Axions in astrophysics

Come close!

Session moderator: M.C. David Marsh (Stockholm University)

DESY, Hamburg, 30th January, 2024

Instructions from organisers:

- Not just a series of talks
- Interactive, discussion-based
- Prepare the ground for possible preprint summary
- “No introductions to the strong CP problem”

Session structure:

- Organised around a series of 7 questions
- Each question opened with two ~5-minute "perspectives"
  single points of relevance that the participant would like to highlight,
  need not be related to one's own work, or be comprehensive in any way.

  By: Malte Buschman, Pierluca Carenza, Jordi Escudé, Sebastian Hoof, Alessandro Lella, Andrei Lobanov, Jamie McDonald, Manuel Meyer, Georg Raffelt, Eike Ravensburg, Andreas Ringwald.
- Free discussion following the "perspectives"

"Code of conduct": we're respectful and generous; we seek to benefit from each others' experiences

Timekeeping: few strict limits; please be mindful; session likely to continue beyond the coffee break

Questions to be addressed (cf. indico):

1. How can the astroparticle community be most useful to, and taken seriously by, the wider community searching for ALPs? What are good standards and practices for communicating possible ”hints”?

2. What is the status of currently proposed hints? Are there regions of parameter space that are particularly important to target?

3. What is the status of current limits on axions? Given systematic and statistical uncertainties, are there search methods that are more suitable as “discovery channels” rather than for placing limits on axion parameters?

4. Considering the astrophysical systems that have led to insights about ALPs before, what improvements can we expect through new observational capabilities over the coming decade(s)?

5. When do (if not already) astrophysical searches for axions become limited by the modelling of the astrophysical environment? What progress can we make from theory, simulations and future observations to reduce these limitations? For example, how can cosmological and astrophysical simulations or future observations inform the magnetic field modelling required for searches relying on axion-photon conversion? Are there systematic errors associated with simple magnetic field models, and if so, what do they miss?

6. Are there new systems or phenomena, perhaps rare events or systems that will only be probed by the next generation of telescopes, that may shed light on axions and ALPs but that haven’t been used to date?

7. What is the role of modern data analysis techniques, including machine learning, in searches for ALPs through astrophysics? Is there a need to homogenise the statistical methods used for data analysis?

1. How can the astroparticle community be most useful to, and taken seriously by, the wider community searching for ALPs?

   What are good standards and practices for communicating possible ”hints”?

Perspectives by:

Pierluca Carenza (Stockholm University)

Sebastian Hoof (University of Padova)

HARD TIMES

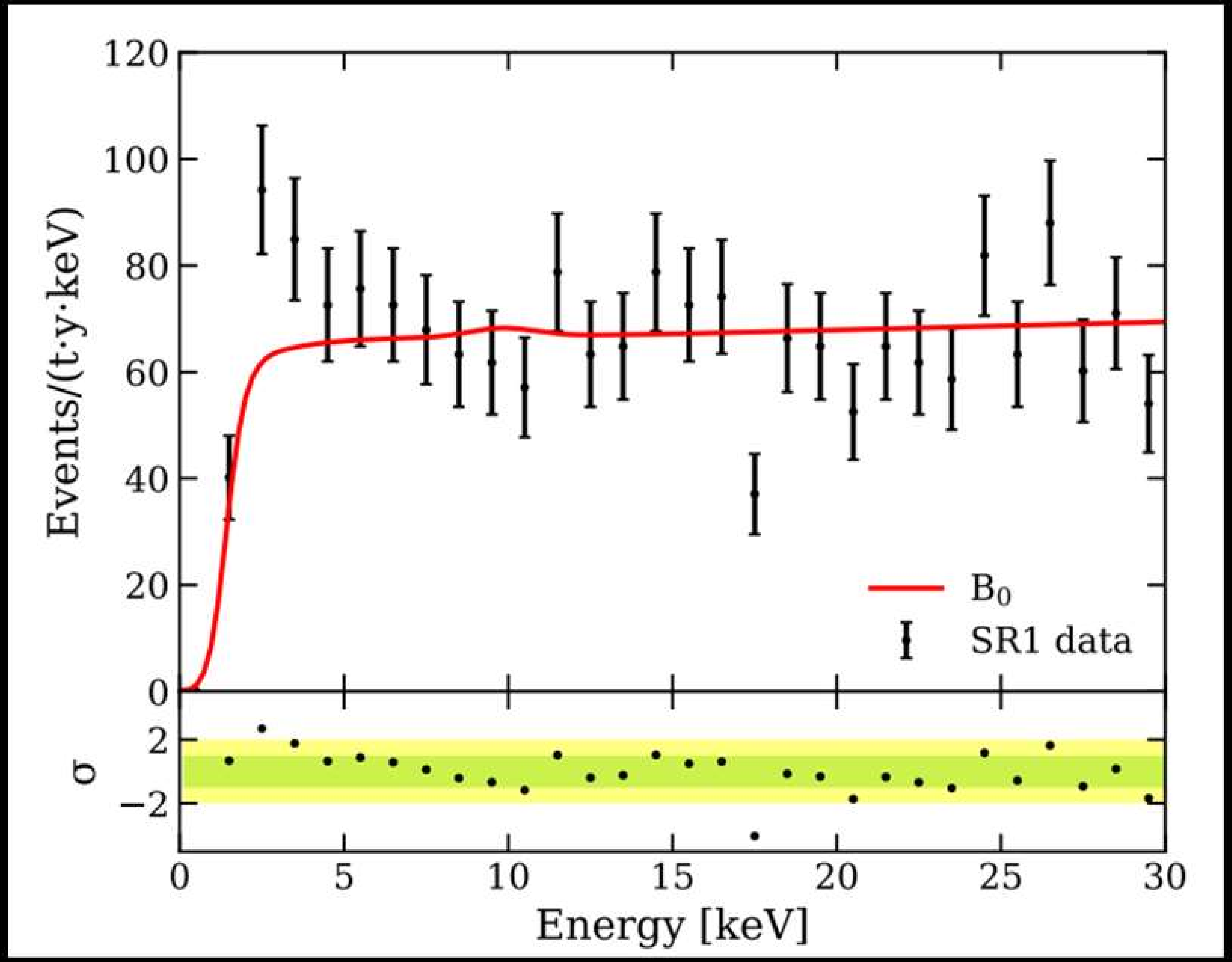
Leo P. Kadanoff

In recent years, physics has seen much of its support base disappear. In Eastern Europe the decline of economy and the changes in the economy have moved interest away from all activities with long-range payoffs. For different reasons, a short-term focus has begun to dominate American life also. Here, all the props for science have begun to weaken. Government has become unpopular. The military has started to shrink. Corporations are concerned with tomorrow's stock value and the next quarterly income statement, and have lost interest in promoting applied research. Antiscientific threads have become evident in many parts of popular thinking. Congress enjoys exposing the misbehavior of some of the leading figures in the biological sciences. Both the animal rights movement and the environmental movement have considerable antiscientific components. Science is in low regard.

our demands and claims become more strident. Very often the expected benefits of any given scientific advance are puffed to many times their real value. Think of cold fusion (or hot), of the statements coming from the Texas Congressional delegation about the SSC, or of the more recent history of high-temperature superconductivity. We are fast approaching a situation in which nobody will believe anything we say in any matter that touches upon our self-interest.

Nothing we do is likely to arrest our decline in numbers, support or social value. Too much of our real base depended on events that are now becoming ancient history: nuclear weapons and radar during World War II, silicon and laser technology thereafter, American optimism and industrial hegemony, socialist belief in rationality as a way of improving the world. Now China and much of Eastern Europe have moved away from science. America's problems cannot

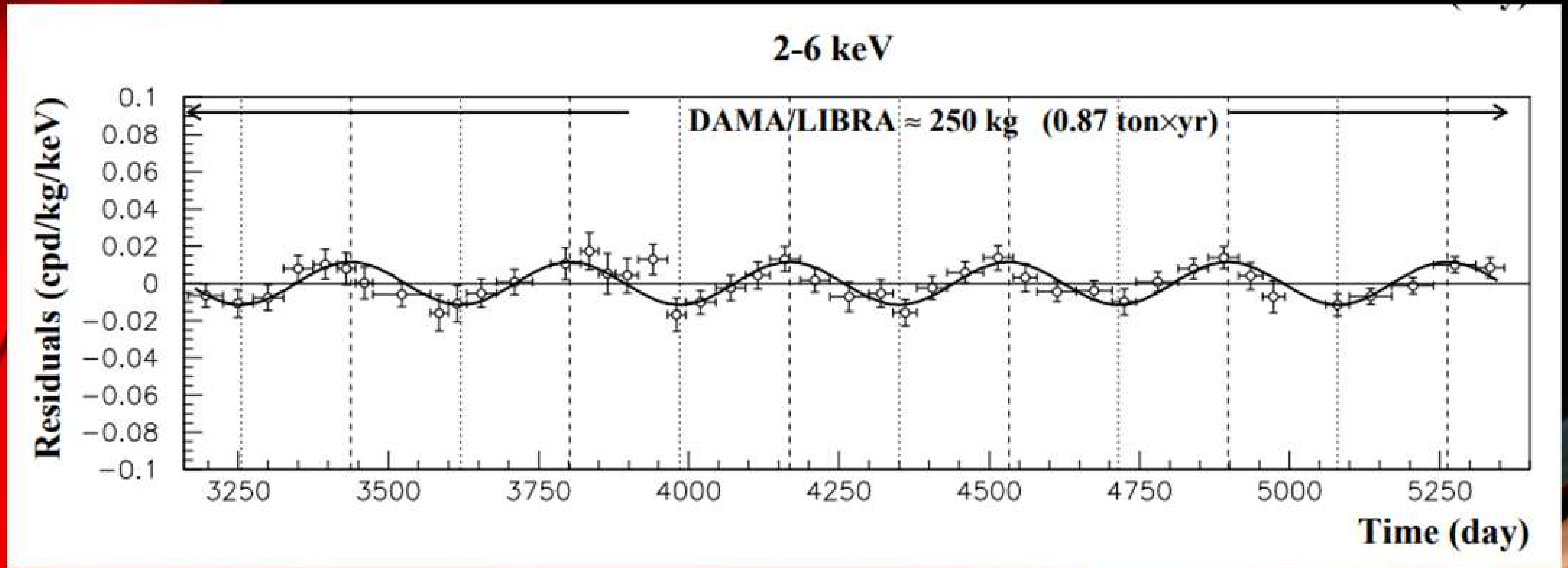
Compatibility with bounds (2006.12487)



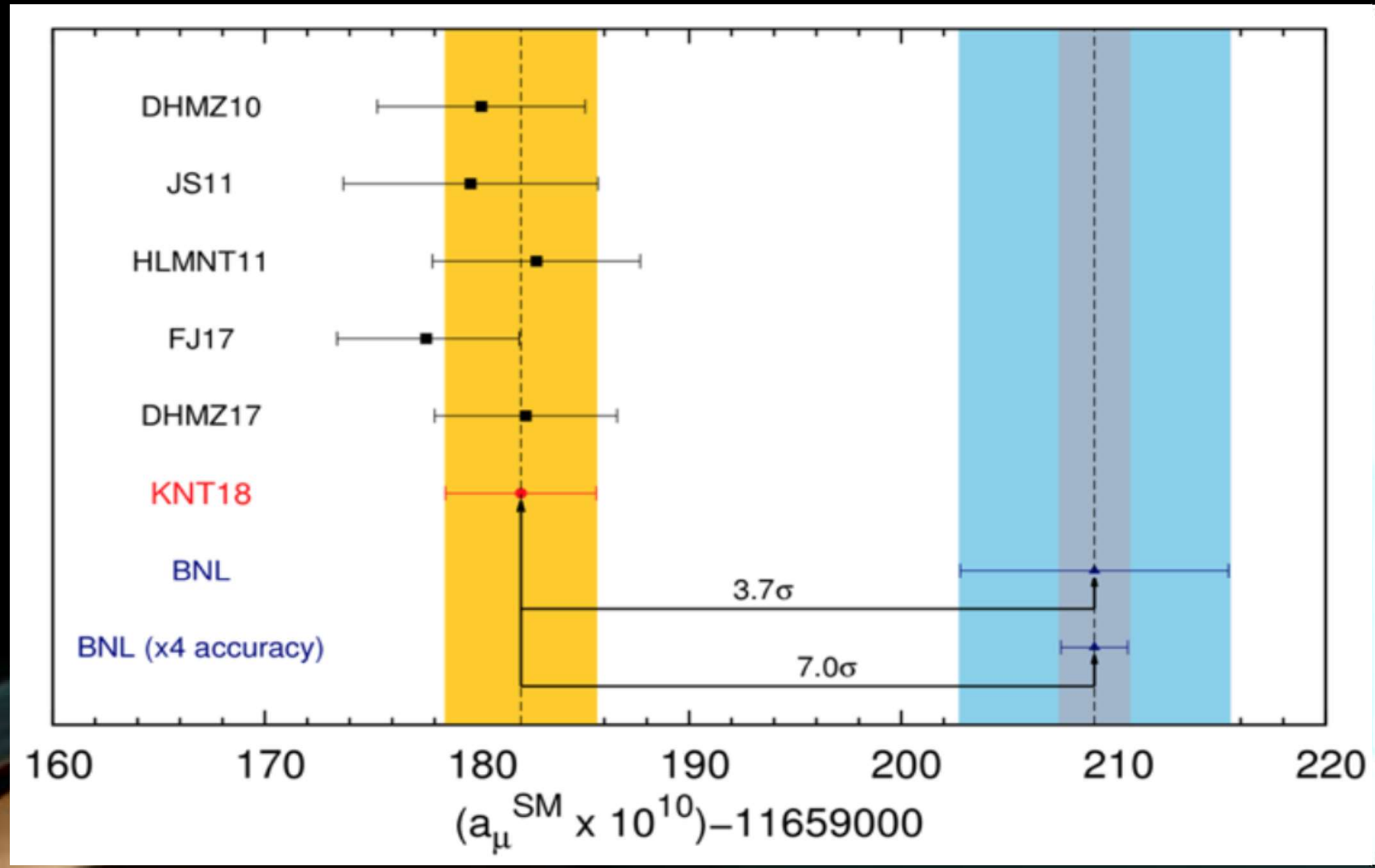
Xenon1t excess, 2006.09721

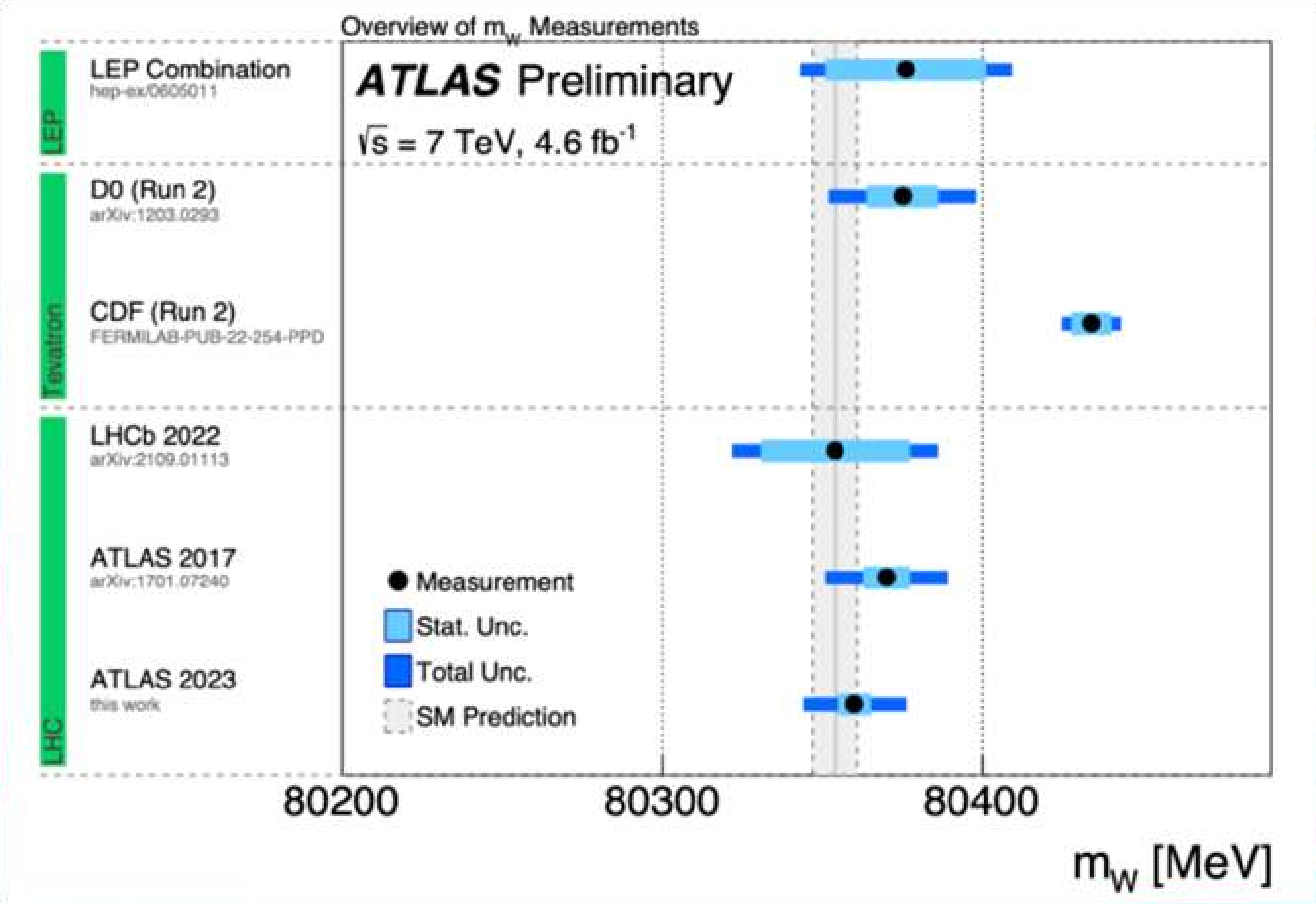
Model-dependent signatures/ Model-independent analyses

Identifying striking signatures



DAMA/LIBRA modulation, 1002.1028





g-2 & W-boson mass

S. Hoof – Community Interactions

Funded by the European Union

"How can the astroparticle community be most useful to, and taken seriously by, the wider community searching for ALPs?"

- Astro(particle) important: access to g_{ae} and other non-photon couplings, strong probes, post-discovery physics ➻ afternoon session
- N.B. Potential positive feedback loop: ALPs can strengthen astro observing grant applications $\Leftrightarrow$ more exposure for ALPs
- IMO: need more reproducible,[see 2309.03254] transparent, readily available astro data (including "intermediate data products", i.e. processed data, likelihoods) and open-source software
- Best practices for reporting "hints"? Guidelines for presenting limits exist[e.g. 2105.00599] $\Rightarrow$ comparability, reference result (at least as an appendix); we could do the same?! Generally: as above, make it easier to build on, cross-check, reproduce results; add summary on assumptions, caveats, . . .

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2. What is the status of currently proposed hints?

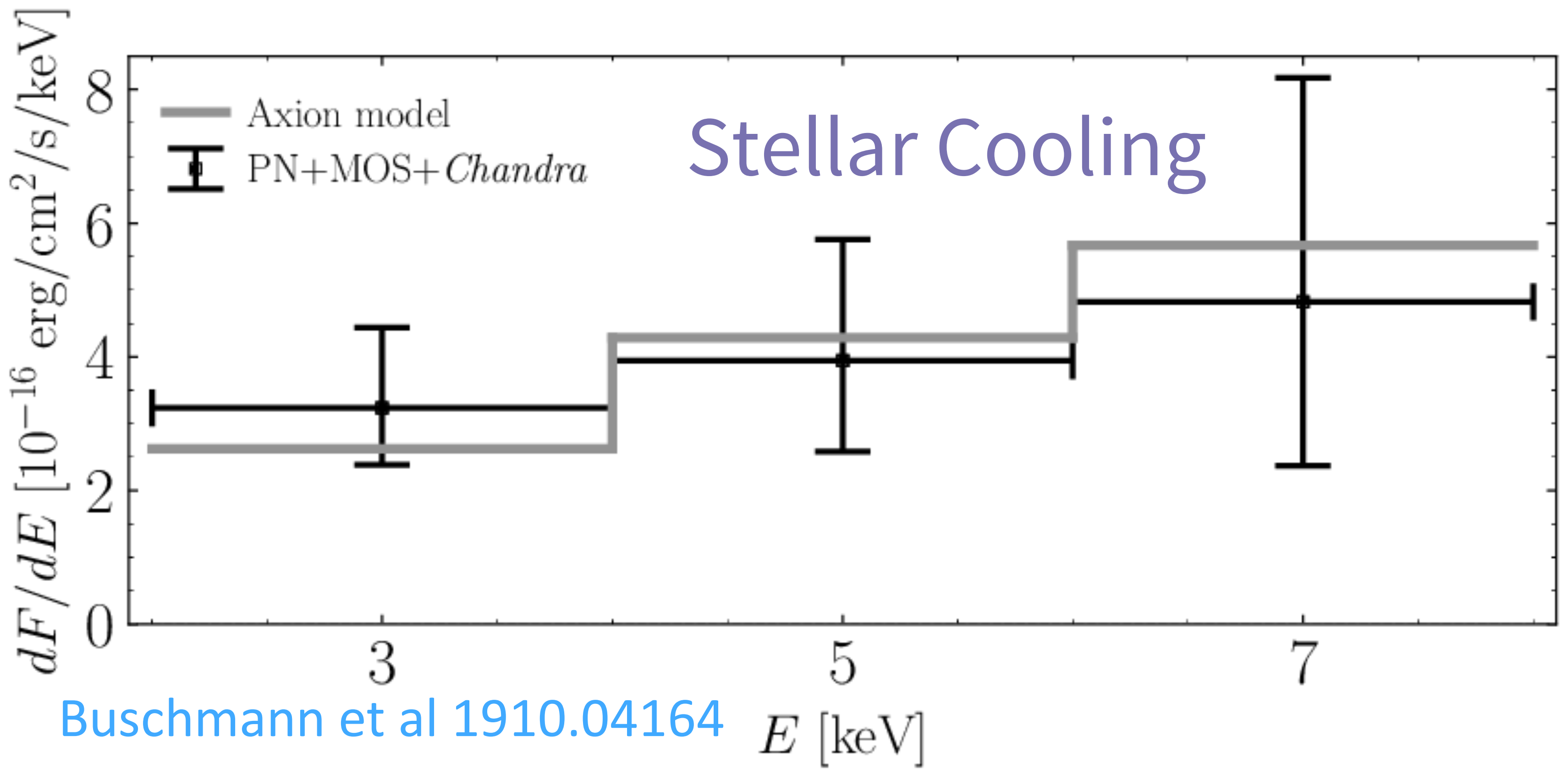
Are there regions of parameter space that are particularly important to target?

Perspectives by:

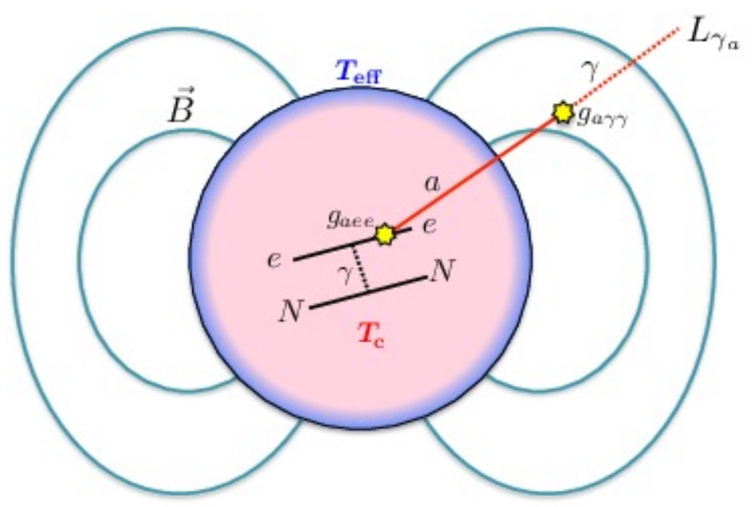
Jamie McDonald (University of Manchester)

Pierluca Carenza (Stockholm University)

Axions And Astrophysics **Jamie McDonald** – University of Manchester



Buschmann et al 1910.04164



What is the Status of Currently Proposed Hints?

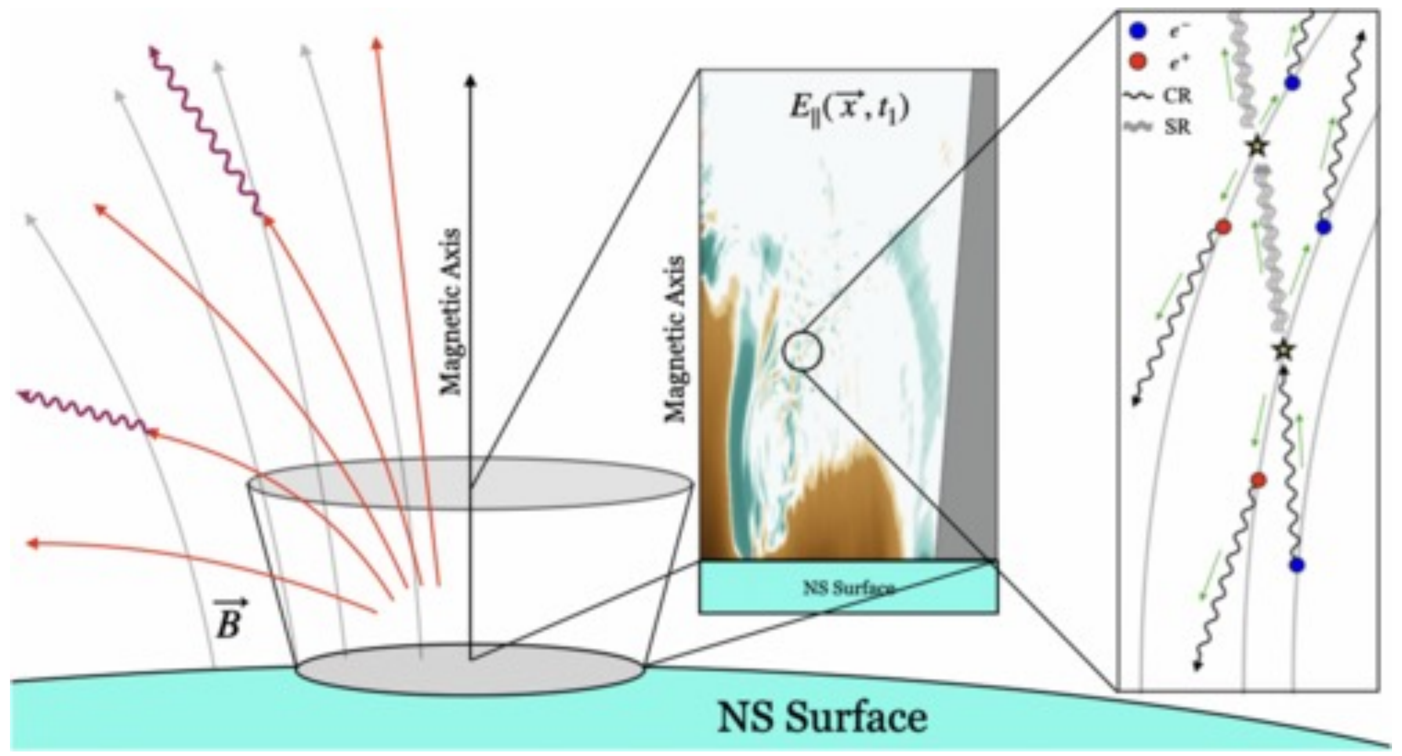
- Stellar Cooling/emission hint?
- Poorly Understood Astrophysics?

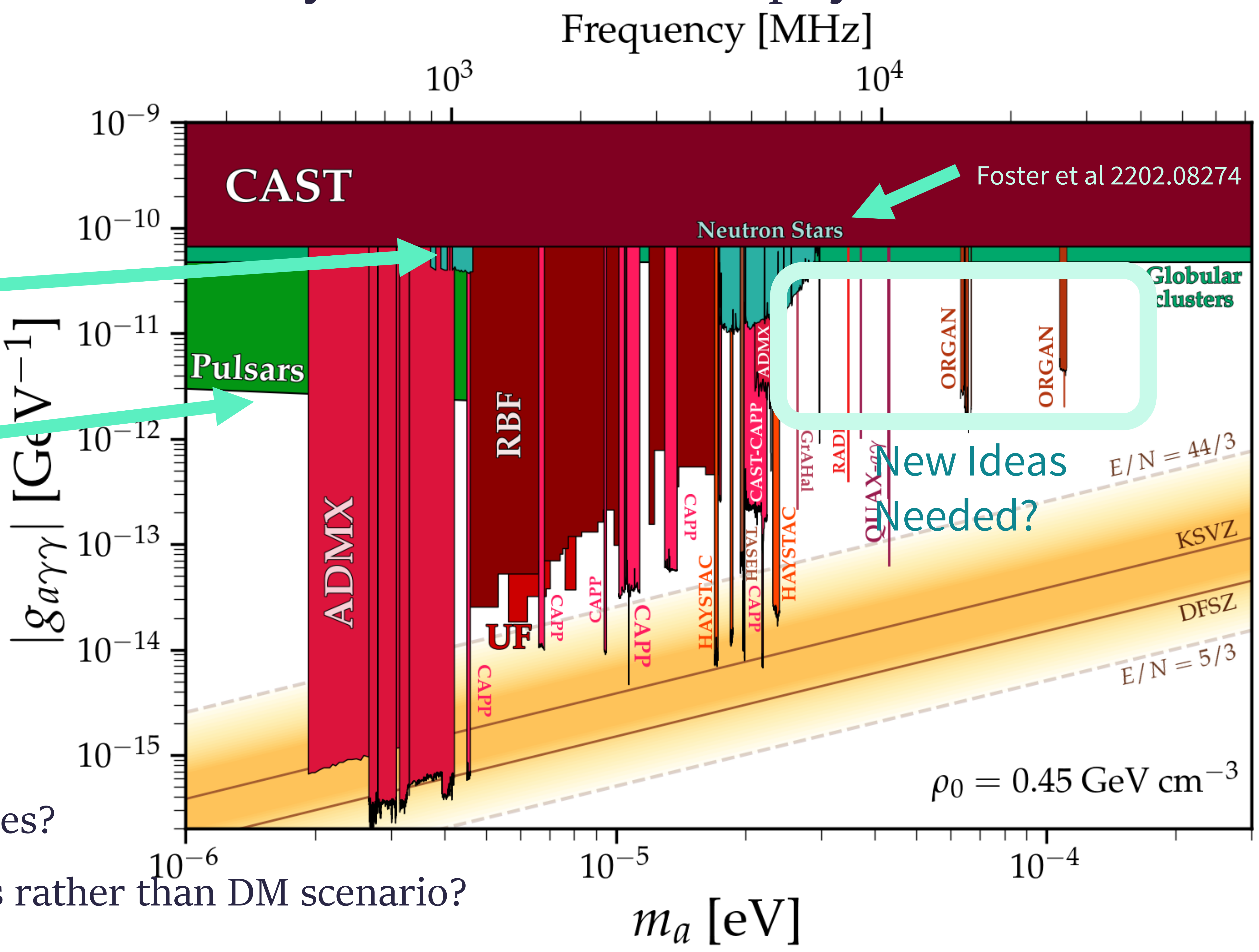
Are there regions of parameter space that are particularly important to target?

-Target gaps between (existing?) experiments

JM 2209.09917
(PSR J2144−3933)

Noordhuis et al 2209.09917





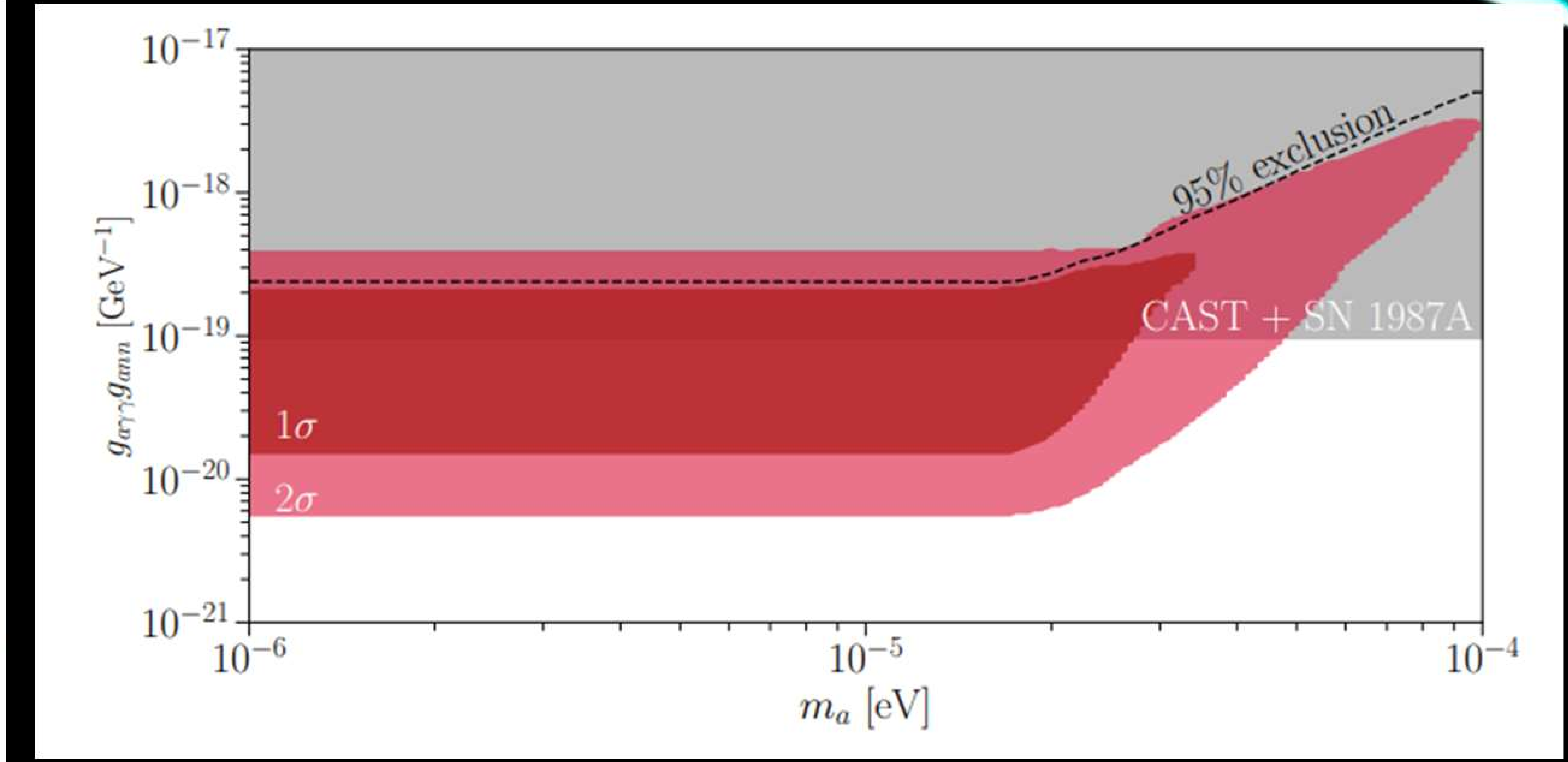
- Nightmare Scenario: axion miniclusters necessitate astro probes?

- Looking to the future : Perhaps Astro better for targeting ALPs rather than DM scenario?

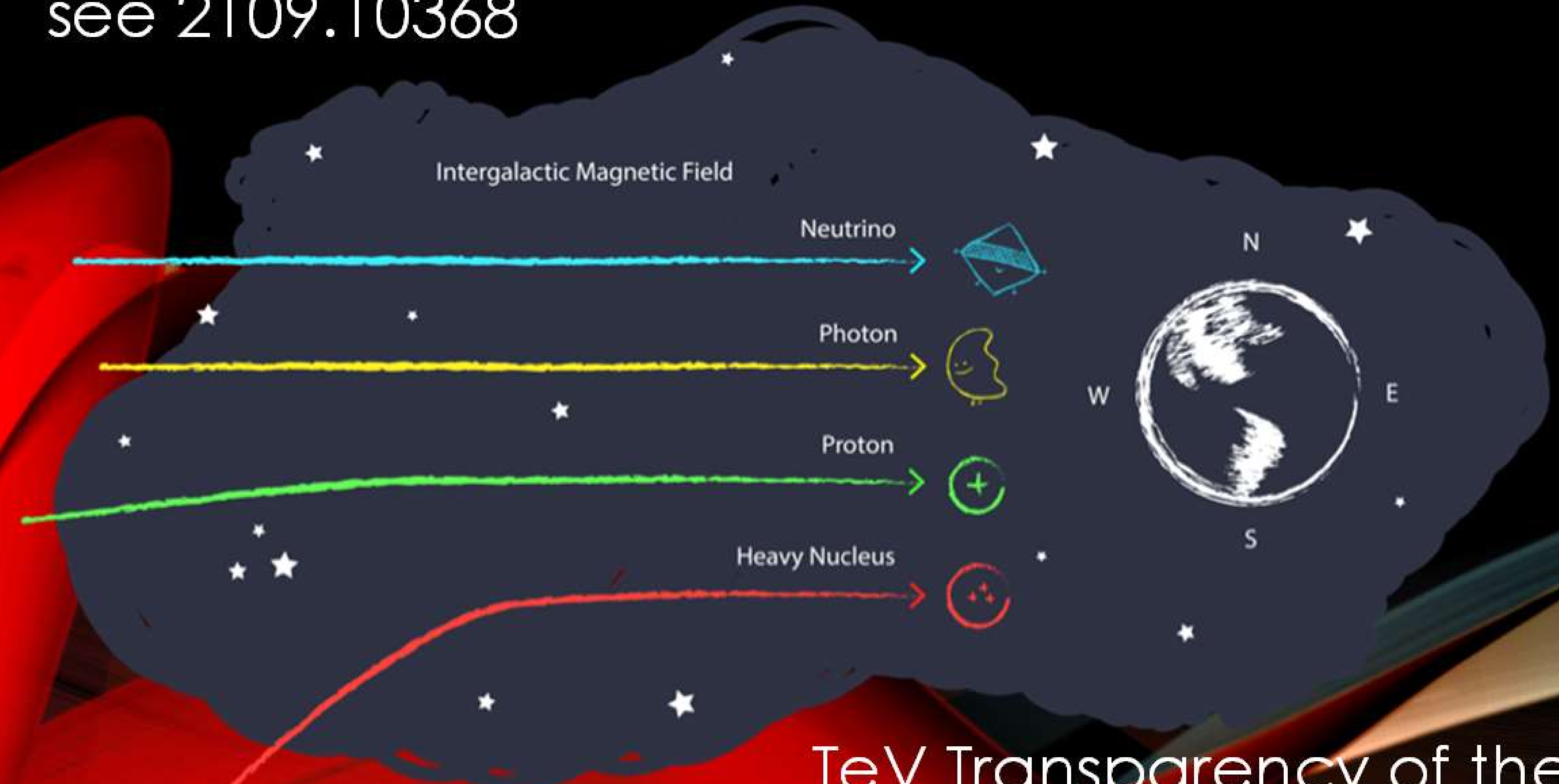
Star	Hint	Bound
Sun	No Hint	$g_{\gamma 10} \leq 2.7$
WDLF	$g_{e13} = 1.5^{+0.3}_{-0.5}$	$g_{e13} \leq 2.1$
WDV	$g_{e13} = 2.9^{+0.6}_{-0.9}$	$g_{e13} \leq 4.1$
RGBT (22 GGCs)	$g_{e13} = 0.60^{+0.32}_{-0.58}$	$g_{e13} \leq 1.5$
RGBT (NGC 4258)	No Hint	$g_{e13} \leq 1.6$
HB	$g_{\gamma 10} = 0.3^{+0.2}_{-0.2}$	$g_{\gamma 10} \leq 0.65$
SN 1987A	No Hint	$g_{aN} \lesssim 9.1 \times 10^{-10}$
NS (CAS A)	No Hint	$(g_{ap}^2 + 1.6\, g_{an}^2)^{1/2} \lesssim 1.0 \times 10^{-9}$
NS (CAS A)	No Hint	$g_{an} \lesssim 3 \times 10^{-10}$
NS (HESS)	No Hint	$g_{an} \leq 2.8 \times 10^{-10}$

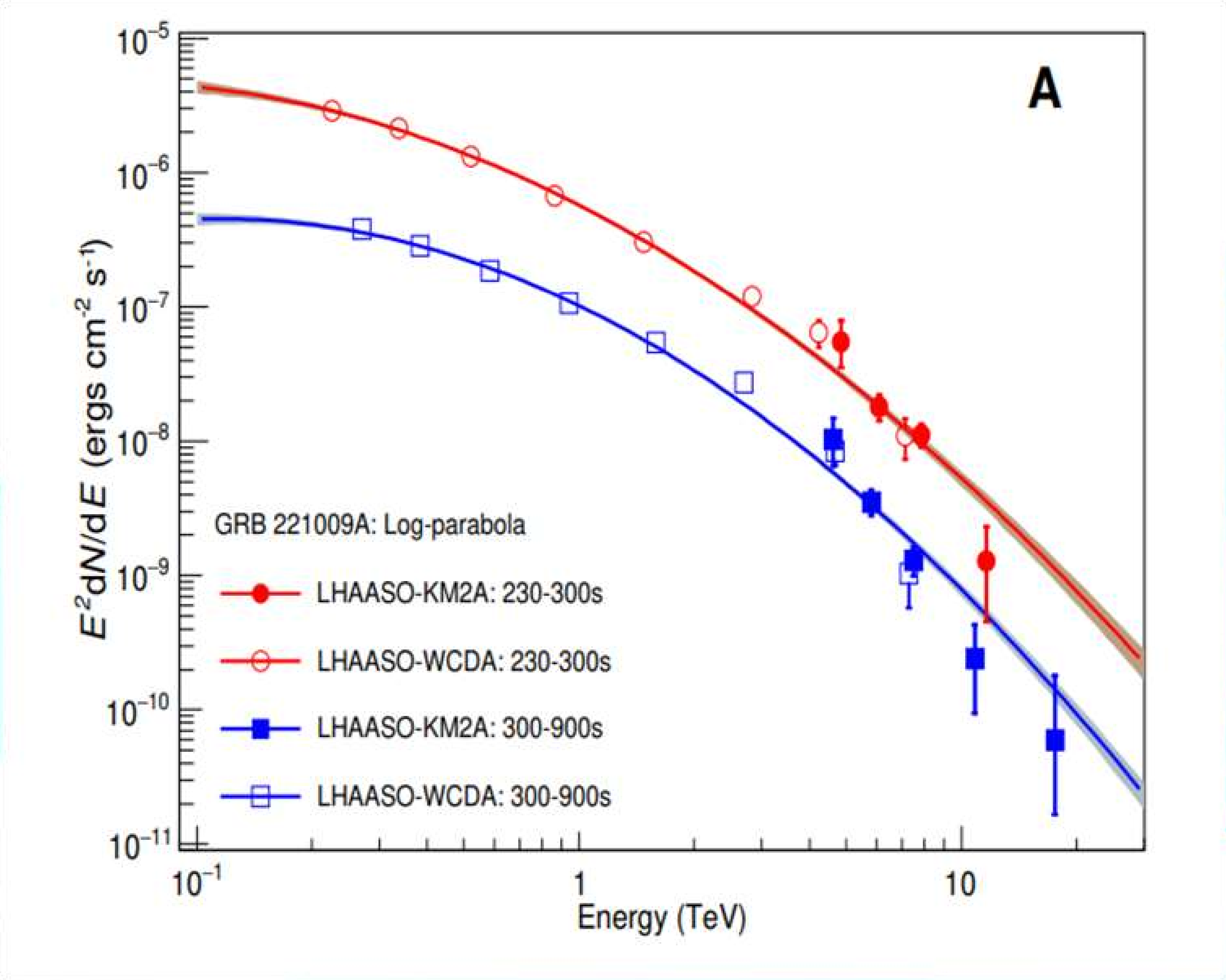
see 2109.10368

Magnificent 7 hint, 1910.04164



GRB221009A (?), 2310.08845





TeV Transparency of the Universe (?)

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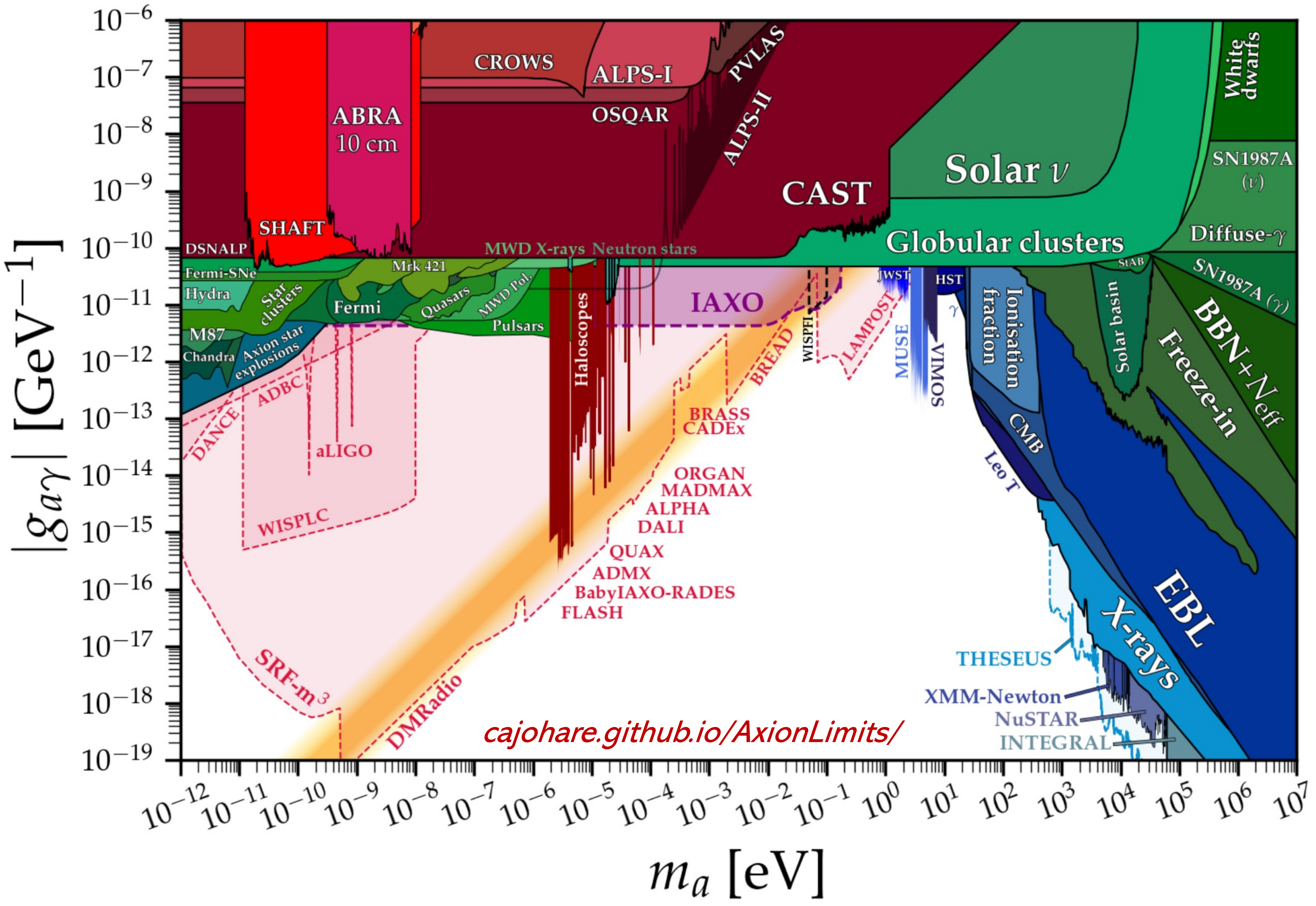
   Given systematic and statistical uncertainties, are there search methods that are more suitable as “discovery channels” rather than for placing limits on axion parameters?

Perspectives by:

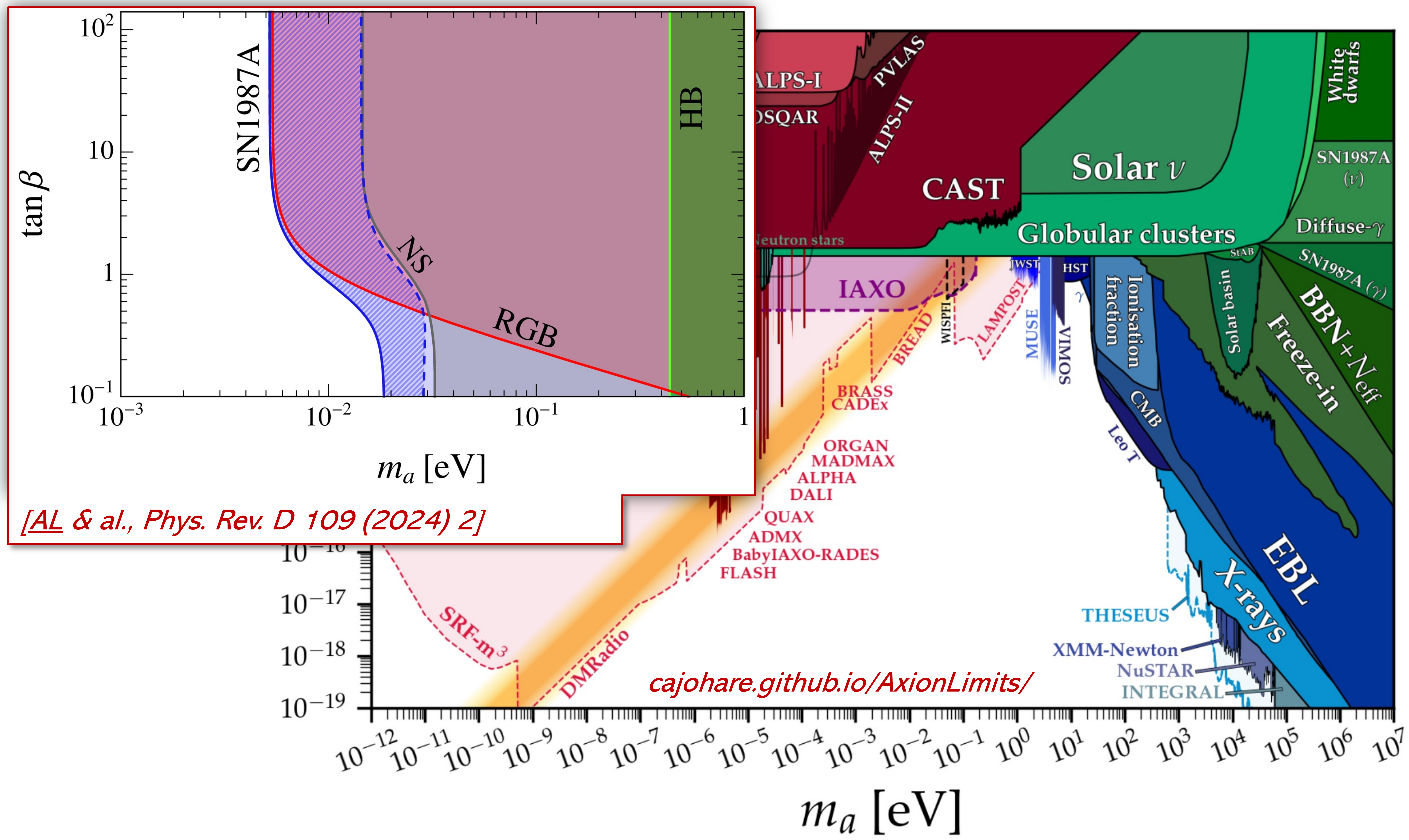
Alessandro Lella (University of Bari)

Georg Raffelt (MPI, Münich)

Perspectives: Axion Limits



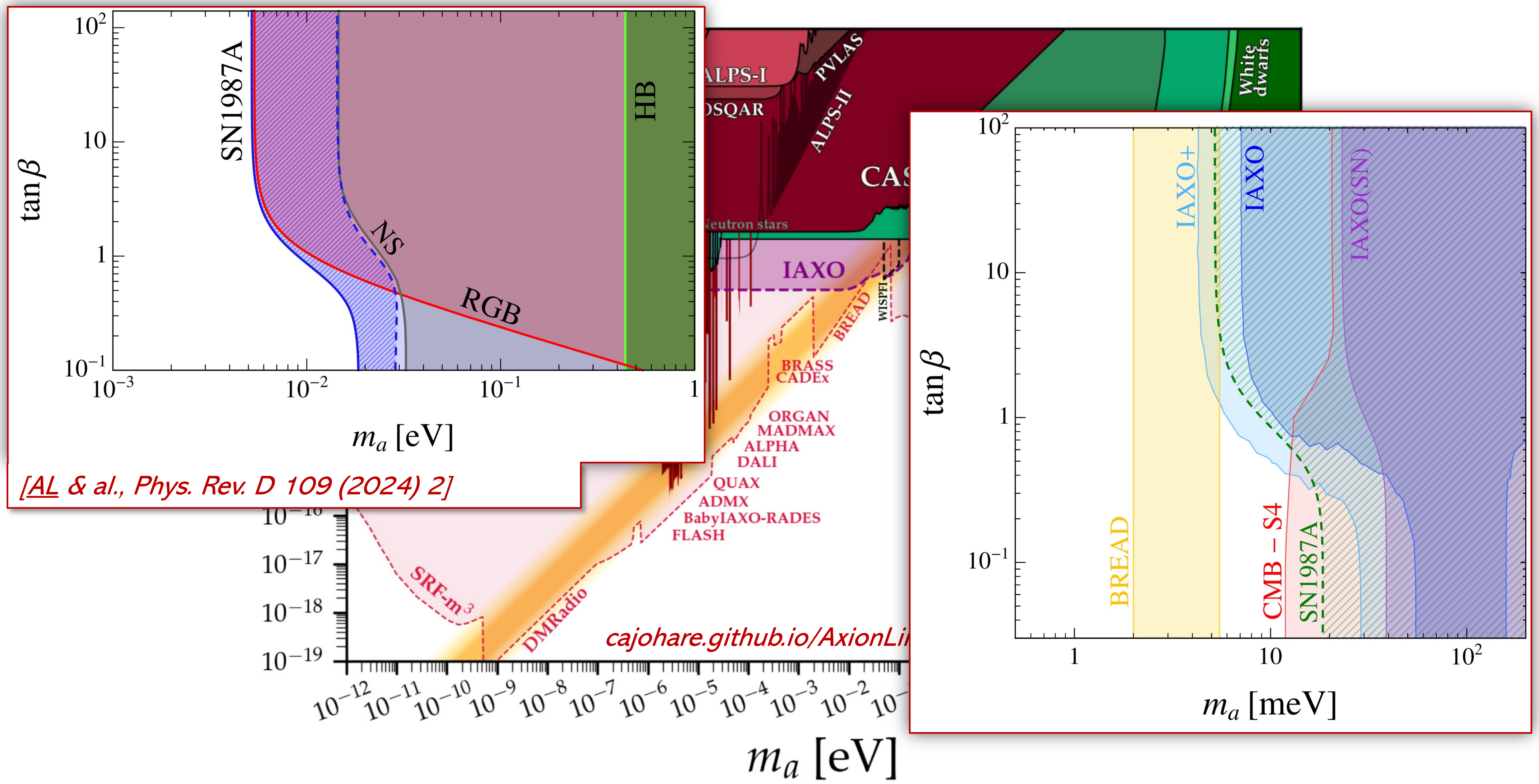
Perspectives: Axion Limits



[AL & al., Phys. Rev. D 109 (2024) 2]

cajohare.github.io/AxionLimits/

Perspectives: Axion Limits

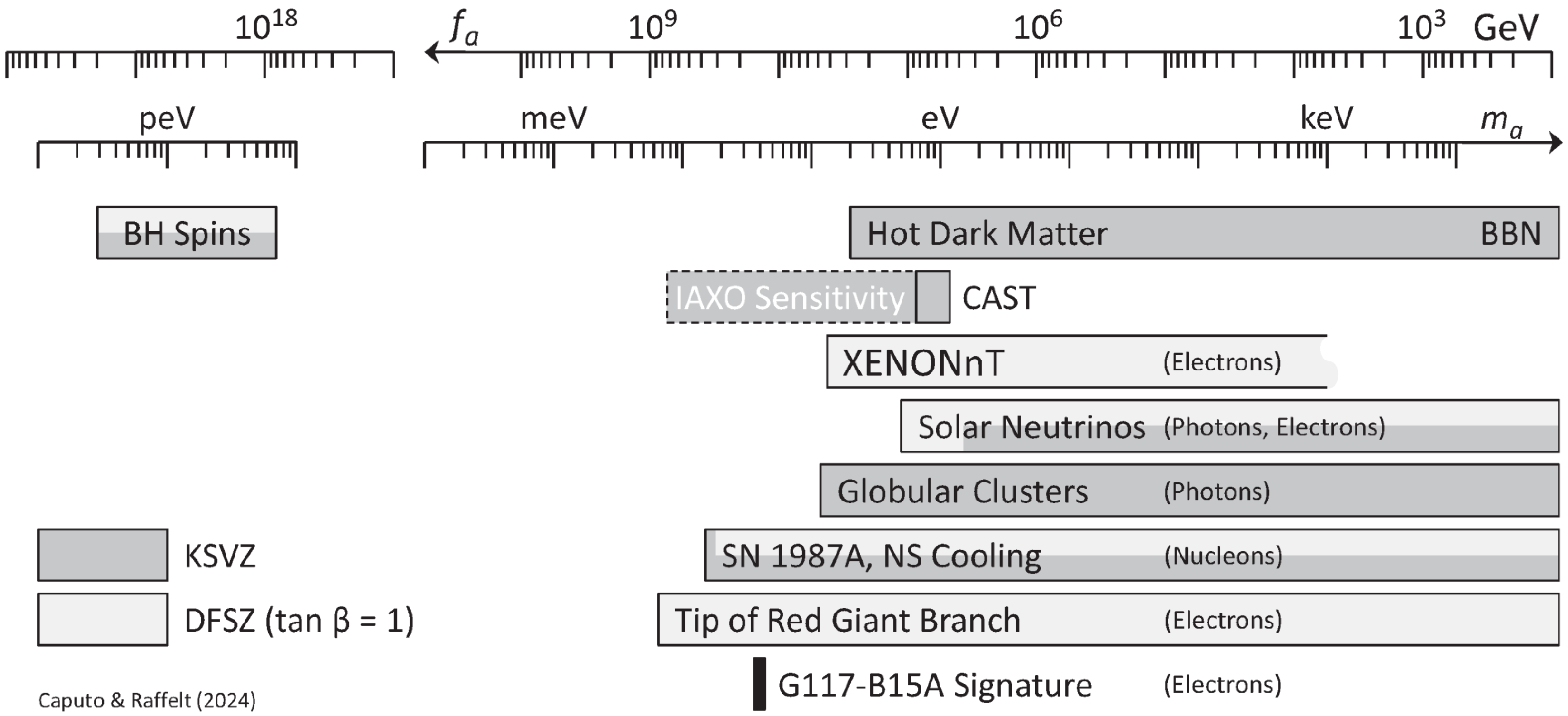


[AL & al., Phys. Rev. D 109 (2024) 2]

Brand New

Astrophysical Axion Bounds

The 2024 Edition, Caputo & Raffelt, arXiv:2401.13728, 24 Jan 2024



- Many improvements over the years, but overall picture the same
- Specific QCD axion signatures hard to expect from cooling effects
- Best stellar detection opportunity probably (Baby)IAXO

3. What is the status of current limits on axions?

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4. Considering the astrophysical systems that have led to insights about ALPs before, what improvements can we expect through new observational capabilities over the coming decade(s)?

Perspectives by:

Eike Ravensburg (Southern Denmark University)

Alessandro Lella (University of Bari)

Improvements in observational capabilities for axion searches with supernovae

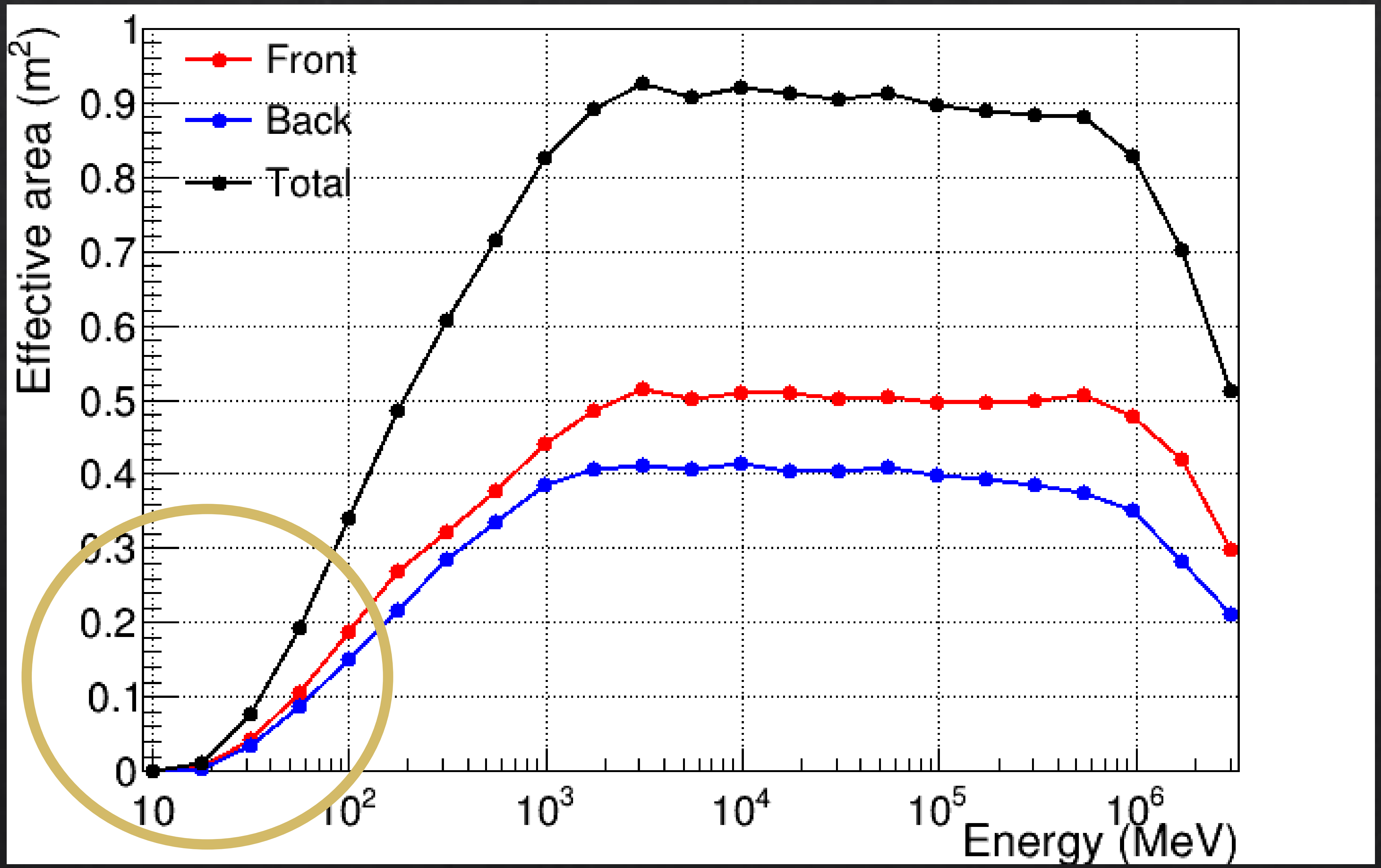
Supernovae can produce both light, $m_a \lesssim 1$ neV, and heavy, $m_a \lesssim 300$ MeV, axions, which can convert or decay into photons with **energies in the O(10-100) MeV range**

This falls into the **"MeV-gap"**, a region in which no existing telescope has great sensitivity

Proposed telescopes will fill this gap: **COSI** (planned to launch 2027), AMEGO, e-ASTROGAM, ComPair, and more

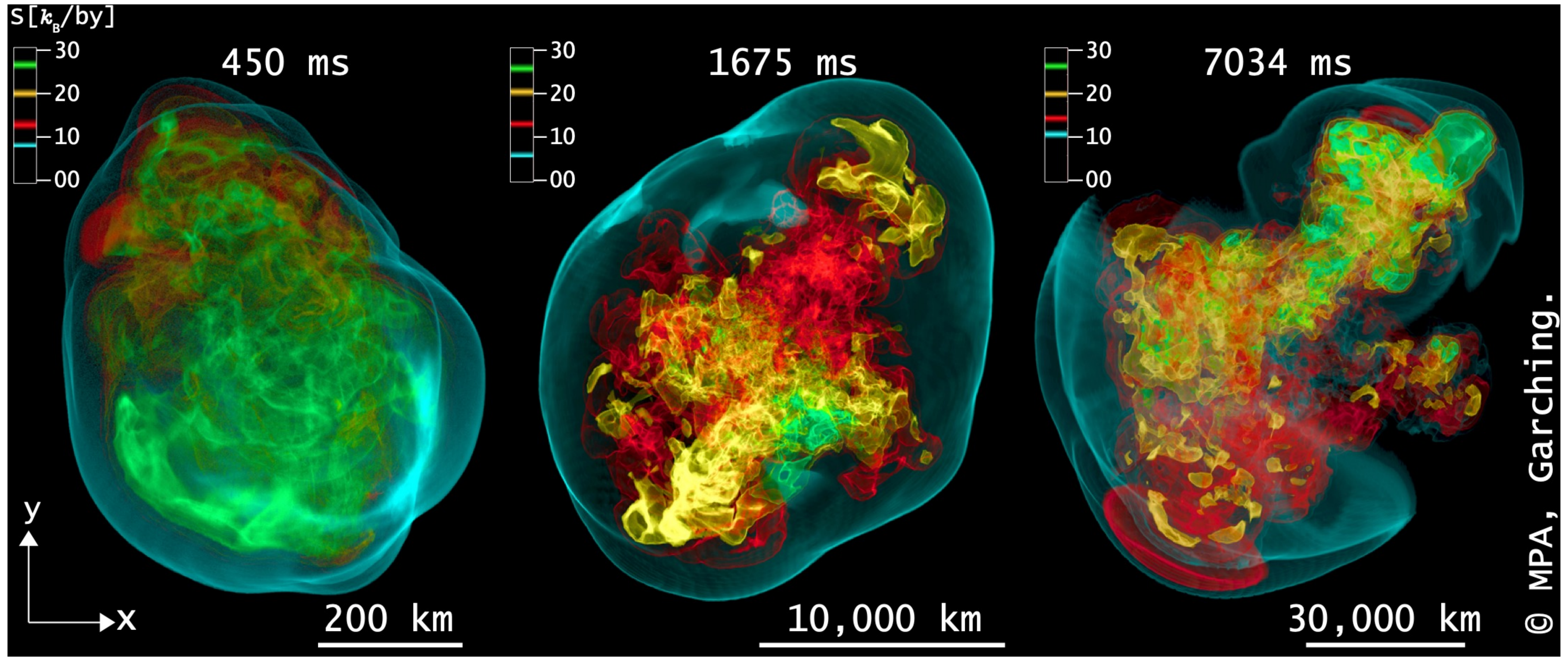
Also, the **Vera-Rubin observatory** will observe many more nearby SNe, for some of which we might be able to narrow down the expected timing of an axion signal

Fermi-LAT effective area:



Perspectives: Future developments

- ALPs self-consistently included in realistic simulations of astrophysical systems



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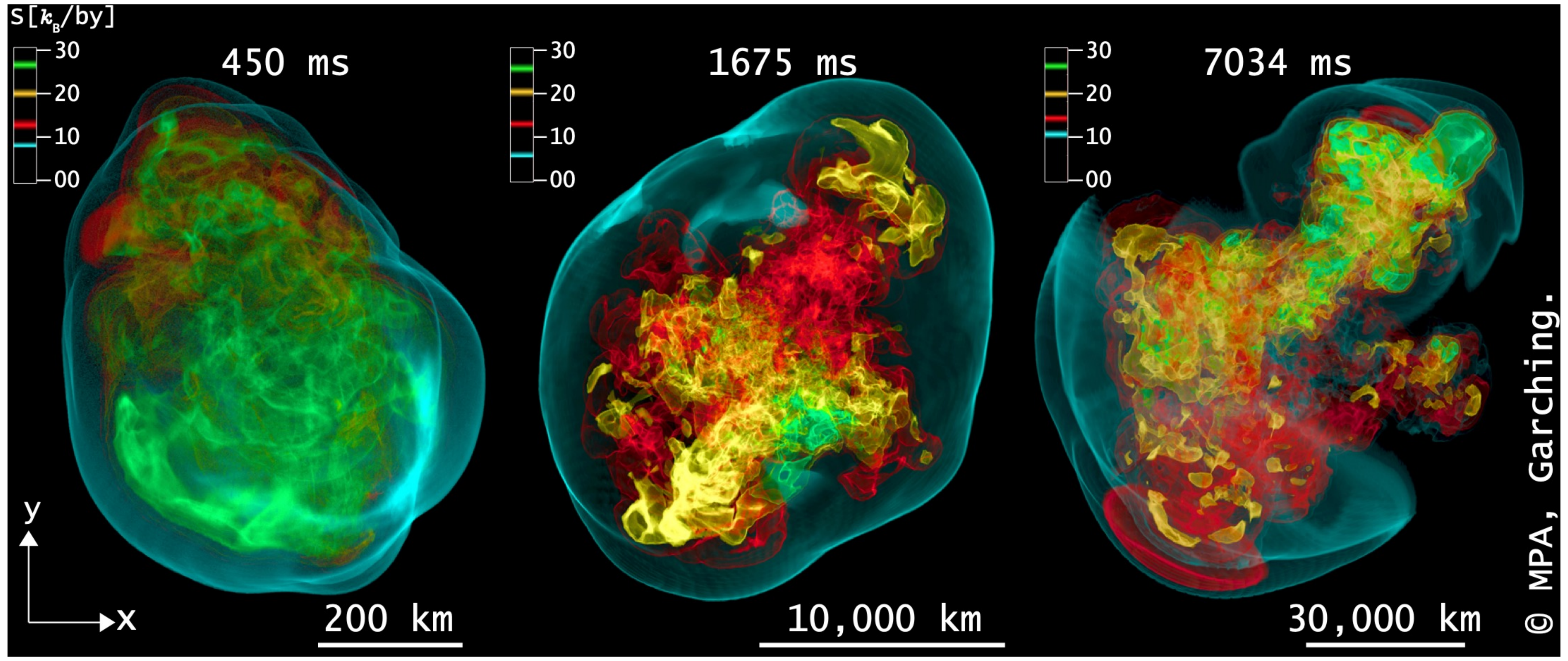
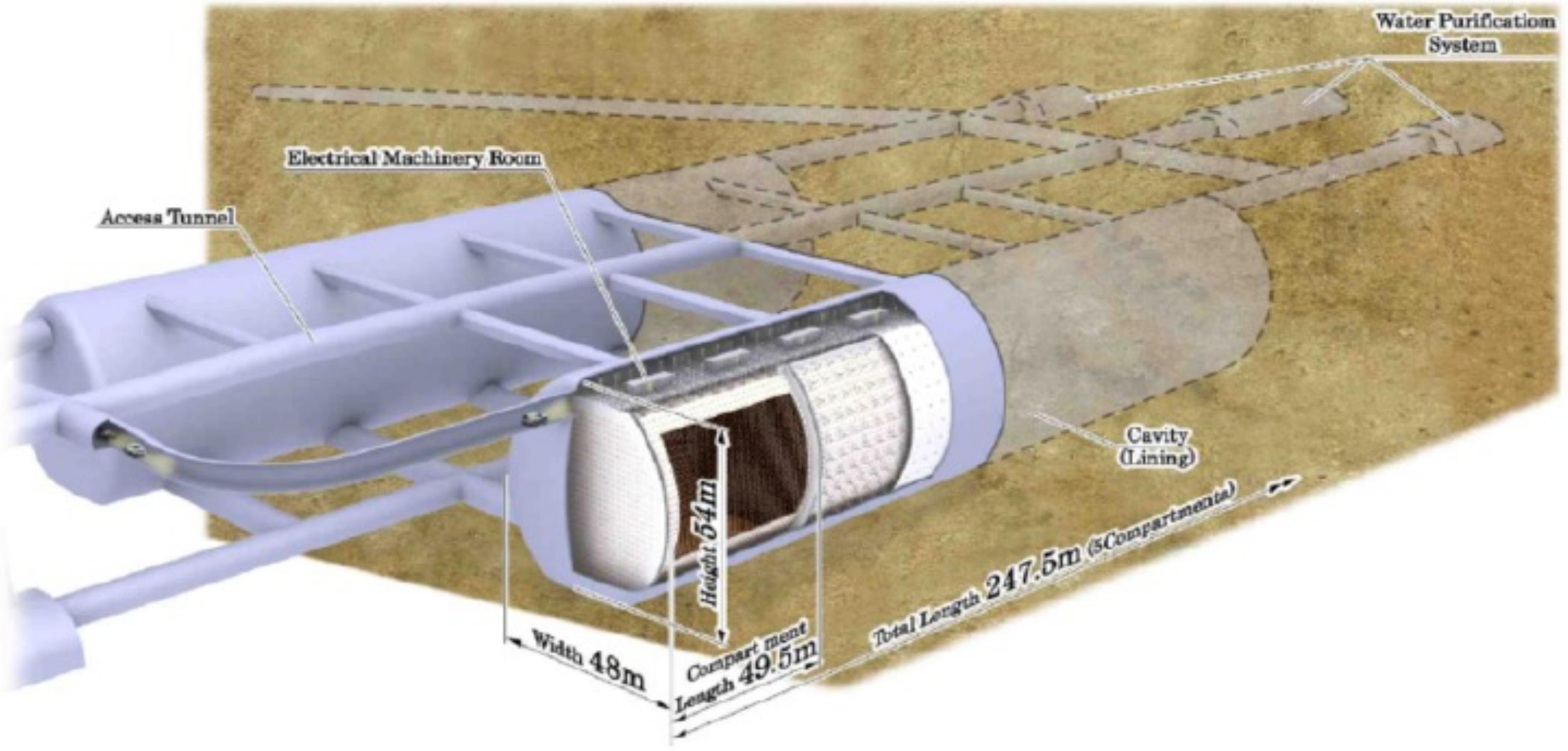


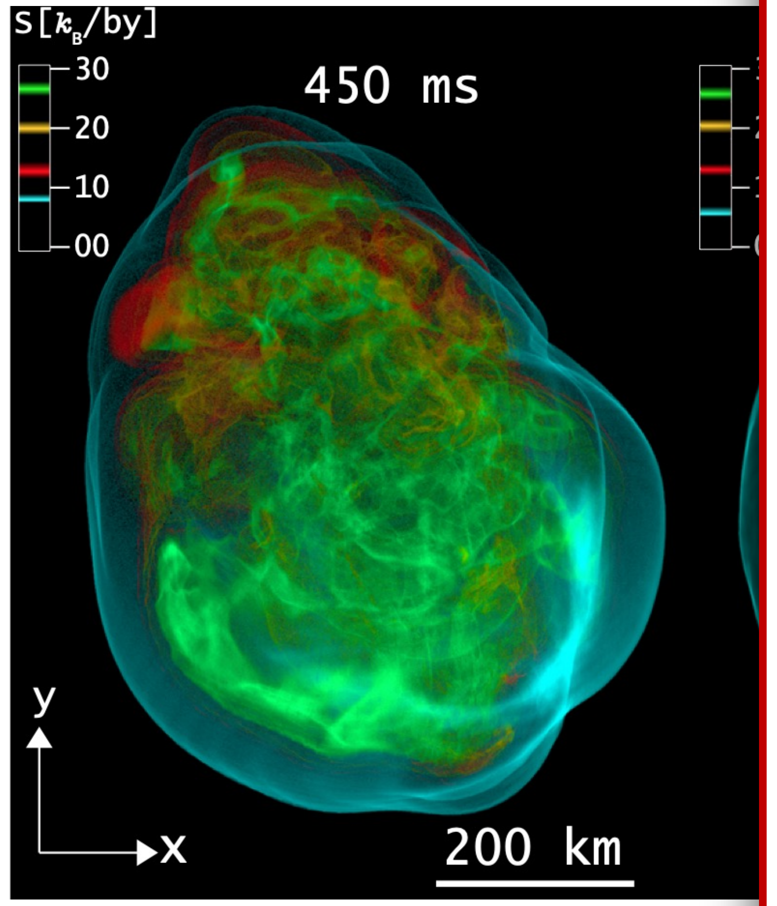


- ALP signatures in next-gen large underground neutrino detectors, e.g. HyperKamiokande.

- Possible observation of an ALP-induced γ-ray signal (need to fill the *MeV sensitivity gap*).

Perspectives: Future developments

- ALPs self-con
  simulations o



round
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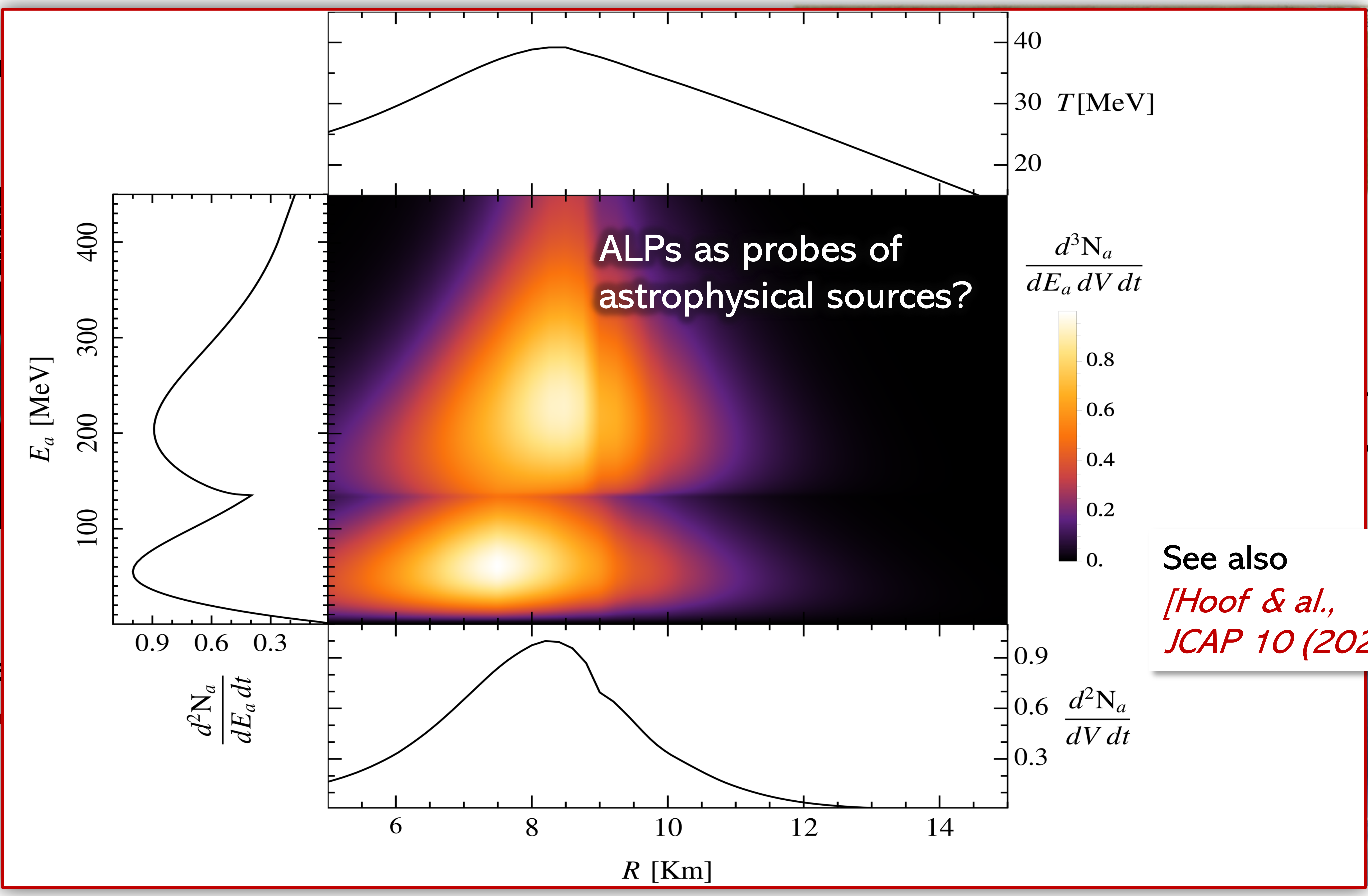
- Possible obse
  signal (need t



See also
[Hoof & al., JCAP 10 (2023) 024]

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   For example, how can cosmological and astrophysical simulations or future observations inform the magnetic field modelling required for searches relying on axion-photon conversion? Are there systematic errors associated with simple magnetic field models, and if so, what do they miss?

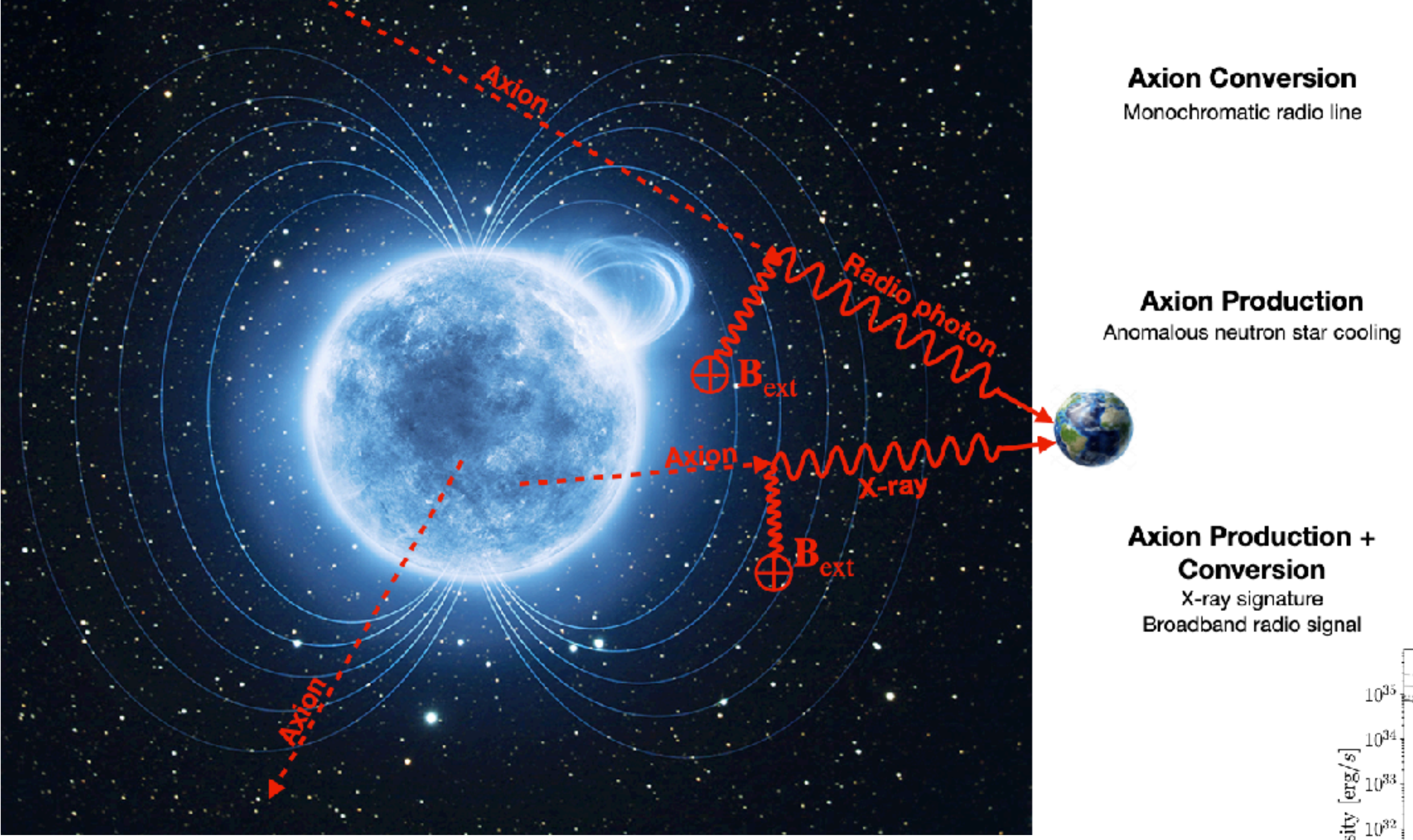
Perspectives by:

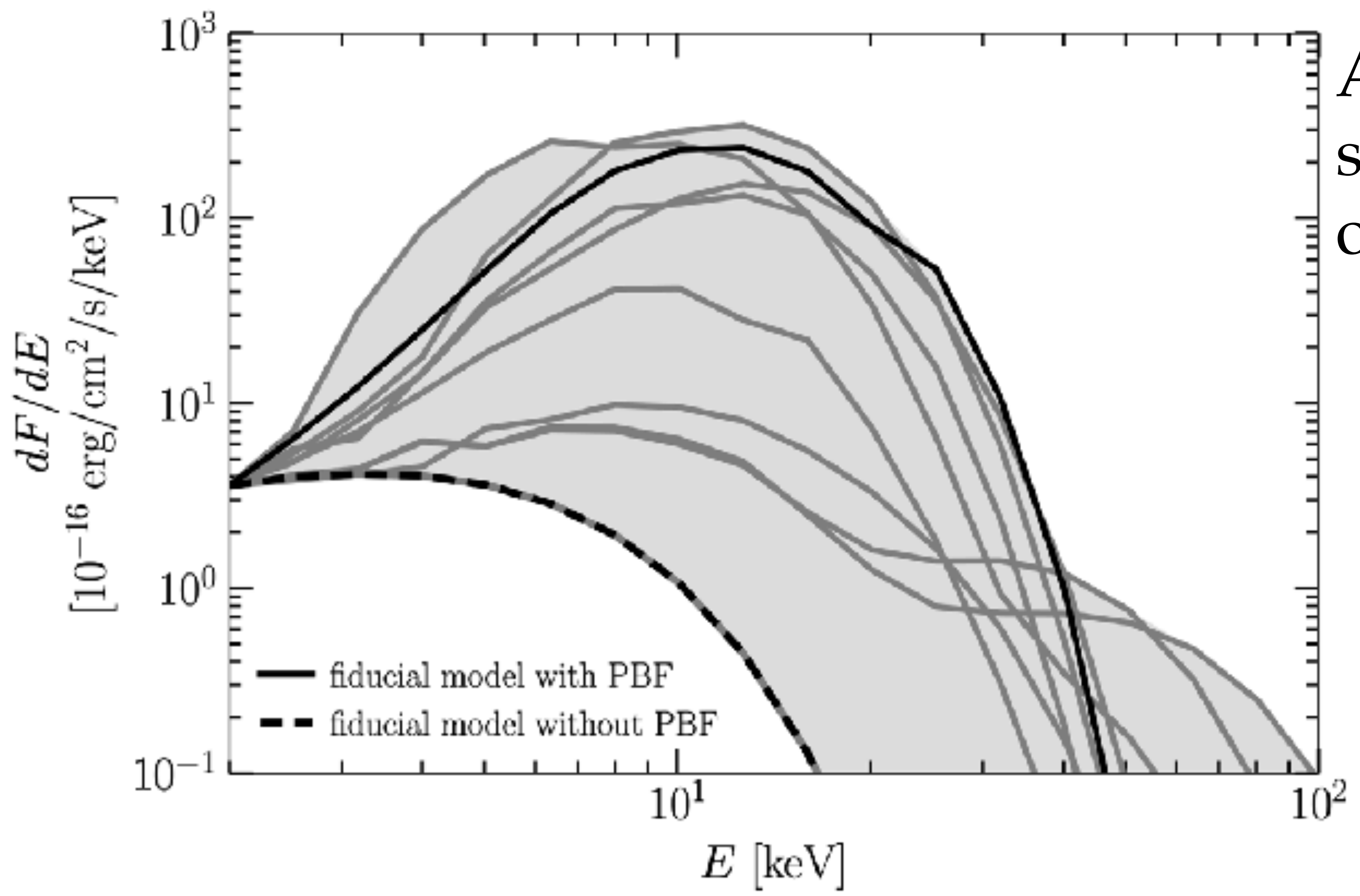
Malte Buschmann (University of Amsterdam)

Andreas Ringwald (DESY)

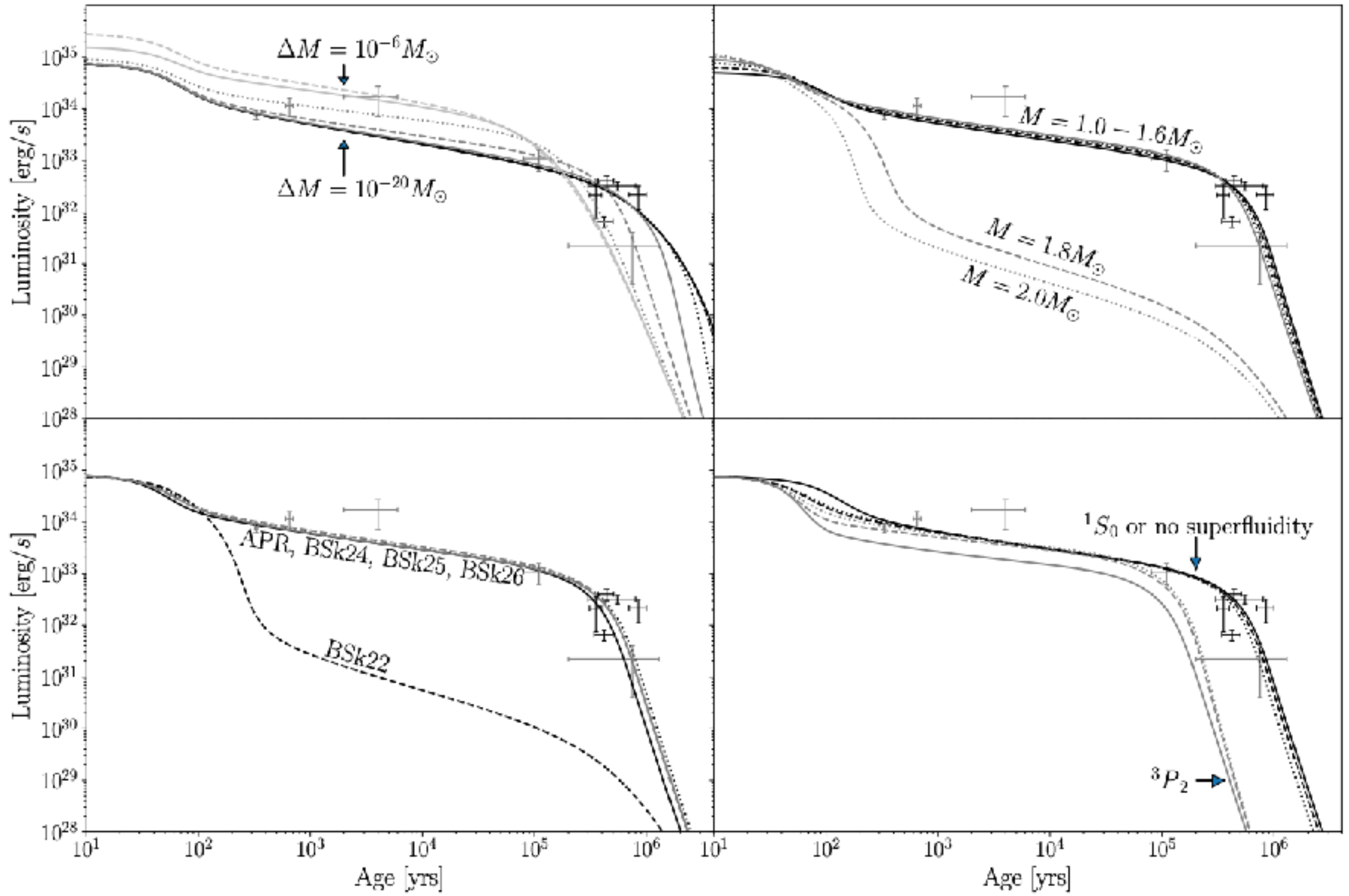
NEUTRON STAR UNCERTAINTIES

- Powerful axion laboratories
- Held back by our lack of knowledge about their equation of state, magnetic field modeling, radius/mass relation, distance to earth etc…
- How can this be improved? Neutron star mergers observations? How helpful will NICER be? Better simulations of magnetosphere?



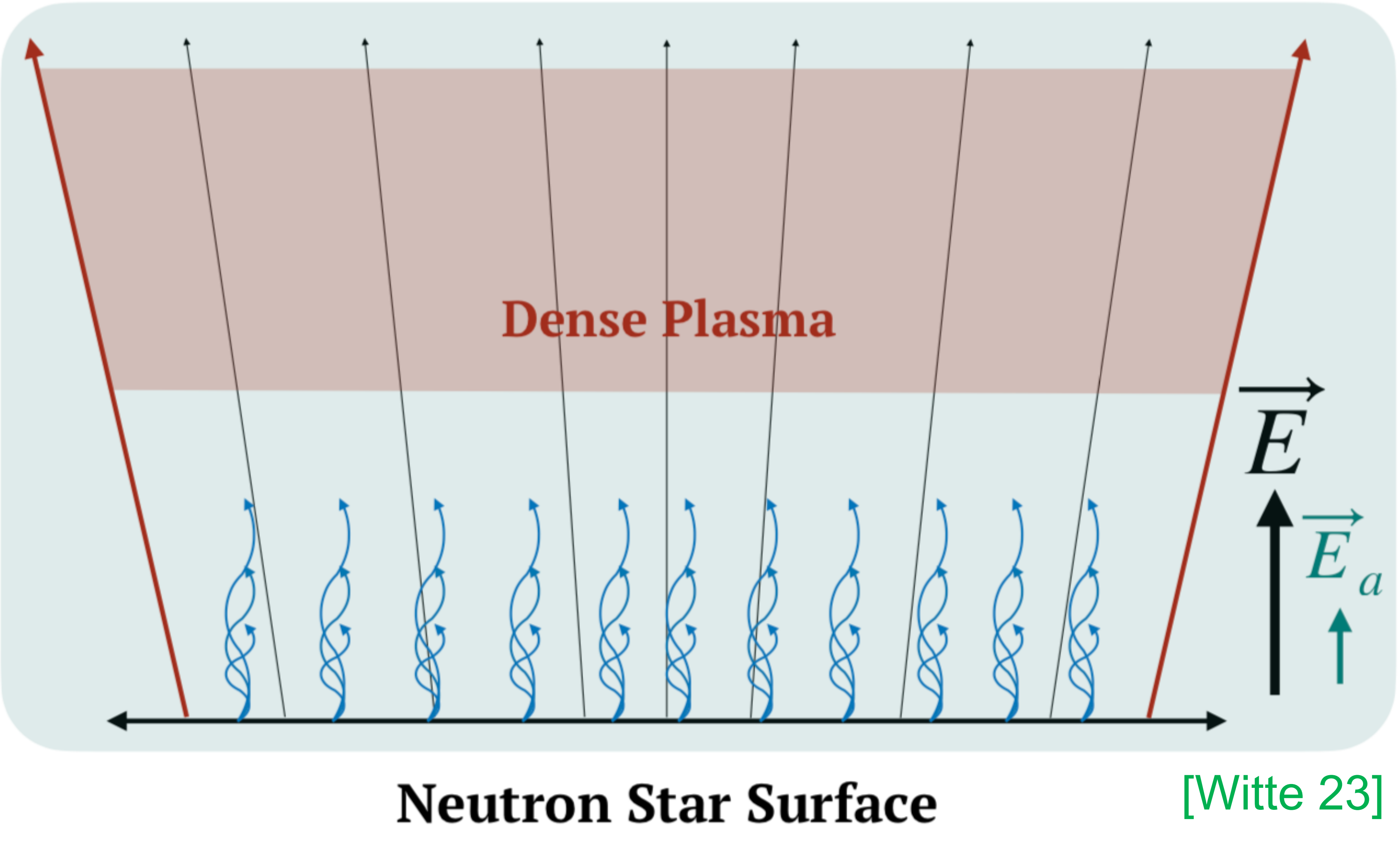


Axion signal depends strongly on equation of state

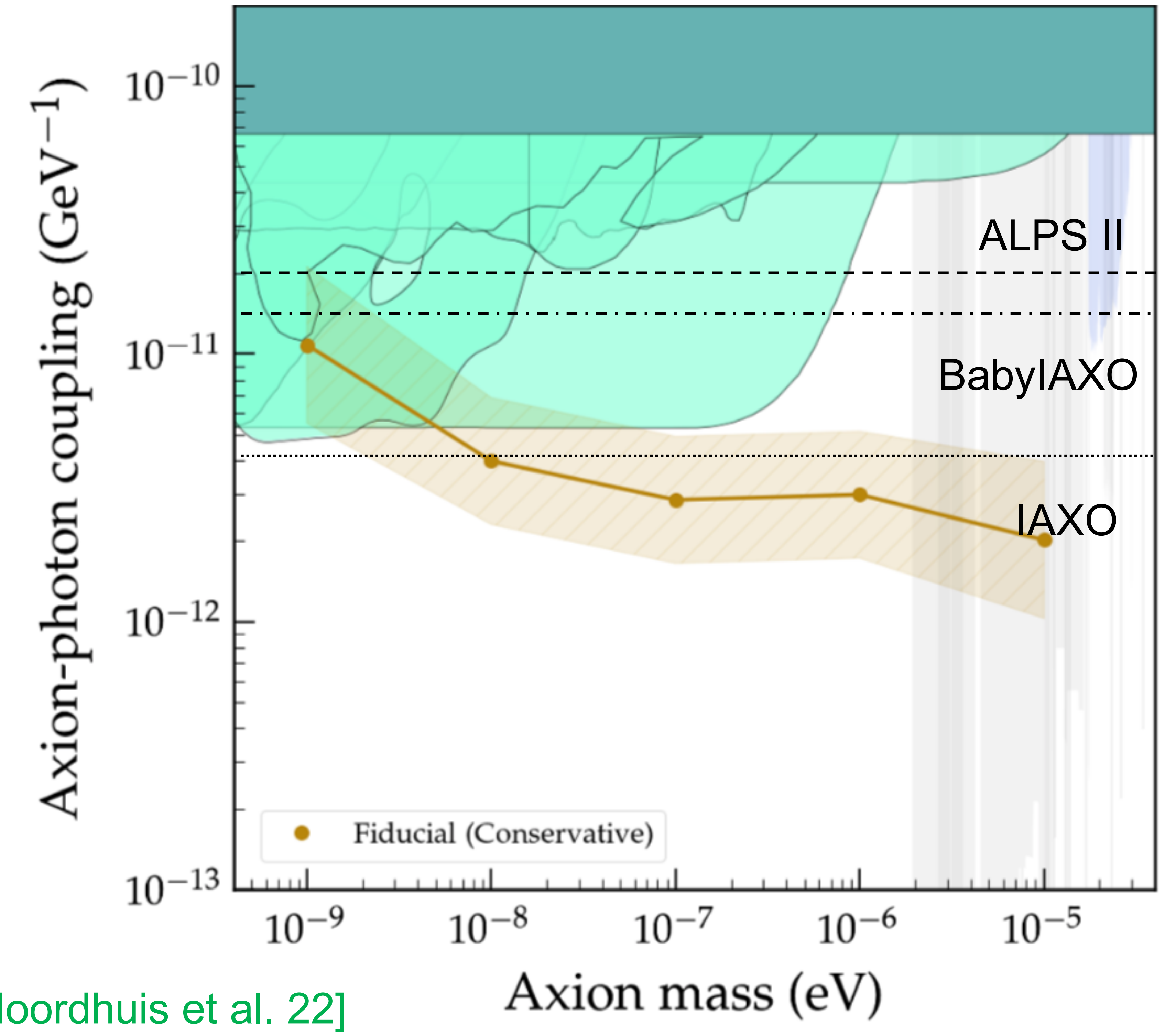


Axion-Photon Conversion in Neutron-Star Magnetospheres

- Axions can be copiously produced in the polar cap regions of pulsars where the ambient plasma is unable to efficiently screen the induced electric field [Prabhu 21; Noordhuis et al. 22; 23; Caputo et al. 23]
- A large broadband contribution to the neutron star's radio flux can be generated by axion-photon conversion in the magnetic field
- Comparing this contribution with radio observations of 27 nearby pulsars and requiring that it does not exceed the observed flux provides upper bound on axion-photon coupling
- Bound cuts deeply into parameter space that will be probed by less model-dependent experiments ALPS II, BabyIAXO and IAXO
- Indicated uncertainty of bound estimated by comparing predictions from 2.5 D particle-in-cell simulations with those derived using a semi-analytic model
  - Both calculations imployed same magnetic field model
  - How does this bound change if alternative magnetic field models are employed?



[Witte 23]



[Noordhuis et al. 22]

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Perspectives by:

Andrei Lobanov (MPIfR, Bonn)

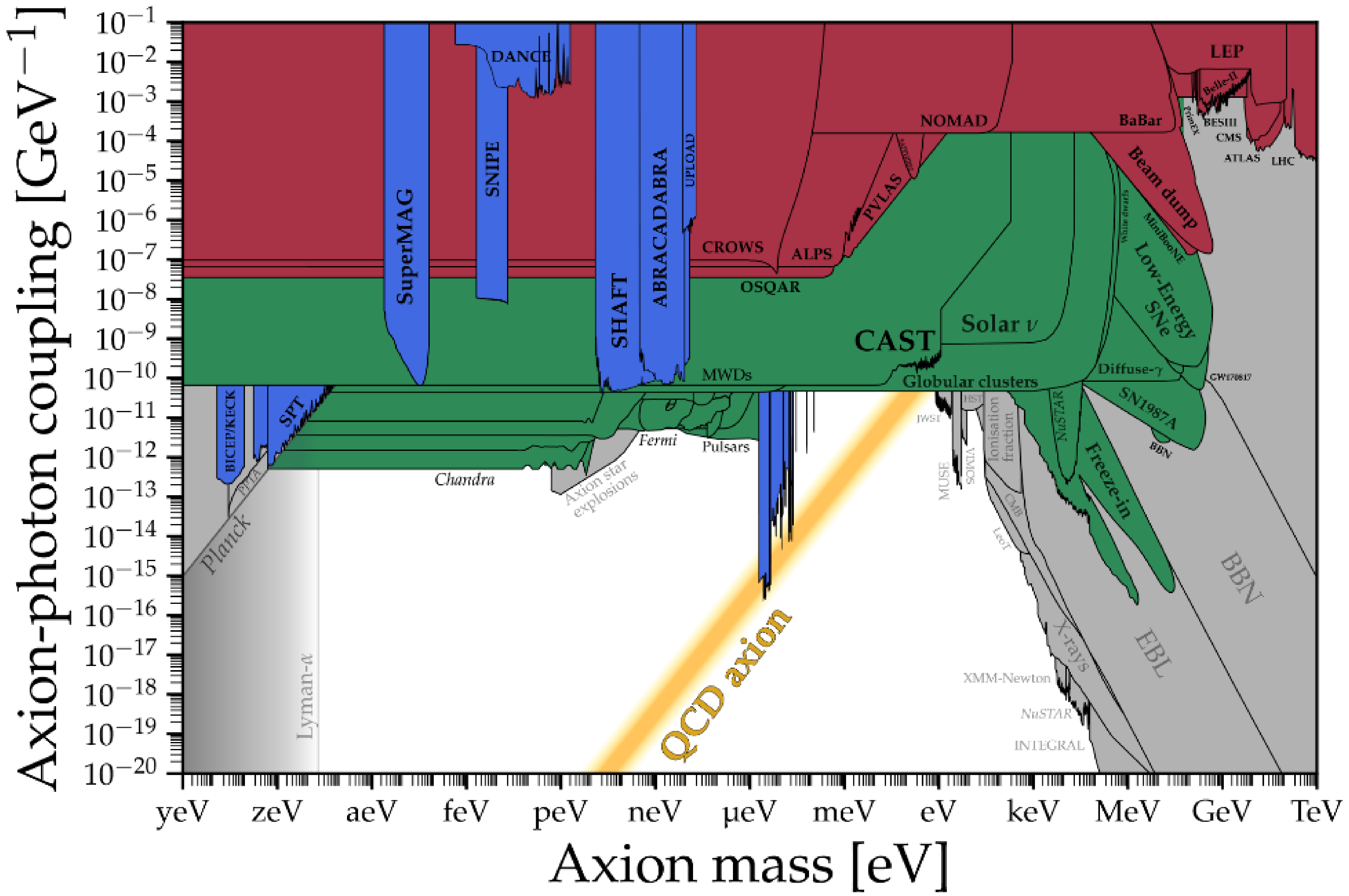
Jordi Miralda Escudé (University of Barcelona)

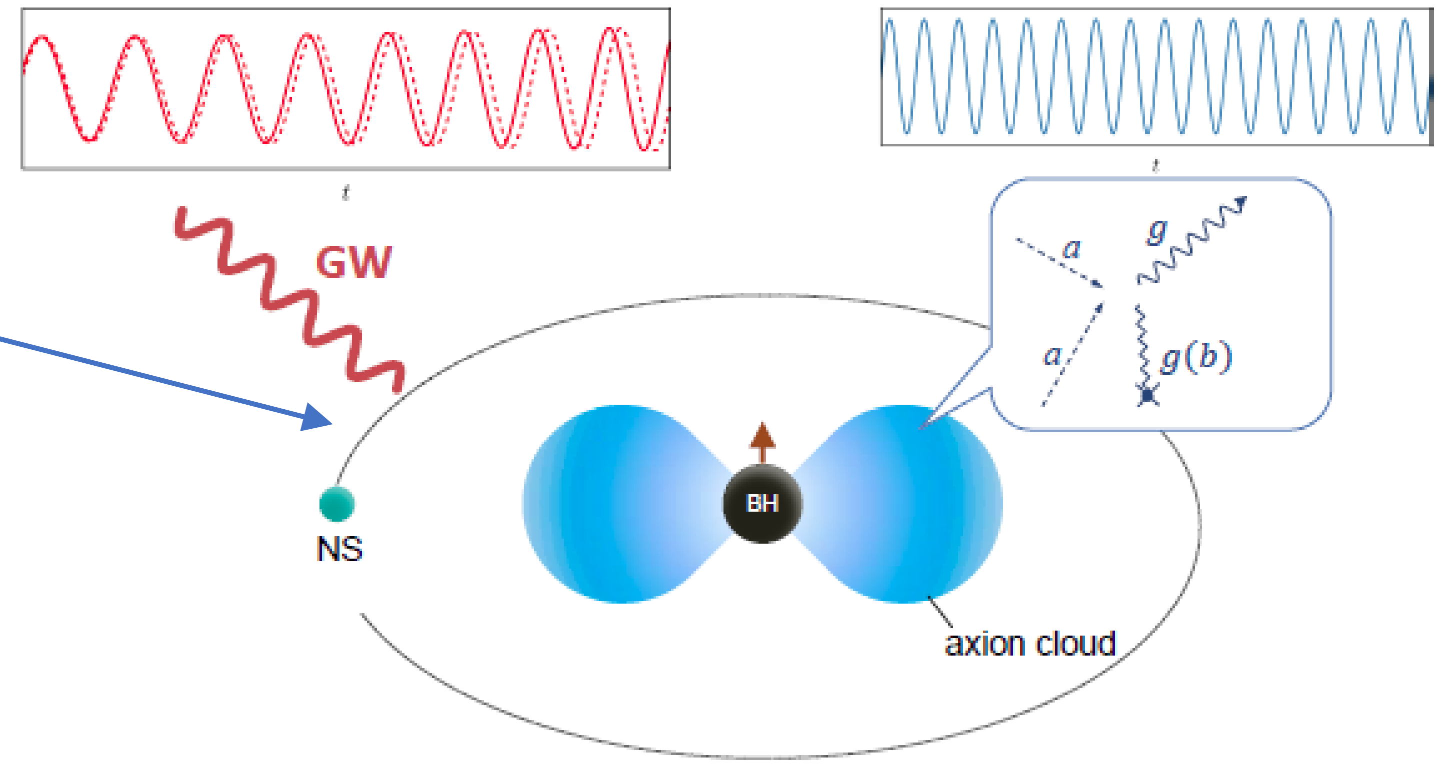
6. Novel Perspectives

- Expect:
  - – detection sensitivity ***x100***: radio, optical, neutrino, GW, pulsar timing;
  - – spectral resolution, polarisation purity ***x10***: radio, X-ray;
  - – strong synoptic and transient capabilities: radio, optical.

- Propagation effects (photon-axion-photon conversion) on much larger scales (profiting from synoptic capabilities and improved models of Galactic magnetic field).
- Neutron stars and supernovae (benefiting from sensitivity improvements).
- Vicinity of black holes at microarcsecond resolution (super-radiance, spin depletion, axion accretion & annihilation).
- BH-NS systems (GW emission; monochromatic waves).
- Tidal disruption events (episodic accretion onto SMBH in presence of surrounding axion cloud).
- Axion matter: axion stars (revealed by interactions with companions/environment)?

https://github.com/cajohare/AxionLimits

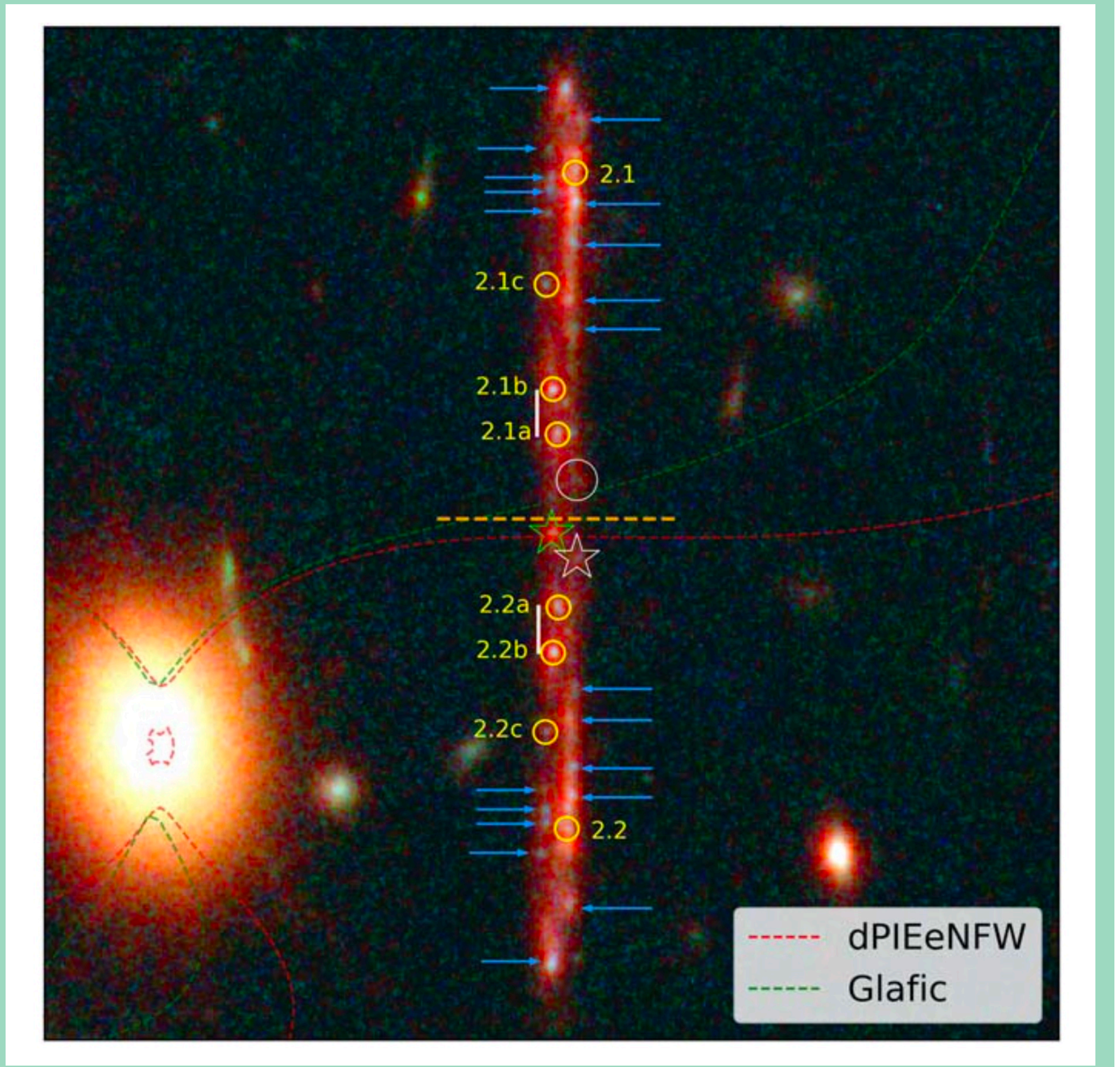




Xie & Huang 2024

Astrophysical phenomena that may lead to probes of axions as dark matter.

- QCD axions that solve the strong CP problem are best motivated. Ultralight axions of galaxy-scale wavelength are already ruled out (except if they are a small fraction of the dark matter).
- Axion minihalos may well be formed in the early Universe, and they may be detectable through gravitational lensing. Difficulty: low mass and surface density. However, for special sources near caustics at high magnification, the lensing effect is boosted and minihalos may be detectable.
- Minihalos may form solitons in their centers as a result of gravitational relaxation, which may grown in mass via minihalo mergers, although axion quartic interaction may limit their mass.
- Any other impact on dark matter dynamics?



Lensed galaxy in MACS0647.7+7015
Meena et al. 2023

Jordi Miralda Escudé
ICREA, Institut de Ciències del Cosmos
Universitat de Barcelona
Hamburg, January 30th 2024

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7. What is the role of modern data analysis techniques, including machine learning, in searches for ALPs through astrophysics?

   Is there a need to homogenise the statistical methods used for data analysis?

Perspectives by:

Sebastian Hoof (University of Padova)

Manuel Meyer (Southern Denmark University)

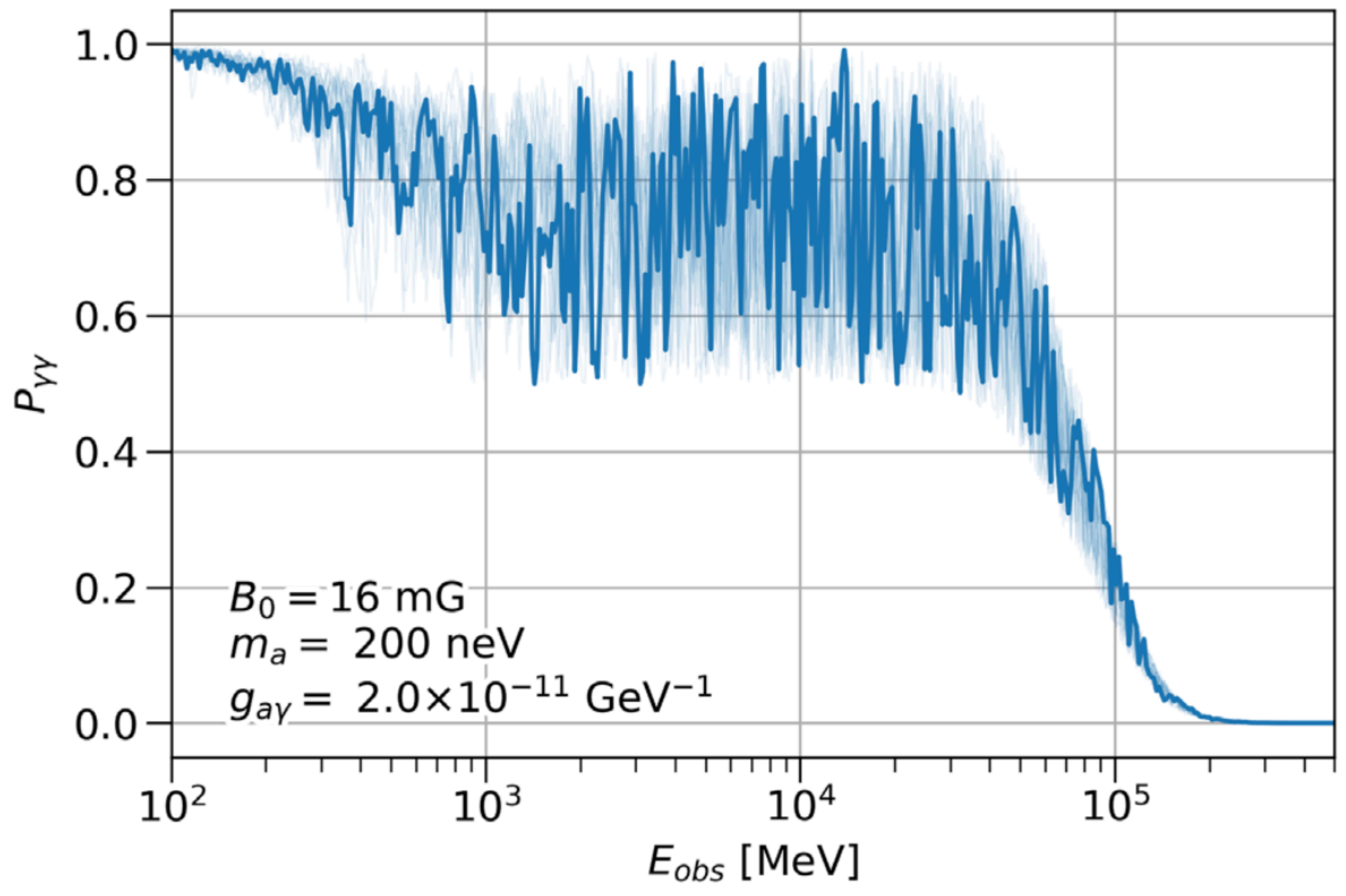
Funded by the European Union

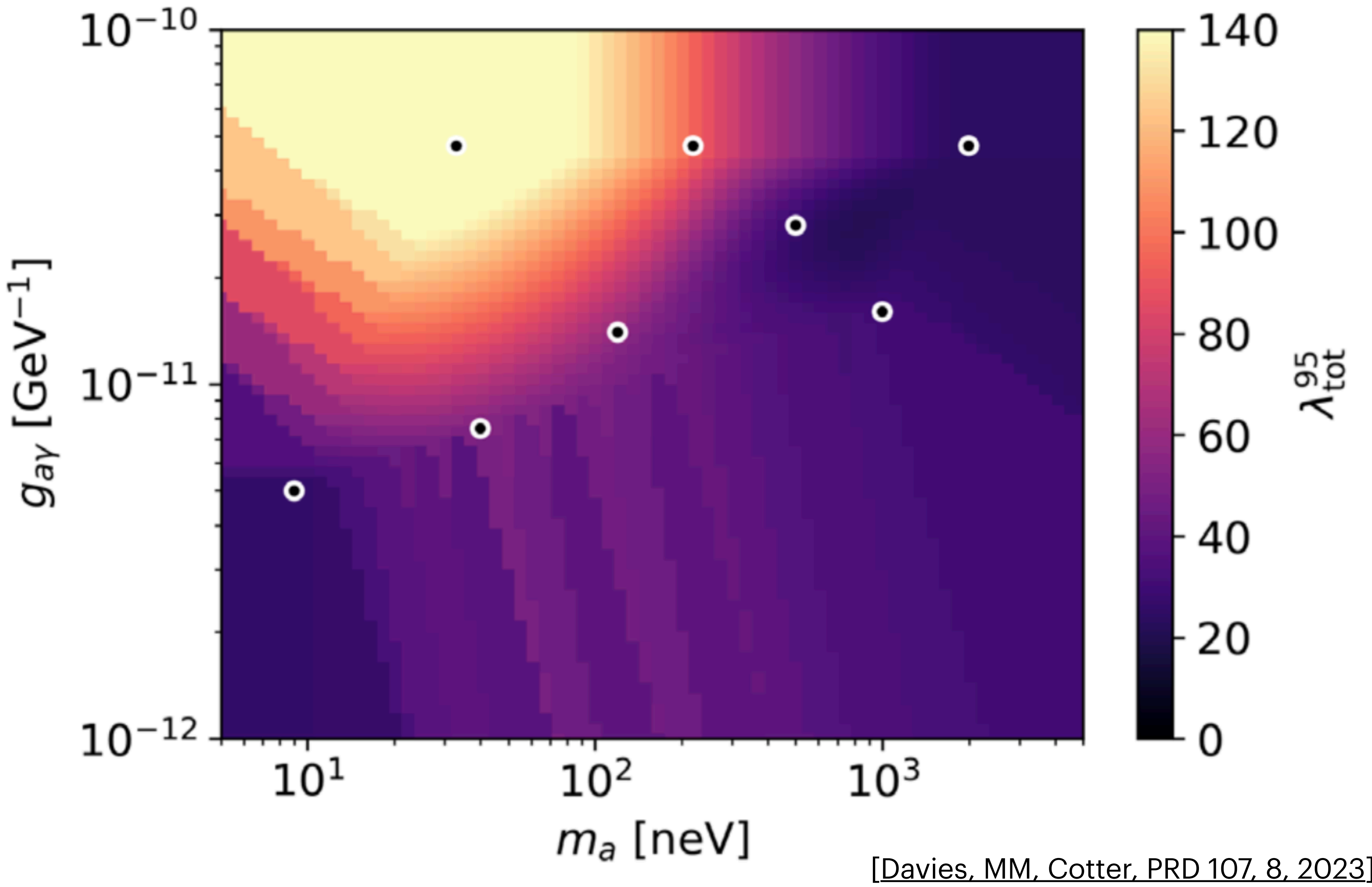
- Homogenise methods? Interdisciplinary field: different challenges, requirements, realities (astro/cosmo $\approx$ Bayesian, HEP $\approx$ frequentist). Homogenising techniques, "enforcing standards" difficult, undesirable?! IMO: Focus on better reproducibility (see my other contribution to this session). Global fits potentially powerful, but require trade-offs
- BUT: similar experiments $\Rightarrow$ similar analyses, at least for comparability (e.g. haloscopes, "low-mass astro region", . . .)
- Machine learning: axion experiments can often be analysed with "old-school stats" and "cheap" likelihoods. In these cases: no inherent need for ML, mostly for curiosity
- BUT: ML, related techniques have a *raison d'être*; potential use for axions in astro data. Watch developments[e.g. EuCAIFCon24]

What is the role of modern data analysis techniques, including machine learning, in searches for ALPs through astrophysics? Is there a need to homogenise the statistical methods used for data analysis?

Manuel's perspective

- When searching for ALP-induced spectral irregularities (at X-rays or gamma rays), we **cannot apply Wilks' theorem** for claiming detection and deriving confidence intervals (thresholds depend on tested ALP parameters!), you need MC simulations → More and more accepted in community
- In case we have model for B field: **we should leave B field parameters free in fitting** / adopt reasonable priors → computationally intensive as photon-axion oscillation probability $P_{a\gamma}$ has to be recalculated (use MCMC, fast computation of $P_{a\gamma}$ through Fourier transforms…)
- We should **account for instrument related systematics** in the analysis (e.g., imperfect knowledge of instrument response)
- Model indecent for e.g. photon-axion oscillations in spectra through anomaly detection?





[Davies, MM, Cotter, PRD 107, 8, 2023]
[Day & Krippendorf, JCAP 3, 46, 2020]
[Marsh et al., PRD 105, 1, 2022]

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   Is there a need to homogenise the statistical methods used for data analysis?

Go to

[menti.com]

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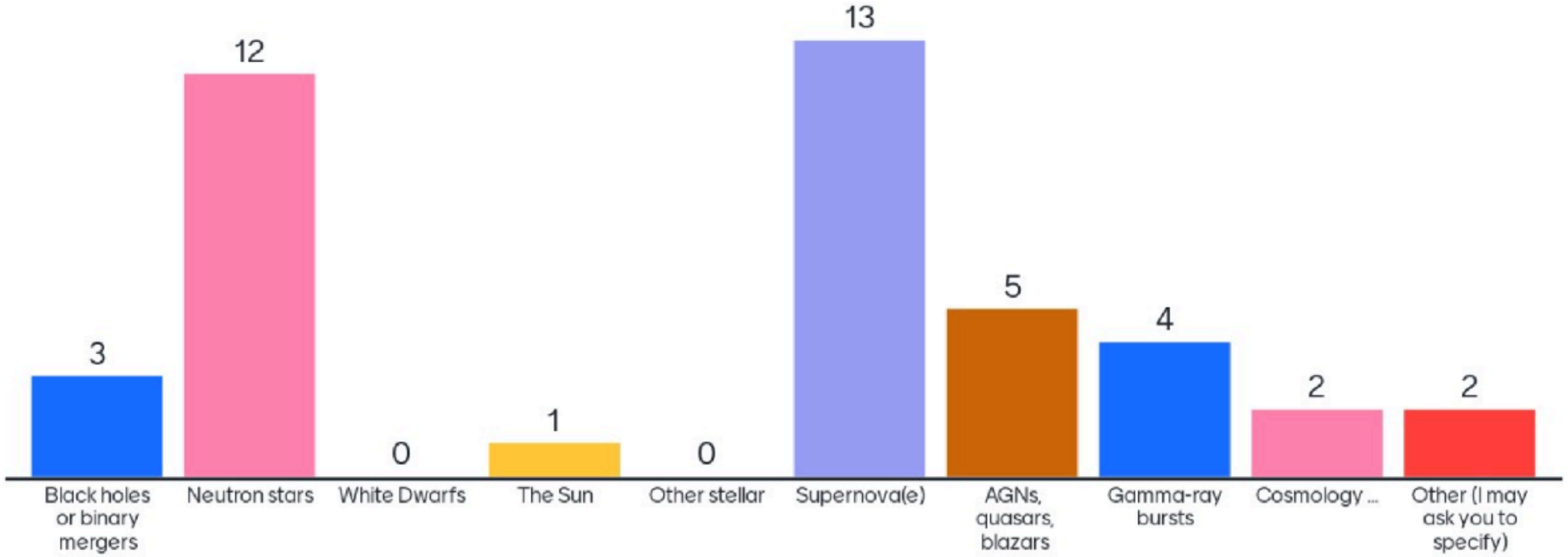
Mentimeter

Suppose that a strong, astrophysical signal characteristic of an ALP is detected in 2024. From what system is it most likely to have come from?



Thanks to all contributors and participants!