Overview of Axion theory

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2006.14598 [PRL 125 (2020) 13, 131806]
2102.10118 [JHEP 05 (2021) 138]
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Outline

- The axion and strong CP problem
- Visible and invisible axion models
- Axion dark matter, ALP and experimental searches
- Summary

The QCD axion and the Strong CP problem

$$\mathscr{L} \supset -\frac{\theta g_s^2}{32\pi^2} G\tilde{G} - \left(\bar{u}_L M_u u_R + \bar{d}_L M_d d_R + \mathrm{h.c.}\right)$$

- The CKM matrix from $M_{u,d}$
  - CP violating phase θ_{CP} ~ 1.2 radian

- QCD induced CP violating phase, $\bar{\theta}$

$$\bar{\theta} = \theta + \arg\left[\det\left[M_u M_d\right]\right]$$

- $\bar{\theta}$ is invariant under quark chiral rotation

$$d^n_{\mathrm{EDM}} \sim \theta \times 10^{-16}\ \mathrm{e\ cm}$$

- According to neutron EDM experiment

$$d^n_{\mathrm{exp}} < 10^{-26}\ \mathrm{e\ cm}$$

$$\bar{\theta} \lesssim 1.3 \times 10^{-10}\ \mathrm{radian}$$

The Peccei-Quinn solution to Strong CP problem

- Experiment requires $\bar{\theta} = \theta + \arg\left[\det\left[M_u M_d\right]\right] \lesssim 10^{-1}\mathrm{rad}$
- PQ: promote the constant $\bar{\theta}$ to a dynamical field, a
- Vafa-Witten theorem: vector-like theory (QCD) has ground state $\langle \theta \rangle = 0$
- Introduce a *global* PQ-symmetry $U(1)_{\mathrm{PQ}}$, *anomalous* under the QCD
  - The massless Goldstone boson a is called *axion*
  - $a \to a + \kappa f_a \;\; \Rightarrow \mathcal{S} \to \mathcal{S} + \frac{\kappa}{32\pi^2}\int d^4x G\tilde{G}$, cancels $\bar{\theta}$
  - Low energy: $\mathcal{L} = \sum_q \bar{q}\left(iD_\mu\gamma^\mu - m_q\right)q - \frac{1}{4}GG + \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G} + \frac{1}{2}\left(\partial_\mu a\right)^2 + \mathcal{L}_{\mathrm{int}}[\partial_\mu a]$

Model independent visible axion properties

- For two flavor QCD, $q = (u, d)^T$
  - $\mathscr{L} \supset \frac{1}{2}\left(\partial_\mu a\right)^2 + \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G} + \frac{1}{4}g^0_{a\gamma}F\tilde{F} - \bar{q}_L M_q q_R + \frac{\partial_\mu a}{2f_a}\bar{q}c^0_q\gamma^\mu\gamma_5 q + h.c.$
  - The three QCD related terms can be eliminated to 2 d.o.f.
  - Choose to eliminate $G\tilde{G}$ term by quark field redefinition in a-related chiral rotation
    - A new quark field: $q' = \exp\left(i\frac{a}{2f_a}\gamma_5 Q_a\right)q$
    - $\mathscr{L} \supset \frac{1}{2}\left(\partial_\mu a\right)^2 + \frac{1}{4}g_{a\gamma}F\tilde{F} - \bar{q}'_L M_{q'} q'_R + \frac{\partial_\mu a}{2f_a}\bar{q}' c_q \gamma^\mu\gamma_5 q' + h.c.$

Model independent visible axion properties

- In the new basis
- $\mathscr{L} \supset \frac{1}{2}\left(\partial_\mu a\right)^2 + \frac{1}{4} g_{a\gamma} F\tilde{F} - \bar{q}'_L M_a q'_R + \frac{\partial_\mu a}{2f_a} \bar{q}' c_q \gamma^\mu \gamma_5 q' + h.c.$
- $c_q = c_q^0 + Q_q\,,\; g_{a\gamma} = g_{a\gamma}^0 - 2N_c \frac{\alpha_{em}}{2\pi f_a} \mathrm{Tr}[Q_a Q^2]$
- Quark mass is complex: $M_a = \exp\left(i\frac{a}{2f_a}Q_a\right) M_q \exp\left(i\frac{a}{2f_a}Q_a\right)$
- Subtle: fix the basis (gauge) and follow through the whole calculation
  - E.g. BR$(K^- \to \pi^- a)$ was overestimated by 40 times for ~35 years

Bauer, Neubert et al: 2102.13112 (PRL)

  - The auxiliary chiral rotation should not affect physical observables

The axion and Chiral Lagrangian

- The generic low energy Lagrangian is

$$\mathscr{L} \supset \frac{1}{2}\left(\partial_\mu a\right)^2 + \frac{1}{4} g_{a\gamma} F\tilde{F} - \bar{q}_L M_a q_R + \frac{\partial_\mu a}{2f_a}\bar{q} c_q \gamma^\mu \gamma_5 q + h.c.$$

- Two flavor quarks $q = (u, d)$; quark mass term $M_a = e^{i\frac{aQ_a}{2f_a}} M_q e^{i\frac{aQ_a}{2f_a}}$

- Below the QCD scale, one needs the chiral axion Lagrangian

$$\mathscr{L}_a^{\chi PT} = \frac{f_\pi^2}{4}\mathrm{Tr}\left[(D^\mu U)^\dagger D_\mu U + 2B_0(UM_a^\dagger + M_a U^\dagger)\right] + \frac{\partial^\mu a}{4f_a}\mathrm{Tr}[c_q \sigma^a] J_\mu^a$$

$$U \equiv e^{i\pi^a \sigma^a / f_\pi}$$

$$J_\mu^a \equiv e^{i\pi^a \sigma^a / f_\pi}$$

Axion mass and interaction with pions

$$\mathcal{L}_a^{\chi PT} = \frac{f_\pi^2}{4}\mathrm{Tr}\left[(D^\mu U)^\dagger D_\mu U + 2B_0(UM_a^\dagger + M_a U^\dagger)\right] + \frac{\partial^\mu a}{4f_a}\mathrm{Tr}[c_q\sigma^a]J_\mu^a$$

- Axion mass: $m_a^2 \simeq (Q_u + Q_d)^2 \frac{m_u m_d}{(m_u + m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2}$
- Axion-π^0 mixing: $\theta_{a\pi} \simeq \frac{(Q_d m_d - Q_u m_u)}{(m_u + m_d)}\frac{f_\pi}{f_a}$
- Axion-pion couplings: $-\frac{3}{2}\frac{\epsilon}{f_a f_\pi}\partial_\mu a\left(2\partial^\mu\pi^0\pi^+\pi^- - \pi^0\partial^\mu\pi^+\pi^- - \pi^0\pi^+\partial^\mu\pi^-\right)$
- Coefficient: $\epsilon = -\frac{1}{2}\left(\frac{Q_d m_d - Q_u m_u}{m_u + m_d} + c_d^0 - c_u^0\right)\frac{f_\pi}{f_a}$

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The visible QCD axion constraints

- The visible axion is highly constrained by pion measurements

experimental limit on observable	translates into bound on model	expectation for generic MeV axions (LO in χPT)	expectation for MeV axion variant in (3.1) (NLO in χPT)	reason
beam dumps (see Fig.1)	$\tau_a \lesssim 10^{-13}$ s (see Fig.1)	$\tau_a < 10^{-12}$ s if $\lvert Q_e^{\mathrm{PQ}}\rvert \sim \mathcal{O}(1)$ $\tau_a \gtrsim 10^{-11}$ s if $Q_e^{\mathrm{PQ}} = 0$	$\lvert Q_e^{\mathrm{PQ}}\rvert \sim \mathcal{O}(1)$ $\tau_a \lesssim 10^{-13}$ s for $m_a \gtrsim 5-10$ MeV	MB
$\mathrm{Br}(\pi^+ \to e^+\nu(a \to e^+e^-)) \lesssim 10^{-10}$	$\lvert\theta_{a\pi}\rvert \lesssim (0.5-0.7)\times 10^{-4}$	$\lvert\theta_{a\pi}\rvert \sim \mathcal{O}(0.01-0.1)\left(\frac{\mathrm{GeV}}{f_a}\right)$	$\theta_{a\pi} \sim (0.2 \pm 3)\times 10^{-3}\left(\frac{\mathrm{GeV}}{f_a}\right)$	PP, NLO
$\Delta\mathrm{Br}(\pi^0 \to e^+e^-) \lesssim 2\times 10^{-8}$	$Q_e^{\mathrm{PQ}} \times \theta_{a\pi} \lesssim 1.6\times 10^{-4}\left(\frac{f_a}{\mathrm{GeV}}\right)$			
$\mathrm{Br}(K^+ \to \pi^+(a \to e^+e^-)) \lesssim 10^{-5}-10^{-6}$	$\lvert\theta_{a\eta_{ud}}\rvert \lesssim 10^{-4}$ if octet enhanced $\lvert\theta_{a\eta_{ud}}\rvert \lesssim 10^{-2}$ if not	$\lvert\theta_{a\eta_{ud}}\rvert \sim \mathcal{O}(10^{-3}-10^{-2})\left(\frac{\mathrm{GeV}}{f_a}\right)$	$\theta_{a\eta_{ud}} \sim (-2 \pm 8)\times 10^{-3}\left(\frac{\mathrm{GeV}}{f_a}\right)$	NLO
$\mathrm{Br}(K^+ \to \pi^+(a \to \gamma\gamma)) \lesssim 10^{-9}$ $\mathrm{Br}(\Phi \to \gamma(a \to e^+e^-)) \lesssim 5\times 10^{-5}$	$\lvert\theta_{a\eta_s}\rvert \lesssim \mathcal{O}(10^{-1})$	$\lvert\theta_{a\eta_s}\rvert \sim \mathcal{O}(10^{-2})\left(\frac{\mathrm{GeV}}{f_a}\right)$	$\theta_{a\eta_s} \sim (1 \pm 2)\times 10^{-2}\left(\frac{\mathrm{GeV}}{f_a}\right)$	NLO
$\mathrm{Br}(K^+ \to \pi^+(a \to \mathrm{inv})) \lesssim 0.5\times 10^{-10}$	$\mathrm{Br}(a \to \mathrm{inv}) \lesssim \mathcal{O}(10^{-4})$ (assuming $\tau_a < 10^{-12}$ s)	$\mathrm{Br}(a \to \nu\bar{\nu}) \sim (Q_\nu^{\mathrm{PQ}} m_\nu / Q_e^{\mathrm{PQ}} m_e)^2$	$\mathrm{Br}(a \to \chi\bar{\chi}) \sim (Q_\chi^{\mathrm{PQ}} m_\chi / Q_e^{\mathrm{PQ}} m_e)^2$ $\chi = \nu_{(e,\mu,\tau,s)}$, sub-MeV DM, ...	MB

Alves, Weiner, 1710.03764, JHEP 07(2018)092

The pionphobic axion and Atomki experiment

- Old solution: pion-phobic axion (not elegant but can work)

$$\theta_{a\pi} \simeq \frac{(Q_d m_d - Q_u m_u)}{(m_u + m_d)} \frac{f_\pi}{f_a} \quad \Rightarrow \theta_{a\pi} \lesssim 10^{-4}$$

$$m_u/m_d \simeq 0.47 \pm 0.06, \ \& \ Q_u \simeq 2Q_d$$

- Atomki anomaly see bumpy feature from $^8\mathrm{Be}*$ and $^4\mathrm{He}*$ decays

$$^8\mathrm{Be}^*(17.64) \ \to \ ^8\mathrm{Be}(0) + e^+e^- \ , \quad \Delta E = 17.64 \text{ MeV}, \quad \Delta I \approx 1 \, ,$$

$$^8\mathrm{Be}^*(18.15) \ \to \ ^8\mathrm{Be}(0) + e^+e^- \ , \quad \Delta E = 18.15 \text{ MeV} \ , \quad \Delta I \approx 0 \, .$$

$$(\mathrm{E0}) \quad ^4\mathrm{He}^*(20.49) \to \ ^4\mathrm{He}(0) + (\gamma^* \to e^+e^-) \, , \quad \Delta E = 20.49 \text{ MeV} \, , \quad \Delta I = 0 \, ,$$

$$(\mathrm{M0}) \quad ^4\mathrm{He}^*(21.01) \to \ ^4\mathrm{He}(0) + (a \ \to e^+e^-) \, , \quad \Delta E = 21.01 \text{ MeV} \, , \quad \Delta I = 0 \, ,$$

- It might be connect to 17MeV pion-phobic axion which couples to electrons.

Alves, 2009.05578, PRD 103(2021)5, 055018

The UV model building

- The visible axion receives stringent constraint, but pion-phobic axion can be safe
- It has to couple to 1st gen fermions with $Q_u = 2Q_d$
- Atomki experiments and electron g-2 can be explained if axion couples to electron
- The requirements of 1st gen quarks coupling, CKM matrix and quark mass generation are non-trivial: fully determines the UV Yukawa
- SM Higgs can decay to axion pair, resulting lepton-jet features

JL, N. McGinnis, C. E.M. Wagner, X.P. Wang 2102.10118 [JHEP]

The UV model building

- Pion-phobic QCD axion with coupling to electron

$$\mathscr{L}_{int} = \sum_{f=e,u,d,} m_f e^{iQ_f a/f_a} \bar{f}_L f_R + h.c. \approx \sum_f g_a^f i a \bar{f} \gamma_5 f, \quad g_a^f = \frac{Q_f m_f}{f_a}.$$

$$g_a^{\gamma\gamma} = \frac{\alpha}{4\pi f_\pi}\left(\theta_{a\pi} + \frac{5}{3}\theta_{a\eta_{ud}} + \frac{\sqrt{2}}{3}\theta_{a\eta_s}\right),$$

- The goal: couples to 1st gen fermions, CKM matrix and quark mass generation

$$\mathscr{L}_{\rm PQ}^{\rm Yuk} \supset -\sum_{i=1,2,3} \left(\bar{Q}^i Y_u^{i1} H_u u_R^1 + \bar{Q}^i Y_d^{i1} H_d d_R^1 + \bar{L}^i Y_e^{i1} H_e e_R^1\right) + h.c.$$

$$\mathscr{L}_{\rm SM}^{\rm Yuk} \supset -\sum_{i=1,2,3}\sum_{j=2,3} \left(\bar{Q}^i Y_u^{ij} \tilde{H} u_R^j + \bar{Q}^i Y_d^{ij} H d_R^j + \bar{L}^i Y_e^{ij} H e_R^j\right) + h.c.$$

Particles	H	H_u	$H_{d,e}$	u_R	d_R	e_R	ϕ_f
$SU(2)_L$	2	2	2	1	1	1	1
$U(1)_Y$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{2}{3}$	$-\frac{1}{3}$	-1	0
$U(1)_{\rm PQ}$	0	$-Q_u$	$-Q_{d,e}$	Q_u	Q_d	Q_e	$-Q_f$

$Q_u = 2,\ Q_d = 1;\ Q_e = 1/2$ or $1/3$

Quark mass and CKM matrix

- Up and Down quark mass diagonalization ($V_R = 1$)

$$M_u \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} Y_u^{11} v_u & Y_u^{12} v & Y_u^{13} v \\ Y_u^{21} v_u & Y_u^{22} v & Y_u^{23} v \\ Y_u^{31} v_u & Y_u^{32} v & Y_u^{33} v \end{pmatrix} = V_{u_L} \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} V_{u_R}^\dagger \qquad V_{\rm CKM} = V_{u_L}^\dagger V_{d_L} .$$

- The specific Higgs H_u couples to 1st gen up-quark only

$$\bar{Q}^i Y_u^{i1} H_u u_R^1 = \overline{Q^m}^i \left(V_{u_L}^\dagger\right)^{ij} Y_u^{j1} H_u u_R^{1,m} = \sqrt{2}\frac{m_u}{v_u} \overline{Q^m}^1 H_u u_R^{1,m}, \qquad \Rightarrow \left(V_{u_L}^\dagger\right)^{ij} Y_u^{j1} = \sqrt{2}\frac{m_u}{v_u}(1,0,0)^T .$$

- The unitary matrix can be decomposed into

$$V_{u_L}^\dagger = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_x & s_x \\ 0 & -s_x & c_x \end{pmatrix} \begin{pmatrix} (Y_u^{j1})_\parallel^T \\ (Y_u^{j1})_{\perp 1}^T \\ (Y_u^{j1})_{\perp 2}^T \end{pmatrix} \qquad Y_u^{j1} = \sqrt{2}\frac{m_u}{v_u} \begin{pmatrix} c_{13} \\ 0 \\ s_{13} \end{pmatrix} \qquad x = \theta_{23}$$

- The Yukawa coupling is fully fixed by requirements: CKM and 1st gen only coupling

The axion couplings

- The scalar potential

$$V_{\rm PQ} = \left(A_u\phi_u^* H\cdot H_u + A_d\phi_d^* H^\dagger H_d + A_e\phi_e^* H^\dagger H_e + A_\phi\phi_u^*\phi_d^2 + B_\phi\phi_d^*\phi_e^n\right) + h.c.,$$

$$V_{\rm dia} = \sum_\Phi -\mu_\Phi^2\Phi^\dagger\Phi + \lambda_\Phi\left(\Phi^\dagger\Phi\right)^2,$$

- The axion as the Goldstone mode

$$\vec{G}_{\rm SM} = \frac{1}{\sqrt{v^2+v_u^2+v_d^2+v_e^2}}\left(v,\ v_u,\ v_d,\ v_e\ 0,\ 0,\ 0\right),$$

$$\vec{G}_{\rm PQ} \approx \frac{1}{\sqrt{\sum_f Q_f^2(v_f^2+v_{\phi_f}^2)}}\times \left(-\frac{\sum_f(-1)^f Q_f v_f^2}{v},\ -Q_u v_u,\ Q_d v_d,\ Q_e v_e,\ Q_u v_{\phi_u},\ Q_d v_{\phi_d},\ Q_e v_{\phi_e}\right)$$

- The axion coupling to SM

$$\sum_{f=u,d,e}\frac{m_f}{f_a}Q_f ia\bar{f}\gamma_5 f + Q_{F,\,\rm eff}^{\rm PQ}\sum_{F=\rm 2nd,3rd}\frac{m_F}{f_a}ia\bar{F}\gamma_5 F,$$

$$Q_{F,\,\rm eff}^{\rm PQ} \equiv -\frac{\sum_f(-1)^f Q_f v_f^2}{v^2}.$$

The invisible axion models

- SM particles does not directly charge under $U(1)_{\rm PQ}$

- KSVZ model:
  - Heavy vector-like quark: $Q_{L,R}$
  - Q_L and Q_R has different charge under $U(1)_{\rm PQ}$
  - A heavy complex scalar $\Phi = re^{ia}$ charge under $U(1)_{\rm PQ}$
  - Yukawa: $y\Phi\bar{Q}_L Q_R \supset \frac{yf_a}{\sqrt{2}} e^{ia/f_a}\bar{Q}_L Q_R$
  - Low energy: $\mathscr{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G}$

The invisible axion models

- Induce a complex scalar with very large vev

- KSVZ model:
  - Heavy vector-like quark: $Q_{L,R}$
  - Q_L and Q_R has different charge under $U(1)_{\rm PQ}$
  - A heavy complex scalar $\Phi = re^{ia}$ charge under $U(1)_{\rm PQ}$
  - Yukawa: $y\Phi \bar{Q}_L Q_R \supset \frac{yf_a}{\sqrt{2}} e^{ia/f_a} \bar{Q}_L Q_R$
  - Low energy: $\mathscr{L} \supset \frac{g_s^2}{32\pi^2} \frac{a}{f_a} G\tilde{G}$

- DFSZ model:
  - Two Higgs doublet $H_{u,d}$ and a complex singlet Φ charged under $U(1)_{\rm PQ}$, with phase factor $e^{i\phi_{u,d,0}}$
  - Similar to previous UV model, but $\langle \Phi \rangle \gg v_h$
  - Yukawa: $\left(\bar{Q} Y_u H_u u_R + \bar{Q} Y_d H_d d_R + \bar{L} Y_e H_d e_R\right) + h.c.$
  - Potential term: e.g. $H_u H_d \Phi^2$,
  - Axion mode: $a = \frac{1}{f_a} \sum_{i=u,d,0} Q_i v_i \phi_i$
  - Low energy: $\mathscr{L} \supset \frac{\alpha_s}{8\pi^2} \frac{a}{f_a} G\tilde{G} + \frac{\alpha_{em}}{8\pi} \frac{E}{N} \frac{a}{f_a} F\tilde{F} - \bar{f}_L M_f f_R + \frac{\partial_\mu a}{2f_a} \bar{f} c_f \gamma^\mu \gamma_5 f$

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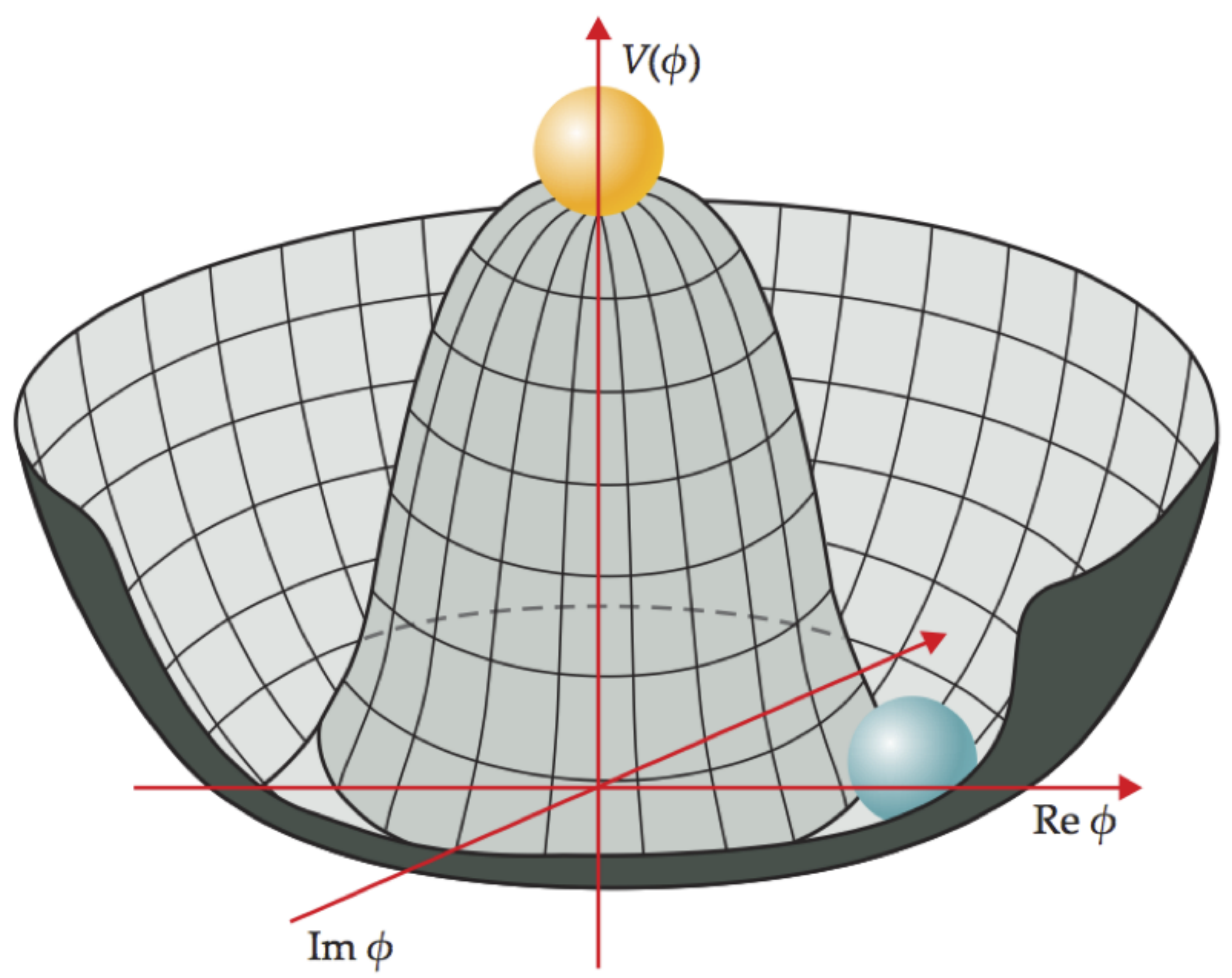
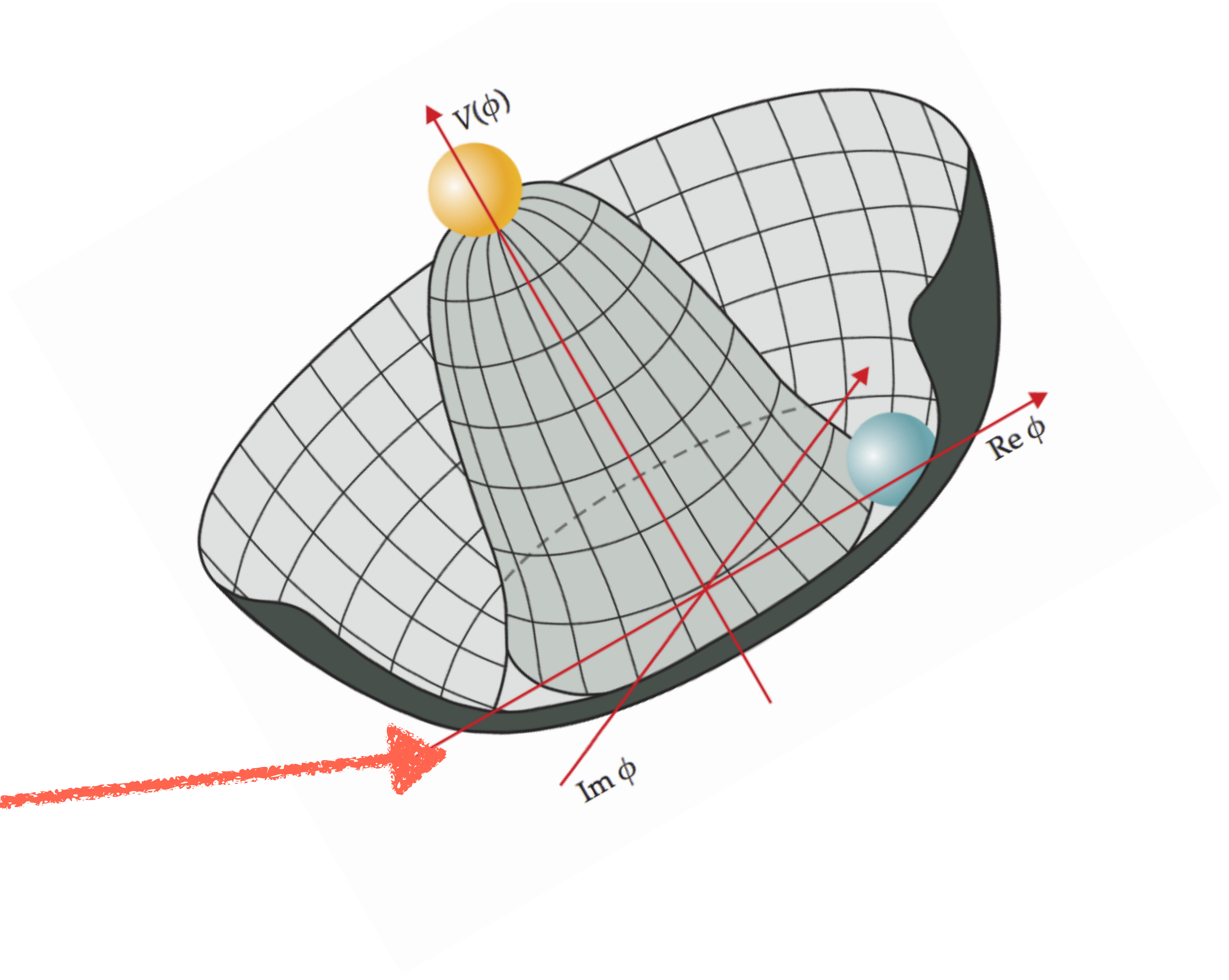
Misalignment and Axion Dark Matter

- Global U(1)$_{PQ}$ symmetry
  - Spontaneous broken leads to massless goldstone (Axion)

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$



- At QCD scale ~ O(1) GeV,
  - Potential from Chiral Lagrangian explicitly breaks the symmetry leads to massive axion
  - Energy stored in coherent oscillation of axion field
  - When $m_\phi \sim \frac{\Lambda^2}{f_\phi} \sim H$, misalignment happens and the fields turns into particles: cold dark matter
  - QCD vacuum picks $\Theta = \theta_{\text{QCD}} + \xi\langle a \rangle / f_a = 0$



Experimental searches for Axion-Like Particles axion

$$\mathcal{L}_{\mathrm{ALP}} = g_{ag}\frac{a}{f_a}G\tilde{G} + g_{a\gamma}\frac{a}{f_a}F\tilde{F} + g_{af}\frac{\partial_\mu a}{2f_a}\bar{f}\gamma^\mu\gamma_5 f$$

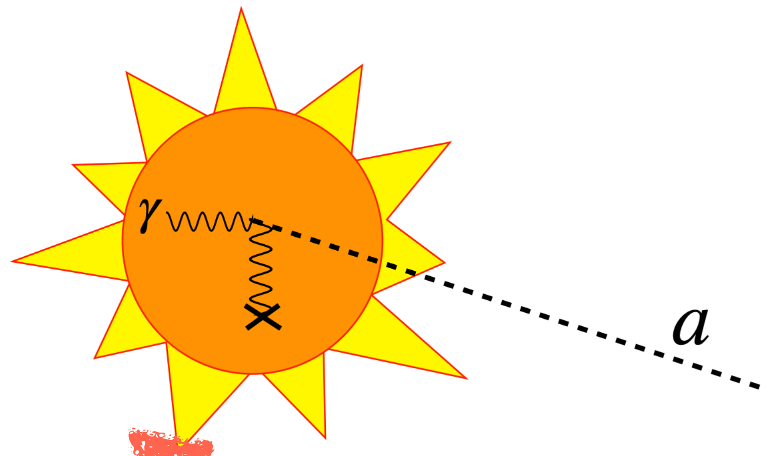
- Sources of ALP:
  - Astrophysical objects: Sun, Horizontal Branch, Neutron Star, SuperNova etc…
  - ALP dark matter from misalignment
  - ALP produced inside laboratory: laser conversion, beam dump, ee collider, pp collider
  - ALP as force mediator

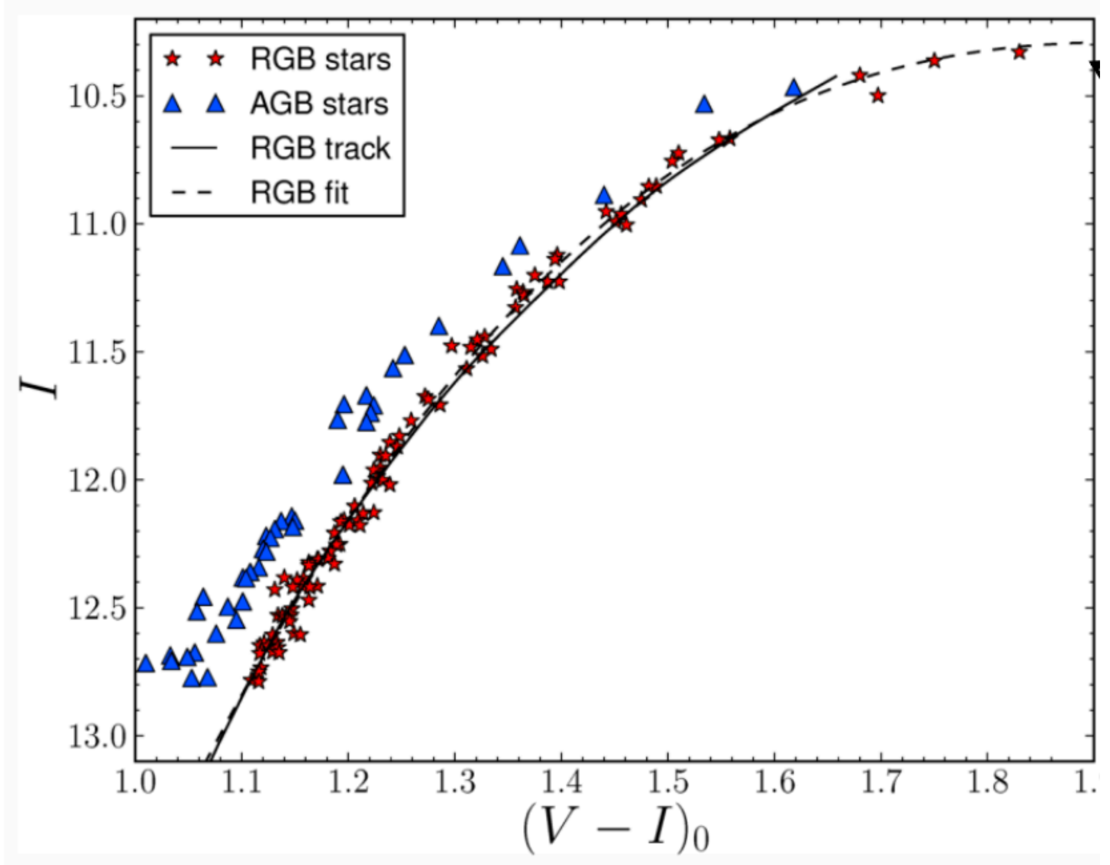
See the axion session 1 and 2 today!

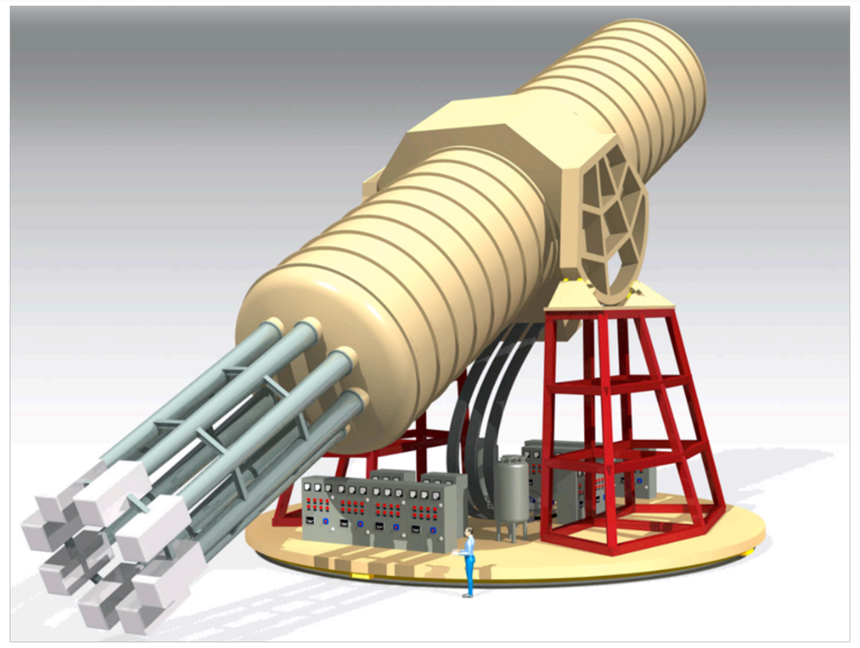
Experimental searches for Axion-Like Particles axion

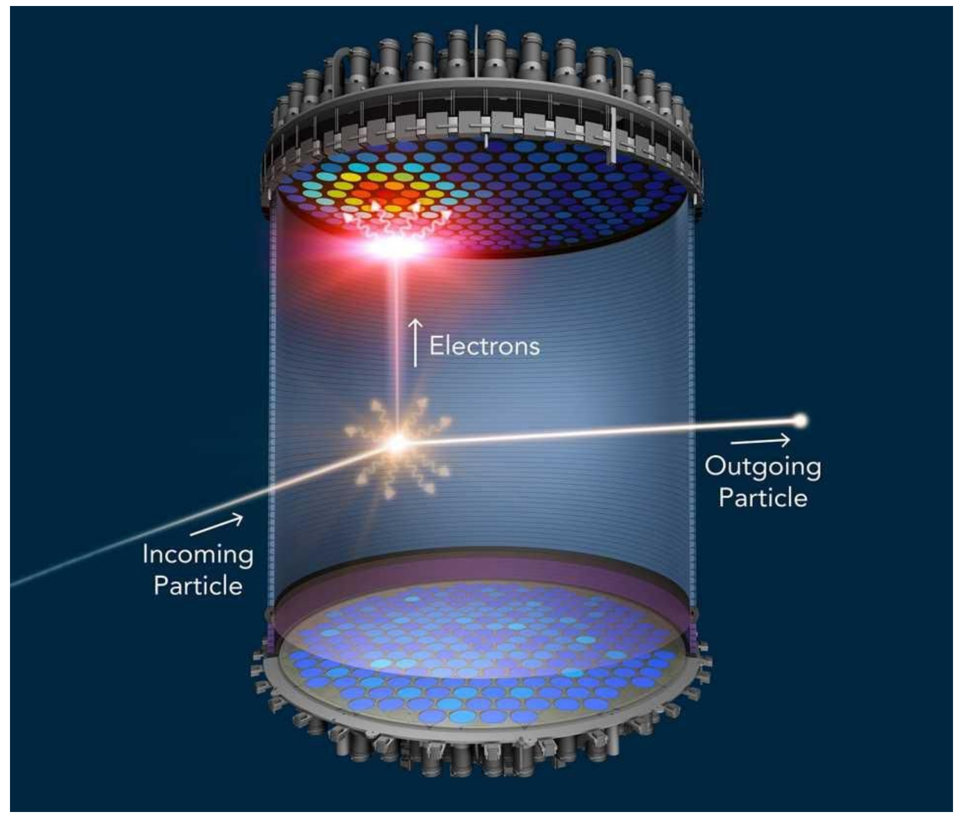
Methodology:

- Dark Matter Axion: haloscopes ..
- Axion independent searches:
  - Rare meson decays
  - Stellar cooling
  - Supernova
  - Helioscopes: solar axion (CAST, IAXO, or DM direct detection searches)
  - Light shining through walls
  - Polarization
  - Fifth force
  - Radio wave detection







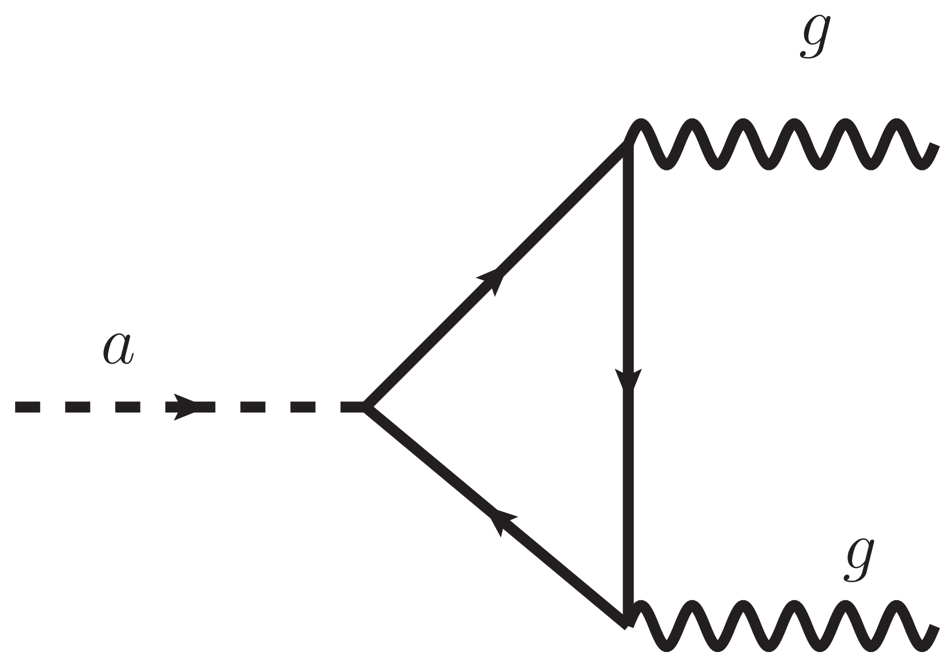


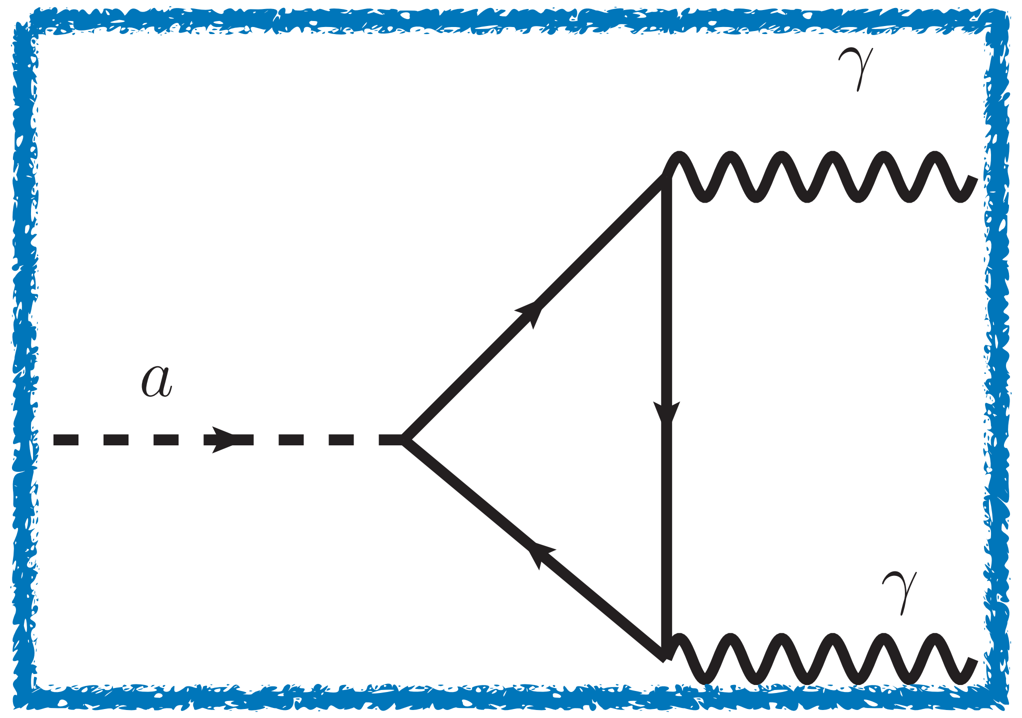
Experimental searches for Axion-Like Particles axion

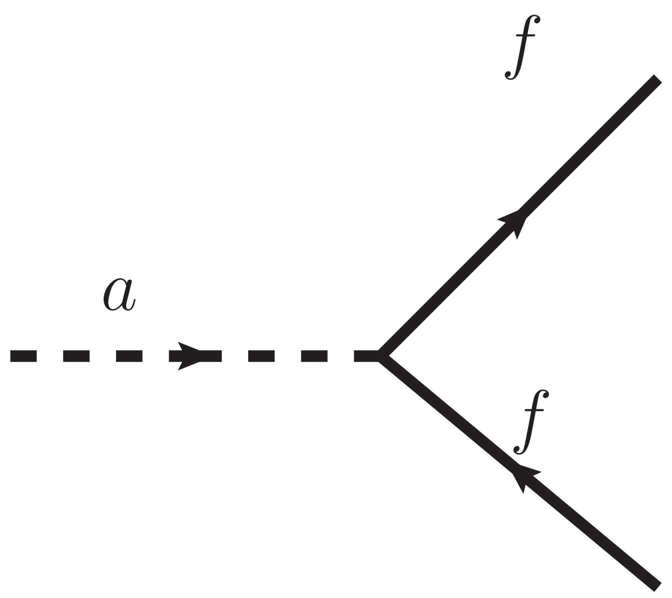
$$\mathscr{L}_{\text{ALP}} = g_{ag}\frac{a}{f_a}G\tilde{G} + g_{a\gamma}\frac{a}{f_a}F\tilde{F} + g_{af}\frac{\partial_\mu a}{2f_a}\bar{f}\gamma^\mu\gamma_5 f$$

- ALP couplings:

$$g_{a\gamma\gamma}aF_{\mu\nu}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta} \sim g_{a\gamma\gamma}a\vec{E}\cdot\vec{B}$$

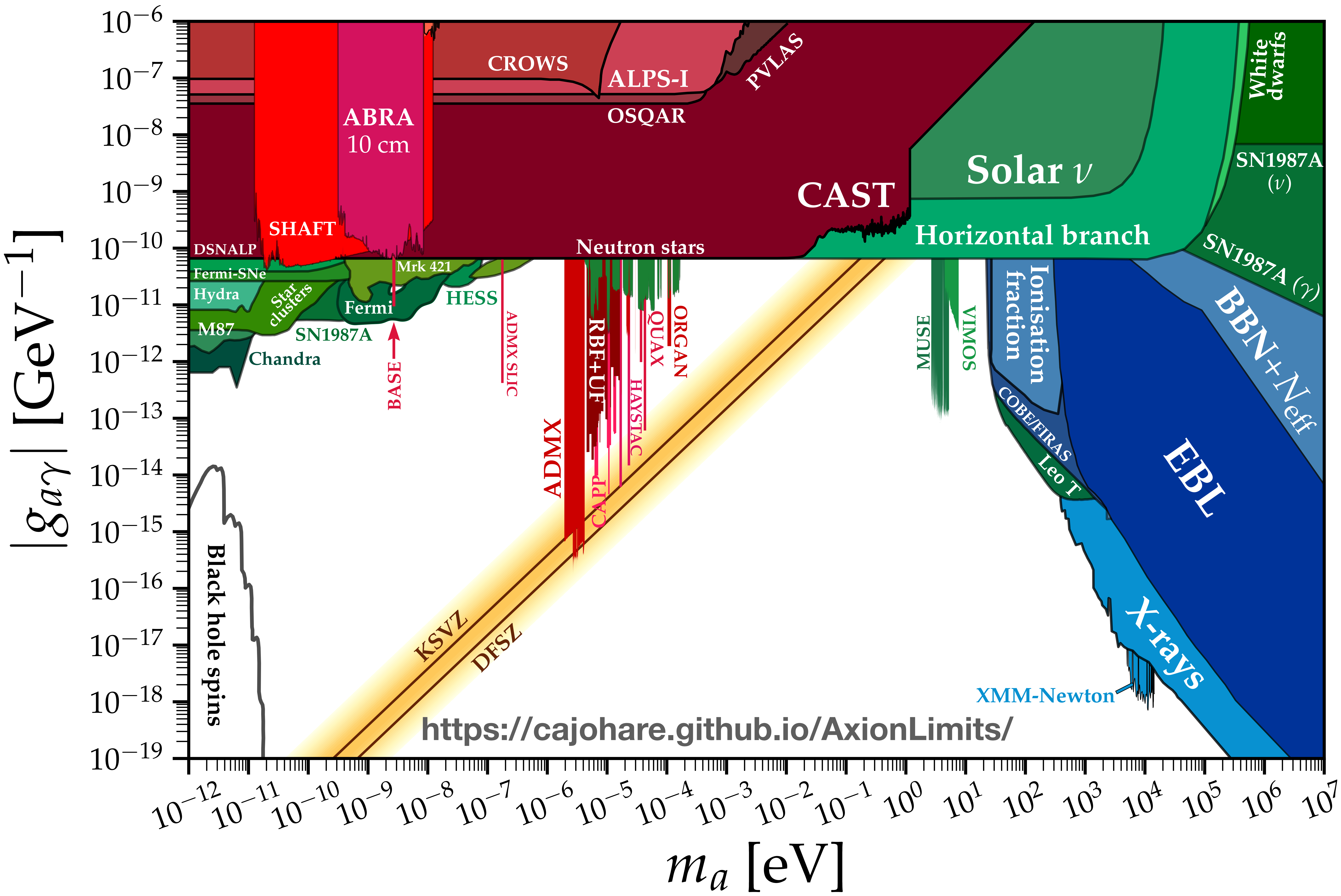




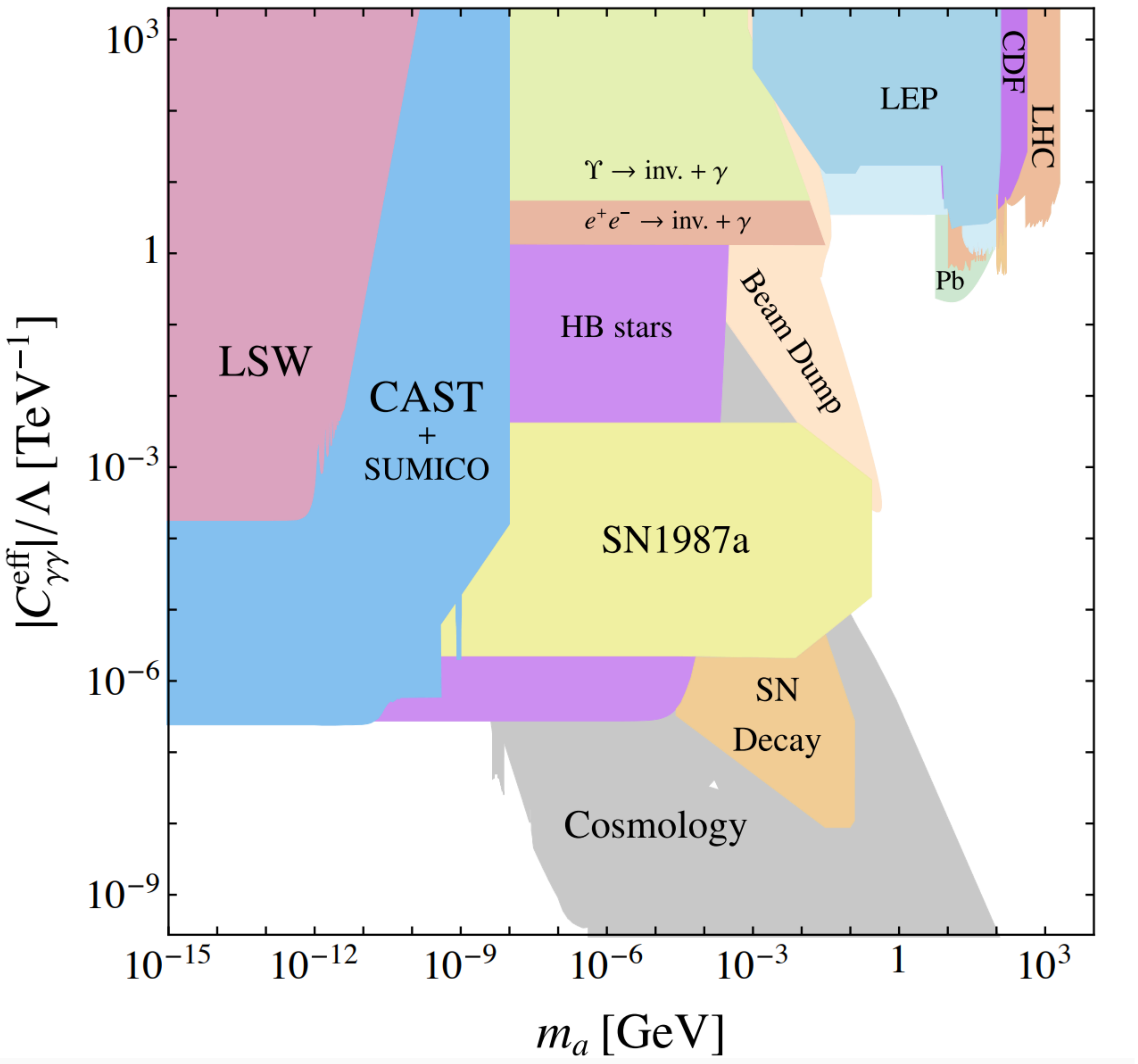


$f = q, \ell, N$

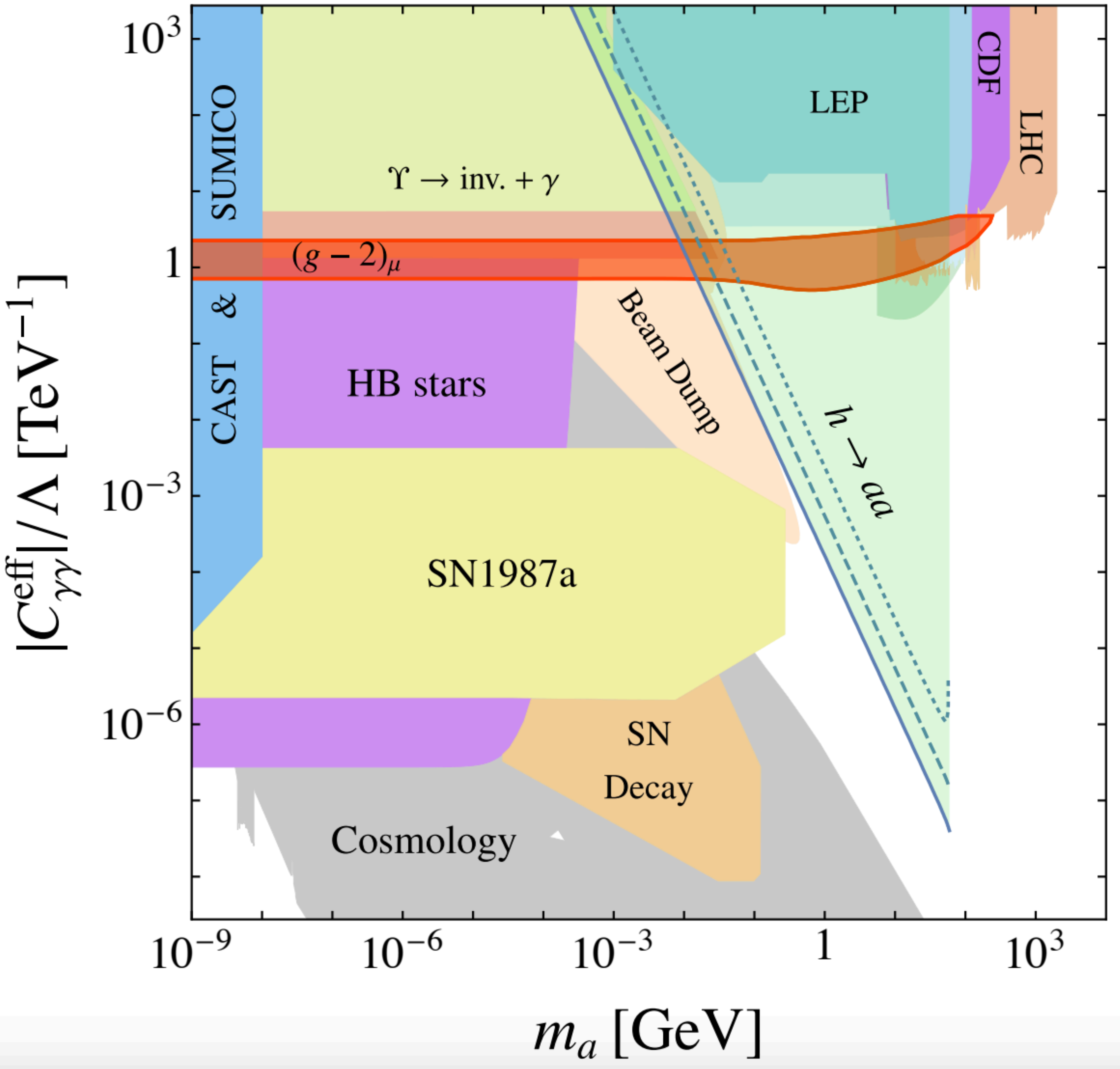
The current status for light/ultralight ALP photon couplings



The current status for heavy ALP photon couplings



Bauer, Neubert, Thamm 1708.00443 [JHEP]



Similar for $h \to Za$

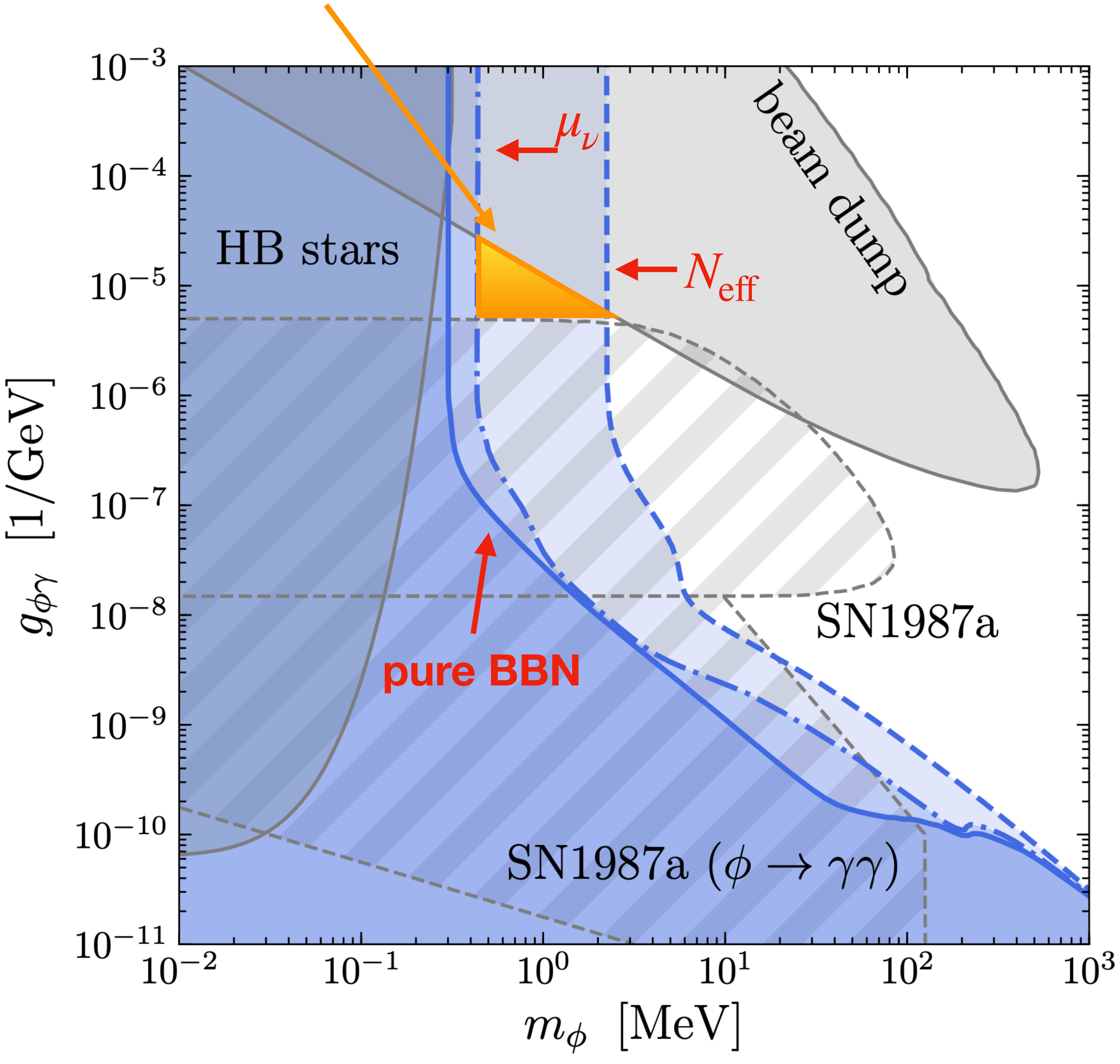
The cosmological triangle

- Referring to Axion-Like Particle searches with photon couplings, works for scalar as well

$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\tau_{\phi\gamma} = \Gamma_{\phi\gamma}^{-1} = \frac{64\pi}{m_\phi^3 g_{\phi\gamma}^2}$$

- If one allows extra cosmological setup: $\Delta N_{\rm eff}$ (e.g. dark radiation), to compensate the low T_ν
  - A triangle area is still allowed for MeV ALP, similar for dark scalar



Depta et al: 2002.08370 (JCAP)

A solution: delayed neutrino decoupling

- Solution: ϕ coupling to ν, delayed neutrino decoupling T_D
  - It forces $T_\nu = T_\gamma$ ($T_\gamma < T_D$), therefore entropy injection from e^+e^- shares in ν/γ sectors
  - Therefore, it effectively raises T_ν and compensate the $\phi \to \gamma\gamma$ entropy injection
  - The new decoupling T_D is determined by s-channel resonant interaction $\nu\nu \leftrightarrow \phi^* \leftrightarrow \gamma\gamma$

$$\frac{dn_\nu}{dt} + 3Hn_\nu = \langle \sigma v \rangle_{\rm res} \left(n_{\nu,\rm eq}^2 - n_\nu^2 \right)$$

$$R \equiv n_\nu^{\rm eq} \langle \sigma v \rangle \approx \frac{8\sqrt{2\pi}}{3\xi(3)} \Gamma_\phi {\rm BR}_{\gamma\gamma} {\rm BR}_{\nu\nu} x^{-3/2} e^{-x}$$

V.S. Hubble rate

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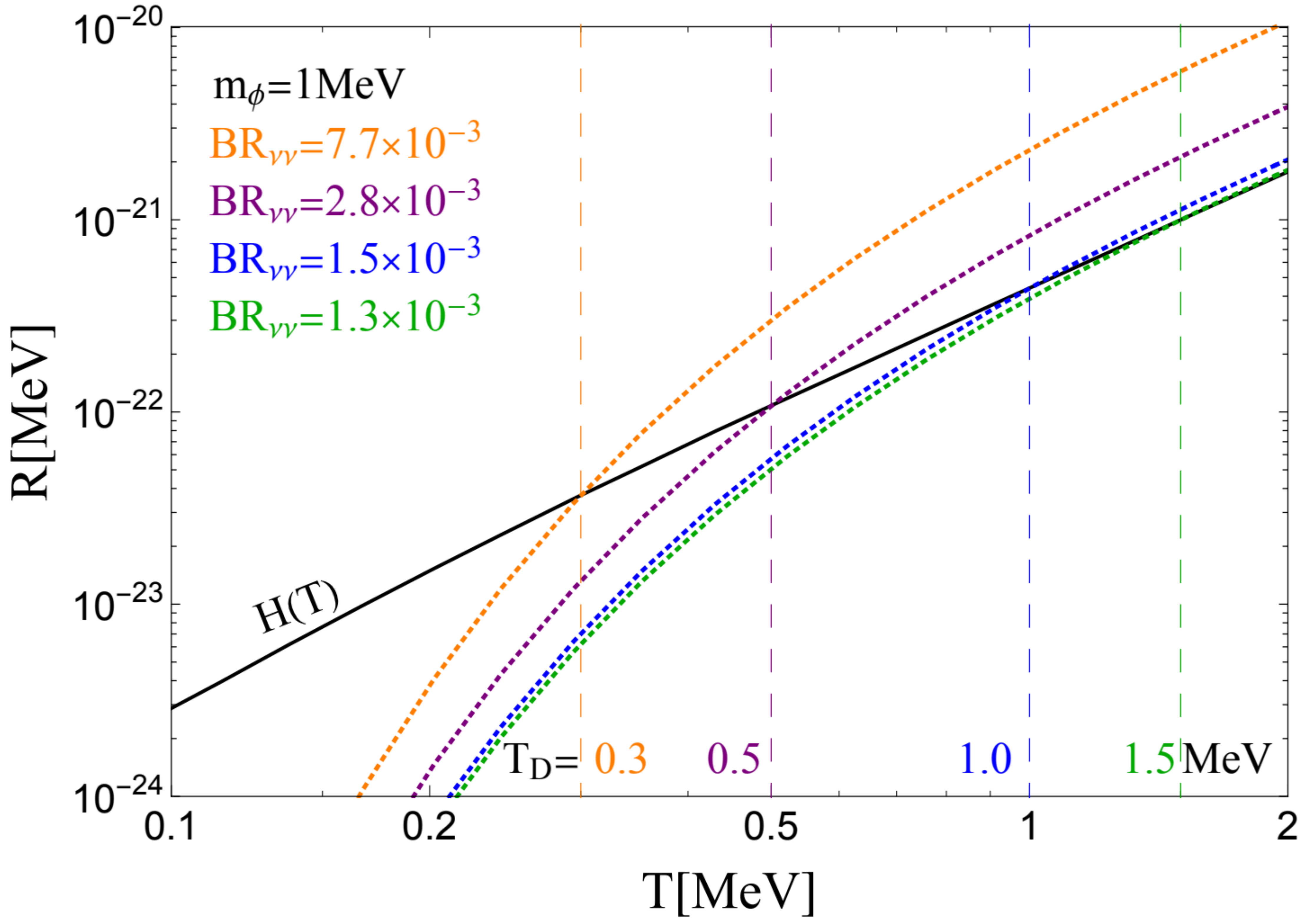
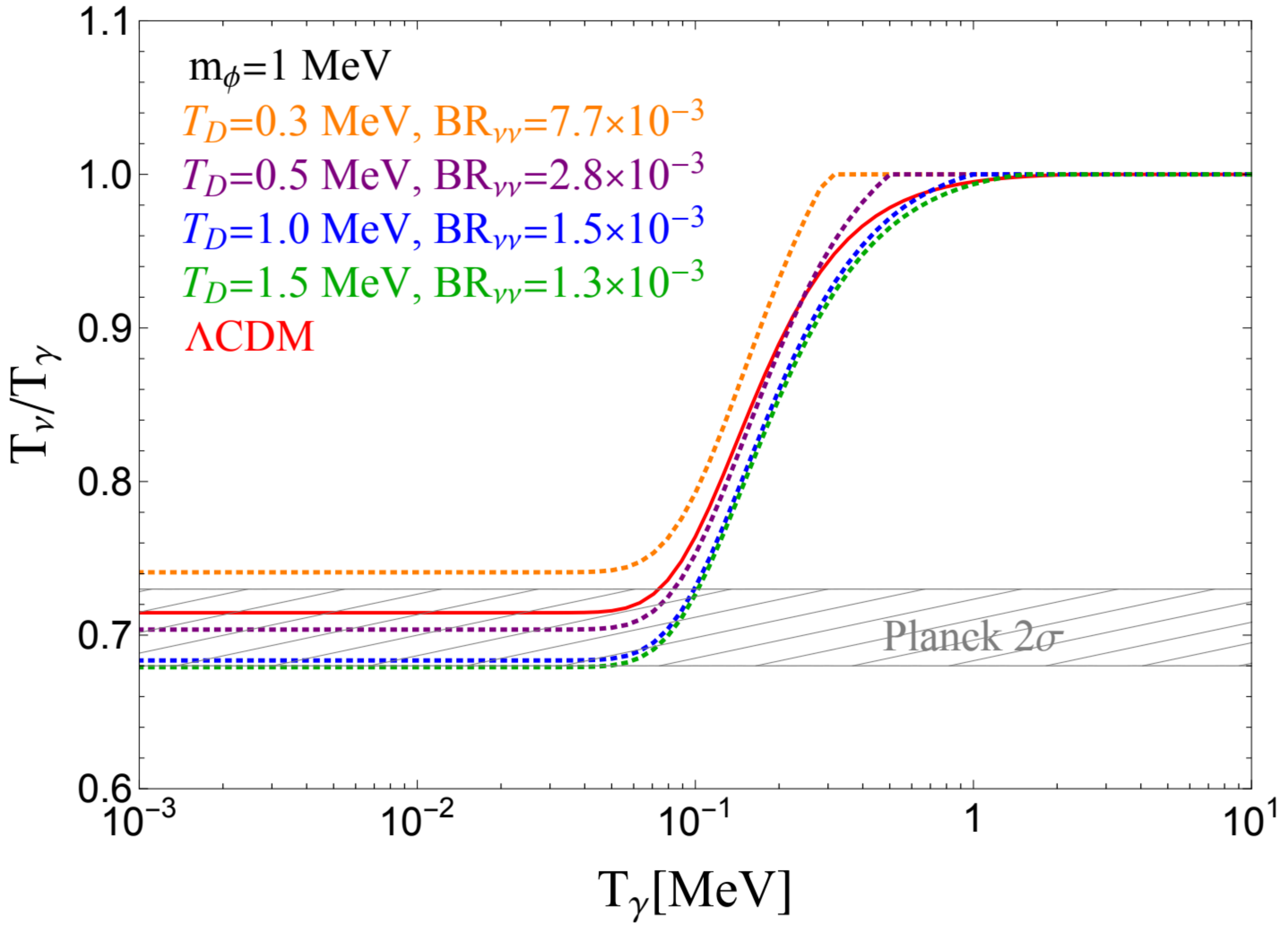
The delayed neutrino decoupling





- Solution: ϕ coupling to ν, delayed neutrino decoupling T_D
  - A small BR($\phi \to \nu\nu$) solve the cosmological triangle problem
  - We check if it also solves the neutrino mass problem

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Summary

- Axion can:
  - solve the Strong CP problem
  - provide a compelling Dark Matter candidate
  - couple to all SM particles, is a phenomenology rich model for experiments
  - ALP has even less constraints and motivates vast experiments both in broadness and depth
- My work related to saving the MeV scale axion
  - Specific pion-phobic visible axion model building
  - Re-opening the cosmological triangle via neutrino coupling

Backup slides