Review on Axions

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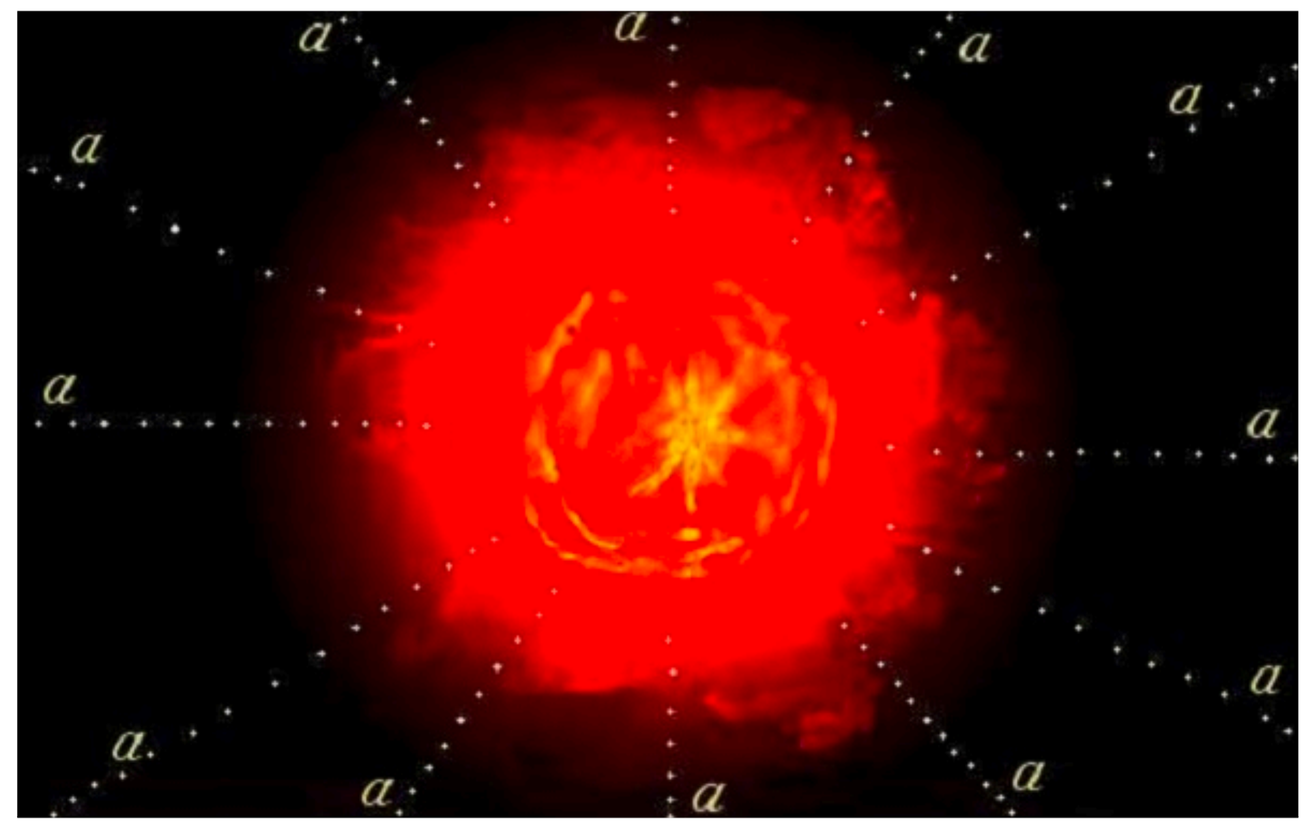
(Barry/Zaragoza)

FULBRIGHT

Fundación Bancaria Ibercaja
y Fundación CAI



Université de Paris, December 15, 2021

Axions

Cosmology

Dark Matter

Particle Physics

Strong-CP problem

Astrophysics

Stellar evolution;
Cooling anomalies

We may detect them soon!
Experimental capabilities to search in well motivated regions of the parameters …

World-wide effort to detect it.

Recent review articles

- *I. Irastorza, J. Redondo, Prog.Part.Nucl.Phys. 102 (2018)*
- *L. Di Luzio, M.G., Nardi, Visinelli, Phys.Rept. 870 (2020)*

Summary

- *Strong CP and axions: a non-historical presentation*
- *The axion parameter space*
- *Current status and future perspectives*
- *Looking at the sky with axions*

The Strong CP problem in a nutshell

The QCD Lagrangian admits a CP violating term

$$L = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + i\bar{\Psi}\gamma^\mu D_\mu \Psi - \bar{\psi}M\psi - \theta\frac{1}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

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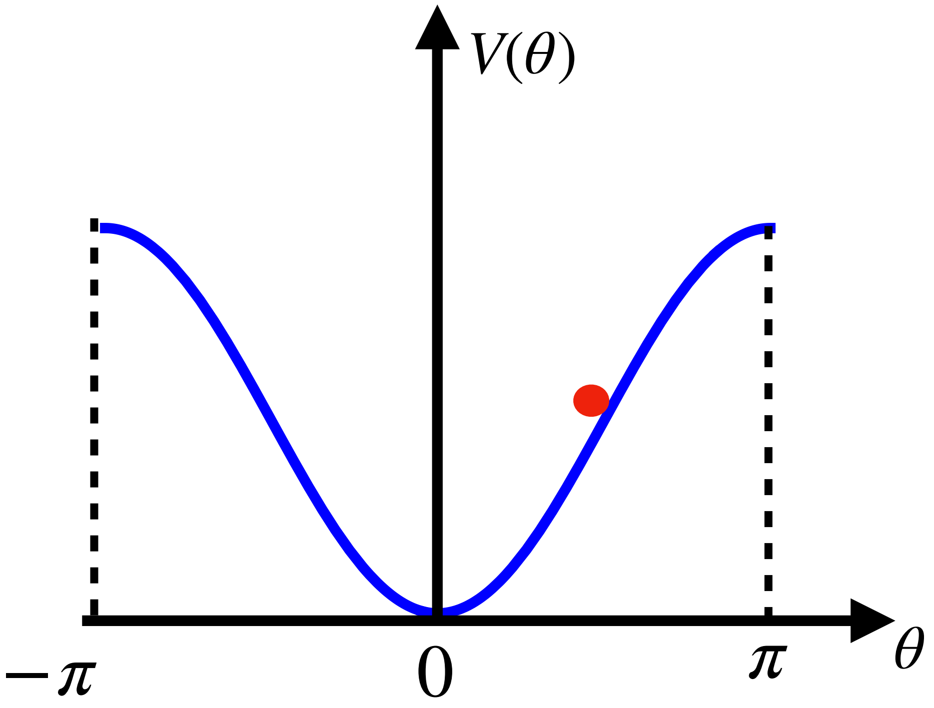


θ is an angular variable and the potential is minimized for $\theta = 0$.

C. Vafa, E. Witten, Phys. Rev. Lett. 53 (1984) 535

The Strong CP problem in a nutshell

The QCD Lagrangian admits a CP violating term

$$L = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + i\bar{\Psi}\gamma^\mu D_\mu\Psi - \bar{\psi}M\psi - \theta\frac{1}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Observable consequence: neutron electric dipole moment (nEDM)

$$d_n \simeq 2.4 \cdot 10^{-16}\,\theta \text{ e cm}$$

Crewther, Vecchia, Veneziano, Witten (1979)

M. Pospelov, A. Ritz, Nucl. Phys. B573 (2000)

Current experiments show that the nEDM is very small!

$$d_n^{\exp} \leq 1.8 \cdot 10^{-26} \text{ e cm}$$

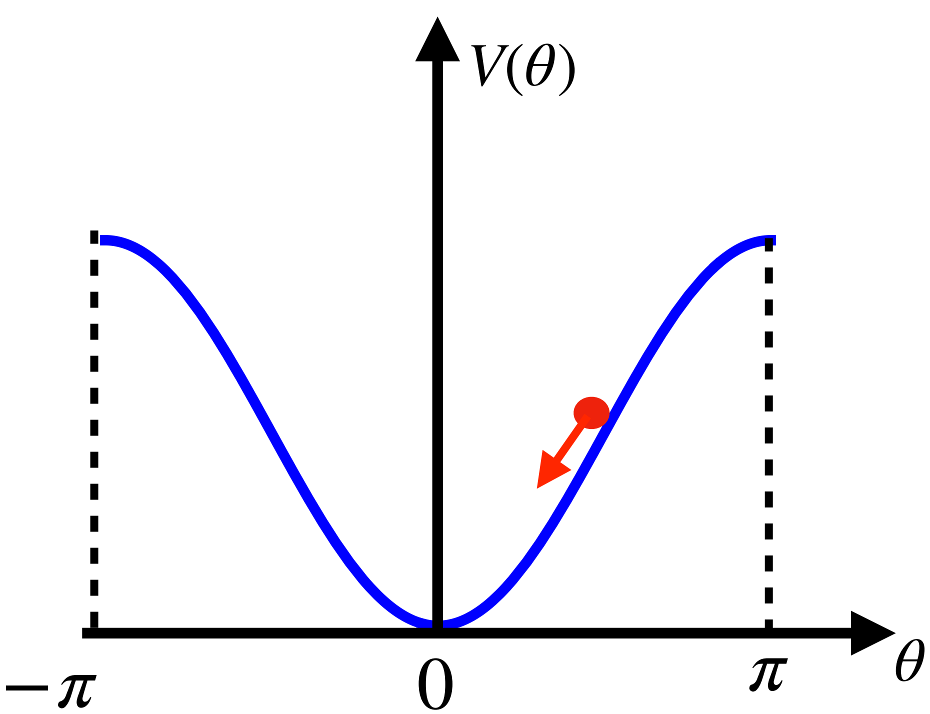
C.Abel,et al.,Phys.Rev.Lett.124 (2020)

Requires extremely small θ

Dynamical Solution

$\theta \rightarrow$ dynamical field

$$L = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + i\bar{\Psi}\gamma^\mu D_\mu \Psi - \bar{\psi}M\psi - \theta\frac{1}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G} + \ldots$$



$$\theta \rightarrow \theta + a/f_a$$

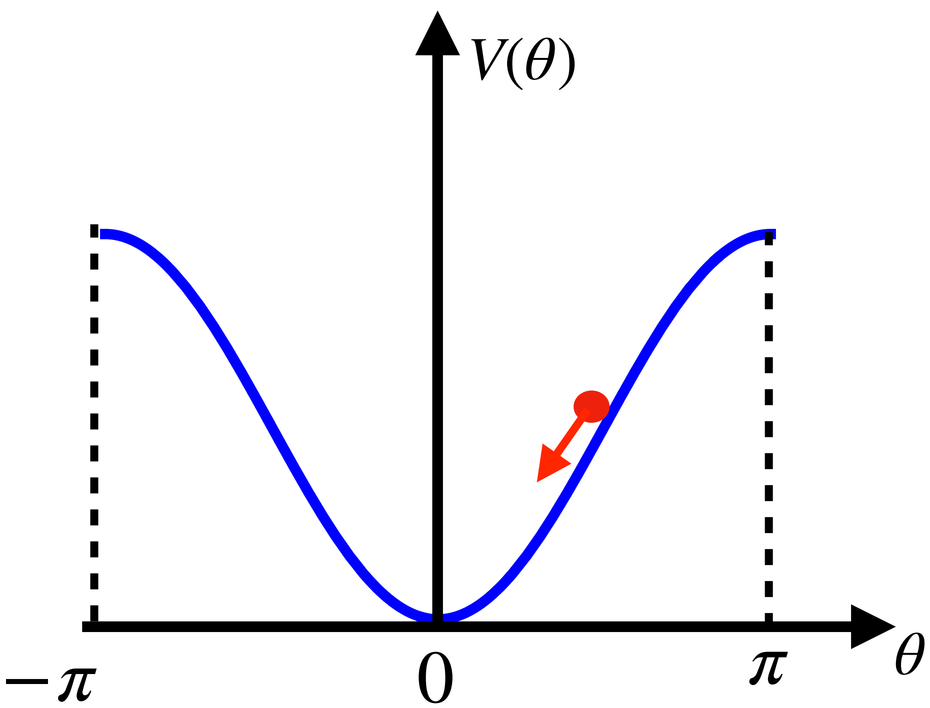
Axion

R. D. Peccei, H. R. Quinn, Phys. Rev. Lett. 38 (1977)
S. Weinberg Phys. Rev. Lett. 40 (1978) 223-226;
F. Wilczek Phys. Rev. Lett. 40 (1978) 279–282

Dynamical Solution

$\theta \to$ dynamical field

$$L = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + i\bar{\Psi}\gamma^\mu D_\mu \Psi - \bar{\psi}M\psi - \theta\frac{1}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G} + \ldots$$



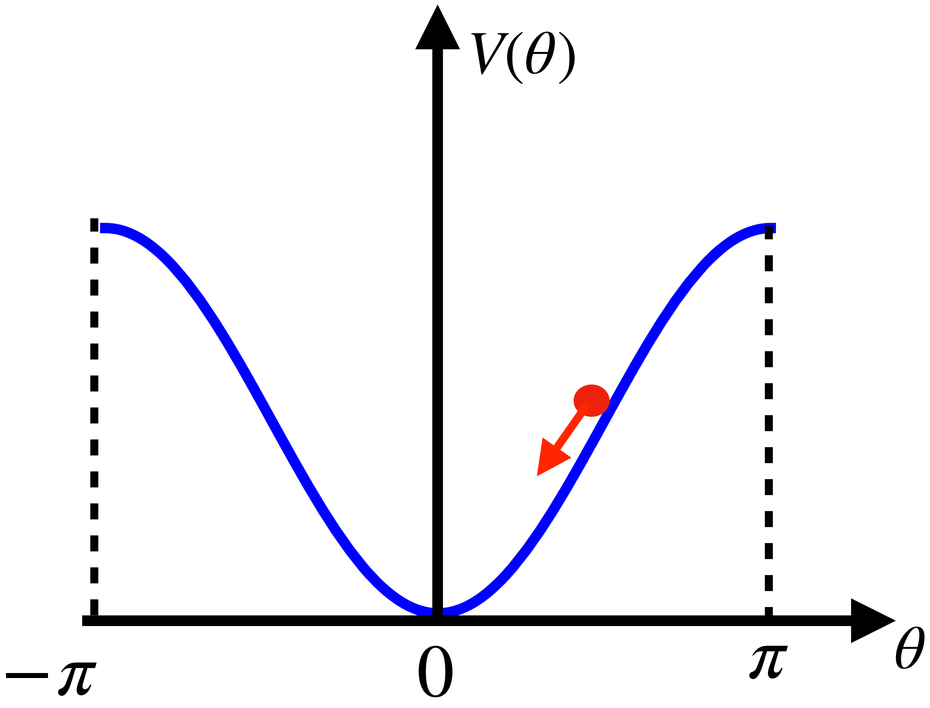
Dimension 5 (non-renormalizeable) interaction term.

Requires a UV completion

Dynamical Solution

$\theta \to$ dynamical field

$$L = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + i\bar{\Psi}\gamma^\mu D_\mu \Psi - \bar{\psi}M\psi - \theta\frac{1}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G} + \dots$$



Peccei and Quinn realization:

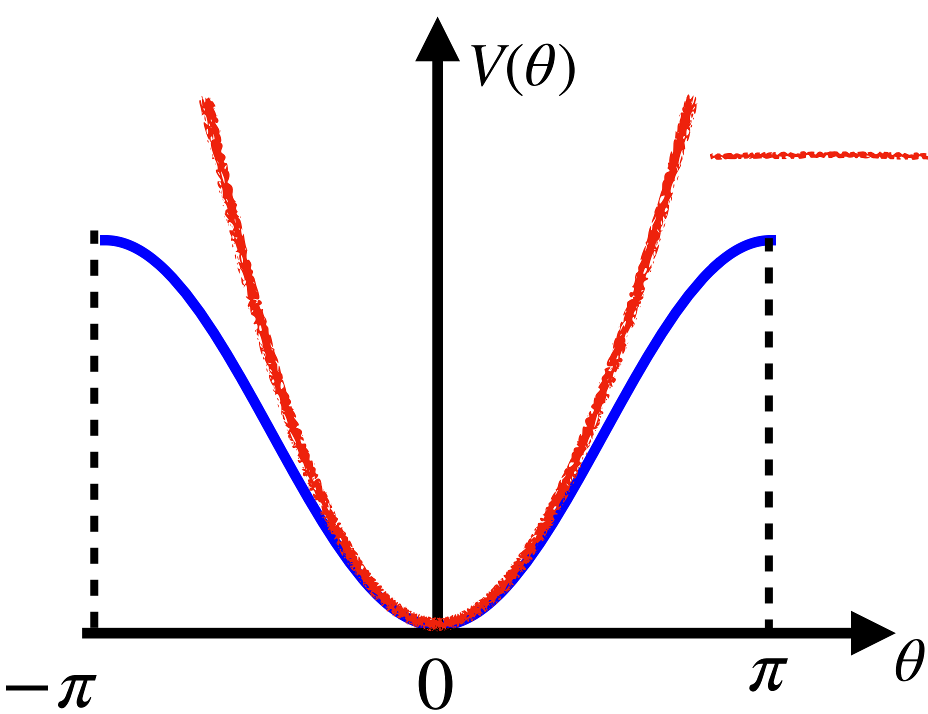
Addition of a new global (axial) symmetry spontaneously, broken at a high energy scale f_a.

Pseudo-Goldstone boson → axion

R. D. Peccei, H. R. Quinn, Phys. Rev. Lett. 38 (1977)

Some facts about QCD Axions

1- The axion potential can be calculated in QCD



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

Grilli di Cortona et al., JHEP 1601 (2016)

Some facts about QCD Axions

1- The axion potential can be calculated in QCD

2- The axion couplings are model dependent.

$$L_{int} = C_{af} \frac{\partial_\mu a}{2f_a} \bar{f}\gamma_5\gamma_\mu f + \frac{1}{4} C_{a\gamma} \frac{\alpha}{2\pi f_a} aF\tilde{F}$$

Fermions (electrons, nucleons)

Photons

QCD contribution to the couplings can be substantially changed according to the particular UV completion

In general: light ↔ weakly coupled

Some facts about QCD Axions

1- The axion potential can be calculated in QCD

2- The axion couplings are model dependent.

3- Required interaction with nEDM

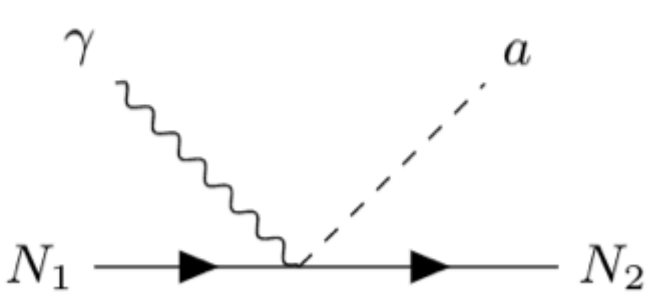
$$L_{int} \supset -\frac{i}{2} g_{dN}\, a\, \bar{n}\, \sigma_{\mu\nu}\gamma_5\, n\, F^{\mu\nu}$$

P. W. Graham, S. Rajendran, Phys. Rev. D88 (2013)

Stellar production (SN bound):

$$\Rightarrow \quad g_{dN} \leq 0.6 \cdot 10^{-7}\,\mathrm{GeV}^{-2}$$

(corresponds to $m_a \lesssim 10\,\mathrm{eV}$)



P. Carenza, G. Lucente et al. (in preparation)

Some facts about QCD Axions

1- The axion potential can be calculated in QCD

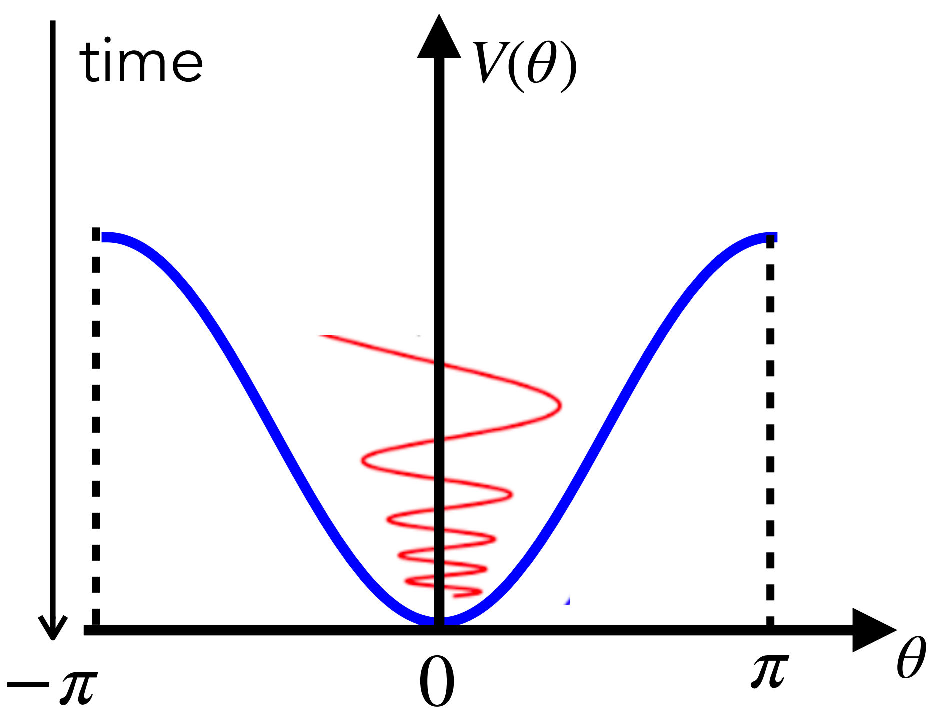
2- The axion couplings are model dependent.

3- Required interaction with nEDM

4- Axion contributes to dark matter

- Preskill, Wise and Wilczek (1983)
- Abbott and Sikivie (1983)
- Dine and Fischler (1983)

The PQ solution is dynamical, not instantaneous

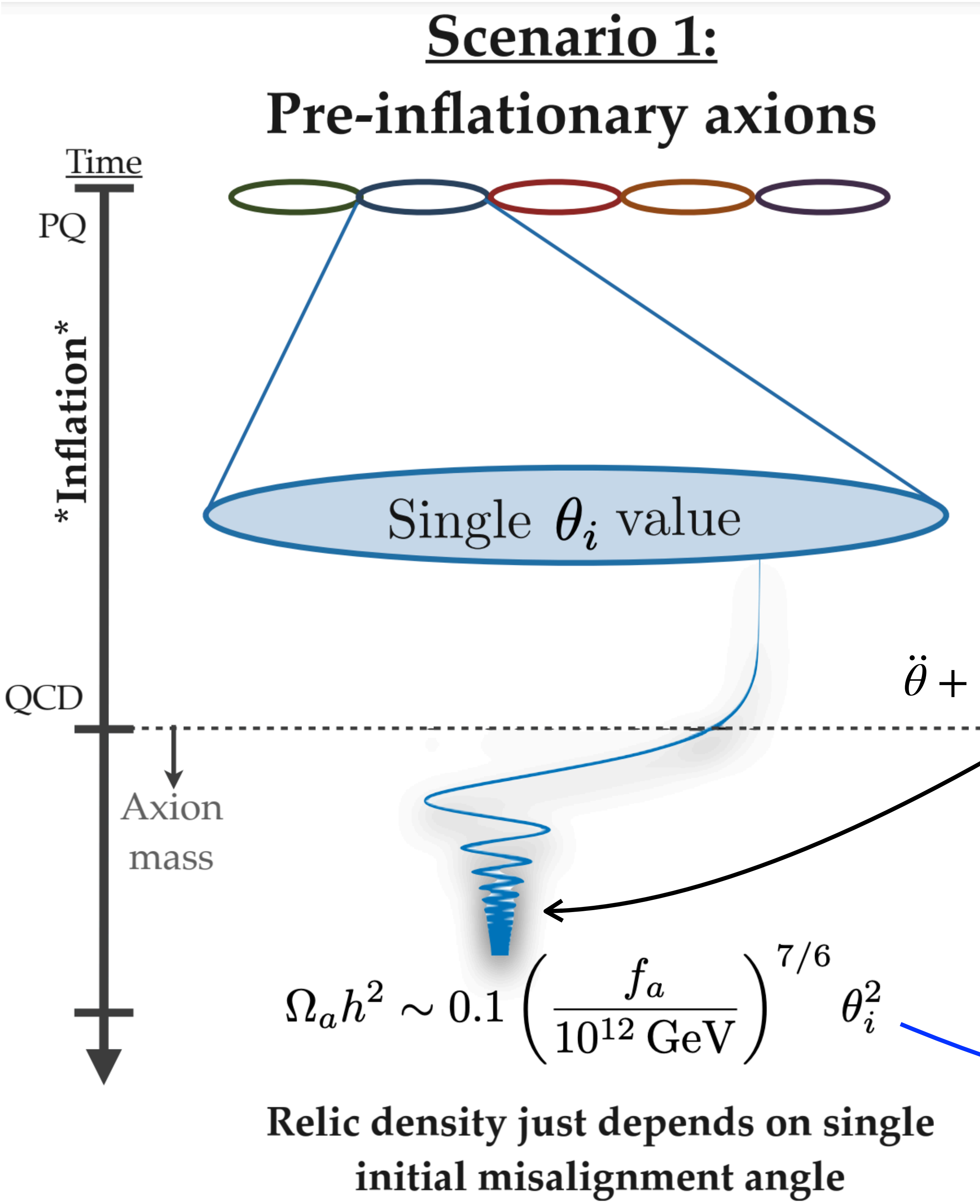


The universe has a finite age

The axion field is still oscillating today around the CP-conserving minimum of the potential

→ Axion is CDM

Axion Dark matter



$$\ddot{\theta} + 3H\dot{\theta} + m_a^2 \sin\theta = 0$$

Calculable axion abundance

but unknown initial conditions

Figure Credits: C. O'Hare (2021)
https://cajohare.files.wordpress.com/2021/10/axions.pdf

Axion Dark matter

Predictable initial angle.

Axion abundance depends also on production from topological defects

Estimating the axion string contribution from topological defects is very difficult. Numerical simulations still make very different predictions.

Important numerical advances thanks to Adaptive Mesh Refinement

- M. Buschmann et al. (2021), arXiv:2108.05368;
- M. Gorghetto, E. Hardy, G. Villadoro, SciPost Phys. 10, 050 (2021)

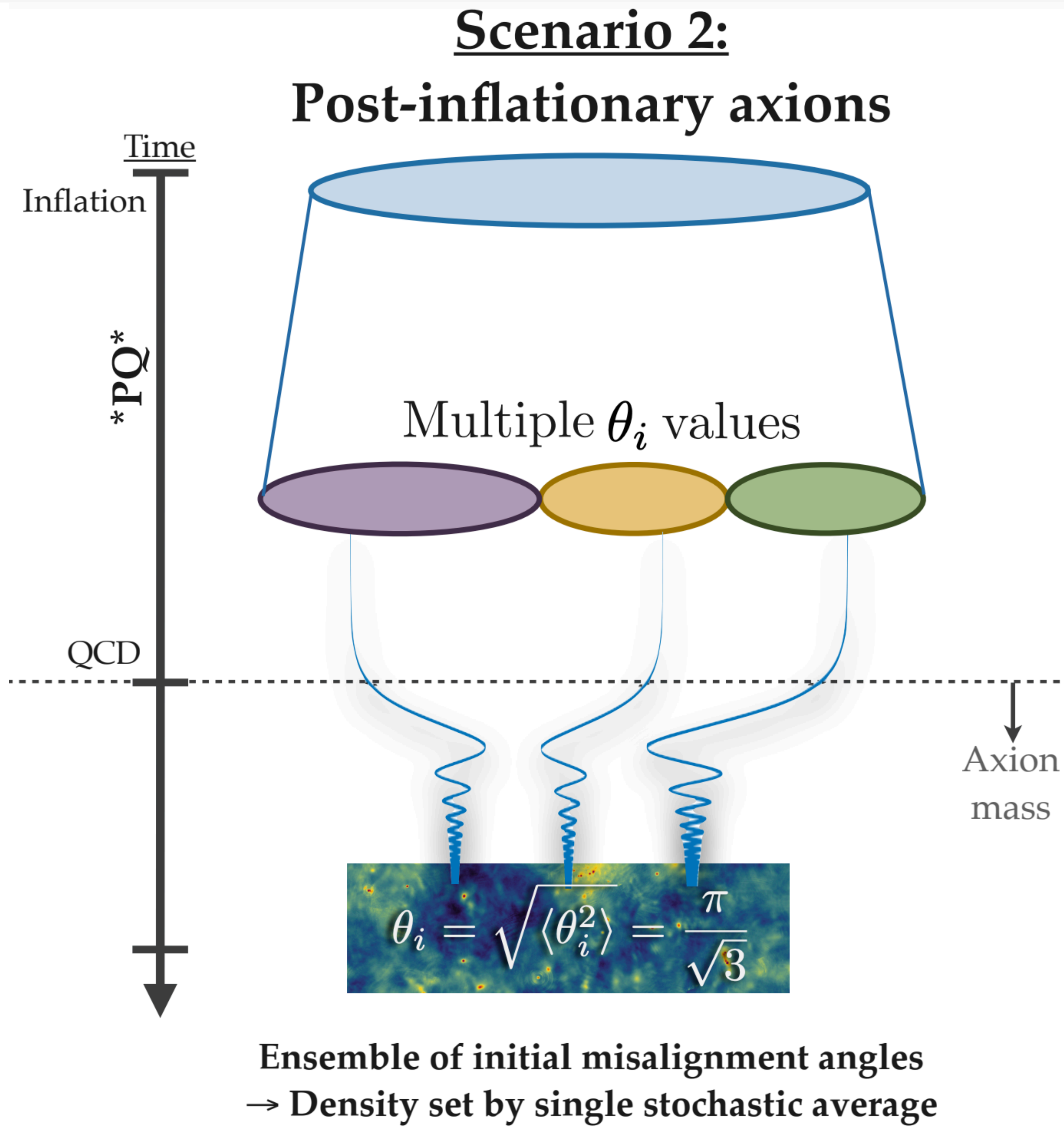


Figure Credits: C. O'Hare (2021)
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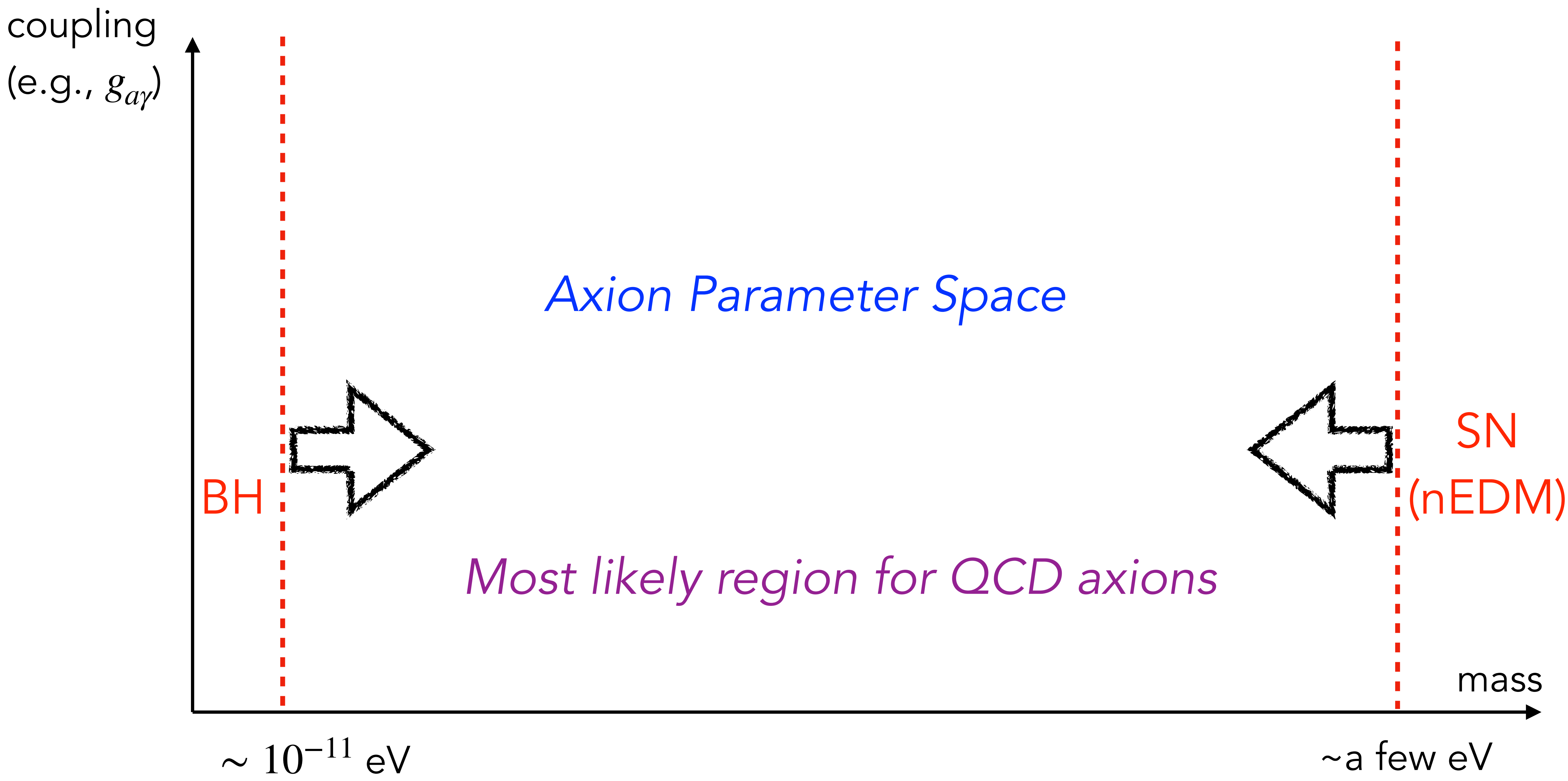
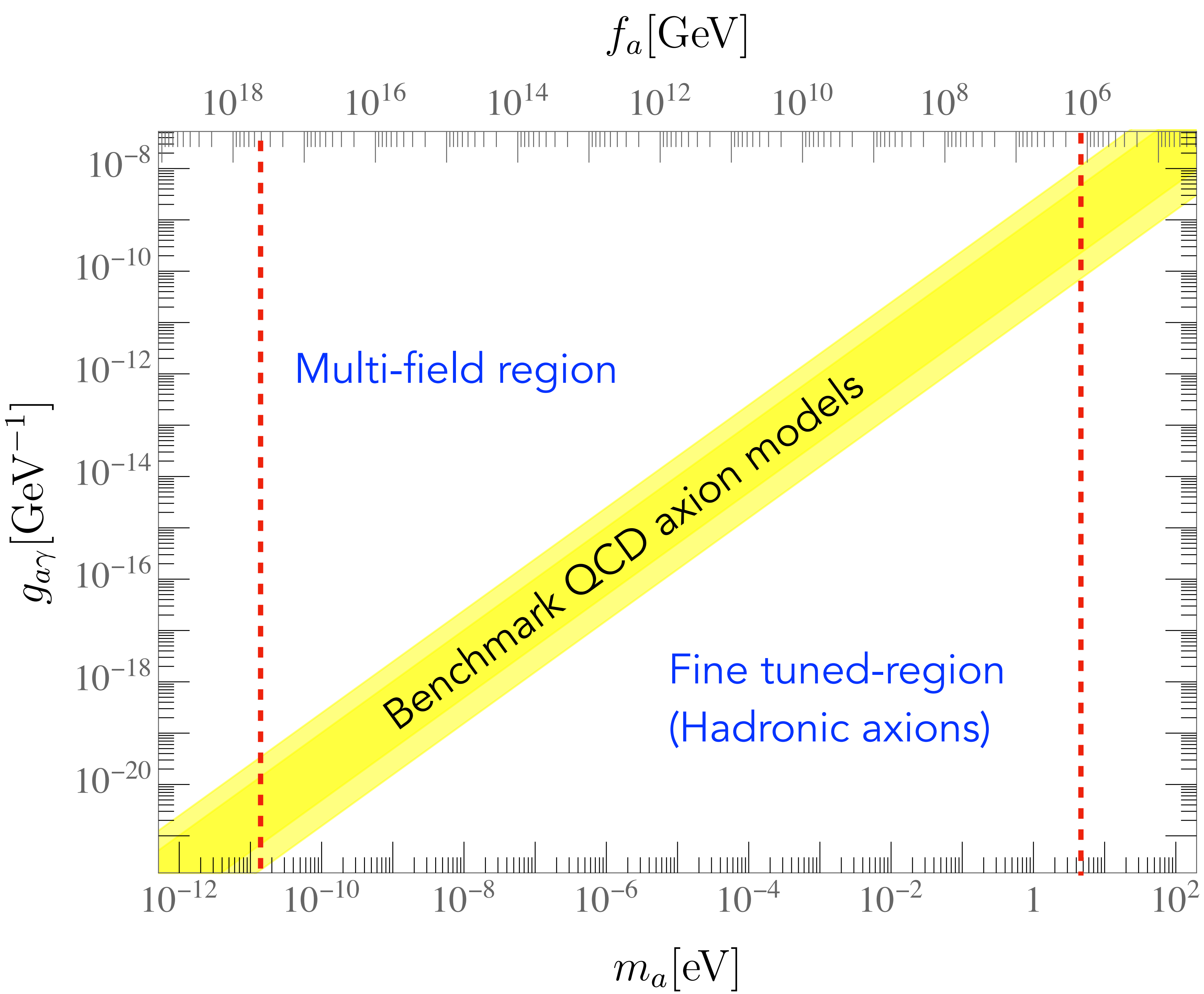
Where are the axions?

Where are the axions?



Where are the axions?



Minimal field extension and basic phenomenological requirements select a narrow band

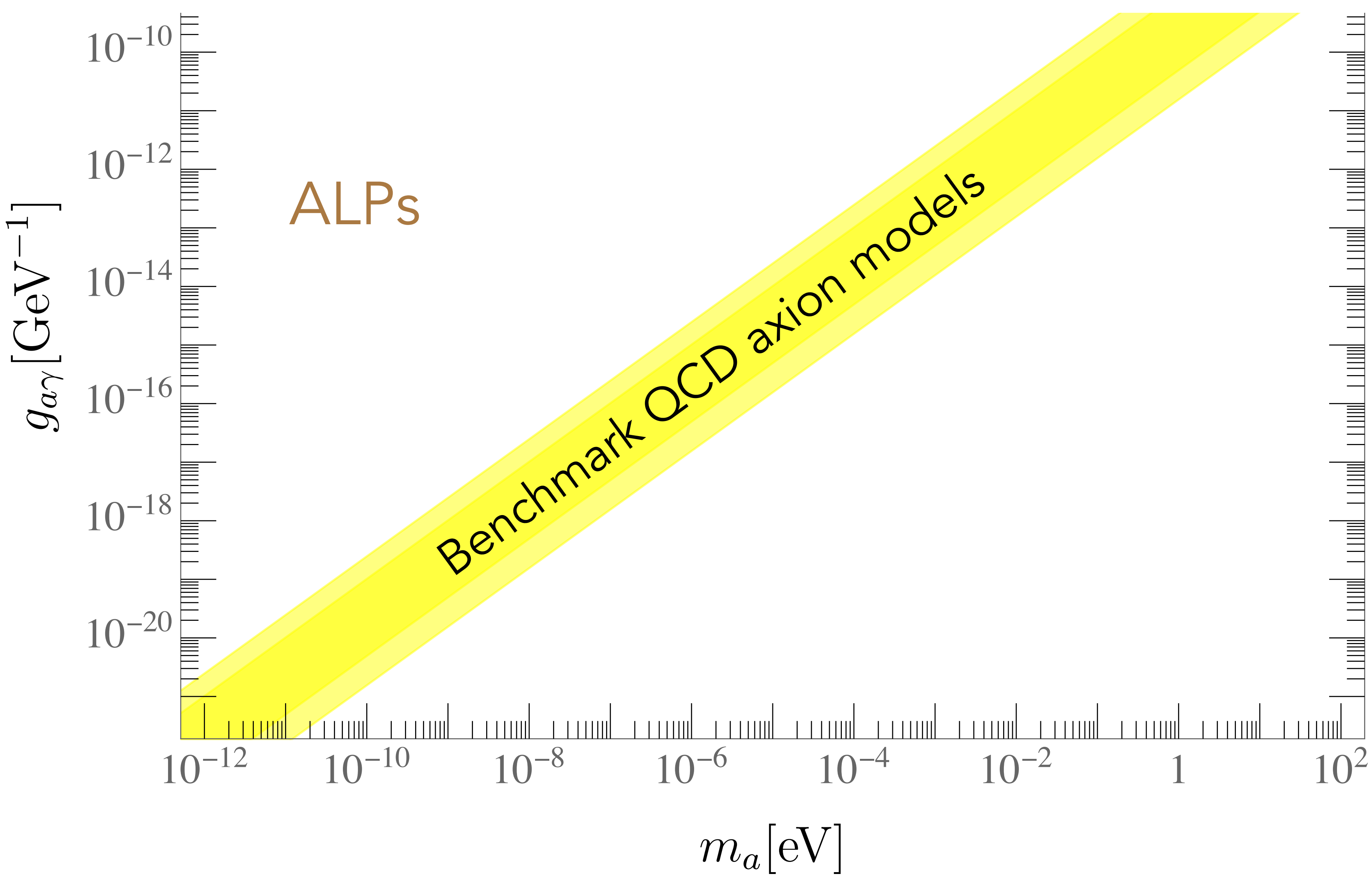
Di Luzio, Mescia, Nardi, Phys.Rev.Lett. 118 (2017), Phys.Rev. D96 (2017)

Di Luzio, Fedele, M.G., Mescia, Nardi, arXiv:2109.10368

Axion-Like Particles (ALPs)

Emerge in several extension of the SM

No specific mass-coupling relation → much larger parameter space allowed



The parameter space extends also to smaller/higher mass.

BH-superradiance eliminates only some mass bands

Brito, Cardoso, Pani, arXiv:1501.06570;

Arvanitaki, Baryakhtar, Huang, Phys.Rev.D 91 (2015) 8

Axions and Axion-Like Particles (ALPs)

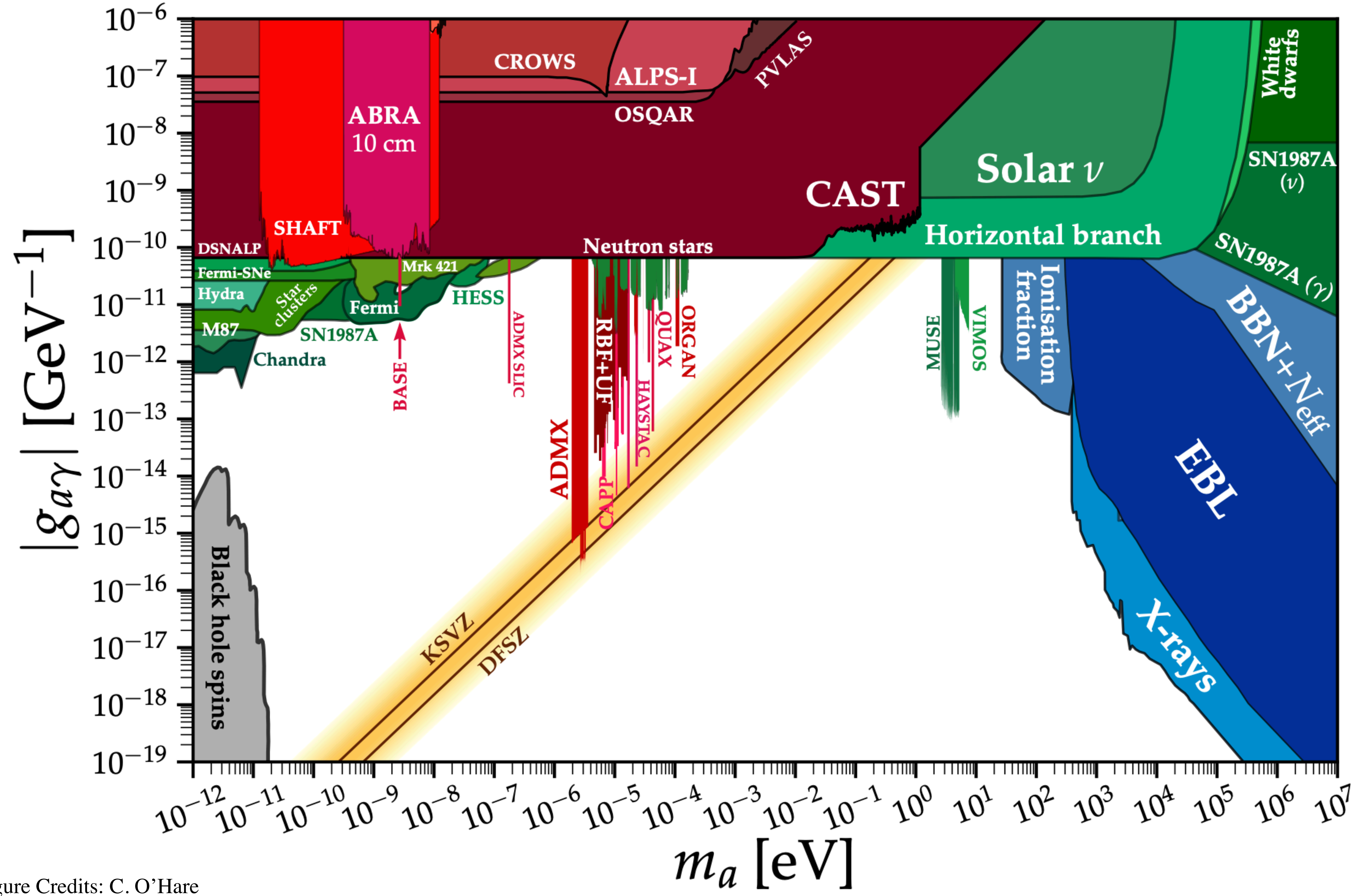
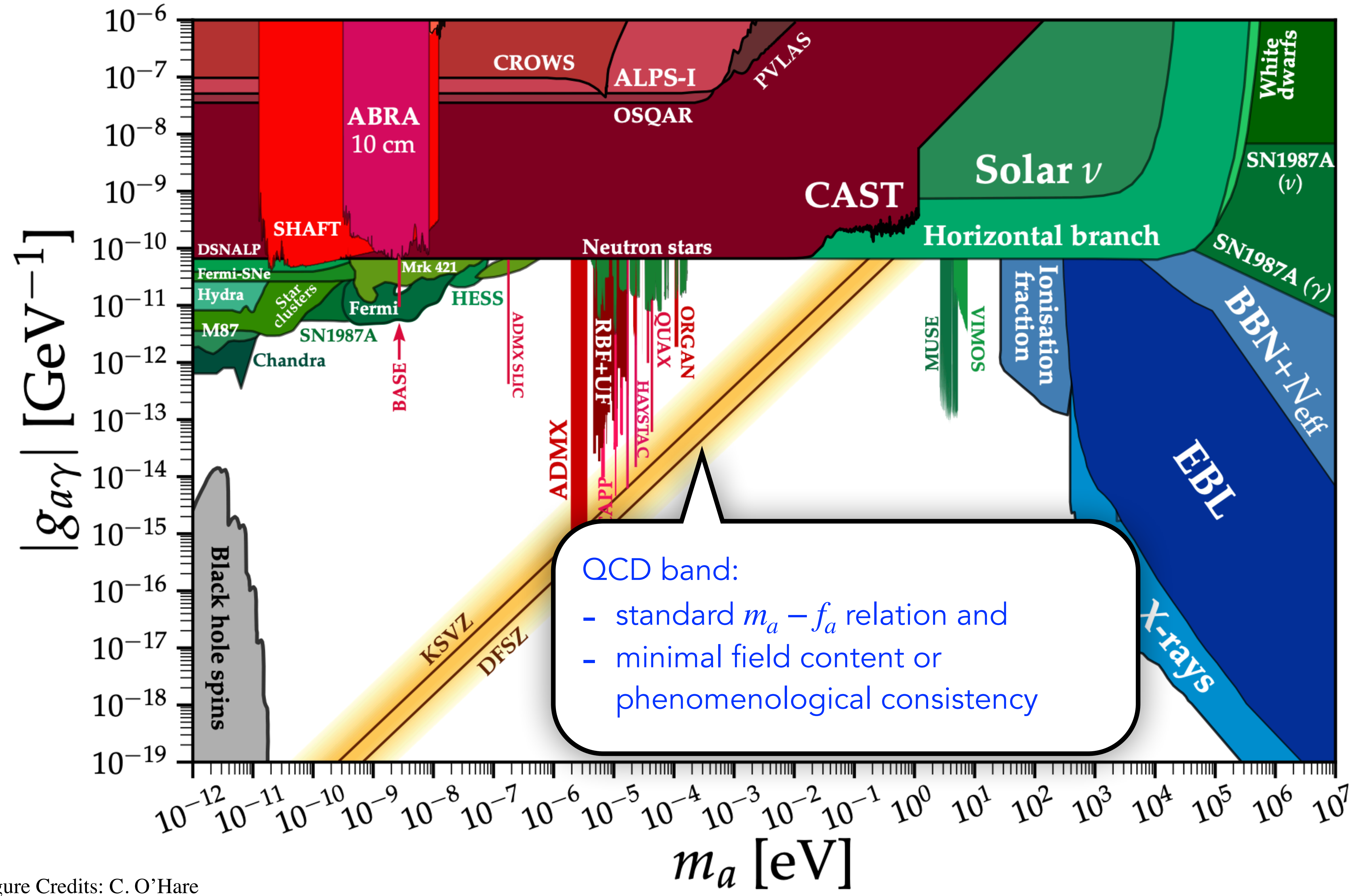


Figure Credits: C. O'Hare
https://cajohare.github.io/AxionLimits/

Axions and Axion-Like Particles (ALPs)



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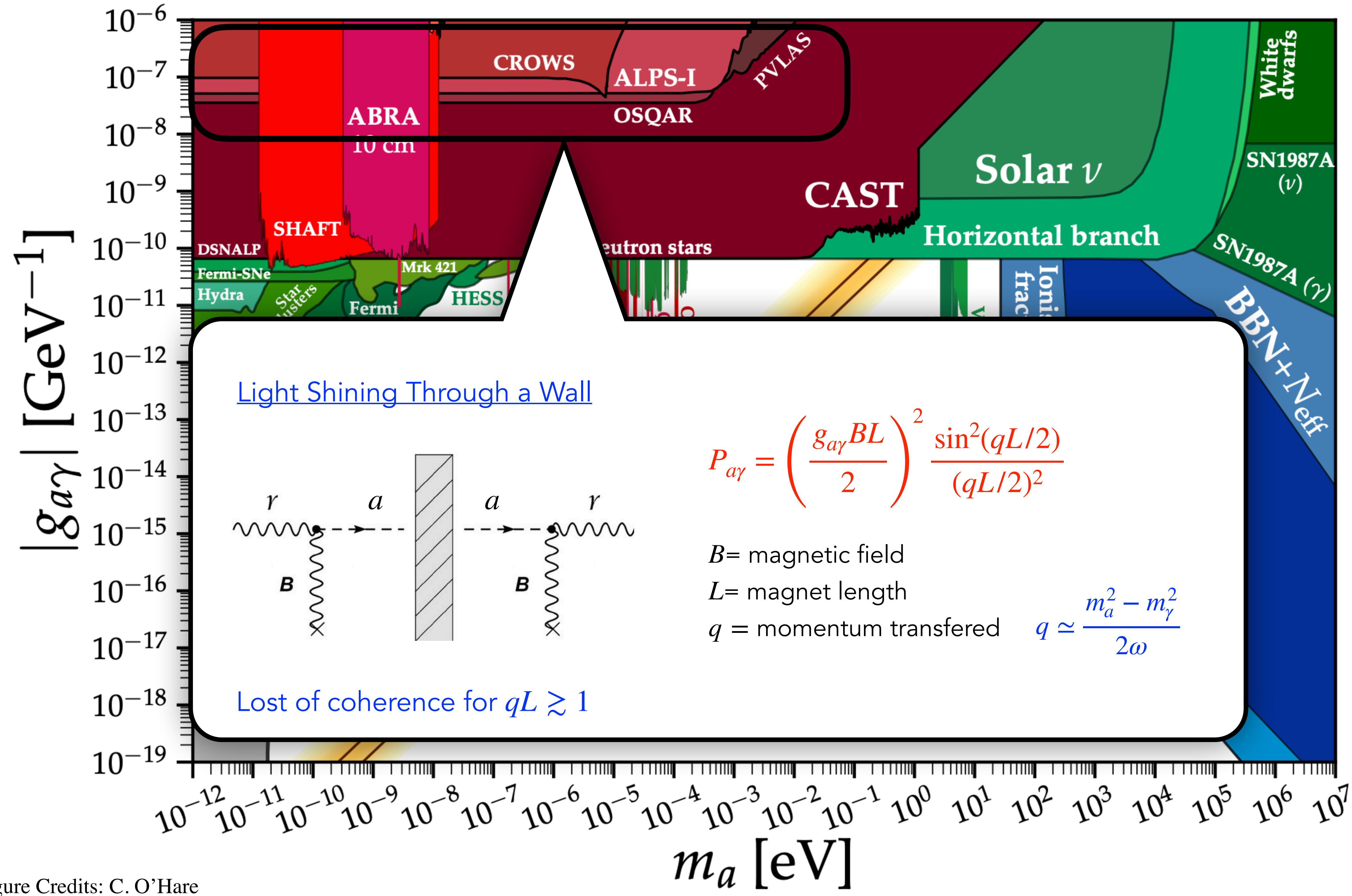


Light Shining Through a Wall

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

B= magnetic field

L= magnet length

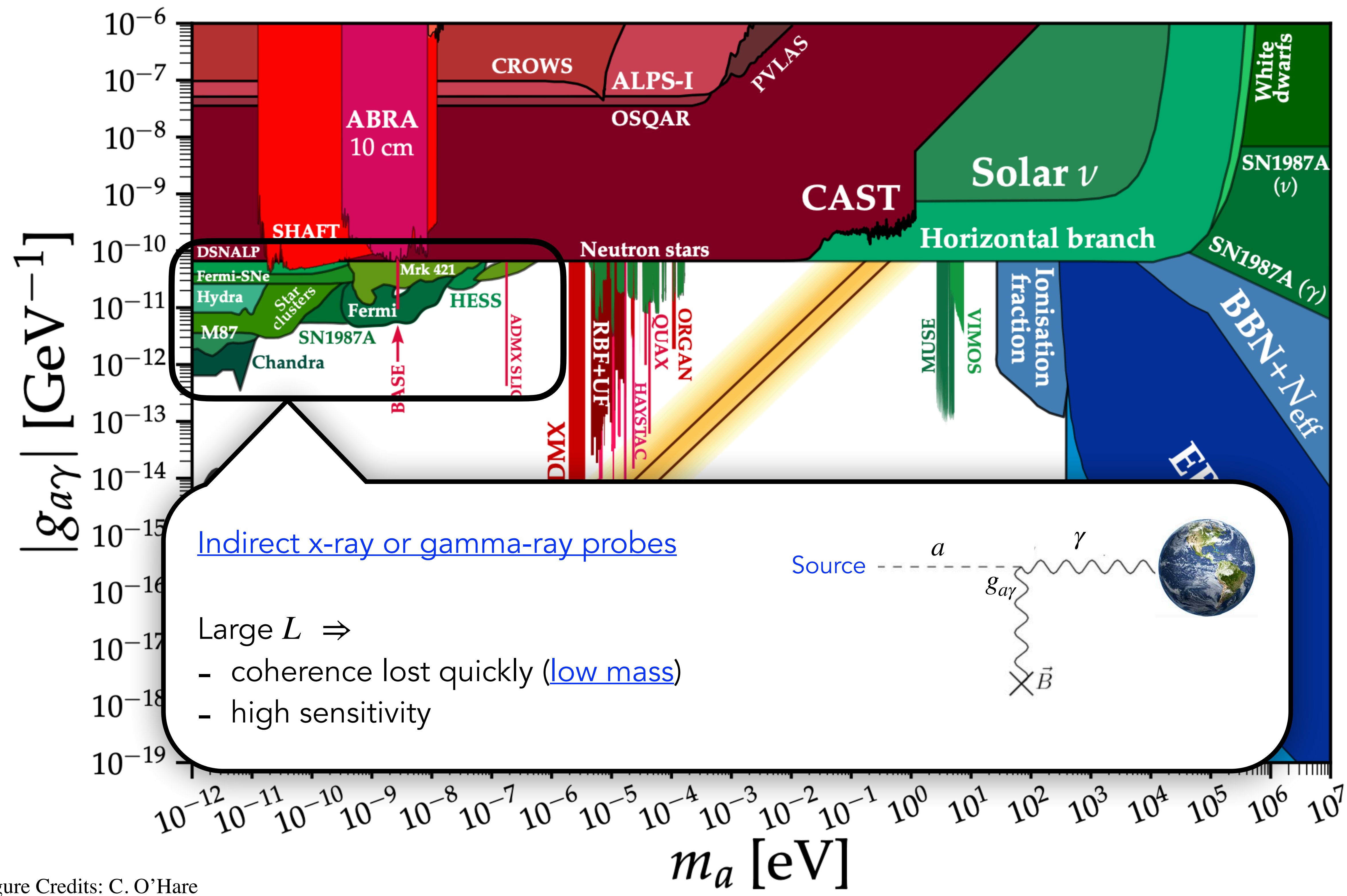
q = momentum transfered

$$q \simeq \frac{m_a^2 - m_\gamma^2}{2\omega}$$

Lost of coherence for $qL \gtrsim 1$

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

Axions and Axion-Like Particles (ALPs)



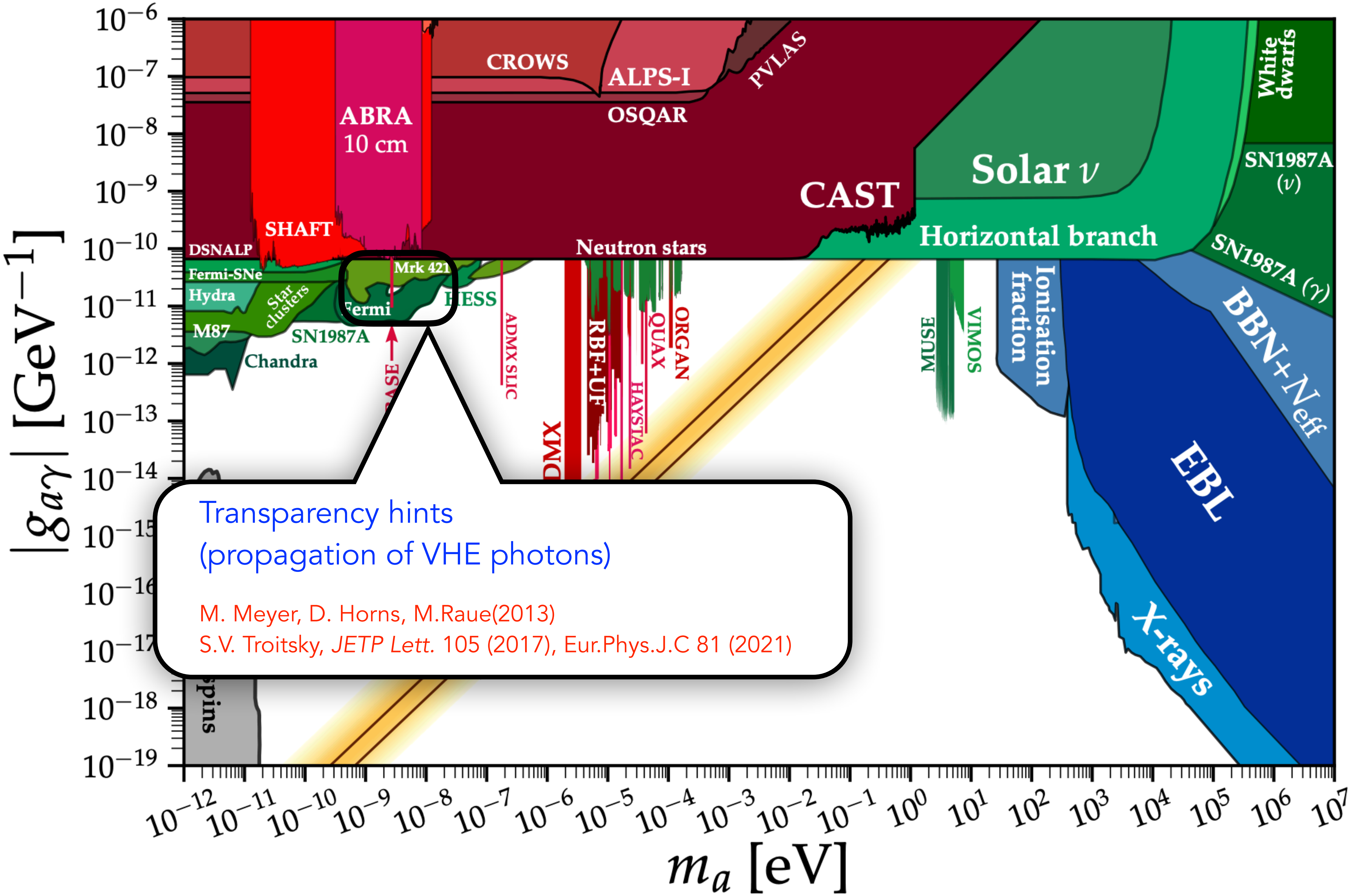
[Indirect x-ray or gamma-ray probes]

Large L $\Rightarrow$

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

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

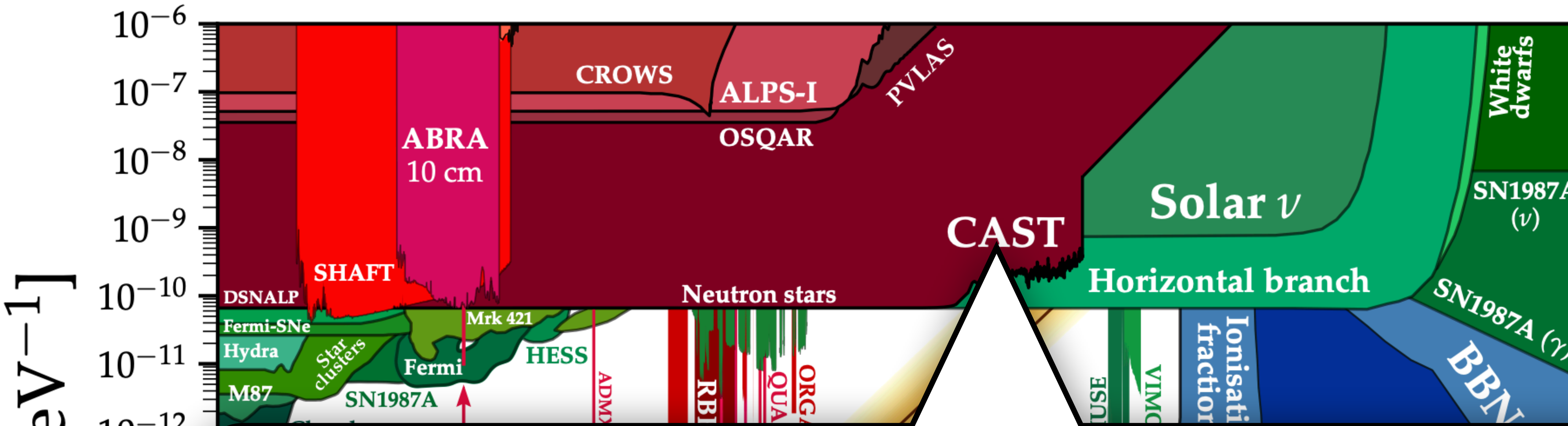
Axions and Axion-Like Particles (ALPs)



Transparency hints
(propagation of VHE photons)

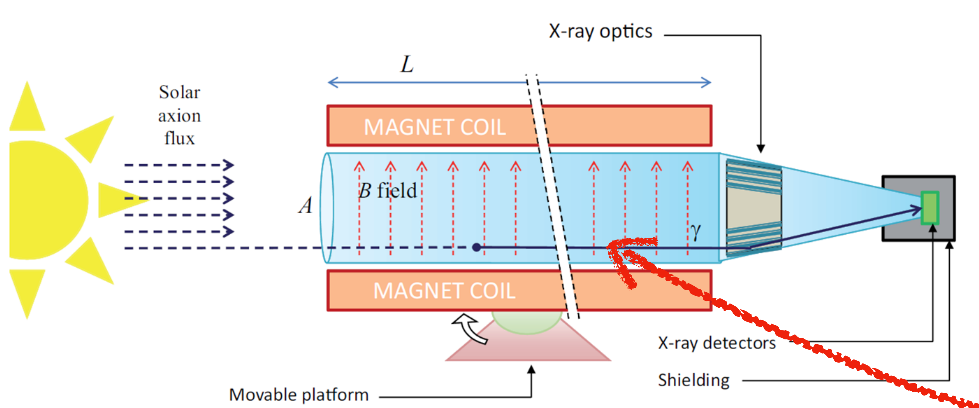
M. Meyer, D. Horns, M.Raue(2013)
S.V. Troitsky, *JETP Lett.* 105 (2017), Eur.Phys.J.C 81 (2021)

Axions and Axion-Like Particles (ALPs)



Helioscope

See next talk (I. Irastorza)

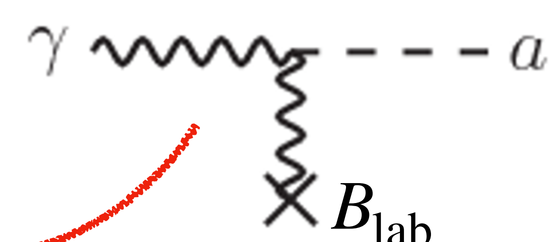


P. Sikivie PRL 51:1415 (1983)

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

$\Rightarrow$ Coherence lost at

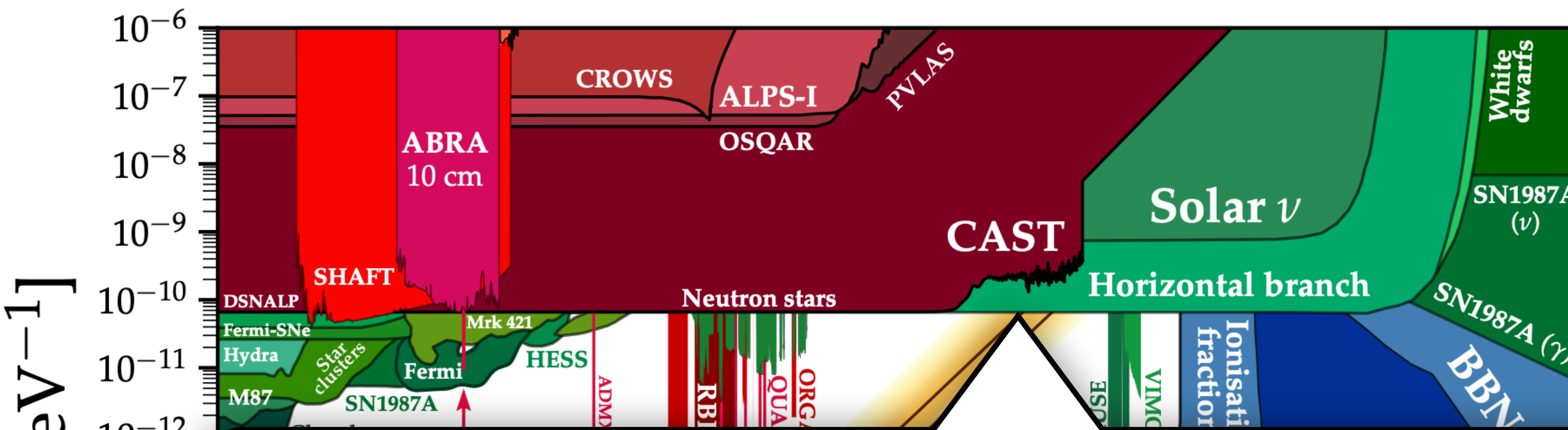
$m_{\rm th} \approx 10\,{\rm meV}\,\omega_{\rm keV}^{-1}\,L_{10}^{-1/2}$



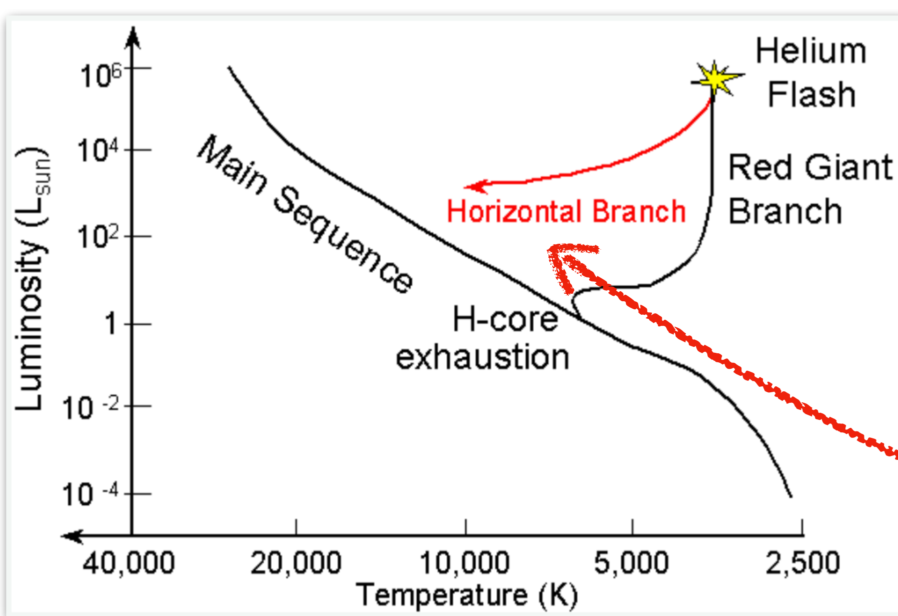
$g_{a\gamma} \leq 6.6 \cdot 10^{-11}\,{\rm GeV}^{-1}$

CAST Coll., Nature Phys. 13 (2017)

Axions and Axion-Like Particles (ALPs)



Stellar cooling (HB) bounds



Thermal production:

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

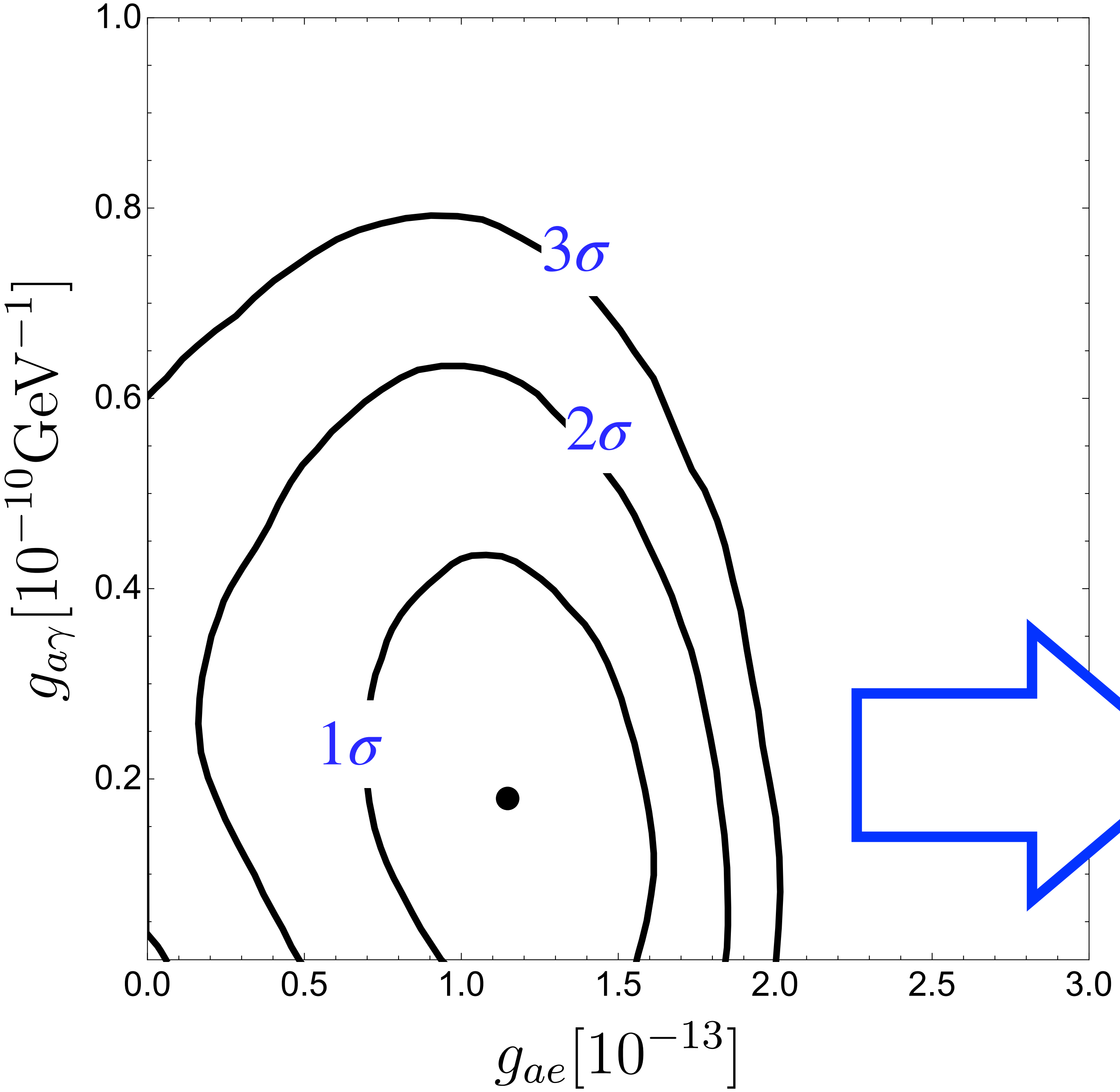
Then, Boltzmann suppressed

Primakoff Process

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

Ayala, Dominguez, M.G., Mirizzi, Straniero, PRL 113 (2014)

Getting more info from stars



Many recent results from stars

*Global analysis of WDs, RGB and HB stars shows a **preference for finite axion couplings** with electrons and photons*

For QCD models →
meV to ~100 meV mass region

Di Luzio, Fedele, M.G., Mescia, Nardi, arXiv:2109.10368 (2021)

Axions and Axion-Like Particles (ALPs)

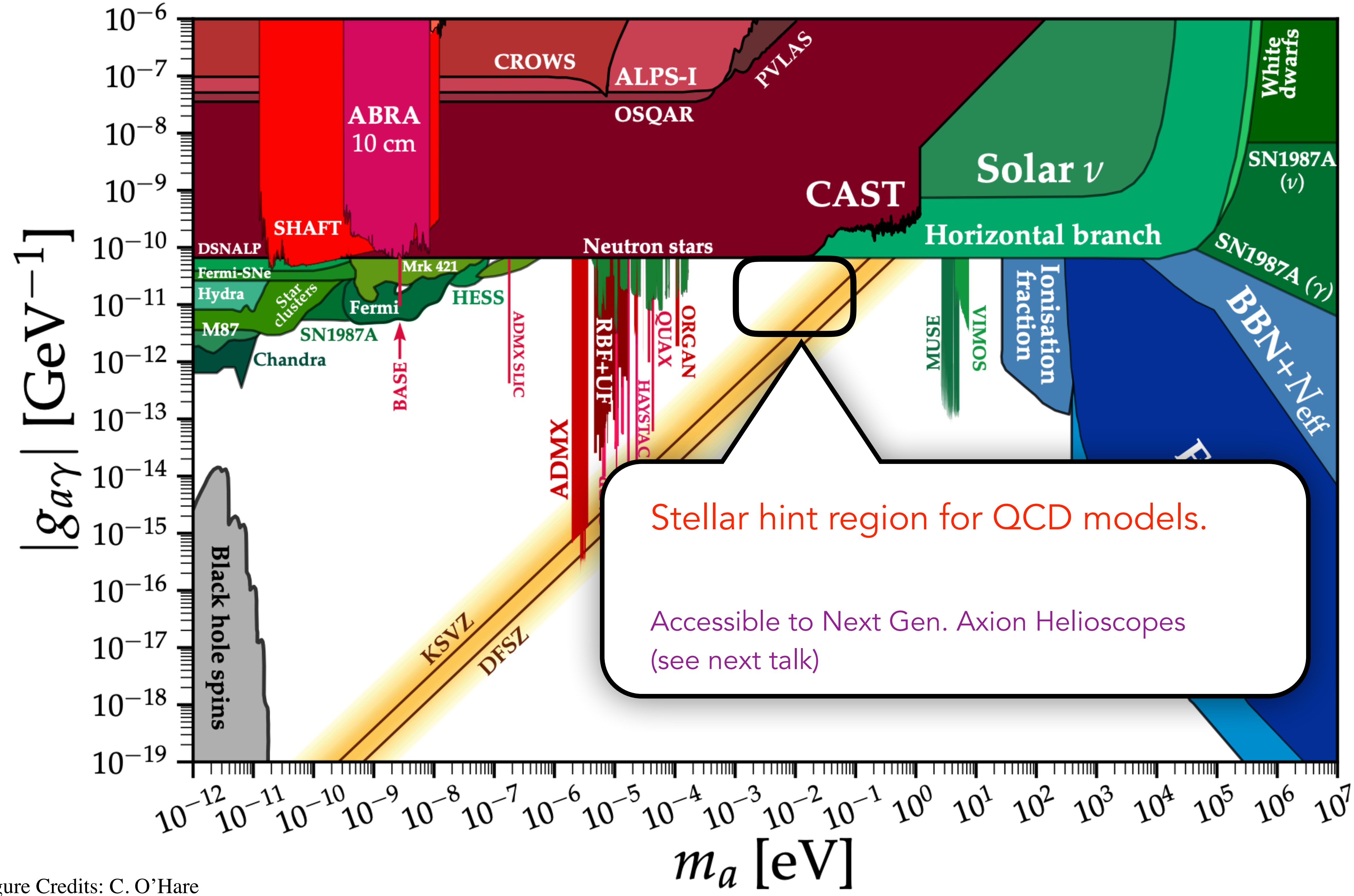
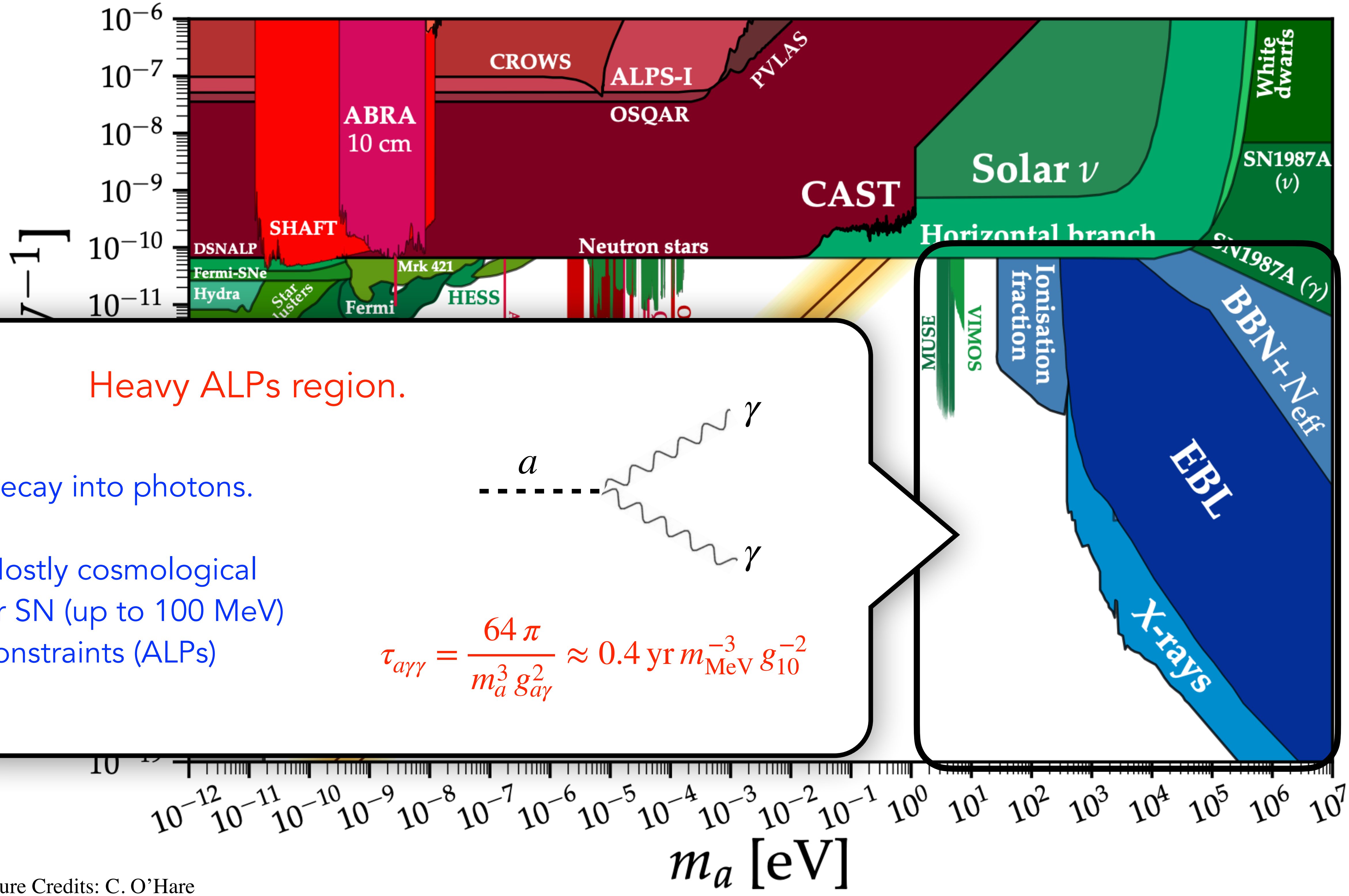


Figure Credits: C. O'Hare
https://cajohare.github.io/AxionLimits/

Axions and Axion-Like Particles (ALPs)



Heavy ALPs region.

Decay into photons.

Mostly cosmological or SN (up to 100 MeV) constraints (ALPs)

$$\tau_{a\gamma\gamma} = \frac{64\,\pi}{m_a^3\, g_{a\gamma}^2} \approx 0.4\,\mathrm{yr}\, m_{\rm MeV}^{-3}\, g_{10}^{-2}$$

Figure Credits: C. O'Hare
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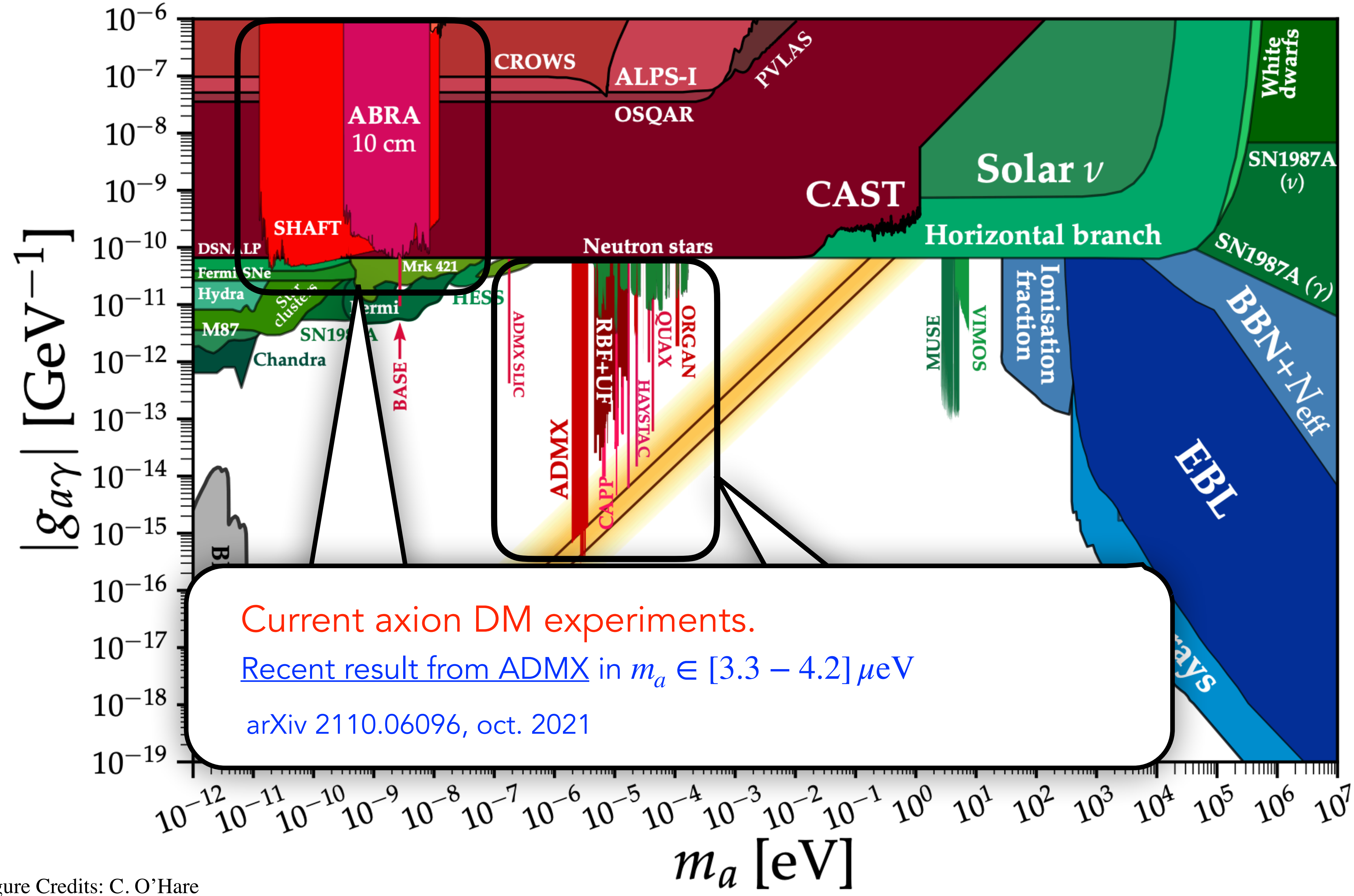
Axions and Axion-Like Particles (ALPs)



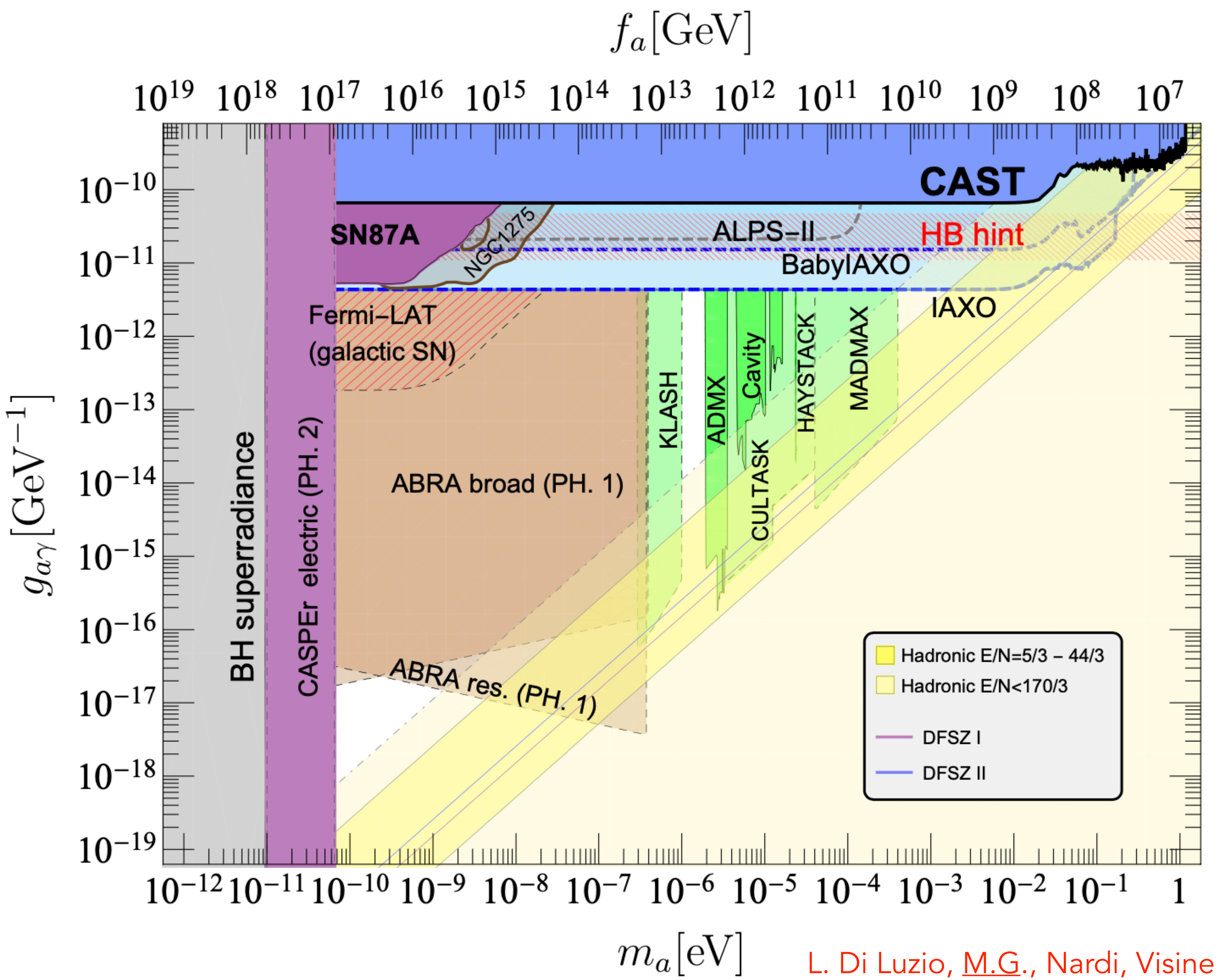
Current axion DM experiments.

[Recent result from ADMX](#) in $m_a \in [3.3 - 4.2]\,\mu$eV

arXiv 2110.06096, oct. 2021

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

The future?

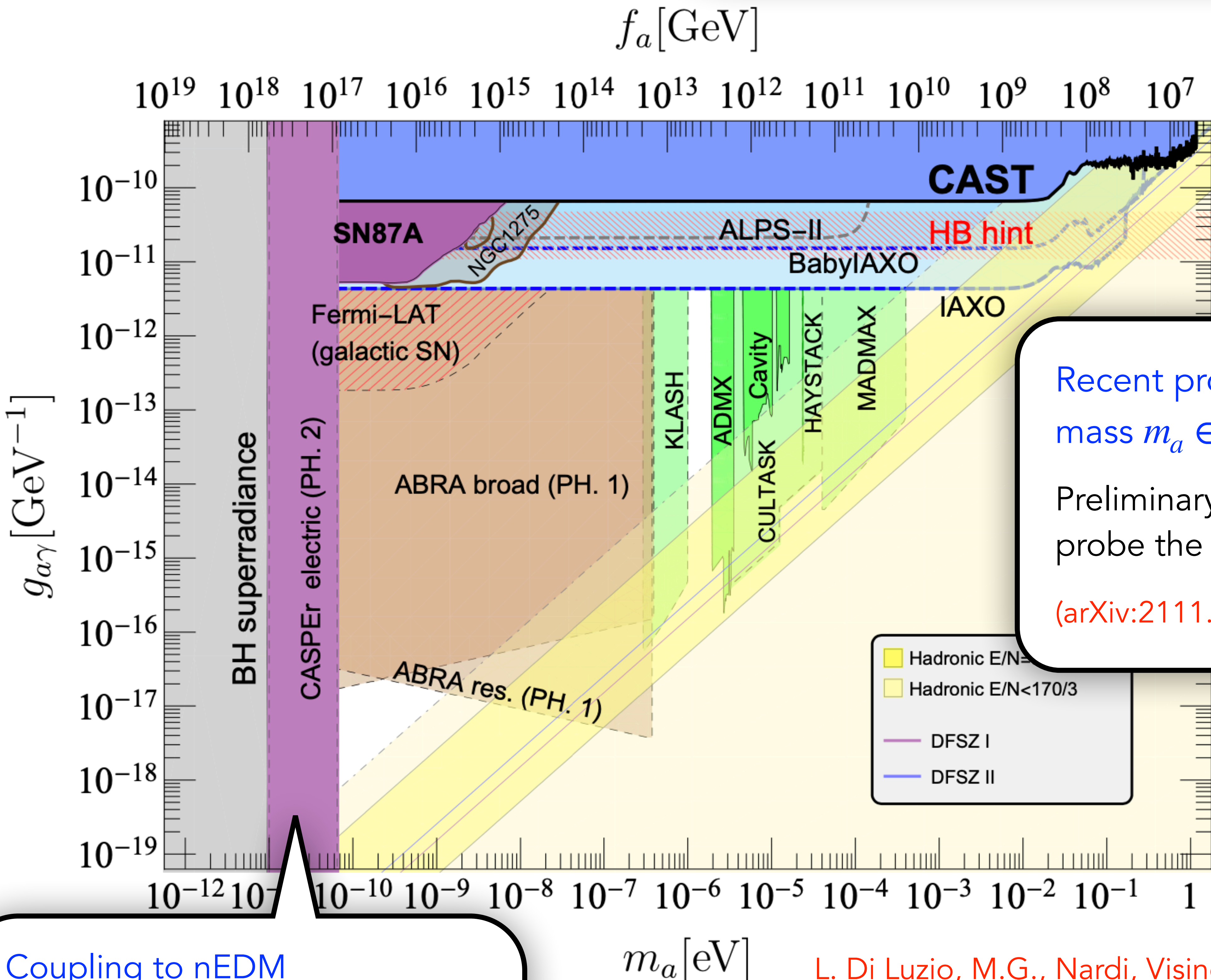


NB. In this plot we assume QCD axion $m_a - f_a$ relation

L. Di Luzio, M.G., Nardi, Visinelli, Phys.Rept. 870 (2020)

The future?

Promising future for axion DM searches



Recent proposal: BREAD, for high mass $m_a \in [10^{-3} - 1]\,\mathrm{eV}$

Preliminary study shows potential to probe the QCD axion band

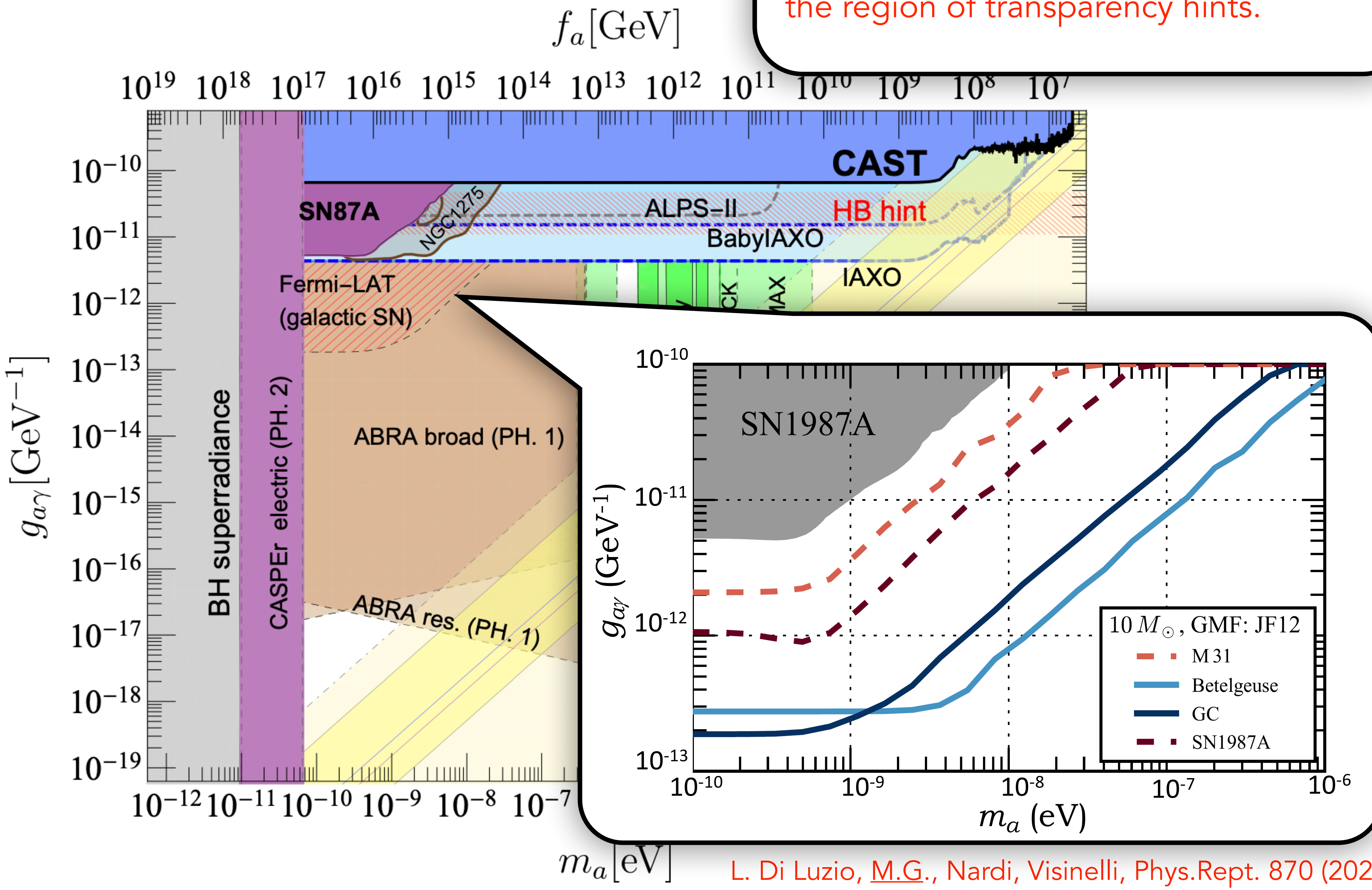
(arXiv:2111.12103, Nov 23, 2021)

Coupling to nEDM transformed into mass range

L. Di Luzio, M.G., Nardi, Visinelli, Phys.Rept. 870 (2020)

The future?

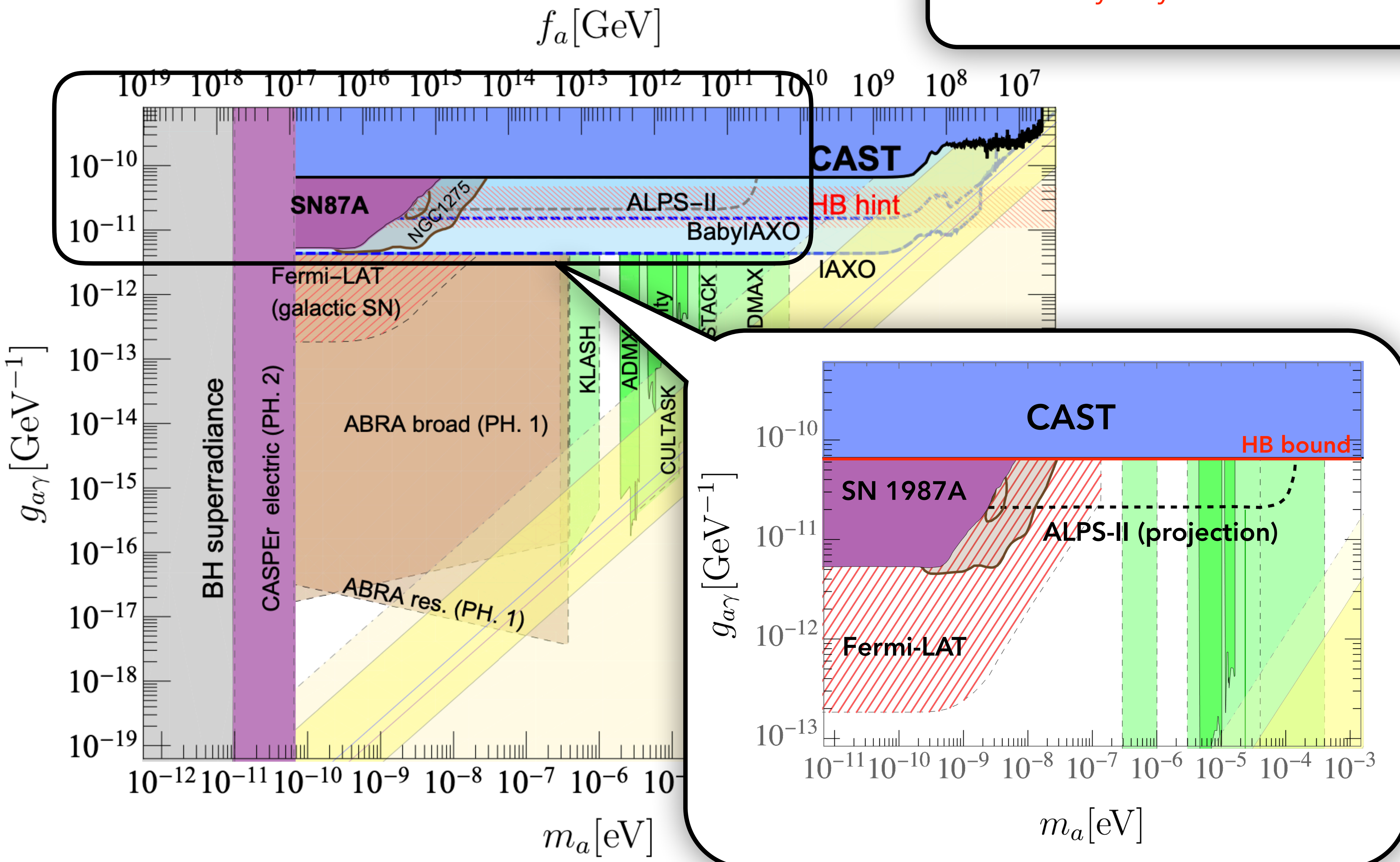
Large area explorable by Fermi LAT with a future galactic SN event. Probe the region of transparency hints.



L. Di Luzio, M.G., Nardi, Visinelli, Phys.Rept. 870 (2020)

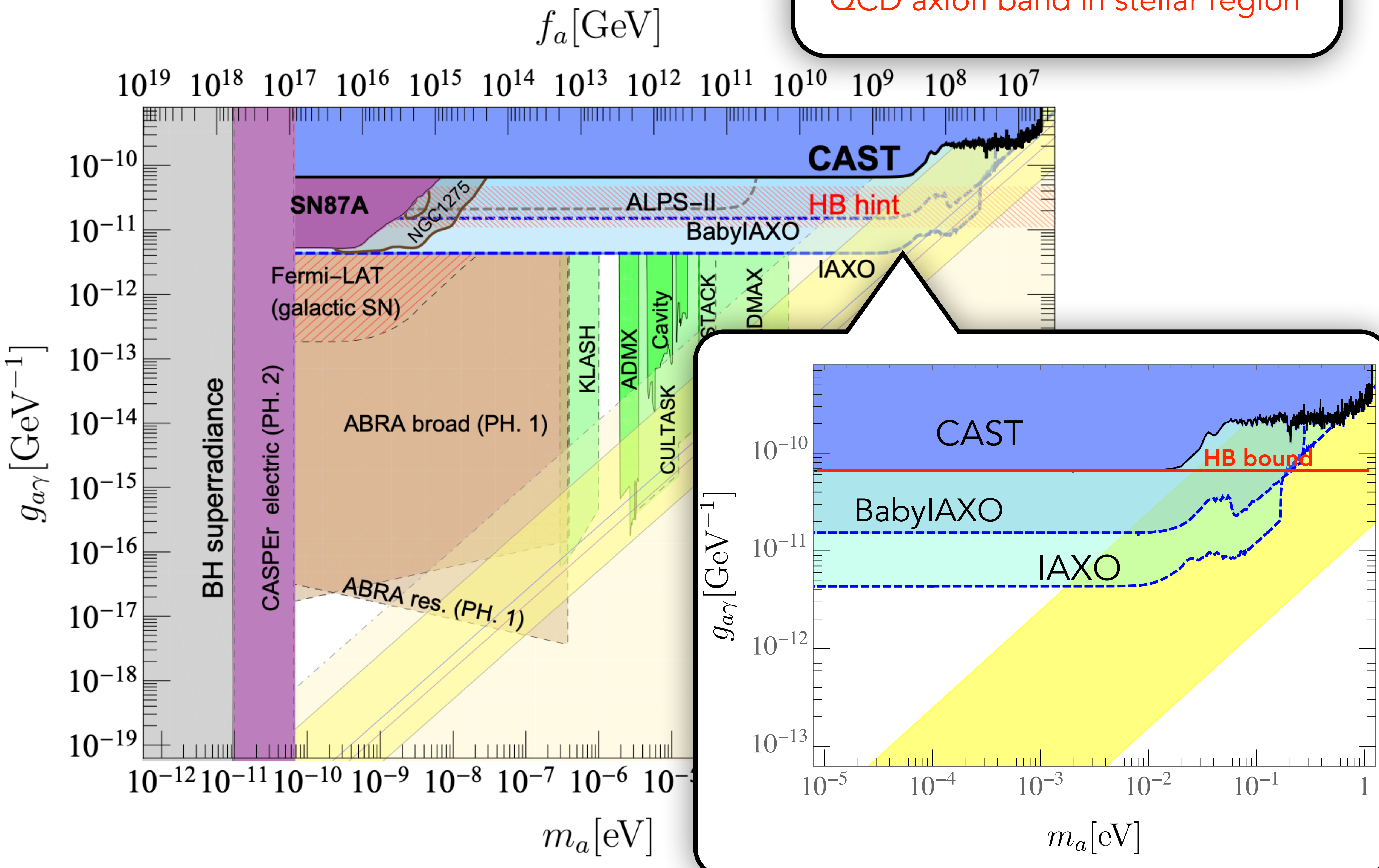
The future?

LSTW experiments will push sensitivity beyond stellar bounds



The future?

Next Gen. Helioscopes will cover QCD axion band in stellar region



Final Comments: Axion telescopes?

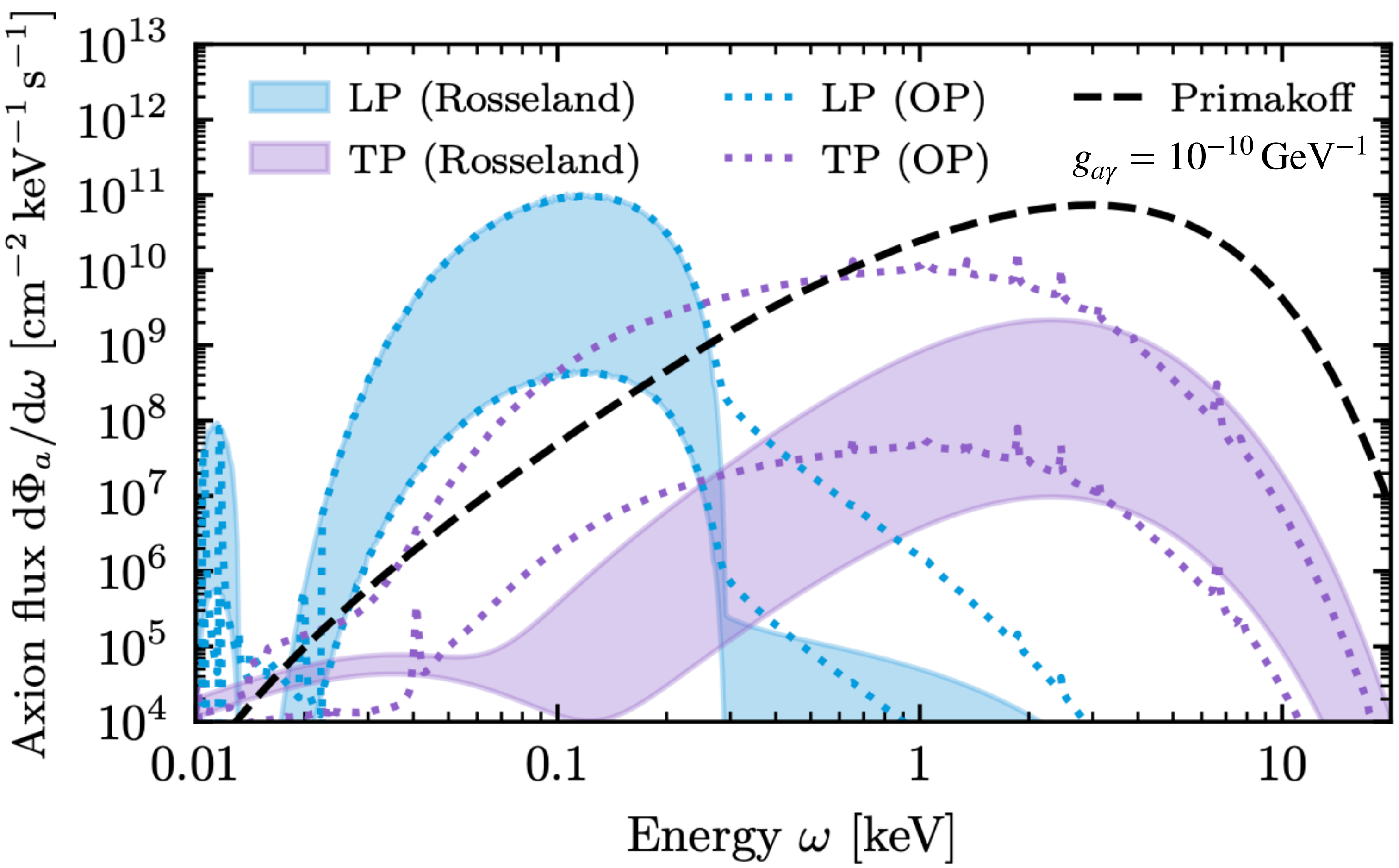
Looking at stars through axions

Axions are allowed to have large enough couplings to be exceptional messenger for stellar astrophysics.

(IAXO will give us the final response on that)

Probing the solar core

Axions could reveal solar magnetic field and more…



With enough resolution could probe B in stellar core.

Requires light ($m_a \lesssim 1$ meV) axions.

Probing Solar Metals?

J. Jaeckel, L. J. Thormaehlen, Phys.Rev.D 100 (2019) 12

S. Hoof, J. Jaeckel, L. J. Thormaehlen, JCAP 09 (2021)

E. Guarini, P. Carenza, J. Galan, M. G., A. Mirizzi, Phys.Rev.D 102 (2020)

A. Caputo, A. J. Millar, E. Vitagliano, Phys.Rev.D 101 (2020)

Best telescope for massive stars

Model	Phase	t_{cc} [yr]	$\log_{10}(L_{\rm eff}/L_\odot)$	$\log_{10}(T_{\rm eff}/{\rm K})$	C	E_0 [keV]	β
			Photons		Axions		
0	He burning	155000	4.90	3.572	1.36	50	1.95
1	before C burning	23000	5.06	3.552	4.0	80	2.0
2	before C burning	13000	5.06	3.552	5.2	99	2.0
3	before C burning	10000	5.09	3.549	5.7	110	2.0
4	before C burning	6900	5.12	3.546	6.5	120	2.0
5	in C burning	3700	5.14	3.544	7.9	130	2.0
6	in C burning	730	5.16	3.542	12	170	2.0
7	in C burning	480	5.16	3.542	13	180	2.0
8	in C burning	110	5.16	3.542	16	210	2.0
9	in C burning	34	5.16	3.542	21	240	2.0
10	between C/Ne burning	7.2	5.16	3.542	28	280	2.0
11	in Ne burning	3.6	5.16	3.542	26	320	1.8
12	beginning of O burning	1.4	5.16	3.542	27	370	1.8

Axion spectrum

$$\frac{d\dot{N}_a}{dE} = \frac{10^{42} C g_{11}^2}{\text{keV s}} \left(\frac{E}{E_0}\right)^{\beta} e^{-(\beta+1)E/E_0}$$

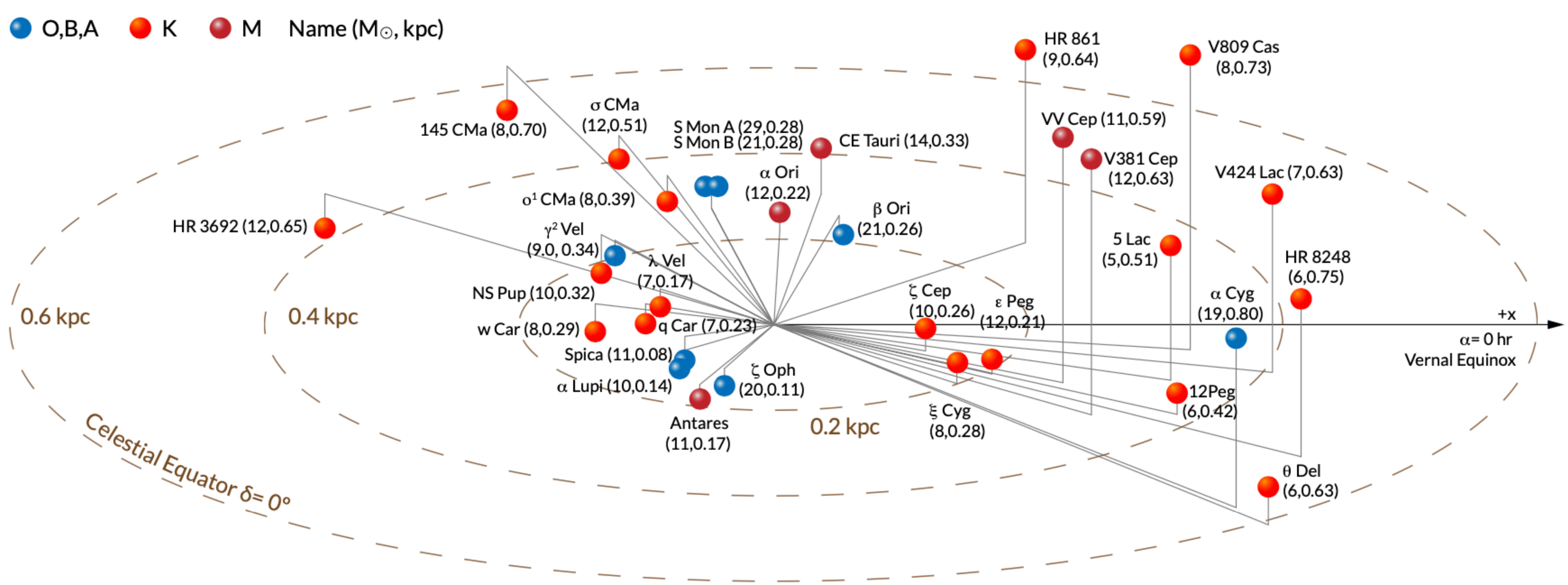
can pin down t_{cc} from $\sim 10^{-5}$ yr

Constant photon spectrum for the last 10^5 yr

Axions are sensitive to all late evolutionary stages. Surface photons are not.

Xiao, Perez, **M.G.**, Straniero, Mirizzi, Grefenstette, Roach, Nynka, Phys.Rev.Lett. 126 (2021)

Best telescope for massive stars



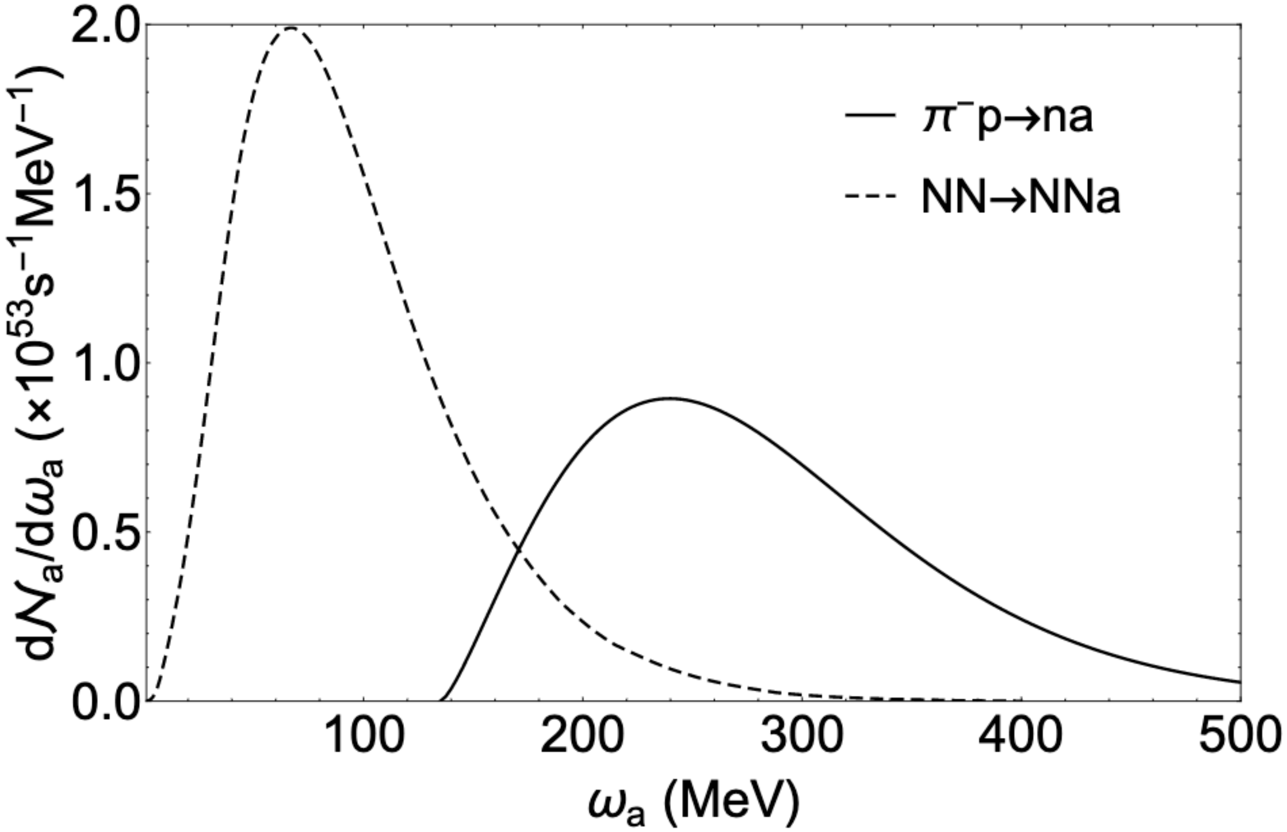
31 candidates within 1 kpc from the sun.

Observable in axions but it requires very low mass ($\lesssim$ neV)

Xiao, Perez, **M.G.**, Straniero, Mirizzi, Grefenstette, Roach, Nynka, Phys.Rev.Lett. 126 (2021)

Look in the SN core

Even neutrinos are trapped in the SN core



Neutrinos tell us about the neutrino sphere but axions could tell us about the core.

Harder spectrum expected from recent analyses

SN axion flux (with allowed couplings) could be detectable by water Cherenkov and possibly also Helioscopes (all this is still under study)

P. Carenza, B. Fore, M.G., A. Mirizzi, S. Reddy, Phys.Rev.Lett. 126 (2021)]
T. Fischer, P. Carenza, B. Fore, M.G., A. Mirizzi, S. Reddy, (2021) [arXiv:2108.13726]

Conclusions and final comments

Axions are a well motivated DM candidates and play a fundamental role in particle physic and in astrophysics

Experiments are finally probing the axion parameter space in regions not excluded (but rather, hinted) by stars

If axions/ALPs are just around the corner (large couplings), they can be exceptional astrophysical messengers

Acknowledgements

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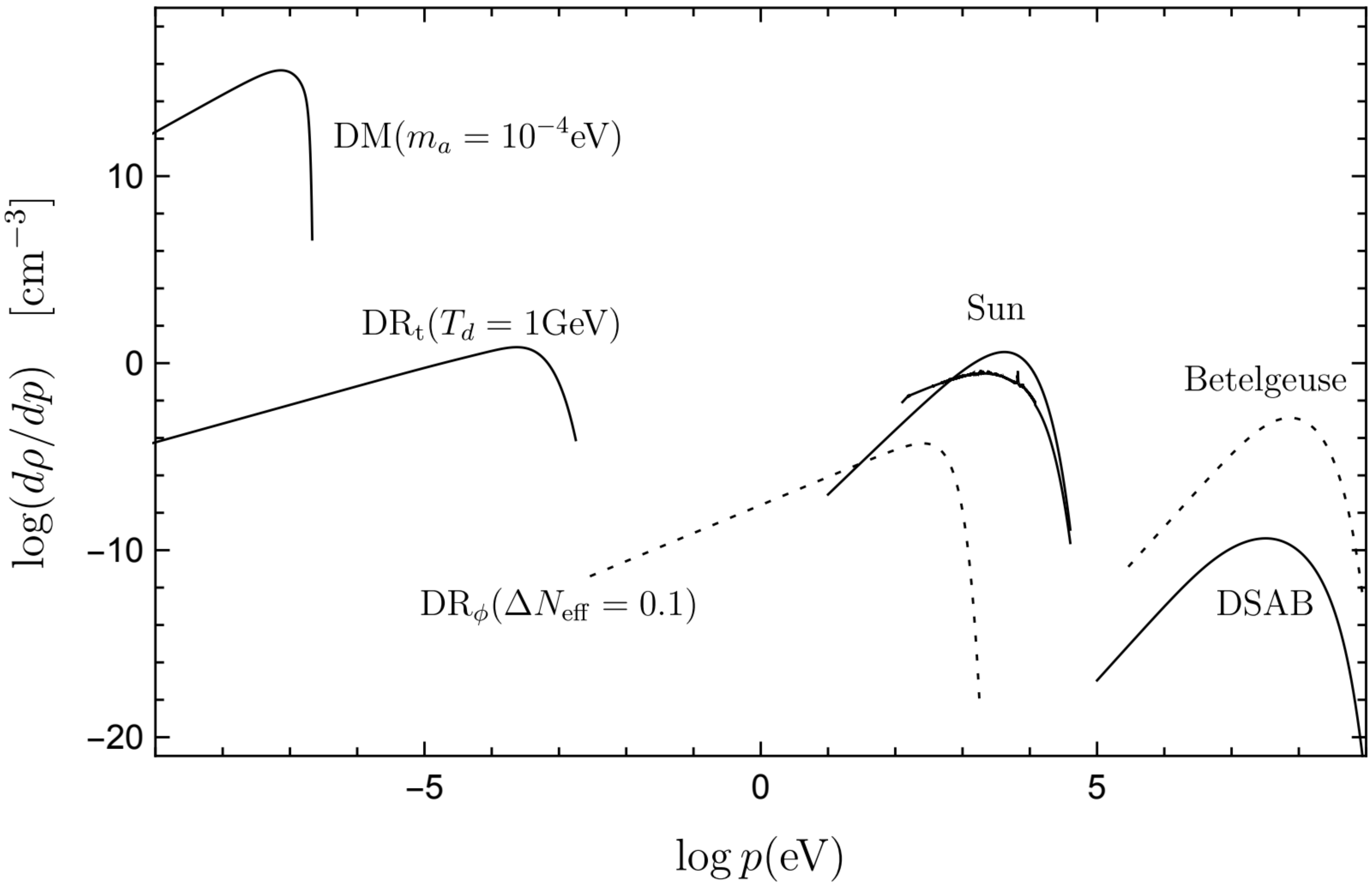
Grant CEX2019-000918-M, by Ministero de Ciencia y Innovación, Agencia Estatal de investigatión

Backup Slides

Natural sources

See https://arxiv.org/pdf/1801.08127.pdf, page 32



Irastorza, redondo, Prog.Part.Nucl.Phys. 102 (2018)

Natural Axion/ALP sources

Cosmological

- Realignment
- Topological Defects

  → Non-thermal: CDM, $E_a \simeq m_a$

- Thermal → HDM

Astrophysical

- Stellar
  - Thermal: $E_a \sim T_{\rm core}$, keV or 100 MeV (SN)
  - Nuclear: $E_a \sim$ keV, MeV
  - Resonant $\gamma + B \to a + B$: $E_a \sim \omega_{pl}$ (eV in the sun)
- Galactic/Extra-Galactic
  - Diffuse SN background: ~100 MeV
  - Conversion of photons in $B_{\rm ext}$: High to very high energy

Natural Axion/ALP sources

Cosmological

- Realignment
- Topological Defects
- Thermal

Direct: Haloscopes (Realignment, Topological Defects)

Indirect: cosmological probes, telescopes ($a \to \gamma\gamma$), …

Astrophysical

- Stellar
  - Thermal
  - Nuclear
  - Resonant $\gamma + B \to a + B$

  Direct: Helioscopes → Sun, SN(?)

  Indirect: NuSTAR/Fermi ($a + B \to \gamma$)

- Galactic/ Extra-Galactic
  - Diffuse SN background — Fermi: Indirect ($a + B \to \gamma$)
  - Conversion of photons in $B_{\rm ext}$ — Indirect ($a + B \to \gamma$) Chandra, NuSTAR,Fermi

Axion Dark matter

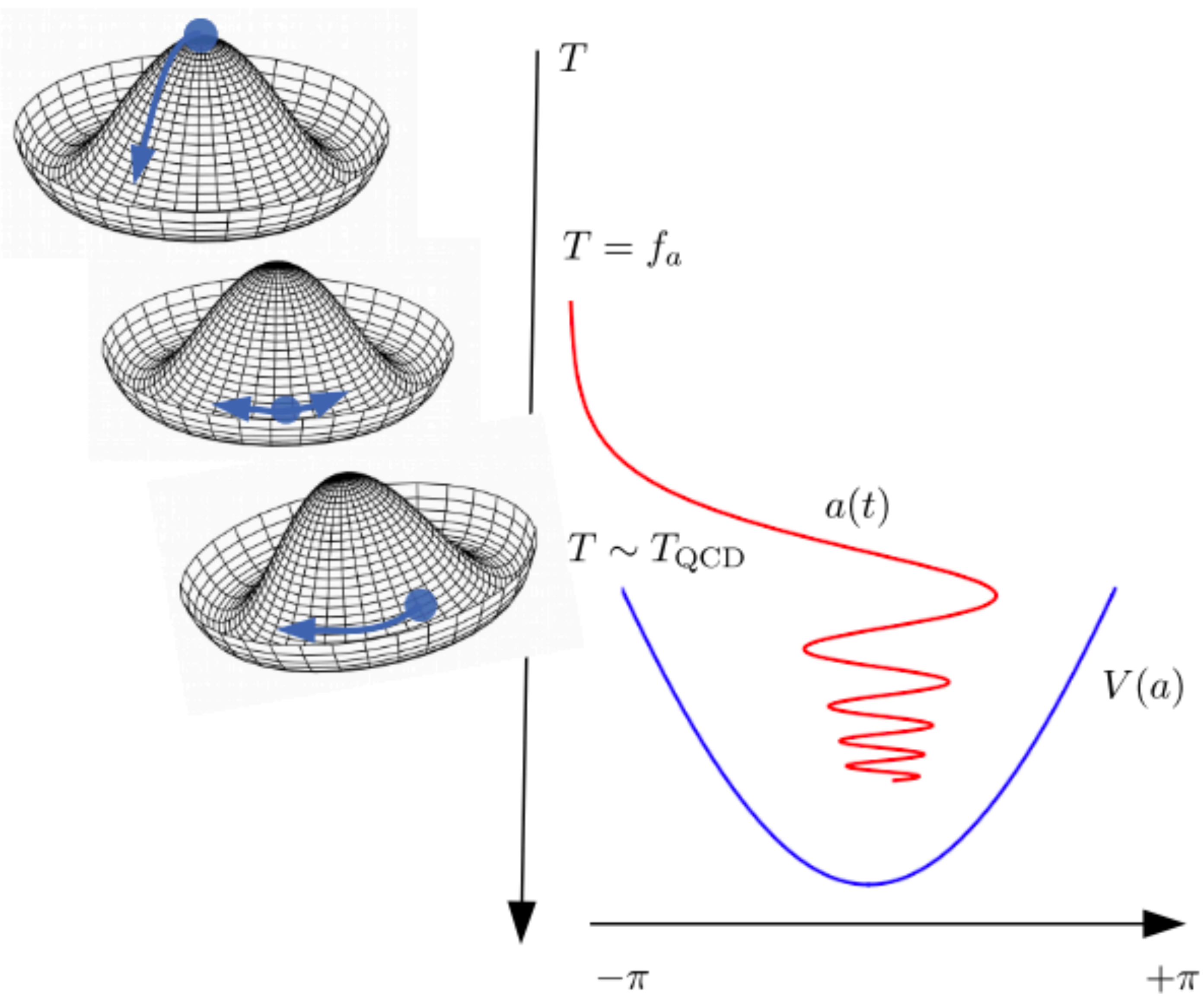


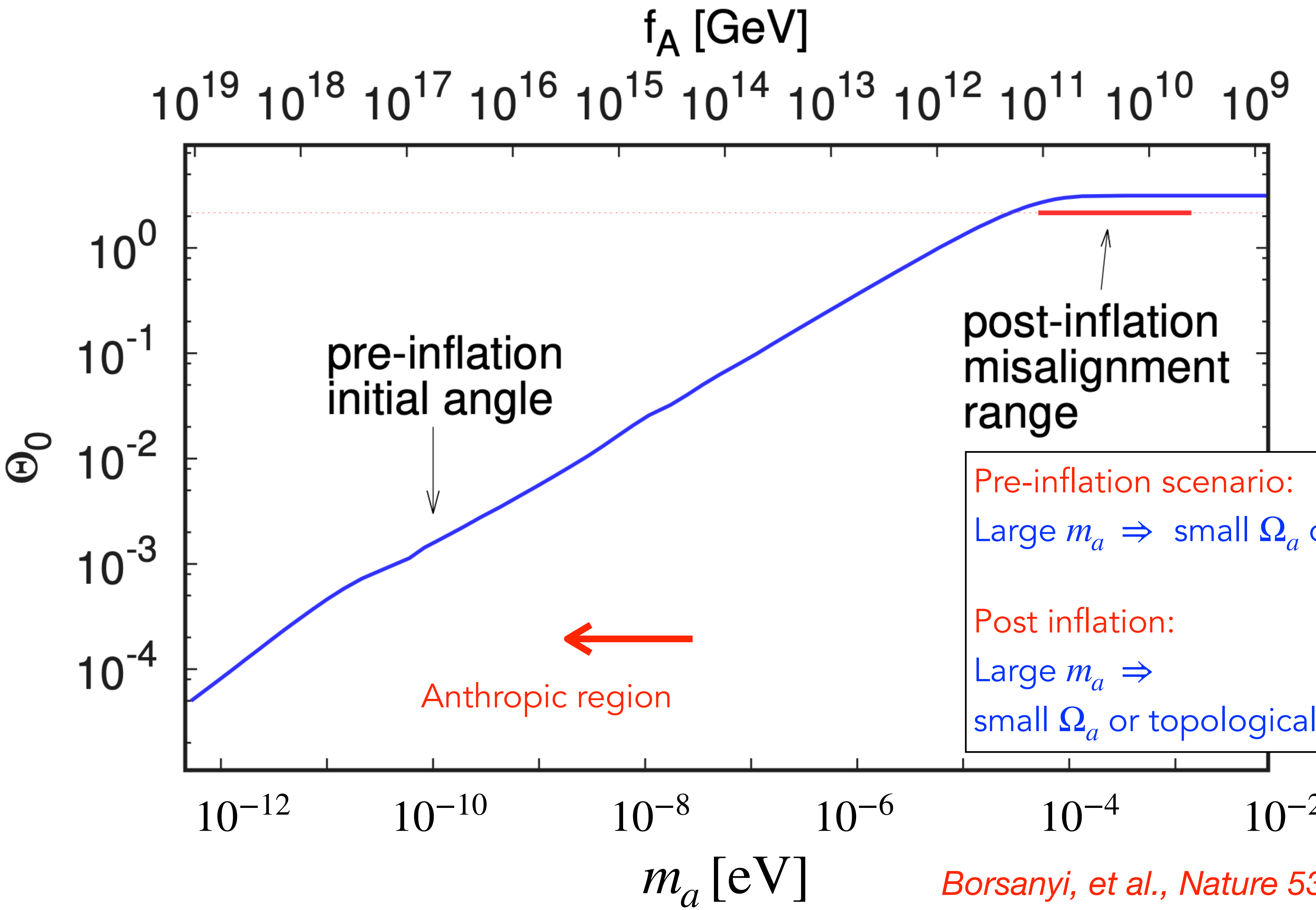
Figure Credits: Andreas Pargner, KIT Ph.D. dissertation (2019)

Unexpected and unavoidable consequence of the PQ mechanism:

If axions exist, they are necessarily a fraction of the cold DM in the universe

- Preskill, Wise and Wilczek (1983)
- Abbott and Sikivie (1983)
- Dine and Fischler (1983)

Axion Dark matter



Pre-inflation scenario:

Large m_a $\Rightarrow$ small Ω_a or large Θ_0

Post inflation:

Large m_a $\Rightarrow$

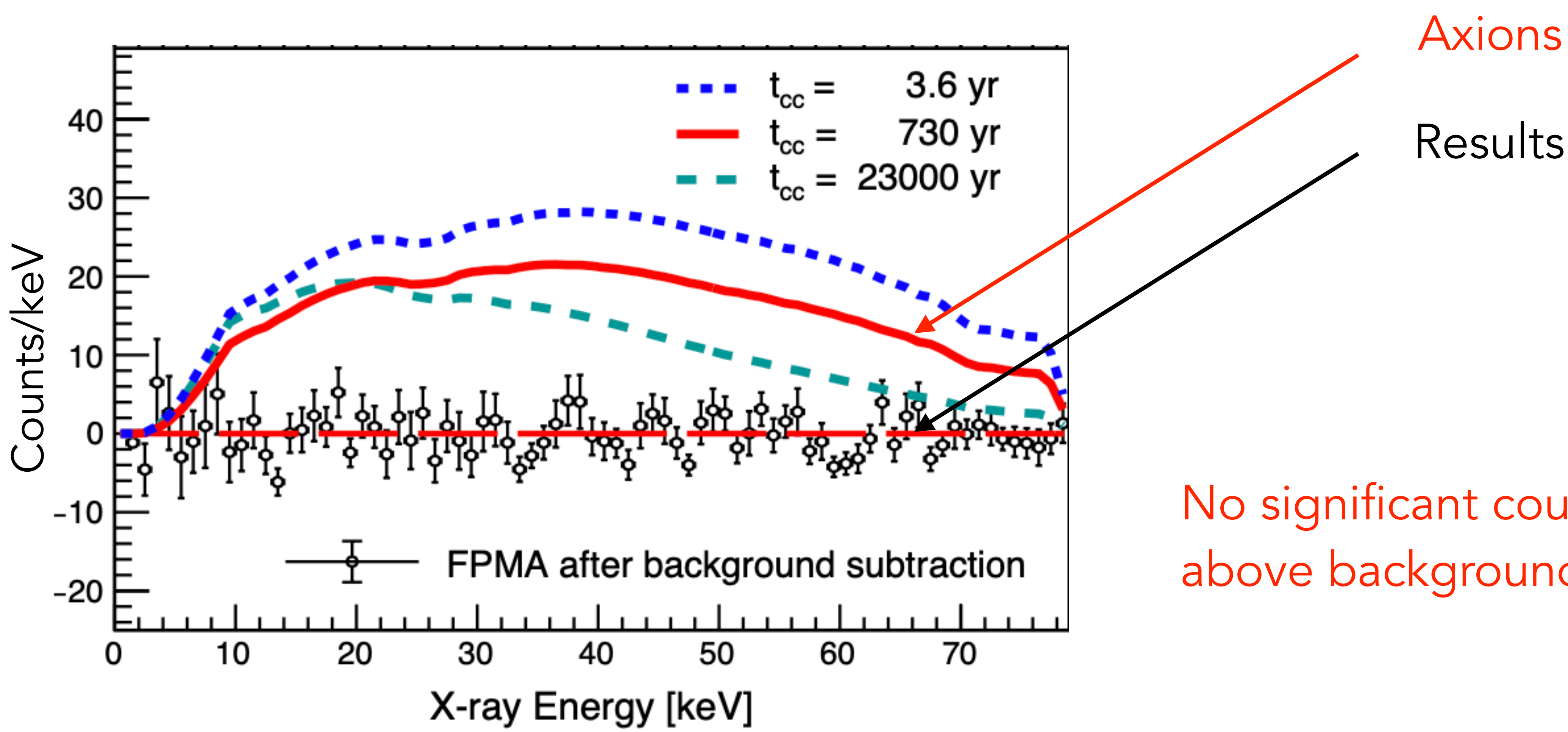
small Ω_a or topological defects

Borsanyi, et al., Nature 539 (2016)

Observing Betelgeuse with axions

First hard X-ray observations of Betelgeuse, using NuSTAR, awarded under NASA Grant No. 80NSSC20K0031 (50 ks observation time, August 2019, ObsID 30501012002):

Kerstin Perez, M.G., Brian Grefenstette, Oscar Straniero, Alessandro Mirizzi.

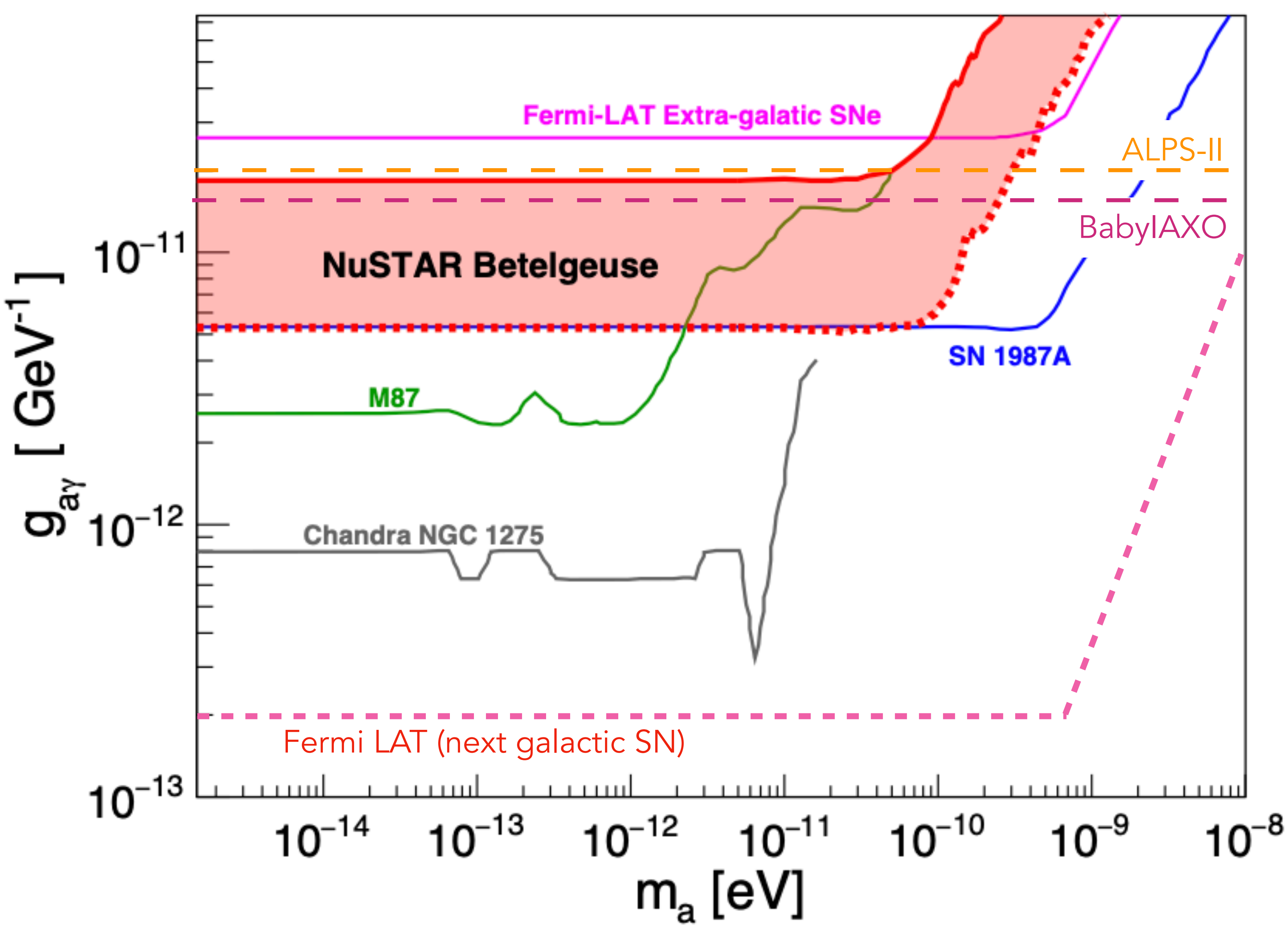


No significant counts above background

Xiao, Perez, M.G., Straniero, Mirizzi, Grefenstette, Roach, Nynka, Phys.Rev.Lett. 126 (2021) [arXiv:2009.09059]

Results

Interesting parameter region. Several analyses, bounds and sensitivity studies using X- and Gamma-Ray surveys



Meyer et al., Phys. Rev. Lett. 124, 231101 (2020),

Xiao et al, to appear in PRL (2020)

Dessert, Foster, Safdi, (2020), to appear in PRL (exclusion region similar to Xiao et al.)

Payez et al., J. Cosm 02, 006 (2015).

M.C. D. Marsh et al., J. Cosmol. Astropart. Phys. 12, 036 (2017),

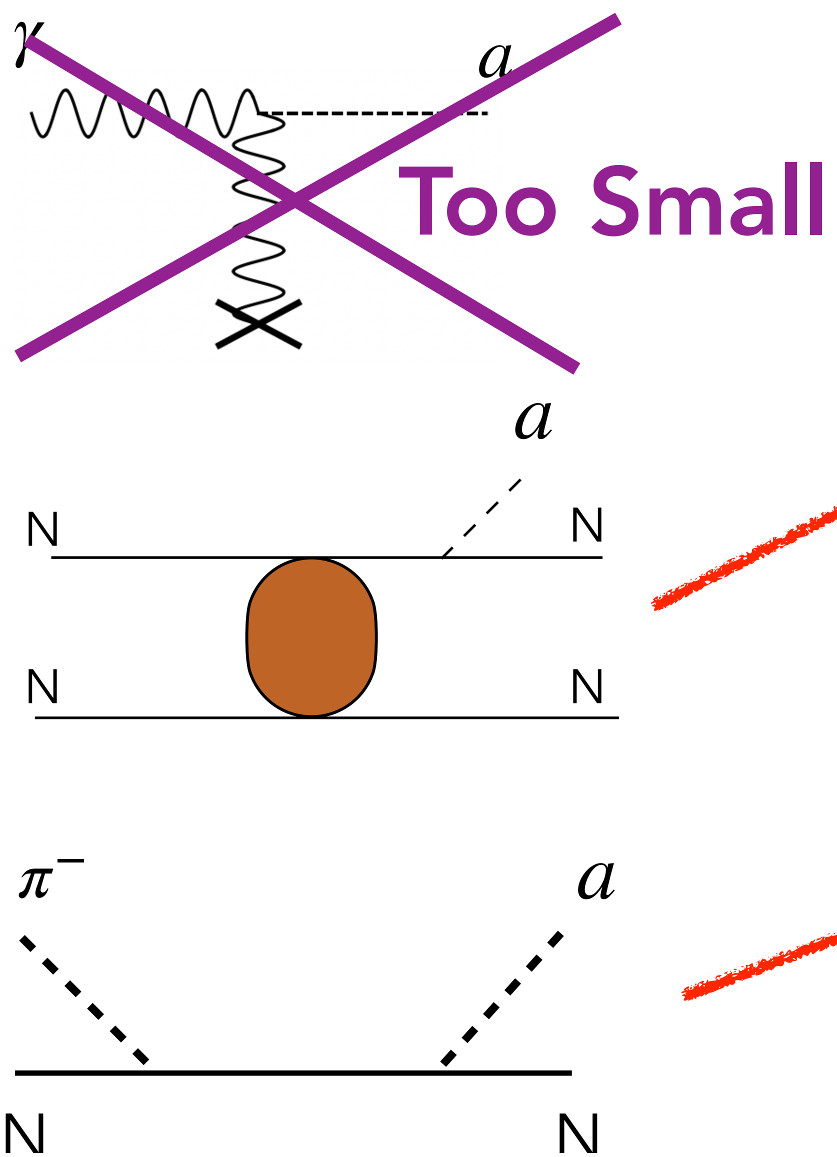
Reynolds et al., Astrophys. J. 890, 59 (2019),

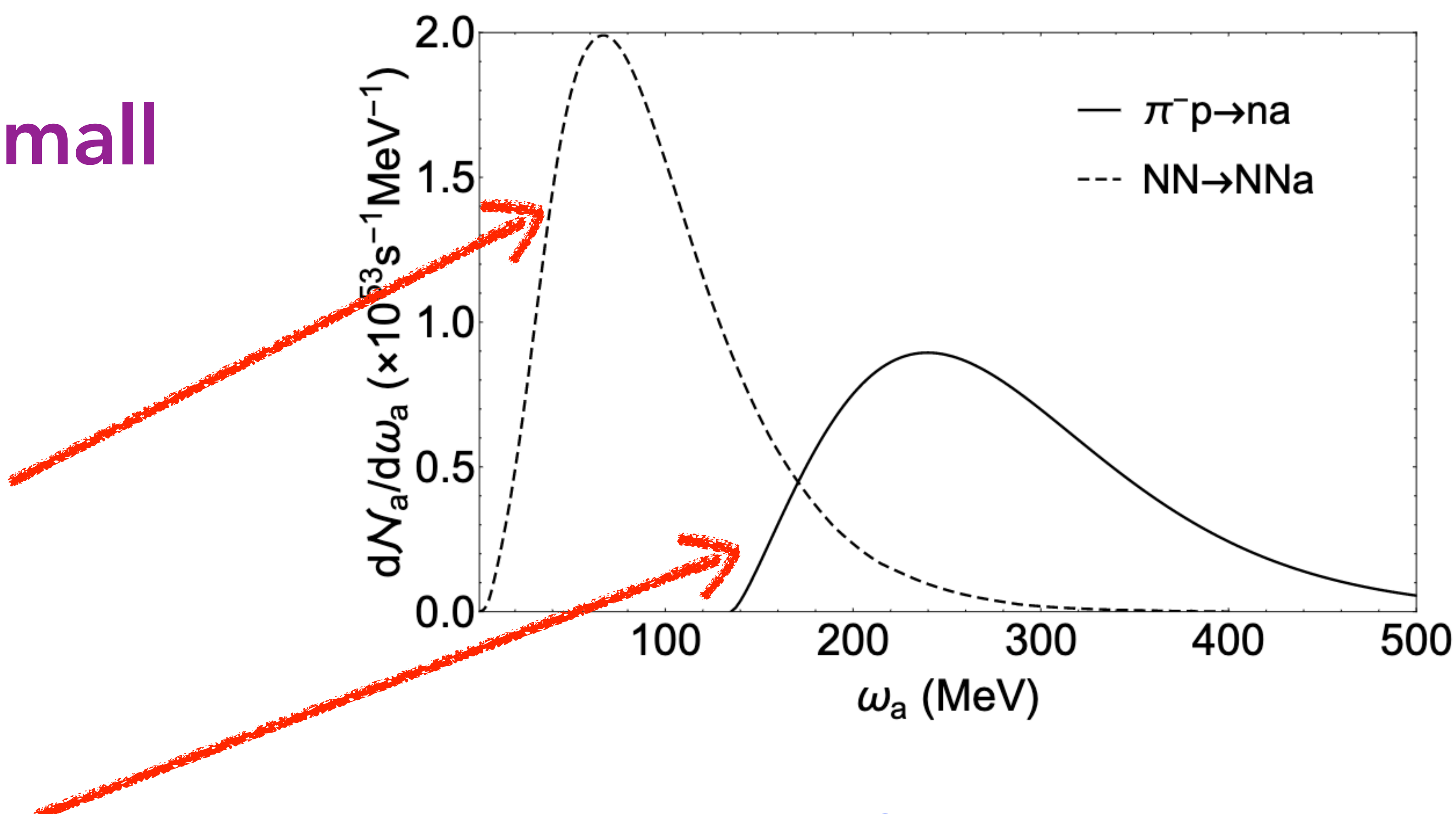
Meyer et al., Phys.Rev.Lett. 118 (2017)

Xiao, Perez, **M.G.**, Straniero, Mirizzi, Grefenstette, Roach, Nynka, Phys.Rev.Lett. 126 (2021)

Supernova axions

Extreme environment $\rho \sim 3 \times 10^{14}\,\mathrm{g\,cm^{-3}}$, $T \sim 30$ MeV.

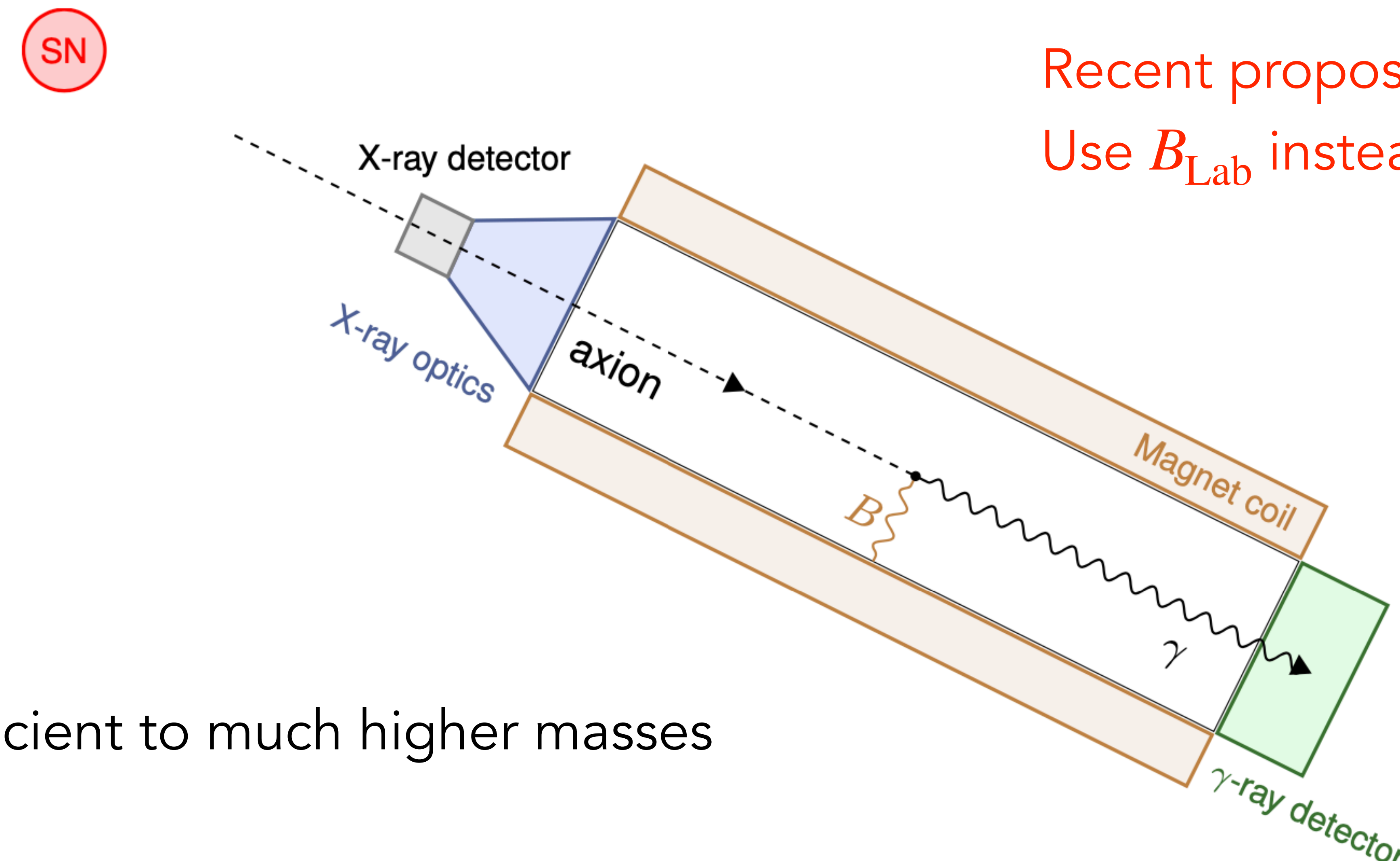




Harder spectrum from pion processes.
Detection in water Cherenkov?

P. Carenza, B. Fore, M.G., A. Mirizzi, S. Reddy, Phys.Rev.Lett. 126 (2021)
T. Fischer, P. Carenza, B. Fore, M.G., A. Mirizzi, S. Reddy, (2021) [arXiv:2108.13726]

Helioscopes as Axion SN-Scopes



Recent proposal.
Use $B_{\rm Lab}$ instead of $B_{\rm galactic}$

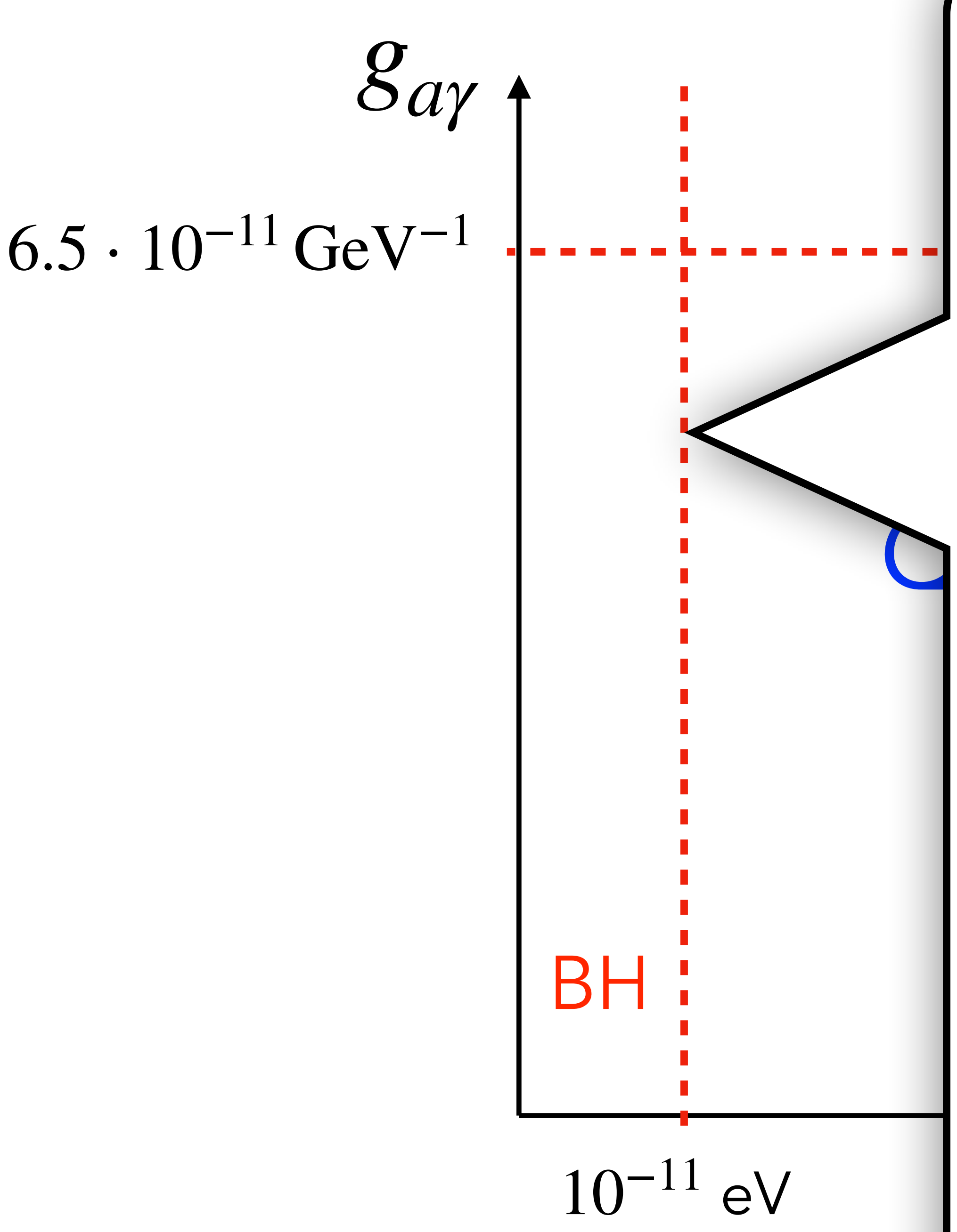
Axion helioscope
turned around

Efficient to much higher masses

Up to ~12 events (Spica), 2 events (Betelgeuse)
with BabyIAXO setup

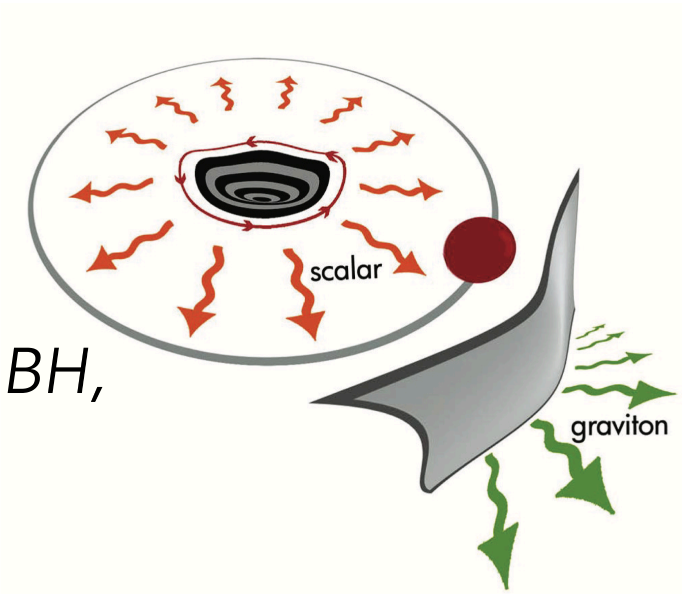
Ge, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa (2020) [arXiv:2008.03924]

The QCD Axion Box



Black Holes

Gravitational Interaction
+ sub-Planckian f_a



Light axions can bind to BH, with occupation number growing through superradiance process. Constraints from angular momentum extracted from BH

Brito, Cardoso, Pani, arXiv:1501.06570;

Arvanitaki, Baryakhtar, Huang, Phys.Rev.D 91 (2015) 8

The QCD Axion Box

$6.5 \cdot 10^{-11}$

Axions must couple to neutron EDM

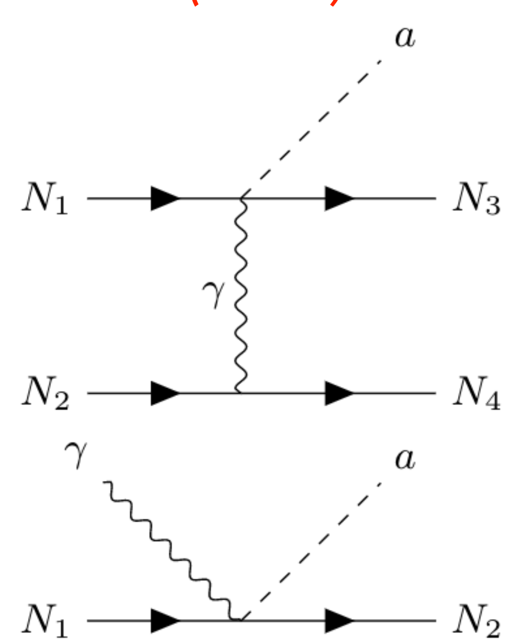
$$L_{int} \supset -\frac{i}{2} g_{dN}\, a\, \bar{n}\, \sigma_{\mu\nu}\gamma_5\, n\, F^{\mu\nu}$$

P. W. Graham, S. Rajendran, Phys. Rev. D88 (2013)

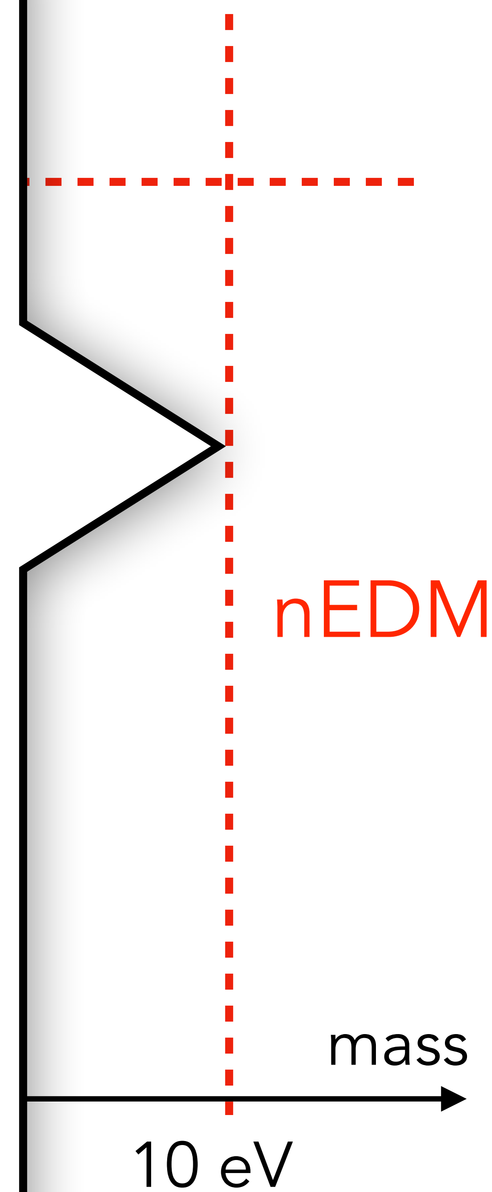
Stellar production (SN bound):

$$\Rightarrow \quad g_{dN} \leq 0.6 \cdot 10^{-7}\, \mathrm{GeV}^{-2}$$

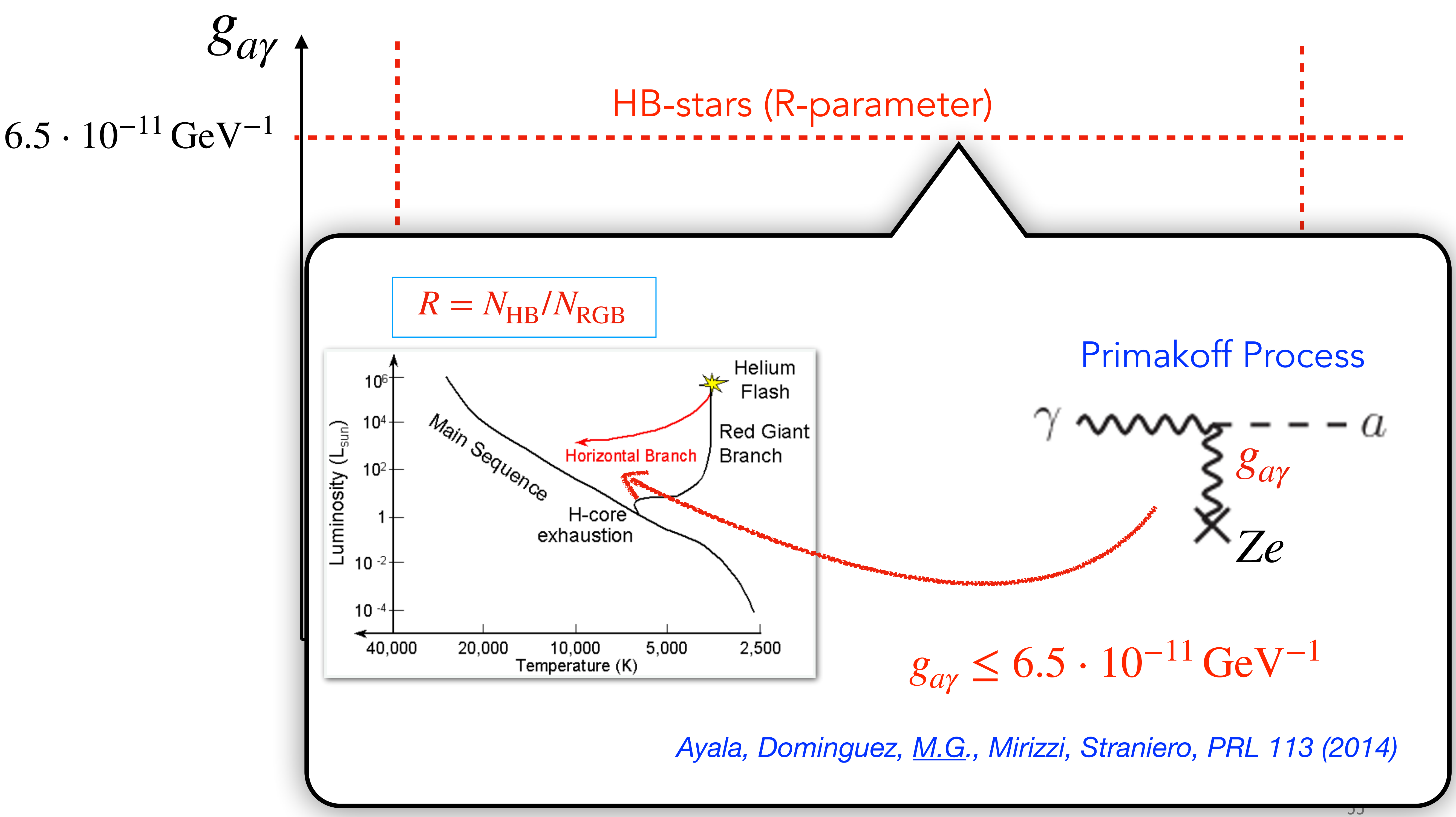
(corresponds to $m_a \lesssim 10\,\mathrm{eV}$)



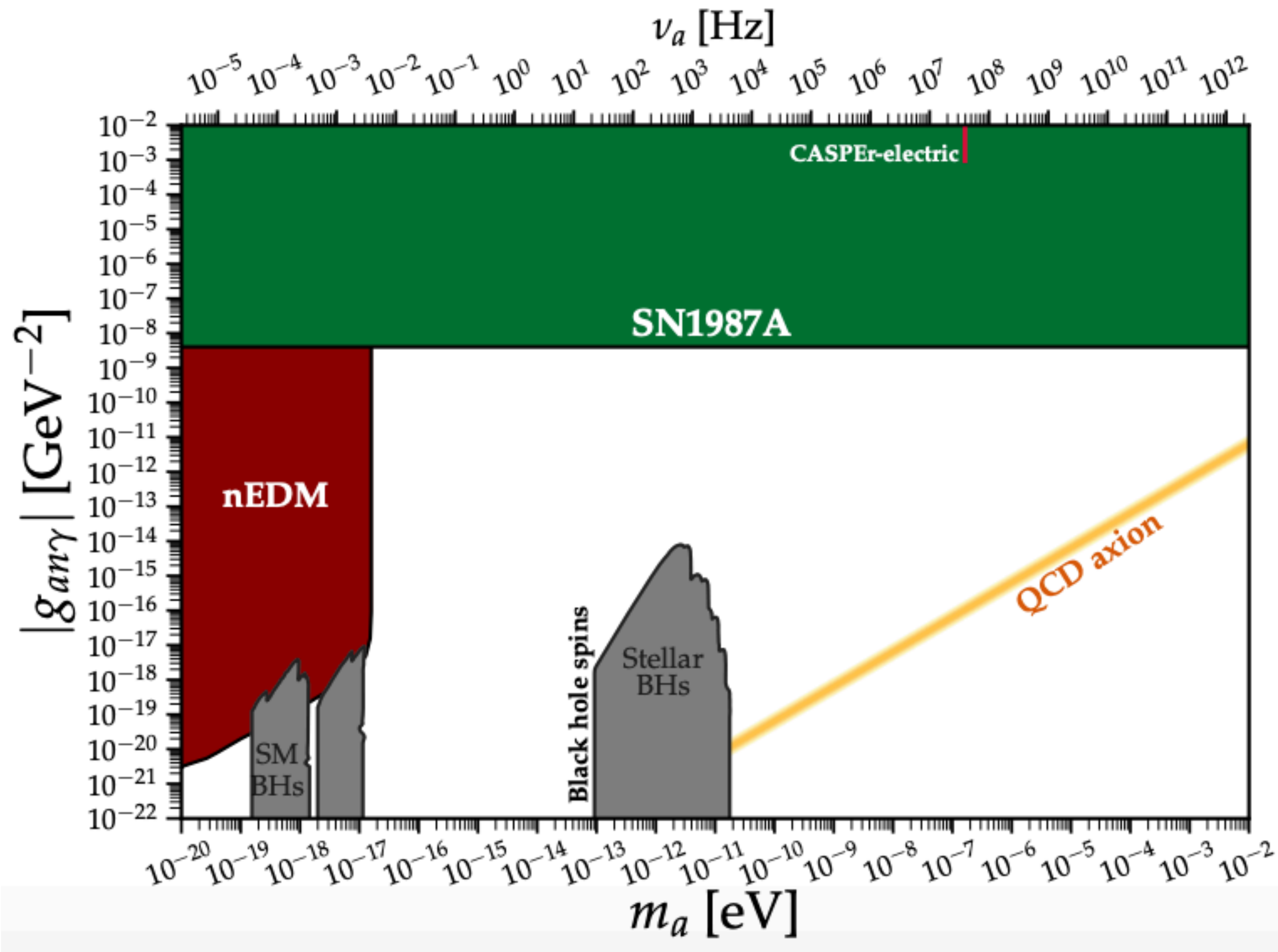
P. Carenza, G. Lucente et al. (in preparation)



The QCD Axion Box



Axion-EDM



ν_a [Hz]
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12}
$|g_{an\gamma}|$ [GeV^{-2}]
10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16} 10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22}
CASPEr-electric
SN1987A
nEDM
SM BHs
Black hole spins
Stellar BHs
QCD axion
10^{-20} 10^{-19} 10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2}
m_a [eV]