The Minimal Flavour Violating Axion as Dark Radiation

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

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The Strong CP Problem

- Non-vanishing gluon field CP violating configuration.

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

- This CP violating term implies a NEDM

Crewther, Di Vecchia, Veneziano & Witten, 1980

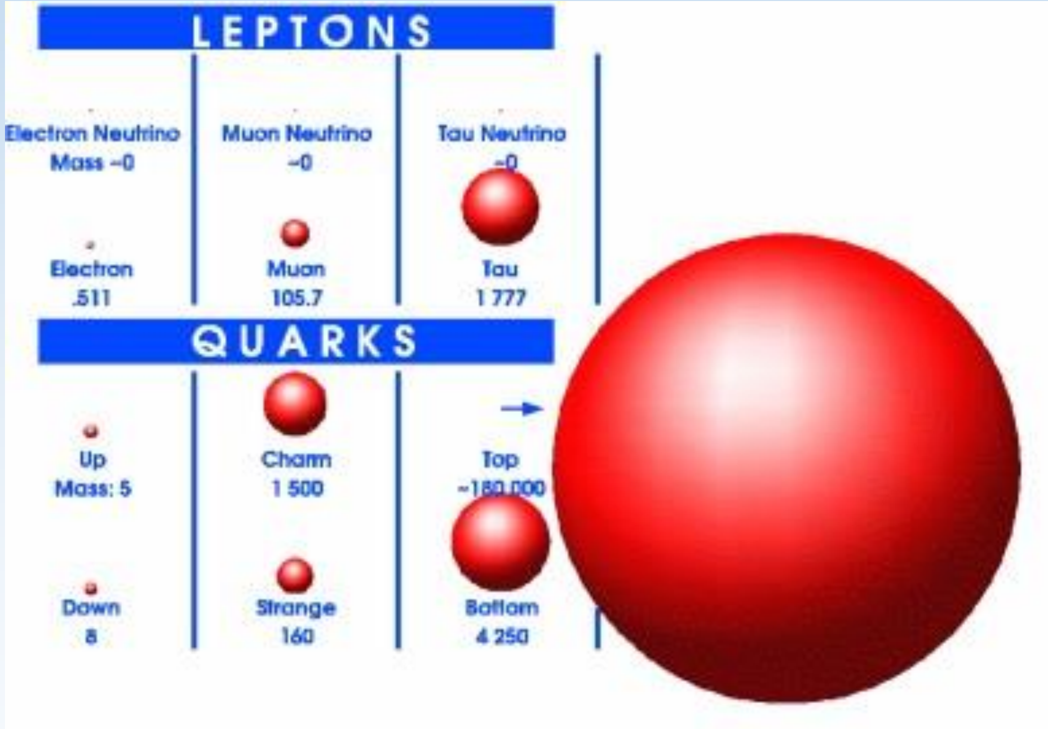
$$\mathrm{SM} \rightarrow d_n \sim \theta \cdot O(10^{-16})\ e \cdot cm$$

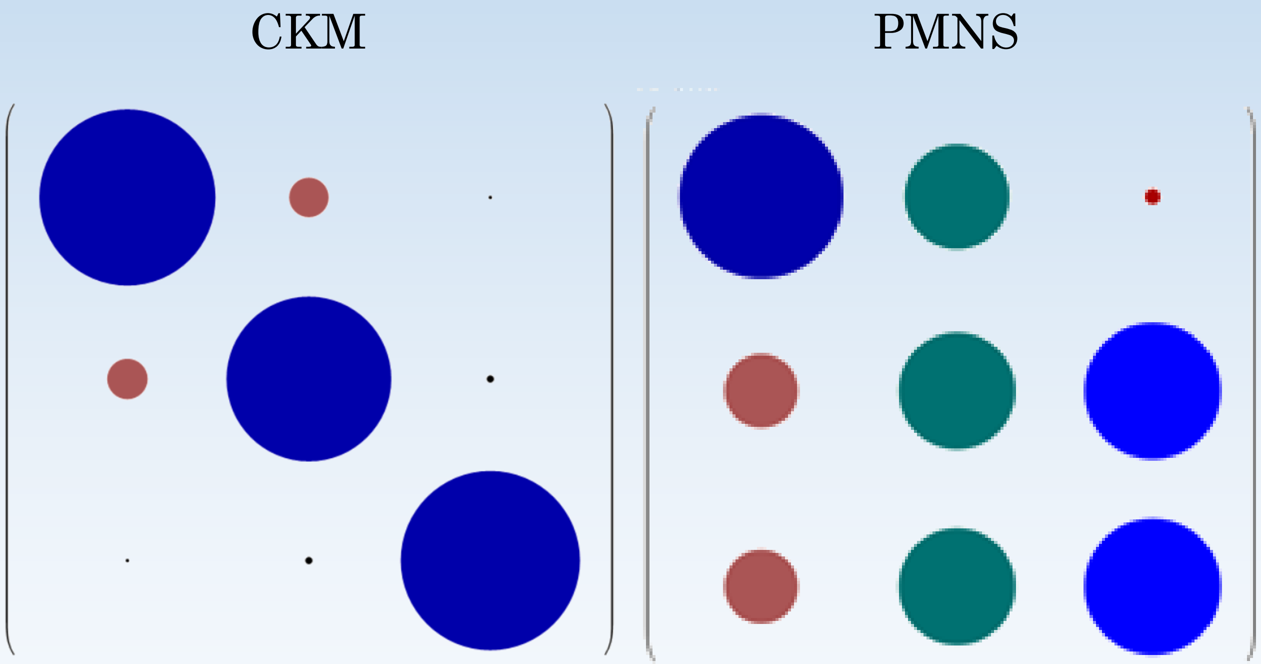
Baker et al., 0602020 Afach et al., 1509.04411

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

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):

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

- Interfamily masses reproduced with non-Abelian symmetries.

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

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

The Minimal Flavour Violating Axion

FAA & Merlo, 1709.07039

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

$$\boxed{Q_L \to Q_L e^{-ix_Q \frac{a}{v_\Phi}}} \qquad \boxed{u_R \to u_R e^{-ix_u \frac{a}{v_\Phi}}} \qquad \boxed{d_R \to d_R e^{-ix_d \frac{a}{v_\Phi}}}$$

$$\boxed{L_L \to L_L e^{-ix_L \frac{a}{v_\Phi}}} \qquad \boxed{e_R \to e_R e^{-ix_e \frac{a}{v_\Phi}}}$$

$$\boxed{\mathscr{L}_Y = \left(\frac{\Phi}{\Lambda_\Phi}\right)^{x_d - x_Q} \bar{Q}_L H \mathcal{Y}_d d_R + \left(\frac{\Phi}{\Lambda_\Phi}\right)^{x_u - x_Q} \bar{Q}_L \tilde{H} \mathcal{Y}_u u_R + \left(\frac{\Phi}{\Lambda_\Phi}\right)^{x_e - x_L} \bar{L}_L H \mathcal{Y}_e e_R + h.c.} \qquad \boxed{\Phi = \frac{\rho + v_\Phi}{\sqrt{2}} e^{ia/v_\Phi}}$$

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

Phenomenology of the MFV Axion

FAA & Merlo, 1709.07039

S0: $x_q = 0 = x_u = x_\ell\,, \qquad x_d = 3 = x_e$

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

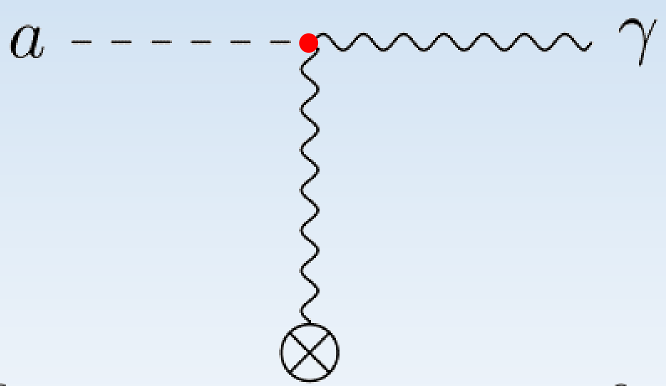
$$f_a = \frac{v_\Phi}{c_{agg}}$$

	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

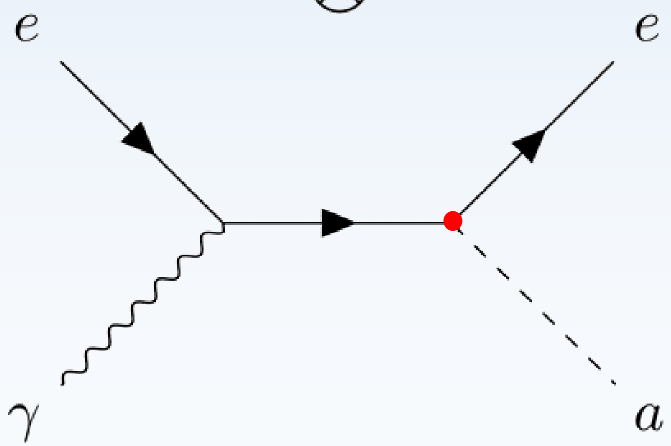
- Astrophysical and cosmological bounds on photon coupling

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



- Astrophysical bounds on electron coupling

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



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

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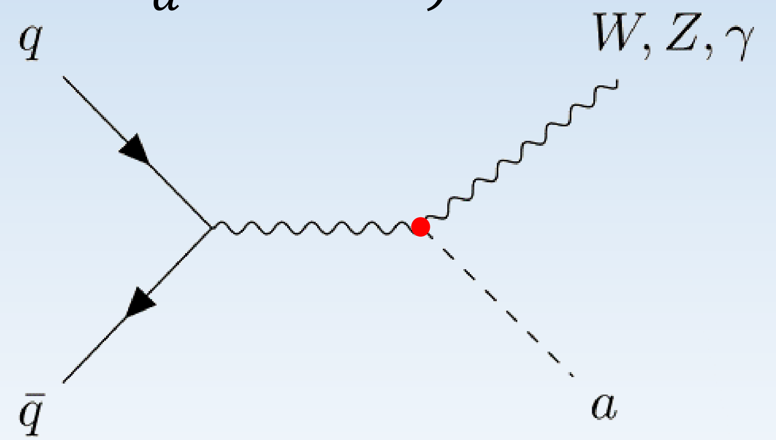
Brivio et al., 1701.05379

- Collider bounds on massive gauge bosons couplings $(0{,}1\ \mathrm{GeV} \lesssim m_a \lesssim 1\ \mathrm{GeV})$

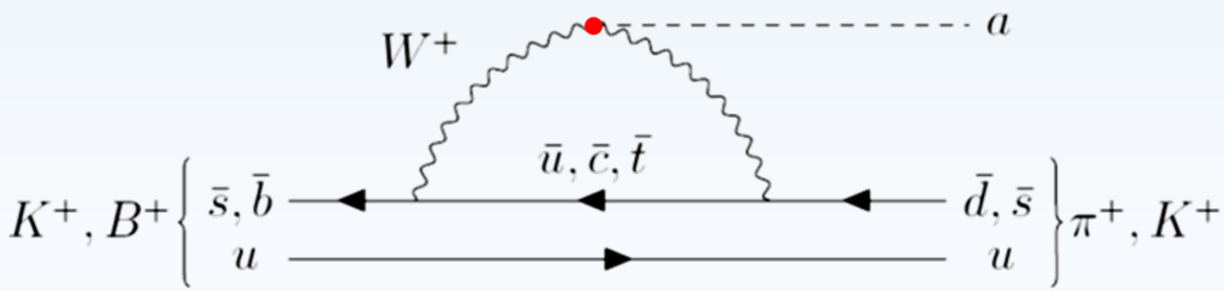
(aWW)	$f_a \gtrsim 6.5$ GeV
(aZZ)	$f_a \gtrsim 5.8$ GeV
$(aZ\gamma)$	$f_a \gtrsim 0.6$ GeV



- Flavour bounds on aWW coupling

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 $0.2\ \mathrm{GeV} \lesssim m_a \lesssim 5$ GeV



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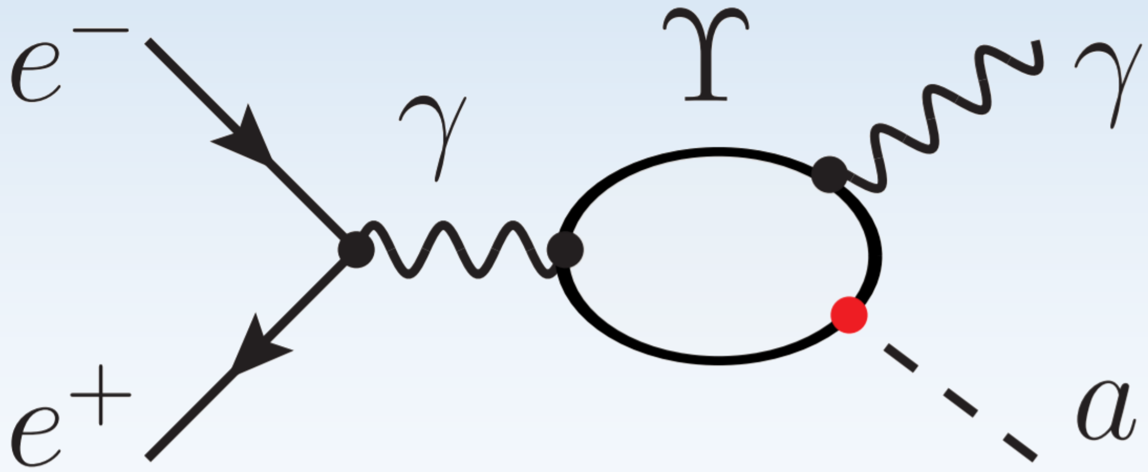
- Flavour bound on bottom coupling through $\Upsilon \to a\gamma$ ($m_a \sim 1$ GeV)

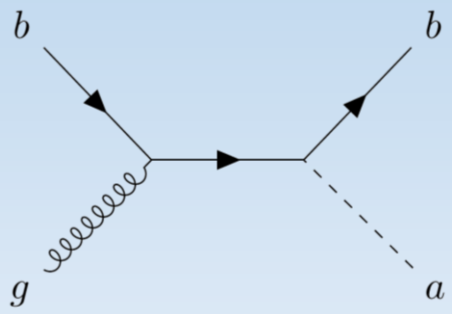
Merlo et al., 1905.03259

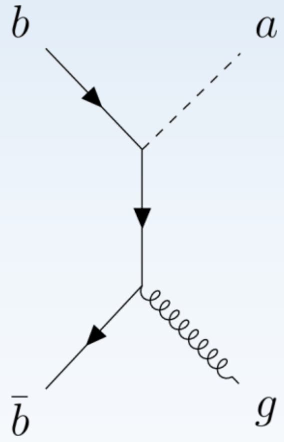
$$\boxed{f_a \gtrsim 830\ \text{GeV}}$$

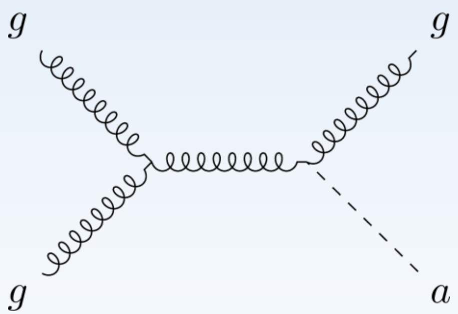


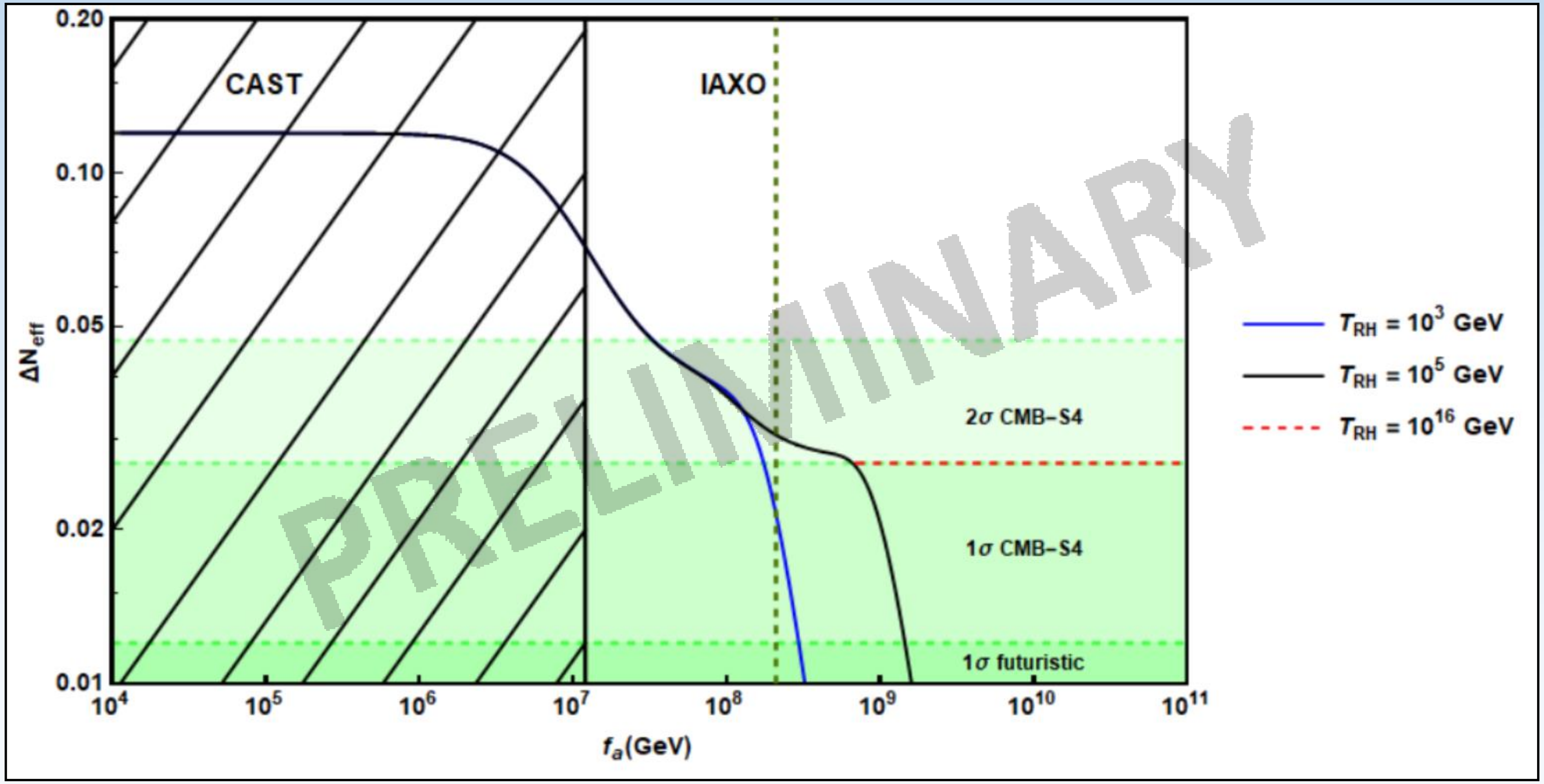
The MFV Axion as Dark Radiation

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









Thank you and see you at the poster session!

Backup slides

The MFV Axion as Dark Radiation

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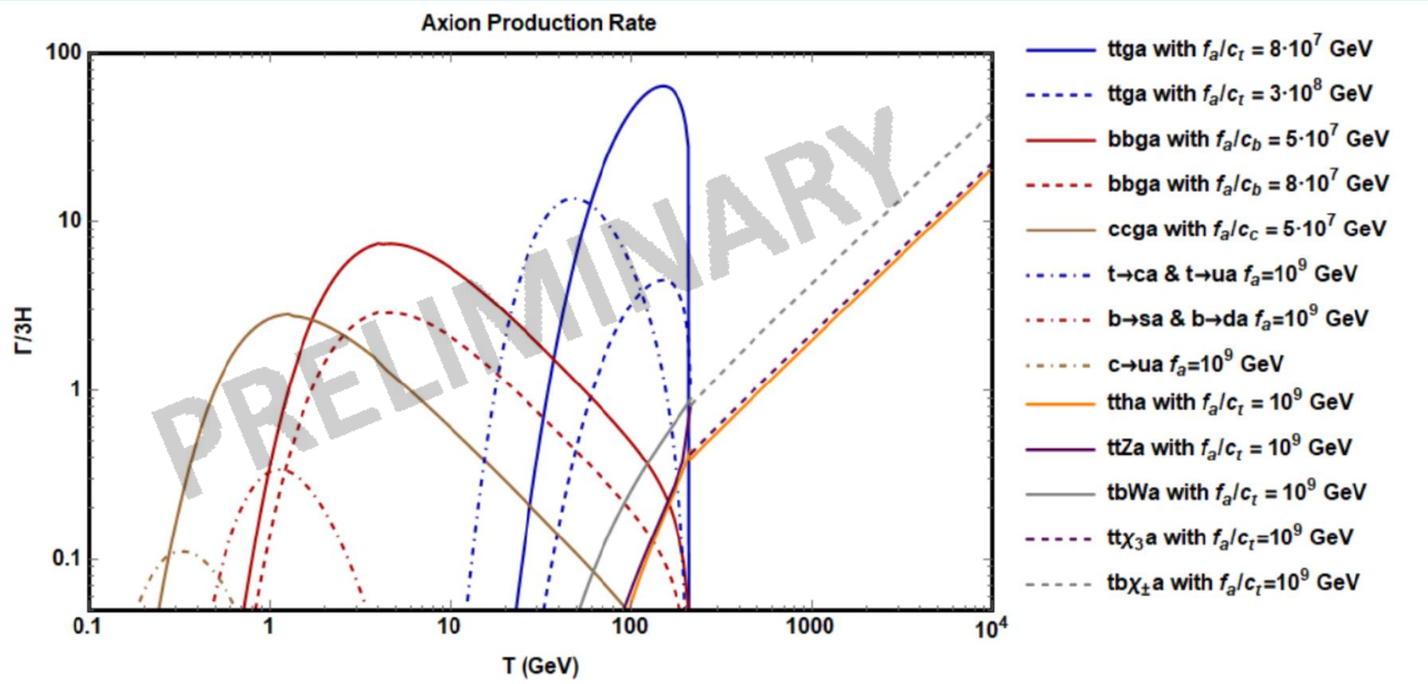
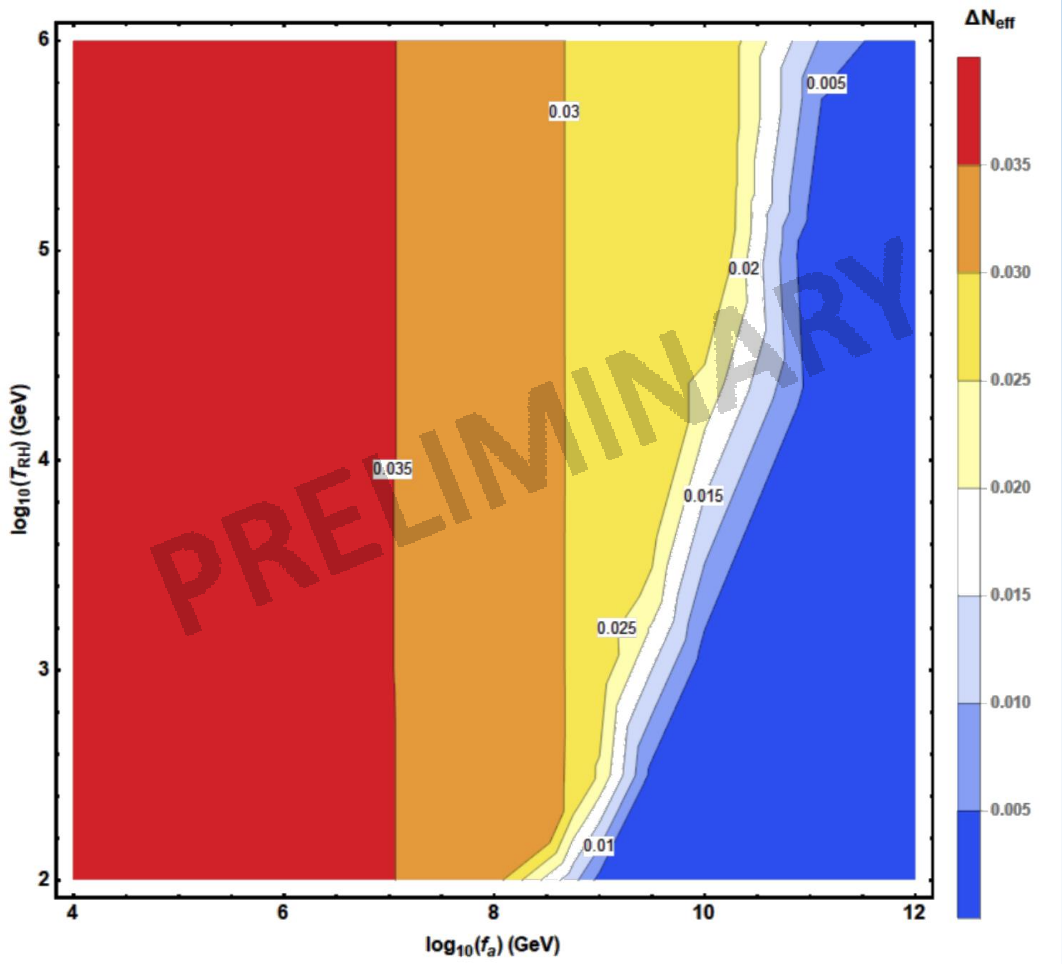
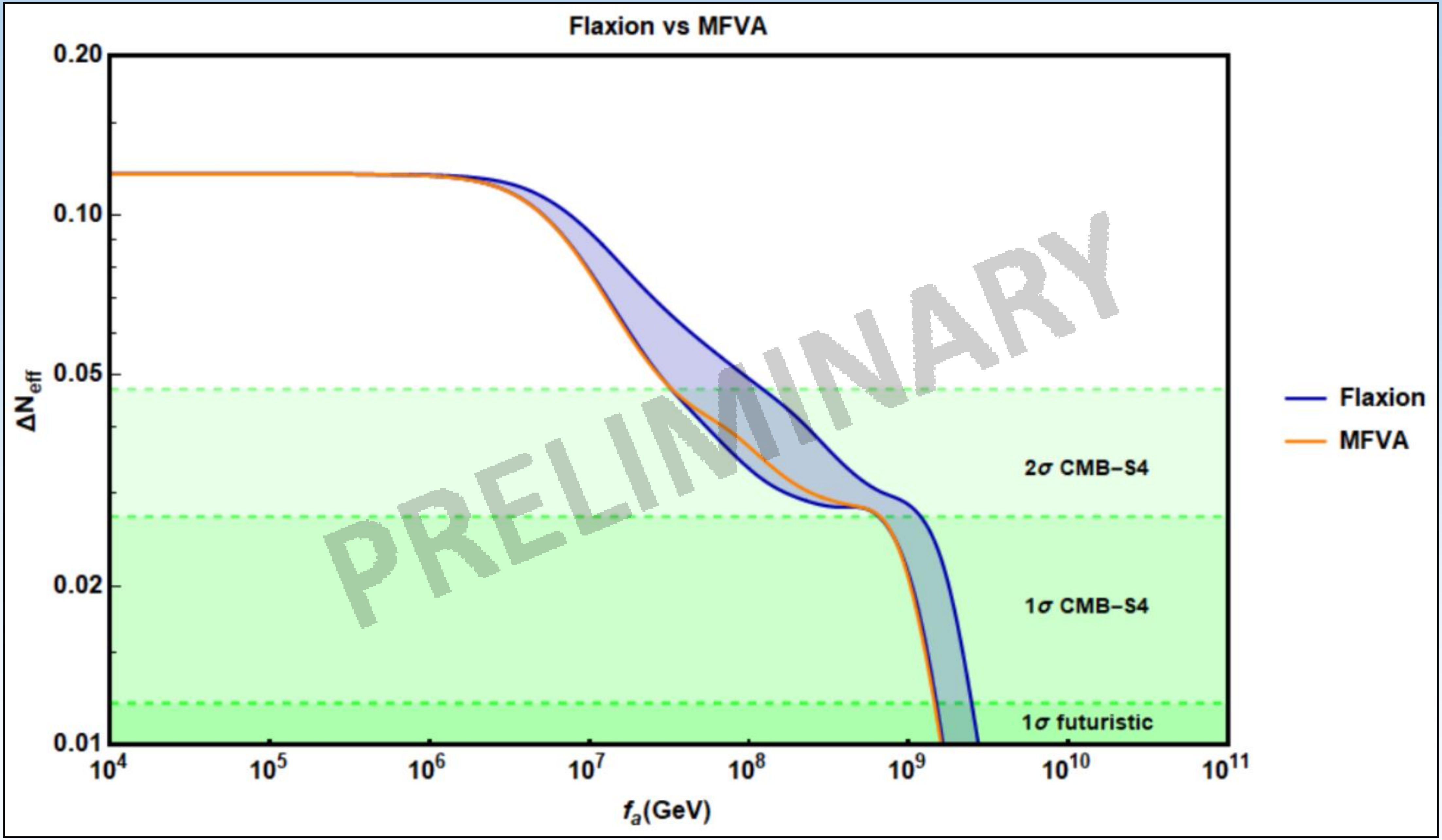
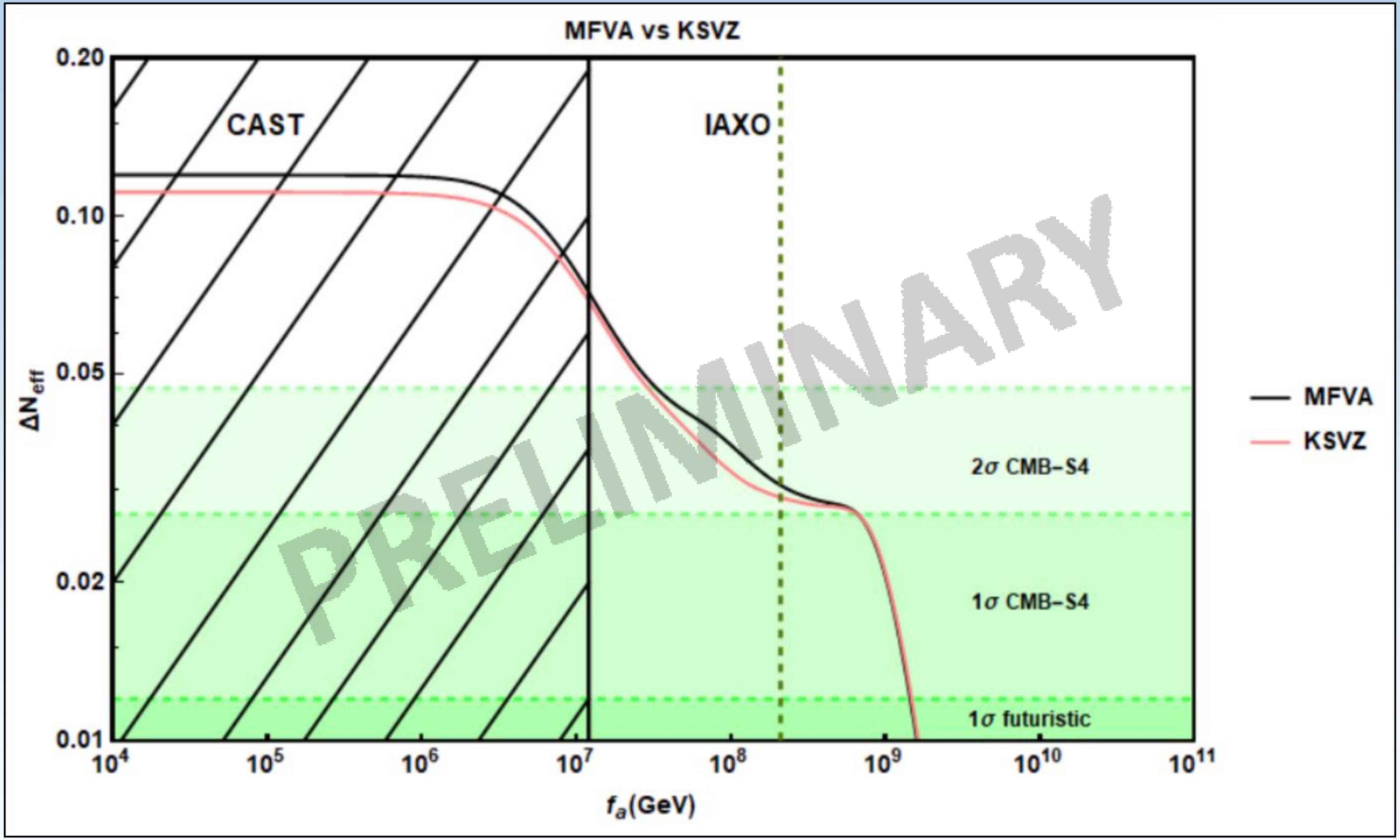
- Interplay of the axion scale and reheating temperature very relevant for some processes






Flaxion vs MFVA
0.20
0.10
0.05
0.02
0.01
ΔN_eff
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
f_a(GeV)
Flaxion
MFVA
2σ CMB–S4
1σ CMB–S4
1σ futuristic
PRELIMINARY



MFVA vs KSVZ
CAST
IAXO
PRELIMINARY
2σ CMB−S4
1σ CMB−S4
1σ futuristic
MFVA
KSVZ
0.20
0.10
0.05
0.02
0.01
ΔN_{eff}
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
f_a(GeV)

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)