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INFN-Torino



Astrophysical probes of Axions: From X-rays to Radio Signals

PPC 2026
UNSW Sydney
Sept 4, 2026

Plan of the talk

- * Brief recap on axion and axion-like particles (ALPs)
 - * Axion flux from the Sun: searches with X-ray observations
 - * Axion dark matter around the Sun: prospects for detection with radio telescopes
 - * X-ray signal from ALP dark matter decays
-

Motivation for the axion

The **strong CP problem**

From the upper limit
on the neutron EDM

$$\mathcal{L}_{QCD} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G_{\mu\nu} \tilde{G}_{\mu\nu}$$

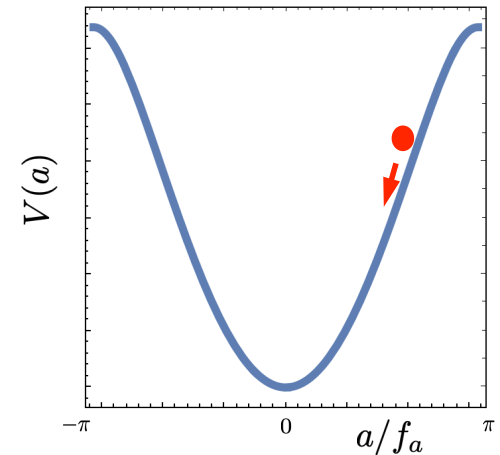
$$|\bar{\theta}| \lesssim 10^{-10}$$

Why $\bar{\theta}$ is so small?

CP violating term

The **axion solution**: $\bar{\theta}$ angle promoted to a dynamical variable

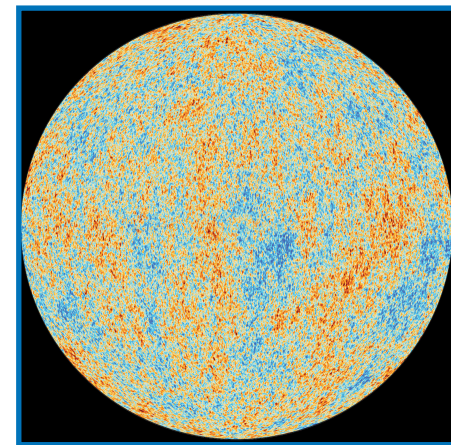
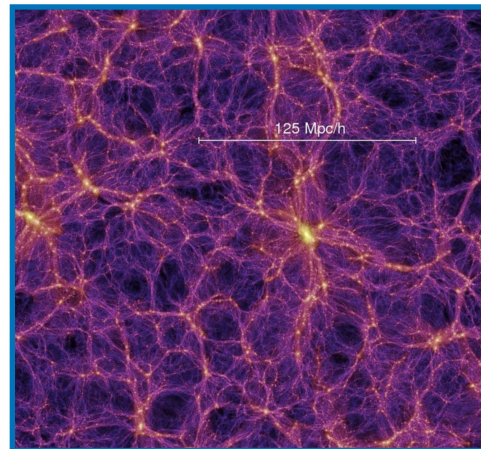
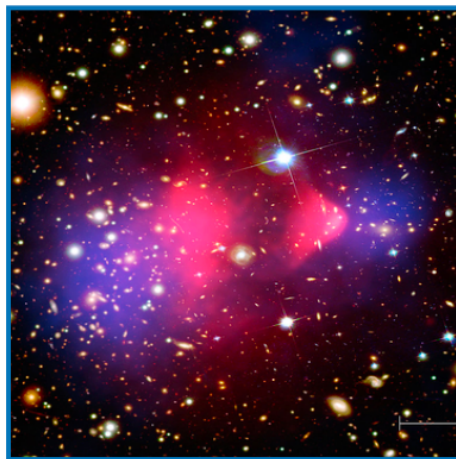
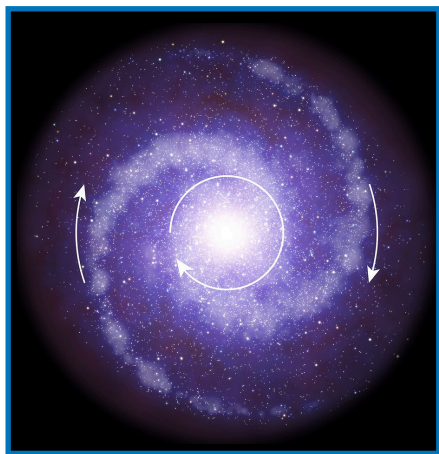
$$\mathcal{L} \supset \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G_{\mu\nu} \tilde{G}_{\mu\nu}$$



Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)

Motivation for the axion

Axion: dark matter candidate



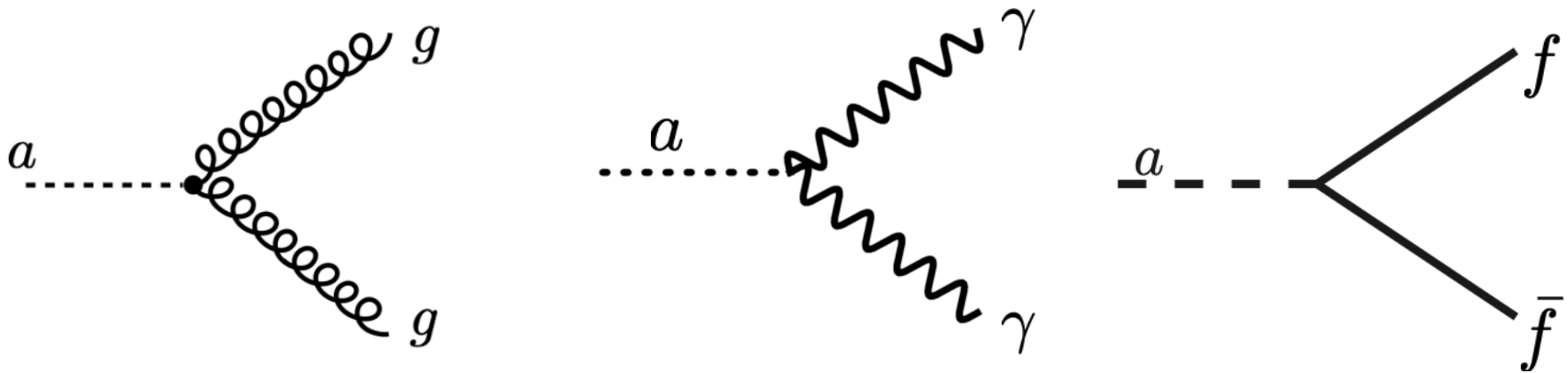
Light axion: very weakly coupled and long-lived

$$m_a = 5.691(51) \left(\frac{10^{12} \text{ GeV}}{f_a} \right) \mu\text{eV}$$

$$\Gamma \sim m_a^3 / f_a^2$$

The axion effective Lagrangian

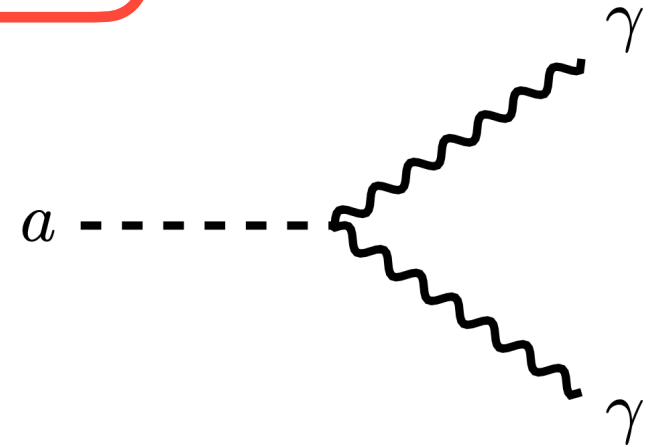
$$\mathcal{L}_{\text{eff}} \supset \frac{1}{2} \partial_\mu a \partial^\mu a + \frac{g_s^2}{32\pi^2} \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{af}}{2m_f} \partial_\mu a \bar{f} \gamma^\mu \gamma_5 f$$



Axion coupling to photons

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

$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a} \left[\frac{E}{N} - 1.92(4) \right]$$

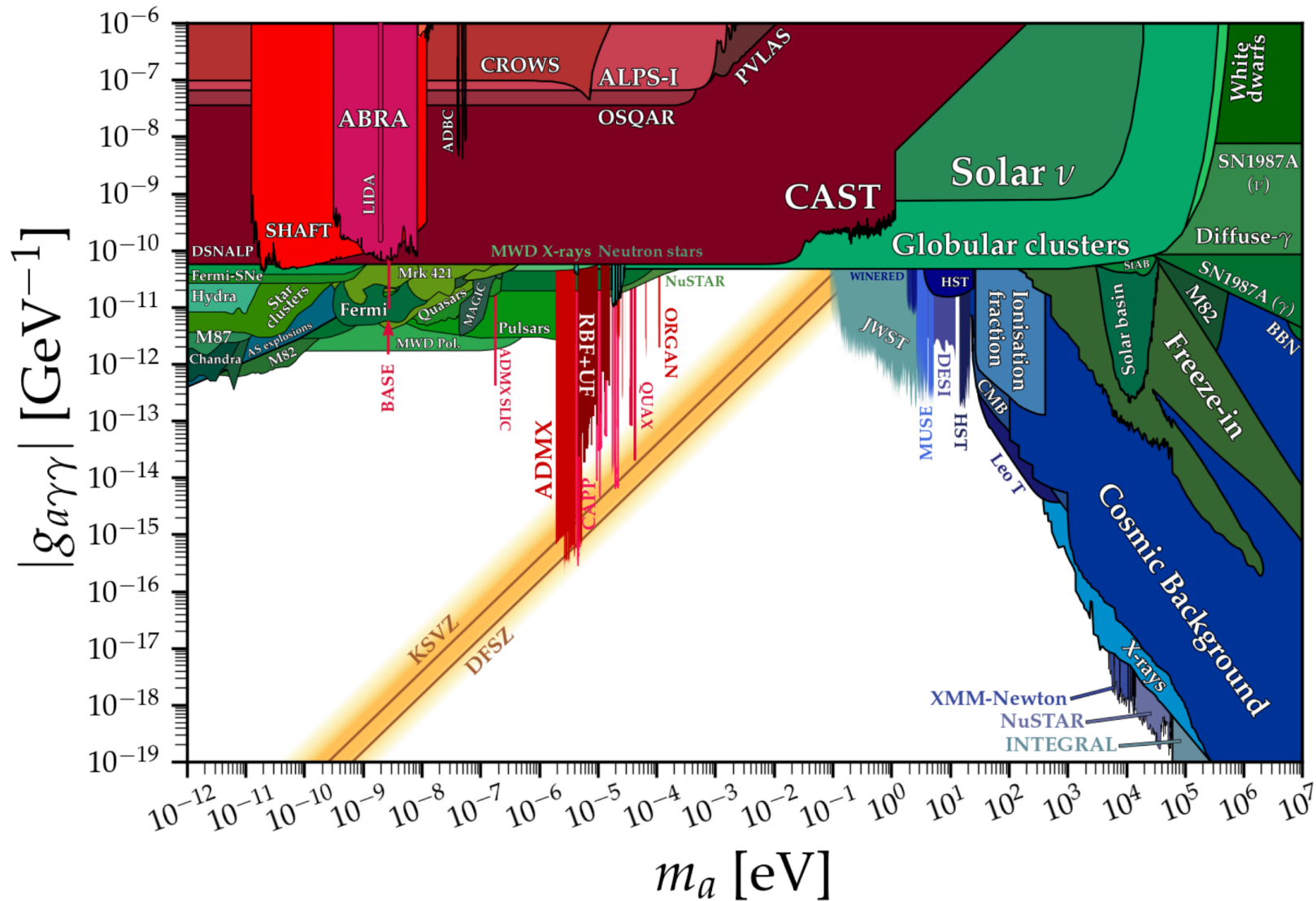


Most of experimental axion searches exploit the axion - photon coupling

Axion and Axion-Like Particles (ALPs)

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

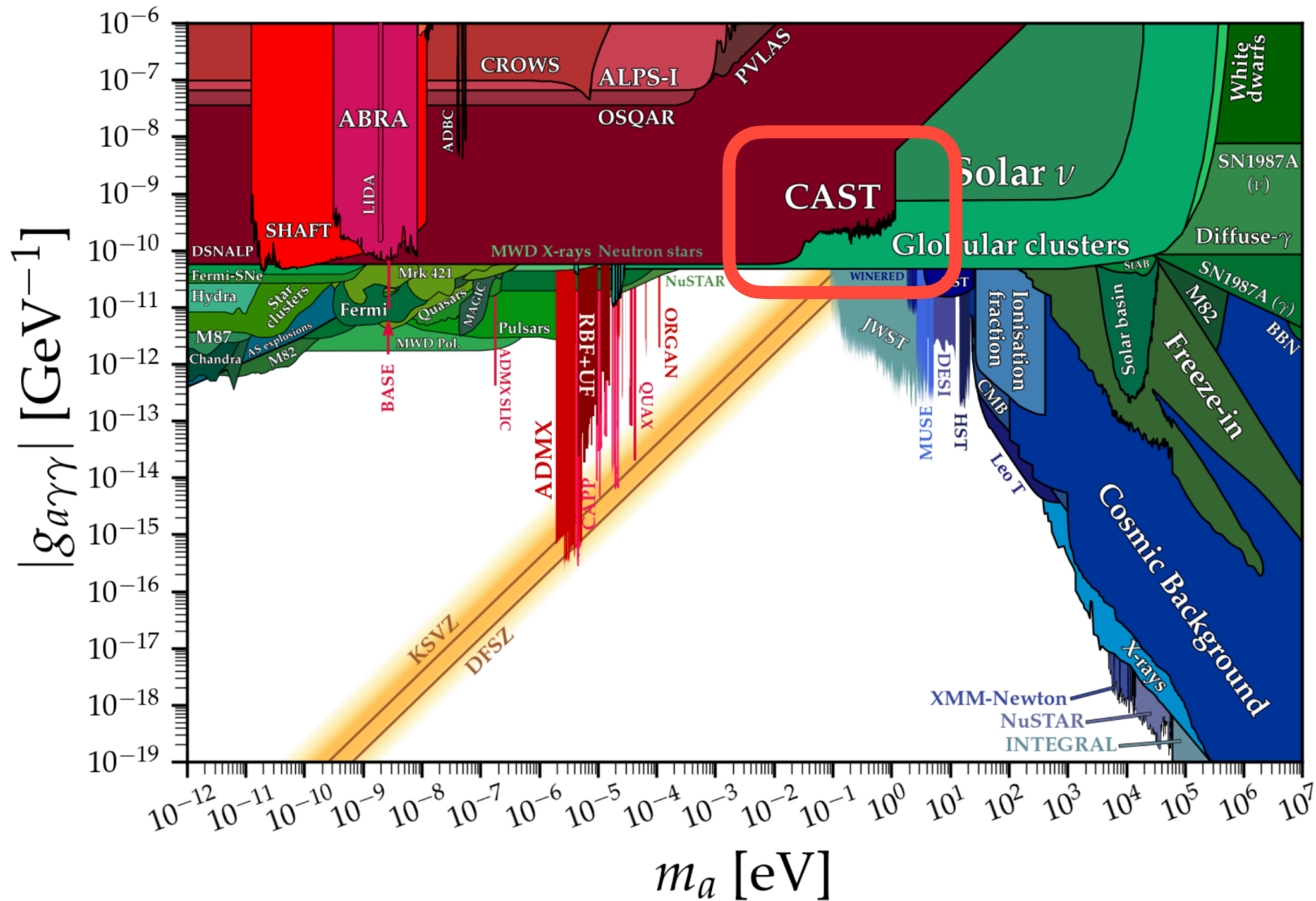
Cajohare AxionLimits



Axion and Axion-Like Particles (ALPs)

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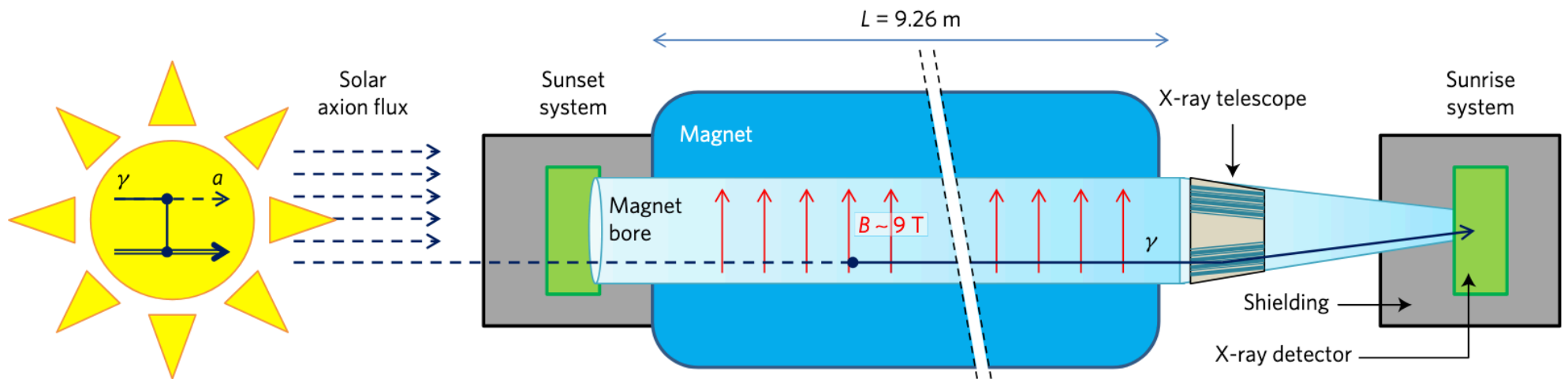
Cajohare AxionLimits



Axion helioscopes

Axion helioscopes: laboratory axion experiments searching for solar axions

CERN AXION SOLAR TELESCOPE (CAST): most powerful helioscope to date



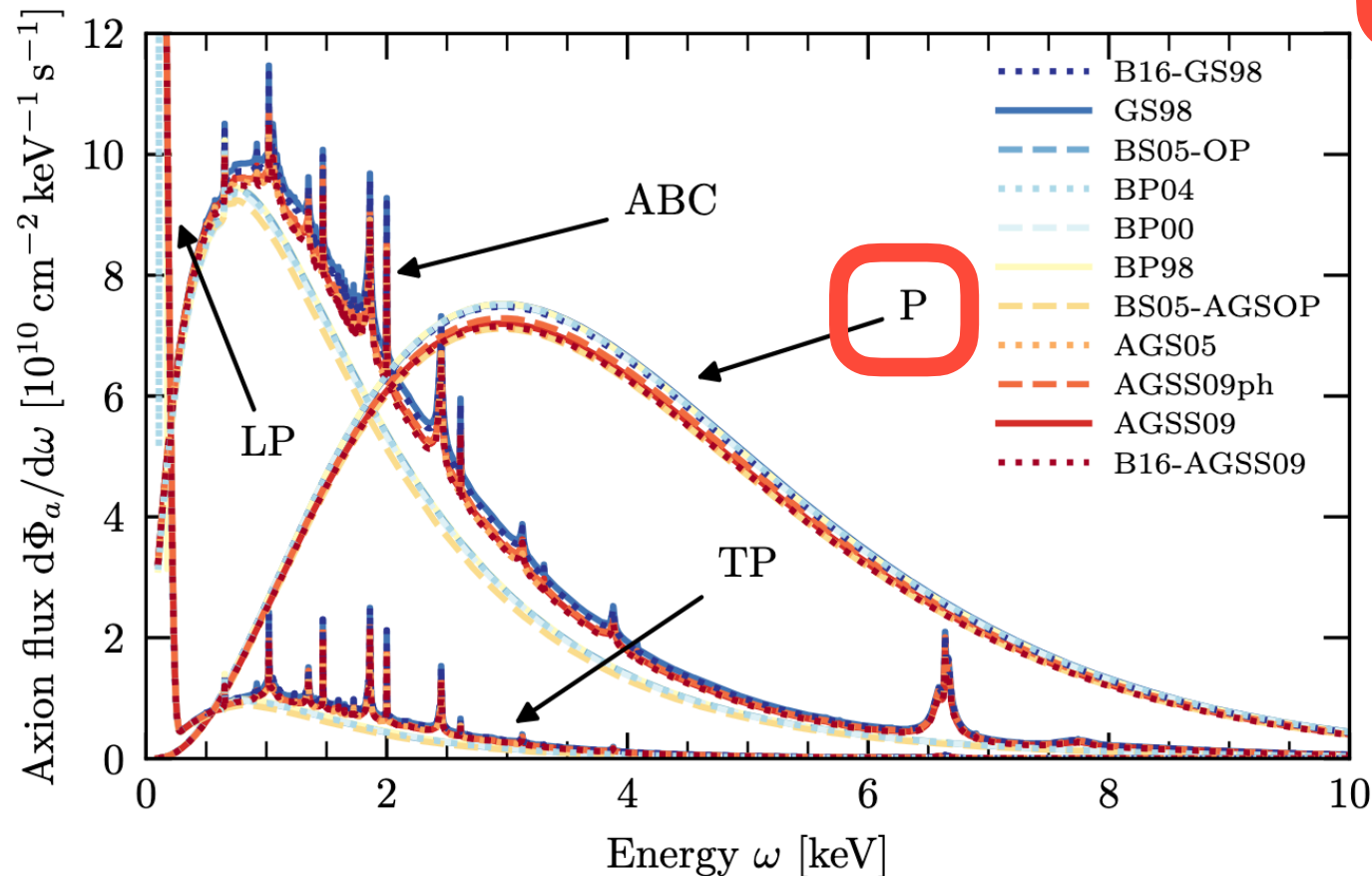
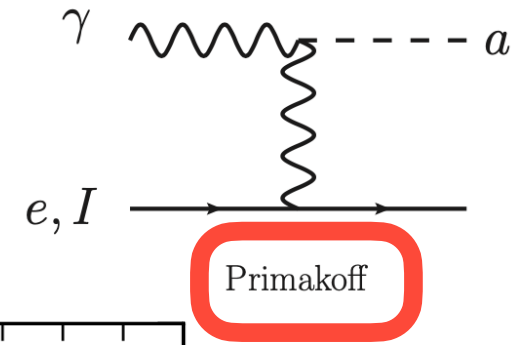
Credit: CAST Collaboration

Relativistic axions from the Sun

Axion flux from the inner solar region

Flux well understood

see e.g. [Hoof, Jaeckel Thormaehlen, JCAP 10 \(2024\) 024](#)

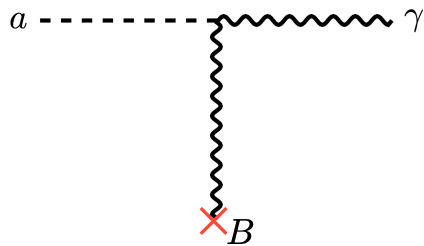


Conversion probability

Axion to photon conversion probability in an homogeneous magnetic field of length L

$$P_{a \rightarrow \gamma} = \left(g_{a\gamma} B \frac{\sin(qL/2)}{q} \right)^2$$

$q = m_a^2/2E$ momentum transfer between axion and photon (in vacuum)



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$$qL/2 \ll 1$$

$$P_{a \rightarrow \gamma} \sim g_{a\gamma}^2 B^2 L^2$$

Coherent regime



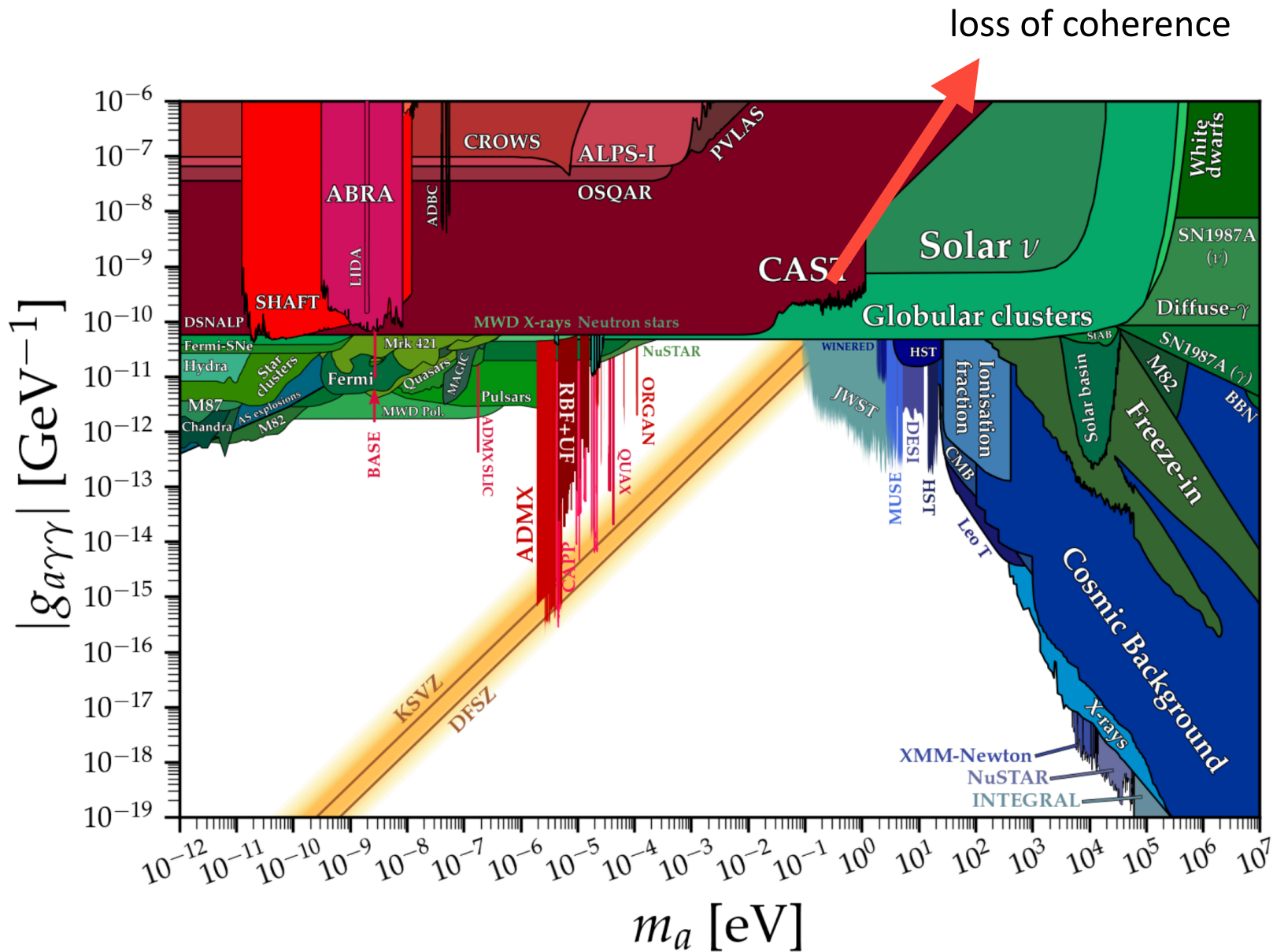
$$qL/2 \gg 1$$

$$P_{a \rightarrow \gamma} \sim g_{a\gamma}^2 B^2 1/q^2$$

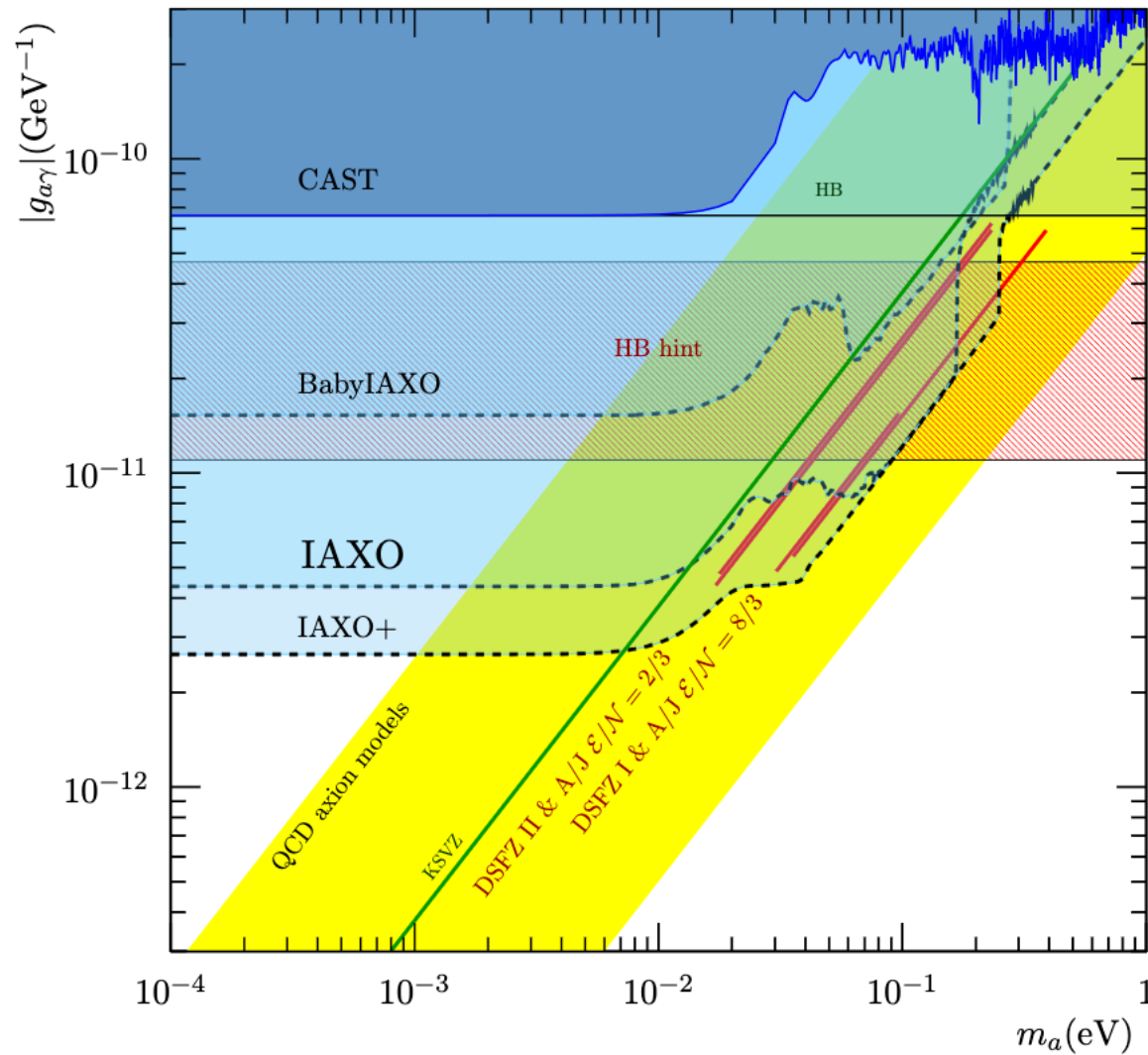
Incoherent regime



Axion and Axion-Like Particles (ALPs)



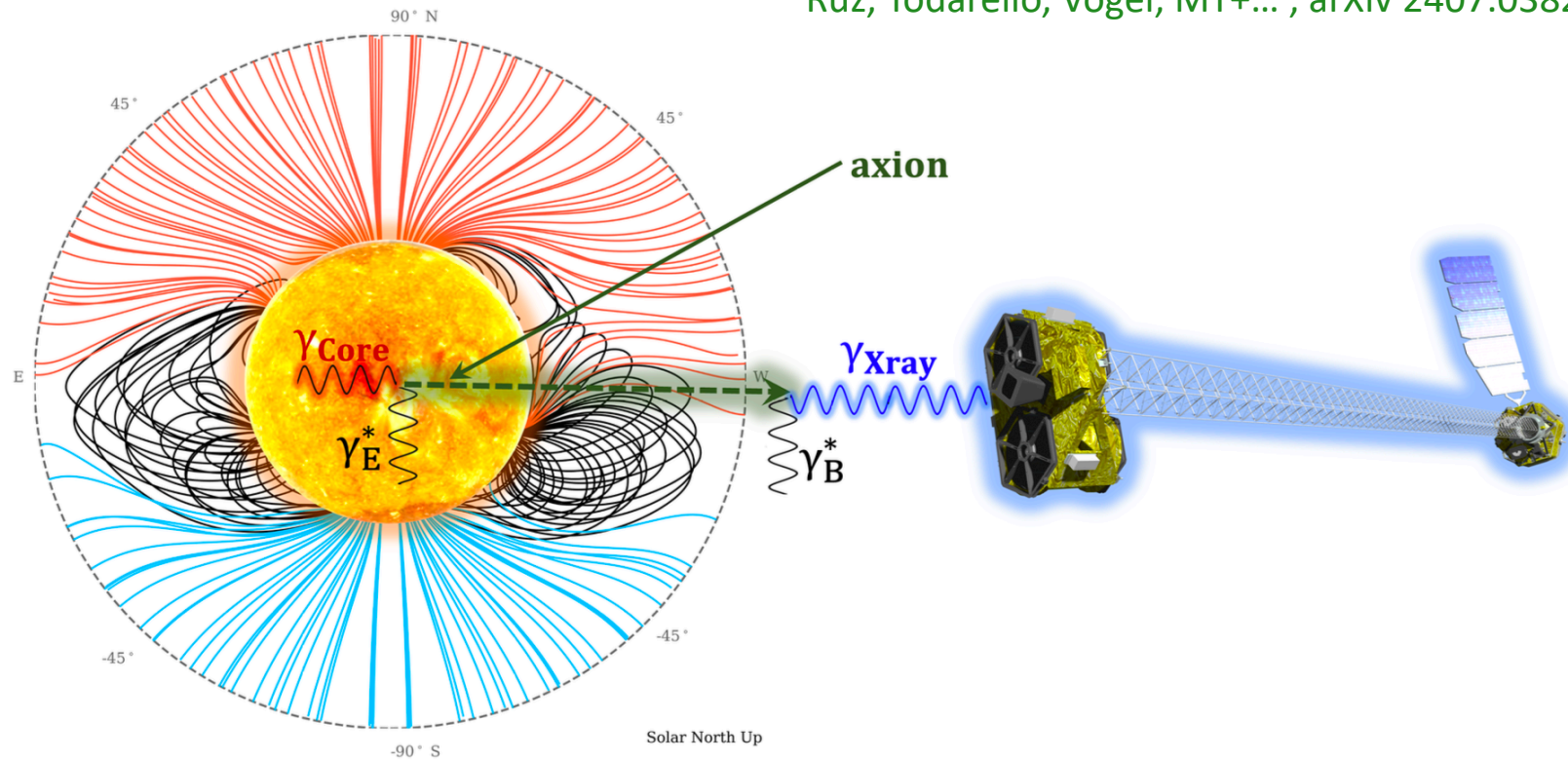
Future helioscopes



CAST Collaboration, JCAP 06 (2019) 047

NuSTAR as an axion Helioscope

Ruz, Todarello, Vogel, MT+... , arXiv 2407.03828, PRL 2025



Conversion probability

$$p_{a\gamma} \simeq g_{a\gamma\gamma}^2 B^2 L^2$$

$$\frac{p_{a\gamma}^{\odot}}{p_{a\gamma}^{\text{CAST}}} \sim \left(\frac{0.1 \text{ G}}{10 \text{ T}} \right)^2 \left(\frac{1 R_{\odot}}{10 \text{ m}} \right)^2 \sim 5 \times 10^3$$

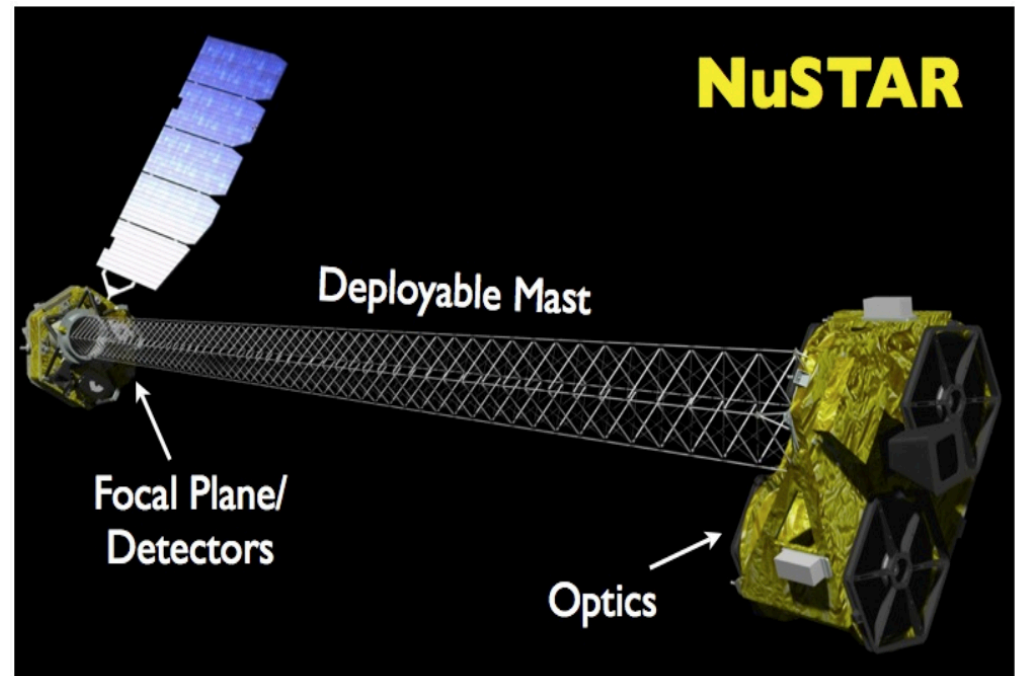
Solar NuSTAR observations

NuSTAR

Nuclear Spectroscopic Telescope Array
is a NASA mission launched in 2012

Focusing X-ray optics in 3-79 keV range

FoV: 10' at 10 keV

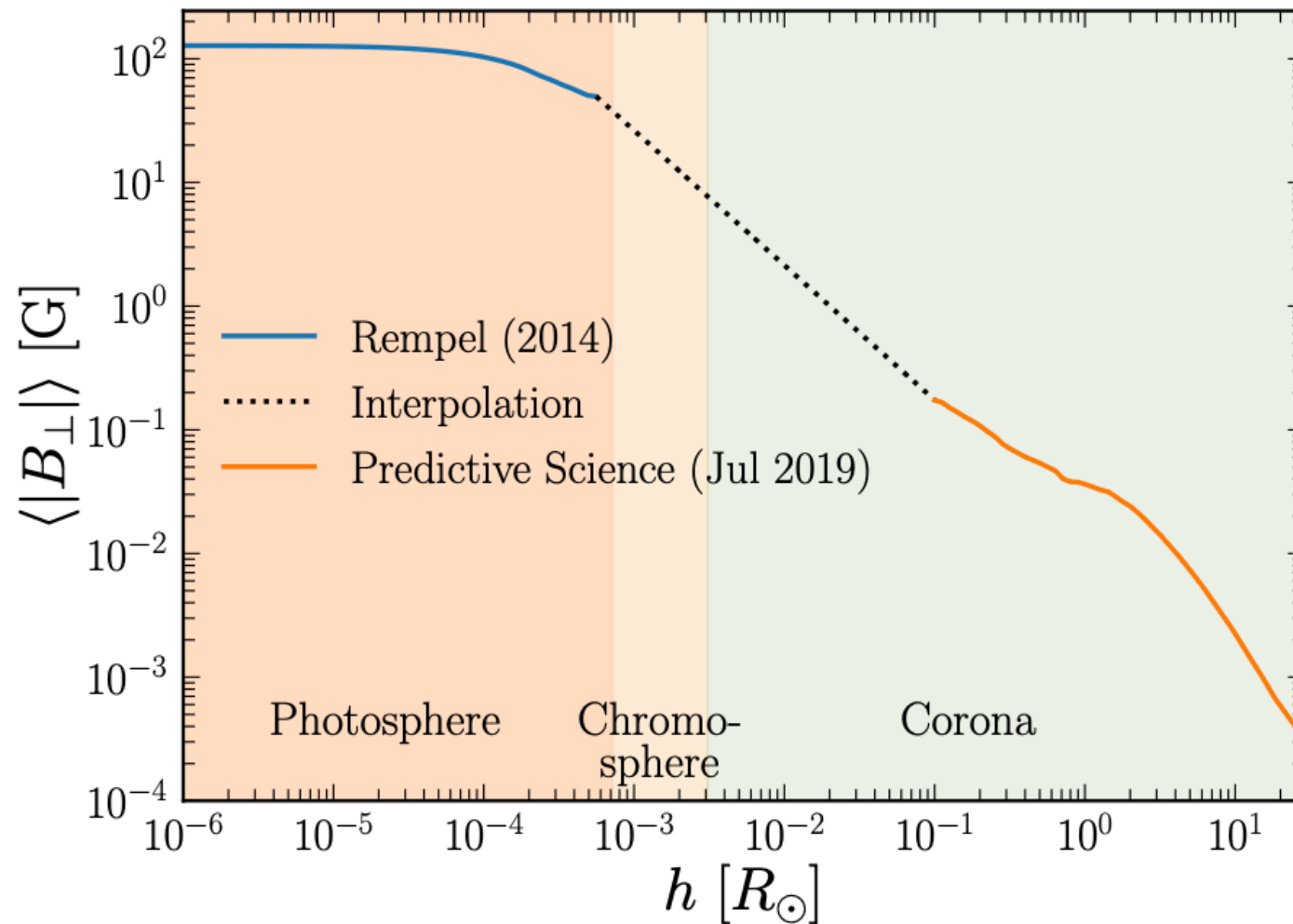


NuSTAR has conducted several observations of the Sun

The most useful for axion searches was performed in 2020 involving significant exposure of the solar disk center and at a time close to the solar minimum

Magnetic field in the solar atmosphere

Magnetic field of the Quiet Sun



Magnetic field in the solar atmosphere

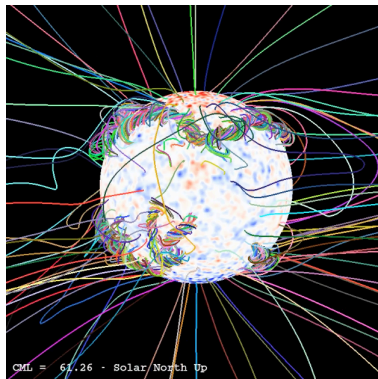
In the **photosphere**: from MHD simulations

Rempel et al. (2014)

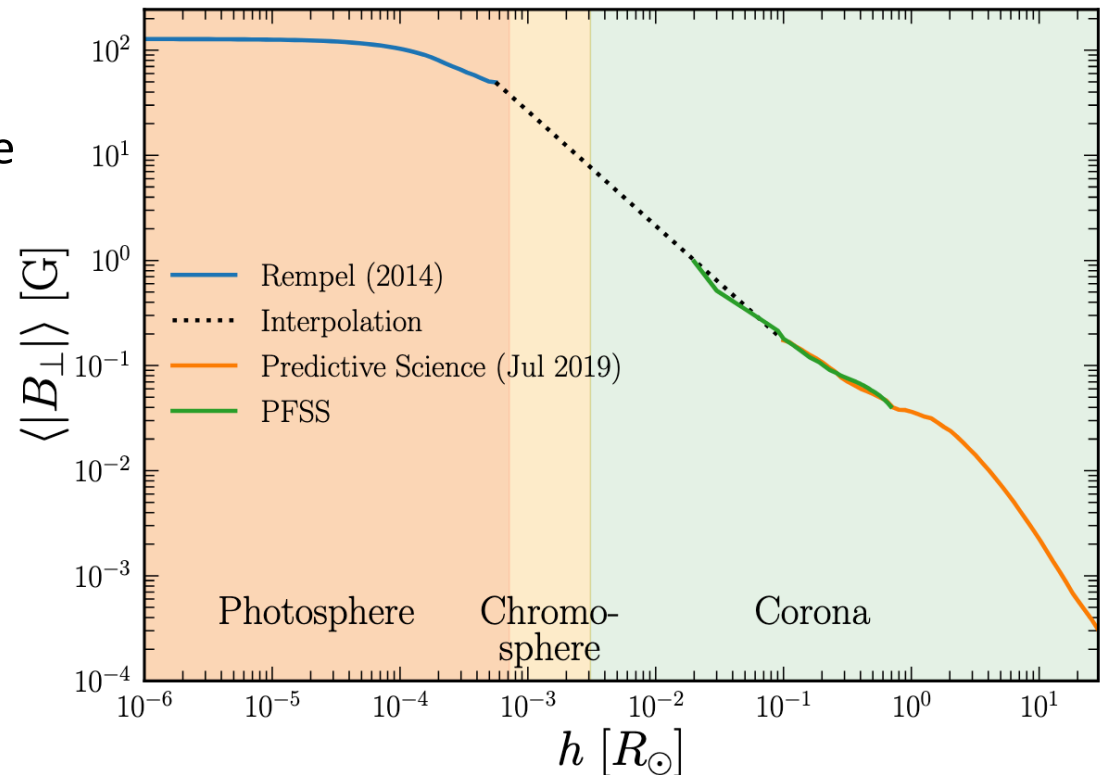
Del Pino Aleman et al. (2018)

Model matches photospheric spectral line polarization signals

In the **Corona**: from the Predictive Science Inc. MHD simulation for solar eclipse of 02/07/2019



Mikic et al 2018



In agreement with Potential-Field-Source-Surface (PFSS) model for the specific day of observation

<https://nso.edu/data/nisp-data/pfss/>

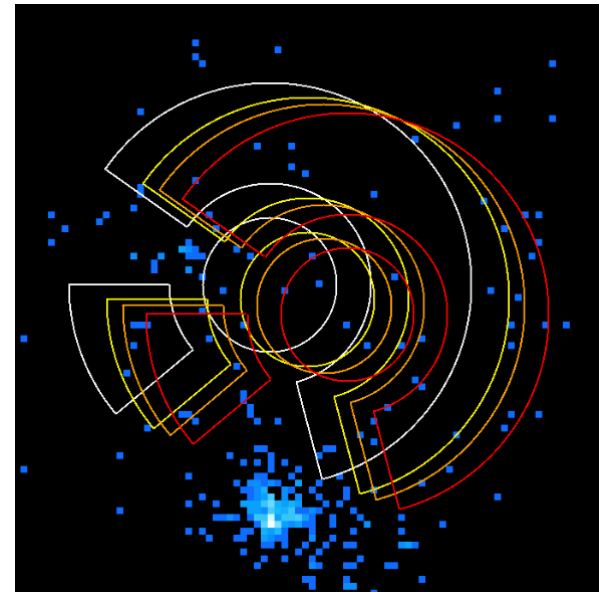
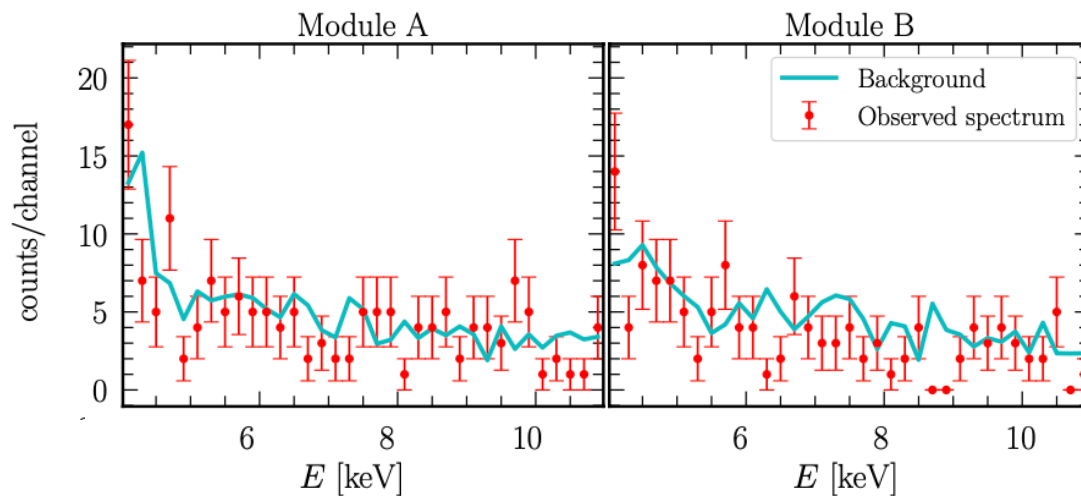
NuSTAR data

NuSTAR X-rays observations of the Sun

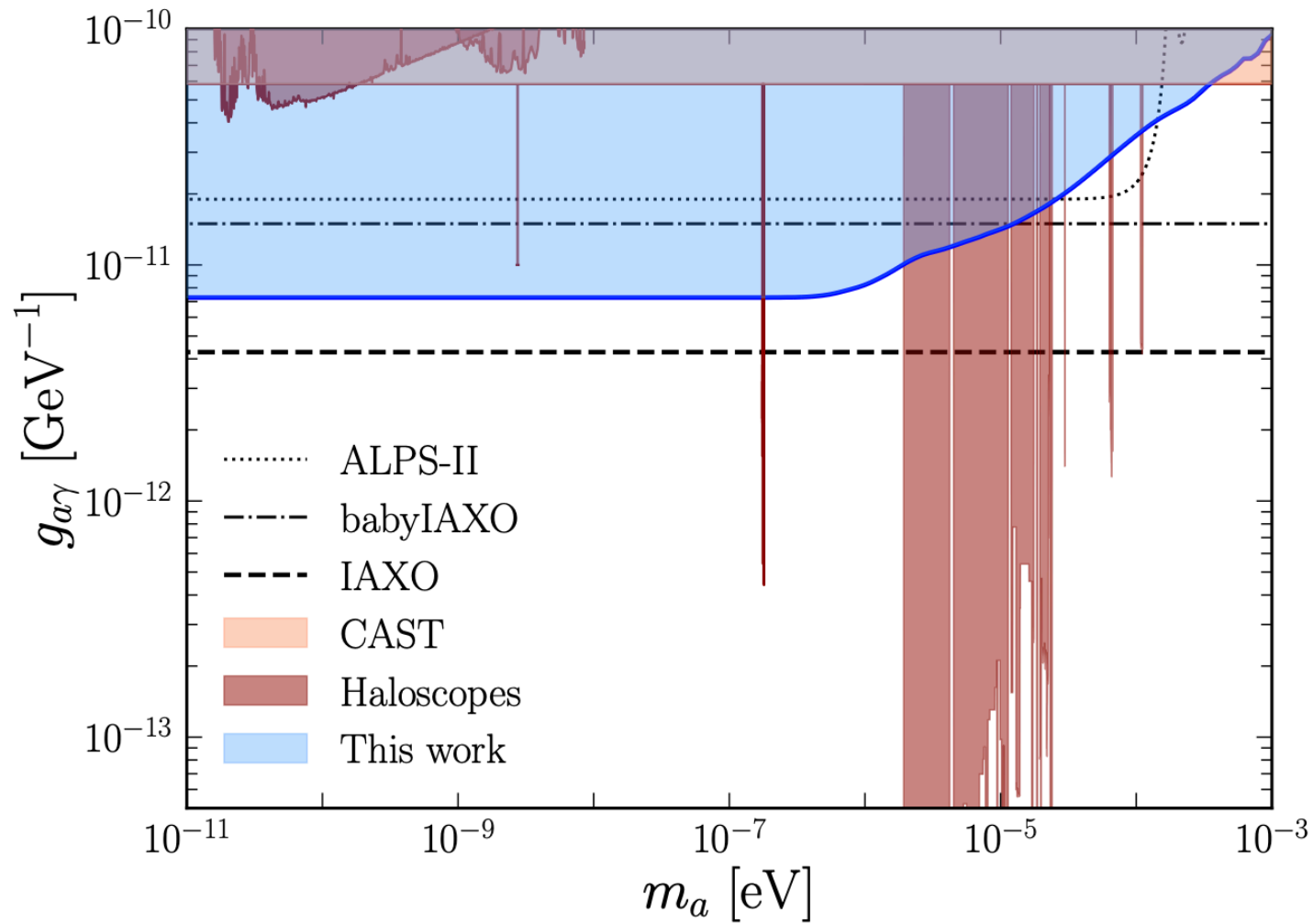
~24ksec observations of the Sun in 2020: close to the solar minimum

Signal region: $r < 0.1R_{\odot}$

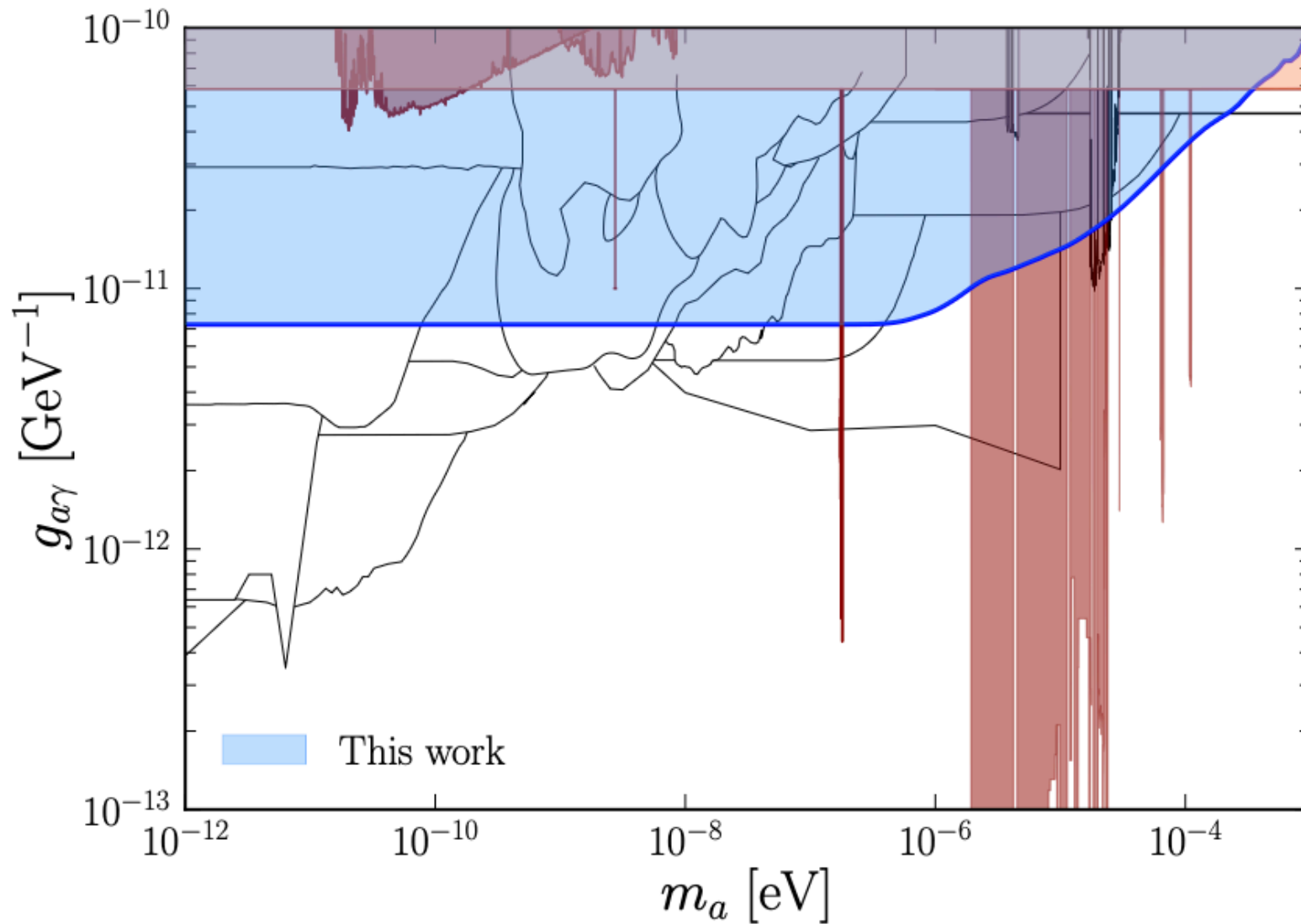
Background region: $0.15R_{\odot} < r < 0.3R_{\odot}$



NuSTAR limits

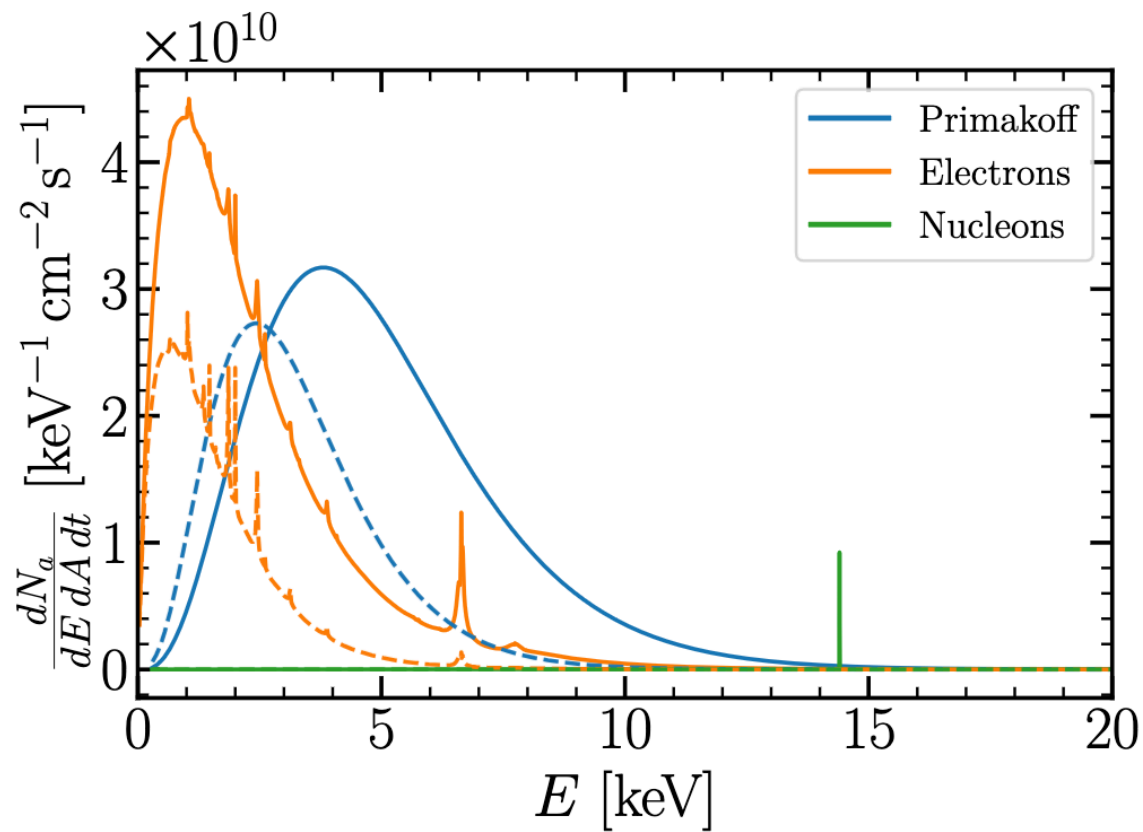


NuSTAR limits



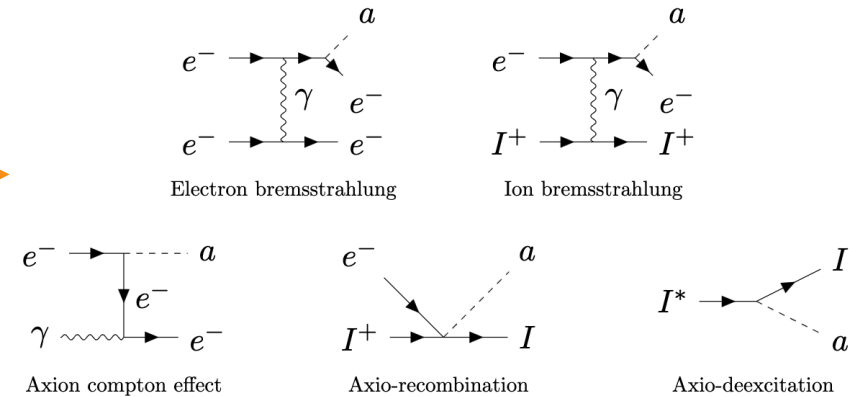
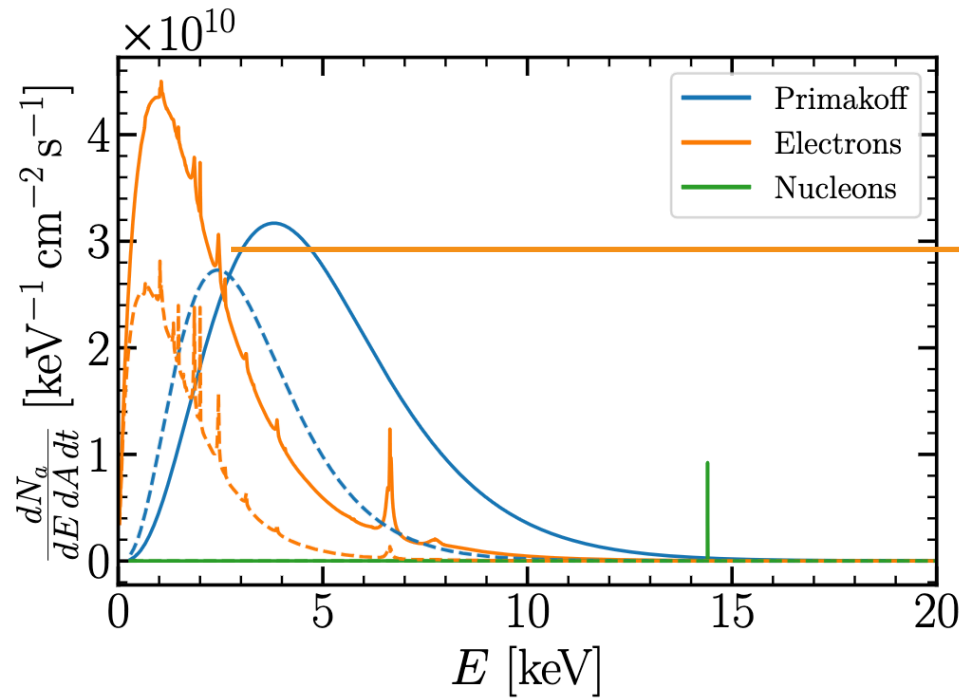
Ruz, Todarello, Vogel, MT+... , arXiv 2407.03828, PRL 2025

Axions from electron and nucleon couplings



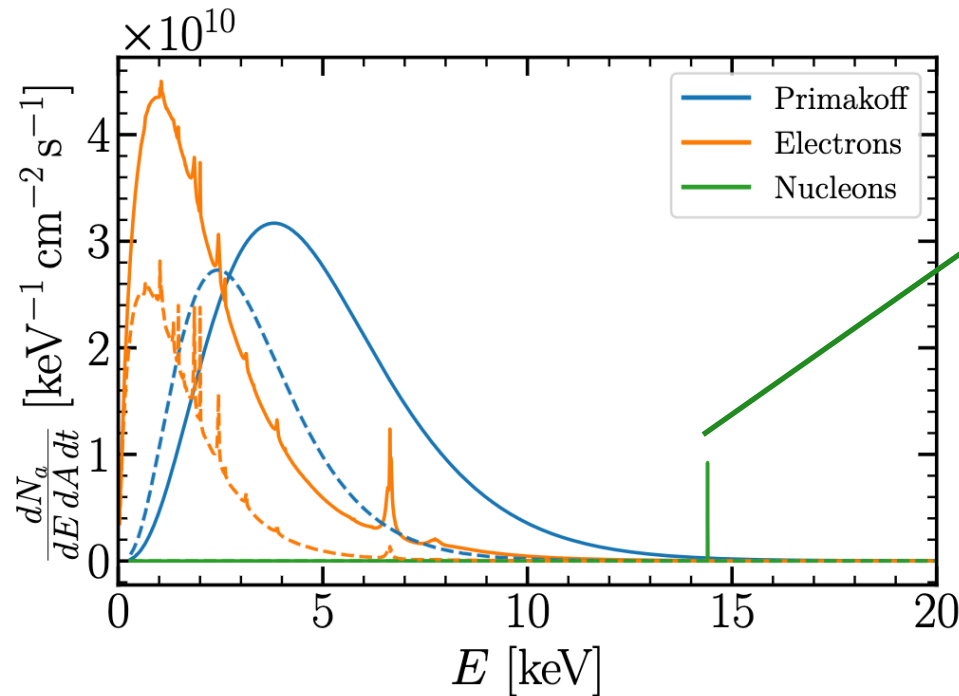
Axions from electron couplings

$$\mathcal{L}_{\text{eff}} \supset \frac{g_{ae}}{2m_e} \partial_\mu a \bar{e} \gamma^\mu \gamma_5 e$$



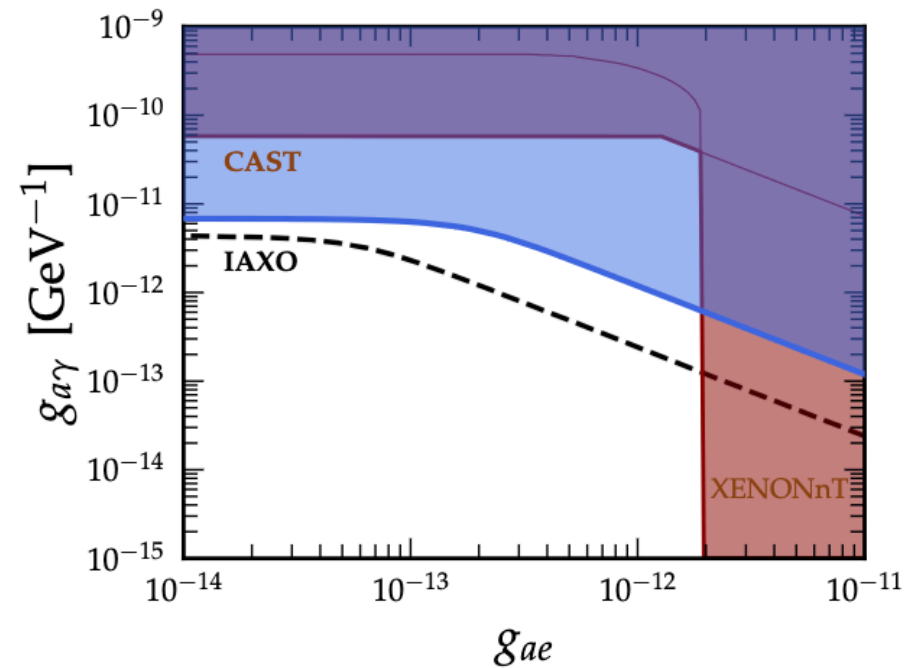
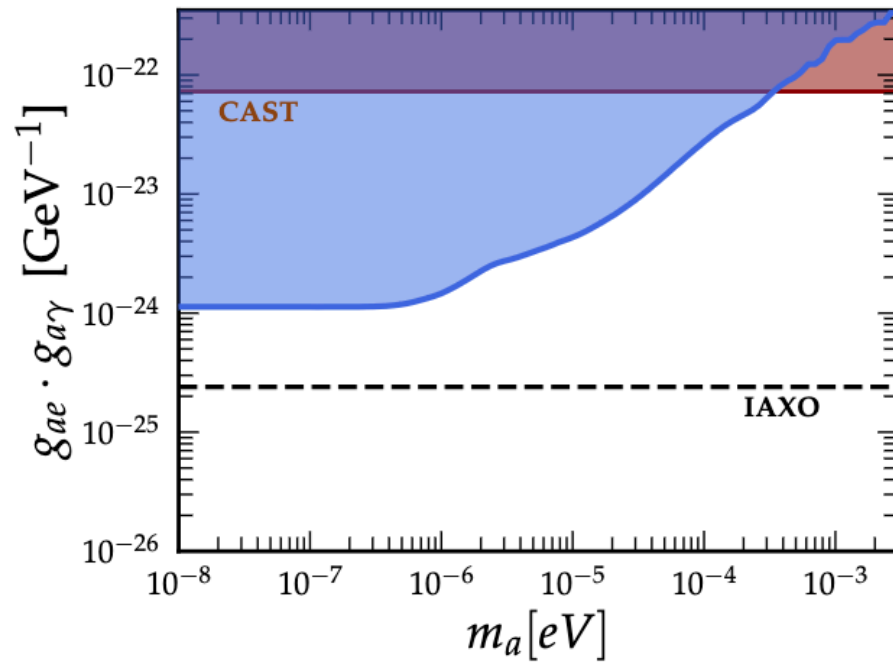
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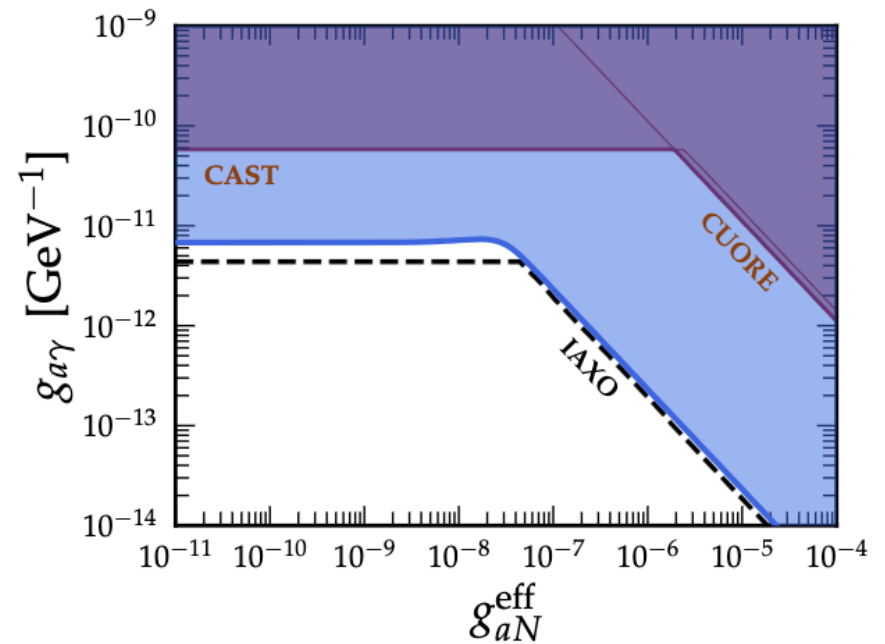
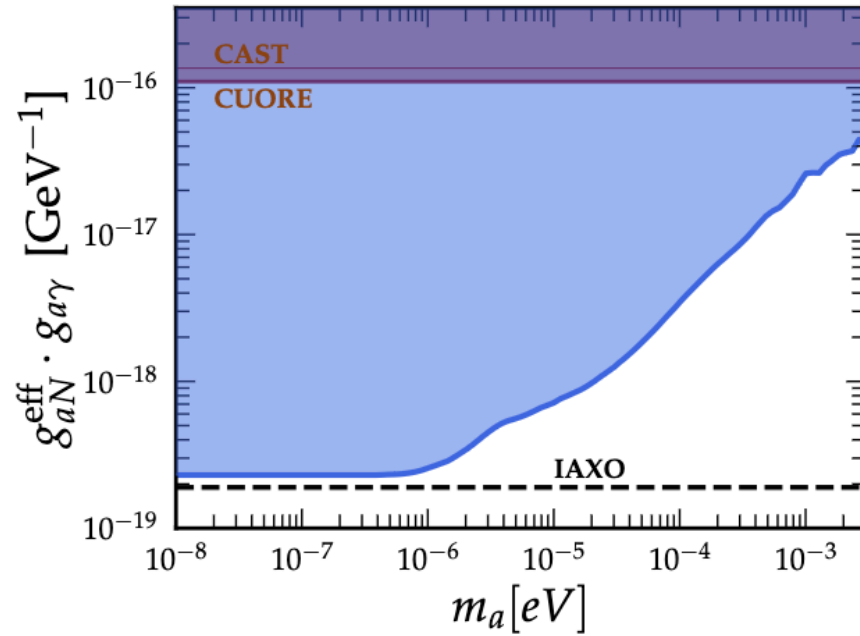
Axion line from nuclear transition
of ^{57}Fe at the excitation energy of
14.4 keV

NuSTAR limits



Zanzarella, MT+... , arXiv 2605.26265

NuSTAR limits



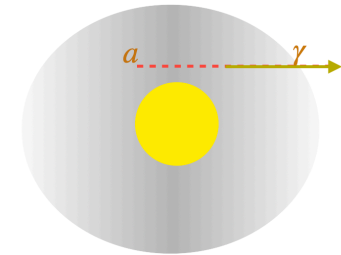
Zanzarella, MT+... , arXiv 2605.26265

Axions radio signals

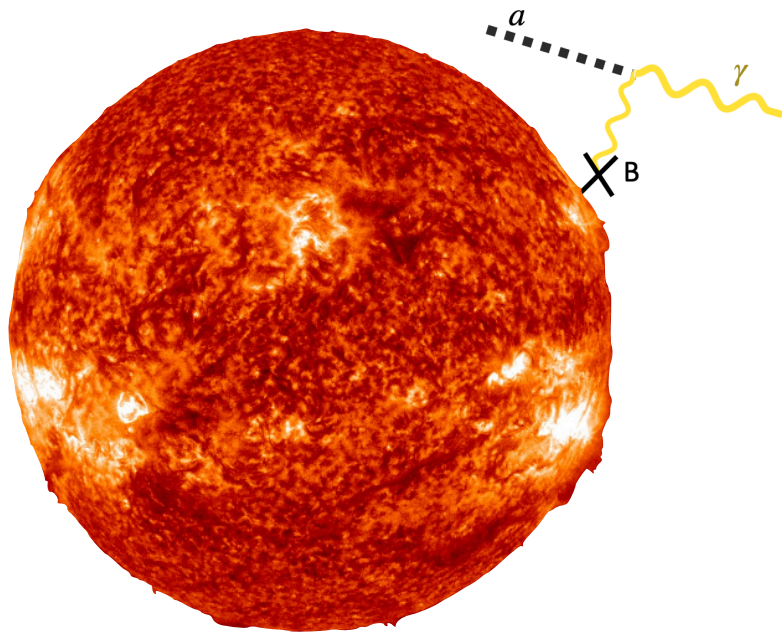
- ✓ ✱ Brief recap on axion and axion-like particles (ALPs)
- ✓ ✱ Axion flux from the Sun: searches with X-ray observations

✱ Axion dark matter around the Sun (and other stars): prospects for detection with radio telescopes

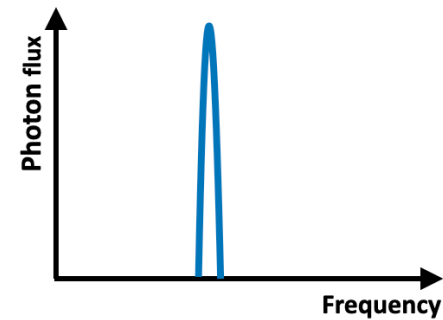
✱ Photon line from ALP dark matter decays



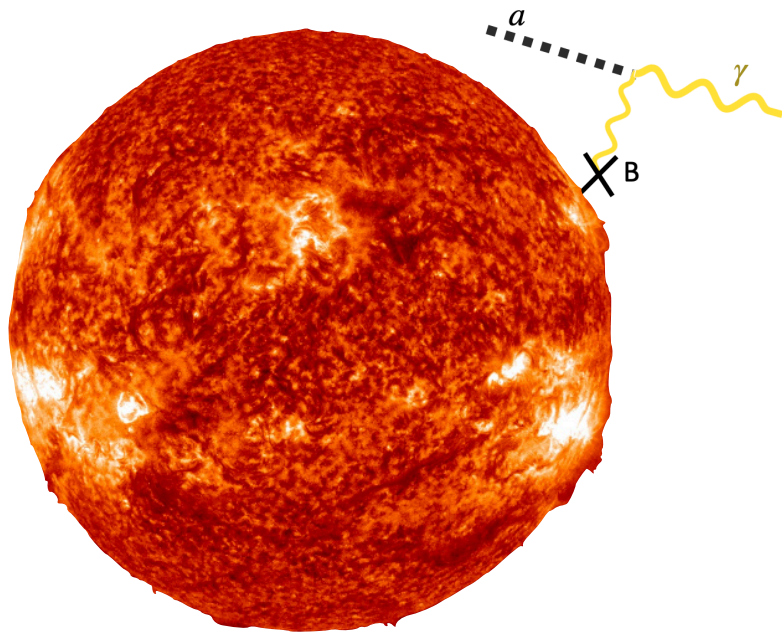
Axion DM conversion around the Sun



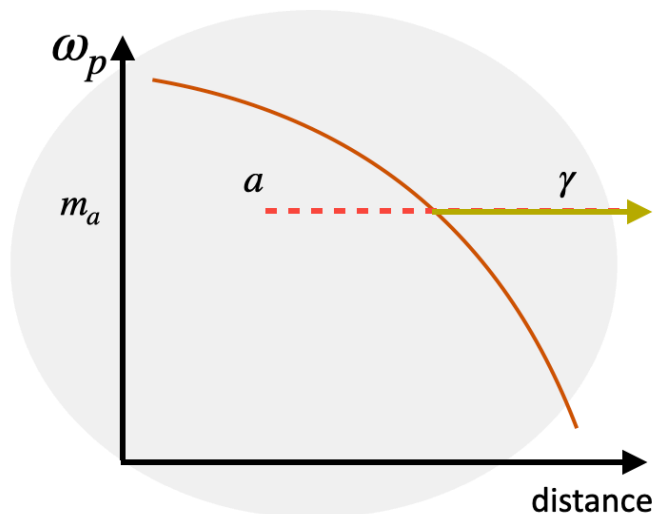
Conversion of axion dark matter in the solar atmosphere



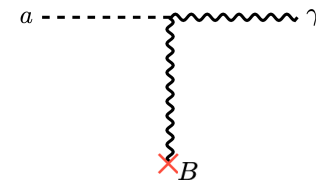
Axion DM conversion around the Sun



Conversion of axion dark matter in the solar atmosphere



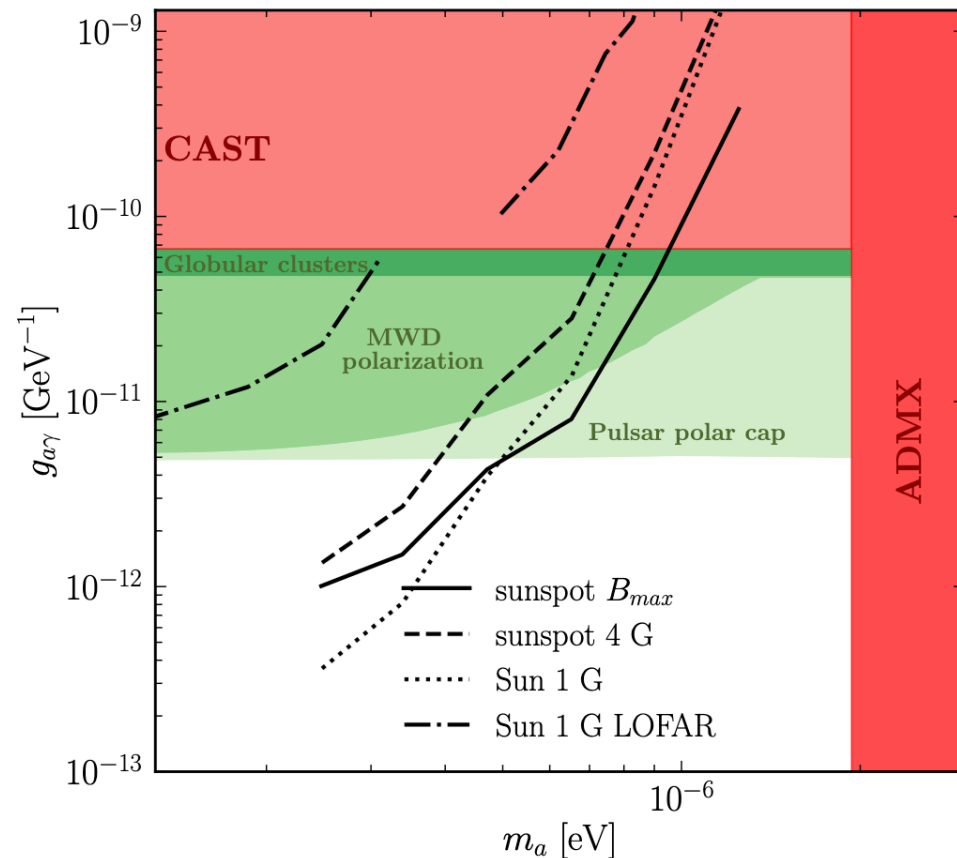
In a plasma: conversion probability can be **resonantly enhanced** when the axion mass matches the plasma frequency (the “effective” photon mass)



Prospects with future radio instruments

Prospects for the
Square Kilometer Array (**SKA**)

Todarello, Regis, MT +, Giannotti, Ruz, Vogel PLB 854(2024)138752



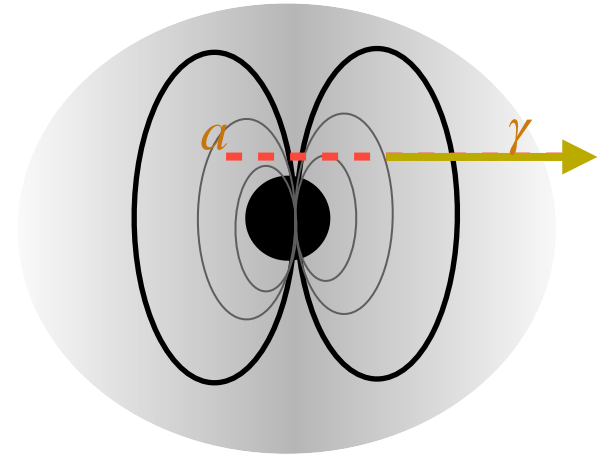
See also: [An et al. 2021, 2023](#)

Axion signals from neutron stars

Ambient axion DM conversion in the neutron star magnetosphere

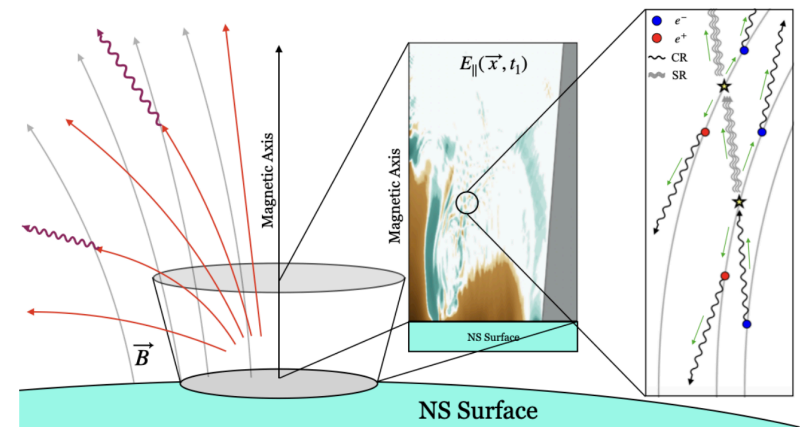
Large B-field + resonant enhanced conversion

Pshirkov, Popov (2009), Huang et al. (2018), Hook et al. (2018)



Axion clouds produced around pulsars from unscreened electric fields

Prabhu (2021), Noordhuis et al. (2023) +...

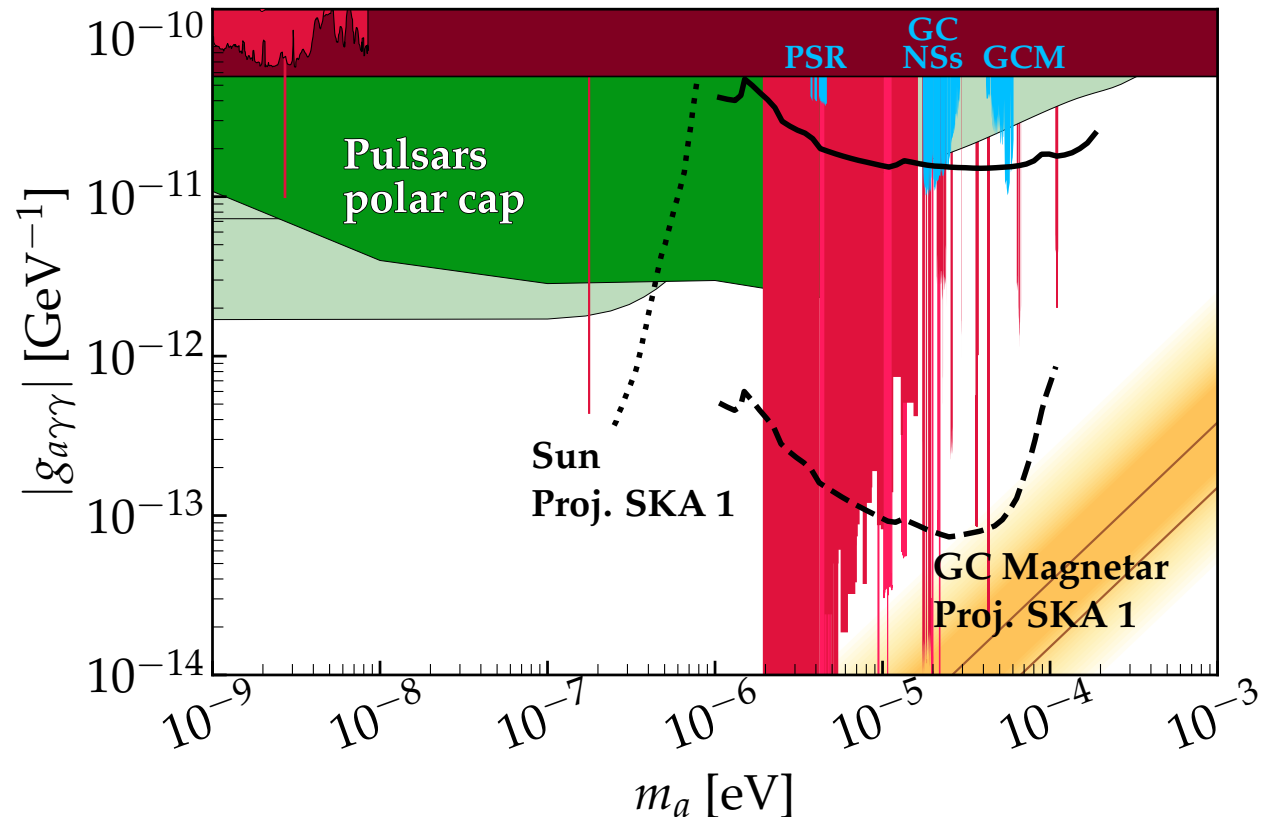


Noordhuis et al. (2023)

Axion signals from neutron stars

Bounds from radio observation
of isolated NS and the
NS population at the GC

Strong improvement in
sensitivity is expected with
SKA radio observations



Plot shows bounds and sensitivities from: Battye et al. (2022), Foster et al. (2022) Battye et al. (2023), Noordhuis et al. (2023), Roy et al. (2025). Impressive recent progress, especially in the signal modeling

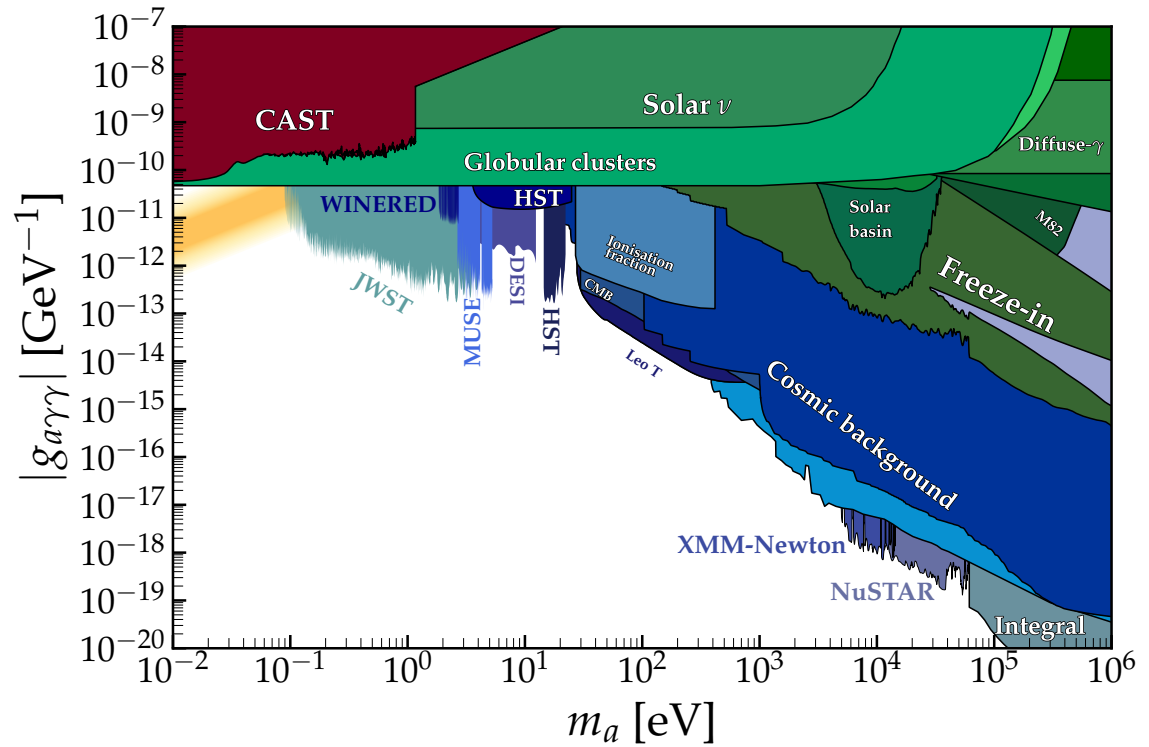
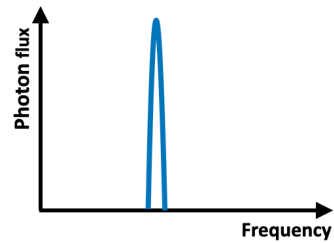
ALP decay signals

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ALP decays

ALPs DM decay into photons

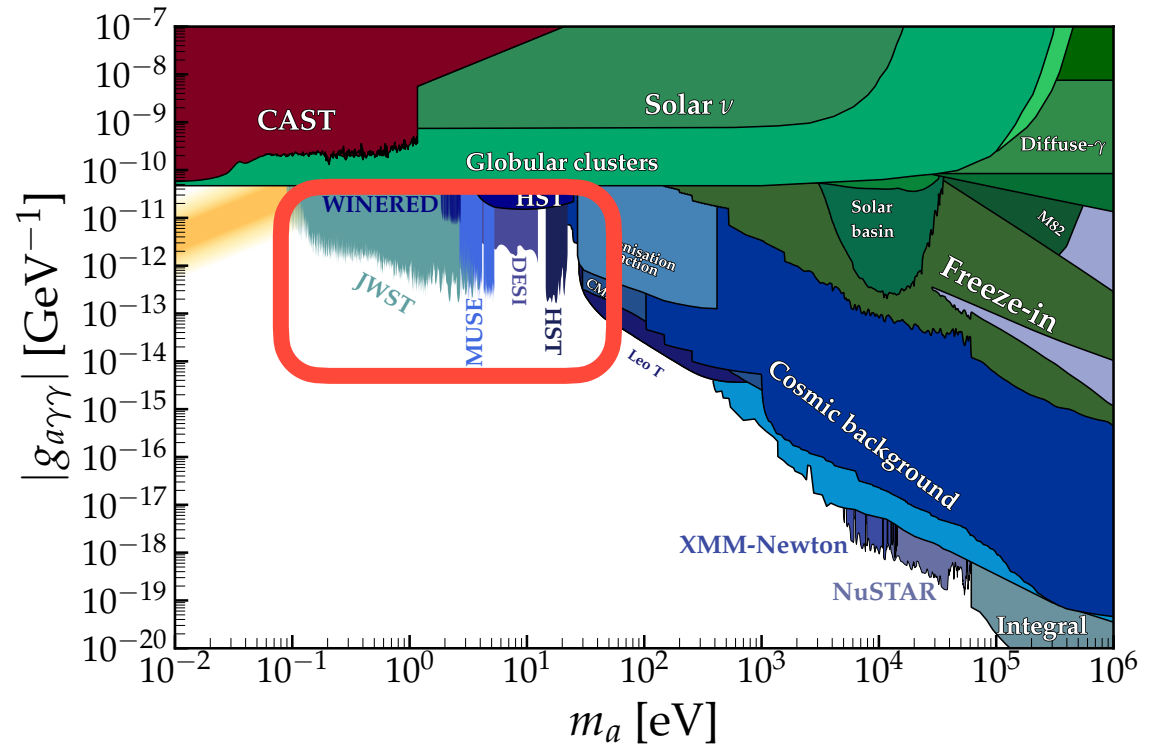
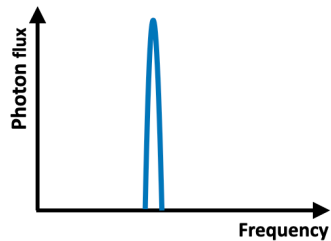
$$\Gamma(a \rightarrow \gamma\gamma) \sim g_{a\gamma\gamma}^2 m_a^3$$



Line from ALP decays

ALPs DM decay into photons

$$\Gamma(a \rightarrow \gamma\gamma) \sim g_{a\gamma\gamma}^2 m_a^3$$



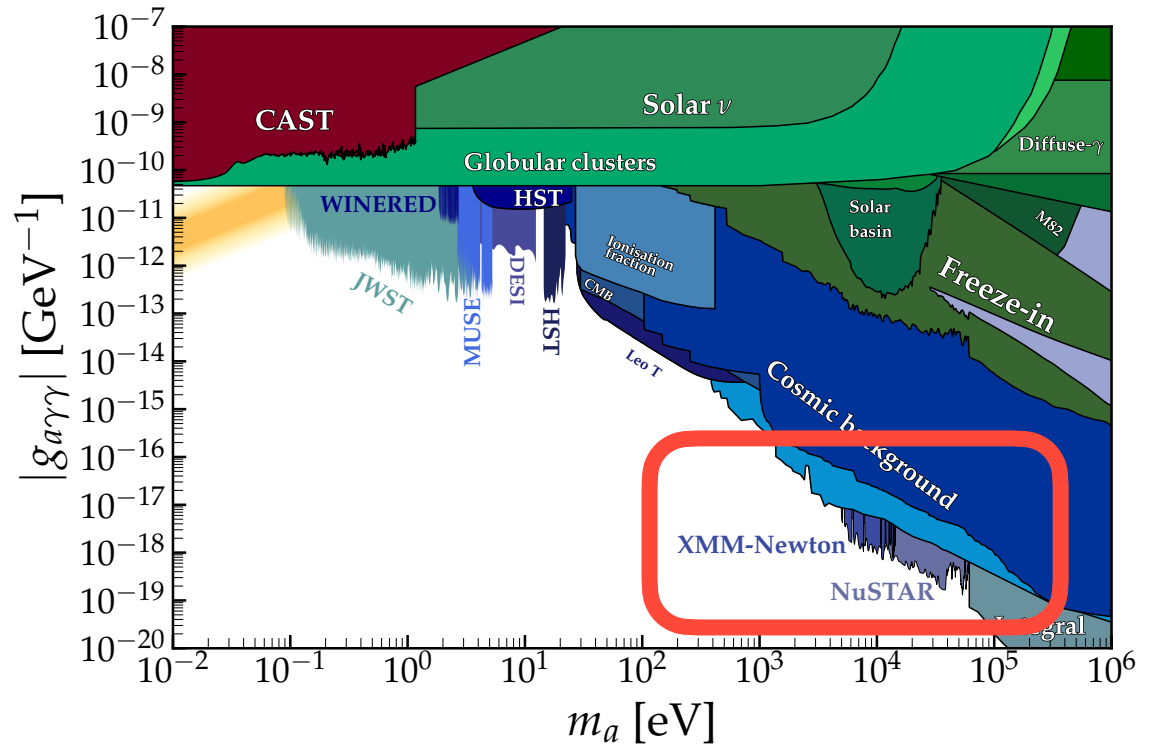
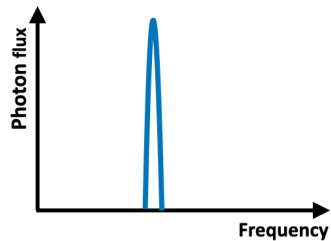
Leading limits from optical/NIR
spectroscopic surveys for $m_a \sim \mathcal{O}(\text{eV})$

Todarello, Regis, MT + (2024),
Regis, MT, Terol-Calvo (2025),
Pinetti (2025), Kumar Saha (2025), Todarello (2025), Yin, et al, 2024,+...

X-ray line from ALP decays

ALPs DM decay into photons

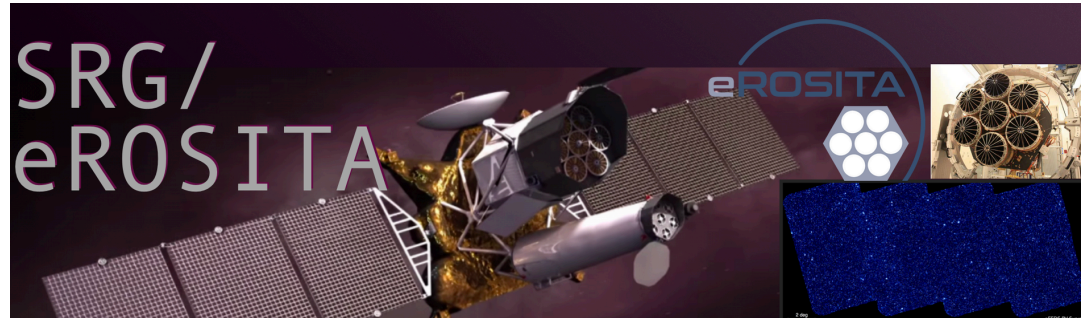
$$\Gamma(a \rightarrow \gamma\gamma) \sim g_{a\gamma\gamma}^2 m_a^3$$



Leading limits from X-ray telescopes for $m_a \sim \mathcal{O}(\text{keV})$

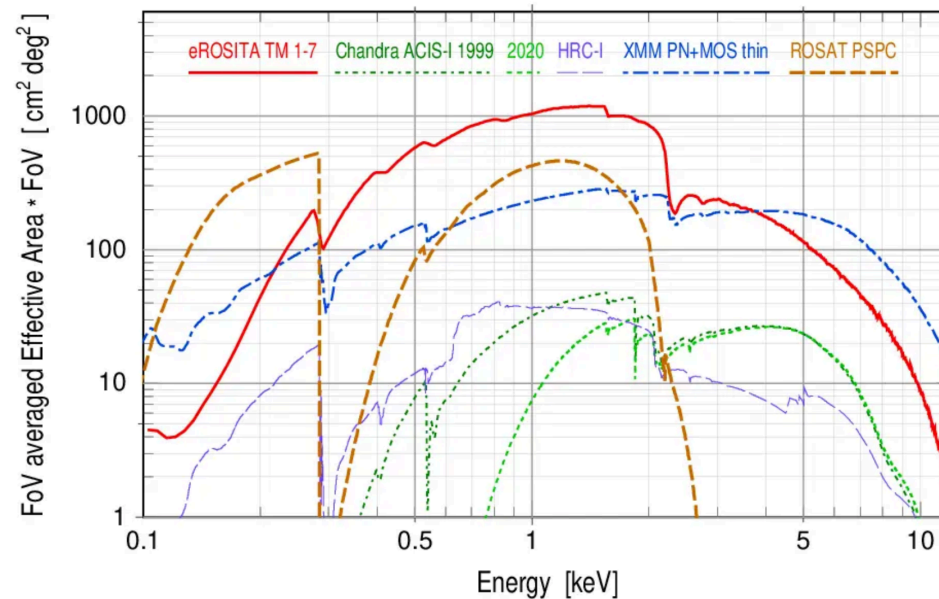
eROSITA

eROSITA



Covers the 0.2-10 keV energy band

Observation of one half of the sky publicly available



eROSITA limits

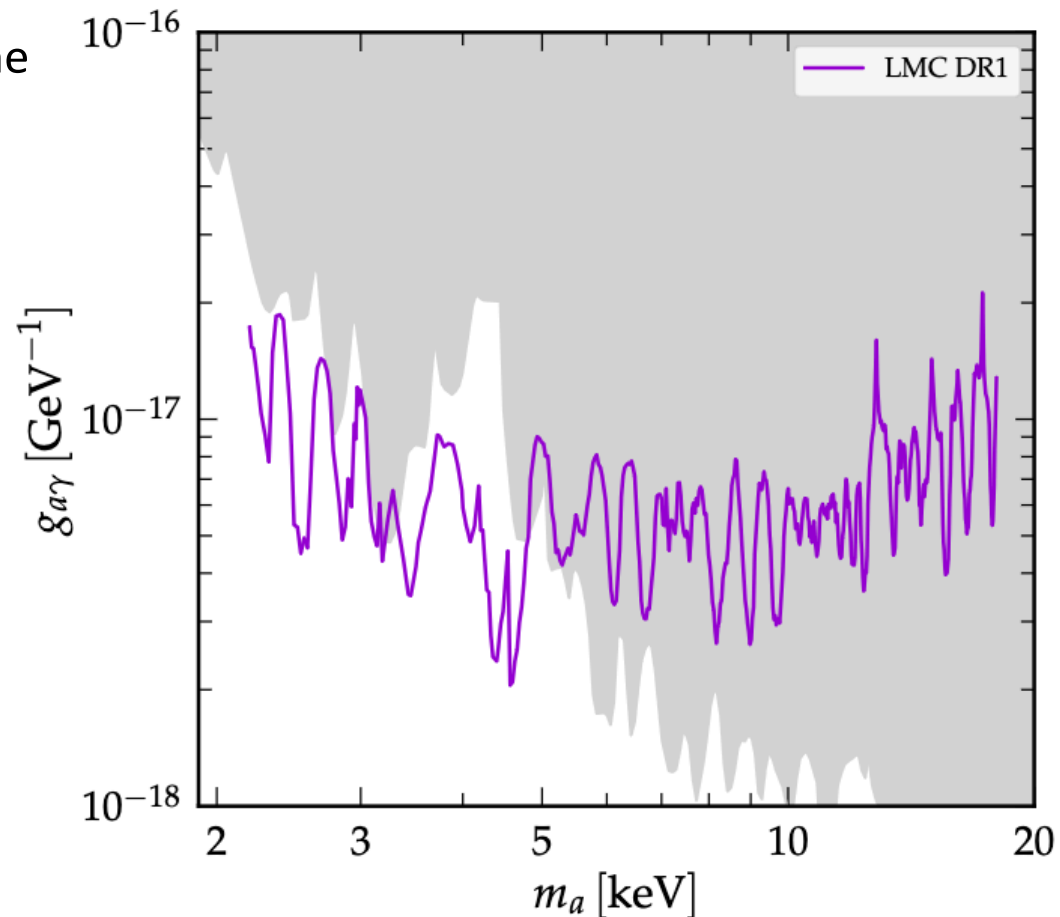
Terol Calvo, Regis, MT, JCAP 2026, 2603.19109

Limits from a search of an X-ray line with eROSITA DR1 observations of the Large Magellanic Cloud

See also [Fong, Ng, Liu \(2025\)](#) for a search with eROSITA eFEDS

Improvement expected from analysis of large sky regions and GC region

Cross-correlation with LSS for cosmological signals, [Caputo, Regis, MT, JCAP 2020](#)



Conclusions

Conversion of relativistic axions in the Sun: strong bounds from NuSTAR X-ray data

$\mathcal{O}(\mu eV)$ ALP dark matter conversion in the Sun: prospects for SKA radio observations

Limits on $\mathcal{O}(\text{keV})$ ALP decays from eROSITA X-ray observations



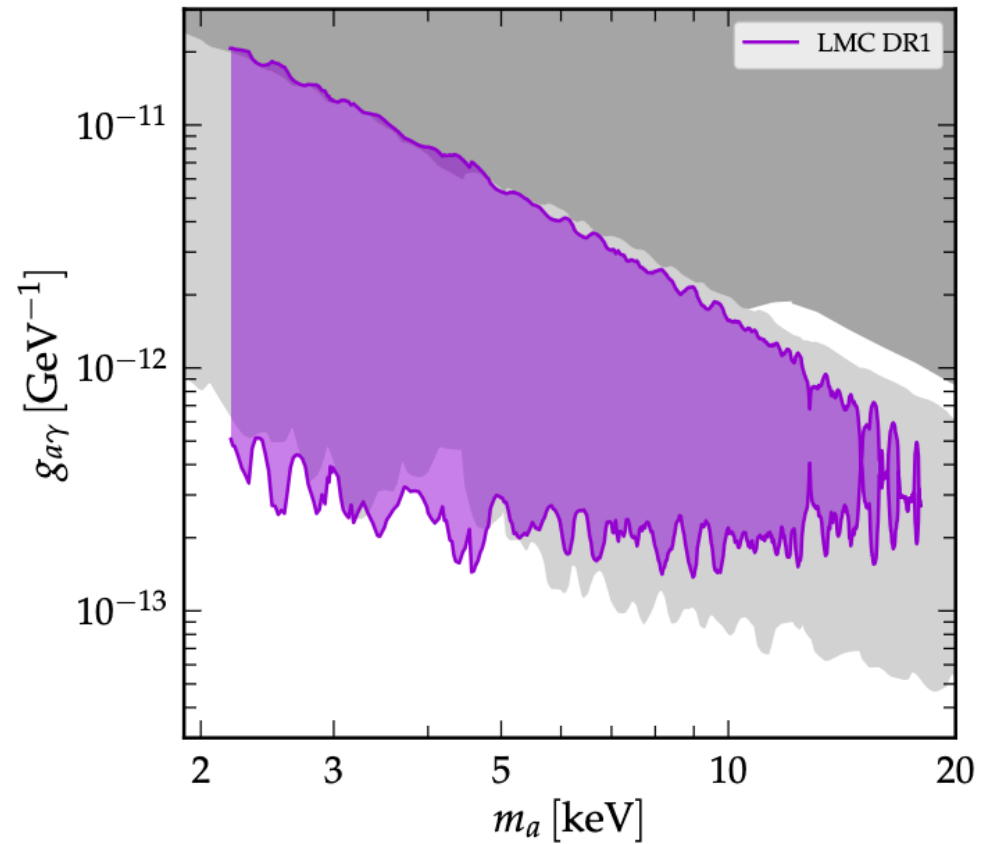
Other material



eROSITA limits

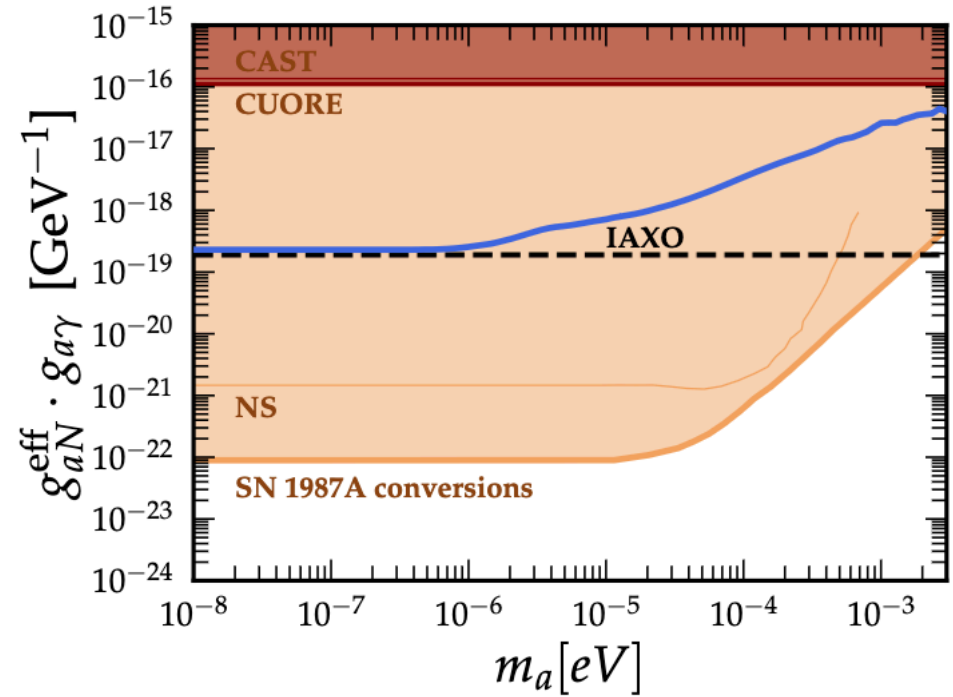
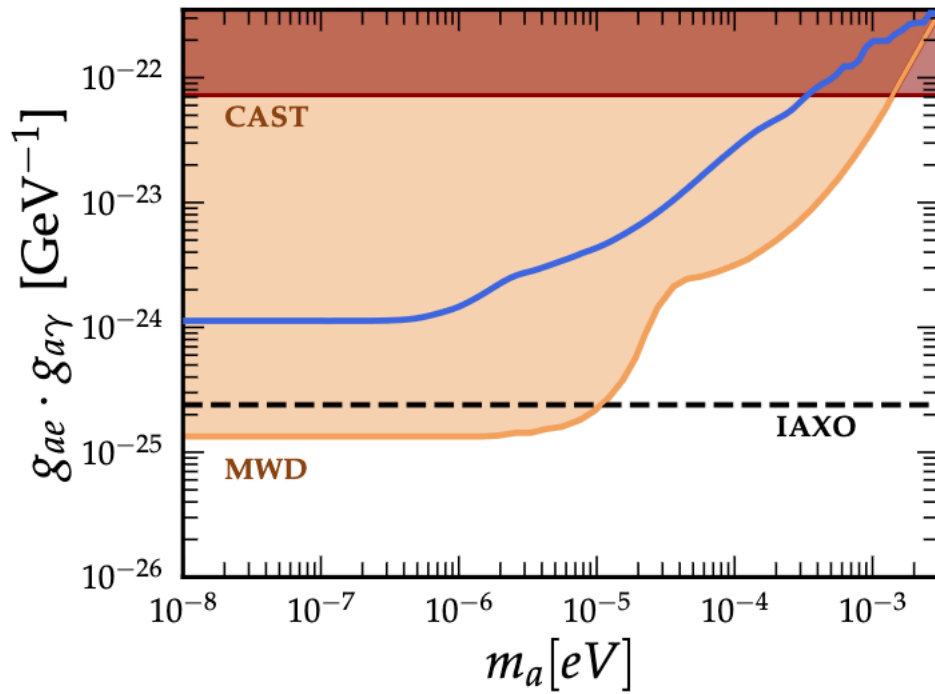
Limits in the context of the
irreducible axion background

Langhoff, Outmezguine, Rodd 2209.06216



Terol Calvo, Regis, MT 2603.19109

NuSTAR limits



Conversion probability

For relativistic axions the conversion probability is

Raffelt, Stodolsky (1998)

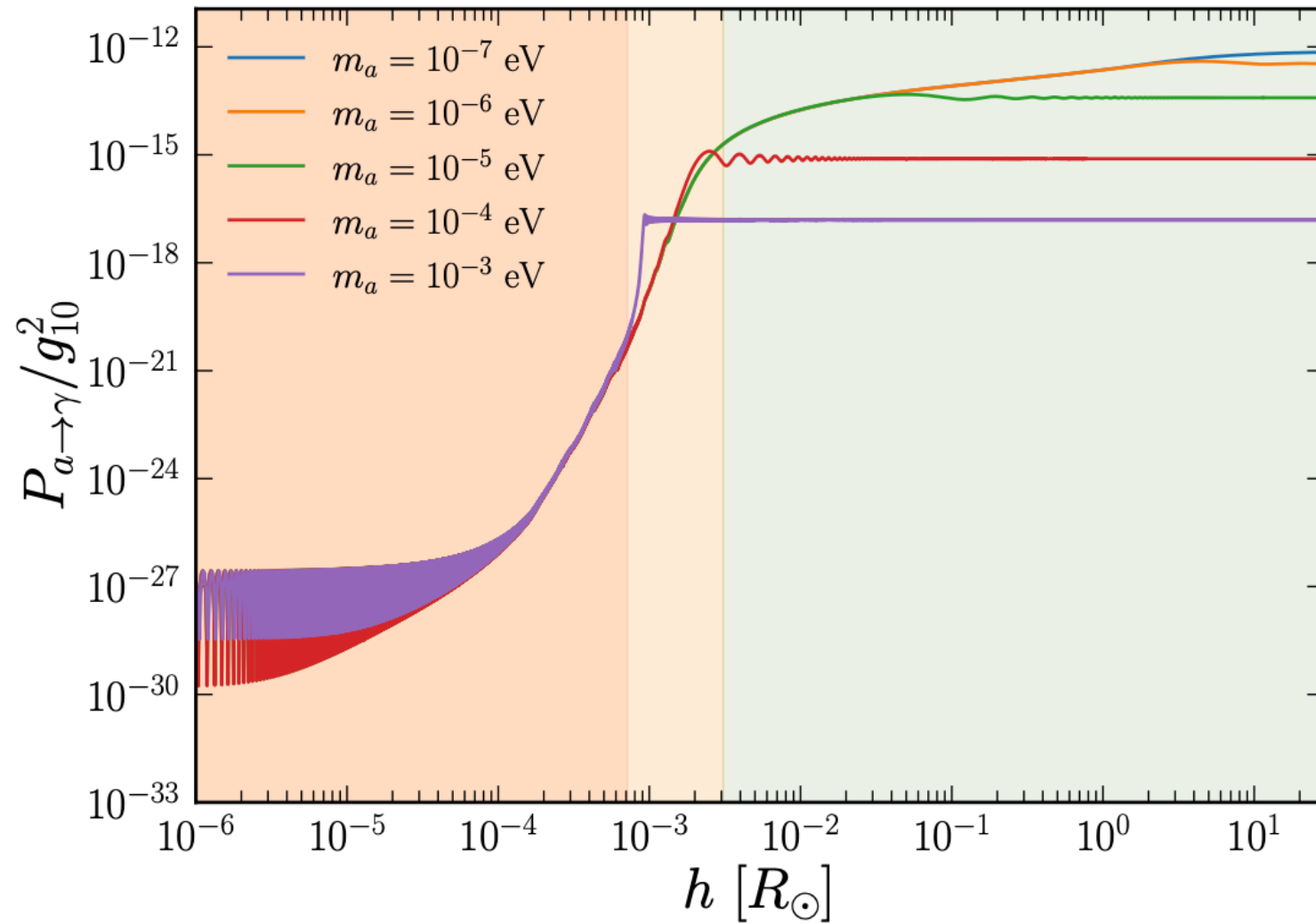
$$P_{a \rightarrow \gamma}(h) = \frac{1}{4} g^2 \left| \int_0^h dh' B_{\perp}(h') e^{i \int_0^{h'} dh'' q(h'')} e^{-\frac{1}{2} \int_{h'}^h dh'' \Gamma(h'')} \right|^2$$

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

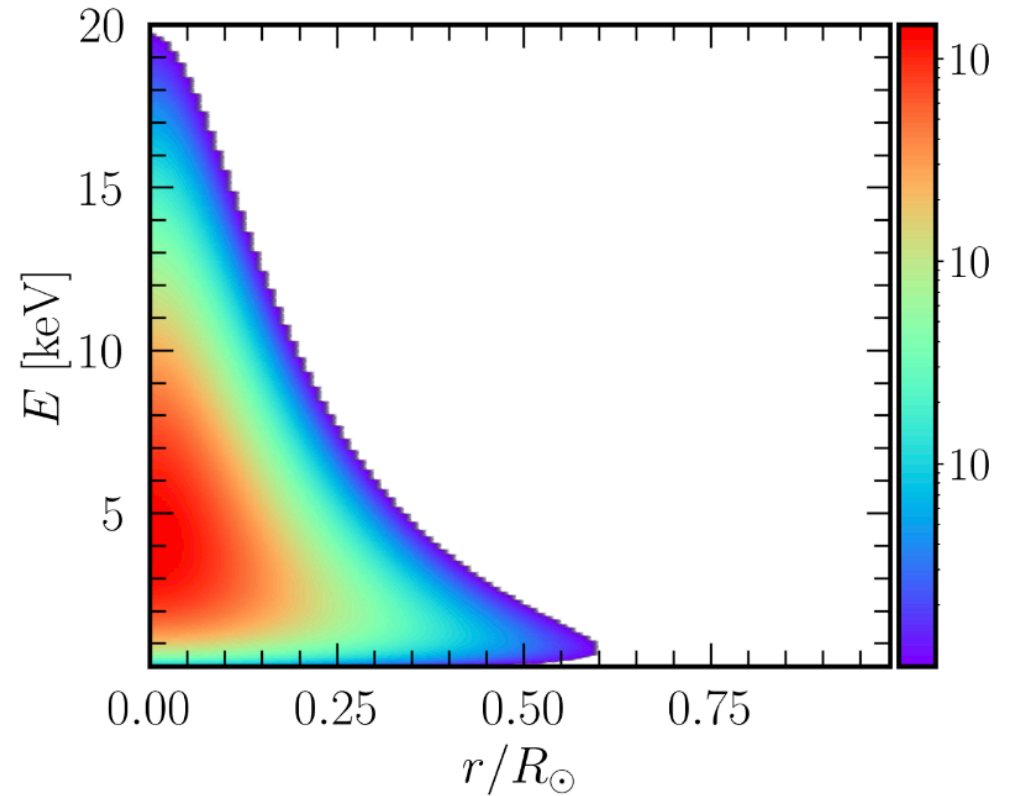
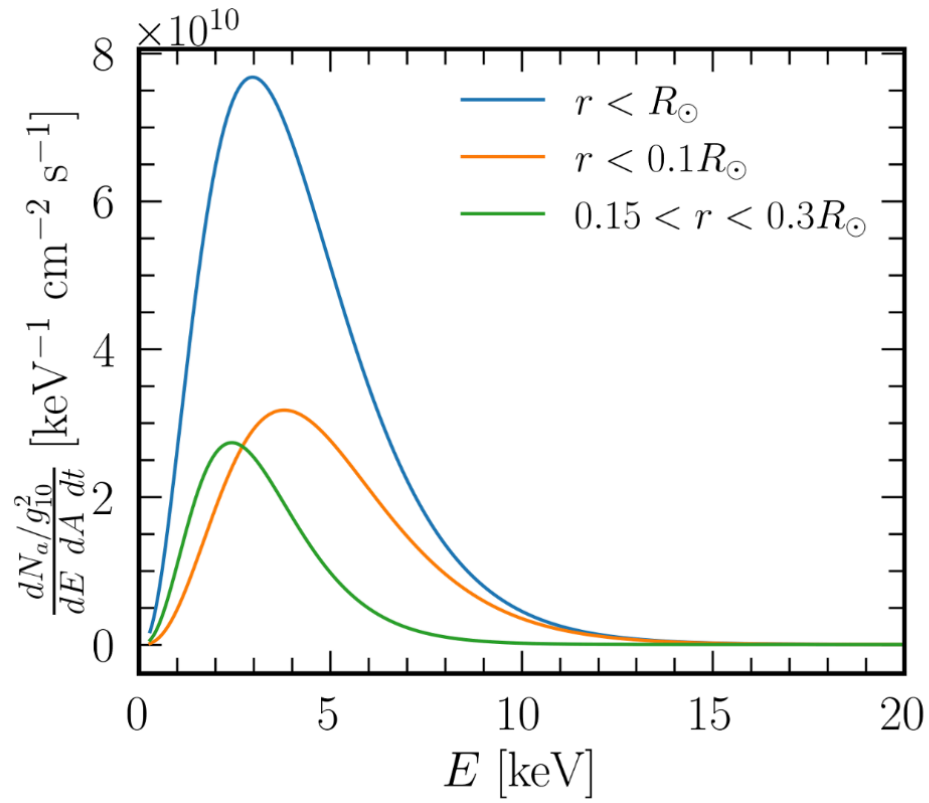
$$\Gamma = \sum_i n_i \sigma_i$$

Absorption coefficient
Element abundances and photon cross-sections from databases
Del Zanna et al. (2021), Berger et al. (2010)

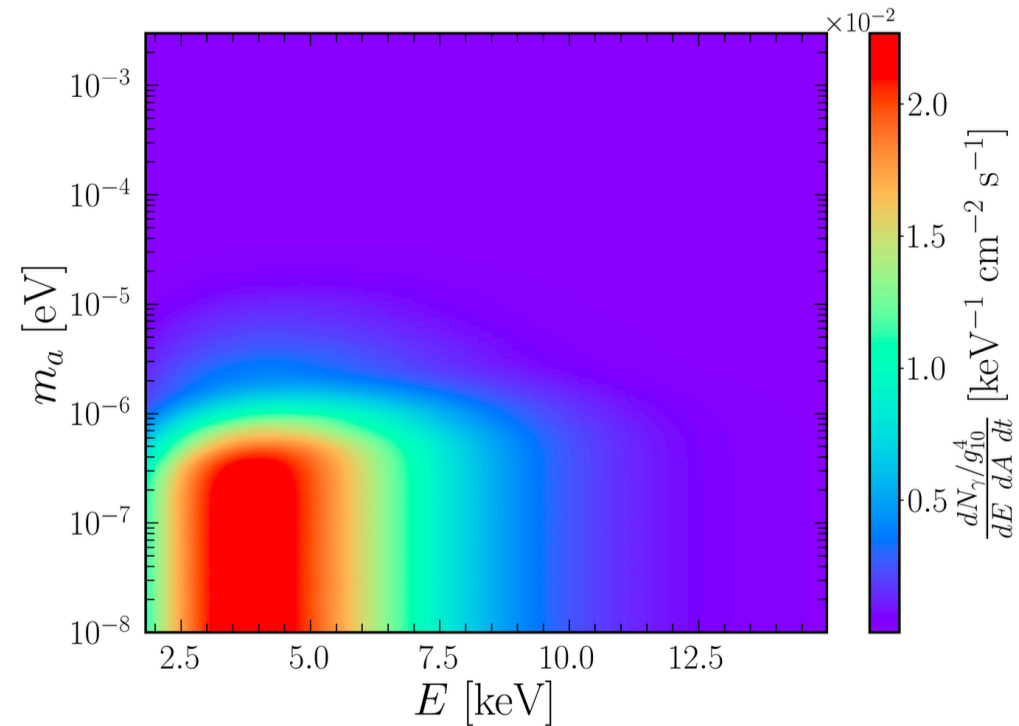
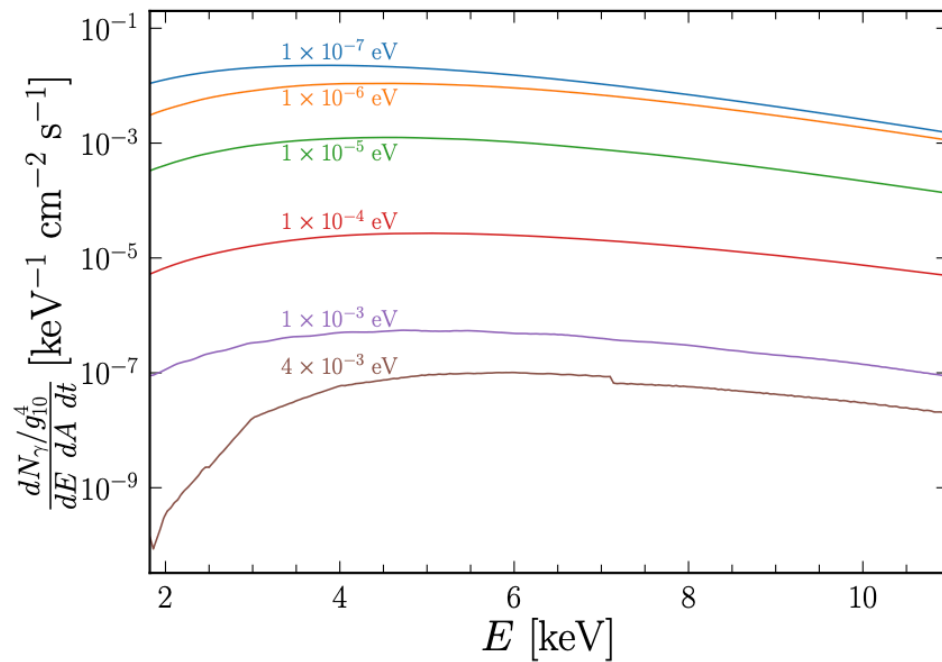
Conversion probability



Axion flux from the Sun

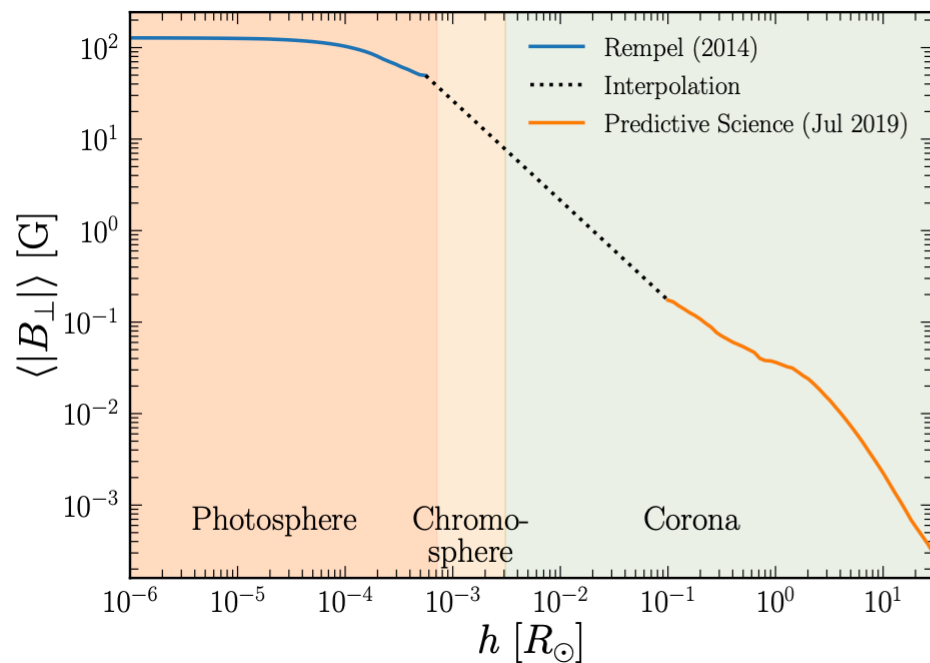


X-ray signal from axions

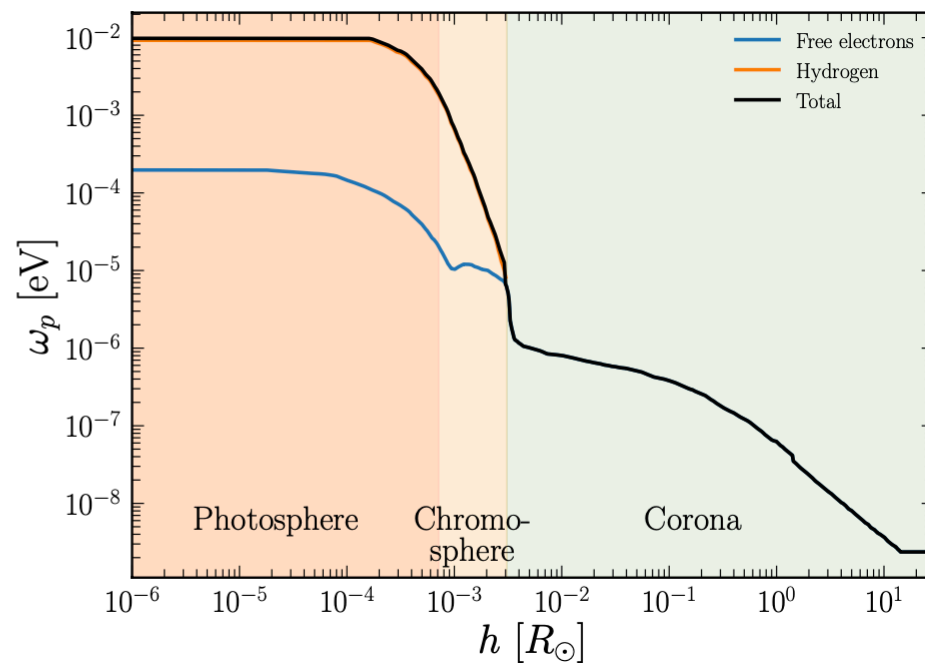


Model of the Quiet Sun

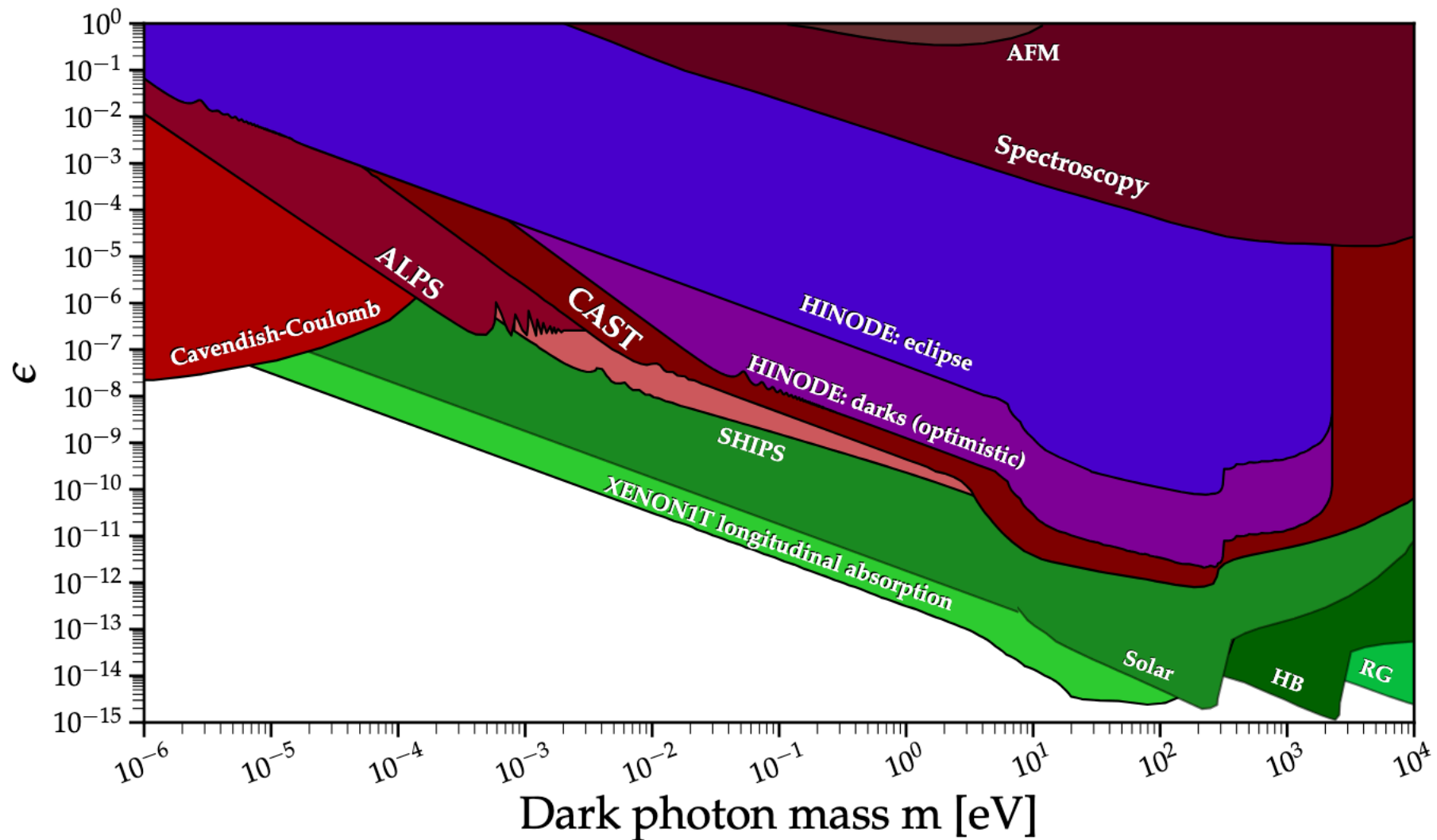
Magnetic field for the Quiet Sun



Plasma frequency $\omega_p^2 = e^2 n_e / m_e$



Hinode solar X-ray observations



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