The Solar Axion Quest

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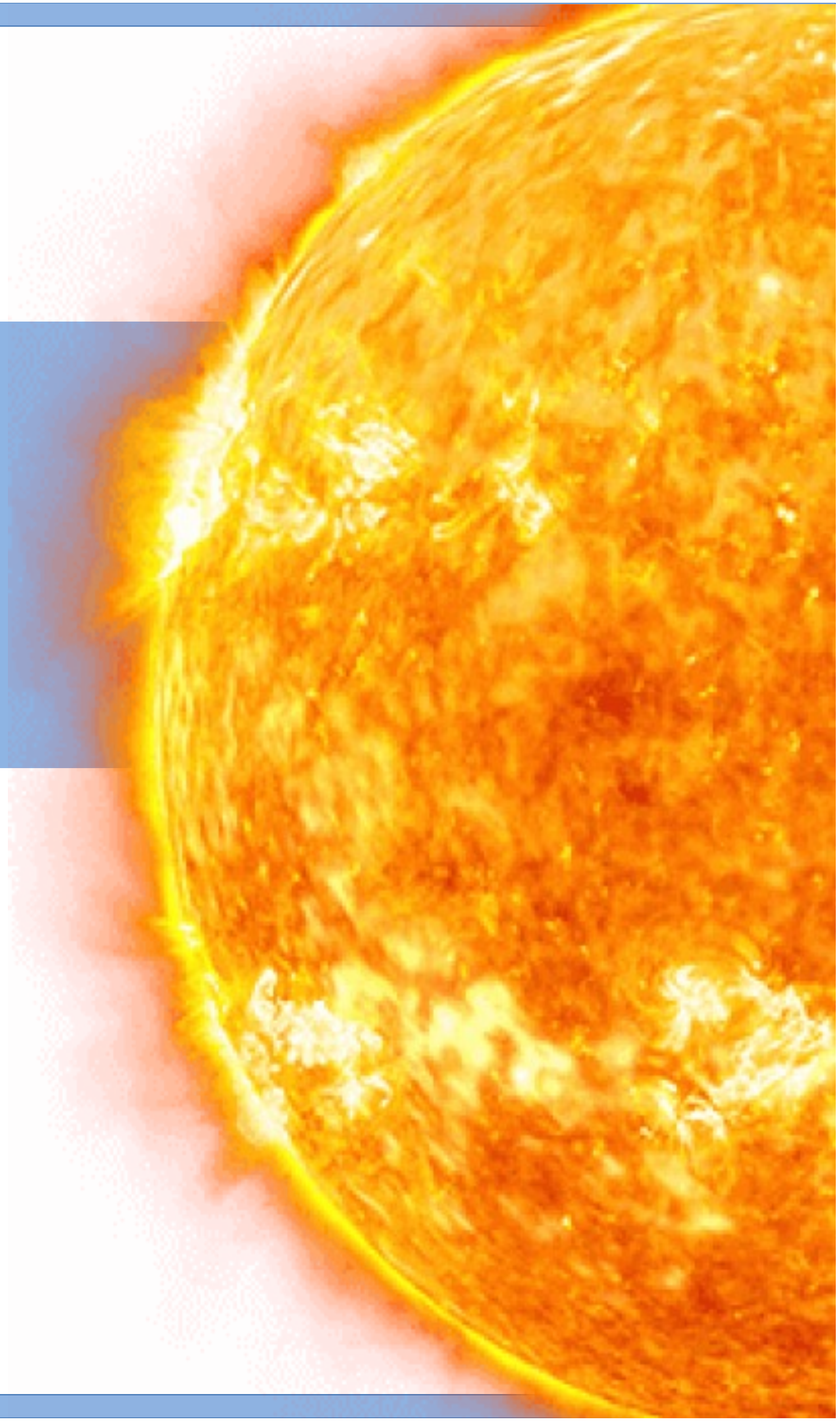
June 26, 2024

Dortmund, Germany



Outline

1. The Axion

2. Detection of Axions. Solar Axion Searches

IAXO and BabyIAXO

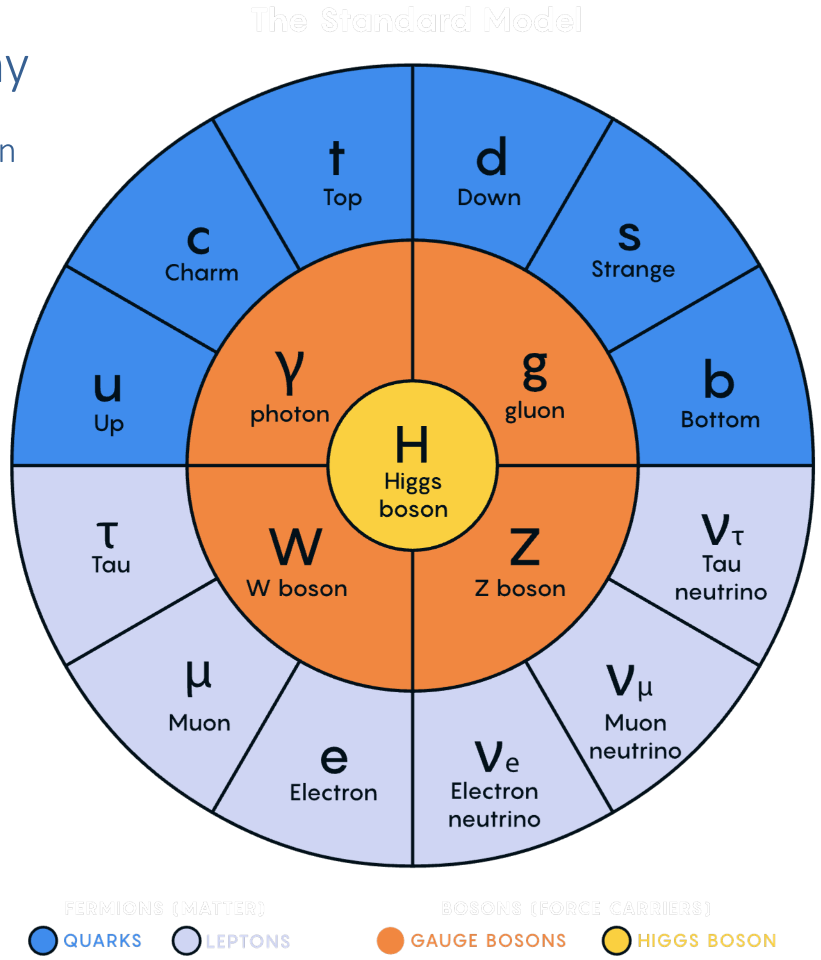
3. New Approaches to Solar Axion detection

Majorana, Radio-axions and NuSTAR

5. Conclusions

STANDARD MODEL (SM) OF PARTICLE PHYSICS

- ✓ Extremely successful theory describing many observations up to energies of ~1000 m_{proton}
- ✓ Merely an effective theory that could be considered the low energy limit of a Theory of Everything
- ✓ Expect observation of new phenomena at higher energies (e.g. LHC at CERN)
- ✓ SM cannot explain:
  - What is the nature of dark matter?
  - Why is the electric dipole moment of the neutron so small?

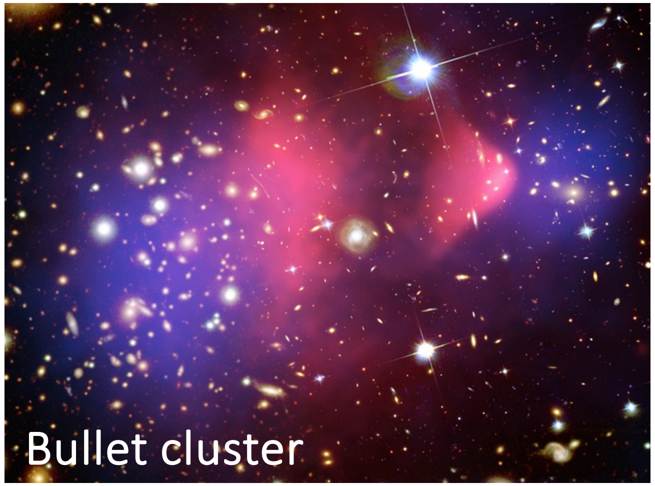


The Axion

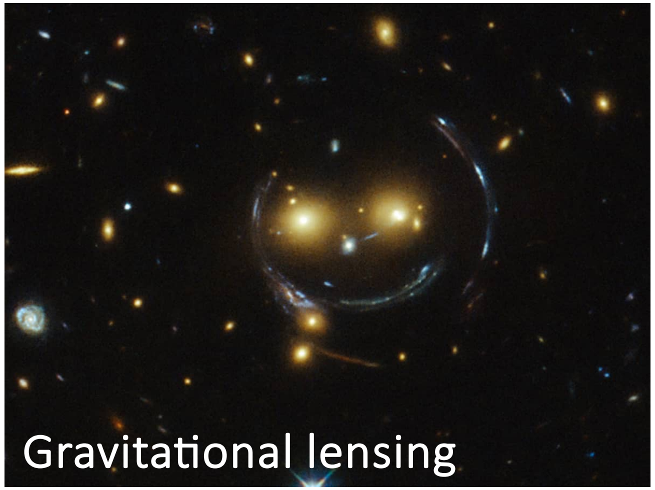
Motivation

EVIDENCE FOR DARK MATTER

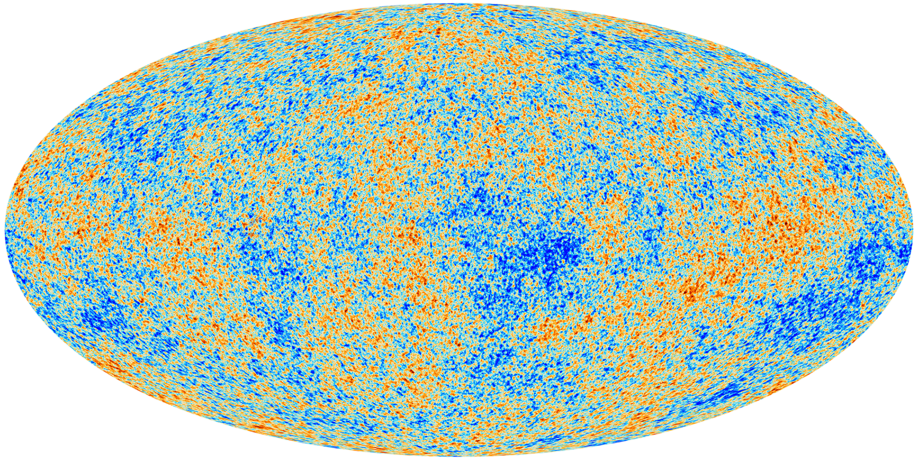
- ✓ Galaxy rotation curves



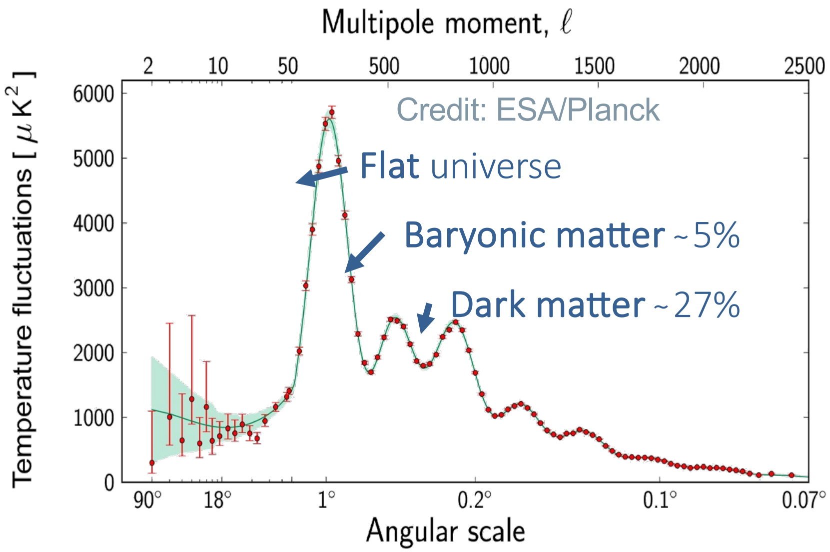
Bullet cluster



Gravitational lensing



PLANCK power spectrum of the CMB radiation temperature anisotropy



Credit: ESA/Planck

Flat universe

Baryonic matter ~5%

Dark matter ~27%

DARK MATTER EXISTS, BUT WHAT IS ITS NATURE?

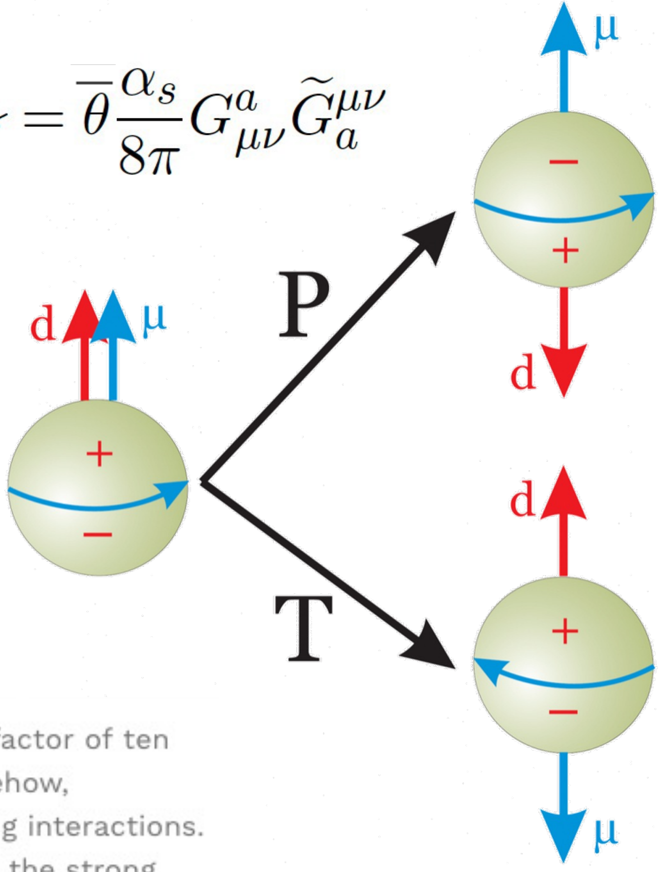
The 'Strong CP Problem' Is The Most Underrated Puzzle In All Of Physics (Forbes Magazine)

Way back in 1956, when writing about quantum physics, Murray Gell-Mann coined what is now known as the totalitarian principle: "Everything not forbidden is compulsory."

In the weak interactions, CP violation occurs at approximately the 1-in-1,000 level, and perhaps one would naively expect that it occurs in the strong interactions at approximately the same level. Yet we've looked for CP violation extensively and to no avail. If it does occur, it's suppressed by more than a factor of one billion (10^9), something so surprising that it would be unscientific to simply chalk this up to chance alone.

QCD Lagragian contains a CP violating term (with θ–parameter of QCD vacuum)

$$\mathcal{L}_{\cancel{CP}} = \overline{\theta}\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a$$



In the Standard Model, the neutron's electric dipole moment is predicted to be a factor of ten billion larger than our observational limits show. The only explanation is that somehow, something beyond the Standard Model is protecting this CP symmetry in the strong interactions. We can demonstrate a lot of things in science, but proving that CP is conserved in the strong interactions can never be done. However, solving the strong CP problem may be closer on the horizon than almost anyone realizes. [-] PUBLIC DOMAIN WORK FROM ANDREAS KNECHT

The Axion


Standard Model
AXION
HYPOTHETICAL ELEMENTARY PARTICLE
PROMISES TO "CLEAN UP" YOUR STRONG CP PROBLEM!

The Axion

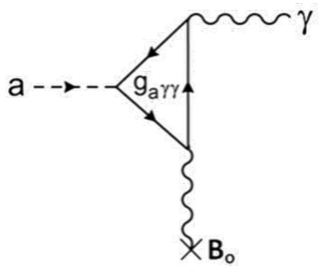
PECCEI QUINN MECHANISM AND AXIONS

Peccei,Quinn 1977; Weinberg 1978; Wilczek 1978

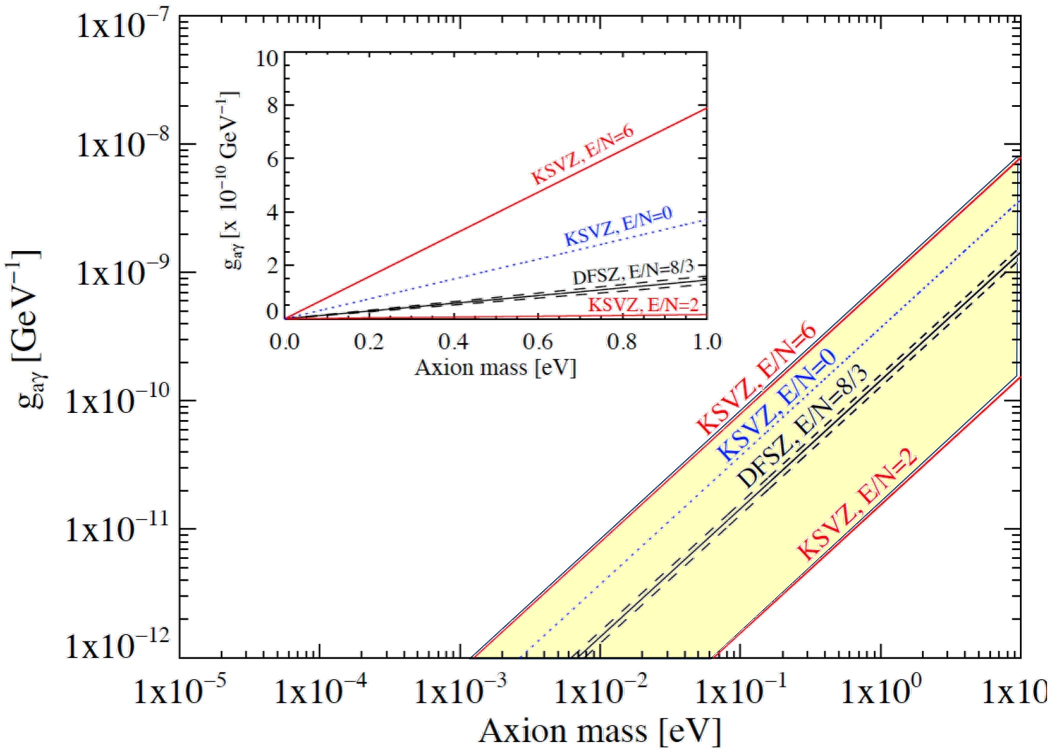
- ✓ Extension of the SM by a complex scalar field featuring a spontaneously broken global U(1) symmetry (Peccei-Quinn (PQ) symmetry)

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

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



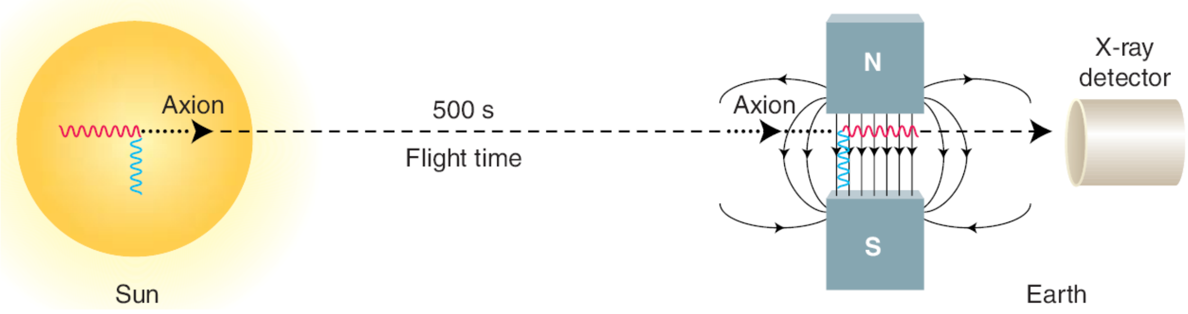
$$g_{a\gamma} \simeq \frac{\alpha}{2\pi f_\pi}\frac{m_a}{m_\pi}\frac{1+z}{\sqrt{z}}\left(\frac{E_Q}{N_Q} - \frac{2}{3}\frac{4+z}{1+z}\right)$$

$$z \equiv m_u/m_d$$

Traditional Solar Axion Searches **Helioscopes**

P. Sikivie 1983 PRL 51 1415

- First axion helioscope proposed by P. Sikivie
  - ✓ Conversion of axions into x-ray photons possible in strong laboratory magnetic field
  - ✓ Experiments NOT RELYING on axions being Dark Matter



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

- Idea refined by K. van Bibber et al.

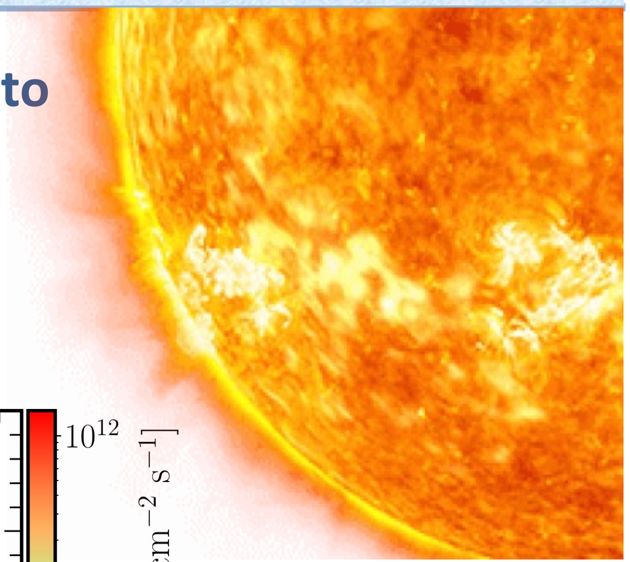
Van Bibber et al 1989 Phys. Rev. D 39 2089

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

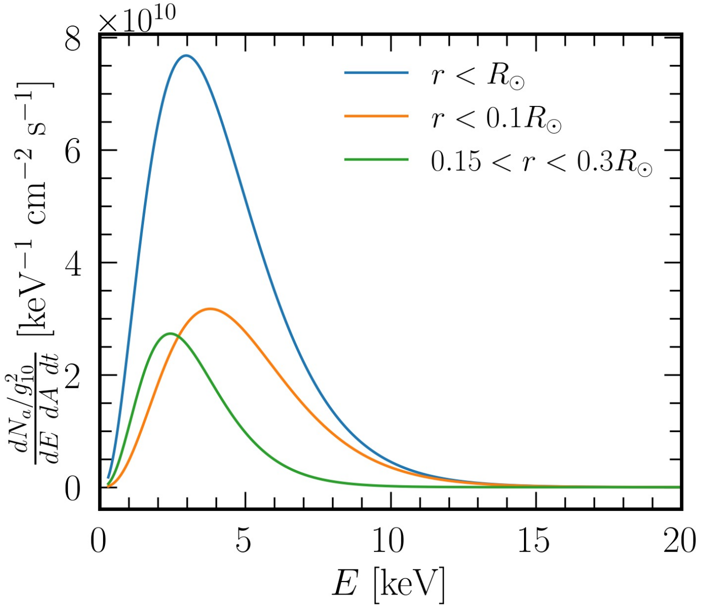
$$P_{a\to\gamma} = \left(\frac{Bg_{a\gamma\gamma}}{2}\right)^2 \frac{1}{q^2+\Gamma^2/4}\left[1+e^{-\Gamma L} - 2e^{-\Gamma L/2}\cos(qL)\right] \quad \text{with} \quad q = \left|\frac{m_\gamma^2 - m_a^2}{2E_a}\right|$$ **GAS**

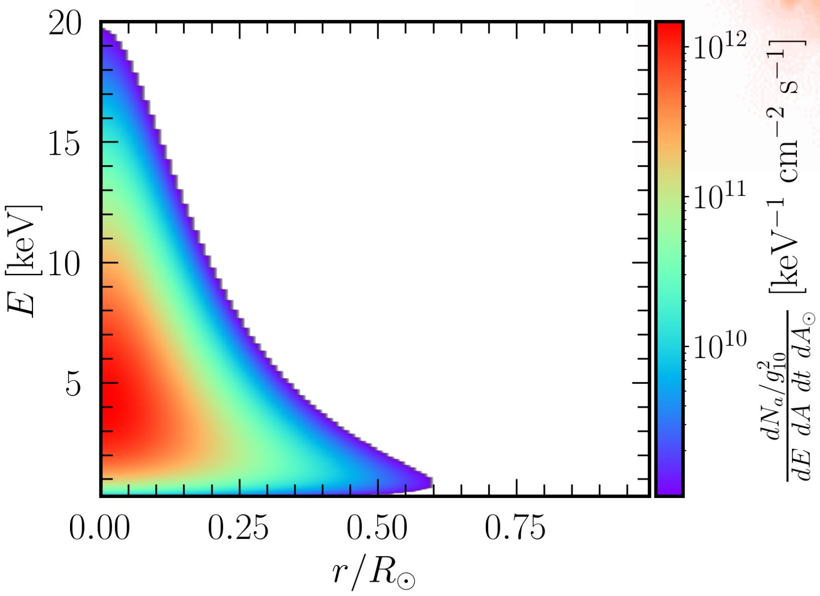
Solar Axion Flux

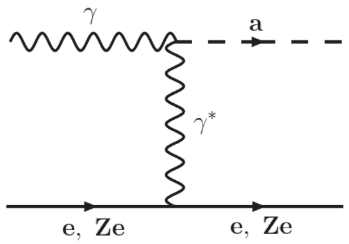
Blackbody photons (keV) in solar core can be converted into axions in the presence of strong electro magnetic fields in the plasma → Primakoff Effect.



$$T_{Core} \sim 1.3 keV$$







Hadronic axions (if the axion couples predominantly to photons ($g_{a\gamma}$))

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

CERN AXION SOLAR TELESCOPE (CAST)

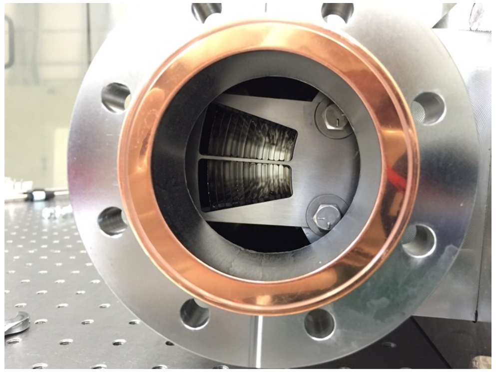
- Most powerful axion helioscope to date
- Superconducting prototype LHC dipole magnet
- X-ray focusing devices and ultralow-background detectors
- Use of buffer gas to extend sensitivity to higher masses (axion band)

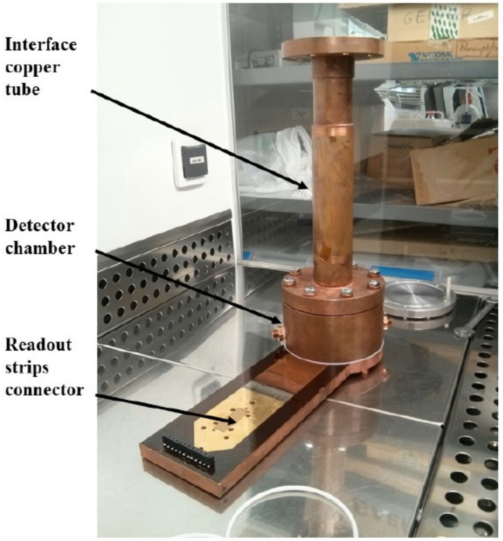
CAST Collaboration 2017 Nature Phys. 13 584-590
Arik et al 2015 PRD 92 021101
Arik et al 2014 PRL 112 091302
Barth et al 2013 JCAP 1305 010
Arik et al2011 PRL107 261302
Zioutas et al 2009 JCAP 0902 008
Zioutas et al 2007 JCAP 0704 010

State-of-the-art Helioscopes

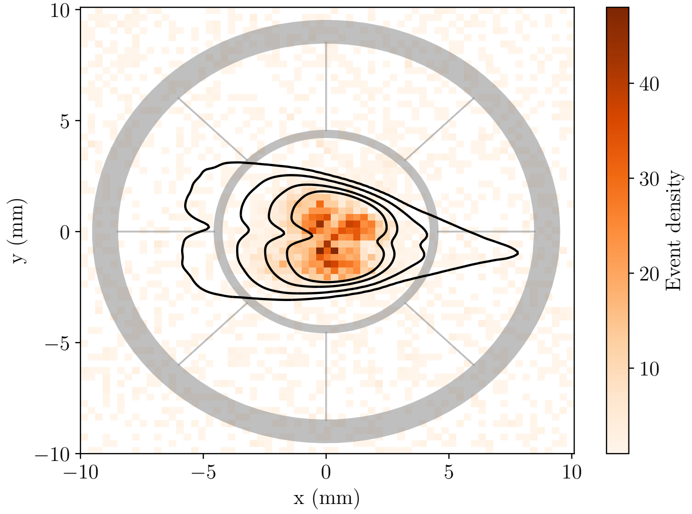
Breaking News from CAST

- Take advantage of first tailor-made x-ray telescope for axions
- Push MMs detector efficiency and background using Xe-mixtures
- Tracking statistics 314.6 hours
- Lowest CAST background. Expected @8 counts per year

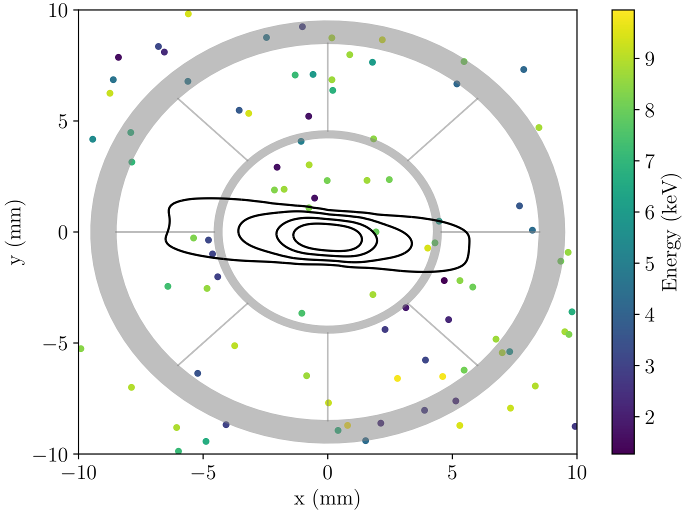




$Xe_{48.85\%} + Ne_{48.85\%} + Isobutene_{2.3\%}$



X-ray finger calibration

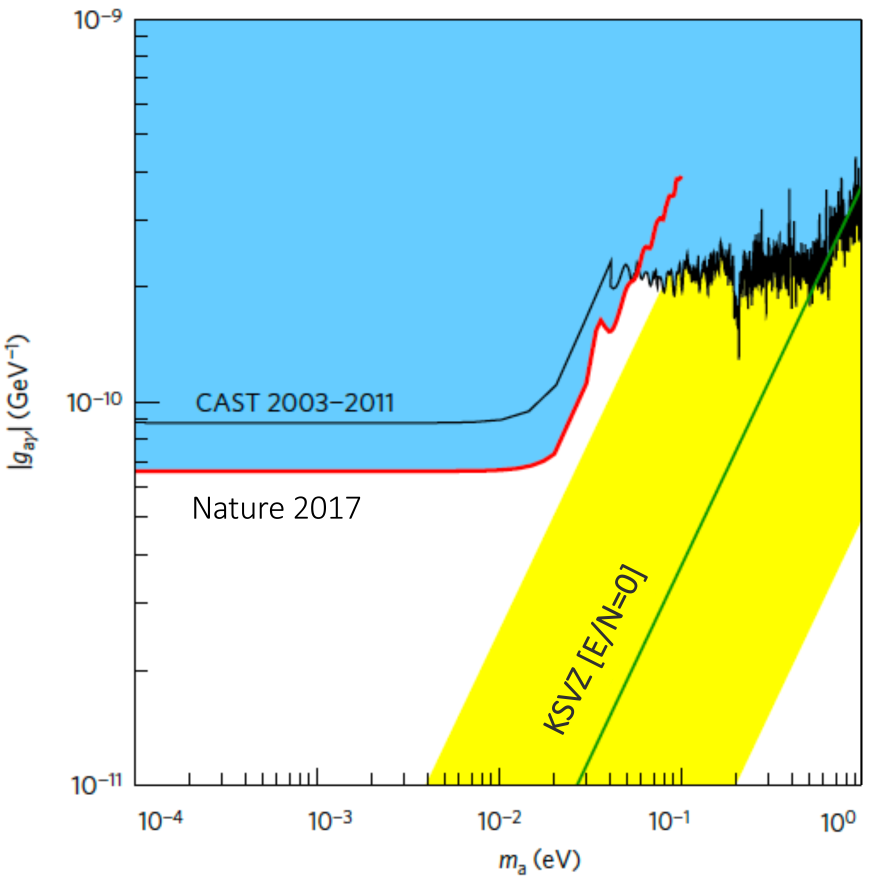


Data

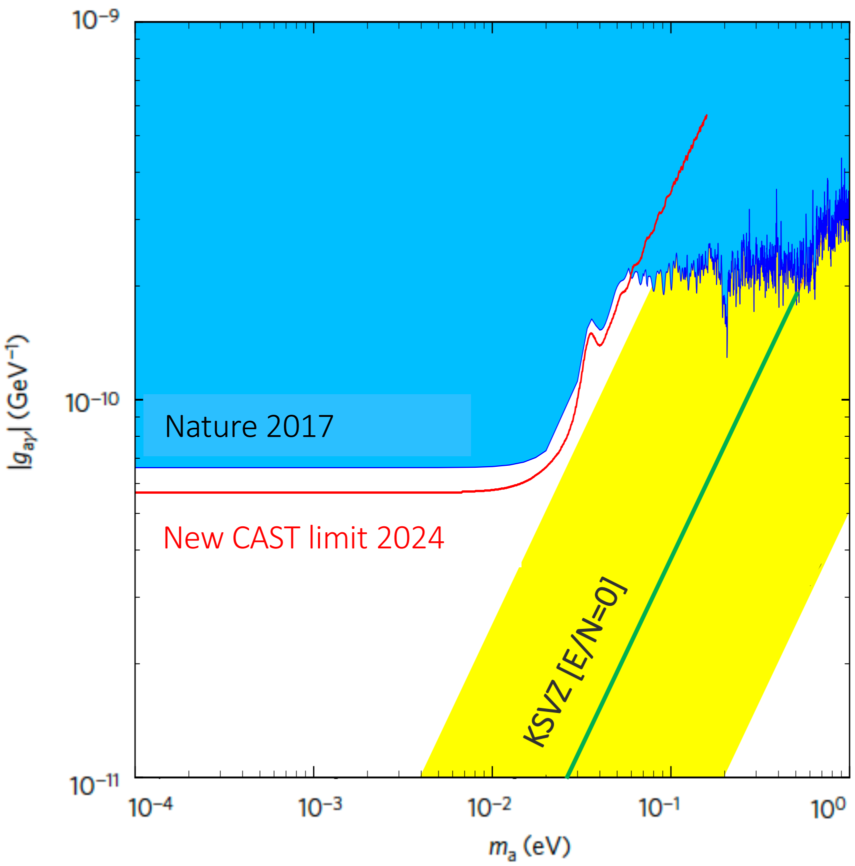
22 years after its first data taking!

State-of-the-art

New axion-photon coupling exclusion limits!



CAST Collaboration
Nature Phys. 13 584 (2017)
g$_{a\gamma}$ < 6.6x10^{-11} GeV^{-1}



CAST Collaboration
PRL submitted (June, 2024)
g$_{a\gamma}$ < 5.7x10^{-11} GeV^{-1}

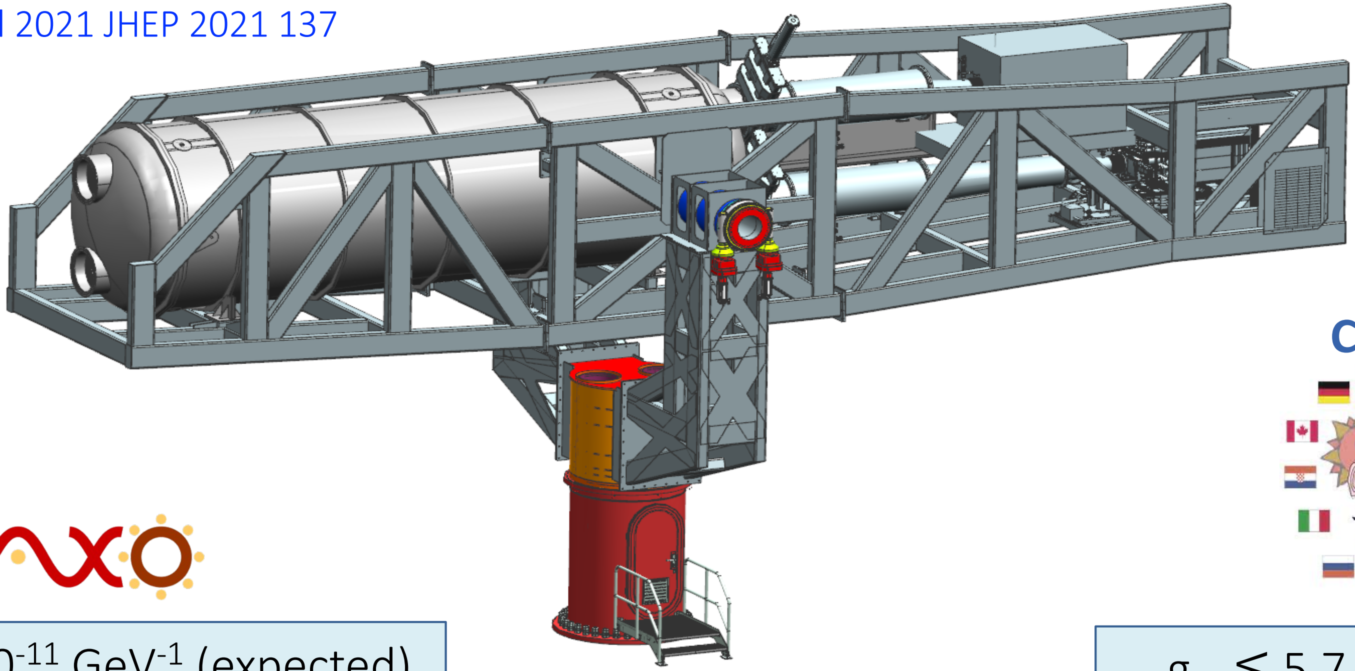
Next-Gen Experiments

BabyIAXO

BABYIAXO =INTERMEDIATE EXPERIMENTAL STAGE BEFORE IAXO

- Technological prototype of IAXO with only two magnet bores (10 m, Ø 70 cm) to be installed at DESY
- Relevant physical outcome (~10✕ CAST B^2L^2A)
- Magnet will be upscalable version for IAXO
- X-ray optics/detectors close to final IAXO configuration

Abeln et al 2021 JHEP 2021 137



Baby IAXO

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

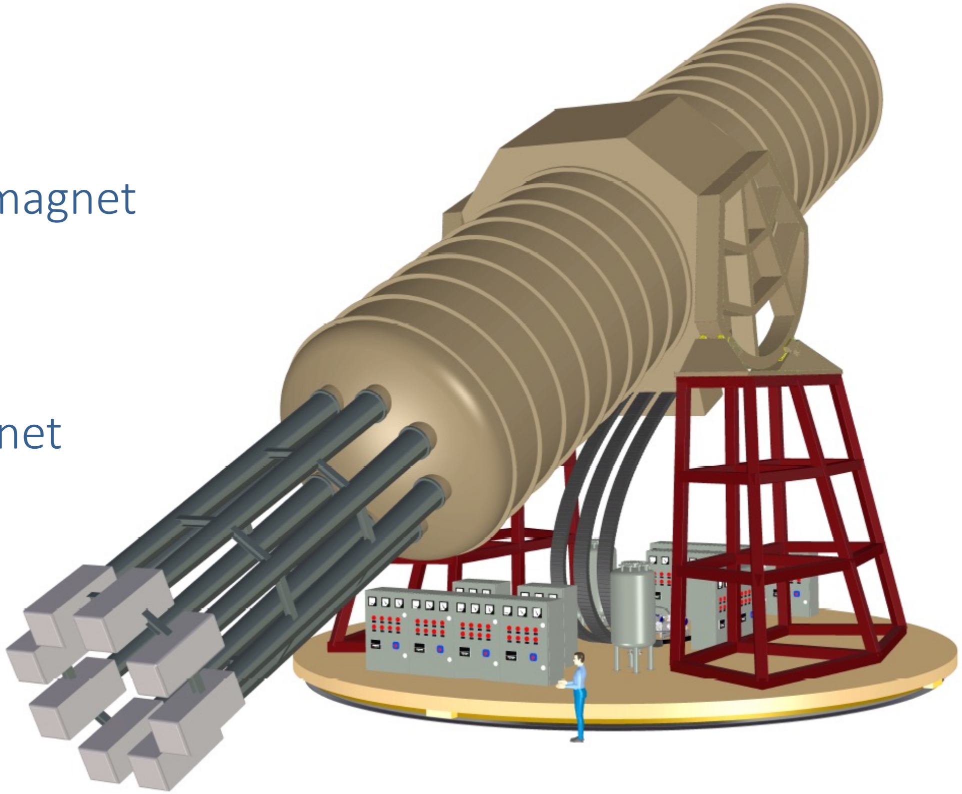
CAST

$g_{a\gamma} \lesssim 5.7 \times 10^{-11}\ \mathrm{GeV}^{-1}$

Next-Gen Experiments

INTERNATIONAL AXION OBSERVATORY (IAXO)

- ✓ Next generation helioscope for solar axions
- ✓ Mature and state-of-the-art technology
- ✓ Purpose-built large-scale superconducting magnet
    - Toroidal geometry
    - 25 meters long, up to 5.4 T.
    - >300 times larger FoM than CAST magnet
    - 8 conversion bores of 60 cm Ø
- ✓ 8 detection lines
    - X-ray optics with 0.2 cm² focal spot
    - Ultra-low bgrd detectors
- ✓ 50% of Sun-tracking time.



iaxo

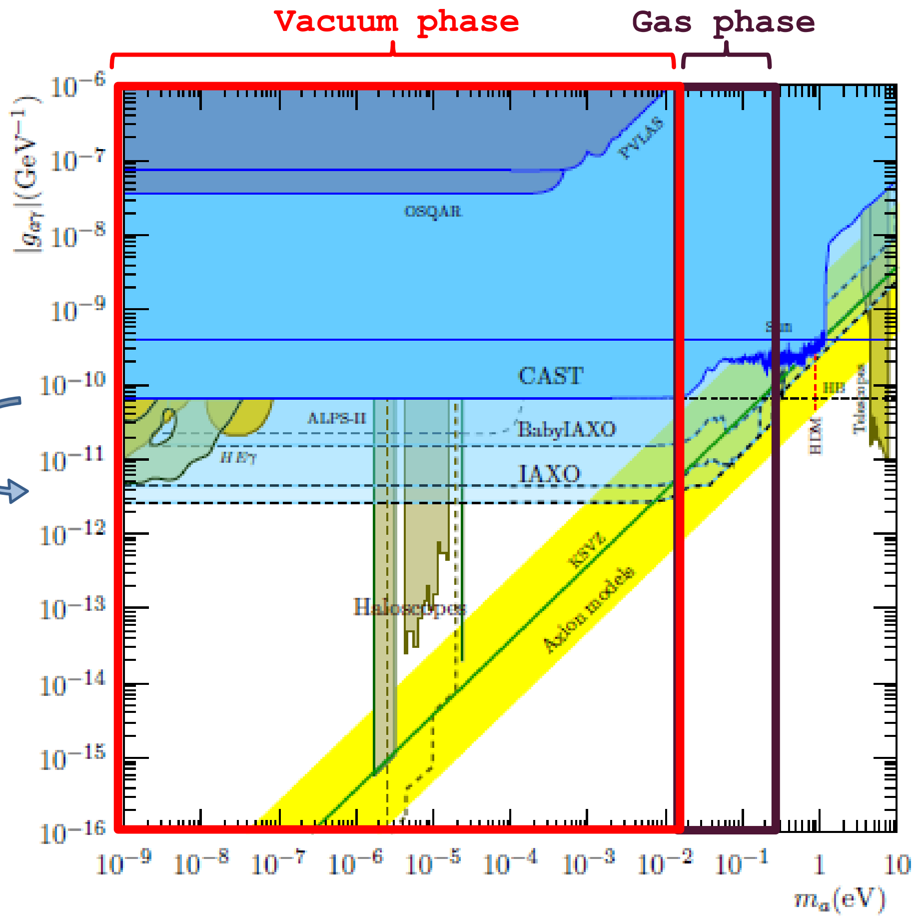
$g_{a\gamma} \lesssim$ few 10^{-12} GeV^{-1} (expected)

Armengaud et al 2014 JINST 9 T05002
Irastorza et al 2011 JCAP 1106, 013

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

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

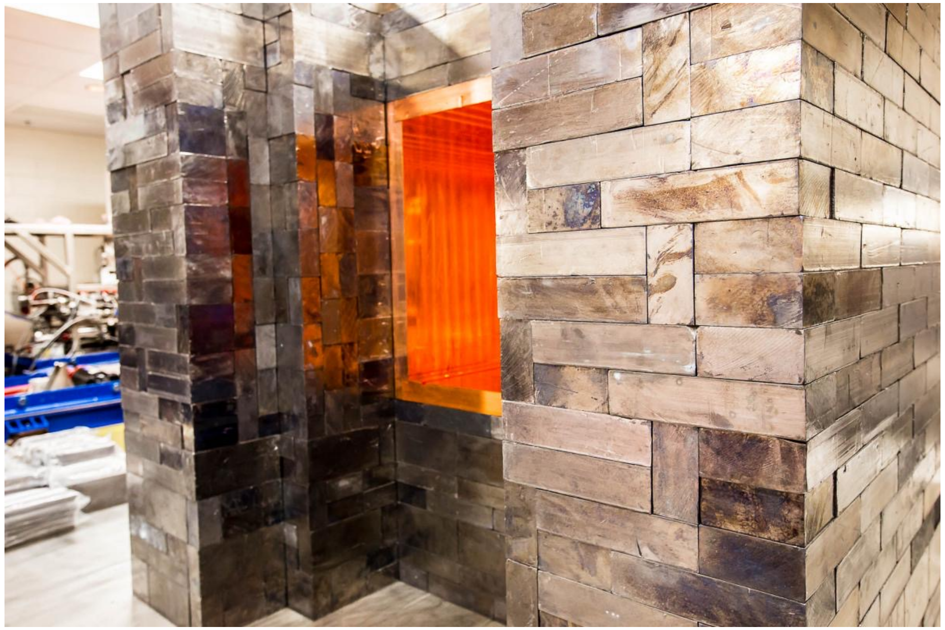


- Experimental conditions BabyIAXO:
  - P_{max}(helium-4) ≃ 1bar
  - T(average) ≃ 295K

Can we get there in a different way?

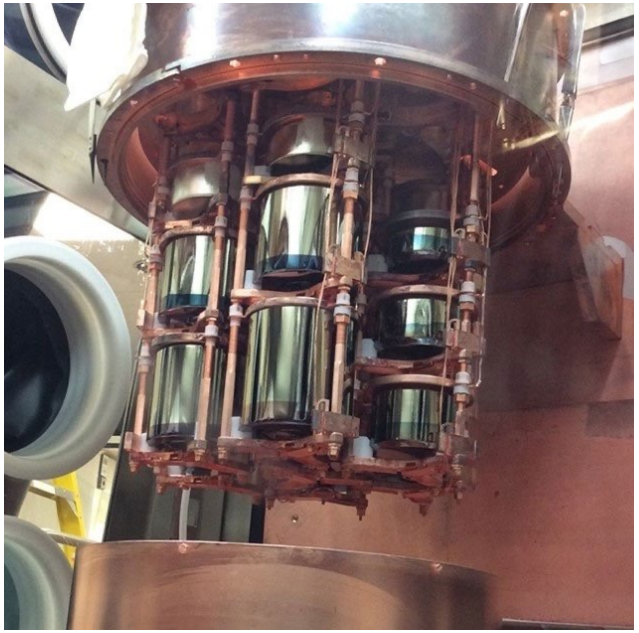
Bragg-scattering

Majorana Demonstrator

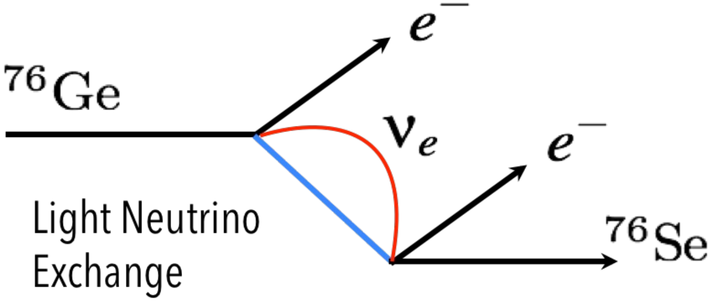


Like a bigger telescope can collect more light to view fainter objects, a greater mass of germanium improves the odds of observing rare decay.

The experiment did not find the decay’s signature. However, the collaboration advanced germanium-based radiation detector technologies and ultra-pure materials development.

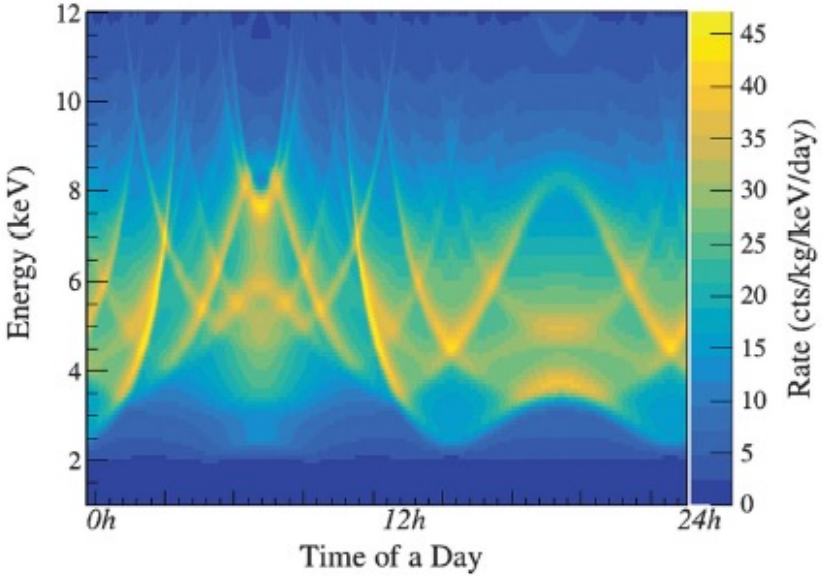


44-kilogram Germanium detectors

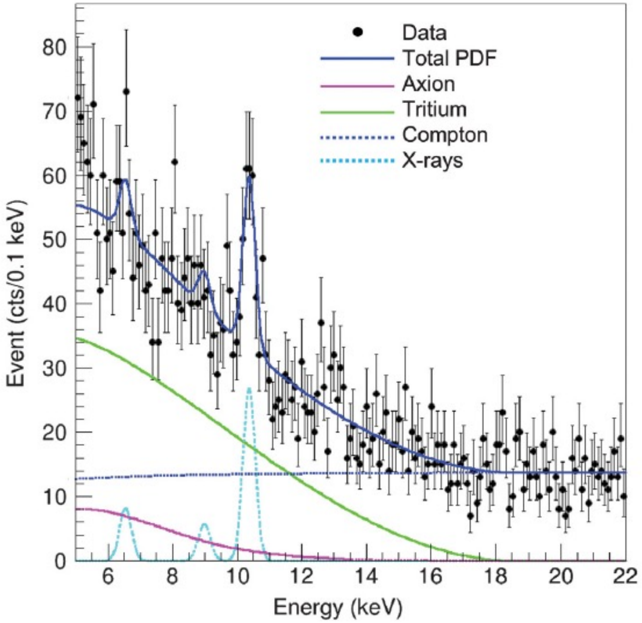


Bragg-scattering Majorana Demonstrator

Search for Solar Axions via Axion-Photon Coupling with the Majorana Demonstrator



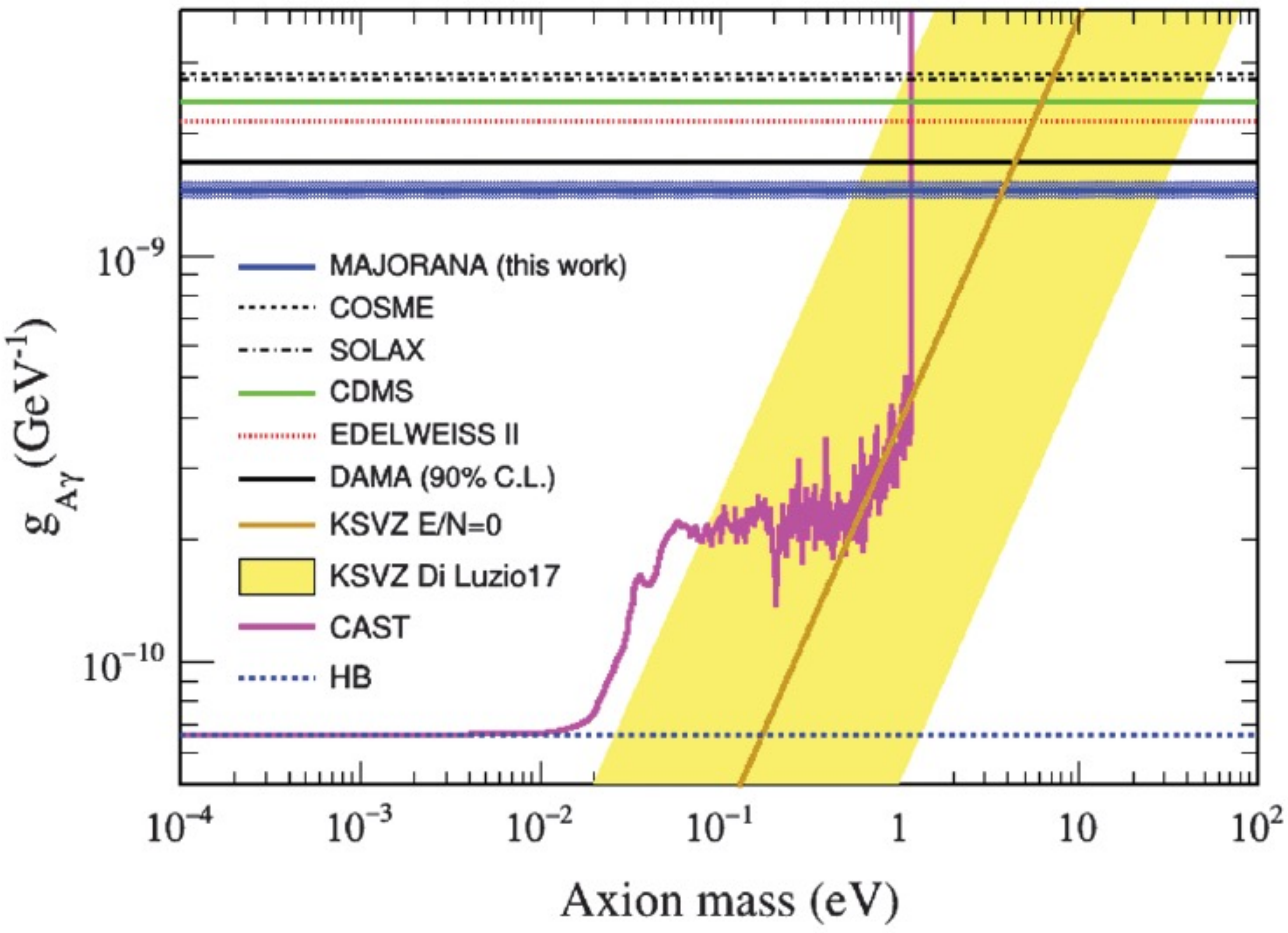
Simulated axion signatures from coherent Primakoff-Bragg scattering averaged over all possible orientations of horizontal crystal planes



Energy spectrum of low energy events (Data), shown along with the best fit of the extended composite model (Total PDF) and individual components.

I.J. Arnquist et al. (Majorana Collaboration)
Phys. Rev. Lett. 129, 081803 – Published 19 August 2022

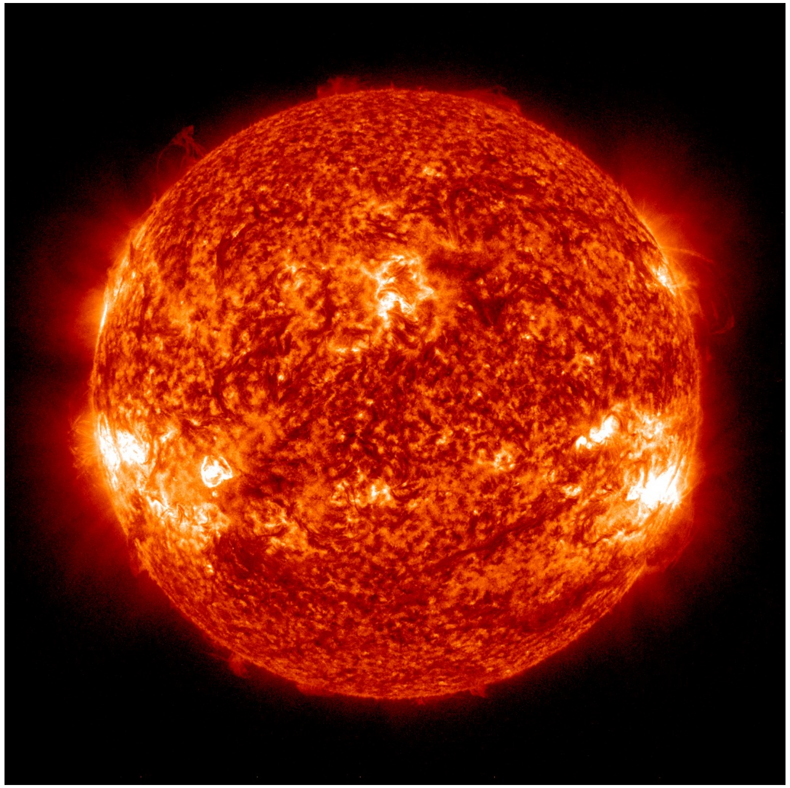
Bragg-scattering Majorana Demonstrator



I.J. Arnquist et al. (Majorana Collaboration)
Phys. Rev. Lett. 129, 081803 – Published 19 August 2022

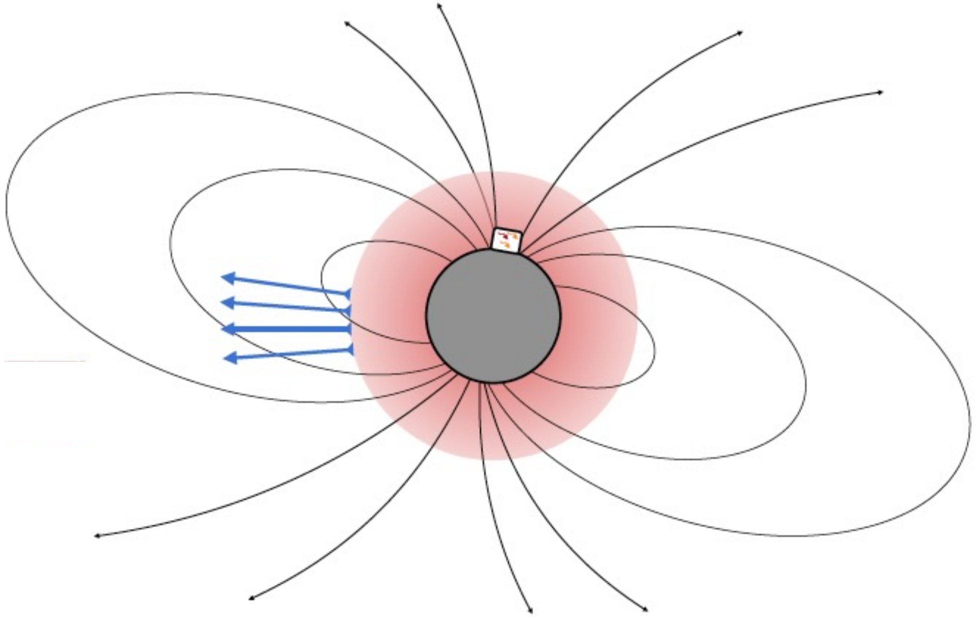
Radio-Axions

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

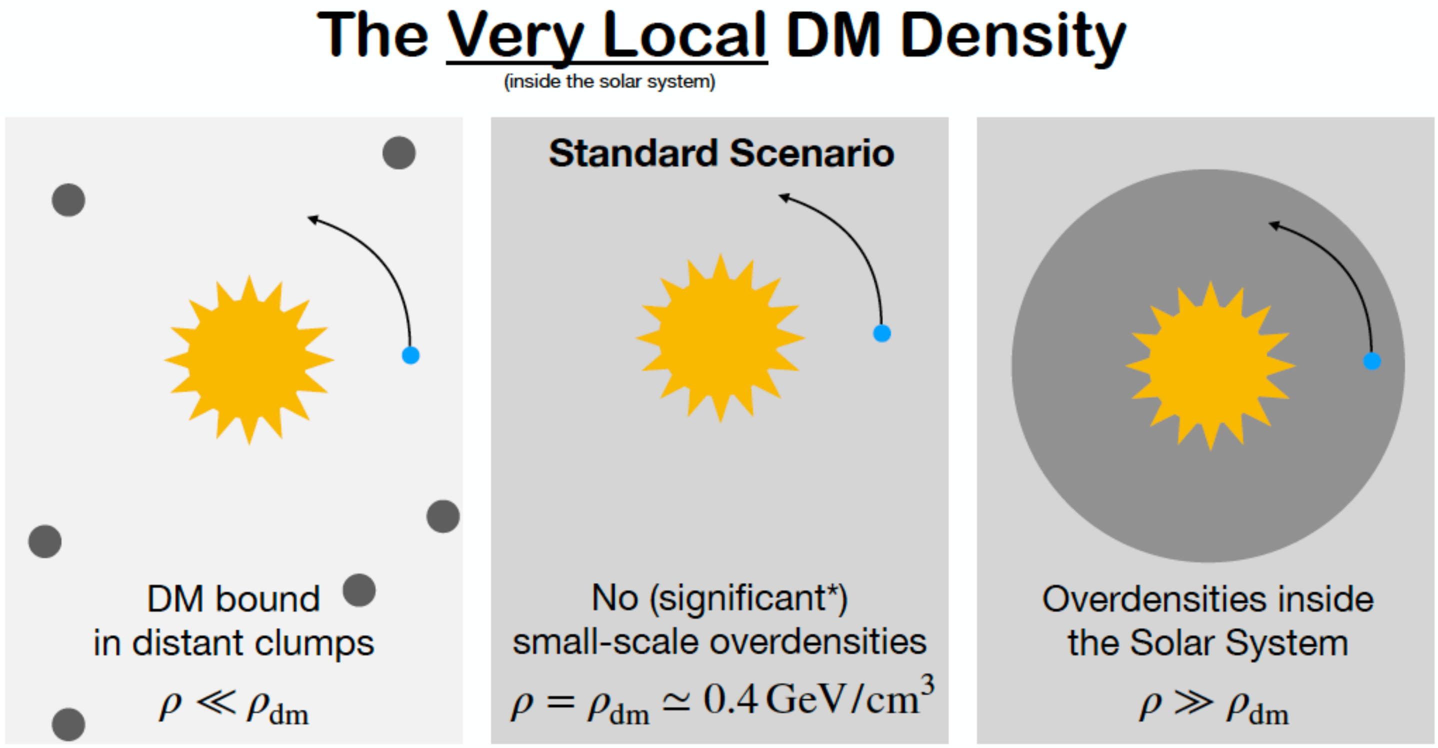


Todarello, Ruz et al., Phys. Lett. B 854, 138752 (2024).

Axions in under-dense plasma produce radio



Novel approaches



The Very Local DM Density

(inside the solar system)

DM bound in distant clumps

$\rho \ll \rho_{\rm dm}$

Standard Scenario

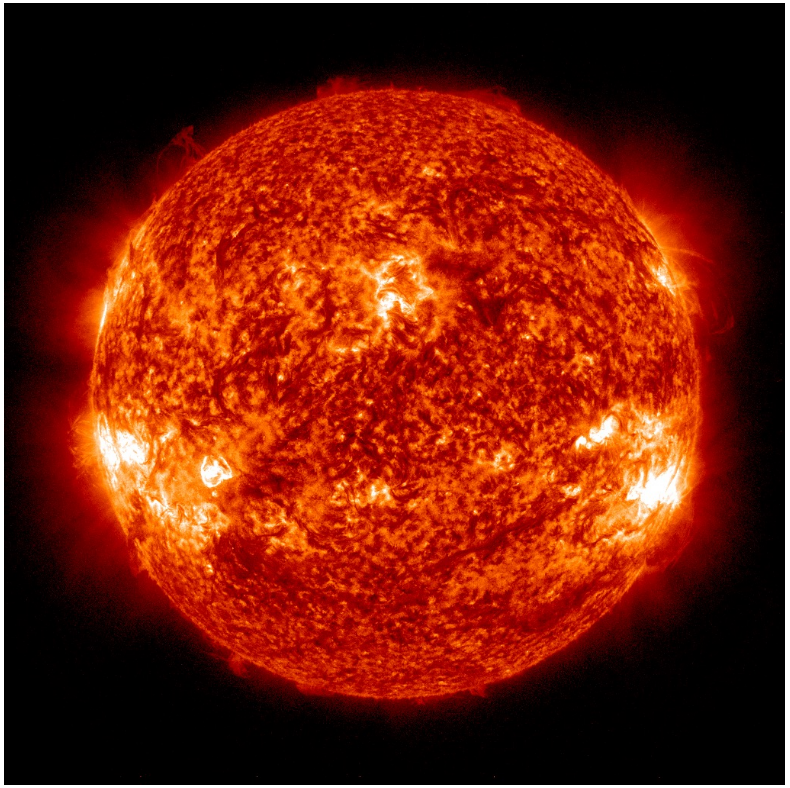
No (significant*) small-scale overdensities

$\rho = \rho_{\rm dm} \simeq 0.4\,{\rm GeV/cm^3}$

Overdensities inside the Solar System

$\rho \gg \rho_{\rm dm}$

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



Todarello, Ruz 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

Signal from a Sun spot of area DA:

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

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

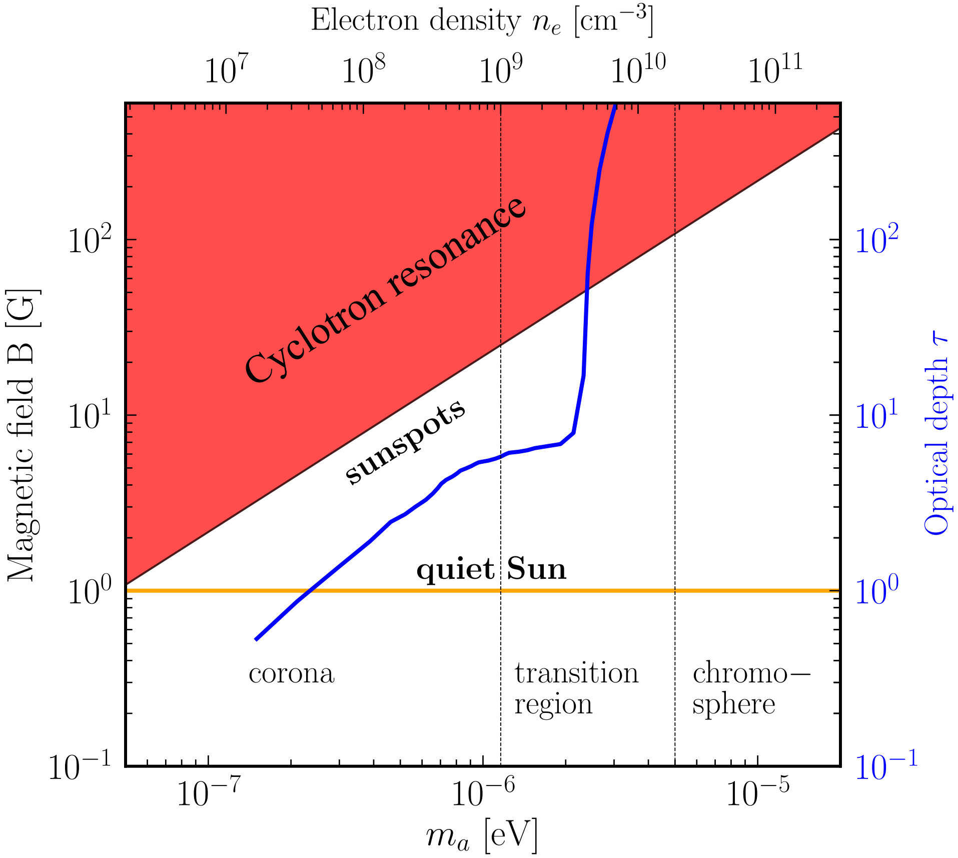
$$\omega_p \propto h^\alpha \longleftarrow \boxed{\alpha \simeq 0.5}$$

$$\downarrow$$

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

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

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

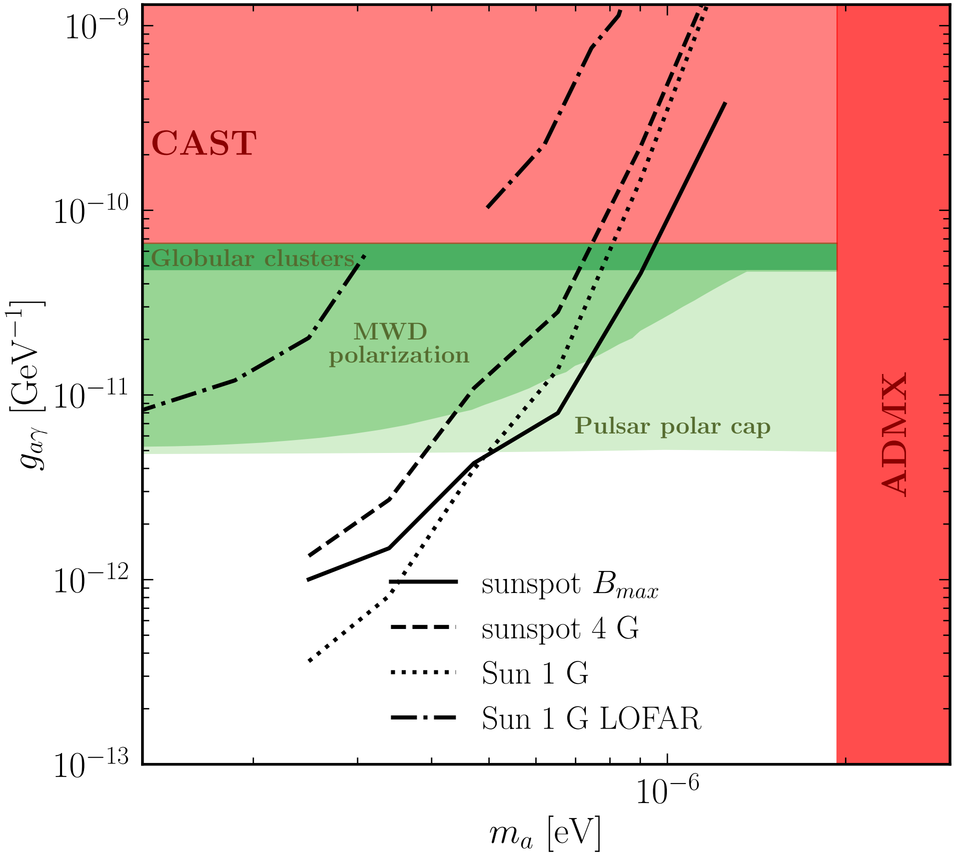


Thermal Bremsstrahlung

Radio-Axions

Novel approaches

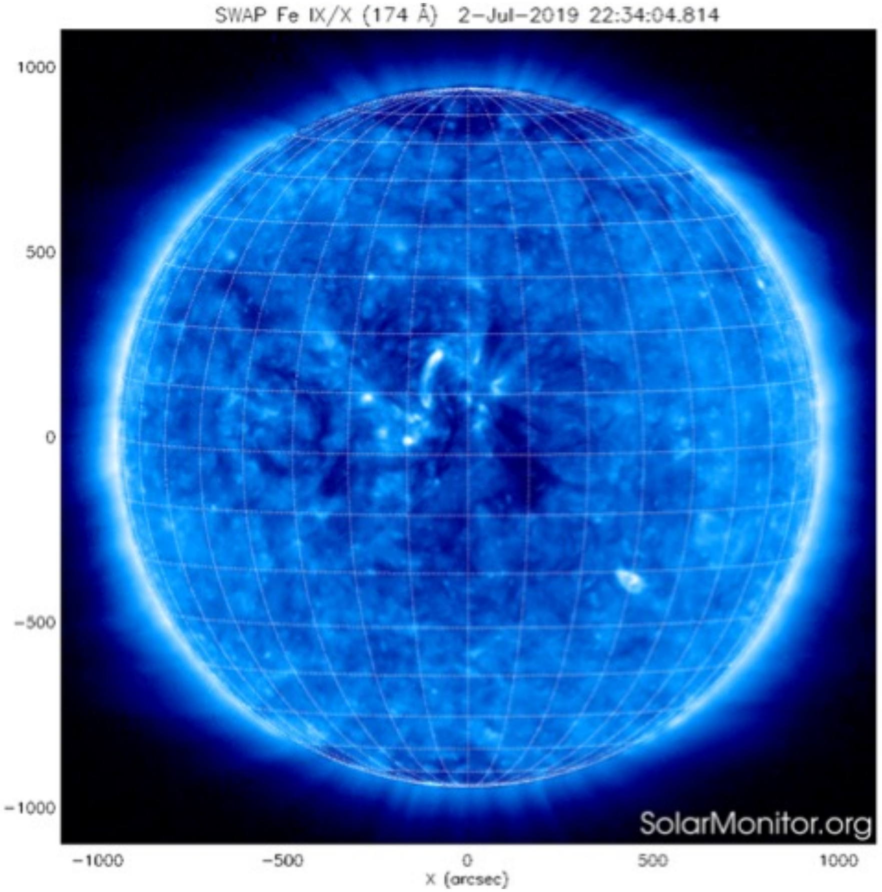
Prospects from SKA:

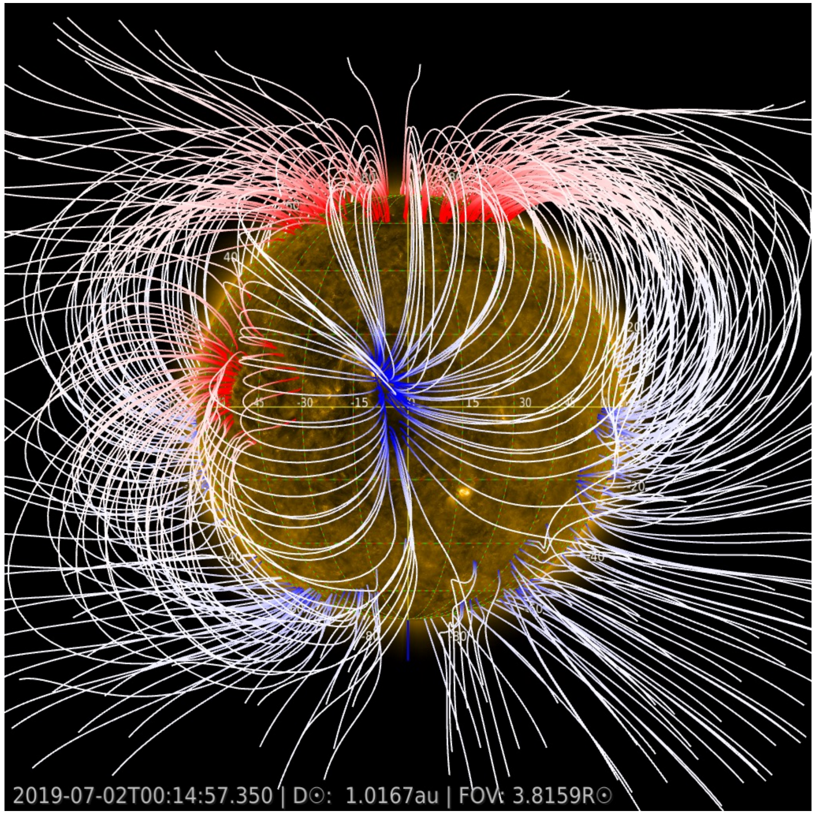


Todarello, Ruz et al., Phys. Lett. B 854, 138752 (2024).

NuSTAR Spacecraft

Observations & Modeling

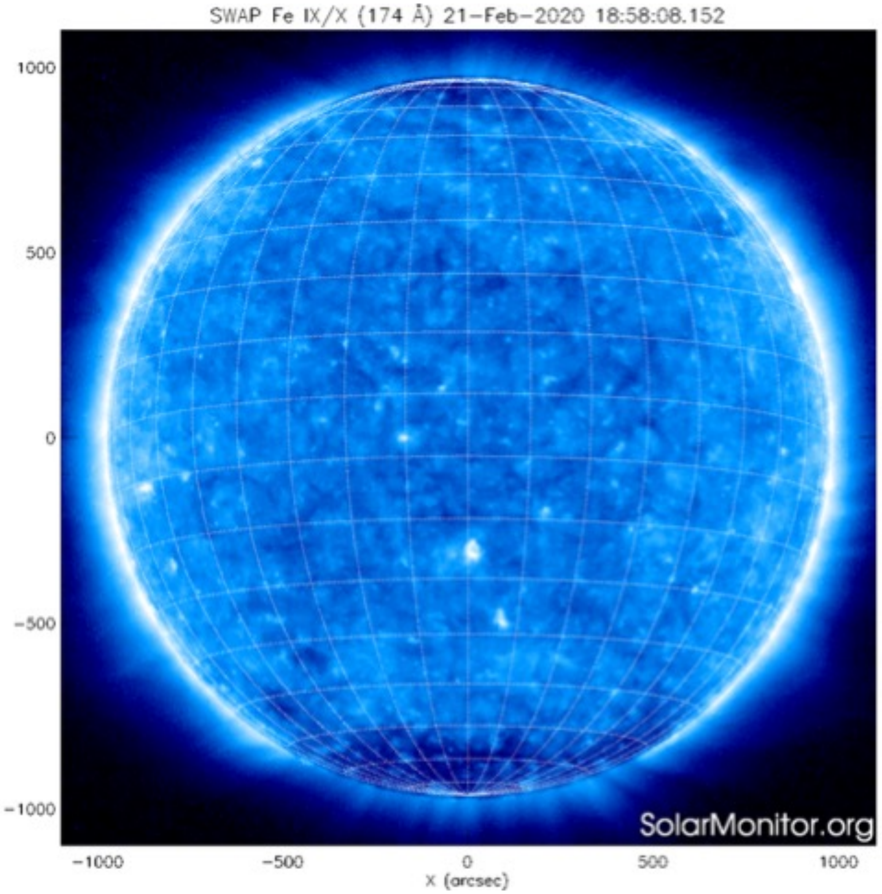


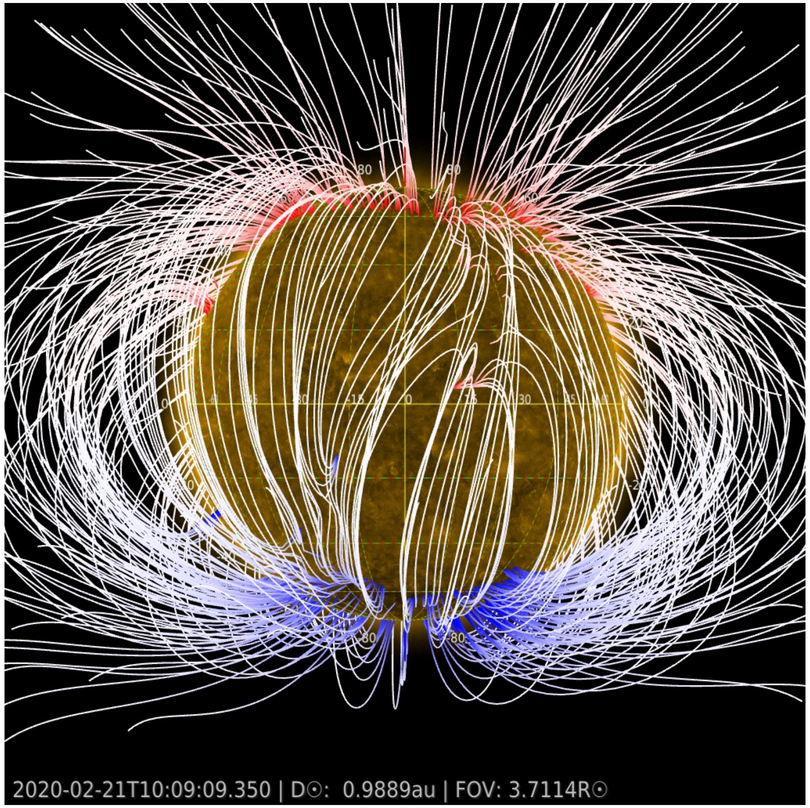


- Snapshots at 174 A from the SWAP spacecraft, showing the million-degree corona during 2019 eclipse (left) and PSI modeling at the time of eclipse (right), showing the presence of a weak active region near disk center.

Novel approaches

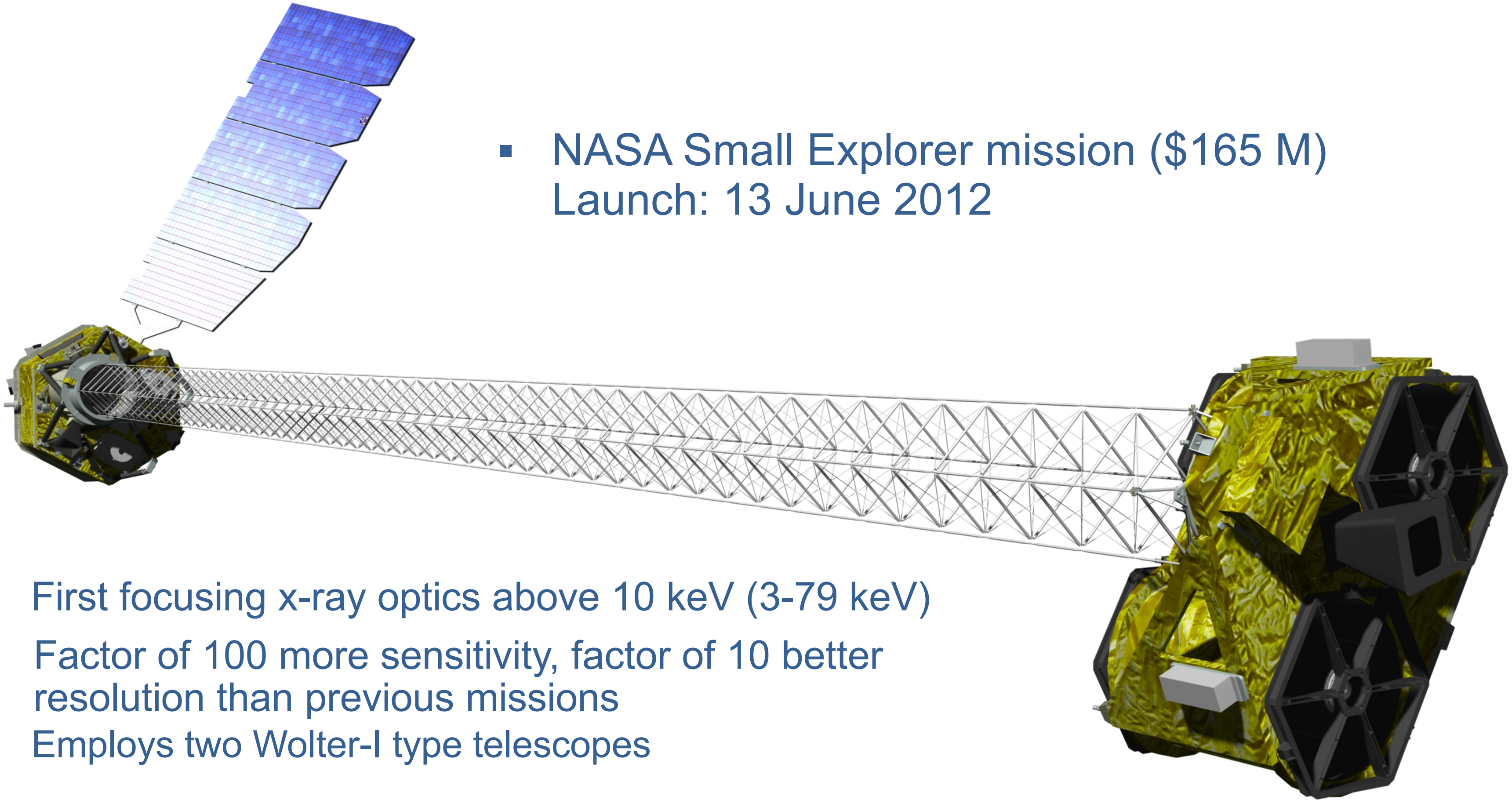
Observations & Modeling





- Snapshots at 174 A from the SWAP spacecraft, showing the million-degree corona during NuSTAR quiet Sun data taking early 2020 (left) and evolution of the PSI modeling for quiet Sun conditions (right).

NASA'S NUCLEAR SPECTROSCOPIC TELESCOPE ARRAY (NuSTAR)



- NASA Small Explorer mission ($165 M)
  Launch: 13 June 2012

- First focusing x-ray optics above 10 keV (3-79 keV)

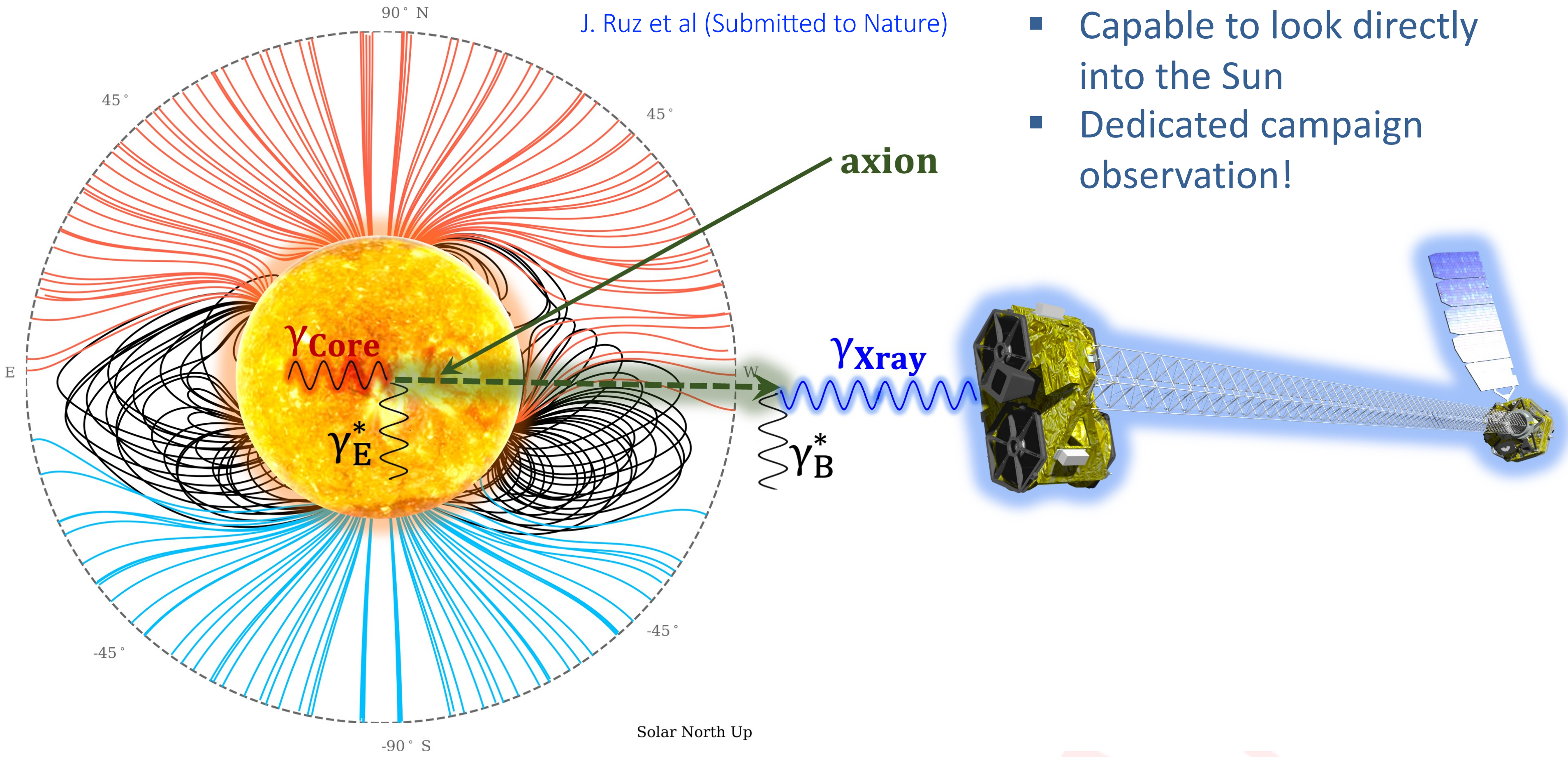
  Factor of 100 more sensitivity, factor of 10 better resolution than previous missions
- Employs two Wolter-I type telescopes
- Diverse Physics reach: Black holes, neutron stars, AGNs, Sun,…

F. A. Harrison et al (NuSTAR Collaboration) 2013 ApJ 770 103.

NuSTAR

Novel approaches

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



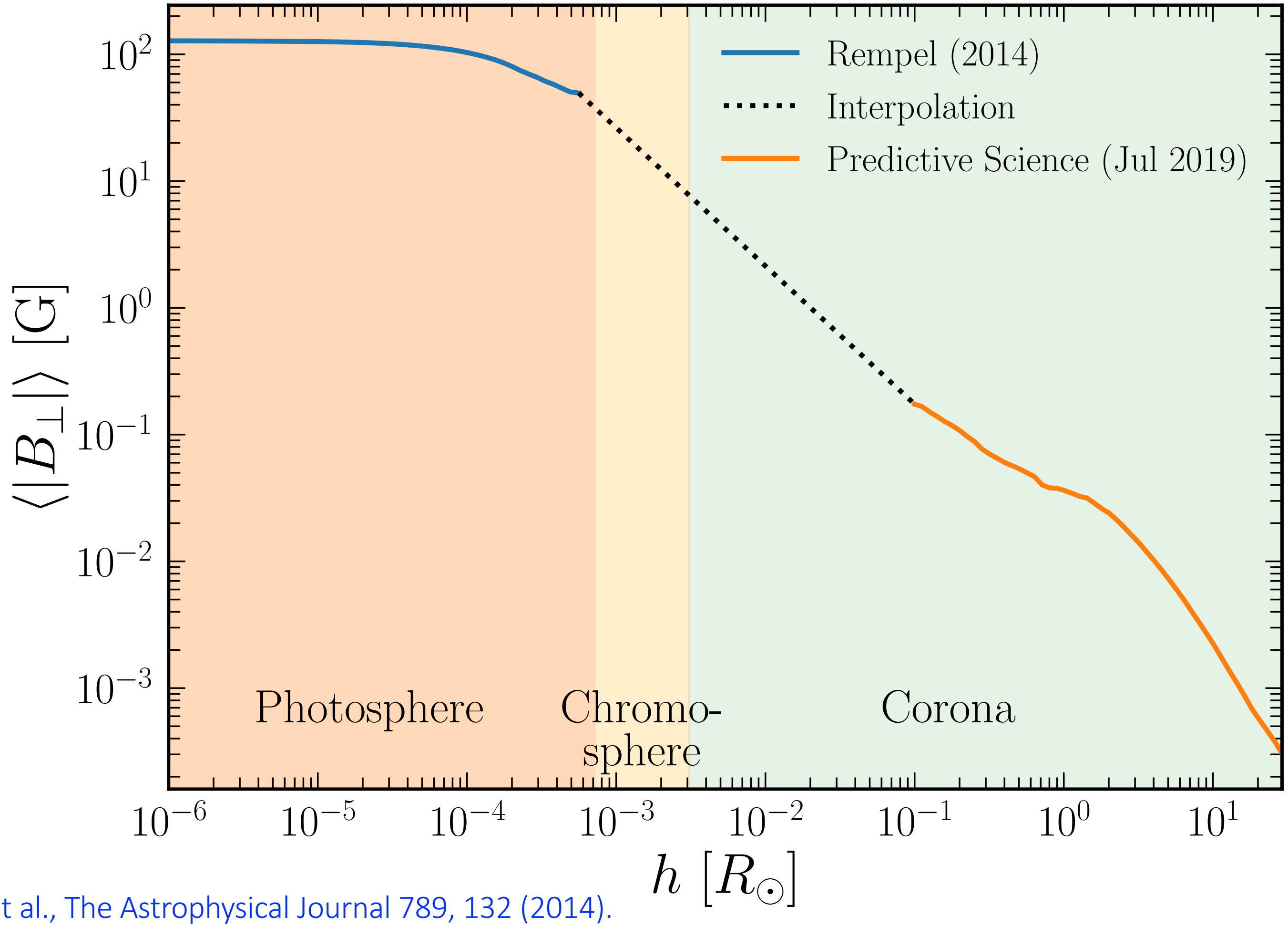
J. Ruz et al (Submitted to Nature)

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

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

Novel approaches

Model the perpendicular component of the solar atmospheric magnetic field.

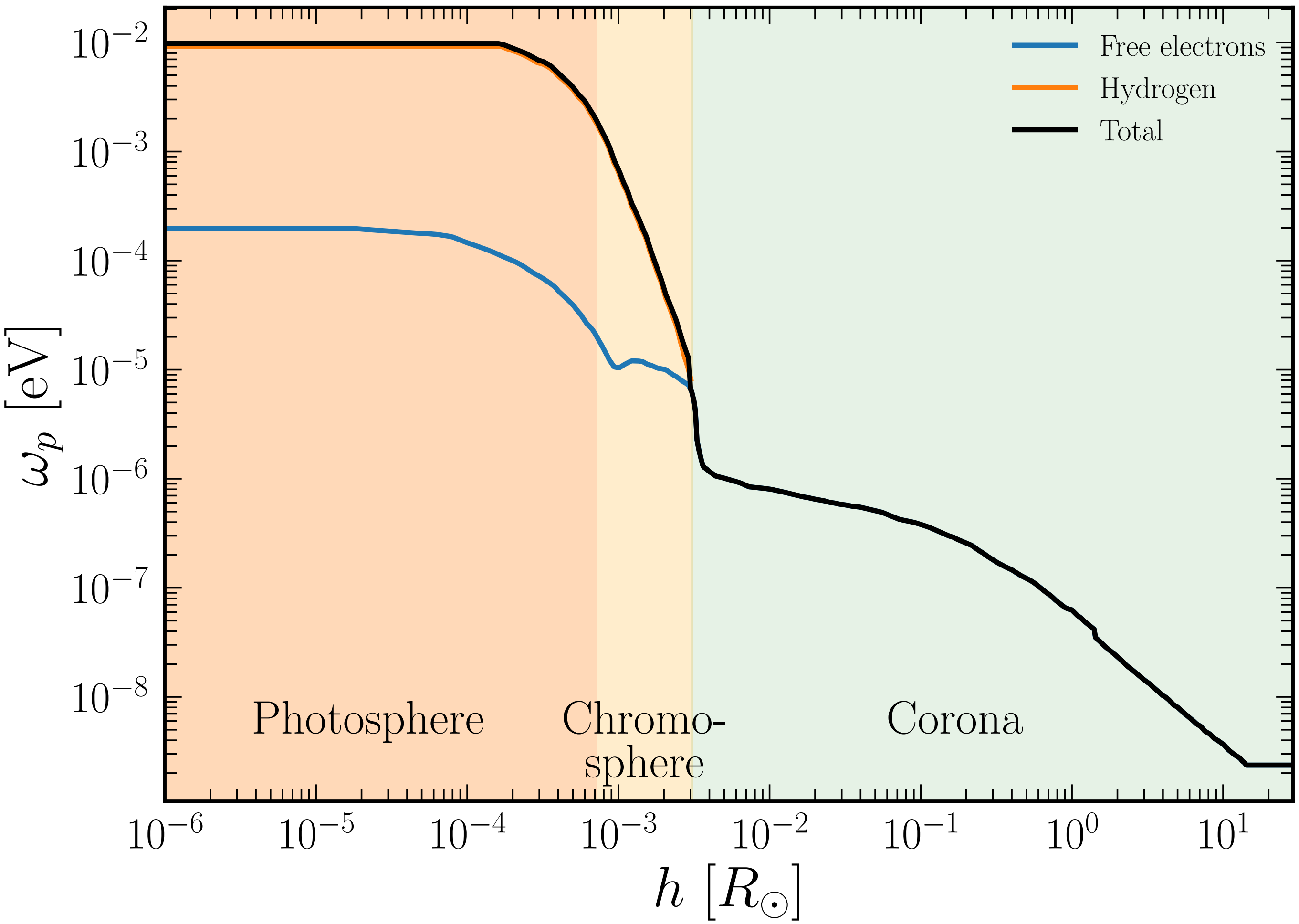


Rempel et al., The Astrophysical Journal 789, 132 (2014).

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

Novel approaches

Determine contributions to axion plasma frequency from free electrons and Hydrogen.

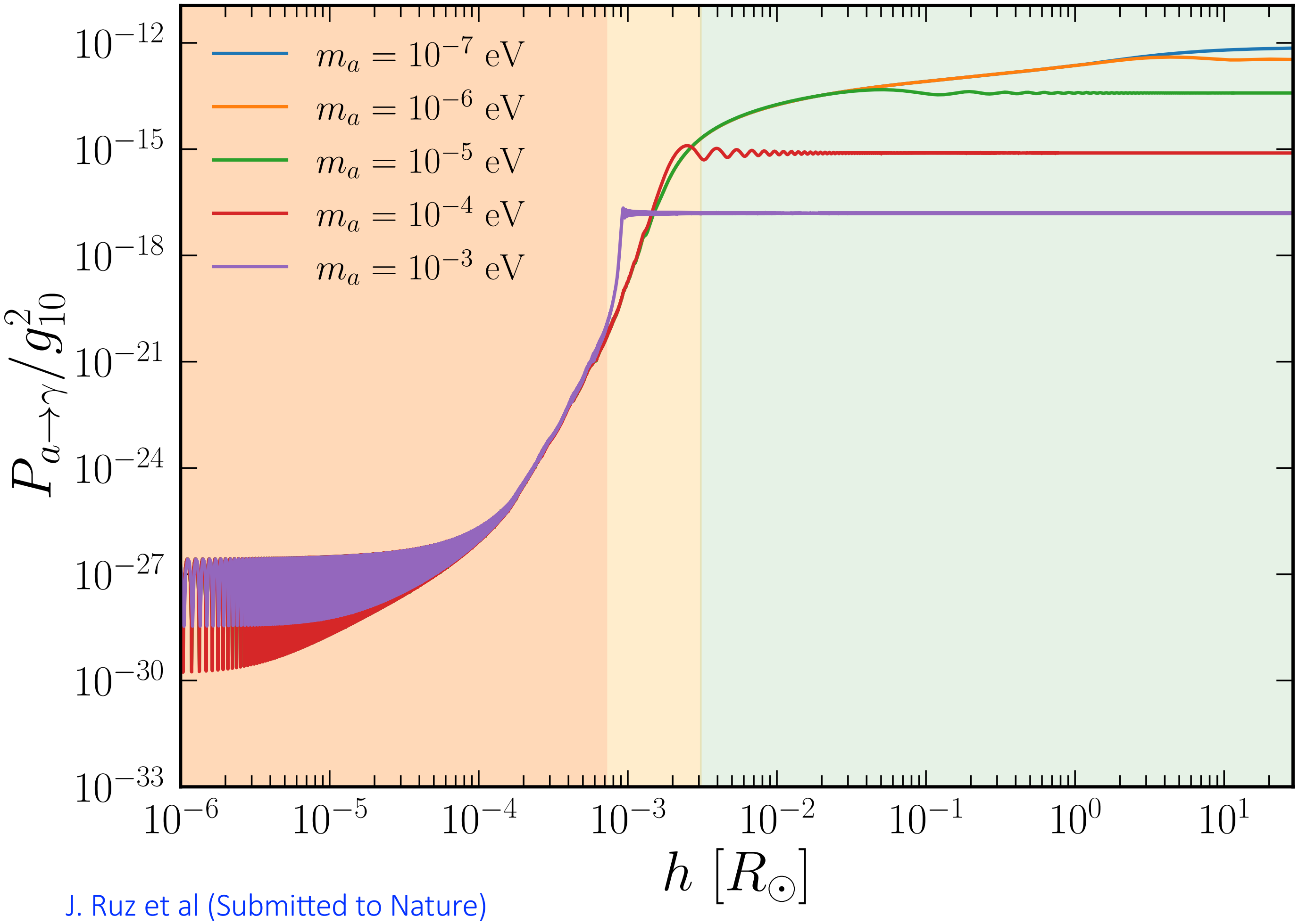


Dere et al., A&AS 125, 149–173 (1997).

NuSTAR

Novel approaches

Establish conversion probability for different regions of the Sun's atmosphere

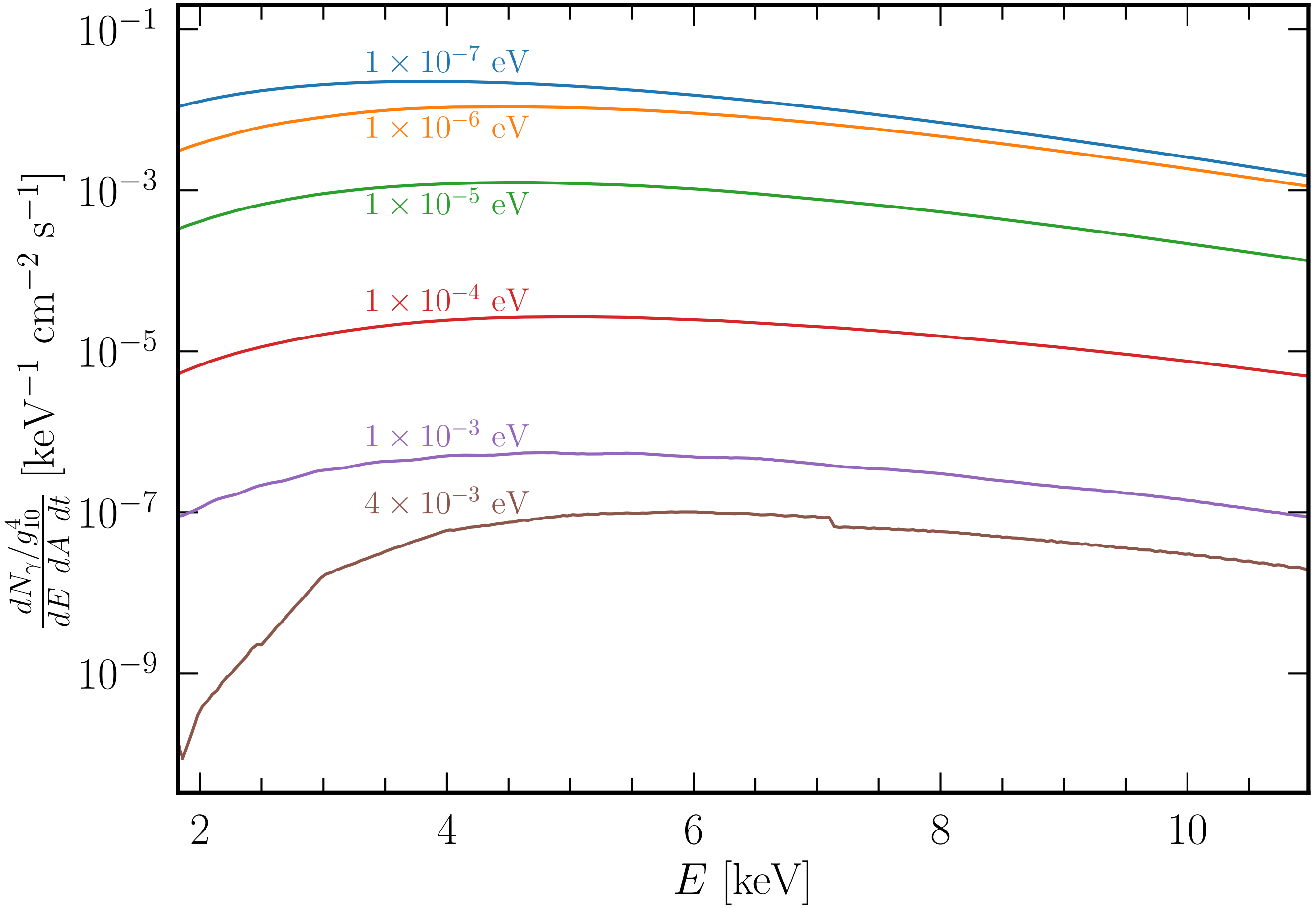


J. Ruz et al (Submitted to Nature)

NuSTAR

Novel approaches

Determine total X-ray flux in NuSTAR. Axion mass dependance of the arriving flux

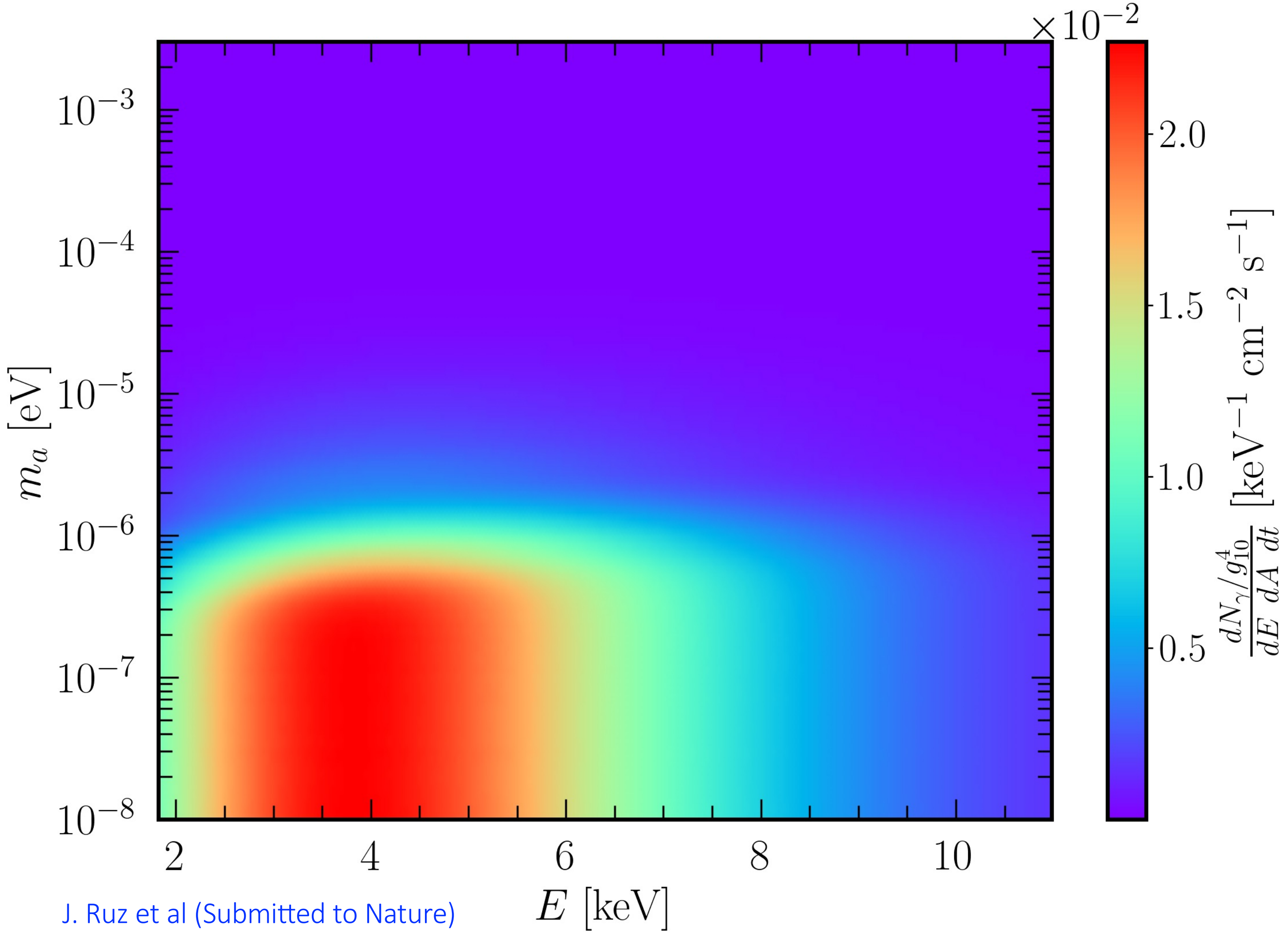


J. Ruz et al (Submitted to Nature)

NuSTAR

Novel approaches

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

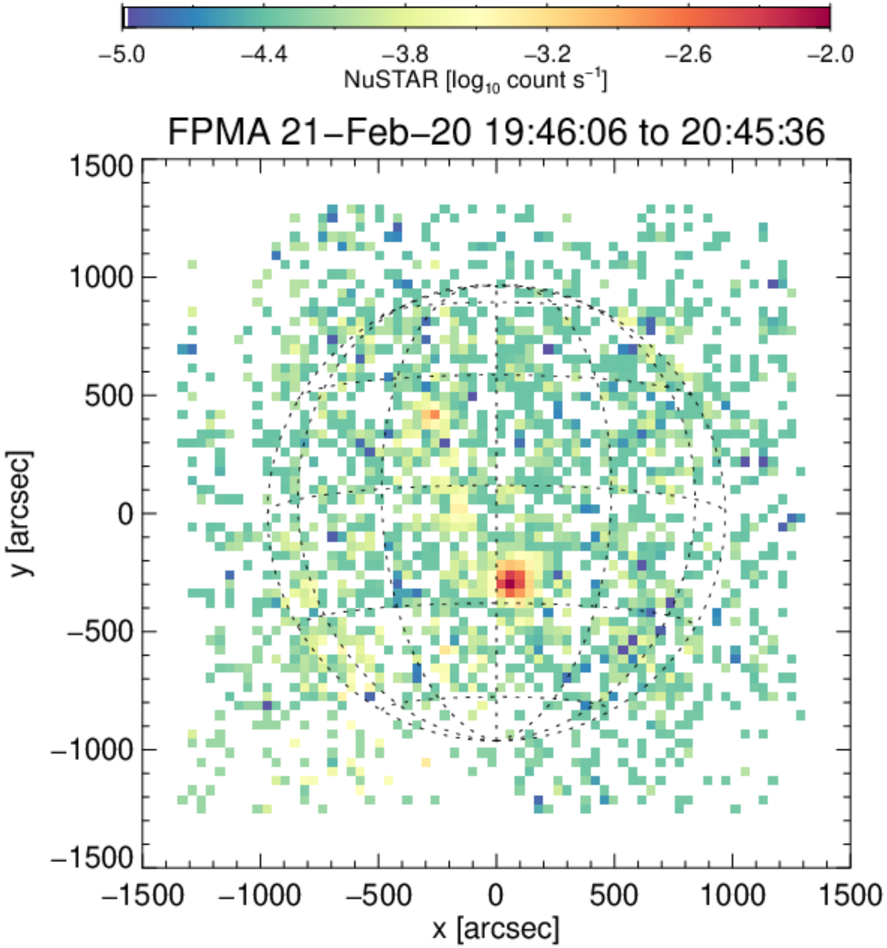


J. Ruz et al (Submitted to Nature)

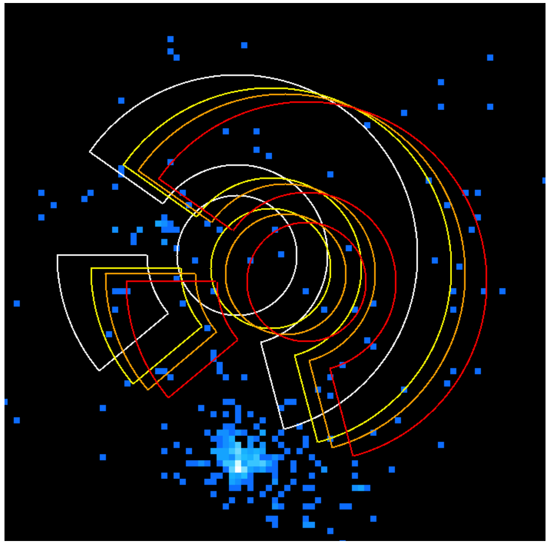
NuSTAR

Novel approaches

Yes, we have good data!



J. Ruz et al (Submitted to Nature)



NuSTAR

Novel approaches

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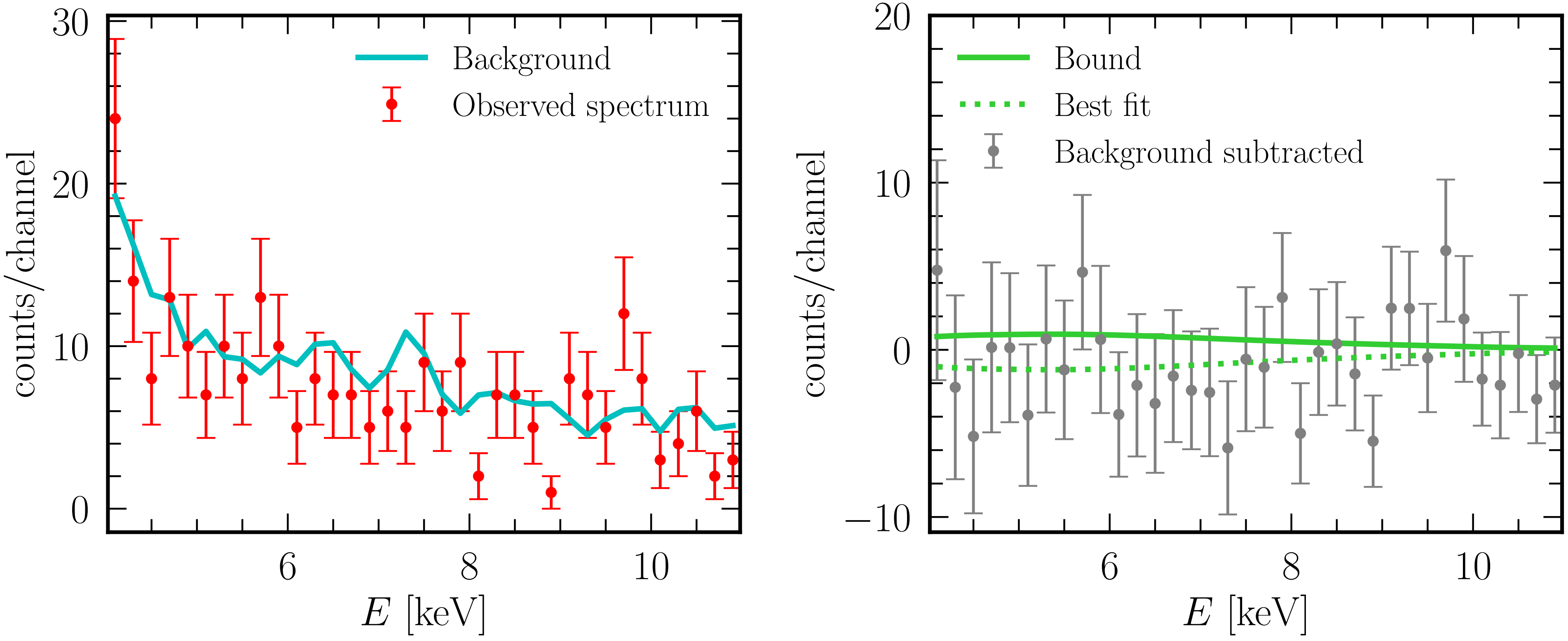
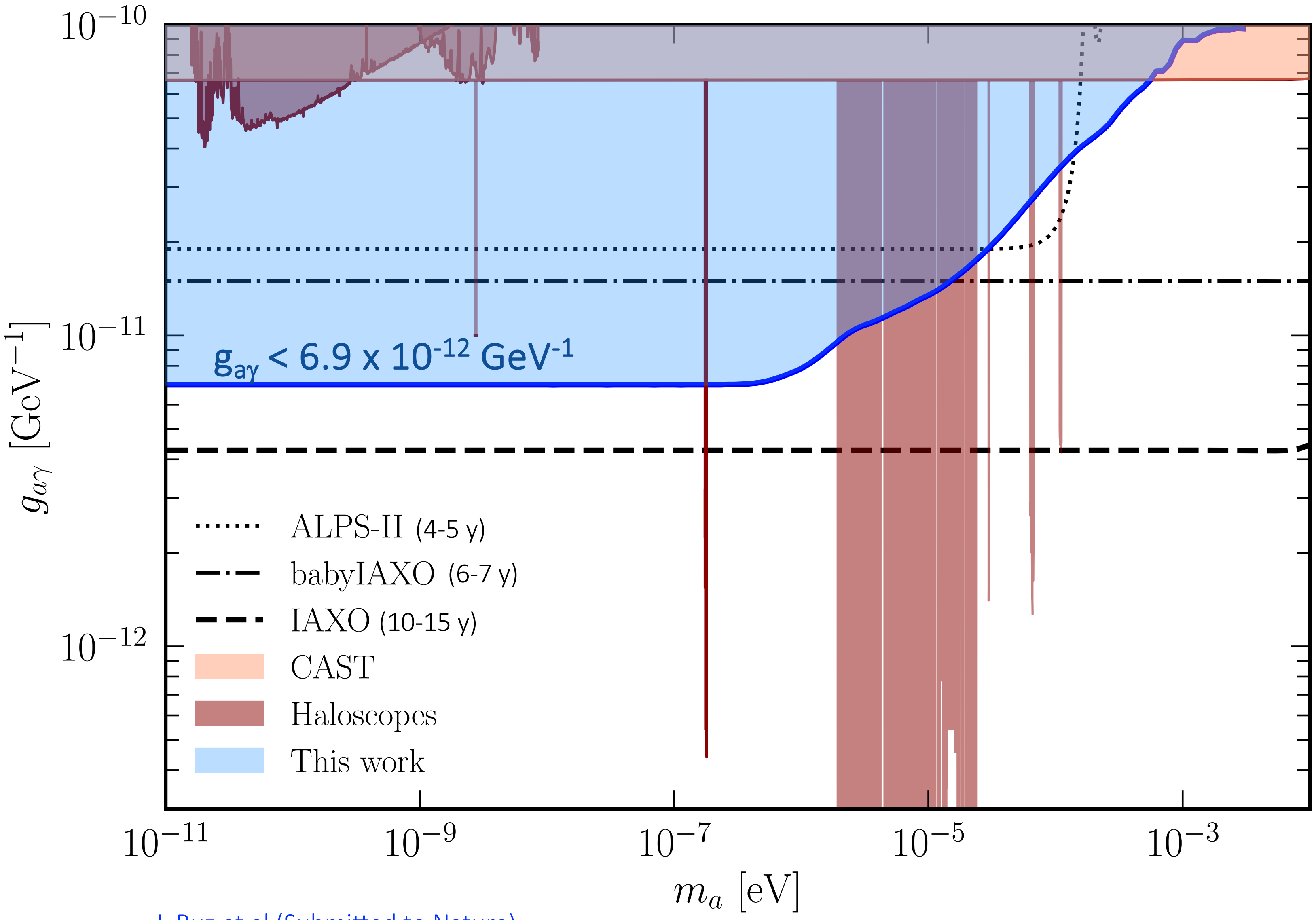


J. Ruz et al (Submitted to Nature)

NuSTAR

Novel approaches



J. Ruz et al (Submitted to Nature)

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
- → CAST new limit $g_{ag} < 5.7 \times 10^{-11}$ GeV^{-1}
- → BabyIAXO and IAXO target axion discovery with between 1.5×10^{-11} and 5×10^{-12} GeV^{-1} respectively. Based in current developments sensitivity could be reached in 2030 (BabyIAXO) and 2035 (IAXO).
- → SKAO could be probing DM axions in the Sun much earlier.
- → NuSTAR has already managed to reach $g_{ag} < 6.9 \times 10^{-12}$ GeV^{-1}

Thank you for your attention!