Theoretical framework for Dark Matter Axions

IDM2024 - L'Aquila

Luca Di Luzio

INFN PADOVA

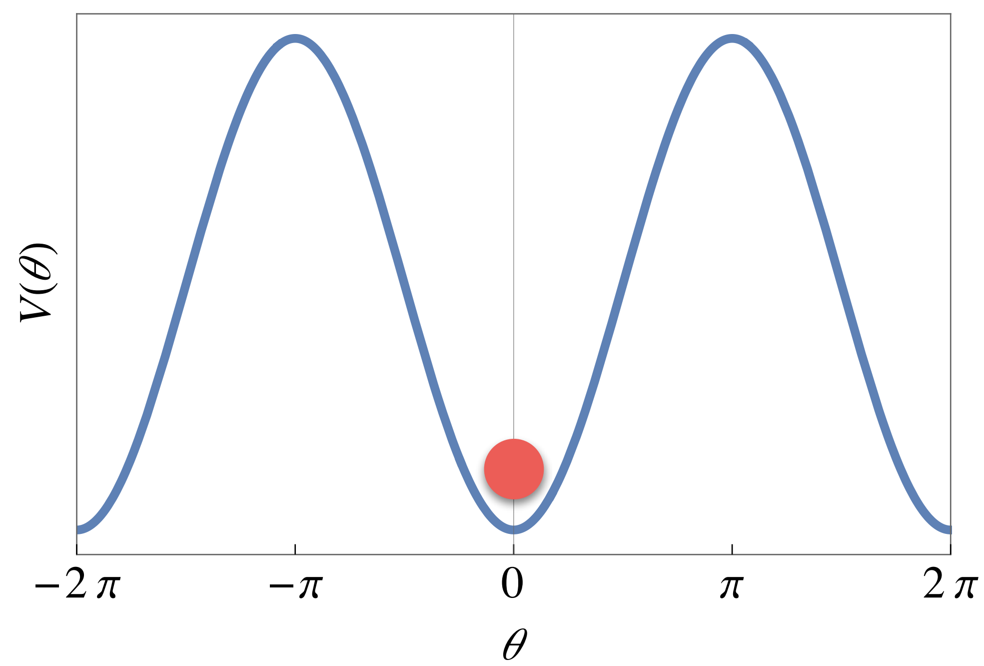
QCD axion & strong CP

- Introduced to address the strong CP problem [Peccei, Quinn '77, Weinberg '78, Wilczek '78]

$$\delta \mathcal{L}_{\rm QCD} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G} \qquad |\theta| \lesssim 10^{-10}$$

- promote θ to a dynamical field (axion): $\theta \to \frac{a}{f_a}$

- acquires a QCD potential and relaxes dynamically to zero



QCD axion & dark matter

- Unavoidably contributes to the energy density of the universe

Ω_{DM} (non-thermal production)

i) misalignment mechanism (axion oscillations)

[Preskill, Wise, Wilczek '83,
Abbott, Sikivie '83,
Dine, Fischler '83]

$$\ddot{a} + 3H\dot{a} + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) = 0$$

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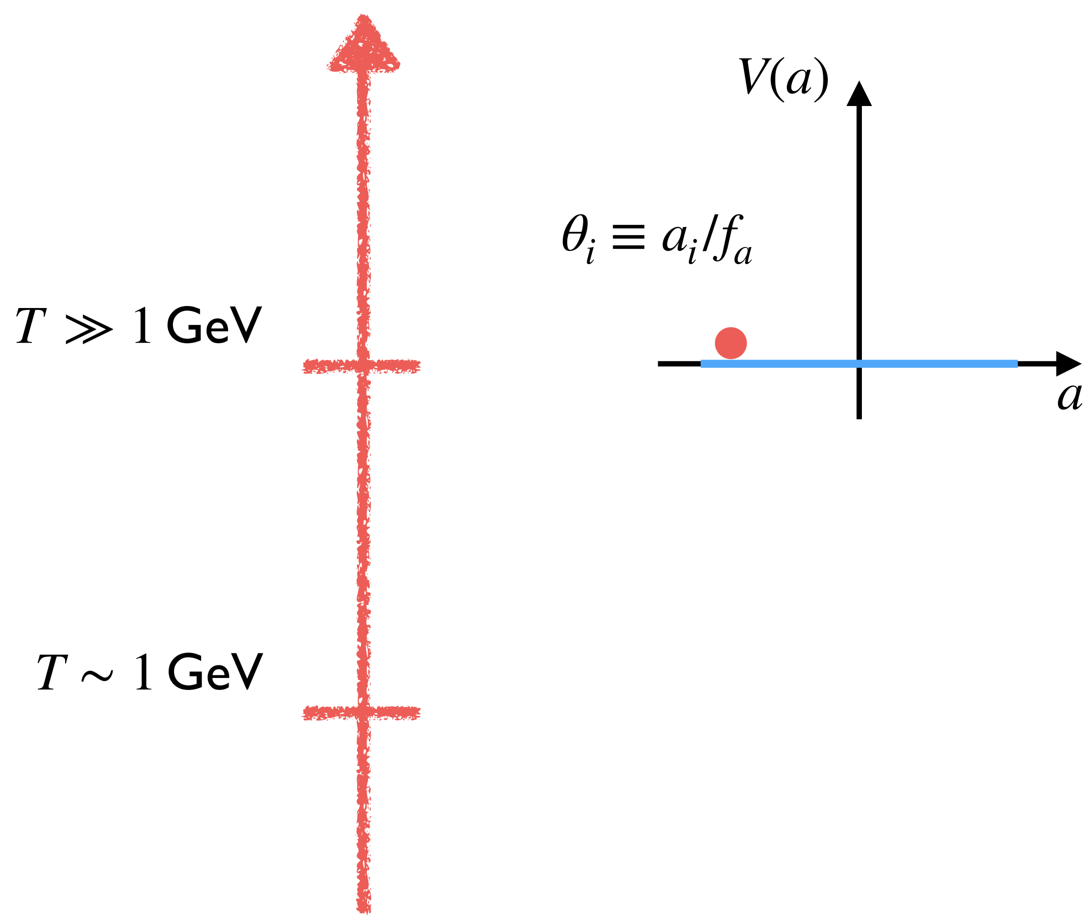

$$\ddot{a} + 3H\dot{a} + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) = 0$$

($T \gg T_c \approx 150$ MeV)

$$m_a^2(T) \approx m_a^2 \left(T/T_c\right)^{-8}$$

[Axion mass at finite T from lattice QCD inputs - see e.g. Borsanyi et al 1606.07494]

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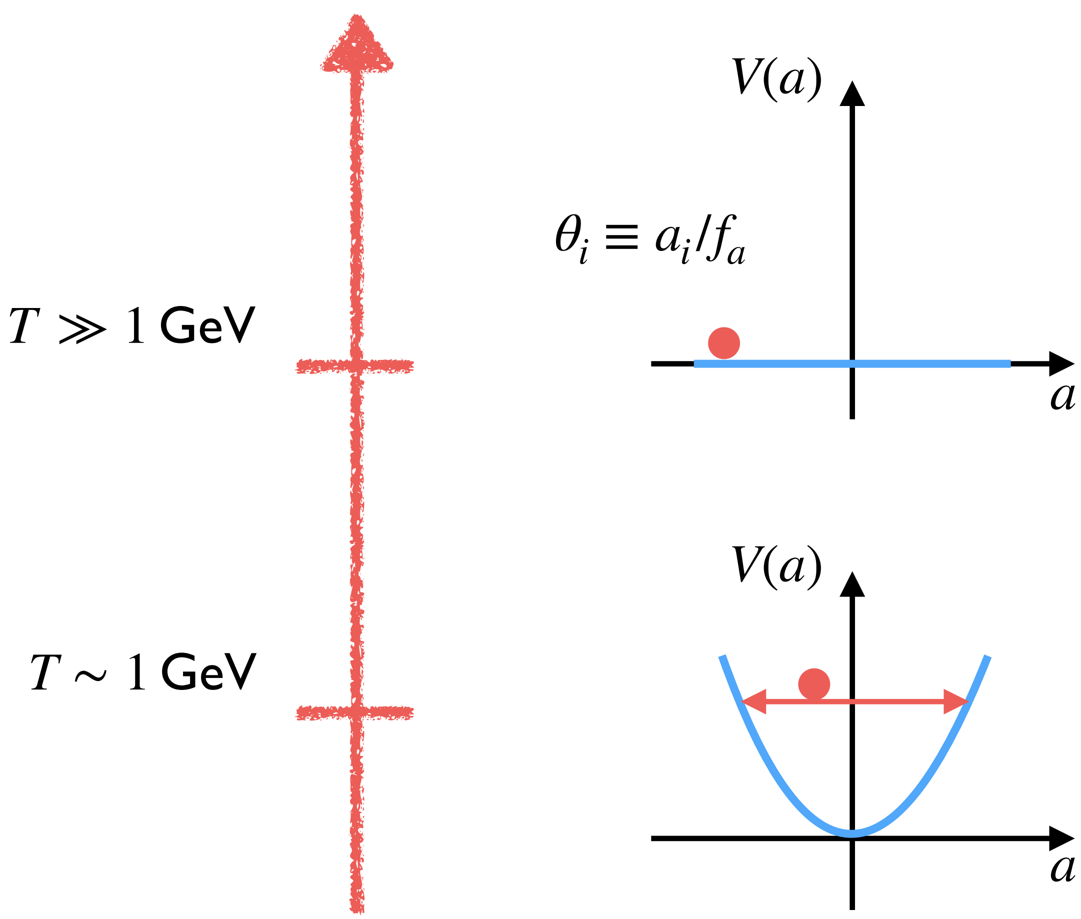

$$\ddot{a} + \cancel{3H}\dot{a} + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) = 0$$

$$\Omega_a h^2 \approx 0.12 \left(\frac{6\,\mu\text{eV}}{m_a}\right)^{1.16} \theta_i^2$$

[Axion mass at finite T from lattice QCD inputs - see e.g. Borsanyi et al 1606.07494]

QCD axion & dark matter

- Unavoidably contributes to the energy density of the universe

$\Omega_{\rm DM}$ (non-thermal production)

i) misalignment mechanism (axion oscillations)

ii) topological defects (axion strings, …) [Davies '86, Harari Sikivie '87, …]

→ absent if PQ symmetry is broken before inflation (Pre-inflation)

QCD axion & dark matter

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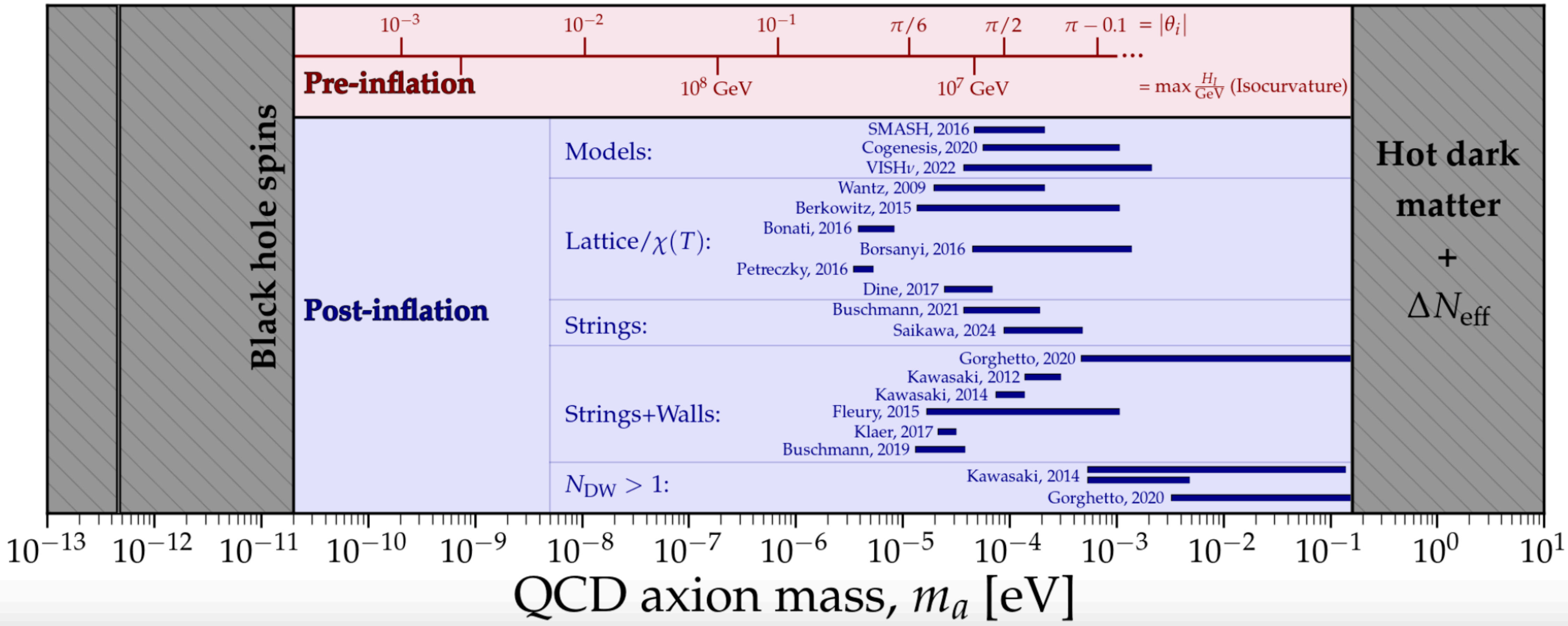
i) misalignment mechanism (axion oscillations)

ii) topological defects (axion strings, ...)

[https://cajohare.github.io/AxionLimits]



QCD axion & dark matter

- Unavoidably contributes to the energy density of the universe

$\Omega_{\rm DM}$ (non-thermal production)

$\Omega_{\rm rad}$ (thermal production) [Turner PRL 59 (1987), Chang, Choi hep-ph/9306216, ...]

$$\rho_{\rm rad} = \rho_\gamma + \rho_\nu + \rho_a = \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{\rm eff}^{\rm SM} + \frac{1}{2}\left(\frac{T_a}{T_\gamma}\right)^4\right]\rho_\gamma \equiv \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{\rm eff}\right]\rho_\gamma$$

[See talk by G. Grilli di Cortona]

Back to PQ mechanism

- New spin-0 boson with a pseudo-shift symmetry $a \to a + \kappa f_a$

broken by $\frac{a}{f_a} \frac{g_s^2}{32\pi^2} G\tilde{G}$ → $E(0) \leq E(\langle a \rangle)$ [Vafa, Witten PRL 53 (1984)]

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$$\theta_{\text{eff}} = \frac{\langle a \rangle}{f_a}$$

$$\begin{aligned} e^{-V_4 E(\theta_{\text{eff}})} &= \int \mathcal{D}\varphi \, e^{-S_0 + i\theta_{\text{eff}} \int G\tilde{G}} \\ &= \left| \int \mathcal{D}\varphi \, e^{-S_0 + i\theta_{\text{eff}} \int G\tilde{G}} \right| \\ &\leq \int \mathcal{D}\varphi \left| e^{-S_0 + i\theta_{\text{eff}} \int G\tilde{G}} \right| = e^{-V_4 E(0)} \end{aligned}$$

- Does the axion really relax to zero ?

→ $\theta_{\text{eff}} \sim G_F^2 f_\pi^4 j_{\text{CKM}} \approx 10^{-18}$ [Georgi, Randall, NPB276 (1986)]

path-integral measure positive definite only for a vector-like theory (e.g. QCD)

Back to PQ mechanism

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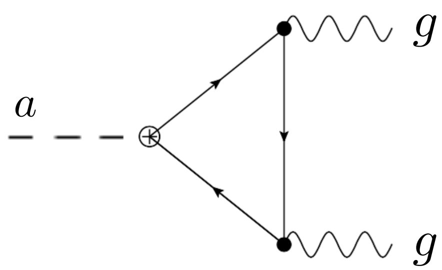
  broken by $\frac{a}{f_a} \frac{g_s^2}{32\pi^2} G\tilde{G}$ → $E(0) \leq E(\langle a \rangle)$ [Vafa, Witten PRL 53 (1984)]

- its origin* can be traced back to a global U(1)$_{PQ}$ [Peccei, Quinn '77, Weinberg '78, Wilczek '78]

  1. spontaneously broken (the axion is the associated pNGB)

  2. QCD anomalous



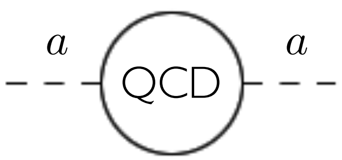
$$\partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi} G \cdot \tilde{G}$$

**axions can also arise as zero modes from string theory compactification* [Witten PLB 149 (1984), …]

Axion properties

- Consequences of $\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$

Axion mass



$$\sim \frac{\Lambda^4_{\rm QCD}}{f_a^2} \quad \longrightarrow \quad m_a \sim \Lambda^2_{\rm QCD}/f_a$$

Axion properties

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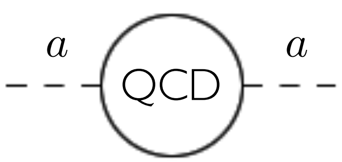
Axion mass



$\sim \frac{\Lambda^4_{\rm QCD}}{f_a^2}$ → $m_a = 5.691(51)\,\text{meV}\left(\frac{10^9\,\text{GeV}}{f_a}\right)$

[Gorghetto, Villadoro 1812.01008 (NNLO chiPT)
Bonati et al, 1512.06746 + Borsanyi et al 1606.07494 (lattice)]

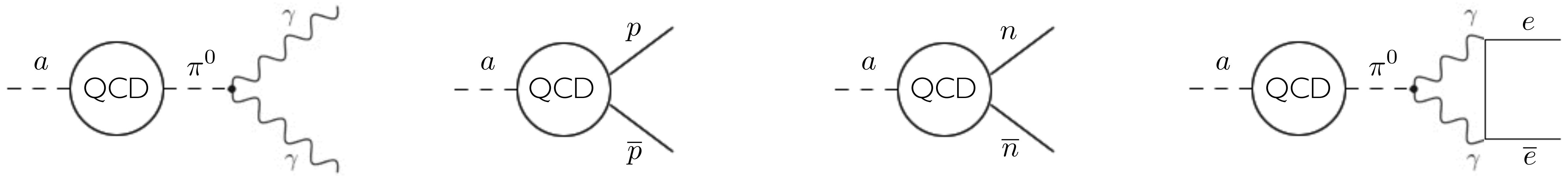
$f_a \gtrsim 10^9$ GeV from astrophysics → very light & weakly coupled

[See talk by M. Meyer for astro constraints]

Axion properties

- Consequences of $\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$

Axion couplings to photons, nucleons, electrons, …



$C_\gamma = -1.92(4)$ $\quad C_p = -0.47(3)$ $\quad C_n = -0.02(3)$ $\quad C_e = -7.8(2)\times 10^{-6}\log\left(\frac{f_a}{m_e}\right)$

$$\mathcal{L}_a \supset \frac{\alpha}{8\pi}\frac{C_\gamma}{f_a}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{C_f}{2f_a}\partial_\mu a\bar{f}\gamma^\mu\gamma_5 f \qquad (f = p, n, e)$$

[Grilli di Cortona, Hardy, Vega, Villadoro 1511.02867 (NLO chiPT)
Lu, Du, Guo, Meißner, Vonk 2003.01625 (NNLO chiPT)]

Axion properties

- Consequences of $\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$

Axion couplings to photons, nucleons, electrons, …

→ *A motivated target for experiments,*
but UV completion can drastically affect low-energy axion properties !

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Benchmark axion models

- global U(1)$_{PQ}$ (QCD anomalous + spontaneously broken)

$$U(1)_{\mathrm{PQ}} \times SU(3)_c^2$$

SM fermions | BSM fermions

2Higgs | 2Higgs+Singlet | Higgs+Singlet

PQWW | DFSZ | KSVZ

[Peccei, Quinn '77, Weinberg '78, Wilczek '78]

[Zhitnitsky '80, Dine, Fischler, Srednicki '81]

[Kim '79, Shifman, Vainshtein, Zakharov '80]

$f_a \sim v$ ruled out

$f_a \gg v$ "Invisible" axion (phase of singlet field)

Benchmark axion models

- global $U(1)_{PQ}$ (QCD anomalous + spontaneously broken)

$$U(1)_{\rm PQ} \times SU(3)_c^2$$

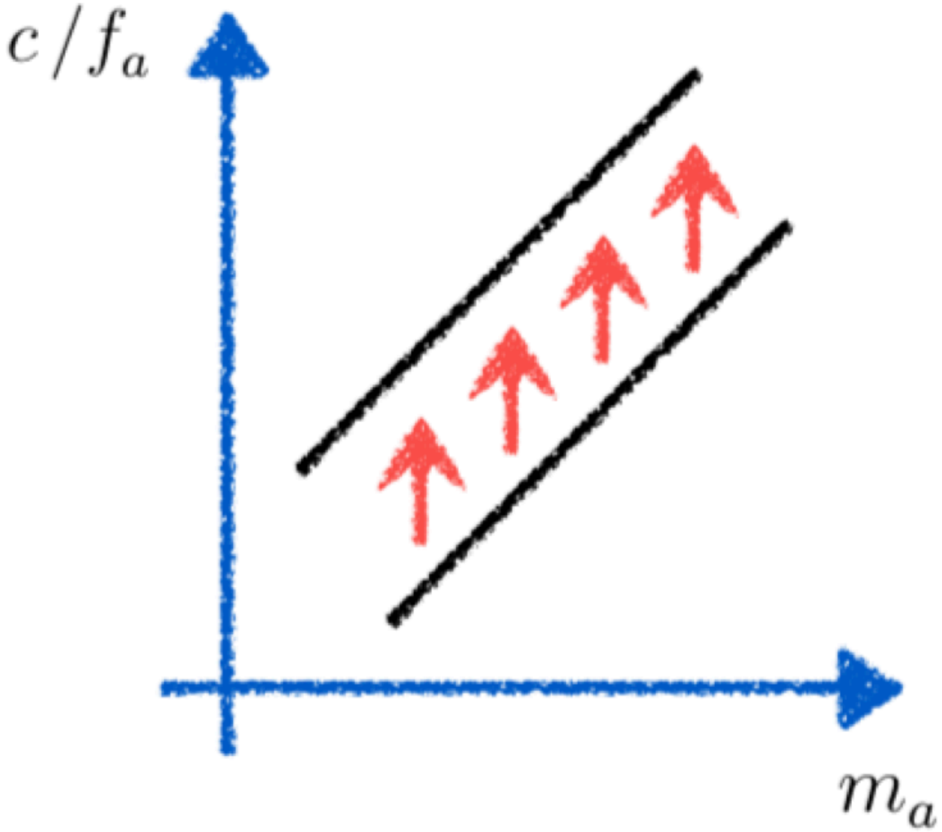
SM fermions → 2Higgs+Singlet → DFSZ

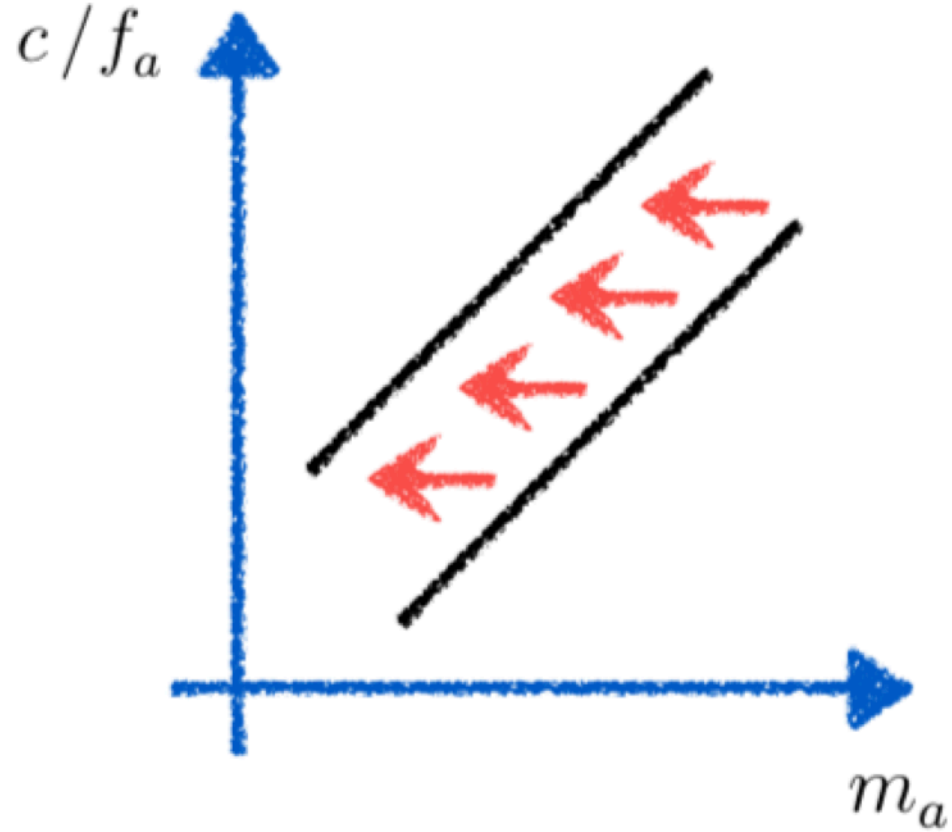
BSM fermions → Higgs+Singlet → KSVZ

$$C_\gamma = E/N - 1.92(4)$$

	DFSZ	KSVZ
	$E/N = 8/3$	$E/N = 0$
	$C_{p,n,e}(\beta) \sim \mathcal{O}(1)$	$C_p \simeq -0.5$
		$C_{n,e} \simeq 0$

Axions beyond benchmarks





enhance Wilson coefficient for fixed m_a

[LDL, Mescia, Nardi 1610.07593 + 1705.05370
Farina, Pappadopulo, Rompineve, Tesi 1611.09855
Agrawal, Fan, Reece, Wang 1709.06085
Darme', LDL, Giannotti, Nardi 2010.15846
Ringwald, Sokolov 2104.02574, …]

suppress axion mass for fixed f_a

[Hook 1802.10093,
LDL, Gavela, Quilez, Ringwald 2102.00012
+ 2102.01082]

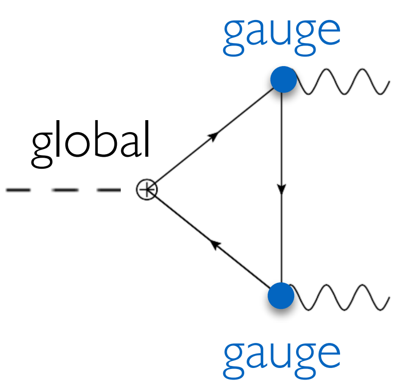
→ *QCD axion parameter space <u>much larger</u> than what traditionally thought*

Enhancing $g_{a\gamma}$

$$g_{a\gamma} = \frac{\alpha}{2\pi} \frac{C_{a\gamma}}{f_a}$$

$$C_{a\gamma} = E/N - 1.92(4)$$

$$\partial^\mu J^{PQ}_\mu = \frac{N\alpha_s}{4\pi} G \cdot \tilde{G} + \frac{E\alpha}{4\pi} F \cdot \tilde{F}$$



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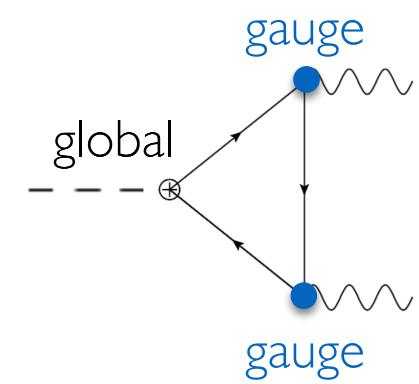

R_Q	$\mathcal{O}_{Qq}$	$\Lambda^{2-\text{loop}}_{\text{Landau}}$[GeV]	E/N
$(3,1,-1/3)$	$\overline{Q}_L d_R$	$9.3\cdot 10^{38}(g_1)$	$2/3$
$(3,1,2/3)$	$\overline{Q}_L u_R$	$5.4\cdot 10^{34}(g_1)$	$8/3$
$(3,2,1/6)$	$\overline{Q}_R q_L$	$6.5\cdot 10^{39}(g_1)$	$5/3$
$(3,2,-5/6)$	$\overline{Q}_L d_R H^\dagger$	$4.3\cdot 10^{27}(g_1)$	$17/3$
$(3,2,7/6)$	$\overline{Q}_L u_R H$	$5.6\cdot 10^{22}(g_1)$	$29/3$
$(3,3,-1/3)$	$\overline{Q}_R q_L H^\dagger$	$5.1\cdot 10^{30}(g_2)$	$14/3$
$(3,3,2/3)$	$\overline{Q}_R q_L H$	$6.6\cdot 10^{27}(g_2)$	$20/3$
$(3,3,-4/3)$	$\overline{Q}_L d_R H^{\dagger 2}$	$3.5\cdot 10^{18}(g_1)$	$44/3$
$(\overline{6},1,-1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$2.3\cdot 10^{37}(g_1)$	$4/15$
$(\overline{6},1,2/3)$	$\overline{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$5.1\cdot 10^{30}(g_1)$	$16/15$
$(\overline{6},2,1/6)$	$\overline{Q}_R \sigma_{\mu\nu} q_L G^{\mu\nu}$	$7.3\cdot 10^{38}(g_1)$	$2/3$
$(8,1,-1)$	$\overline{Q}_L \sigma_{\mu\nu} e_R G^{\mu\nu}$	$7.6\cdot 10^{22}(g_1)$	$8/3$
$(8,2,-1/2)$	$\overline{Q}_R \sigma_{\mu\nu} \ell_L G^{\mu\nu}$	$6.7\cdot 10^{27}(g_1)$	$4/3$
$(15,1,-1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$8.3\cdot 10^{21}(g_3)$	$1/6$
$(15,1,2/3)$	$\overline{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$7.6\cdot 10^{21}(g_3)$	$2/3$

- Pheno preferred hadronic axions

  1. *Q-fermions short lived (no coloured relics)*
  2. *No Landau poles below Planck*

→ $E/N \in [5/3, 44/3]$

[LDL, Mescia, Nardi 1610.07593]

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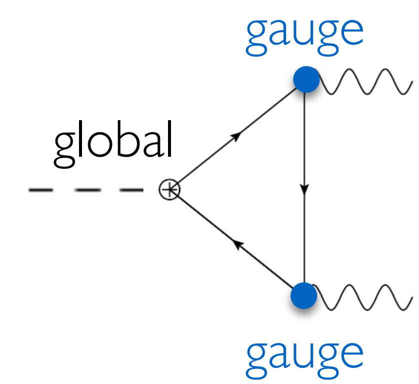

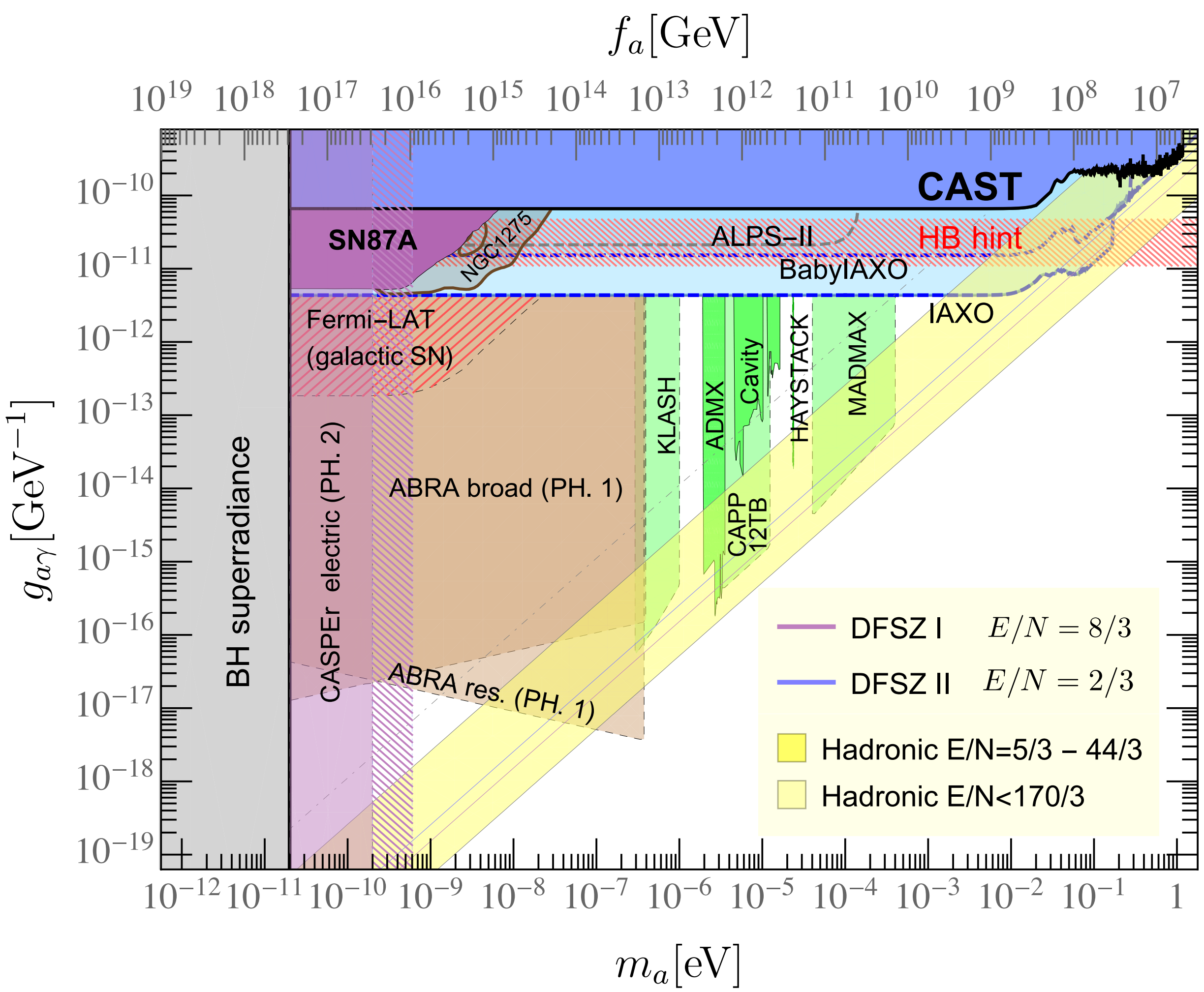

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[LDL, Giannotti, Nardi, Visinelli 2003.01100]

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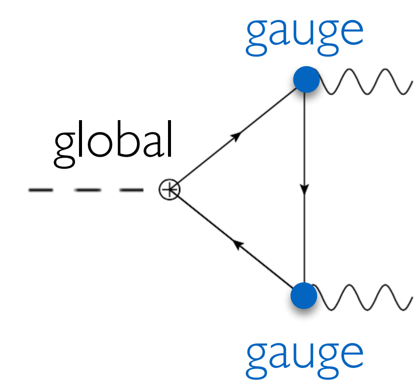

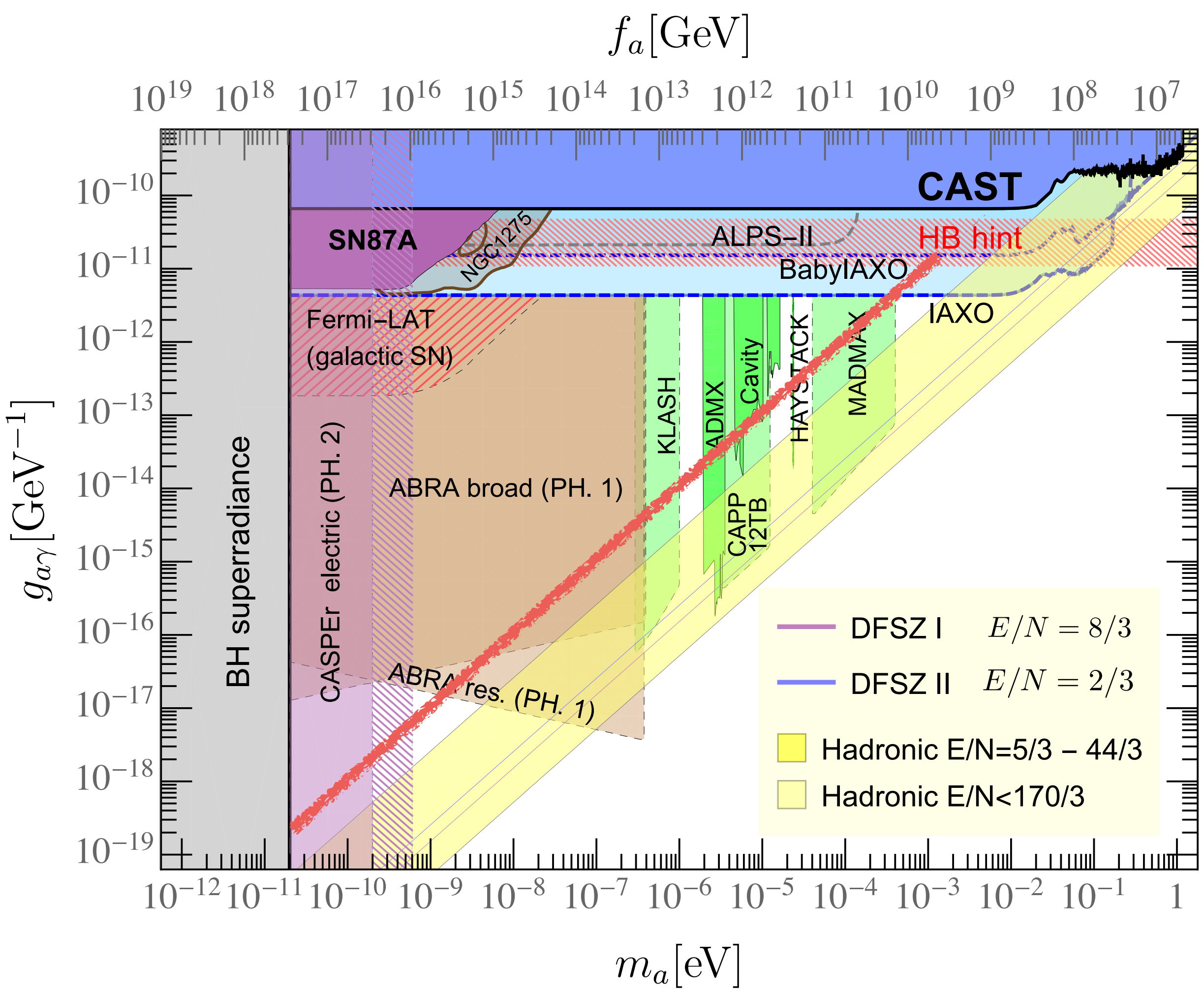

- Pheno preferred hadronic axions

More Q's ? [LDL, Mescia, Nardi 1705.05370 Plakkot, Hoof 2107.12378]

$E/N < 170/3$ *(perturbativity)*

[LDL, Giannotti, Nardi, Visinelli 2003.01100]

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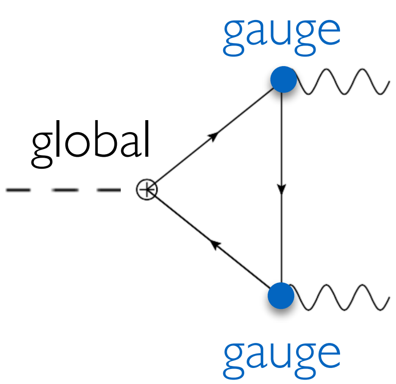

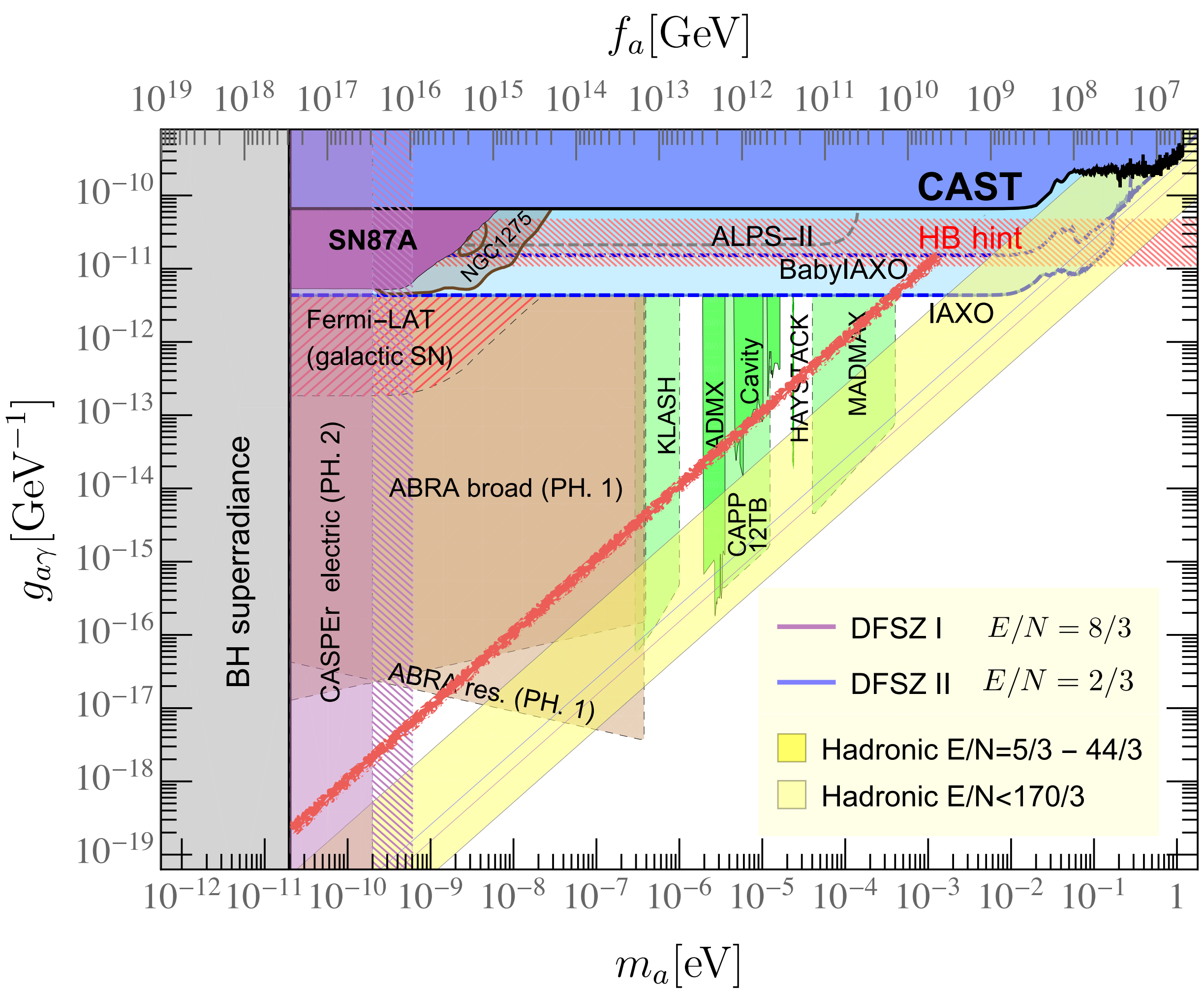

[LDL, Giannotti, Nardi, Visinelli 2003.01100]

- Pheno preferred <u>hadronic axions</u>

  More Q's ? [LDL, Mescia, Nardi 1705.05370 Plakkot, Hoof 2107.12378]

  $E/N < 170/3$ *(perturbativity)*

- Going <u>above</u> E/N = 170/3 ?

  - *boost global charge (clockwork)*

    [Farina, Pappadopulo, Rompineve, Tesi 1611.09855 Darme', LDL, Giannotti, Nardi 2010.15846]

  - *be agnostic, E/N is a free parameter*

CP-violating axions

$$\mathcal{L} \supset g^S_{aN} a \overline{N} N + g^P_{af} a \overline{f} i \gamma_5 f \qquad g^S_{aN} \sim \frac{f_\pi}{f_a} \theta_{\rm eff}$$

← from UV sources of CP-violation or PQ breaking

[Moody, Wilczek PRD 30 (1984)
Barbieri, Romanino, Strumia hep-ph/9605368
Pospelov hep-ph/9707431
Bertolini, LDL, Nesti 2006.12508
Okawa, Pospelov, Ritz, 2111.08040
Dekens, de Vries, Shain, 2203.11230]

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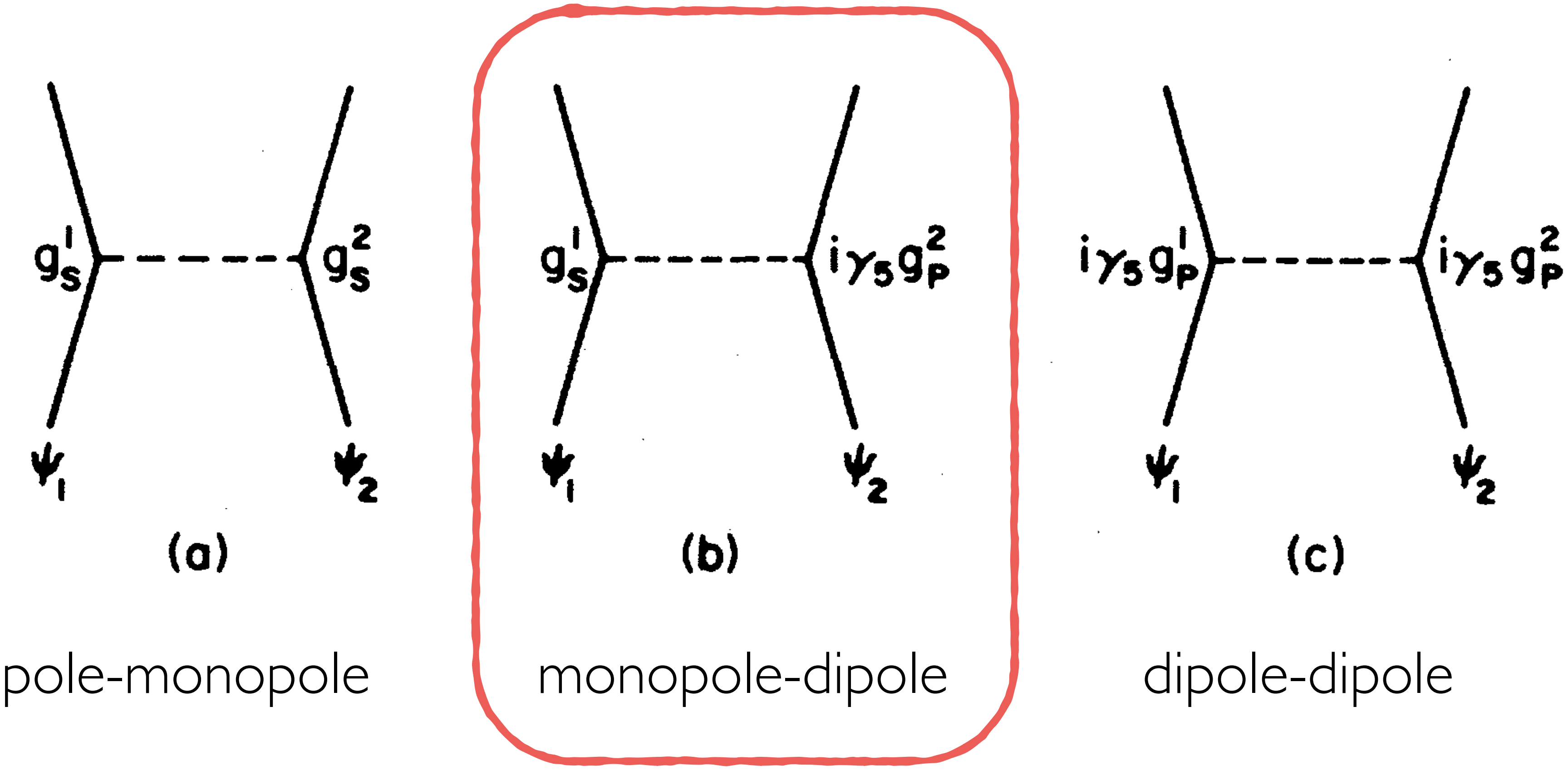
← from UV sources of CP-violation or PQ breaking

New macroscopic forces from non-relativistic potentials [Moody, Wilczek PRD 30 (1984)]



monopole-monopole | monopole-dipole | dipole-dipole

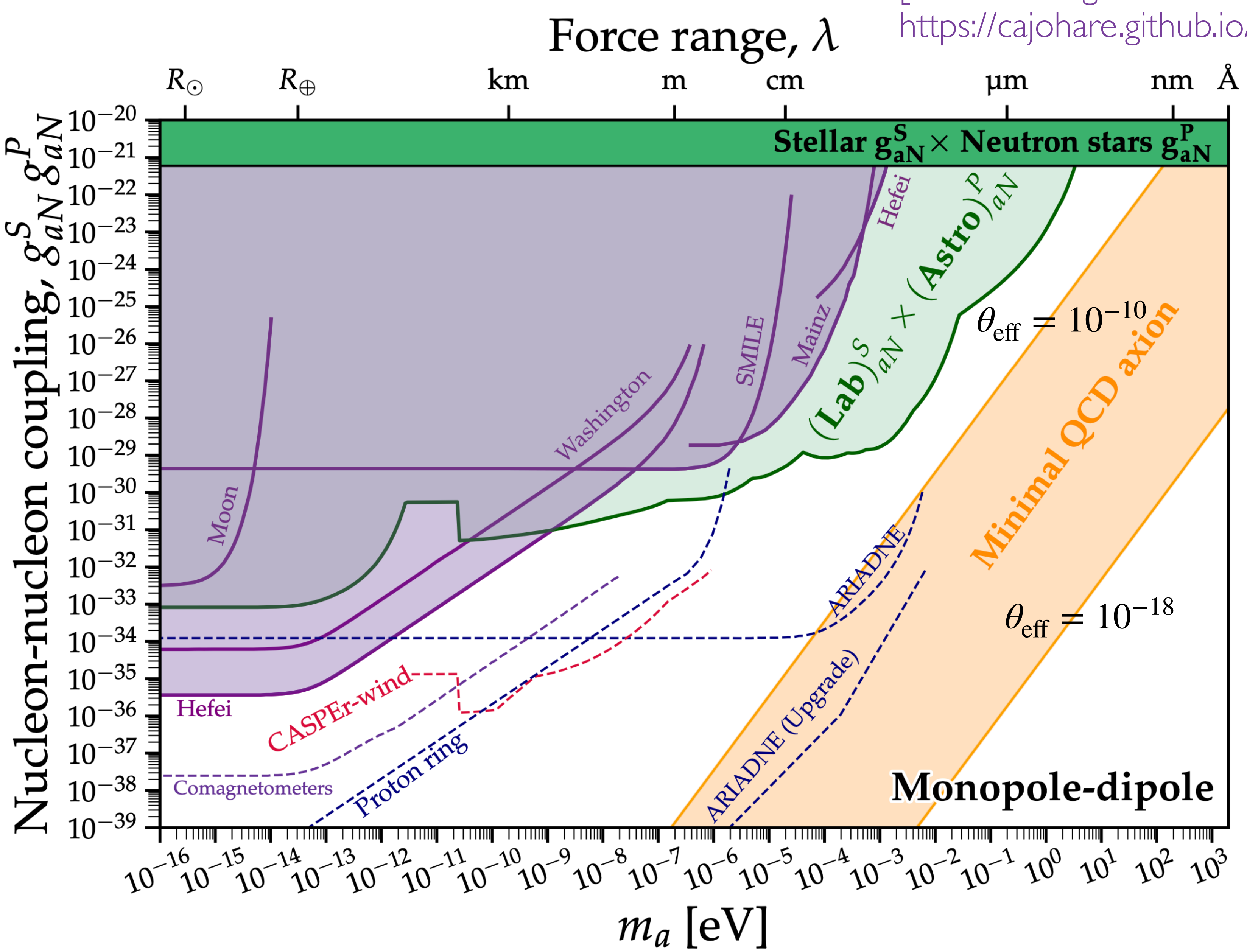
ARIADNE, QUAX-gpgs, …

CP-violating axions

$$\mathcal{L} \supset g^S_{aN} a \overline{N} N + g^P_{af} a \overline{f} i \gamma_5 f \qquad g^S_{aN} \sim \frac{f_\pi}{f_a} \theta_{\text{eff}}$$

from UV sources of CP-violation or PQ breaking

[O'Hare, Vitagliano 2010.03889 https://cajohare.github.io/AxionLimits]



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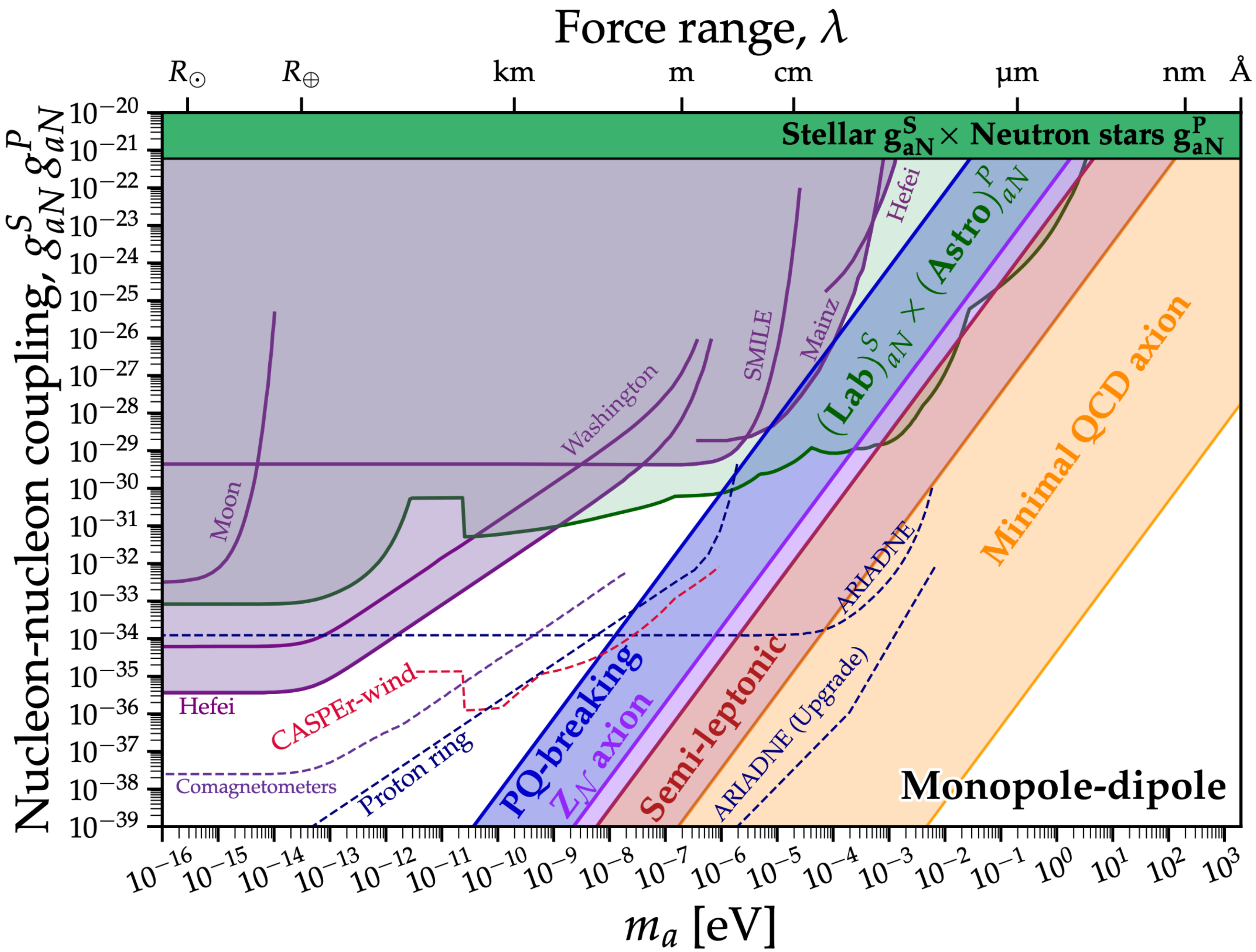
from UV sources of CP-violation or PQ breaking

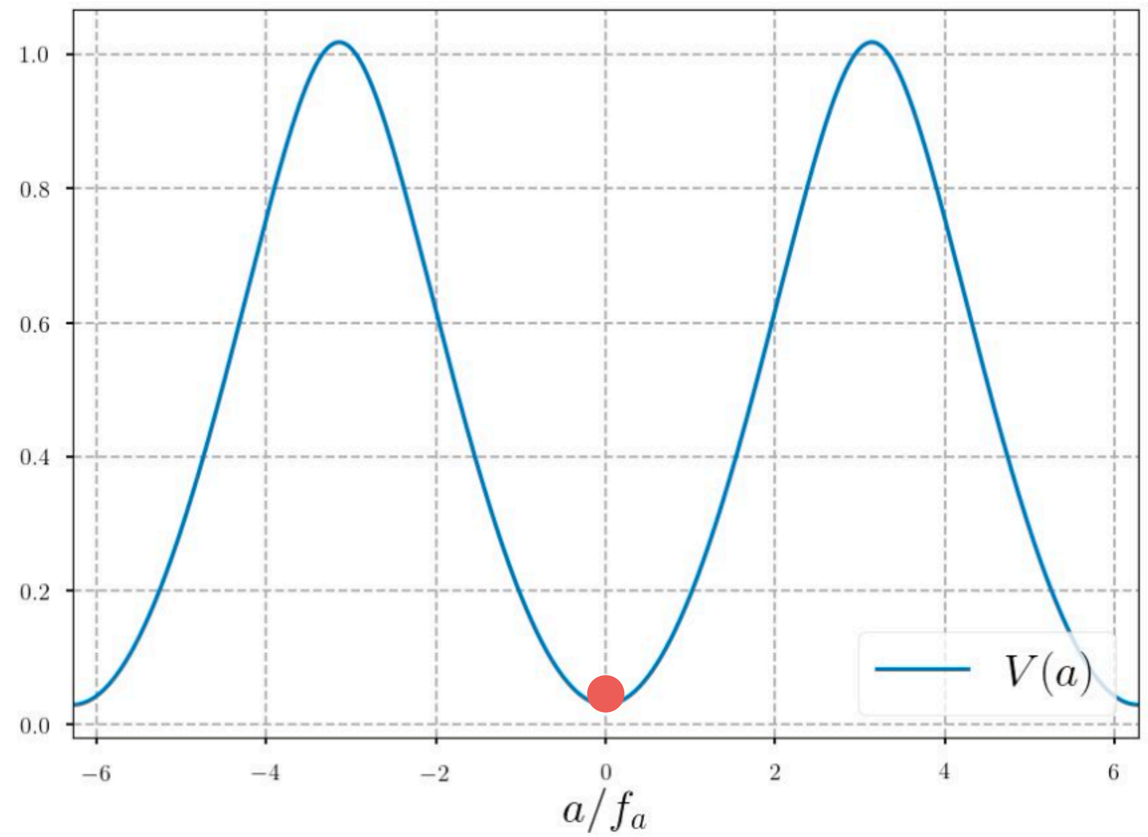
[LDL, Gisbert, Nesti, Sørensen - to appear]



Modified m_a - f_a relation

- Standard QCD axion

$$\frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} \quad \longrightarrow \quad V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a}\right)}$$



Modified m_a - f_a relation

- Z_2 axion: mirror world

$$\mathrm{SM} \longleftrightarrow \mathrm{SM}'$$
$$a \longrightarrow a$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SM'} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta\right) G\widetilde{G} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta\right) G'\widetilde{G}'$$

→ *previously invoked to obtain* *<u>heavier</u>* *QCD axion*

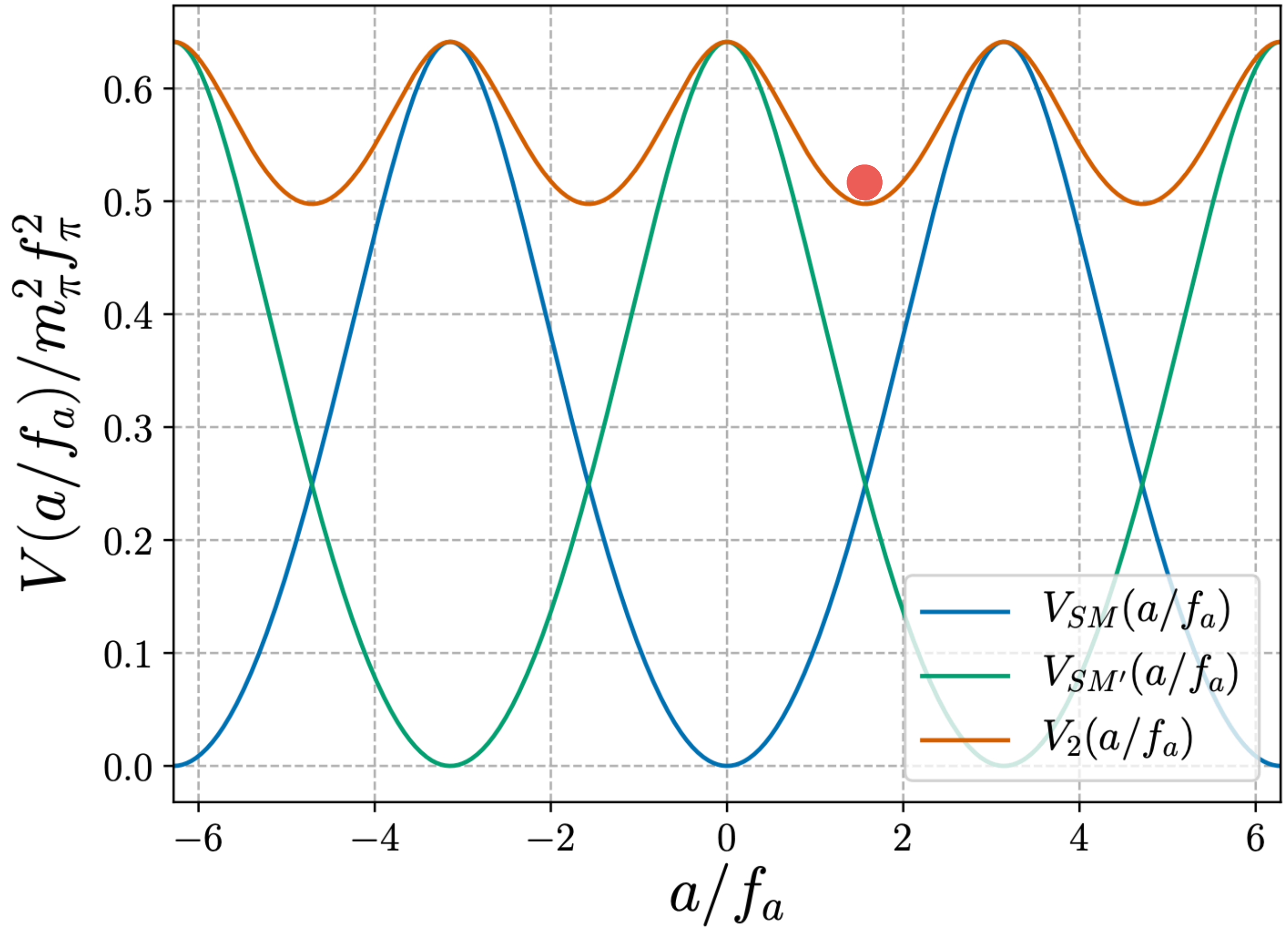
[Rubakov hep-ph/9703409
Berezhiani, Gianfagna, Giannotti hep-ph/0009290
Gianfagna, Giannotti, Nesti hep-ph/0409185, …]

Modified m_a - f_a relation

- Z_2 axion: mirror world

$$\mathrm{SM} \longleftrightarrow \mathrm{SM}'$$
$$a \longrightarrow a + \pi f_a$$

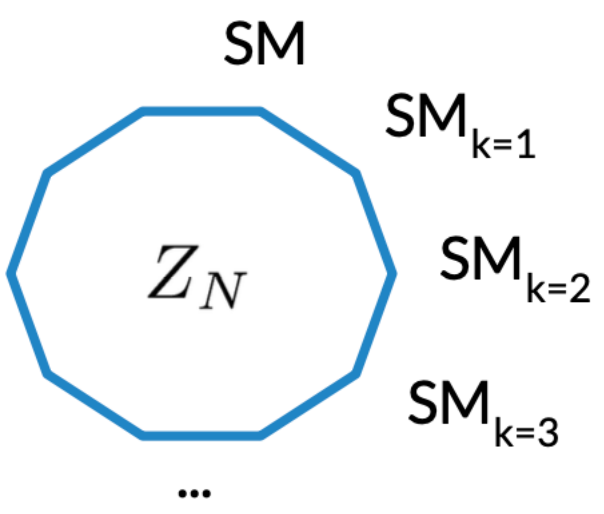
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{SM}'} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta\right) G\widetilde{G} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta + \pi\right) G'\widetilde{G}'$$



axion mass is suppressed but minimum in $\pi/2$

Z_N axion

- Z_N axion: N mirror worlds [Hook 1802.10093]



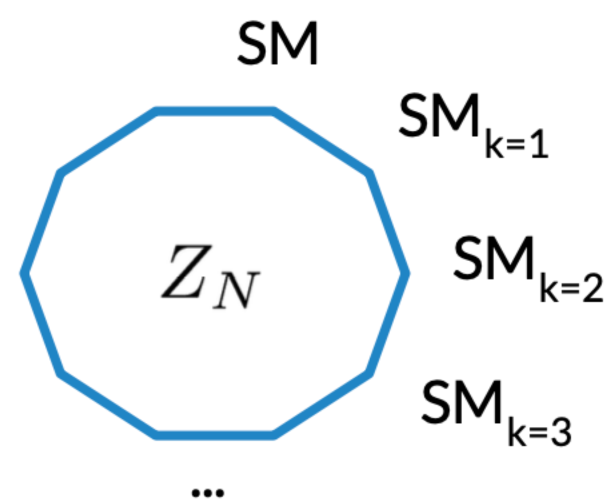
$$\mathrm{SM}_k \longrightarrow \mathrm{SM}_{k+1\,(\mathrm{mod}\,\mathcal{N})}$$
$$a \longrightarrow a + \frac{2\pi k}{\mathcal{N}} f_a \,,$$

the axion ($\theta_a \equiv a/f_a$) realizes the Z_N symmetry non-linearly

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

Z_N axion

- Z_N axion: N mirror worlds [Hook 1802.10093]



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

[LDL, Gavela, Quilez, Ringwald 2102.00012]

$$V_{\mathcal{N}}(\theta_a) = -m_\pi^2 f_\pi^2 \sum_{k=0}^{\mathcal{N}-1} \sqrt{1 - \frac{4z}{(1+z)^2} \sin^2\left(\frac{\theta_a}{2} + \frac{\pi k}{\mathcal{N}} \right)}$$

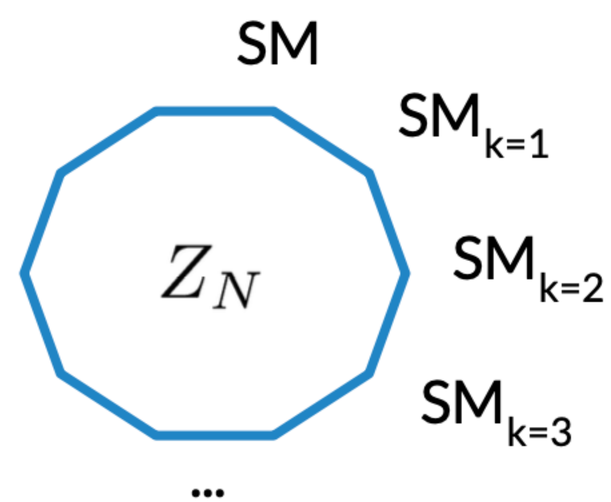
$$z \equiv \frac{m_u}{m_d} \sim 1/2$$

$$\simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}} \mathcal{N}^{-1/2} (-1)^{\mathcal{N}} z^{\mathcal{N}} \cos(\mathcal{N}\theta_a)$$

axion potential exponentially suppressed at large N

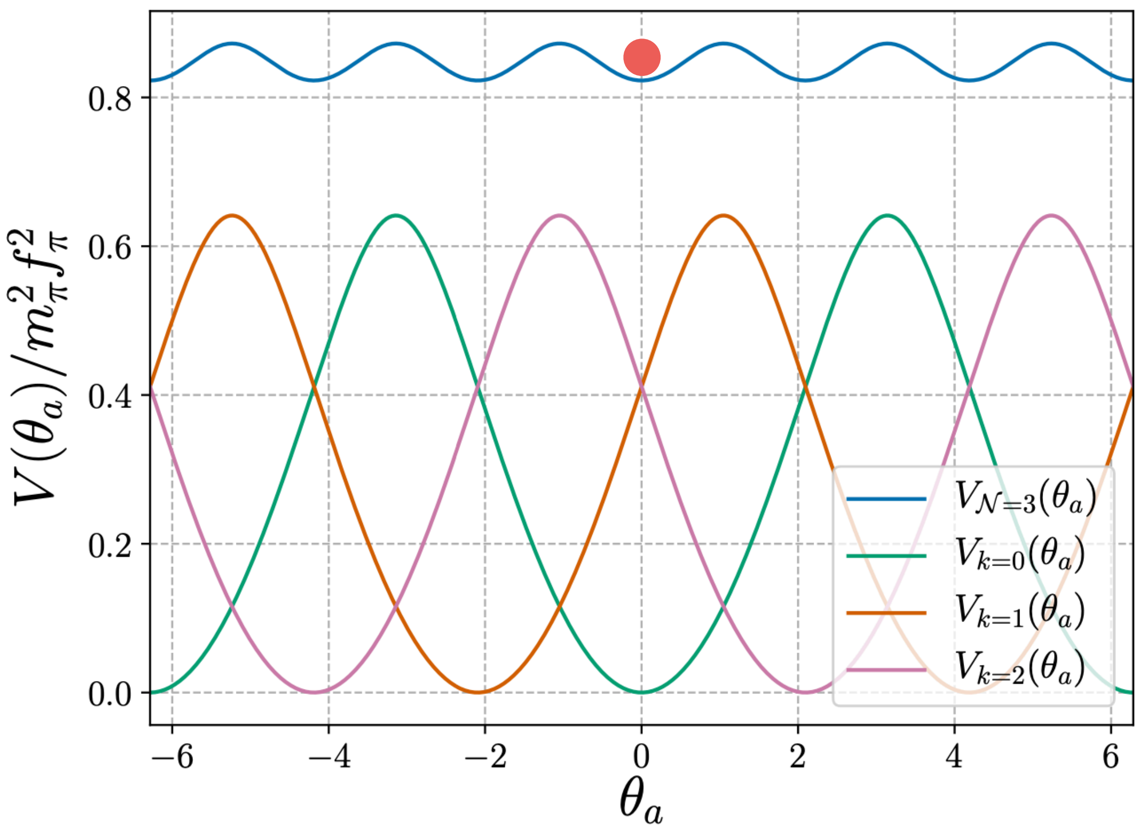
Z_N axion

- Z_N axion: N mirror worlds [Hook 1802.10093]



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

e.g. Z_3 axion



[LDL, Gavela, Quilez, Ringwald 2102.00012]

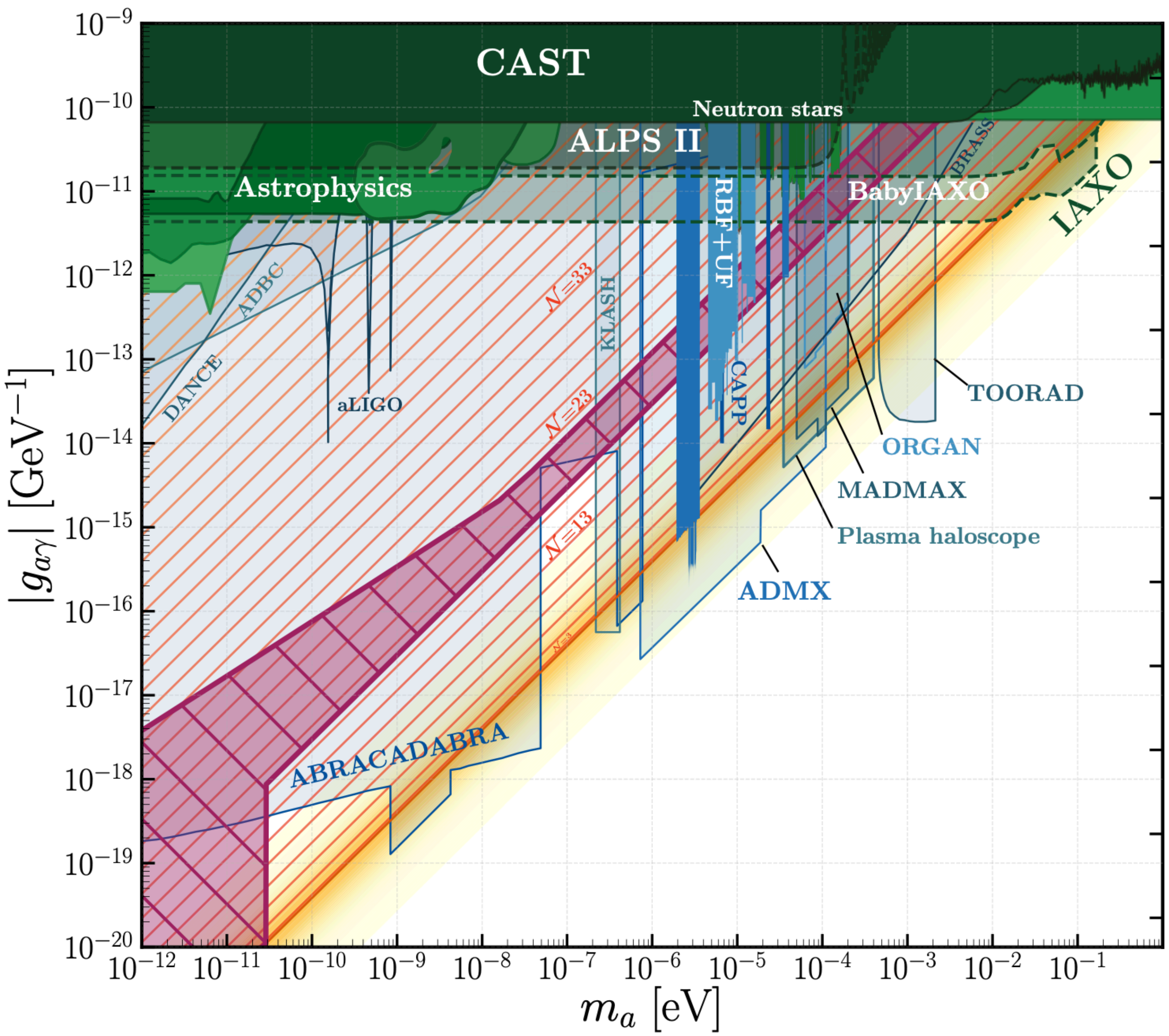
N needs to be odd in order to have a minimum in zero

(strong CP problem is solved with 1/N probability)

Z_N axion

- Z_N axion: N mirror worlds

[LDL, Gavela, Quilez, Ringwald 2102.00012 + 2102.01082]



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

<u>universal enhancement</u> of all axion couplings w.r.t. standard QCD axion

RadioAxion-α

- Time modulation of α-radioactivity from axion dark matter [Broggini, Di Carlo, LDL, Toni 2404.18993]

RadioAxion-α

- Time modulation of α-radioactivity from axion dark matter [Broggini, Di Carlo, LDL, Toni 2404.18993]

$$\mathscr{L}_\theta = \frac{g_s^2\theta}{32\pi^2} G\tilde{G}$$

→ θ-dependence impacts nuclear physics (studied in the anthropic context)

[Ubaldi 0811.1599
Lee, Meißner, Olive, Shifman, Vonk 2006.12321]

$$\theta(t) \simeq \frac{\sqrt{2\rho_{\rm DM}}}{m_a f_a} \cos(m_a t)$$

→ time modulation of radioactive decays

[Tritium-decay previously considered in Zhang, Houston, Li 2303.09865]

$$I_{\rm exp}(t) \equiv (N(t) - \langle N \rangle)/\langle N \rangle$$

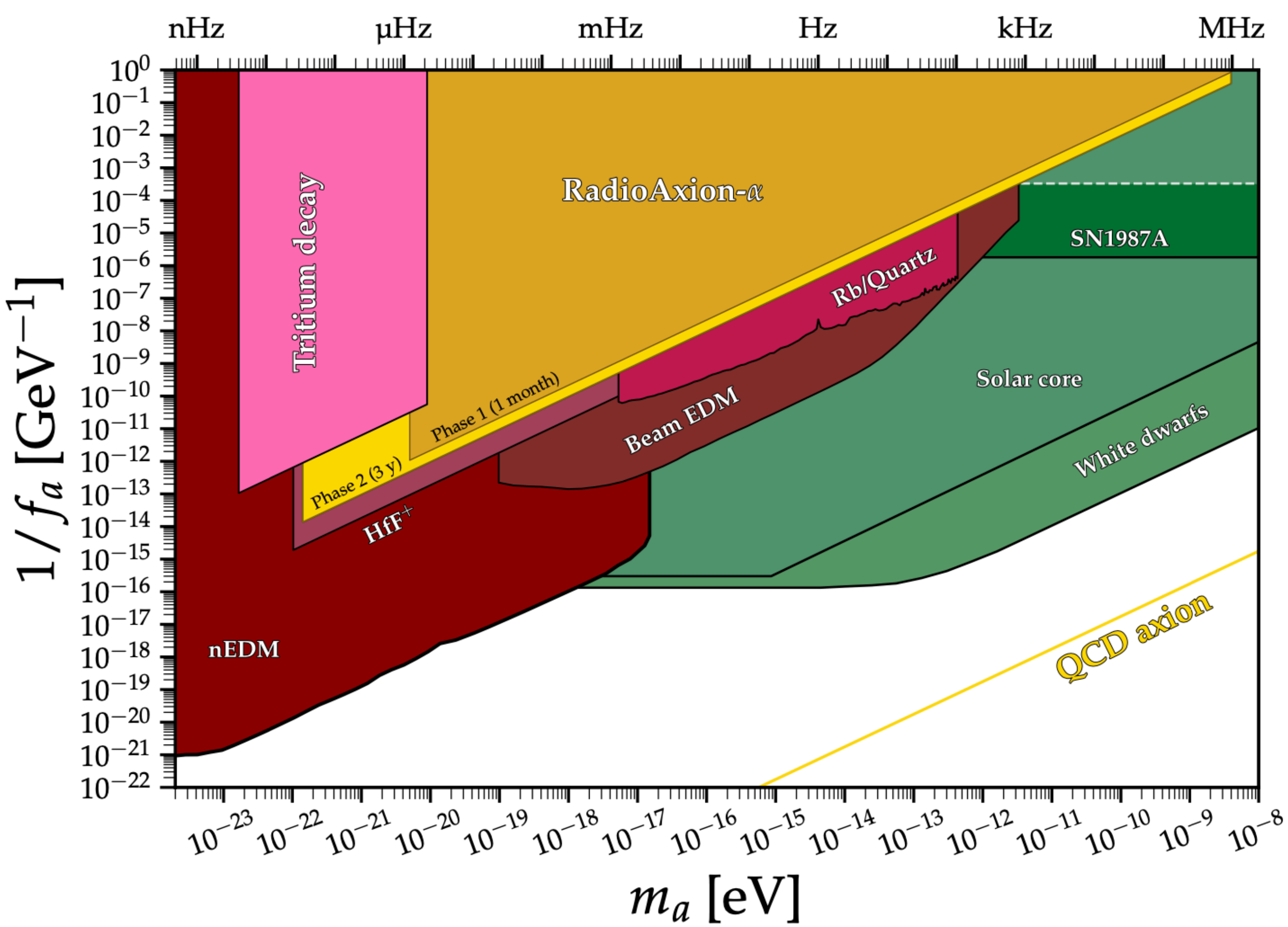
RadioAxion-α

- Time modulation of α-radioactivity from axion dark matter [Broggini, Di Carlo, LDL, Toni 2404.18993]

we computed expected time modulation for α*-decay* [see backup slides]

we started data taking with an ^{241}*Am source in the Gran Sasso Labs*

$$I_{\rm exp}(t) \equiv (N(t) - \langle N \rangle)/\langle N \rangle$$
$$= -4.3 \times 10^{-6} \cos(2m_a t)\left(\frac{\rho_{\rm DM}}{0.45\,{\rm GeV/cm^3}}\right)$$
$$\times \left(\frac{10^{-16}\,{\rm eV}}{m_a}\right)^2 \left(\frac{10^8\,{\rm GeV}}{f_a}\right)^2,$$



Conclusions

- The QCD axion provides a guide for where to search in the dark matter landscape
- Experimentally driven phase [See talk by J.Vogel + parallel sessions]
- Take home message

Axion properties are UV dependent

1. enhanced/suppressed axion couplings
2. modified m_a - f_a relation
3. flavour violating axions [see backup slides]
4. CP-violating axions

Backup slides

θ-dependence of α-decay

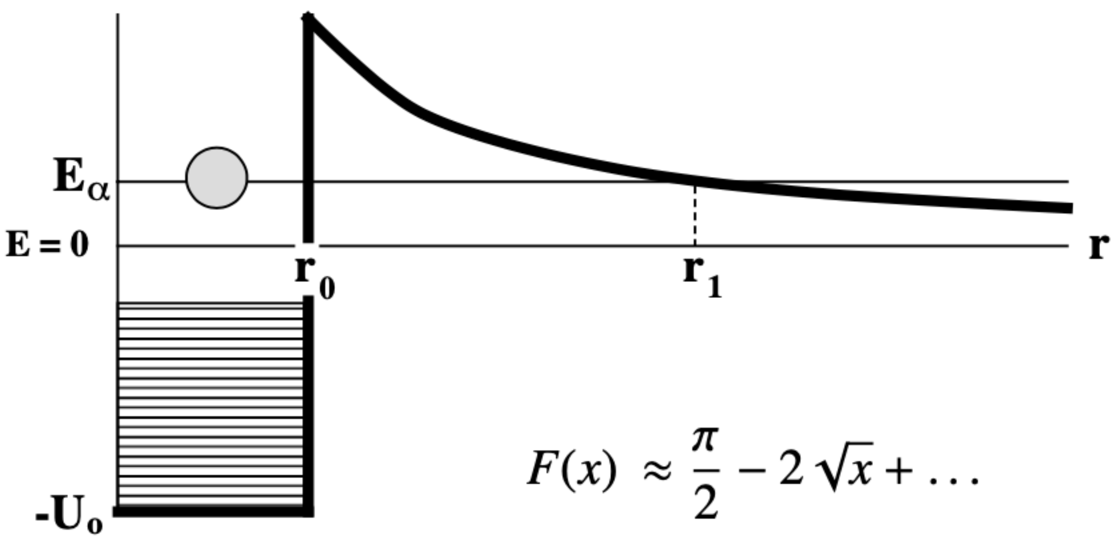
- Gamow theory of α-decay

[Broggini, Di Carlo, LDL, Toni 2404.18993]

$$T_{1/2} = \frac{\ln 2}{\nu_0} \exp(K)$$

$$K = 2 \int_{r_1}^{r_2} dr \, \sqrt{2\mu[V_{\rm tot}(r) - Q_\alpha]}$$

$$= Z_\alpha Z_d \alpha_{\rm QED} \left(\frac{8\mu}{Q_\alpha} \right)^{1/2} F\left(\frac{Q_\alpha R_{\rm well}}{Z_\alpha Z_d \alpha_{\rm QED}} \right)$$



$$F(x) \approx \frac{\pi}{2} - 2\sqrt{x} + \ldots$$

- half-life is highly sensitive to Q-value $\quad Q_\alpha = \mathrm{BE}(A-4, Z-2) + \mathrm{BE}(4,2) - \mathrm{BE}(A,Z)$

- θ-term changes the size of the scalar (attractive) and vector (repulsive) nuclear interaction

$$H = G_S(\bar{N}N)(\bar{N}N) + G_V(\bar{N}\gamma_\mu N)(\bar{N}\gamma^\mu N)$$

$$\eta_S = \frac{G_S(\theta)}{G_S(\theta = 0)}, \quad \eta_V = \frac{G_V(\theta)}{G_V(\theta = 0)}$$

$$Q_\alpha(\theta) = Q_\alpha(\theta = 0) - 97 \text{ MeV } (\eta_S(\theta) - 1) \times ((A-4)^{2/3} + 4^{2/3} - A^{2/3}) \, .$$

[Damour, Donoghue 0712.2968]

θ-dependence of α-decay

- Gamow theory of α-decay

[Broggini, Di Carlo, LDL, Toni 2404.18993]

$$T_{1/2} = \frac{\ln 2}{\nu_0}\exp(K) \qquad T_{1/2}(\theta) \approx T_{1/2}(0) + \mathring{T}_{1/2}(0)\theta^2$$

$$I(t) \equiv \frac{T^{-1}_{1/2}(\theta(t)) - \langle T^{-1}_{1/2}\rangle}{\langle T^{-1}_{1/2}\rangle} \qquad \theta(t) = \theta_0 \cos(m_a t),$$

$$\approx -\frac{1}{2}\frac{\mathring{T}_{1/2}(0)}{T_{1/2}(0)}\theta_0^2 \cos(2m_a t) \qquad \theta_0 = \frac{\sqrt{2\rho_{\rm DM}}}{m_a f_a}$$

$$= -4.3\times 10^{-6}\cos(2m_a t)\left(\frac{\rho_{\rm DM}}{0.45\,{\rm GeV/cm^3}}\right)$$

$$\times\left(\frac{10^{-16}\,{\rm eV}}{m_a}\right)^2\left(\frac{10^8\,{\rm GeV}}{f_a}\right)^2,$$

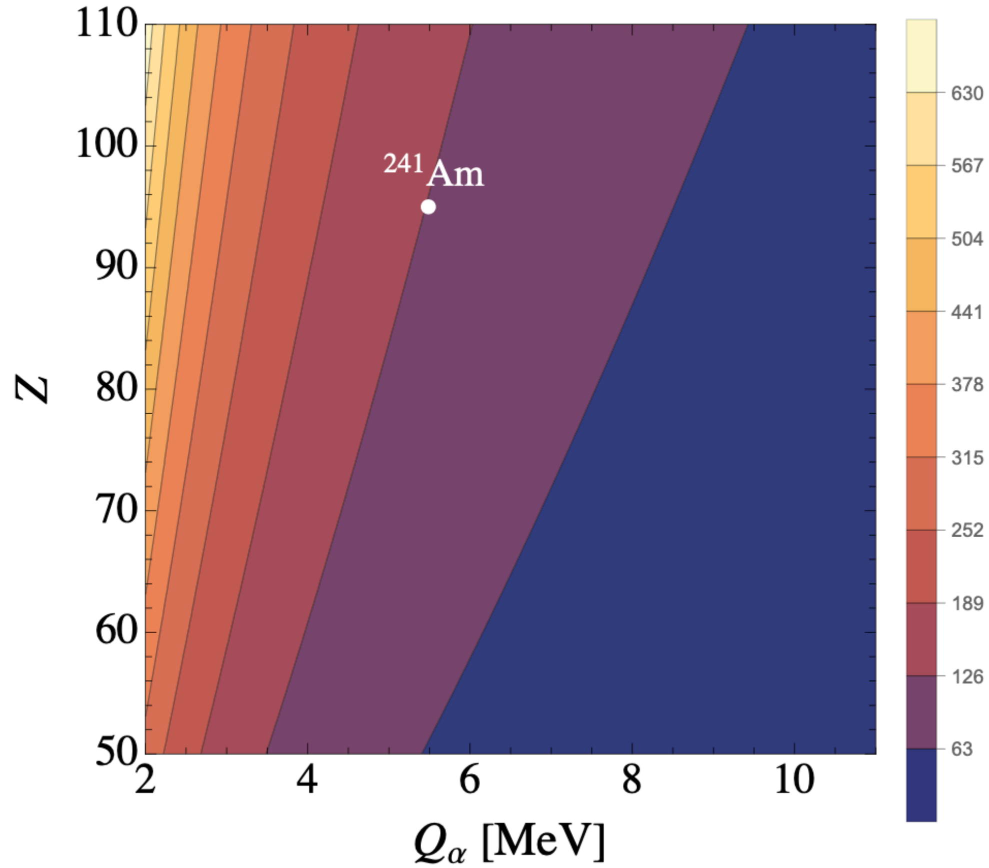


Figure A.3: Contours of $\mathring{T}_{1/2}(0)/T_{1/2}(0)$ in the (Q_α, Z) plane for $A = 241$. The case of ^{241}Am is indicated by a white dot.

$$\frac{\mathring{T}_{1/2}(0)}{T_{1/2}(0)} \approx \mathring{K} \approx \frac{\partial K}{\partial Q_\alpha}\,\mathring{Q}_\alpha \approx 8.45\,(Z-2)\left[4^{2/3} - \frac{8}{3A^{1/3}}\right]\left(\frac{\rm MeV}{Q_\alpha}\right)^{3/2}$$

$\approx$ 125 (for Americium-241)

Flavour-violating axions

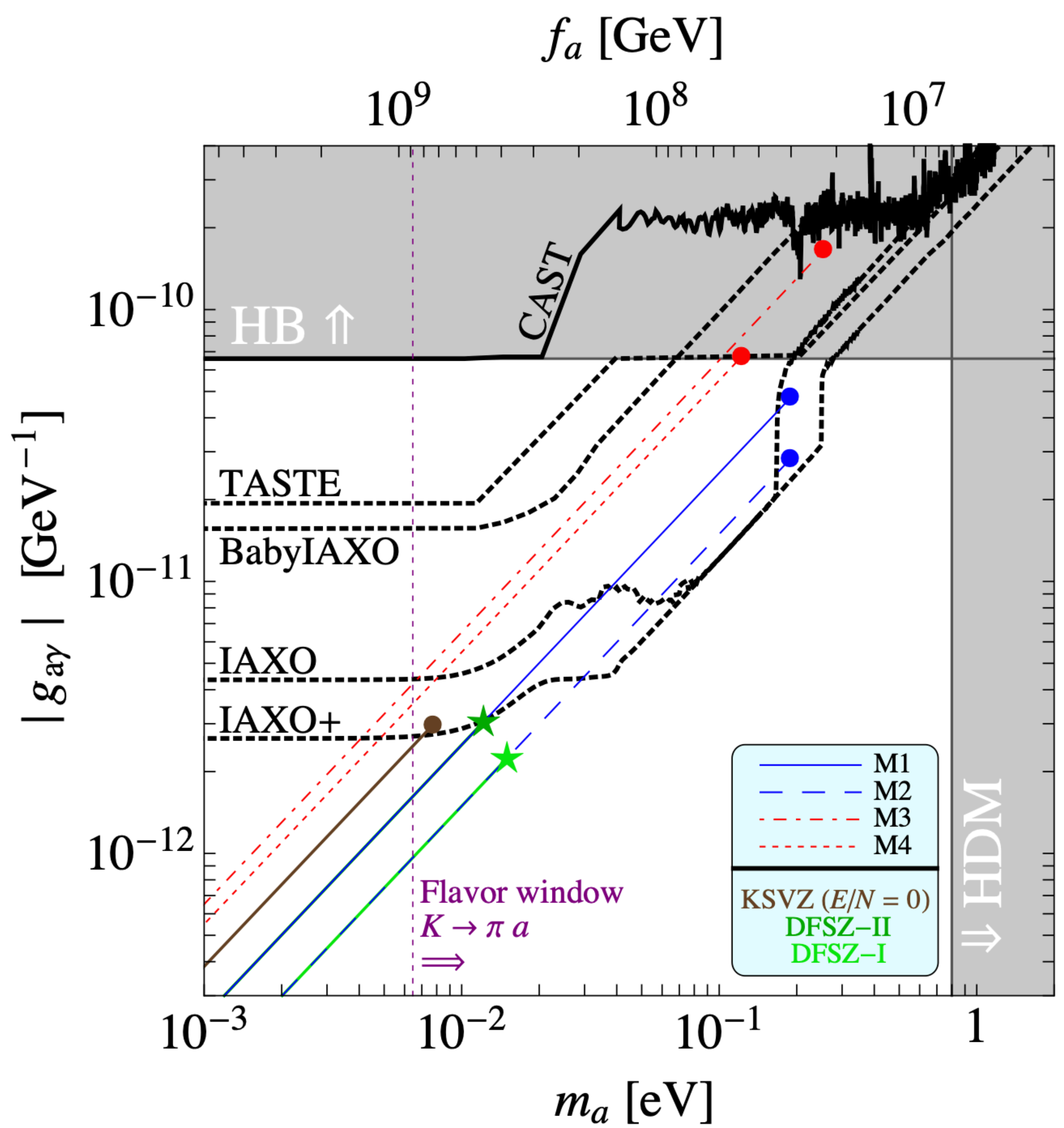
$$\mathscr{L}_a \supset \frac{\partial_\mu a}{2 f_a} \overline{\psi}_i \gamma^\mu (C^V_{ij} + C^A_{ij} \gamma_5) \psi_j$$

$J^\mu_{\rm PQ}$

enhance/suppress $C_{p,n,e}$

flavour-violating axion coupling

["Astrophobic Axions" with non-universal PQ allow to relax SN1987A + WD/RGB bounds by ~ 1 order of magnitude LDL, Mescia, Nardi, Panci, Ziegler, 1712.04940 + 1907.06575]



Flavour-violating axions

$$\mathscr{L}_a \supset \frac{\partial_\mu a}{2 f_a} \underbrace{\overline{\psi}_i \gamma^\mu (C^V_{ij} + C^A_{ij} \gamma_5) \psi_j}_{J^\mu_{\mathrm{PQ}}}$$

enhance/suppress $C_{p,n,e}$

flavour-violating axion coupling

$C^{V,A}_{i \neq j} \propto (V^\dagger_\psi \mathrm{PQ}_\psi V_\psi)_{i \neq j} \neq 0$ if PQ_ψ non-universal

→ PQ as a flavour symmetry ?

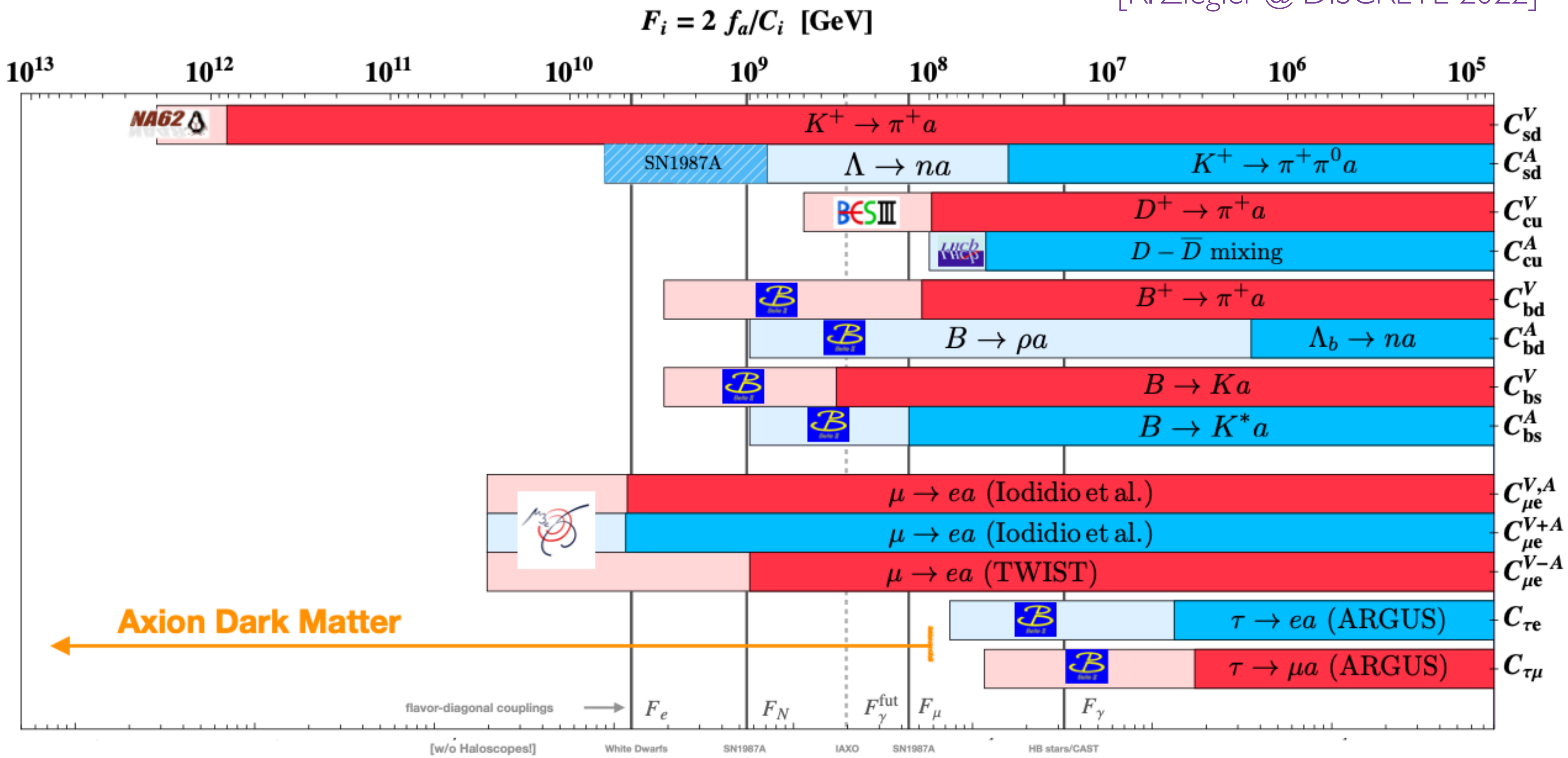
[Davidson, Wali PRL 48 (1982)
Wilczek PRL 49 (1982)
Berezhiani, PLB 129B (1983) + PLB 150B (1985)
…
Ema, Hamaguchi, Moroi, Nakayama 1612.05492
Calibbi, Goertz, Redigolo, Ziegler, Zupan 1612.08040
Arias-Aragon, Merlo 1709.07039
Björkeroth, LDL, Mescia, Nardi 1811.09637]

Flavour-violating axions

$$\mathscr{L}_a \supset \frac{\partial_\mu a}{2f_a}\overline{\psi}_i\gamma^\mu(C^V_{ij} + C^A_{ij}\gamma_5)\psi_j$$

$C^{V,A}_{i\neq j} \propto (V^\dagger_\psi \mathrm{PQ}_\psi V_\psi)_{i\neq j} \neq 0$ if PQ_ψ non-universal

[R. Ziegler @ DISCRETE 2022]



for $C_i = \{C_\gamma, C_e, C_N, C_{sd}, C_{bs}, C_{bd}, C_{\mu e}\} = 1$ *flavour beats astrophysics !*