FLASY 2022

Unconventional axions and ALPs

Lisbon, June 27- July 1 2022

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H2020 HIDDeν Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Why ?

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

Or simply the first one discovered?

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Or simply the first one discovered?

What about a singlet (pseudo) scalar?

Strong motivation from fundamental issues of the SM

Many small unexplained SM parameters

Hidden symmetries
can explain small parameters

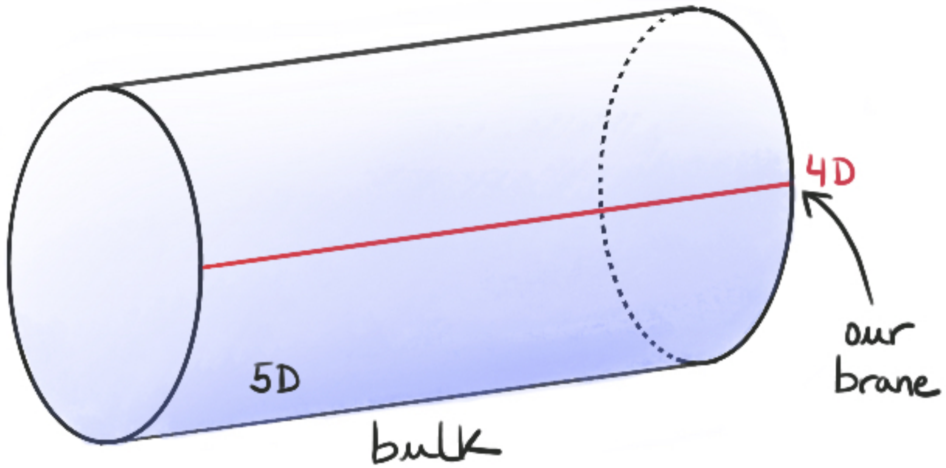
↓

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)

……

The strong CP problem: Why is the QCD θ parameter so small?

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

$$\tilde{G}_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma}\, G_{\mu\nu}$$

The strong CP problem: Why is the QCD θ parameter so small?

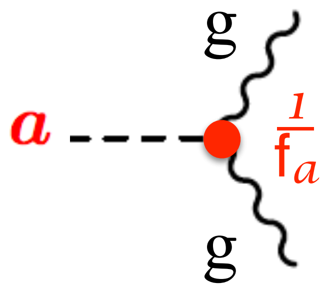
$$\bar{\theta} \leq 10^{-10}$$

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

$$\tilde{G}_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma} G^{\rho\sigma}$$

A dynamical $U(1)_A$ solution ?

The strong CP problem: Why is the QCD θ parameter so small?



$$\mathcal{L}_{QCD} \supset \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

A dynamical $U(1)_A$ solution

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

→ the axion a couplings~ $\partial_\mu a$

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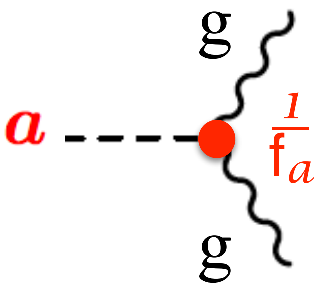

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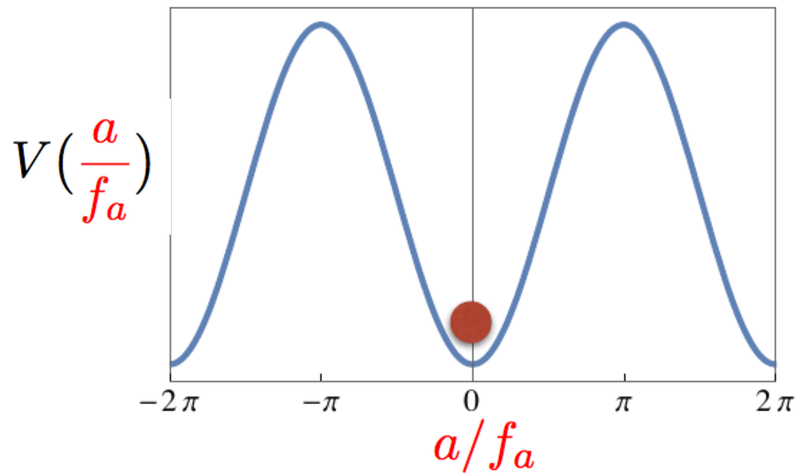

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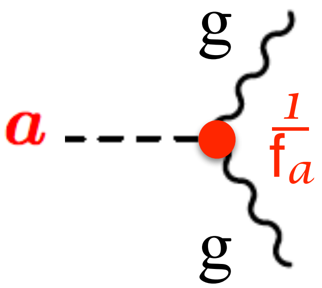

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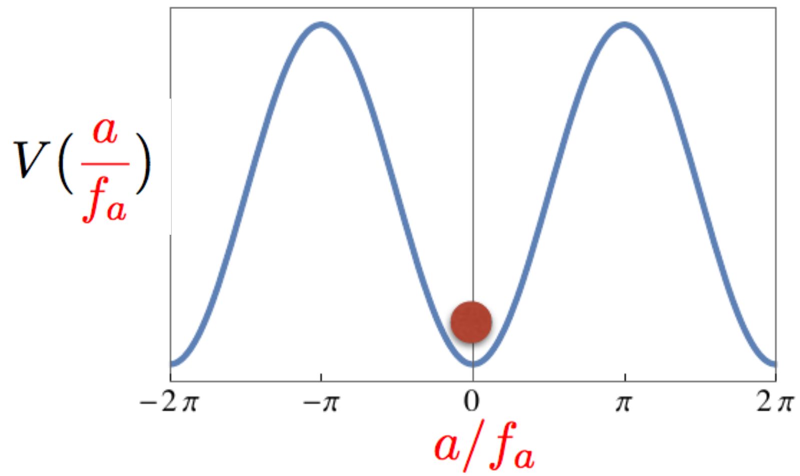
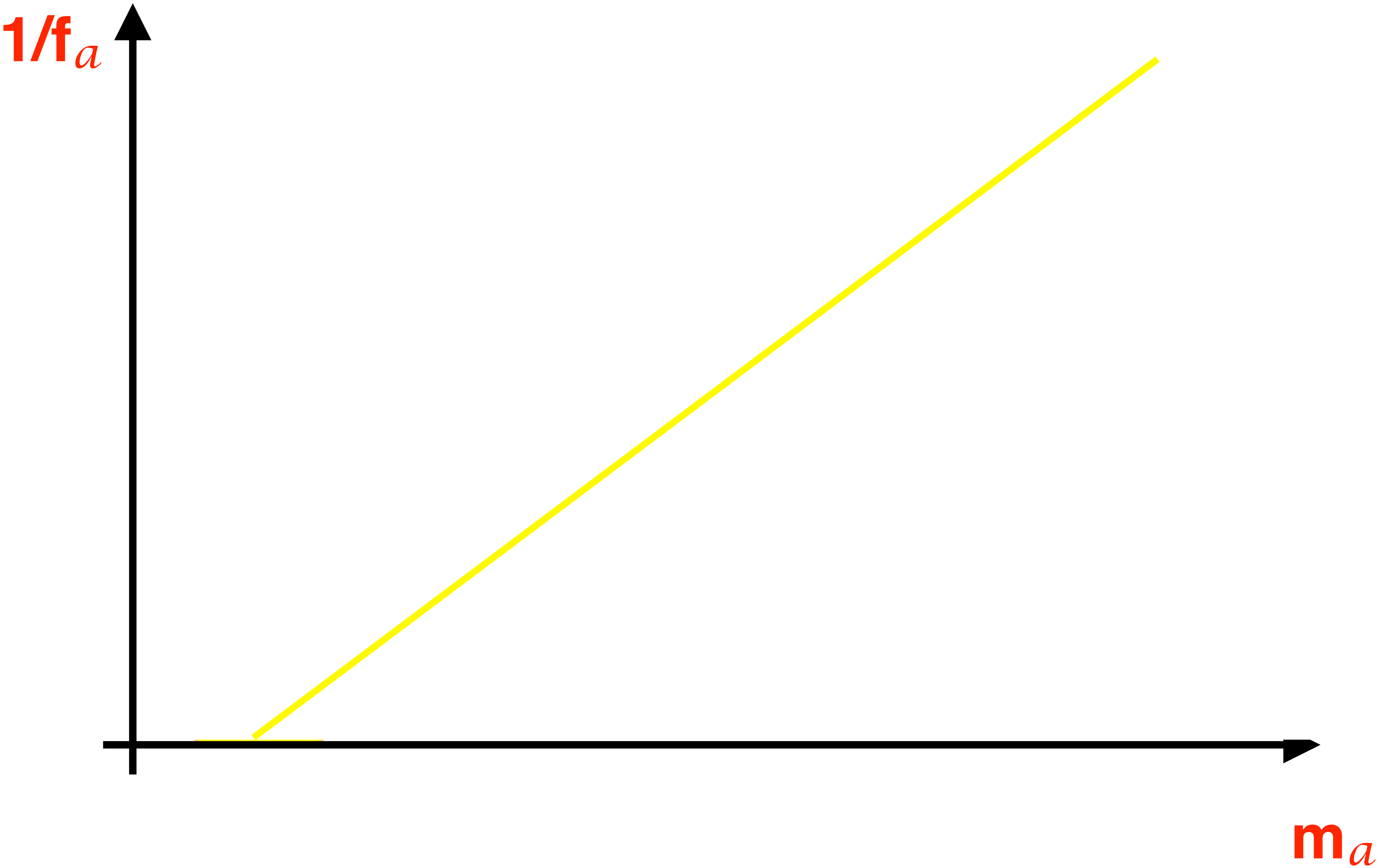


Excellent DM candidate

[Abbot+Sikivie, 83]
[Dine and W. Fischler, 83]
[Preskil et al, 91]

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

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



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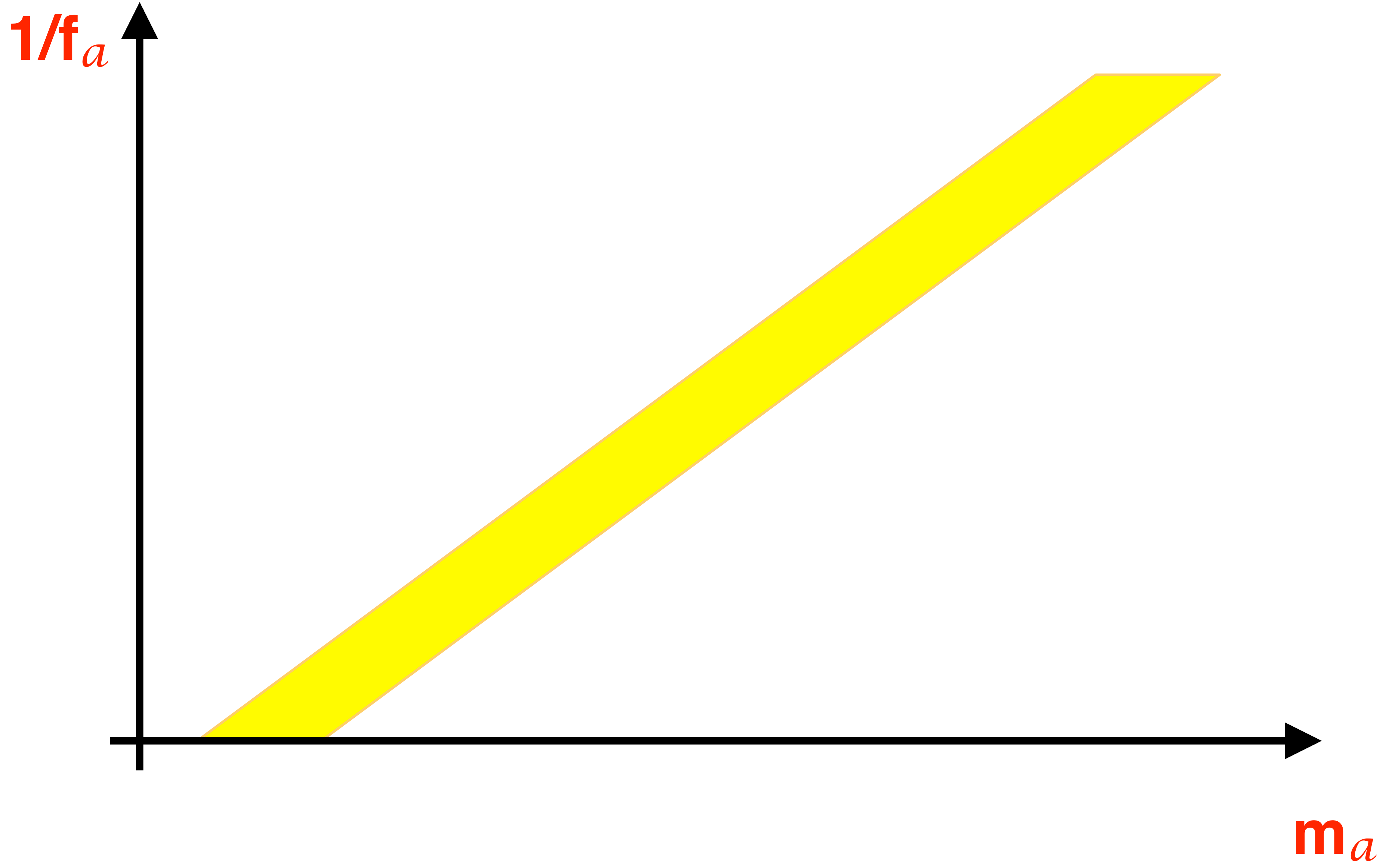

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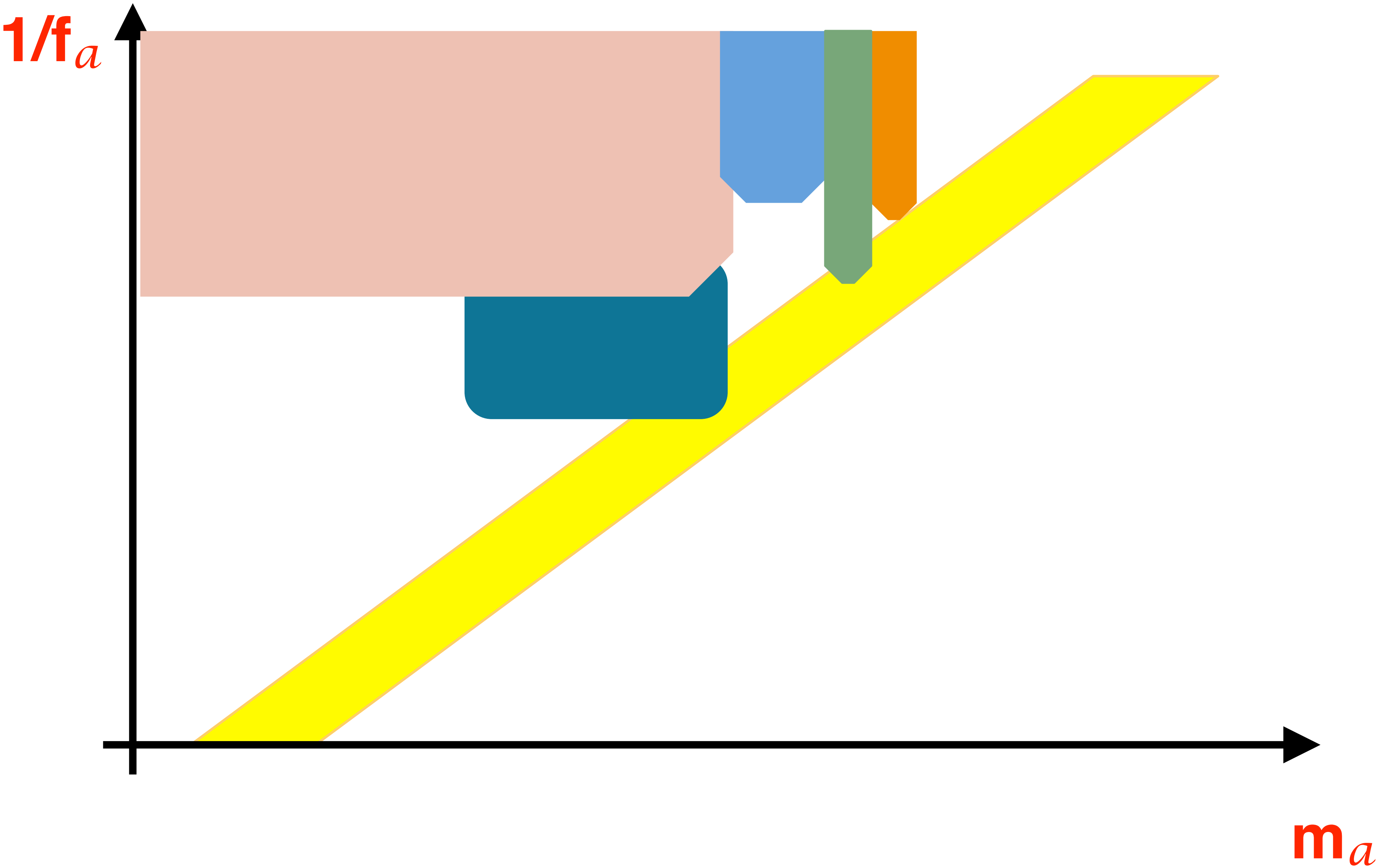

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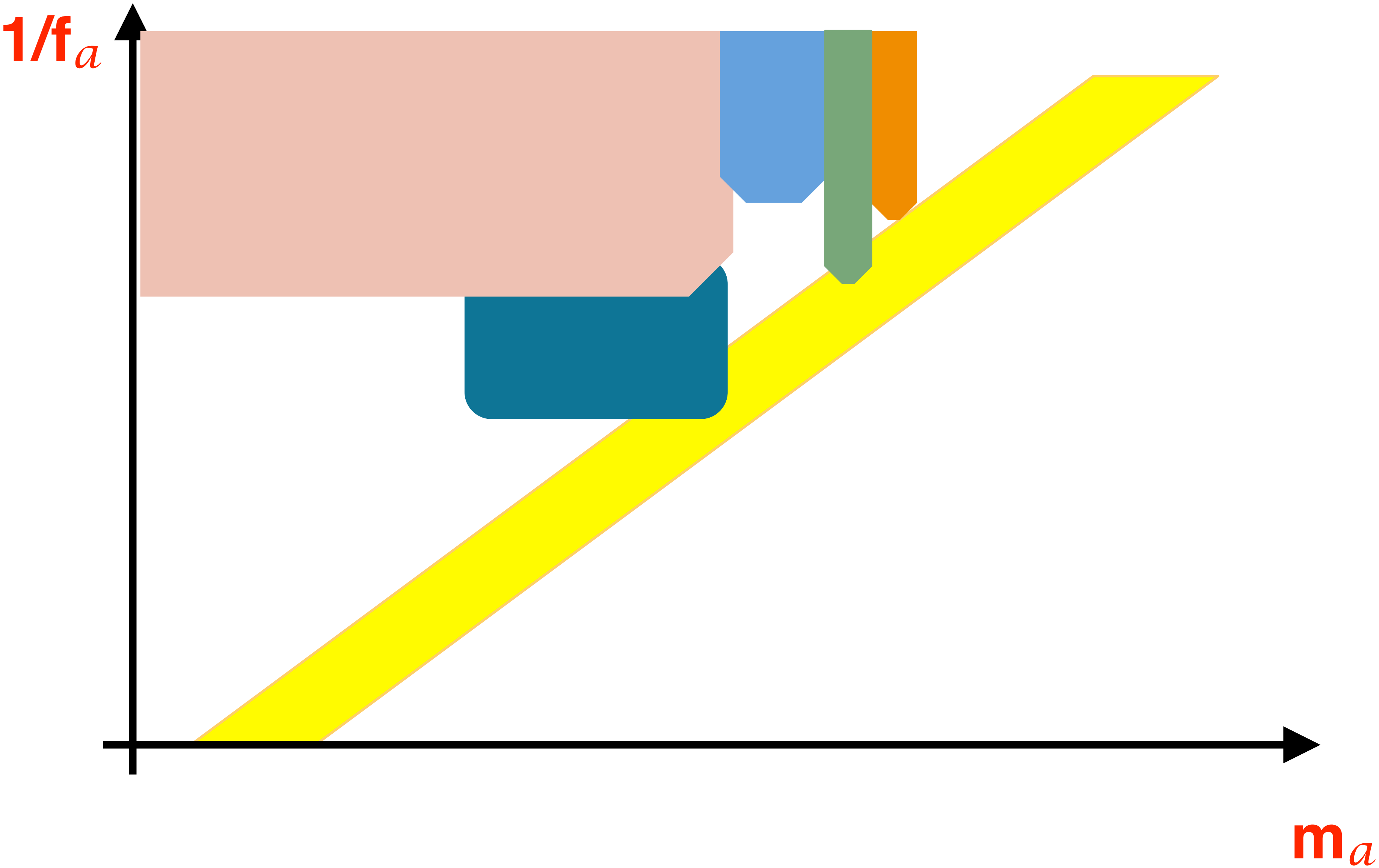
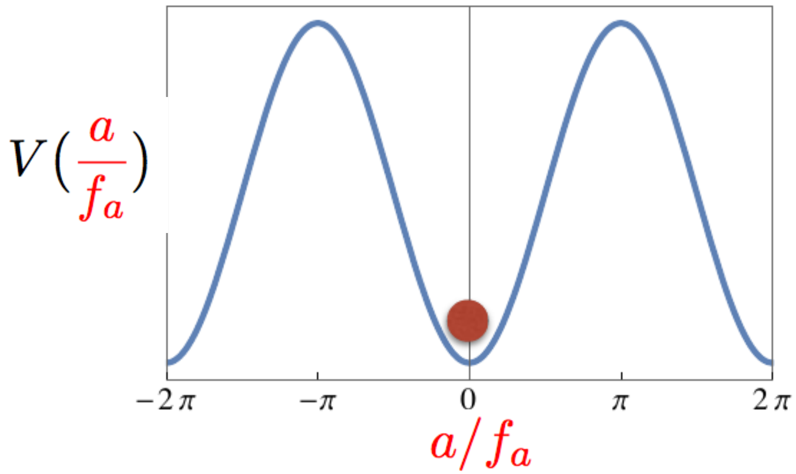


The value of the constant is determined by the strong gauge group

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

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

*** If the confining group is QCD:**



$\leftarrow \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$

$$V_{SM}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a}\right)}$$

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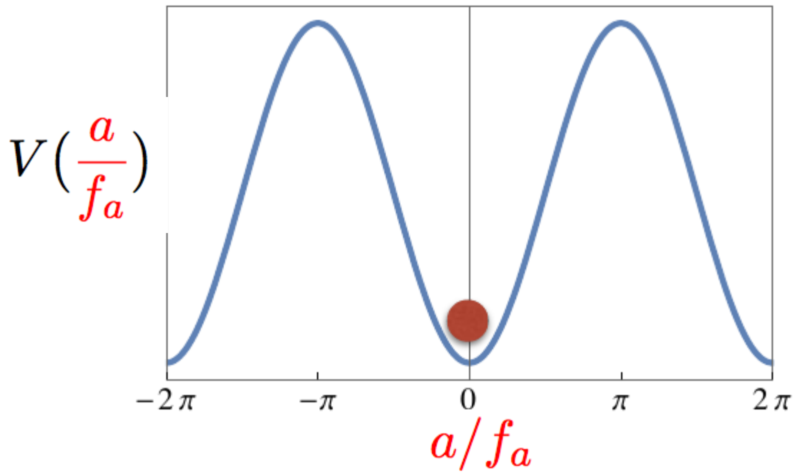

$\longleftarrow \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$

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

canonical QCD axion

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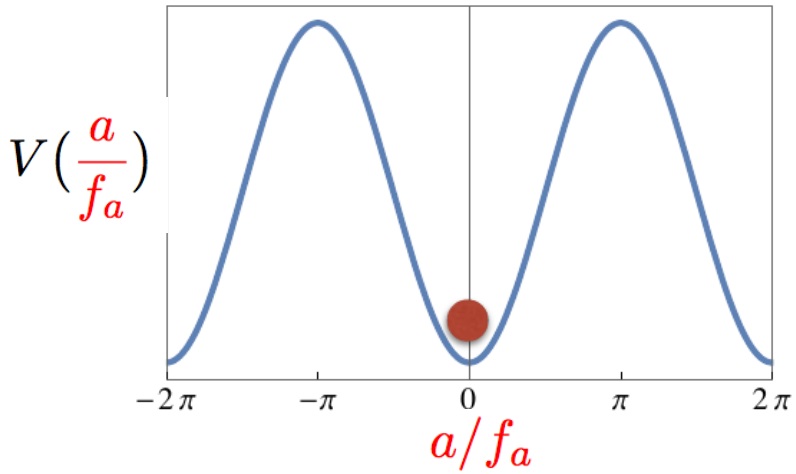

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canonical QCD axion

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

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

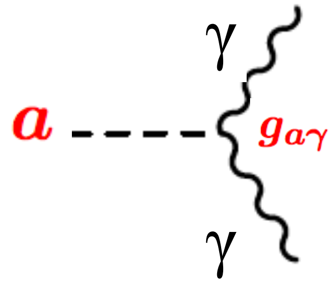
*** If the confining group is QCD:** $m_a^2 f_a^2 = m_\pi^2 f_\pi^2$

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

Because of SN and hadronic data,
if axions light enough to be emitted

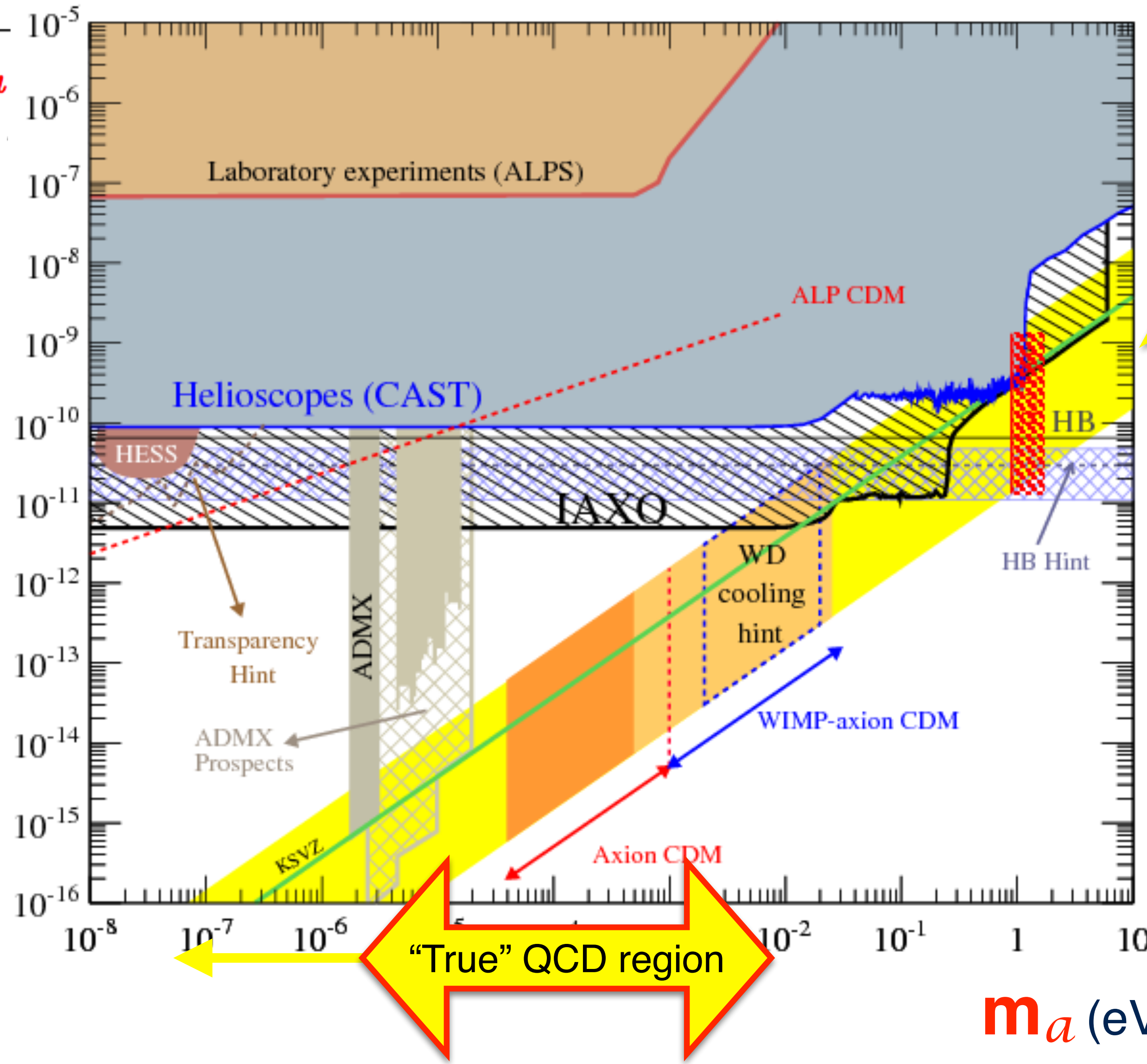
“Invisible axion”

Intensely looked for experimentally…



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

(GeV^{-1})



m_a (eV)

“True” QCD axion band

=

“Invisible axion”
e.g. KSVZ, DFSZ…

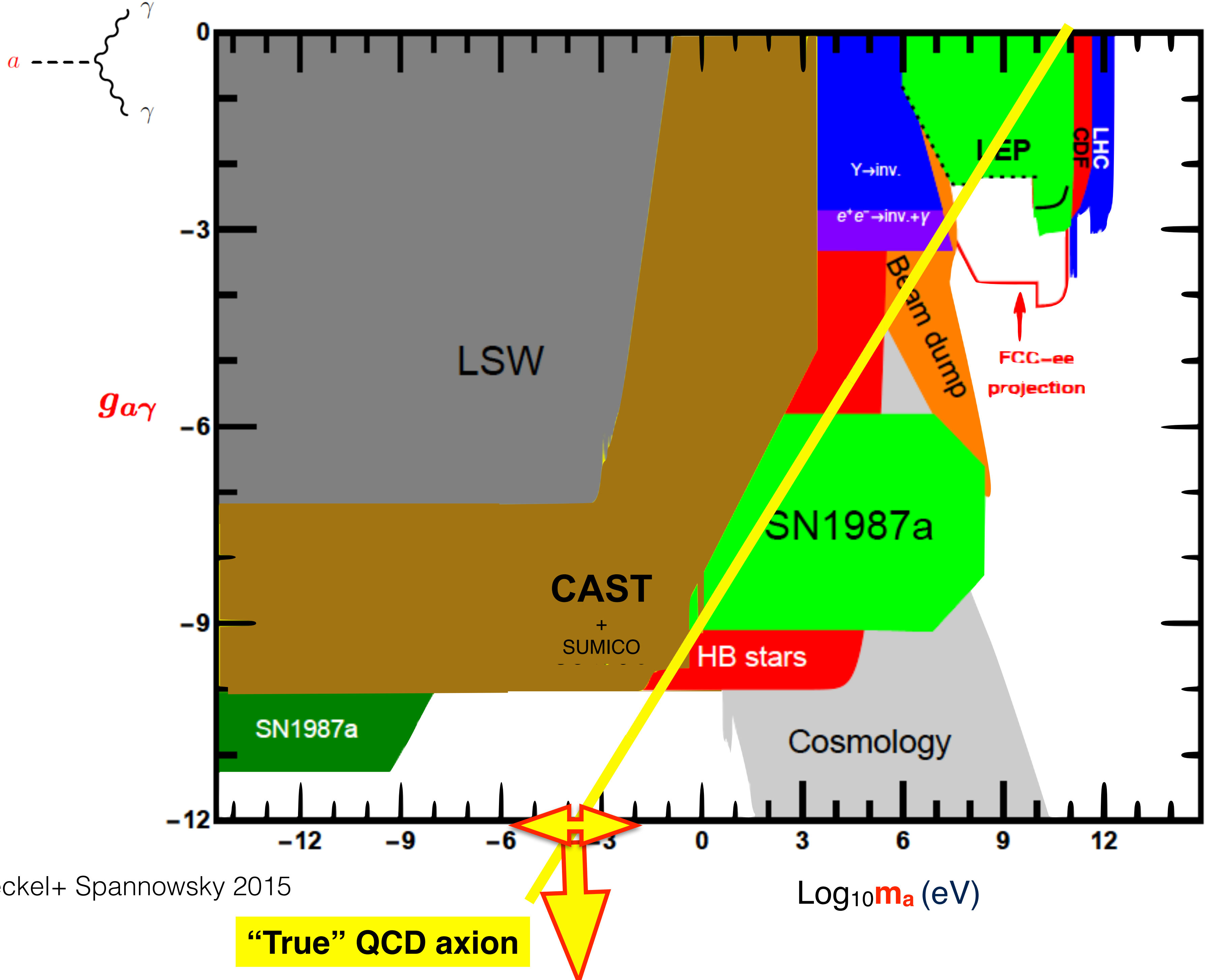
v<< f_a —>

EW hierarchy problem
+ gravitational tunings ?

… and theoretically

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

ALPs (axion-like particles) territory



Jaeckel+ Spannowsky 2015

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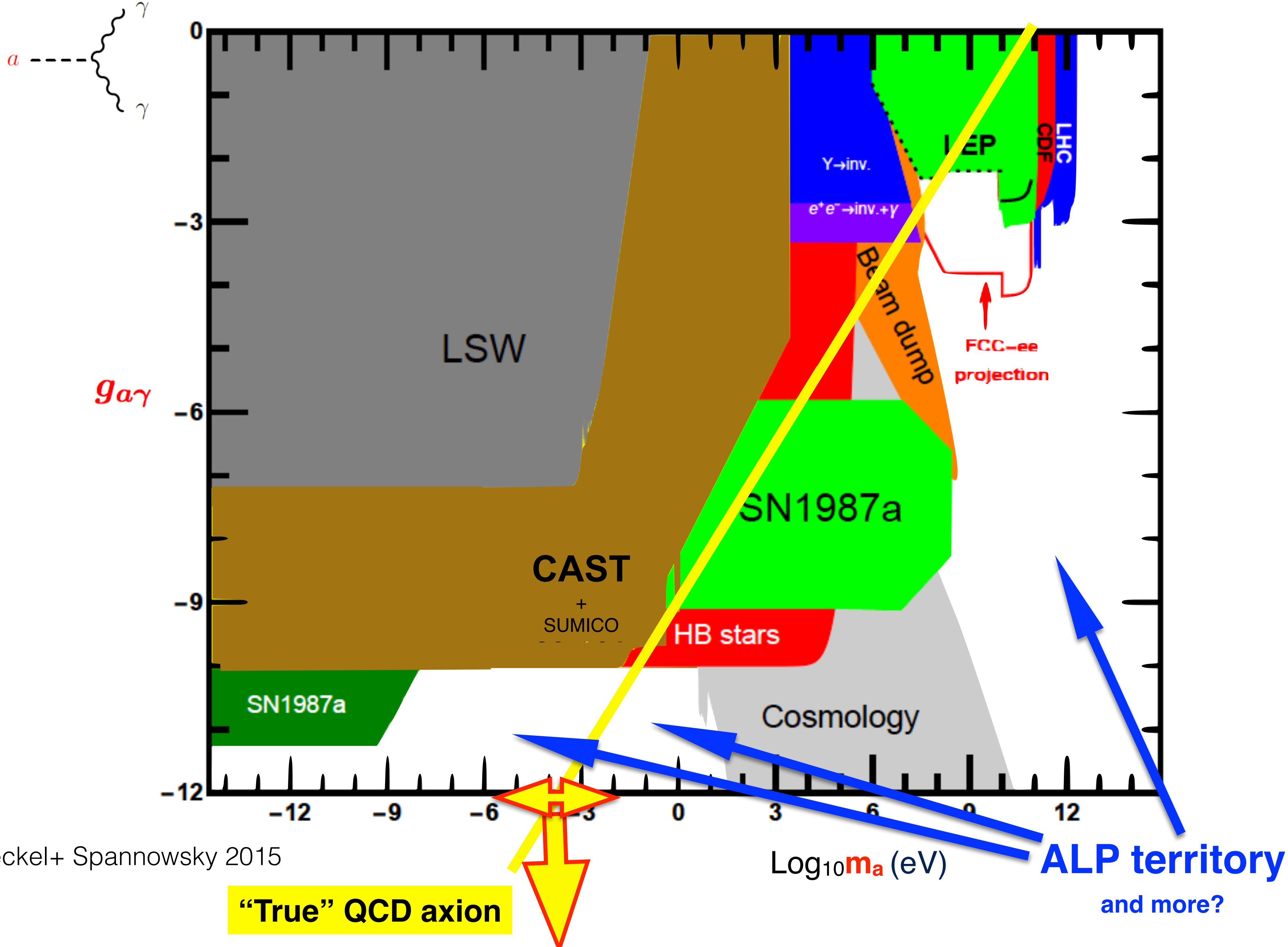
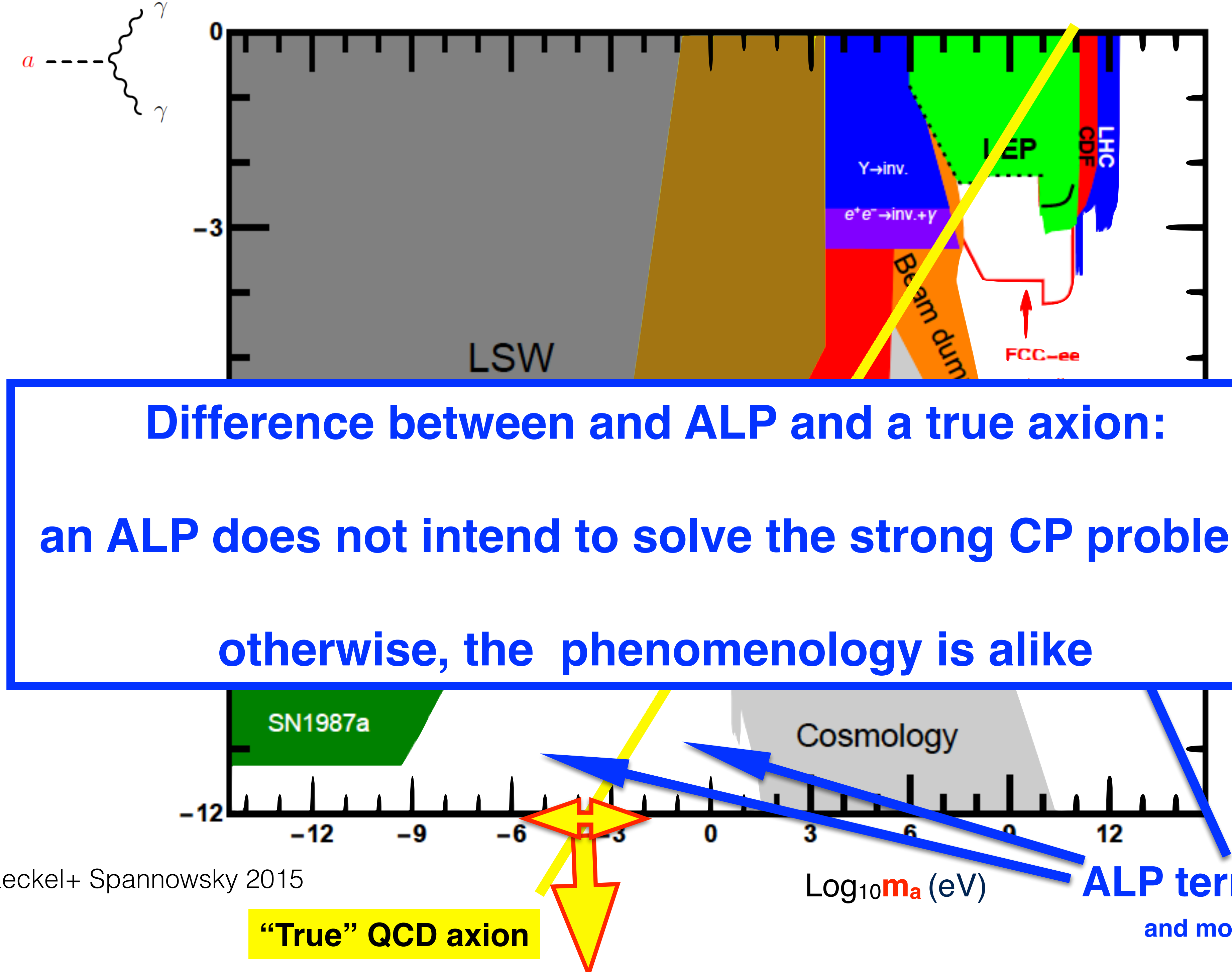


ALPs territory: can they be true axions ?(i.e. solve strong CP)



Difference between and ALP and a true axion:

an ALP does not intend to solve the strong CP problem

otherwise, the phenomenology is alike

Jaeckel+ Spannowsky 2015

“True” QCD axion

ALP territory

and more?

ALP-Linear effective Lagrangian at NLO

||
SM EFT

Complete basis (bosons+fermions):

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_i^{\text{total}} c_i \mathbf{O}_i^{d=5}$$

$$\mathbf{O}_{\tilde{B}} = -B_{\mu\nu}\tilde{B}^{\mu\nu}\frac{a}{f_a} \qquad \mathbf{O}_{\tilde{G}} = -G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\frac{a}{f_a}$$

$$\mathbf{O}_{\tilde{W}} = -W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\frac{a}{f_a} \qquad \frac{\partial_\mu a}{f_a}\sum_{\substack{\psi=Q_L,Q_R,\\ L_L,L_R}}\bar{\psi}\gamma_\mu X_\psi \psi$$

where X_ψ is a general 3x3 matrix in flavour space

Georgi + Kaplan + Randall 1986
Choi + Kang + Kim, 1986
Salvio + Strumia + Shue, 2013

The field of axions and ALPs is BLOOMING

in Experiment … and Theory

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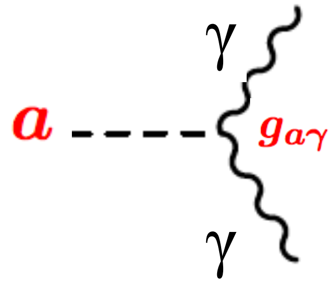
in Experiment … and Theory

Intensely looked for experimentally…



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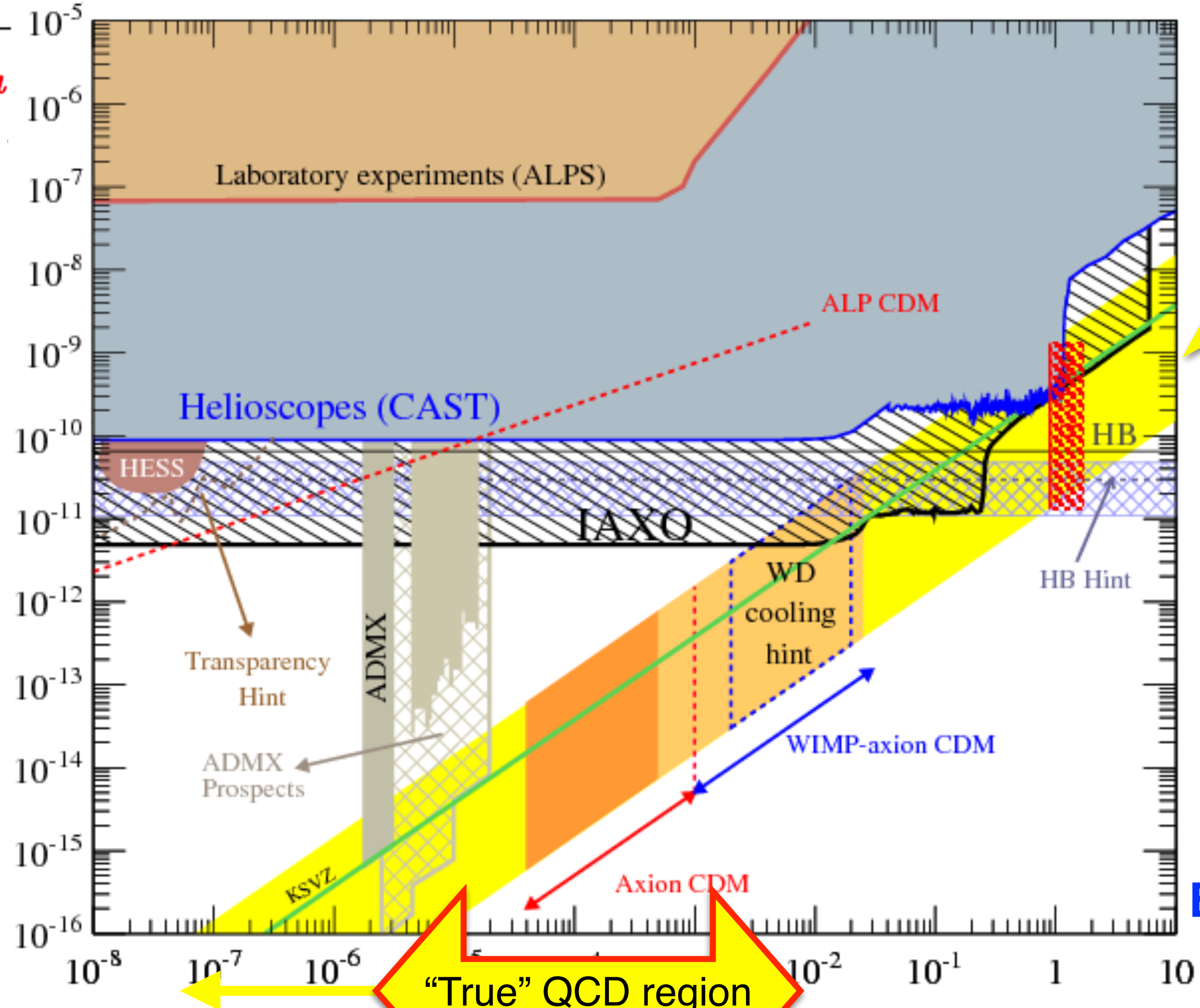

"True" QCD axion band

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"Invisible axion"
e.g. KSVZ, DFSZ…

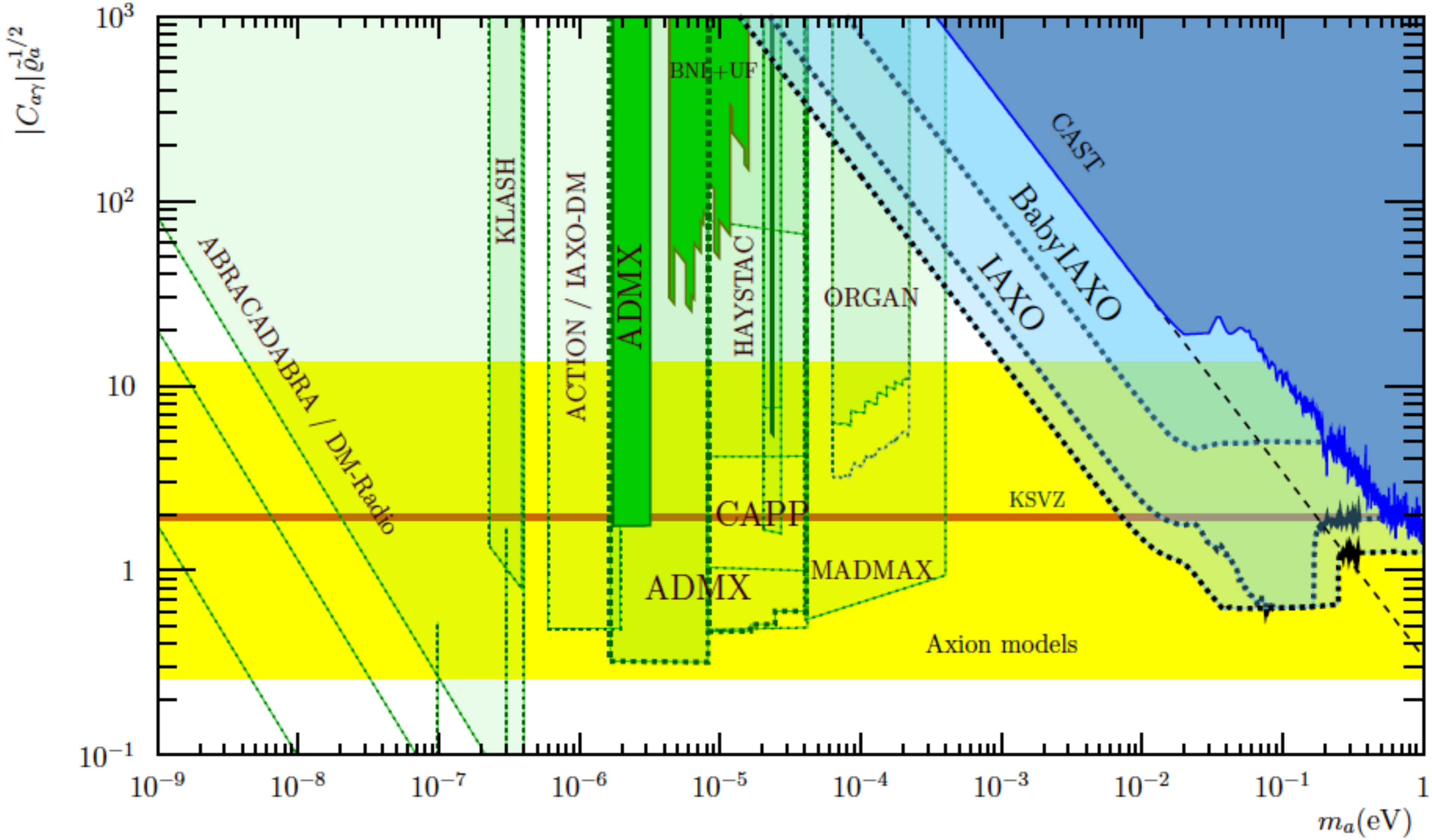
m_a (eV)

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

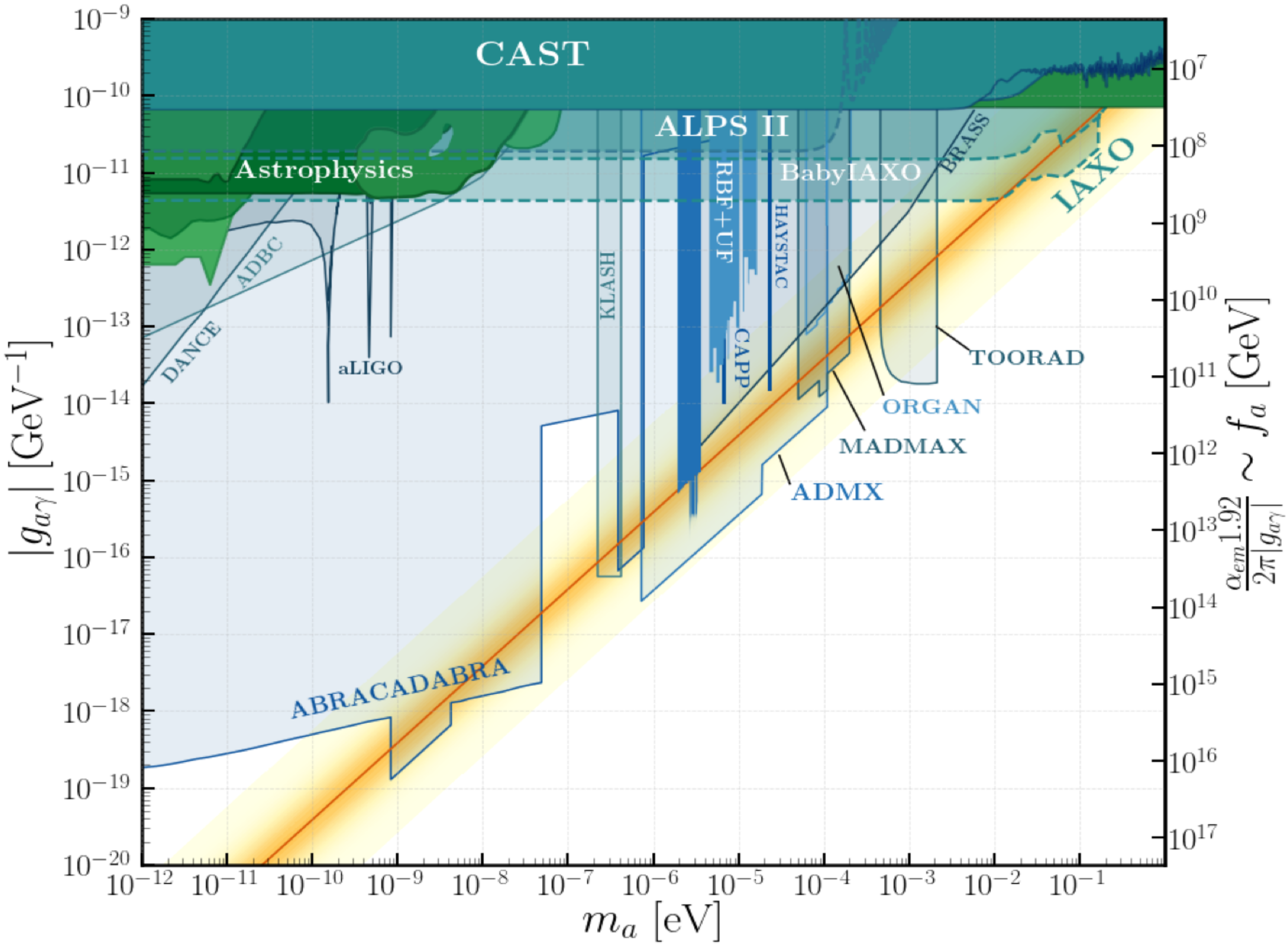
… and theoretically

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

Advances on Haloscopes



Irastorza and Redondo, arXiv:1801.08127



courtesy of Pablo Quilez

The field is BLOOMING

in Experiment … and Theory

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

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

* If the confining group is QCD:

$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2$$

* If the confining group is larger than QCD:

$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2 \pm \text{extra}$$

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

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* If the confining group is QCD:

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* If the confining group is larger than QCD:

If $m_a^2 f_a^2 =$ **LARGE constant**

the true-axion parameter space relaxes

A heavy true axion?

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

e.g., and additional confining group

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

QCD QCD´

e.g., and additional confining group

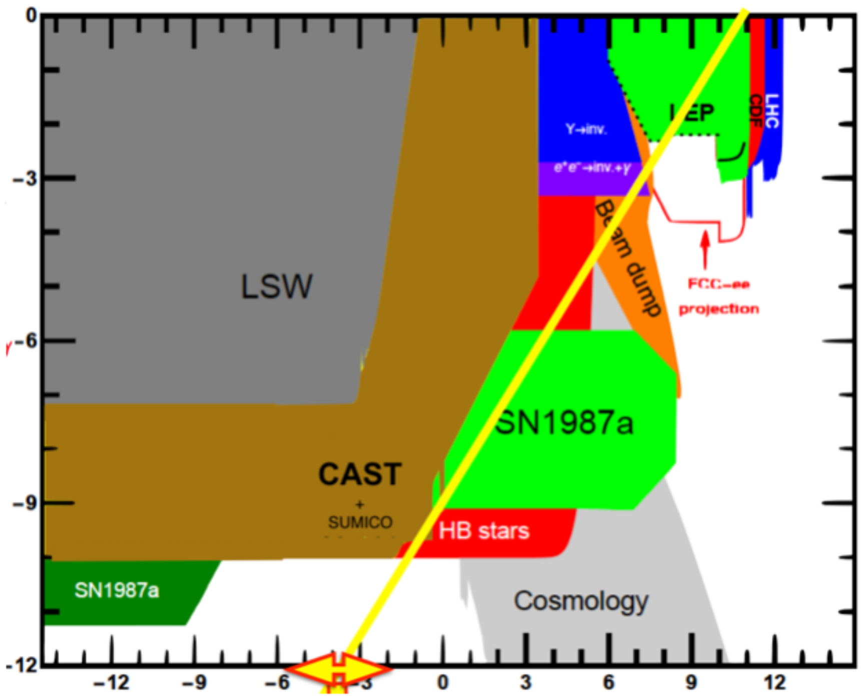
$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2 + \Lambda'^4 \qquad \Lambda' \gg \Lambda_{QCD}$$

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

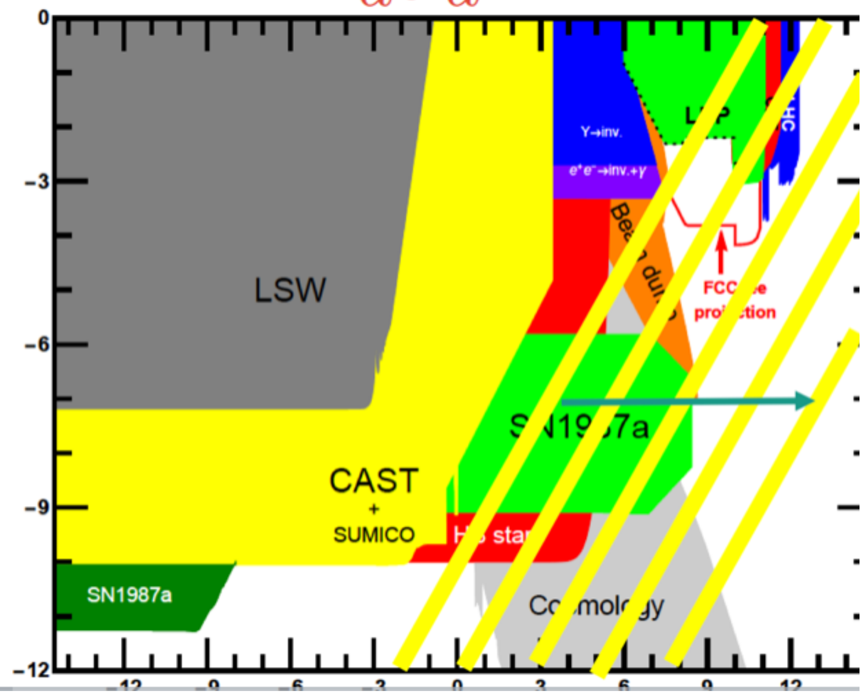
QCD: $\Lambda = \Lambda_{QCD}$

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

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



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



HEAVY axions

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

[Rubakov, 97]
[Berezhiani et al ,01]
[Fukuda et al, 01]
[Hsu et al, 04]
[Hook et al, 14]
[Chiang et al, 16]
[Khobadize et al,]
[Dimopoulos et al, 16]
[Gherghetta et al, 16]
[Agrawal et al, 17]
[Gaillard et al, 18]
[Fuentes-Martin et al, 19]
[Csaki et al, 19]
[Gherghetta et al, 20]

an old idea,
strongly revived lately

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

Compare the number of pseudoscalars-coupled to anomalous currents:

N_{ps} : η'_{QCD} a_1 a_2 a_3 ……

with how many different sources of (instanton) masses

N_{inst} : $G\tilde{G}$ $G'\tilde{G}'$ $G''\tilde{G}''$ ……

QCD ($G\tilde{G}$)

other sources of instantons ($G'\tilde{G}'$, $G''\tilde{G}''$, ……)

If $N_{ps} \leqq N_{inst}$ all axions heavy

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

Compare the number of pseudoscalars-coupled to anomalous currents:

N_{ps} : η'_{QCD} a_1

N_{inst} : $G\tilde{G}$

QCD

With only QCD:

one combination must be (almost) **massless**

–> "Invisible axion"

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QCD

With only QCD:

one combination must be (almost) **massless**

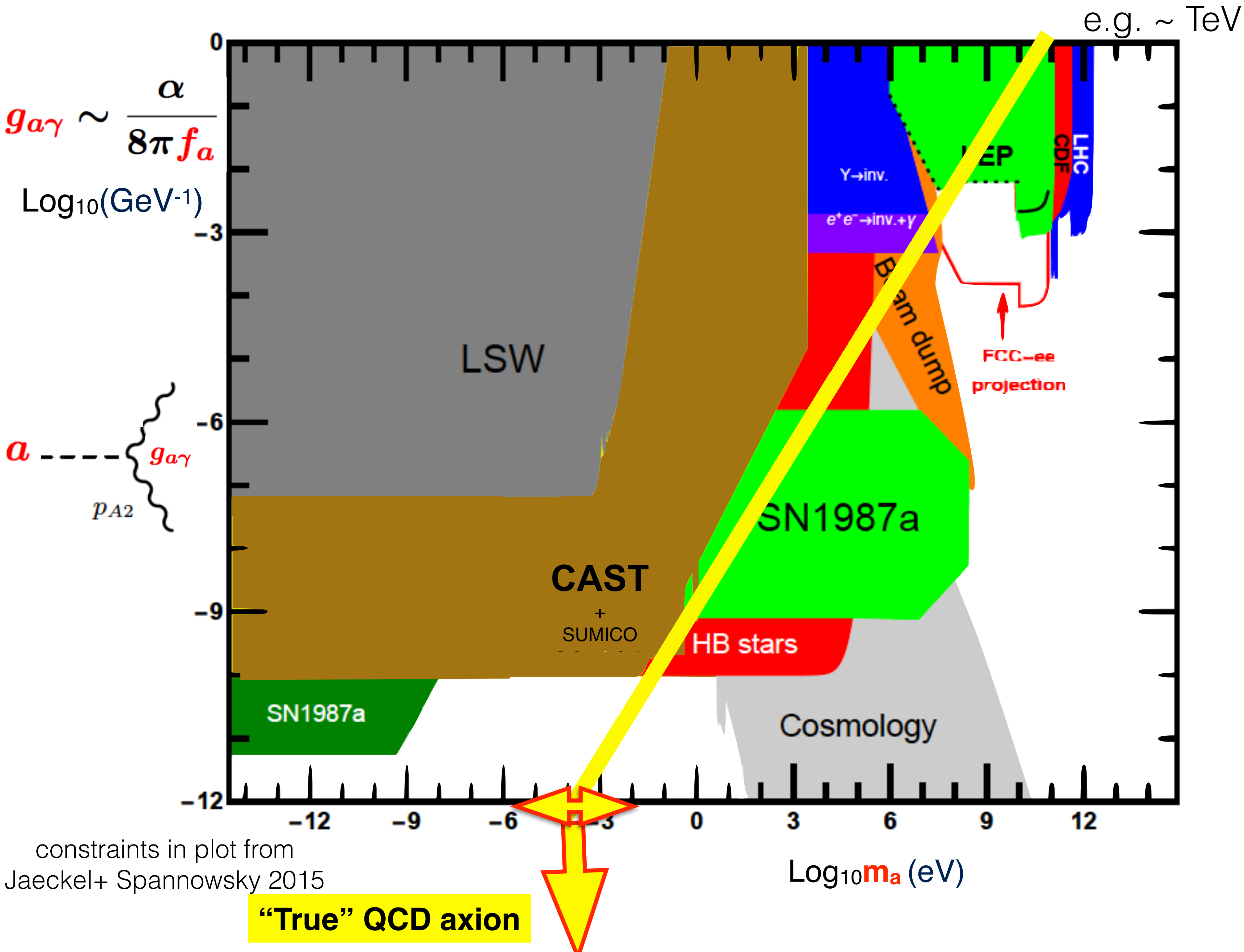
–> **"Invisible axion"**

The tiny axion mass is due to mixing with η' and pion:

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

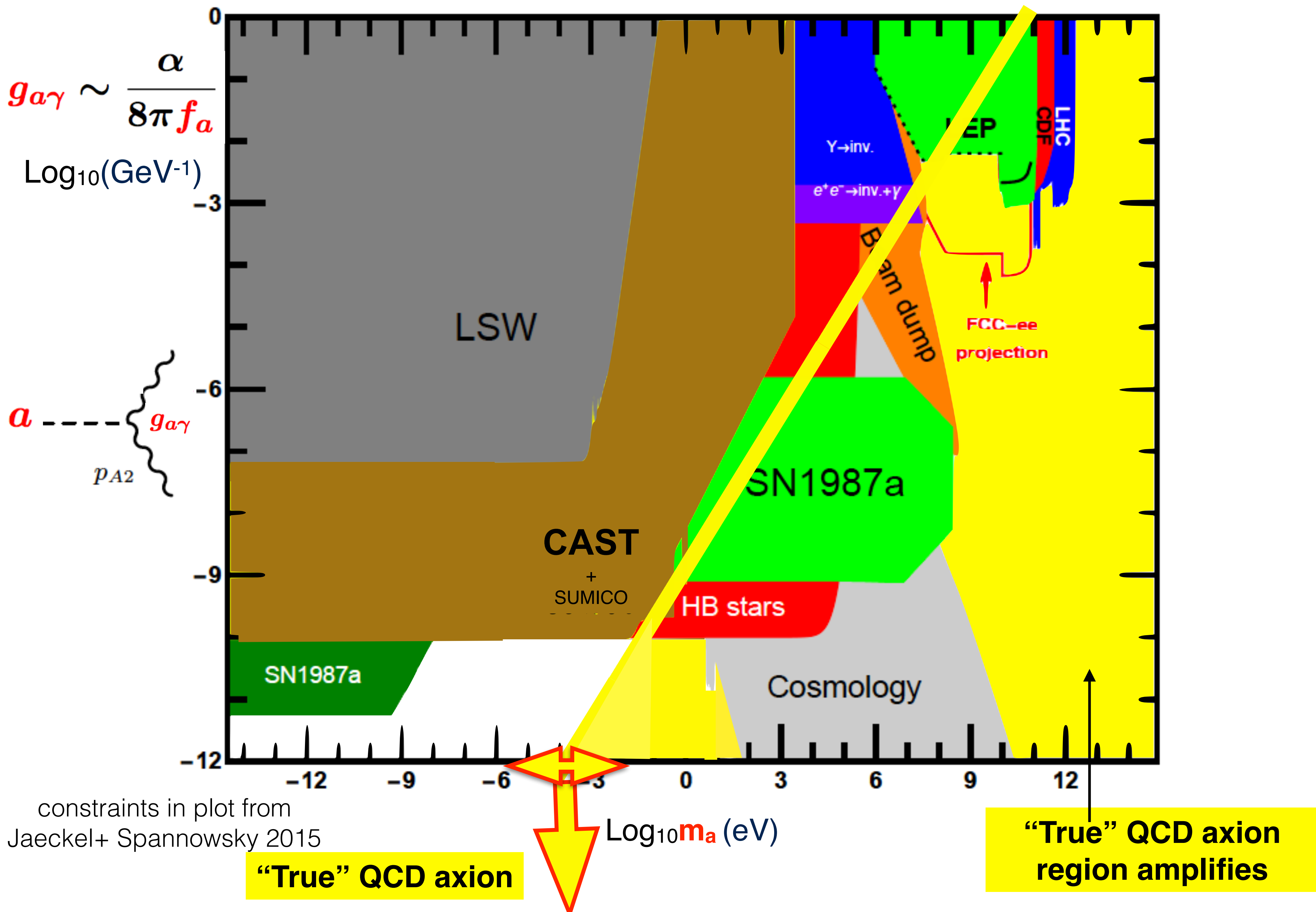
independently of the axion model

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



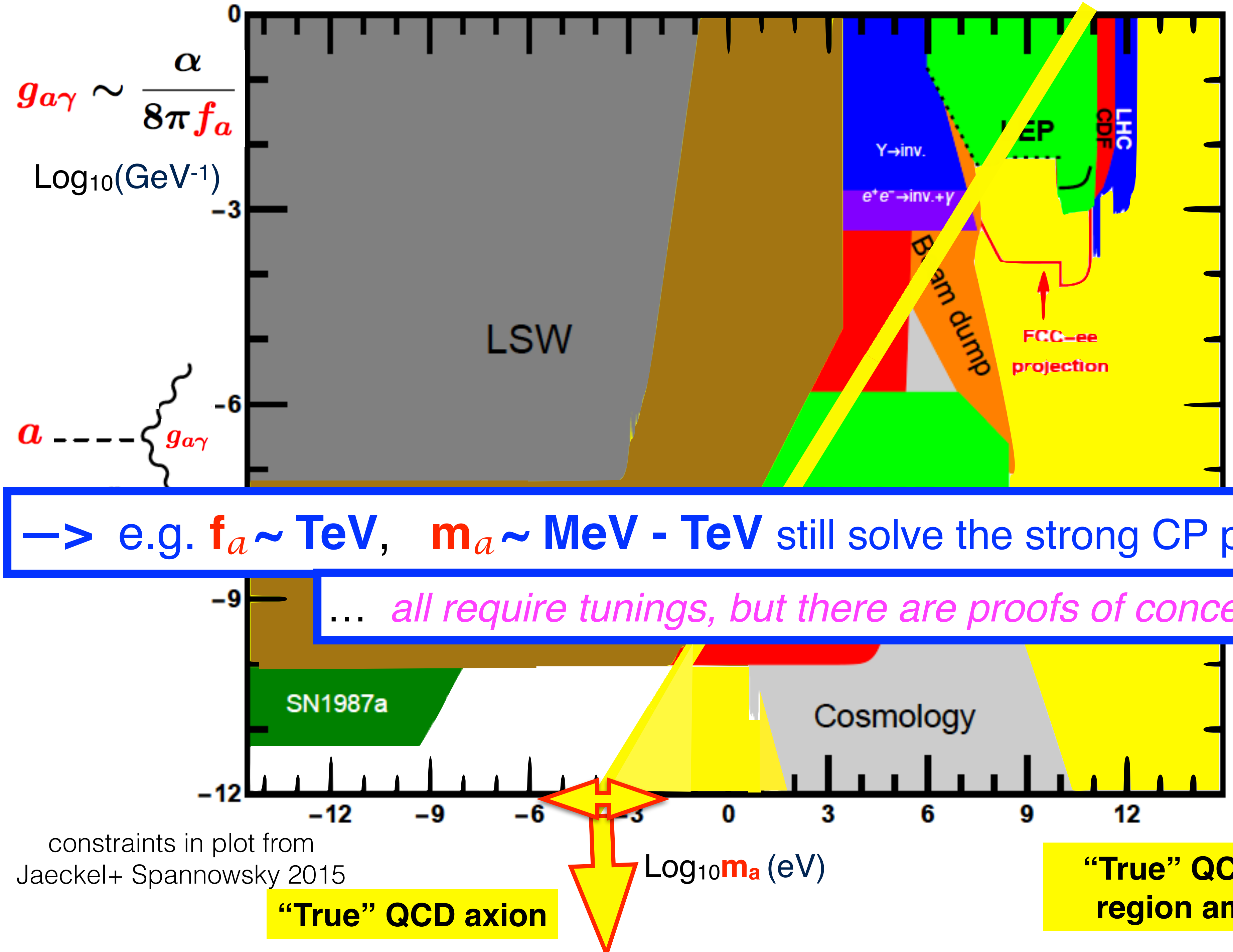
ALPs territory: they can be true axions

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



constraints in plot from
Jaeckel+ Spannowsky 2015

ALPs territory: they can be true axions



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

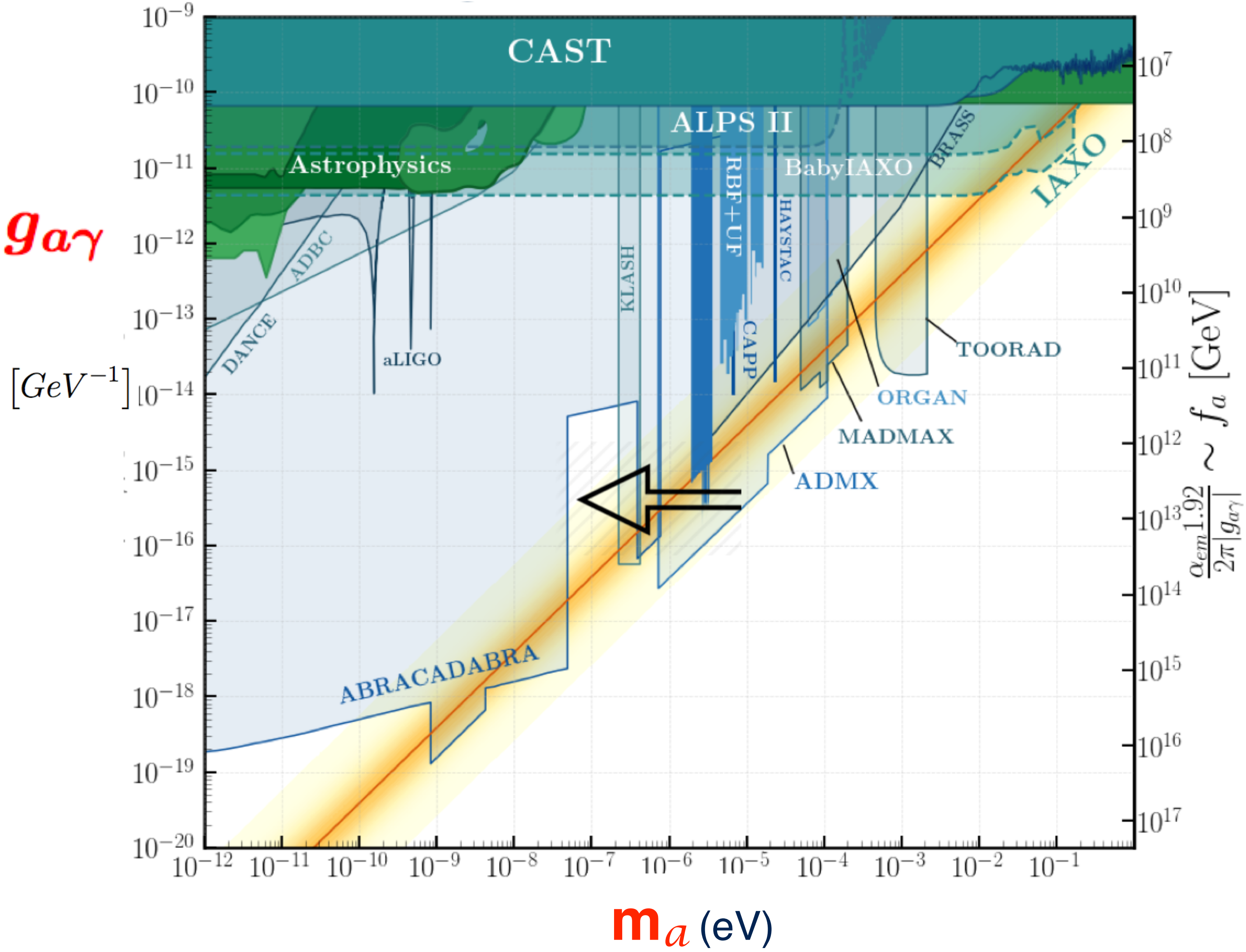
… *all require tunings, but there are proofs of concept*

constraints in plot from
Jaeckel+ Spannowsky 2015

“True” QCD axion

“True” QCD axion region amplifies

LIGTHER than usual axions ?



LIGTHER than usual axions

$m_a^2 f_a^2 =$ SMALL **constant**

How to do that without fine-tunings?

Luca de Luzio, Pablo Quilez, Andreas Ringwald & BG:

*** And solve the strong CP problem:** arXiv 2102.00012

*** And solve the strong CP and DM problems:** arXiv 2102.01082

LIGTHER than usual axions

$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2 \quad - \quad \textbf{extra}$$

How to do that without fine-tunings?

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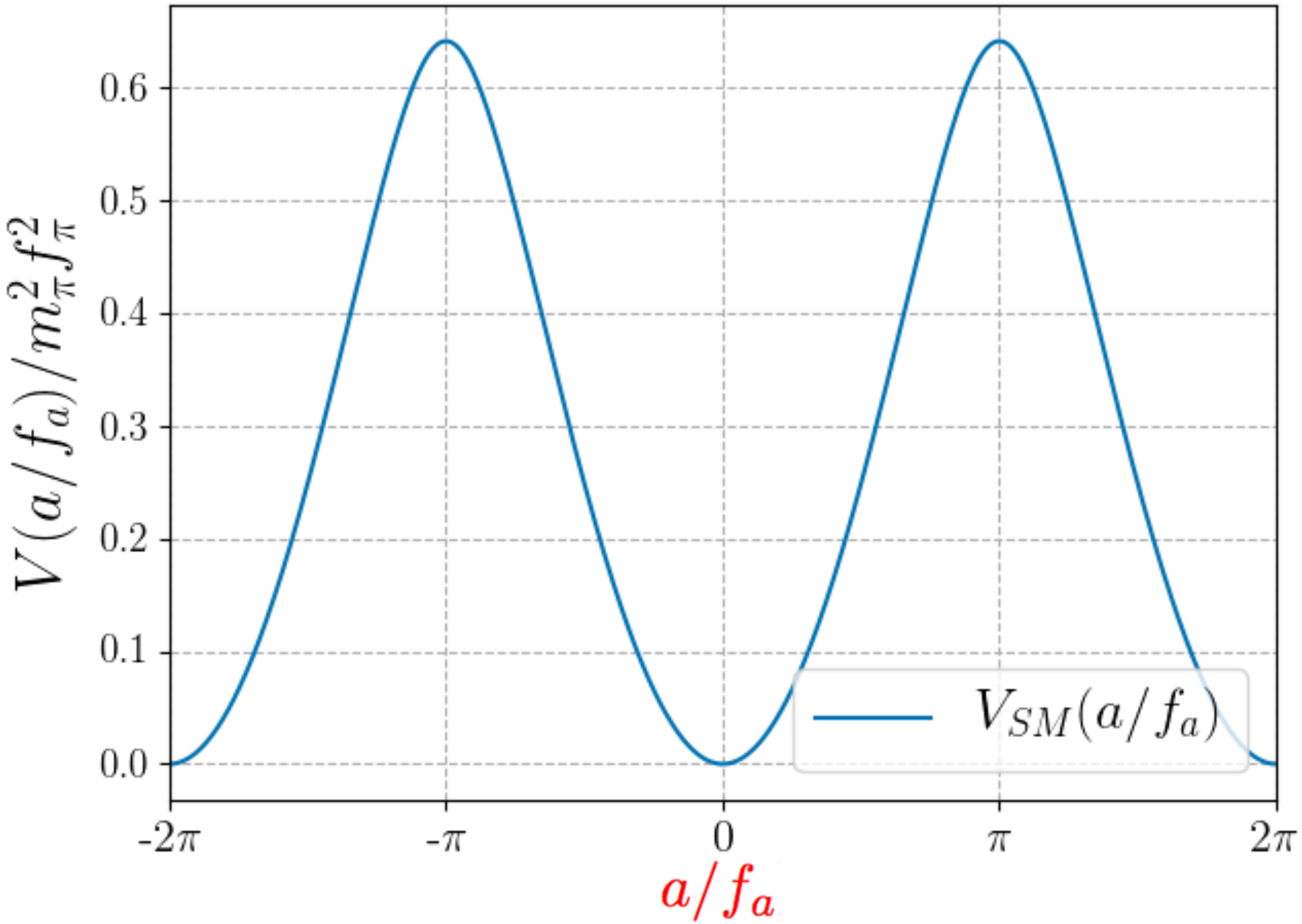
*** And solve the strong CP and DM problems:** arXiv 2102.01082

Can you naturally solve the strong CP problem with a lighter-than usual axion ?

(forget dark matter for the moment)

You want a lighter axion—> you want a flatter potential

Canonical QCD axion: $V_{SM}(\frac{a}{f_a}) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a}\right)}$



how to add something that naturally flattens it?

A Z_2 (or Z_N) symmetry : mirror degenerate worlds

[Hook, 18]

$$Z_2 : \quad \mathrm{SM} \longrightarrow \mathrm{SM}'$$

$$a \longrightarrow a + \pi f_a$$

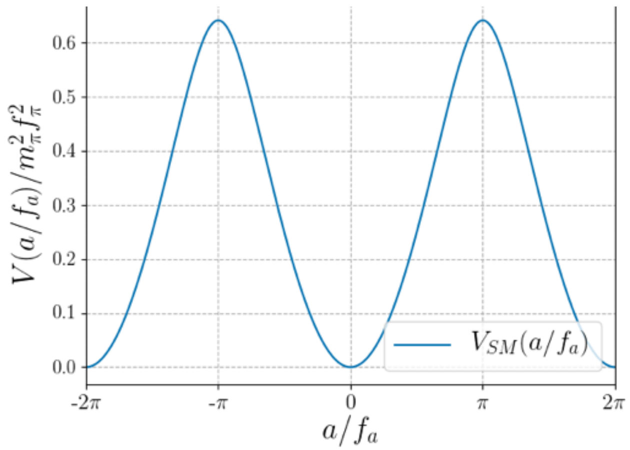
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{SM}'} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta\right) G\widetilde{G} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta + \pi\right) G'\widetilde{G}'$$

QCD

QCD’

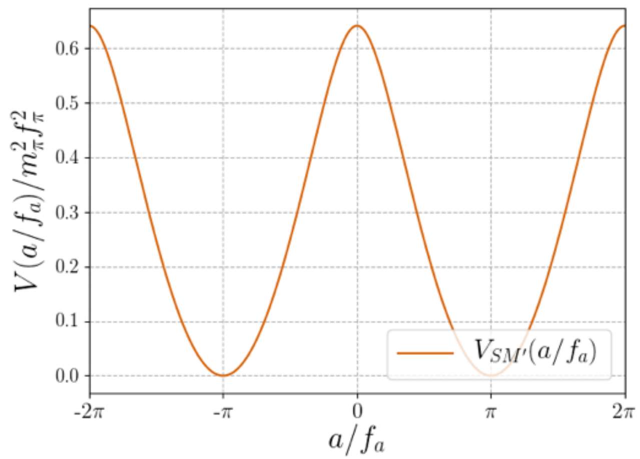
$$V_{SM}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2}\sin^2\left(\frac{a}{2f_a}\right)}$$

SM



$$\longleftarrow \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

SM'



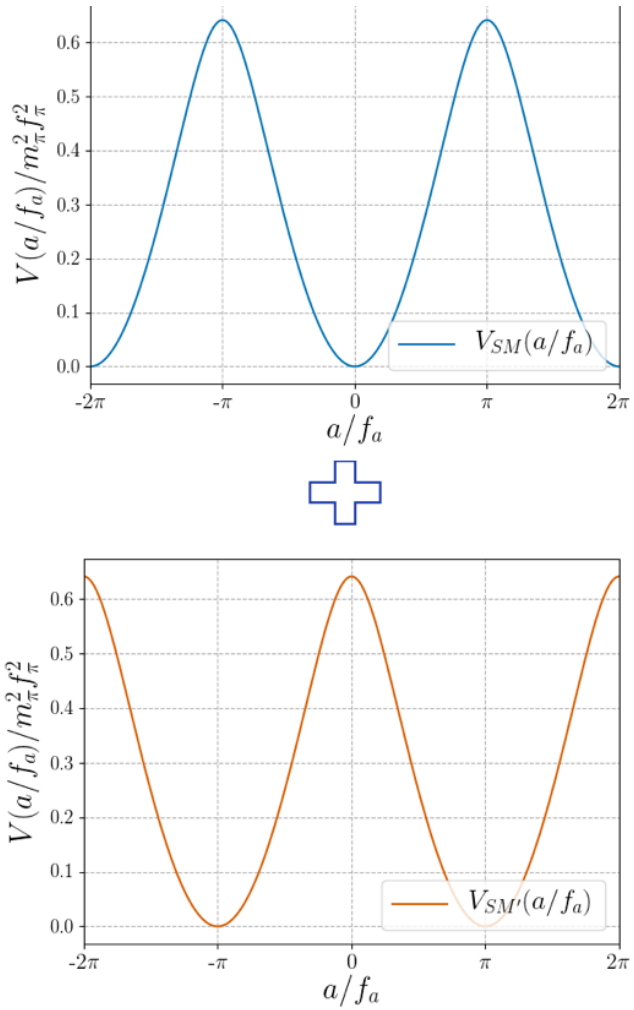
$$\longleftarrow \left(\frac{a}{f_a} + \pi\right) G'_{\mu\nu}\tilde{G}'^{\mu\nu}$$

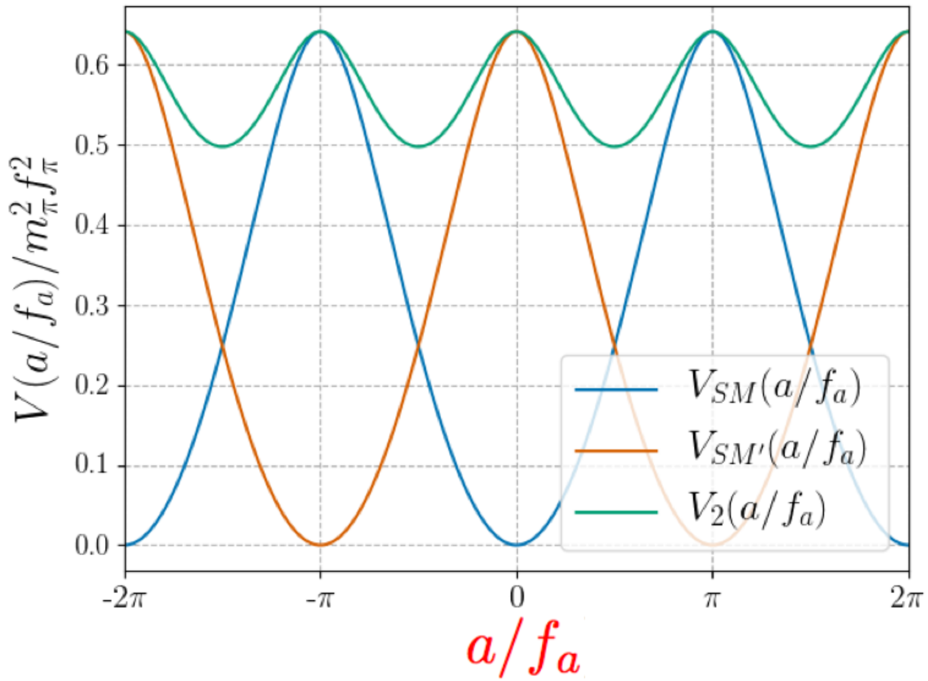
$$V_{SM'}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2}\sin^2\left(\frac{a}{2f_a} + \frac{\pi}{2}\right)}$$

$$V_{SM}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2}\sin^2\left(\frac{a}{2f_a}\right)}$$

SM

SM’





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[Hook, 18]

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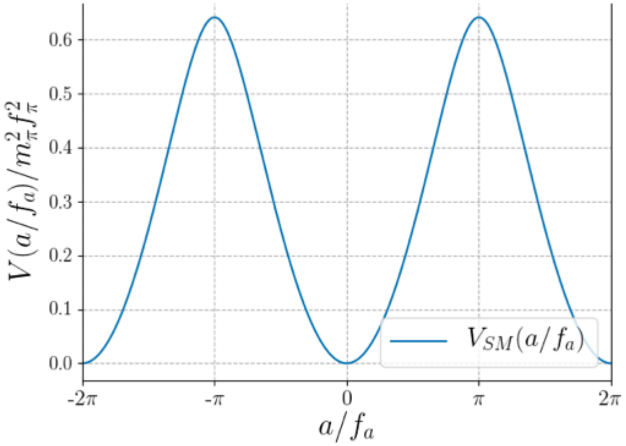
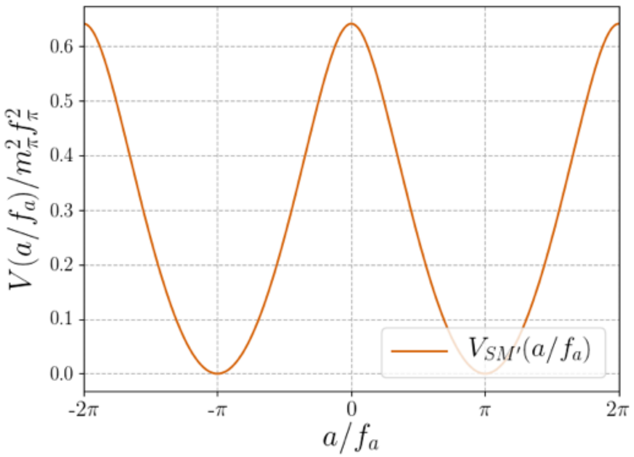
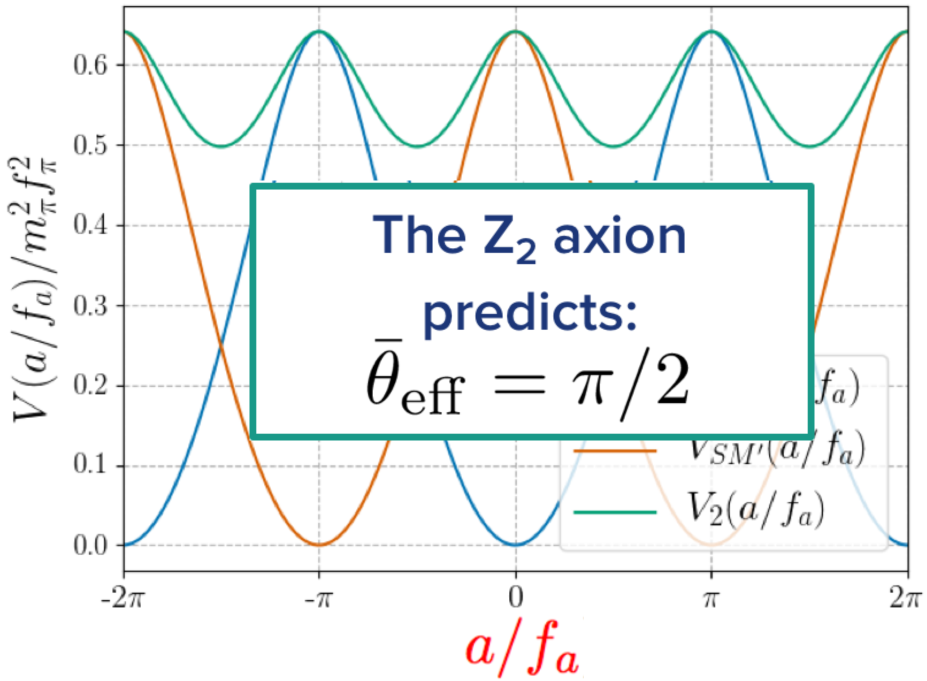
SM



SM’



$$V_{SM'}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a} + \frac{\pi}{2}\right)}$$



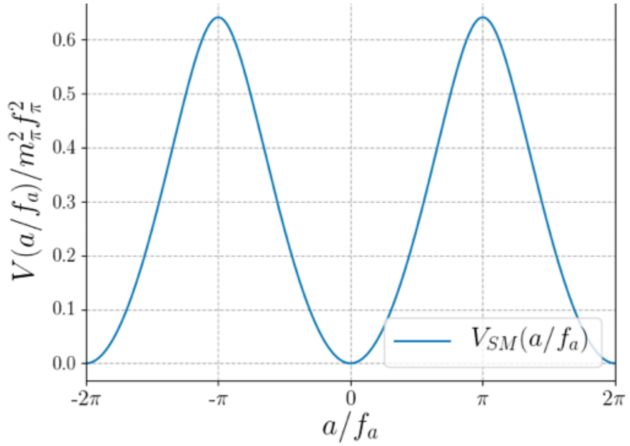
The Z_2 axion predicts:

$$\bar{\theta}_{\rm eff} = \pi/2$$

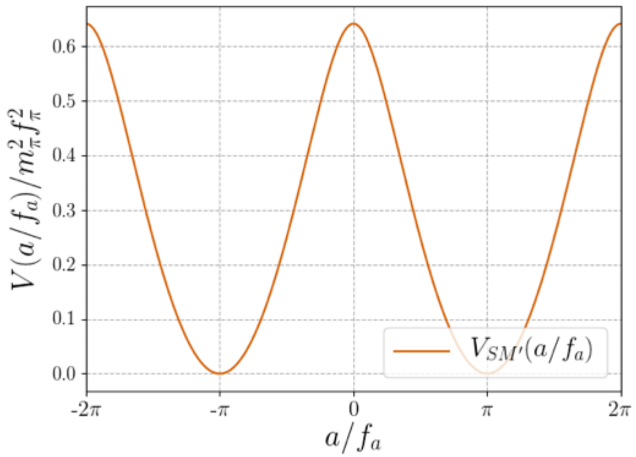
[Hook, 18]

$$V_{SM}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a}\right)}$$

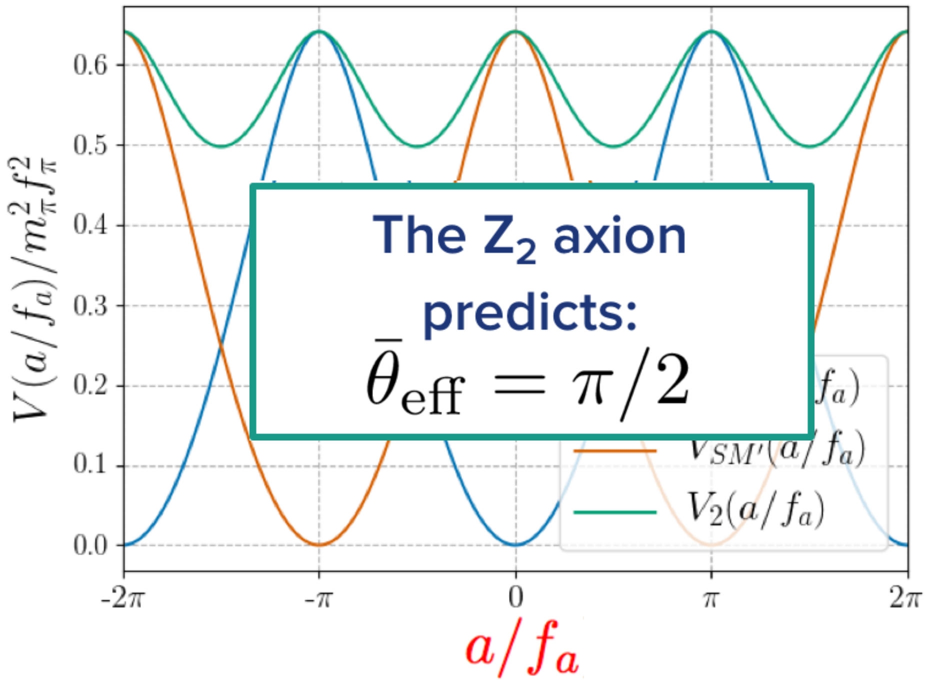
SM



SM'

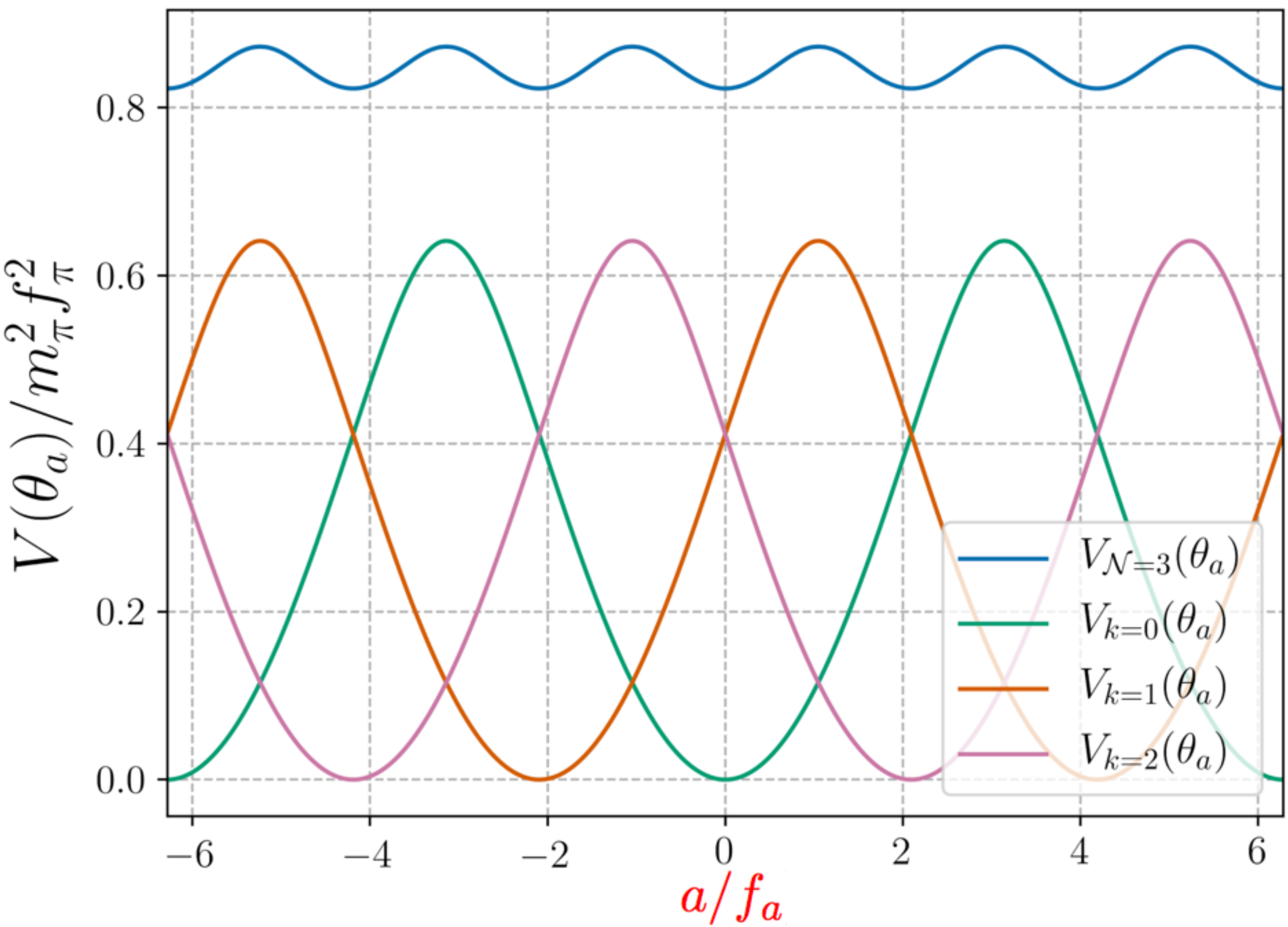


$$V_{SM'}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a} + \frac{\pi}{2}\right)}$$



you need N=odd

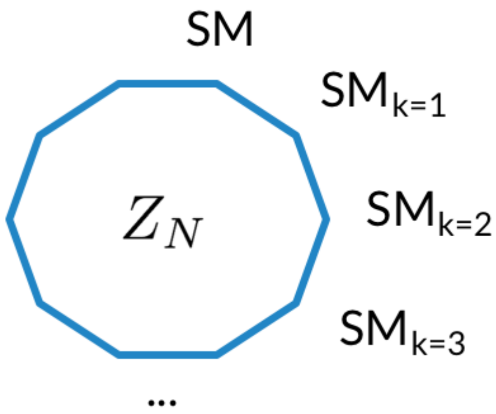
Example: Z_3



$V(\theta_a)/m_\pi^2 f_\pi^2$
0.0
0.2
0.4
0.6
0.8
−6
−4
−2
0
2
4
6
a/f_a
$V_{\mathcal{N}=3}(\theta_a)$
$V_{k=0}(\theta_a)$
$V_{k=1}(\theta_a)$
$V_{k=2}(\theta_a)$

$Z_{N\ \text{axion}}$: N mirror degenerate worlds [Hook, 18]

$$Z_N: \quad \mathrm{SM} \longrightarrow \mathrm{SM}^k$$
$$a \longrightarrow a + \frac{2\pi k}{N} f_a$$



➔ The axion realizes the Z_N non-linearly.

➔ N degenerate worlds with the same couplings as in the SM except for the theta parameter

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

Compact analytical formula for Z_N axion mass

di Luzio, Quilez, Ringwald, BG arXiv 2102.00012

➔ Using Fourier decomposition and Gauss hypergeometric functions we managed to show that:

- The total Z_N axion potential approaches a cosine:

$$V_{\mathcal{N}}\left(\frac{a}{f_a}\right) \simeq -\frac{m_a^2 f_a^2}{\mathcal{N}^2} \cos\left(\mathcal{N}\frac{a}{f_a}\right)$$

- Compact analytical formula for the axion mass

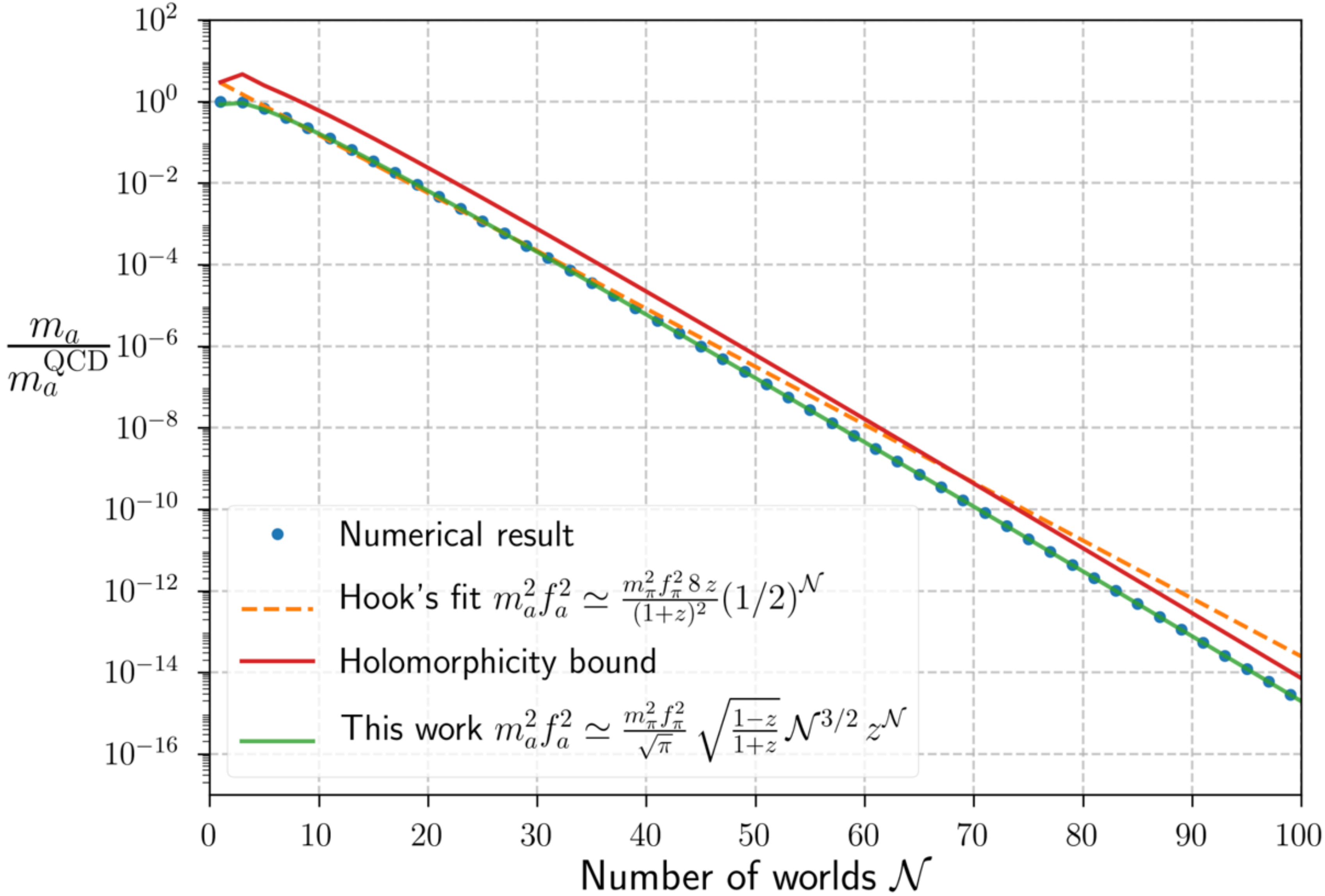
$$m_a^2 f_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}} \mathcal{N}^{3/2} z^{\mathcal{N}}$$

$$z = m_u/m_d$$

exponentially suppressed ⟶

$$\frac{m_a^2 f_a^2}{m_\pi^2 f_\pi^2} \propto z^{\mathcal{N}} \sim 2^{-\mathcal{N}}$$

Z_N axion mass formula



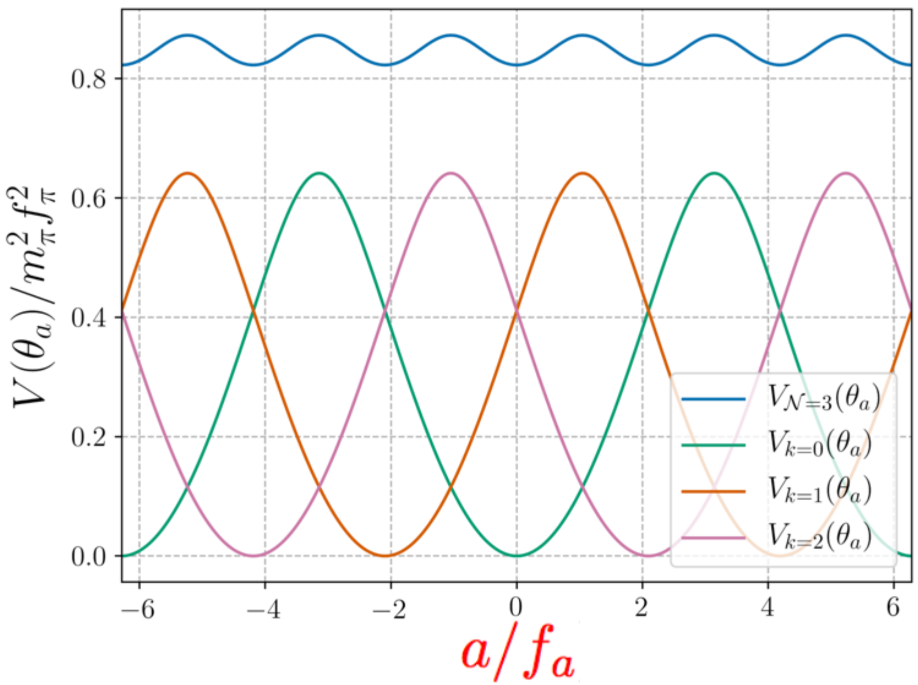
excellent agreement with numerical already for N=3

di Luzio, Quilez, Ringwald, BG arXiv 2102.00012

Caveat:

—> There are N minima: we **''only''** solve strong CP with 1/N prob.

$$\theta_a = \{\pm 2\pi\ell/\mathcal{N}\} \qquad \text{for} \quad \ell = 0, 1, \ldots, \frac{\mathcal{N}-1}{2},$$



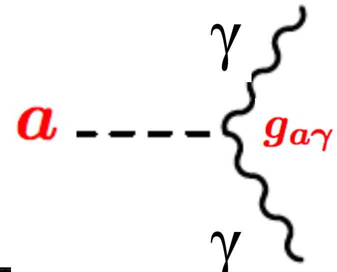
$$\bar{\theta} \lesssim 10^{-10}$$

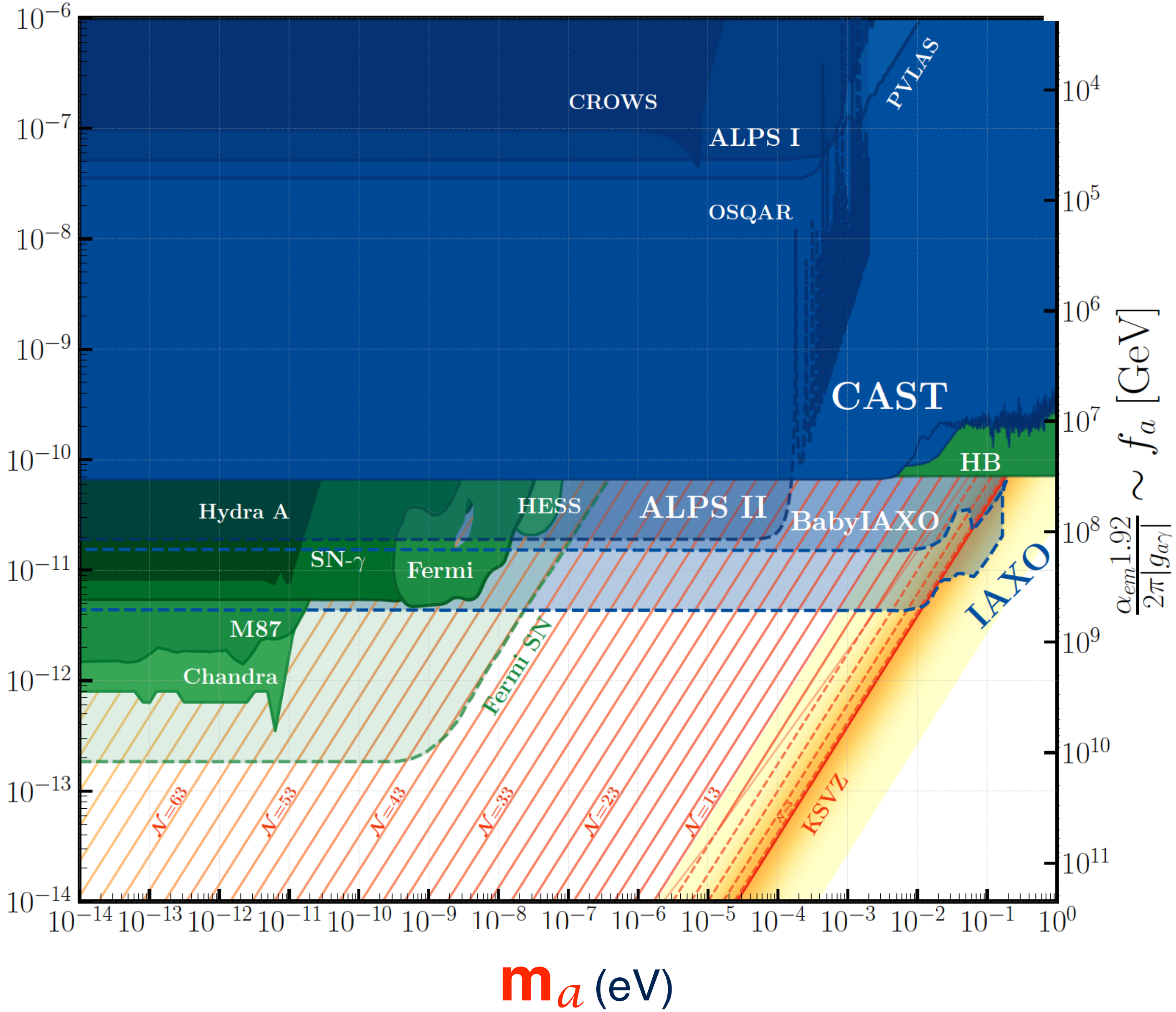
↓

$1/\mathcal{N}$ probability

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

$[GeV^{-1}]$

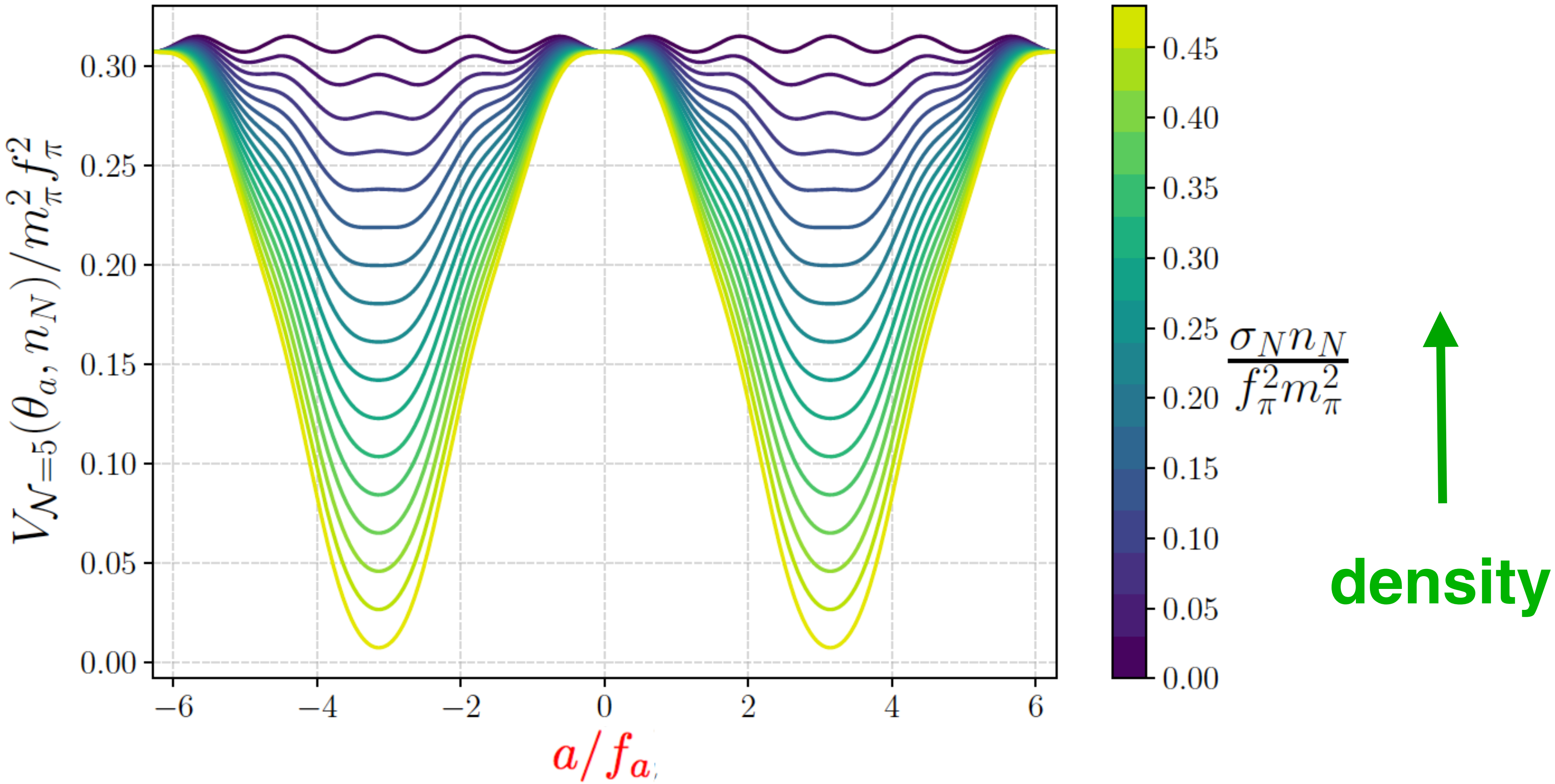




di Luzio, Quilez, Ringwald, BG arXiv 2102.00012

Model-independent bounds from high-density objects

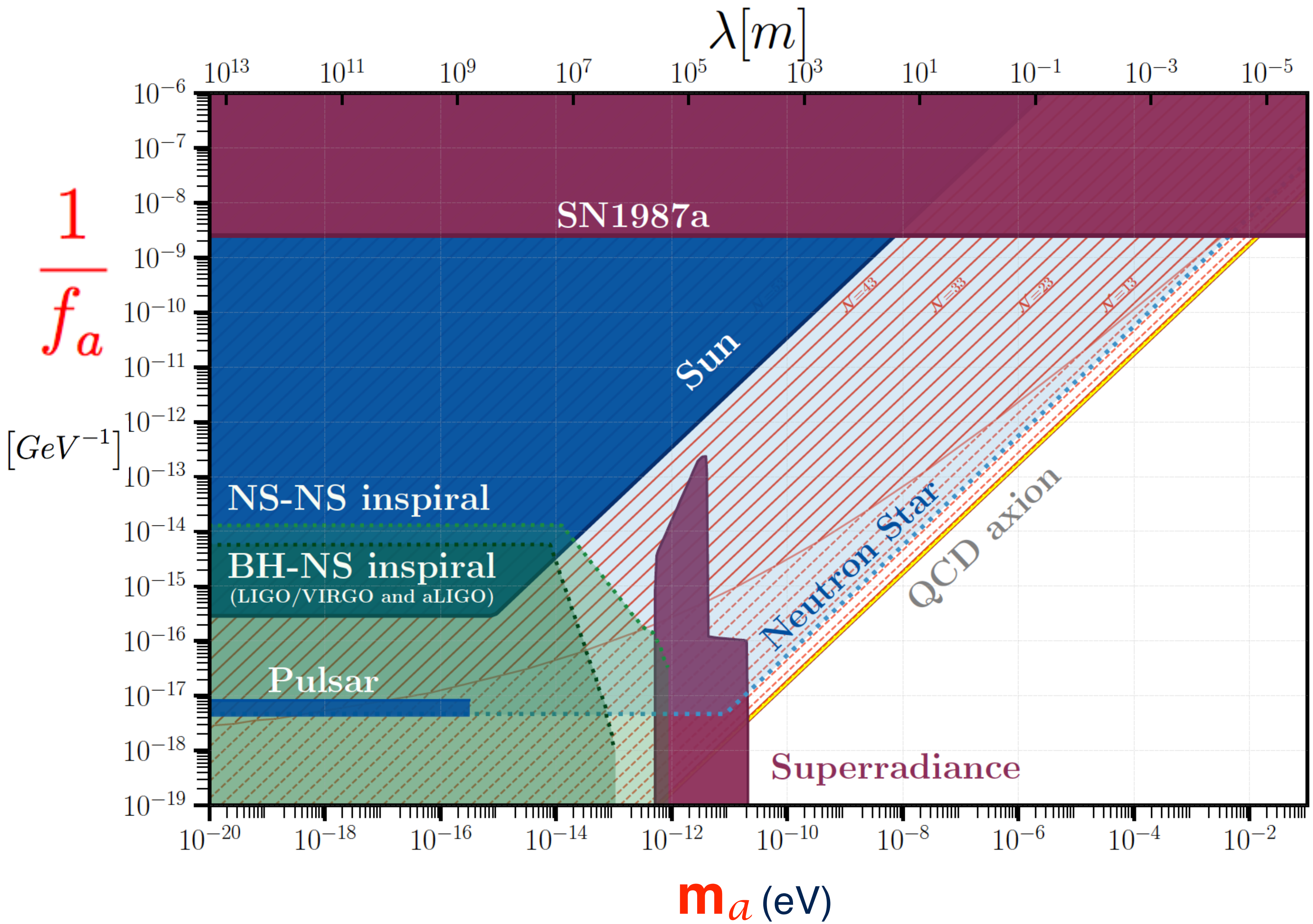
A stellar object of high (SM) density is a background that breaks explicitly Z_N



the potential minimum is at π (instead of 0)

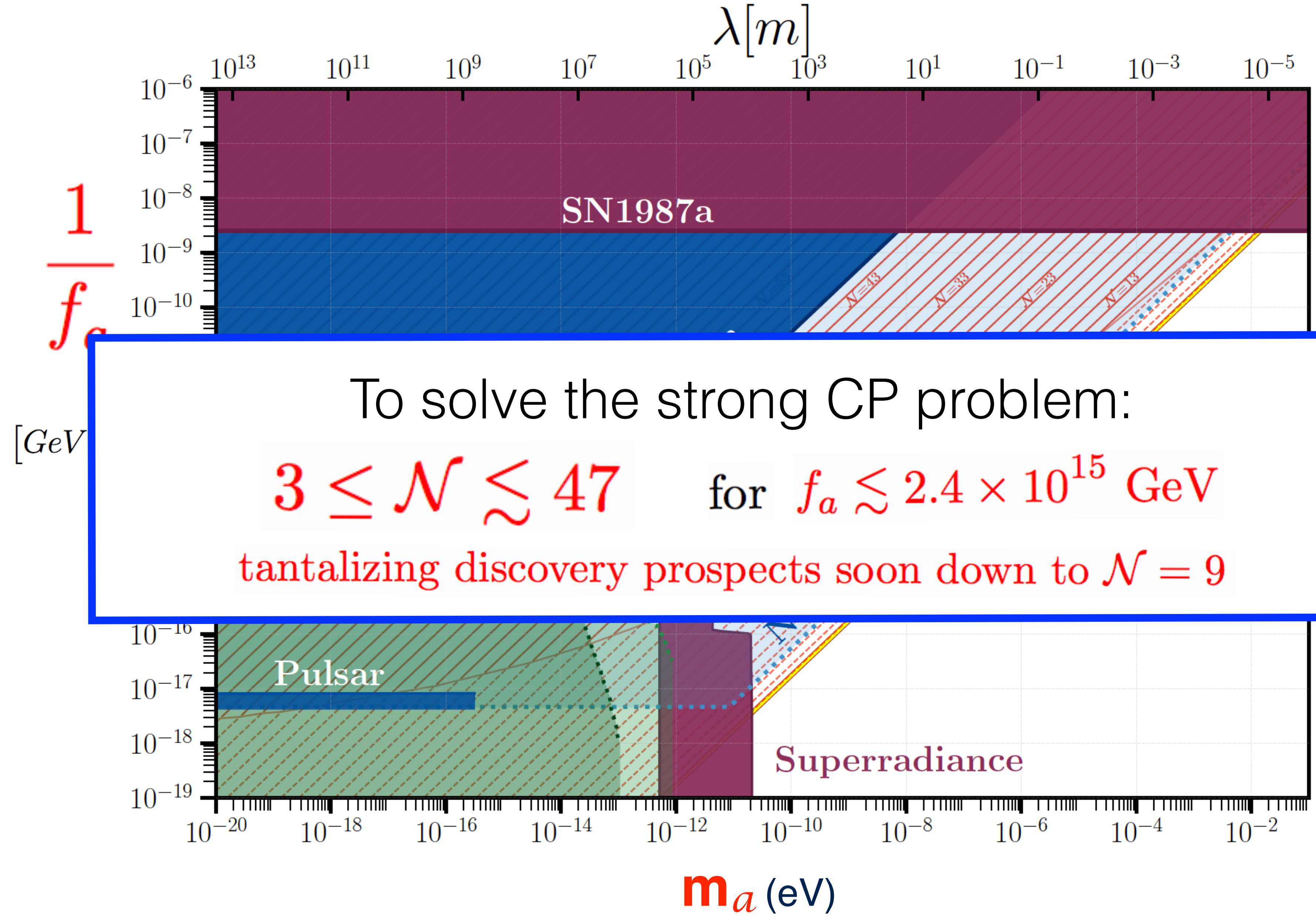
Hook, Huang 2018
Di Luzio, Quilez, Ringwald, BG arXiv 2102.00012

Model-independent bounds from high-density objects



from Di Luzio, Quilez, Ringwald, BG arXiv 2102.00012

Model-independent bounds from high-density objects



To solve the strong CP problem:

$$3 \leq \mathcal{N} \lesssim 47 \quad \text{for} \quad f_a \lesssim 2.4 \times 10^{15}\ \text{GeV}$$

tantalizing discovery prospects soon down to $\mathcal{N} = 9$

Di Luzio, Quilez, Ringwald, BG arXiv 2102.00012

Dark matter from the Z_N axion

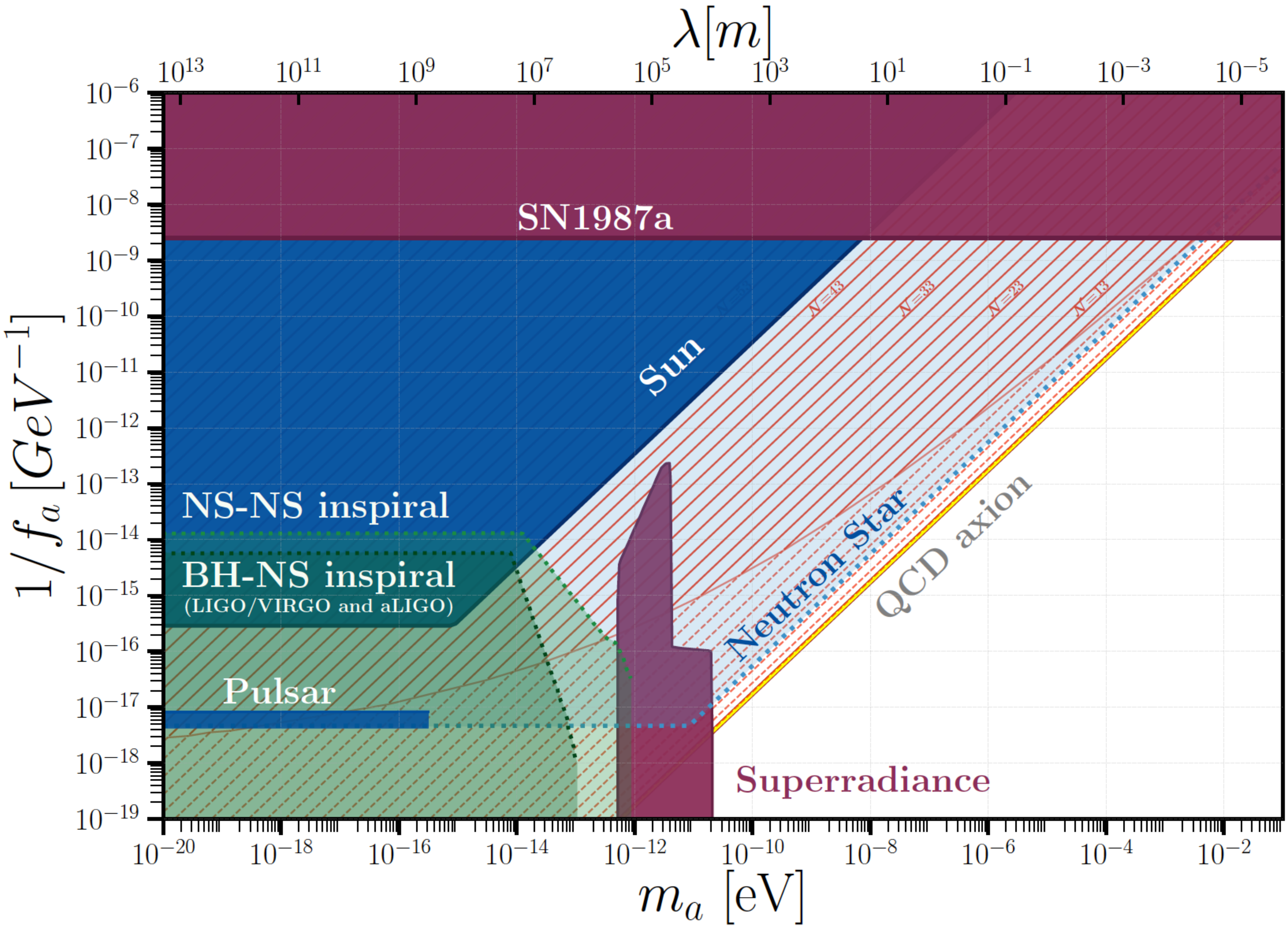
For instance:

* Could CASPER-Electric Phase-I find a true axion?

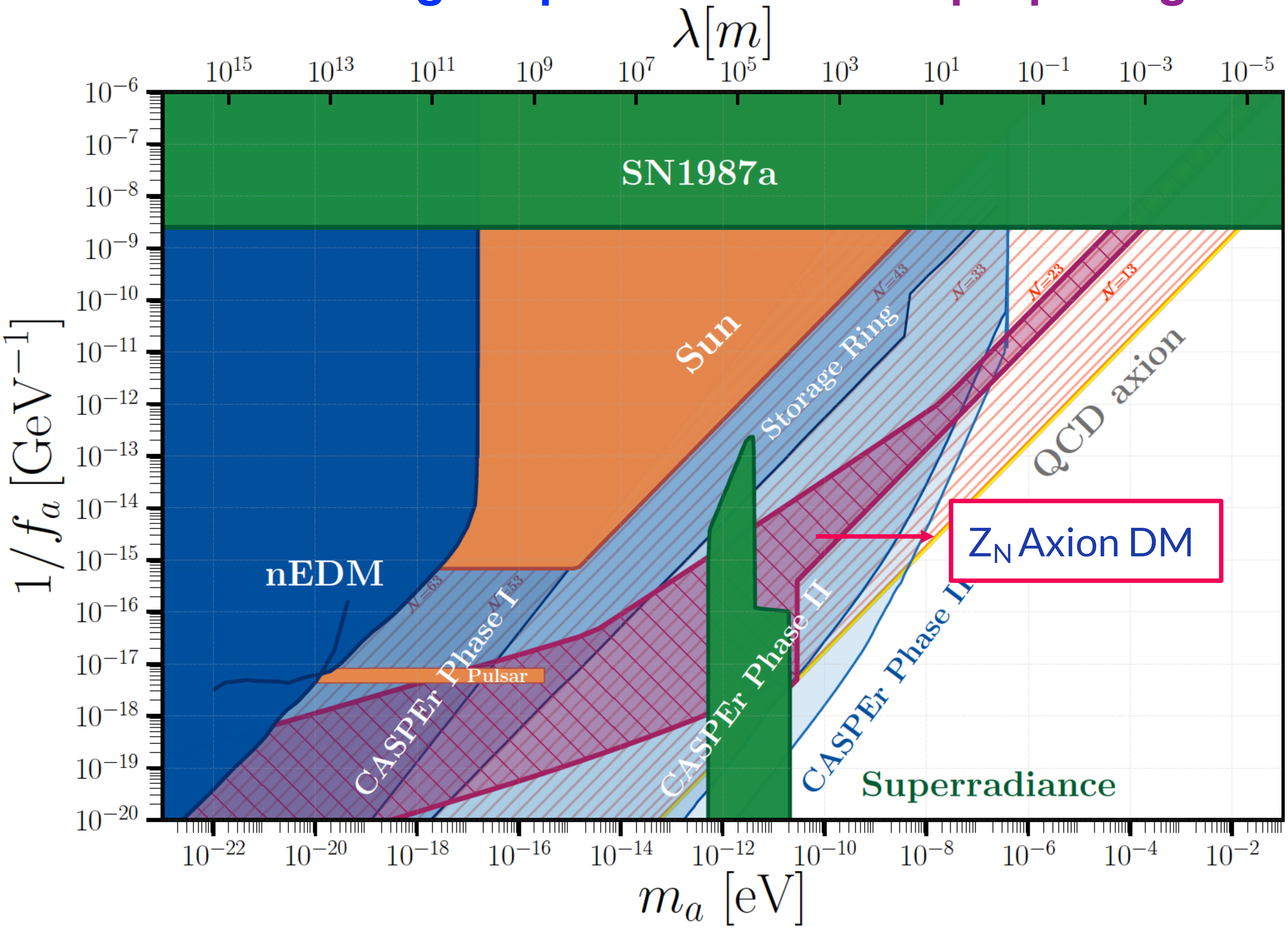
* Could fuzzy DM ($m_{DM} \sim 10^{-22}$ eV) be a true axion?

di Luzio, Quilez, Ringwald, BG arXiv 2102.01082

This was without asking the true axion to solve DM:

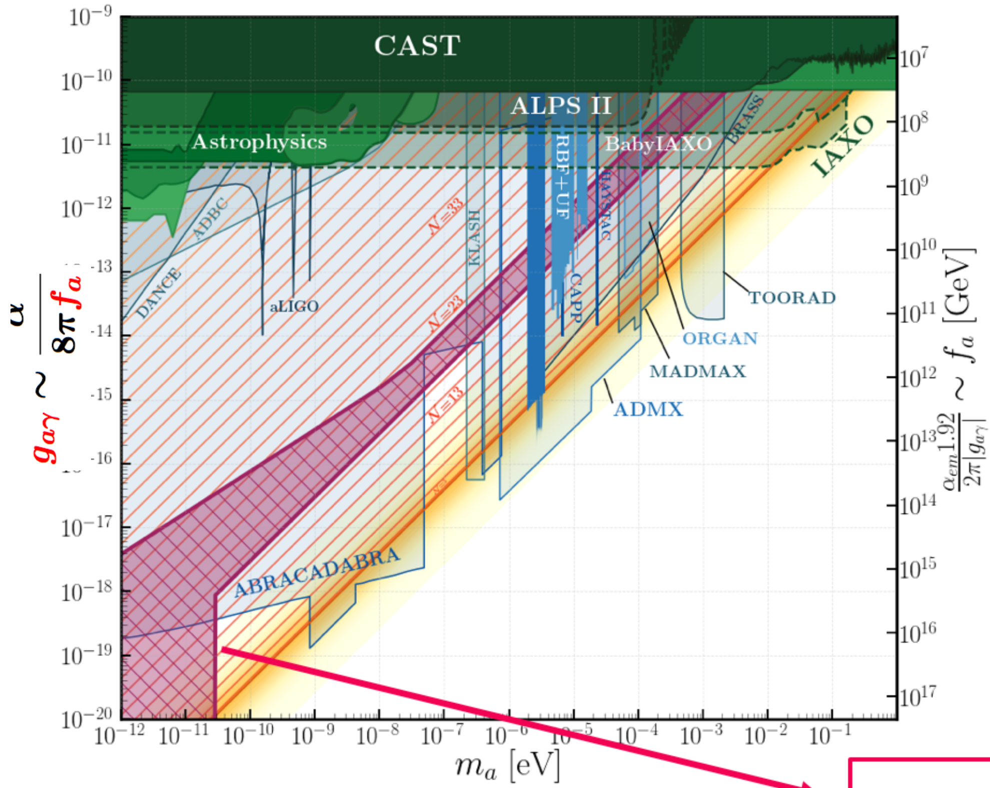


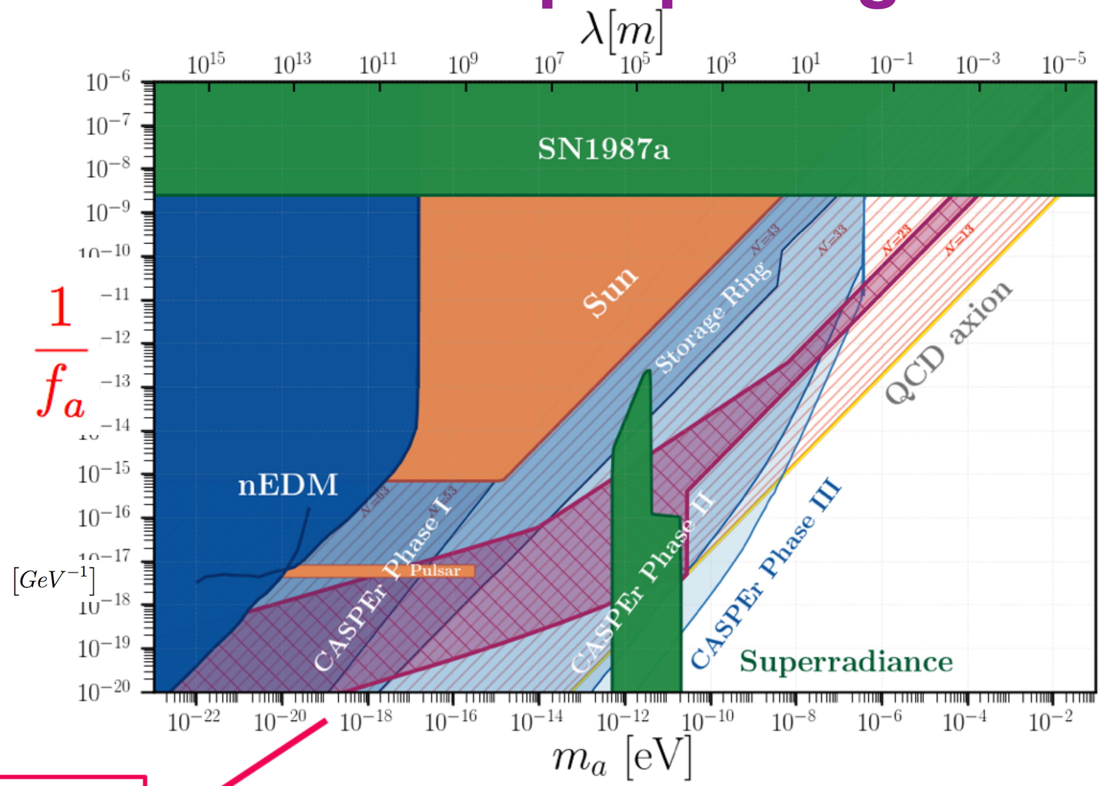
To solve the strong CP problem *and* DM: purple region



di Luzio, Quilez, Ringwald, BG arXiv 2102.01082

To solve the strong CP problem *and* DM: purple region





Z_N Axion DM

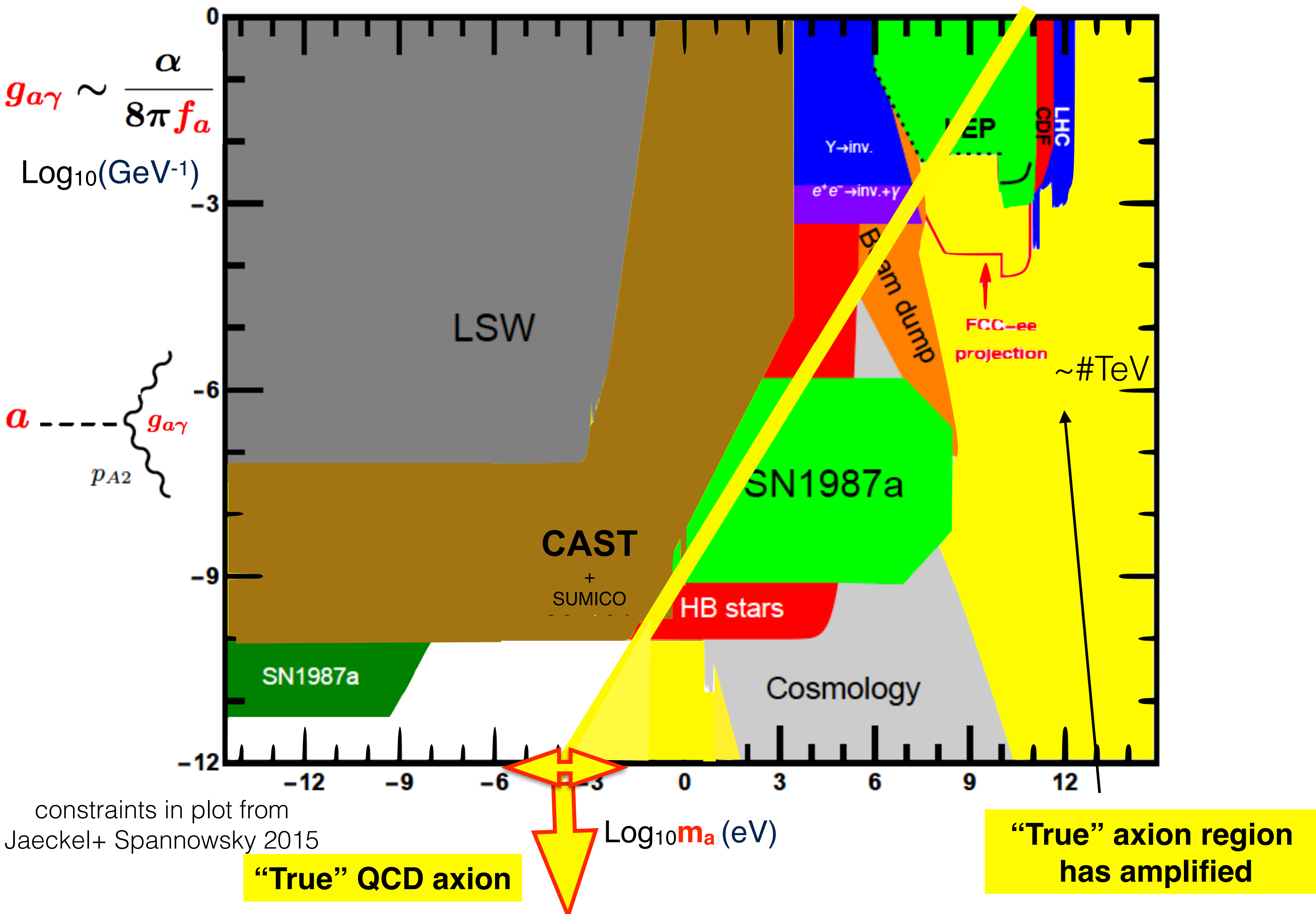
$$3 \leq \mathcal{N} \lesssim 65 \text{ allowed}$$

$$\text{Solutions for } 10^{-22} \text{ eV} \leq m_a \leq m_a^{QCD}$$

First "fuzzy dark matter" true axion

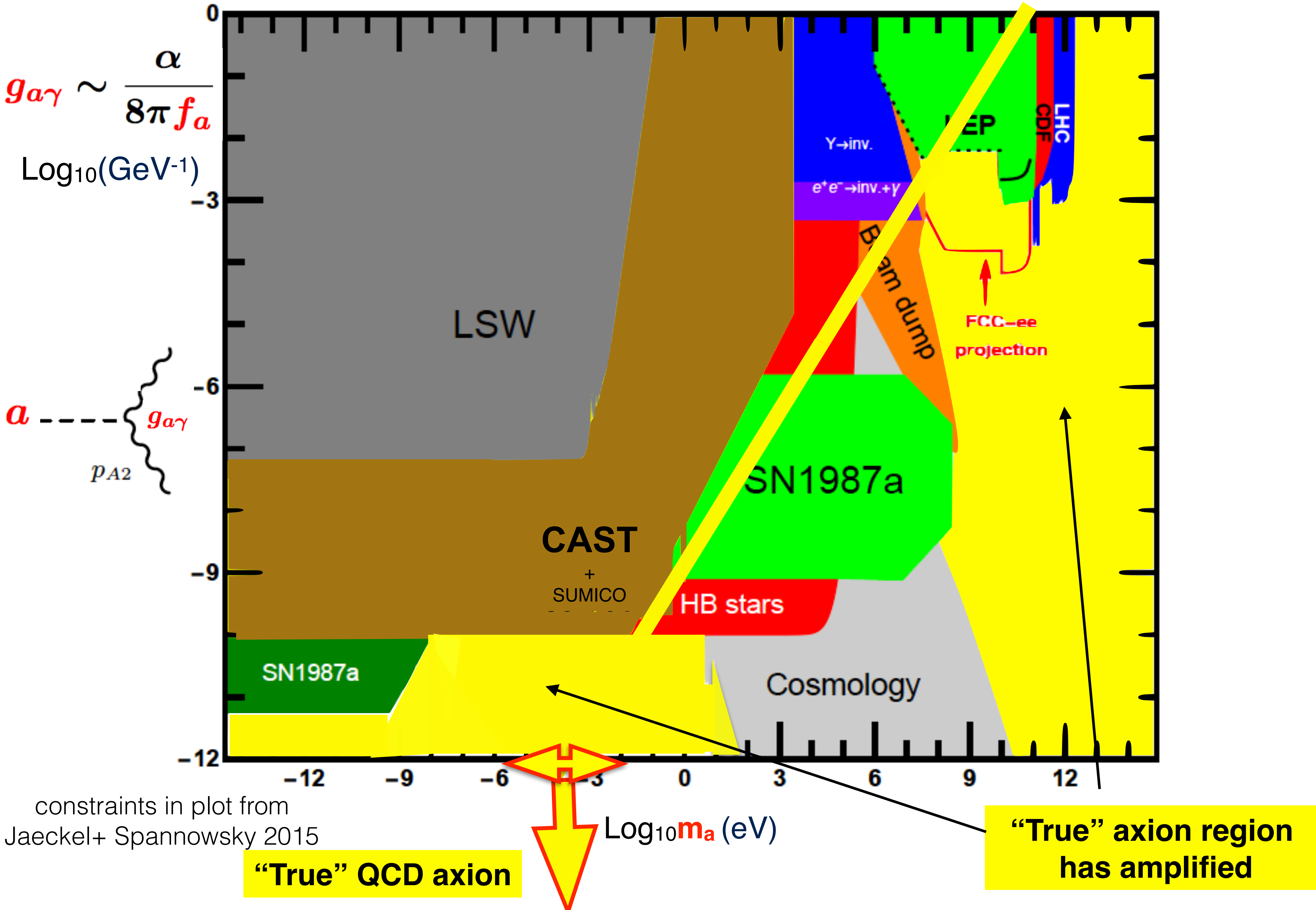
di Luzio, Quilez, Ringwald, BG arXiv 2102.01082

ALPs territory: they can be true axions



constraints in plot from
Jaeckel+ Spannowsky 2015

ALPs territory: they can be true axions



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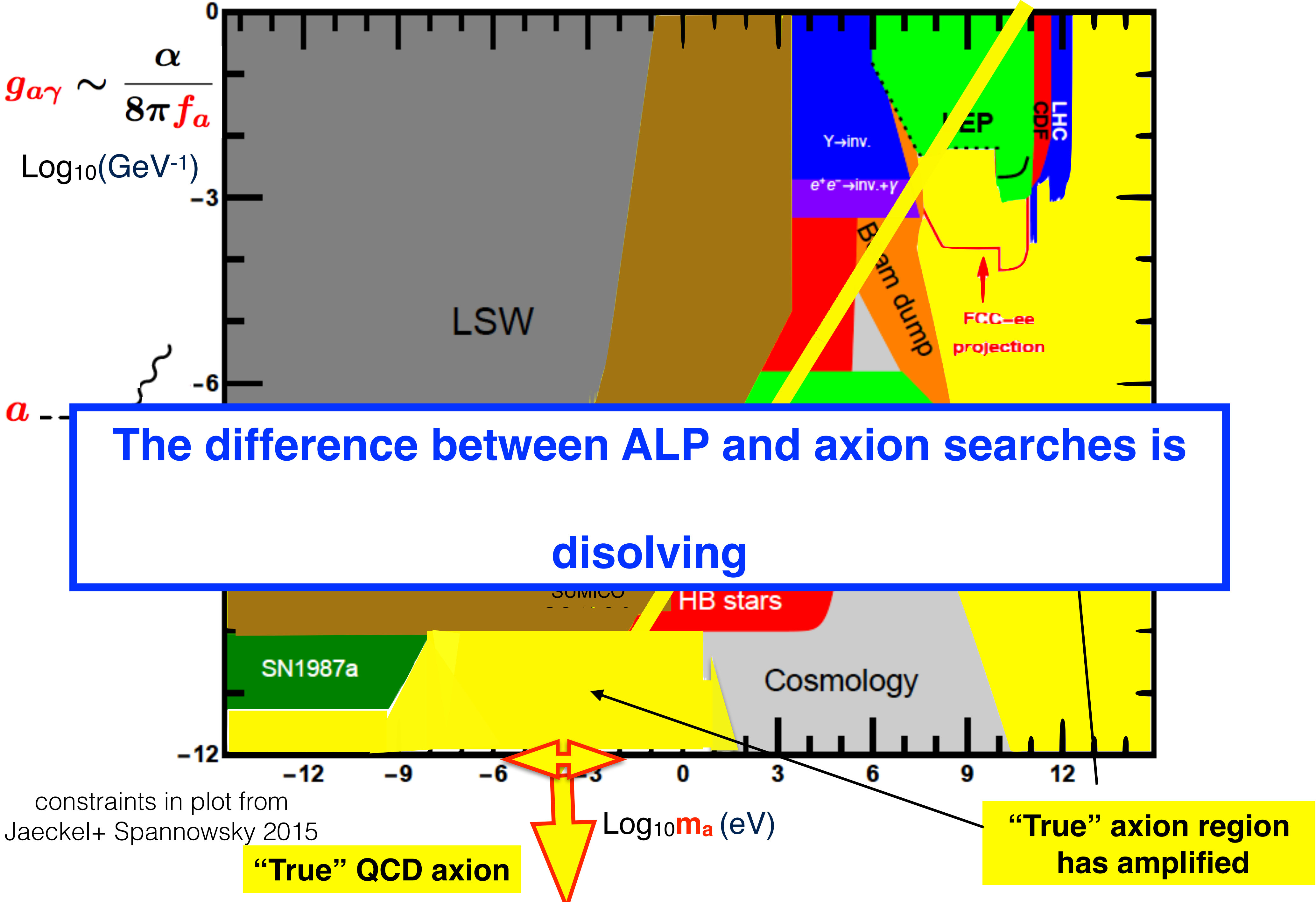
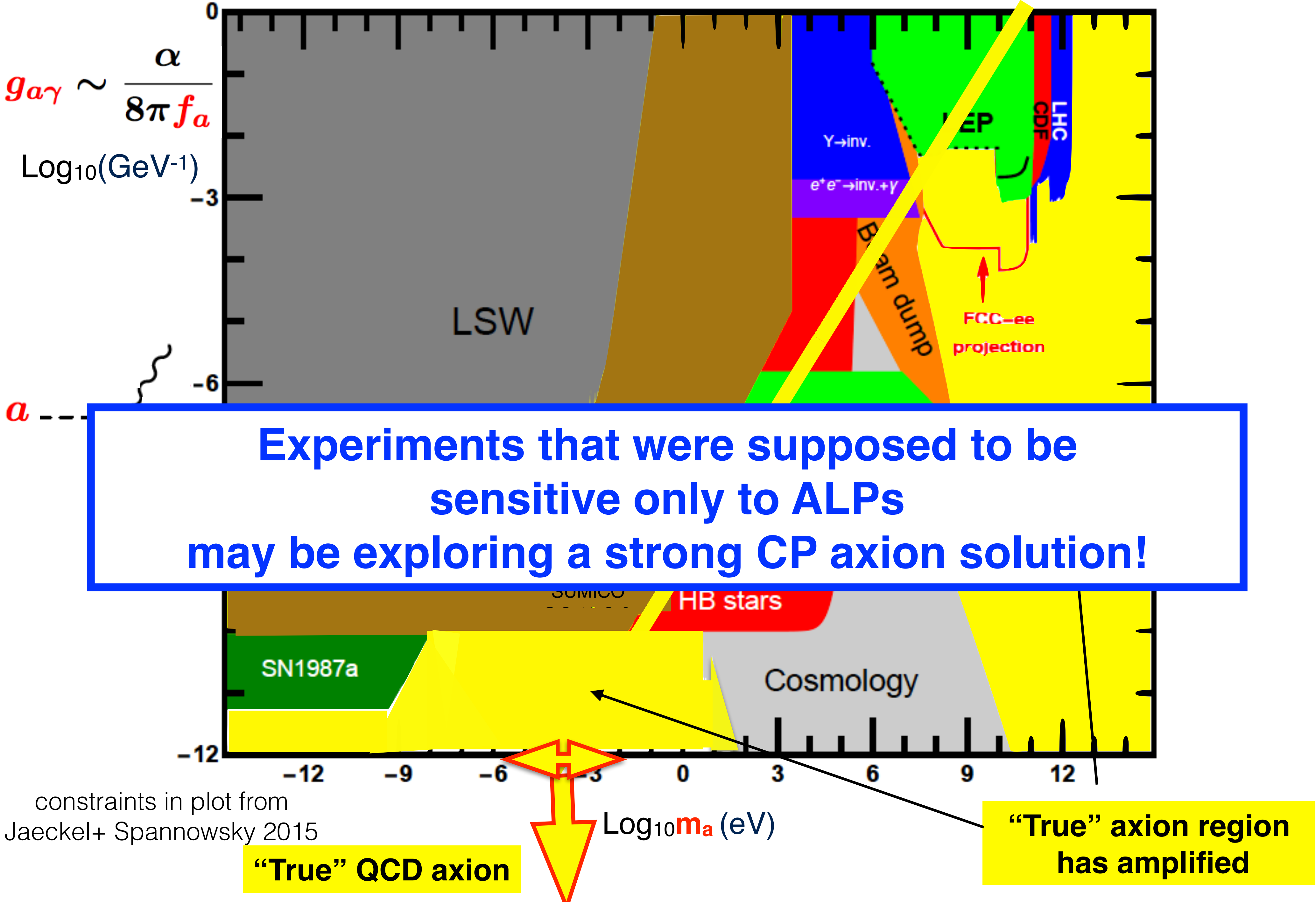
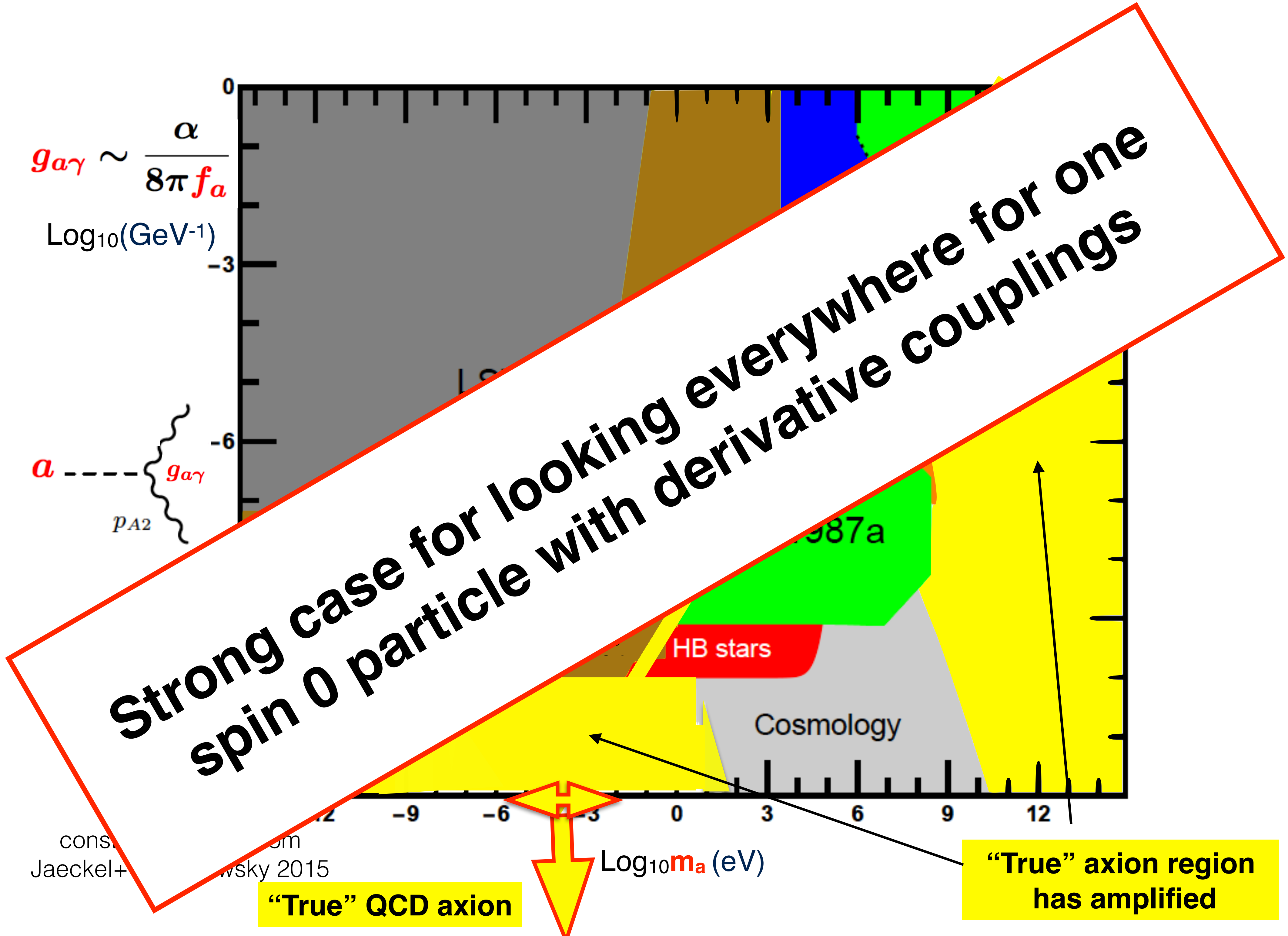


The difference between ALP and axion searches is disolving

ALPs territory: they can be true axions



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



Strong case for looking everywhere for one spin 0 particle with derivative couplings
$g_{a\gamma} \sim \frac{\alpha}{8\pi f_a}$
Log10(GeV-1)
0
-3
-6
a
$g_{a\gamma}$
p_{A2}
HB stars
Cosmology
-9
-6
-3
0
3
6
9
12
Log10 ma (eV)
“True” QCD axion
“True” axion region has amplified

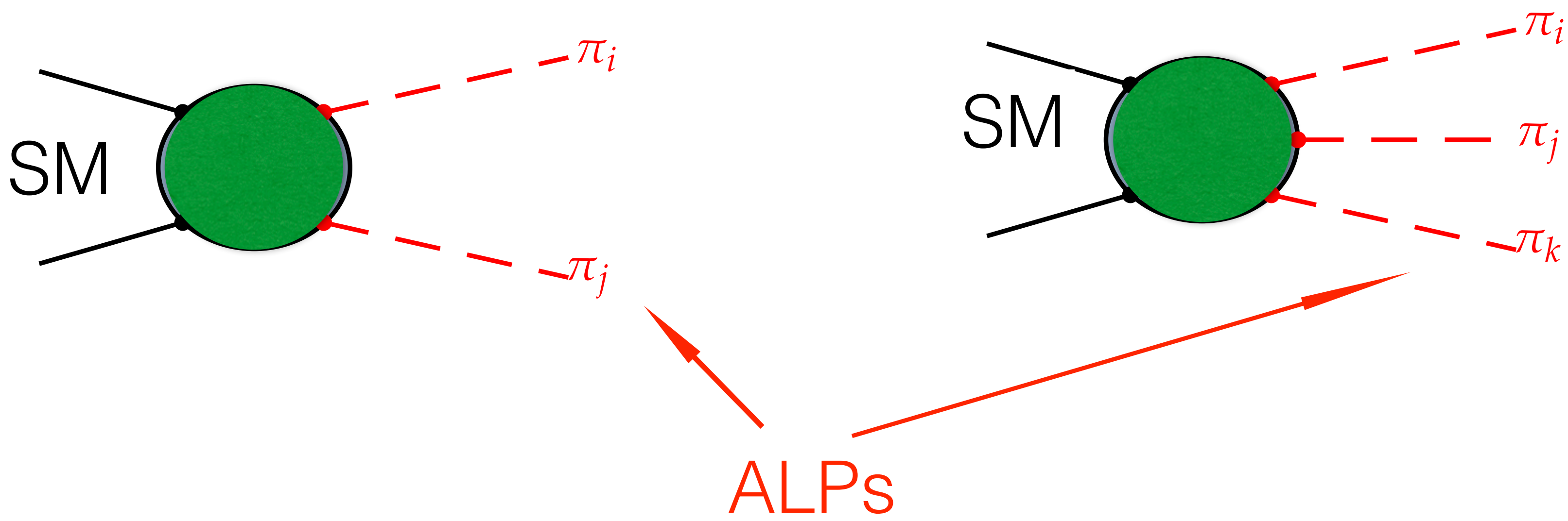
Strong case for looking everywhere for 2, 3...?
spin 0 particle with derivative couplings

Degenerate ALPs

What happens if the ALP is charged under some unbroken dark symmetry D?

The ALP would then necessarily be in a multiplet of D

If the SM sector is uncharged —> no single ALP production



Discrete Goldstone Bosons

Spontaneously broken discrete symmetries
can ameliorate the UV convergence of theories with scalars !

(Das-Hook)

The byproduct is degenerate multiplets of ALPs

B. Gavela, R. Houtz, P. Quilez, V. Enguita-Vileta **arXiv:2205.09131**

—> see talk by Victor Enguita

Consider a triplet of real scalars $\Phi \equiv (\phi_1, \phi_2, \phi_3)$

and a typical SSB condition $\phi_1^2 + \phi_2^2 + \phi_3^2 = f^2$

* Within SO(3), two massless GBs result ϕ (π_1, π_2)

—> explicit breaking needed to give them masses

$$V(\phi_1, \phi_2, \phi_3) \supset \Lambda^2 \left(\epsilon_1 \phi_1^2 + \epsilon_2 \phi_2^2 + \epsilon_3 \phi_2^2\right) + \lambda \phi_1^4 + \cdots$$

arbitrary and sensitive to quadratic corrections

* Within A_4 (or A_5..) $\subset$ SO(3)

—> two massive π_1, π_2 result without breaking the symmetry

—> NOT sensitive to quantum quadratic corrections

The point is that SB discrete symmetries allow invariant potentials

* but very few invariant terms possible, e.g. for A_4

$$\mathcal{I}_2 = \phi_1^2 + \phi_2^2 + \phi_3^2$$
$$\mathcal{I}_3 = \phi_1 \phi_2 \phi_3$$
$$\mathcal{I}_4 = \phi_1^4 + \phi_2^4 + \phi_3^4$$

The most general potential is an arbitrary function of them:

$$V(\phi_1, \phi_2, \phi_3) = V(\mathcal{I}_2, \mathcal{I}_3, \mathcal{I}_4)$$

The point is that SB discrete symmetries allow invariant potentials

* but very few invariant terms possible, e.g. for A_4

$$\mathcal{I}_2 = \phi_1^2 + \phi_2^2 + \phi_3^2$$

this is the only quadratic invariant

$$\mathcal{I}_3 = \phi_1 \phi_2 \phi_3$$

$$\mathcal{I}_4 = \phi_1^4 + \phi_2^4 + \phi_3^4$$

The most general potential is an arbitrary function of them:

$$V(\phi_1, \phi_2, \phi_3) = V(\mathcal{I}_2, \mathcal{I}_3, \mathcal{I}_4)$$

The point is that SB discrete symmetries allow invariant potentials

* but very few invariant terms possible, e.g. for A_4

at low energy
$$\mathcal{I}_2 = \phi_1^2 + \phi_2^2 + \phi_3^2 \;= f^2$$
$$\mathcal{I}_3 = \phi_1\phi_2\phi_3$$
$$\mathcal{I}_4 = \phi_1^4 + \phi_2^4 + \phi_3^4$$

The point is that SB discrete symmetries allow invariant potentials

* but very few invariant terms possible, e.g. for A_4

at low energy $\mathcal{I}_2$ is irrelevant for π_1, π_2

$$\mathcal{I}_3 = \phi_1 \phi_2 \phi_3$$

$$\mathcal{I}_4 = \phi_1^4 + \phi_2^4 + \phi_3^4$$

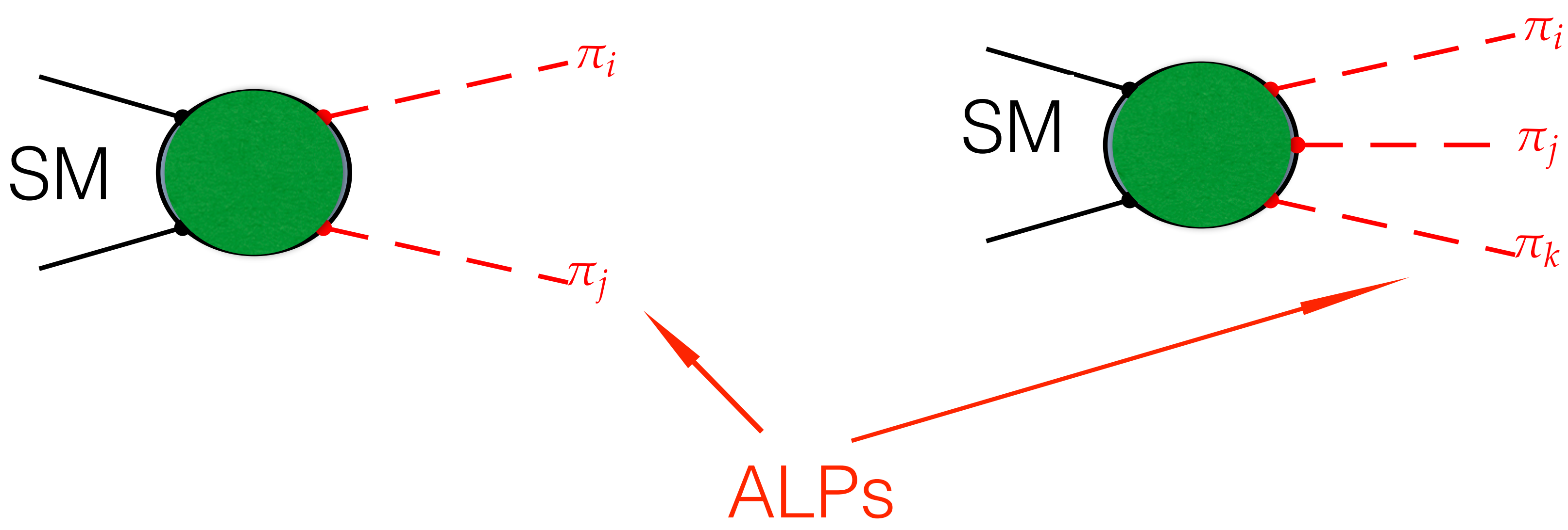
In consequence, the most general potential for π_1, π_2 is:

$$V(\pi_1, \pi_2) = V(\mathcal{I}_3, \mathcal{I}_4)$$

* We explored the natural minima and discovered that **a discrete subgroup remains explicit in the spectrum, i.e. ``à la Wigner''**

Z_3 for A_4 **—> degenerate π_1, π_2 doublet**

no single ALP emission possible



* **The endpoint of distributions** (e.g. invariant mass, m_T…) **differentiates easily one from more than one invisible particles emitted**

* We explored the natural minima and discovered that **a discrete subgroup remains explicit in the spectrum, i.e. ``à la Wigner''**

Z_3 for triplet of A_4 **—> degenerate π_1, π_2 doublet**

Z_3 and Z_5 for triplet of A_5 **—> degenerate π_1, π_2 doublet**

A_4 for quadruplet of A_5 **—> degenerate π_1, π_2, π_3 triplet**

↑

non-abelian

etc.

Conclusions

Axions and ALPs: blooming experiments and theory

—> The parameter space to find a true axion that solves the strong CP problem has expanded **beyond the QCD axion band: heavier and lighter true axions, e.g. first ``fuzzy DM´´ axion**

—> Searches for ALPs and true axions merging

—> Discrete Goldstone bosons are massive ALPs protected from quadratic divergences and produced in degenerate multiplets

Strong physics case to look everywhere for one or more axions or ALPs

Conclusions

Axions and ALPs: blooming experiments and theory

—> The parameter space to find a true axion that solves the strong CP problem has expanded **beyond the QCD axion band: heavier and lighter true axions, e.g. first ``fuzzy DM´´ axion**

—> Searches for ALPs and true axions merging ← **Talks J. Machado, J. Bonilla**

—> Discrete Goldstone bosons ← **Talk by Victor Enguita**

Strong physics case to look everywhere for one or more axions or ALPs

Conclusions

Axions and ALPs: blooming experiments and theory

Theory:

—> **The parameter space to find a true axion that solves the strong CP problem has expanded beyond the QCD axion band.**

Heavier then usual and lighter than usual axions possible. They can also explain DM.

—> e.g. first ``fuzzy DM´´ axion

Experiment:

—> **Searches for ALPs and true axions merging**

Strong physics case to look everywhere for singlet scalars with couplings proportional to momenta

Conclusions / Outlook

It is a deep pleasure to be here today

Thank you very very much for the invitation!

😊

Backup

ALPs

We will consider the SM plus a generic scalar field a

with derivative (+ anomalous) couplings to SM particles

and scale f_a:

an ALP (axion-like particle)

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

general effective couplings

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

Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz 2017 arXiv:1701.05379

An example of

HEAVY axion theory

which solves the strong CP problem

use Massless Quarks

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

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

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

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

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

K. Choi, J.E. Kim 1985

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} $\tilde{\Lambda}$

solves strong CP problem with massless SU(6) fermion

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solves strong CP problem with massless SU(6) fermion

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

……… —> backup slides

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} $\tilde{\Lambda}$

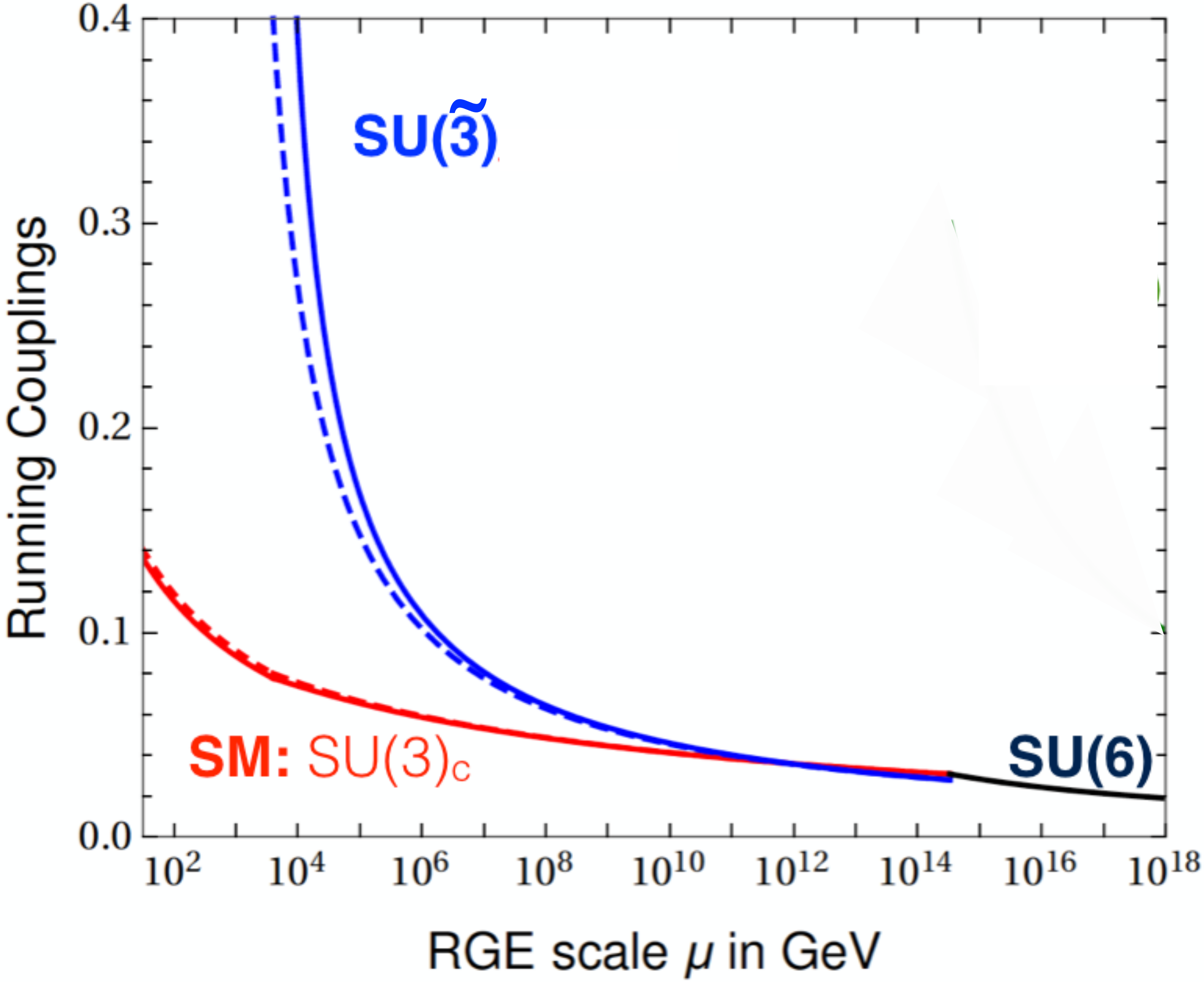
Solve strong CP problem with massless SU(6) fermion

- 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 $\tilde{\Lambda}$ ~ TeV >> Λ_{QCD}

You would like to achieve:



BUT HOW???

The SM fermions

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

SM — SM — SM

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

These are the troublemakers

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')

Both $SU(3)_c$ and $SU(3)_{diag}$ unbroken and confining, $\Lambda_{diag} >> \Lambda_{QCD}$

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

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

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

	$SU(3)$	$SU(3)_{\mathrm{diag}}$	$SU(2)_L$
ψ	$\square$	$\bar{\square}$	1
χ	1	$\square$	1
$2\psi_\nu$	1	1	1

The two massless quarks

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

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

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

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	$\mathbf{1}$	$\square$	$\mathbf{1}$
Ψ	20	$\mathbf{1}$	$\mathbf{1}$
Δ	$\square$	$\overline{\square}$	$\mathbf{1}$

- We can form terms like:

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

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

Scalar field responsible for CUT breaking (Δ)

The CUT breaking

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

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

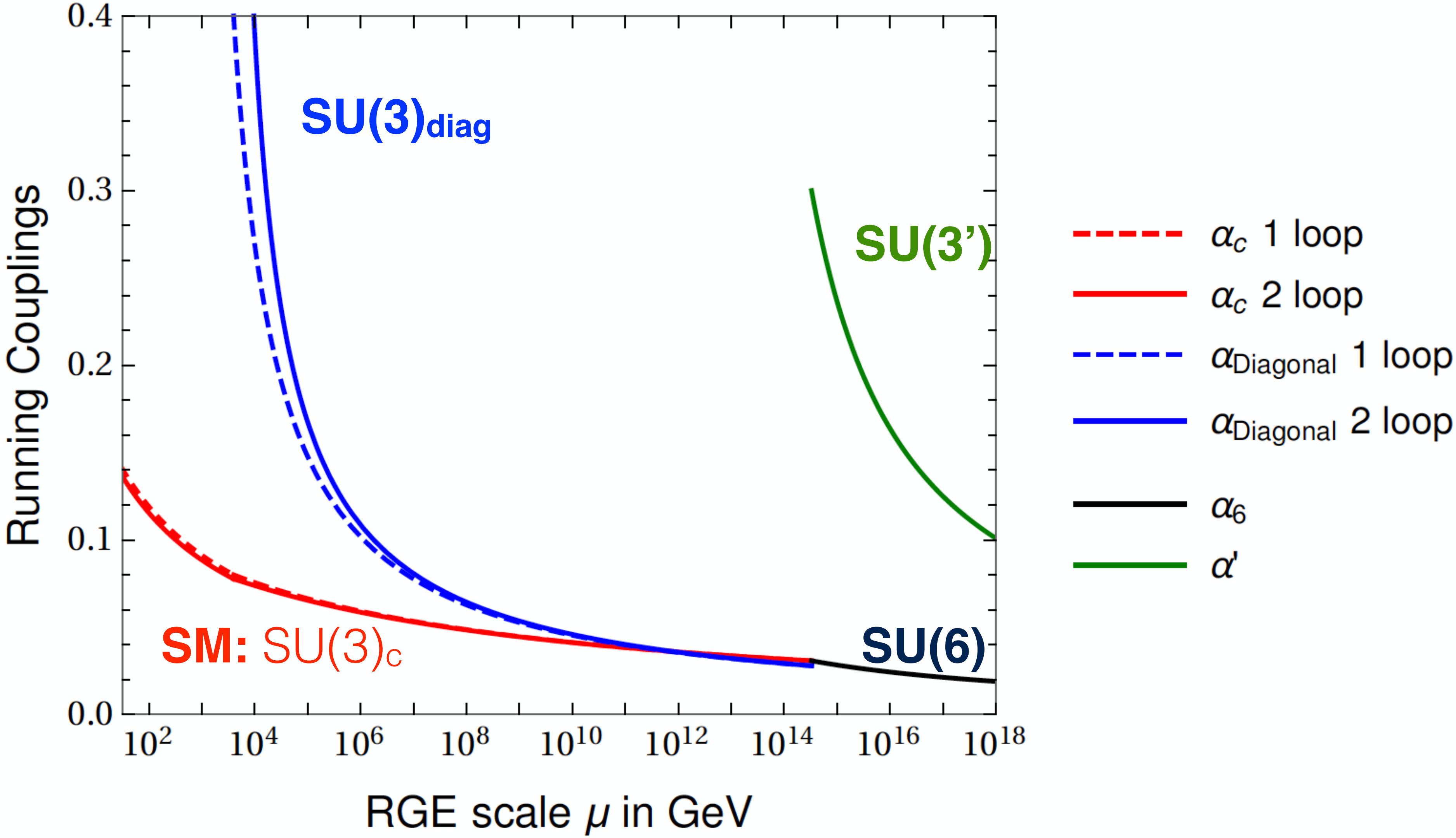
$$\langle \Delta \rangle = \Lambda_{\rm CUT} \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

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

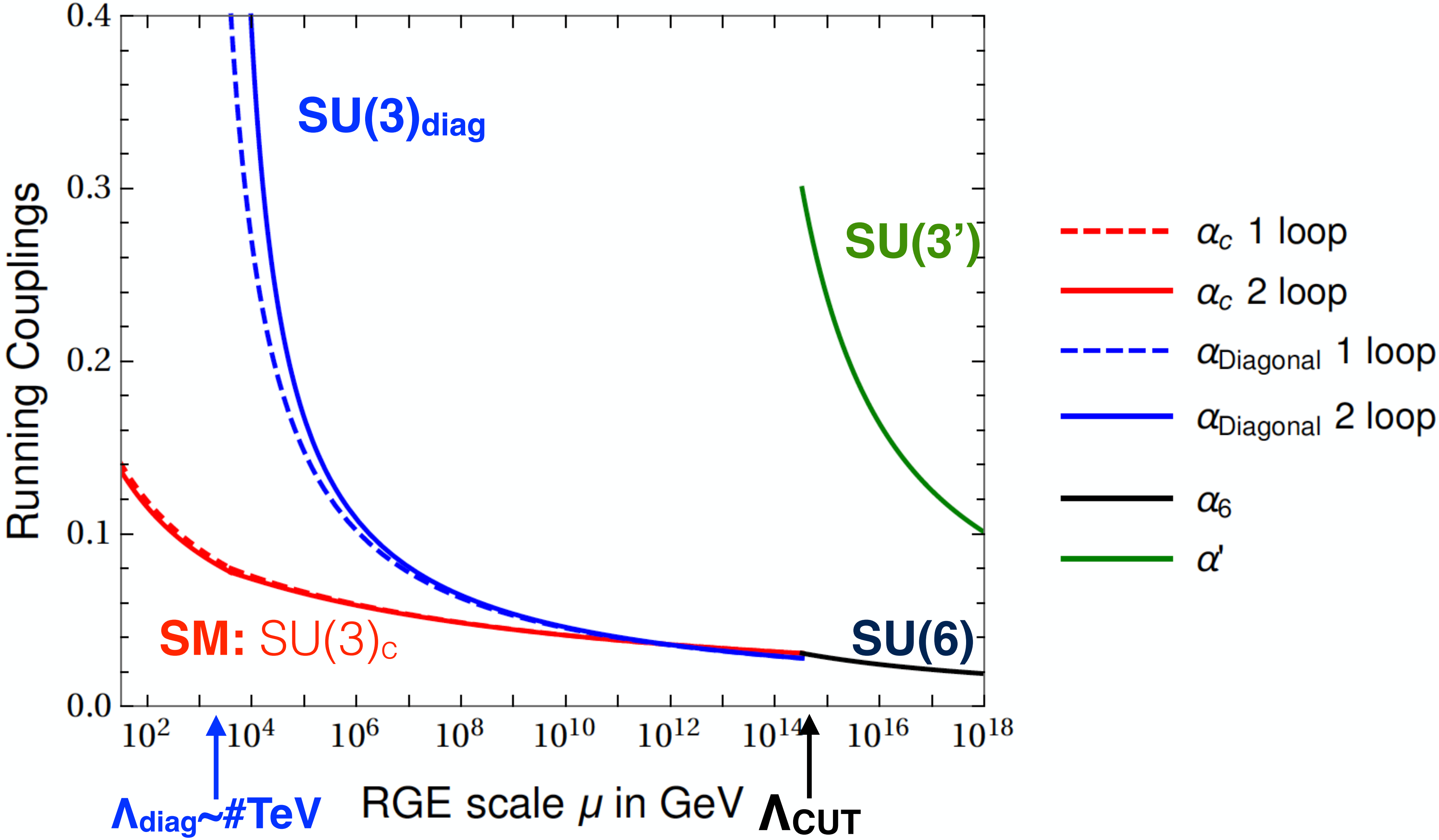
$$\mathcal{L} \ni \Lambda_{\rm CUT} \left(\kappa_q \overline{q'_R} \tilde{q}_L + \kappa_u u'_L \overline{\tilde{u}_R} + \kappa_d d'_L \overline{\tilde{d}_R} \right) + \text{h.c.}$$

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

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	1
χ	1	□

—> 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 ?**

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

Small Size Instantons (SSI) and Axion Mass

Instantons effects are exponentially suppressed

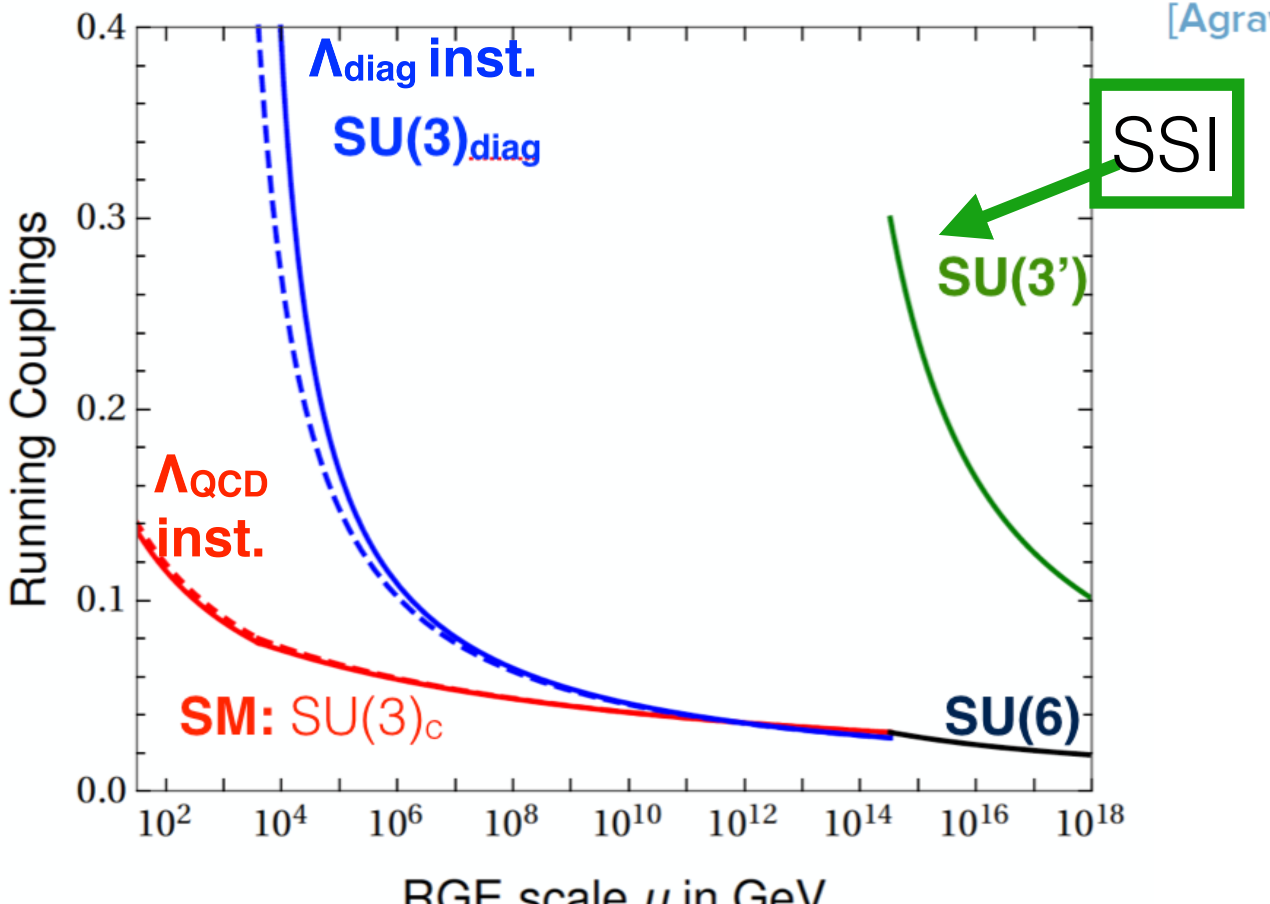
$$D[\alpha'(\mu)] \propto e^{-2\pi/\alpha'(\mu)}$$

Usually sizable only at the confinement scale

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

But SSI relevant in high-scale SSB theories

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



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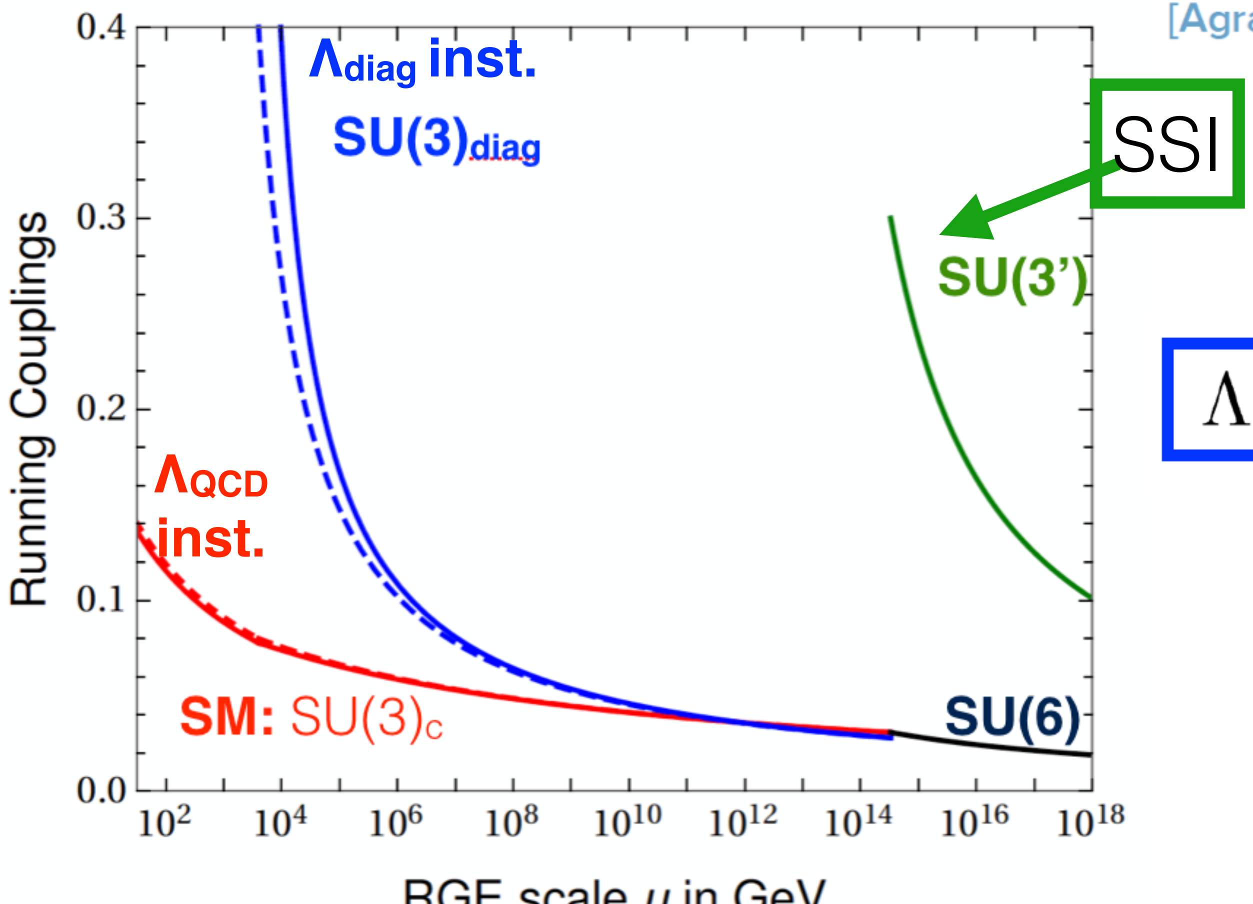


$$\Lambda_{SSI} \gtrsim 20\, TeV$$

The effective potential for the three singlet pseudoscalars:

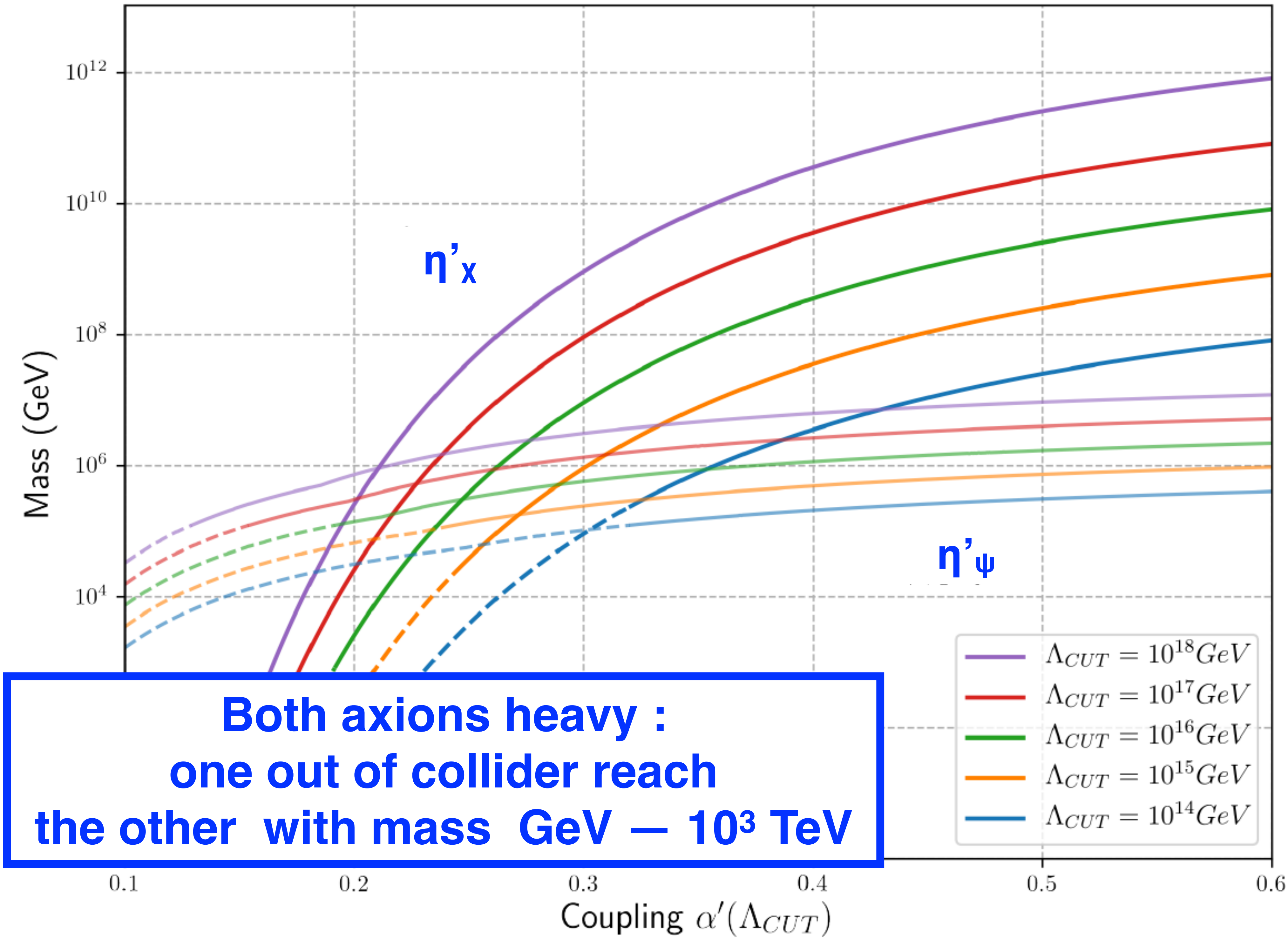
η'_{QCD} η'_{ψ} η'_{χ}

axions (η'_{ψ}, η'_{χ})

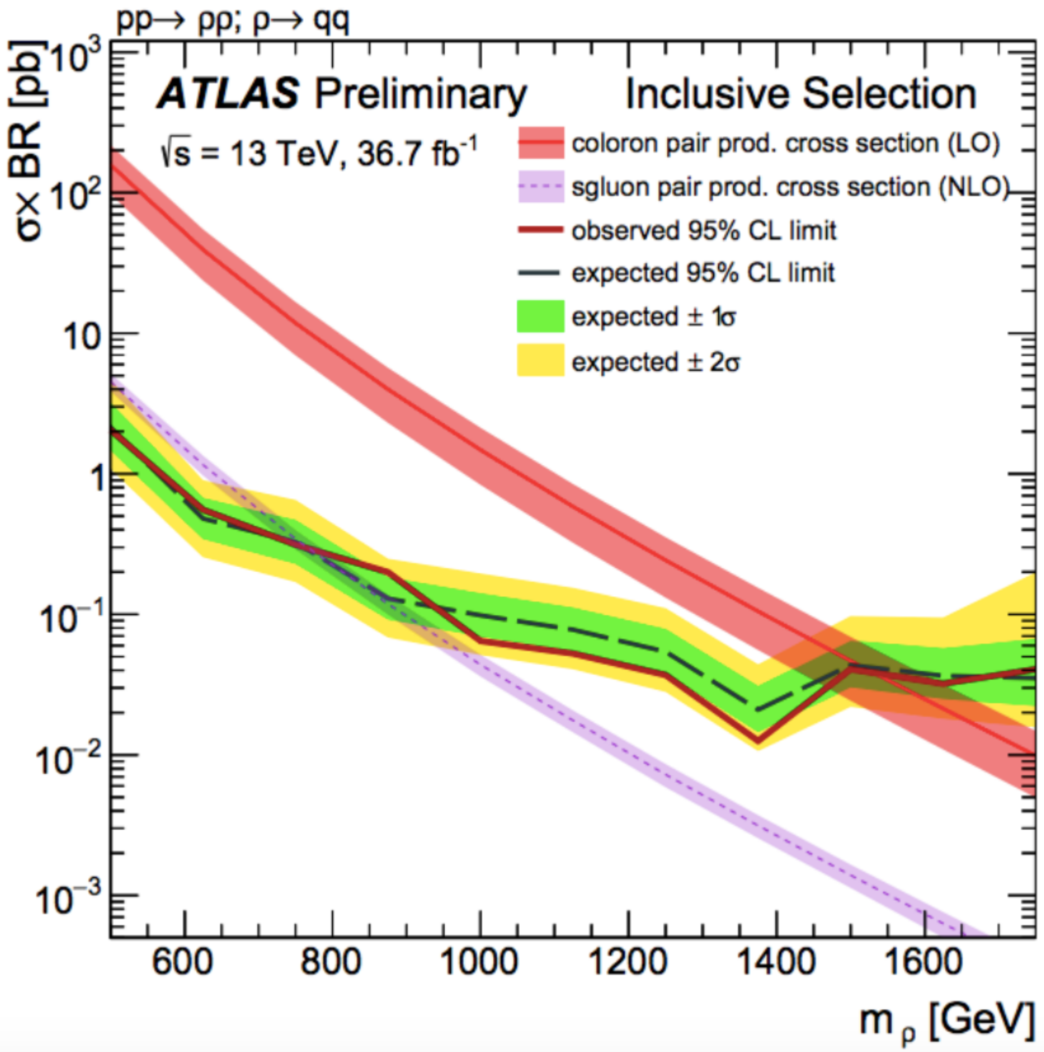
$$V_{eff} = \underbrace{\frac{\Lambda^4_{\rm SSI}}{2}\left(2\,\frac{\eta'_\chi}{f_{\rm d}}\right)^2}_{SU(3')\ \text{SSI Instantons}} + \underbrace{\frac{\Lambda^4_{\rm diag}}{2}\left(2\,\frac{\eta'_\chi}{f_{\rm d}} + \sqrt{6}\,\frac{\eta'_\psi}{f_{\rm d}}\right)^2}_{SU(3)_{\rm diag}\ \text{Instantons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

has three sources of mass —> two massive axions

η'_{QCD} plus two axions: η'_ψ and η'_χ



Collider Phenomenology



- We have a bound on color octet scalars

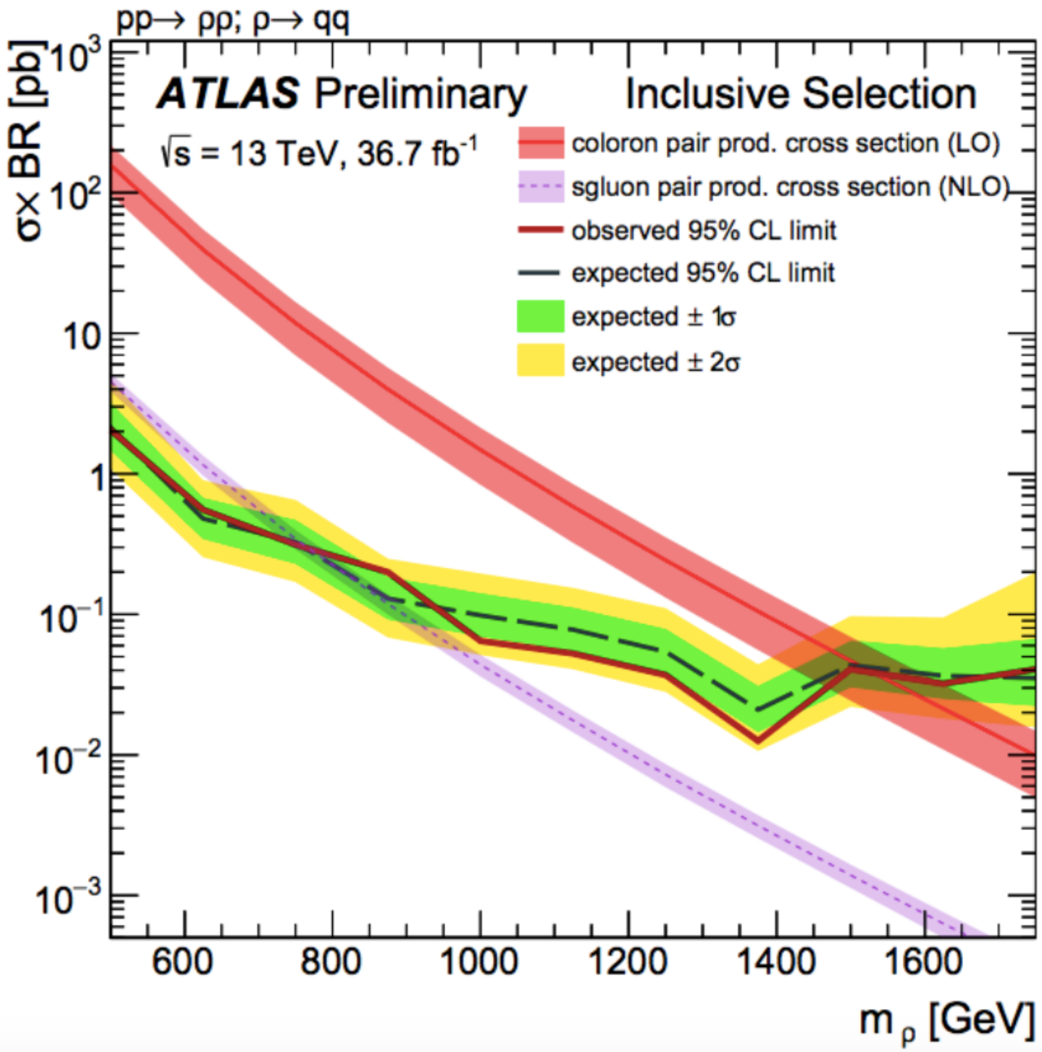
$$m(\pi_d) \gtrsim 700 \text{ GeV}$$

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

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

and this is the PQ scale !

Collider Phenomenology



- We have a bound on color octet scalars

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

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

$$f_a \approx 3\ \text{TeV}$$

and this is the PQ scale !

The low-energy spectrum is observable

e.g. with large Yukawas:

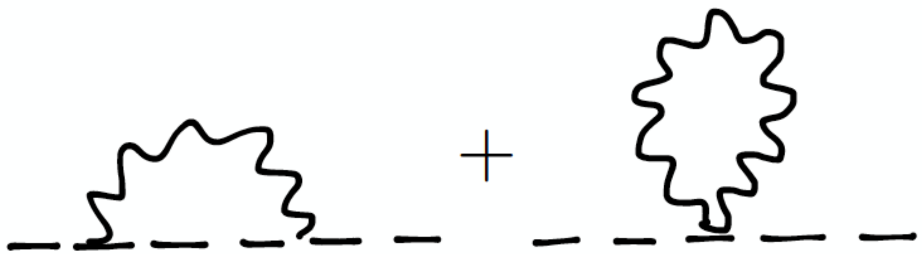
- The U(3) flavor symmetry is broken by condensate $\langle\psi\psi\rangle$

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

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



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

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

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

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:

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

- ➔

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

- ➔ 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

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

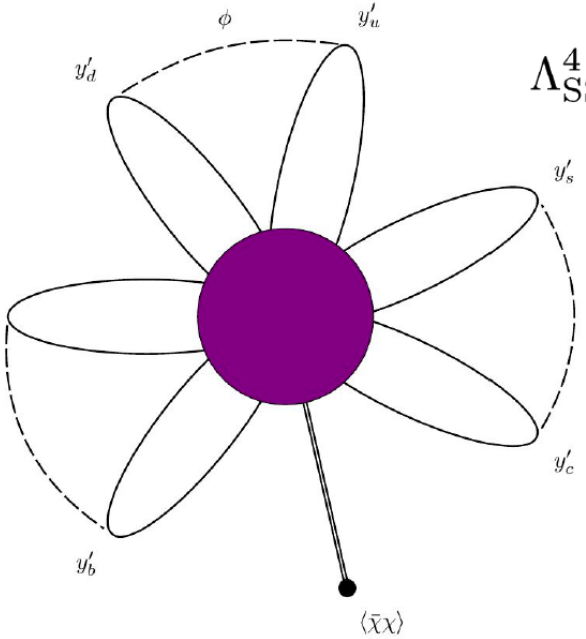
$$M^2_{\eta'_\chi,\,\eta'_\psi,\,\eta'_{\rm QCD}} = \begin{pmatrix} 4\,\frac{\left(\Lambda^4_{\rm SSI}+\Lambda^4_d\right)}{f^2_{\rm d}} & 2\sqrt{6}\,\frac{\Lambda^4_d}{f^2_d} & 0 \\ 2\sqrt{6}\,\frac{\Lambda^4_d}{f^2_d} & 6\,\frac{\left(\Lambda^4_d+\Lambda^4_{\rm QCD}\right)}{f^2_{\rm d}} & 2\sqrt{6}\,\frac{\Lambda^4_{\rm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

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]

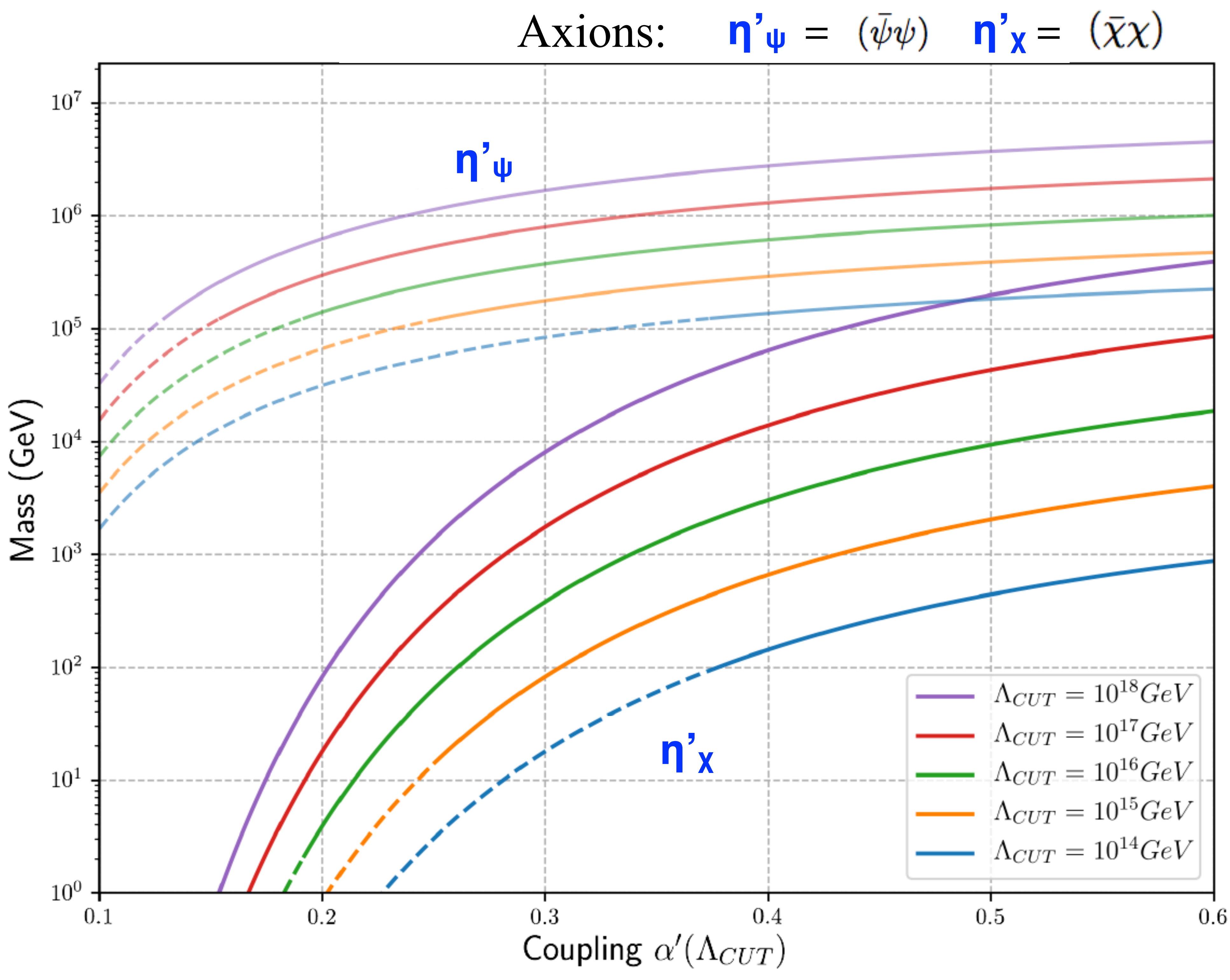


$$\Lambda^4_{\rm SSI} = \underbrace{-C_{inst}\int\frac{d\rho}{\rho^5}\left(\frac{2\pi}{\alpha'(\rho)}\right)^{2N_c} e^{-2\pi/\alpha'(\rho)}}_{\text{Pure Yang-Mills Instanton}}\underbrace{\left(\frac{2}{3}\pi^2\rho^3\langle\bar{\chi}\chi\rangle\right)\frac{1}{(4\pi)^6}\prod_i y'^i_u y'^i_d}_{\text{Fermionic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

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

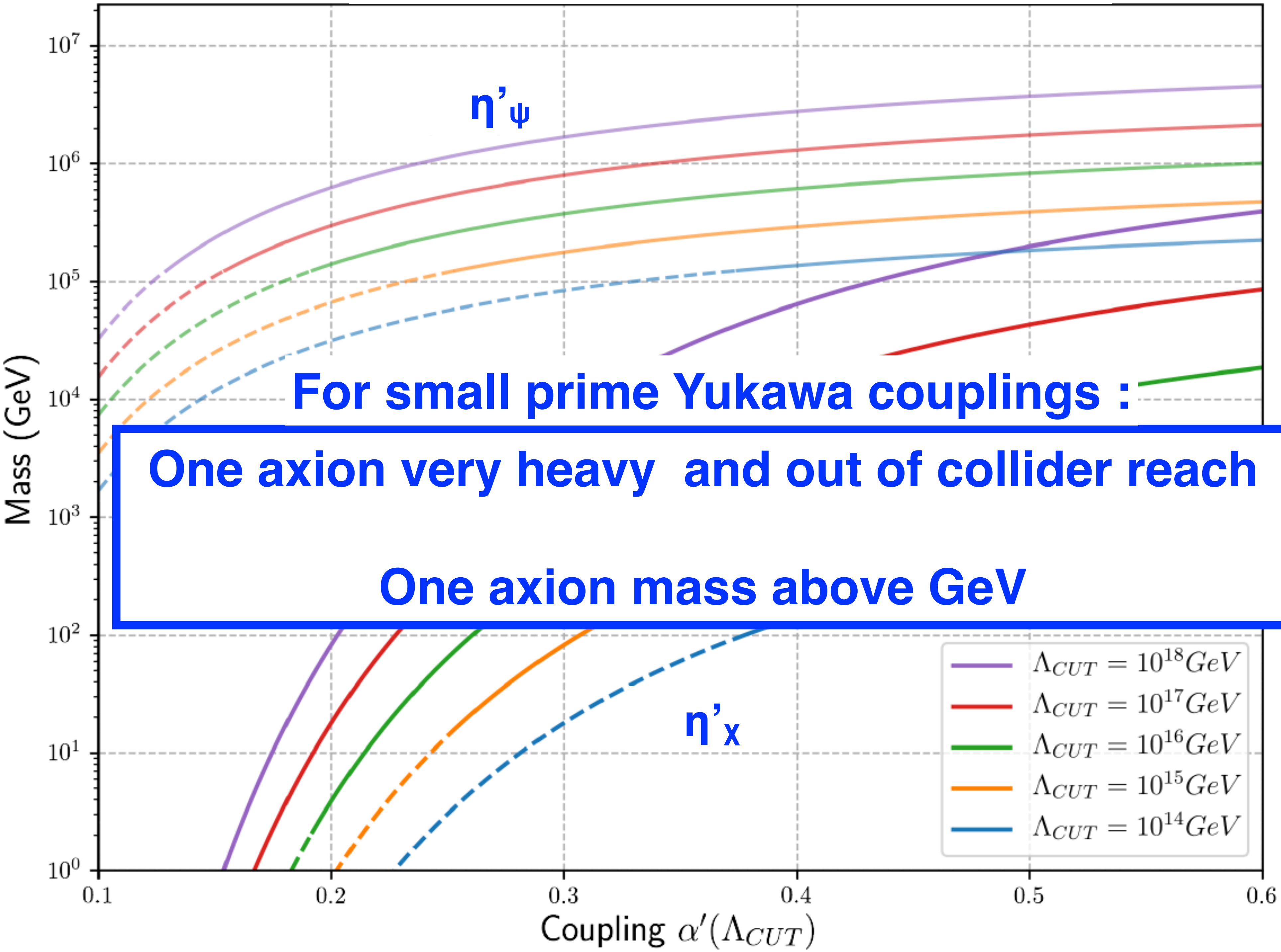
$$\boxed{\Lambda_{SSI} \gtrsim 20\,TeV}$$

arXiv:1805.06465



Axions: η'ψ = ($\bar{\psi}\psi$) η'χ = ($\bar{\chi}\chi$)
η'ψ
η'χ
Mass (GeV)
Coupling $\alpha'(\Lambda_{CUT})$
$\Lambda_{CUT} = 10^{18} GeV$
$\Lambda_{CUT} = 10^{17} GeV$
$\Lambda_{CUT} = 10^{16} GeV$
$\Lambda_{CUT} = 10^{15} GeV$
$\Lambda_{CUT} = 10^{14} GeV$

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



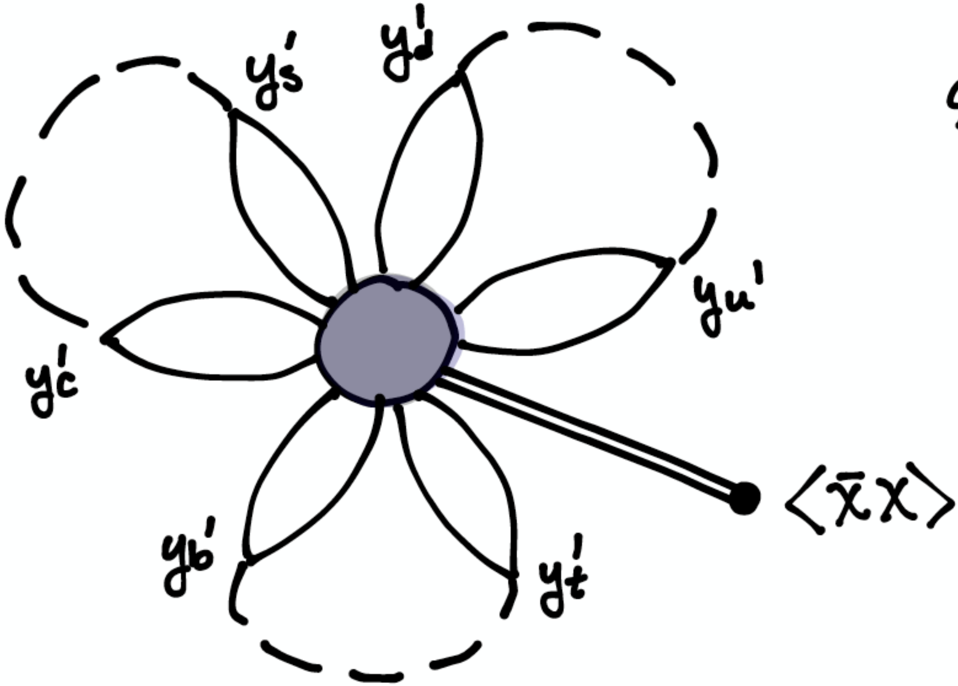
For small prime Yukawa couplings :

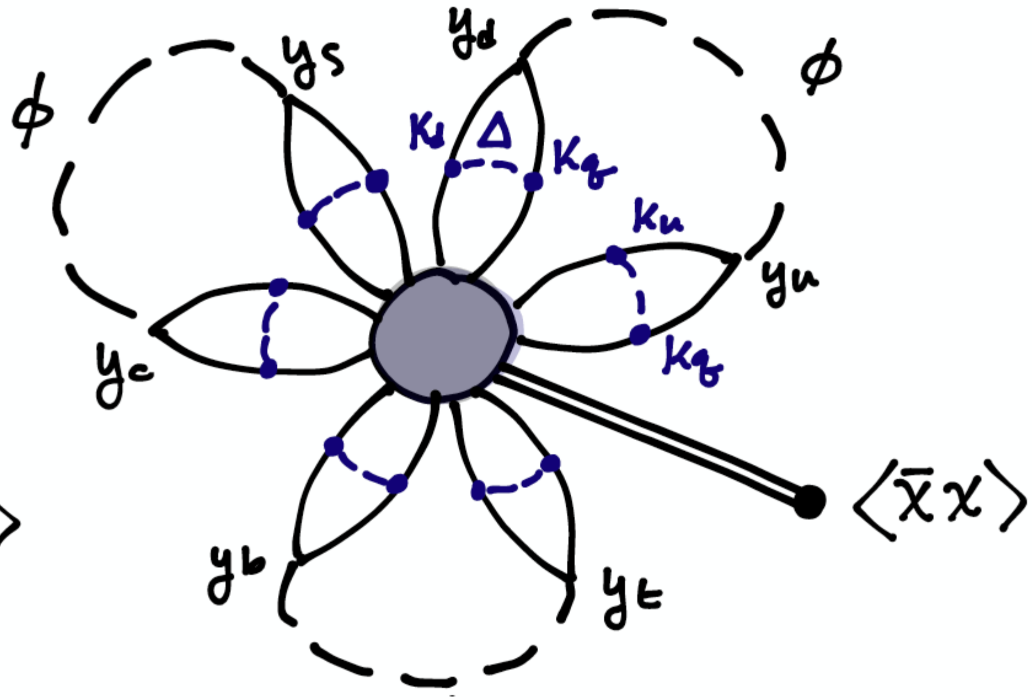
One axion very heavy and out of collider reach

One axion mass above GeV

Small Size Instantons with Fermions

- Adding fermion effects gives an instanton suppression

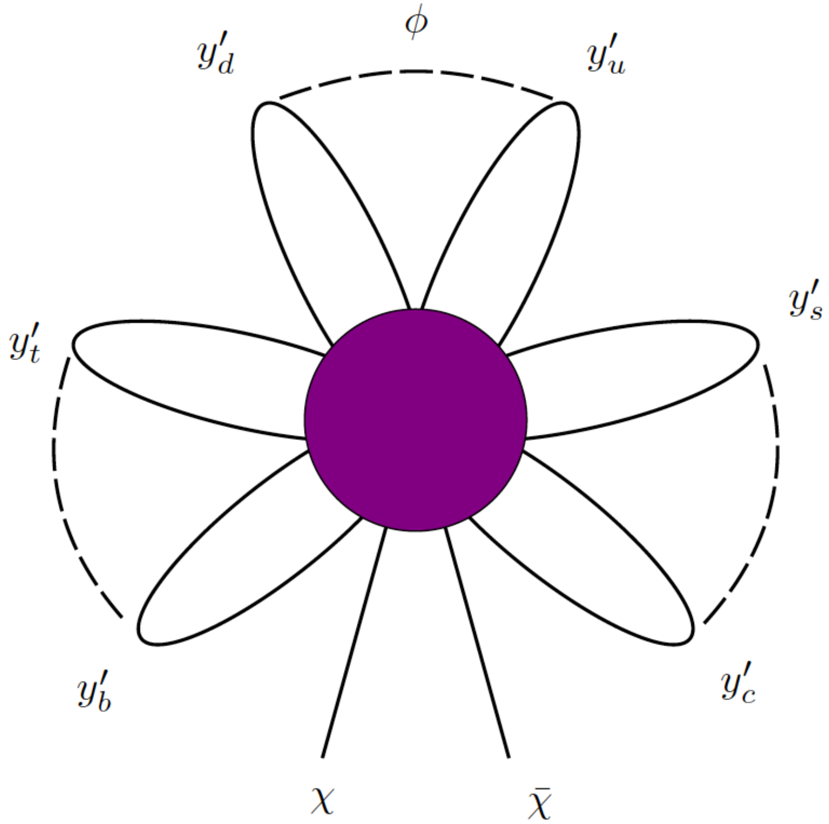




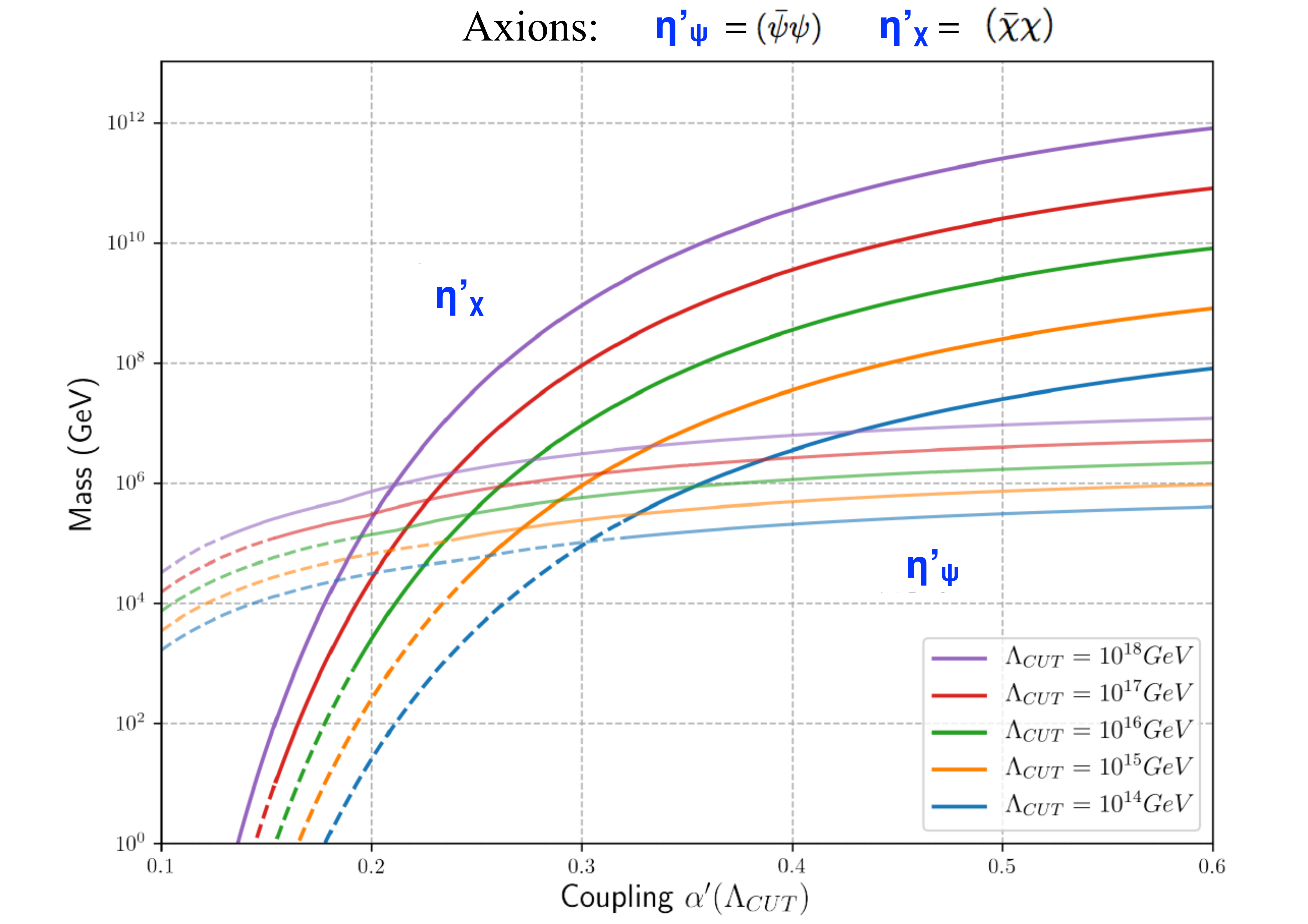
$$\Lambda_{SSI}^4 = -\int \frac{d\rho}{\rho^5} D[\alpha'(1/\rho)] \left(\frac{2}{3}\pi^2\rho^3\langle\bar{\chi}\chi\rangle\right) \frac{1}{(4\pi)^{18}} \prod_i Y_{u_i}^{SM} Y_{d_i}^{SM} \left(\kappa_q^i\right)^2 \kappa_u^i \kappa_d^i$$

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

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



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



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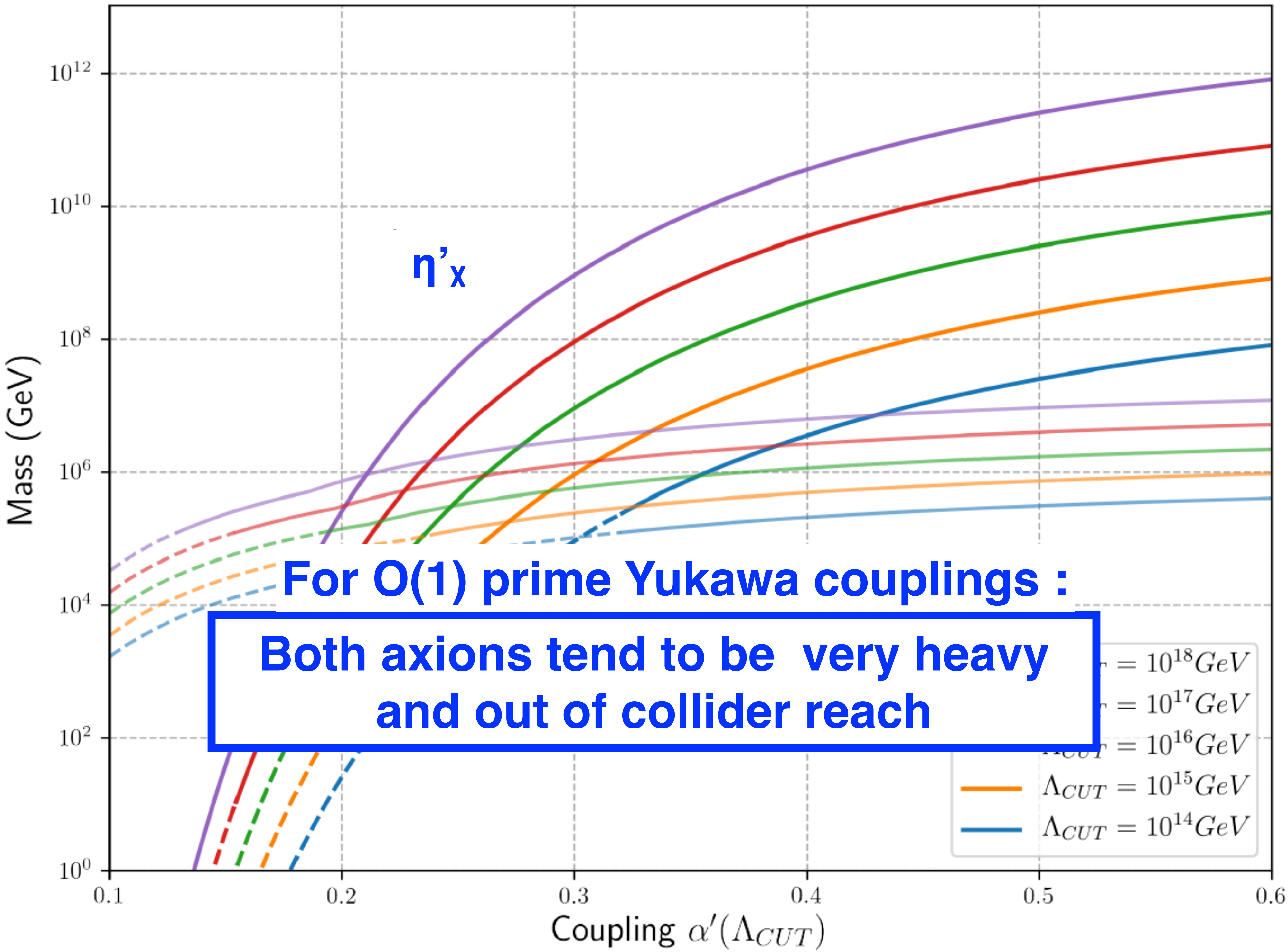
$\Lambda_{CUT} = 10^{16} GeV$
$\Lambda_{CUT} = 10^{15} GeV$
$\Lambda_{CUT} = 10^{14} GeV$

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



For O(1) prime Yukawa couplings :

Both axions tend to be very heavy and out of collider reach

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	1
χ	1	$\square$

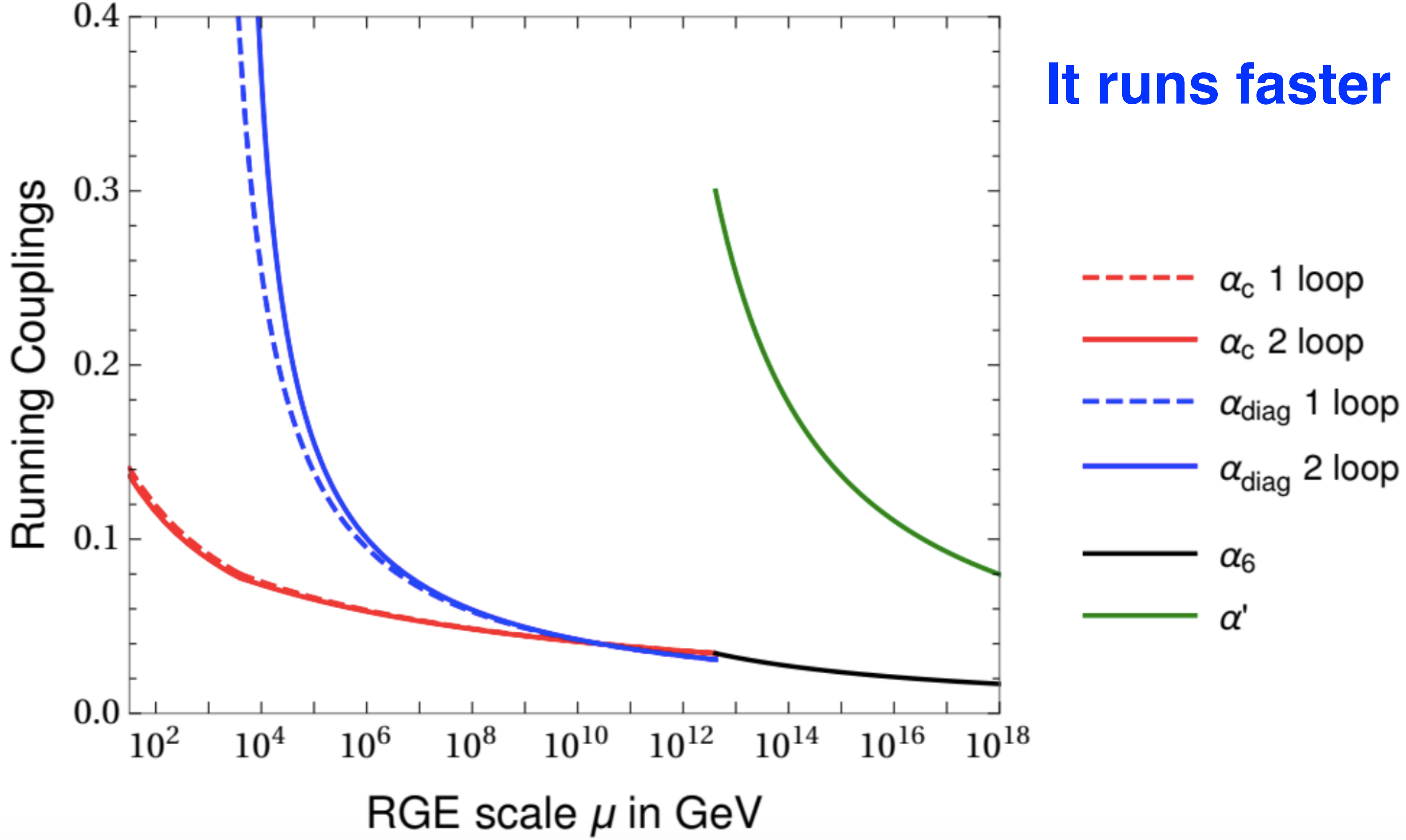
we added a second scalar Δ_2 :

model II:

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

Δ , Δ_2 and the prime fermions have now PQ charges

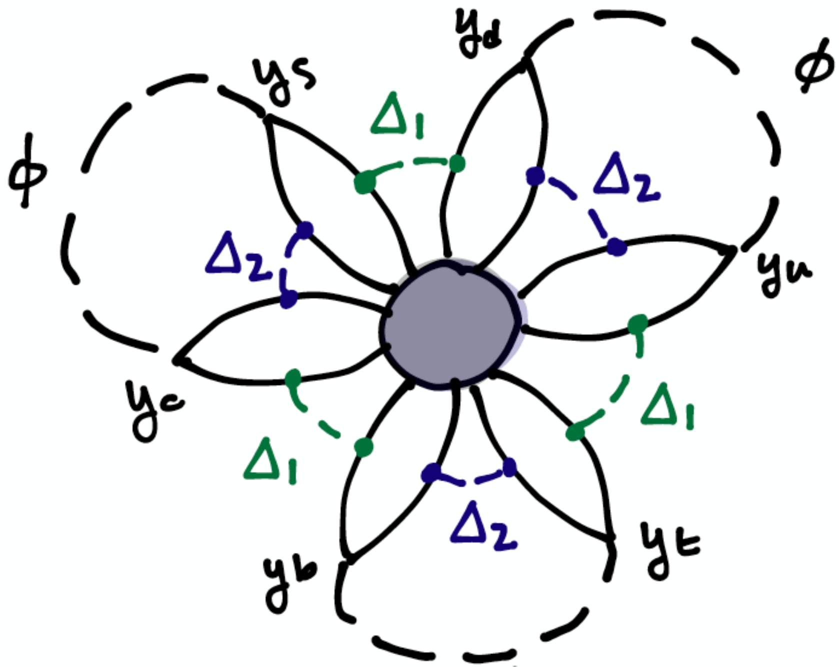
Model II: Small Size Instanton Contribution



It runs faster

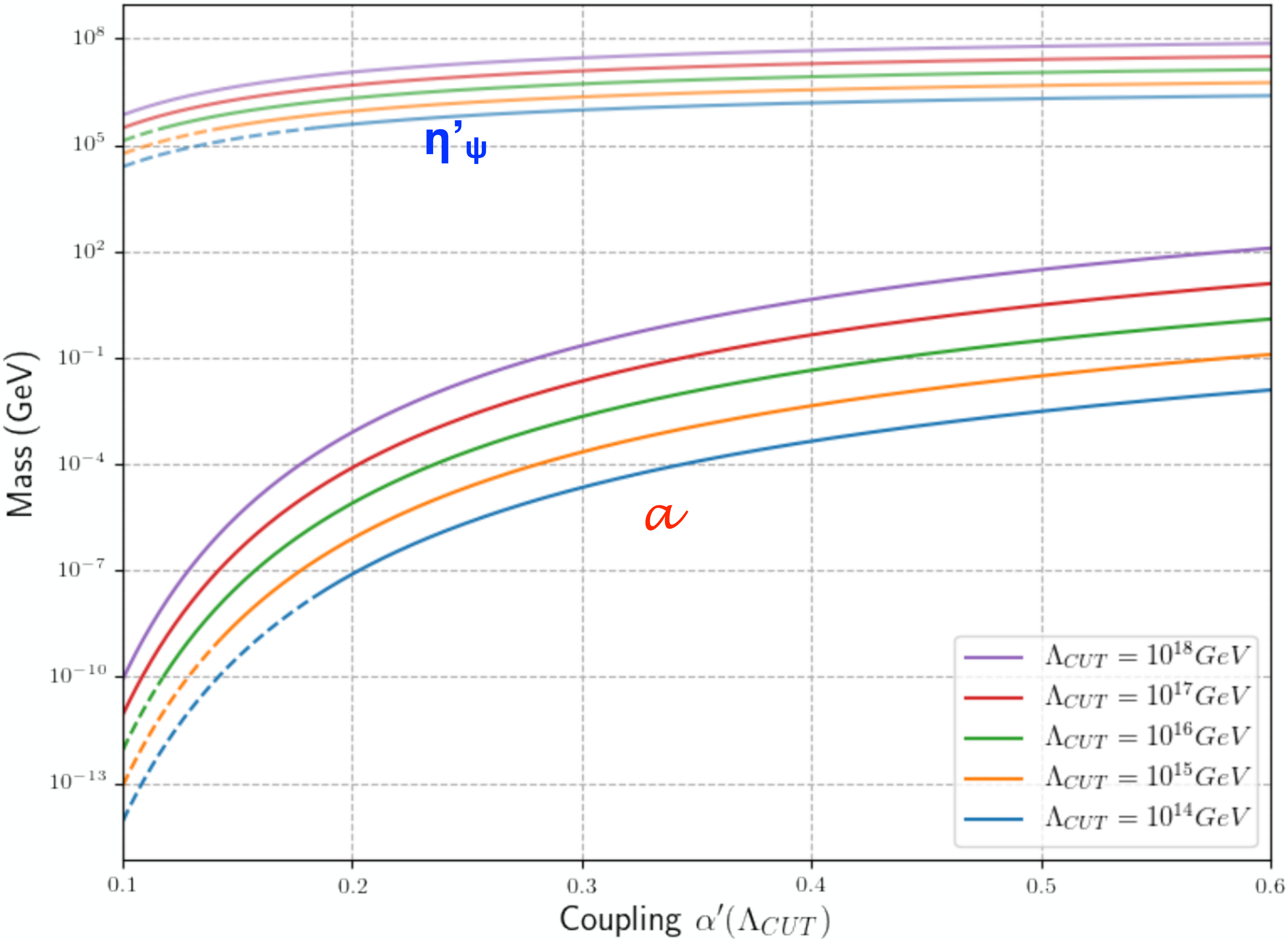
Model II: Small Size Instanton Contribution

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

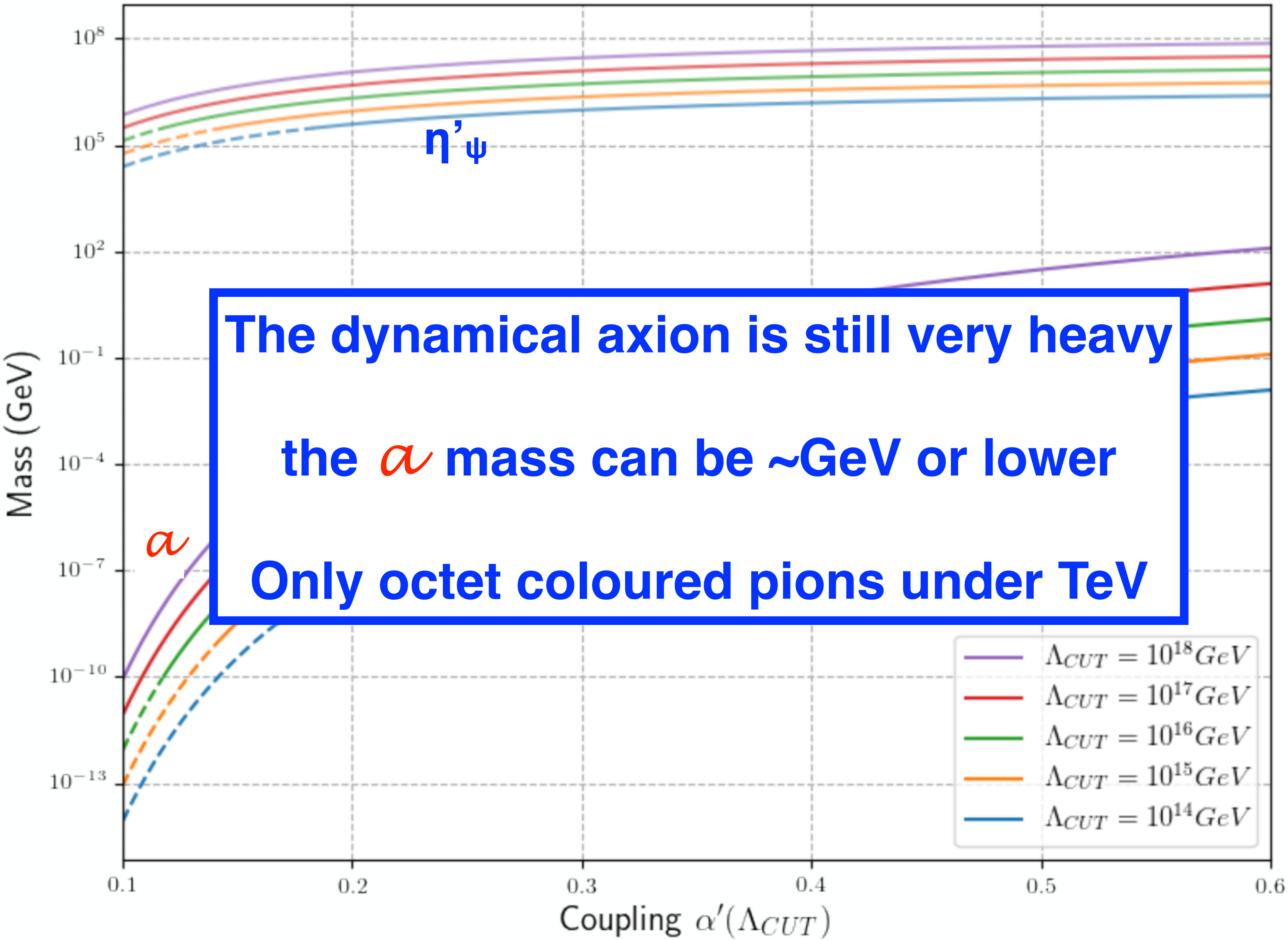


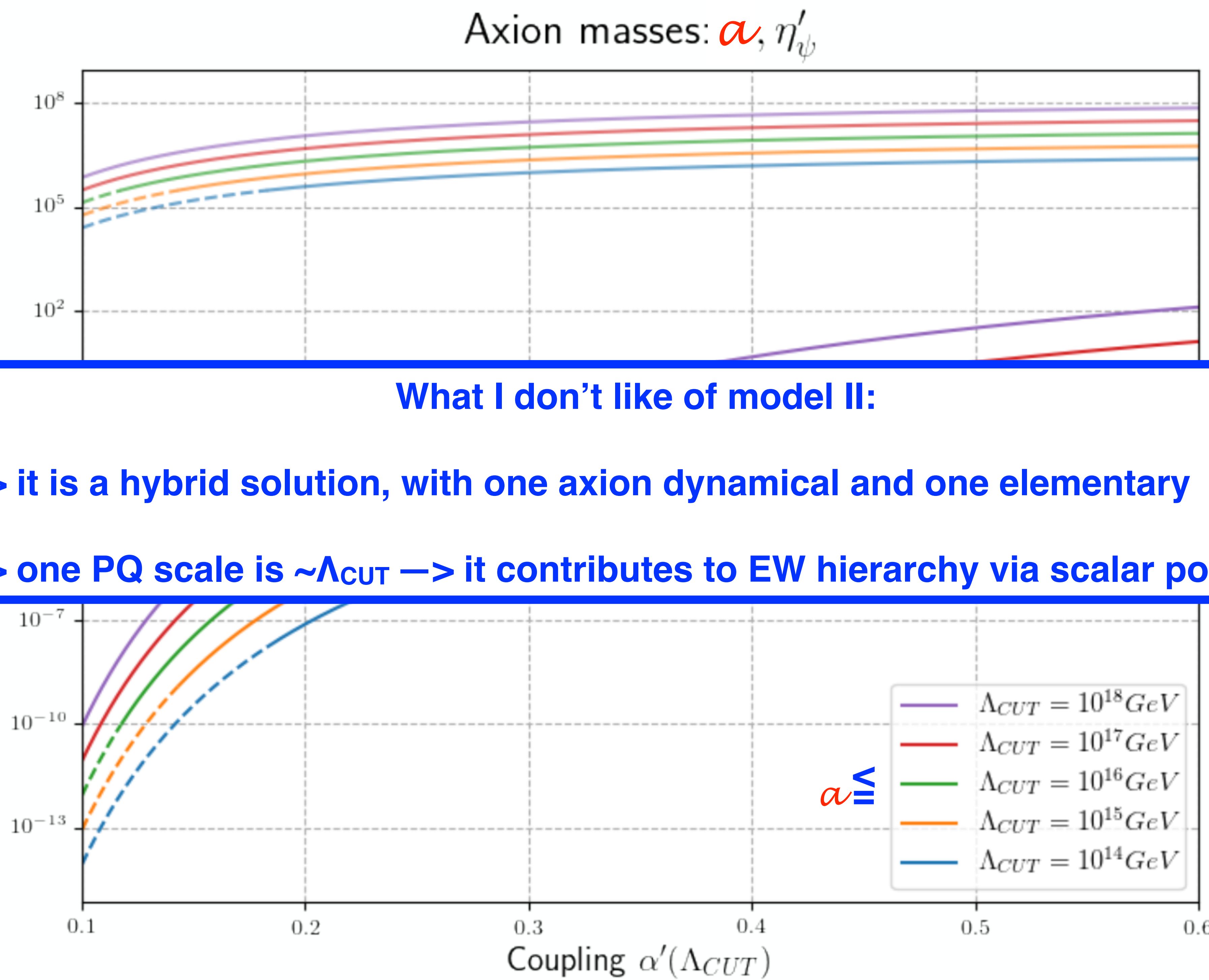
$$\Lambda_{SSI}^{4} = -\int \frac{d\rho}{\rho^5} D[\alpha'(1/\rho)] \frac{1}{(4\pi)^{18}} \prod_i Y_{u_i}^{SM} Y_{d_i}^{SM} \left(\kappa_q^i\right)^2 \kappa_u^i \kappa_d^i$$

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



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





What I don't like of model II:

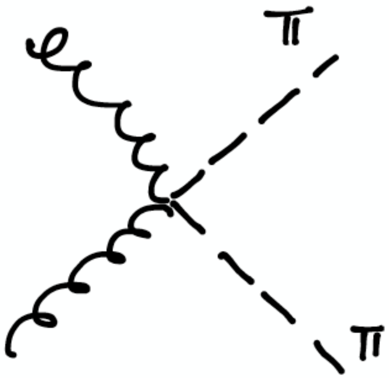
—> it is a hybrid solution, with one axion dynamical and one elementary

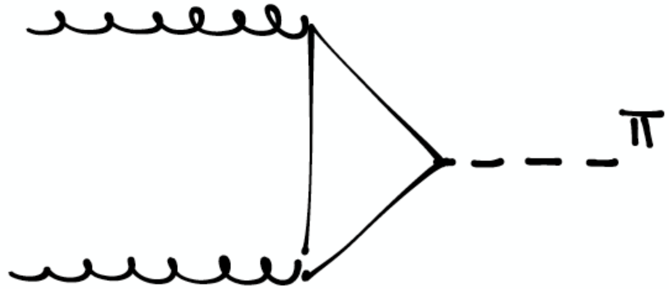
—> one PQ scale is ~Λ_{CUT} —> it contributes to EW hierarchy via scalar potential

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

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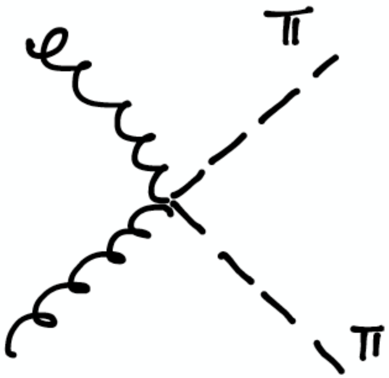
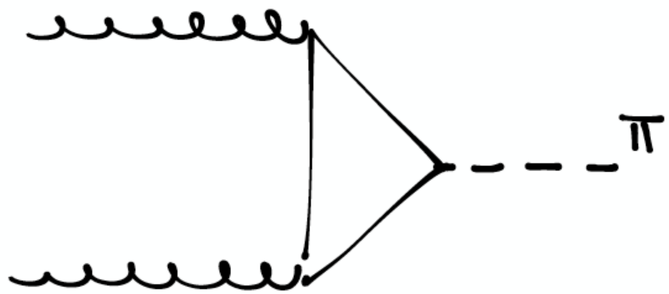
$$\mathcal{L} \ni D_\mu \pi_d D^\mu \pi_d + \frac{\pi_d^a}{f_d} \frac{\alpha_s}{16\pi} d_{abc} G^b_{\mu\nu} \tilde{G}^{c\mu\nu}$$



dominates production



dominates decay

The low-energy observable spectrum

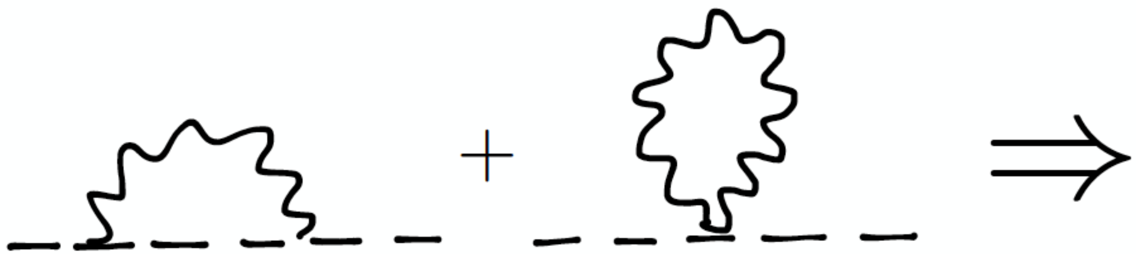
a) for small Yukawa couplings in the prime sector:

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

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

- 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



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

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

The low-energy observable spectrum

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QCD-colored "pions"

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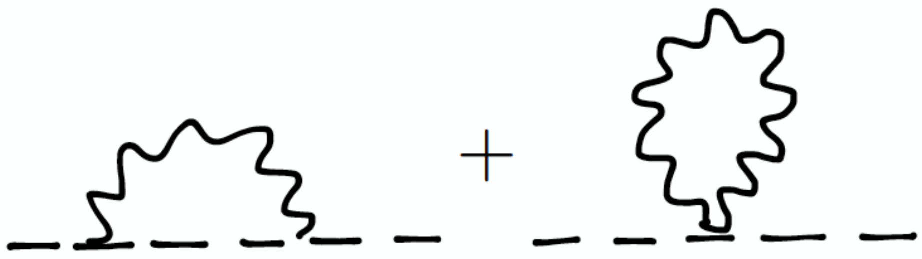


$$\Rightarrow$$

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

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

The η' Pseudoscalars

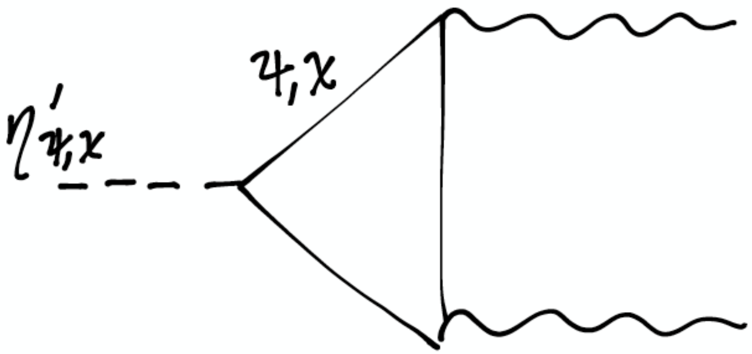
- The associated currents of the QCD singlets are:

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

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

- $t^9 = \frac{1}{\sqrt{6}}\mathbf{1}_{3\times3}$
- f_d is the pGB scale:

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



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

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

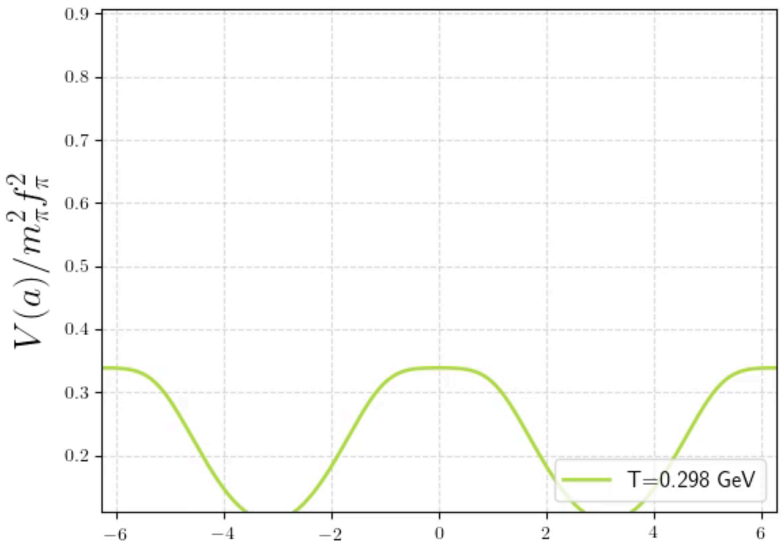
A crucial fact:

at high T, the potential minimum shifts from 0 to π

* Mirror worlds need to be colder than SM world:

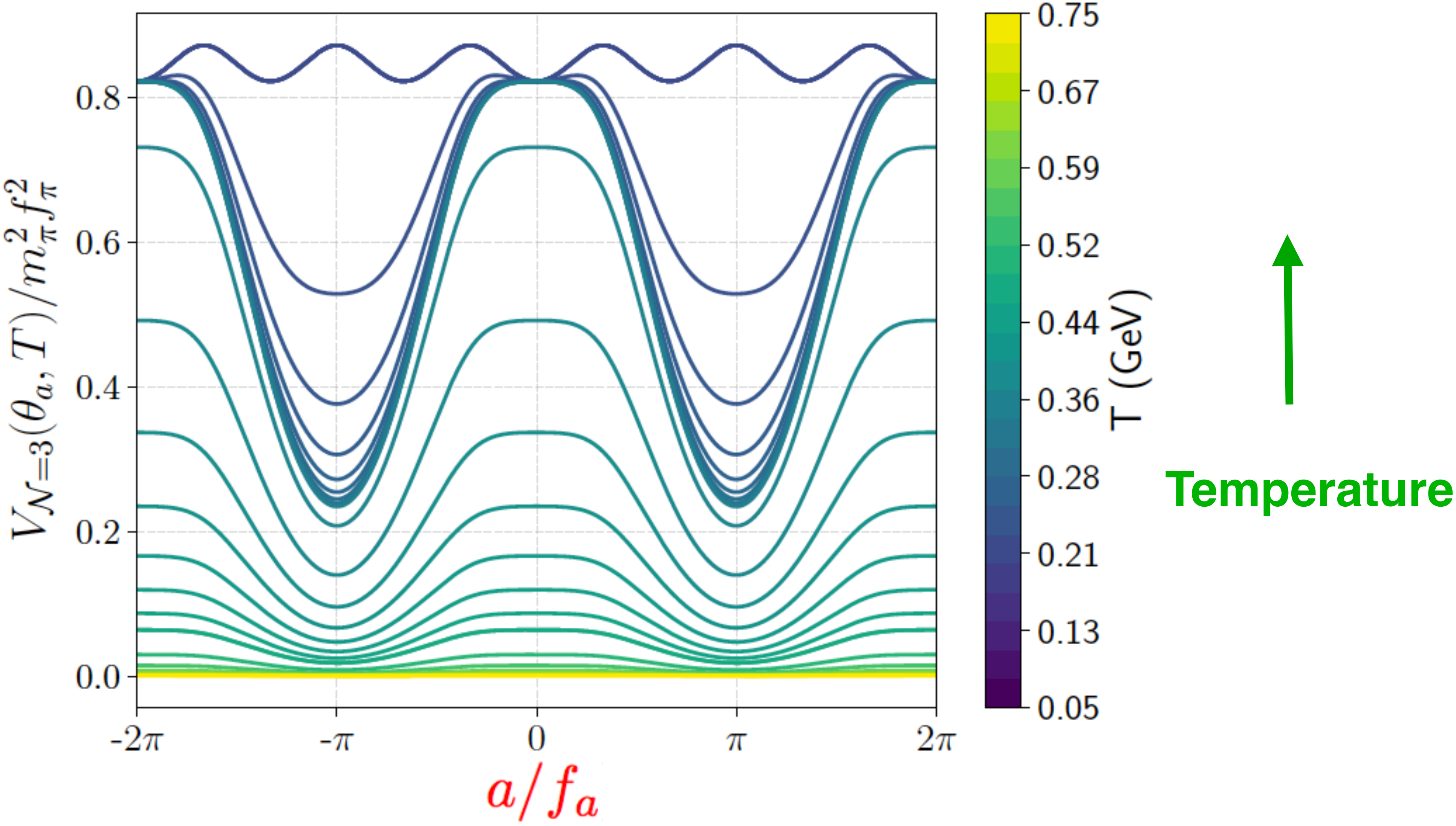
$$\text{BBN: } N_{\text{eff}} = 2.89 \pm 0.57\,, \qquad \text{CMB: } N_{\text{eff}} = 2.99^{+0.34}_{-0.33}\,. \qquad \frac{T'}{T} < \frac{0.51}{(\mathcal{N}-1)^{1/4}}$$

—> SM temperature effects break explicitly Z_N



$$V_{\mathcal{N}}\left(\frac{a}{f_a}\right) \simeq -V_{SM}\left(\frac{a}{f_a}\right)$$

At high T, the potential minimum shifts from 0 to π



The axion gets trapped in π : Trapped Misalignment

di Luzio, Quilez, Ringwald, BG arXiv 2102.01082

Trapped misalignment: a pure temperature effect

* At high temperatures, the axion is trapped in the wrong minimum

* The onset of oscillations is delayed

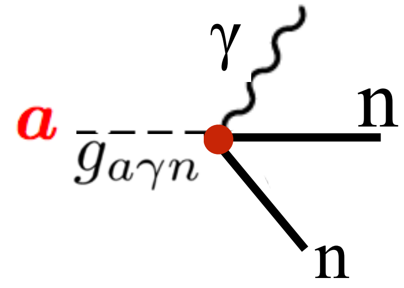
* Less dilution = more DM

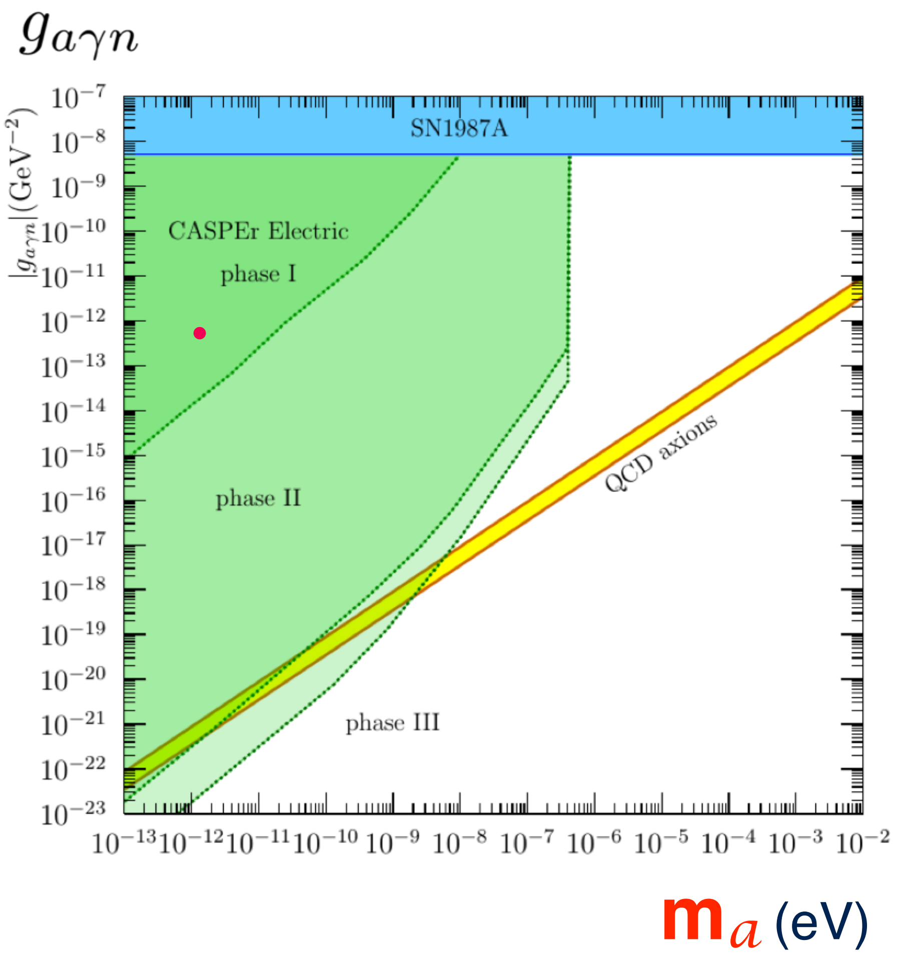
* After trapping, the axion can have enough kinetic energy to overfly many times the barrier—> further dilution: **trapped +kinetic** mislaign.

The Z_N axion can explain DM *and* solve the strong CP (with 1/N probab.)

di Luzio, Quilez, Ringwald, BG arXiv 2102.01082

Could Casper Phase I detect an axion ?





Canonical QCD axion:

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi} G\tilde{G}$$

$$\delta\mathcal{L} \equiv -\frac{i}{2}\frac{0.011\, e}{m_n}\frac{a}{f_a}\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}$$

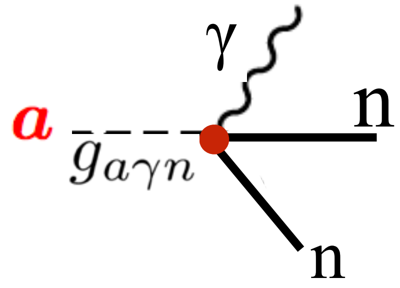
$$\equiv g_{a\gamma n}$$

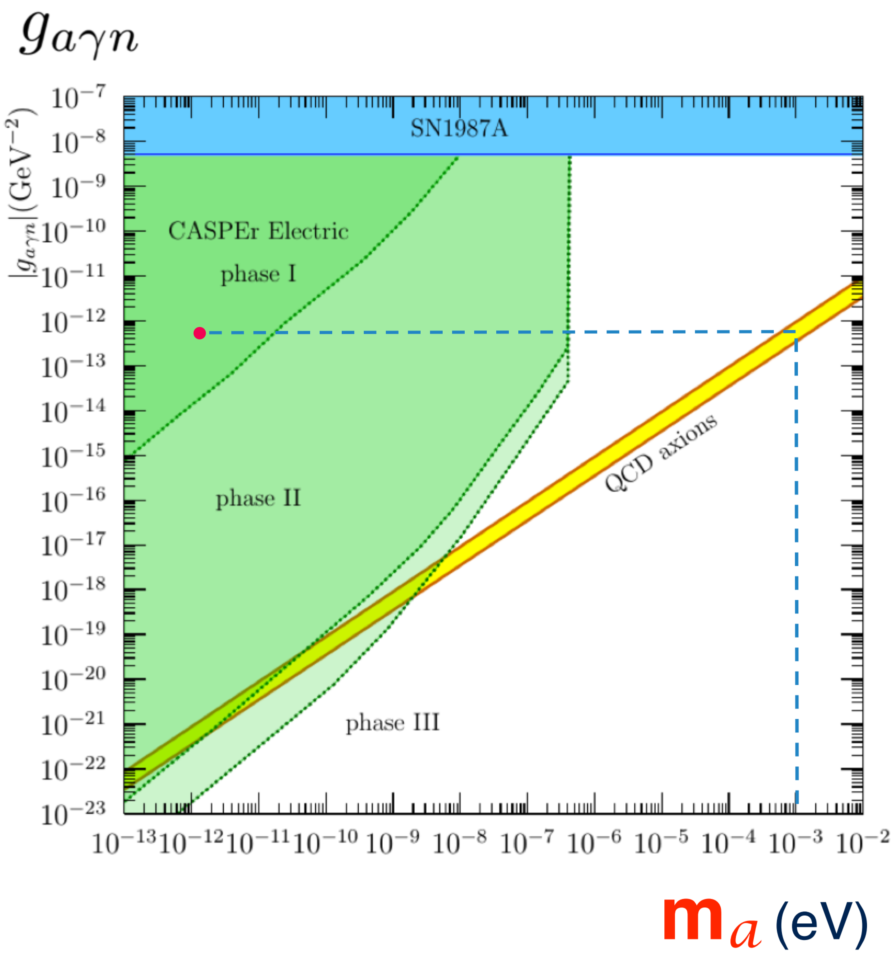
$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u + m_d)^2}$$

Coupling to the nEDM

Axion mass

Could Casper Phase I detect an axion ?





Canonical QCD axion:

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G}$$

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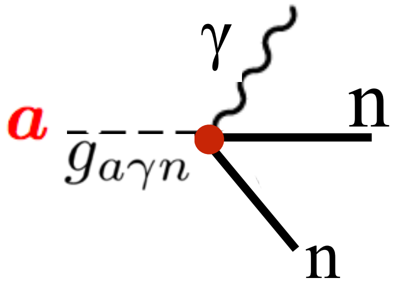

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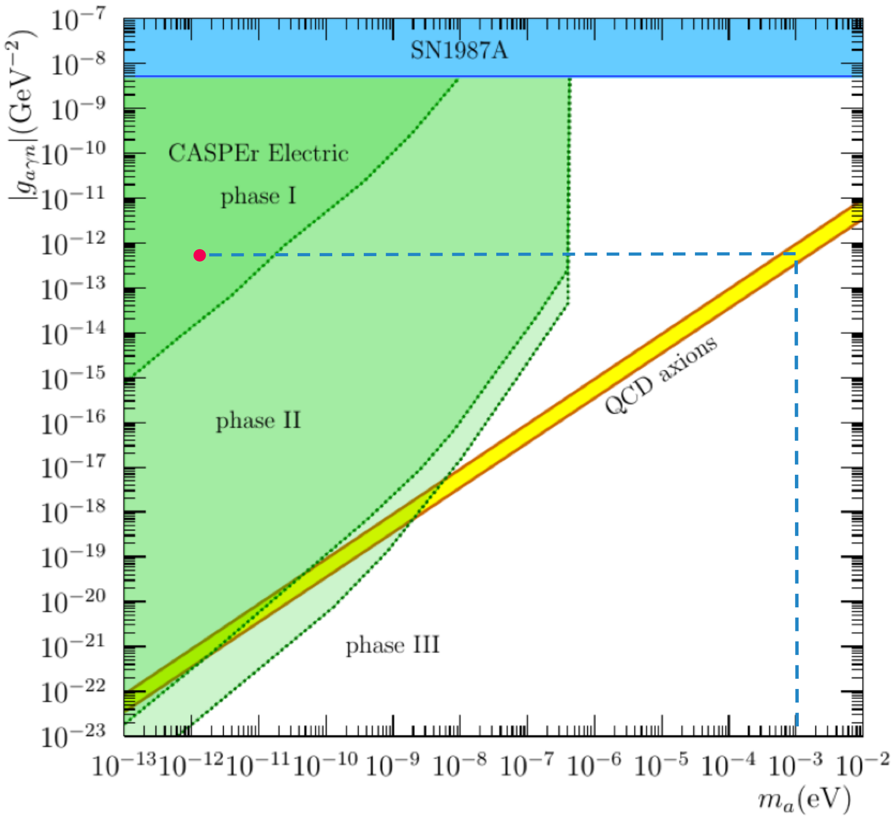

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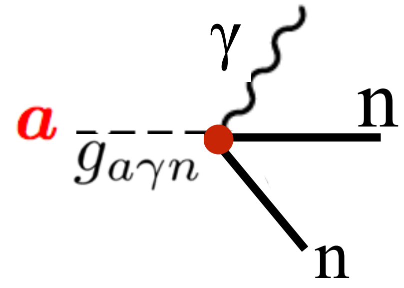
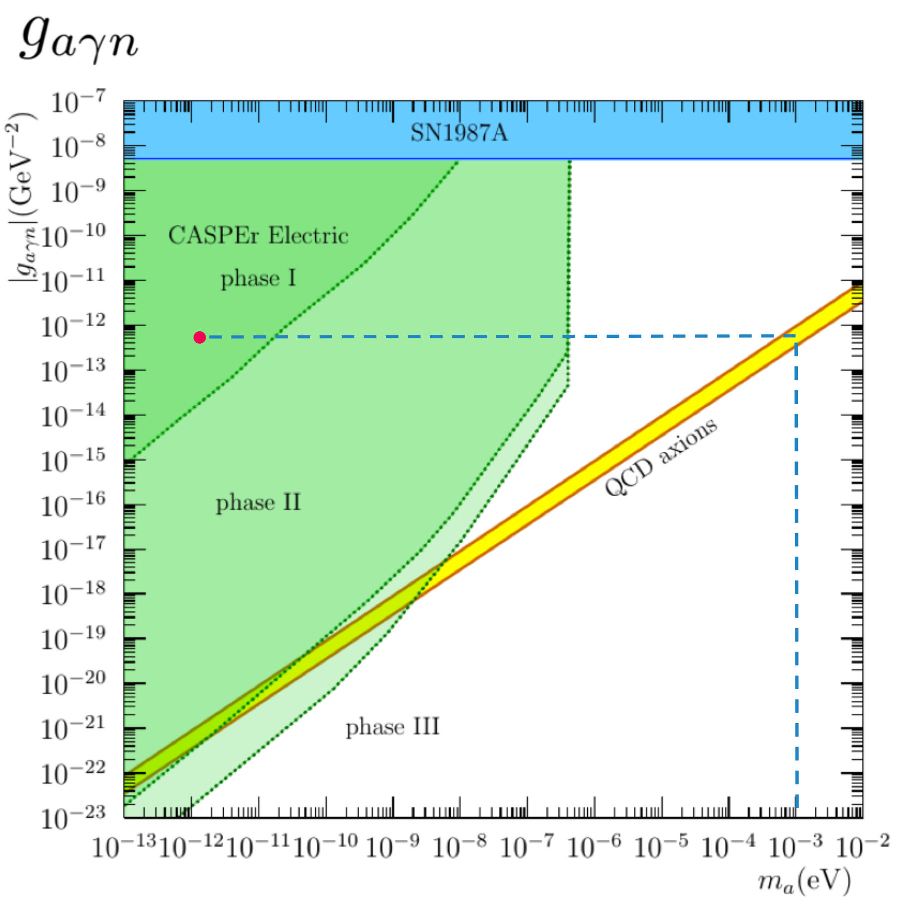
Coupling to the nEDM

Axion mass

No signal possible from a canonical QCD axion

Could Casper Phase I detect an axion ?





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Coupling to the nEDM

Axion mass

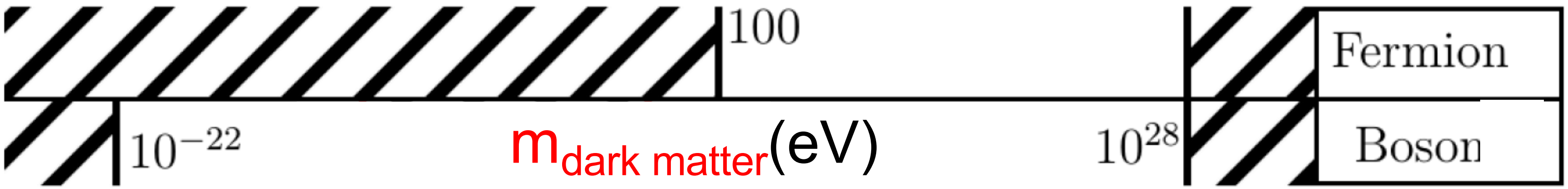
No signal possible from a canonical QCD axion

Signal possible from a Z_N axion

85% of matter is dark

what is it?

Is it a new type of particle? **what mass?**

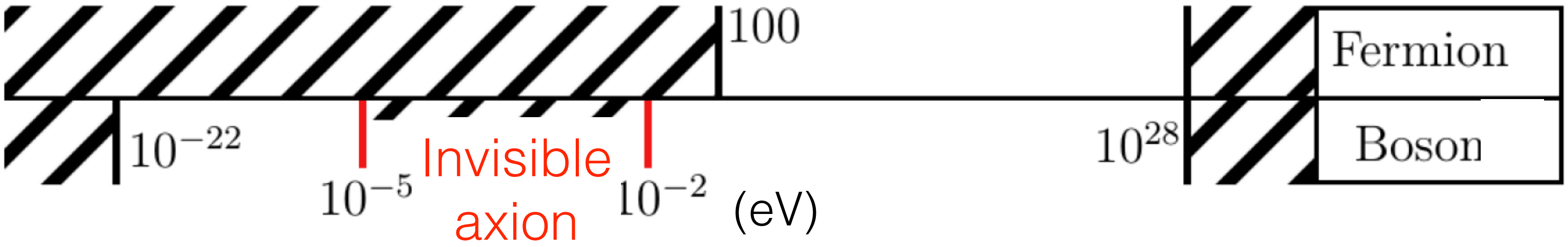


Does it feel anything else than gravity?

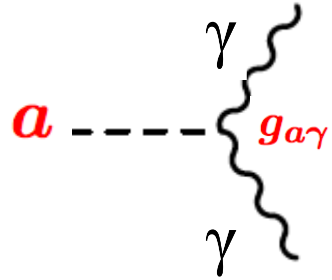
85% of matter is dark

what is it?

Is it a new type of particle? **what mass?**

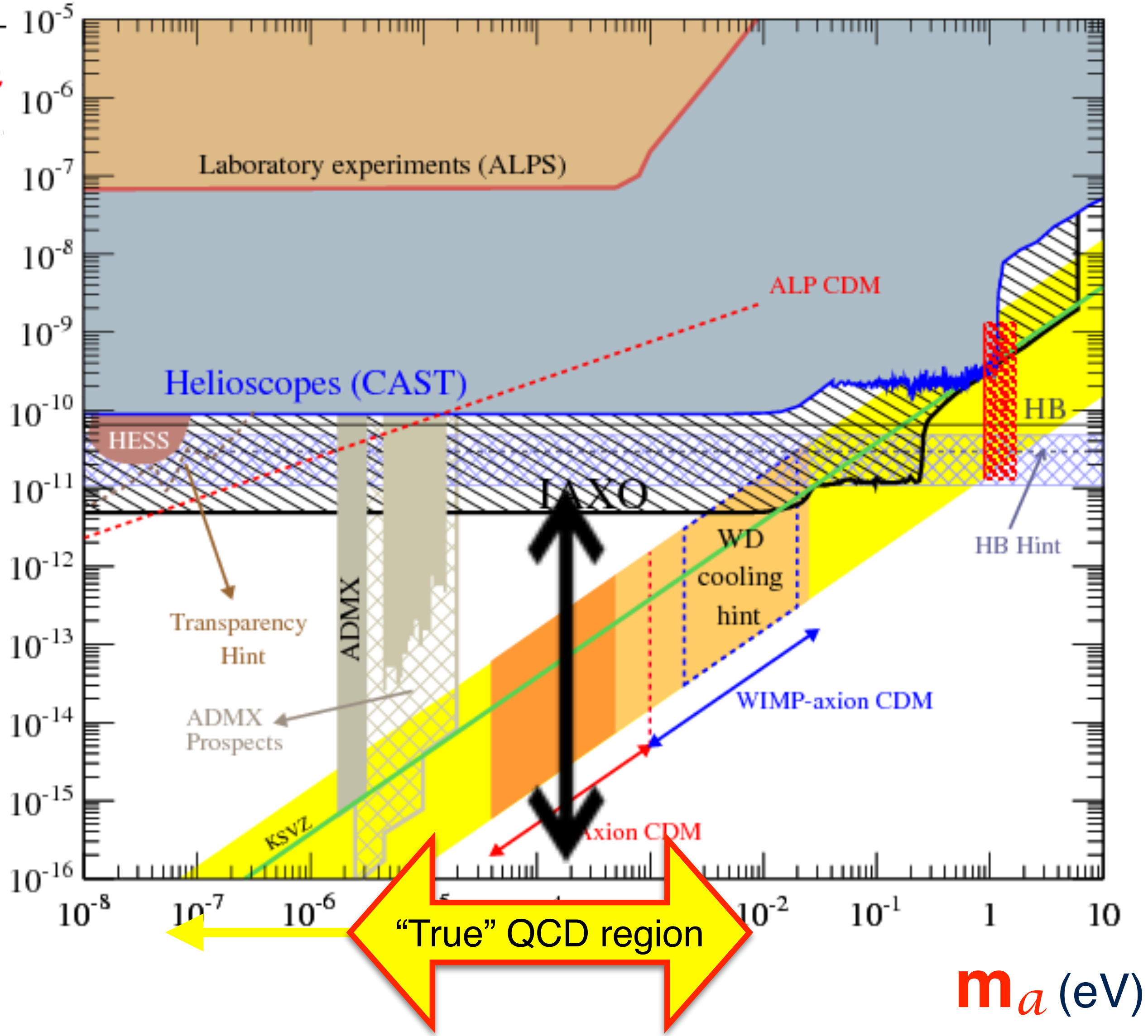


Intensely looked for experimentally…



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

(GeV-1)



[Farina et al, 17]
[Craig et al, 18]
[Di Luzio+Nardi et al, 17]

… and theoretically

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

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

Experiment: new experiments and new detection ideas

e.g. in Haloscopes

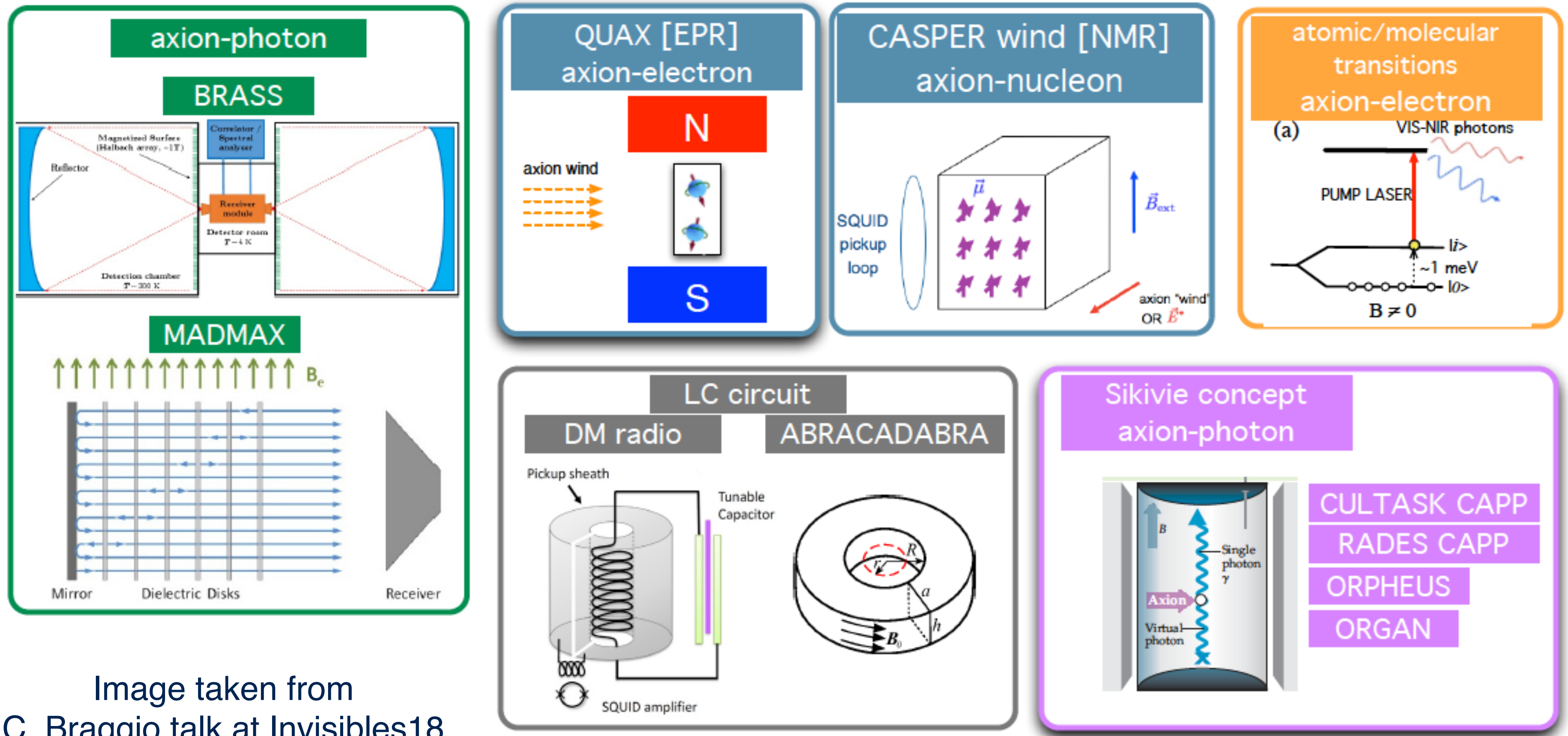
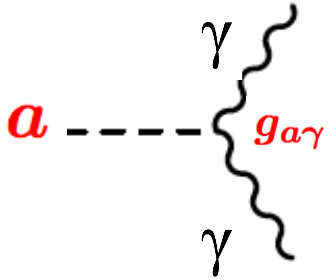


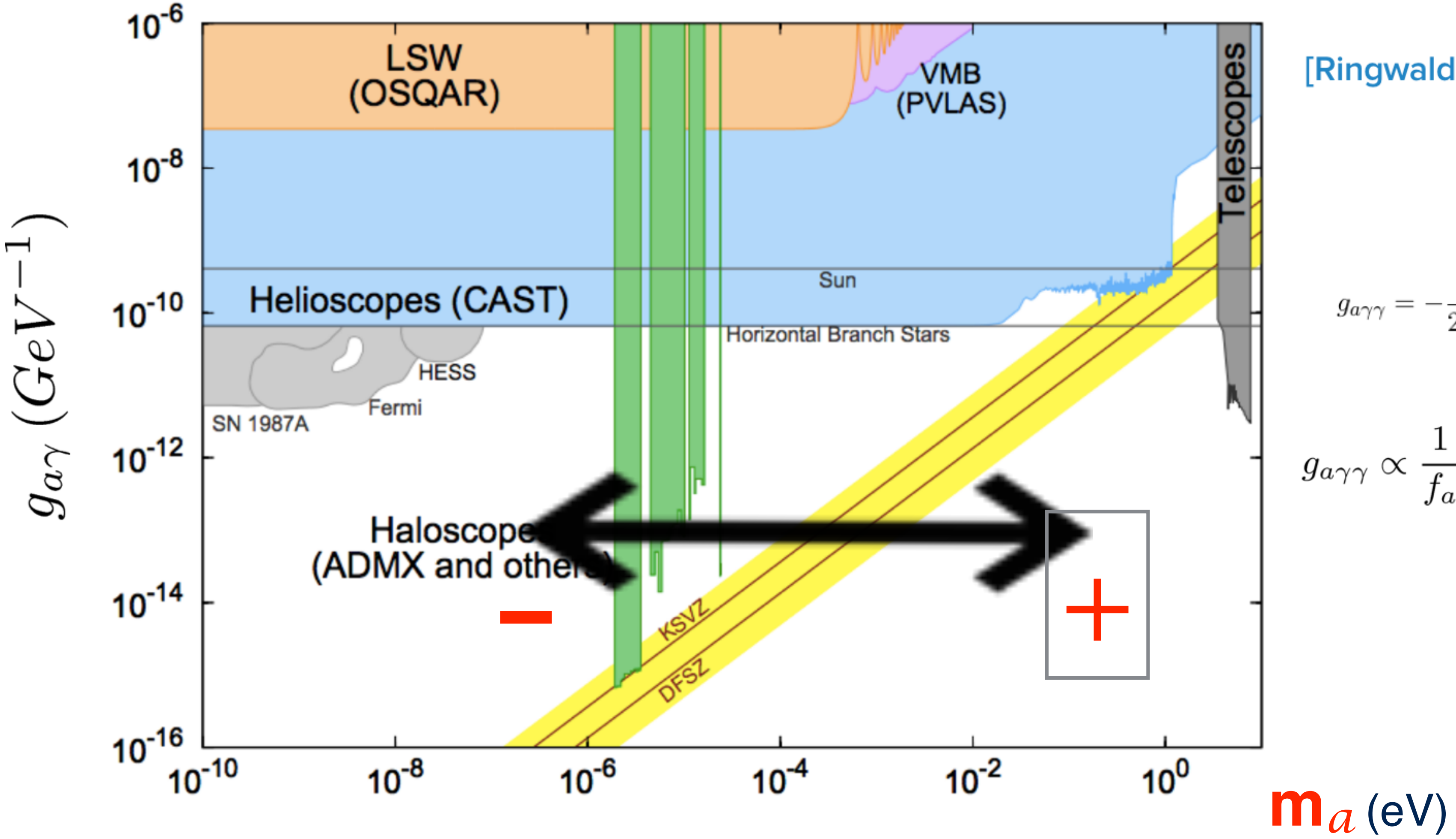
Image taken from
C. Braggio talk at Invisibles18

plus LHC !

Intensely looked for experimentally…

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





[Ringwald, PDG 17]

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - 1.92(4)\right)$$

$$g_{a\gamma\gamma} \propto \frac{1}{f_a} \quad \Longrightarrow \quad g_{a\gamma\gamma} \propto m_a$$

… and theoretically