Axions

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TAE, Benasque
September 15, 2023

Axions

Cosmology

Dark Matter

Particle Physics

Strong-CP problem

Astrophysics

Stellar evolution; Cooling anomalies;
Transparency hints (ALPS)

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

World-wide effort to detect it.

Summary

- *Motivations*
- *Axions as a fundamental QCD ingredient*
- *Model independent results*
- *Axion astrophysics/cosmology*
- *The search for axions*

Part 1: Theory

Motivations

- Strong CP Problem: Axions may be required to make QCD work properly → QCD axions

QCD (appears to) give wrong predictions for some observables, e.g., the electric dipole moment of the neutron (nEDM)

Motivations

- Strong CP Problem: Axions may be required to make QCD work properly → QCD axions

- In spite of being light, axions (and ALPs) can be CDM, thanks to non-thermal production mechanisms.

Very light DM behaves like waves.
Requires specific technologies. Extremely fruitful research field.

"Discovery of dark matter waves would provide a glimpse into the earliest moments in the origin of the universe and the laws of nature at ultrahigh energies, beyond what can be probed in colliders"
(Kolb et al., https://doi.org/10.2172/1659757, 2018)

Motivations

- Strong CP Problem: Axions may be required to make QCD work properly → QCD axions

- In spite of being light, axions (and ALPs) can be CDM, thanks to non-thermal production mechanisms.

- Example of Feebly Interacting Particles (FIPs), expected as a low energy manifestation of BSM theories → ALPs

See effective field theory approach to FIPs e.g. in M. Pospelov talk @ FIPs 2022

Very fruitful research in both theory and experiments, since it requires new approaches and technologies

See FIPs 2022 Report

QCD in a nutshell

See, e.g., Burgess, Ch. 8.1.2

The QCD Lagrangian is

$$L = -\frac{1}{4}G^2 + \bar{q}(i\gamma^\mu D_\mu - m_q)q + \theta\frac{1}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Gluon kinetic term

Quark kinetic and mass term, plus quark gluon interactions

θ-term: Violates CP

For now, let's ignore this term, since it is a total derivative

$$G^{a\mu\nu}\tilde{G}^a_{\mu\nu} = \partial_\mu K^\mu = \partial_\mu \epsilon^{\mu\alpha\beta\gamma}\left(A^a_\alpha G^a_{\beta\gamma} - \frac{g_s}{3}f^{abc}A^a_\alpha A^b_\beta A^c_\gamma\right)$$

Low energy QCD

Burgess, Ch. 8
Schwartz, Ch. 28.2

There are 2 light quarks in QCD, u and d

→ QCD has an *approximate symmetry*: $U(2)_V \times U(2)_A$

corresponding to transformations

$$q \to e^{i(\alpha\cdot\tau+\gamma_5\beta\cdot\tau)}q$$

with $q = (u,d)^T$, $\alpha = (\alpha_0, \vec{\alpha})$ and $\beta = (\beta_0, \vec{\beta})$ are real parameters, and $\tau = (\tau_0, \vec{\tau})$, with $\tau_0 = 1$ the identity and $\vec{\tau}$ the Pauli matrices.

Phenomenologically, we observe that
the $U(2)_V$ part is (approximately) realized, while the $U(2)_A$ must be spontaneously broken.

The Missing Meson Problem

Burgess, Ch. 8
Schwartz, Ch. 28.2

The description of the breaking of $SU(2) \times SU(2) \to SU(2)_V$ from the condensate

$$\left\langle 0 \left| \bar{q}_i q_j \right| 0 \right\rangle = \Lambda^3 \delta_{ij} \neq 0$$

is a great success of the theory since it explains the spectrum of the low mass mesons.

However, the meson associated with the breaking of $U(1) \times U(1) \to U(1)_V$ does not exist. It should be associated with the η' meson. However, as shown by Weinberg in 1975, this meson is too heavy to be the Goldstone associated with the SSB.

This issue is known as the *U(1) problem, or missing meson problem*.

The Missing Meson Problem

The solution of the missing meson problem is to be found in the anomaly of the $U(1)_A$ current.

Quantum corrections → the current associated with the $U(1)_A$ symmetry is not conserved, not even in the chiral limit. For example, the divergence of the current associated with the axial rotation around the up quark is

$$\partial^\mu j_\mu^5 = -2m_u \bar{u}\gamma_5 u + \underbrace{2\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{\mu\nu}_a}$$

Anomaly (emerges at 1 loop)

Known since 1969 !

1. S. L. Adler, Physical Review 177 (5): 2426–2438 (1969)
2. J. S.Bell, R. Jackiw, Il Nuovo Cimento A. 60 (1): 47–61 (1969).

→ Additional term in the action since the path integral measure is not invariant under anomalous transformations.

The θ-term

Remember what we wrote before. The QCD Lagrangian is

$$L = -\underbrace{\frac{1}{4}G^2}_{\text{Gluon kinetic term}} + \underbrace{\bar{q}(i\gamma^\mu D_\mu - m_q)q}_{\text{Quark kinetic and mass term, plus quark gluon interactions}} + \overbrace{\theta \frac{1}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}}^{\theta\text{-term: Violates CP}}$$

θ-term: Violates CP

Gluon kinetic term

Quark kinetic and
mass term, plus quark
gluon interactions

The $\theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$ term is a total derivative. However, there are configurations which contribute to the action integral. These are called **instantons** ⇒ this term cannot be thrown away and has phenomenological consequences.

One consequence is to give mass to the η' meson. In fact, all the terms which explicitly break the symmetry (so, both mass term and anomaly term) contribute to the mass of the Goldstone boson.

For the math inclined, beautiful relation with topology. See, e.g., Coleman, Aspects of Symmetry

The θ-term

See, e.g., Schwartz, Ch. 30.5.2

It is hard to calculate the η' mass. One method is lattice.

Veneziano and Witten (1979) showed that the η' mass is related to the topological susceptibility $\chi_t \equiv \left\langle \left(G\tilde{G}\right)\left(G\tilde{G}\right)\right\rangle$ as

$$\chi_t = \frac{f_\pi^2}{12}\left(m_\eta^2 + m_{\eta'}^2 - 2m_K^2\right)$$

→ if $G\tilde{G}$ had no effect then $\chi_T = 0$ and the η' mass would be small. In particular, in the chiral limit $m_\eta, m_K \to 0$ one would find also $m_{\eta'} = 0$.

→ The experimental evidence that η' is not a Goldstone boson (it is "heavy") suggests that the instantons do play a role in QCD.

The θ-term

- The vacuum energy depends on θ
  It is minimized for $\theta = 0$

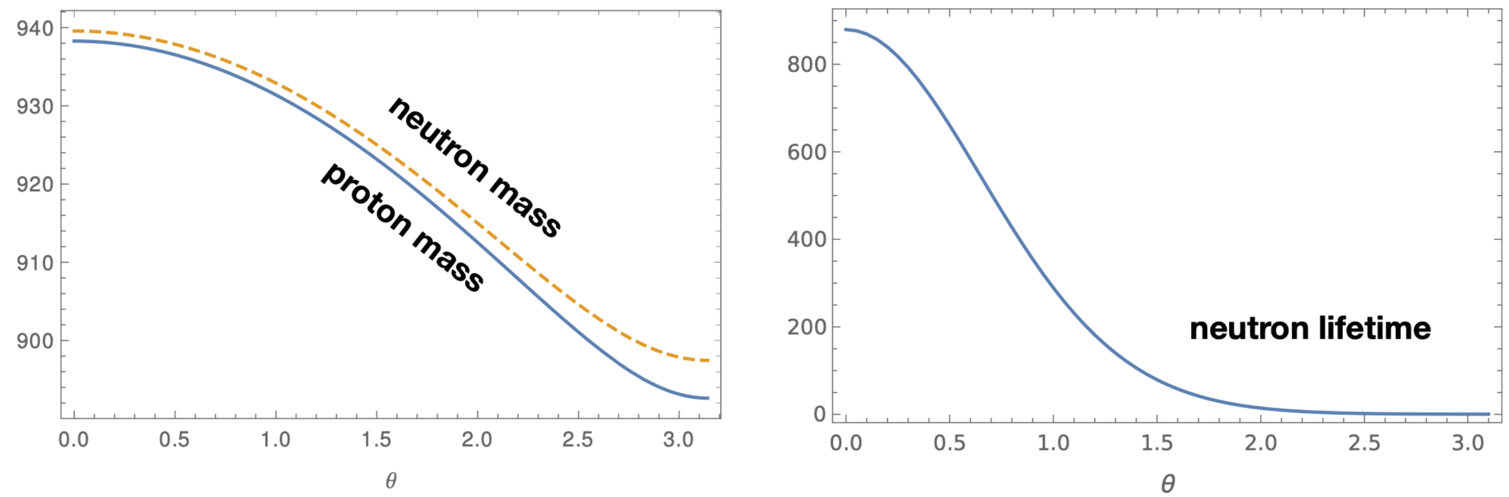
C. Vafa, E. Witten, Phys. Rev. Lett. 53 (1984) 535

- The nucleon masses depend on θ
  $\Rightarrow$ the neutron lifetime $\Rightarrow$ nucleosynthesis depend on theta.

- L. Ubaldi, Phys. Rev. D81 (2010) 025011
- M. Dine, L. Stephenson Haskins, L. Ubaldi, D. Xu,JHEP 05 (2018) 171

$$m_n - m_p \simeq \left(1.29 + 0.21\,\theta^2 + \mathcal{O}(\theta^4)\right)\,\mathrm{MeV}$$

- Lee, Meißner, Olive, Shifman, Vonk, Phys.Rev.Res. 2 (2020) 3, 033392 (2020)



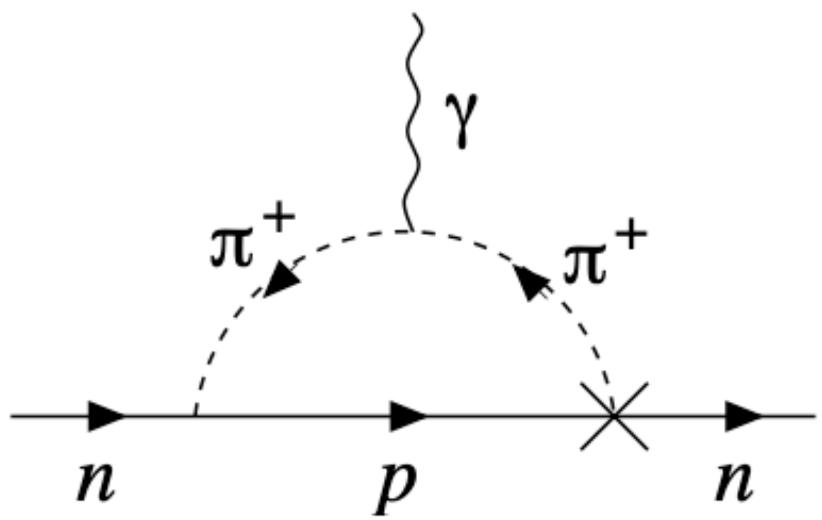
See Nick Houston talk at
→ Axions beyond boundaries, GGI-2023

The θ-term and Strong CP

The θ-term generates a neutron EDM

M. Pospelov, A. Ritz (2020)

$\rightarrow \quad d_n \approx 2.4(1.0) \times 10^{-16}\, \theta\, e \cdot \text{cm}$



This gives the strongest constraint

See PhD dissertation by Drew Backhouse, University of Oxford (2021), arXiv:2108.04285, for a pedagogical introduction

The latest experimental search found

$$\left| d_n^{\text{exp}} \right| < 1.8 \cdot 10^{-26} e \text{ cm} \quad (90\,\%\text{ CL}) \quad \Rightarrow \quad \theta \lesssim 10^{-10}$$

Strong CP Problem

Abel et al., Phys.Rev.Lett. 124 (2020) 8, 081803

How can we solve the Strong CP Problem?

$$L = -\frac{1}{4}G^2 + \bar{q}(i\gamma^\mu D_\mu - m_q)q + \theta\frac{1}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Here is the problem

What we need is a *symmetry which is exact except for a shift in the action*

$$S \rightarrow S + \frac{\alpha}{32\pi^2}\int d^4x G\tilde{G}$$

→ This symmetry can be used to rotate away the θ-term,

⇒ the θ-term becomes unphysical (→ no observable can depend on θ)

Massless Quark Solution

Suppose that one quark (say, the up) has zero mass.

$\Rightarrow$ $u \to e^{i\alpha\gamma_5}u$ is a symmetry of the action
except for a change in the path integral measure

$\Rightarrow$ use $u \to e^{i\alpha\gamma_5}u$ to remove the θ-term,
(through the change in the path integral measure)

Note: this symmetry would be spontaneously broken by $\langle \bar{u}u \rangle \neq 0$
$\rightarrow$ there would be an associated Goldstone boson, the η'.

Clarification: The η' would still be heavy, since it would receive contributions from the $G\tilde{G}$ terms (Witten-Veneziano result). In other words, the U(1) problem is still solved.

However, **the zero quark solution is essentially ruled out!**

→ *See some proposals for dedicated tests (R. Kitano) and calibrations (Dine, Draper, Festuccia)*

In particular,

→ *See M. Dine Lectures at Axions Beyond Boundaries, (2023)*

Adding another massless quark *by hand* would not work: it would change dramatically the hadron spectrum

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$$L = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \bar{q}\,(i\gamma^\mu D_\mu - \bar{q}Me^{i\theta_q\gamma_5})\,q - \theta\frac{1}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

If quarks have masses, then the chiral rotation may eliminate the θ-term but only to move it in the quark mass matrix.

$\Rightarrow$ θ is physical unless at least one quark is massless

$$q \to e^{i\alpha\gamma_5} q \Rightarrow$$

$$\begin{cases} \theta_q \to \theta_q + 2\alpha \\ \theta \to \theta - 2\alpha \end{cases}$$

Peccei-Quinn Solution

Very similar to the $m_u = 0$ solution. However, the new axial symmetry is added *by hand:*

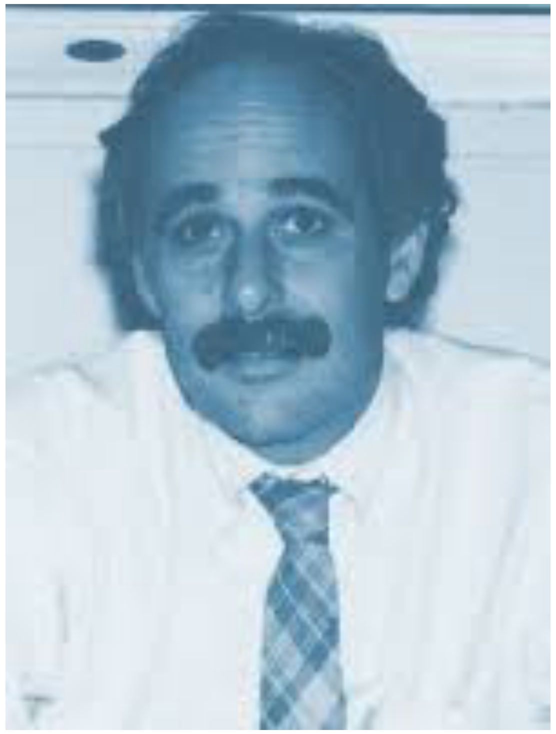
New $U(1)_{PQ}$, spontaneously broken at some energy scale.

The associated Goldstone boson, the axion, has a Lagrangian

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

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

θ is promoted to a dynamical field, the axion



Peccei and Quinn solution:
θ is dynamical → Settles to 0
(Vafa-Witten theorem)

Peccei, Quinn (1977)

The Axion

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

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

Axion

Note the need for a new energy scale, f_a, from a pure dimensional argument.

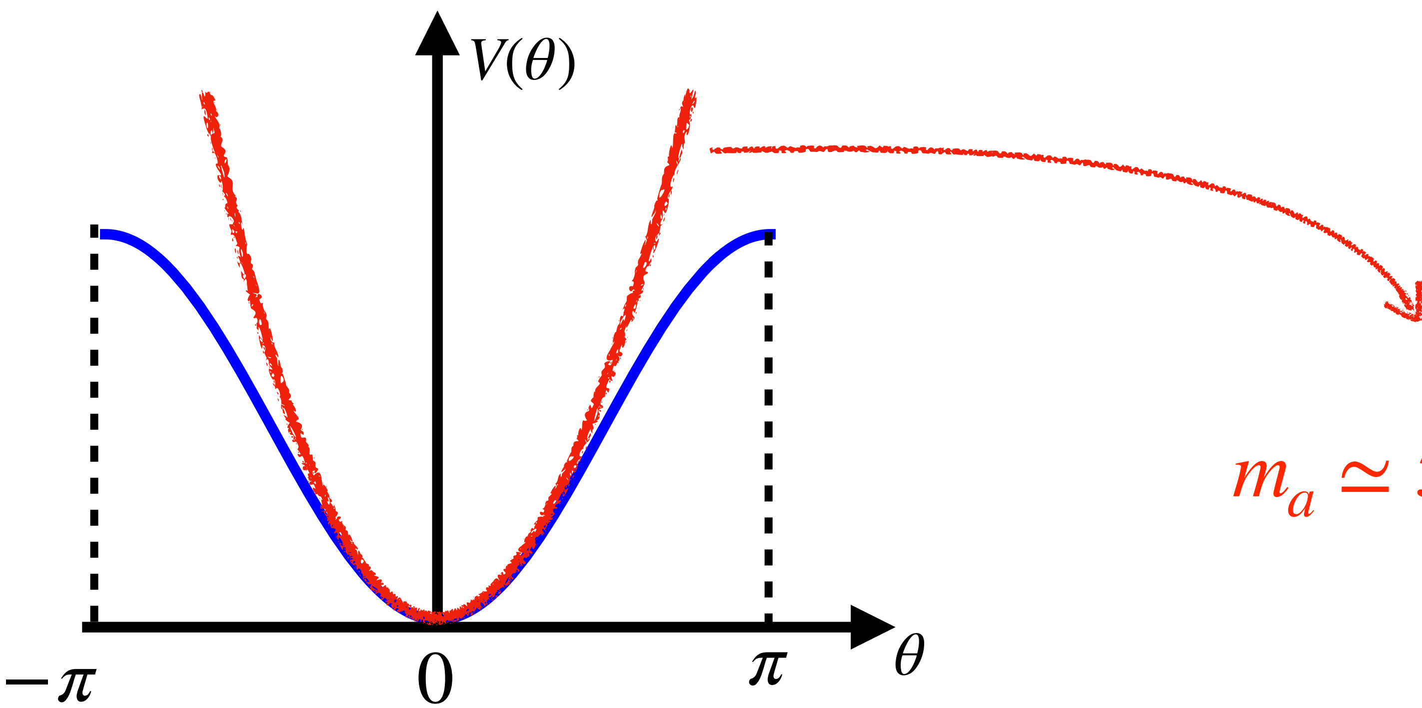
This is related (but not necessarily equal to) the scale at which $U(1)_{PQ}$ is spontaneously broken.

S. Weinberg Phys. Rev. Lett. 40 (1978) 223-226;

F. Wilczek Phys. Rev. Lett. 40 (1978) 279–282

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)

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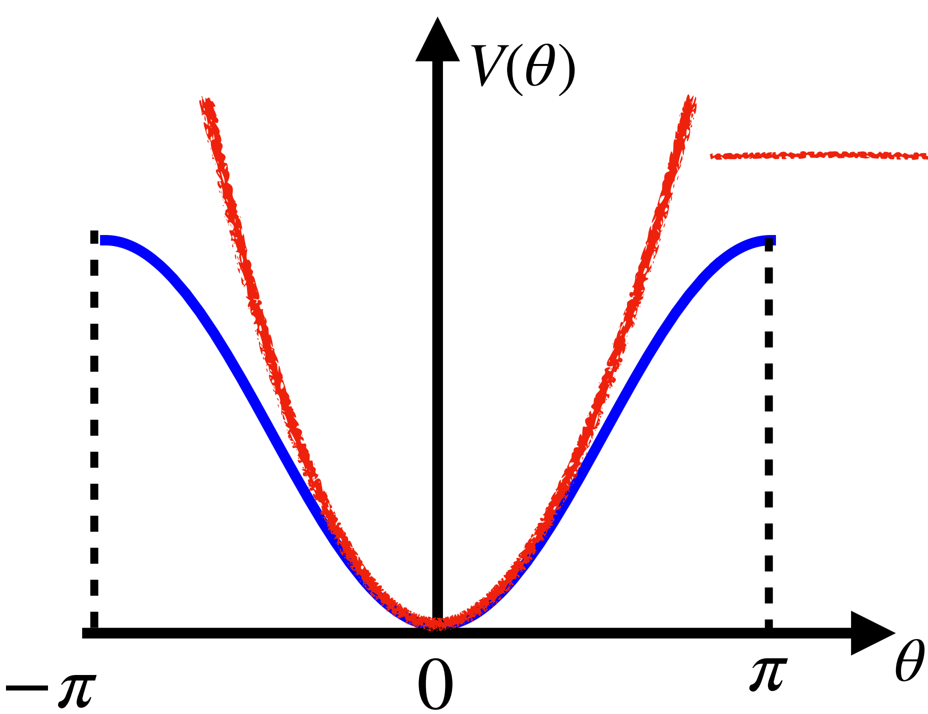

Axions can get mass only from terms that break explicitly the PQ symmetry. The only thing that does that is the anomaly. So, the axion mass can only come from $G\tilde{G}$.

Not surprisingly, the resulting mass term is related to the topological susceptibility χ_T, just like in the case of the η'.

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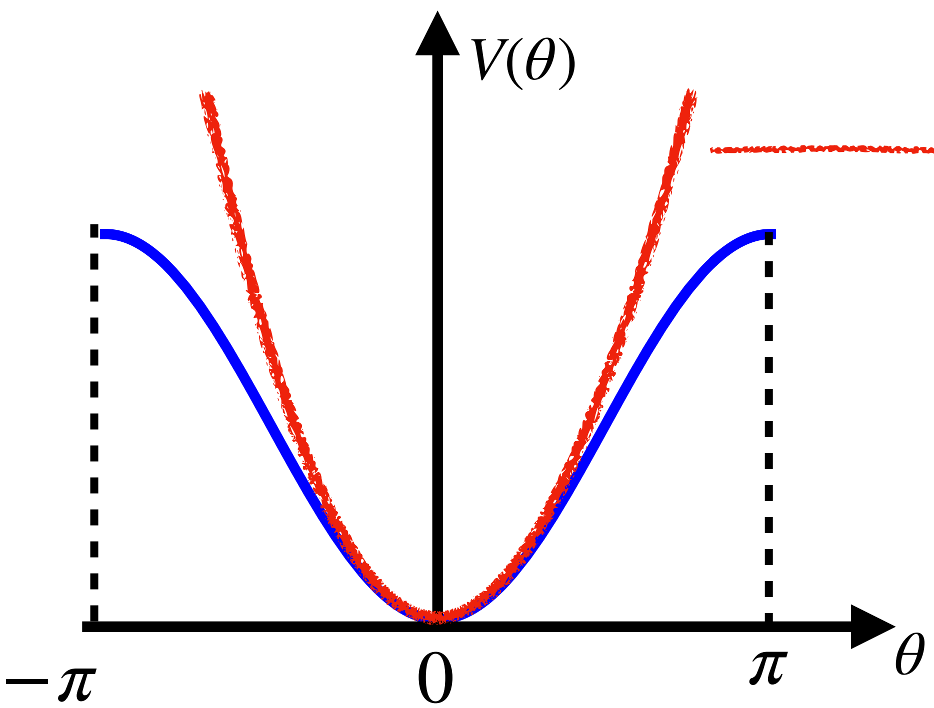

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Relaxing the $m_a - f_a$ relation requires substantial changes to QCD, for example the addition of a new QCD sector. This is all theoretically possible. However, here we will disregard this possibility for now. See sec. 6.6.2 of L. Di Luzio, M.G., Nardi, Visinelli, Phys.Rept. 870 (2020) for some options.

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.

There are 2 sources for the axion couplings:

- The model independent $aG\tilde{G}$ coupling; it generates couplings to quarks and photons. Not to electrons (at tree level)

- Model dependent contributions from the specific UV completion

Some facts about QCD Axions

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

Photons

Fermions (electrons, nucleons)

Spin-density coupling with matter

Two photon coupling of the form $a\mathbf{E}\cdot\mathbf{B}$, from electromagnetic anomaly

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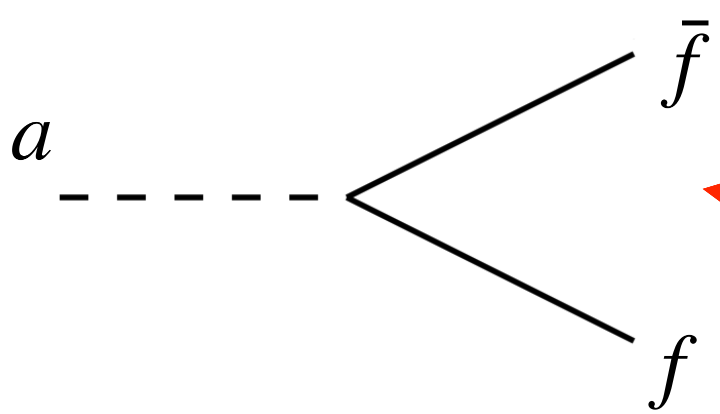

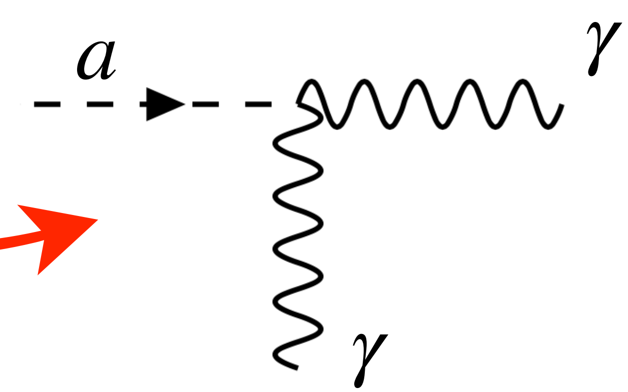

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f_a suppression (Remember $m_a \propto 1/f_a$)

In general: light ↔ weakly coupled

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

… in principle, the coupling to fermions can be significantly reduced: $C_{af} \to 0$.

However, difficult for C_{aN}

- Di Luzio, Mescia, Nardi, Panci, Ziegler, Phys.Rev.Lett. 120 (2018)
- M. Badziak, K. Harigaya, arXiv:2301.09647 (2023);
- F. Takahashi, W. Yin, arXiv:2301.10757 (2023)

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$$C_{a\gamma} = \frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_u + m_d} = \frac{E}{N} - 1.92(4)$$

Model dependent contribution

Model independent contribution

… The coupling to photons is also model dependent and can (in principle) be tuned to $C_{a\gamma} \ll 1$

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

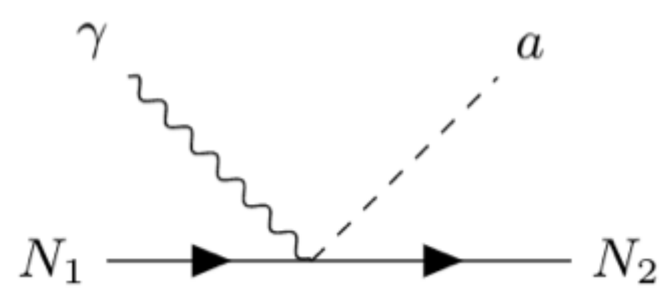
$$L_{int} \supset -\frac{i}{2} g_{dN}\, a\, \bar{n}\, \sigma_{\mu\nu}\gamma_5\, n\, F^{\mu\nu}$$

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

Stellar production (SN bound):

$$\Rightarrow \quad g_{dN} \leq 8 \cdot 10^{-6}\, \mathrm{GeV}^{-2}$$

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



G. Lucente et al., Phys.Rev.D 105 (2022) 12

Some facts about QCD Axions

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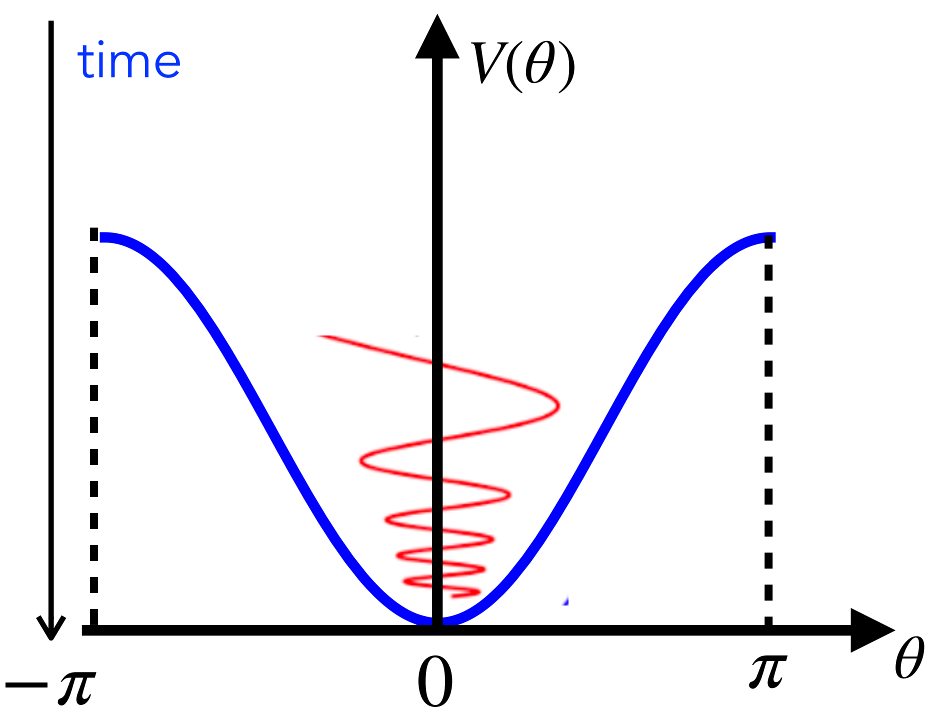
3- Required interaction with nEDM

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

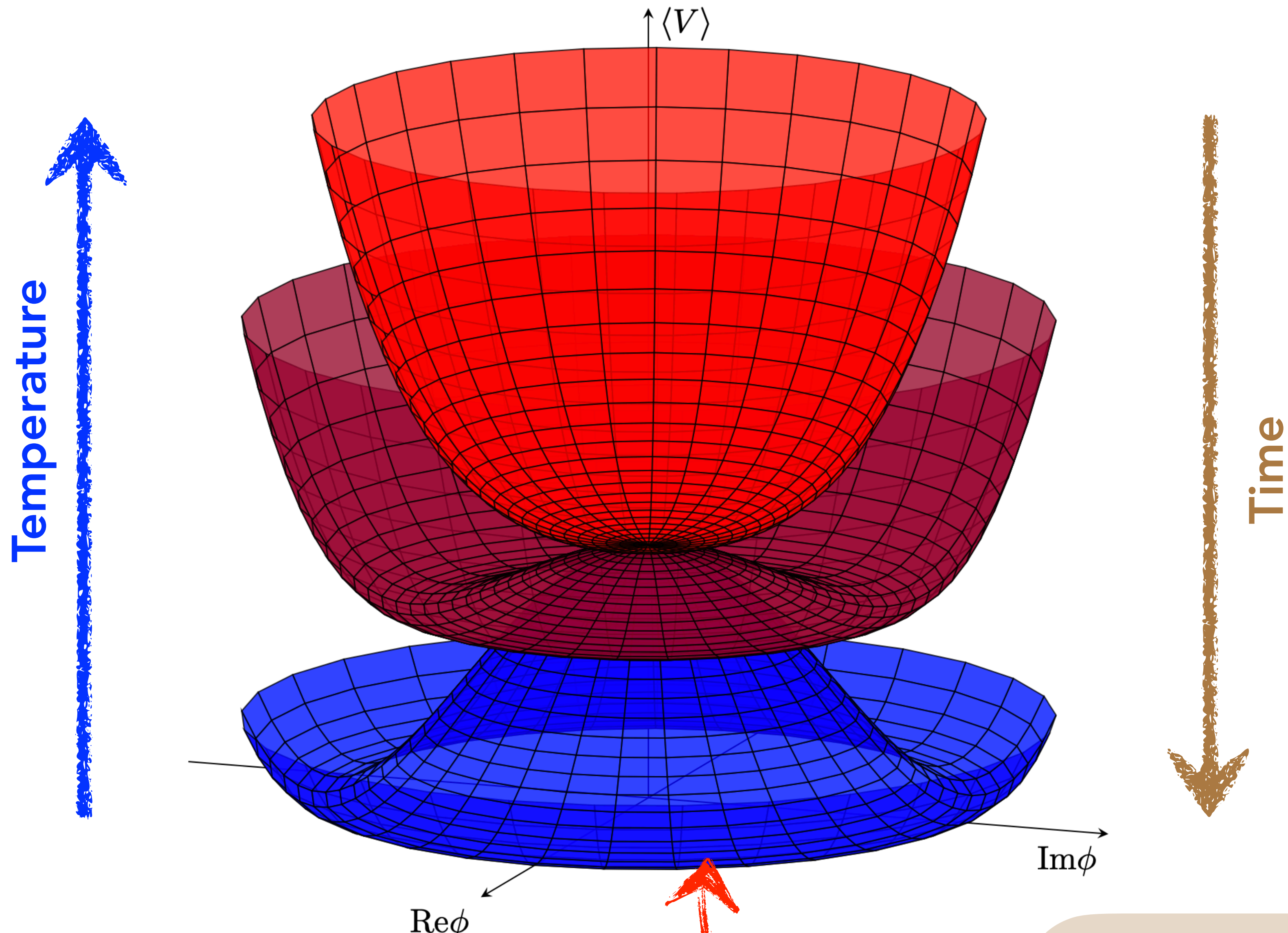


Figure from Francesco Schiavone (unpublished)

At low enough temperature the PQ symmetry is spontaneously broken.

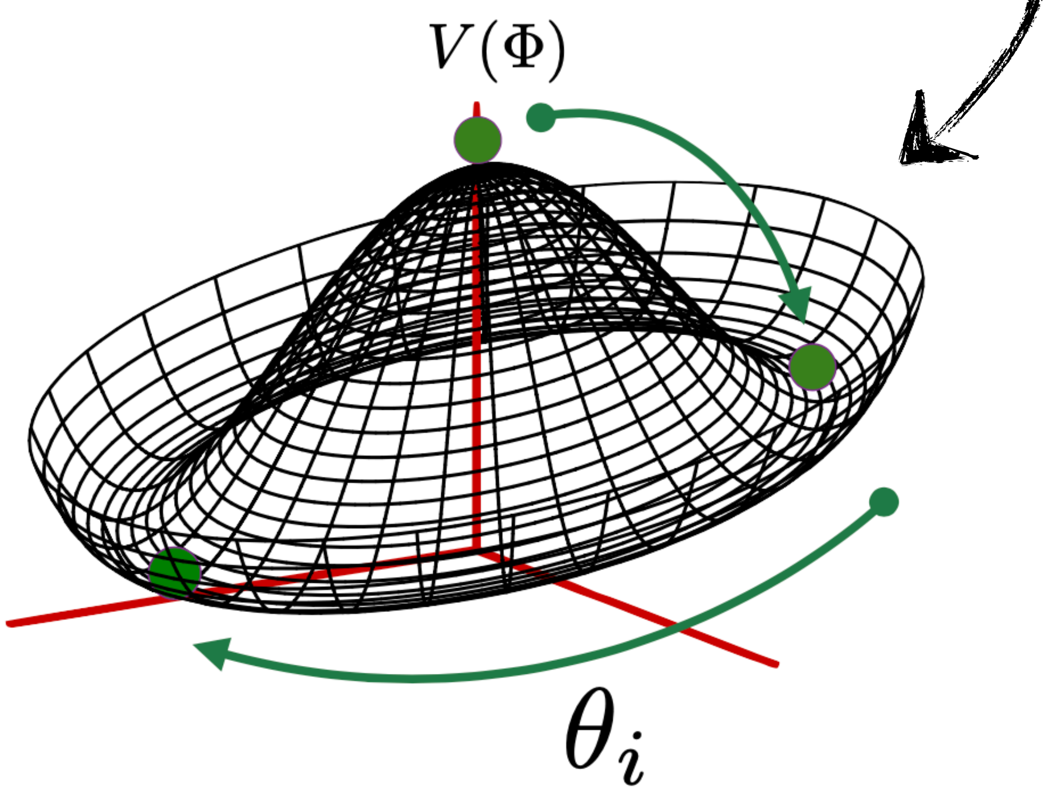
The axion emerges from the phase of the scalar field

$$\phi = \frac{1}{\sqrt{2}} \left(v_a + \rho\right) e^{ia/v_a}$$

After PQ is spontaneously broken, the θ angle is randomly selected. The axion is the massless d.o.f. in the flat direction of the potential

Axion Misalignment Production

The QCD axion potential "tilts" the Mexican hat potential of ϕ .



Figures from OHare (2022)

→ Equation of motion

$$\ddot{a} + 3\frac{\dot{R}}{R}\dot{a} - \nabla^2 a + \frac{\partial}{\partial a}V(\theta) = 0$$

Close to the minimum of V

$$V \simeq \frac{1}{2}\chi_T\theta^2 + \ldots = \frac{1}{2}m_a^2 a^2 + \ldots$$

$$\ddot{a} + 3H\dot{a} - \nabla^2 a + m_a^2 a = 0$$

damped harmonic oscillator

Axion Misalignment Production

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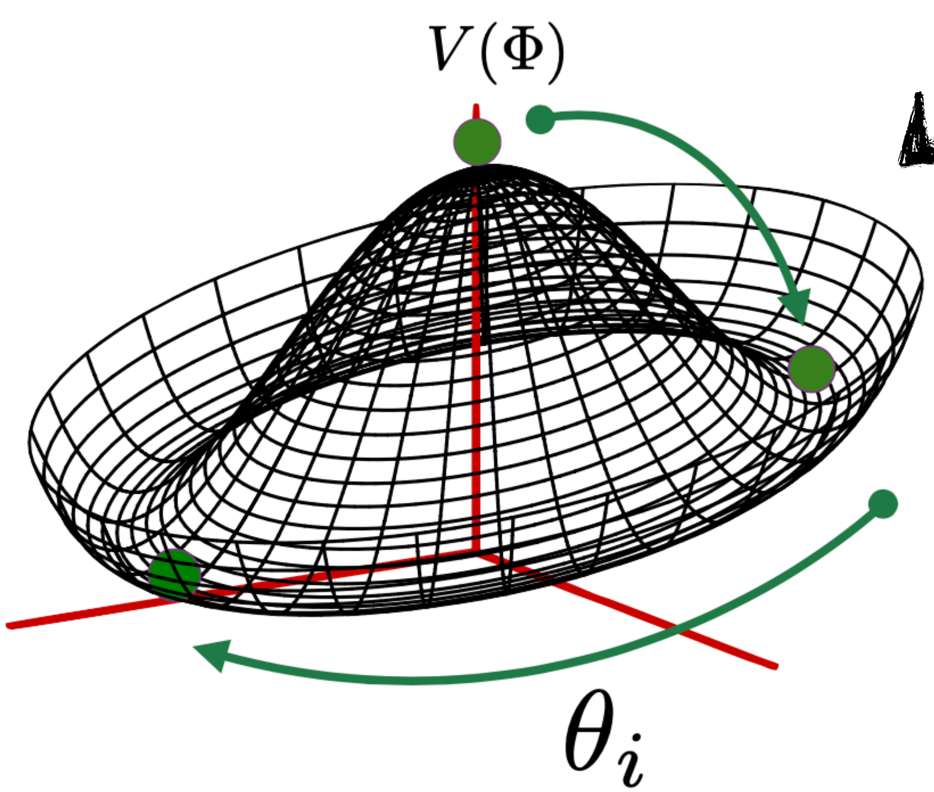
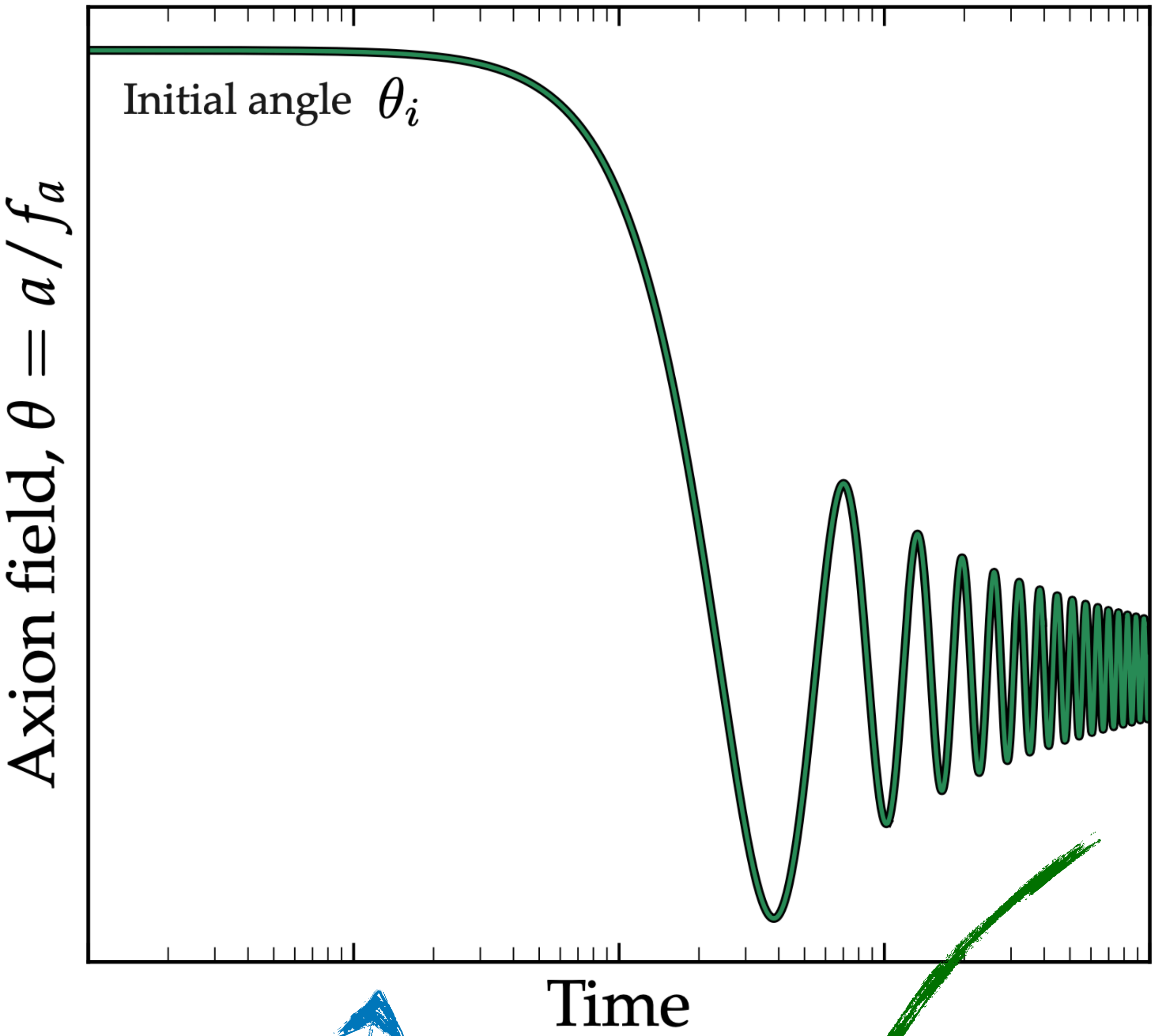


Figures from [OHare (2022)]

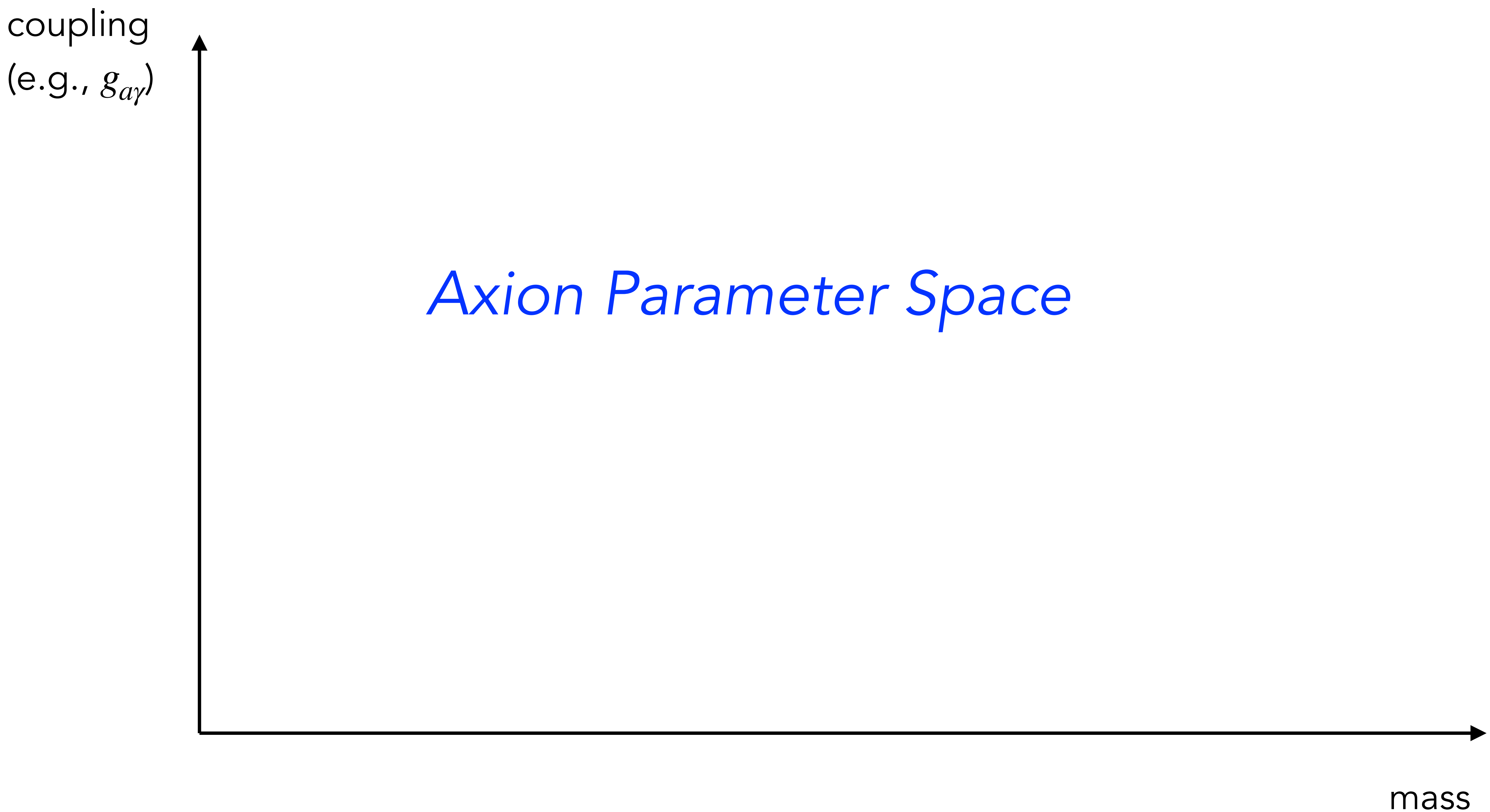


At $T \sim$ GeV, the axion mass overcomes the Hubble rate and the axion field starts oscillating around the minimum of the potential.

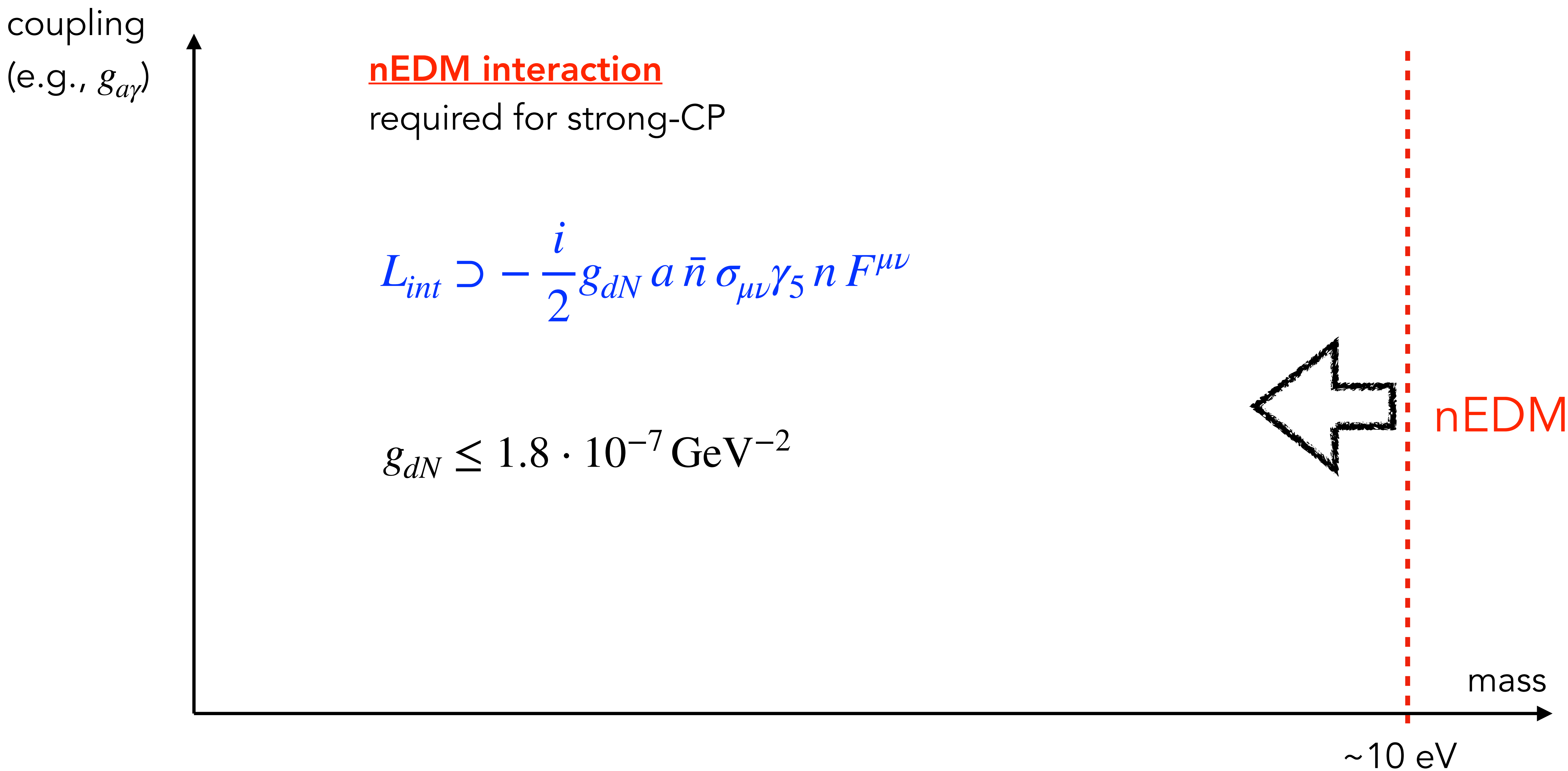
Amount of DM $\propto \theta_i^2 m_a^{-7/6}$

So, where are the axions?

So, where are the axions?



The axion parameter space



nEDM interaction

required for strong-CP

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

$$g_{dN} \leq 1.8 \cdot 10^{-7}\,\mathrm{GeV}^{-2}$$

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The axion parameter space

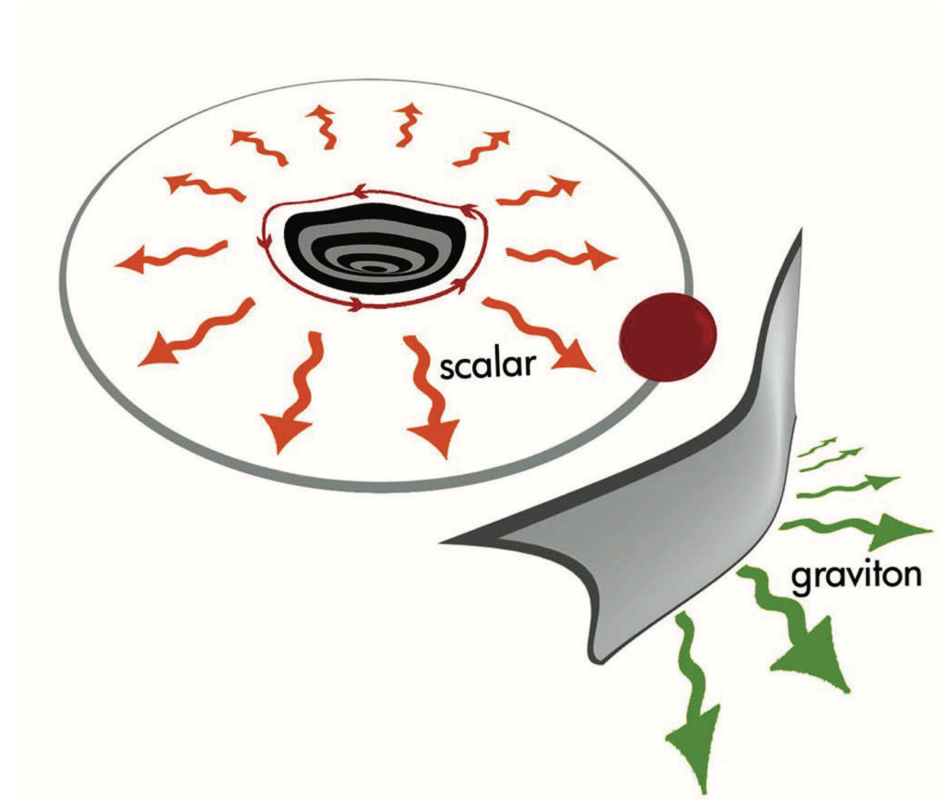
coupling
(e.g., $g_{a\gamma}$)

Gravitational interaction

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

$\sim 10^{-11}$ eV

mass

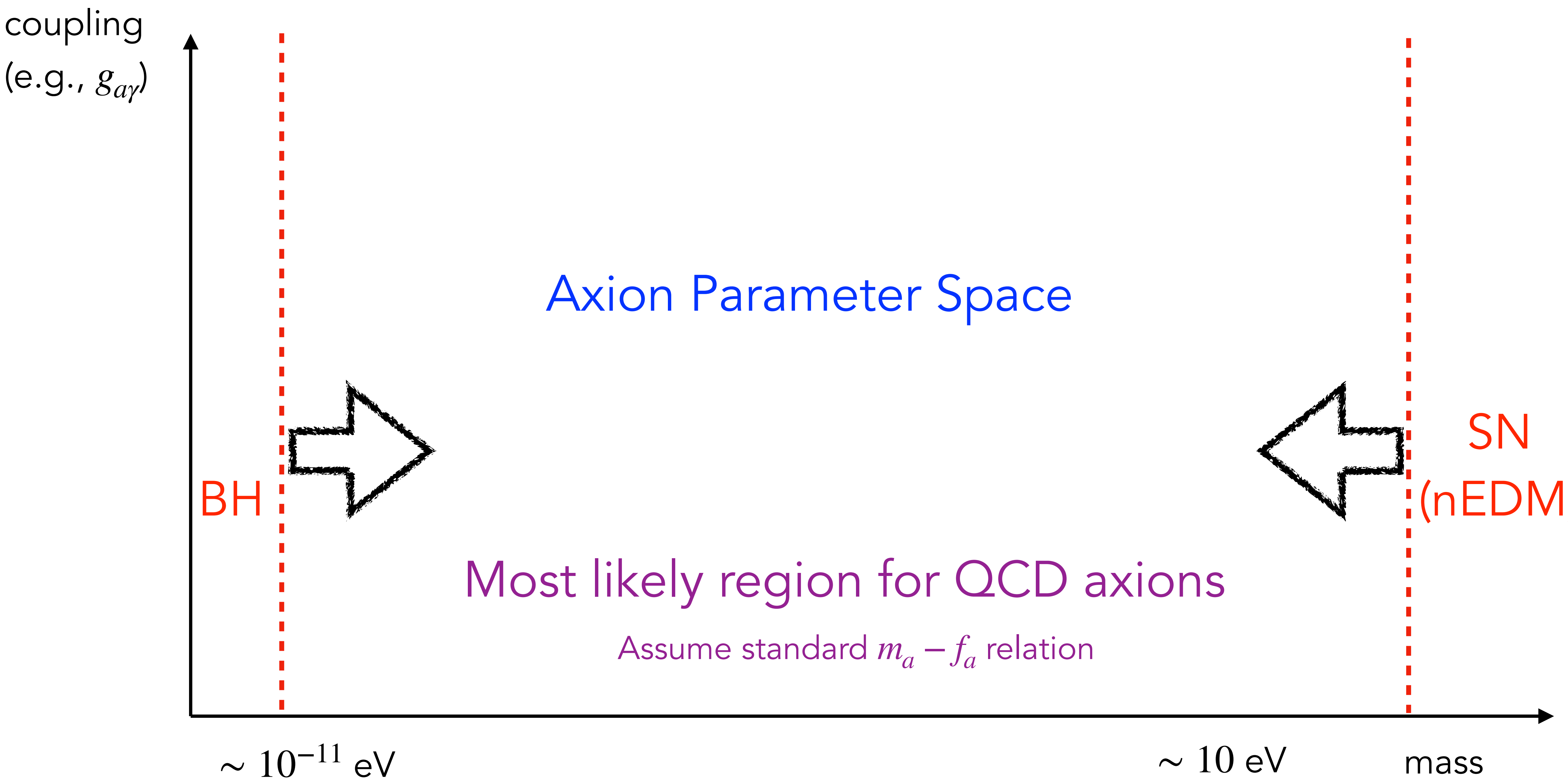


Brito, Cardoso, Pani, arXiv:1501.06570;

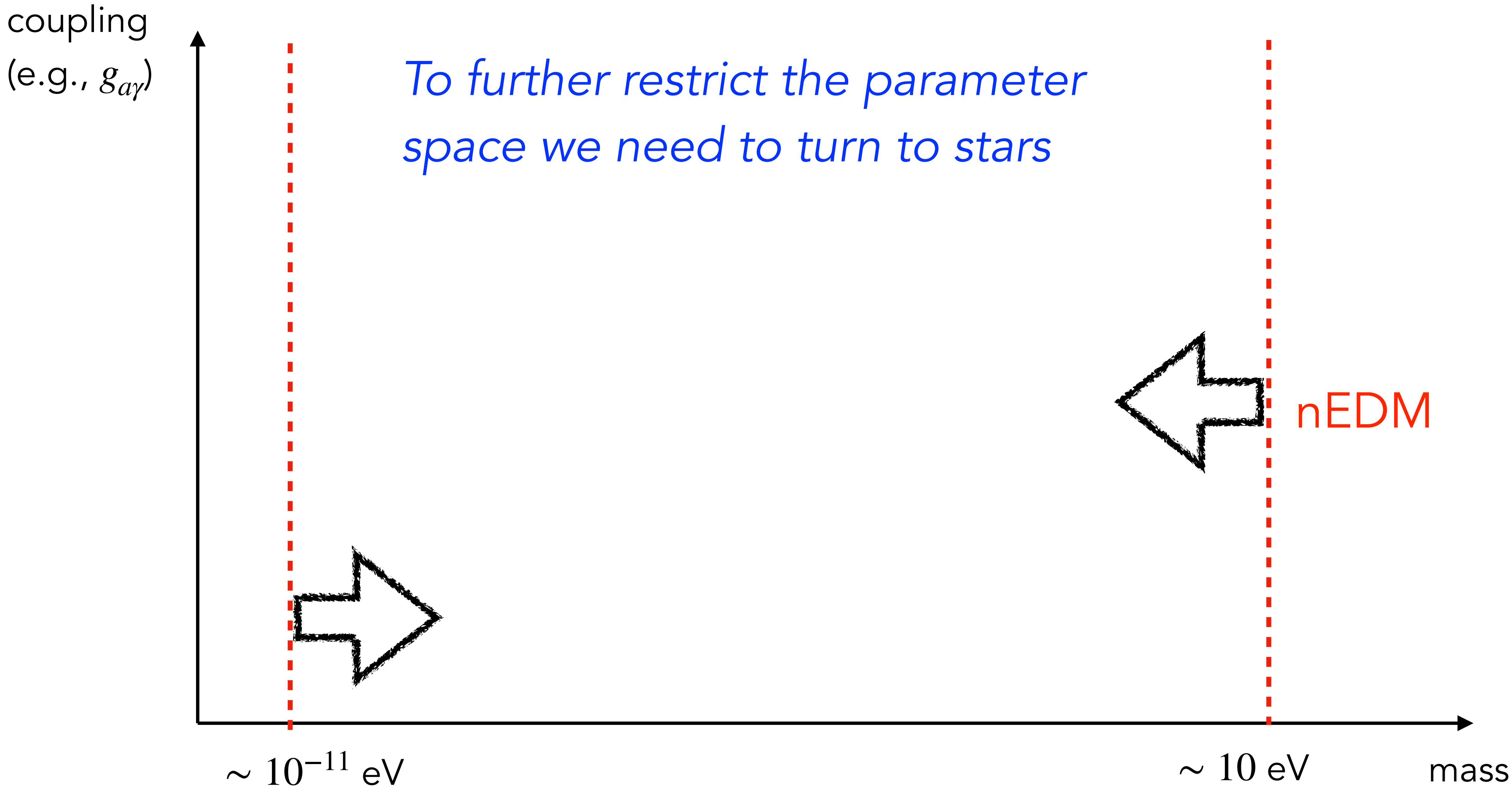
Arvanitaki, Baryakhtar, Huang, Phys.Rev.D 91 (2015) 8

Black hole superradiance. Potential GW detection.
Very active research field

Where are the axions?

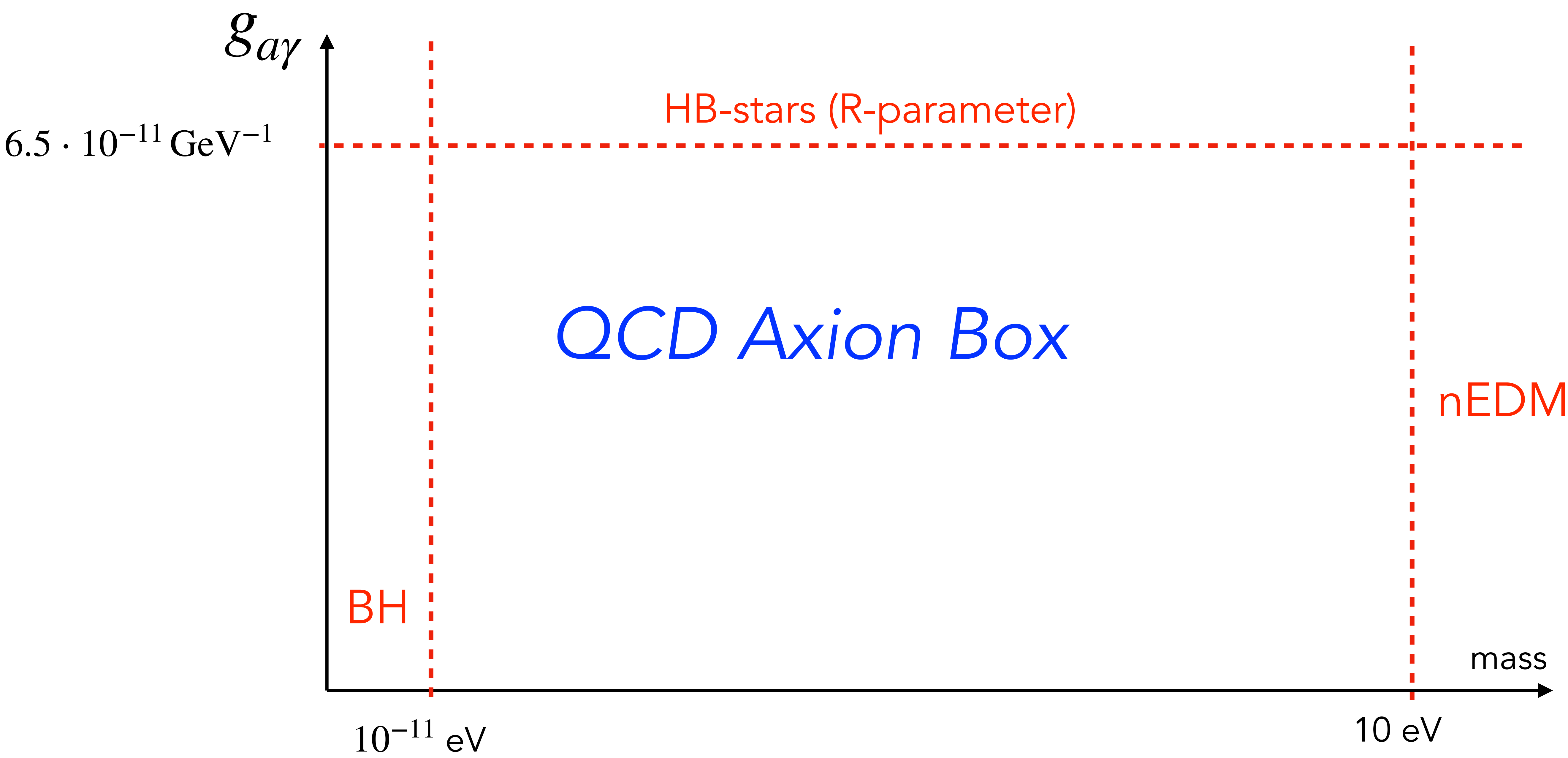


Where are the axions?



To further restrict the parameter space we need to turn to stars

The axion parameter space



Cosmology as a guiding principle in the Axion Box

Unexpected and unavoidable consequence of the PQ mechanism:

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

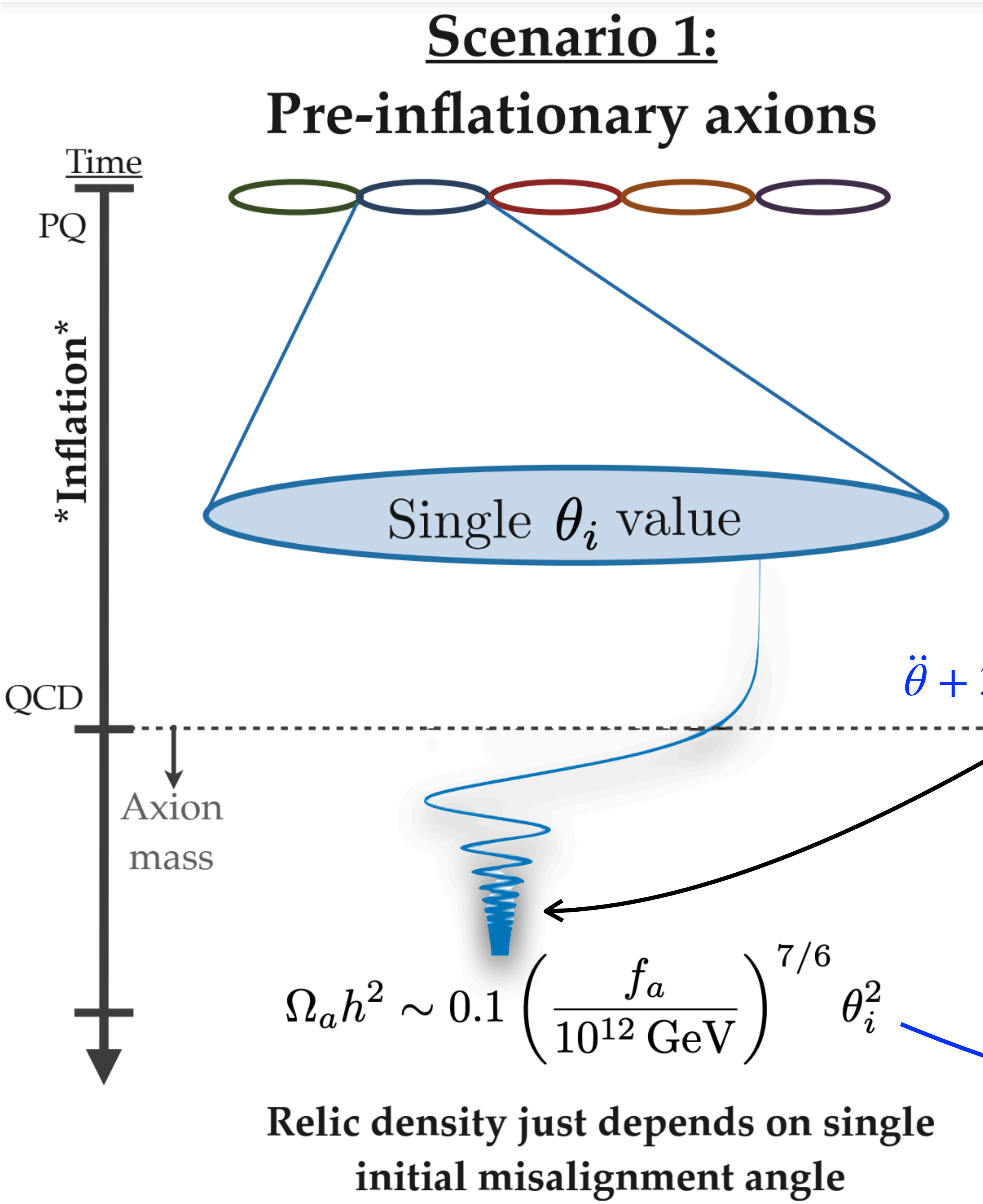
Preskill, Wise and Wilczek (1983)

Abbott and Sikivie (1983)

Dine and Fischler (1983)

Can cosmology help select motivated sections of the parameter space?

Axion Dark matter: Pre-inflationary scenario

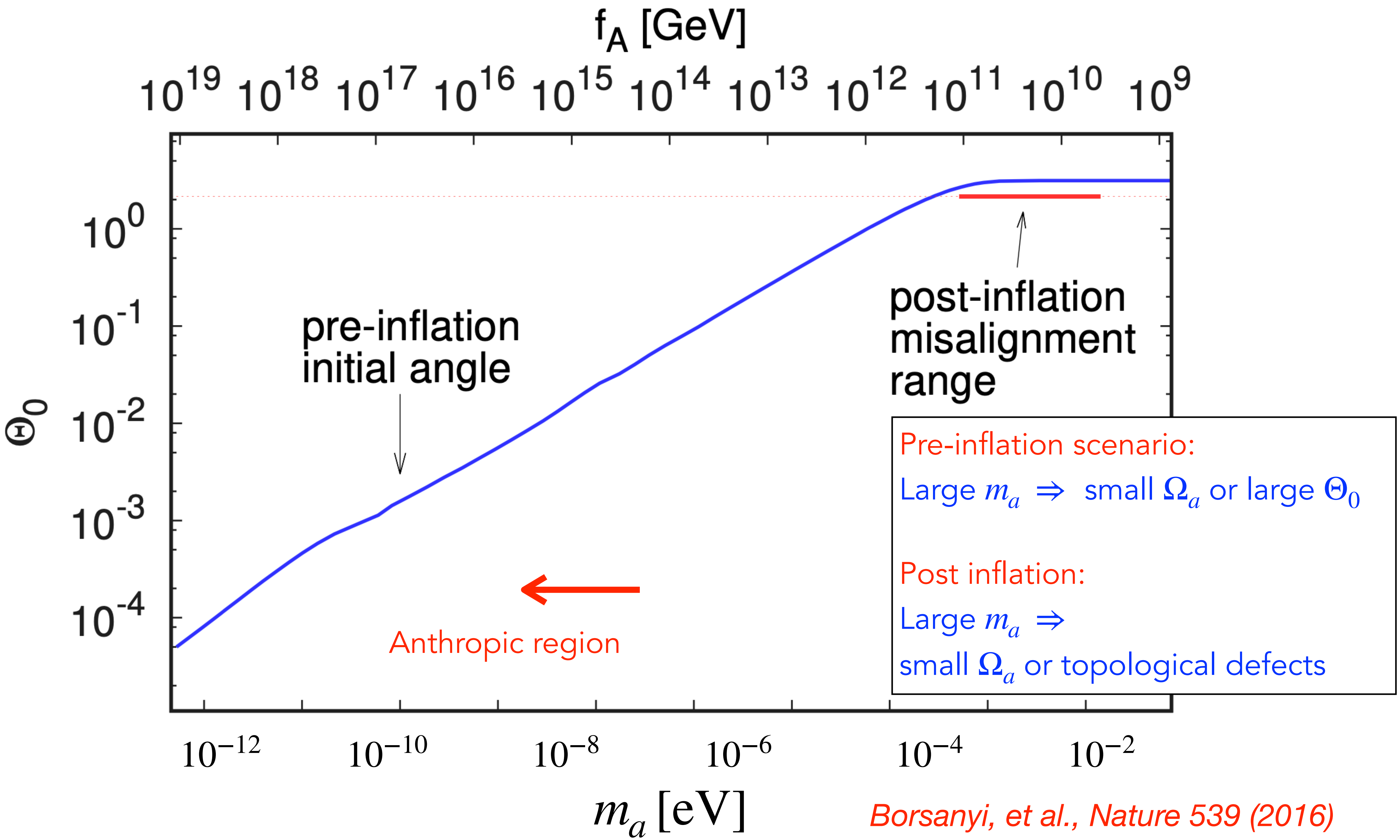


$$\ddot{\theta} + 3H\dot{\theta} + m_a^2 \sin\theta = 0$$

Calculable axion abundance but unknown initial conditions

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

Axion Cosmology



Borsanyi, et al., Nature 539 (2016)

Axion Dark matter: Post-inflationary scenario

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., *Nature Commun.* 13 (2022) 1, 1049.

Still controversial. More work required.

- M. Gorghetto, E. Hardy, arXiv:2212.13263
- O'Hare, Pierobon, Redondo, Wong, Phys.Rev.D 105 (2022)
- M. Gorghetto, E. Hardy, G. Villadoro, SciPost Phys. 10, 050 (2021)

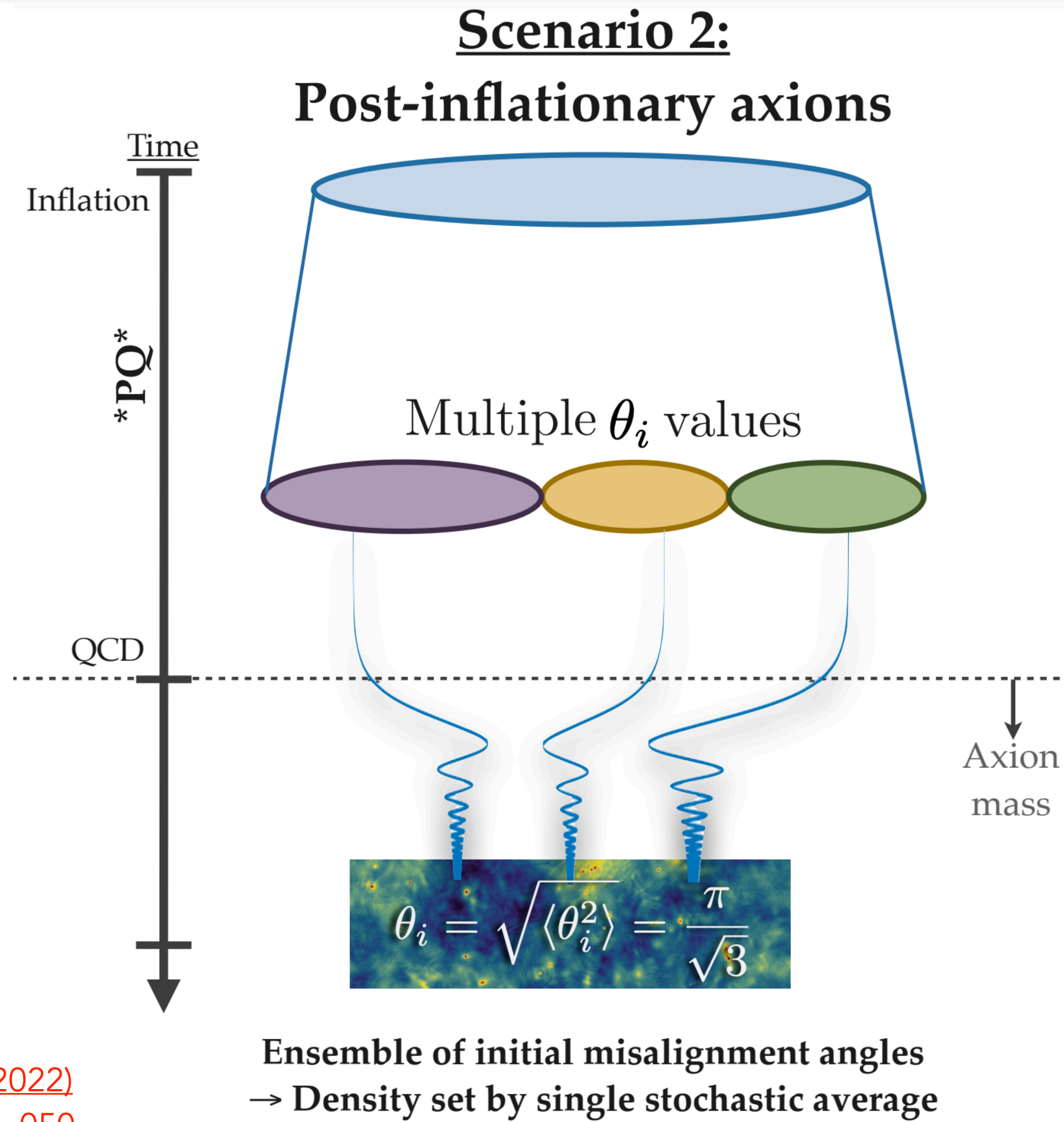
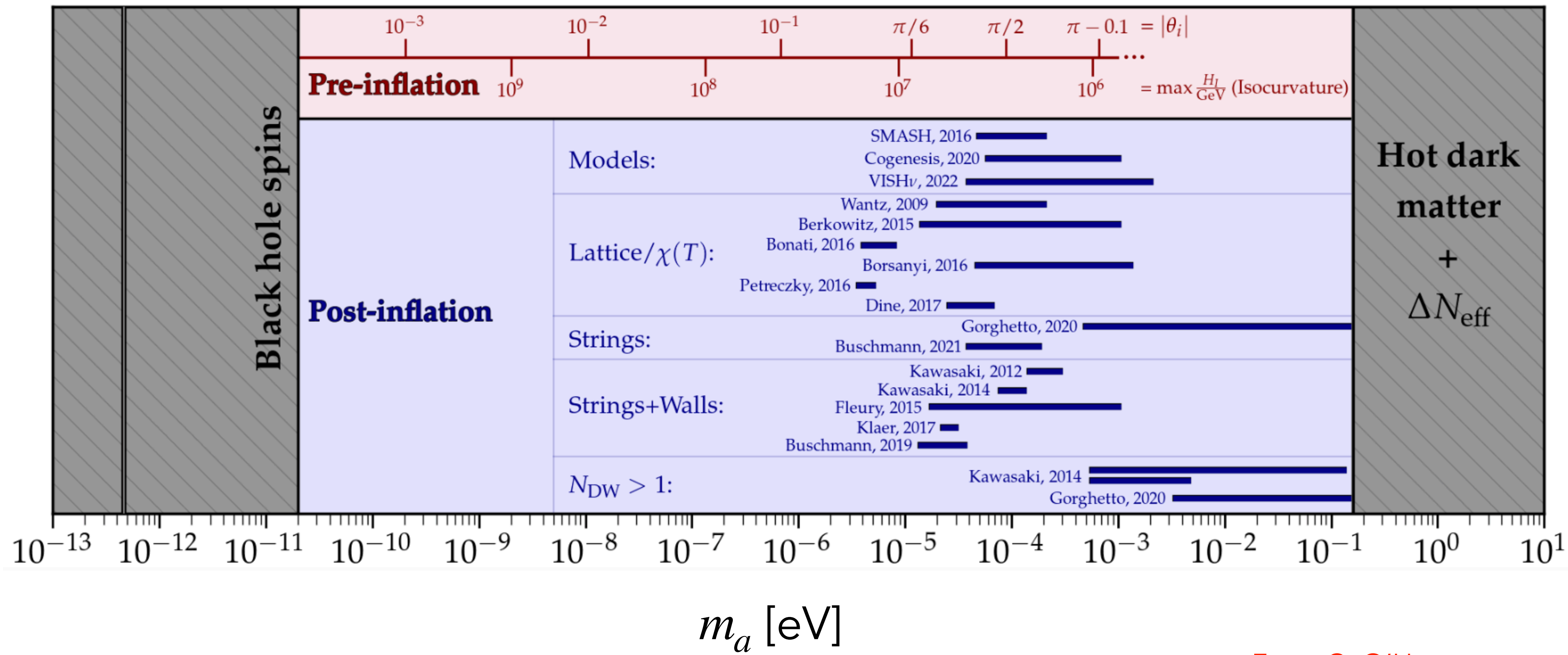


Figure Credits: C. O'Hare (2021)
https://cajohare.files.wordpress.com/2021/10/axions.pdf

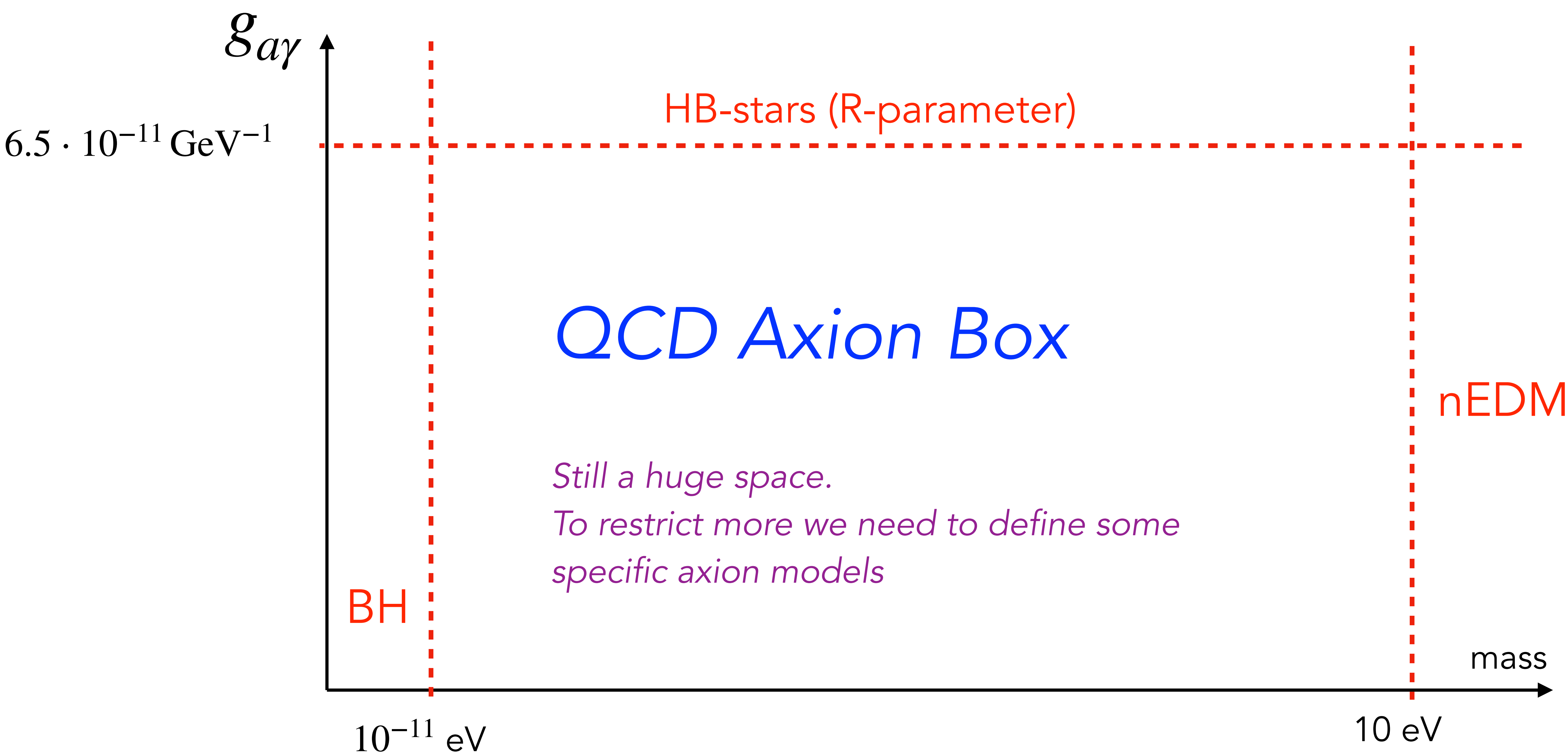
Dark Matter Mass Predictions



From C. O'Hare

Predictions in post-inflation point at $m_a \gtrsim \mu\text{eV}$

The axion parameter space



Benchmark Axion Models: KSVZ

Ingredients (Beyond SM):

- Heavy (colored and PQ charged) fermion fields Q
- a singlet (PQ charged) scalar field Φ

The scalar field has a Mexican Hat potential which features a SSB.

The axion emerges from the phase of the scalar field

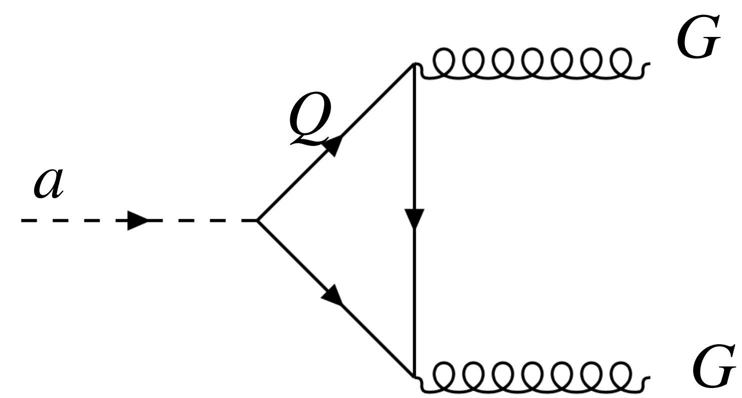
$$\Phi = \frac{1}{\sqrt{2}} \left(v_a + \rho \right) e^{ia/v_a}$$

Axion electron coupling emerges only at loop level
→ it is suppressed.

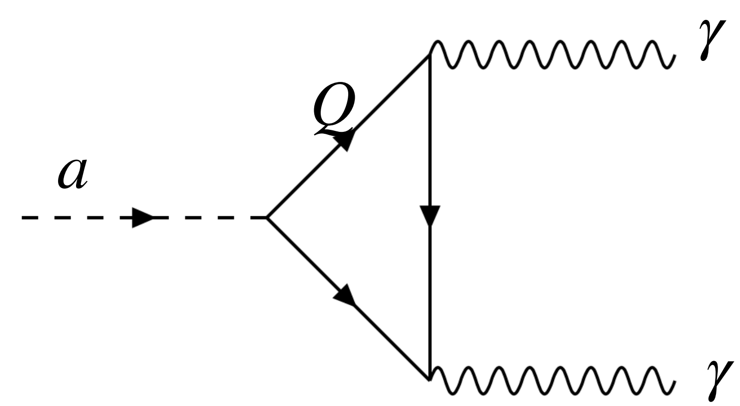
For this reason, it is also called **hadronic axion**.

Benchmark Axion Models: KSVZ

The required **coupling to Gluons** (color anomaly) is generated by the heavy quarks

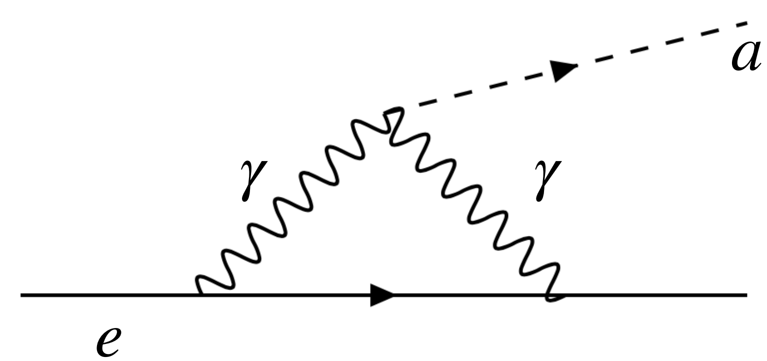


This coupling, in turn, generates a **coupling with the quarks,** and hence to **nucleons**



The **coupling with photons** is generated by the electromagnetic anomaly

There is no tree-level **coupling with leptons**. This coupling can be generated at loop level, though the axion-photon coupling



Benchmark Axion Models: DFSZ

Ingredients (Beyond SM):

- An additional Higgs field. Hence, this model features two Higgs fields, with VEV v_u and v_d, with $v_{\rm ew} = \sqrt{v_u^2 + v_d^2}$

- a singlet (PQ charged) scalar field Φ

The axion emerges from a combination of the phases of the scalar and the two Higgs fields

There are **tree level couplings with photons, hadrons and leptons**.

There is an additional parameter, which plays a significant role:

$$\tan\beta = \frac{v_u}{v_d}$$

The leptons can be getting mass from either Higgs.
This distinguishes two submodules: DFSZ 1 and DFSZ 2.

Minimal Field Axion Model Extension

Hadronic (KSVZ-like):	Non hadronic (DFSZ-like):
Heavy fermion + a new scalar field.	2 Higgs fields + a new scalar field.
Couplings to electrons: NO Coupling to nucleons: YES Coupling to Photons: YES	Couplings to electrons: YES Coupling to nucleons: YES Coupling to Photons: YES

J. E. Kim, Phys. Rev. Lett. 43 (1979) 103

M. A. Shifman, A. I. Vainshtein, V. I. Zakharov, Nucl. Phys. B166 (1980) 493

A. R. Zhitnitsky, Sov. J. Nucl. Phys. 31 (1980) 260

M. Dine, W. Fischler, M. Srednicki, Phys. Lett. B104 (1981)

L. Di Luzio, F. Mescia, E. Nardi, P. Panci, and R. Ziegler, Phys. Rev. Lett. 120 no. 26, (2018)

F. Bjorkeroth, L. Di Luzio, F. Mescia, and E. Nardi, JHEP 02 (2019) 133

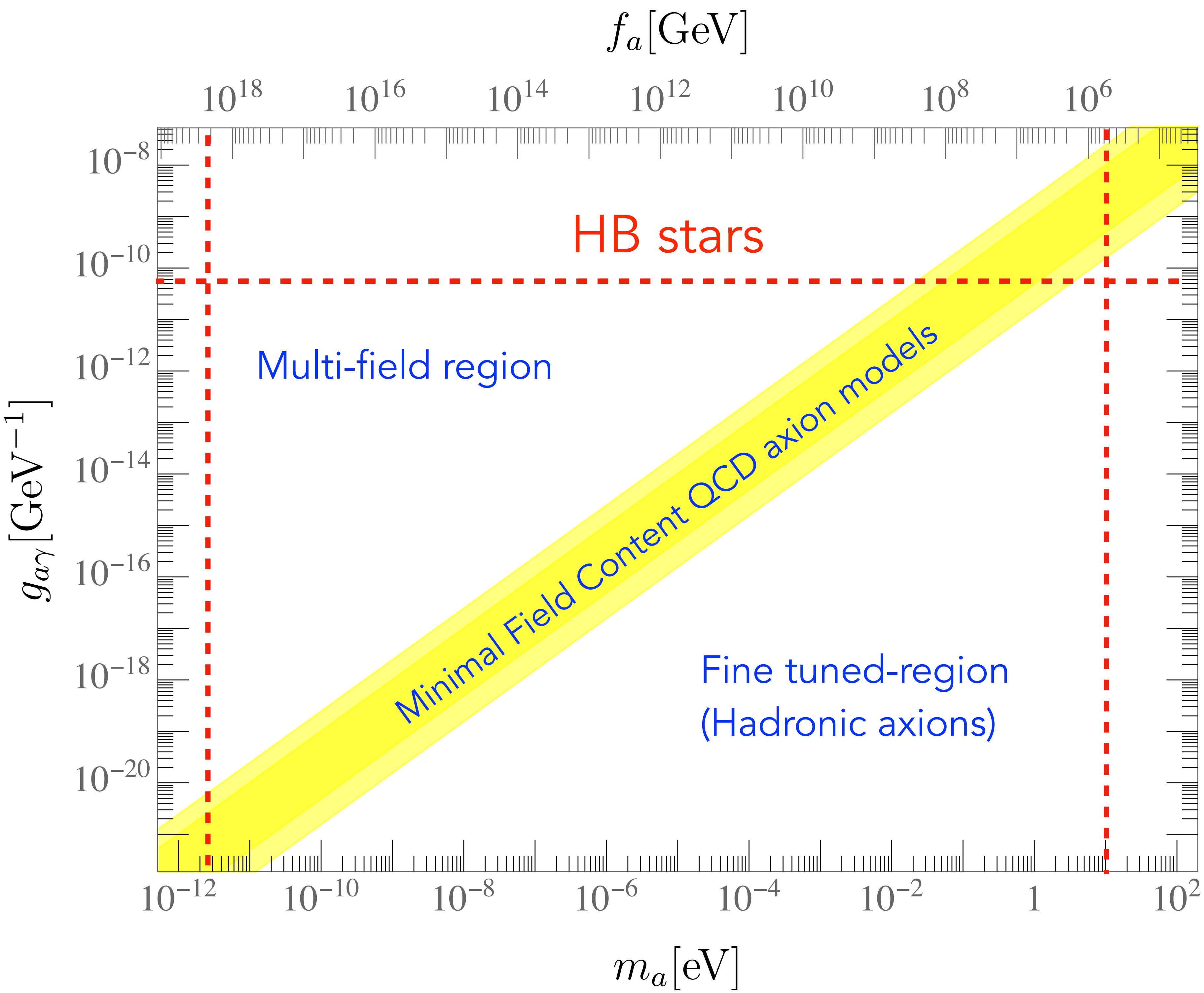
Minimal Field Axion Model Extension

Hadronic (KSVZ):	Non hadronic (DFSZ):
Heavy fermion + a new scalar field.	2 Higgs fields + a new scalar field.
Couplings to electrons: NO Coupling to nucleons: YES	Couplings to electrons: YES Coupling to nucleons: YES
Photons: $0.25 \lesssim C_{a\gamma} \lesssim 12.7$	Photons: $0.08 \lesssim C_{a\gamma} \lesssim 5.25$
Di Luzio, Mescia, Nardi, Phys.Rev.Lett. 118 (2017), Phys.Rev. D96 (2017)	*Di Luzio, Fedele, M.G., Mescia, Nardi, arXiv:2109.10368*

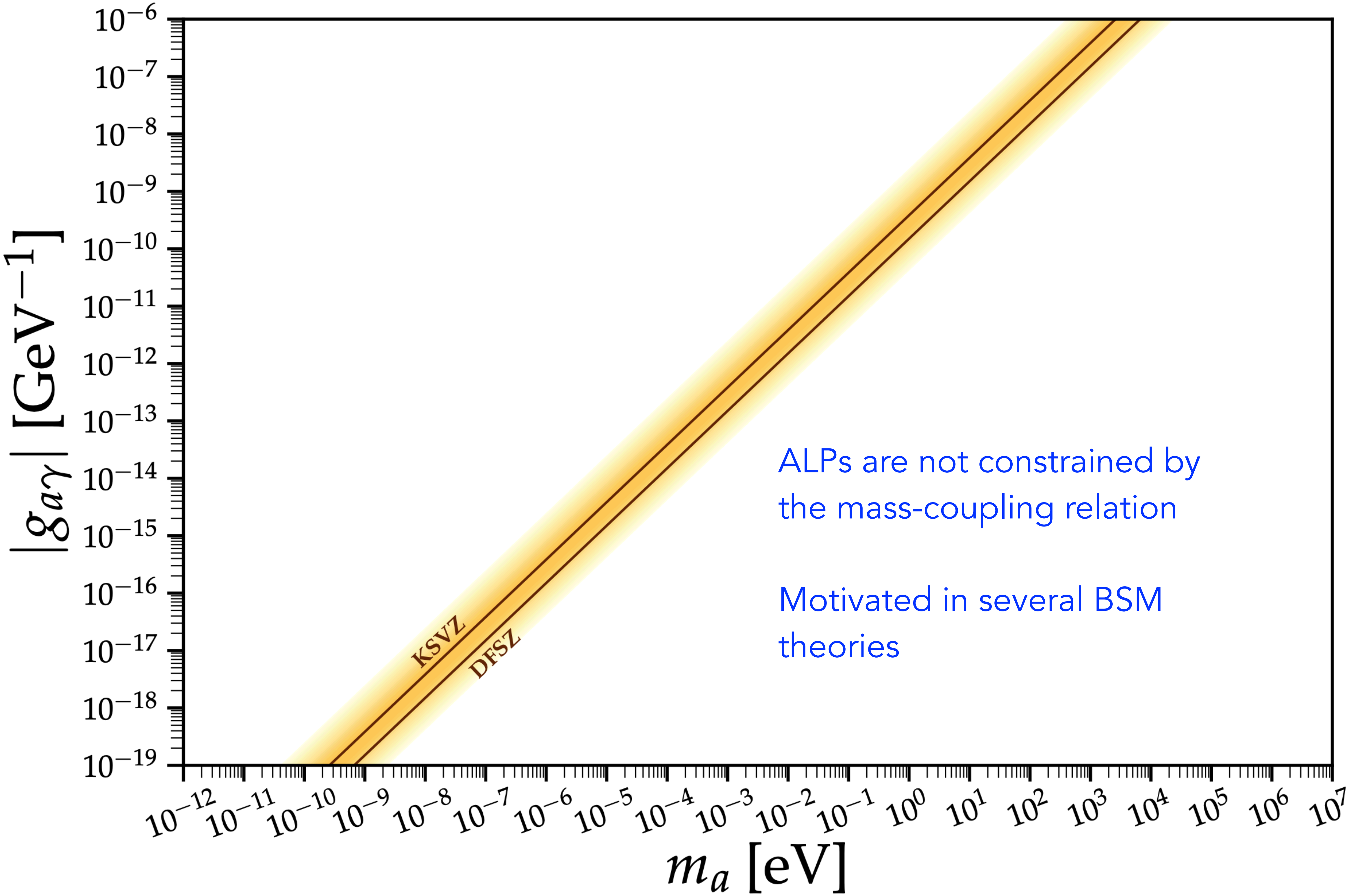
Having couplings outside this region is possible but it requires more complex models, e.g., with several scalar fields (clockwork).

see also V. Plakkot, S. Hoof, Phys.Rev.D 104 (2021) 7

The axion parameter space



Axion-Like Particles (ALPs)



ALPs are not constrained by the mass-coupling relation

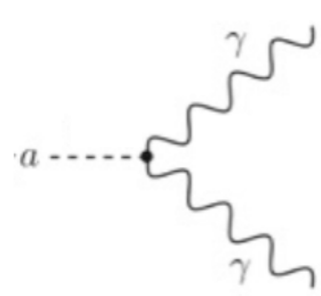
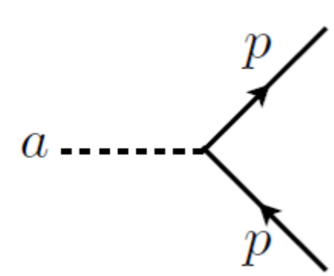
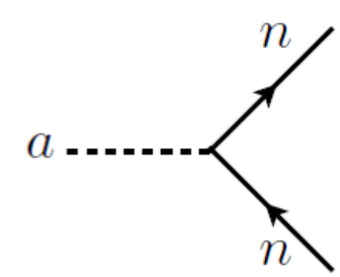
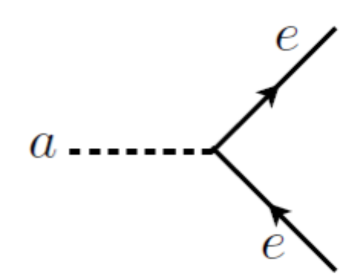
Motivated in several BSM theories

Part 2: Phenomenology and Astrophysics

Axions Interactions with SM Fields

Most of what follows apply to both Axions and ALPs.

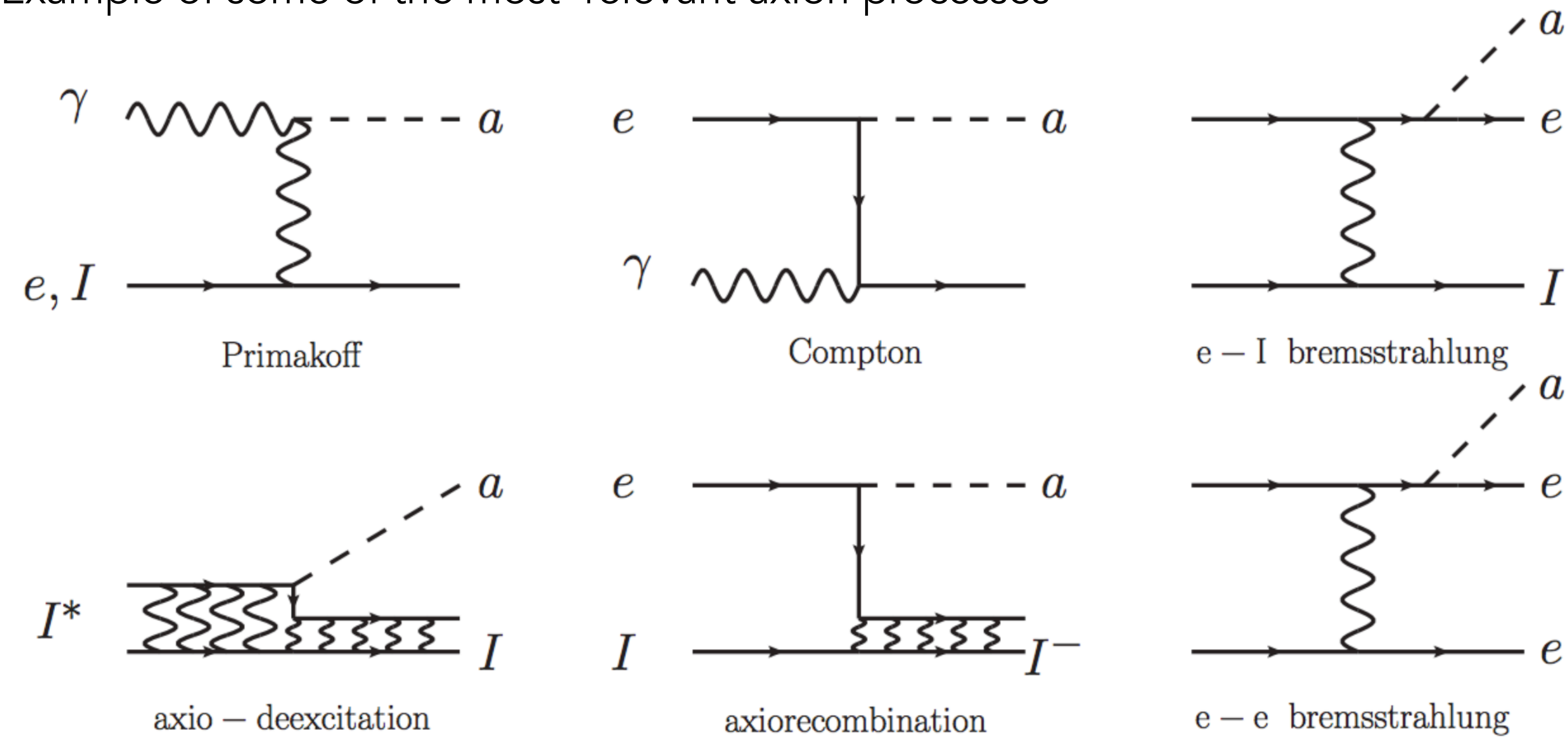
<u>Axions (ALPS) interact with SM fields</u>. This allow for a rich and interesting phenomenology, and for their possible detection (see part 3)

2 photon	proton	neutron	electron
$\frac{\alpha C_{a\gamma}}{2\pi}\frac{a}{f_a}\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4}$ +	$C_{ap}m_p\frac{a}{f_a}[i\bar{p}\gamma_5 p]$ +	$C_{an}m_n\frac{a}{f_a}[i\bar{n}\gamma_5 n]$ +	$C_{ae}m_e\frac{a}{f_a}[i\bar{e}\gamma_5 e]$ +
			

$g_{a\gamma} = \frac{C_{a\gamma}\alpha}{2\pi f_a}$ $\quad g_{ap} = C_{ap}\frac{m_p}{f_a}$ $\quad g_{ap} = C_{an}\frac{m_n}{f_a}$ $\quad g_{ap} = C_{ae}\frac{m_e}{f_a}$

Axions Interactions with SM Fields

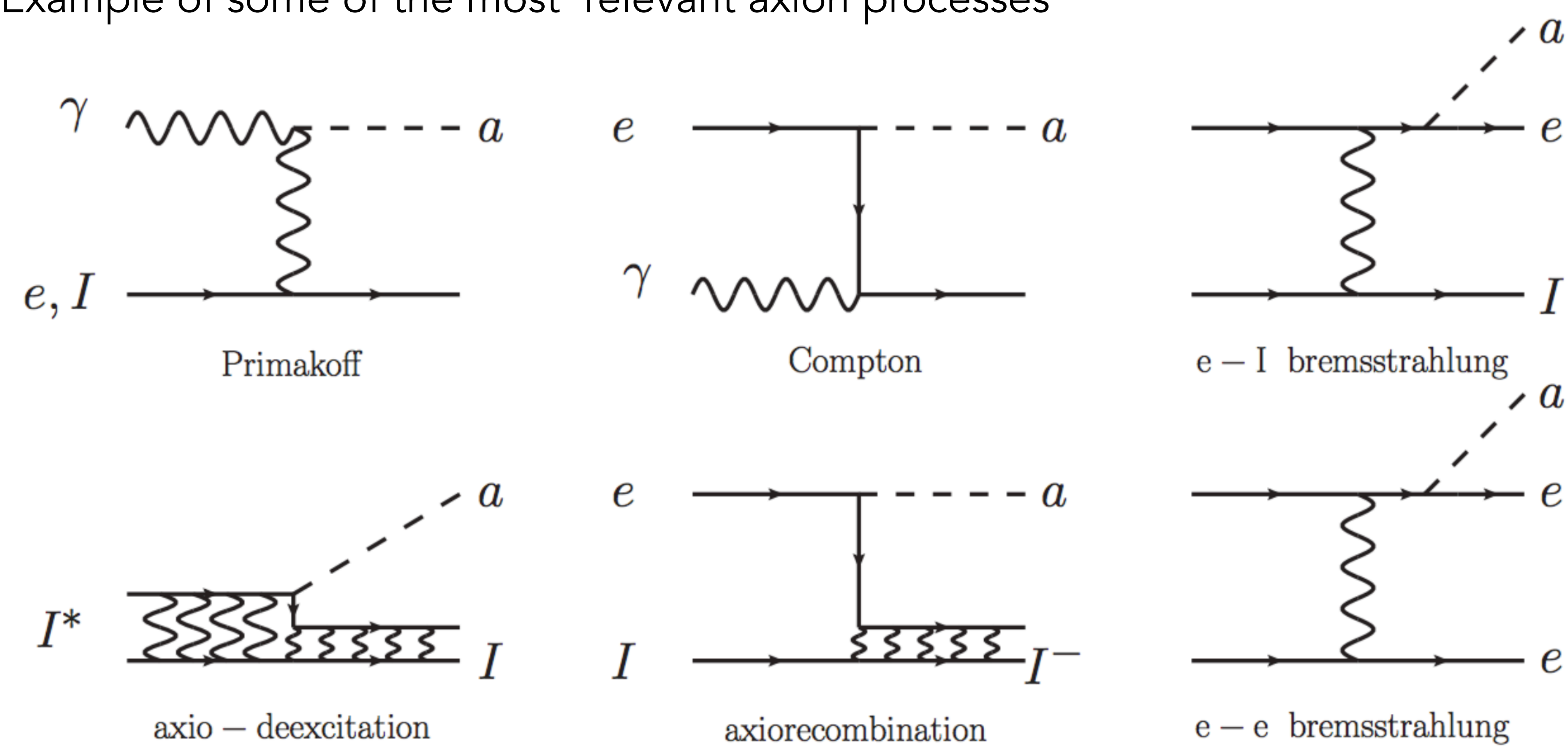
Example of some of the most relevant axion processes



… Plus, interaction with nuclei

Axions Interactions with SM Fields

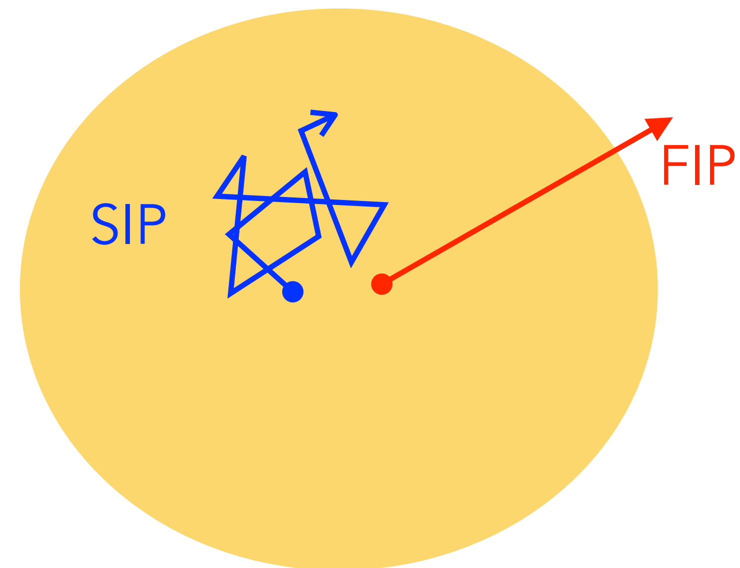
Example of some of the most relevant axion processes

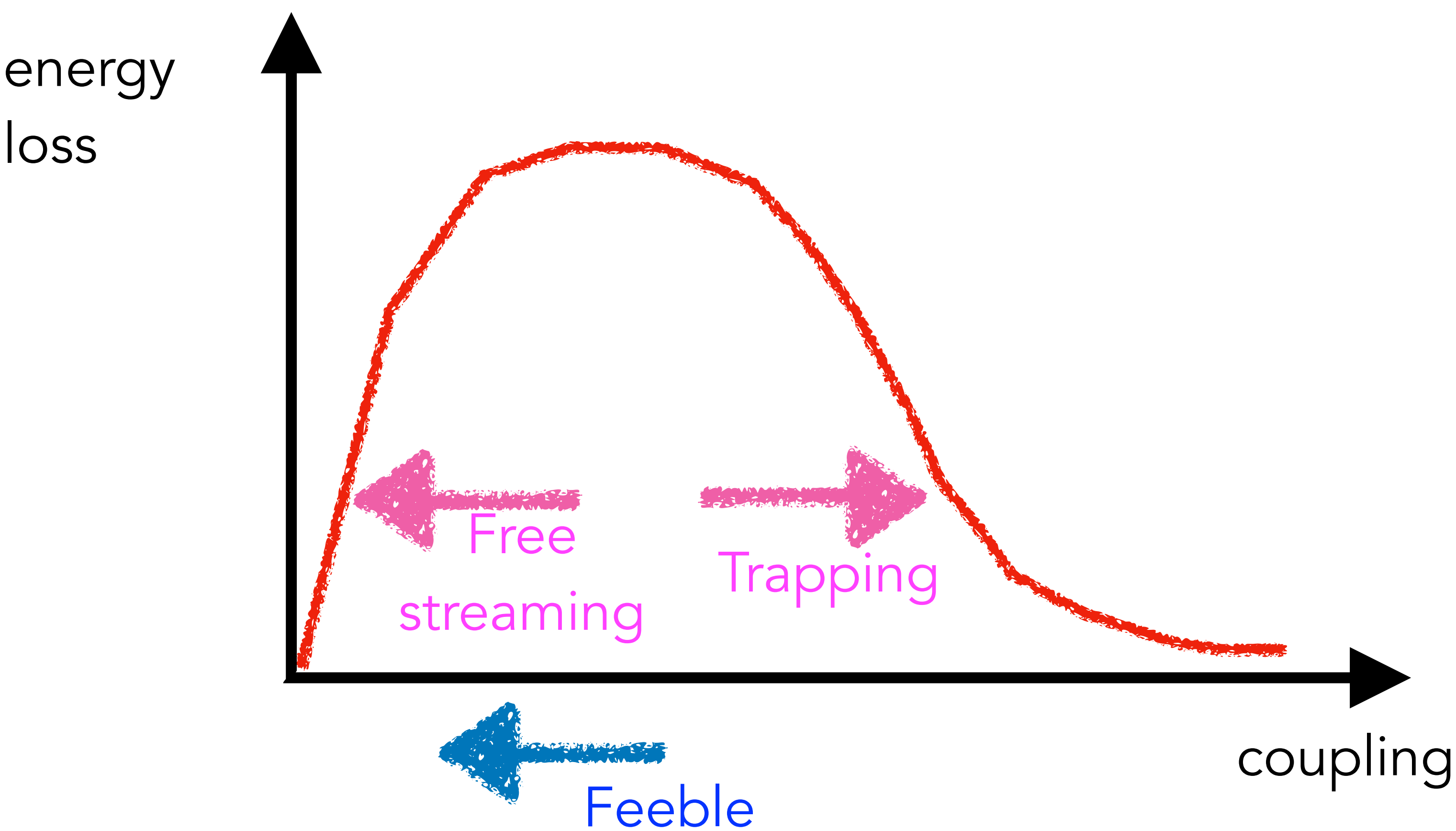


Thanks to these processes, axions can be produced in several natural sources. Particularly important are Stars and Labs

The Role of Axions in Stars

Light particles, $m \lesssim T$, can be efficiently thermally produced in stellar core





neutrions,
axions, …

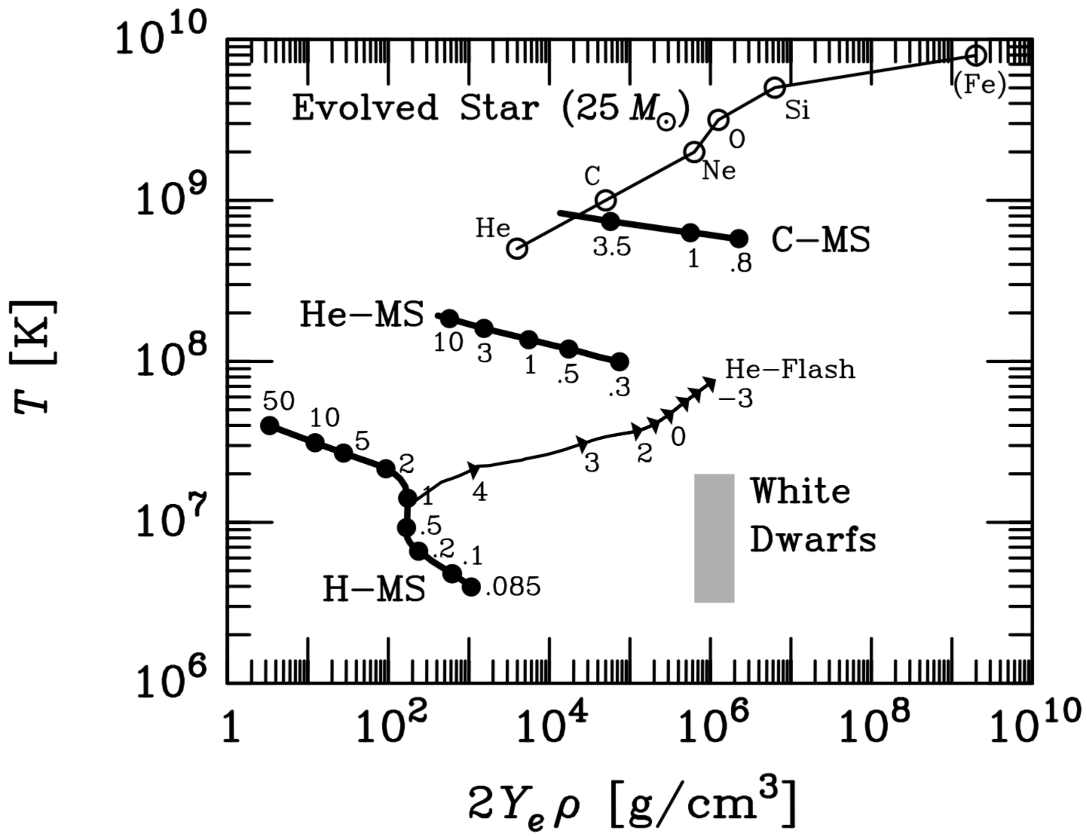
photons,
electrons, …

Observing the Stars

We can observe (almost) only the surface of stars

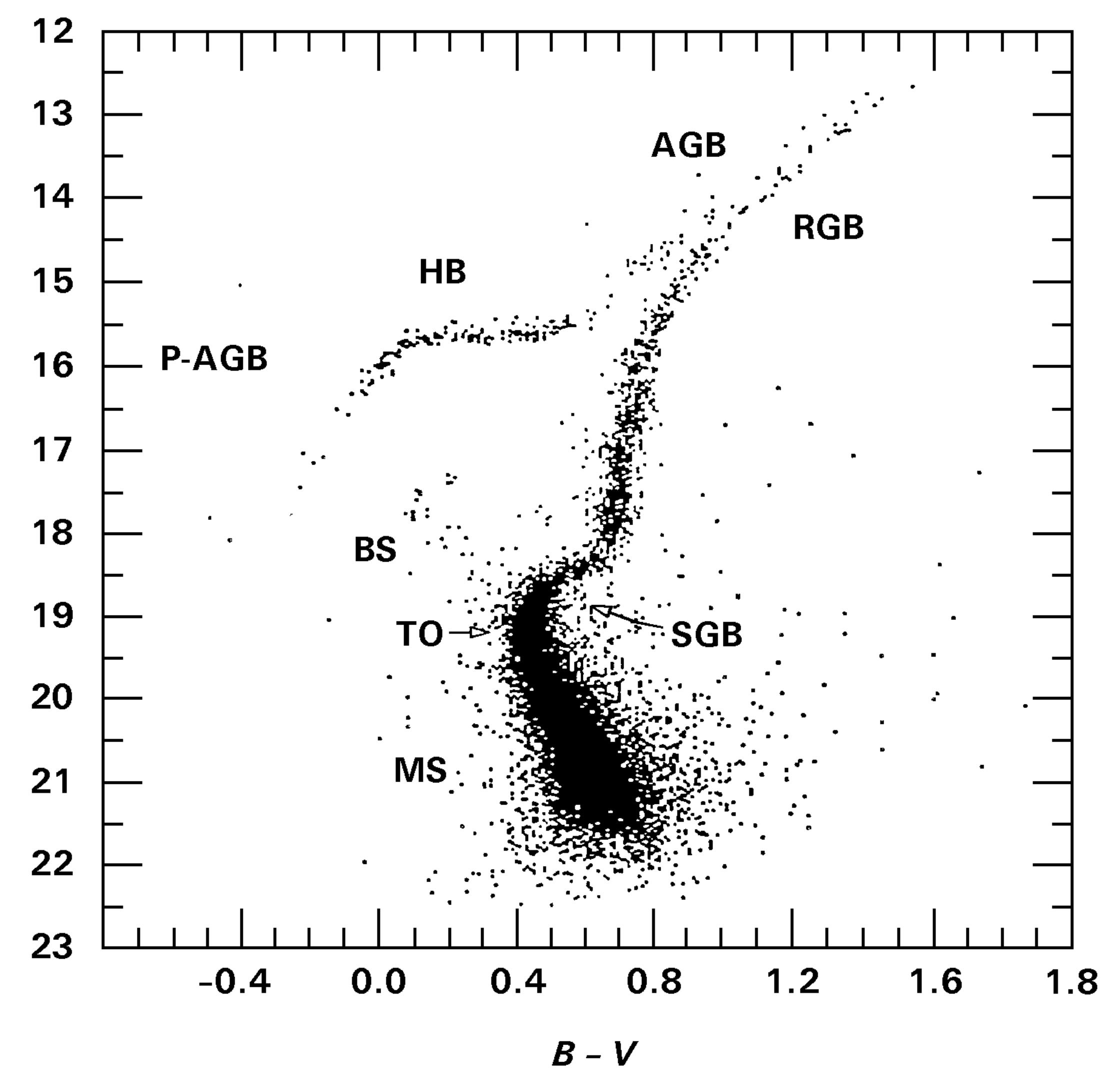
Numerical codes provide the link with core properties

Core



G. Raffelt, Stars as Laboratories (1996).

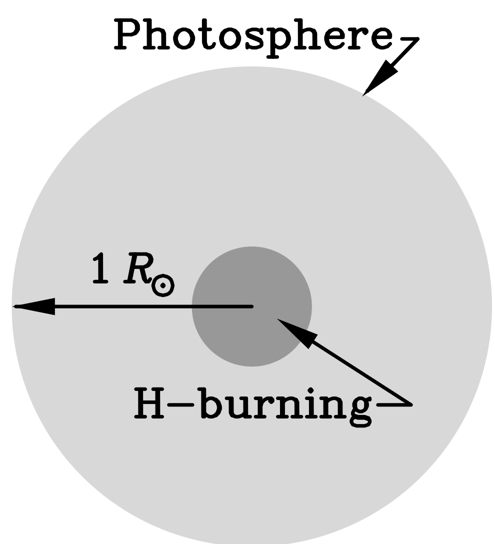
Surface



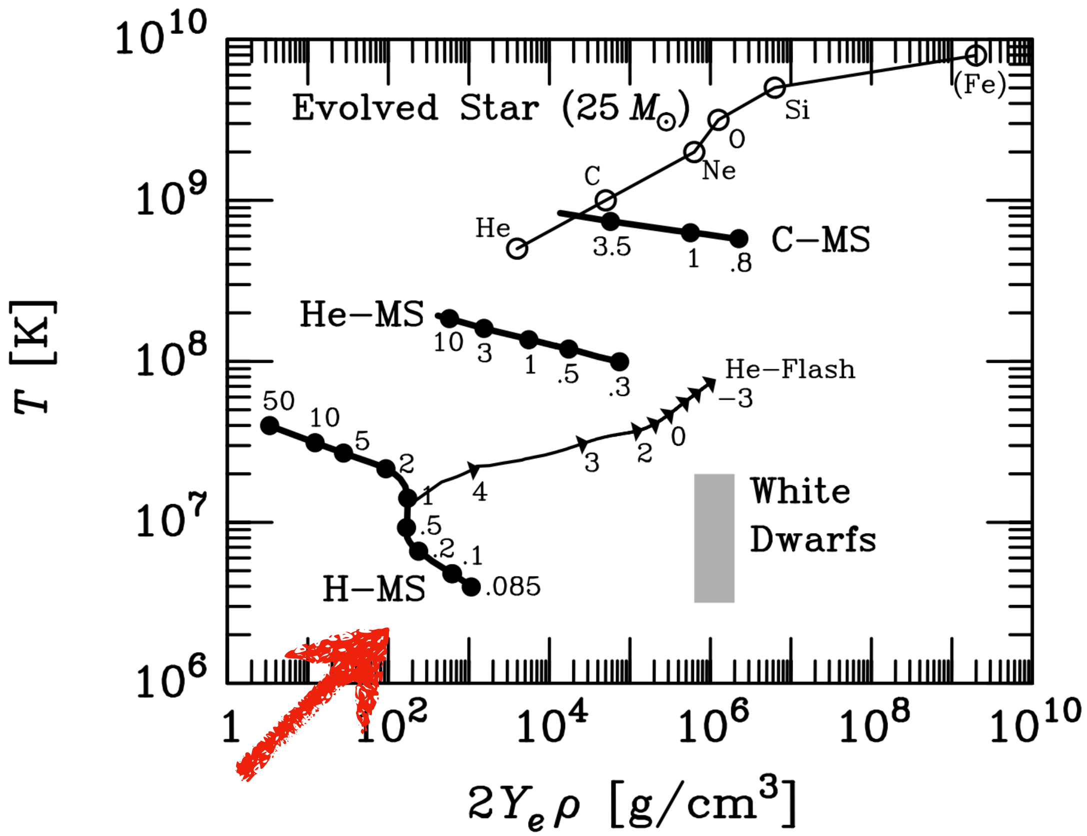
L

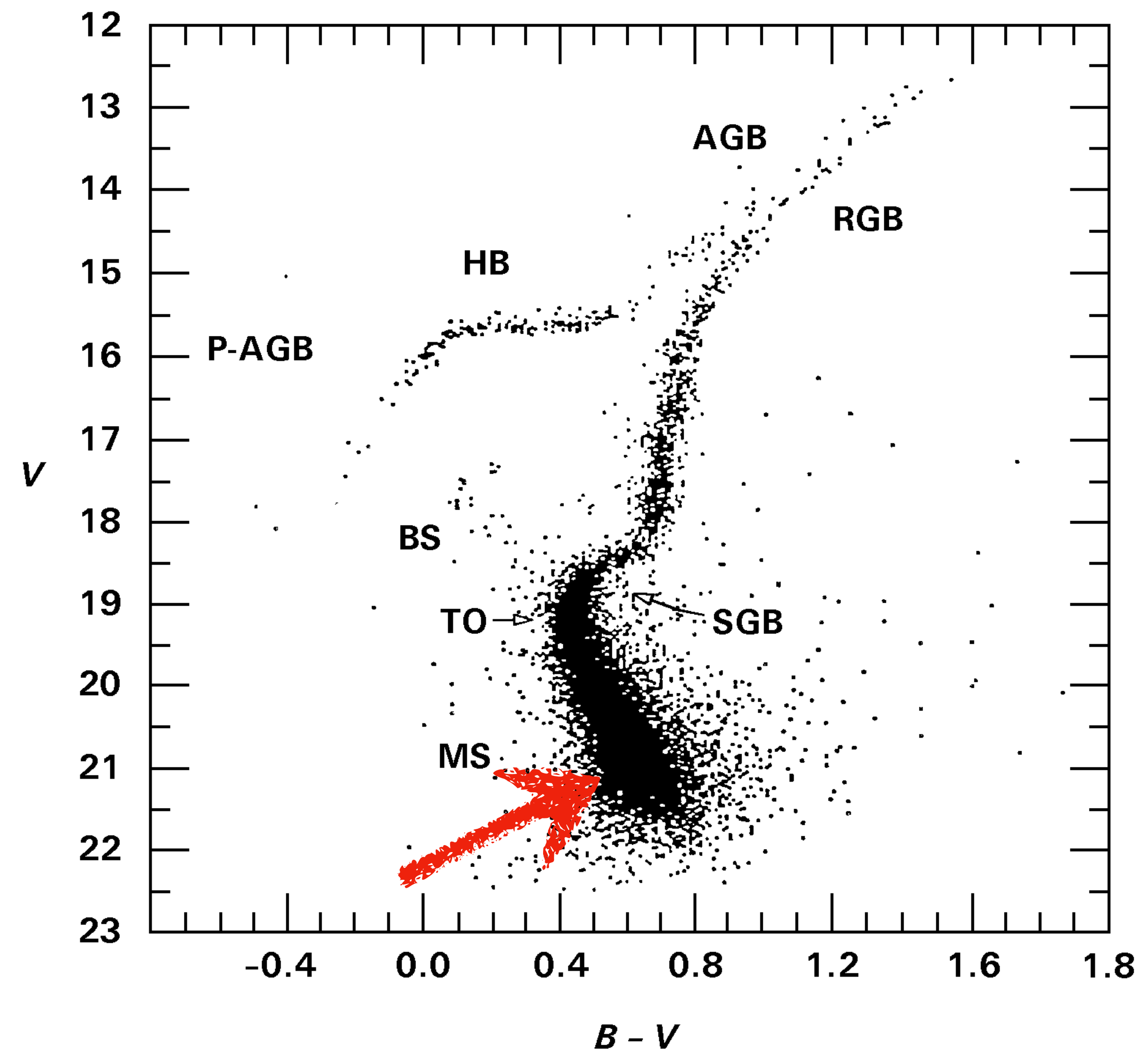
$T_{\rm eff}$

Stellar Evolution → Main Sequence Stars



Most of the stellar life is spent burning H into He in the core





G. Raffelt, Stars as Laboratories (1996).

Solar bounds on axions

The sun is a good (not excellent) lab for axions.

The flux of neutrinos from B8 is extremely sensitive to the temperature $\phi_{B8} \sim T_c^{18}$

$\rightarrow \quad g_{a\gamma} < 7 \cdot 10^{-10}\,\mathrm{GeV}^{-1} \quad (3\,\sigma)$

P. Gondolo and G. Raffelt,
Phys. Rev. D 79 (May, 2009)

A more complete analysis gives

$\rightarrow \quad g_{a\gamma} < 4.1 \cdot 10^{-10}\,\mathrm{GeV}^{-1} \quad (3\,\sigma)$

Vinyoles, Serenelli, Villante, Basu,
Redondo & Isern, JCAP 10 (2015) 015

Solar bounds on axions

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→ $g_{a\gamma} < 7 \cdot 10^{-10}\,\mathrm{GeV}^{-1}$ (3 σ)

A more complete analysis gives

→ $g_{a\gamma} < 4.1 \cdot 10^{-10}\,\mathrm{GeV}^{-1}$ (3 σ)

$\sim 6 \times 10^{12}\,\mathrm{axions\ cm^{-2}\,s^{-1}}$

on Earth, peaked at ~ keV.

Excluded by direct experimental searches

Other MS stars?

Other MS have similar properties of the Sun but are much further away.

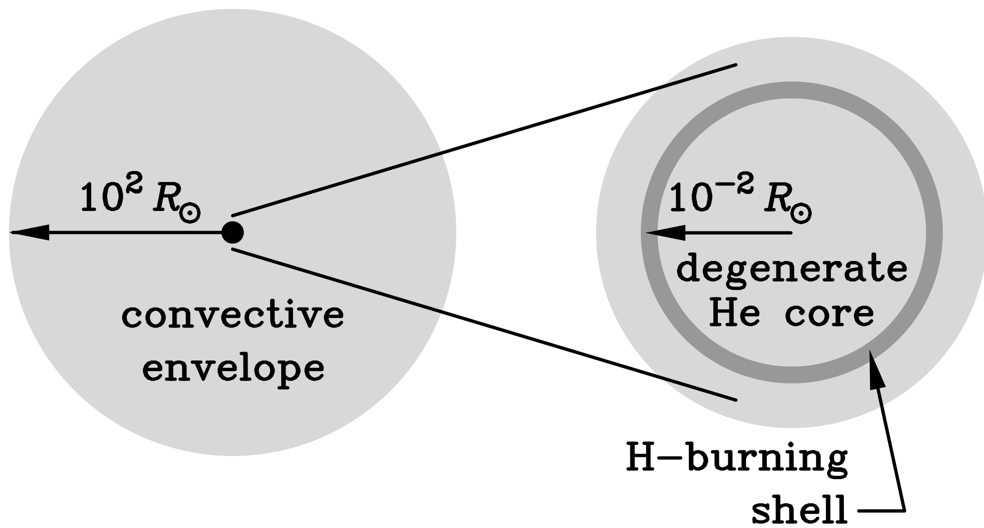
→ Likely much less interesting.

Yet, there are many of them. Diffuse axion flux recently calculated

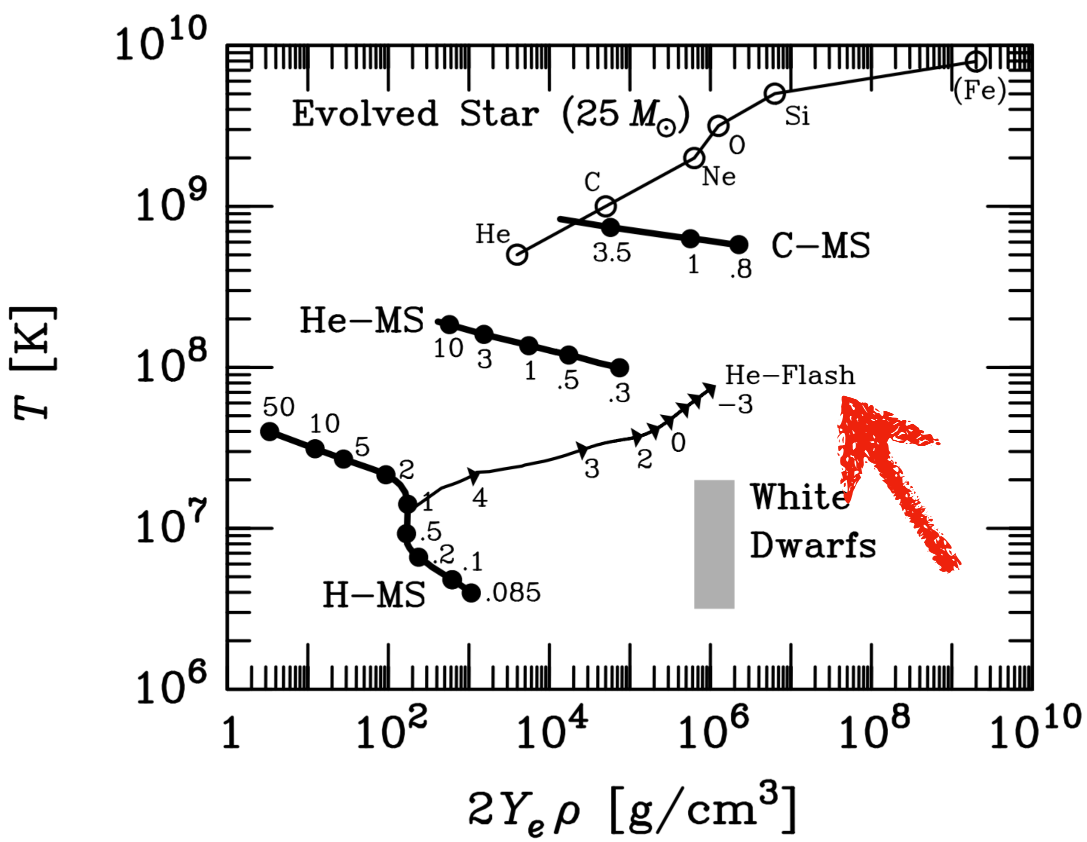
If ALPs are sufficiently heavy, their decay produces a (possibly detectable) x-ray diffuse background

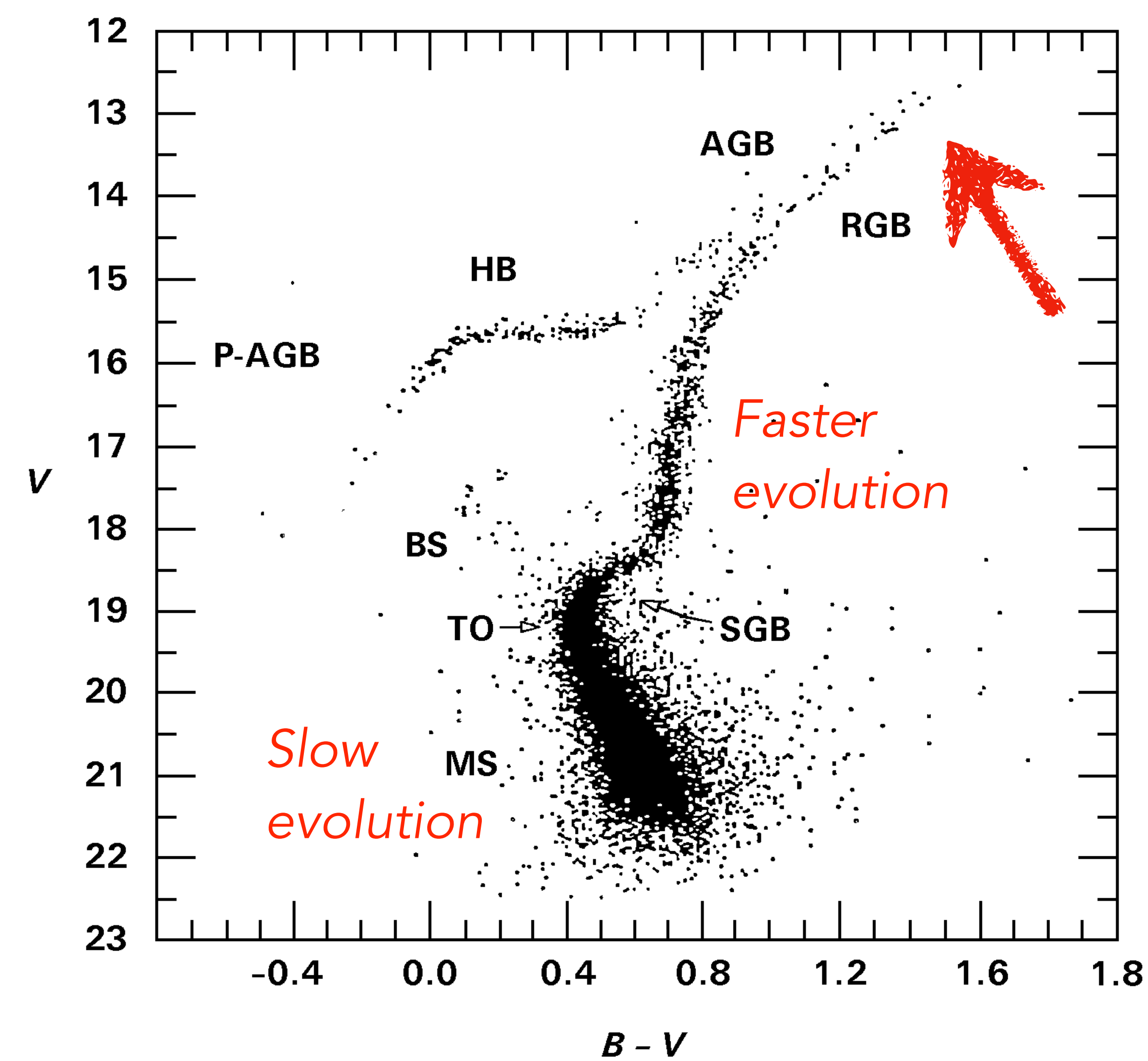
See → N. H. Nguyen, E. H. Tanin, M. Kamionkowski arXiv:2307.11216

Stellar Evolution → Red Giant Branch



After the H in the core is exhausted, a light star star moves in the RGB. The surface luminosity keeps increasing, till the He-flash. That is the tip of the RGB

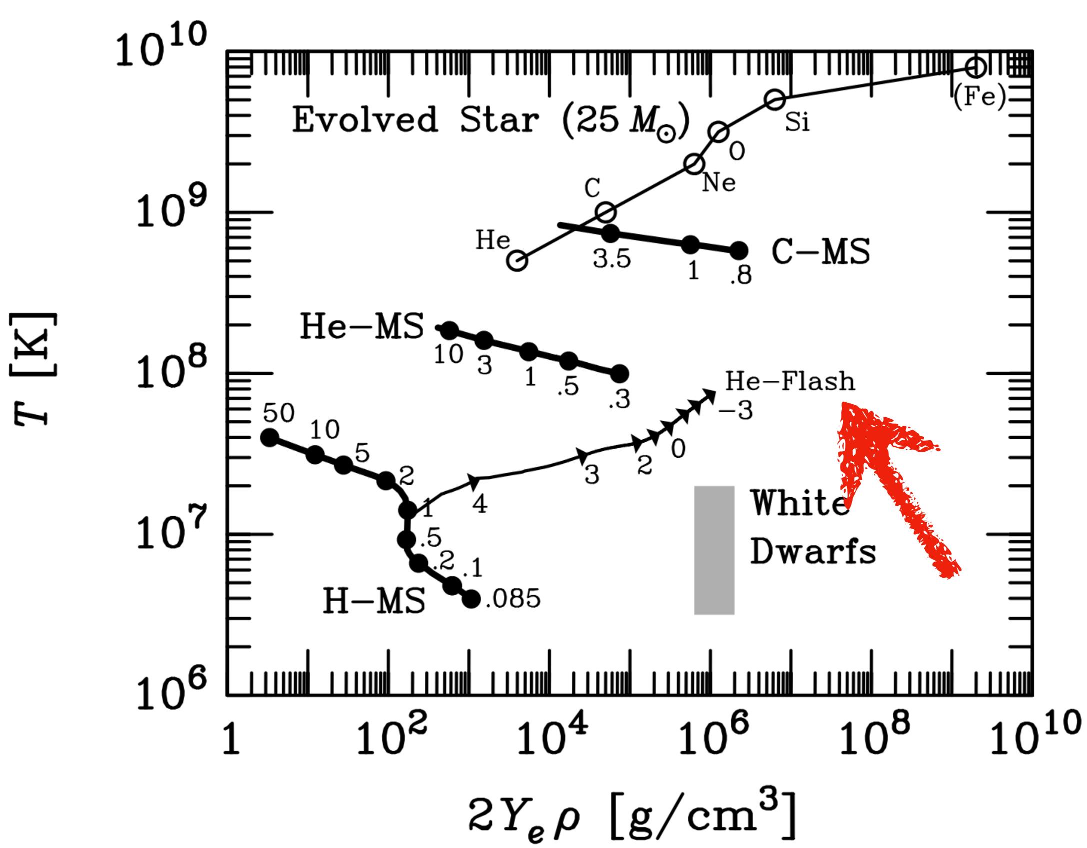




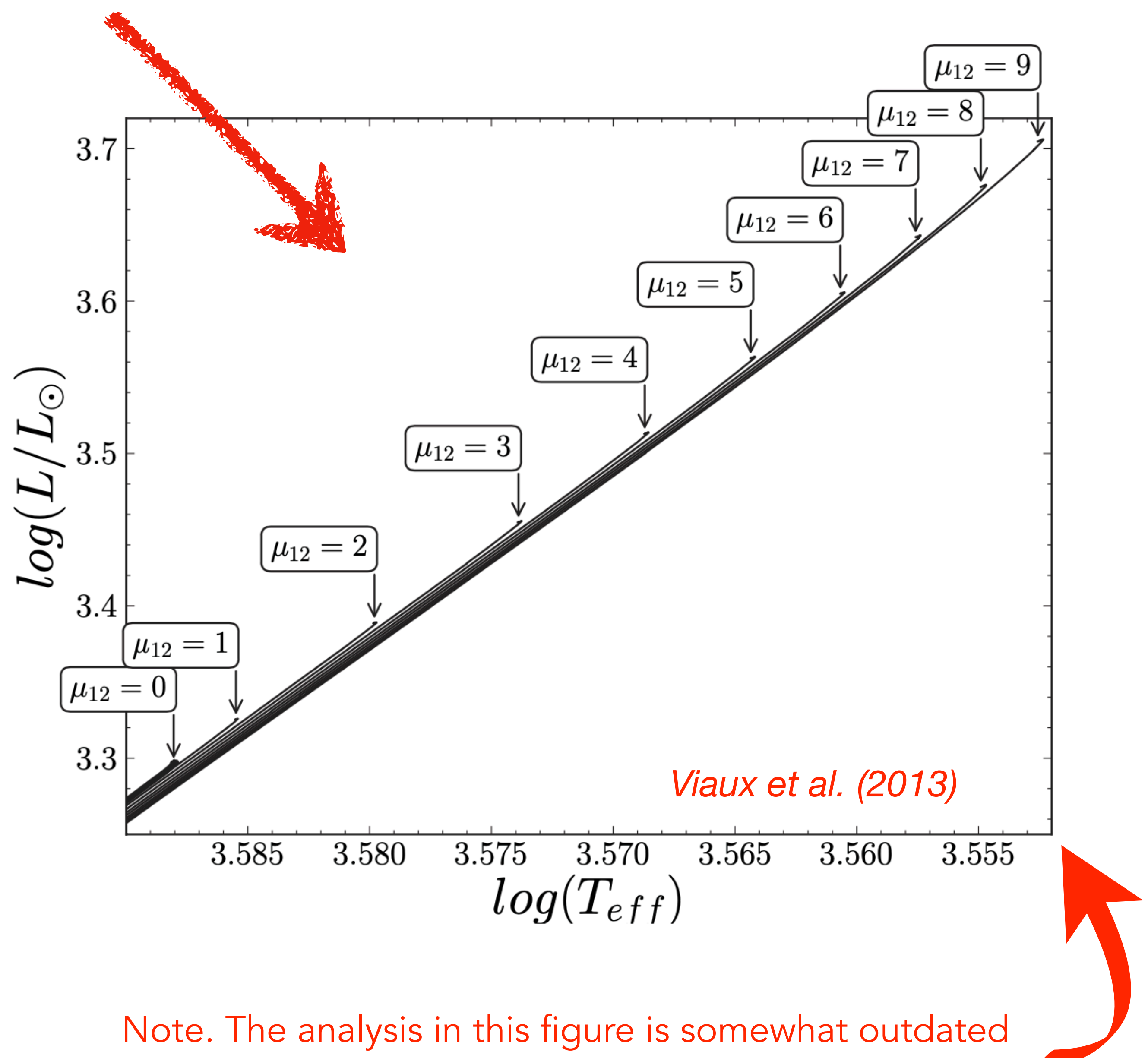
G. Raffelt, Stars as Laboratories (1996).

Stellar Evolution → Red Giant Branch

Additional cooling delays the He-ignition, moving the RGBT to higher luminosities



G. Raffelt, Stars as Laboratories (1996).



Note. The analysis in this figure is somewhat outdated and should serve only as a qualitative example.

Stellar Evolution $\rightarrow$ Red Giant Branch

Currently, the RGB Tip analysis provides the strongest bounds on:

Axion-electron coupling:

$$g_{ae} \sim 0.60^{+0.32}_{-0.58} \times 10^{-13},$$

$$g_{ae} \leq 1.48 \times 10^{-13} \quad (95\,\%\ \mathrm{C.L.})$$

- O. Straniero et al., Astron.Astrophys. 644 (2020)
- F. Capozzi, G. Raffelt, Phys.Rev.D 102 (2020) 8

Recently, the bounds from RGB have been questioned in two publications

The criticism is that the uncertainties are much larger than those used in the papers which derived the bonds. However, the uncertainties proposed in seem largely inflated.

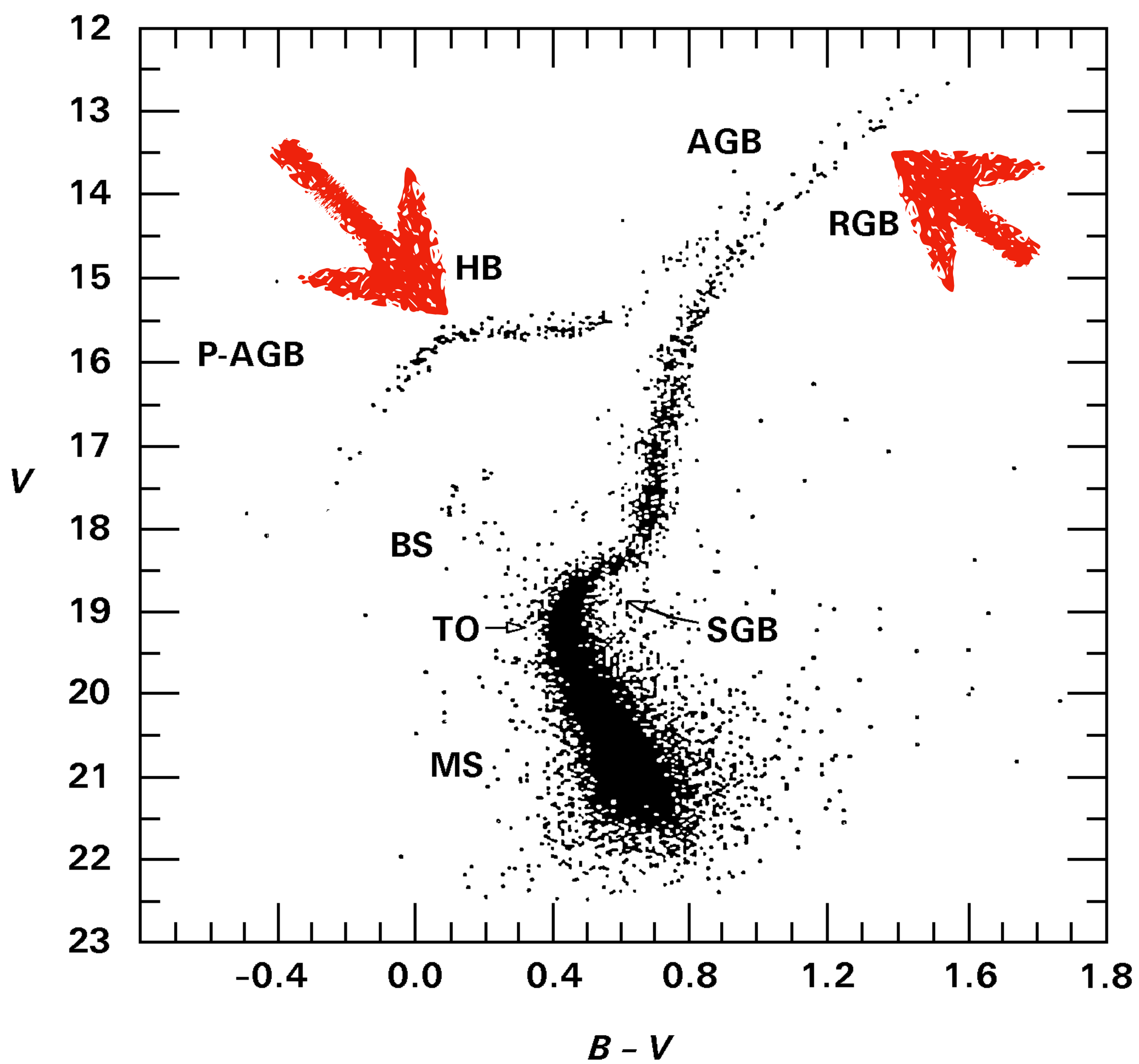
- N Franz, M Dennis, J Sakstein, arXiv:2307.13050
- M Dennis, J Sakstein, arXiv:2305.03113

Stellar Evolution → Horizontal Branch

R-parameter: number ratio of HB and RGB

$$R = \frac{N_{\rm HB}}{N_{\rm RGB}}$$

Test new physics

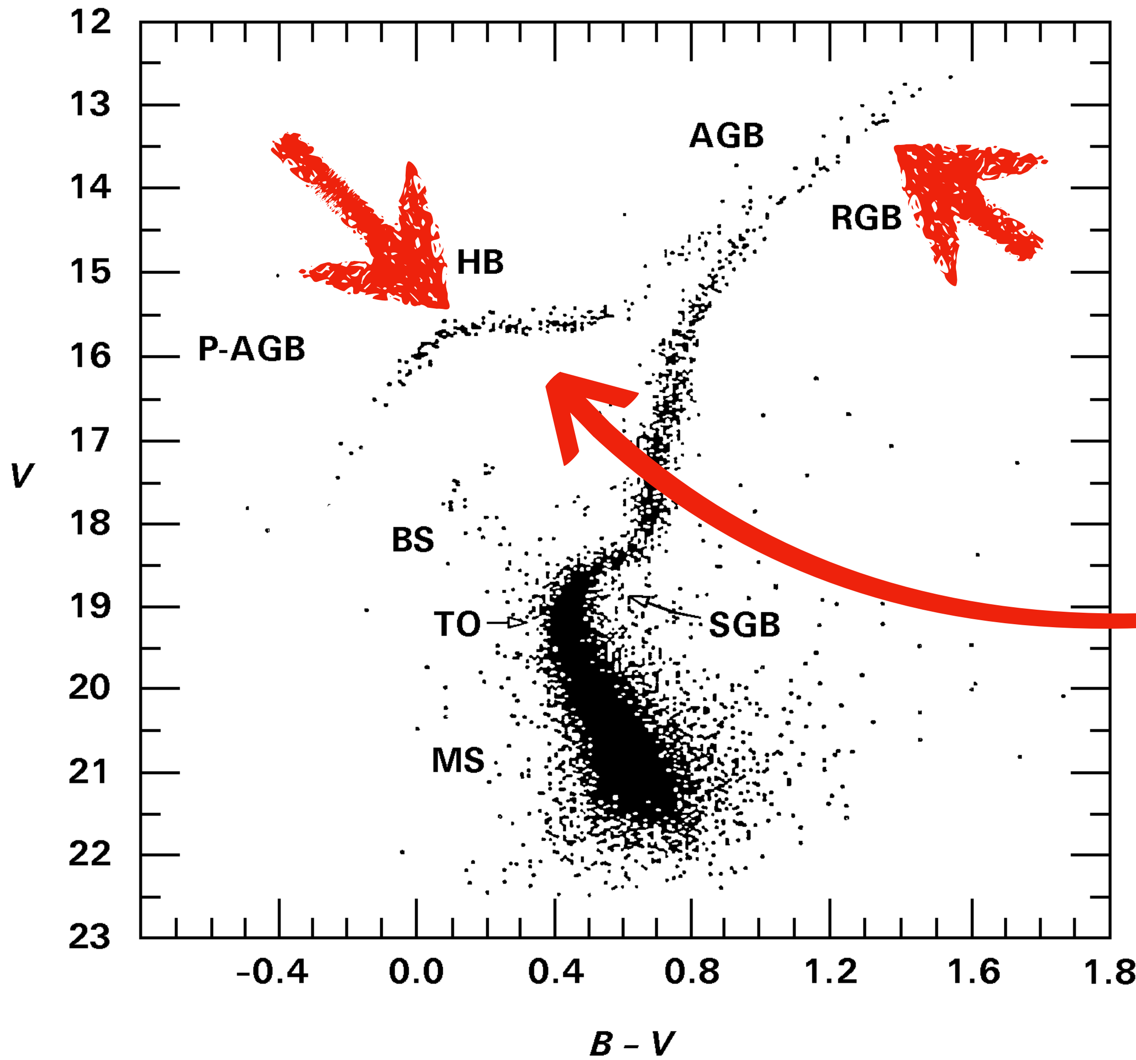


The ratio depends on the efficiency of the energy loss in the two evolutionary stages

Stellar Evolution → Horizontal Branch

R-parameter: number ratio of HB and RGB

$$R = \frac{N_{\mathrm{HB}}}{N_{\mathrm{RGB}}}$$



Primakoff Process

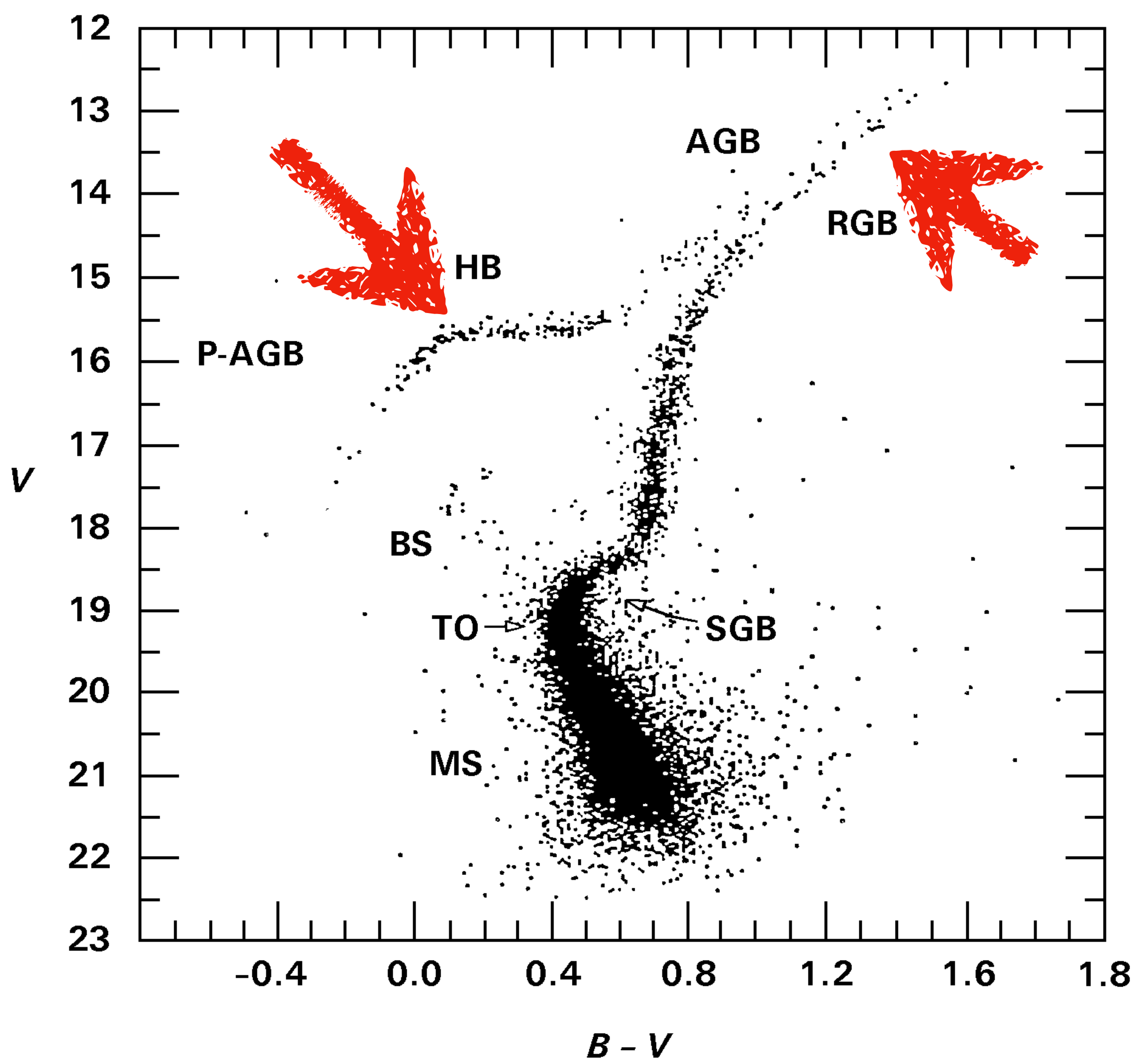
$$g_{a\gamma} \leq 6.5 \cdot 10^{-11}\,\mathrm{GeV}^{-1}$$

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

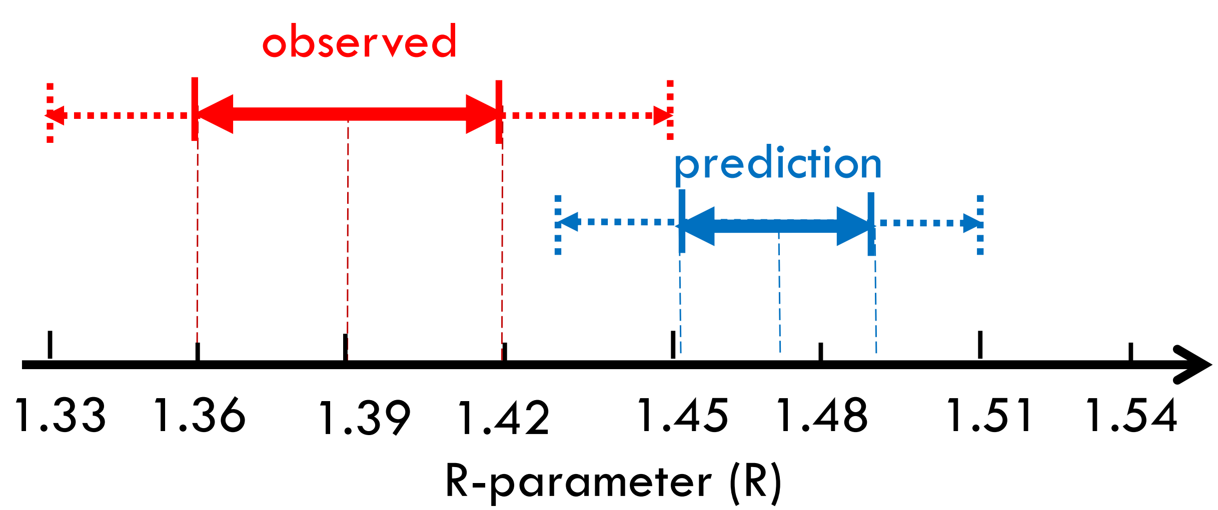
Stellar Evolution → Horizontal Branch

The number ratio of HB and RGB is the R-parameter

$$R = \frac{N_{\mathrm{HB}}}{N_{\mathrm{RGB}}}$$



The analysis showed a slight discrepancy between the predicted and observed R-parameter.

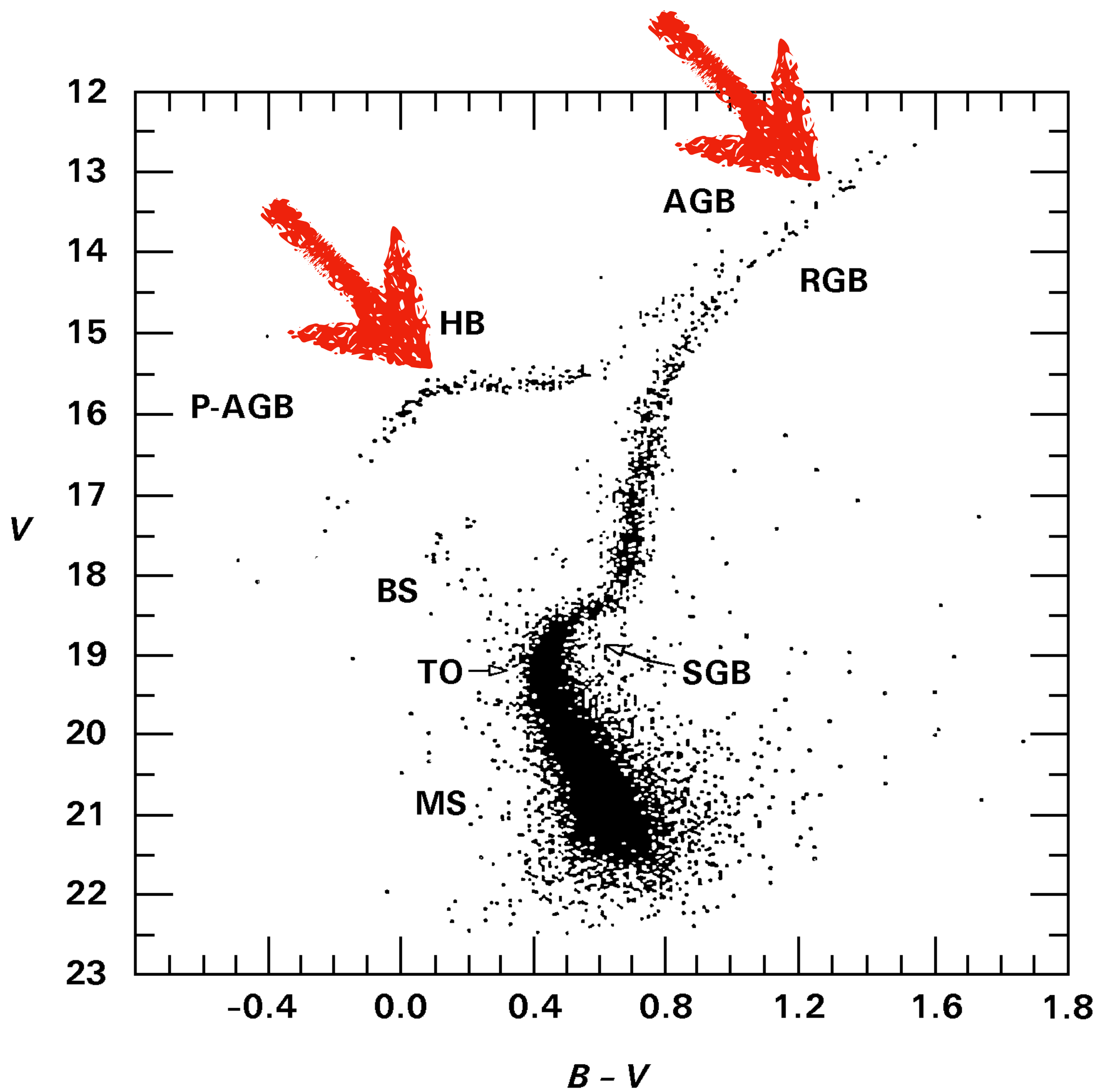


Ayala et al., PRL 113 (2014)

Stellar Evolution → AGB and R2

The number ratio of AGB over HB is the R_2-parameter

$$R_2 = \frac{N_{\mathrm{AGB}}}{N_{\mathrm{HB}}}$$



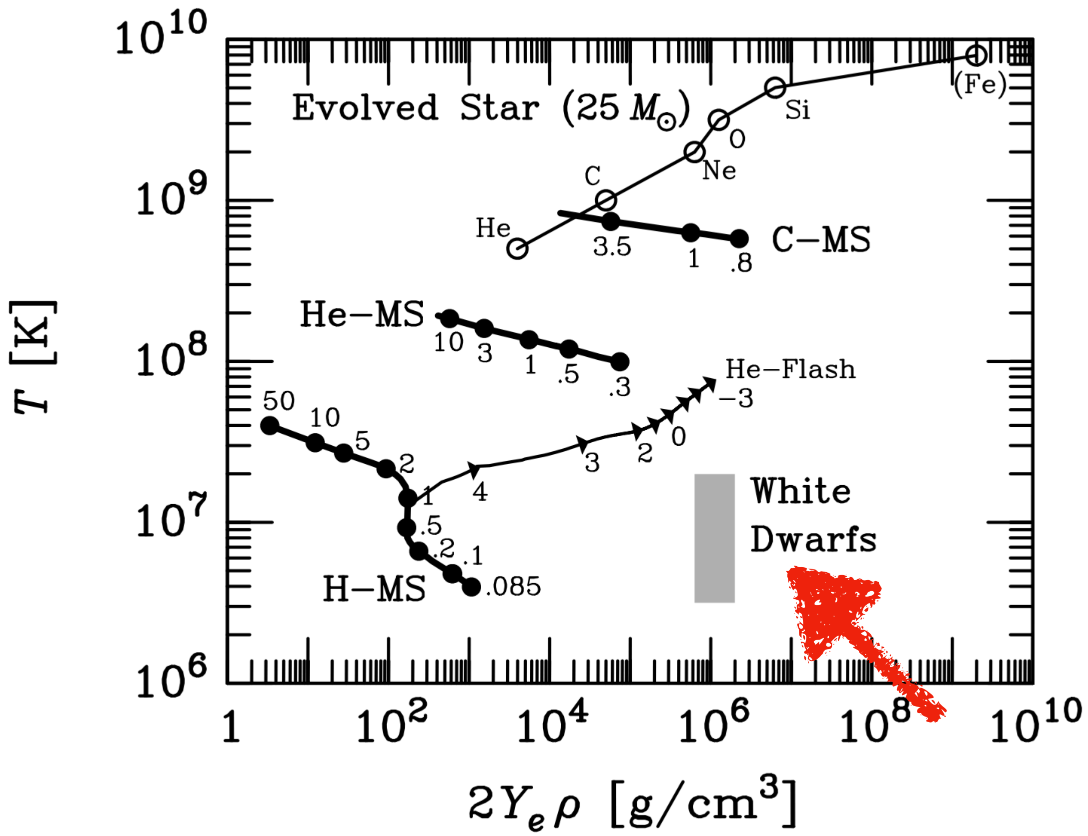
Recent bound using measurements of R_2 from Hubble Space Telescope photometry of 48 globular clusters

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

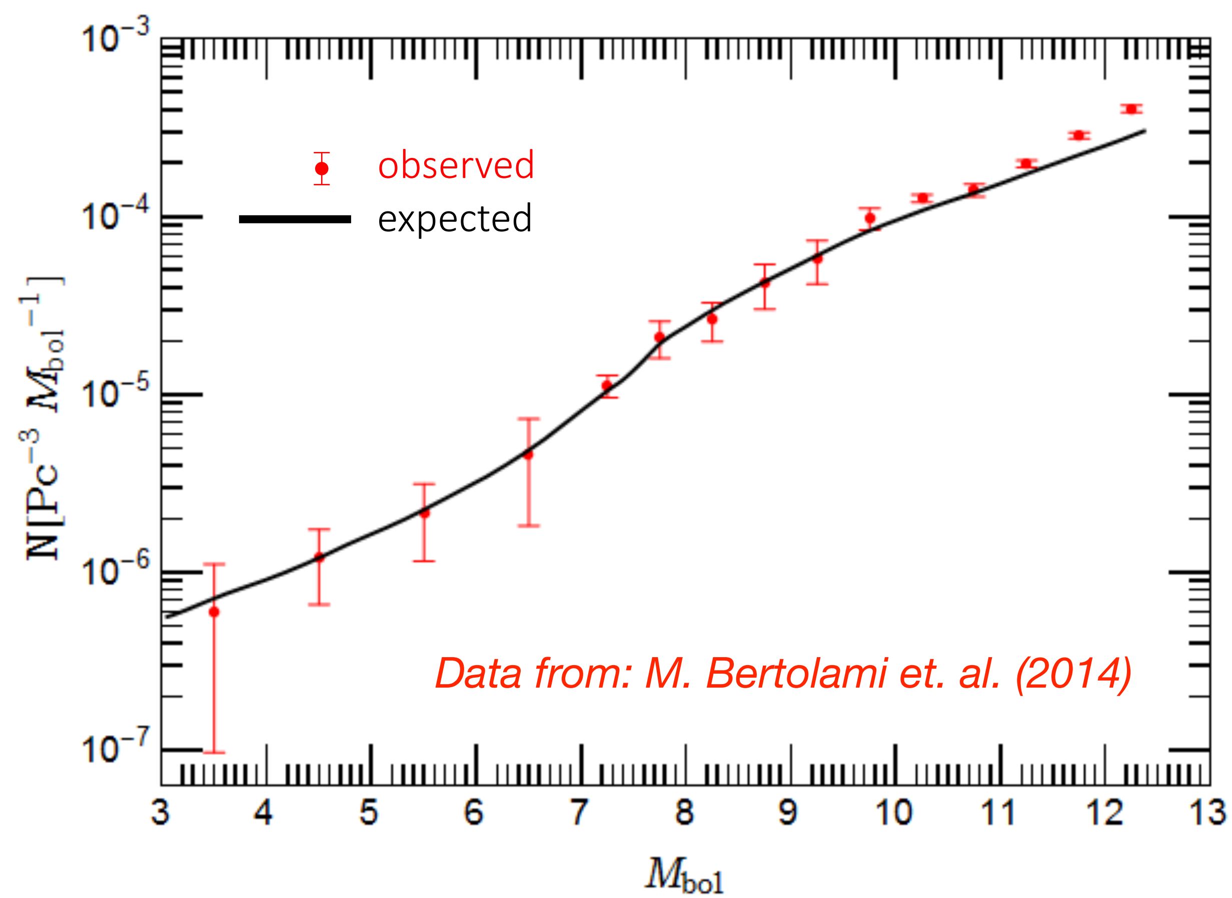
Dolan, Hiskens, Volkas, JCAP 10 (2022)

Stellar Evolution → White Dwarfs

Lighter stars go to the AGB at the end of the central He, and end up as CO White Dwarfs.



G. Raffelt, Stars as Laboratories (1996).



The WDLF is a powerful way to measure the cooling efficiency

$$\frac{dN_{\rm WD}}{dV\,dL} \propto \frac{1}{L_\gamma + L_\nu + L_x}$$

Stellar Evolution: WD

WD Variables (WDV)

Measures of the period change rate in WD variables offer a way to test the cooling of WDs

$$\dot{P}/P \propto \dot{T}/T$$

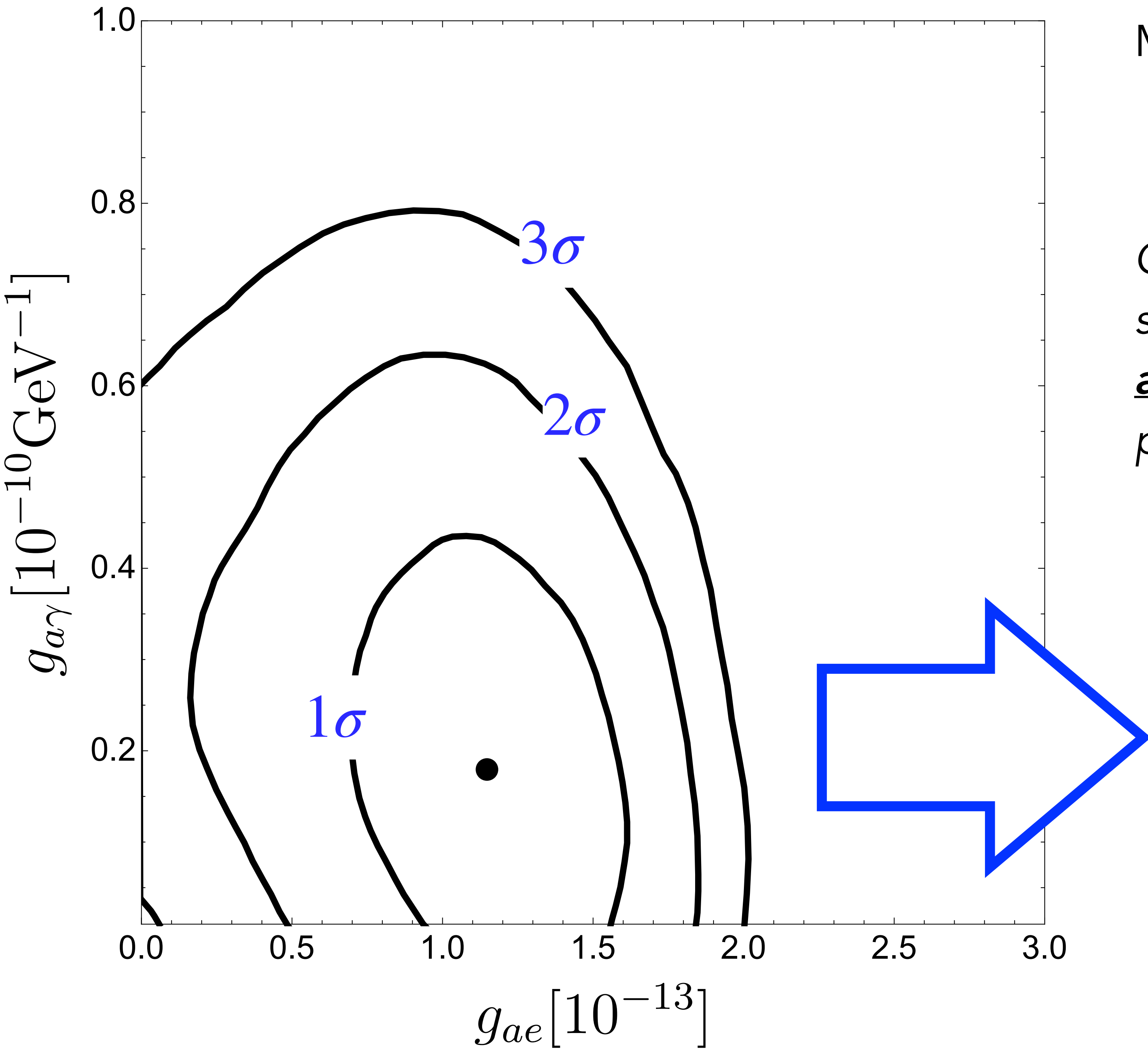
Star	P(s)	$\dot{P}_{obs}$(s/s)	$\dot{P}_{th}$(s/s)
G117 - B15A	215	$(4.2 \pm 0.7) \times 10^{-15}$	$(1.25 \pm 0.09) \times 10^{-15}$
R548	213	$(3.3 \pm 1.1) \times 10^{-15}$	$(1.1 \pm 0.09) \times 10^{-15}$
PG 1351+489	489	$(2.0 \pm 0.9) \times 10^{-13}$	$(0.81 \pm 0.5) \times 10^{-13}$
L 19-2 (113)	113	$(3.0 \pm 0.6) \times 10^{-15}$	$(1.42 \pm 0.85) \times 10^{-15}$
L 19-2 (192)	192	$(3.0 \pm 0.6) \times 10^{-15}$	$(2.41 \pm 1.45) \times 10^{-15}$

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

Observations over the past ~30 yr showed consistently $\dot{P}_{obs} > \dot{P}_{th}$, which seems to imply an overly efficient cooling.

Many works starting form Isern, Hernanz, Garcıa-Berro (1992)

Global Fits



Many recent results from stars

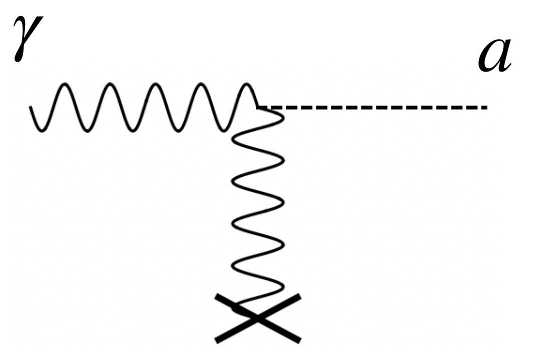
Global analysis of WDs, RGB and HB stars shows a ***preference for finite axion couplings*** *with electrons and photons*

For QCD models →
meV to ~100 meV mass region

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

Supernova axions

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

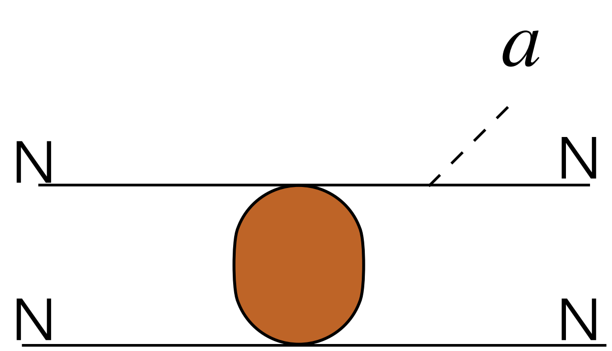


Primakoff requires $\propto g_{a\gamma}^2$

J. Brockway, E. Carlson, G. Raffelt, Phys. Lett. B 383, 439 (1996);

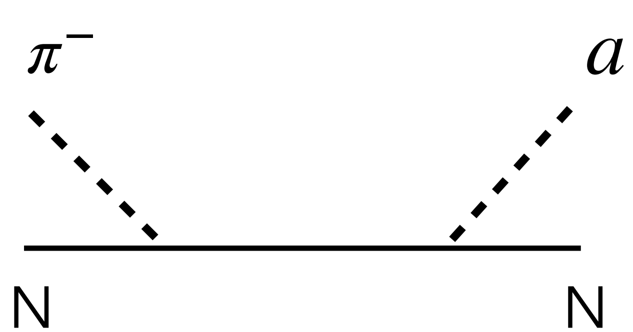
J. Grifols, E. Masso, R. Toldra, Phys. Rev. Lett. 77, 2372 (1996)

A. Payez, C. Evoli, T. Fischer, M. G., A. Mirizzi, A. Ringwald, JCAP 1502 (2015).



Bremsstrahlung $\propto g_{aN}^2$

P. Carenza et al., JCAP 10 (2019) 10, 016

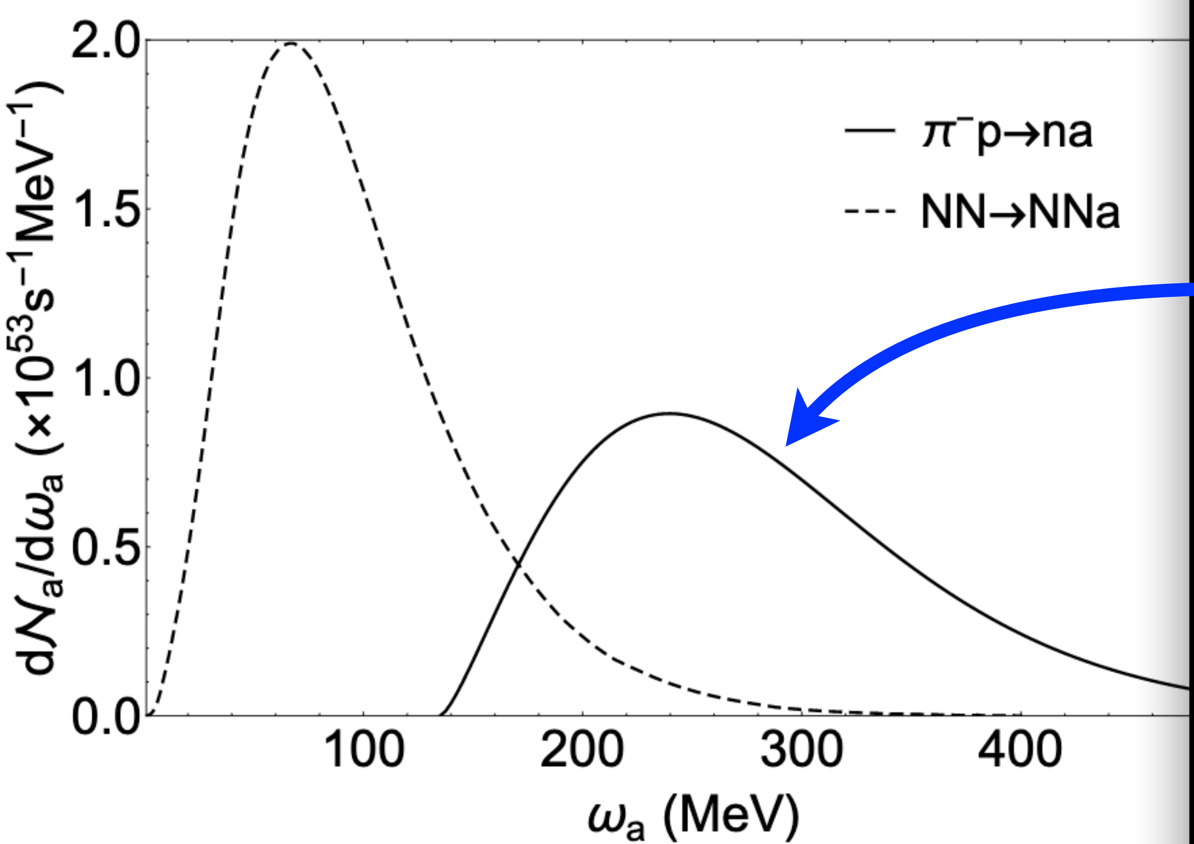


Pion induced $\propto g_{aN}^2$

P. Carenza, B. Fore, M.G., A. Mirizzi, S. Reddy, Phys.Rev.Lett. 126 (2021)

Pion abundance was underestimated. Breakthrough result in
B. Fore and S. Reddy, Phys. Rev. C 101, 035809 (2020)

Supernova axions



- Pions in SN: Larger than expected fraction of π^-

  B. Fore and S. Reddy, Phys.Rev.C 101 (2020);
  B. Fore et al., arXiv:2301.07226 (2023)

- Significance of the $\pi + N \to N + a$ processes.
  Dominates the axion emission rate.
  Harder spectrum.

  P. Carenza et al., Phys.Rev.Lett. 126 (2021);
  A. Lella et al, *Phys.Rev.D* 107 (2023) 10

- Inclusion of the axion-pion contact interaction.
  Significant contribution to $\pi + N \to N + a$.
  Irrelevant contribution to $N + N \to N + N + a$

  K. Choi et al., *JHEP* 02 (2022) 143

- Inclusion of the Δ resonance contribution in pion process

  Ho, Kim, Ko, Park, *Phys.Rev.D* 107 (2023) 7

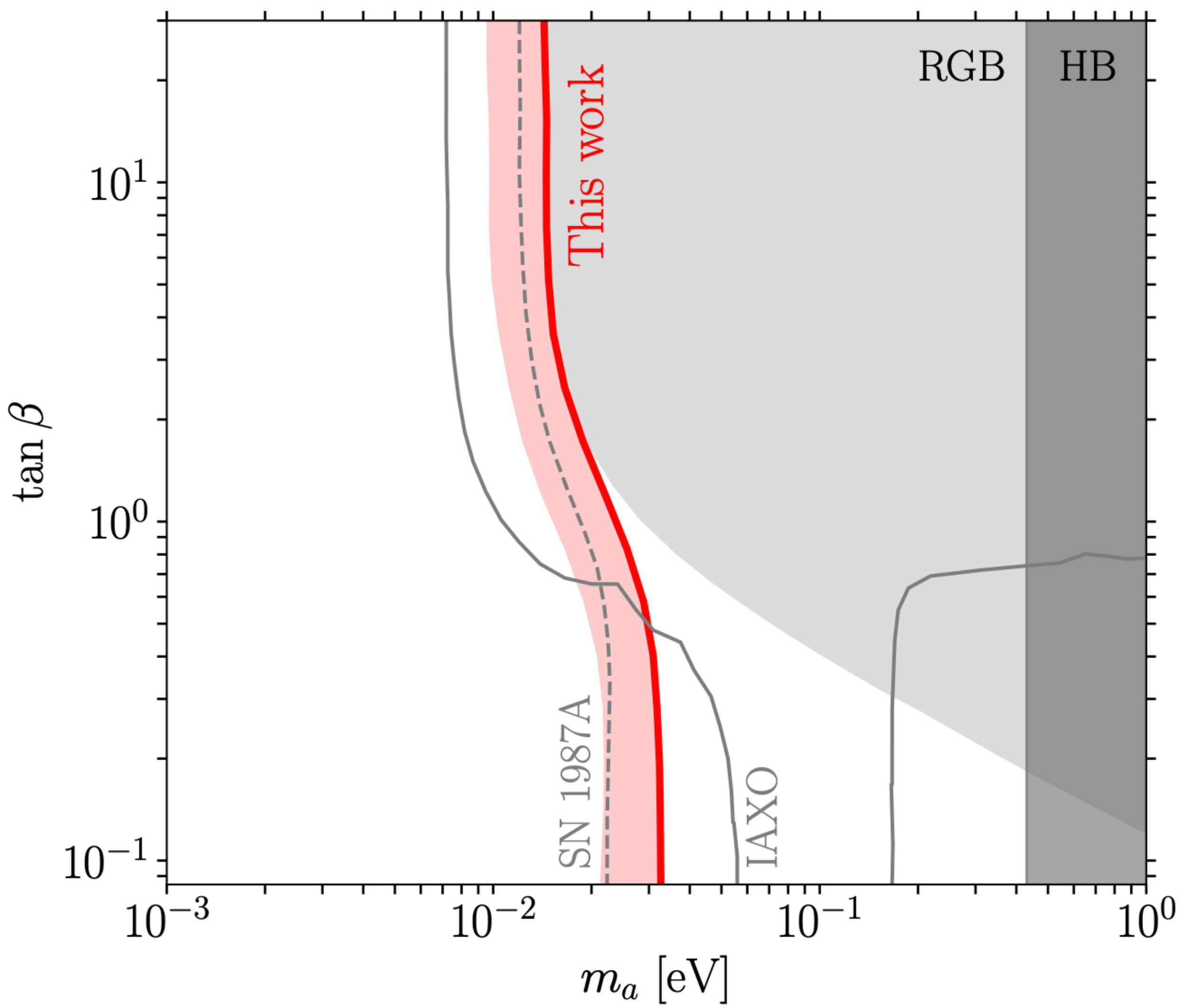
- Direct detection of SN axions

  Ge, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa, JCAP 11 (2020);
  Vonk, Guo, Meißner, *Phys.Rev.D 105 (2022)*

Significant theoretical progress in last 2 years

Neutron Stars

A lot of progress also with the Neutron Star bound



The cooling of a NS can be observed through many years. Exotic cooling would modify these observations.

- D M. Beznogov et al. *Phys.Rev.C* 98 (2018) 3
- K. Hamaguchi et al. *Phys.Rev.D* 98 (2018) 10
- Armen Sedrakian, *Phys.Rev.D* 99 (2019) 4
- M. Buschmann et al., Phys.Rev.Lett. 128 (2022) 9

Bound on the DFSZ axion

M. Buschmann et al., Phys.Rev.Lett. 128 (2022) 9

Axion Telescopes?

Axions could be excellent astrophysics messengers.
They could be far superior to photons and neutrinos to study some aspects of stellar evolution.

Dedicated axion experiments could be used to access the solar core and to learn about various solar properties:

- Solar magnetic field

  C. A. J. O'Hare, A. Caputo, A. J. Millar, E. Vitagliano Phys.Rev.D 102 (2020) 4

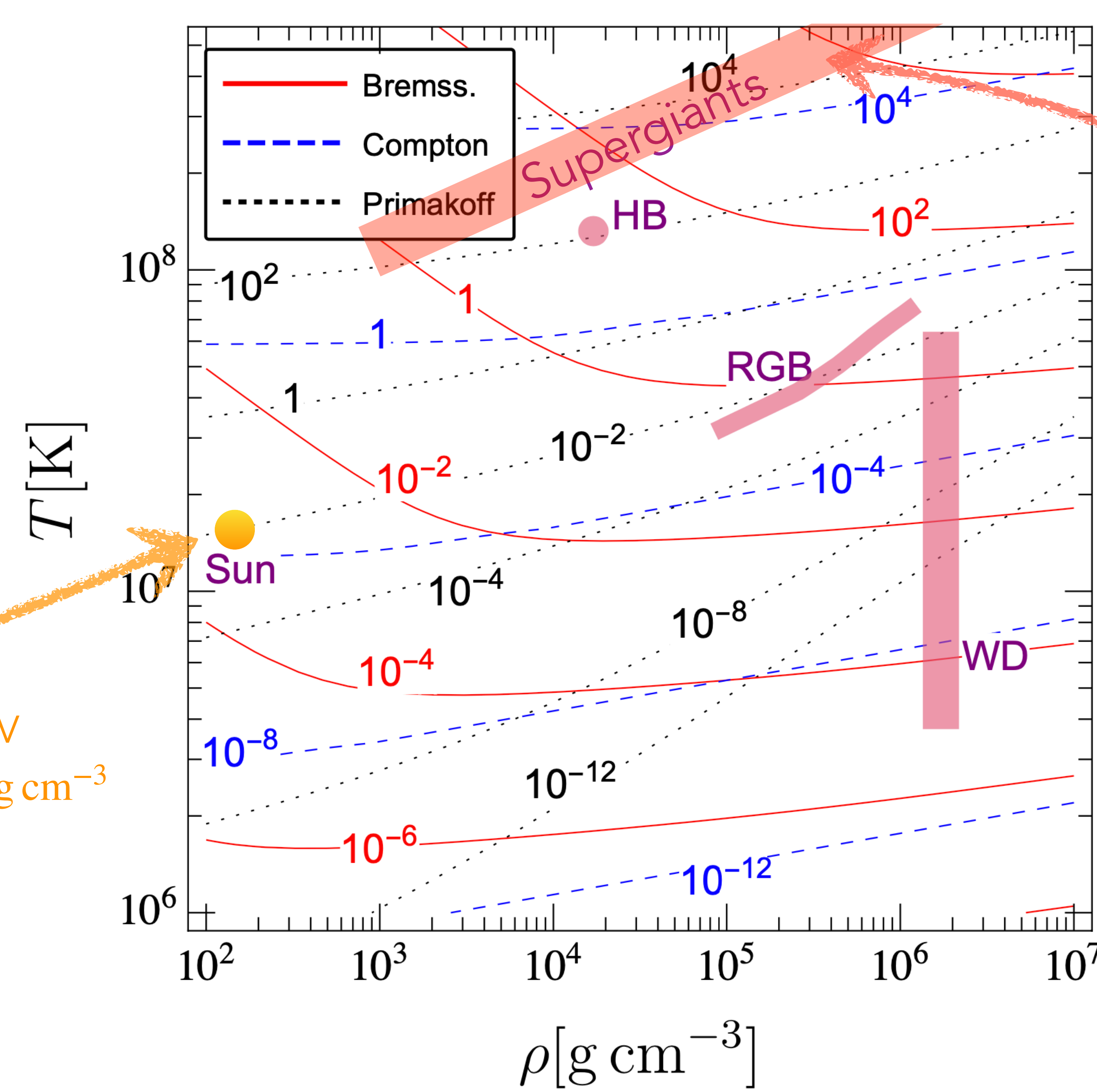
- Solar temperature profile

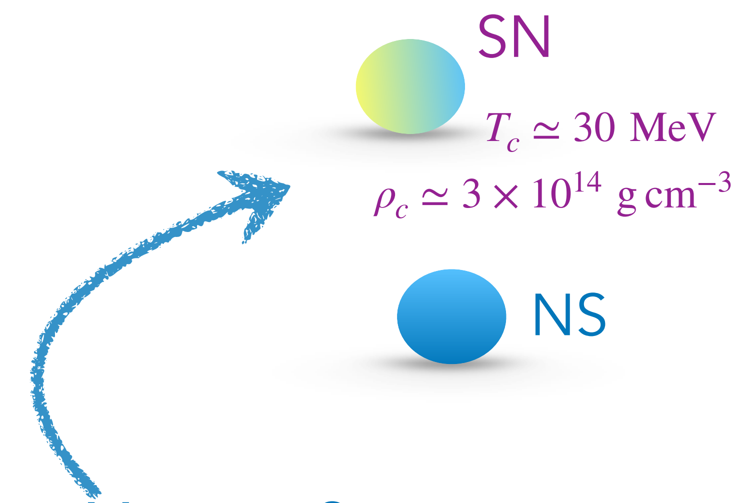
  S. Hoof, J. Jaeckel, L. J. Thormaehlen, arXiv:2306.00077

- Solar chemical composition

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

Other stars?





(See talk by A. Lella)

Sun:
$T_c \sim 1$ keV
$\rho_c \sim 10^2$ g cm^{-3}

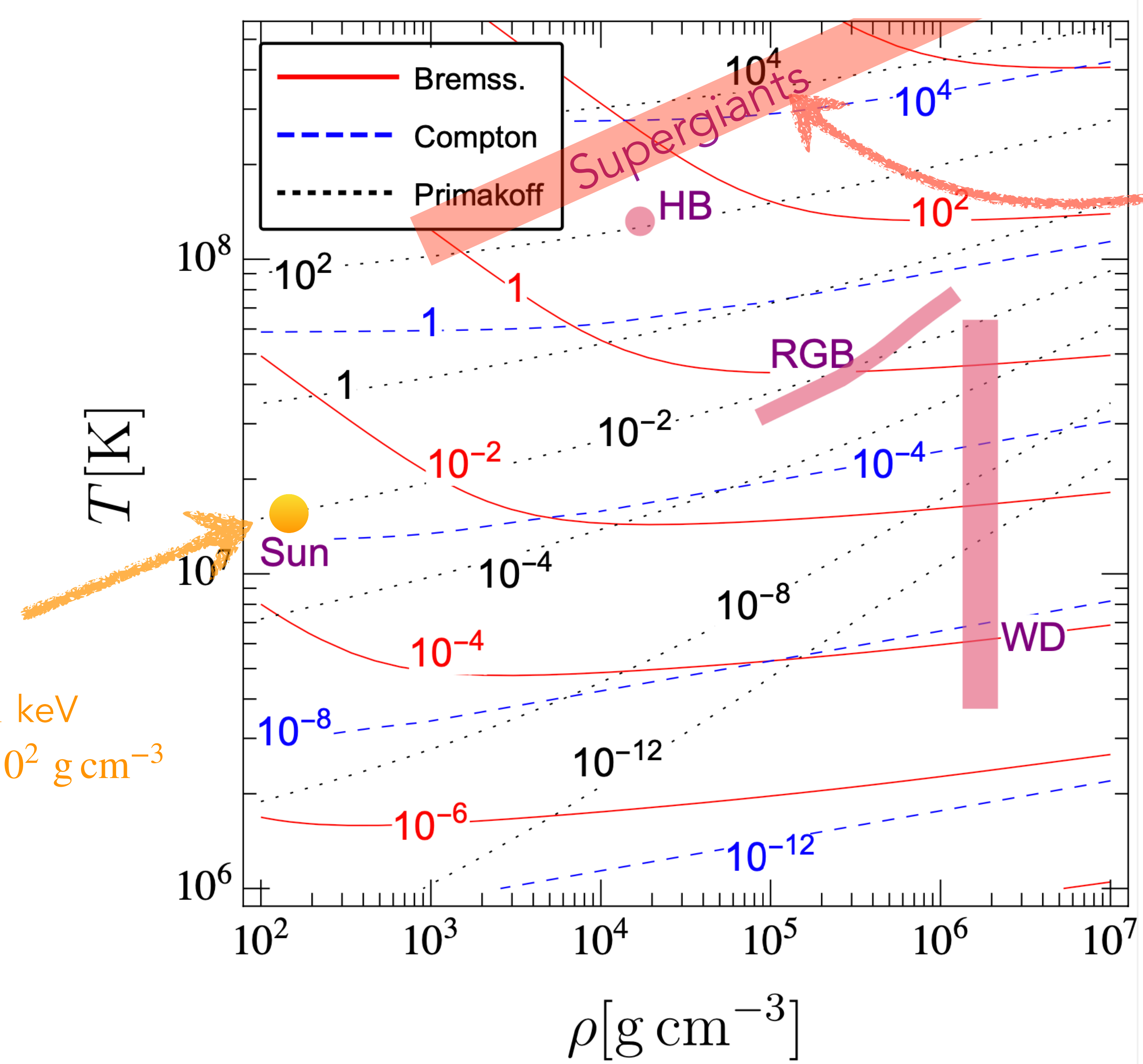
Supergiants:
T_c and ρ_c depend on mass and evolutionary stage

The sun is quite an unremarkable star… but yet, likely, our best bet

Di Luzio, MG, Nardi, Visinelli, Phys.Rept. 870 (2020)

Supergiant Stars

Axion production is very sensitive to temperature



Sun:
$T_c \sim 1$ keV
$\rho_c \sim 10^2\ \mathrm{g\,cm^{-3}}$

Supergiant stars are much hotter than the sun, especially in late evolutionary stages
→ efficient axion production.

The axion spectrum would offer a very precise map of the supergiant evolution
→ Excellent telescope for supergiant

Di Luzio, MG, Nardi, Visinelli, Phys.Rept. 870 (2020)

Axion telescopes for massive stars

			Photons		Axions		
Model	Phase	$t_{\rm cc}$ [yr]	$\log_{10}(L_{\rm eff}/L_\odot)$	$\log_{10}(T_{\rm eff}/{\rm K})$	C	E_0 [keV]	β
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

Axions are sensitive to the evolution and can pin down t_{cc} from $\sim 10^{-5}$ yr M. Xiao et al., Phys.Rev.Lett. 126 (2021) 3, 031101

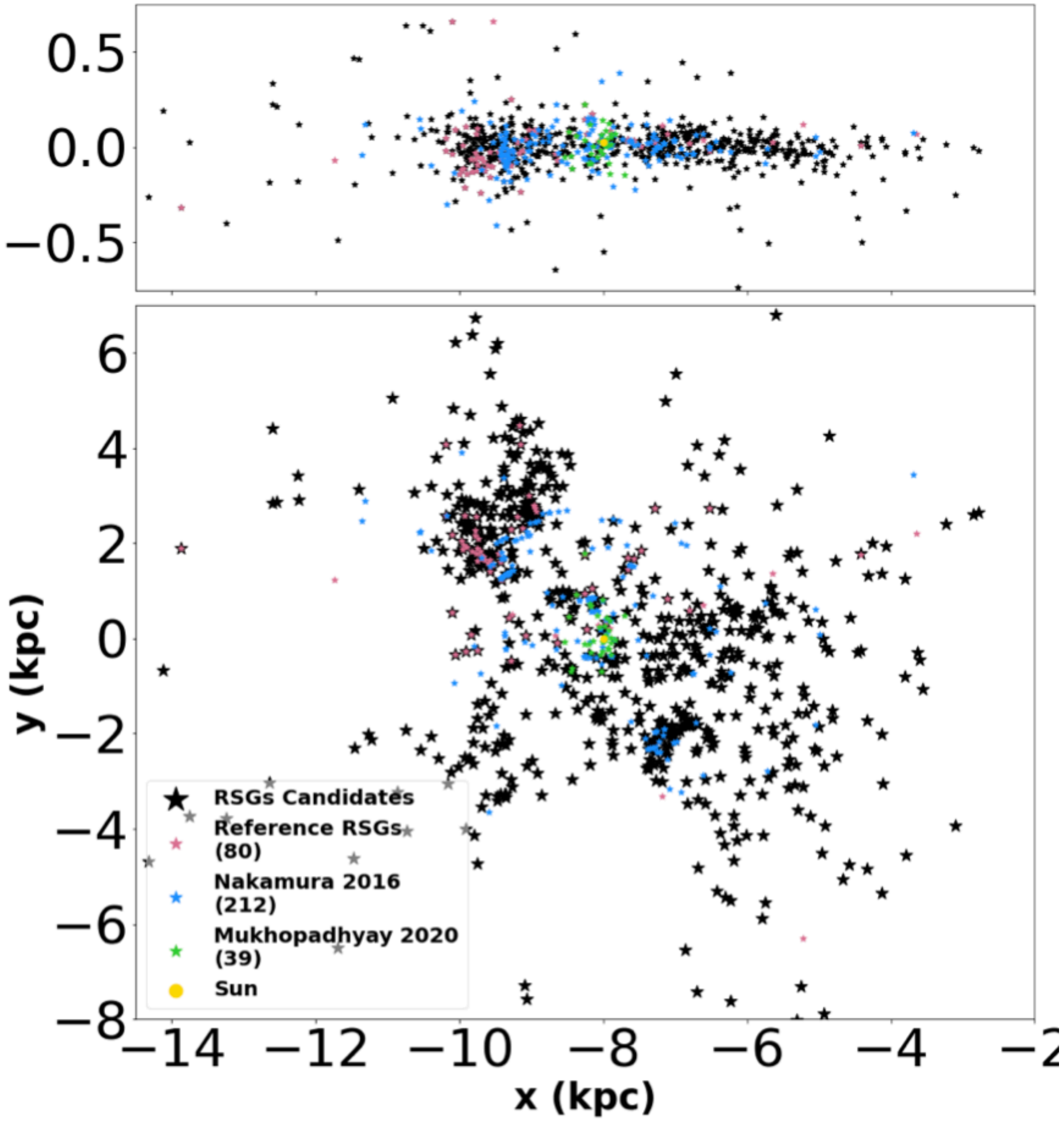
$$\frac{d\dot{N}_a}{dE} = \frac{10^{42} C g_{11}^2}{\text{keV s}} \left(\frac{E}{E_0}\right)^{\beta} e^{-(\beta+1)E/E_0}$$

Axion spectrum

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

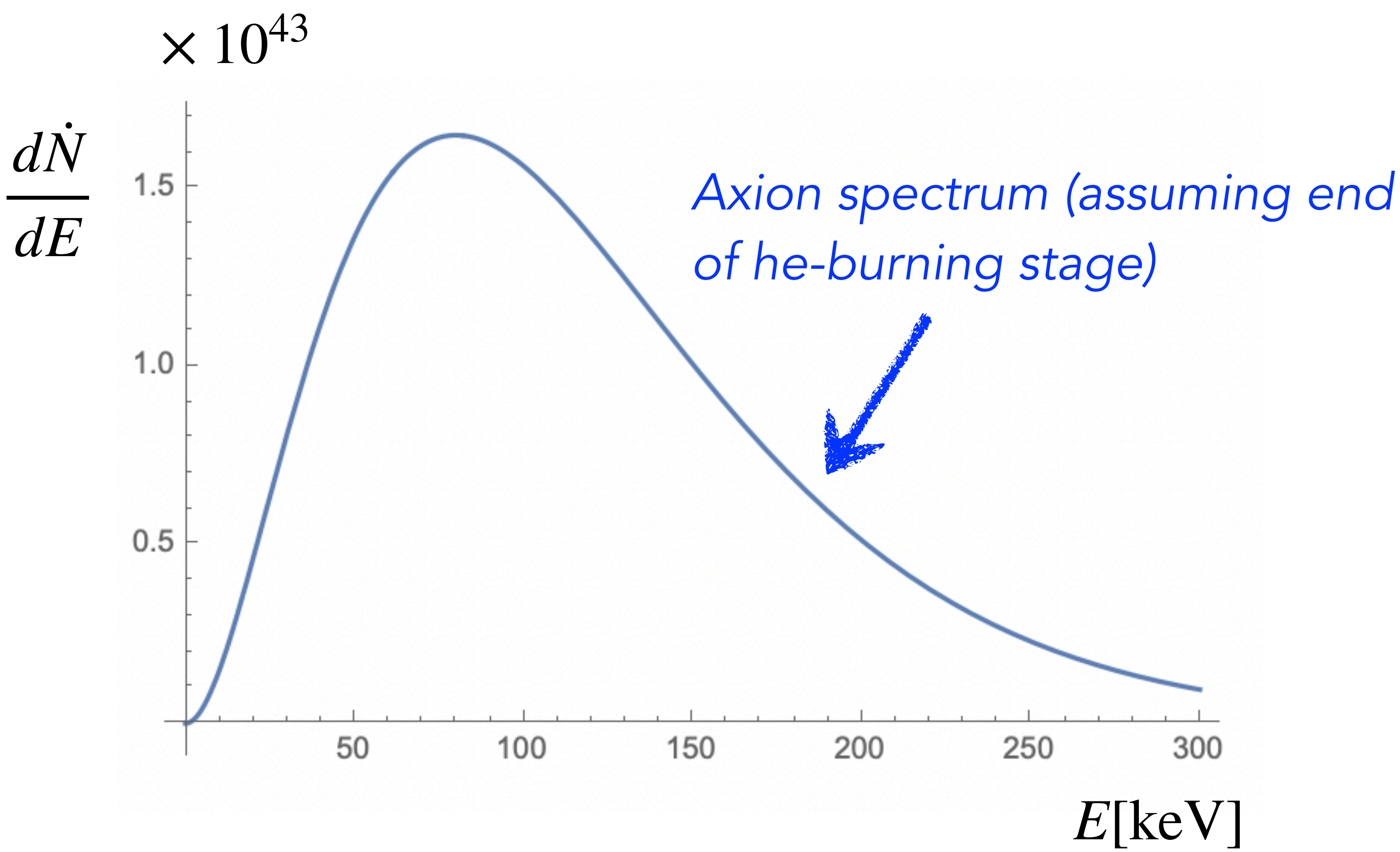
Where should we look ?

Brand new catalog of Red SG, Sarah Healy et al., arXiv:2307.08785



Many stars are at a few kpc from the Sun.

Axion telescopes for massive stars. Is it feasible?



Total: $\sim 10^{45}$ axions/s, (many more than from the sun) peaked at $\sim 100\,\mathrm{keV}$

… however, in the case of Betelgeuse (~200 pc from us) ⇒ $0(10^3)$ axions $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Too little for current experiments!

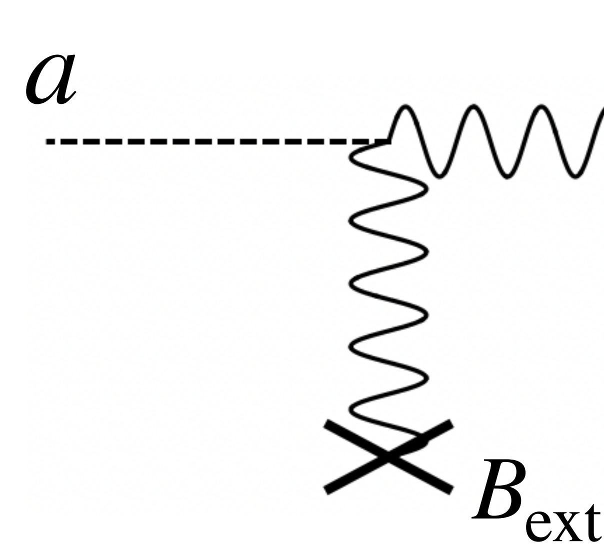
Axion telescopes for massive stars. Is it feasible?

Axions can convert into photons in the magnetic field between us and the star

$$P_{a\gamma} = 8.7 \times 10^{-6} g_{11}^2 \left(\frac{B_T}{1\ \mu\text{G}}\right)^2 \left(\frac{d}{197\,\text{pc}}\right)^2 \frac{\sin^2 q}{q^2}$$

(Assuming B uniform)

$g_{11} \leq 6.5$ from helioscope (CAST) bound



Axion telescopes for massive stars. Is it feasible?

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(Assuming B uniform)

$g_{11} \leq 6.5$ from helioscope (CAST) bound

There is a very high price to pay!

This term effetely limits to $m_a \lesssim 10^{-10}\,\mathrm{eV}$

Axion telescopes for massive stars. Is it feasible?

Axions can convert into photons in the magnetic field between us and the star

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(Assuming B uniform)

$g_{11} \leq 6.5$ from helioscope (CAST) bound

There is a very high price to pay!

This term effetely limits to $m_a \lesssim 10^{-10}\,\mathrm{eV}$

However, if we limit ourselves to $m_a \lesssim 10^{-10}\,\mathrm{eV}$, then $q \ll 1$ and the distance (practically) drops from the flux! We may get a very large flux ~ 100 keV X-rays.

Can we see massive stars with an axion telescope?

Detecting Supernova axions?

General criterion (Raffelt) from observed ν-signal form SN 1987A:

$$\varepsilon_x \lesssim 10^{19}\,\mathrm{erg\,g^{-1}s^{-1}} \qquad @ \qquad \rho = 3\times 10^{14}\,\mathrm{g\,cm^{-3}},\ T = 30\,\mathrm{MeV}$$

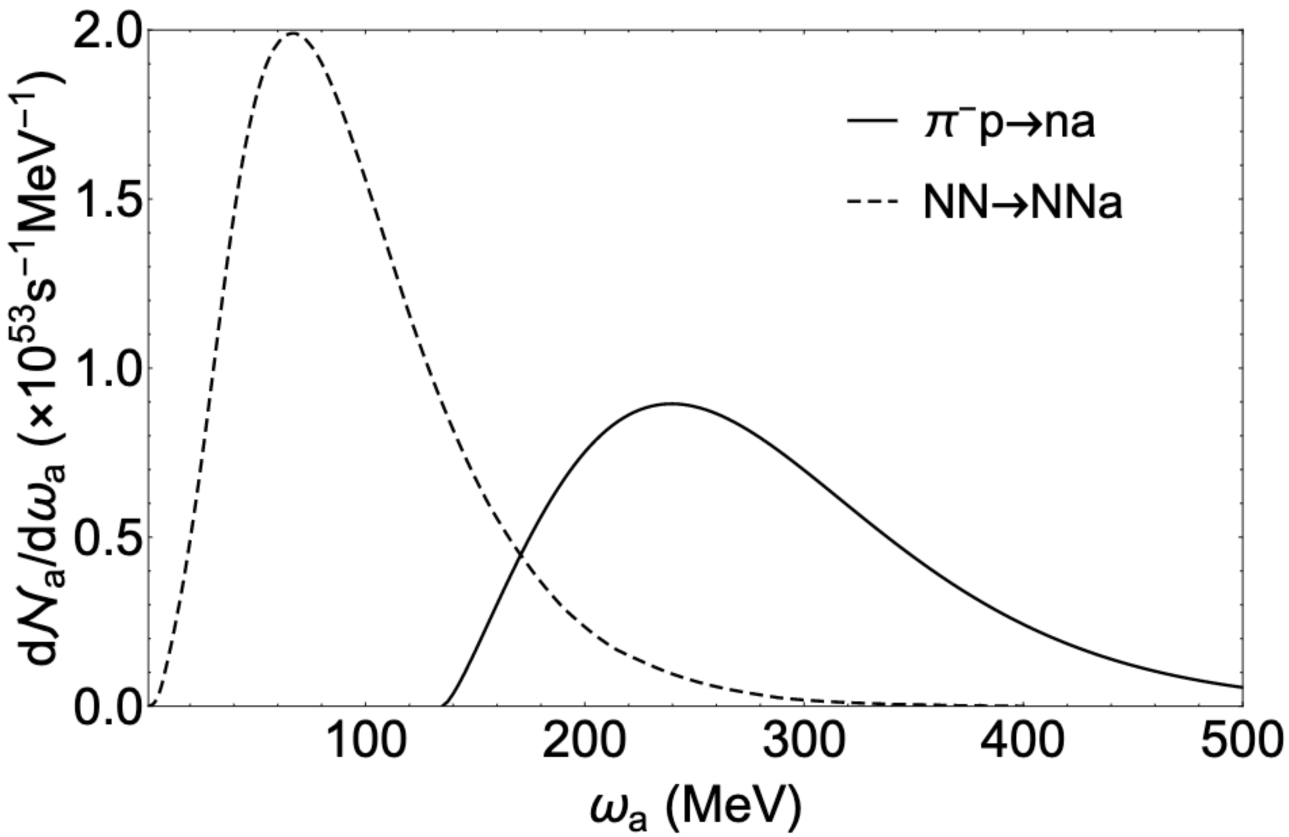
$\Rightarrow \sim 10^{52}\,\mathrm{erg/s}$ for ~10 s in axions

Corresponds to $\sim 10^{56}\,\mathrm{axions/\,s}$.

About $\sim 10^{13}\,\mathrm{cm^{-2}\,s^{-1}}$ axions on Earth from Betelgeuse

Huge flux… but short!

Looking into the SN core



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

A SN might produce a huge ALP flux on Earth $\sim 10^{13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ from Betelgeuse, larger than the flux from the Sun. However, short.

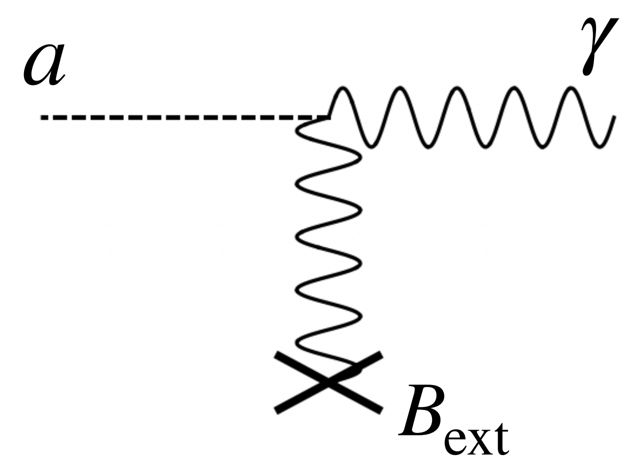
Direct Detection? Water Cherenkov? Helioscopes?
All this is still under study

Carenza et al. (2023)
arXiv:2306.17055

Fermi LAT as Axion SN-Scope

SN axions:

→ photons in galactic B



M. Meyer , M. G., A. Mirizzi, J. Conrad, M.A. Sánchez-Conde, Phys.Rev.Lett. 118 (2017)

probes very low (sub neV) mass region, down to

$g_{a\gamma} \sim 4 \times 10^{-12}\,\mathrm{GeV}^{-1}$

Calore et al. arXiv:2306.03925

Very efficient at low mass

SN axions:

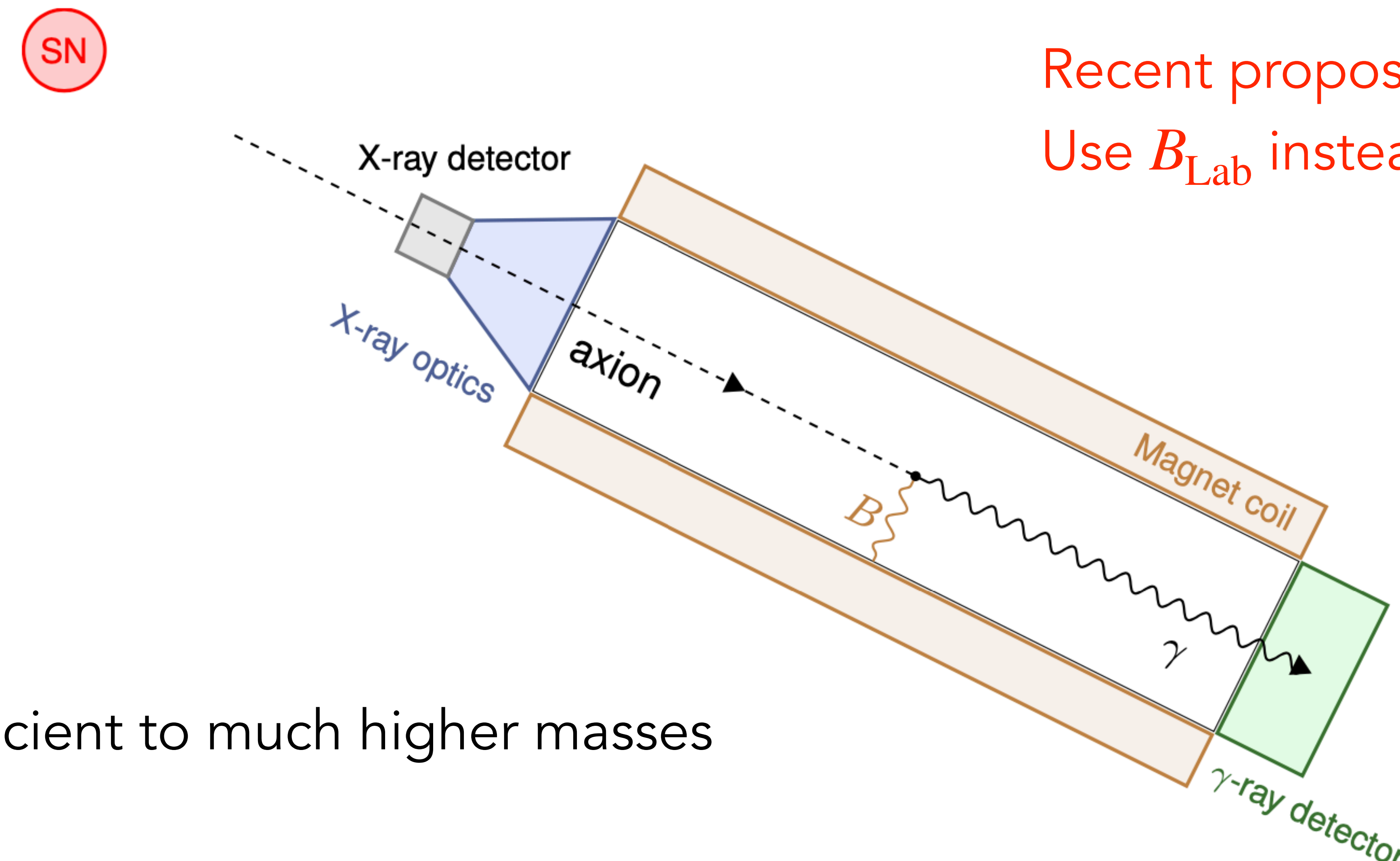
→ photons from decay into γ

ALP decay into photons: constraints in the massive region $m_a \sim 1 - 100$ MeV,

$g_{a\gamma} \sim 10^{-11} - 10^{-12}\,\mathrm{GeV}^{-1}$

E. Mulle et al., arXiv:2304.01060

Helioscopes as Axion SN-Scopes



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

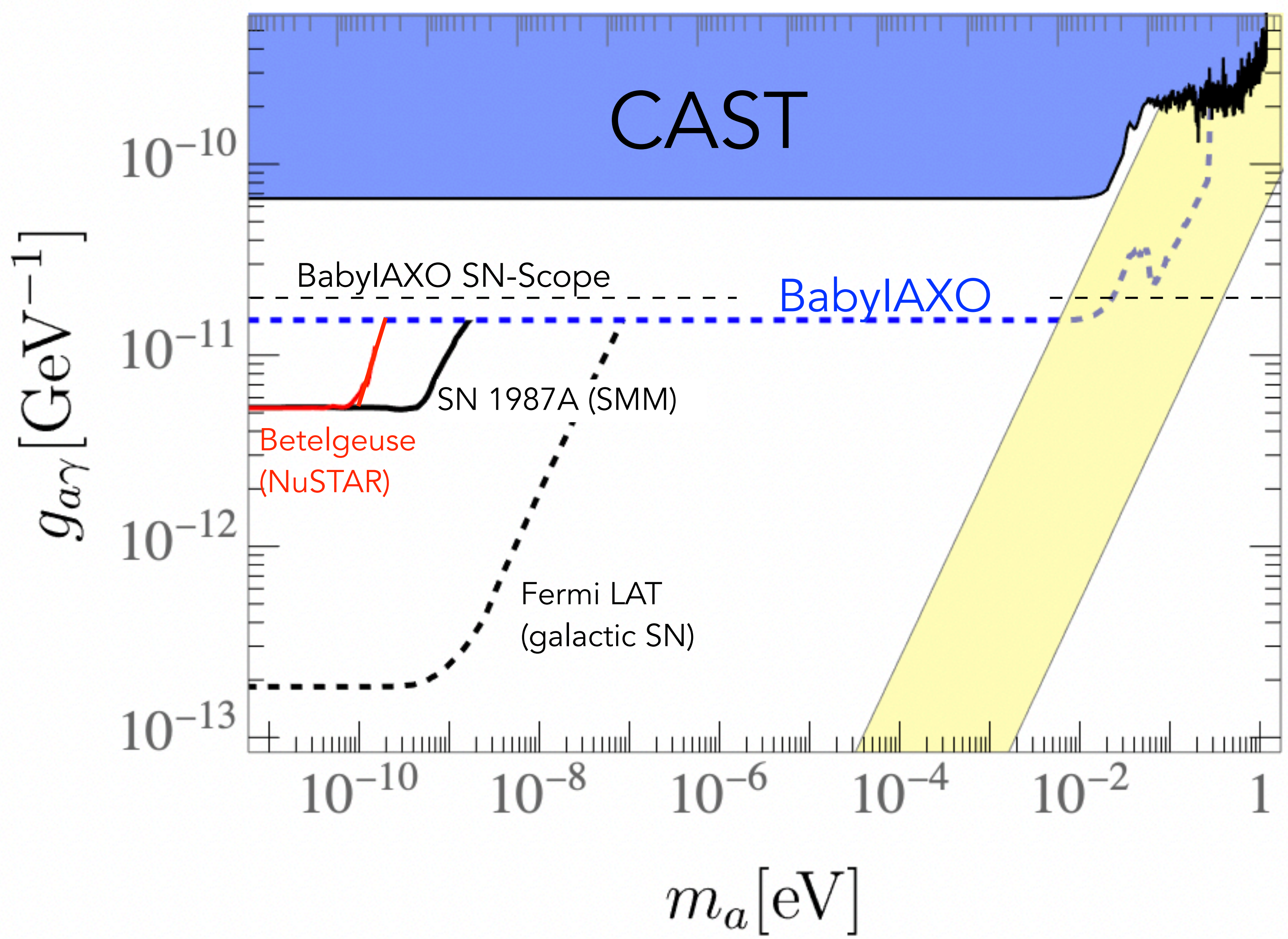
Axion helioscope
turned around

Efficient to much higher masses

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

Ge, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa JCAP 11 (2020) 059

Summary: Detecting stellar axions



Legend:

Solar Axion

Pre-SN Axions

SN Axions

Current bounds

Estimated sensitivities

Benchmark QCD models

Part 3: Experimental Hunts

Natural Axion/ALP sources

Cosmological	Realignment	Non-thermal: CDM	$E_a \simeq m_a$
	Topological Defects		
	Thermal	HDM	

Astrophysical	Stellar	Thermal	$E_a \sim T_{\rm core}$, keV or 100 MeV (SN)
		Nuclear	$E_a \sim$ keV, MeV
		Resonant $\gamma + B \rightarrow a + B$	$E_a \sim \omega_{pl}$ (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

Realignment, Topological Defects → Direct: Haloscopes

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_{ext} — Indirect ($a + B \to \gamma$) Chandra, NuSTAR,Fermi…

Hunting down the elusive axions

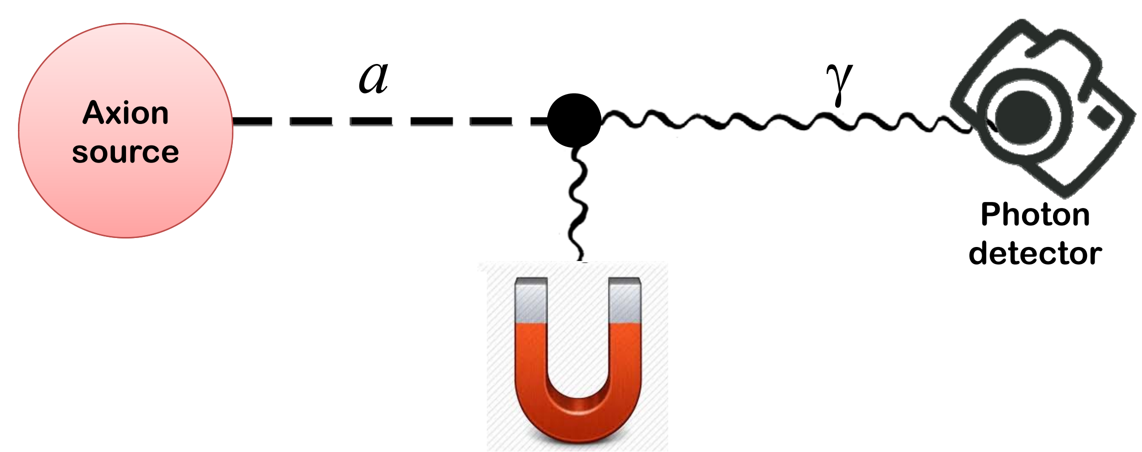
Our focus: $m_a \lesssim 1\mathrm{eV}$.

Specific experimental challenges, and combination of specific know-hows

→ **cross-disciplinary technology transfer:**
E.g.,high-field magnets, super-conduction, RF techniques, X-ray optics, low background detection, low radioactivity techniques, quantum sensors, atomic physics, etc.

Most (but not all) of the axion detection strategies rely on the axion-photon coupling $g_{a\gamma}$.

In many (but not all) cases detection strategies make use of the axion-photon coupling
$a\,\vec{E}\cdot\vec{B}$



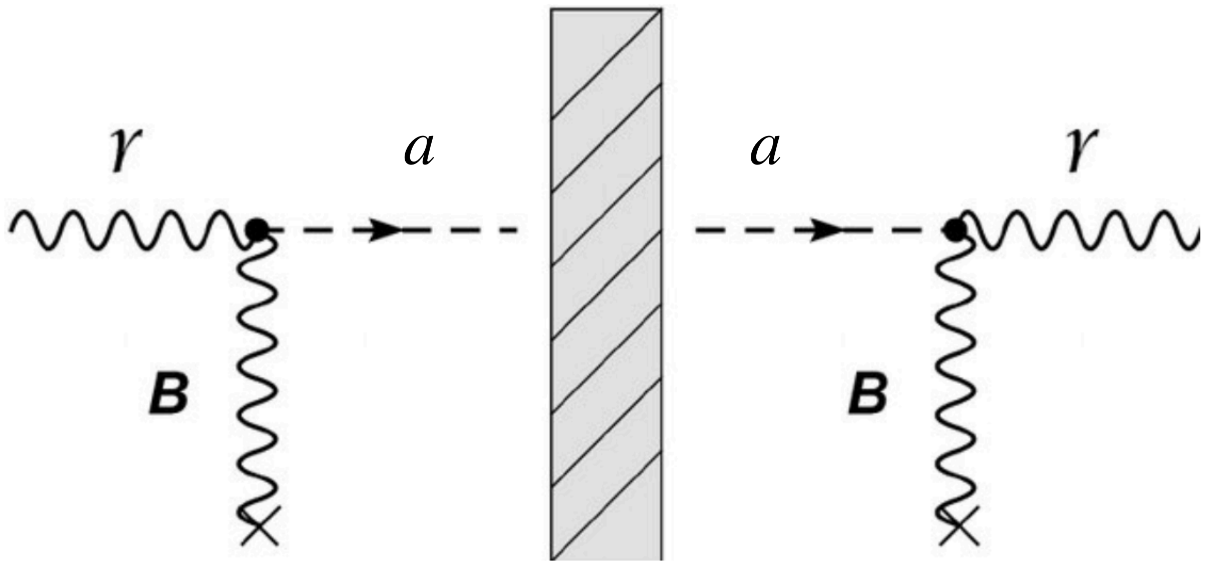
Sikivie (1983)

Detection method	$g_{a\gamma}$	g_{ae}	g_{aN}	$g_{A\gamma n}$	$g_{a\gamma}g_{ae}$	$g_{a\gamma}g_{aN}$	$g_{ae}g_{aN}$	$g_N\bar{g}_N$	**Model dependency**
Light shining through wall	×								no
Polarization experiments	×								no
Spin-dependent 5th force			×				×	×	no
Helioscopes	×				×	×			Sun
Primakoff-Bragg in crystals	×				×				Sun
Underground ion. detectors	×	×	×			×	×		Sun*
Haloscopes	×								DM
Pick up coil & LC circuit	×								DM
Dish antenna & dielectric	×								DM
DM-induced EDM (NMR)			×	×					DM
Spin precession in cavity		×							DM
Atomic transitions		×	×						DM

Table 3: List of the axion detection methods discussed in the review, with indication of the axion couplings (or product of couplings) that they are sensitive to, as well as whether they rely on astrophysical (axions/ALPs are produced by the Sun) or cosmological (the dark matter is made of axions/ALPs) assumptions. *Also "DM" when searching for ALP DM signals, see section 6.2

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

Light Shining Through a Wall



Relativisti axions:

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

B= magnetic field
L= magnet length
q = momentum transfered

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

Lost of coherence for $qL \gtrsim 1$

Everything is under control. However, signal suppressed as $g_{a\gamma}^4$

Light Shining Through a Wall

→ **ALPS** @ DESY and the **OSQAR** @ CERN are active LSW experiments.
Use powerful accelerator dipole magnets, from HERA (ALPS) and LHC (OSQAR).
In both cases the sensitivity drops above $m_a \sim 10^{-4}$ eV .

→ **CROWS** experiment @ CERN

Uses a different wavelength: microwaves!

Large scale MW LSW studied and proposed in the literature → **STAX**
LSW at X-rays also explored in the past (not large power)

→ Next Gen: **JURIA**. Concept being discussed at the Physics Beyond Colliders (PBC) group at CERN

- L ~ 1km, B ~13T, P~2.5 MW,... Very challenging parameters...
- Physics case to be settled (it may depend if positive signal in other exps)

Relativisti axions:

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

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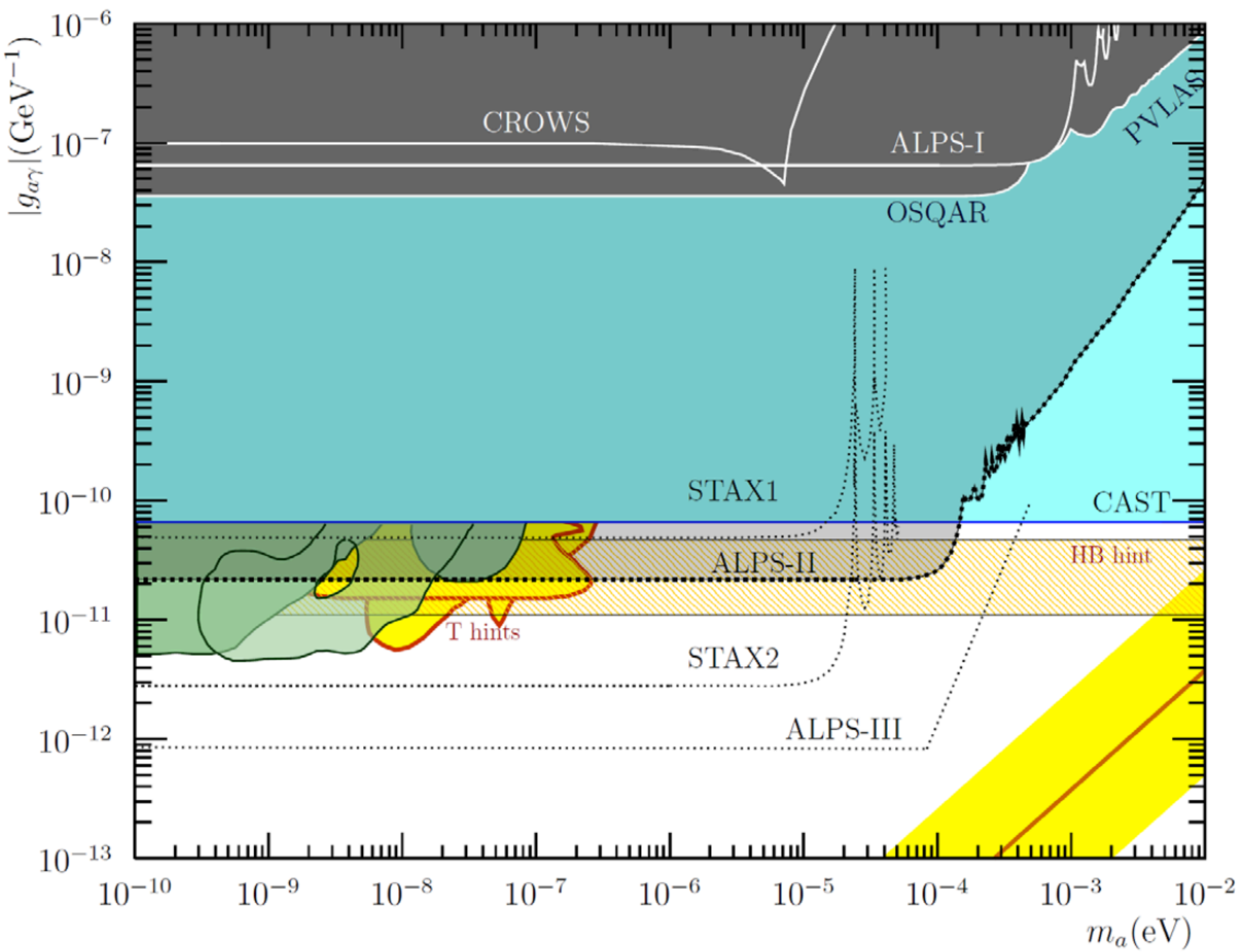
Light Shining Through a Wall



LSW experiments

Figure and table from I. Irastorza, J. Redondo, Prog.Part.Nucl.Phys. 102 (2018)

Experiment	status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma}[\mathrm{GeV}^{-1}]$
ALPS-I [433]	completed	5	4.3	4	300	1	5×10^{-8}
CROWS [435]	completed	3	0.15	50	10^4	10^4	9.9×10^{-8}(*)
OSQAR [434]	ongoing	9	14.3	18.5	-	-	3.5×10^{-8}
ALPS-II [436]	in preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [437]	concept	13	426	200	12500	10^5	10^{-12}
STAX1 [438]	concept	15	0.5	10^5	10^4	-	5×10^{-11}
STAX2 [438]	concept	15	0.5	10^6	10^4	10^4	3×10^{-12}

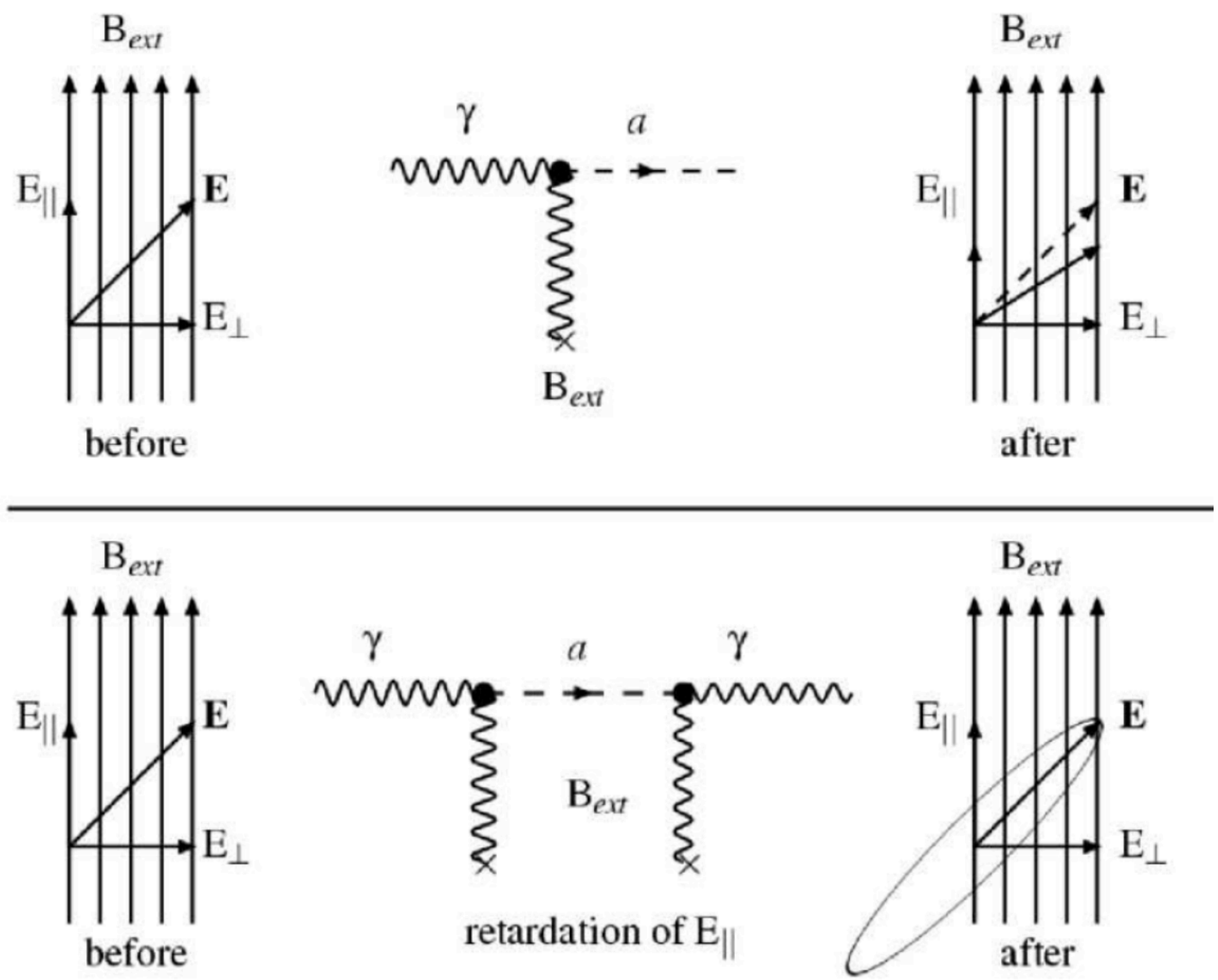
Polarization experiments

Dichroism:

Production of real particles

Ellipticity:

Production of massive virtual particles



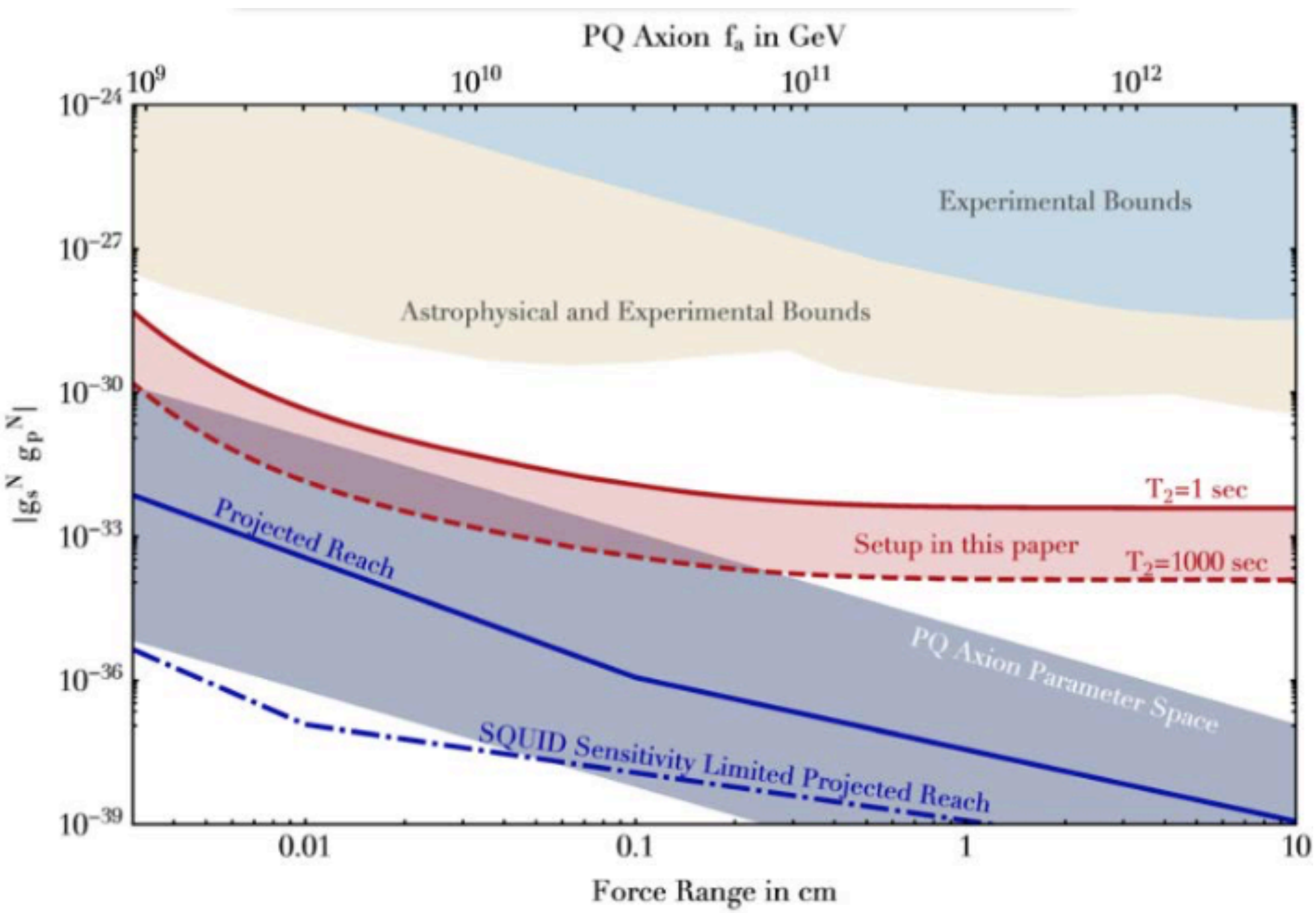
PVLAS experiment: study QED vacuum birefringence (standard effect), but also sensitivity to ALPs:

Future project under discussion at PBC: VMB@CERN

Long-range macroscopic forces

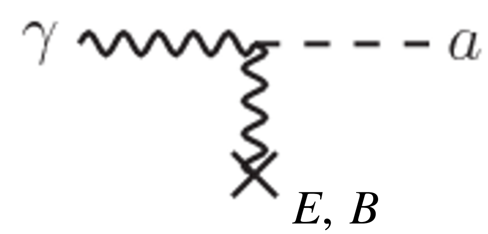
Recently proposed: ARIADNE experiment Short-range force by NMR technique
Good prospects for sub-meV axion

Notice, however, that the bounds shown are valid only under strong theoretical assumptions



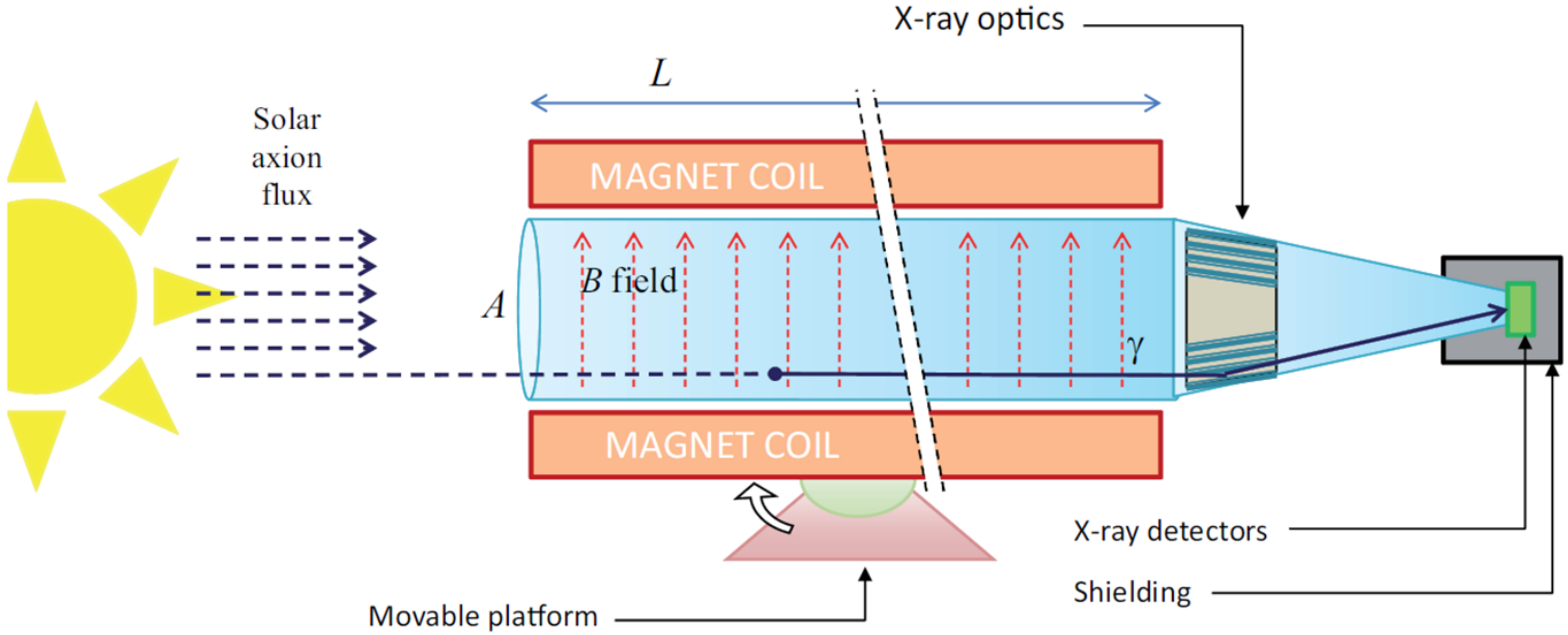
Arvanitaki, Geraci
Phys. Rev. Lett. 113, 161801 (2014)

The Hunt for Solar Axions

Coupling	Process	Energy
$g_{a\gamma}$	Primakoff (E) 	$\sim (3-4)\,\mathrm{keV}$
	Primakoff (B)	$\sim (10-200)\,\mathrm{eV}$ (LP) $\lesssim 1\,\mathrm{keV}$ (TP)
g_{ae}	ABC e.g., $e + Z_e \to Ze + e + a$	$\sim 1\,\mathrm{keV}$
g_{aN}	nuclear reactions $p + d \to {}^3\mathrm{He} + a$	$5.5\,\mathrm{MeV}$
	Nuclear de-excitation ${}^{57}\mathrm{Fe}^* \to {}^{57}\mathrm{Fe} + a$	$14.4\,\mathrm{keV}$
	${}^7\mathrm{Li}^* \to {}^7\mathrm{Li} + a$	$0.478\,\mathrm{MeV}$
	${}^{83}\mathrm{Kr}^* \to {}^{83}\mathrm{Kr} + a$	$9.4\,\mathrm{keV}$

Hunting Solar Axions:
Sikivie Helioscope

P. Sikivie PRL 51:1415 (1983)



Rescalable: increasing collecting area, length, and B.

Sensitivity

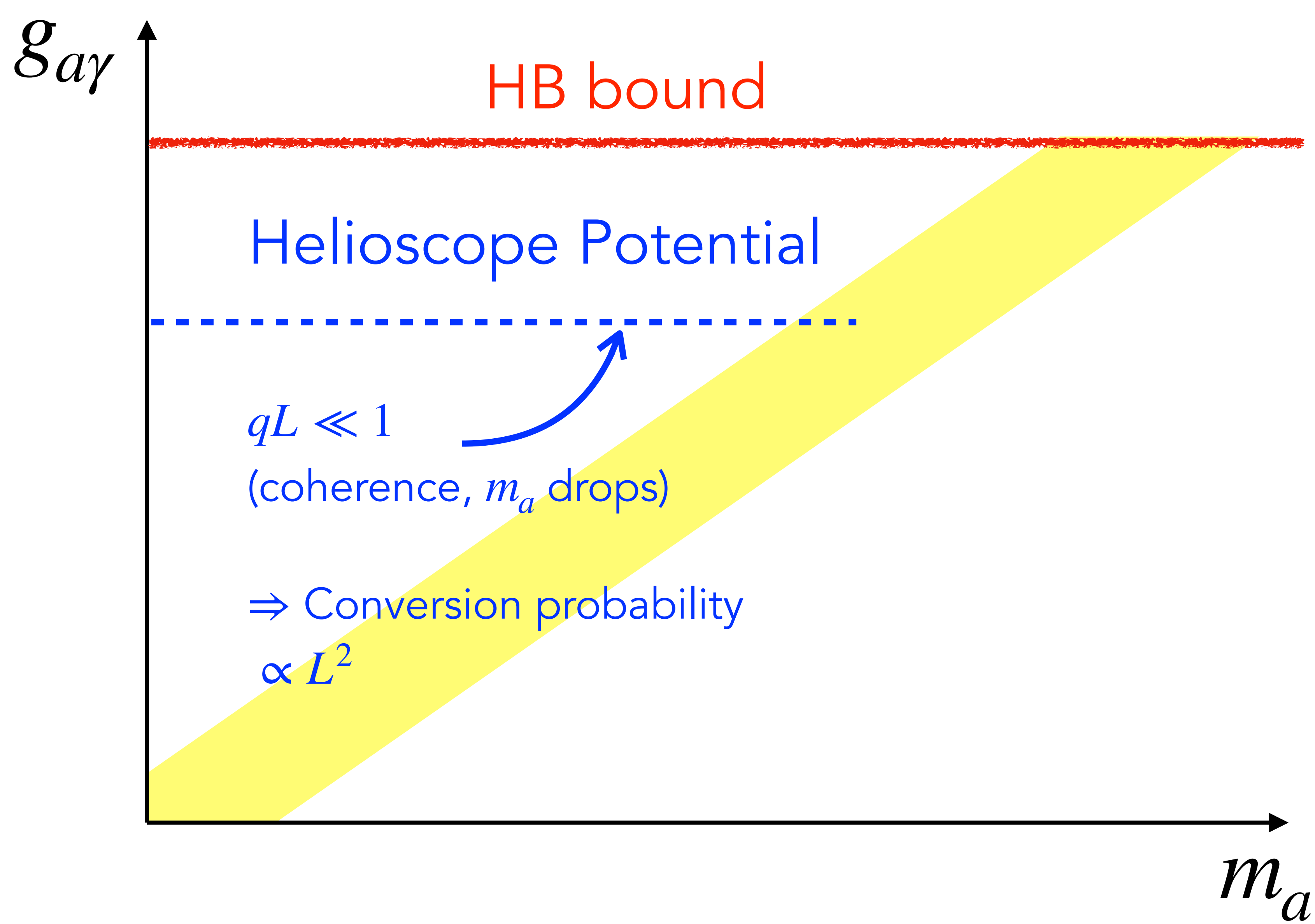
$$P_{a\gamma} = \left(\frac{g_{a\gamma} B L}{2}\right)^2 \frac{\sin^2(qL/2)}{(qL/2)^2}$$

B= magnetic field

L= magnet length

q= momentum transfer

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



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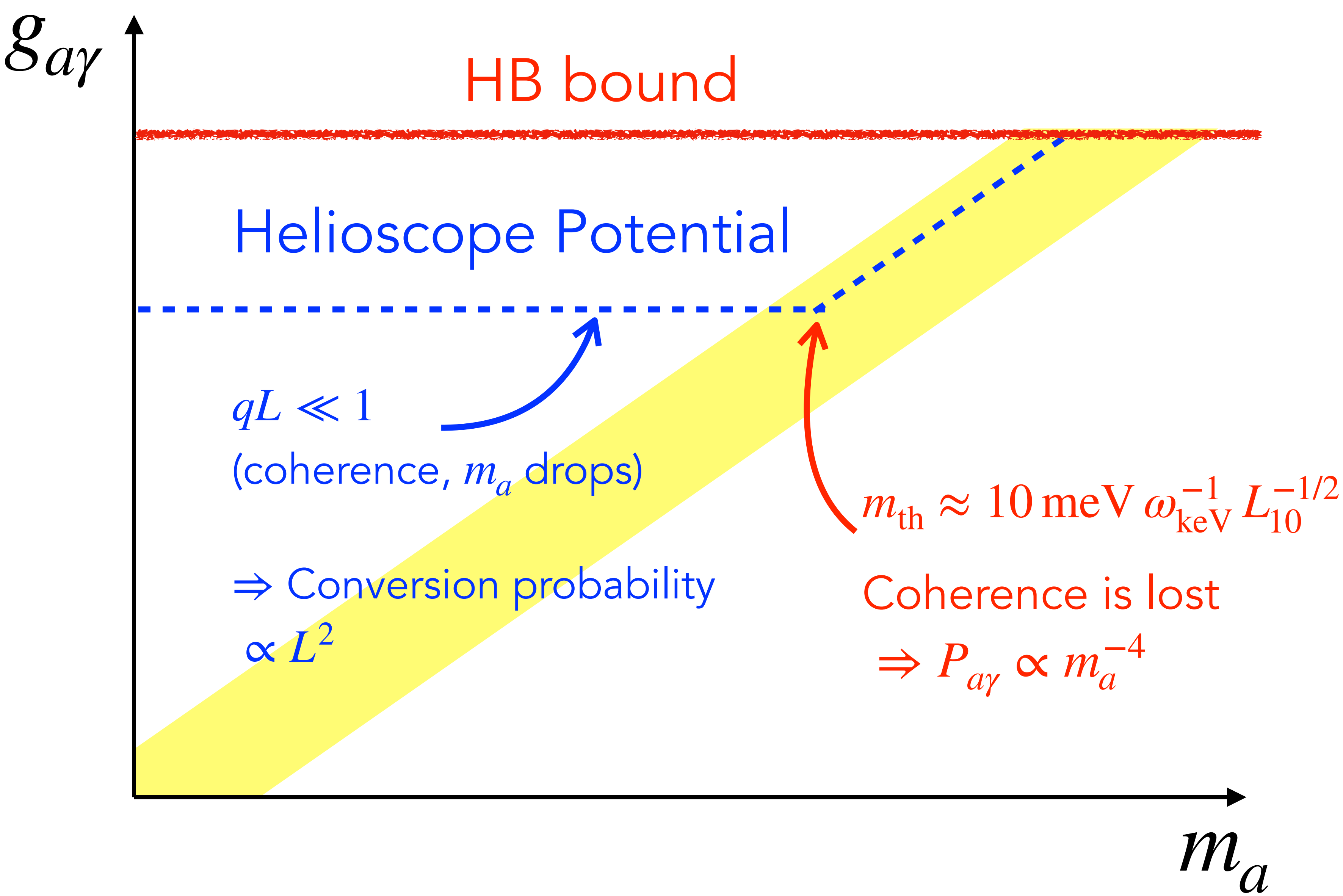

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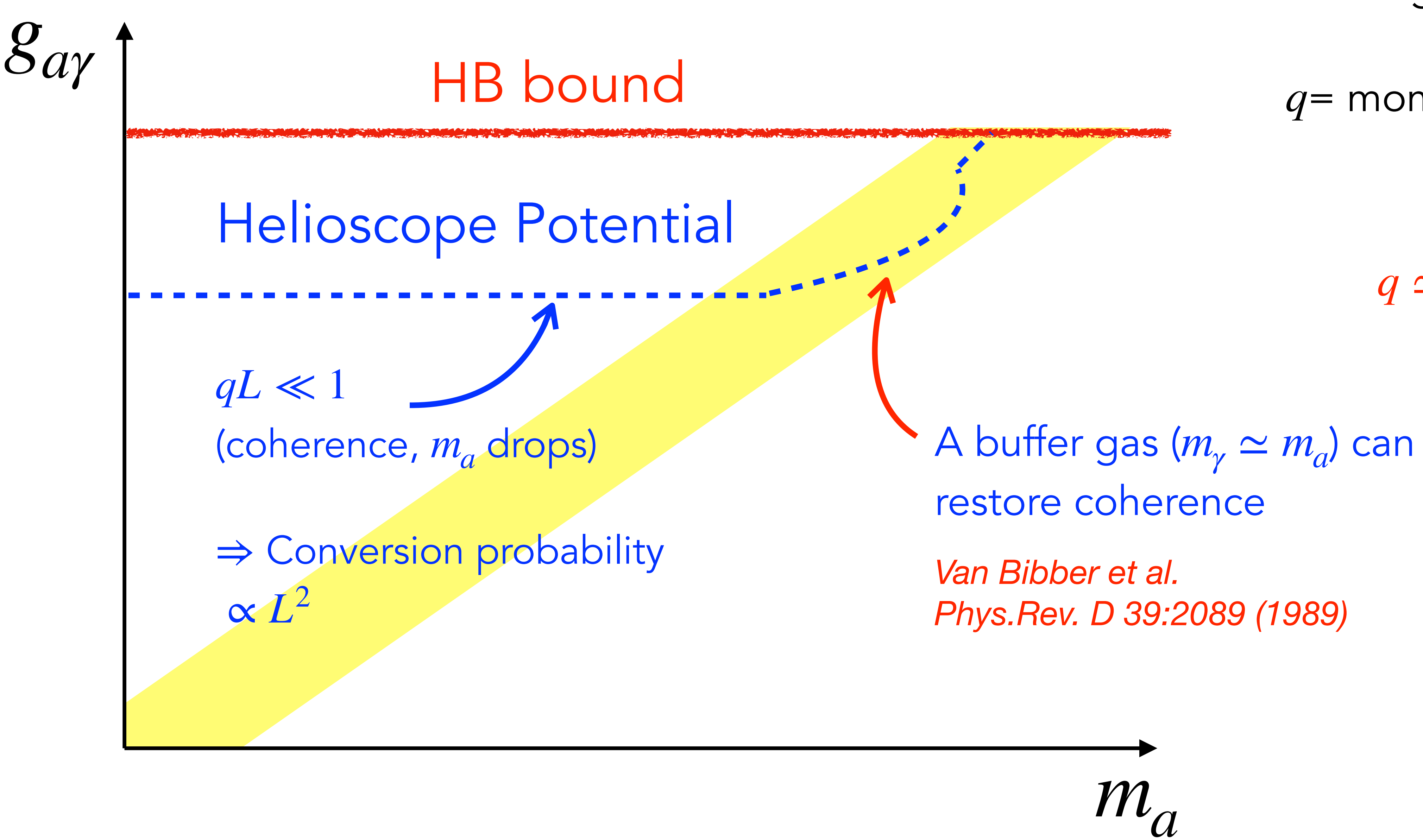
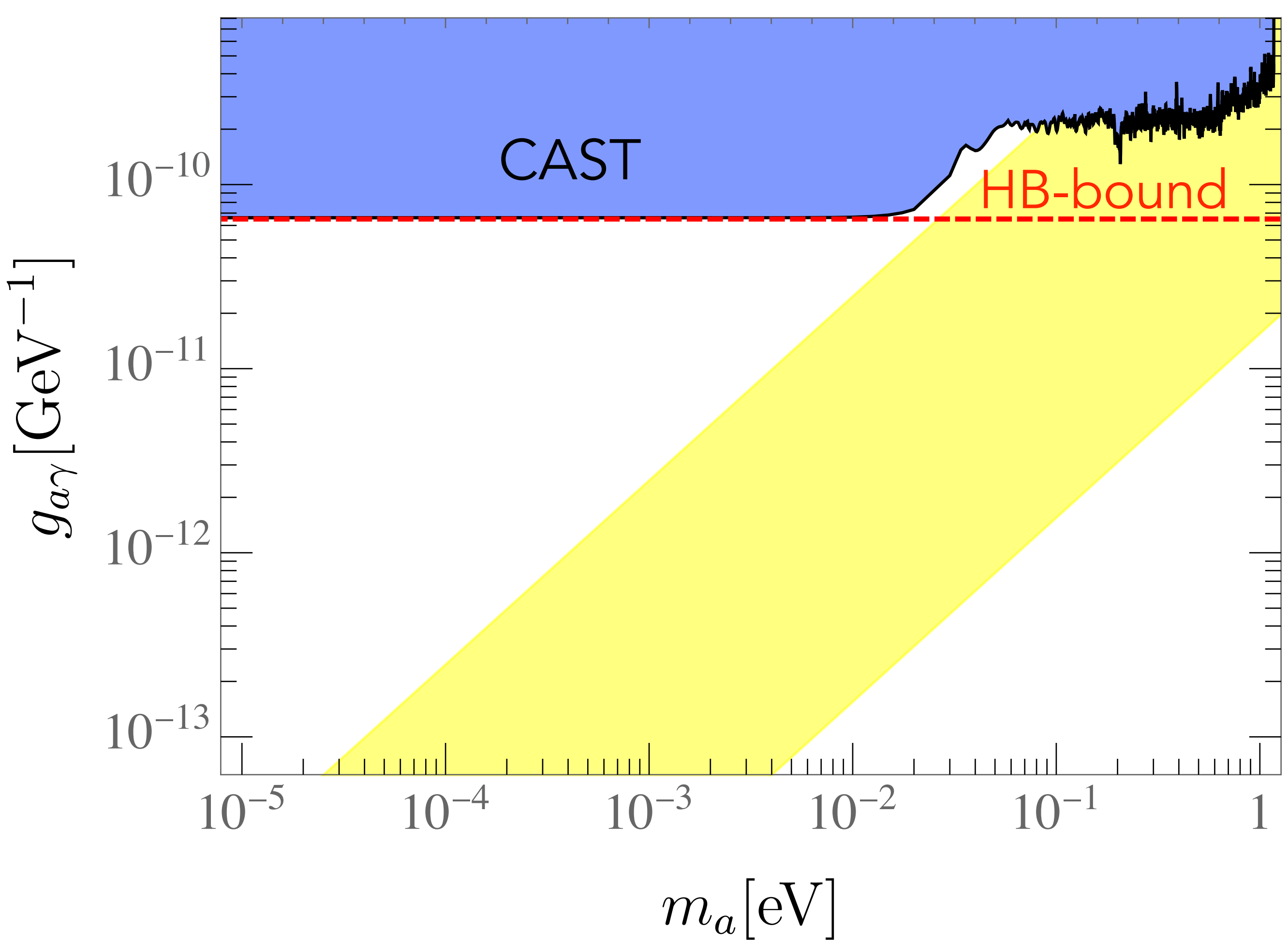


The CERN Axion Solar Telescope (CAST)

Reached the HB bound for the first time

V. Anastassopoulos, et al., Nature Phys. 13 (2017)



Decommissioned LHC test magnet,
B=9T, D=43 mm, L= 9.3 m

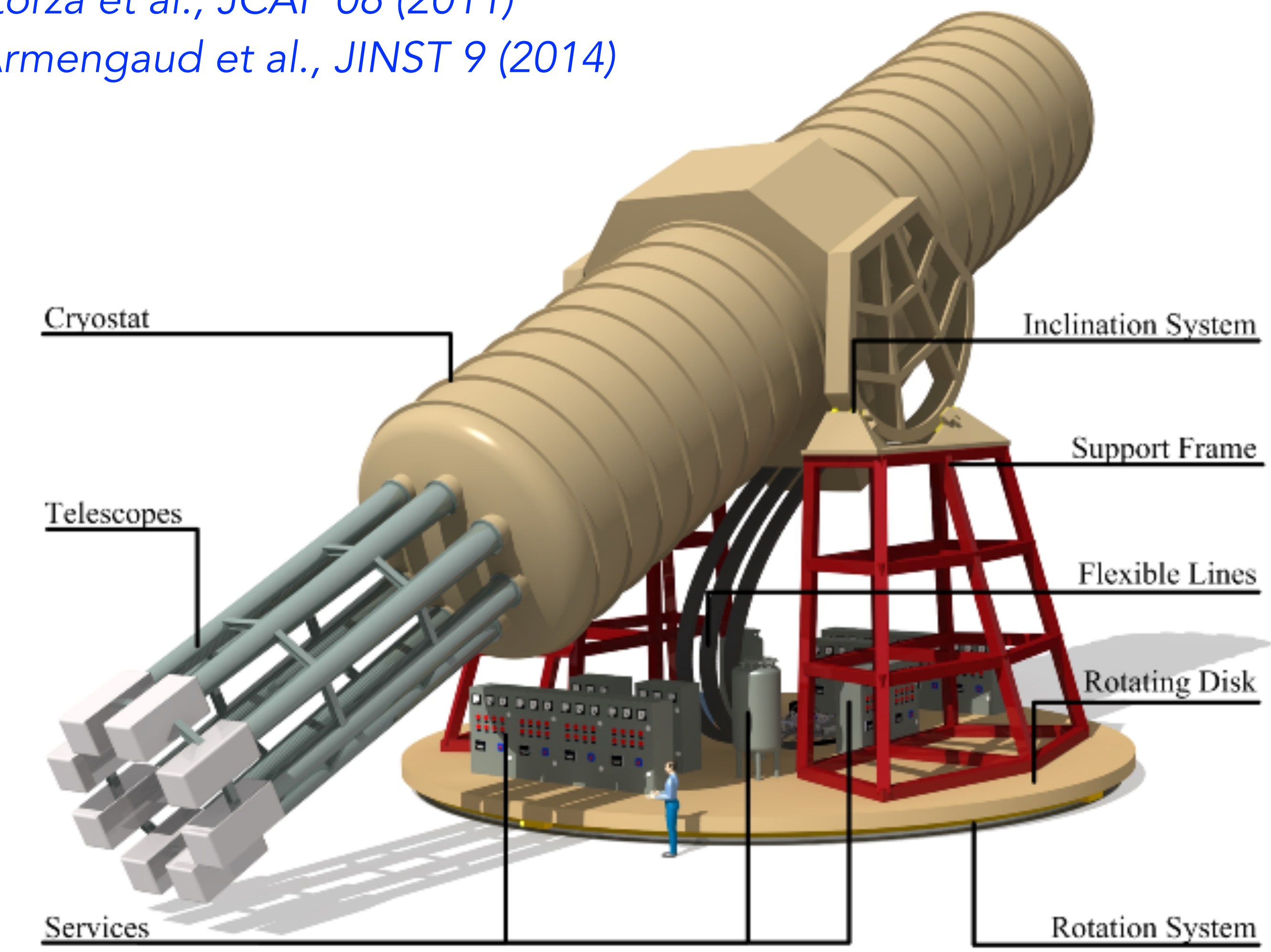
~2 h tracking/day

X-ray optics

The International AXion Observatory

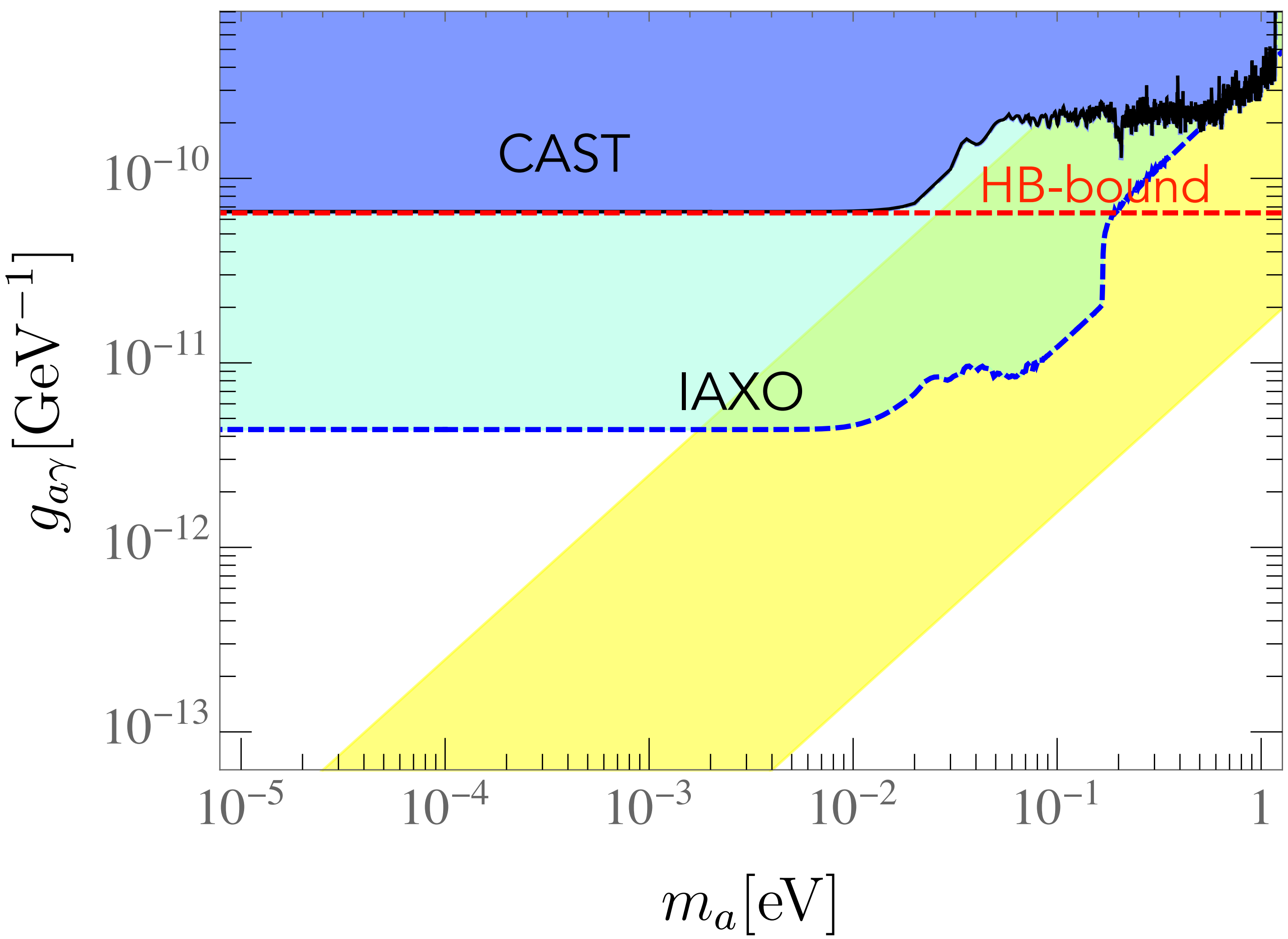
Irastorza et al., JCAP 06 (2011)
E. Armengaud et al., JINST 9 (2014)

- Large toroidal 8-coil magnet *L* = ~20 m
- 8 bores: 60 cm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services



IAXO will consist of a superconducting toroid magnet with eight custom x-ray telescopes that focus the reconverted photons onto ultra-low background detectors.

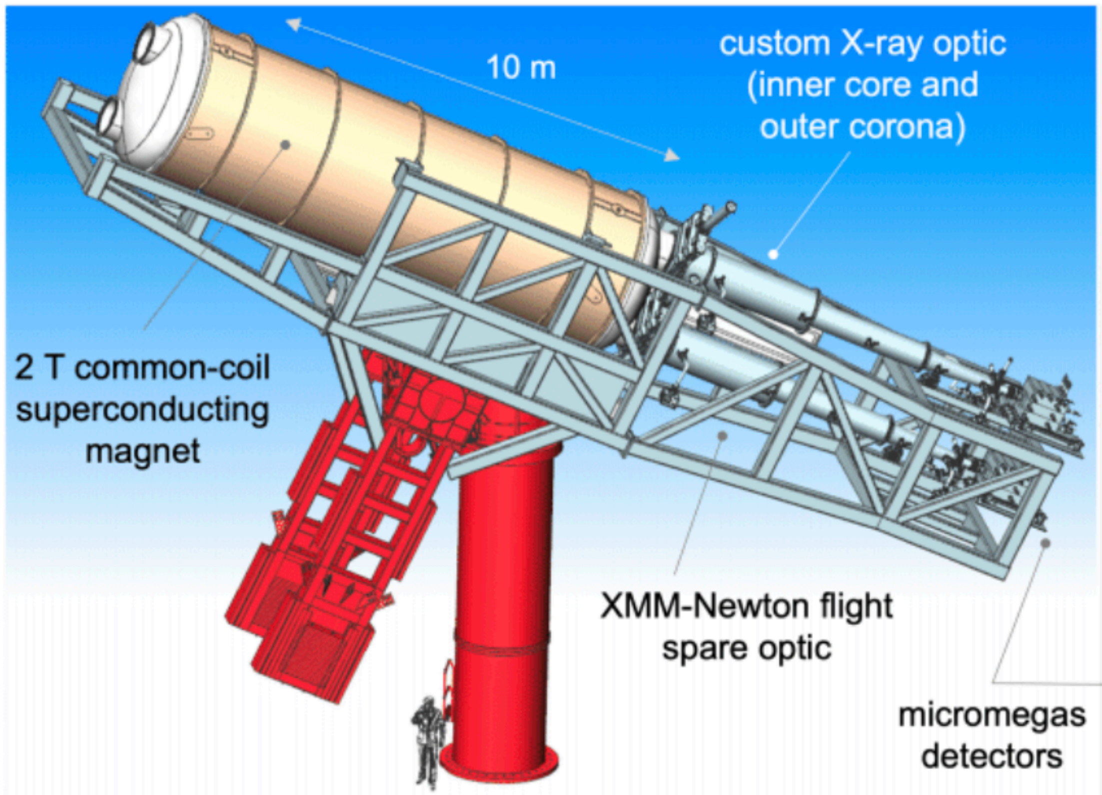
The International AXion Observatory

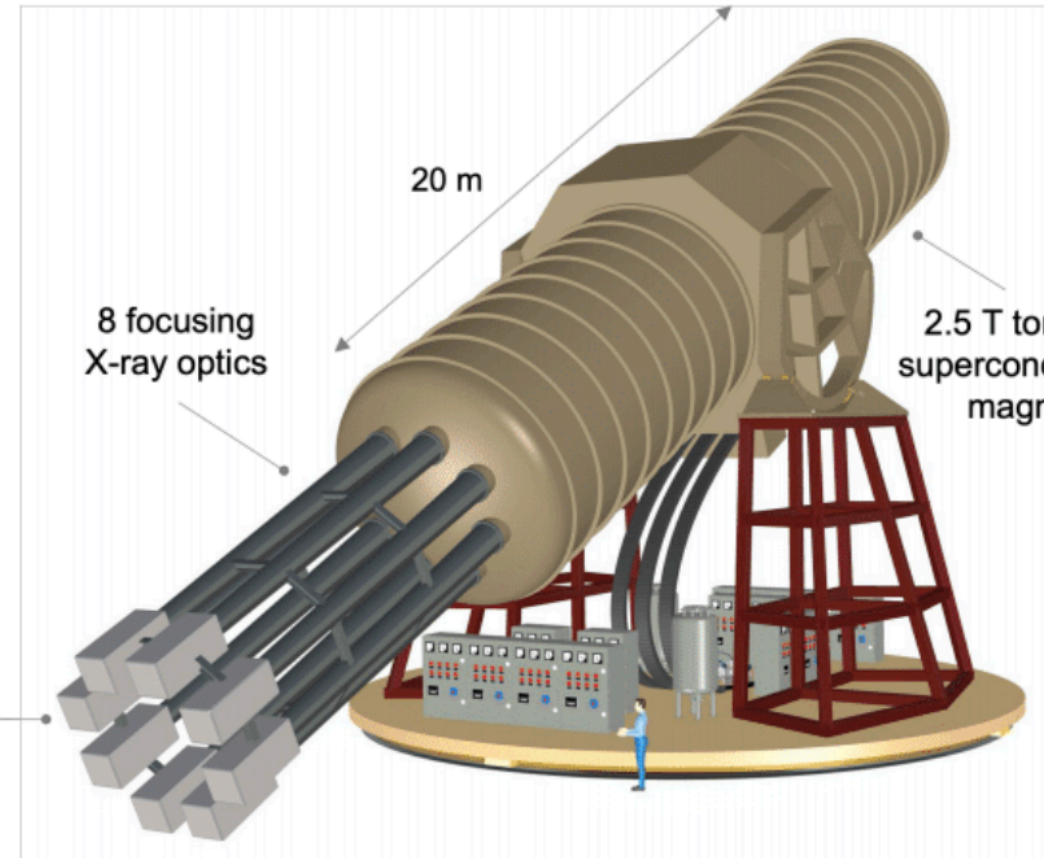


Strong potential to probe the high (>meV) mass region (stellar window)

Physics potential of the International Axion Observatory (IAXO) JCAP 1906 (2019) 047

BabyIAXO



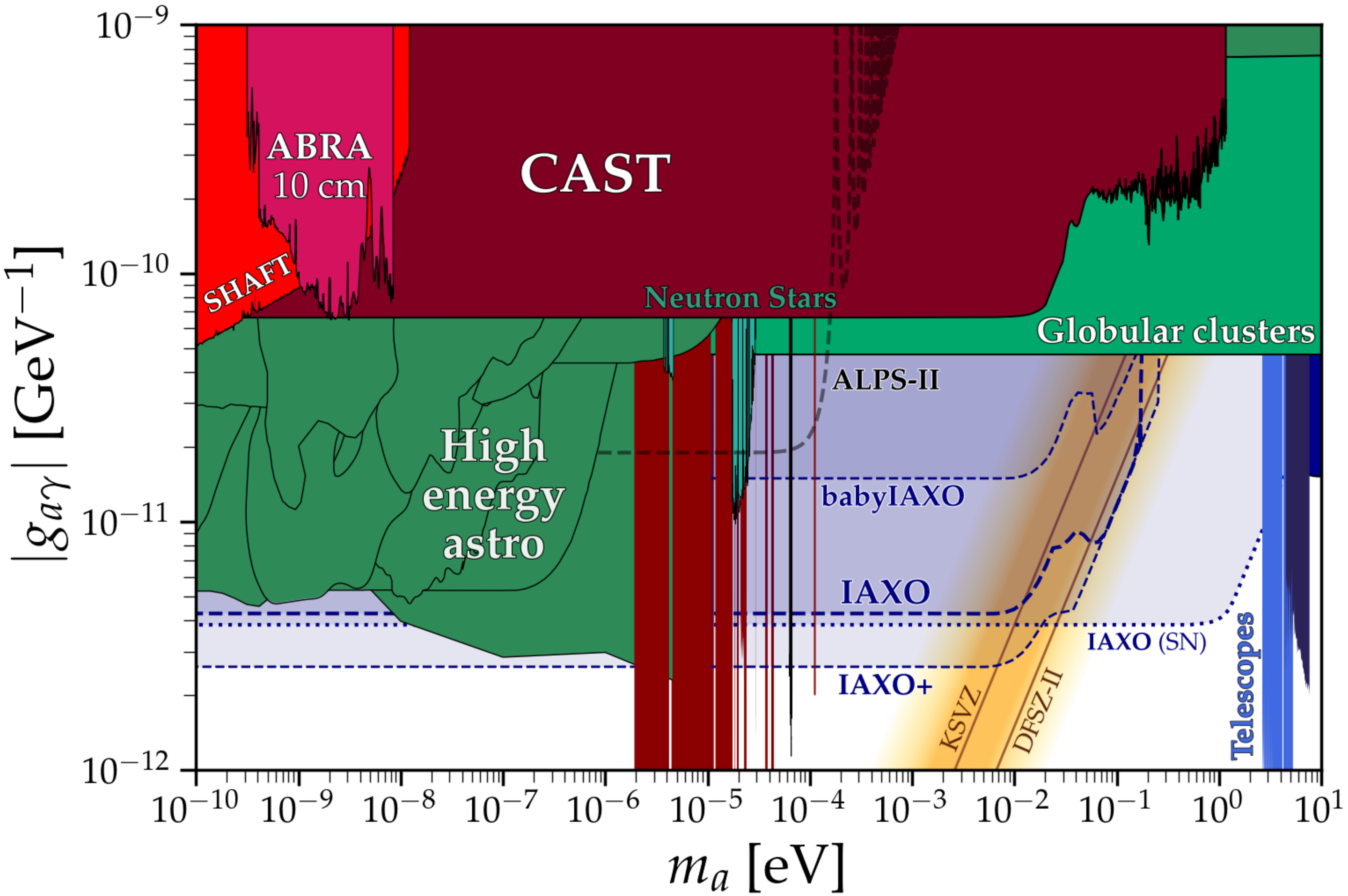


- Prototype: Intermediate experimental stage before IAXO
- Test & improve all systems. Risk mitigation for full IAXO.
- Physics: expected relevant physics outcome (~100 x CAST FOM)

2017 ERC advanced grant by I. Irastorza to support the development

DESY PRC endorsed BabyIAXO in

Heliscope Summary



Other detection strategies for solar axions

Helioscopes based on Axioelectric effect: LUX, XENON1T, …

Large underground DM detectors.
Axioelectric = axion analog to the photoelectric (pe) effect

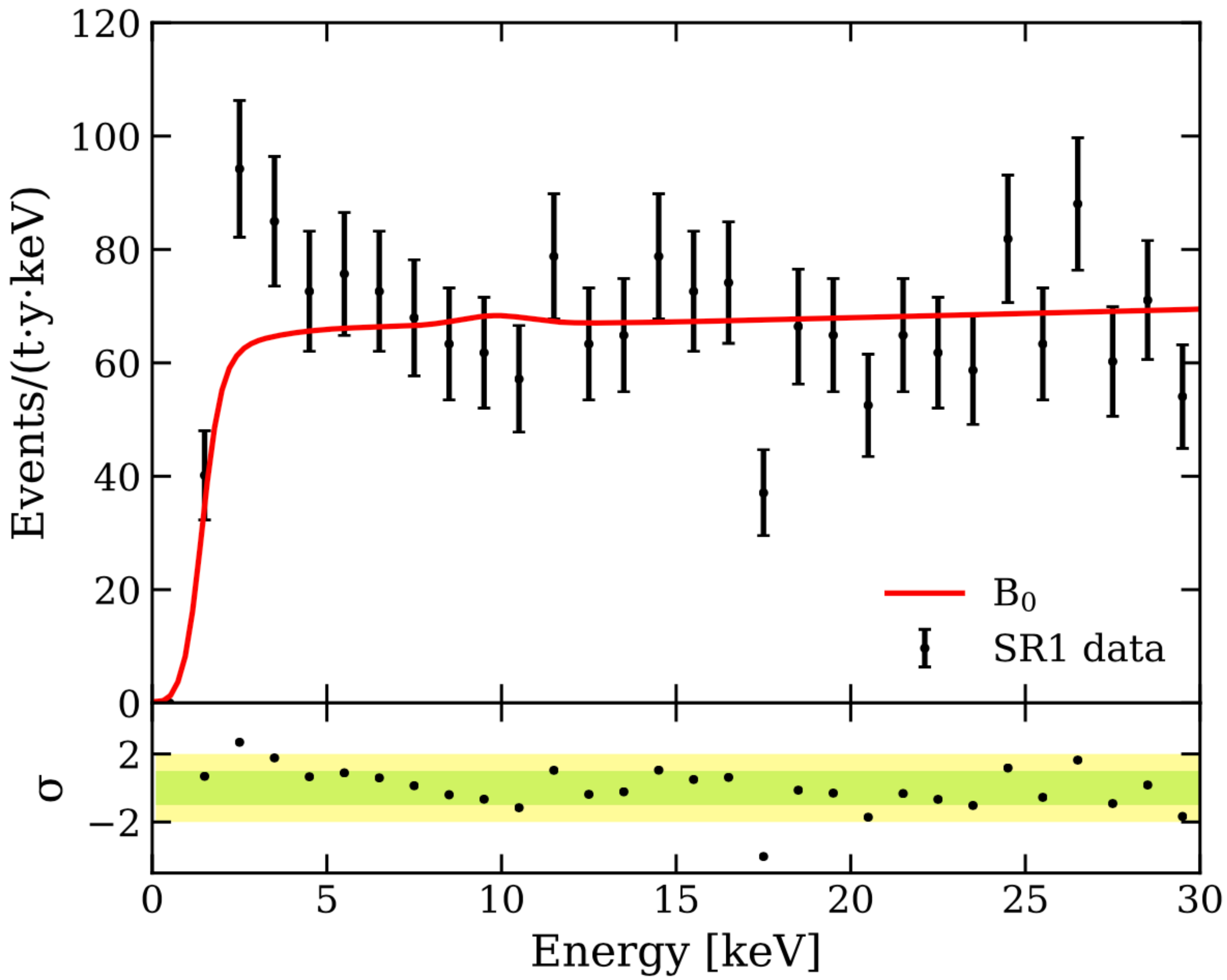
$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$$

Low energy suppression $(E_a/m_e)^2$

However, they can reach higher masses

Excess Electronic Recoil Events in XENON1T

Solar axions?



Stimulated a lot of interesting work on the low energy frontier

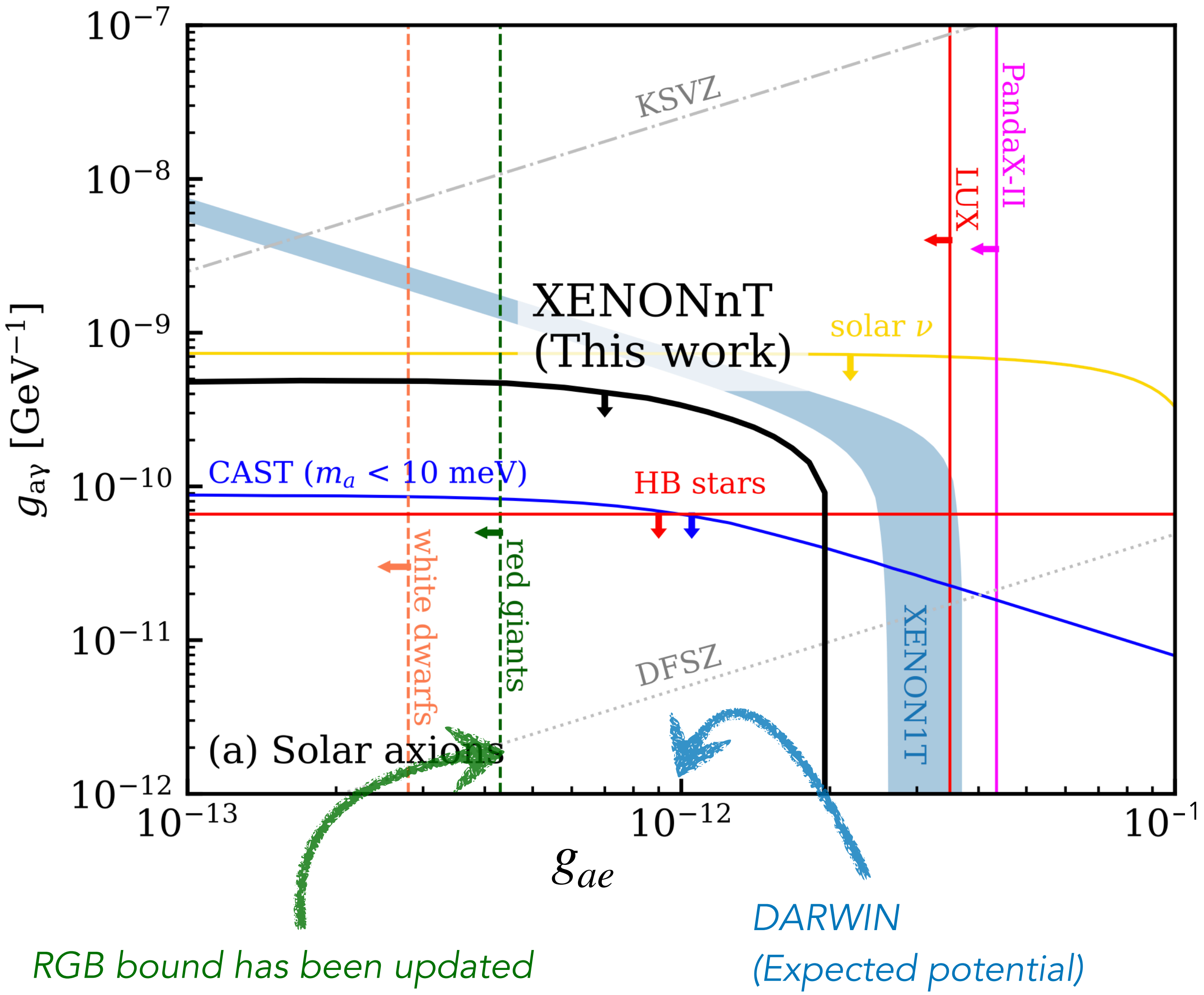
E.g., axions with $g_{ae} \sim 3 \times 10^{-12}$

The value is very large and in tension with stellar evolution
(see talk by O. Straniero)

E. Aprile et al., PHYSICAL REVIEW D 102, 072004 (2020)

New results: XENONnT

Solar axions?



Hint conclusively dismissed by the first science run of the XENONnT dark matter experiment (Jul 22, 2022), which confirmed the origin as decays from trace amounts of tritium

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

E. Aprile et al., e-Print: 2207.11330 [hep-ex] (2022)

Solar axions from Nuclear Reactions

Recent progress in the search for axions from nuclear reactions in the sun.
Important examples:

$p + d \rightarrow {}^3\mathrm{He} + a$

- Searched by CAST *JCAP* 03 (2010)
- Borexino *Phys.Rev.D* 85 (2012)
- and using previous SNO data Phys.Rev.Lett. 126 (2021)
- Recent analysis of the JUNO sensitivity shows potential to search in unexplored regions G. Lucente, N. Nath, F. Capozzi, MG, A. Mirizzi, Phys.Rev.D 106 (2022) 12

${}^{57}\mathrm{Fe}^* \rightarrow {}^{57}\mathrm{Fe} + a$

- Searched by CAST *JCAP 12 (2009)*
- BabyIAXO potential studied in *Eur.Phys.J.C 82 (2022)* *(See backup slides)*

${}^{7}\mathrm{Li}^* \rightarrow {}^{7}\mathrm{Li} + a$

- Searched by Borexino *Eur.Phys.J.C 54 (2008)*
- CAST *JCAP* 03 (2010)

Comprehensive discussion in R. Massarczyk, P.H. Chu, S.R. Elliott, Phys.Rev.D 105 (2022)

Axion Dark Matter Searches

For an observed DM density of $\rho \sim 0.2 - 0.56\,\mathrm{GeV/cm^3}$

Axion number density

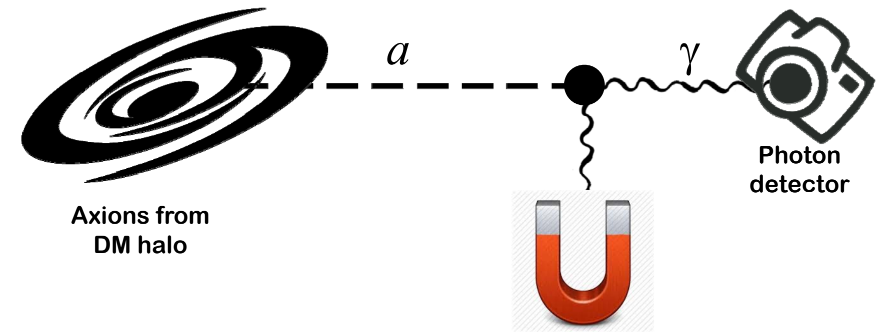
$$n_a \sim \rho_a / m_a \sim 4 \times 10^{13} \left(\frac{10\mu\mathrm{eV}}{m_a} \right) \text{ axions } /\mathrm{cm}^3$$

Axion DB wavelength ($v \sim 10^{-3}$): $\lambda_{\mathrm{dB}} = \frac{h}{p} = \frac{h}{mv} \simeq 120\,\mathrm{m} \left(\frac{10\mu\mathrm{eV}}{m_a} \right)$

So, the axion occupation number= number of axions in a reduced de Broglie volume, is $\sim 10^3$ for $m_a \sim 1$ eV.

→ Very large. Axion DM behaves like waves.

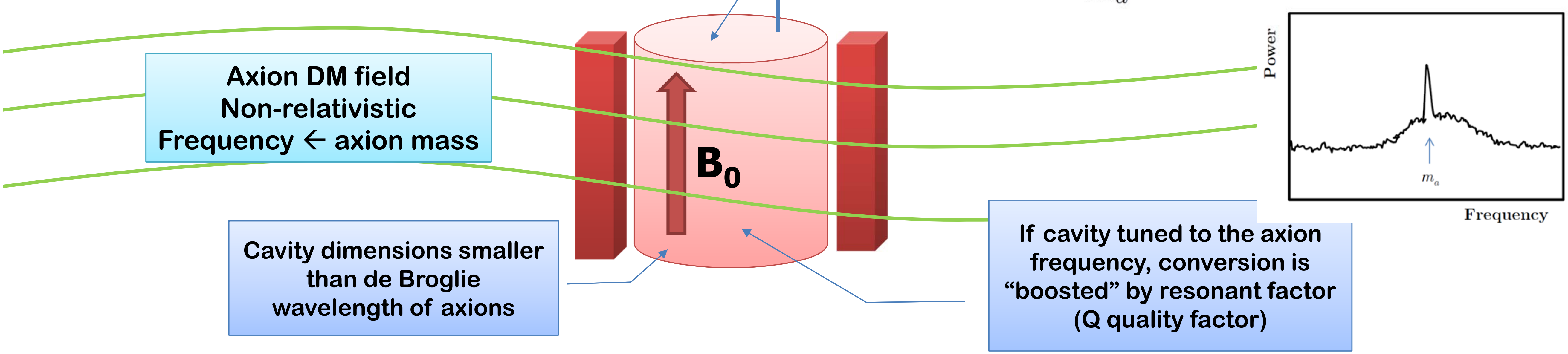
Hunting Axions: Haloscopes



- **Assumption: DM is mostly axions**
- **Resonant cavities (Sikivie,1983)**
  - **Primakoff conversion inside a "tunable" resonant cavity**
  - **Energy of photon = $m_a c^2 + O(b^2)$**

Primakoff conversion of DM axions into microwave photons inside cavity

$$P_s = \kappa \frac{Q}{m_a} g_{a\gamma}^2 B_e^2 |\mathcal{G}_m|^2 V \varrho_a$$



Slide from I. Irastorza, Bruno Touschek School, Frascati (2018)

Cavity Experiments

P. Sikivie, "Experimental tests of the invisible axion"
Phys. Rev. Lett. 51 (1983) 1415

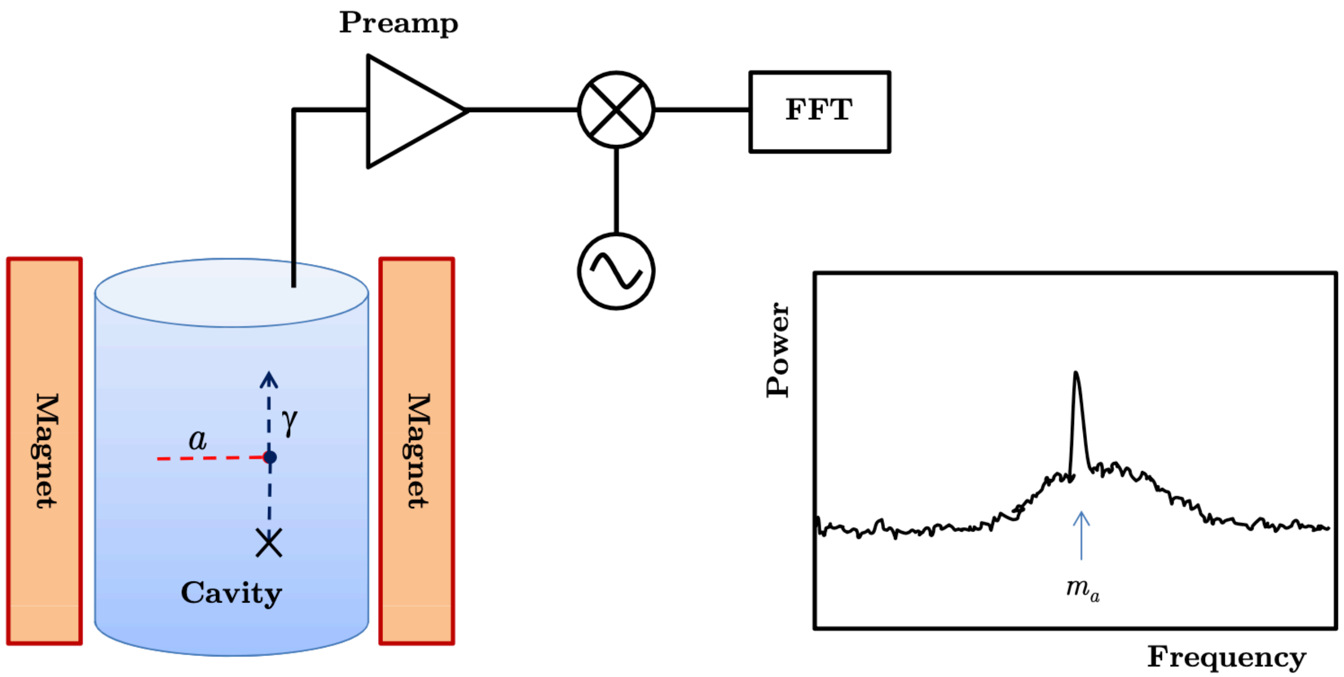


Figure 14: Conceptual arrangement of an axion haloscope. If m_a is within $1/Q$ of the resonant frequency of the cavity, the axion will show as a narrow peak in the power spectrum extracted from the cavity.

Figure and table from I. Irastorza, J. Redondo, Prog.Part.Nucl.Phys. 102 (2018)

Axion production rate greatly enhanced when the resonant frequency of the cavity $\sim m_a$.

The signal (S) to noise (N) as a function of the measurement time (Δt) in a frequency bin ($\Delta \nu$) → Dicke's radiometer equation

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{P_s}{T_{\mathrm{sys}}}\sqrt{\frac{\Delta t}{\Delta \nu}}$$

- P_s= power
- T_{sys}= effective noise (amplifier + thermal fluctuations).

Cavity Experiments

Micro eV mass range:

Most experience.

- ADMX: proven sensitivity to few μeV

High Mass:

Difficult: higher masses requires smaller volume → lower sensitivity. Possible solutions:

- lower noise
- matching more cavities or new multicavity designs
- More powerful magnets
- Dielectric Haloscopes
- …

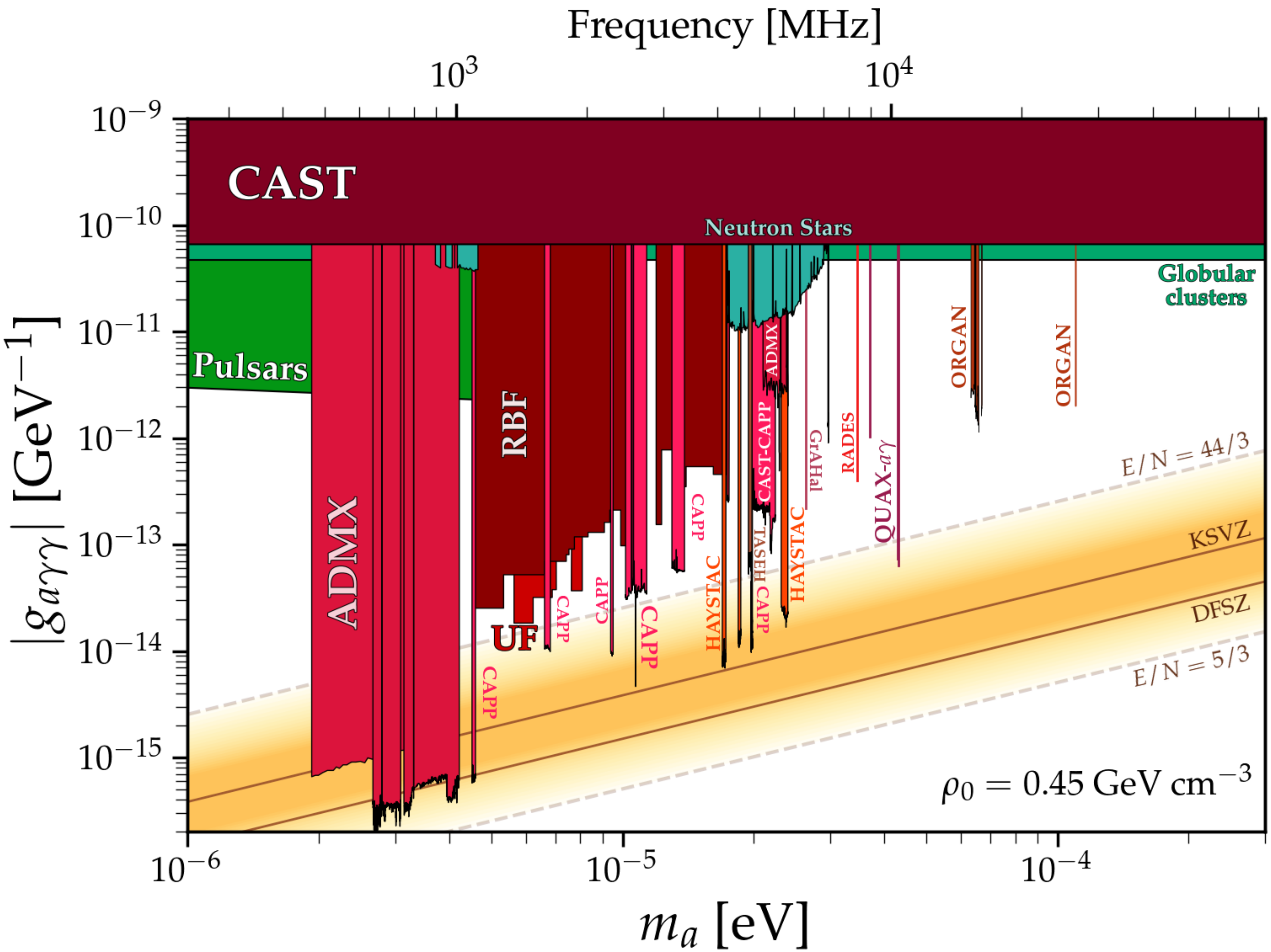
Many projects: HAYSTAC, CAPP, MADMAX,

Low Mass:

Technologically simpler. However, expensive. Needs large magnets

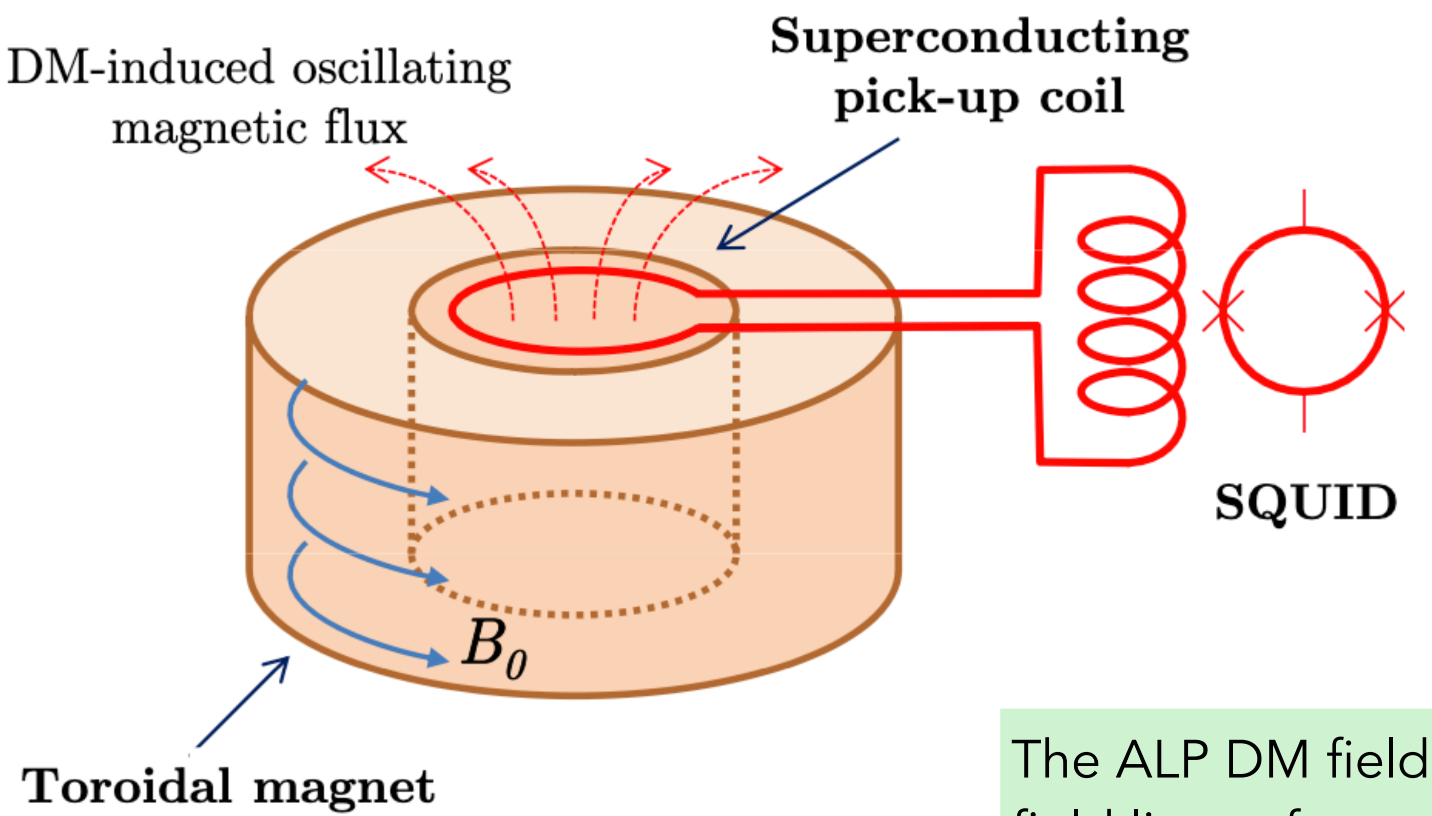
- KLASH/FLASH (concept)
- BabyIAXO (to be built)
- IAXO

Cavity Experiments



Other DM Detection Strategies

Very low mass:
It becomes very difficult since we cannot have huge haloscopes. New concepts like ABRACADABRA (now Dark Matter Radio)

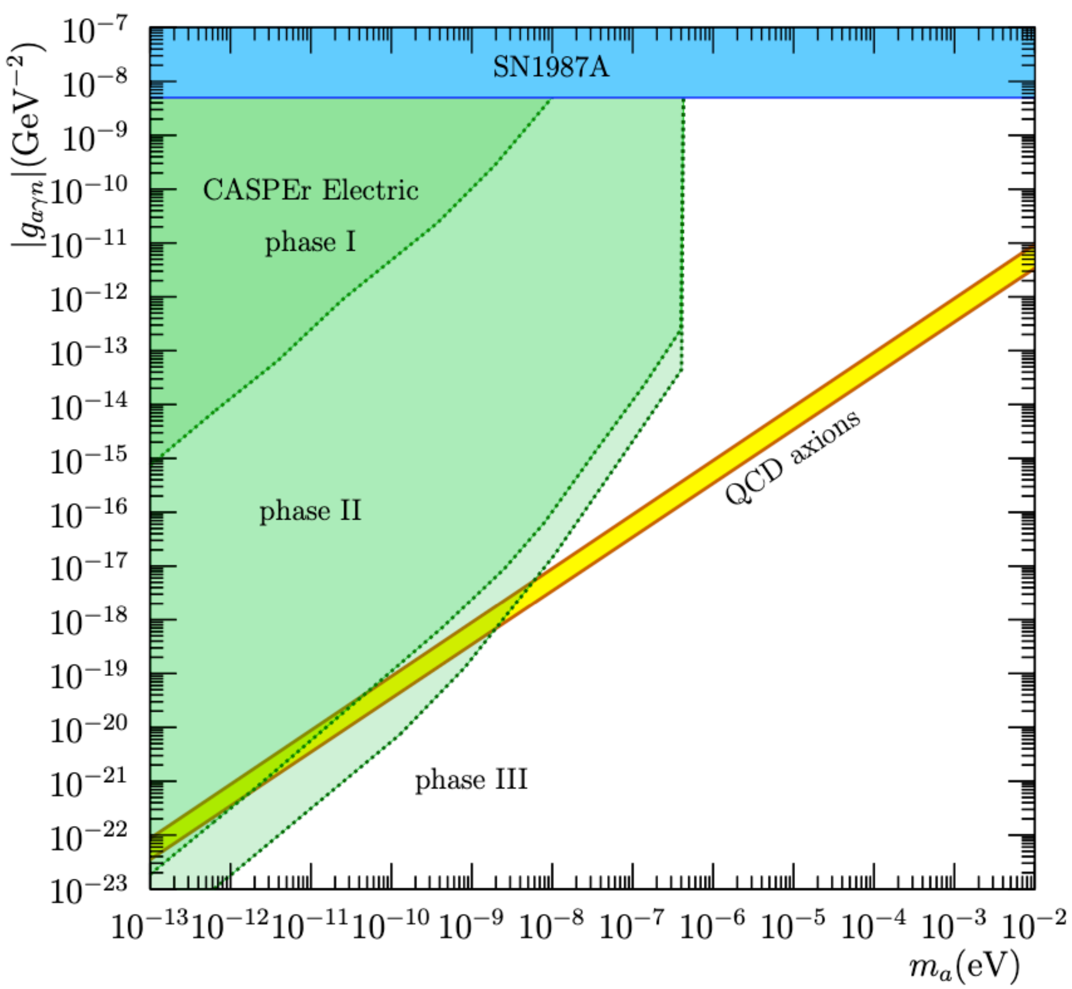


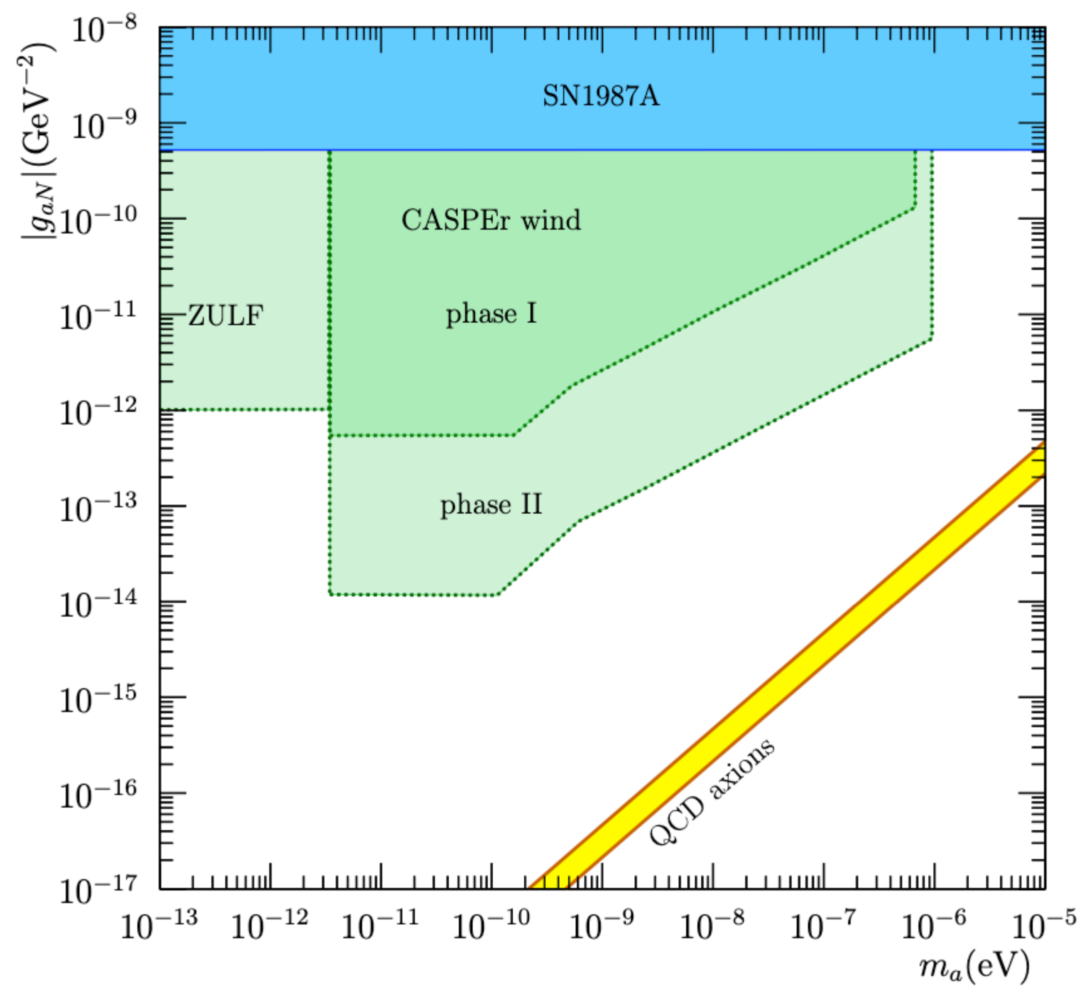
The ALP DM field excites an oscillating E_a field along the field lines of a static toroidal field B_e.

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

Spin precession experiments

DM-induced spin precession → it can be detected with very sensitive NMR techniques

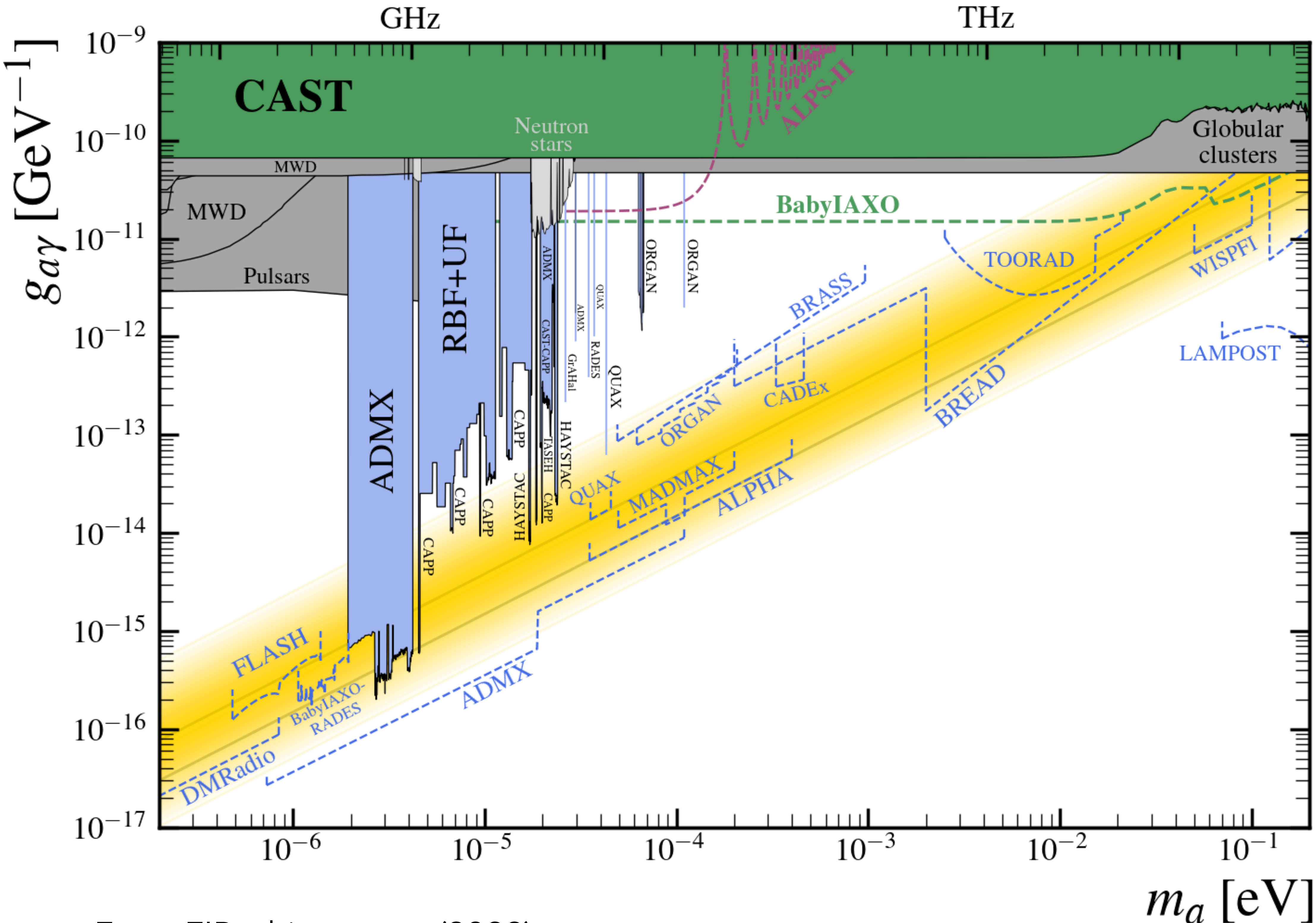




CASPEr electric.
Model independent coupling
to gluons $\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$

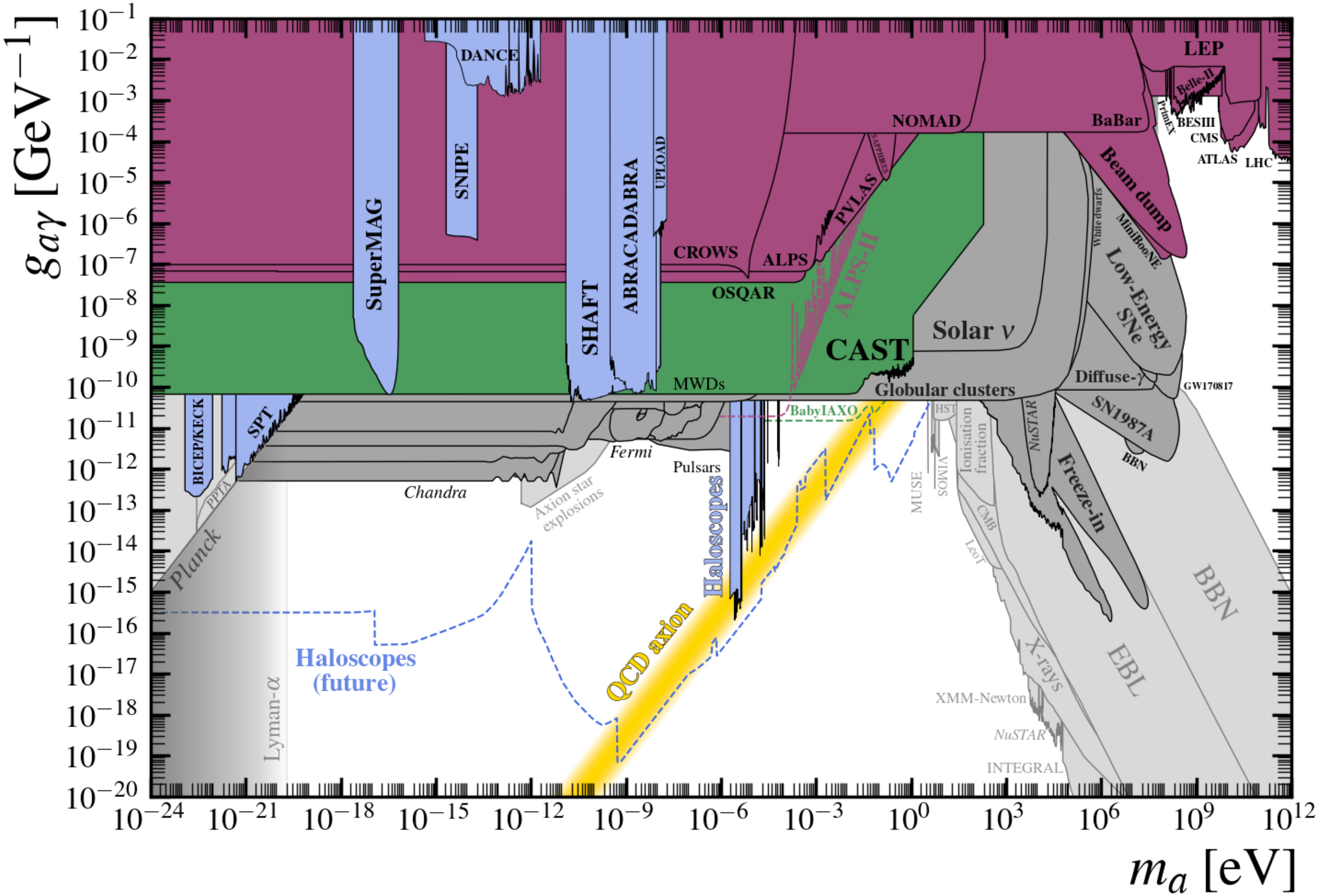
CASPEr gradient (formerly, CASPEr wind):
Model dependent coupling to fermions:
$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$

Future Perspectives

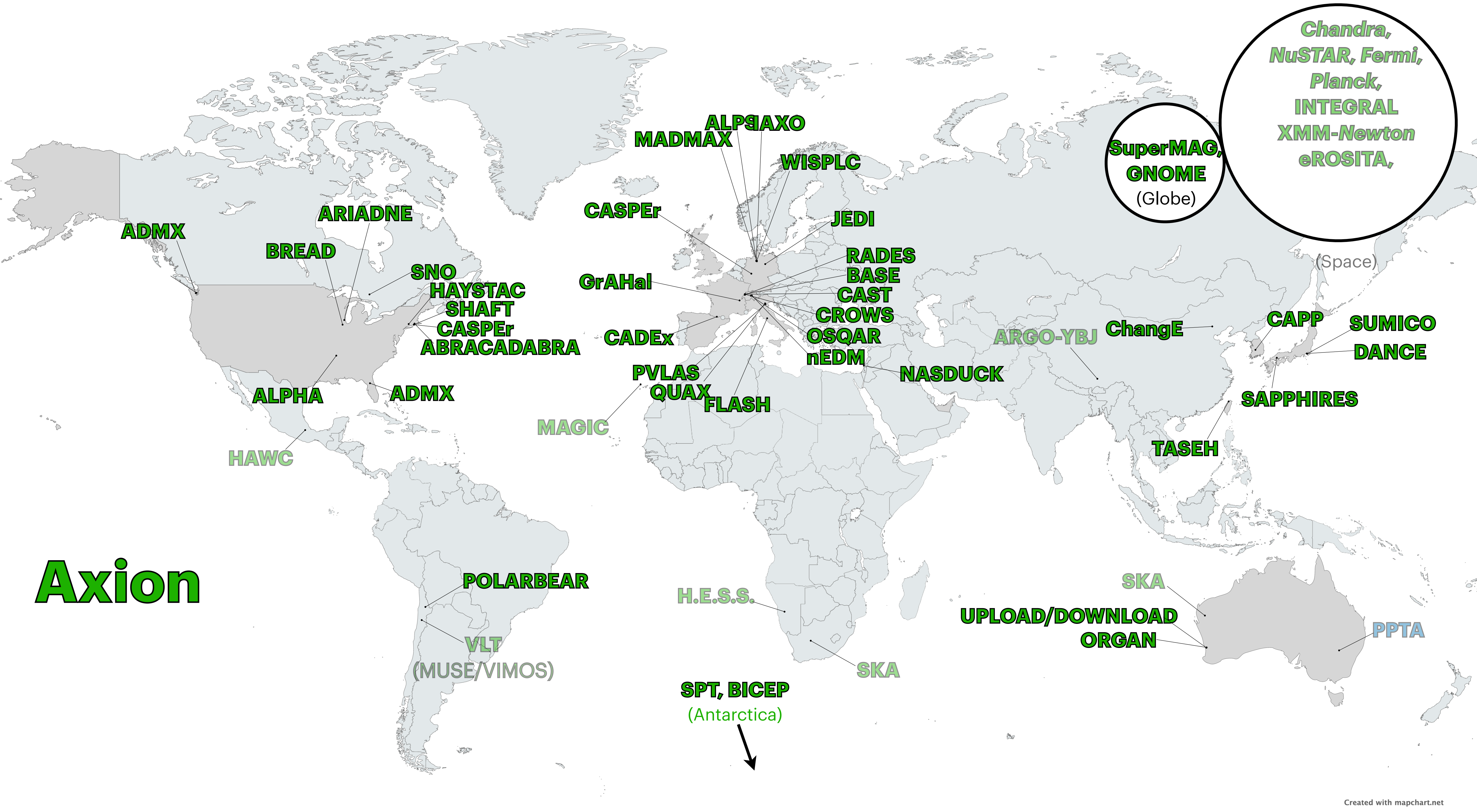


From FIP white paper (2022)

Future Perspectives



MG, G. Lanfranchi, Y. Stadnik, et al., Feebly Interacting Particles: FIPs 2022



Axion
ALPS
IAXO
MADMAX
WISPLC
CASPEr
JEDI
RADES
BASE
CAST
CROWS
OSQAR
nEDM
GrAHal
CADEx
PVLAS
QUAX
FLASH
NASDUCK
MAGIC
ADMX
ARIADNE
BREAD
SNO
HAYSTAC
SHAFT
CASPEr
ABRACADABRA
ALPHA
ADMX
HAWC
SuperMAG,
GNOME
(Globe)
Chandra,
NuSTAR, Fermi,
Planck,
INTEGRAL
XMM-Newton
eROSITA,
(Space)
ARGO-YBJ
ChangE
CAPP
SUMICO
DANCE
SAPPHIRES
TASEH
POLARBEAR
VLT
(MUSE/VIMOS)
H.E.S.S.
SKA
SPT, BICEP
(Antarctica)
SKA
UPLOAD/DOWNLOAD
ORGAN
PPTA
Created with mapchart.net

References

- A soft and enjoyable introduction is the (very recent) article by David J. E. Marsh: *Axions for amateurs* arXiv:2308.16003

- More technical: L. Di Luzio, M.G., E. Nardi, L. Visinelli, *The landscape of QCD axion models*, Phys.Rept. 870 (2020)

- Especially good for theory:
  - Villadoro Lectures GGI 2015, GGI 2023
  - Anson Hook, TASI Lectures, arXiv:1812.02669

- For experiments: I. Irastorza, J. Redondo, *New experimental approaches in the search for axion-like particles*, Prog.Part.Nucl.Phys. 102 (2018)

Background information:

- C. P. Burgess, *Introduction to Effective Field Theory*, Cambridge University Press (2020)

- Matthew D. Schwartz, *Quantum Field Theory and the Standard Model*, Cambridge University Press (2013)

Comments and Conclusions

- ALPs, and especially axions, are very well motivated new physics candidates, with very interesting phenomenology.

- Great effort recently to search for axions.