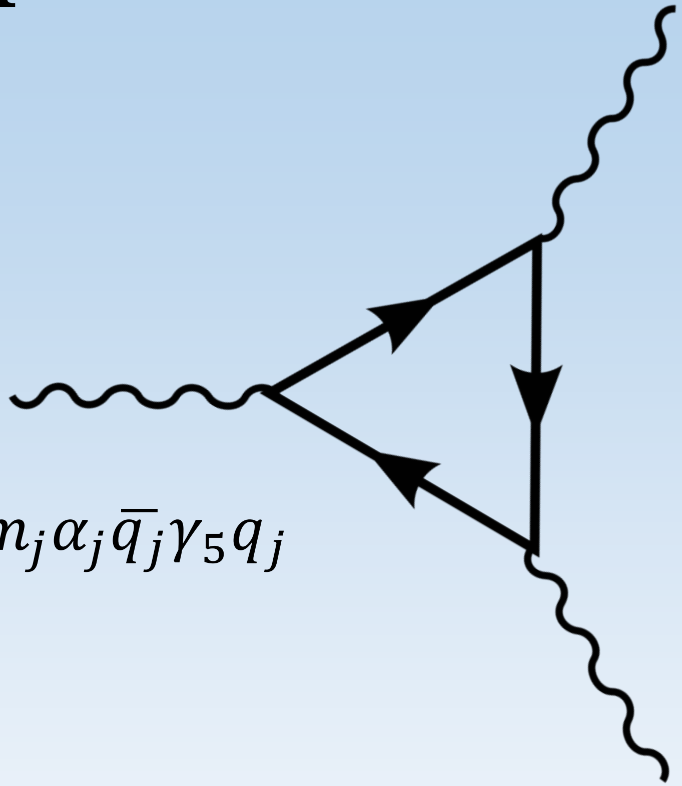
The Minimal Flavour Violating Axion

Based on: 1709.07039, FAA, L. Merlo.
To appear, FAA, F. D’Eramo, L. Merlo, A. Notari, R. Zambujal Ferreira.

Fernando Arias Aragón
fernando.arias@uam.es

The Strong CP Problem



- Two sources of CP violation in the SM:
  - Non-vanishing gluon field CP violating configuration.

$$L_{QCD} \supset -\theta_{QCD} \frac{g_s^2}{32\pi^2} G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

  - Complex phase in the CKM matrix.

$$\bar{q}Mq = m_j \cos\alpha_j \, \bar{q}_j q_j - i m_j \sin\alpha_j \, \bar{q}_j \gamma_5 q_j \approx m_j \bar{q}_j q_j - i m_j \alpha_j \bar{q}_j \gamma_5 q_j$$

- The observable theta parameter is thus:

$$\bar{\theta} = \theta_{QCD} + Arg(det(M))$$

- This CP violating term implies a NEDM

Crewther, Di Vecchia, Veneziano & Witten, 1980

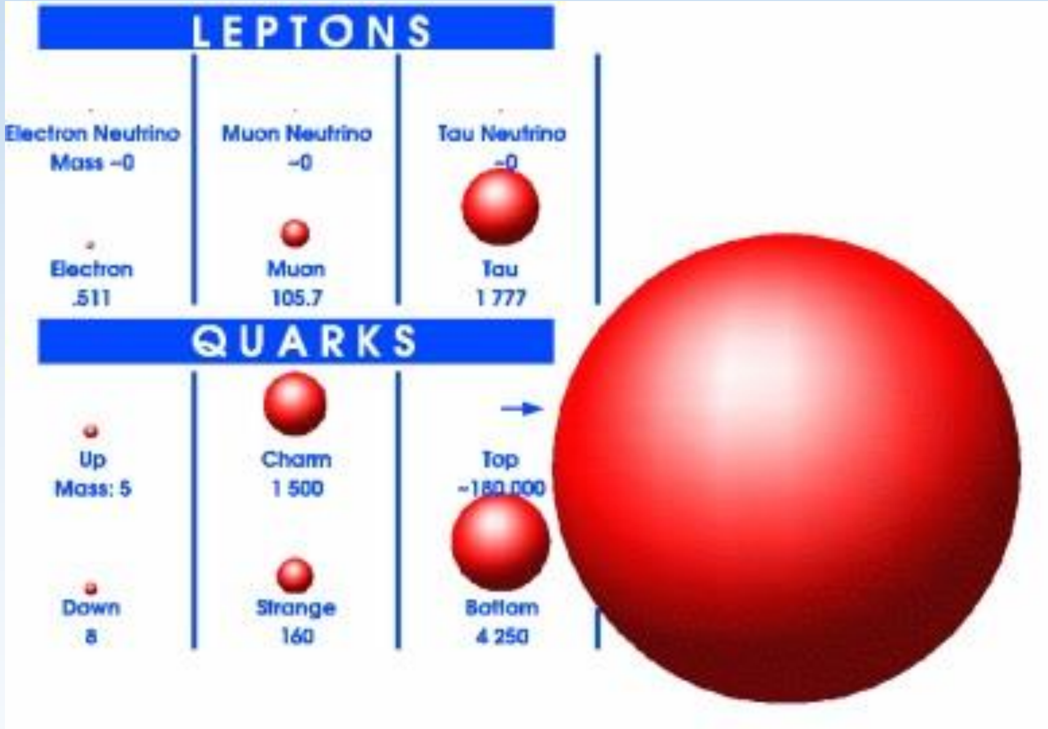
$$\text{SM} \rightarrow d_n \sim \bar{\theta} \cdot O(10^{-16}) \; e \cdot cm$$

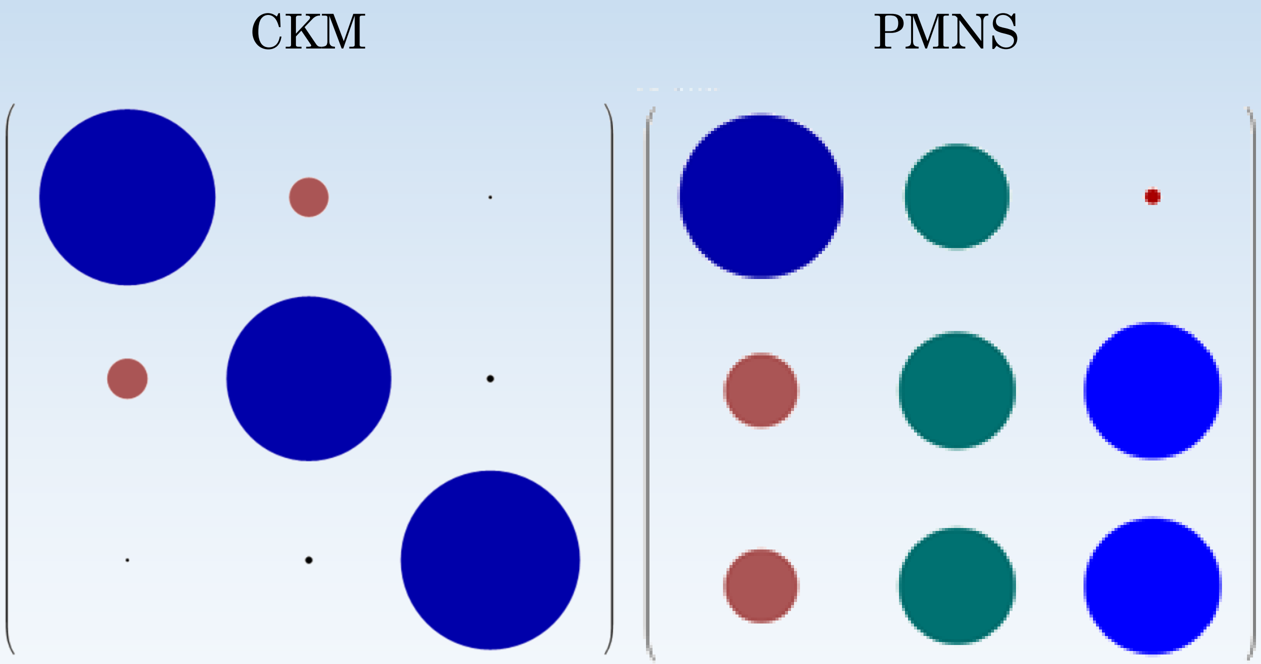
Baker et al., 0602020 Afach et al., 1509.04411

$$EXP \rightarrow \; d_n < 0{,}30 \cdot 10^{-25} \; e \cdot cm \Rightarrow \; \bar{\theta} \leq 10^{-10}$$

The Flavour Puzzle

- Fermion Yukawas, expected to be order one, are spread through a large range of values.





Scenario: Minimal Flavour Violation

R. S. Chivukula and H. Georgi, PLB **188**, 99-104 (1987)

- Only Yukawas violate flavour symmetry.
- Flavour symmetry group identified in the limit of vanishing Yukawas (D'Ambrosio et al, 020736; Cirigliano et al, 0507001):

$$\mathcal{G}_F = SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R} \times SU(3)_{L_L} \times SU(3)_{e_R} \times U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{PQ} \times U(1)_{e_R}$$

- Interfamily masses reproduced with non-Abelian symmetries.

$$\mathcal{Y}_u \sim (3, \bar{3}, 1)_{SU(3)_q^3}$$

$$\mathcal{Y}_d \sim (3, 1, \bar{3})_{SU(3)_q^3}$$

- $\frac{m_b}{m_t}$ and $\frac{m_\tau}{m_t}$ explained with $U(1)_{PQ}$.

The Minimal Flavour Violating Axion

FAA & Merlo, 1709.07039

- Generation independent charges → flavour conserving, but non universal, couplings to fermions.

$$\mathscr{L}_Y = \left(\frac{\Phi}{\Lambda_\Phi}\right)^{x_d - x_Q} \bar{Q}_L H d_R \mathcal{Y}_d + \left(\frac{\Phi}{\Lambda_\Phi}\right)^{x_u - x_Q} \bar{Q}_L \tilde{H} u_R \mathcal{Y}_u + \left(\frac{\Phi}{\Lambda_\Phi}\right)^{x_e - x_L} \bar{L}_L H e_R \mathcal{Y}_e + h.c.$$

$$\Phi = \frac{\rho + v_\Phi}{\sqrt{2}} e^{ia/v_\Phi}$$

$$Y_u = \left(\frac{v_\Phi}{\sqrt{2}\Lambda_\Phi}\right)^{x_u - x_Q} \mathcal{Y}_u, \quad Y_d = \left(\frac{v_\Phi}{\sqrt{2}\Lambda_\Phi}\right)^{x_d - x_Q} \mathcal{Y}_d, \quad Y_e = \left(\frac{v_\Phi}{\sqrt{2}\Lambda_\Phi}\right)^{x_e - x_L} \mathcal{Y}_e$$

$$Q_L \to Q_L e^{-i x_Q \frac{a}{v_\Phi}} \qquad u_R \to u_R e^{-i x_u \frac{a}{v_\Phi}} \qquad d_R \to d_R e^{-i x_d \frac{a}{v_\Phi}}$$

$$L_L \to L_L e^{-i x_L \frac{a}{v_\Phi}} \qquad e_R \to e_R e^{-i x_e \frac{a}{v_\Phi}}$$

Phenomenology of the MFV Axion

FAA & Merlo, 1709.07039

S0:	$x_q = 0 = x_u = x_\ell\,, \qquad x_d = 3 = x_e$
S1:	$x_q = 0 = x_u\,, \quad x_\ell = 1\,, \quad x_d = 3\,, \quad x_e = 4$

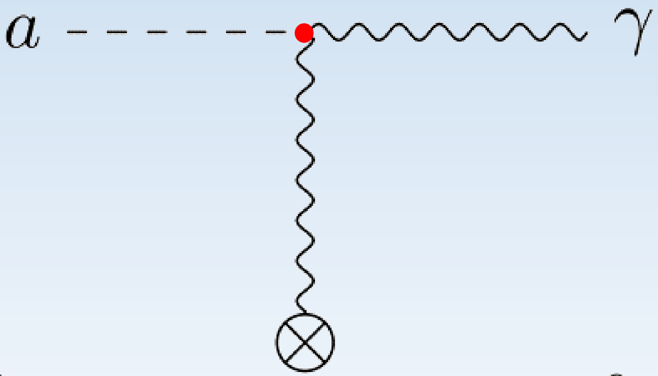
$$f_a = \frac{v_\Phi}{c_{agg}}$$

	x_ℓ	x_e	c_{au}	c_{ad}	c_{ae}	c_{agg}	$c_{a\gamma\gamma}$	c_{aZZ}	$c_{a\gamma Z}$	c_{aWW}
$S0$	0	3	0	-3	-3	-9	-24	-35.8	8.8	-81
$S1$	1	4	0	-3	-3	-9	-24	-35.8	8.8	-81

Jaeckel and Spannowsky, 1509.00476; Bauer et al., 1708.00443

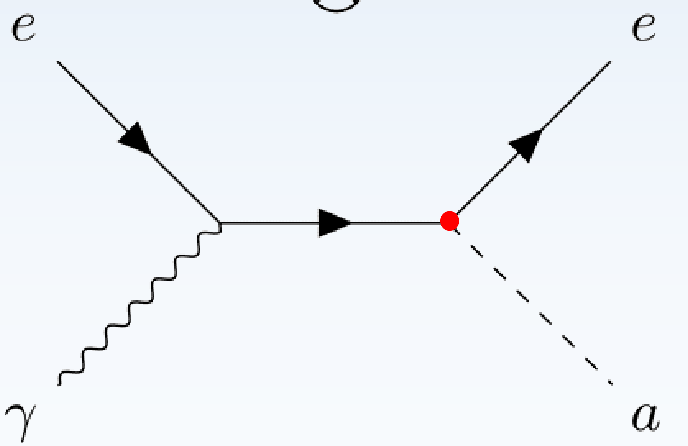
- Astrophysical and cosmological bounds on photon coupling

$f_a \gtrsim 1.2 \times 10^7$ GeV	for $m_a \lesssim 10$ meV
$f_a \gtrsim 8.7 \times 10^6$ GeV	for $10 \text{ meV} \lesssim m_a \lesssim 10$ eV
$f_a \gg 8.7 \times 10^8$ GeV	for $10 \text{ eV} \lesssim m_a \lesssim 0.1$ GeV
$f_a \gtrsim 3$ GeV	for $0.1 \text{ GeV} \lesssim m_a \lesssim 1$ TeV



- Astrophysical bounds on electron coupling

$$f_a \gtrsim 3.9 \times 10^8 \text{ GeV for } m_a \lesssim 1 \text{ eV}$$
$$f_a \gtrsim 6.4 \times 10^6 \text{ GeV for } 1 \text{ eV} \lesssim m_a \lesssim 10 \text{ MeV}$$

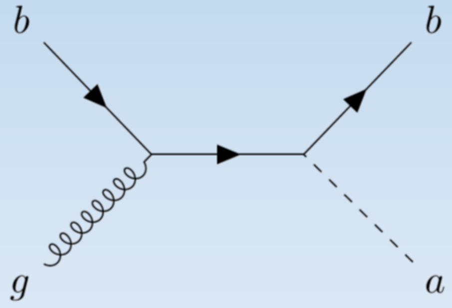


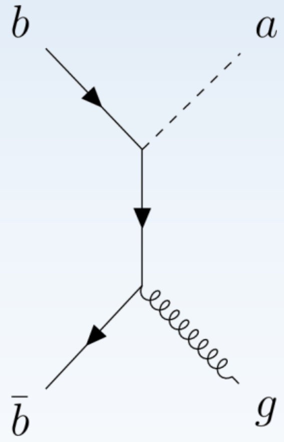
Borexino Collaboration, Bellini et al., 1203.6258; Armengaud et al. 1307.1488; Viaux et al., 1311.1669

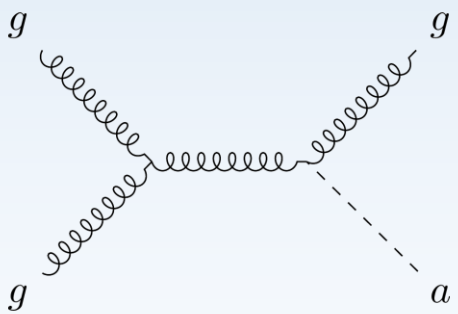
The MFV Axion as Dark Radiation

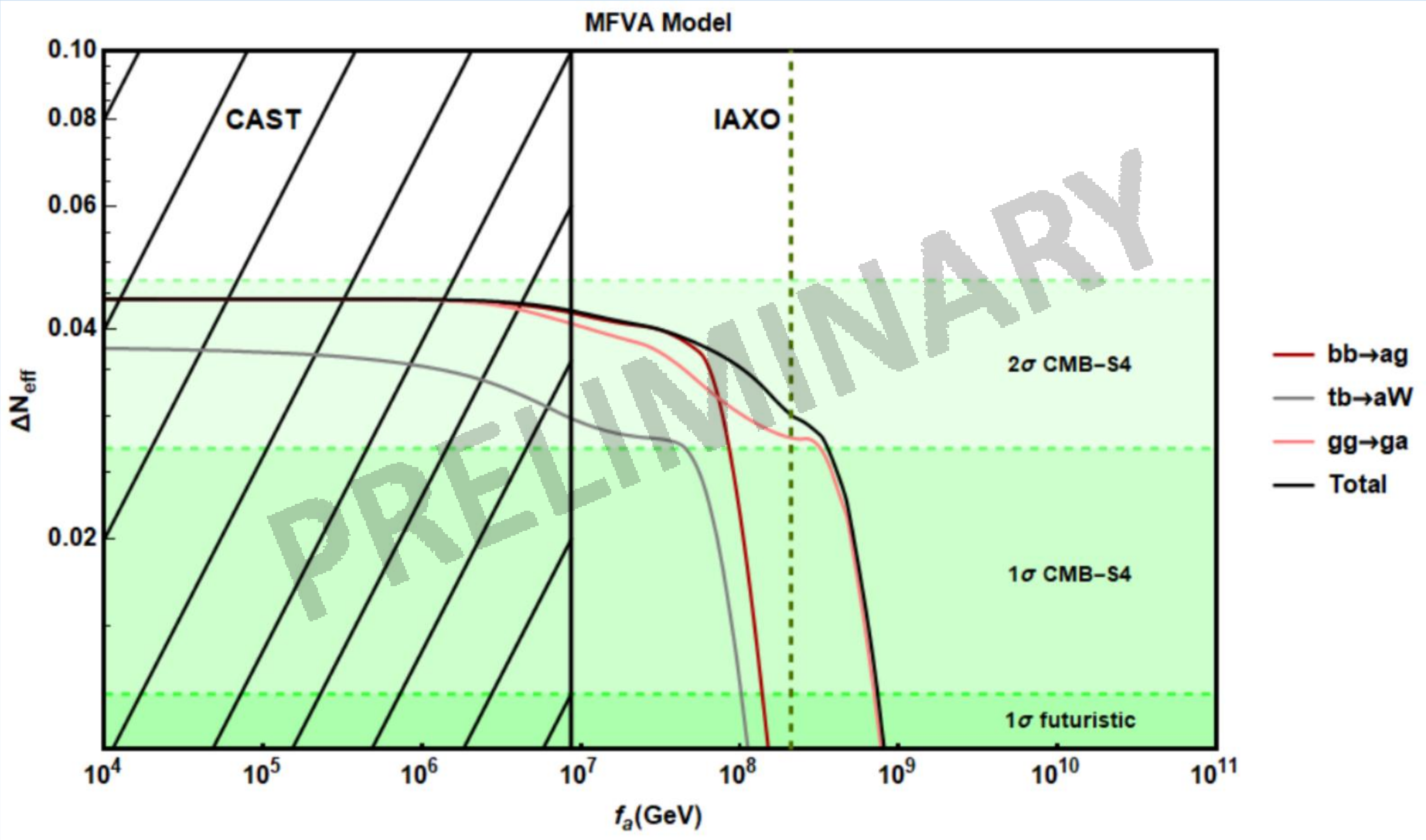
FAA, D'Eramo, Ferreira, Merlo & Notari, to appear

- In the case of a very light axion, its presence can affect N_{eff}









Phenomenology of the MFV ALP

FAA & Merlo, 1709.07039

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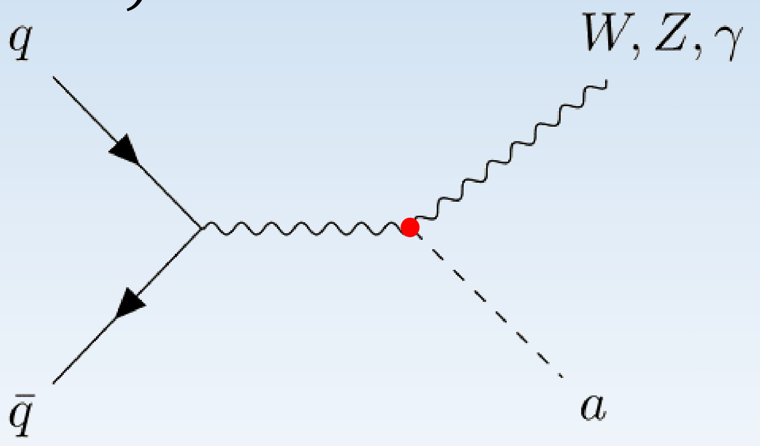
Brivio et al., 1701.05379

- Collider bounds on massive gauge bosons couplings ($m_a \lesssim 1$ GeV)

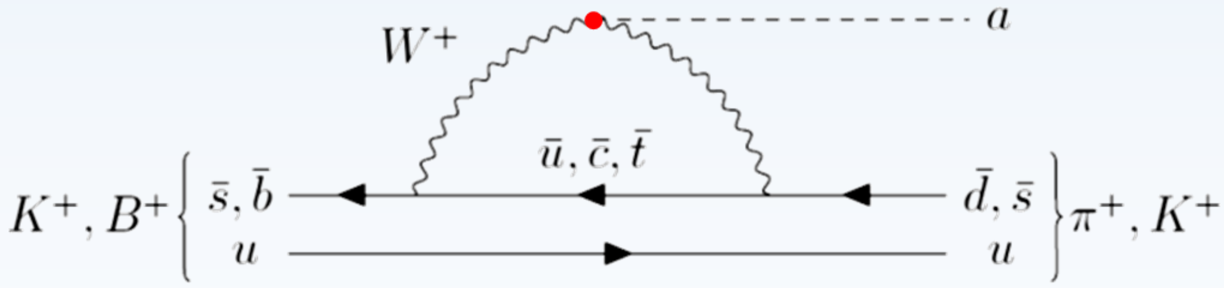
(aWW)	$f_a \gtrsim 6.5$ GeV
(aZZ)	$f_a \gtrsim 5.8$ GeV
$(aZ\gamma)$	$f_a \gtrsim 0.6$ GeV



- Flavour bounds on aWW coupling (only S1)

Izaguirre et al., 1611.09355

$f_a \gtrsim 3.5 \times 10^3$ GeV	for $m_a \lesssim 0.2$ GeV
$f_a \gtrsim 105$ GeV	for $0.2\text{ GeV} \lesssim m_a \lesssim 5$ GeV



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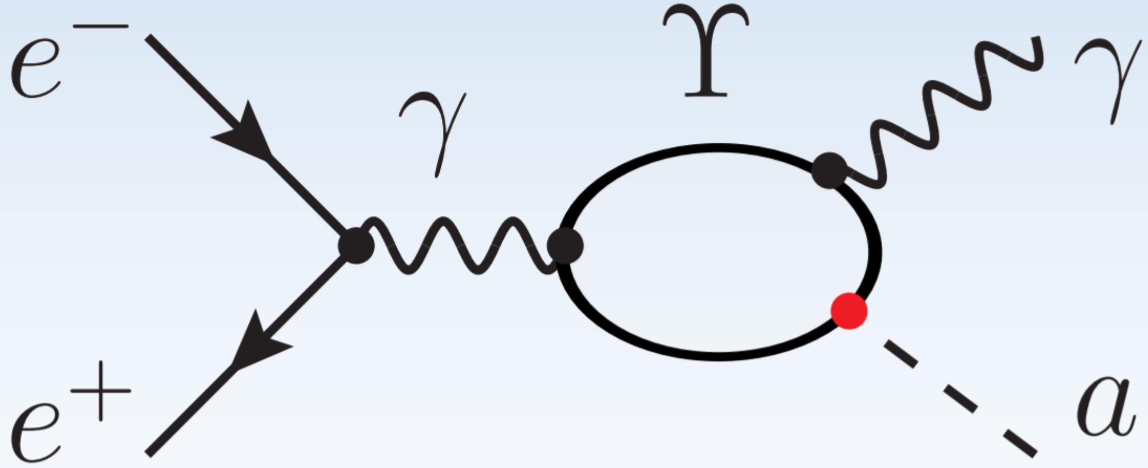
- Flavour bound on bottom coupling through $\Upsilon \to a\gamma$ ($m_a \sim 1$ GeV)

Merlo et al., 1905.03259

$$f_a \gtrsim 830\ \text{GeV}$$



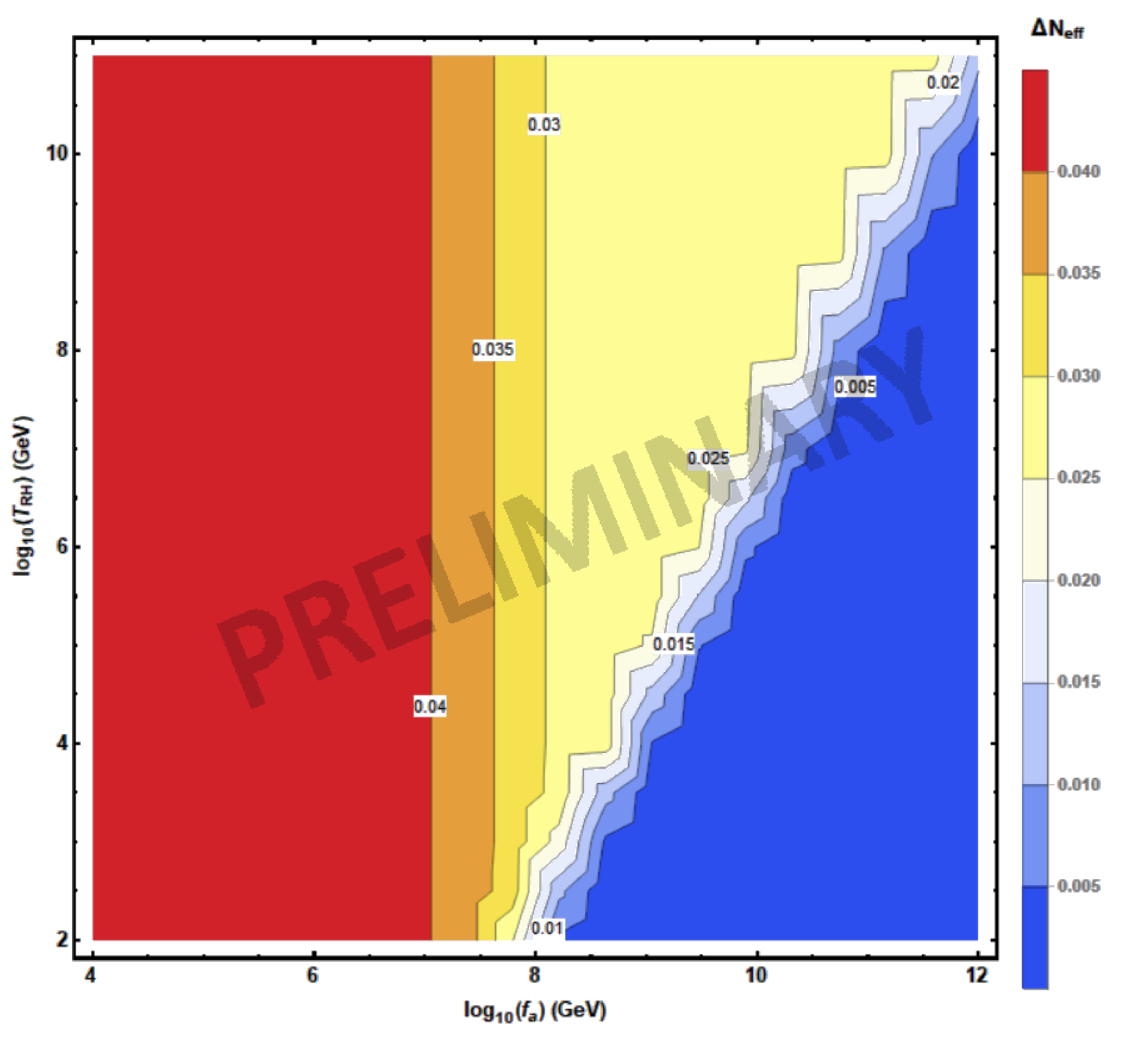
The MFV Axion as Majoron

Y. Chikashige, R. N. Mohapatra, and R. D. Peccei, Phys. Lett. B98 (1981)
J. Schechter and J. W. F. Valle, Phys. Rev. D25 (1982)

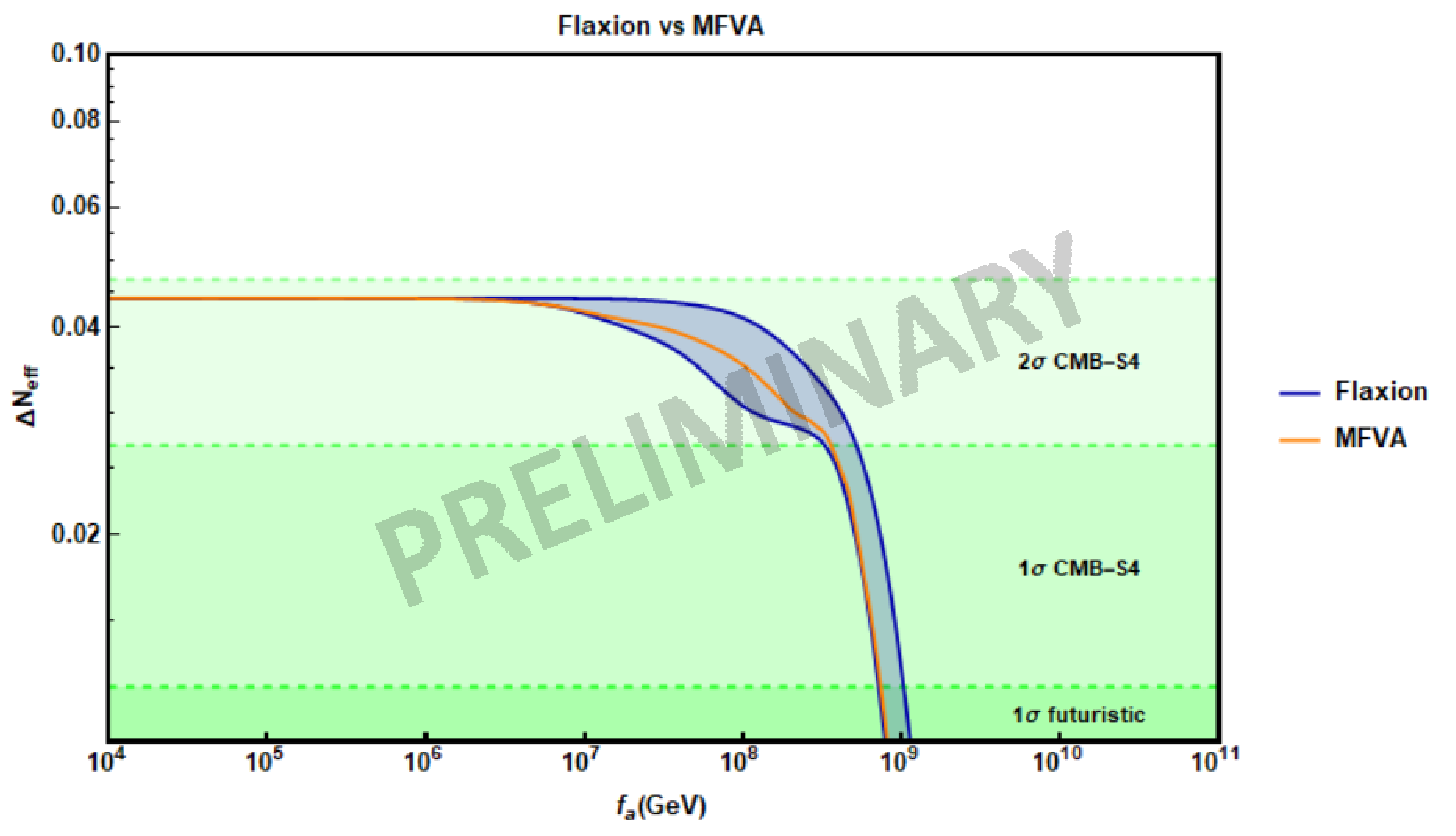
- m_ν? They have to be made invariant
- $U(1)_{PQ} \equiv U(1)_L$
- Minimal Flavour Violating Majoron!
- Phenomenology at $0\nu 2\beta$ decays with Majoron emission

Thank you for your attention

Backup slides



ΔNeff
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.02
0.03
0.035
0.005
0.025
0.015
0.04
0.01
PRELIMINARY
log10(TRH) (GeV)
log10(fa) (GeV)
2
4
6
8
10
12



Flaxion vs MFVA
0.10
0.08
0.06
0.04
0.02
ΔN_{eff}
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
f_a(GeV)
2σ CMB-S4
1σ CMB-S4
1σ futuristic
PRELIMINARY
Flaxion
MFVA

Approaches to solve the Flavour Puzzle

- The Froggatt-Nielsen Mechanism
  - $U(1)_{FN}$ global axial symmetry, spontaneously broken.
  - Powers of breaking scalar fields introduced in the Yukawas.
  - Fermions of different generations have different charges under $U(1)_{FN}$.

$$L_Y \supset \left(\frac{\Phi}{\Lambda}\right)^{-x_{q_i}+x_{u_j}} Y_u \bar{q}_L \widetilde{H} u_R + \left(\frac{\Phi}{\Lambda}\right)^{-x_{q_i}+x_{d_j}} Y_d \bar{q}_L H d_R + h.c.$$

$$m_{f_{ij}} = Y_{f_{ij}} \varepsilon^{-x_{q_i}+x_{f_j}}, \qquad \varepsilon = \frac{\langle\Phi\rangle}{\Lambda}$$

Phenomenology – Axiflavon

- Bounds from flavour processes

$v_\Phi \geq 2 \cdot 10^{11}\ GeV$ (Kaon decay)
$v_\Phi \geq 10^{8}\ GeV$ (B meson decay)

$v_\Phi \geq 1{,}35 \cdot 10^{8}\ GeV$ (D meson decay)
$v_\Phi \geq 1{,}21 \cdot 10^{7}\ GeV$ (D_s meson decay)