QCD axions off the beaten tracks

Based on: "Astrophobic Axions" Phys.Rev.Lett. 120 (2018) no.26, 261803 [arXiv:1712.04940]
In collaboration with L. Di Luzio (IPPP, Durham), F. Mescia (Barcelona U.), P. Panci (CERN) and R. Ziegler (CERN)

"Redefining the Axion window" Phys.Rev.Lett. 118 (2017) no.3, 031801 [arXiv:1610.07593]
"Window for preferred Axion models" Phys.Rev. D96 (2017) no.7, 075003 [arXiv:1705.05370]
In collaboration with Luca Di Luzio (IPPP, Durham) and Federico Mescia (Barcelona U.)

"The KLASH Conceptual Design Report: The physics case" (to appear)
In collaboration with Maurizio Giannotti (Barry U.) and Luca Visinelli (Uppsala U. & Nordita)

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15th PATRAS Workshop - Freiburg, June 3-7, 2019

Strong CP: a small value problem

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If Multiverse, $\bar{\theta}$ becomes the most urgent s.v. problem in the SM

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- Assume a global $U(1)_{PQ}$:

  (i) Spontaneously broken

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- Assume a global $U(1)_{PQ}$:

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- Implies a PNGB of $U(1)_{PQ}$: the Axion.

Axion field comes equipped with a shift symmetry: $a(x) \to a(x) + \delta\alpha\, f_a$

$$\mathcal{L}_{\text{eff}} = \left(\bar{\theta} + \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu} - \frac{1}{2}\partial^\mu a \partial_\mu a + \mathcal{L}(\partial_\mu a, \psi)$$

$\theta_{\text{eff}}(x)$

and with a periodic potential $V(\theta_{\text{eff}}) \to V_{min}$ when $\theta_{\text{eff}} \to 0$

Axion models

- PQWW axion:

  Axion identified with the phase of the Higgs in a 2HDM
  ($f_a \sim V_{EW}$ was quickly ruled out long ago) [Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]

Viable models require $f_a \gg V_{EW}$:

Most viable axion models fall in two classes:

- DSFZ Axion: SM quarks and Higgses, charged under PQ.

  Requires 2HDM + 1 scalar singlet. SM leptons are also PQ charged.
  [Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)]

- KSVZ Axion (or **hadronic axion**):

  All SM fields are neutral under PQ. QCD anomaly induced by new quarks, vectorlike under SM, chiral under PQ + 1 scalar singlet
  [Kim (1979), Shifman, Vainshtein, Zakharov (1980)]

We need to know where to search

The "canonical" axion window

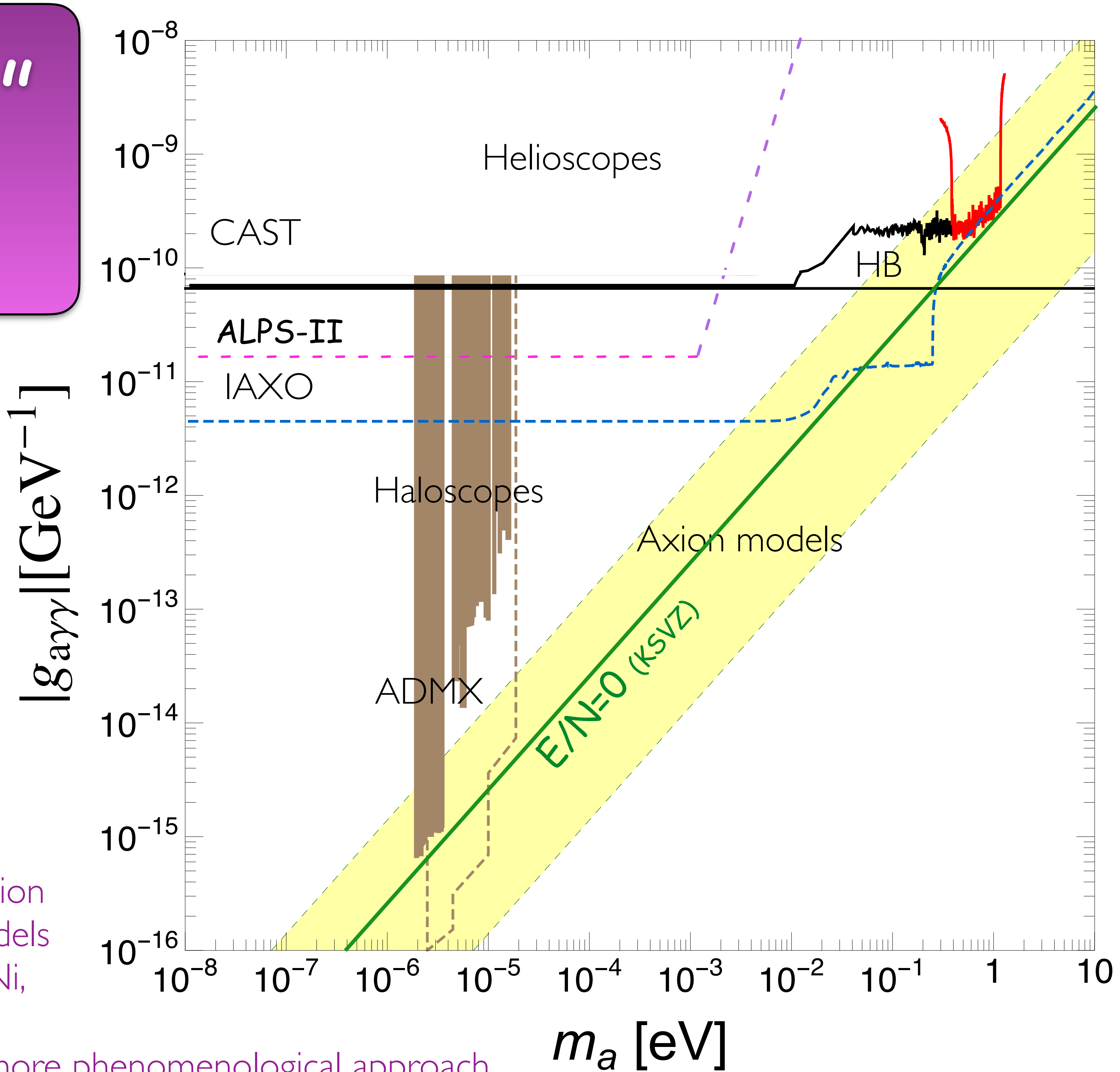
Central value:

$$g_{a\gamma\gamma} \sim \frac{\alpha}{2\pi}\frac{m_a}{f_\pi m_\pi} \sim \frac{10^{-10}}{\mathrm{GeV}}\left(\frac{m_a}{\mathrm{eV}}\right)$$

Model dependence:

$$g_{a\gamma\gamma} = \frac{m_a}{\mathrm{eV}}\frac{2.0}{10^{10}\ \mathrm{GeV}}\left(\frac{E}{N} - 1.92\right)$$

$$|E/N - 1.92| \in [0.07, 7]$$



Particle Data Group: Since the end of 90's, Axion window chosen to include representative models from: Kaplan, NPB 260 (1985); Cheng, Geng, Ni, PRD 52 (1995); Kim, PRD 58 (1998).
Since 2017: **E/N ∈ (5/3, 44/3)** based on a more phenomenological approach

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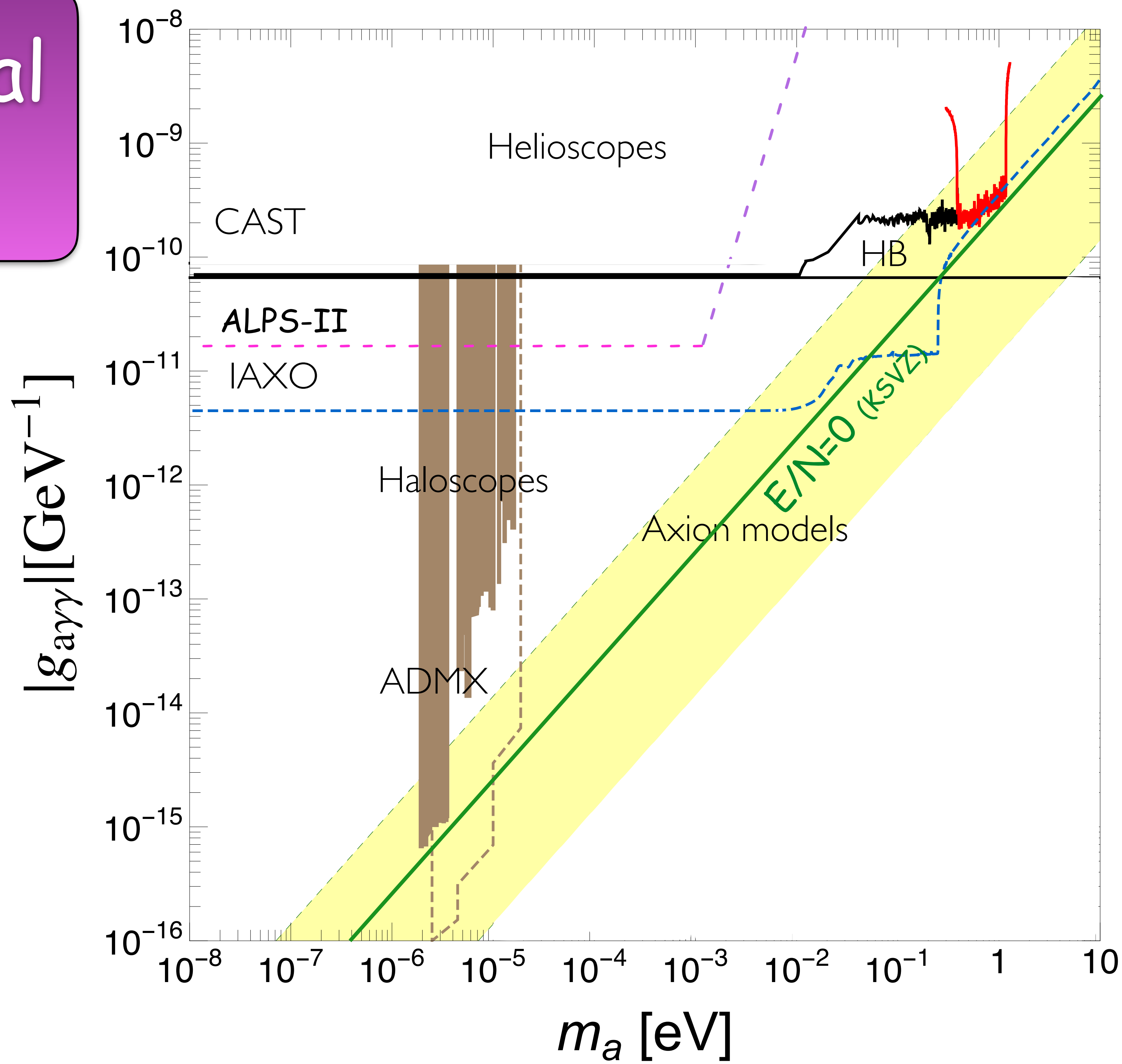
$\Omega_a \approx \Omega_{CDM}$ canonical mass windows:



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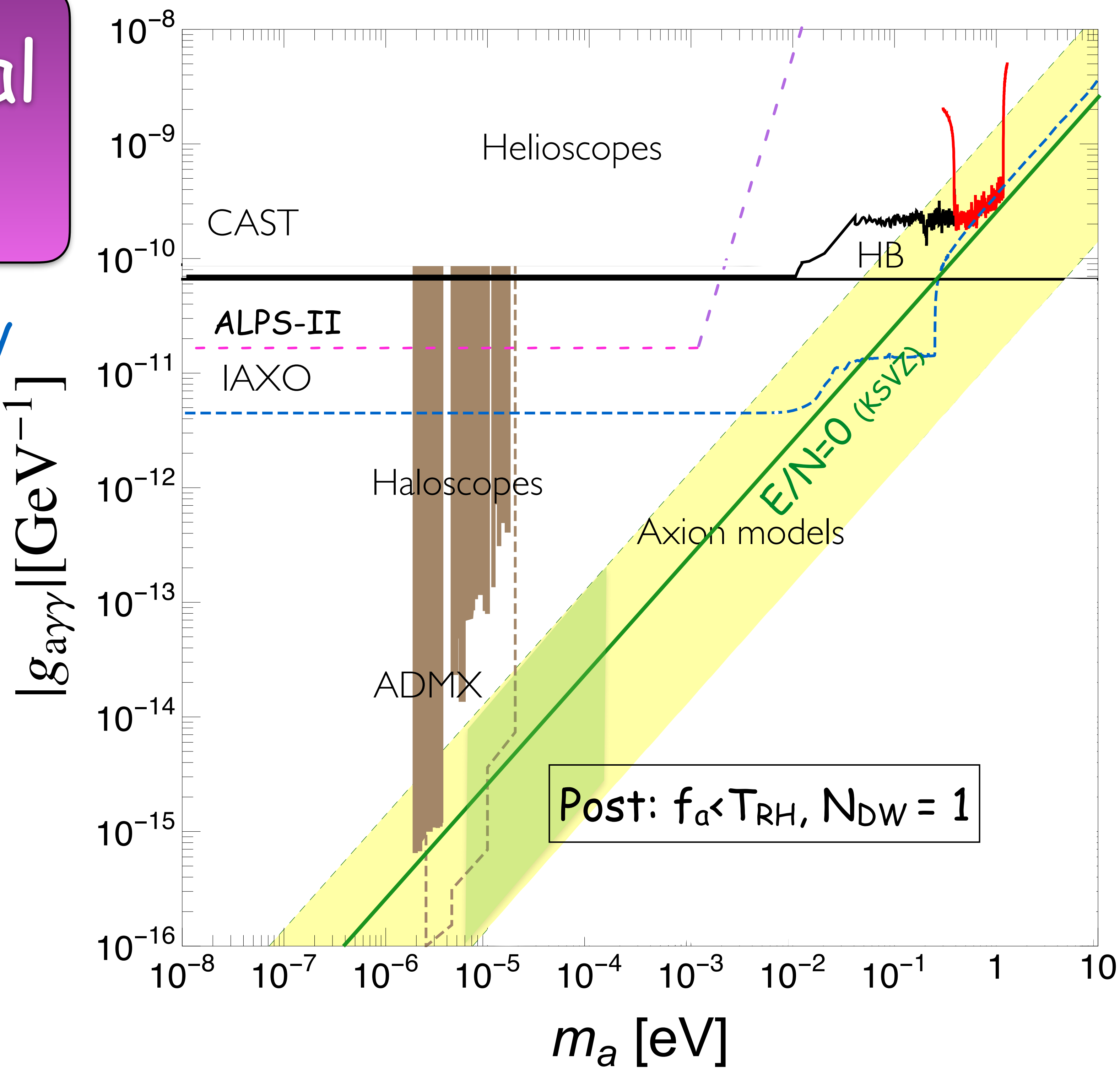
post-inflationary $\langle\theta_i\rangle \simeq 2$, $N_{DW}=1$



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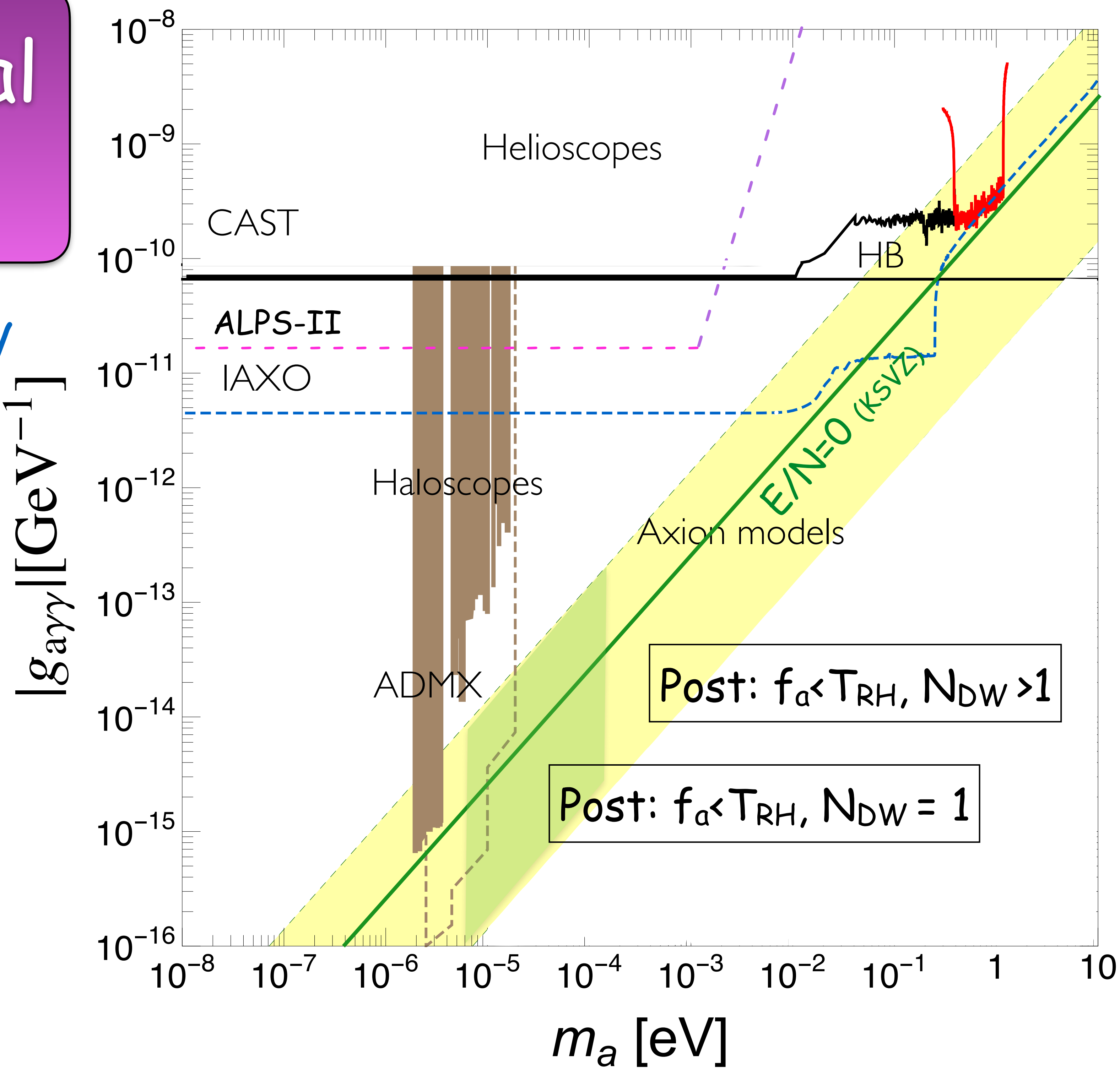

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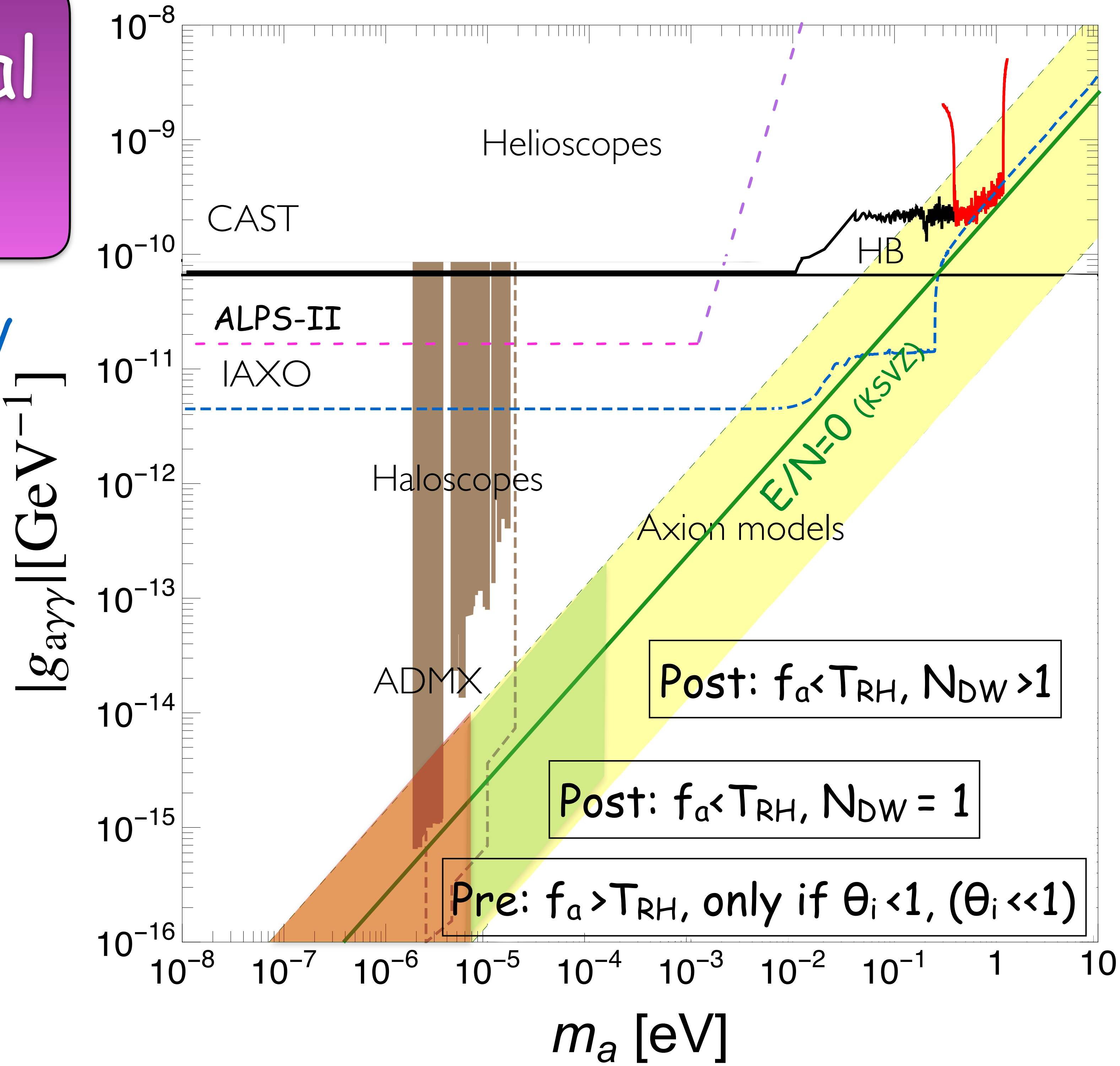

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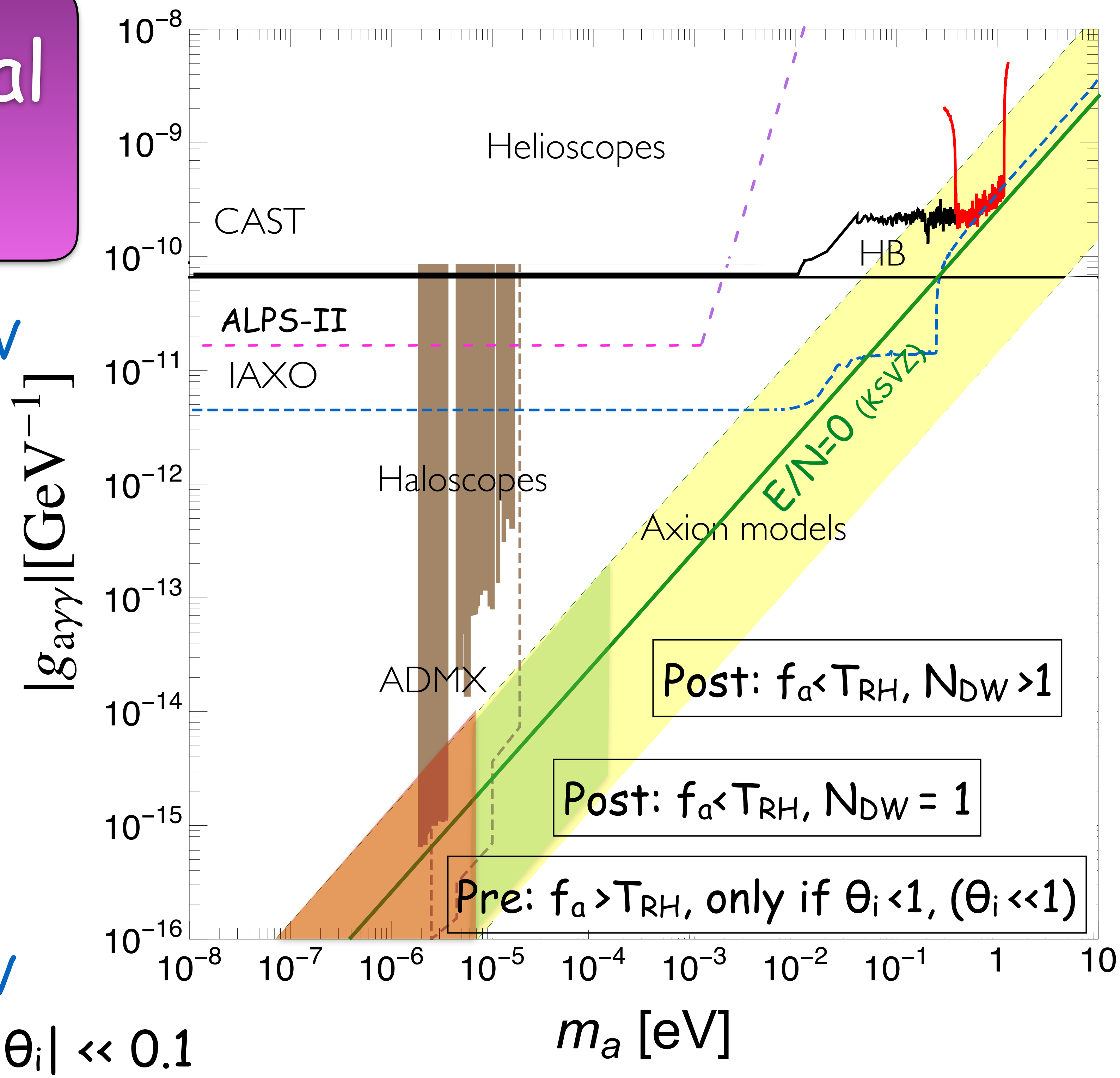
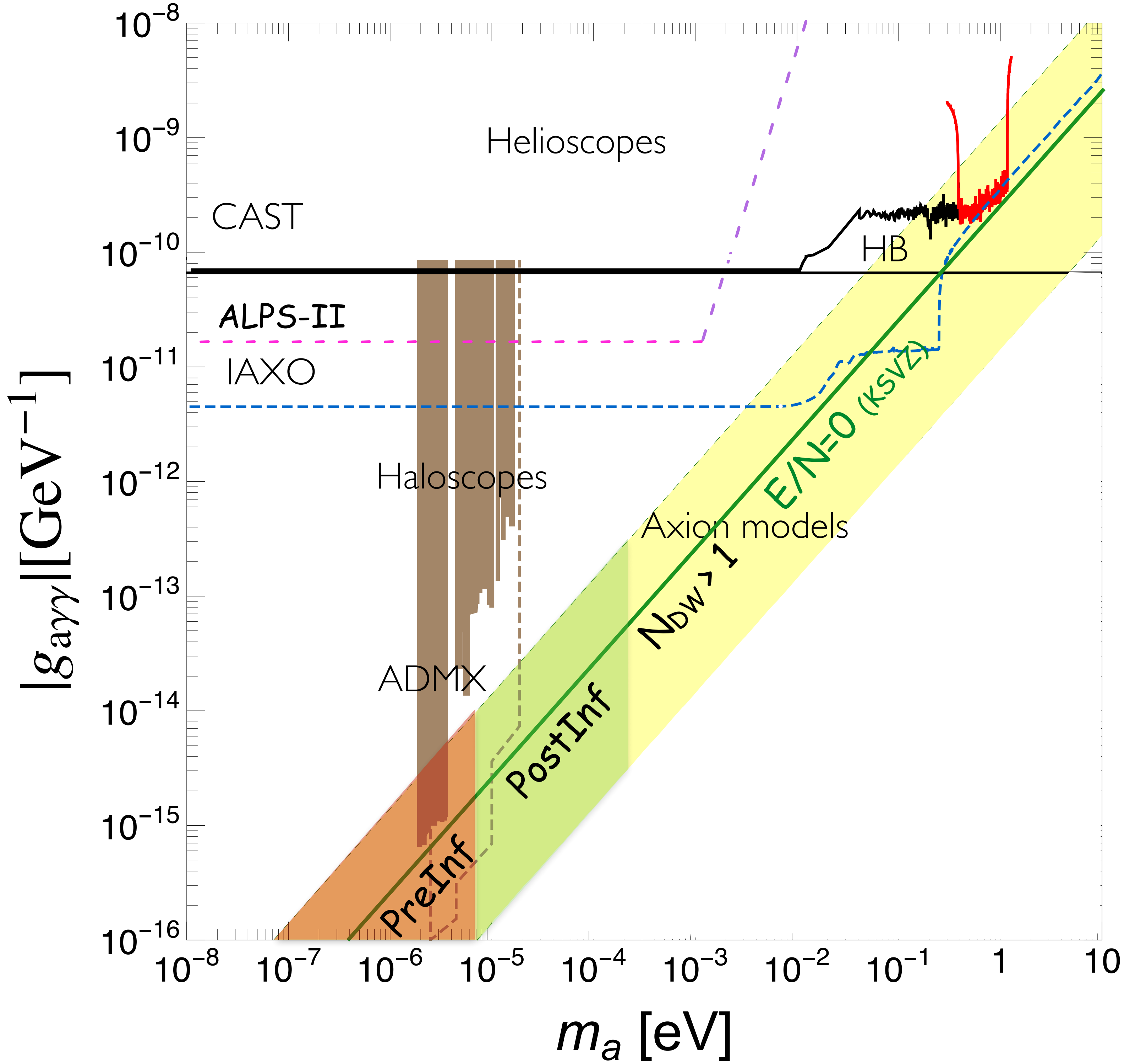
Much smaller: $m_a \ll 0.1\ \mu eV$

pre-inflationary, "anthropic" window: $|\theta_i| \ll 0.1$



Sometimes limits from astrophysics on g_{ae}, g_{aN}, $g_{a\pi}$ are fed into $g_{a\gamma}$-m_a plots



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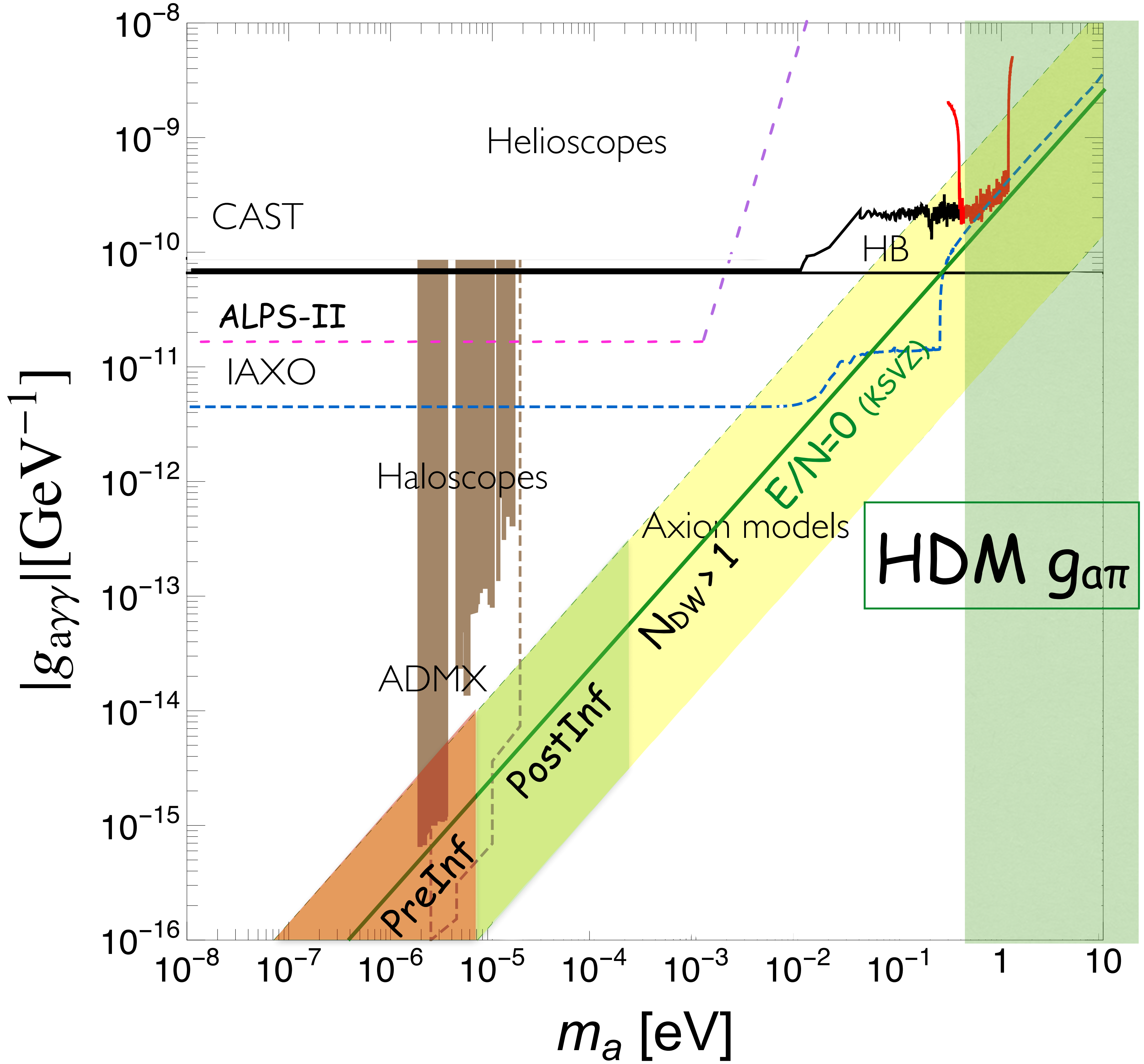
Hot DM ($\pi\pi \leftrightarrow \pi a$):

$g_{a\pi} \sim (f_a f_\pi)^{-1} \lesssim 2 \times 10^{-7}$ GeV^{-2}

$g_{a\pi} \xrightarrow{\text{(model)}} f_a \xrightarrow{(\ldots)} m_a$



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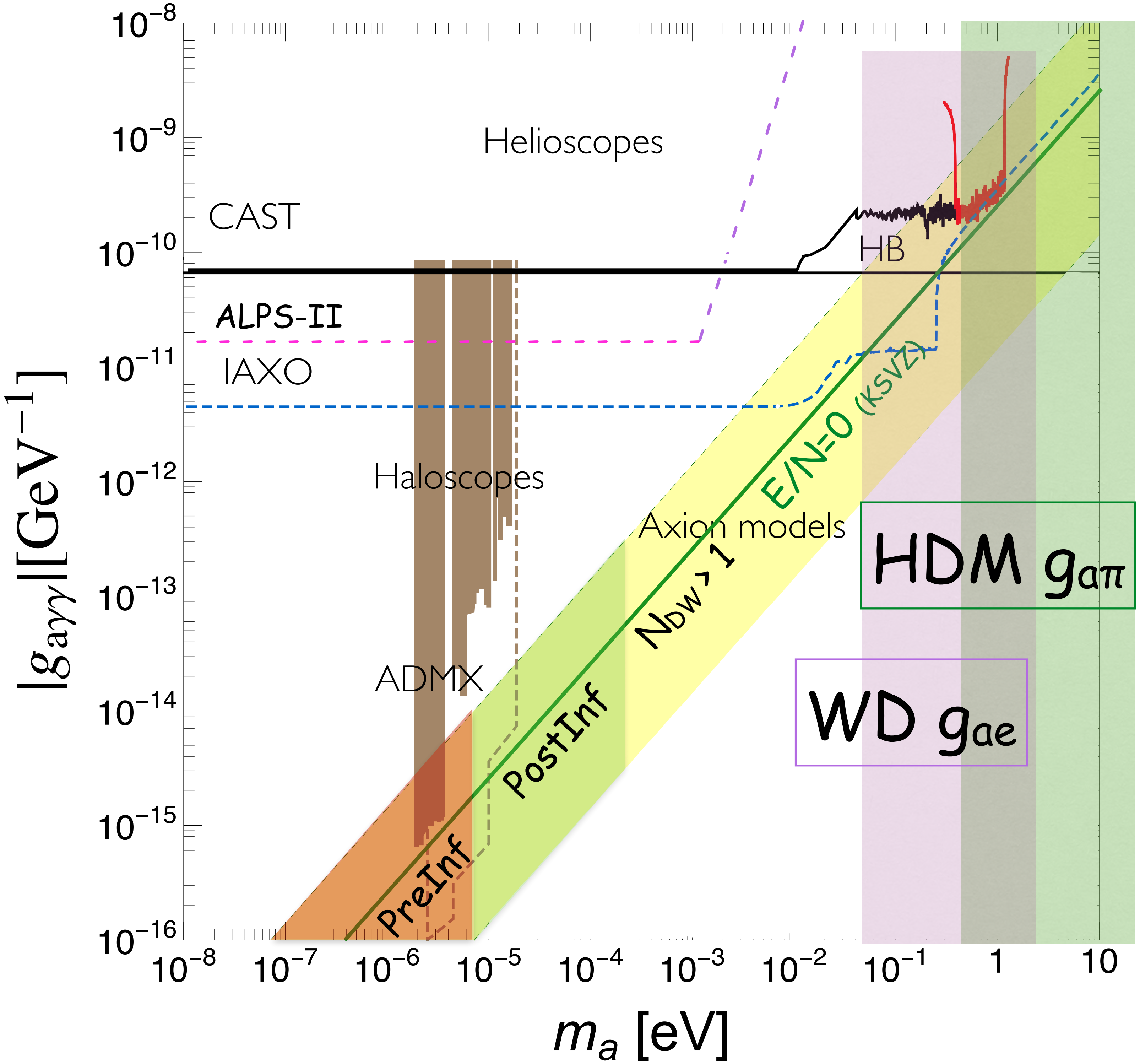

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(see P.Carenza talk)

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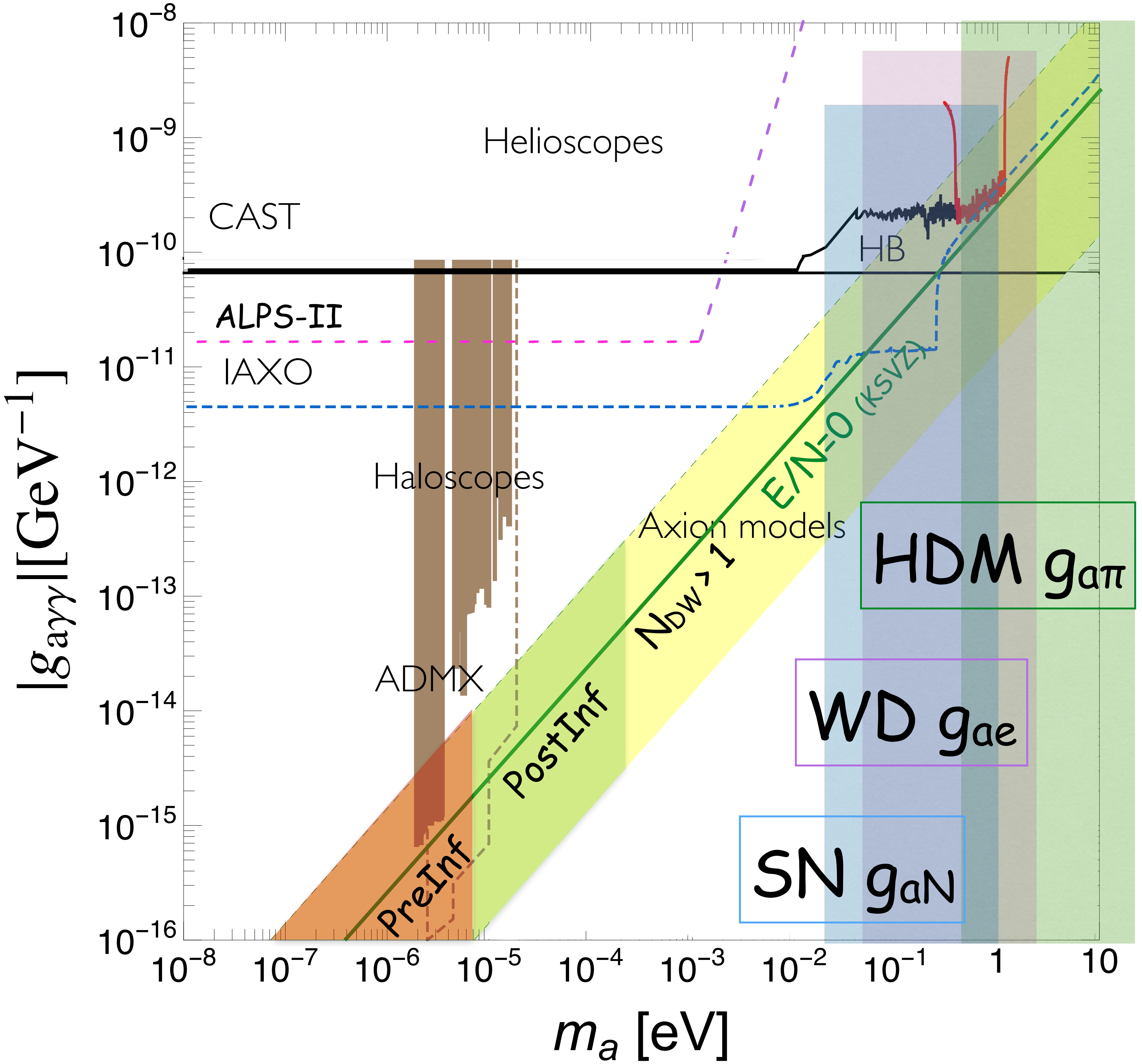

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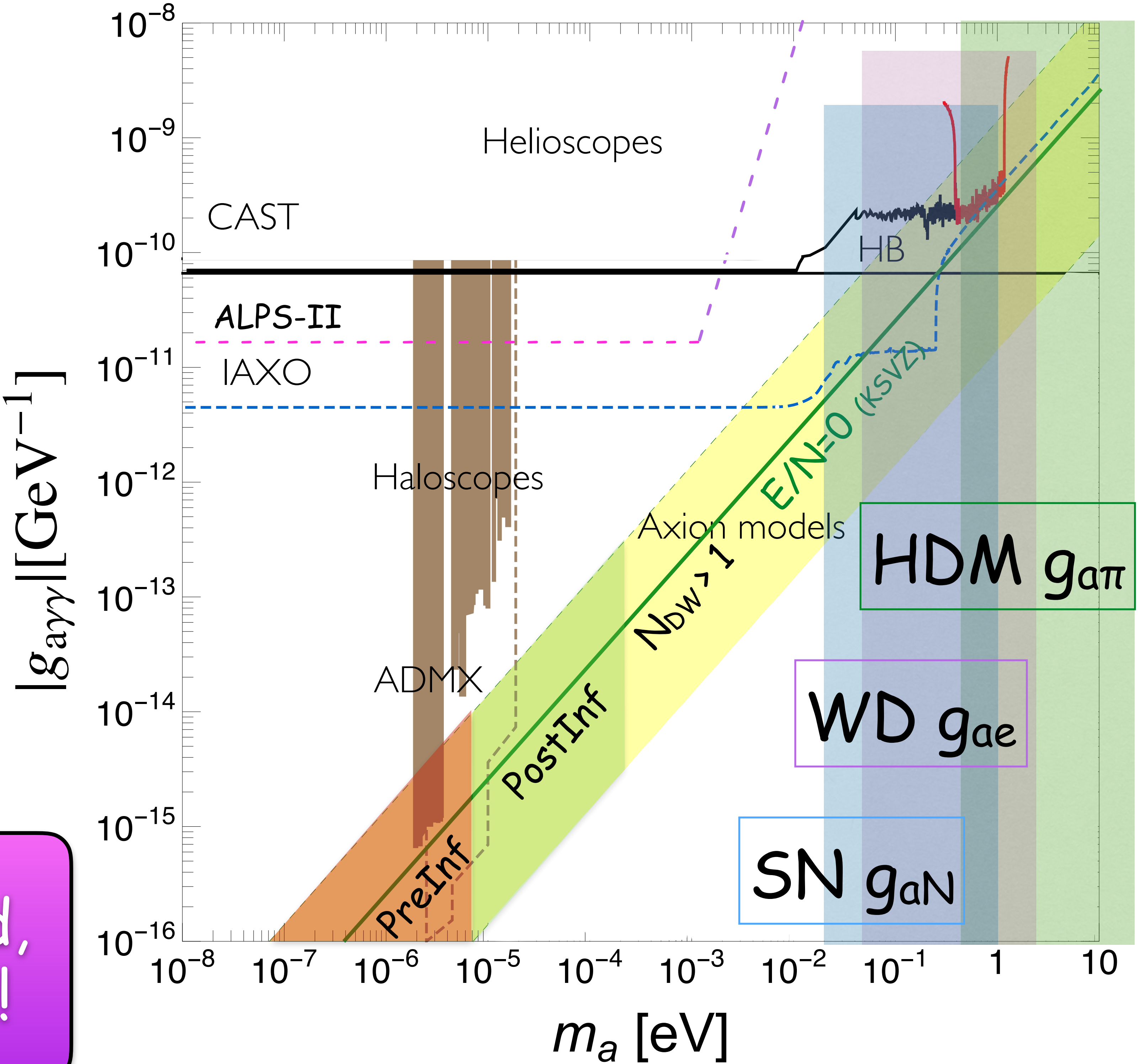
This should be avoided, it can be misleading !



Axion-photon coupling $g_{a\gamma}$: KSVZ-type

Original KSVZ: new Q's SM singlets: E=0

Simplest, but cosmo issues with Q stability

$$g_{a\gamma\gamma} = \frac{m_a}{\mathrm{eV}} \frac{2.0}{10^{10}\ \mathrm{GeV}} \left(\frac{E}{N} - 1.92(4)\right)$$

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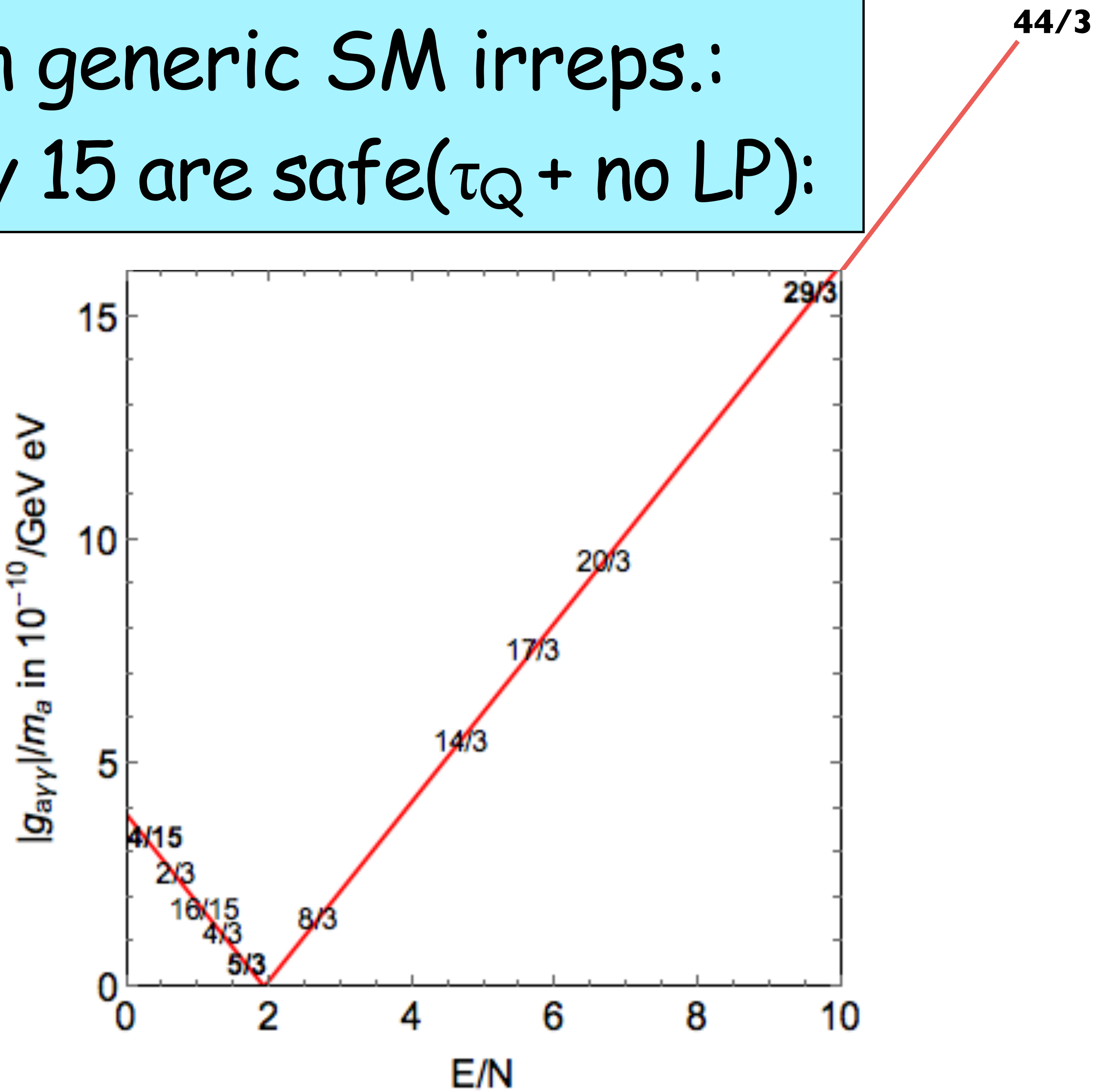
Q in generic SM irreps.:

Only 15 are safe(τ_Q + no LP):



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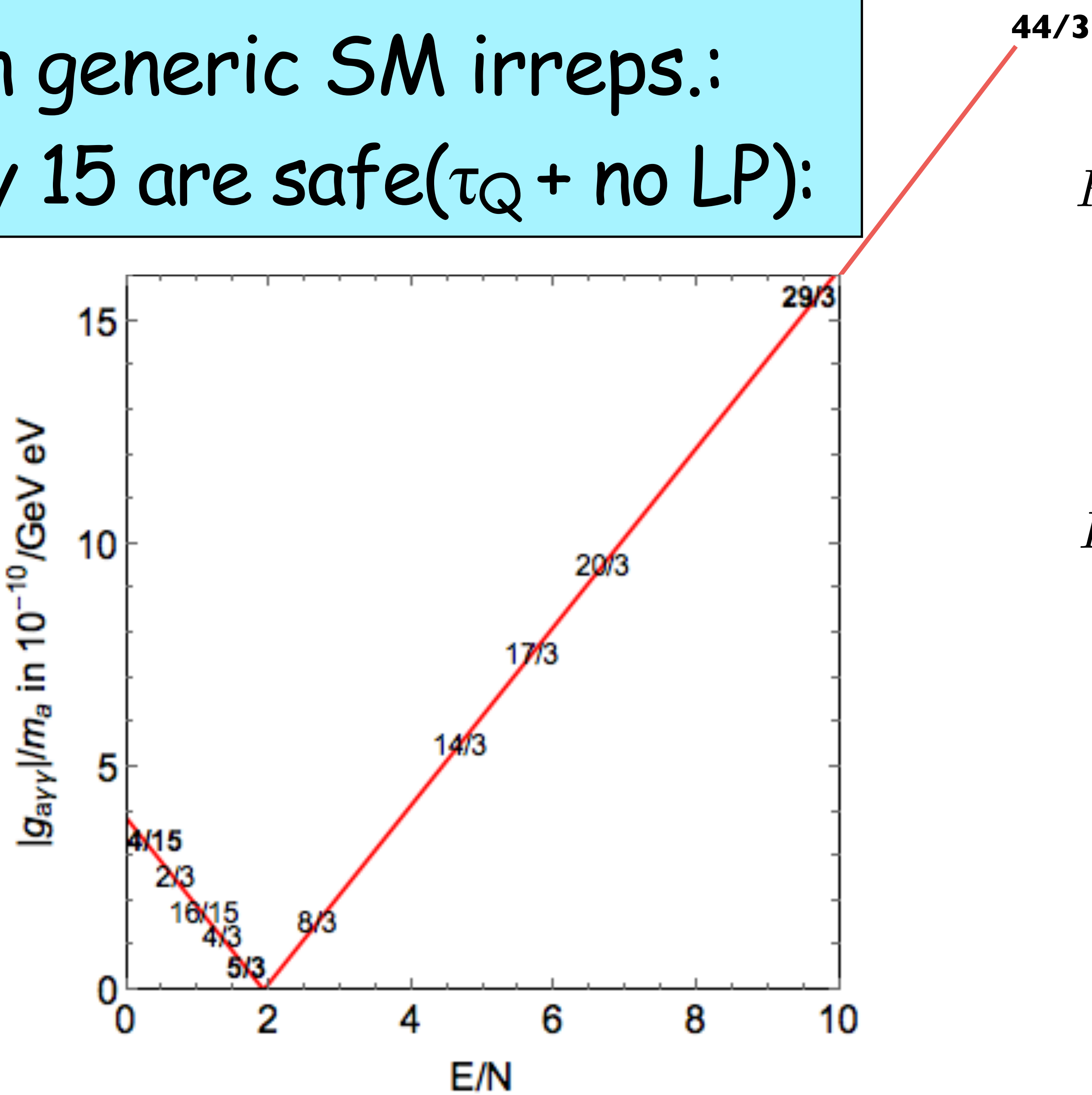

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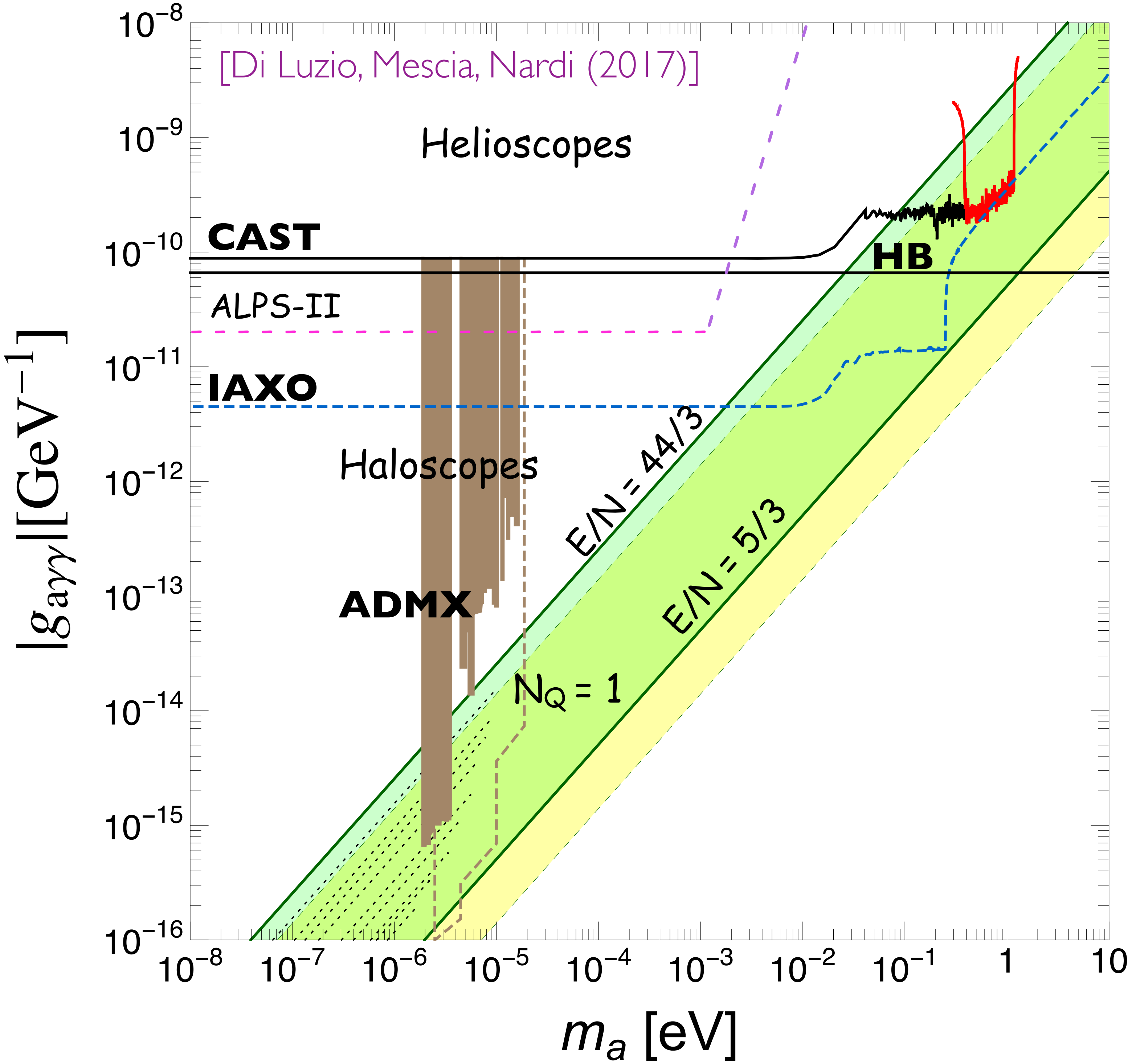
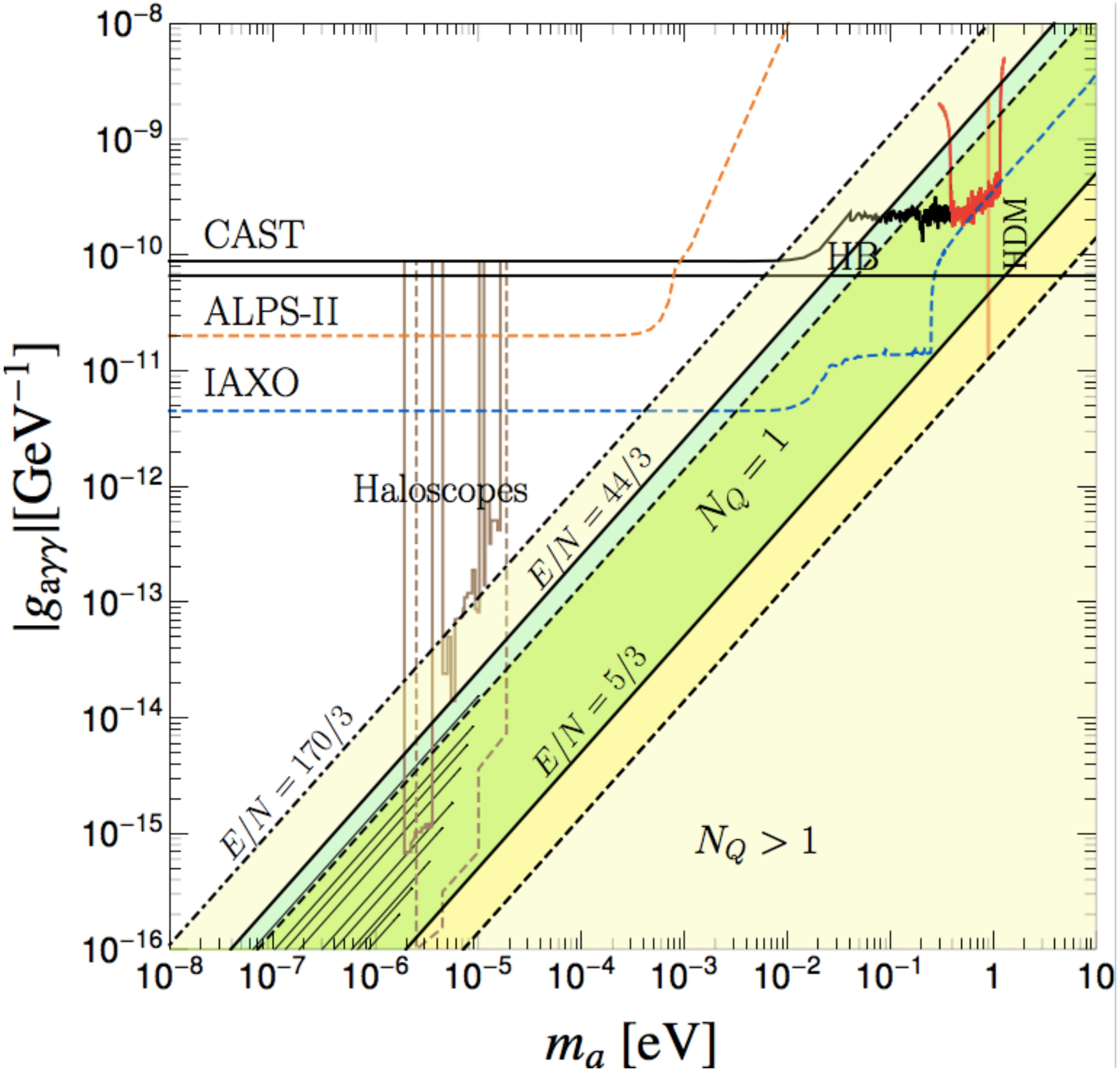
Redefining the KSVZ axion window



KSVZ: More Q representations



[Di Luzio, Mescia, Nardi (2017)]

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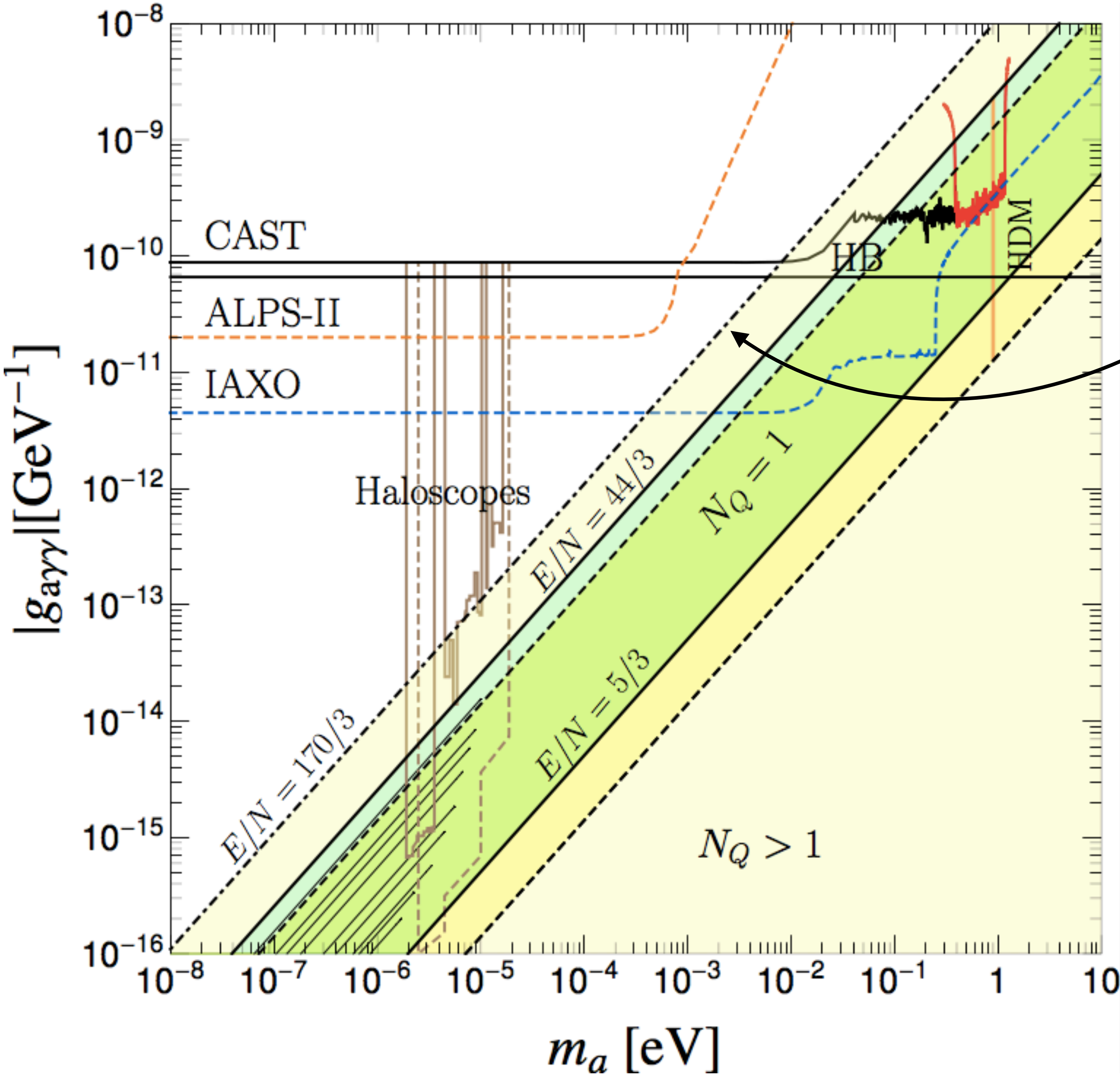

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The strongest possible coupling E_c/N_c=170/3 (3 R_Q)

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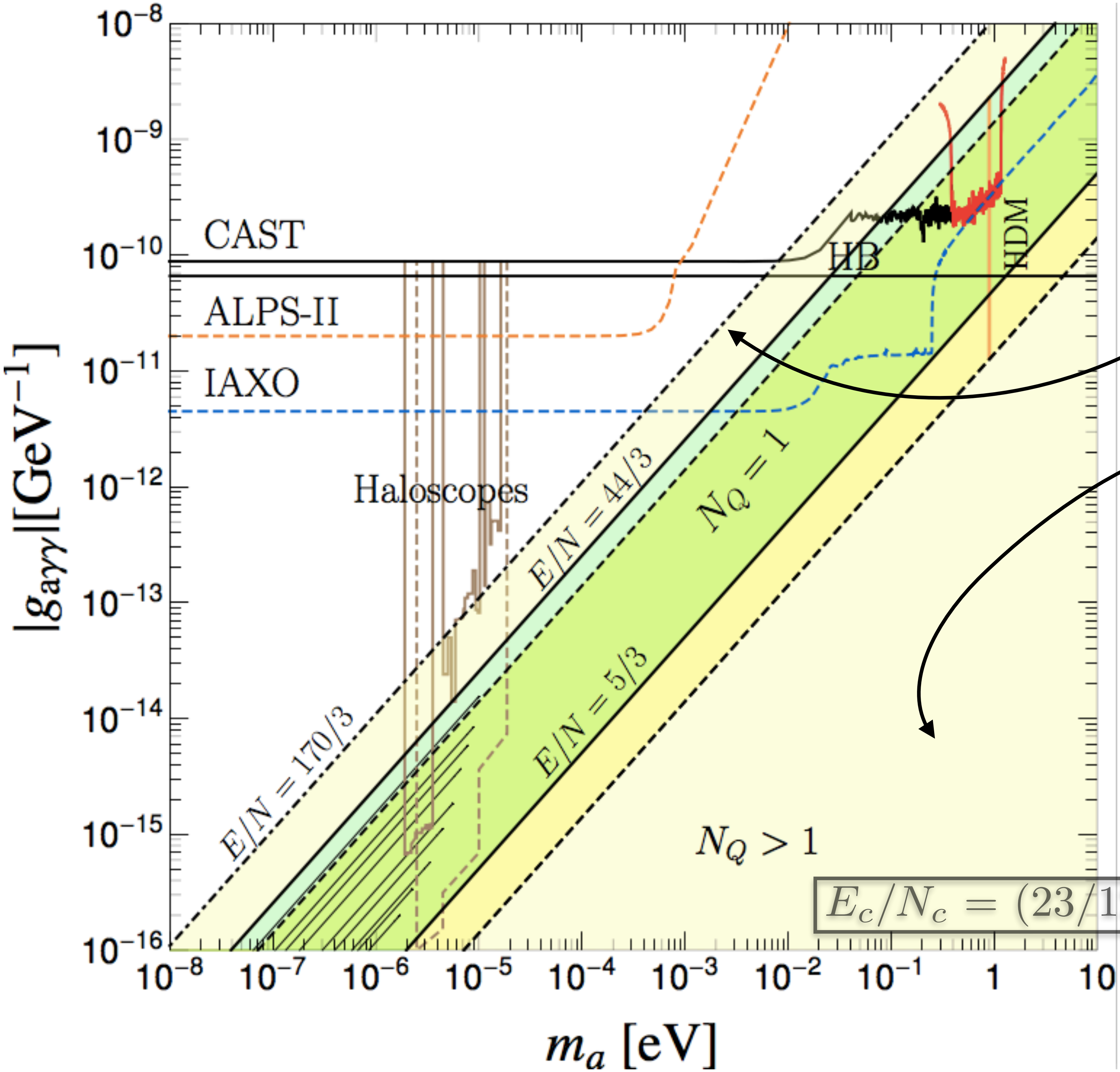

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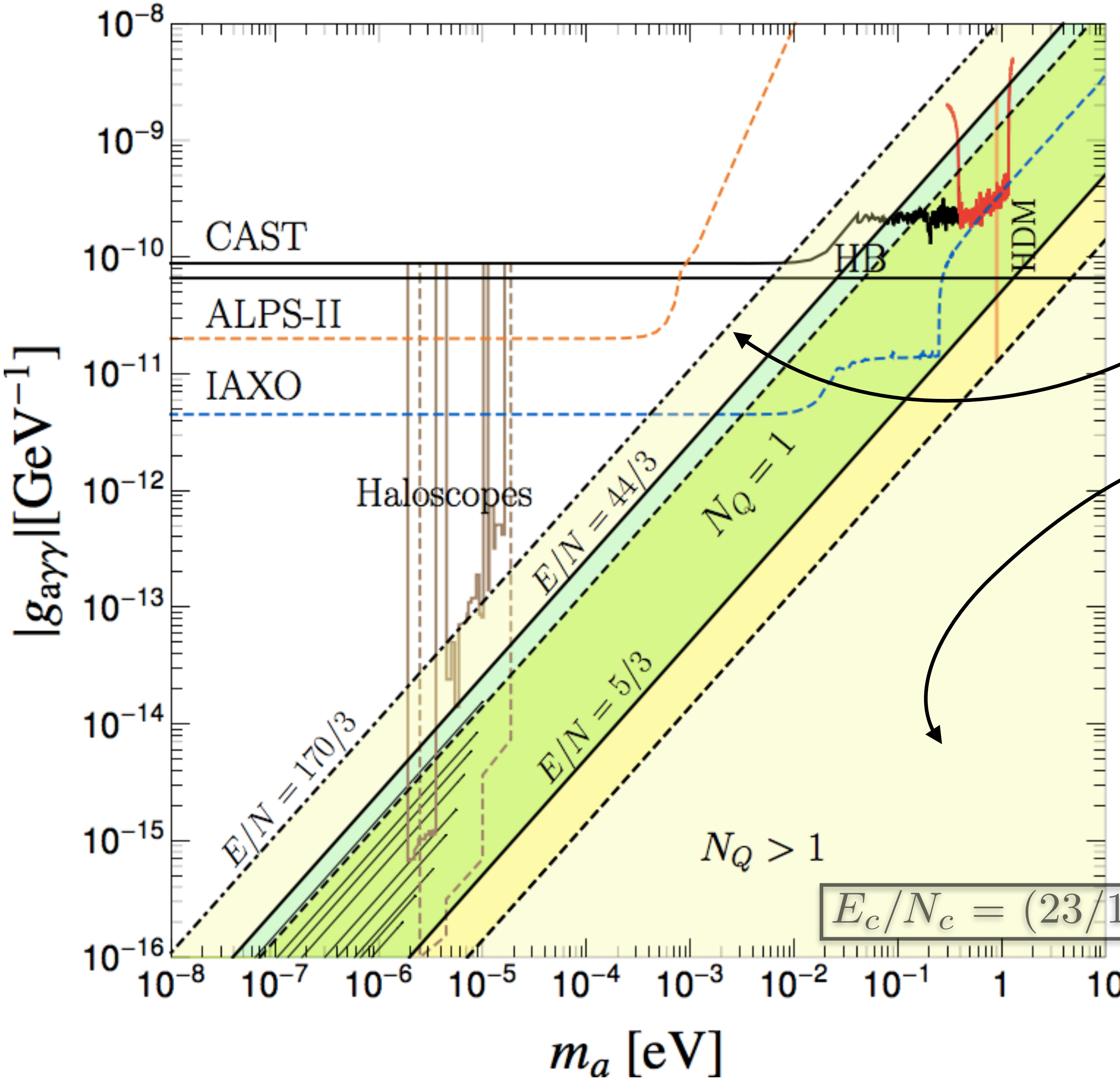
Axion-photon decoupling
(within theoretical errors)
can also occur !

$$(3, 3, -1/3) \oplus (\overline{6}, 1, -1/3)$$
$$(\overline{6}, 1, 2/3) \oplus (8, 1, -1)$$
$$(3, 2, -5/6) \oplus (8, 2, -1/2)$$

$$E_c/N_c = (23/12, 64/33, 41/21) \approx (1.92, 1.94, 1.95)$$

KSVZ: More Q representations



[Di Luzio, Mescia, Nardi (2017)]

The strongest possible coupling $E_c/N_c=170/3$ (3 R_Q)

$$g_{a\gamma\gamma} = \frac{m_a}{\text{eV}} \frac{2.0}{10^{10}\ \text{GeV}} \left(\frac{E}{N} - 1.92(4)\right)$$

Axion-photon decoupling (within theoretical errors) can also occur !

$$\left.\begin{array}{c}(3,3,-1/3) \oplus (\overline{6},1,-1/3) \\ (\overline{6},1,2/3) \oplus (8,1,-1) \\ (3,2,-5/6) \oplus (8,2,-1/2)\end{array}\right\}$$

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"Immoral but not fine tuned"

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$$u_R^j \rightarrow \exp\left(iX_{uj}\right) u_R^j\,,$$
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DFSZ-I : $X_e = X_d\,,$ $E/N = 8/3$

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DFSZ-III: $X_e \neq X_{u,d},$ $E/N_{(max)} = -4/3$

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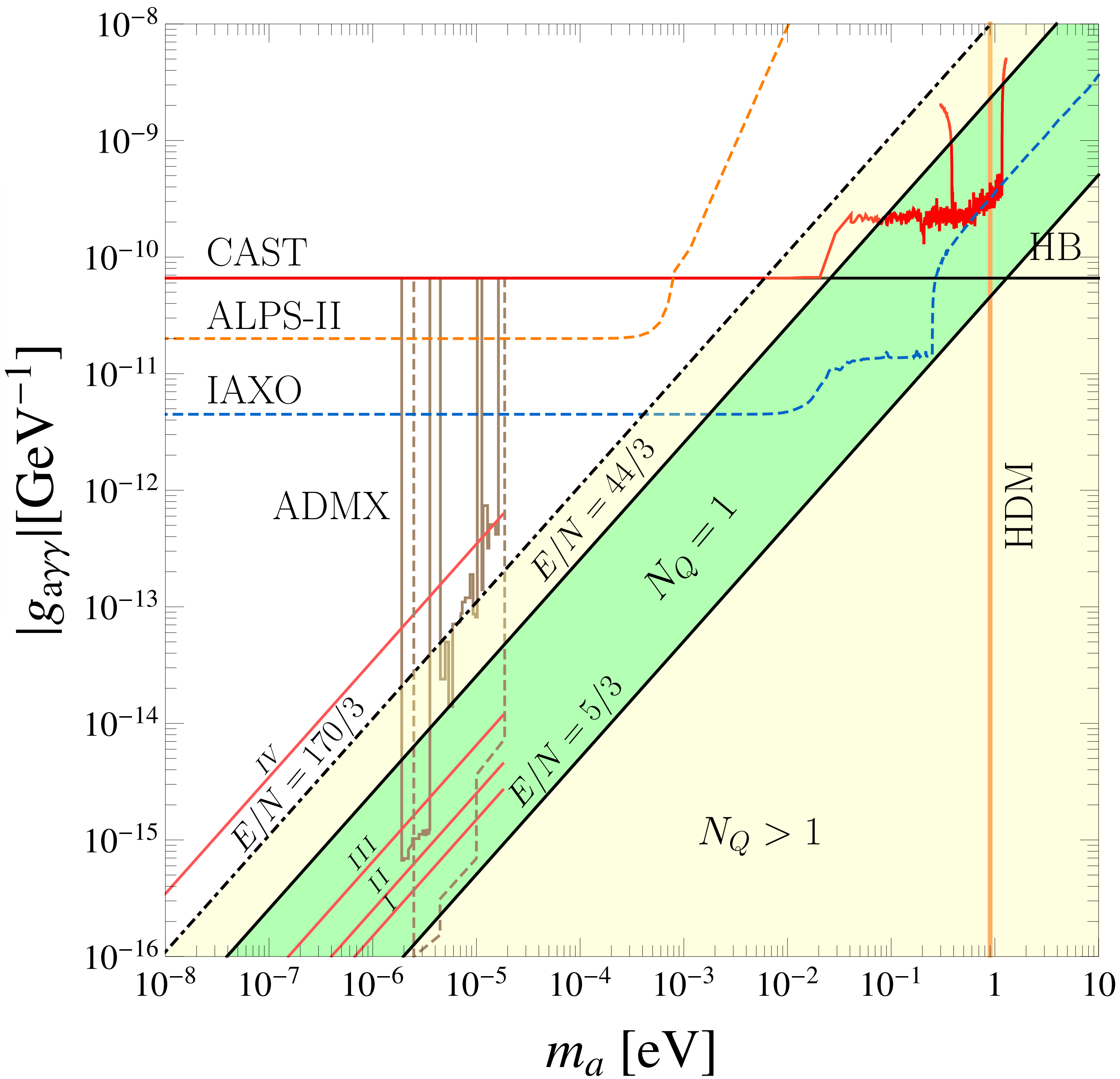
	$E/N(g_{a\gamma\gamma}^{\max})$	$E/N(g_{a\gamma\gamma}^{\min})$
KSVZ ($N_Q = 1$)	44/3	5/3
KSVZ ($N_Q > 1$)	170/3	23/12
DFSZ-I-II ($n_H = 2$)	2/3	8/3
DFSZ-III ($n_H = 3$)	−4/3	8/3
DFSZ-IV ($n_H = 9$)	524/3	23/12

- For generation dependent charges (max. of 9 Higgs doublets H_{f_j}):

DFSZ-IV ($X_{ej}\ X_{dj}, X_{uj}$): $E/N_{(max)} = 524/3 = 3 \cdot E/N_{(max)}(\text{KSVZ})$

KSVZ/DFSZ: enlarged $g_{a\gamma}$ window

The region where generic KSVZ and DFSZ axion models can live:



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(1):\quad C_p + C_n &= (c_u + c_d)\,(\Delta_u + \Delta_d) - 2\delta_s \qquad [\delta_s \approx O(10\%)] \\
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So that, independently of the matrix elements:

$$\begin{aligned} (1): \quad C_p + C_n &\approx 0 \quad \text{if} \quad c_u + c_d = 0 \\ (2): \quad C_p - C_n &= 0 \quad \text{if} \quad c_u - c_d = 0 \end{aligned}$$

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Goldstone of Hyperchage:

$\varphi_Y = (v_2\, \varphi_2 - v_1\, \varphi_1)/v$

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With $v_2^2/v_1^2 \approx 2$ ($c_\beta^2 \approx 1/3$) —> $X_u - X_d = X_1 + X_2 \approx -1/3$

then $c_u - c_d \approx 0$ and approximate a-N,π decoupling $g_{aN} \approx 0$

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2nd Nucleophobia condition

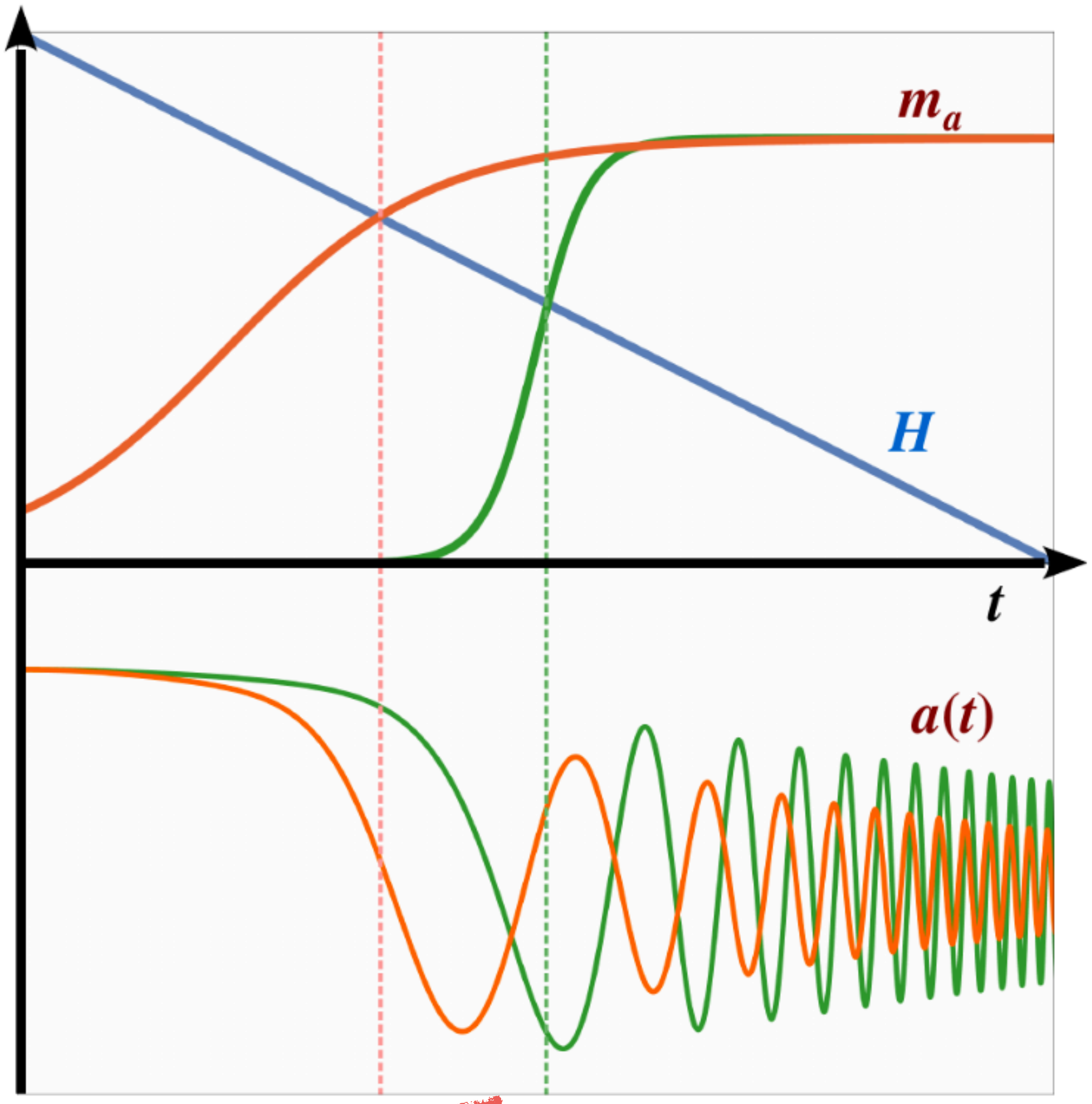
Lepton-axion decoupling: $\mathcal{X}_3 \approx 0$

occurs for specific values $m_d/m_u \approx$ **2**, 1, 1/2 with no additional tuning required

Axion relic density $\Omega_a = \rho_a / \rho_c$

$$\rho_a = m_a^2 a^2$$

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



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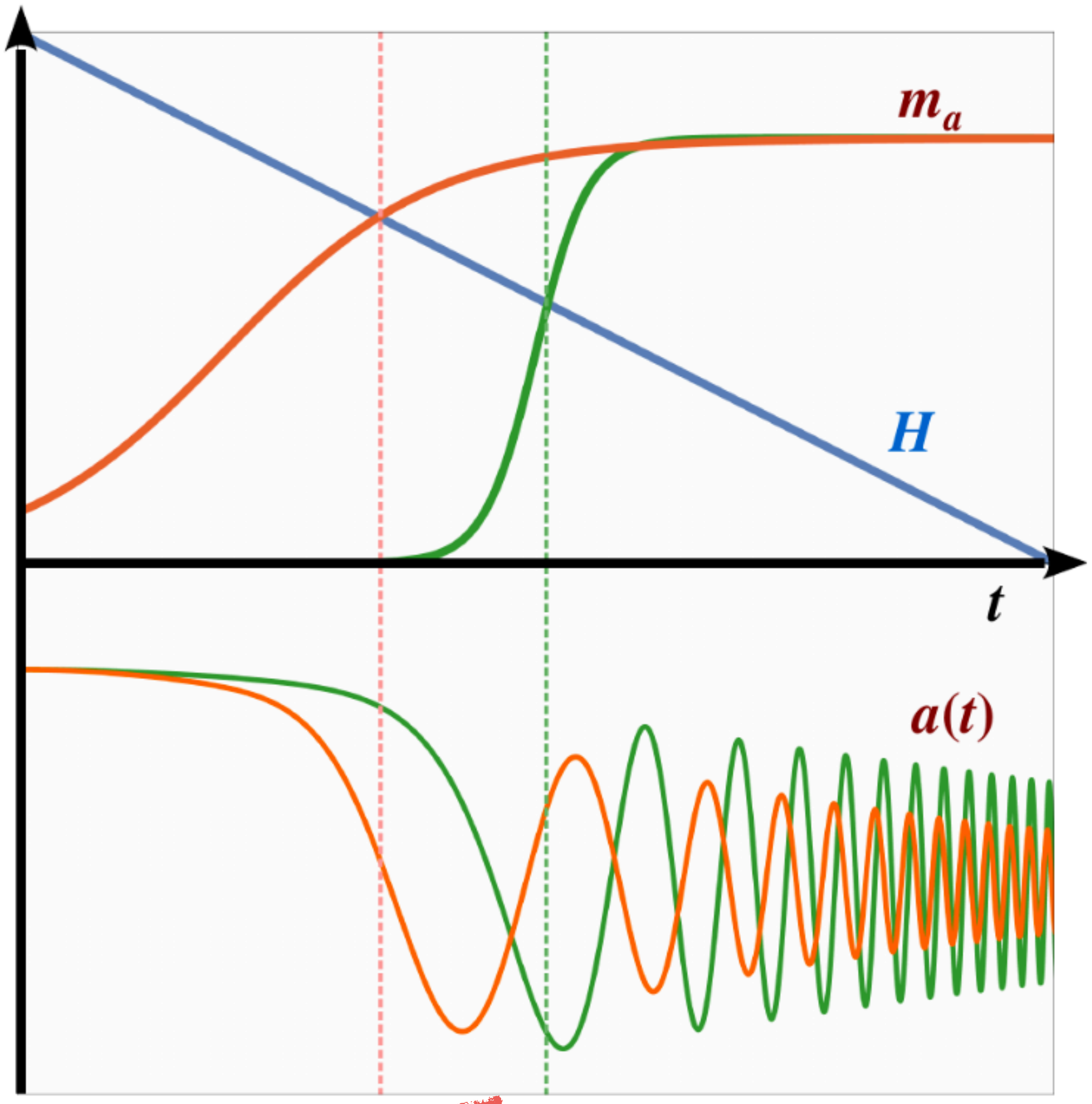

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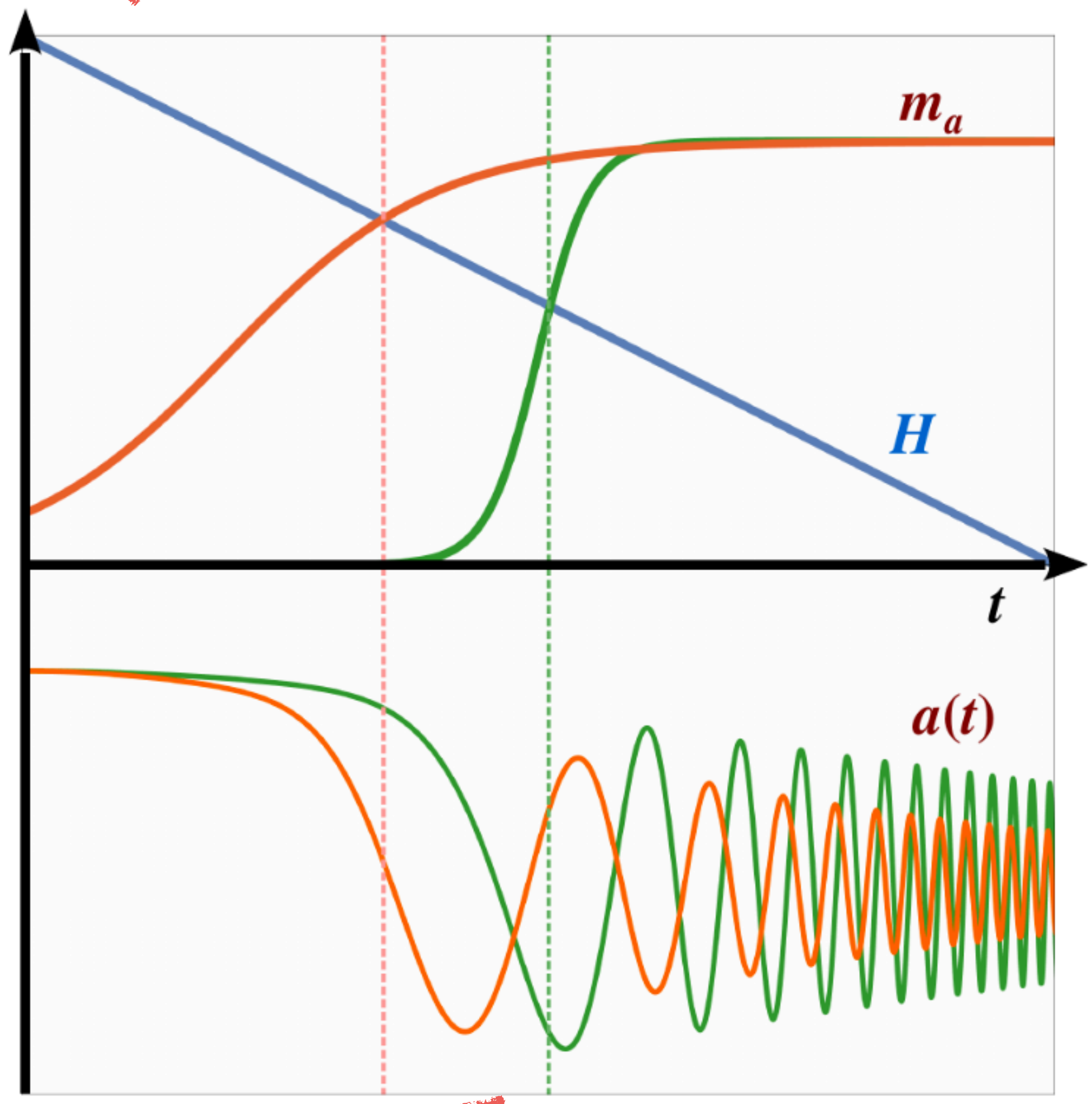
(eq. st.: $w_{eff}=1/3$, rad.dom.)



Credits to G. Villadoro

Axion relic density $\Omega_a = \rho_a / \rho_c$

$$\rho_a = m_a^2 a^2$$

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

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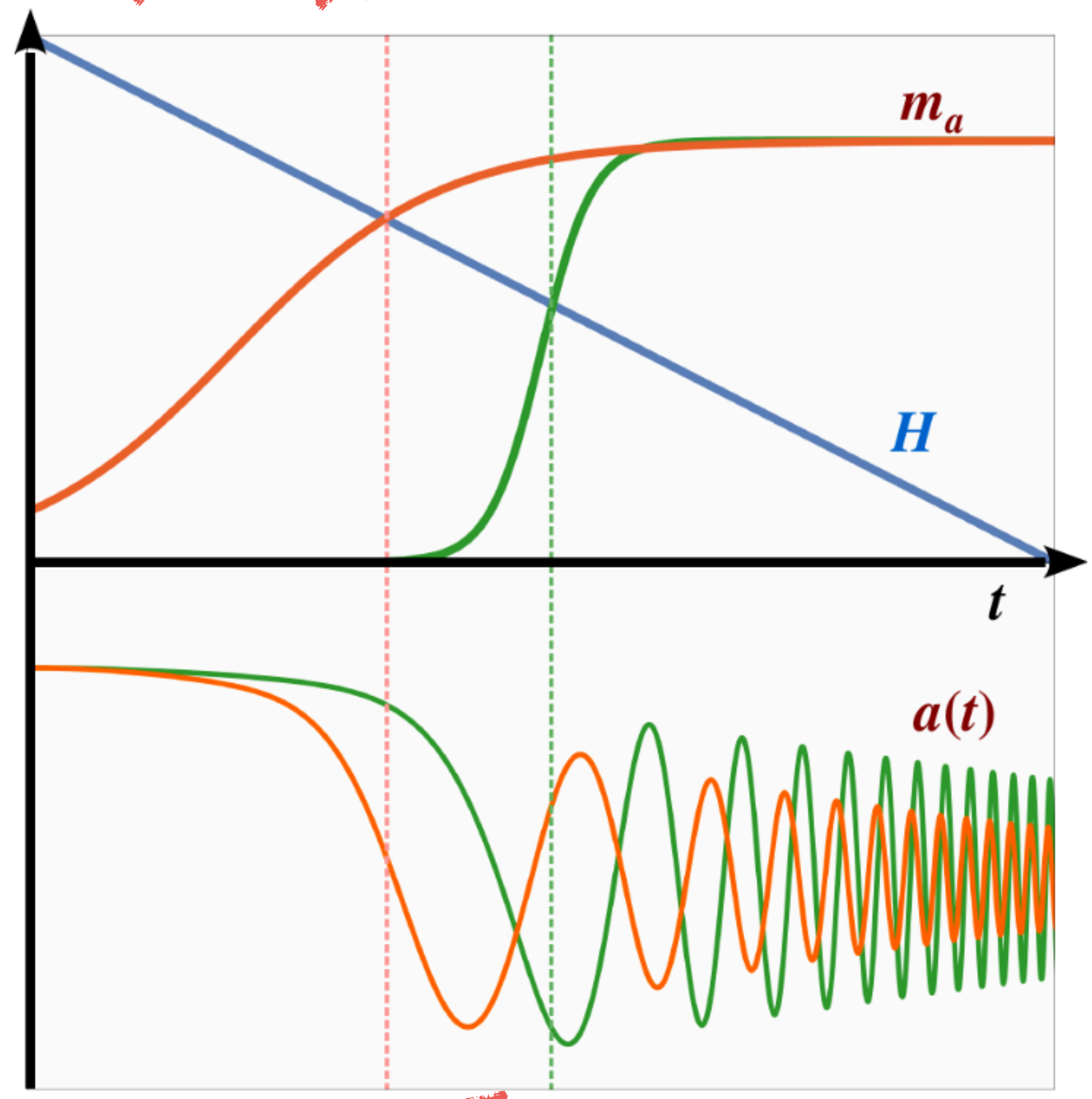

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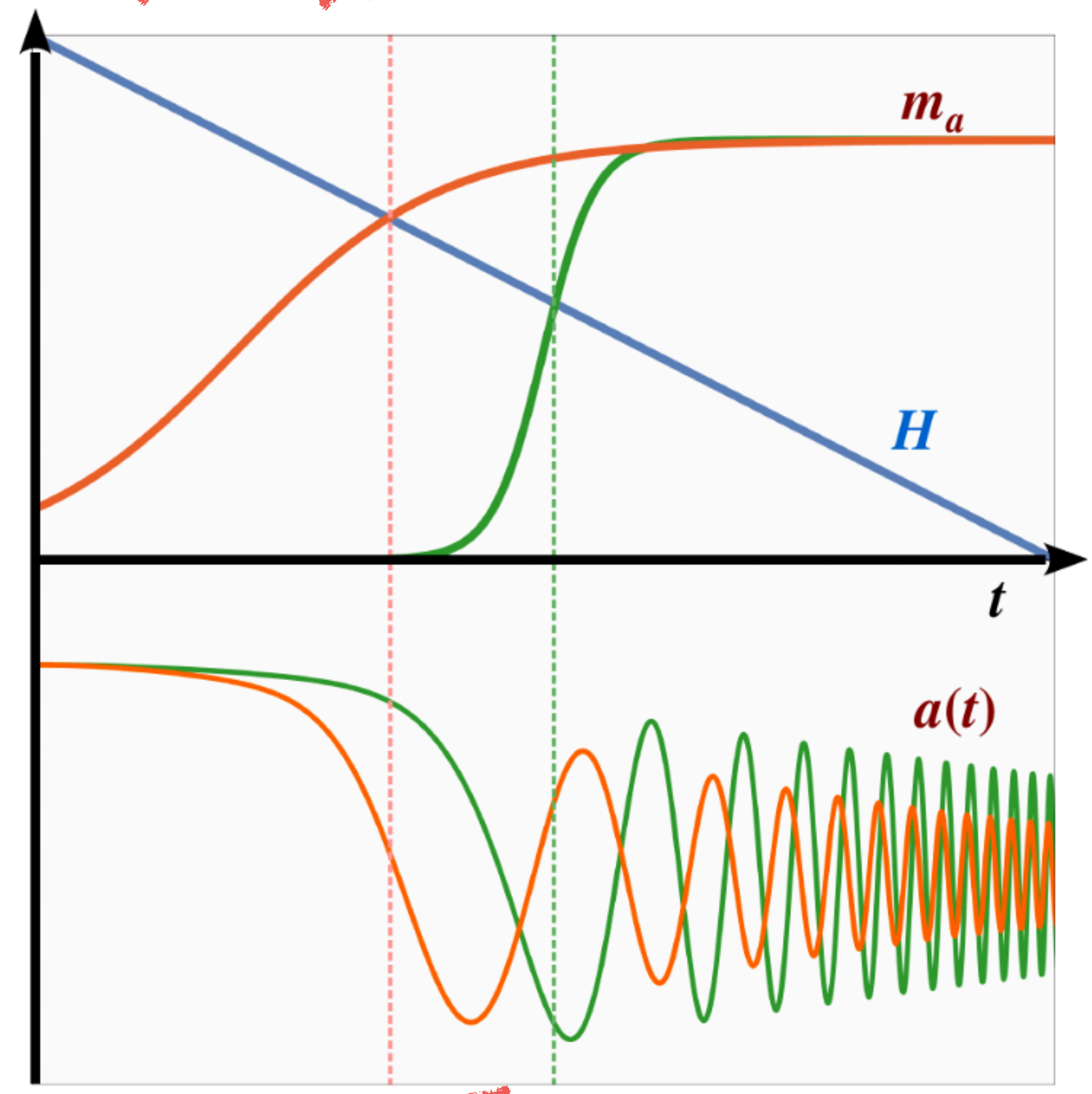

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[P.W. Graham, A. Scherlis 1805.07362, F. Takahashi, W. Yin, A. H. Guth 1805.08763]

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Beyond GR: [work in progress]

- Scalar-tensor theories:

  (conformal) boosted $H(T)$: $m_a \uparrow$

  (disformal ?) quenched $H(T)$: $m_a \downarrow$

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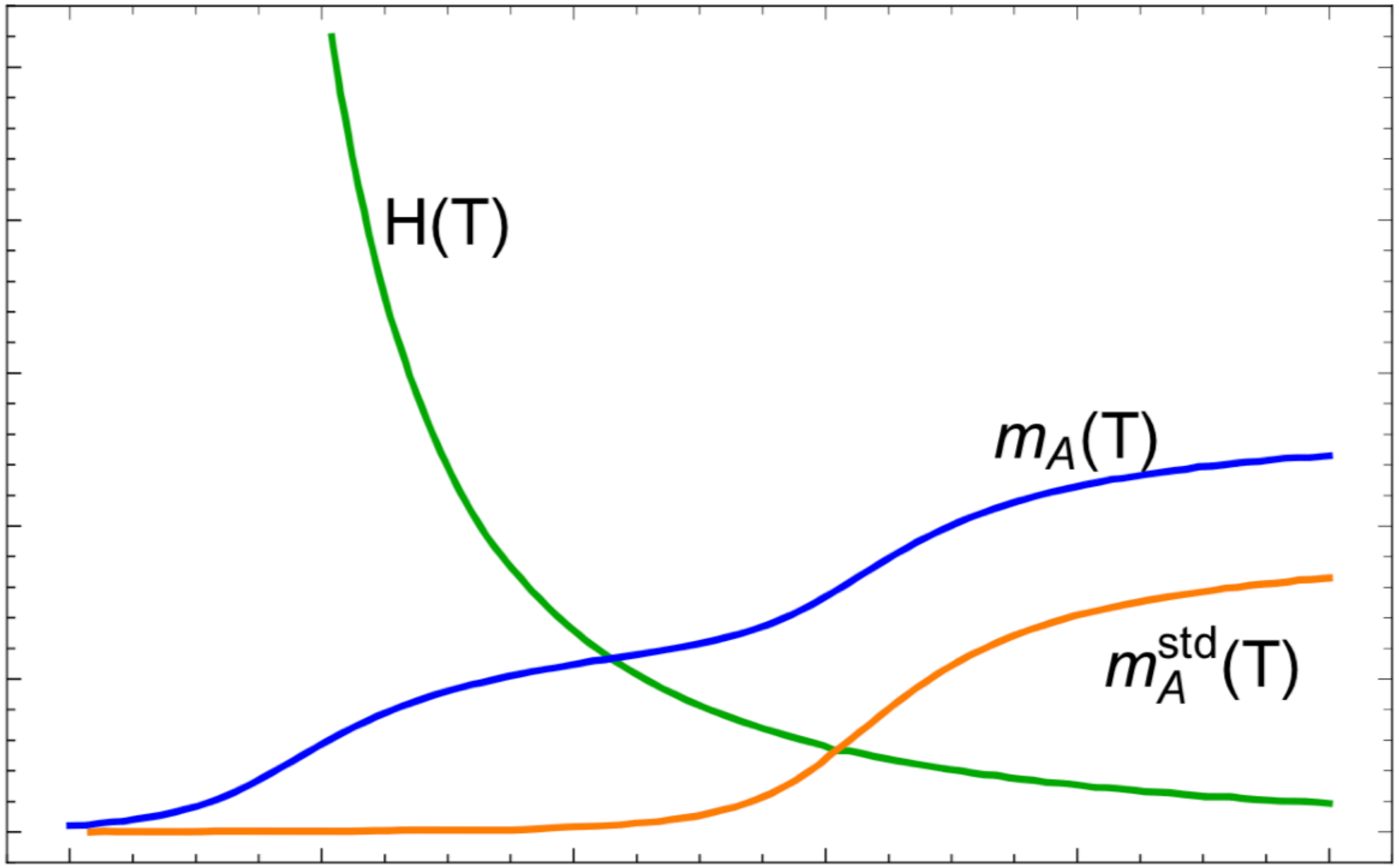
- **Modify $m_a(T)$:**

  Additional contributions from mirror instantons:
  (earlier onset of oscillations)

  $m_a \downarrow$ [Giannotti, astro-ph/0504636]

[For $m_a \uparrow$ see P. Quilez talk]



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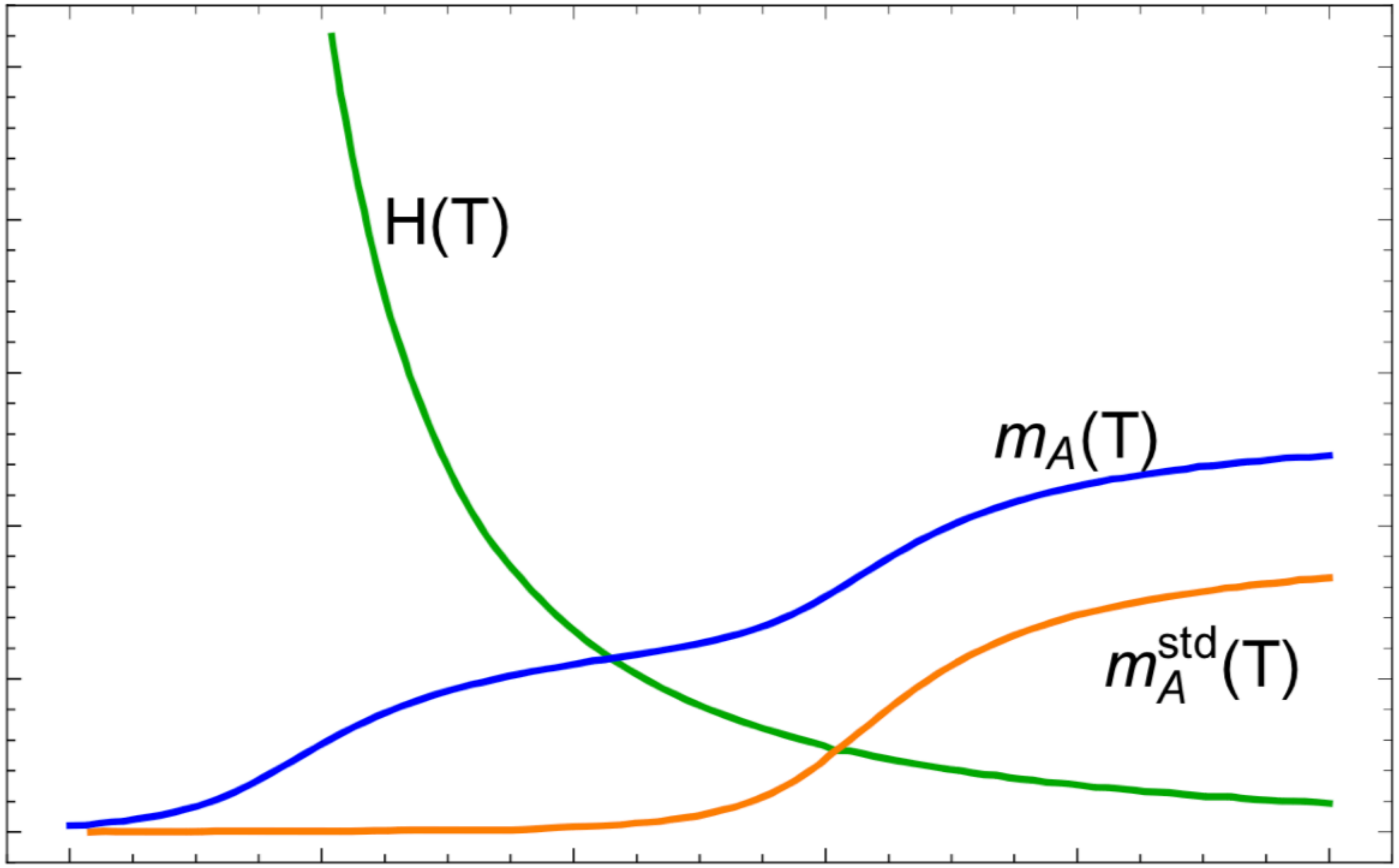

- **Modify m_a:**
  N copies of QCD related by a $\mathbb{Z}_N$ symmetry [A. Hook, 1802.10093]

$$m_a(N) = 2^{2-N/2} \times m_a \,, \qquad \text{for } N > 4 \quad m_a \downarrow$$

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- Working group to classify **axion models off the beaten tracks** (M. Giannotti, L. Di Luzio, EN, L. Visinelli). Full report to be expected after the summer.

Thanks for your attention