Phenomenological and Cosmological Aspects of Axions and Other NGB

Fernando Arias Aragón

Outline

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- Fundamentals and Motivation

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- The Minimal Flavour Violating Axion

FAA, L. Merlo, 1709.07039
FAA, E. Fernández-Martínez, M. González-López, L. Merlo, 2009.01848
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- Axiond Dark Radiation and ΔN_{eff}

FAA, F. D'Eramo, R. Z. Ferreira, L. Merlo, A. Notari, 2007,06579
FAA, F. D'Eramo, R. Z. Ferreira, L. Merlo, A. Notari, 2012.04736

FAA, C. Bouthelier-Madre, J. M. Cano, L. Merlo, 2003.05941 also published

Fundamentals and Motivation

SM and Open Problems:

Flavour Puzzle and Strong CP Problem

The SM and its Open Problems

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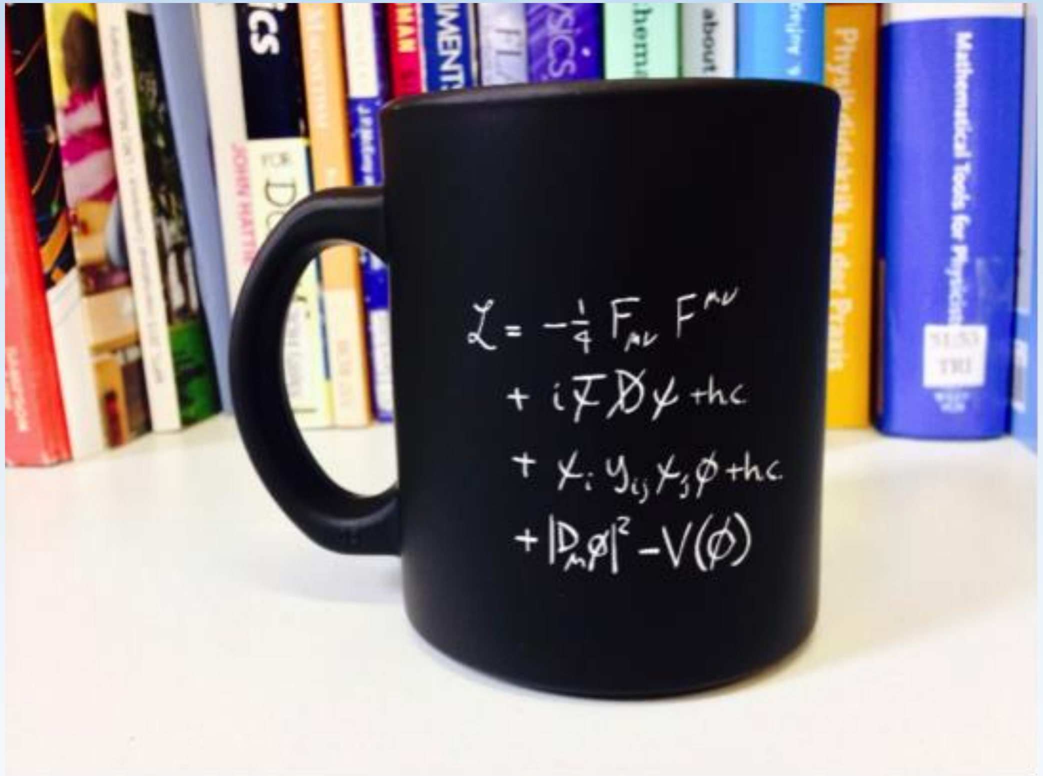

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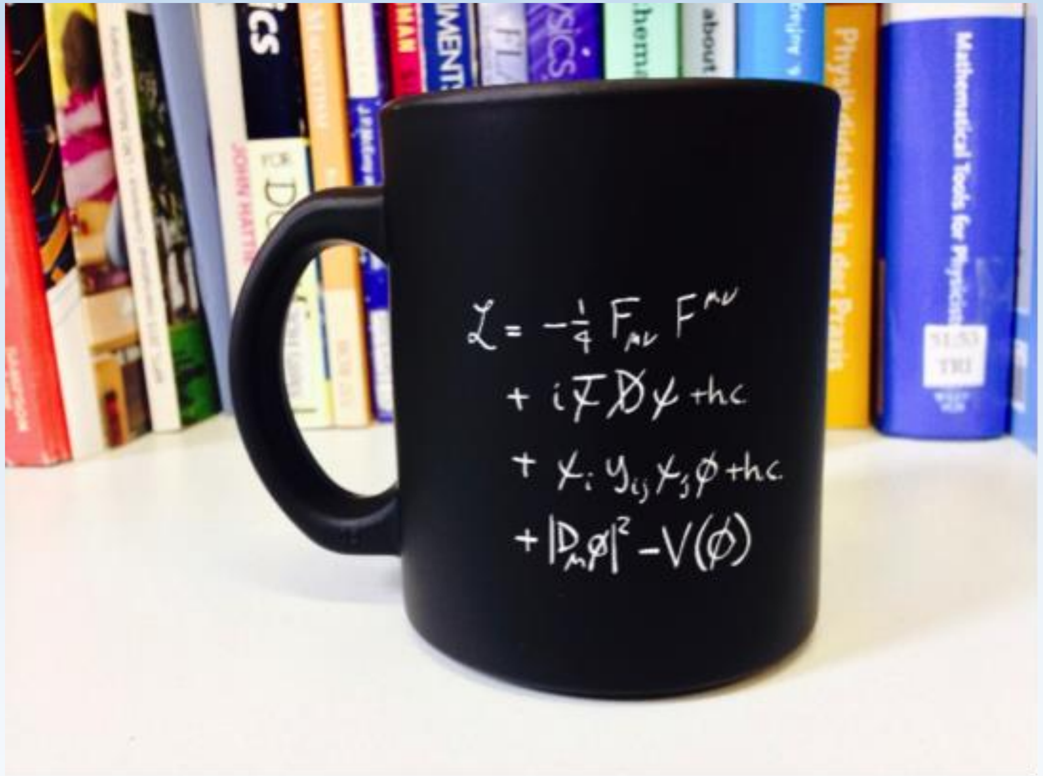

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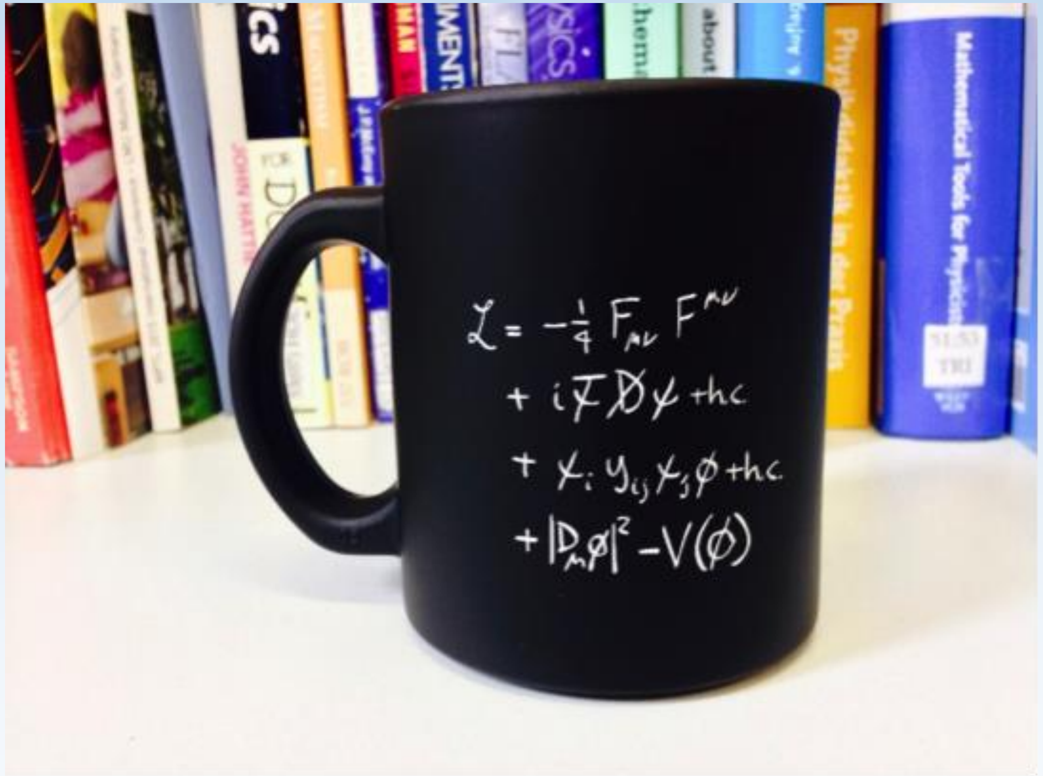

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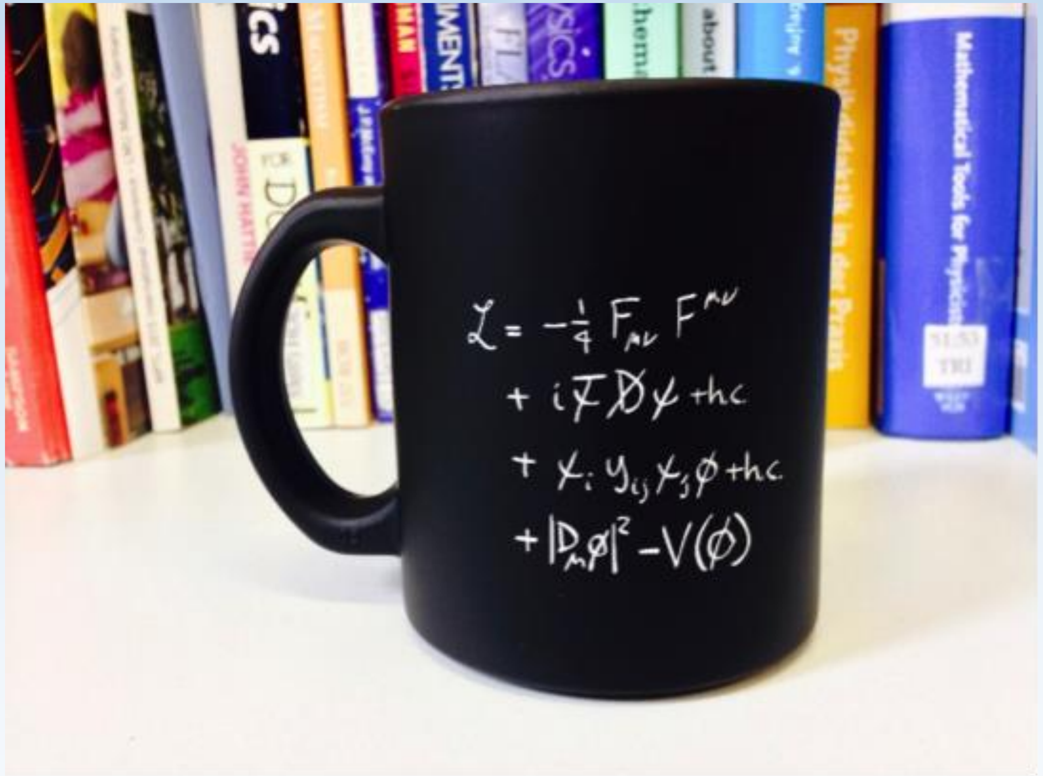

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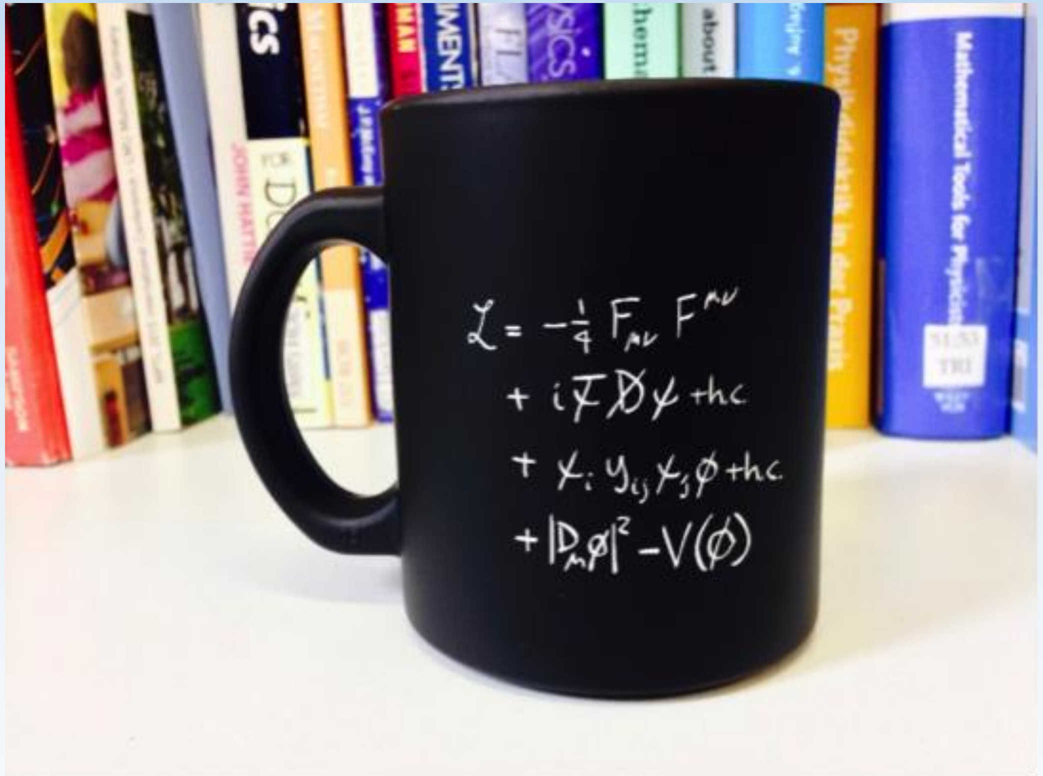

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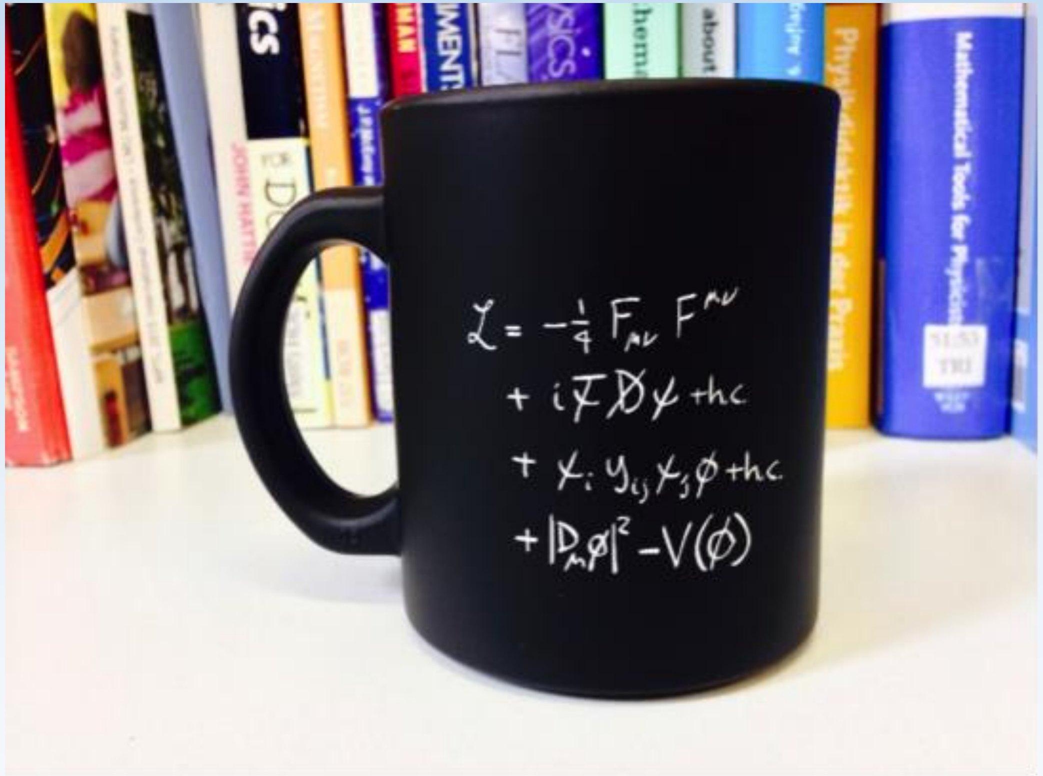

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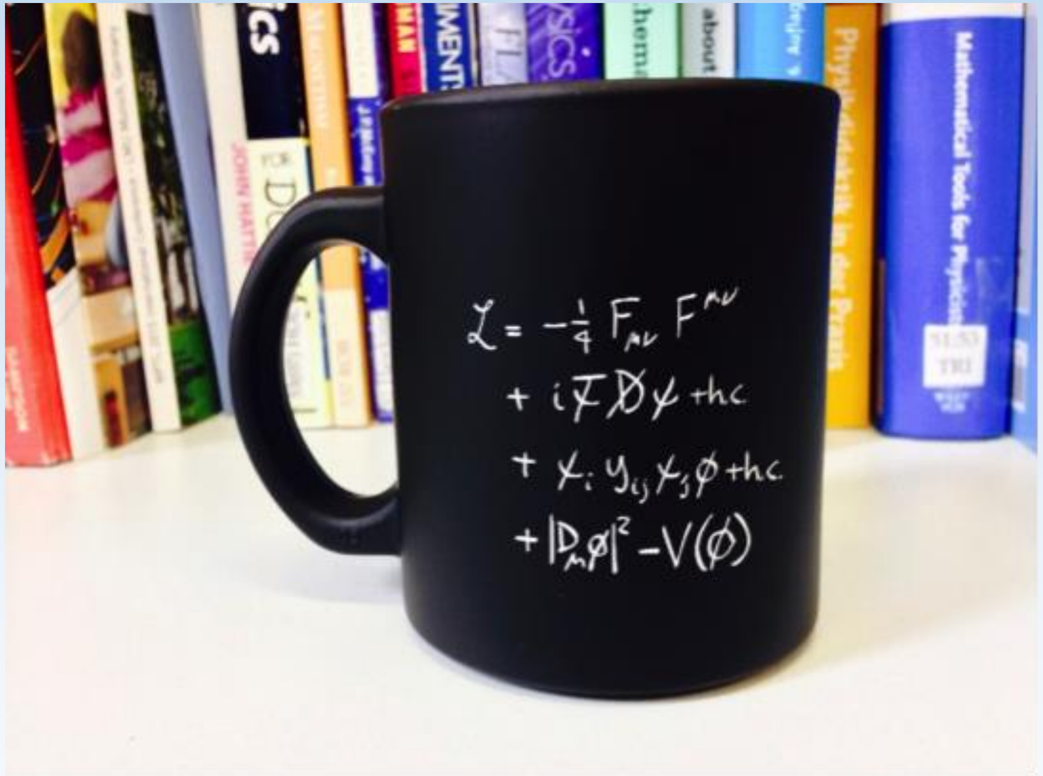

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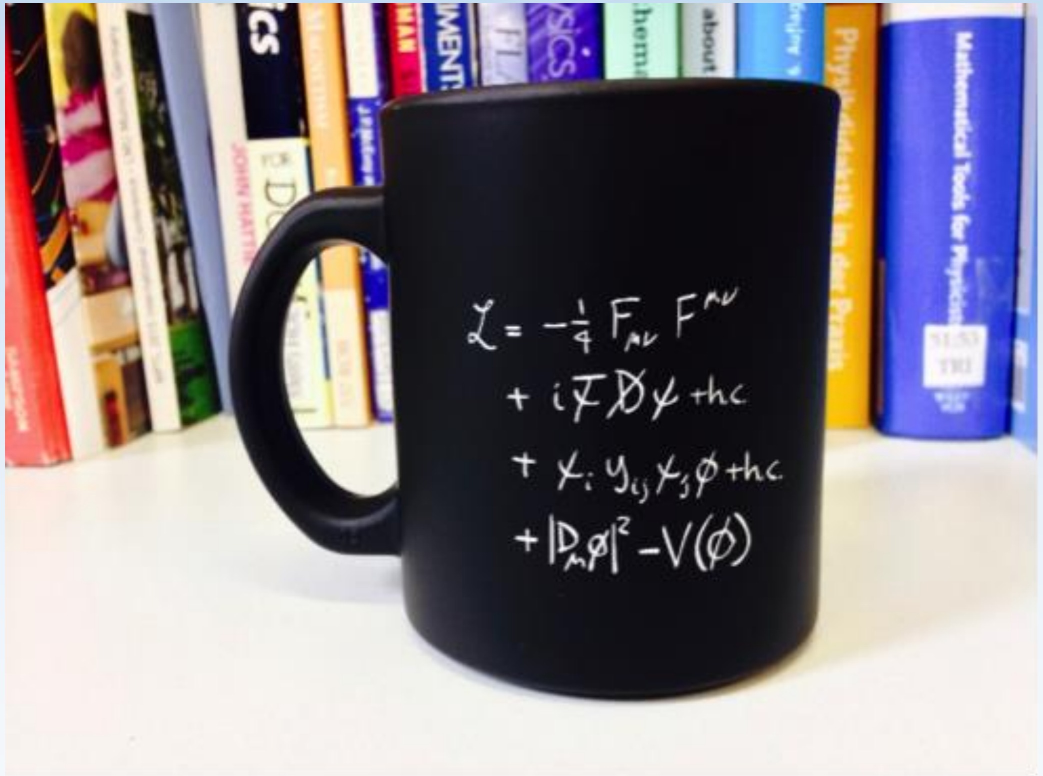

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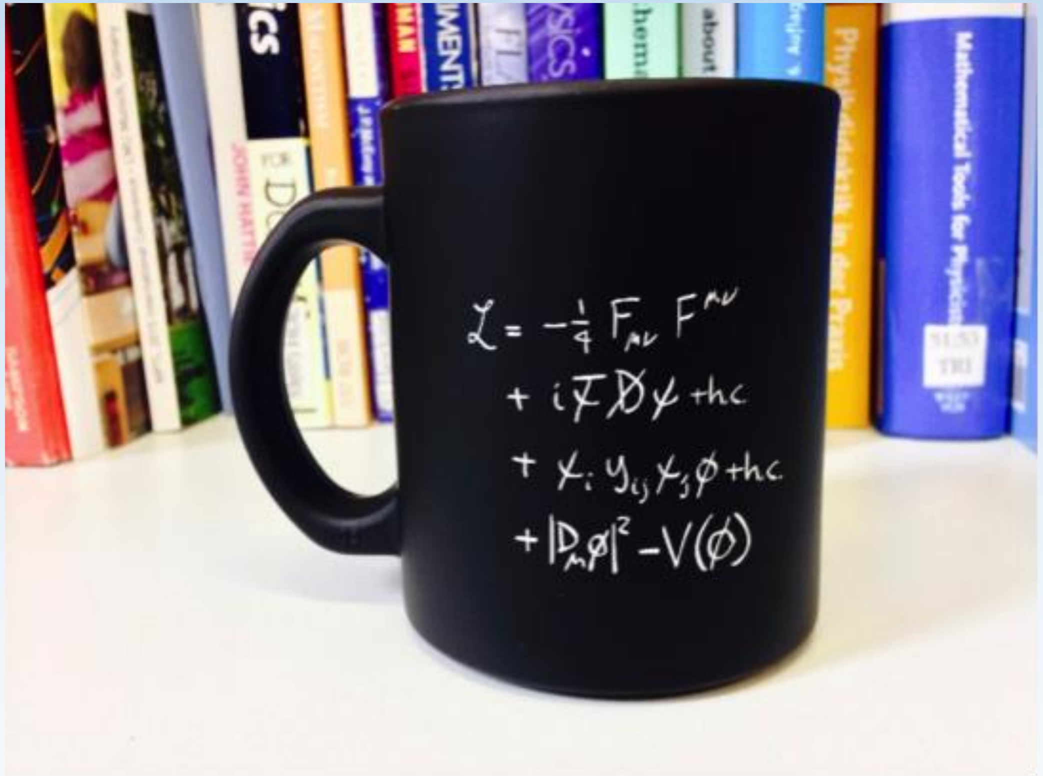

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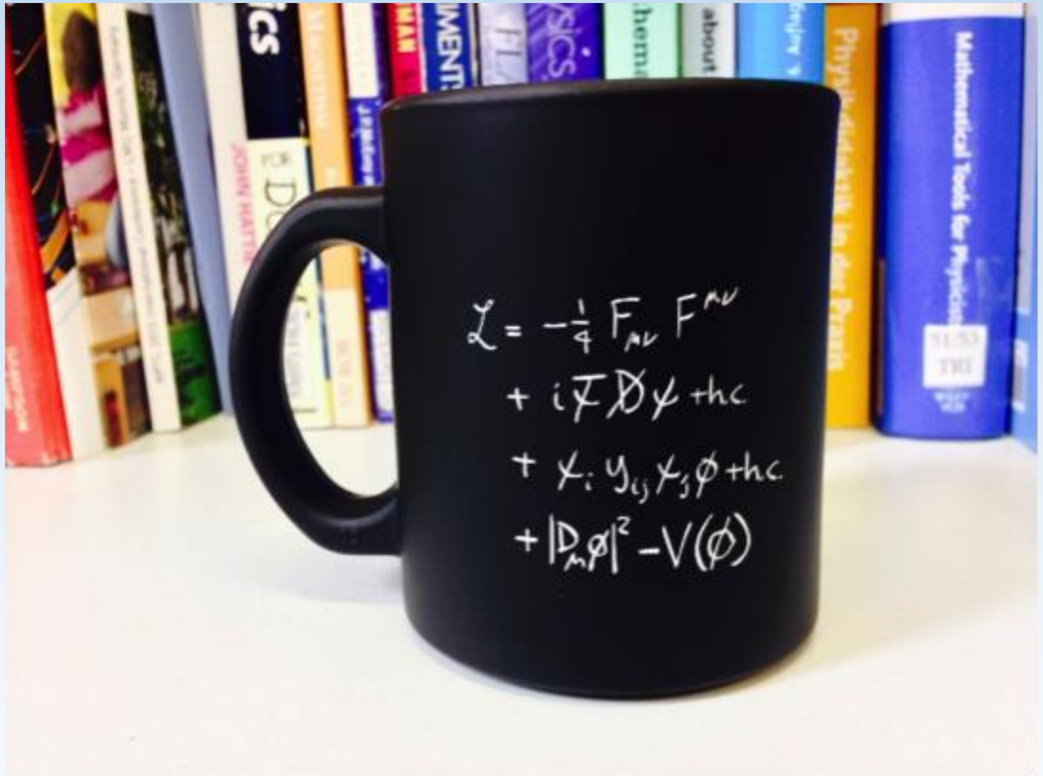

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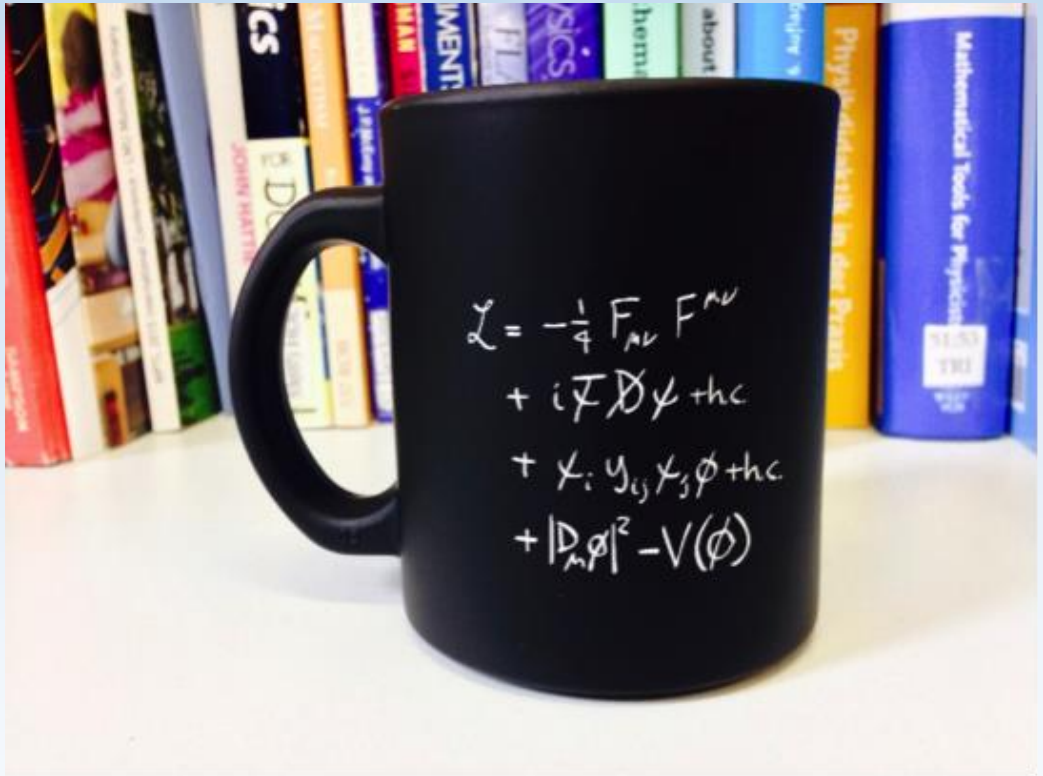

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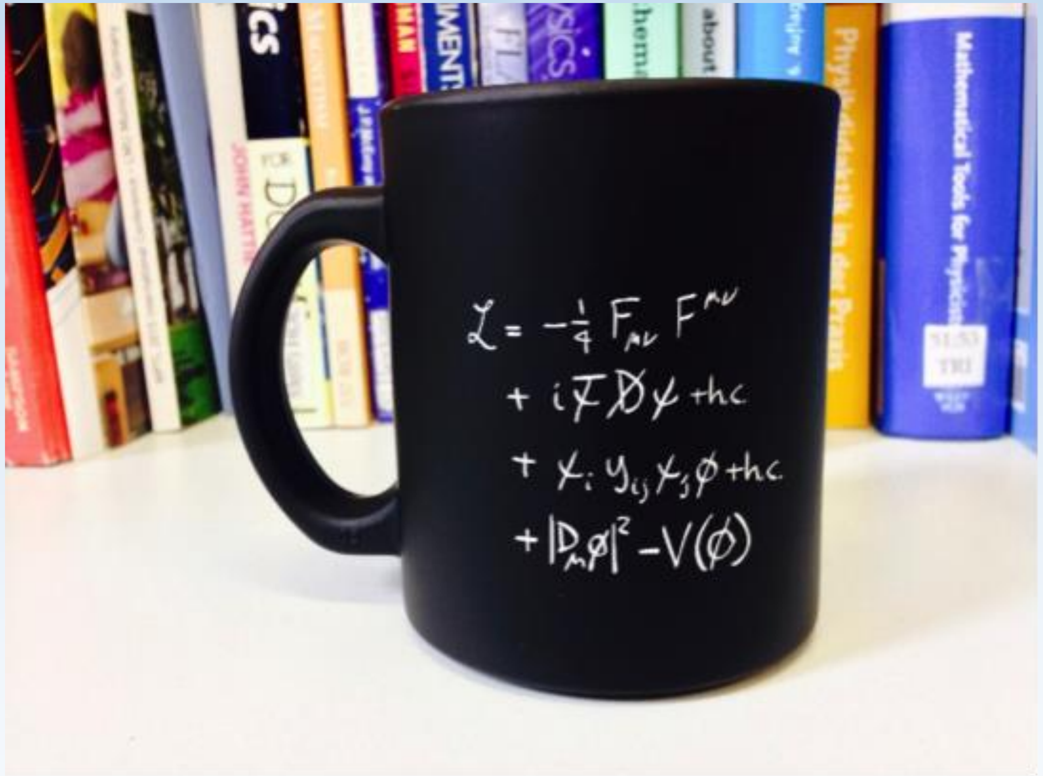

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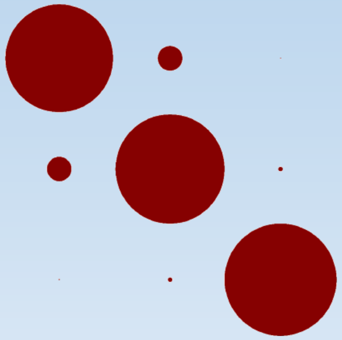

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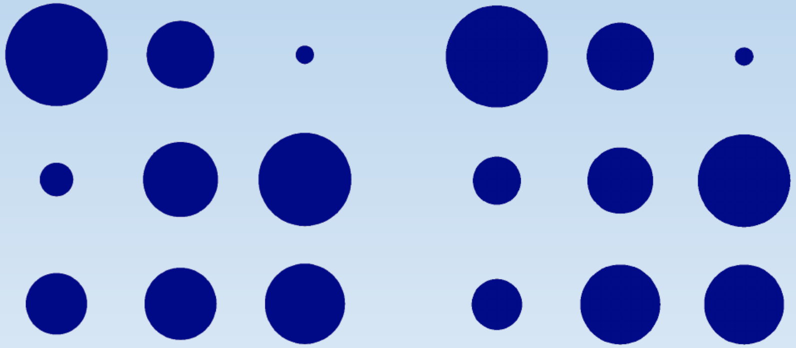

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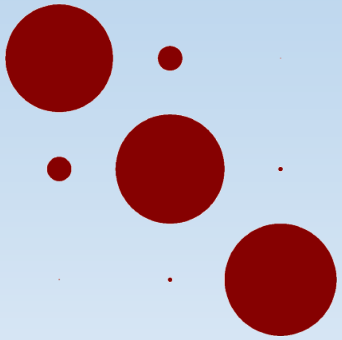

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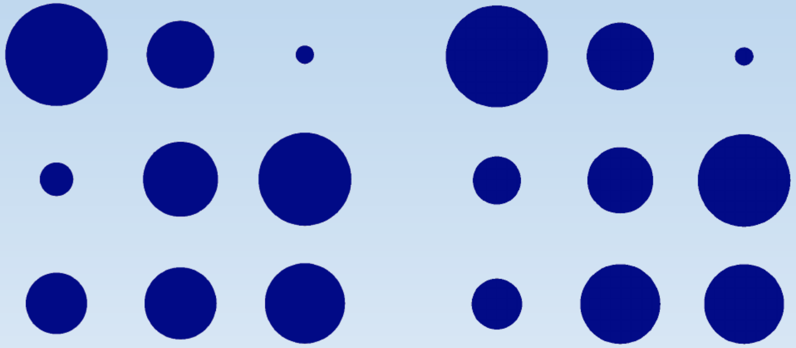

$\nu = \bar{\nu}$ vs $\nu \neq \bar{\nu}$

	First Generation	Second Generation	Third Generation
Up-type quarks	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-2})$	1
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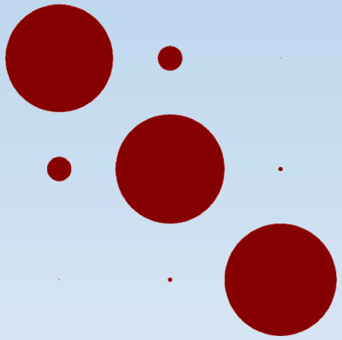

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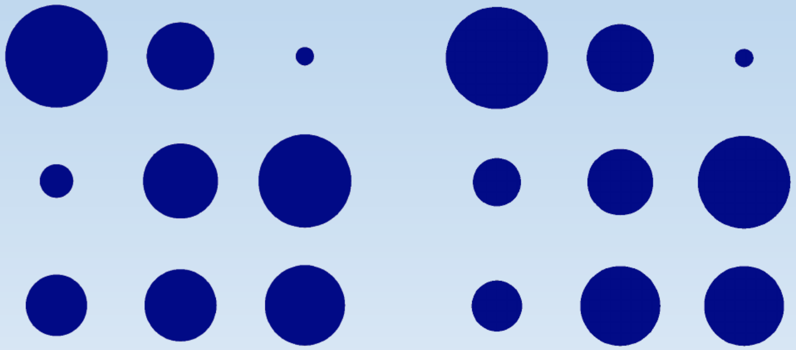

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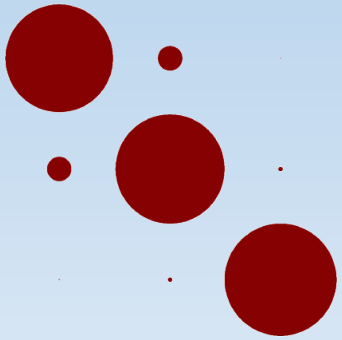

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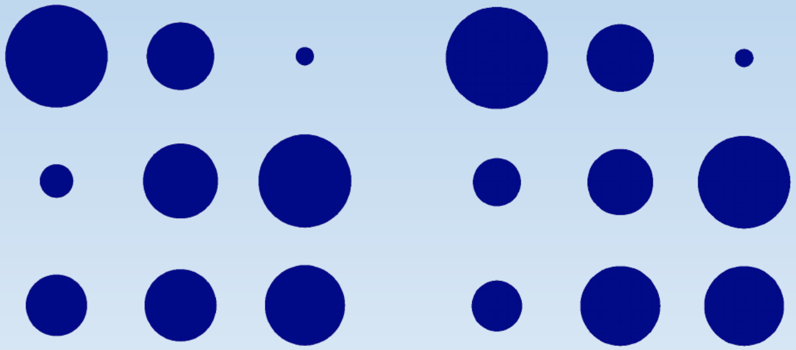

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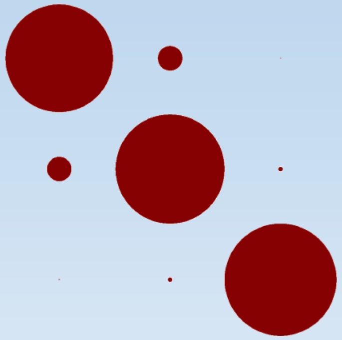

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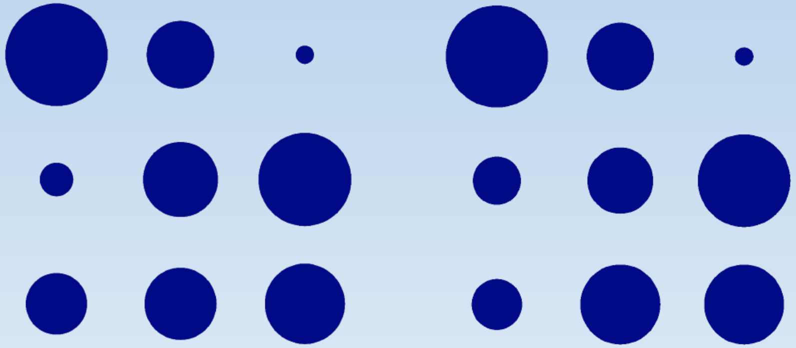

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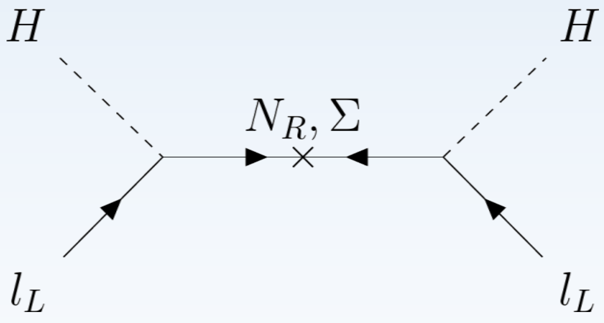
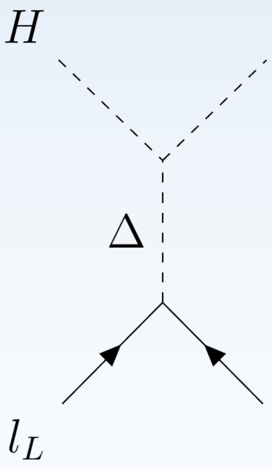
Mohapatra and Senjanovic. PRD 23 (1981) 165
Lazarides, Shafi and Wetterich, NPB 181 (1981) 287-300
Schechter and Valle, PRD 25 (1982) 774



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



The BSM Flavour Problem and MFV

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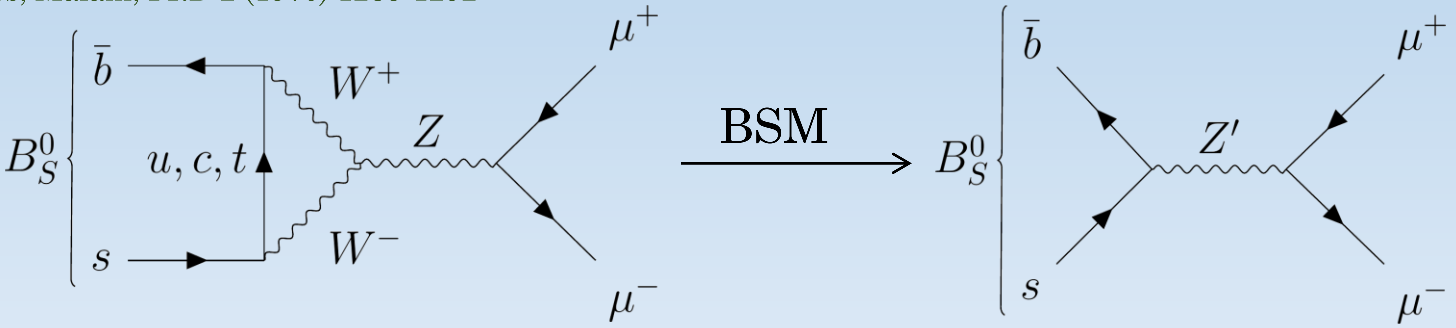
- SM flavour sensitive to new loop contributions and BSM FCNCs

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



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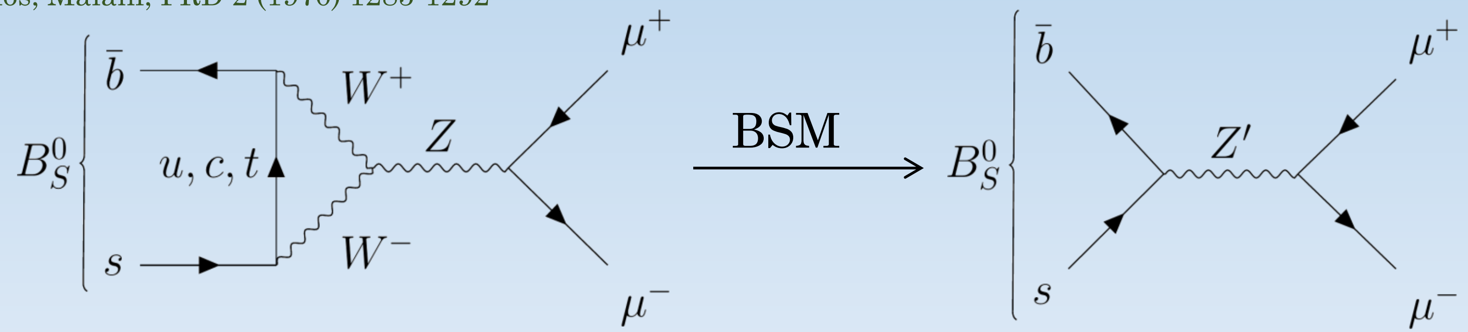

- Without observed deviations $\Lambda_{\mathrm{NP}} \gtrsim \mathcal{O}(10^4\ \mathrm{TeV})$ Isidori et al., 1002.0900, Ellis et al., 1910.11775

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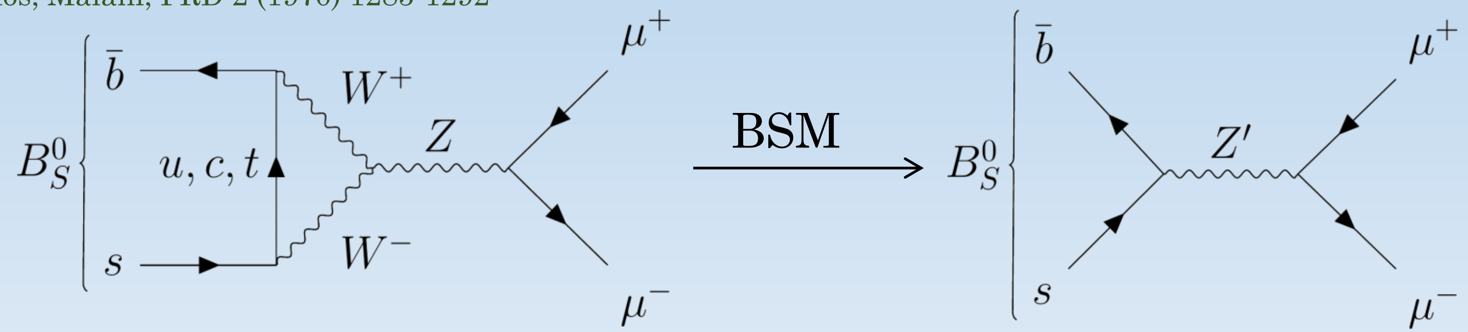

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$$\mathcal{L}_{Kin} \Rightarrow \mathcal{G}_F = U(3)_{q_L} \times U(3)_{u_R} \times U(3)_{d_R} \times U(3)_{l_L} \times U(3)_{e_R}$$

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

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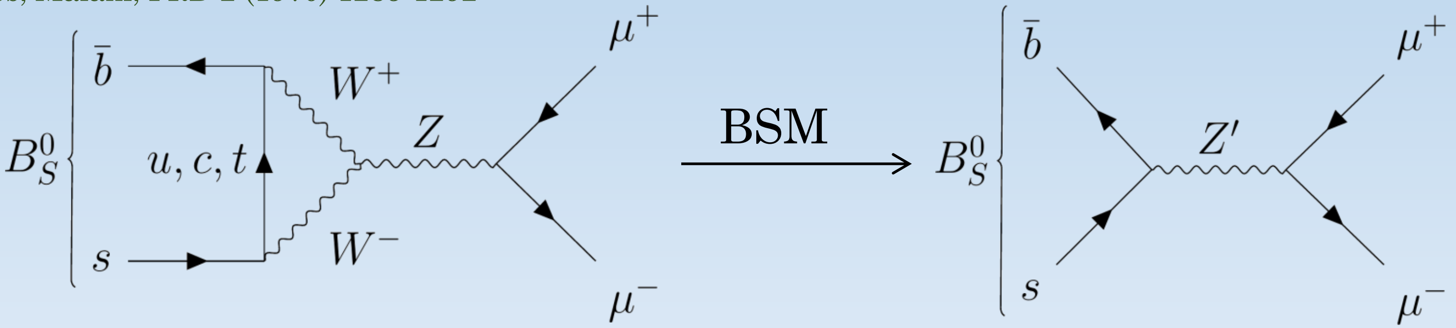

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- Yukawas suppress all NR operators, lowering the NP scale to a few TeVs

The Strong CP Problem

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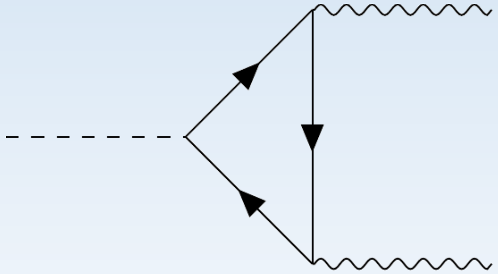
- The $G\tilde{G}$ term is related to quark masses through the chiral anomaly



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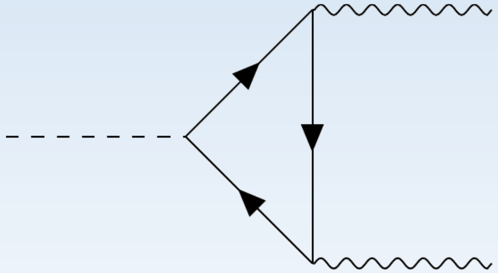

$$\bar{\theta}=\theta_{QCD}+\mathrm{Arg}\left(\mathrm{Det}\left(M_uM_d\right)\right)$$

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

Crewther, Di Vecchia, Veneziano & Witten, 1980

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

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

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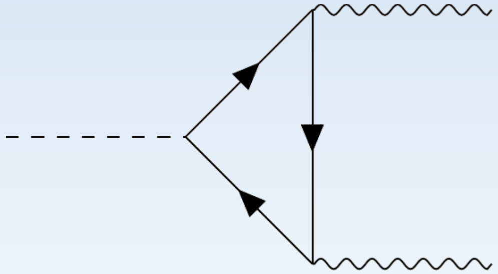

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$$d_n \sim \bar{\theta} \times 10^{-16} e \cdot cm, \qquad \bar{\theta} \lesssim \mathcal{O}(10^{-10})$$

- Why is a dimensionless parameter so small?

The Strong CP Problem – The Axion Mechanism

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

- $\bar{\theta}$ becomes dynamical by introducing an axial global symmetry $U(1)_{PQ}$, broken spontaneously

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- Its NGB, the axion a, couples to gluons through the chiral anomaly

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

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The Strong CP Problem – The Axion Mechanism

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- DFSZ and KSVZ models avoid this problem

A. R. Zhitnitsky, Sov. J. Nucl. Phys. 31 (1980)
M. Dine, W. Fischler, M. Srednicki, Phys. Lett. B104 (1981)

J. E. Kim, PRL 43 (1979)
M. A. Shifman, A. I. Vainshtein, V. I. Zakharov, Nucl. Phys. B166 (1980)

The Minimal Flavour Violating Axion

Setup and Phenomenology

FAA, L. Merlo, 1709.07039

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- Perturbativity of the Weinberg operator + predictability in $\mu \to e$ in Au nuclei spurion fix x_l

$$\mathscr{L}_5 = \left(\frac{\Phi}{\Lambda_\Phi}\right)^{2x_l} \times \frac{\left(\overline{l_L^c}\widetilde{H}^*\right)\mathcal{G}_\nu\left(\widetilde{H}^\dagger l_L\right)}{\Lambda_L} \longrightarrow \Lambda_L \simeq \frac{v^2}{2}\frac{g_\nu\,\epsilon^{2x_l}}{\sqrt{\Delta m^2_{\text{atm}}}} \lesssim 6\times 10^{14}\ \text{GeV} \times \epsilon^{2x_l}$$

$$\text{S0:} \qquad x_q = 0 = x_u = x_l\,, \qquad x_d = 3 = x_e$$

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Minimal Flavour Violating Axion

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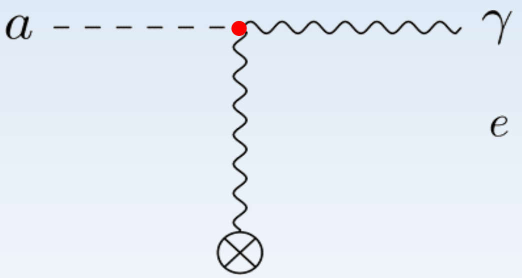

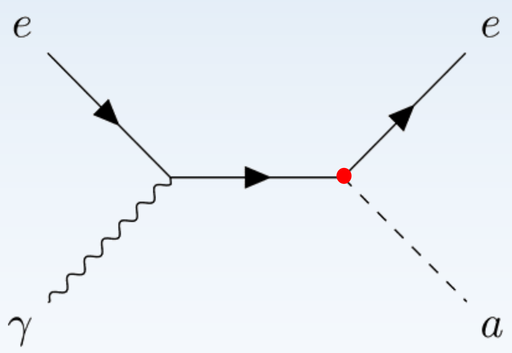

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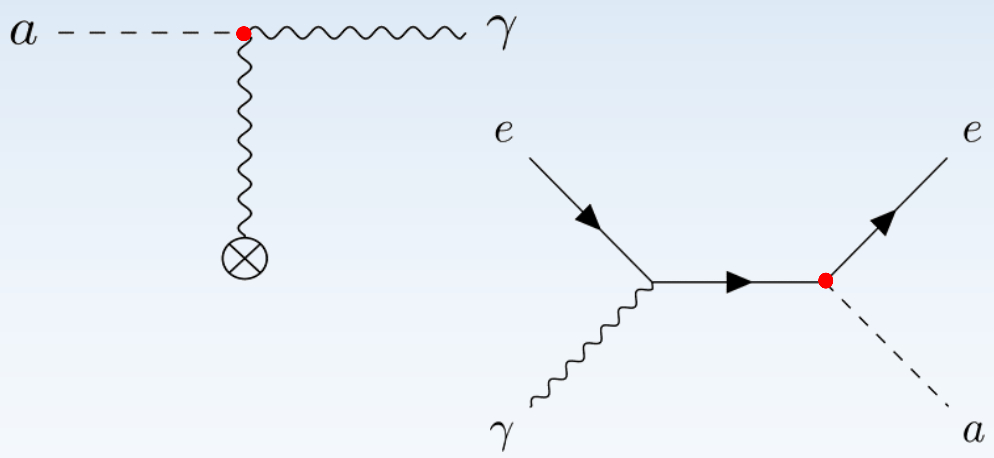

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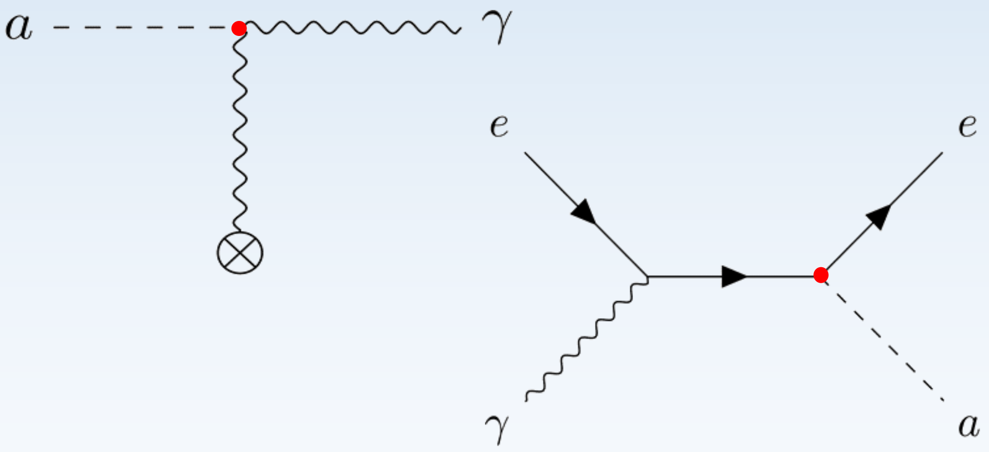

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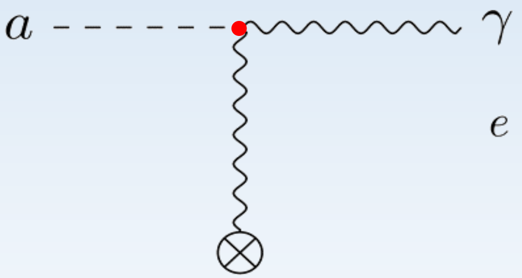

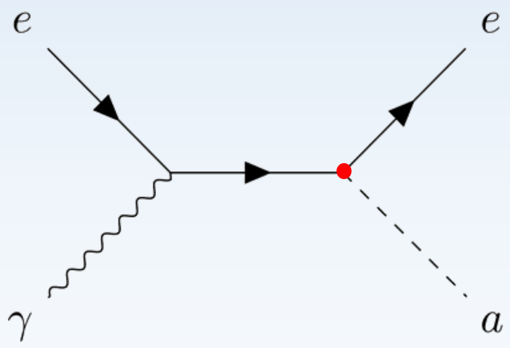

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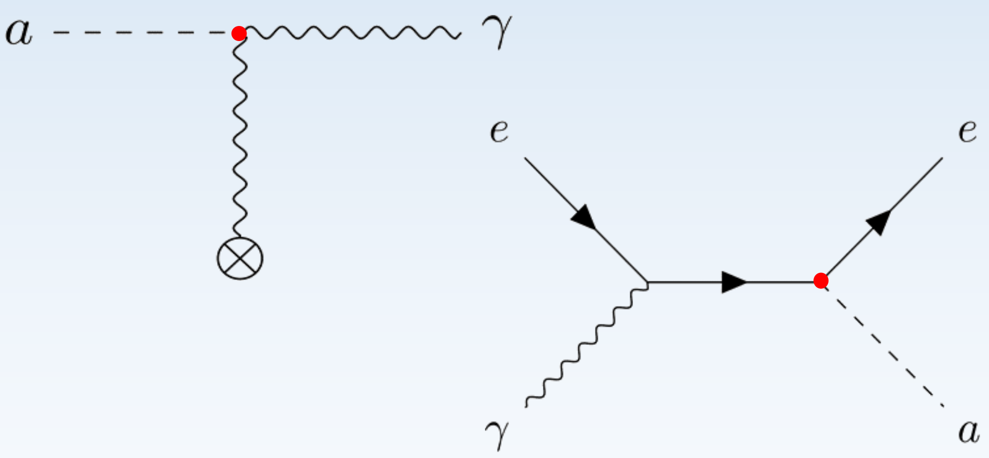

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$$m_a \sim 1\ \mathrm{GeV}$$

Brivio et al., 1701.05379

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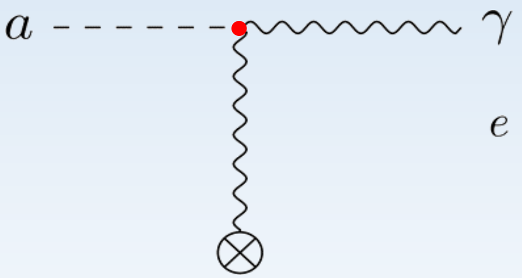

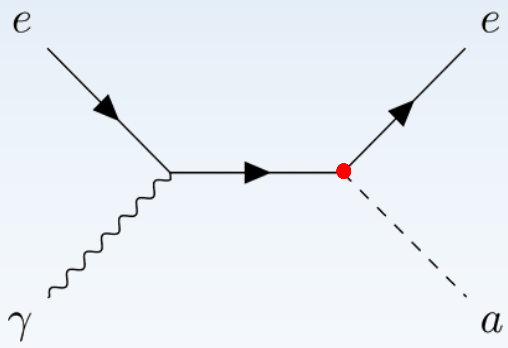

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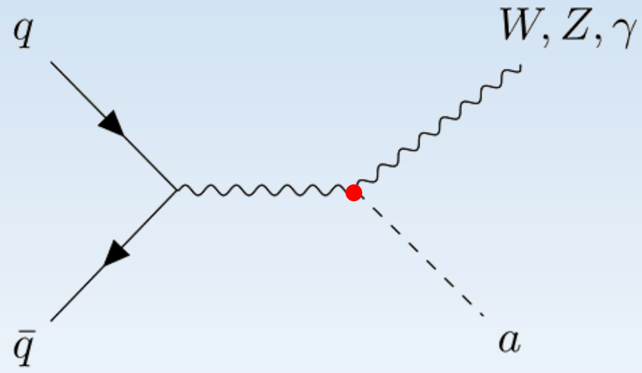

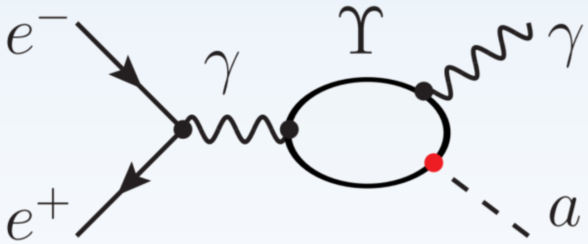

Axion Dark Radiation and ΔN_{eff}

Production Across EWPT and

Complementarity with XENON1T

FAA, F. D'Eramo, R. Z. Ferreira, L. Merlo, A. Notari, 2007,06579
FAA, F. D'Eramo, R. Z. Ferreira, L. Merlo, A. Notari, 2012.04736

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- N_{eff} probed in the future (CMB-S4, LiteBIRD, Simons Observatory)

CMB-S4 Collaboration, K. N. Abazajian et. al., CMB-S4 Science Book, First Edition, 1610.02743
https://astro.unibonn.de/ kbasu/ObsCosmo/Slides2019/sciencelitebird final.pdf
Simons Observatory Collaboration, P. Ade et. al., JCAP 1902 (2019) 056, 1808.07445

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	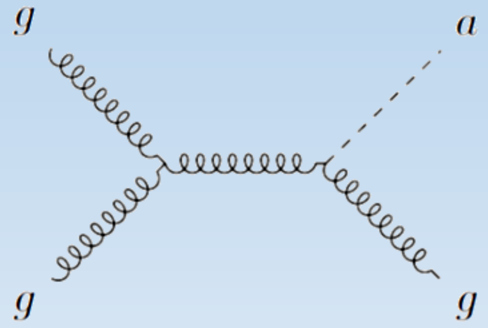	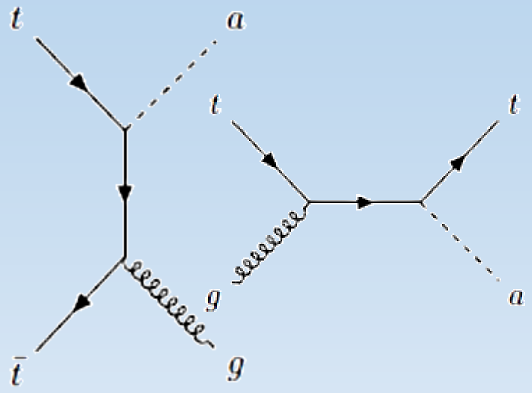	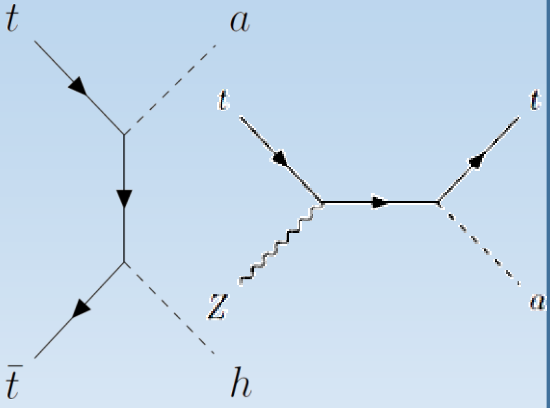
EWSB	$\updownarrow$	$\downarrow$	$\updownarrow$
Production rate	$\alpha_X^3 c_X^2 \frac{T^3}{f_a^2}$	$\alpha_X c_\psi^2 m_\psi^2 \frac{T}{f_a^2}, T > m_\psi$	$c_X^2 y_\psi^2 \frac{T^3}{f_a^2}, T > m_\psi$
Main production	Gluons, high T	Gluons, heavy fermions $T \sim m_\psi$	Heavy fermions, high T

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

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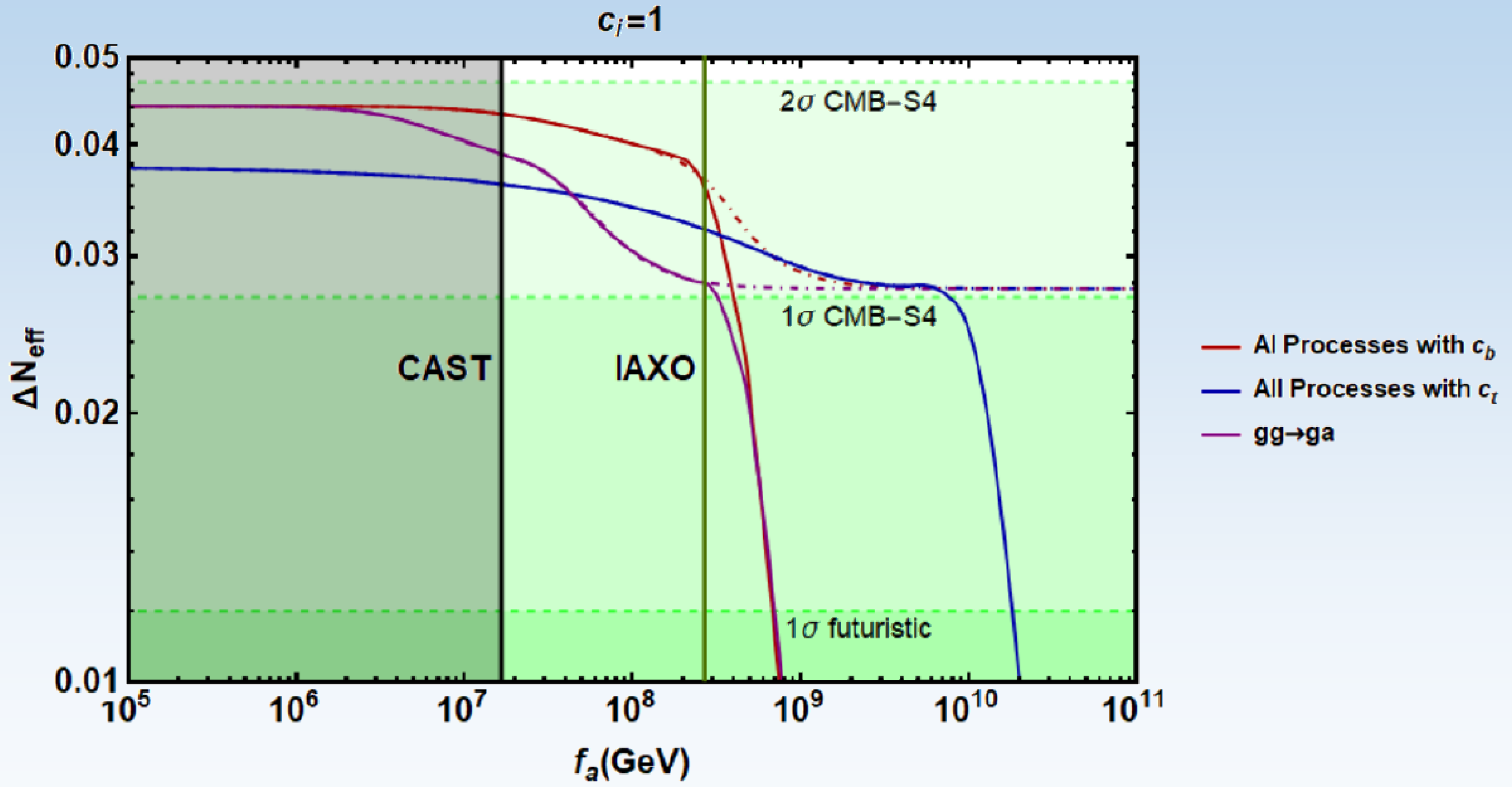

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XENON Collaboration, Phys.Rev.D 102 (2020), 2006.09721

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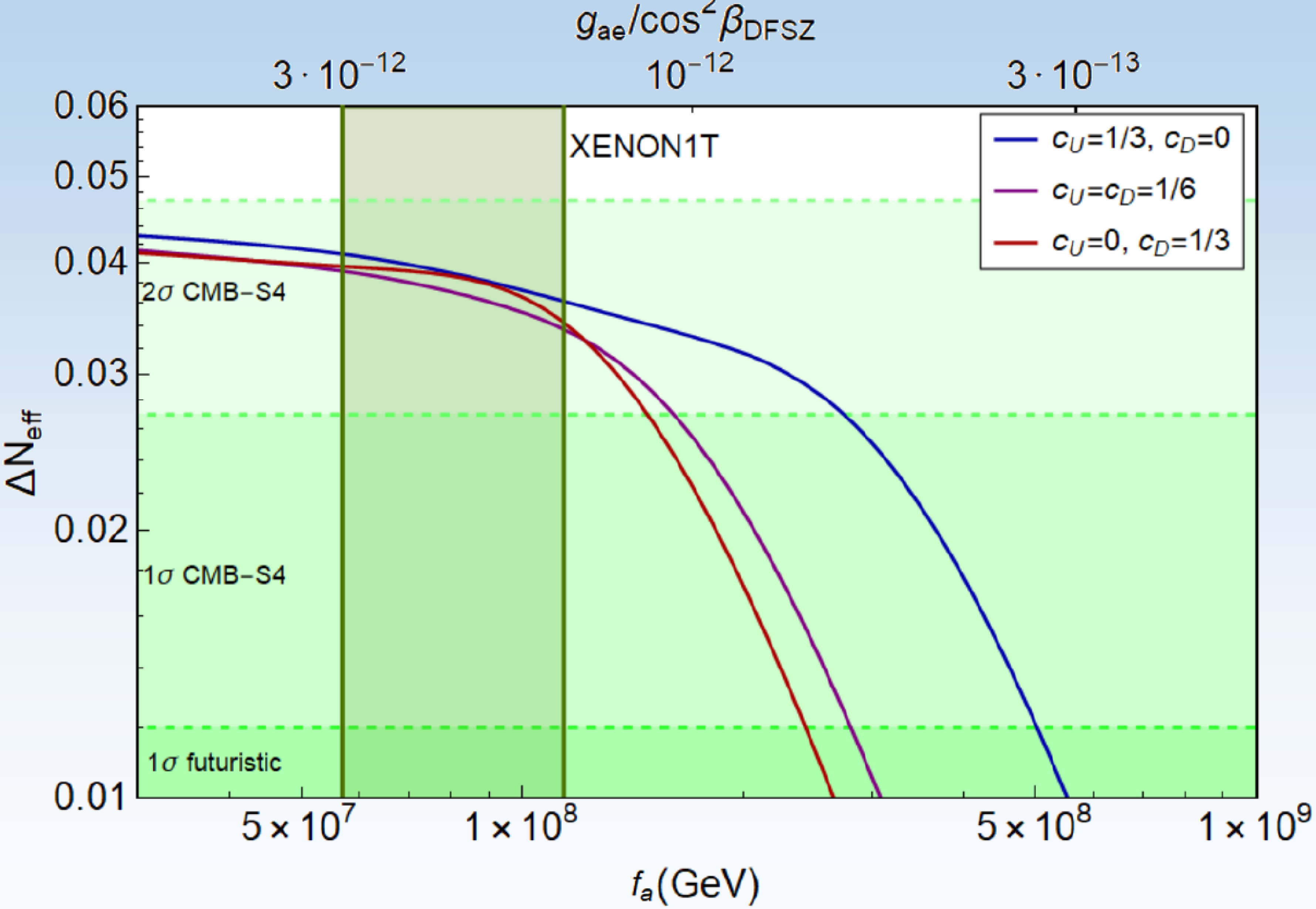
- Using the expected axion-electron coupling, we look at the expected ΔN_{eff} produced by these light relics in the DFSZ Model

Axion Dark Radiation and ΔN_{eff} – XENON1T



Thank you for your attention

Backup slides

Thermal History of the Universe: Λ_{CDM}

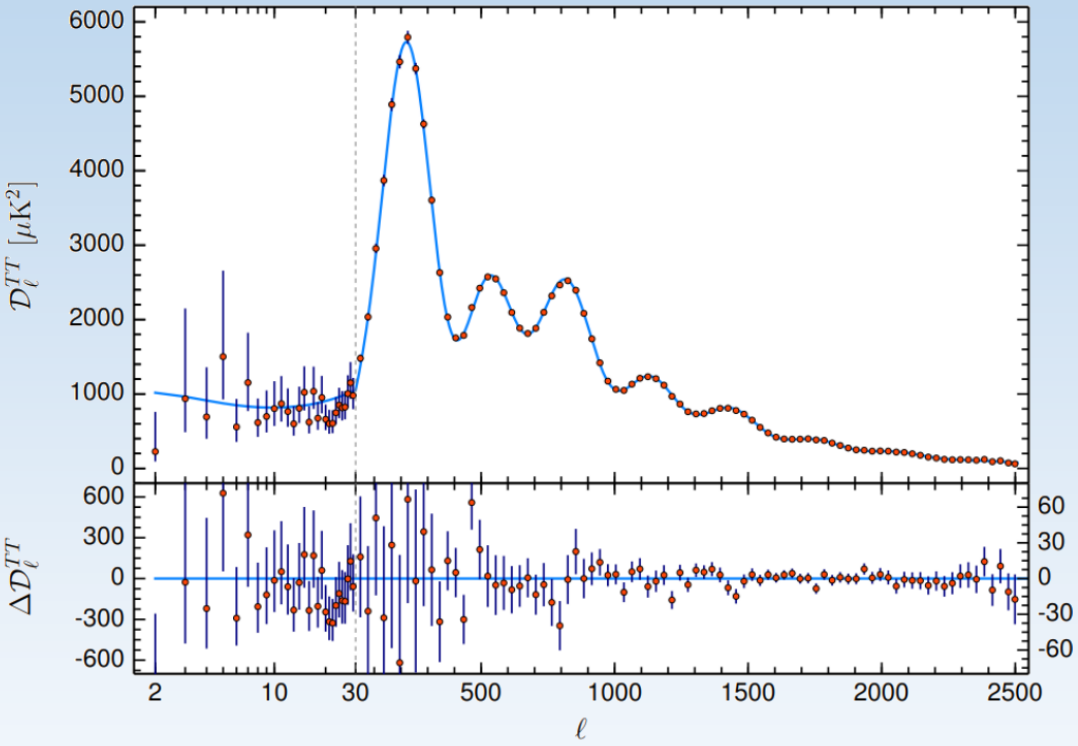
- Cosmological Principle + Einstein's Eqs. → Friedmann Equations

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3}, \qquad \frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}(\rho + 3p)$$

- Early radiation-dominated era
  - Baryogenesis
  - EWPT
  - QCDPT
  - **$\boldsymbol{\nu}$ decoupling and $\boldsymbol{e^+ e^-}$ annihilation** → $T_\nu = \left(\frac{4}{11}\right)^{1/3} T$
  - Big Bang Nucleosynthesis

Thermal History of the Universe: Λ_{CDM}

- When matter dominates, photons decouple after recombination → CMB



- Allows to infer an interesting observable: N_{eff}

$$\rho_{rad} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{eff}\right)$$

The Strong CP Problem – Invisible Axions

- DFSZ Axion
A. R. Zhitnitsky, Sov. J. Nucl. Phys. 31 (1980)
M. Dine, W. Fischler, M. Srednicki, Phys. Lett. B104 (1981)
  - Adds a new scalar SM singlet, ϕ, to the PQWW particle content
  - ϕ is charged under $U(1)_{PQ}$ with $x_\phi = -\frac{1}{2}$ and has a VEV $v_\phi \gg v \approx 246\text{ GeV}$
  - The axion arises as a combination of the different pseudoscalars, with a scale $f_a \simeq \frac{v_\phi}{2} \gg v$
- KSVZ Axion
J. E. Kim, PRL 43 (1979)
M. A. Shifman, A. I. Vainshtein, V. I. Zakharov, Nucl. Phys. B166 (1980)
  - The SM is neutral under $U(1)_{PQ}$, only a new singlet heavy quark Q and complex scalar σ have PQ charges
  - The axion is the angular part of σ, invisible thanks to the large VEV $v_\sigma \gg v$
  - KSVZ axion couples to SM fermions at a two-loop level
- Axion-gluon coupling implies a scale-mass relation shared by all these axions

$$m_a = 5.691(51)\left(\frac{10^9\text{ GeV}}{f_a}\right)\text{ meV}$$

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

$$\mathcal{G}_L^{NA} \to SU(3)_{l_L} \times SU(3)_{e_R} \times SO(3)_{N_R} \times CP$$

$$\downarrow$$

$$m_\nu \simeq \frac{v^2}{2\mu_{LN}} \mathcal{Y}_\nu \mathcal{Y}_\nu^T$$

R. Alonso et al., 1103.5461

$$\mathcal{G}_L^{NA} \to SU(3)_{l_L+N_R} \times SU(3)_{e_R}$$

$$\downarrow$$

$$m_\nu \simeq \frac{v^2}{2\mu_{LN}} \mathcal{Y}_N^{-1}$$

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 – Setup

- The axion arises as the angular part of Φ

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

- After integrating out ρ, the axion couplings read

$$-e^{i(x_u - x_q)a/v_\Phi} \overline{q}_L \widetilde{H} Y_u u_R - e^{i(x_d - x_q)a/v_\Phi} \overline{q}_L H Y_d d_R - e^{i(x_e - x_l)a/v_\Phi} \overline{l}_L H Y_e e_R$$

$$\downarrow$$

$$c_{a\psi} \frac{\partial_\mu a}{2 v_\Phi} \overline{\psi} \gamma^\mu \gamma_5 \psi$$

$$c_{au} = x_q - x_u$$

$$c_{ad} = x_q - x_d$$

$$c_{ae} = x_l - x_e$$

$$c_{agg} = 3(c_{au} + c_{ad}), \quad c_{aWW} = \frac{3}{2 s_\theta^2} \left(3 \left(c_{au} + c_{ad}\right) + c_{ae}\right),$$

$$c_{aZZ} = \frac{t_\theta^2}{4} \left(17 c_{au} + 5 c_{ad} + 15 c_{ae}\right) + \frac{3}{4 t_\theta^2} \left(3(c_{au} + c_{ad}) + c_{ae}\right),$$

$$c_{a\gamma Z} = \frac{t_\theta}{4} \left(17 c_{au} + 5 c_{ad} + 15 c_{ae}\right) - \frac{3}{4 t_\theta} \left(3(c_{au} + c_{ad}) + c_{ae}\right),$$

$$c_{a\gamma\gamma} = 2(4 c_{au} + c_{ad} + 3 c_{ae})$$

$$c_{agg} \neq 0$$

$$\frac{c_{agg}}{c_{a\gamma\gamma}} = 8/3$$

The MFVA – Phenomenology

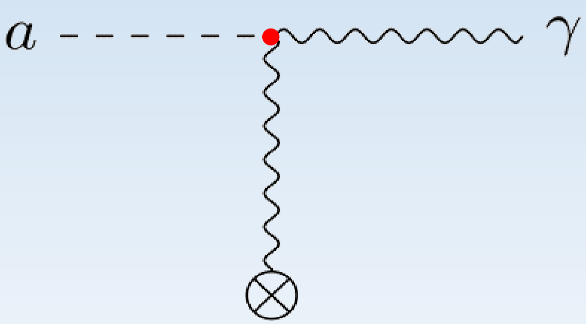
$$\boxed{f_a = \frac{v_\Phi}{c_{agg}}}$$

	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

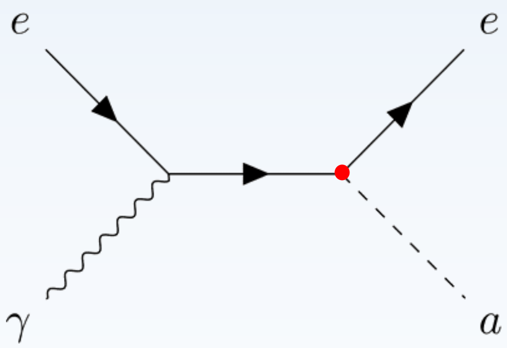
$$\begin{aligned} f_a &\gtrsim 1.2\times 10^7\ \text{GeV} && \text{for} && m_a \lesssim 10\ \text{meV},\\ f_a &\gtrsim 8.7\times 10^6\ \text{GeV} && \text{for} && 10\ \text{meV} \lesssim m_a \lesssim 10\ \text{eV},\\ f_a &\gg 8.7\times 10^8\ \text{GeV} && \text{for} && 10\ \text{eV} \lesssim m_a \lesssim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



- 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

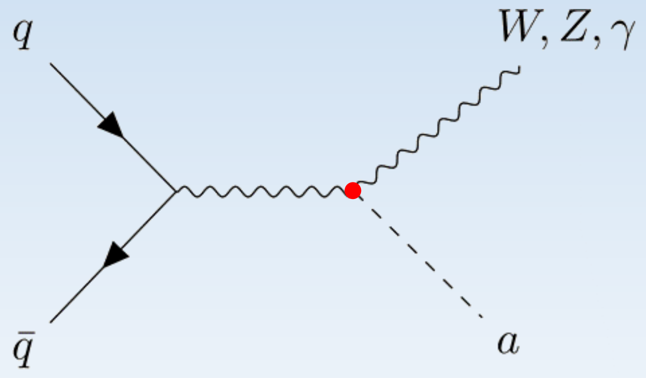
Brivio et al., 1701.05379

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

$$(aWW) \qquad f_a \gtrsim 6.4\ \text{GeV}$$

$$(aZZ) \qquad f_a \gtrsim 5.7\ \text{GeV}$$

$$(aZ\gamma) \qquad f_a \gtrsim 17.8\ \text{GeV}$$

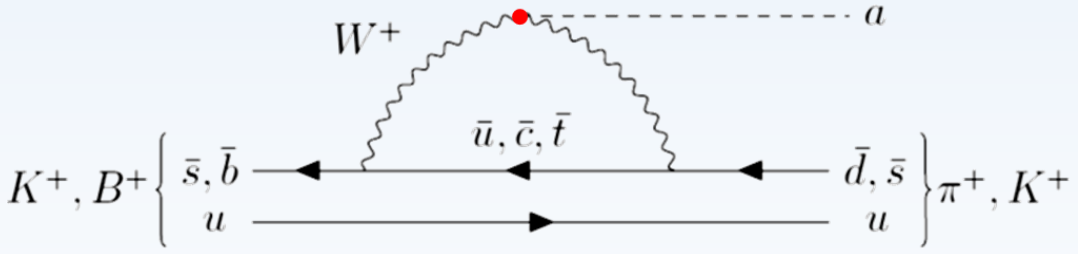


- Flavour bounds on aWW coupling

Izaguirre et al., 1611.09355

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

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



The MFVA – Phenomenology

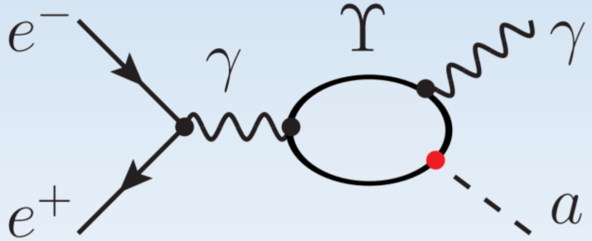
$$\boxed{f_a = \frac{v_\Phi}{c_{agg}}}$$

	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

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

The Minimal Flavour Violating Axion

Setup and Phenomenolog

+ Majoron

FAA, E. Fernández-Martínez, M. González-López, L. Merlo, 2009.01848

MFVω: m_ν and H_0 tension

- The Hubble Tension:

L. Verde, T. Treu, and A. Riess, 1907.10625
K. C. Wong et. al., H0LiCOW XIII, 1907.04869

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

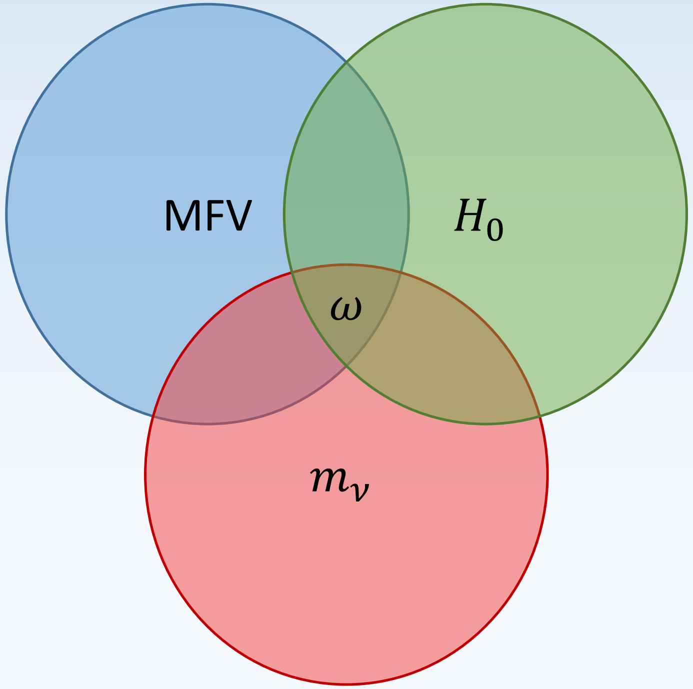
M. Escudero and S. J. Witte, 1909.04044

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

$$m_\omega \in [0.1, 1]\ \text{eV}$$

$$\lambda_{\omega\nu\nu} \in [5\times 10^{-14}, 10^{-12}]$$

- Phenomenology of this Majoron in a Type-I Seesaw
  - Collider signatures: N_R, Higgs invisible decay, new scalar
  - Astrophysical effects: CAST and Red Giant observations
  - Majoron emission in $0\nu\beta\beta$ decays



MFVω: m_ν and H_0 tension – The Majoron Mechanism

- SM extended with 3 RH neutrinos and a singlet scalar χ, with LN $-\boldsymbol{L_N}$ and $\boldsymbol{L_\chi}$ respectively

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

$$x_{q_L} = x_{l_L} = x_{u_R} = x_{N_R} = 0$$

- Heavy and light neutrino masses generated after LN SSB

$$x_{d_R} = x_{e_R} = 3$$

$$m_\nu = \frac{\varepsilon_\chi^{\frac{2+L_\chi}{L_\chi}} v^2}{\sqrt{2} v_\chi} \mathcal{Y}_\nu \mathcal{Y}_N^{-1} \mathcal{Y}_\nu^T, \qquad M_N = \varepsilon_\chi^{\frac{2L_N - L_\chi}{L_\chi}} \frac{v_\chi}{\sqrt{2}} \mathcal{Y}_N \qquad \varepsilon_\chi = \frac{v_\chi}{\sqrt{2}\Lambda_\chi}$$

- Axion coupling to light neutrinos:

$$\mathcal{L}_\omega^{low-energy} \supset i \frac{\lambda_{\omega\nu\nu}}{2} \omega \bar{\nu}_L \nu_L^c, \qquad \lambda_{\omega\nu\nu} = 2 \frac{m_\nu}{L_\chi v_\chi}$$

MFVω: m_ν and H_0 tension – The Majoron Mechanism

- SM extended with 3 RH neutrinos and a singlet scalar χ, with LN $-\boldsymbol{L_N}$ and $\boldsymbol{L_\chi}$ respectively

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

$$x_{q_L} = x_{l_L} = x_{u_R} = x_{N_R} = 0$$

$$x_{d_R} = x_{e_R} = 3$$

	L_N	L_χ	v_χ	ε_χ	$\langle M_N \rangle$	Λ_χ
CASE NR1	1	1	$[0.1, 2]$ TeV	$[0.49, 1.4] \times 10^{-4}$	$[3.5, 200]$ MeV	$[1.4 - 11] \times 10^3$ TeV
CASE NR2	1	2	$[0.05, 1]$ TeV	$[2.4, 11] \times 10^{-7}$	$[35.4, 707]$ GeV	$[1.4 - 6.5] \times 10^5$ TeV

MFVω: m_ν and H_0 tension – The Majoron Mechanism

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

$$|L_\chi| \varepsilon_\chi^{\frac{2+L_\chi}{L_\chi}} \mathcal{Y}_\nu \mathcal{Y}_N^{-1} \mathcal{Y}_\nu^T \in [1.2 \times 10^{-13}, 2.4 \times 10^{-12}]$$

$$\frac{\varepsilon_\chi^{\frac{2L_N - L_\chi}{L_\chi}}}{|L_\chi|} \mathcal{Y}_N \gg 3.5 \times 10^{-14}$$

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

$$L_N = -1, L_\chi = -2 \Rightarrow \mathcal{Y}_\nu \mathcal{Y}_N^{-1} \mathcal{Y}_\nu^T \in [1.2 \times 10^{-13}, 2.4 \times 10^{-12}]$$

- 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 $3N_R$

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

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

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

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

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

$$m_\nu = \frac{\varepsilon_\chi^{\frac{2+L_\chi}{L_\chi}} v^2}{\sqrt{2} v_\chi} \mathcal{Y}_\nu \mathcal{Y}_\nu^T$$

  - $\mathcal{G}_L^{NA} = SU(3)_{l_L + N_R} \times SU(3)_{e_R} \Rightarrow \mathcal{Y}_\nu \propto \mathbb{1}$

$$m_\nu = \frac{\varepsilon_\chi^{\frac{2+L_\chi}{L_\chi}} v^2}{\sqrt{2} v_\chi} \mathcal{Y}_N^{-1}$$

MFVω: m_ν and H_0 tension – Phenomenology

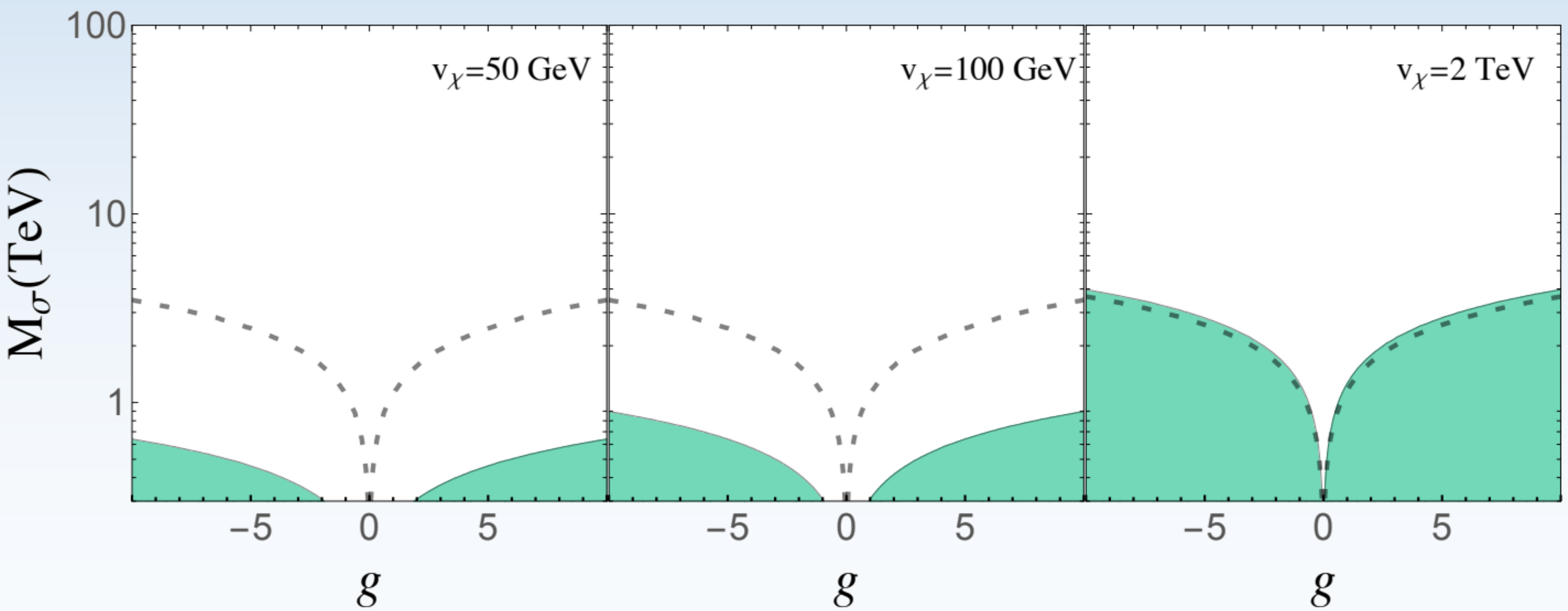
$$\chi = \frac{v_\chi + \sigma}{\sqrt{2}} e^{i\frac{\omega}{v_\chi}}$$

$$g H^\dagger H \chi^* \chi \qquad g = \frac{M_\sigma^2 - M_h^2}{2 v v_\chi} \sin 2\vartheta \qquad \sin^2\vartheta \lesssim 0.11$$

ATLAS Collaboration, 1909.02845

$$\Gamma_{h\to\omega\omega} = \frac{\sin^2\vartheta\, M_h^3}{32\pi v_\chi^2} \lesssim 0.8\text{ MeV} \Rightarrow \frac{v_\chi}{|\sin\vartheta|} \gtrsim 5\text{ TeV}$$

CMS collaboration, 1809.05937



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
- $N \to 3\nu$ 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

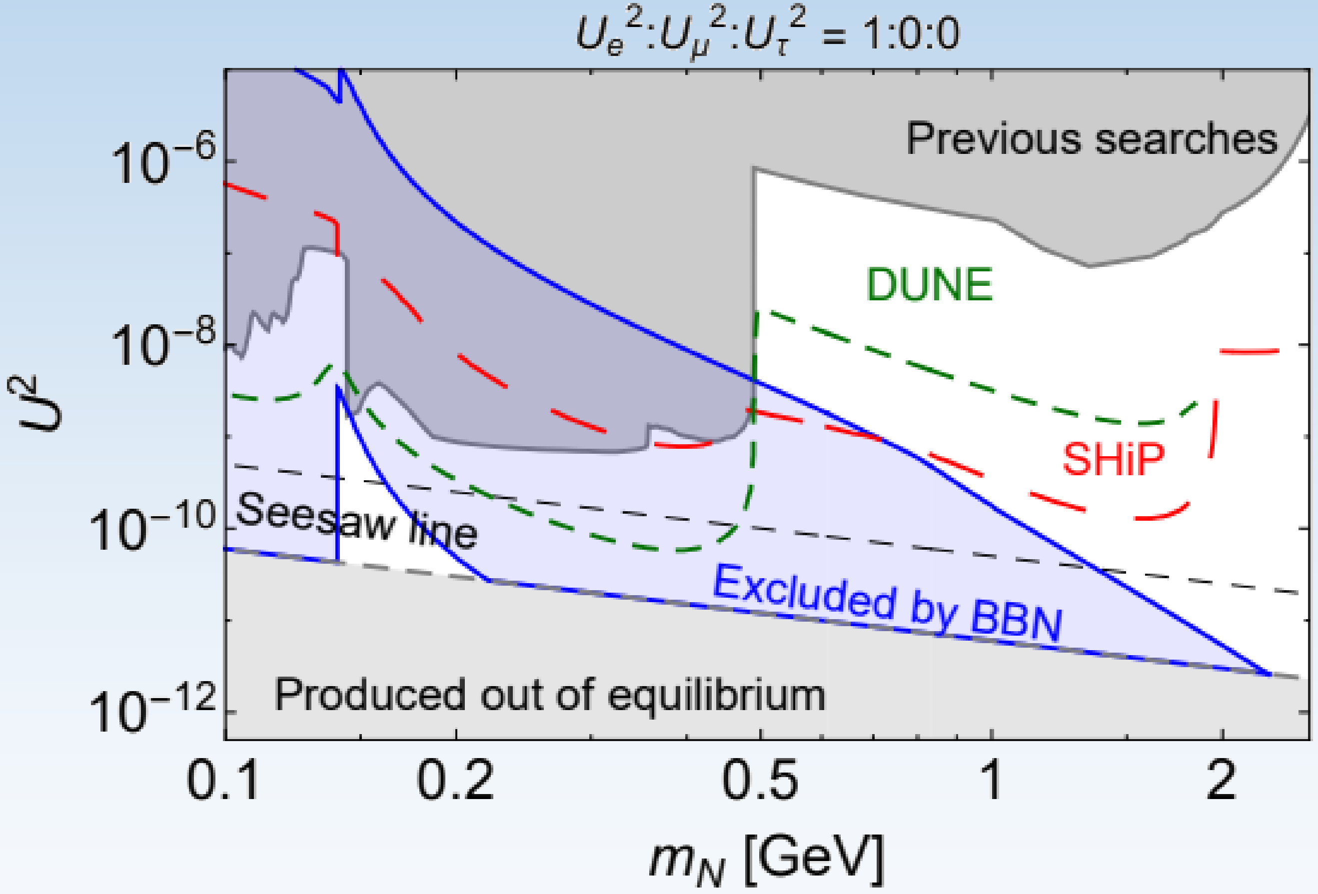
$$\sin^2\theta_s \equiv \frac{\langle m_\nu \rangle}{\langle M_N \rangle} \lesssim 10^{-15} - 10^{-17}$$

A. C. Vincent et al., 1408.1956

  - 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

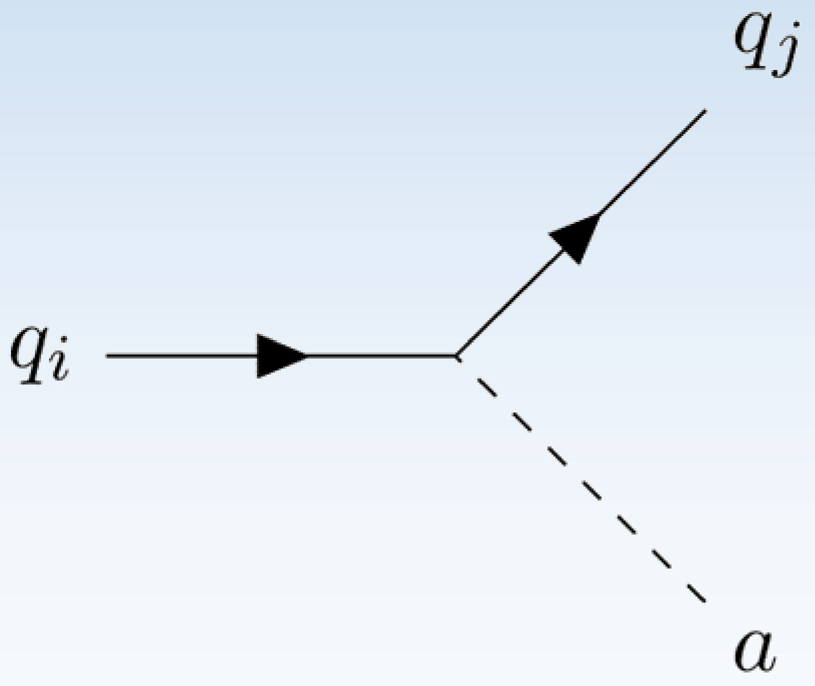
	$\langle M_N \rangle$	$\sin^2\theta_s$
CASE NR1	$[3.5, 200]$ MeV	$[2.5\times10^{-10},\ 1.4\times10^{-8}]$

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

- Flavour violating axion interactions

$$\mathscr{L}^{(a)}_{\text{F.V. quarks}} = \frac{\partial_\mu a}{f_a} \sum_{i,j} \left[\bar{u}_i \gamma^\mu \left(c^{(ij)}_{V_u} + c^{(ij)}_{A_u} \gamma_5 \right) u_j + \bar{d}_i \gamma^\mu \left(c^{(ij)}_{V_d} + c^{(ij)}_{A_d} \gamma_5 \right) d_j , \right]$$

- Decays existing only below EWPT
  - Boltzmann suppressed for $T < m_\psi$
  - Production rate for $T > m_\psi$: $\Gamma \propto c_{ij}^2 \frac{m_i^3}{f_a^2}$
  - Heavy fermions dominate. Γ/H peaks at $T \sim m_\psi$



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

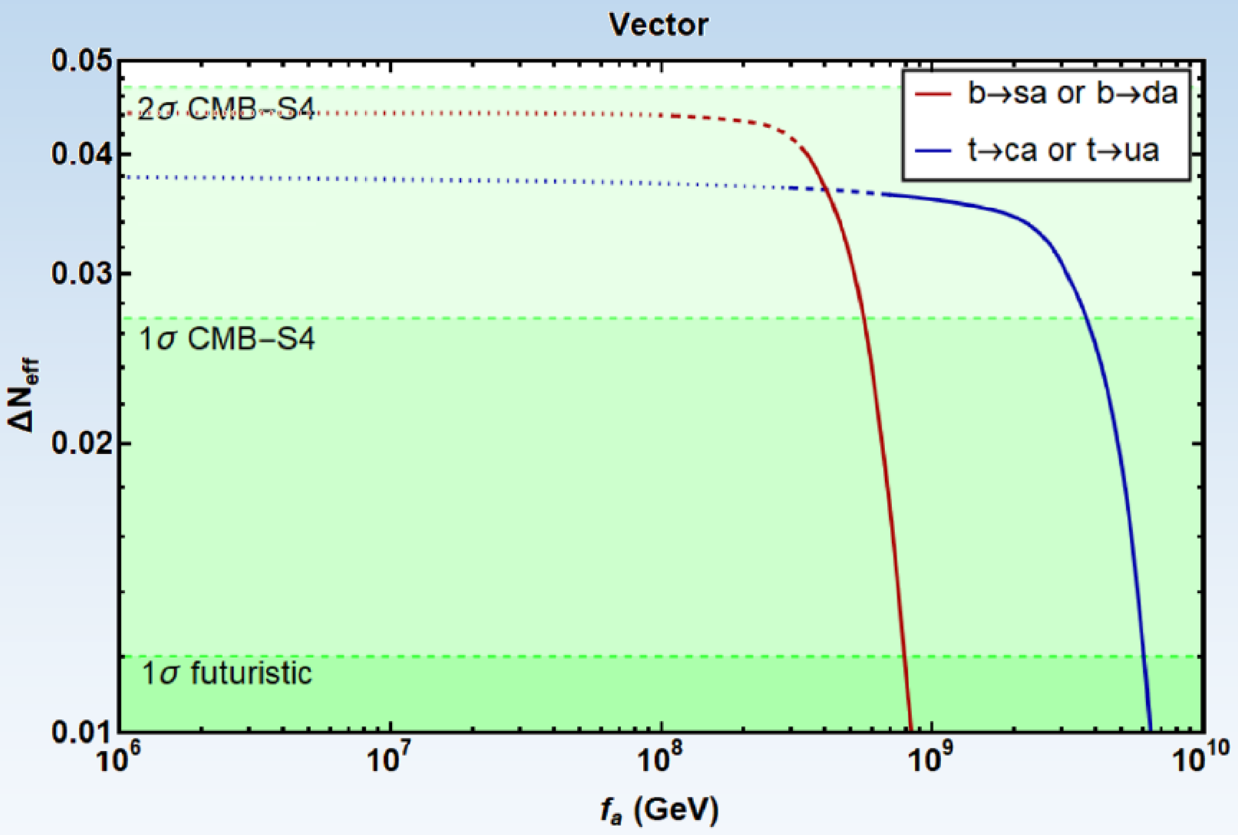
- General axion interactions

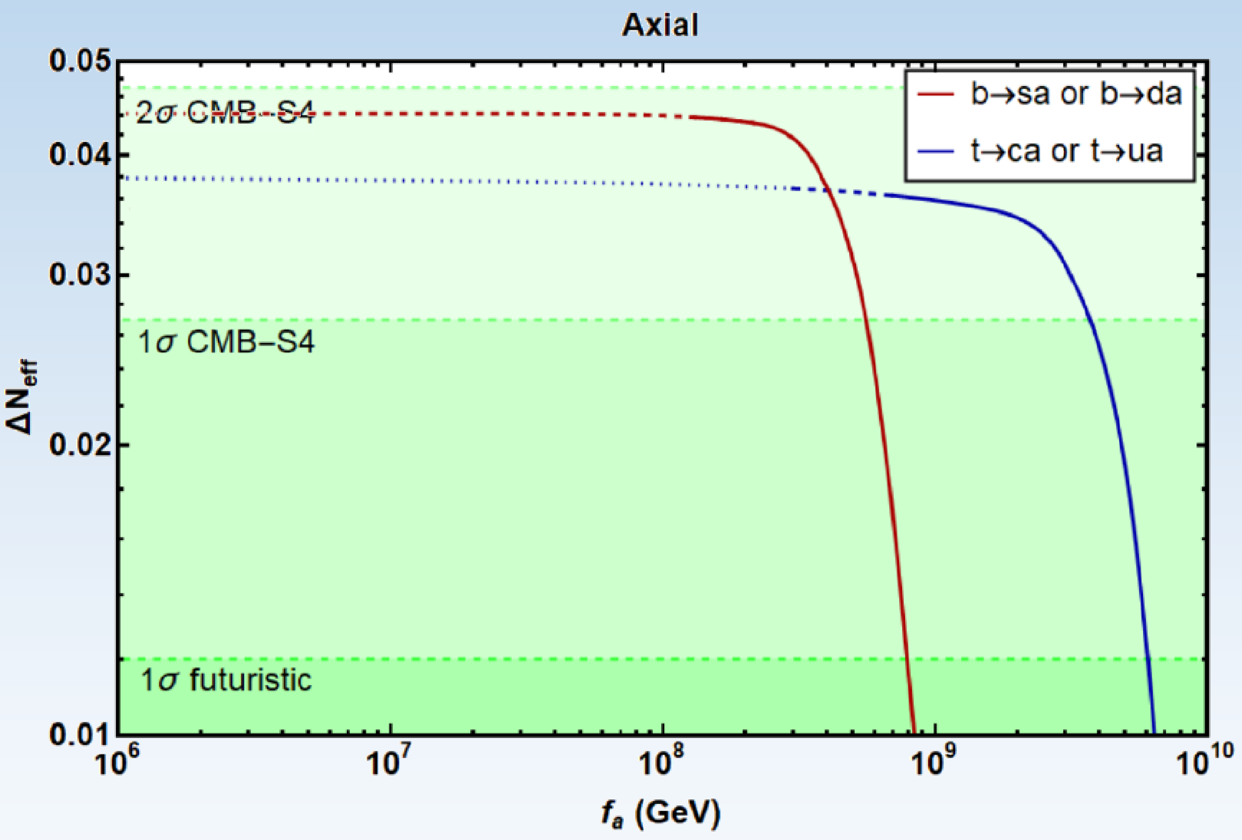
$$\mathscr{L}_{\text{axion-int}} \supset \frac{1}{f_a}\left[a\, c_X \frac{\alpha_X}{8\pi} X^{a\mu\nu}\widetilde{X}^a_{\mu\nu} + \partial_\mu a\; c_\psi \overline{\psi}\gamma^\mu\psi\right]$$

$$X = \{G, W, B\}$$
$$\psi = \{Q_L, u_R, d_R, E_L, e_R\}$$

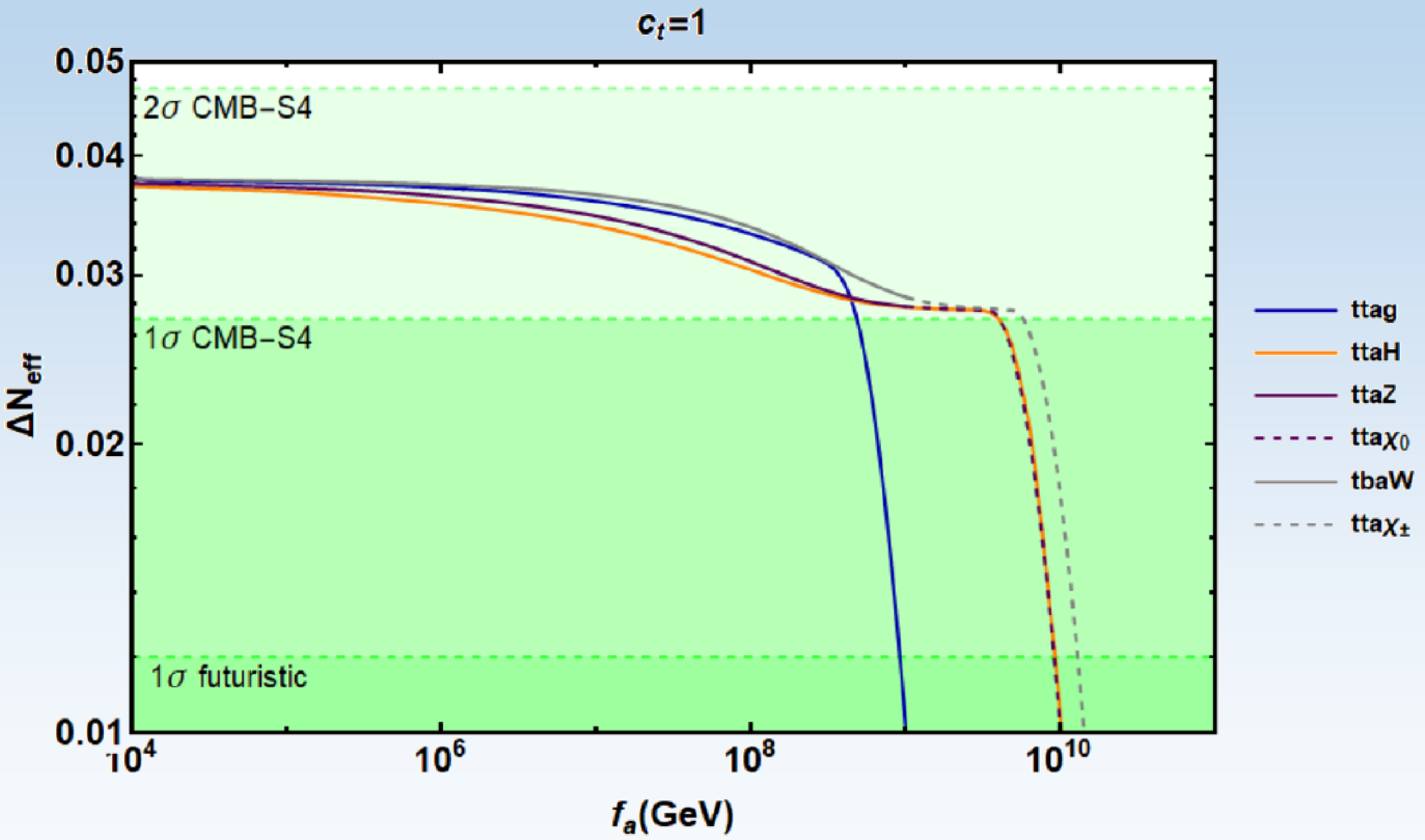
- Three classes of processes
  - $X + X \to X + a$
  - $\psi + X \to \psi + a,\ \psi + \bar{\psi} \to X + a$
  - $\psi + H \to \psi + a,\ \psi + \bar{\psi} \to H + a$
- Production is efficient when production rate Γ exceeds Hubble rate, H

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





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

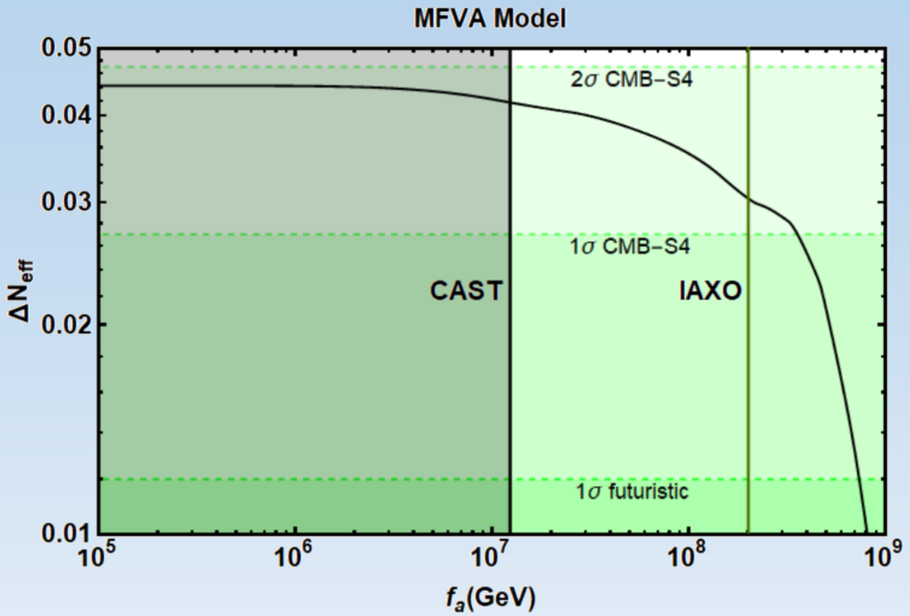


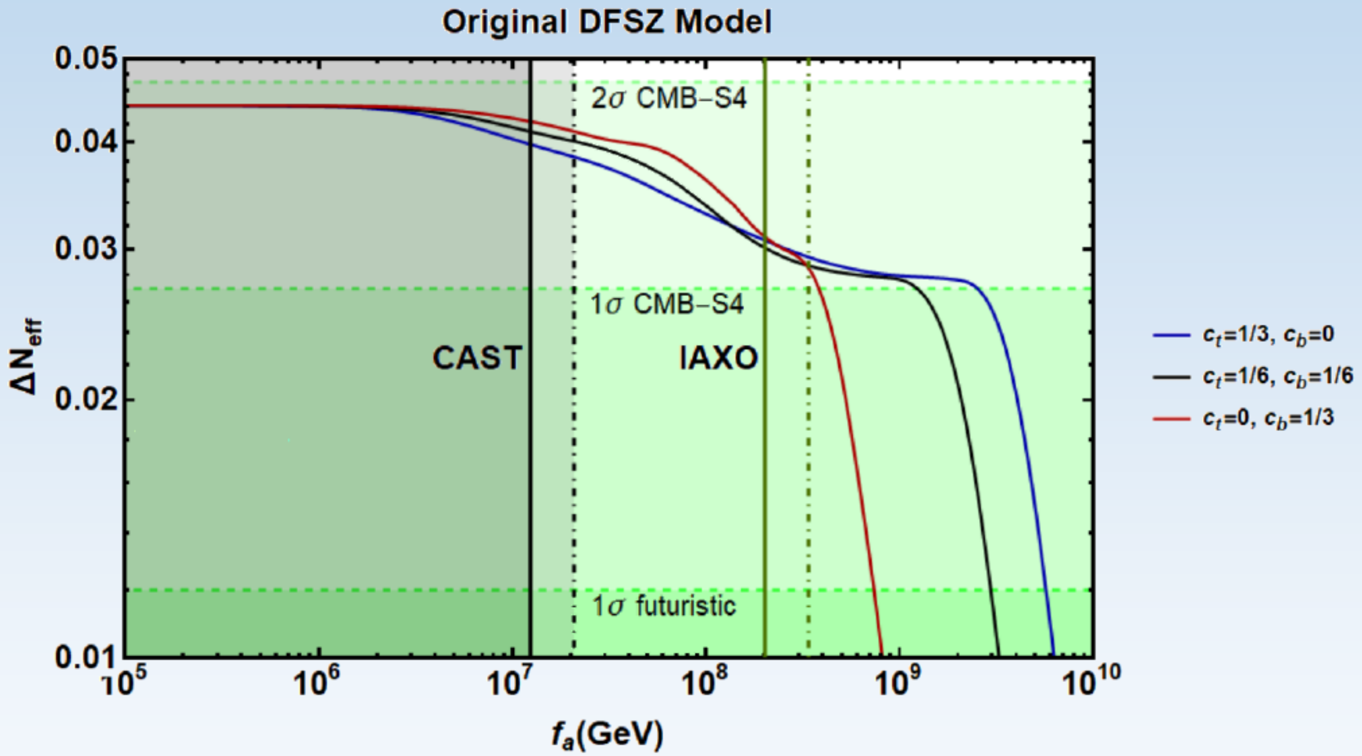
Axion Dark Radiation and ΔN_{eff} – Production Across EWPT

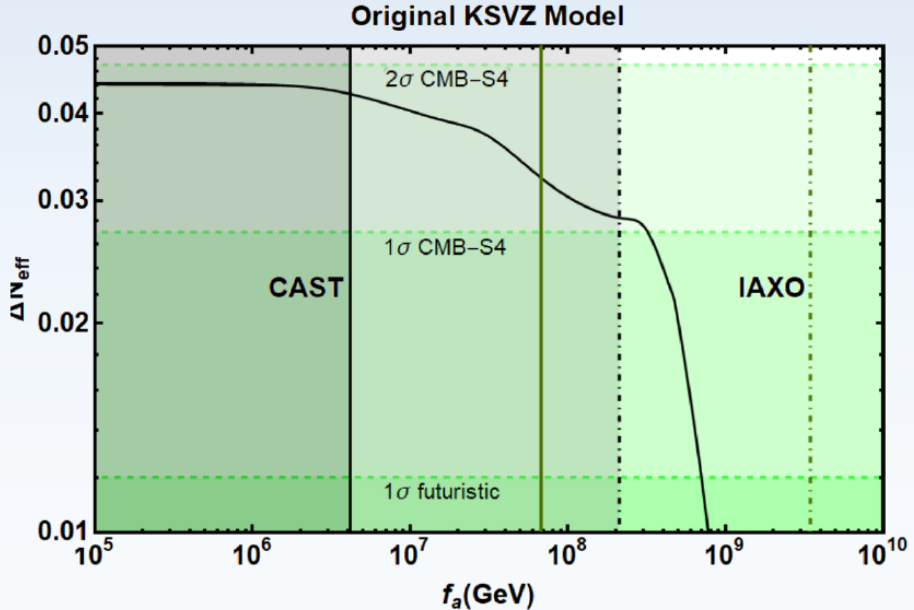
❖ UV Complete Models

- 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. $c_t = 0, E/N = 8/3$

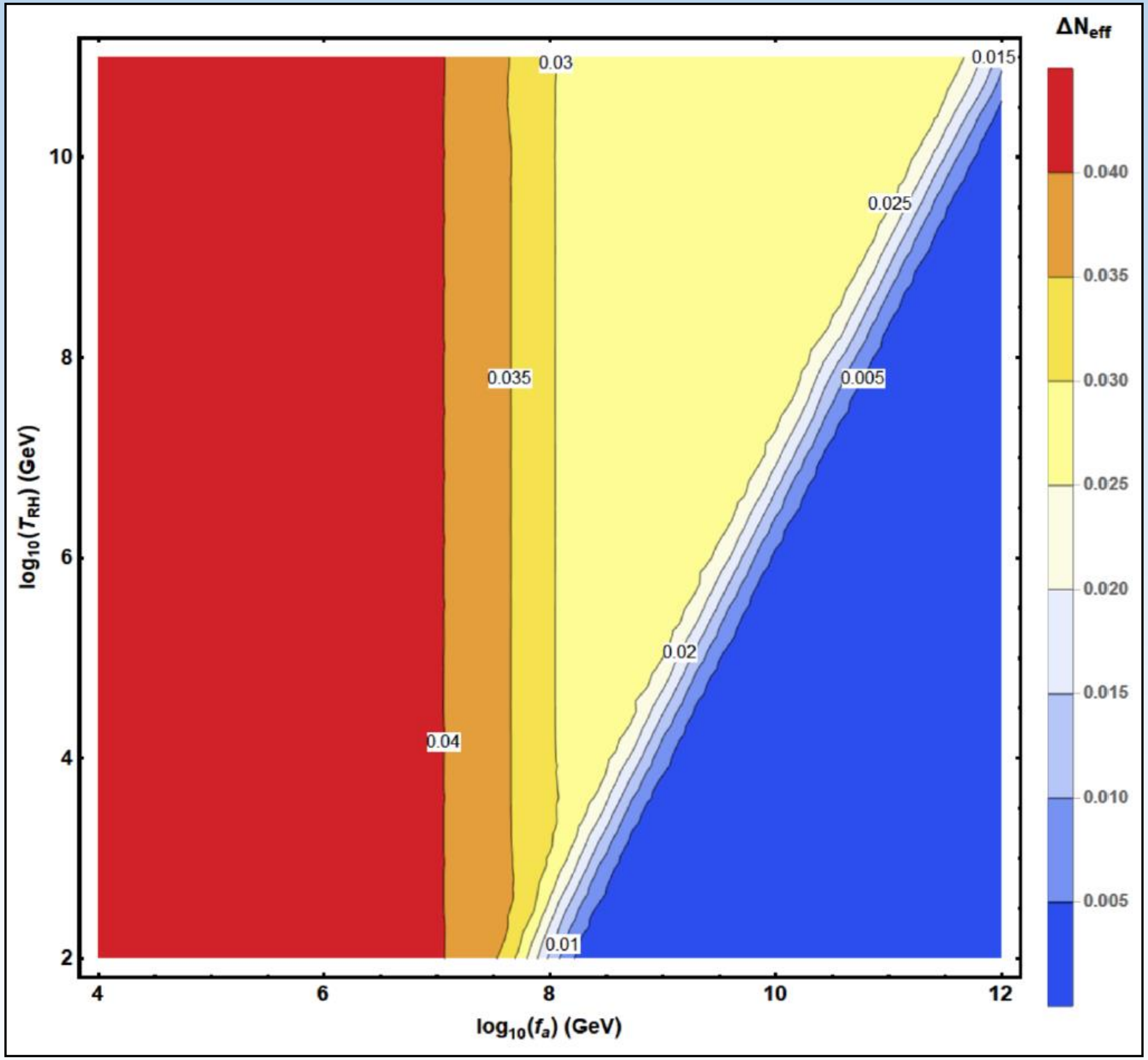
Axion Dark Radiation and ΔN_{eff} – Production Across EWPT



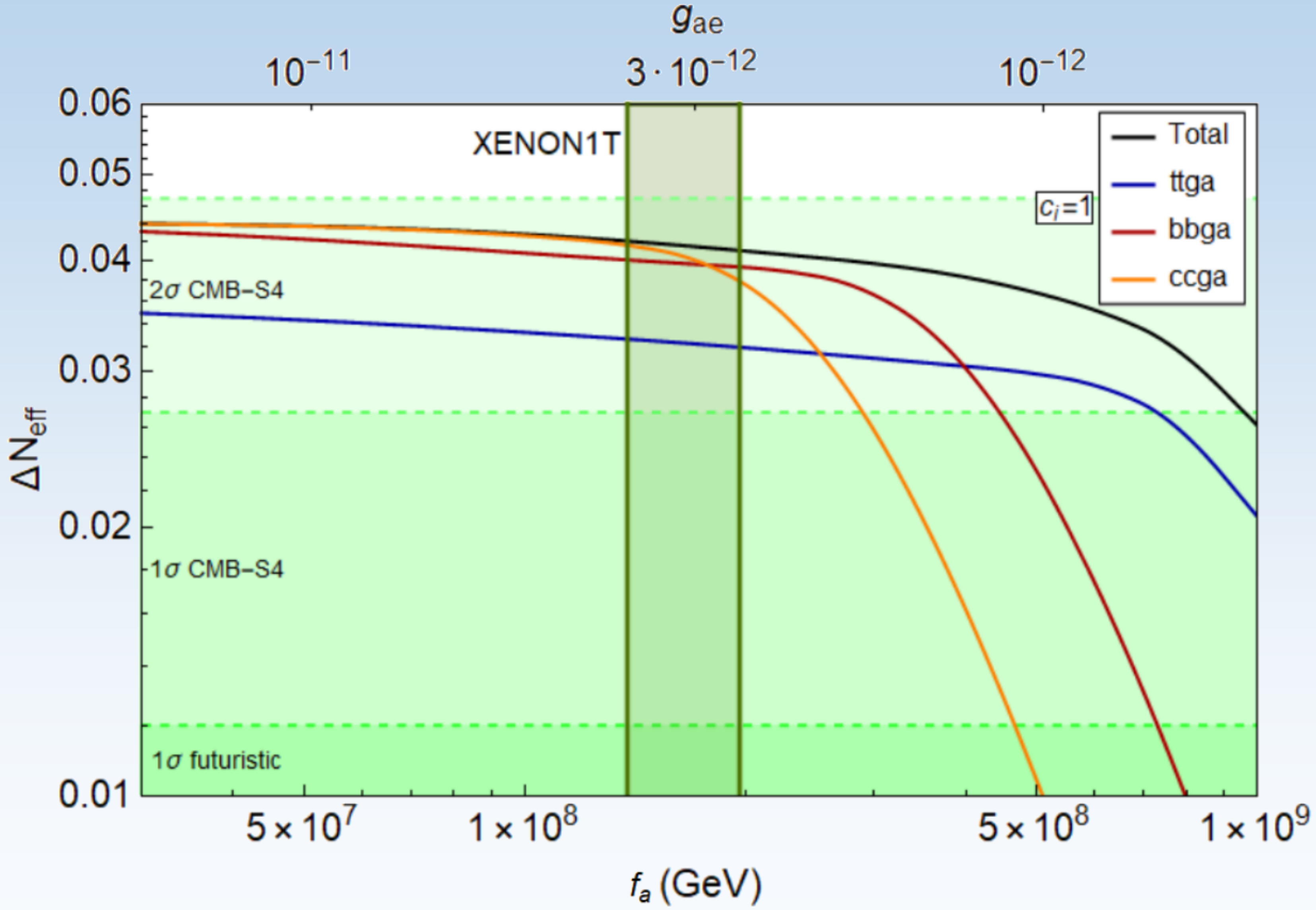




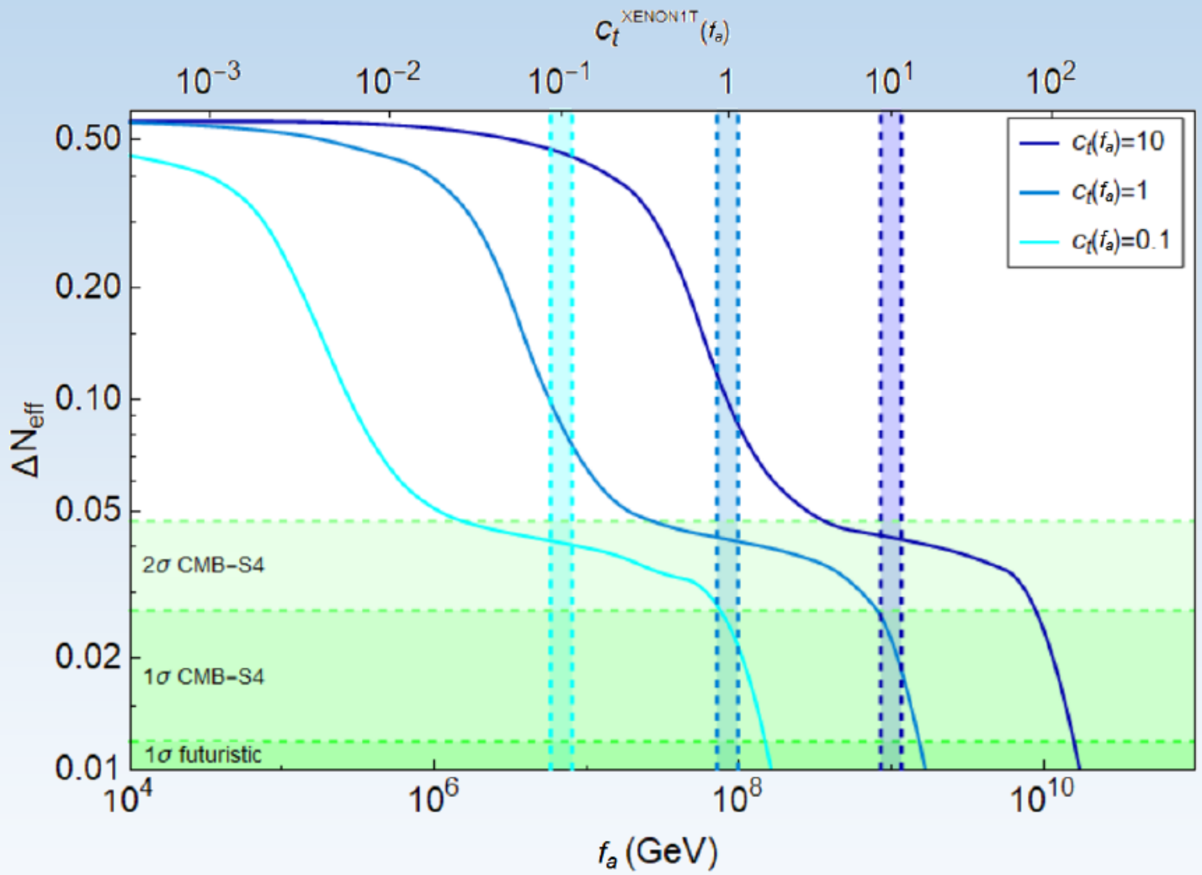
Interplay of T_{RH} and f_a

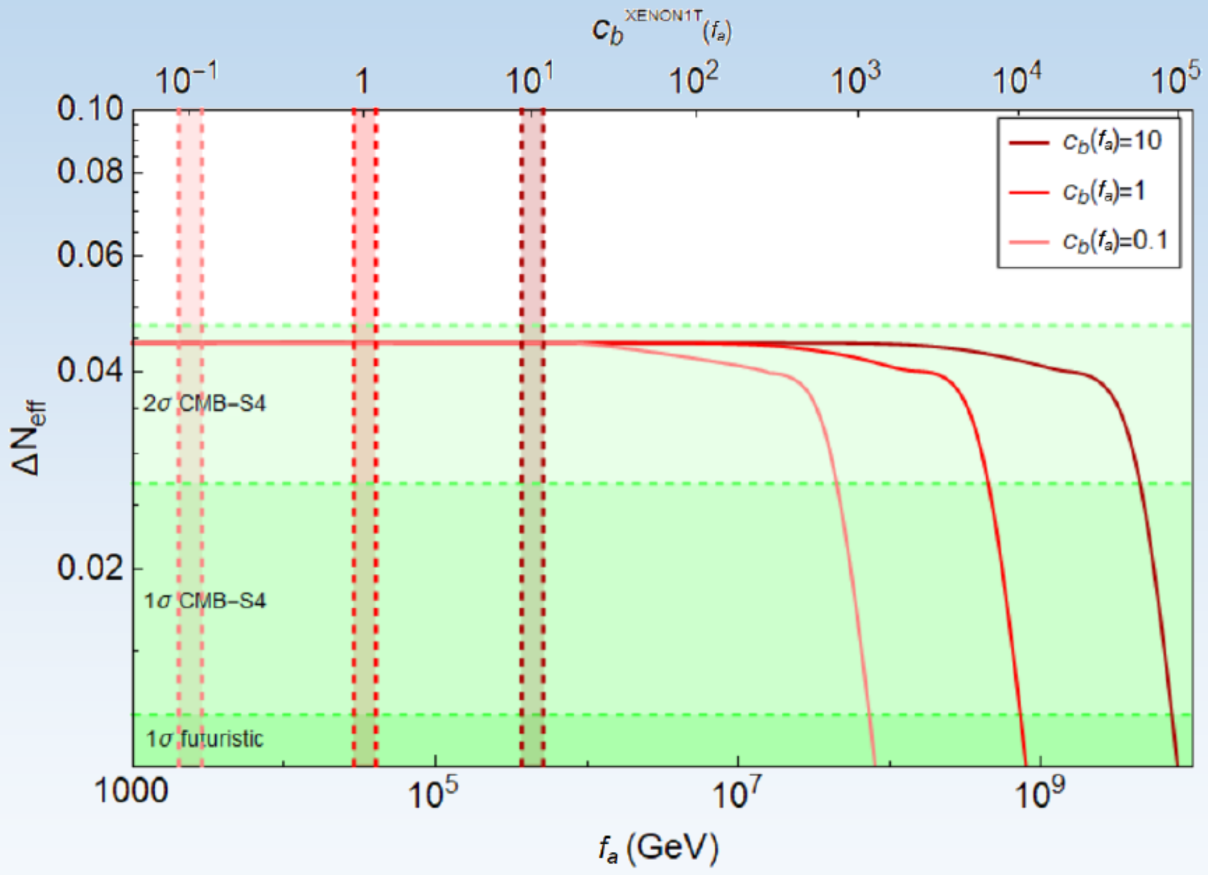


Axion Dark Radiation and ΔN_{eff} – XENON1T

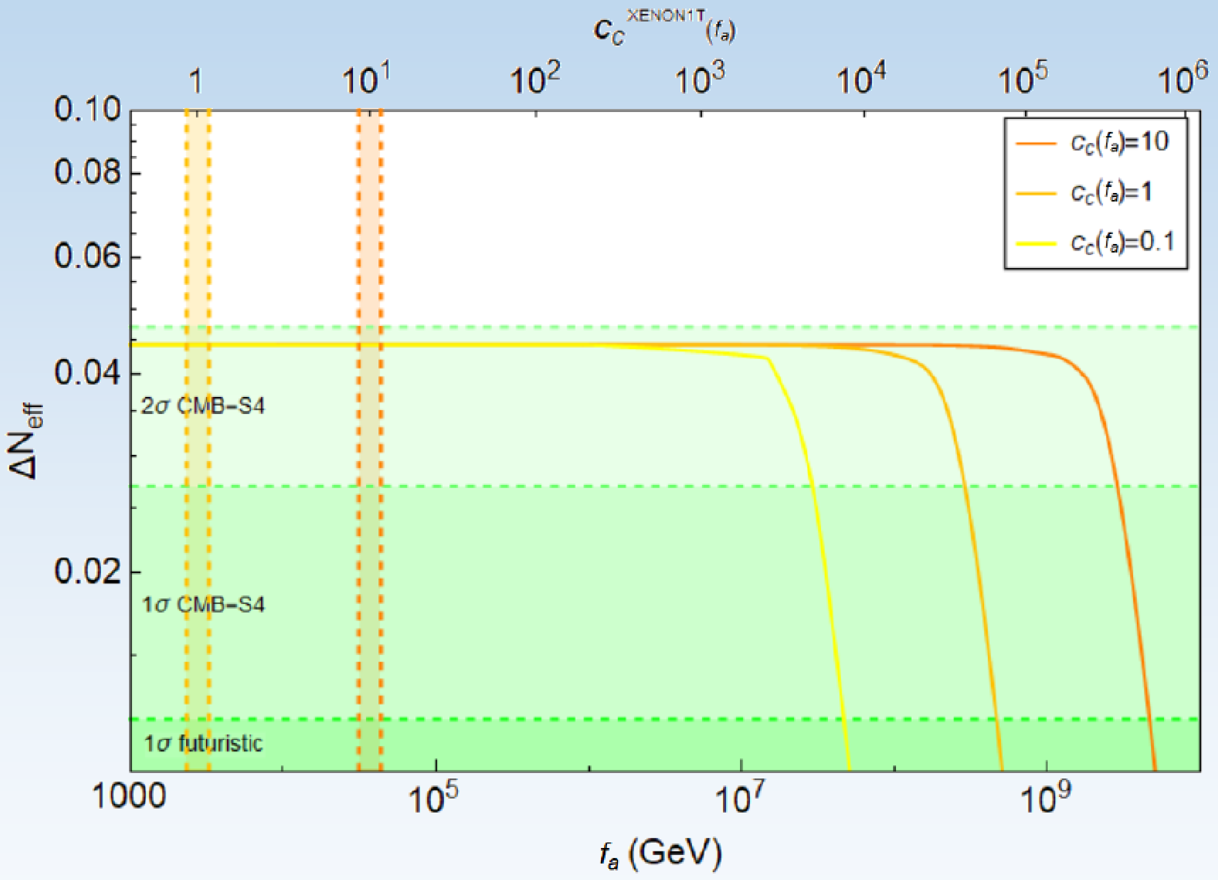


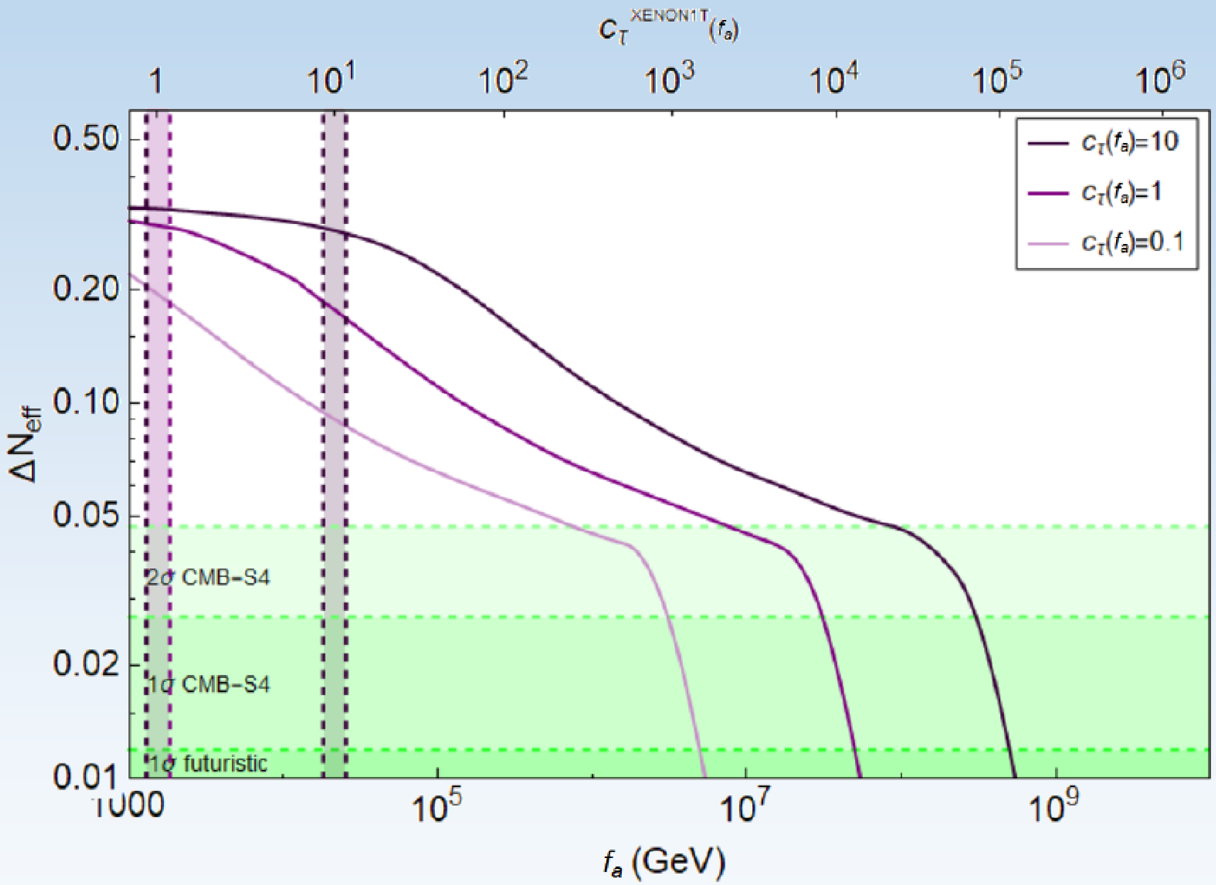
Axion Dark Radiation and ΔN_{eff} – XENON1T





Axion Dark Radiation and ΔN_{eff} – XENON1T





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

- 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