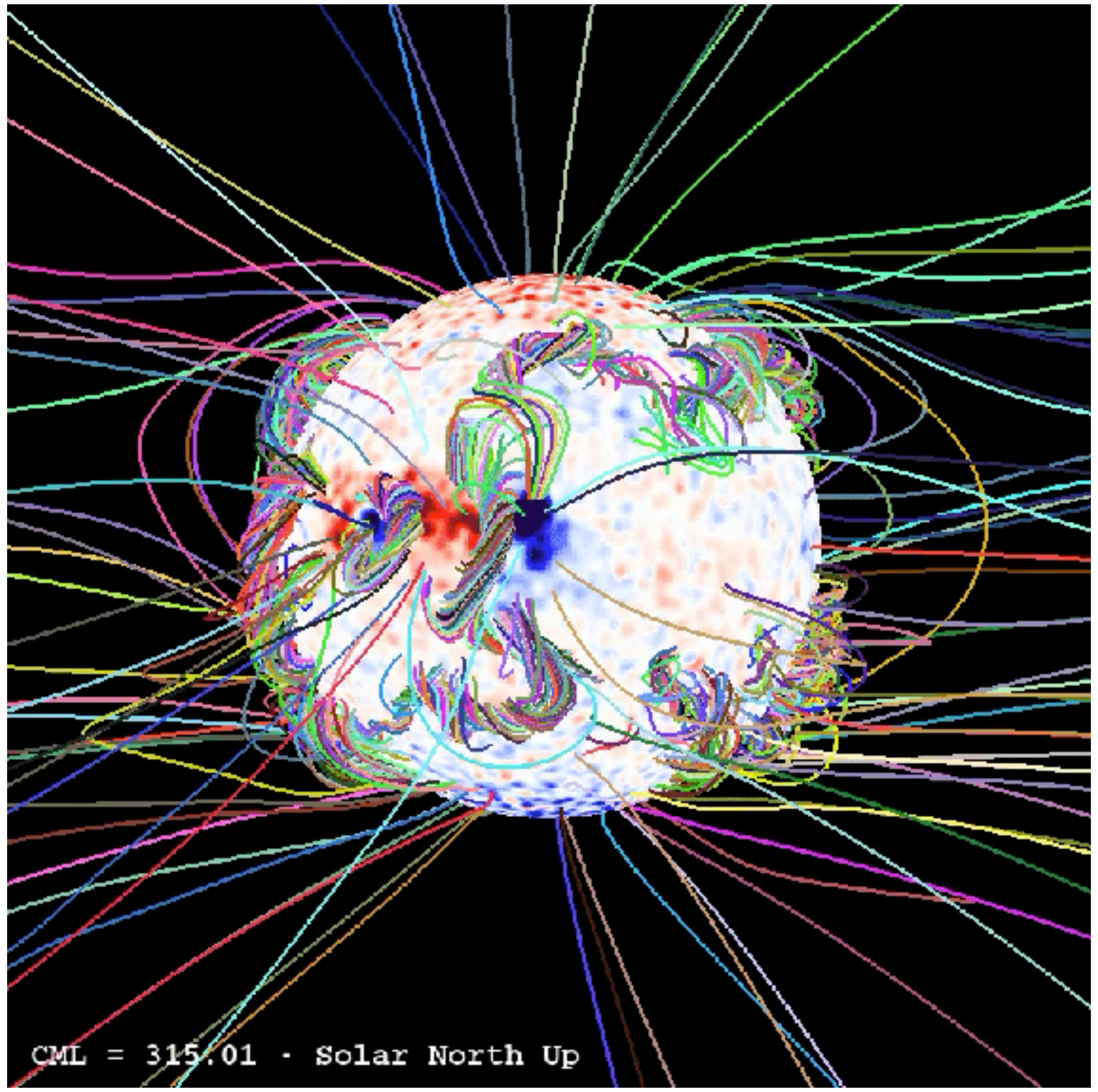
Magnetic Field

Photosphere (Rempel, 2014 ApJ 789 132)

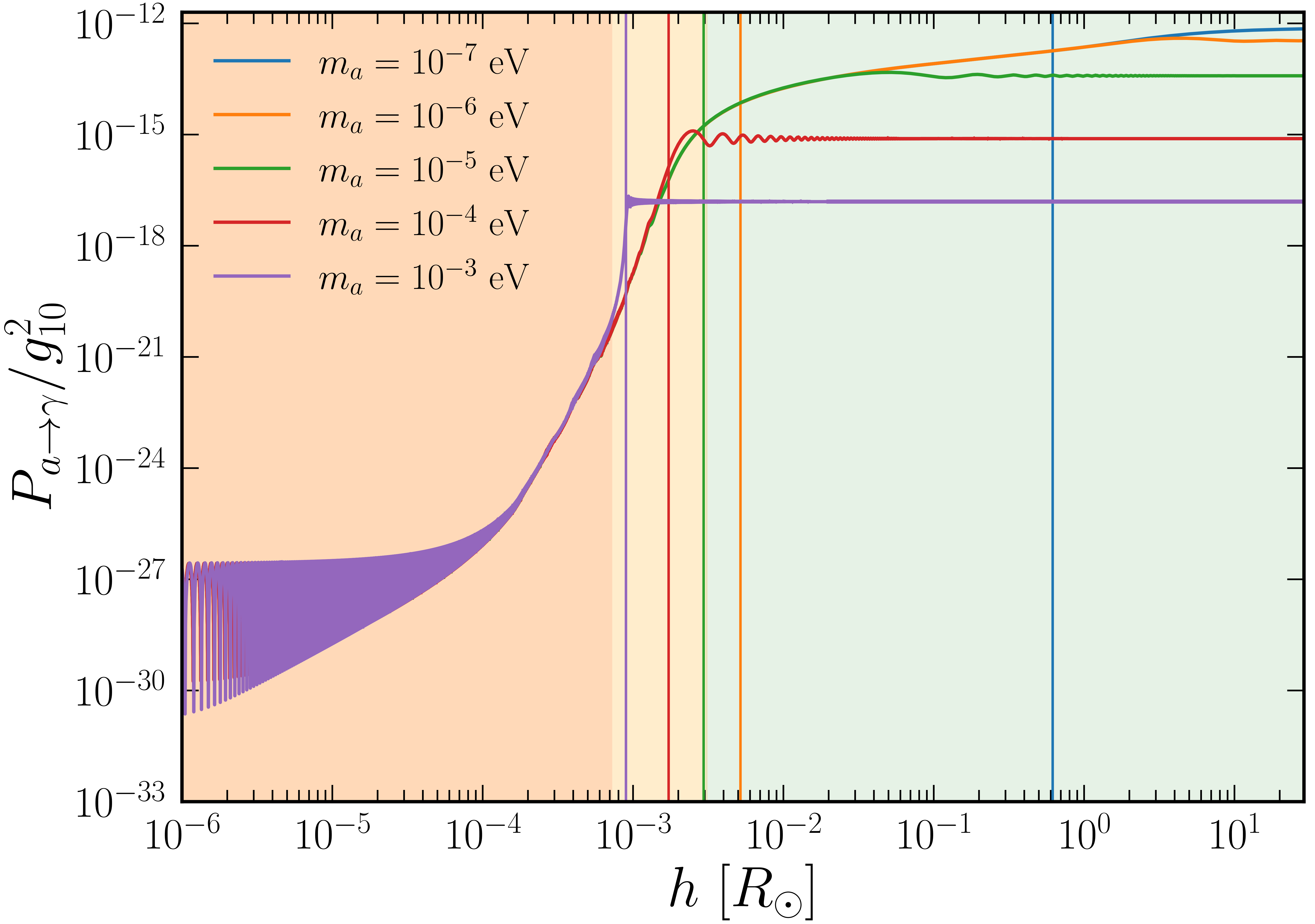


Interpolation

Corona (Predictive Science Inc. for 2019 eclipse)

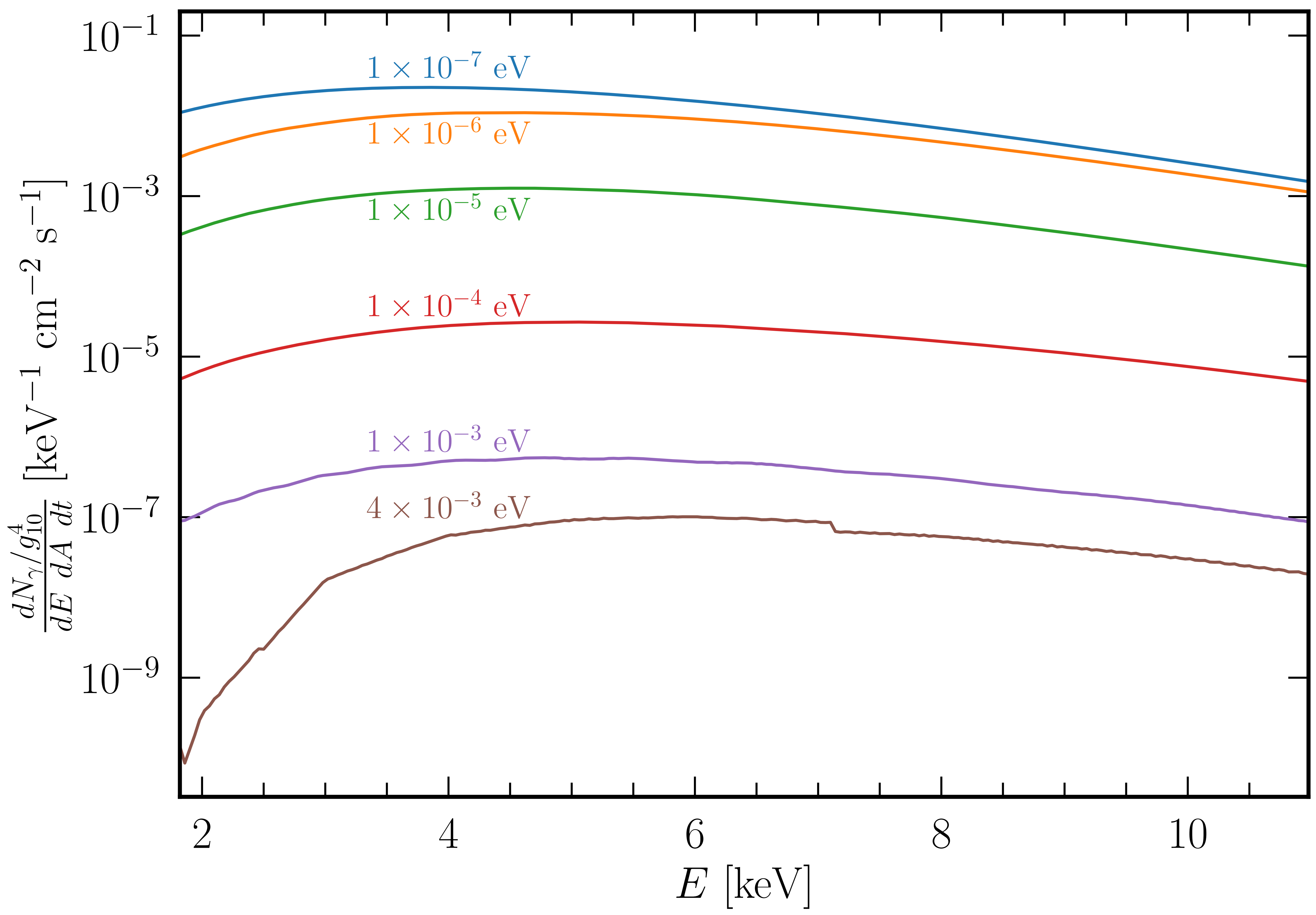


Conversion Probability

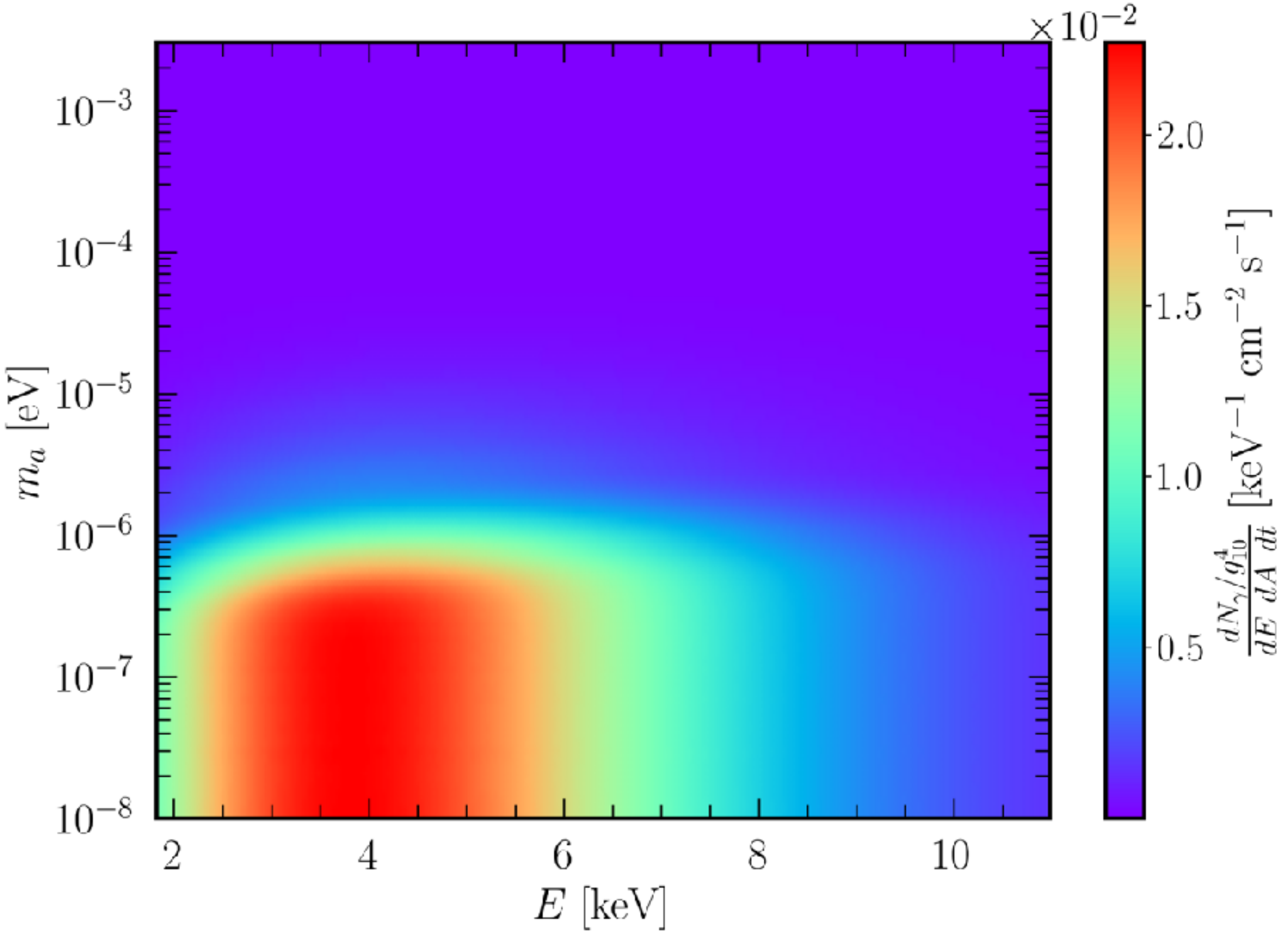


$$q = k - k_a \approx \frac{\omega_p^2 - m_a^2}{2E}$$

X-ray Flux

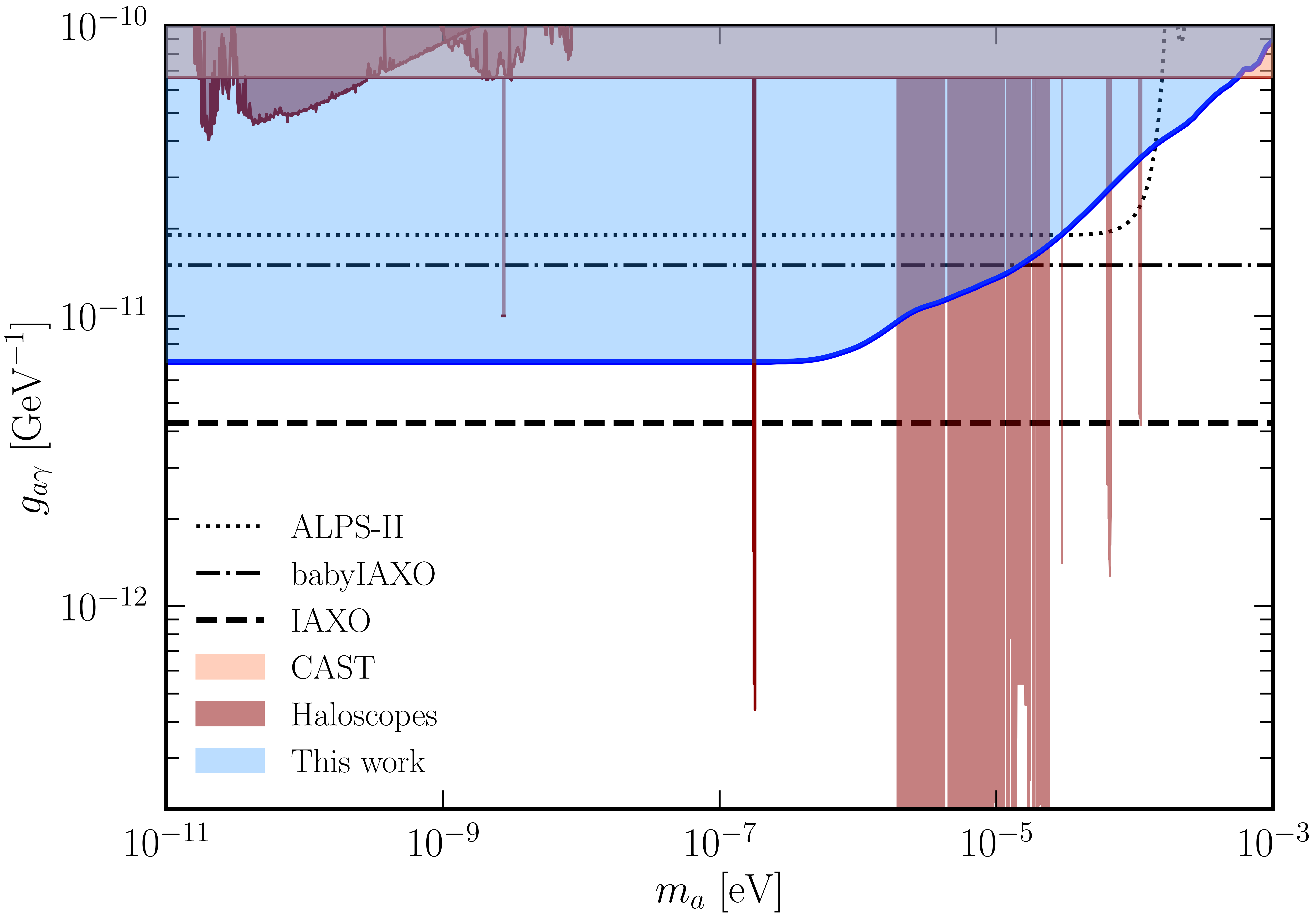


1×10^{-7} eV
1×10^{-6} eV
1×10^{-5} eV
1×10^{-4} eV
1×10^{-3} eV
4×10^{-3} eV
$\frac{dN_\gamma/g_{10}^4}{dE\ dA\ dt}$ [keV^{-1} cm^{-2} s^{-1}]
E [keV]

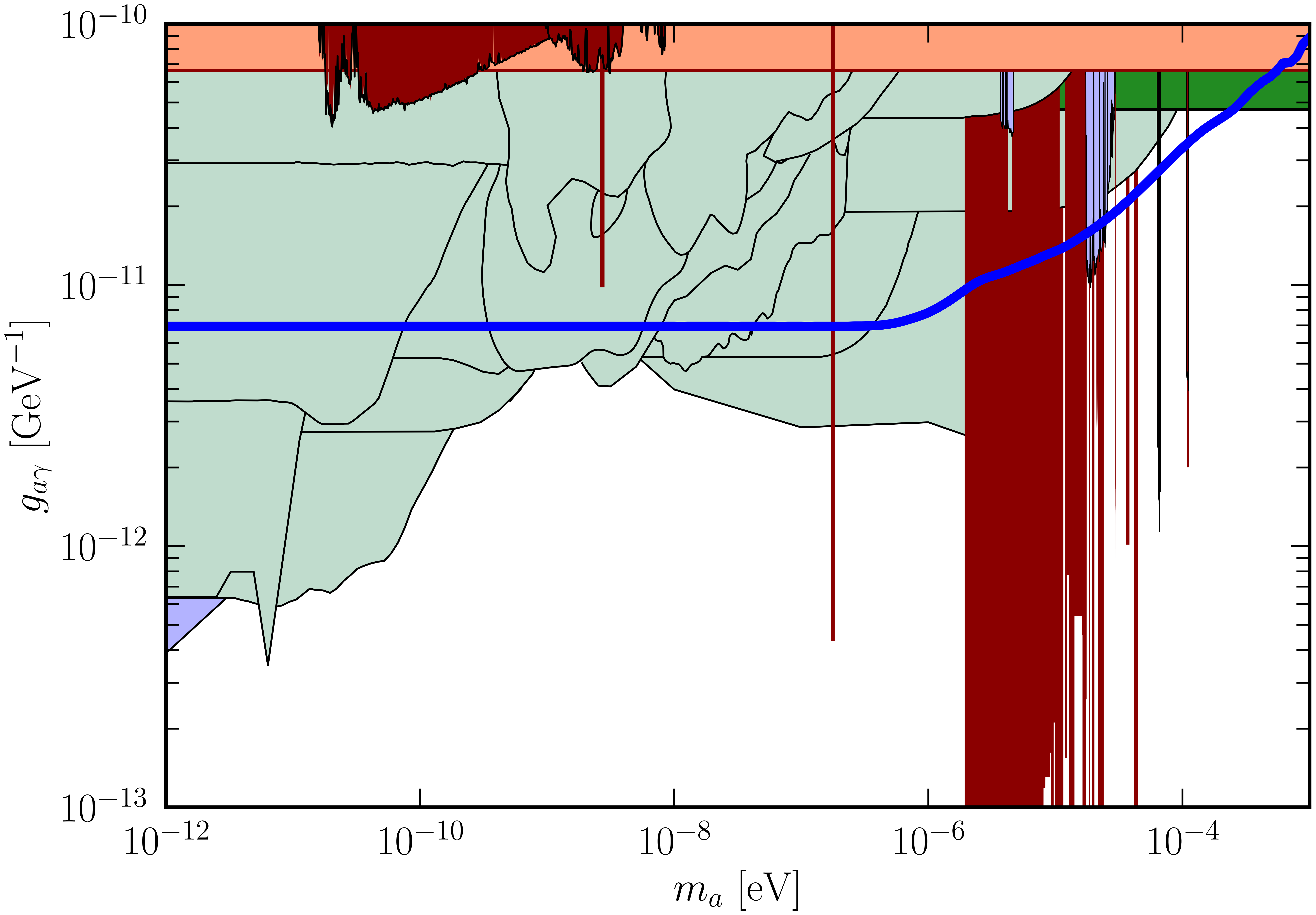


m_a [eV]
E [keV]
$\times 10^{-2}$
$\frac{dN_\gamma/g_{10}^4}{dE\ dA\ dt}$ [keV^{-1} cm^{-2} s^{-1}]

NuSTAR as an Helioscope



NuSTAR as an Helioscope



THANK YOU