Production of Thermal Axions across the EWPT

ICHEP 2020 | PRAGUE

Based on: 2007.06579 and more to appear, FAA, F. D'Eramo, L. Merlo, A. Notari, R. Zambujal Ferreira.

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Outline

- Motivation
- Setup
- Results
- UV complete models
- Complementarity with XENON1T
- Summary

Motivation

- Light or massless new DoF appear frequently in BSM

- Axions are particularly well motivated:
  - Solution to the Strong CP Problem

Crewther, Di Vecchia, Veneziano & Witten, 1980

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

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

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

  - Possible DM candidate D. J. E. Marsh, 1510.07633
  - Arise naturally from string theories Aravnitaki et al., 0905.4720
  - **Possible explanation for XENON1T excess!** XENON Collabotation, 2006.09721

Motivation

- Many strategies to search for the axion:
  - Helioscopes
  - Haloscopes
  - Light shining through wall
  - Dark matter recoil
  - Star cooling
- In addition to this, there is a cosmological probe

$$\Delta N_{eff} \simeq 74.85\ Y_a^{4/3}$$

- Probed in the future (CMB-S4, LiteBIRD, Simons Observatory)
- ΔN_{eff} depends on its production, thus on its couplings and its decay constant

Setup

- General axion interactions

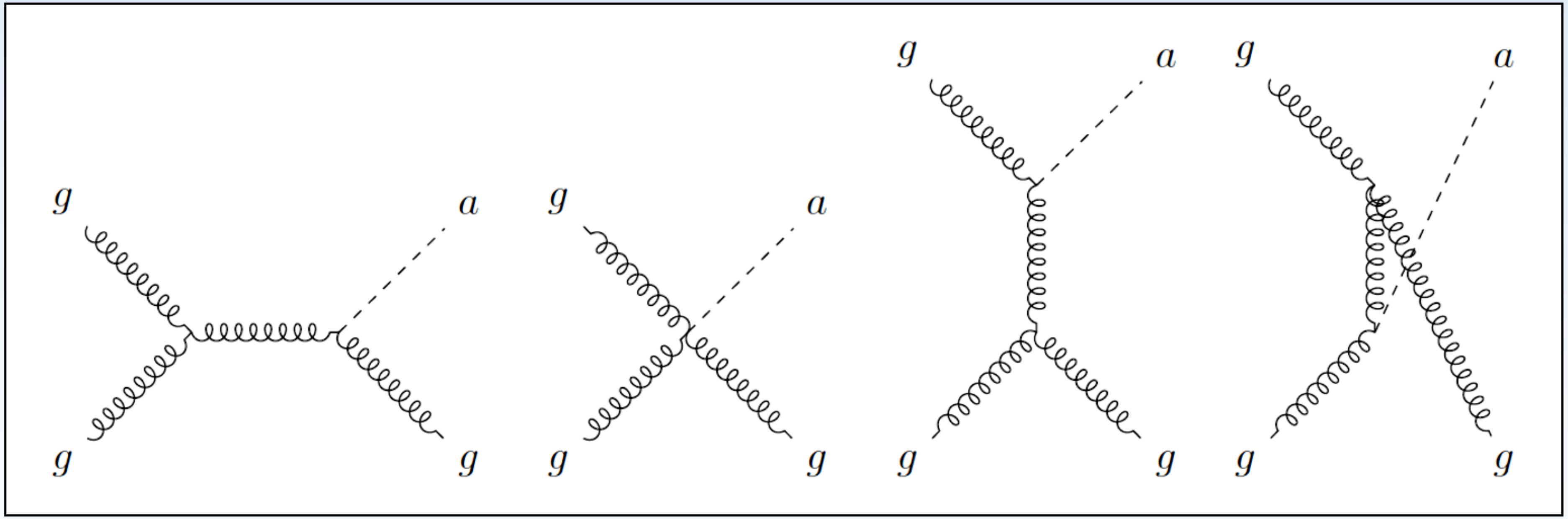
$$\mathscr{L}_{\mathrm{axion-int}} \supset \frac{1}{f_a}\left[a\, c_X \frac{\alpha_X}{8\pi} X^{a\mu\nu} \widetilde{X}^a_{\mu\nu} + \partial_\mu a\ c_\psi \overline{\psi}\gamma^\mu \psi\right]$$

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

- Three classes of processes
  - $X + X \rightarrow X + a$
  - $\psi + X \rightarrow \psi + a,\ \psi + \bar{\psi} \rightarrow X + a$
  - $\psi + H \rightarrow \psi + a,\ \psi + \bar{\psi} \rightarrow H + a$
- Production is efficient when production rate Γ exceeds Hubble rate, with $H \propto T^2$

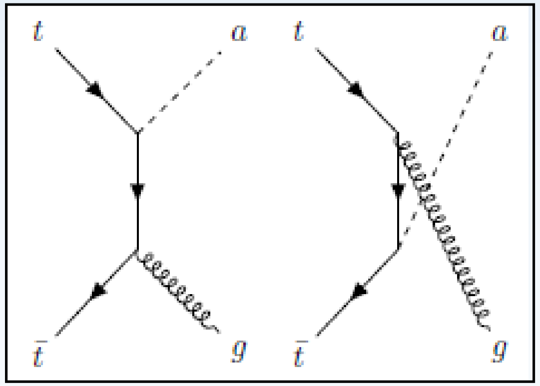
Setup

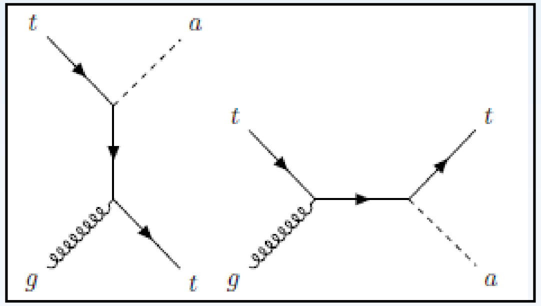
- $\boldsymbol{X + X \to X + a}$
  - Existing both above and below the EWPT
  - Production rate: $\Gamma \simeq \alpha_X^3 c_X^2 \frac{T^3}{f_a^2}$
  - Gluons dominate. Mostly relevant at high T, where $\Delta N_{eff} \simeq 0{,}027$ if there is thermalization

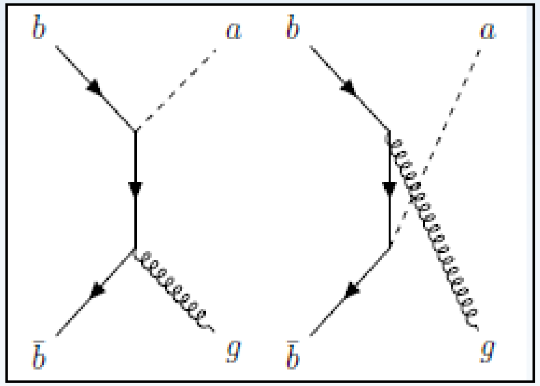


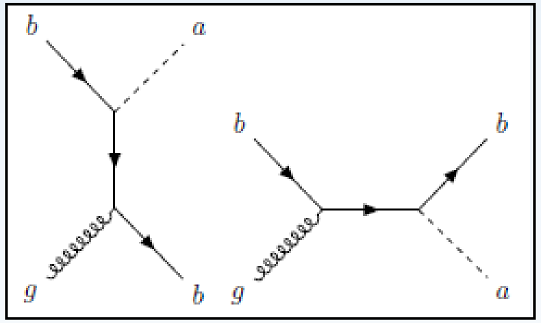
Setup

- **$\boldsymbol{\psi + X \to \psi + a,\ \psi + \bar{\psi} \to X + a}$**
  - Existing only below the EWPT
  - Boltzmann suppressed for $T < m_\psi$
  - Production rate for $T > m_\psi$: $\Gamma \simeq \alpha_X c_\psi^2 m_\psi^2 \frac{T}{f_a^2}$
  - Gluons and heavy fermions dominate. Γ/H peaks at $T \sim m_\psi$



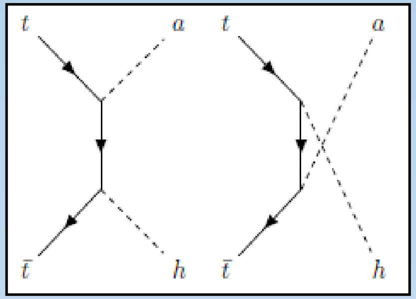


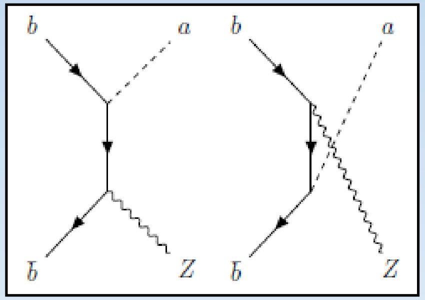


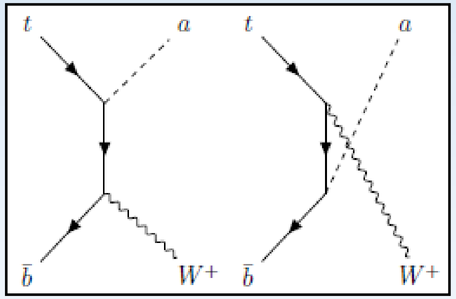


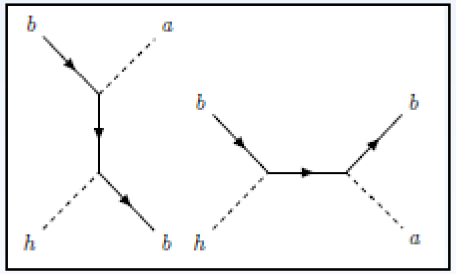
Setup

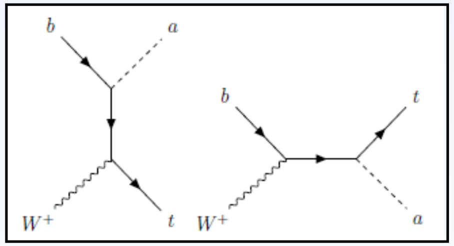
- $\boldsymbol{\psi + H \to \psi + a,\ \psi + \bar{\psi} \to H + a}$
  - Above EWSB: any of the four real components of the Higgs doublet
  - Below EWSB: physical Higgs h and the longitudinal components of W and Z bosons
  - Boltzmann suppressed for $T < m_\psi$
  - Production rate for $T > m_\psi$: $\Gamma \simeq c_X^2 y_\psi^2 \frac{T^3}{f_a^2}$
  - Heavy fermions dominate. Can thermalize at high T.

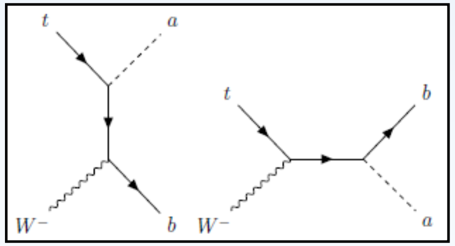


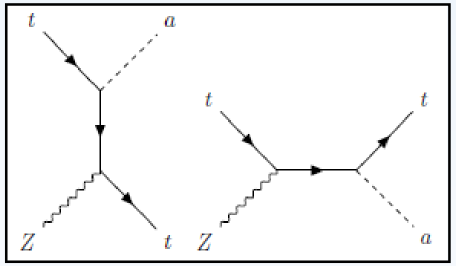




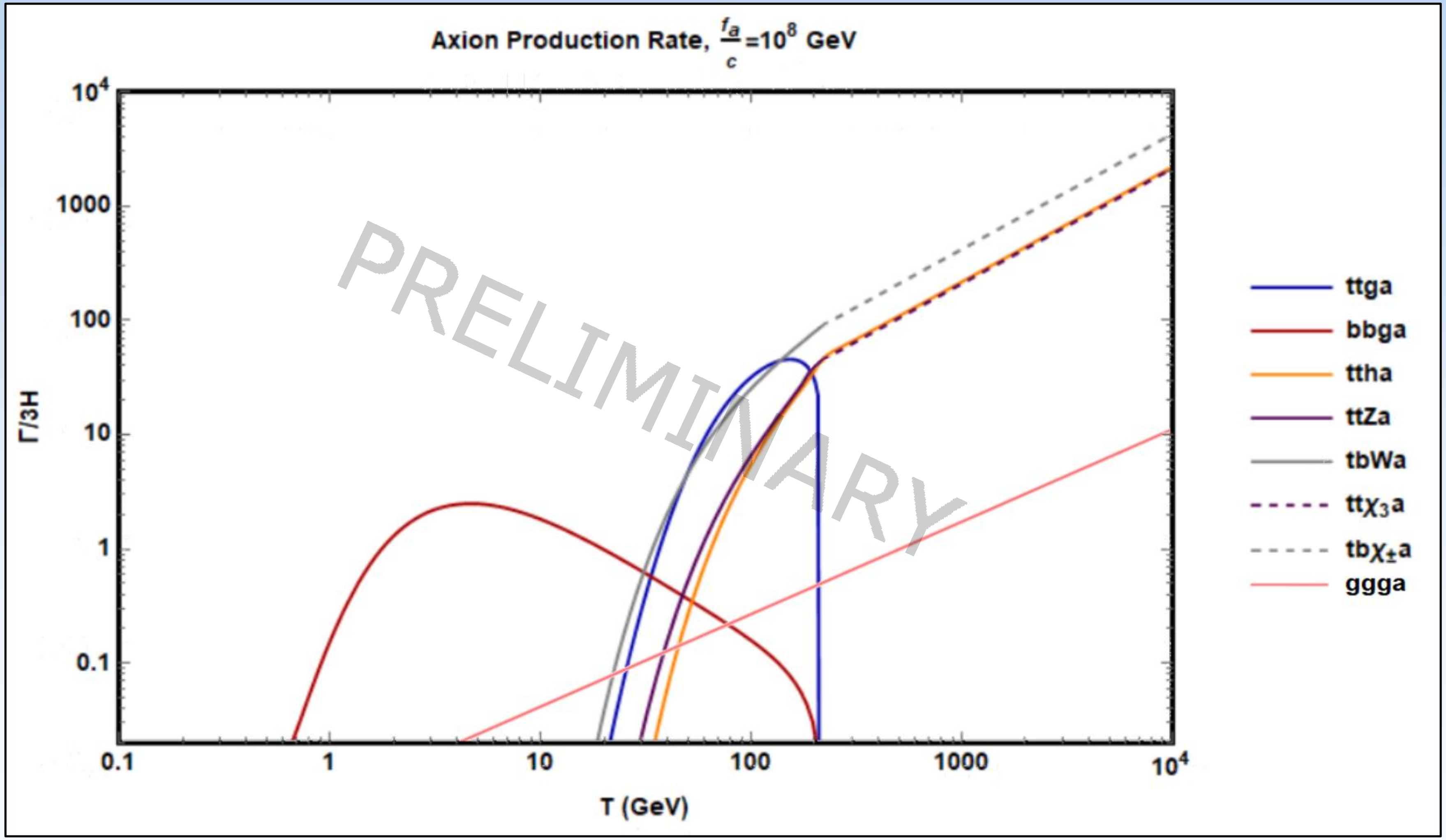








Setup

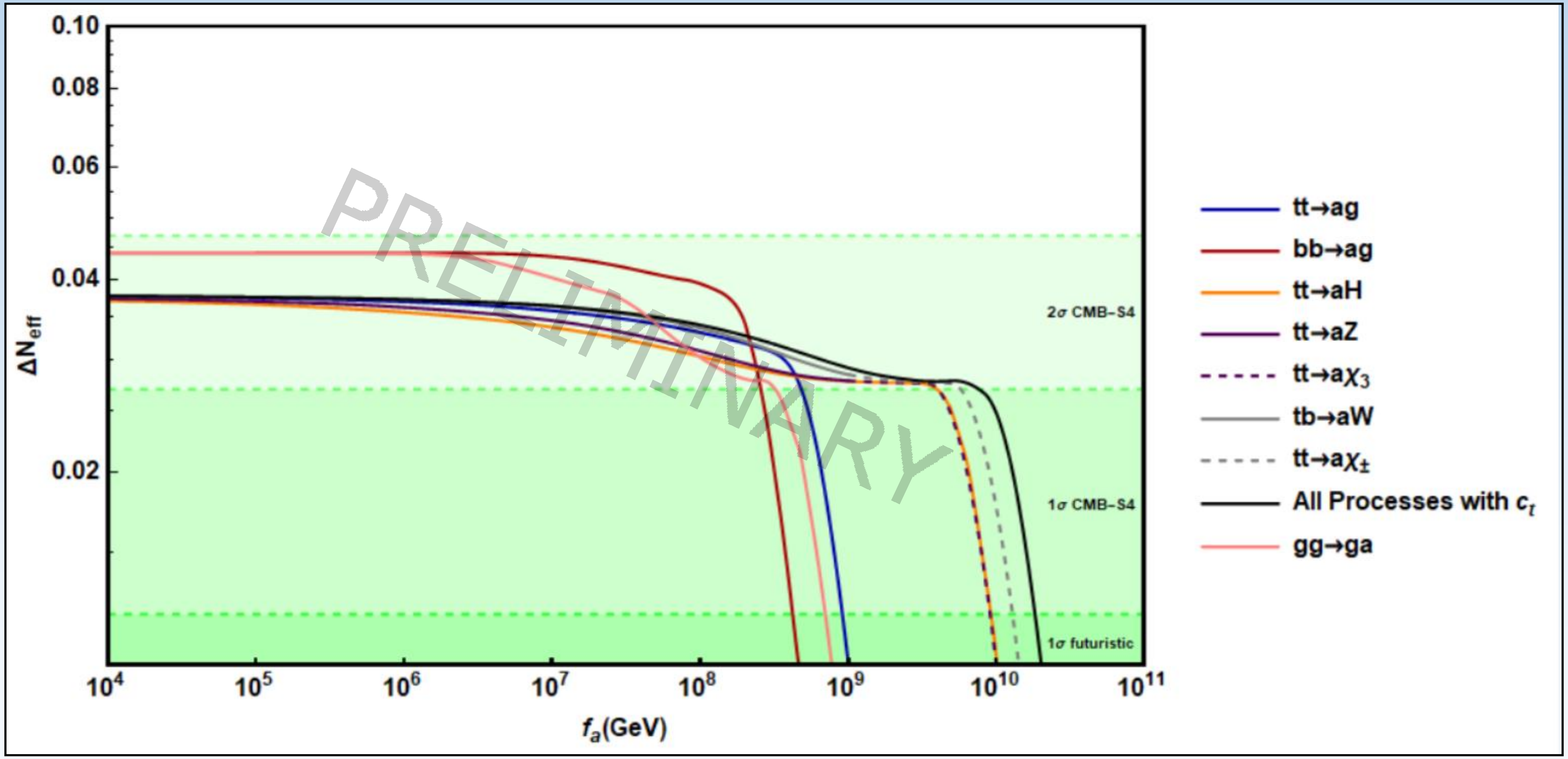


Axion Production Rate, $\frac{f_a}{c}=10^8$ GeV
10^4
1000
100
10
1
0.1
Γ/3H
0.1
1
10
100
1000
10^4
T (GeV)
PRELIMINARY
ttga
bbga
ttha
ttZa
tbWa
ttχ₃a
tbχ±a
ggga

Results

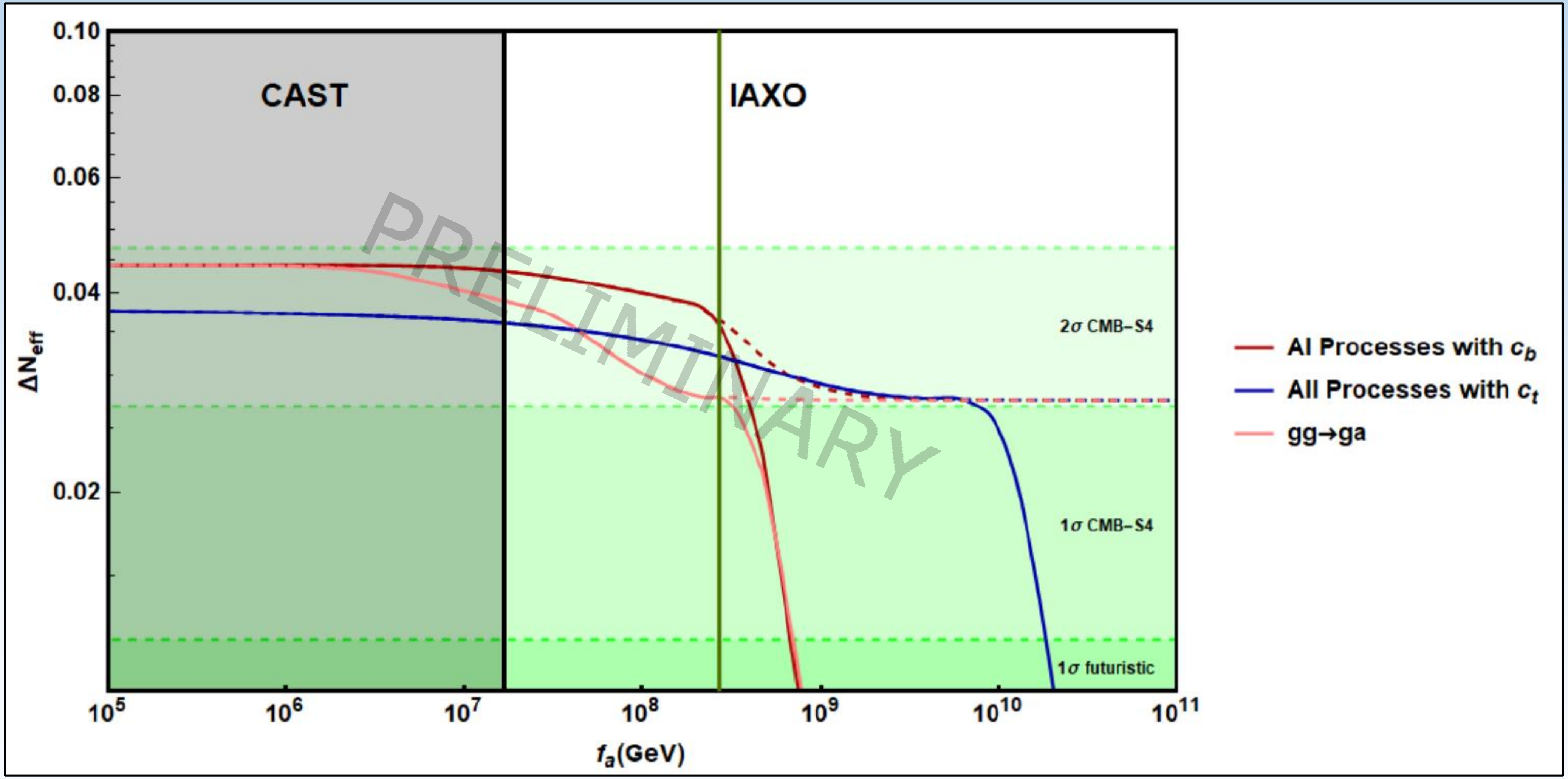
- Model independent approach
- Operator-by-operator analysis: assume only one axion coupling at a time
- Solve the Boltzmann equation and find ΔN_{eff} for each set of processes
- Stop the equation at 1 GeV to keep strong interactions perturbative
- Result sensitive to Early Universe conditions:
  - Initial condition: zero or thermal abundance
  - Reheating temperature

Results



PRELIMINARY
0.10
0.08
0.06
0.04
0.02
ΔN_eff
2σ CMB-S4
1σ CMB-S4
1σ futuristic
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
f_a(GeV)
tt→ag
bb→ag
tt→aH
tt→aZ
tt→aχ3
tb→aW
tt→aχ±
All Processes with c_t
gg→ga

Results

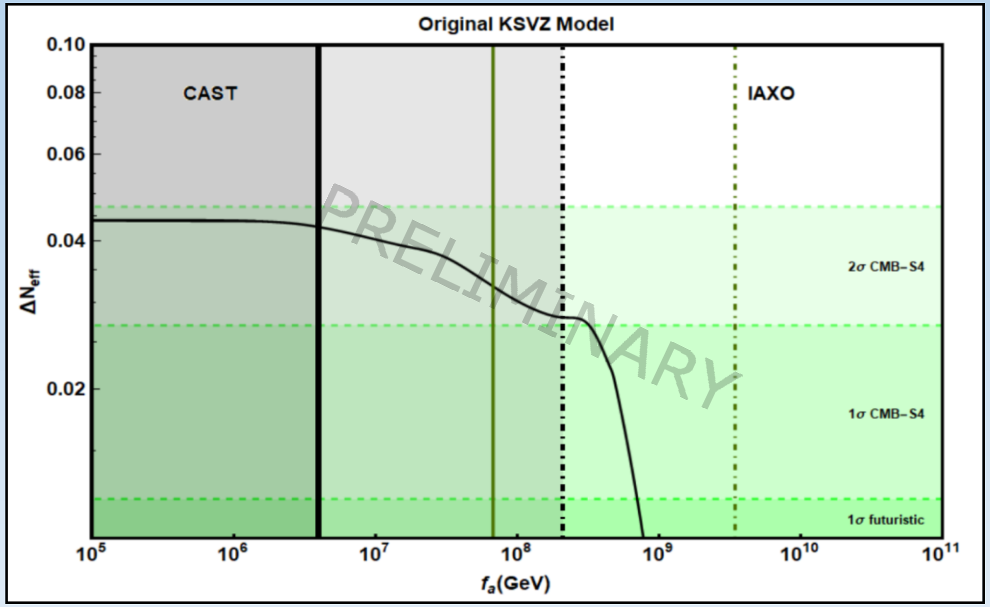


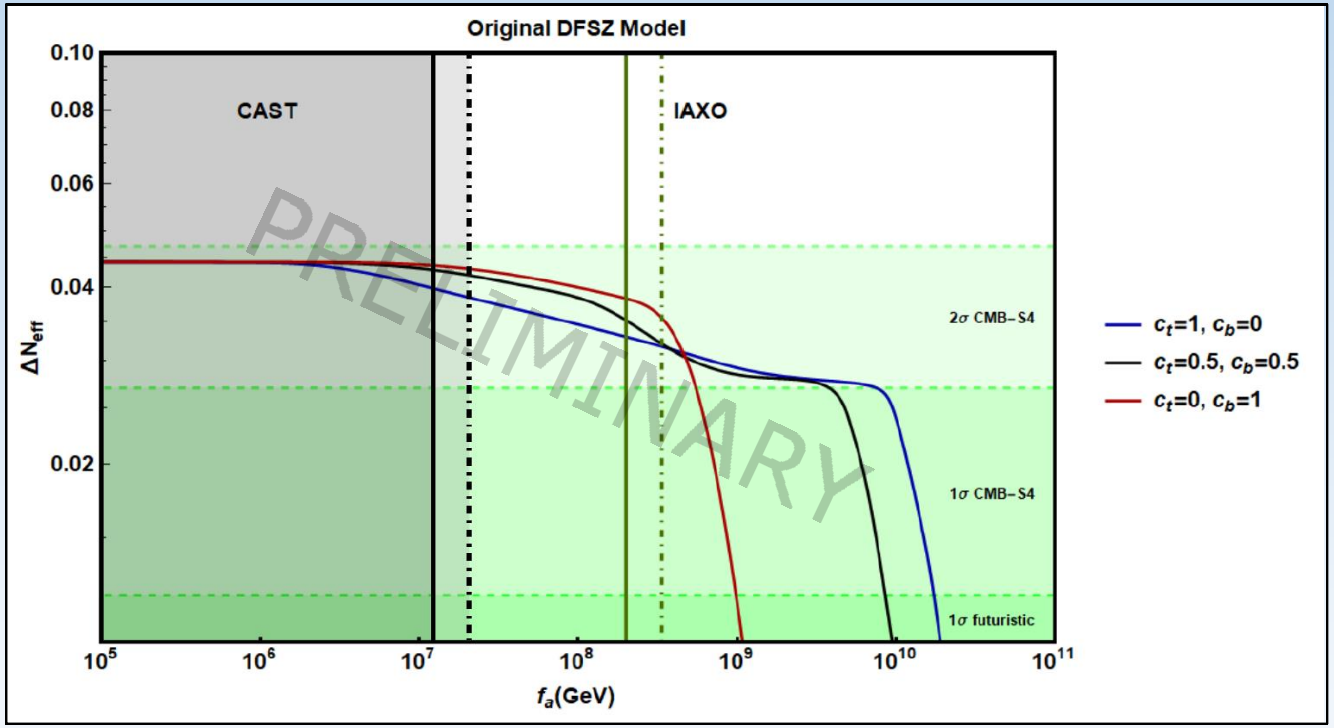
0.10
0.08
0.06
0.04
0.02
ΔN_eff
CAST
IAXO
PRELIMINARY
2σ CMB-S4
1σ CMB-S4
1σ futuristic
10^5
10^6
10^7
10^8
10^9
10^10
10^11
f_a(GeV)
Al Processes with c_b
All Processes with c_t
gg→ga

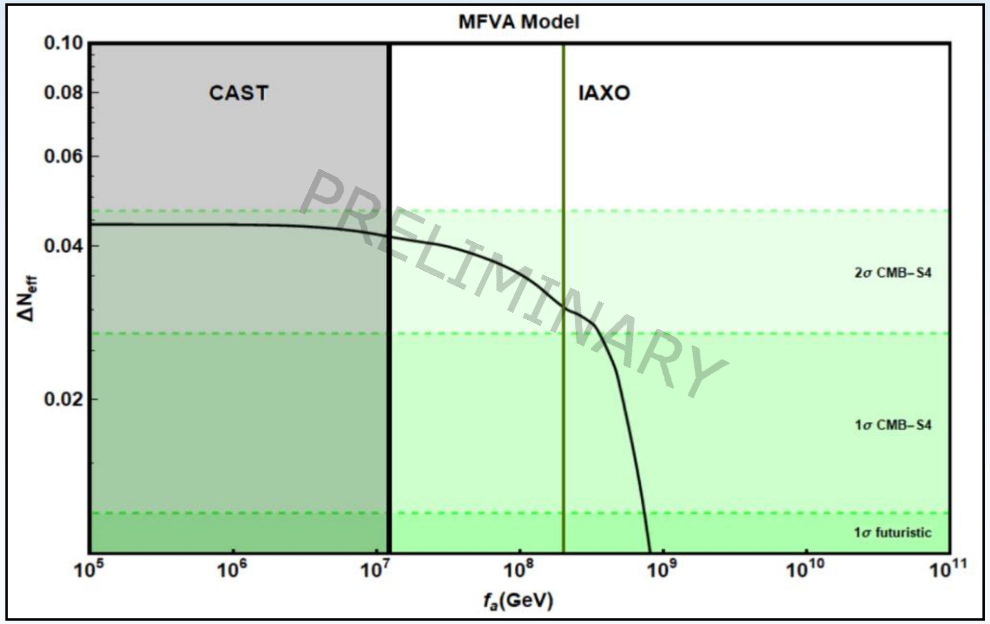
UV complete models

- Specific models give a single prediction for $\Delta N_{eff}(f_a)$
- Two classical invisible axion scenarios:
  - DFSZ. $c_t + c_b = 1, E/N$ has two possible values
    M. Dine, W. Fischler, and M. Srednicki, Phys. Lett.B104.
    A. R. Zhitnitsky, Sov. J. Nucl. Phys.31(1980) 260
  - KSVZ. Only gluon process, many values for E/N
    J. E. Kim, Phys. Rew. Lett. 43 (1979) 103
    M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov, Nucl. Phys.B166(1980) 493–506
- An example of a flavourful axion model:
  - The Minimal Flavour Violating Axion. $c_t = 0, E/N = 8/3$
    FAA & Merlo, 1709.07039

UV complete models







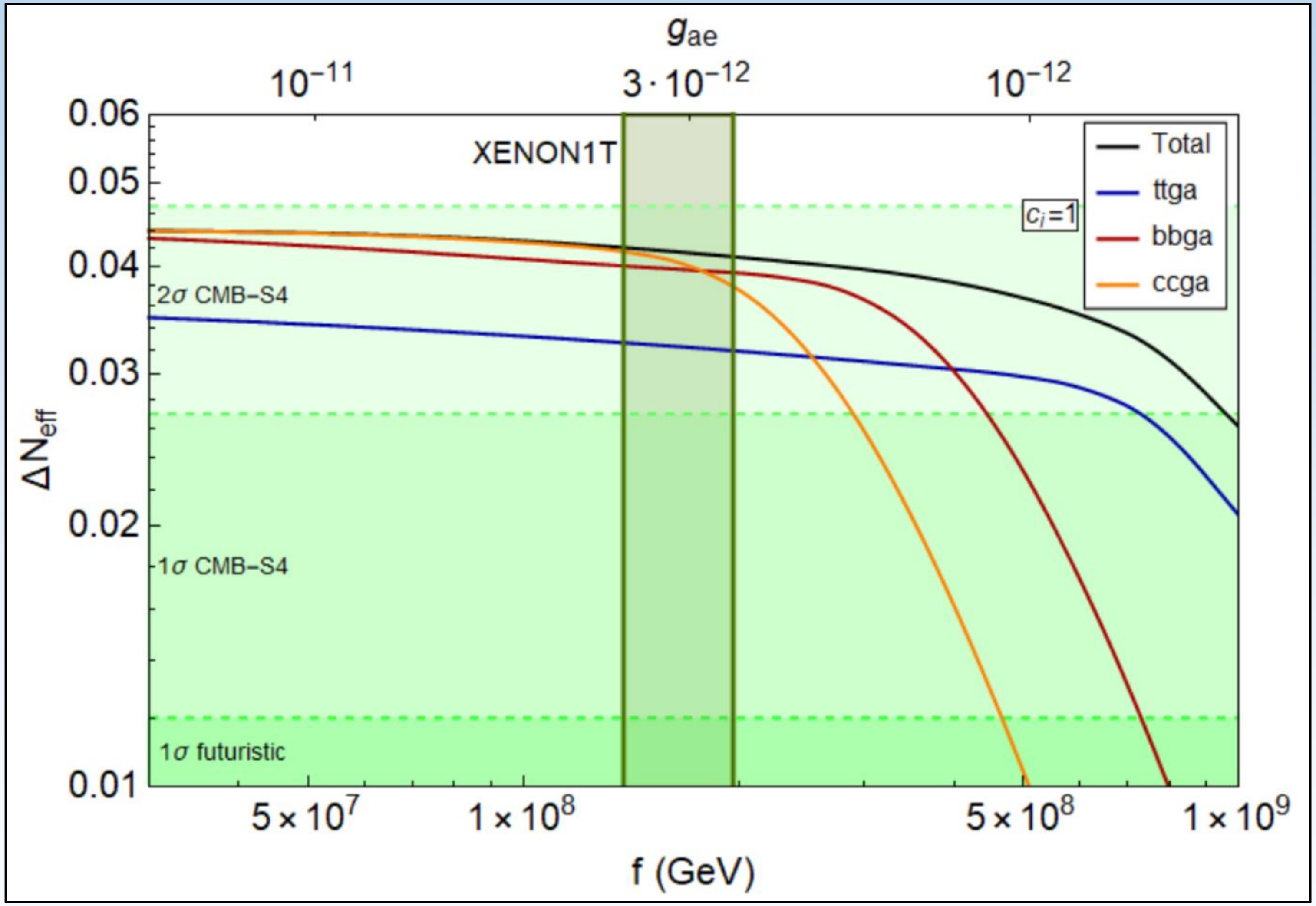
Complementarity with XENON1T

FAA, F. D'Eramo, R. Z. Ferreira, L. Merlo, A. Notari, 2007.06579

- An excess has been measured by XENON1T, compatible with solar axions
- They could also leave an imprint on the Early Universe through N_{eff}
- Using the expected axion-electron coupling, we look at the expected ΔN_{eff} produced by these light relics in three scenarios:
    - Democratic non-anomalous ALP, with all couplings $c_\psi = 1$
    - Non-anomalous ALP with only one coupling at tree level, inducing the rest at 1 loop
    - DFSZ axion

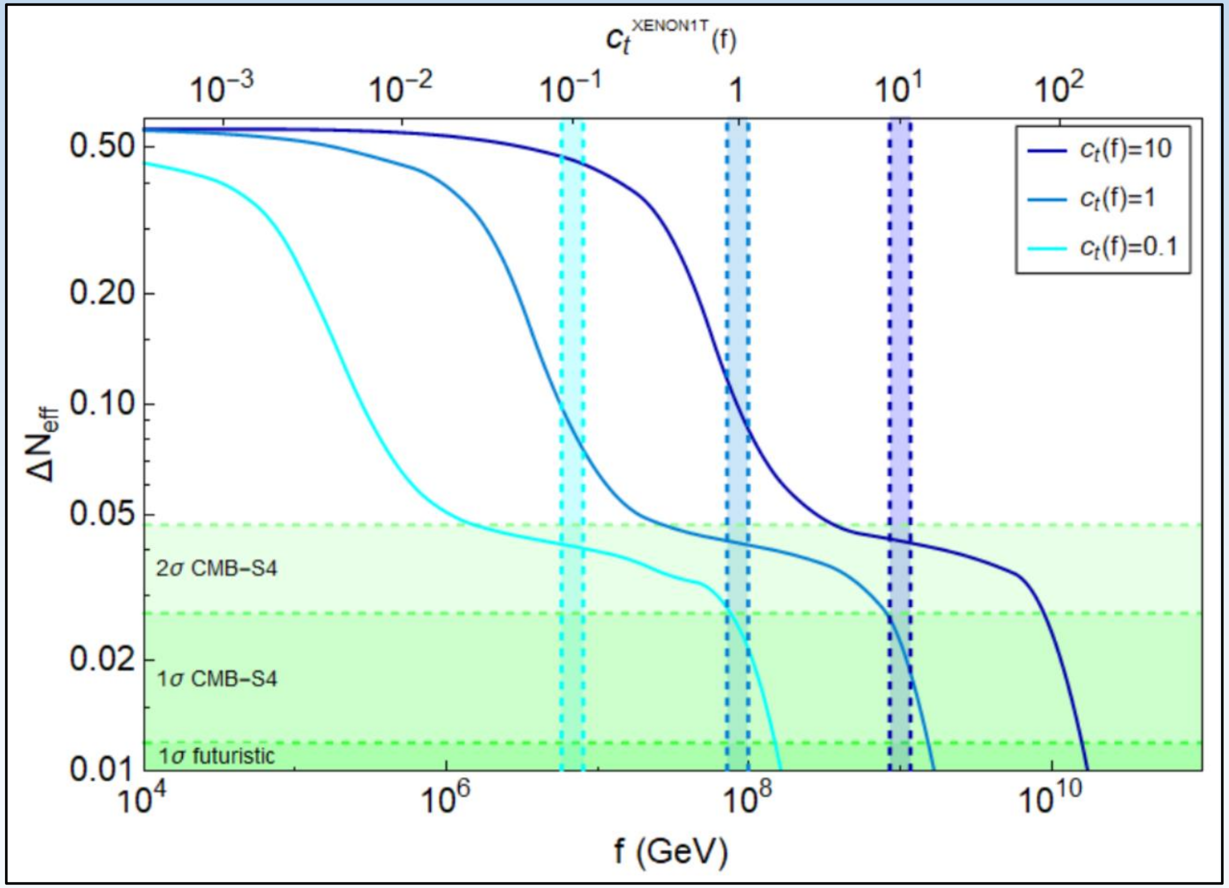
XENON1T – Democratic

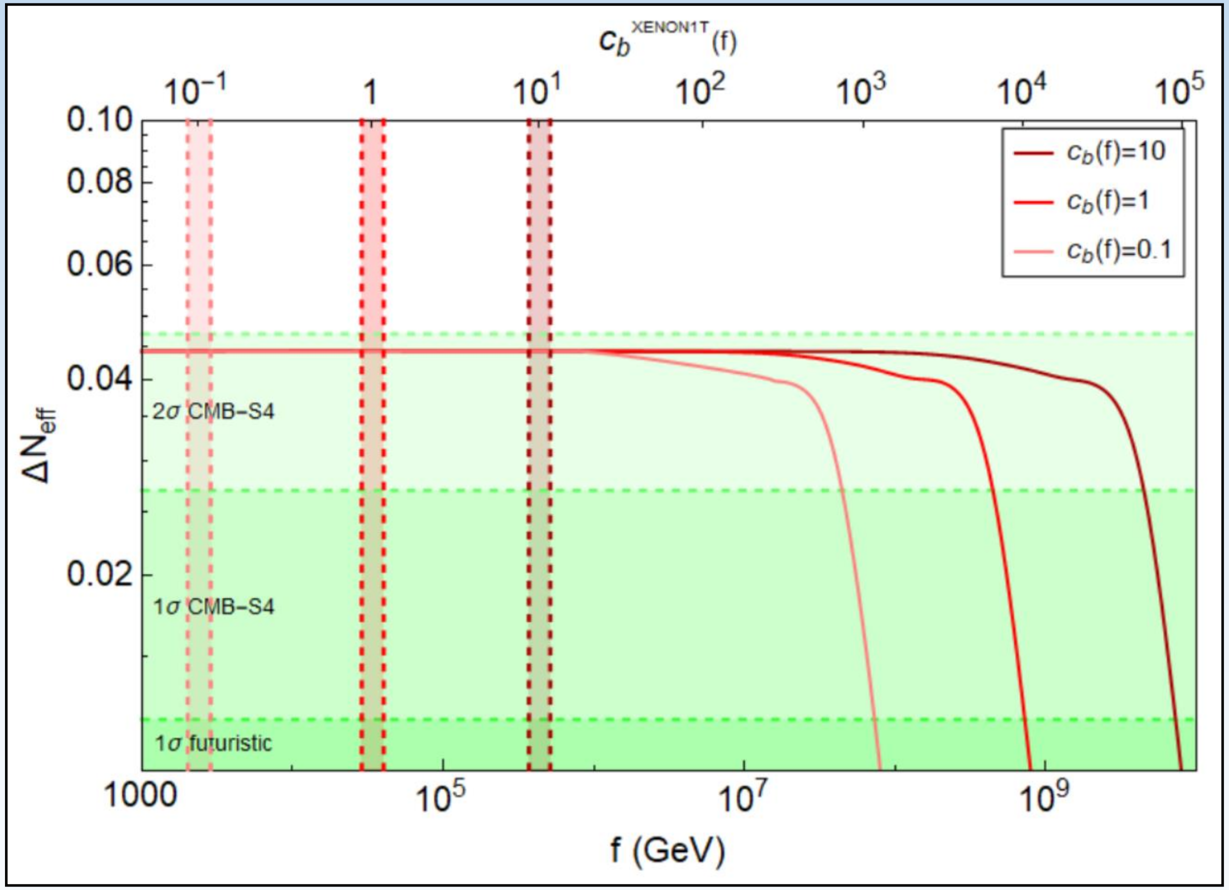
FAA, F. D'Eramo, R. Z. Ferreira, L. Merlo, A. Notari, 2007.06579



XENON1T – Loop-induced c_e

FAA, F. D'Eramo, R. Z. Ferreira, L. Merlo, A. Notari, 2007.06579





XENON1T – Loop-induced c_e

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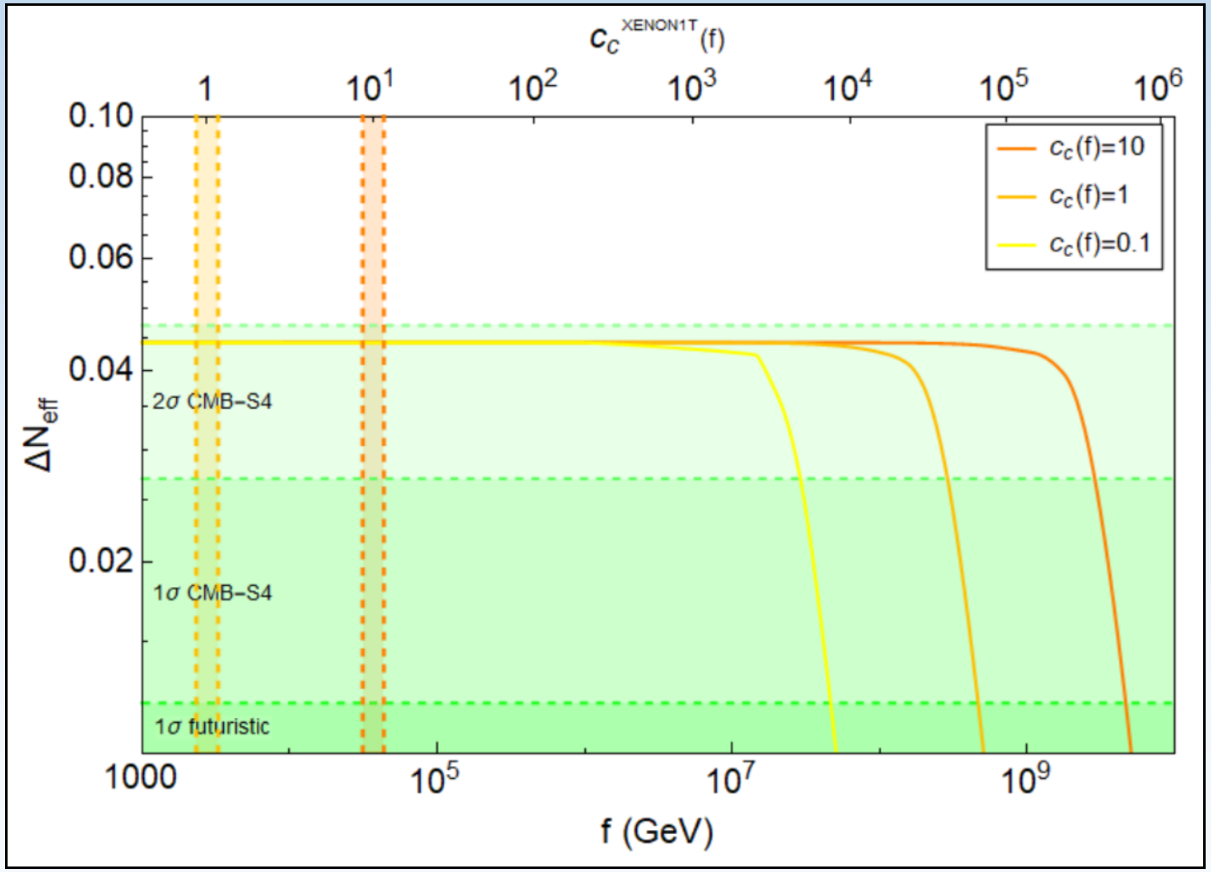
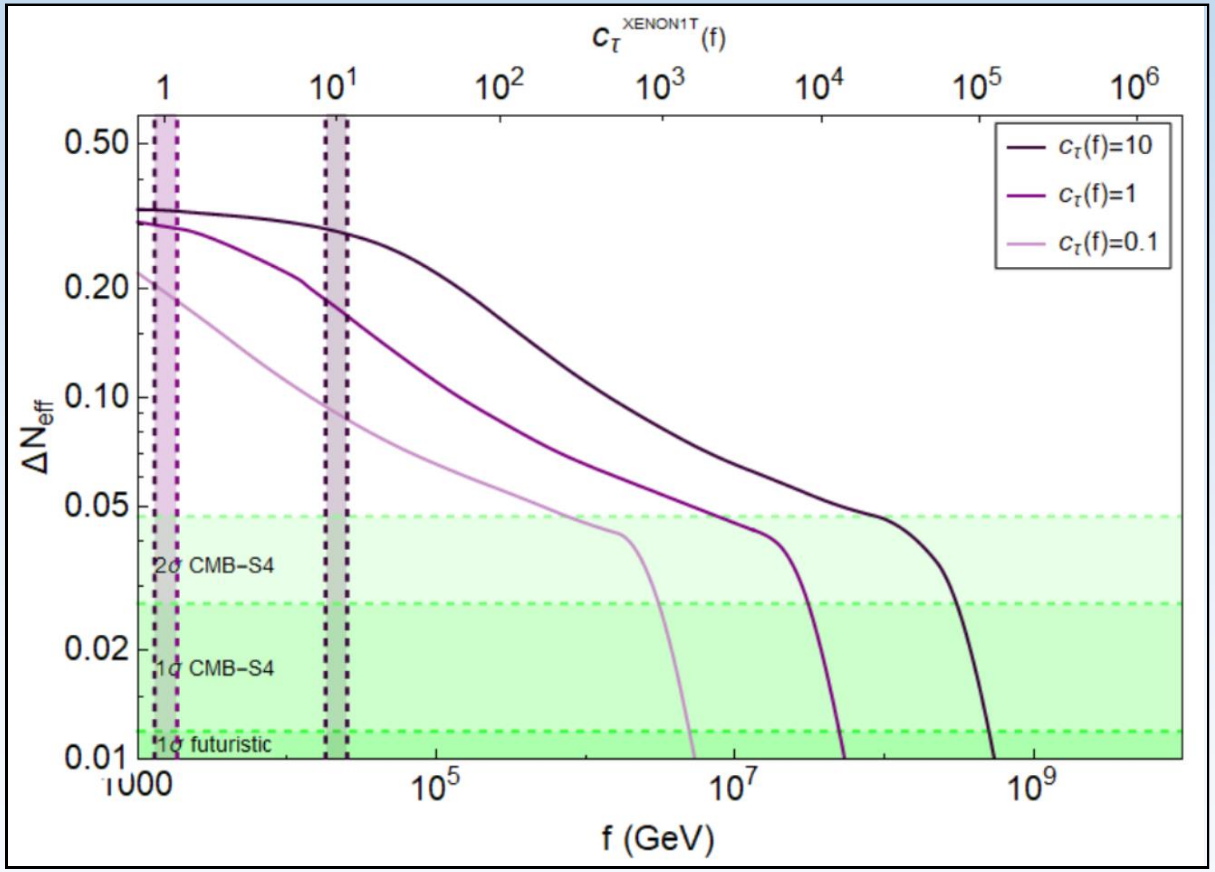
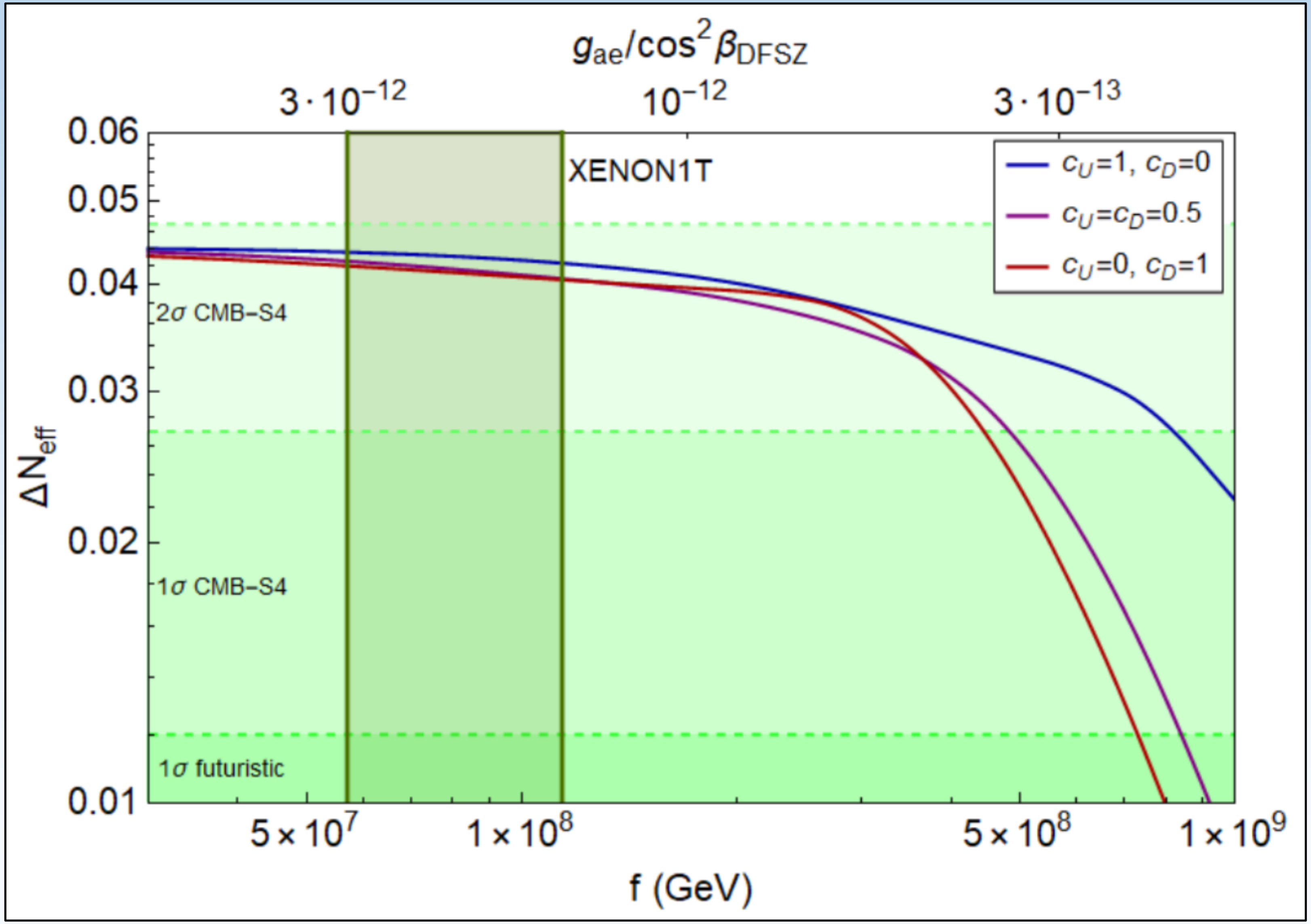




XENON1T – DFSZ

FAA, F. D'Eramo, R. Z. Ferreira, L. Merlo, A. Notari, 2007.06579



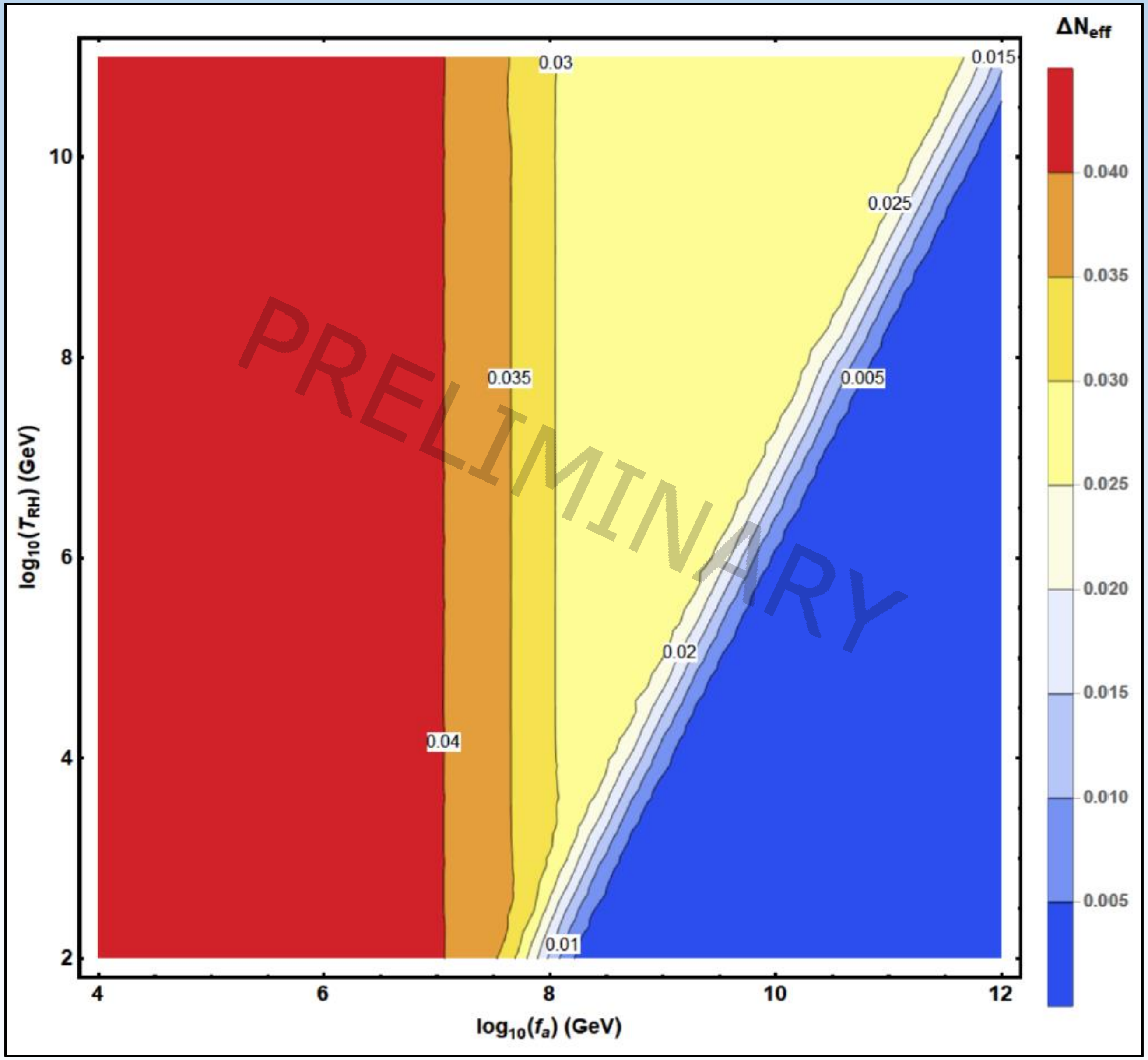
Summary

- Axions are a very well motivated and useful extension to the SM
- N_{eff} is an interesting observable, complementary to other searches
- It can reward us with knowledge about the axion couplings and/or Early Universe details
- If measured with enough precision, it can help distinguish different models
- Measurable at, at least, 2σ with the CMB-S4 experiment if XENON1T is confirmed to be an axion!

Thank you for your attention

Backup slides

Results



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

UV complete models – DFSZ

- Two Higgs doublets: one for up and another for down quarks
- Same axion couplings to all three generations
- Axion-quark couplings satisfy this relation:

$$c_t + c_b = 1$$

- Charged leptons can couple to either of the Higgs doublets
- Two possible axion-photon couplings
- Different $\Delta N_{eff}(f)$ predictions depending on specific c_t and c_b

UV complete models – KSVZ

- Axion does not couple to SM particles at tree level
- Axion couples to heavy exotic quarks through a new EW singlet scalar
- Many axion-photon couplings depending on heavy quark representations
- $\Delta N_{eff}(f)$ driven solely by gluon process

UV complete models – MFVA

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

- Minimal Flavour Violation: only the SM Yukawas break flavour
- PQ symmetry identified within the MFV symmetry group

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

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

- Flavour conserving non-universal couplings, with $c_t = 0$

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

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

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