Axion and Axion-like Particles

recent progress

Bethe Forum ``Axions´´

Bonn October 10-14 2022

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Univ. Autónoma de Madrid and IFT

UNIVERSIDAD AUTONOMA DE MADRID

ift

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?

The spin 0 window

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

The spin 0 window

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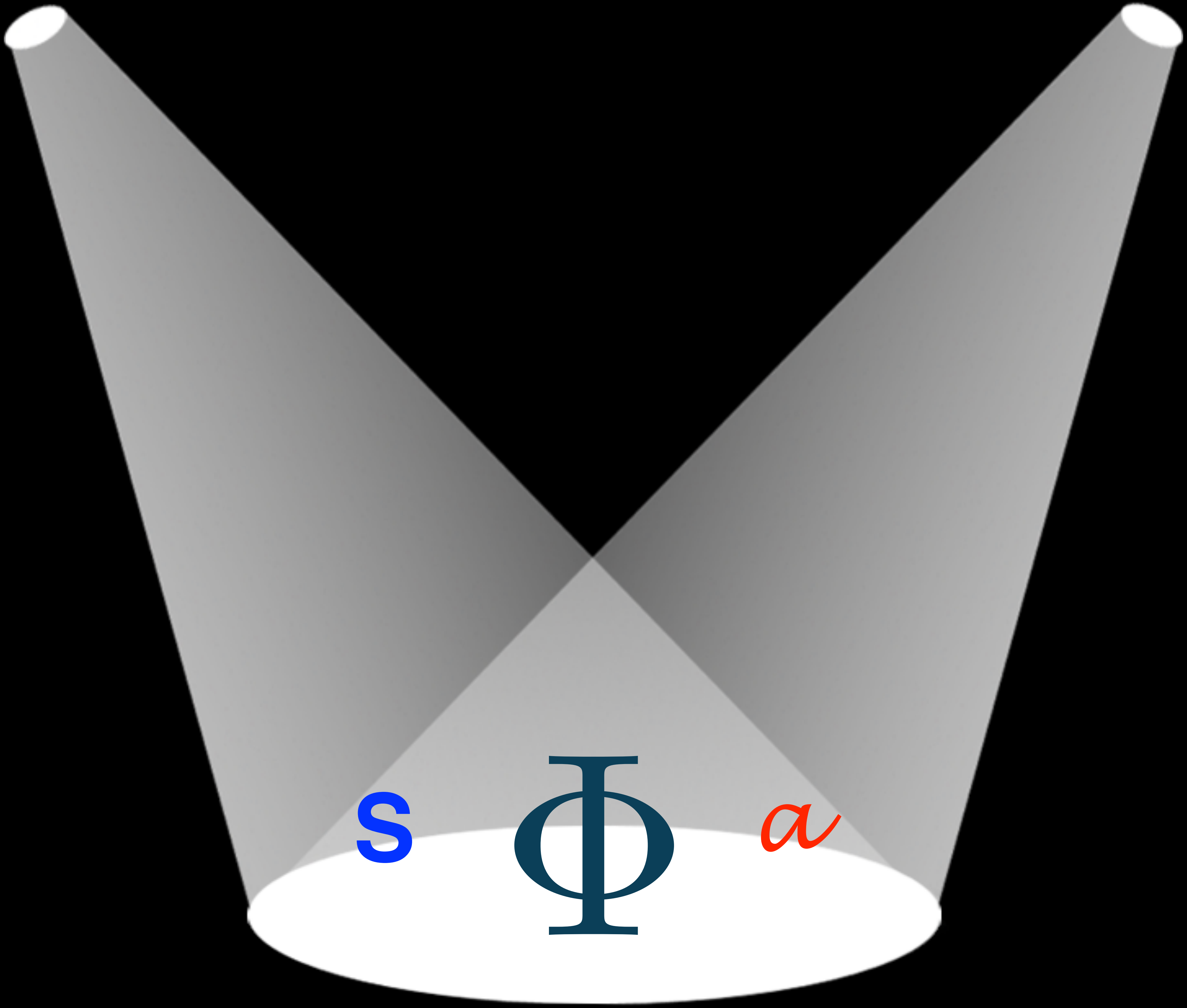
What about a singlet (pseudo) scalar?

Strong motivation from fundamental problems of the SM



Rocio del Rey

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

The nature of DM is unknown

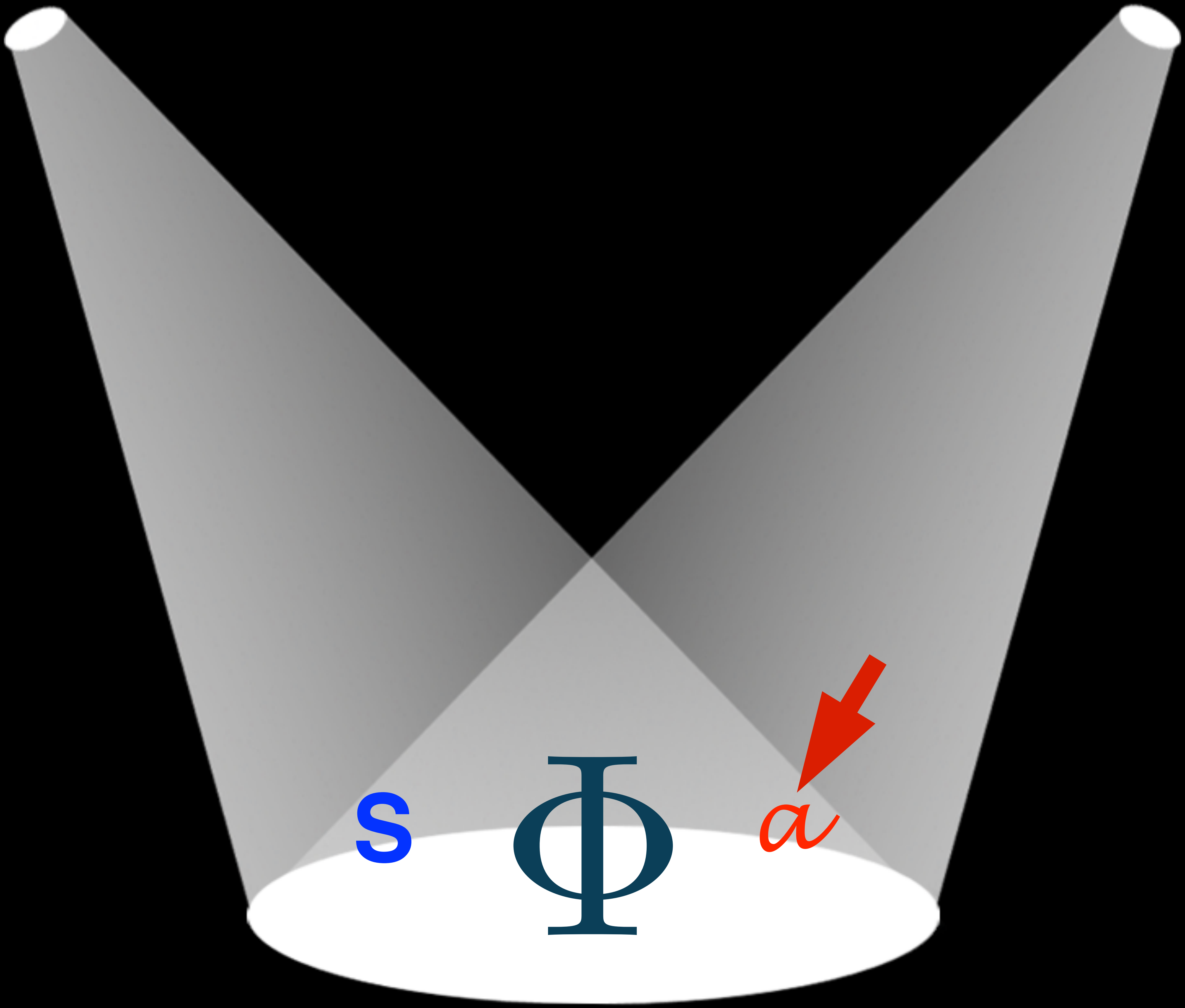
It may be a (SM singlet) scalar S

the "Higgs portal"

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

S has polynomial couplings

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



Rocio del Rey

Many small unexplained SM parameters

Hidden symmetries
can explain small parameters

↓

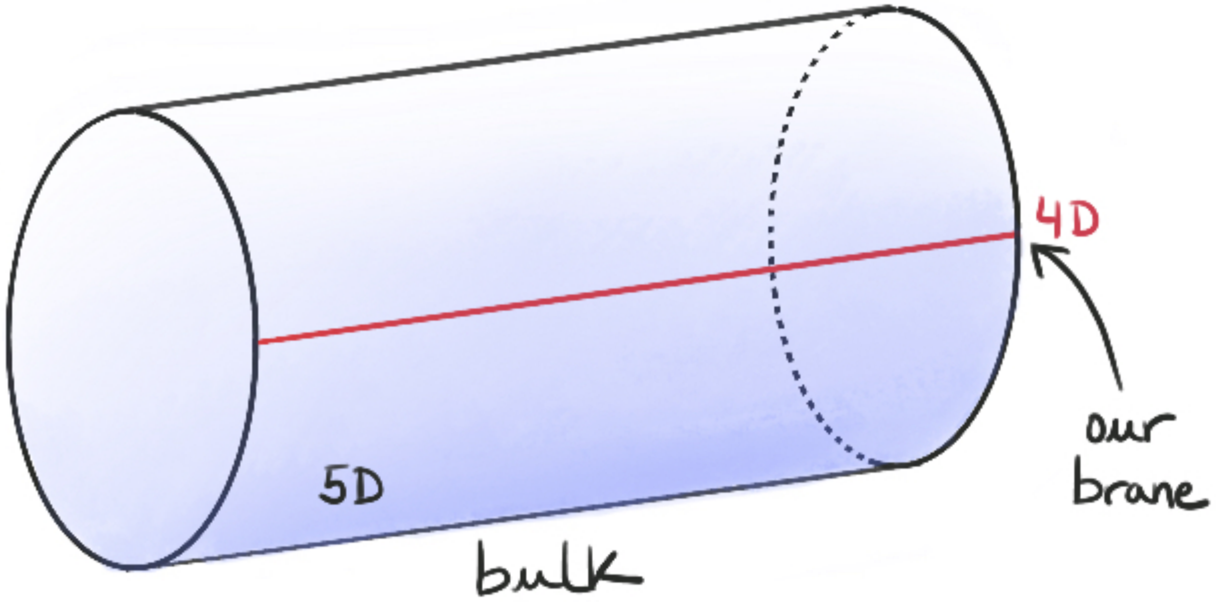
If spontaneously broken:
Goldstone bosons a

—> derivative couplings to SM particles

(Pseudo)Goldstone Bosons appear in many BSM theories

* e.g. Extra-dim Kaluza-Klein: 5d gauge field compactified to 4d

The Wilson line around the circle is a GB, which behaves as an axion in 4d



* Majorons, for dynamical neutrino masses

* From string models

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

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

……

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

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The strong CP problem

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

A dynamical $U(1)_A$ solution

→ a pGB: the axion a

couplings prop. to $\partial_\mu a$

i.e., invariant under $a \longrightarrow a$ +cte.

(plus anomalous couplings)

Peccei+Quinn; Wilczek…

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

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

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

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

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

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

$$\vec{E}^2 - \vec{B}^2$$

(CP even)

$$\theta\, \vec{E} \cdot \vec{B}$$

(CP odd)

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

?

$$G_{\mu\nu}\tilde{G}^{\mu\nu} = \partial_\mu(2\epsilon^{\mu\nu\sigma\rho}A_\nu\partial_\sigma A_\rho) \equiv \partial_\mu K^\mu$$

is a total derivative, but for non-abelian gauge symmetries it may have physical impact

(due to field configurations that do not die fast enough at infinity : instants)

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

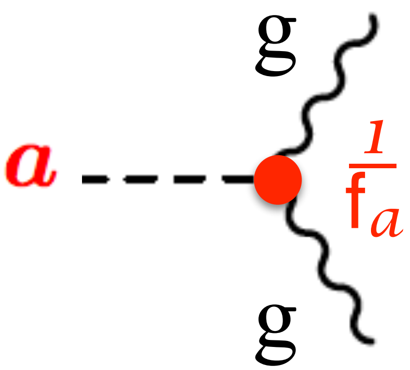
$\bar{\theta} \leq 10^{-10}$

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

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

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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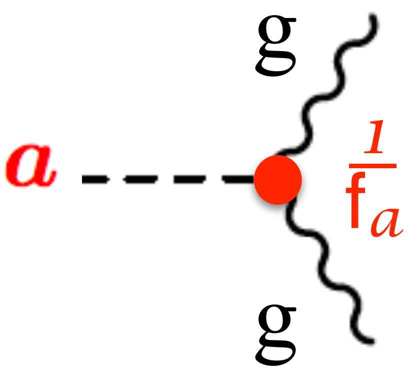

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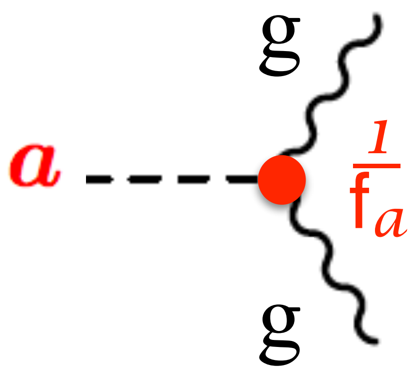

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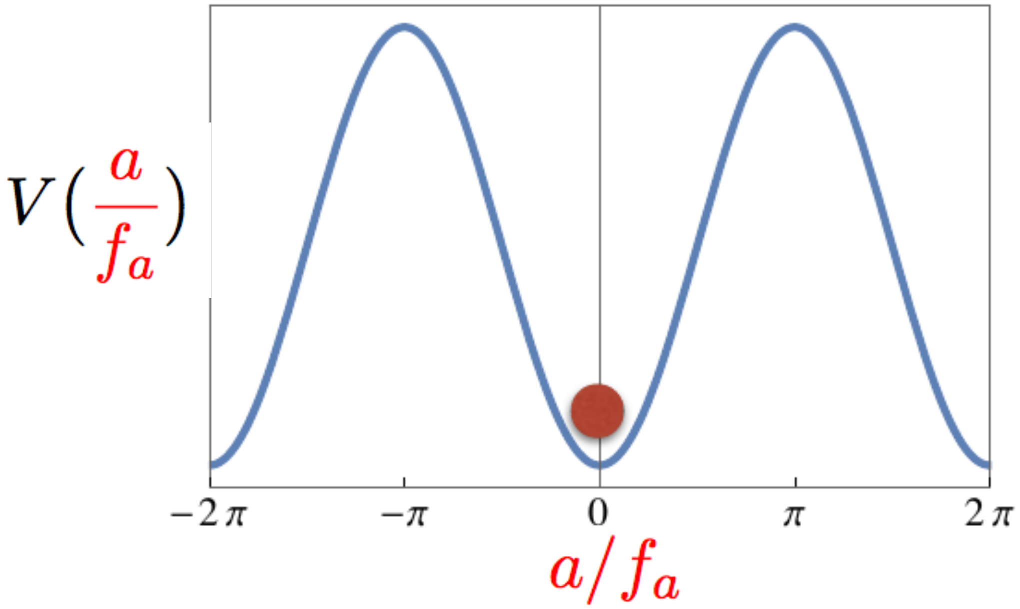

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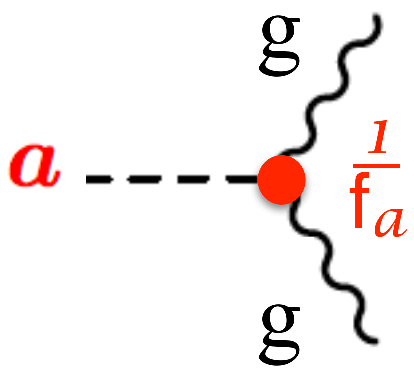

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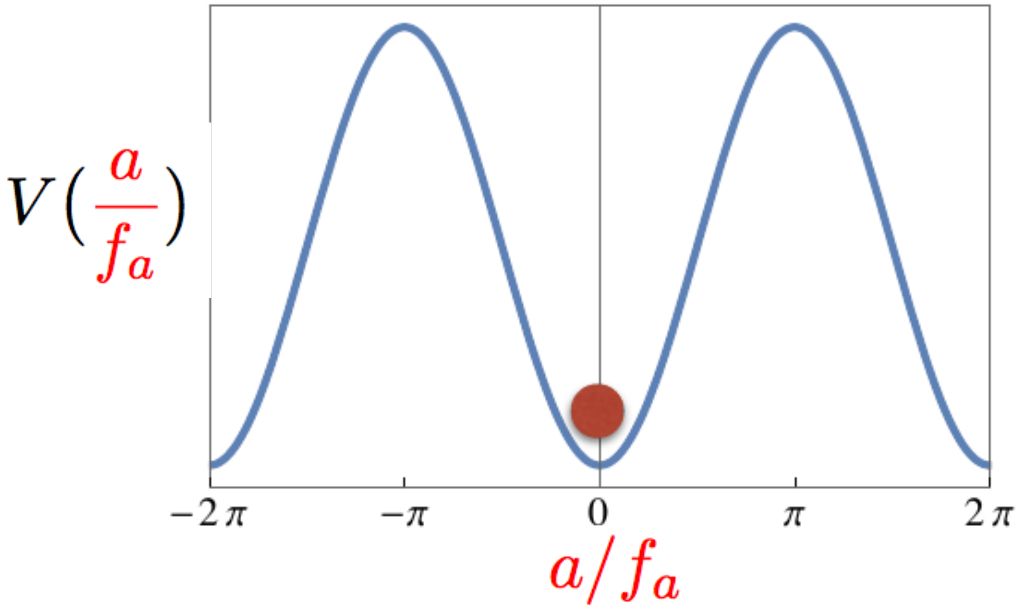
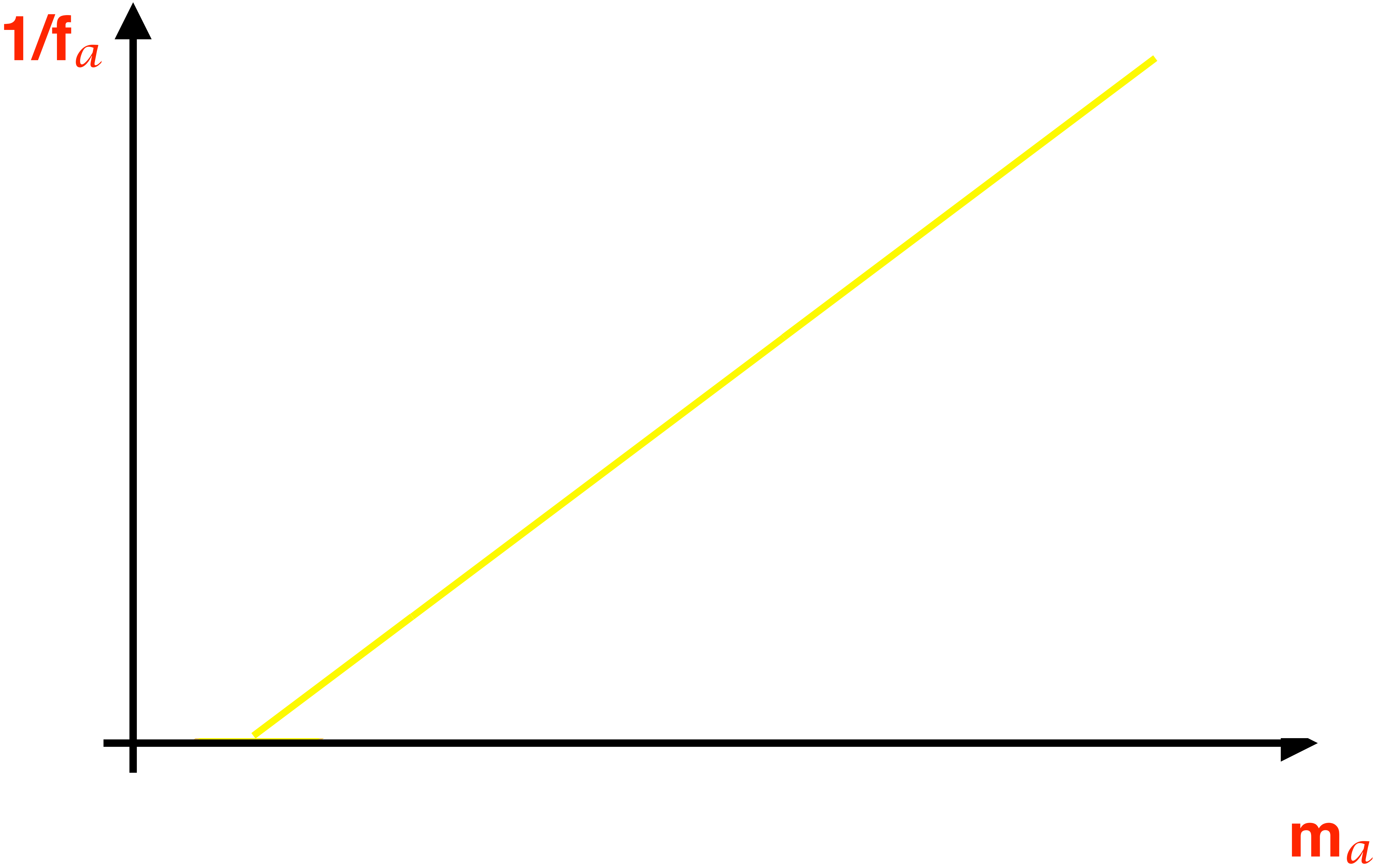


Excellent DM candidate

[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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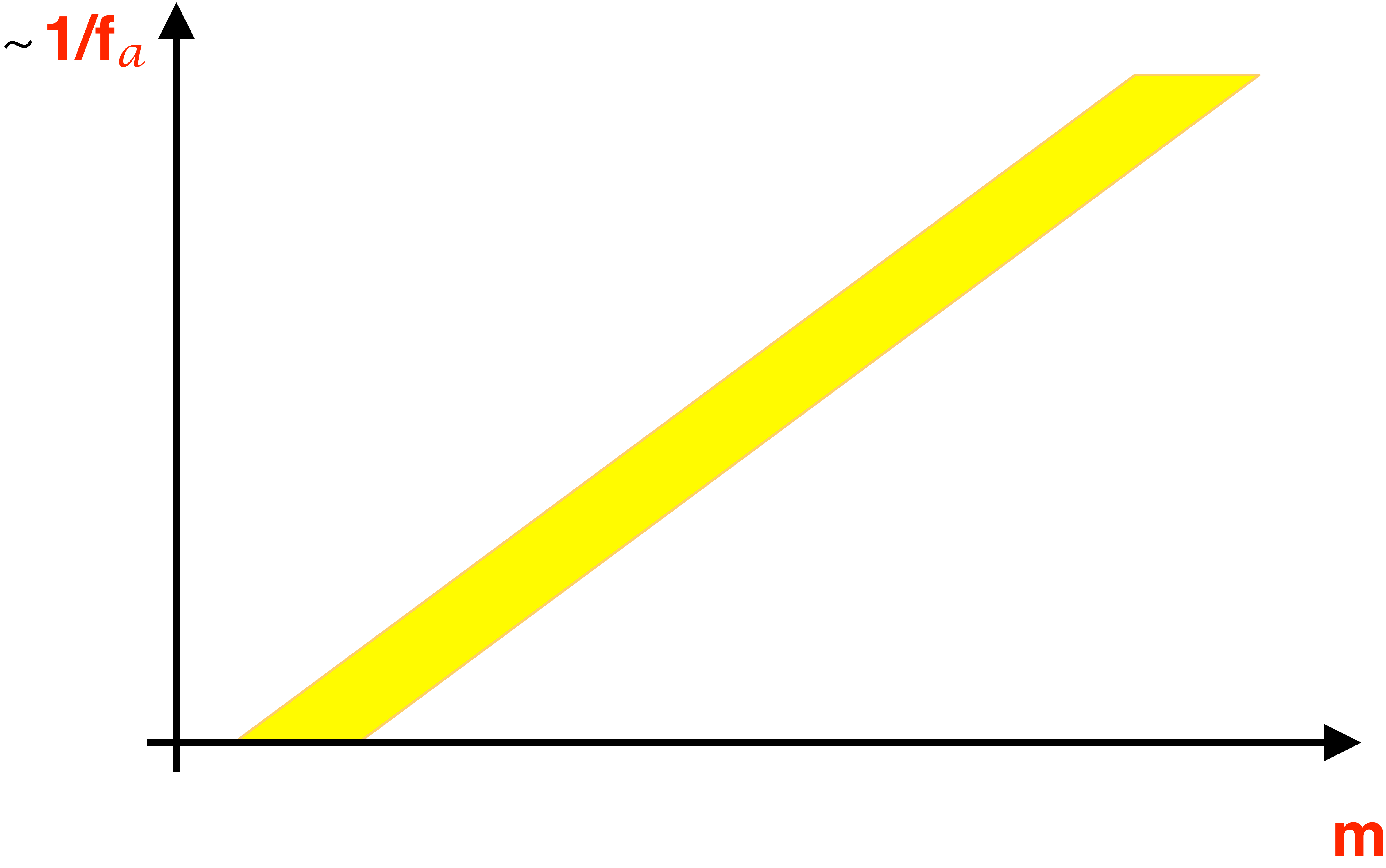

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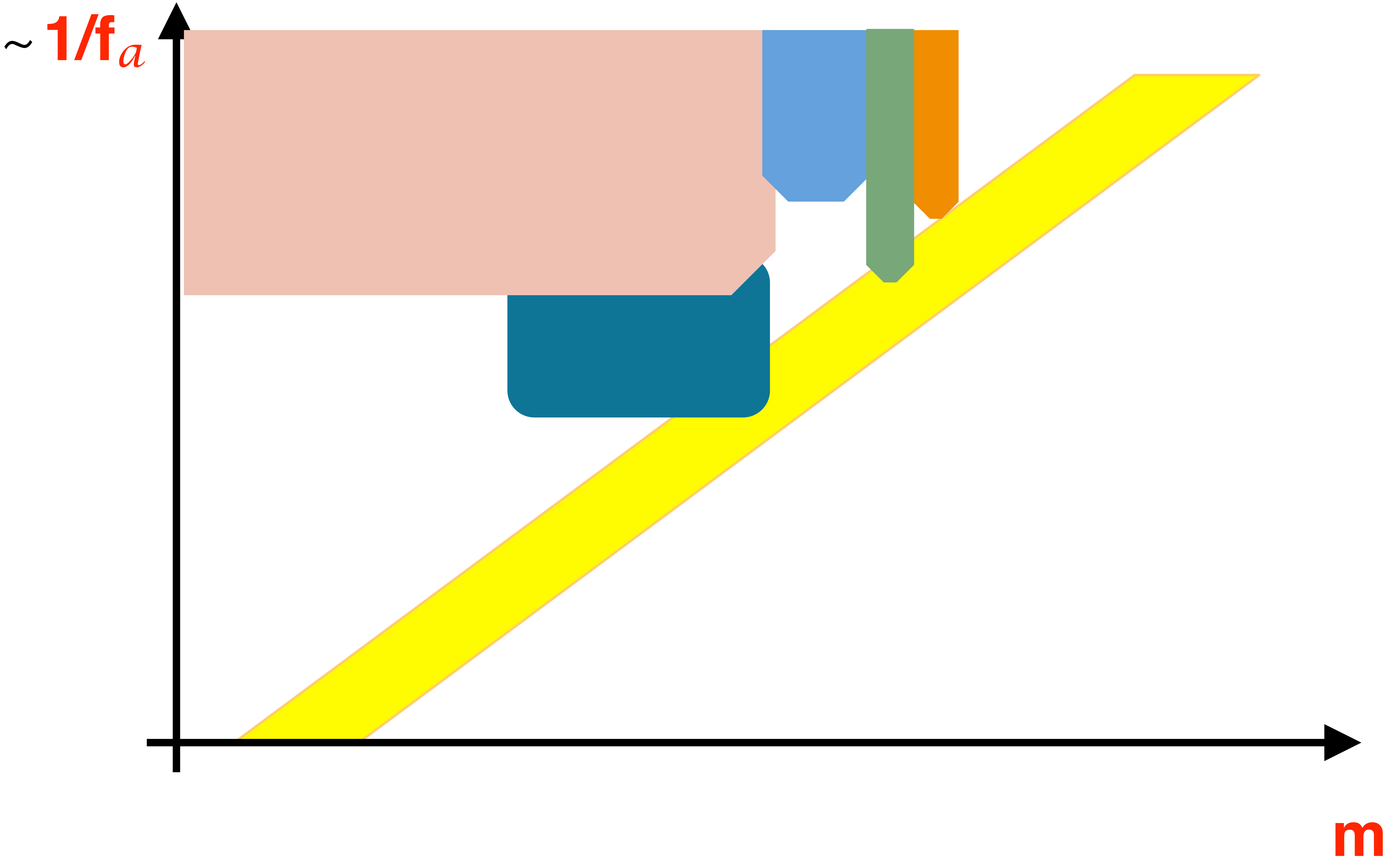

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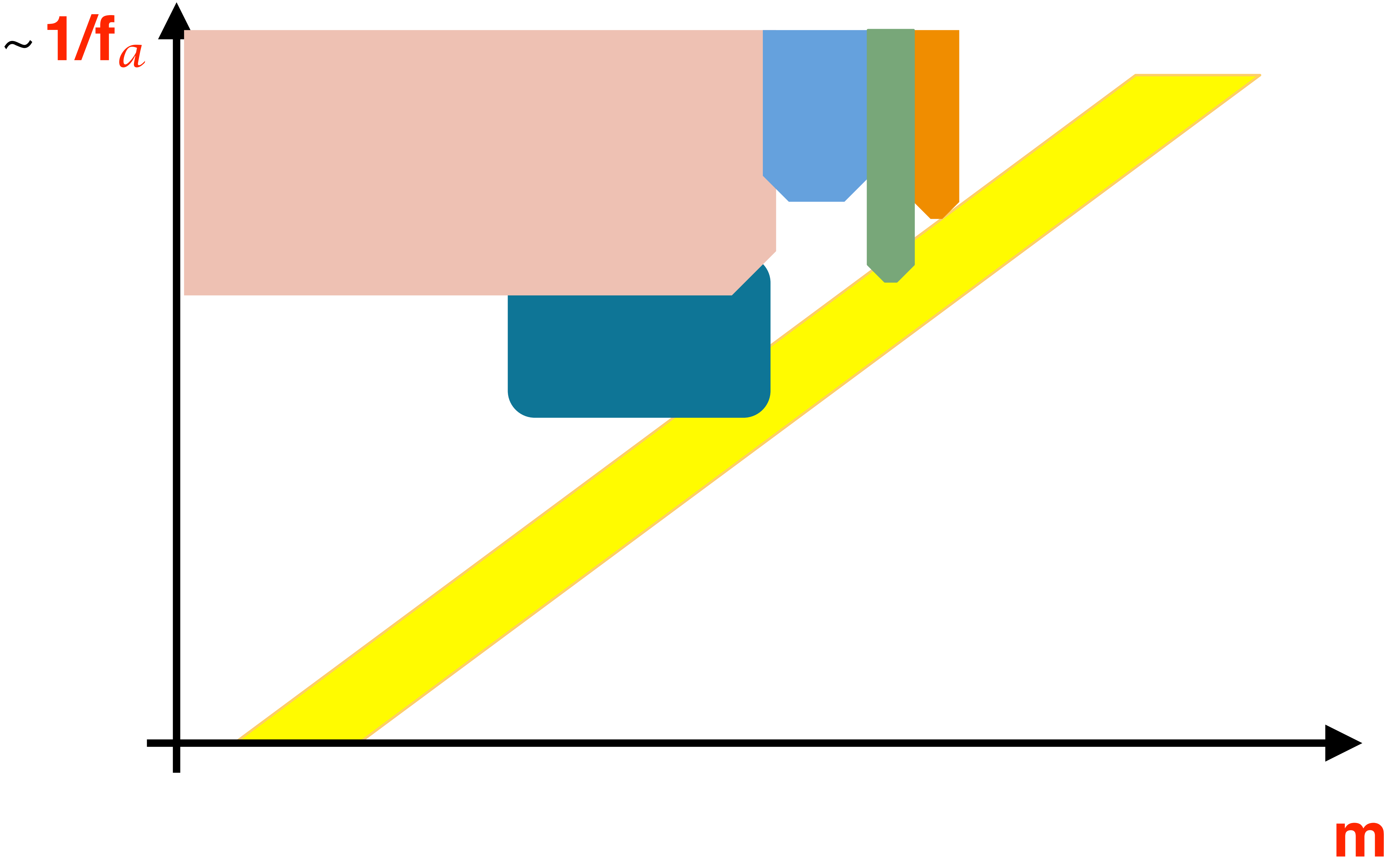

The value of the constant is determined by the strong gauge group

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

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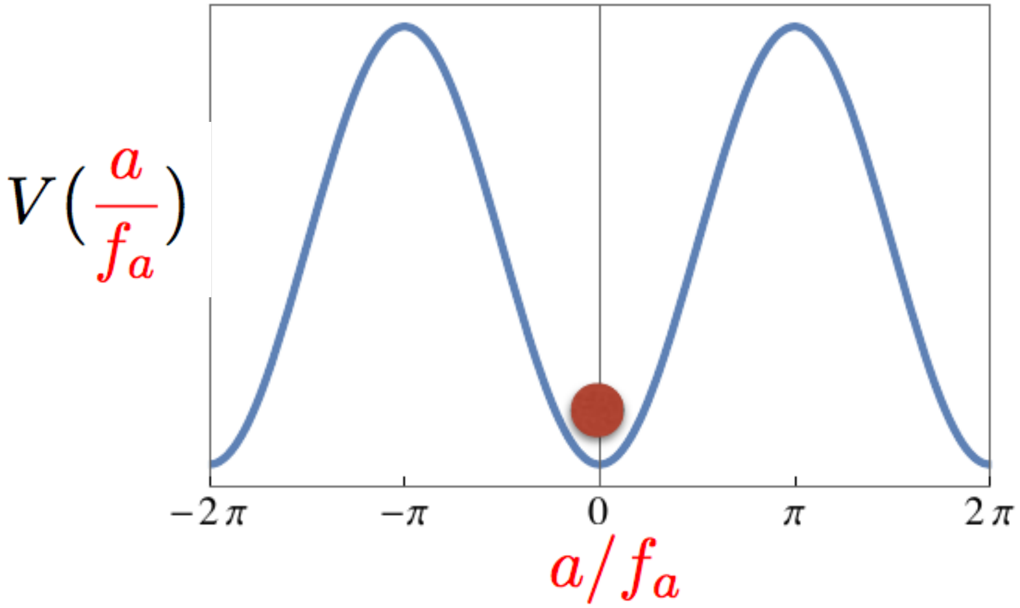
* If the confining group is QCD:



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

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

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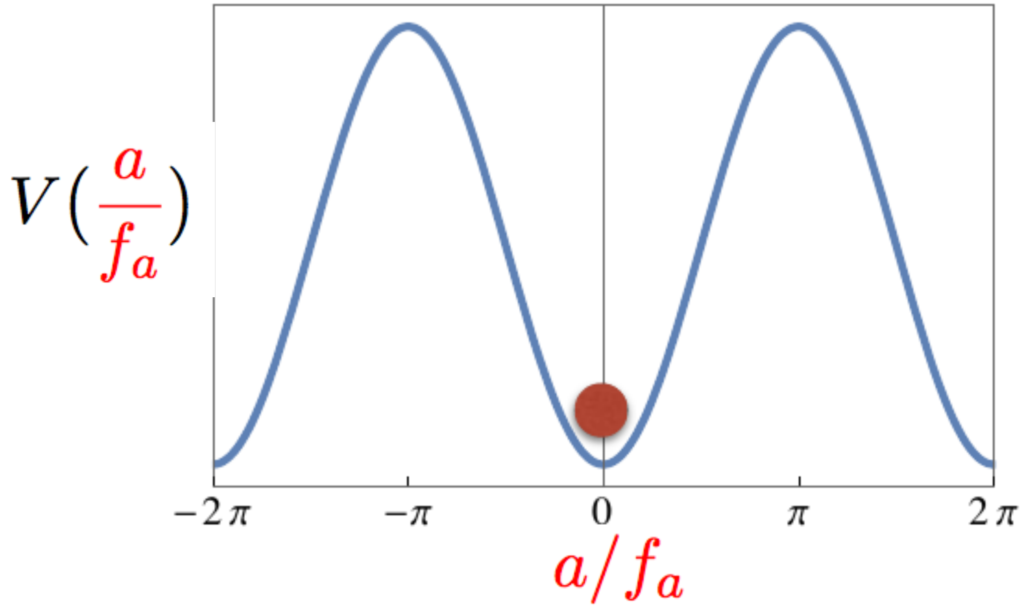

$$\longleftarrow \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

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

canonical QCD axion

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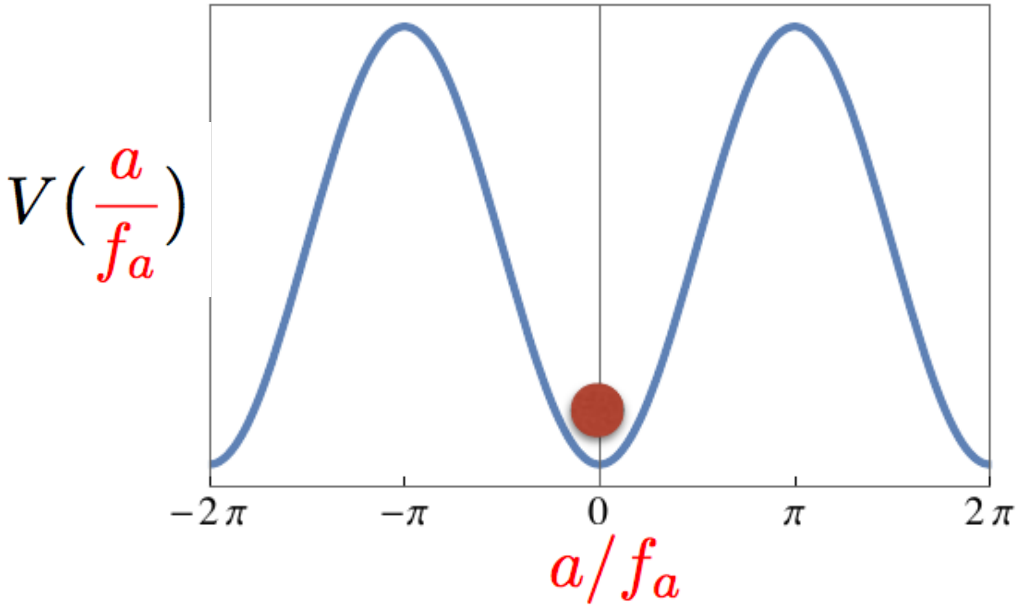

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$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2$$

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

<u>With only QCD:</u>

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

–> "Invisible axion"

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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):

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

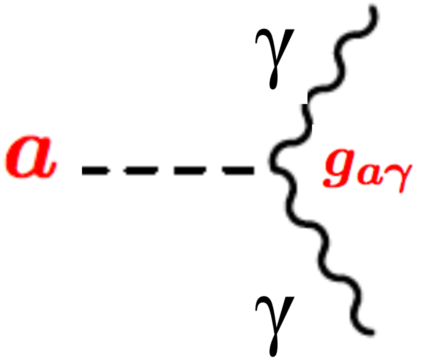
*** If the confining group is QCD:** $m_a^2 f_a^2 = m_\pi^2 f_\pi^2$

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

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

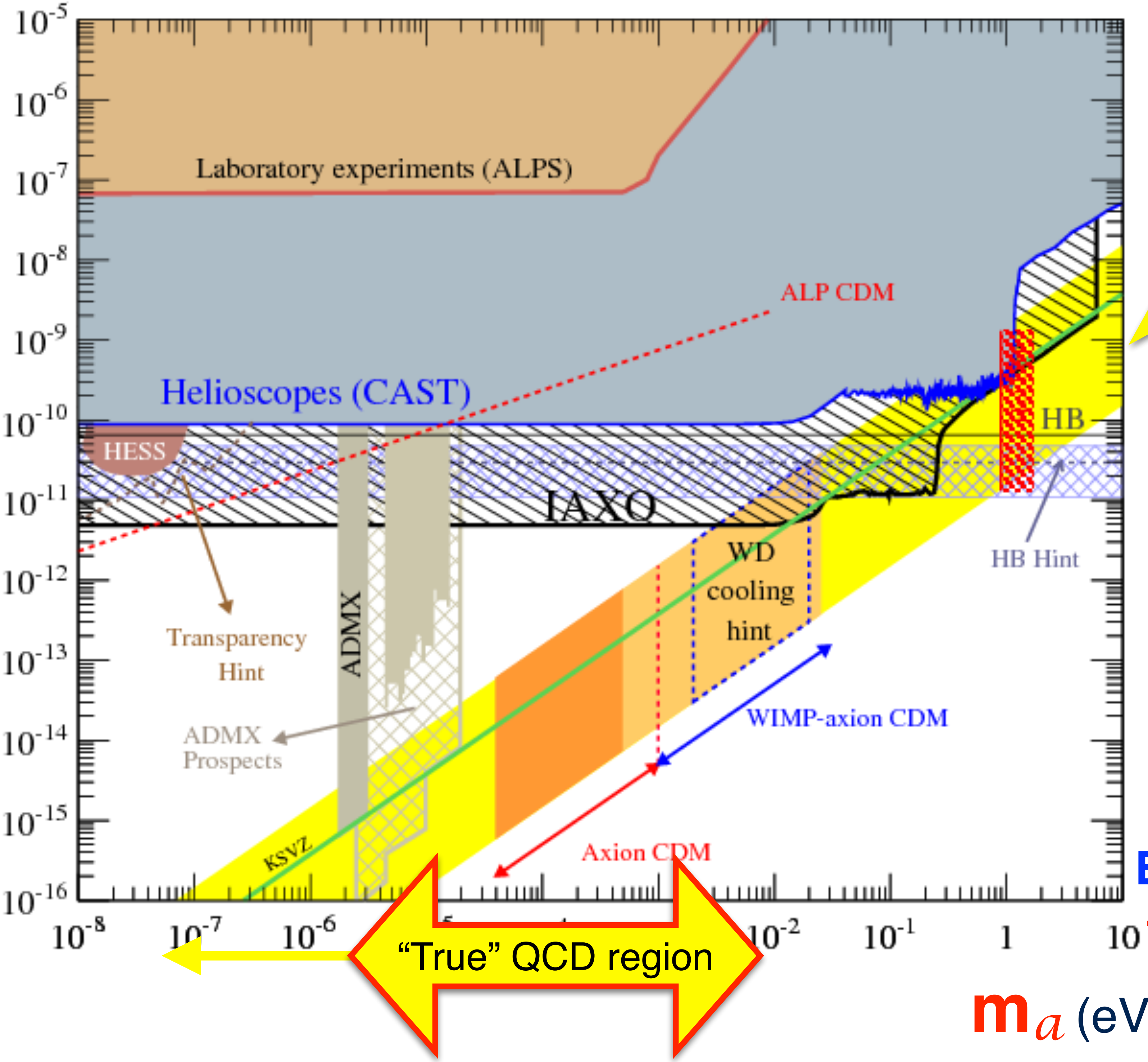
“Invisible axion”

Intensely looked for experimentally…



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

(GeV^{-1})



"True" QCD axion band

=

"Invisible axion"

e.g. KSVZ, DFSZ…

v<< f_a —>

EW hierarchy problem

+ gravitational tunings ?

… and theoretically

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

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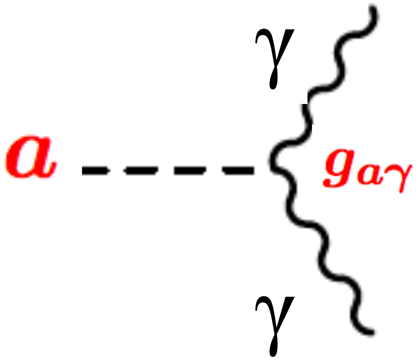

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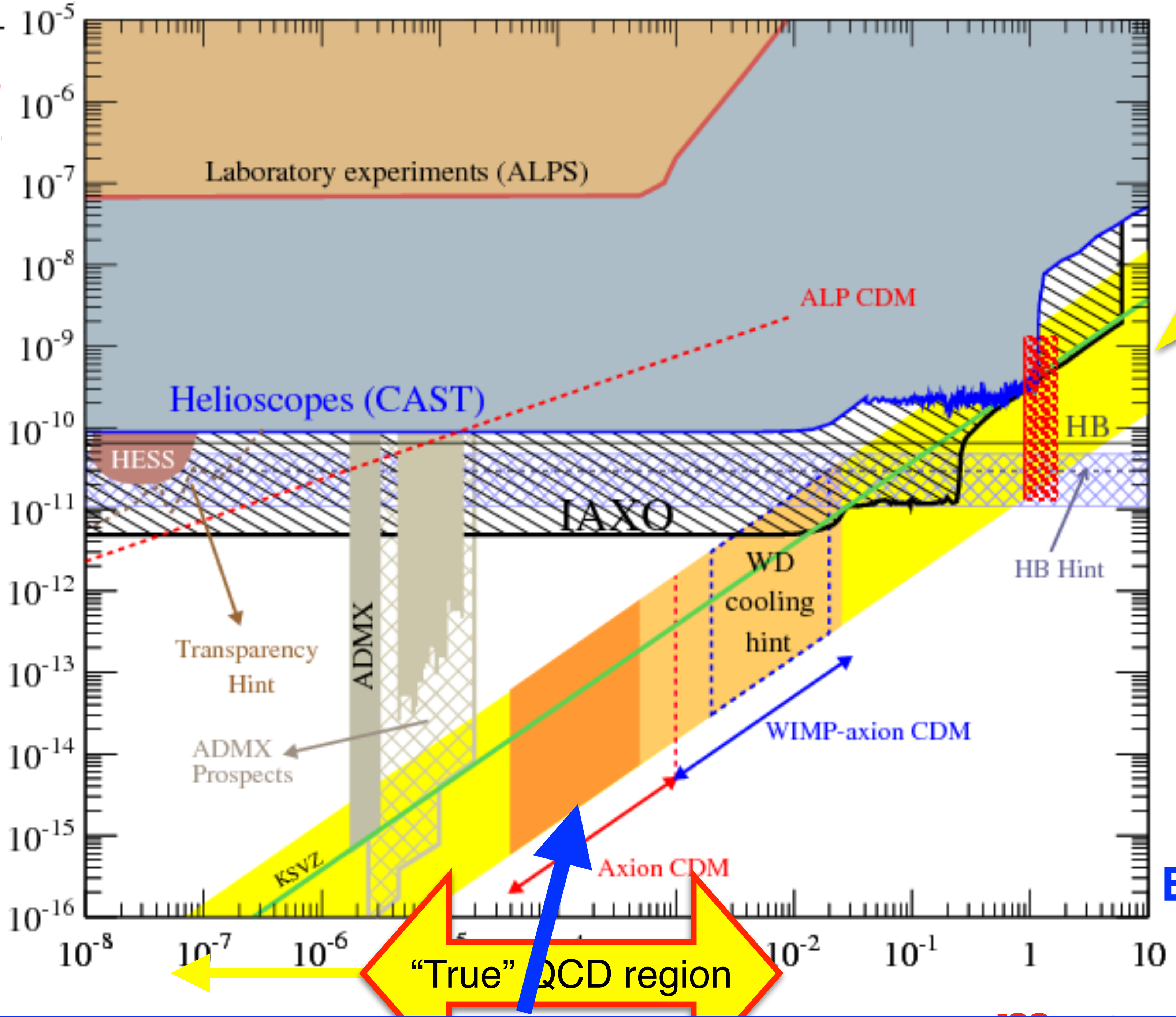
Lattice QCD



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EW hierarchy problem

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

https://arx

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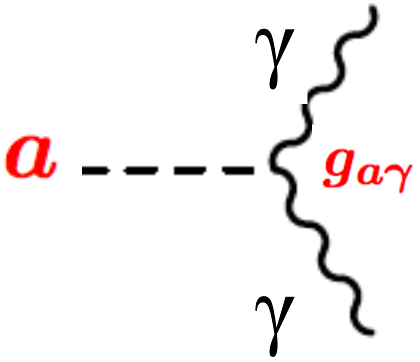

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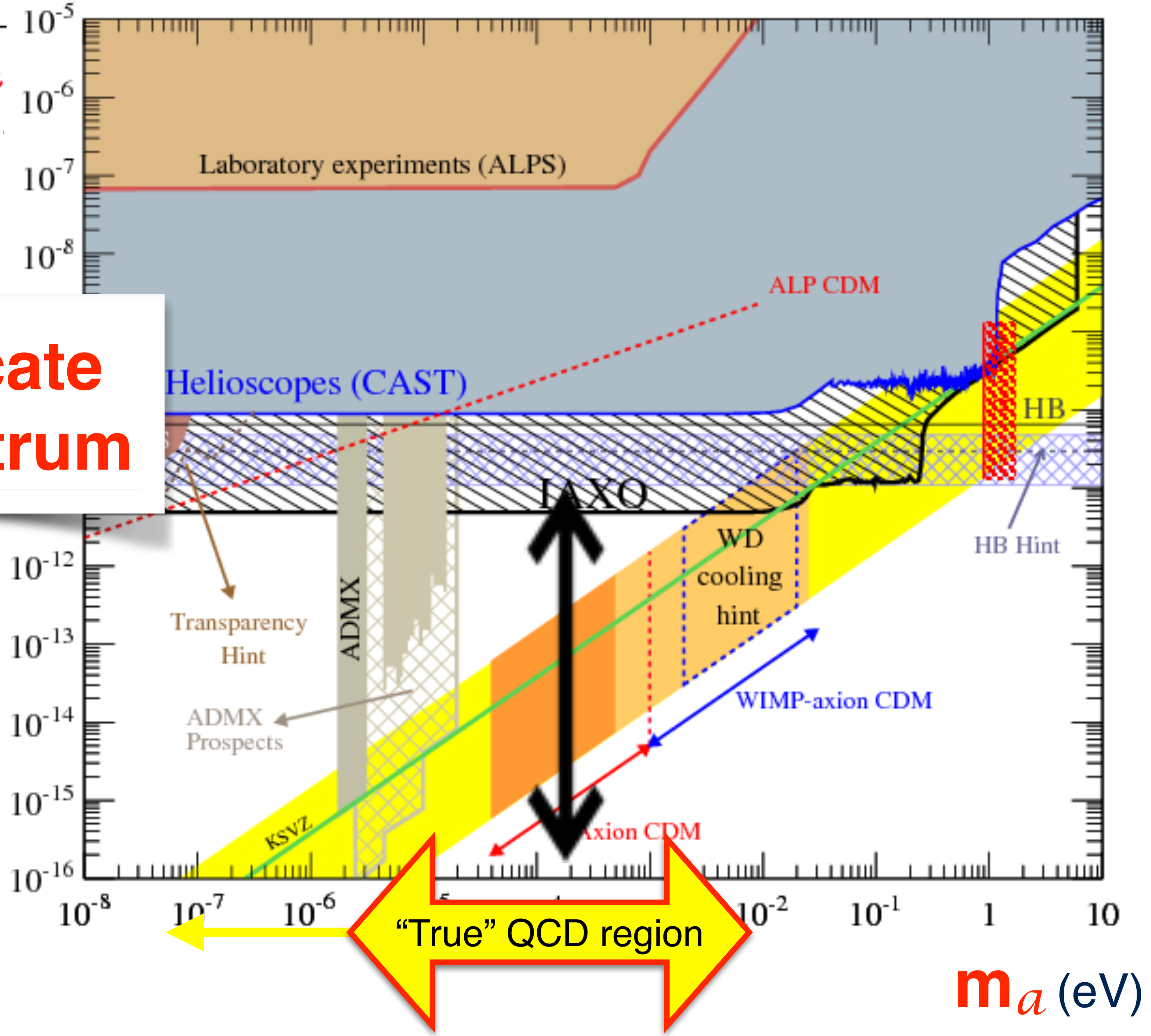

Complicate the spectrum

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

… and theoretically

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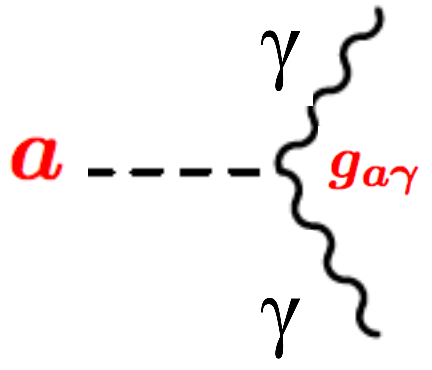

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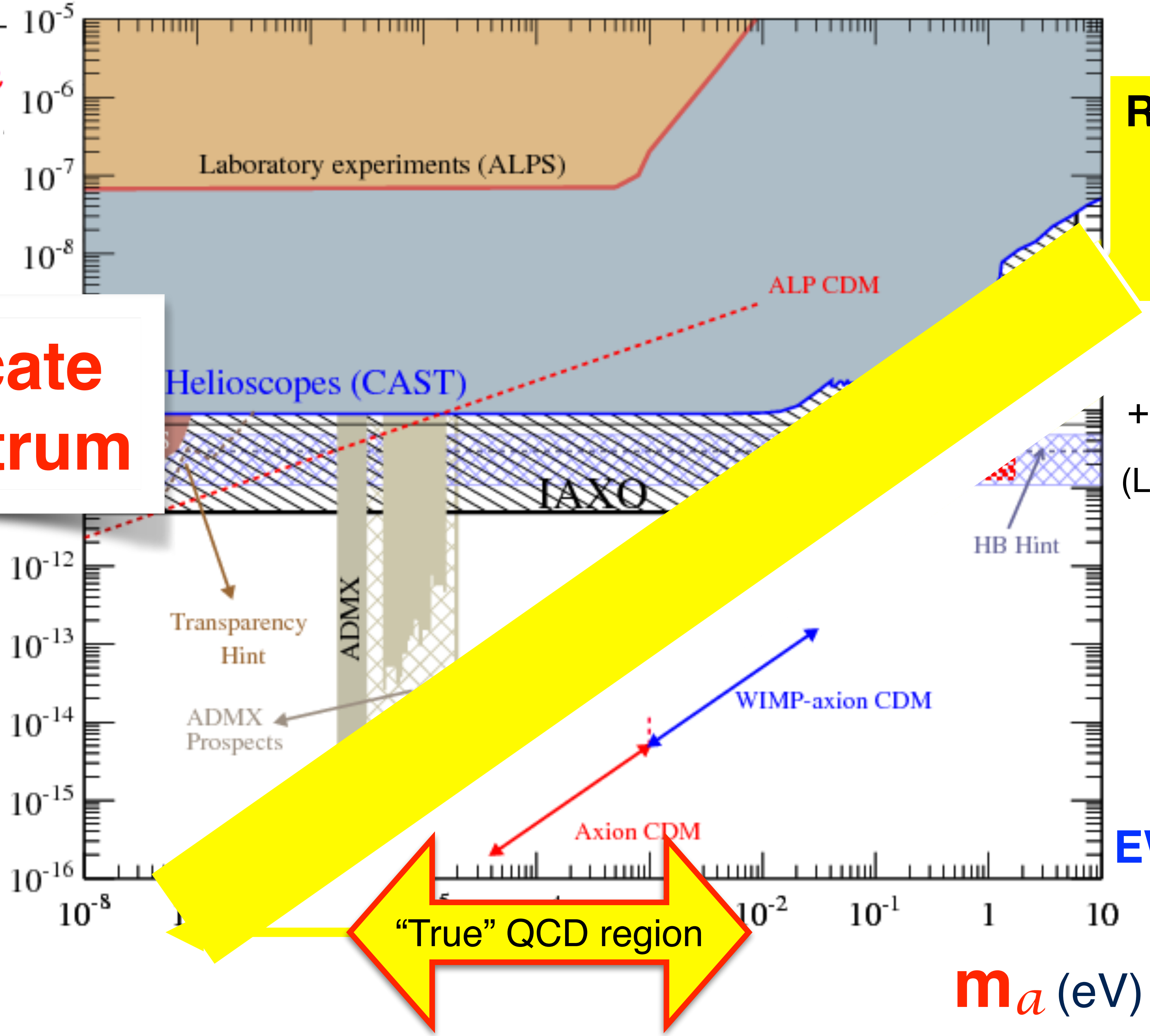

Refined KSVZ axion band:
up and thinner

from Ω_{DM}
+ Landau-poles analysis
(Luzio+Mescia+Nardi 2017-18)

Complicate the spectrum

“True” QCD region

v<< f_a —>
EW hierarchy problem

m_a (eV)

… and theoretically

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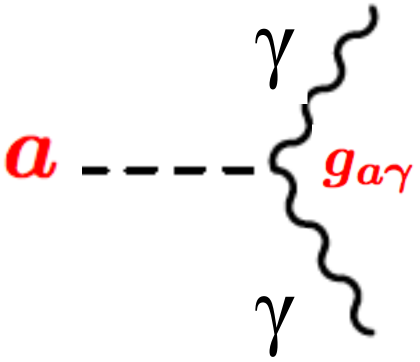

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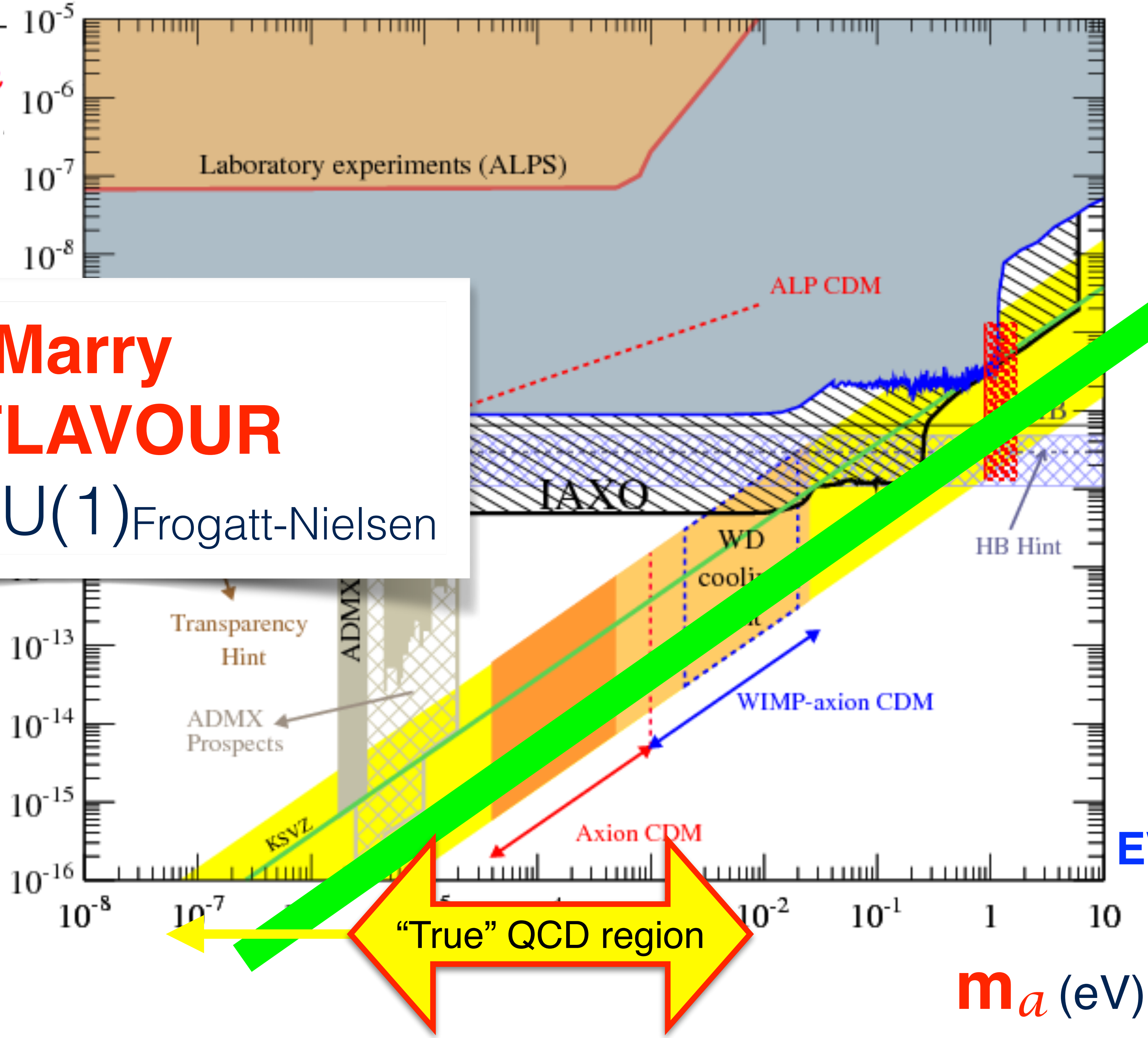

"True" QCD region

m$_a$ (eV)

Marry
to FLAVOUR

U(1)$_{PQ}$ = U(1)$_{\text{Frogatt-Nielsen}}$

QCD axiflavon band
(creative view)

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

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

v<< f$_a$ —>
EW hierarchy problem

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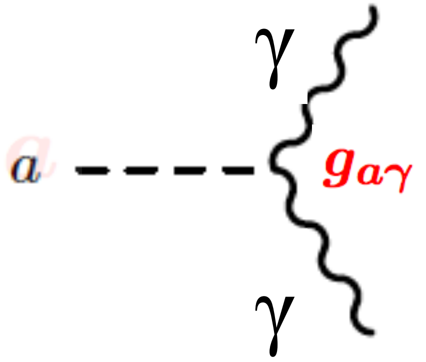

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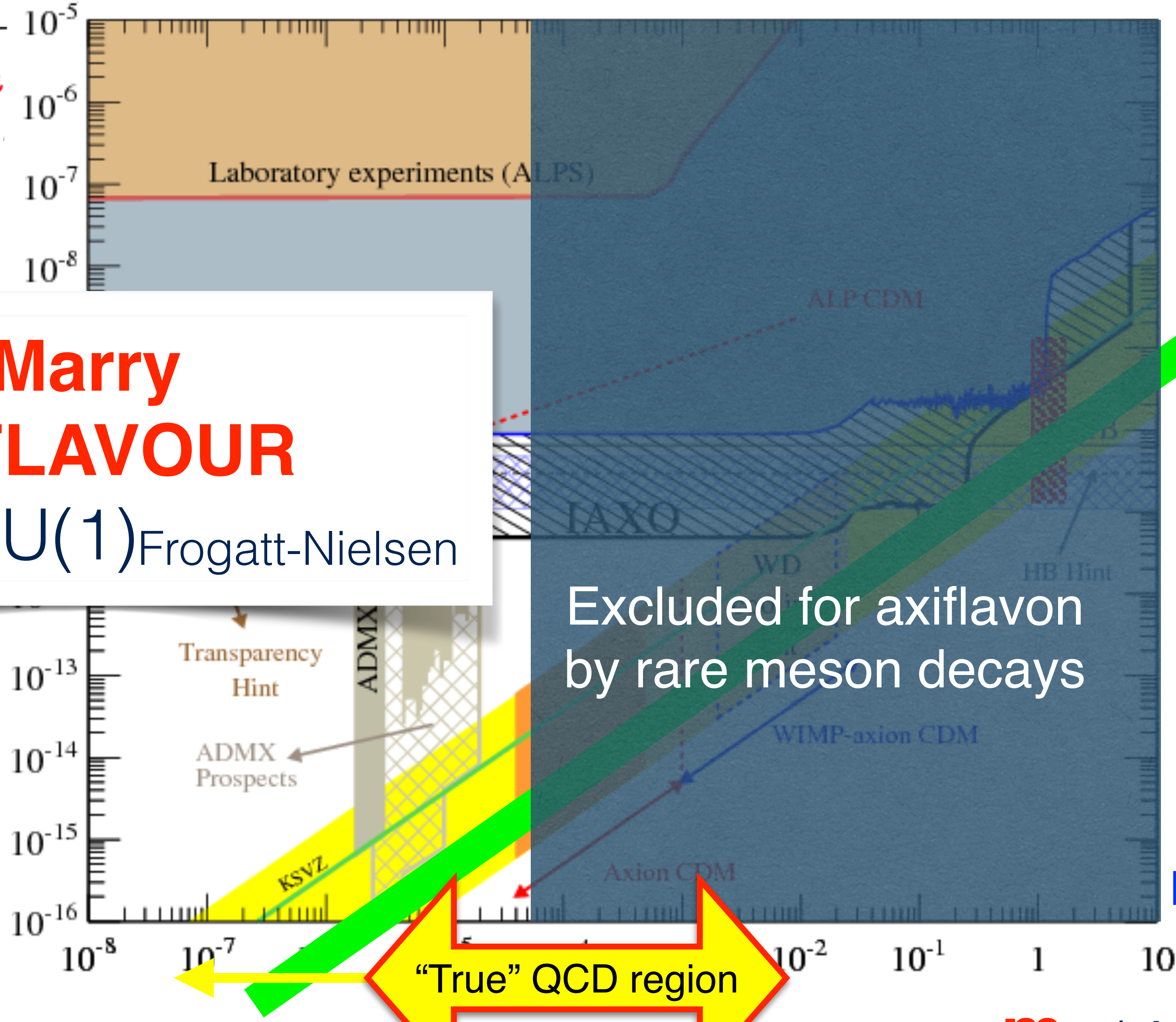

Marry to FLAVOUR

$U(1)_{PQ} = U(1)_{\text{Frogatt-Nielsen}}$

Excluded for axiflavon by rare meson decays

"True" QCD region

m_a (eV)

$v \ll f_a$ —>

EW hierarchy problem

… and theoretically

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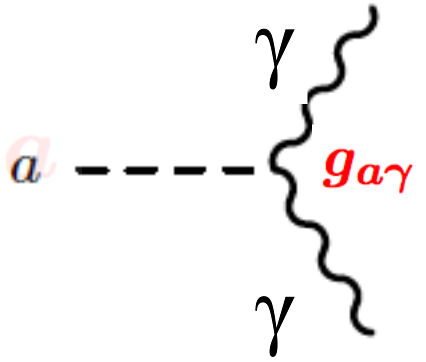

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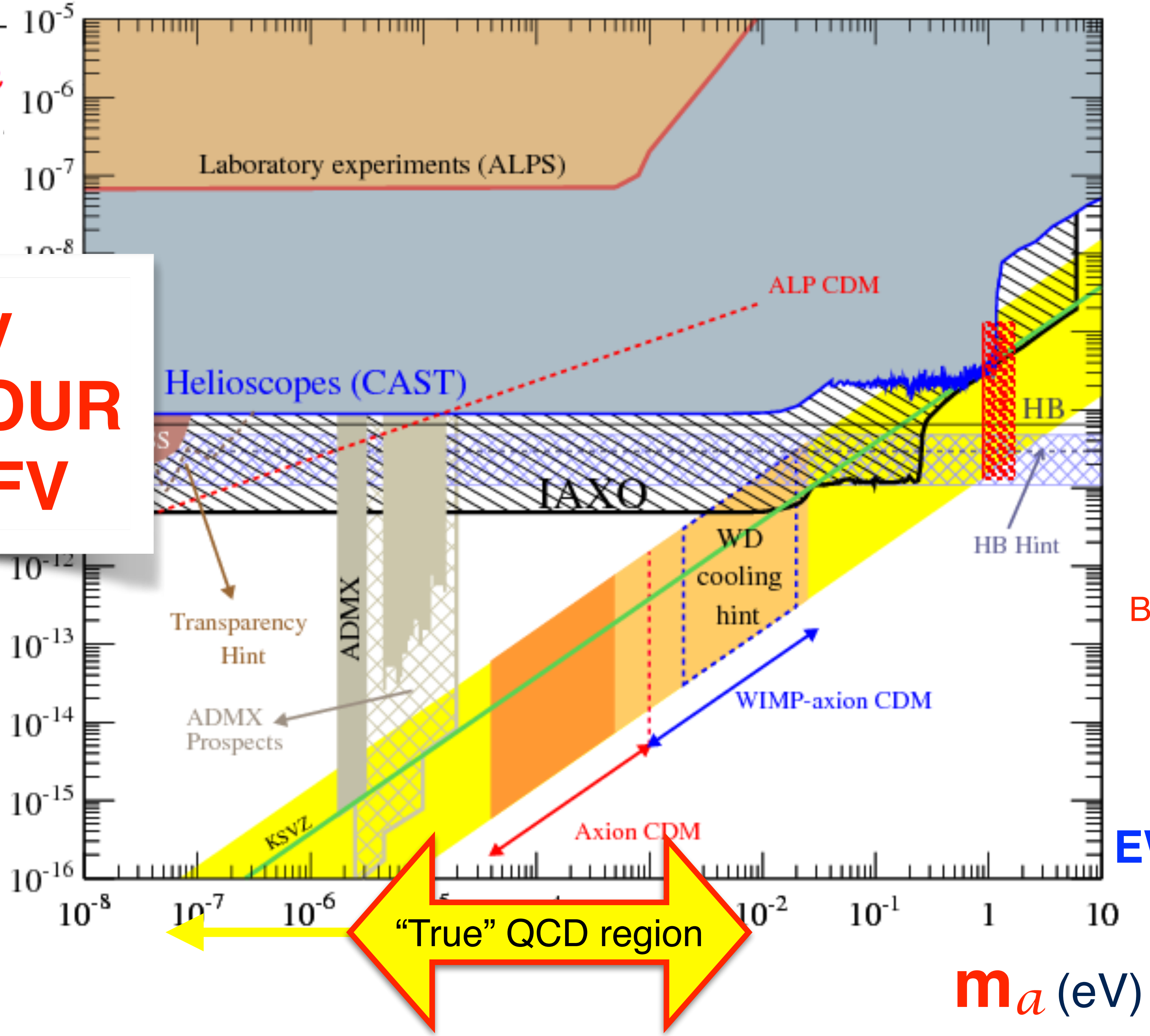

m_a (eV)

Marry to FLAVOUR with MFV

with **MFV:**
Arias & Merlo 2017
Bjorkeroth, Chun & King 2018

v<< f_a —>
EW hierarchy problem

… and theoretically

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

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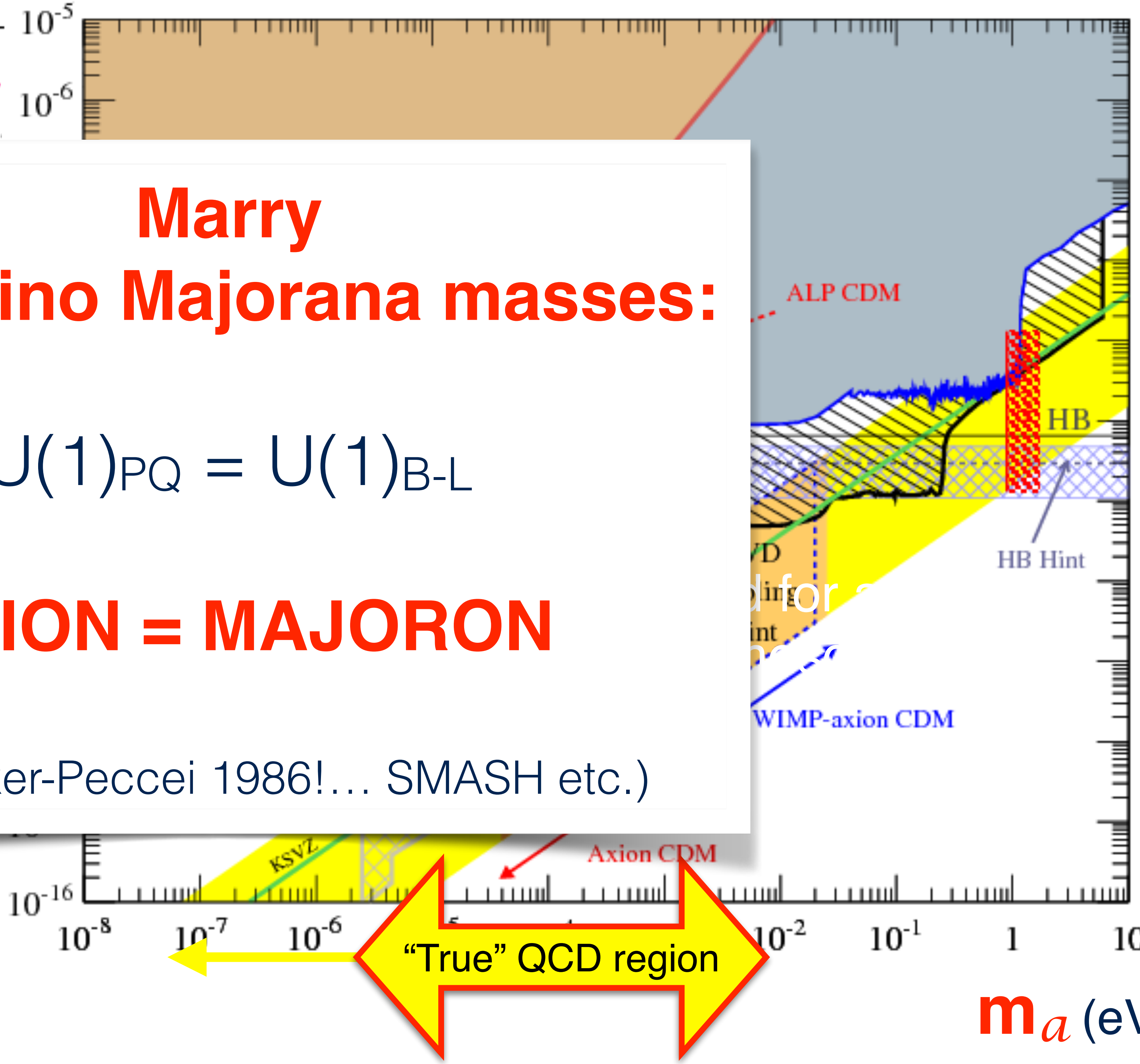
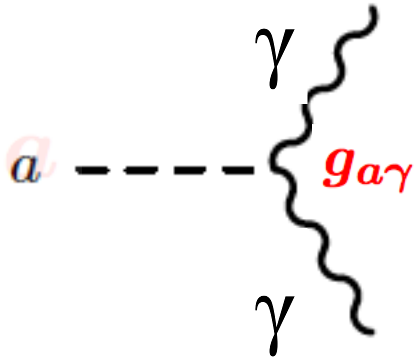


Marry to neutrino Majorana masses:

$U(1)_{PQ} = U(1)_{B\text{-}L}$

AXION = MAJORON

(Langacker-Peccei 1986!… SMASH etc.)



v<< f_a —>

EW hierarchy problem

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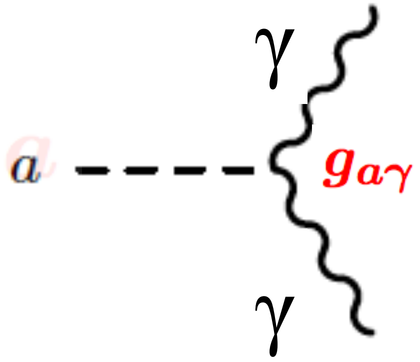

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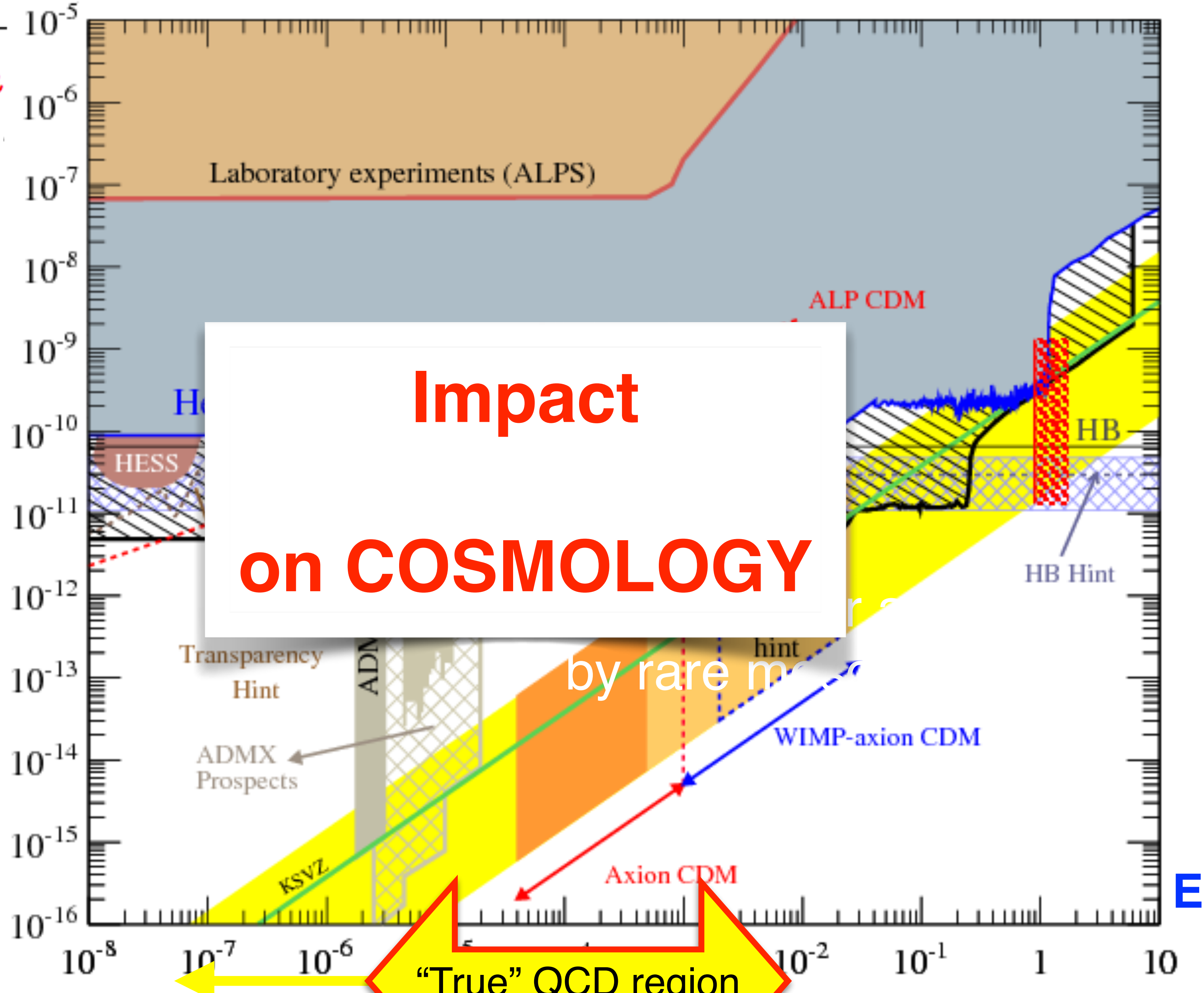

Impact

on COSMOLOGY

“True” QCD region

v<< f_a —>

EW hierarchy problem

m$_a$ (eV)

… and theoretically

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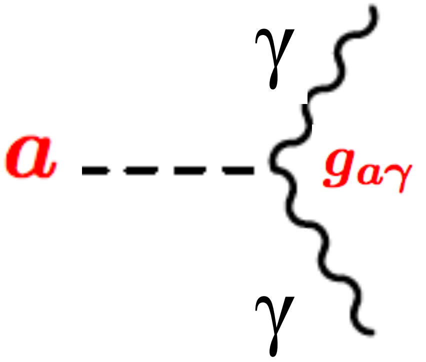
Intensely looked for experimentally…



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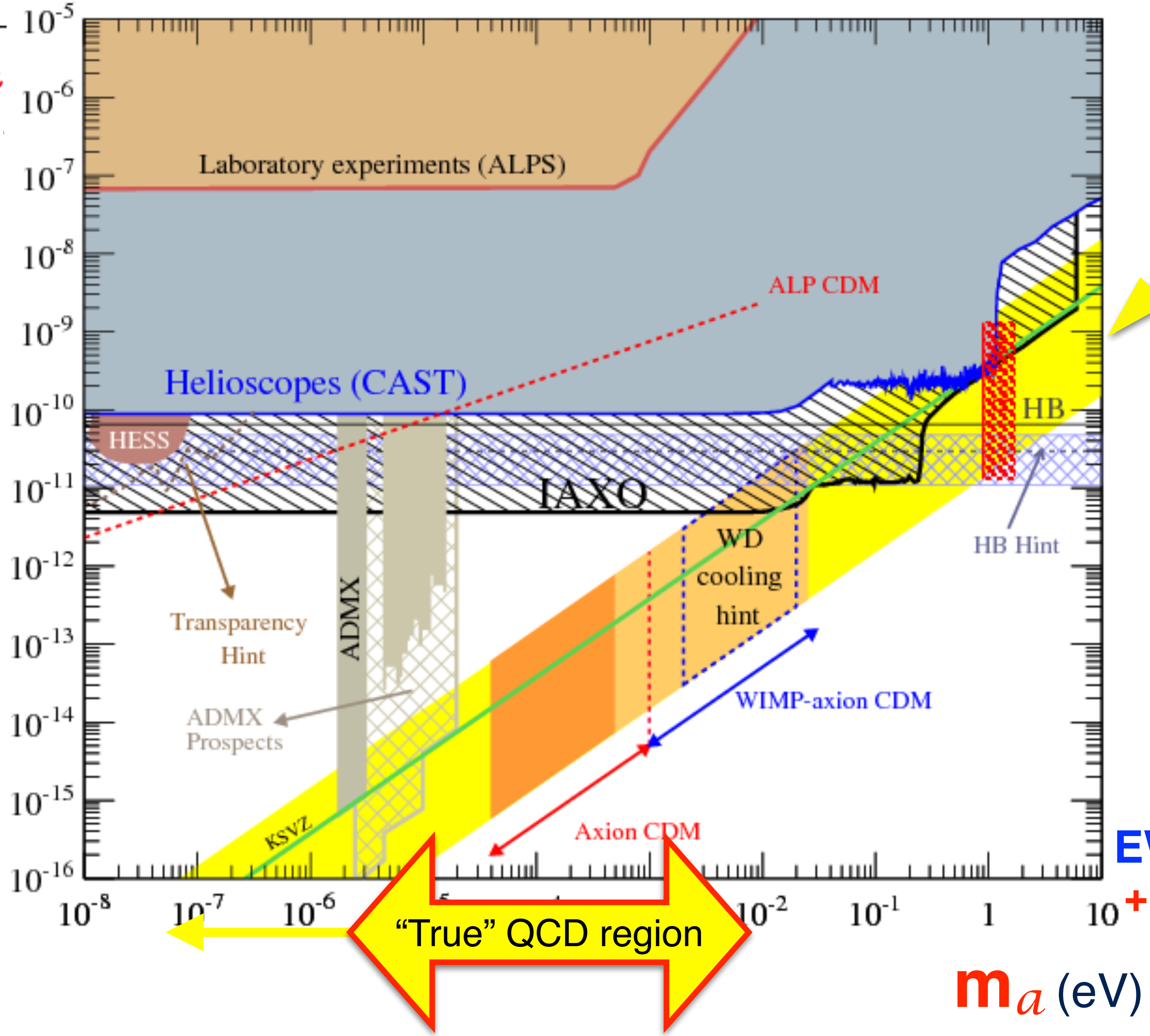

“True” QCD axion band

II

“Invisible axion”
e.g. KSVZ, DFSZ…

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

… and theoretically

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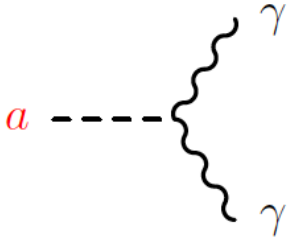
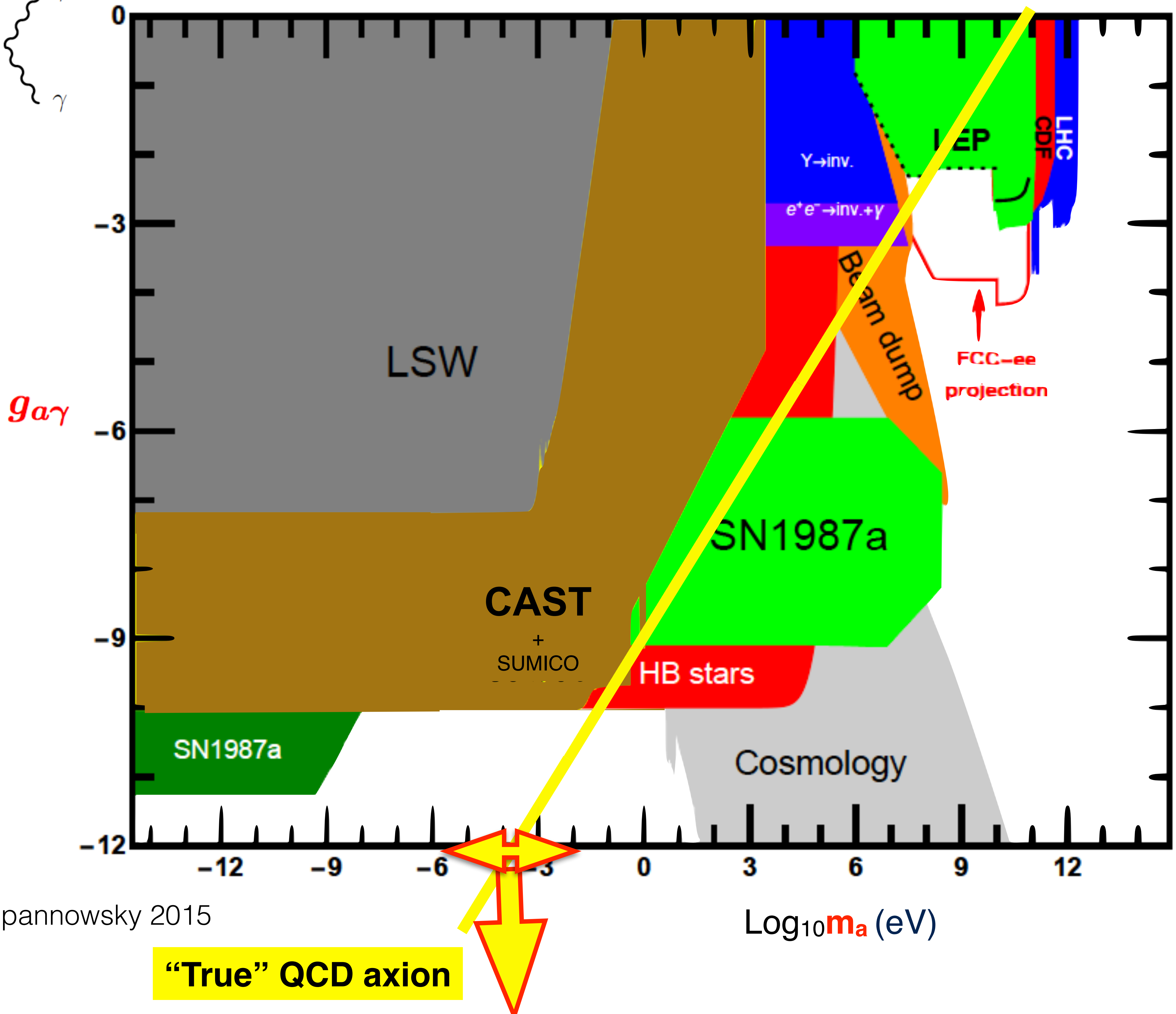
ALPs (axion-like particles) territory

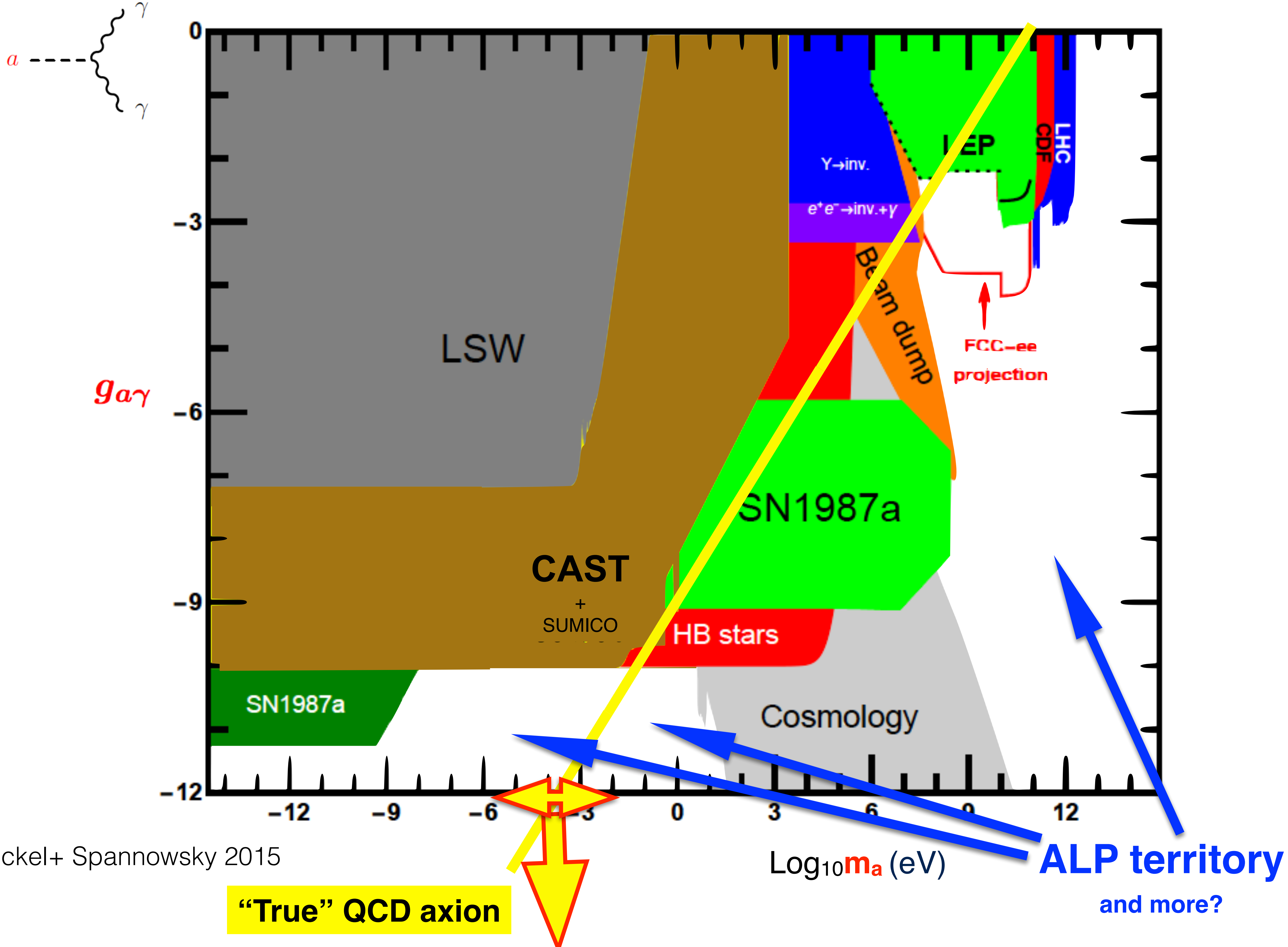




Jaeckel+ Spannowsky 2015

“True” QCD axion

ALPs (axion-like particles) territory



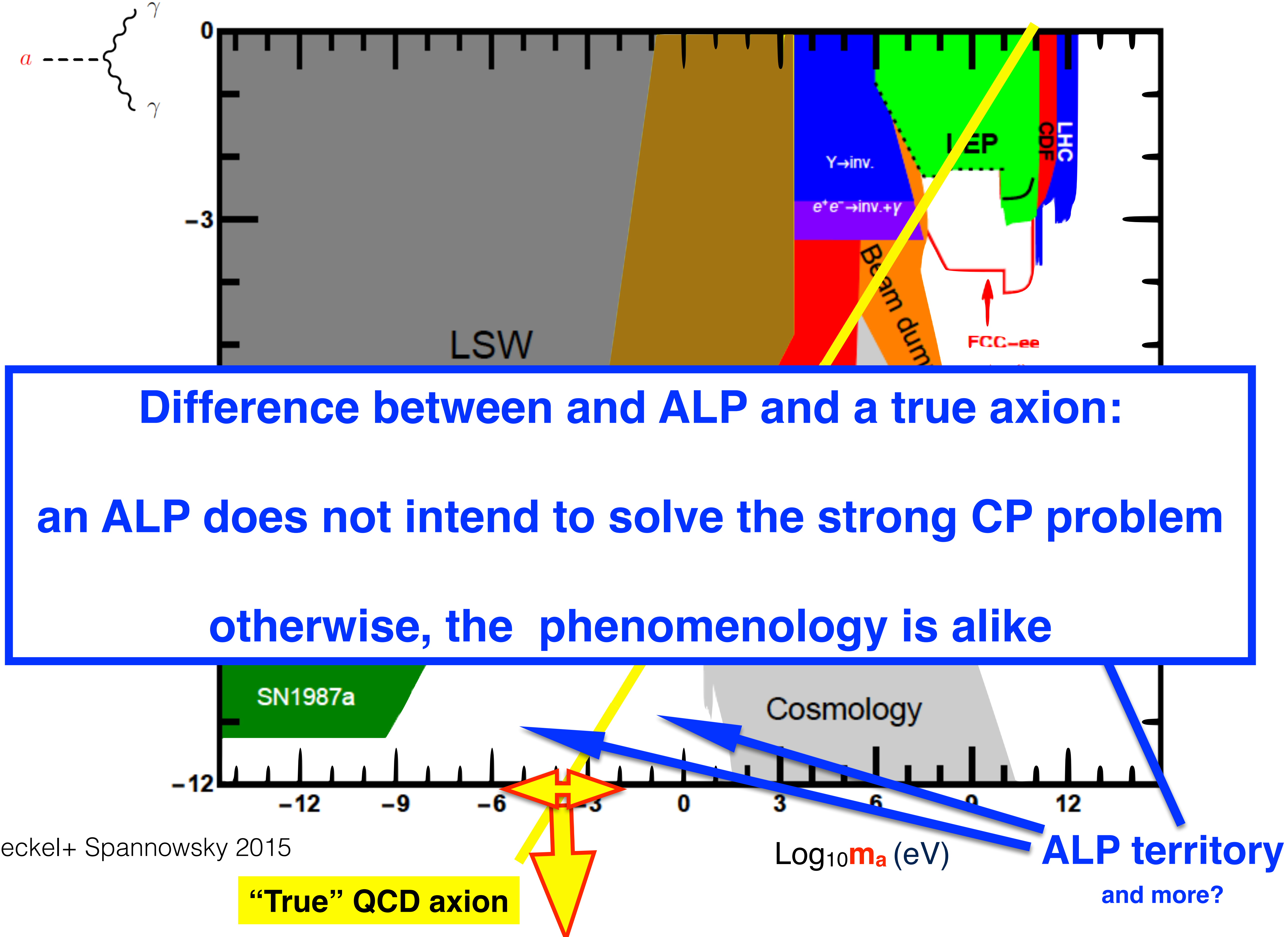
Jaeckel+ Spannowsky 2015

“True” QCD axion

ALP territory

and more?

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

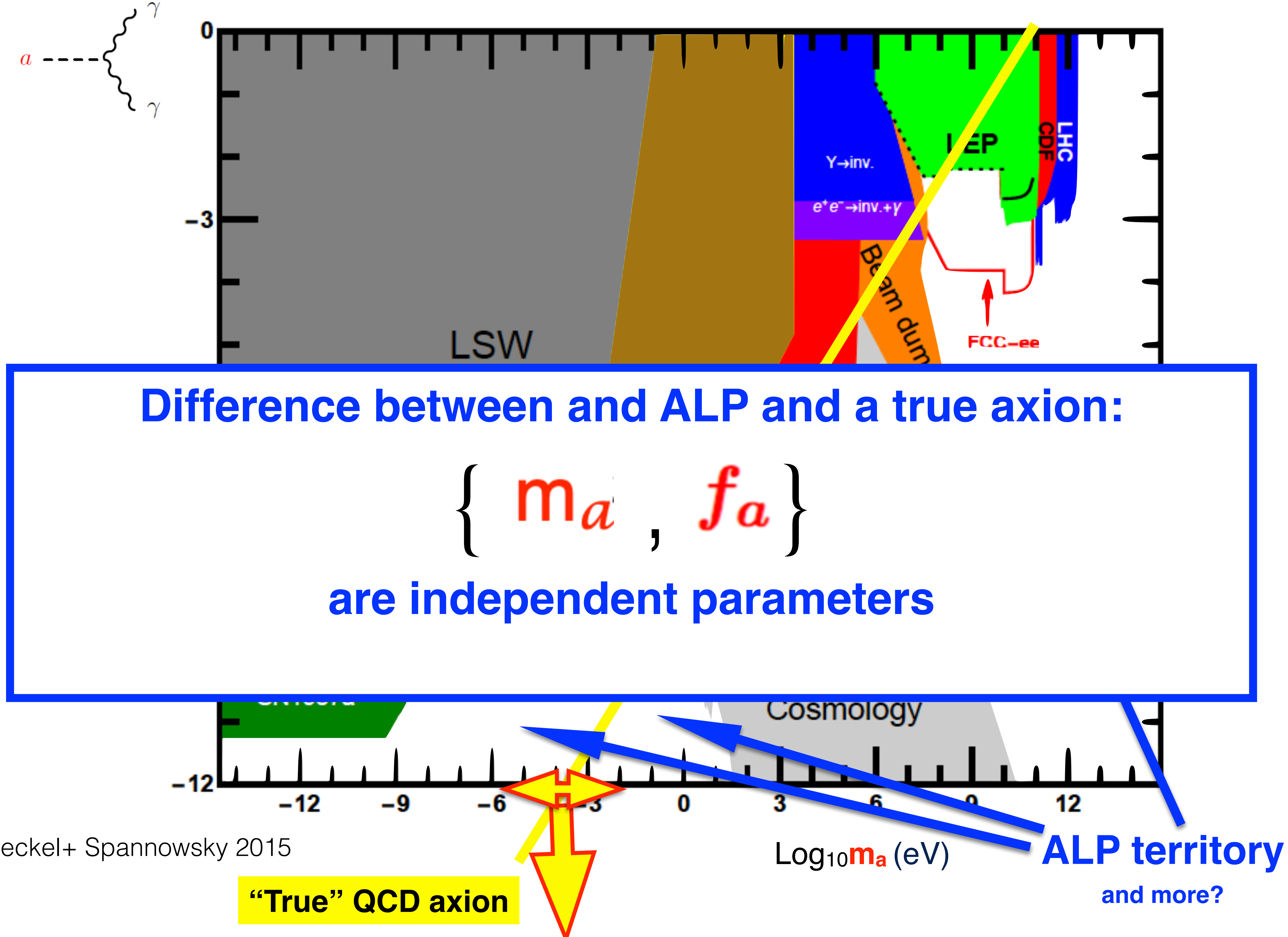
Jaeckel+ Spannowsky 2015

“True” QCD axion

ALP territory

and more?

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



Jaeckel+ Spannowsky 2015

“True” QCD axion

ALP territory

and more?

Difference between and ALP and a true axion:

$$\{ \, m_a \; , \; f_a \, \}$$

are independent parameters

An ALP (axion-like particle) is a generic scalar field a

with derivative couplings to SM particles

and free scale f_a:

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

general effective couplings

$$\{m_a, f_a\}$$

An ALP (axion-like particle) is a generic scalar field a

with derivative couplings to SM particles

and free scale f_a:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{\partial_\mu a}{f_a} \times \mathrm{SM}^{\mu} + c_i \frac{a}{f_a} X_{\mu\nu}\widetilde{X}^{\mu\nu} + \ldots\ldots\ldots$$

general effective couplings

$X^{\mu\nu} = F^{\mu\nu}, G^{\mu\nu}, Z^{\mu\nu}, W^{\mu\nu}....$

$$\{m_a, f_a\}$$

An ALP (axion-like particle) is a generic scalar field a with derivative couplings to SM particles and free scale f_a:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{\partial_\mu a}{f_a} \times \mathrm{SM}^{\mu} + c_i \frac{a}{f_a} X_{\mu\nu}\widetilde{X}^{\mu\nu} + \ldots\ldots\ldots$$

general effective couplings

$X^{\mu\nu} = F^{\mu\nu}, G^{\mu\nu}, Z^{\mu\nu}, W^{\mu\nu}....$

$$\left\{ m_a , \frac{c_i}{f_a} \right\}$$

ALP-Linear effective Lagrangian at NLO

||

SM EFT

Complete basis (bosons+fermions):

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

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

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

where X_ψ is a general 3x3 matrix in flavour space

Georgi + Kaplan + Randall 1986

Choi + Kang + Kim, 1986

Salvio + Strumia + Shue, 2013

ALP-Linear effective Lagrangian at NLO

II
SM EFT

Complete basis (bosons+fermions):

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_{i}^{\rm total} c_i \mathbf{O}^{d}$$

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

$$\mathbf{O}_{\tilde{W}} \quad = \quad -W^a_{\mu\nu}\tilde{W}$$

$$f_a$$

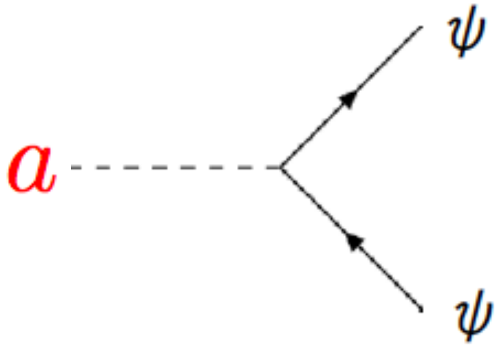
$$\sum_{Q_L, Q_R, \atop L_L, L_R} \bar{\psi}\gamma_\mu X_\psi \psi$$

where X_ψ is a general 3x3 matrix in flavour space

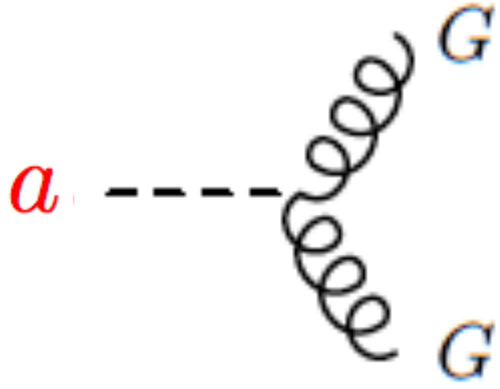
analysis parameters: $\frac{c_i}{f_a}$, m_a

an + Randall 1986
+ Kang + Kim, 1986
S vio + Strumia + Shue, 2013

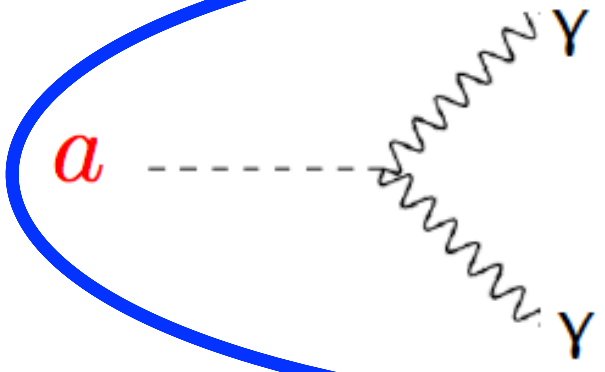
Up to date, phenomenological studies have mostly focused on ALP couplings to fermions, gluons, and especially photons



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

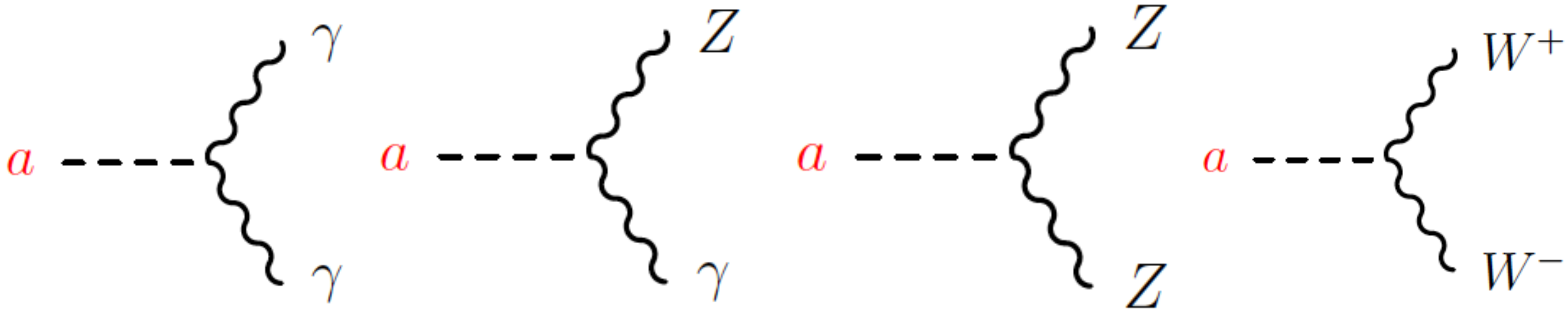


$$a\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$



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

But because of SU(2)xU(1) gauge invariance, *a*-γγ should come together with *a*-γZ, *a*-ZZ and *a*-W^+W^- :



+ ….

THEORY plus NEW SIGNALS at colliders

Jaeckel+Spanowski 2016 …..Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz 2017

The field of axions and ALPs is BLOOMING

in Experiment … and Theory

The field of axions and ALPs is BLOOMING

in Experiment … and Theory

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**!

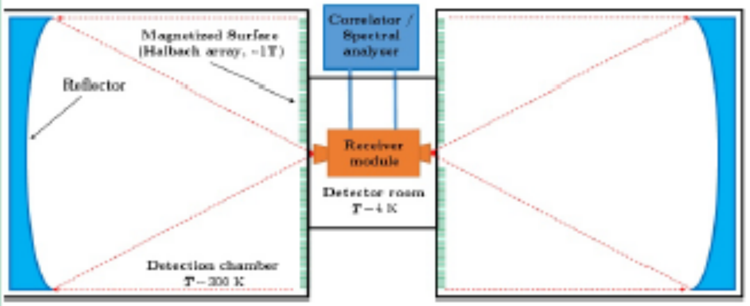
see C. Braggio talk at Invisibles18

Experiment: new experiments and new detection ideas

e.g. in Haloscopes

axion-photon

BRASS



MADMAX

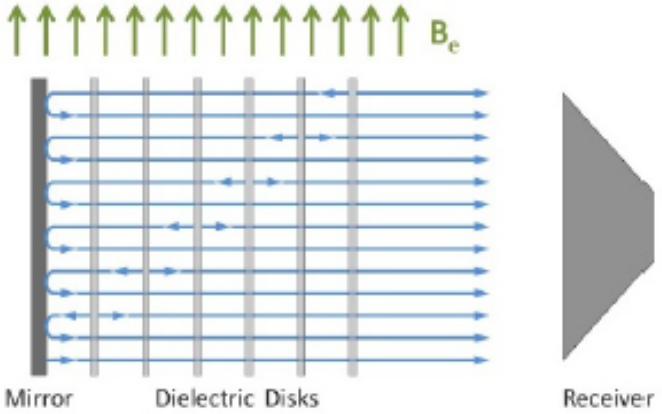
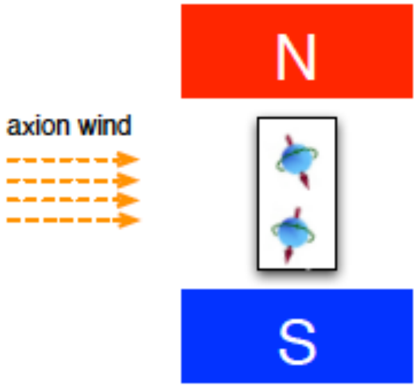
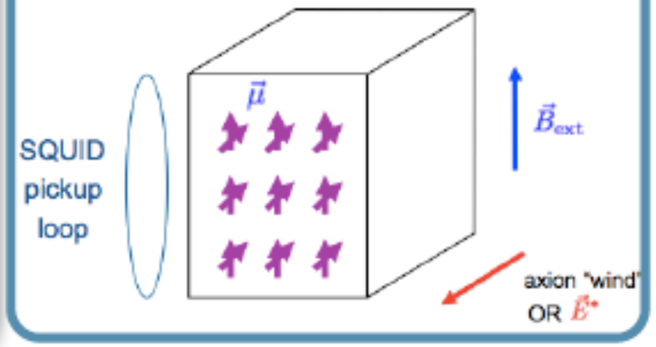


Image taken from
C. Braggio talk at Invisibles18

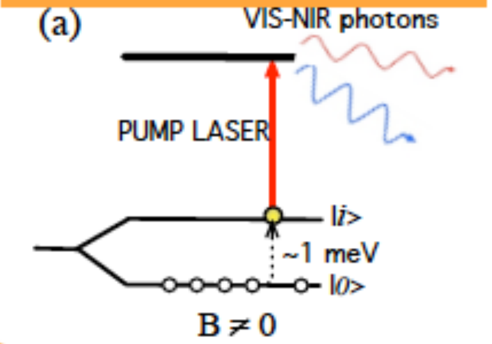
QUAX [EPR]
axion-electron



CASPER wind [NMR]
axion-nucleon

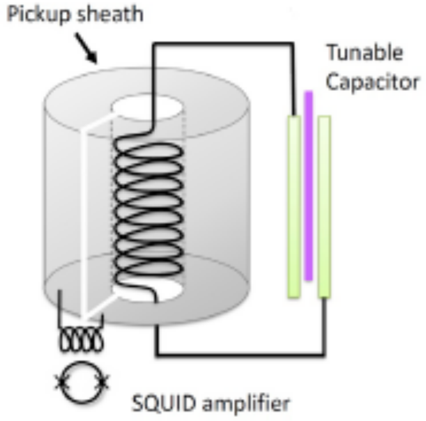


atomic/molecular transitions
axion-electron

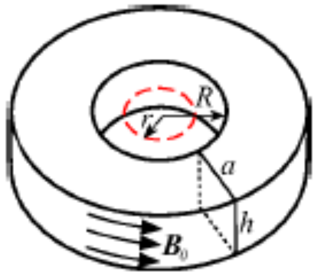


LC circuit

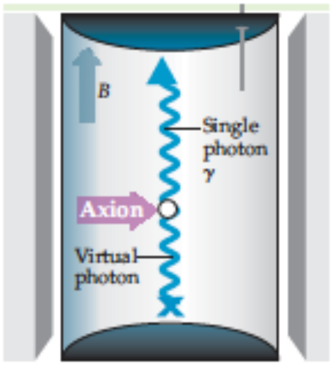
DM radio



ABRACADABRA

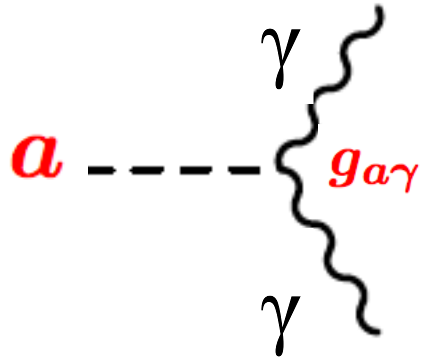


Sikivie concept
axion-photon



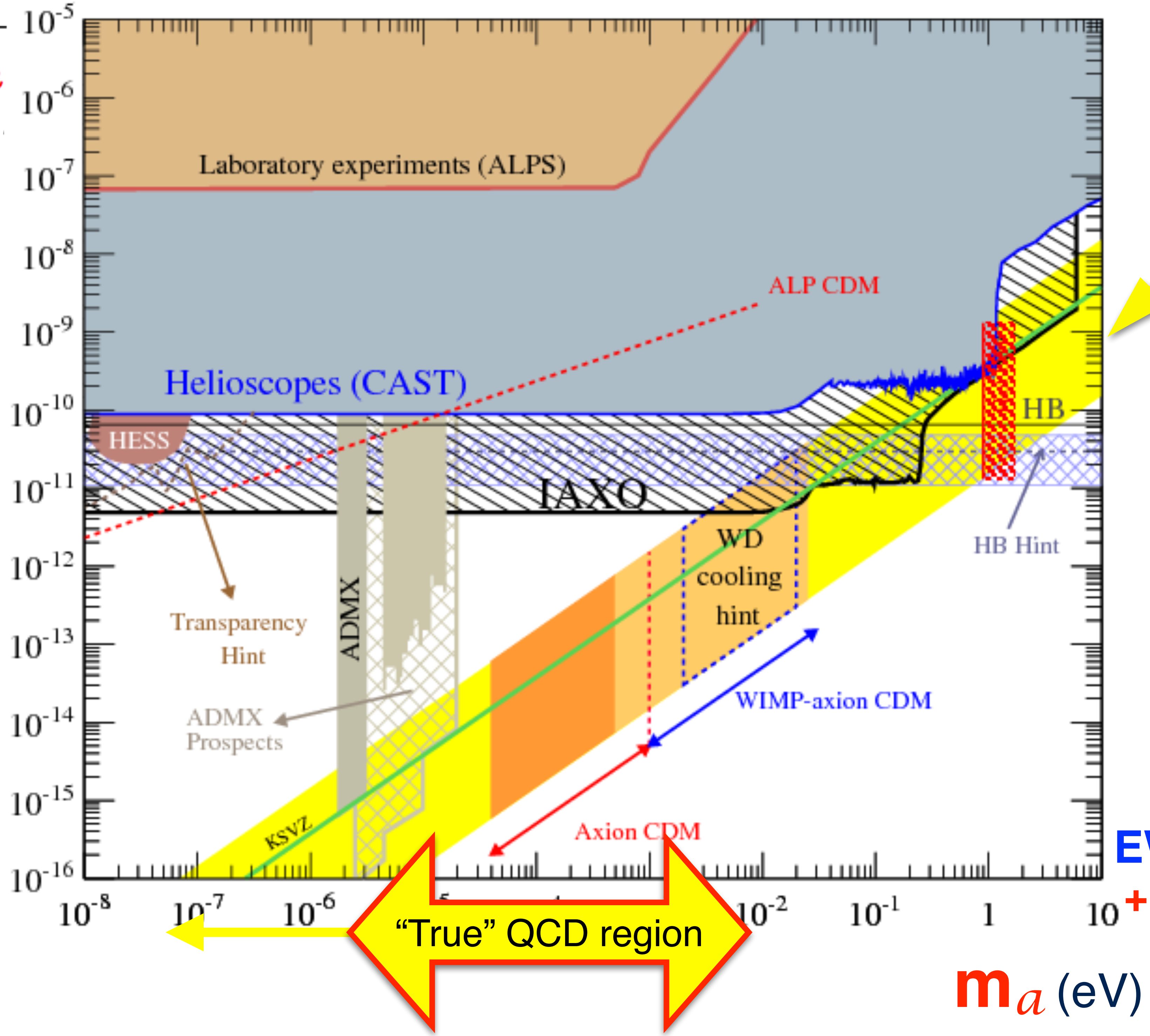
- CULTASK CAPP
- RADES CAPP
- ORPHEUS
- ORGAN

Intensely looked for experimentally…



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

(GeV-1)



"True" QCD region

"True" QCD axion band

=

"Invisible axion"

e.g. KSVZ, DFSZ…

v<< f_a —>

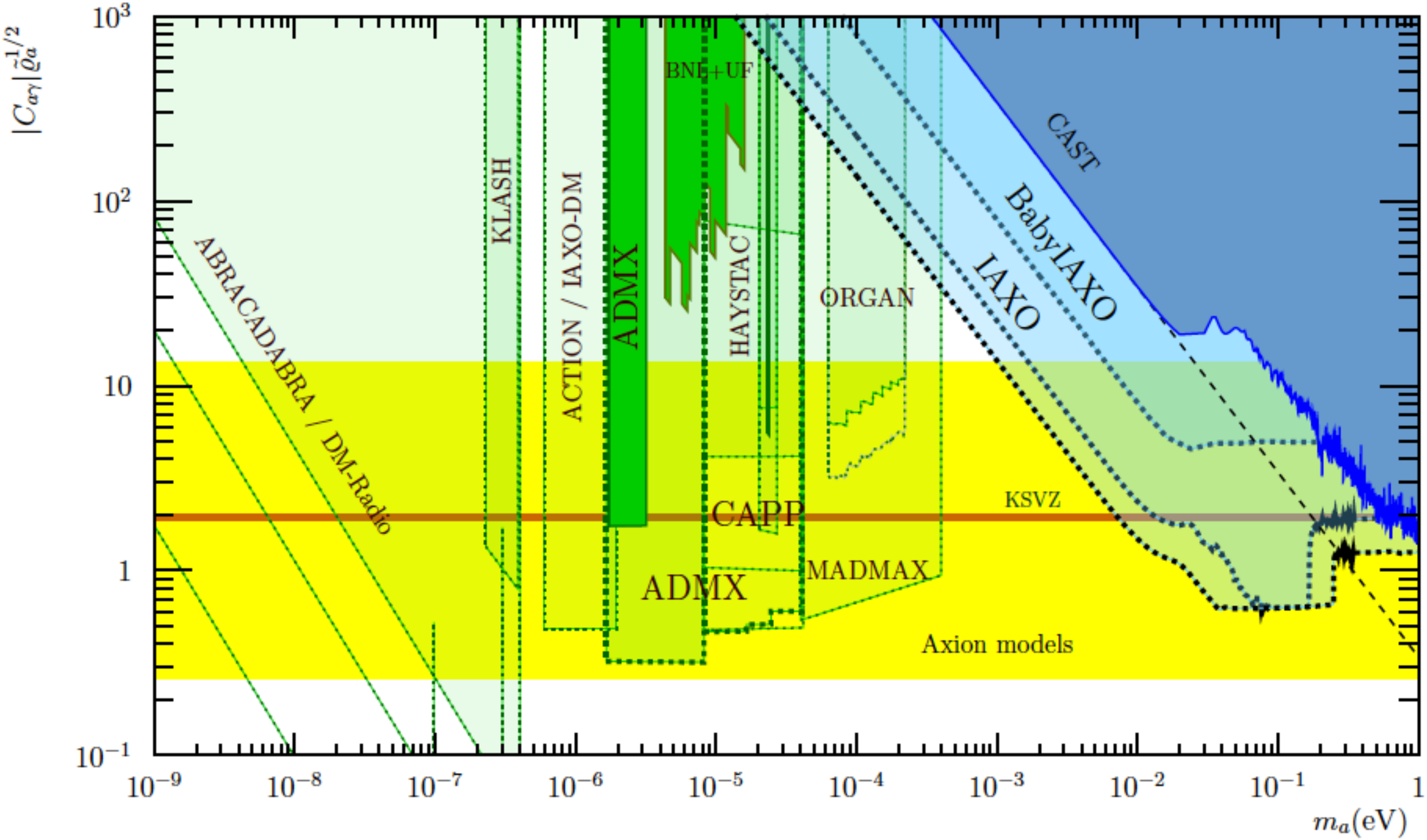
EW hierarchy problem

+ gravitational tunings ?

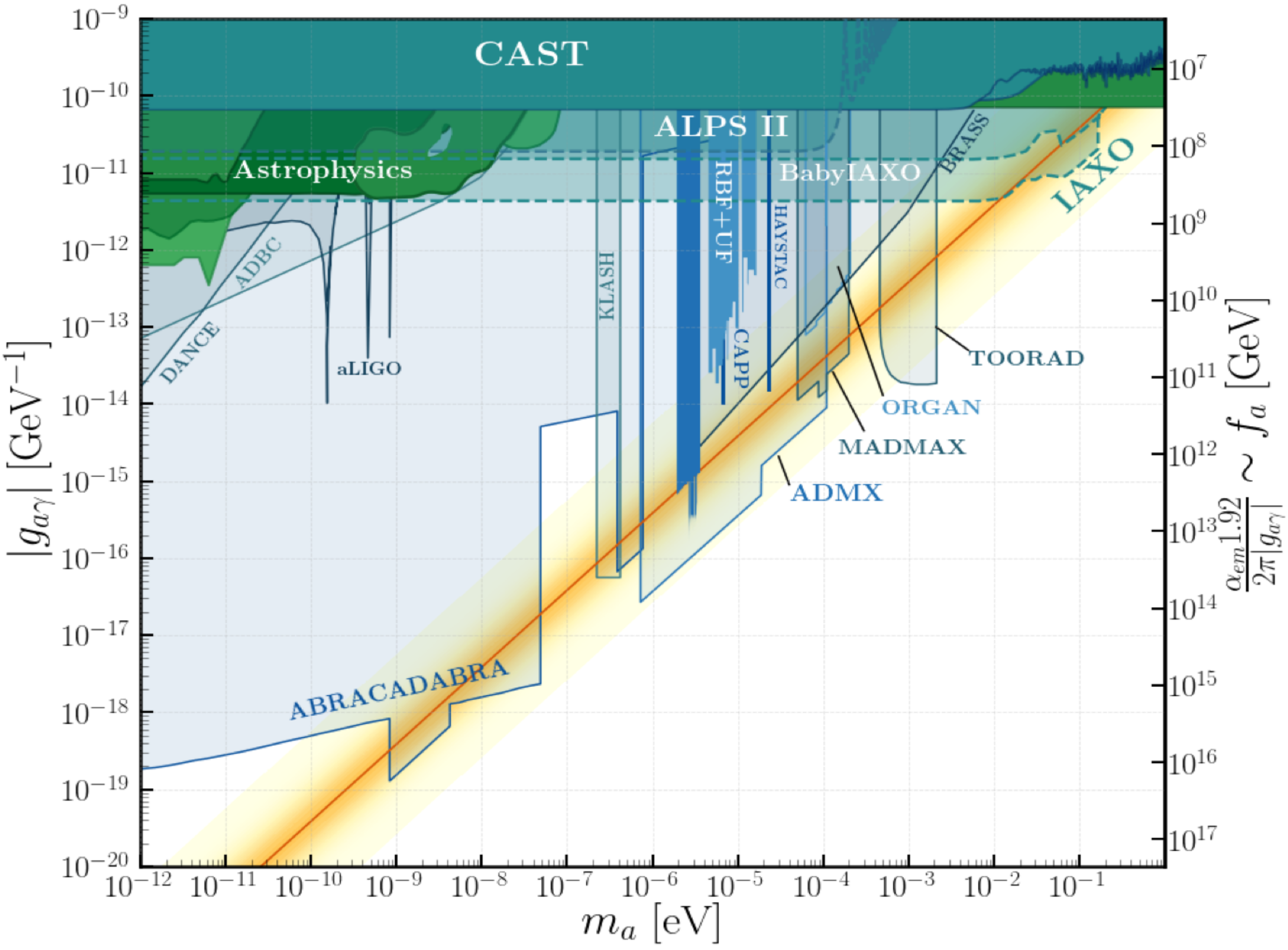
… and theoretically

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

Advances on Haloscopes



Irastorza and Redondo, arXiv:1801.08127



courtesy of Pablo Quilez

But also ALP searches in:

* LHC

* Rare meson decays

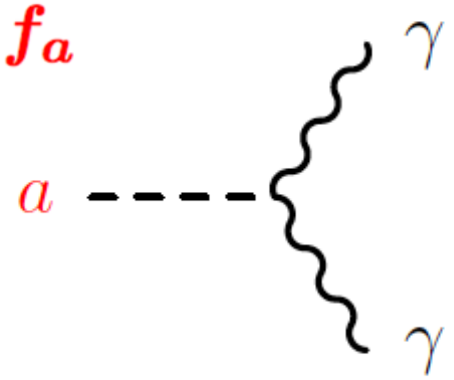
ALPs at the LHC

ALP collider searches

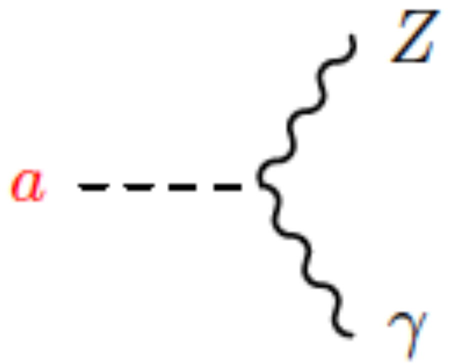
- **Stable ALP searches**:
  - Mono-W, Z and γ K. Mimasu, V. Sanz [1409.4792], ATLAS [2011.05259], I. Brivio, M.B. Gavela, L. Merlo, K. Mimasu, J.M. No, R. del Rey, V. Sanz [1701.05379]
  - Mono-jet and di-jet K. Mimasu, V. Sanz [1409.4792], G. Haghighat, D.H. Raissi, M.M. Najafabadi [2006.05302], ATLAS [2102.10874], F.A. Ghebretinsae , K. Wang, Z.S. Wang [2203.01734]
  - $pp \to W\gamma a, pp \to t\bar{t}a$ I. Brivio, M.B. Gavela, L. Merlo, K. Mimasu, J.M. No, R. del Rey, V. Sanz [1701.05379], M. Bauer, (M. Heiles), M. Neubert, A. Thamm [1708.00443], [1808.10323]
- **Resonant searches**:
  - $pp \to \gamma\gamma$ resonant production J. Jäckel, M. Jankowiak, M. Spannowsky [1212.3620], (Cid Vidal), A.Mariotti, D. Redigolo, F. Sala, K. Tobioka [1710.01743], [1810.09452], M. Bauer, M. Heiles, M. Neubert, A. Thamm [1808.10323]
  - $\gamma\gamma \to \gamma\gamma$ in Pb-Pb collisions S. Knapen, T. Lin, H.K. Lou, T. Melia [1607.06083], [1709.07110], C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon [1803.10835], CMS [1810.04602], ATLAS [2008.05355]
  - $pp \to V_1 a \to V_1 V_2 V_3$ tri-boson production J. Jäckel, M. Spannowsky [1509.00476], N. Craig, A. Hook, S. Kasko [1805.06538], (J. Ren), D. Wang, L. Wu, J.M. Yang, M. Zhang [2102.01532], [2106.07018]

A general, largely unexplored, ALP characteristic: all couplings are derivative = grow with 4-momentum

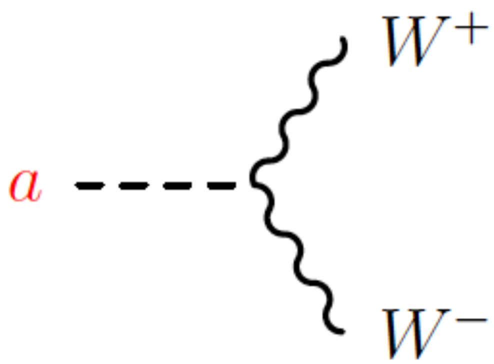
e.g. $\frac{a}{f_a} X_{\mu\nu}\widetilde{X}^{\mu\nu}$



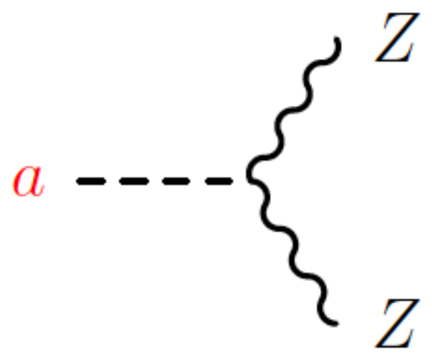
$$-\frac{4i}{f_a} p_{A1\alpha} p_{A2\beta} \varepsilon^{\mu\nu\alpha\beta} \left(c_\theta^2 c_{\tilde{B}} + s_\theta^2 c_{\tilde{W}}\right)$$



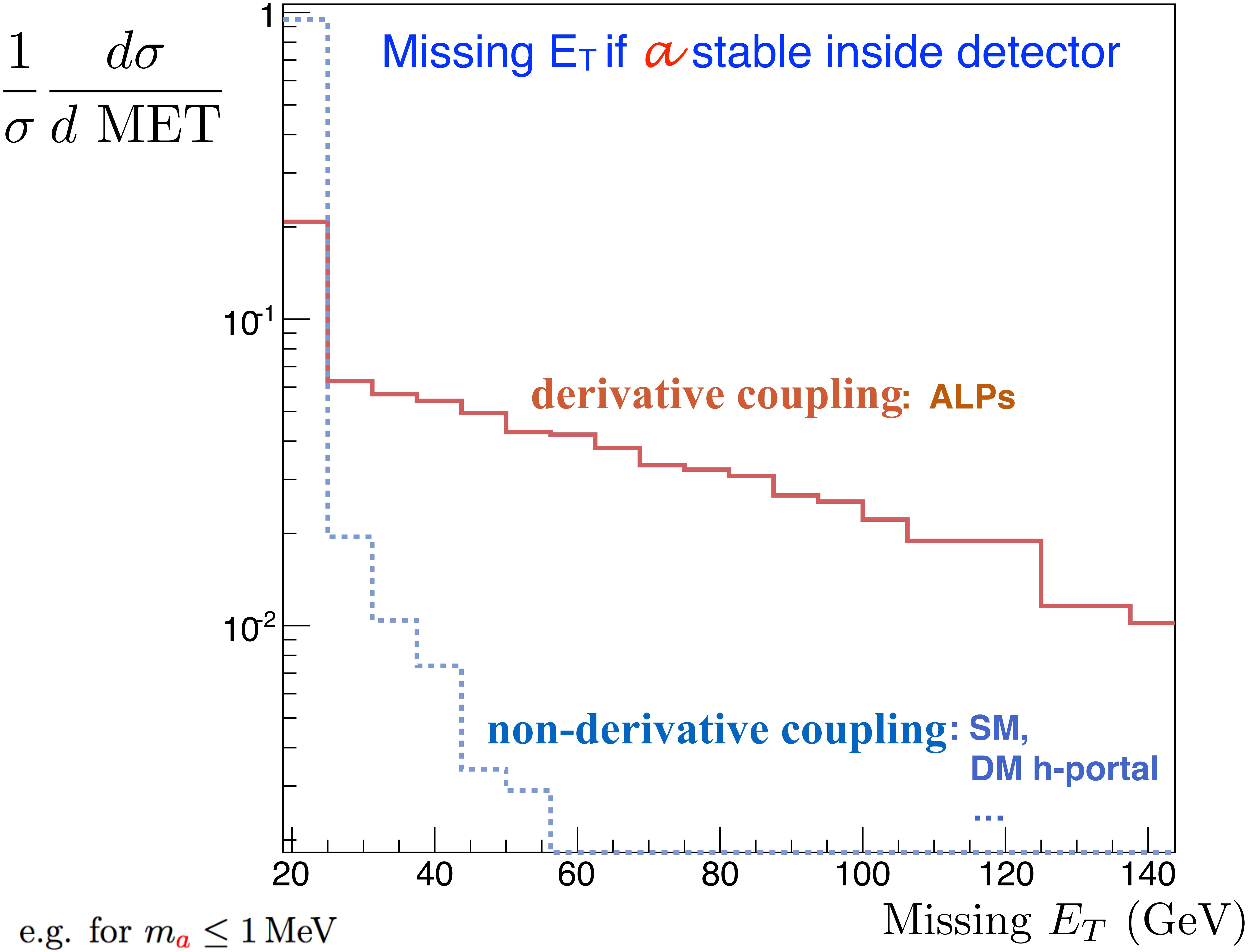
$$\frac{2is_{2\theta}}{f_a} p_{Z\alpha} p_{A\beta} \varepsilon^{\mu\nu\alpha\beta} \left(c_{\tilde{B}} - c_{\tilde{W}}\right)$$



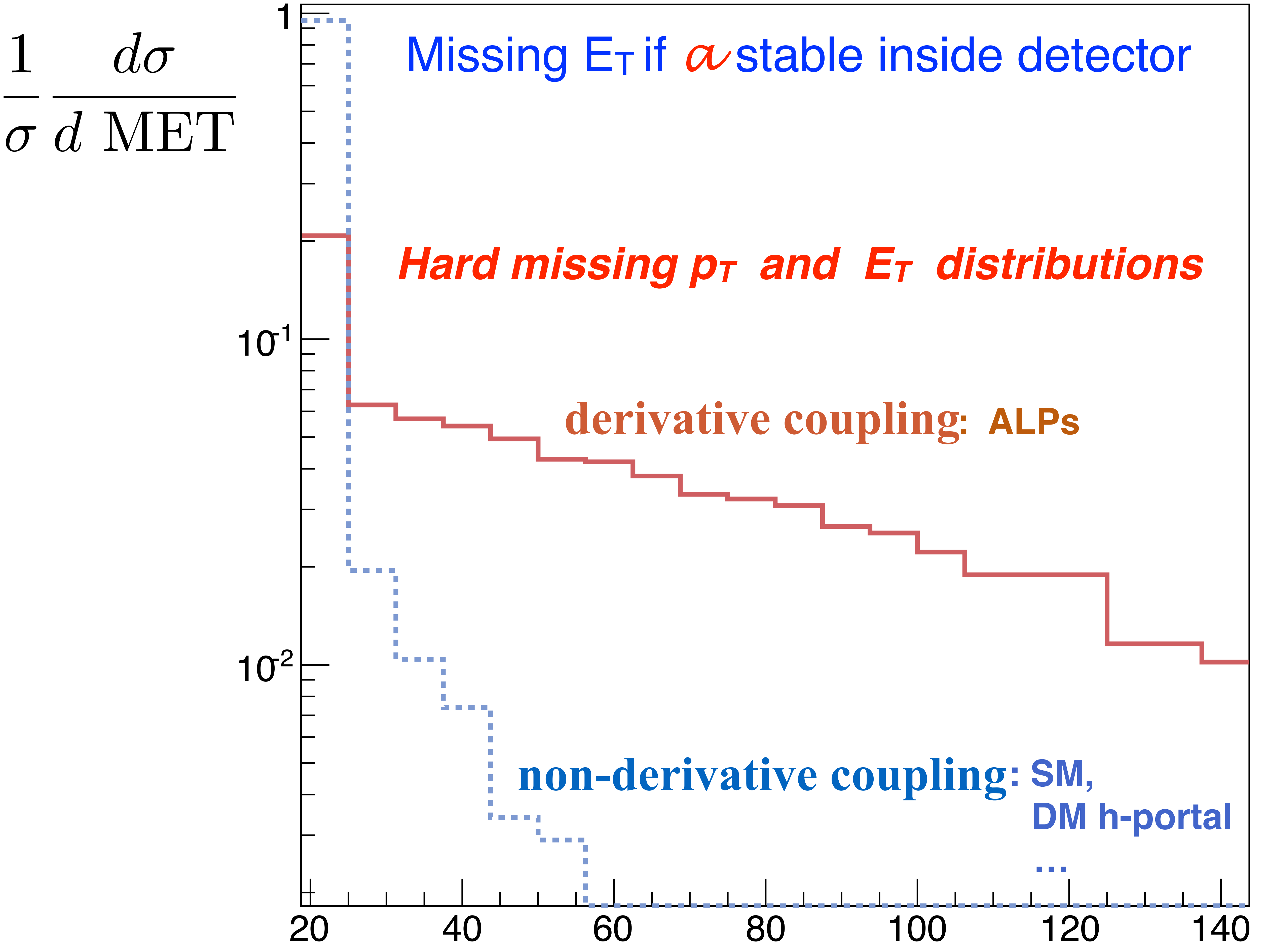
$$-\frac{4i}{f_a} c_{\tilde{W}} p_{+\alpha} p_{-\beta} \varepsilon^{\mu\nu\alpha\beta}$$



$$-\frac{4i}{f_a} p_{Z1\alpha} p_{Z2\beta} \varepsilon^{\mu\nu\alpha\beta} \left(s_\theta^2 c_{\tilde{B}} + c_\theta^2 c_{\tilde{W}}\right)$$



e.g. for $m_a \leq 1\,\mathrm{MeV}$



Missing E_T if a stable inside detector

Hard missing p_T and E_T distributions

derivative coupling: ALPs

non-derivative coupling: SM, DM h-portal ...

e.g. for $m_a \leq 1\,\mathrm{MeV}$

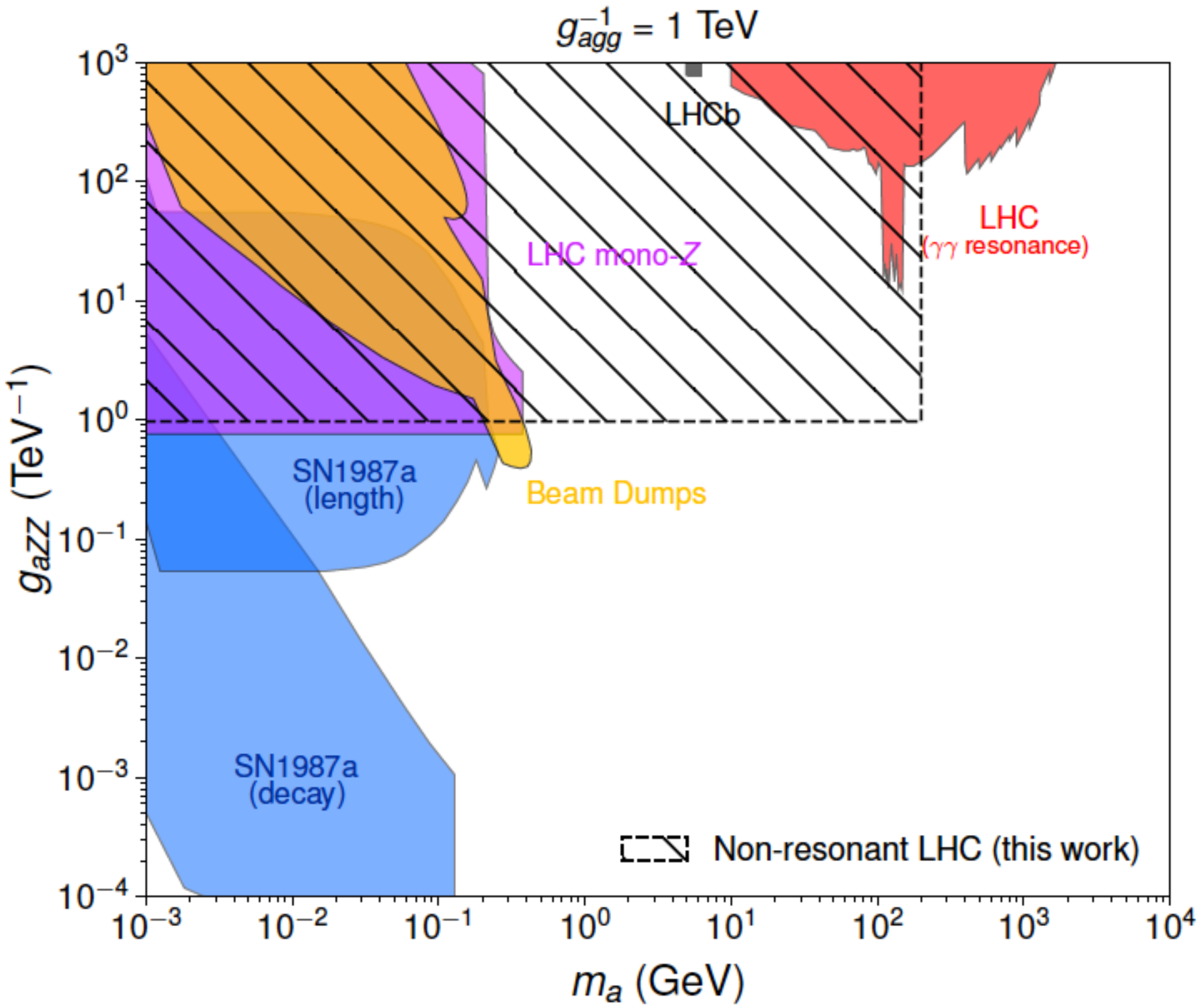
Other new ways to probe ALPs at LHC

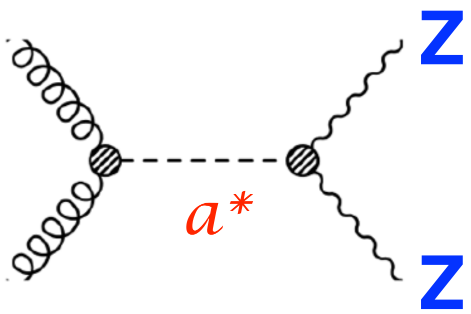
(Fdez. de Troconiz, Gavela, No, Sanz, 2019)

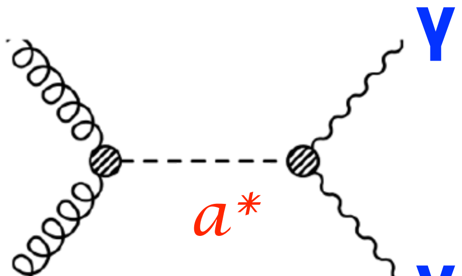
Non - resonant diboson searches

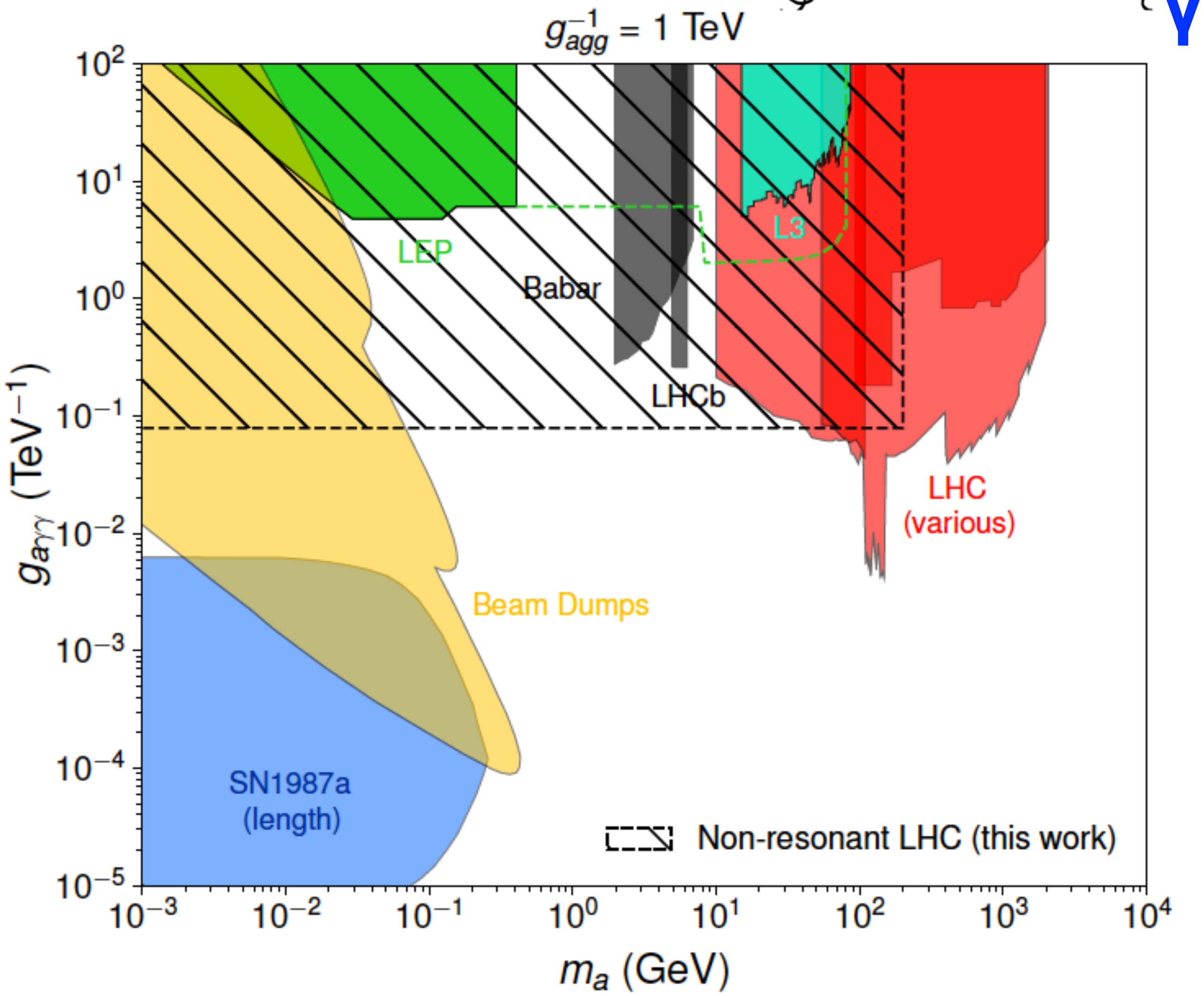
see also:
S. Carrá, *et al.* [2106.10085]
(WW and Zγ channels)

and CMS-B2G-20-013

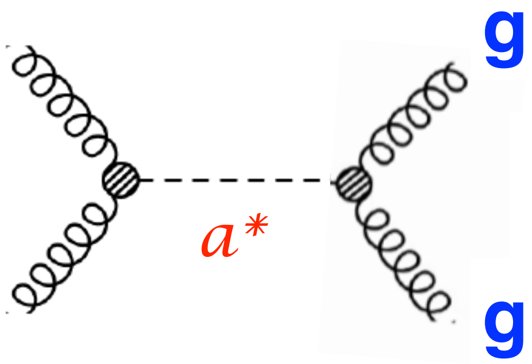








We also looked at two jets:

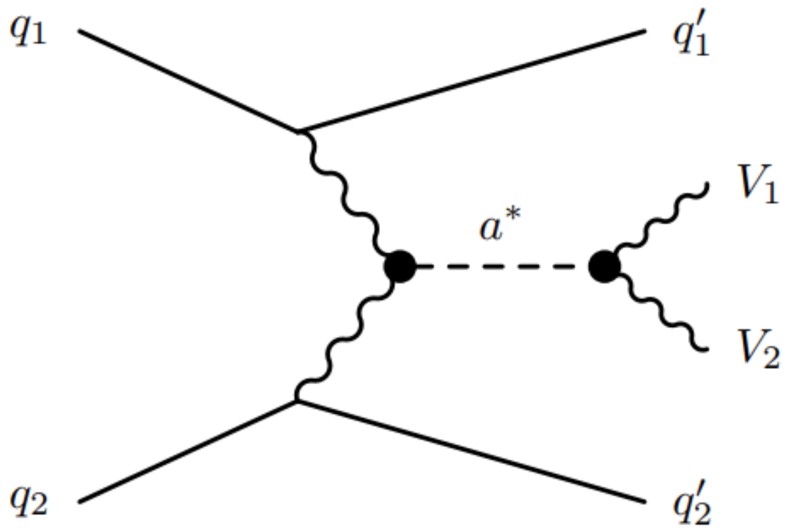


—-> $f_a/c_{\tilde{G}} > 2.5 \text{ TeV}$

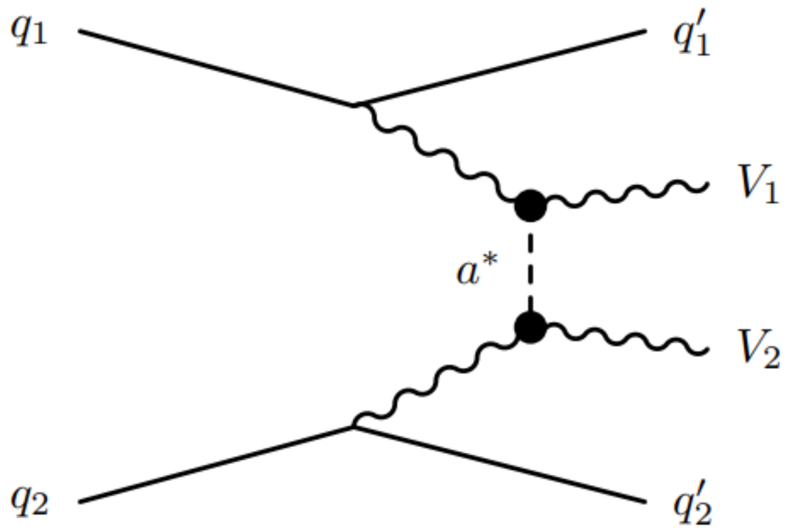
2022: **ALP-mediated EW VBS (vector-boson fusion)**

- **Vector Boson Scattering**
  → production of a diboson pair + 2 face-to-face jets with high invariant mass
  → explore **ALP EW couplings** with reduced dependence on the gluon coupling

- EW ALP-mediated processes $q_1 q_2 \rightarrow q_1' q_2' V_1 V_2$



VBS s-channel

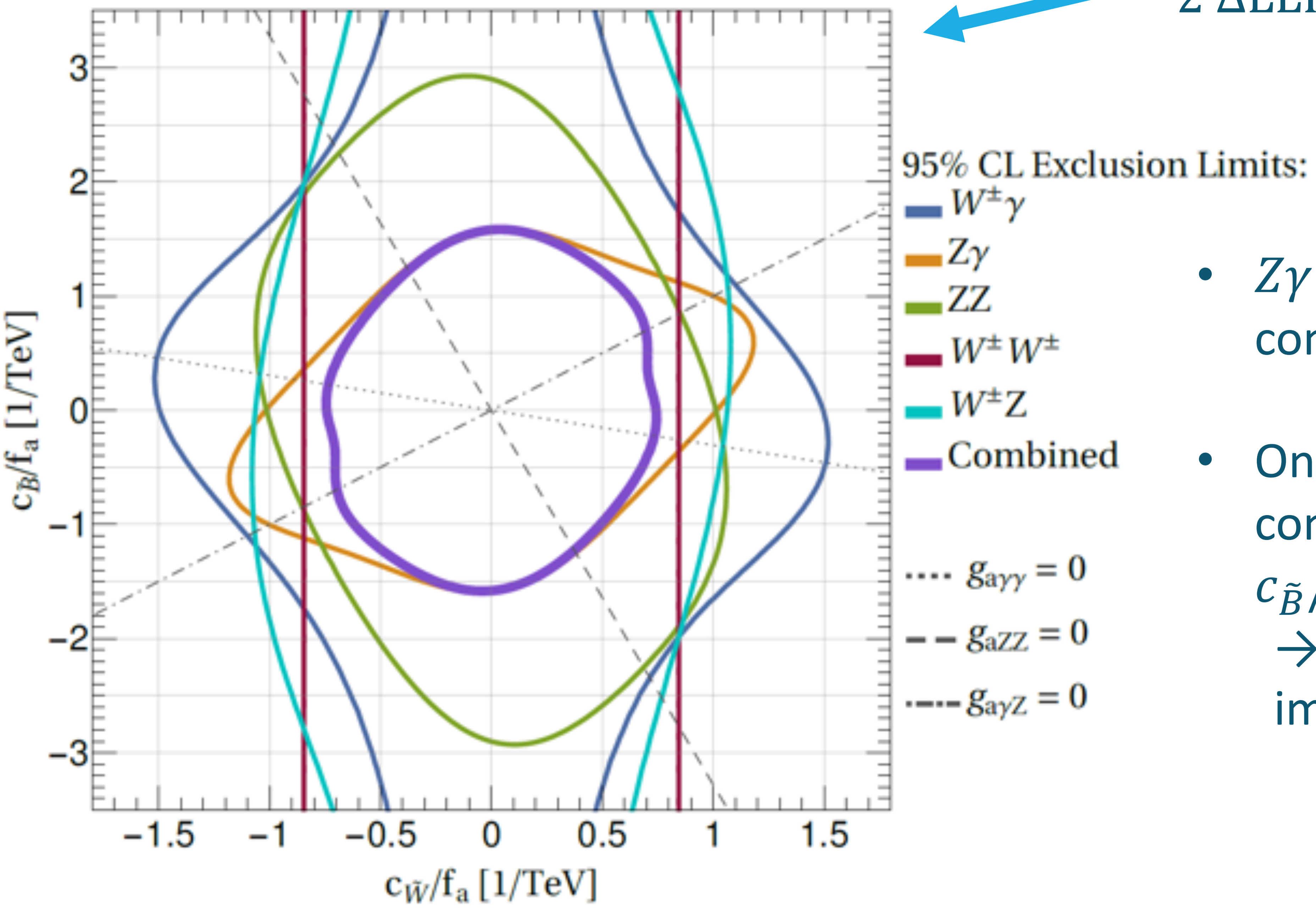


VBS t-channel

Reinterpretation of Run 2 CMS analysis:
$V_1V_2 = ZZ, Z\gamma, W^{\pm}\gamma, W^{\pm}Z, W^{\pm}W^{\pm}$

CMS-SMP-20-001, CMS-SMP-20-016,
CMS-SMP-19-008, CMS-SMP-19-012

RESULTS



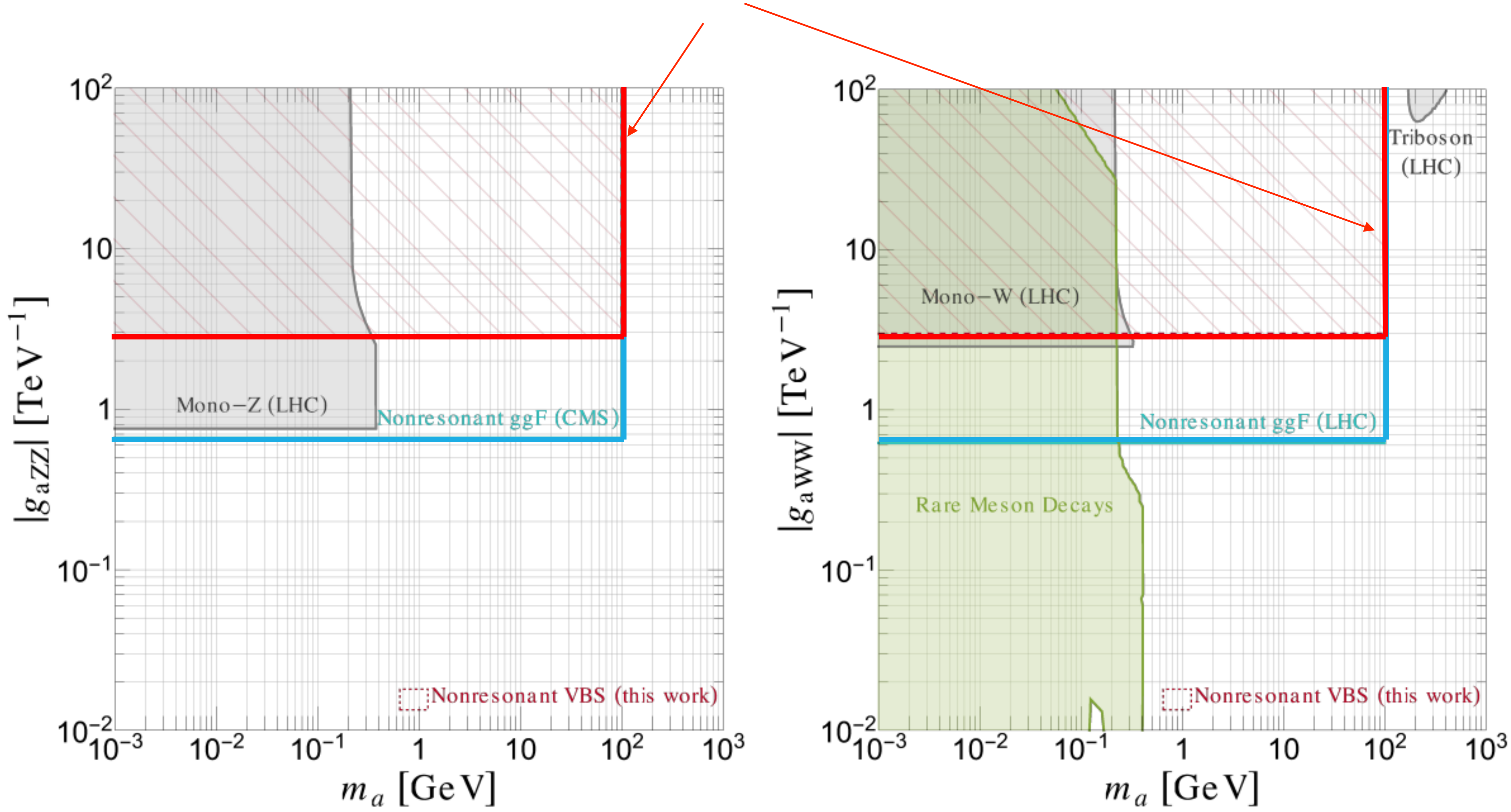
$-2\ \Delta\text{LLR} = 3.84$

- $Z\gamma$ and $W^\pm W^\pm$ are the most constraining channels
- Only $Z\gamma$ and ZZ can constraint the plane in the $c_{\tilde{B}}/f_a$ direction.
  → high-mass $\gamma\gamma$ channel can improve it

J. Bonilla, I. Brivio, J. Machado-Rodríguez and J. F. de Trocóniz [2202.0345]

Comparison with existing bounds

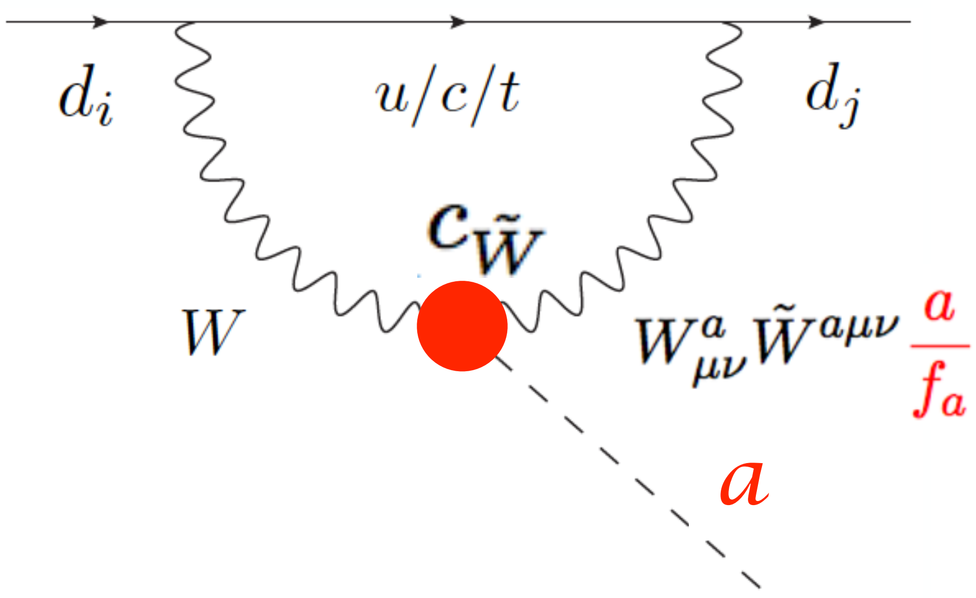
J. Bonilla, I. Brivio, J. Machado-Rodríguez and J. F. de Trocóniz [2202.0345]

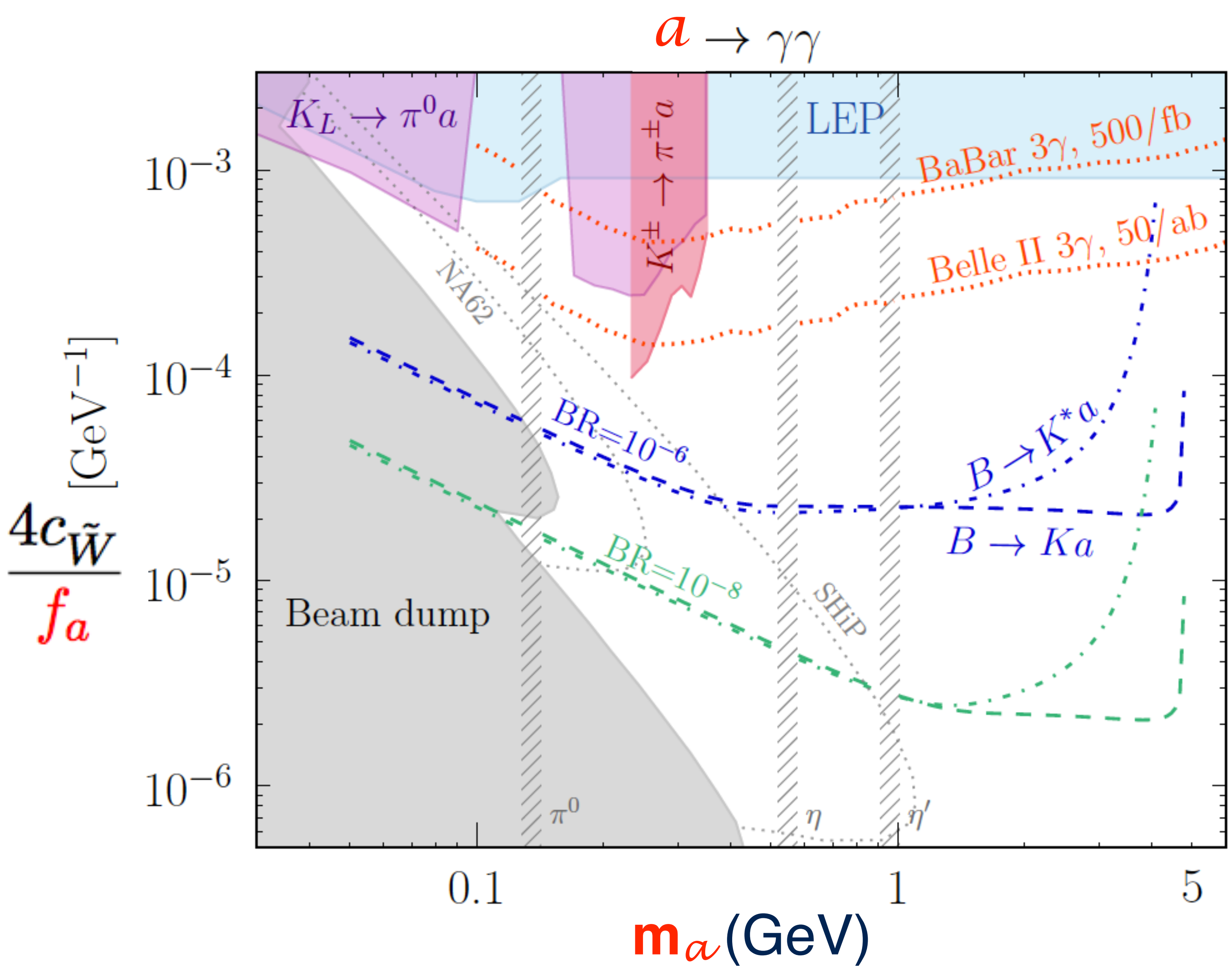


ALPs in FLAVOUR searches

$c_{\tilde{W}}$ from rare meson decays

B —> K a , K—>π a….. a —>γγ

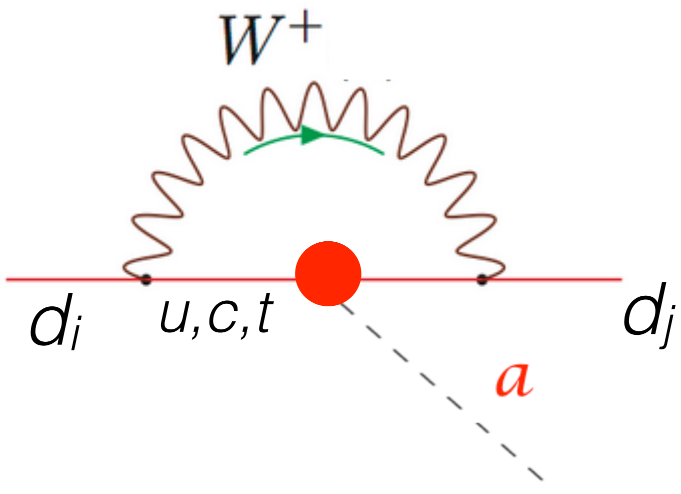




Izaguirre+Lin+Shuve 2016

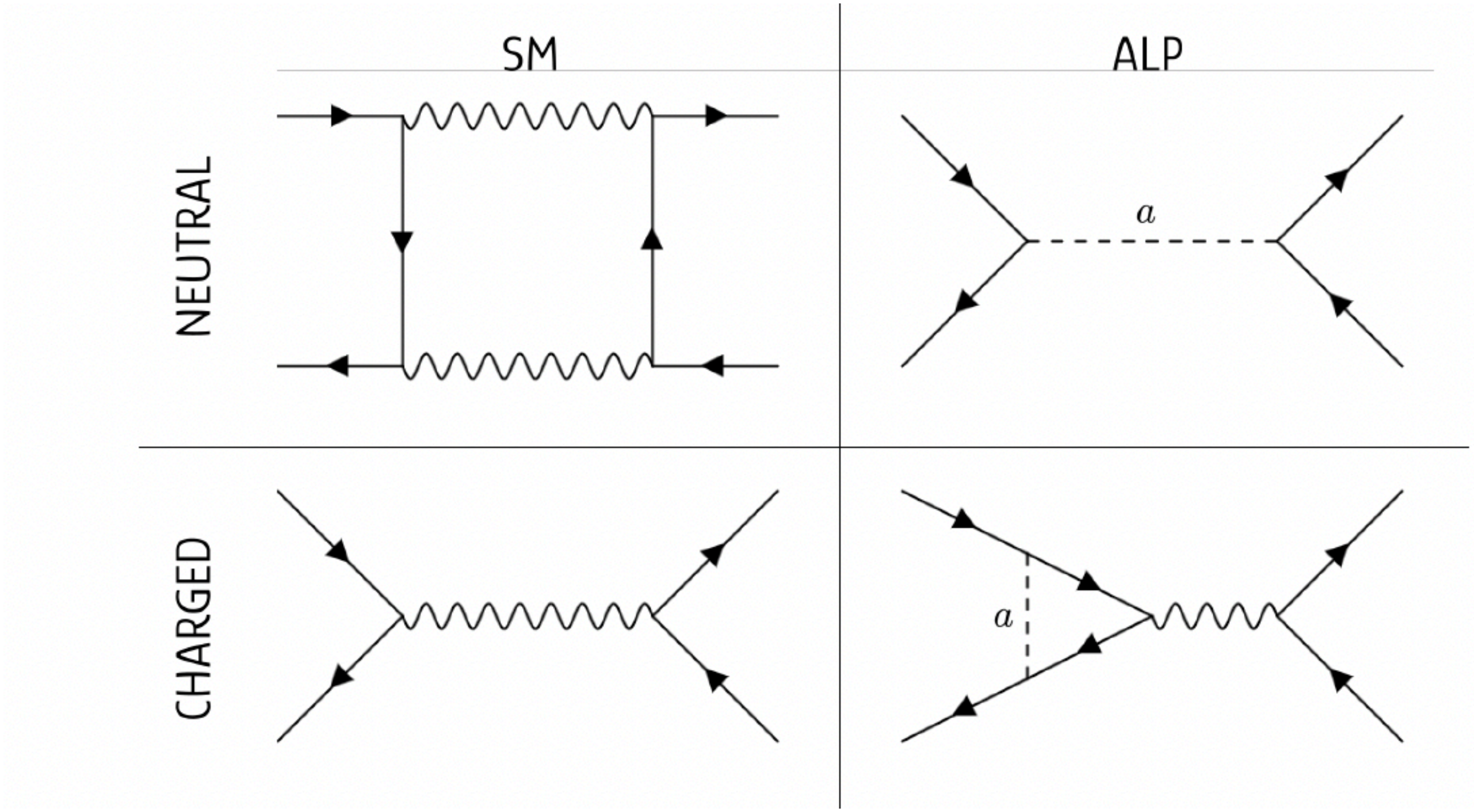
But several ops. may contribute:

$$\{c_{\tilde{W}}, c_{a\Phi}, c_{\psi_i}\}$$



+Del Rey et al. 2018

B anomalies: can ALP exchange account for them?



difficult…but R_K and R_{K^*}

(i.e. anomalies in B—> X $\mu^+ \mu^-$ / B—> X $e^+ e^-$)

could be explained

via on-shell ALP exchange

Bauer et al. arXiv 2110.10698; Bonilla et al. arXiv 2209.11247

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:**

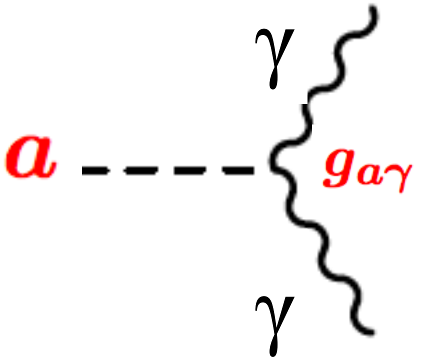
$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2$$

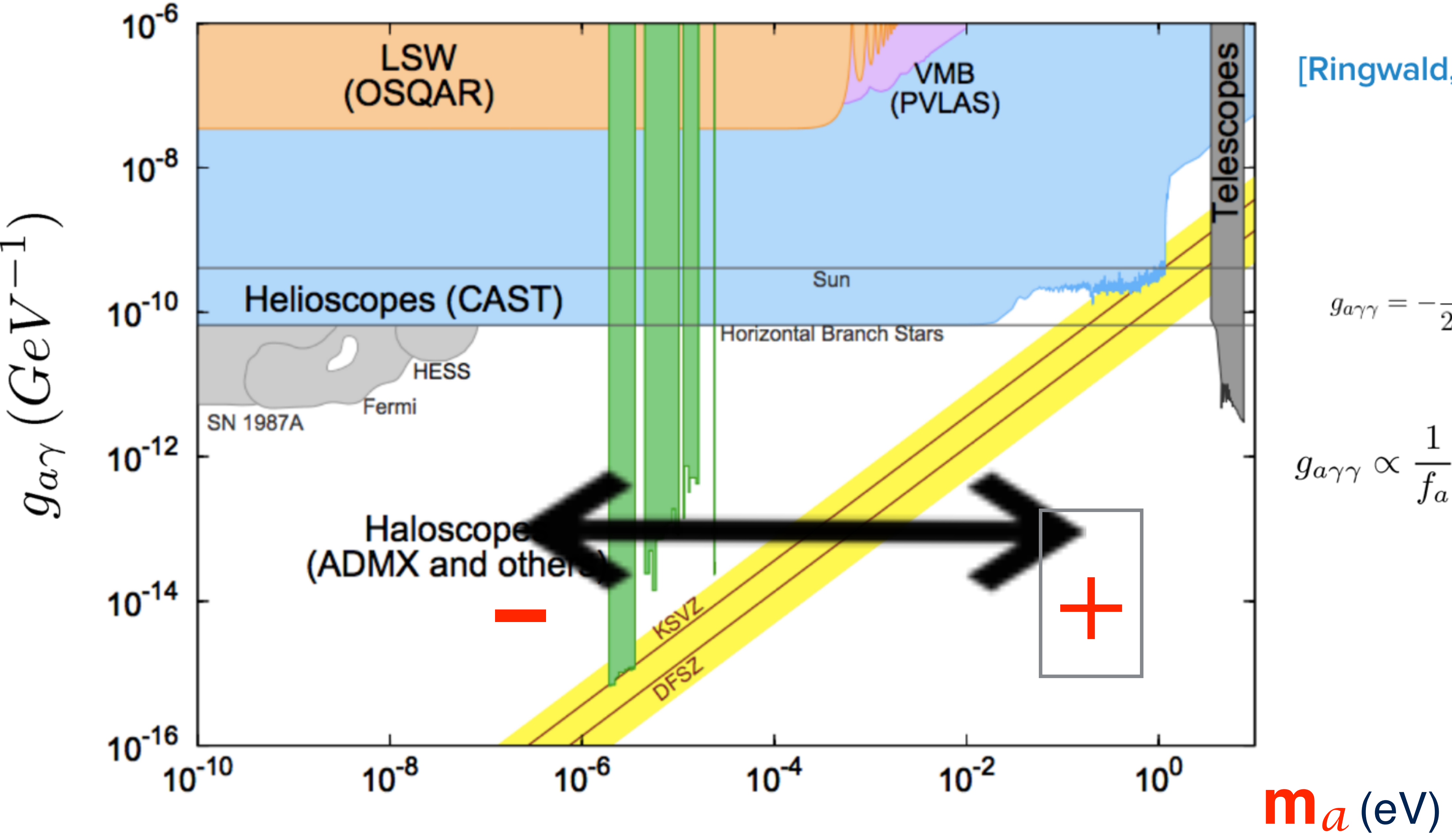
*** If the confining group is larger than QCD:**

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

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

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:**

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

the true-axion parameter space relaxes

A heavy true axion

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

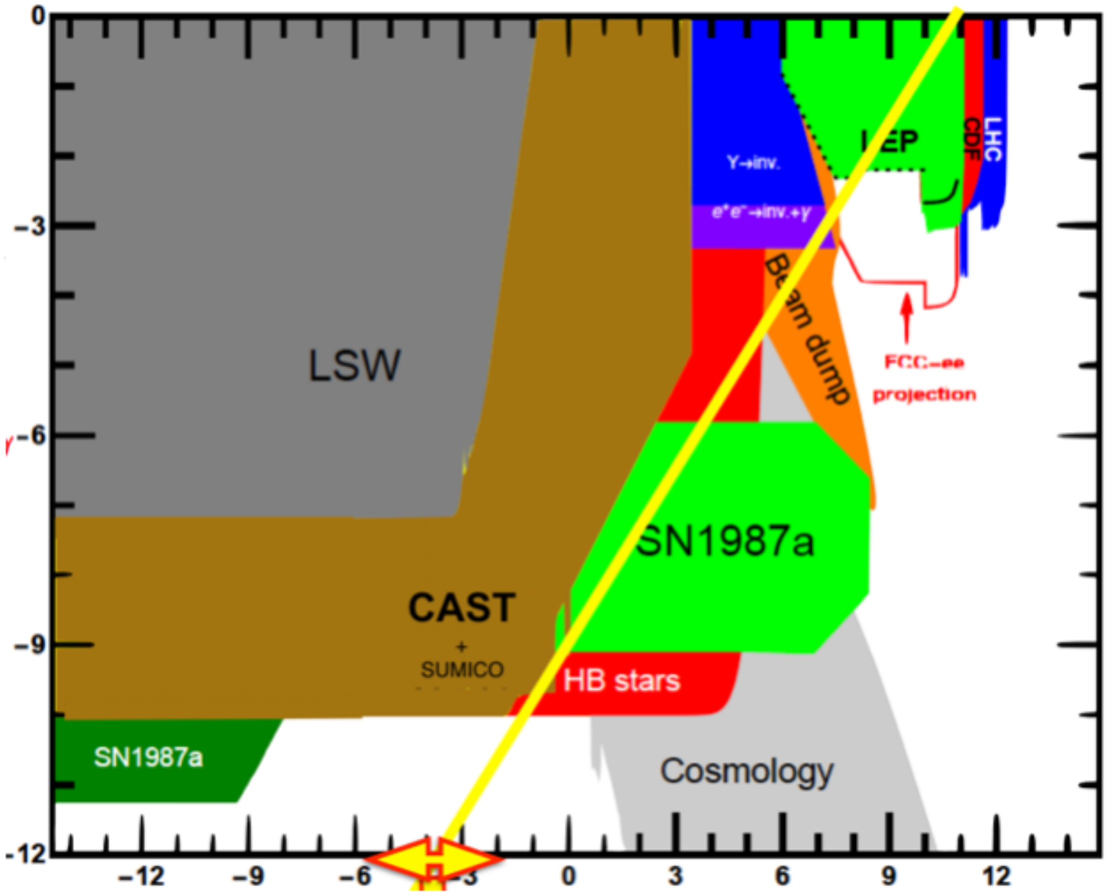
$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2 + \Lambda'^4 \qquad \Lambda' \gg \Lambda_{\rm QCD}$$

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

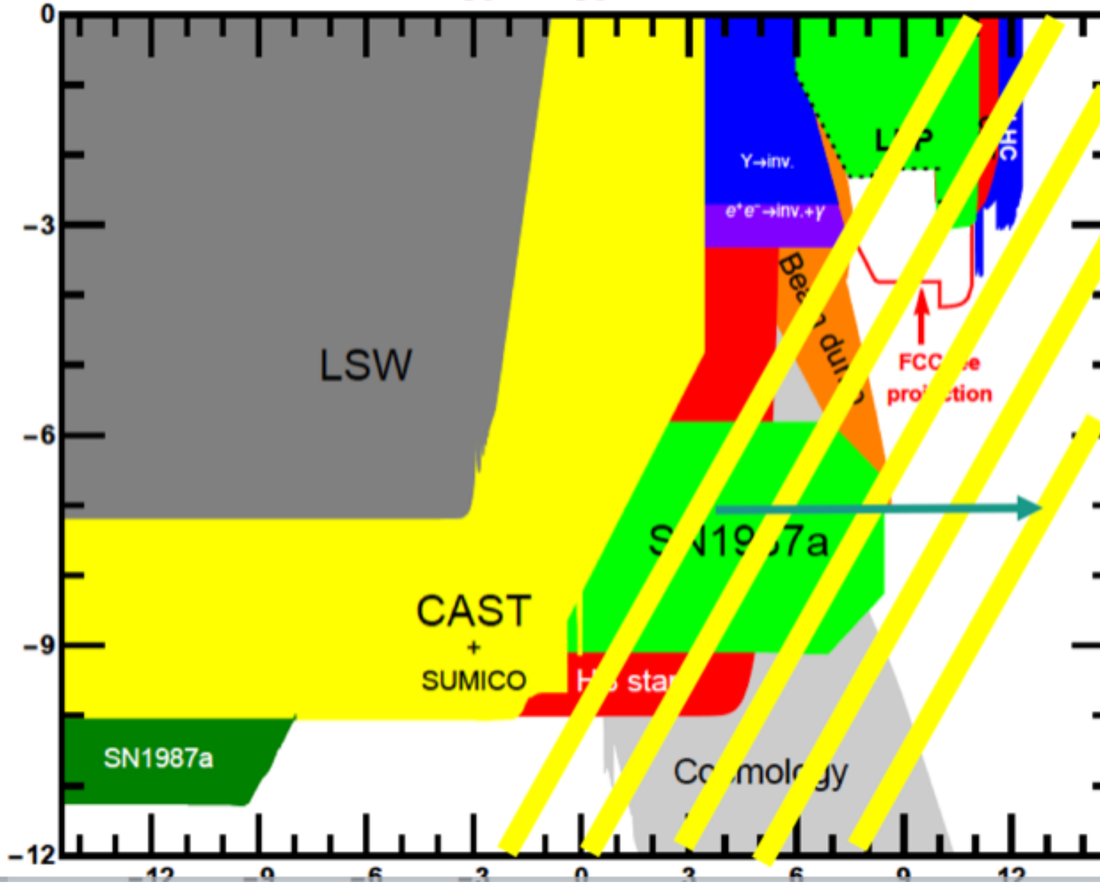
QCD: $\Lambda = \Lambda_{\rm QCD}$

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

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



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



$m_a^2 f_a^2 =$ **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]

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

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 ~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"

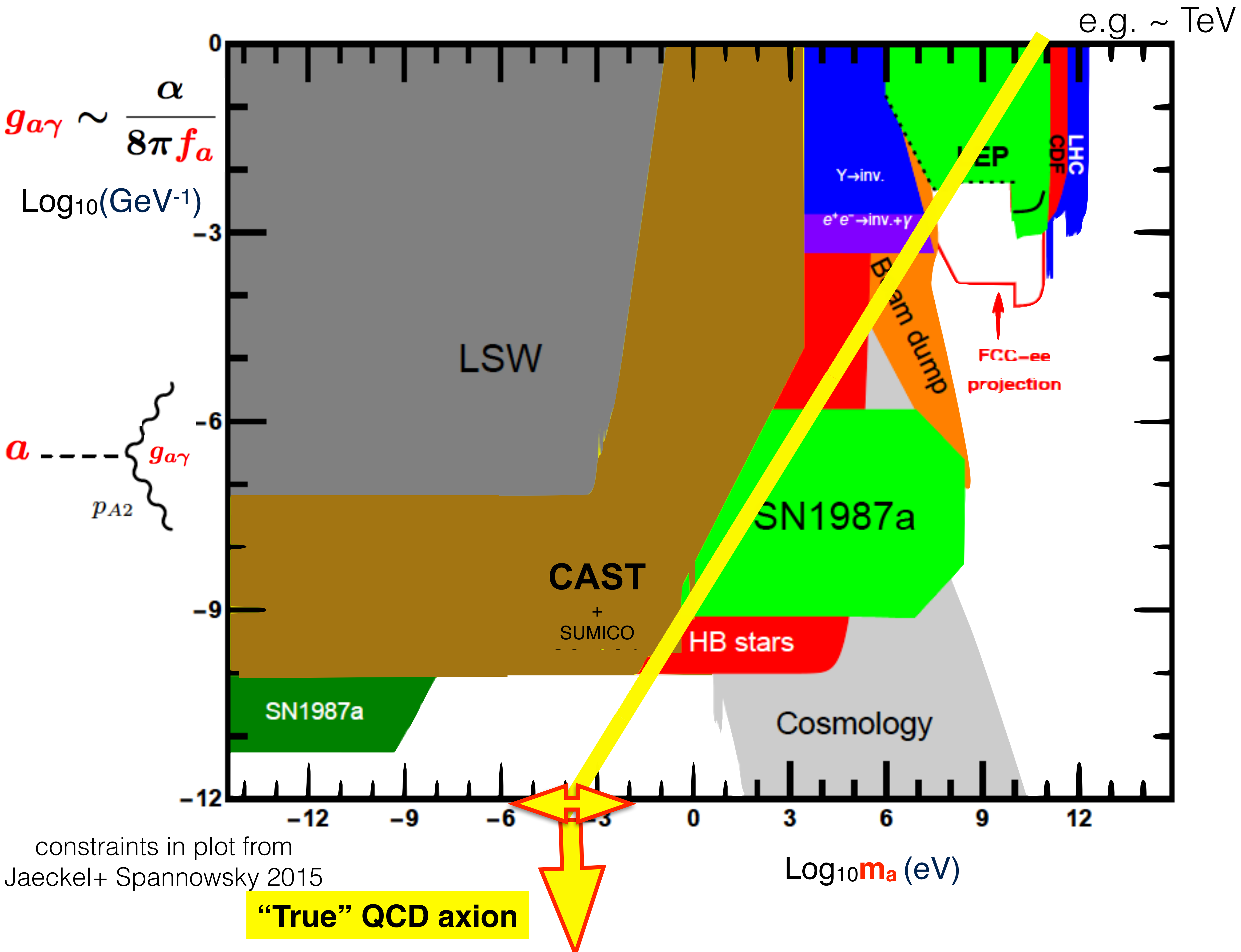
The tiny axion mass is due to mixing
with η' and pion:

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

independently of the axion model

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

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

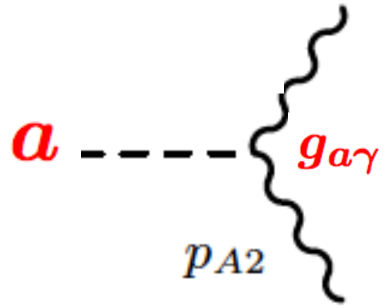


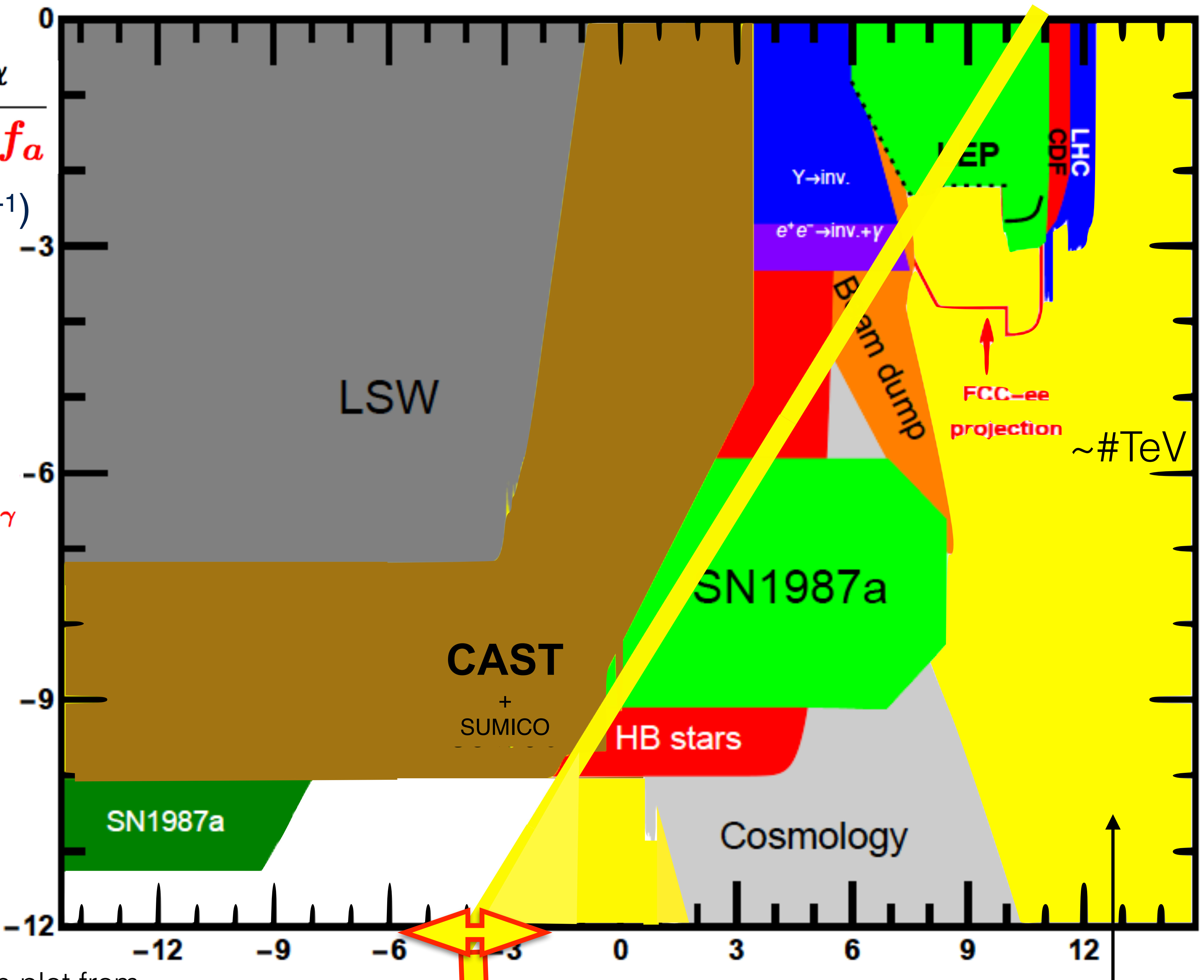
constraints in plot from
Jaeckel+ Spannowsky 2015

ALPs territory: they can be true axions

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

Log10(GeV-1)





Log10ma (eV)

constraints in plot from
Jaeckel+ Spannowsky 2015

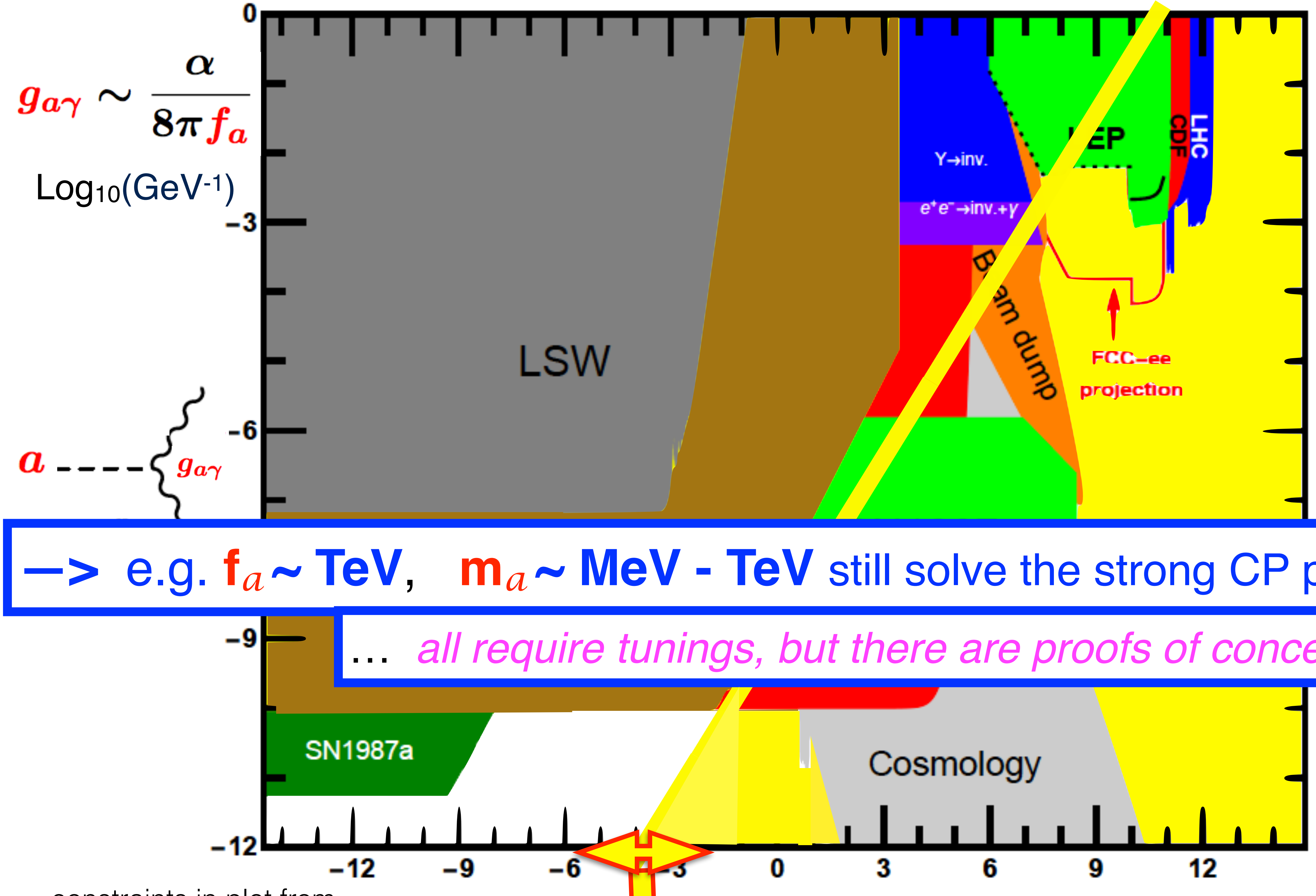
“True” QCD axion

“True” QCD axion region amplifies

ALPs territory: they can be true axions

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

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



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

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

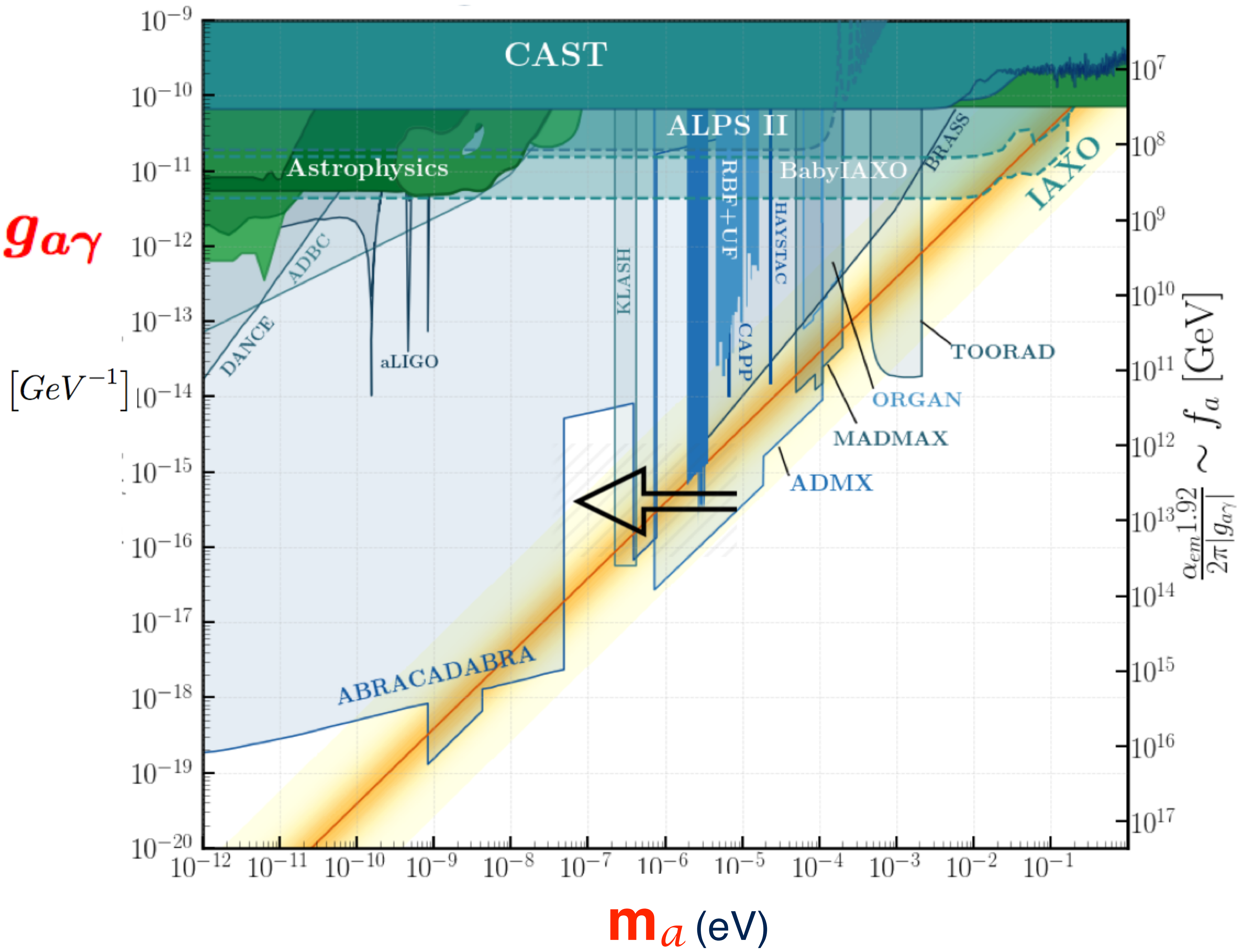
constraints in plot from
Jaeckel+ Spannowsky 2015

$\text{Log}_{10}\, m_a$ (eV)

“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

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

How to do that without fine-tunings?

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

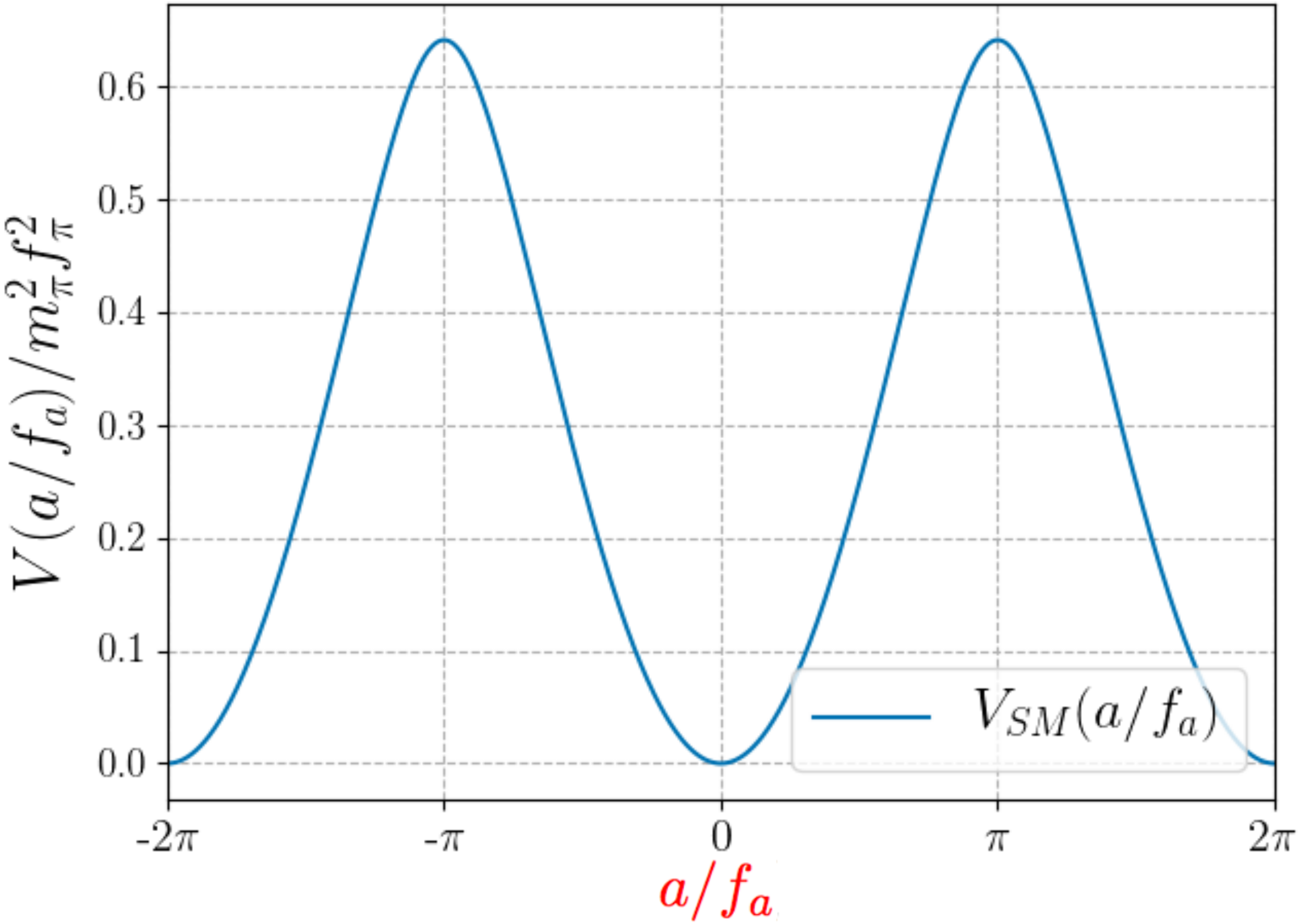
*** And solve the strong CP problem:** arXiv 2102.00012

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



how to add something that naturally flattens it?

A Z_2 (or Z_N) symmetry : mirror degenerate worlds

[Hook, 18]

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

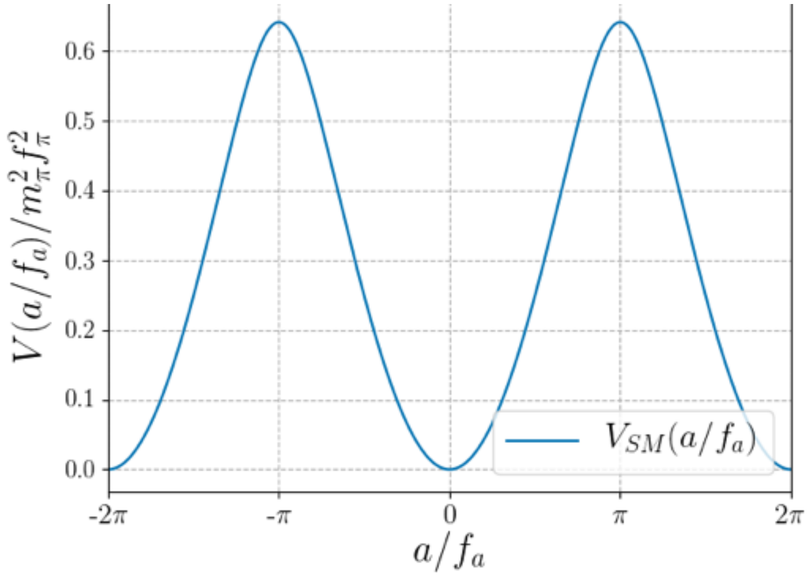
$$a \longrightarrow a + \pi f_a$$

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

QCD **QCD'**

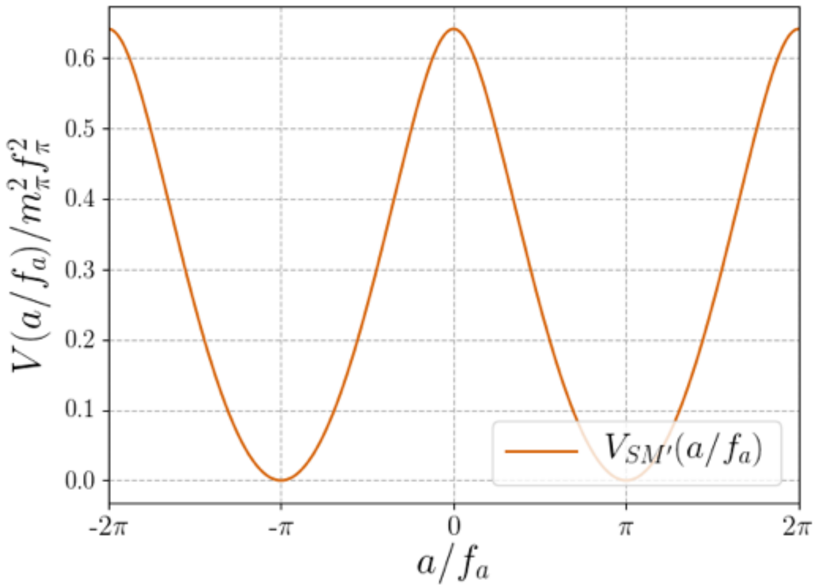
$$V_{SM}(\frac{a}{f_a}) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a}\right)}$$

SM



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

SM’

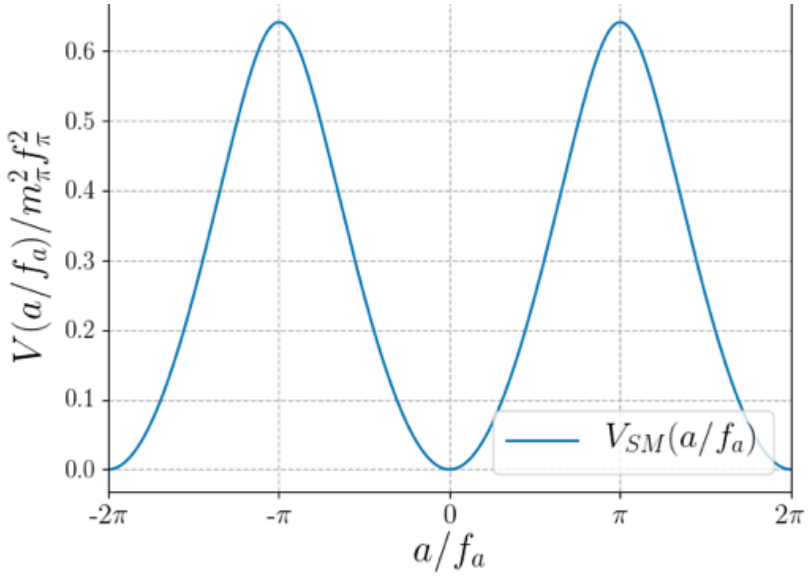


← $(\frac{a}{f_a} + \pi) G'_{\mu\nu}\tilde{G}'^{\mu\nu}$

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

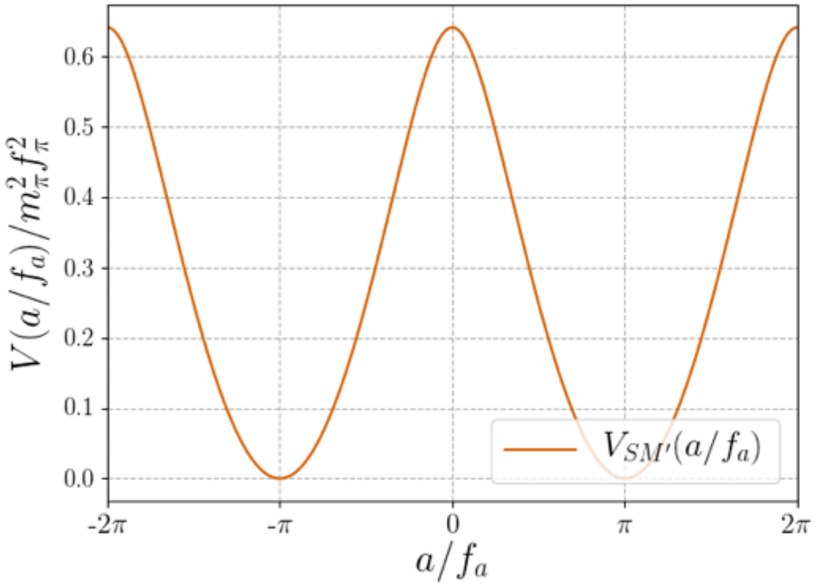
$$V_{SM}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a}\right)}$$

SM

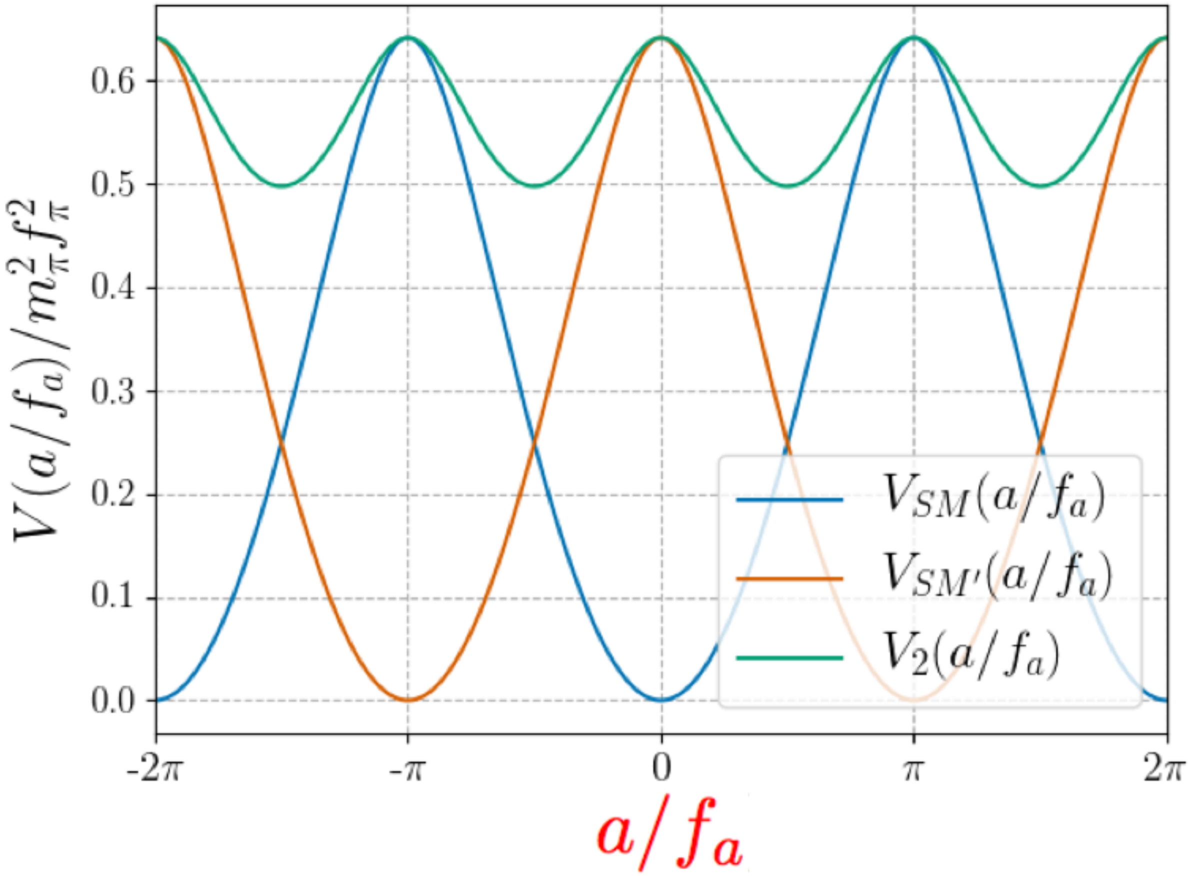


+

SM’



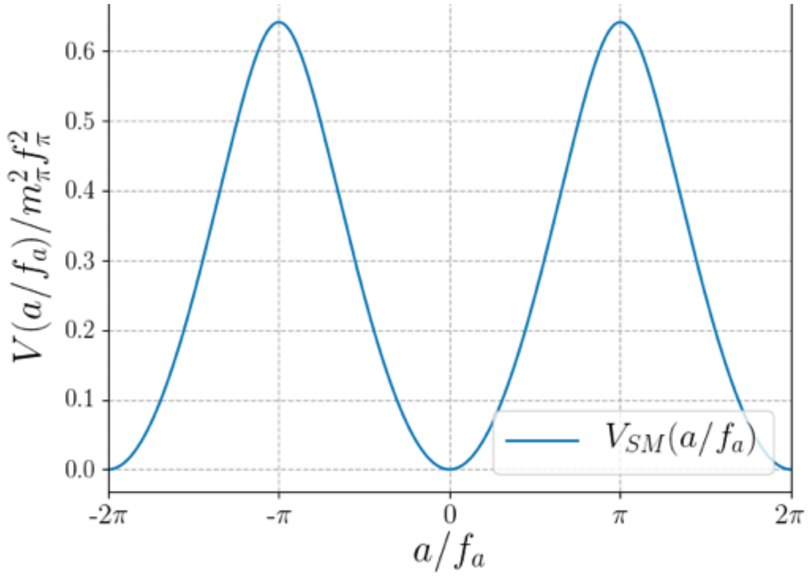
$$V_{SM'}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a}+\frac{\pi}{2}\right)}$$



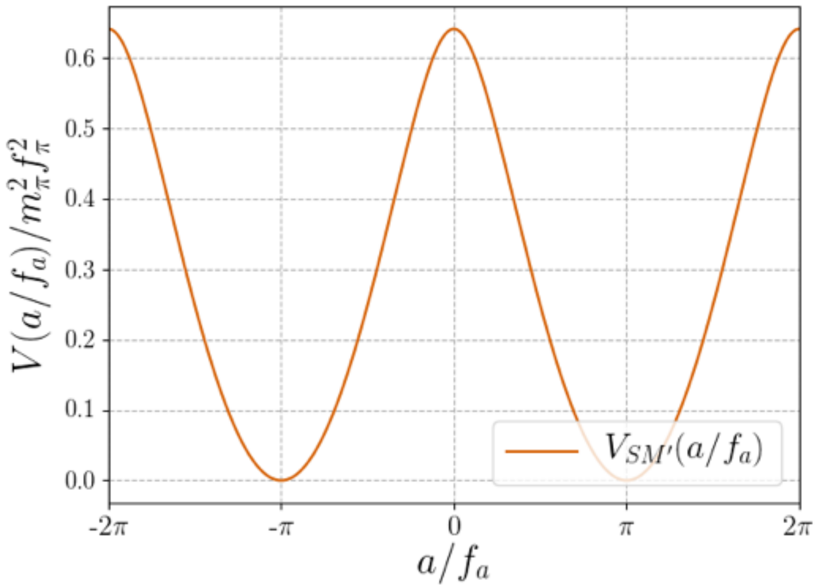
[Hook, 18]

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

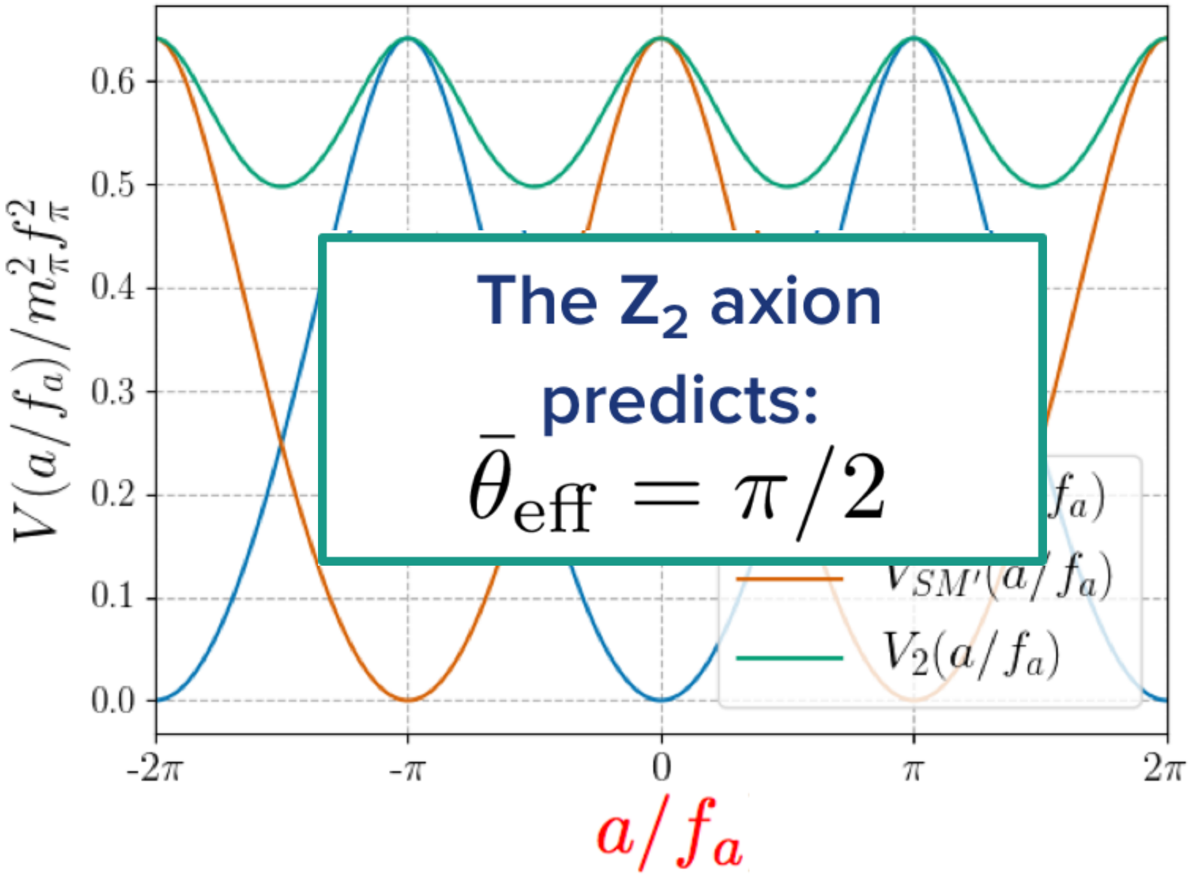
SM



SM'



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



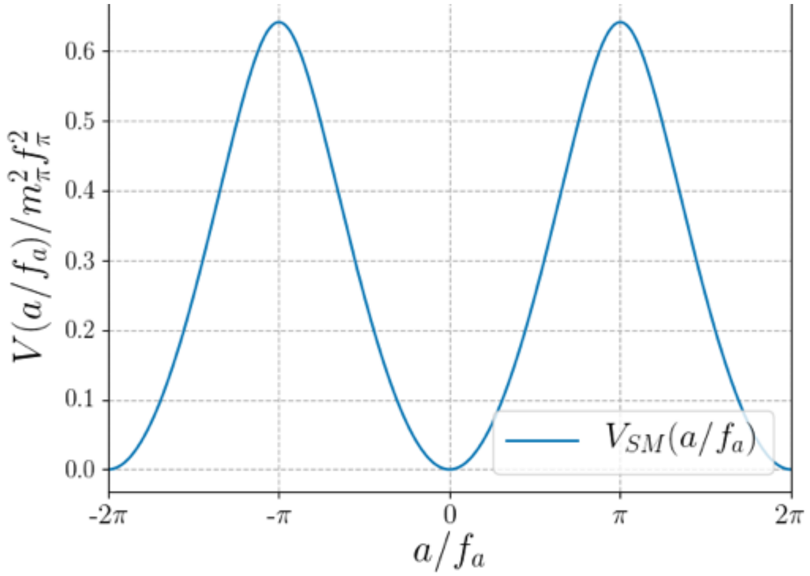
The Z_2 axion predicts:

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

[Hook, 18]

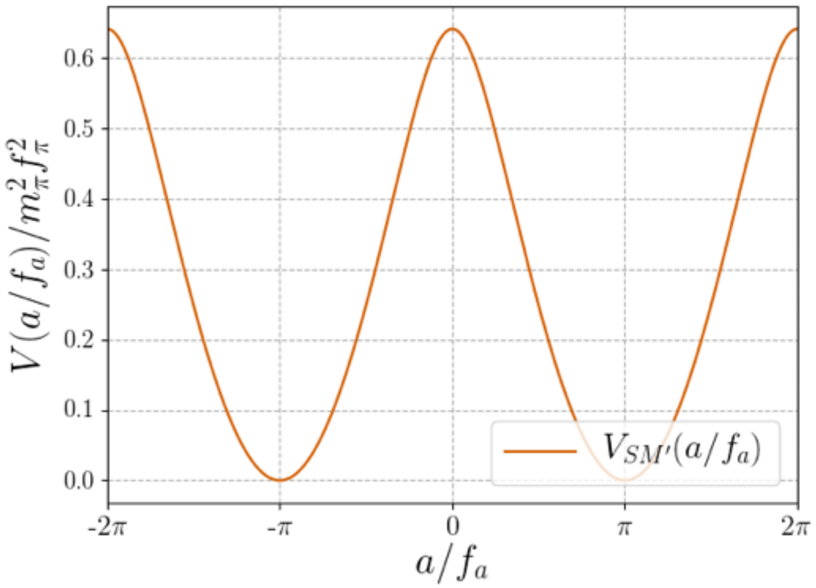
$$V_{SM}\left(\frac{a}{f_a}\right) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a}\right)}$$

SM

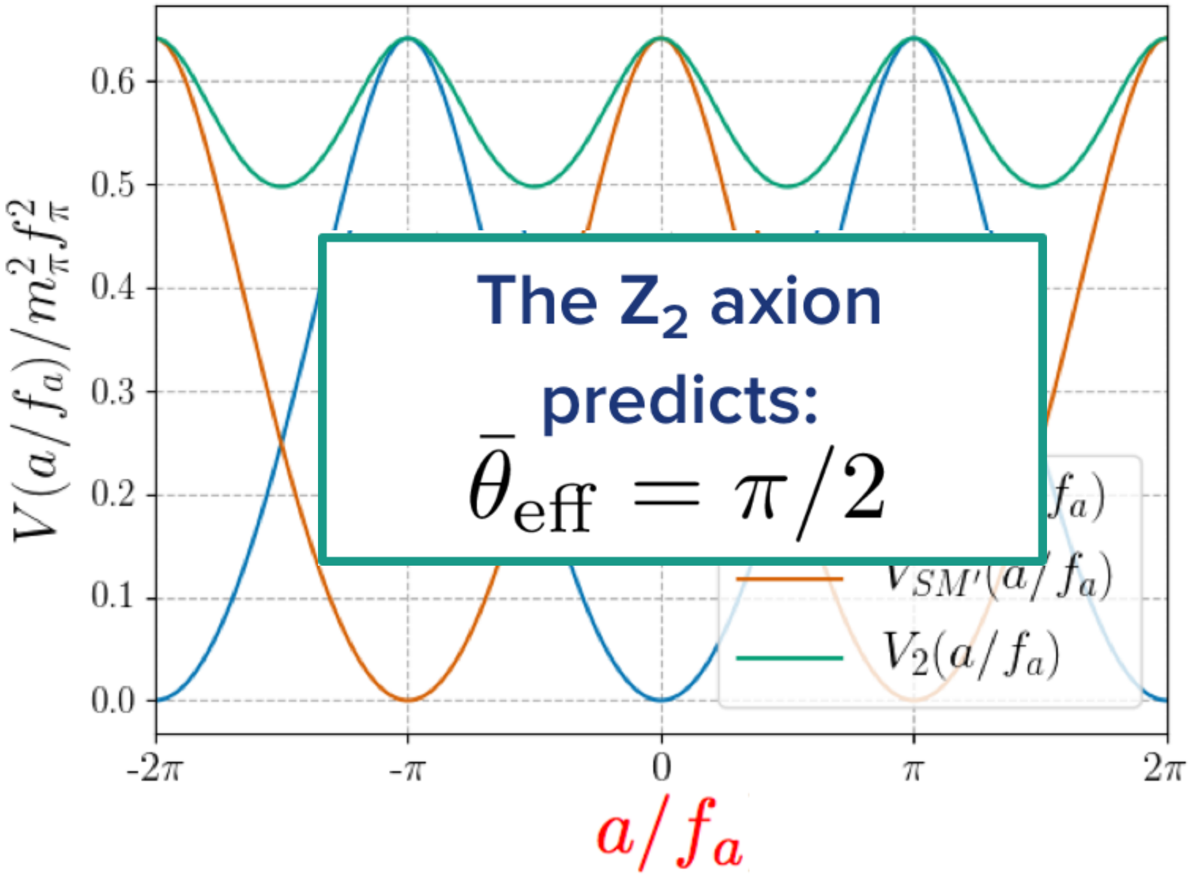


+

SM’



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

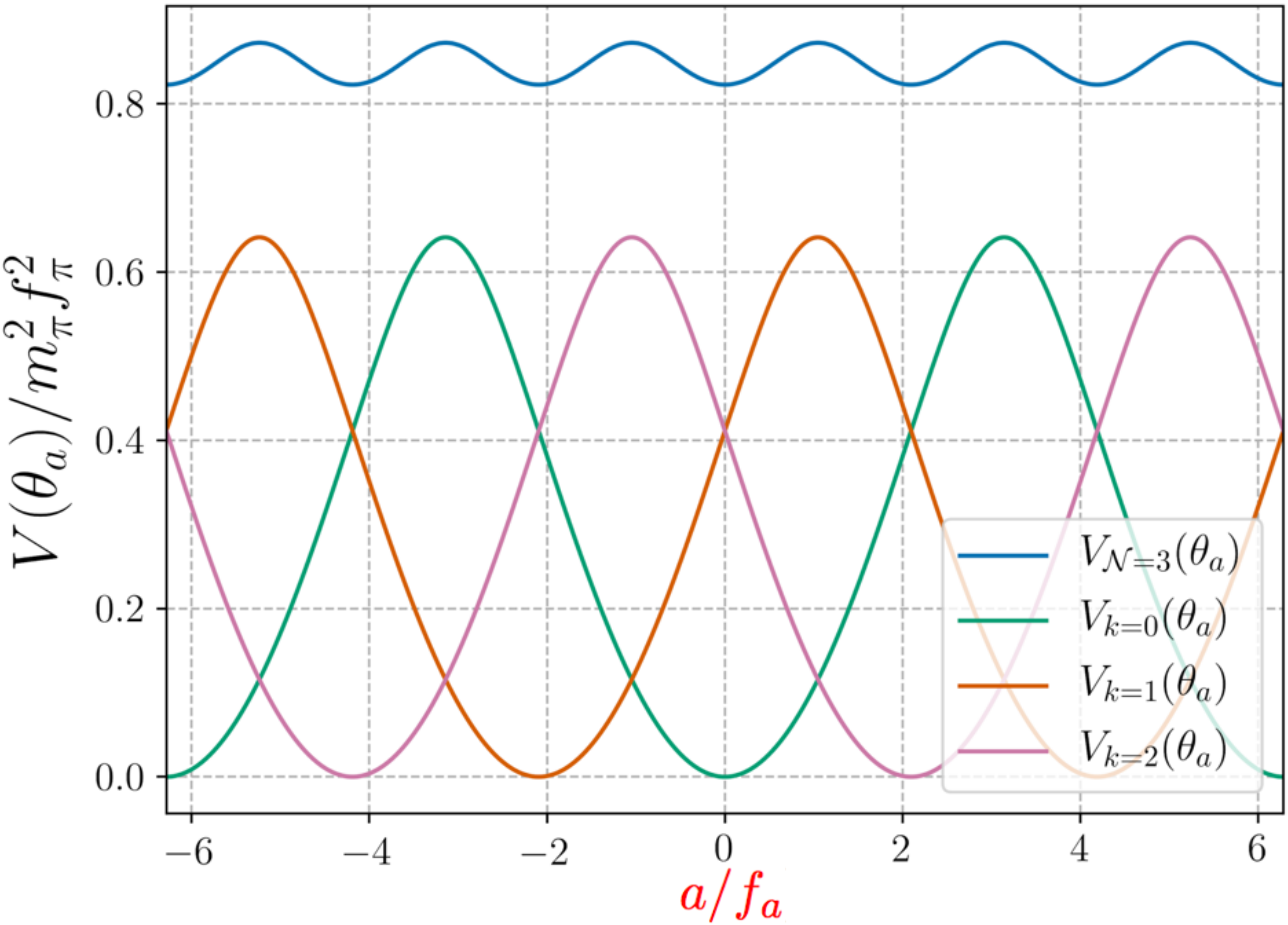


The Z_2 axion predicts:

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

you need N=odd

Example: Z_3



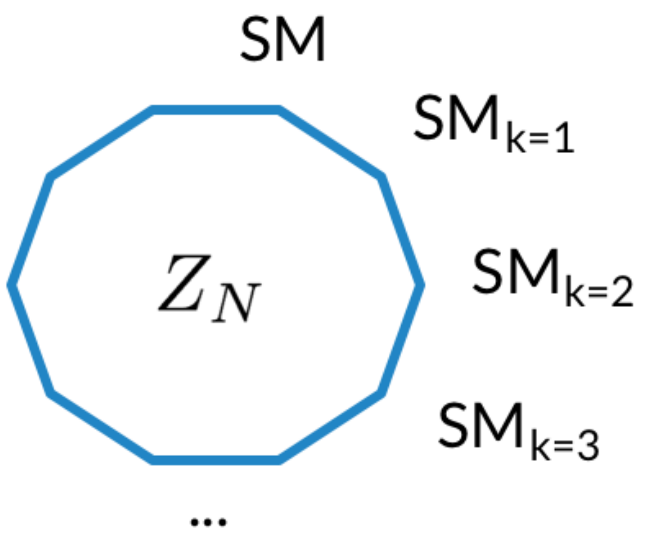
$V(\theta_a)/m_\pi^2 f_\pi^2$
0.0
0.2
0.4
0.6
0.8
−6
−4
−2
0
2
4
6
a/f_a
$V_{\mathcal{N}=3}(\theta_a)$
$V_{k=0}(\theta_a)$
$V_{k=1}(\theta_a)$
$V_{k=2}(\theta_a)$

$Z_{N\text{ axion}}$: 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

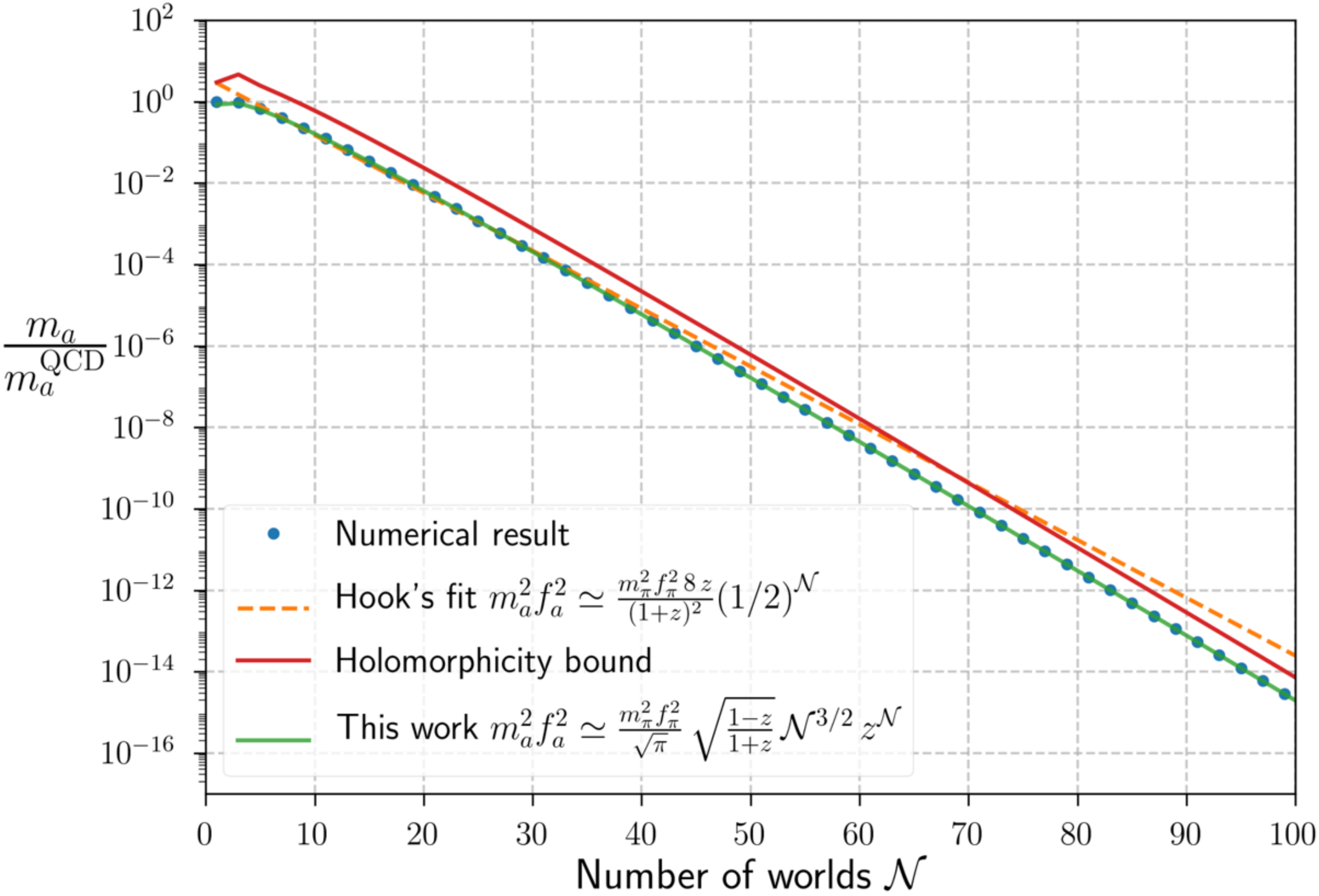
$$\boxed{m_a^2\, f_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}}\, \mathcal{N}^{3/2}\, z^{\mathcal{N}}}$$

$$z = m_u/m_d$$

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



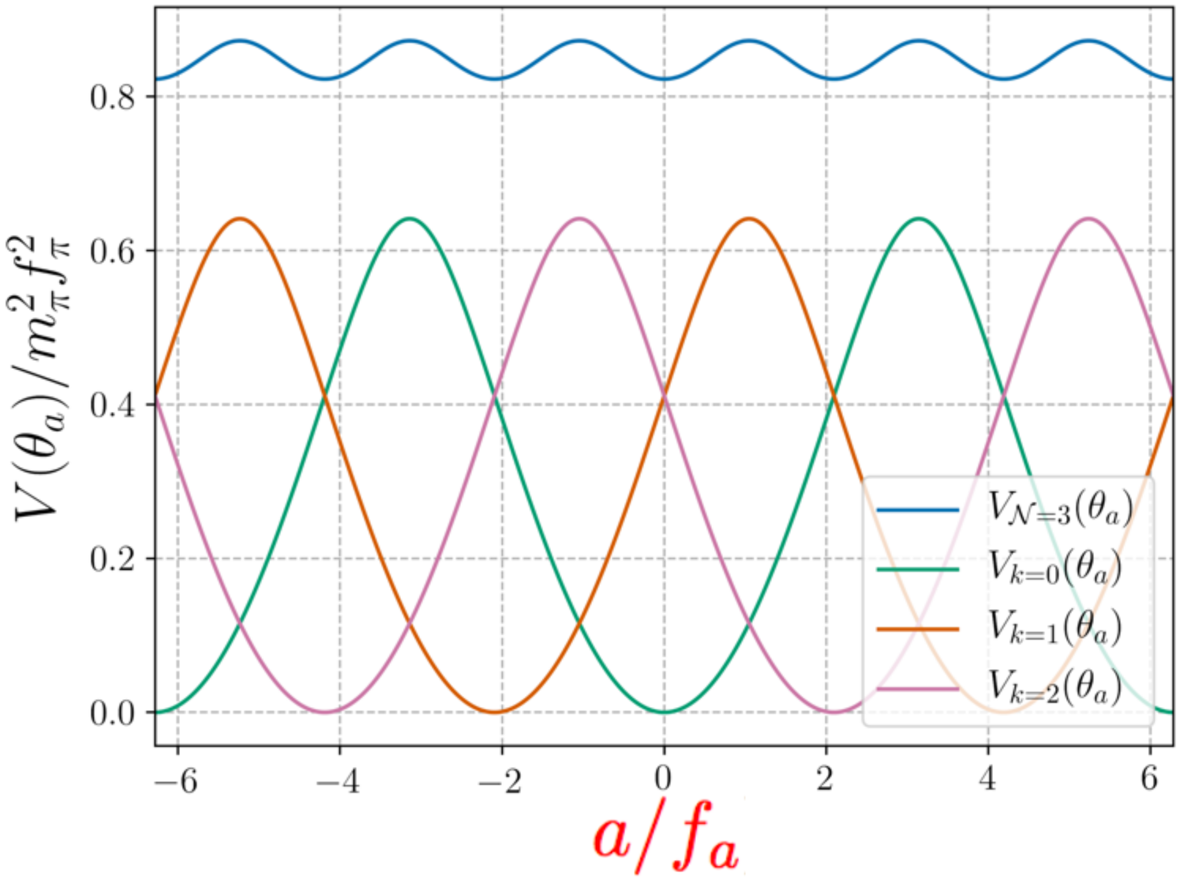
excellent agreement with numerical already for N=3

di Luzio, Quilez, Ringwald, BG arXiv 2102.00012

Caveat:

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

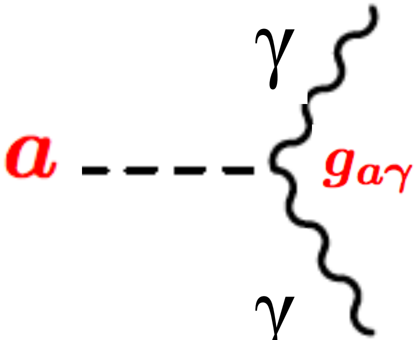
$$\theta_a = \{\pm 2\pi\ell/\mathcal{N}\} \qquad \text{for} \quad \ell = 0, 1, \ldots, \frac{\mathcal{N}-1}{2},$$



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

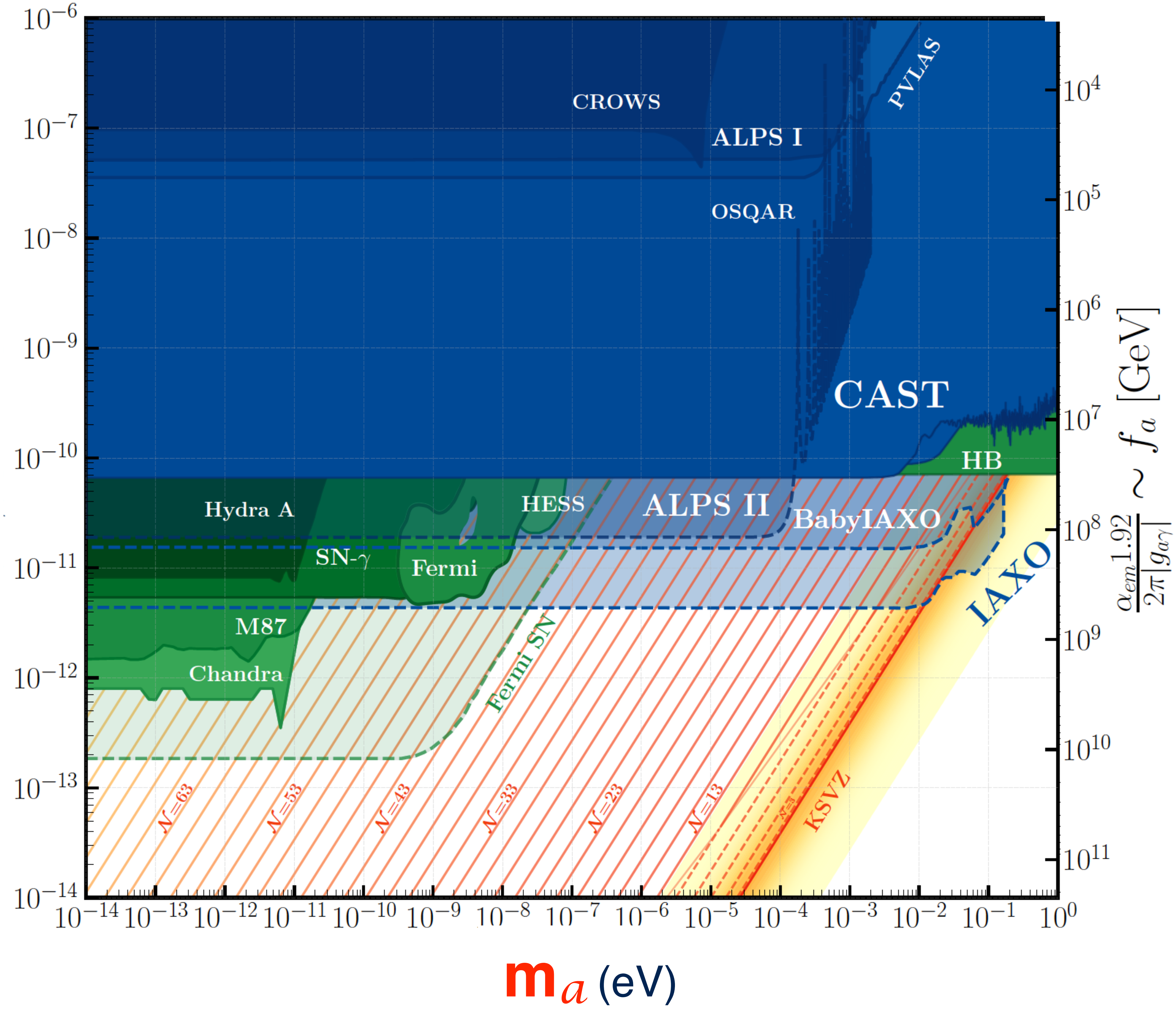
↓

$1/\mathcal{N}$ probability



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

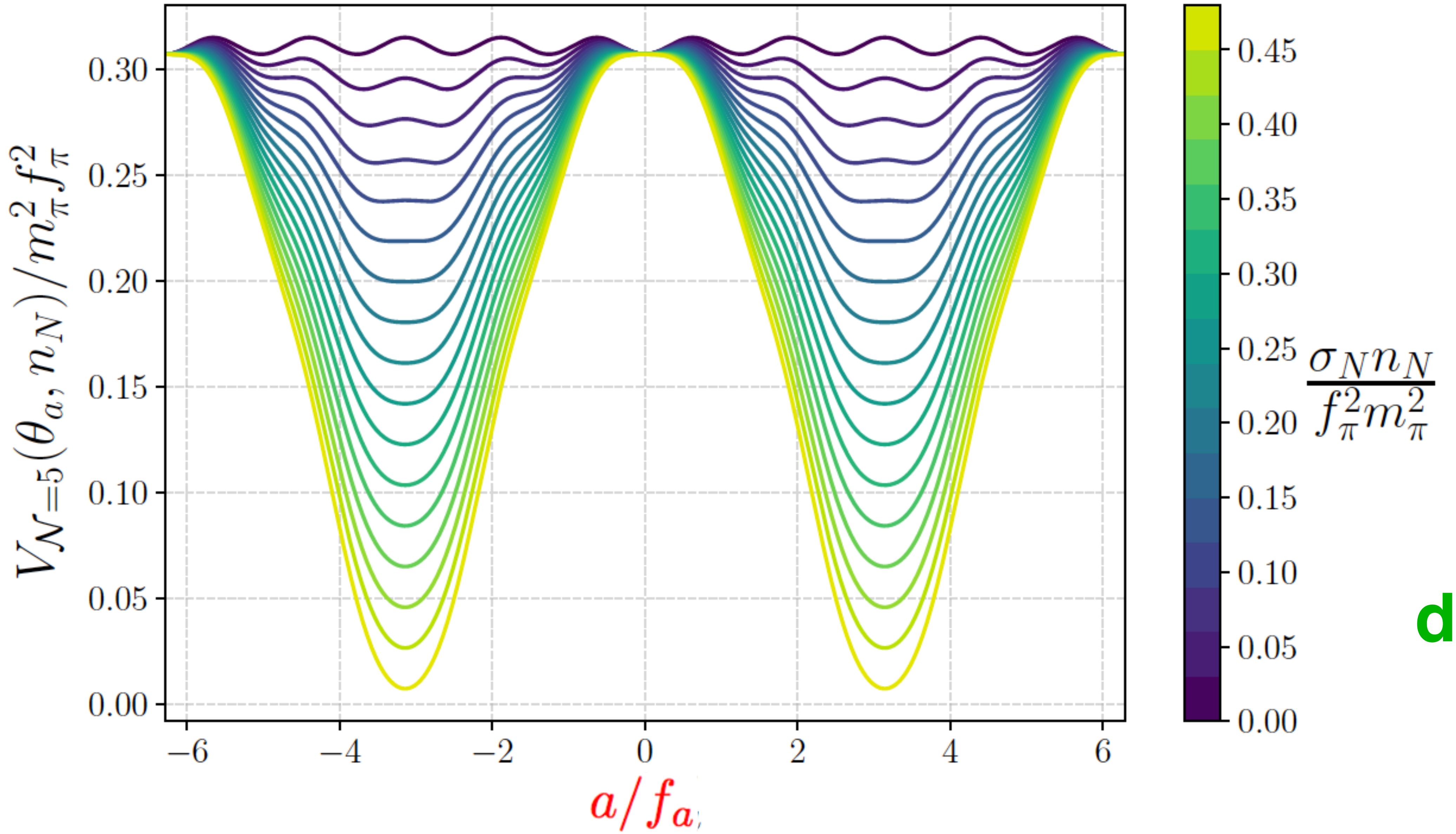
$[GeV^{-1}]$



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

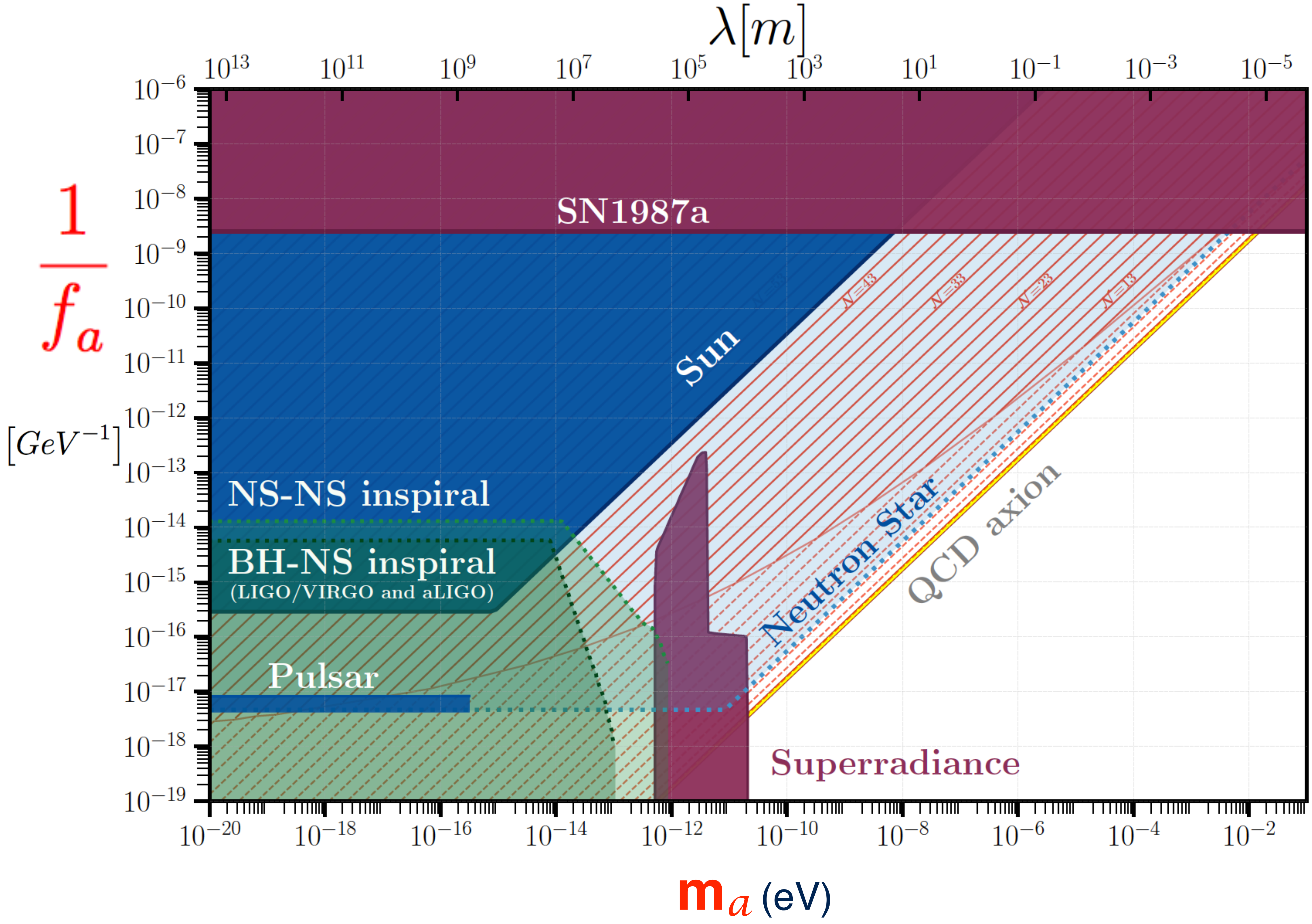


density

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

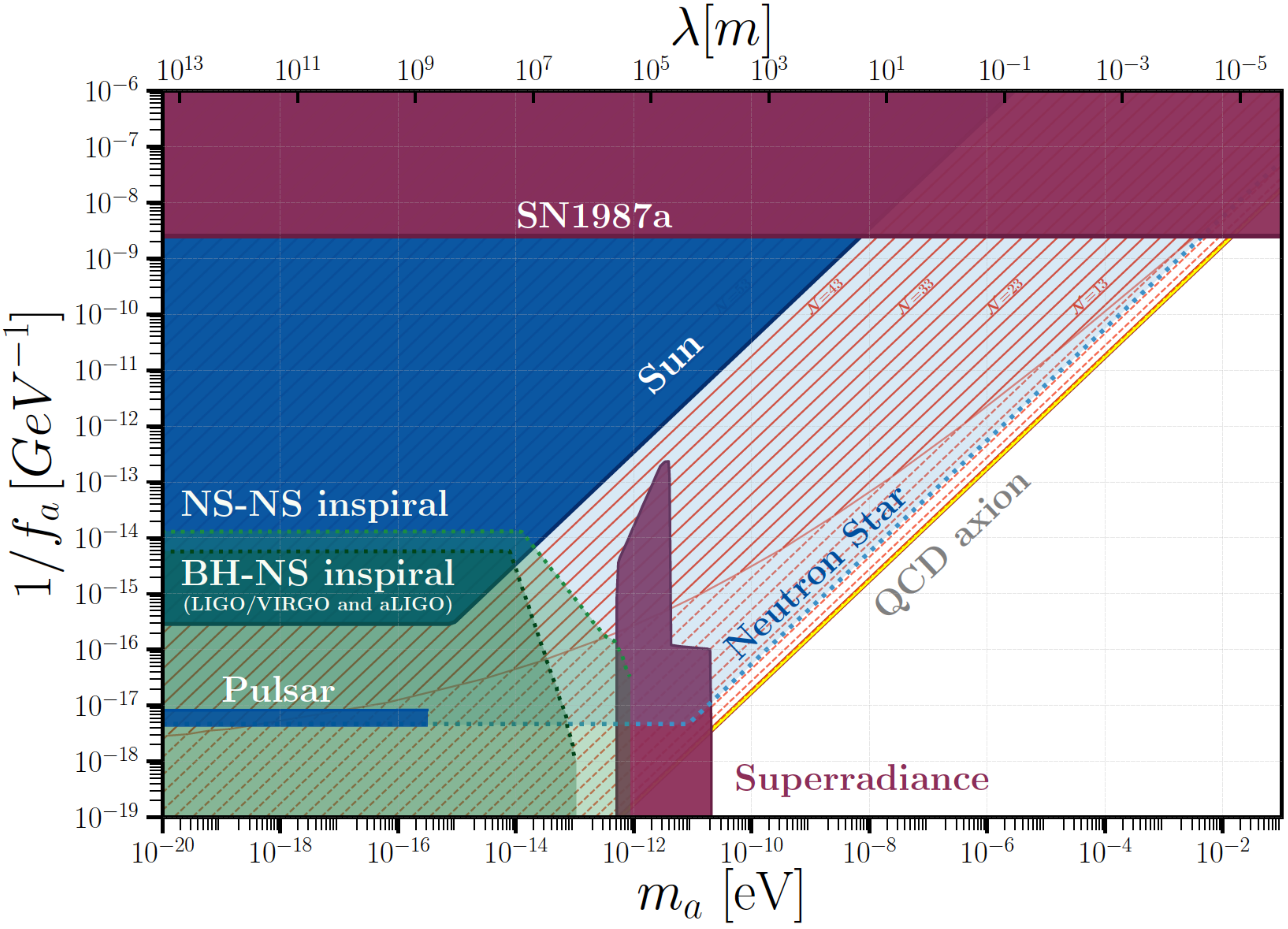
For instance:

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

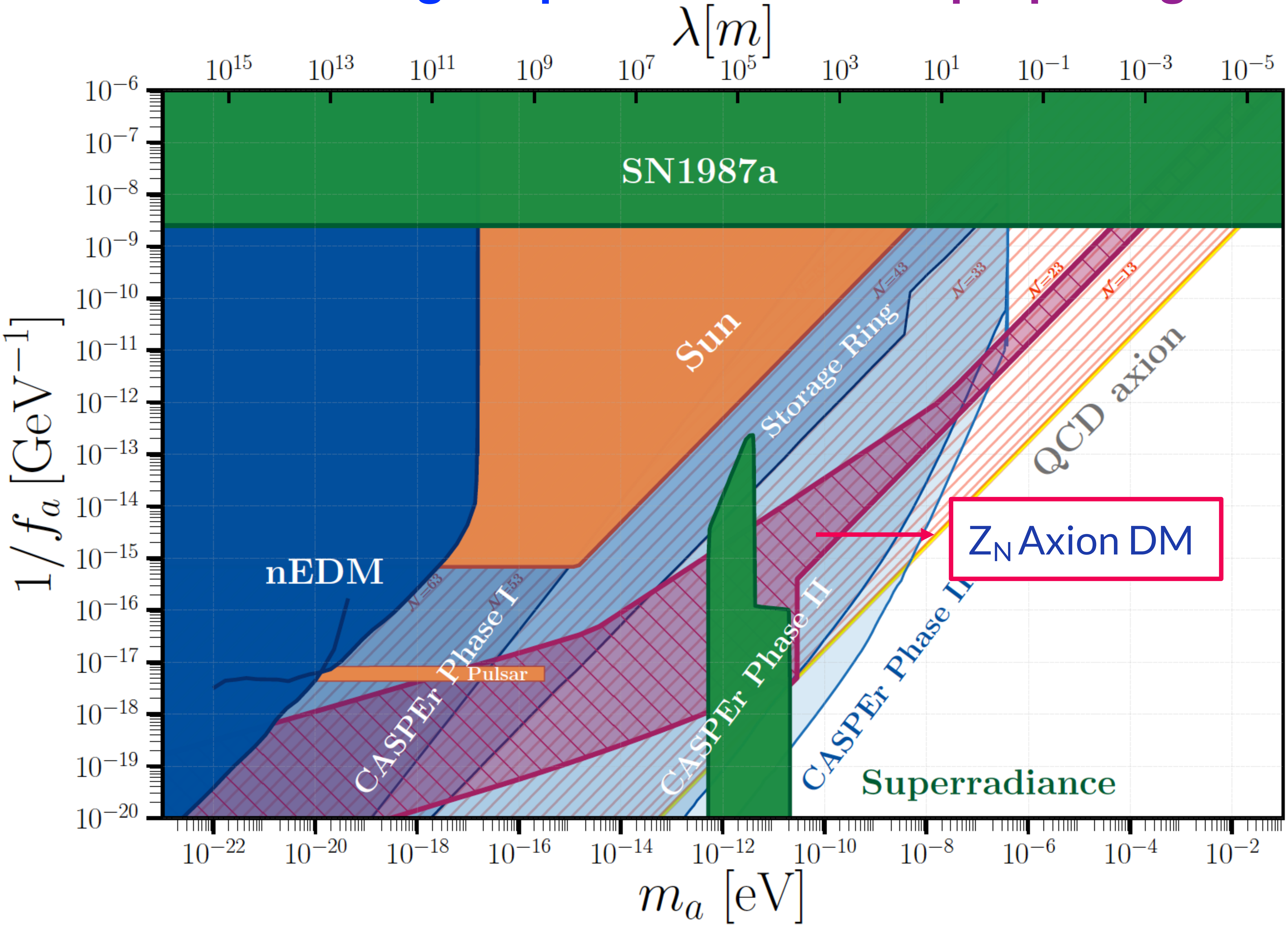
* Could fuzzy DM (m_{DM}~10^{-22} eV) be a true axion?

di Luzio, Quilez, Ringwald, BG arXiv 2102.01082

This was without asking the true axion to solve DM:



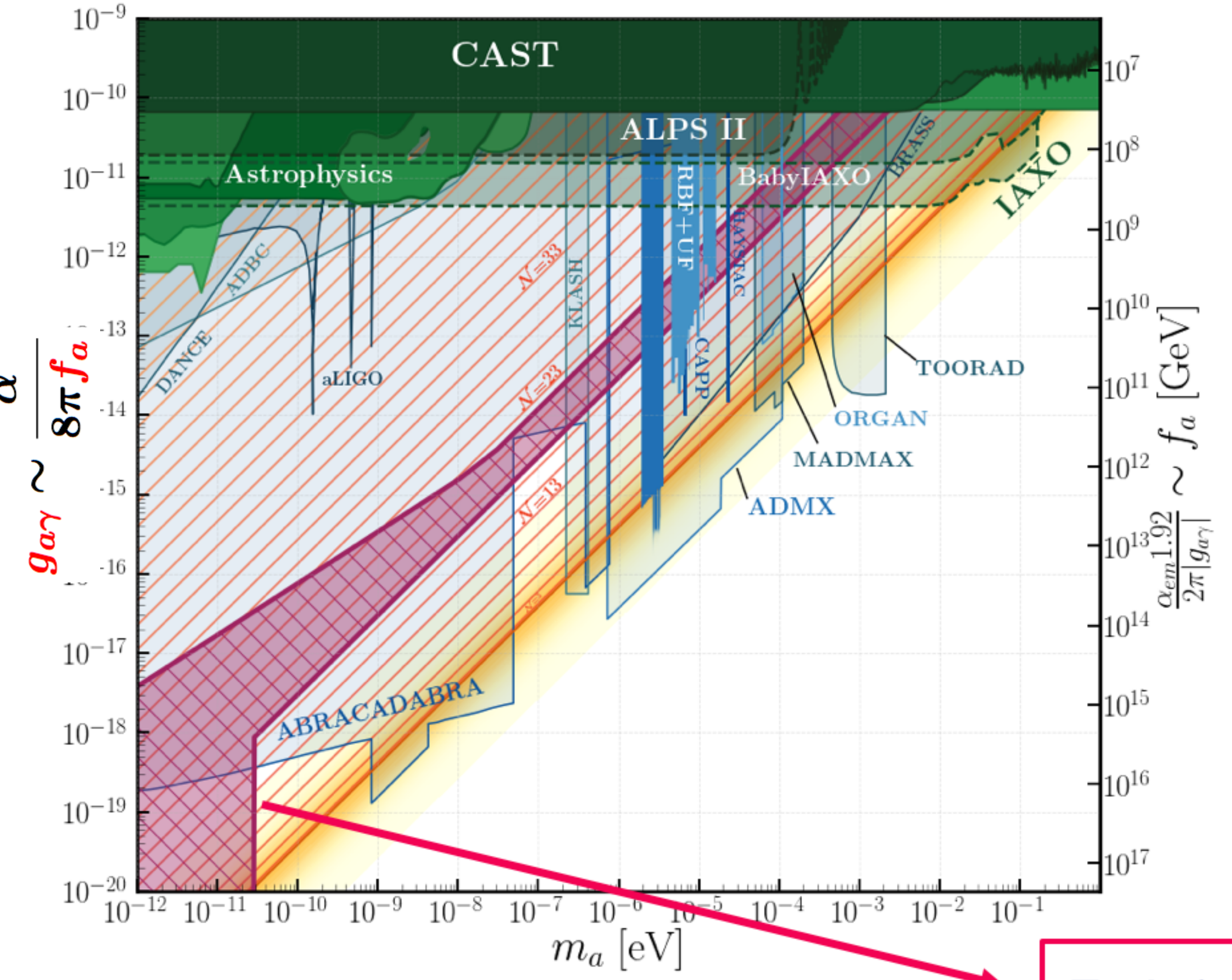
To solve the strong CP problem *and* DM: purple region

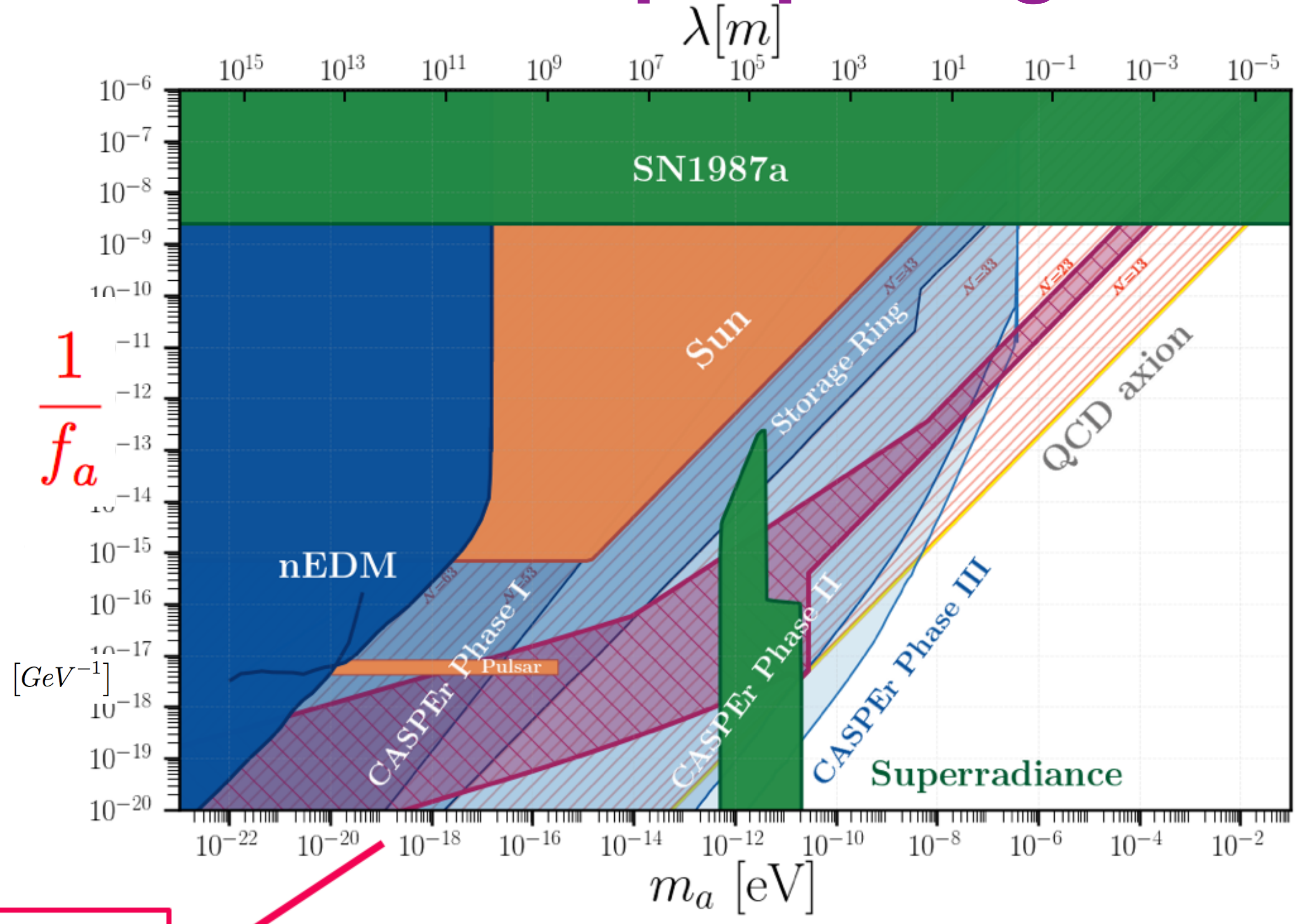


Z_N Axion DM

di Luzio, Quilez, Ringwald, BG arXiv 2102.01082

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





Z_N Axion DM

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

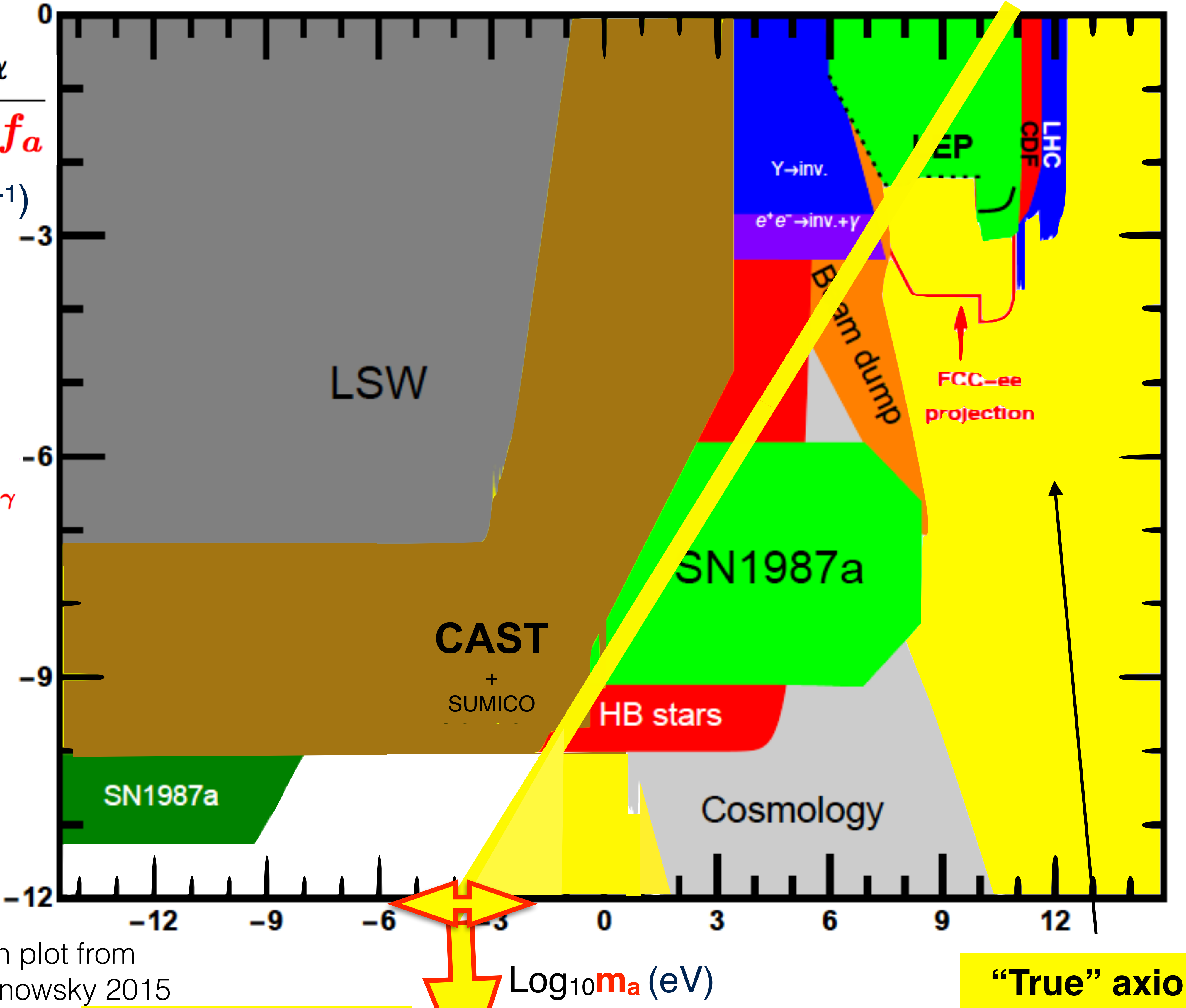
$$\text{Solutions for } 10^{-22}\text{ eV} \leq m_a \leq m_a^{QCD}$$

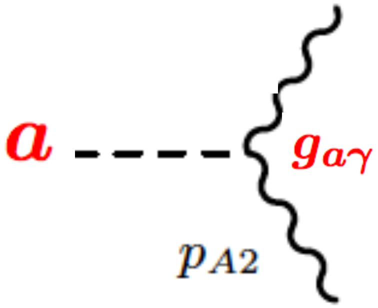
First "fuzzy dark matter" true axion

di Luzio, Quilez, Ringwald, BG arXiv 2102.01082

ALPs territory: they can be true axions

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



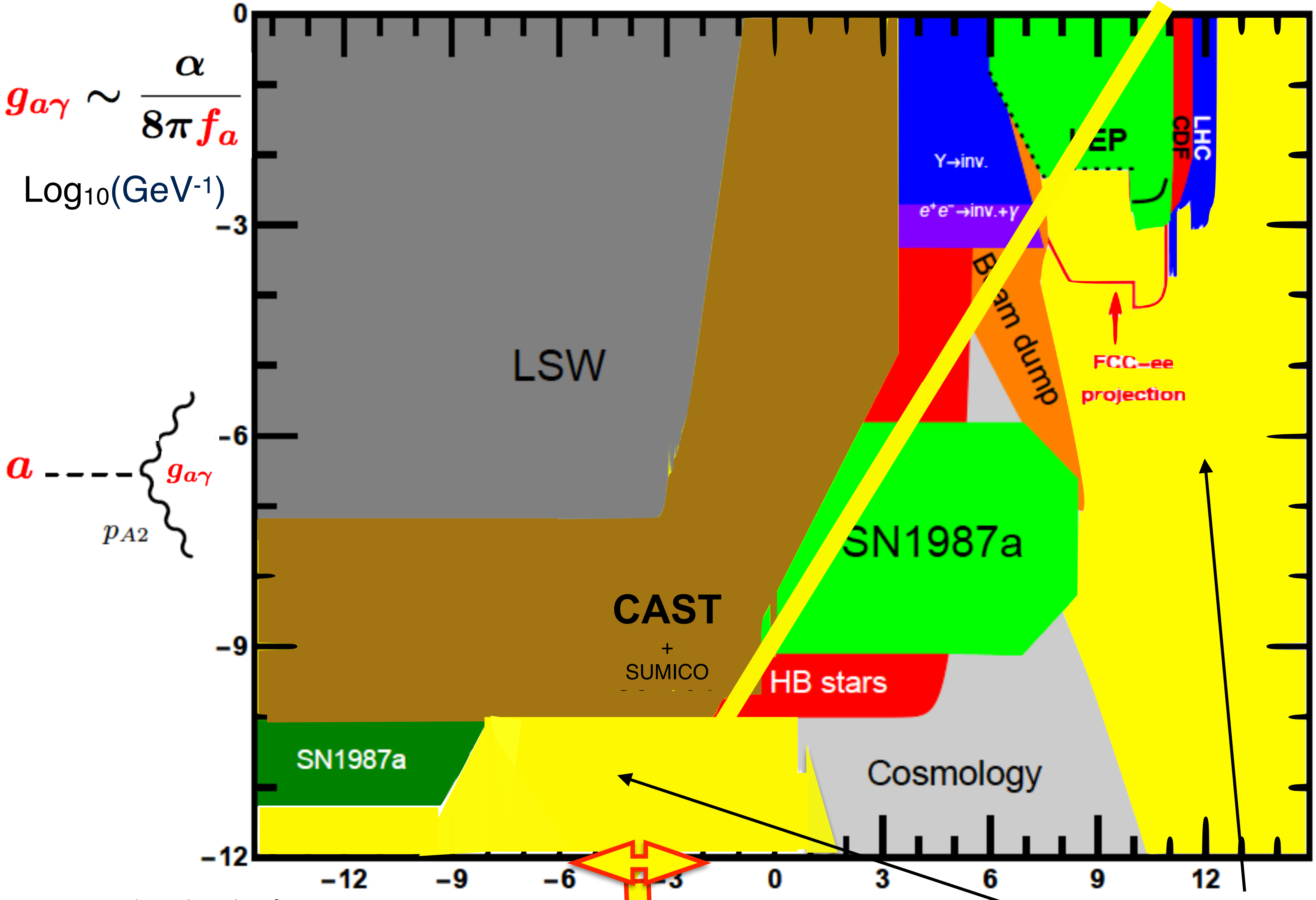


constraints in plot from
Jaeckel+ Spannowsky 2015

"True" QCD axion

"True" axion region
has amplified

ALPs territory: they can be true axions


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

Log10ma (eV)

constraints in plot from
Jaeckel+ Spannowsky 2015

"True" QCD axion

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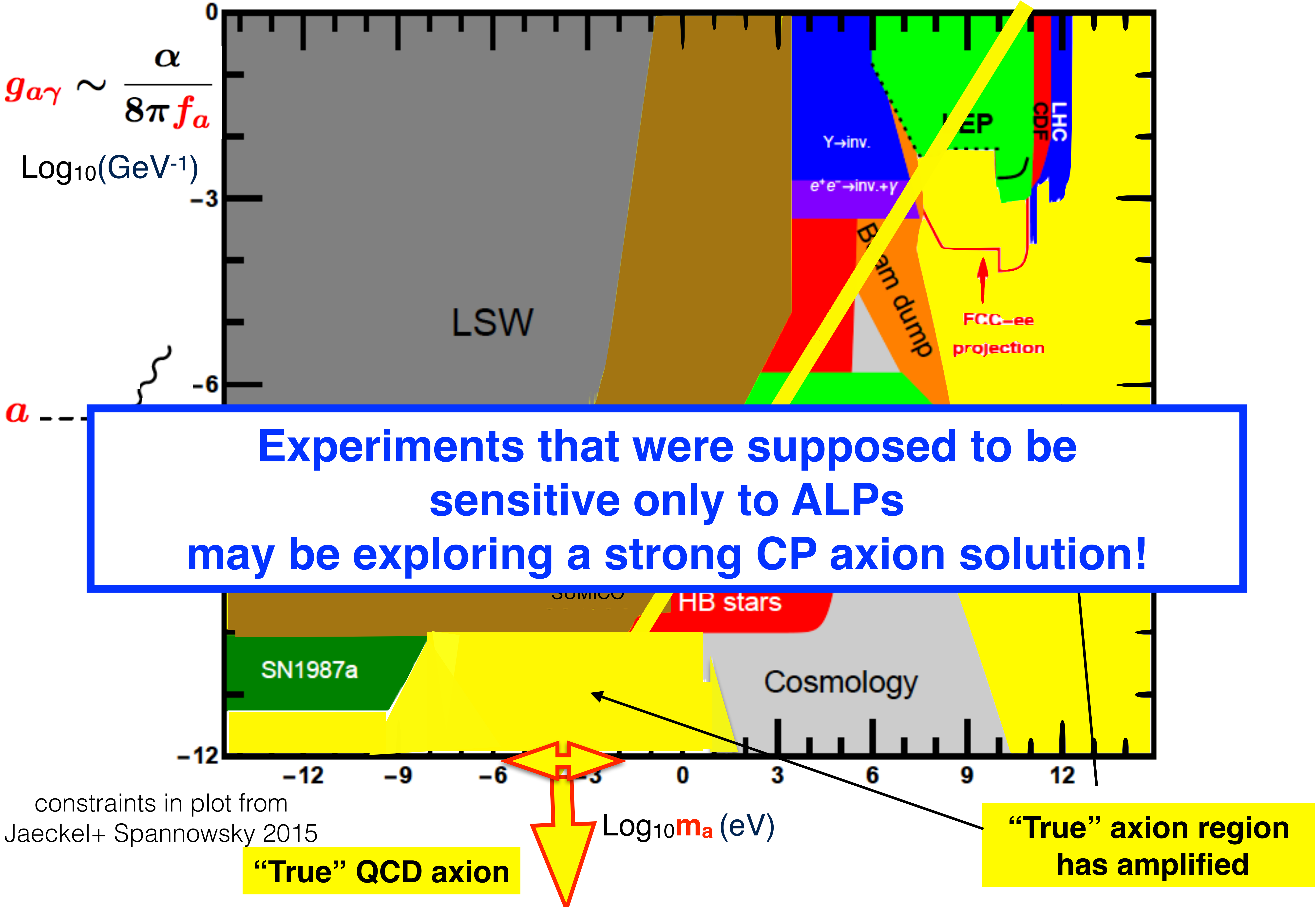
ALPs territory: they can be true axions



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

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

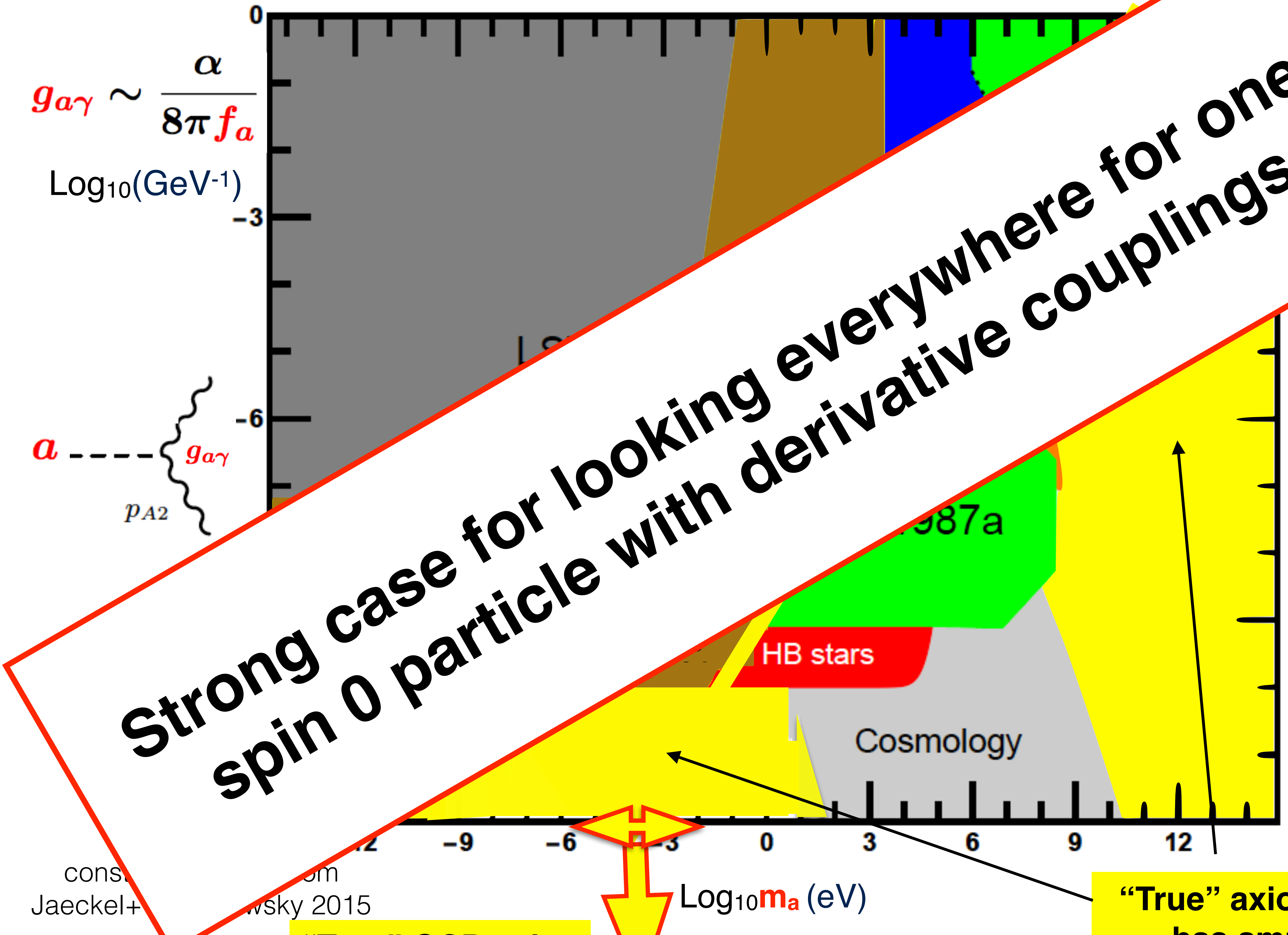
constraints in plot from Jaeckel+ Spannowsky 2015

“True” QCD axion

“True” axion region has amplified

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

Log10(GeV-1)



Strong case for looking everywhere for one spin 0 particle with derivative couplings

cons om
Jaeckel+ wsky 2015

Log10**ma** (eV)

“True” QCD axion

“True” axion region has amplified

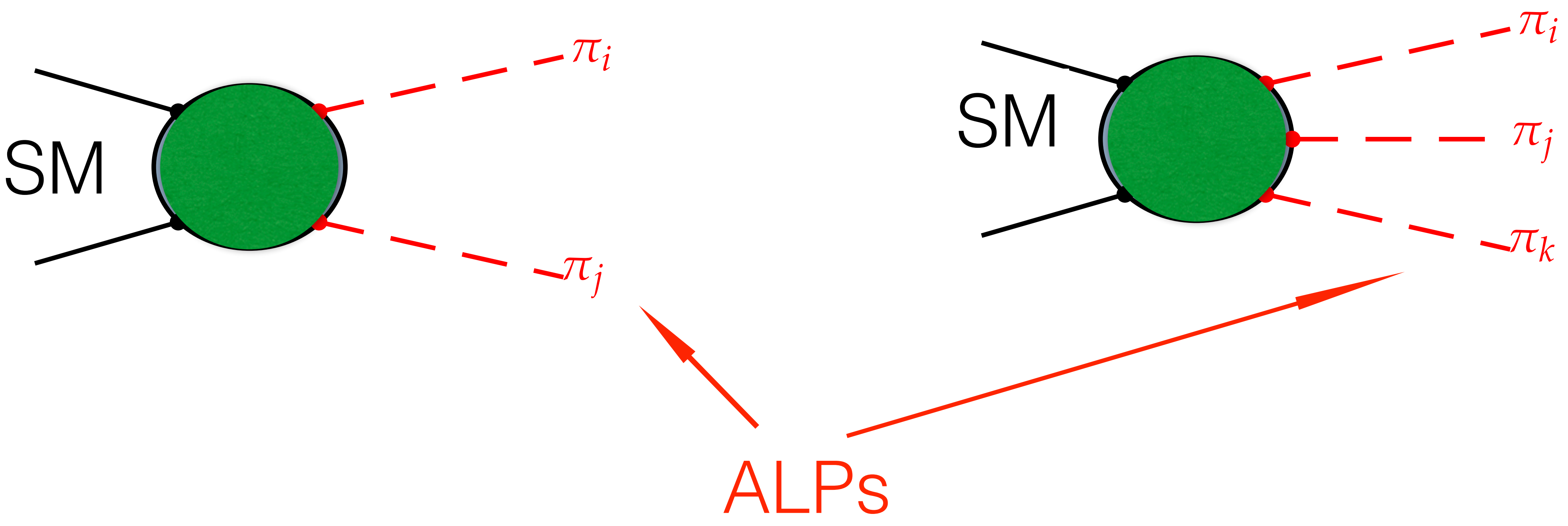
Strong case for looking everywhere for 2, 3…?
spin 0 particle with derivative couplings

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 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 massive π_1, π_2 result without breaking the discrete symmetry

—> increased insensitivity 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

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

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:

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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

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

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

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

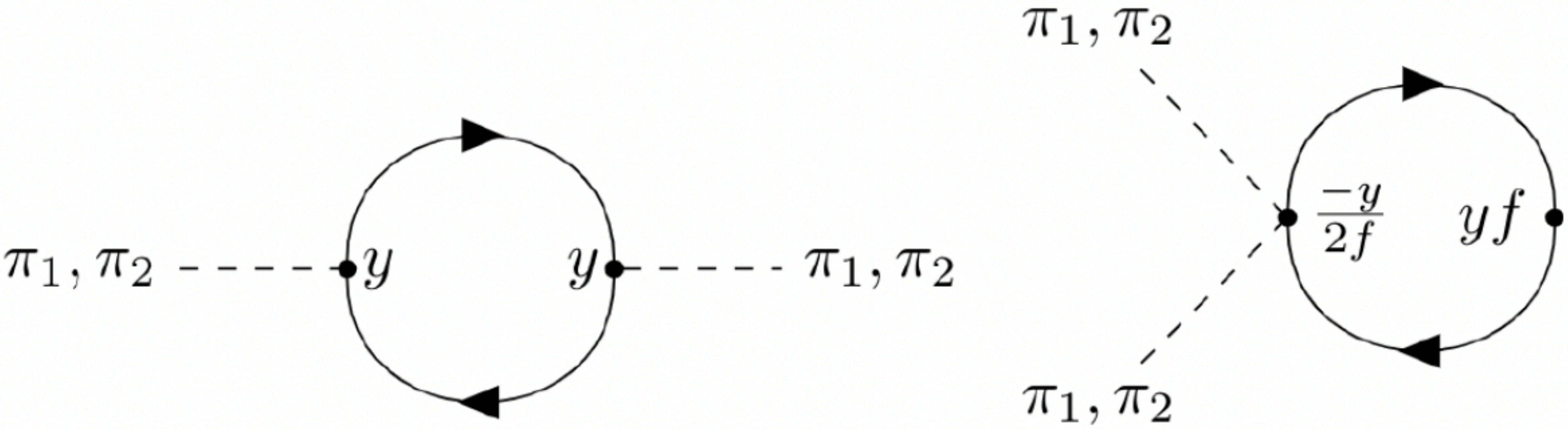
$$\mathcal{L}_{\text{int}} = \left[y_{\not{G}}\begin{pmatrix} \{\overline{\Psi}_2\Psi_3\} \\ \{\overline{\Psi}_3\Psi_1\} \\ \{\overline{\Psi}_1\Psi_2\} \end{pmatrix} + y_G\begin{pmatrix} [\overline{\Psi}_2\Psi_3] \\ [\overline{\Psi}_3\Psi_1] \\ [\overline{\Psi}_1\Psi_2] \end{pmatrix}\right]\cdot\phi$$

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

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

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

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

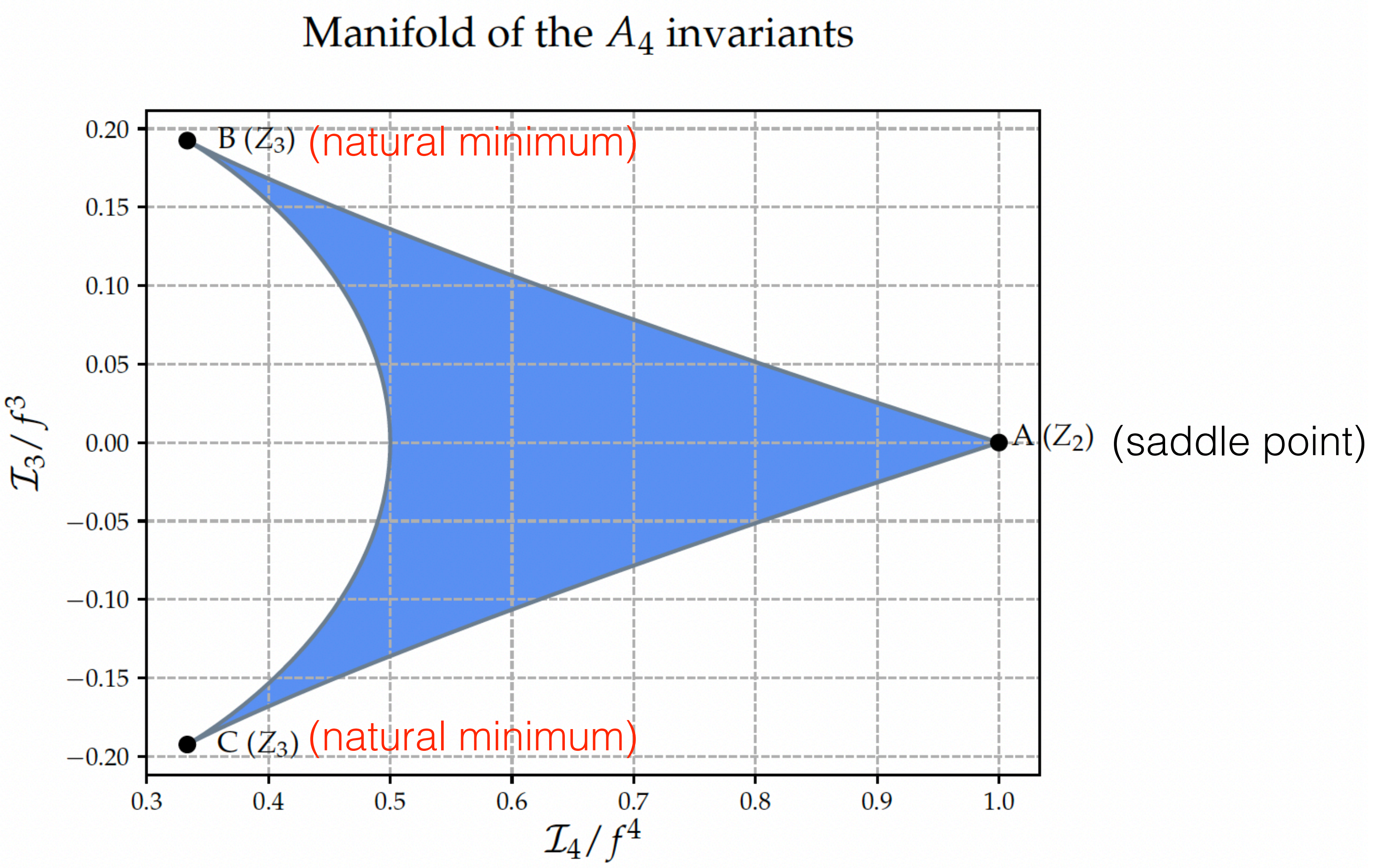
$$V(\pi_1, \pi_2) = V(\mathcal{I}_3, \mathcal{I}_4)$$

``Natural extrema”

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

they are extrema of all the possible invariants

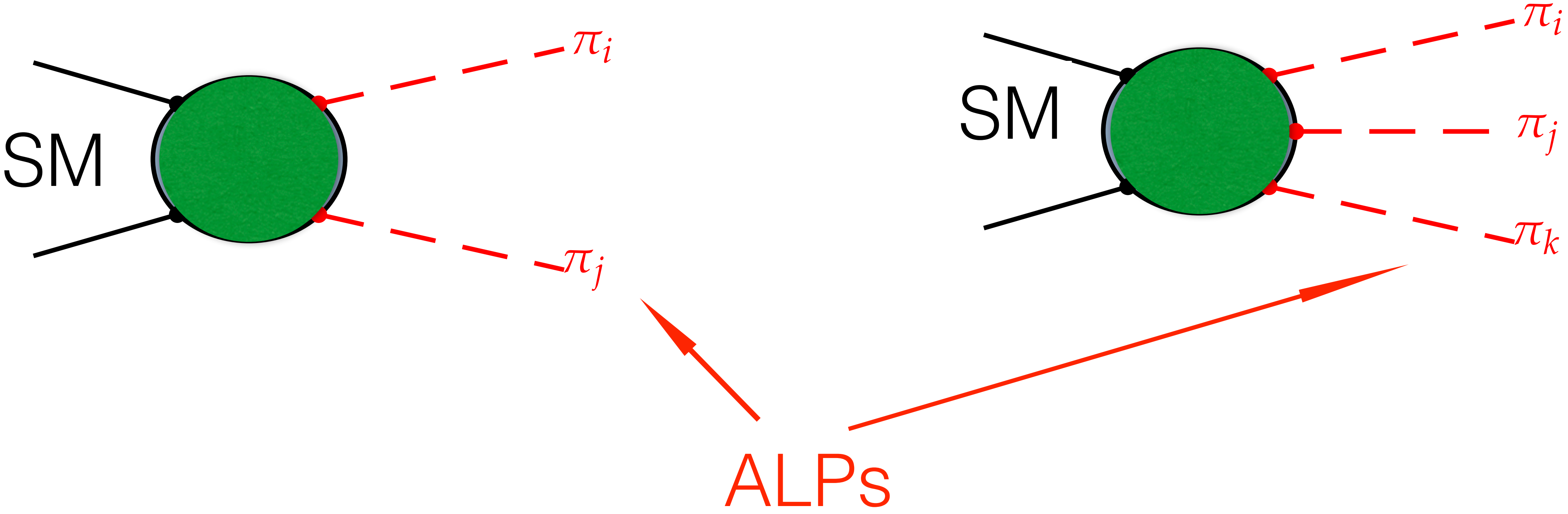
e.g. a scalar triplet of A$_4$:



- 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**

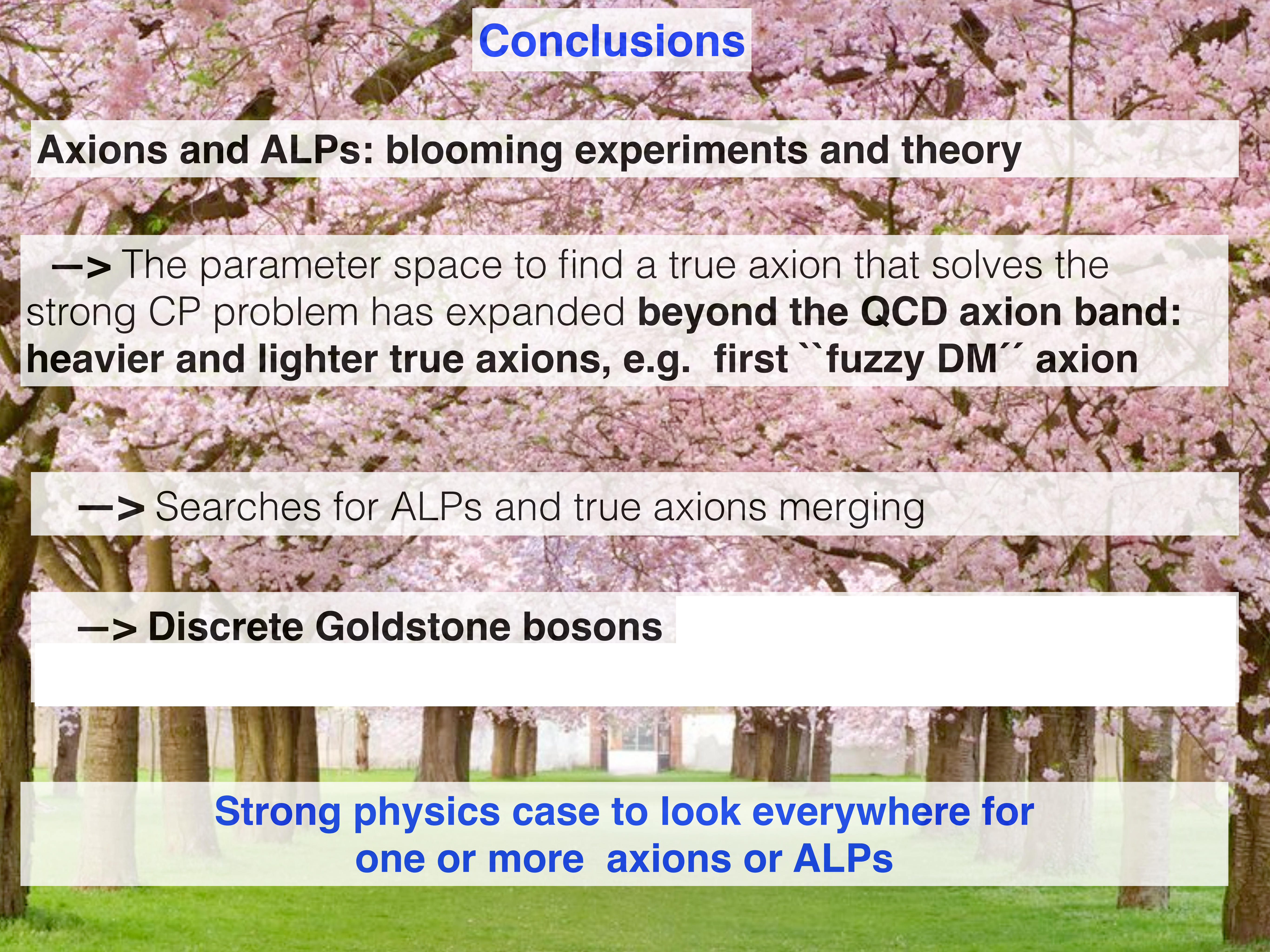
Z_3 and Z_5 for triplet of A_5 **—> degenerate π_1, π_2 doublet**

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

If a SM quark was massless (e.g. m_u)

the SM Lagrangian would have a U(1)$_A$ global symmetry:
it would solve the strong CP problem

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

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

U(1)$_A$ global would be exact classically, and explicitly broken by instantons

$$\partial_\mu j^\mu_{PQ} = 2\frac{\alpha_s}{8\pi}G_{a\mu\nu}\tilde{G}^{a\mu\nu}$$

But all SM quarks have non-zero masses!

$$\partial_\mu j^\mu_5 = 2im\overline{\psi}\gamma^5\psi + 2\beta\frac{\alpha_s}{8\pi}G_{a\mu\nu}\tilde{G}^{a\mu\nu}$$

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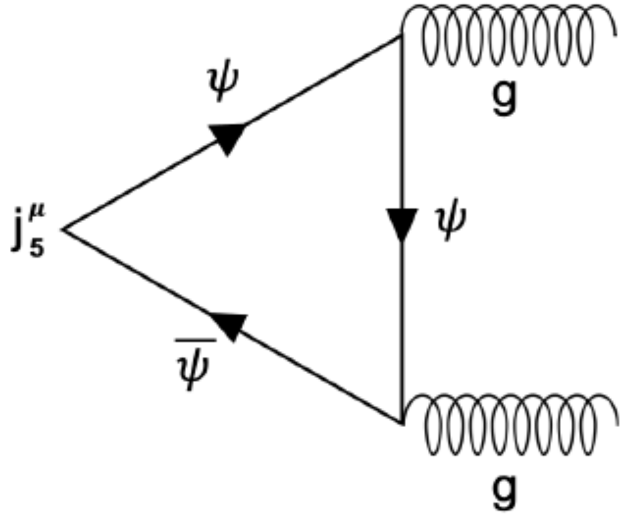

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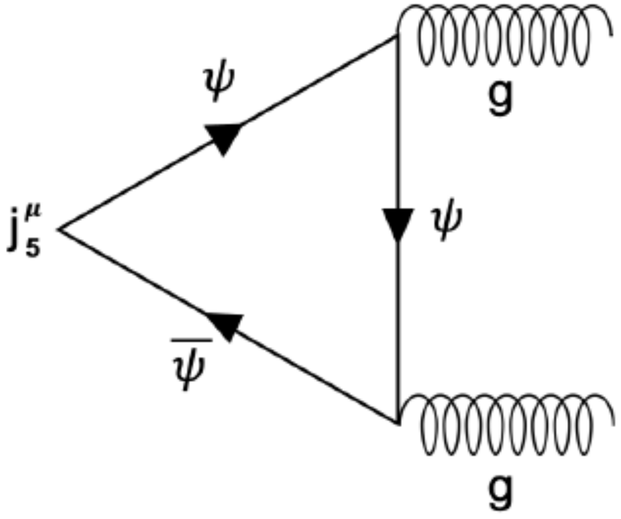

$U(1)_A$ global would be exact classically, and explicitly broken by instantons

$$\partial_\mu j^\mu_{PQ} = 2\frac{\alpha_s}{8\pi}G_{a\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\boxed{\bar{\theta} = \theta + arg[det(M)]}$$

If a SM quark was massless (e.g

the SM Lagrangian would have a U(1)$_A$ glob

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

$$\theta$$

U(1)$_A$ glob

d explicitly broken by instantons

$$2\frac{\alpha_s}{8\pi}G_{a\mu\nu}\tilde{G}^{a\mu\nu}$$

quarks have non-zero masses!

$$\partial_\mu j_5^\mu = 2im\overline{\psi}\gamma^5\psi + 2\beta\frac{\alpha_s}{8\pi}G_{a\mu\nu}\tilde{G}^{a\mu\nu}$$

message: impose some classical global axial U(1) ,
which is broken explicitly at quantum level

pseudo-

An **axion** a is any Goldstone Boson of a global U(1)

symmetry which is exact at classical level

but is explicitly broken only by instantons pseudo-

An axion a is any Goldstone Boson of a global U(1)

symmetry which is exact at classical level

but is explicitly broken only by instantons

a can be elementary or composite (= dynamical)

Trapped misalignment: a pure temperature effect

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

* The onset of oscillations is delayed

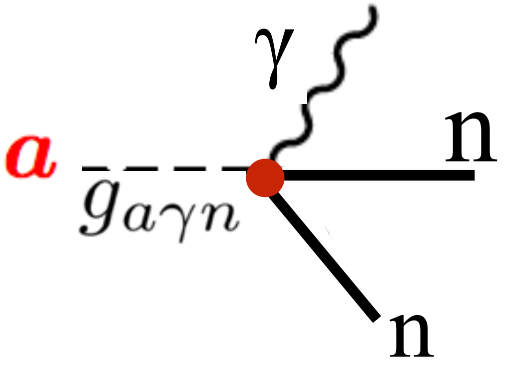
* Less dilution = more DM

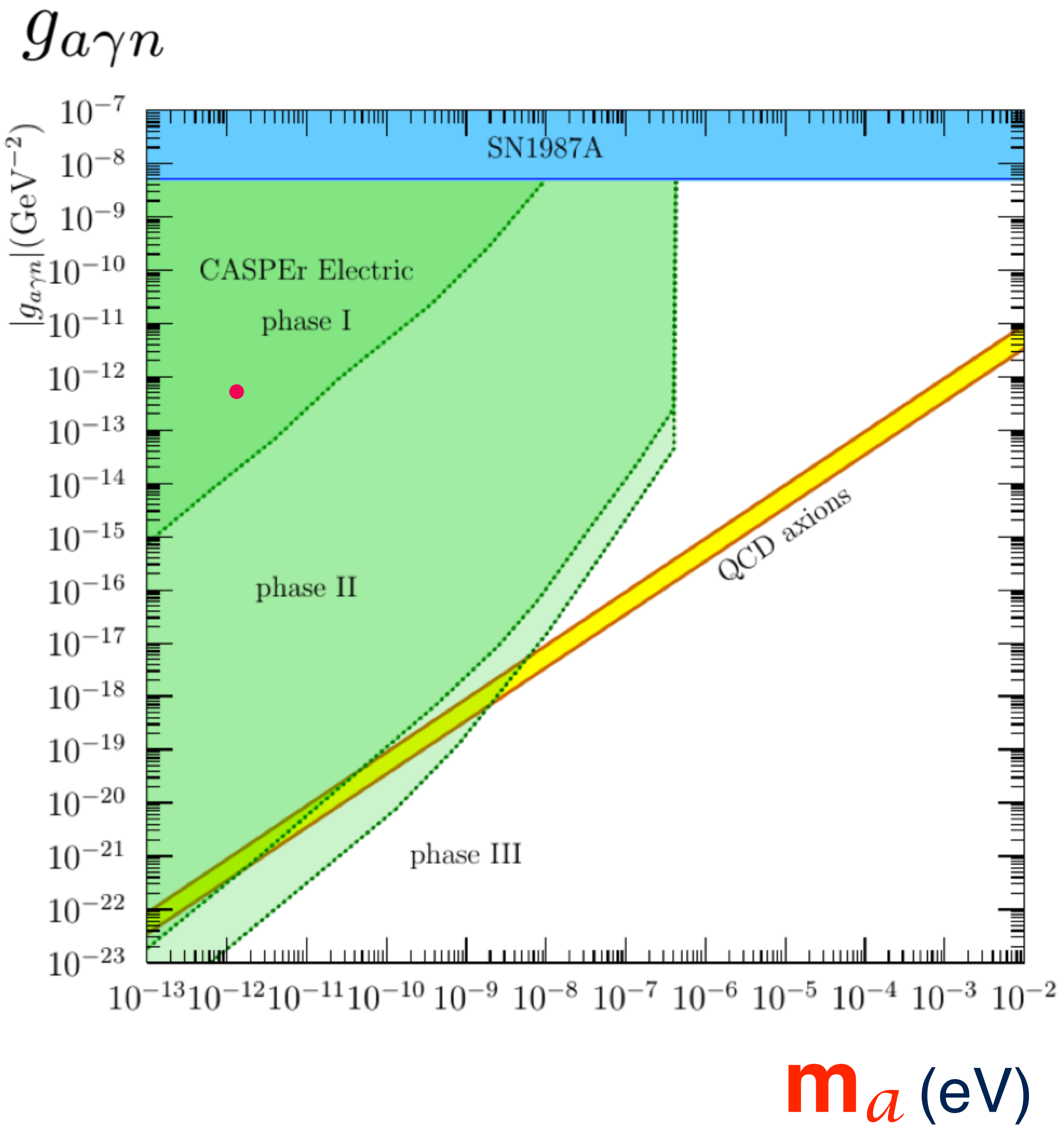
* After trapping, the axion can have enough kinetic energy to overfly many times the barrier—> further dilution: **trapped +kinetic** mislaign.

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:

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

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

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

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

Coupling to the nEDM

Axion mass

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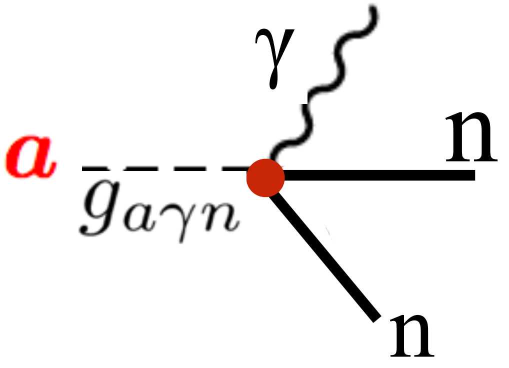

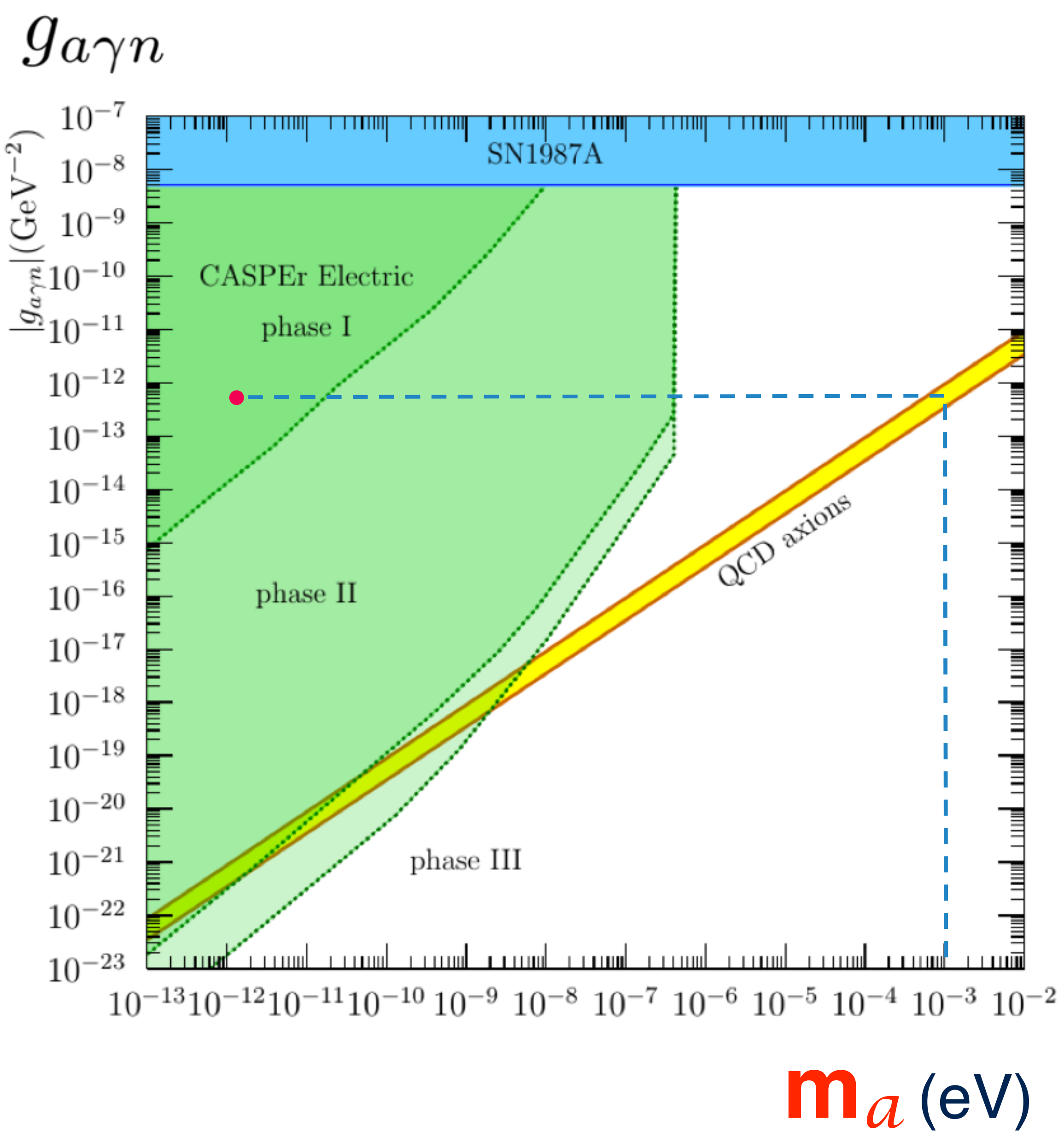

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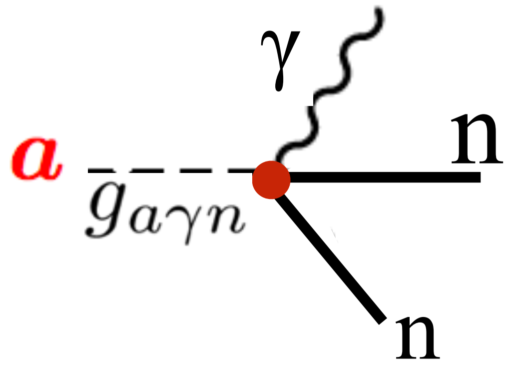

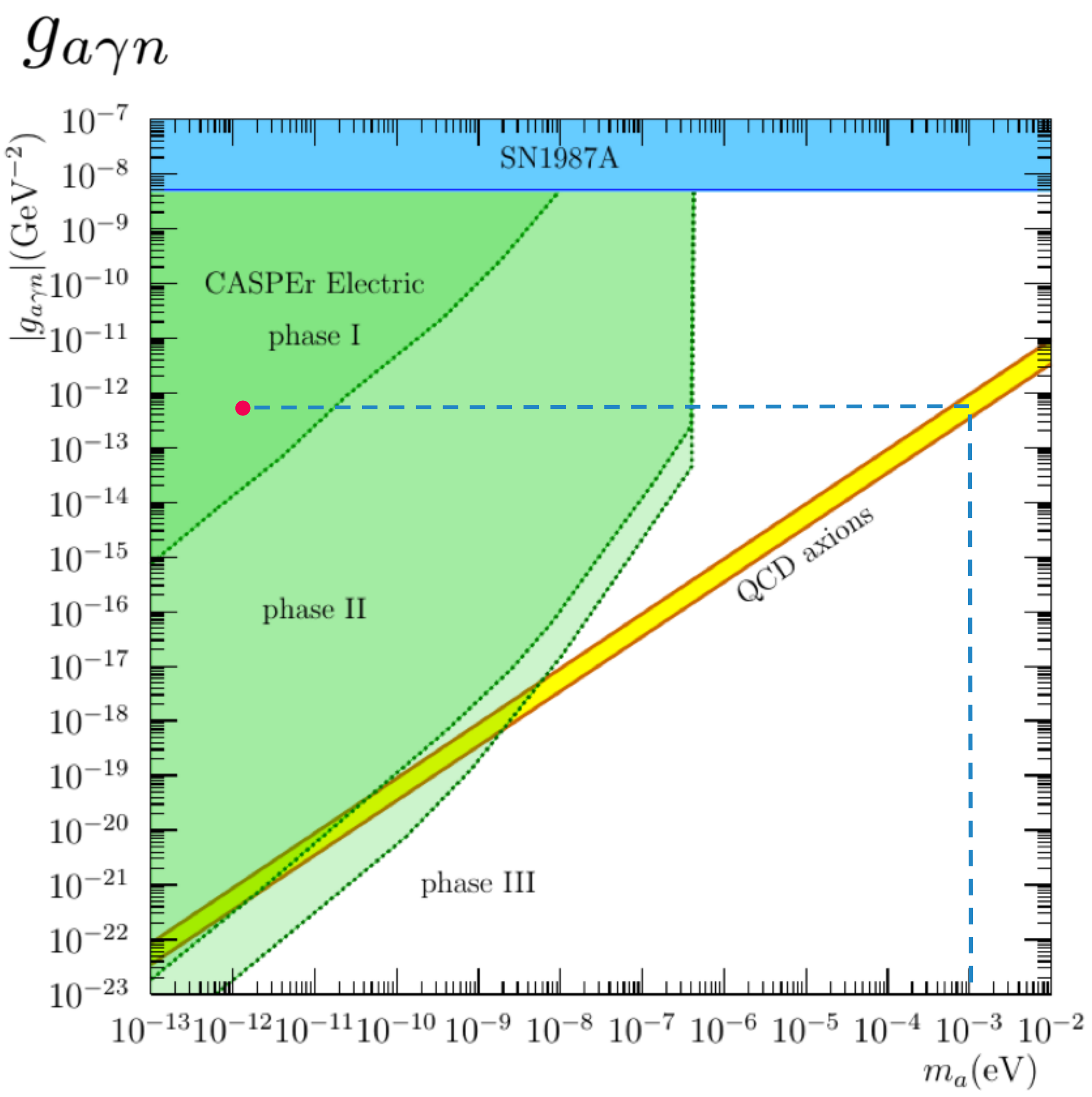

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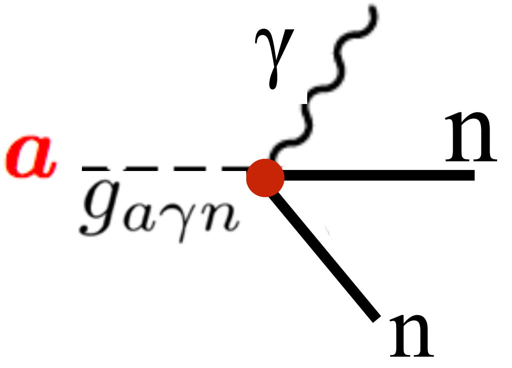
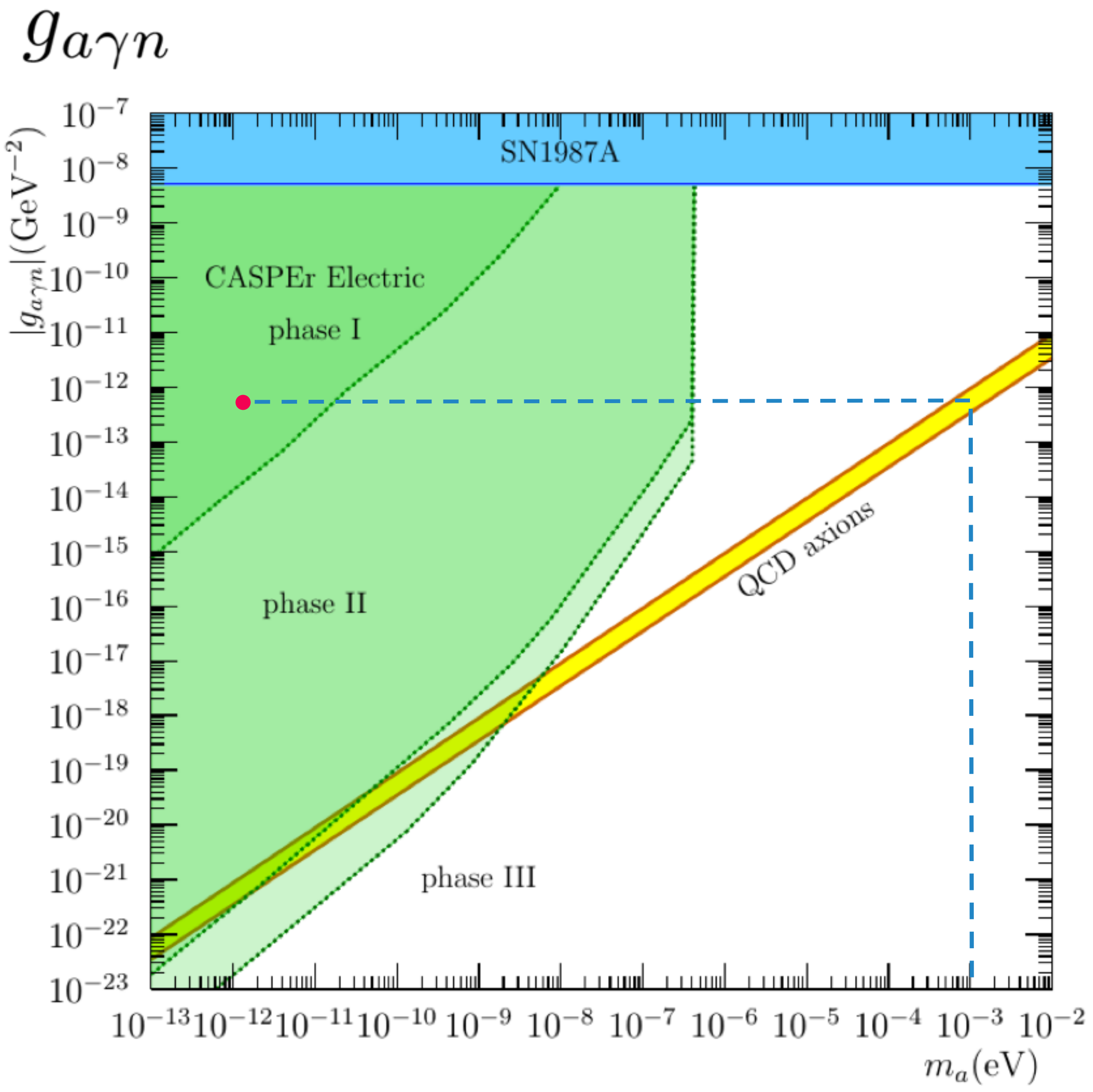
Coupling to the nEDM

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

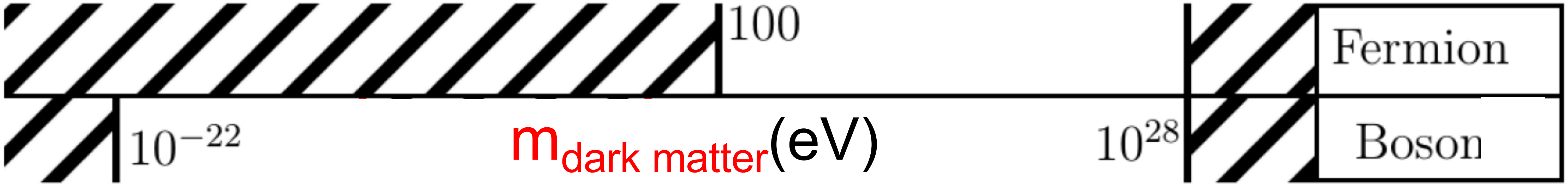
No signal possible from a canonical QCD axion

Signal possible from a Z_N axion

85% of matter is dark

what is it?

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

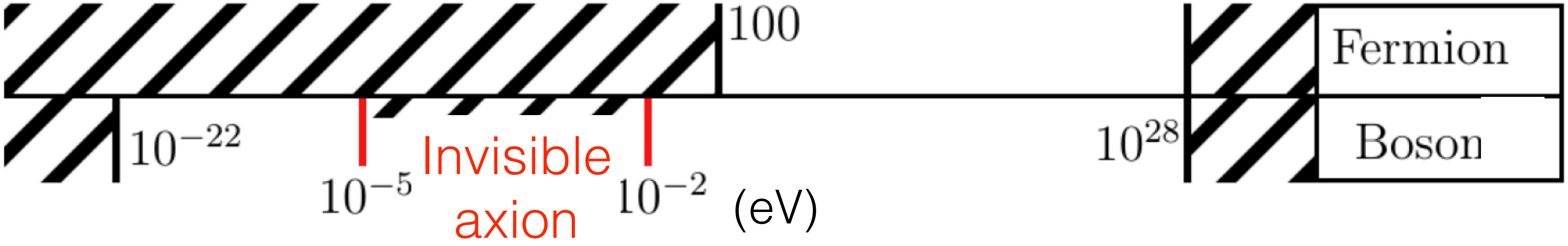


Does it feel anything else than gravity?

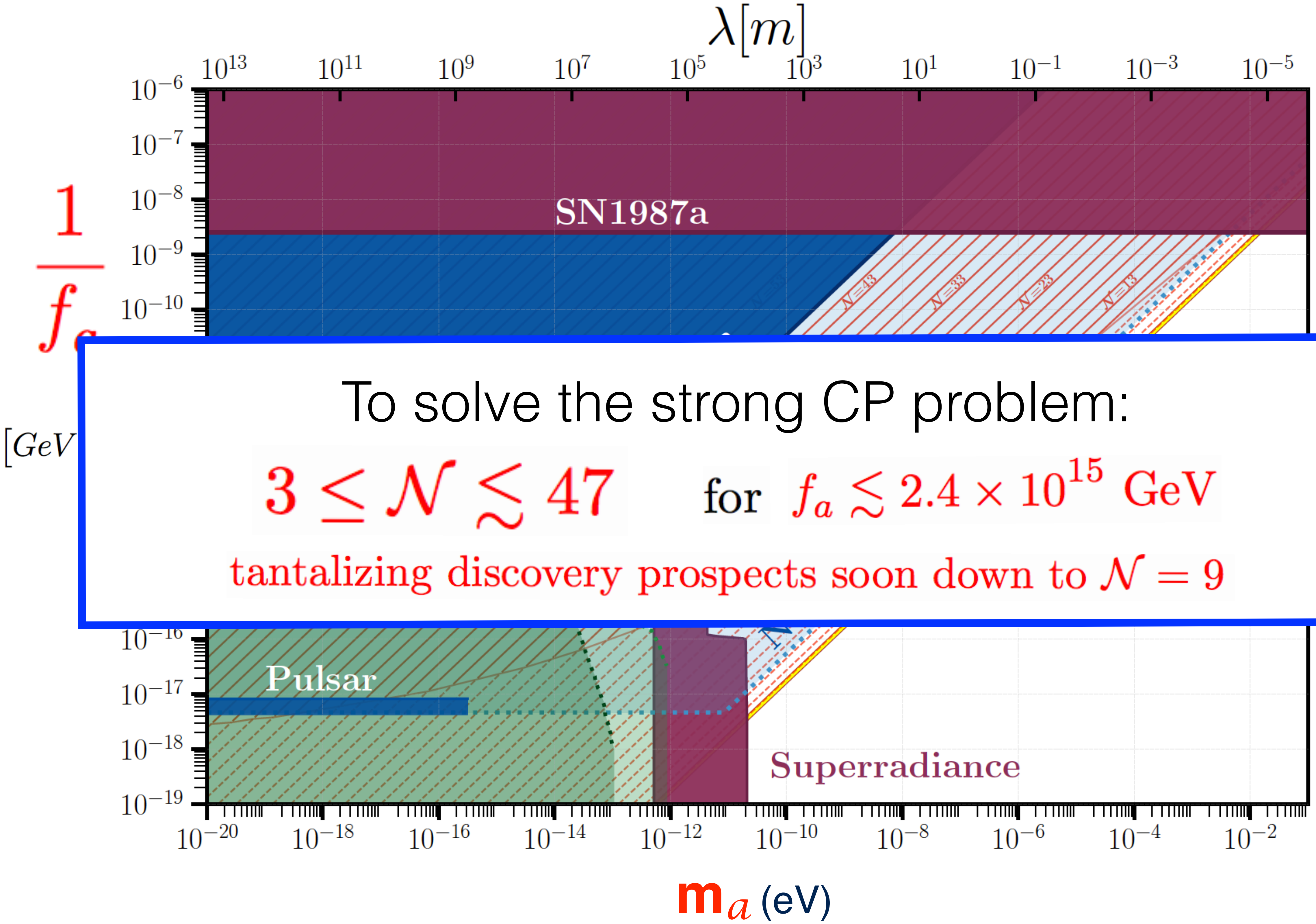
85% of matter is dark

what is it?

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



Model-independent bounds from high-density objects



To solve the strong CP problem:

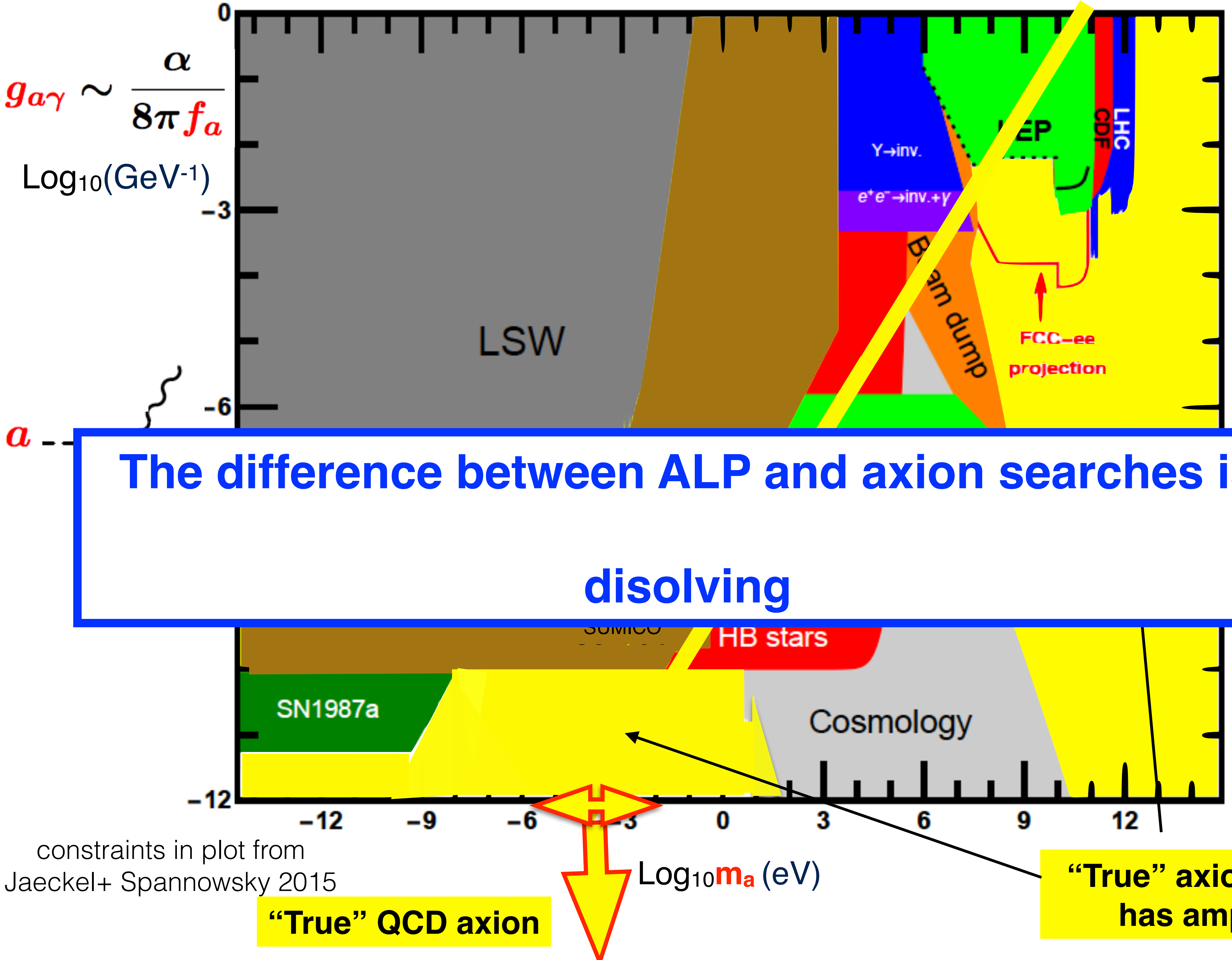
$3 \leq \mathcal{N} \lesssim 47$ for $f_a \lesssim 2.4 \times 10^{15}$ GeV

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

Di Luzio, Quilez, Ringwald, BG arXiv 2102.00012

ALPs territory: they can be true axions

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



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

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)

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

The nature of DM is unknown

It may be a (SM singlet) scalar S

the "Higgs portal"

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

S has polynomial couplings

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

The strong CP problem

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

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

A dynamical $U(1)_A$ solution

→ the axion a

It is a pGB: ~only derivative couplings

$$\partial_{\mu}\, a$$

Also excellent DM candidate

Peccei+Quinn; Wilczek…

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

- L ou

  PVLAS (vacuum pol.)….. and LHC!

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

later: same approach
with ALP decaying
inside detector

ALPs at colliders:

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

One-loop corrections to ALP couplings

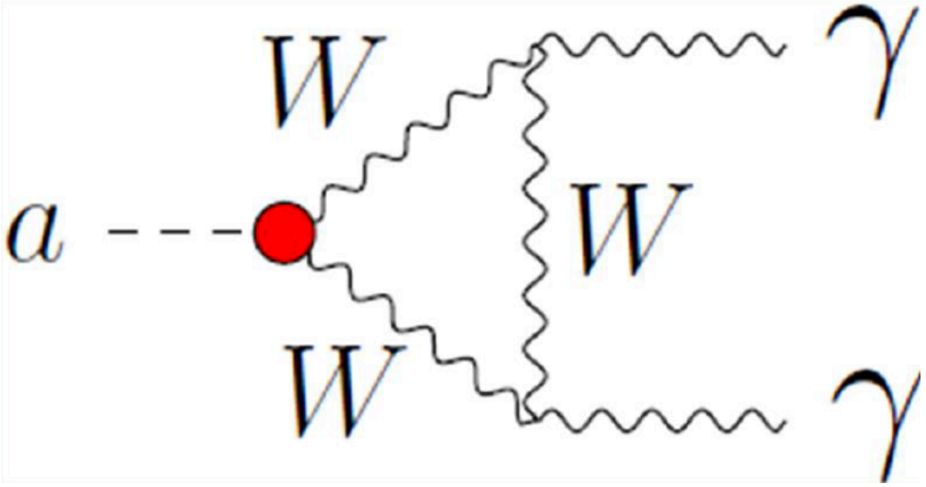
Why?

* Experiments have reached enough precision

* ALPs are being tracked at different energy scales

* New experimental constraints on ALP parameter space

Precision in some couplings is large enough to constrain others better than directly



One-loop corrections to ALP couplings

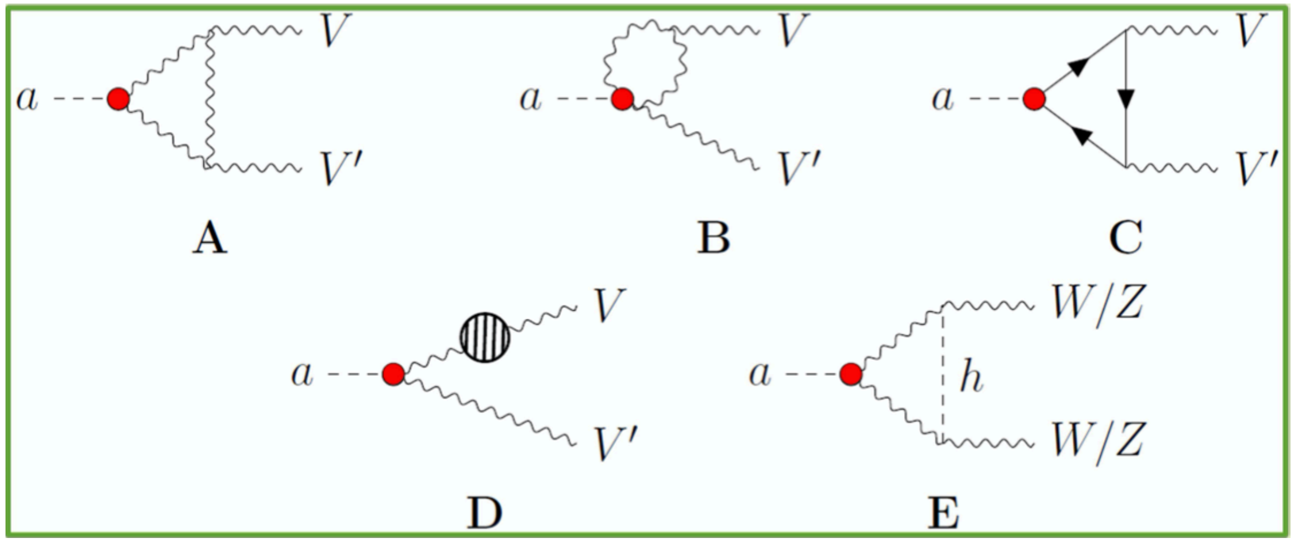
* RG evolution: M. Bauer et al. [1708.00443], M. Chala et al. [2012.09017]

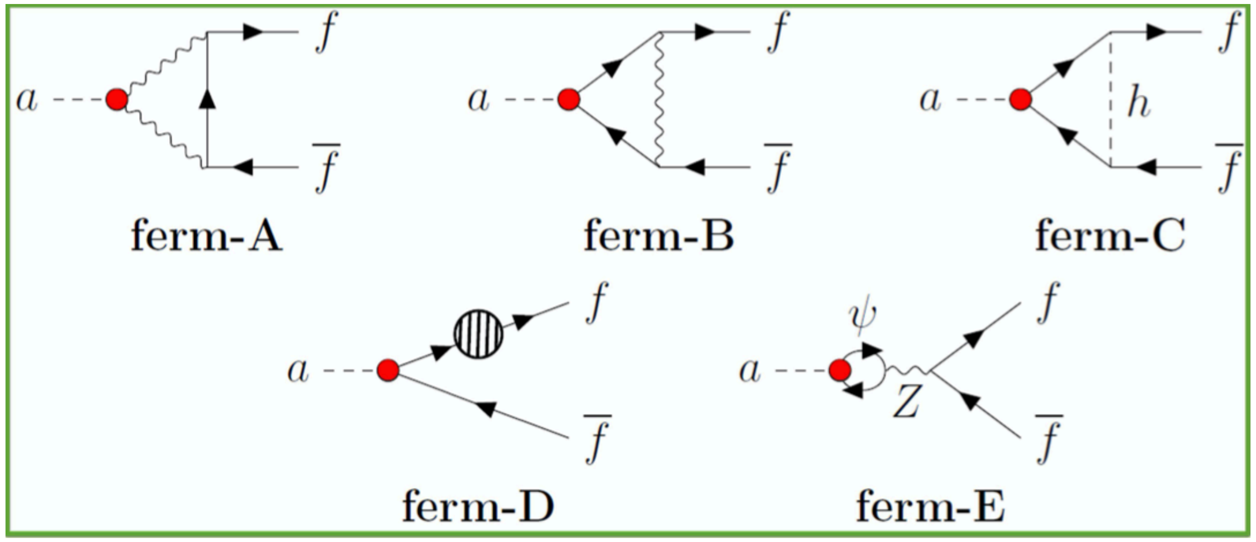
M. Bauer et al. [2012.12272],

* Complete corrections with all finite terms:

(+ clarification of redundant bases)

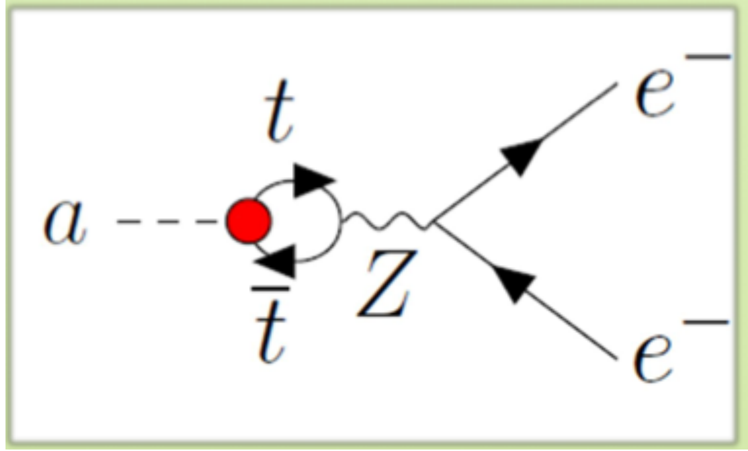
J. Bonilla et al. [1708.00443],





e.g. relevant for XENON, LUX…

Murayama et al., Bonilla et al.



Outline

1) Selective intro on (standard) axions and ALPs…

and then some work since pandemic started:

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The strong CP problem

couplings function of:

$$\partial_\mu a$$

plus anomalous couplings