Thermal Axions: What's Next?

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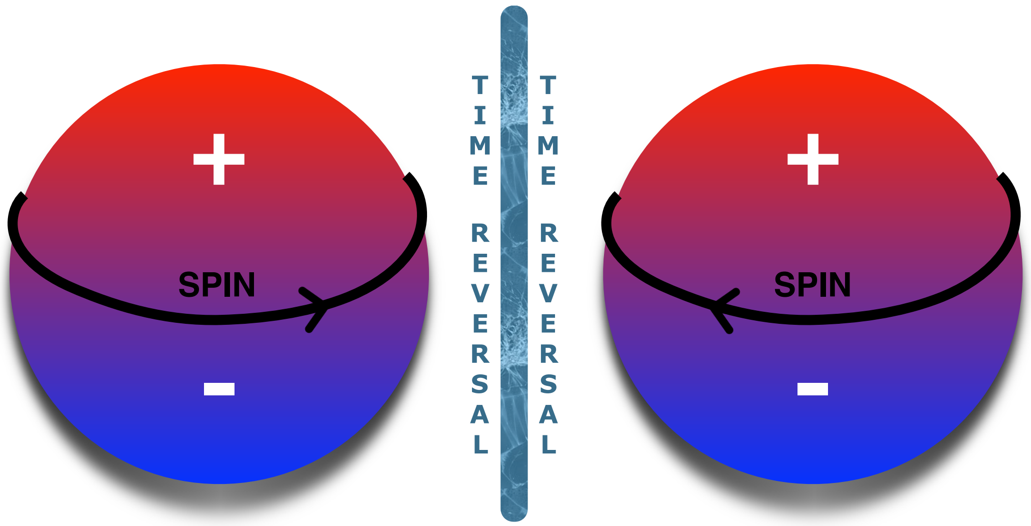
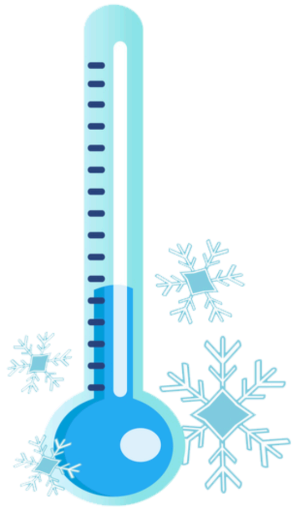
Virtues of the QCD Axion

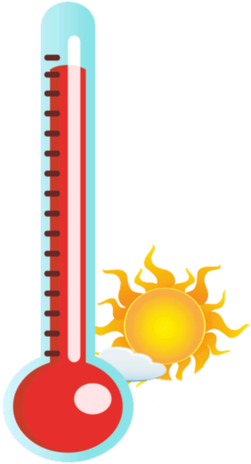
Strong CP



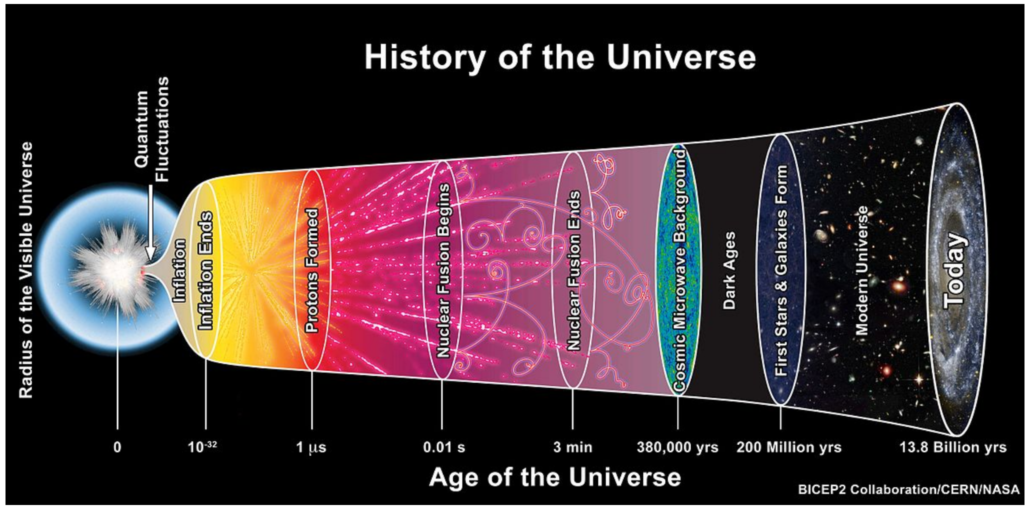
Cold Dark Matter



Plan for today: Hot Axions



Axions produced with kinetic energy much larger than their mass (i.e. "hot")

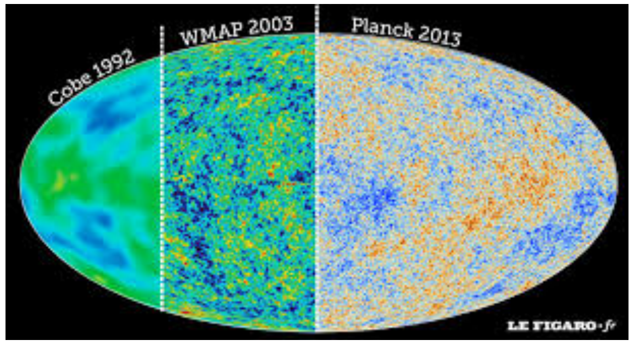


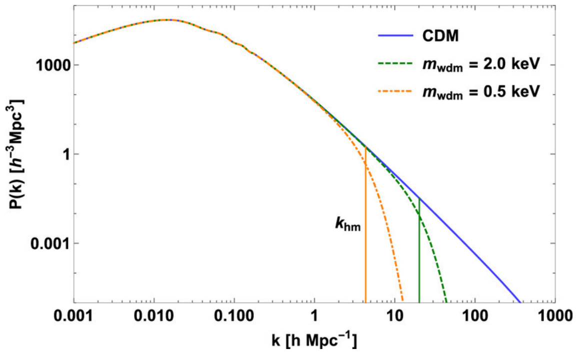
1. Production

Processes with particles from the primordial thermal bath

2. Signals

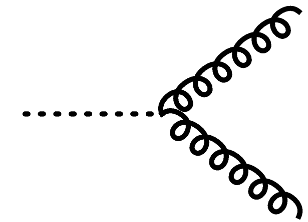
Dark radiation or warm dark matter



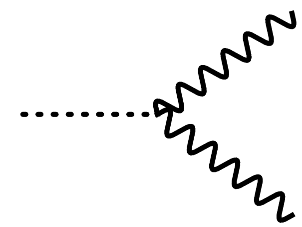


Thermal Production

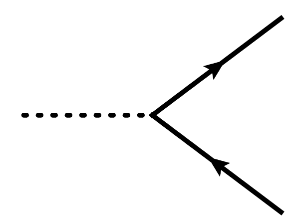
Scatterings and/or decays involving primordial thermal bath particles (axion energy ≫ m_a, i.e. "hot")



$$\frac{\alpha_s}{8\pi}\frac{a}{f_a}G^{\mu\nu}\widetilde{G}_{\mu\nu}$$



$$c_{\gamma\gamma}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F^{\mu\nu}\widetilde{F}_{\mu\nu}$$



$$c_\psi\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$$

<u>Unavoidable Production Source!</u>

Observable Effects

Dark Radiation

Additional radiation at:

- BBN ($m_a \lesssim$ MeV)
- CMB formation ($m_a \lesssim 0.3$ eV)

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

$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_a}{\rho_\gamma}$$

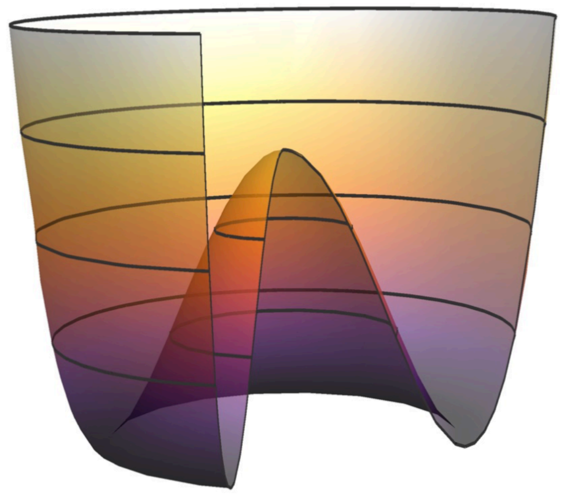
Warm Dark Matter

If $m_a \sim$ eV we have a warm dark matter component (exactly as neutrinos in the standard model)

QCD Axion or ALPs?

Axion-Like-Particles (ALPs) are ubiquitous in extension of the standard model

- Pseudo-Nambu-Goldstone-bosons
- Axions in string theory



QCD Axion

$$m_a \simeq 5.7 \left(\frac{10^9 \, \mathrm{GeV}}{f_a} \right) \mathrm{meV}$$

ALPs

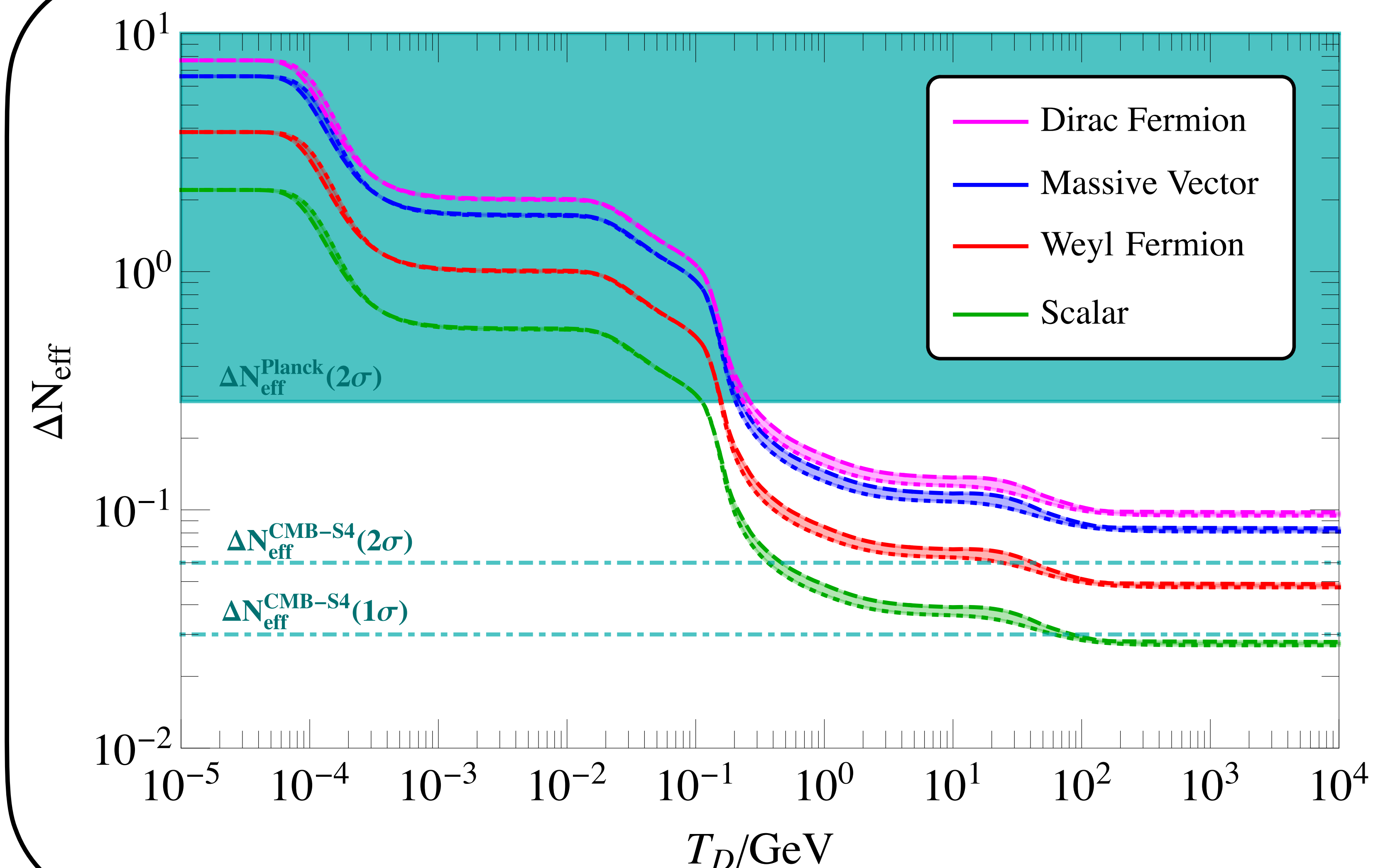
$$m_a \simeq \Lambda_X^2 / f_X$$

Results in this talk mostly about the QCD axion (easily generalized when the mass is negligible)

How to Predict ΔN_{eff}

ΔNeff - I: Instantaneous decoupling

- Assume they thermalize at early times
- Estimate the decoupling temperature from $\Gamma(T_D) = H(T_D)$



$$\Delta N_{\rm eff} \simeq 0.027 \left(\frac{106.75}{g_{*s}(T_D)}\right)^{4/3}$$

FD, Hajkarim, Yun, **JHEP 10 (2021)**

How to Predict ΔN_{eff}

ΔNeff - I: Instantaneous decoupling

- Assume they thermalize at early times
- Estimate the decoupling temperature from $\Gamma(T_D) = H(T_D)$

ΔNeff - II: Boltzmann equation for n_a

- Track the number density of axions
- Convert the asymptotic result via the equilibrium distribution

$$\frac{dn_a}{dt} + 3Hn_a = \sum_\alpha \gamma_\alpha$$

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

$$\alpha = \text{Production processes}$$

How to Predict ΔN_{eff}

ΔNeff - I: Instantaneous decoupling

- Assume they thermalize at early times
- Estimate the decoupling temperature from $\Gamma(T_D) = H(T_D)$

ΔNeff - II: Boltzmann equation for n_a

- Track the number density of axions
- Convert the asymptotic result via the equilibrium distribution

Equilibrium thermodynamics for the conversion to energy

Spectral distortions neglected

Maxwell-Boltzmann statistics (i.e., no quantum effects)

Static thermal bath (i.e., no energy exchanged)

Scenarios for Hot Axions

Single Coupling Switched On

Axion production controlled by its interaction with a given Standard Model field

Ferreira, Notari, **Phys.Rev.Lett. 120 (2018)**
FD et al, **JCAP 11 (2018)**
Arias-Aragón et al., **JCAP 11 (2020)**
and **JCAP 03 (2021)**
Green at al., **JCAP 02 (2022)**

UV Completions

FD, Hajkarim, Yun, **JHEP 10 (2021)**

- **KSVZ Axion:** Standard Model fields are PQ-neutral and color anomaly from heavy colored and PQ-charged fermion Ψ

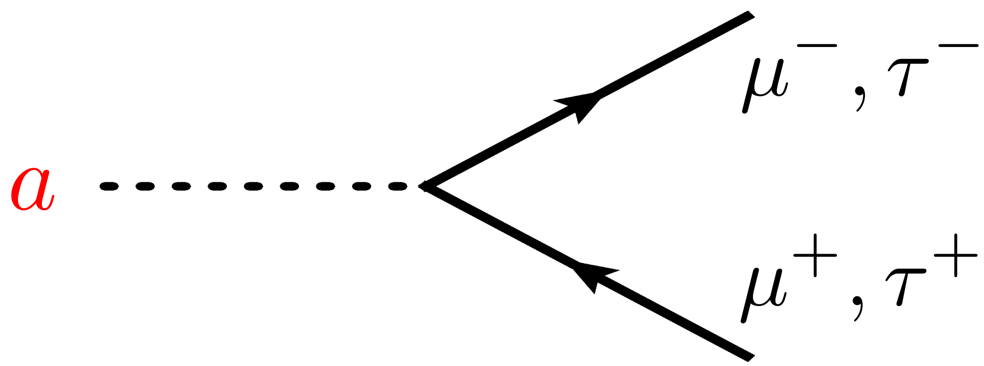
Kim, PRL 43 (1979)
Shifman, Vainshtein, Zakharov, NPB 166 (1980)

- **DFSZ Axion:** Standard Model fields charged (two Higgs doublets) and color anomaly from quarks

Zhitnitsky, SJNP 31 (1980)
Dine, Fischler, Srednicki, PLB 104 (1981)

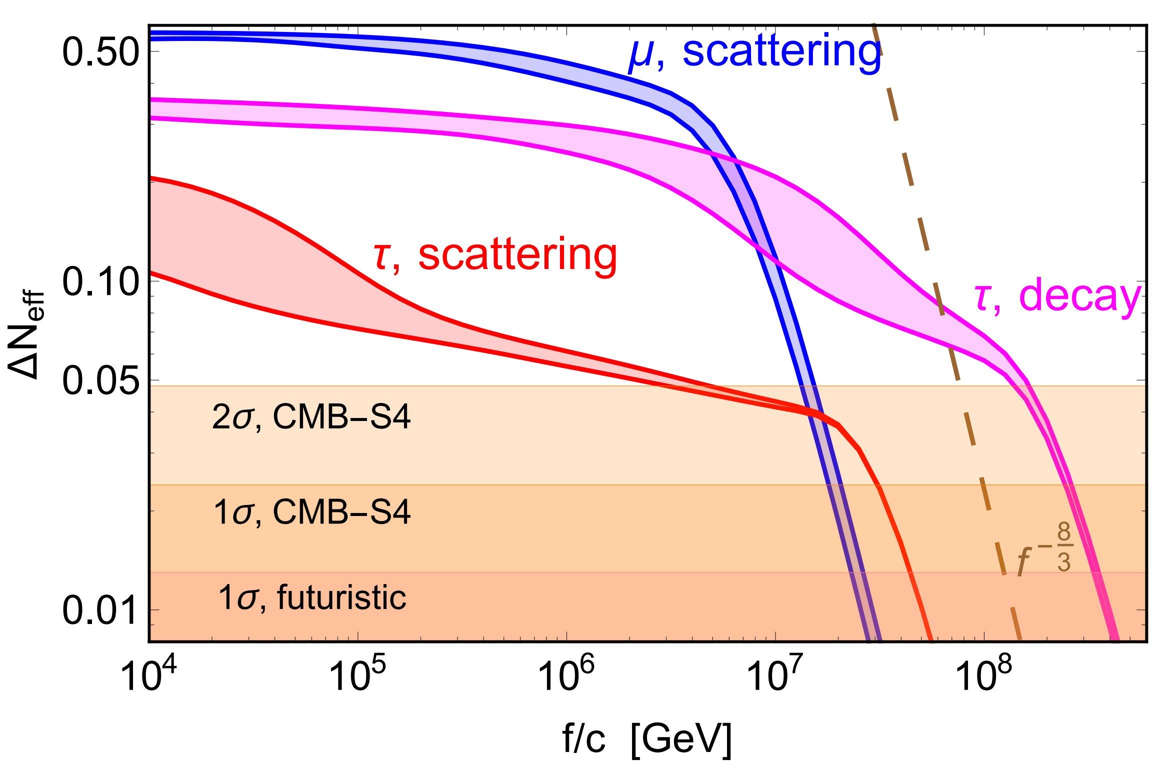
A Leptophilic Axion

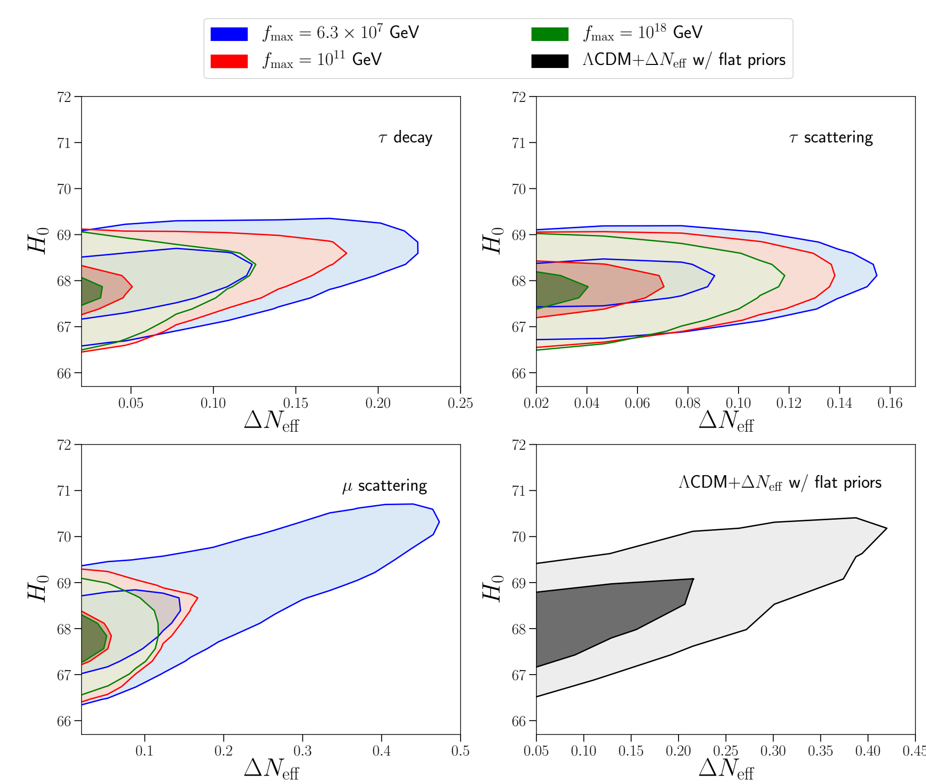
Leptons



FD, Ferreira, Notari, Bernal, **JCAP 1811 (2018)**

They can alleviate **the Hubble tension**

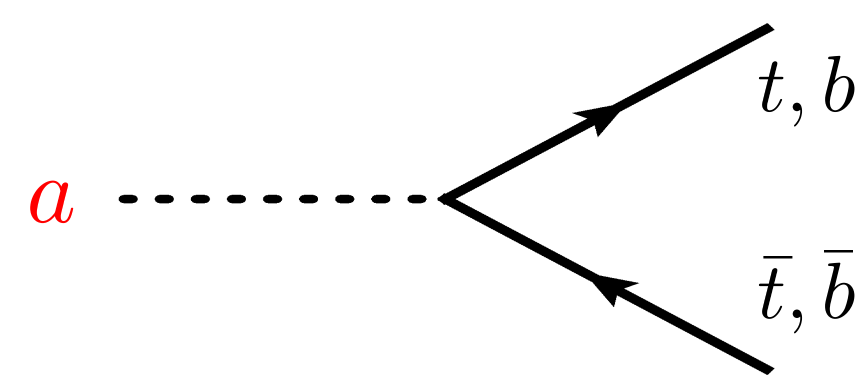




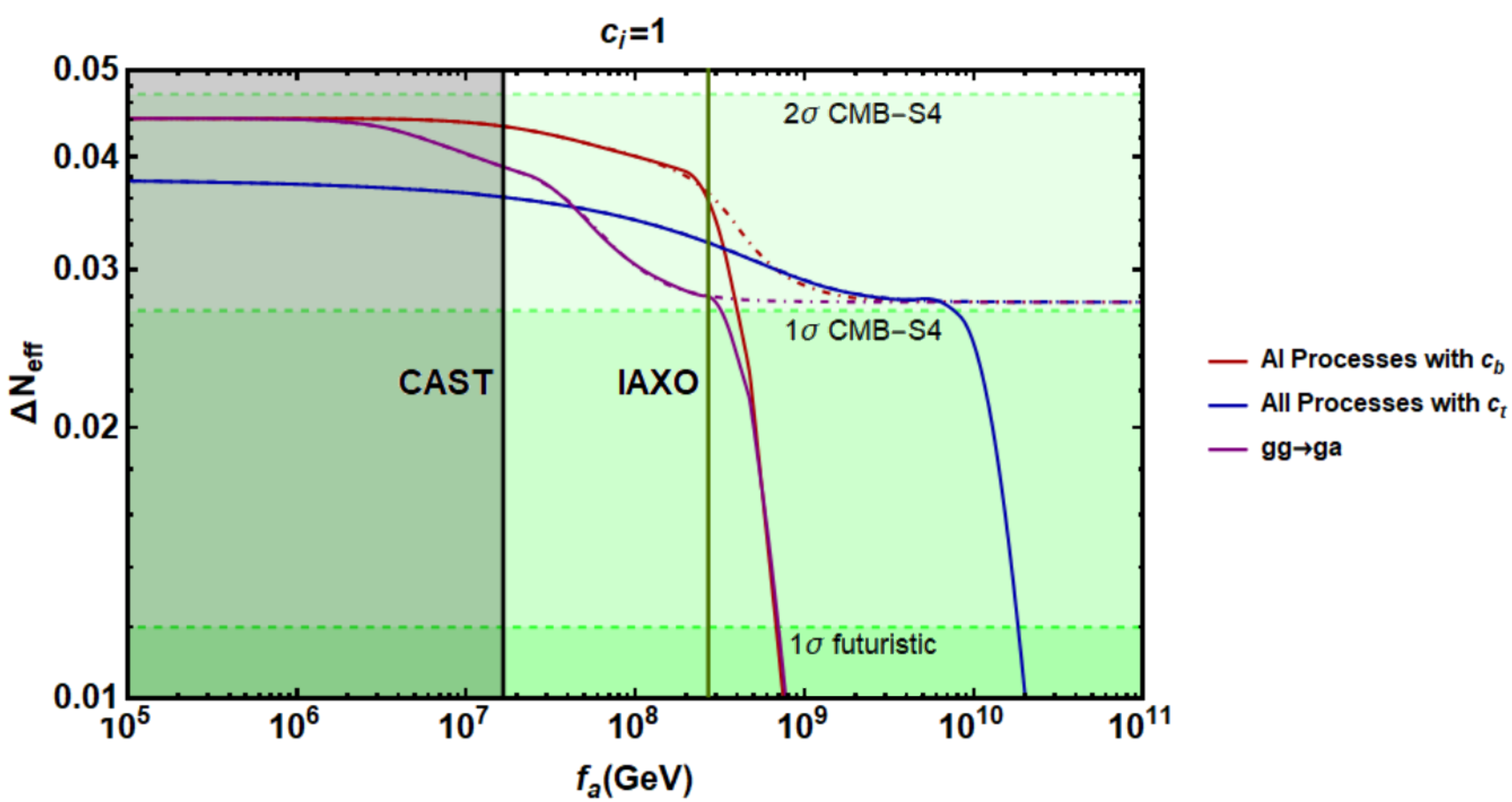
Axion Coupled to Heavy Quarks

Smooth rate across EWPT, within reach of **CMB-S4 surveys**

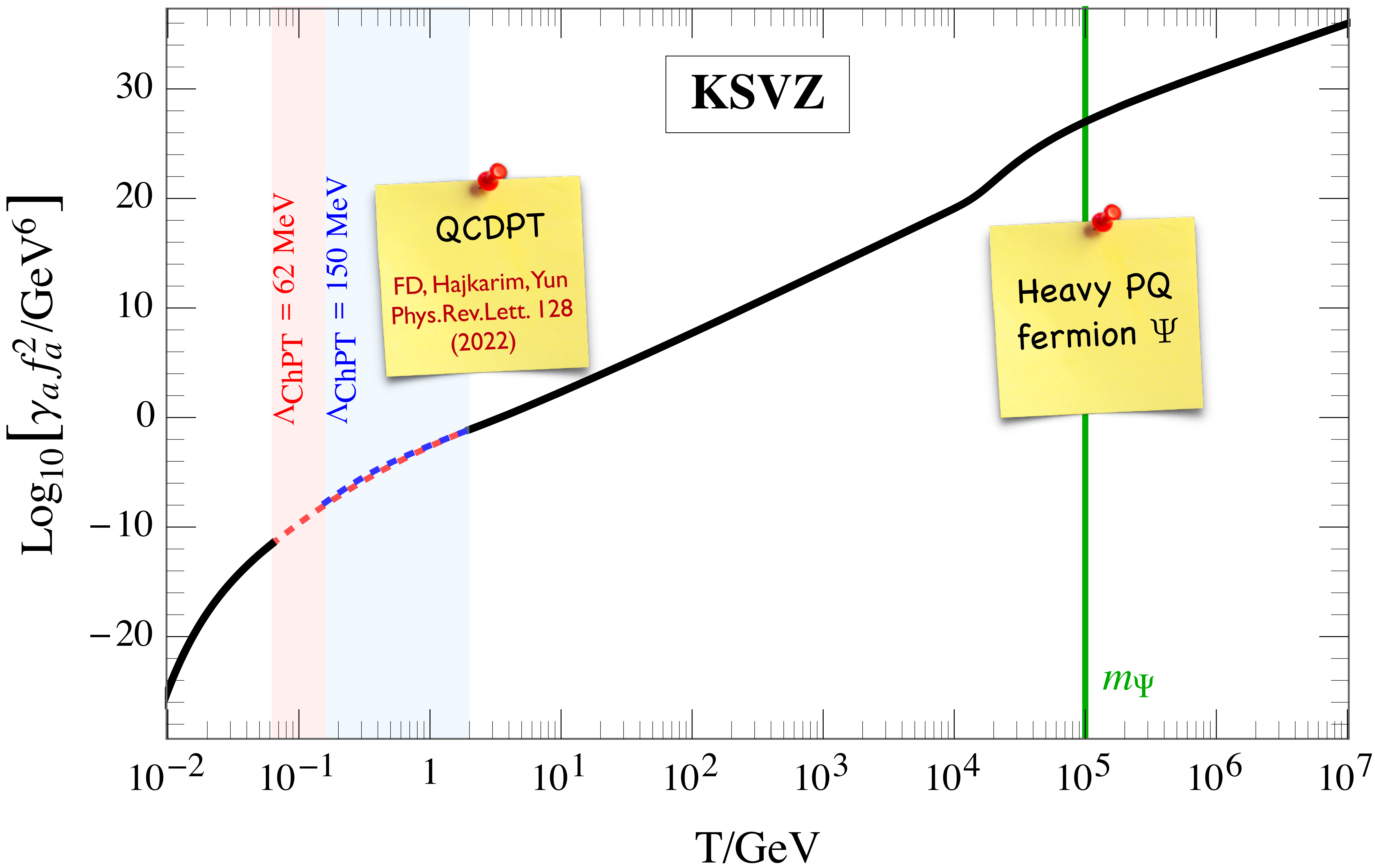
3rd Gen. Quarks



Arias-Aragon, FD, Ferreira, Merlo, Notari, **JCAP 03 (2021)**

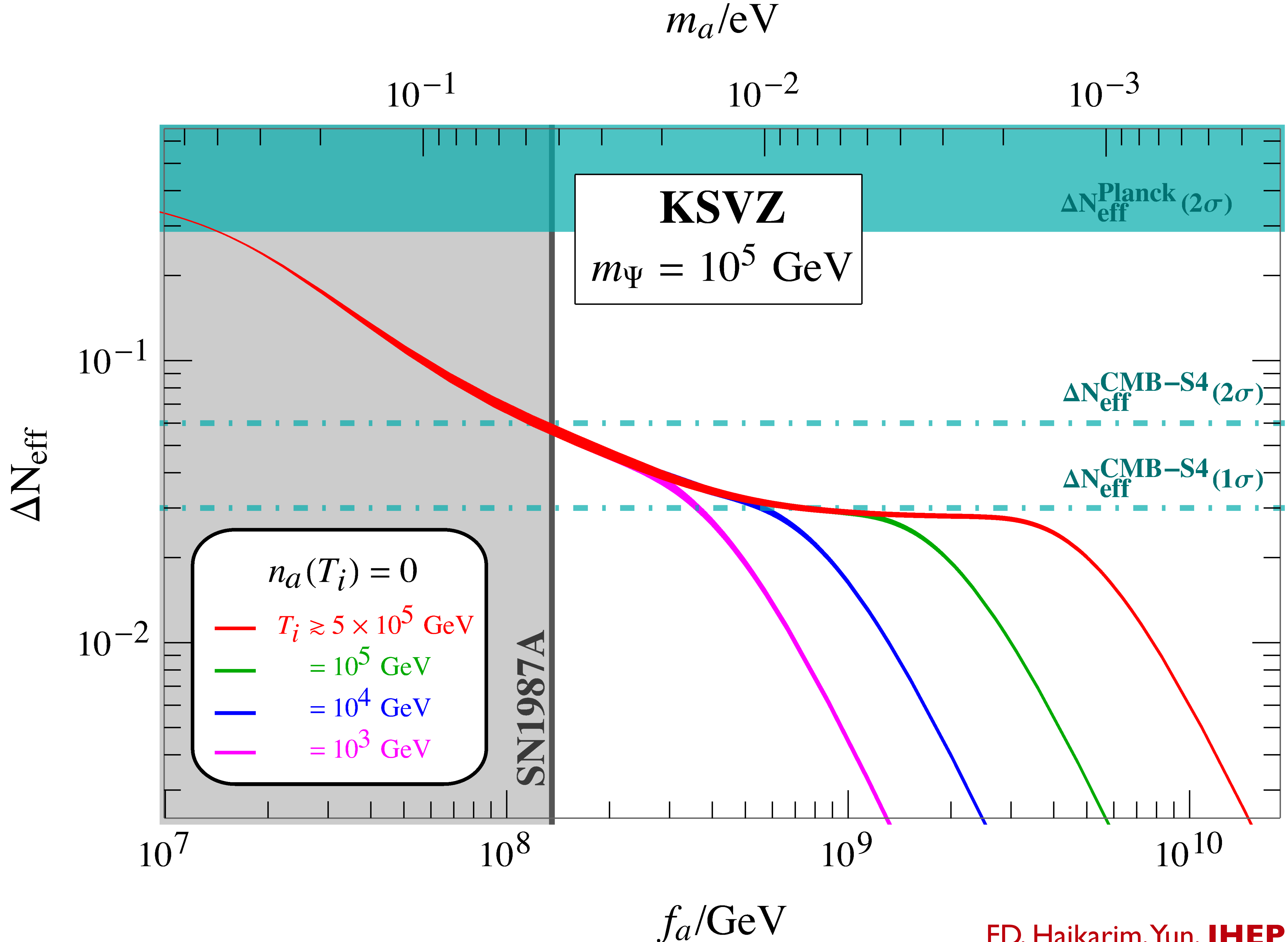


KSVZ Axion — Production Rate



FD, Hajkarim, Yun, **JHEP 10 (2021)**

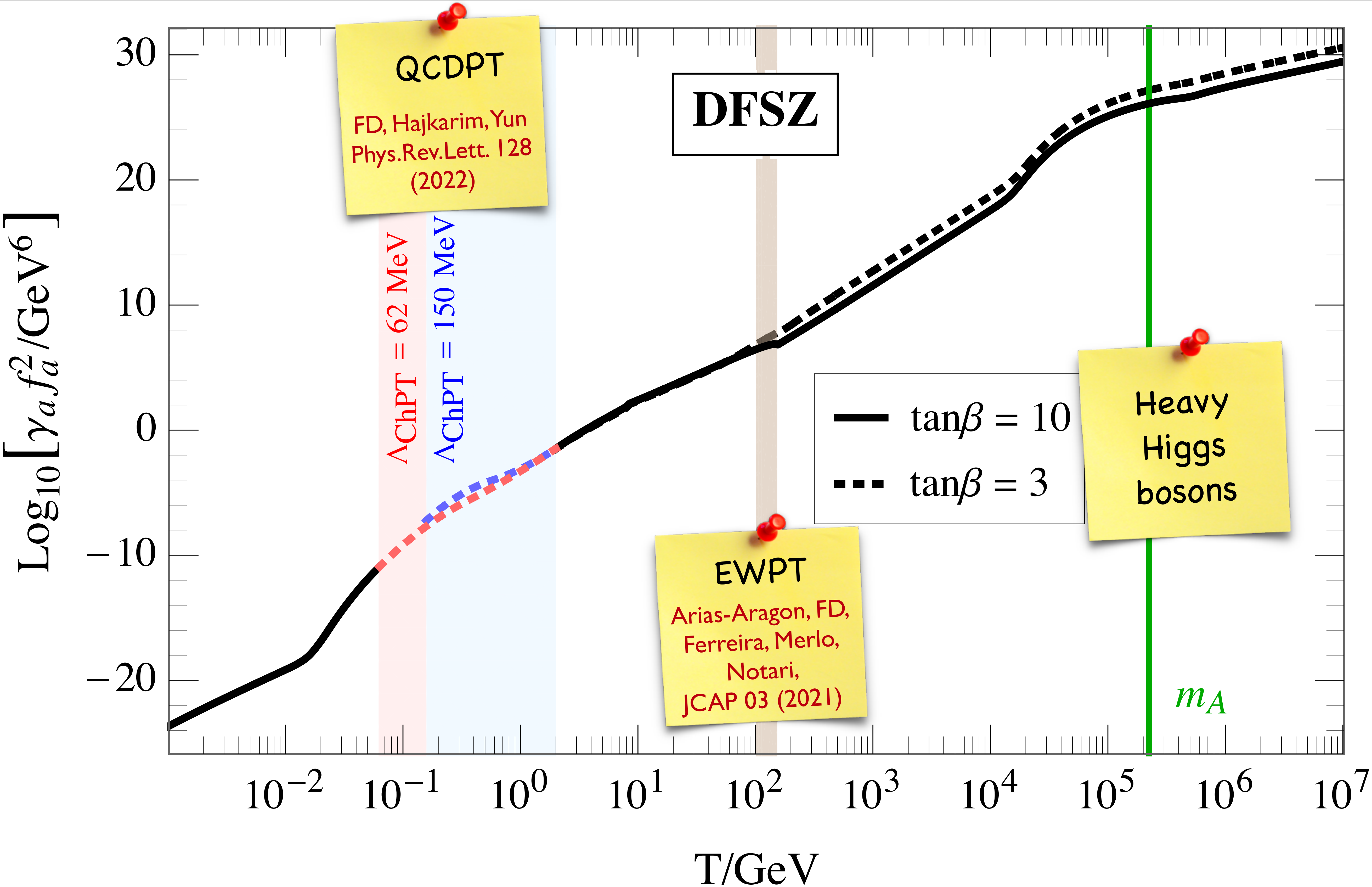
KSVZ Axion — Results for ΔN_{eff}



FD, Hajkarim, Yun, **JHEP 10 (2021)**

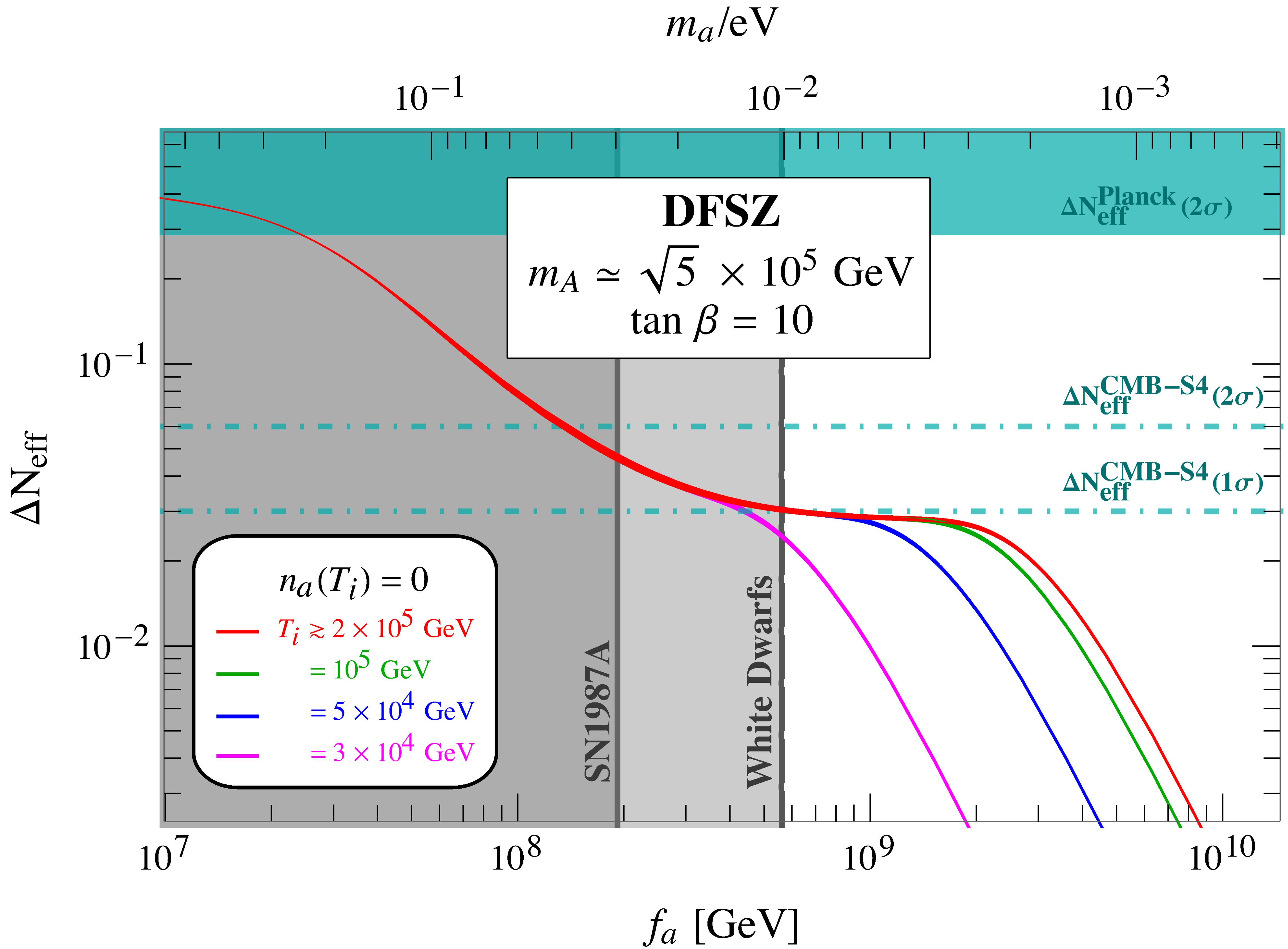
FD, Hajkarim, Yun, **Phys.Rev.Lett. 128 (2022)**

DFSZ Axion — Production Rate



FD, Hajkarim, Yun, **JHEP 10 (2021)**

DFSZ Axion — Results for ΔN_{eff}



FD, Hajkarim, Yun, **JHEP 10 (2021)**

Finite QCD Axion Mass Effects?

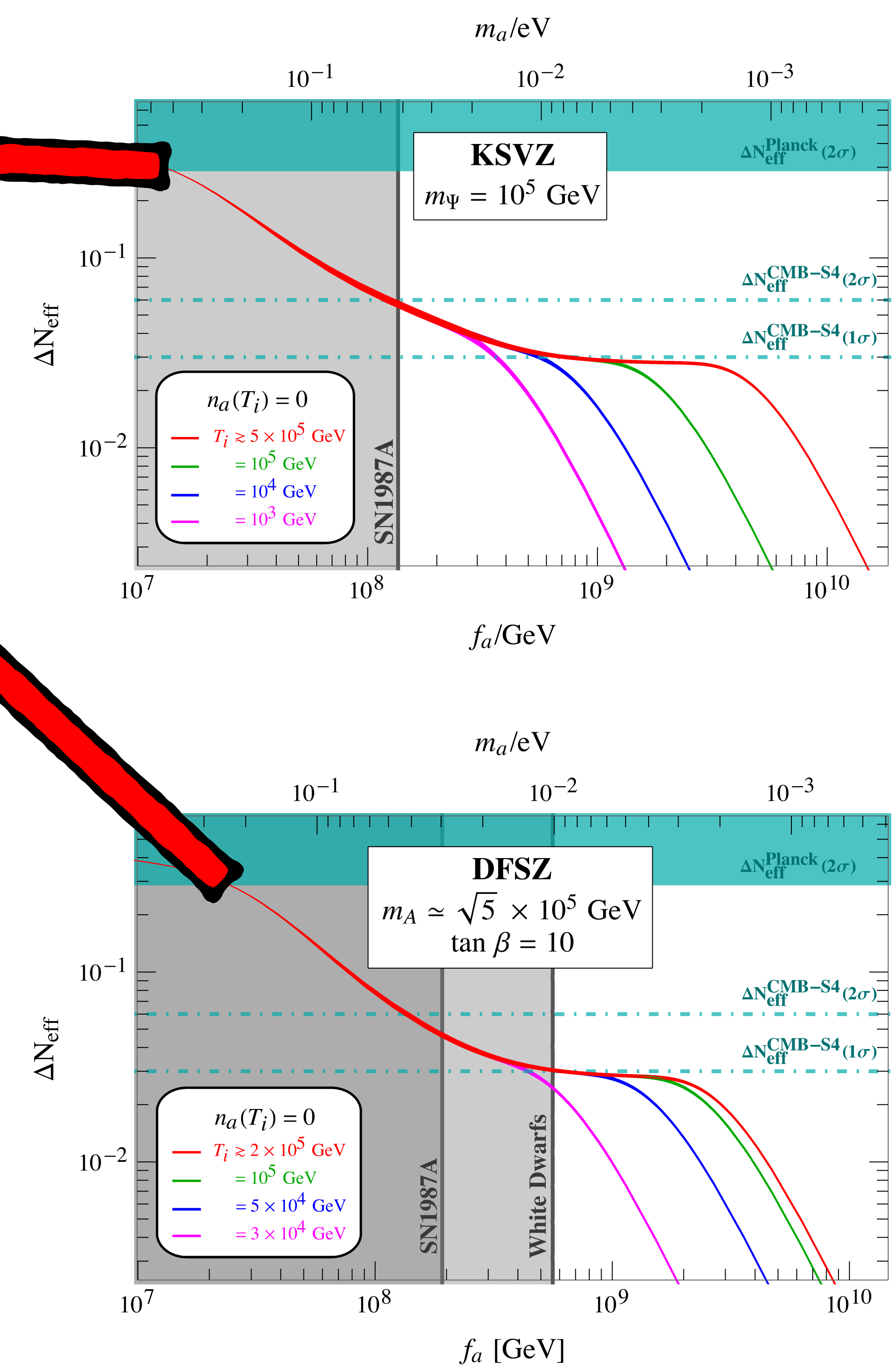
Planck: tension with astrophysics and axion mass non-negligible

Finite axion mass

- Pion scatterings
  Ferreira et al., **Phys.Rev.D 103 (2021)**
  Notari et al., **Phys.Rev.Lett. 131 (2023)**
  Bianchini et al., **arXiv:2310.08169**

- Gluon, photon couplings
  Caloni et al., **JCAP 09 (2022)**

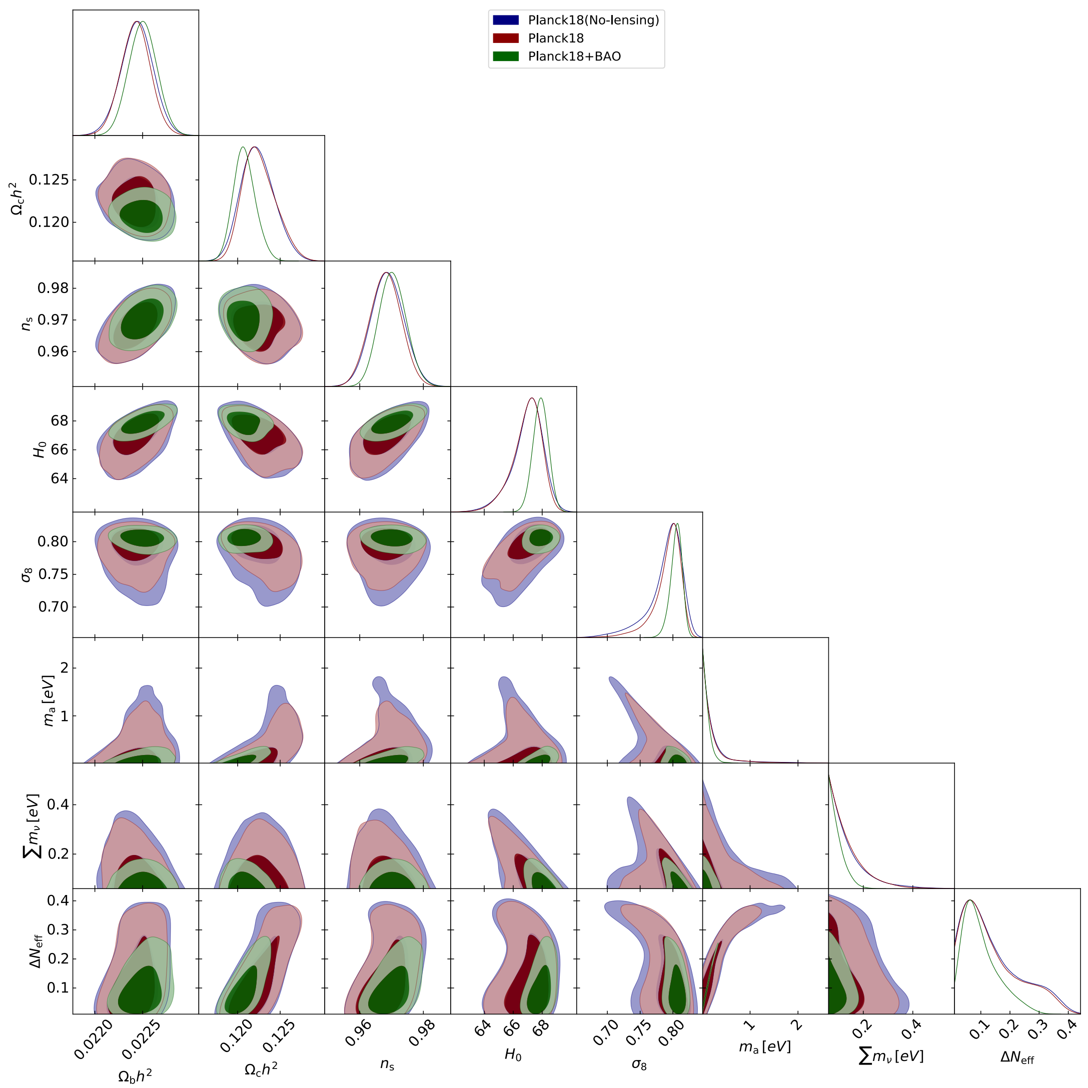
- KSVZ and DFSZ
  FD et al., **JCAP 09 (2022)**



FD, Hajkarim, Yun, **JHEP 10 (2021)**

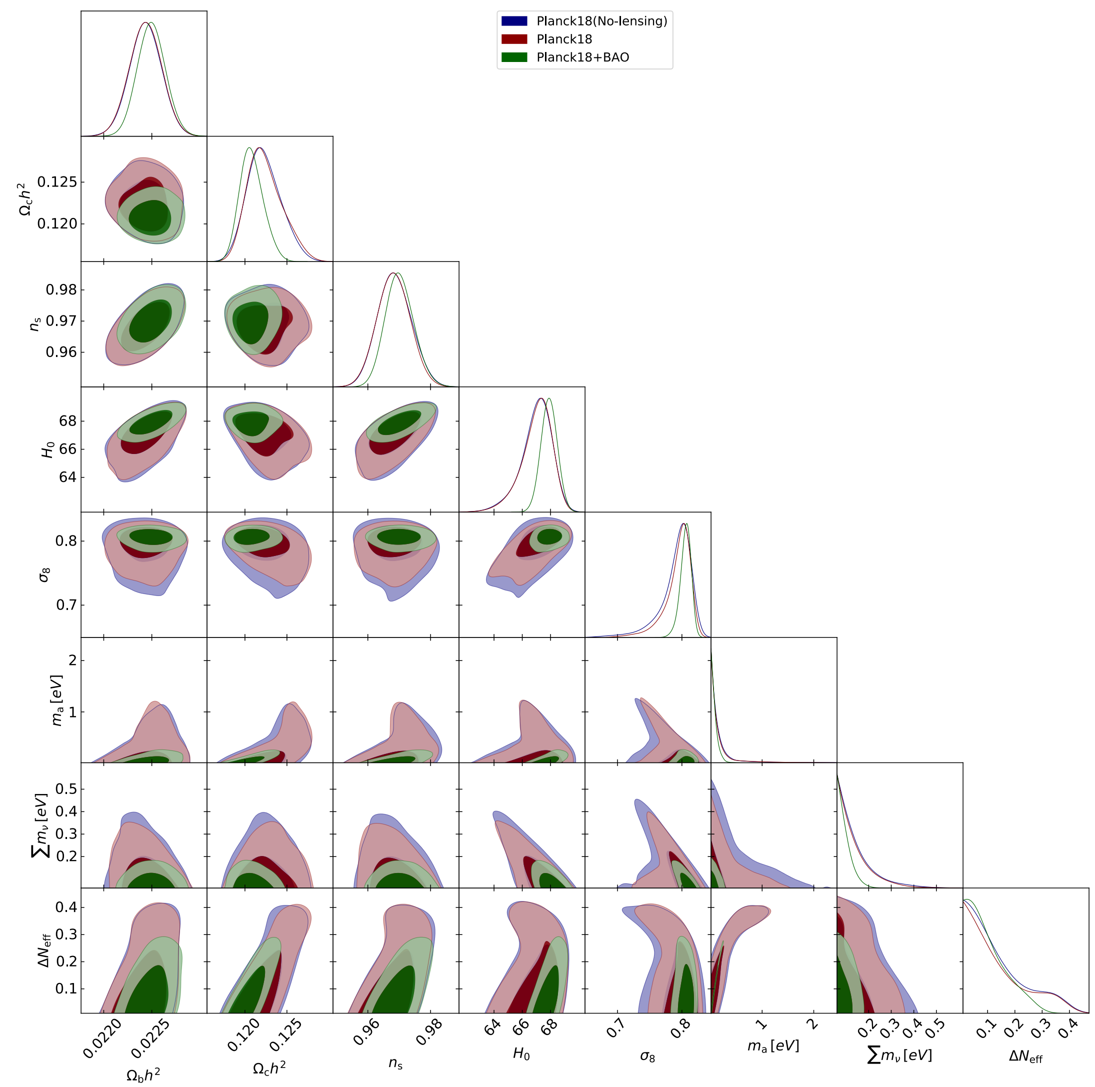
Axion Mass Bound

KSVZ



$$m_a \leq 0.282(0.420)\,\mathrm{eV}$$

DFSZ



$$m_a \leq 0.209(0.293)\,\mathrm{eV}$$

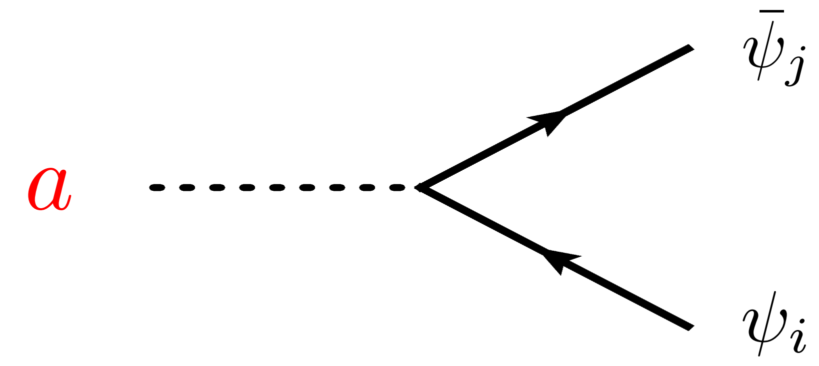
FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, **JCAP 09 (2022)**

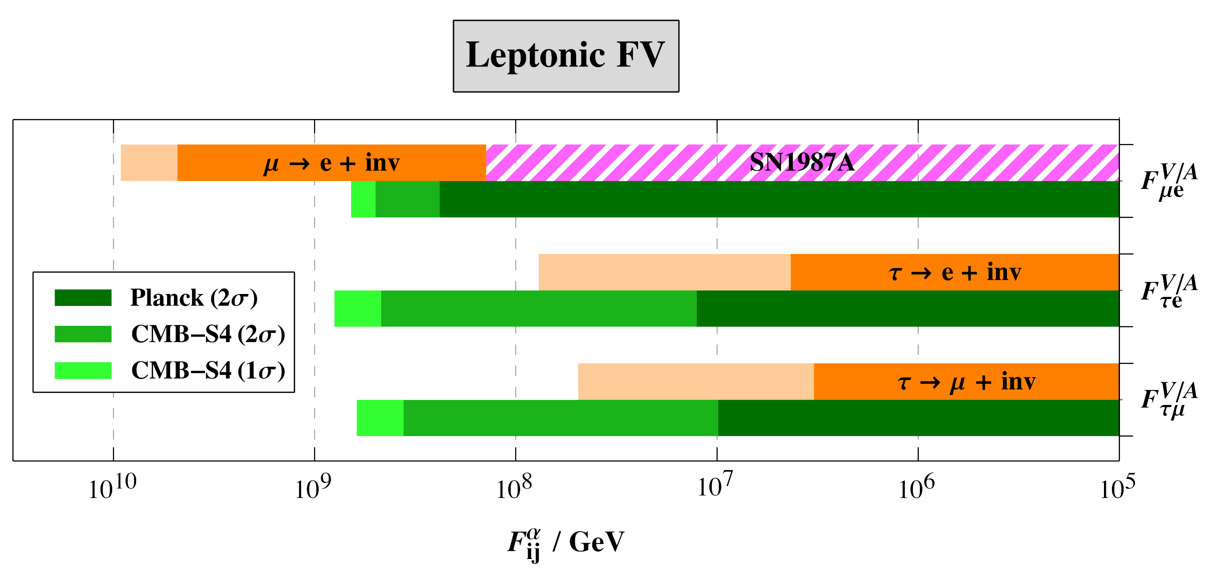
A Minor Variation: FV Axions

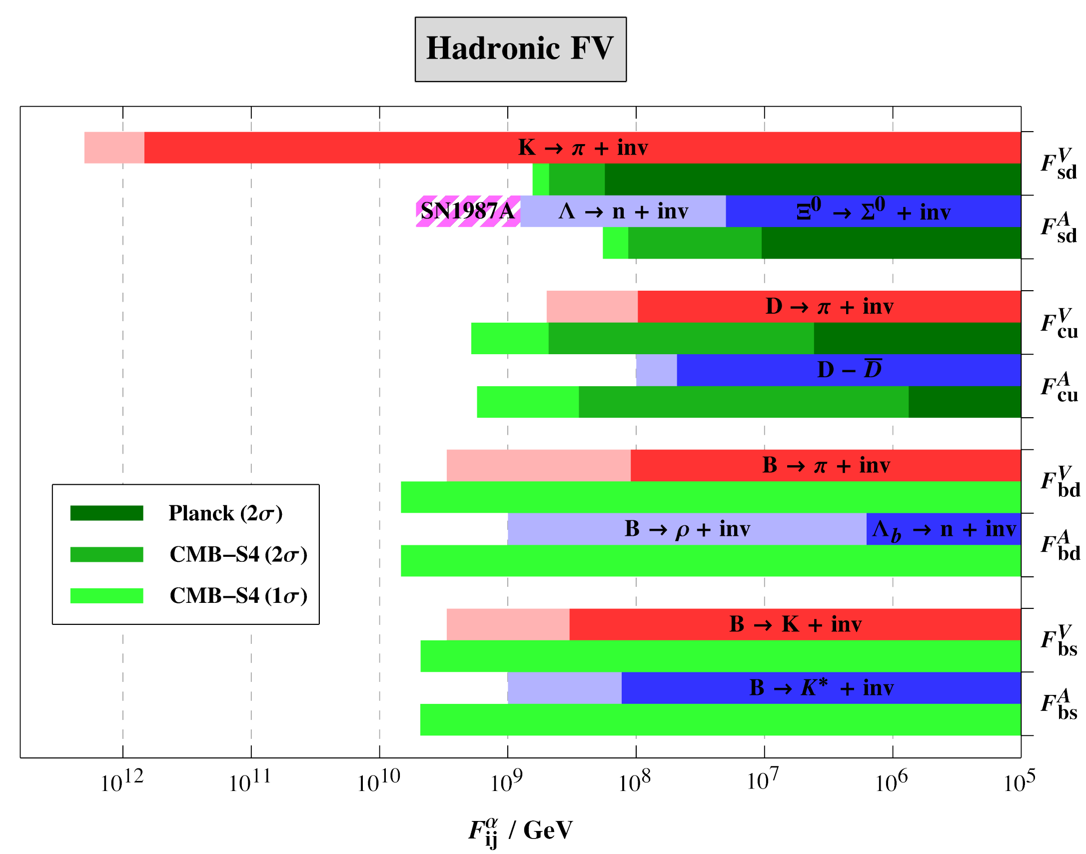
Target of several terrestrial experiments

What about their role in the early universe?

$$\mathcal{L}^{(a)}_{\rm FV} = \frac{\partial_\mu a}{2 f_a} \sum_{\psi_i \neq \psi_j} \bar{\psi}_i \gamma^\mu \left(c^V_{\psi_i \psi_j} + c^A_{\psi_i \psi_j} \gamma^5 \right) \psi_j$$



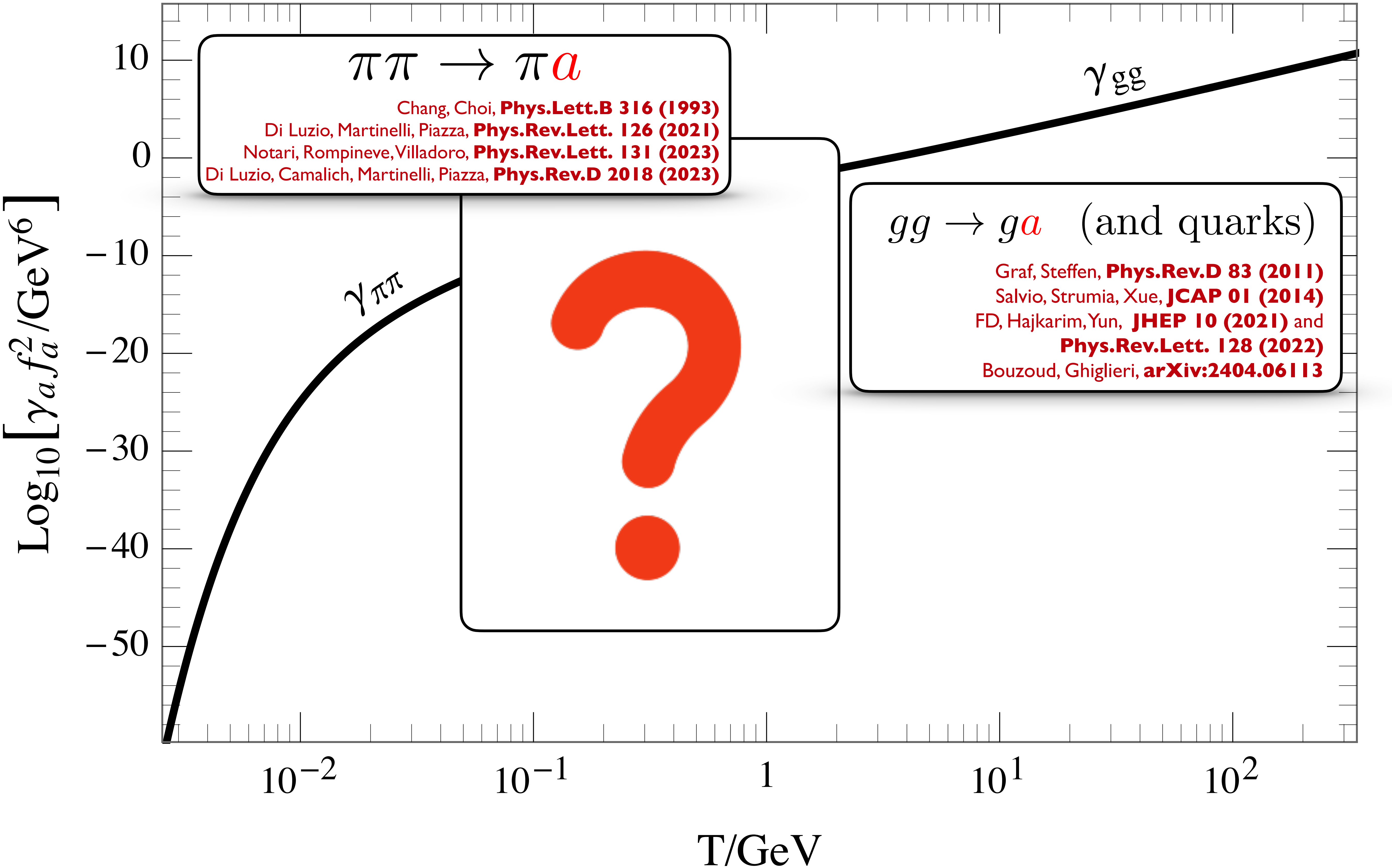




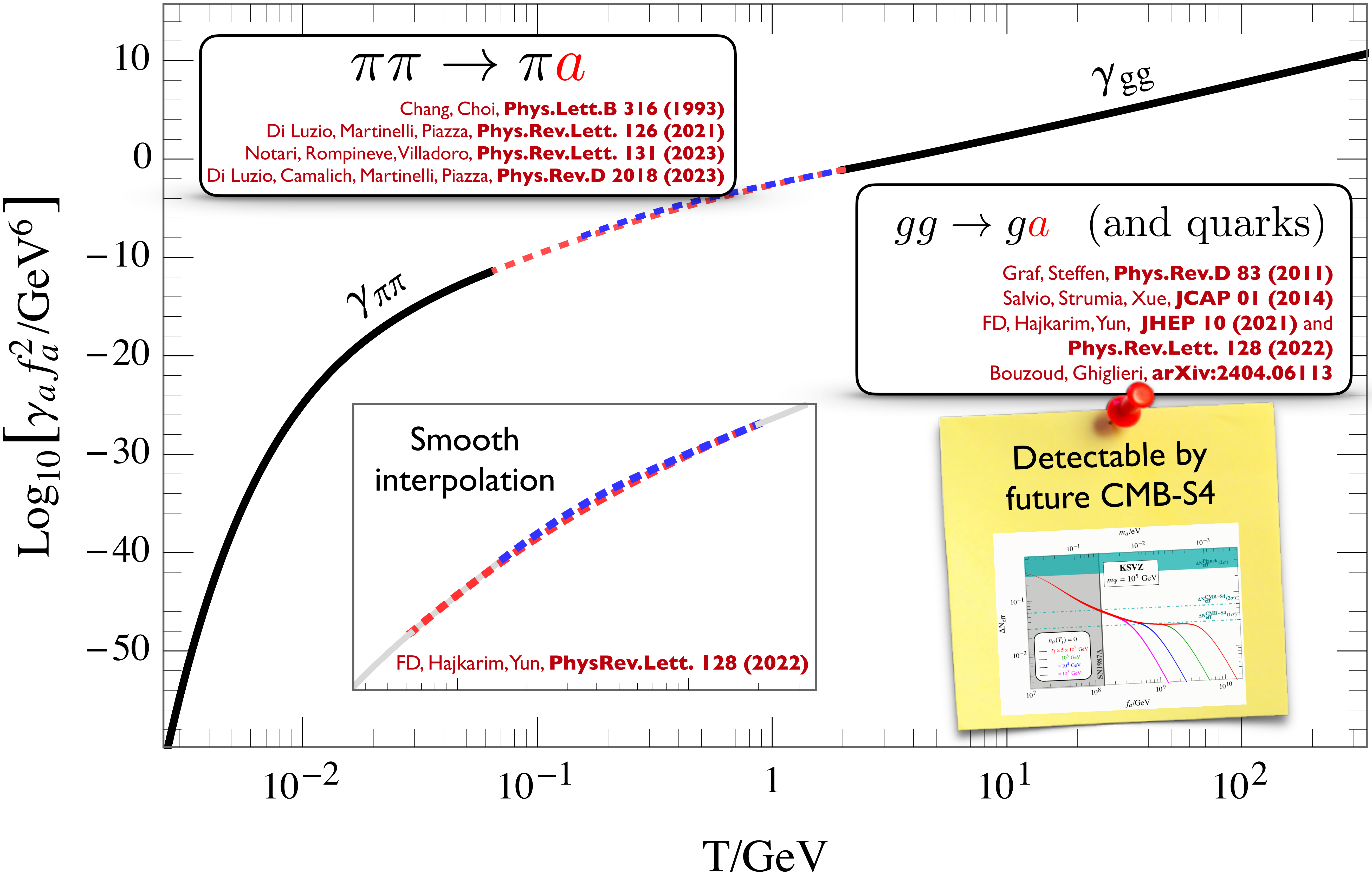
Current and future cosmological bounds competitive (or sometimes even better!) than terrestrial searches

FD, Yun, **Phys.Rev.D 105 (2022)**

Where Do We Stand?



Where Do We Stand?



What's Next?

Axion production rate

across the confinement scale still unknown

$$\gamma_a = n_i n_j \times \langle \sigma_{ij \to ja} v_{\rm rel} \rangle$$

Thermal bath Particle Physics

1. Pion cross section beyond LO? Other hadrons?
2. Thermal bath description between 150 MeV and fews GeV?
3. Boltzmann equation evolution and cosmological observables?

Back to the Phase-Space

Model-independent analysis:

generic production of a light X

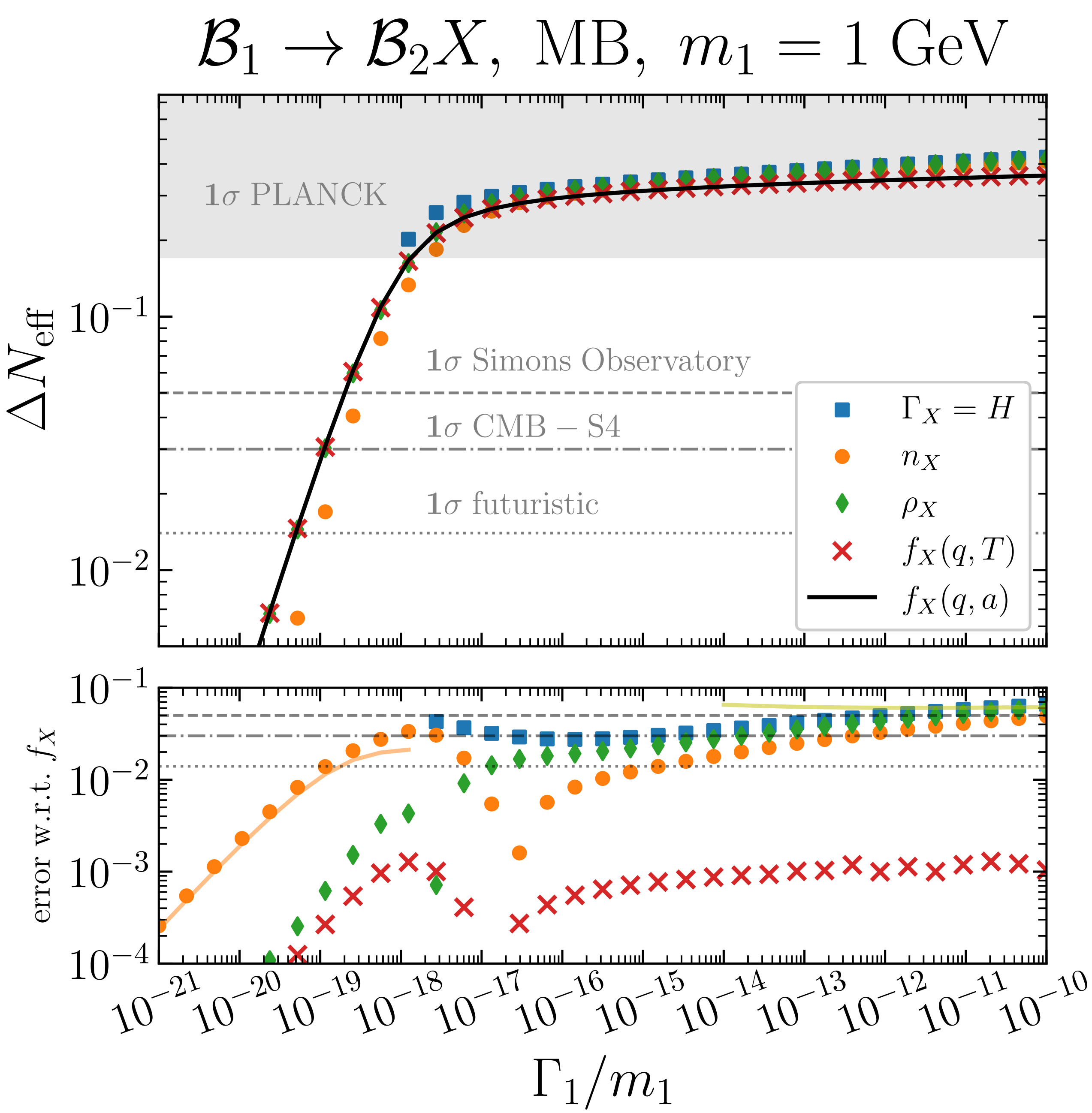
$$\mathcal{B}_1 \ldots \mathcal{B}_n \to \mathcal{B}_{n+1} \ldots \mathcal{B}_m \, X$$

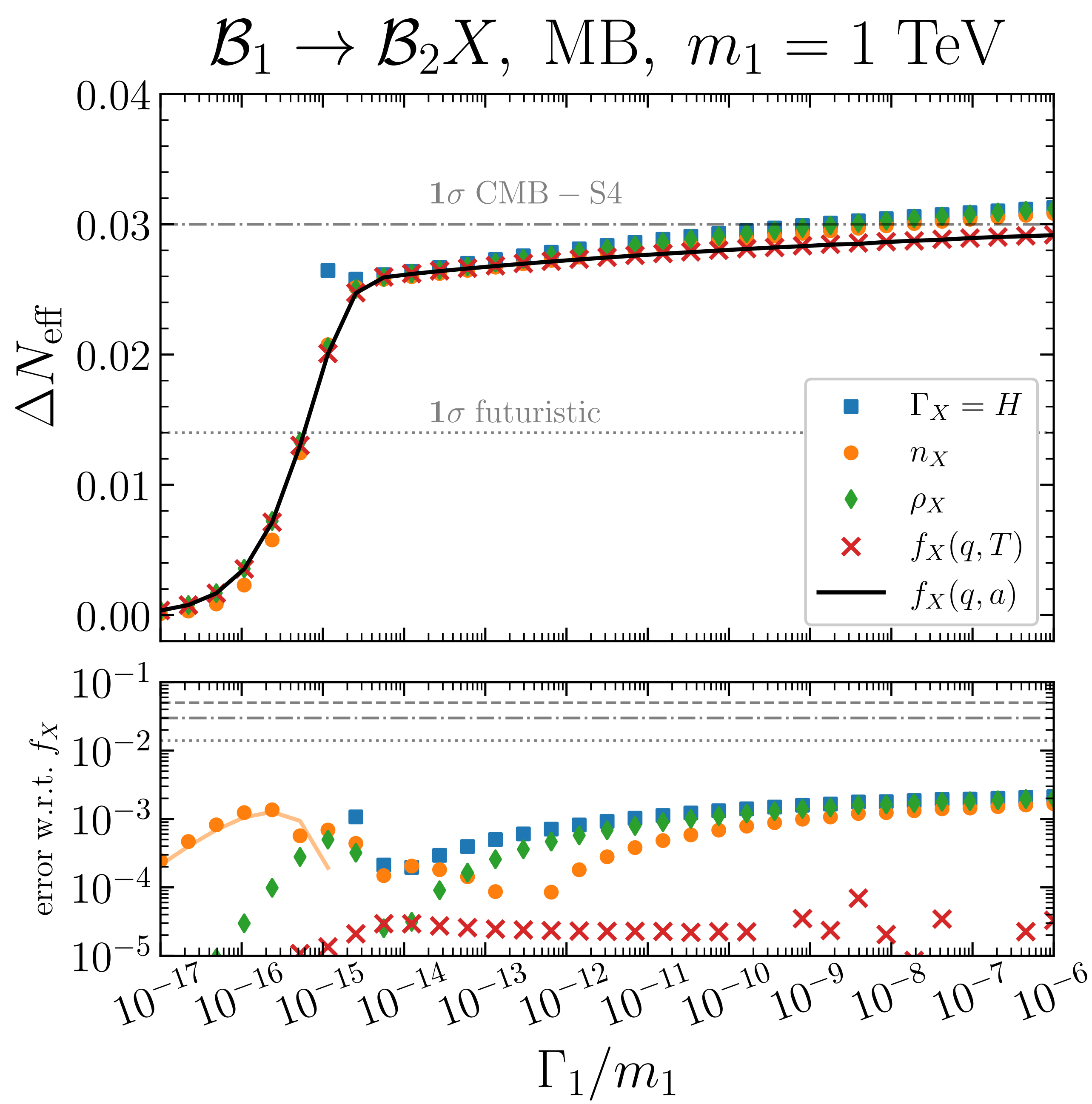
$$\frac{df_X(k,t)}{dt} = \left(1 - \frac{f_X(k,t)}{f_X^{\rm eq}(k,t)}\right) \mathcal{C}_{n\to mX}(k,t)$$

1. Keep track of phase-space and compute the energy density
2. Quantum statistical effects take into account
3. Energy exchanged with the thermal bath accounted for

FD, Hajkarim, Lenoci, **JCAP 03 (2024)**

Error in predicting $\Delta N_{\rm eff}$





FD, Hajkarim, Lenoci, **JCAP 03 (2024)**

Axion-Fermion Interactions

$$\mathcal{L}_{\rm int} = \frac{\partial_\mu a}{2 f_a} \sum_\psi c_\psi \overline{\psi} \gamma^\mu \gamma_5 \psi$$

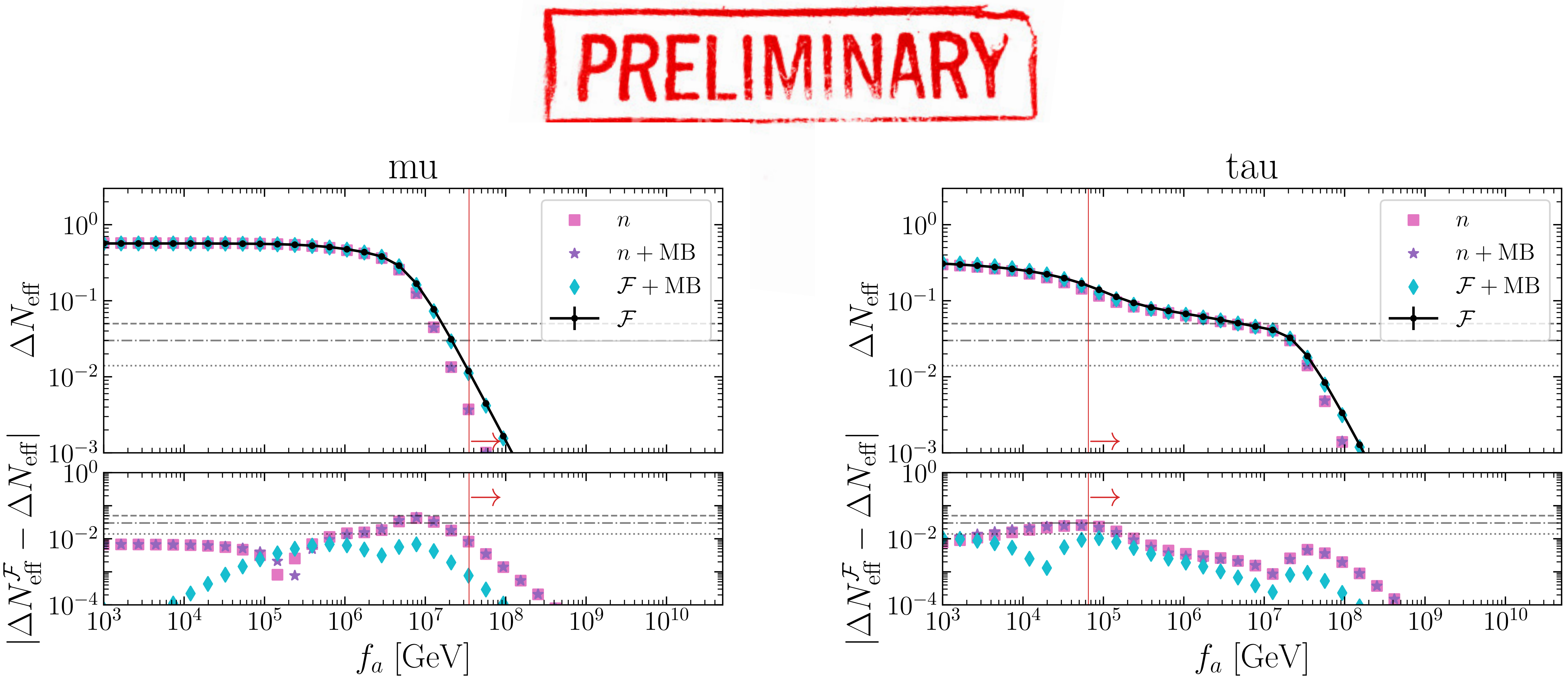
Recent studies performed by tracking the axion number density

Baumann et al, **Phys.Rev.Lett. 117 (2016)**
Ferreira, Notari, **Phys.Rev.Lett. 120 (2018)**
FD et al, **JCAP 11 (2018)**
Arias-Aragón et al., **JCAP 11 (2020)**
Arias-Aragón et al., **JCAP 03 (2021)**
Green at al., **JCAP 02 (2022)**

Will it change if we go back to the phase space?

FD, Lenoci, **in preparation**

Axion-Fermion Interactions

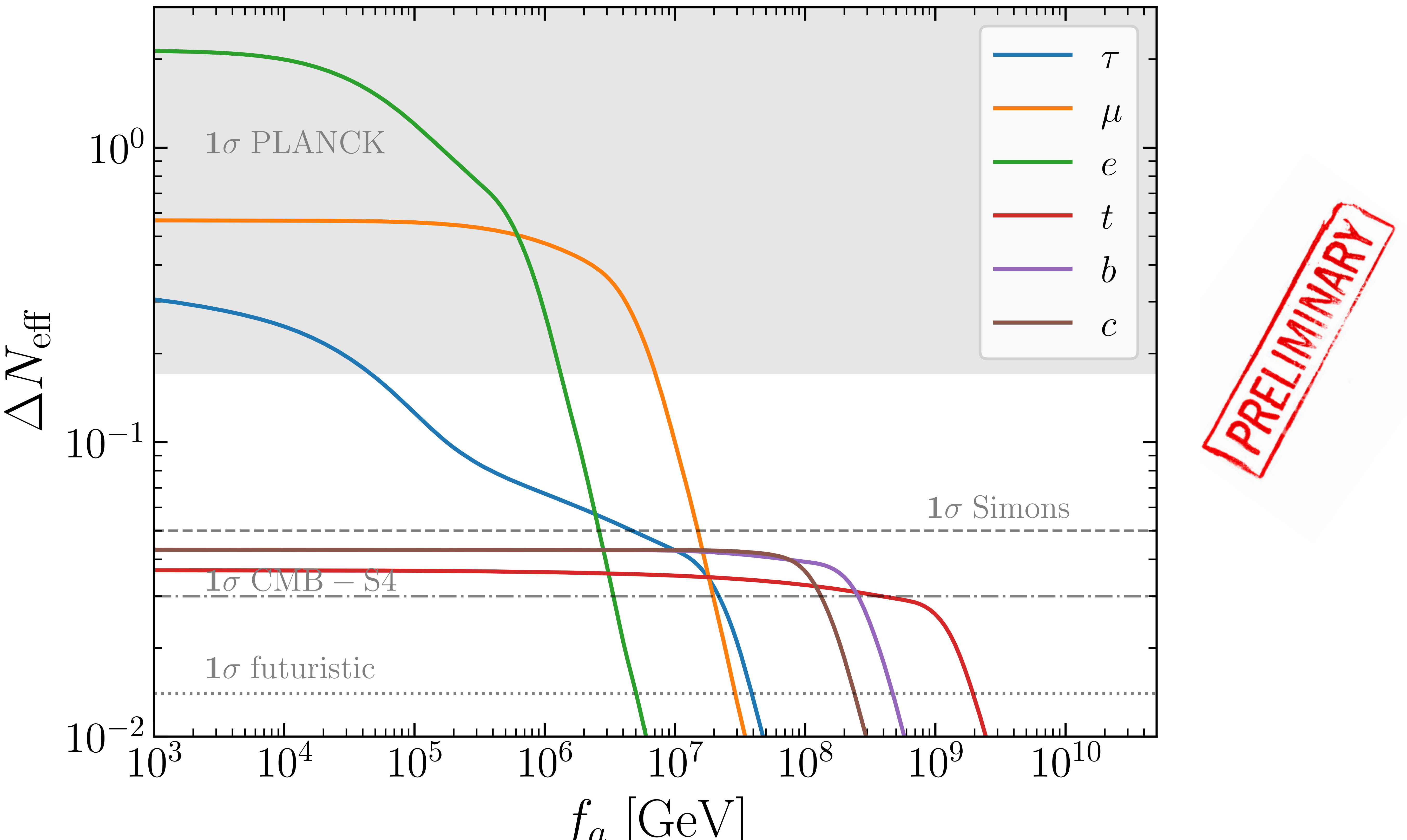


<u>Difference detectable by future CMB-S4 surveys!</u>

- MUON: effect maximum in regions in tension with stellar bounds
- TAU: effect maximum in allowed regions

FD, Lenoci, **in preparation**

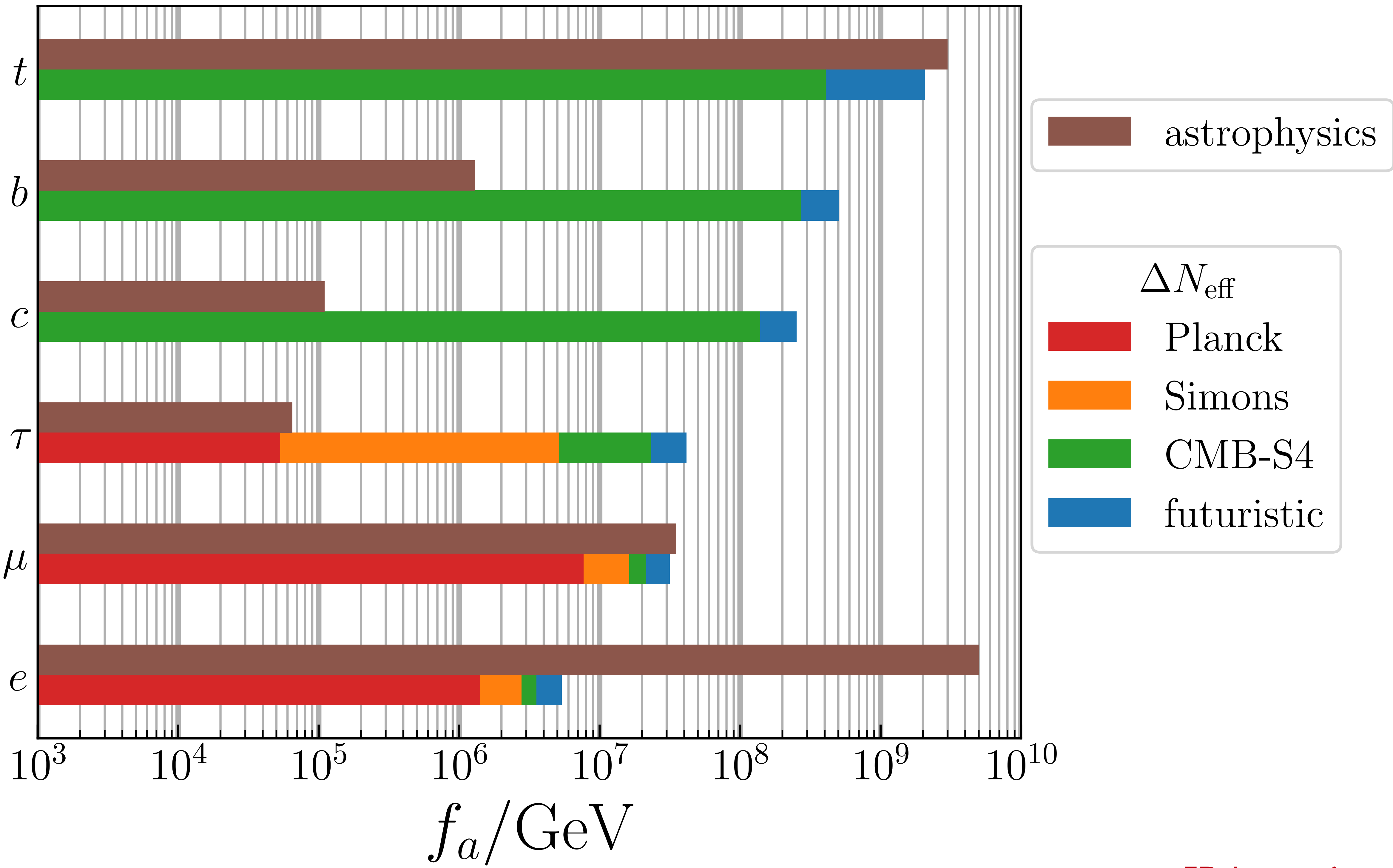
Axion-Fermion Interactions



FD, Lenoci, **in preparation**

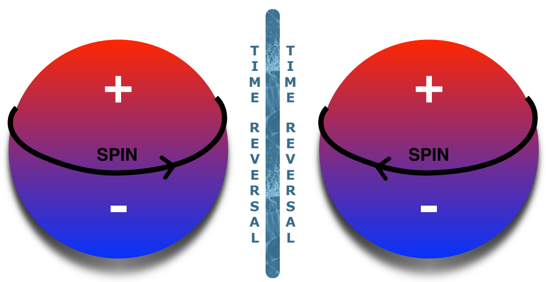
Axion-Fermion Interactions

PRELIMINARY



FD, Lenoci, **in preparation**

Outlook



Peccei-Quinn Mechanism and the QCD Axion

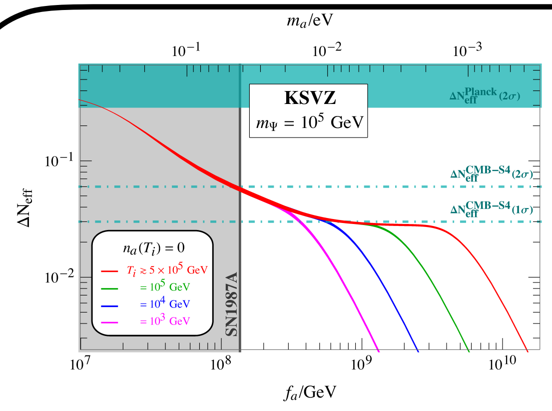
Motivated and testable scenario rich of cosmological consequences

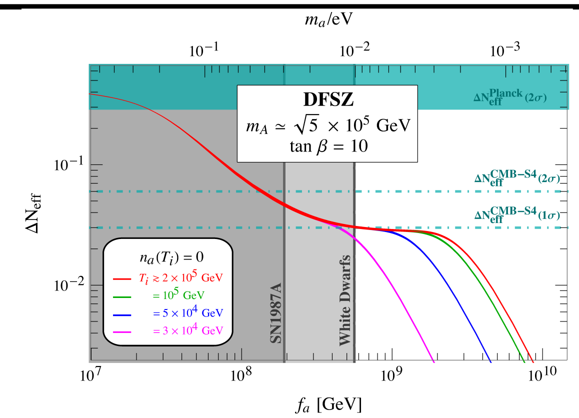
Thermal Axions

Complementary to other probes of the PQ mechanism

Distinct signatures of ALPs coupled to standard model particles

Outlook



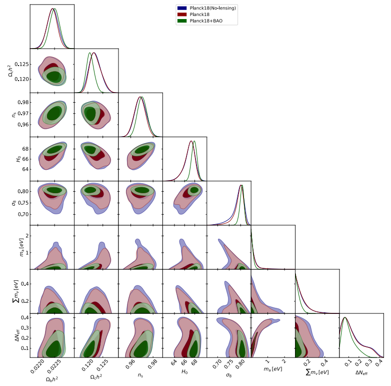


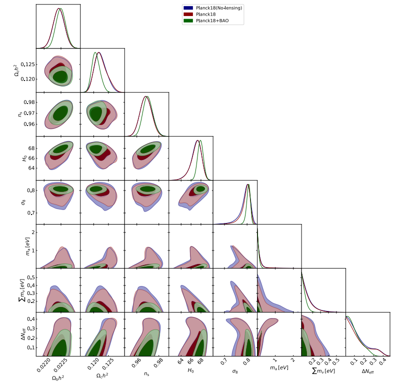
$\Delta N_{\rm eff}$ tracking the number density

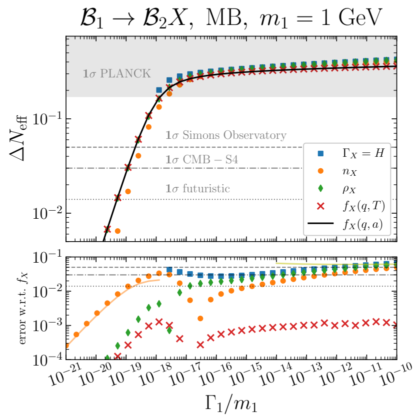
FD, Hajkarim, Yun, **JHEP 10 (2021)**
FD, Hajkarim, Yun, **Phys.Rev.Lett. 128 (2022)**

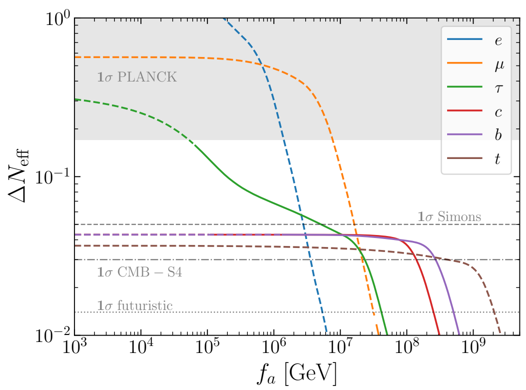
FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, **JCAP 09 (2022)**

Axion cosmological mass bound









Importance of a phase space analysis

FD, Hajkarim, Lenoci, **JCAP 03 (2024)**
FD, Lenoci, **in preparation**

Outlook

$\Delta N_{\rm eff}$ tracking the number d…ity

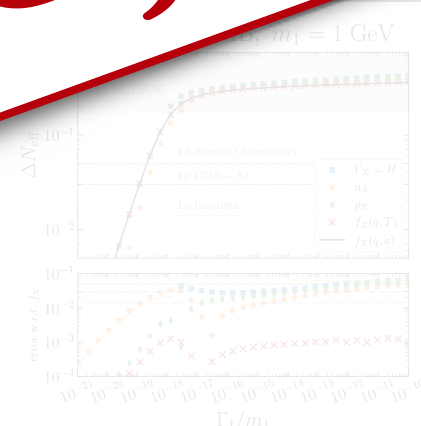
FD, Ha…

FD, Hajkar…

FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, **JCAP 09 (2022)**

Axion cosmological mass bo…

TEŞEKKÜRLER!



Importance of a phase space analysis

FD, Hajkarim, Lenoci, **JCAP 03 (2024)**

FD, Lenoci, **in preparation**