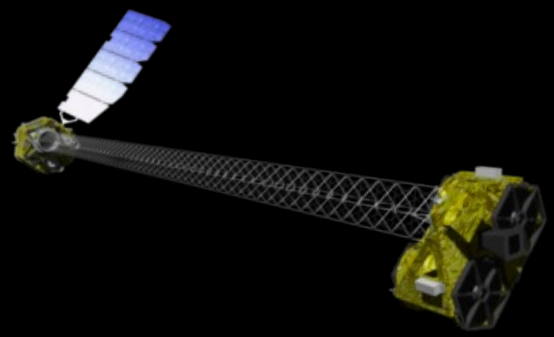


X-ray observations and their applications to the physics of axions (or other WISPs)

Jaime Ruz

COST 3rd General Meeting COSMIC WISPers

Sofia, Bulgaria

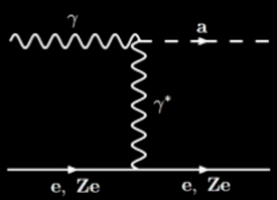
September 9-12th, 2025

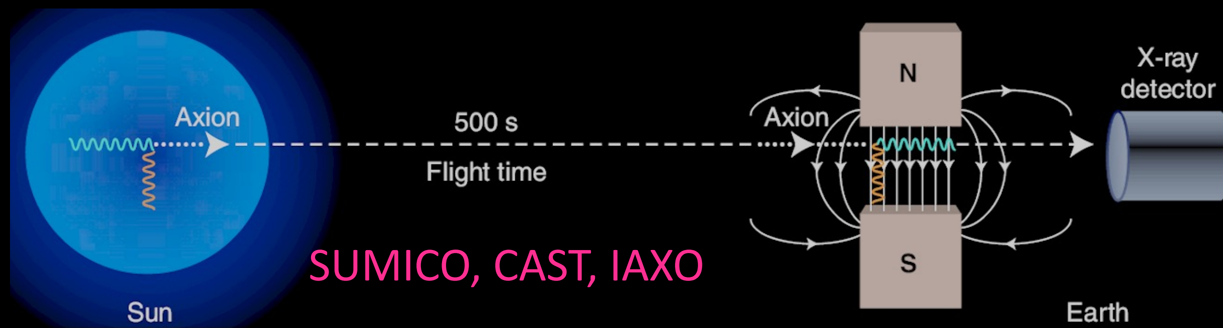
Outline

1. **X-ray signals from different axion-couplings**
   1. Helioscopes
   2. State of the art
   3. Future experiments
   4. Space Missions (exciting results!)
2. **Beyond Solar Axion Searches**
   1. Red Super Giants
   2. M82 & M87
   3. Alpha Centauri
   4. Modulation in underground experiments
3. **Conclusions**

- **HELIOSCOPES:** Experiment NOT RELYING on axions being DM

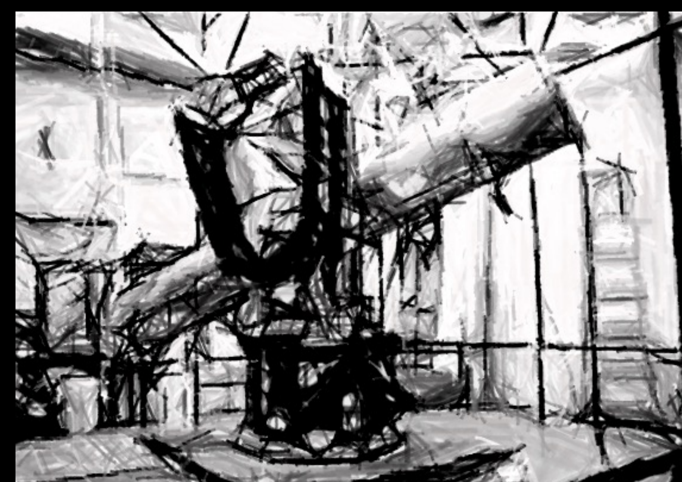
P. Sikivie 1983 PRL 51 1415





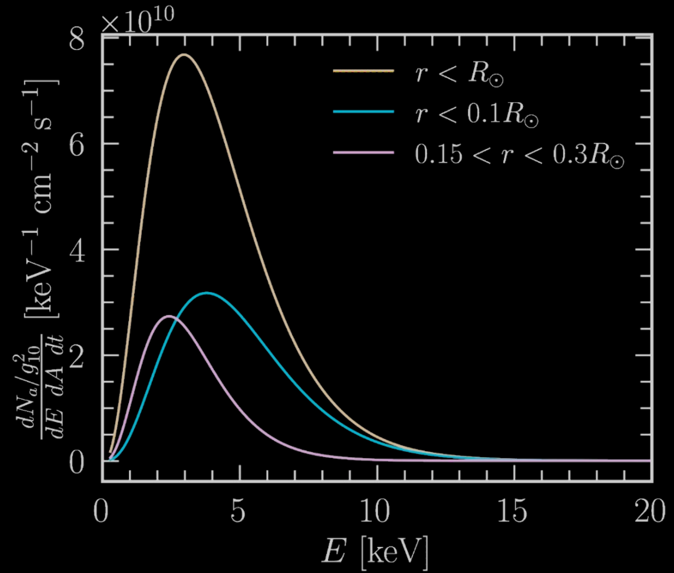
SUMICO, CAST, IAXO

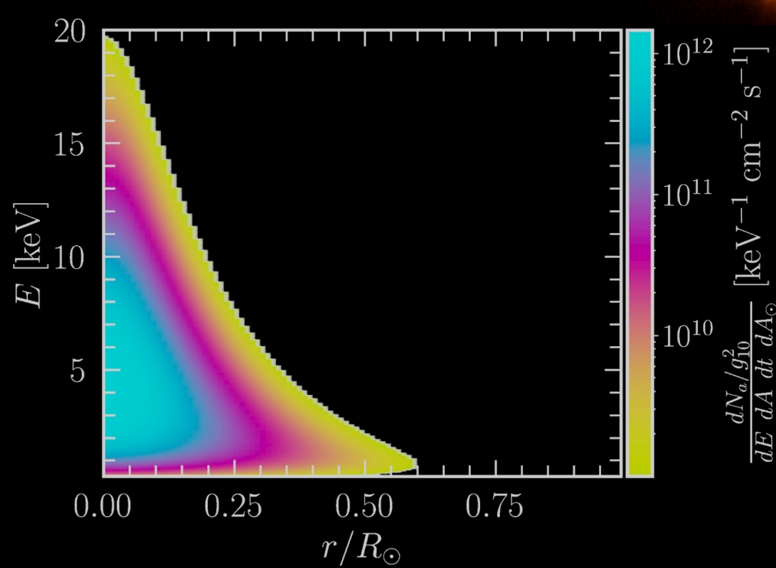
Concept:
- Axions produced in strong electromagnetic fields of the core of the Sun
- Solar axion conversion into x-ray (keV) photons in transverse laboratory B-field



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

- **Primakoff Effect**
  - ✓ Blackbody photons (keV) in solar core can be converted into axions in the presence of strong electro magnetic fields in the plasma ($T_{Core} \sim 1.3 keV$)



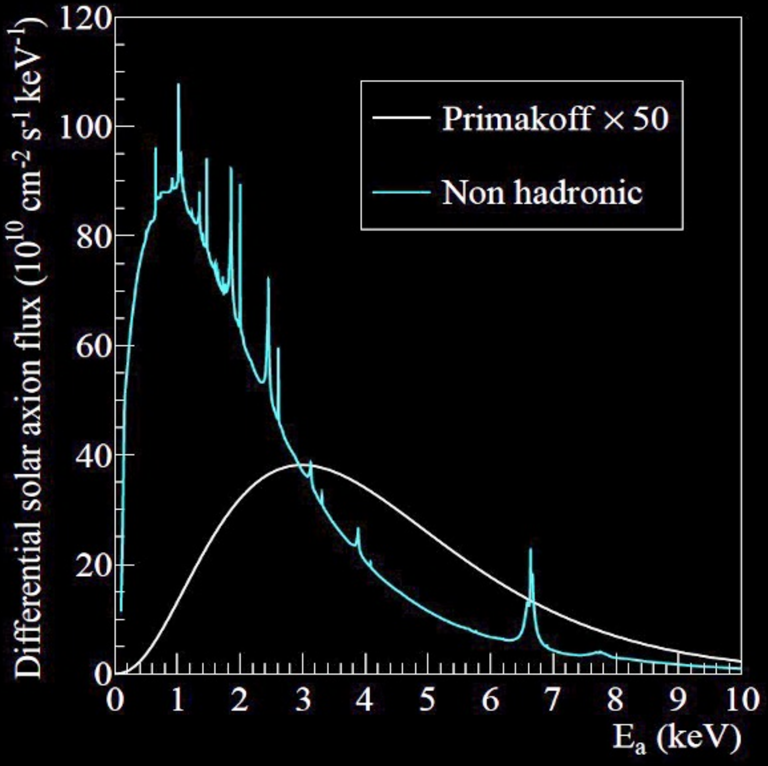


Hadronic axions (if the axion couples predominantly to photons, $g_{a\gamma}$)

$$\frac{d\Phi_a}{dE} = 6.02\times10^{10}\left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 E^{2.481} e^{-E/1.205} \frac{1}{\mathrm{cm}^2\ \mathrm{s\ keV}}$$

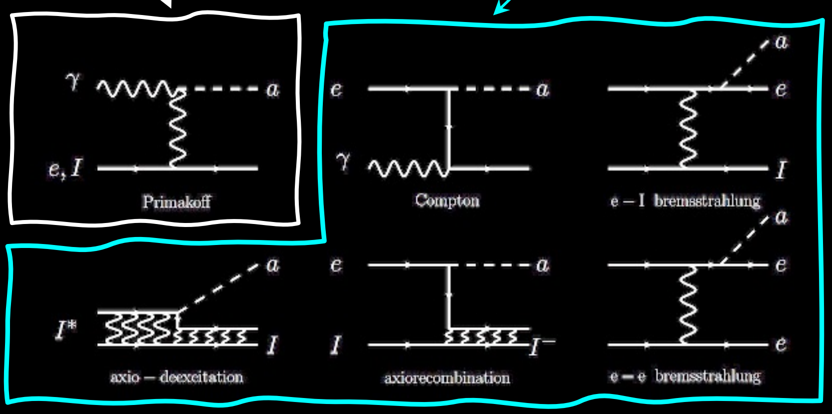
- **Non-hadronic (axion couples to electrons, g_{ae})**

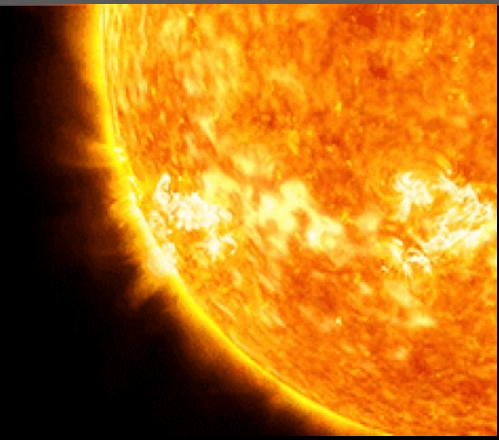
Redondo, JCAP 1312 008
Barth et al 2013 JCAP 1305 010

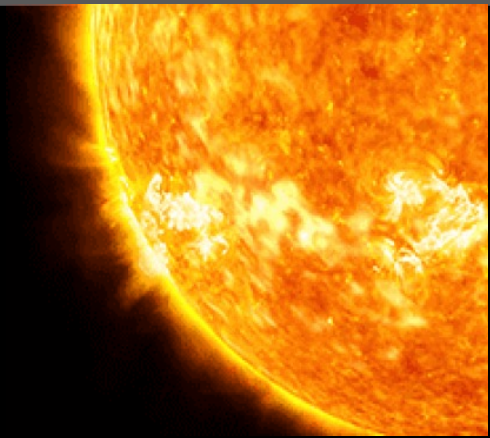


Primakoff axions

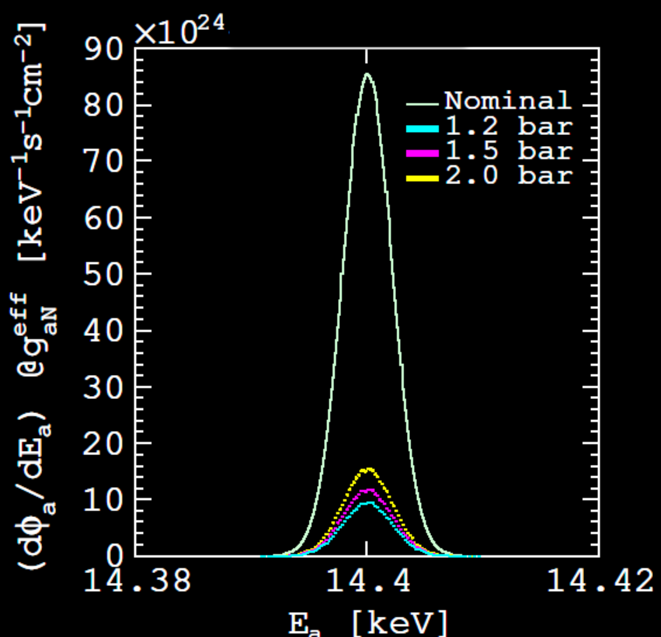
Non-hadronic "BCA" solar axion flux at Earth
JCAP 1312 008







- **Monochromatic lines from nuclear transitions**
  - ✓ keV axions emitted in the M1 transition of Fe-57 nuclei (14.4 keV) and Tm-169 (8.4keV)
  - ✓ MeV axions from ^7Li (0.478 MeV) and $D(p;g)^3He$ (5.5 MeV)



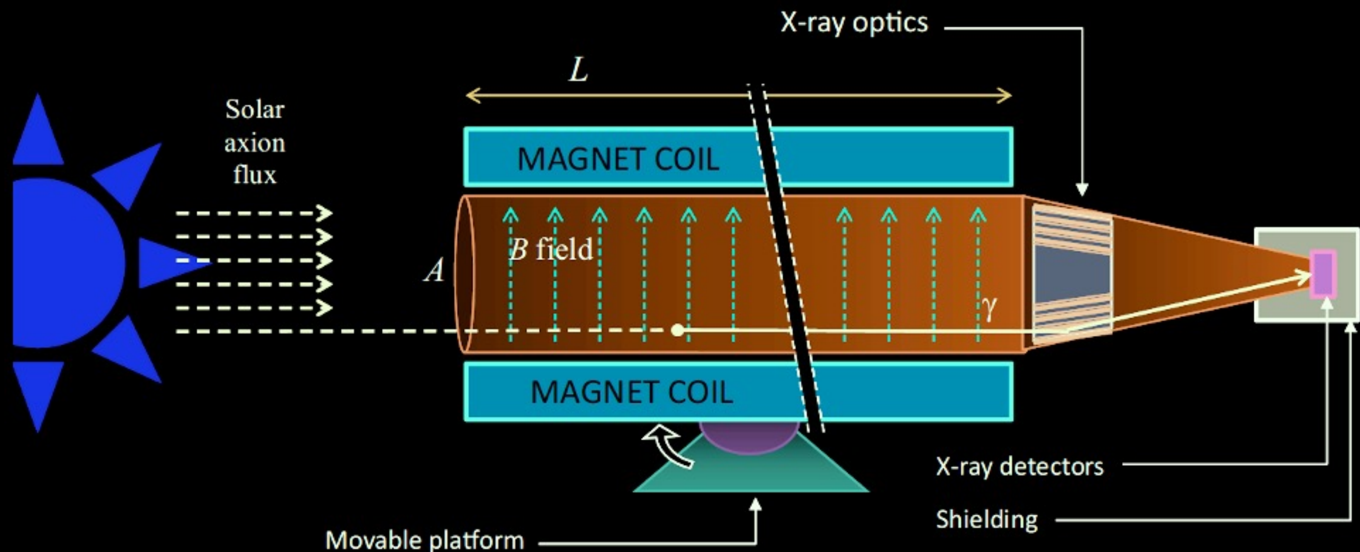
$$\Phi_a(^{57}Fe) = 5.06\times10^{23}\left(g_{aN}^{eff}\right)^2 cm^{-2}s^{-1}$$

- ✓ Axions-nucleon coupling g_{aN} especially intriguing: if the axion has couples via g_{aN} , it is most likely a QCD axion

Di Luzio et al 2022 Eur. Phys. J. C 82:120
CAST collaboration et al 2009 JCAP 12 002
D. Miller et al 2010 JCAP 1003 032
Derbin et al 2023 Jetp Lett. 118, 160

Sensitivity drivers

Enhanced axion helioscope:
Irastorza et al 2011 JCAP 1106, 013



Measure of sensitivity to axion-photon interaction:

$$\propto \underbrace{(BL)^{-2} A^{-1}}_{\textbf{magnet}} \times \underbrace{t^{-1/2}}_{\textbf{exposure}} \times \underbrace{s^{1/2}\varepsilon_0^{-1}}_{\textbf{optics}} \times \underbrace{b^{1/2}\varepsilon^{-1}}_{\textbf{detectors}}$$

magnet
- B = magnetic field
- L = magnet length
- A = cross-sectional area

exposure
- t = time

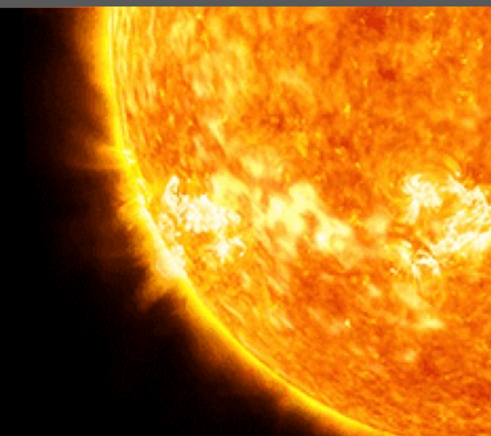
optics
- s = spot size
- ε_0 = efficiency

detectors
- b = background
- ε = efficiency

The smaller g_{ag} the better!

Expect improvement for next gen (International Axion Observatory):
1–1.5 orders of magnitude in sensitivity to $g_{a\gamma}$ (factor of 10000-20000 in S/N)

▸ 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

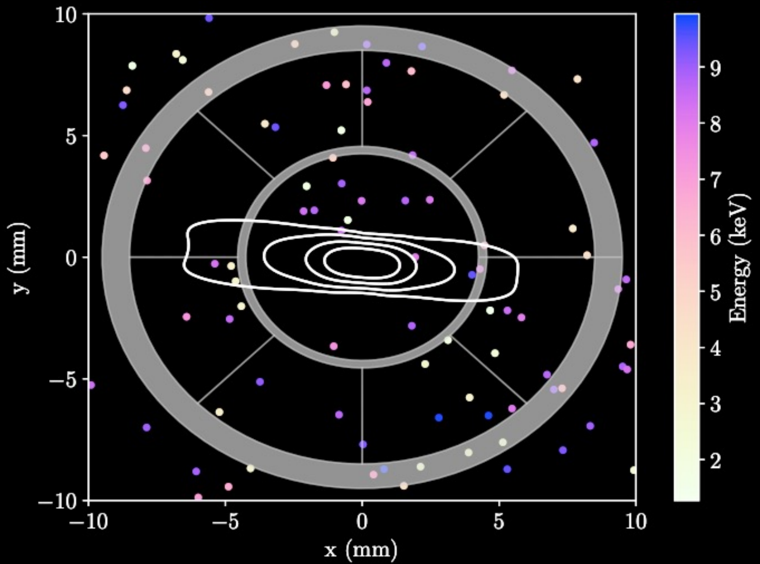
CAST Collaboration, Phys. Rev. Lett. 133, 221005 (2024)
CAST Collaboration , Nature Phys. 13 584-590 (2017)
CAST Collaboration, Phys. Rev. D 92 021101 (2015)
CAST Collaboration Phys. Rev. Lett. 112 091302 (2014)
CAST Collaboration, JCAP 1305 010 (2013)
CAST Collaboration, Phys. Rev. Lett. 107 261302 (2011)
CAST Collaboration, JCAP 0902 008 (2009)
CAST Collaboration, JCAP 0704 010 (2007)

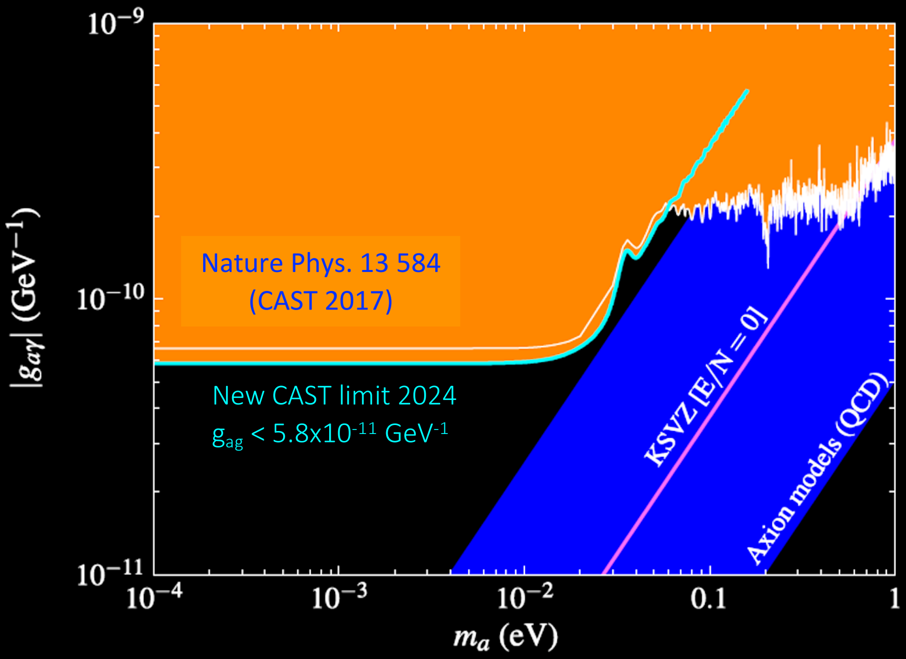
▸ CERN AXION SOLAR TELESCOPE (CAST)

- ✓ Tailor-made x-ray telescope for axions
- ✓ Push MMs detector efficiency and background

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

- ✓ Tracking statistics 314.6 hours
- ✓ Background ~8 counts per year





CAST Collaboration
Phys. Rev. Lett. 133, 221005 (November, 2024)

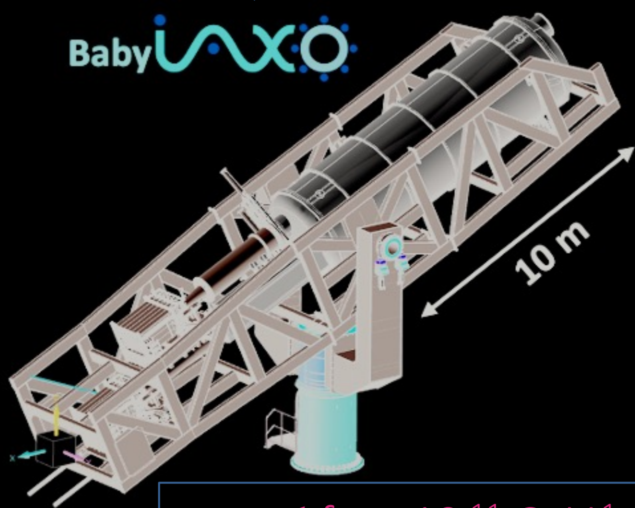
22 years after its first data taking and still ticking!

Solar axion searches

Future experiments

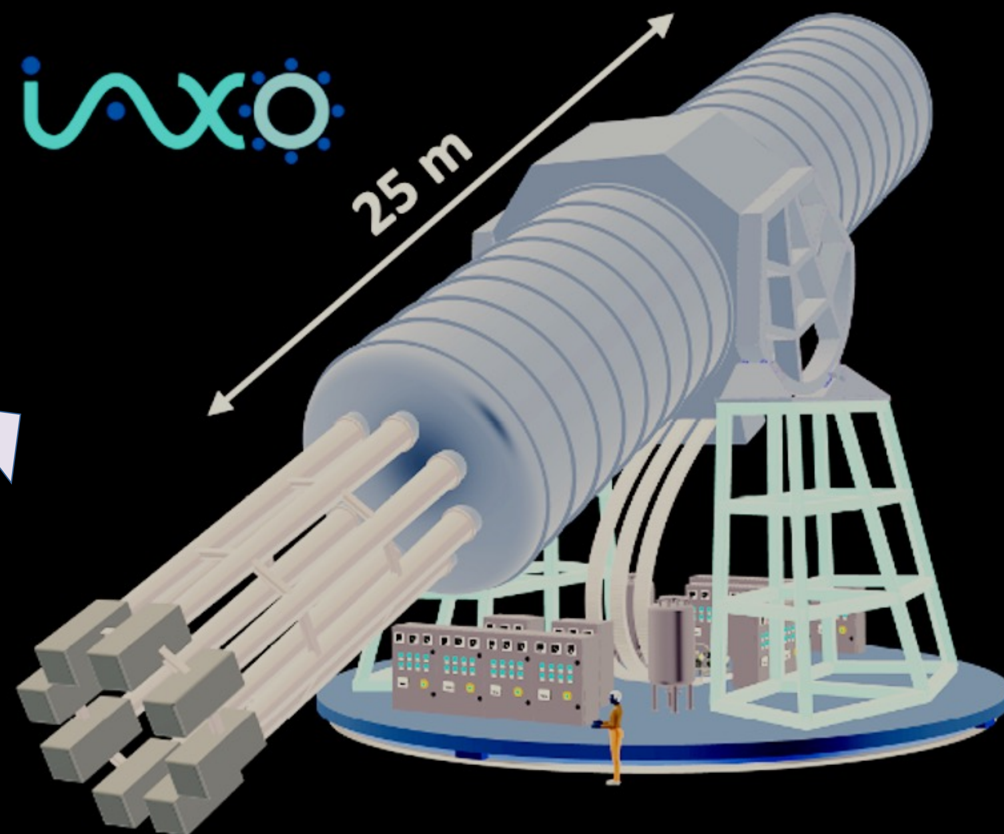
$g_{a\gamma} \lesssim 0.58 \times 10^{-10}$ GeV^{-1}

BabyIAXO



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

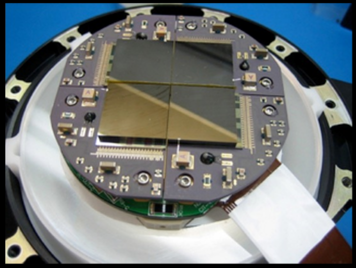
IAXO



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

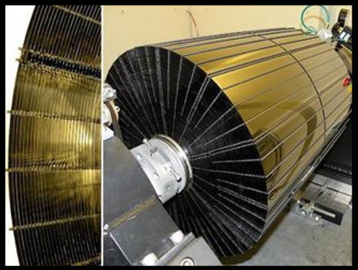
NASA'S NUCLEAR SPECTROSCOPIC TELESCOPE ARRAY (NuSTAR)

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



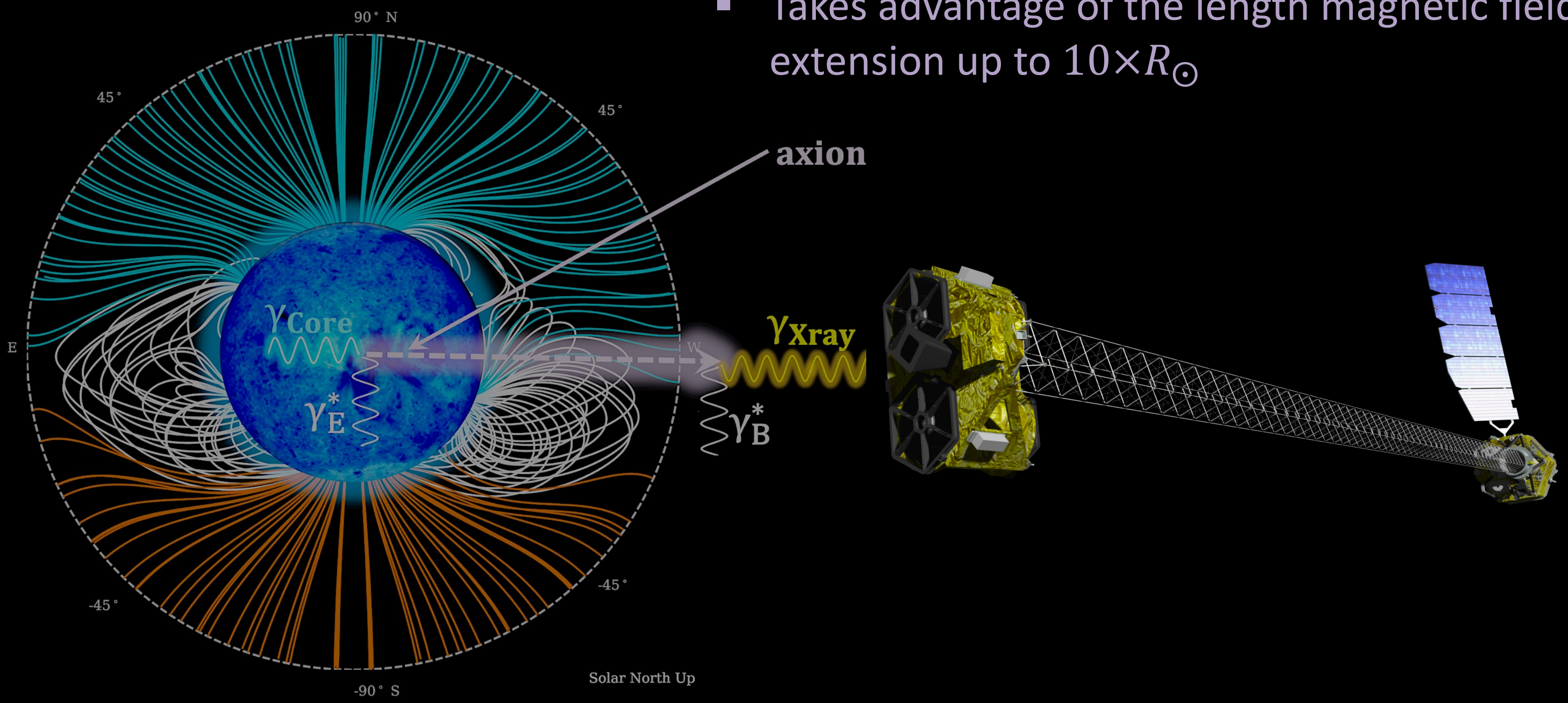
F. A. Harrison et al (NuSTAR Collaboration) 2013 ApJ 770 103.

- 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,…



Solar axion searches

- **Capable to look directly into the Sun**
- **Dedicated campaign observation during Solar Minimum!**
  - Takes advantage of the length magnetic field extension up to $10\times R_\odot$



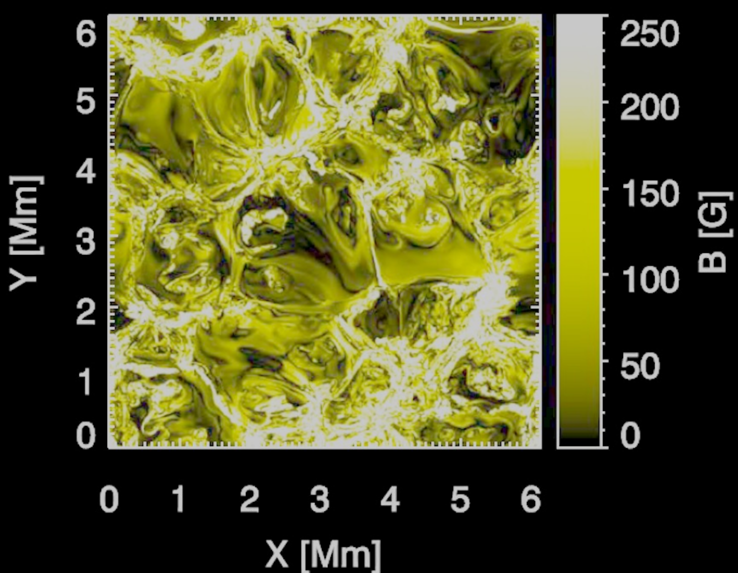
$$P_{a\to\gamma}(h, m_a) = \left(\frac{1}{4} g_{a\gamma}^2\right) \times \left| \int_0^h dh' B_\perp(h') e^{i\int_0^{h'} dh'' q(h'')} e^{-\frac{1}{2}\int_{h'}^{h} dh'' \Gamma(h'')} \right|^2$$

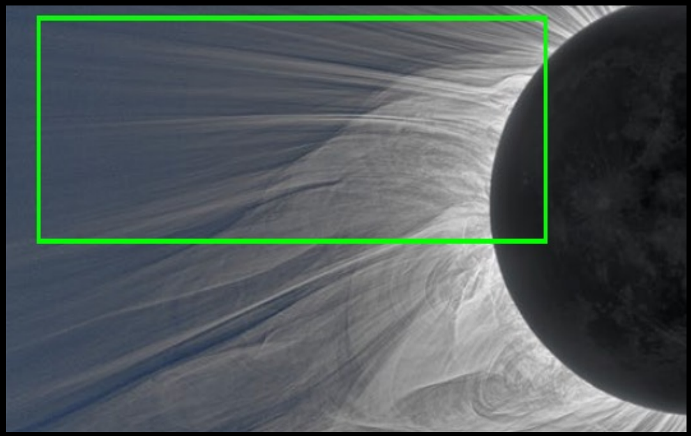
Van Bibber et al 1989 Phys. Rev. D 39 2089

Novel approach

- ✓ For altitudes below 400 km, MURaM radiative Magneto Hydro-Dynamics (**MHD**) code
- ✓ For the coronal magnetic field, Predictive Science Inc. (**PSI**) MHD simulation corresponding to the July 2, 2019 solar eclipse, during a quiet phase of solar activity that aligns with the conditions of our observations
- ✓ We perform an interpolation between the photo spheric and coronal magnetic field models, which is further validated by the Potential-Field-Source-Surface (PFSS) model for the specific day of observation.

del Pino Aleman et al., ApJ 863 164 (2018)

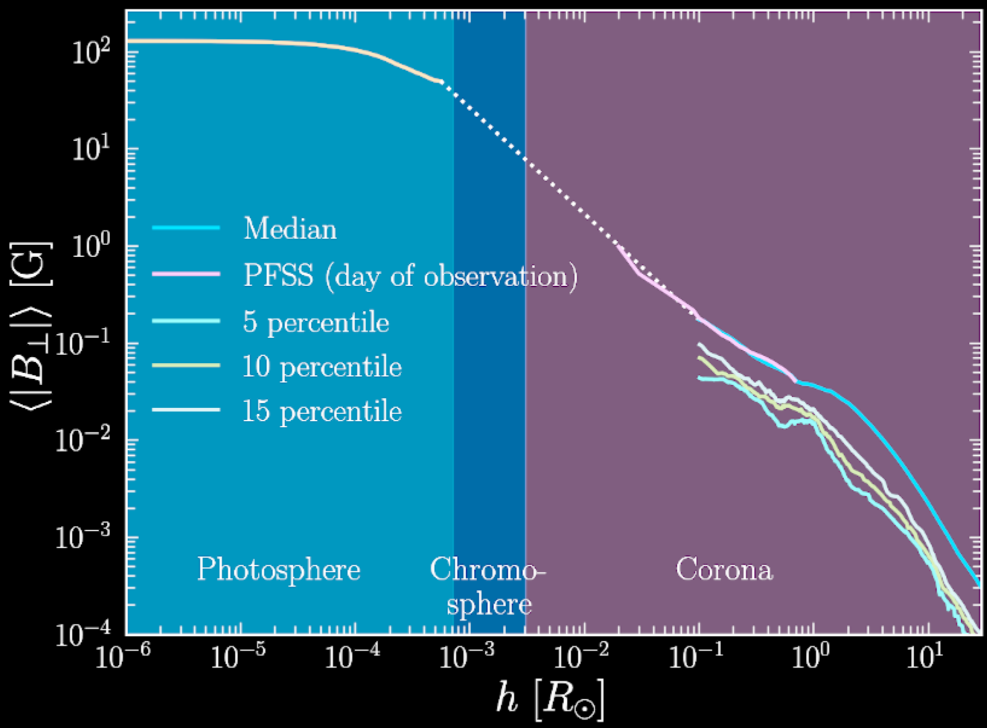




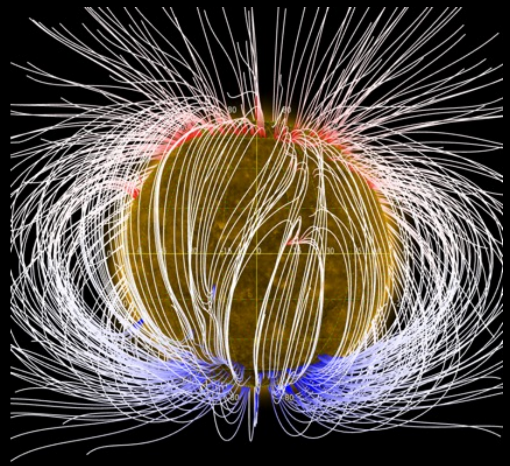
Mikic et al., Nature Astronomy 2, 913–921 (2018)

Process is repeated 120 times, each time rotating the model by an azimuthal angle of 3° Finally, for each altitude h, we calculate the median of these 120 values of $\langle|B_\perp|\rangle$

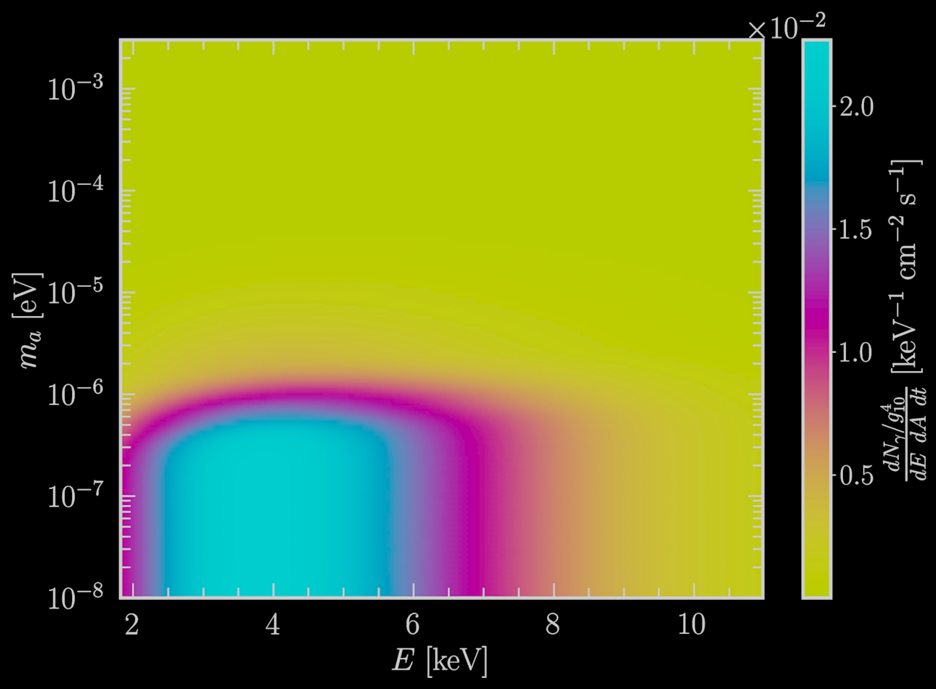
- **Model the perpendicular component of the solar atmospheric magnetic field.**

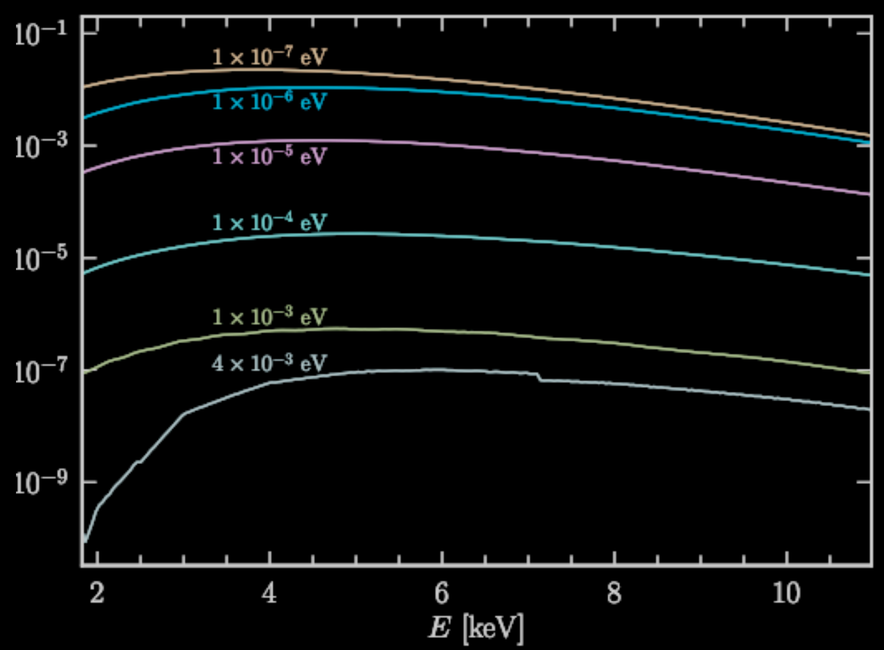


Rempel et al., The Astrophysical Journal 789, 132 (2014)
del Pino Aleman et al., ApJ 863 164 (2018)
Mikic et al., Nature Astronomy 2, 913–921 (2018)



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



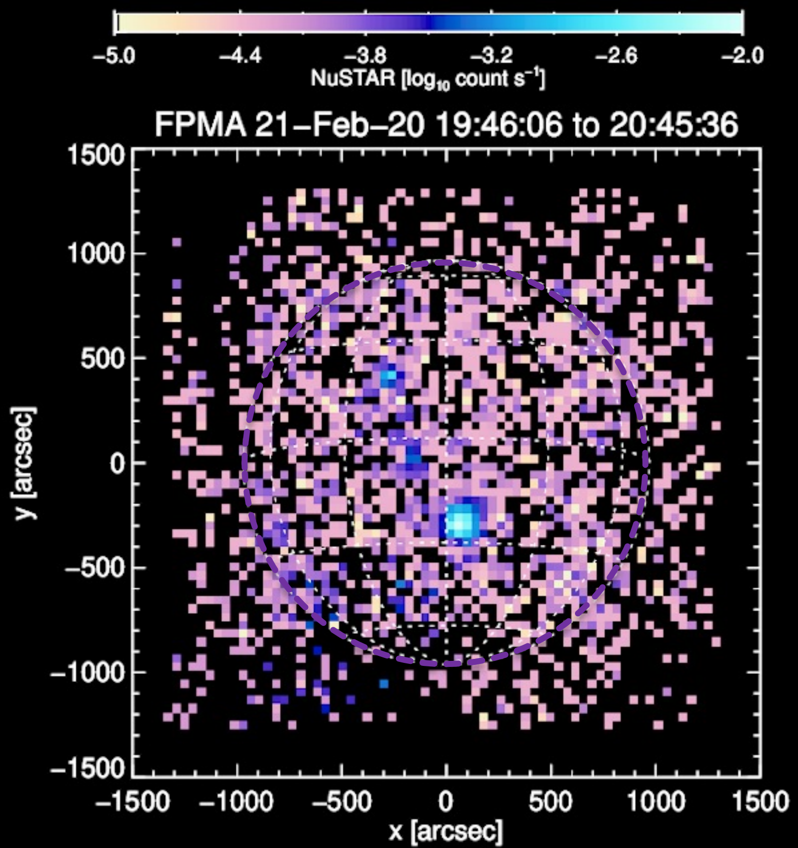


$$\frac{dN_\gamma}{dE\, dA\, dt\, d\Omega} = \frac{dN_a}{dE\, dA\, dt\, d\Omega} P_{a\rightarrow\gamma}$$

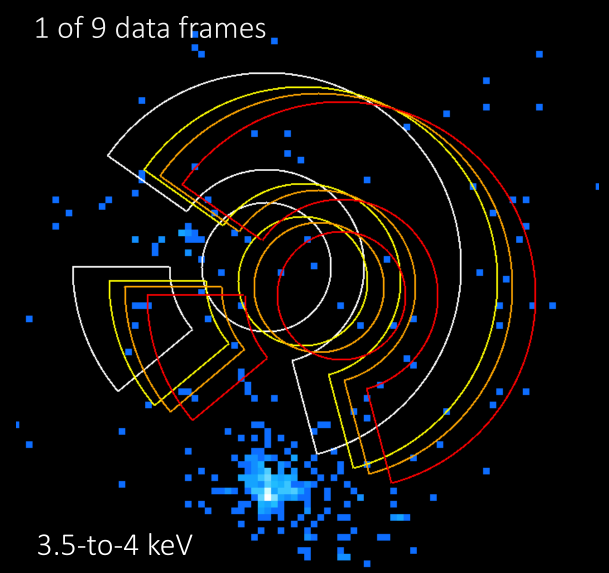
Consider photon cross-section:

- ✓ X-ray attenuation due to coherent scattering
- ✓ Incoherent scattering (Compton)
- ✓ Photoelectric absorption

- **2020 data taking campaign corresponding to Solar minima**

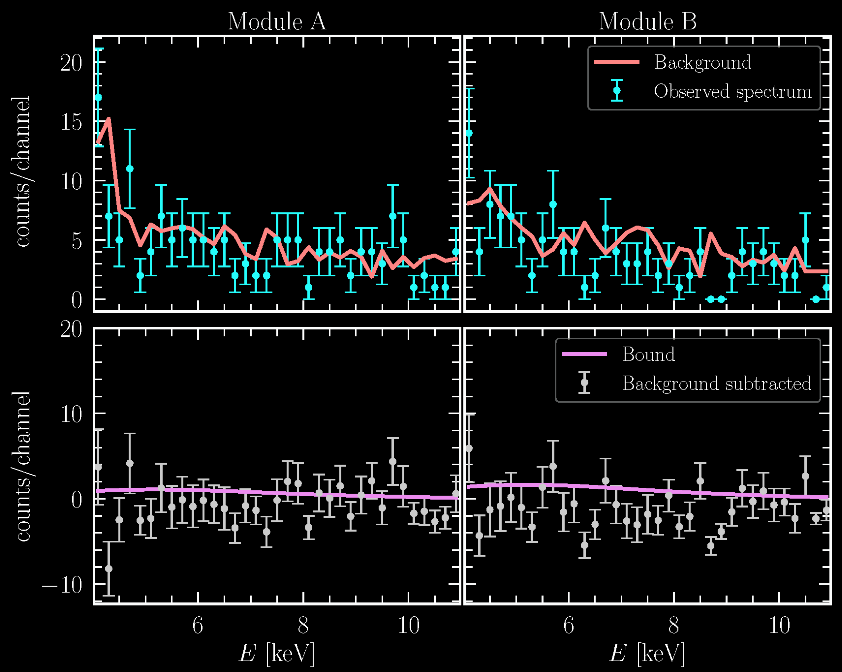


Dedicated Sun observation 7h exposure

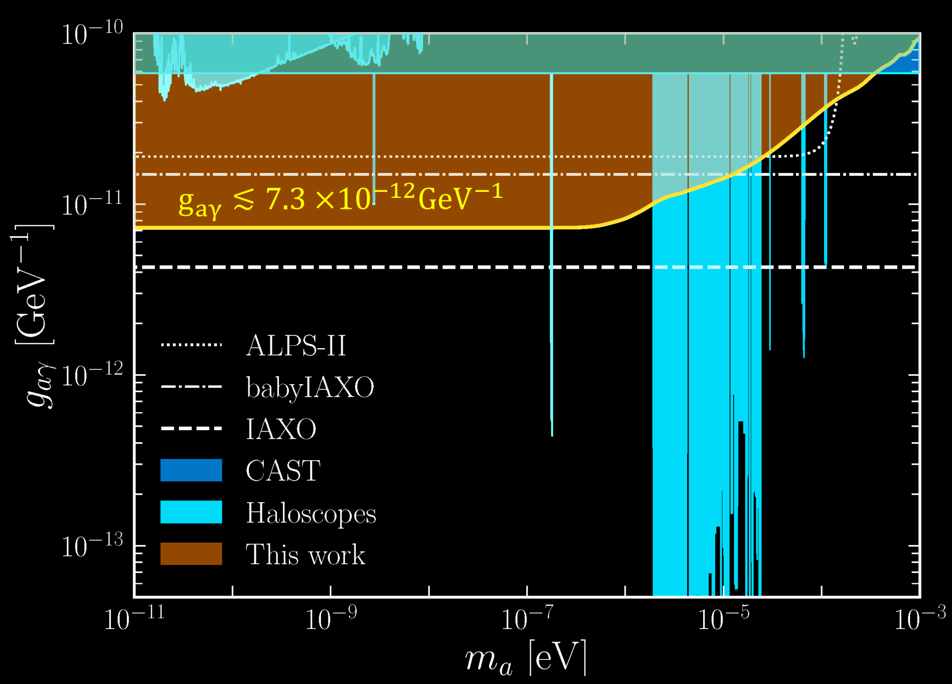


Observation near minimum of the Sun's 11-year activity cycle → ideal environment by minimizing interference from bright active regions or solar flares

- **Dedicated analysis to extract signal and background spectra.**
  - ✓ Source selection 0.1 $R_{\odot}$ to avoid contamination from a bright spot
  - ✓ Background selection 0.15-to-0.3 $R_{\odot}$ (other criteria also explored for systematics)



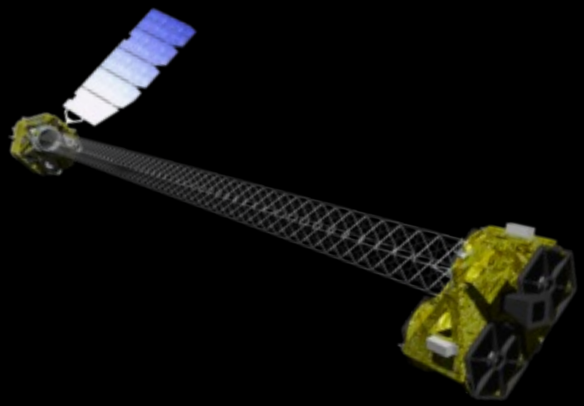
J. Ruz et al., PRL accepted (2025)



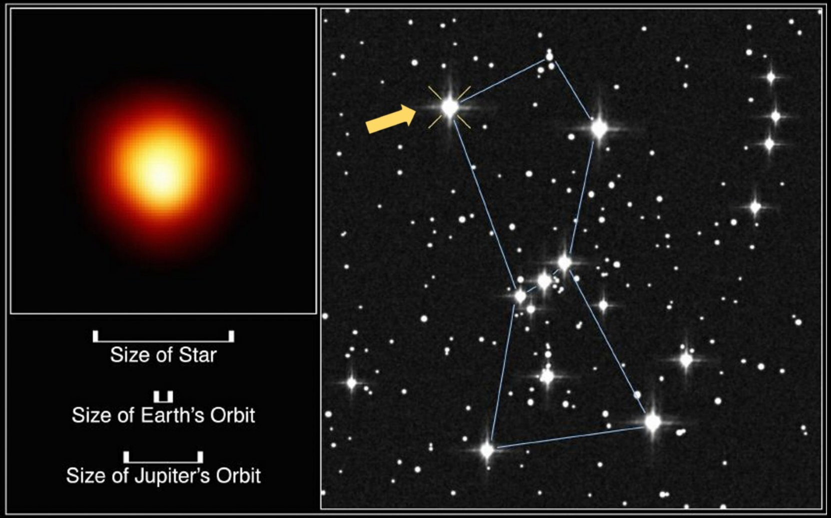
NuSTAR as an Axion Helioscope

J. Ruz,[1,2,*] E. Todarello,[3,4,5,†] J. K. Vogel,[1,2,‡] F. R. Candón,[1,2] M. Giannotti,[2,6] B. Grefenstette,[7] H. S. Hudson,[8] I. G. Hannah,[8] I. G. Irastorza,[2] C. S. Kim,[9] M. Regis,[4,5] D. M. Smith,[10] M. Taoso,[5] and J. Trujillo Bueno[11,12]

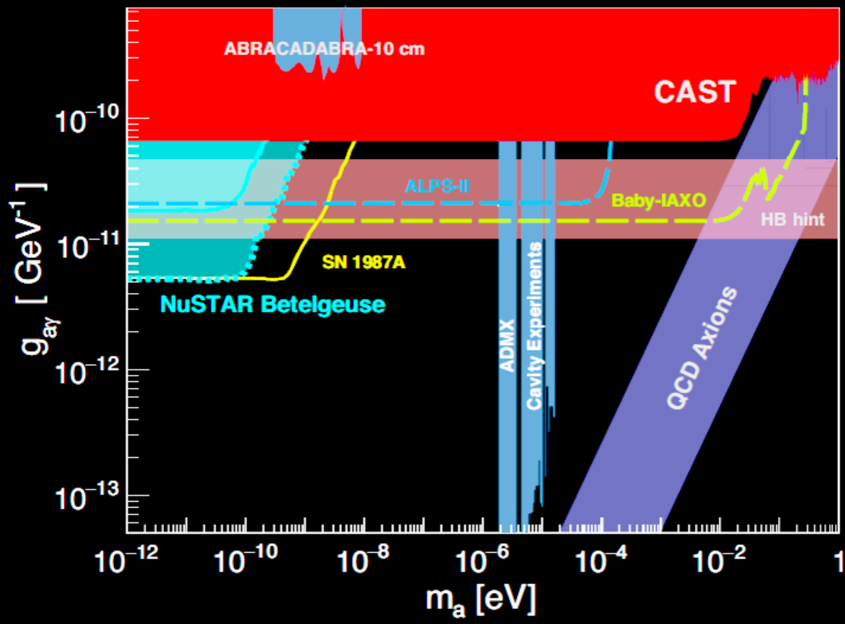
Beyond solar axion searches — Space Missions

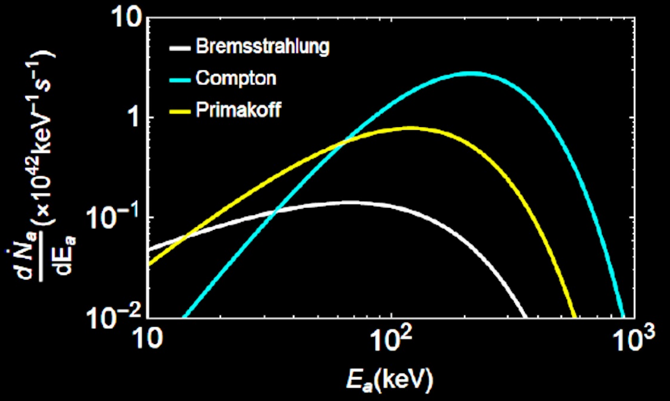


Probing axion-photon Couplings with Supergiant Stars (in preparation)



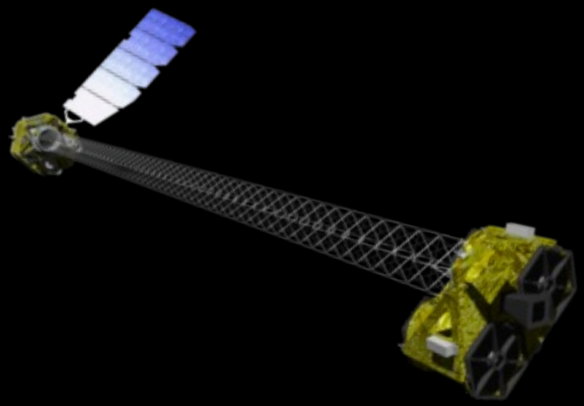
Betelgeuse



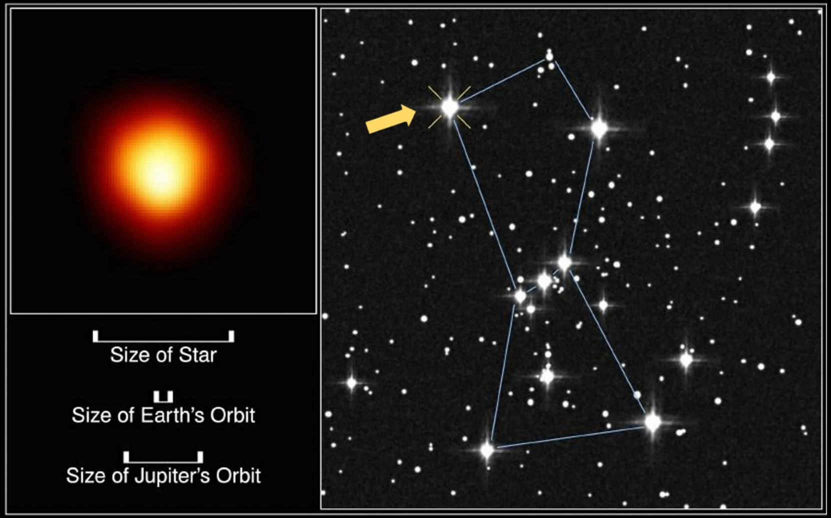


Beyond solar axion searches

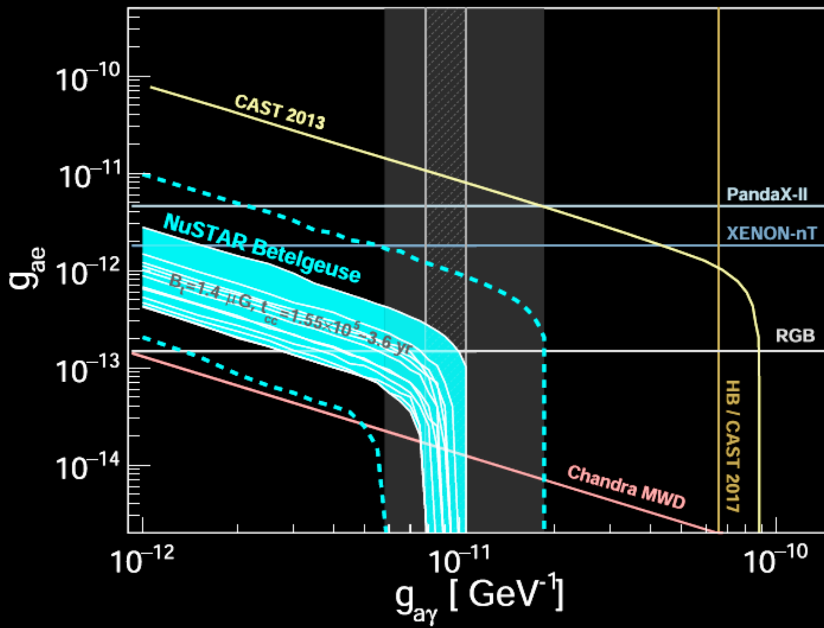
Space Missions

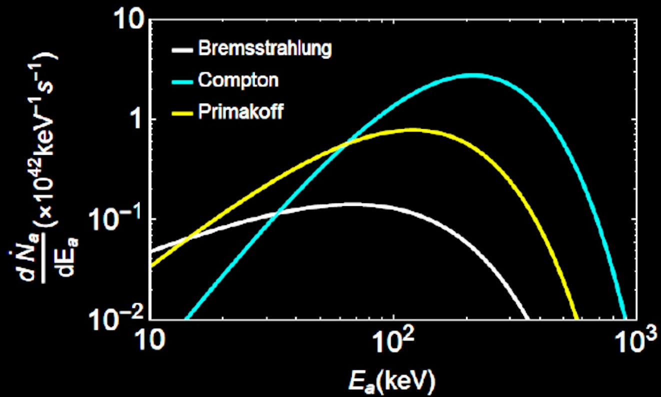


Probing axion-electron Couplings
with Supergiant Stars (in preparation)



Betelgeuse

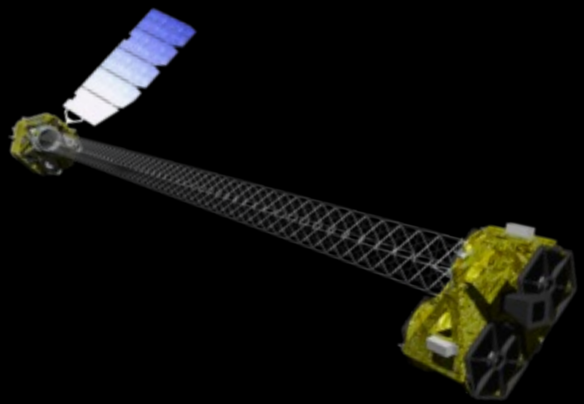




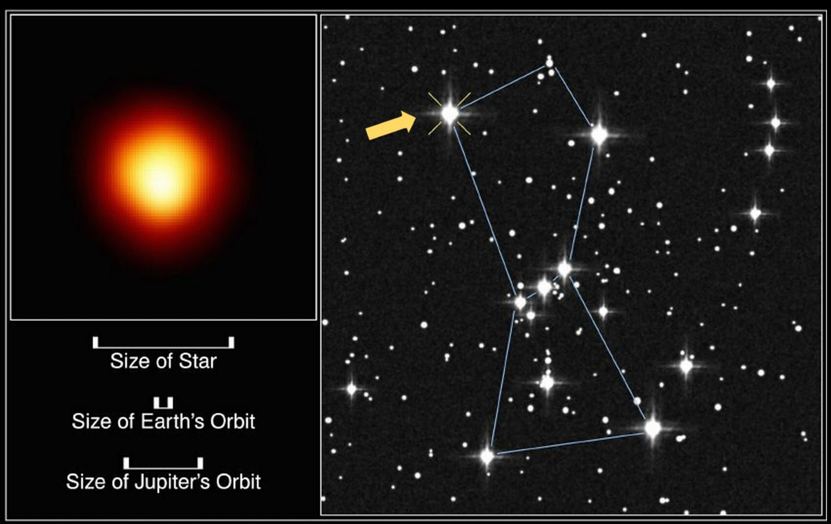
Xiao et al., Phys. Rev. D 106, 123019

Beyond solar axion searches

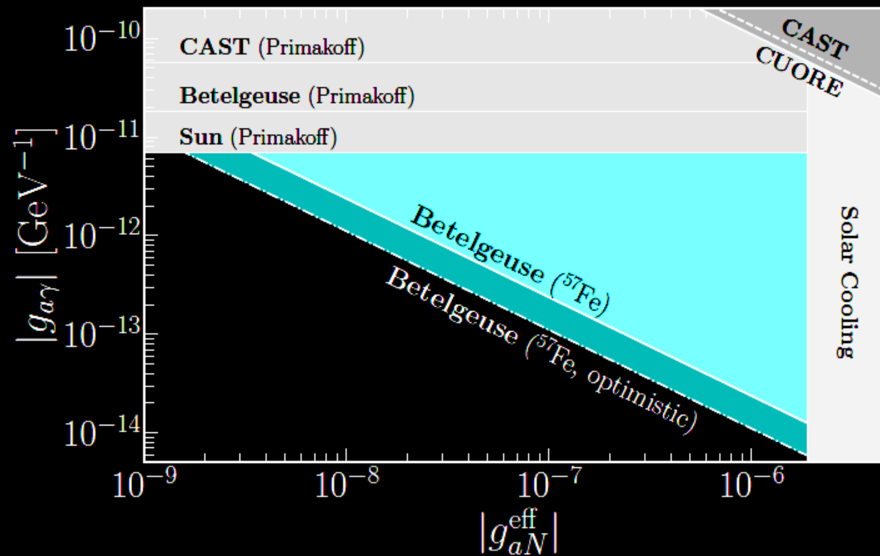
Space Missions



Probing axion-nucleon Couplings with Supergiant Stars (in preparation)



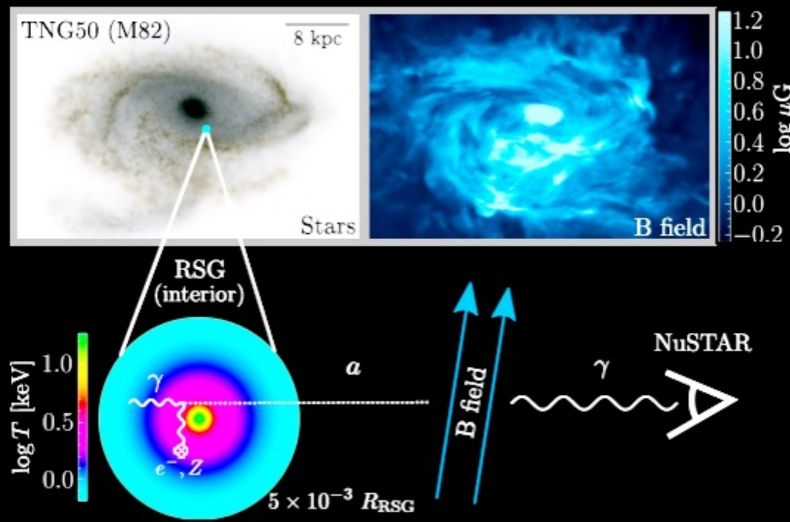
Betelgeuse

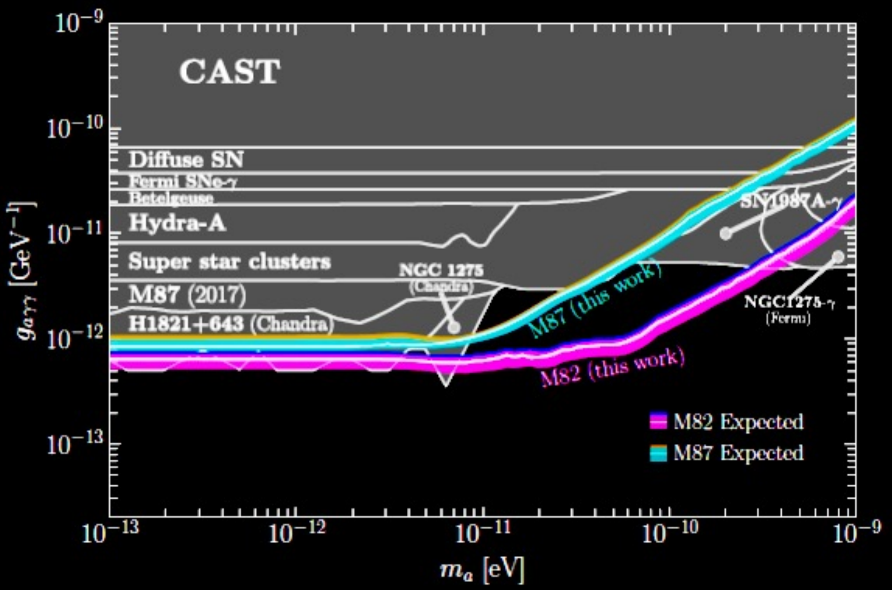


Candon et al., arXiv:2504.21107

Stay tunned for F. Candón presentation

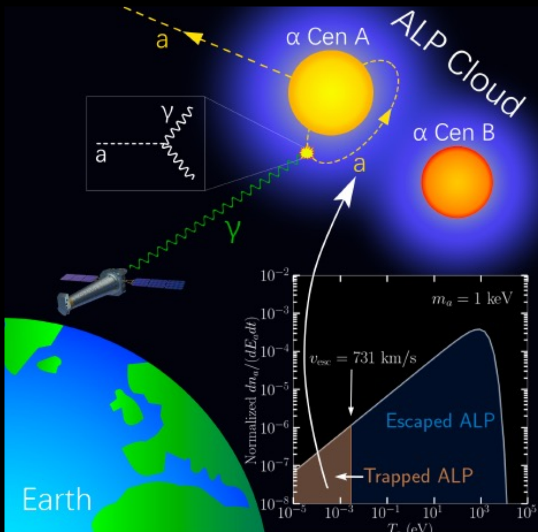
NuSTAR Observations of M82 and M87



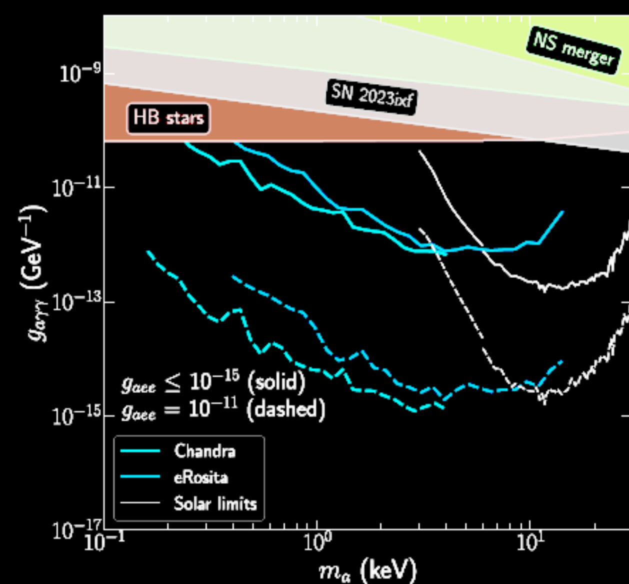


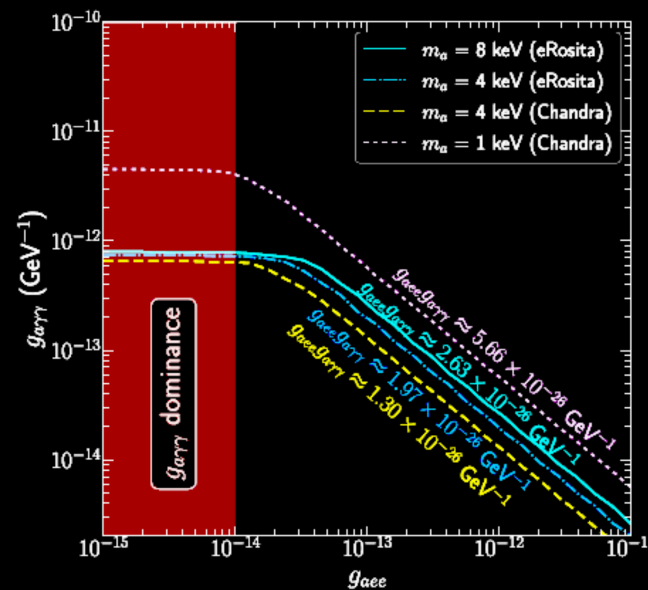
Safdi et al., Phys. Rev. Lett. 134, 171003

Probing axion couplings with Alpha Centauri

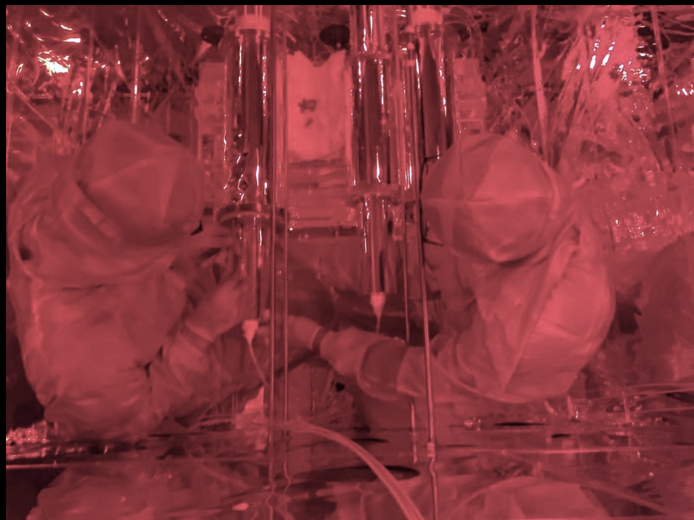


Chen et al., Phys. Rev. Lett. **134**, 241001





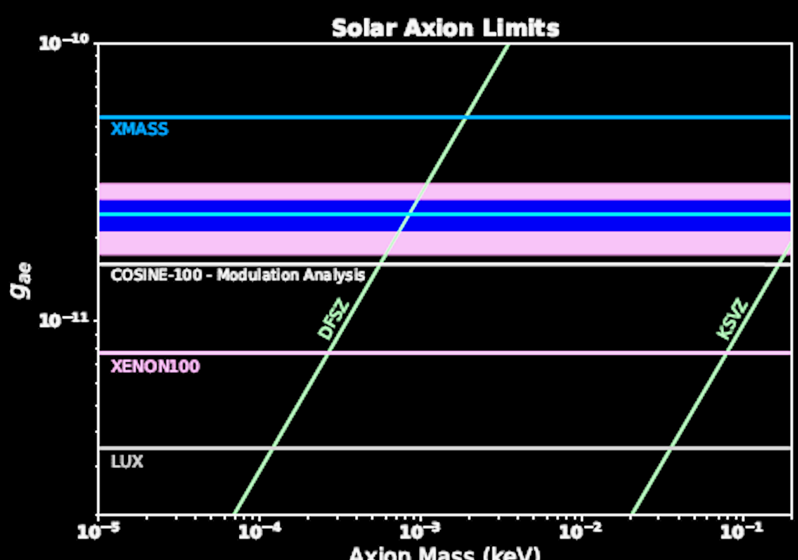
Beyond solar axion searches — Underground

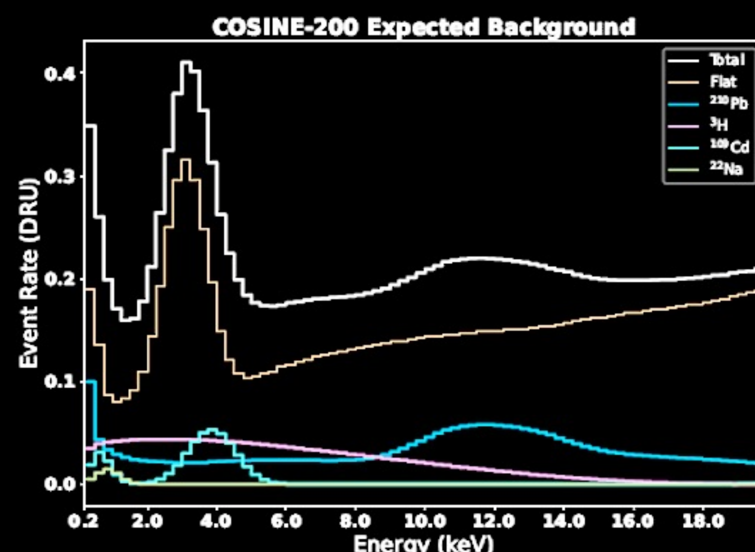


- **Axio-electric cross sections in Na and I atoms:**

$$\sigma_{ae} = \sigma_{pe} \frac{3E_a^2 g_{ae}^2}{16\pi\alpha m_e^2 \beta_a}\left(1 - \frac{\beta_a^{2/3}}{3}\right)$$

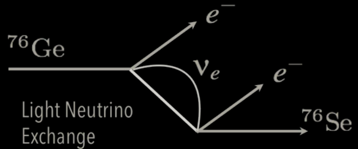
where σ_{pe} is the photoelectric cross section, E_a is the axion energy, α is the fine structure constant, m_a is the axion mass and β_a is the axion velocity as $\beta_a = \sqrt{1 - m_a^2/E_a^2}$





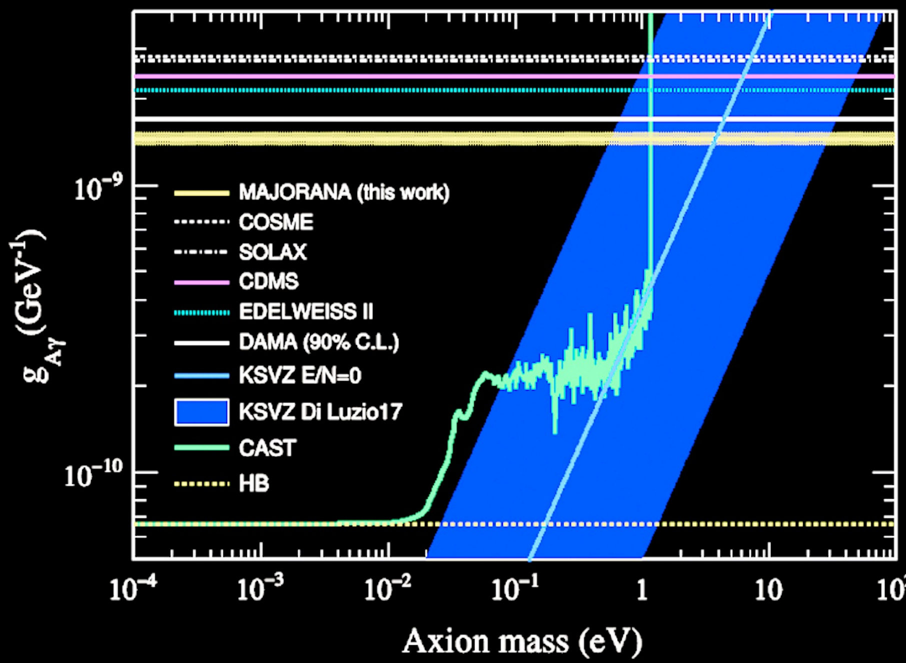
Beyond solar axion searches — Underground

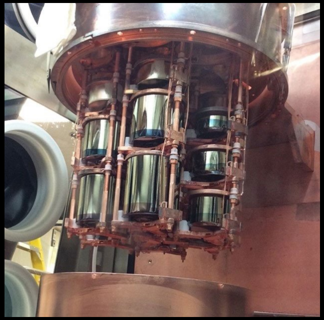
Like a bigger telescope can collect more light to view fainter objects, a greater mass of germanium improves the odds of observing rare decay.



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

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





Bragg-Scattering
44 kg
Germanium

Conclusions

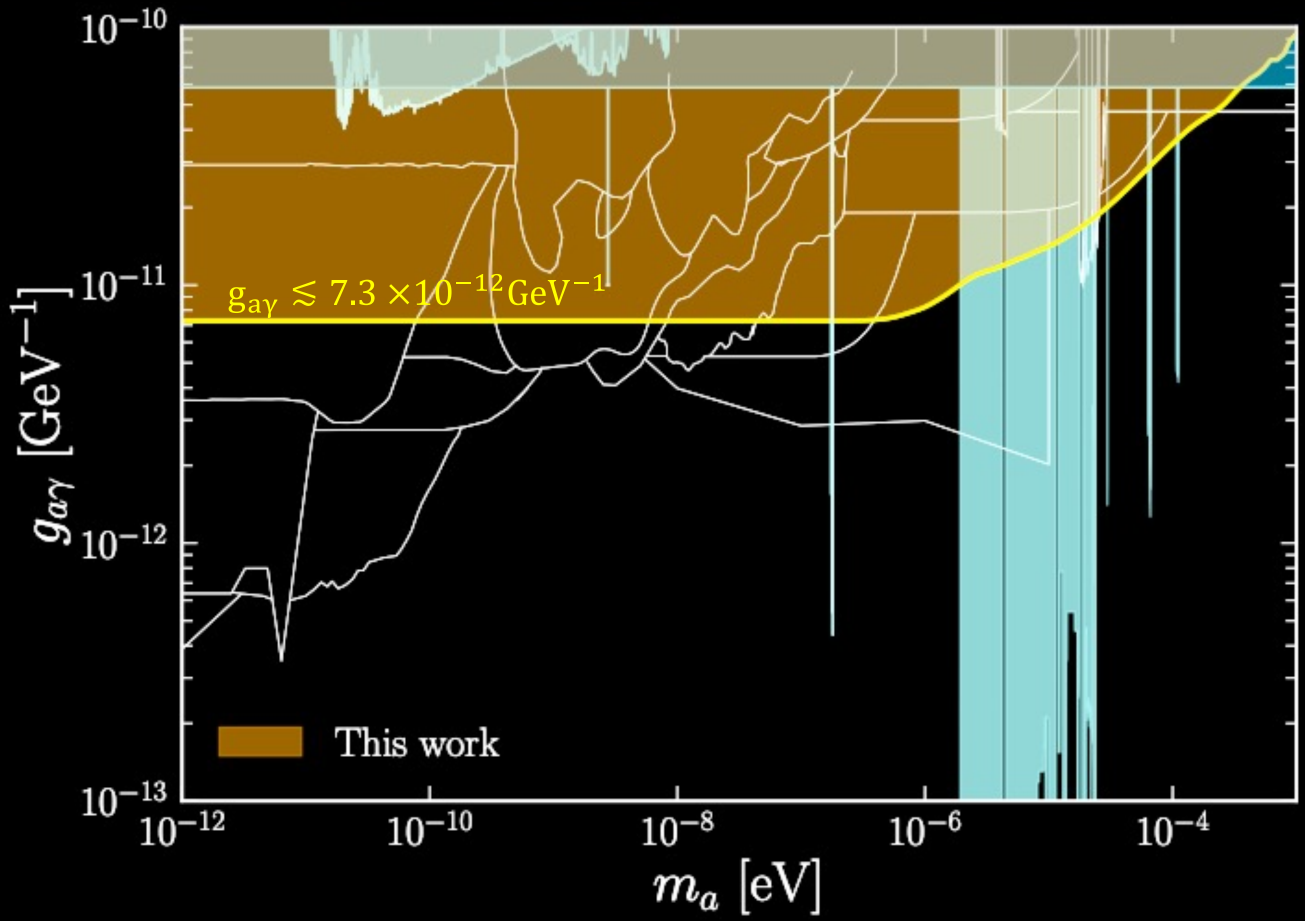
- ✓ Axions are may leave distinctive X-ray signals in helioscopes
- ✓ The nature of the observed spectra could determine the production axion-coupling. Fo instance, Primakoff, BCA or axion-nucleon in the Sun
- ✓ Solar axion searches probe different axion couplings and large regions of well-motivated axion parameter space.
- ✓ NuSTAR, a new helioscope approach, provides with the new Solar Axion reference limit $g_{a\gamma} < 7.3 \times 10^{-12}$ GeV^{-1} for axion masses up to 5×10^{-7} eV, almost an order of magnitude better than the latest published CAST result and already surpassing future laboratory experiments like BabyIAXO
- ✓ There are other X-ray signals from axions that can be measured in orbit. For instance, Betelgeuse, M82 & M87, Alpha Centauri, … should we check for Antares?
- ✓ Underground laboratories also look for axion signals on the keV regime. For instance, axion-electron annual modulation has been studied by COSINE and Bragg scattering continues to be motive of study by the Majorana experiment

Back-up slides

NuSTAR

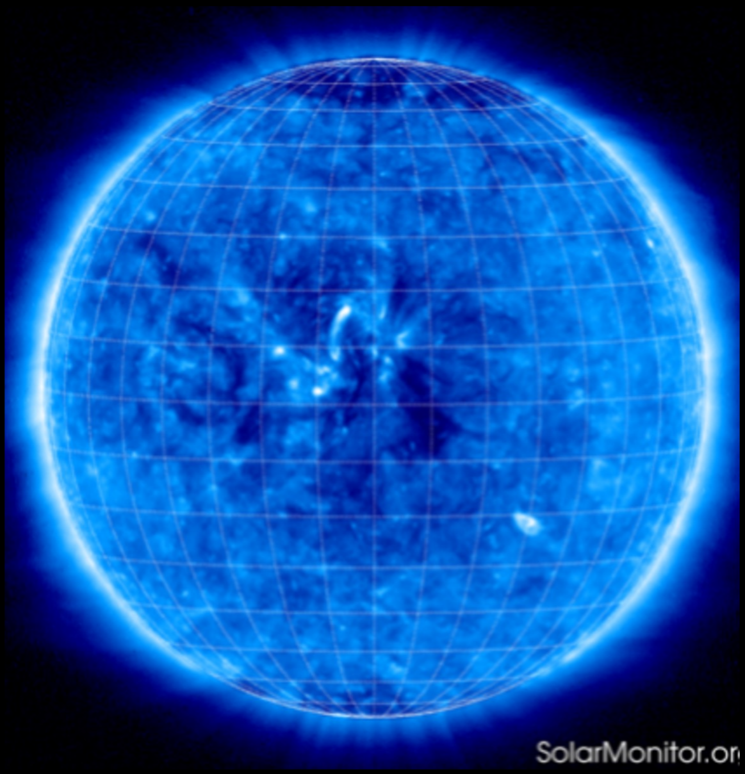
Comparison

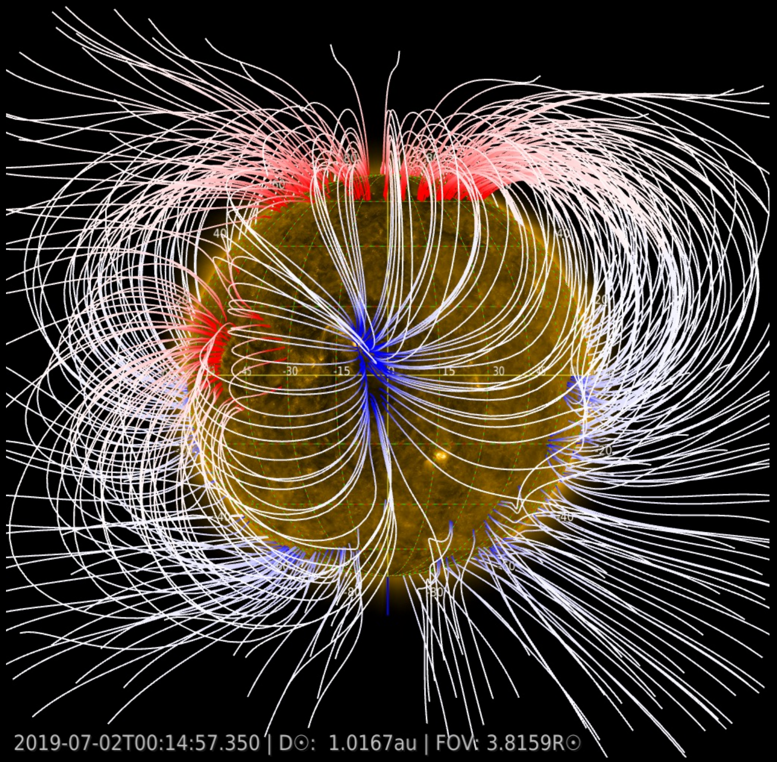
J. Ruz et al (arXiv:2407.03828) PRL accepted



https://doi.org/10.1103/18sn-hxtb

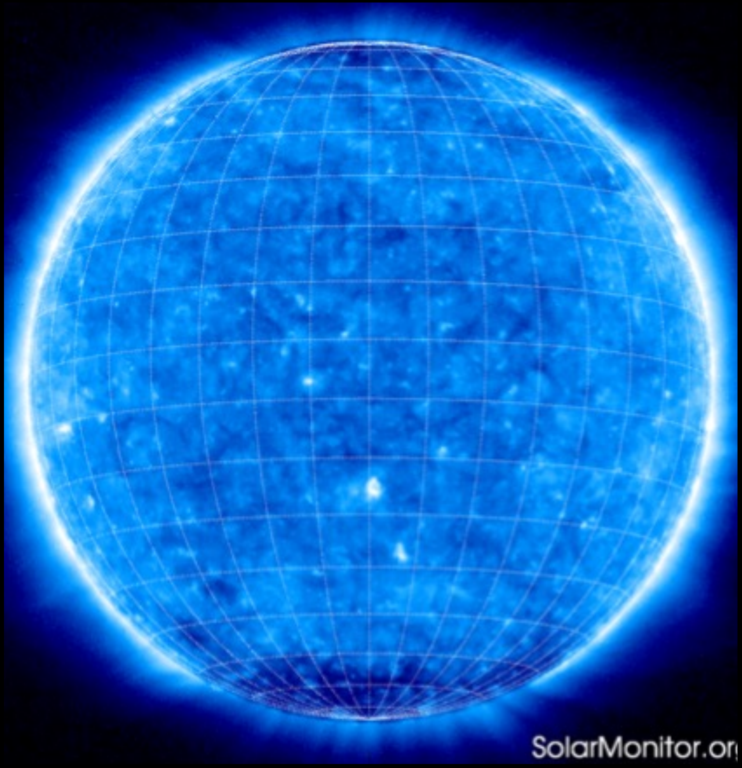
Observations & Modeling

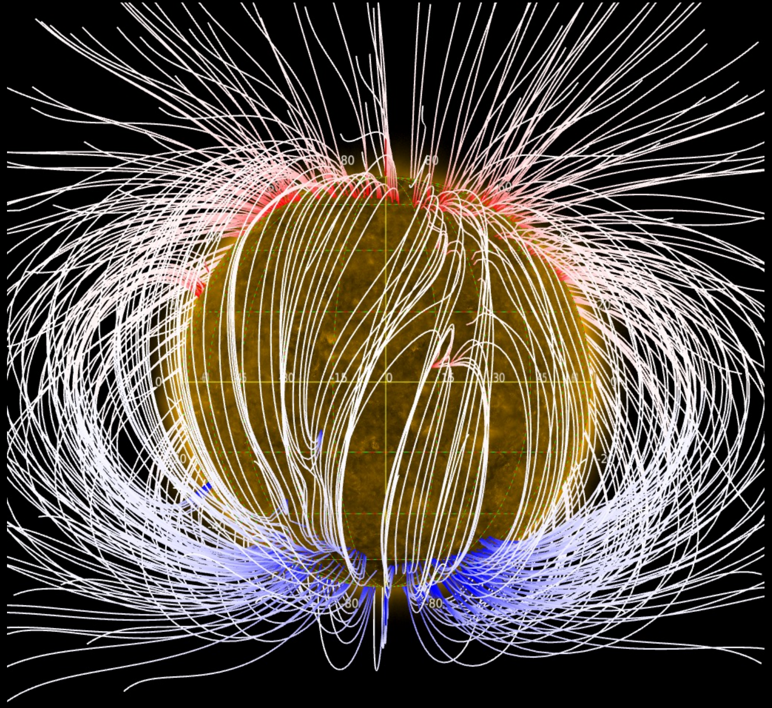




- Snapshots at 174 A from the SWAP spacecraft, showing the million-degree corona during 2019 eclipse (left) and PSI modeling at the time of eclipse (right), showing the presence of a weak active region near disk center.

Observations & Modeling





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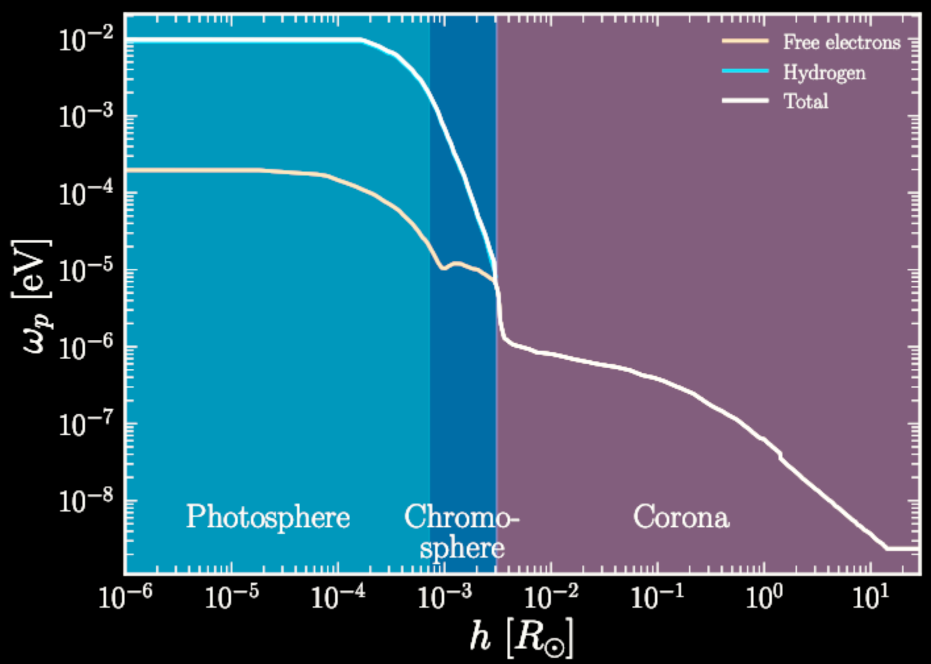
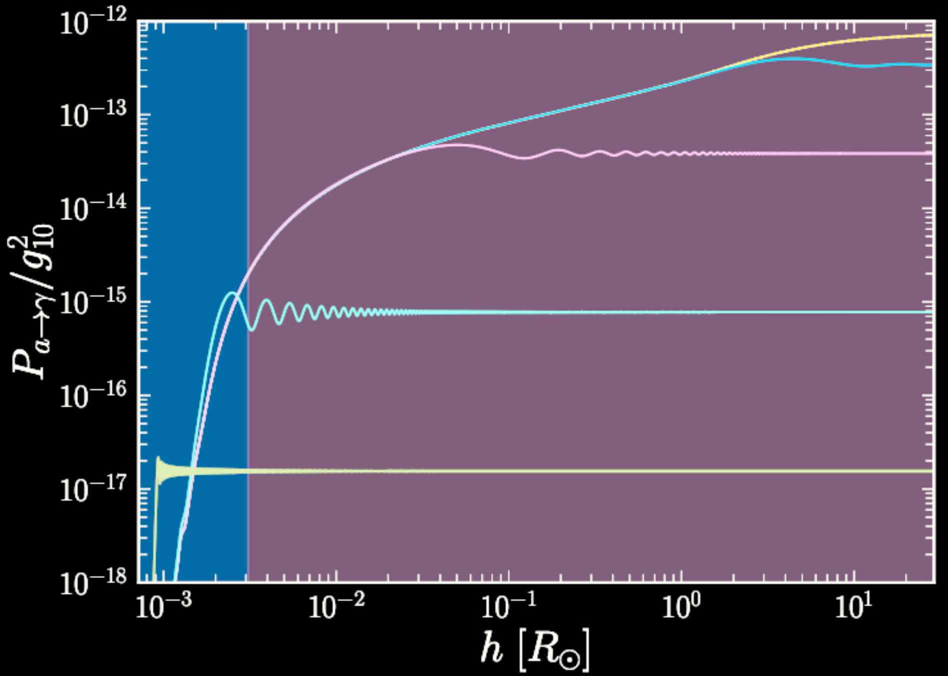
- Snapshots at 174 A from the SWAP spacecraft, showing the million-degree corona during **NuSTAR quiet Sun data taking** early 2020 (left) and evolution of the PSI modeling for quiet Sun conditions (right).

- **Model free electron and Hydrogen**
  - ✓ Determine contributions to axion plasma frequency
  - ✓ Establish conversion probability for different regions of the Sun's atmosphere



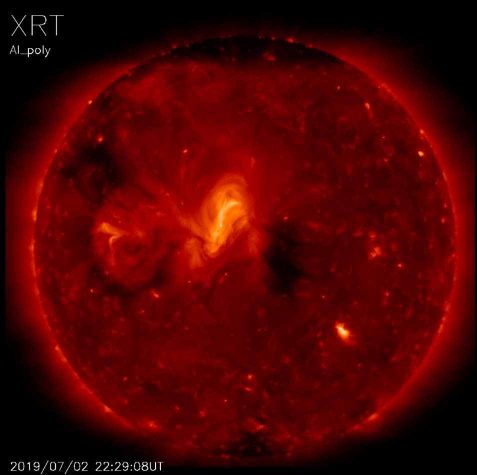


We include elements up to atomic number Z = 30 in our calculation, using elemental abundances from the CHIANTI database.

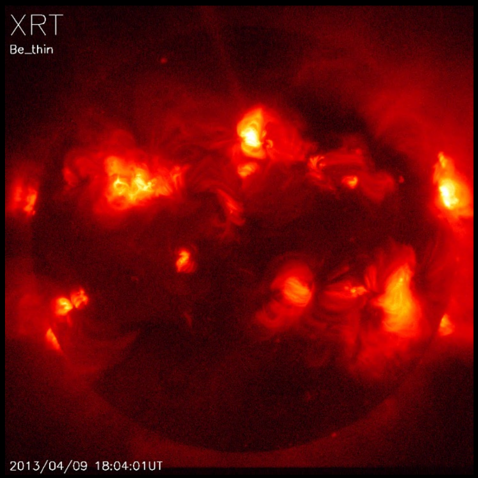
Space missions

Novel approach

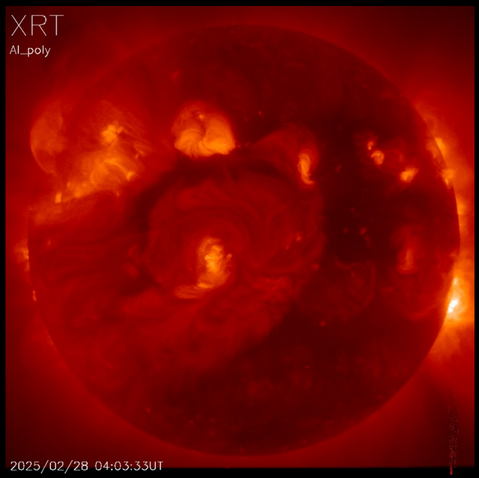
Eclipse day



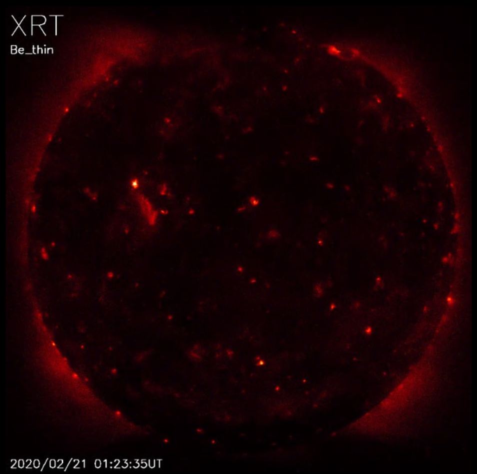
Solar maximum



Feb 2025



Observation day



Hinode XRT archival data

https://solar.physics.montana.edu/HINODE/XRT/SCIA/

Observation near minimum of the Sun's 11-year activity cycle

ideal environment by minimizing interference from bright active regions or solar flares