Colour Unified Dynamical Axion

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Univ. Autónoma de Madrid and IFT

PASCOS 2018

Case Western Reserve Univ., Cleveland

H2020

Why ?

Is the Higgs the only (fundamental?) scalar in nature?

Or simply the first one discovered?

The spin 0 window

The SM Higgs is a ~ doublet of $SU(2)_L$

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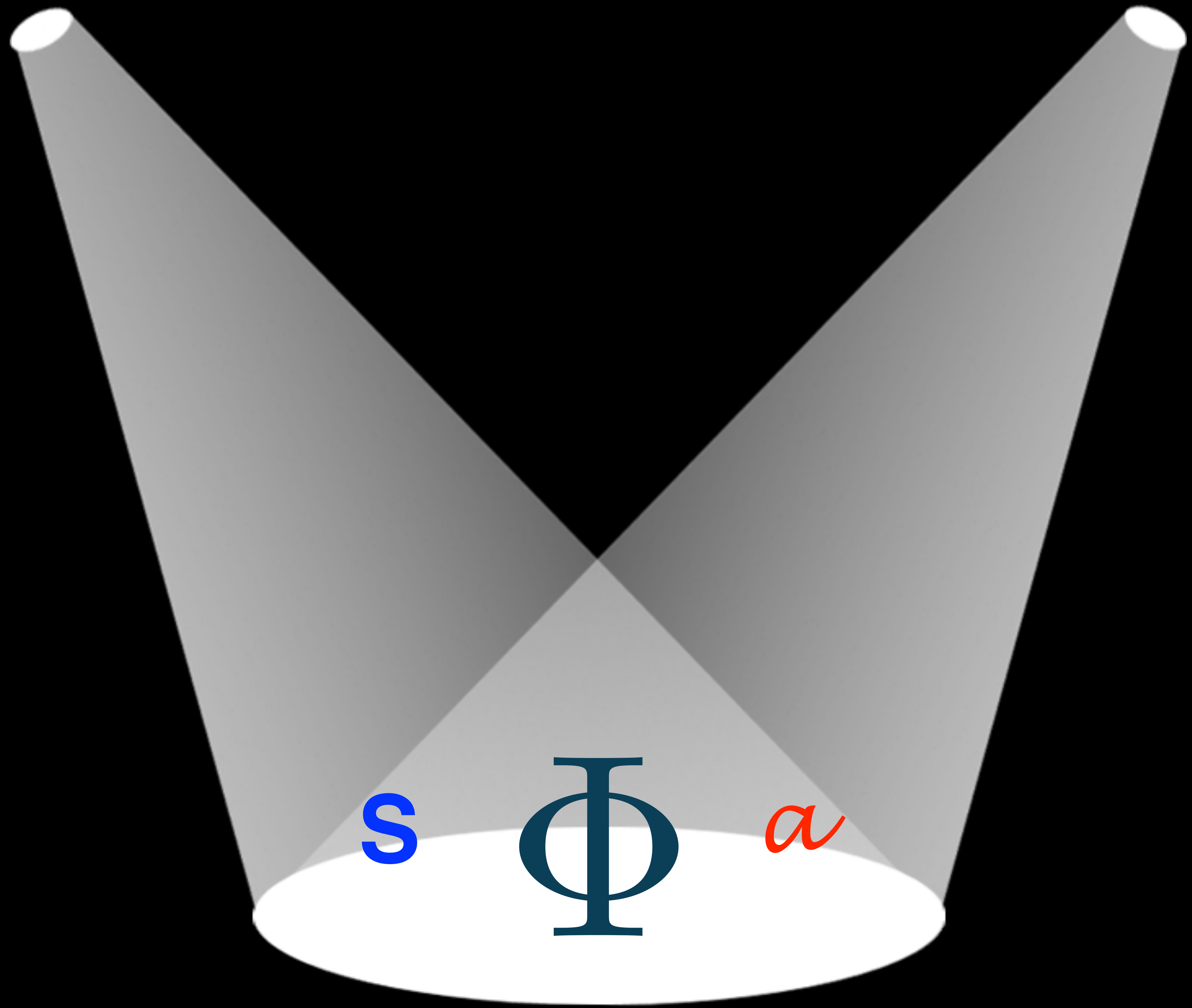
What about a singlet (pseudo) scalar?

Strong motivation from fundamental problems of the SM



Rocio del Rey

Strong motivation for singlet (pseudo)scalars from fundamental SM problems

The nature of DM is unknown

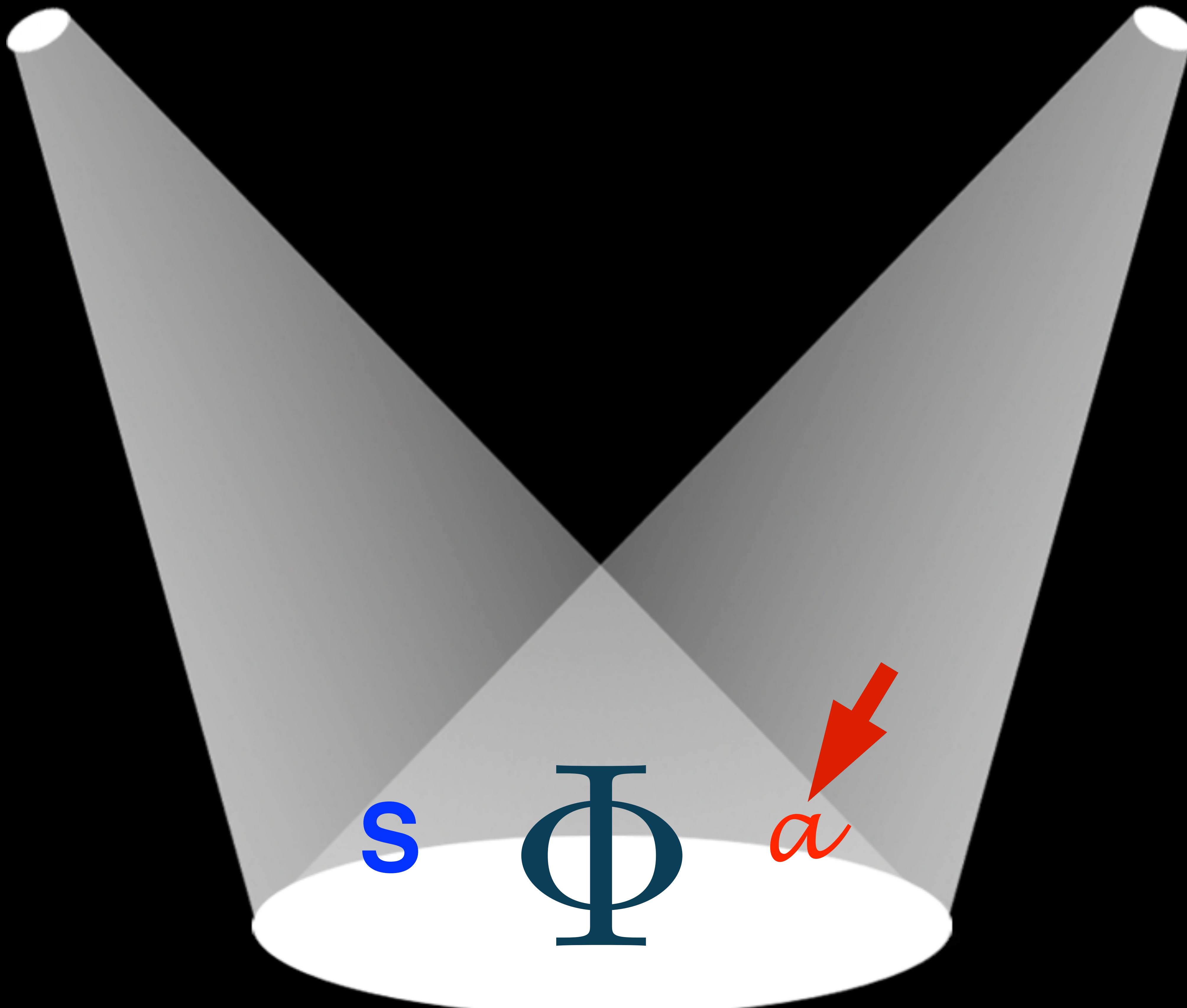
It may be a (SM singlet) scalar S

the "Higgs portal"

$$\delta\mathcal{L} = \Phi^{+}\Phi\, S^{2}$$

S has polynomial couplings

Silveira+Zee; Veltman+Yndurain; Patt+Wilczek…



Rocio del Rey

Many small unexplained SM parameters

Hidden symmetries
can explain small parameters

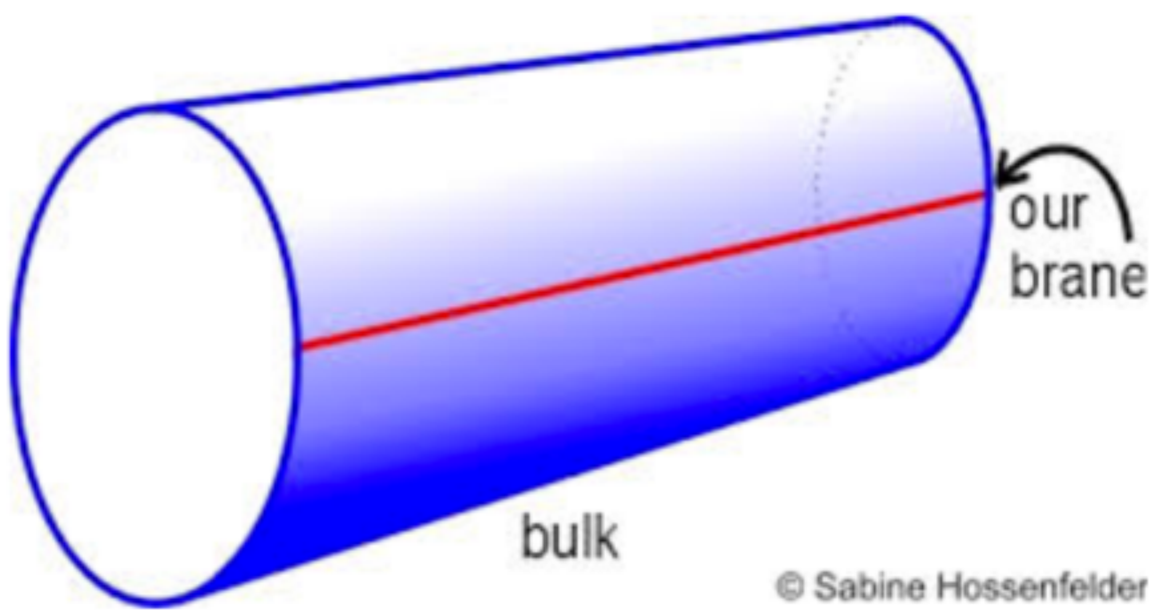
↓

If spontaneously broken:
Goldstone bosons a

—> derivative couplings to SM particles

(Pseudo)Goldstone Bosons appear in many BSM theories

* e.g. Extra-dim Kaluza-Klein: 5d gauge field compactified to 4d
 the Wilson line around the circle is a GB, which behaves as an axion in 4d



* Majorons, for dynamical neutrino masses

* From string models

* The Higgs itself may be a pGB ! ("composite Higgs" models)

* Axions a that solve the strong CP problem, and ALPs (axion-like particles)

……

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The strong CP problem

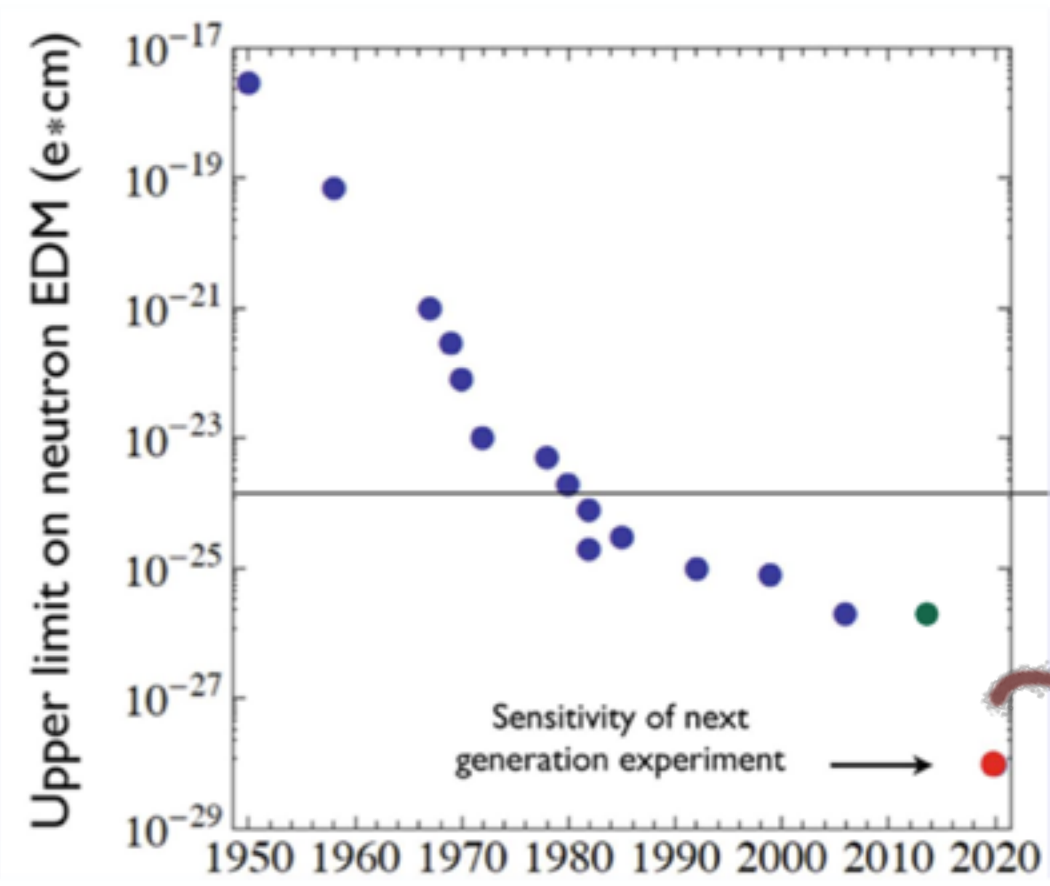
Why is the QCD **θ** parameter so small?

$$\mathcal{L}_{QCD} \supset \theta\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

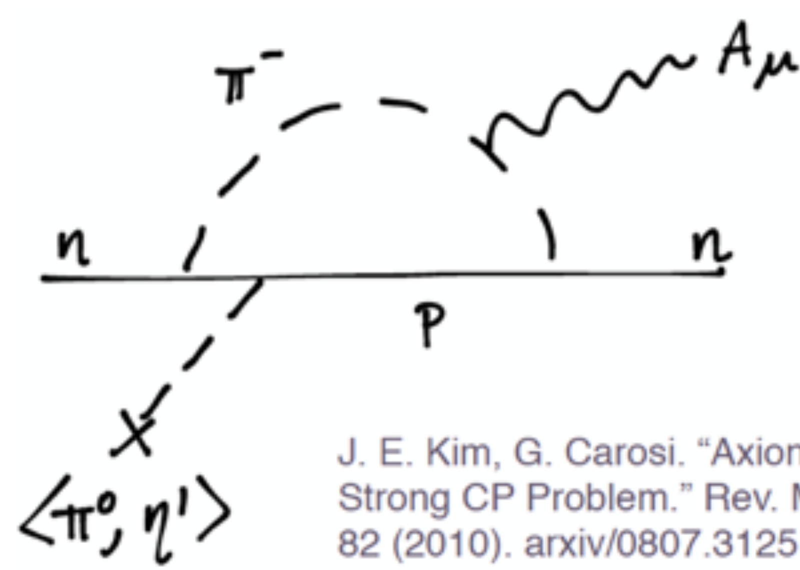
STRONG CP PROBLEM

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \frac{g^2\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \bar{q} M q$$

the only physical parameter is $\bar{\theta} = \theta + \arg\det M$



[B. Fillipone]



J. E. Kim, G. Carosi. "Axions and the Strong CP Problem." Rev. Mod. Phys. 82 (2010). arxiv/0807.3125

$$\bar{\theta} < 10^{-10}$$

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→ the axion a

It is a pGB: ~only derivative couplings

$$\partial_\mu a$$

Also excellent DM candidate

Peccei+Quinn; Wilczek…

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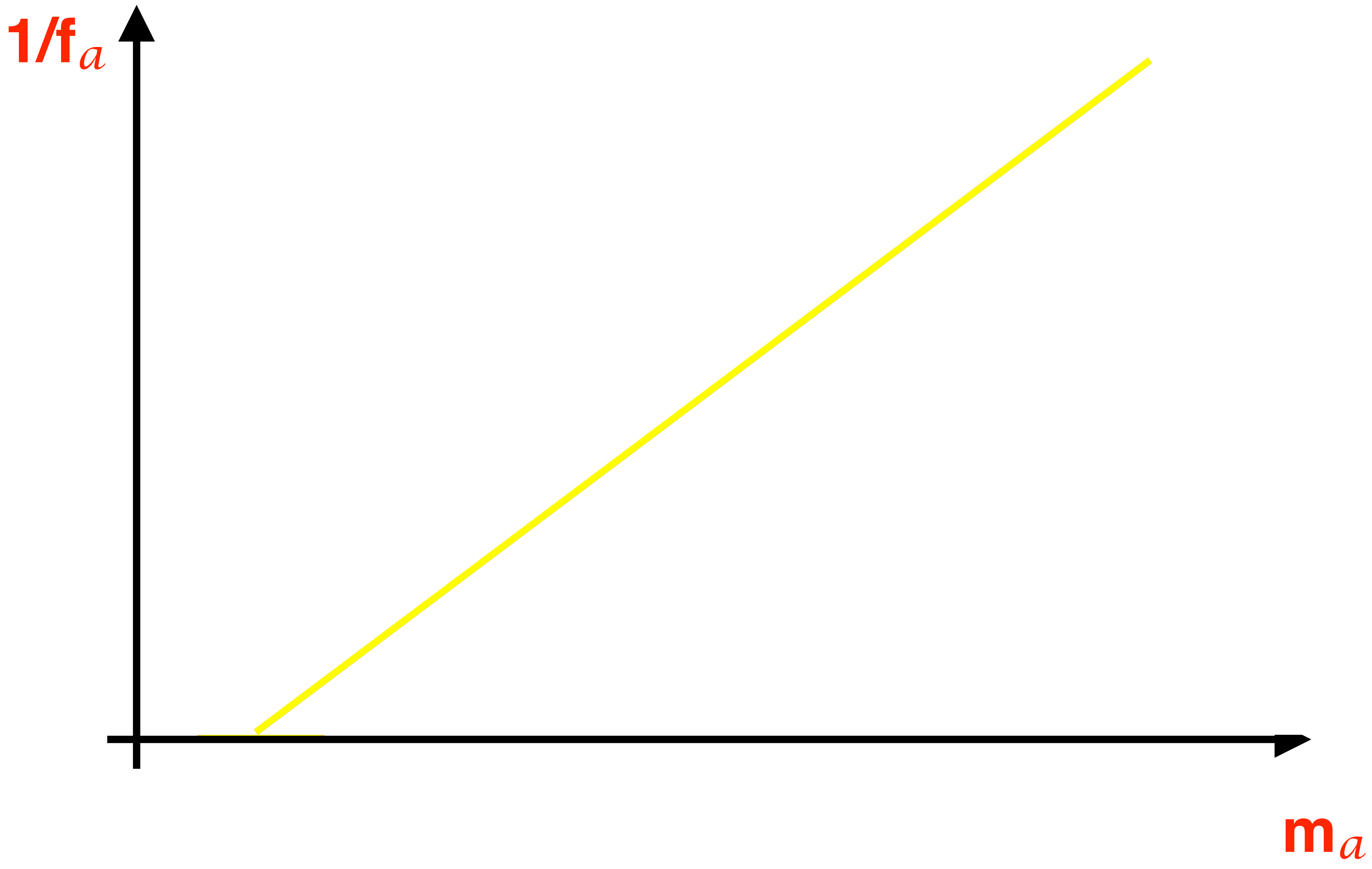
In “true axion” models (= which solve the strong CP problem):

$\mathbf{m}_a \, \mathbf{f}_a = \mathrm{cte.}$



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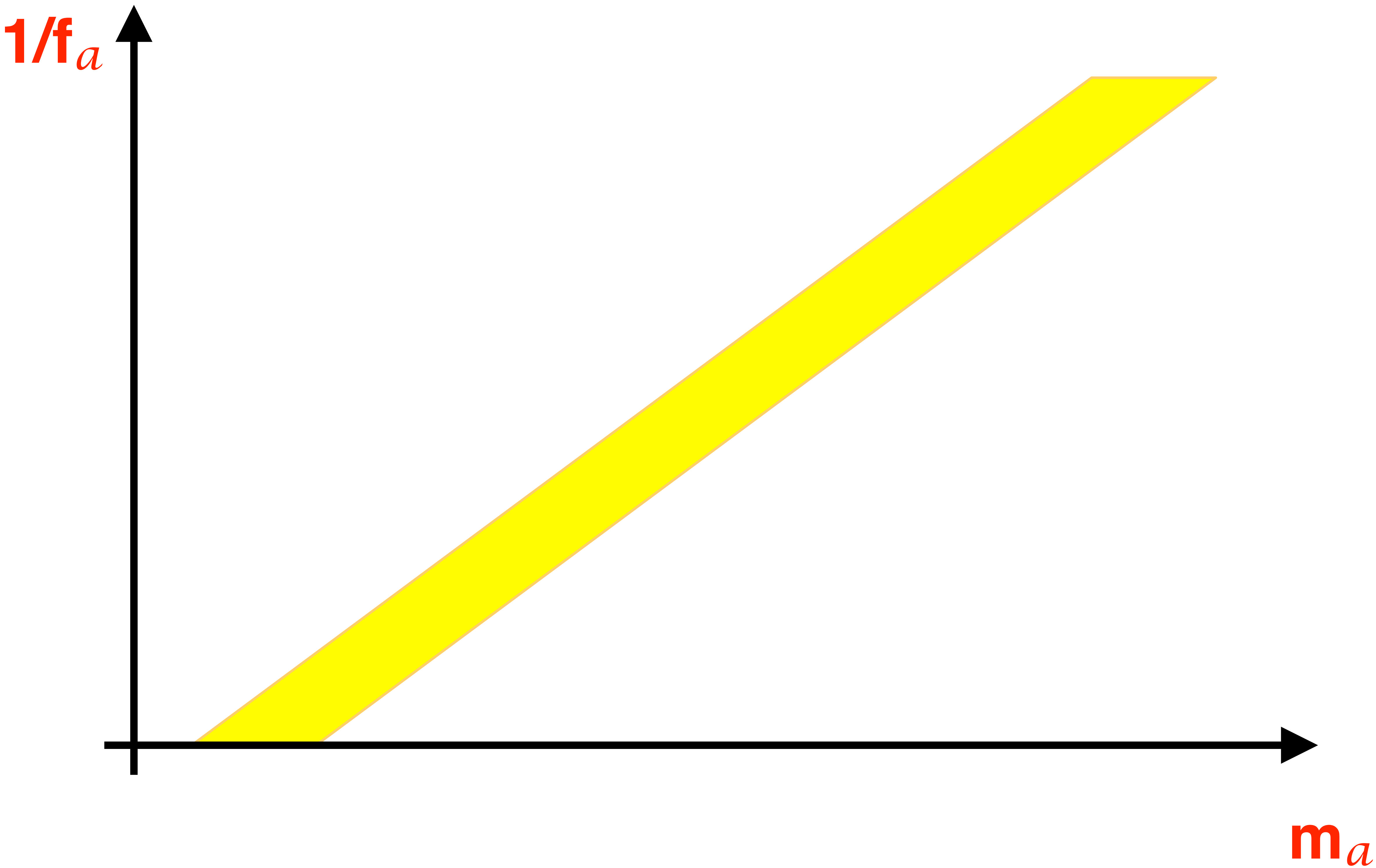

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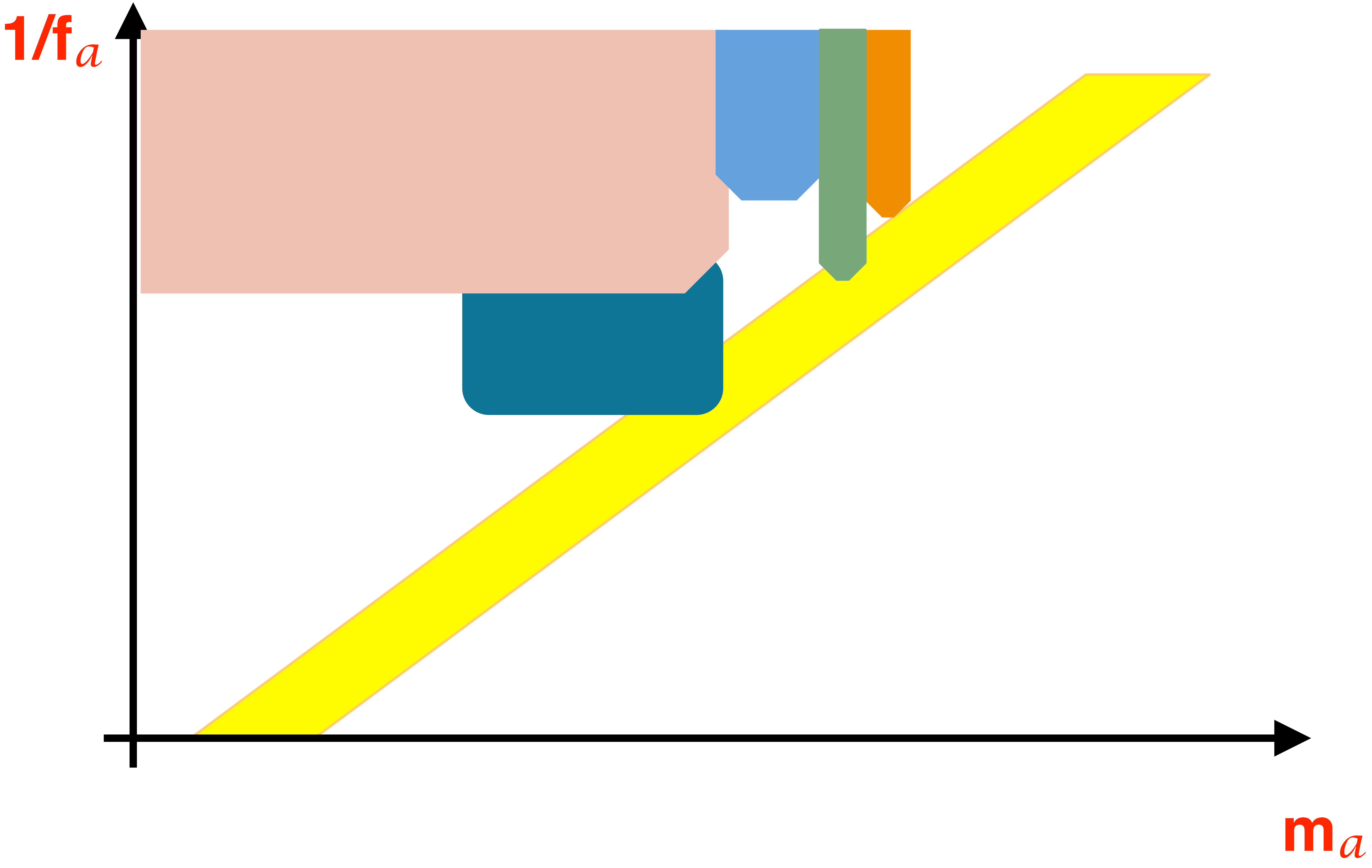

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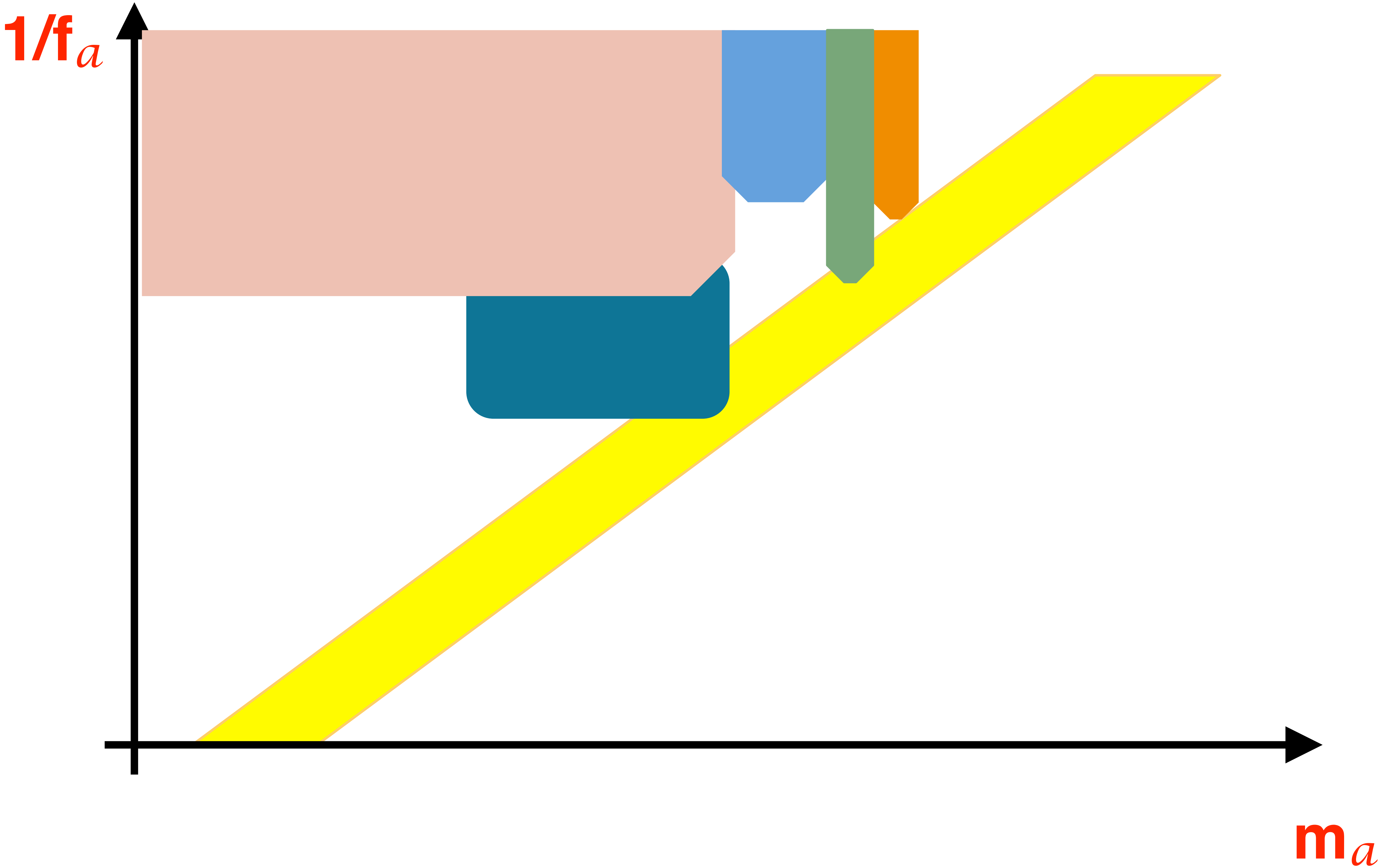

The value of the constant is determined by the strong gauge group

$\mathbf{m}_a$ vs scale $\mathbf{f}_a$

$\mathbf{g}_a \sim 1/\mathbf{f}_a$

In QCD-like theory $m_a^2 \neq 0$ because of explicit U(1)$_A$ breaking at quantum level (instantons, Λ)

$$m_a^2 f_a^2 = \frac{\Lambda^4}{1 + \Lambda^4/(2m_q < \bar{\Psi}\Psi >)}$$

$\Lambda \gg m_q$: $\quad m_q < \bar{\Psi}\Psi > \simeq m_\pi^2 f_\pi^2$ QCD

$\Lambda \ll m_q$: $\quad \Lambda^4$

Choi et al. 1986

The "invisible axion" mass versus the η'_{QCD} mass

ANY model with only the SM QCD gauge group has to obey:

$$m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2}$$

which in the limit $m_q \rightarrow 0$ vanishes

The reason is that there is only one anomalous current

$$G_c \tilde{G}_c \quad \text{(of QCD)} \quad \longleftrightarrow \quad \Lambda_{QCD}$$

for two singlet (pseudo) Golsdtone bosons coupling to it:

$$\eta'_{QCD} \qquad a$$

—> one must remain (almost) **massless**

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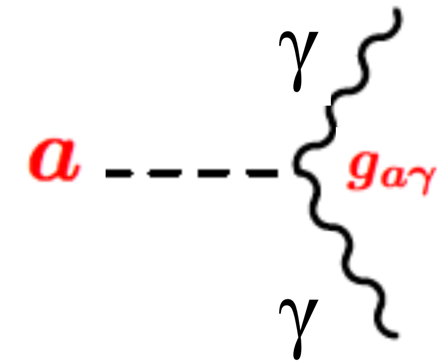
*** Models assuming SM gauge group:** $10^{-5} < m_a < 10^{-2}$ eV , $10^9 < f_a < 10^{12}$ GeV

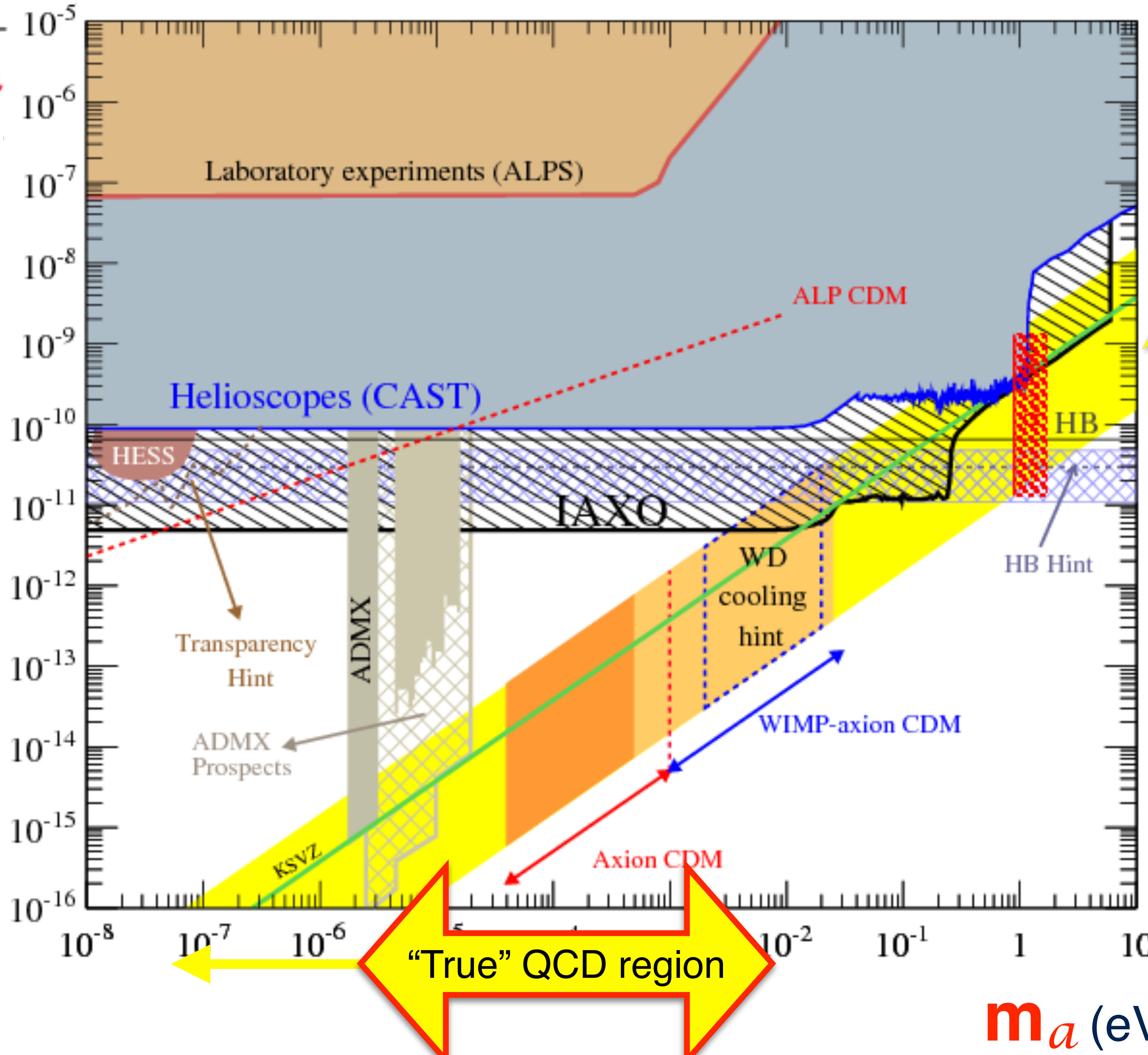
Because of SN and hadronic data, if axions light enough to be emitted (and $m_a f_a$ = **cte.**)

"Invisible axion"

Intensely looked for experimentally…



$g_{a\gamma} \sim \dfrac{\alpha}{8\pi f_a}$ (GeV^{-1})



"True" QCD axion band

=

"Invisible axion"

e.g. KSVZ, DFSZ…

v<< f_a —>

EW hierarchy problem

m_a (eV)

… and theoretically

https://arxiv.org/pdf/1611.04652.pdf

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*** Models enlarging the strong SM gauge sector, with scale Λ' ?**

Dimopoulos+Susskind 79, Tye 81…**Rubakov 97…**Berezhiani+Gianfagna+Gianotti 01… Hsu+Saninno 04…

Fukuda et a. 15…. Gherghetta+Nagata+Shifman, Chiang et al., Khobadize…

Hook and many collaborators, Dimopoulos et al. …

2017: Agrawal+Howe….

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$$m_a^2 f_a^2 = \text{QCD part} + \textbf{extra} \; ,$$

extra source of instantons $G'\tilde{G}'$

m_a vs scale f_a

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$$\Lambda^4$$

? < m_a , f_a < ?

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$$m_a^2 f_a^2 = \quad m_\pi^2 f_\pi^2 \quad + \Lambda'^4 \quad , \quad \Lambda' \gg \Lambda_{QCD}$$

relax the parameter space

Heavy axions

$m_a \neq 0$ due to explicit $U(1)_{PQ}$ breaking at QCD confinement scale Λ

$$\frac{a}{f_a} G \cdot \tilde{G} \longrightarrow m_a^2 f_a^2 = \frac{\Lambda^4}{1 + \Lambda^4/(2 m_q < \bar{\psi}\psi >)}$$

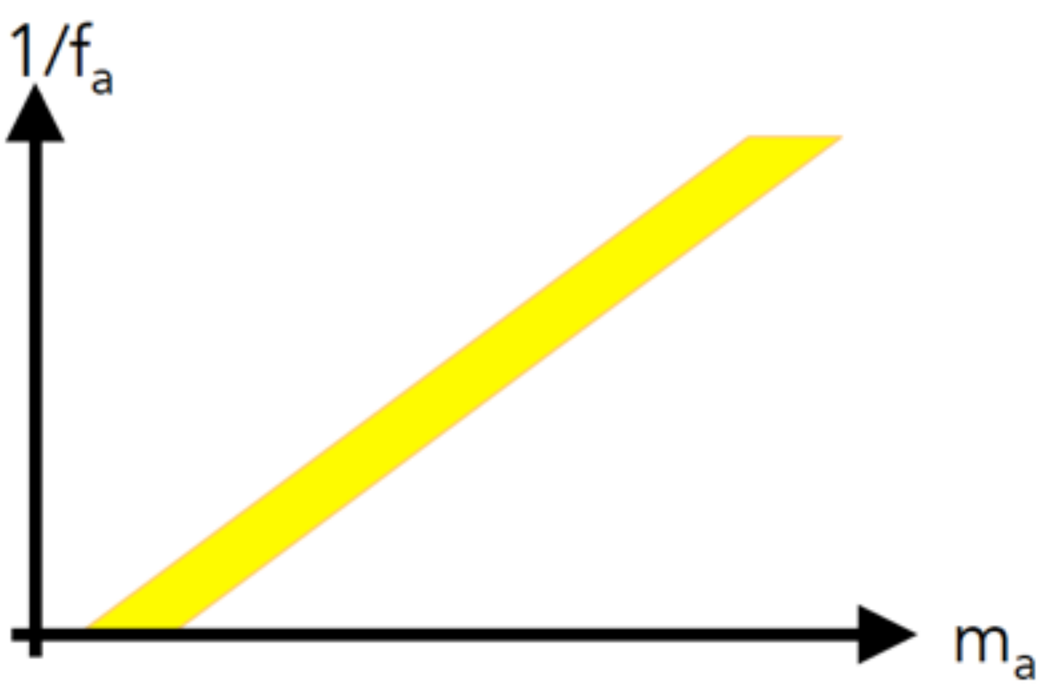
[Choi et al. 1966]

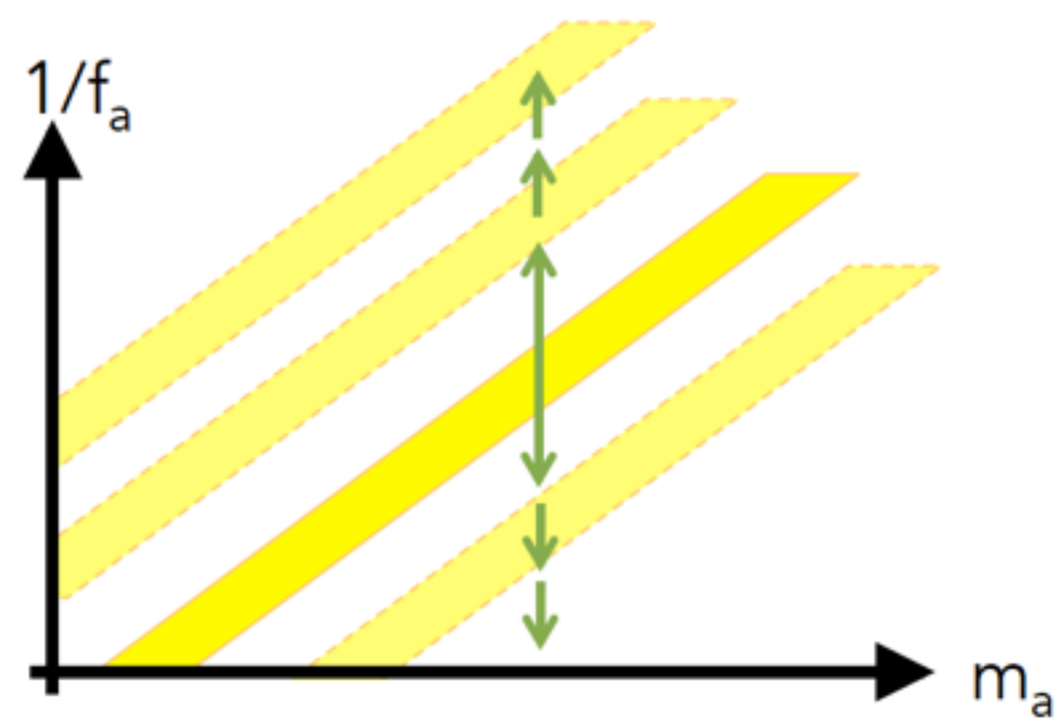
QCD: $\Lambda = \Lambda_{QCD}$

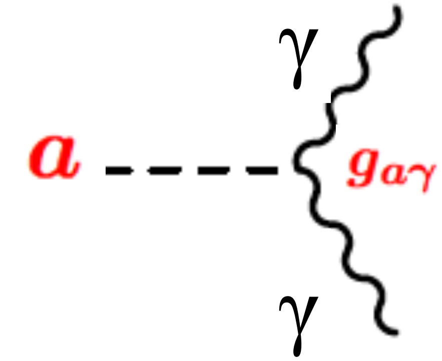
$$m_a^2 f_a^2 = m_q < \bar{\psi}\psi > \simeq m_\pi^2 f_\pi^2$$

Extra confining group:
$\Lambda = \Lambda' >> \Lambda_{QCD}$

$$m_a^2 f_a^2 \sim \Lambda'^4$$







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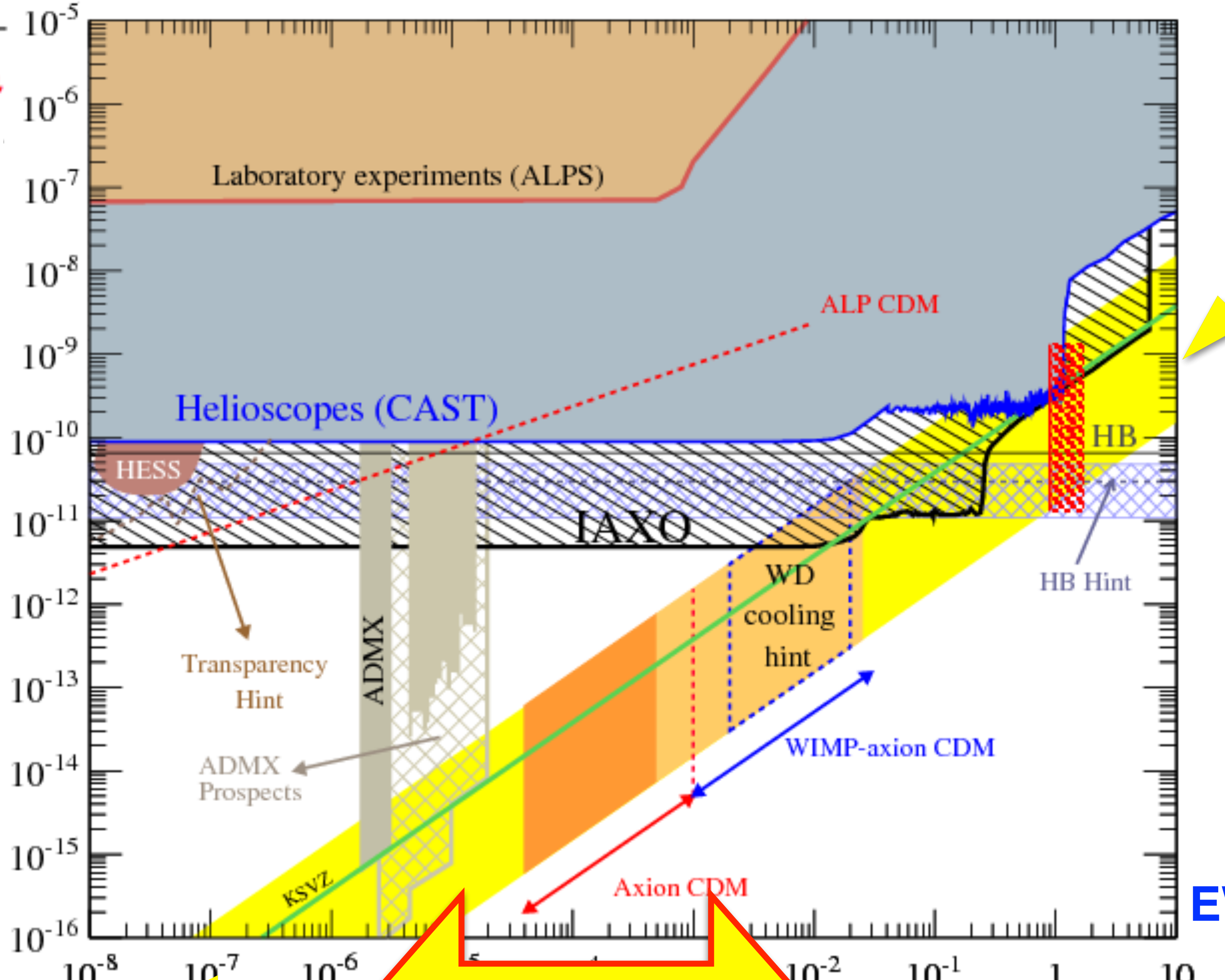

"True" QCD region

m_a (eV)

"True" QCD axion band

II

"Invisible axion"

e.g. KSVZ, DFSZ…

v<< f_a —>

EW hierarchy problem

… let us zoom out

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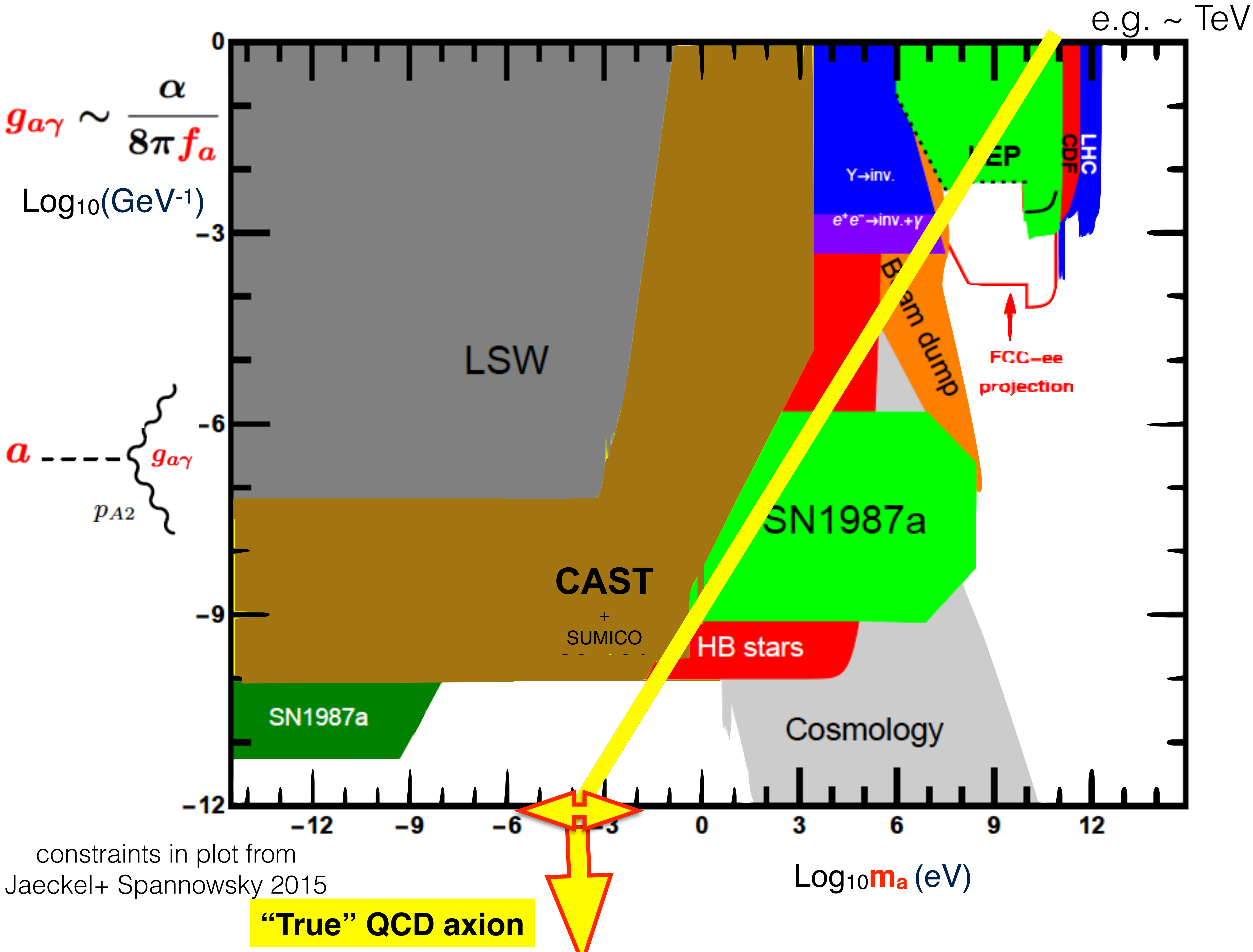
* **Much territory to explore for heavy 'true" axions and for ALPs**



constraints in plot from
Jaeckel+ Spannowsky 2015

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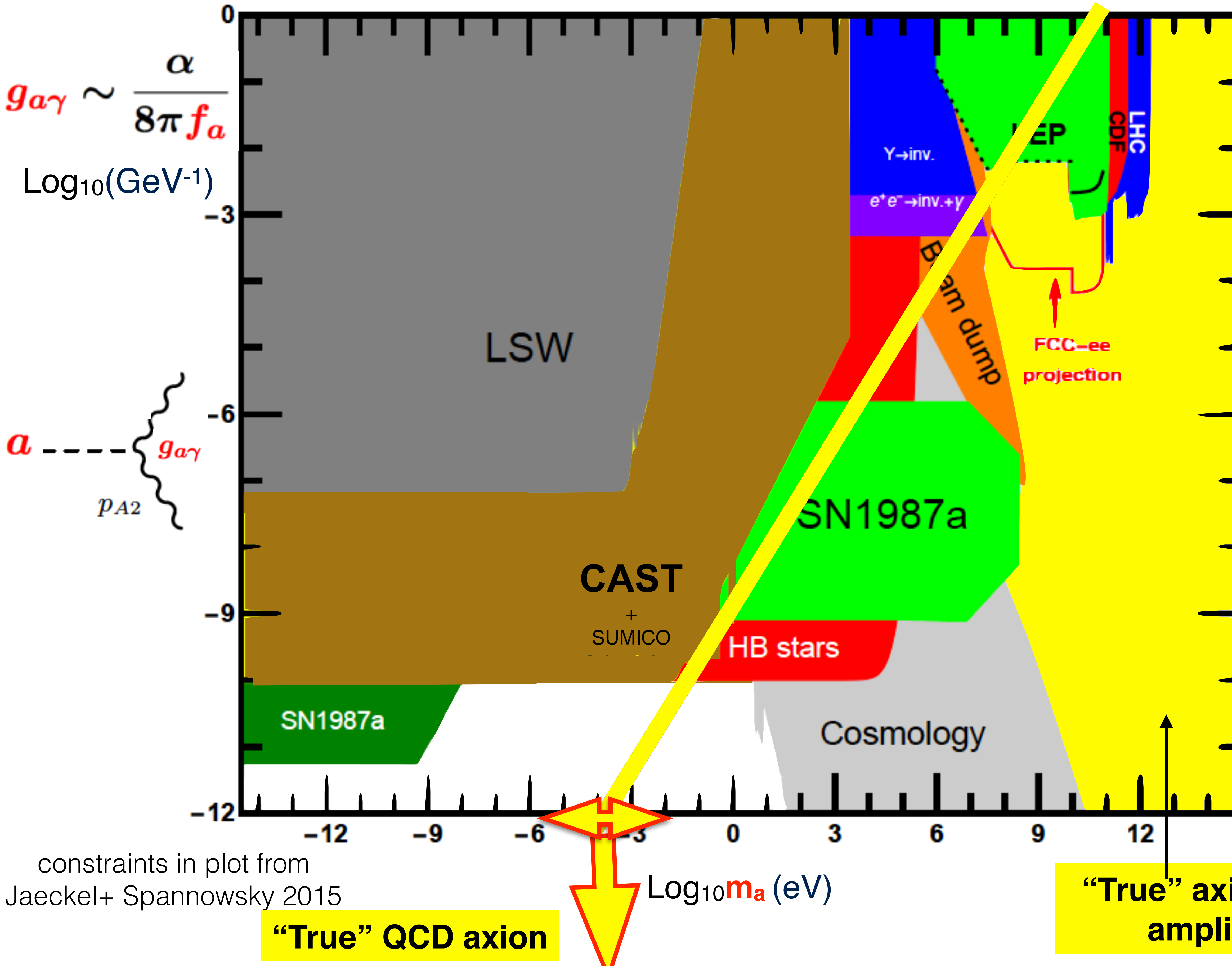

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“True” QCD axion

“True” axion region
amplifies??

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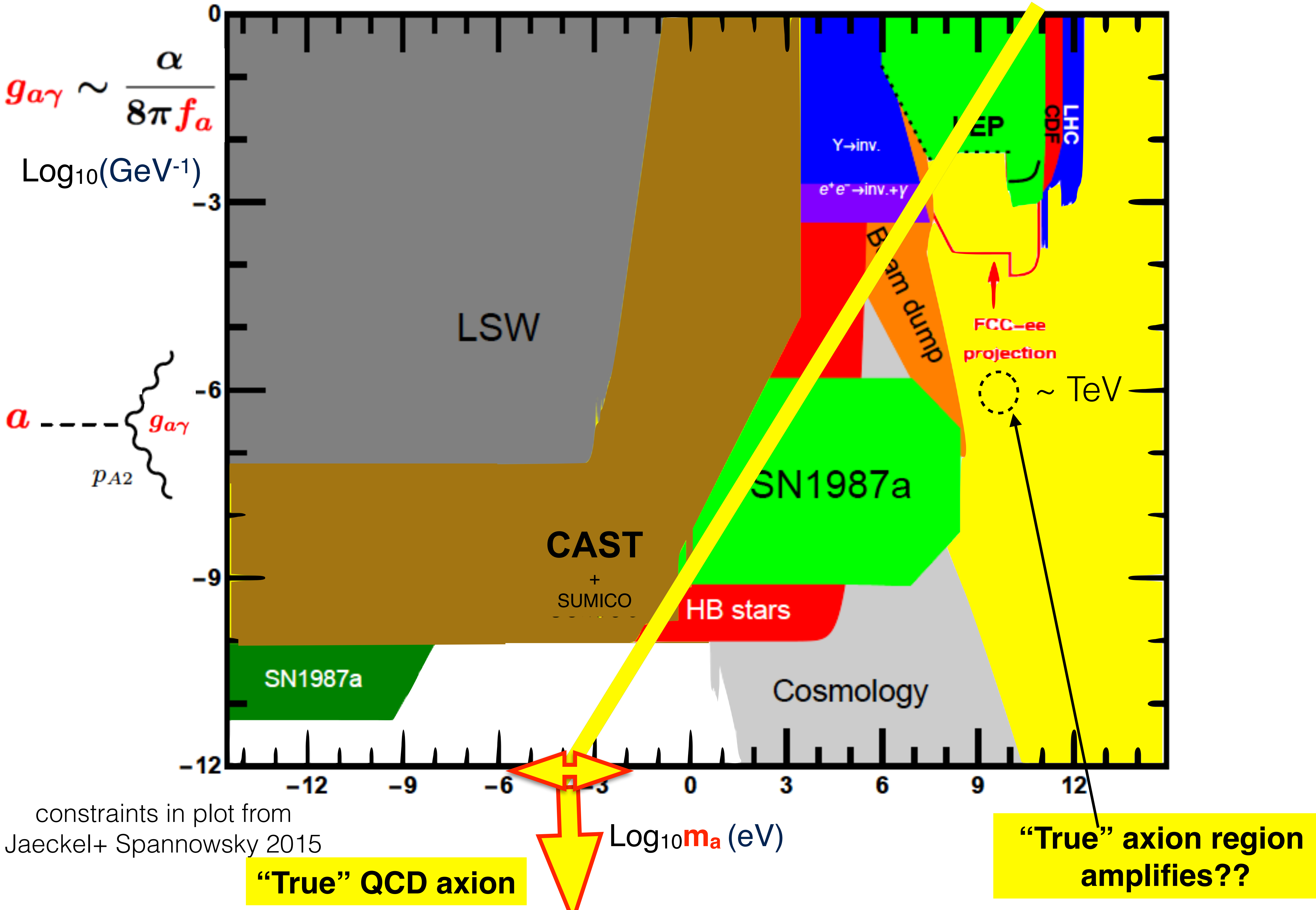

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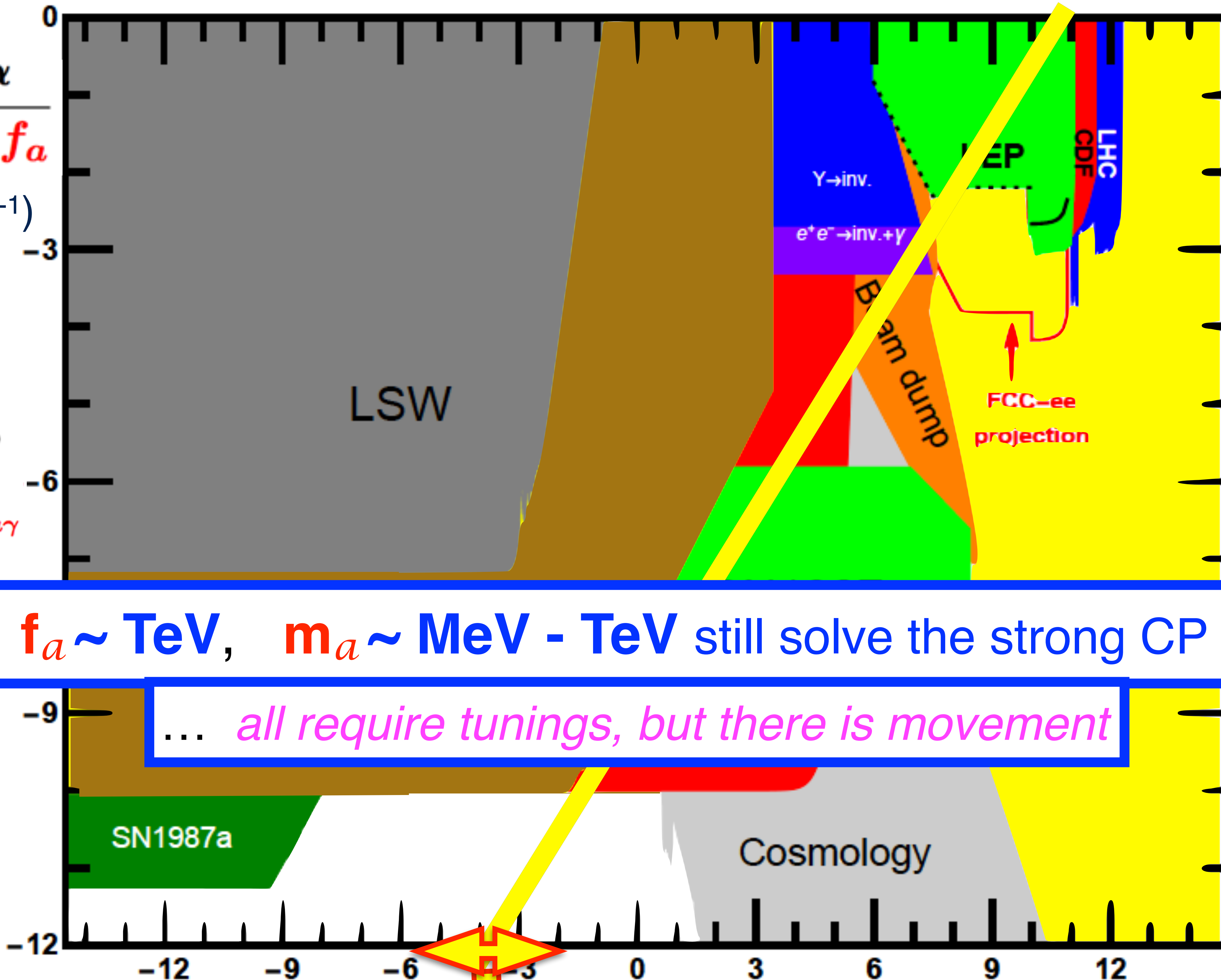
Log$_{10}$(GeV^{-1})

a - - - - $g_{a\gamma}$



—> e.g. f_a ~ **TeV**, m_a ~ **MeV - TeV** still solve the strong CP problem

… *all require tunings, but there is movement*

Log$_{10}$$m_a$ (eV)

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"True" QCD axion

"True" axion region amplifies??

A COLOR-UNIFIED DYNAMICAL AXION

New model to solve the SM strong CP problem, with heavy axions

First colour-unified model with massless quarks

M.K. Gaillard, M.B. Gavela, P. Quilez, R. Houtz, R. del Rey   arXiv:1805.06465

Strong CP Problem and Massless Quarks

Under a chiral rotation:

$$\mathcal{L} \ni -m_q \bar{q} q - \theta \frac{g^2}{32\pi^2} G\tilde{G}$$

$$\to -m_q \bar{q} e^{2i\gamma_5 \alpha} q - (\theta - 2\alpha) \frac{g^2}{32\pi^2} G\tilde{G}$$

If $m_q = 0$, then this rotation is just a shift $\theta \to \theta - 2\alpha$

. 't Hooft. "Computation of the Quantum
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$m_q = 0$ → $U(1)_A$ classically exact

+ only broken by anomalies

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e.g. m_u=0 → η'_{QCD} is the axion

….. this SM solution does not seem to be realised (?)

Axicolor

K. Choi, J.E. Kim, "Dynamical axion" 1985

Massless quark charged under QCD and another confining group

$SU(3)_c \times SU(\tilde{N})$ $\Lambda_{QCD} \ll \tilde{\Lambda}$

need to reabsorb θ_c and $\tilde{\theta}$

Massless quark content

	$SU(3)_c$	$SU(\tilde{N})$
ψ	$\square$	$\square$
χ	$\mathbb{1}$	$\square$

* When $SU(\tilde{N})$ confines:

$$SU(4)_L \times SU(4)_R \to SU(4)_V$$

$$15 = 8 + 3 + \bar{3} + 1$$

$$U(1)_L \times U(1)_R \to U(1)_V$$

the $\tilde{\eta}'$: 1

two singlets + η'_{QCD}

vs.

two instanton sources:

—> one m~0 invisible axion and very high f_a

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$$\eta'_\chi = (\bar{\chi}\chi)$$

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To know whether how heavy are the axion(s) of your BSM theory

Compare the number of pseudoscalars-coupled to anomalous currents:

η'_{QCD} $\quad a_1 \quad a_2 \quad a_3 \quad \ldots\ldots$

with how many sources of (instanton) masses

$G_c\tilde{G}_c \quad G'\tilde{G}' \quad G''\tilde{G}'' \quad \ldots\ldots$

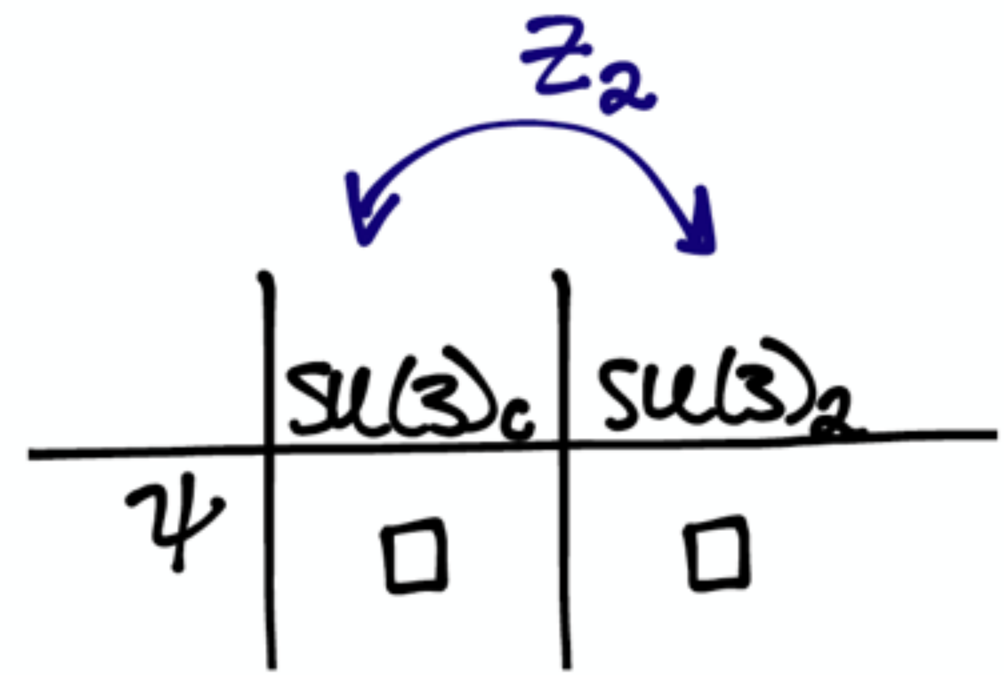
QCD

other sources of instantons

Massless Quarks and a Z_2

- Only one massless quark
- Complete Z_2 copy of the SM
- The $SU(3)_2$ θ-angle doesn't introduce new CP violating effects

$\longrightarrow$ only one dynamical axion, heavy



A. Hook, "Anomalous solutions to the strong CP problem," Phys. Rev. Lett. 114 (2015)

- Set up one Higgs VEV to be very large:

$$v_2 \gg v \quad \Rightarrow \quad m_q' \gg m_q \quad \Rightarrow \quad \Lambda_{QCD}' \gg \Lambda_{QCD}$$

it requires a complete mirror of SM and strong fine-tunings

Colour Unified Dynamical Axion

M.K. Gaillard, M.B. Gavela, P. Quilez, R. Houtz, R. del Rey

arXiv:1805.06465

$$SU(6) \supset SU(3)_c \times SU(\tilde{3})$$

Confinement scales: Λ_{QCD} $\tilde{\Lambda}$

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Confinement scales: Λ_{QCD} $\tilde{\Lambda}$

Solve strong CP problem with massless SU(6) fermion

We aim at $\tilde{\Lambda} \sim \textbf{TeV} \gg \Lambda_{QCD}$

Colour Unified Dynamical Axion

$$SU(6) \xrightarrow{\Lambda_{\mathrm{CUT}}} SU(3)_c \times SU(\tilde{3}) \times U(1)$$

- The massless quark to absorb the unified group's θ_6

	$SU(6)$	$SU(2)_L$	$U(1)_Y$
Ψ_L	20	1	0

- Below unification scale:

$$\Psi(20) \to (1,1)(-3) + (1,1)(+3) + (3,\bar{3})(-1) + (\bar{3},3)(+1)$$

	$SU(3)_c$	$SU(\tilde{3})$
ψ_L	$\square$	$\bar{\square}$
$(\psi^c)_L$	$\bar{\square}$	$\square$
ψ_{v_1}	1	1
ψ_{v_2}	1	1

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$(\psi^c)_L$	$\bar{\square}$	$\square$
ψ_{ν_1}	1	1
ψ_{ν_2}	1	1

Confined by $\tilde{\Lambda} >> \Lambda$

$+$ Sterile neutrinos

Colour Unified Dynamical Axion

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- The massless quark to absorb the unified group's θ_6

	$SU(6)$	$SU(2)_L$	$U(1)_Y$
Ψ_L	20	1	0

- Below unification scale:

we would have one <u>massive</u> dynamical axion

η'$_\psi$ $= (\bar{\psi}\psi)$

	$SU(3)_c$	$SU(\tilde{3})$
ψ_L	$\square$	$\overline{\square}$
$(\psi^c)_L$	$\overline{\square}$	$\square$
ψ_{ν_1}	1	1
ψ_{ν_2}	1	1

The SM fermions

There is a problem: SM quarks have now SU(6) partners

SM SM SM

$$Q_L^{(6)} \equiv (q, \tilde{q})_L \qquad U_R^{(6)} \equiv (u, \tilde{u})_R \qquad D_R^{(6)} \equiv (d, \tilde{d})_R$$

1. Equal mass partners are phenomenologically forbidden

$$m_{\tilde{q}} > m_q \qquad m_{\tilde{u}} > m_u \qquad m_{\tilde{d}} > m_d$$

2. The partner fields need to decouple in order to separate the running of $SU(3)_c$ and $SU(\tilde{3})$

Removing the Unification Partners

Makes things difficult

SM

$$Q_L^{(6)} \equiv (q, \tilde{q})_L$$

- Any scalar that gives $\tilde{q}, \tilde{u}, \tilde{d}$ a mass would have to be an $SU(2)_L$ doublet with a high VEV, affecting the W and Z bosons

$$\tilde{v} >> v$$

- Leaving the quarks massless and in the theory when $SU(\tilde{3})$ confines would trigger EWSB at the confinement scale

$$\tilde{\Lambda} >> v$$

➡ This requires more model building

Matter content above and below the CUT breaking

$$SU(6) \xrightarrow{\Lambda_{\mathrm{CUT}}} SU(3)_c \times SU(\tilde{3})$$

	$SU(6)$	$SU(2)_L$
Q_L	$\square$	$\square$
$\overline{U}_R$	$\overline{\square}$	$\mathbb{1}$
$\overline{D}_R$	$\overline{\square}$	$\mathbb{1}$
Ψ	20	$\mathbb{1}$

$\xrightarrow{\Lambda_{\mathrm{CUT}}}$

	$SU(3)$	$SU(\tilde{3})$	$SU(2)_L$
q_L	$\square$	$\mathbb{1}$	$\square$
$\overline{u}_R$	$\overline{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\overline{d}_R$	$\overline{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\tilde{q}_L$	$\mathbb{1}$	$\square$	$\square$
$\overline{\tilde{u}}_R$	$\mathbb{1}$	$\overline{\square}$	$\mathbb{1}$
$\overline{\tilde{d}}_R$	$\mathbb{1}$	$\overline{\square}$	$\mathbb{1}$
ψ	$\square$	$\overline{\square}$	$\mathbb{1}$
$2\psi_L$	$\mathbb{1}$	$\mathbb{1}$	$\mathbb{1}$

Goal: provide a mechanism for these fields to form mass terms

Matter content above and below the CUT breaking

Spoiler: we're going to introduce a new set of quarks to form mass terms with the tilde quarks

$$\kappa_q \, \overline{q'} \tilde{q}$$

$$\kappa_d \, \overline{d'} \tilde{d}$$

$$\kappa_u \, \overline{u'} \tilde{u}$$

	$SU(3)$	$SU(\tilde{3})$	$SU(2)_L$
q_L	$\square$	$\mathbb{1}$	$\square$
$\overline{u}_R$	$\overline{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\overline{d}_R$	$\overline{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\tilde{q}_L$	$\mathbb{1}$	$\square$	$\square$
$\overline{\tilde{u}}_R$	$\mathbb{1}$	$\overline{\square}$	$\mathbb{1}$
$\overline{\tilde{d}}_R$	$\mathbb{1}$	$\overline{\square}$	$\mathbb{1}$
ψ	$\square$	$\overline{\square}$	$\mathbb{1}$
$2\psi_\nu$	$\mathbb{1}$	$\mathbb{1}$	$\mathbb{1}$

Goal: provide a mechanism for these fields to form mass terms

A UV complete solution

Add a new group outside the CUT group

$$\boxed{SU(6) \times SU(3') \xrightarrow{\Lambda_{\mathrm{CUT}}} SU(3)_c \times SU(3)_{\mathrm{diag}}}$$

with prime fermions charged only under SU(3')

A UV complete solution

Add a new group outside the CUT group

$$\boxed{SU(6) \times SU(3') \xrightarrow{\Lambda_{\rm CUT}} SU(3)_c \times SU(3)_{\rm diag}}$$

with prime fermions charged only under SU(3')

	$SU(6)$	$SU(3')$	$SU(2)_L$
Q_L	$\square$	$\mathbb{1}$	$\square$
$\overline{U}_R$	$\overline{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\overline{D}_R$	$\overline{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\overline{q}'_R$	$\mathbb{1}$	$\overline{\square}$	$\square$
u'_L	$\mathbb{1}$	$\square$	$\mathbb{1}$
d'_L	$\mathbb{1}$	$\square$	$\mathbb{1}$
Φ	20	$\mathbb{1}$	$\mathbb{1}$
Δ	$\square$	$\overline{\square}$	$\mathbb{1}$

- We can form terms like:

$$\overline{q'_R}\,\Delta^*\,Q_L$$

$\overline{q}'_R$, u'_L, d'_L: These fields pair up with the tilde fields to form masses

Δ: Scalar field responsible for CUT breaking

The CUT breaking

$$\boxed{SU(6) \times SU(3') \xrightarrow{\Lambda_{\rm CUT}} SU(3)_c \times SU(3)_{\rm diag}}$$

$$\mathcal{L} \ni \kappa_q \overline{q'_R}\, \Delta^*\, Q_L + \kappa_u u'_L\, \Delta\, \overline{U_R} + \kappa_d d'_R\, \Delta\, \overline{D_R} + \text{h.c.}$$

$$\langle \Delta \rangle = \Lambda_{\rm CUT} \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

- This VEV pattern grabs only the tilde quarks out of the spectrum

$$\mathcal{L} \ni \Lambda_{\rm CUT} \left(\kappa_q \overline{q'_R} \tilde{q}_L + \kappa_u u'_L \overline{\tilde{u}_R} + \kappa_d d'_L \overline{\tilde{d}_R} \right) + \text{h.c.}$$

★ This accomplishes the task of forming mass terms for the SU(6) partner fields $\tilde{q}, \tilde{u}, \tilde{d}$

The axion spectrum of the CUT theory

$$SU(6) \times SU(3')$$

θ_6 $\theta_{3'}$

two massless fermions so as to rebasorb both θ_6 and θ'

	$SU(6)$	$SU(3')$
Ψ	20	$\mathbb{1}$
χ	$\mathbb{1}$	$\square$

—> two dynamical axions with scale set by Λ_{diag}:

$\eta'_\psi = (\bar{\psi}\psi)$ $\eta'_\chi = (\bar{\chi}\chi)$

	$SU(6)$	$SU(3')$	$SU(2)_L$
Ψ	20	$\mathbb{1}$	$\mathbb{1}$
χ	$\mathbb{1}$	$\square$	$\mathbb{1}$

$$\xrightarrow{\Lambda_{\mathrm{CUT}}}$$

	$SU(3)$	$SU(3)_{\mathrm{diag}}$	$SU(2)_L$
ψ	$\square$	$\overline{\square}$	$\mathbb{1}$
χ	$\mathbb{1}$	$\square$	$\mathbb{1}$
$2\psi_L$	$\mathbb{1}$	$\mathbb{1}$	$\mathbb{1}$

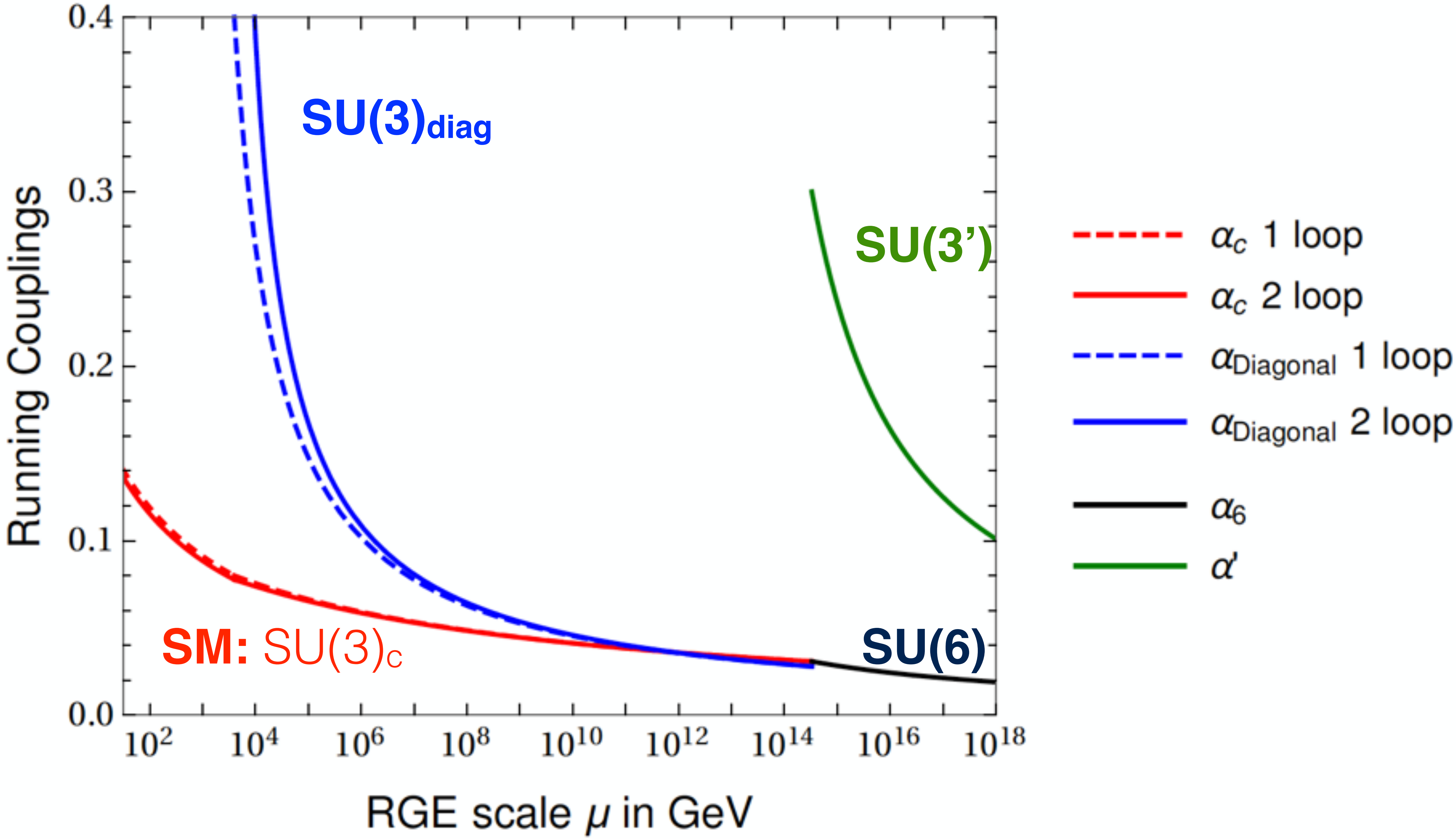
The two massless quarks

- Goal: $SU(3)_{\mathrm{diag}}$ confines at a higher scale than $SU(3)_c$

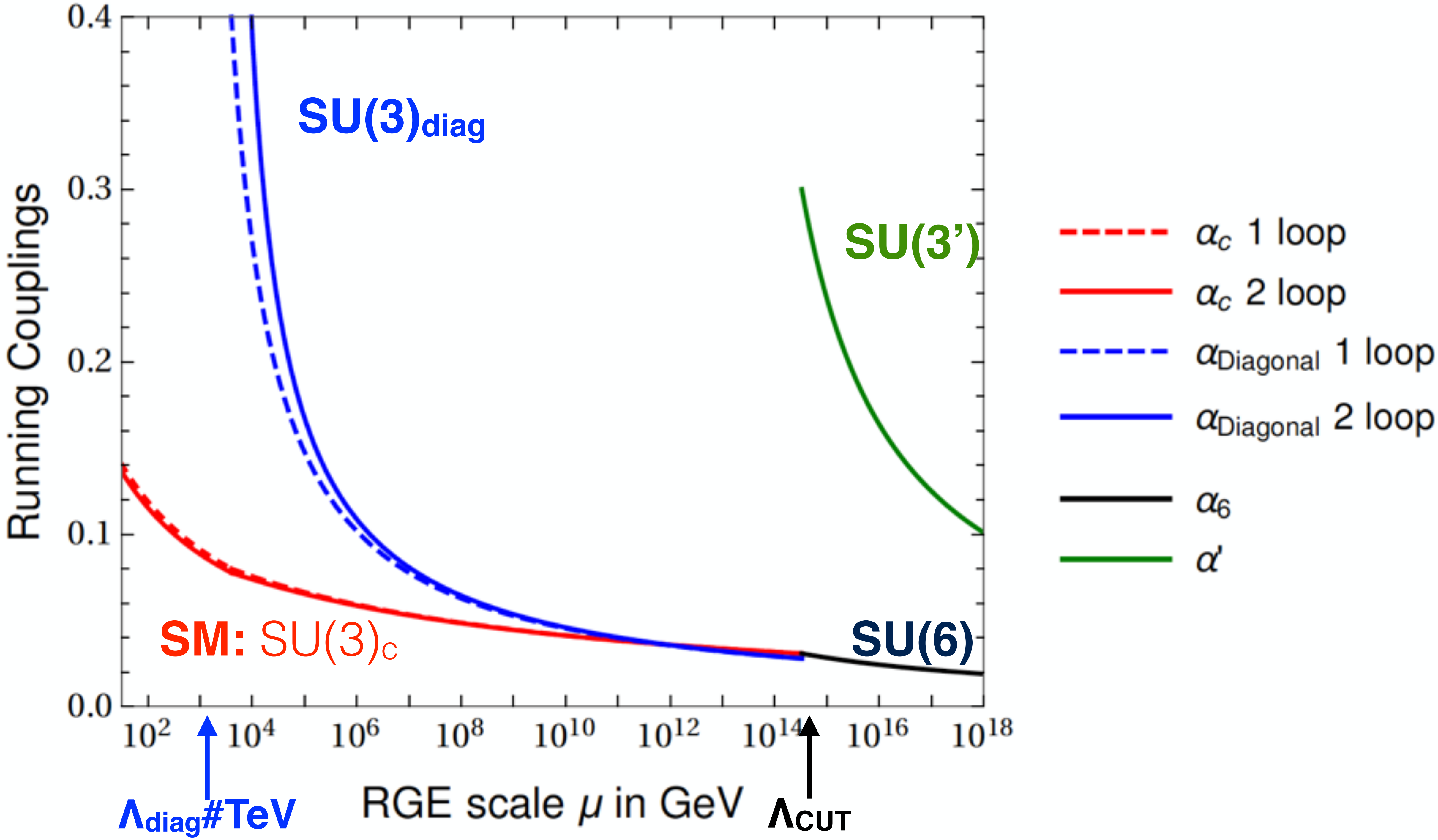
$$\frac{1}{\alpha_{\mathrm{diag}}(\mu)} = \frac{1}{\alpha_6(\mu)} + \frac{1}{\alpha'(\mu)} \qquad \mu = \Lambda_{CUT}$$

$$\alpha_c(\Lambda_{CUT}) = \alpha_6(\Lambda_{CUT})$$

Model I: Unification and Confinement



Model I: Unification and Confinement



What are the masses of the two dynamical axions?

There are **three** pseudo scalars-coupled to anomalous currents:

η'_{QCD} $\quad$ **η'_{ψ}** $\quad$ **η'_{χ}**

axions

For how many sources of (instanton) masses ? **Two or three ?**

$G_{\rm diag}\tilde{G}_{\rm diag}$ $\qquad$ $G_c\tilde{G}_c$ $\qquad$ and…. ?

What are the masses of the two dynamical axions?

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axions

For how many sources of (instanton) masses ? **Two or three ?**

$$G_{\rm diag}\tilde{G}_{\rm diag} \qquad\qquad G_c\tilde{G}_c$$

and…. ?

$$\mathcal{L}_{eff} = \Lambda^4_{\rm diag}\cos\left(\frac{2\eta'_\chi}{f_d} + \sqrt{6}\frac{\eta'_\psi}{f_d}\right) + \Lambda^4_{\rm QCD}\cos\left(\frac{2\eta'_{\rm QCD}}{f_\pi} + \sqrt{6}\frac{\eta'_\psi}{f_d}\right)$$ +…. ?

$$\Lambda_{\rm diag} \leq 4\pi f_d$$

Small Size Instantons (SSI) and Axion Mass

- ➔ Typically, at high energies (= small size) couplings are very small.
- ➔ The instanton density has an exponential suppression:

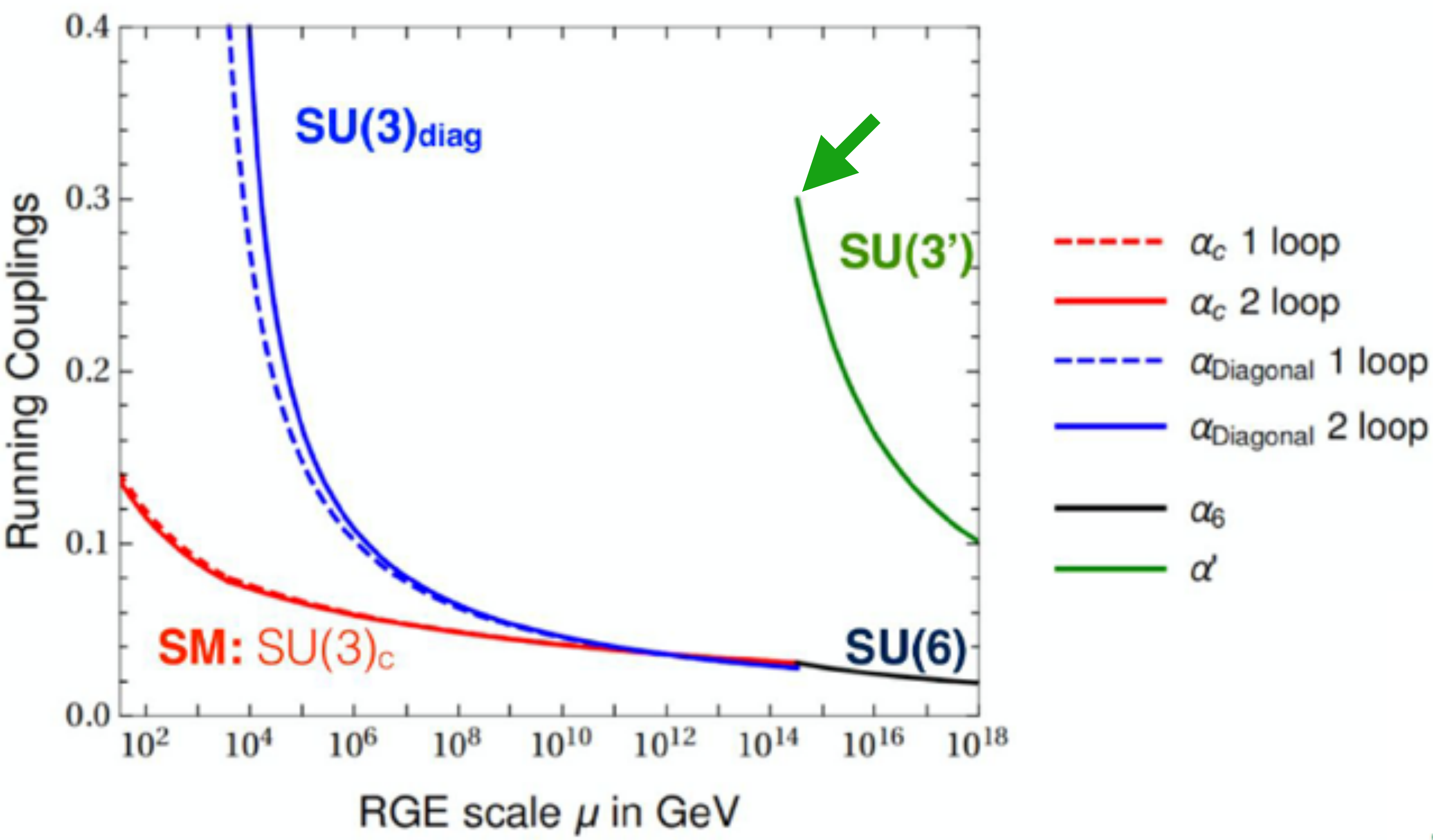
$$D[\alpha'(\mu)] \propto e^{-2\pi/\alpha'(\mu)}$$

Usually sizable only at the confinement scale

$$\left(e^{-2\pi/0.1} \sim 10^{-28}\right)$$

- ➔ New Physics can change the RG flow and induce a new source of axion mass

[Holdom+Peskin, 82]
[Dine+Seiberg, 86]
[Flynn+Randall, 87]
[Agrawal+Howe, 17]



- ➔ Large coupling $\alpha' \sim 0.3$
- ➔ Large breaking scale

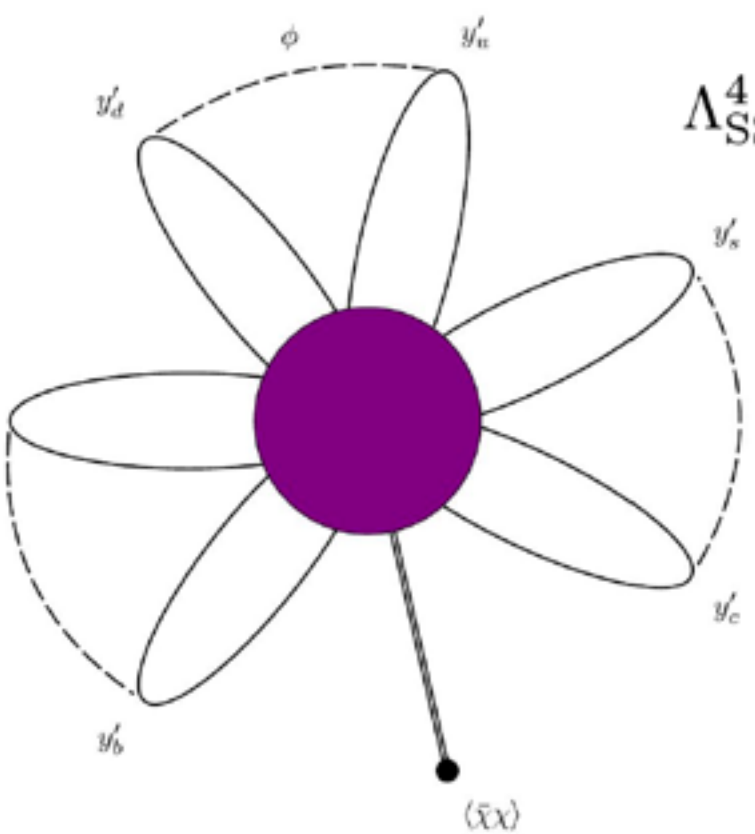
$$\Lambda_{CUT} \sim 10^{14-18}\, GeV$$

New sizable contribution to the axion mass!!

Small Size Instantons (SSI) and Axion Mass

➔ Dilute Instanton Gas approximation:

[t'Hooft, 73]
[Callan+Dashen+Gross, 77]
[Shifman+Vainshtein+Zakharov, 80]



$$\Lambda_{\mathrm{SSI}}^4 = \underbrace{-C_{inst}\int \frac{d\rho}{\rho^5}\left(\frac{2\pi}{\alpha'(\rho)}\right)^{2N_c} e^{-2\pi/\alpha'(\rho)}}_{\text{Pure Yang-Mills Instanton}} \underbrace{\left(\frac{2}{3}\pi^2\rho^3\langle\bar{\chi}\chi\rangle\right)\frac{1}{(4\pi)^6}\prod_i y'^{\,i}_u y'^{\,i}_d}_{\text{Fermionic suppression}}$$

$$\mathcal{L}_{eff} = \Lambda_{\mathrm{SSI}}^4 \cos\left(2\,\frac{\eta'_\chi}{f_{\mathrm{d}}}\right) \qquad \Lambda_{SSI} \gtrsim 20\,TeV$$

arXiv:1805.06465

The effective potential for the three singlet pseudoscalars:

η'_{QCD} η'_{ψ} η'_{χ}

$$\mathcal{L}_{eff} = \Lambda^4_{\mathrm{SSI}} \cos\left(2\,\frac{\eta'_\chi}{f_{\mathrm{d}}}\right) + \Lambda^4_{\mathrm{diag}} \cos\left(2\,\frac{\eta'_\chi}{f_{\mathrm{d}}} + \sqrt{6}\,\frac{\eta'_\psi}{f_{\mathrm{d}}}\right) + \Lambda^4_{\mathrm{QCD}} \cos\left(2\,\frac{\eta'_{\mathrm{QCD}}}{f_\pi} + \sqrt{6}\,\frac{\eta'_\psi}{f_{\mathrm{d}}}\right)$$

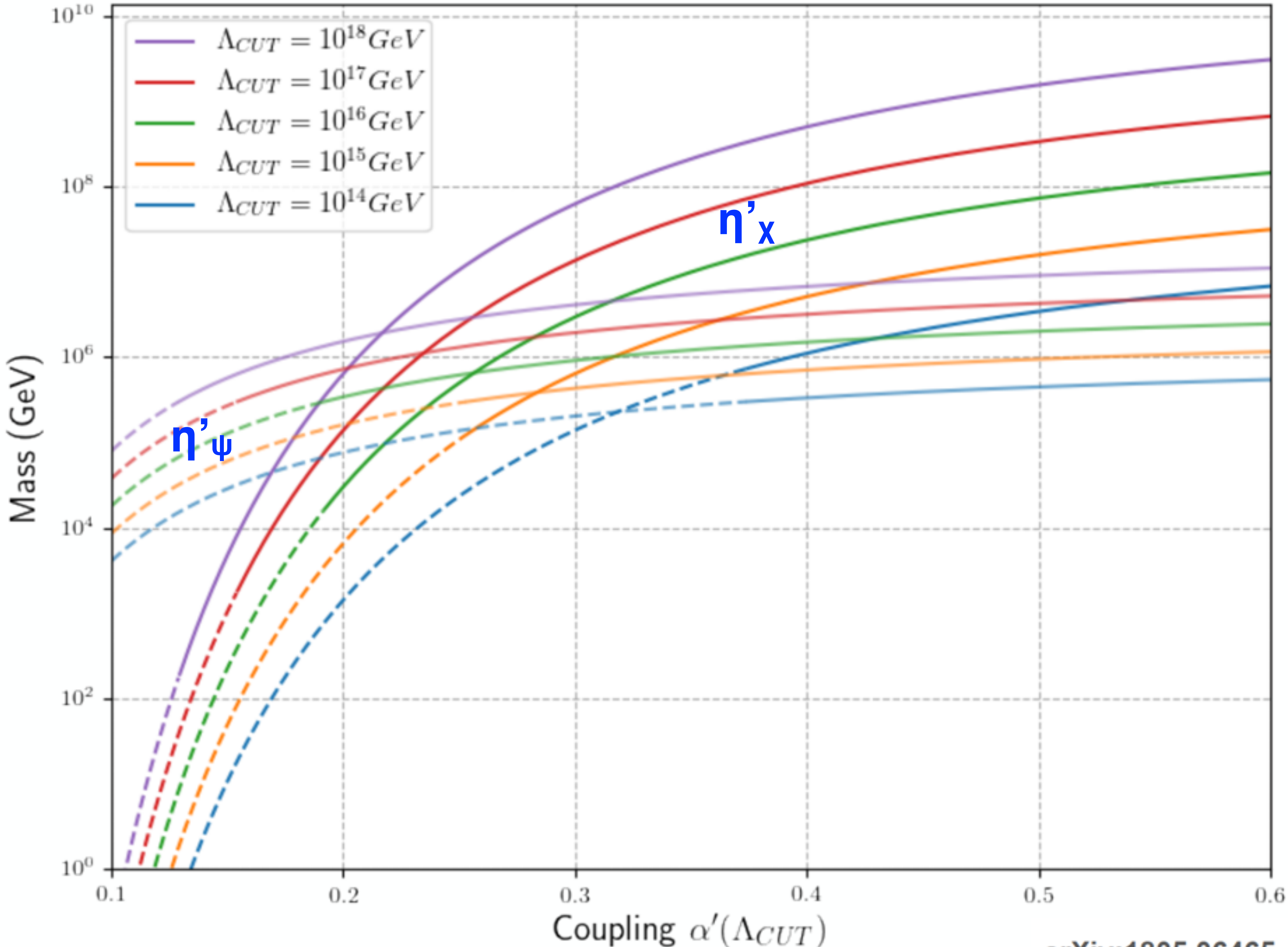
has three sources of mass —> two massive axions

Pseudoscalar potential and masses

$$\mathcal{L}_{eff} = \underbrace{\Lambda_{\rm SSI}^4 \cos\left(2\,\frac{\eta'_\chi}{f_{\rm d}}\right)}_{SU(3')\ \text{SSI Instantons}} + \underbrace{\Lambda_{\rm diag}^4 \cos\left(2\,\frac{\eta'_\chi}{f_{\rm d}} + \sqrt{6}\,\frac{\eta'_\psi}{f_{\rm d}}\right)}_{SU(3)_{\rm diag}\ \text{Instantons at conf.}} + \underbrace{\Lambda_{\rm QCD}^4 \cos\left(2\,\frac{\eta'_{\rm QCD}}{f_\pi} + \sqrt{6}\,\frac{\eta'_\psi}{f_{\rm d}}\right)}_{SU(3)_{\rm c}\ \text{Instantons at conf.}}$$

$$M^2_{\eta'_\chi,\,\eta'_\psi,\,\eta'_{\rm QCD}} = \begin{pmatrix} 4\frac{\left(\Lambda_{\rm SSI}^4+\Lambda_d^4\right)}{f_{\rm d}^2} & 2\sqrt{6}\,\frac{\Lambda_d^4}{f_d^2} & 0 \\ 2\sqrt{6}\,\frac{\Lambda_d^4}{f_d^2} & 6\,\frac{\left(\Lambda_d^4+\Lambda_{\rm QCD}^4\right)}{f_{\rm d}^2} & 2\sqrt{6}\,\frac{\Lambda_{\rm QCD}^4}{f_\pi f_{\rm d}} \\ 0 & 2\sqrt{6}\,\frac{\Lambda_{\rm QCD}^4}{f_\pi f_{\rm d}} & 4\frac{\Lambda_{\rm QCD}^4}{f_\pi^2} \end{pmatrix}$$

Axion masses: $\eta'_\psi = (\bar{\psi}\psi)$ $\eta'_\chi = (\bar{\chi}\chi)$



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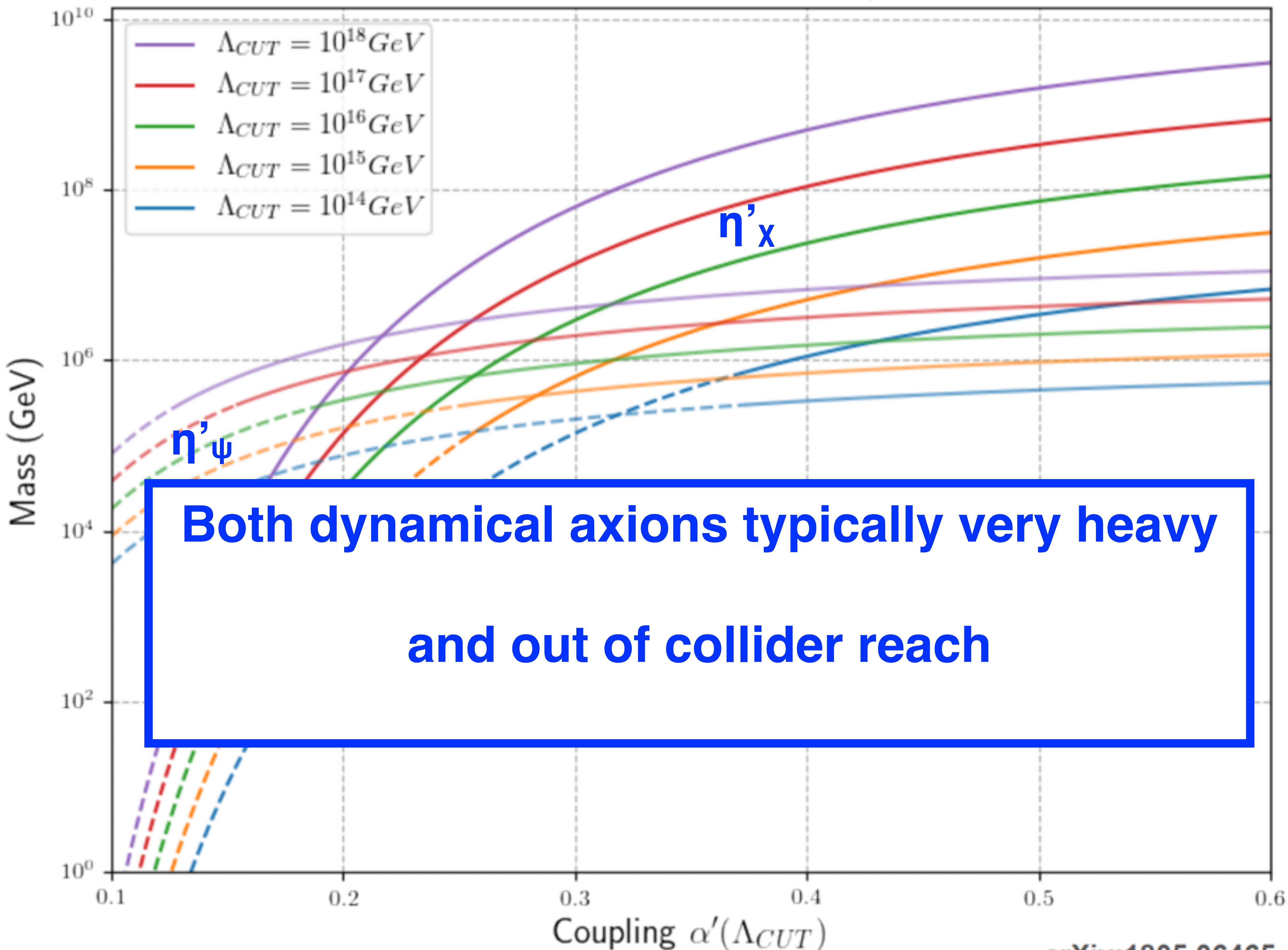


arXiv:1805.06465

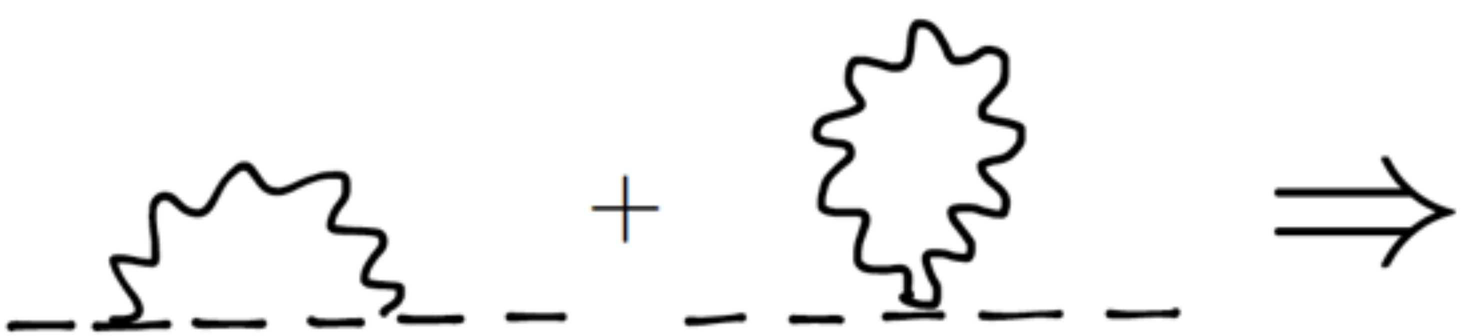
The low-energy observable spectrum

- The U(4) flavor symmetry is broken by condensates: $\langle\psi\psi\rangle \; \langle\bar{\chi}\chi\rangle$

$$U(4)_L \times U(4)_R \to U(4)_V$$

- This results in 16 pGB's. $16 = 8_c + \bar{3}_c + 3_c + 1_c + 1_c$

- The "pion" masses get pushed up to the cutoff of the theory via interactions with gluons



$$m^2(8_c) \approx \frac{9\alpha_c}{4\pi}\Lambda^2_{\rm diag}$$

$$m^2(3_c) \approx \frac{\alpha_c}{\pi}\Lambda^2_{\rm diag}$$

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- The U(4) flavor symmetry is broken by condensates: $\langle \psi\psi \rangle \ \langle \bar{\chi}\chi \rangle$

$$U(4)_L \times U(4)_R \to U(4)_V$$

QCD-colored "pions"

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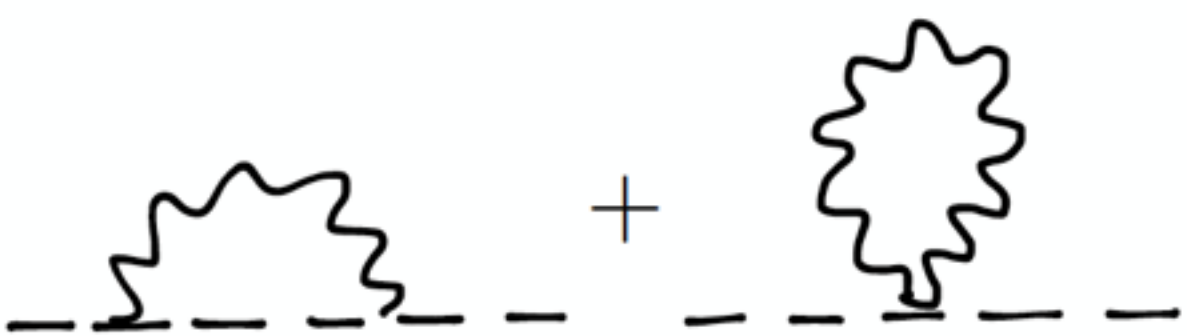


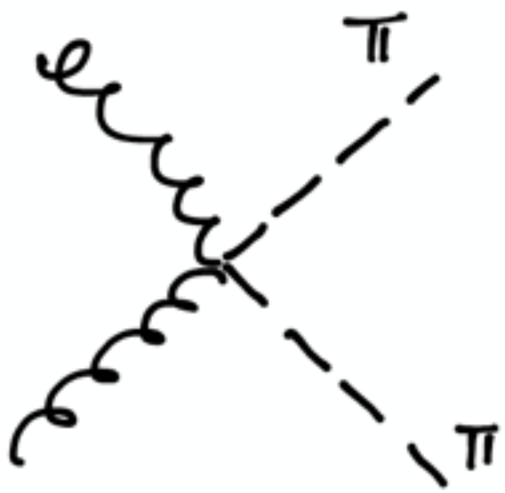
$$\Rightarrow \quad m^2(8_c) \approx \frac{9\alpha_c}{4\pi}\Lambda^2_{\rm diag}$$

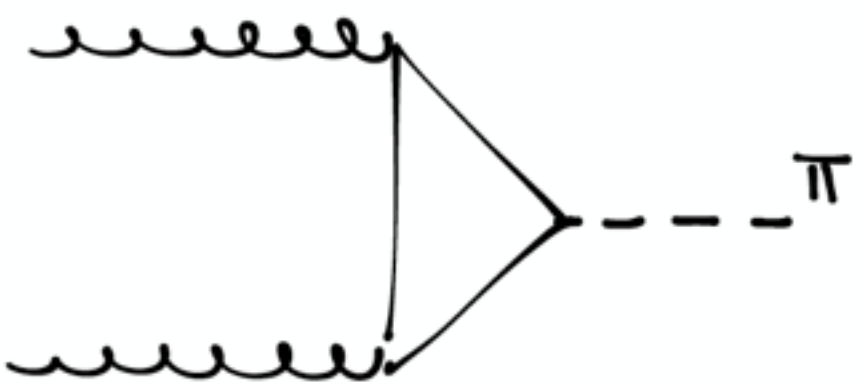
$$m^2(3_c) \approx \frac{\alpha_c}{\pi}\Lambda^2_{\rm diag}$$

Collider Phenomenology

- Collider accessible states are QCD colored “pions”

$$\mathcal{L} \ni D_\mu \pi_d D^\mu \pi_d + \frac{\pi_d^a}{f_d}\frac{\alpha_s}{16\pi} d_{abc} G^b_{\mu\nu}\tilde{G}^{c\mu\nu}$$



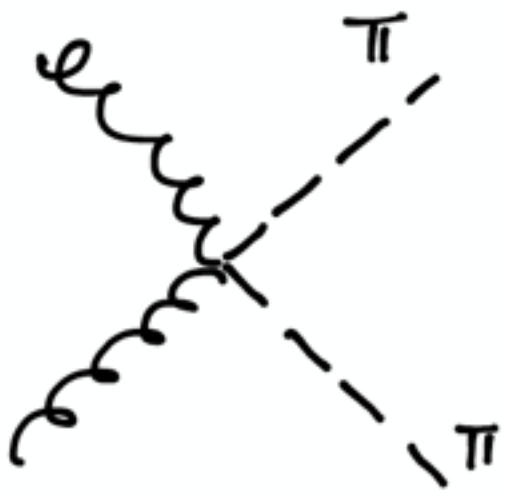


- Pair produced
- Anomalous production

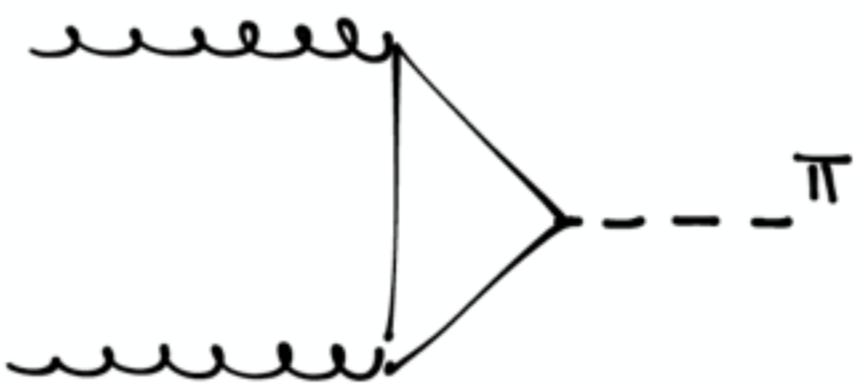
Collider Phenomenology

- Collider accessible states are QCD colored “pions”

$$\mathcal{L} \ni D_\mu \pi_d D^\mu \pi_d + \frac{\pi_d^a}{f_d} \frac{\alpha_s}{16\pi} d_{abc} G^b_{\mu\nu} \tilde{G}^{c\mu\nu}$$



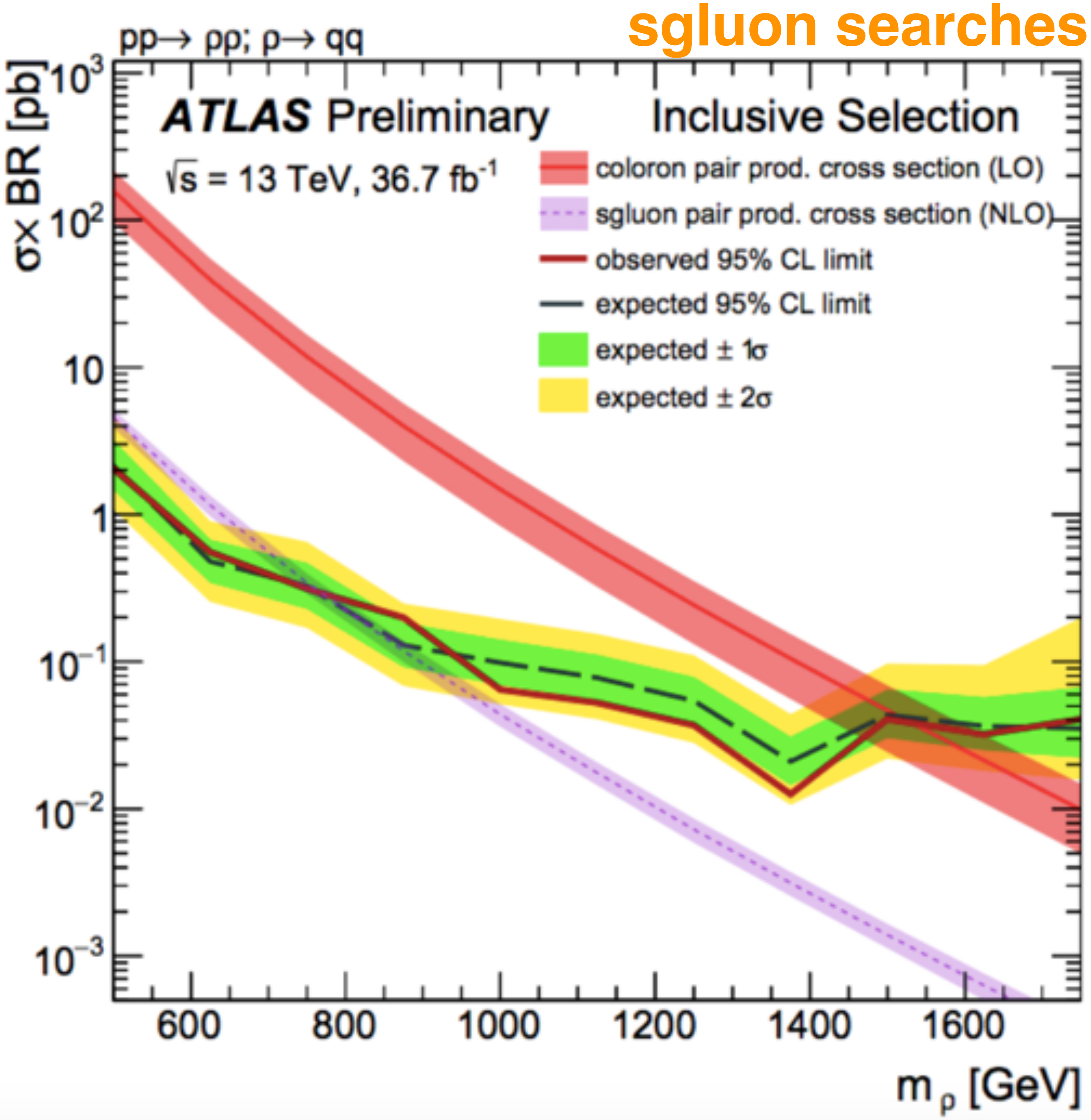
dominates production



dominates decay

Collider Phenomenology

sgluon searches



- We have a bound on color octet scalars

$$m(\pi_d) \gtrsim 700 \text{ GeV}$$

$$m^2(8_c) \approx \frac{9\alpha_c}{4\pi}\Lambda^2_{\rm diag}$$

$$\Lambda_{\rm diag} \approx 3 \text{ TeV}$$

We also developed another UV completion

Same CUT gauge group

$$\boxed{SU(6) \times SU(3') \xrightarrow{\Lambda_{\rm CUT}} SU(3)_c \times SU(3)_{\rm diag}}$$

but instead of adding a second massless fermion as in

model I:

	$SU(6)$	$SU(3')$
Ψ	20	$\mathbb{1}$
χ	$\mathbb{1}$	$\square$

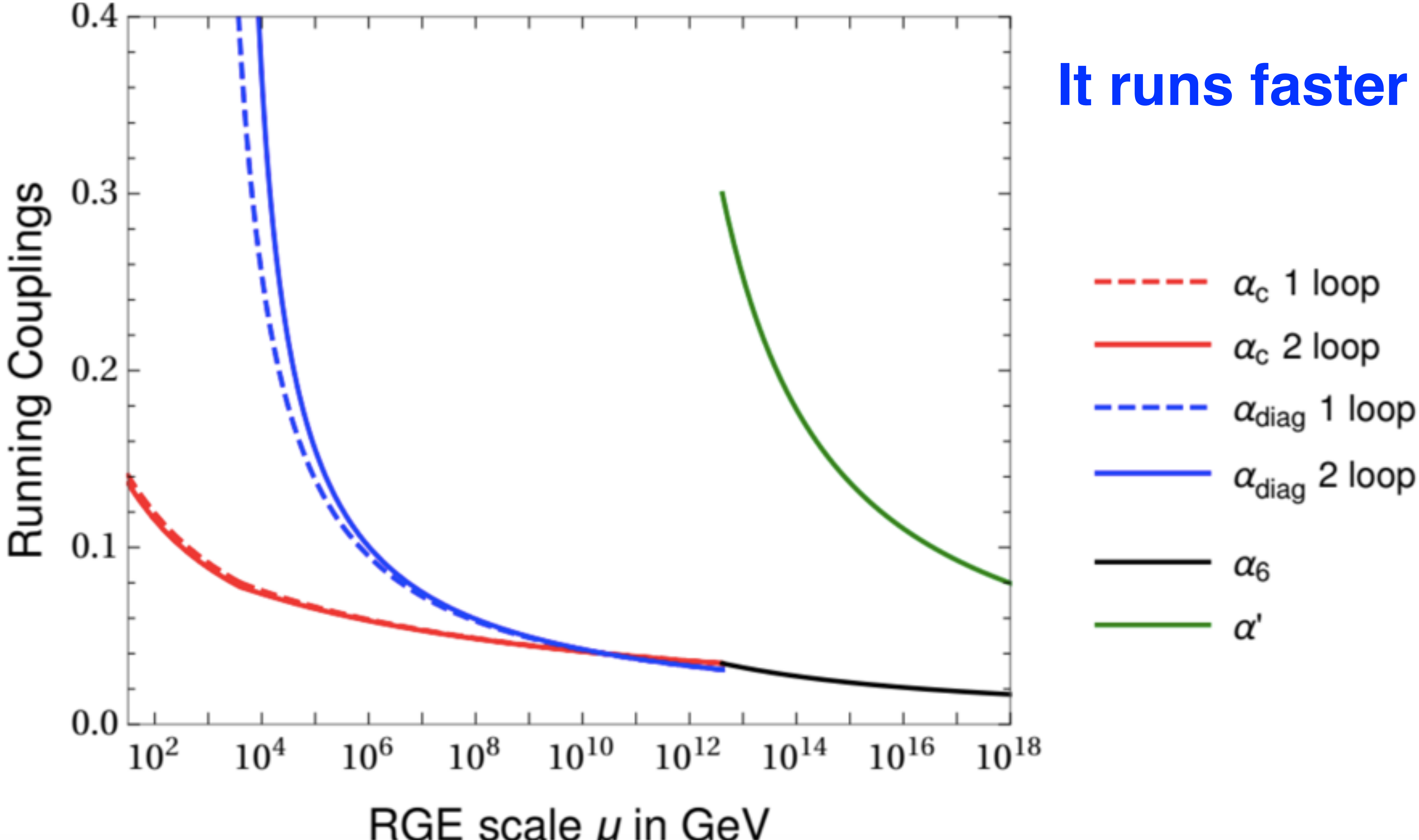
we added a second scalar Δ_2 :

model II:

	$SU(6)$	$SU(3')$
Ψ	20	$\mathbb{1}$
Δ_2	$\square$	$\overline{\square}$

Δ , Δ_2 and the prime fermions have now PQ charges

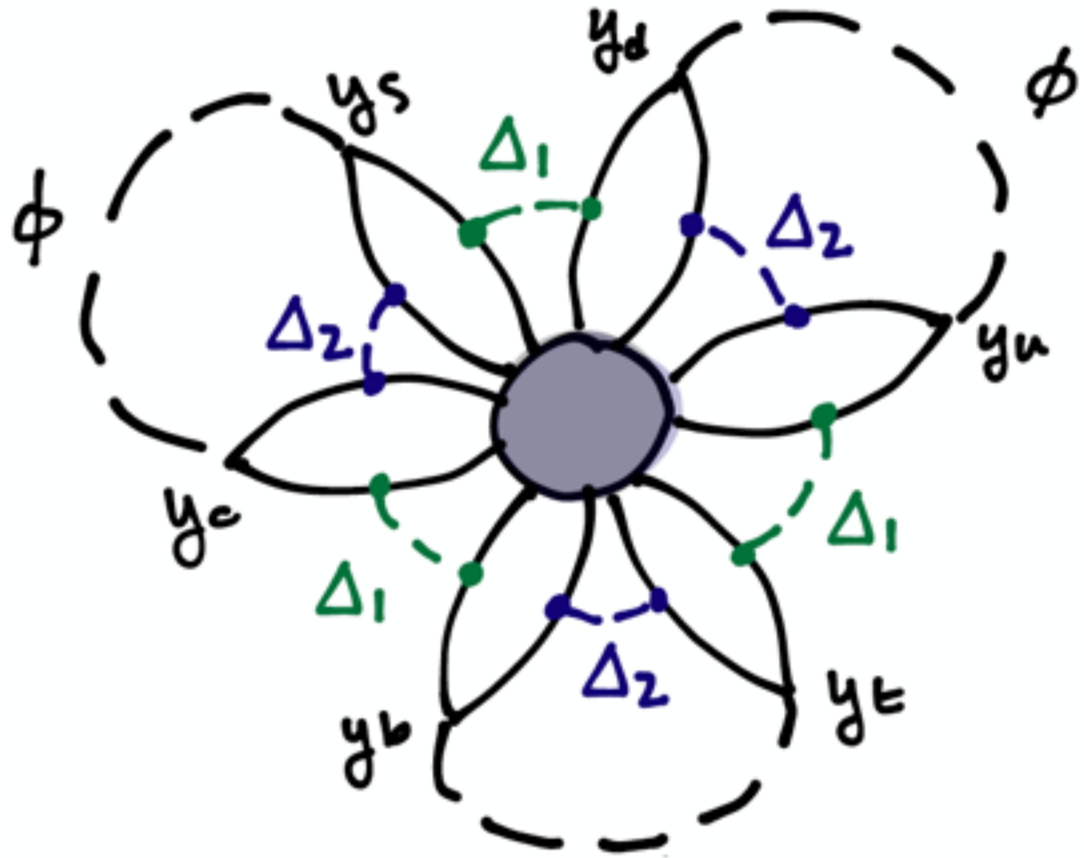
Model II: Small Size Instanton Contribution



It runs faster

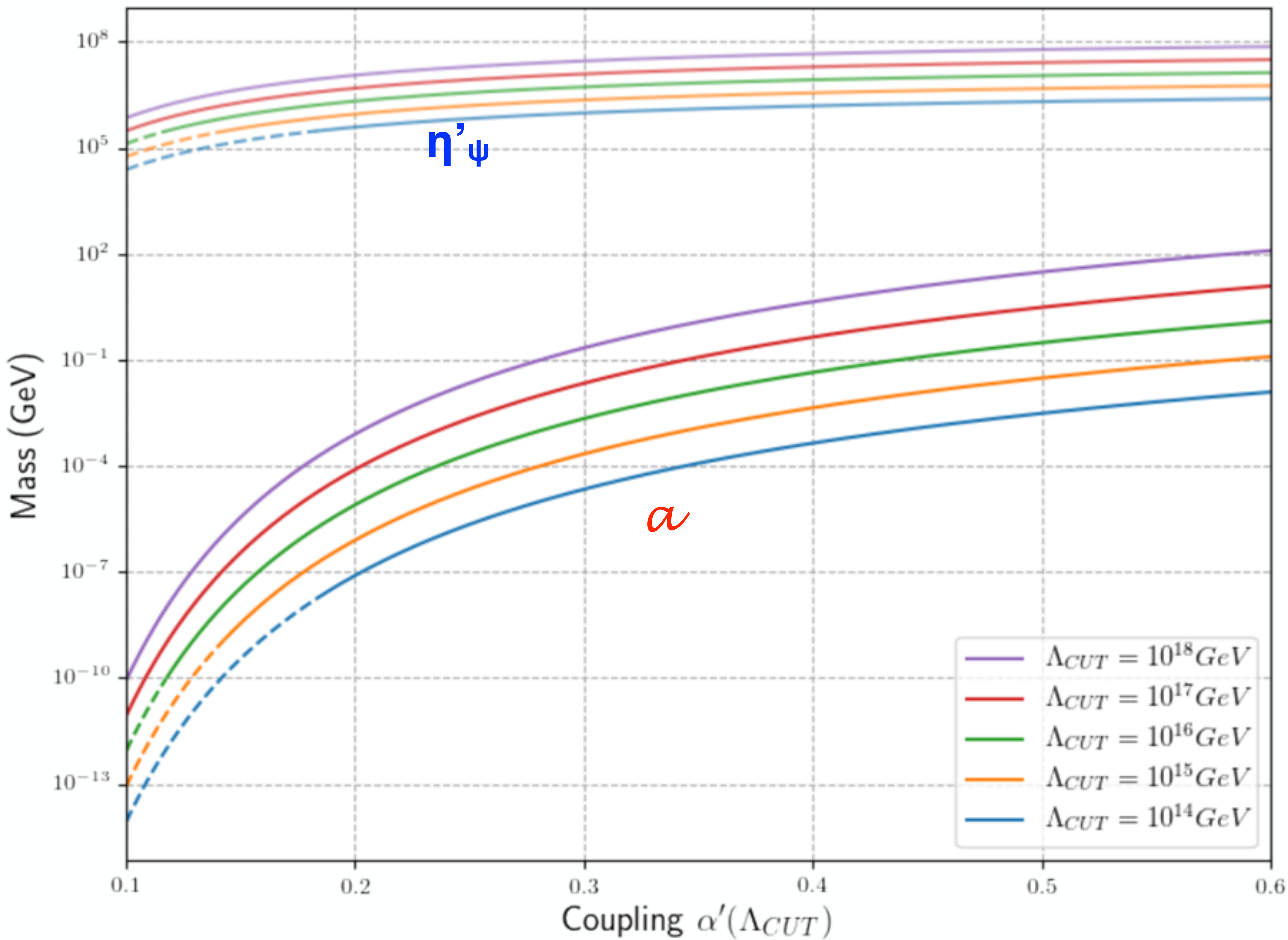
Model II: Small Size Instanton Contribution

The prime Yukawa couplings to the Higgs are now forbidden by PQ symmetry

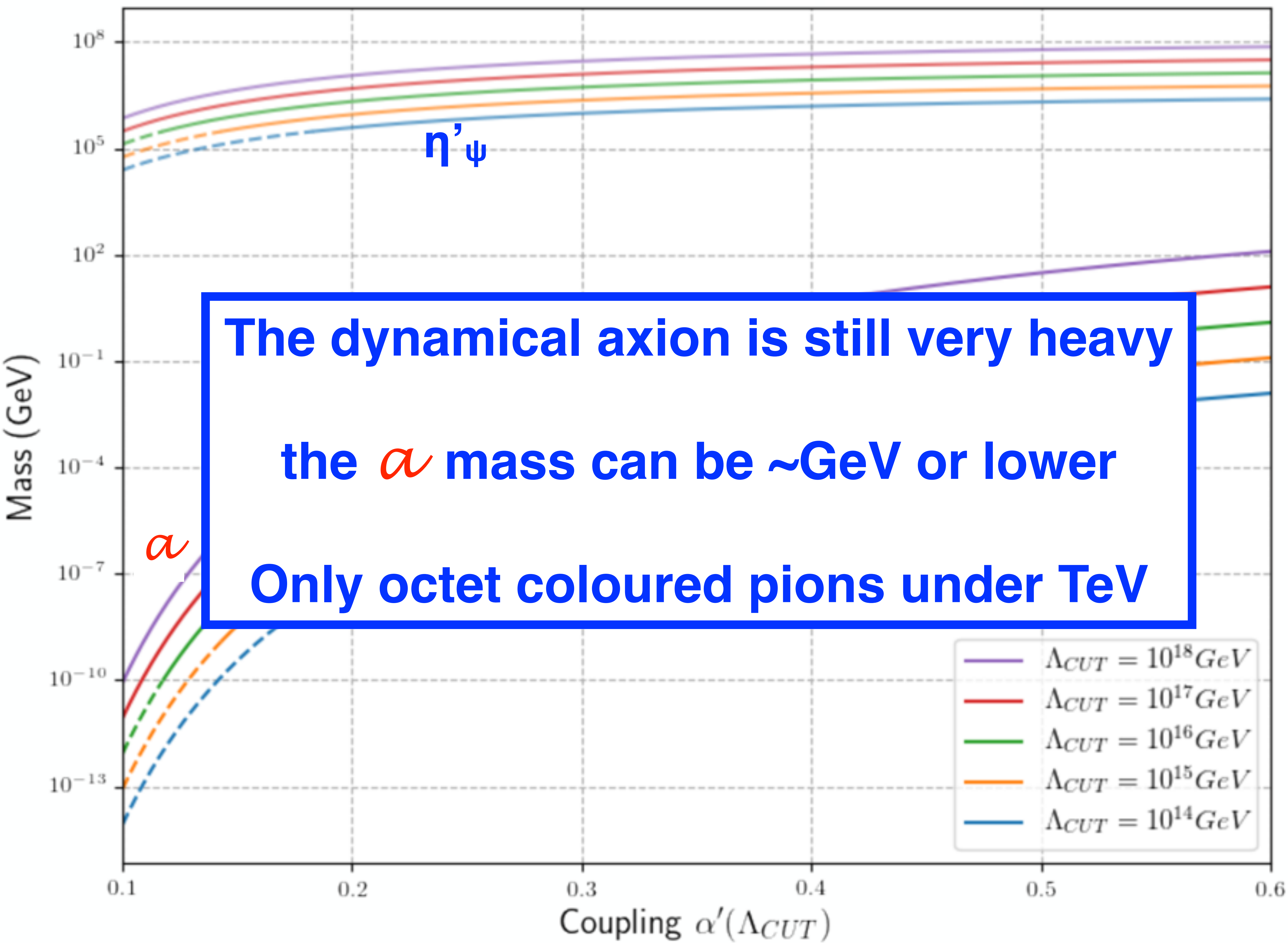


$$\Lambda_{SSI}^4 = -\int \frac{d\rho}{\rho^5} D[\alpha'(1/\rho)] \frac{1}{(4\pi)^{18}} \prod_i Y_{u_i}^{SM} Y_{d_i}^{SM} \left(\kappa_q^i\right)^2 \kappa_u^i \kappa_d^i$$

Axion masses: a, $\eta'_\psi = (\bar{\psi}\psi)$



Axion masses: a, $\eta'_\psi = (\bar{\psi}\psi)$

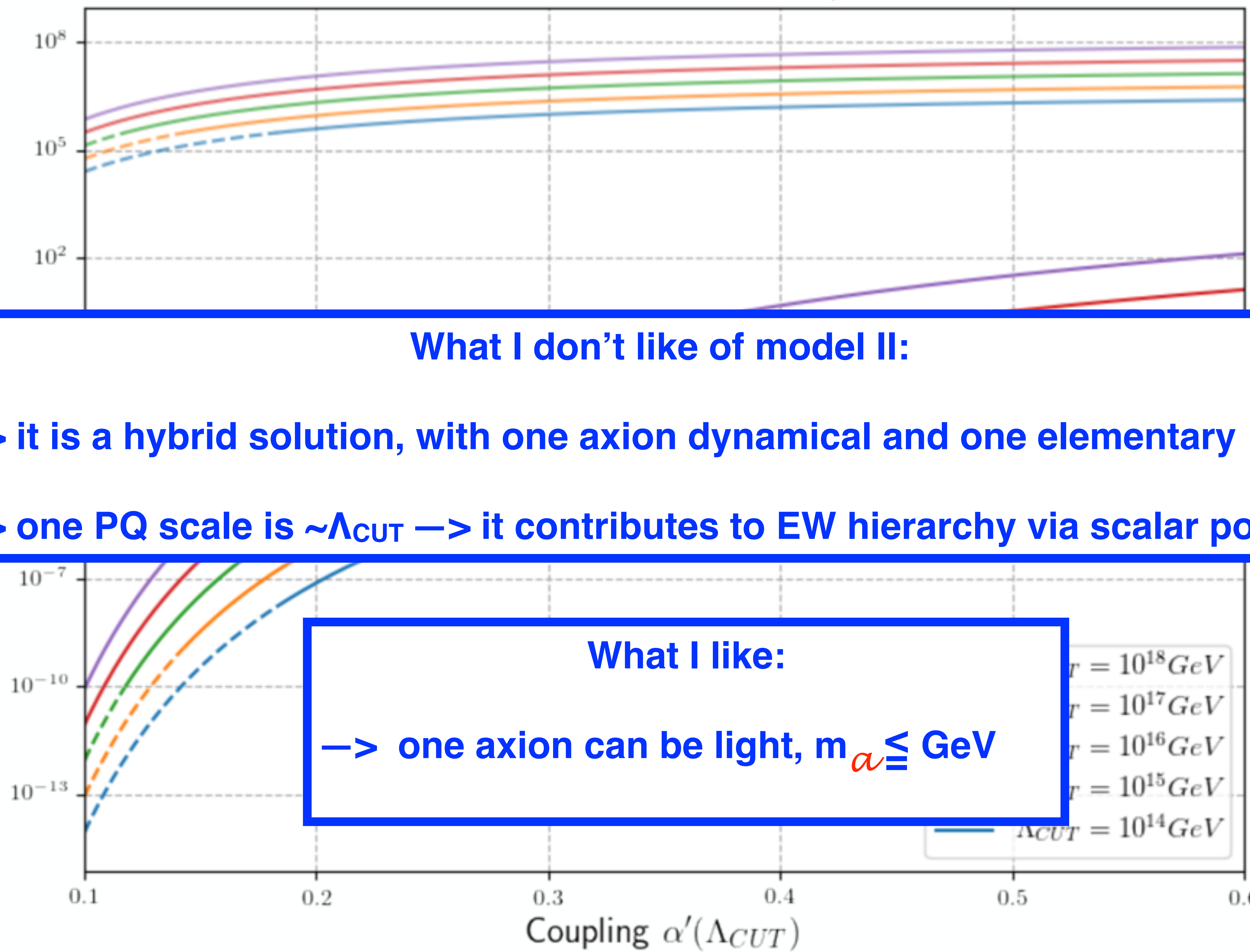


The dynamical axion is still very heavy

the a mass can be ~GeV or lower

Only octet coloured pions under TeV

Axion masses: a, η'_{ψ}



What I don't like of model II:

—> it is a hybrid solution, with one axion dynamical and one elementary

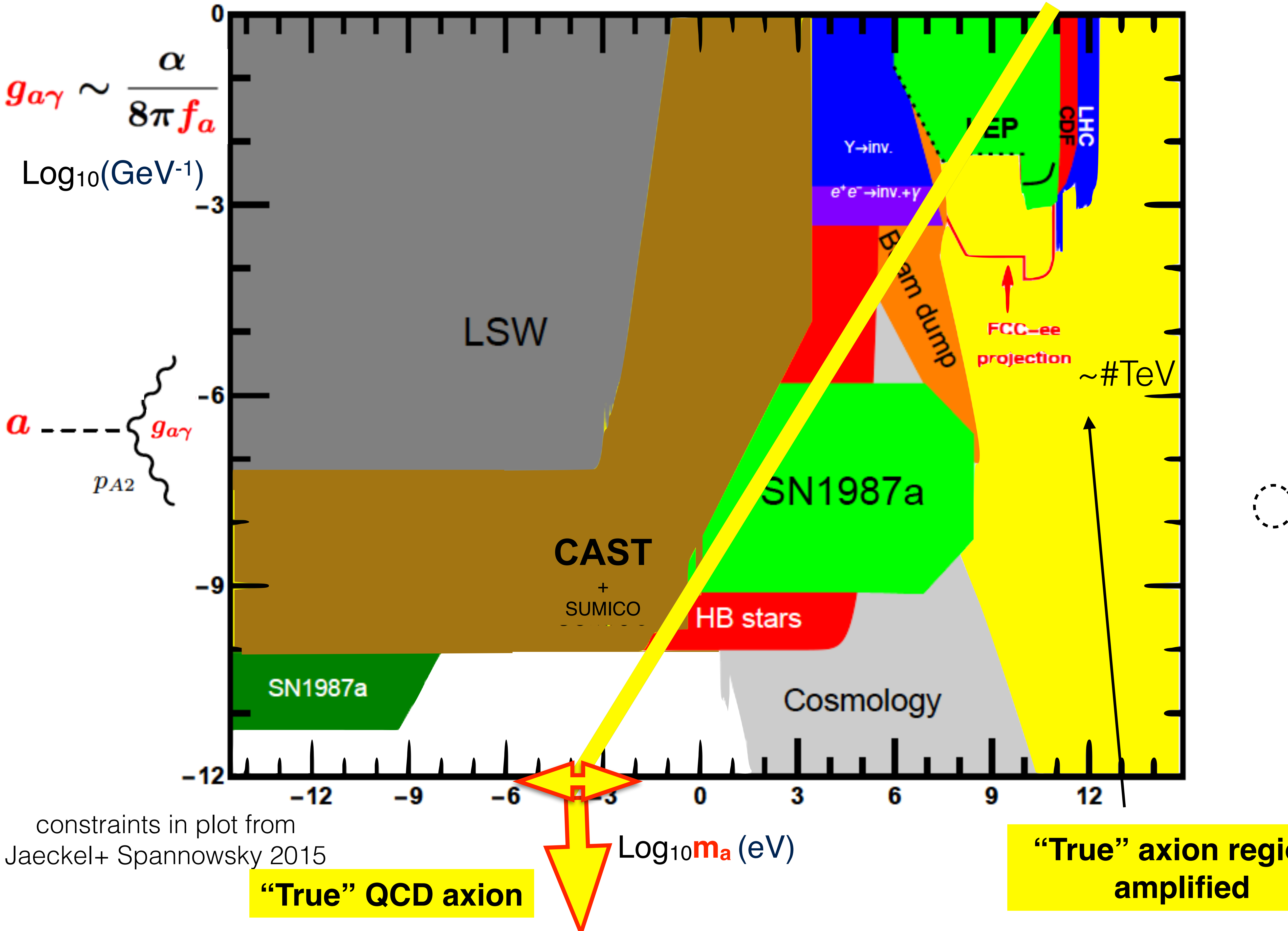
—> one PQ scale is ~Λ_{CUT} —> it contributes to EW hierarchy via scalar potential

What I like:

—> one axion can be light, $m_{a} \lesssim$ GeV

* Much territory to explore for heavy 'true" axions

$$g_{a\gamma} \sim \frac{\alpha}{8\pi f_a}$$



constraints in plot from
Jaeckel+ Spannowsky 2015

"True" QCD axion

"True" axion region
amplified

Conclusions

New solution to strong the CP problem:

Colour unification with massless quarks SU(6)xSU(3')

This is a proof of concept

—> Axions heavy due to small-size instantons

—> (~massless) Sterile neutrinos, basically invisible

—> Colored mesons observable at colliders

The $\{m_a, f_a\}$ region that solves the strong CP problem is amplified

Backup

Massless Quarks and a Z_2

- Only one massless quark
- Complete Z_2 copy of the SM
- The $SU(3)_2$ θ-angle doesn't introduce new CP violating effects

Z_2

	$SU(3)_c$	$SU(3)_2$
ψ	$\square$	$\square$

A. Hook, "Anomalous solutions to the strong CP problem," Phys. Rev. Lett. 114 (2015)

- Set up one Higgs VEV to be very large:

$$v_2 \gg v \quad \rightarrow \quad m_q' \gg m_q \quad \rightarrow \quad \Lambda_{QCD}' \gg \Lambda_{QCD}$$

it requires a complete mirror of SM and strong fine-tunings

The η' Pseudoscalars

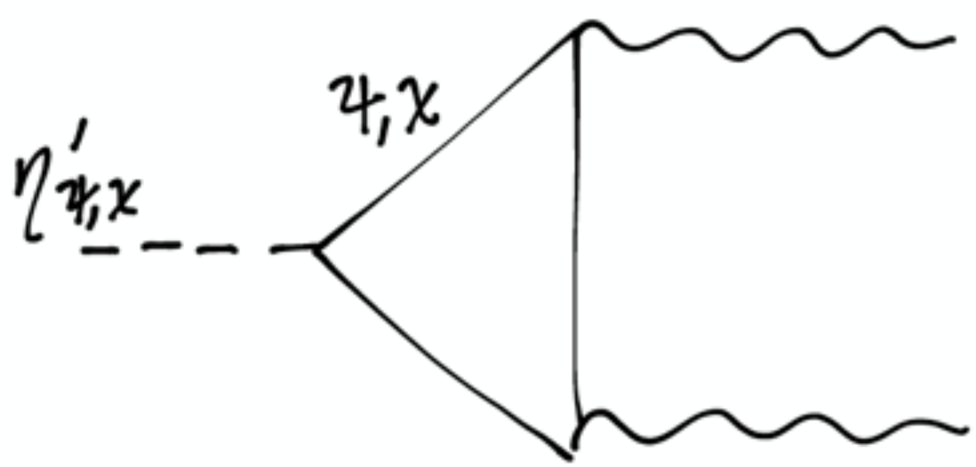
- The associated currents of the QCD singlets are:

$$j^\mu_{\psi_A} = \overline{\psi}\gamma^\mu\gamma^5 t^9 \psi \equiv f_d\,\partial^\mu \eta'_\psi$$

$$j^\mu_{\chi_A} = \overline{\chi}\gamma^\mu\gamma^5 \chi \equiv f_d\,\partial^\mu \eta'_\chi$$

- $t^9 = \frac{1}{\sqrt{6}} \mathbf{1}_{3\times 3}$
- f_d is the pGB scale:

$$\Lambda_{\rm diag} \leq 4\pi f_d$$



$$\partial_\mu j^\mu_{\psi_A} = -\sqrt{6}\,\frac{\alpha_6}{8\pi} G_6 \tilde{G}_6$$

$$\partial_\mu j^\mu_{\chi_A} = -2\,\frac{\alpha'}{8\pi} G' \tilde{G}'$$

The θ' Issue

$$\mathcal{L} \ni \theta_6 \frac{\alpha_6}{8\pi} G_6 \tilde{G}_6 + \theta' \frac{\alpha'}{8\pi} G' \tilde{G}'$$

$$\Downarrow$$

$$\mathcal{L} \ni (\theta_6 + \theta') \frac{\alpha_{\rm diag}}{8\pi} G_{\rm diag} \tilde{G}_{\rm diag} + \theta_6 \frac{\alpha_c}{8\pi} G_c \tilde{G}_c$$

- The θ' can contaminate the visible sector via Δ
- θ' must be removed ➡ This requires more model building
- Note that this comes from the problem of decoupling unification partners

Solution to the Strong CP problem

- ➔ Any source of axion mass breaks the PQ symmetry, do SSI spoil the Strong CP solution?
- ➔ Breaking pattern imposes:

$$\mathcal{L} \supset \bar{\theta}_6 \frac{\alpha_6}{8\pi} G_6 \tilde{G}_6 + \bar{\theta}' \frac{\alpha'}{8\pi} G' \tilde{G}' \longrightarrow (\bar{\theta}_6 + \bar{\theta}') \frac{\alpha_{\rm diag}}{8\pi} G_{\rm diag} \tilde{G}_{\rm diag} + \bar{\theta}_6 \frac{\alpha_c}{8\pi} G_c \tilde{G}_c$$

- ➔ Therefore the potential reads:

$$\mathcal{L}_{eff} = \Lambda^4_{\rm SSI} \cos\left(-2\frac{\eta'_\chi}{f_{\rm d}} + \bar{\theta}'\right) + \Lambda^4_{\rm diag} \cos\left(-2\frac{\eta'_\chi}{f_{\rm d}} - \sqrt{6}\frac{\eta'_\psi}{f_{\rm d}} + \bar{\theta}' + \bar{\theta}_6\right) + \Lambda^4_{\rm QCD} \cos\left(-\sqrt{6}\frac{\eta'_\psi}{f_{\rm d}} + \bar{\theta}_6\right)$$

- ➔ The alignment of the 3 terms in the potential result in a CP-conserving minimum

$$\left\langle \bar{\theta}' - 2\frac{\eta'_\chi}{f_{\rm d}} \right\rangle = 0\,, \qquad \left\langle \bar{\theta}_6 - \sqrt{6}\frac{\eta'_\psi}{f_{\rm d}} \right\rangle = 0$$

Strong CP problem solved

Matter Content Above and Below CUT Breaking

	$SU(6)$	$SU(3')$	$SU(2)_L$
Q_L	$\square$	$\mathbb{1}$	$\square$
$\bar{U}_R$	$\overline{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\bar{D}_R$	$\overline{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\bar{q}'_R$	$\mathbb{1}$	$\overline{\square}$	$\square$
u'_L	$\mathbb{1}$	$\square$	$\mathbb{1}$
d'_L	$\mathbb{1}$	$\square$	$\mathbb{1}$
Ψ	20	$\mathbb{1}$	$\mathbb{1}$
Δ	$\square$	$\overline{\square}$	$\mathbb{1}$

$$\xrightarrow{\Lambda_{\mathrm{CUT}}}$$

	$SU(3)$	$SU(3)_{diag}$	$SU(2)_L$
q_L	$\square$	$\mathbb{1}$	$\square$
$\bar{u}_R$	$\overline{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\bar{d}_R$	$\overline{\square}$	$\mathbb{1}$	$\mathbb{1}$
ψ	$\square$	$\overline{\square}$	$\mathbb{1}$
$2\psi_\nu$	$\mathbb{1}$	$\mathbb{1}$	$\mathbb{1}$
$\tilde{q}_L$	$\mathbb{1}$	$\square$	$\square$
$\bar{\tilde{u}}_R$	$\mathbb{1}$	$\overline{\square}$	$\mathbb{1}$
$\bar{\tilde{d}}_R$	$\mathbb{1}$	$\overline{\square}$	$\mathbb{1}$
$\bar{q}'_R$	$\mathbb{1}$	$\overline{\square}$	$\square$
u'_L	$\mathbb{1}$	$\square$	$\mathbb{1}$
d'_L	$\mathbb{1}$	$\square$	$\mathbb{1}$

Massless quark sector

Obtain mass near the CUT breaking scale

Prime sector

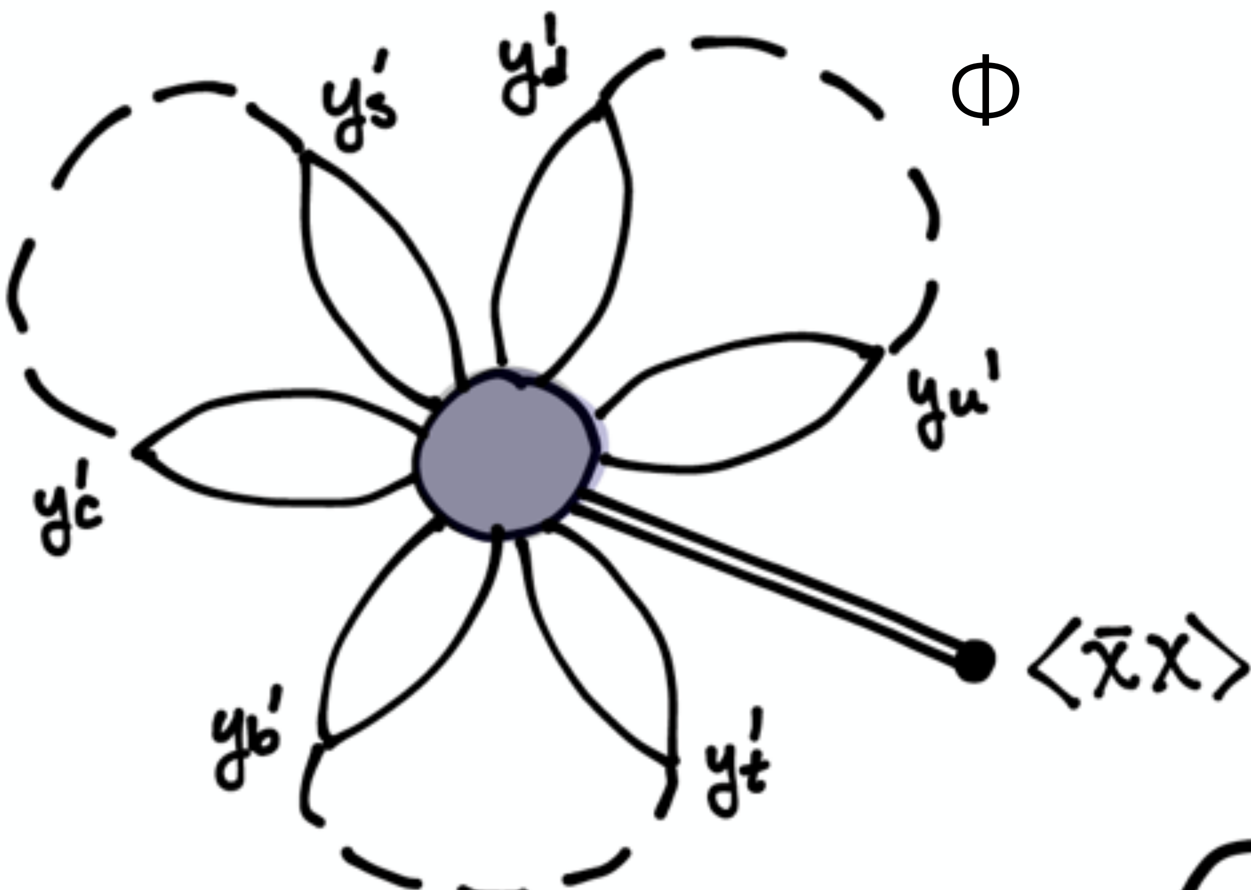
The most general Lagrangian includes also Higgs-prime fermions Yukawa couplings:

$$\mathcal{L} \ni y'_u \, q'_L \Phi u'^c_L + y'_d \, q'_L \tilde{\Phi} d'^c_L \, + \, \mathrm{h.c.}$$

Numerically they give irrelevant corrections

Small Size Instantons with Fermions

- Adding fermion effects gives an instanton suppression



M. A. Shifman, A. I. Vainshtein, V. I. Sakharov, "Instanton Density in a Theory with Massless Quarks," Nucl. Phys. B163 (1980)

J. Flynn, L. Randall, "A computation of the small instanton contribution to the axion potential." Nucl. Phys. B208 (1987)

$$\Lambda_{SSI}^4 = -\int \frac{d\rho}{\rho^5} D[\alpha'(1/\rho)] \overbrace{\left(\frac{2}{3}\pi^2\rho^3\langle\bar{\chi}\chi\rangle\right)\frac{1}{(4\pi)^6}\prod_i {y'_u}^i {y'_d}^i}^{\text{instanton suppression factor}}$$

Small Size Instantons with Fermions

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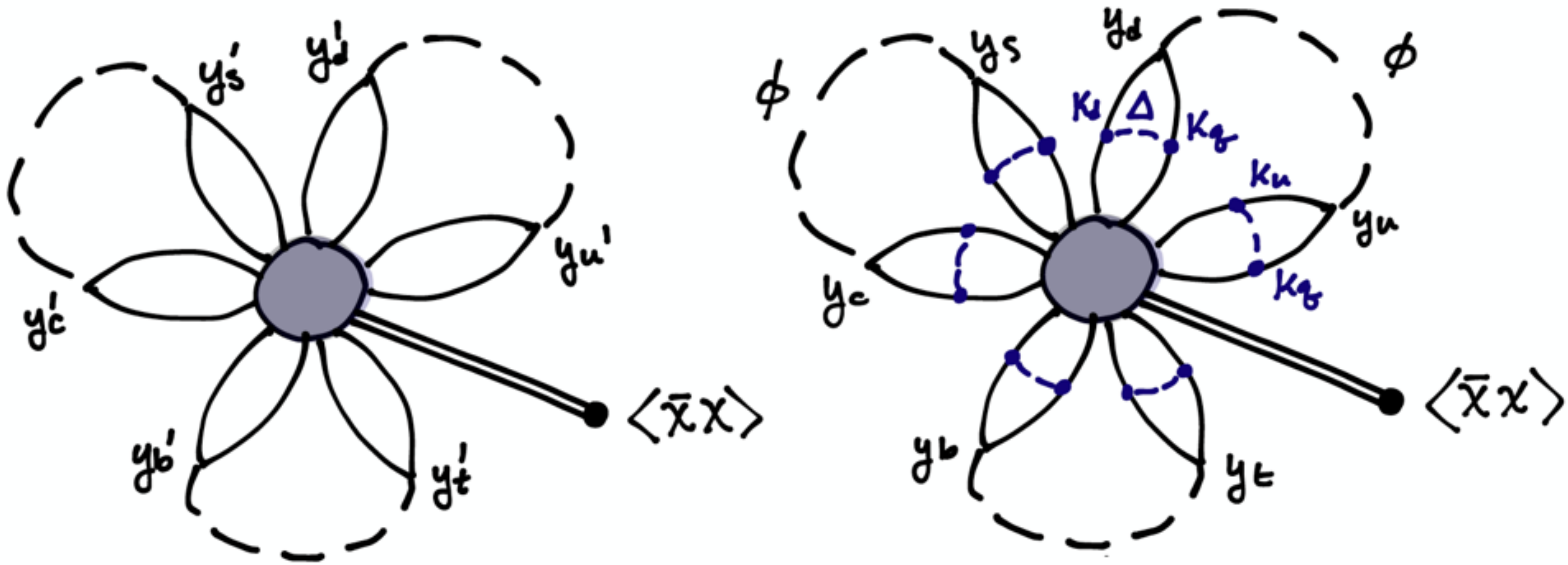


$$\Lambda_{SSI}^4 = -\int \frac{d\rho}{\rho^5} D[\alpha'(1/\rho)] \left(\frac{2}{3}\pi^2\rho^3\langle\bar{\chi}\chi\rangle\right) \frac{1}{(4\pi)^{18}} \prod_i {Y_u}_i^{SM} {Y_d}_i^{SM} \left(\kappa_q^i\right)^2 \kappa_u^i \kappa_d^i$$

Small Size Instantons and Axion Mass

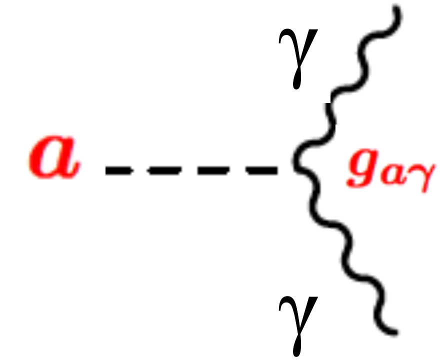
- With the fermion suppression, the benchmark $\alpha'(\Lambda_{\rm CUT}) = .3$ gives:

$$\Lambda_{SSI}^4 \simeq 5.8 \times 10^{-11} \Lambda_{\rm diag}^3 \Lambda_{CUT} \Rightarrow \Lambda_{SSI} \sim \text{few TeV}$$

- The instanton effects generate a new contribution to the effective potential

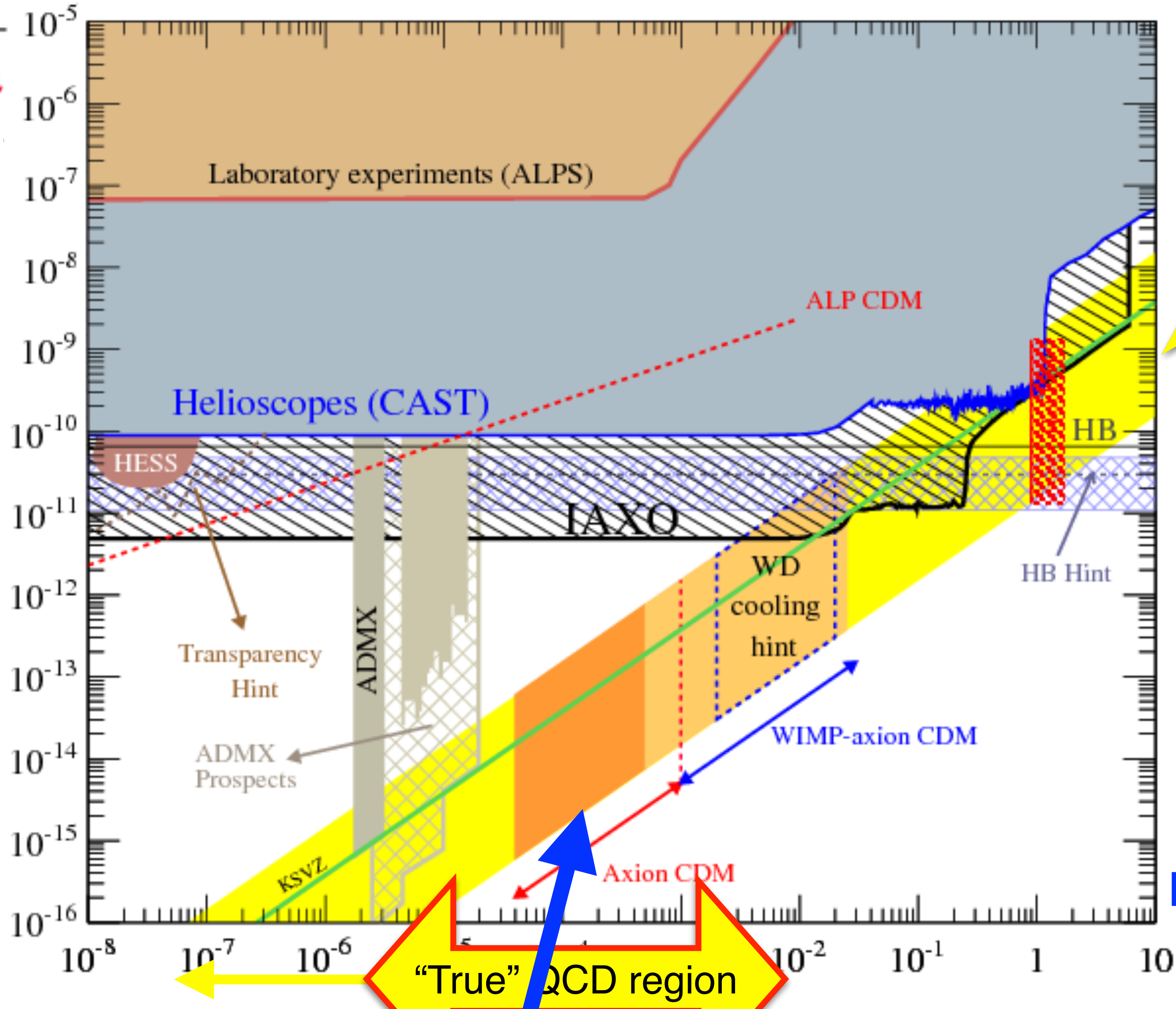
$$\delta\mathcal{L}_{eff} = \Lambda_{SSI}^4 \cos\left(2\frac{\eta'_\chi}{f_d}\right)$$

Intensely looked for experimentally…



$$g_{a\gamma} \sim \frac{\alpha}{8\pi f_a}$$

(GeV-1)



"True" QCD axion band

II

"Invisible axion"

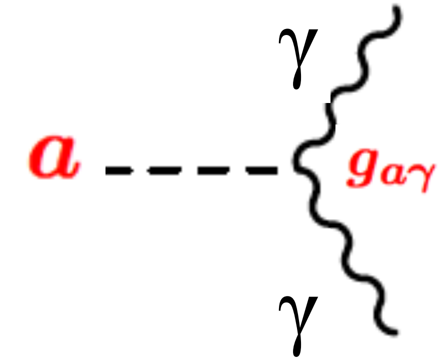
e.g. KSVZ, DFSZ…

v<< f_a —>

EW hierarchy problem

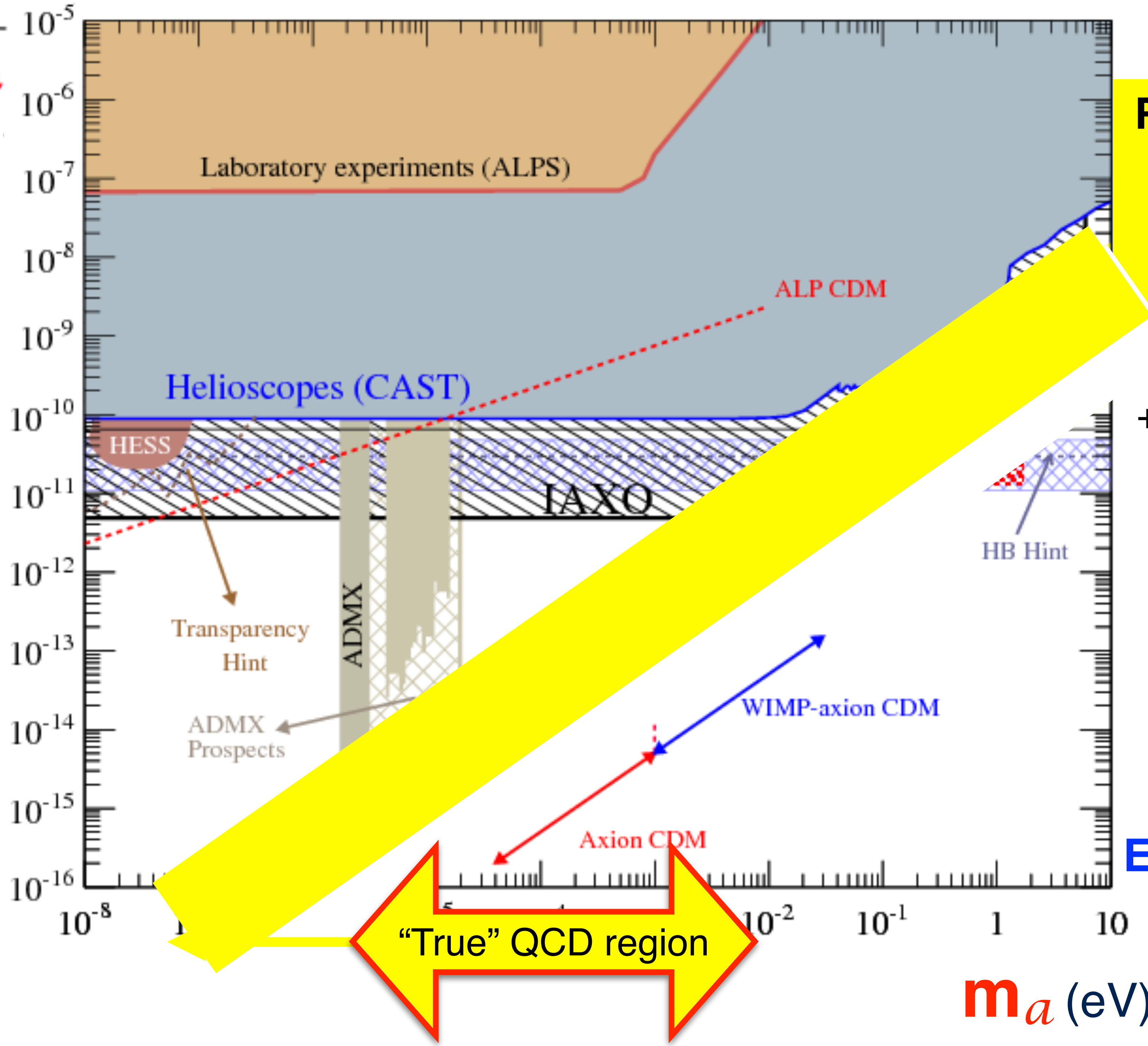
https://arx

Much activity in estimating the value of the "cte."= m_a f_a with lattice QCD. 2015: Cortona et al. ;Trunin et al.; 2016: Borsanyi et al., Petreczky et al., Taniguhi et al., Frison et al.



$$g_{a\gamma} \sim \frac{\alpha}{8\pi f_a}$$

(GeV^{-1})



Refined KSVZ axion band: up and thinner

from Ω_{DM}
+ Landau-poles analysis

(Luzio+Mescia+Nardi 2017)

v<< f_a —>
EW hierarchy problem

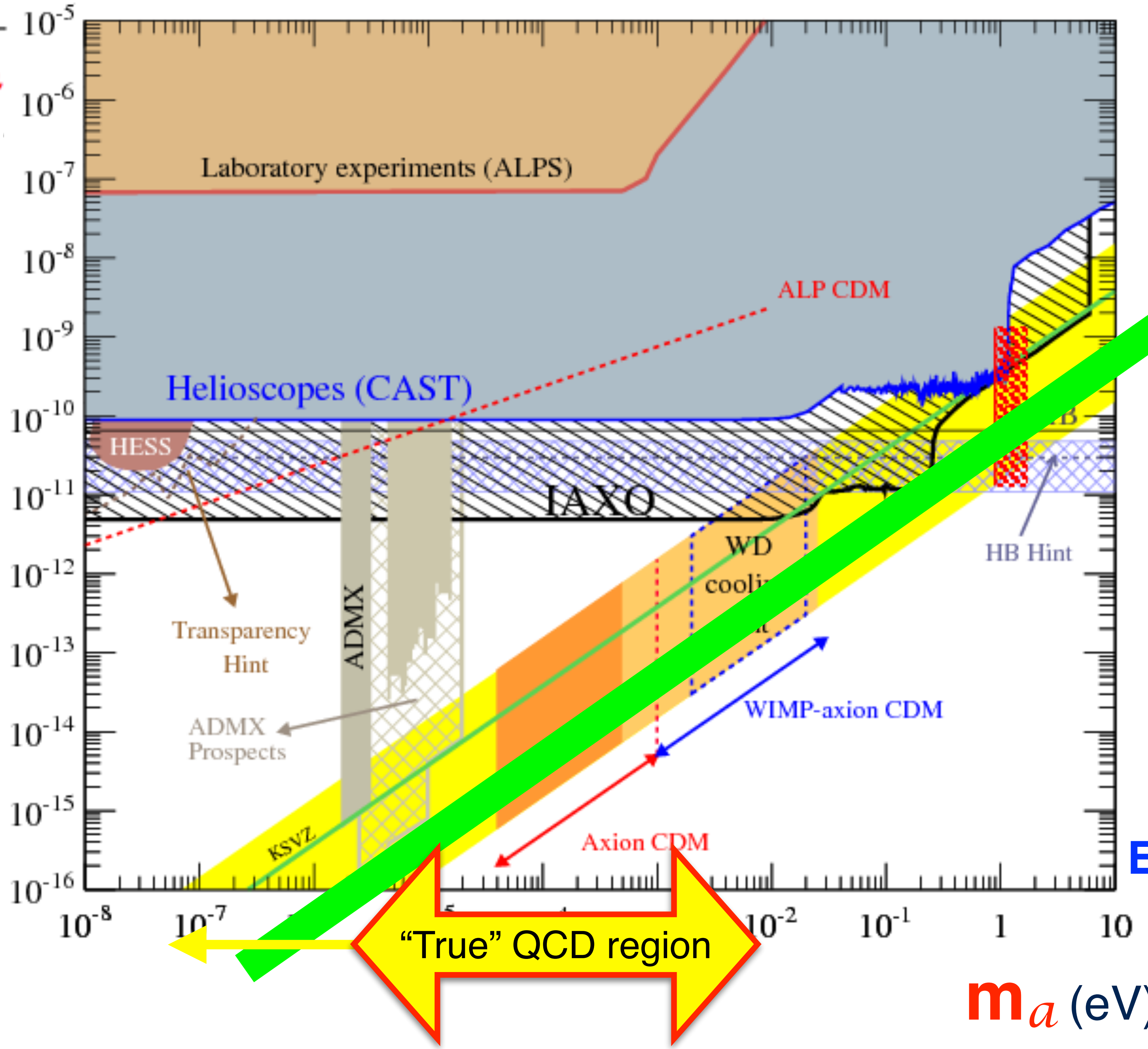
m_a (eV)

… and theoretically

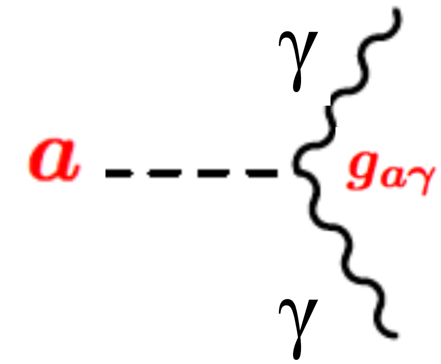
https://arxiv.org/pdf/1611.04652.pdf

$$g_{a\gamma} \sim \frac{\alpha}{8\pi f_a}$$

(GeV^{-1})



m_a (eV)



QCD axiflavon band
(creative view)

(Wilczek 82,
Calibbi et al. 2016)

Identify U(1) of
Peccei-Quinn
with Froggat-Nielsen's

v<< f_a —>
EW hierarchy problem

… and theoretically

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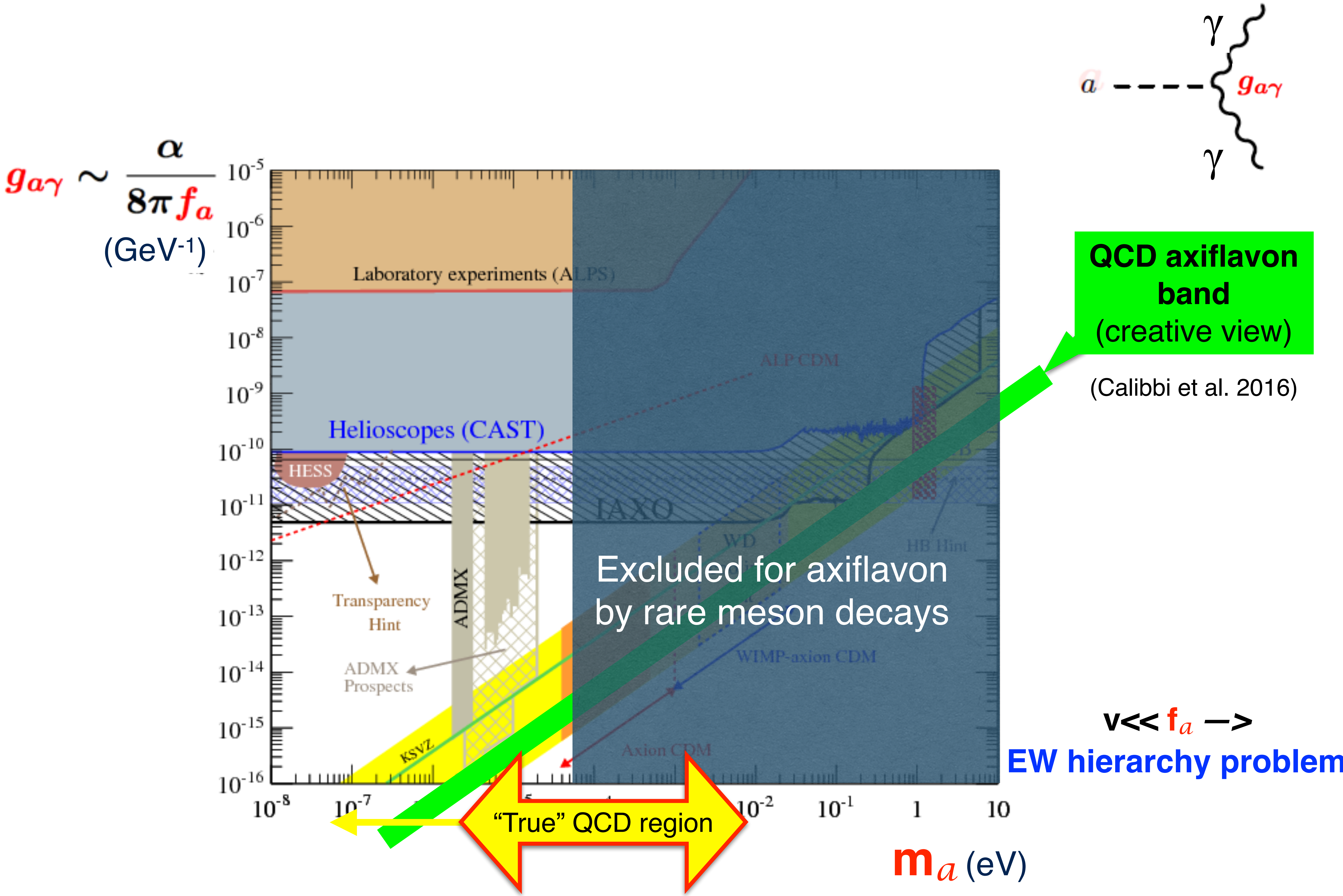

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