MAJORONS AND AXIONS: TWO VERSATILE GOLDSTONE BOSONS

FERNANDO ARIAS ARAGÓN

Based on: JHEP 09 (2022) 210 and PRD 106 (2022) 5, 055034

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- NGB to solve SM problems
  - Strong CP Problem
  - Flavour puzle and neutrino masses
  - Hierarchy Problem
  - Baryogenesis
  - Dark matter

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- Also relevant for cosmology
  - Topological defects: monopoles, cosmic strings and domain walls
  - Inflation
  - Dark radiation
  - Alterations to thermal history of the Universe

Why Majorons?

- Neutrinos are massive

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Minkowski, PLB 67 (1977) 421-428
Mohapatra and Senjanovic. PRL 44 (1980) 912
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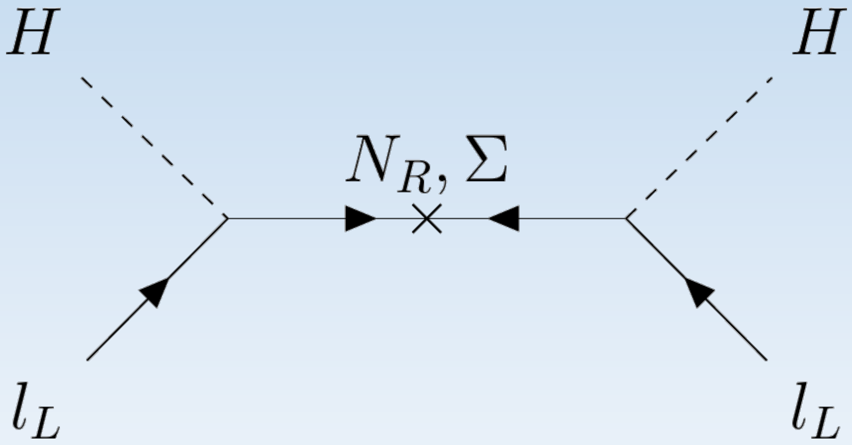
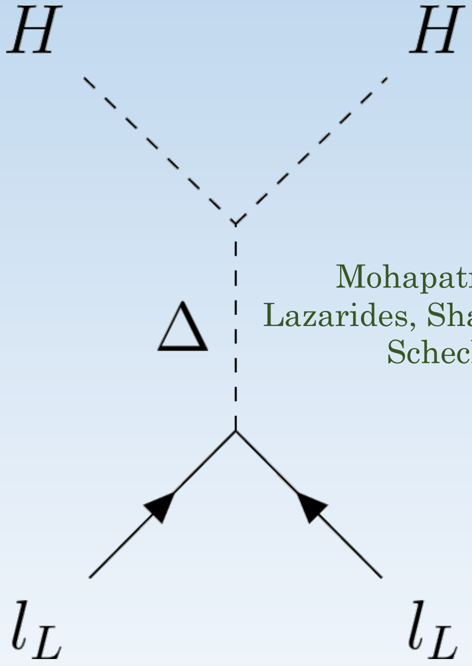
- Neutrinos are massive → BSM Physics → Seesaw Mechanism

Foot, Lew, He and Joshi, ZPC 44 (1989) 441





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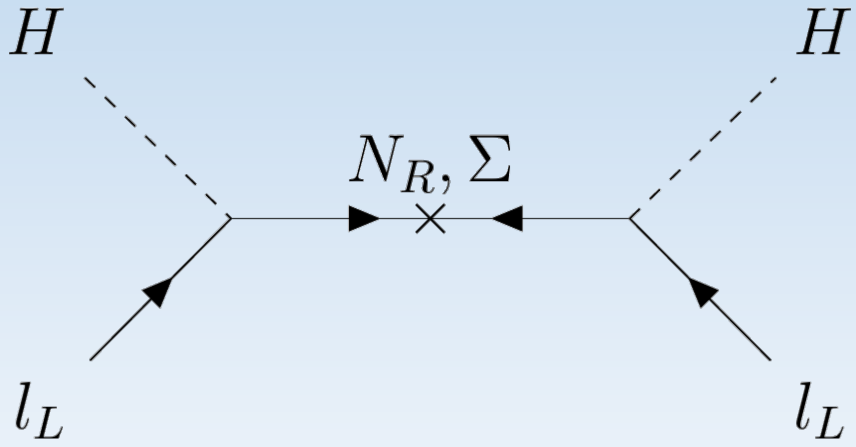

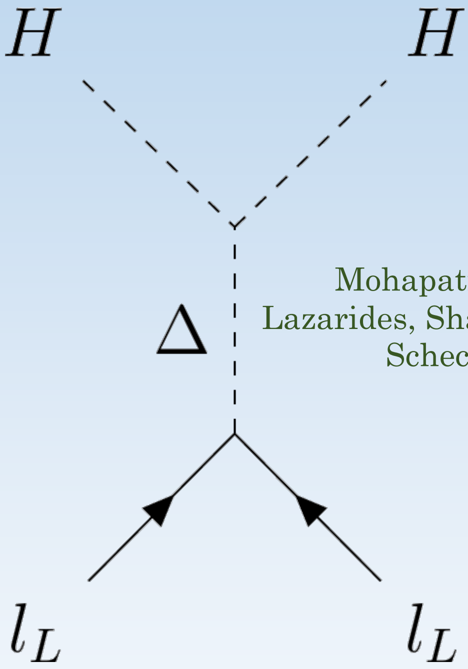

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Schechter and Valle, PRD 25 (1982) 774

- If Lepton Number spontaneously broken → Majoron

Chikashige, Mohapatra, Peccei, PRL 45 (1980) 1926
Gelmini, Roncadelli, PLB 99 (1981) 411-415
Georgi, Glashow, Nussinov, NPB 193 (1981) 297,316
Schechter, Valle, PRD 25 (1982) 774

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- An interesting cosmological anomarly: The Hubble Tension:

Verde, Treu, and Riess, 1907.10625

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- Early Universe vs local measurements of H_0 differ up to $4 - 6\ \sigma$

- This may be solved by Particle physics. E.g.: a Majoron

Escudero, Witte, EPJC 80 (2020) no. 4 294
FAA, Fernández-Martínez, González-López, Merlo, 2009.01848

Why Axions?

- Purely gauge terms proportional to total derivatives can be added to the SM Lagrangian

$$\theta_{QCD}\frac{\alpha_s}{8\pi}G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

$$\frac{\alpha_X}{8\pi}X^{a\mu\nu}\tilde{X}^a_{\mu\nu}=\partial_\mu K^\mu;\ K^\mu=\frac{\alpha_X}{4\pi}\varepsilon^{\mu\nu\alpha\beta}\left(X^a_\nu\partial_\alpha X^a_\beta+\frac{1}{3}f_{abc}X^a_\nu X^b_\alpha X^c_\beta\right)$$

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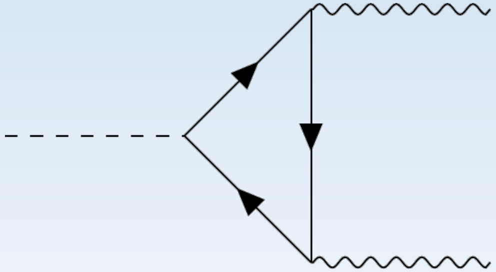
- The $G\tilde{G}$ term is related to quark masses through the chiral anomaly



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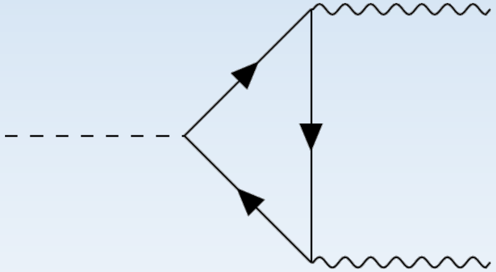

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- The observable parameter, $\bar{\theta}$ is bound by its relation to the neutron EDM, d_n

$$d_n\sim\bar{\theta}\times10^{-16}e\cdot cm,\qquad\bar{\theta}\lesssim\mathcal{O}(10^{-10})$$

Crewther, Di Vecchia, Veneziano & Witten, 1980

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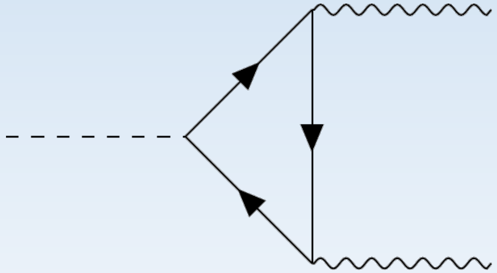

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- Why is a dimensionless parameter so small?

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Peccei and Quinn, PRL 38 (1977) 1440-1443 and PRD 16 (1977) 1791-1797

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Weinberg, PRL 40 (1978) 223-226
Wilczek, PRL 40 (1978) 279-282

$$\mathscr{L}_{aGG} = \frac{a}{f_a}\frac{\alpha_s}{8\pi} G^{a\mu\nu}\tilde{G}^a_{\mu\nu} \longrightarrow \theta_{eff} = \bar{\theta} + \frac{a}{f_a}$$

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- Non-perturbative QCD creates a potential that ensures CP conservation

$$V_{eff} \sim 1 - \sqrt{1 + \cos\left(\bar{\theta} + \frac{a}{f_a}\right)} \longrightarrow \langle a \rangle = -f_a\bar{\theta}$$

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- Axions appear in all kinds of environments
  - Flavour **FAA**, Merlo, JHEP 11 (2019) 152
  - Inflation
  - Axion Dark Radiation
  - Produced through cosmic strings and domain walls

FAA, D'Eramo, Merlo, Notari, Zambujal Ferreira, JCAP 11 (2020) 025 and JCAP 03 (2021) 090

Dynamical Minimal Flavour Violating Inverse Seesaw

FAA, Fernández-Martínez, González-López, Merlo, JHEP 09 (2022) 210

Low Scale Seesaws

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- Low scale SS: 2 types of HNL, N_R and S_R **with opposite LN**

Wyler and Wolfenstein, NPB 218 (1983) 205-214
Mohapatra and Valle, PRD 34 (1986) 1642

$$\chi \equiv (\nu_L, N_R^c, S_R^c), \mathcal{L}_Y \supset \frac{1}{2}\,\bar{\chi}\mathcal{M}_\chi\chi + \mathrm{h.c.},$$

$$\mathcal{M}_\chi = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}}\mathcal{Y}_\nu & \boxed{\epsilon\frac{v}{\sqrt{2}}\mathcal{Y}'_\nu} \\ \frac{v}{\sqrt{2}}\mathcal{Y}_\nu^T & \mu' & \Lambda \\ \epsilon\frac{v}{\sqrt{2}}\mathcal{Y}'^T_\nu & \Lambda^T & \boxed{\mu} \end{pmatrix}, \qquad m_\nu \simeq \frac{v^2}{2}\left[\left(\underbrace{\mathcal{Y}_\nu\frac{1}{\Lambda^T}\mu\frac{1}{\Lambda}\mathcal{Y}_\nu^T}_{\text{Inverse}}\right) - \epsilon\left(\underbrace{\mathcal{Y}'_\nu\frac{1}{\Lambda}\mathcal{Y}_\nu^T + \mathcal{Y}_\nu\frac{1}{\Lambda^{\mathrm{T}}}\mathcal{Y}'^T_\nu}_{\text{Linear}}\right)\right]$$

Minimal Lepton Flavour Violation

- Naïve new flavour physics should live around $\Lambda_{NP} \gtrsim 10^4$ TeV

Isidori et al., 1002.0900
Ellis et al., 1910.11775

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D'Ambrosio et al, 020736; Cirigliano et al, 0507001

$$\mathcal{L}_{Kin} \Rightarrow \mathcal{G}_F = U(3)_{q_L} \times U(3)_{u_R} \times U(3)_{d_R} \times U(3)_{l_L} \times U(3)_{e_R} \times U(3)_{N_R} \times U(3)_{S_R}$$

$$Y_u \to \mathcal{Y}_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}, \mathbf{1}, \mathbf{1}), \quad Y_d \to \mathcal{Y}_d \sim (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}}, \mathbf{1}, \mathbf{1}), \quad Y_e \to \mathcal{Y}_e \sim (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{3}, \bar{\mathbf{3}})$$

$$\mathcal{Y}_\nu \sim (\mathbf{3}, 1, \overline{\mathbf{3}}, 1)\,, \qquad \mathcal{Y}'_\nu \sim (\mathbf{3}, 1, 1, \overline{\mathbf{3}})\,.$$

$$\langle \mathcal{Y}_u \rangle = c_t V^\dagger_{CKM} \mathrm{diag}\left(\frac{m_u}{m_t}, \frac{m_c}{m_t}, 1\right), \quad \langle \mathcal{Y}_d \rangle = c_b \mathrm{diag}\left(\frac{m_d}{m_b}, \frac{m_s}{m_b}, 1\right), \quad \langle \mathcal{Y}_e \rangle = c_\tau \mathrm{diag}\left(\frac{m_e}{m_\tau}, \frac{m_\mu}{m_\tau}, 1\right)$$

$$\mu' \sim (1, 1, 1, \overline{\mathbf{6}})\,, \qquad \mu \sim (1, 1, \overline{\mathbf{6}}, 1)\,, \qquad \Lambda \sim (1, 1, \overline{\mathbf{3}}, \overline{\mathbf{3}})\,.$$

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- No predictive power in the lepton sector → Simplifications

Cirigliano et al., 0507001

Davidson and Palorini, hep-ph/0607329

Alonso et al., 1103.5461

$$SU(3)_{N_R} \times SU(3)_{S_R} \longrightarrow SU(3)_{N_R+S_R}\,,$$

$$\mathcal{Y}_\nu \sim \mathcal{Y}'_\nu \sim (\mathbf{3}, 1, \overline{\mathbf{3}})\,, \qquad \mu \sim \mu' \sim \Lambda \sim (1, 1, \overline{\mathbf{6}})\,,$$

$$\begin{tikzcd}
 & SU(3)_{\ell_L} \times SO(3)_{N_R+S_R} \\
SU(3)_{\ell_L} \times SU(3)_{N_R+S_R} \arrow[ur] \arrow[dr] & \\
 & SU(3)_{\ell_L+N_R+S_R}
\end{tikzcd}$$

Dynamical ISS in MFV – Phenomenology

	LFV	M_{N1} (TeV)	Best Probes
Case A	✓	$\gtrsim \mathcal{O}(1)$	Colliders Indirect
Case B	✓	$\gtrsim \mathcal{O}(10)$	Indirect
Case C	✗	$\gtrsim \mathcal{O}(1)$ [2.4,2.9](CDF)	Colliders

One U(1) To Rule Them All: In the Realm of Leptoquarks, the Axion Shines

FAA, Smith, PRD 106 (2022) 5, 055034

Motivation

Doršner, Fajfer, Greljo, Kamenik, Košnik, Phys. Rept. 641 (2016) 1

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- How could they entangle with the axion symmetry?

$$U(1)_\phi \otimes U(1)_\mathcal{B} \otimes U(1)_\mathcal{L} \overset{\text{Explicit}}{\rightarrow} U(1)_\mathcal{B} \otimes U(1)_\mathcal{L} \simeq U(1)_{PQ} \otimes U(1)_X \overset{\text{Spontaneous}}{\rightarrow} U(1)_X$$

$$U(1)_X = U(1)_\mathcal{B} \otimes U(1)_\mathcal{L},\ U(1)_{\mathcal{B}\pm\mathcal{L}}\ , U(1)_\mathcal{B}\ ,\ U(1)_\mathcal{L},\ U(1)_{3\mathcal{B}\pm\mathcal{L}}\ , \ldots$$

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- May answer a cosmological question: DM relic density related to the barionic one?

Procedure

- Many possible states and couplings to consider

$(\mathbf{3},\mathbf{3},-2/3):S_3^{2/3}$

$(\mathbf{3},\mathbf{2},+1/3):S_2^{1/3}$

$(\mathbf{3},\mathbf{2},+7/3):S_2^{7/3}$

$(\mathbf{3},\mathbf{1},-2/3):S_1^{2/3}$

$(\mathbf{3},\mathbf{1},+4/3):S_1^{4/3}$

$(\mathbf{3},\mathbf{1},-8/3):S_1^{8/3}$

$(\mathbf{3},\mathbf{3},+4/3):V_{3,\mu}^{4/3}$

$(\mathbf{3},\mathbf{2},+1/3):V_{2,\mu}^{1/3}$

$(\mathbf{3},\mathbf{2},-5/3):V_{2,\mu}^{5/3}$

$(\mathbf{3},\mathbf{1},+4/3):V_{1,\mu}^{4/3}$

$(\mathbf{3},\mathbf{1},10/3):V_{1,\mu}^{10/3}$

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- Choose some couplings of LQs to SM fermions and to scalars breaking $U(1)_{PQ}$ but preserving $\mathcal{B}$ and $\mathcal{L}$

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- Identify $U(1)_X$ and field charges

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$(\mathbf{3},\mathbf{2},-5/3):V_{2,\mu}^{5/3}$
$(\mathbf{3},\mathbf{1},+4/3):V_{1,\mu}^{4/3}$
$(\mathbf{3},\mathbf{1},10/3):V_{1,\mu}^{10/3}$
$(\mathbf{3},\mathbf{1},-2/3):V_{1,\mu}^{2/3}$

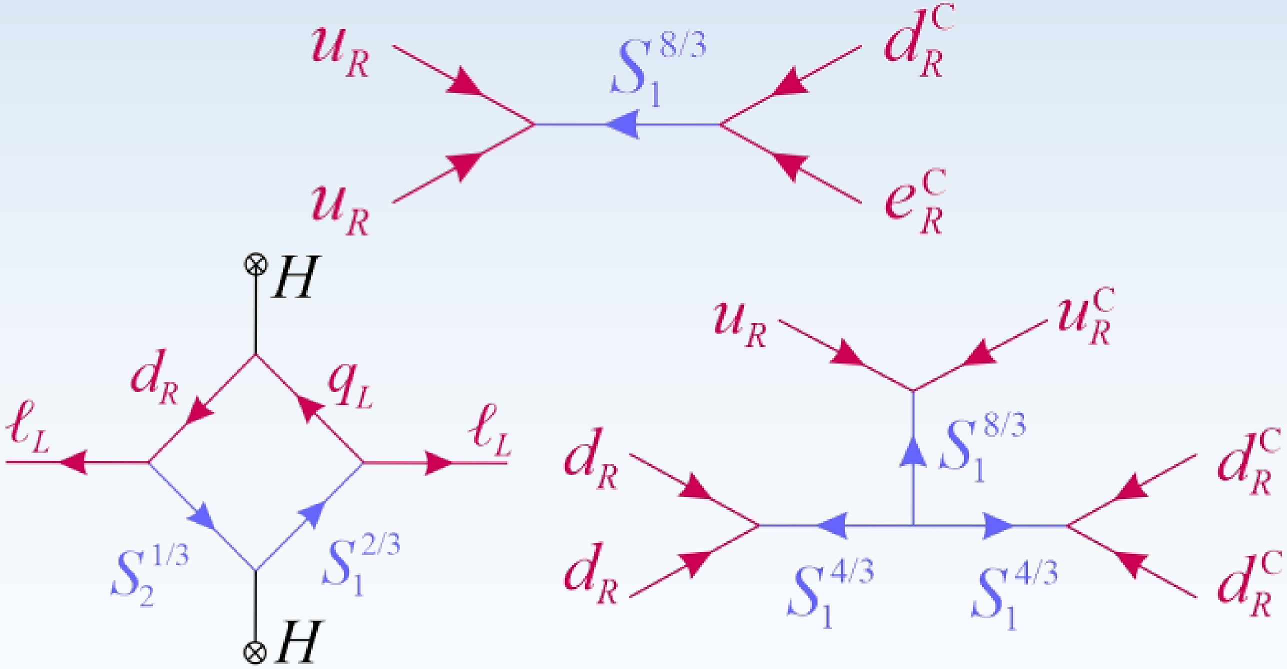
$$\mathcal{L}_{\mathrm{KSVZ+LQ}} = \mathcal{L}_{\mathrm{KSVZ}} + S_1^{8/3}\bar{d}_R e_R^{\mathrm{C}} + \tilde{S}_1^{8/3}\bar{u}_R^{\mathrm{C}} u_R + \phi^2 S_1^{8/3\dagger}\tilde{S}_1^{8/3} + h.c.$$

	ϕ	$S_1^{8/3}$	$\tilde{S}_1^{8/3}$	q_L	u_R	d_R	ℓ_L	e_R	ν_R
$U(1)_{\mathcal{B}}$	$1/2$	$1/3$	$-2/3$	$1/3$	$1/3$	$1/3$	0	0	0
$U(1)_{\mathcal{L}}$	$1/2$	1	0	0	0	0	1	1	1

Results

Results

- Proton decay, neutrino masses and $n-\bar{n}$ oscillations induced by LQ and SSB of $U(1)_{PQ}$



Results

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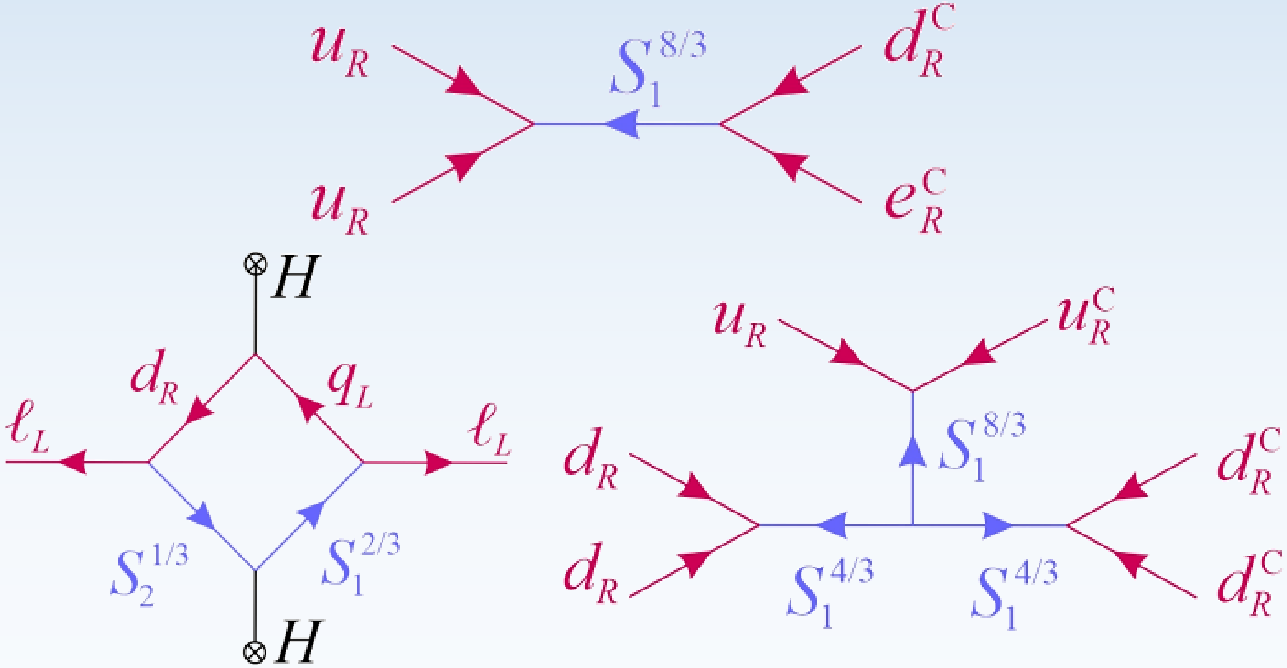
- Including $\partial_\mu \phi$ couplings to LQ forces the axion to appear in the previous processes



Results

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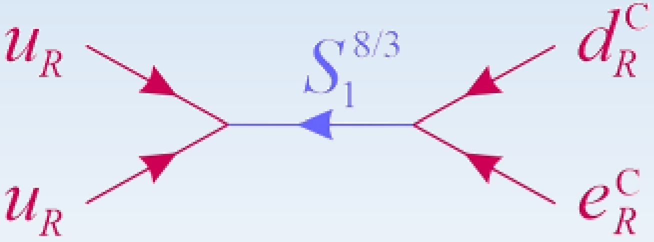
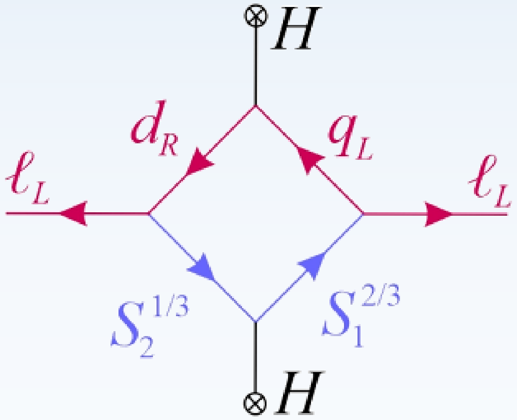
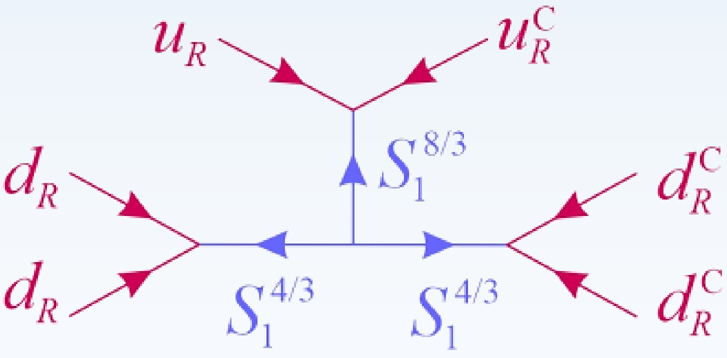
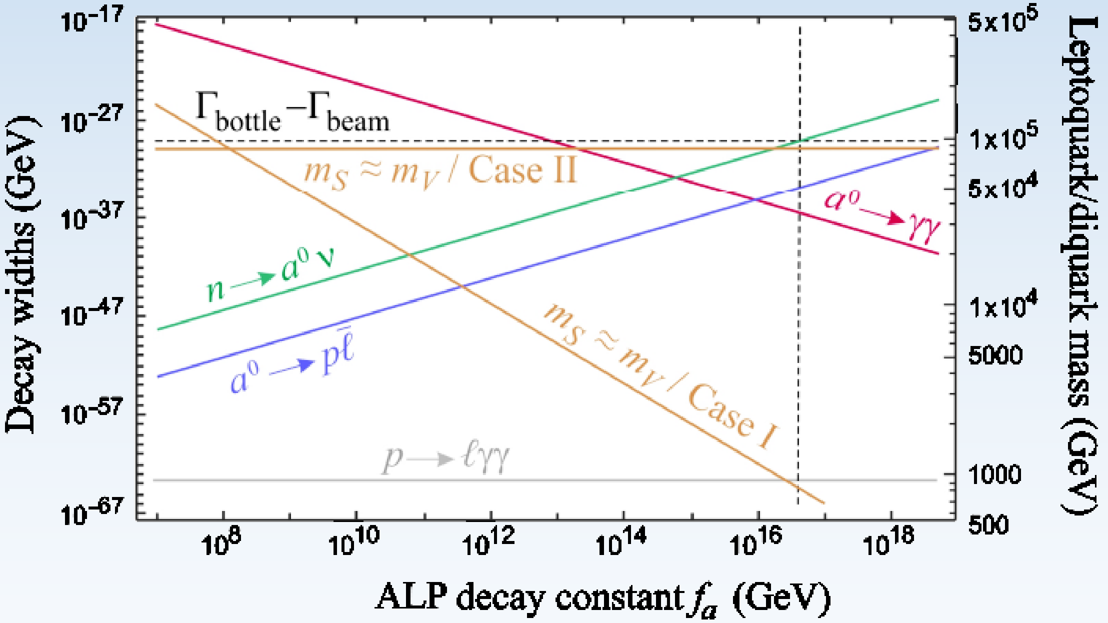
- May be relevant for the neutron lifetime anomaly



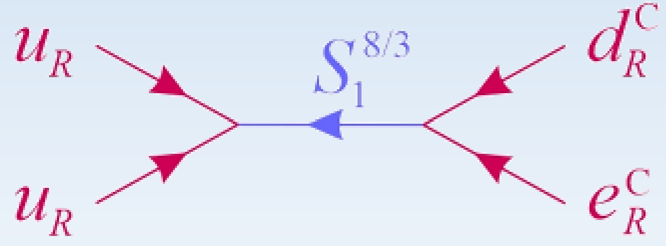


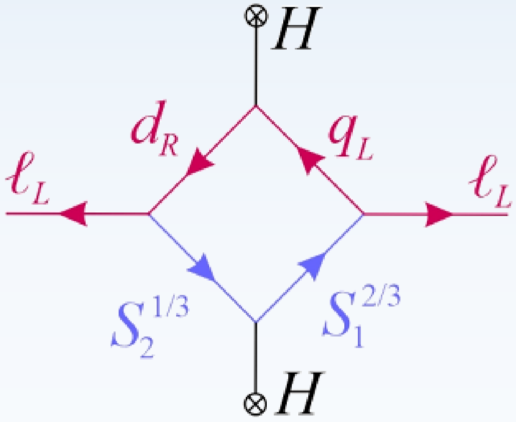


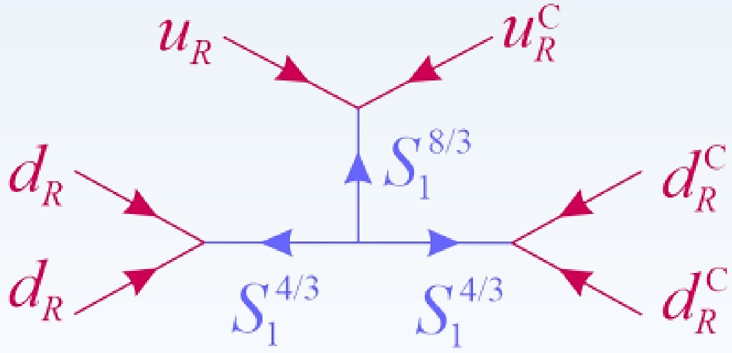


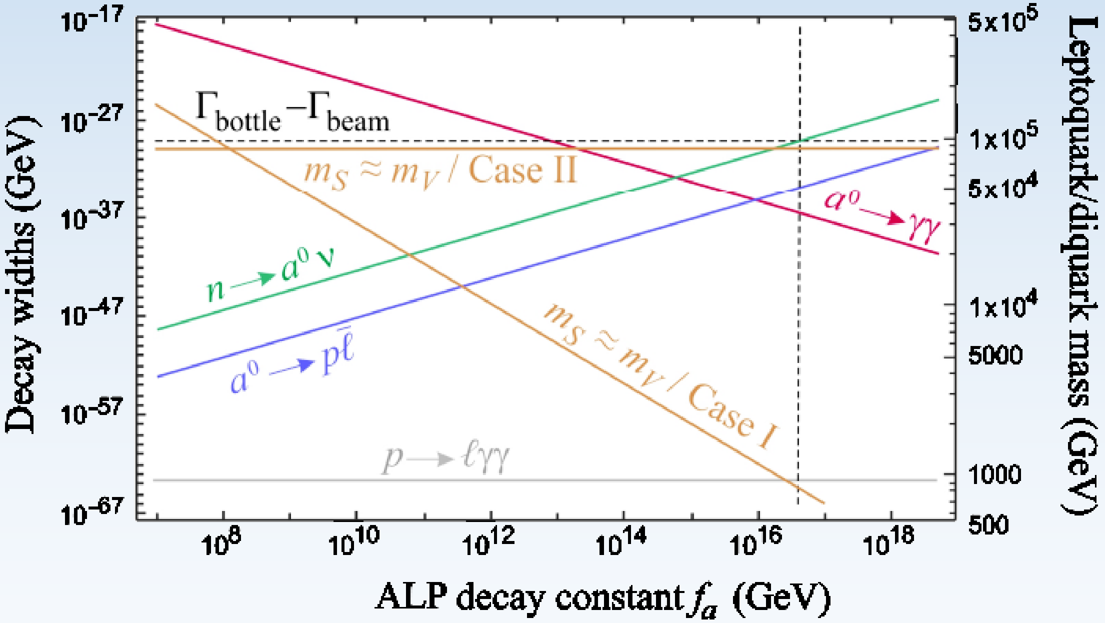
Results

- Proton decay, neutrino masses and $n - \bar{n}$ oscillations induced by LQ and SSB of $U(1)_{PQ}$
- Including $\partial_\mu \phi$ couplings to LQ forces the axion to appear in the previous processes
- May be relevant for the neutron lifetime anomaly
- May link DM production and baryogenesis









THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES

The Flavour Puzzle – Flavour Symmetries

- The SS Mechanism provides the overall neutrino mass scale, but not the hierarchies
- New symmetries in the flavour sector are a useful tool to help with this
  - Gauged or **global**
  - Discrete or **continuous**
  - **Abelian** or non-Abelian
- An interesting proposal: Froggatt-Nielsen models
  - $U(1)_{FN}$ flavour symmetry with different charges for each fermion flavour and a new flavoured scalar Φ

Froggatt and Nielsen, NPB 147, (1979), 277-298

$$\left(\frac{\Phi}{\Lambda}\right)^{x_j^{f_R}-x_i^{f_L}} \quad \bar{f}_{L_i} H Y_f^{ij} f_{R_j}$$

$$x_\Phi = -1$$

The BSM Flavour Problem – MLFV

- In a Type-I SS with 3 RH neutrinos $\mathcal{G}_F$ gets an extra $U(3)_{N_R}$, plus new spurions $\mathcal{Y}_\nu$ and $\mathcal{Y}_N$
- Spurions cannot be written in terms of light neutrino masses and oscillation parameters

$$m_\nu \simeq \frac{v^2}{2\mu_{LN}} \mathcal{Y}_\nu \mathcal{Y}_N^{-1} \mathcal{Y}_\nu^T, \qquad \langle \mathcal{Y}_\nu \rangle \langle \mathcal{Y}_N^{-1} \rangle \langle \mathcal{Y}_\nu^T \rangle = \frac{2\mu_{LN}}{v^2} U^T \hat{m}_\nu U$$

- The symmetry group must be reduced, with two possibilities

Cirigliano et al., 0507001

S. Davidson and F. Palorini, hep-ph/0607329

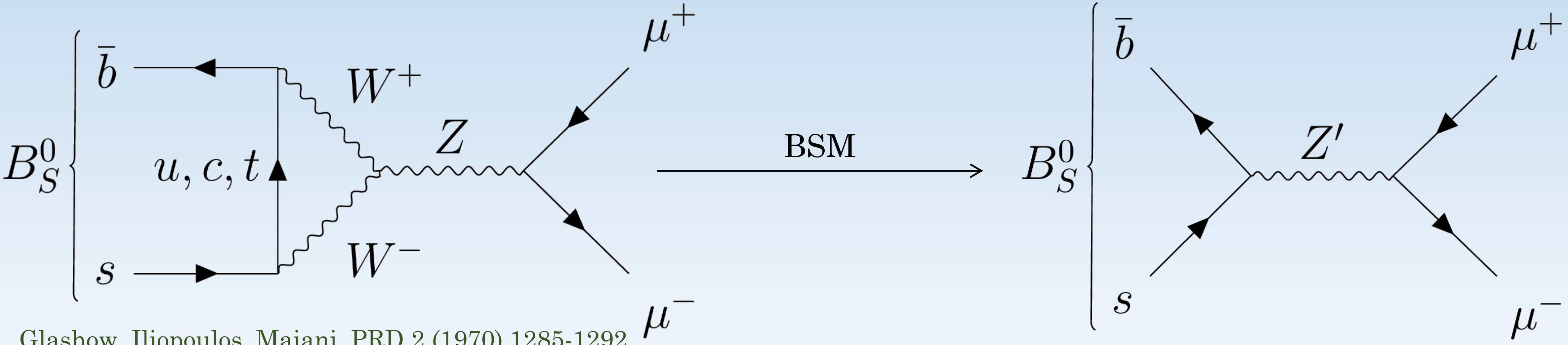
$$\begin{tikzcd}
\mathcal{G}_L^{NA} \to SU(3)_{l_L} \times SU(3)_{e_R} \times SO(3)_{N_R} \times CP \arrow[d] \\
m_\nu \simeq \dfrac{v^2}{2\mu_{LN}} \mathcal{Y}_\nu \mathcal{Y}_\nu^T
\end{tikzcd}$$

R. Alonso et al., 1103.5461

$$\begin{tikzcd}
\mathcal{G}_L^{NA} \to SU(3)_{l_L+N_R} \times SU(3)_{e_R} \arrow[d] \\
m_\nu \simeq \dfrac{v^2}{2\mu_{LN}} \mathcal{Y}_N^{-1}
\end{tikzcd}$$

The BSM Flavour Problem

- Solving the SM Open Problems may introduce new states and loop effects
- SM flavour is very sensitive to new loop contributions and posible tree level BSM FCNCs



Glashow, Iliopoulos, Maiani, PRD 2 (1970) 1285-1292

- Deviations in these processes should be easily measurable
- Their absence sets the NP scale to be $\Lambda \gtrsim \mathcal{O}(10^4 \text{ TeV})$

Isidori et al., 1002.0900
Ellis et al., 1910.11775

Dynamical ISS in MFV – Setup

- Froggatt-Nielsen + MFV: $U(1)_{FN} \equiv U(1)_{PQ} \supset \mathcal{G}_F$

FAA, L. Merlo, 1709.07039

- Flavon Φ introduced for PQ invariance, $x_\Phi = -1$

$$\mathcal{L}_Y \supset y_\psi\, \bar{\psi}_L H \psi_R \left(\frac{\Phi}{\Lambda_\Phi}\right)^{x_{\psi_R}-x_{\psi_L}}, \qquad \varepsilon \equiv \frac{v_\Phi}{\sqrt{2}\Lambda_\Phi},$$

$$m_\psi = y_\psi \frac{v}{\sqrt{2}} \varepsilon^{x_{\psi_R}-x_{\psi_L}}$$

$$x_d - x_u = x_e - x_\ell = \begin{cases} 1 & \text{for} \quad \varepsilon = 0.01\,, \\ 3 & \text{for} \quad \varepsilon = 0.23\,, \end{cases}$$

$$x_u - x_Q = 0, \qquad x_d - x_u \simeq \log_\varepsilon \frac{m_b}{m_t}, \qquad x_e - x_\ell \simeq \log_\varepsilon \frac{m_\tau}{m_t}$$

- Three scenarios:

CASE A	CASE B	CASE C
$\mathcal{G}_F^{\rm NA} = SU(3)_{\ell_L} \times SU(3)_{e_R} \times SU(3)_{N_R+S_R}$	$\mathcal{G}_F^{\rm NA} = SU(3)_{\ell_L} \times SU(3)_{e_R}$	$\mathcal{G}_F^{\rm NA} = SU(3)_{\ell_L} \times SU(3)_{e_R}$
$\mu, \mu', \Lambda \propto \mathbb{1} \quad \mathcal{Y}_\nu \sim \mathcal{Y}'_\nu \sim (\mathbf{3}, 1, \bar{\mathbf{3}})$	$N_R, S_R \sim (\mathbf{3}, 1)$	$N_R \sim (\mathbf{3}, 1), \bar{S}_R \sim (\mathbf{3}, 1)$
	$\mathcal{Y}_\nu,\, \mathcal{Y}'_\nu \propto \mathbb{1} \quad \mu \sim \mu' \sim \Lambda \sim (\bar{\mathbf{6}}, 1)$	$\mathcal{Y}_\nu,\, \Lambda \propto \mathbb{1} \quad \mu' \sim \mathcal{Y}'^\dagger_\nu \sim \mu^\dagger \sim (\bar{\mathbf{6}}, 1)$

Dynamical ISS in MFV – Case A

$$\mathcal{G}_F^{\mathrm{NA}} = SU(3)_{\ell_L} \times SU(3)_{e_R} \times SO(3)_{N_R+S_R}$$

$$\begin{aligned} -\mathscr{L}_Y^{\mathrm{A}} = {} & \overline{\ell_L} H Y_e e_R \left(\frac{\Phi}{\Lambda_\Phi}\right)^{x_e - x_\ell} + \overline{\ell_L} \widetilde{H} Y_\nu N_R + c_\nu \overline{\ell_L} \widetilde{H} Y_\nu S_R \left(\frac{\Phi}{\Lambda_\Phi}\right)^{2x_\ell} + \\ & + \frac{1}{2} c_N \overline{N_R^c} N_R \Phi \left(\frac{\Phi}{\Lambda_\Phi}\right)^{2x_\ell - 1} + \frac{1}{2} c_S \overline{S_R^c} S_R \Phi^\dagger \left(\frac{\Phi^\dagger}{\Lambda_\Phi}\right)^{2x_\ell - 1} + \Lambda \overline{N_R^c} S_R + \mathrm{h.c.} \end{aligned}$$

$$\mathcal{M}_\chi = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y_\nu & \boxed{c_\nu} \frac{v}{\sqrt{2}} \varepsilon^{2x_\ell} \boxed{Y_\nu} \\ \frac{v}{\sqrt{2}} Y_\nu^T & \boxed{c_N} \frac{v_\Phi}{\sqrt{2}} \varepsilon^{\boxed{2x_\ell} - 1} & \boxed{\Lambda} \\ c_\nu \frac{v}{\sqrt{2}} \varepsilon^{2x_\ell} Y_\nu^T & \Lambda & \boxed{c_S} \frac{v_\Phi}{\sqrt{2}} \varepsilon^{2x_\ell - 1} \end{pmatrix}$$

$$Y_\nu = \frac{1}{f^{1/2}} U \widehat{m}_\nu^{1/2} \mathcal{H}^T$$

$$U \equiv R_{23}(\theta_{23}) \cdot R_{13}(\theta_{13},\, \delta_{\mathrm{CP}}) \cdot R_{12}(\theta_{12}) \cdot \mathtt{diag}\left(1,\, e^{i\,\alpha_2},\, e^{i\,\alpha_3}\right)$$

$$f \equiv \frac{v^2\, \varepsilon^{2x_\ell - 1}}{2\sqrt{2}\,\Lambda^2} \left(c_S\, v_\Phi - 2\sqrt{2}\, c_\nu\, \varepsilon\, \Lambda\right)$$

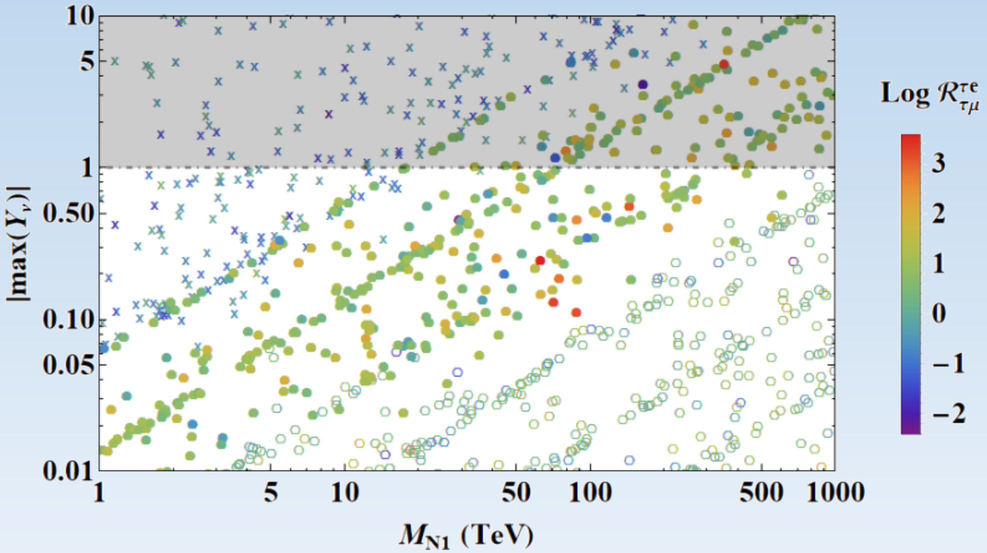
$$\mathcal{H} \equiv e^{i\phi} = \mathbb{1} - \frac{\cosh r - 1}{r^2} \phi^2 + i \frac{\sinh r}{r} \phi$$

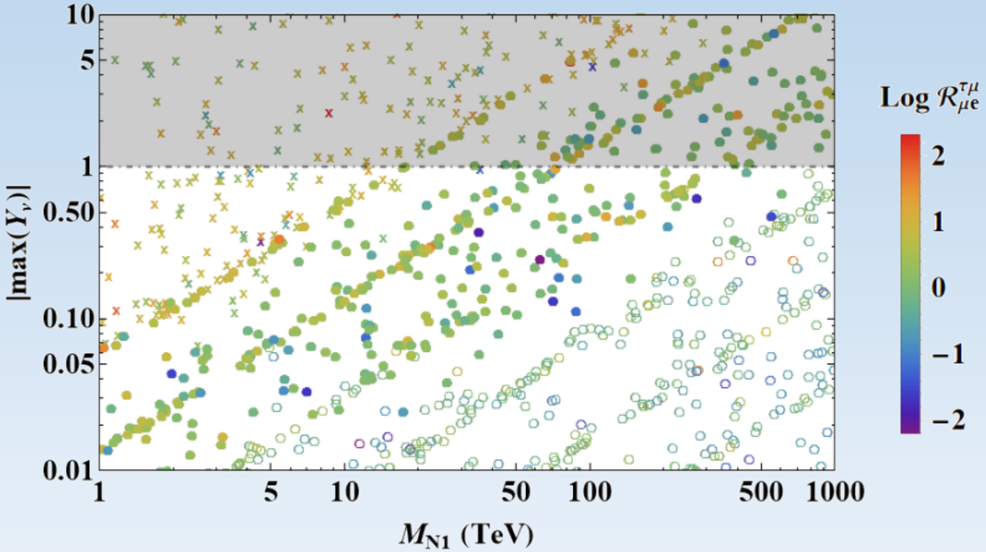
$$M_N \simeq \Lambda$$

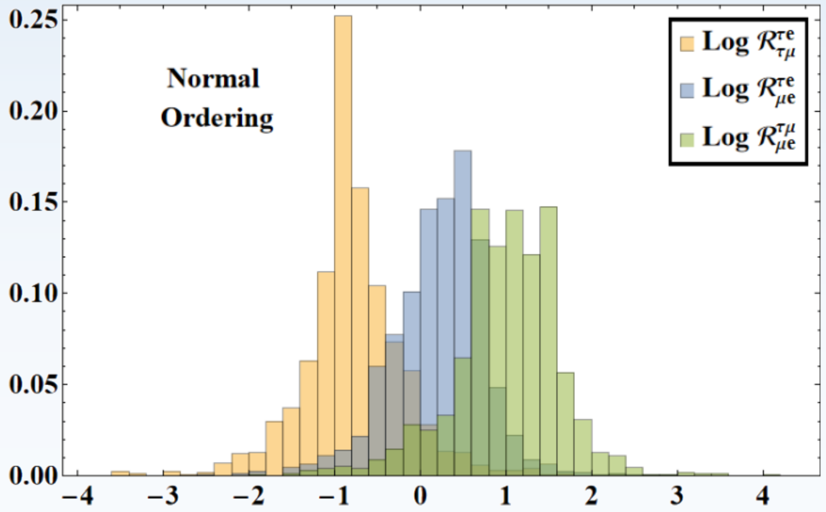
$$\phi = \begin{pmatrix} 0 & \phi_1 & \phi_2 \\ -\phi_1 & 0 & \phi_3 \\ -\phi_2 & -\phi_3 & 0 \end{pmatrix} \qquad r \equiv \sqrt{\phi_1^2 + \phi_2^2 + \phi_3^2}$$

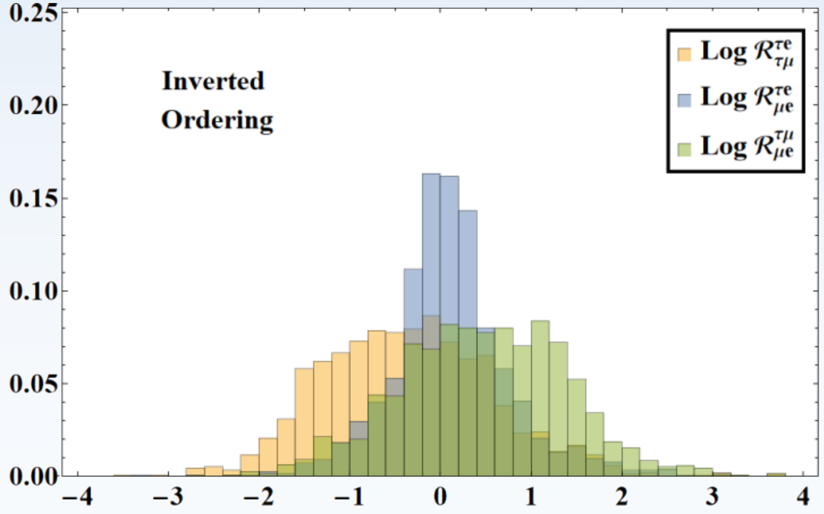
Dynamical ISS in MFV – Case A

$$\mathcal{N} = (\mathbb{1} - \eta)\, U \qquad \eta = \frac{v^2}{4 f \Lambda^2} U \, \widehat{m}_\nu^{1/2} \, \mathcal{H}^T \, \mathcal{H}^* \, \widehat{m}_\nu^{1/2} \, U^\dagger$$









Dynamical ISS in MFV – Case B

$$\mathcal{G}_F^{\rm NA} = SU(3)_V \times SU(3)_{e_R}$$

$N_R, S_R \sim (\mathbf{3}, 1)$

$$\begin{aligned} -\mathscr{L}_Y^{\rm B} = \; & \overline{\ell_L} H Y_e e_R \left(\frac{\Phi}{\Lambda_\Phi}\right)^{x_e - x_\ell} + c_{\nu N}\overline{\ell_L}\widetilde{H} N_R + c_{\nu S}\overline{\ell_L}\widetilde{H} S_R \left(\frac{\Phi}{\Lambda_\Phi}\right)^{2x_\ell} + \\ & + \frac{1}{2} c_N \overline{N_R^c} Y_N N_R \Phi \left(\frac{\Phi}{\Lambda_\Phi}\right)^{2x_\ell-1} + \frac{1}{2} \overline{S_R^c} Y_N S_R \Phi^\dagger \left(\frac{\Phi^\dagger}{\Lambda_\Phi}\right)^{2x_\ell-1} + \\ & + \Lambda\, \overline{N_R^c} Y_N S_R + \text{h.c.}\,, \end{aligned}$$

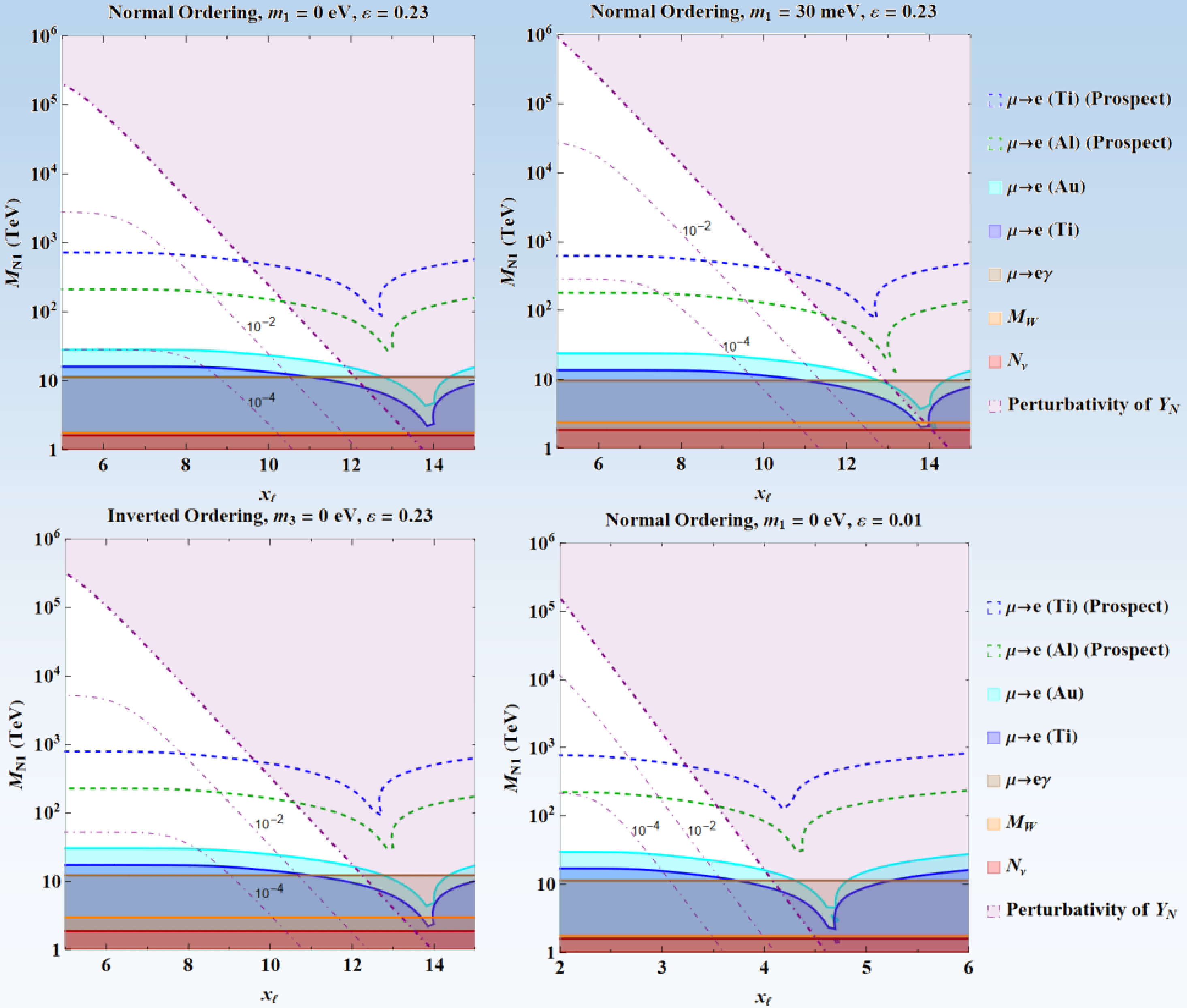
$$\mathcal{M}_\chi = \begin{pmatrix} 0 & c_{\nu N}\dfrac{v}{\sqrt{2}} & c_{\nu S}\dfrac{v}{\sqrt{2}}\varepsilon^{2x_\ell} \\ c_{\nu N}\dfrac{v}{\sqrt{2}} & c_N\dfrac{v_\Phi}{\sqrt{2}}\varepsilon^{2x_\ell-1}\,Y_N & \Lambda\,Y_N \\ c_{\nu S}\dfrac{v}{\sqrt{2}}\varepsilon^{2x_\ell} & \Lambda\,Y_N & \dfrac{v_\Phi}{\sqrt{2}}\varepsilon^{2x_\ell-1}\,Y_N \end{pmatrix}$$

$$Y_N = f\, U^* \widehat{m}_\nu^{-1} U^\dagger\,, \qquad f \equiv \frac{v^2}{2}\varepsilon^{2x_\ell-1}\left(\frac{c_{\nu_N}^2 v_\Phi}{\sqrt{2}\Lambda^2} - \frac{2c_{\nu_N}c_{\nu_S}\varepsilon}{\Lambda}\right) \qquad M_N \simeq \Lambda\,Y_N$$

Dynamical ISS in MFV – Case B

$$\mathcal{N} = (\mathbb{1} - \eta)\, U$$

$$\eta = \frac{c_{\nu N}^2 v^2}{4 f^2 \Lambda^2} U\, \widehat{m}_\nu^2\, U^\dagger$$



Dynamical ISS in MFV – Case C

$$\mathcal{G}_F^{\rm NA} = SU(3)_V \times SU(3)_{e_R}$$

$N_R \sim (\mathbf{3}, 1), \bar{S}_R \sim (\mathbf{3}, 1)$

$$\begin{aligned} -\mathscr{L}_Y^{\rm C} = \; & \overline{\ell_L} H Y_e e_R \left(\frac{\Phi}{\Lambda_\Phi}\right)^{x_e - x_\ell} + c_{\nu N} \overline{\ell_L} \widetilde{H} N_R + c_{\nu S} \overline{\ell_L} \widetilde{H}\, Y_N^\dagger S_R \left(\frac{\Phi}{\Lambda_\Phi}\right)^{2x_\ell} + \\ & + \frac{1}{2} c_N \overline{N_R^c} Y_N N_R \Phi \left(\frac{\Phi}{\Lambda_\Phi}\right)^{2x_\ell - 1} + \frac{1}{2} \overline{S_R^c} Y_N^\dagger S_R \Phi^\dagger \left(\frac{\Phi^\dagger}{\Lambda_\Phi}\right)^{2x_\ell - 1} + \\ & + \Lambda\, \overline{N_R^c} S_R + \text{h.c.}\,, \end{aligned}$$

$$\mathcal{M}_\chi = \begin{pmatrix} 0 & c_{\nu N} \dfrac{v}{\sqrt{2}} & c_{\nu S} \dfrac{v}{\sqrt{2}} \varepsilon^{2x_\ell}\, Y_N^\dagger \\ c_{\nu N} \dfrac{v}{\sqrt{2}} & c_N \dfrac{v_\Phi}{\sqrt{2}} \varepsilon^{2x_\ell - 1}\, Y_N & \Lambda \\ c_{\nu S} \dfrac{v}{\sqrt{2}} \varepsilon^{2x_\ell}\, Y_N^\dagger & \Lambda & \dfrac{v_\Phi}{\sqrt{2}} \varepsilon^{2x_\ell - 1}\, Y_N^\dagger \end{pmatrix}$$

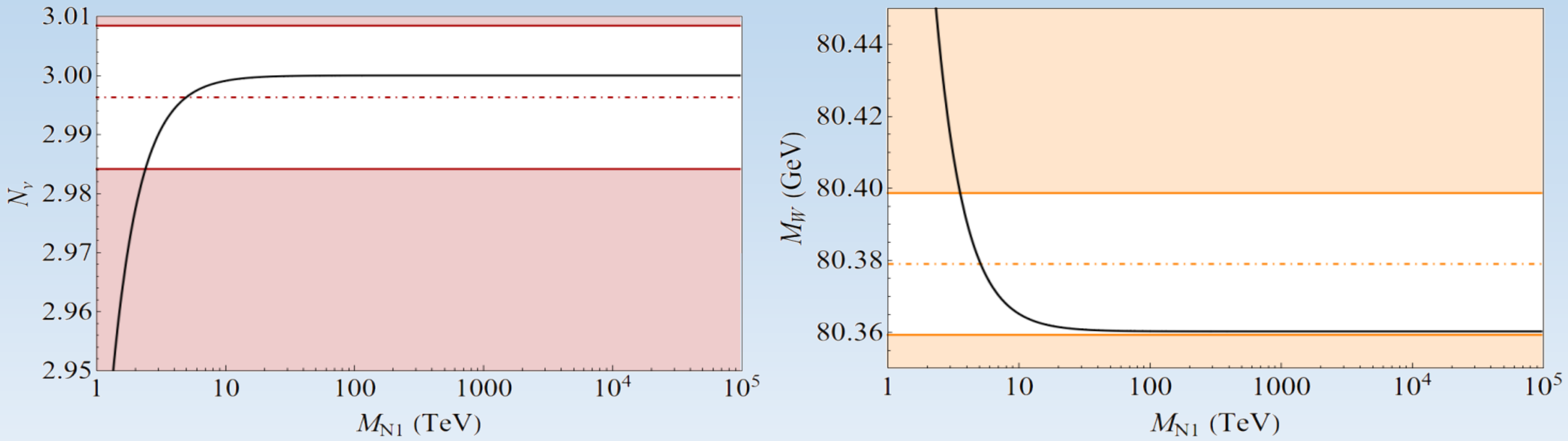
$$Y_N = \frac{1}{f}\, U^* \widehat{m}_\nu\, U^\dagger$$

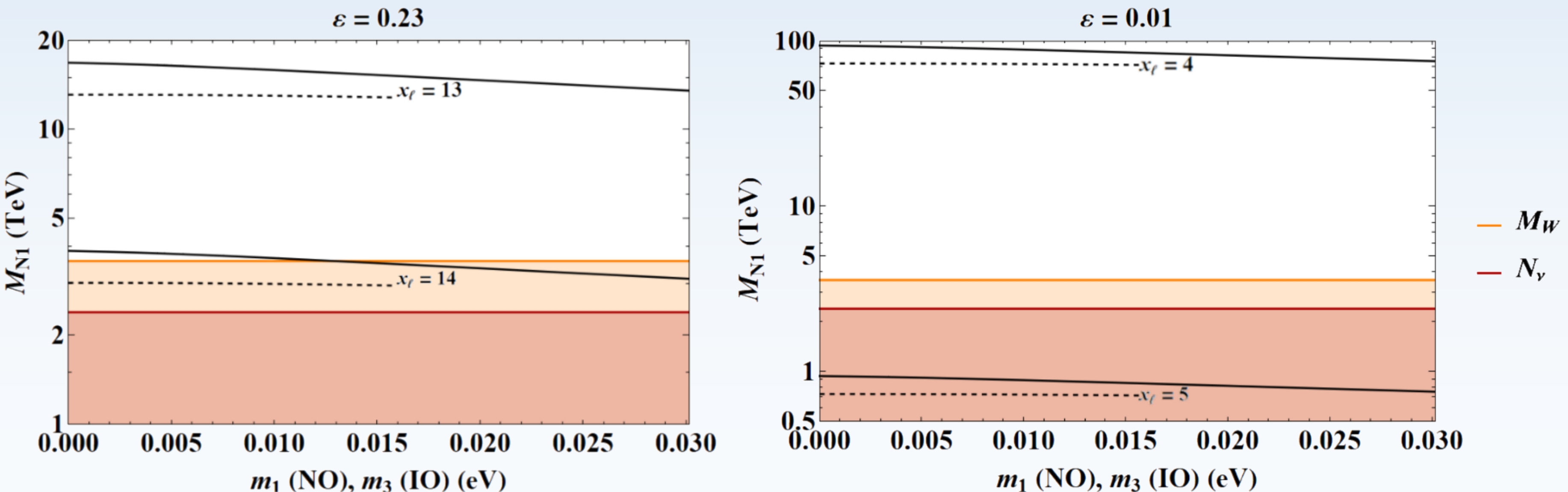
$$f \equiv \frac{v^2}{2} \varepsilon^{2x_\ell - 1} \left(\frac{c_{\nu_N}^2 v_\Phi}{\sqrt{2}\Lambda^2} - \frac{2 c_{\nu_N} c_{\nu_S} \varepsilon}{\Lambda} \right)$$

$$M_N \simeq \Lambda$$

Dynamical ISS in MFV – Case C

$$\mathcal{N} = (\mathbb{1} - \eta)\,U \qquad \eta = \frac{c_{\nu N}^2 v^2}{4\Lambda^2}\,\mathbb{1}$$





The Strong CP Problem – Proposed Solutions

- Massless quarks
  - One null eigenvalue in either quark matrix would render θ_{QCD} non-physical
  - Lattice greatly disfavours this proposal
  - Modern models still make use of this idea

Hook, 1411.3325
Gaillard, Gavela, Houtz and Quílez, 1805.06465
Gavela, Ibe, Quílez and Yanagida, 1812.08174

- Nelson-Barr models Nelson, PLB 136 (1984) 384-391 Barr, PRL 53 (1984) 329 Bento et al., PLB 267 (1991) 95-99
  - Consider CP a symmetry of the Lagrangian, broken spontaneously
  - Must reproduce the observed CP violation in the SM while keeping $\bar{\theta} = 0$
  - New particles and/or symmetries may be introduced to achieve this
  - High-dimensional operators or loop corractions can be troublesome
- A solution with just one symmetry and one particle: the Axion

The MFVA – Phenomenology

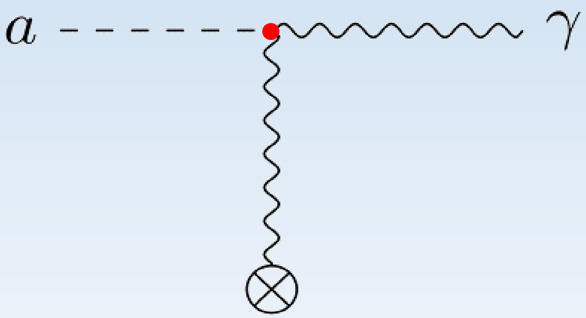
$$\boxed{f_a = \frac{v_\Phi}{c_{agg}}}$$

	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

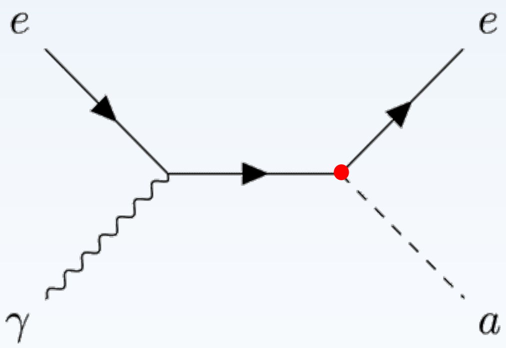
$$\begin{aligned} f_a &\gtrsim 1.2 \times 10^7 \text{ GeV} && \text{for} && m_a \lesssim 10 \text{ meV}, \\ f_a &\gtrsim 8.7 \times 10^6 \text{ GeV} && \text{for} && 10 \text{ meV} \lesssim m_a \lesssim 10 \text{ eV}, \\ f_a &\gg 8.7 \times 10^8 \text{ GeV} && \text{for} && 10 \text{ eV} \lesssim m_a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



- Astrophysical bounds on electron coupling

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

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



The MFVA – Phenomenology

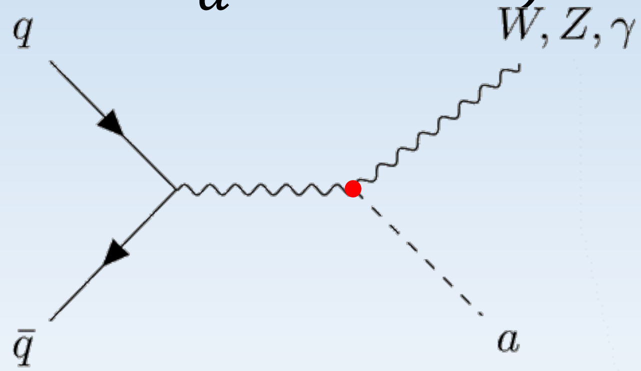
$$\boxed{f_a = \frac{v_\Phi}{c_{agg}}}$$

	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

Brivio et al., 1701.05379

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

(aWW)	$f_a \gtrsim 6.4\,\text{GeV}$
(aZZ)	$f_a \gtrsim 5.7\,\text{GeV}$
$(aZ\gamma)$	$f_a \gtrsim 17.8\,\text{GeV}$

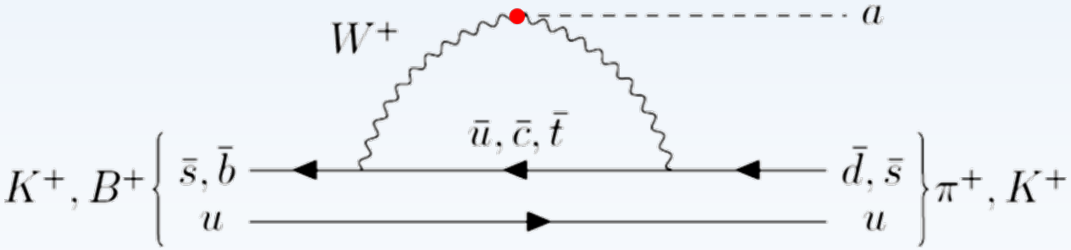


- Flavour bounds on aWW coupling

Izaguirre et al., 1611.09355

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

$f_a \gtrsim 105\,\text{GeV}$ for $0.2\,\text{GeV} \lesssim m_a \lesssim 5\,\text{GeV}$



The MFVA – Phenomenology

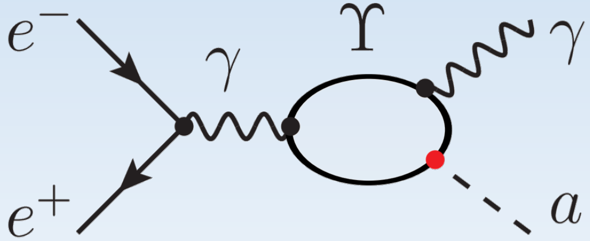
$$\boxed{f_a = \frac{v_\Phi}{c_{agg}}}$$

	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

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

Merlo et al., 1905.03259

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



- Axion-bottom coupling bound from CLEO ($0{,}4 \lesssim m_a \lesssim 4{,}8$ GeV, decaying axion)

CLEO Collaboration, PRL 80 (1998) 1150-1155

$$f_a \gtrsim 667 \text{ GeV}$$

MFVω: m_ν and H_0 tension – The Majoron Mechanism

- Combining those expressions with the bound on $\lambda_{\omega\nu\nu}$

$$|L_\chi|\varepsilon_\chi^{\frac{2+L_\chi}{L_\chi}}\mathcal{Y}_\nu\mathcal{Y}_N^{-1}\mathcal{Y}_\nu^T \in [1.2\times10^{-13}, 2.4\times10^{-12}]$$

$$\frac{\varepsilon_\chi^{\frac{2L_N-L_\chi}{L_\chi}}}{|L_\chi|}\mathcal{Y}_N \gg 3.5\times10^{-14}$$

- A renormalizable scenario is possible, but it is very fine-tuned

$$L_N = -1, L_\chi = -2 \Rightarrow \mathcal{Y}_\nu\mathcal{Y}_N^{-1}\mathcal{Y}_\nu^T \in [1.2\times10^{-13}, 2.4\times10^{-12}]$$

- Other possibilities
  - $L_N > 0, L_\chi < 0 \Rightarrow \chi \leftrightarrow \chi^\dagger$
  - $L_N < 0, L_\chi > 0 \Rightarrow$ non-local
  - $L_N = L_\chi = -1 \Rightarrow m_\nu \propto \varepsilon_\chi^{-1}$, highly fine-tuned

MFVω: m_ν and H_0 tension – Majoron within MFV

- Minimal Flavour Violating Axion framework plus $3N_R$

$$\mathcal{G}_F = U(3)_{q_L} \times U(3)_{u_R} \times U(3)_{d_R} \times U(3)_{l_L} \times U(3)_{N_R} \times U(3)_{e_R}$$

$$x_{q_L} = x_{l_L} = x_{u_R} = x_{N_R} = 0, x_{d_R} = x_{e_R} = 3$$

$$\mathcal{G}_F \supset \mathcal{G}_F^A = U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{PQ} \times U(1)_{e_R} \times U(1)_{N_R}$$

$$-\mathcal{L}_Y$$
$$= \bar{q}_L \widetilde{H} \mathcal{Y}_u u_R + \left(\frac{\Phi}{\Lambda_\Phi}\right)^3 \bar{q}_L H \mathcal{Y}_d d_R + \left(\frac{\Phi}{\Lambda_\Phi}\right)^3 \bar{l}_L H \mathcal{Y}_e e_R + \left(\frac{\chi}{\Lambda_\chi}\right)^{\frac{1+L_N}{L_\chi}} \bar{l}_L \widetilde{H} \mathcal{Y}_\nu N_R$$
$$+ \frac{1}{2}\left(\frac{\chi}{\Lambda_\chi}\right)^{\frac{2L_N - L_\chi}{L_\chi}} \chi \bar{N}_R^c \mathcal{Y}_N N_R + \mathrm{h.c.}$$

- After recovering predictability in the lepton sector
  - $\mathcal{G}_L^{NA} = SU(3)_{l_L} \times SU(3)_{e_R} \times SO(3)_{N_R} \times CP \Rightarrow \mathcal{Y}_N \propto \mathbb{1}, \mathcal{Y}_\nu \in \mathbb{R}$

$2+L_\chi$

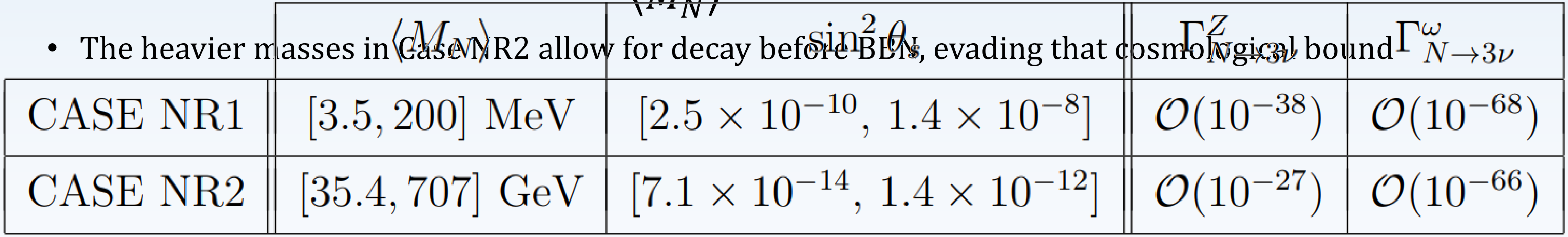
MFVω: m_ν and H_0 tension – Phenomenology

- Heavy neutrinos
  - Case NR1 testable at beam dump experiments or near detectors at oscillation experiments like DUNE or SHiP
  - Case NR2 interesting for production at LHC or future colliders
- $N \rightarrow 3\nu$ in the early universe may disfavour some scenarios
  - If it happens after BBN, as it may happen in Case NR1 with $\langle M_N \rangle \in [3.5, 200]$ MeV, the light-heavy neutrino mixing θ_s is bound by

A. C. Vincent et al., 1408.1956

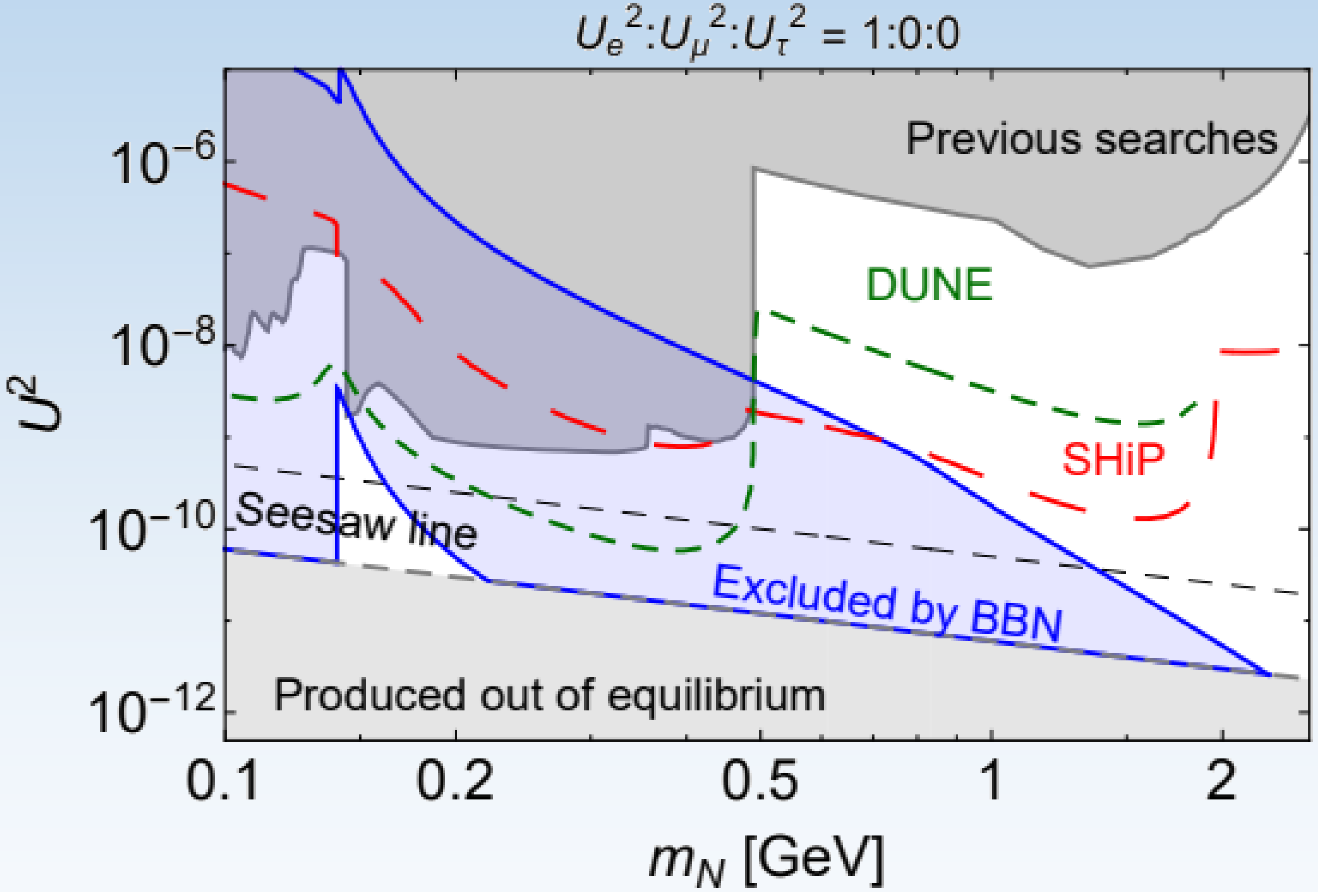
$$\sin^2 \theta_s \equiv \frac{\langle m_\nu \rangle}{\langle M_N \rangle} \lesssim 10^{-15} - 10^{-17}$$

  - The heavier masses in Case NR2 allow for decay before BBN, evading that cosmological bound

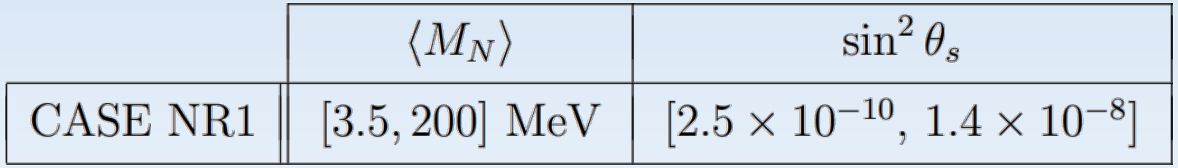


	$\langle M_N \rangle$	$\sin^2\theta_s$	$\Gamma^Z_{N\to 3\nu}$	$\Gamma^\omega_{N\to 3\nu}$
CASE NR1	$[3.5, 200]$ MeV	$[2.5\times 10^{-10},\, 1.4\times 10^{-8}]$	$\mathcal{O}(10^{-38})$	$\mathcal{O}(10^{-68})$
CASE NR2	$[35.4, 707]$ GeV	$[7.1\times 10^{-14},\, 1.4\times 10^{-12}]$	$\mathcal{O}(10^{-27})$	$\mathcal{O}(10^{-66})$

MFVω Phenomenological Signatures

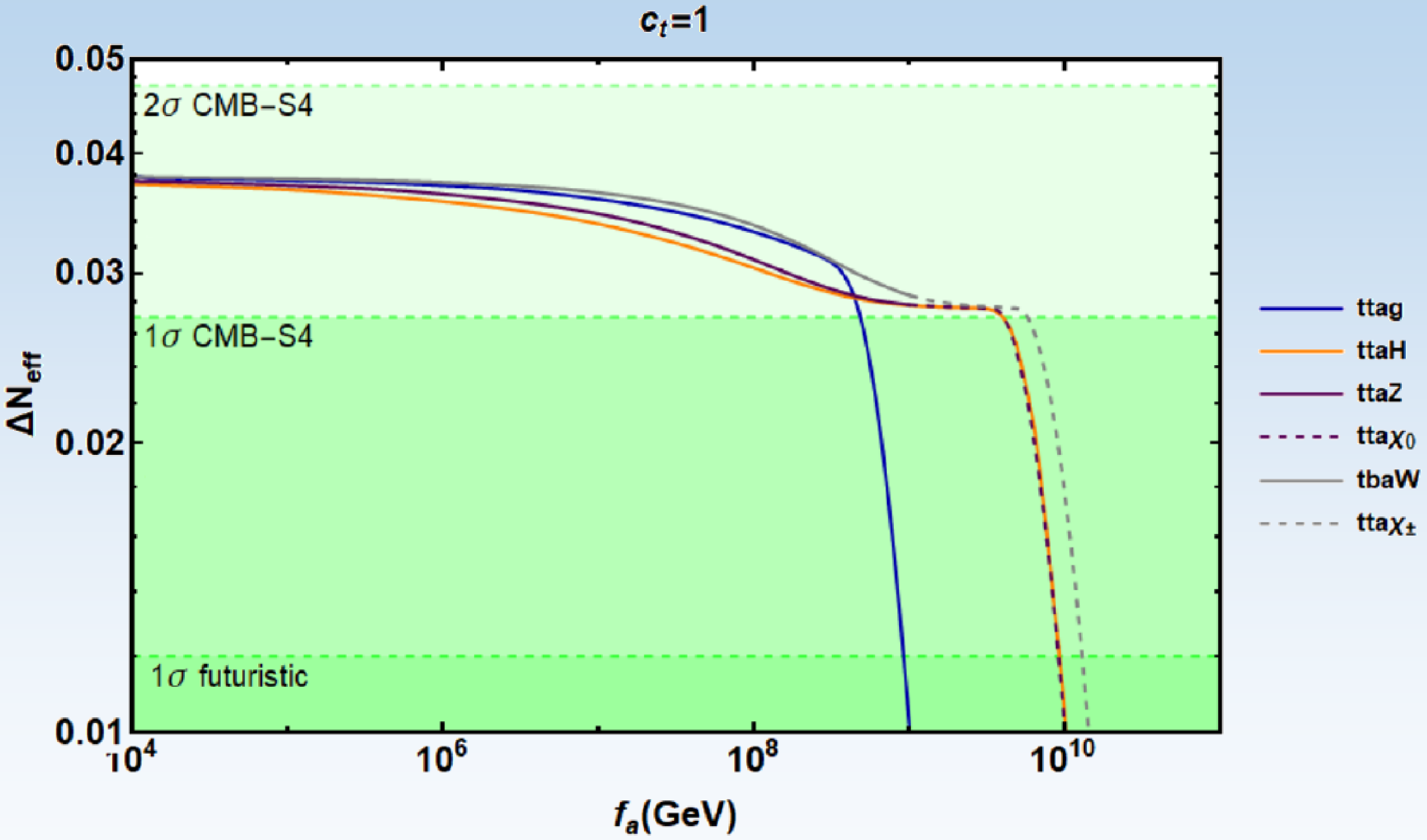


Plot from Boyarsky, Ovchynnikov, Ruchayskiy and Syvolap, 2008.00749



	$\langle M_N \rangle$	$\sin^2\theta_s$
CASE NR1	$[3.5, 200]$ MeV	$[2.5 \times 10^{-10}, 1.4 \times 10^{-8}]$

Axion Dark Radiation and ΔN_{eff} – Production Across EWPT

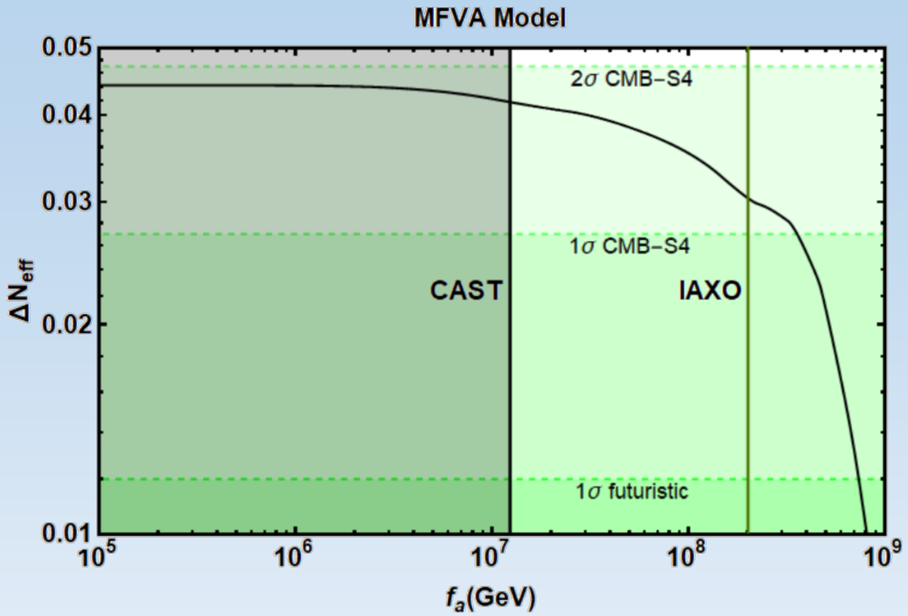


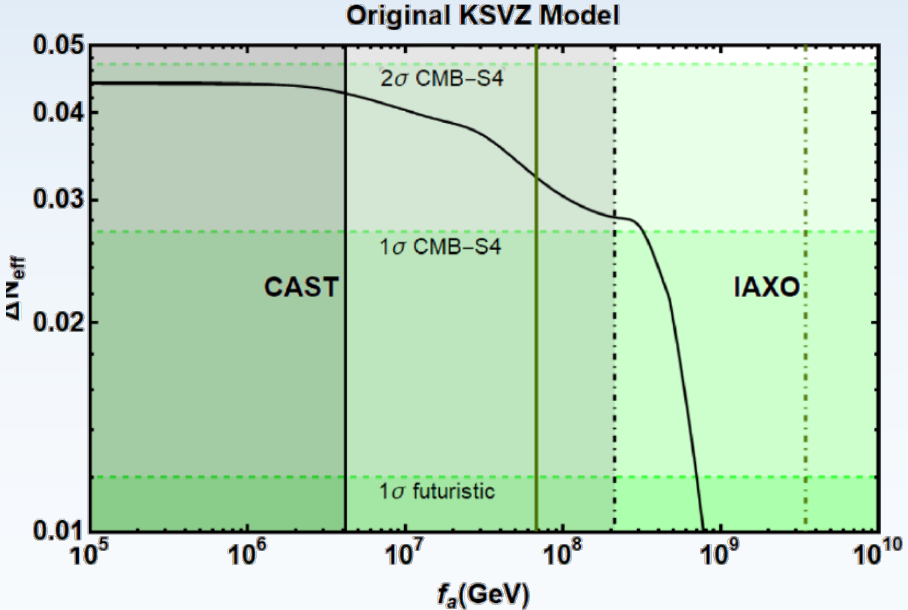
Axion Dark Radiation and ΔN_{eff} – Production Across EWPT

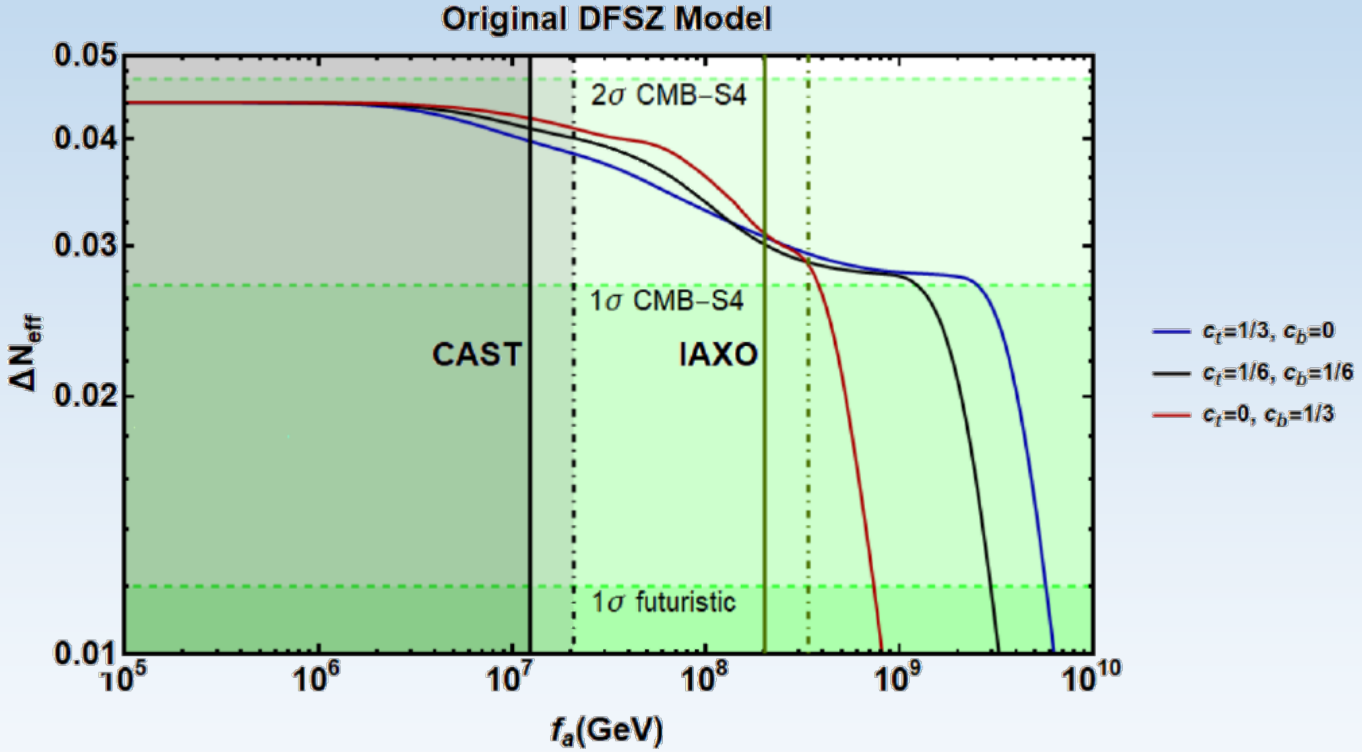
❖ **UV Complete Models**

- Specific models give a single prediction for $\Delta N_{eff}(f_a)$
- Two classical invisible axion scenarios:
    - DFSZ. $c_t + c_b = 1/3\,, E/N$ has two possible values
    - KSVZ. Only gluon process, many values for E/N
- An example of a flavourful axion model:
    - The Minimal Flavour Violating Axion. $c_t = 0, E/N = 8/3$

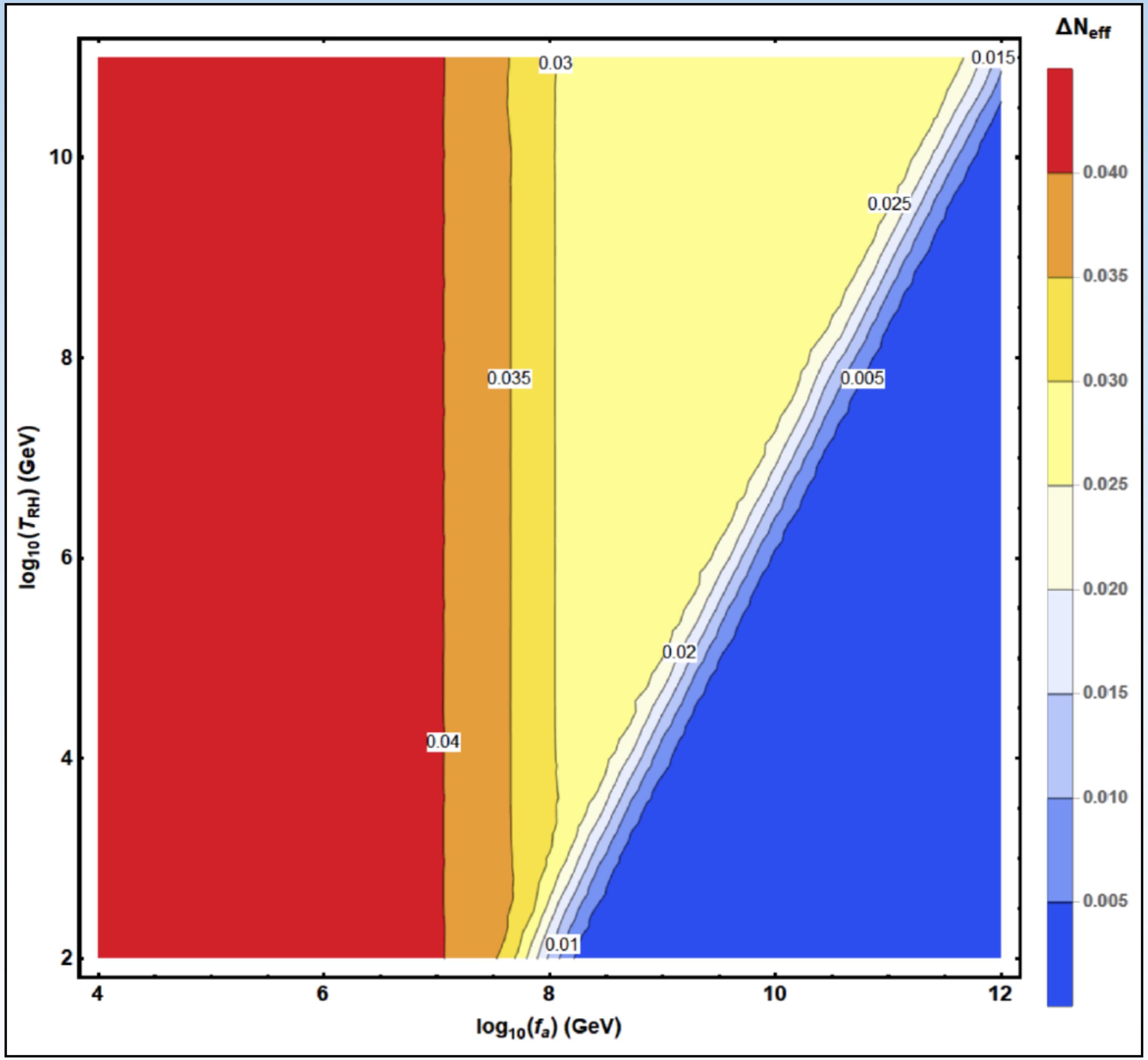
Axion Dark Radiation and ΔN_{eff} – Production Across EWPT



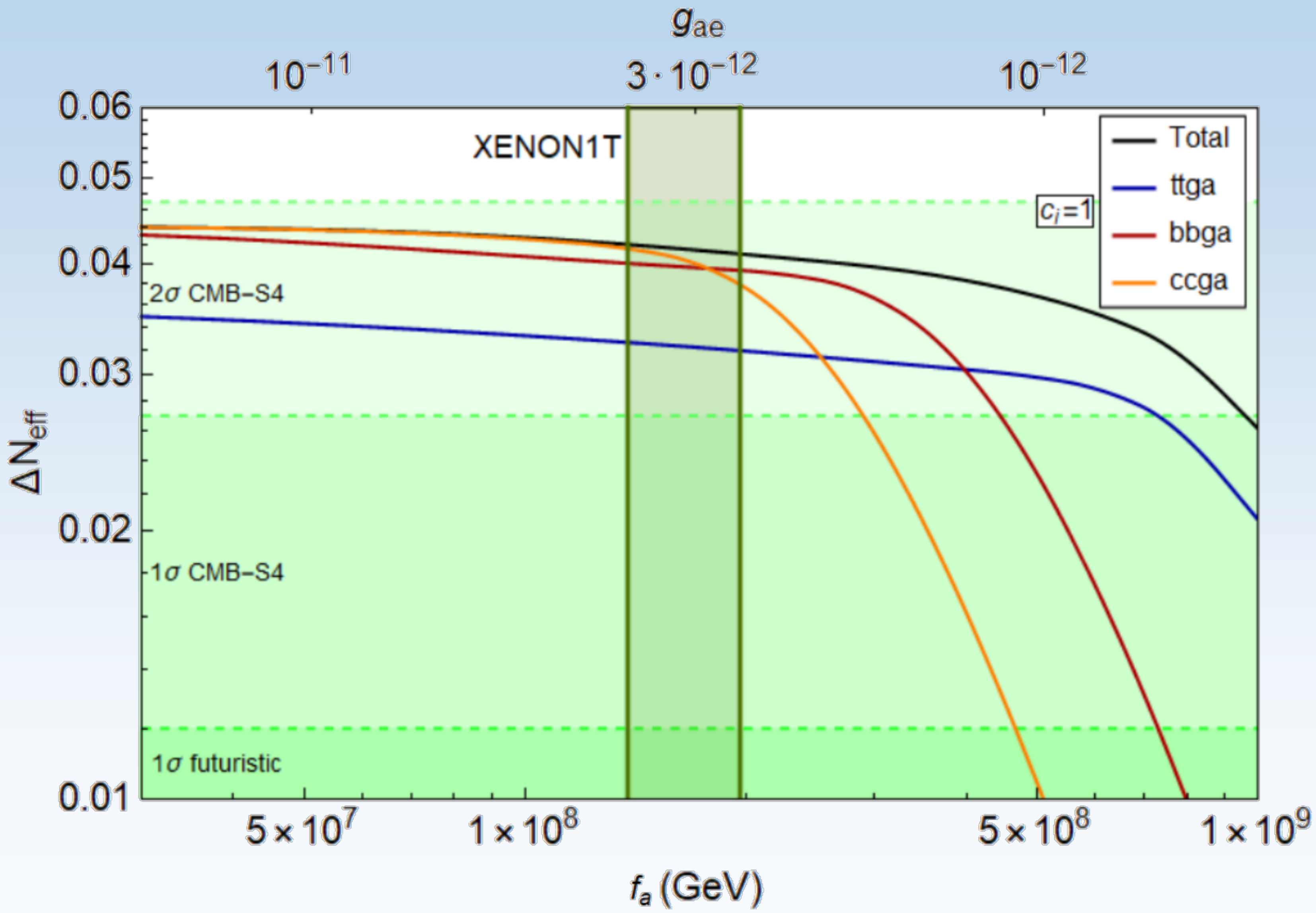




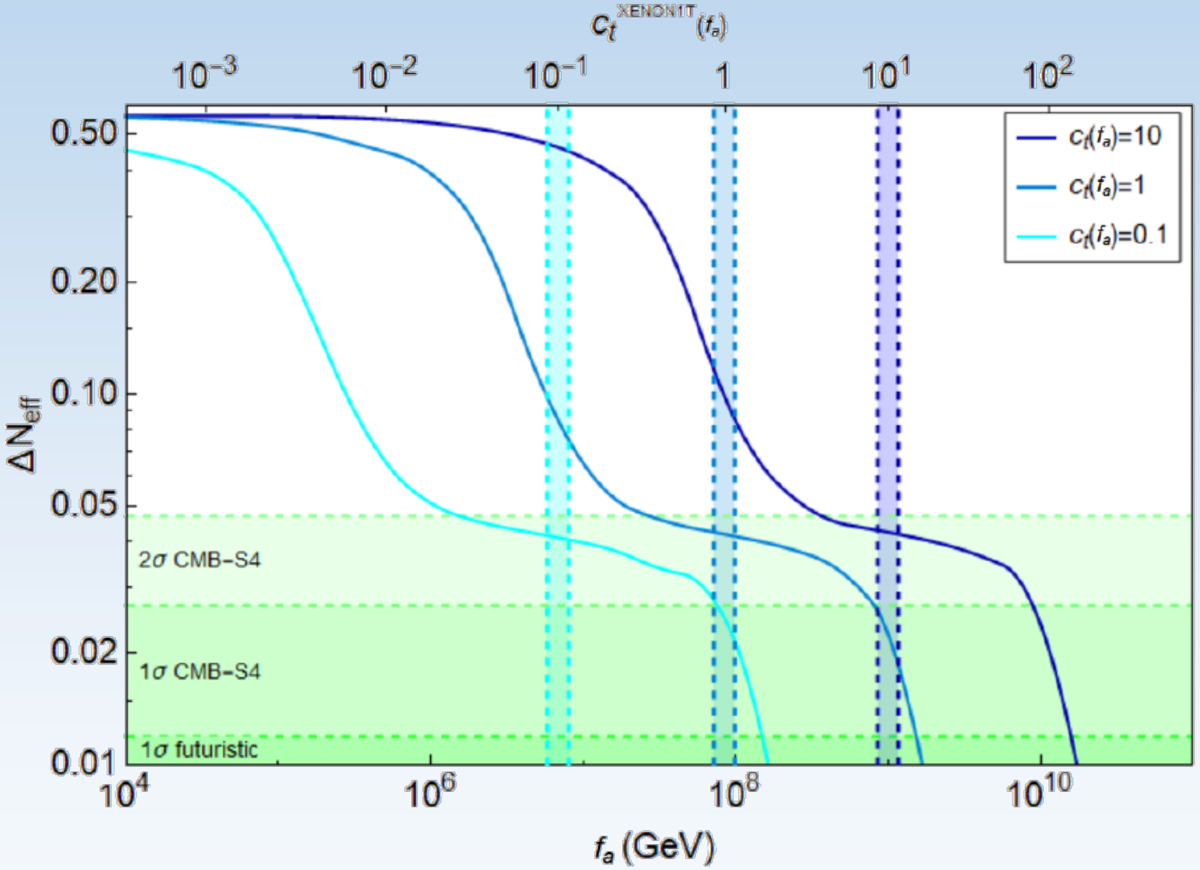
Interplay of T_{RH} and f_a

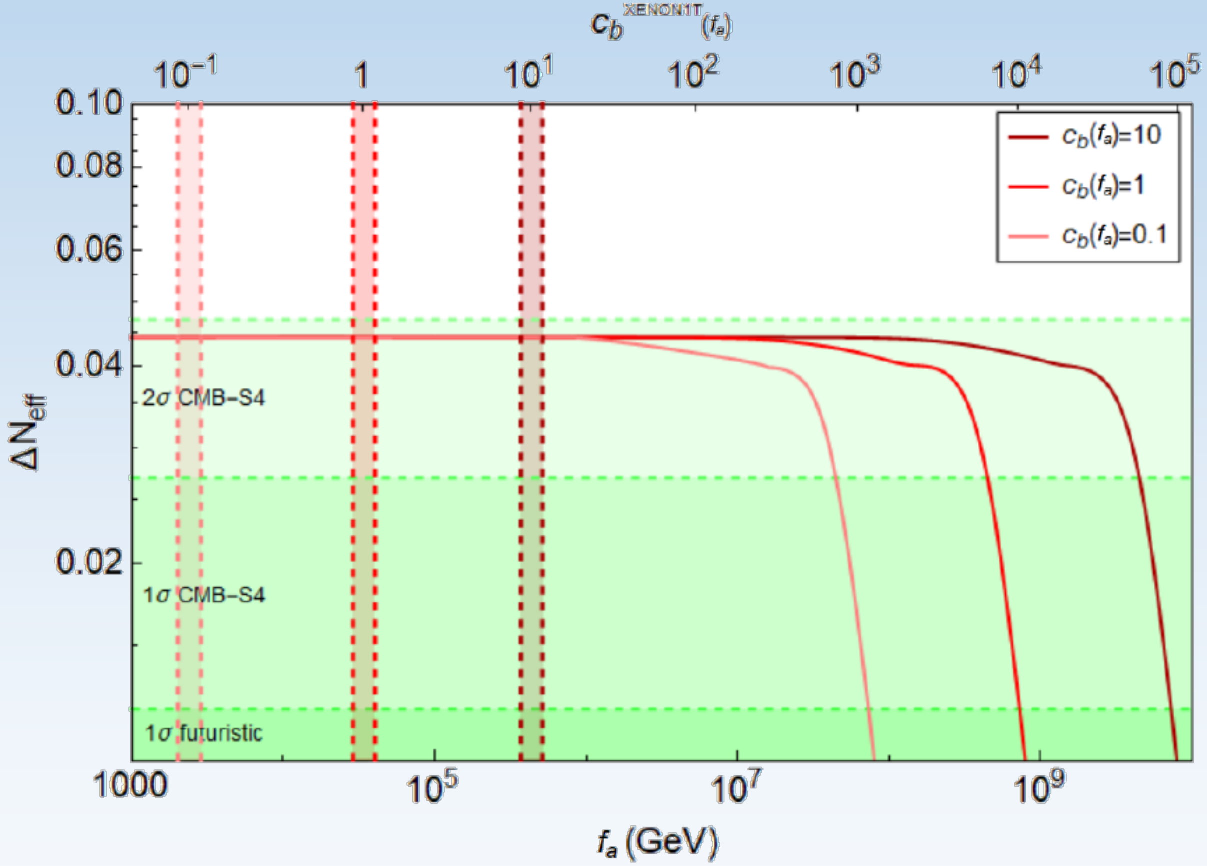


Axion Dark Radiation and ΔN_{eff} – XENON1T

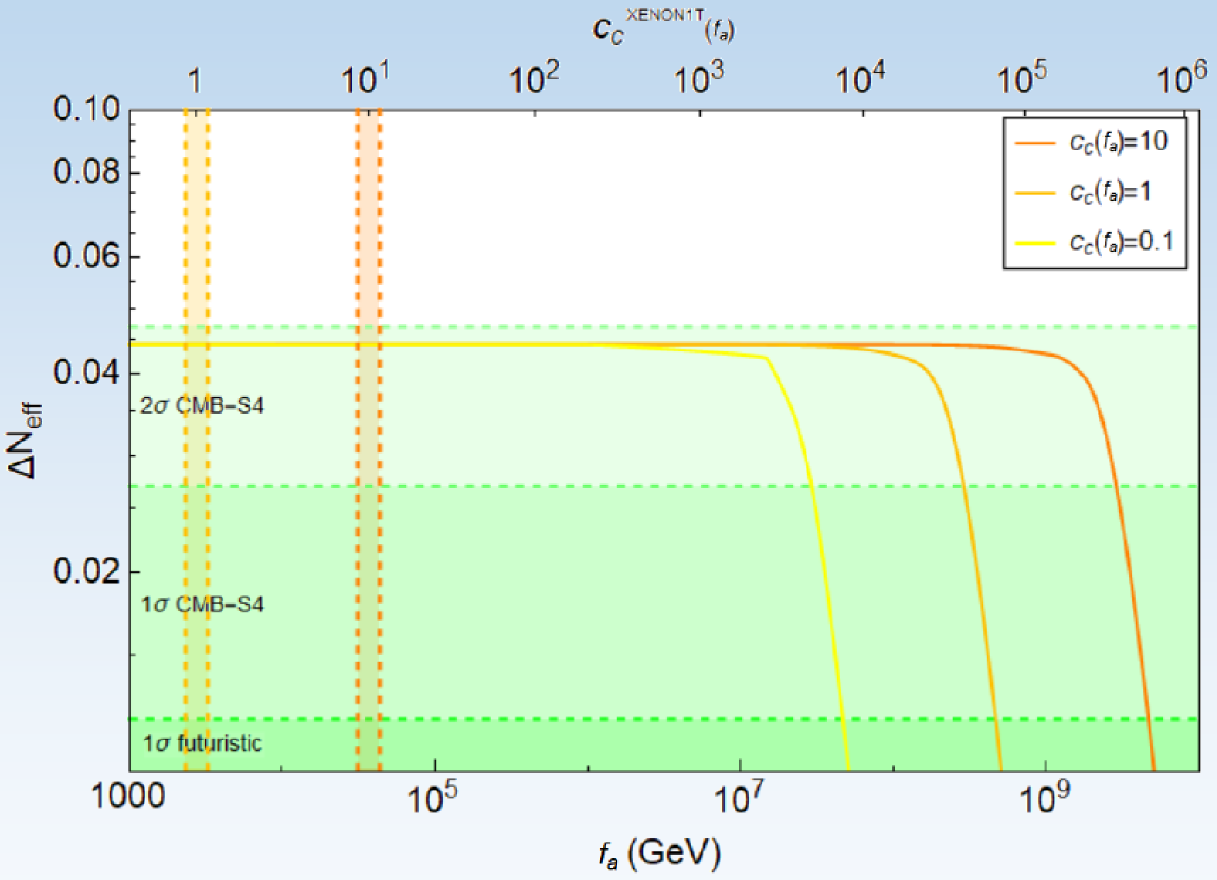


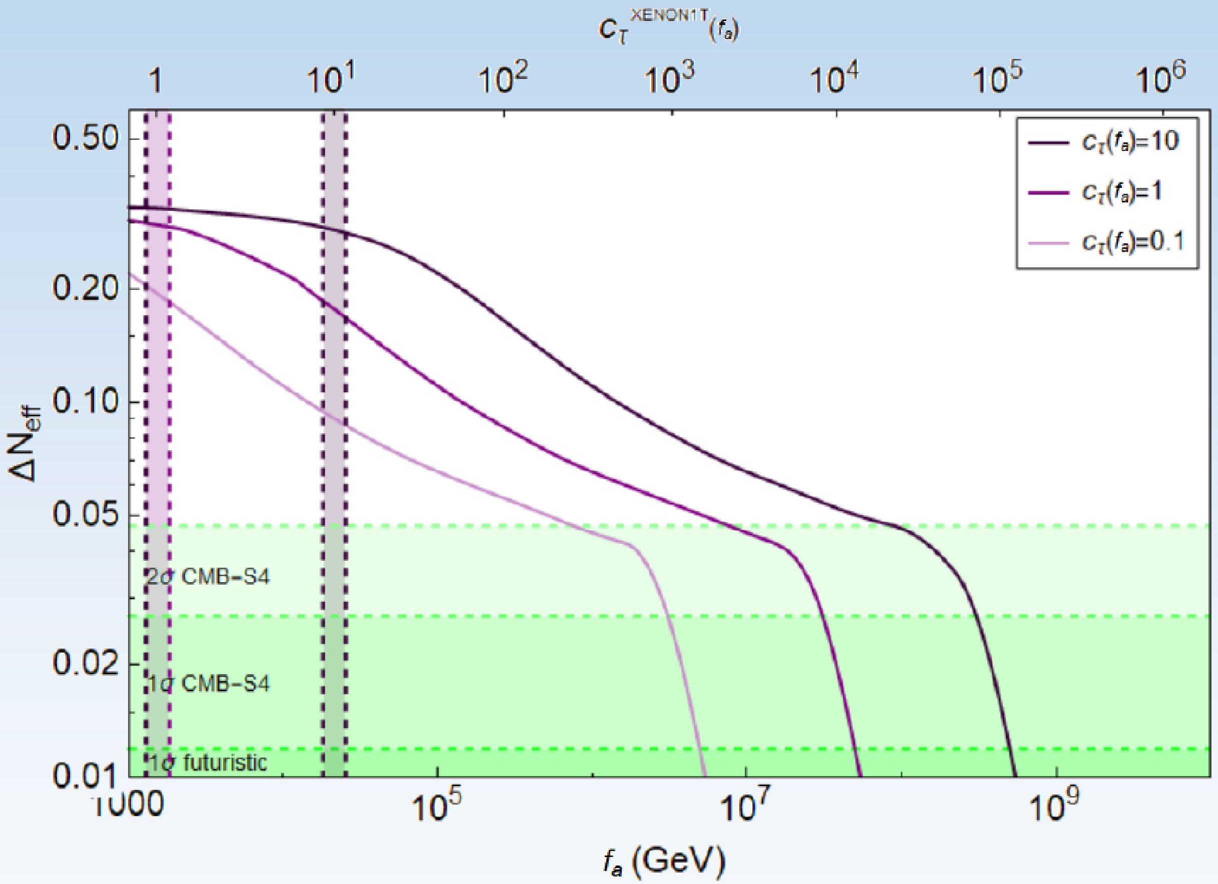
Axion Dark Radiation and ΔN_{eff} – XENON1T





Axion Dark Radiation and ΔN_{eff} – XENON1T





Axion Dark Radiation and ΔN_{eff} – $\Delta N_{eff} > 0$

- No detection or $\Delta N_{eff} \lesssim 0{,}03$: none or small axion-heavy quark coupling

- $\Delta N_{eff} \sim 0{,}03 - 0{,}05$: hint towards axion-heavy quark coupling. Possibility to test c_ψ / c_e for models with fixed PQ charges

- $\Delta N_{eff} \gtrsim 0{,}05$: either $c_\tau \neq 0$ with low f_a or production through bottom and/or charm quark below 1 GeV