MASS GENERATION FOR ALPS

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The Strong CP Problem

CP Violation sources in the SM, besides CKM and PMNS:

Pure QCD + Fermion phases effects:

$$\mathcal{L} \supset \bar{\theta}\frac{g_s^2}{16\pi^2}G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

$$\bar{\theta} \equiv \theta + \arg\det M_q$$

Neutron Electric Dipole moment

$$d_n^{\rm exp} < 1.8 \times 10^{-26}\, e\ {\rm cm} \quad \longrightarrow \quad \bar{\theta} \lesssim 10^{-10}$$

Abel et al., PRL 124(2020)

Dynamical solution with a scalar field getting a vev!

SM + a $\longrightarrow$ $\mathcal{L} \supset \left(\frac{a}{f_a} + \bar{\theta}\right)\frac{g_s^2}{16\pi^2}G_{\mu\nu}\widetilde{G}^{\mu\nu}$

$$\langle a \rangle = -\bar{\theta} f_a$$

Traditional method is with a being an angular component, that is a GB!

Solutions: PQWW Axion

- **SM +** $U(1)_{PQ}$ anomalous under QCD

2HDM has enough new dofs

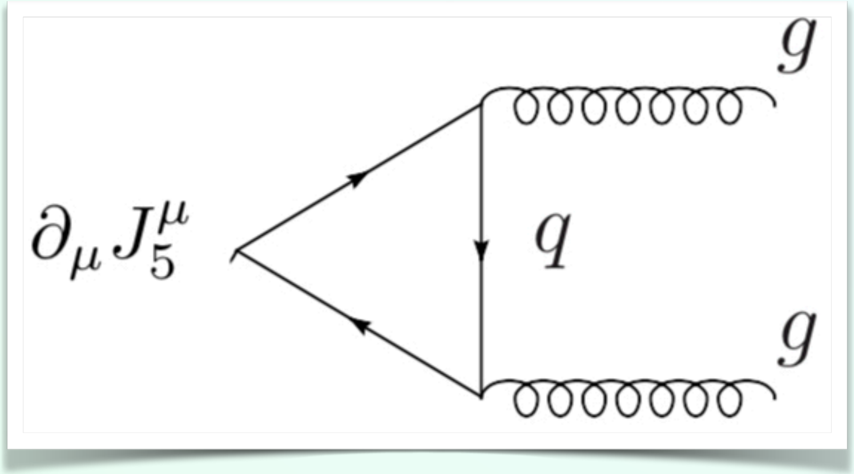
Peccei & Quinn, PRL38 (1977)
Weinberg, PRL40 (1978)
Wilczek, PRL40 (1978)

$$-\mathcal{L}_Y = \bar{Q}_L\, Y_D\, \Phi_1\, D_R + \bar{Q}_L\, Y_U\, \Phi_2\, U_R$$

$$U(1)_{PQ} \begin{cases} \psi_i \to e^{i\alpha x_{\psi_i}} \psi_i \\ \Phi_1 \to e^{i\alpha(x_{Q_L} - x_{D_R})} \Phi_1 \\ \Phi_2 \to e^{i\alpha(x_{Q_L} - x_{U_R})} \Phi_2 \end{cases}$$

$$x_{U_R} \neq x_{D_R}$$

The **AXION** arises as a combination of the GBs in Φ_1 and Φ_2!



$$\bar{\theta} + \frac{a}{v_a}(2x_{Q_L} - x_{U_R} - x_{D_R})$$

As a is a GB, shift symmetry can be used to absorb $\bar{\theta}$

$$\bar{\theta} + \frac{a}{v_a}\left(2x_{Q_L} - x_{U_R} - x_{D_R}\right) \longrightarrow \mathcal{L}_{QCD} \subset \frac{\alpha_s}{8\pi}\frac{a}{f_a} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

IF the axion acquires a **vanishing** VEV, then the Strong CP Problem is solved!

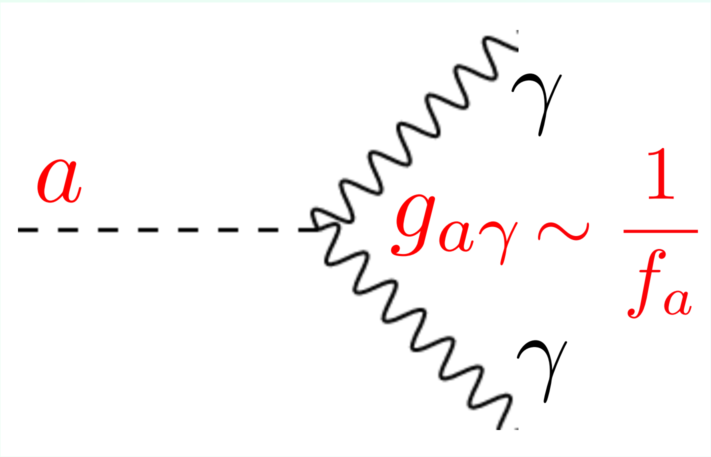
By using the chiral perturbation theory, it is possible to derive the effective scalar potential of the axion: See Grilli, Hardy, Pardo & Villadoro, 1511.02867

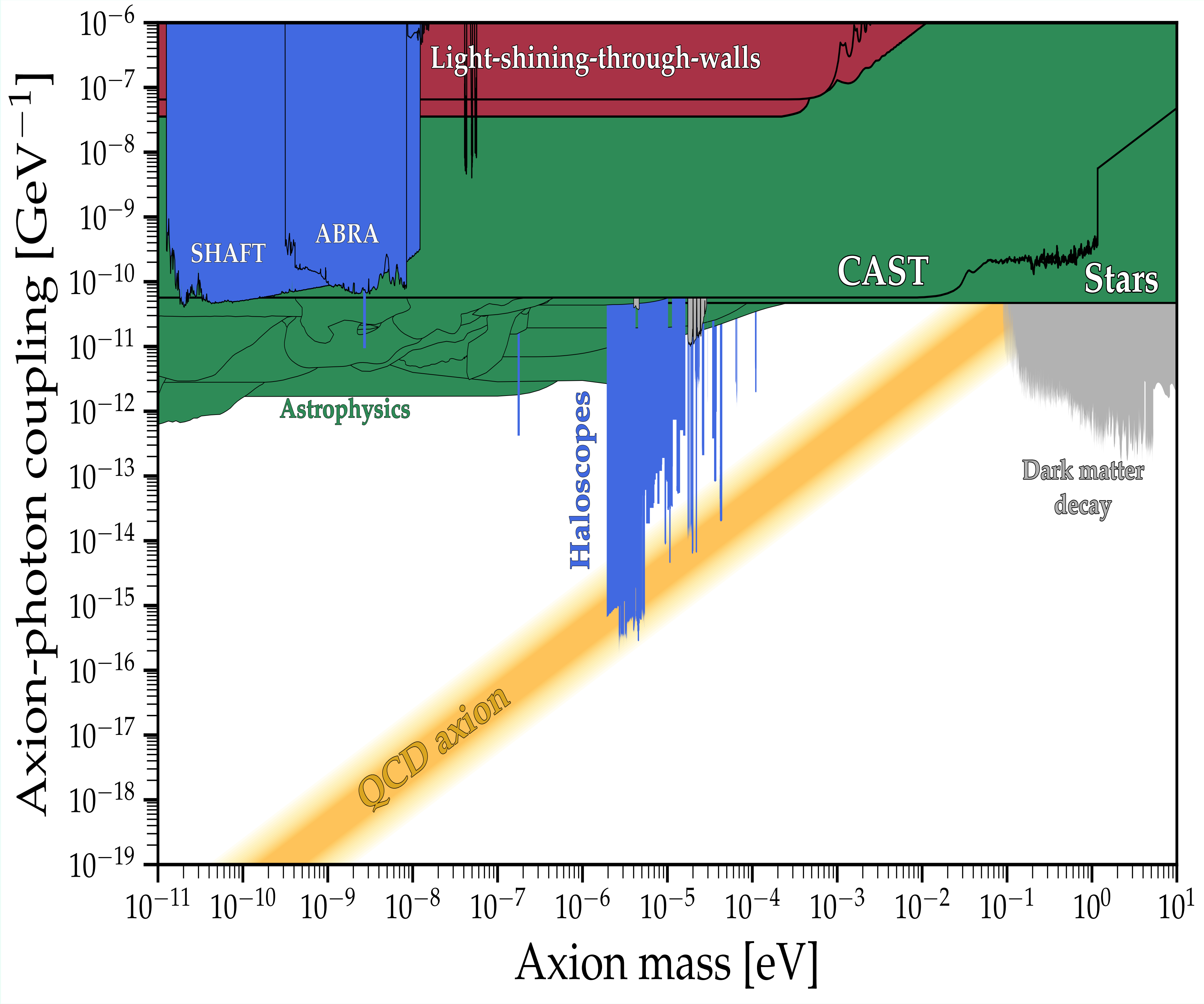
$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2}\sin^2\left(\frac{a}{2f_a}\right)}$$

Minimum indeed in $\langle a \rangle = 0$ and $m_a^2 = \frac{m_u\, m_d}{(m_u + m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2}$

$$\longrightarrow m_a \simeq 5.7\,\mu\text{eV}\left(\frac{10^{12}\ \text{GeV}}{f_a}\right)$$

Everything seems working BUT $f_a \sim \sqrt{v_1^2 + v_2^2} \sim 100\,\mathrm{GeV}$ and the axion coupling to photons is strongly constrained!





QCD axion:

$$m_a f_a = \mathrm{const}$$

$$f_a > 10^9\,\mathrm{GeV}$$

PQWW model excluded!!

Credit to Ciaran O'Hare, https://cajohare.github.io/AxionLimits/

Solutions: Invisible Axions

Add additional NP such that $f_a \gg v_{\rm EW}$

DFSZ Models

Zhitnitsky 1980
Dine, Fescler, Sredniki 1981

SM fermions

2 EW scalar doublet

1 EW scalar singlet

KSVZ Models

Kim 1979,
Shifman, Vainshtein, Zakharov 1980

SM + Exotic quarks

1 EW scalar doublet

1 EW scalar singlet

Idea: the VEV of the new singlet is the axion scale!

Other Solutions (Exotics/Baroques)

- Models with DARK QCD sector and kinetic mixing with SM QCD [many papers]
- Models with multiple axions [many papers]
- Axions from CHM LM, Pobbe & Rigolin, EPJC78 (2018)
  Brivio et al., Chin. J. Phys. 61 (2019)
  Gherghetta & Nguyen, JHEP12 (2020)
- Models with axion arising in the flavour sector

Wilczek, 1982

Flaxion: $U(1)_{PQ} \equiv U(1)_{FN}$

Ema, Hamaguchi, Moroi & Nakayama, JHEP 1701 (2017)
Calibbi, Goertz, Redigolo, Ziegler & Zupan, PR D95 (2017)

MFV Axion: $U(1)_{PQ} \subset U(3)^5$

Arias-Aragón & LM, JHEP 1710 (2017) 168

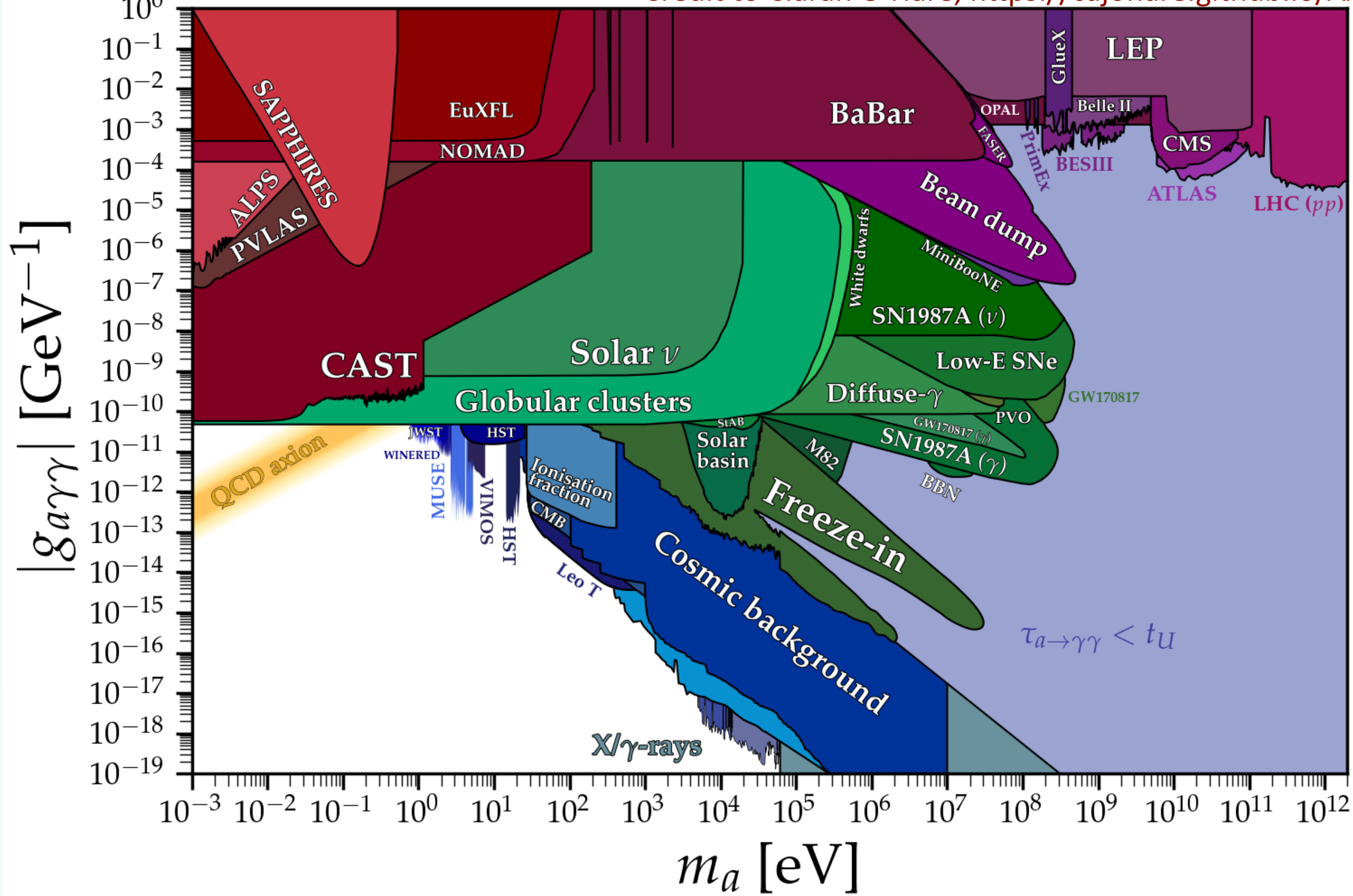
Extended Majoron: $U(1)_{PQ} \equiv U(1)_L$

Majoron: Y. Chikashige et al, PRL45 (1980), PRL98 (1981)
Gelmini & Roncadelli, PRL99 (1981)
Extended: de Giorgi, LM, Ponce & Rigolin, JHEP03 (2024)

Axion-Like-Particles (ALPs)

In the presence of NP: m_a outside this range and $m_a \not\propto 1/f_a$

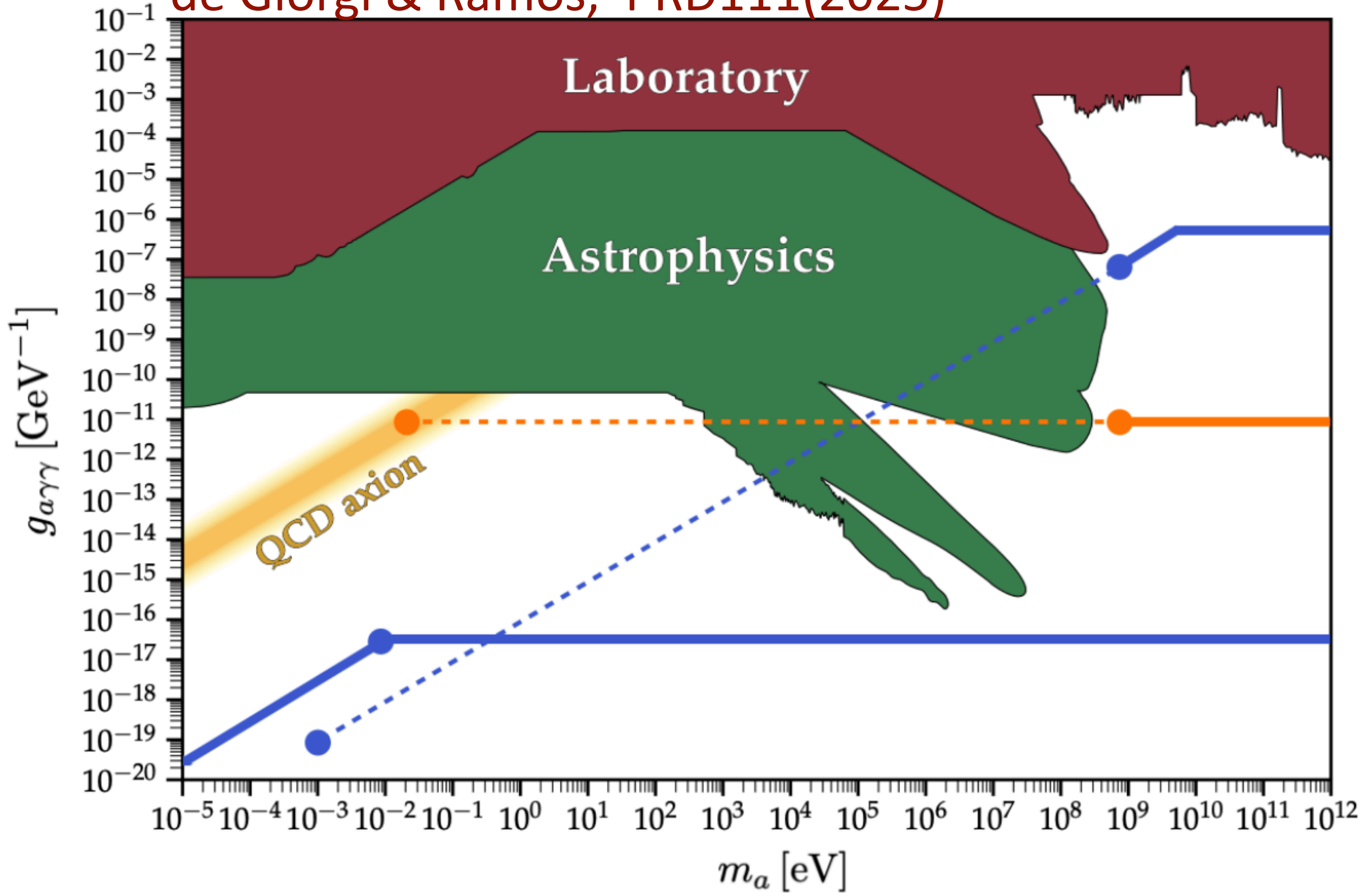
Credit to Ciaran O'Hare, https://cajohare.github.io/AxionLimits/



Axion-Like-Particles (ALPs)

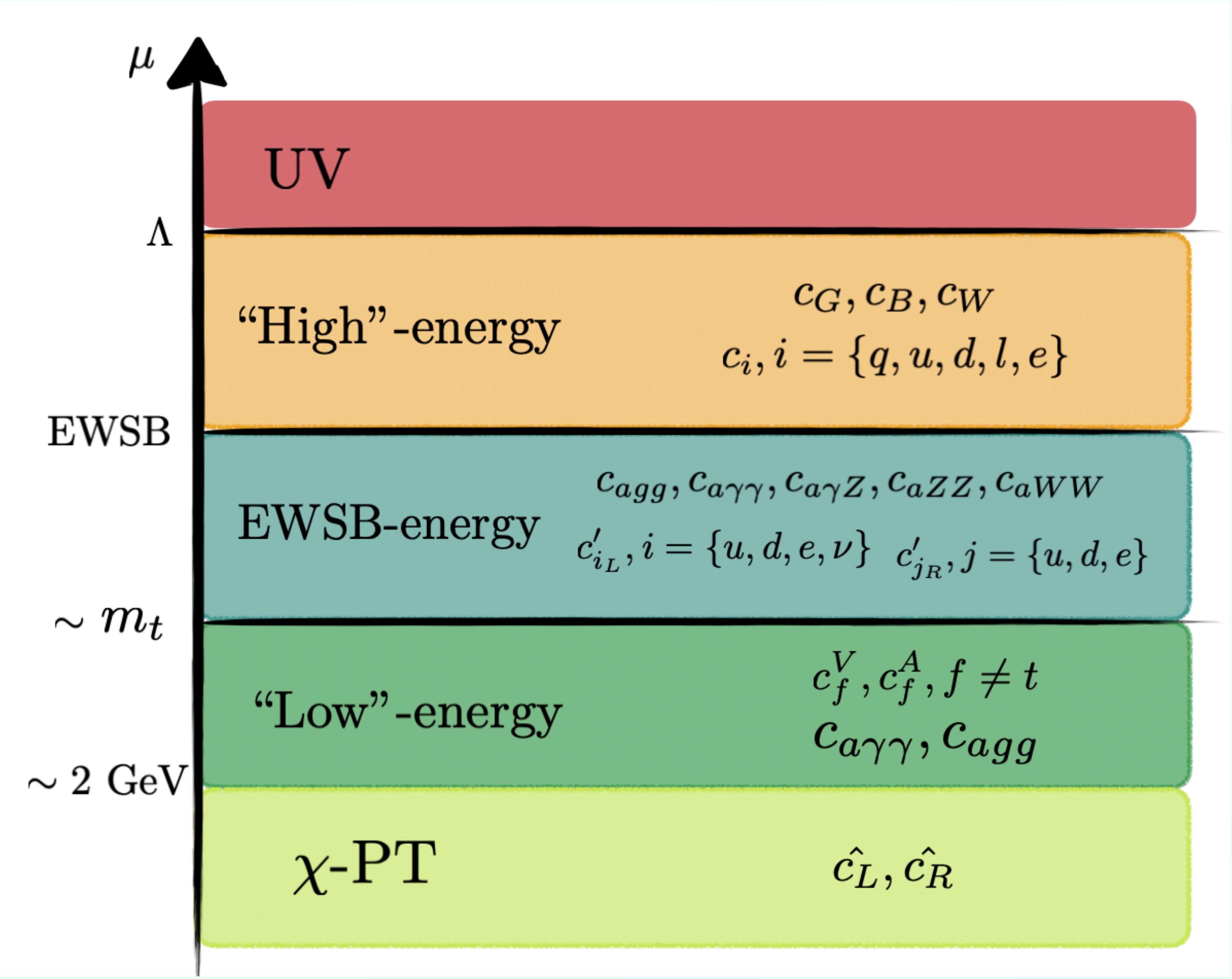
- Pseudo scalar field
- Derivative couplings with fermions
- Anomalous terms
- Generic mass term with $m_a \ll f_a$
- Not necessarily solves the Strong CP problem, but…

de Giorgi & Ramos, PRD111(2025)



The QCD axion could have a much larger mass than traditionally believed!

Axion-Like-Particles (ALPs)



Either UV model or EFT

Running
+
matching

Exp. observables

In general, FV couplings are always present at low-energy!

The ALP EFT: high energy

The model independent approach is best described by the EFT

Georgi, Kaplan & Randall, PLB169 (1986)
Mimasu & Sanz, JHEP06 (2015)
Brivio, LM, et al., EPJC77 (2017)
Chala et al., EPJC81 (2021)
Bonilla et al., JHEP11 (2021)
Bauer et al., PRL127 (2021)

$$\begin{aligned}\mathcal{L} =& \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2} a^2 + \\ &+ c_{\widetilde{B}} \mathcal{O}_{\widetilde{B}} + c_{\widetilde{W}} \mathcal{O}_{\widetilde{W}} + c_{\widetilde{G}} \mathcal{O}_{\widetilde{G}} + \\ &+ c_Q \mathcal{O}_Q + c_L \mathcal{O}_L + c_u \mathcal{O}_u + c_d \mathcal{O}_d + c_e \mathcal{O}_e\end{aligned}$$

$$\mathcal{O}_{\widetilde{B}} = \frac{a}{f_a} B_{\mu\nu} \widetilde{B}^{\mu\nu}$$

$$\mathcal{O}_{\widetilde{W}} = \frac{a}{f_a} W^i_{\mu\nu} \widetilde{W}^{i\mu\nu}$$

$$\mathcal{O}_{\widetilde{G}} = \frac{a}{f_a} G^\alpha_{\mu\nu} \widetilde{G}^{\alpha\mu\nu}$$

Anomalous terms

$$\mathcal{O}_{f,ij} = \frac{\partial_\mu a}{f_a} \left(\overline{f_i} \gamma^\mu f_j\right)$$

Shift invariant terms

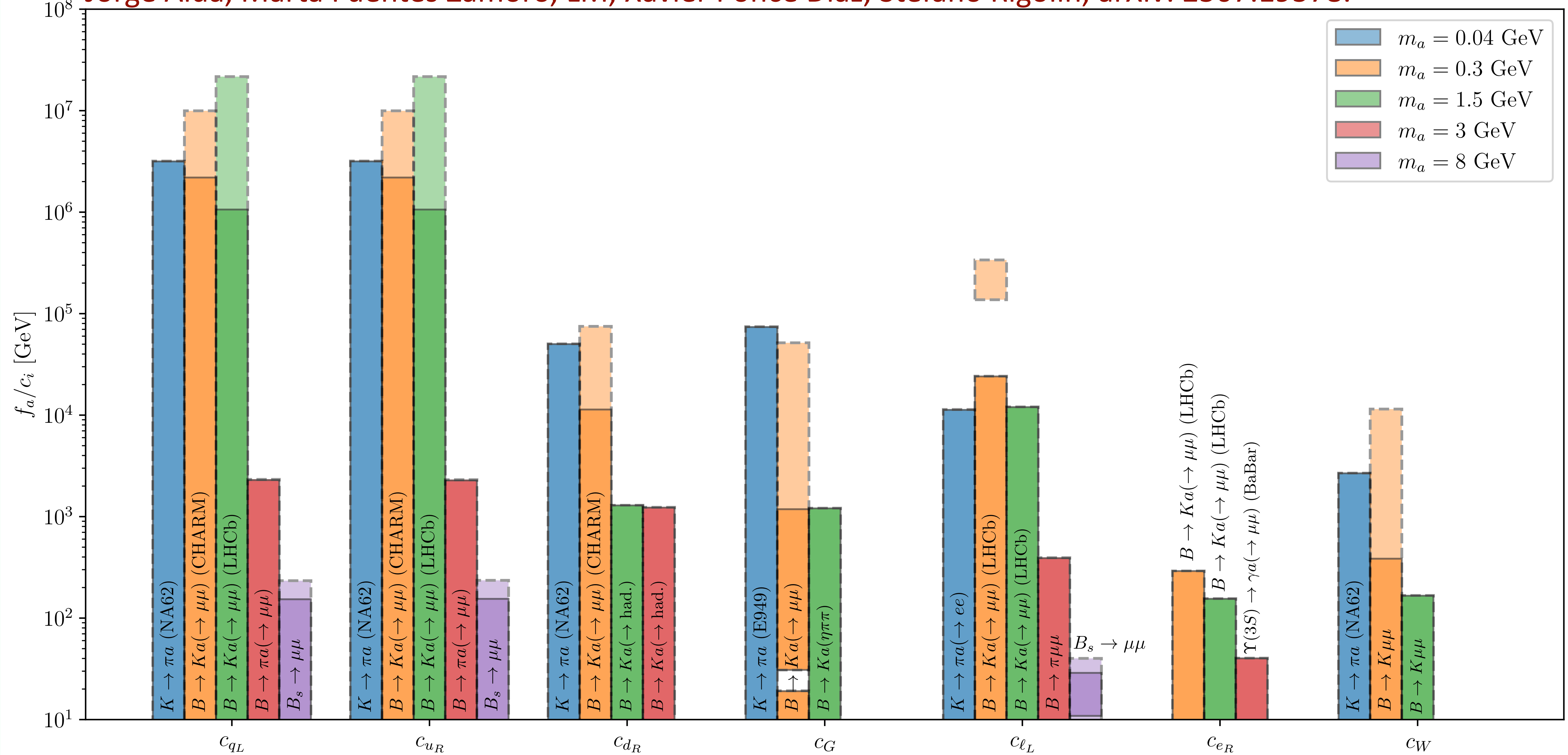
$$a \to a + const.$$

ALP-automated computing algorithm

Jorge Alda, Marta Fuentes Zamoro, LM, Xavier Ponce Diaz, Stefano Rigolin, arXiv: 2508.08354.

Global Result: 1 op. at a time at UV

Jorge Alda, Marta Fuentes Zamoro, LM, Xavier Ponce Diaz, Stefano Rigolin, arXiv: 2507.19578.



BaBar: $B \to K$'hadrons', $B \to \pi\mu\mu$

SHIP: future $B \to K\mu\mu$

CMS & LHCb: $B_s \to \mu\mu$

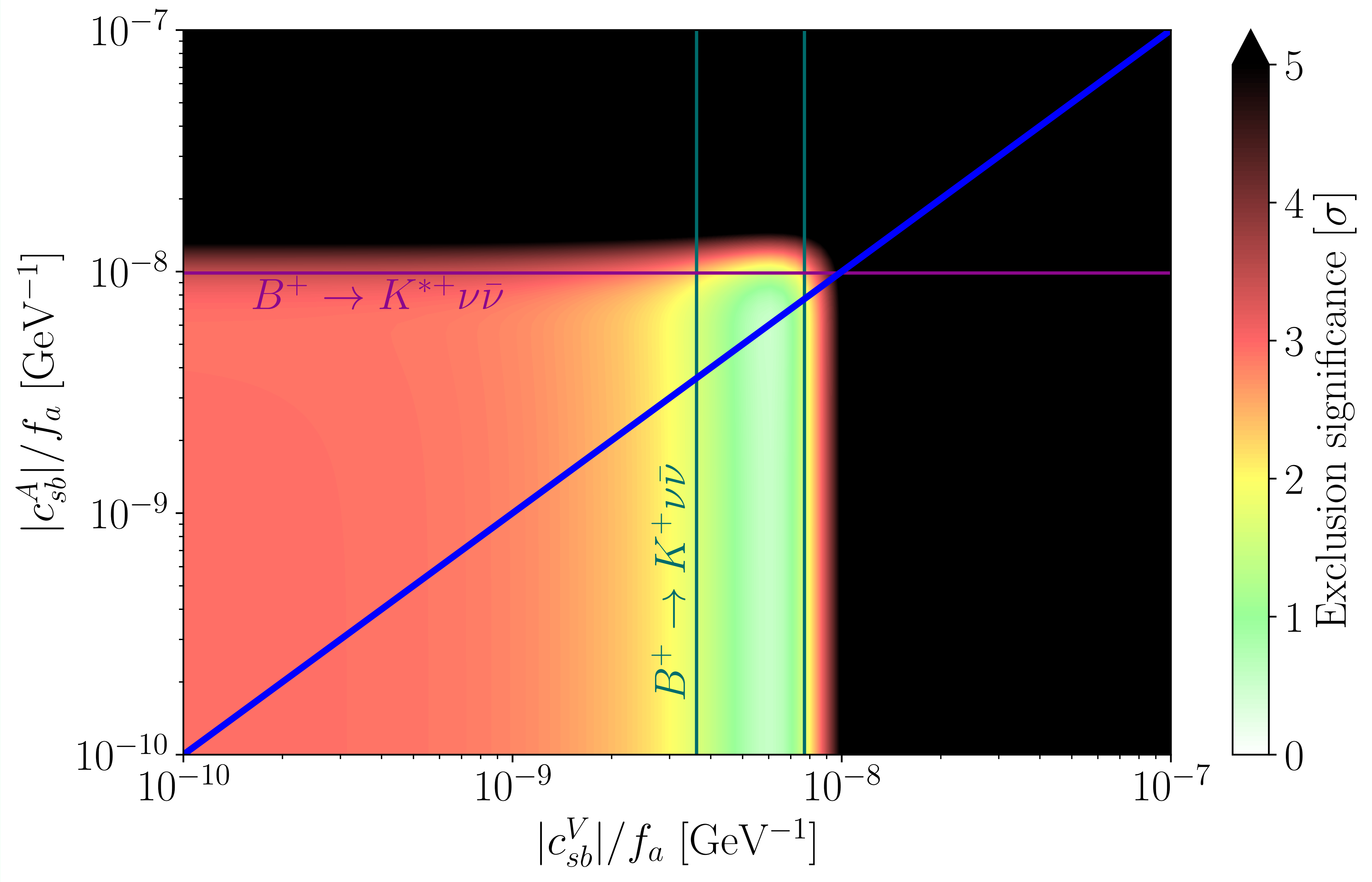
HL-LHCb: future $B_s \to \mu\mu$

Example: Belle II Anomaly

$$B^+ \to K^+ \overline{\nu} \nu \approx 2.8\,\sigma$$

$$\mathcal{L} = \frac{\partial_\mu a}{f_a} \left(c_{sb}^V \overline{s} \gamma^\mu b + c_{sb}^A \overline{s} \gamma^\mu \gamma_5 b \right) \qquad m_a = 2 \text{ GeV}$$

Atmannshofer et al., PRD109 (2024)



Specific coupling setup:
ALP needs to be long lived!

ALP Mass Generation

→ Is there a mechanism to give (this) mass to the ALP?

We are looking for:

- SB that leads to ALP: $U(1)_{\rm PQ}$ SSB
- SB that provides a mass to the ALP: breaking of the shift symmetry
- Connection to other physics, otherwise equivalent to add $m_a^2 a^2$

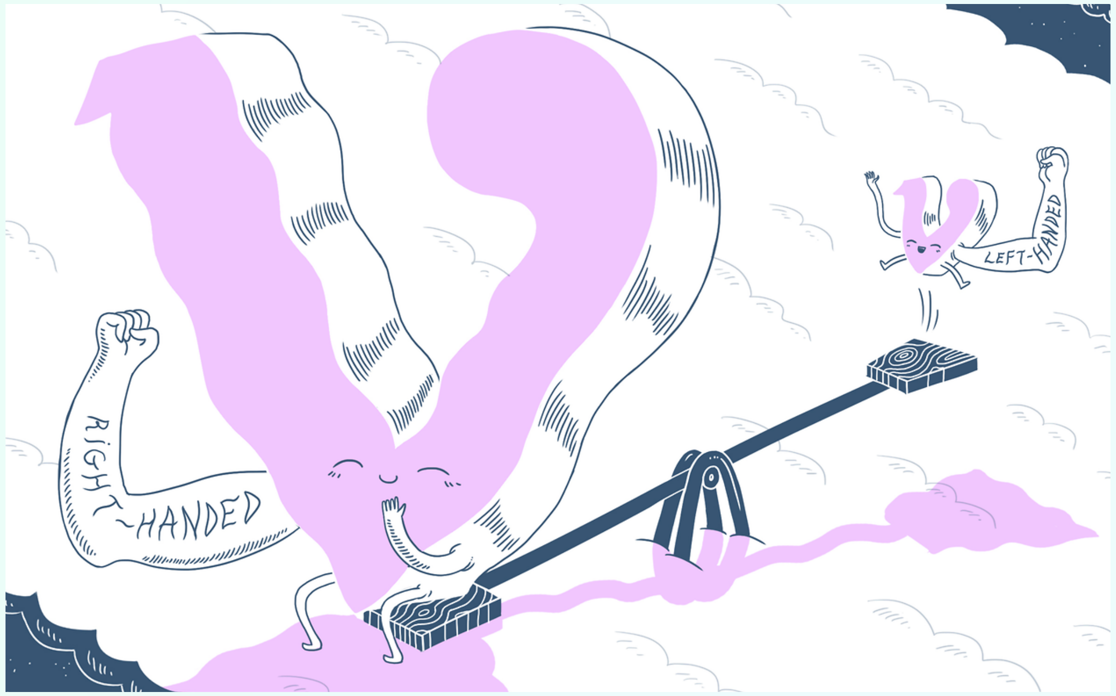
→ **Minimal Massive Majoron Model**

Connects the generation of the active neutrino masses with the ALP and provides a mass m_a

De Giorgi, LM, Ponce, Rigolin, JHEP03 (2024)
(De Giorgi, Fuentes, LM, FP73 (2025))

The Majoron

$$\mathcal{L}_{\text{type-I}} = \overline{\ell_L} H Y_N N_R + \frac{1}{2}\overline{N_R}\Lambda N_R^{c} + \text{h.c.}$$



$$m_\nu \simeq \frac{v^2}{2} Y_N \Lambda^{-1} Y_N^T$$

$$\Lambda \simeq 10^{14} - 10^{15}\text{GeV}$$

$$\mathcal{L}_{\text{majoron}} = \overline{\ell_L} H Y_N N_R + \frac{1}{2}\overline{N_R} Y_{NN}\phi N_R^{c} + \text{h.c.}$$

$$\phi = \frac{\rho + f_a}{\sqrt{2}} e^{ia/f_a}$$

$$\begin{cases} \Lambda = Y_{NN}\dfrac{f_a}{\sqrt{2}} \\ f_a \simeq 10^{14} - 10^{15}\text{GeV} \end{cases}$$

Dynamical neutrino mass generation!

The Majoron

$$\phi = \frac{\rho + f_a}{\sqrt{2}} e^{ia/f_a}$$ → a Majoron: GB of LN SSB

Within this minimal setup, a Majoron mass could be generated by gravity:

$$V_{\text{grav.}} = g \frac{\phi^n}{M_{\text{Pl}}^{n-4}}$$

Akhmedov et al., PLB299 (1993)
Babu et al., NPB403 (1993)
Alonso & Urbano, JHEP02 (2019)

- not precise - free coefficients
- Majoron mass independent from other parameters, but expected to be tiny due to Planck mass.

Non minimal Seesaw mechanisms provide an alternative, where gravity does not play any role!

Low-Scale Seesaws

Generic neutral lepton mass Lagrangian:

$$-\mathcal{L}_{\nu N} \supset \frac{1}{2}\overline{\chi_L}\mathcal{M}_\chi \chi_L^c \qquad \chi_L^T = \begin{pmatrix}\nu_L & N_R^c & S_R^c\end{pmatrix}$$

$$L(N_R) = L(S_R) \longrightarrow \mathcal{M}_\chi^{\text{type-I}} = \begin{pmatrix} 0 & m_D \\ m_D^T & \Lambda \end{pmatrix}$$

$$m_\nu \simeq m_D \Lambda^{-1} m_D^T$$

$$L(N_R) \neq L(S_R) \longrightarrow \mathcal{M}_\chi^{\text{LSS}} = \begin{pmatrix} 0 & m_N & \epsilon m_S \\ m_N^T & 0 & m_{NS} \\ \epsilon m_S^T & m_{NS} & 0 \end{pmatrix}$$

Mohapatra, PRL56 (1986)
Mohapatra & Valle, PRD34 (1986)

$$m_\nu^{\text{LSS}} \simeq \epsilon \frac{m_S m_N^T + m_N m_S^T}{m_{NS}}$$

$$\epsilon m_S \sim 10\text{eV} \qquad m_{NS} \sim 1\text{TeV}$$

Low-Scale Seesaws

$$L(N_R) \neq L(S_R)$$

$$\mathcal{M}_\chi^{\rm LSS} = \begin{pmatrix} 0 & m_N & \epsilon m_S \\ m_N^T & 0 & m_{NS} \\ \epsilon m_S^T & m_{NS} & 0 \end{pmatrix}$$

$$m_\nu^{\rm LSS} \simeq \epsilon \frac{m_S m_N^T + m_N m_S^T}{m_{NS}}$$

$$\epsilon m_S \sim 10 \mathrm{eV} \qquad m_{NS} \sim 1 \mathrm{TeV}$$

Low-scale HNLs, but at the price of a small explicit breaking!

(ϵ could also be a SSB)

De Romeri et al., JHEP10 (2017)

$$\mathcal{M}_\chi^{\rm ISS} = \begin{pmatrix} 0 & m_N & 0 \\ m_N^T & 0 & m_{NS} \\ 0 & m_{NS} & \epsilon m_{SS} \end{pmatrix}$$

Akhmedov et al., PLB368 (1996)

Malinsky et al., PRL95 (2005)

$$m_\nu^{ISS} \simeq \epsilon m_{SS} \frac{m_N m_N^T}{m_{NS}^2}$$

$$\epsilon m_{SS} \sim 1 \mathrm{keV} \qquad m_{NS} \sim 1 \mathrm{TeV}$$

The MMM Model

The strategy is:

- Identify LN and PQ symmetries
- Promote the LN conserving terms to $U(1)_{\rm PQ}$ SSB terms

$$\overline{N_R} m_{NS} S_R^c \longrightarrow \overline{N_R} Y_{NS} S_R^c \phi$$

- Use the LN explicit breaking terms to also explicitly break $U(1)_{\rm PQ}$

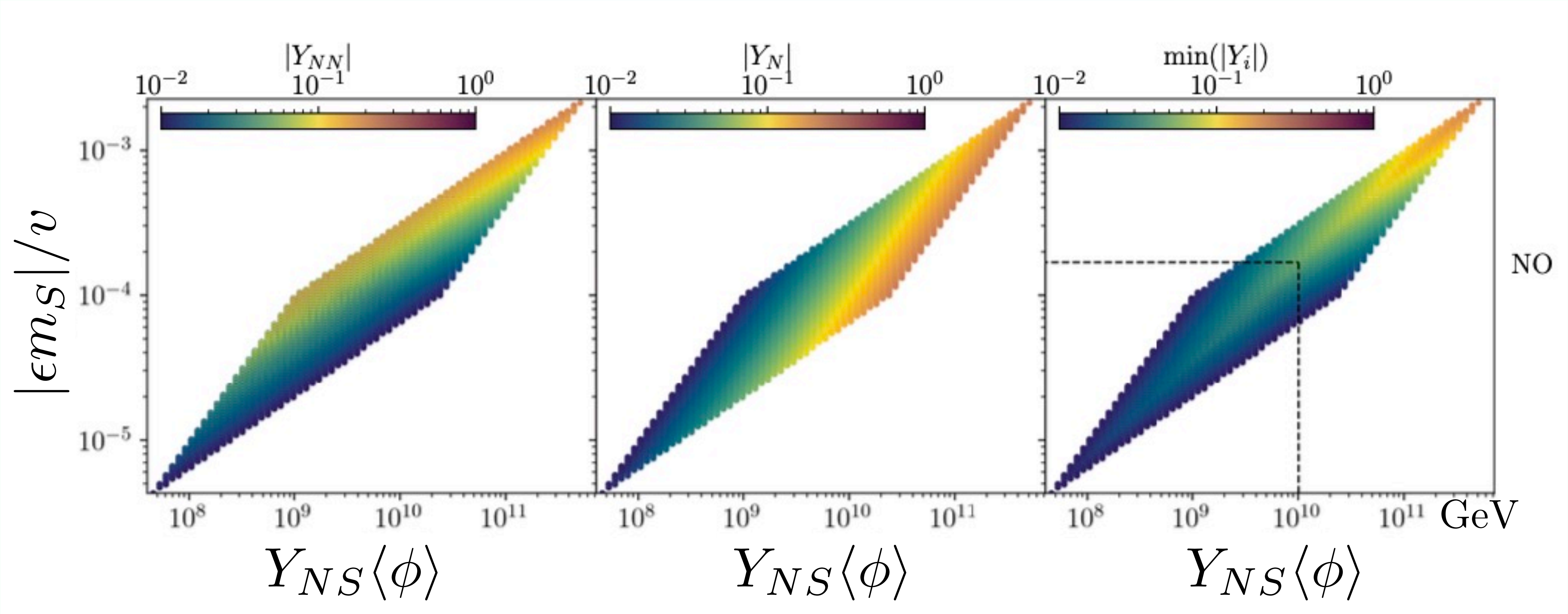
All in all:

$$\mathcal{M}_\chi^{\rm MMM} = \begin{pmatrix} 0 & m_N & \epsilon m_S \\ m_N^T & m_{NN}\langle\phi\rangle & Y_{NS}\langle\phi\rangle \\ \epsilon m_S^T & Y_{NS}^T\langle\phi\rangle & 0 \end{pmatrix}$$

$$m_\nu^{\rm MMM} \simeq \epsilon \frac{m_S m_N^T + m_N m_S^T}{Y_{NS}\langle\phi\rangle} + \epsilon^2 \frac{Y_{NN}}{Y_{NS}} \frac{m_S m_S^T}{Y_{NS}\langle\phi\rangle}$$

The MMM Model

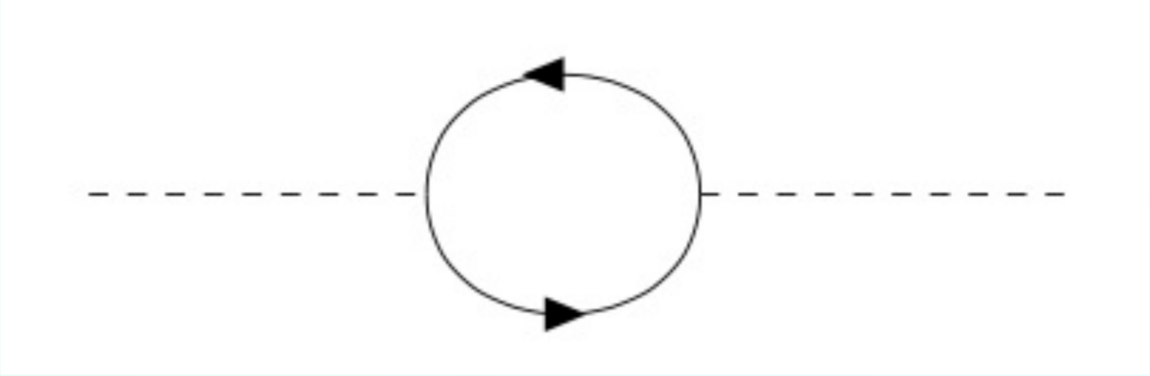
$$m_\nu^{\rm MMM} \simeq \epsilon \frac{m_S m_N^T + m_N m_S^T}{Y_{NS}\langle\phi\rangle} + \epsilon^2 \frac{Y_{NN}}{Y_{NS}} \frac{m_S m_S^T}{Y_{NS}\langle\phi\rangle}$$

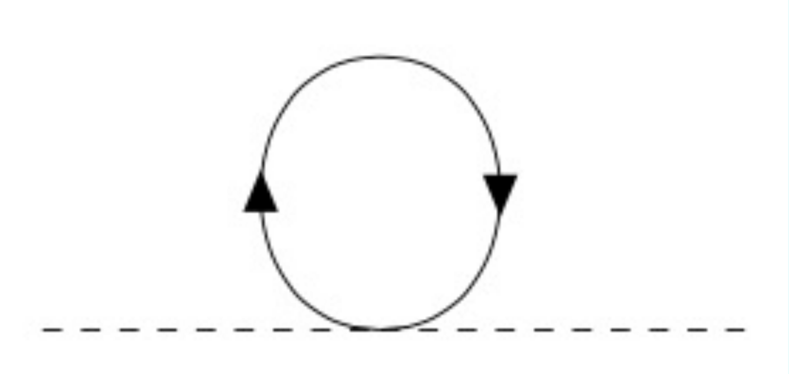


Shaded region agrees with active neutrino oscillation data.

The MMM Model

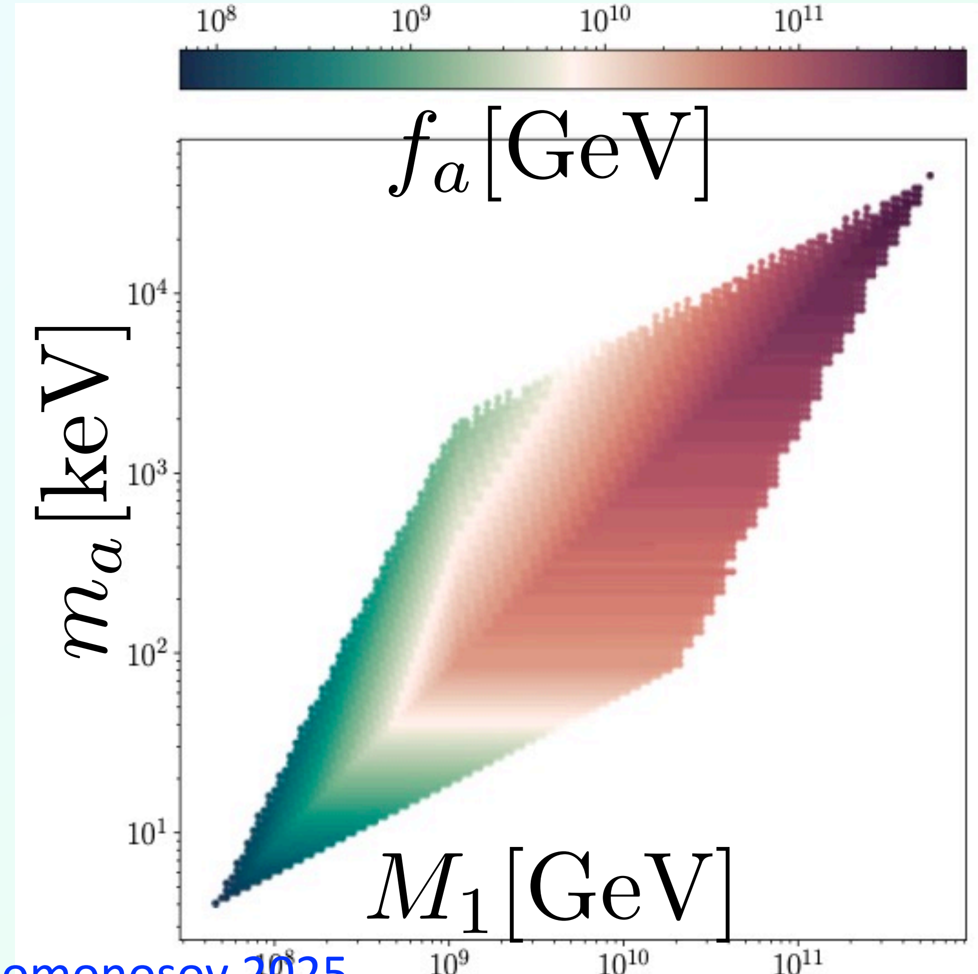
The Majaron mass is given by





$$m_a^2 \sim \epsilon \frac{v^2}{\pi^2} \ll f_a^2$$

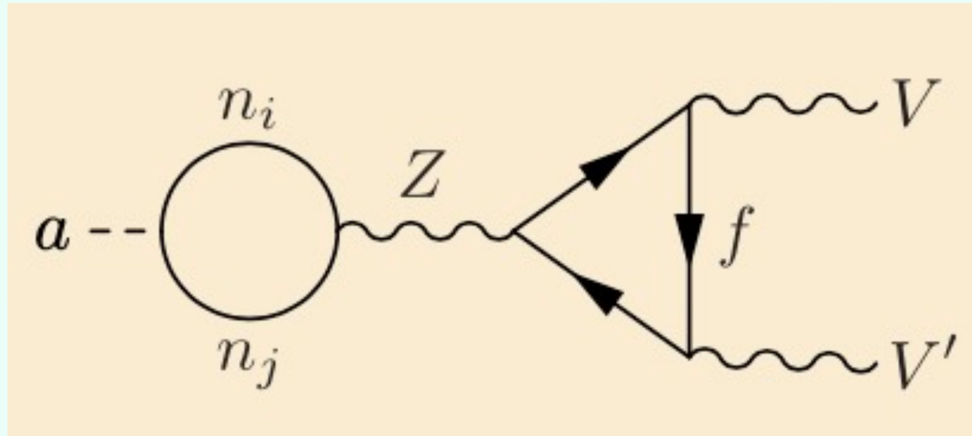
The suppression is due to neutrino mass dependence!

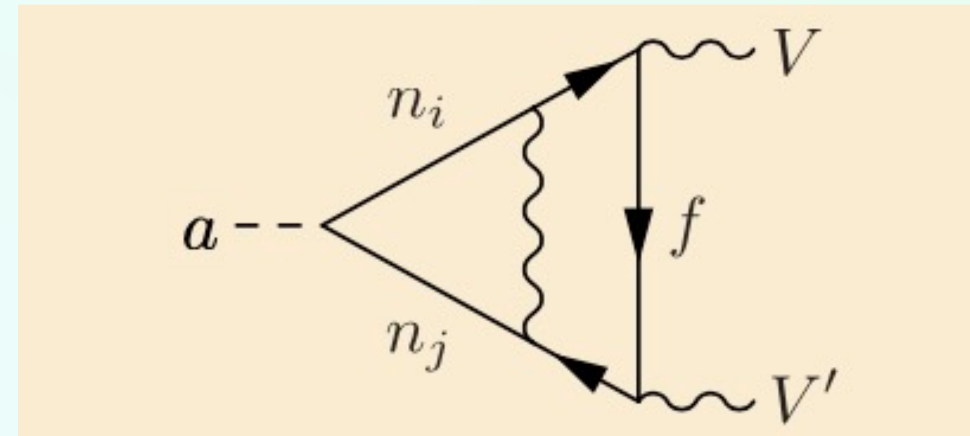


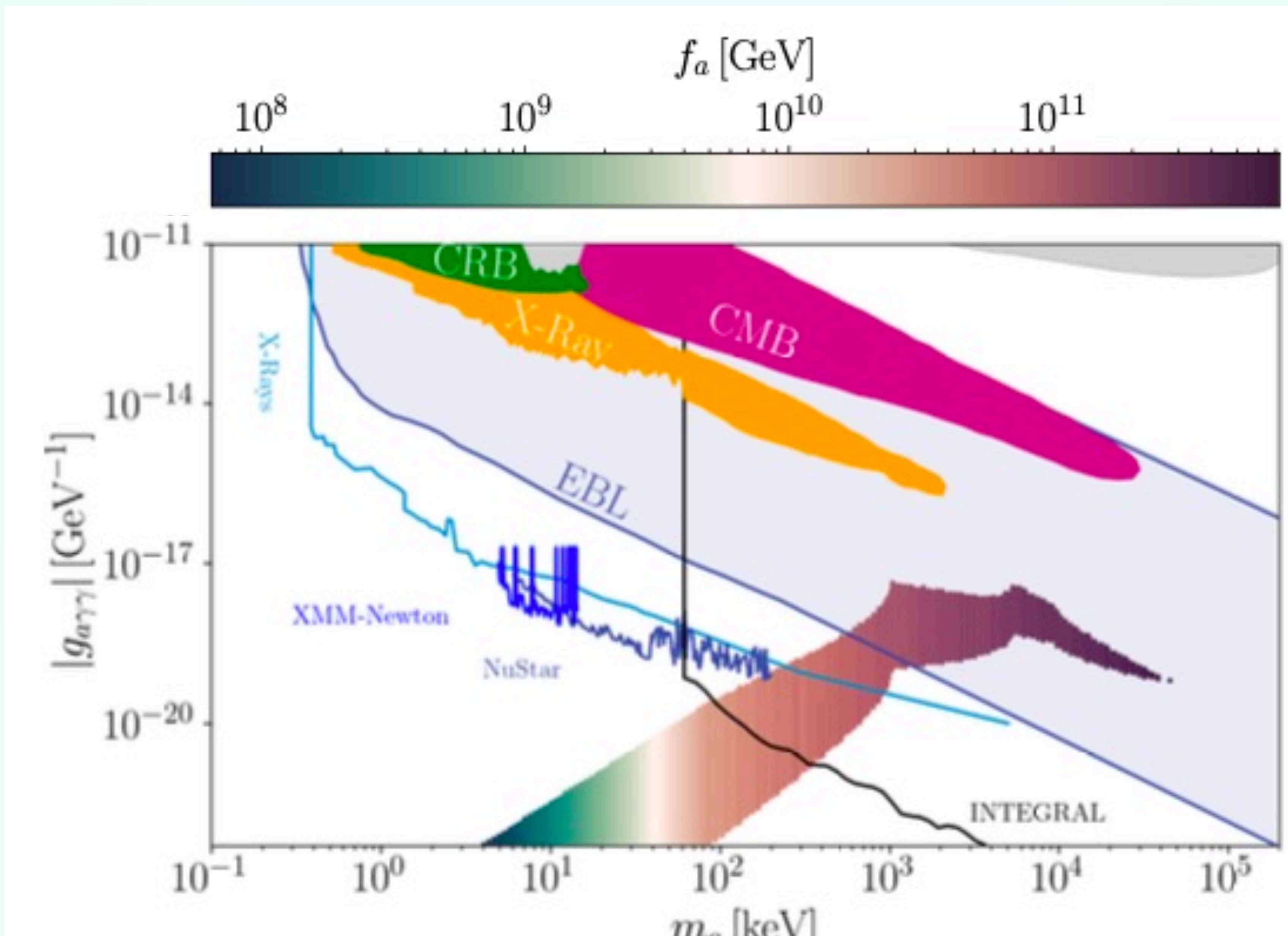
$$\begin{cases} f_a \sim [10^8,\, 10^{11}]\ \text{GeV} \\ m_a \sim [1\ \text{keV},\, 10\ \text{MeV}] \end{cases}$$

The MMM Model

Coupling $a\gamma\gamma$



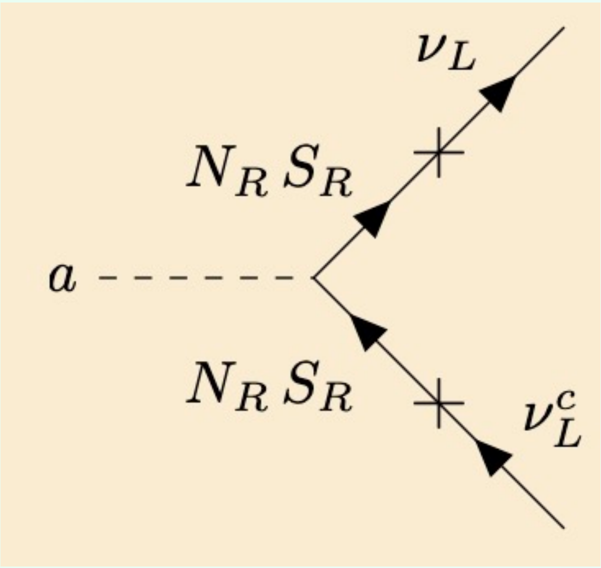


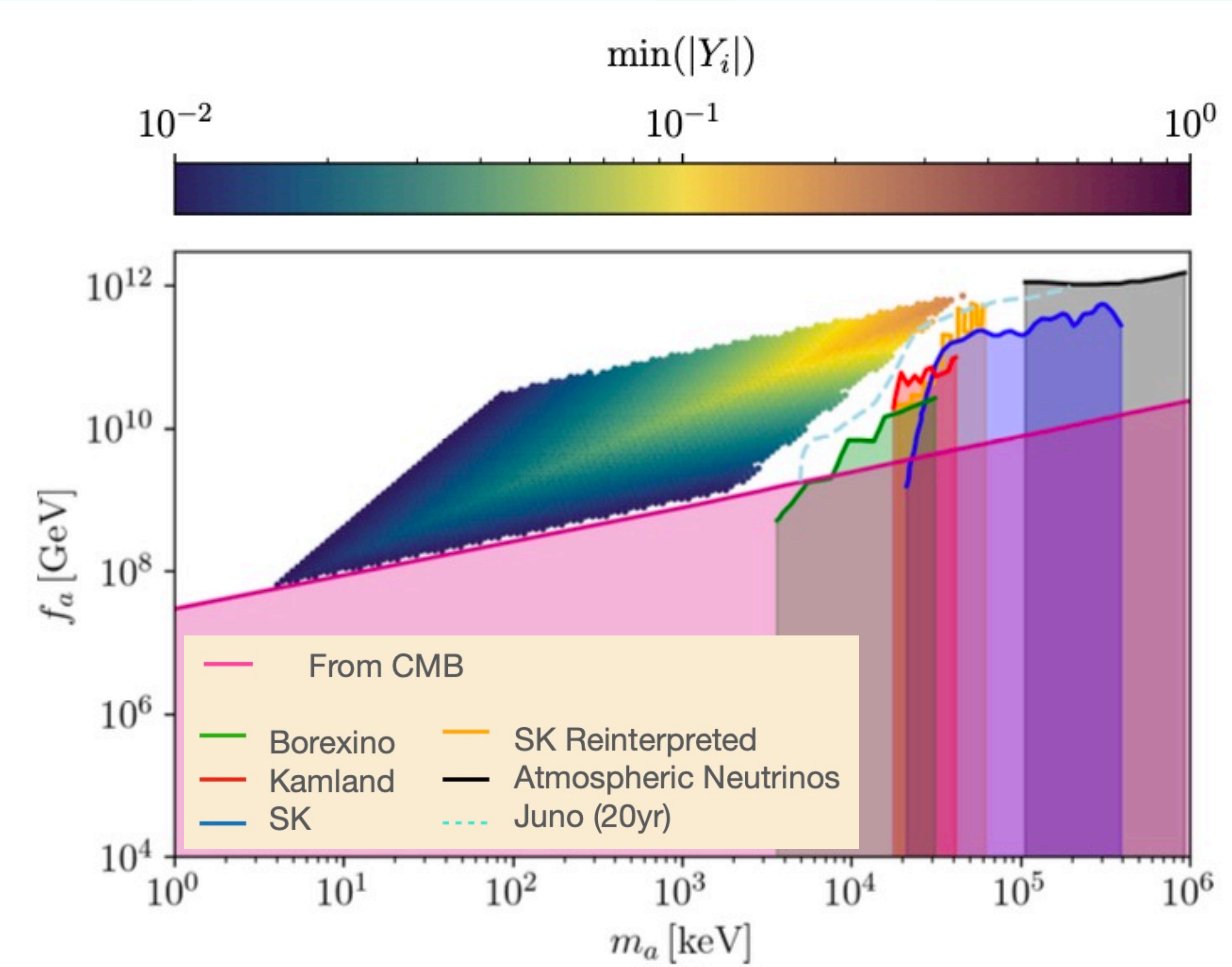


Luca Merlo, Mass Generation for ALPs, Lomonosov 2025

DM Candidate?

Coupling $a\nu\nu$





Possible DM Candidate!

Conclusions

- Axion and ALP physics is a very active research topic at the moment
- Great results from the experimental collaborations
- Theoreticians advanced a lot in model building and effective description

- ALPs can help understanding the Belle II excess, but
  - ALP mass $m_a = 2\ \mathrm{GeV}$
  - specific UV realisations to guarantee a long lived ALP

- The ALP mass generation is a long standing open problem: the MMM is an example, but it is just the tip of the iceberg:
  - MMM could be testable soon and it is a possible DM candidate
  - MMM does not help with the Belle II excess (too light)
  - Other textures may work

Thanks