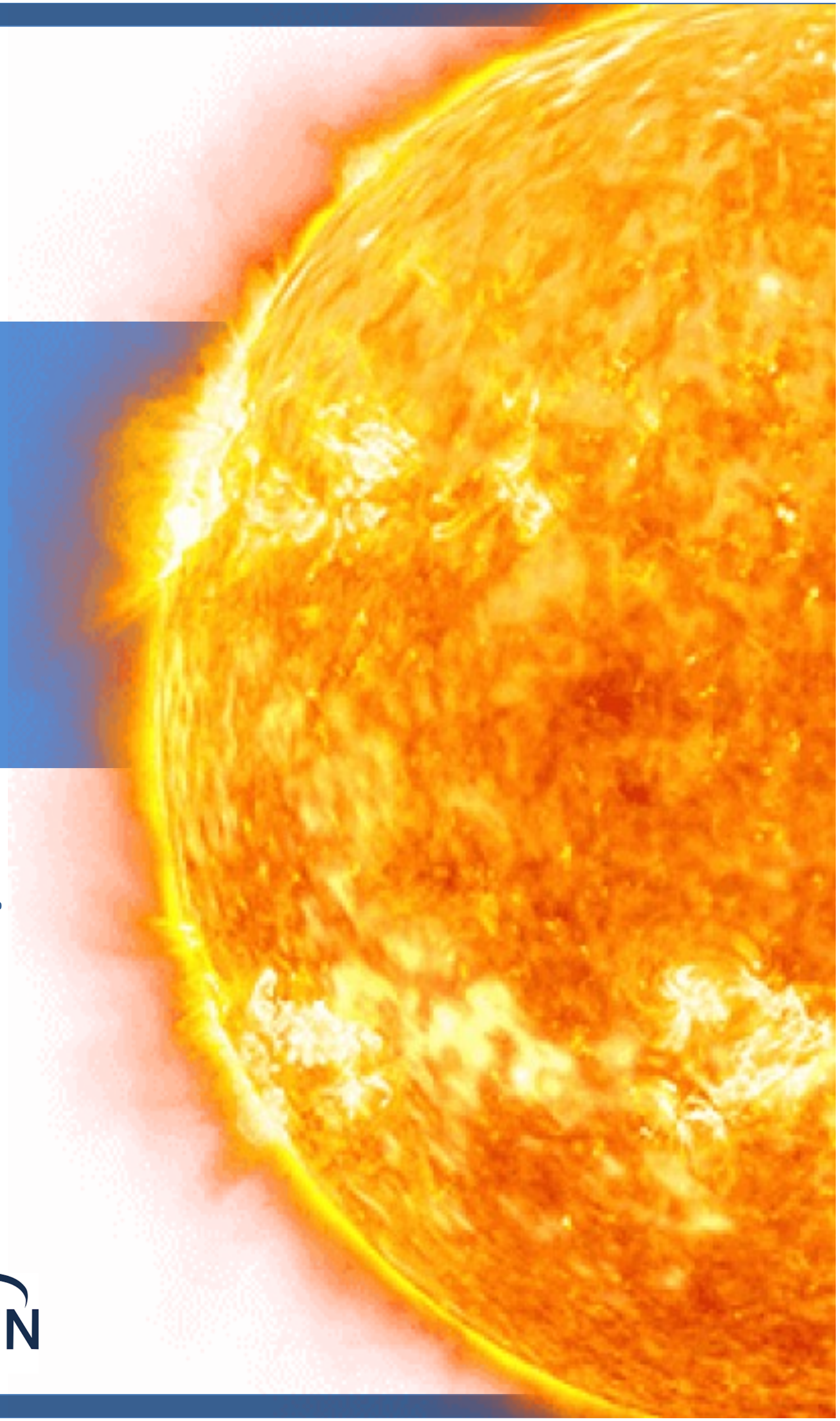
Axions in the sky!

BAM

Barolo Astroparticle Meeting

Photon emission from ALPs in the Sun



J. Ruz, E. Todarello, M. Giannotti, M. Regis, M. Taoso and J. K. Vogel

June 12-15, 2024

Barolo, Italy

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

UNIVERSITÀ DI TORINO

INFN

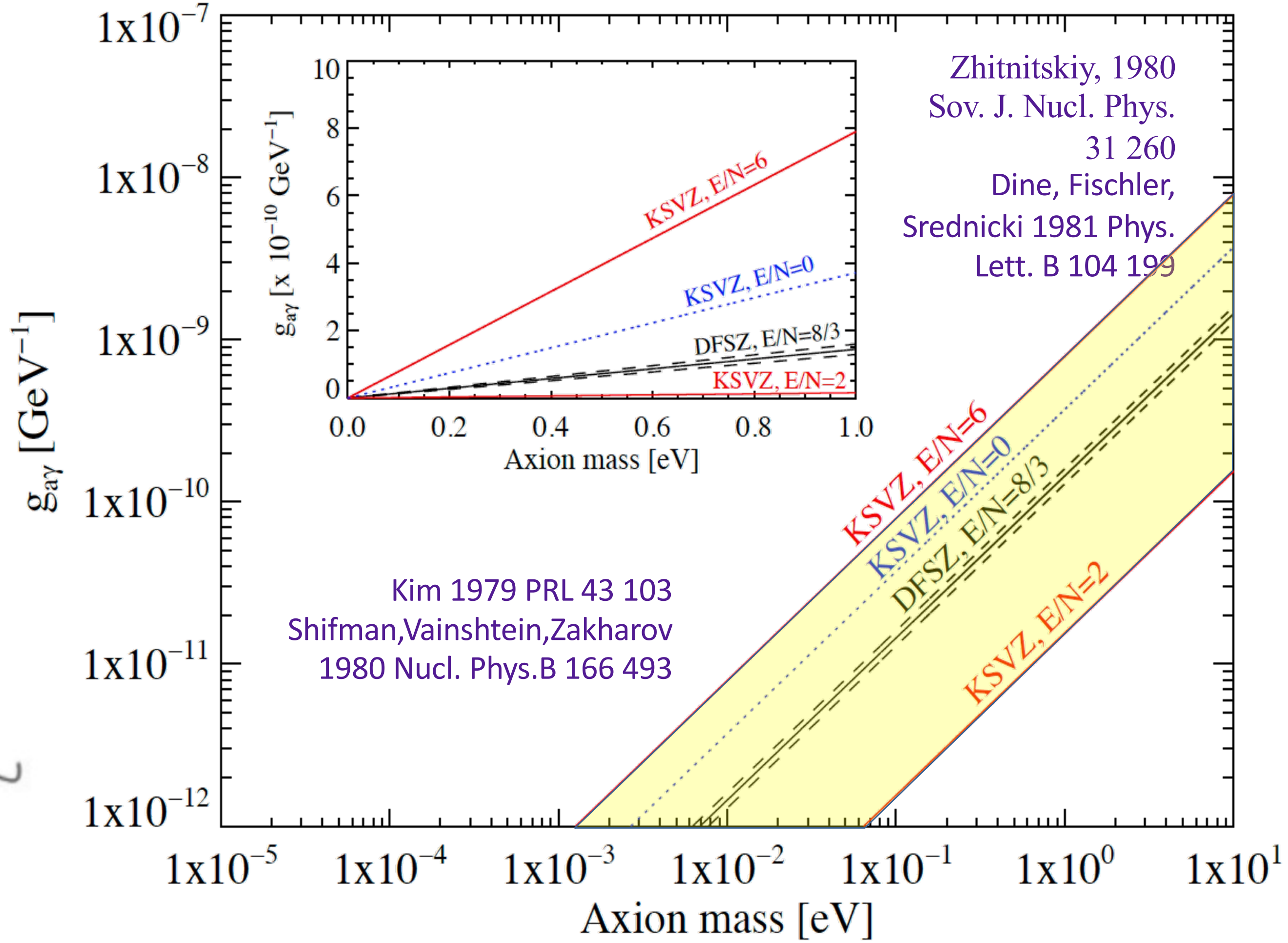
Outline

1. The Axion
2. Detection of Axions. Solar Axion Searches
3. Helioscopes: IAXO and BabyIAXO
4. New Approaches to Solar Axion detection
5. Conclusions

The Axion

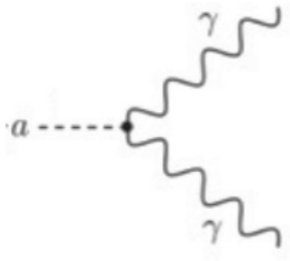
Properties

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$



Zhitnitskiy, 1980
Sov. J. Nucl. Phys.
31 260
Dine, Fischler,
Srednicki 1981 Phys.
Lett. B 104 199

Kim 1979 PRL 43 103
Shifman,Vainshtein,Zakharov
1980 Nucl. Phys.B 166 493

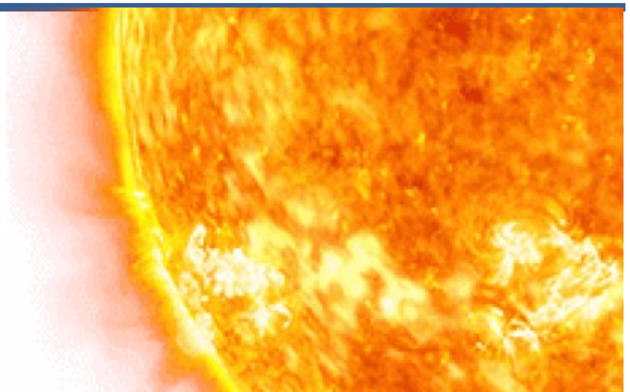


$$g_{a\gamma} \simeq \frac{\alpha}{2\pi f_\pi}\,\frac{m_a}{m_\pi}\,\frac{1+z}{\sqrt{z}}\left(\frac{E_Q}{N_Q} - \frac{2}{3}\,\frac{4+z}{1+z}\right)$$

$z \equiv m_u/m_d$

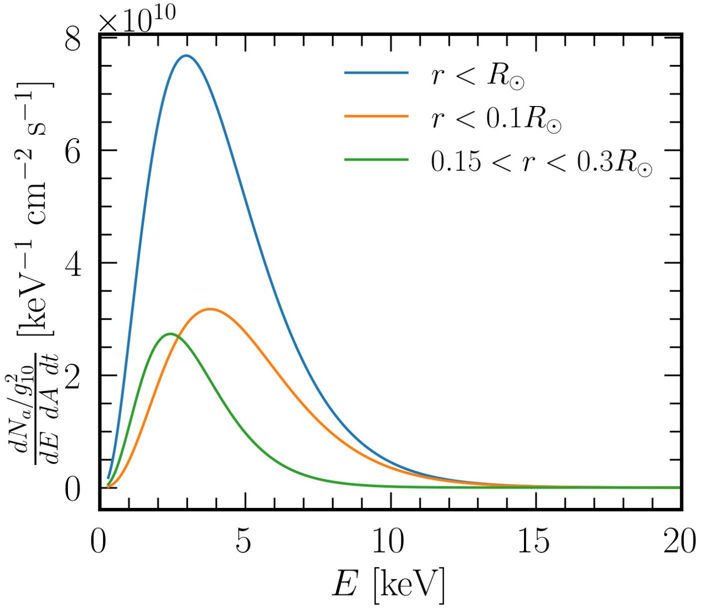
Solar Axion Flux

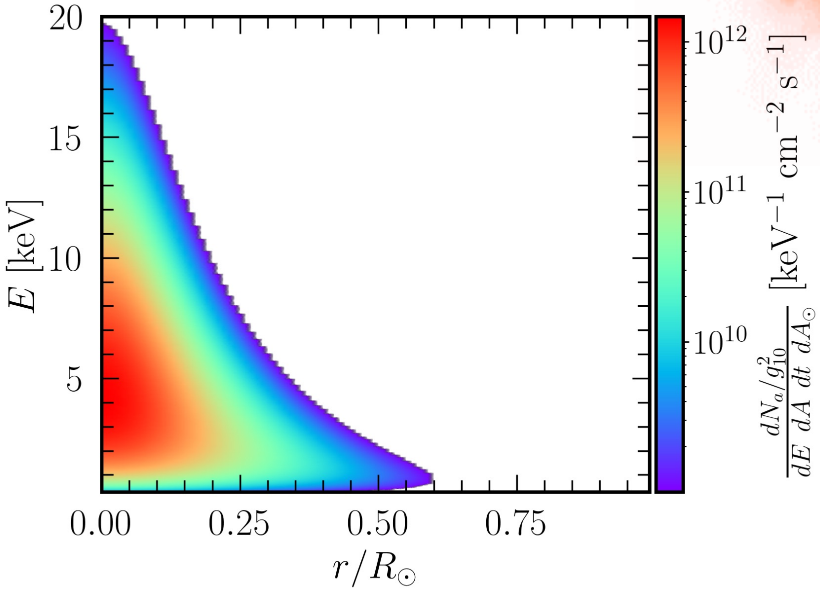
Primakoff

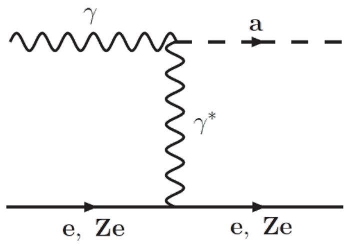


- Blackbody photons (keV) in solar core can be converted into axions in the presence of strong electro magnetic fields in the plasma → Primakoff Effect.

$T_{Core} \sim 1.3 keV$







Hadronic axions (if the axion couples predominantly to photons (g_{ag}))

$$\frac{\mathrm{d}\Phi_\mathrm{a}}{\mathrm{d}E} = 6.02 \times 10^{10} \left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}} \right)^2 E^{2.481} e^{-E/1.205} \frac{1}{\mathrm{cm}^2\ \mathrm{s\ keV}}$$

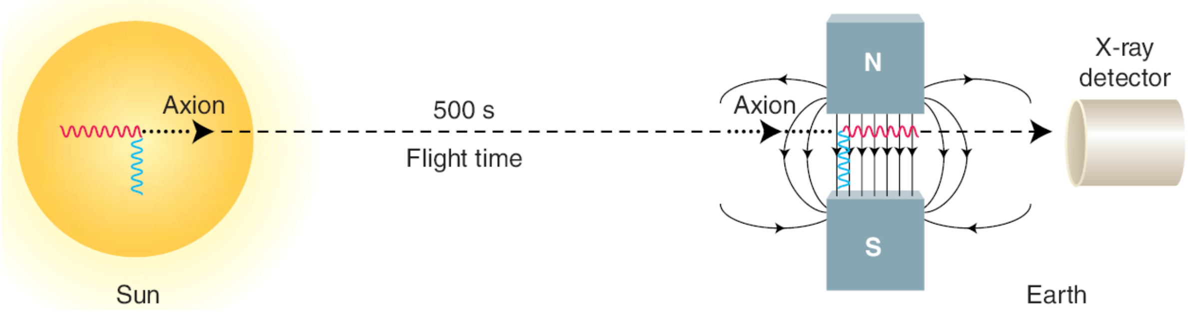
Traditional Solar Axion Searches

Helioscopes

P. Sikivie 1983 PRL 51 1415

- First axion helioscope proposed by P. Sikivie

Reconversions of axions into x-ray photons possible in strong laboratory magnetic field



$$P_{a\to\gamma} = \left(\frac{BLg_{a\gamma\gamma}}{2}\right)^2 \quad \text{for} \quad \frac{qL}{2} < \pi \quad \text{with} \quad q = \frac{m_a^2}{2E_a}$$

VACUUM

- Idea refined by K. van Bibber et al.

Van Bibber et al 1989 Phys. Rev. D 39 2089

Buffer gas to restore coherence over long magnetic field and access higher axion masses

$$P_{a\to\gamma} = \left(\frac{Bg_{a\gamma\gamma}}{2}\right)^2 \frac{1}{q^2+\Gamma^2/4}\left[1+e^{-\Gamma L}-2e^{-\Gamma L/2}\cos(qL)\right] \quad \text{with} \quad q = \left|\frac{m_\gamma^2 - m_a^2}{2E_a}\right|$$

GAS

State-of-the-art

Helioscopes

EXPERIMENTS NOT RELYING ON AXIONS BEING DARK MATTER

- ➢ AXION HELIOSCOPES: laboratory axion searches looking for solar axions

CERN AXION SOLAR TELESCOPE (CAST)

- ▪ Most powerful axion helioscope to date
- ▪ Superconducting prototype LHC dipole magnet
- ▪ X-ray focusing devices and ultralow-background detectors
- ▪ Use of buffer gas to extend sensitivity to higher masses (axion band)

CAST Collaboration 2017 Nature Phys. 13 584-590
Arik et al 2015 PRD 92 021101
Arik et al 2014 PRL 112 091302
Barth et al 2013 JCAP 1305 010
Arik et al2011 PRL107 261302
Zioutas et al 2009 JCAP 0902 008
Zioutas et al 2007 JCAP 0704 010

CERN AXION SOLAR TELESCOPE

CAST Collaboration
Nature Phys. 13 584 (2017)

STATE-OF-THE-ART … SO FAR …

Next-Gen Experiments

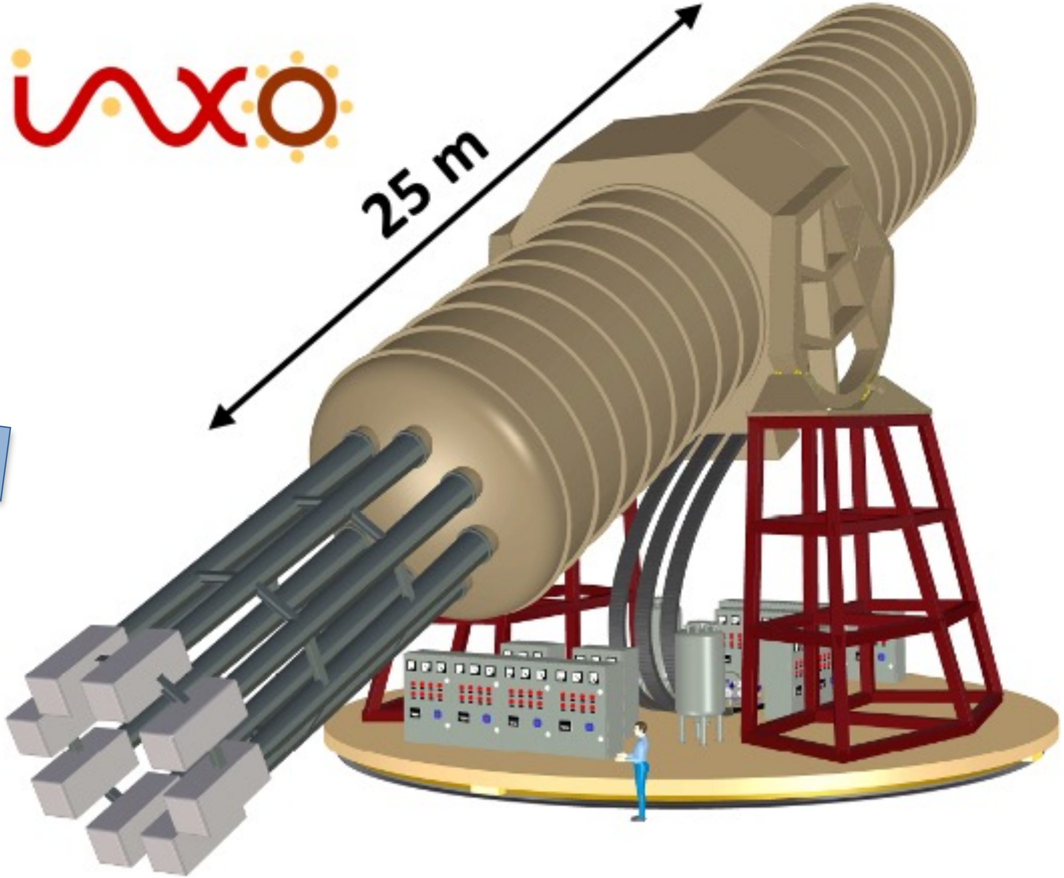
CAST

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

BabyIAXO

$g_{a\gamma} \lesssim \text{few}\ \ 10^{-11}\ \mathrm{GeV}^{-1}$ (expected)

IAXO



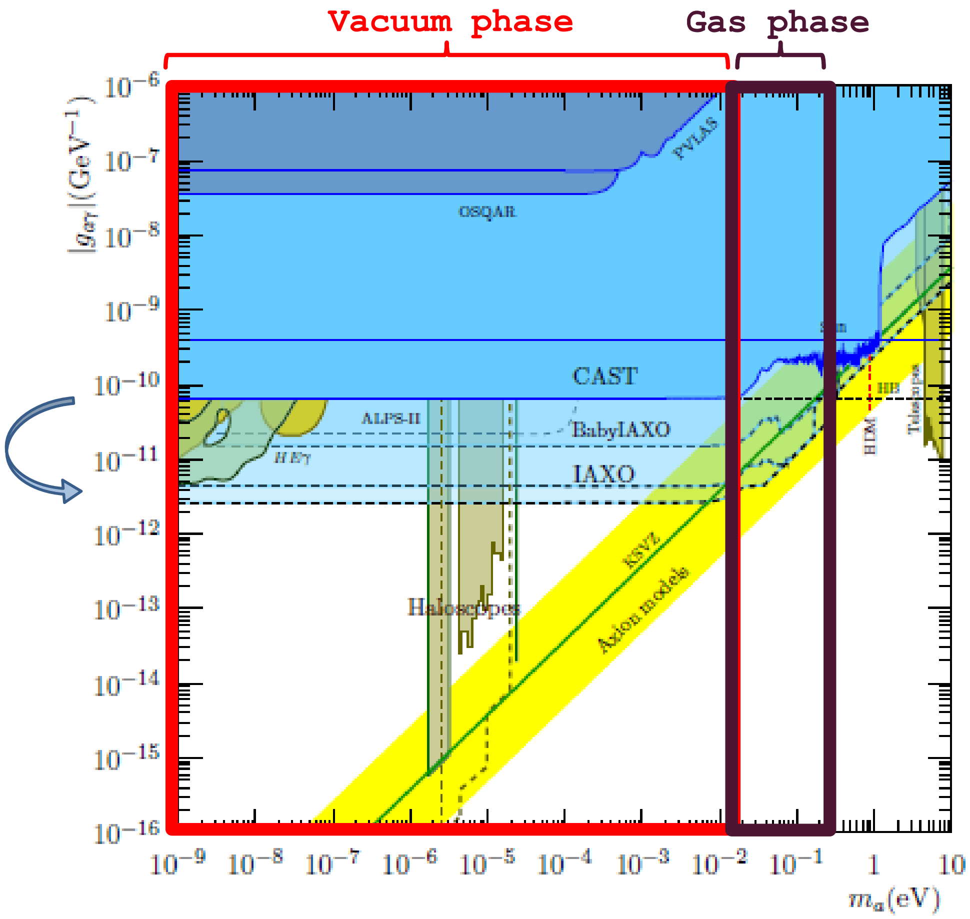
$g_{a\gamma} \lesssim \text{few}\ \ 10^{-12}\ \mathrm{GeV}^{-1}$ (expected)

Current and Next-Generation Sensitivity

- Vacuum Phase:
    - Coherence condition valid for $m_a \lesssim 0.02$ eV
- Gas Phase:
    - Extends coherence condition valid from $0.02 \text{ eV} \lesssim m_a \lesssim 0.26$ eV

$$m_\gamma = 4.498716\sqrt{\frac{P_{He}[\text{atm}]}{T_{He}[\text{K}]}}\,\text{eV}.$$

- Experimental conditions for BabyIAXO:
    - P_{max}(helium-4) ≃ 1bar
    - T(average) ≃ 295K

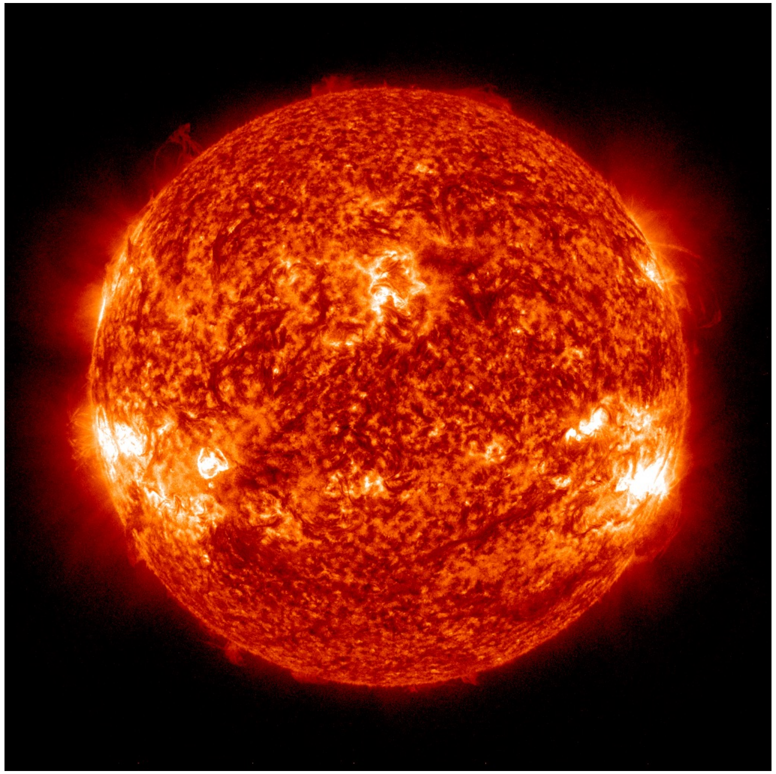


Can we get there in a different way?

Radio-Axions

Radio-Axions

Sunspots might be environments hosting copious axion-photon conversions in their magnetic field



Todarello et al., Phys. Lett. B 854, 138752 (2024).

- DM-axions converting into photons in the realm of Sun spots.

$$P_{a\to\gamma} \simeq \frac{\pi}{2}\frac{g_{a\gamma}^2 B_\perp^2}{v_a \omega'_{q|res}} \qquad \omega'_{q|res} = d\omega_q/dr$$

- Near-future low-frequency radio telescopes, such as the SKA Low, may access regions of unexplored parameter space for $m_a \lesssim 10{-}6$ eV.

$$\omega_q(r) = 1.17\mu eV\sqrt{n_e(r)/(10^9 cm^{-3})}$$

↓

Radio emission

Radio-Axions

- Signal from a Sun spot of area ΔA:

$$S = \int \frac{d\Omega}{4\pi\,\Delta\nu}\rho_a v_a\, P_{a\to\gamma}\, e^{-\tau} \simeq \frac{\Delta A}{4\pi\,\Delta\nu\, d^2}\,\rho_a\, v_a\, P_{a\to\gamma}\, e^{-\tau} = \frac{\Delta A}{8\,\Delta\nu\, d^2}\,\rho_a \frac{g_{a\gamma}^2 B_\perp^2}{\omega'_{q|res}} e^{-\tau}$$

$$\Delta A = \pi \ell_S^2$$

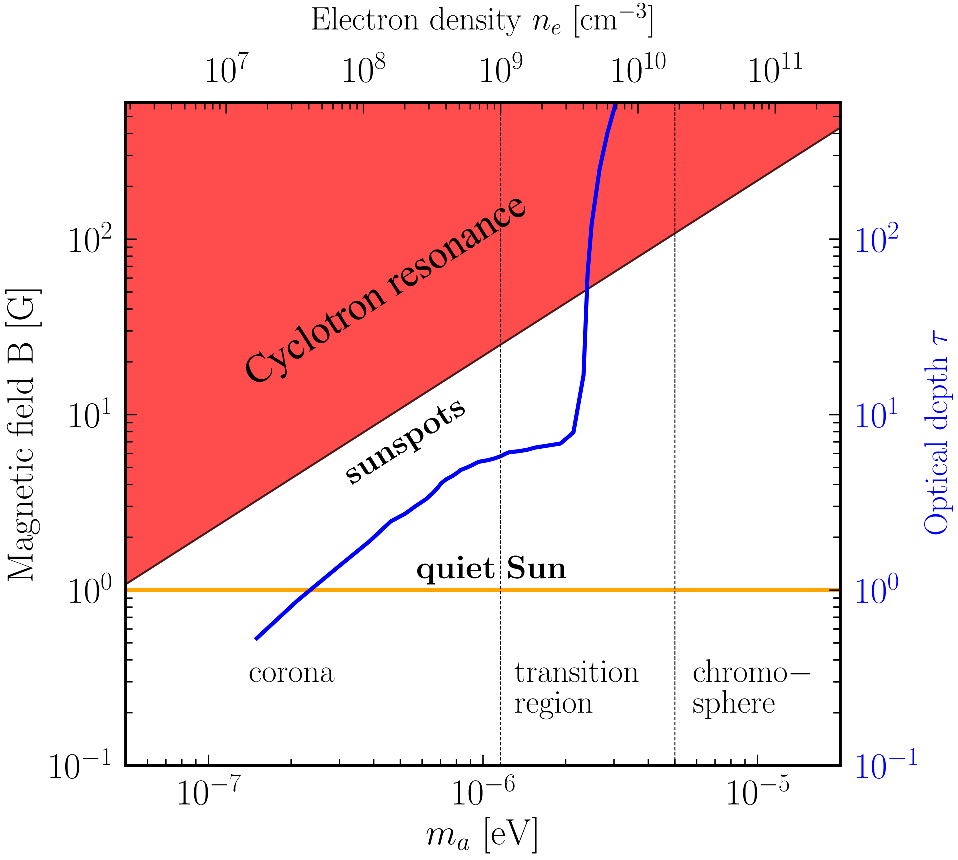
$$\omega_p \propto h^\alpha \longleftarrow \boxed{\alpha \simeq 0.5}$$

$$\downarrow$$

$$\omega'_{q|res} = \alpha\omega_p / h_C$$

$\rho_\infty = 0.3\ \mathrm{GeVcm}^{-3}$
with gravitational focusing
$v \simeq 10^{-3}$

$$S = 0.7\mathrm{mJy}\left(\frac{10^{-6}}{\Delta\nu/\nu}\right) \times \left(\frac{\ell_S}{4\times10^4\mathrm{km}}\right)^2 \left(\frac{\rho_a}{1.0\ \mathrm{GeV/cm}^3}\right)\left(\frac{g_{a\gamma}}{10^{-12}\mathrm{GeV}^{-1}}\right)^2 \times \left(\frac{B_\perp}{10\ \mathrm{G}}\right)^2 \left(\frac{\mu\mathrm{eV}}{m_a}\right)^2 \left(\frac{0.5}{\alpha}\right)\left(\frac{h_C}{3\times10^3\mathrm{km}}\right) e^{-\tau}$$

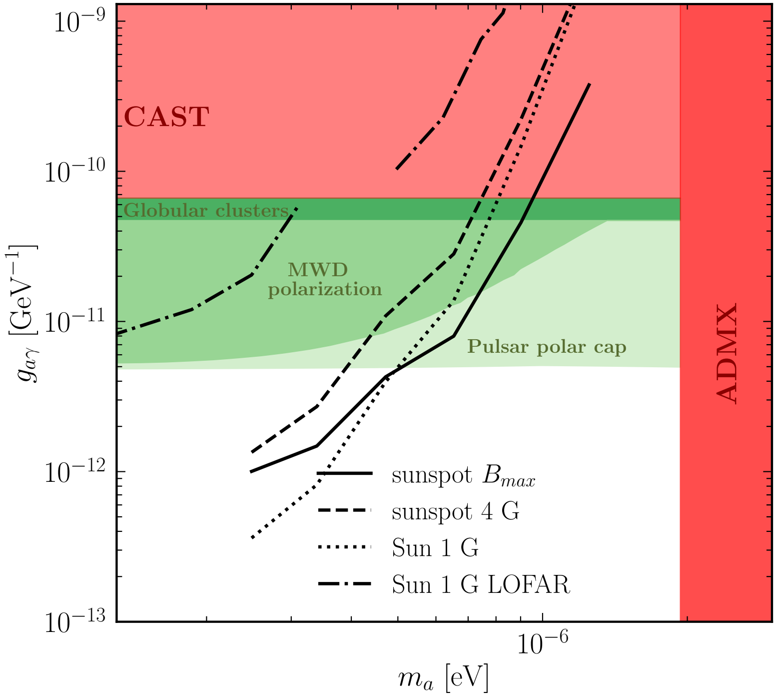


Thermal Bremsstrahlung

Radio-Axions

Novel approaches

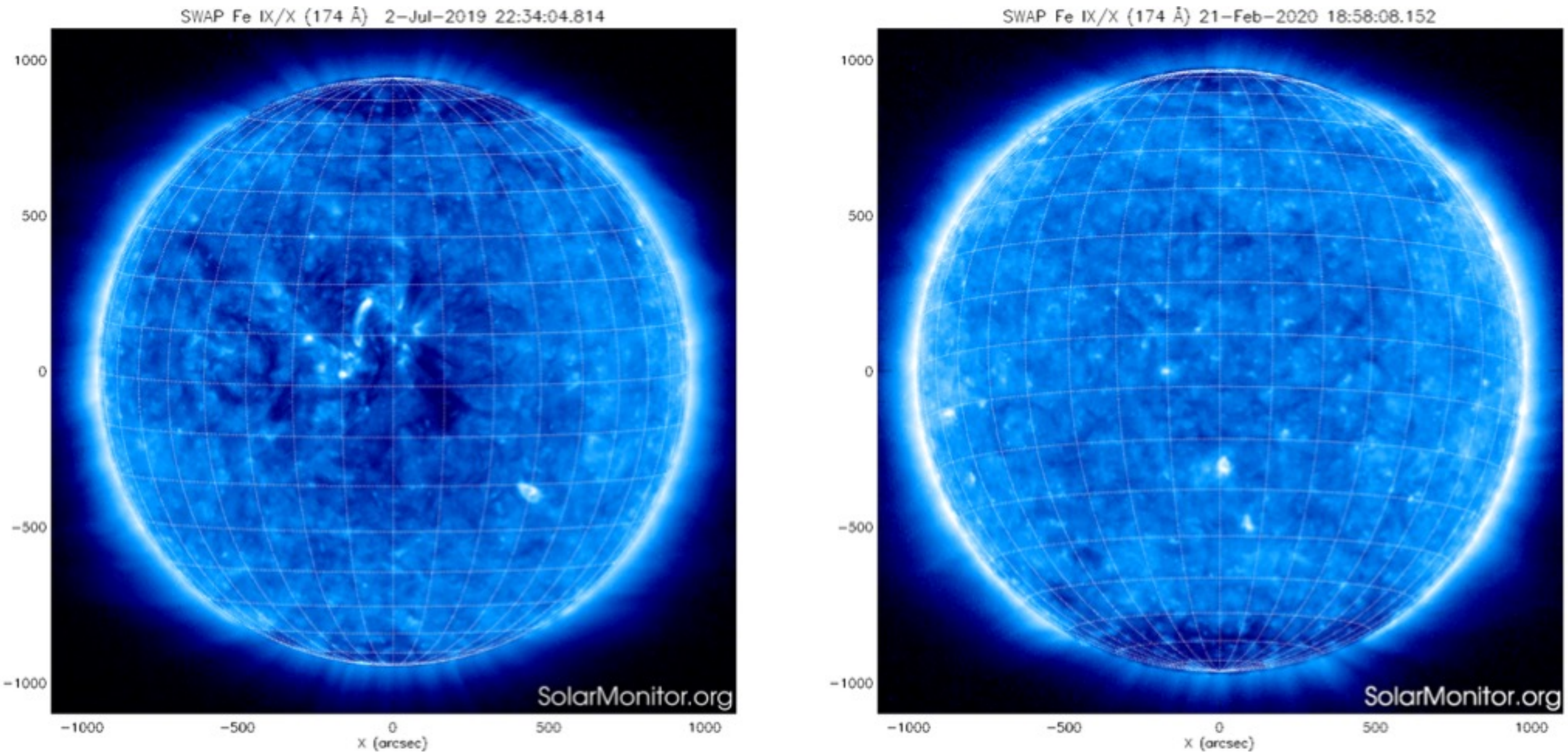
- Prospects from SKA:



Todarello et al., Phys. Lett. B 854, 138752 (2024).

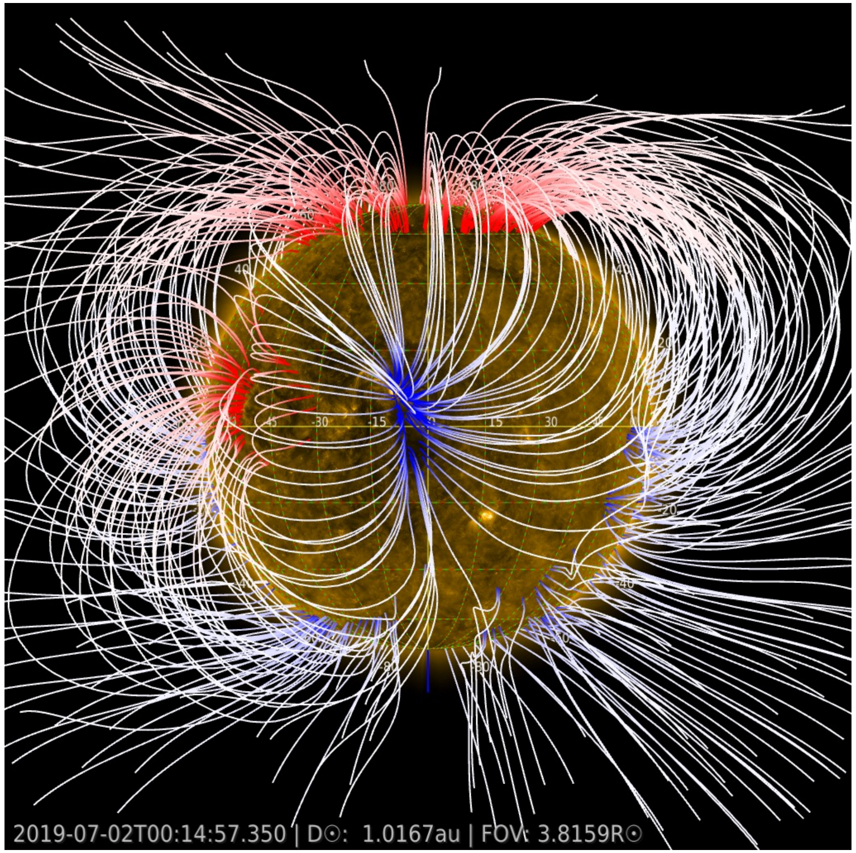
NuSTAR spacecraft

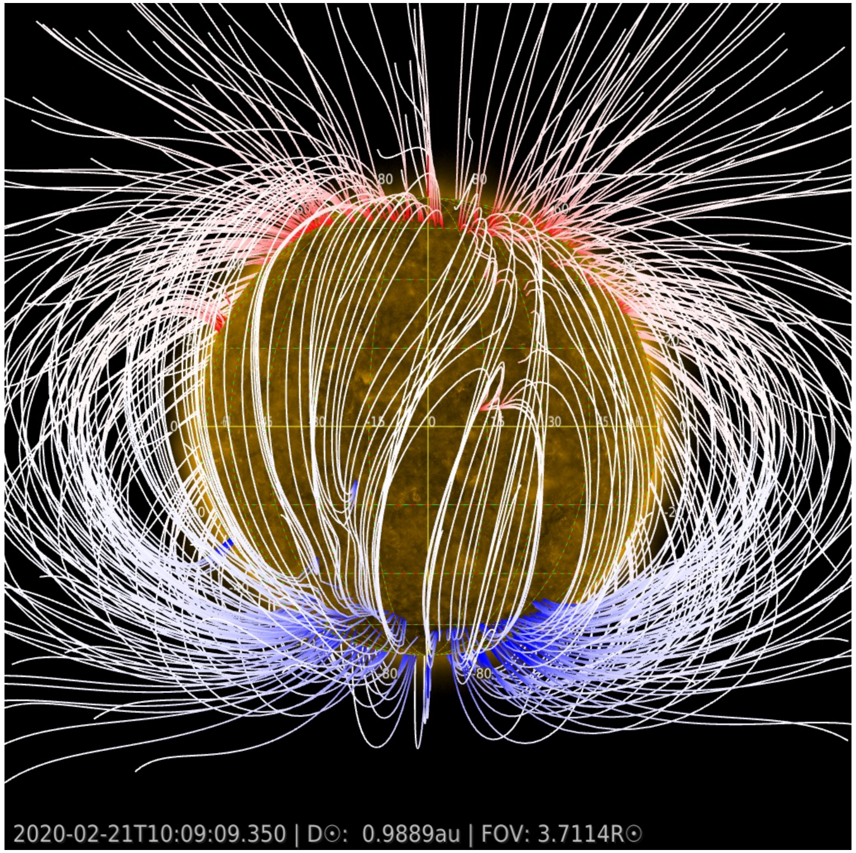
Observations



- Snapshots at 174 A from the SWAP spacecraft, showing the million-degree corona.
- The 2019 image (left), at the time of the PSI modeling, shows the presence of a weak active region near disk center.

Simulations

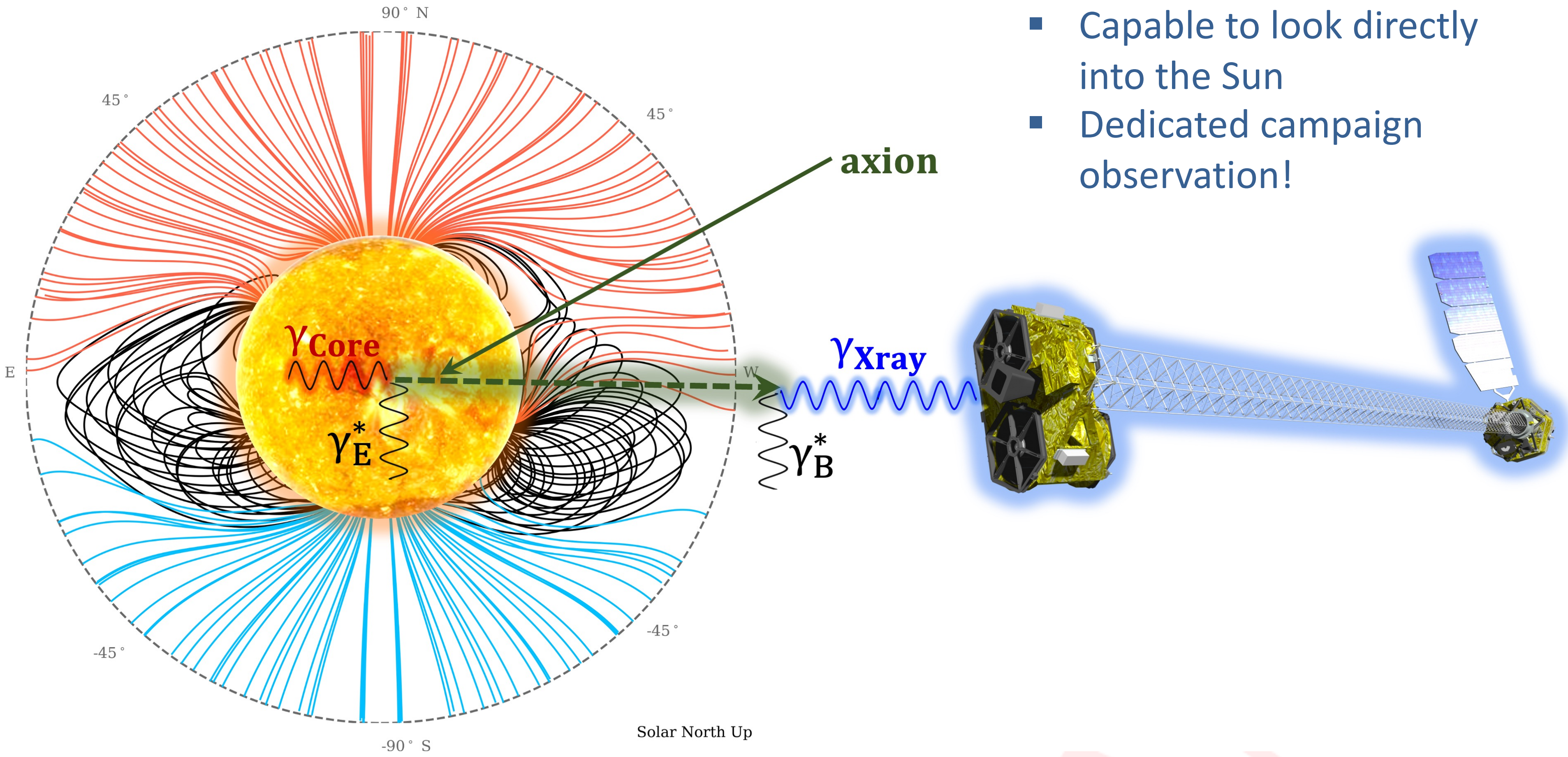




- PFSS model – see attached for a quick plot on the 2019 and 2020 dates for some randomly selected field lines, with AIA 171 EUV image for context. Quite different on the 2019 due to more activity.

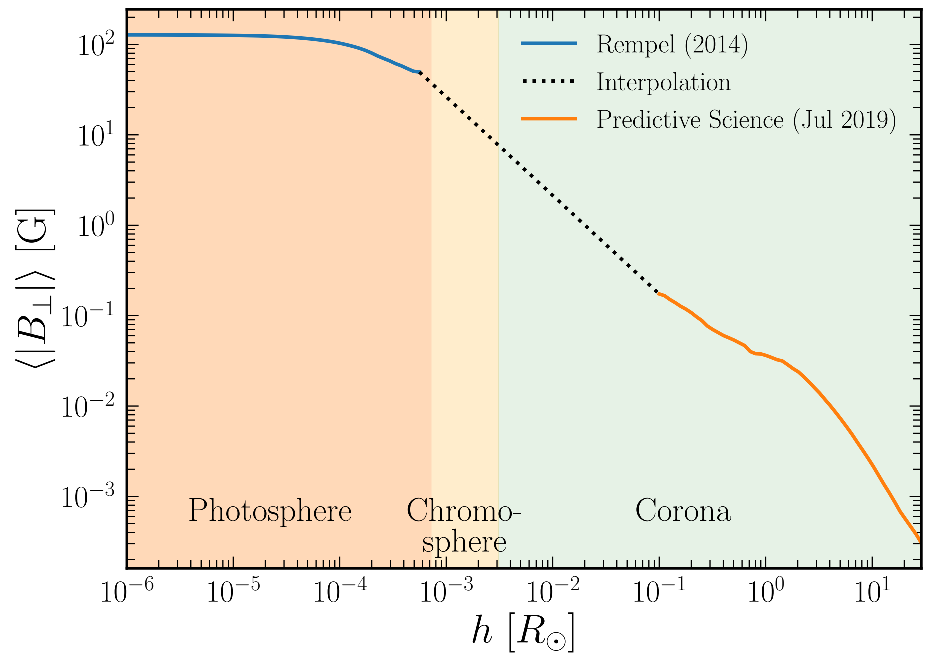
NuSTAR

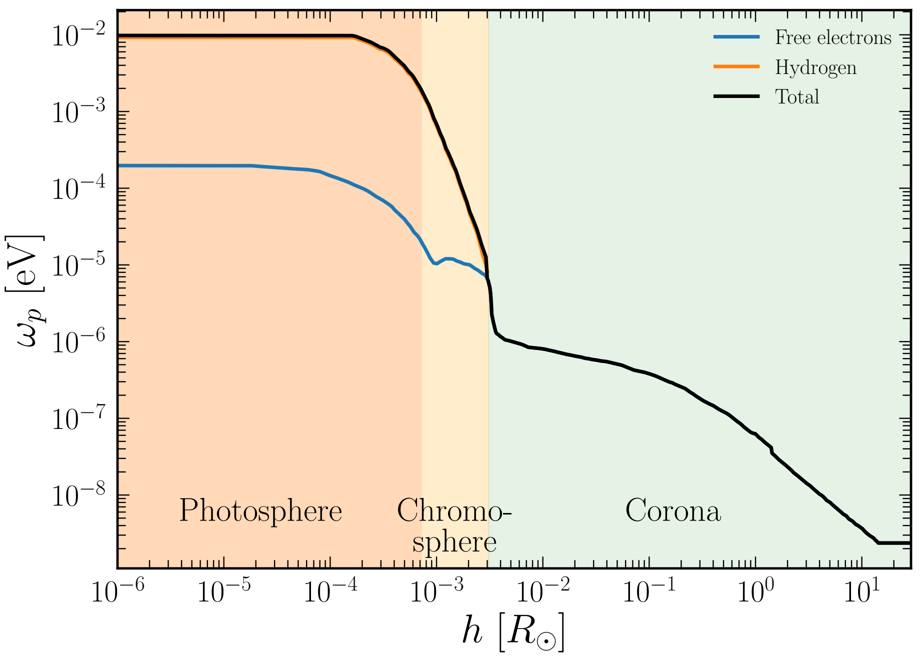
- Capable to look directly into the Sun
- Dedicated campaign observation!



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

Novel approaches





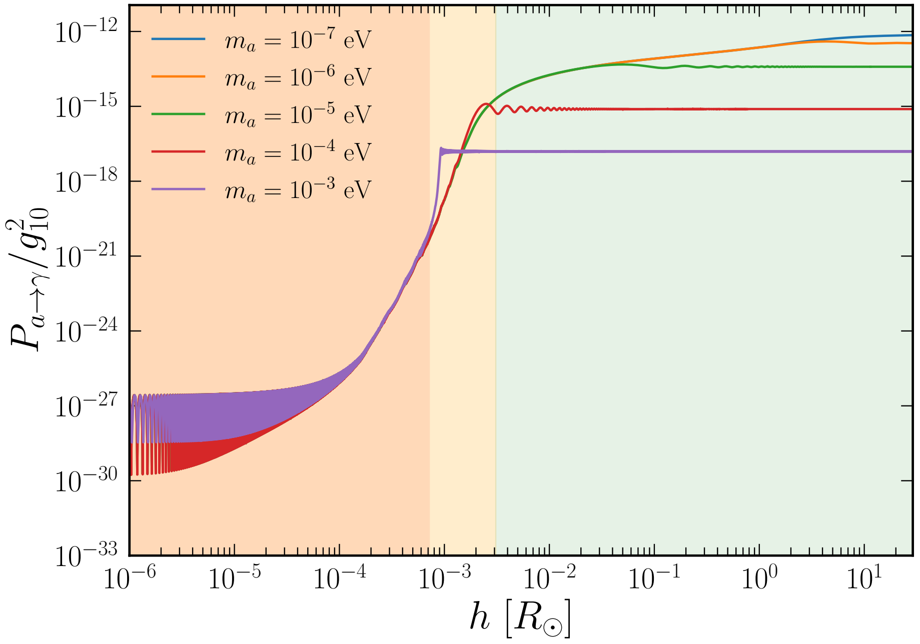
Rempel et al., The Astrophysical Journal 789, 132 (2014).

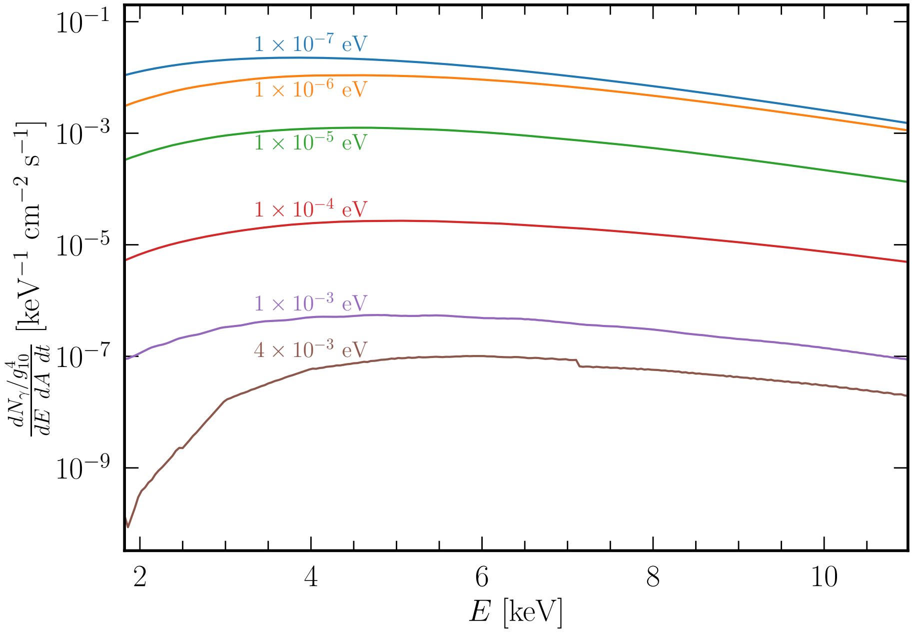
Mikic et al., Nature Astronomy 2, 913–921 (2018).

Dere et al., A&AS 125, 149–173 (1997).

- Model the perpendicular component of the solar atmospheric magnetic field.
- Determine contributions to axion plasma frequency from free electrons and Hydrogen

NuSTAR



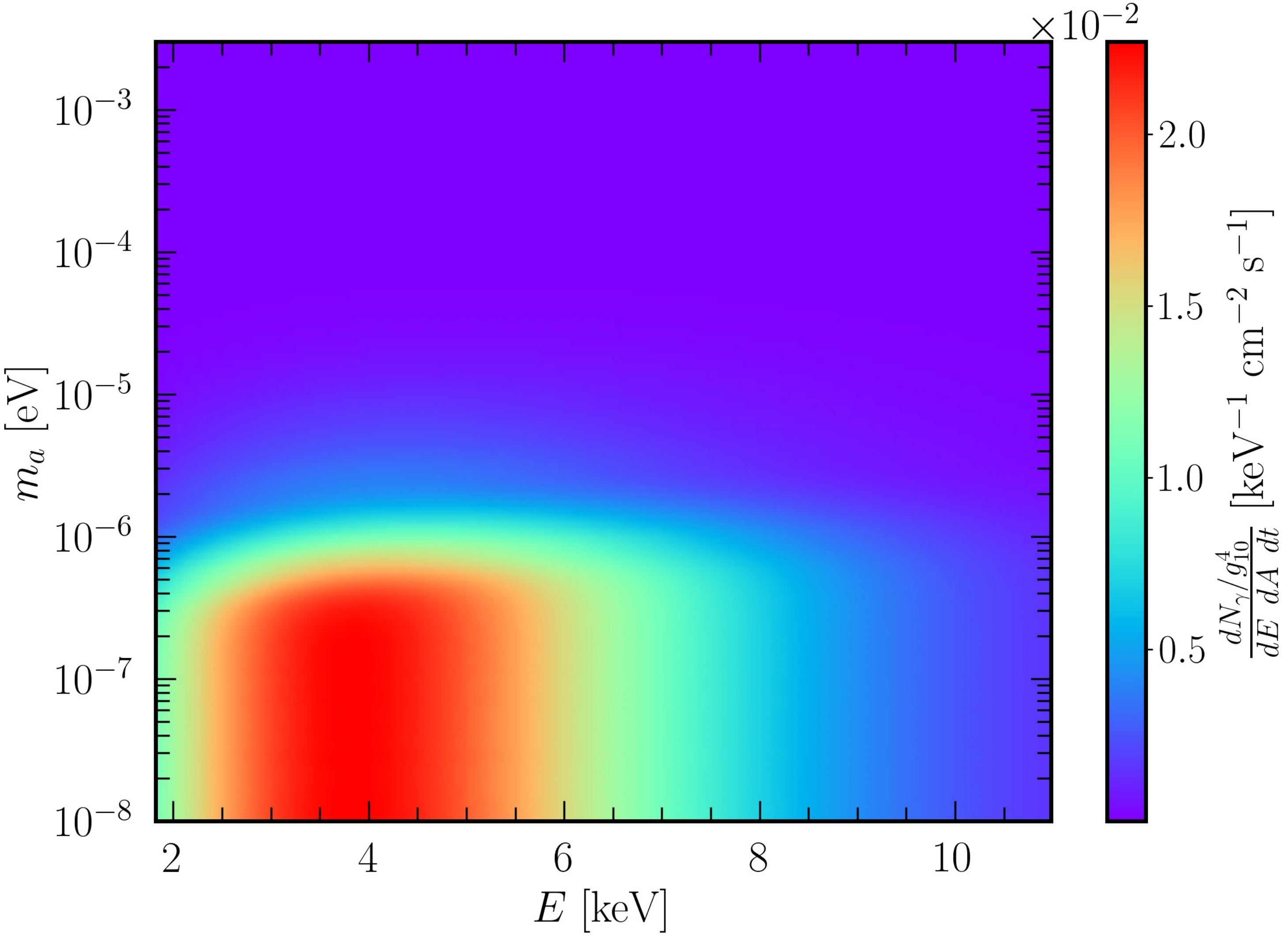


- Establish conversion probability for different regions of the Sun’s atmosphere
- Determine total X-ray flux in NuSTAR. Axion mass dependance of the arriving flux

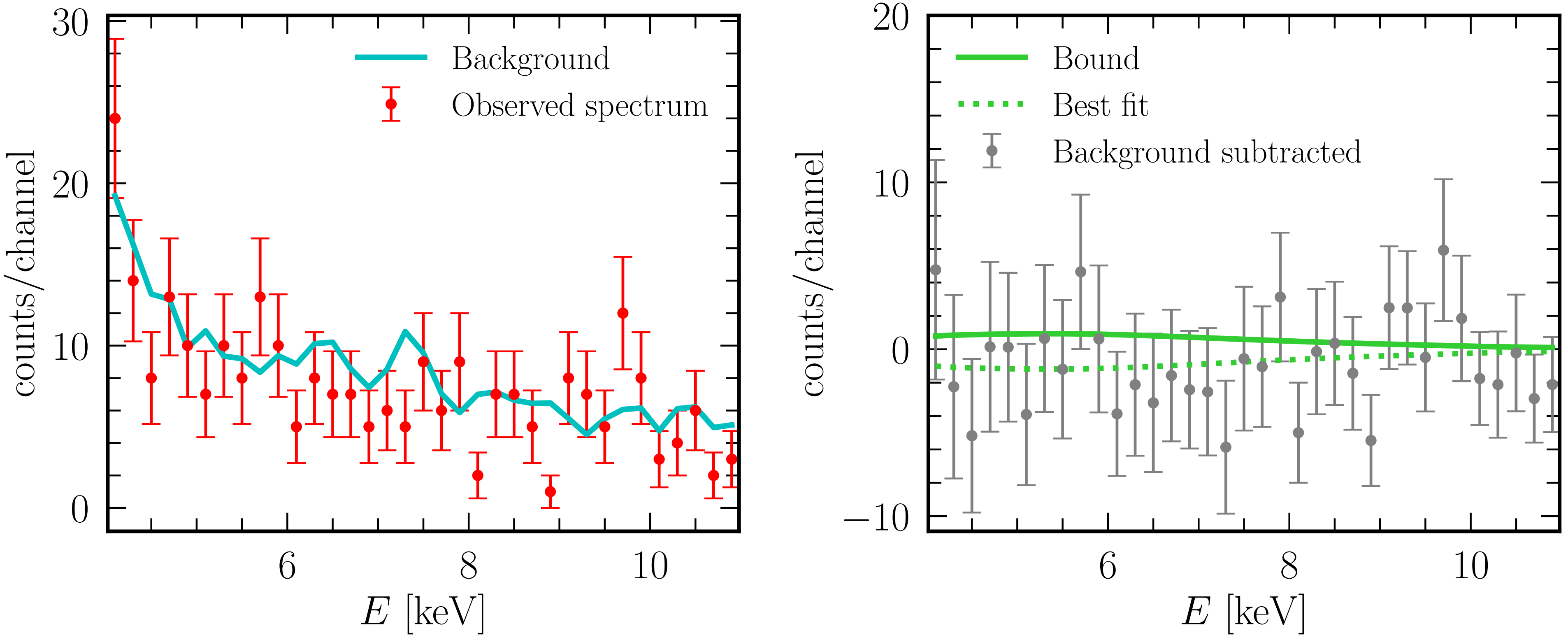
NuSTAR

Novel approaches

$$\frac{dN_\gamma}{dE\,dA\,dt\,d\Omega} = \frac{dN_a}{dE\,dA\,dt\,d\Omega} P_{a\to\gamma}$$



Yes, we have good data!



NuSTAR

Novel approaches

Stay tunned for the
Breaking News Session!!

Conclusions

- ✓ Axions are well motivated dark matter candidates simultaneously solving strong CP
- ✓ Axions (and axion-like particles) can be searched for in a variety of solar axion experiments: Helioscopes, Radio-Observatories and space missions
- ✓ Solar axion searches probe large regions of well-motivated axion parameter space
- ✓ IAXO targets axion discovery with sensitivities down to a few 10^{-11} (10^{-12}) GeV^{-1} in $g_{a\gamma}$
- ✓ SKAO and NuSTAR could be probing much earlier. Stay tuned for Breaking News session