True axions
&
their true couplings

Gonzalo Alonso-Álvarez

Based on work with: Belén Gavela, Pablo Quílez **(arXiv:1811.05466)**

Particle physics seminar
University of Sussex, 13 May 2019

elusives
neutrinos, dark matter & dark energy physics
Horizon 2020
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
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Goals & Motivation

We always hear that “axions” are well motivated:

- Strong CP problem
- Pseudo Nambu-Goldstone bosons
- String theory axiverse
- DM candidate

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Symmetries allow for the operator $\mathcal{L}_{\mathrm{QCD}} \supset \theta_{\mathrm{QCD}}\, G_{\mu\nu}\tilde{G}^{\mu\nu}$

However, experimentally $d_{\mathrm{n}} < 3 \cdot 10^{-26}\, e \cdot \mathrm{cm} \Rightarrow \theta_{\mathrm{QCD}} \lesssim 10^{-10}$

Pendlebury *et al* (15)

Solution: make θ_{QCD} dynamical

$$\theta_{\mathrm{QCD}} \to \langle\theta\rangle + \frac{\hat{a}}{f_a}$$

$\langle\theta\rangle = 0$ automatically. Vafa, Witten (84)

$\hat{a}$ is a new particle: the (QCD) axion.

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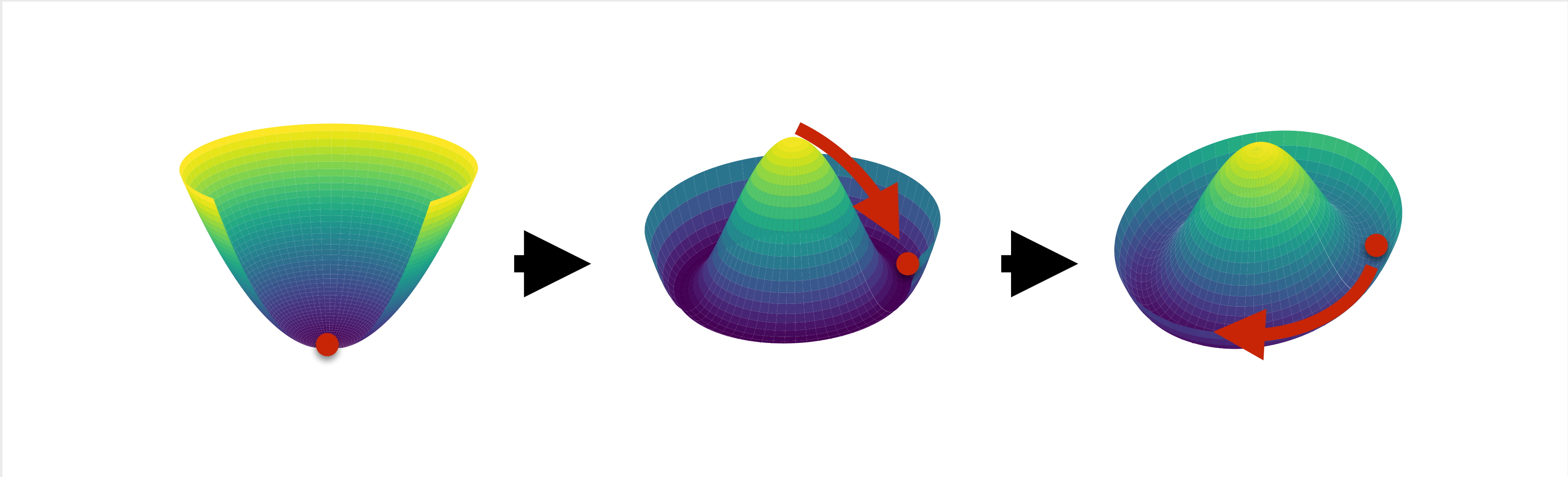
Arising from spontaneously broken global symmetries



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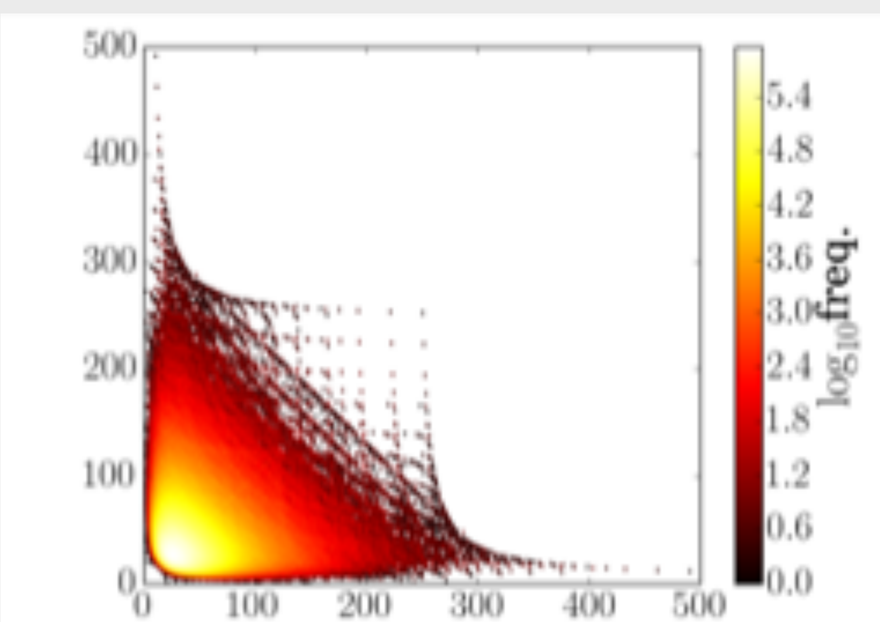

Marsh (15)

Axions appear as the Kaluza-Klein zero modes of antisymmetric tensors when compactifying extra dimensions.

$\longrightarrow$ String Theory *axiverse*.

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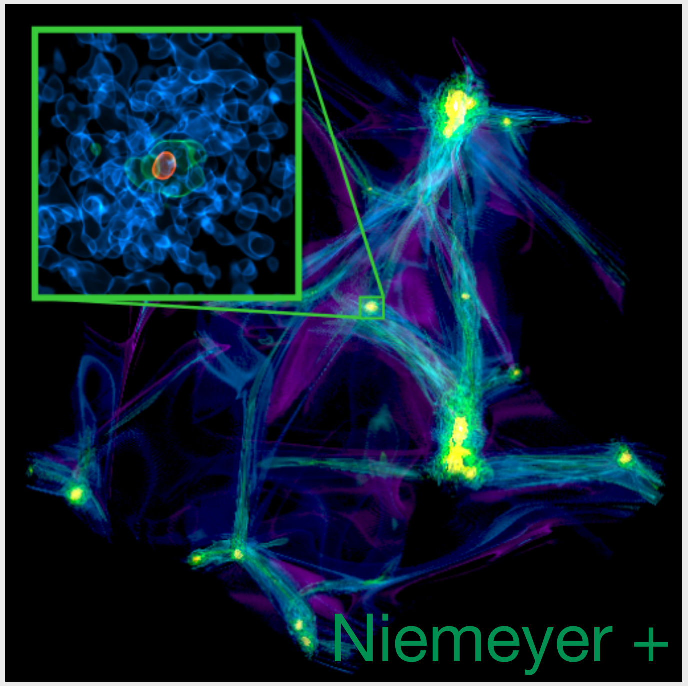

Coherent oscillations of the axion field behave as cold dark matter.

A wide range of masses is possible.

$$10^{-22}\,\mathrm{eV} \lesssim m_a \lesssim 1\,\mathrm{keV}$$

Goals & Motivation

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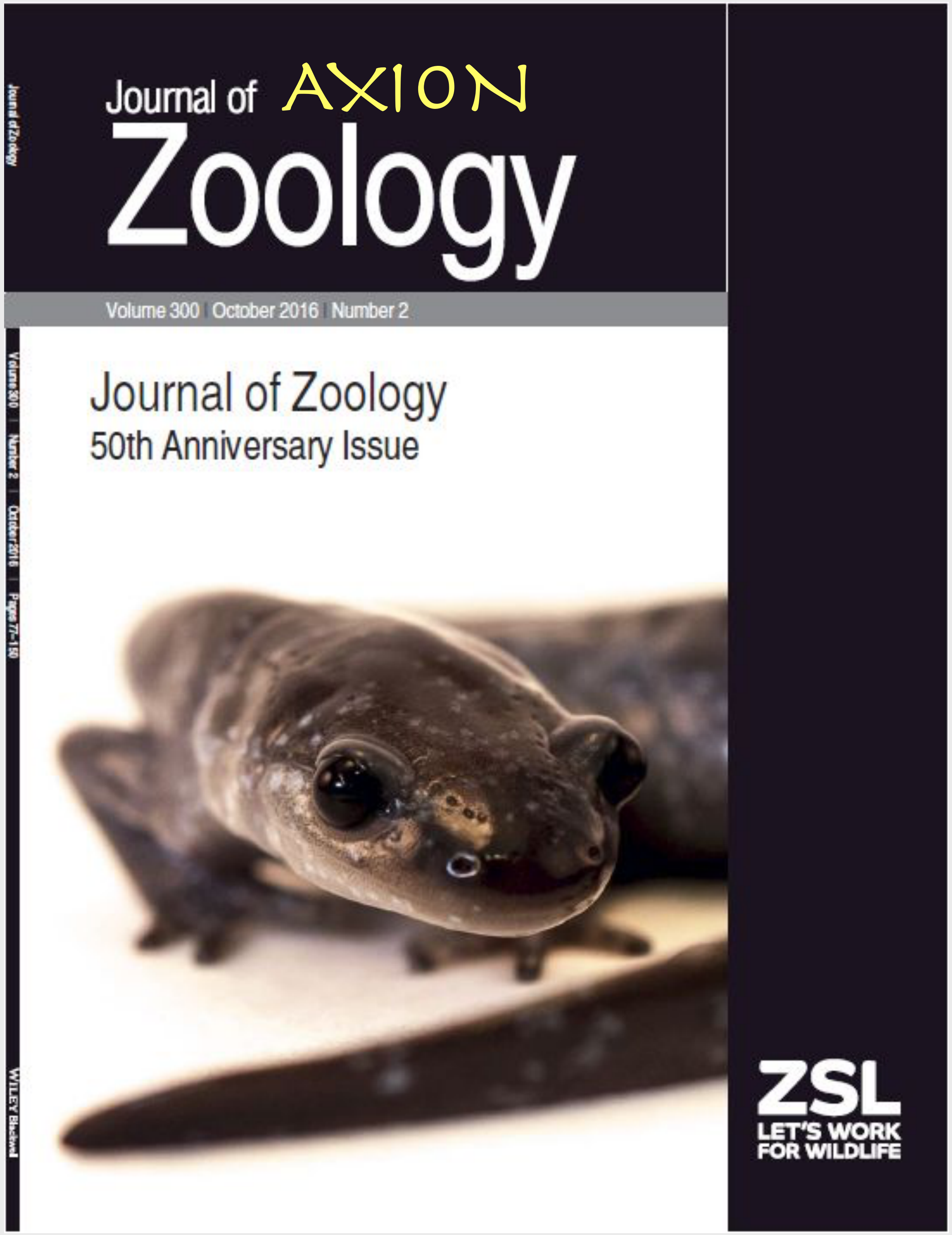
Are all these the same axion? Different axions?

What about axion-like particles (ALPs)?

How can we distinguish them?

Axion zoology



Axion zoology

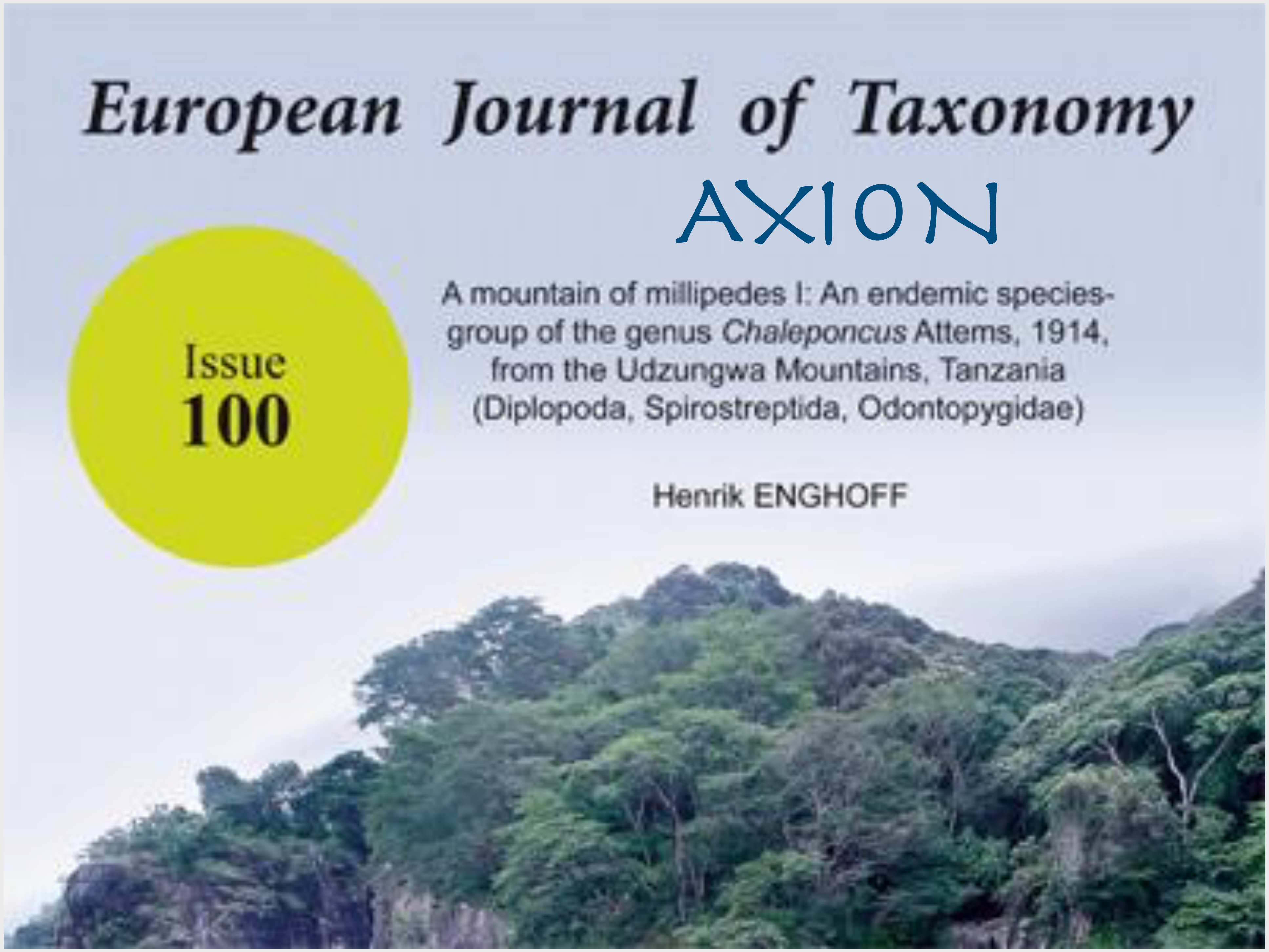
- **Axion taxonomy**: What different kind of axions are there?

- **Axion ecology**: How do axions interact with other particles?

- **Axion ethology**: How do axions “behave” in high-energy physics experiments?

- For another time, **axion astrobiology:** Axions as DM & their role in cosmology and astrophysics.

Axion taxonomy



The *pseudoscalar* GB kingdom

Pseudoscalar GB kingdom

Quantum Field Theory: pseudoscalar Goldstone bosons of spontaneously broken global chiral symmetries.

- Classical shift symmetry: $a(\mathbf{x}) \equiv a(\mathbf{x}) + \mathrm{const.}$
- Examples:
  - Neutral pion and eta meson.
  - CP-odd composite Higgs boson.
  - QCD Axions.

String Theory & Supergravity "axions": also pseudoscalar fields associated to the geometry of compact dimensions.

The *true axion* and *ALP* families

Pseudoscalar GB kingdom

- True axion family
- ALP family
- Meson family
- ...

Two families are most important to us:

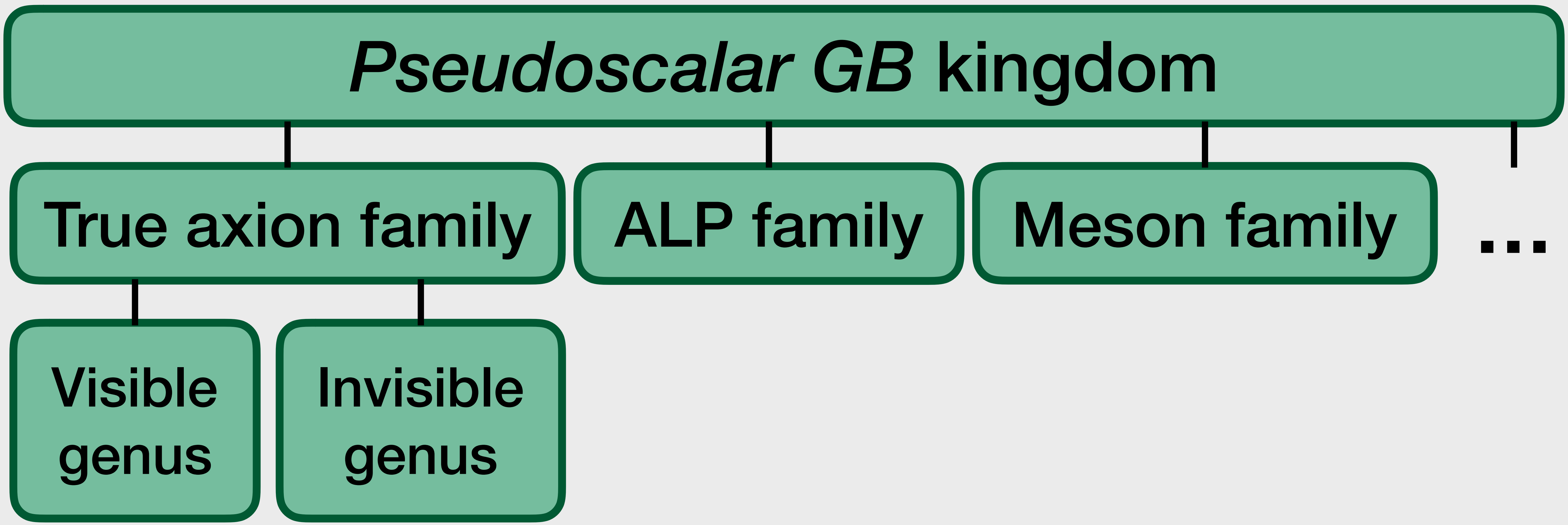
– **<u>(True) axions</u>**: solve strong CP problem
– **<u>ALPs</u>**: don't solve the strong CP problem

How to solve the strong CP problem:

$$\mathcal{L} \supset \left(\theta + \frac{a}{f_a}\right) G\tilde{G} + V(a)$$

The potential has to be minimised at $a = -f_a\theta$

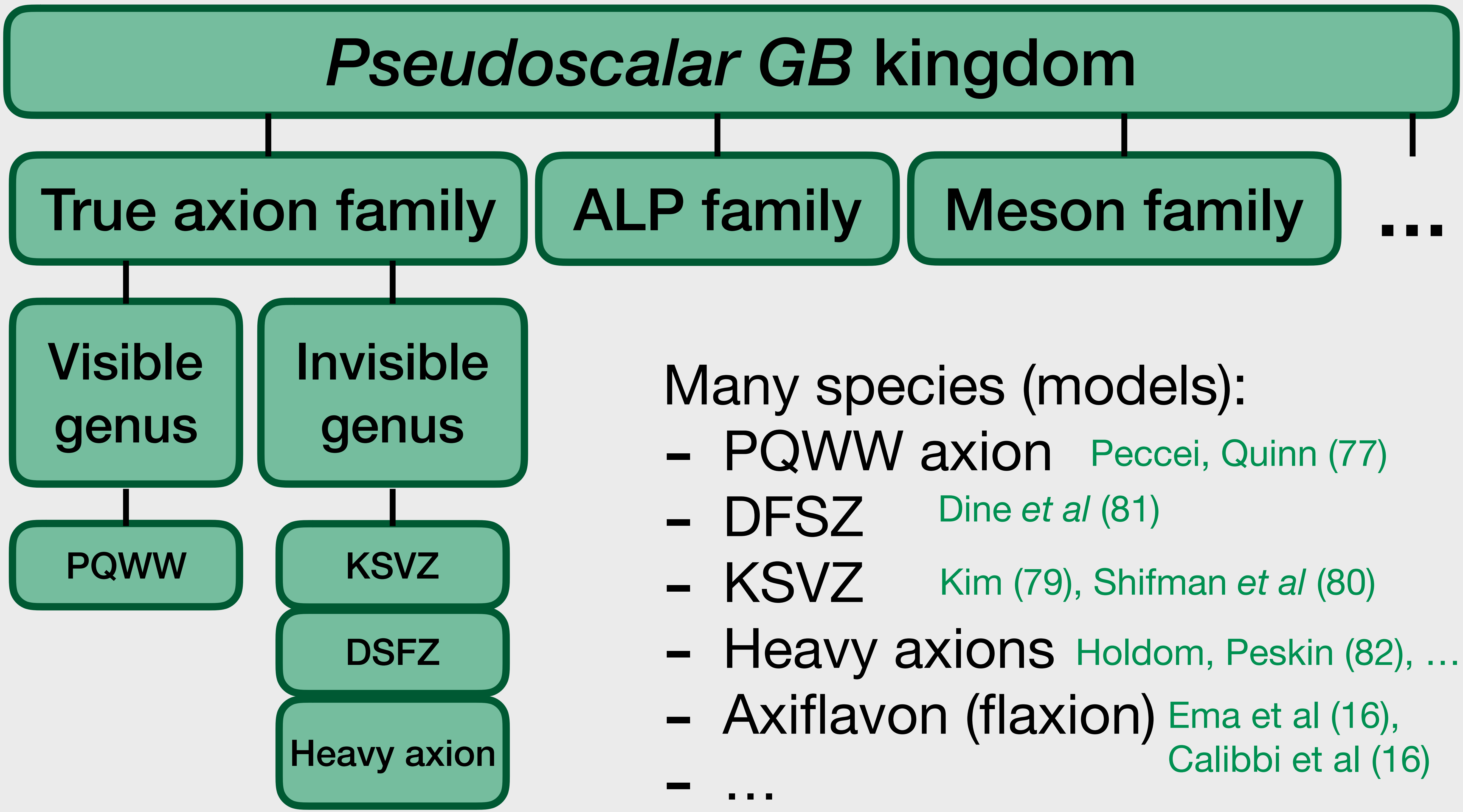
The *true axion* family



We distinguish 2 basic different types of true axions:

- **<u>Visible axion:</u>** it appears at the EW scale
  - Large couplings, ruled out experimentally
- **<u>Invisible axion:</u>** it appears at some large scale f_a
  - Couplings are suppressed by this large scale

Species in the *true axion* family



Many species (models):

- PQWW axion Peccei, Quinn (77)
- DFSZ Dine *et al* (81)
- KSVZ Kim (79), Shifman *et al* (80)
- Heavy axions Holdom, Peskin (82), …
- Axiflavon (flaxion) Ema et al (16), Calibbi et al (16)
- …

Species in the *ALP* family

Pseudoscalar GB kingdom

True axion family | ALP family | Meson family | ...

$$V(a) = \frac{1}{2} M_a^2 a^2$$

The mass and decay constant are independent parameters

ULA

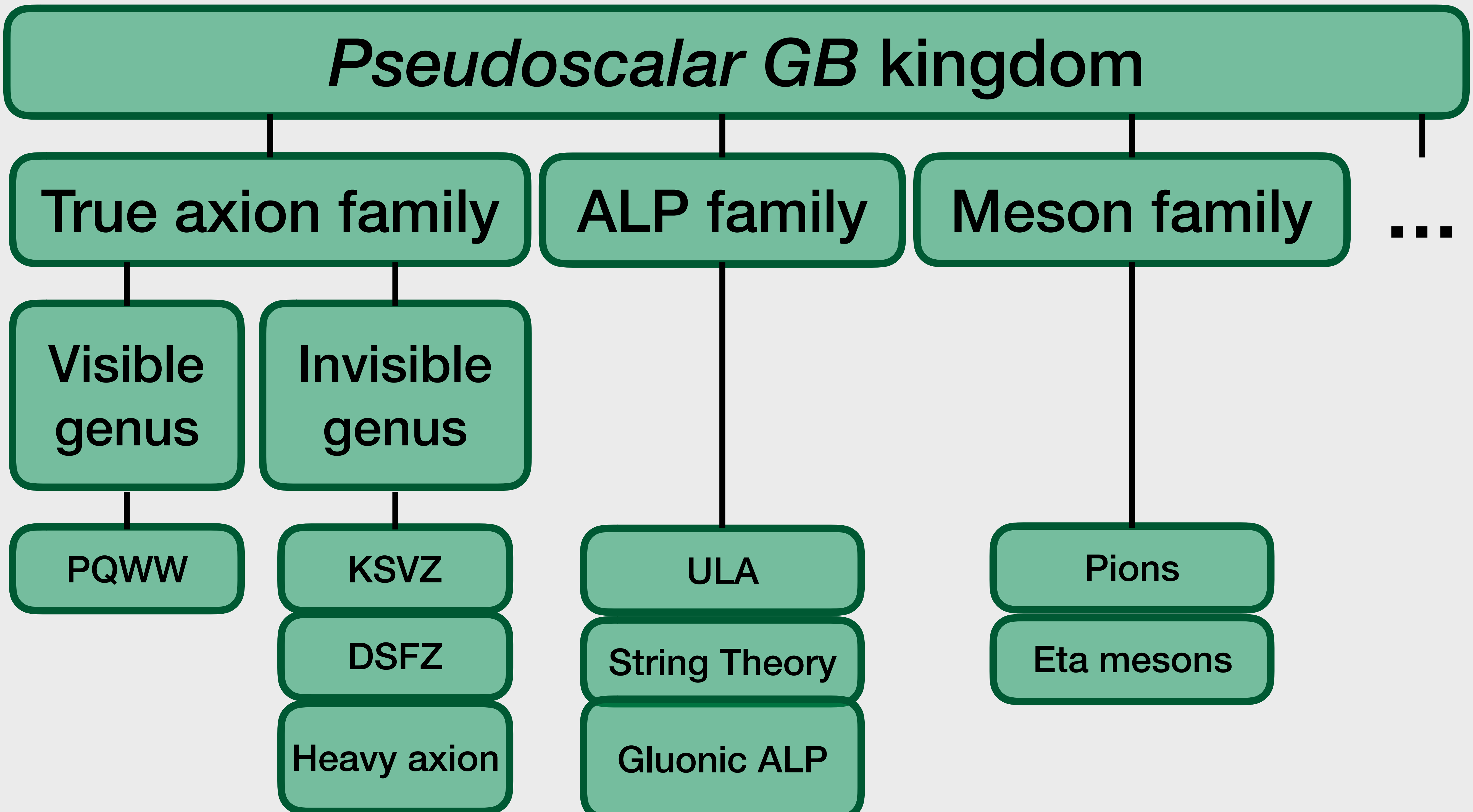
String Theory

Gluonic ALP

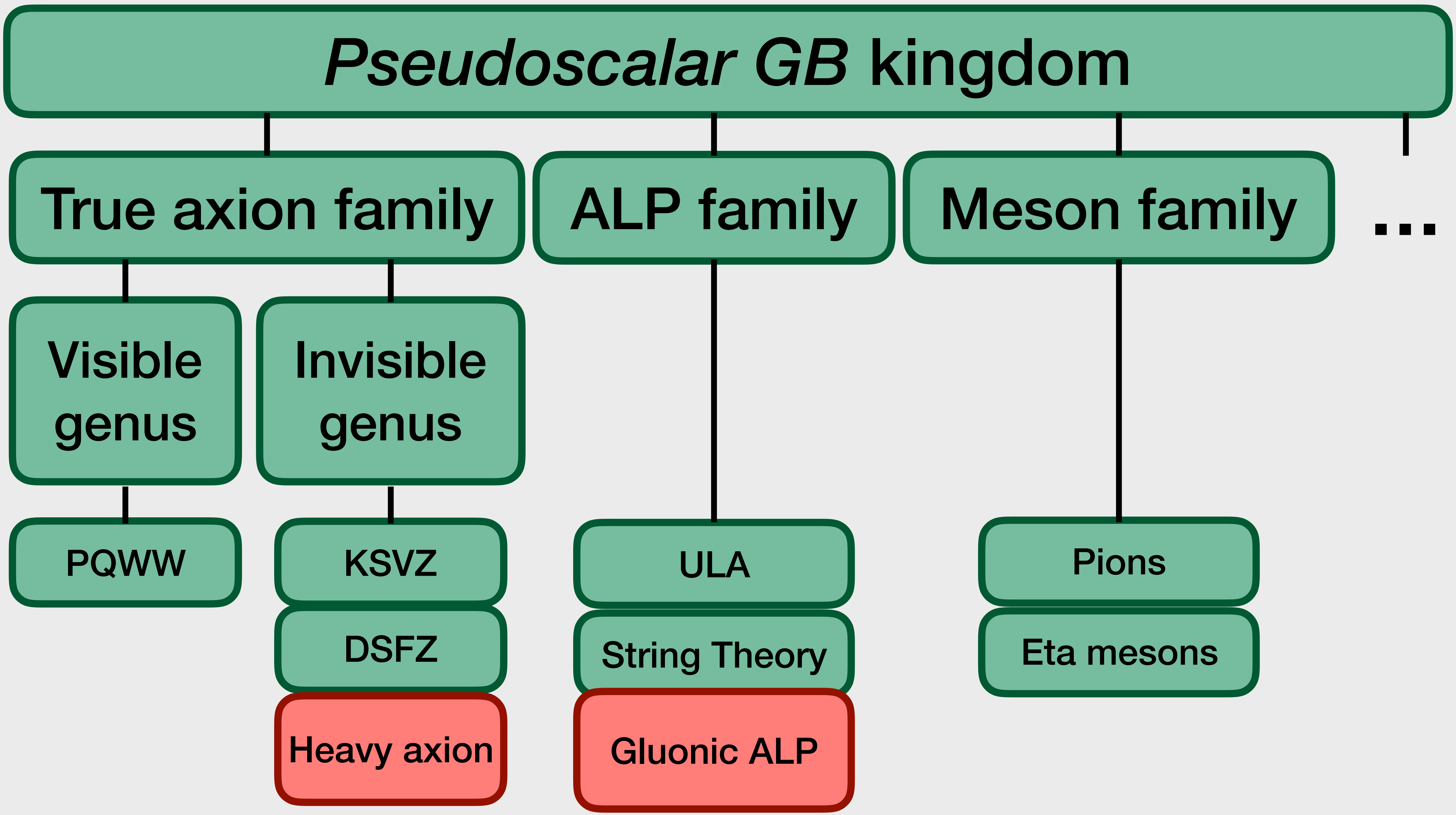
Even more species:

- String theory axions
  Arvanitaki *et al* (09)
- Ultra Light axions
  Marsh (15)
- Gluonic ALPs
- Photophobic ALP
  Craig, Hook, Kasko (18)
- ...

Everything at a glance



Everything at a glance



Axion ecology

Axion ecology

Classically, two equivalent couplings to fermions:

$$\frac{\partial_\mu a}{f_a}\,\bar{\psi}\gamma^\mu\gamma^5\psi \quad \xleftrightarrow{\ \psi \,\to\, e^{i\gamma^5 \frac{a}{2f_a}}\psi\ } \quad m\,\bar{\psi}\,e^{i\gamma^5\frac{a}{f_a}}\,\psi$$

"Derivative coupling" "Phase in mass matrix"

$\Rightarrow$ Only ***one*** independent coupling.

The shift symmetry is preserved, the axion is <u>massless</u>.

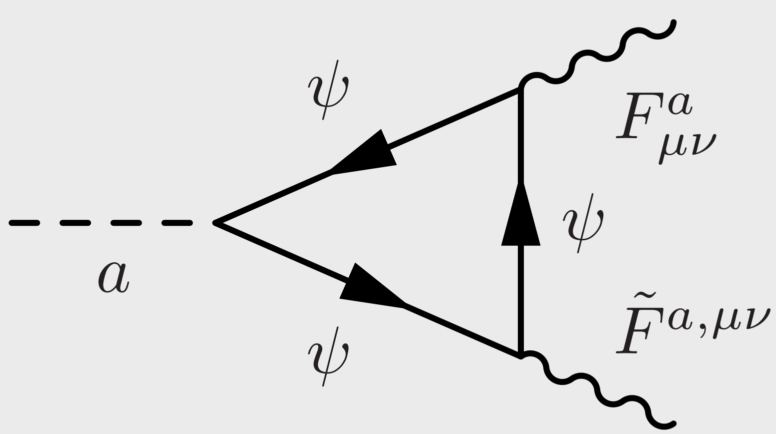
$$a \longleftrightarrow a + \text{const.}$$

Axion ecology

Quantum mechanically, the chiral symmetry can be anomalous:

$$\psi \;\to\; \mathrm{e}^{i\gamma^5 \frac{a}{2f_a}}\,\psi$$

$$\frac{\partial_\mu a}{f_a}\,\bar{\psi}\gamma^\mu\gamma^5\psi \qquad\qquad m\,\bar{\psi}\,\mathrm{e}^{i\gamma^5\frac{a}{f_a}}\,\psi$$



$$\frac{\alpha}{8\pi}\,\frac{a}{f_a}\,F^a_{\mu\nu}\tilde{F}^{a,\,\mu\nu}$$

“Anomalous coupling”

$\Rightarrow$ ***Two*** independent couplings.

If the shift symmetry is broken, the axion can get a mass.

$$a \;\longleftrightarrow\; a + 2\pi f_a$$

Axion ecology

Abuse of language: the physical coupling to gauge bosons are actually *independent* of the anomaly!

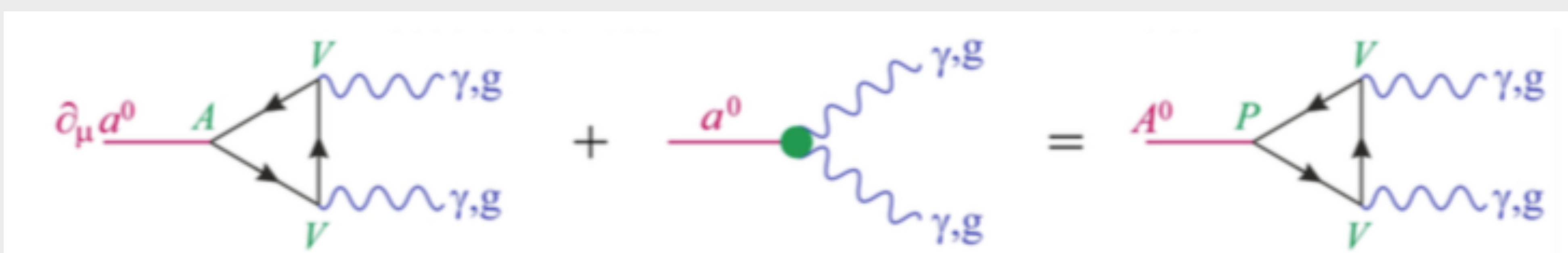
Axions are blind to anomalies

Jérémie Quevillon[1] and Christopher Smith[2]

Laboratoire de Physique Subatomique et de Cosmologie,
Université Grenoble-Alpes, CNRS/IN2P3, Grenoble INP, 38000 Grenoble, France.

Quevillon, Smith (19)

Linearly vs non-linearly realised sigma model.



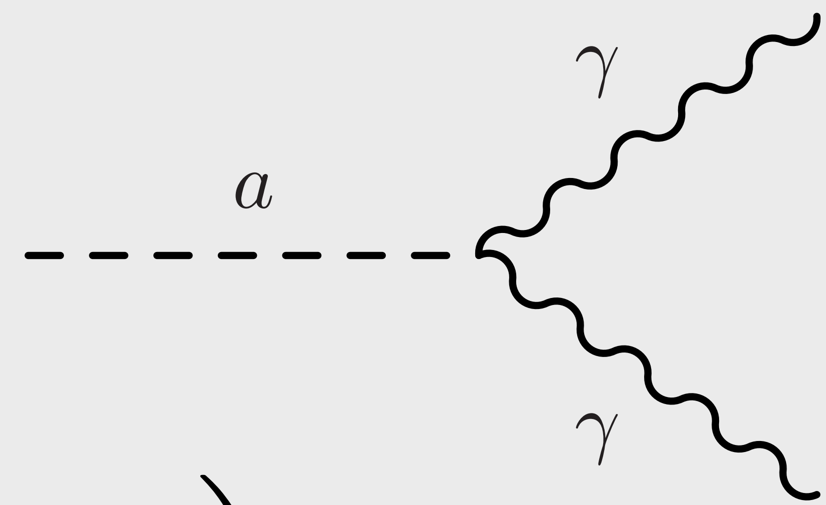
$$\frac{\partial_\mu a}{f_a}\,\bar\psi\gamma^\mu\gamma^5\psi \quad + \quad \frac{\alpha}{8\pi}\,\frac{a}{f_a}F^a_{\mu\nu}\tilde{F}^{a,\,\mu\nu} \quad = \quad m_\psi\,\frac{a}{f_a}\,\bar\psi\gamma^5\psi$$

The distinction is important for heavy gauge bosons.

True axion ecology

SM example: **true axion** coupling to two photons.

$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$



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

Model dependent: anomaly coefficients

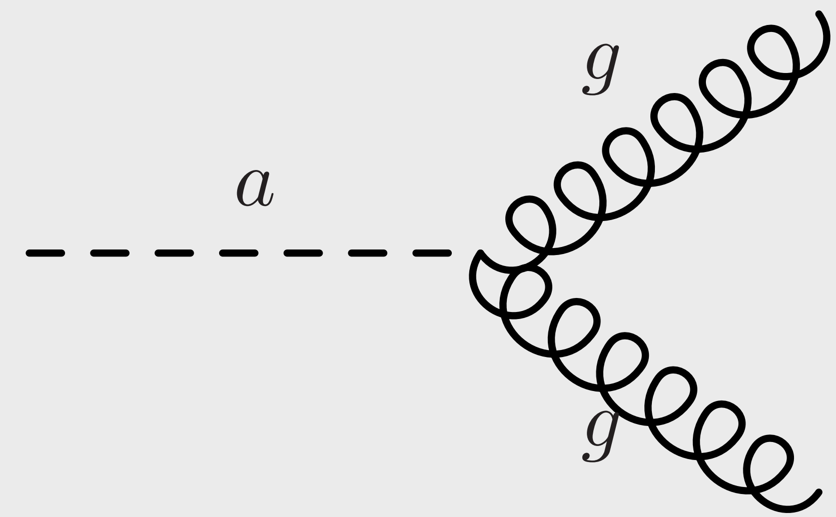
Model independent: where does this come from?

True axion ecology

A special one: the coupling to gluons.

Above confinement: Perturbation theory.

$$\mathcal{L} \supset \frac{1}{4} g_{agg}\, a\, G^{a}_{\mu\nu} \tilde{G}^{a,\,\mu\nu}$$



$$g_{agg} = \frac{\alpha_{\mathrm{s}}}{2\pi} \frac{1}{f_a} N$$

Model dependent: anomaly coefficient

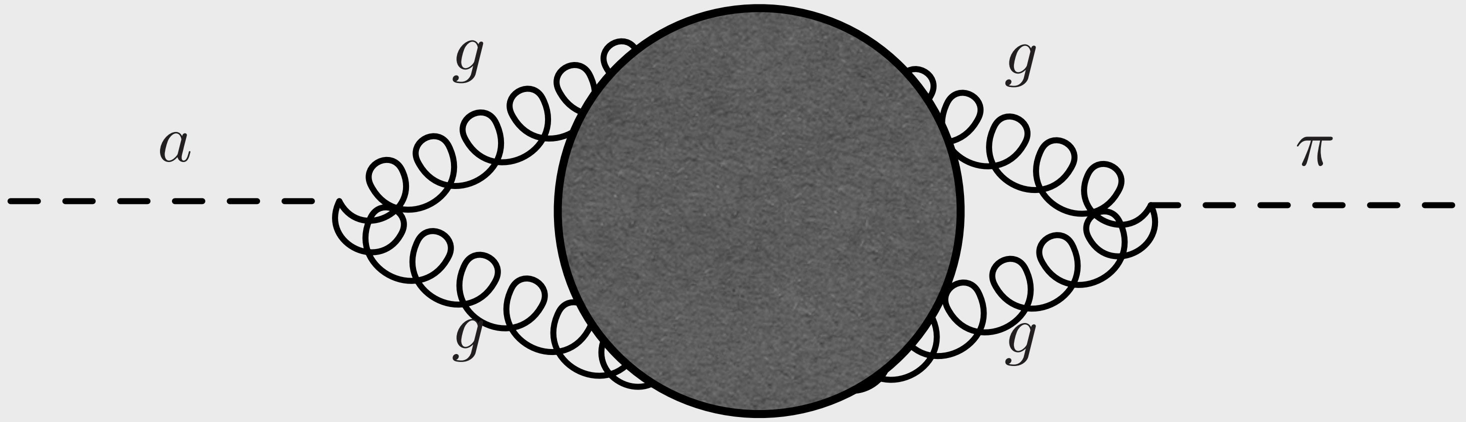
Essentially the same as for the photon coupling.

True axion ecology

<u>A special one</u>: the coupling to gluons.

Below confinement: Non-perturbative theory.

$$\mathcal{L} \supset \frac{1}{4} g_{agg}\, a\, G^{a}_{\mu\nu} \tilde{G}^{a,\,\mu\nu}$$



We expect couplings of the axion to mesons and baryons to arise.

$\Rightarrow$ Use chiral perturbation theory to calculate them.

True axion ecology

Below confinement: chiral perturbation theory.

$$\begin{array}{cccc} & \pi & \eta & a \\ M^2_{\{\pi,\eta,a\}} = & \multicolumn{3}{c}{\begin{pmatrix} B_0\left(m_u+m_d\right) & B_0\left(m_u-m_d\right) & 0 \\ B_0\left(m_u-m_d\right) & 4K/f_\pi + B_0(m_u+m_d) & 2K/(f_\pi f_a) \\ 0 & 2K/(f_\pi f_a) & K/f_a^2 \end{pmatrix}} \end{array}$$

Diagonalise to get

- eigenvalues: $m_\pi^2\,,\quad m_\eta^2\,,\quad m_a^2 \sim \dfrac{\Lambda^2_{\mathrm{QCD}}}{f_a}$
- eigenvectors: $\begin{cases} a \simeq a + \theta_{a\pi}\pi + \theta_{a\eta}\eta \\ \pi \simeq \pi + \theta_{\pi\eta}\eta + \theta_{\pi a}a \\ \eta \simeq \eta + \theta_{\eta a}a + \theta_{\eta\pi}\pi \end{cases}$ with $\boxed{\theta_{aX} \propto \dfrac{f_\pi}{f_a}}$

True axion ecology

Below confinement: chiral perturbation theory.

Because of the mixing, the axion inherits couplings from the pion and eta.

$$g_{a\gamma\gamma} = g^0_{a\gamma\gamma} + \theta_{a\pi}\, g_{\pi\gamma\gamma} + \theta_{a\eta}\, g_{\eta\gamma\gamma}$$

$$\propto \frac{f_\pi}{f_a} \qquad\qquad \propto \frac{\alpha_{\rm em}}{f_\pi}$$

$$g_{a\gamma\gamma} = -\frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - \frac{2}{3}\,\frac{m_u + 4\,m_d}{m_u + m_d}\right)$$

di Cortona et al (16)

$\simeq 2.03$ –>1.92 @ NLO in CPT

True axion ecology

Below confinement: chiral perturbation theory.

We can compute the equivalent contribution to all gauge boson couplings.

GA, Gavela, Quílez (19)

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - 2.03\right)$$

$$g_{aWW} = -\frac{1}{2\pi f_a}\frac{\alpha_{\rm em}}{s_w^2}\left(\frac{L}{N} - 0.75\right)$$

$$g_{aZZ} = -\frac{1}{2\pi f_a}\frac{\alpha_{\rm em}}{s_w^2 c_w^2}\left(\frac{Z}{N} - 0.52\right)$$

$$g_{a\gamma Z} = -\frac{1}{2\pi f_a}\frac{\alpha_{\rm em}}{s_w c_w}\left(\frac{2R}{N} - 0.74\right)$$

Gluonic ALPs & heavy axions

The QCD axion acquires its mass when QCD confines.

A mass can also be generated if the axial symmetry is explicitly broken,

$$\mathcal{L} \supset \left(\theta + \frac{a}{f_a}\right) G\tilde{G} + \frac{1}{2} M^2 (a - \langle v \rangle)^2 \quad , \quad \langle v \rangle \ \text{ unrelated to } \theta$$

Gluonic ALP, doesn't solve the strong CP problem.

Two parameter model: (f_a, m_a)

Gluonic ALPs & heavy axions

The QCD axion acquires its mass when QCD confines.

What if it also couples to another confining group?

$$m_{\mathrm{QCD}} \sim \frac{\Lambda_{\mathrm{QCD}}^2}{f_a} \qquad m_{\mathrm{new}} \sim \frac{\Lambda_{\mathrm{new}}^2}{f_a}$$

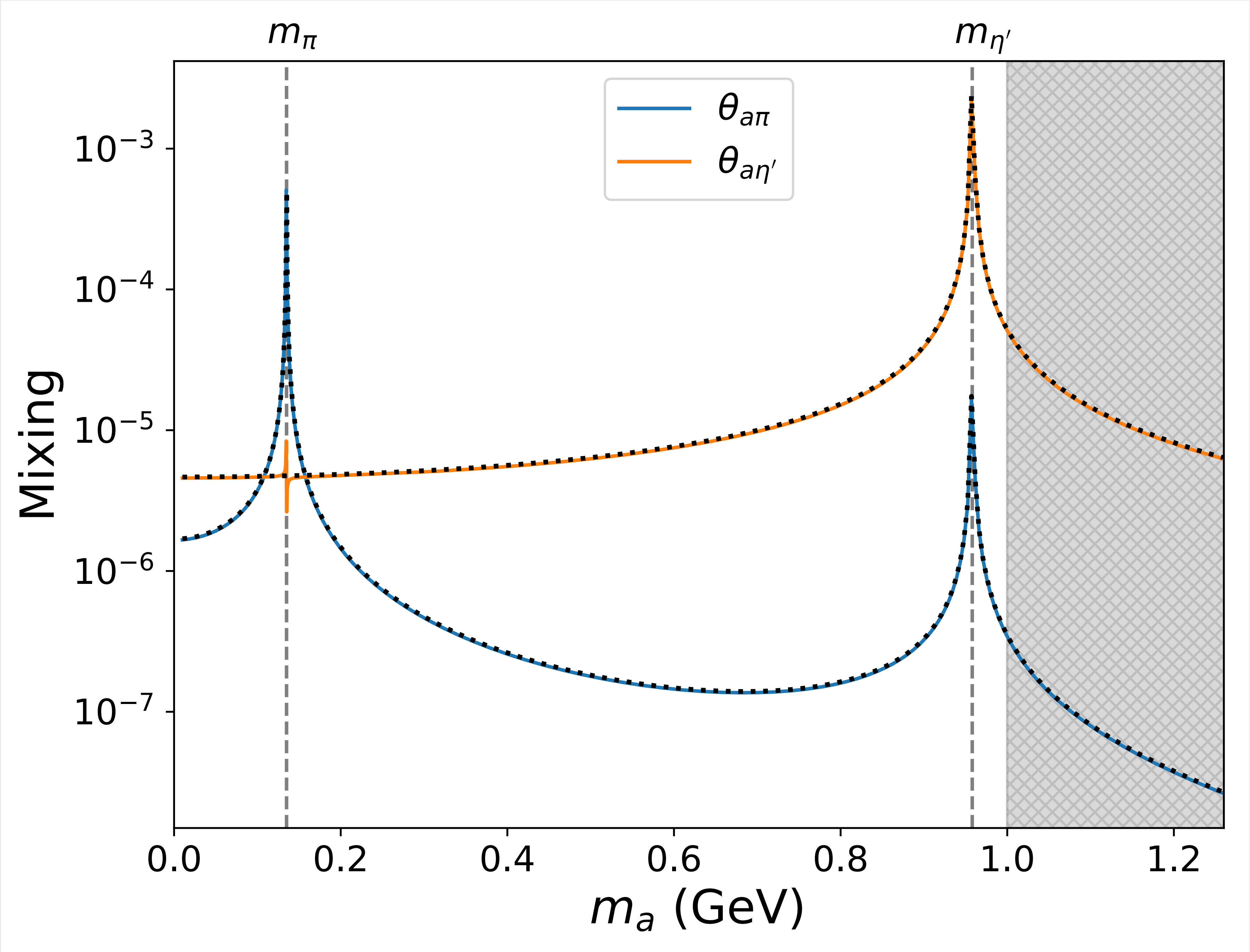
If $\Lambda_{\mathrm{new}} \gg \Lambda_{\mathrm{QCD}} \Rightarrow m_{\mathrm{new}} \gg m_{\mathrm{QCD}}$

Heavy axion, can still solve the strong CP problem.

Two parameter model: (f_a, m_a)

Heavy axion ecology

The mixing with mesons now depends on the axion mass.



Heavy axion ecology

The couplings also depend explicitly on the mass.

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - \left(1.67 + 0.36\frac{1}{1-\left(\frac{m_a}{m_\pi}\right)^2}\right)\frac{1}{1-\left(\frac{m_a}{m_\eta}\right)^2}\right)$$

$$g_{aWW} = -\frac{1}{2\pi f_a}\frac{\alpha_{\rm em}}{s_w^2}\left(\frac{L}{N} - 0.75\frac{1}{1-\left(\frac{m_a}{m_\eta}\right)^2}\right)$$

$$g_{aZZ} = -\frac{1}{2\pi f_a}\frac{\alpha_{\rm em}}{s_w^2 c_w^2}\left(\frac{Z}{N} - \left(0.50 + 0.02\frac{1}{1-\left(\frac{m_a}{m_\pi}\right)^2}\right)\frac{1}{1-\left(\frac{m_a}{m_\eta}\right)^2}\right)$$

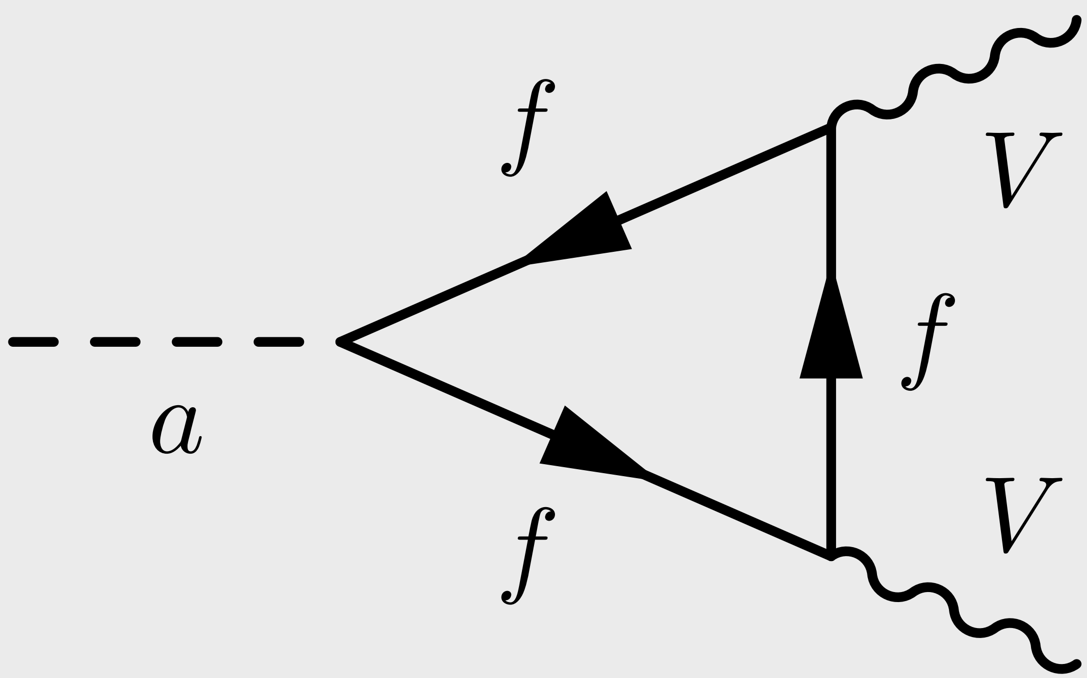
$$g_{a\gamma Z} = -\frac{1}{2\pi f_a}\frac{\alpha_{\rm em}}{s_w c_w}\left(\frac{2R}{N} - \left(0.76 - 0.02\frac{1}{1-\left(\frac{m_a}{m_\pi}\right)^2}\right)\frac{1}{1-\left(\frac{m_a}{m_\eta}\right)^2}\right)$$

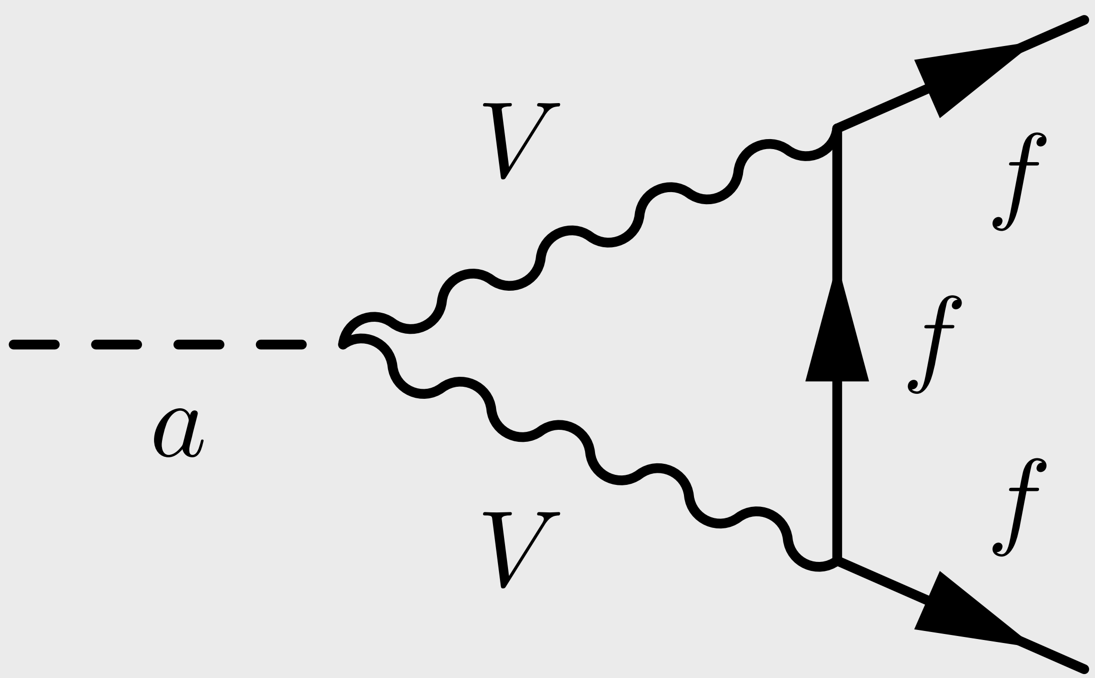
The model-independent part vanishes at large masses.

Loop-induced couplings

Even if a coupling is not present at tree level, it can be generated at loop level.

Bauer, Neubert, Thamm (17)





Particularly important for the decay of light axions.

Axion ethology

Axion ethology

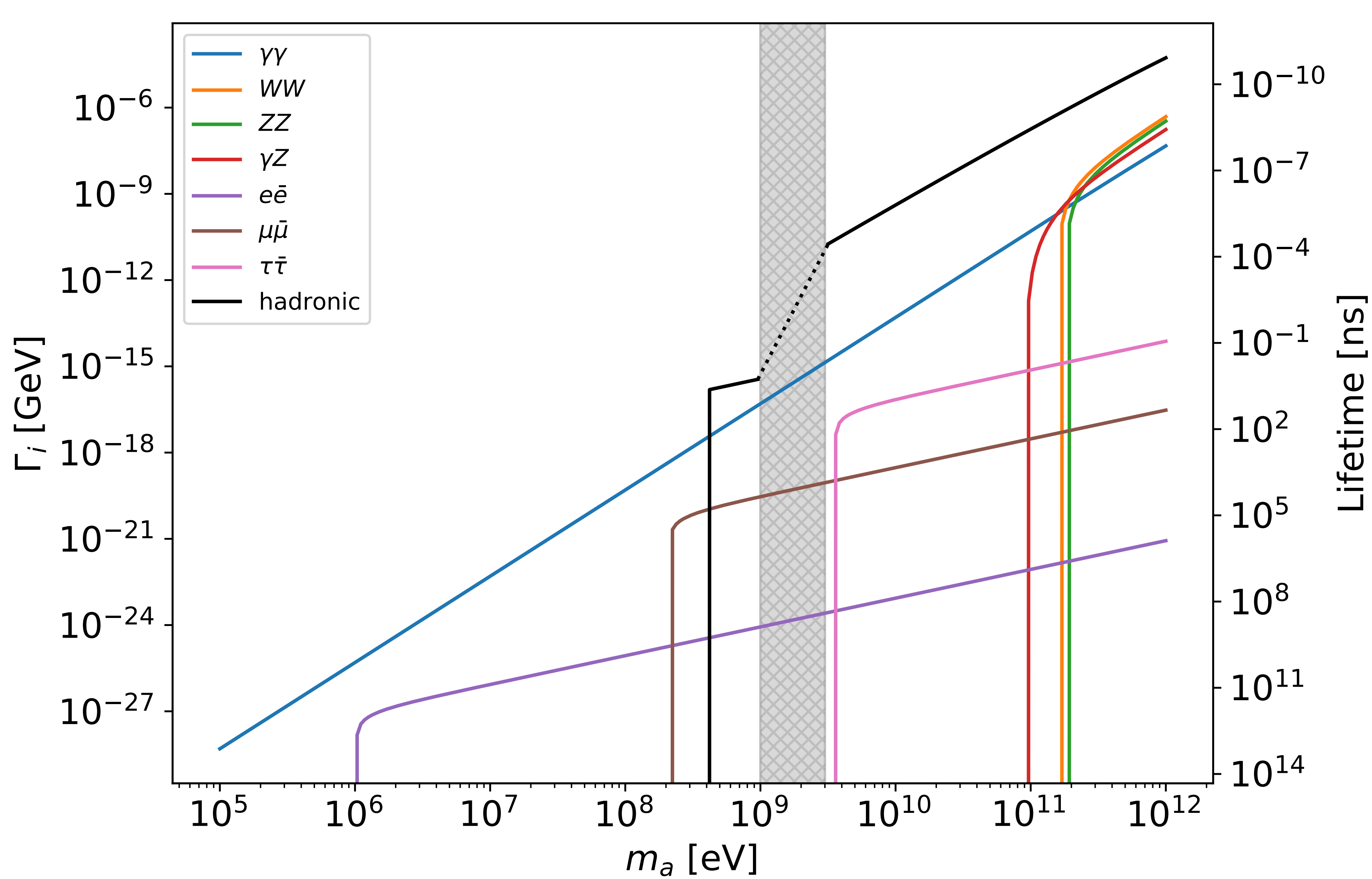
Many opportunities to look for axions in high-energy experiments:

- Colliders (LEP, LHC…)
  - Direct production & decay — Jaeckel, Spannowsky (12), …
  - Long lived searches — Alimena *et al* (19), …
  - Heavy ion collisions — Knapen *et al* (17), …

- Rare decays
  - Flavour (LHCb, Babar, Belle…) — Izaguirre, Lin, Shuve (17), …
  - Beam dumps — Döbrich *et al* (16), …

In addition to all the low-energy experiments.

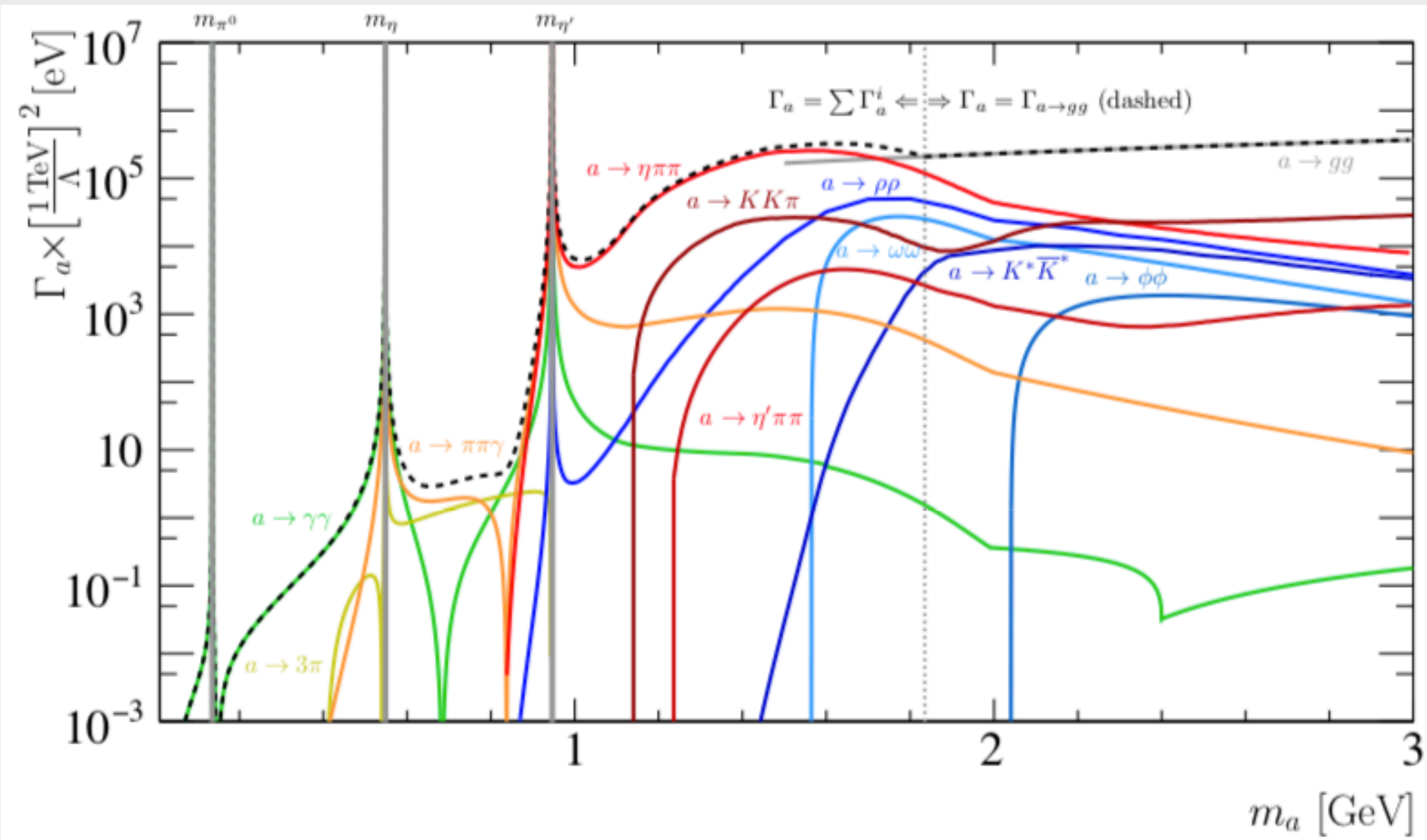
Heavy axion decays



Benchmark: $g_{a\gamma\gamma} = 10^{-7}\,\mathrm{GeV}^{-1}, \quad \dfrac{g_{aX}}{g_{aY}} = \dfrac{\alpha_X}{\alpha_Y}$

Heavy axion decays

The region 1-3 GeV contains many hadronic resonances.

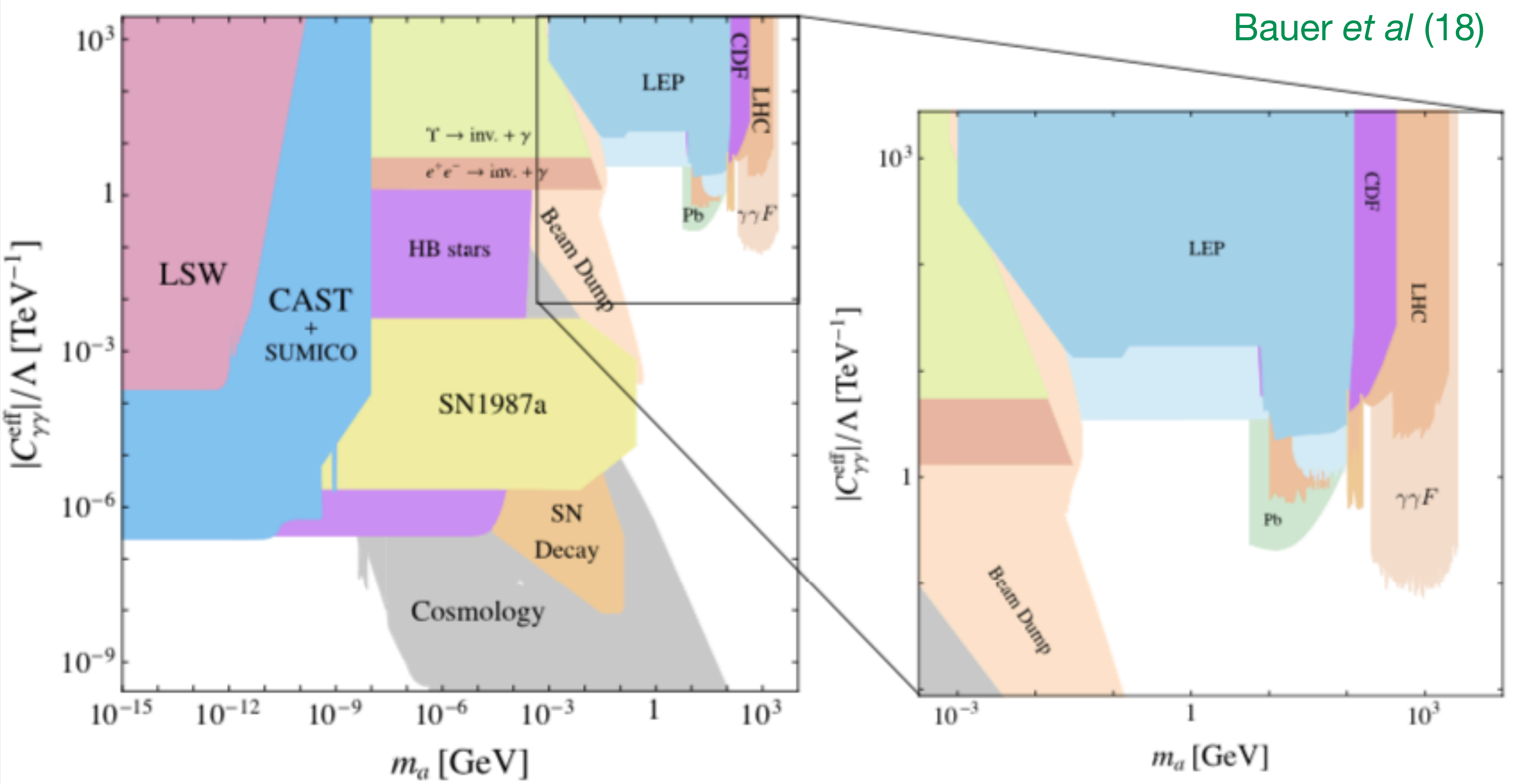


Aloni, Soreq, Williams (18)

Axion ethology

Example: coupling to photons (most constrained one)

Bauer *et al* (18)



True axion ethology

Usually, only one coupling at a time is considered.

But for true axions, the gluon coupling is always present.

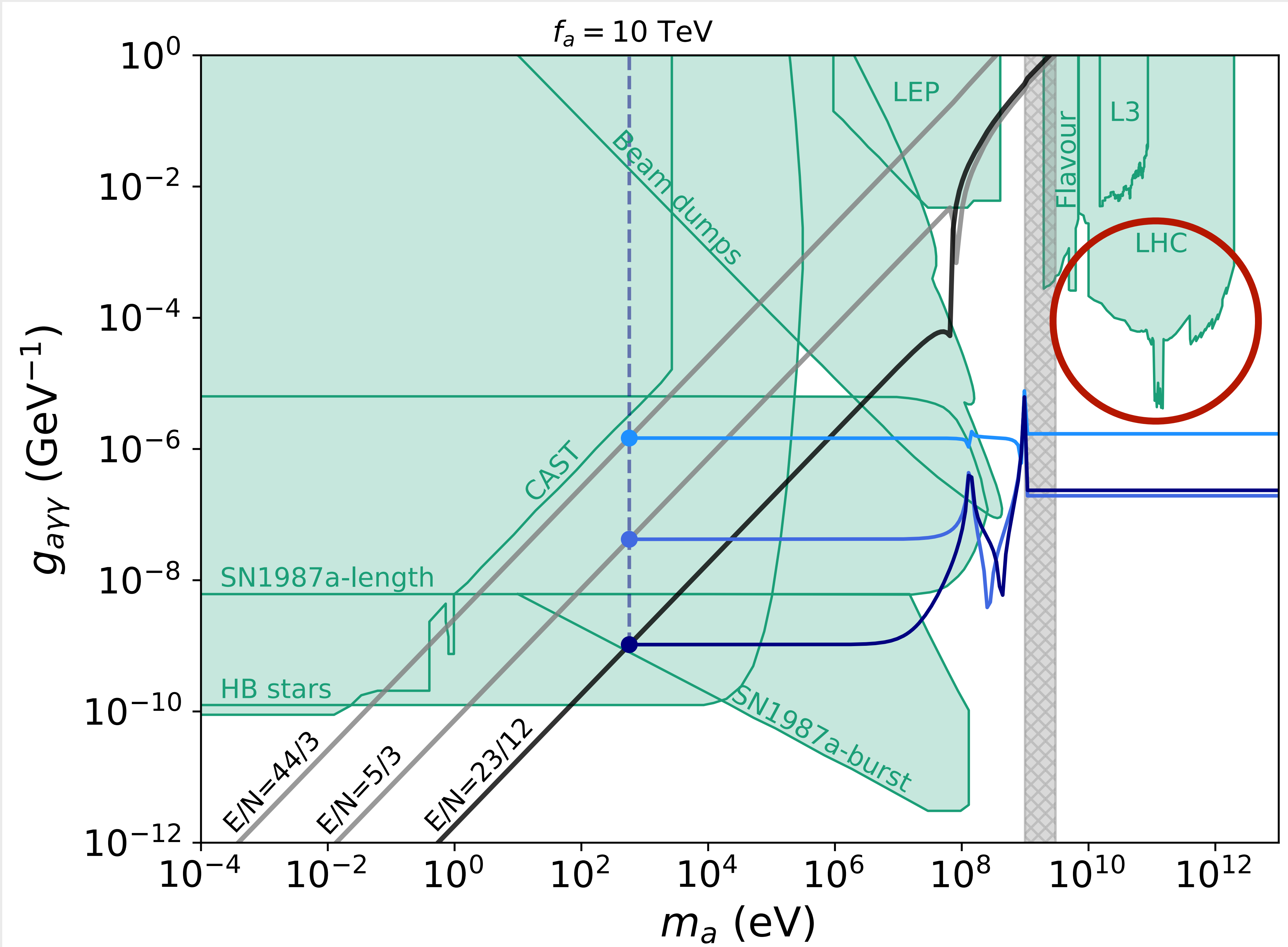
Two-coupling-at-a-time approach:
- Gluon coupling g_{agg}
- One EW coupling g_{aXY}
- + all loop-induced couplings

Great perspectives at the LHC:

$$\sigma(pp \to a) \times \mathrm{BR}(a \to XY) \propto \frac{g_{agg}^2\, g_{aXY}^2}{8 g_{agg}^2 + g_{aXY}^2} \xrightarrow{g_{agg} \gtrsim g_{aXY}} \frac{g_{aXY}^2}{8}$$

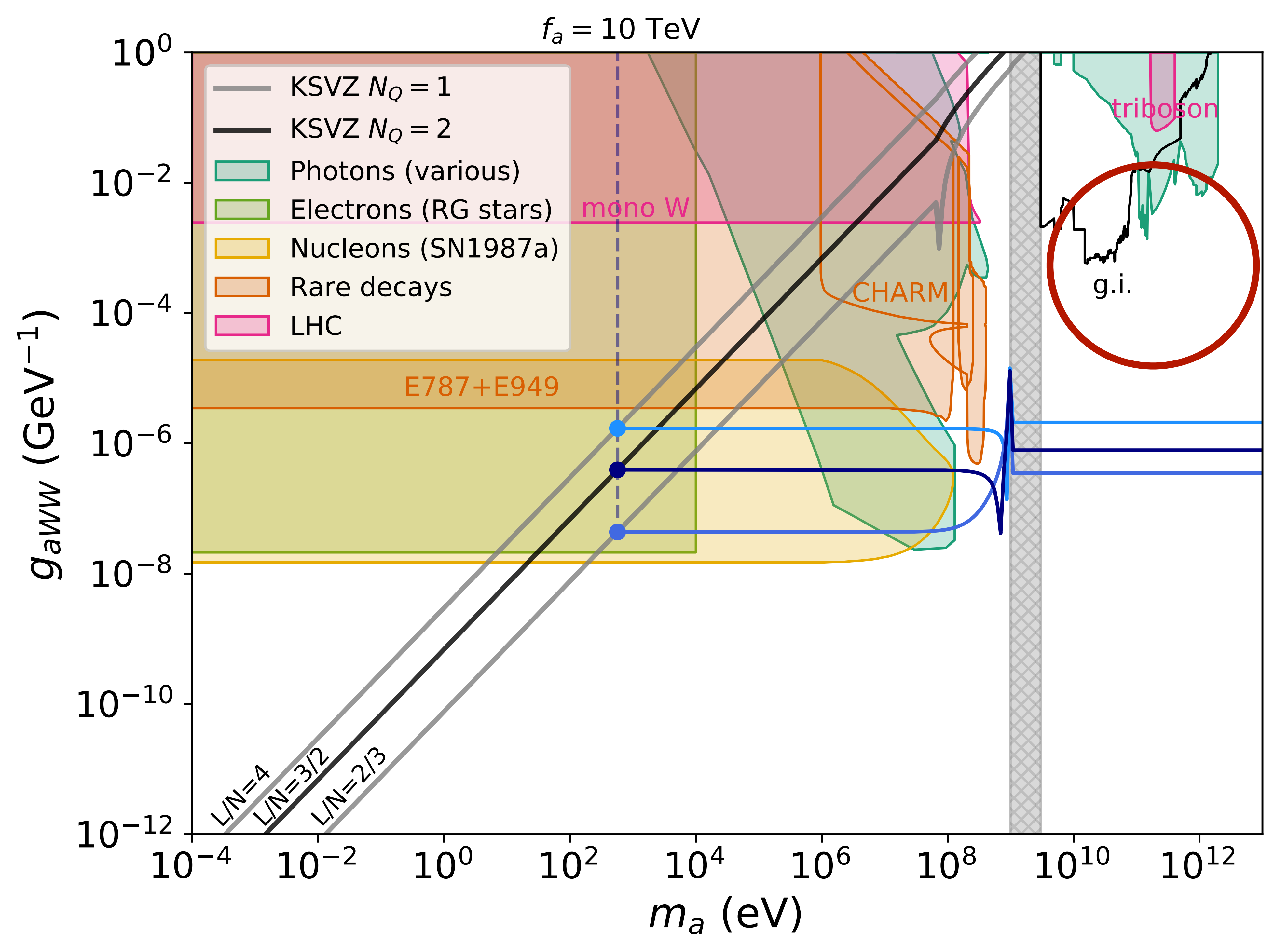
True axions and EW boson couplings

Photons



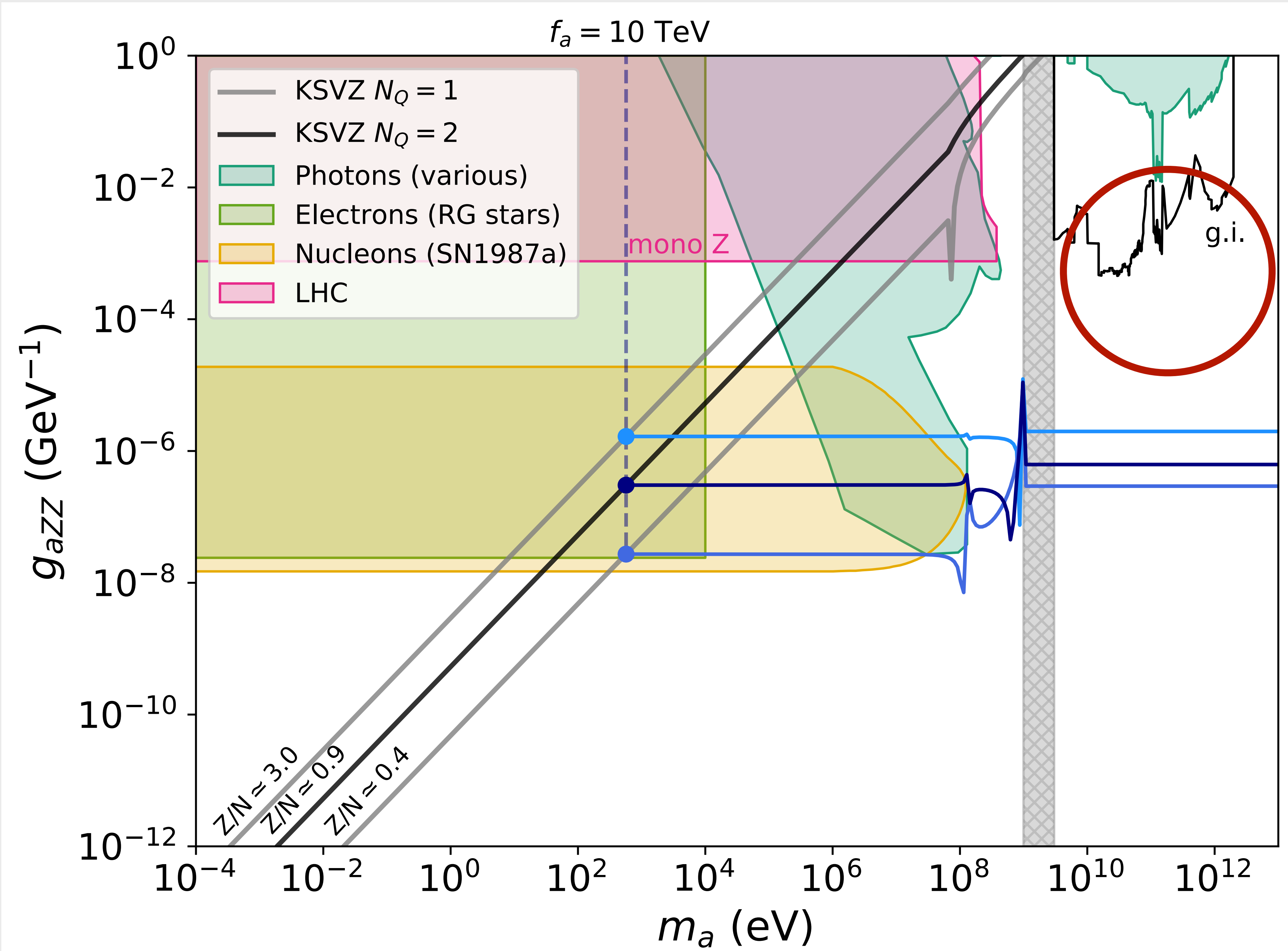
True axions and EW boson couplings

W bosons



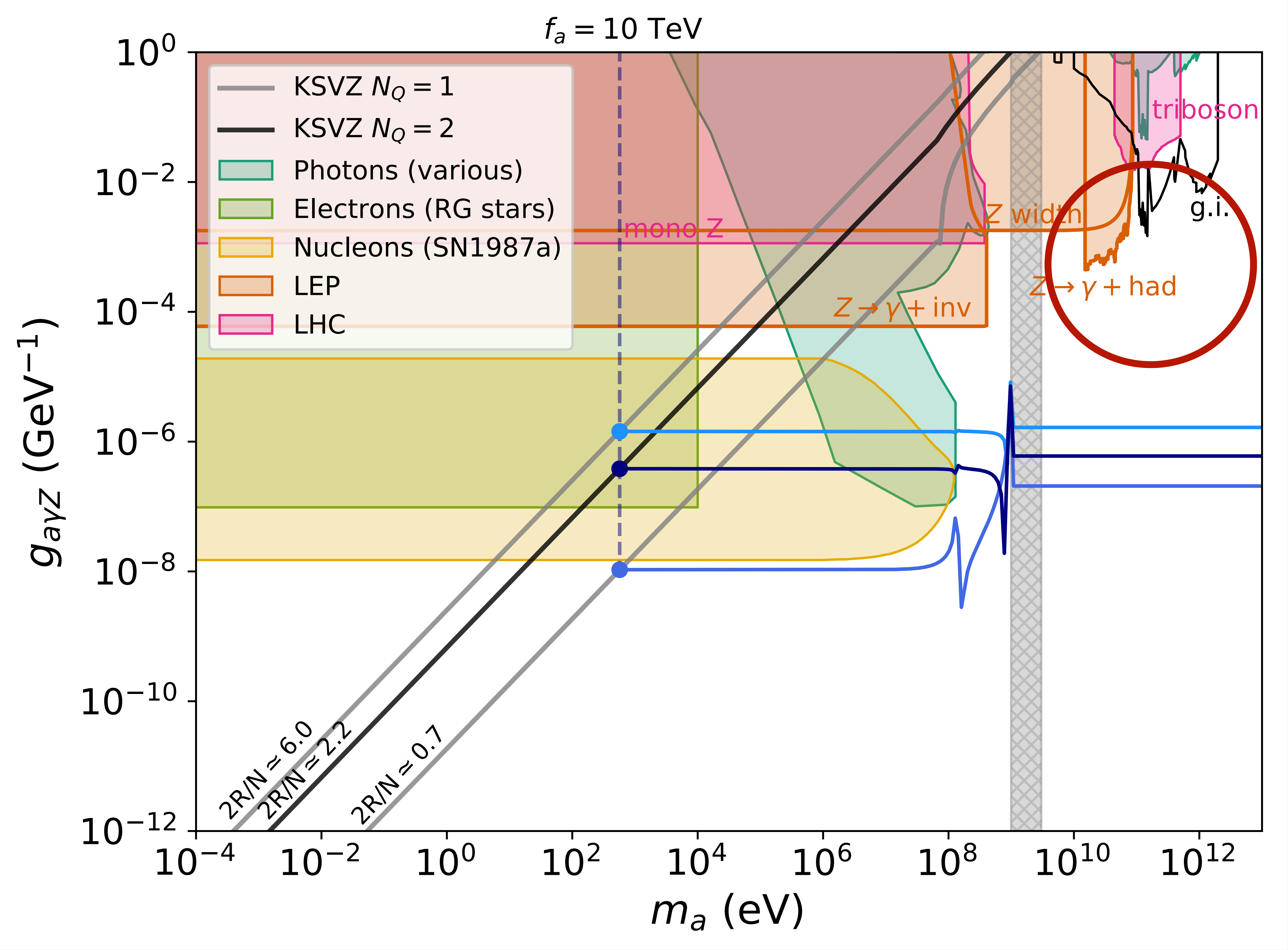
True axions and EW boson couplings

Z bosons



True axions and EW boson couplings

Photon - Z boson



Conclusions

1. **Taxonomy**: We need to know what kind of axion we are talking about.

2. **Ecology**: Contributions to couplings are generated in many different ways.

3. **Ethology**: It's important to take into account multiple couplings simultaneously.

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Thanks!

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True axions and EW boson couplings

Gluon coupling