New Avenues to Axions

Belén Gavela
Univ. Autónoma de Madrid and IFT

**The Future of Particle Physics:
A Quest for Guiding Principles**

KIT, Karlsruhe, October 1-2 2018

UNIVERSIDAD AUTONOMA DE MADRID ift H2020 elusives invisiblesPlus

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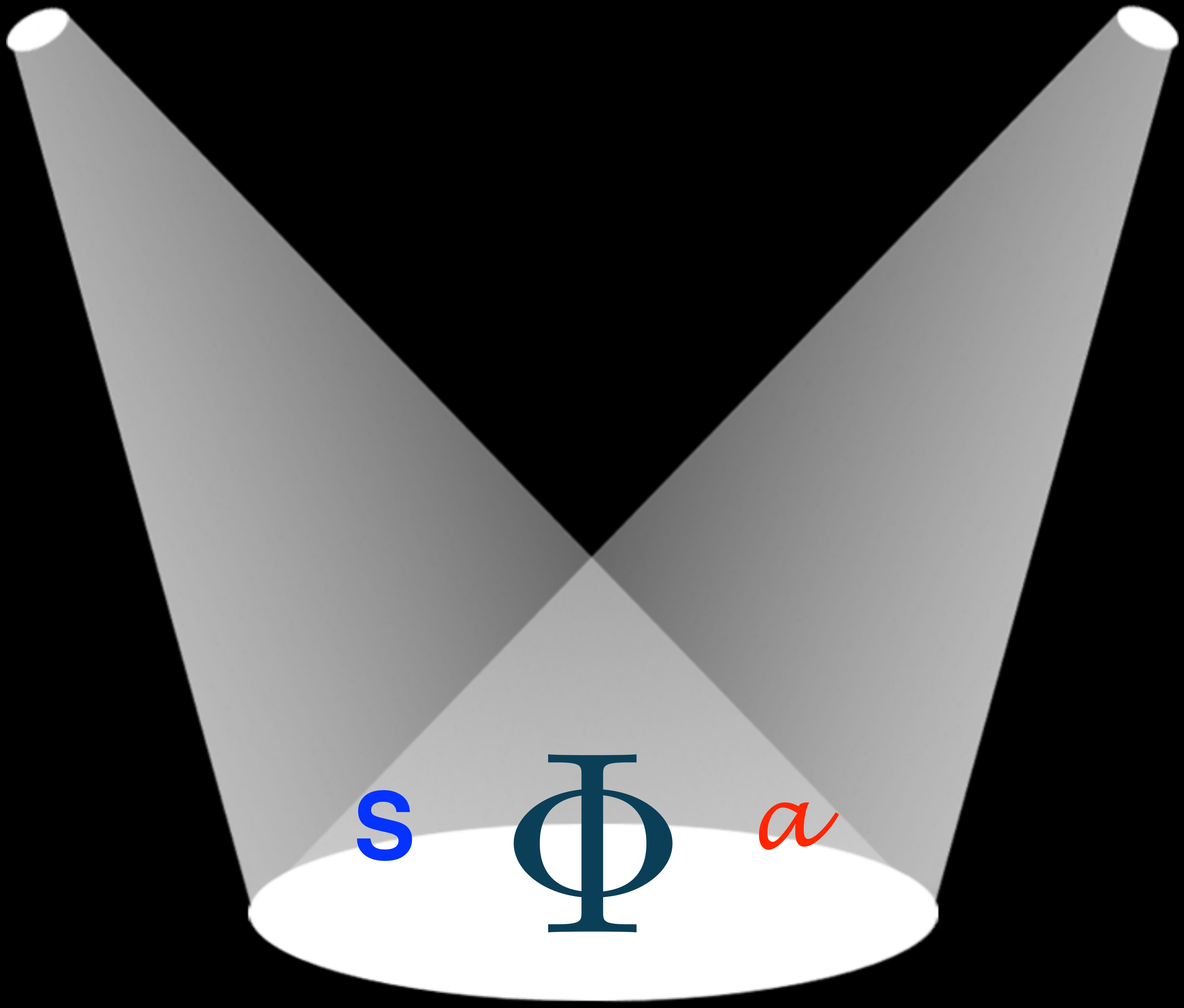
The SM Higgs is a ~ doublet of $SU(2)_L$

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

↓

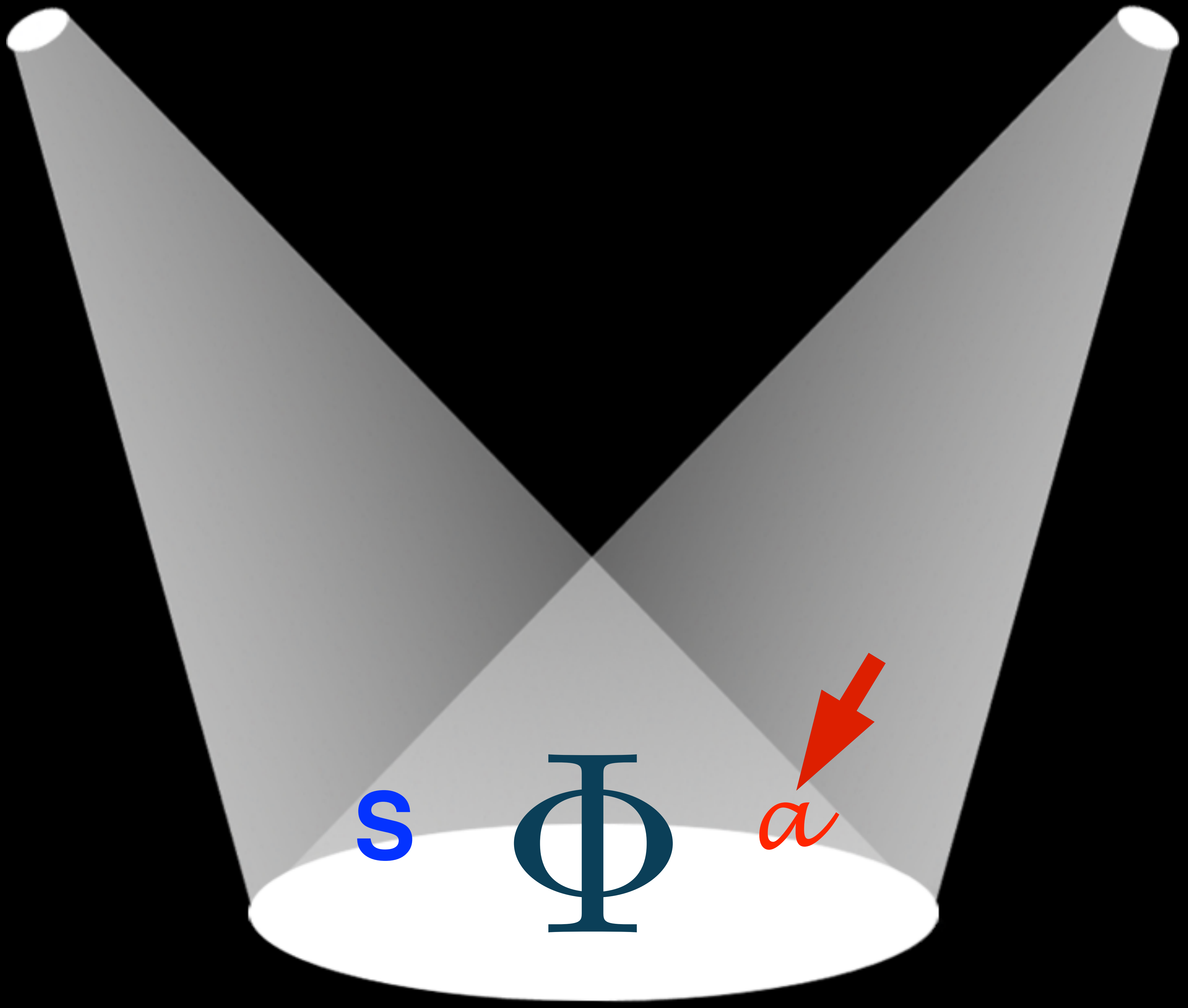
It may be a (SM singlet) scalar S

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

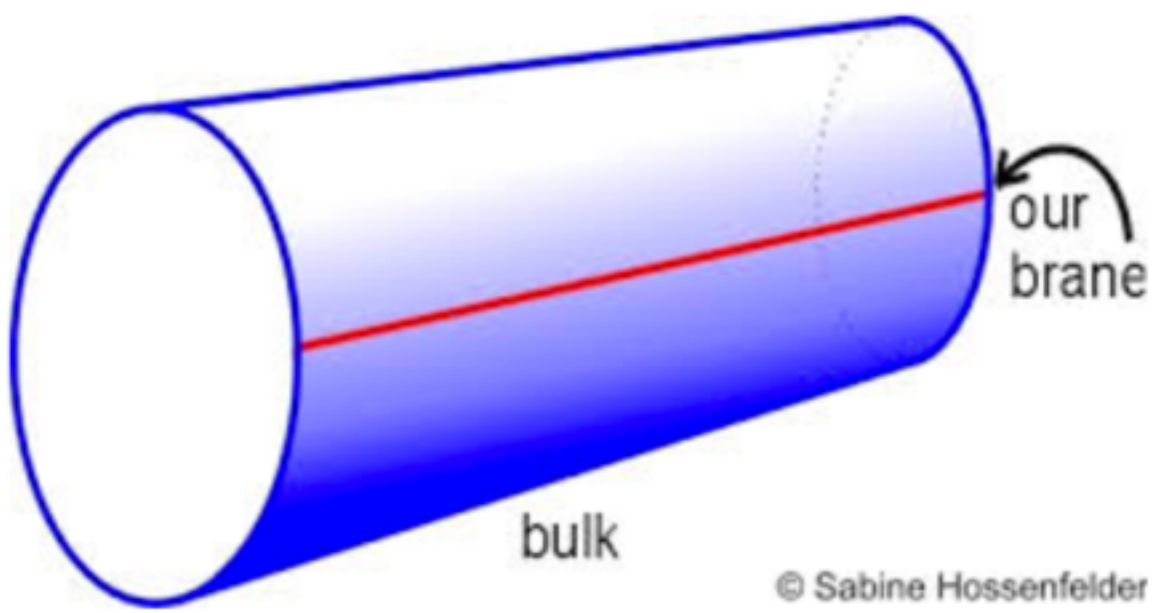
↓

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

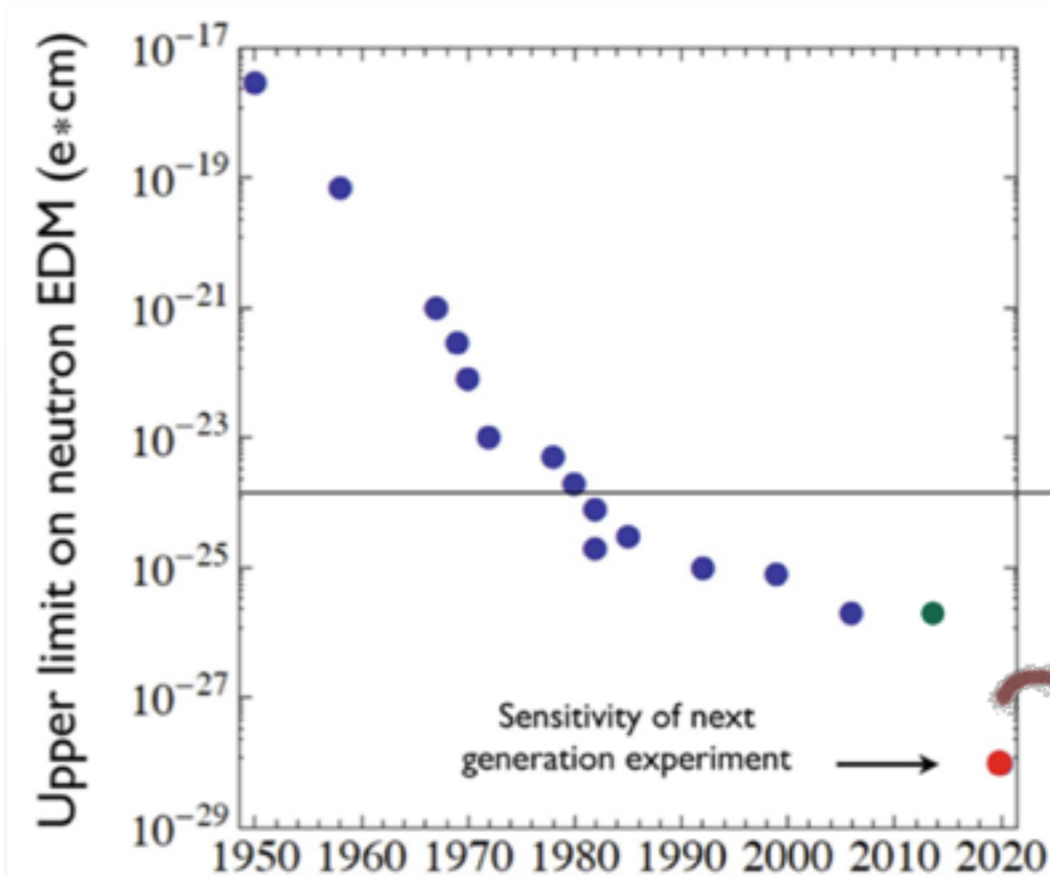
Why is the QCD **θ** parameter so small?

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

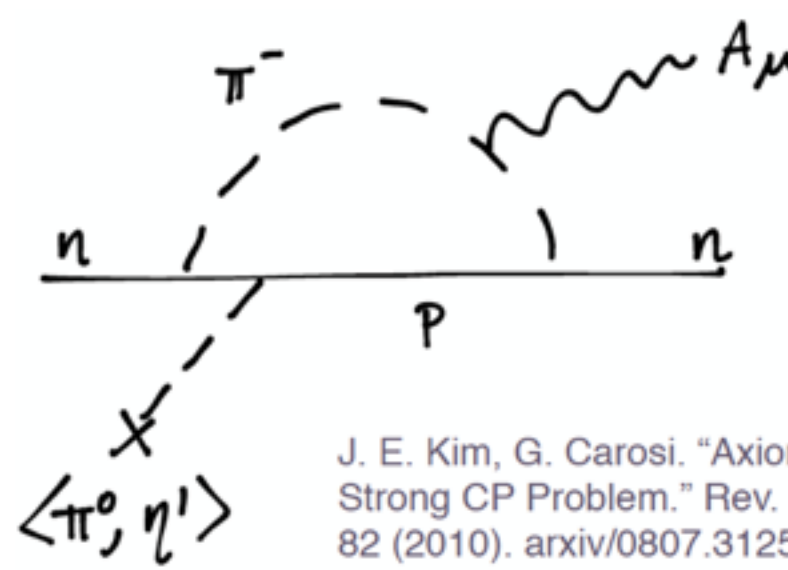
STRONG CP PROBLEM

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

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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A dynamical $U(1)_A$ solution

→ the axion a

It is a pGB: ~only derivative couplings

$$\partial_\mu a$$

Also excellent DM candidate

Peccei+Quinn; Wilczek…

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An axion a is any Goldstone Boson of a global U(1) symmetry which is exact at classical level but is explicitly broken <u>only</u> by instantons

pseudo- ↓

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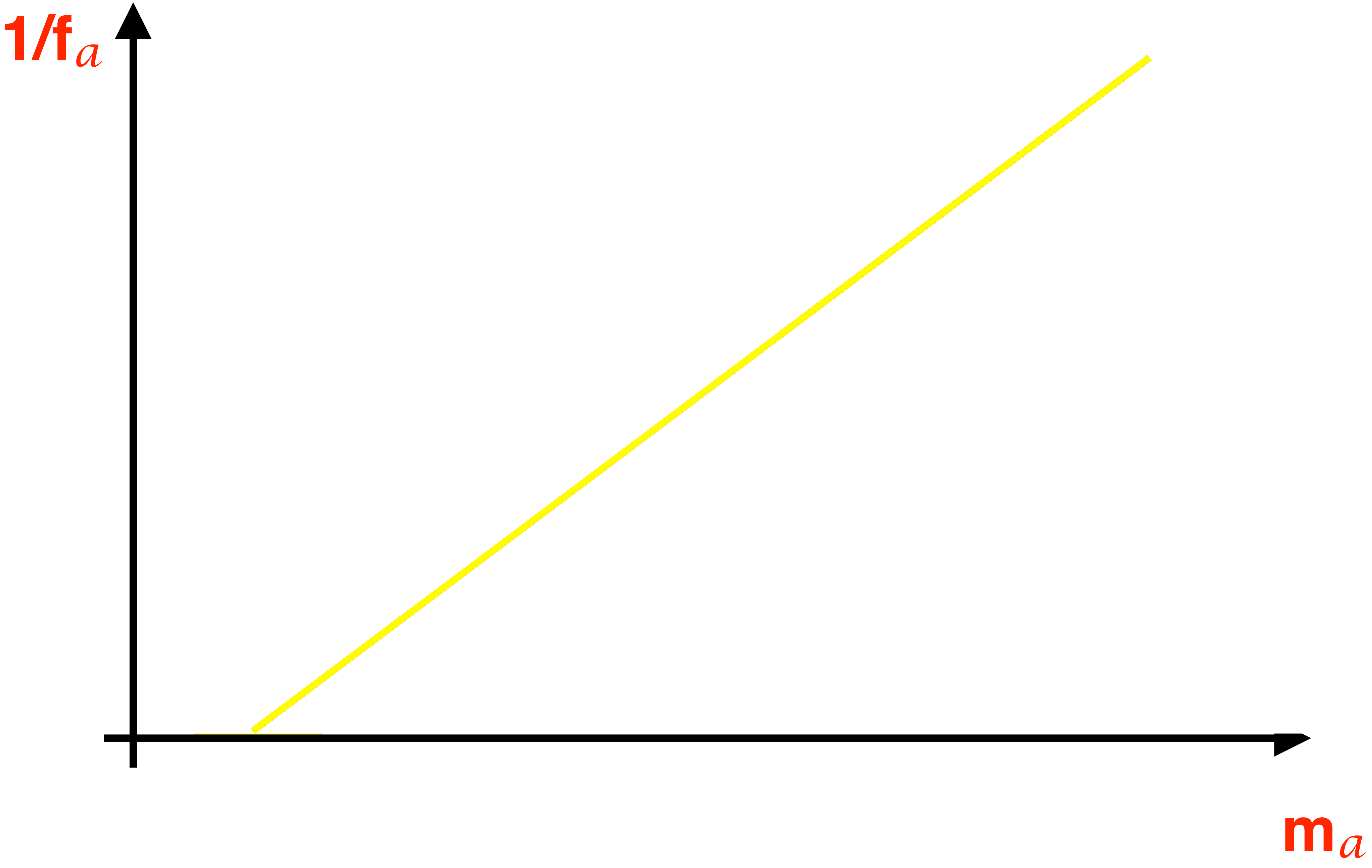
a can be elementary or composite (= dynamical)

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

$$m_a f_a = \text{cte.}$$



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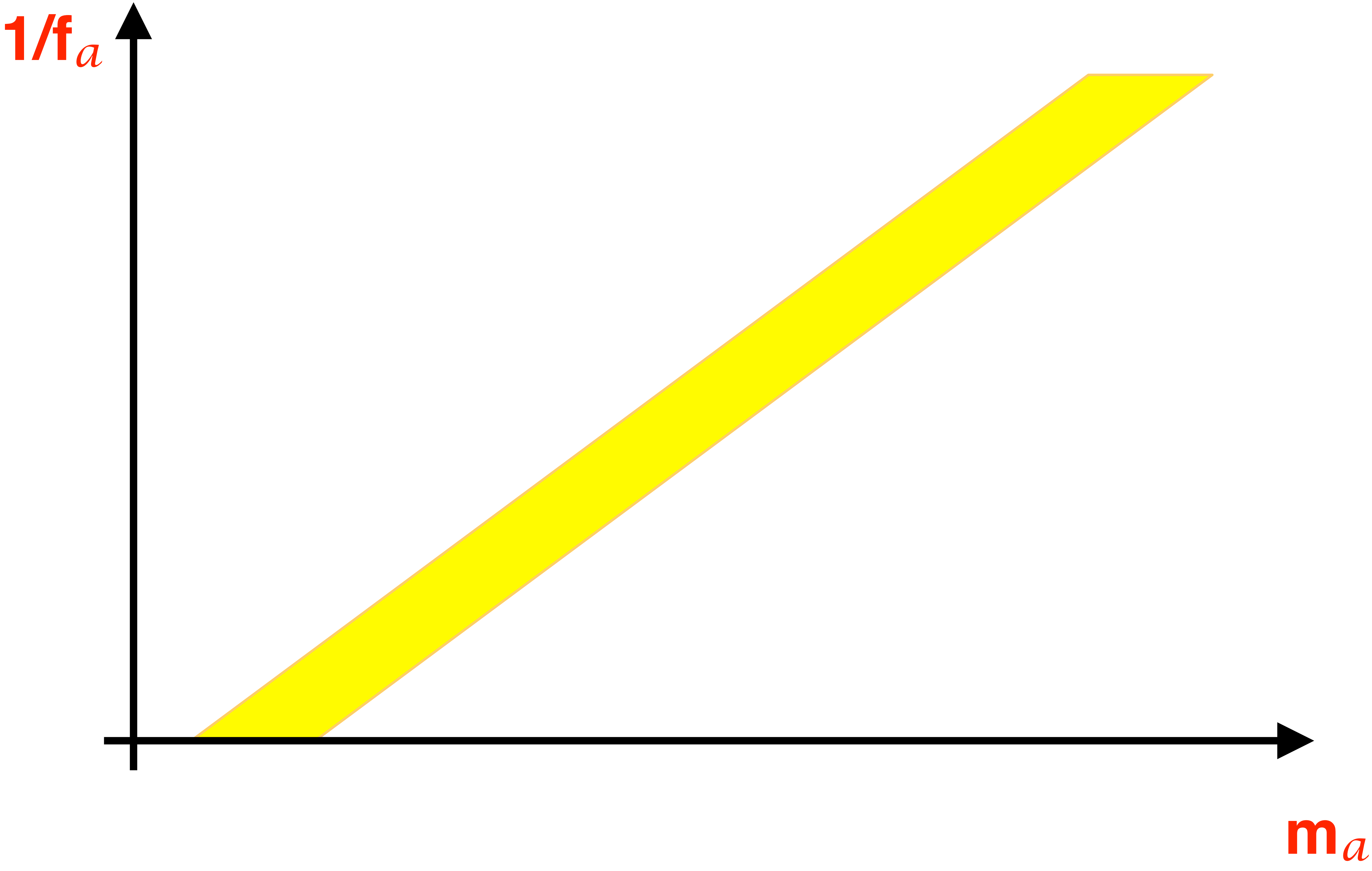

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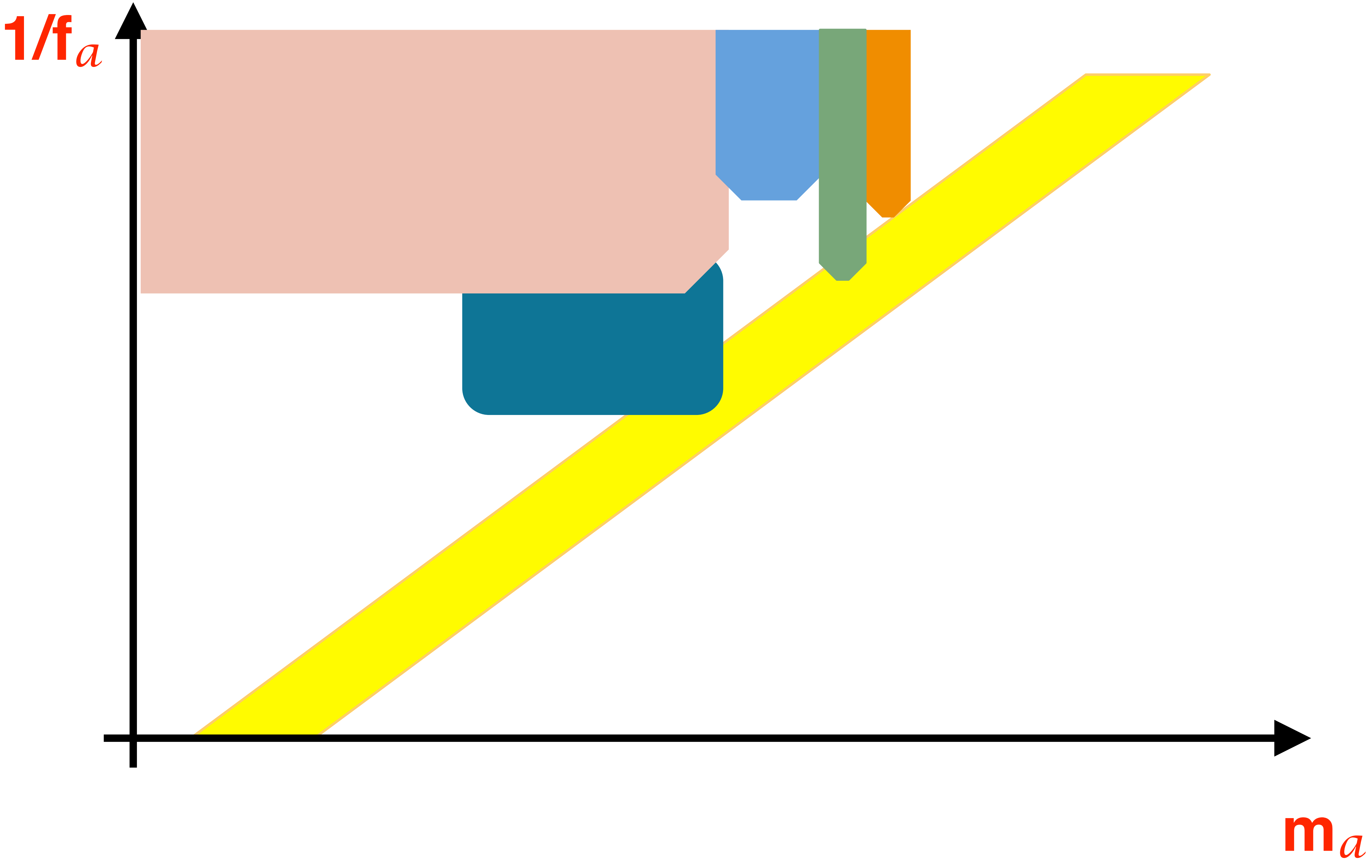

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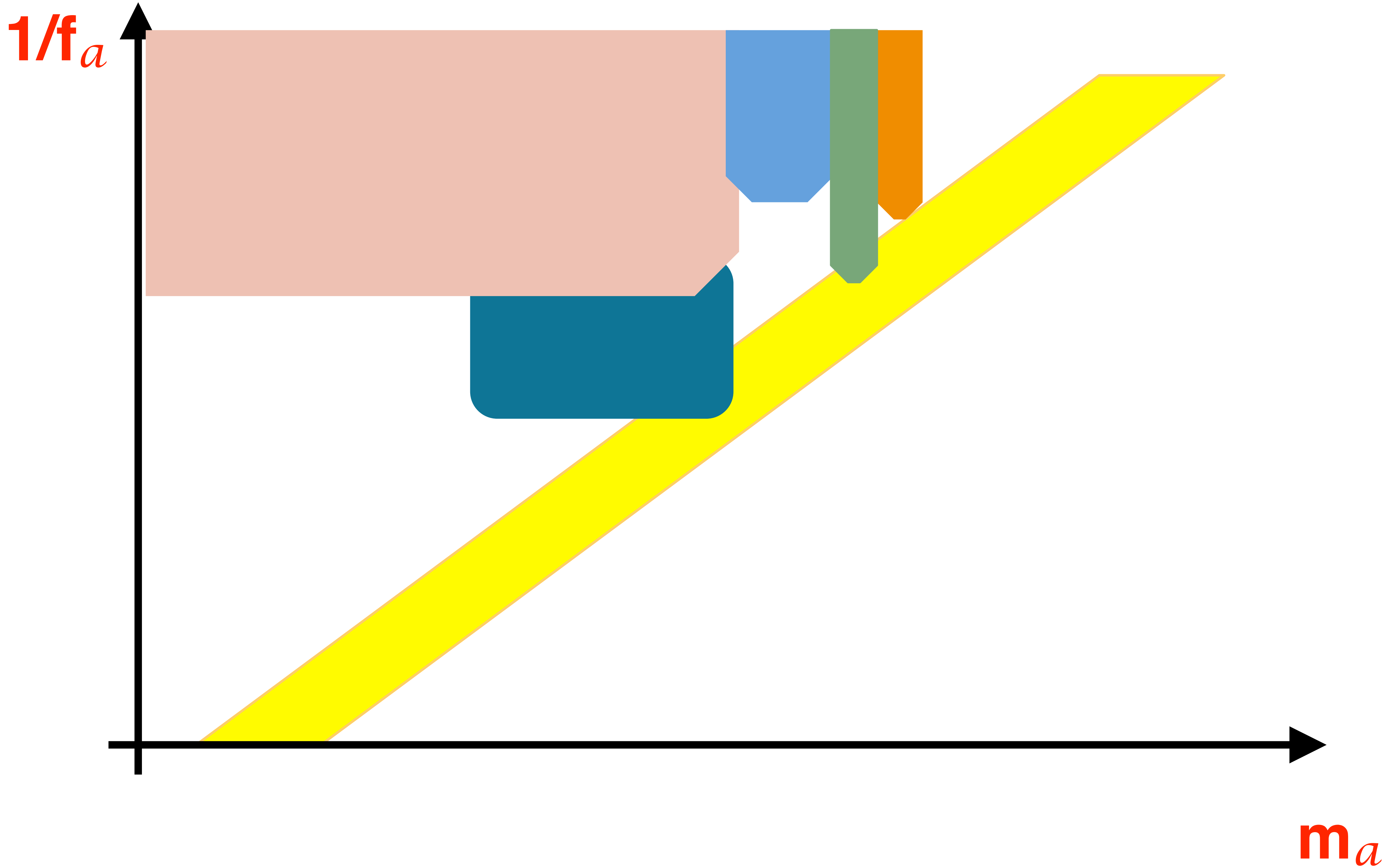

The value of the constant is determined by the strong gauge group

m_a vs scale f_a

$g_a \sim 1/f_a$

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

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

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

$\Lambda \ll m_q$: Λ^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 $m_q \longrightarrow 0$ vanishes

The reason is that there is only one anomalous current

$G_c \tilde{G}_c$ (of QCD) $\longleftrightarrow$ Λ_{QCD}

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

η'_{QCD} a

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

and that one is the "Invisible axion" as $f_a \sim 1/m_a$

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

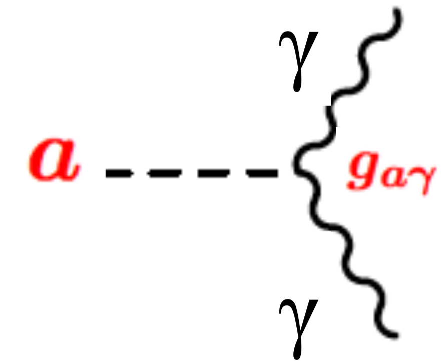
$\Lambda \ll m_q$: Λ^4

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

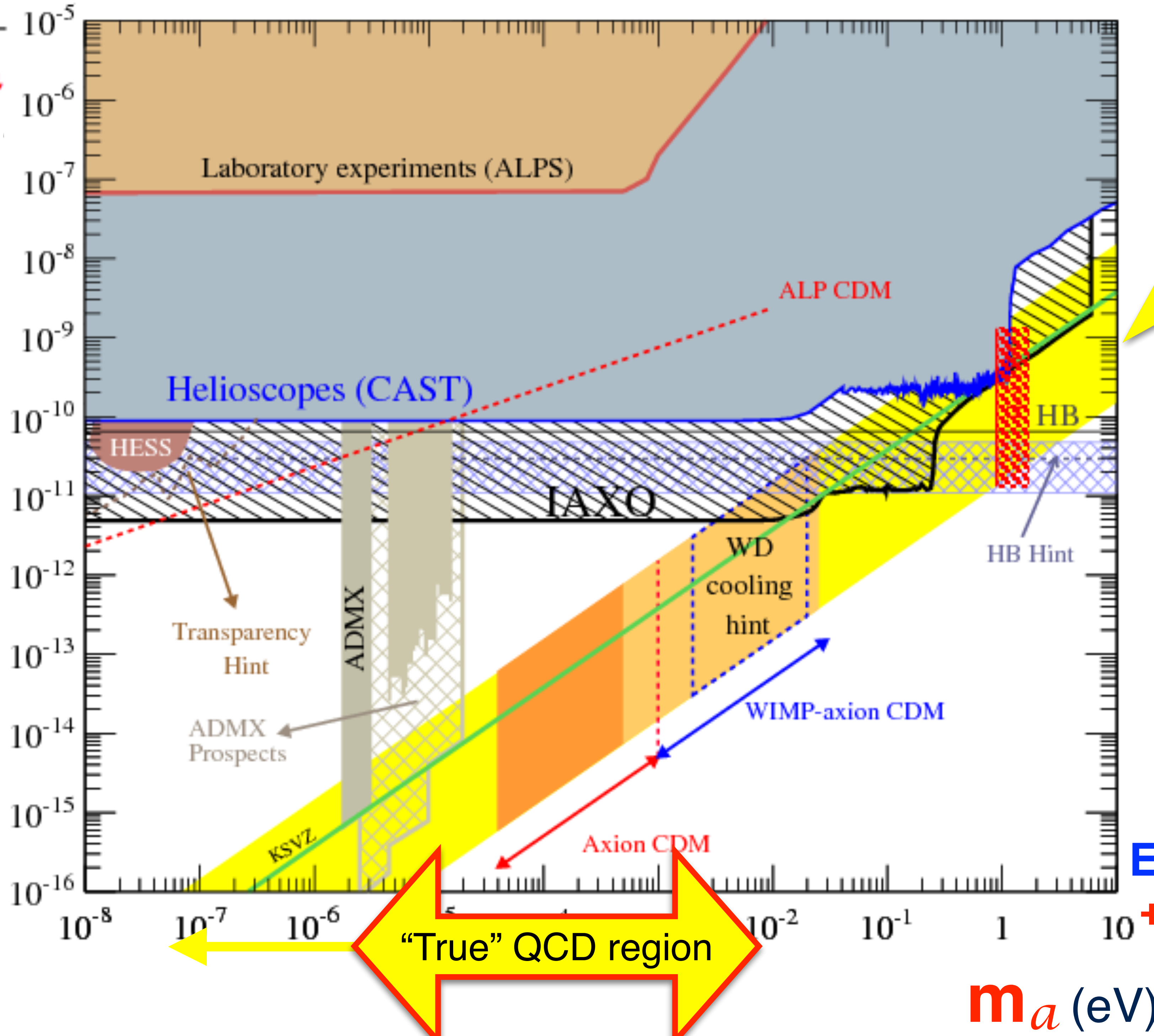
Because of SN and hadronic data, if axions light enough to be emitted (and $m_a f_a$ = **cte.**)

"Invisible axion"

Intensely looked for experimentally…



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



“True” QCD axion band
=
“Invisible axion”
e.g. KSVZ, DFSZ…

v<< f_a —>
EW hierarchy problem
+ gravitational tunings ?

… and theoretically

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

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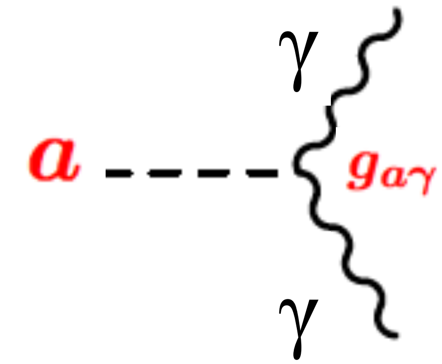

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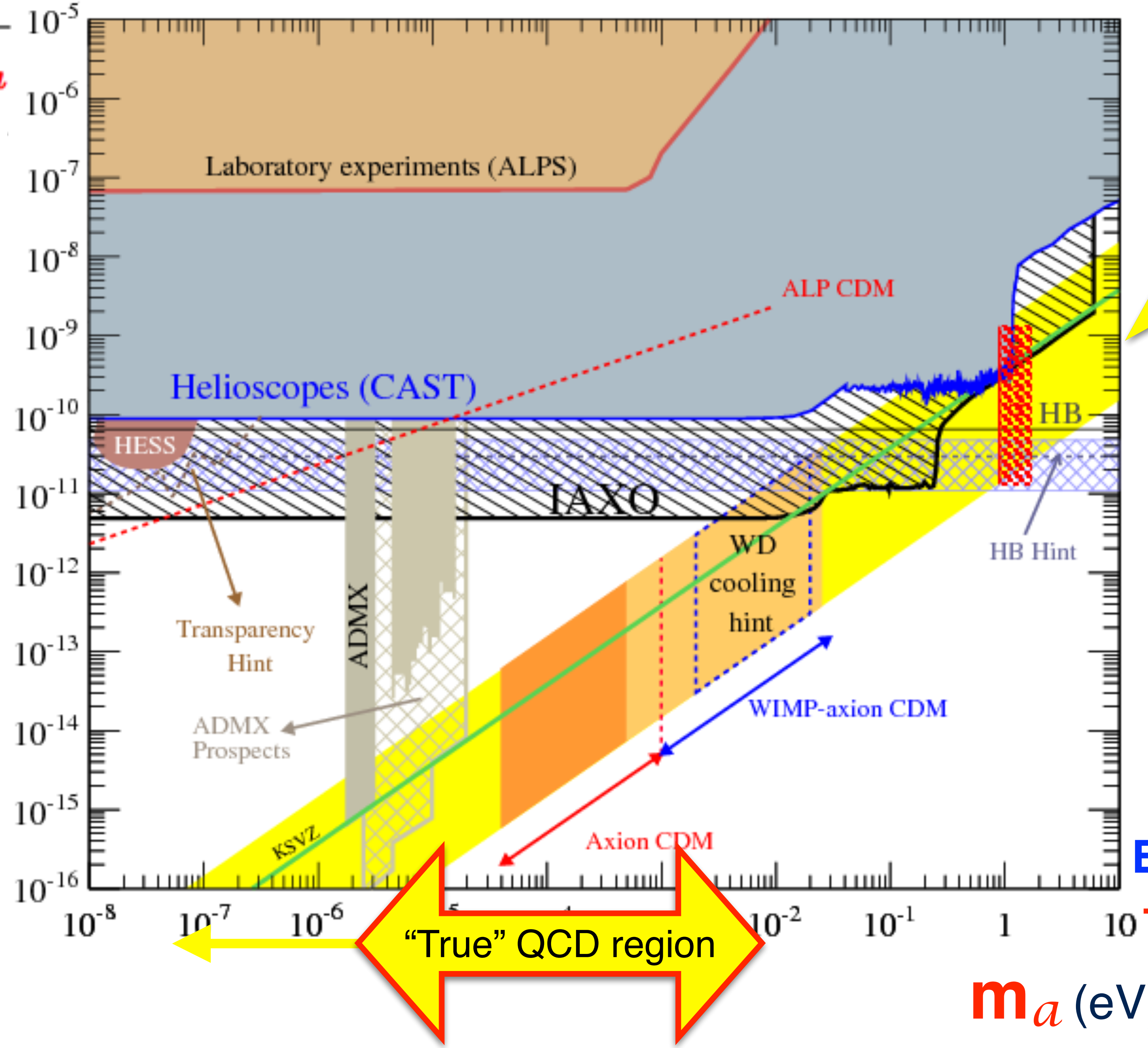
(GeV^{-1})



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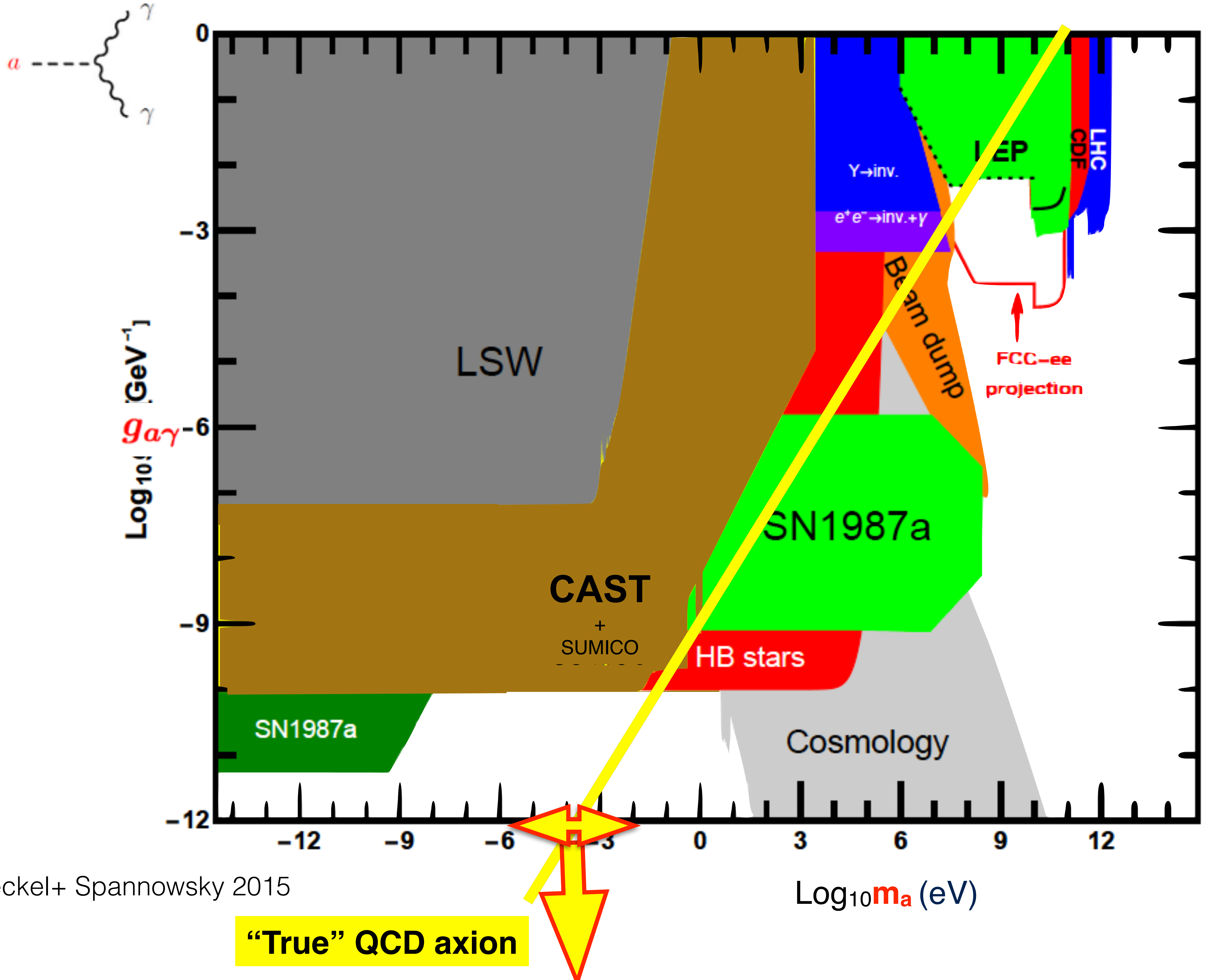
* Territory to explore for ‘true” axions and for ALPs

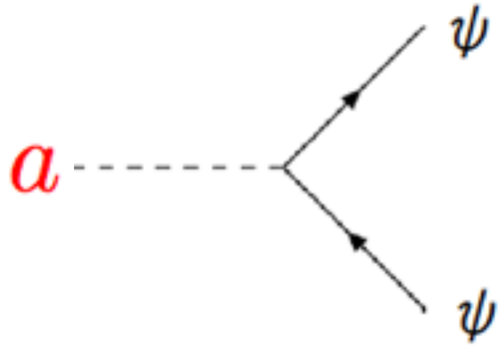


Jaeckel+ Spannowsky 2015

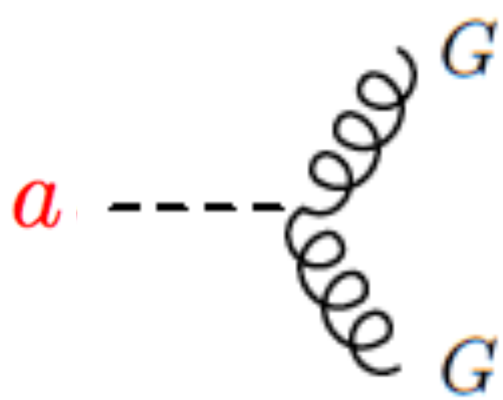
The field is BLOOMING

in Experiment … and Theory

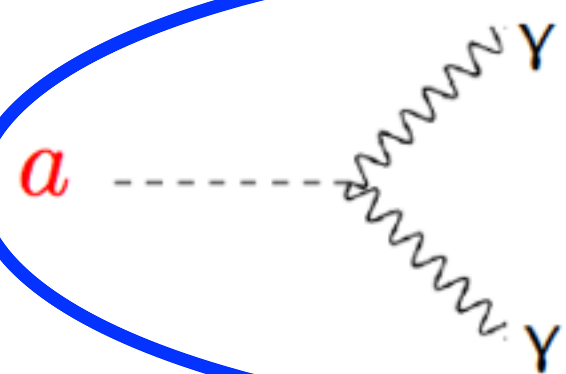
Most efforts focus on axion and ALP couplings to fermions, gluons, and **especially photons**



$$\partial_\mu a\, \bar{\psi}\gamma_\mu\psi$$



$$a\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$



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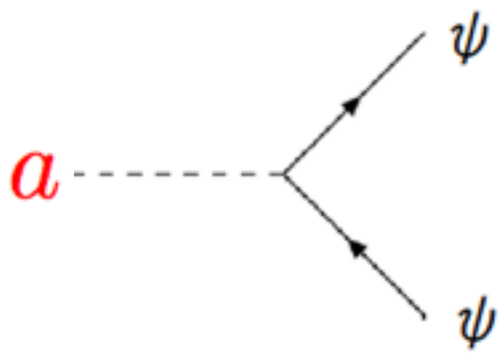

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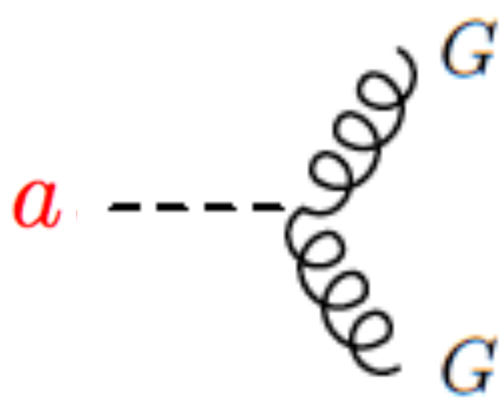

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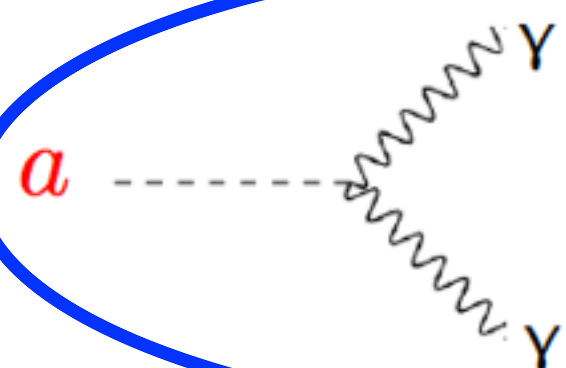

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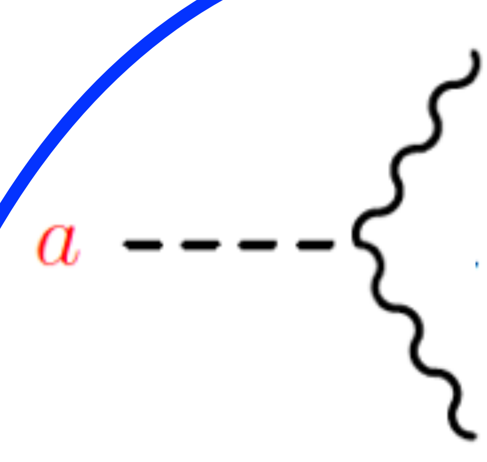
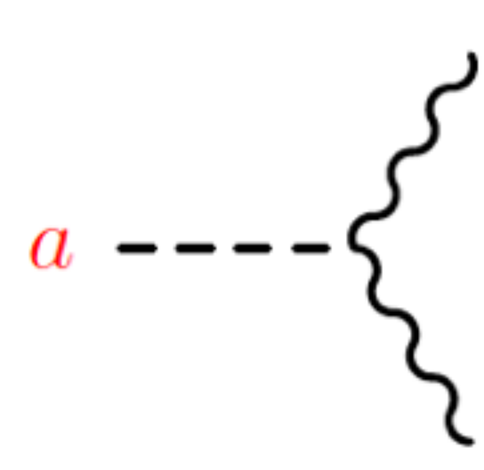
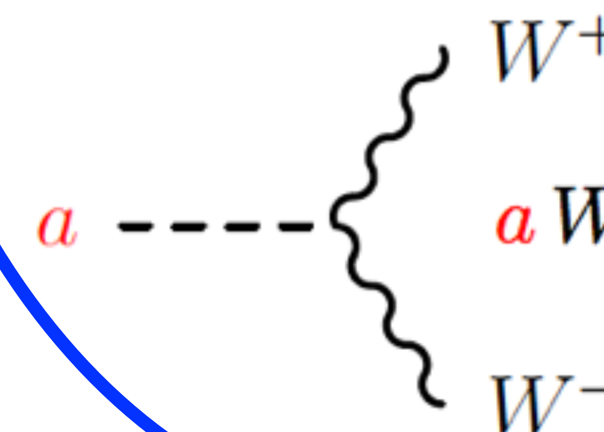


$$a\,F_{\mu\nu}\tilde{Z}^{\mu\nu}$$



$$a\,Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$



$$a\,W_{\mu\nu}\tilde{W}^{\mu\nu}$$

arXiv:1701.05379

…. plus W and Z because of gauge invariance, and even the Higgs

Mimasu+Sanz 2015, Jaeckel and Spannowsky 2015, Brivio et al. 2017, Bauer et al. 2017…..

Experiment: new experiments and new detection ideas

* Helioscopes: axions produced in the sun.

  CAST, Baby-IAXO, TASTE, SUMICO

* Haloscopes: assume that all DM are axions

  ADMX, HAYSTACK, QUAX, CASPER, Atomic

* Traditional DM direct detection: axion/ALP DM

  XENON100

* Lab. search: LSW (light shining through wall,ALPS, OSQAR)

  PVLAS (vacuum pol.)…… and **LHC**!

see C. Braggio talk at Invisibles18

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ALP decaying outside detector:
mono-W, -Z, -H, H->inv
first proposed

later: same approach
with ALP decaying
inside detector

* L ... ou

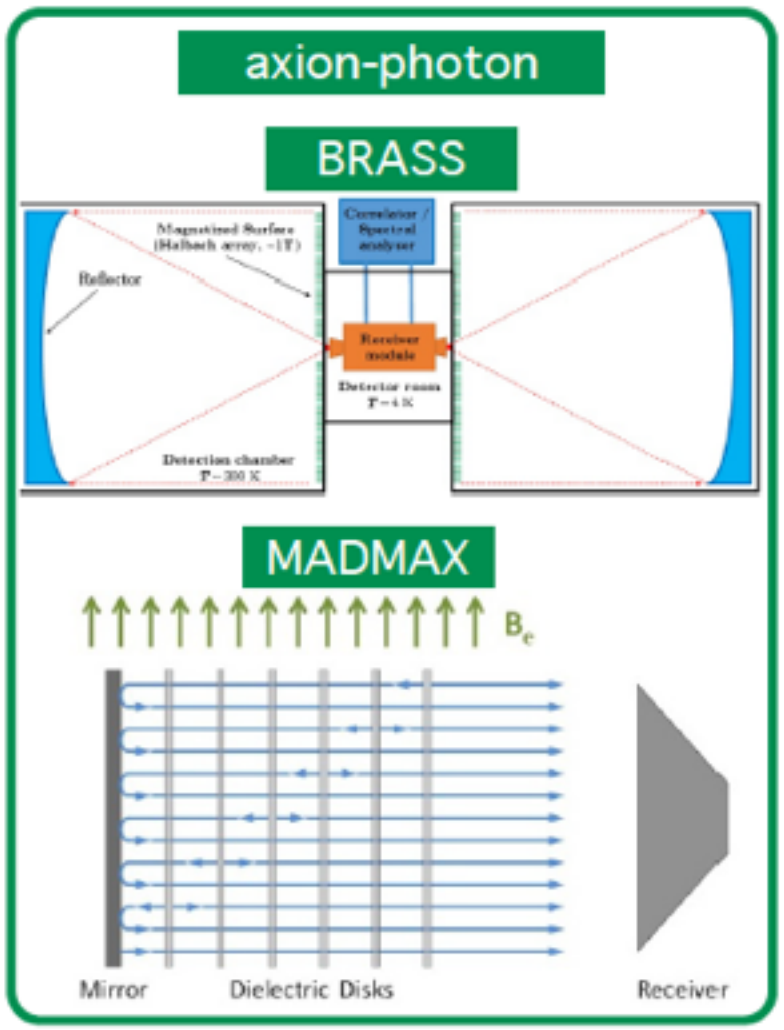
  PVLAS (vacuum pol.)..... and LHC.

ALPs at colliders:

Mimasu+Sanz 2015, Jaeckel and Spannowsky 2015, Brivio et al. 2017, Bauer et al. 2017…..

Experiment: new experiments and new detection ideas

e.g. in Haloscopes



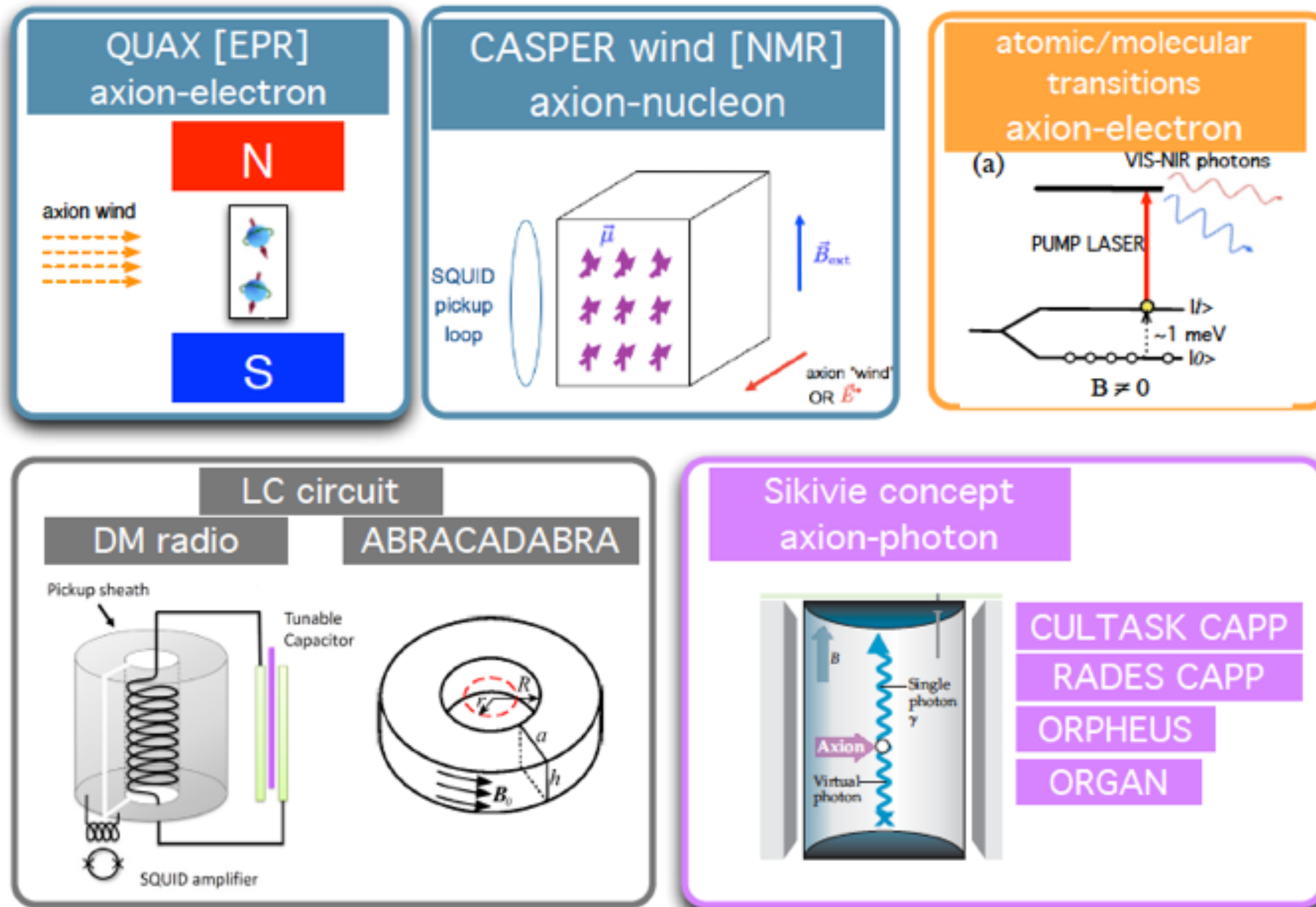
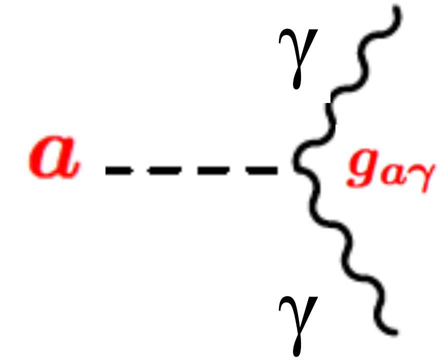


Image taken from
C. Braggio talk at Invisibles18

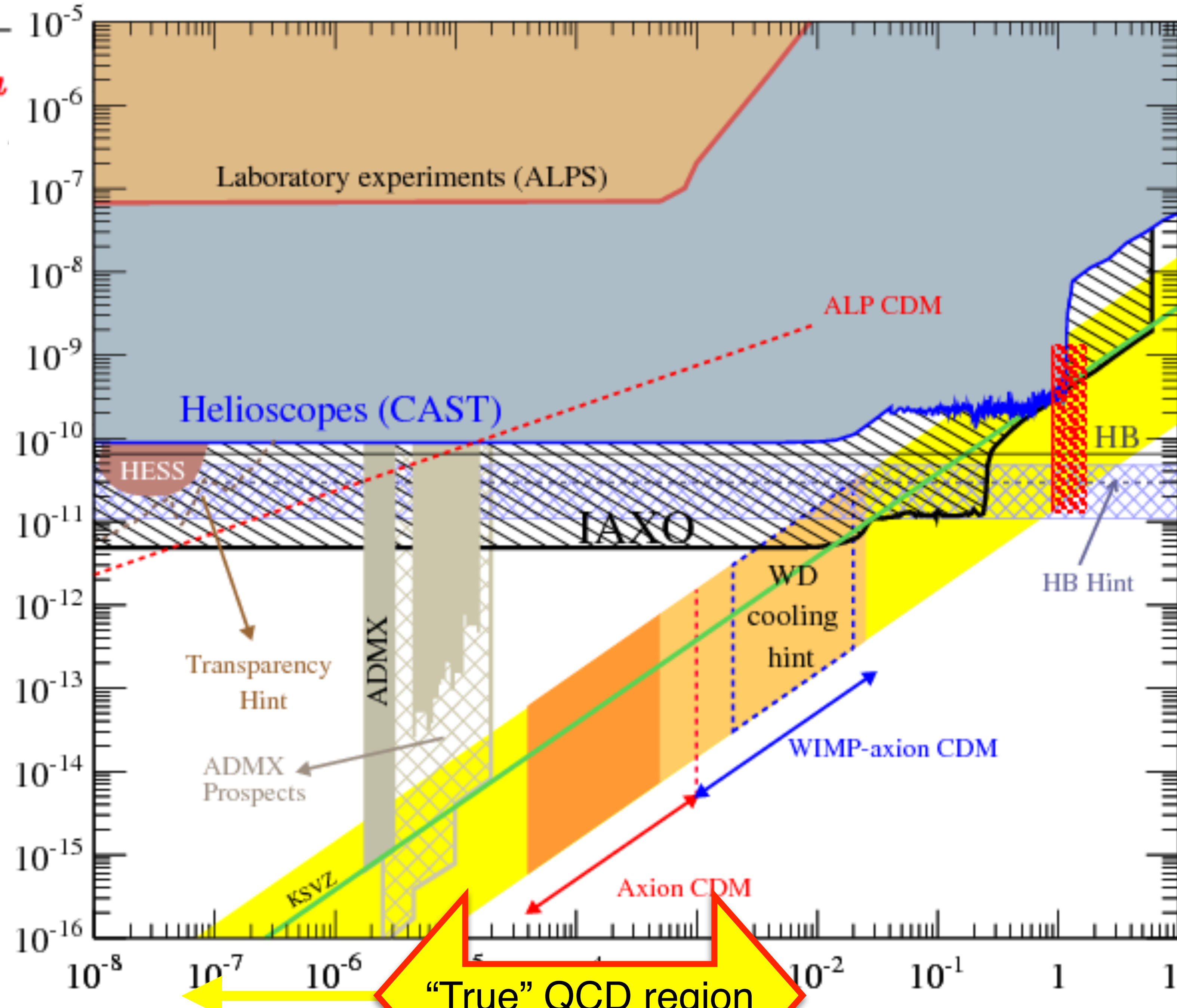
plus LHC !

Intensely looked for experimentally…



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

(GeV^{-1})



“True” QCD region

“True” QCD axion band

II

“Invisible axion”

e.g. KSVZ, DFSZ…

v<< f_a —>

EW hierarchy problem

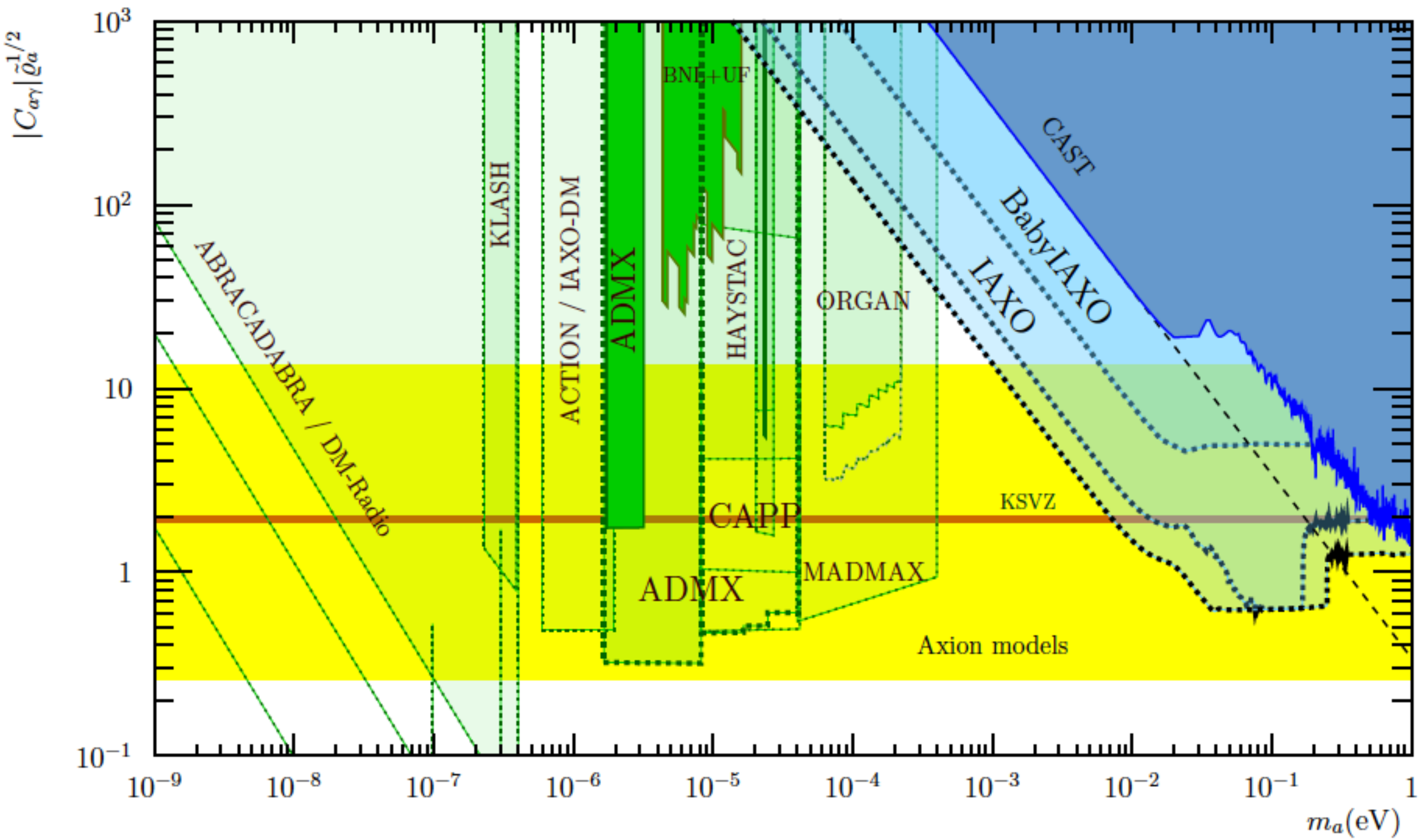
+ gravitational tunings ?

m_a (eV)

… and theoretically

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

Advances on Haloscopes



Irastorza and Redondo, arXiv:1801.08127

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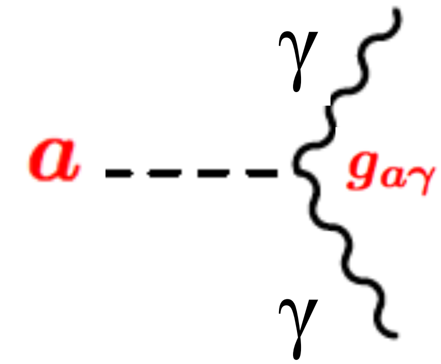

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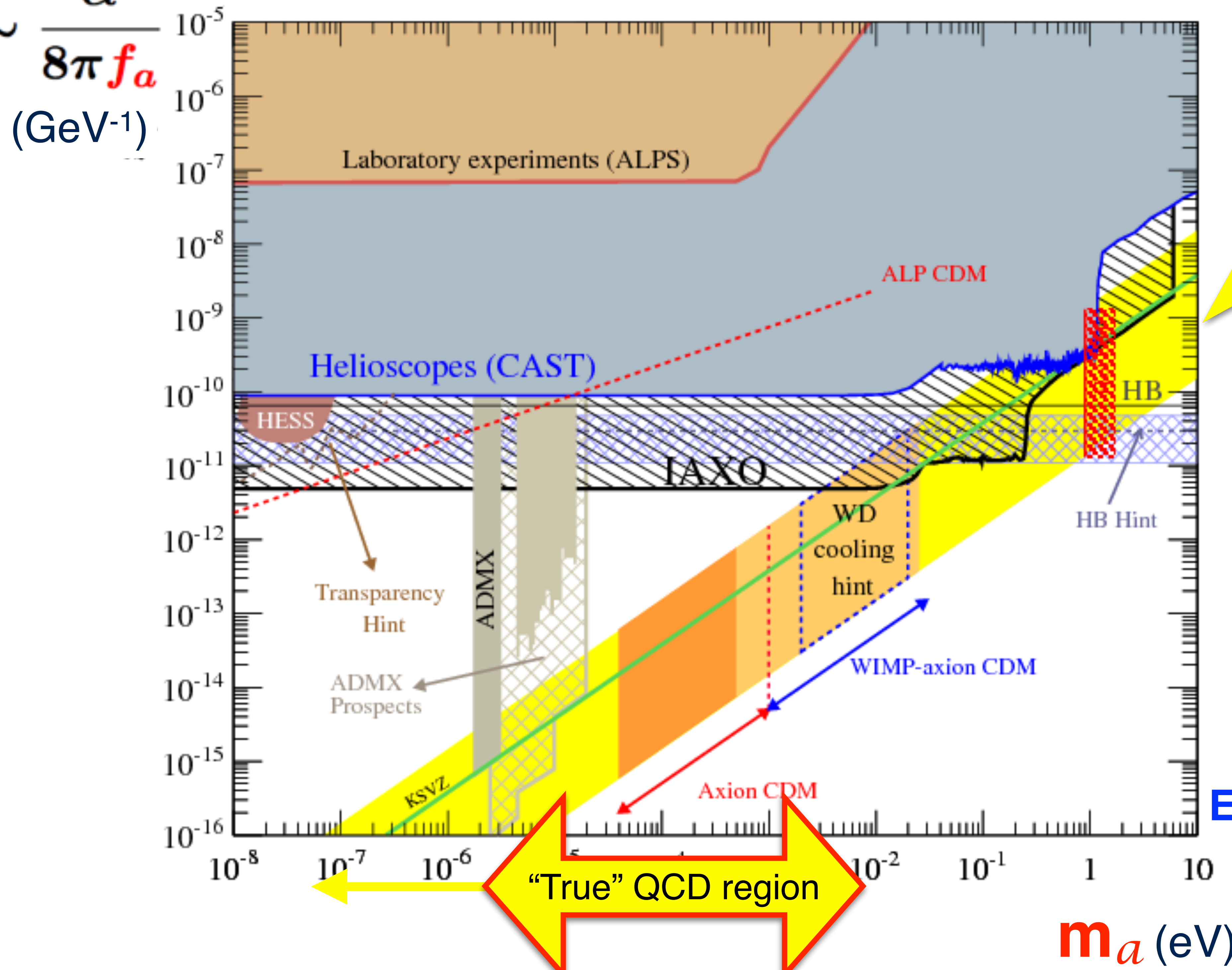

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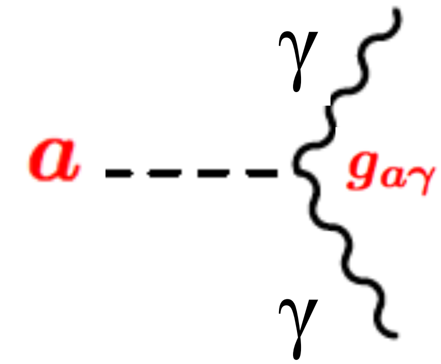

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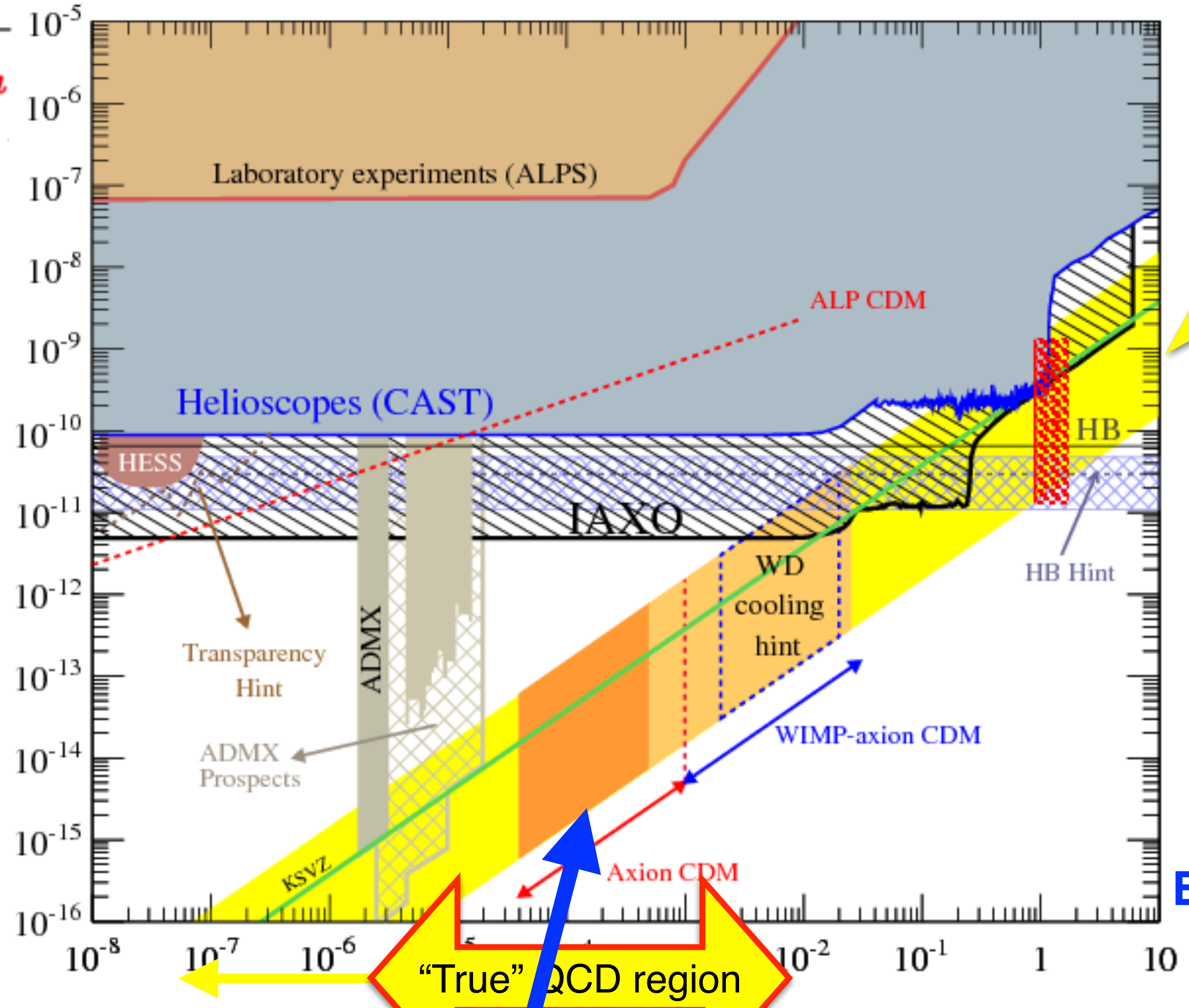

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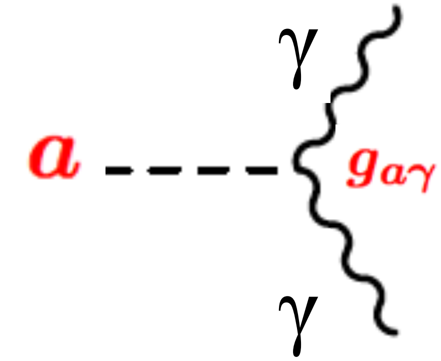
EW hierarchy problem

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

https://ar



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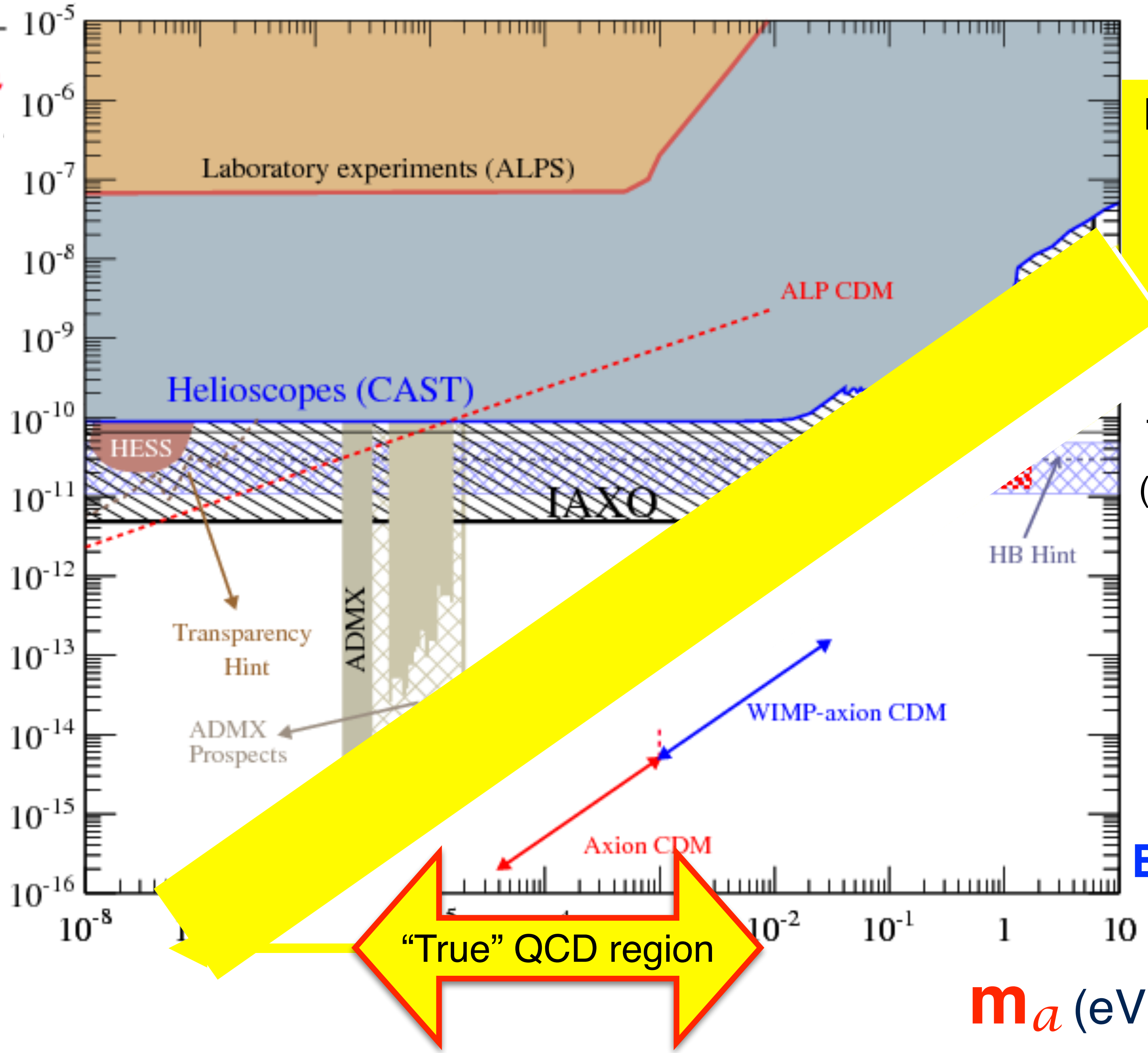

m_a (eV)

Refined KSVZ axion band: up and thinner

from Ω_{DM}
+ Landau-poles analysis

(Luzio+Mescia+Nardi 2017-18)

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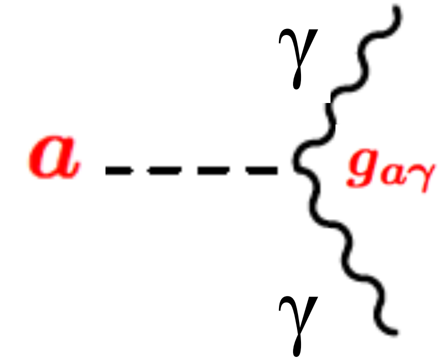

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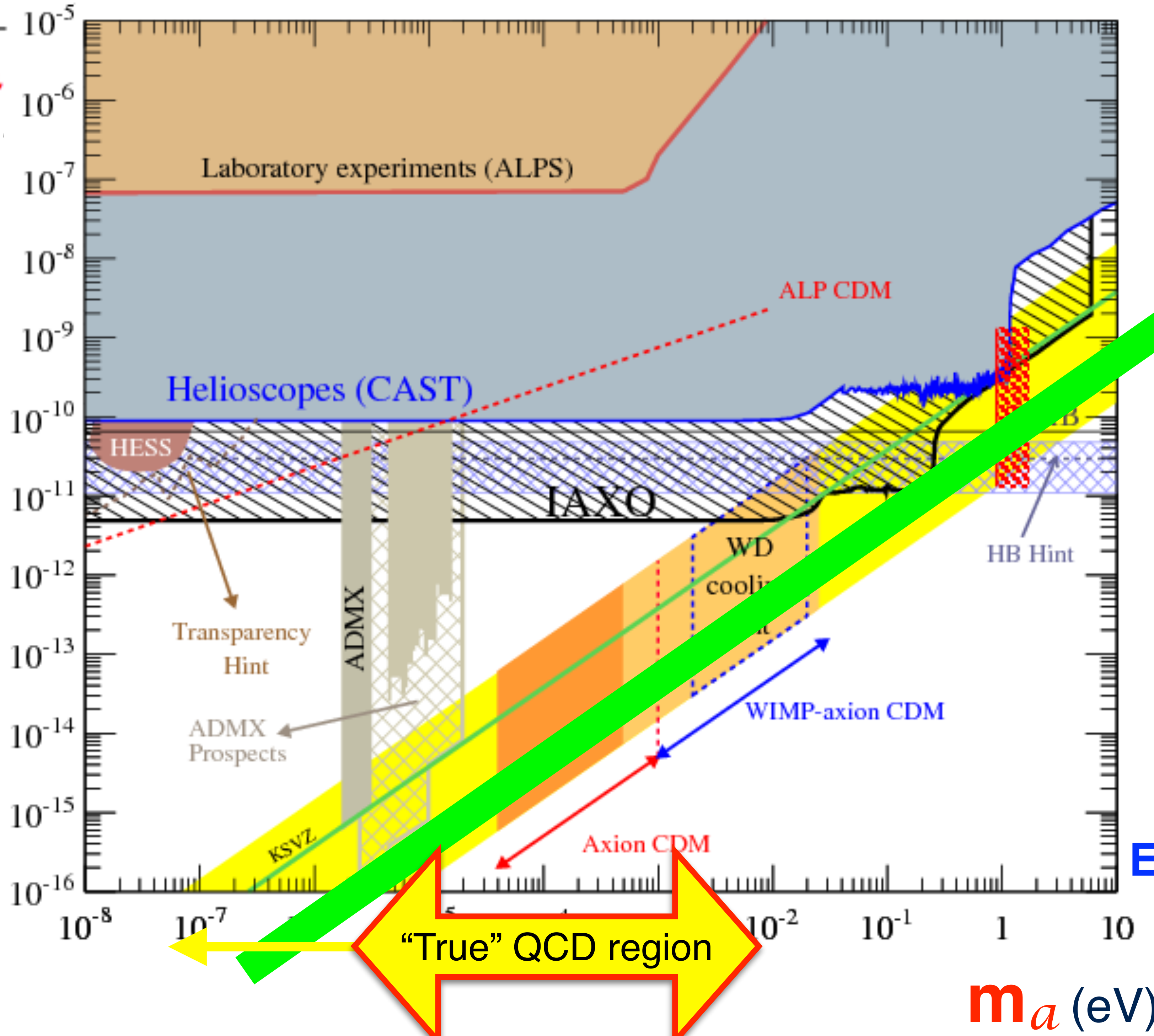

QCD axiflavon band

(creative view)

(Wilczek 82,
Calibbi et al. 2016
Ema et al (flaxion) 2017

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

v<< f_a —>
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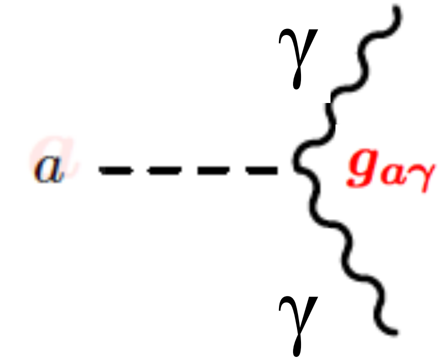

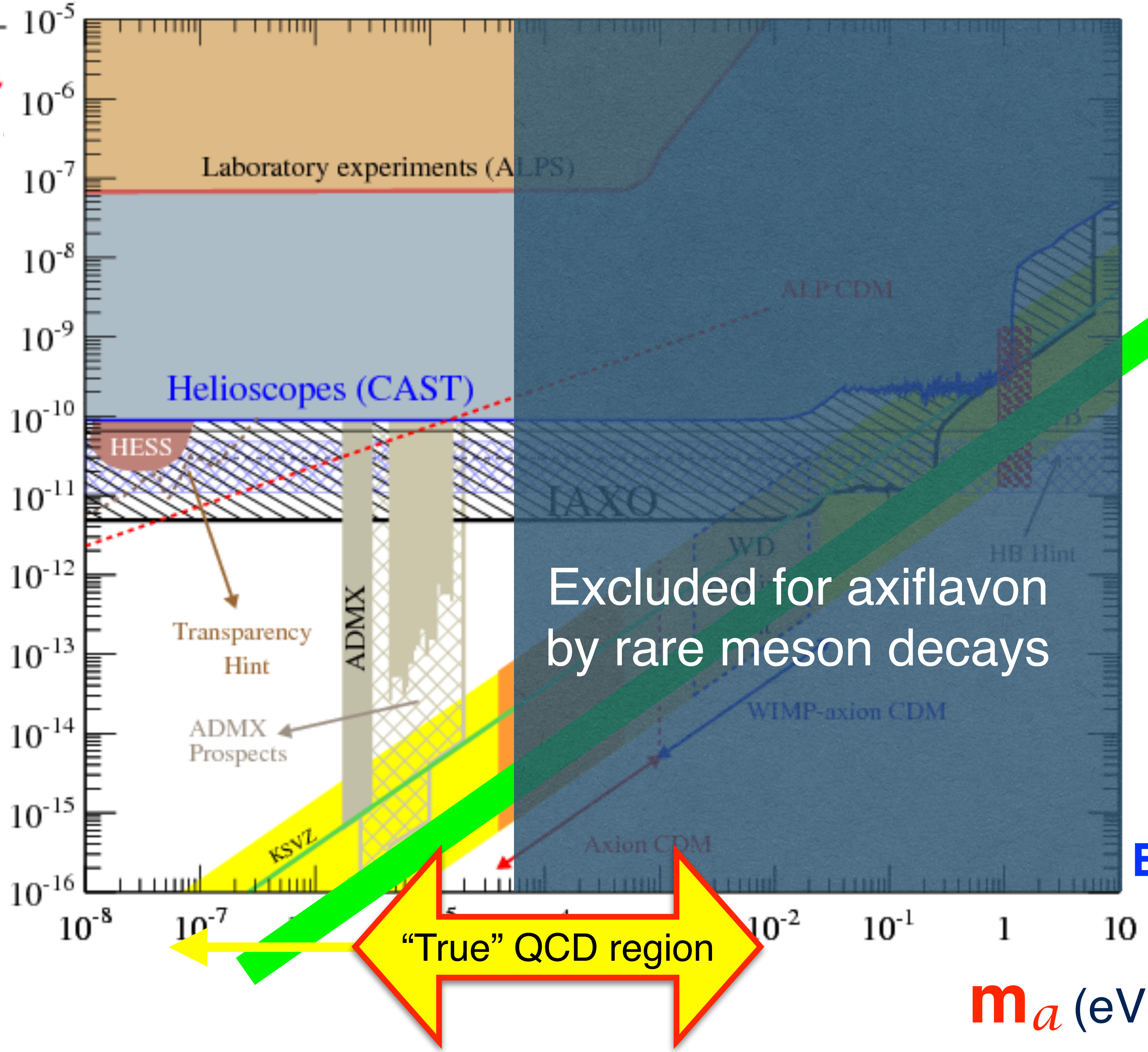

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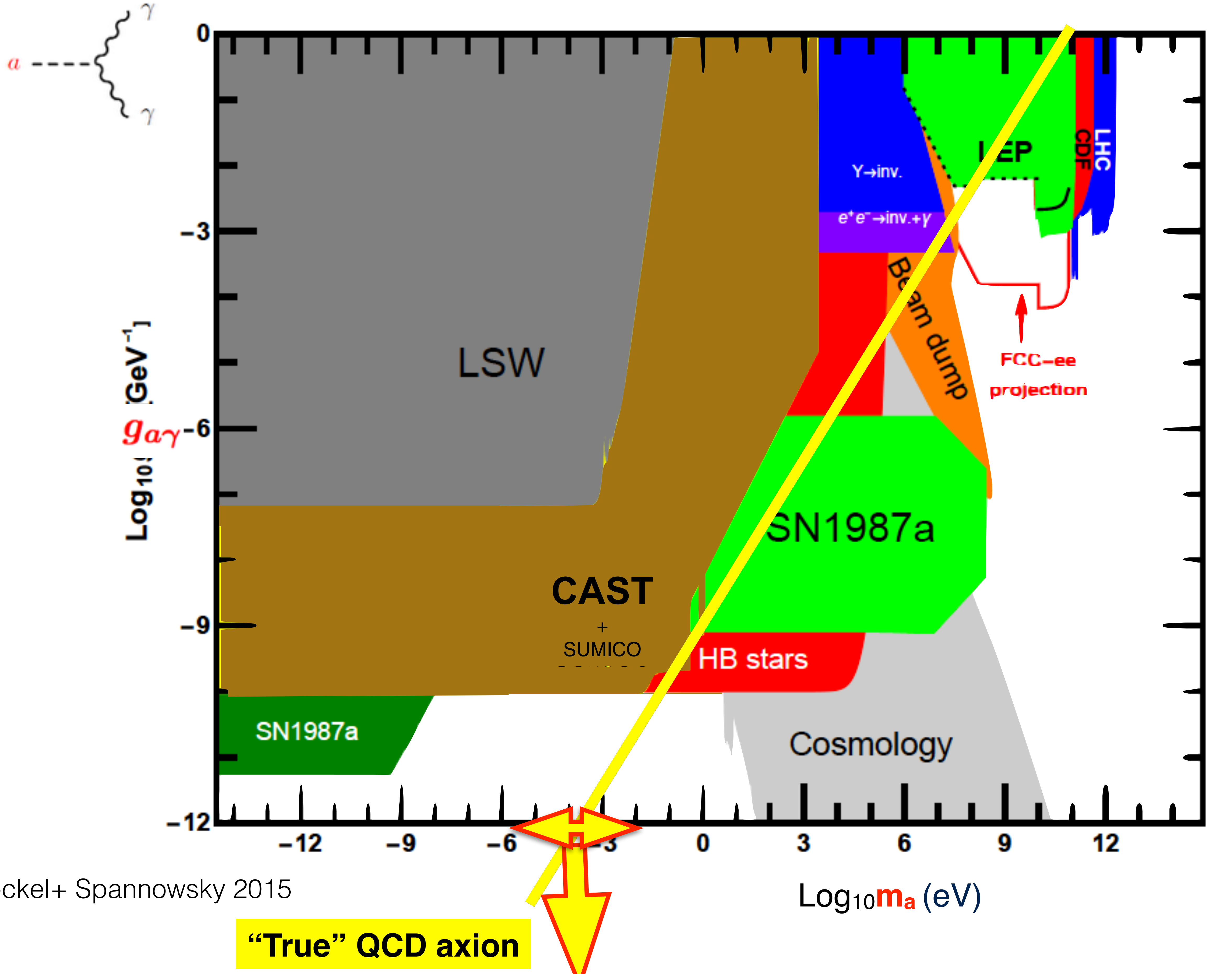

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Choi et al. 1986

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

$\Lambda \ll m_q$: Λ^4

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

m_a vs scale f_a

$g_a \sim 1/f_a$

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

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

m_a vs scale f_a

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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, Hariyaga, Ibe, Yanagida 15, Gherghetta+Nagata+Shifman 16,

Hook and many collaborators: Dimopoulos, Hook, Huang, Marques-Tavares 16, Hook 17

2017: Agrawal+Howe, **2018** M.K. Gaillard et al.

m_a vs scale f_a

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

Choi et al. 1986

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

$\Lambda \ll m_q$: Λ^4

$10^{-5} < m_a <$ ~~10^{-2}~~ eV , ~~10^9~~ $< f_a < 10^{12}$ GeV

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

$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2 + \textbf{extra} ,$$

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

m_a vs scale f_a

$g_a \sim 1/f_a$

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

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

Choi et al. 1986

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

$\Lambda \ll m_q$: Λ^4

$10^{-5} < m_a < 10^{-2}$ eV , $10^{9} < f_a < 10^{12}$ GeV

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

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

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

m_a vs scale f_a

$g_a \sim 1/f_a$

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

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

Choi et al. 1986

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

$\Lambda \ll m_q$: Λ^4

$? < m_a$, $f_a < ?$

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

$m_a^2 f_a^2 =$ **LARGE NUMBER**

relaxes the true axion parameter space

A heavy QCD axion?

Heavy axions

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

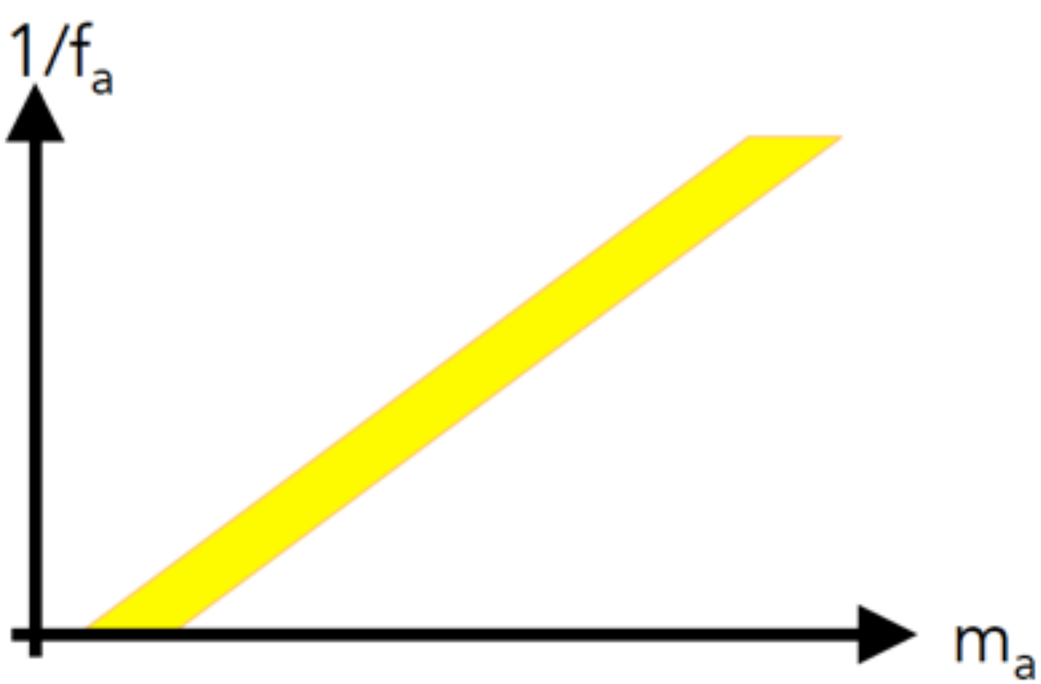
$$\frac{a}{f_a} G \cdot \tilde{G} \quad \rightarrow \quad m_a^2 f_a^2 = \frac{\Lambda^4}{1 + \Lambda^4 / (2 m_q < \bar{\psi}\psi >)}$$

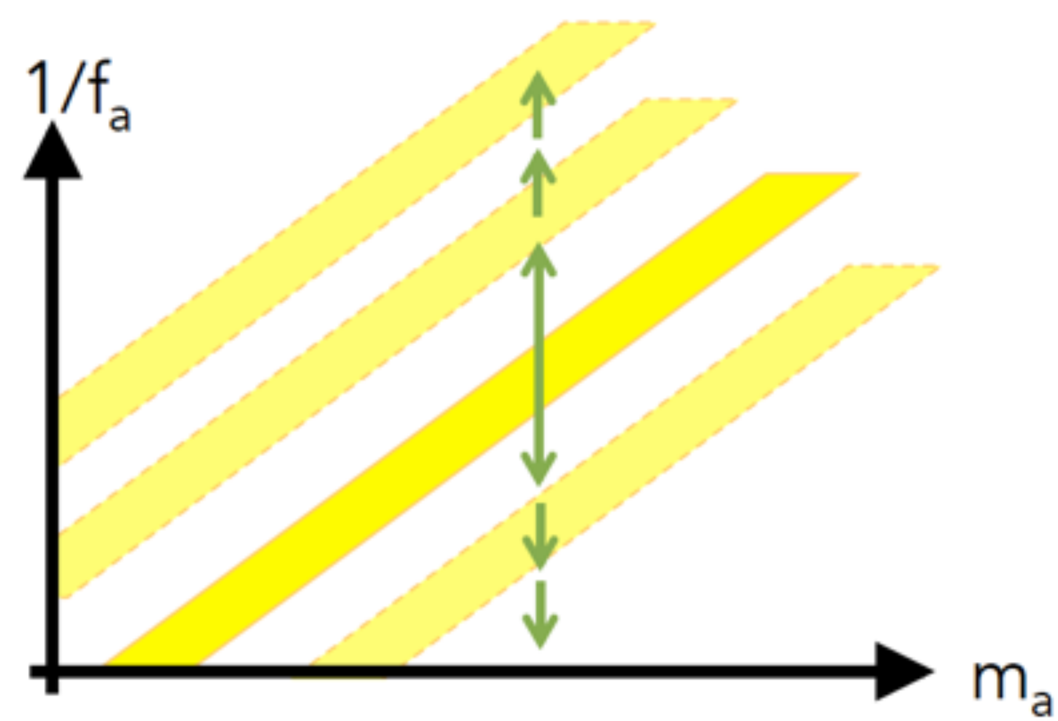
QCD: $\Lambda = \Lambda_{QCD}$

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

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

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





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

Compare the number of pseudoscalars-coupled to anomalous currents:

η'_{QCD} a_1 a_2 a_3 ……

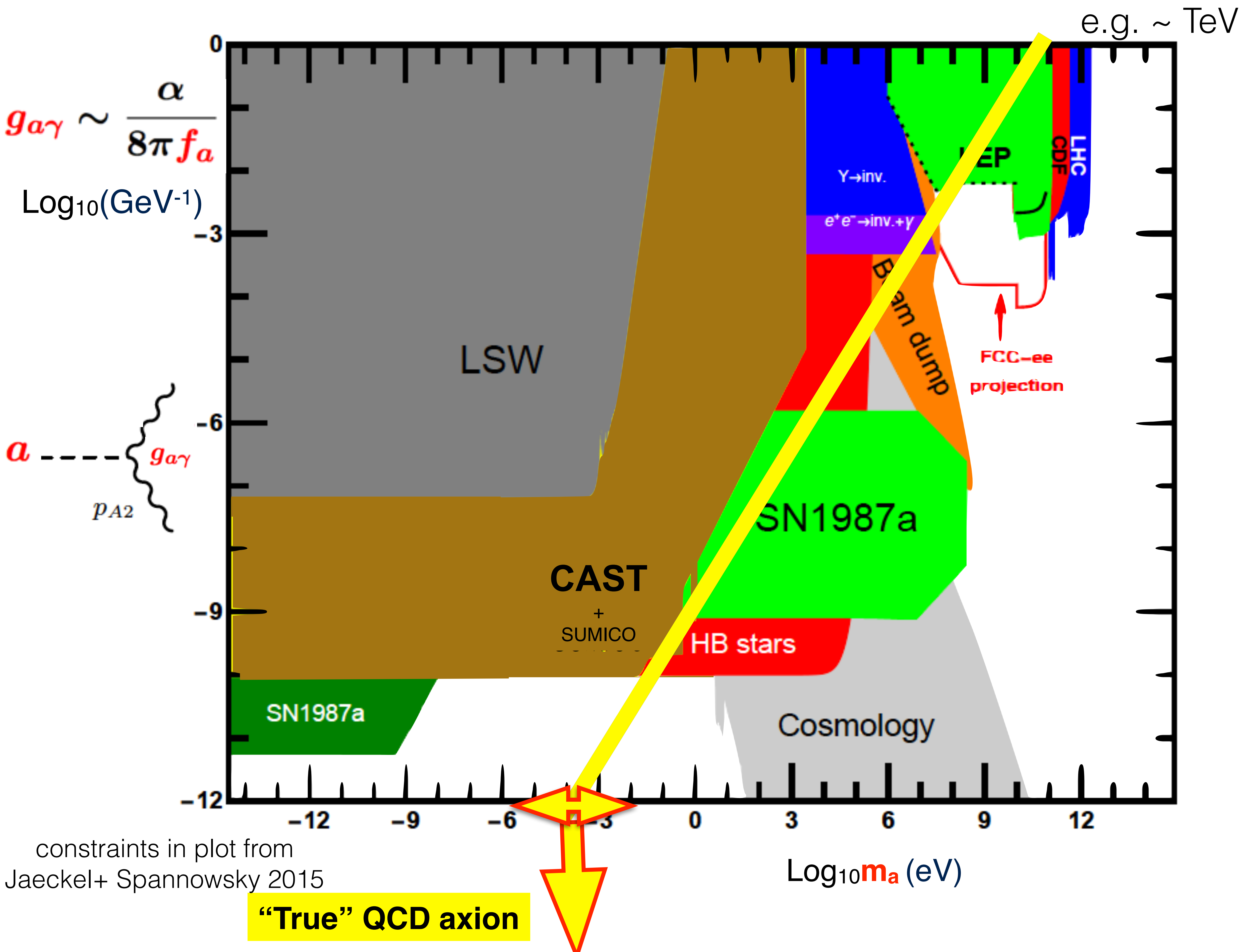
with how many sources of (instanton) masses

$G_c\tilde{G}_c$ $G'\tilde{G}'$ $G''\tilde{G}''$ ……

QCD

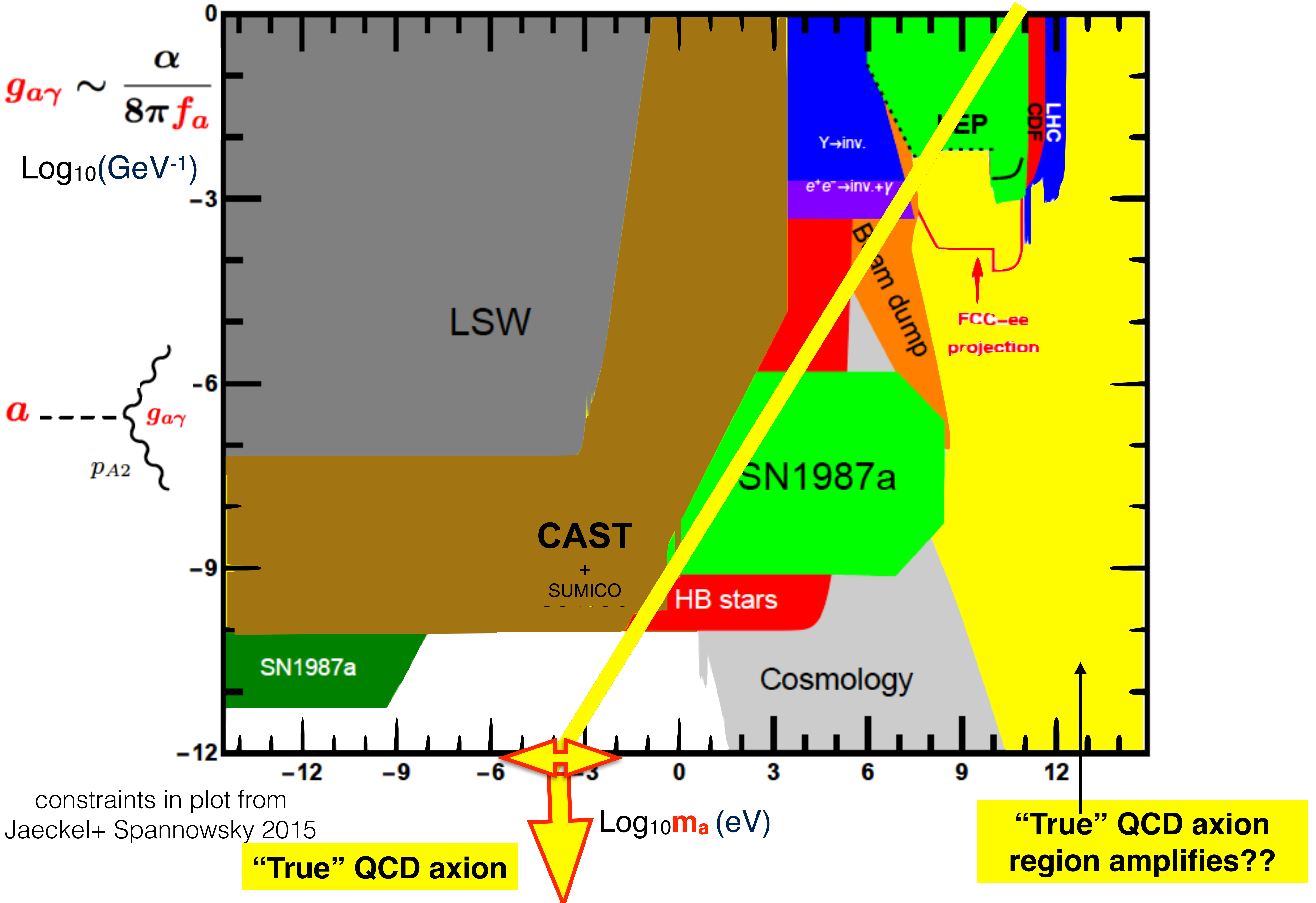
other sources of instantons

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



constraints in plot from
Jaeckel+ Spannowsky 2015

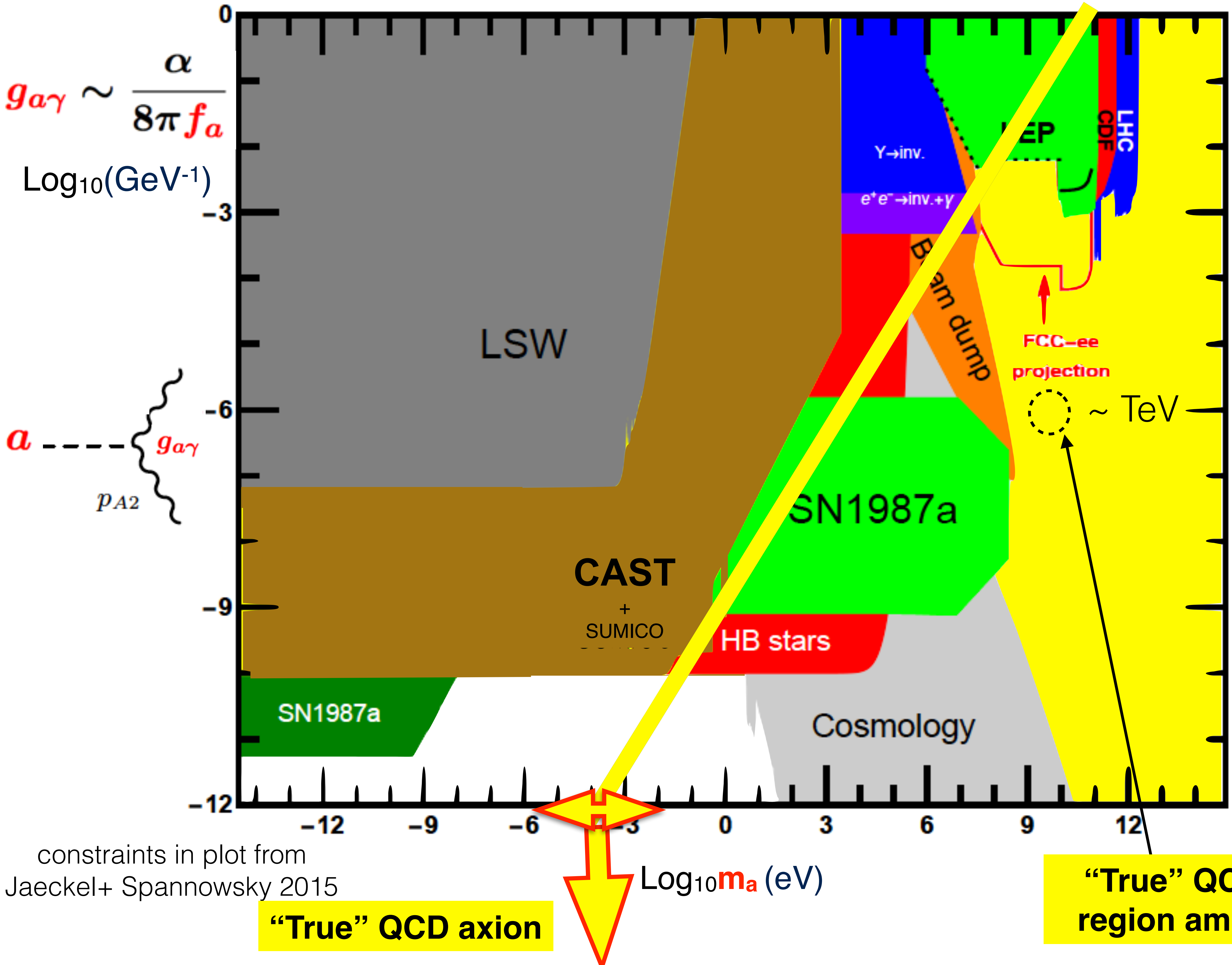
* **Much territory to explore for heavy 'true" axions and for ALPs**



constraints in plot from
Jaeckel+ Spannowsky 2015

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

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



constraints in plot from
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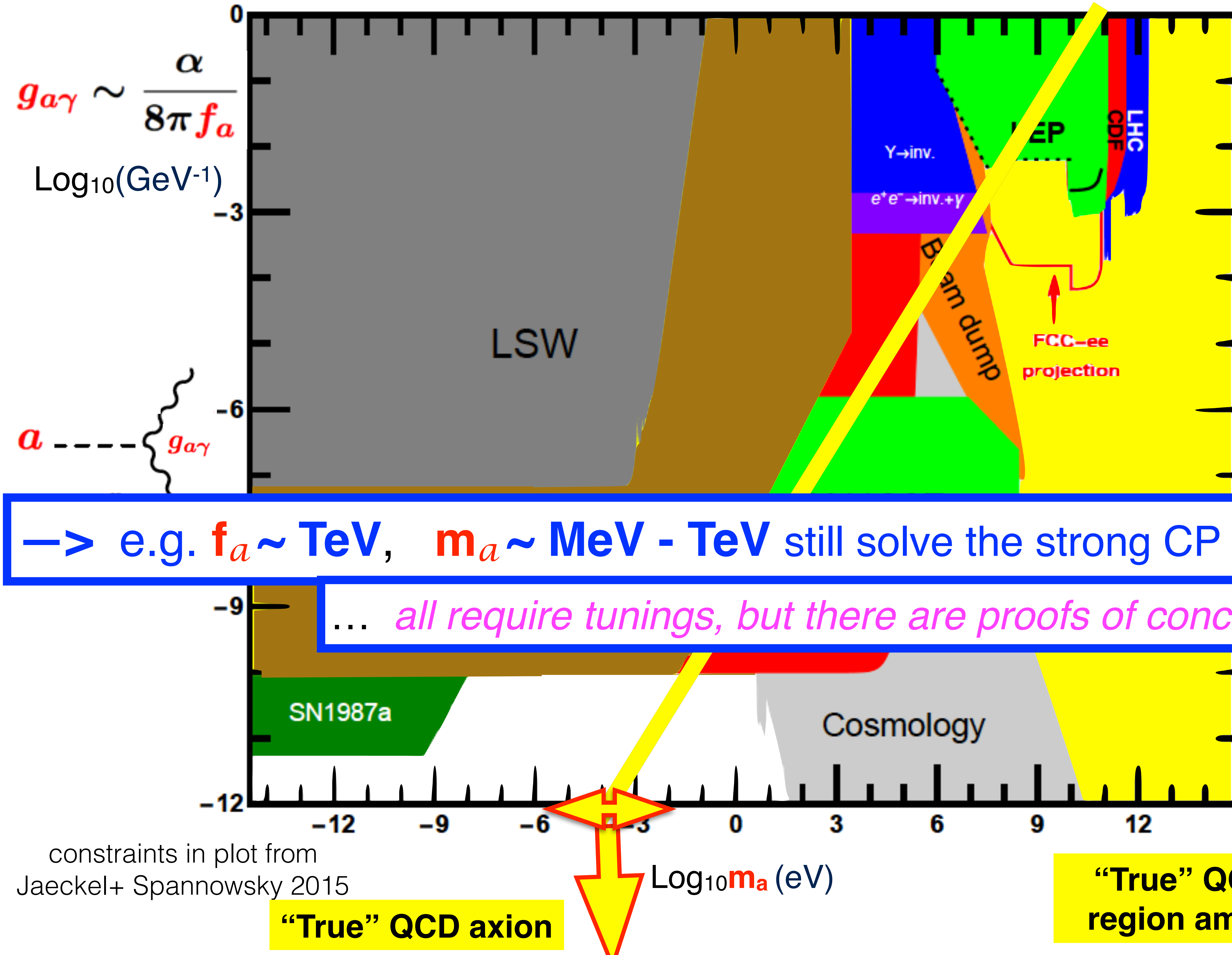
"True" QCD axion

"True" QCD axion
region amplifies??

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



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

… *all require tunings, but there are proofs of concept*

constraints in plot from
Jaeckel+ Spannowsky 2015

"True" QCD axion region amplifies??

BLOOMING Theory

for a true (heavy) axion

BLOOMING Theory

for a true (heavy) axion

* With elementary axions: Agrawal and Howe, 2017

* With dynamical axions, via a massless coloured quark:

—> A Z_2 model, Hook 2015

—> With flavour, Agrawal and Howe 2017

—> First color-unified axion model, M. K. Gaillard et al. 2018

Massless Quarks

A QCD-colored massless quark has a $U(1)_A$ symmetry:
it solves the strong CP problem

$$\psi \to e^{i\alpha\gamma_5}\psi$$

$$\theta \to \theta + \frac{\alpha_s}{8\pi}\phi$$

$m_q = 0$ $U(1)_A$ classically exact

+ only broken by anomalies

e.g. m_u=0 ➞ η'_{QCD} is the axion

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

Massless Quarks

A new QCD-colored <u>massless</u> quark has a $U(1)_A$ symmetry:
it solves the strong CP problem

$$\psi \to e^{i\alpha\gamma_5}\psi$$

$$\theta \to \theta + \frac{\alpha_s}{8\pi}\phi$$

Hide the massless coloured quark in heavy states
bound by the new strong force

$$\sim \Lambda_{\mathrm{new}}$$

K. Choi, J.E. Kim 1985

Axicolor

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

Massless quark charged under QCD and another confining group

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

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

Massless quark content

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

* 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

Axicolor

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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	1	$\square$

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

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

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

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:

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

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

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

two singlets + η'_{QCD}
vs.
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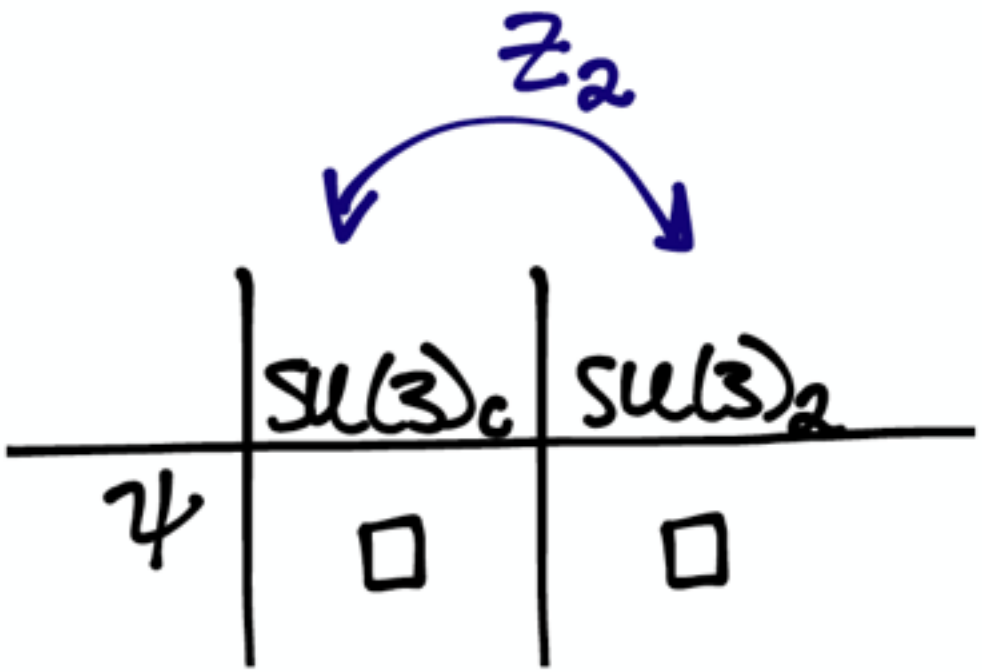
—> one m~0 invisible axion and very high f_a

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

⟶ 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
CUT

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} $\tilde{\Lambda}$

Colour Unified Dynamical Axion

First colour-unified model with massless quarks

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

$\theta_c = \tilde{\theta} = \theta_6$

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

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

Colour Unified Dynamical Axion

First colour-unified model with massless quarks

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$\theta_c = \tilde{\theta} = \theta_6$

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

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

Solve strong CP problem with massless SU(6) fermion

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

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

We aim at $\tilde{\Lambda} \sim$ **TeV >>** Λ_{QCD}

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 $SU(\tilde{3})$

A UV complete solution

Add a new group outside the CUT group

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

with prime fermions charged only under SU(3')

A UV complete solution

Add a new group outside the CUT group

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

with prime fermions charged only under SU(3')

* The role of prime fermions is to pair with the quark partners and make them heavy

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

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

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

$\xrightarrow{\Lambda_{\rm CUT}}$

	$SU(3)$	$SU(3)_{\rm diag}$	$SU(2)_L$
ψ	$\square$	$\bar{\square}$	1
χ	1	$\square$	1
$2\psi_L$	1	1	1

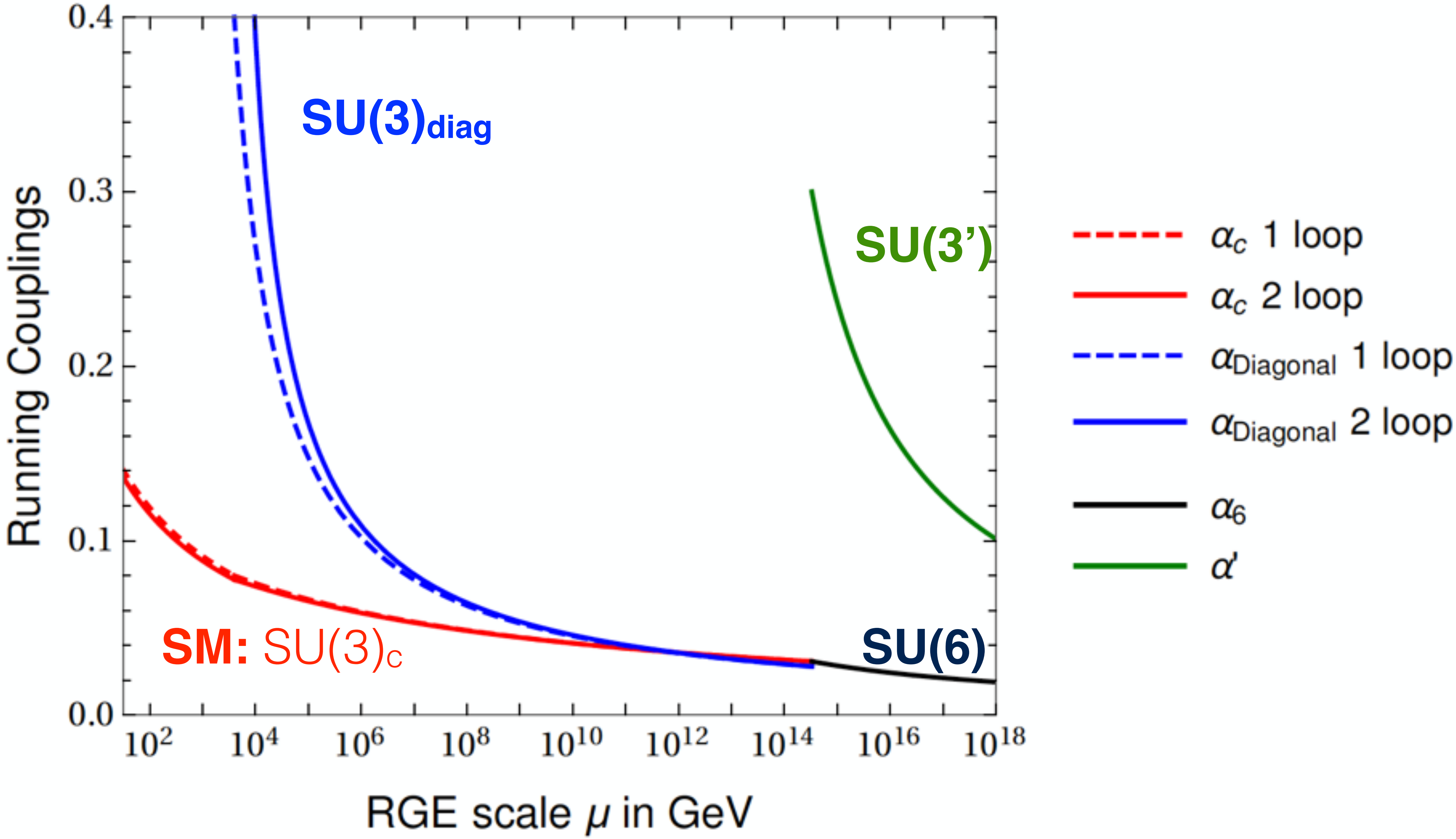
The two massless quarks

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

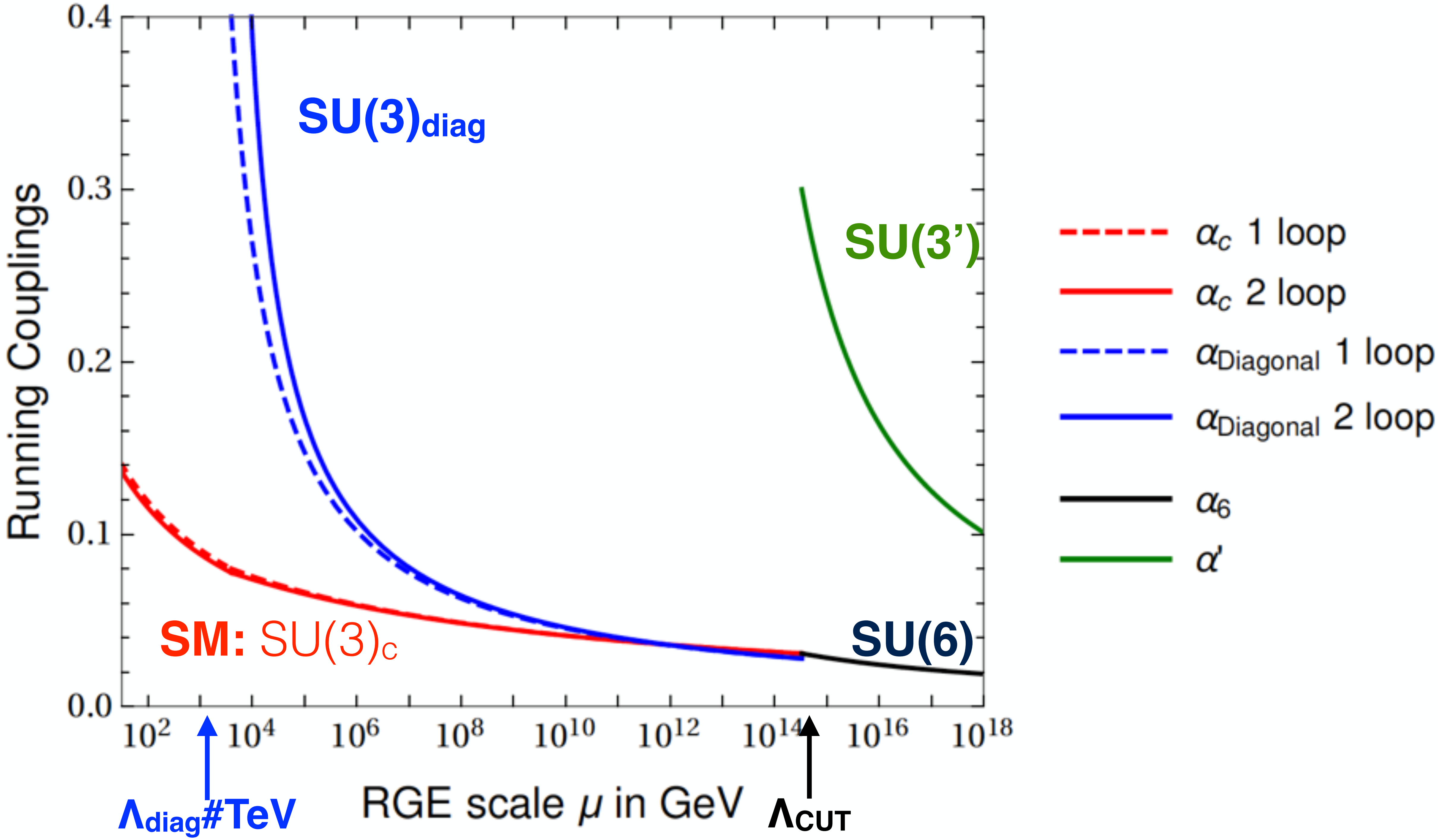
$$\frac{1}{\alpha_{\rm diag}(\mu)} = \frac{1}{\alpha_6(\mu)} + \frac{1}{\alpha'(\mu)} \qquad \mu = \Lambda_{CUT}$$

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

Model I: Unification and Confinement



Model I: Unification and Confinement



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}:

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

What are the masses of the two dynamical axions?

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

η'_{QCD} η'_{ψ} η'_{χ}

axions

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

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

What are the masses of the two dynamical axions?

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

η'_{QCD} η'_{ψ} η'_{χ}

axions

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

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

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

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

Small Size Instantons (SSI) and Axion Mass

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

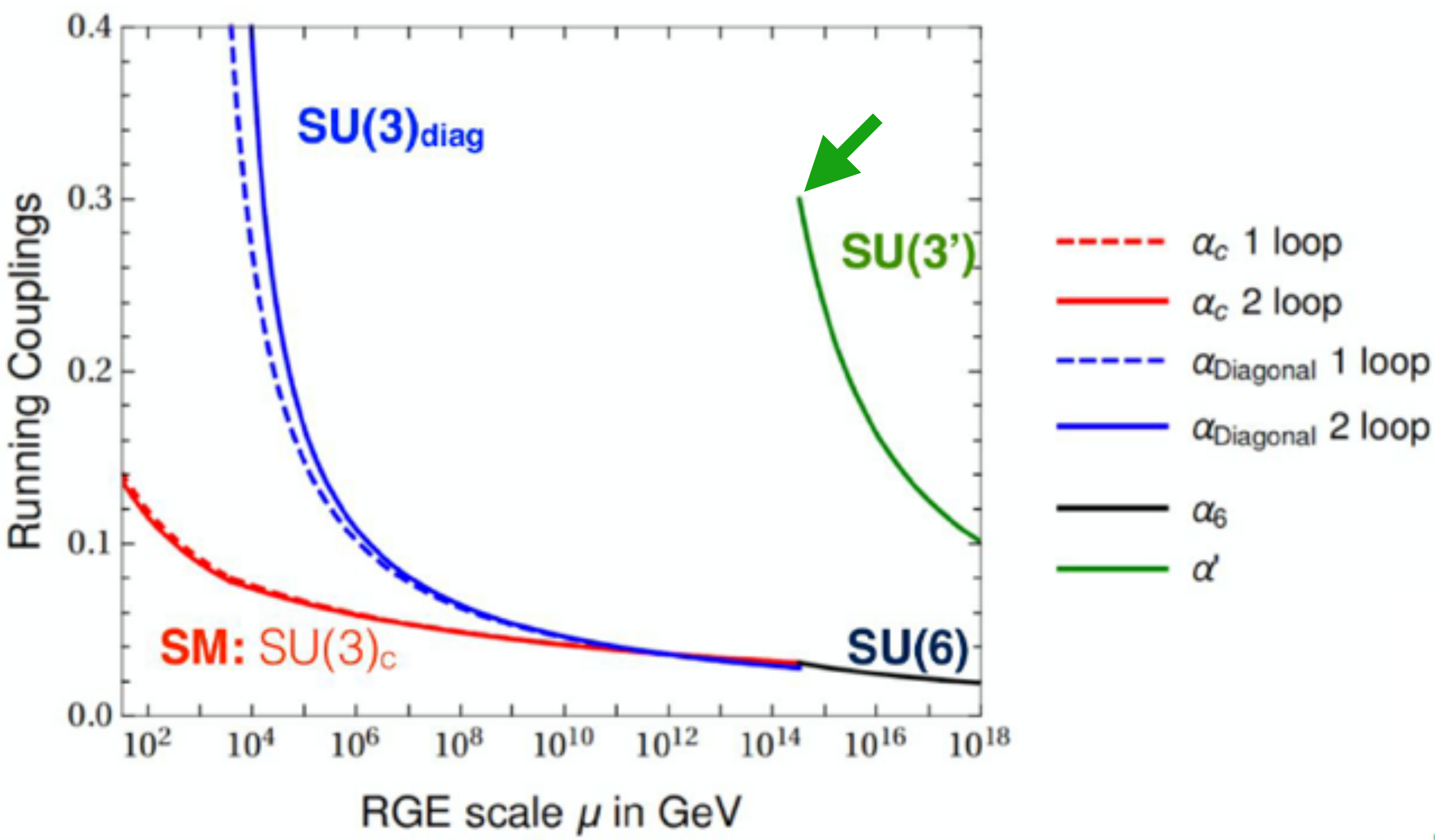
$$D[\alpha'(\mu)] \propto e^{-2\pi/\alpha'(\mu)}$$

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

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

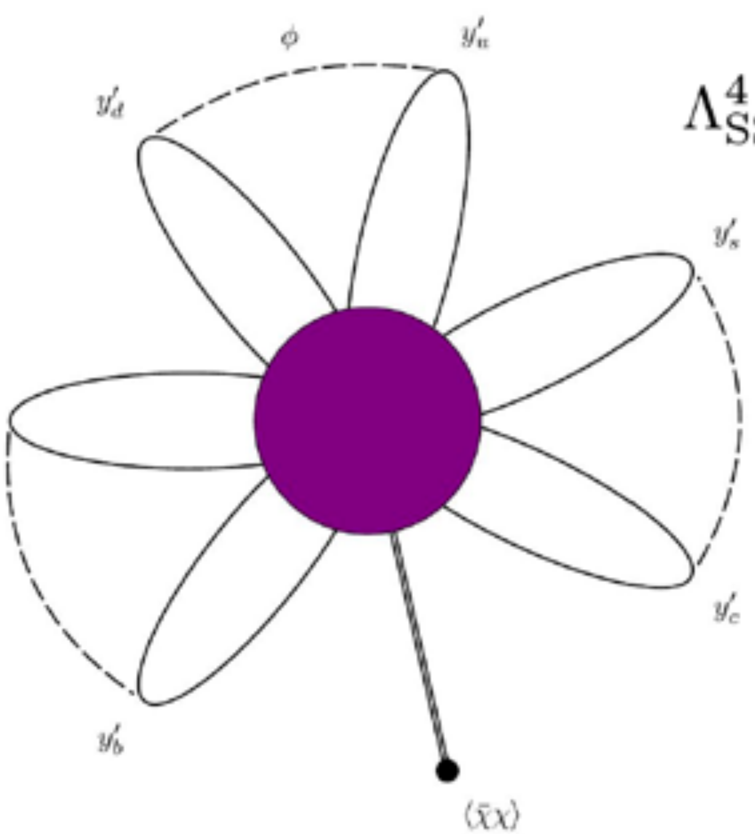
New sizable contribution to the axion mass!!

Small Size Instantons (SSI) and Axion Mass

a) for small Yukawa couplings in the prime sector:

→ Dilute Instanton Gas approximation:

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



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

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

arXiv:1805.06465

The effective potential for the three singlet pseudoscalars:

η'_{QCD} η'_{ψ} η'_{χ}

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

has three sources of mass —> two massive axions

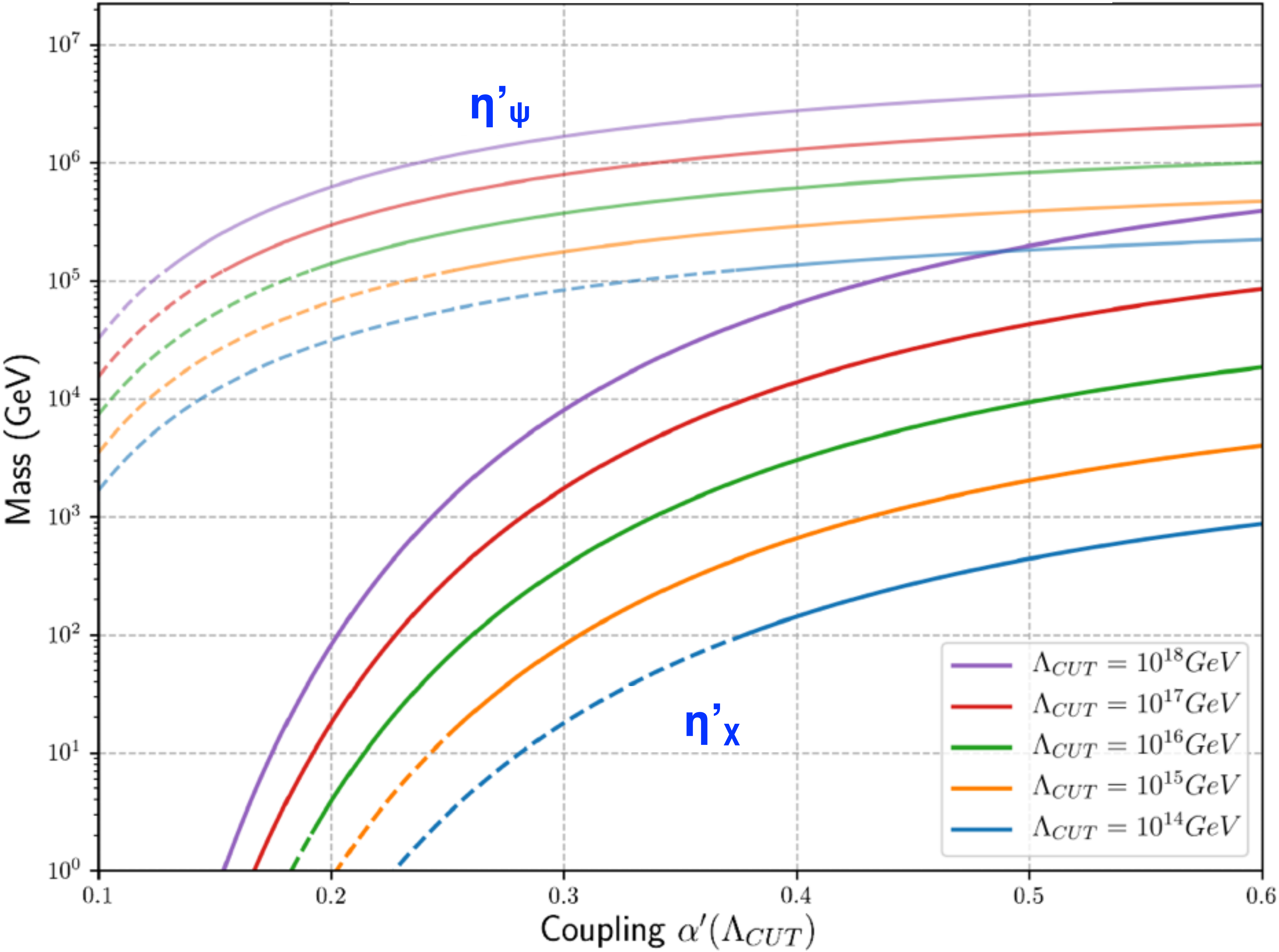
The effective potential for the three singlet pseudoscalars:

η'_{QCD} η'_{ψ} η'_{χ}

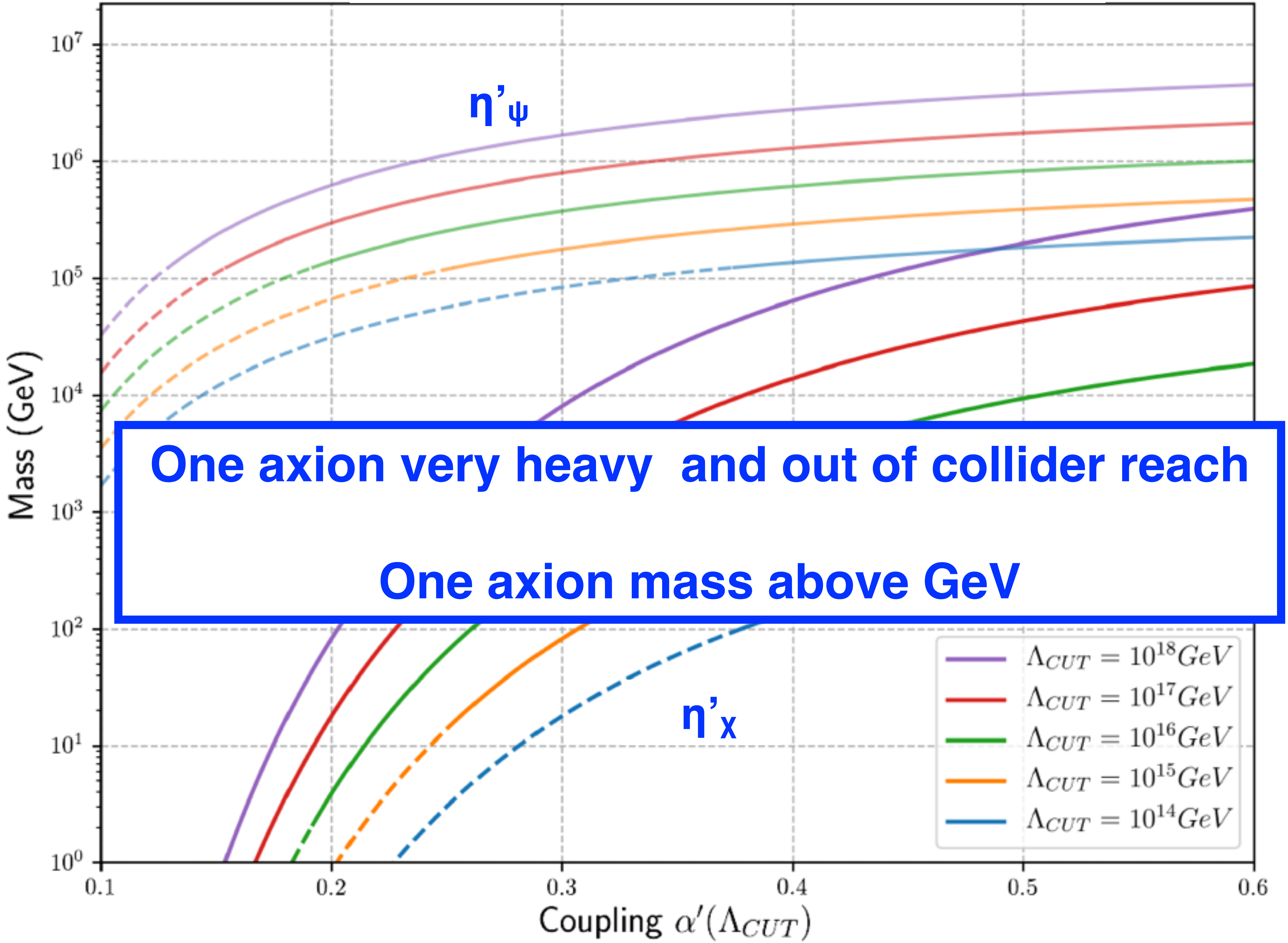
$$\mathcal{L}_{eff} = \underbrace{\Lambda^4_{\mathrm{SSI}} \cos\left(2\,\frac{\eta'_\chi}{f_\mathrm{d}}\right)}_{SU(3')\ \text{SSI Instantons}} + \underbrace{\Lambda^4_{\mathrm{diag}} \cos\left(2\,\frac{\eta'_\chi}{f_\mathrm{d}} + \sqrt{6}\,\frac{\eta'_\psi}{f_\mathrm{d}}\right)}_{SU(3)_{\mathrm{diag}}\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

has three sources of mass —> two massive axions

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

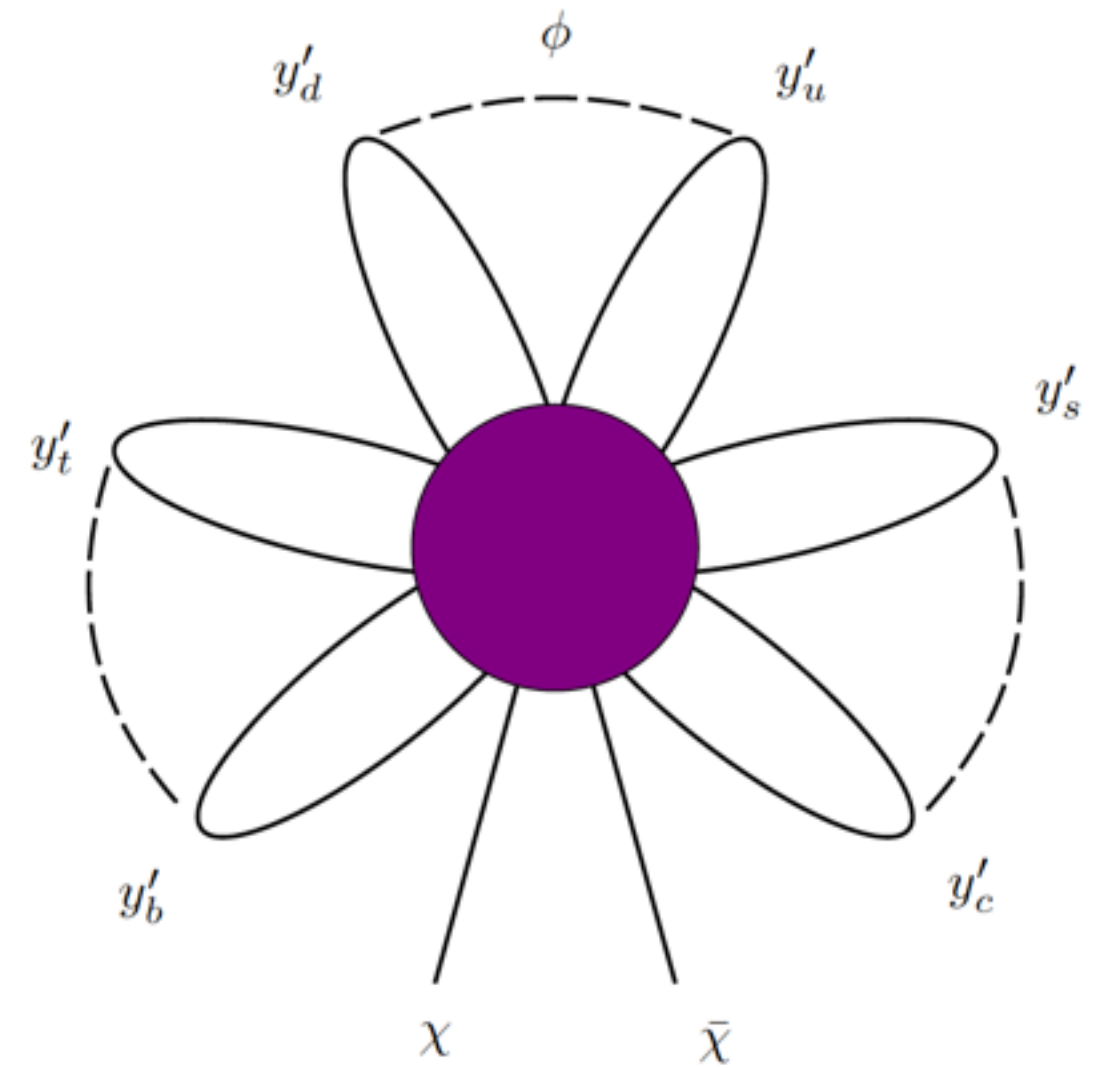


Axions: $\eta'_\psi = (\bar{\psi}\psi)$ $\eta'_\chi = (\bar{\chi}\chi)$



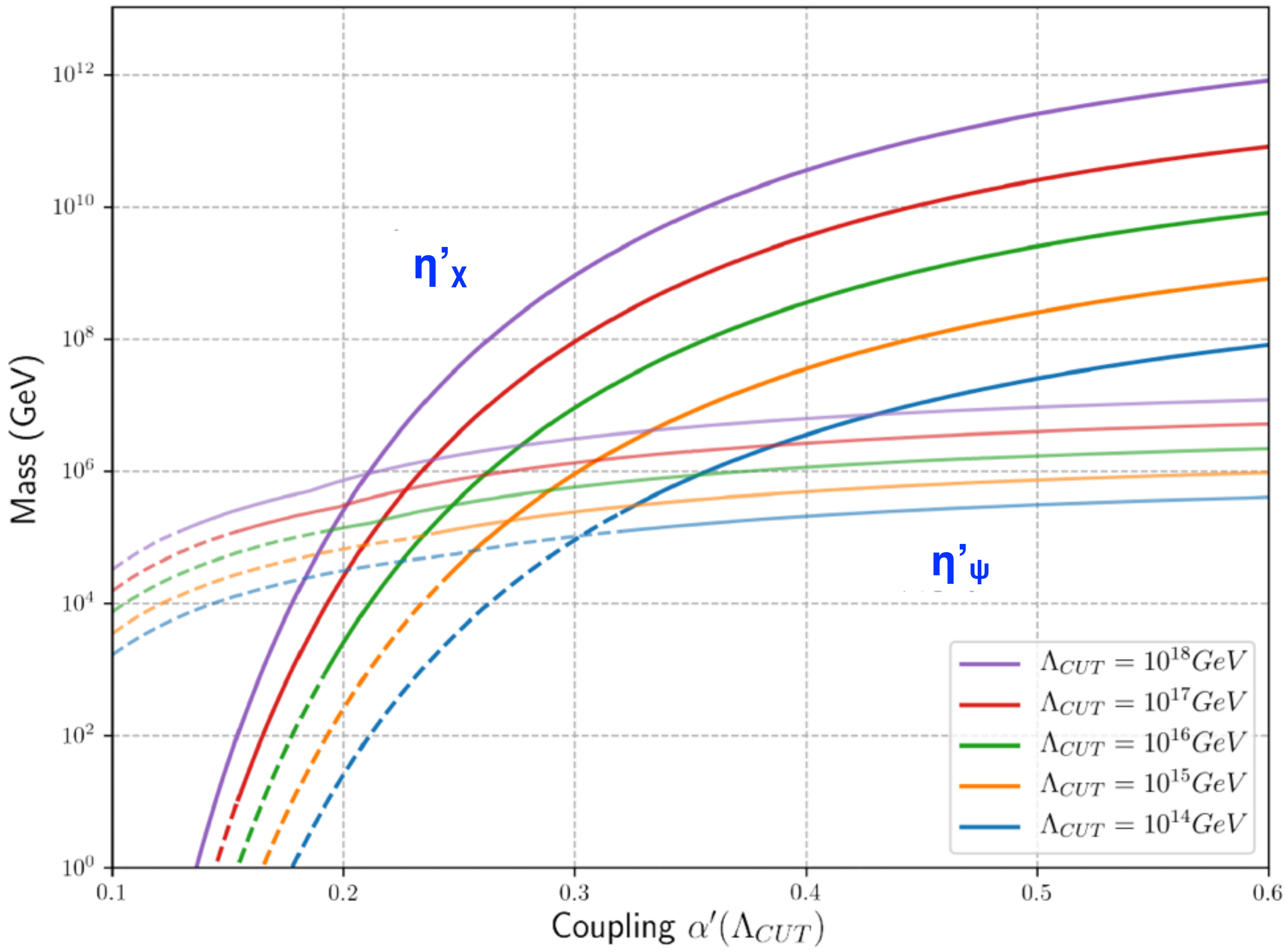
b) for O(1)Yukawa couplings in the prime sector:

The prime sector instantons generate a large effective mass for the χ fermion

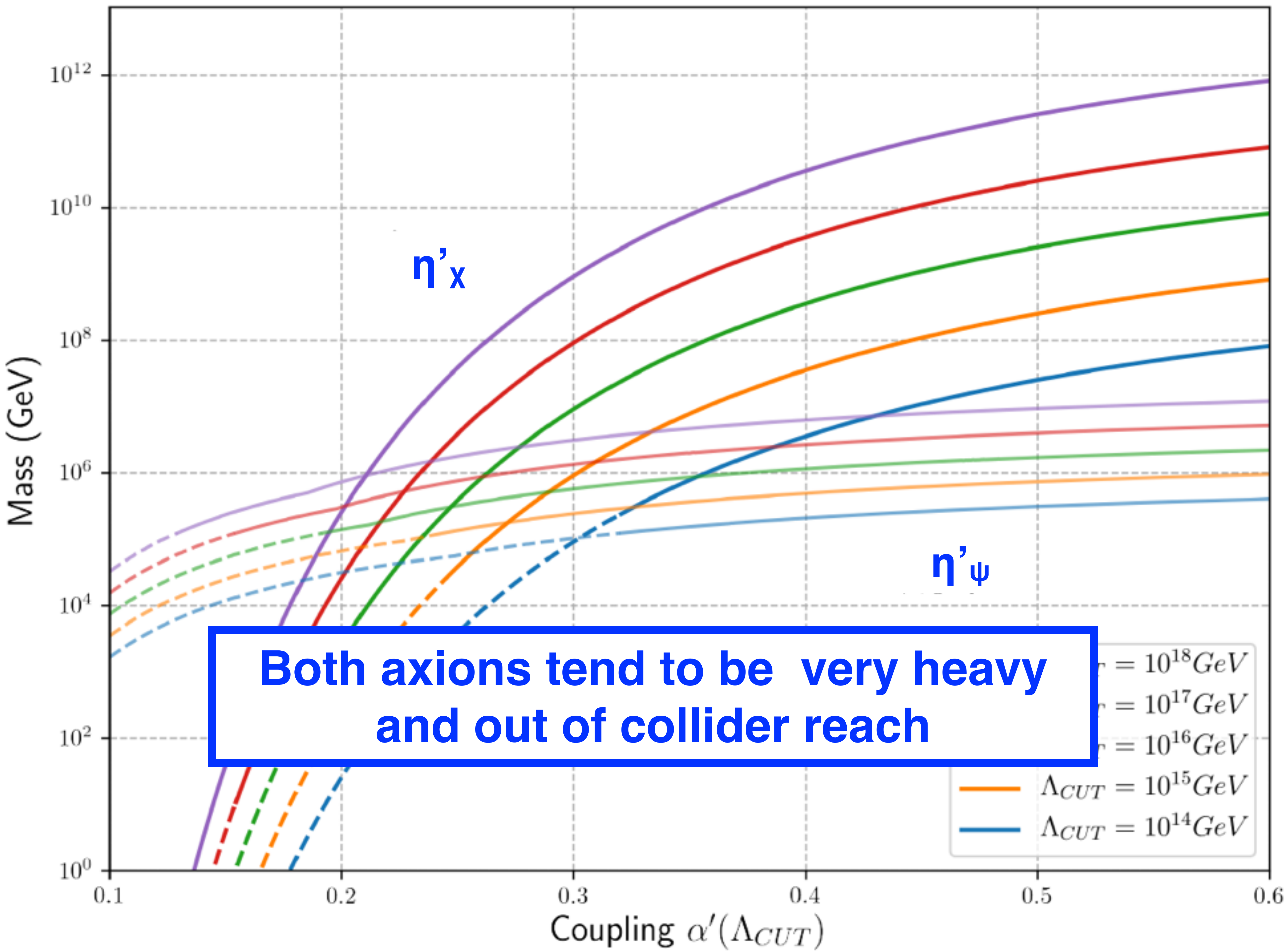


$$\mathcal{L}_{eff} = -m_\chi \bar{\chi}\chi \qquad m_\chi \simeq 4.1 \times 10^{-10} \Lambda_{\rm CUT}$$

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



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



The low-energy observable spectrum

a) for large Yukawa couplings in the prime sector:

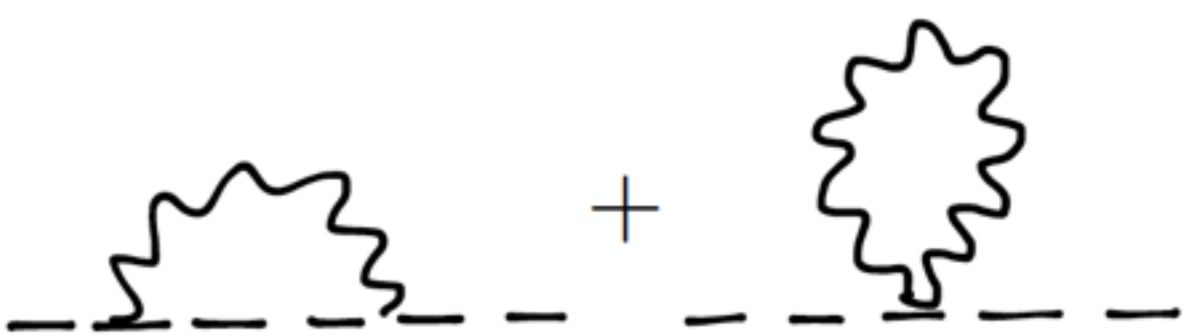
- The U(3) flavor symmetry is broken by condensate $\langle\psi\psi\rangle$

$$U(3)_L \times U(3)_R \longrightarrow U(3)_V$$

QCD-colored “pions”

- This results in 9 pGB’s. $9 = 1_c + 8_c$

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

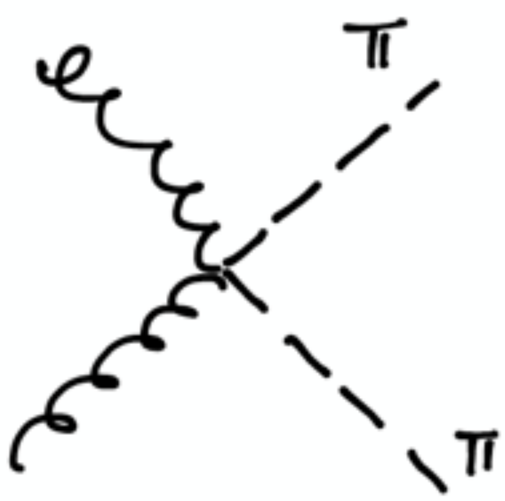


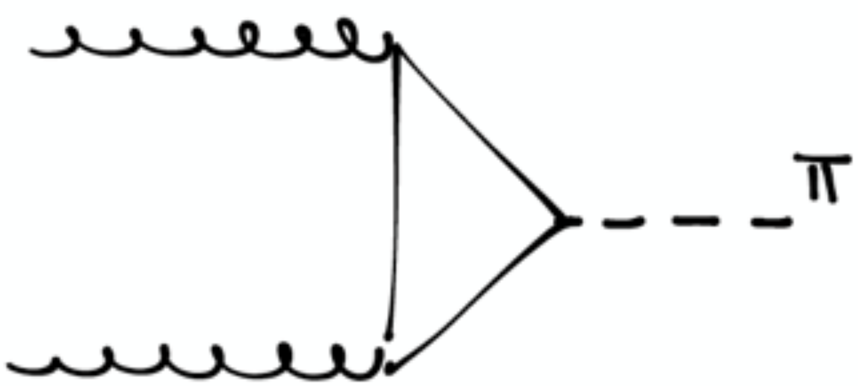
$$\Rightarrow \quad m^2(8_c) \approx \frac{9\alpha_c}{4\pi}\Lambda^2_{\text{diag}}$$

Collider Phenomenology

- Collider accessible states are QCD colored “pions”

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



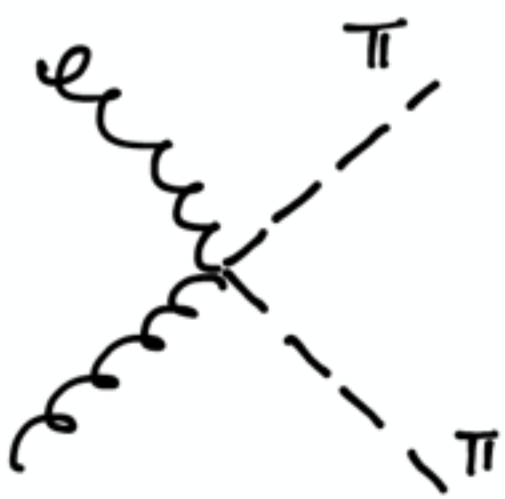


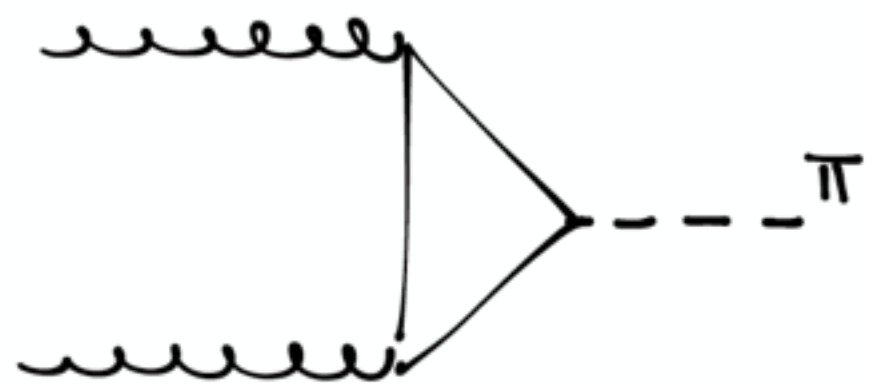
- Pair produced
- Anomalous production

Collider Phenomenology

- Collider accessible states are QCD colored "pions"

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

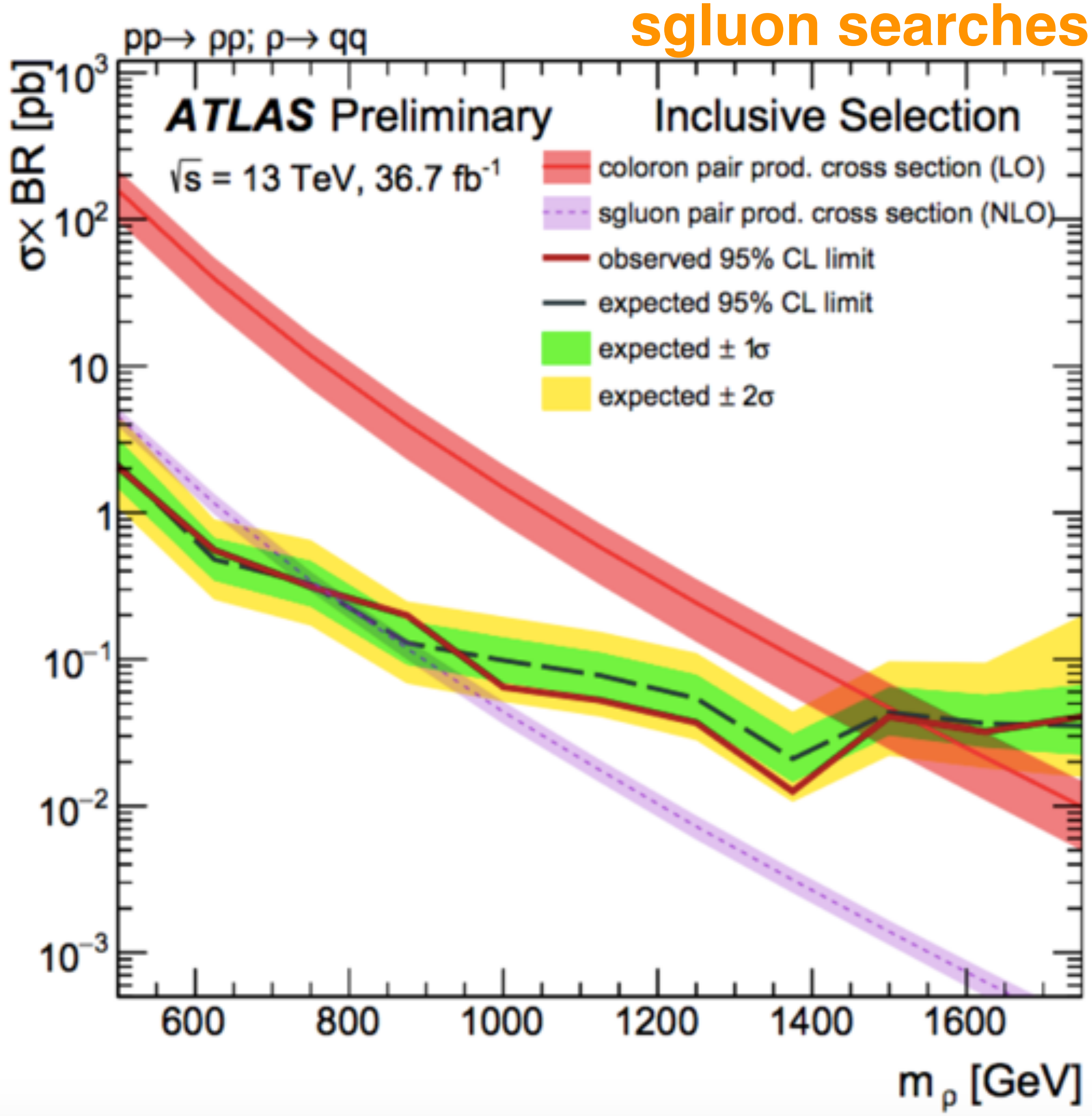




dominates production **dominates decay**

Collider Phenomenology

sgluon searches



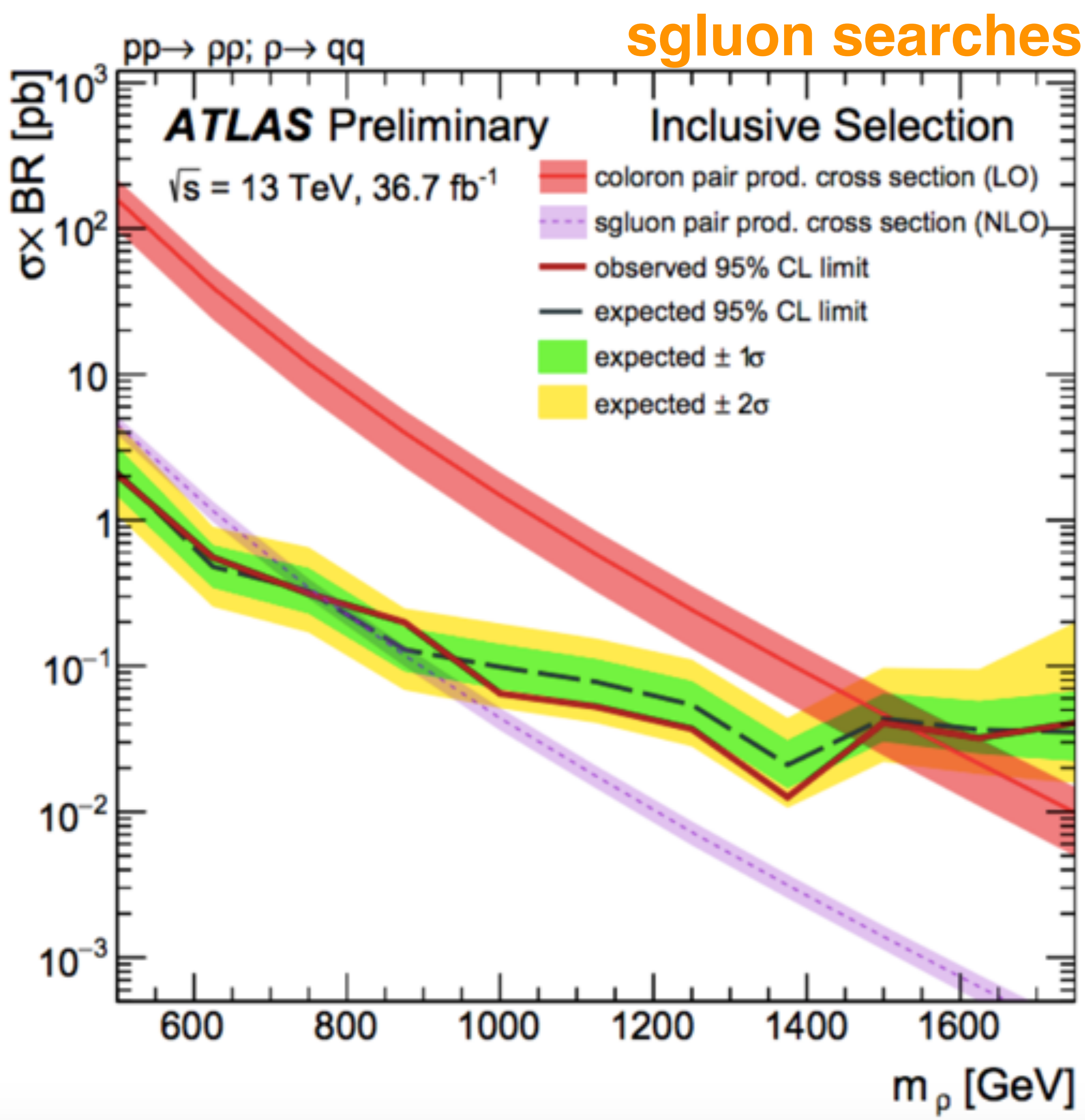
- We have a bound on color octet scalars

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

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

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

Collider Phenomenology



- We have a bound on color octet scalars

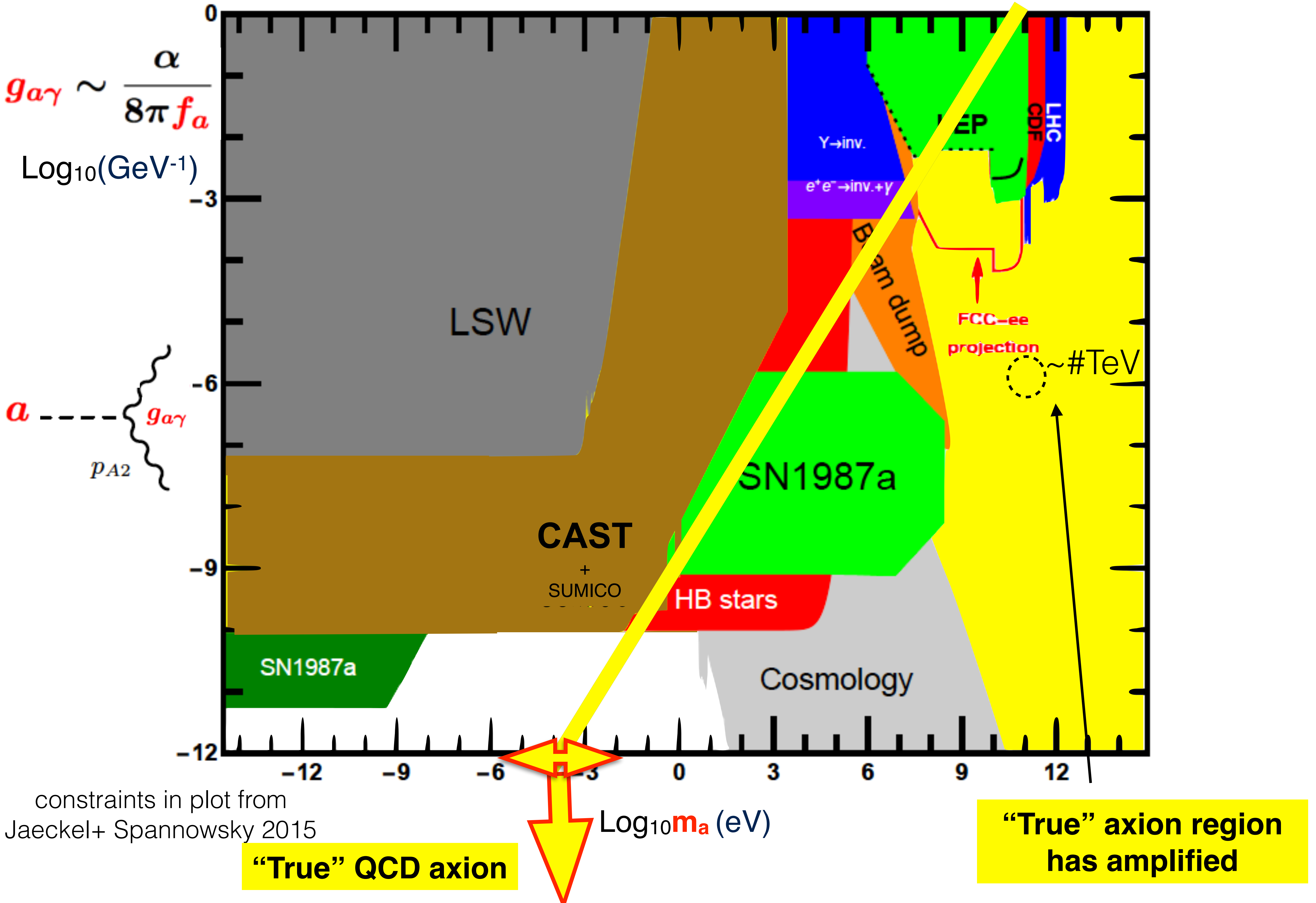
$$m(\pi_d) \gtrsim 700 \text{ GeV}$$

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

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

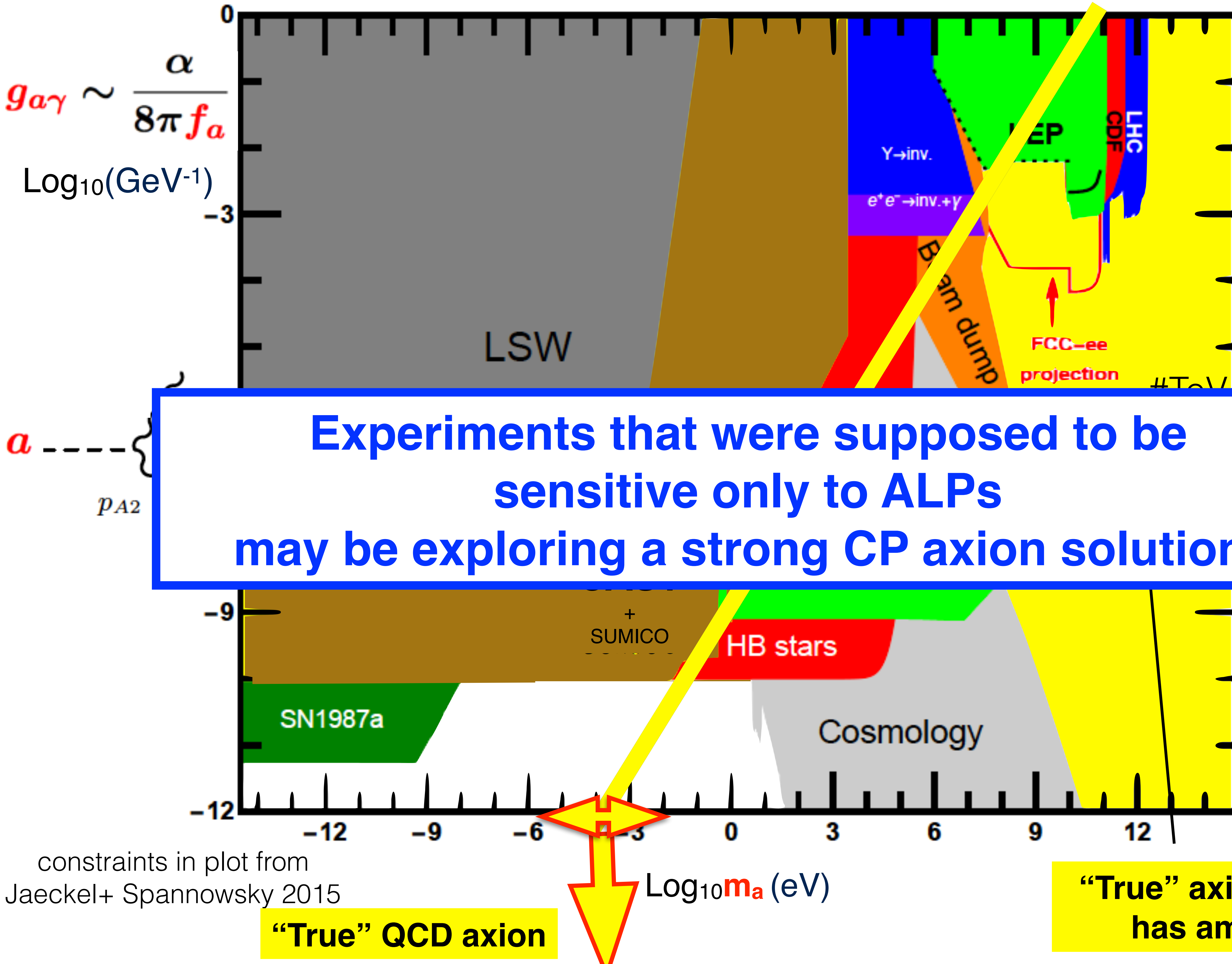
and this is the PQ scale !

* Much territory to explore for heavy 'true" axions, solving strong CP



constraints in plot from Jaeckel+ Spannowsky 2015

* Much territory to explore for heavy 'true" axions, solving strong CP



Experiments that were supposed to be sensitive only to ALPs may be exploring a strong CP axion solution!

constraints in plot from Jaeckel+ Spannowsky 2015

"True" QCD axion

"True" axion region has amplified

Conclusions

Pseudo-Goldstone Bosons in solutions to fundamental SM problems—> derivative couplings to be hunted

Rapidly expanding experimental search

New solution to strong the CP problem:
Colour unification with massless quarks SU(6)xSU(3')

—> Axions heavy due to small-size instantons
—> Colored mesons observable at colliders

The **{m$_a$, f$_a$}** ***region that solves the strong CP problem is being amplified***

Backup

The low-energy observable spectrum

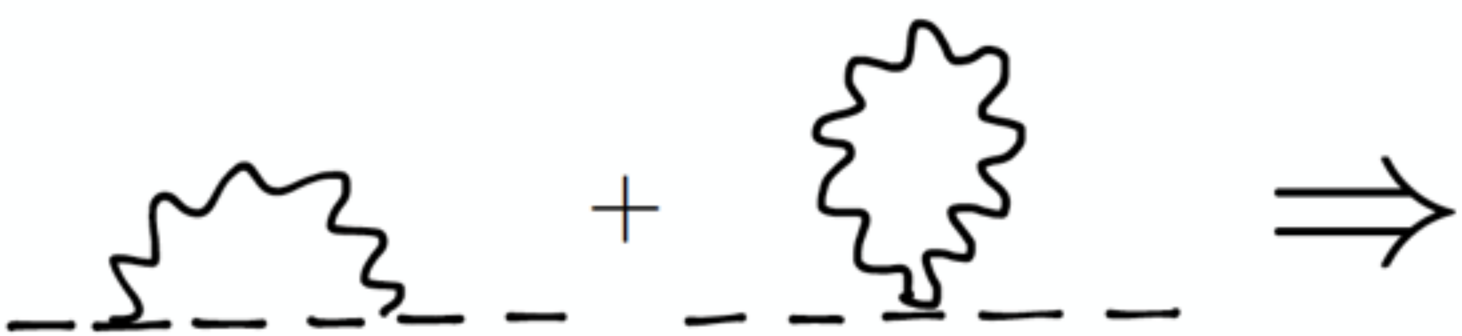
a) for small Yukawa couplings in the prime sector:

- 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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QCD-colored "pions"

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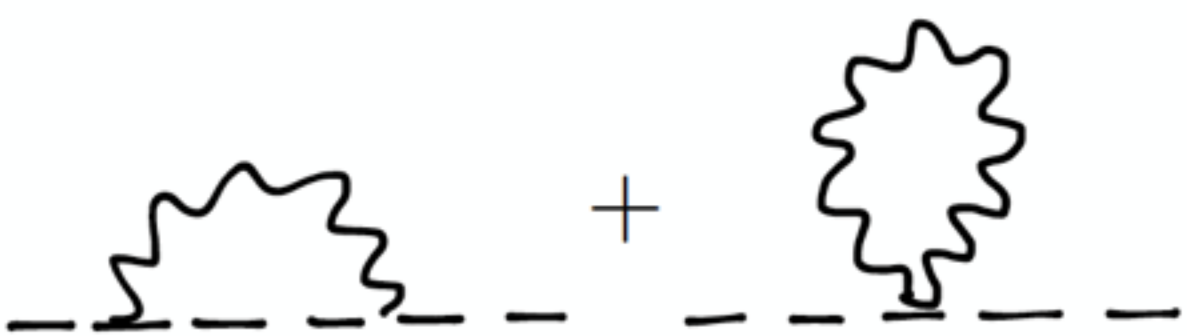


$$\Rightarrow$$

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

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

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

Pseudoscalar potential and masses

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

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

We also developed another UV completion

Same CUT gauge group

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

but instead of adding a second massless fermion as in

model I:

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

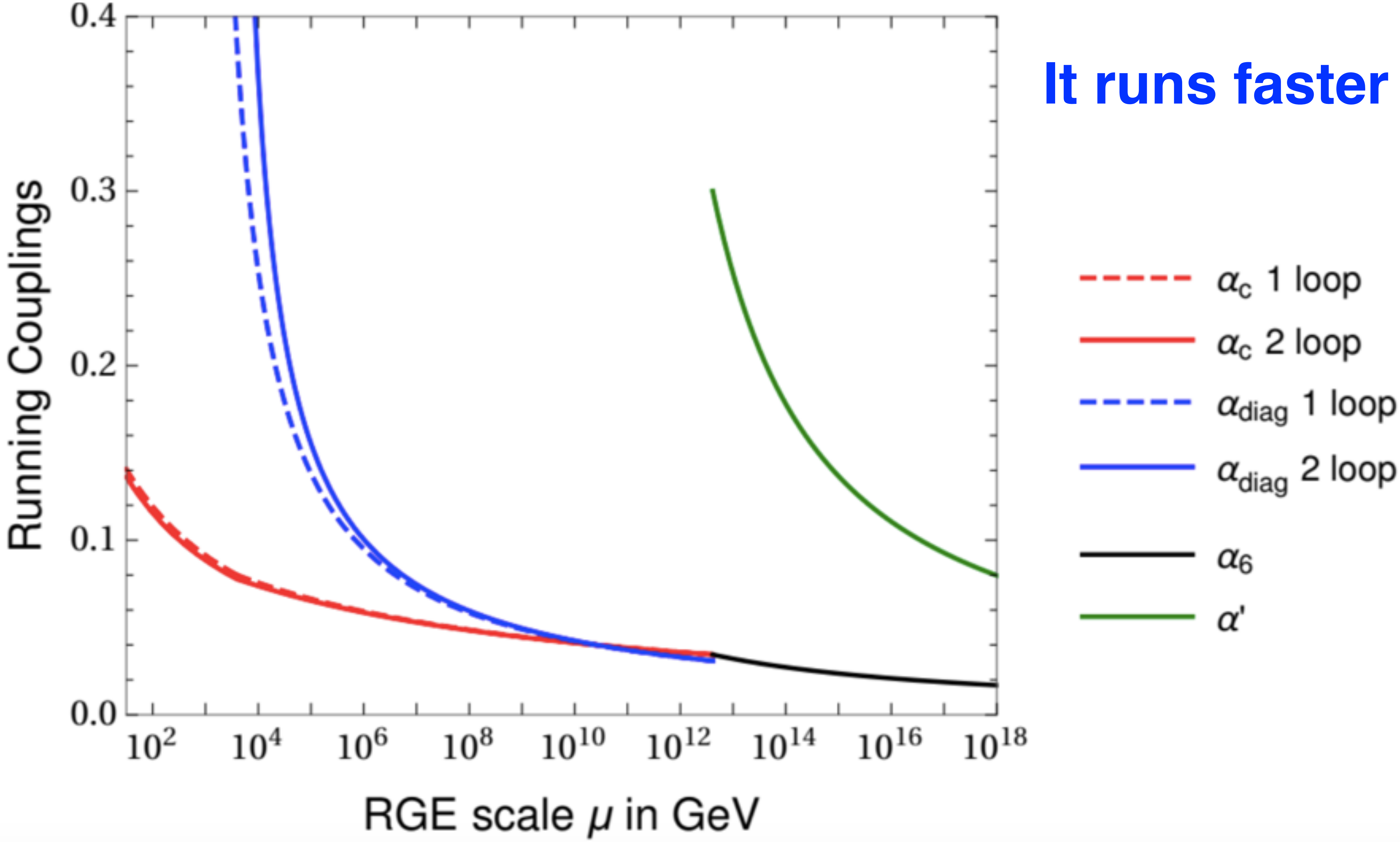
we added a second scalar Δ_2 :

model II:

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

Δ , Δ_2 and the prime fermions have now PQ charges

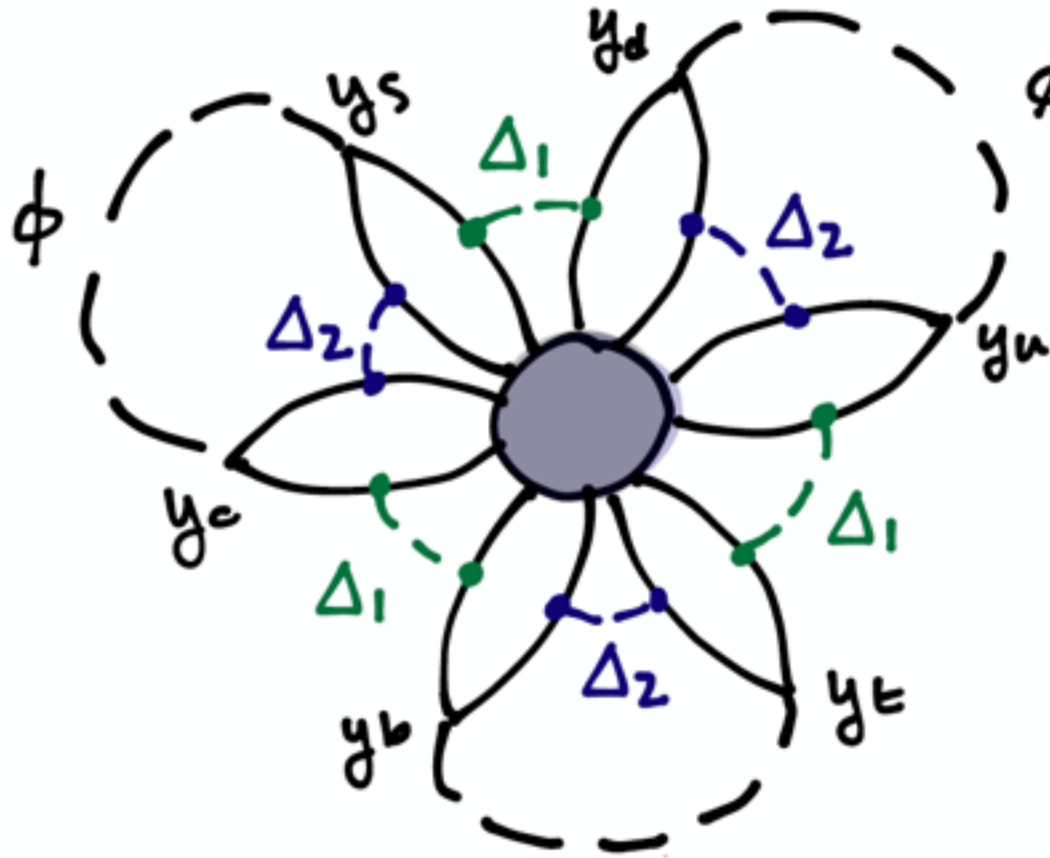
Model II: Small Size Instanton Contribution



It runs faster

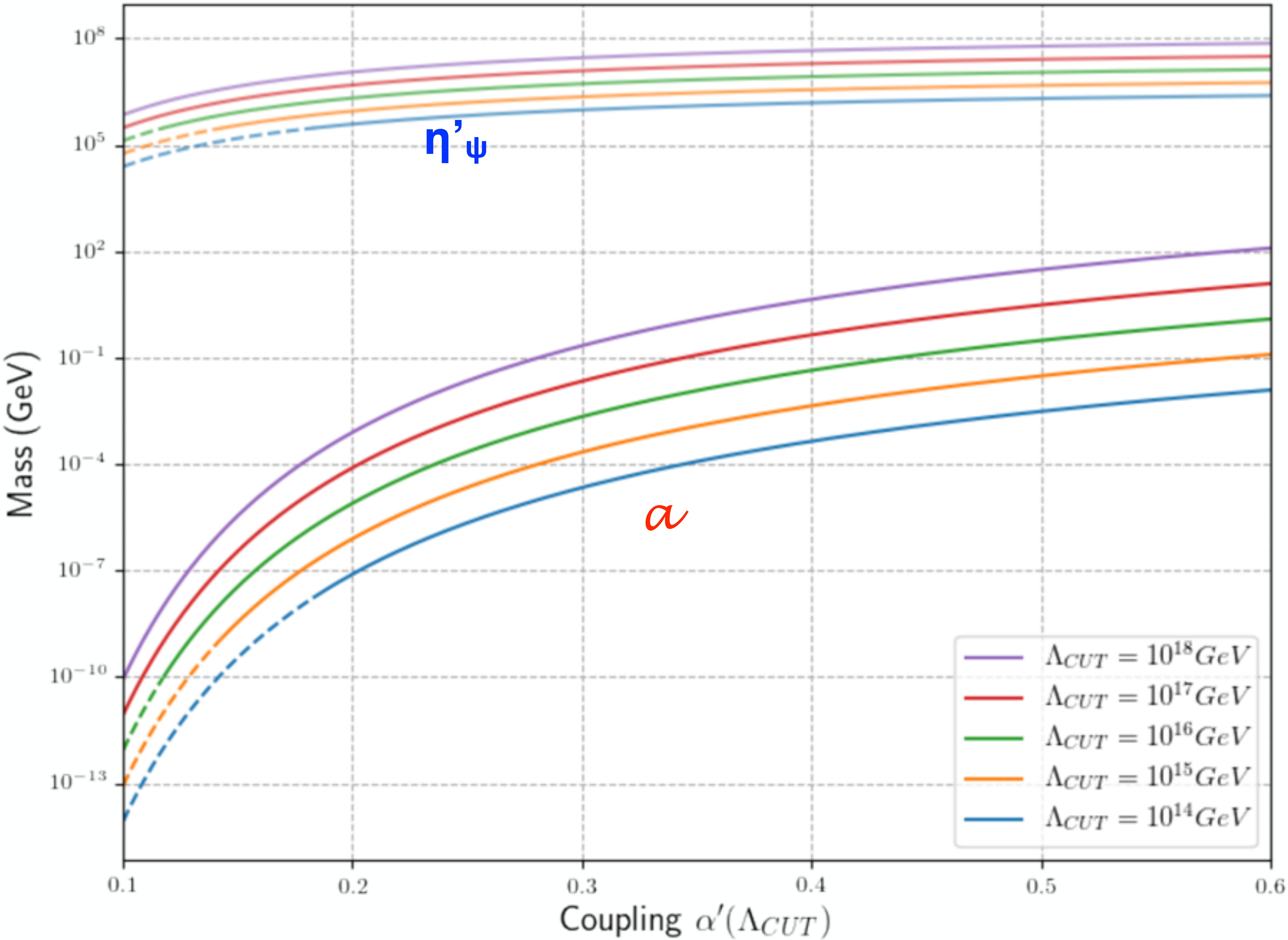
Model II: Small Size Instanton Contribution

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

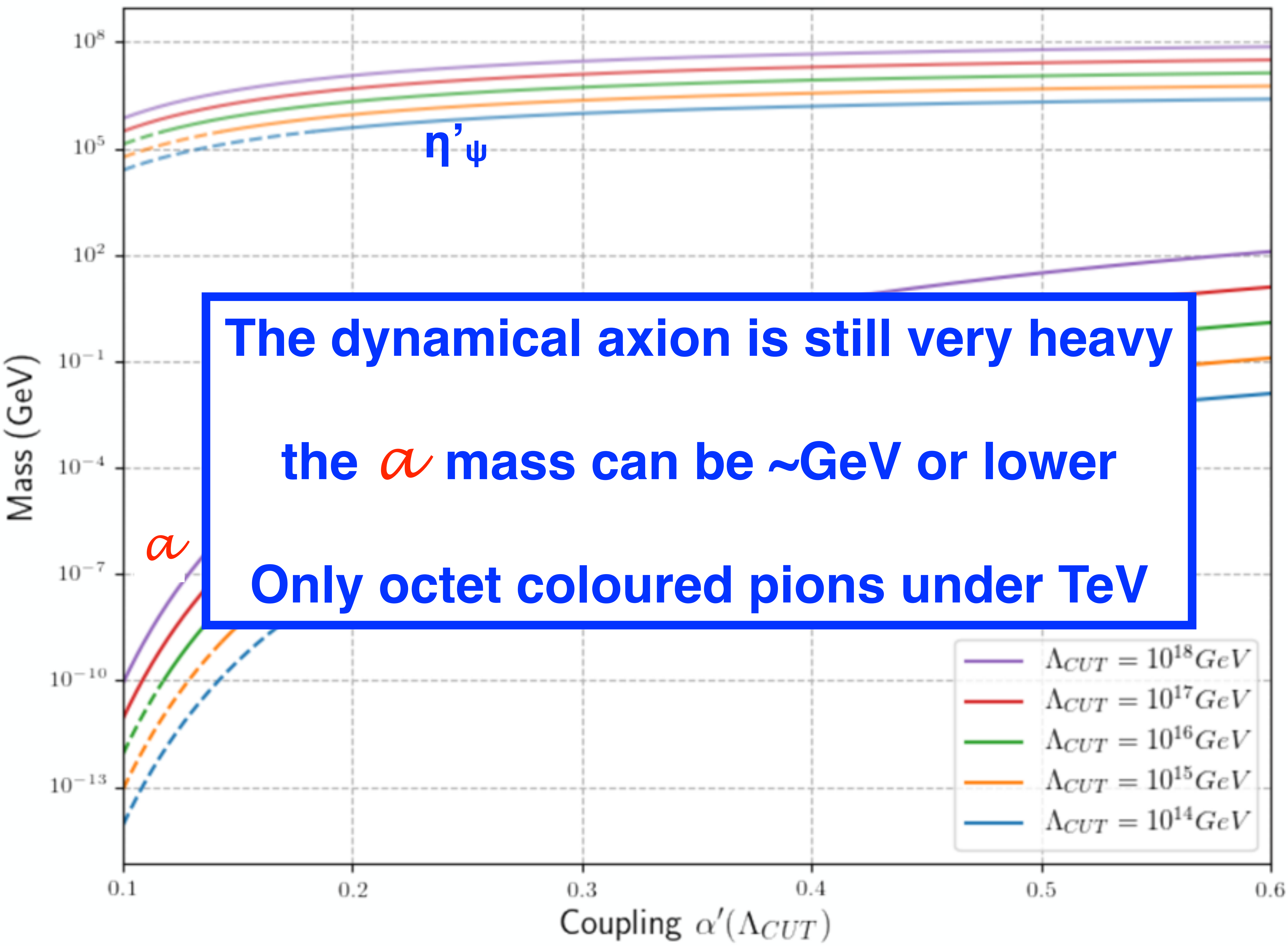


$$\Lambda_{SSI}^4 = -\int \frac{d\rho}{\rho^5} D[\alpha'(1/\rho)] \frac{1}{(4\pi)^{18}} \prod_i Y_{u_i}^{SM} Y_{d_i}^{SM} \left(\kappa_q^i\right)^2 \kappa_u^i \kappa_d^i$$

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



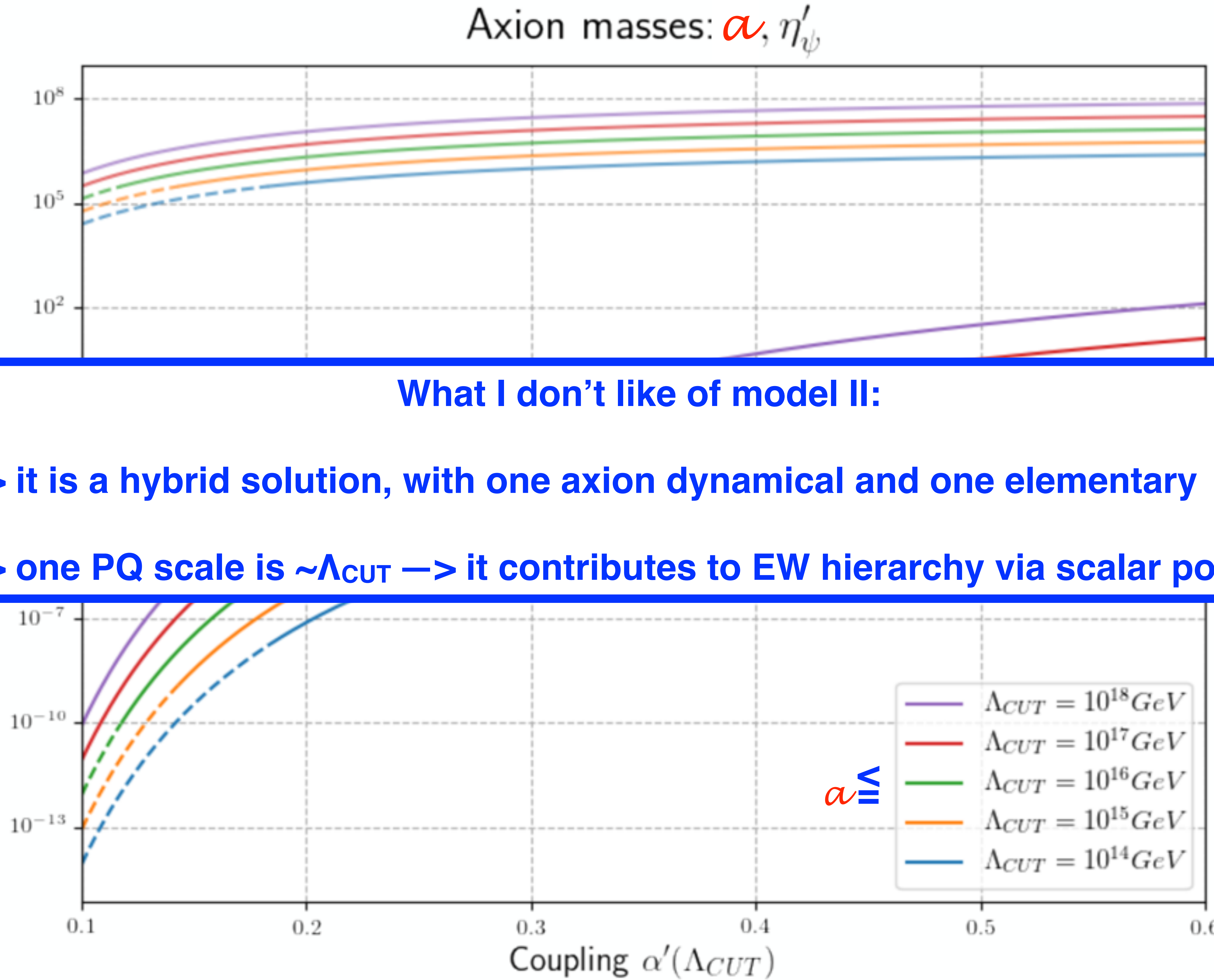
Axion masses: a, $\eta'_\psi = (\bar{\psi}\psi)$



The dynamical axion is still very heavy

the a mass can be ~GeV or lower

Only octet coloured pions under TeV



What I don't like of model II:

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

—> one PQ scale is $\sim\Lambda_{CUT}$ —> it contributes to EW hierarchy via scalar potential

Should we worry about effective operators from gravitational origin, which may threaten the stability of the CP- conserving minimum?

NO! :

—> in model I the PQ scale is close to the TeV, so no worries at all.

—> in model II, one of the PQ scales is indeed high and near Plank scale, and it involves a scalar charged under PQ.

But even in this last case no problem, the argument has been recently desactivated:

There is an important recent result by R. Alonso and A. Urbano, in which they compute explicitly the gravitational instanton contributions and find them to be negligible ay least in the strong regime, even for very high scales: arXiv:1706.07415

The η' Pseudoscalars

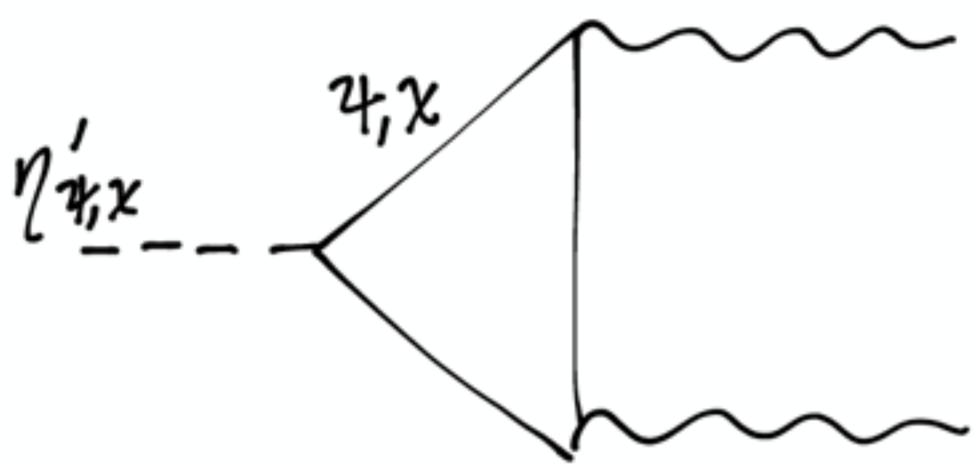
- The associated currents of the QCD singlets are:

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

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

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

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



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

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

Matter Content Above and Below CUT Breaking

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

$\xrightarrow{\Lambda_{\rm CUT}}$

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

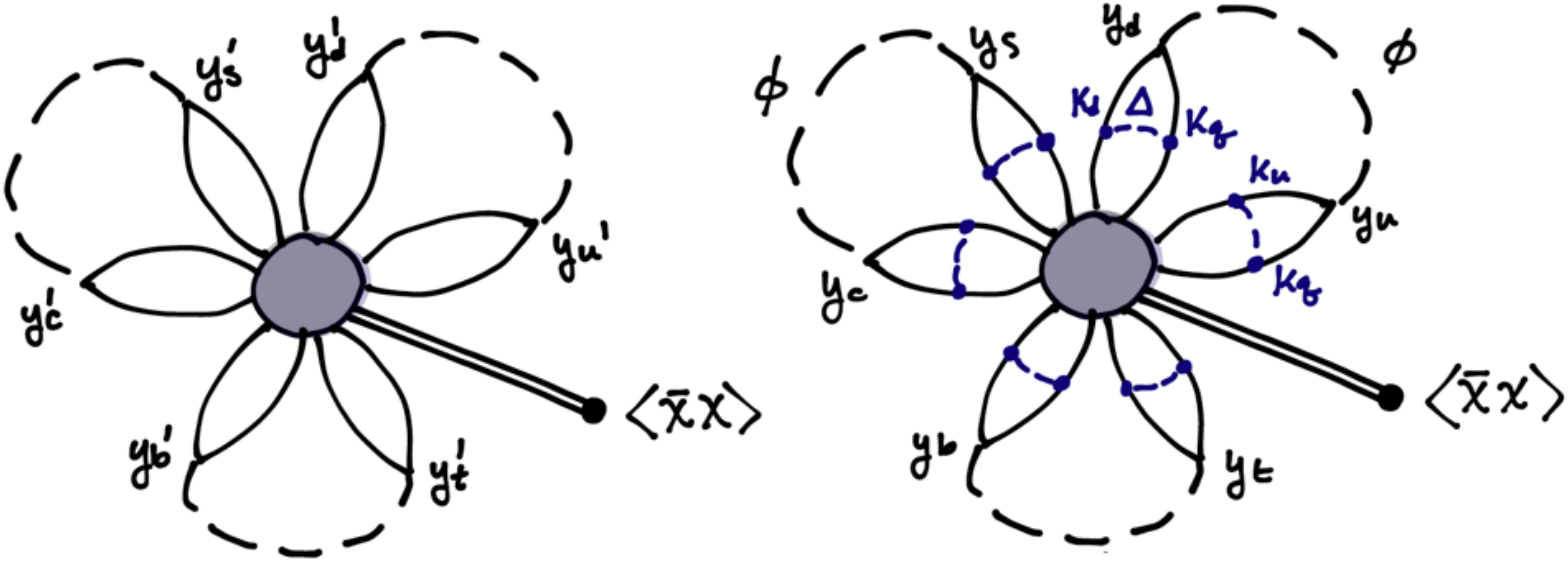
Massless quark sector (ψ, $2\psi_L$)

Obtain mass near the CUT breaking scale ($\tilde{q}_L$ through d'_L)

Prime sector ($\overline{q}'_R$, u'_L, d'_L)

Small Size Instantons with Fermions

- Adding fermion effects gives an instanton suppression



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

Small Size Instantons and Axion Mass

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

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

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

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

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

Colour Unified Dynamical Axion

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

Confined by $\tilde{\Lambda} >> \Lambda$ (→ ψ_L, $(\psi^c)_L$)

$+$ Sterile neutrinos (→ ψ_{ν_1}, ψ_{ν_2})

Colour Unified Dynamical Axion

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

- 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:

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

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

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

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	$\square$	$\square$
$\overline{U}_R$	$\bar{\square}$	$\mathbb{1}$
$\overline{D}_R$	$\bar{\square}$	$\mathbb{1}$
Φ	20	$\mathbb{1}$

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

	$SU(3)$	$SU(\tilde{3})$	$SU(2)_L$
q_L	$\square$	$\mathbb{1}$	$\square$
$\overline{u}_R$	$\bar{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\overline{d}_R$	$\bar{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\tilde{q}_L$	$\mathbb{1}$	$\square$	$\square$
$\overline{\tilde{u}}_R$	$\mathbb{1}$	$\bar{\square}$	$\mathbb{1}$
$\overline{\tilde{d}}_R$	$\mathbb{1}$	$\bar{\square}$	$\mathbb{1}$
ψ	$\square$	$\bar{\square}$	$\mathbb{1}$
24_ν	$\mathbb{1}$	$\mathbb{1}$	$\mathbb{1}$

Goal: provide a mechanism for these fields ($\tilde{q}_L$, $\overline{\tilde{u}}_R$, $\overline{\tilde{d}}_R$) 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	$\square$	$\mathbb{1}$	$\square$
$\bar{u}_R$	$\overline{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\bar{d}_R$	$\overline{\square}$	$\mathbb{1}$	$\mathbb{1}$
$\tilde{q}_L$	$\mathbb{1}$	$\square$	$\square$
$\bar{\tilde{u}}_R$	$\mathbb{1}$	$\overline{\square}$	$\mathbb{1}$
$\bar{\tilde{d}}_R$	$\mathbb{1}$	$\overline{\square}$	$\mathbb{1}$
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

A UV complete solution

Add a new group outside the CUT group

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

with prime fermions charged only under SU(3')

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

- We can form terms like:

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

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

← (Δ) Scalar field responsible for CUT breaking

The CUT breaking

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

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

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

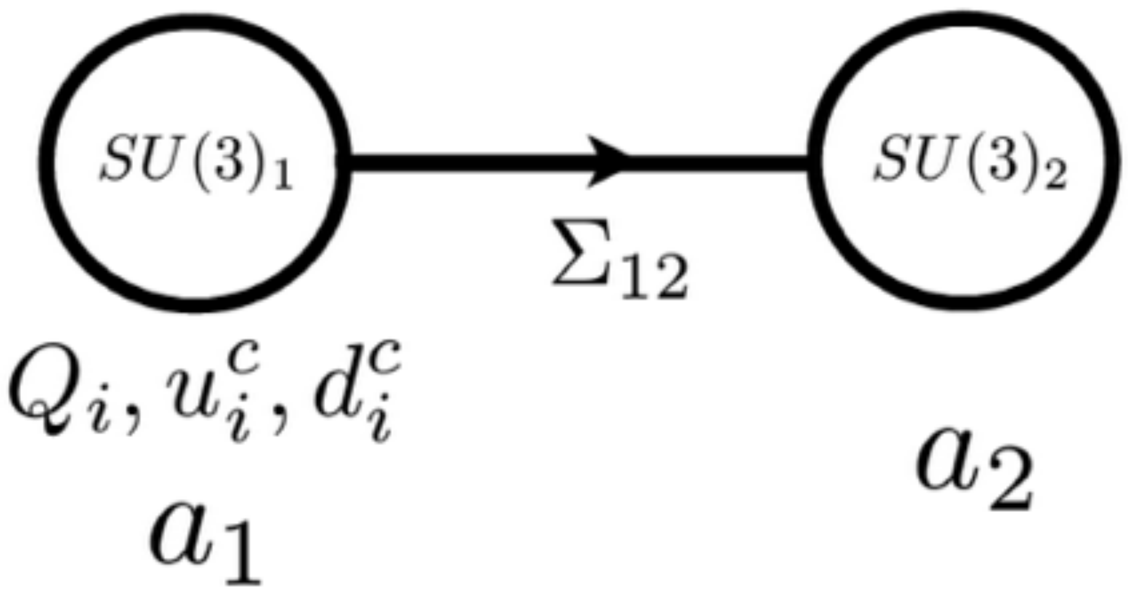
- This VEV pattern grabs only the tilde quarks out of the spectrum

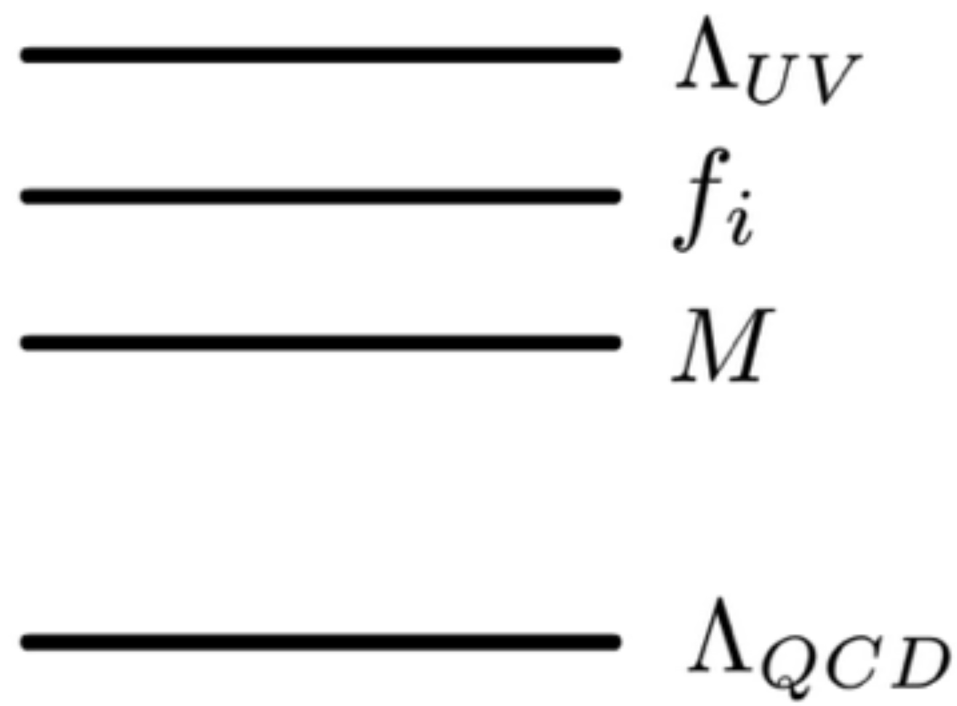
$$\mathcal{L} \ni \Lambda_{\rm CUT} \left(\kappa_q \overline{q'_R} \tilde{q}_L + \kappa_u u'_L \overline{\tilde{u}_R} + \kappa_d d'_L \overline{\tilde{d}_R} \right) + \text{h.c.}$$

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

SU(3)$_1$ x SU(3)$_2$ $\xrightarrow{M}$ SU(3)$_{QCD}$

Agrawal and Howe





$$\mathcal{L} = -\frac{1}{4}(G_1)^a_{\mu\nu}\,(G_1)^{a,\mu\nu} + \frac{g_{s1}^2}{32\pi^2}\left(\frac{a_1}{f_1} - \theta_1\right)(\widetilde{G}_1)^a_{\mu\nu}\,(G_1)^{a,\mu\nu}$$
$$- \frac{1}{4}(G_2)^a_{\mu\nu}\,(G_2)^{a,\mu\nu} + \frac{g_{s2}^2}{32\pi^2}\left(\frac{a_2}{f_2} - \theta_2\right)(\widetilde{G}_2)^a_{\mu\nu}\,(G_2)^{a,\mu\nu}$$

$$V_\Sigma = -m_\Sigma^2 \mathrm{Tr}(\Sigma_{12}\Sigma_{12}^\dagger) + \frac{\lambda}{2}[\mathrm{Tr}(\Sigma_{12}\Sigma_{12}^\dagger)]^2 + \frac{\kappa}{2}\mathrm{Tr}(\Sigma_{12}\Sigma_{12}^\dagger\Sigma_{12}\Sigma_{12}^\dagger)$$

$SU(3)_1 \times SU(3)_2 \xrightarrow{M} SU(3)_{QCD}$

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

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

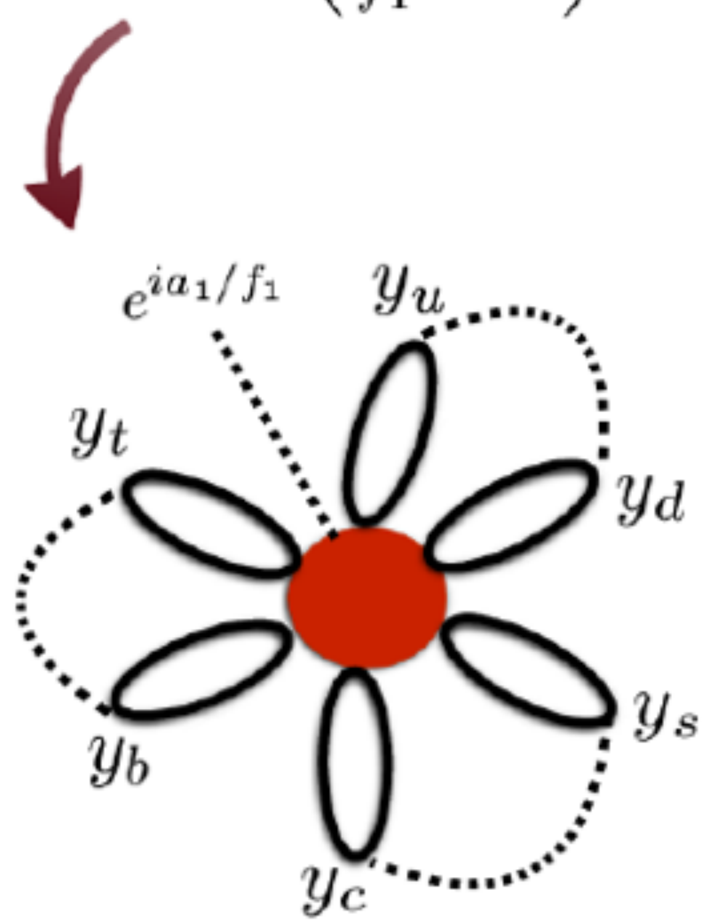
- ➔ New Physics can change the RG flow and induce a new source of axion mass

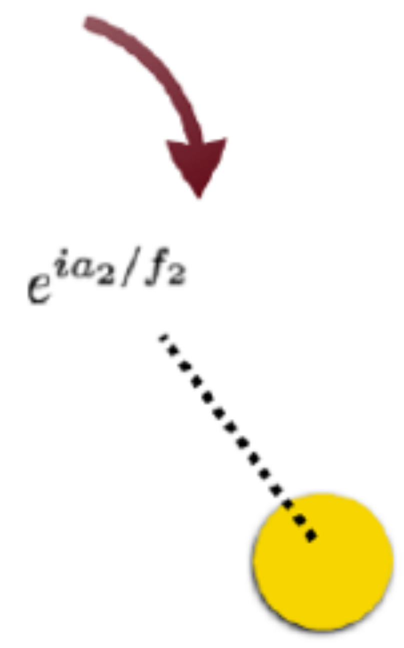
[Holdom+Peskin, 82]
[Dine+Seiberg, 86]
[Flynn+Randall, 87]
[Agrawal+Howe, 17]

$SU(3)_1 \times SU(3)_2 \xrightarrow{M} SU(3)_{QCD}$

Lagrangian below the scale M

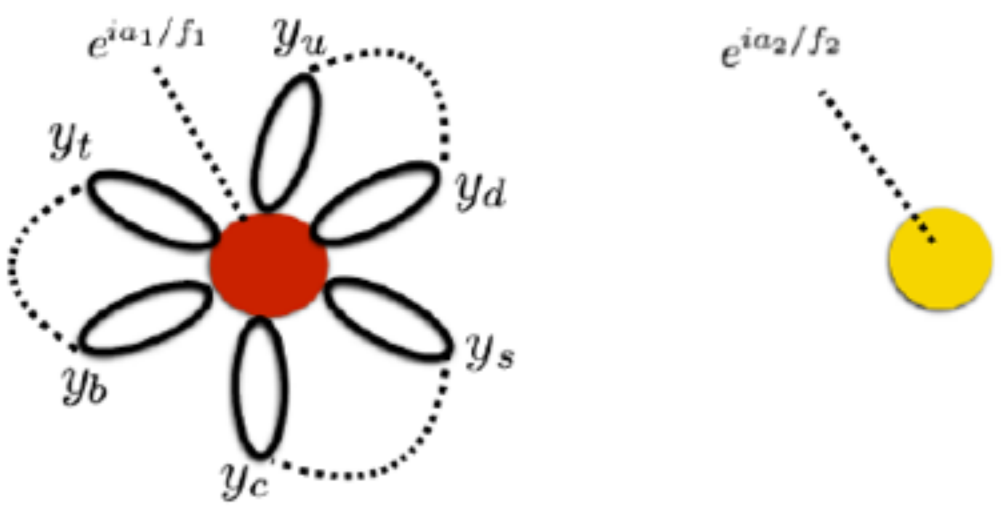
$$\mathcal{L}_a = -\frac{1}{4}G^a_{\mu\nu}G^{a,\mu\nu} + \frac{g_s^2}{32\pi^2}\left(\left(\frac{a_1}{f_1} - \bar{\theta}_1\right) + \left(\frac{a_2}{f_2} - \bar{\theta}_2\right)\right)G\tilde{G}$$
$$+ \Lambda_1^4 \cos\left(\frac{a_1}{f_1} - \bar{\theta}_1\right) + \Lambda_2^4 \cos\left(\frac{a_2}{f_2} - \bar{\theta}_2\right)$$



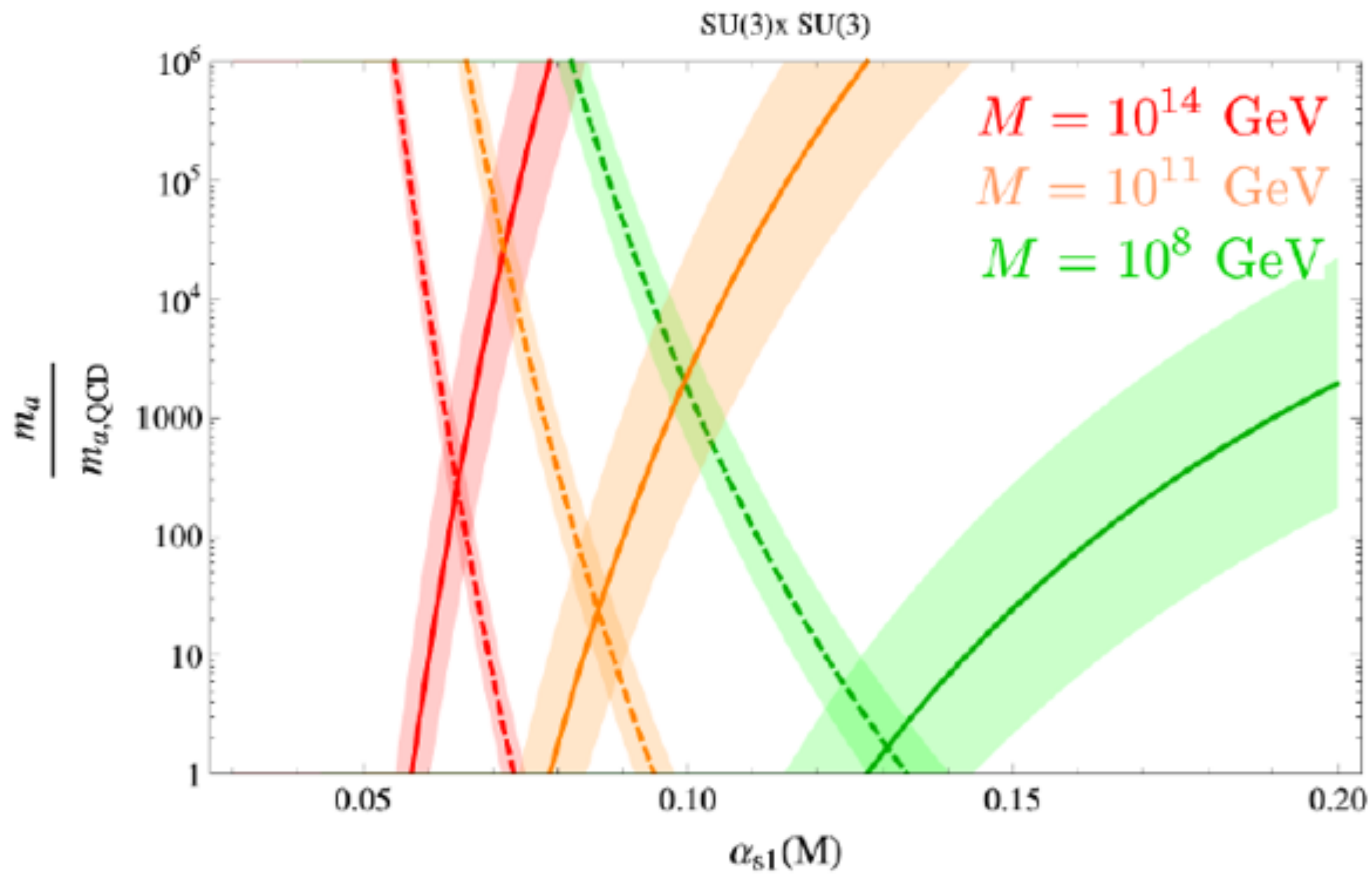


$$\bar{\theta}_{eff} = \left\langle \left(\frac{a_1}{f_1} + \bar{\theta}_1\right) + \left(\frac{a_2}{f_2} + \bar{\theta}_2\right) \right\rangle = 0$$

SU(3)$_1$ x SU(3)$_2$ —> SU(3)$_{QCD}$
M



$$\frac{1}{\alpha_s(\mu)} = \frac{1}{\alpha_{s_1}(\mu)} + \frac{1}{\alpha_{s_2}(\mu)}, \qquad \mu = M$$



$$\Lambda_1^4 \simeq K\frac{4}{5}D[\alpha_{s_1}(M)]M^4$$

$$\Lambda_2^4 = \frac{4}{13}D[\alpha_{s_2}(M)]M^4$$

$$D[\alpha] = D_0 e^{-2\pi/\alpha}\left(\frac{2\pi}{\alpha}\right)^6$$

$$K = \left(\frac{y_u}{4\pi}\right)\left(\frac{y_d}{4\pi}\right)\left(\frac{y_c}{4\pi}\right)\left(\frac{y_s}{4\pi}\right)\left(\frac{y_t}{4\pi}\right)\left(\frac{y_b}{4\pi}\right) \approx 10^{-23}.$$

ALP (axion-like particle): a generic scalar field a

with derivative couplings to SM particles

and free scale f_a:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\partial_\mu a}{f_a} \times {\rm SM}^\mu$$

↑ general effective couplings

This is shift symmetry invariant: $a \to a + {\rm cte.}$ → **~ Goldstone boson**

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with derivative couplings to SM particles

and free scale f_a:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\partial_\mu a}{f_a} \times {\rm SM}^\mu \quad + \quad ....$$

general effective couplings

anomalous couplings and/or small mass

This is (almost) shift symmetry invariant: $a \rightarrow a + {\rm cte.}$ → **~ (pseudo) Goldstone boson**

ALP (axion-like particle): a generic scalar field a

with derivative couplings to SM particles

and free scale f_a:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\partial_\mu a}{f_a} \times {\rm SM}^\mu \quad + \quad \ldots.$$

general effective couplings

anomalous couplings

e.g. $a\, G_{\mu\nu}\tilde{G}^{\mu\nu}$ $\quad a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$