Status and Perspectives on Axion searches

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Universidad de Zaragoza & CAPA
Barry University

2nd General Meeting of COST Action COSMIC WISPers

3 September, 2024

The large context: FIPs And WISPs

Theoretical, **Phenomenological** and **Experimental** motivations

- In 2018, the dark matter community produced a Basic Research Needs Report (BRN) for Dark Matter New Initiatives (DMNI) (Kolb et al, 2018) Beyond G2, which currently funds ADMX. Pushes Sub-GeV searches and phase 3 specifically Sub-eV.

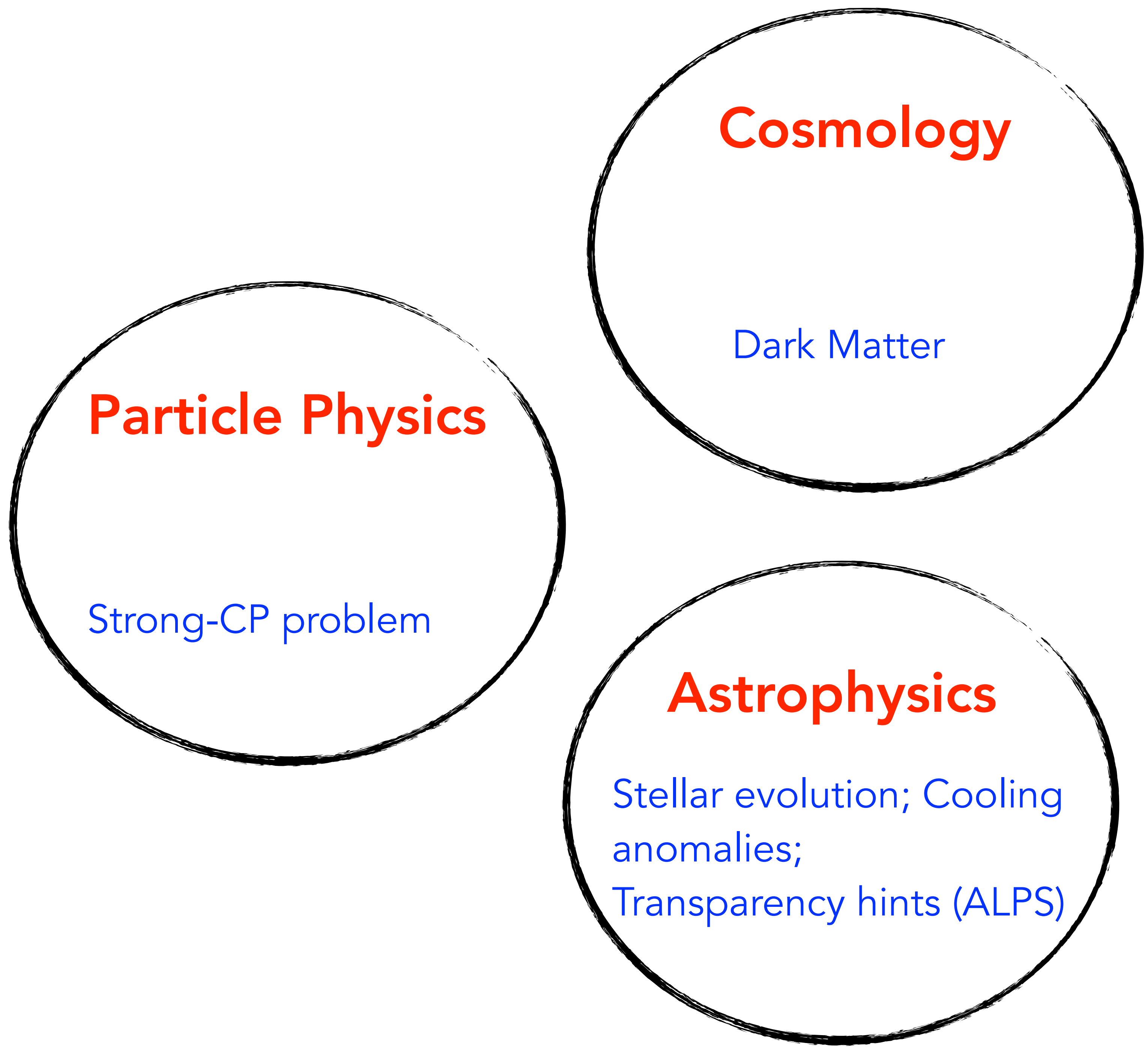
- Significant emphasis in Snowmass (2021) and from the APPEC (2022). Recommendations/Opportunities include:

  - Pursue the QCD Axion with a Collection of Small-Scale Experiments
  - Support Enabling Technologies
  - Support Theory and Astrophysics Beyond the QCD Axion
  - Interconnection between Axion DM and quantum computing communities for R&D towards quantum sensing

- WISP COST Action: CA21106 - COSMIC WISPers in the Dark Universe (2022)

  FPC: Feebly Interacting Particles Physics Center (2020)

Axions



Review articles

- I. Irastorza, J. Redondo, Prog.Part.Nucl.Phys. 102 (2018)
- L. Di Luzio, M.G., Nardi, Visinelli, Phys.Rept. 870 (2020)
- A. Caputo, G. Raffelt, PoS COSMICWISPers (2024)

A few facts about QCD Axions

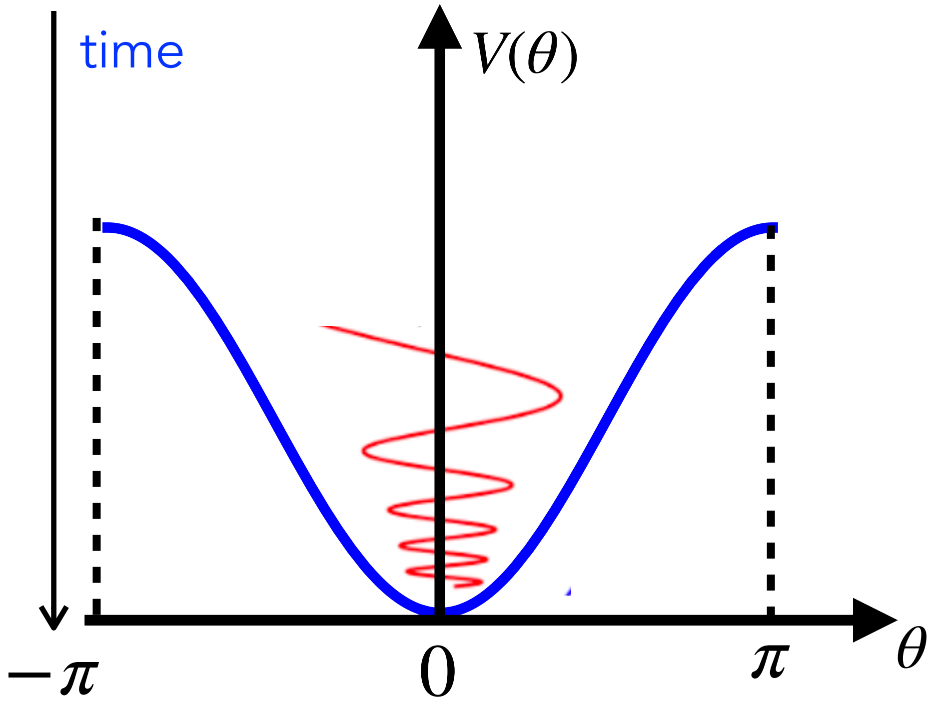
1- The axion potential can be calculated in QCD

$$m_a \simeq 5.7 \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right) \mu\mathrm{eV}$$

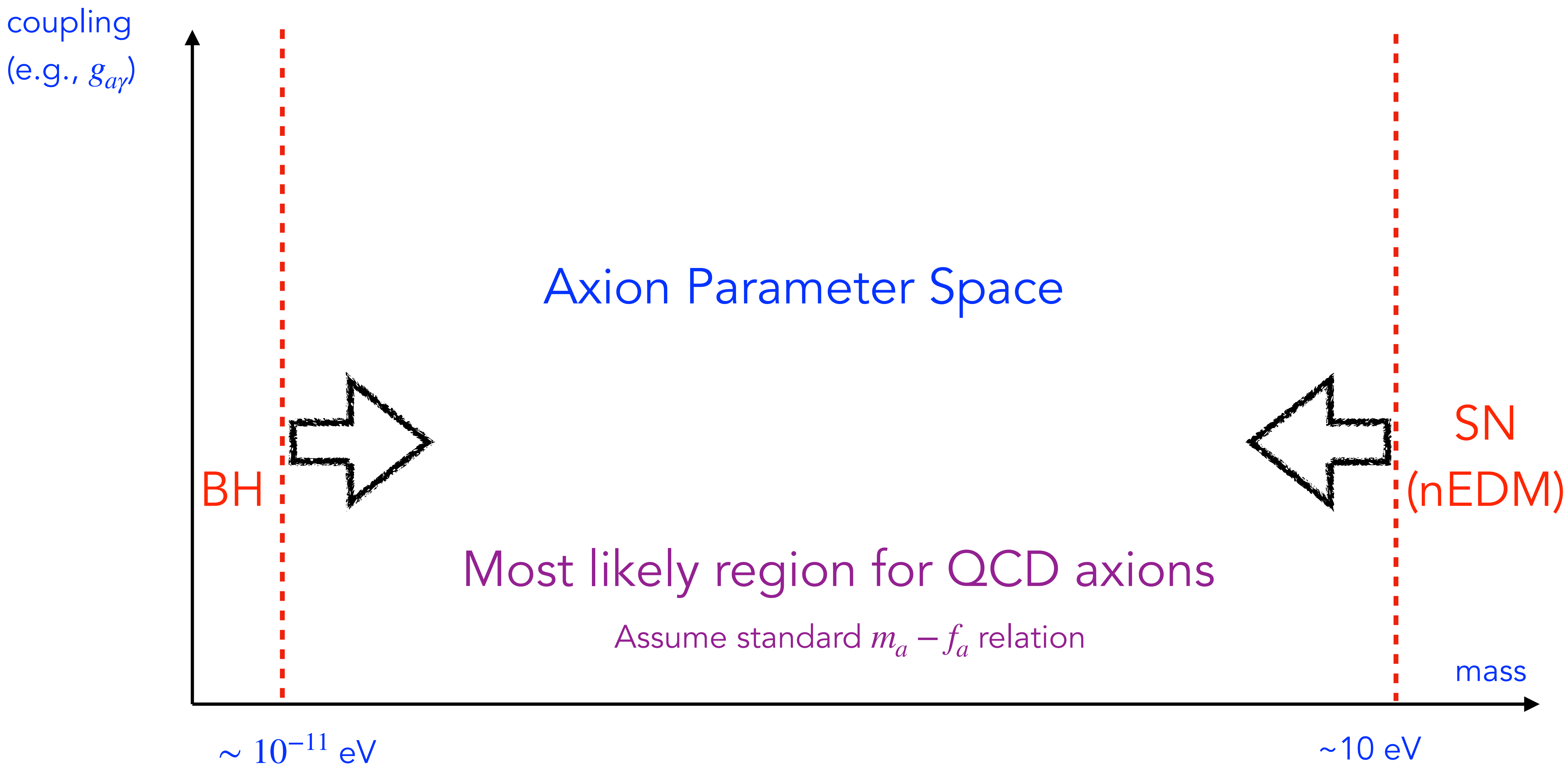
2- The axion couplings are model dependent

3- Requires interaction with nEDM (besides with gravity)

4- Axion contributes to dark matter



Where are the axions?



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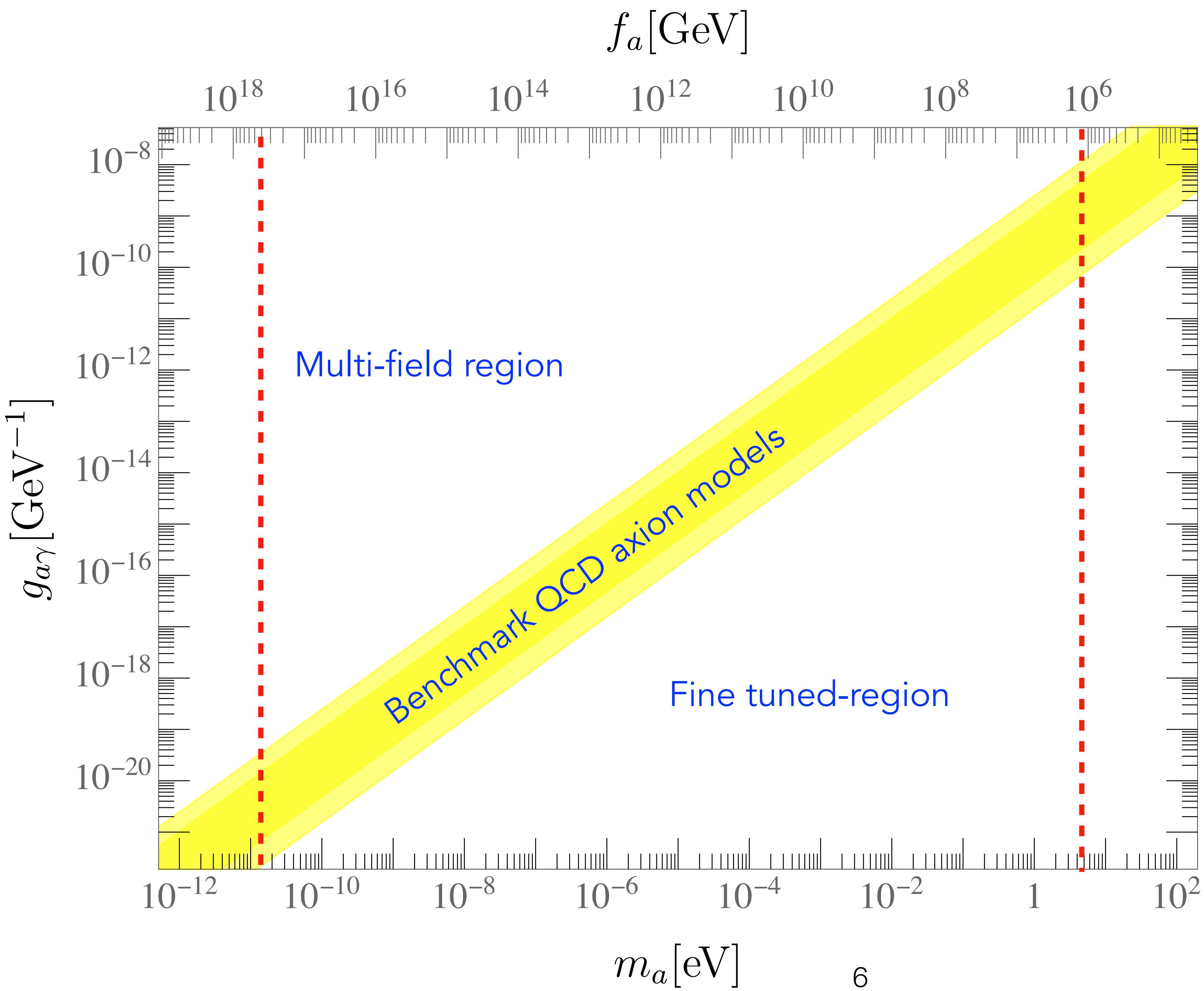
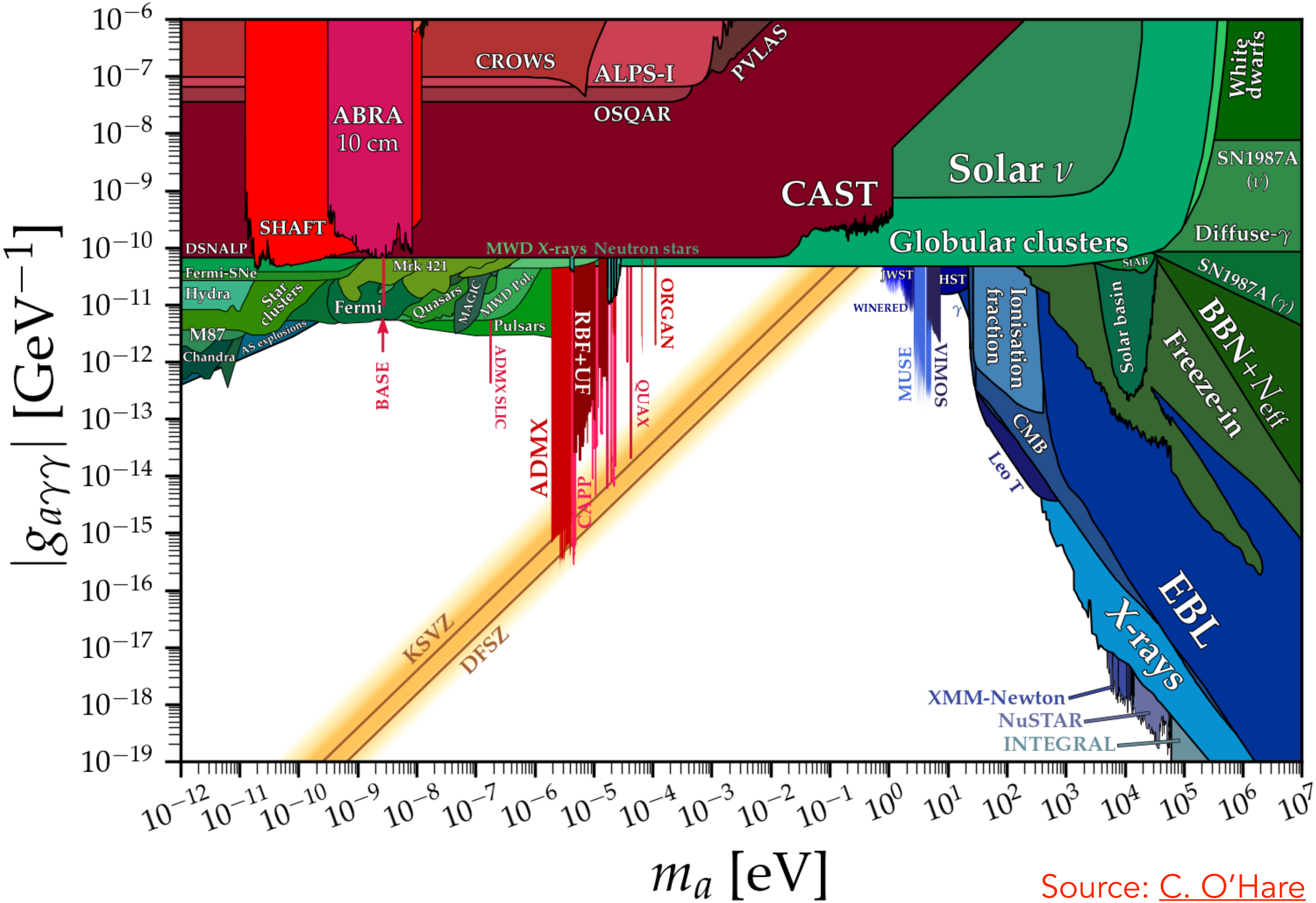


Minimal field extension and basic phenomenological requirements select a narrow band

Di Luzio, Mescia, Nardi, Phys.Rev.Lett. 118 (2017), Phys.Rev. D96 (2017)

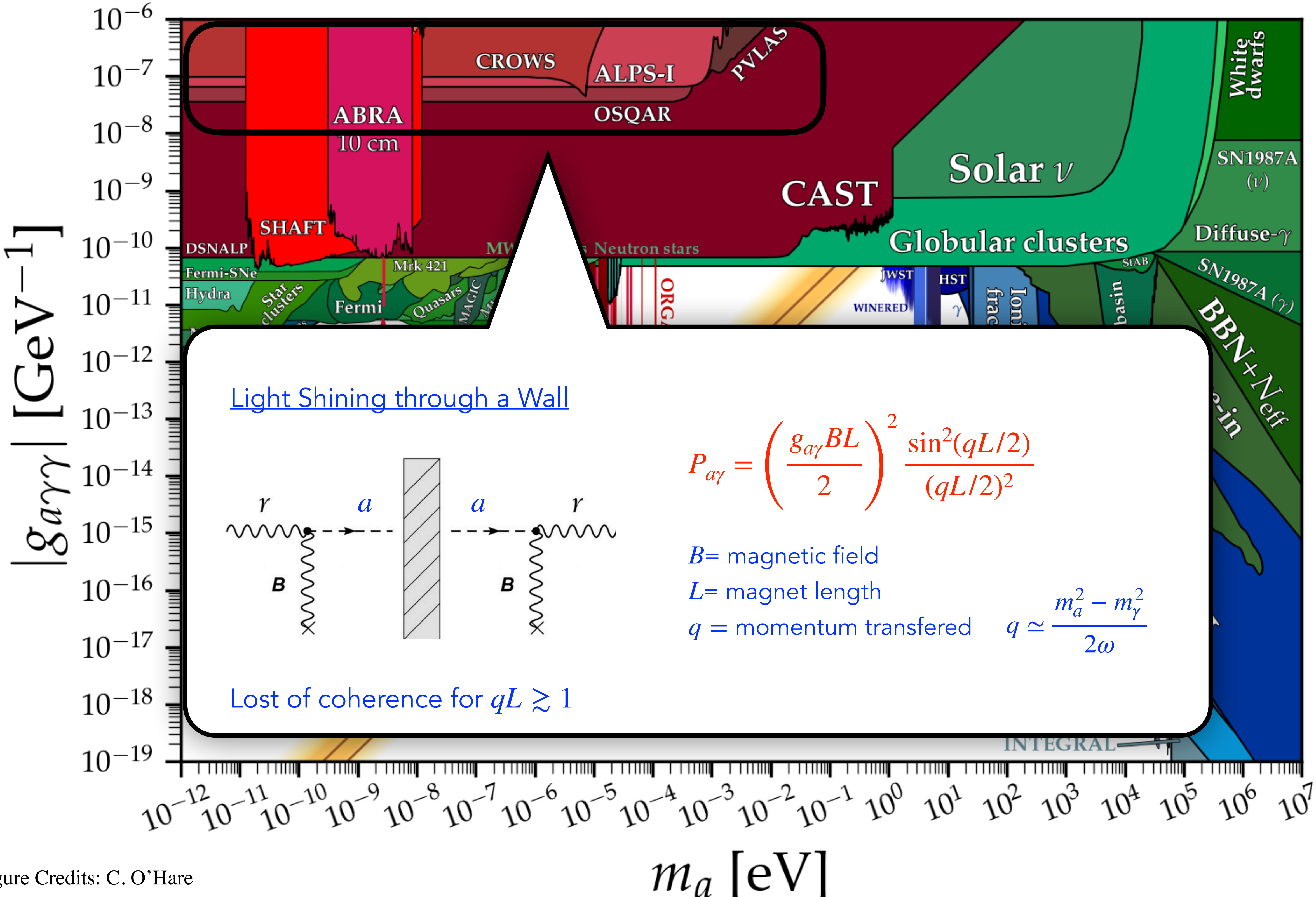
Di Luzio, Fedele, M.G., Mescia, Nardi, *JCAP* 02 (2022) 02, 035

ALP Parameter Space



Source: C. O'Hare

Laboratory Searches



Light Shining through a Wall

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

B= magnetic field

L= magnet length

q = momentum transfered $\quad q \simeq \dfrac{m_a^2 - m_\gamma^2}{2\omega}$

Lost of coherence for $qL \gtrsim 1$

Figure Credits: C. O'Hare
https://cajohare.github.io/AxionLimits/

ALPS II

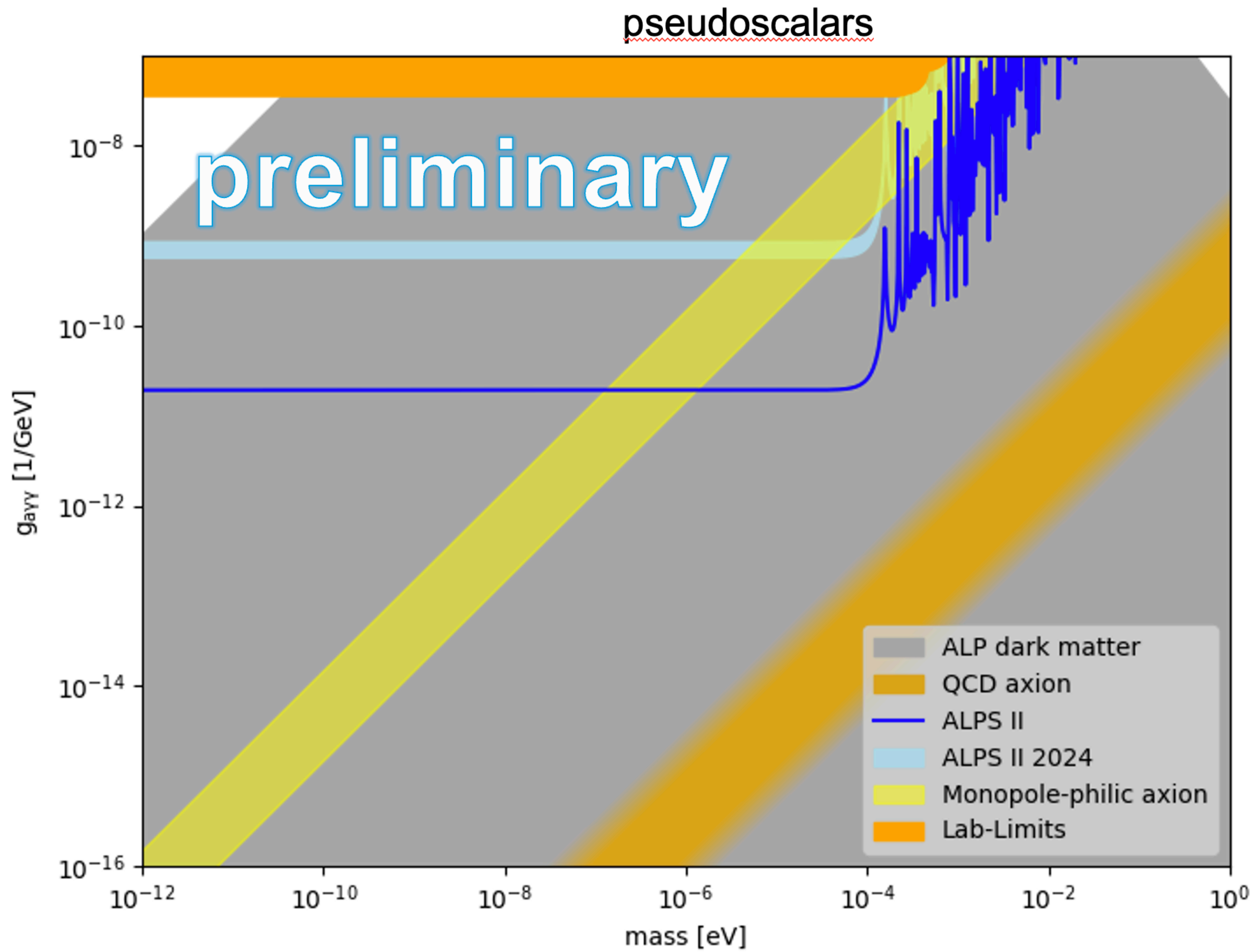
First runs finished

→ 6 May 2024.

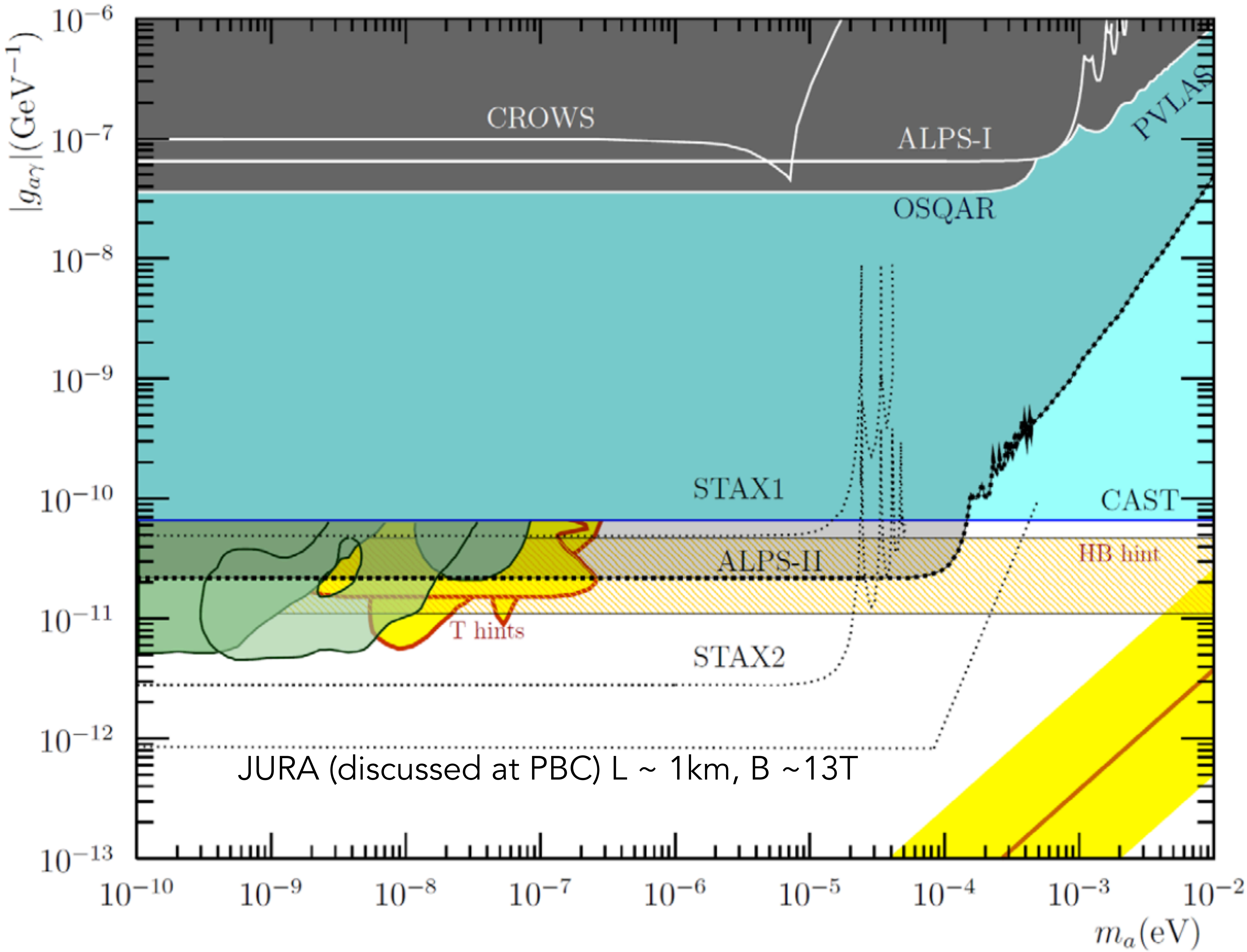
New paper soon (optics performance and boson searches).

Next steps:

→ Full optics in 2025

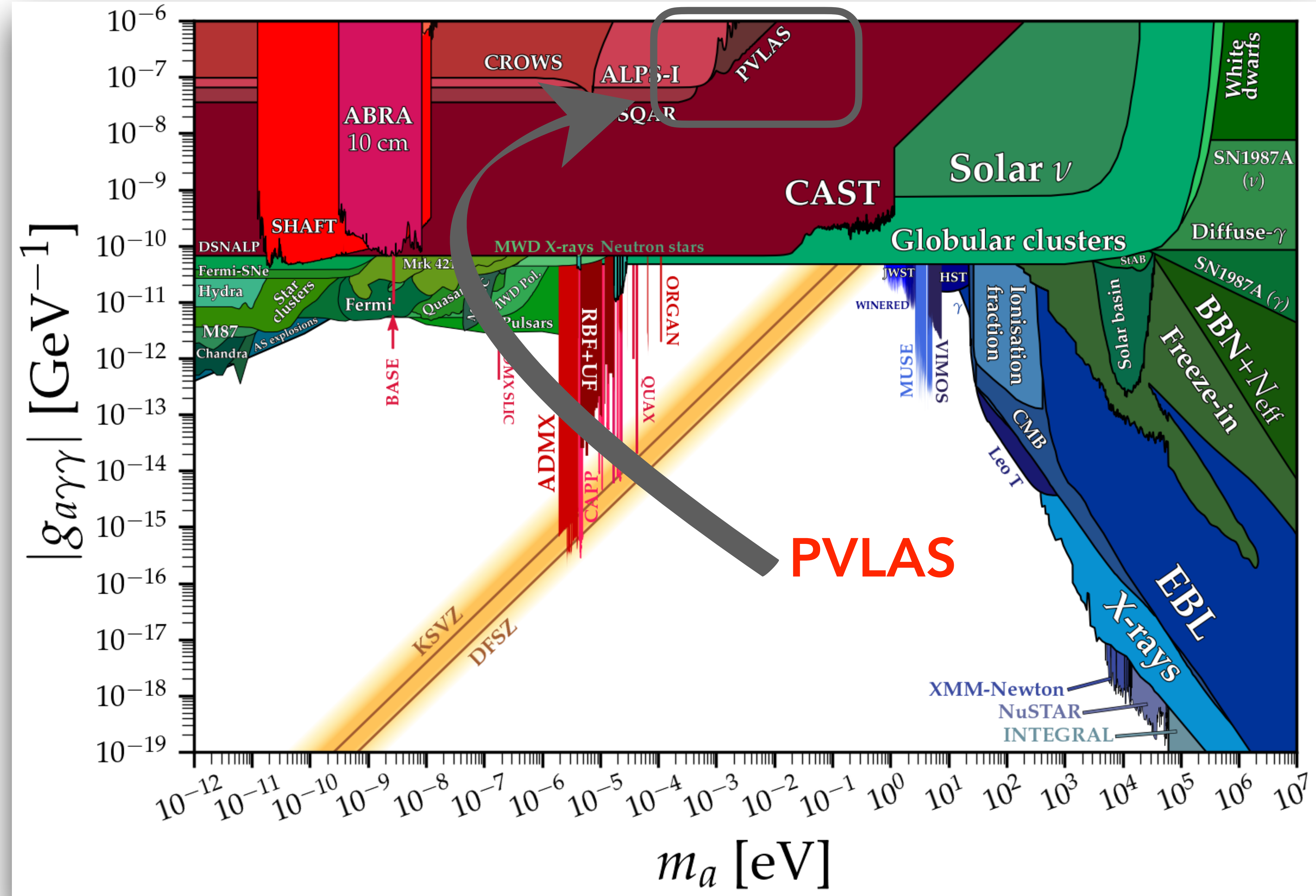


A. Lindner, Heidelberg July 2024



I. Irastorza, J. Redondo, Prog.Part.Nucl.Phys. 102 (2018)

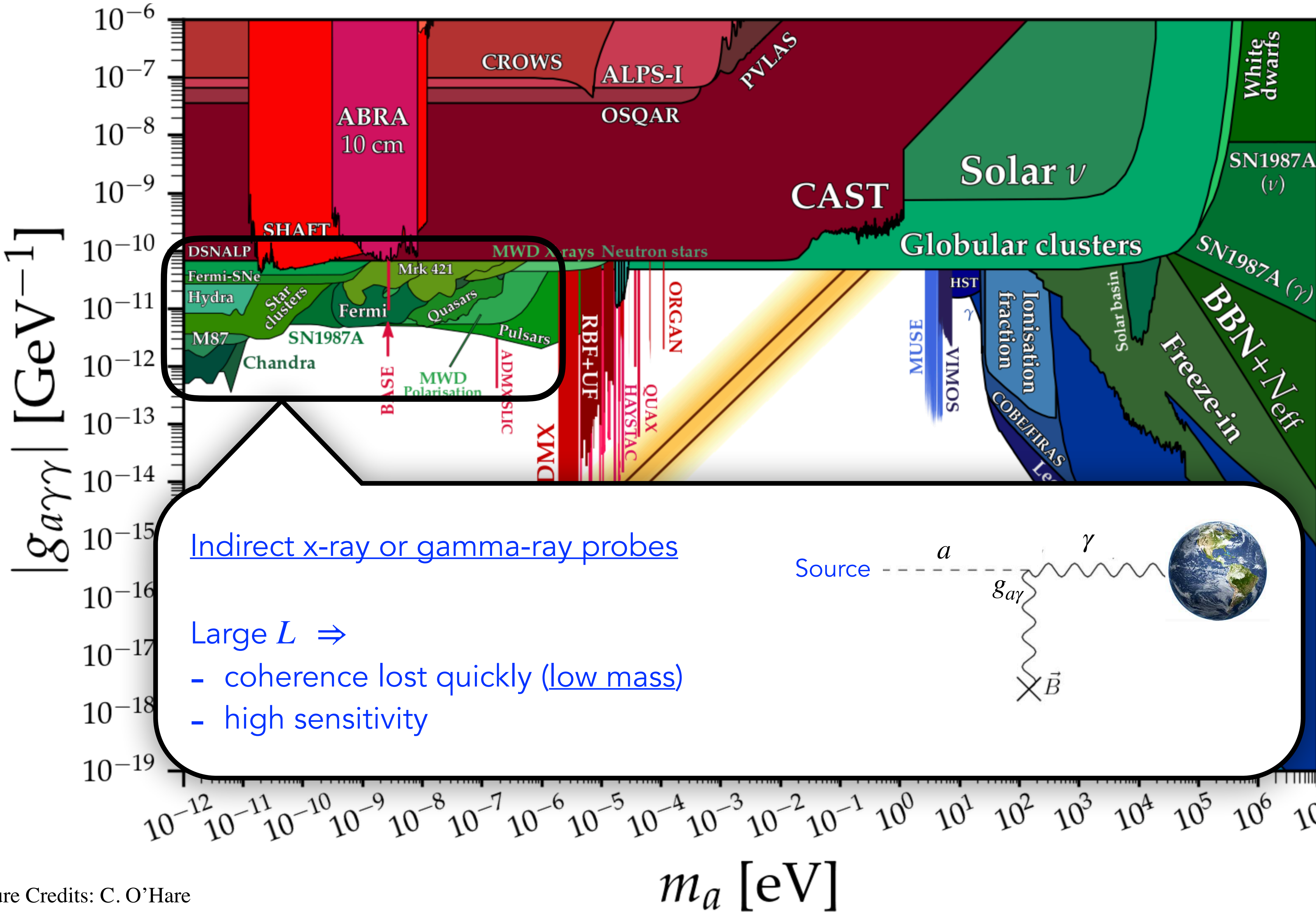
Polarization experiments



Future project under discussion (as of 2024) at PBC: VMB@CERN.

See Proceeding of 1st COST General Meeting: PoS COSMICWISPers (2024) 032 , April 2024

Astrophysical sources



[Indirect x-ray or gamma-ray probes]

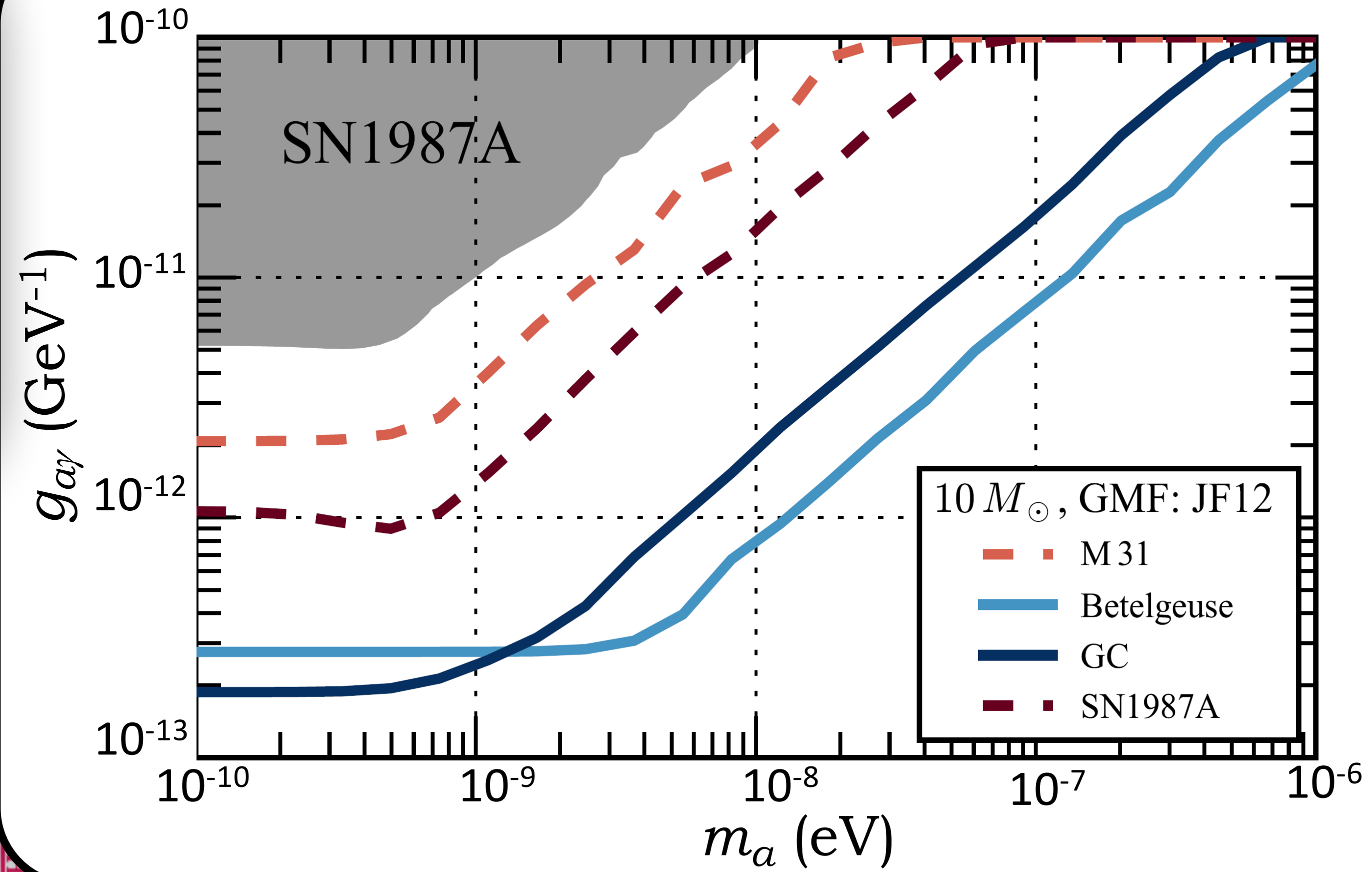
Large L $\Rightarrow$

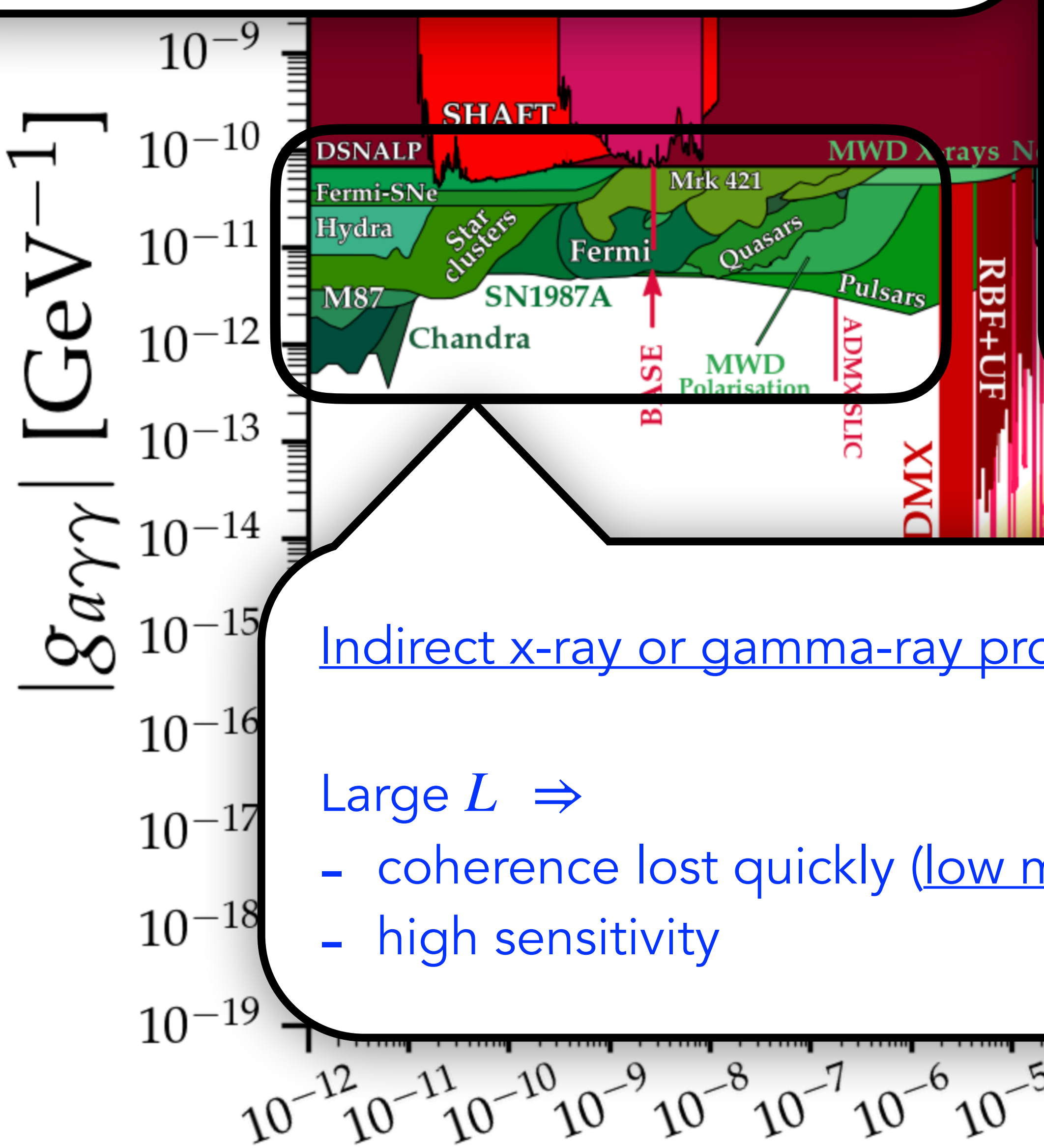
- coherence lost quickly ([low mass])
- high sensitivity

Figure Credits: C. O'Hare
https://cajohare.github.io/AxionLimits/

Large area explorable by Fermi LAT with a future galactic SN event. Covers the region of transparency hints.

- M. Meyer et al., Phys.Rev.Lett. 118 (2017)
- Calore, Carenza, Eckner, MG, Lucente, Mirizzi, Sivo, Phys.Rev.D 109 (2024) 4





Indirect x-ray or gamma-ray probes

Large L $\Rightarrow$
- coherence lost quickly (low mass)
- high sensitivity

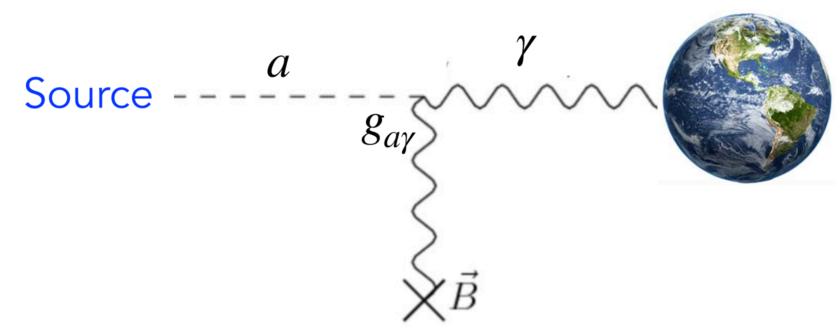


Figure Credits: C. O'Hare
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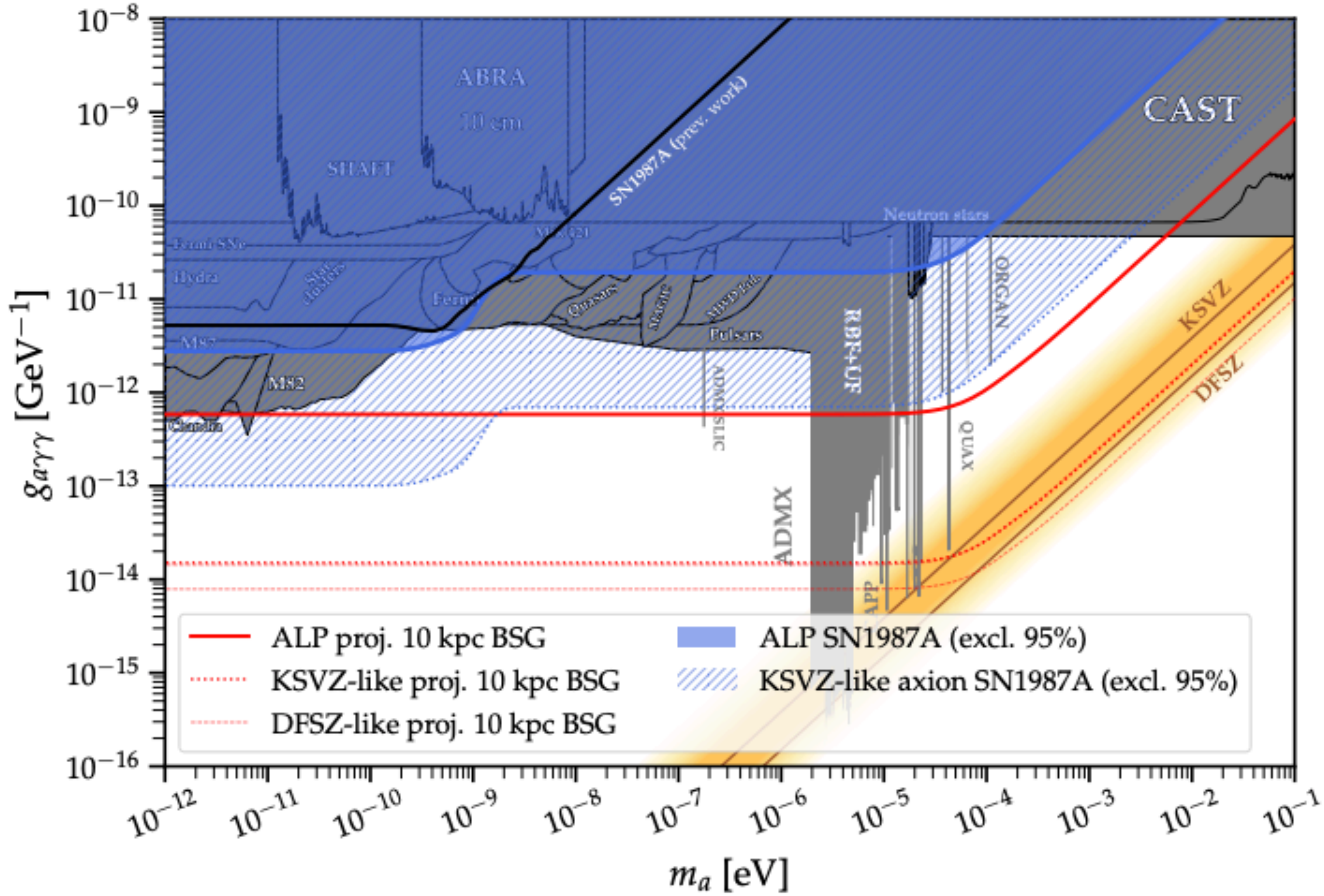
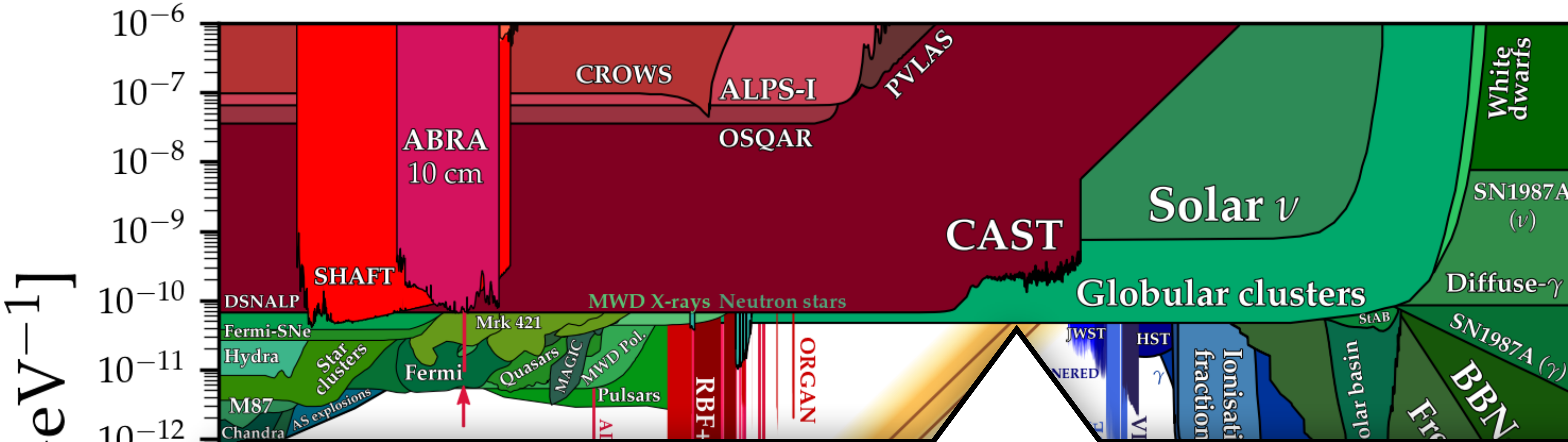
Accounting for (possible) progenitor magnetic field

Accounting for possible progenitor magnetic field

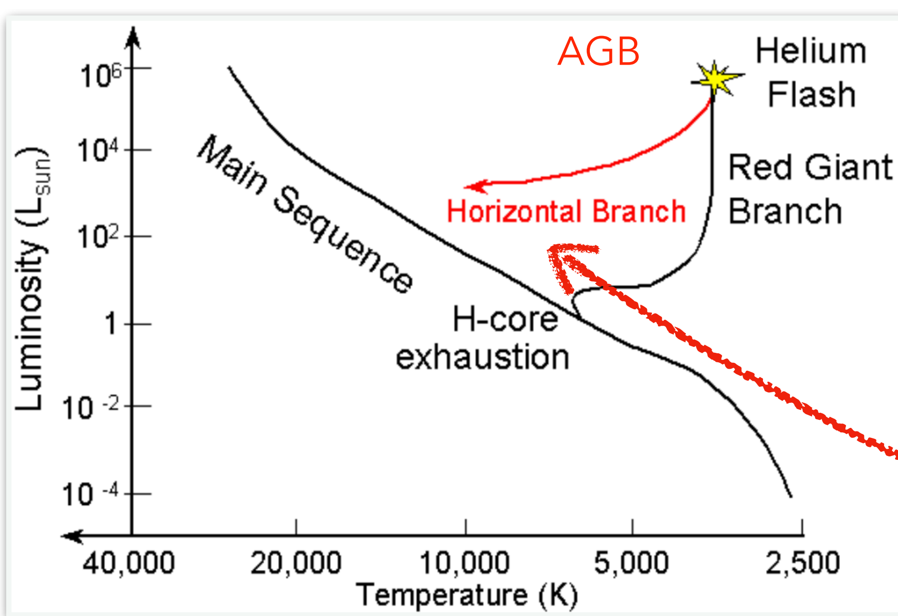


Manzari, Park, Safdi, Savoray arXiv: 2405.19393

Stellar Bounds



Stellar cooling (HB) bounds



Thermal production:

Mass independent up to $m_a \sim T_{\rm core} \sim 10$ keV.

Then, Boltzmann suppressed

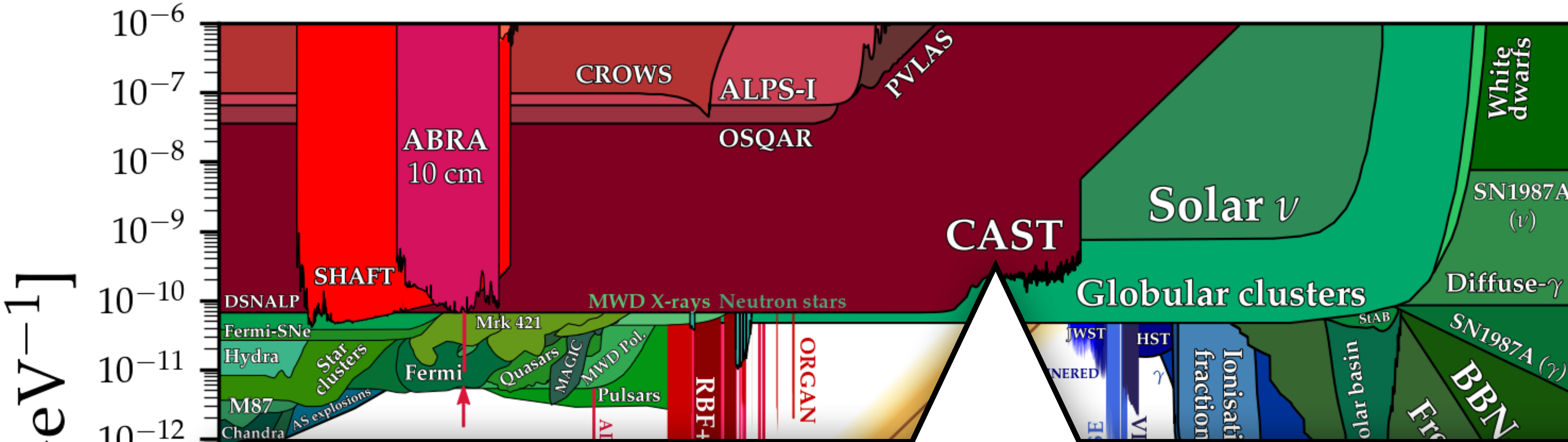
Primakoff Process

- *Ayala, Dominguez, M.G., Mirizzi, Straniero, PRL 113 (2014)*
- *Dolan, Hiskens, Volkas, JCAP 10 (2022) 096*

$g_{a\gamma} \leq 6.5 \cdot 10^{-11}\,\mathrm{GeV}^{-1}$

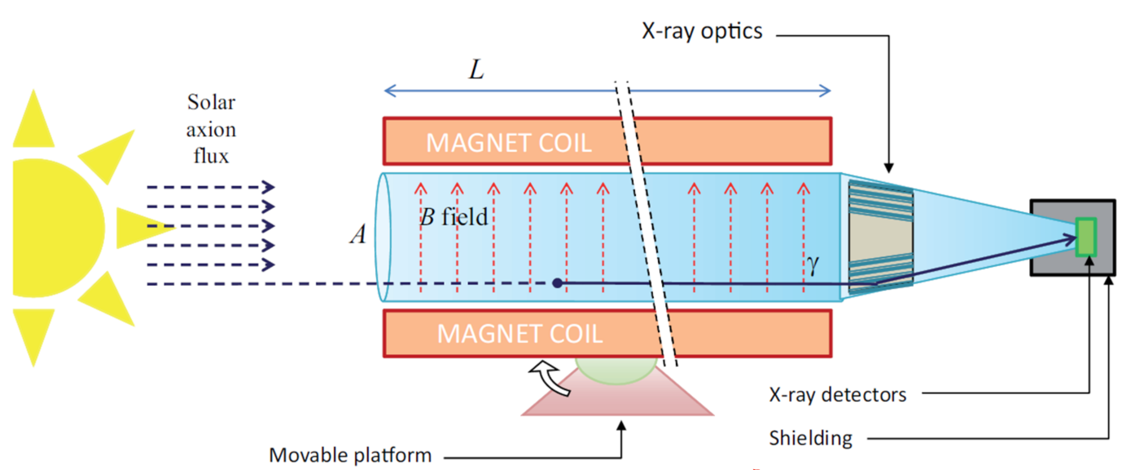
$g_{a\gamma} \leq 4.7 \cdot 10^{-11}\,\mathrm{GeV}^{-1}$

Detection of Solar Axions



Helioscope

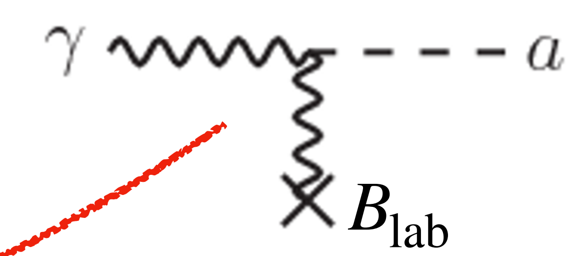
P. Sikivie PRL 51:1415 (1983)



$\omega_a \sim$ keV, $L \sim 10$ m

$\Rightarrow$ Coherence lost at

$m_{\rm th} \approx 10\,{\rm meV}\,\omega_{\rm keV}^{-1}\,L_{10}^{-1/2}$



P. Sikivie PRL 51:1415 (1983)

$g_{a\gamma} \leq 6.6 \cdot 10^{-11}\,{\rm GeV}^{-1}$

CAST Coll., Nature Phys. 13 (2017)

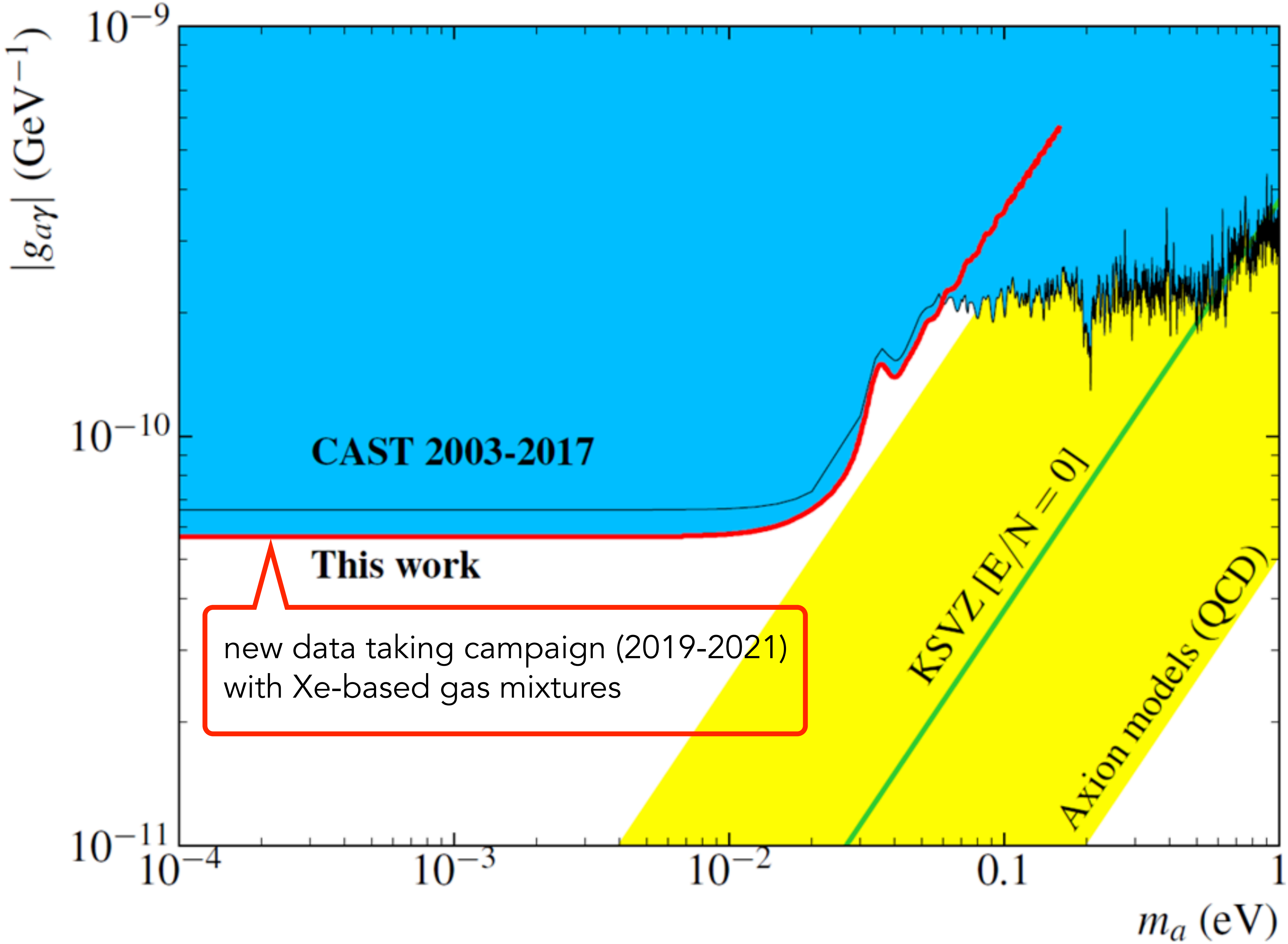
The CERN Axion Solar Telescope

Most sensitive axion helioscope:

- 9m superconducting LHC prototype dipole magnet
- X-ray optics
- Detectors

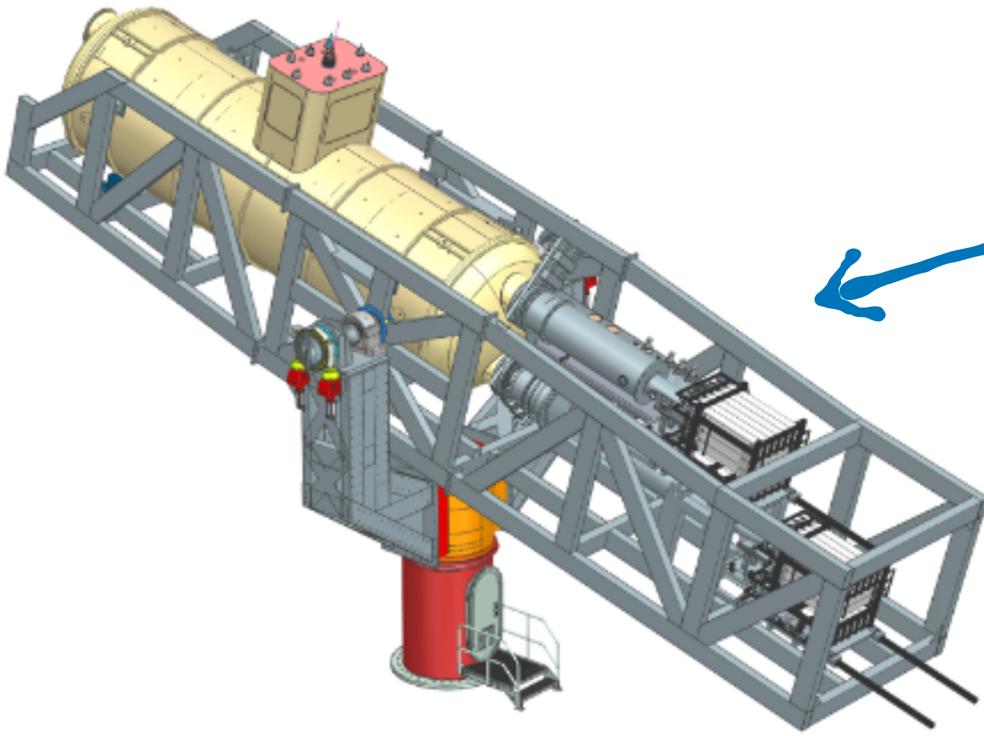
→ Solar WISPs
→ DM axions
→ Dark Energy
…

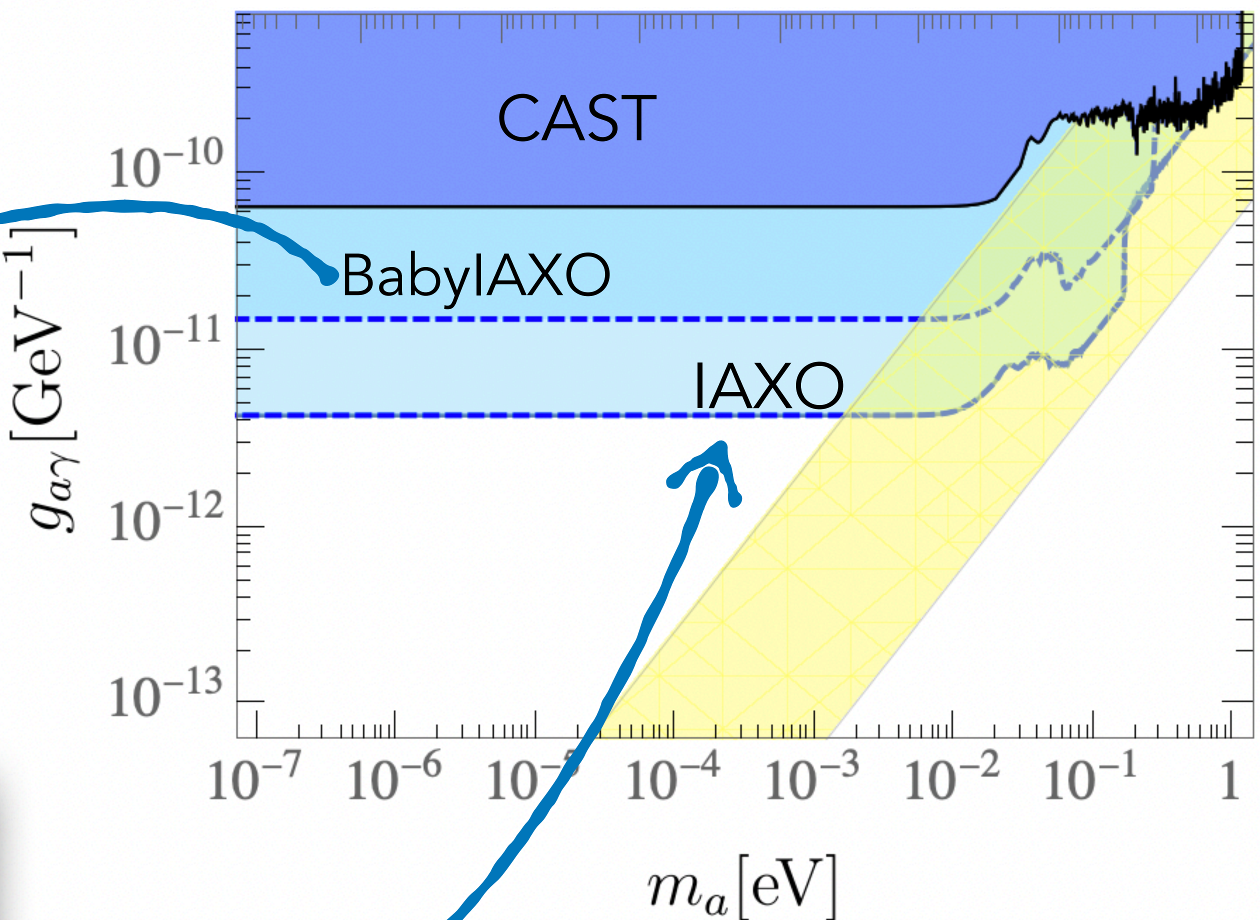
New CAST Bound

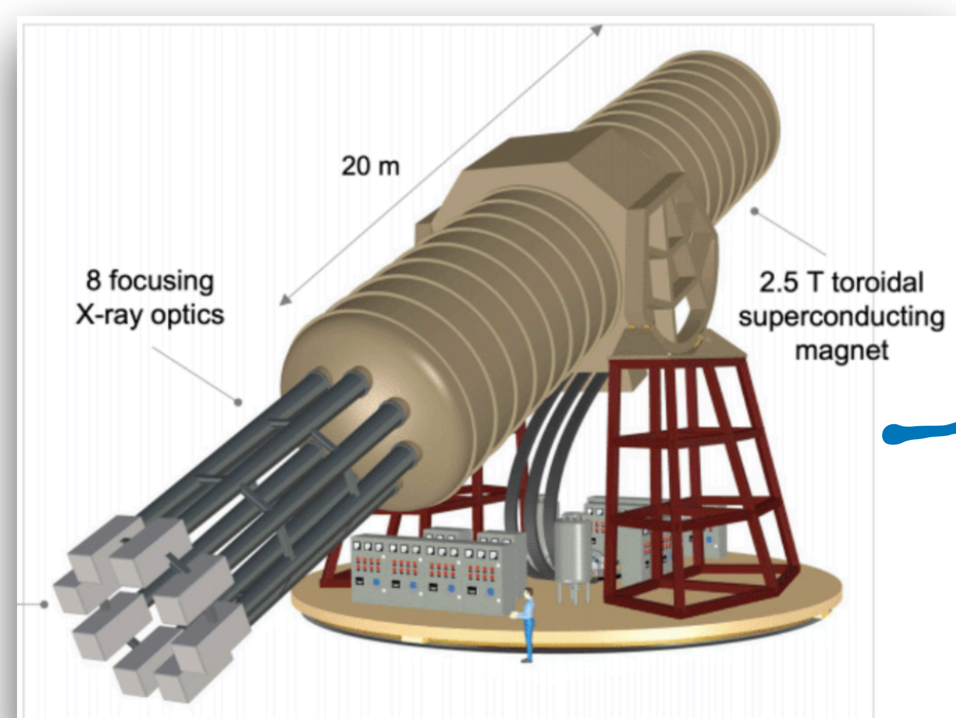


C. Margalejo Blasco, J. Ruz, et al (CAST collaboration, 2024) arXiv:2406.16840

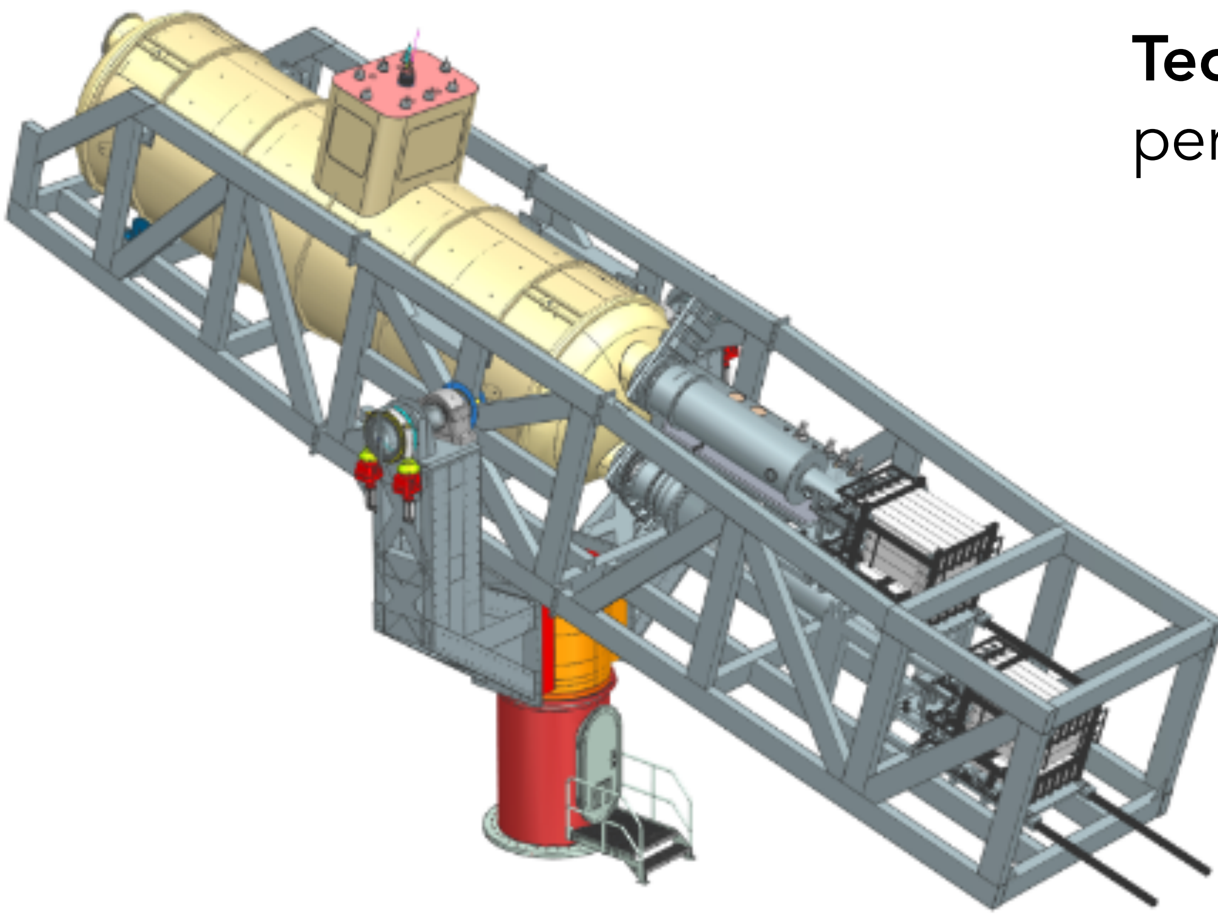
Solar Axions: the Next Generation







BabyIAXO

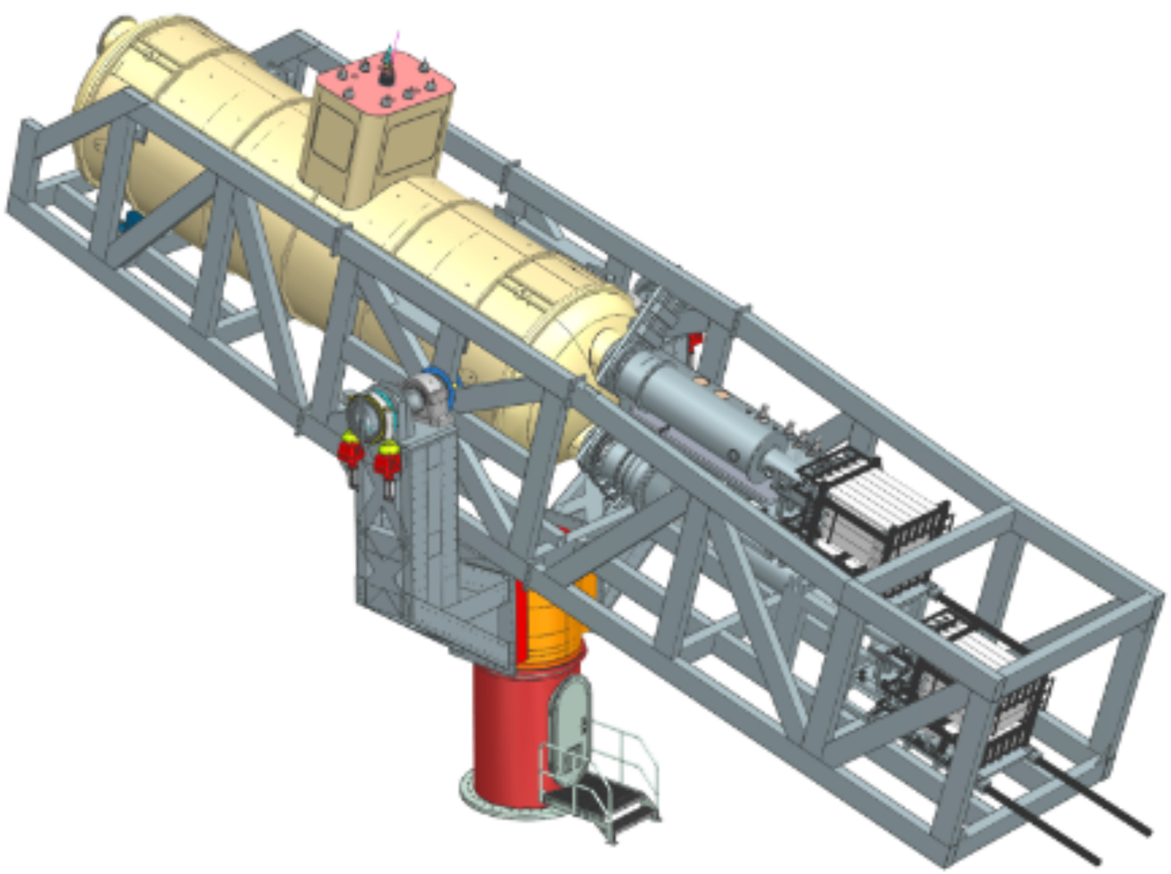


Technological prototype of IAXO with high performance and discovery potential

- Two magnet bores (10 m, Ø 70 cm). 10 m & 2T magnet
- Custom X-ray optic + XMM-Newton flight spare optic

- Relevant physical outcome (~10× CAST B^2L^2A)
- Magnet will be upscalable version for IAXO
- X-ray optics/detectors close to final IAXO configuration (focal length, performance)

BabyIAXO



- Approved by DESY in 2019.
- Commissioning expected by 2027

To be installed in HERA South

- A magnet Conceptual Design Report (CDR) was produced and reviewed in April 2024 → very positive outcome.

ERC Synergy Grant DarkQuantum obtained !

- Develop quantum tech for axions
- Quantum-enhanced haloscope in BabyIAXO
- Connection with experts (cryo, quantum,...)
- Contribution to magnet

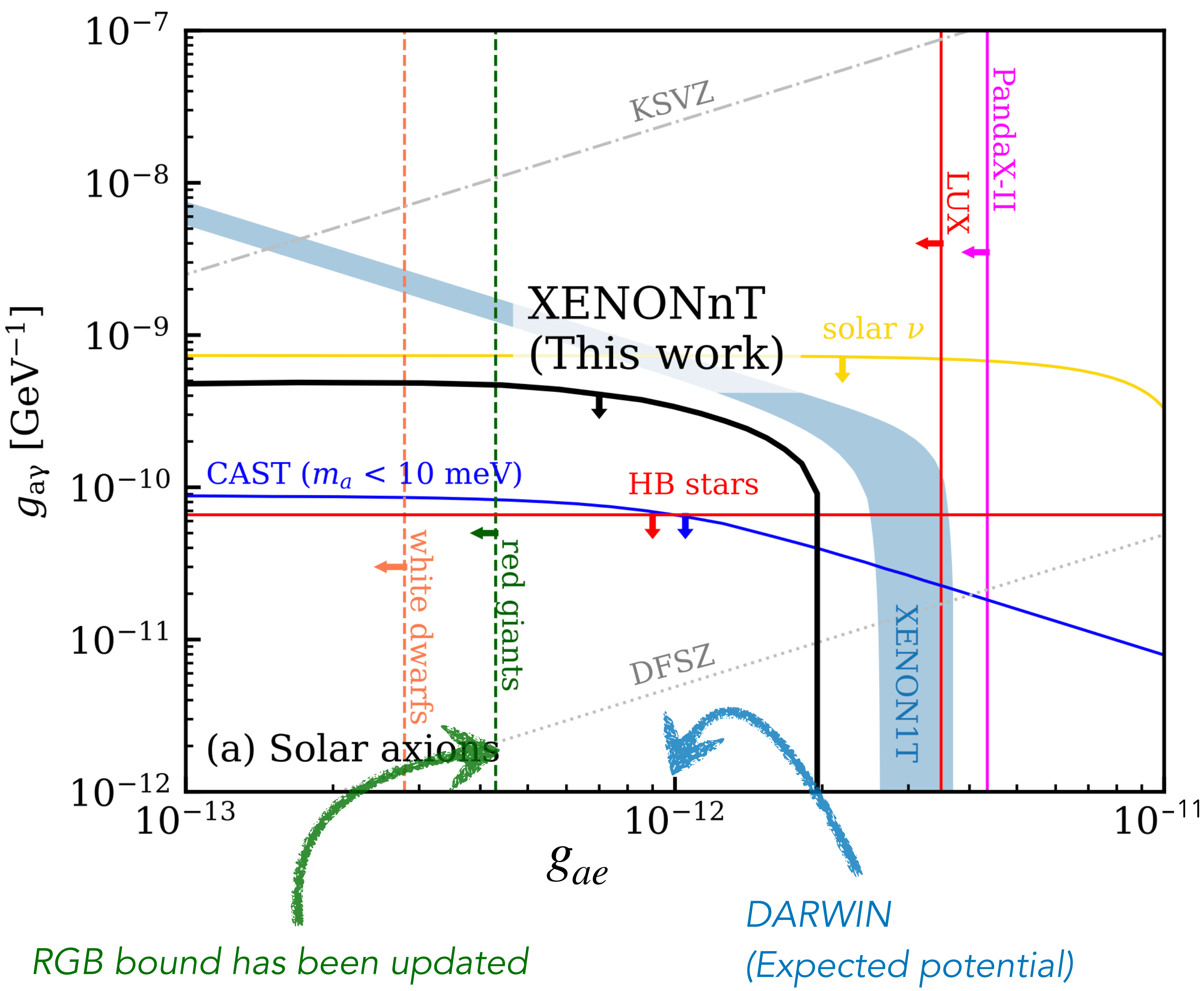
DarkQuantum

I. Irastorza (U. Zaragoza), T. Kontos (École Normale Supérieure de Paris), S. Paraoanu (Aalto University), W. Wernsdorfer (KIT)

Axioelectric Helioscopes

Large underground DM detectors.

Axioelectric = axion analog to the photoelectric effect $\sigma_{ae} \propto \left(\frac{E_a}{m_e}\right)^2$

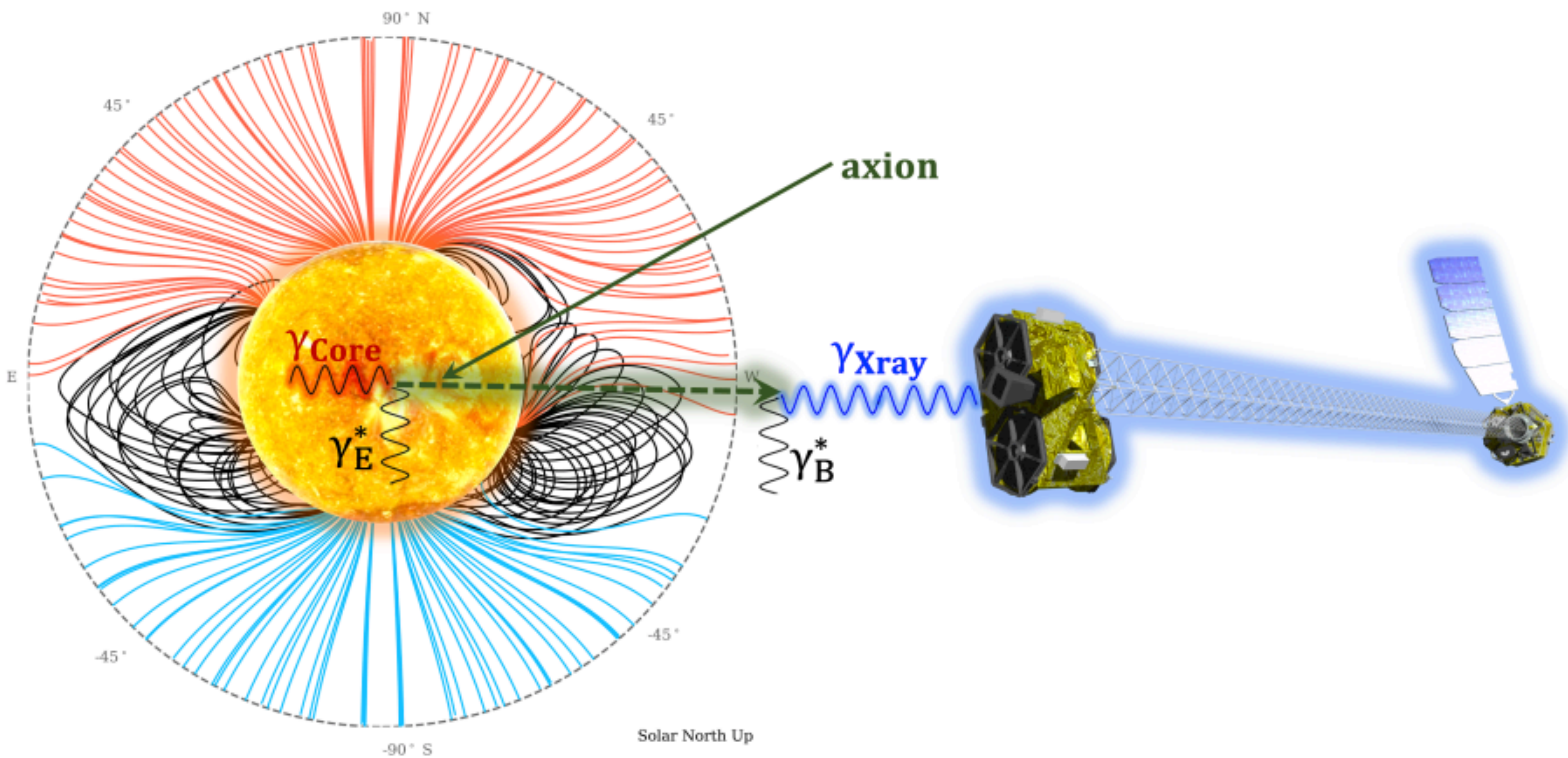


Previous hint conclusively dismissed by the first science run of the XENONnT

$g_{ae} \lesssim 2 \times 10^{-12}$

E. Aprile et al., Phys.Rev.Lett. 129 (2022)

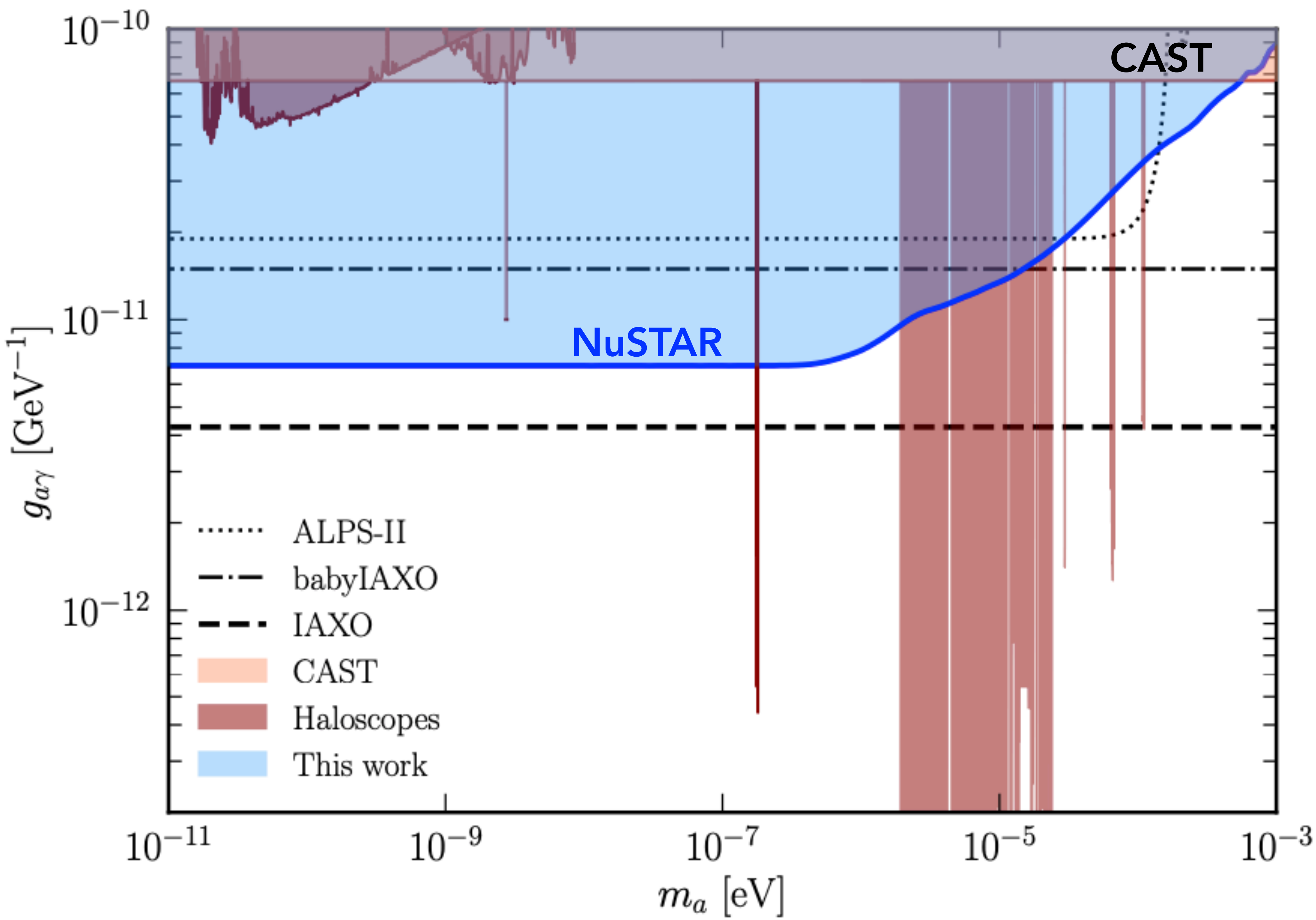
Hunting Solar Axions: NuSTAR



- J. Ruz, E. Todarello et al. arXiv:2407.03828

  (With Jiri Stepan for solar magnetic field modeling)

Hunting Solar Axions: NuSTAR



J. Ruz, E. Todarello et al. [arXiv:2407.03828]

Haloscopes

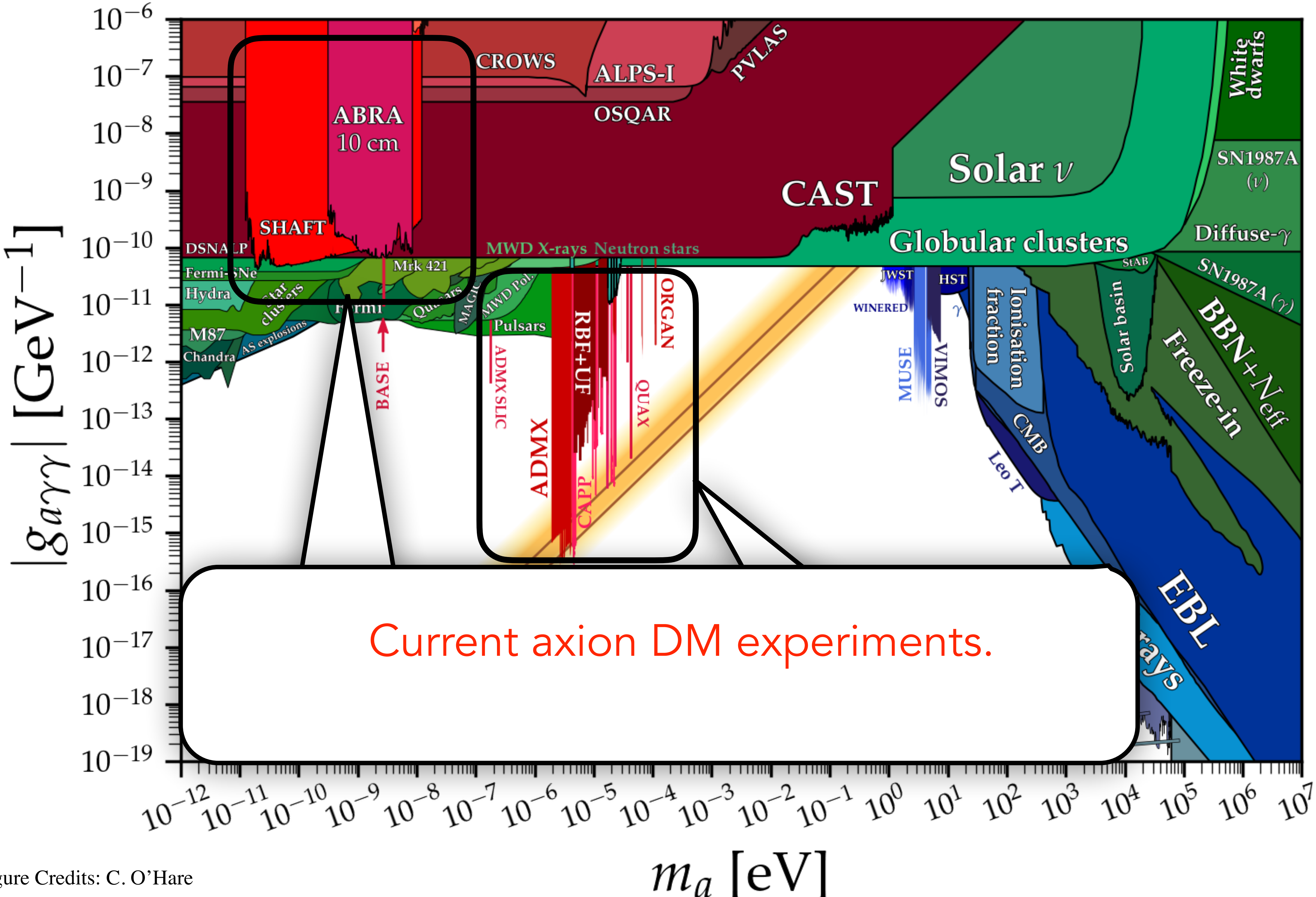
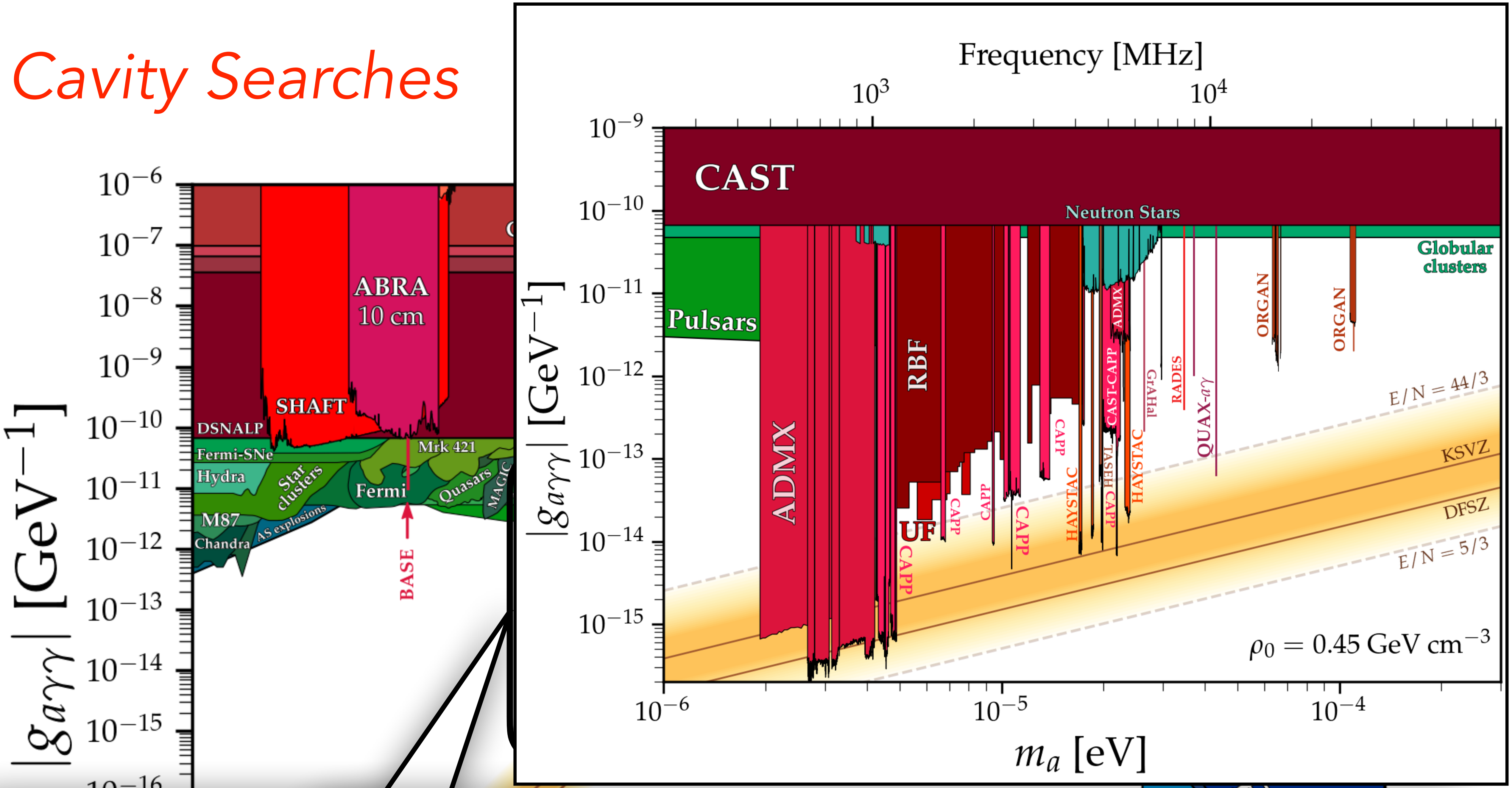


Figure Credits: C. O'Hare
https://cajohare.github.io/AxionLimits/

Cavity Searches



Some Recent Results:

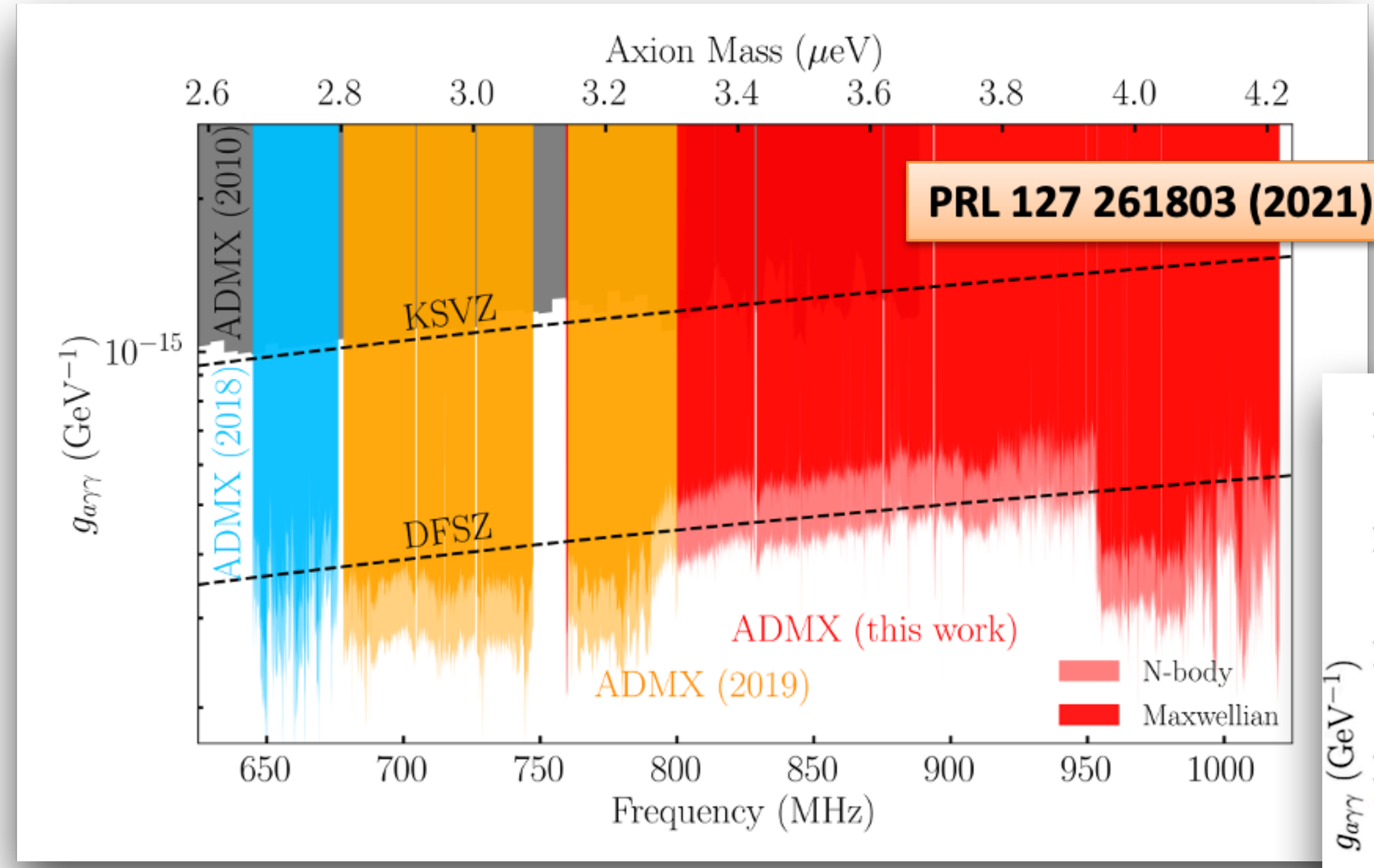
- ORGAN Phase 1b exclude $g_{a\gamma\gamma} \geq 4 \times 10^{-12}\mathrm{GeV}^{-1}$ with 95% in the 107.42-111.93 μeV mass range. Quiskamp et al, Phys.Rev.Lett. 132 (2024) 3
- QUAX: probed $g_{a\gamma\gamma}$ below $10^{-13}\mathrm{GeV}^{-1}$ for m_a in the range 42.8178 − 42.8190 eV. R. Di Vora et al, Phys.Rev.D 108 (2023) 6
- CAPP 12T, @$m_a \simeq 22\,\mu\mathrm{eV}$, Y. Kim et al., submitted Dec. 2023
- RADES, @$m_a \simeq 36.6\,\mu\mathrm{eV}$,, submitted March 2024

Cavity Searches

Micro eV mass range:

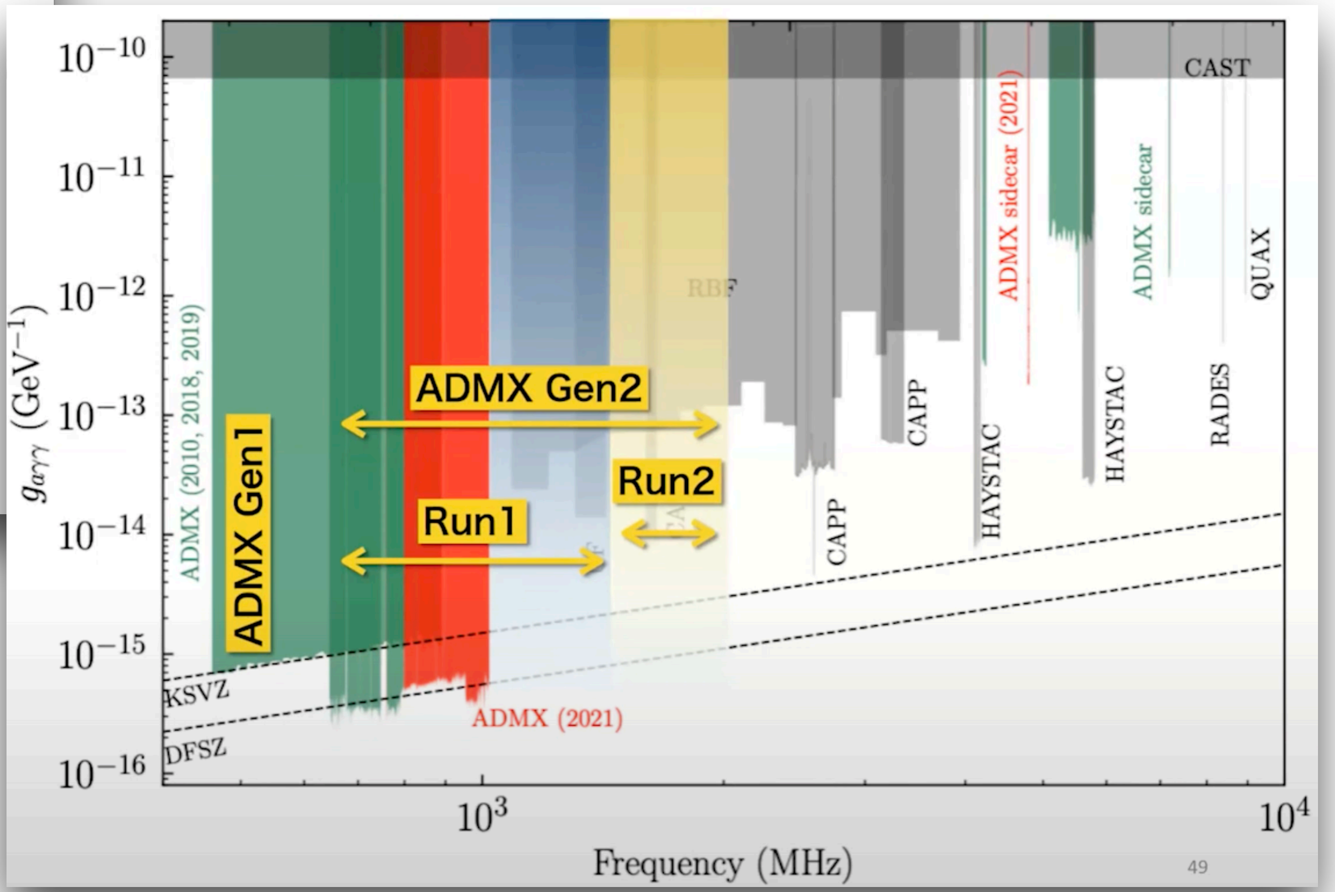
Most experience.

- ADMX: proven sensitivity to few μeV



Future:

Move to multicavity designs



Gray Rybka @ GGI 2023

Cavity Searches

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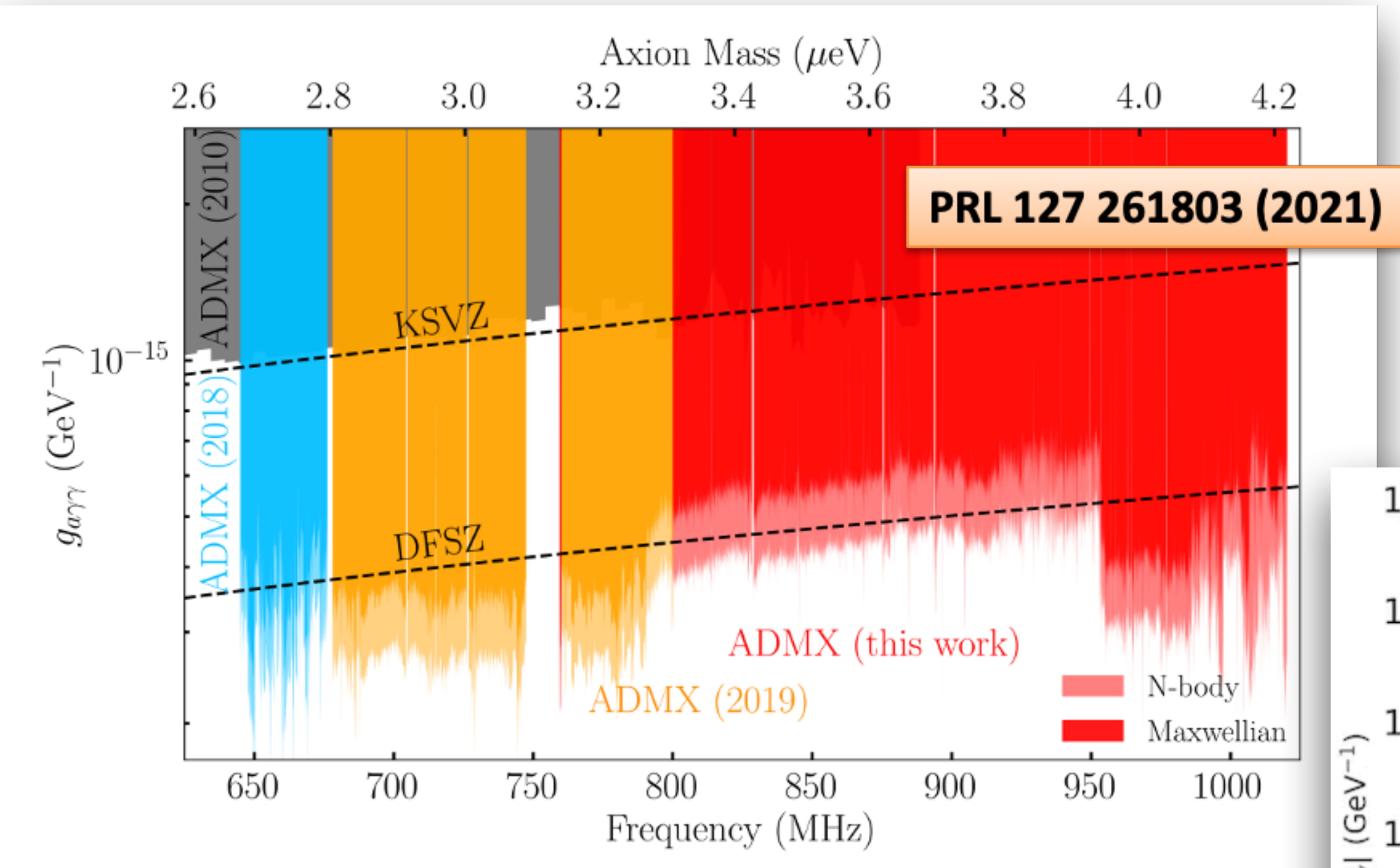
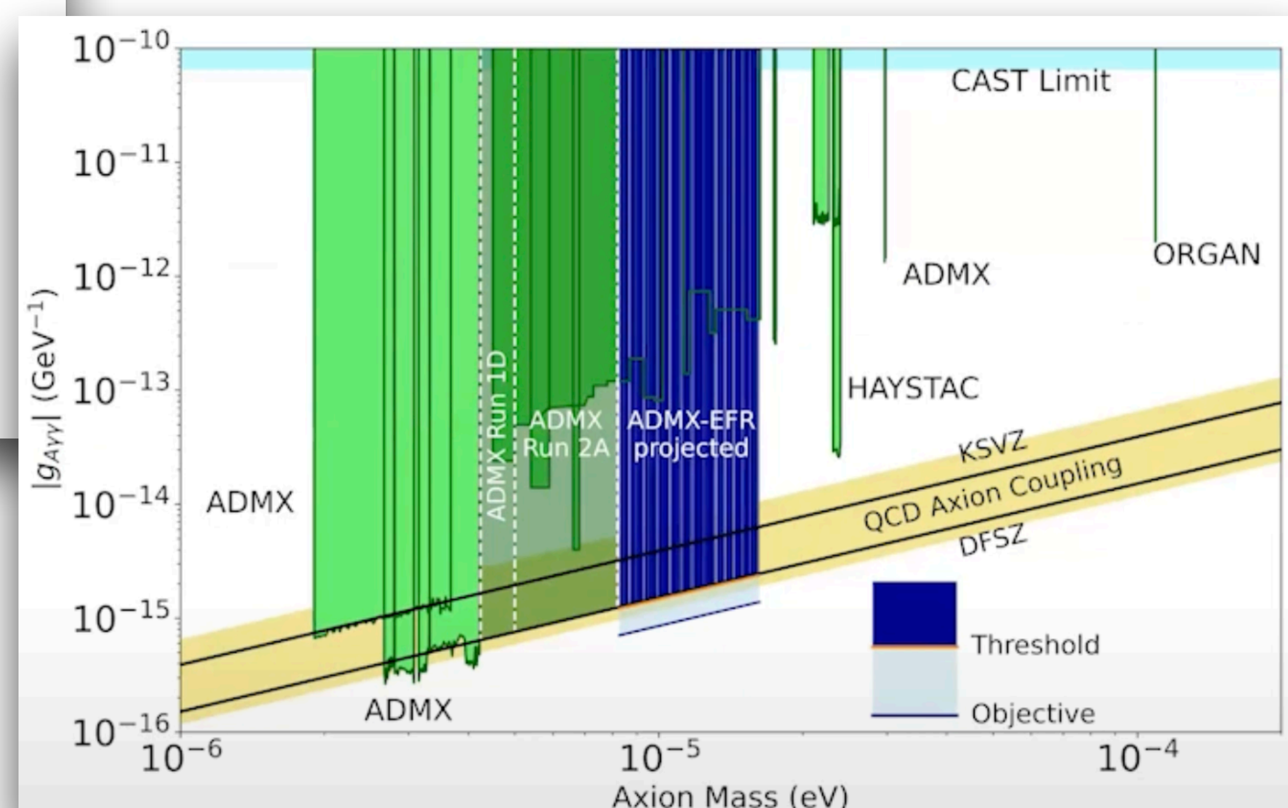


Future:

ADMX - EFR

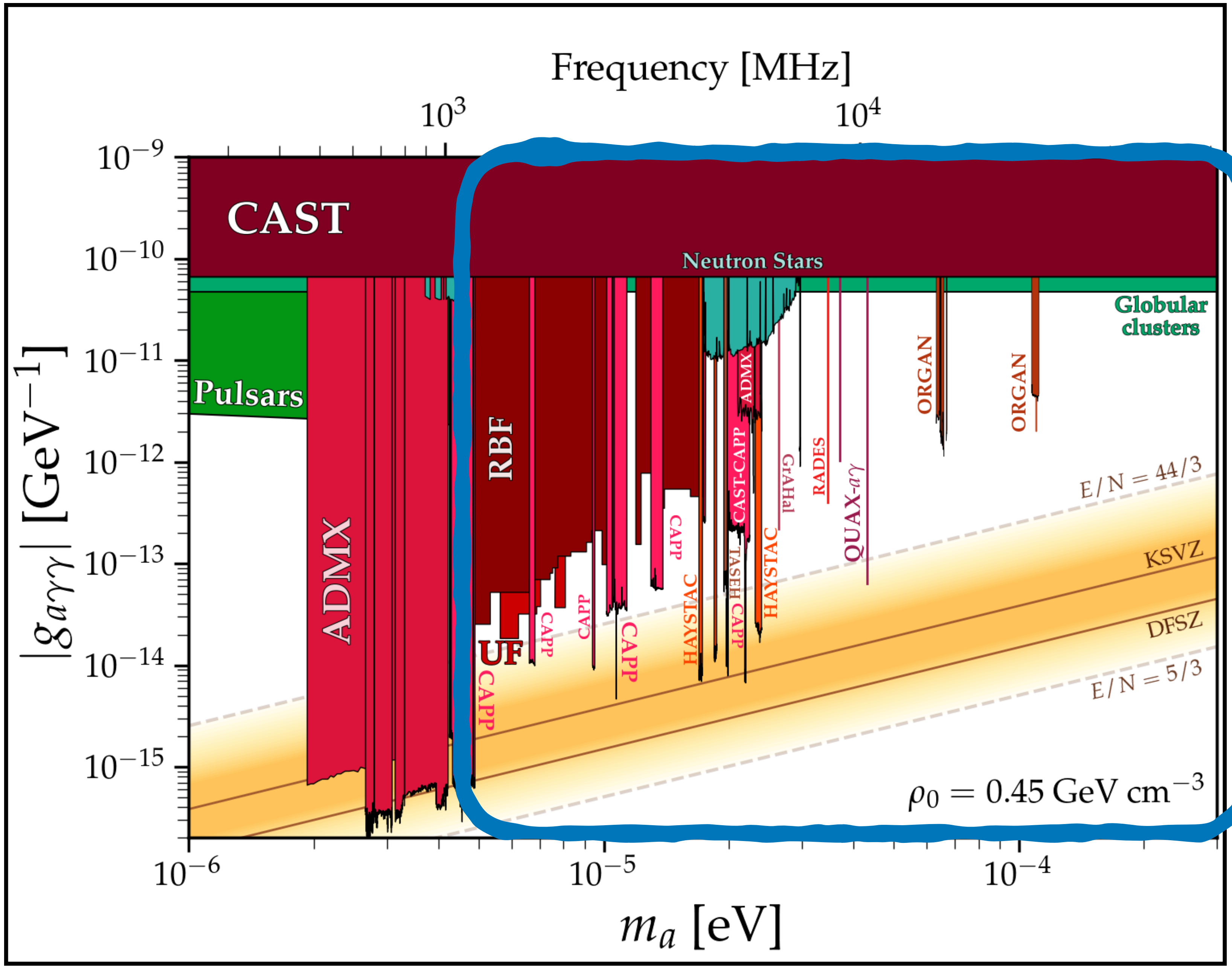
(Extended Frequency Reach)



Gray Rybka @ GGI 2023

Cavity Searches

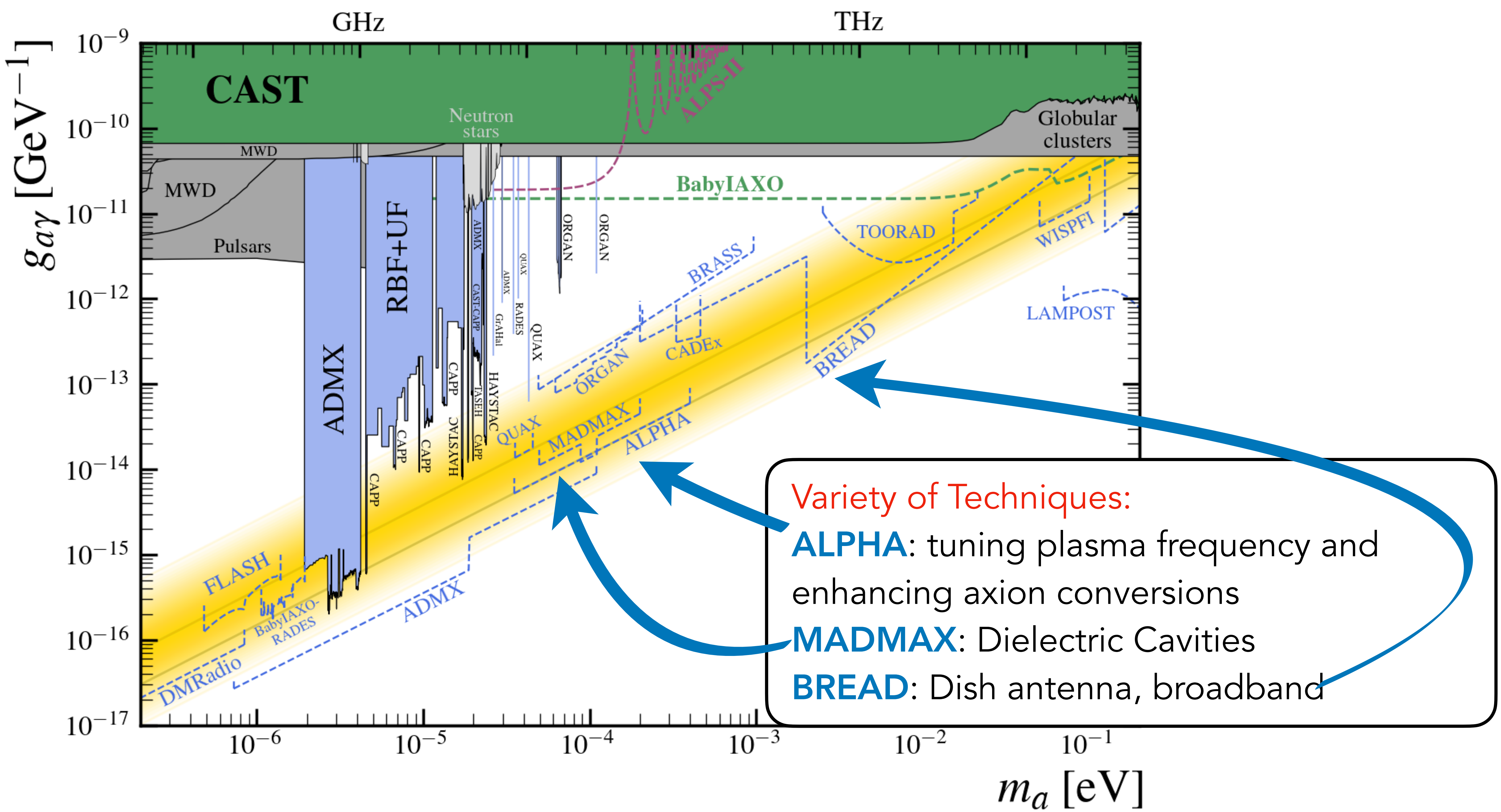
High mass:
HAYSTAC, CAPP, MADMAX, QUAX, ORGAN etc.



- Significant advances from CAPP
- CAPP, QUAX, HAYSTAC touch the QCD band
- Experimental application of quantum technologies for axion searches by HAYSTAC [Nature 590 238 (2021)]: double the scanning rate for axions

Cavity Searches

Many proposals to probe the higher mass region



Variety of Techniques:

ALPHA: tuning plasma frequency and enhancing axion conversions

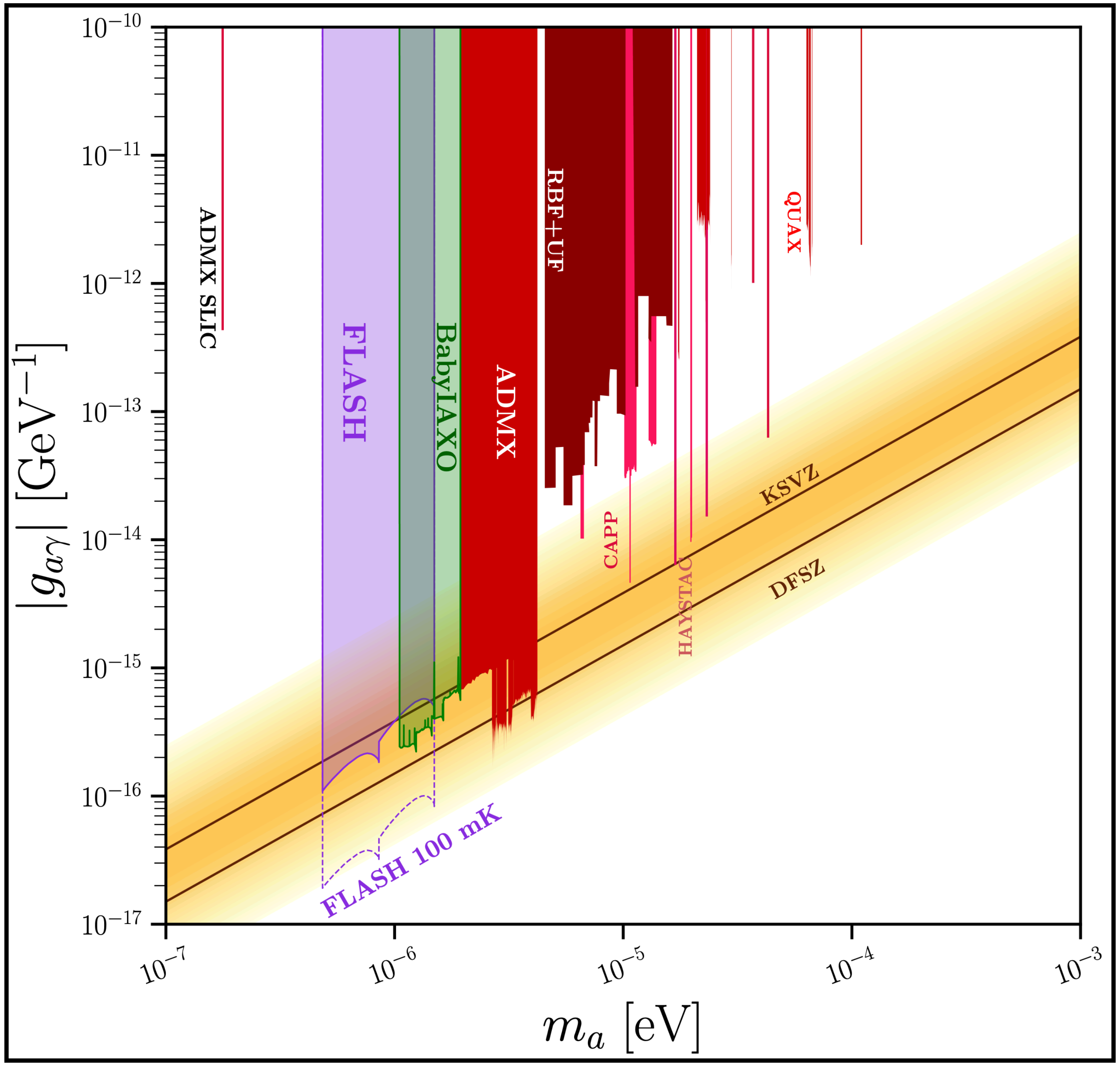
MADMAX: Dielectric Cavities

BREAD: Dish antenna, broadband

From FIP white paper (2022)

Cavity Searches

Low mass:
FLASH and BabyIAXO (RADES)



FLASH and BabyIAXO will cover the region left of ADMX.

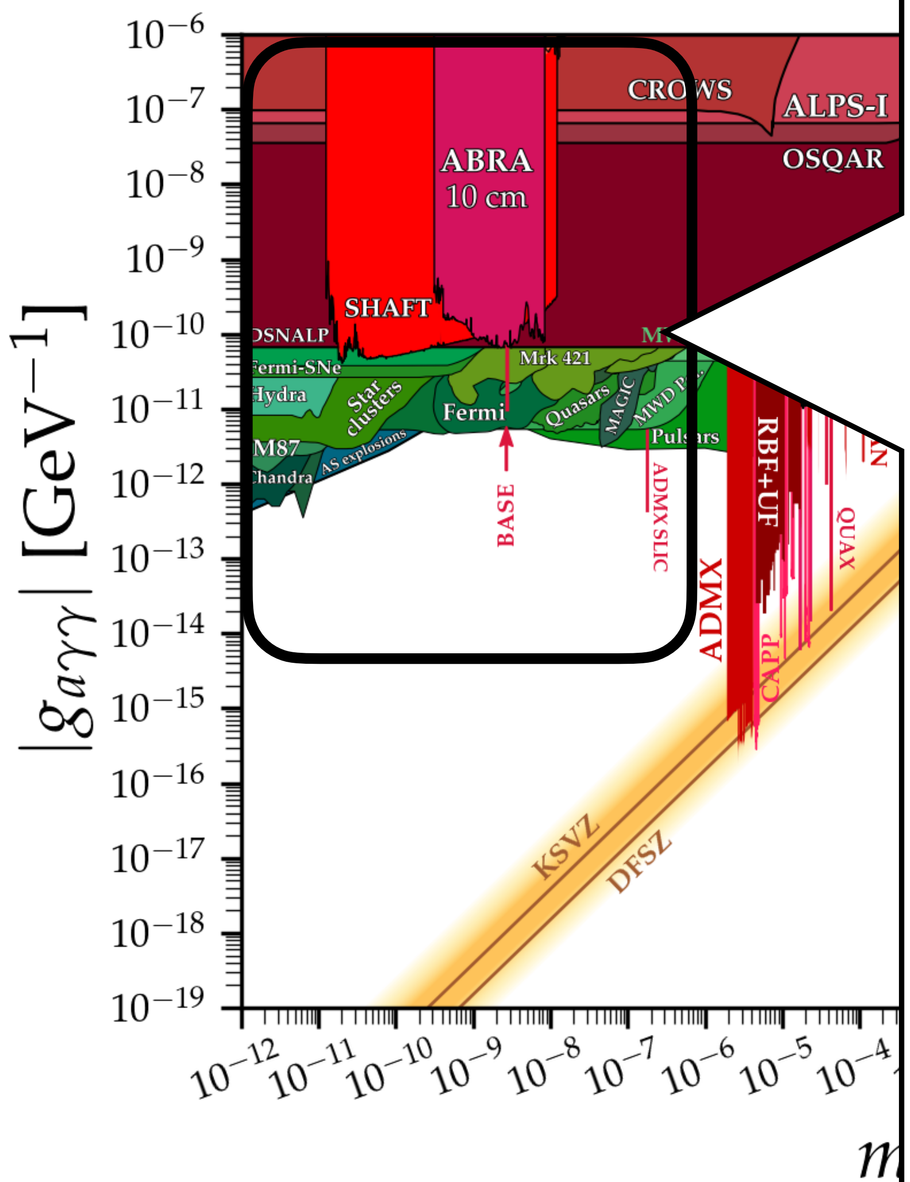
Preparing for TDR

Expected to reach the QCD band.

Jan 19th 2024: FINUDA cooled down to 4K and energized with a current of 2706 A, generating a magnetic field of 1.05 T

Very Low Mass Haloscopes

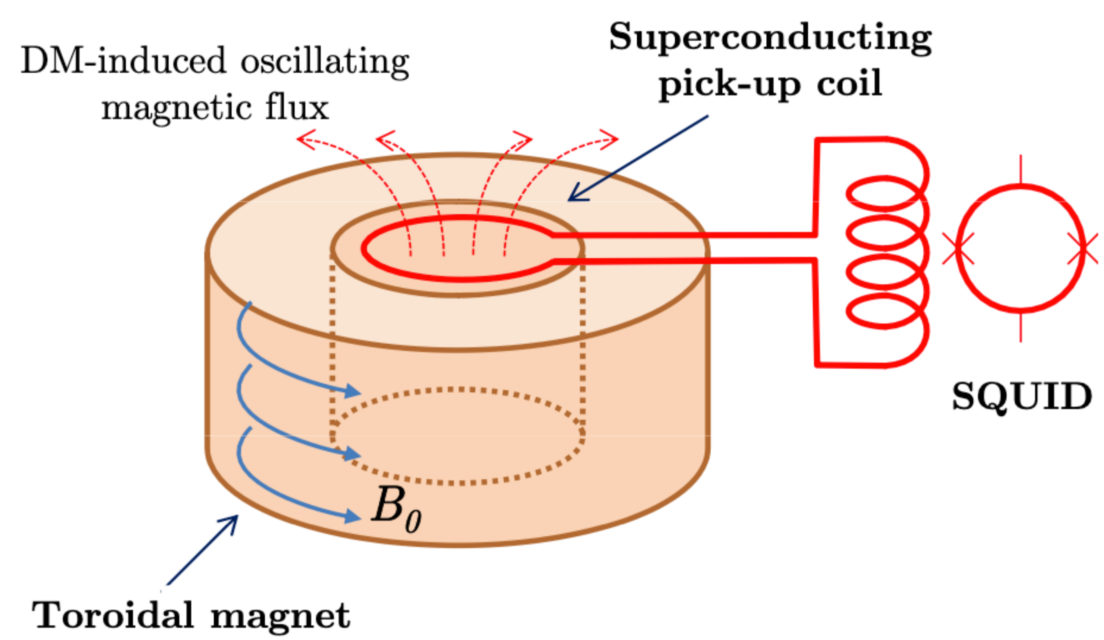
Very Low mass:
ABRA, SHAFT, ADMX SLIC



Very low mass: other techniques:

ADMX SLIC → LC circuit,

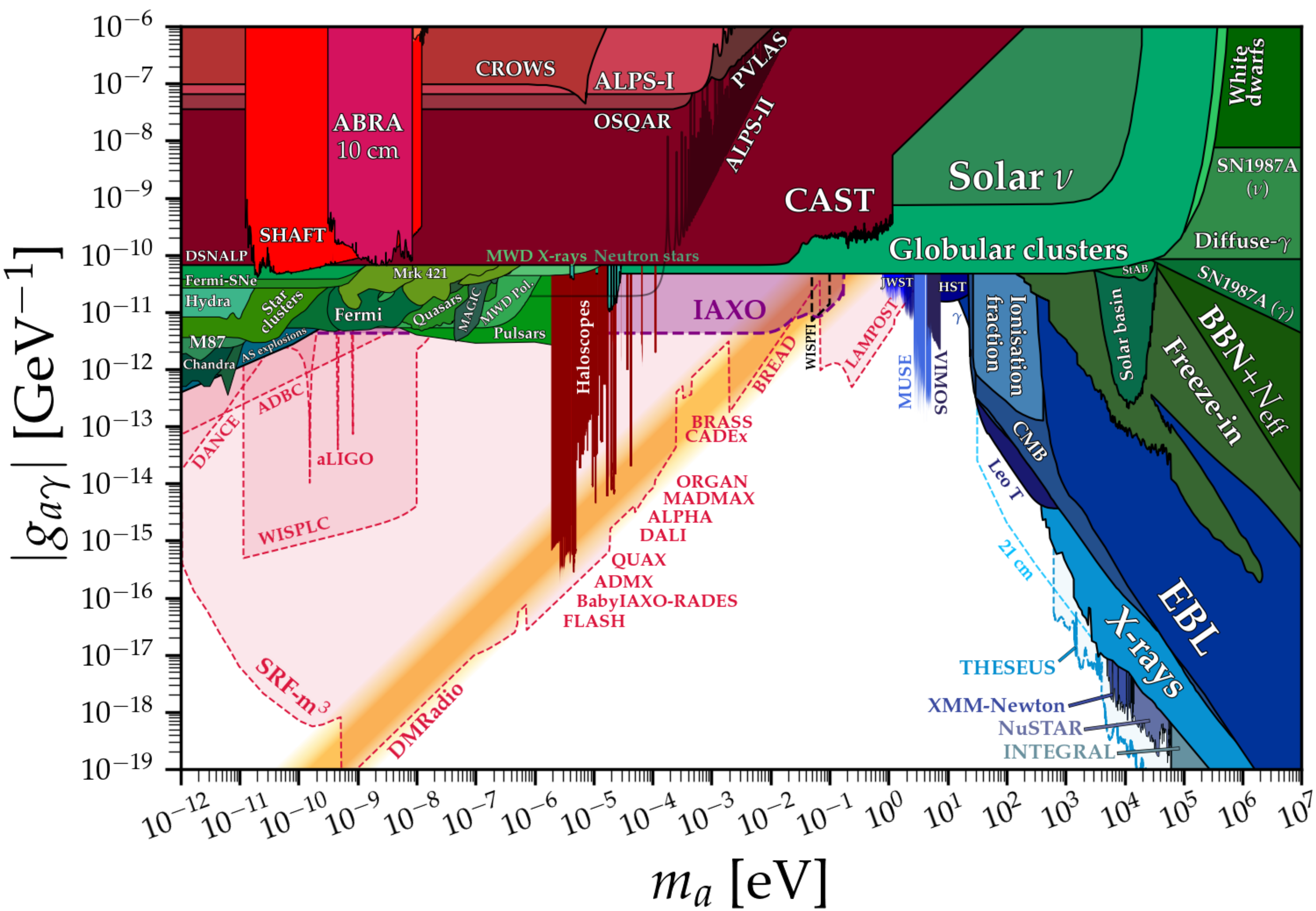
ABRA (to become DM radio) → toroidal magnet configuration



The ALP DM field excites an oscillating E_a field along the field lines of a static toroidal field B_e.

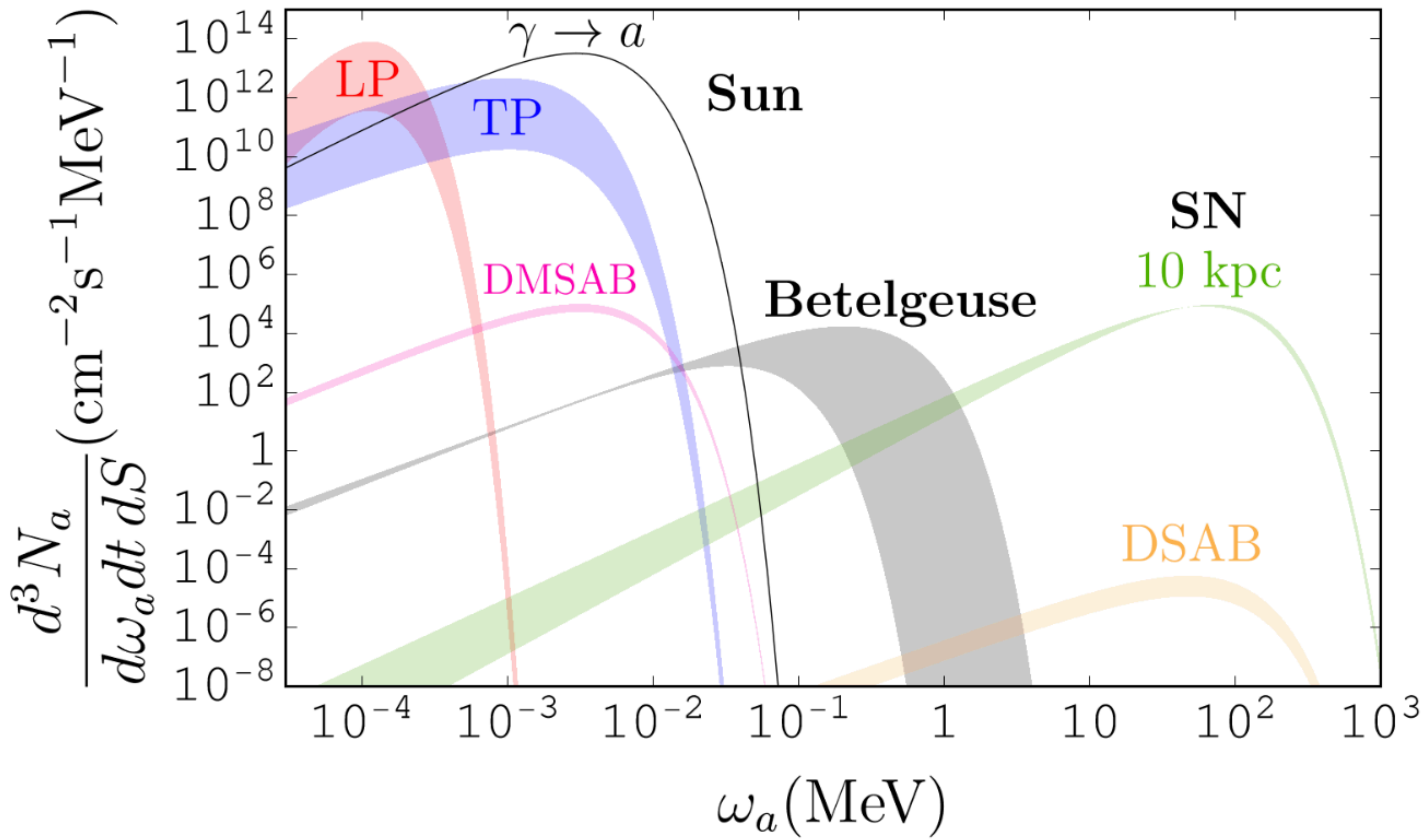
The oscillating E_a induces an oscillating B_e field along the symmetric axis read by a pickup coil connected to a SQUID.

Global Effort to Probe the Full QCD-Axion Band



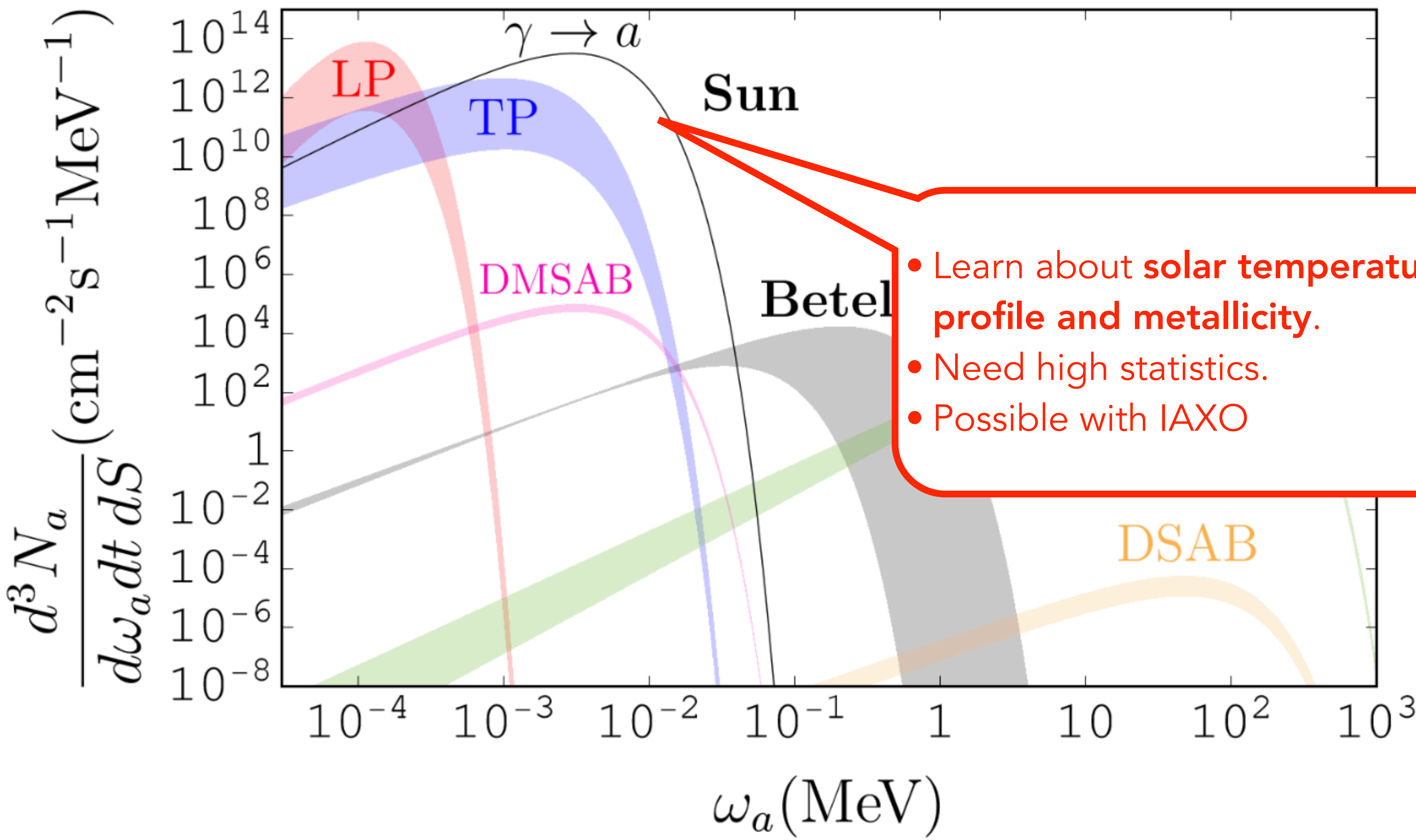
From C. O'Hare

Opportunities: Axion Telescopes?



P. Carenza, M.G., J.Isern, A. Mirizzi, O. Straniero, in preparation

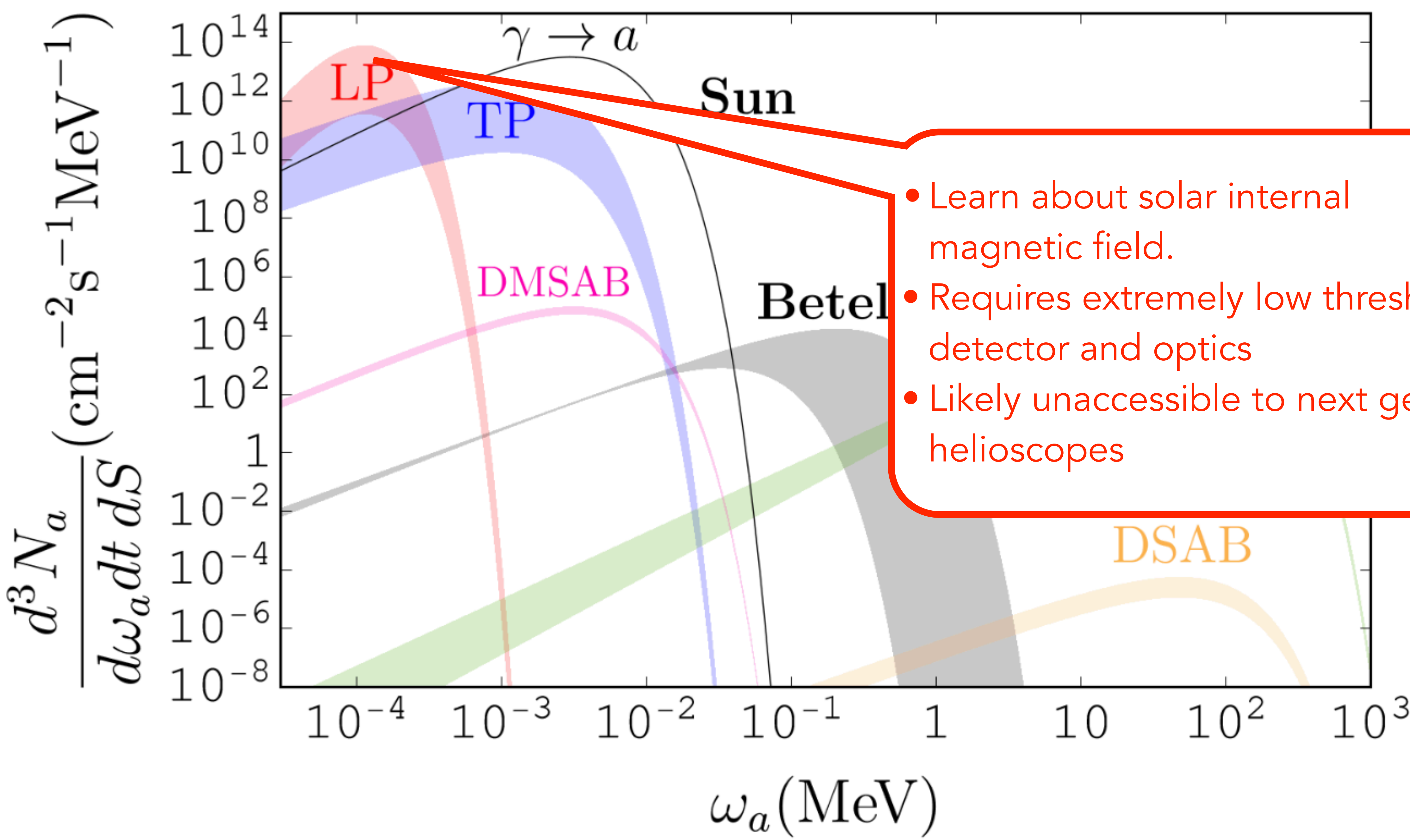
Opportunities: Axion Telescopes?



- Learn about **solar temperature profile and metallicity**.
- Need high statistics.
- Possible with IAXO

P. Carenza, M.G., J.Isern, A. Mirizzi, O. Straniero, in preparation

Opportunities: Axion Telescopes?

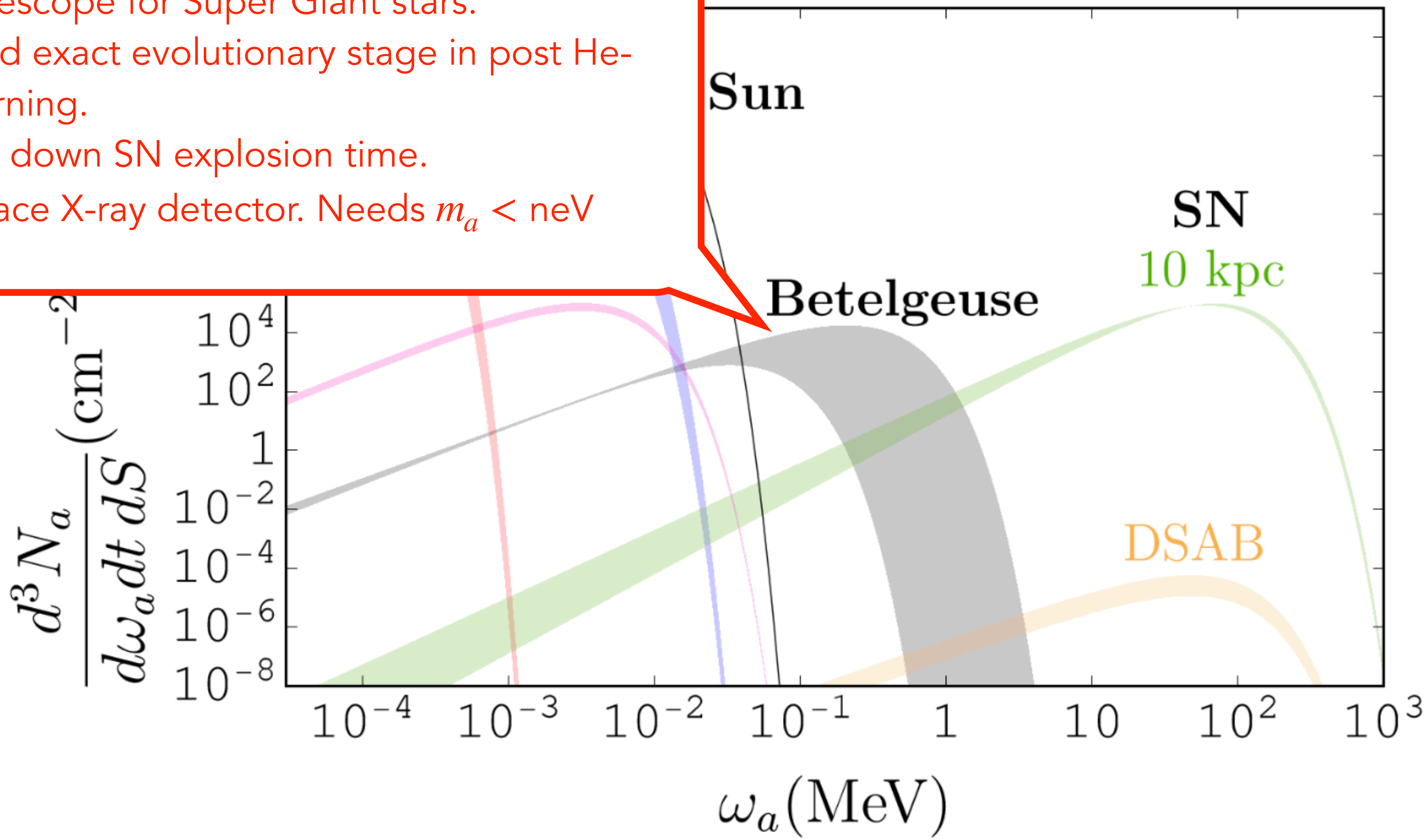


- Learn about solar internal magnetic field.
- Requires extremely low threshold detector and optics
- Likely unaccessible to next gen helioscopes

P. Carenza, M.G., J.Isern, A. Mirizzi, O. Straniero, in preparation

Opportunities: Axion Telescopes?

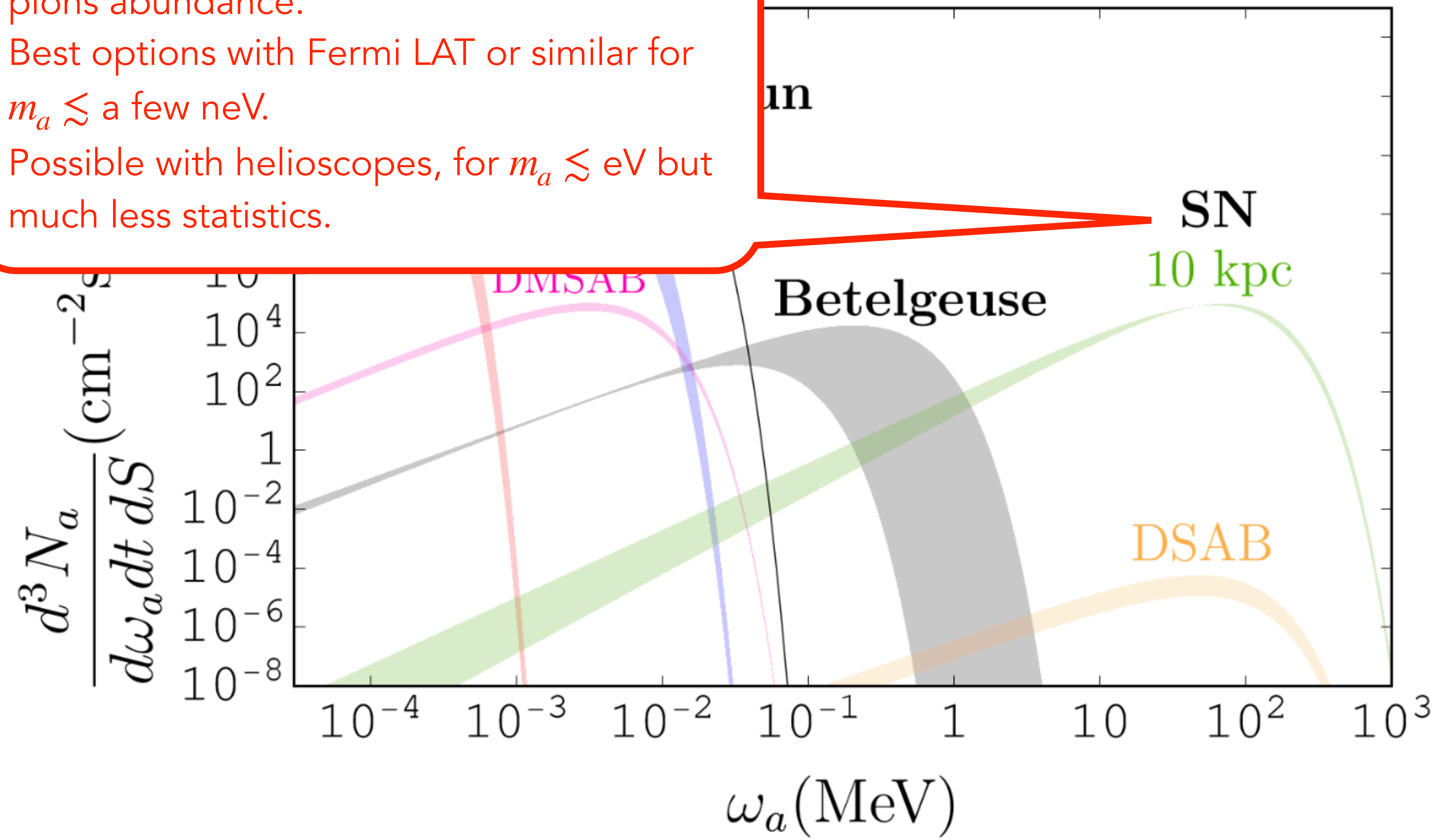
- Telescope for Super Giant stars.
- Find exact evolutionary stage in post He-burning.
- Pin down SN explosion time.
- Space X-ray detector. Needs $m_a <$ neV



P. Carenza, M.G., J.Isern, A. Mirizzi, O. Straniero, in preparation

Opportunities: Axion Telescopes?

- Could reveal temperature, density and pions abundance.
- Best options with Fermi LAT or similar for $m_a \lesssim$ a few neV.
- Possible with helioscopes, for $m_a \lesssim$ eV but much less statistics.



P. Carenza, M.G., J.Isern, A. Mirizzi, O. Straniero, in preparation

Conclusions and Comments

- Important progress in last years in the attempts to detect axions in all fronts:
  - ✓ Huge progress with cavity haloscopes + several new proposals
  - ✓ Major LSW experiment starting (ALPS II)
  - ✓ Major new Helioscope proposal under progress (IAXO)
  - ✓ Several innovative ideas

- Most interesting parameter space accessible to Next Gen. Experiments → a groundbreaking discovery is possible

- Axions with couplings at the current thresholds would excellent astrophysical messengers.