Unconventional axions and ALPs

BLV2022

Brussels Sept. 5-8 2022

Belén Gavela
Univ. Autónoma de Madrid and IFT

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

Why ?

Many small unexplained SM parameters

Hidden symmetries
can explain small parameters

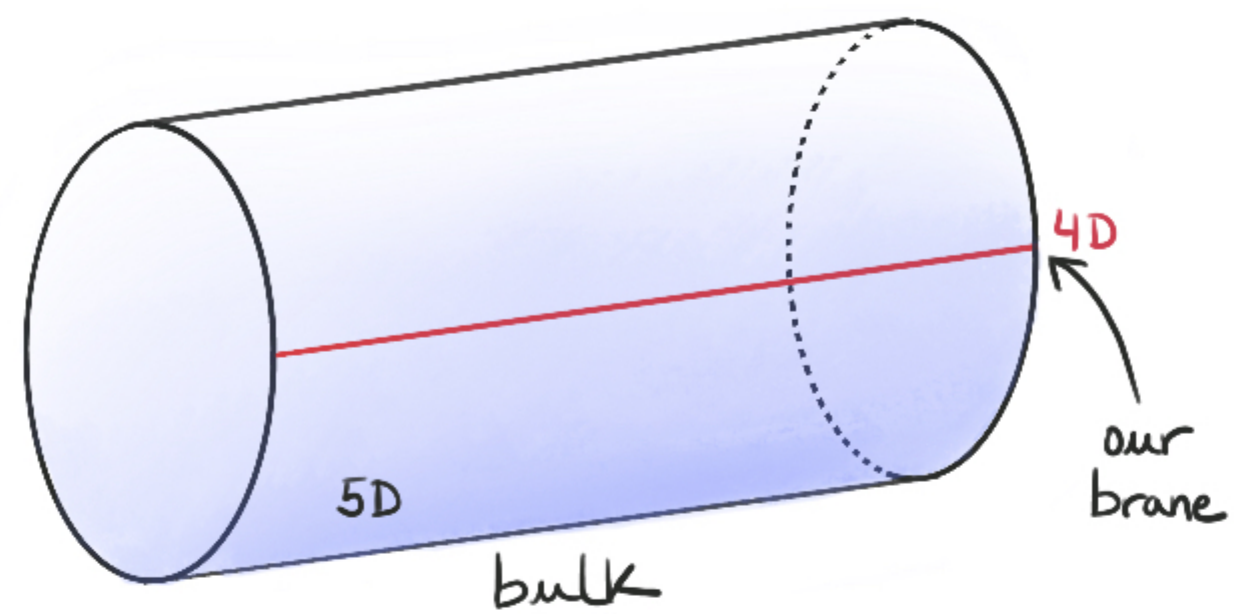
↓

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)

……

Outline

After some intro on axions and ALPs…

some work since pandemic started:

1) Lighter-than-usual true axions (i.e. which solve the QCD strong CP problem) (2021)

2) Degenerate axions and ALPs <——> Discrete GBs (2022)

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?

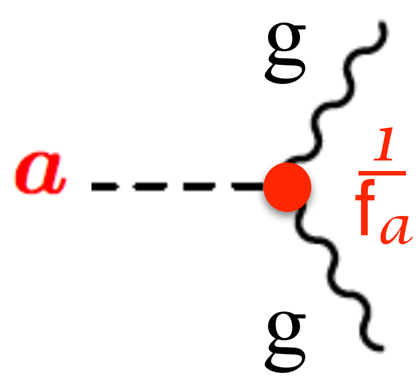
$$\bar{\theta} \leq 10^{-10}$$

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

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

A dynamical $U(1)_A$ solution ?

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



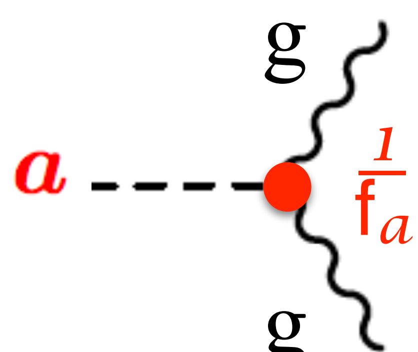
$$\mathcal{L}_{QCD} \supset \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

A dynamical $U(1)_A$ solution

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

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

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

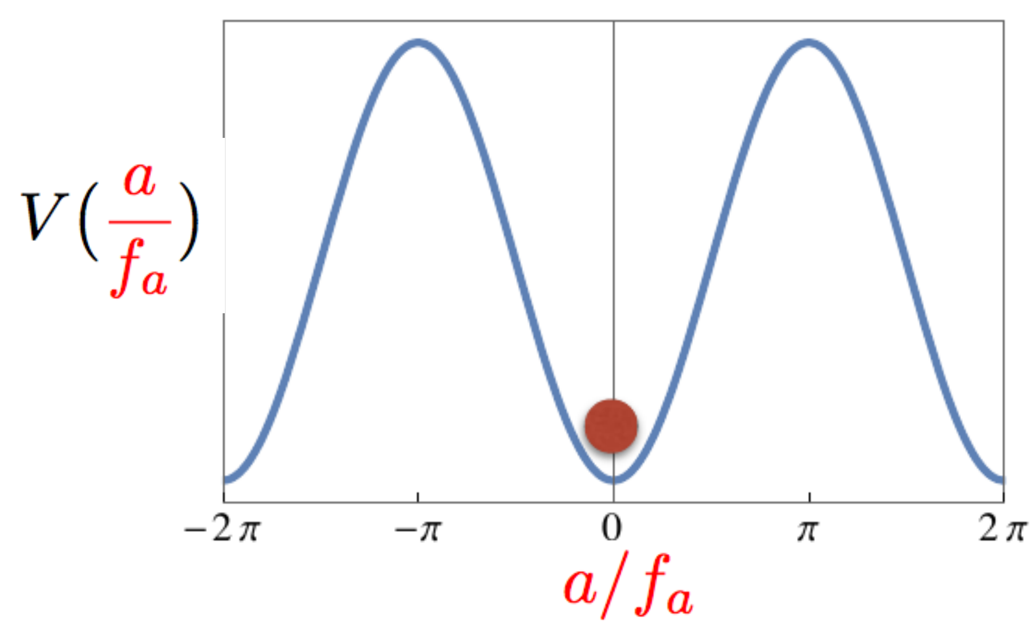


$$\mathcal{L}_{QCD} \supset \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

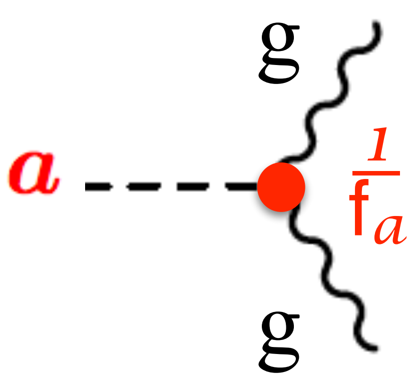
A dynamical $U(1)_A$ solution

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

It is a **pGB**:



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

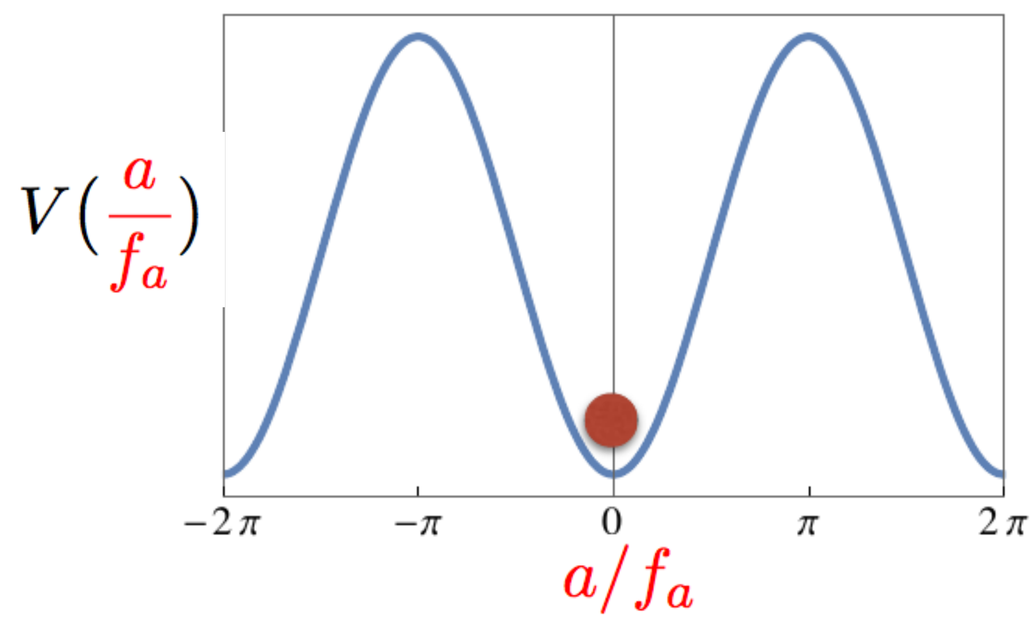


$$\mathcal{L}_{QCD} \supset \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

A dynamical $U(1)_A$ solution

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

It is a **pGB**:

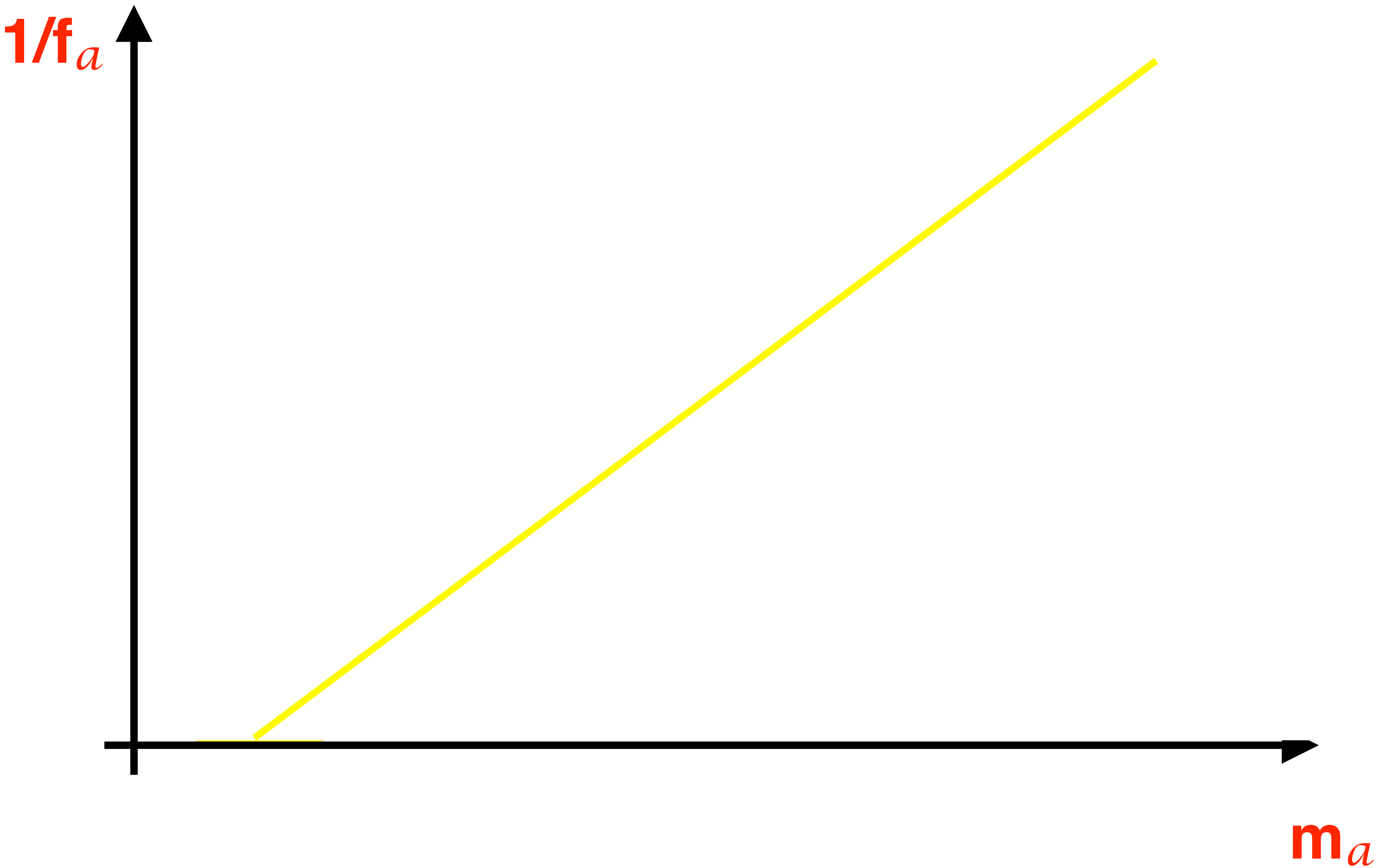


Excellent DM candidate

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

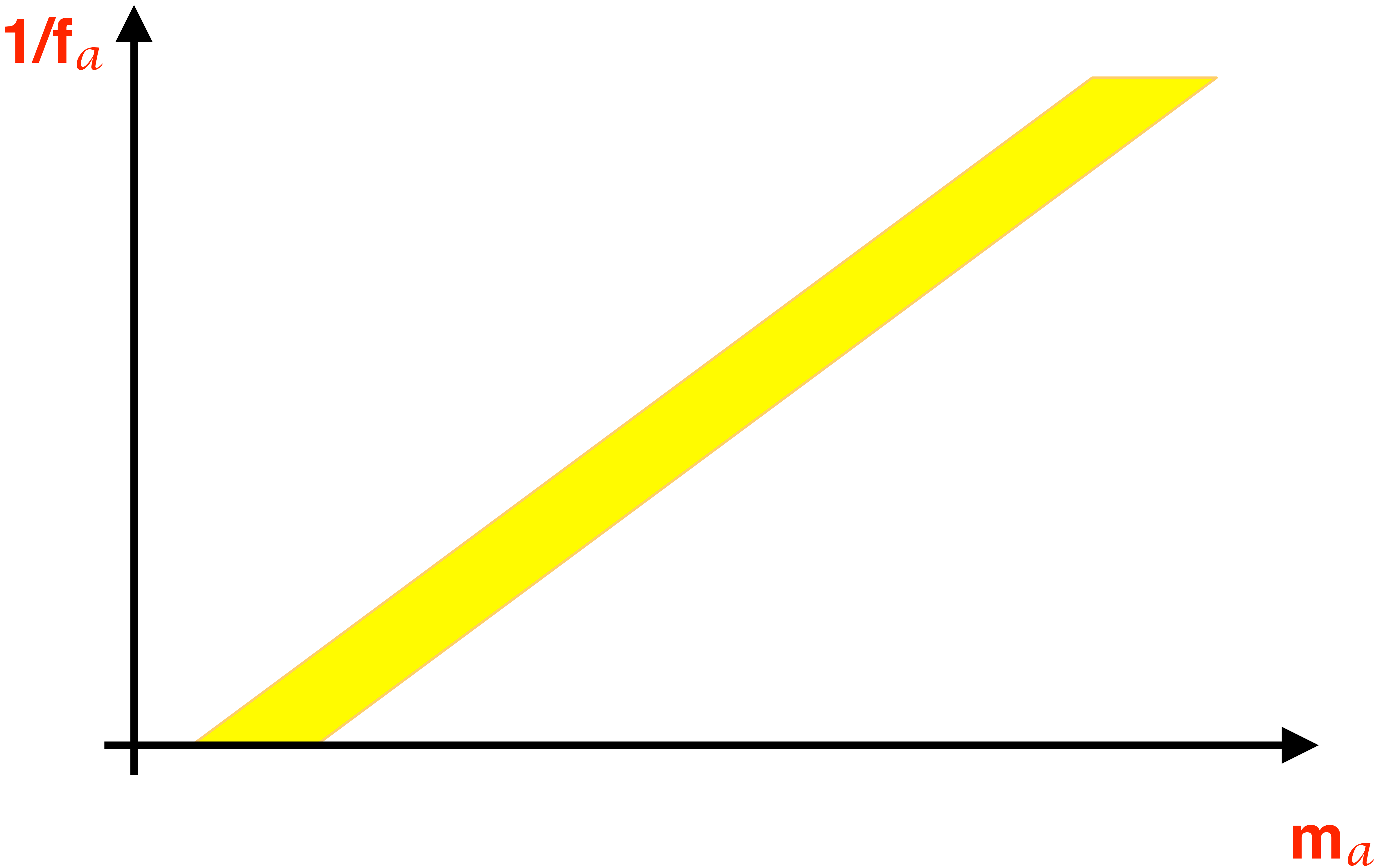
In "true axion" models (= which solve the strong CP problem):

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



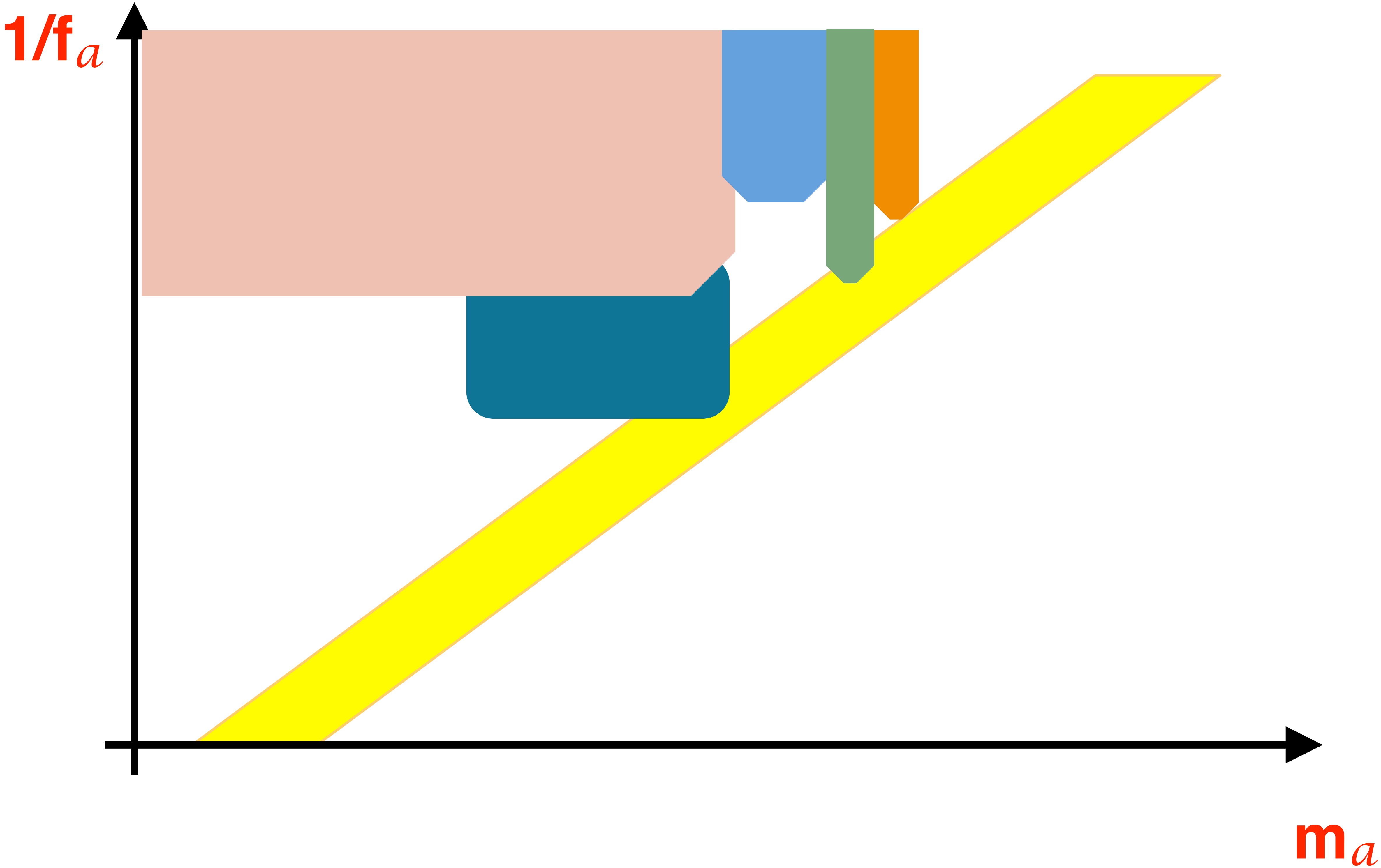
In “true axion” models (= which solve the strong CP problem):

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



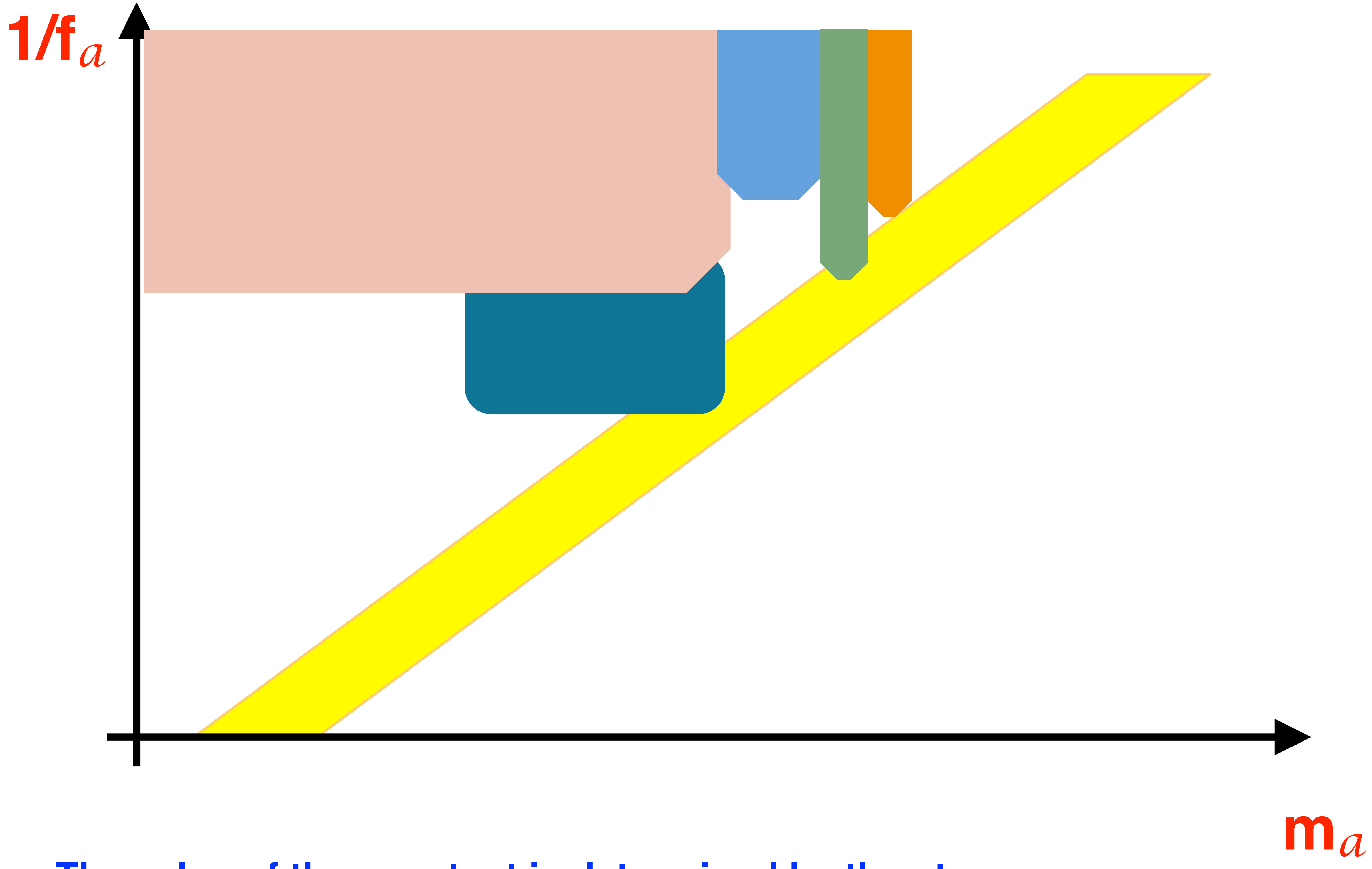
In “true axion” models (= which solve the strong CP problem):

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



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

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

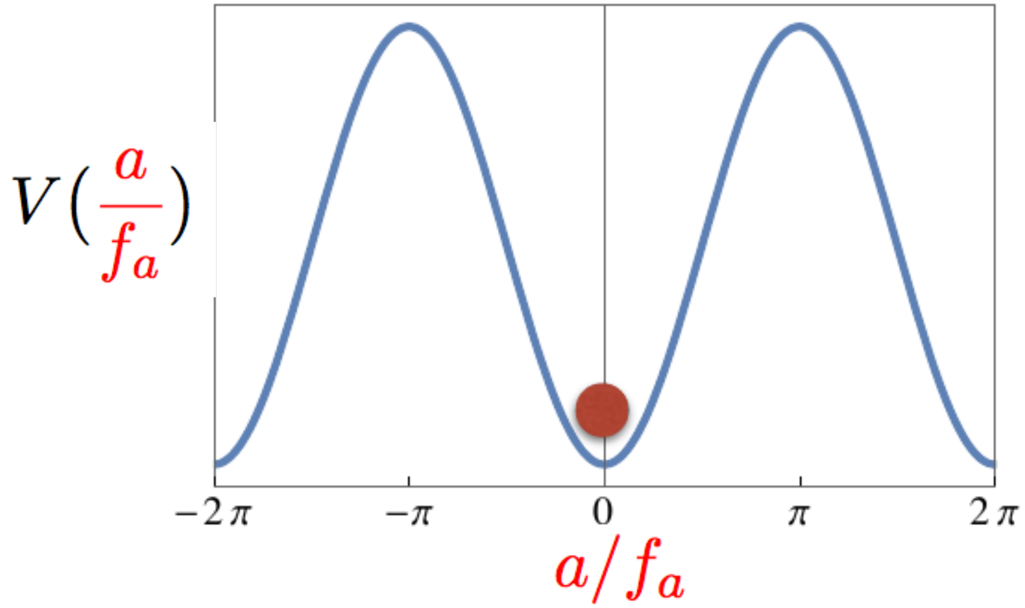


The value of the constant is determined by the strong gauge group

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

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

* If the confining group is QCD:



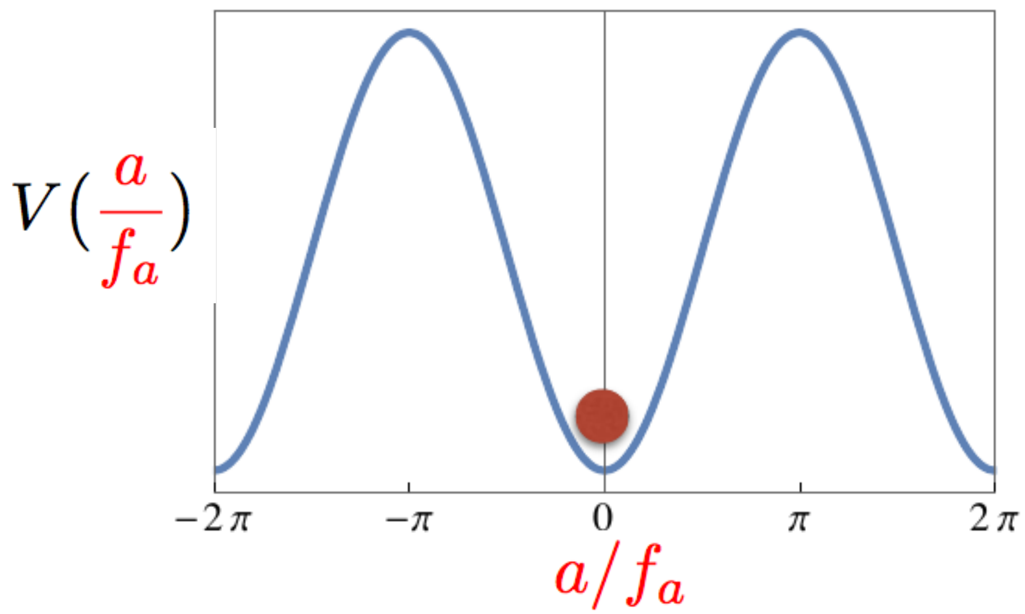
$\longleftarrow \quad \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$

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

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

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

* If the confining group is QCD:



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

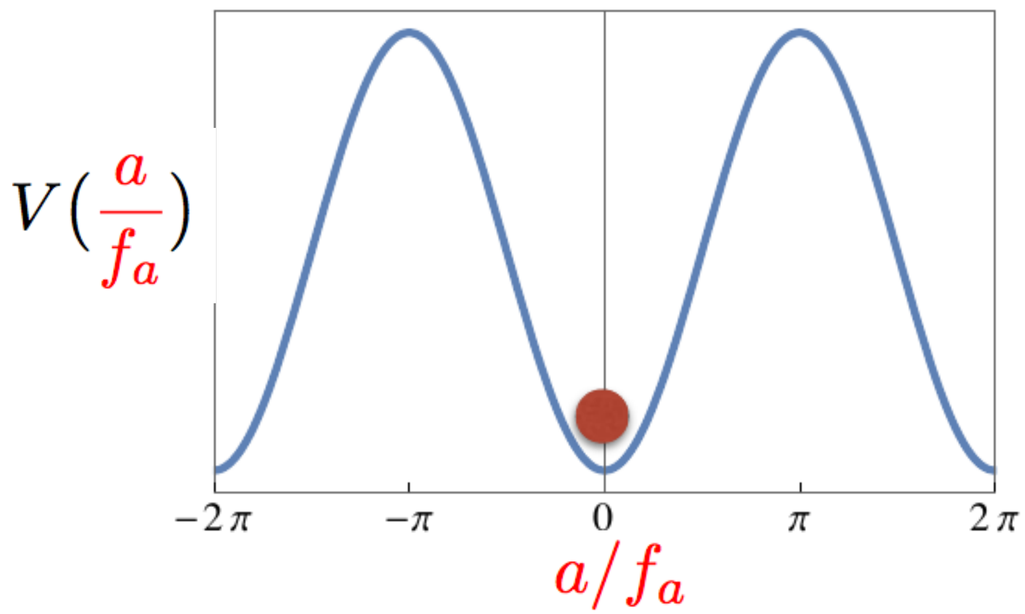
$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2}$$

canonical QCD axion

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

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

* If the confining group is QCD:



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

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

canonical QCD axion

How come the QCD axion mass is NOT ~Λ_{QCD}

Because two pseudo scalars couple to the QCD anomalous current :

N_{ps} : η'_{QCD} a_1

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

QCD

With only QCD:

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

–> "Invisible axion"

How come the QCD axion mass is NOT $\sim\Lambda_{QCD}$

Because two pseudo scalars couple to the QCD anomalous current :

N_{ps} : **η'_{QCD}** a_1

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

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

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

$$\mathbf{m}_a \mathbf{f}_a = \text{cte.}$$

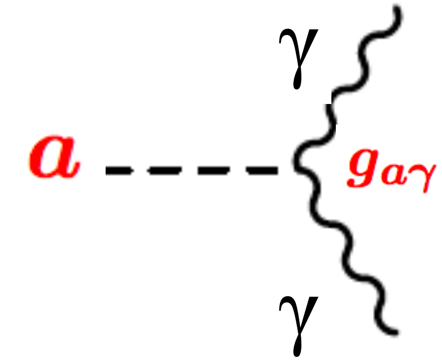
*** If the confining group is QCD:** $m_a^2 f_a^2 = m_\pi^2 f_\pi^2$

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

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

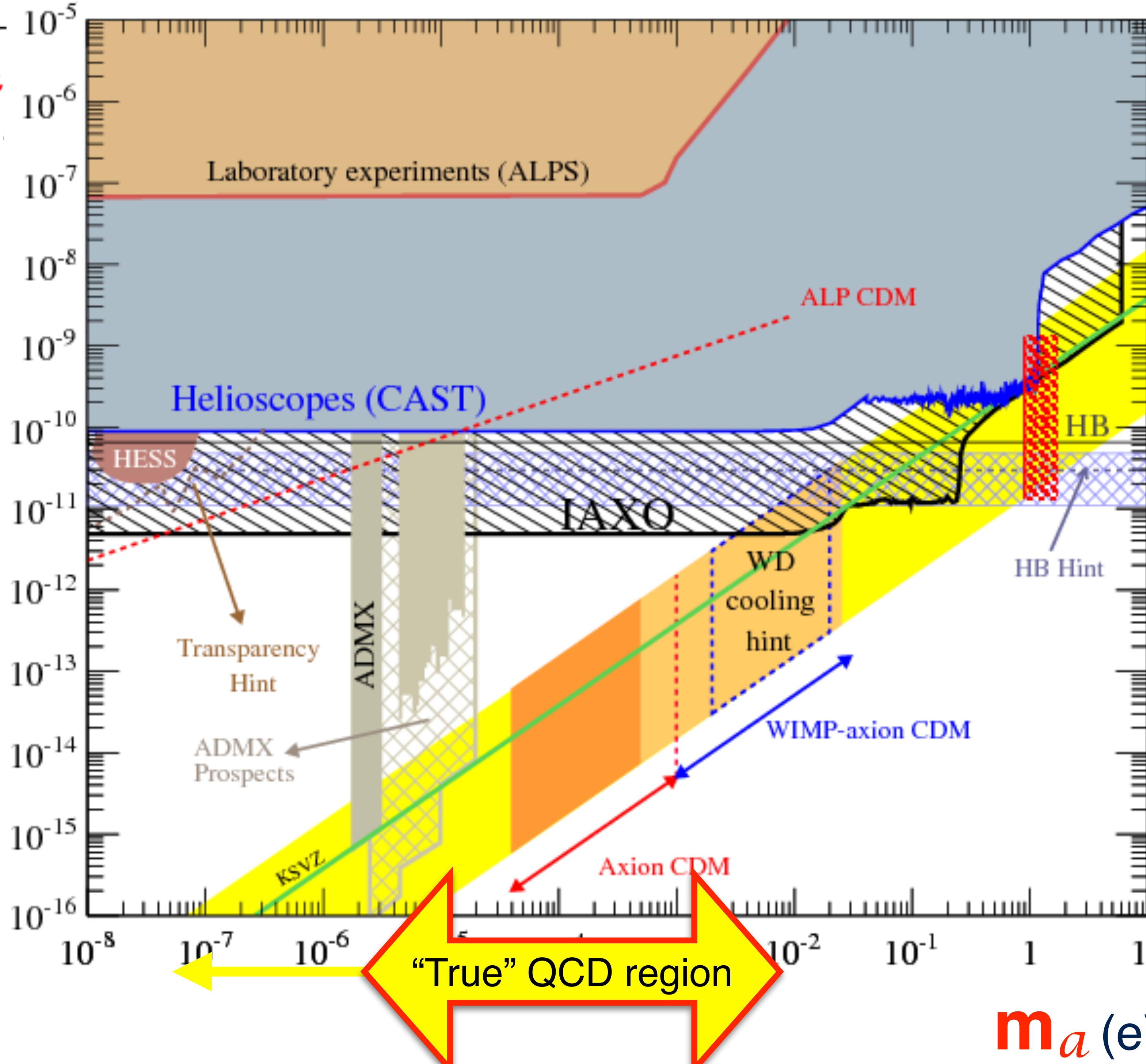
"Invisible axion"

Intensely looked for experimentally…



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

(GeV^{-1})



"True" QCD axion band

II

"Invisible axion"

e.g. KSVZ, DFSZ…

v<< f_a —>

EW hierarchy problem

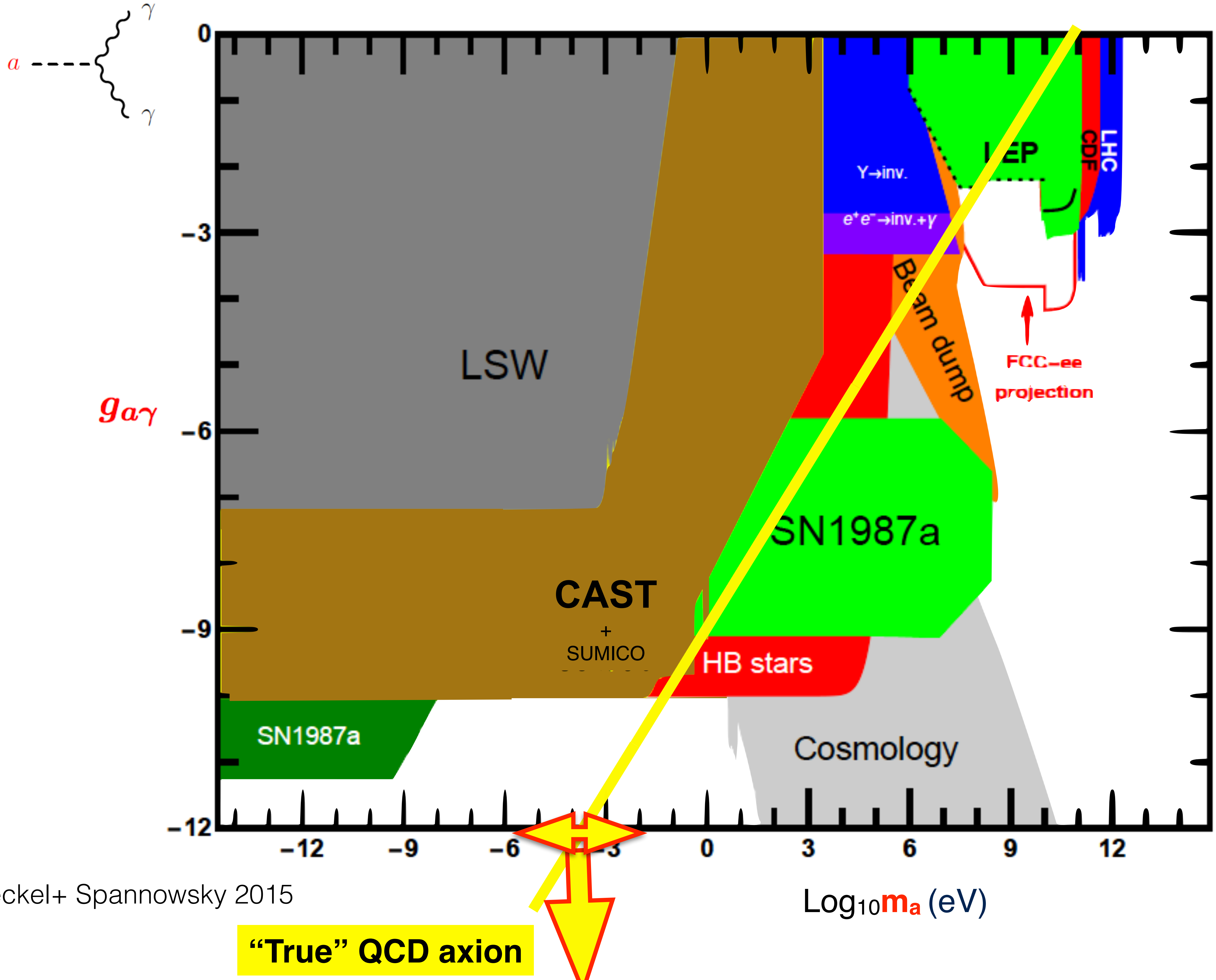
+ gravitational tunings ?

m_a (eV)

… and theoretically

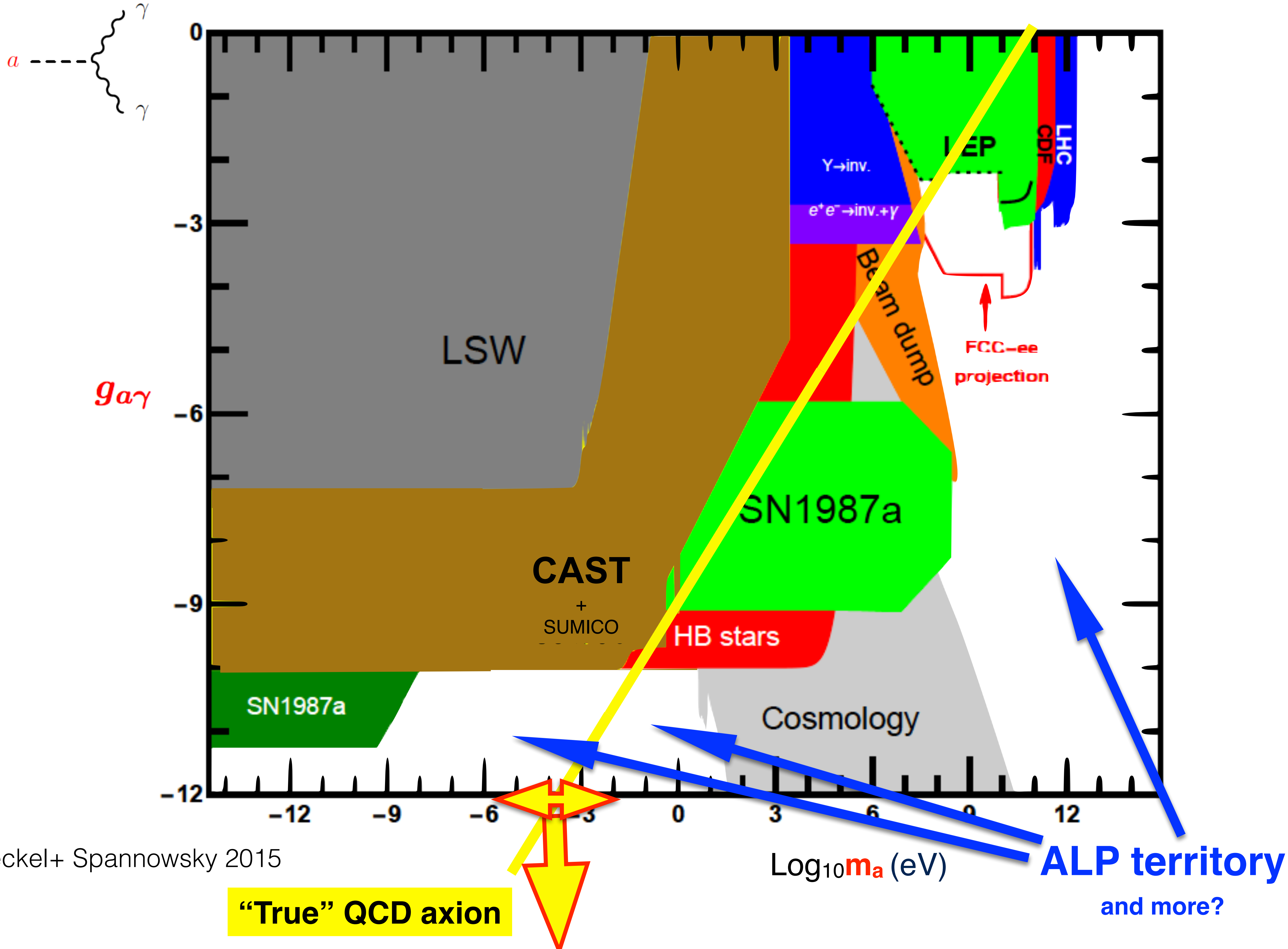
https://arxiv.org/pdf/1611.04652.pdf

ALPs (axion-like particles) territory



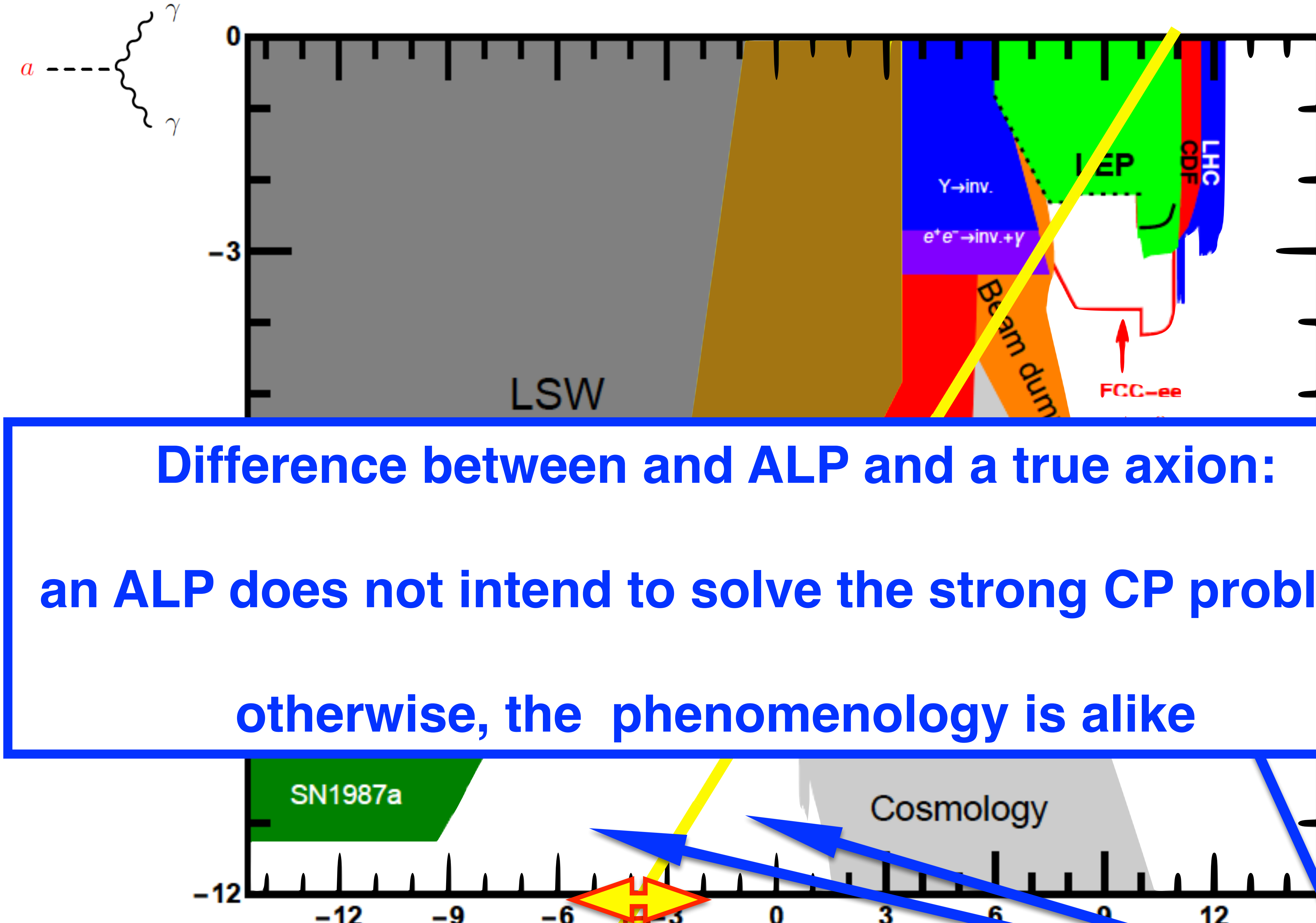
Jaeckel+ Spannowsky 2015

ALPs (axion-like particles) territory



Jaeckel+ Spannowsky 2015

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

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

ALP territory

and more?

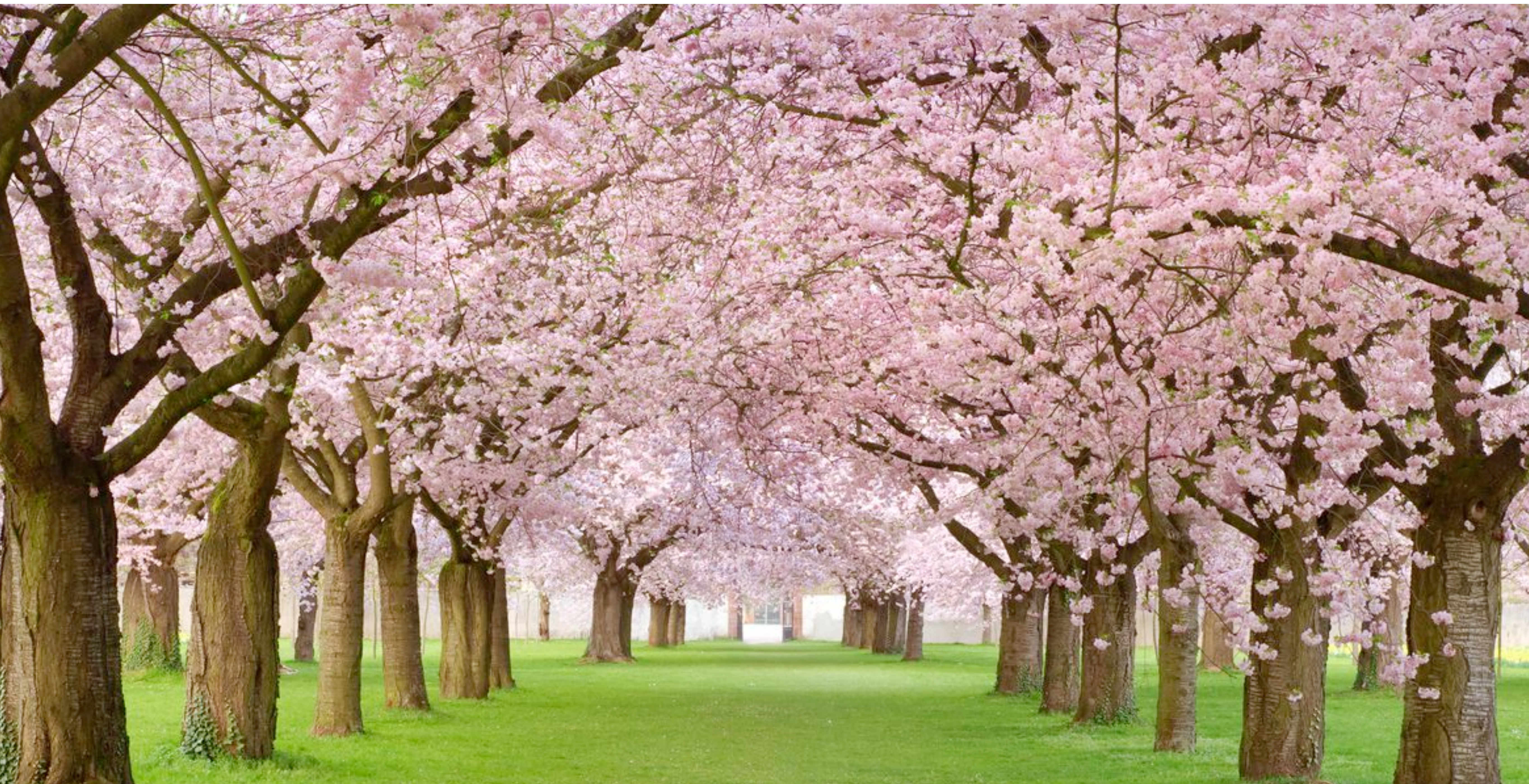
“True” QCD axion

The field of axions and ALPs is BLOOMING

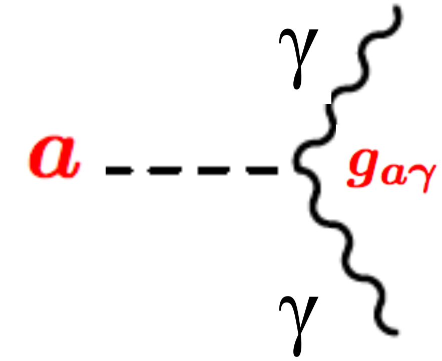
in Experiment … and Theory

The field of axions and ALPs is BLOOMING

in Experiment … and Theory

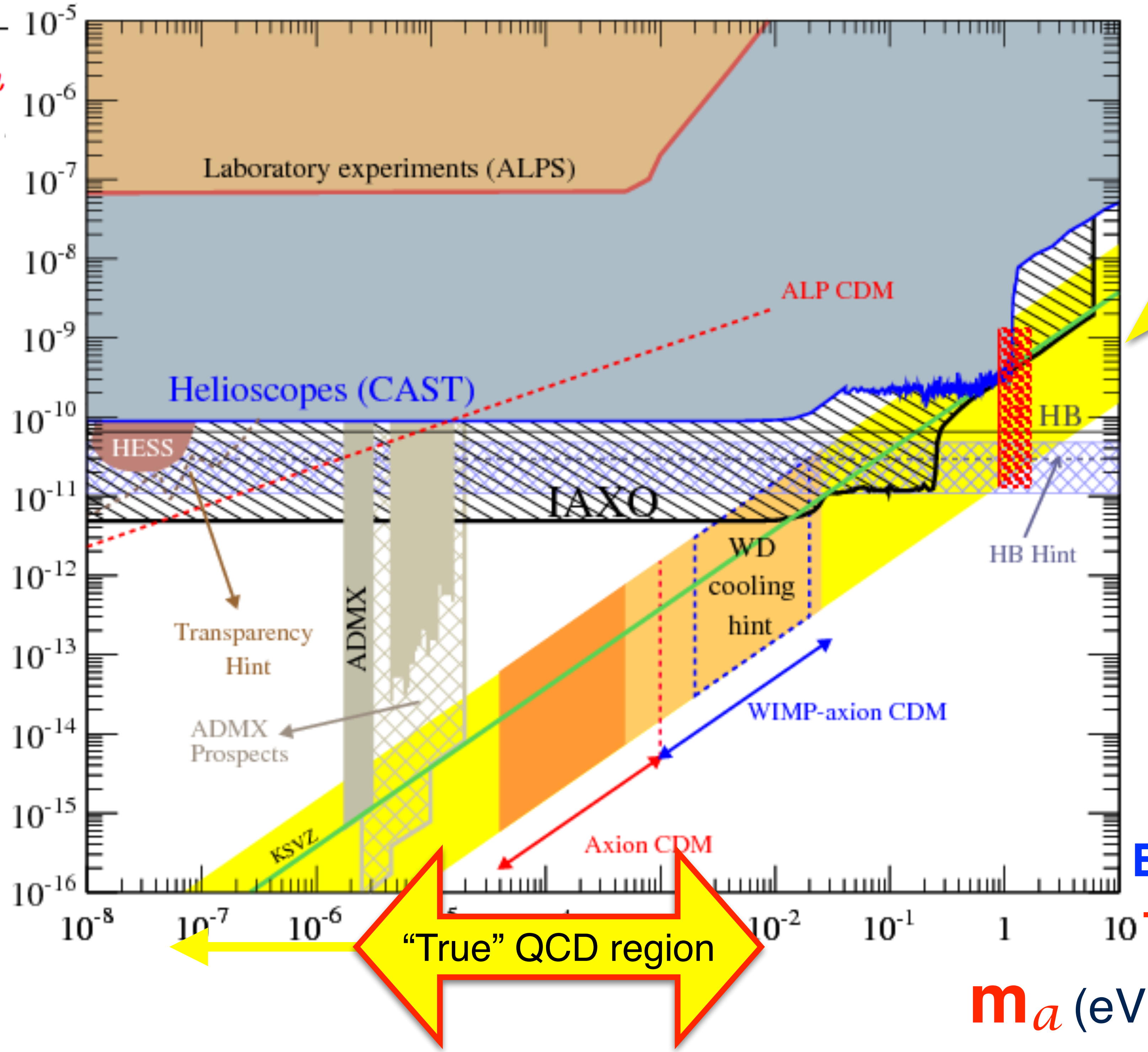


Intensely looked for experimentally…



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

(GeV-1)



"True" QCD axion band

||

"Invisible axion"
e.g. KSVZ, DFSZ…

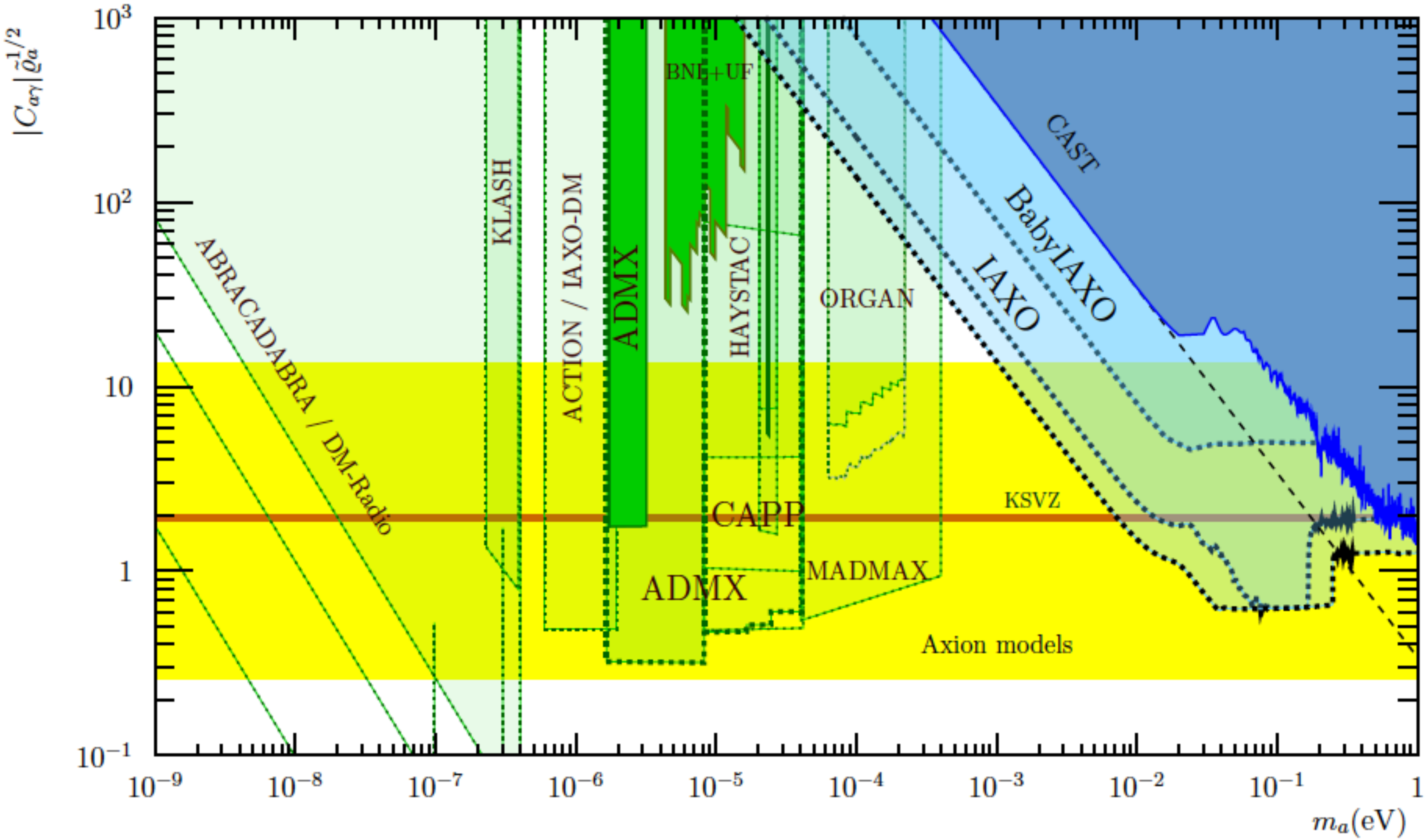
v<< f_a —>
EW hierarchy problem
+ gravitational tunings ?

m_a (eV)

… and theoretically

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

Advances on Haloscopes



Irastorza and Redondo, arXiv:1801.08127

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:

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

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 <u>confining group is larger than QCD</u>:**

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

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 <u>confining group is larger than QCD</u>:

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**

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

an old idea,
revived lately

[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]

… [Valenti, Vecchi, Xu, 2022]

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

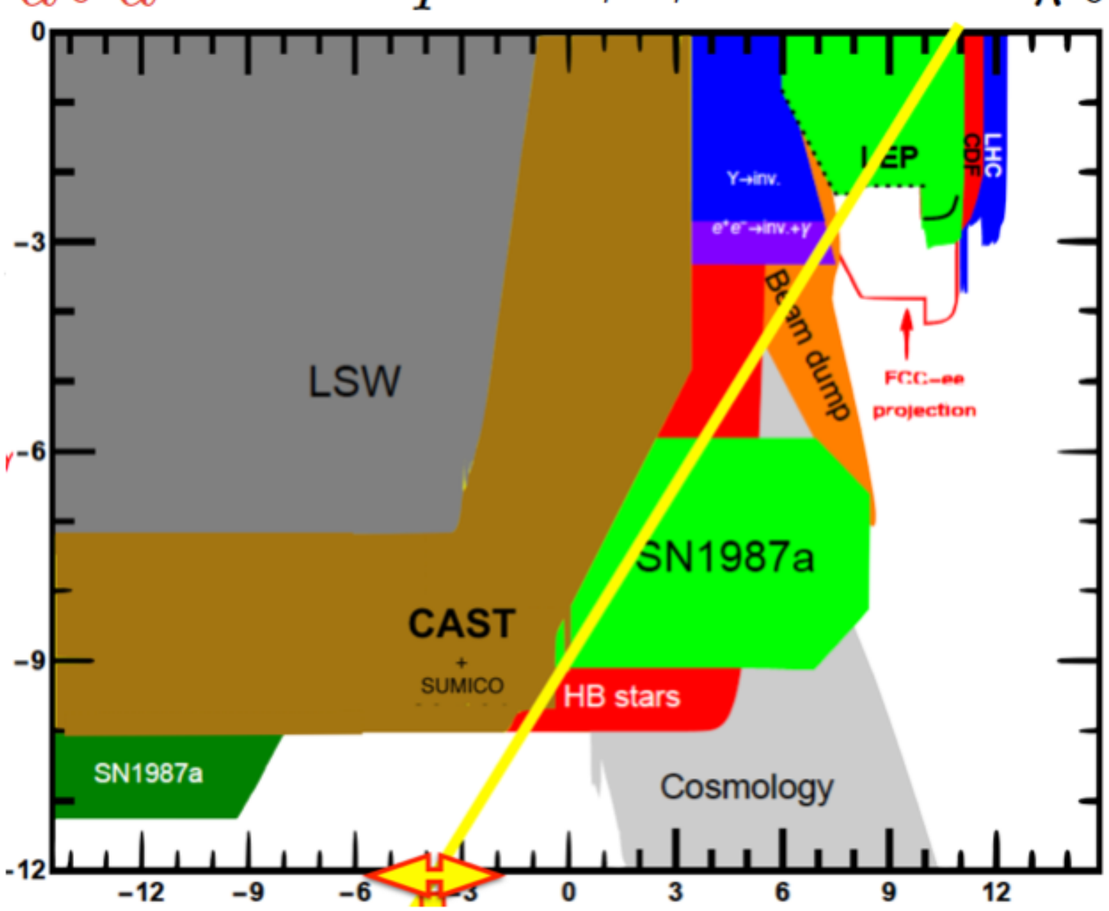
$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2 + \Lambda'^4 \qquad \Lambda' \gg \Lambda_{\rm QCD}$$

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

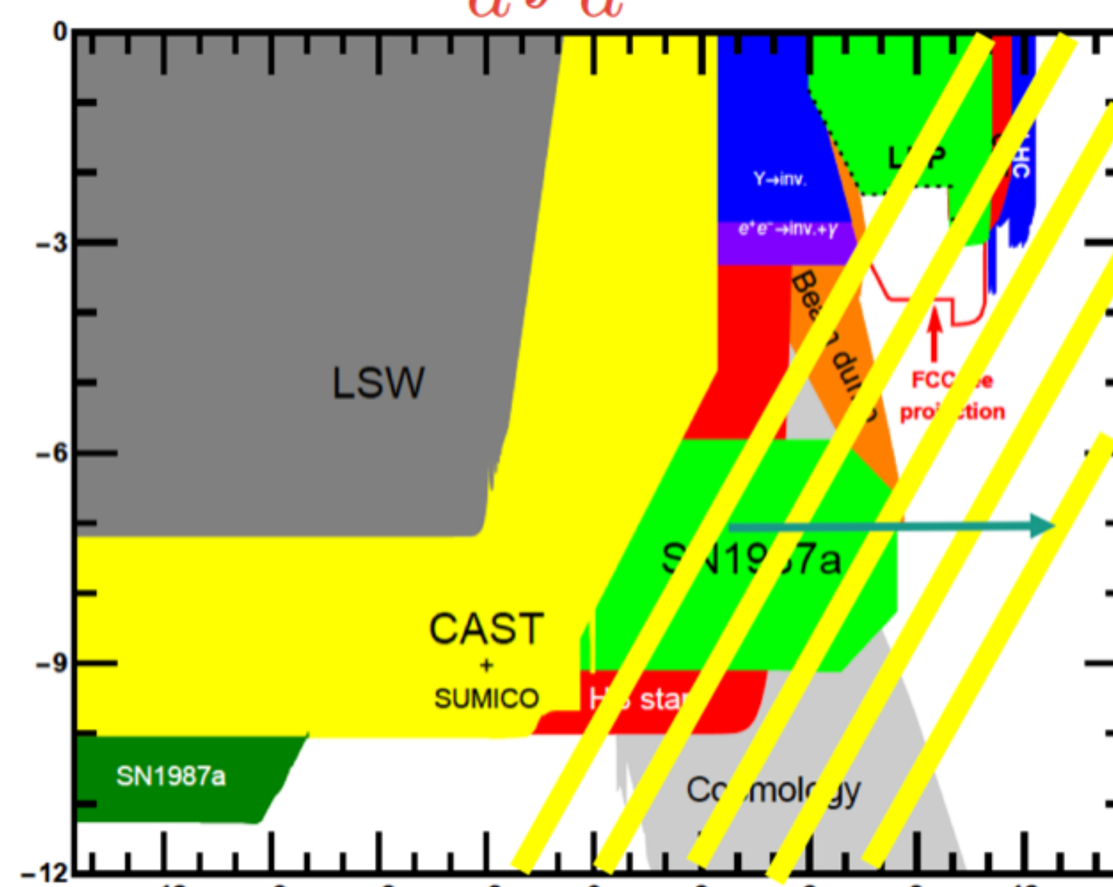
QCD: $\Lambda = \Lambda_{\rm QCD}$

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

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



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



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

With only QCD:

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

–> "Invisible axion"

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

QCD

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"

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

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

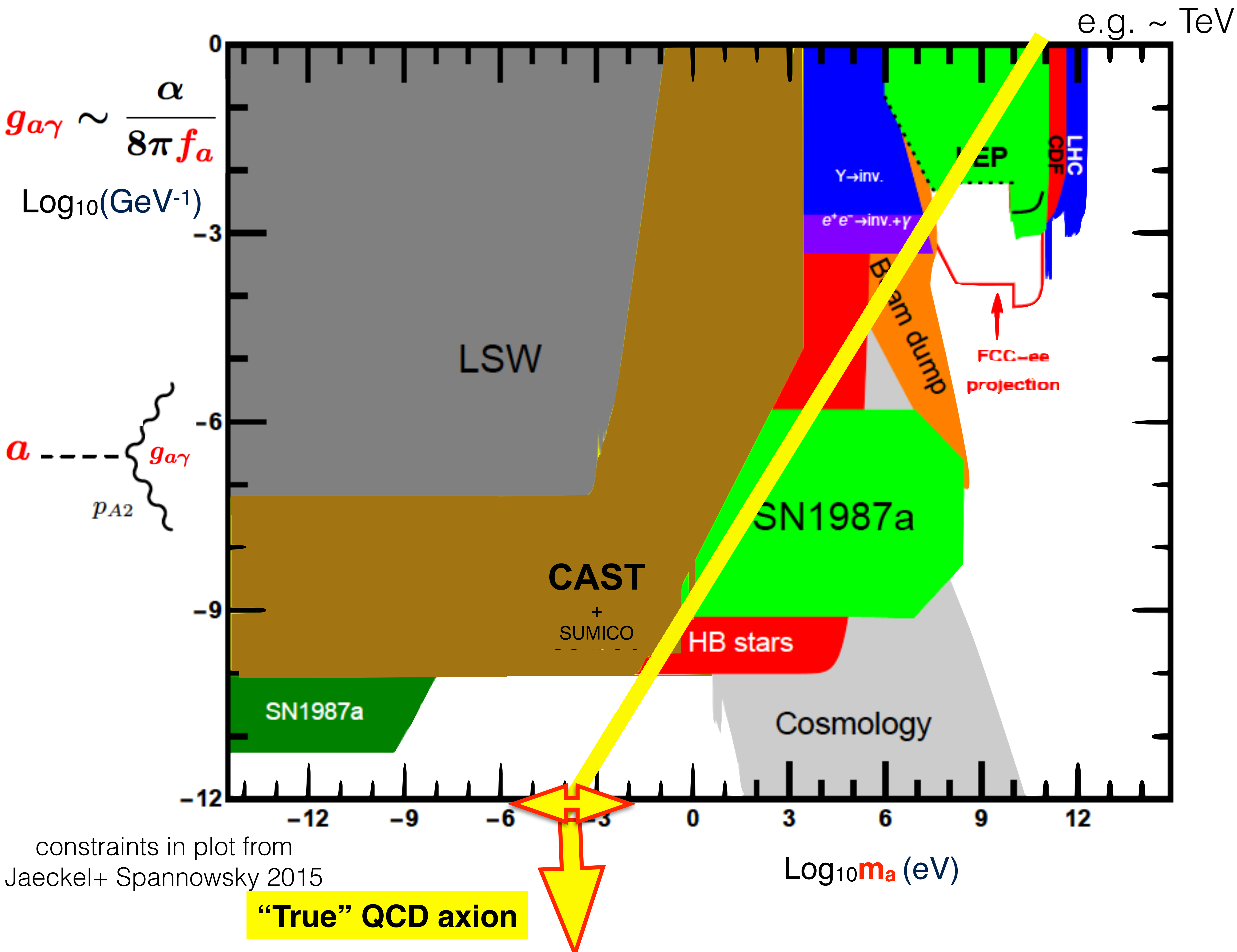
N_{inst} : $G\tilde{G}$ $G'\tilde{G}'$ $G''\tilde{G}''$ ......

QCD

other sources of instantons

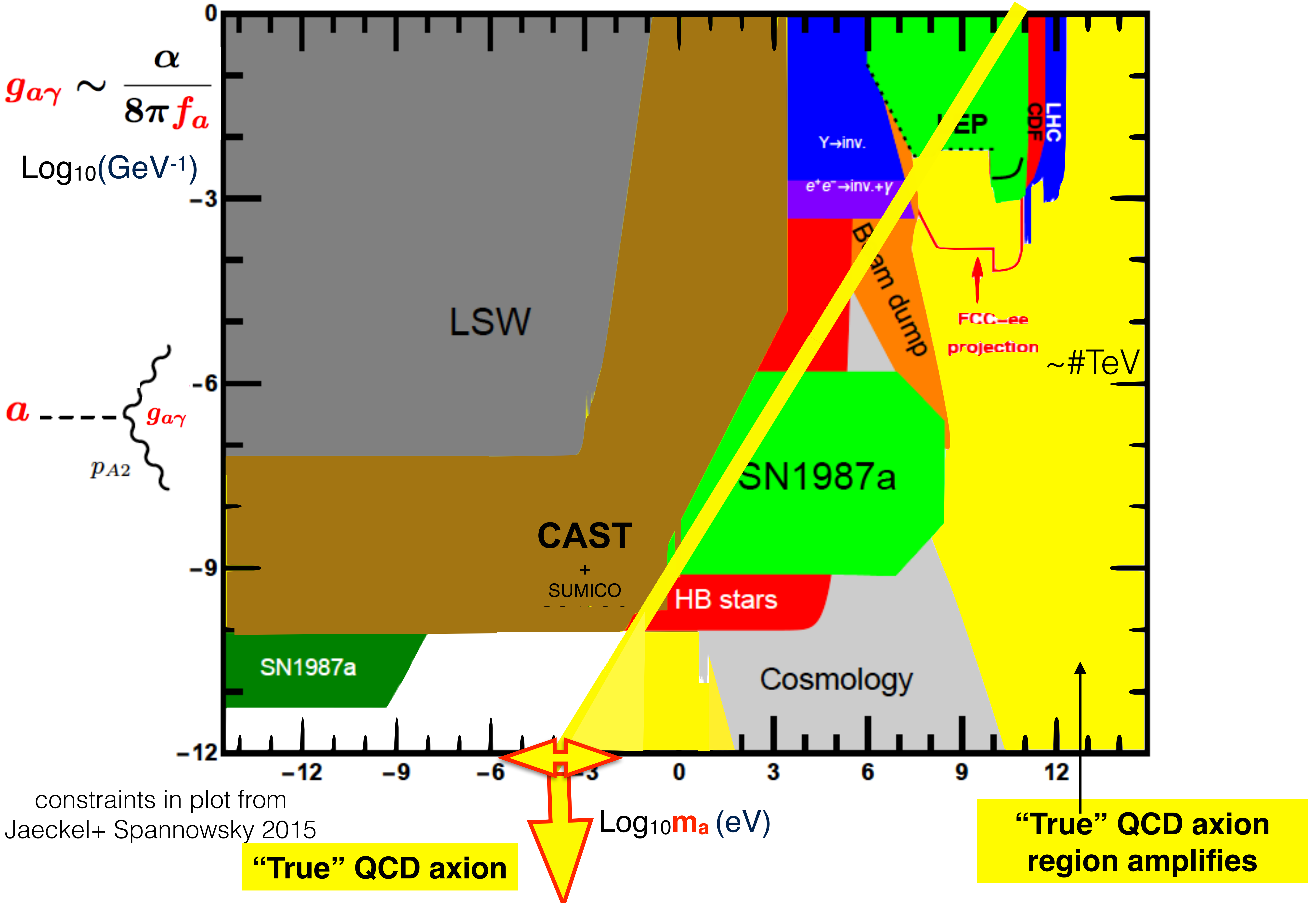
If $N_{ps} \leqq N_{inst}$ all axions heavy

Much territory to explore for heavy ‘true” axions and for ALPs



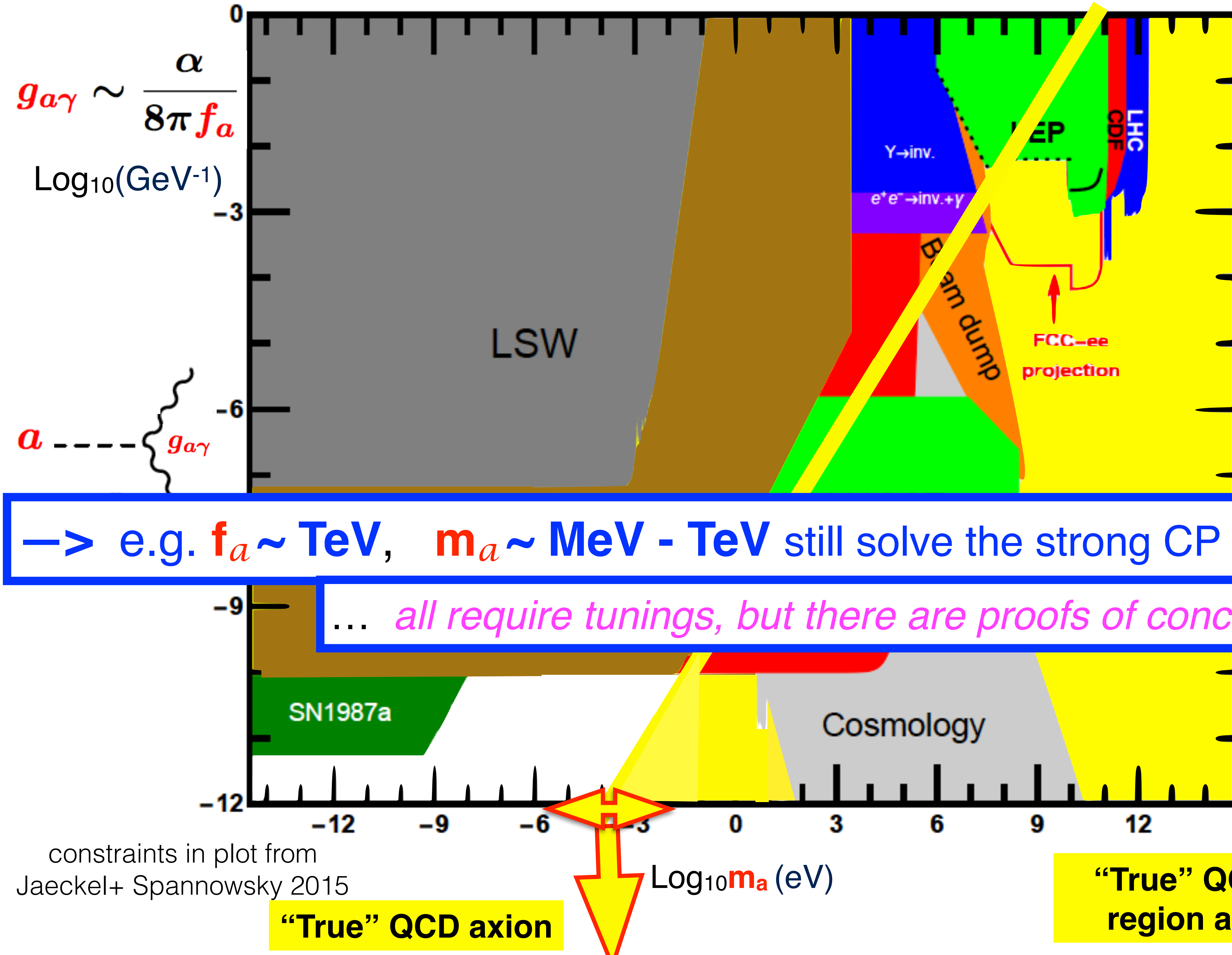
constraints in plot from
Jaeckel+ Spannowsky 2015

ALPs territory: they can be true axions



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

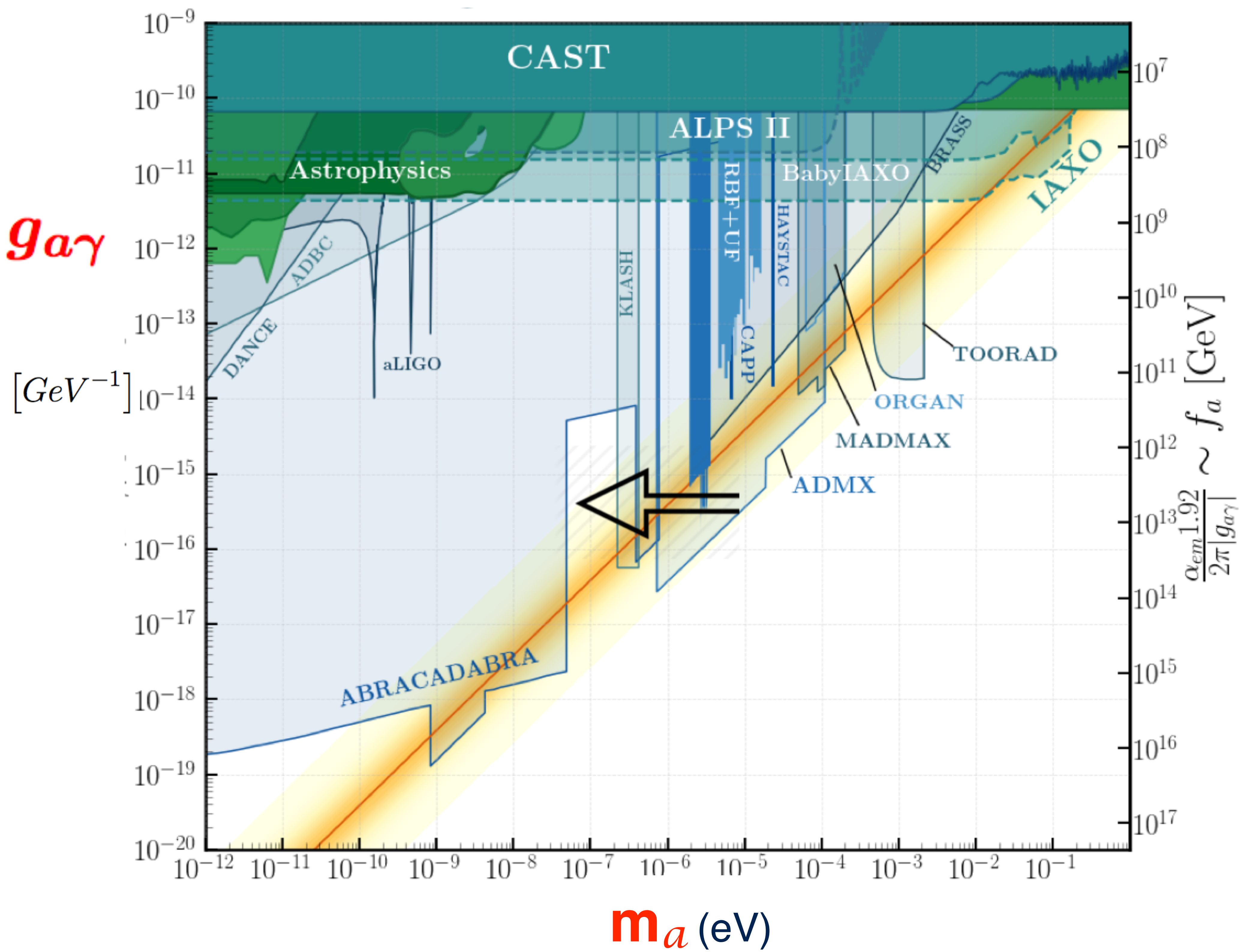
… *all require tunings, but there are proofs of concept*

constraints in plot from Jaeckel+ Spannowsky 2015

"True" QCD axion

"True" QCD axion region amplifies

LIGTHER than usual axions ?



LIGTHER than usual axions

$$m_a^2 f_a^2 = \quad \text{SMALL} \quad \textbf{constant}$$

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?

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

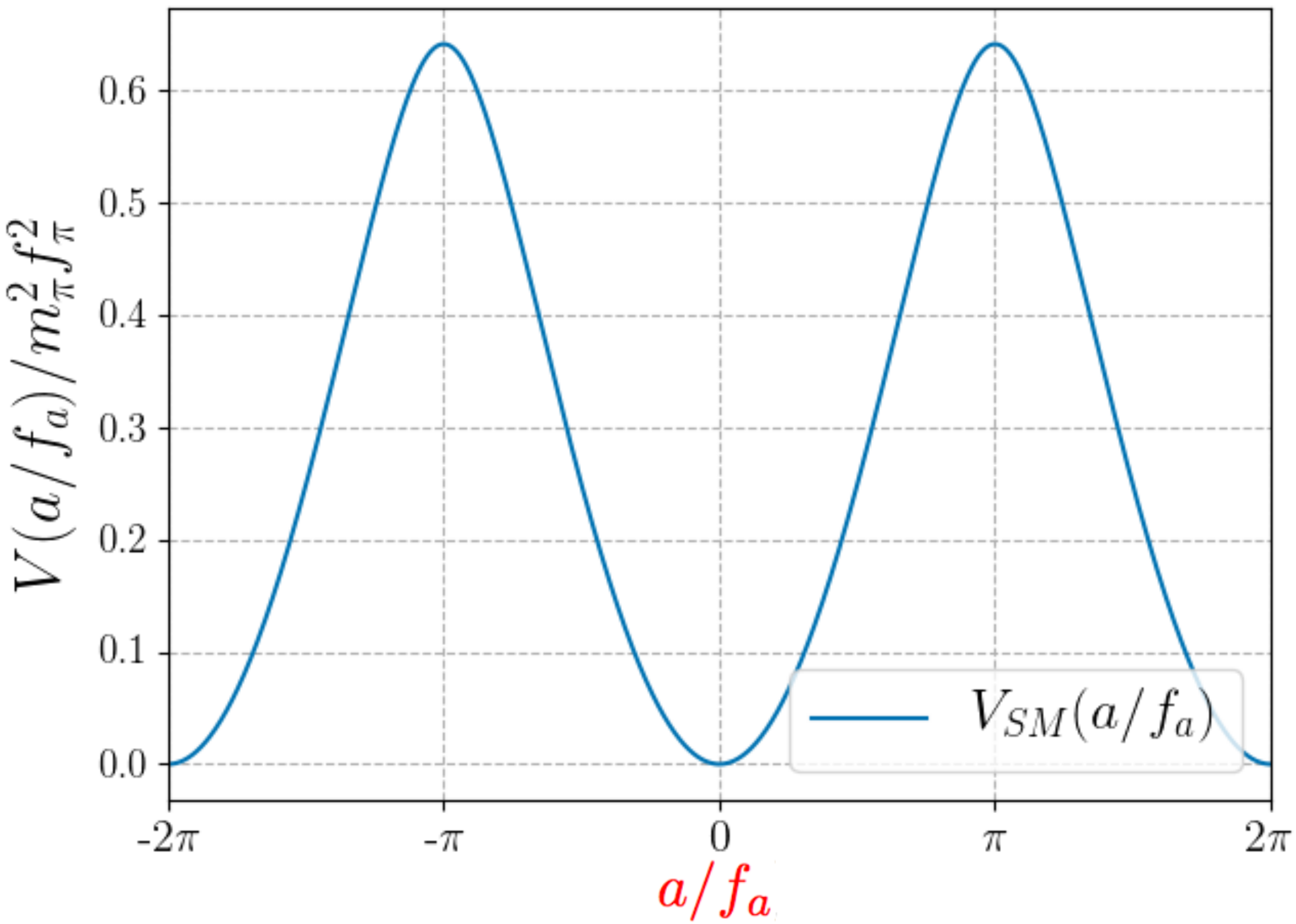
*** And solve the strong CP problem:** arXiv 2102.00012

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

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

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

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



how to add something that naturally flattens it?

A Z_2 (or Z_N) symmetry : mirror degenerate worlds

[Hook, 18]

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

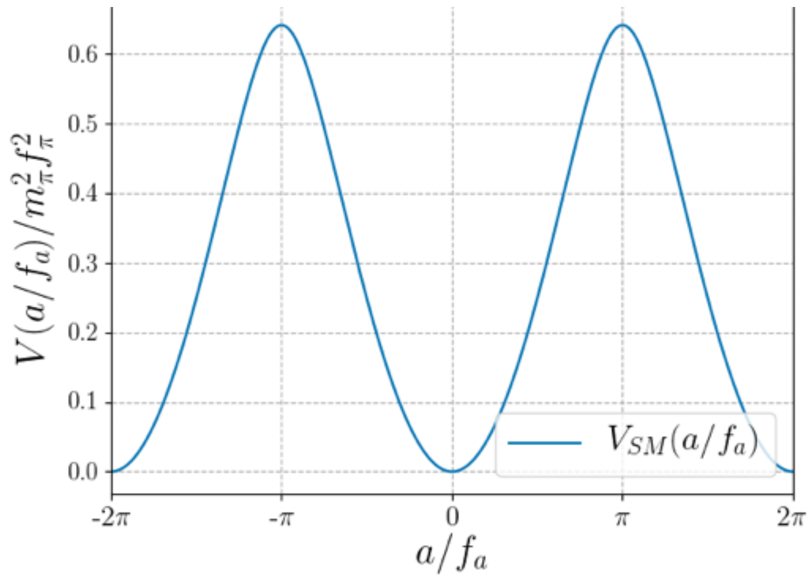
$$a \longrightarrow a + \pi f_a$$

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

QCD **QCD'**

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

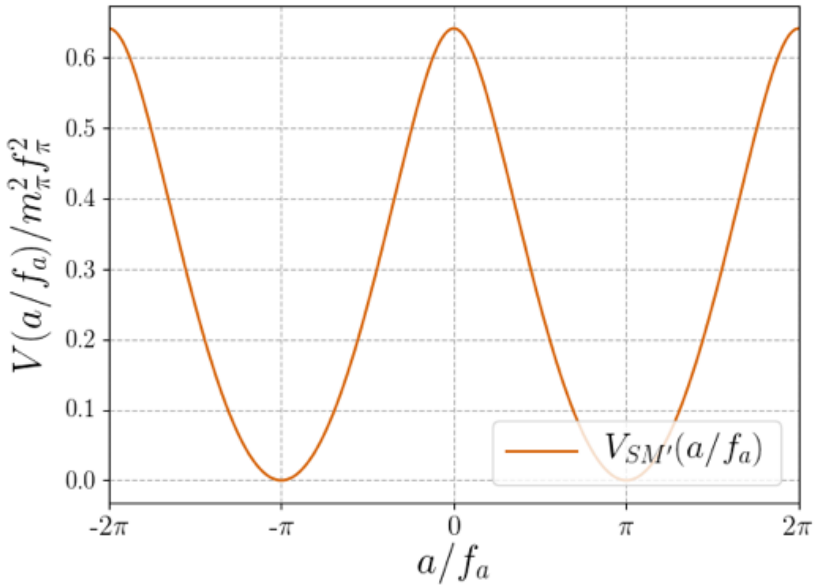
SM



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

$+$

SM'

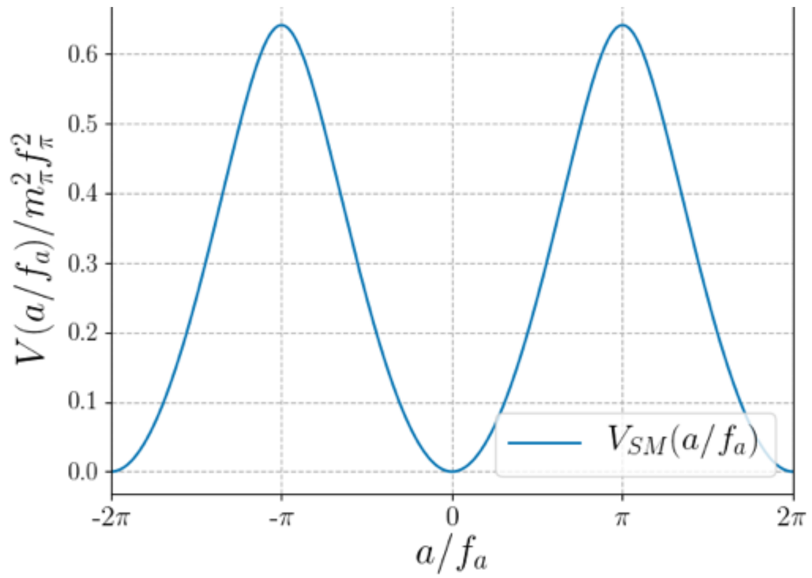


$$\leftarrow \left(\frac{a}{f_a} + \pi\right) G'_{\mu\nu}\tilde{G}'^{\mu\nu}$$

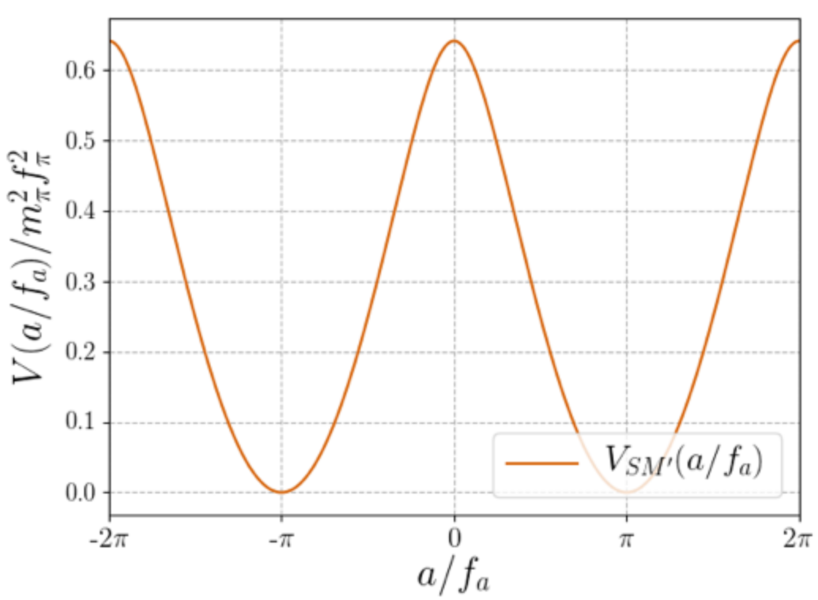
$$V_{SM'}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a} + \frac{\pi}{2}\right)}$$

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

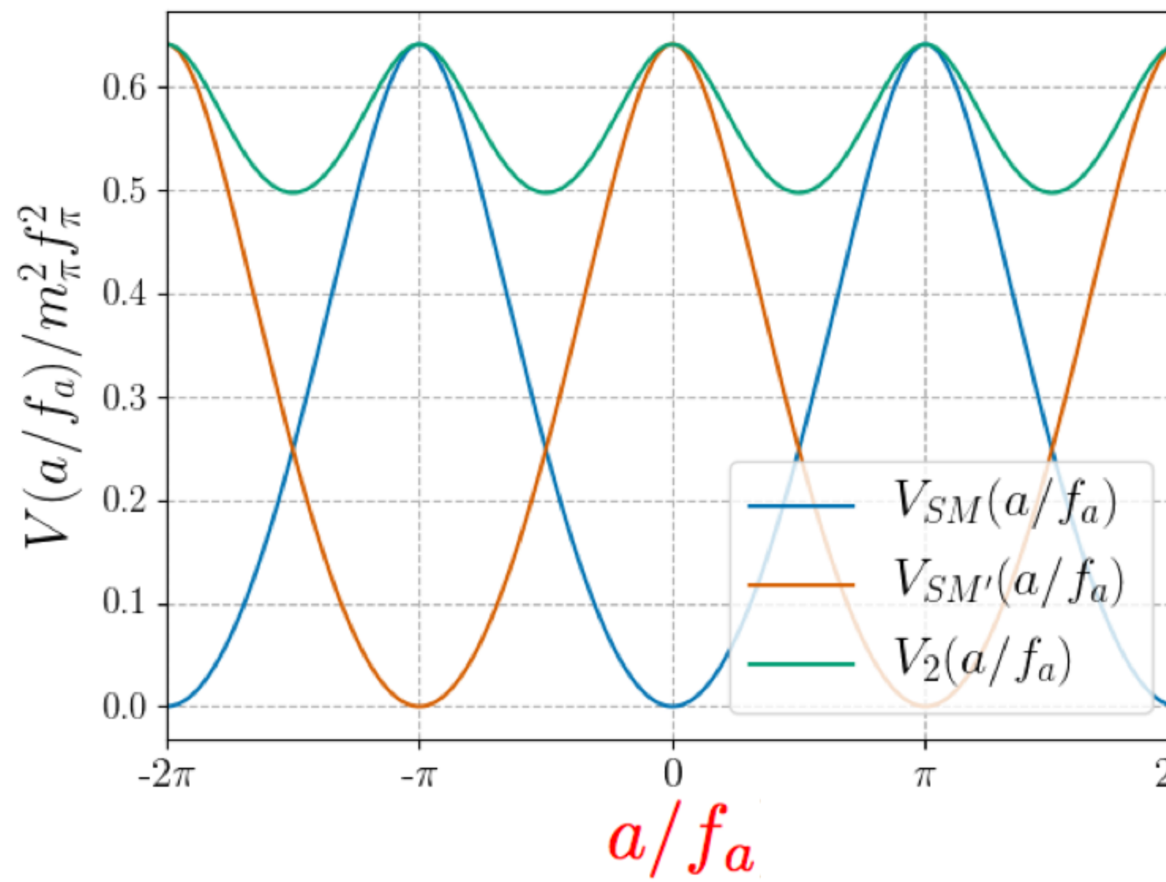
SM



SM'



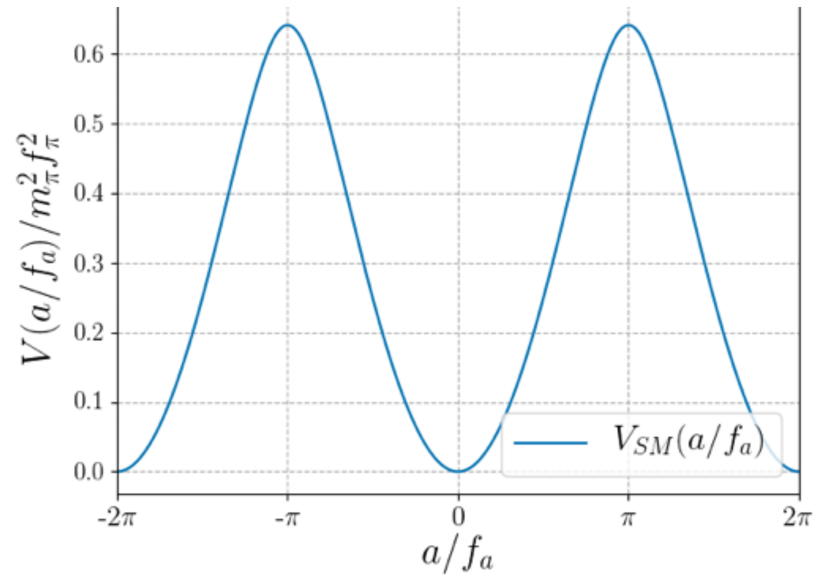
$$V_{SM'}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a} + \frac{\pi}{2}\right)}$$



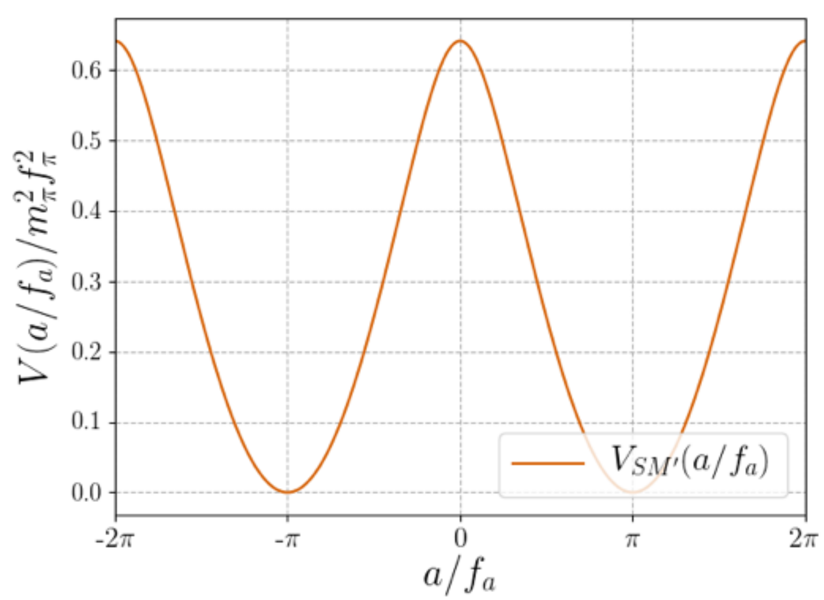
$$V_{SM}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a}\right)}$$

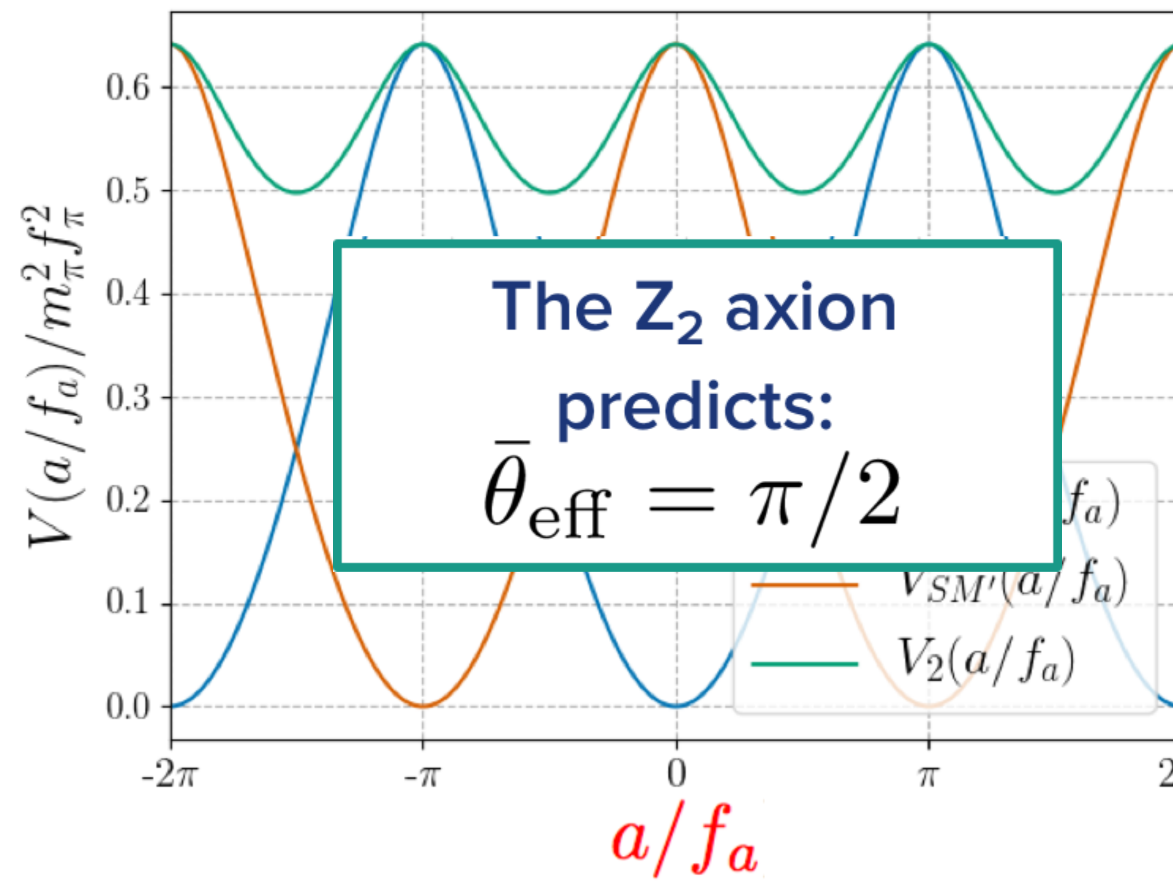
[Hook, 18]

SM



SM'



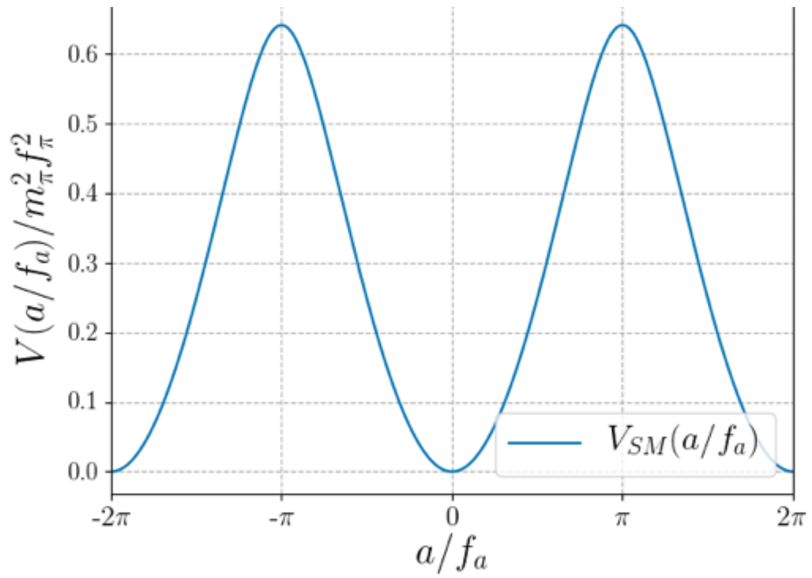


$$V_{SM'}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a}+\frac{\pi}{2}\right)}$$

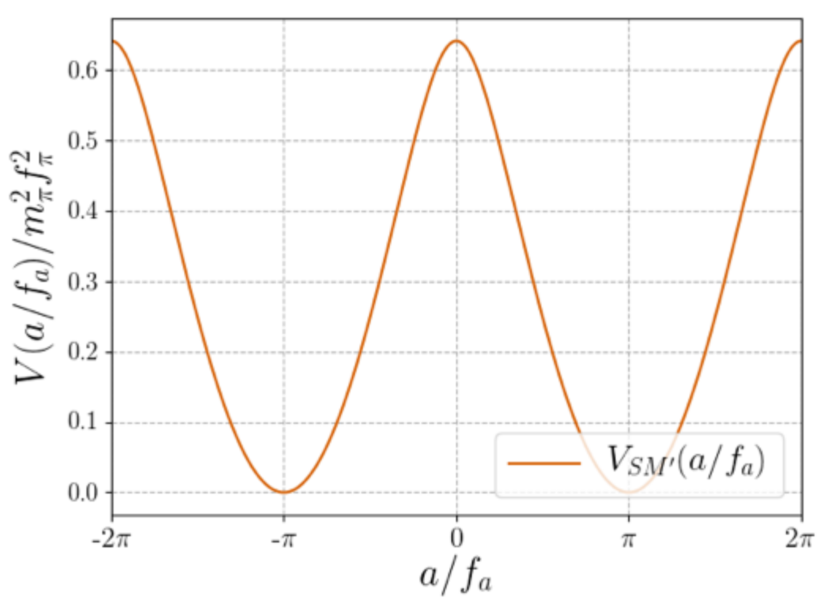
[Hook, 18]

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

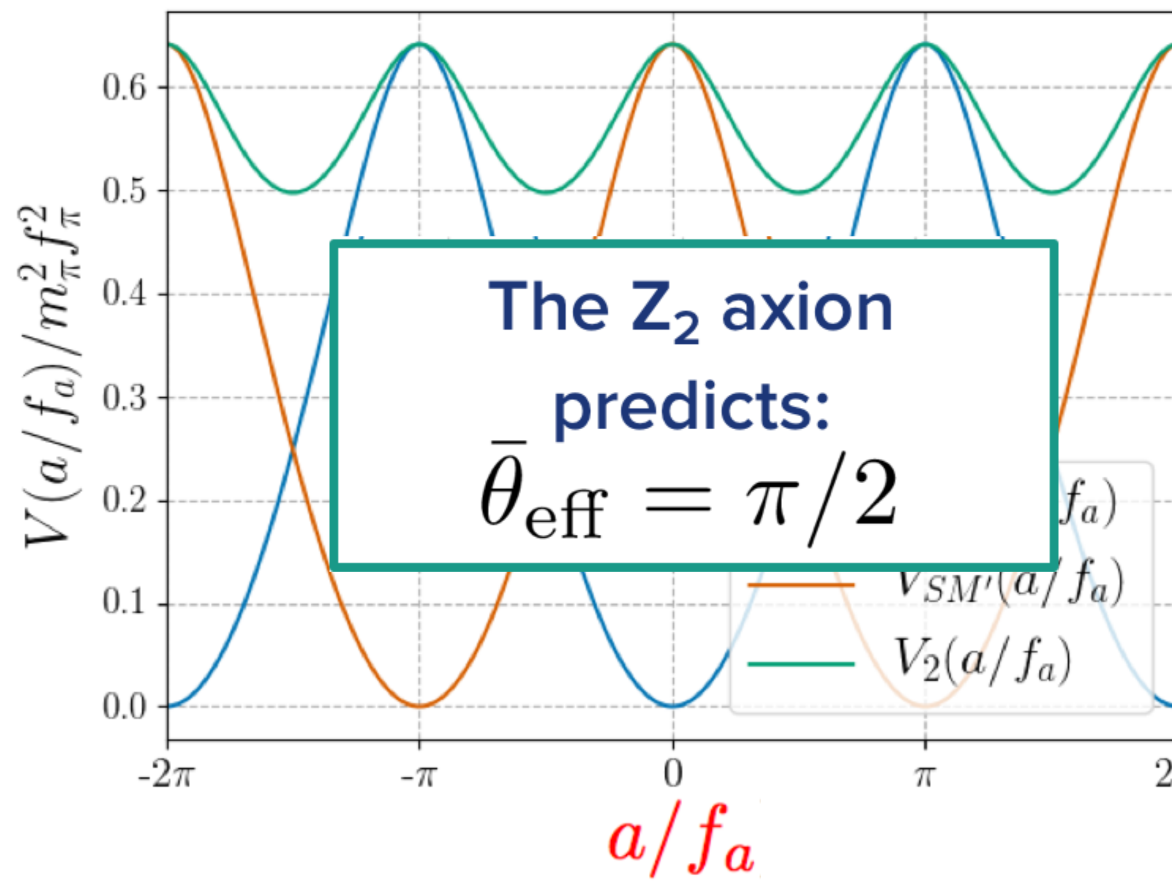
SM



SM'



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

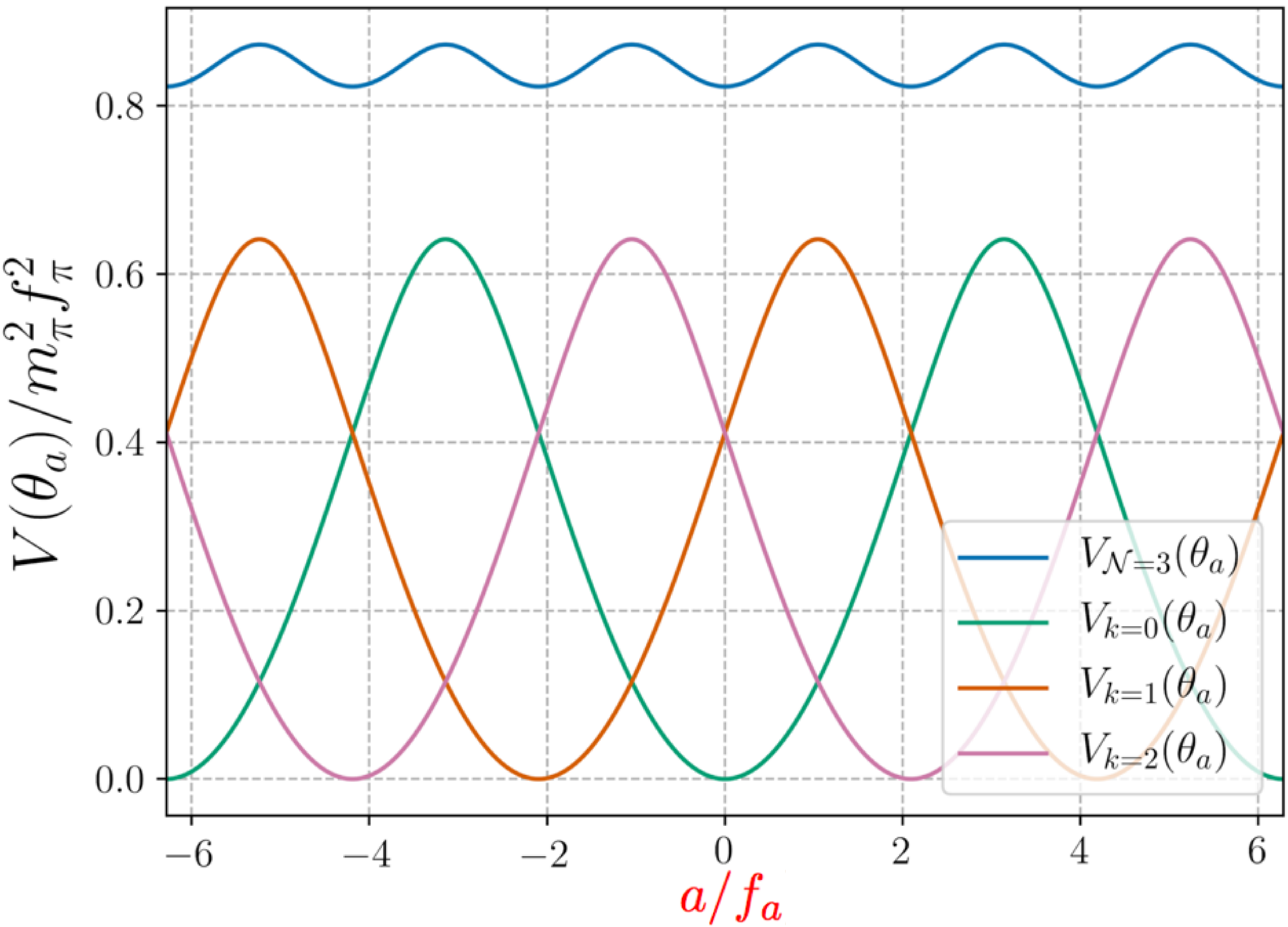


The Z_2 axion predicts:

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

you need N=odd

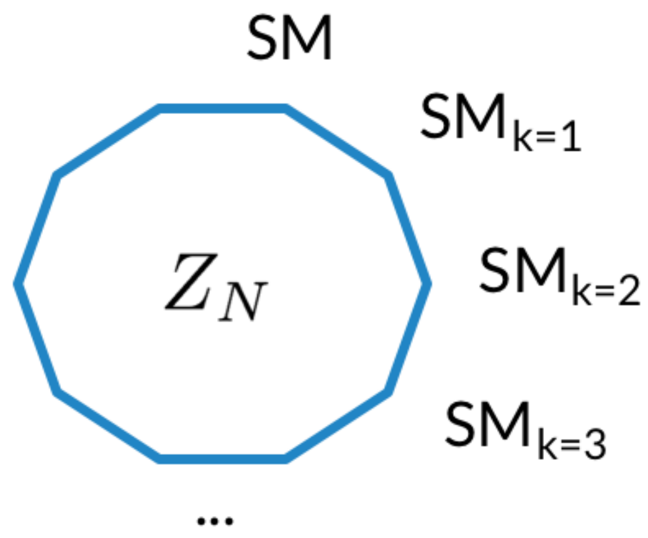
Example: Z_3



0.8
0.6
0.4
0.2
0.0
$V(\theta_a)/m_\pi^2 f_\pi^2$
−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} 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:

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

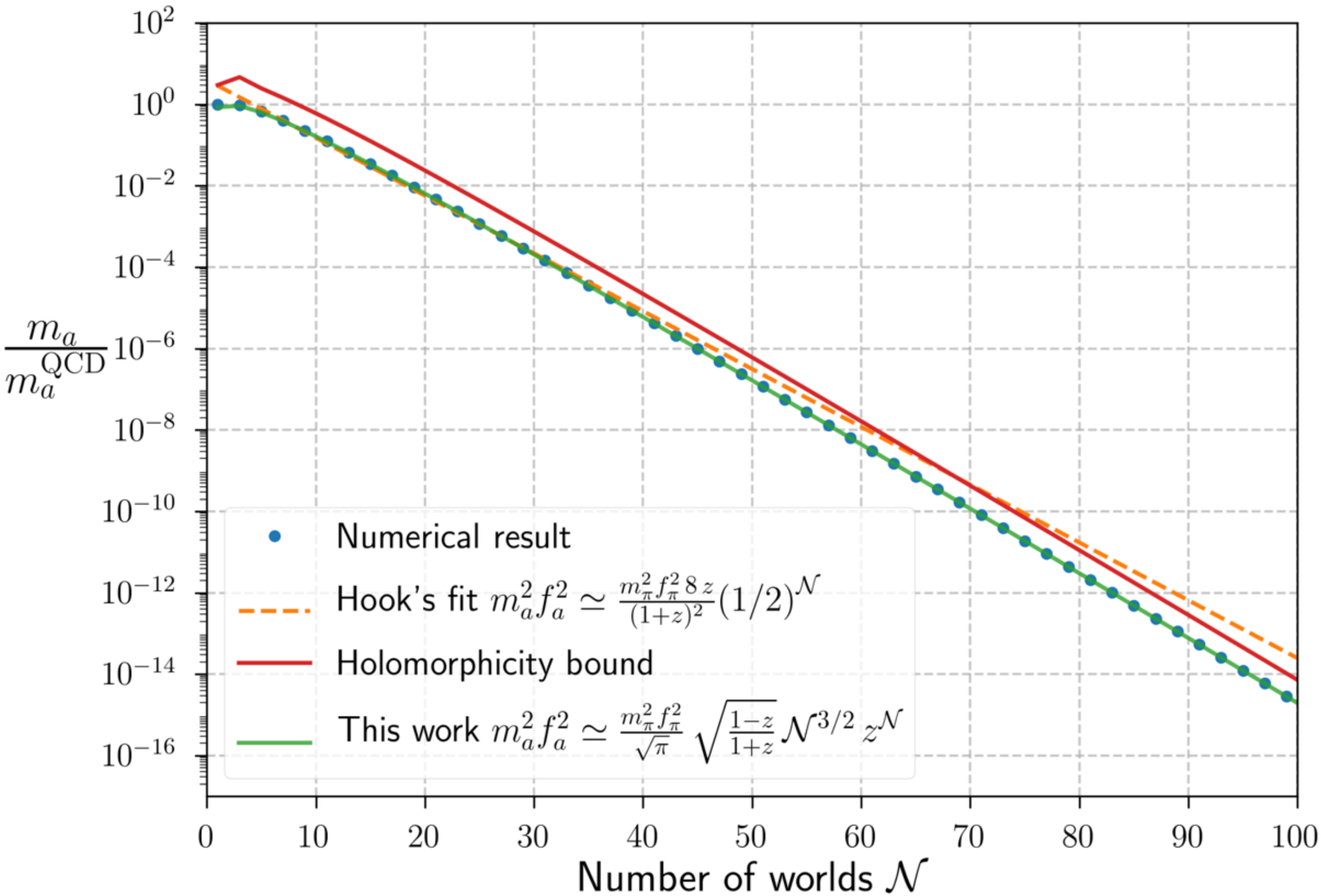
- Compact analytical formula for the axion mass

$$\boxed{m_a^2\, f_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}}\, \mathcal{N}^{3/2}\, z^{\mathcal{N}}} \qquad z = m_u/m_d$$

exponentially suppressed ⟶

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

Z_N axion mass formula



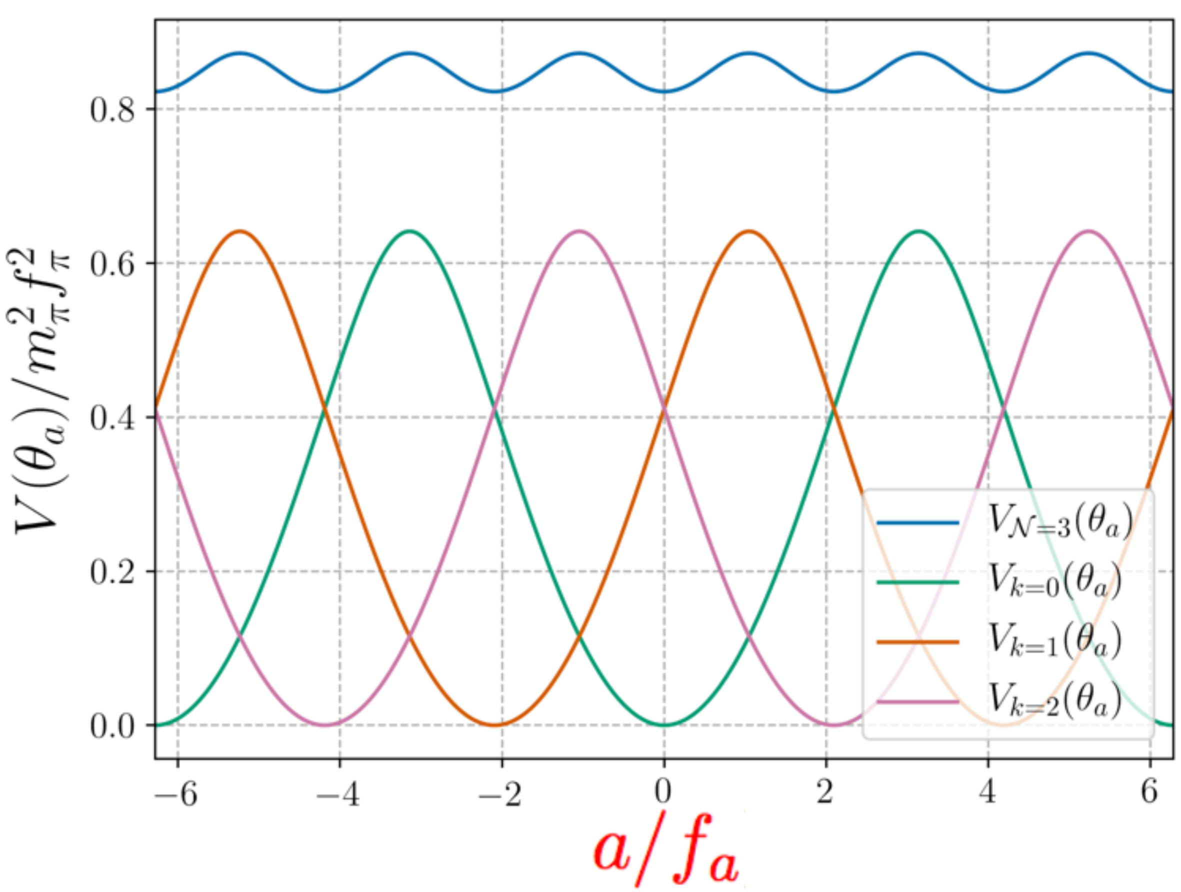
excellent agreement with numerical already for N=3

di Luzio, Quilez, Ringwald, BG arXiv 2102.00012

Caveat:

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

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



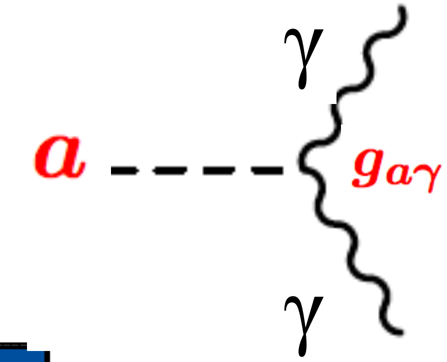
$$\bar{\theta} \lesssim 10^{-10}$$

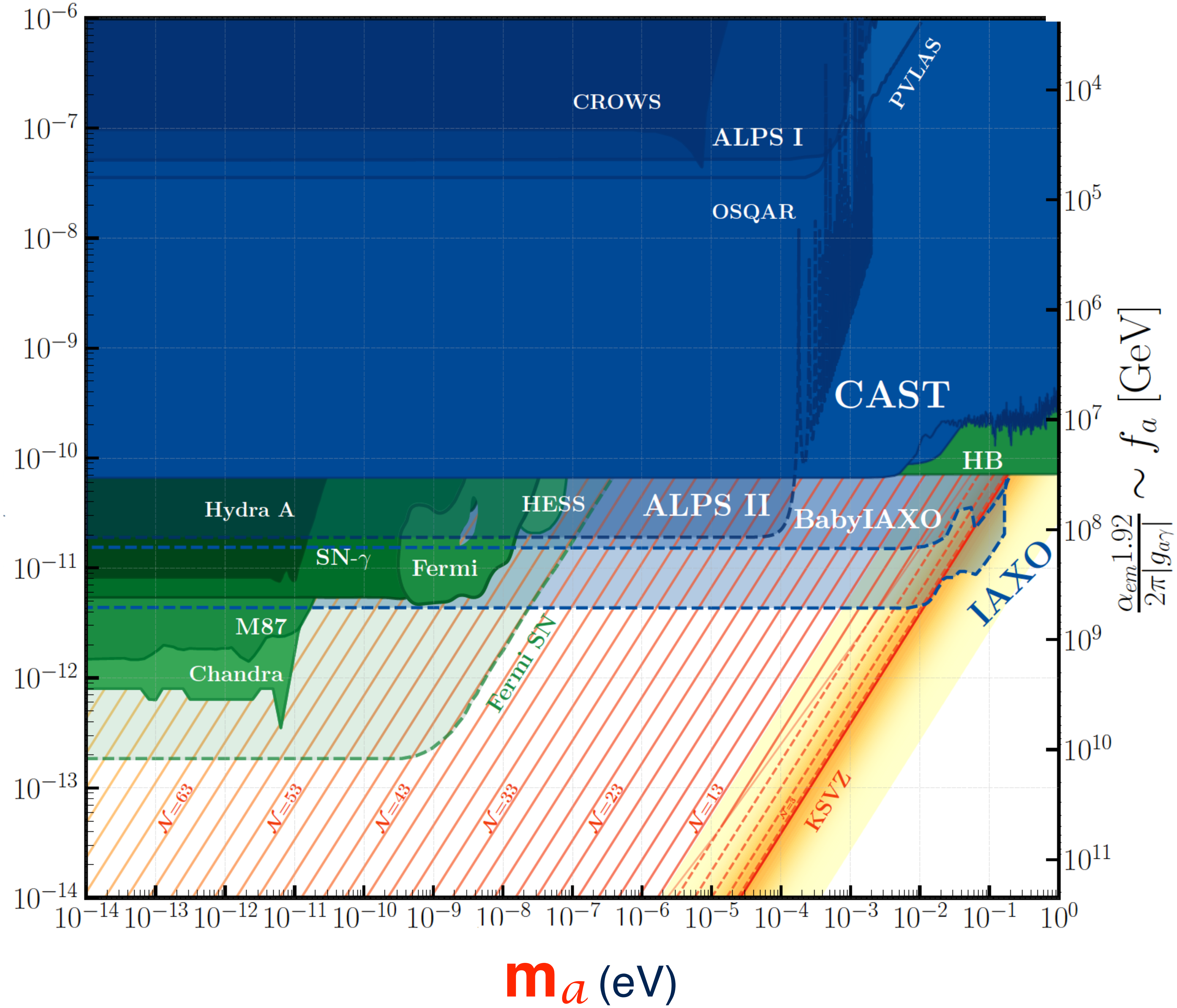
$$\downarrow$$

$$1/\mathcal{N} \text{ probability}$$

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

$[GeV^{-1}]$

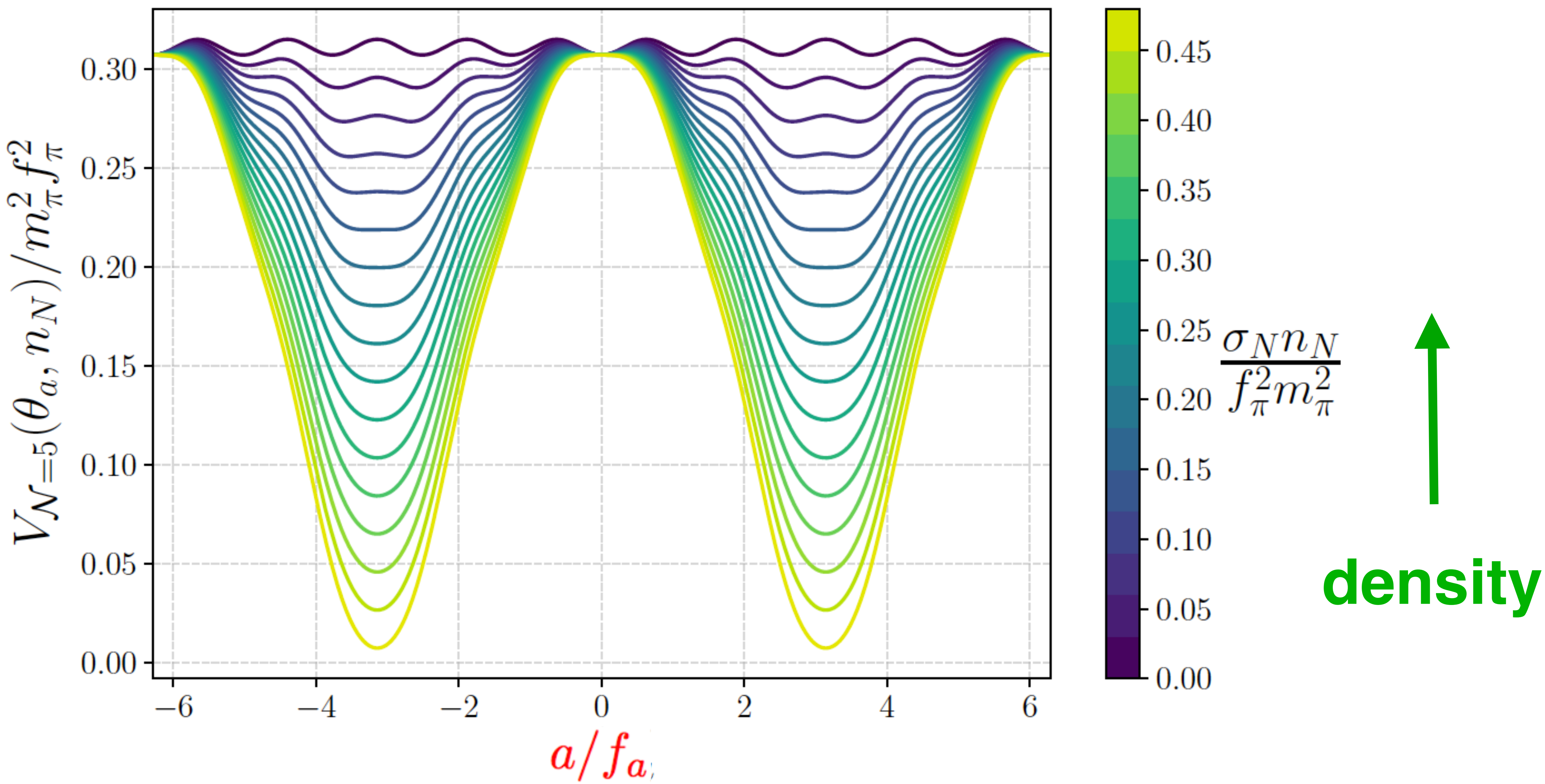




di Luzio, Quilez, Ringwald, BG arXiv 2102.00012

Model-independent bounds from high-density objects

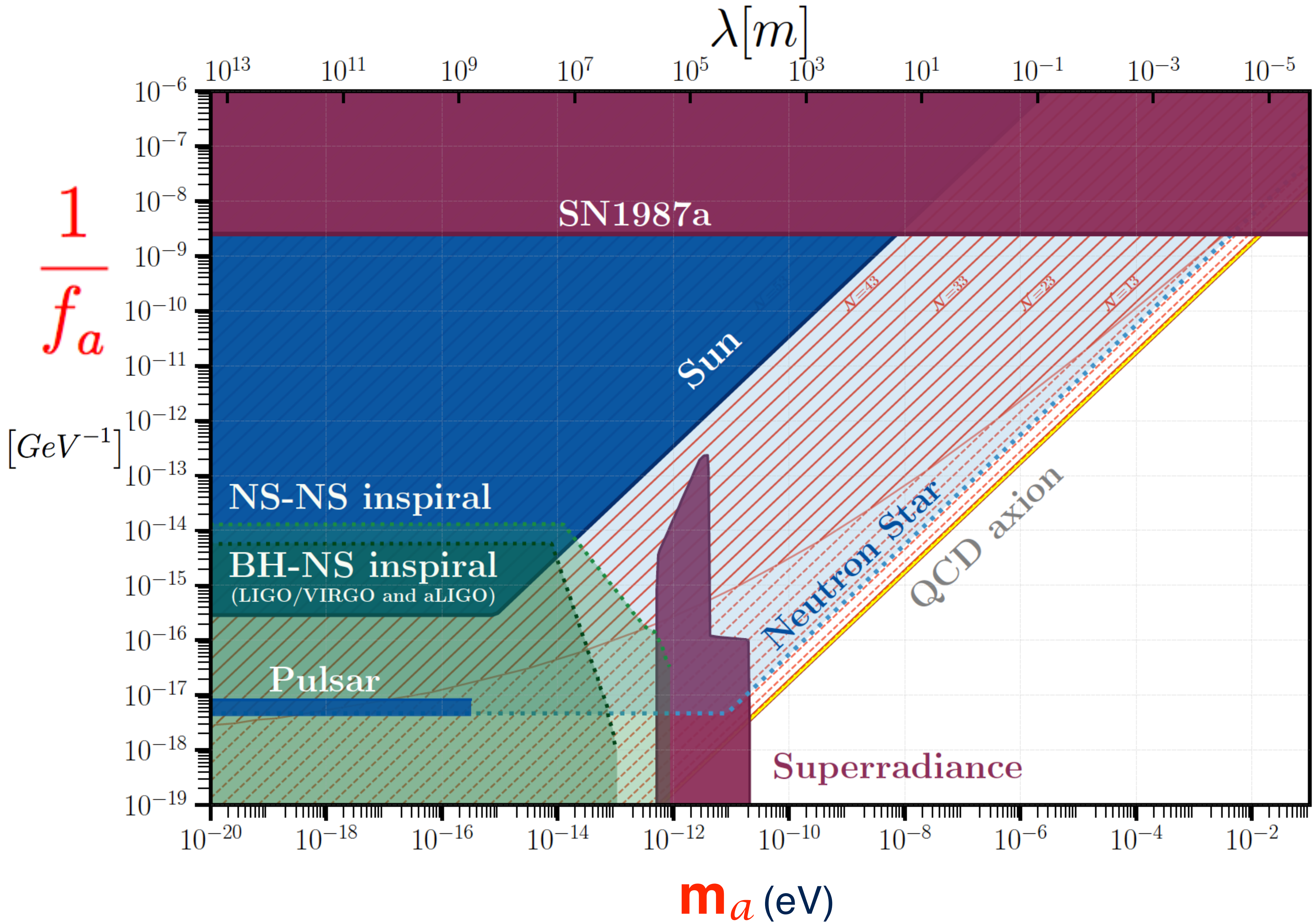
A stellar object of high (SM) density is a background that breaks explicitly Z_N



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

Dark matter from the Z_N axion

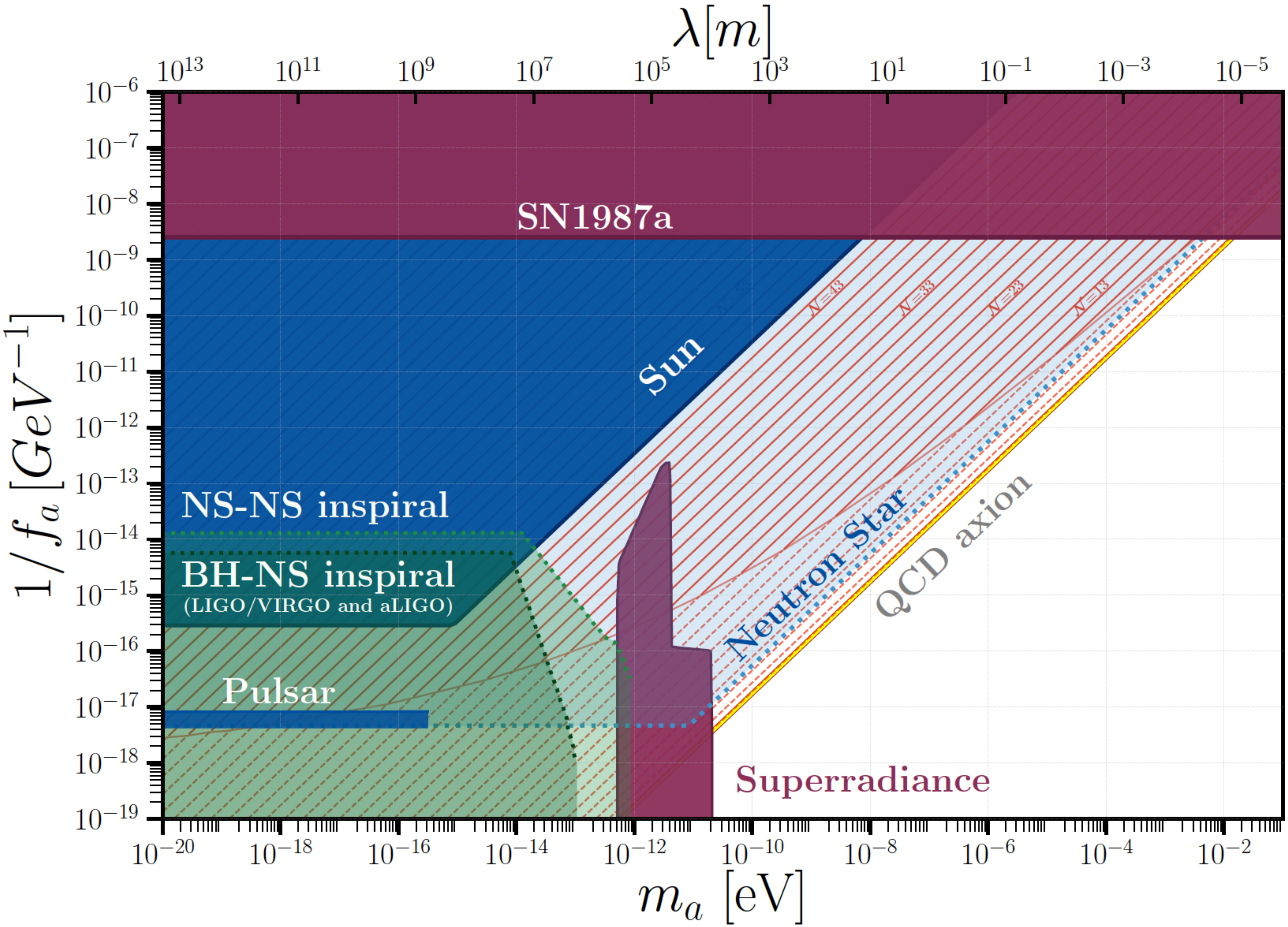
For instance:

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

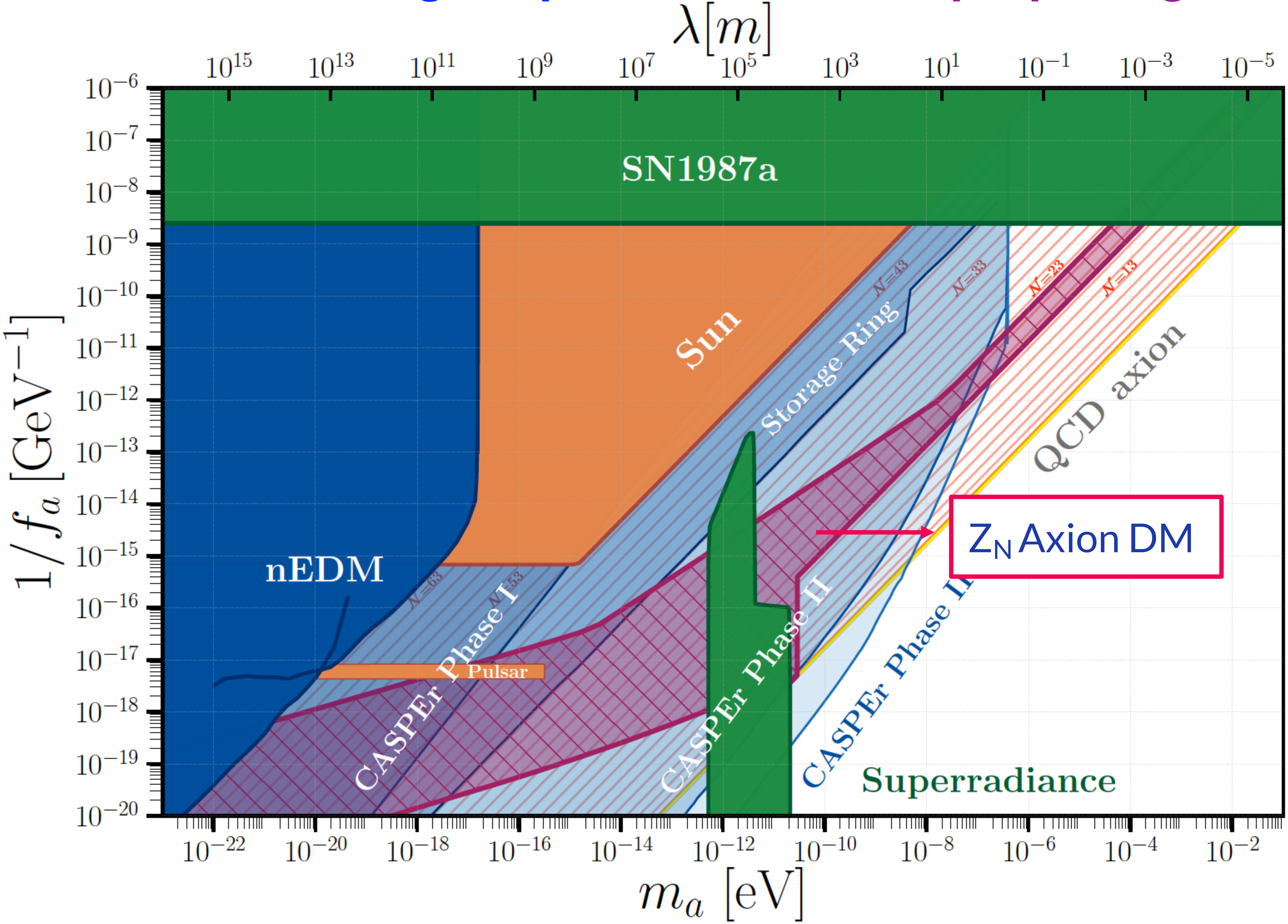
* Could fuzzy DM (m_{DM}~10^{-22} eV) be a true axion?

di Luzio, Quilez, Ringwald, BG arXiv 2102.01082

This was without asking the true axion to solve DM:

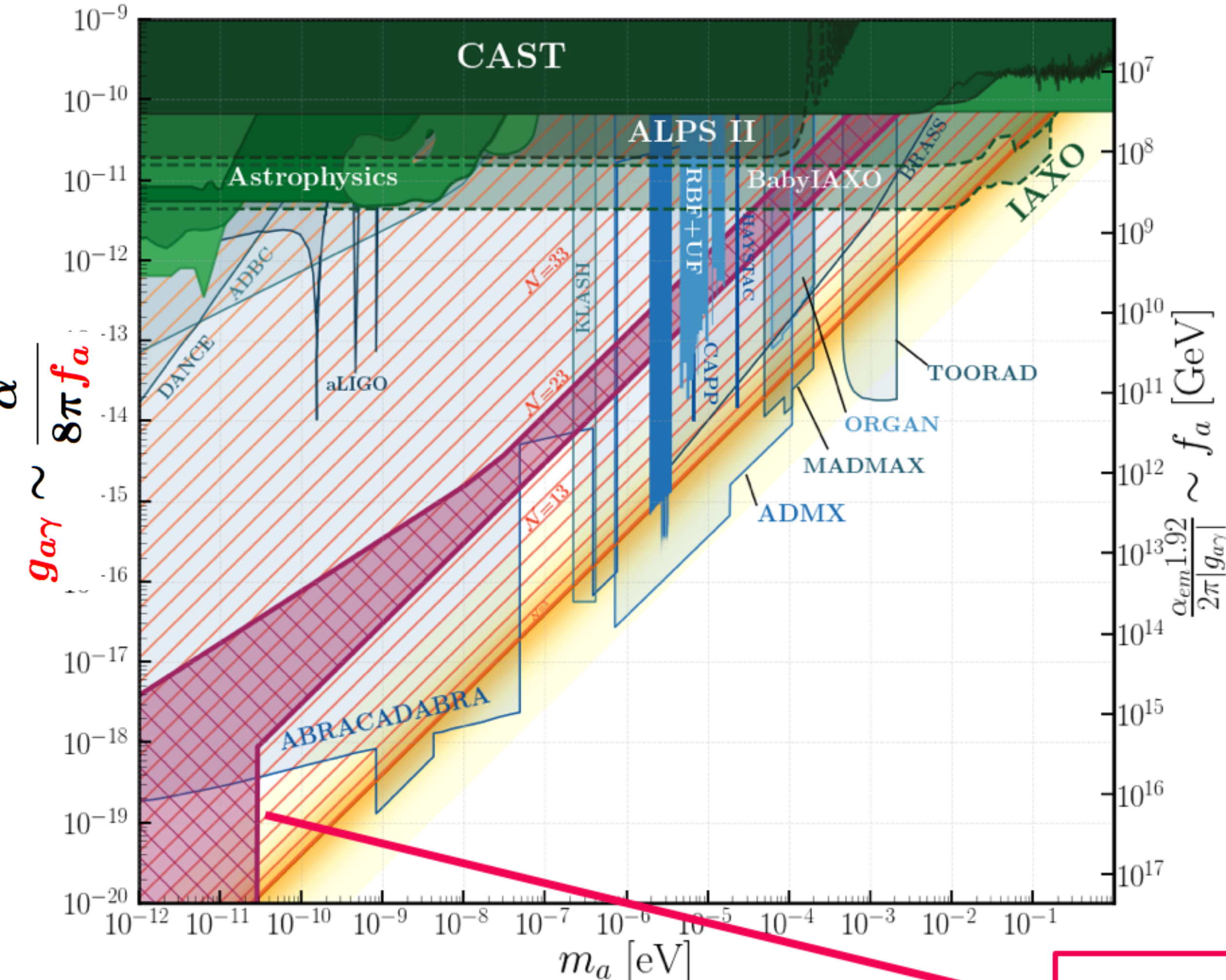


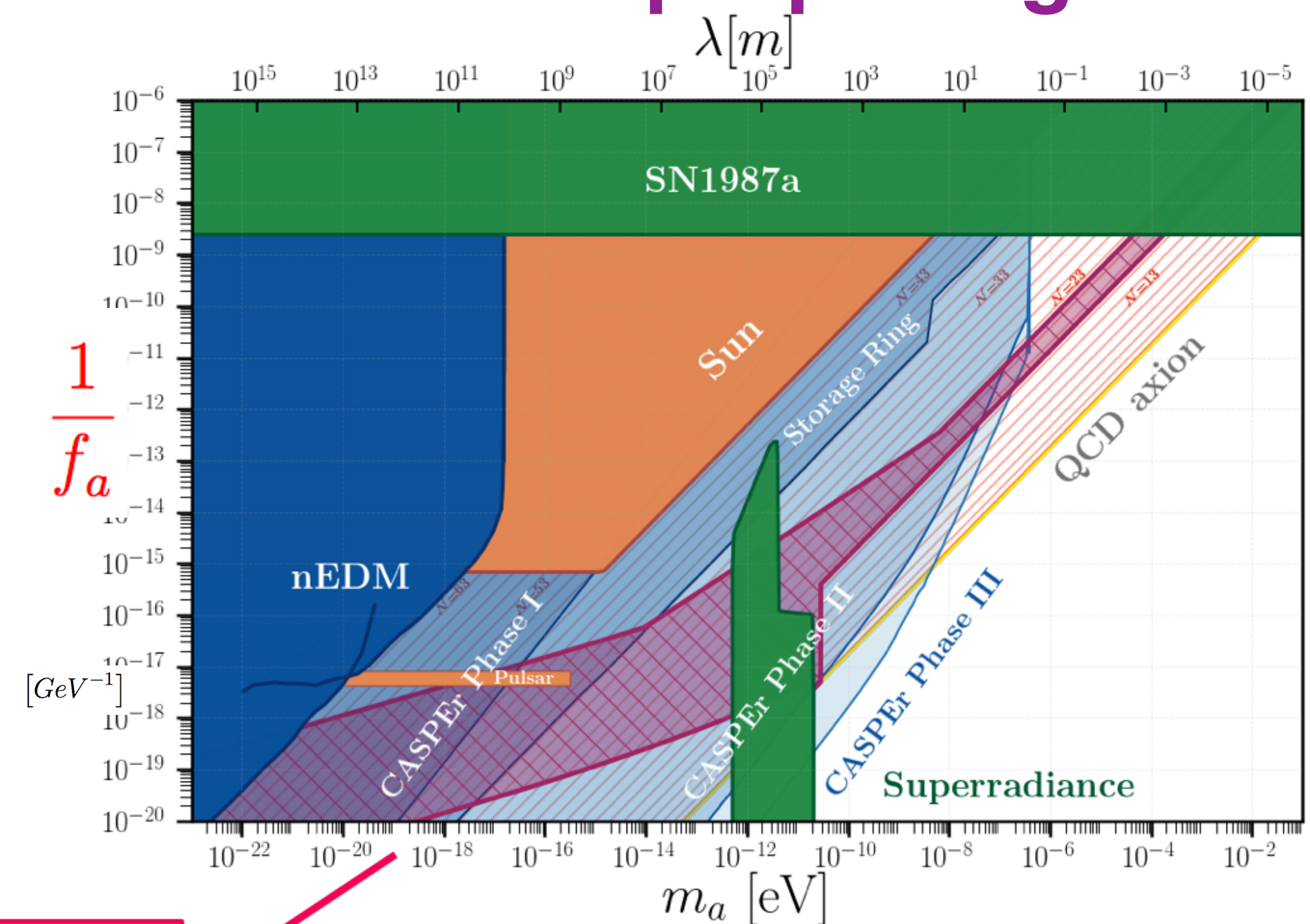
To solve the strong CP problem *and* DM: purple region



di Luzio, Quilez, Ringwald, BG arXiv 2102.01082

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





Z_N Axion DM

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

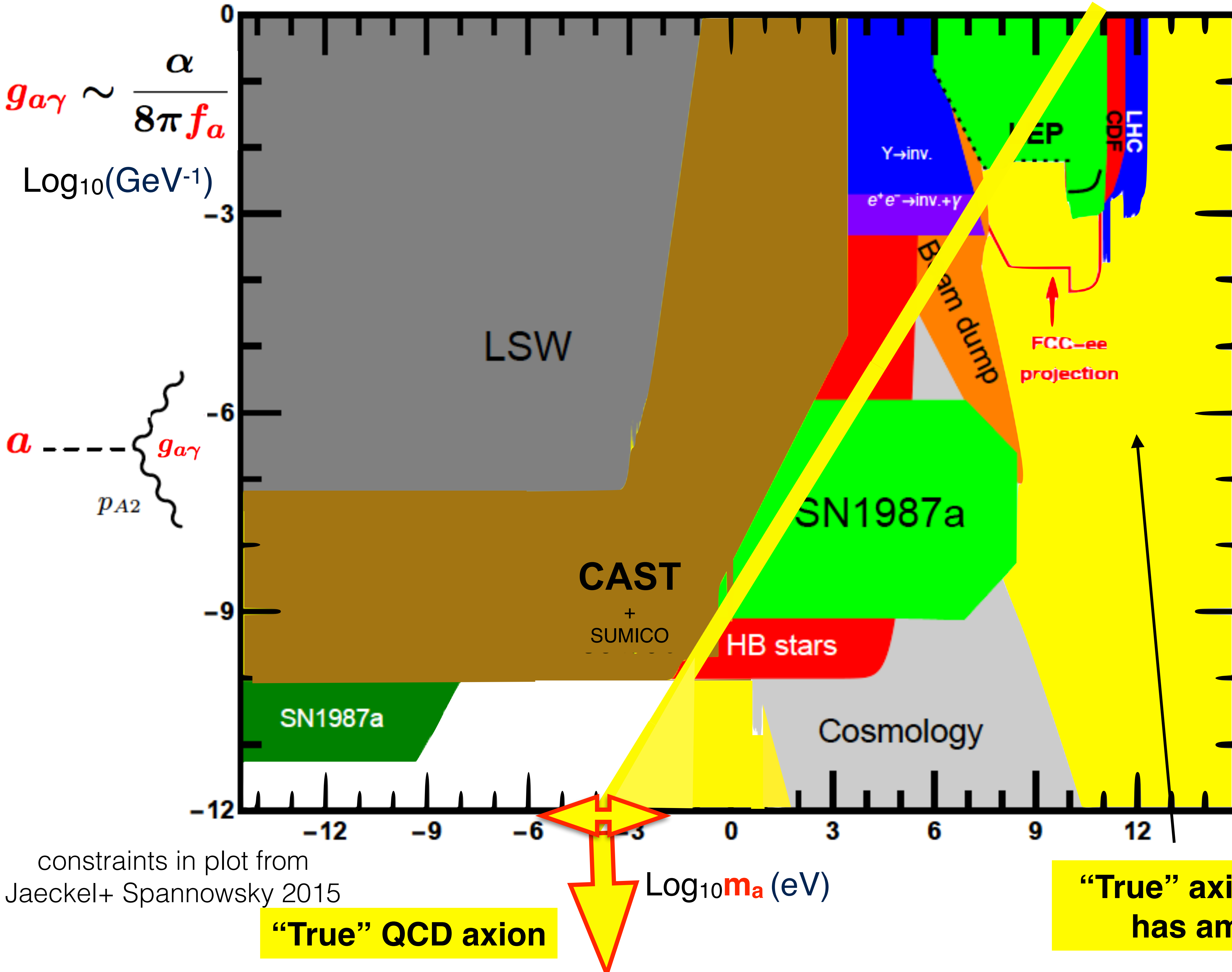
$$\text{Solutions for } 10^{-22} \text{ eV} \leq m_a \leq m_a^{QCD}$$

First "fuzzy dark matter" true axion

di Luzio, Quilez, Ringwald, BG arXiv 2102.01082

ALPs territory: they can be true axions

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

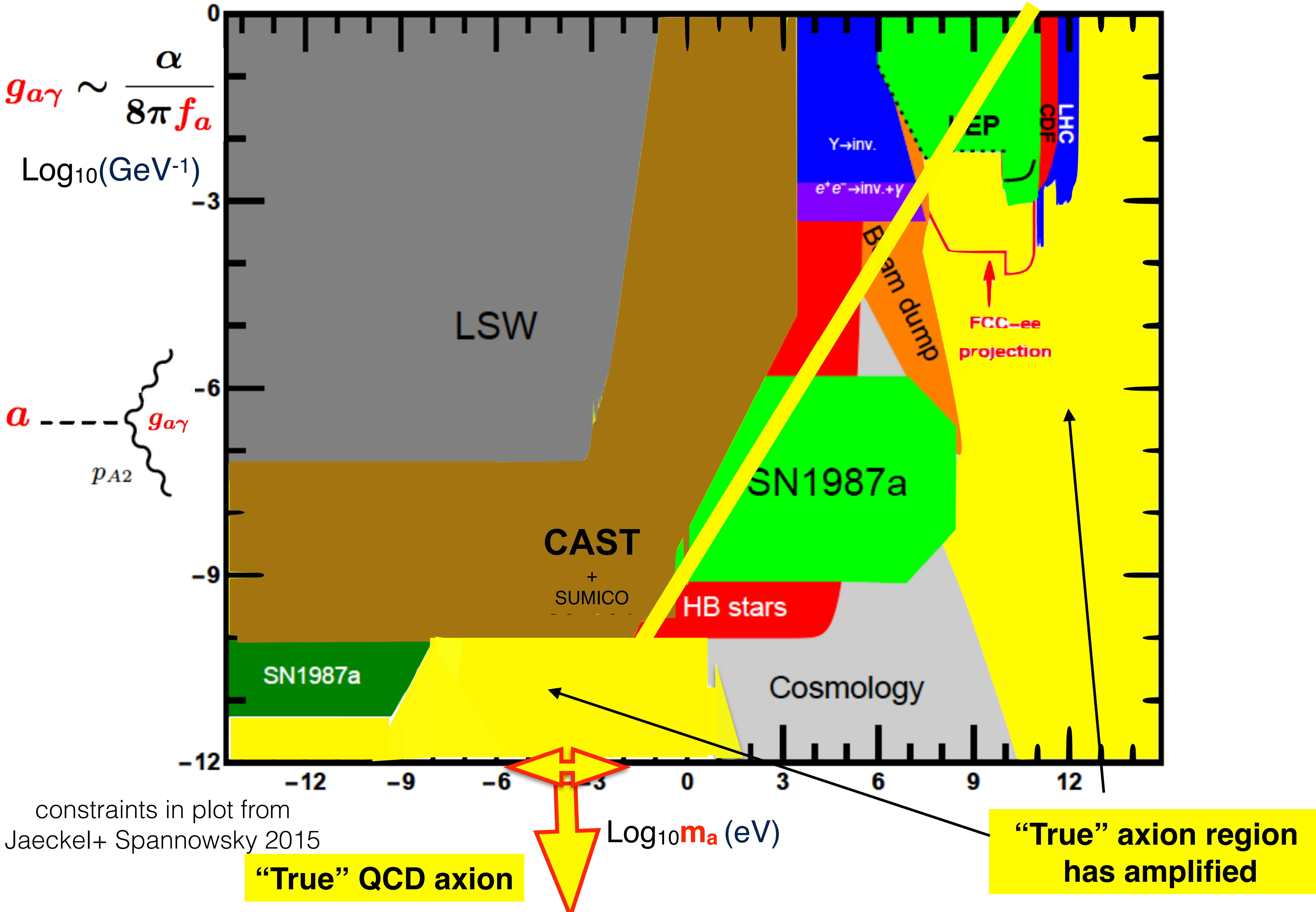


constraints in plot from
Jaeckel+ Spannowsky 2015

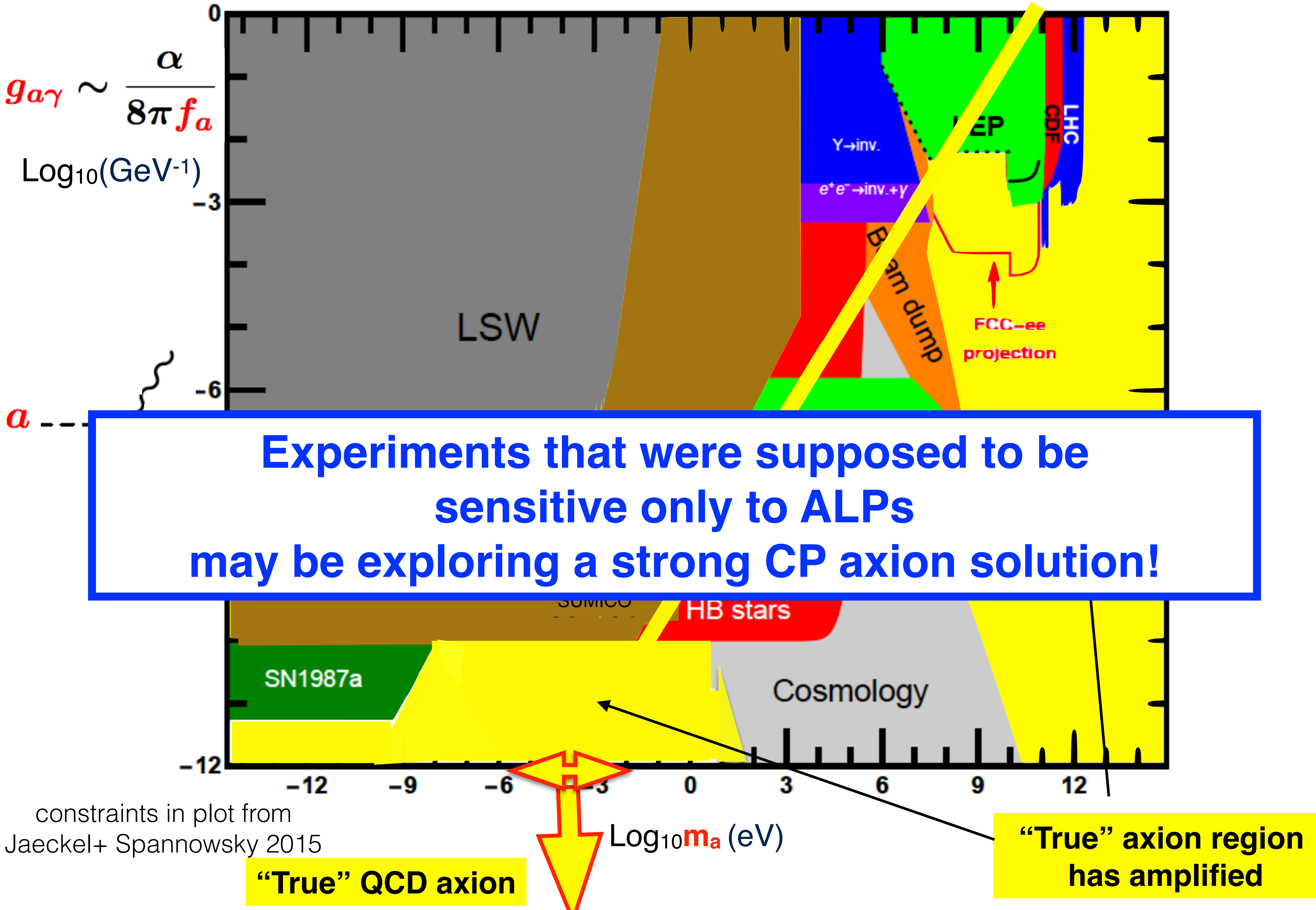
“True” QCD axion

“True” axion region has amplified

ALPs territory: they can be true axions

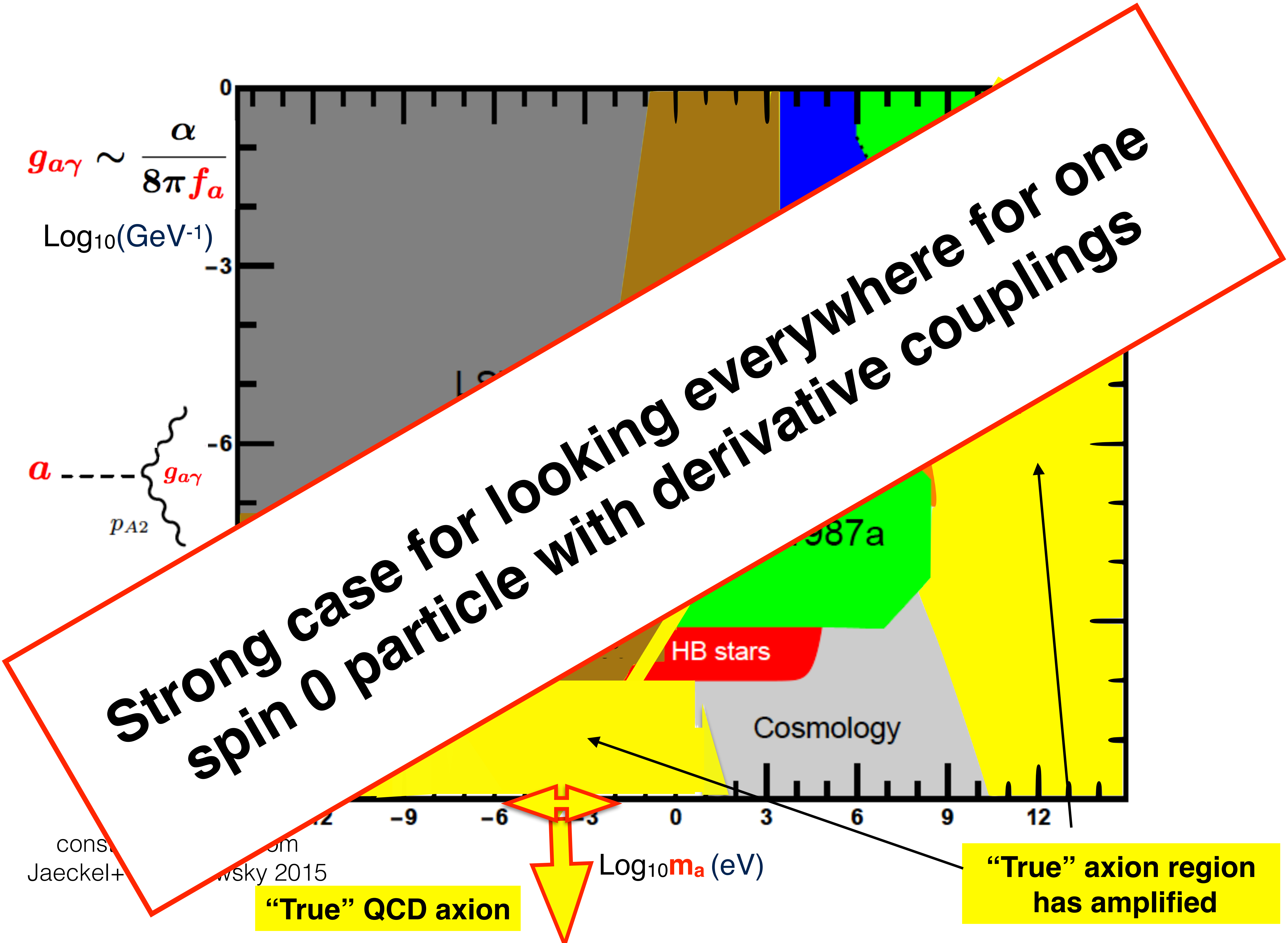


ALPs territory: they can be true axions



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

constraints in plot from Jaeckel+ Spannowsky 2015



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}
987a
HB stars
Cosmology
-9
-6
-3
0
3
6
9
12
Log10ma (eV)
cons
om
Jaeckel+
wsky 2015
"True" QCD axion
"True" axion region has amplified

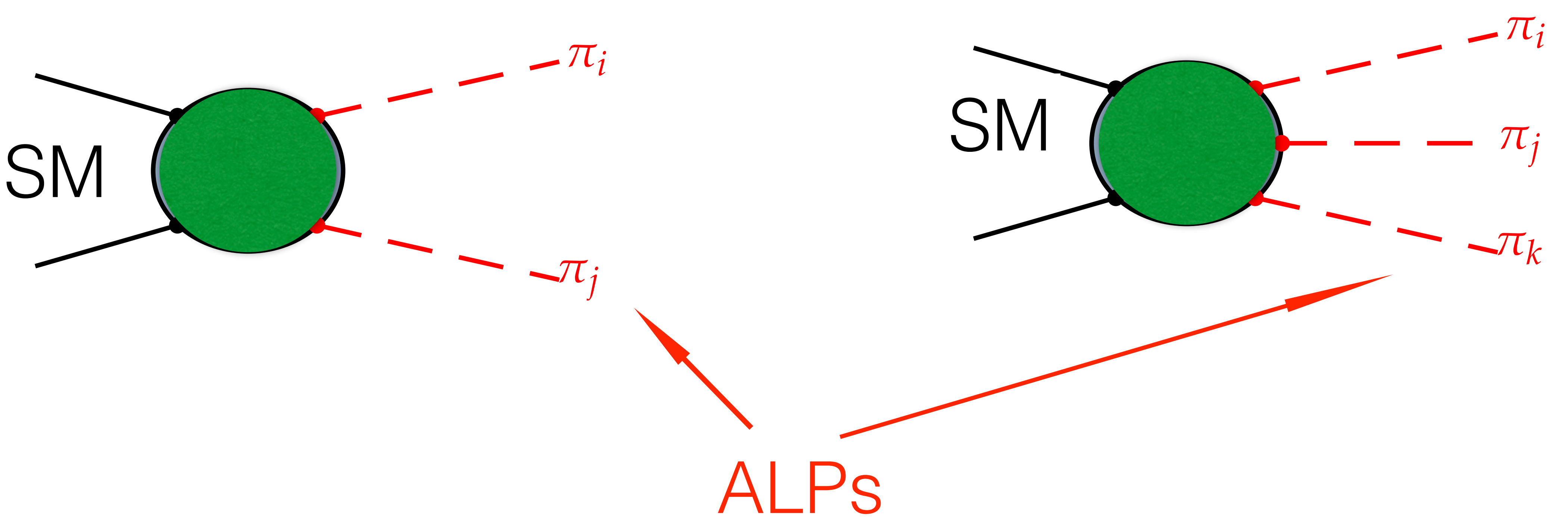
Strong case for looking everywhere for 2, 3…?
spin 0 particle with derivative couplings

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 can be degenerate multiplets of ALPs

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

The gist of the protection

SSB of continuous global symmetry G —-> **massless** pions

To give pion masses: explicit symmetry-breaking potential

* In all generality, the pion masses are quadratically sensitive to other heavy scales

* But they are **not** sensitive if the potential remains **invariant under a discrete subgroup** of G

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 <u>massive</u> π_1, π_2 result <u>without breaking the discrete symmetry</u>

—> <u>increased insensitivity</u> 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:

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

An UV complete example

triplet of scalars ϕ
+
triplet of fermions Ψ

$$\mathcal{L}_{\text{tree}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{V}(\phi)} + \mathcal{L}_{\text{int}}$$

$$\mathcal{L}_{\text{kin}} = \frac{1}{2}\partial^\mu \phi^T \partial_\mu \phi + \overline{\Psi}\left(i\gamma^\mu \partial_\mu\right)\Psi$$

$$\mathcal{L}_{\text{V}(\phi)} = \frac{m^2}{2}\phi^T\phi - \frac{\lambda}{4}\left(\phi^T\phi\right)^2$$

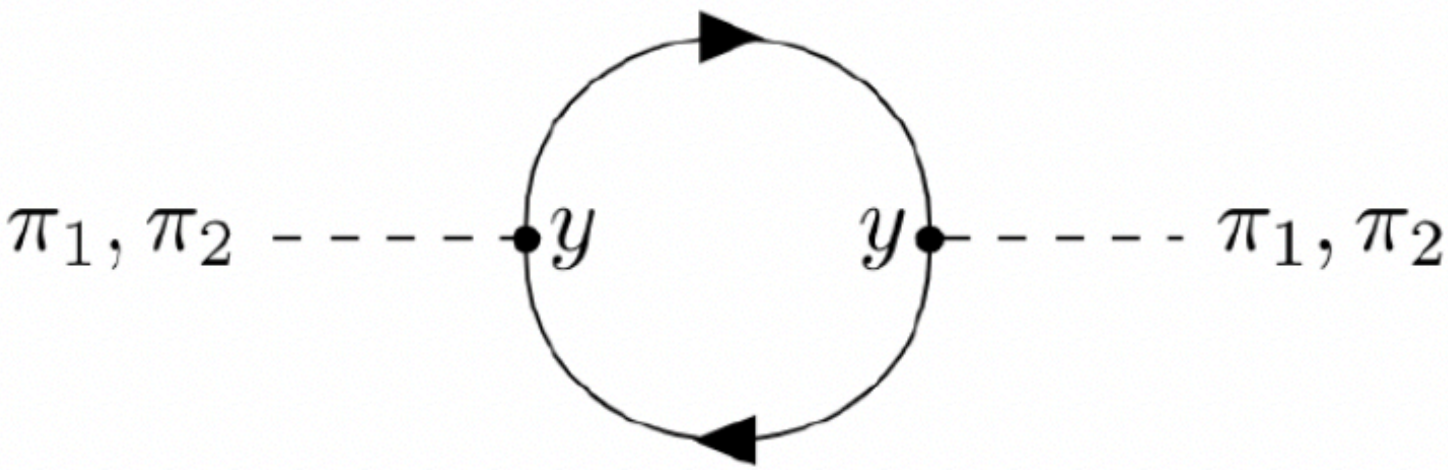
$$\mathcal{L}_{\text{int}} = \left[y_{\not{G}} \begin{pmatrix} \{\overline{\Psi}_2\Psi_3\} \\ \{\overline{\Psi}_3\Psi_1\} \\ \{\overline{\Psi}_1\Psi_2\} \end{pmatrix} + y_G \begin{pmatrix} [\overline{\Psi}_2\Psi_3] \\ [\overline{\Psi}_3\Psi_1] \\ [\overline{\Psi}_1\Psi_2] \end{pmatrix} \right] \cdot \phi$$

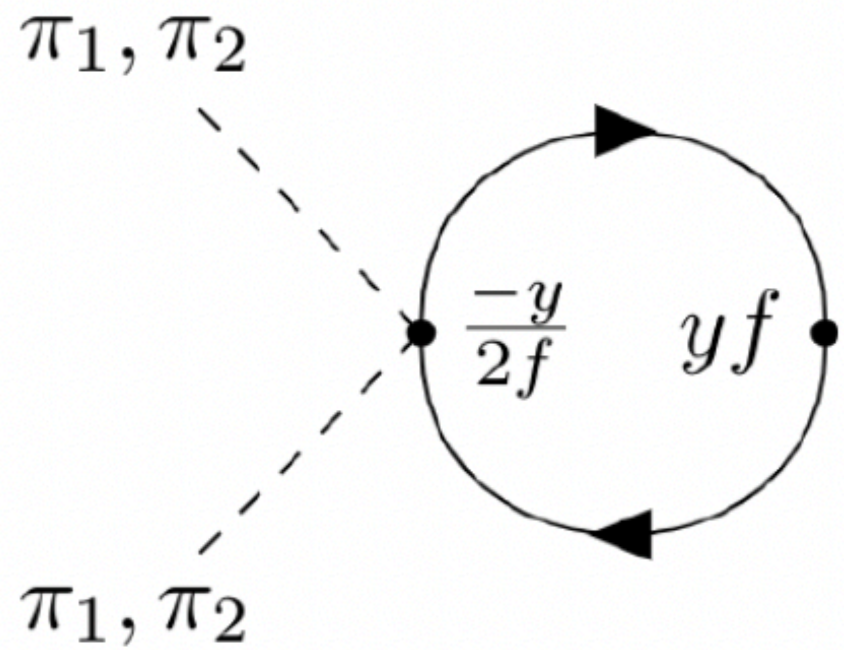
SO(3) breaking
and
A$_4$ invariant

SO(3) invariant

$A_4 \subset SO(3)$

the quantum quadratic corrections





exactly cancel:

$$\delta m^2_{\pi_{1,2}} \propto \quad \frac{1}{2} y_{\not{G}}^2 \Lambda^2 - \frac{y_{\not{G}}}{2f} y_{\not{G}} f \Lambda^2 = 0$$

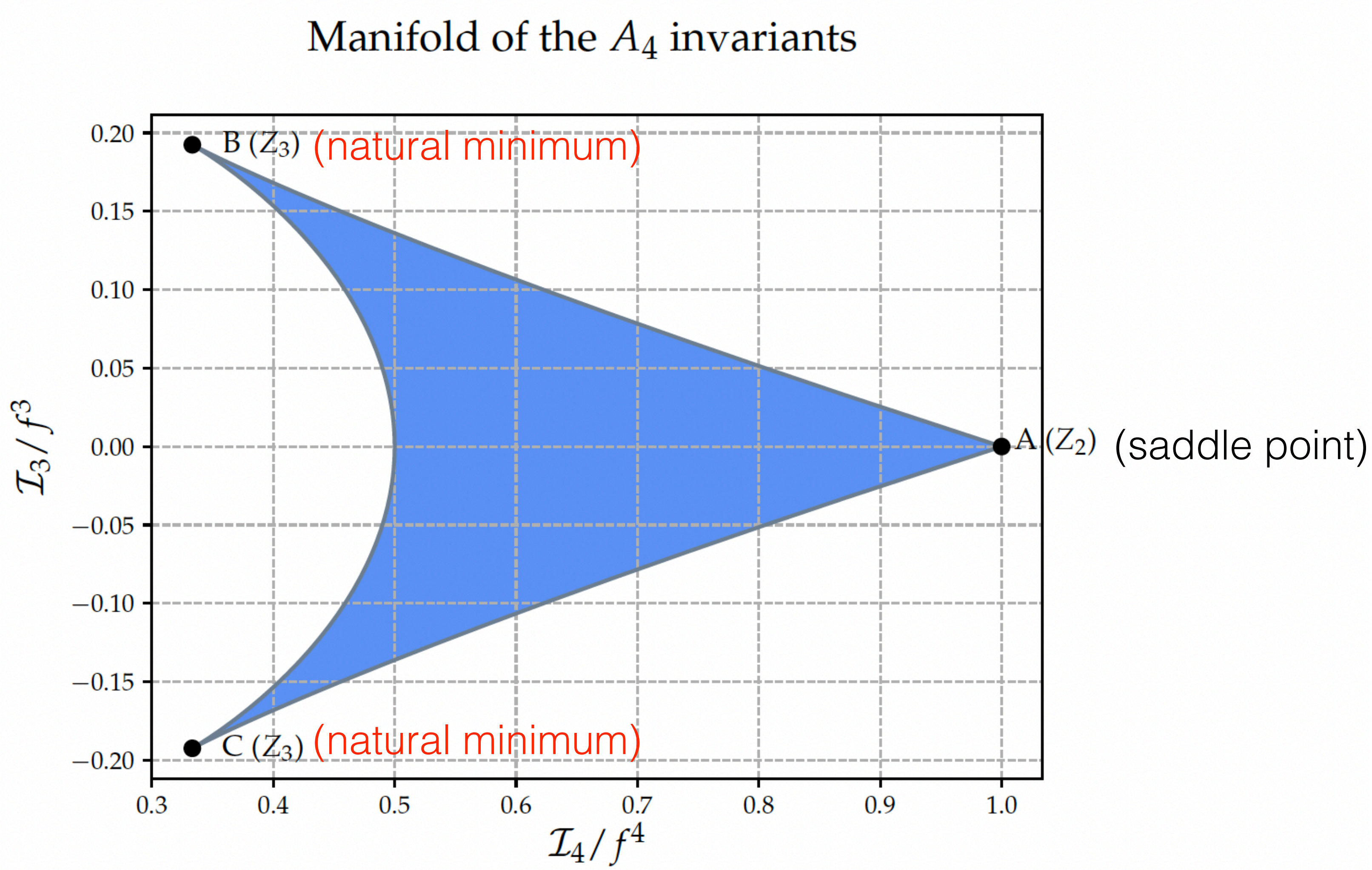
—> The same happens with loops of BSM scalars

``Natural extrema''

are those that do not depend on the parameters of the potential:

they are extrema of all the possible invariants

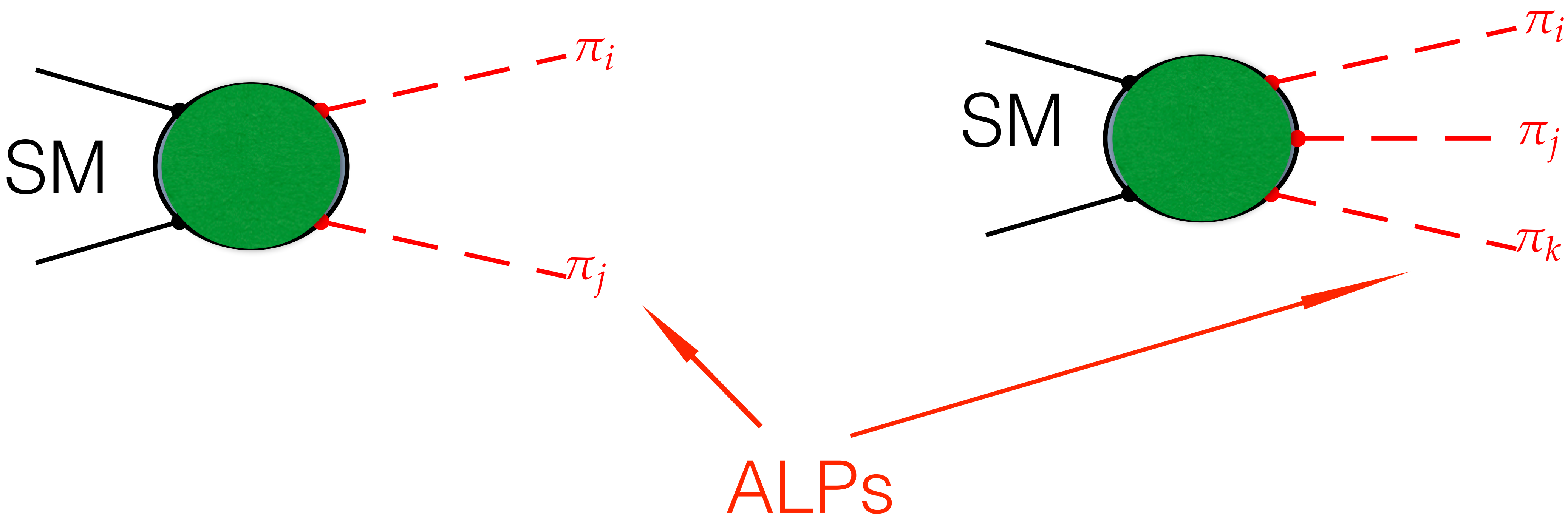
e.g. a scalar triplet of A_4:



* We explored the natural minima and discovered that **a discrete subgroup remains explicit in their 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 their 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

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

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)

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

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

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

Trapped misalignment: a pure temperature effect

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

* The onset of oscillations is delayed

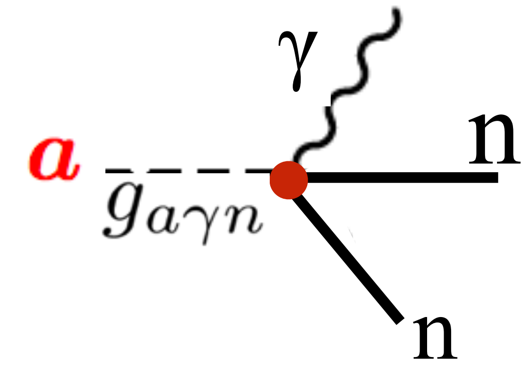
* Less dilution = more DM

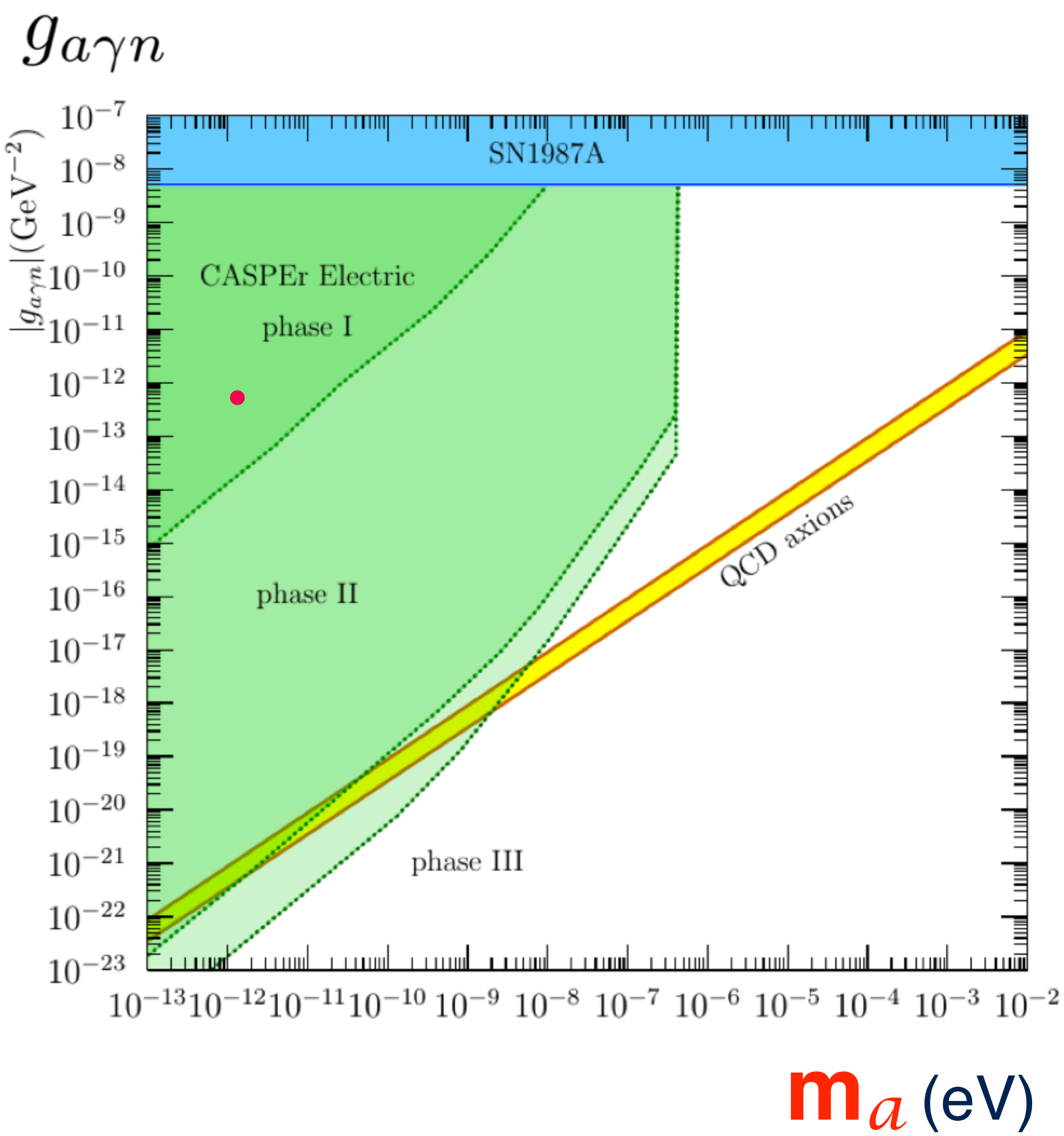
* After trapping, the axion can have enough kinetic energy to overfly many times the barrier—> further dilution: **trapped +kinetic** mislaign.

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:

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

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

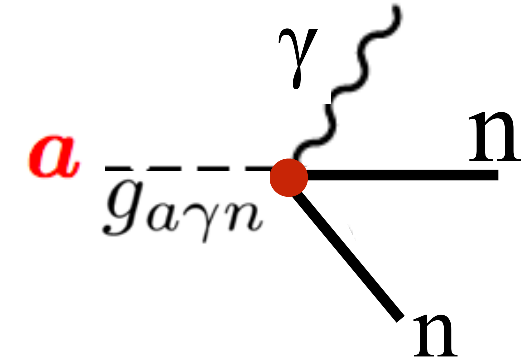
$$\equiv g_{a\gamma n}$$

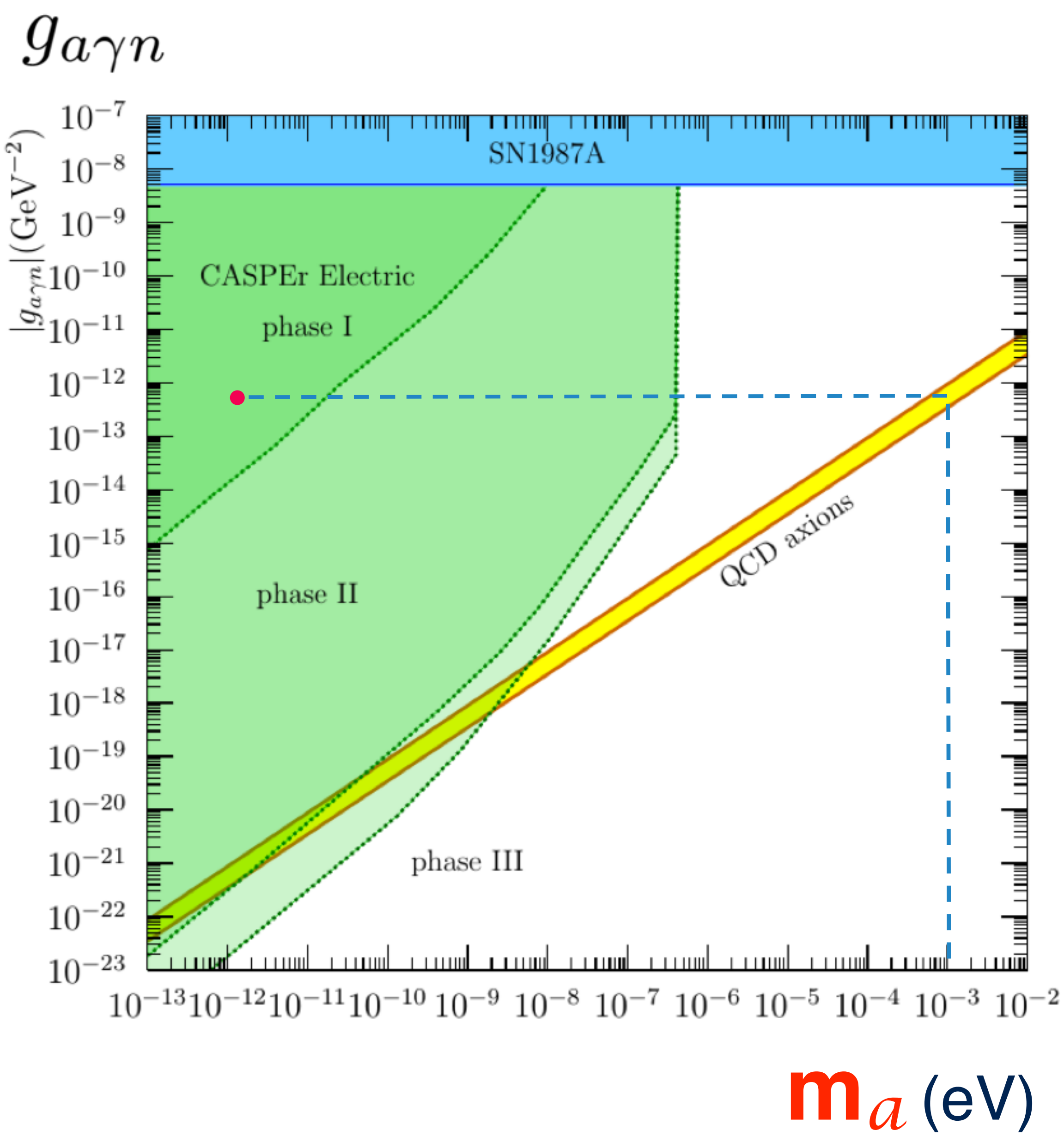
$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u+m_d)^2}$$

Coupling to the nEDM

Axion mass

Could Casper Phase I detect an axion ?





Canonical QCD axion:

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

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

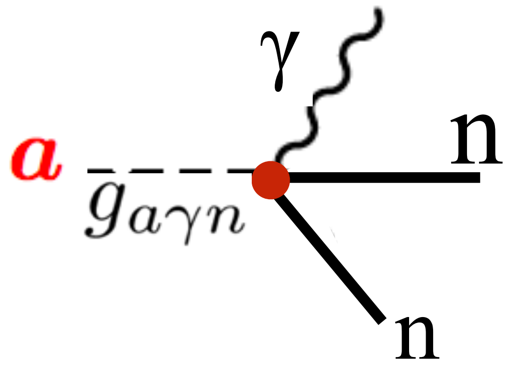
$$\equiv g_{a\gamma n}$$

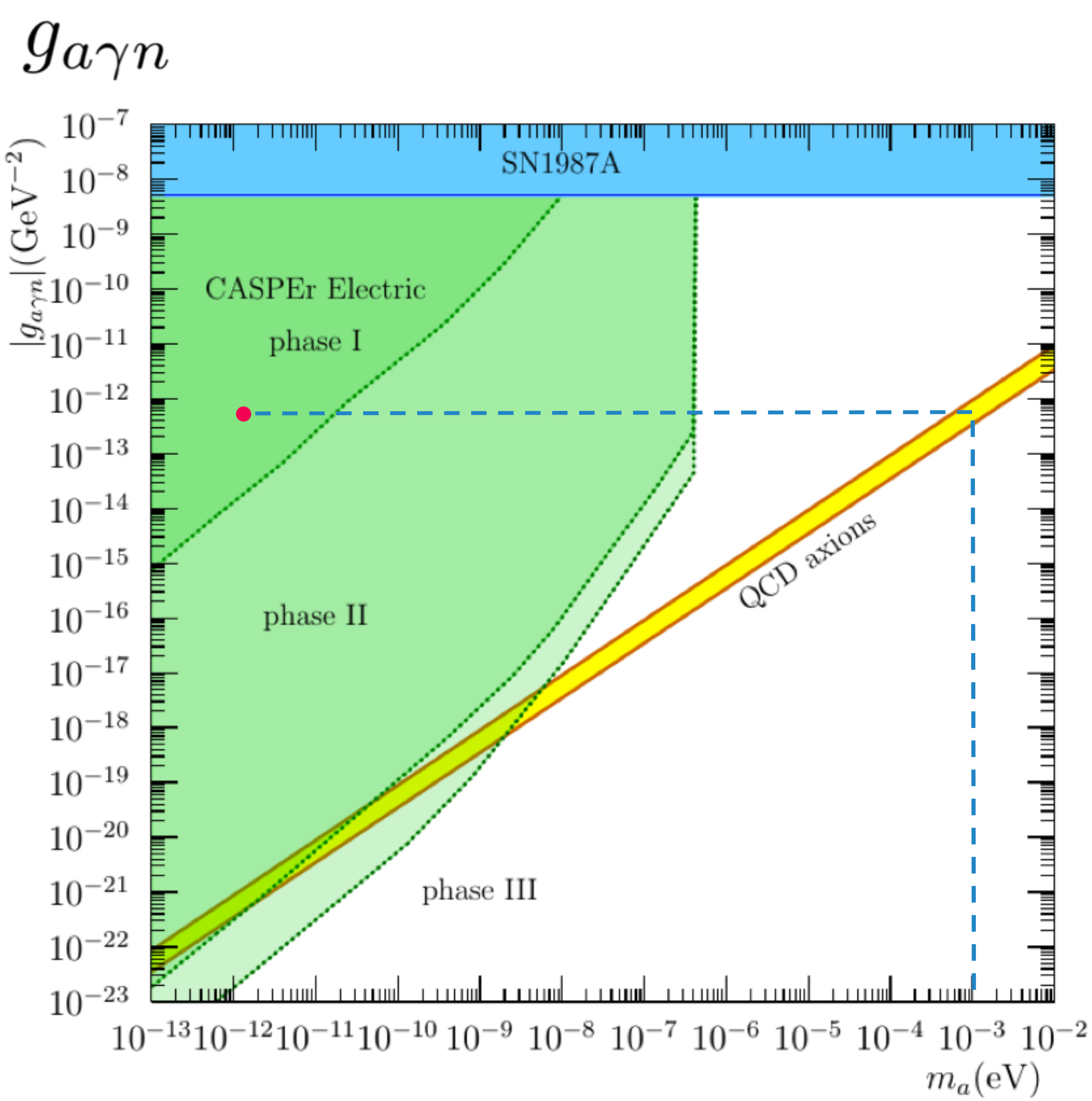
Coupling to the nEDM

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

Axion mass

Could Casper Phase I detect an axion ?





Canonical QCD axion:

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

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

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

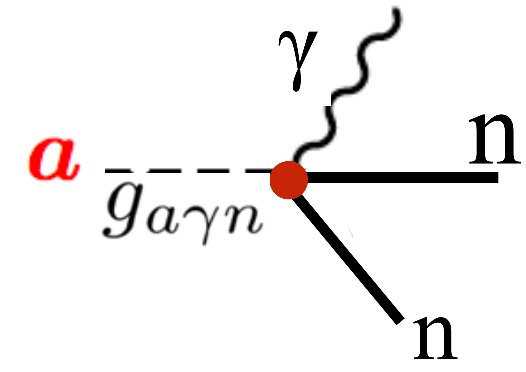
Coupling to the nEDM

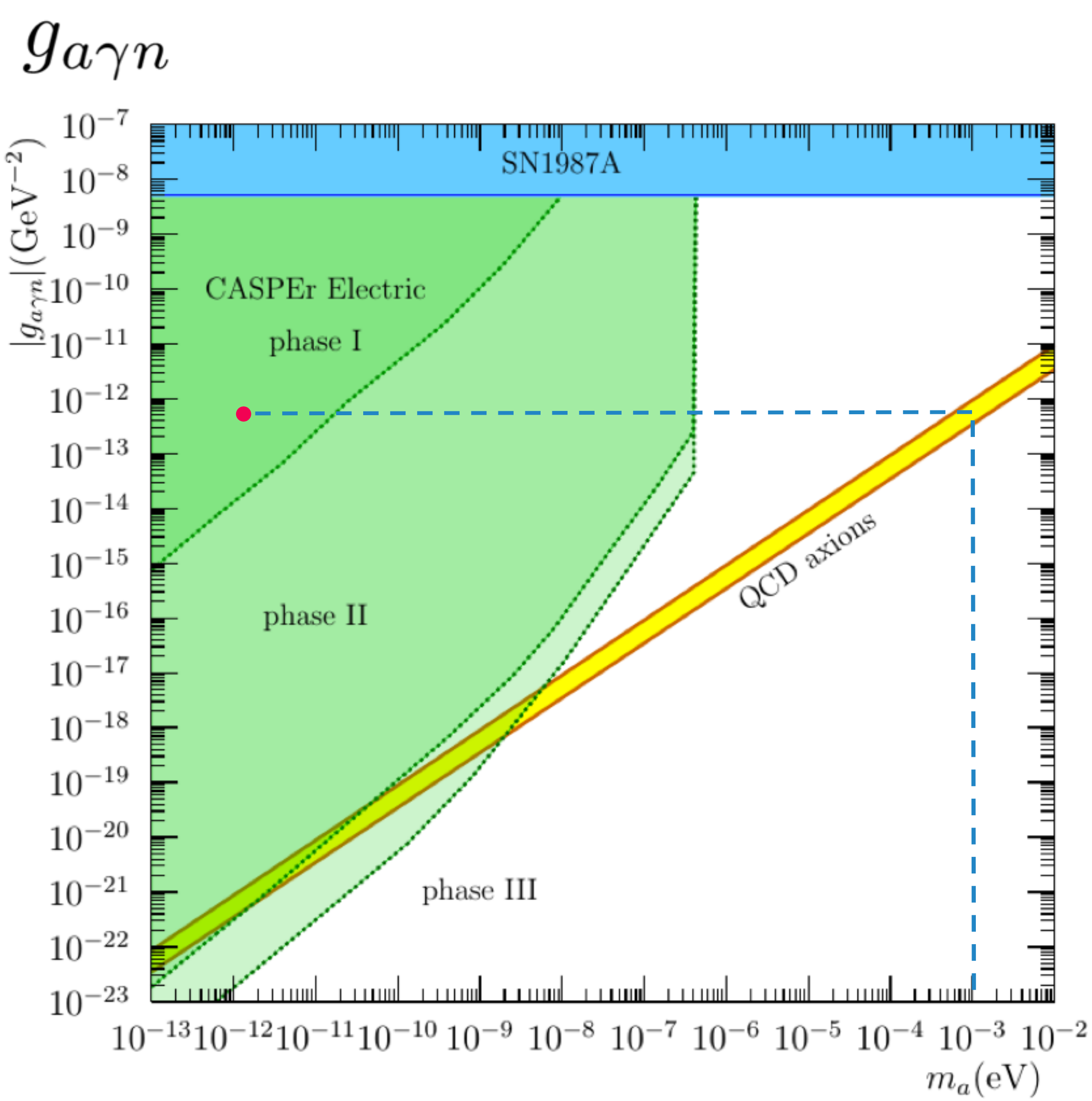
$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u+m_d)^2}$$

Axion mass

No signal possible from a canonical QCD axion

Could Casper Phase I detect an 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

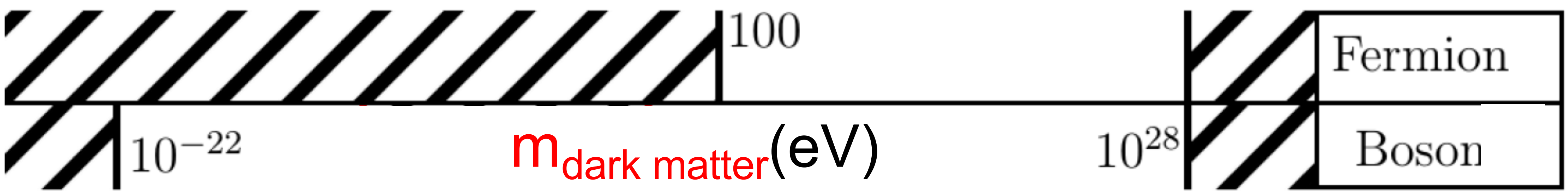
No signal possible from a canonical QCD axion

Signal possible from a Z_N axion

85% of matter is dark

what is it?

Is it a new type of particle? what mass?

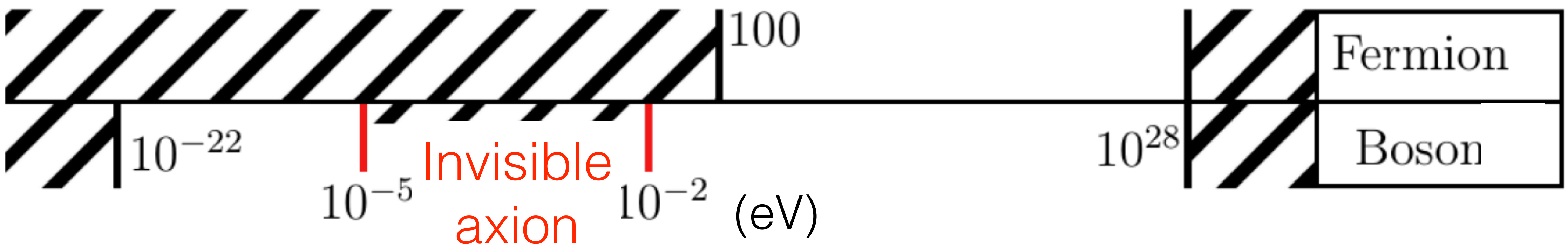


Does it feel anything else than gravity?

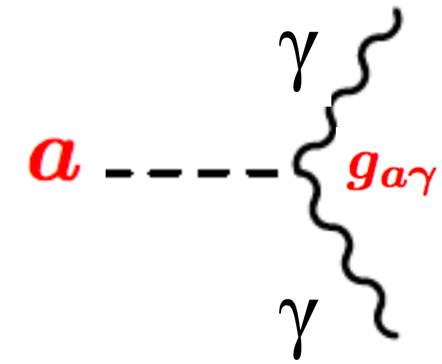
85% of matter is dark

what is it?

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

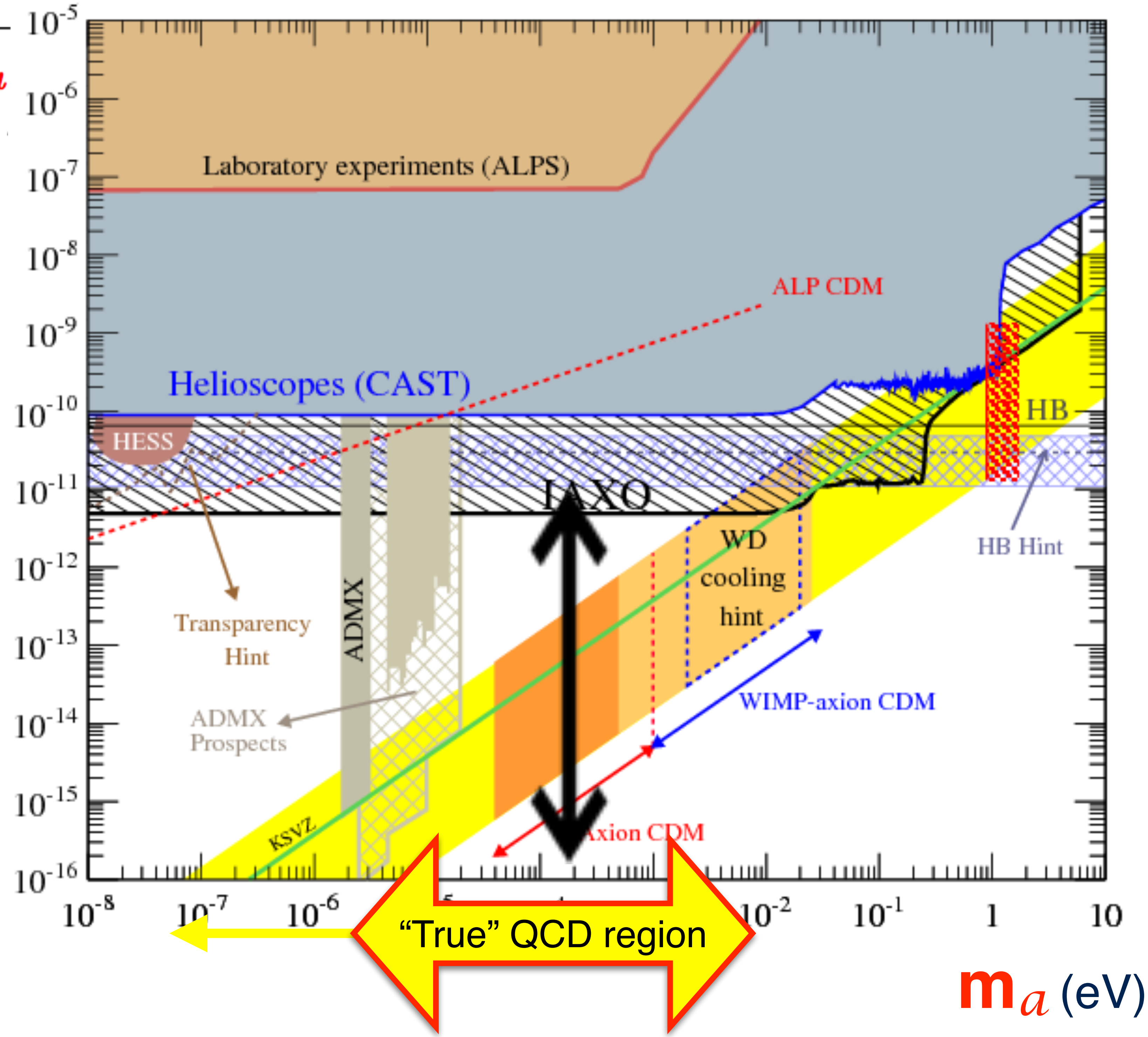


Intensely looked for experimentally…



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

(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

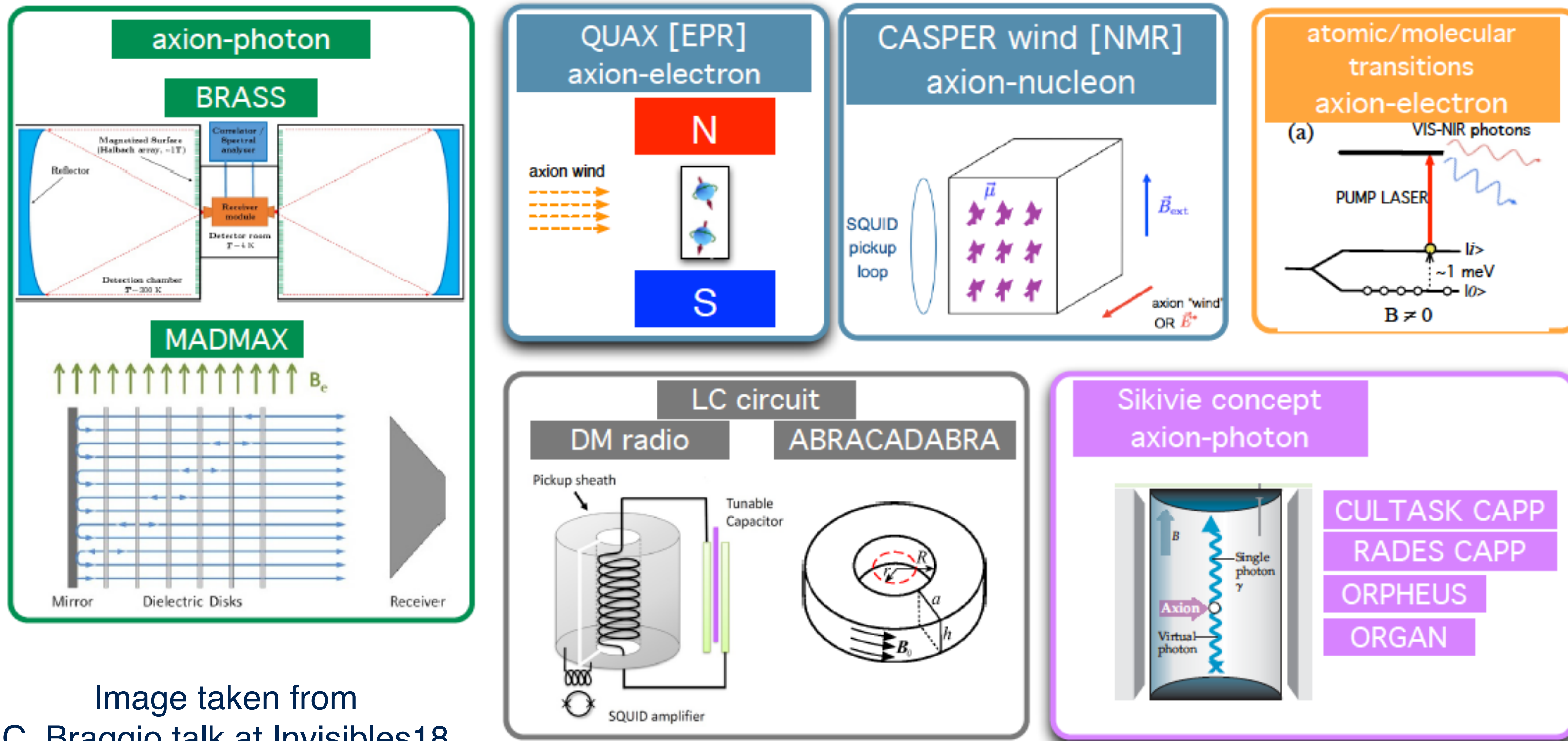
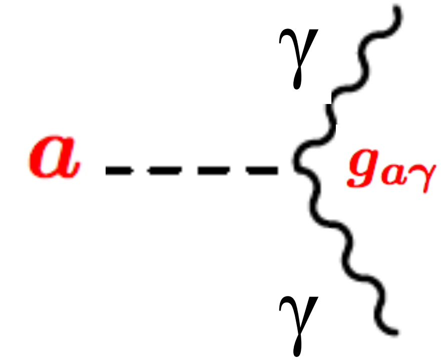


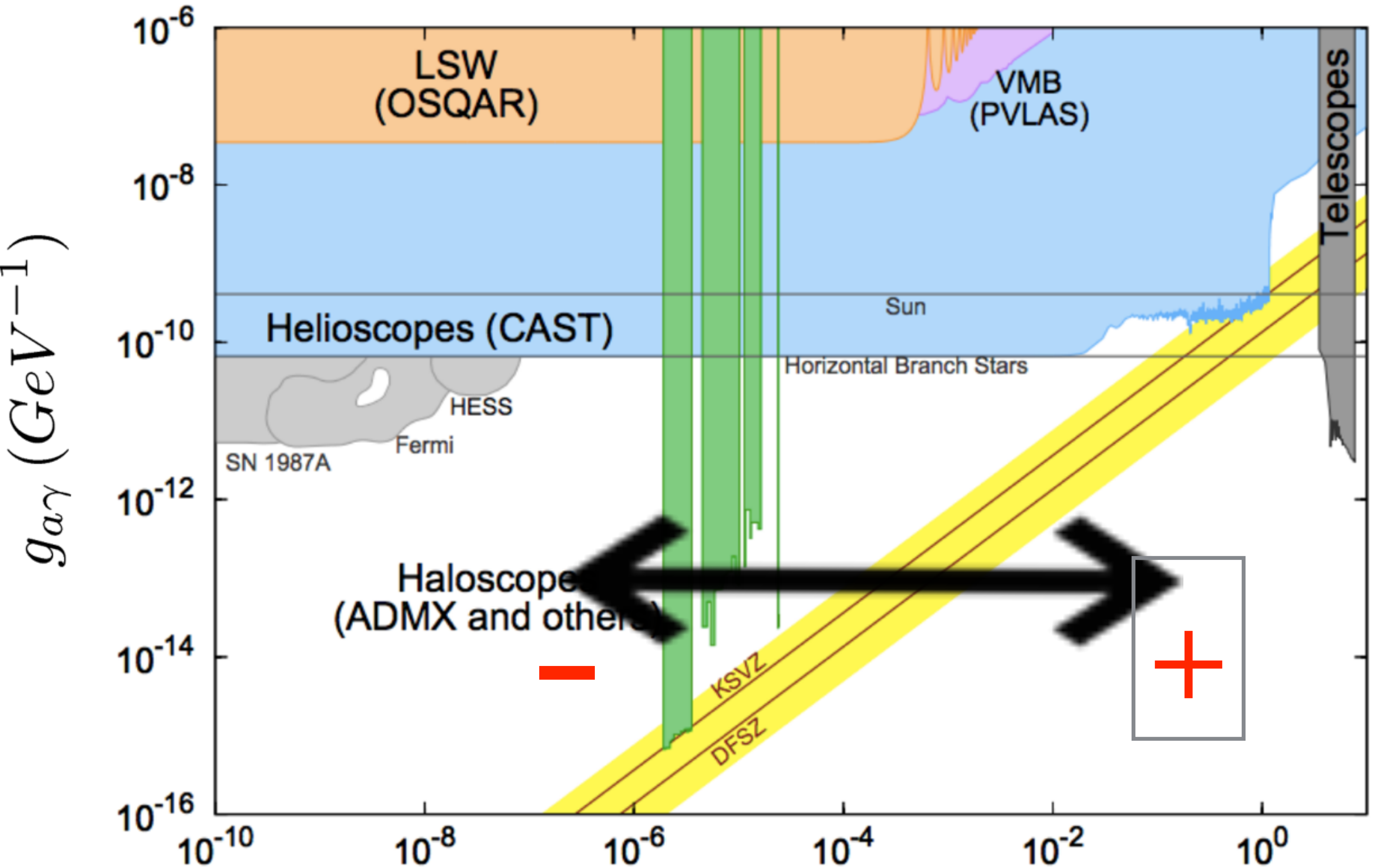
Image taken from
C. Braggio talk at Invisibles18

plus LHC !

Intensely looked for experimentally…



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



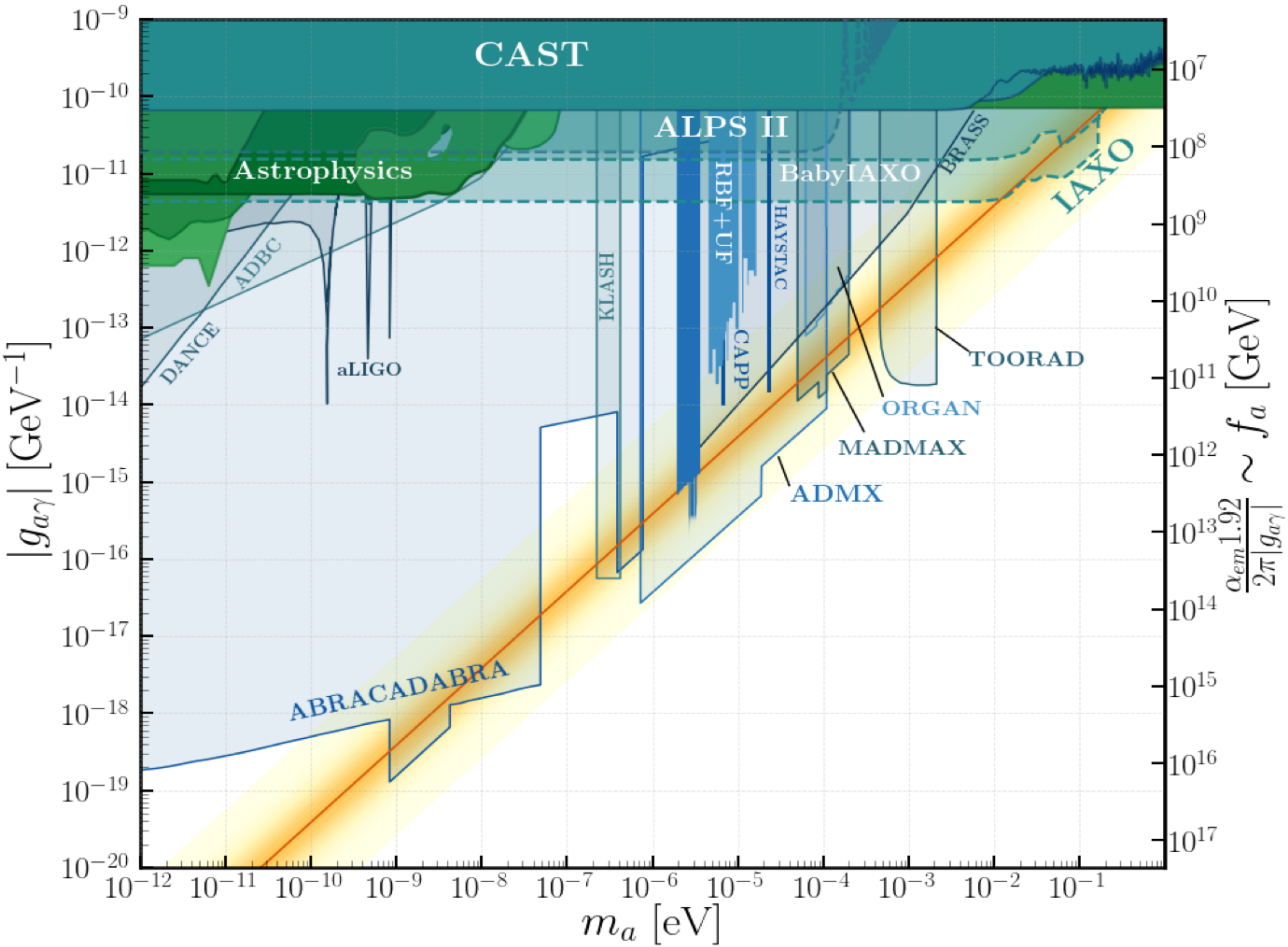
m_a (eV)

[Ringwald, PDG 17]

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

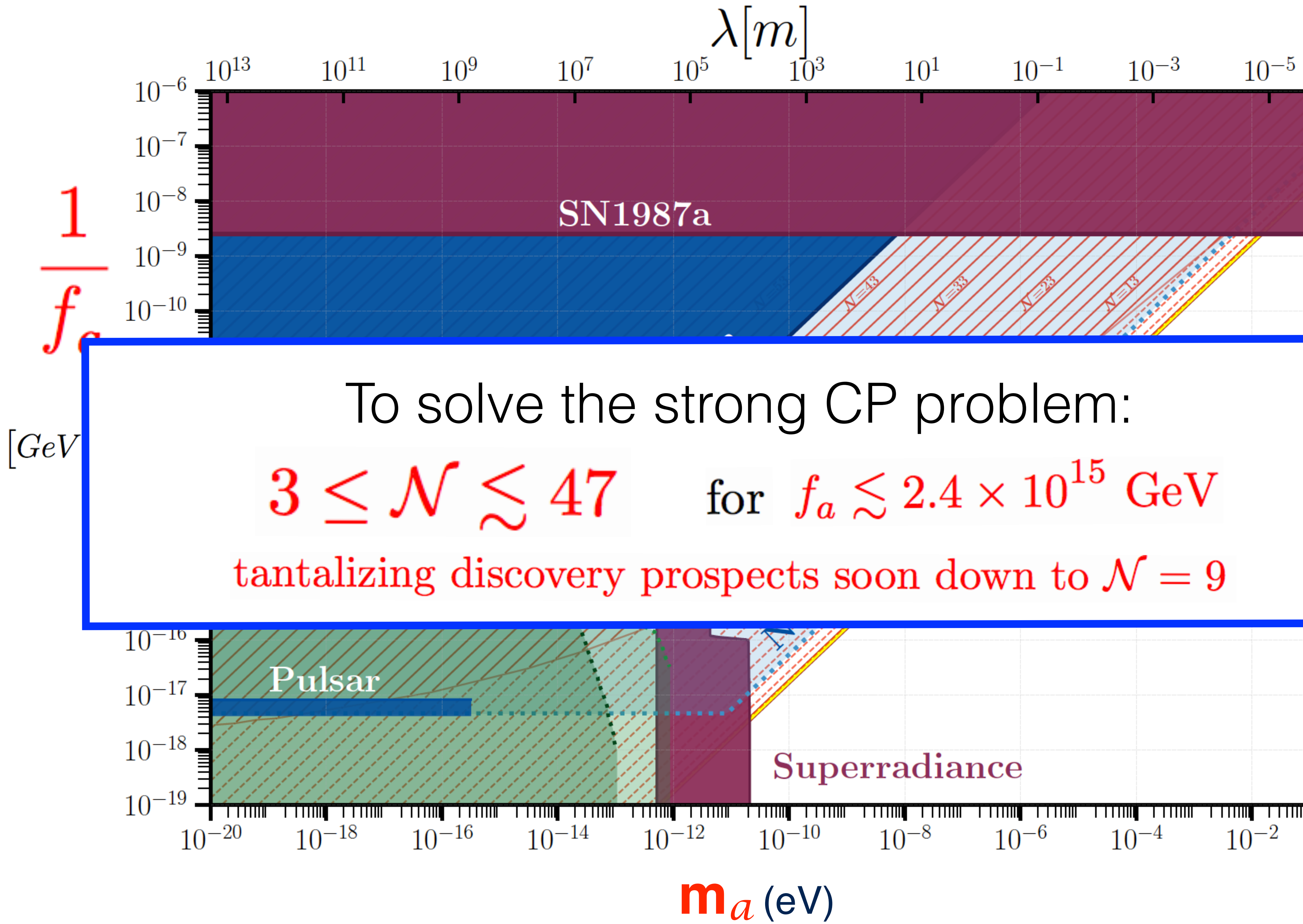
$$g_{a\gamma\gamma} \propto \frac{1}{f_a} \quad \Longrightarrow \quad g_{a\gamma\gamma} \propto m_a$$

… and theoretically



courtesy of Pablo Quilez

Model-independent bounds from high-density objects



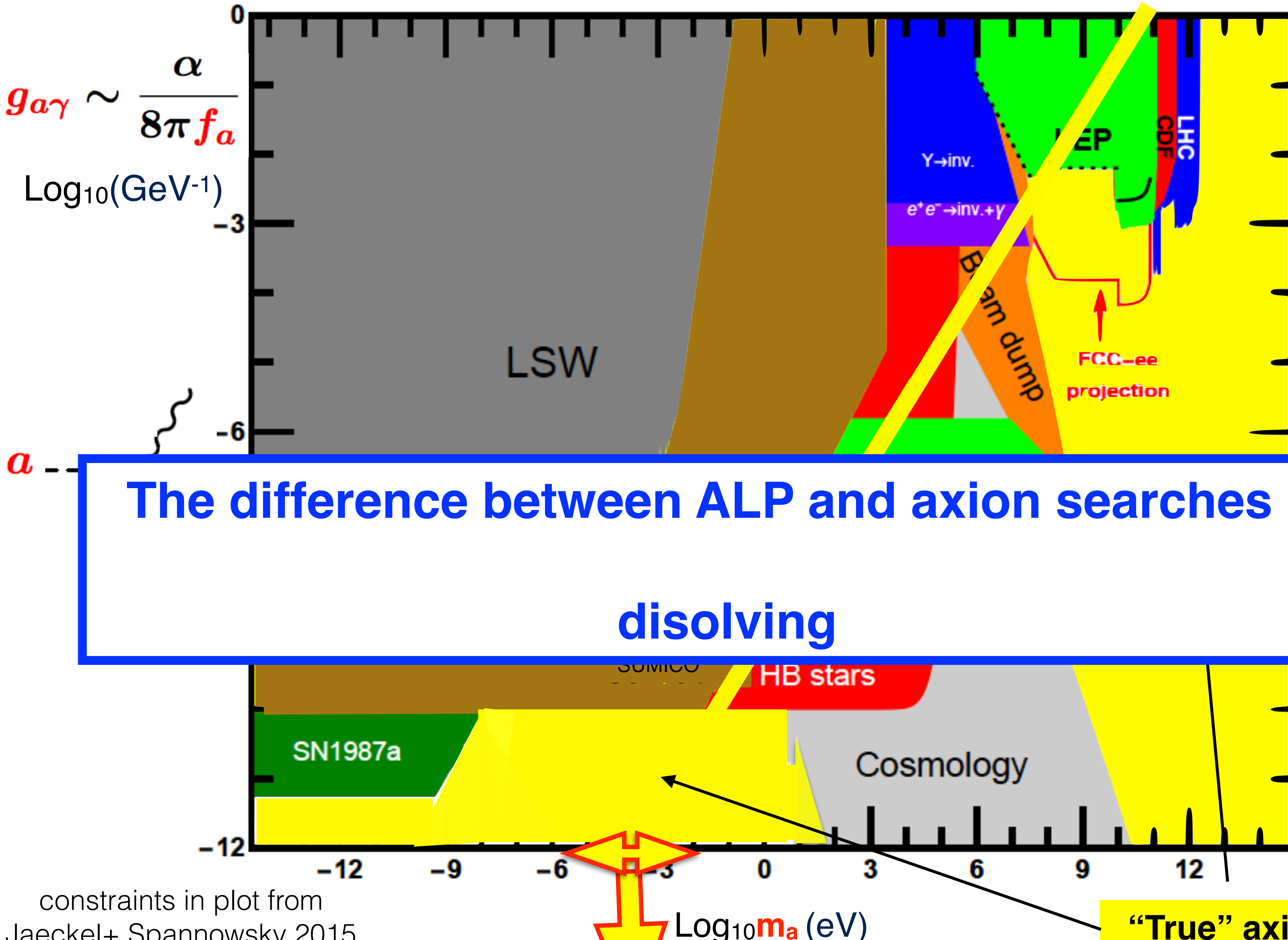
To solve the strong CP problem:

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

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

Di Luzio, Quilez, Ringwald, BG arXiv 2102.00012

ALPs territory: they can be true axions



The difference between ALP and axion searches is disolving

constraints in plot from Jaeckel+ Spannowsky 2015

"True" QCD axion

"True" axion region has amplified

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

Or simply the first one discovered?

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

Or simply the first one discovered?

What about a singlet (pseudo) scalar?

Strong motivation from fundamental issues of the SM