Axions as Dark Matter Candidates

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Today’s Plan

- Vacuum Structure in Quantum Chromodynamics
- Strong CP Puzzle
- **The Axion (continued)**
- Axion Dark Matter
- Axion Experiments

The Axion

Recap: Replace theta parameter by dynamical theta field

- Add to SM Nambu-Goldstone field, $\theta(x) \equiv a(x)/f_a \in [-\pi, \pi]$, respecting a non-linearly realized $U(1)_{\rm PQ}$ symmetry ($\theta(x) \to \theta(x) + {\rm const.}$), broken only by coupling to gluonic topological charge density: [Peccei,Quinn 77]

$$\mathcal{L} \supset -\theta(x)\, q(x)\,; \qquad q(x) \equiv \frac{\alpha_s}{8\pi}\, G^b_{\mu\nu}(x)\tilde{G}^{b,\mu\nu}(x)$$

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$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\left[\overline{\theta} + \theta(x)\right] G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$$

  by shift $\theta(x) \to \theta(x) - \overline{\theta}$

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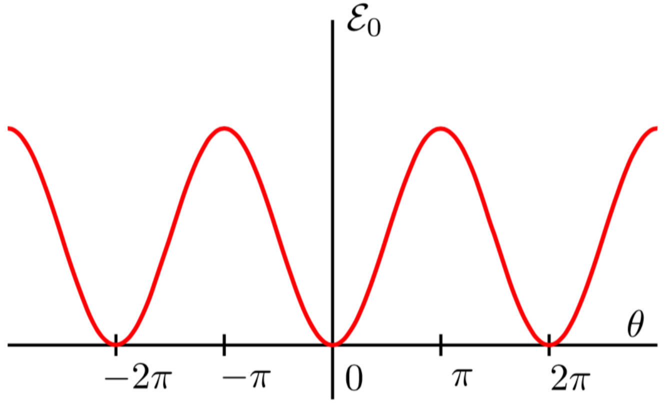
  - Effective potential at energies below $\Lambda_{\rm QCD}$ has absolute minimum at $\theta = 0$ and thus predicts vanishing vev, $\langle\theta(x)\rangle = 0$
    No strong CP violation in vacuum [Vafa,Witten 84]



$$V(\theta) = m_\pi^2 f_\pi^2 \left(1 - \frac{\sqrt{1+z^2+2z\cos\theta}}{1+z}\right)$$

[Di Vecchia,Veneziano `80; Leutwyler,Smilga 92]

$$z \equiv m_u/m_d \approx 1/2$$

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    No strong CP violation in vacuum [Vafa,Witten 84]
  - Particle excitation: "axion" [Weinberg 78; Wilczek 78]
  - It is a pseudo Nambu-Goldstone boson with mass parametrically suppressed by inverse PQ scale:

$$m_a \simeq \frac{\sqrt{z}}{1+z}\,\frac{m_\pi f_\pi}{f_a} \approx 6\ {\rm meV}\left(\frac{10^9\ {\rm GeV}}{f_a}\right)$$

$$z \equiv m_u/m_d \approx 1/2$$

The Axion

Axion couplings to SM at energies below QCD scale

$$\mathcal{L}_a \supset -\frac{i}{2}\frac{eC_{\rm NEDM}}{f_a}\, a\,\overline{\Psi}_N\sigma_{\mu\nu}\gamma_5\Psi_N F^{\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}\frac{C_{af}}{f_a}\,\partial_\mu a\,\overline{\Psi}_f\gamma^\mu\gamma_5\Psi_f$$

- „Invisible axion“: [Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]
  - Couplings to SM suppressed by inverse power of $f_a \gg v = 246\,{\rm GeV}$
  - Since mass inversely proportional to decay constant: couplings proportional to mass

The Axion

Coupling to the nucleon EDM

- Axion has a model-independent coupling to the EDM of the nucleon:

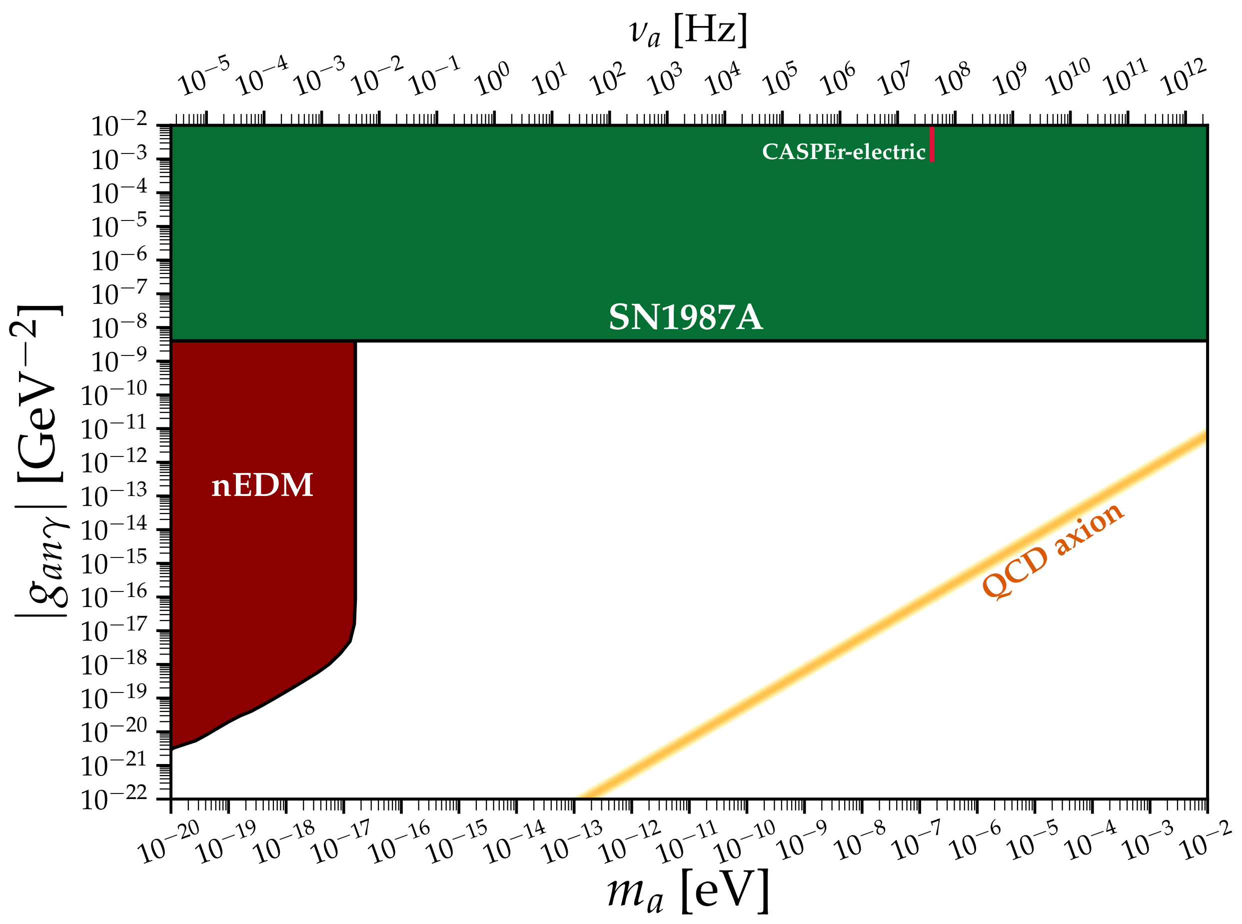
$$\mathcal{L}_{aN\gamma} = -\frac{i}{2} g_{aN\gamma}\, a\, \overline{\Psi}_N \sigma_{\mu\nu}\gamma_5 \Psi_N F^{\mu\nu}$$

$$g_{an\gamma} = -g_{ap\gamma} = e\,\frac{C_{\rm NEDM}}{f_a}$$

$$C_{\rm NEDM} = 2.4(1.0)\times 10^{-16}\,{\rm cm}$$

[Pospelov,Ritz 00]

- This is phenomenologically important for experi-ments searching for axion dark matter via osci-llating nucleon electric dipole moments such as nEDM and CASPEr-electric



[AR,Rosenberg,Rybka in: 2021 Update of Review of Particle Physics]

[adapted from https://github.com/cajohare/AxionLimits]

The Axion

Coupling to photons

- From mixing with the pion, the axion inherits at energy scales below the QCD scale, a model-independent contribution to its coupling with two photons:

$$\mathcal{L}_{a\gamma\gamma} \supset \frac{1}{4}\, g_{a\gamma}^{(\mathrm{mi})}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$g_{a\gamma}^{(\mathrm{mi})} = \frac{\alpha}{2\pi f_a}\, C_{a\gamma}^{(\mathrm{mi})}$$

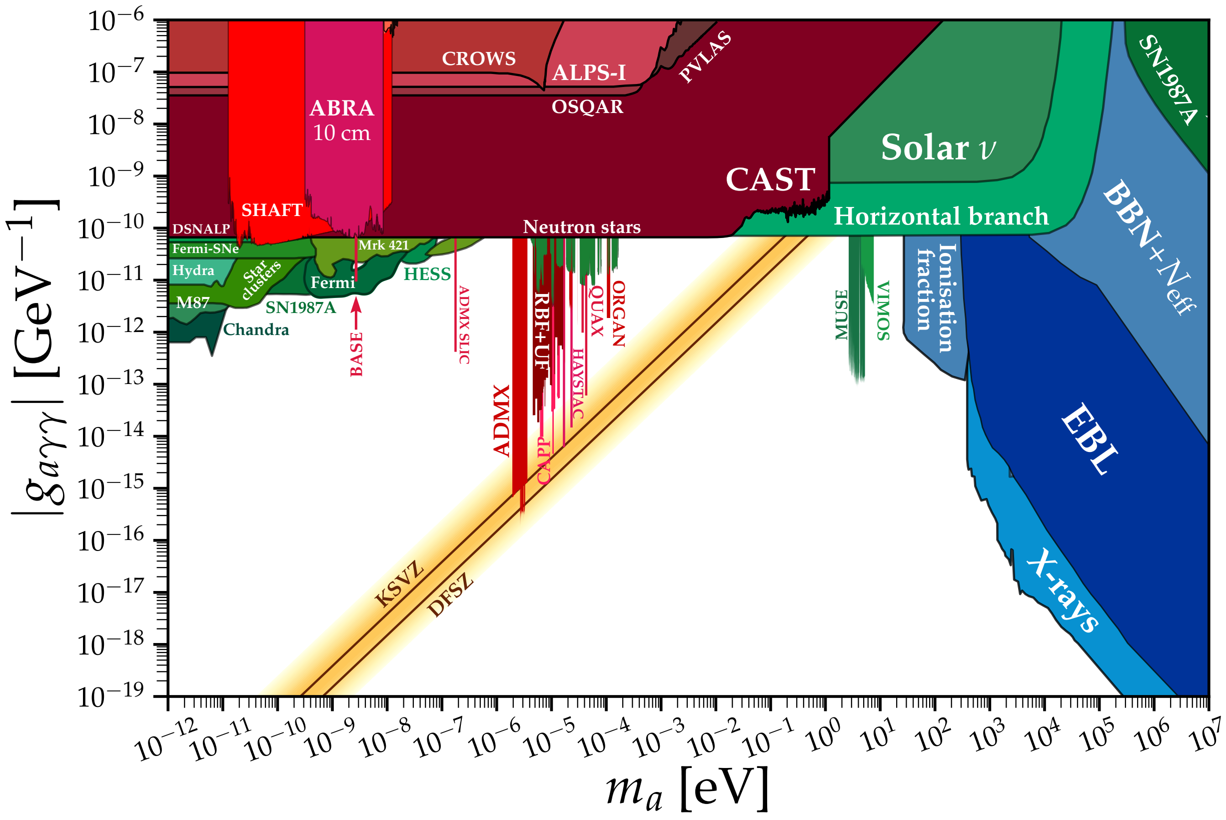
  - LO chiral perturbation theory:

$$C_{\mathrm{a}\gamma}^{(\mathrm{mi})} \simeq -\frac{2}{3}\frac{4+z}{1+z} \approx -2$$ [Kaplan 85;Srednicki `85]

  - Precise NLO determination

$$C_{a\gamma}^{(\mathrm{mi})} = -1.92(4)$$ [Grilli di Cortona et al. `16]

- Phenomenologically important for experiments searching for axions via coupling to photons



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$$\mathcal{L}_{aNN} \supset -\frac{1}{2}\frac{g_{AN}^{(\mathrm{mi})}}{m_N}\,\partial_\mu a\;\overline{\Psi}_N\gamma^\mu\gamma_5\Psi_N$$

$$g_{aN}^{(\mathrm{mi})} = \frac{C_{aN}^{(\mathrm{mi})}\,m_N}{f_a}$$

  - NLO chiral determination: [Grilli di Cortona et al. `16]

$$C_{ap}^{(\mathrm{mi})} = -0.47(3)$$
$$C_{an}^{(\mathrm{mi})} = -0.02(3)$$

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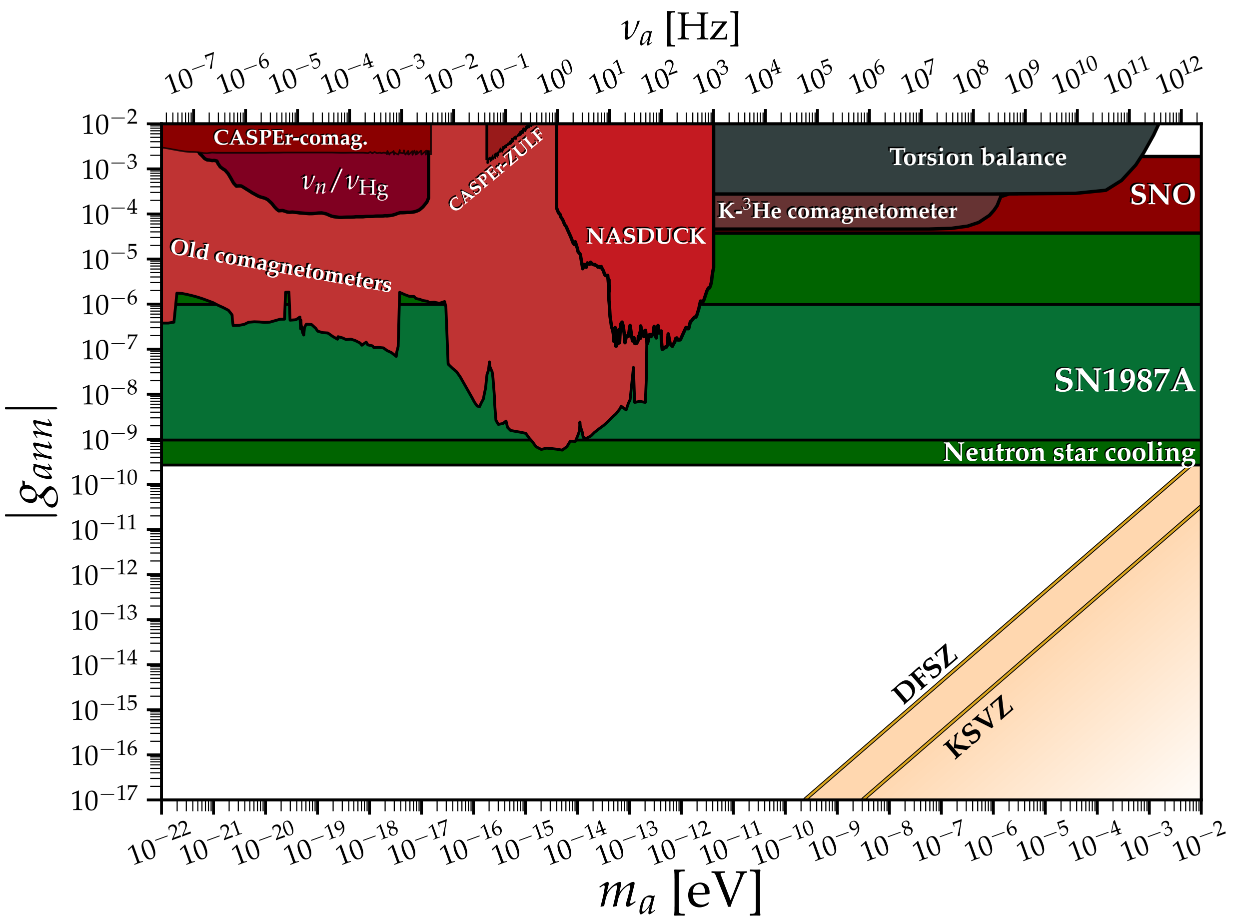

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KSVZ model

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- Add to SM a singlet complex scalar field σ, featuring a spontaneously broken global $U(1)_{\rm PQ}$ symmetry and a vector-like fermion $\mathcal{Q} = \mathcal{Q}_L + \mathcal{Q}_R$ in the fundamental of colour, singlet under $SU(2)_L$ and neutral under hypercharge.

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- Assuming that under $U(1)_{\rm PQ}$ the fields transform as

$$\sigma \to e^{i\alpha}\sigma\,, \qquad \mathcal{Q}_L \to e^{i\alpha/2}\mathcal{Q}_L\,, \qquad \mathcal{Q}_R \to e^{-i\alpha/2}\mathcal{Q}_R$$

the most general renormalizable Lagrangian can be written as

$$\mathcal{L}_{\rm KSVZ} = |\partial_\mu \sigma|^2 - \lambda_\sigma \left(|\sigma|^2 - \frac{v_\sigma^2}{2} \right)^2 + \overline{\mathcal{Q}}\, i\gamma_\mu D^\mu \mathcal{Q} - \left(y_{\mathcal{Q}} \overline{\mathcal{Q}}_L \mathcal{Q}_R \sigma + \text{h.c.} \right)$$

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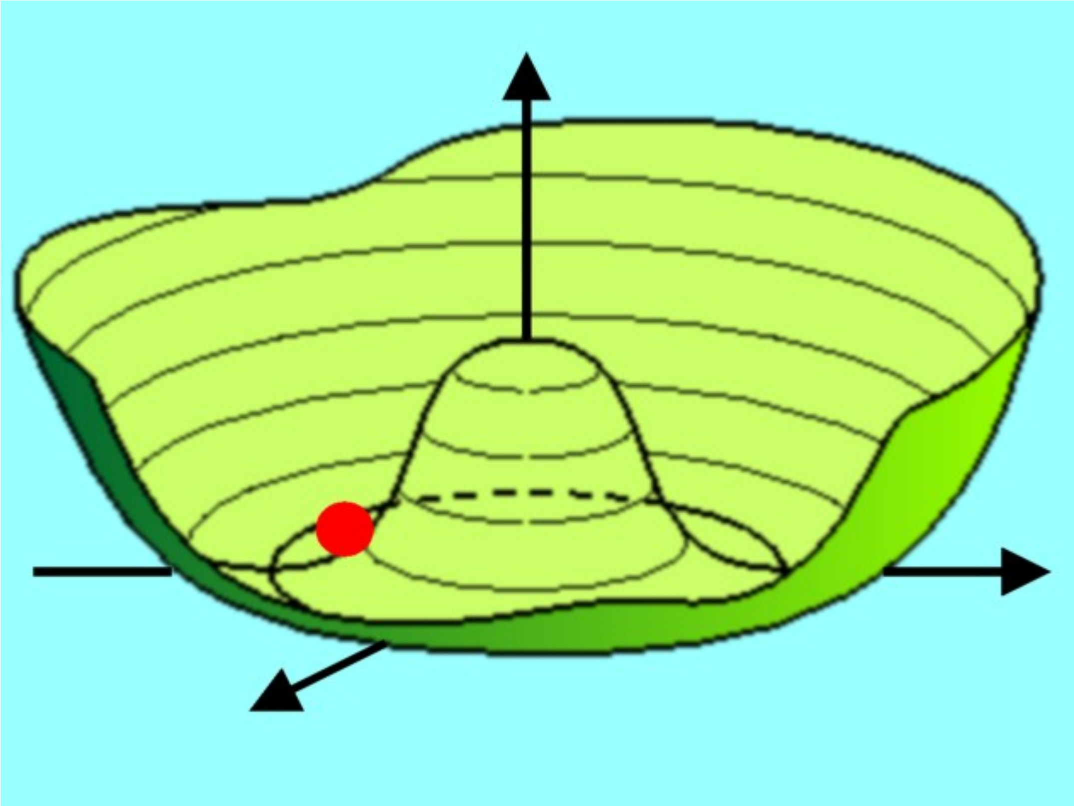
- Decomposing the scalar field in polar coordinates,

$$\sigma(x) = \frac{1}{\sqrt{2}} \left(v_\sigma + \rho(x) \right) {\rm e}^{i a(x)/v_\sigma}$$

  we see that this model features three BSM particles



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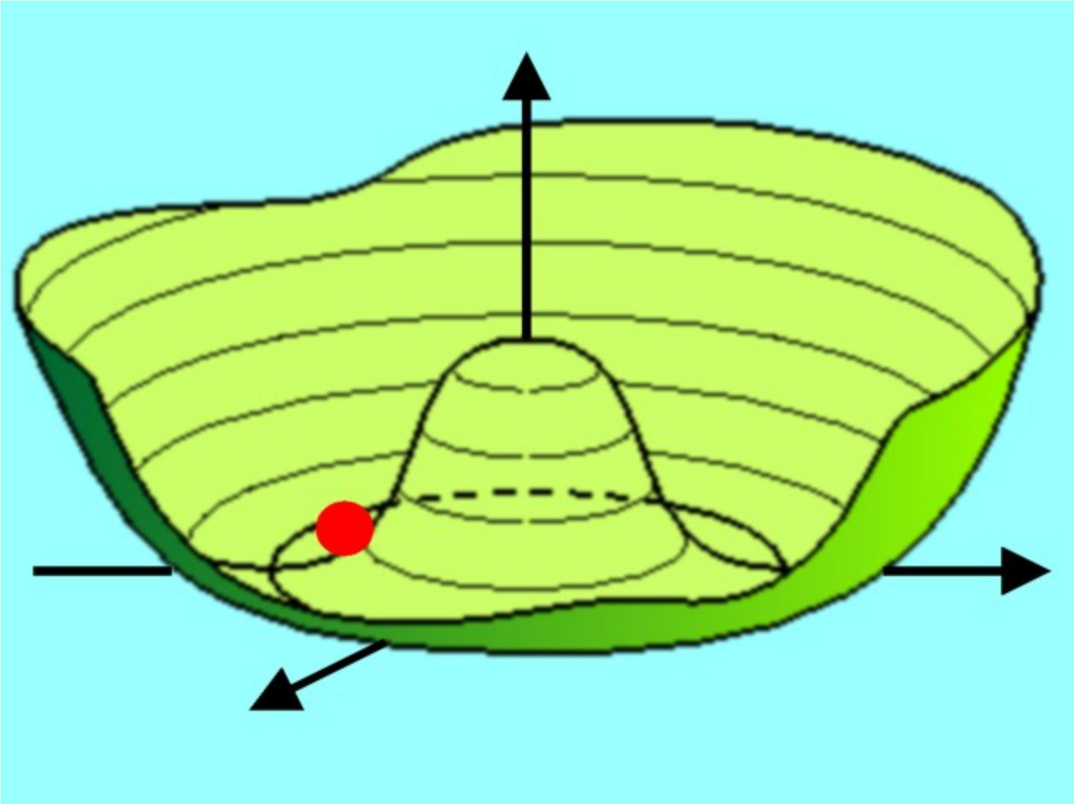

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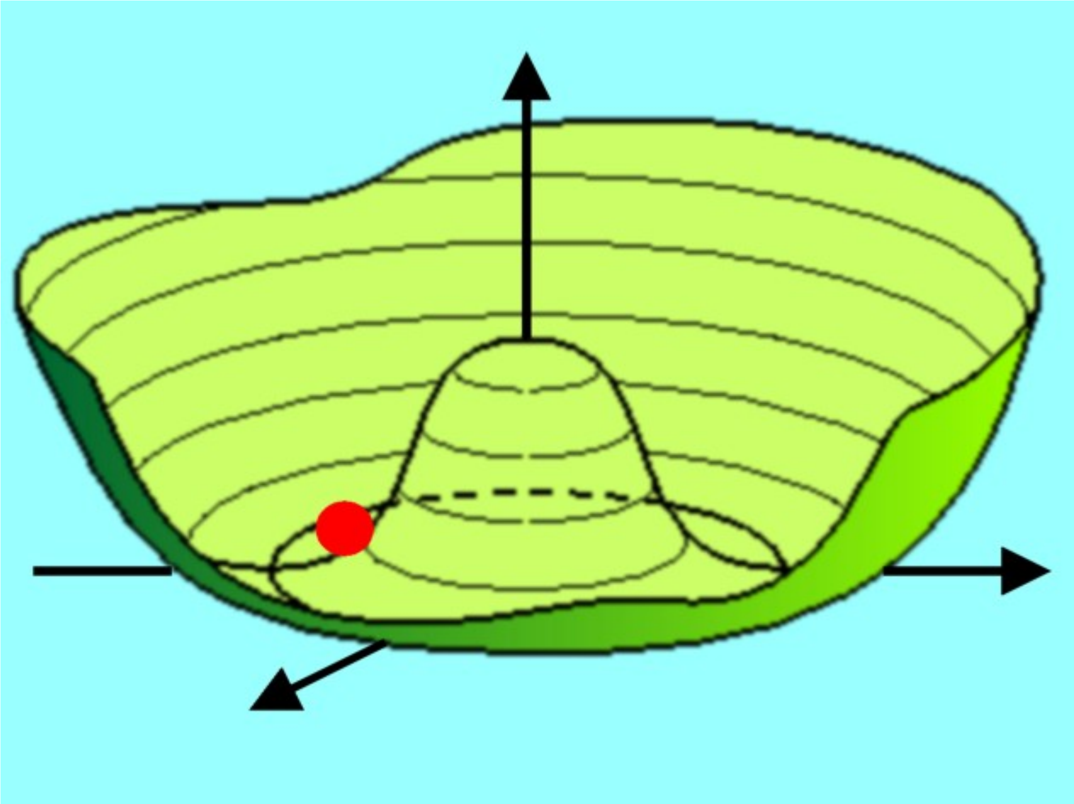

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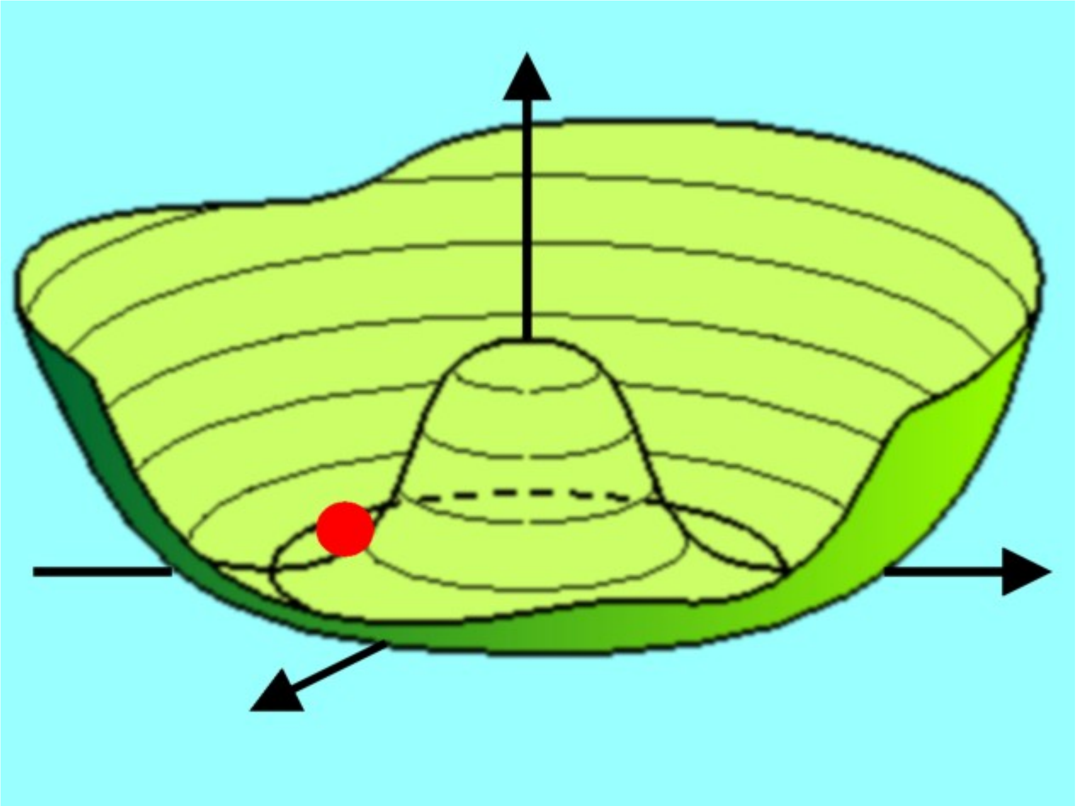

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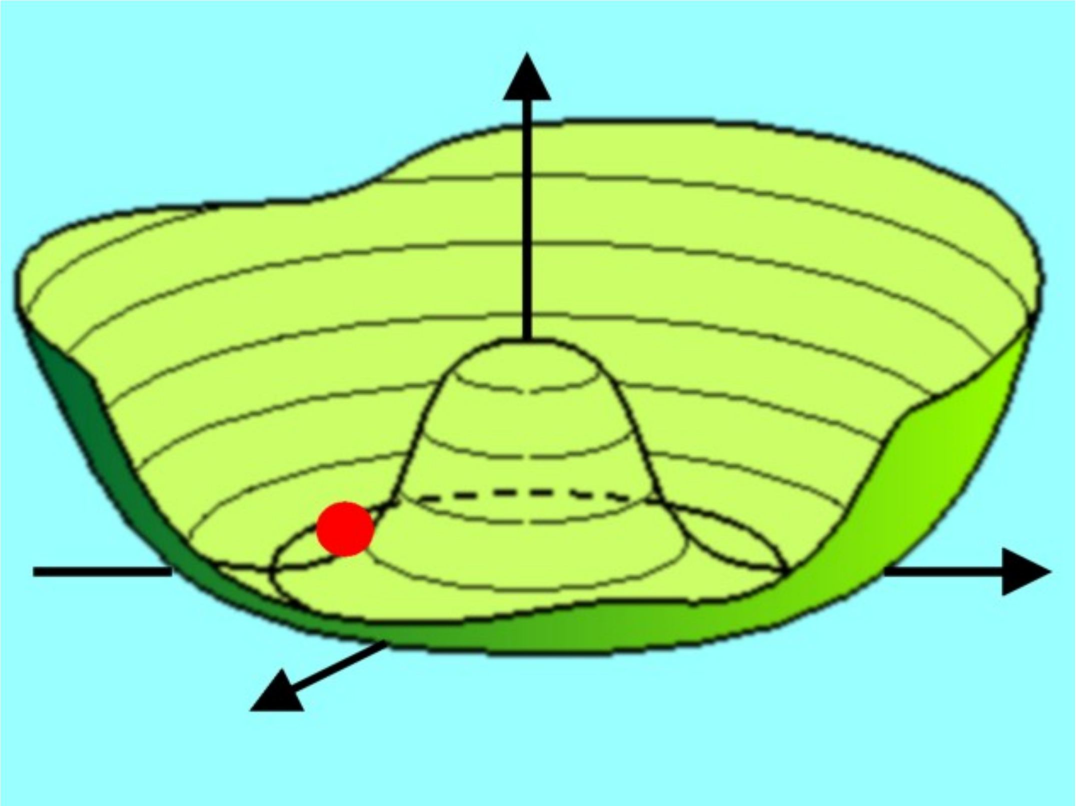
- For large PQ breaking scale v_σ, the latter two are heavy and may be integrated out, if we are only interested at the effective theory at energies much less than the breaking scale



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- However, because the fermionic measure is not invariant under axial transformations, cf.

$$\mathcal{D}\mathcal{Q}\mathcal{D}\bar{\mathcal{Q}} \to \left(e^{i \frac{g_s^2}{32\pi^2} \int d^4x \, \frac{a(x)}{v_\sigma} G(x) \tilde{G}(x)} \right) \mathcal{D}\mathcal{Q}\mathcal{D}\bar{\mathcal{Q}}$$

[Fujikawa 79]

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- The Goldstone field $a(x)/v_\sigma$ acts like a dynamical theta parameter: it is an axion

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- The Goldstone field $a(x)/v_\sigma$ acts like a dynamical theta parameter: it is an axion

- KSVZ axion has decay constant $f_a = v_\sigma$ and its couplings to SM are the model-ind. ones discussed earlier

The Axion

KSVZ-like models

- If the vector-like quark carries also a $U(1)_Y$ charge, then also model dep. photon coupling:

$$\mathcal{L}''_{\rm KSVZ} \supset \frac{1}{2}\partial^\mu a\,\partial_\mu a + \frac{\alpha_s}{8\pi}\frac{a}{v_\sigma}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + \frac{\alpha}{8\pi}C^{(\rm md)}_{a\gamma}\frac{a}{v_\sigma}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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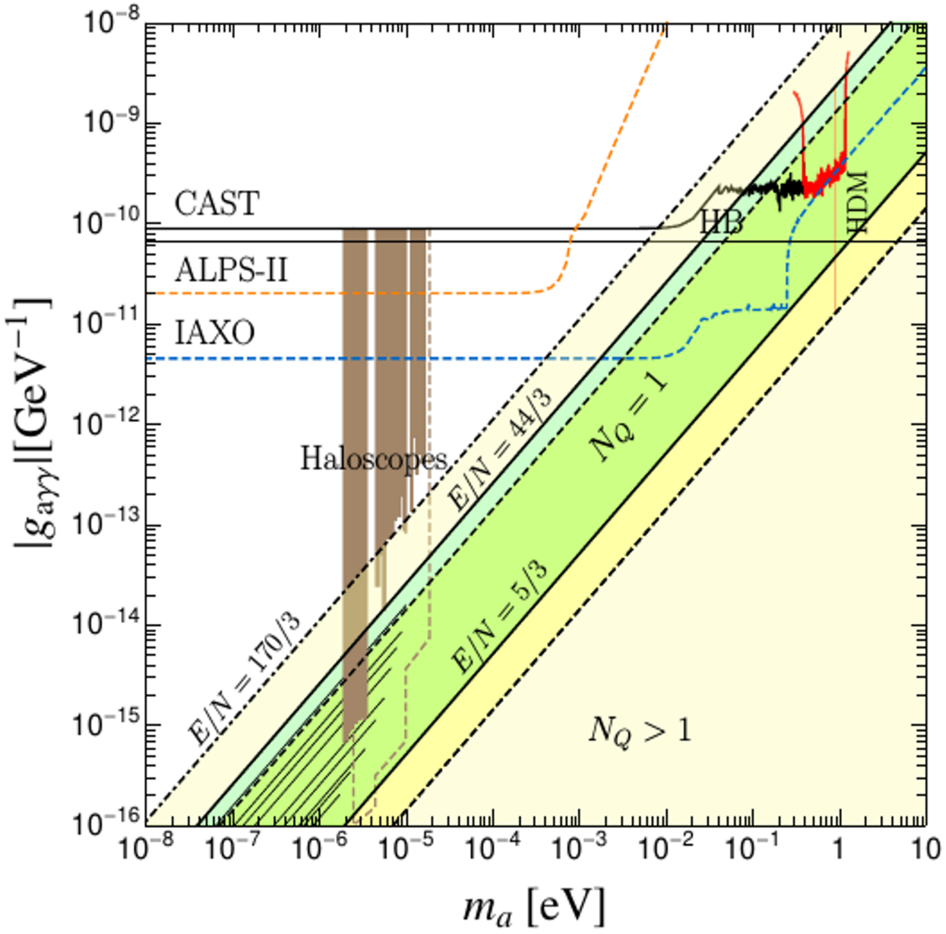

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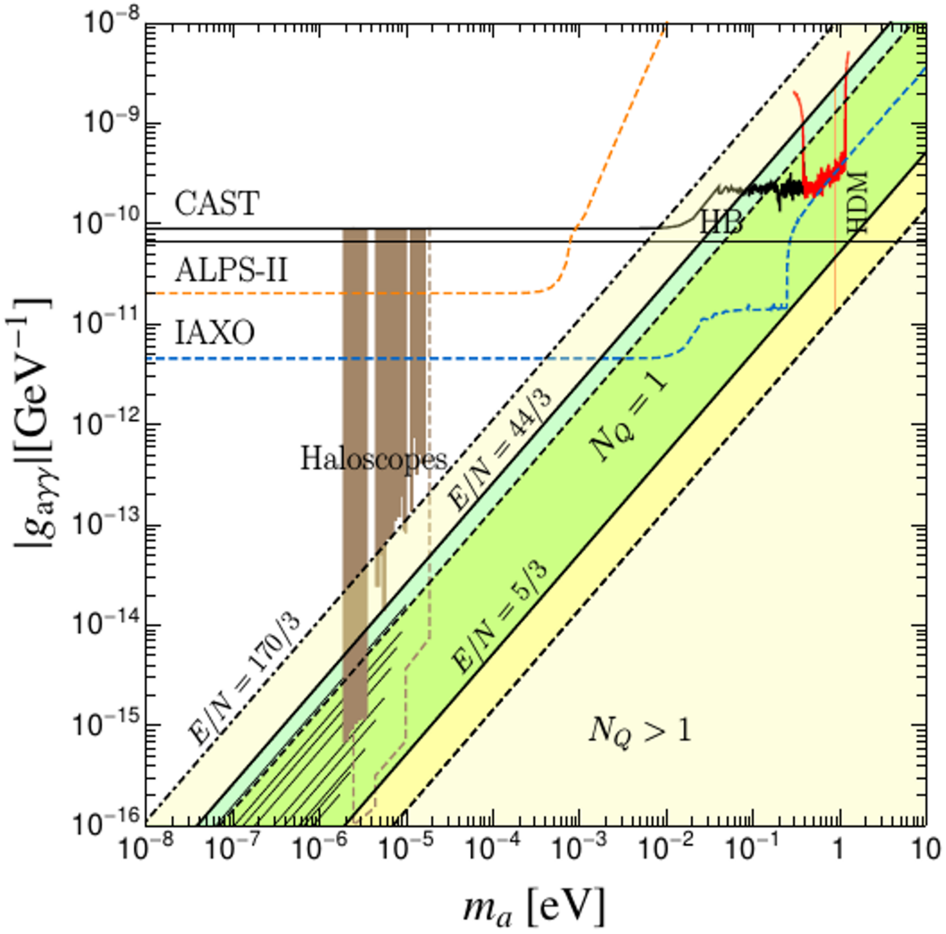
- There is only a finite number which do not lead to Landau poles at high energies $\quad C^{(\mathrm{md})}_{a\gamma} \leq 170/3$



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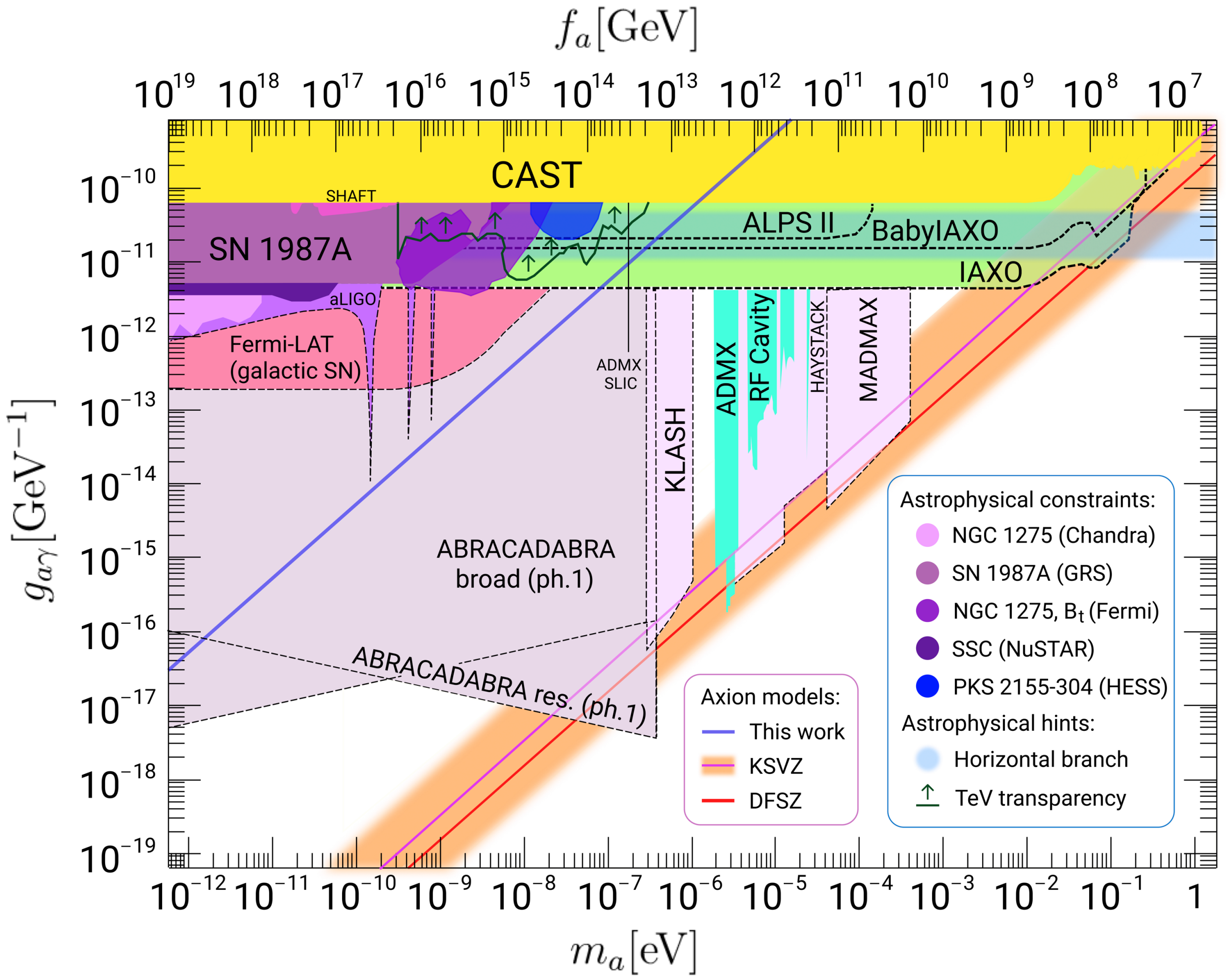

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$$
\begin{aligned}
\sigma &\to e^{i\alpha}\sigma\,,\\
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with $X_u + X_d = 2$

- Leaves Yukawa interactions of type II 2HDM, $\mathcal{L}_Y = Y_{ij}\bar{q}_{iL}H_d d_{jR} + \Gamma_{ij}\bar{q}_{iL}\tilde{H}_u u_{jR} + h.c.$, invariant.

The Axion

DFSZ model

[Kim 79;Shifman,Vainshtein,Zakharov 80]

- Effective Lagrangian at energies below EW symmetry breaking scale, but above QCD scale:

$$\mathcal{L}''_{\rm DFSZ} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{\alpha_s}{8\pi}\frac{a}{f_a} G^c_{\mu\nu}\tilde{G}^{c,\mu\nu} - \frac{\alpha}{8\pi}\frac{8}{3}\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{\partial_\mu a}{f_a}\sum_f C_f \overline{f}\gamma^\mu\gamma_5 f$$

$$f_a \simeq \frac{v_\sigma}{6}; \qquad C_{ae} = C_{ad} = \frac{\sin^2\beta}{3}; \qquad C_{au} = \frac{\cos^2\beta}{3}; \qquad \tan\beta = \frac{v_u}{v_d}$$

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$$\mathcal{L}'''_{\rm DFSZ} \supset \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - C_{a\gamma}\frac{\alpha}{8\pi}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{\partial_\mu a}{f_a}\sum_f C_{af}\bar{f}\gamma^\mu\gamma_5 f$$

  - Photon coupling:

$$C_{a\gamma} = \frac{8}{3} + C_{a\gamma}^{(\rm mi)} = \frac{8}{3} - 1.92(4)$$

  - Nucleon coupling:

$$C_{Ap} = -0.435\sin^2\beta + (-0.182 \pm 0.025)\,; \quad C_{An} = 0.414\sin^2\beta + (-0.16 \pm 0.025)$$

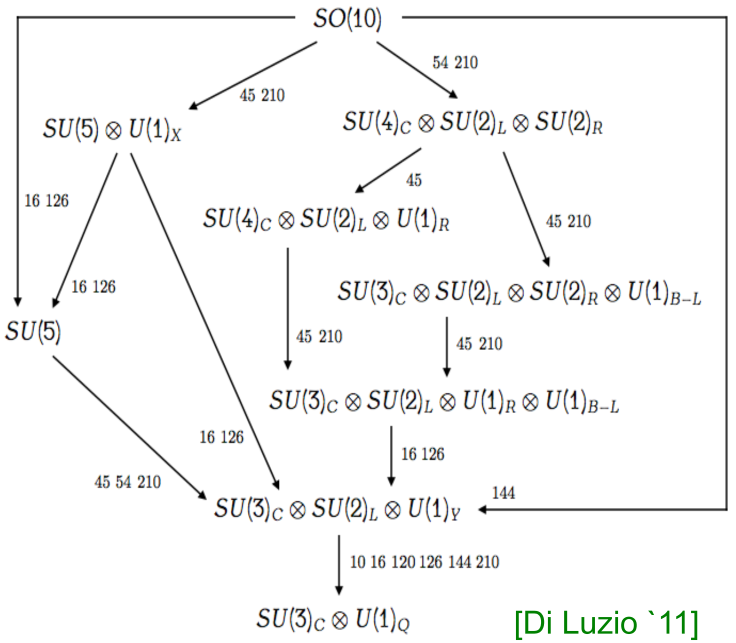
[Grilli di Cortona et al. `16]

The Axion

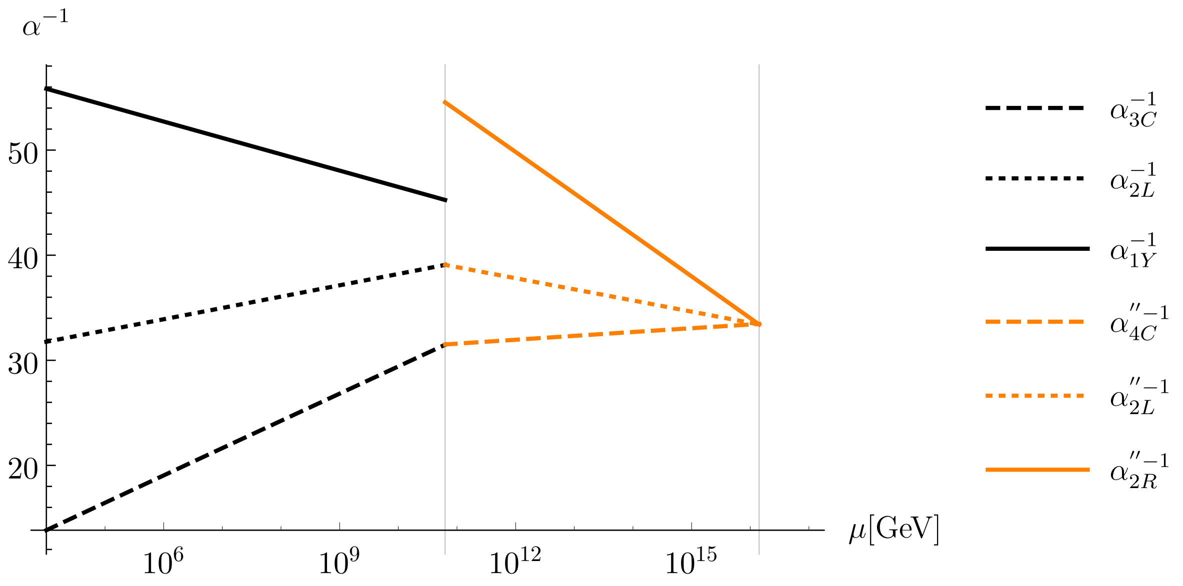
SO(10) x U(1)$_{PQ}$ GUT model

- Gauge coupling unification needs at least one intermediate scale; often discussed SSB chain:

$$SO(10) \overset{M_U - 210_H}{\longrightarrow} SU(4)_C \times SU(2)_L \times SU(2)_R$$
$$\overset{M_{BL} - 126_H}{\longrightarrow} SU(3)_C \times SU(2)_L \times U(1)_Y$$
$$\overset{M_Z - 10_H}{\longrightarrow} SU(3)_C \times U(1)_{em}$$



[Di Luzio `11]



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- SO(10) GUT with three copies of 16_F automatically features
  - neutrino masses and mixing
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$SO(10)$	$4_C 2_L 2_R$	$4_C 2_L 1_R$	$3_C 2_L 1_R 1_{B-L}$	$3_C 2_L 1_Y$	scale
16_F	$(4,2,1)$	$(4,2,0)$	$(3,2,0,\frac{1}{3})$	$(3,2,\frac{1}{6}) := Q$	M_Z
			$(1,2,0,-1)$	$(1,2,-\frac{1}{2}) := L$	M_Z
	$(\bar{4},1,2)$	$(\bar{4},1,\frac{1}{2})$	$(\bar{3},1,\frac{1}{2},-\frac{1}{3})$	$(\bar{3},1,\frac{1}{3}) := d$	M_Z
			$(1,1,\frac{1}{2},1)$	$(1,1,1) := e$	M_Z
		$(\bar{4},1,-\frac{1}{2})$	$(\bar{3},1,-\frac{1}{2},-\frac{1}{3})$	$(\bar{3},1,-\frac{2}{3}) := u$	M_Z
			$(1,1,-\frac{1}{2},1)$	$(1,1,0) := N$	$M_{\rm BL}$

- Most general Yukawas:

$$\mathcal{L}_Y = 16_F \left(Y_{10} 10_H + \tilde{Y}_{10} 10_H^* + Y_{126} \overline{126}_H \right) 16_F$$

- SSB vevs:

$$v_L \equiv \left\langle (\overline{10},3,1)_{126} \right\rangle , \qquad v_R \equiv \left\langle (10,1,3)_{126} \right\rangle ,$$
$$v^{10}_{u,d} \equiv \left\langle (1,2,2)^{10}_{u,d} \right\rangle , \qquad v^{126}_{u,d} \equiv \left\langle (15,2,2)^{126}_{u,d} \right\rangle$$

- Fermion masses/mixing:

$$\begin{aligned} M_u &= Y_{10} v_u^{10} + \tilde{Y}_{10} v_d^{10^*} + Y_{126} v_u^{126} , \\ M_d &= Y_{10} v_d^{10} + \tilde{Y}_{10} v_u^{10^*} + Y_{126} v_d^{126} , \\ M_e &= Y_{10} v_d^{10} + \tilde{Y}_{10} v_u^{10^*} - 3 Y_{126} v_d^{126} , \\ M_D &= Y_{10} v_u^{10} + \tilde{Y}_{10} v_d^{10^*} - 3 Y_{126} v_u^{126} , \\ M_R &= Y_{126} v_R , \\ M_L &= Y_{126} v_L . \end{aligned}$$

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- SO(10) GUT with three copies of 16_F automatically features
  - neutrino masses and mixing
  - baryogenesis via leptogenesis
- PQ extension adds
  - predictivity of fermion masses/mixing
  - solution of strong CP problem
  - DM candidate: axion

[Bajc et al. 06; Altarelli,Meloni 13; Babu,Khan 15]

- PQ symmetry imposed:

$$\begin{aligned} 16_F &\to 16_F e^{i\alpha}, \\ 10_H &\to 10_H e^{-2i\alpha}, \\ \overline{126}_H &\to \overline{126}_H e^{-2i\alpha}, \\ 210_H &\to 210_H e^{4i\alpha} \end{aligned}$$

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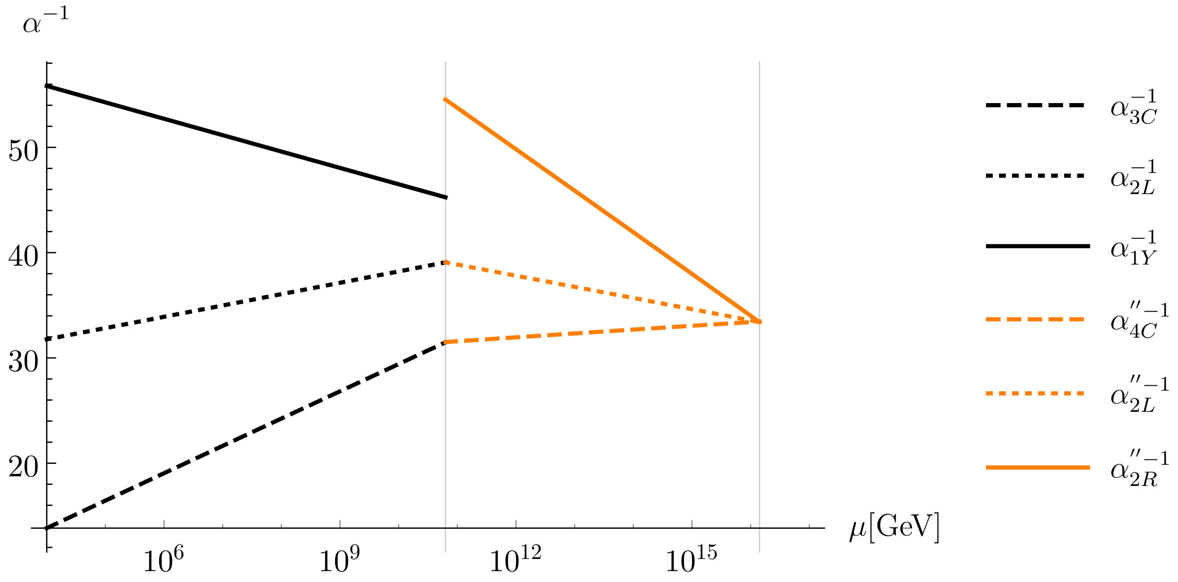
- Axion decay constant:

$$f_A \simeq \frac{1}{3}\frac{M_U}{g_U}$$

- From gauge coupling unification, assuming minimal scalar threshold corrections:

$$m_A \equiv \frac{\sqrt{\chi}}{f_A} \simeq 0.74\,\mathrm{neV}$$



[Ernst, AR, Tamarit, arXiv:1801.04906]

$$M_\mathrm{U} = 1.4 \times 10^{16}\,\mathrm{GeV},\ \ \alpha_\mathrm{U}(M_\mathrm{U})^{-1} = 33.6$$

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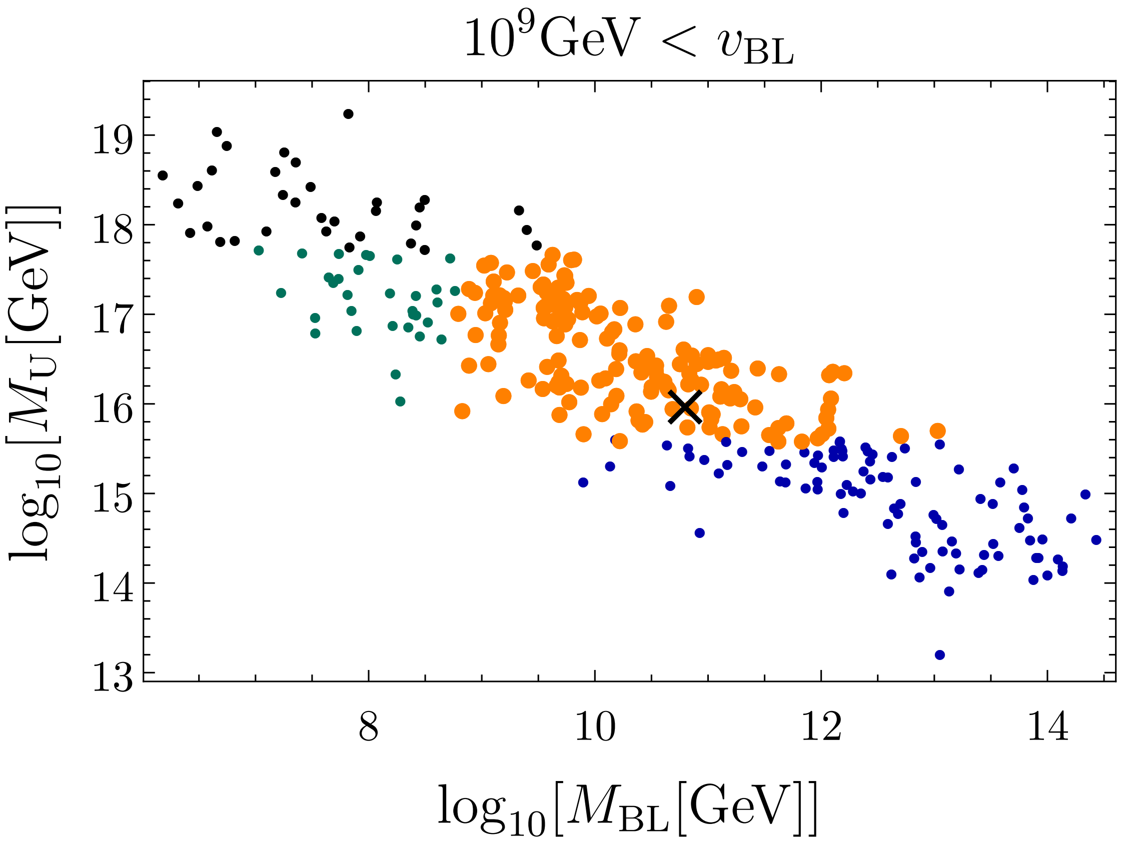

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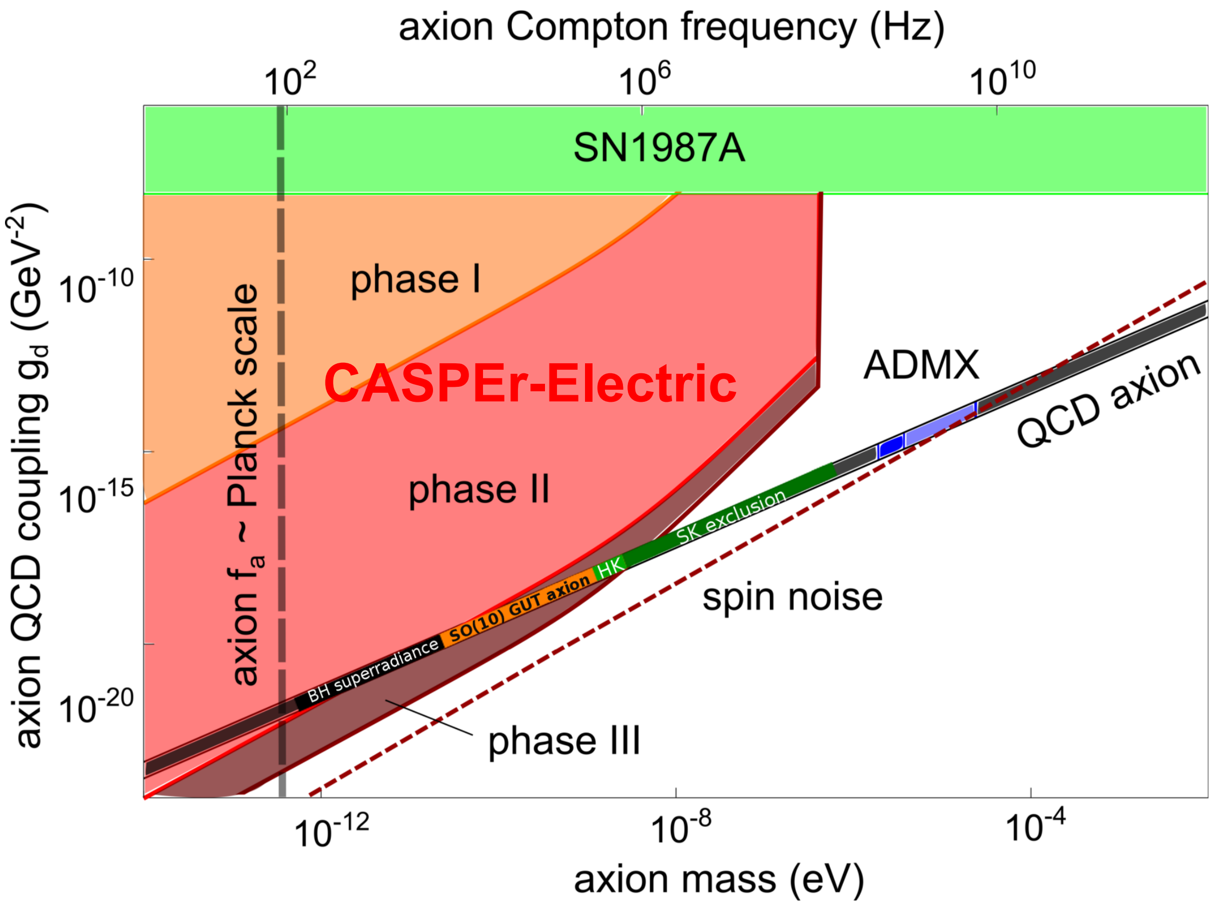
- May be probed by axion DM experiments



[Ernst 18; CASPEr prospects from Kimball et al. 17]

The Axion

Z_N axion in mirror world extension of SM

- We consider now $\mathcal{N}$ copies of the SM that are interchanged under a $Z_{\mathcal{N}}$ symmetry which is non-linearly realized by the axion field: [Hook, arXiv:1802.10093]

$$Z_{\mathcal{N}}: \quad \mathrm{SM}_k \longrightarrow \mathrm{SM}_{k+1\,(\mathrm{mod}\,\mathcal{N})}\,, \qquad a \longrightarrow a + \frac{2\pi k}{\mathcal{N}} f_a$$

- The most general Lagrangian implementing this symmetry describes $\mathcal{N}$ mirror worlds whose couplings take exactly the same values as in the SM, with the exception of the effective θ-parameter: for each copy the effective θ value is shifted by $2\pi/\mathcal{N}$ with respect to that in the neighbour k sector,

$$\mathcal{L} = \sum_{k=0}^{\mathcal{N}-1} \left[\mathcal{L}_{\mathrm{SM}_k} + \frac{\alpha_s}{8\pi} \left(\frac{a}{f_a} + \frac{2\pi k}{\mathcal{N}} \right) G_k \widetilde{G}_k \right] + \ldots$$

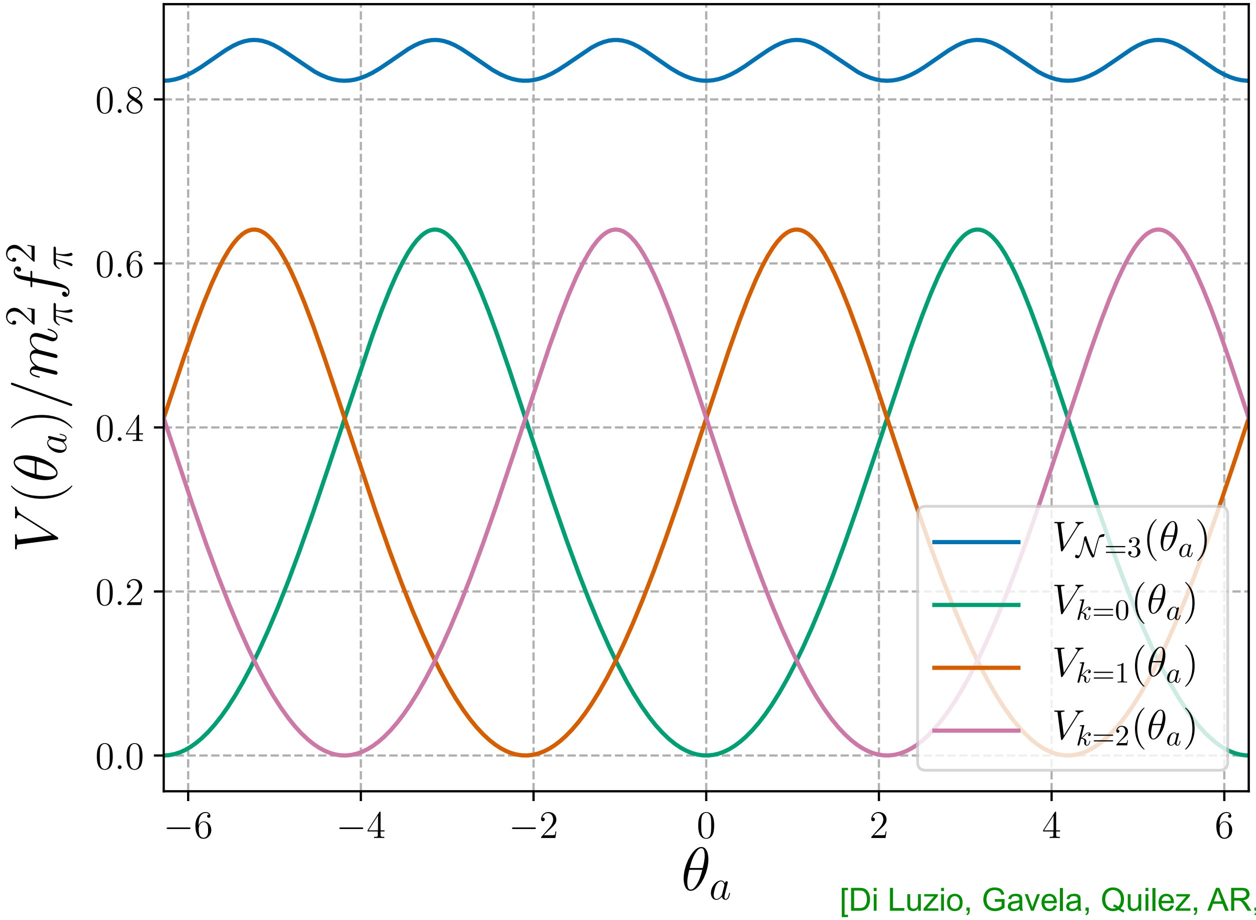
- Each QCD_k sector contributes to the axion potential, which in leading order chiral expansion reads

$$V_{\mathcal{N}}(a) = -\frac{m_\pi^2 f_\pi^2}{1+z} \sum_{k=0}^{\mathcal{N}-1} \sqrt{1 + z^2 + 2z\cos\left(\frac{a}{f_a} + \frac{2\pi k}{\mathcal{N}} \right)}$$

The Axion

Z_N axion in mirror world extension of SM

- For $\mathcal{N}$ odd, strong CP problem solved: potential has $\mathcal{N}$ minima located at $a = \{\pm 2\pi\ell/\mathcal{N}\} f_a$, for $\ell = 0, 1, \ldots, (\mathcal{N}-1)/2$, including the origin, $a = 0$



[Di Luzio, Gavela, Quilez, AR, arXiv:2102.00012]

The Axion

Z_N axion in mirror world extension of SM

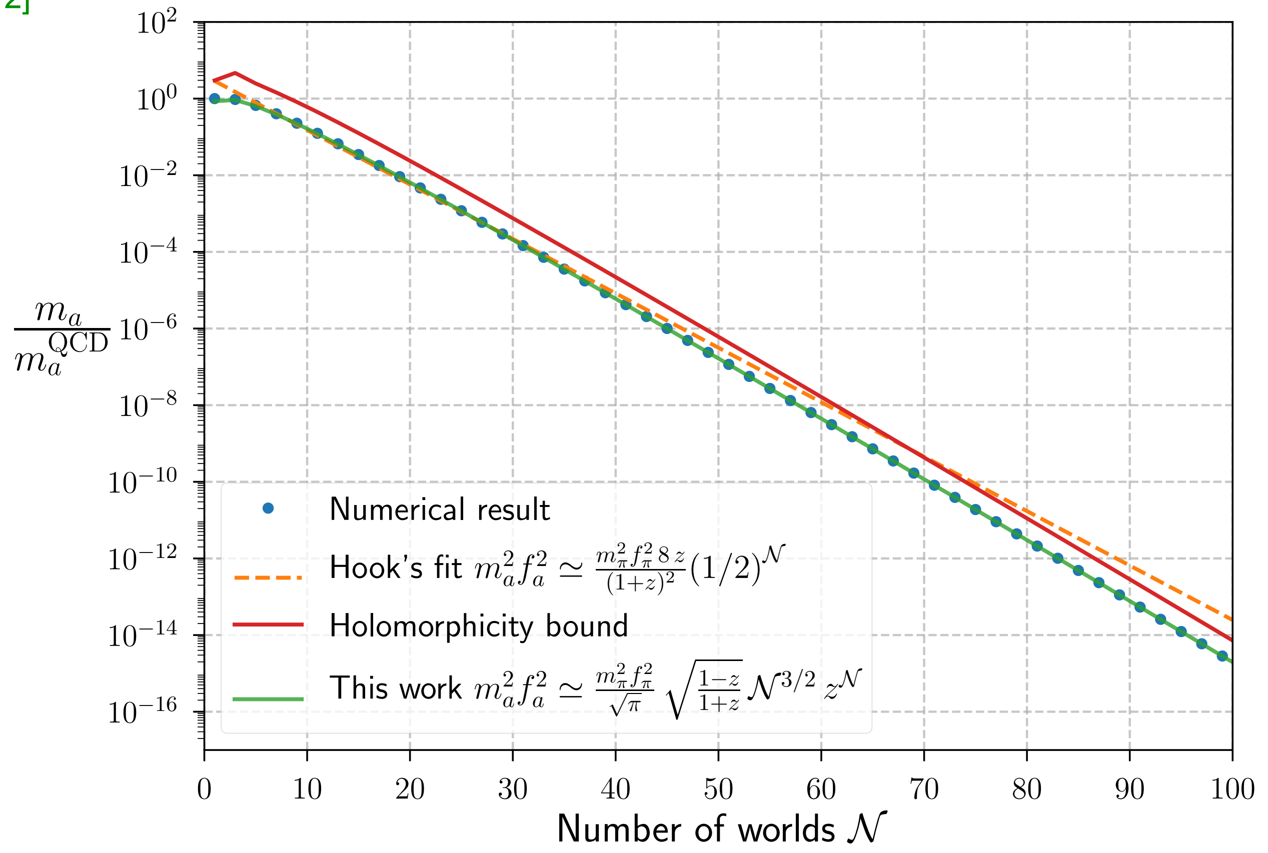
- In the large $\mathcal{N}$ limit: [Di Luzio, Gavela, Quilez, AR, arXiv:2102.00012]

$$V_{\mathcal{N}}(a) \simeq -\frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}}\, \mathcal{N}^{-1/2}\, z^{\mathcal{N}} \cos\left(\mathcal{N}\frac{a}{f_a}\right)$$

  - In particular:

$$m_a^2\, f_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}}\, \mathcal{N}^{3/2}\, z^{\mathcal{N}}$$

  - Mass exponentially smaller by factor $z^{\mathcal{N}/2} \sim 2^{-\mathcal{N}/2}$ as compared to the canonical axion mass

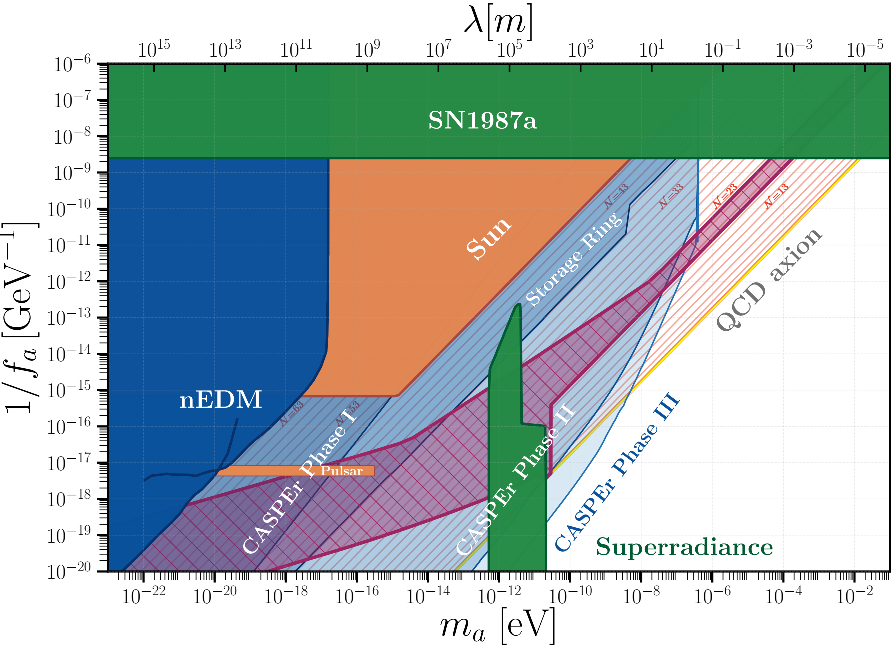


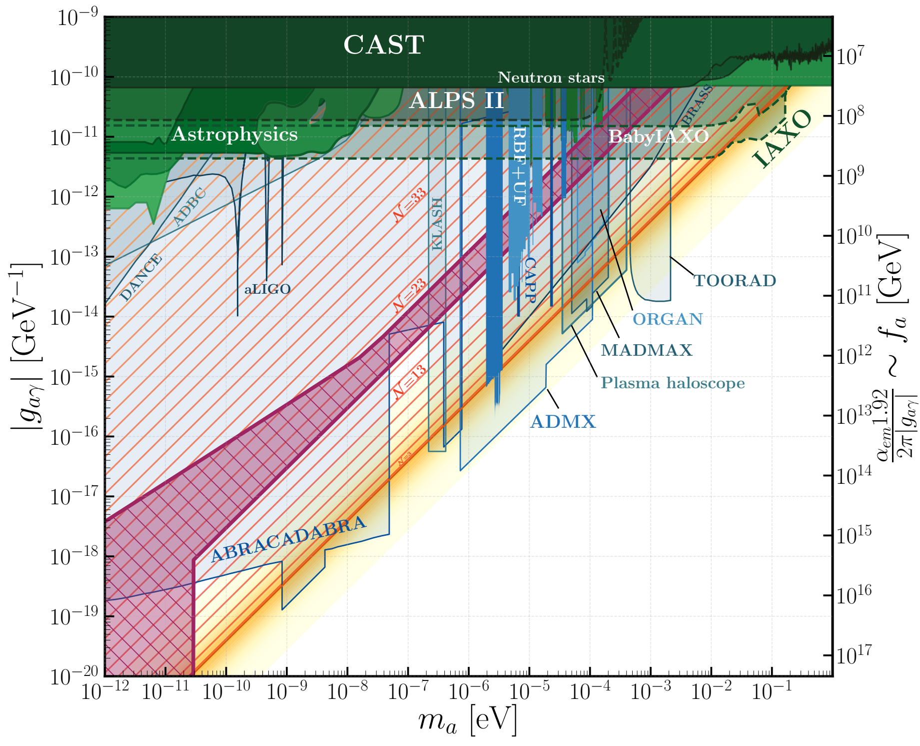
[Di Luzio, Gavela, Quilez, AR, arXiv:2102.00012]

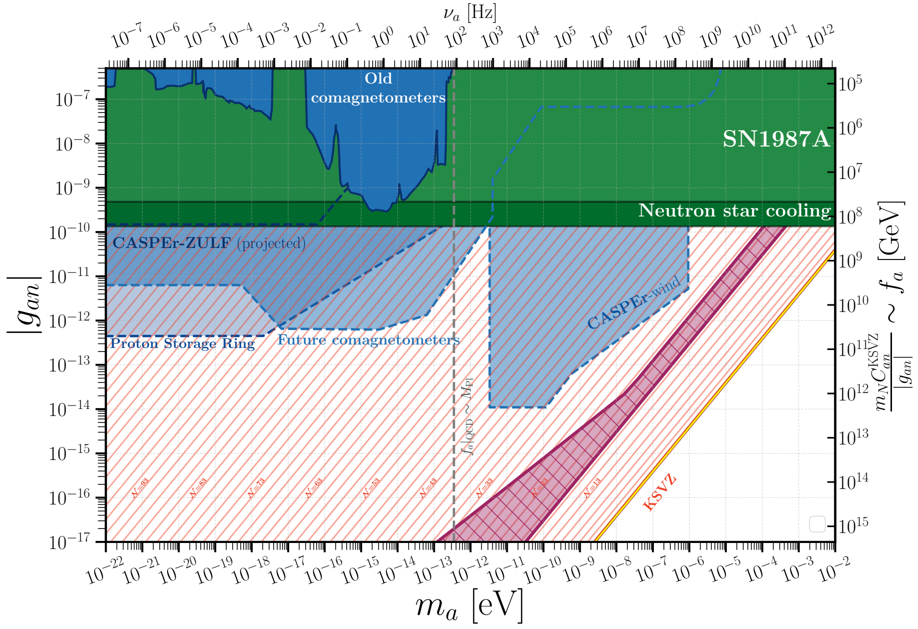
The Axion

Z_N axion in mirror world extension of SM

- Universal increase of axion couplings to SM by factor $z^{-\mathcal{N}/2} \sim 2^{\mathcal{N}/2}$:





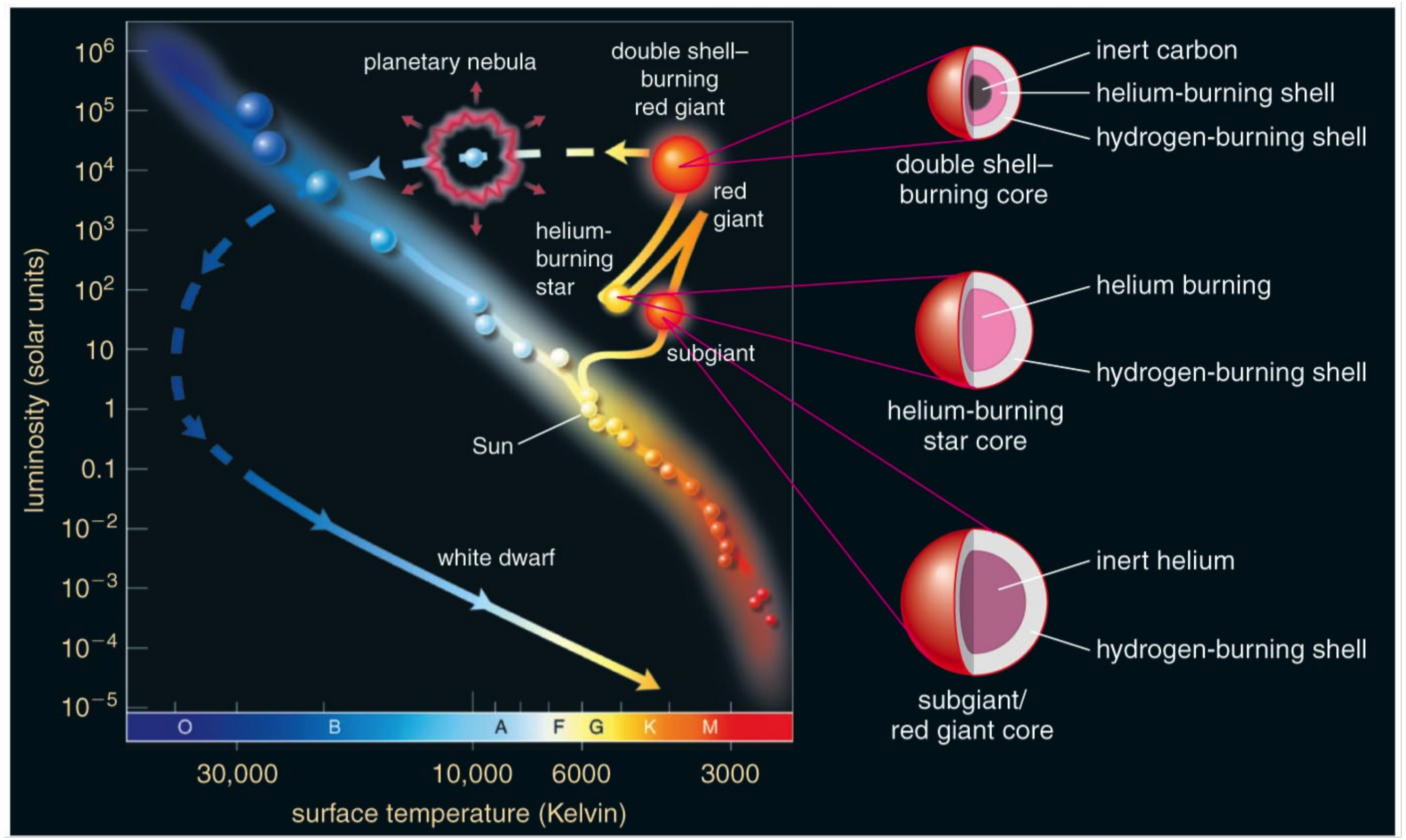


[Di Luzio, Gavela, Quilez, AR, arXiv:2102.01082]

The Axion

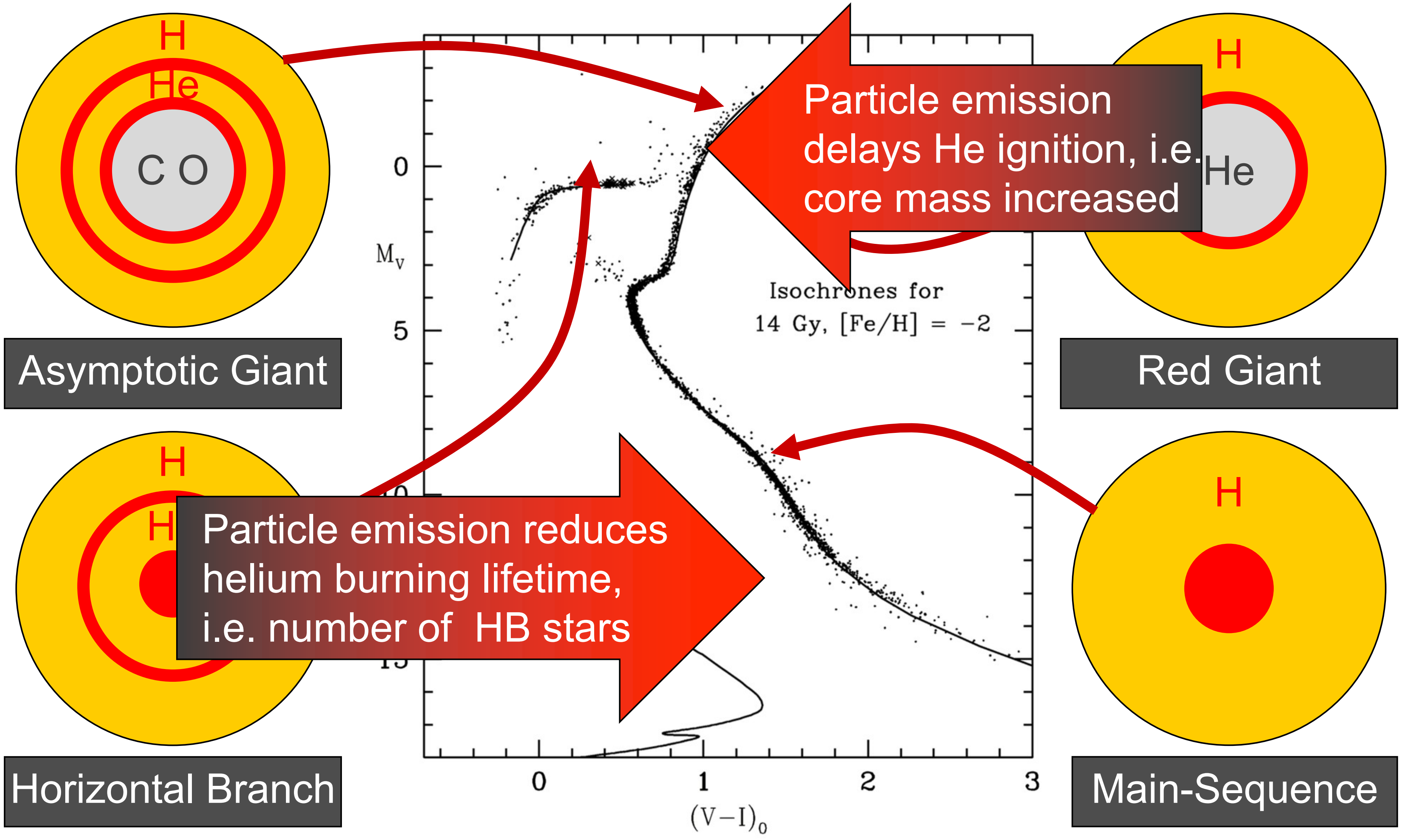
Stellar energy loss constraints

- Evolution of stars (Main Sequence – Red-Giant (RG) – Helium Burning (HB) – White Dwarf (WD)) sensitive to additional energy losses



[Copyright Addison Wesley]

The Axion

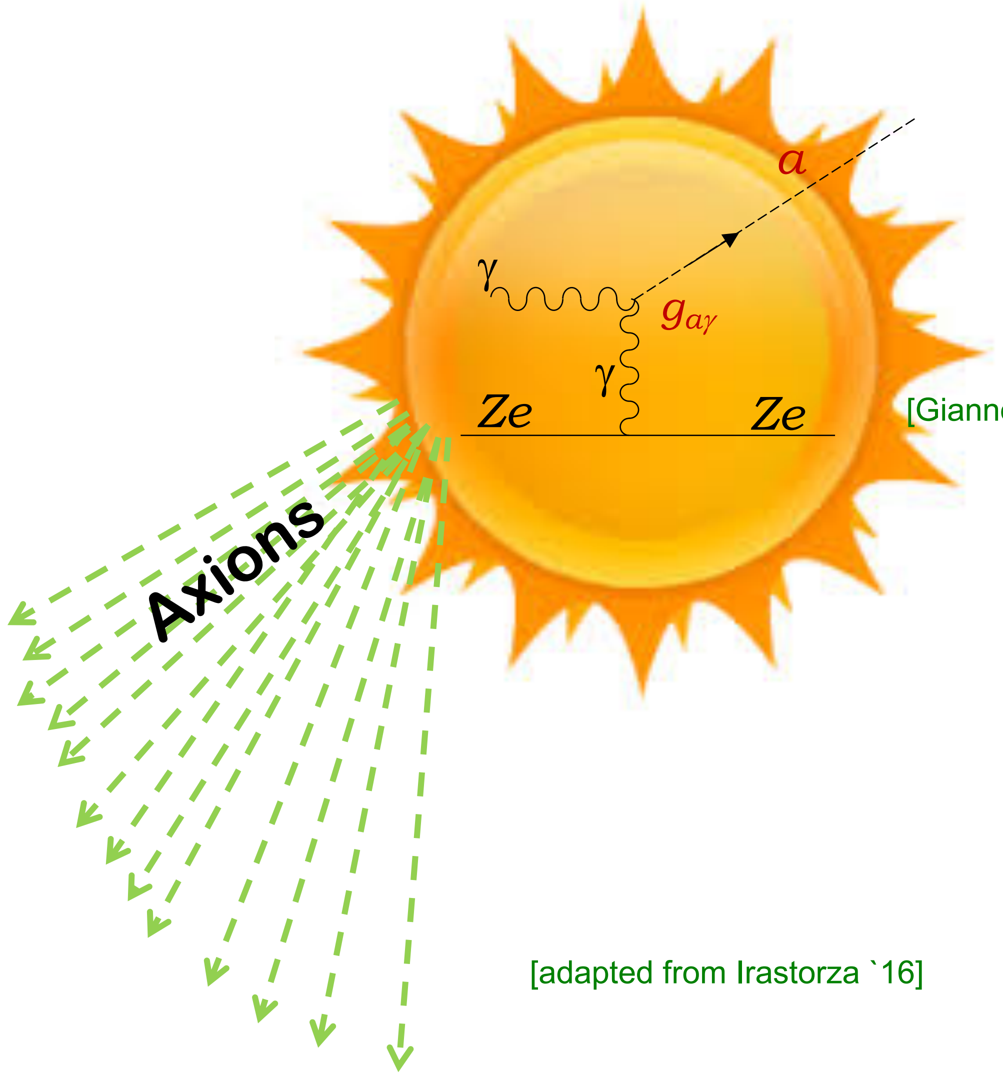


[Raffelt 14]

The Axion

Stellar energy loss constraints

- Axions may be produced in stellar plasma by **Primakoff process**



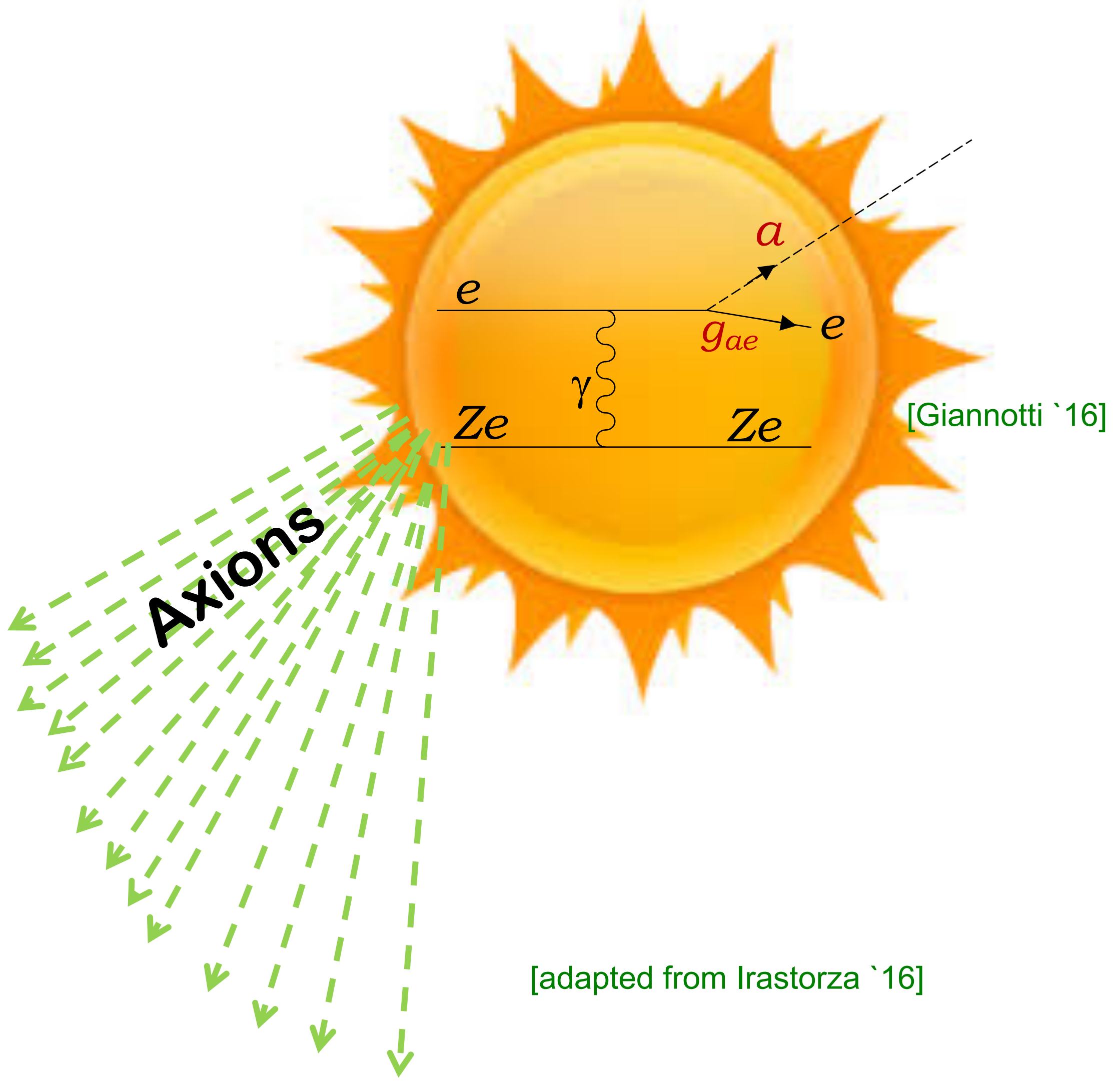
[Giannotti `16]

[adapted from Irastorza `16]

The Axion

Stellar energy loss constraints

- Axions may be produced in stellar plasma by Primakoff process or **bremsstrahlung**



[adapted from Irastorza `16]

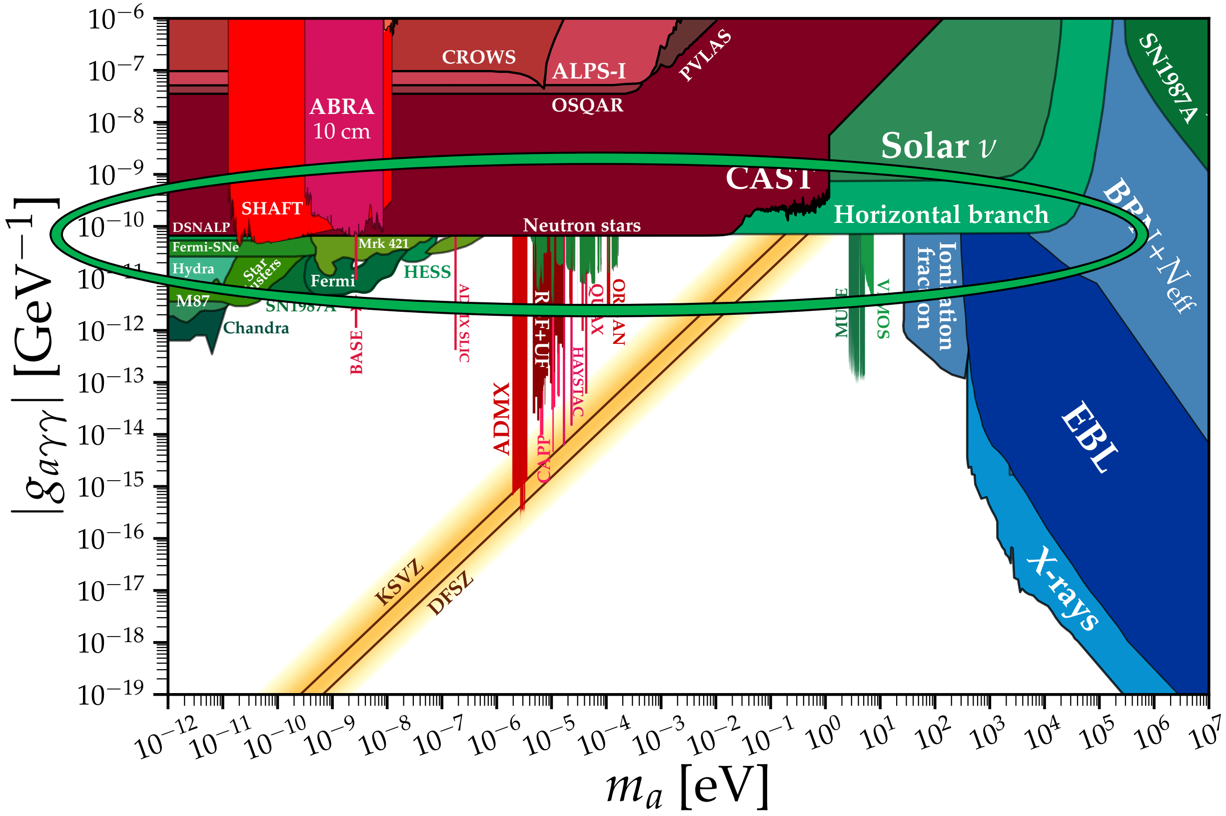
The Axion

Stellar energy loss constraints

- Axions may be produced in stellar plasma by Primakoff process or bremsstrahlung
  - Number of HB stars vs. number of RGs in color-magnitude diagram of globular clusters agrees with SM:

$$|g_{A\gamma\gamma}| \equiv \frac{\alpha}{2\pi f_A}|C_{A\gamma}| < 6.6 \times 10^{-11}\,\mathrm{GeV}^{-1}$$

[Ayala et al. 14]



[AR,Rosenberg,Rybka in: 2021 Update of Review of Particle Physics]

[adapted from https://github.com/cajohare/AxionLimits]

The Axion

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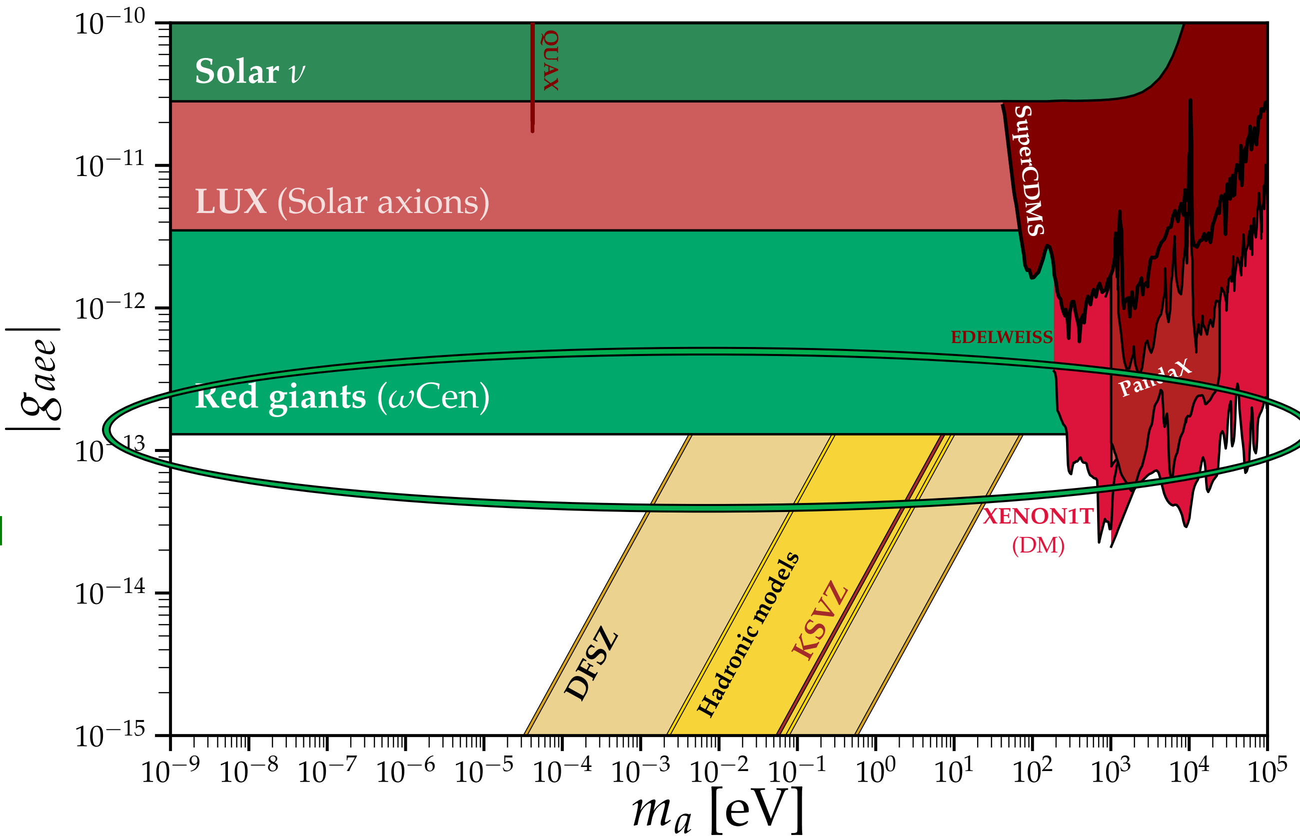
  - Brightness of tip of RG branch in color-magnitude diagram of globular clusters agrees with SM:

$$|g_{aee}| \equiv \frac{m_e}{f_a}|C_{ae}| < 1.4\times 10^{-13}$$ [Capozzi,Raffelt 20;Straniero et al. 20]

  - White dwarf luminosity function agrees with SM:

$$|g_{Aee}| \equiv \frac{m_e}{f_A}|C_{Ae}| < 2.7\times 10^{-13}$$ [Isern et al. 08-12]



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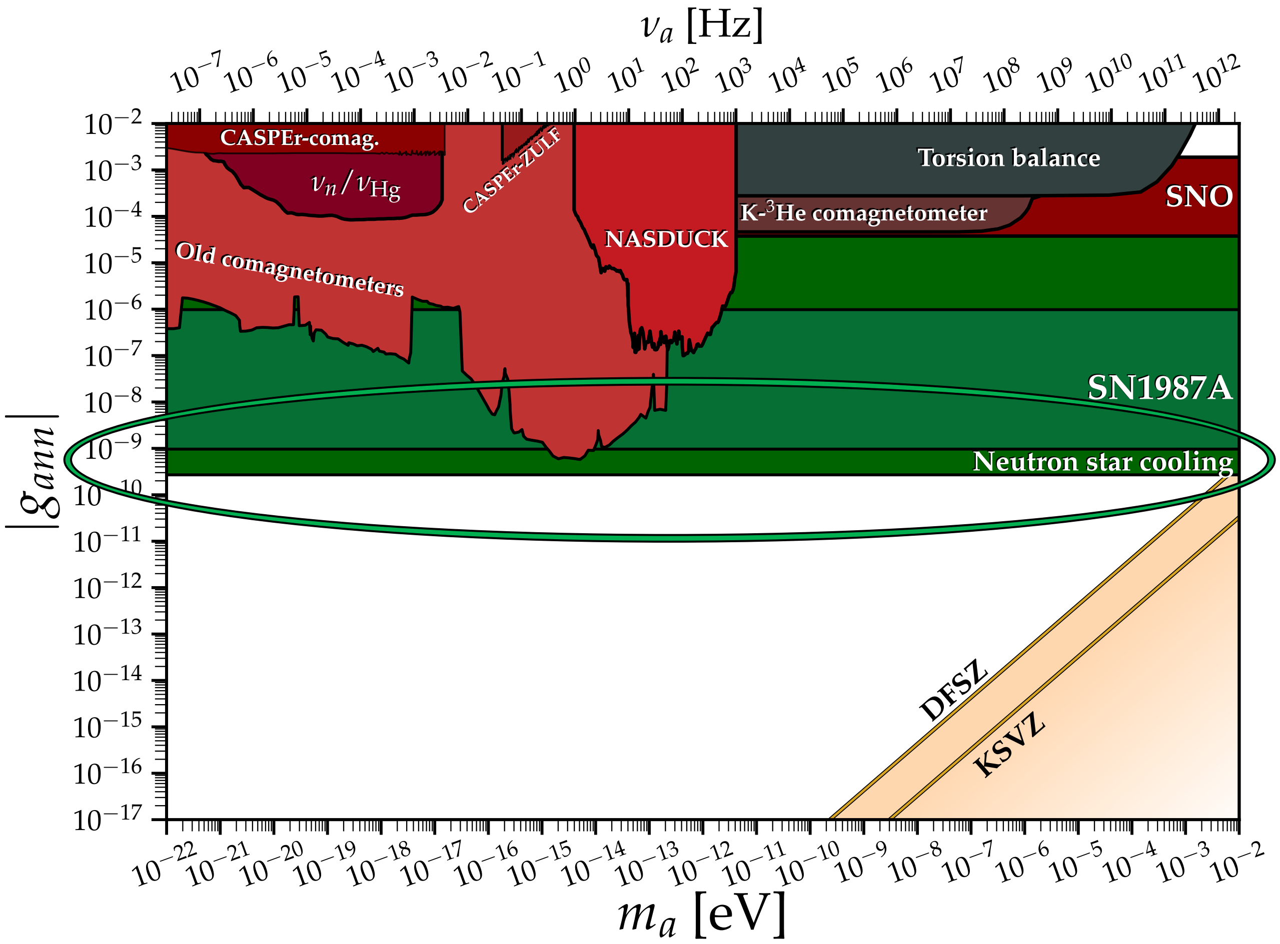
  - Duration of neutrino burst of SN1987A and temperature evolution of neutron stars agees with SM: upper bounds on nucleon couplings

[Raffelt 08; Fischer et al. 16; Giannotti et al. 17; Chang et al. 18; Carenza et al. 19]

[Keller,Sedrakian 13; Sedrakian 16; Hamaguchi et al. 18; Beznogov et al. 18]



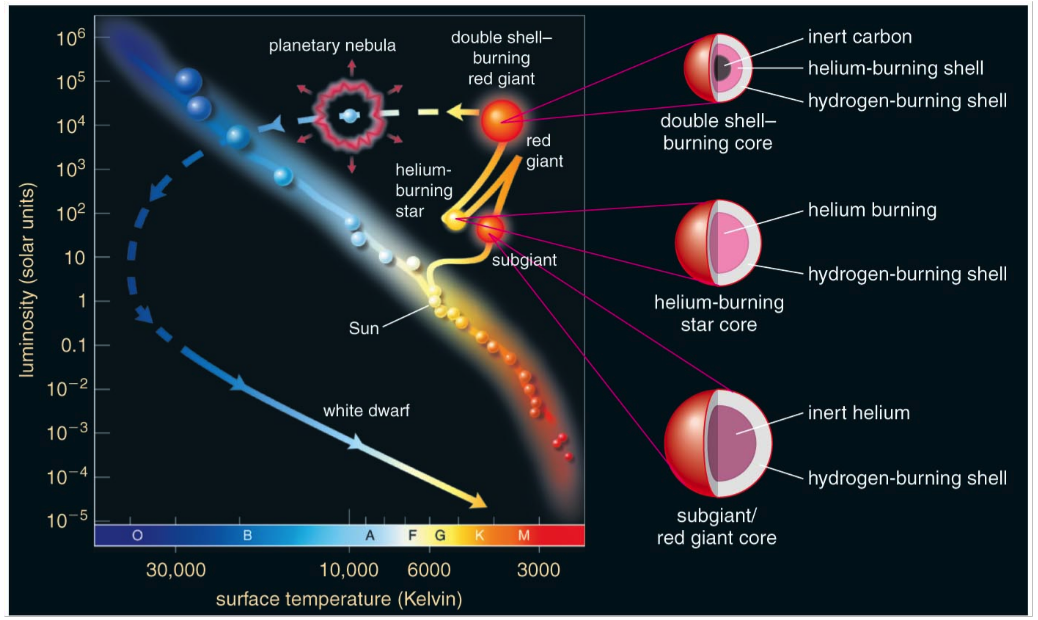
[AR,Rosenberg,Rybka in: 2021 Update of Review of Particle Physics]

[adapted from https://github.com/cajohare/AxionLimits]

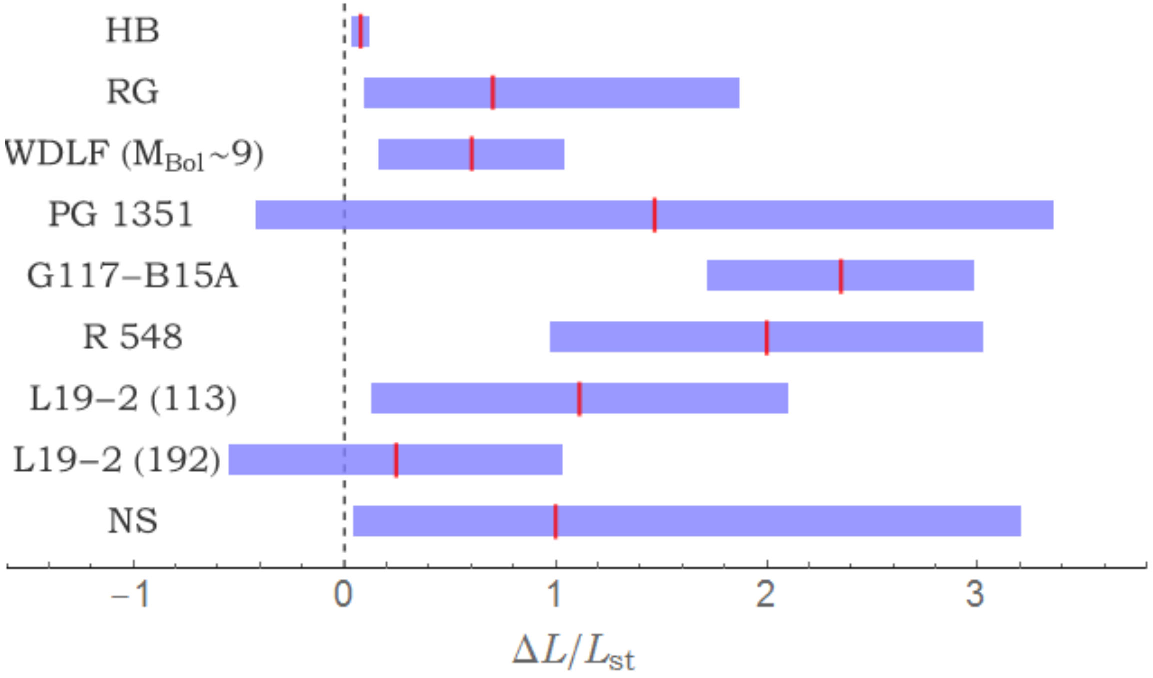
The Axion

Astrophysical hints for axions

- There are hints from astrophysics which may ex-plained by axions:
  - Excessive energy losses of stars in various stages of their evolution



[Copyright Addison Wesley]



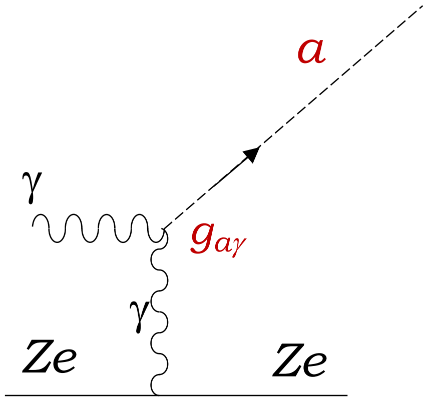
[Giannotti, Irastorza, Redondo, AR 15]

The Axion

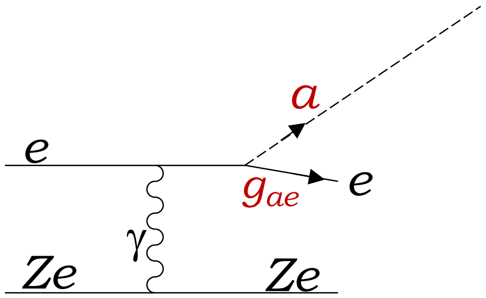
Astrophysical hints for axions

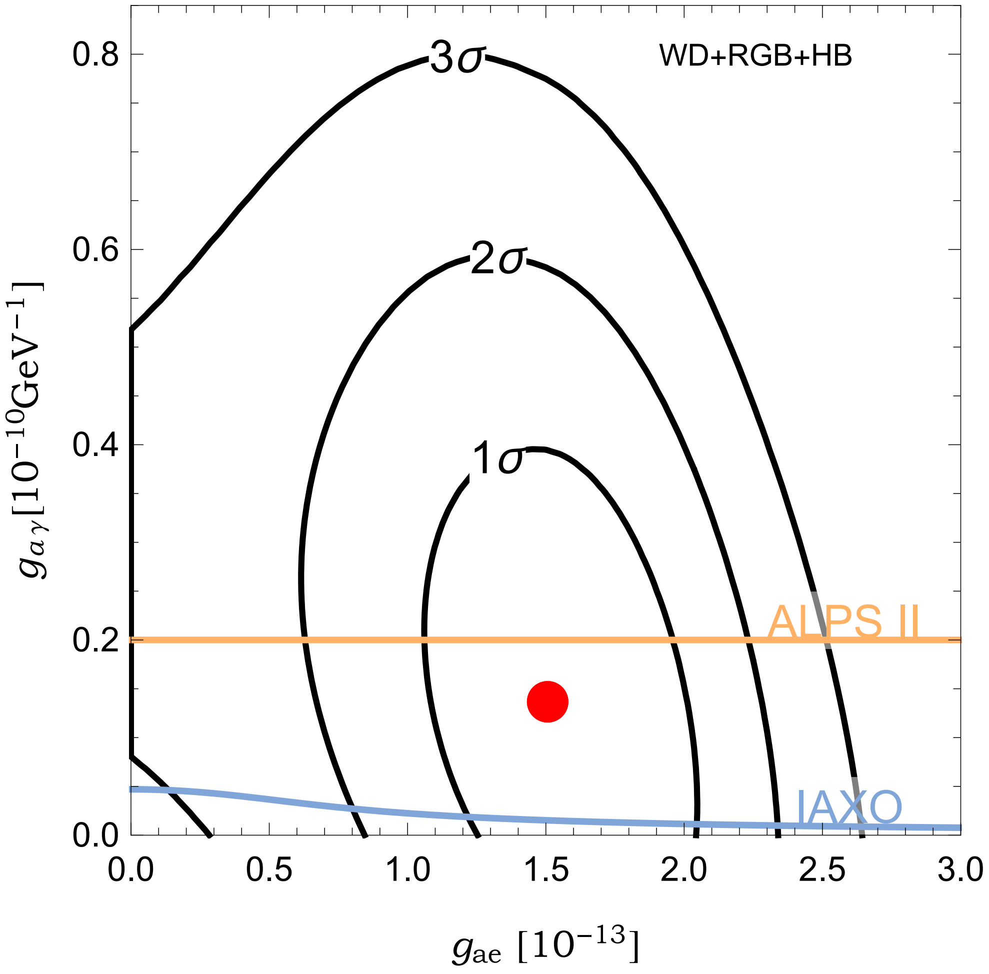
- There are hints from astrophysics which may explained by axions:
  - Excessive energy losses of stars in various stages of their evolution: may be explained by axion production

$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$



$$\mathcal{L} \supset -ig_{ae}\, a\, \overline{\psi}_e \gamma_5 \psi_e$$



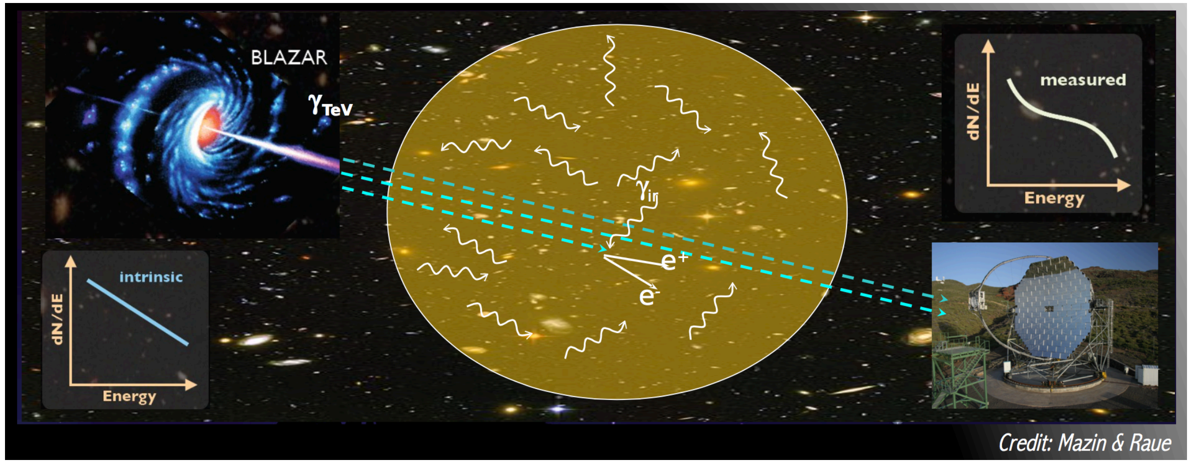


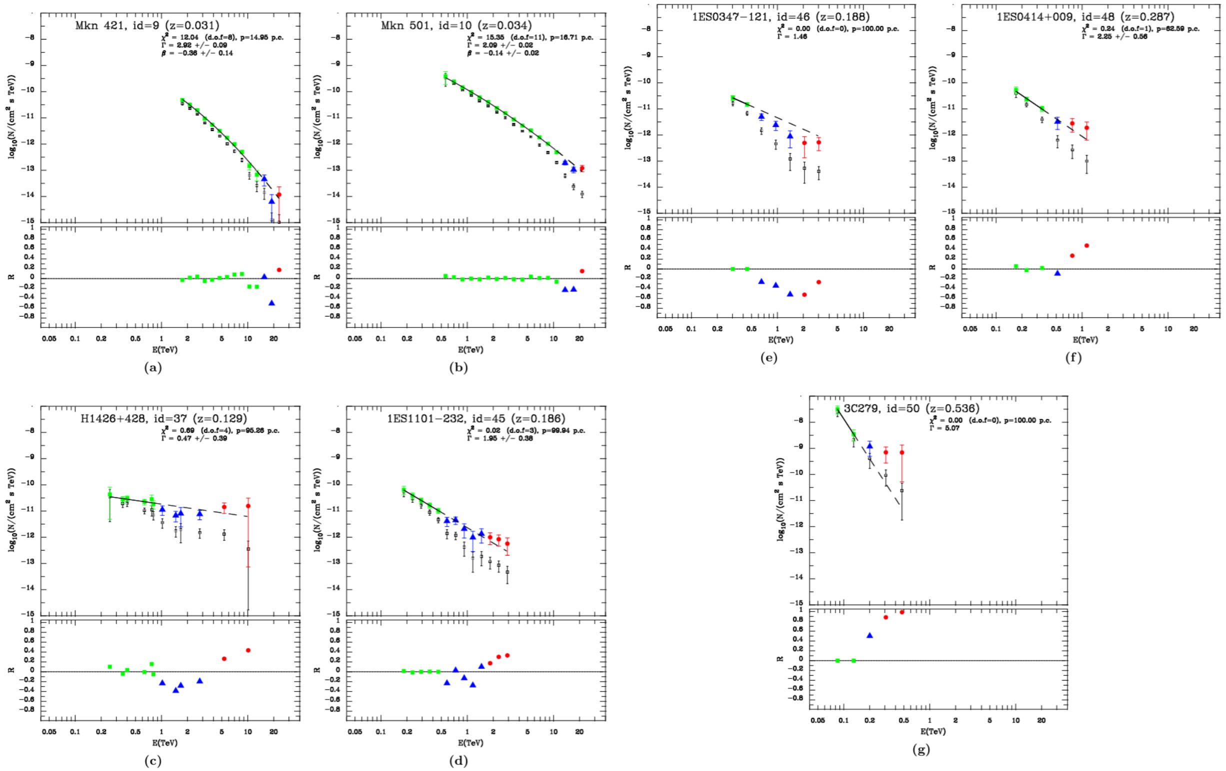
[Giannotti et al. 17]

The Axion

Astrophysical hints for axions

- There are hints from astrophysics which may explained by axions:
  - Excessive energy losses of stars in various stages of their evolution
  - Excessive transparency of the universe for TeV gamma rays





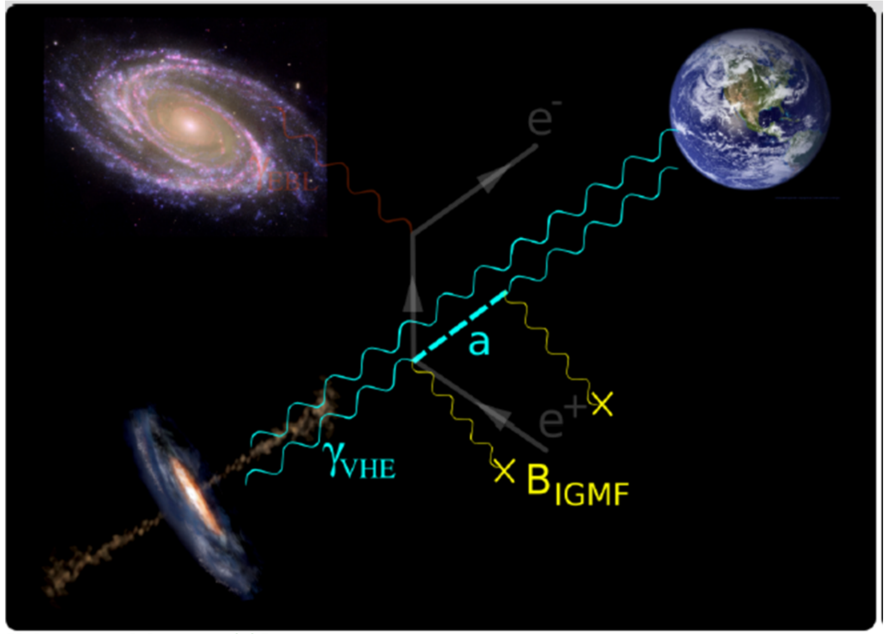
[Horns,Meyer 12]

The Axion

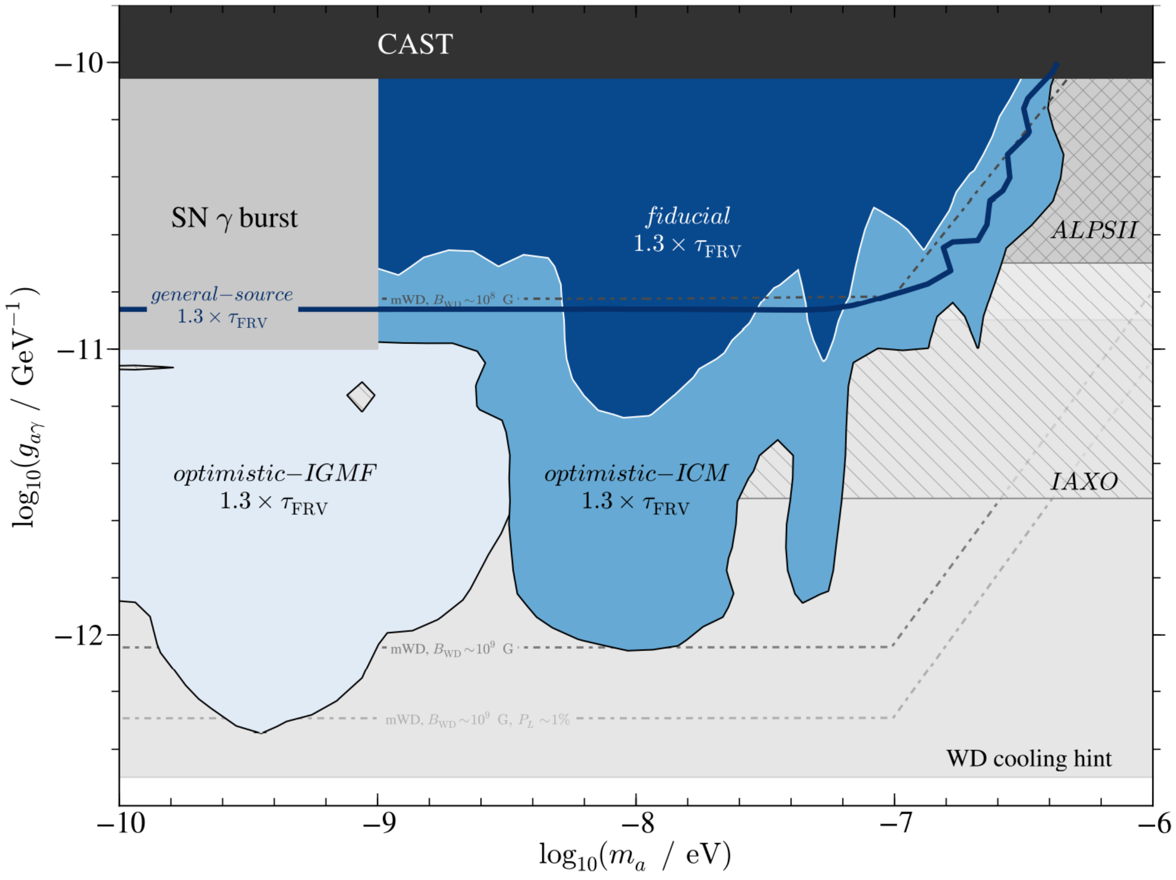
Astrophysical hints for axions

- There are hints from astrophysics which may explained by axions:
  - Excessive energy losses of stars in various stages of their evolution
  - Excessive transparency of the universe for TeV gamma rays: may be explained by photon $\leftrightarrow$ axion conversion

	IGMF			ICM					
Name	$B^0_{\rm IGMF}$ (nG)	$\lambda^c_{\rm IGMF}$ (Mpc)	$n^0_{\rm el,IGM}$ ($\times 10^{-7}$ cm^{-3})	$B^0_{\rm ICMF}$ (μG)	$\lambda^c_{\rm ICMF}$ (kpc)	$r_{\rm cluster}$ (Mpc)	$n^0_{\rm el,ICM}$ ($\times 10^{-3}$ cm^{-3})	$r_{\rm core}$ (kpc)	η
General source	Only conversion in GMF, but $\rho_{\rm init} = 1/3{\rm diag}(e^{-\tau}, e^{-\tau}, 1)$								
Optimistic IGMF	5	50	1	...	...	...	...	...	...
Optimistic ICM	...	...	...	10	10	2	10	200	0.5
Fiducial	0.01	10	1	1	10	2/3	1	...	...



[Manuel Meyer 12]



[Meyer,Horns,Raue 13]