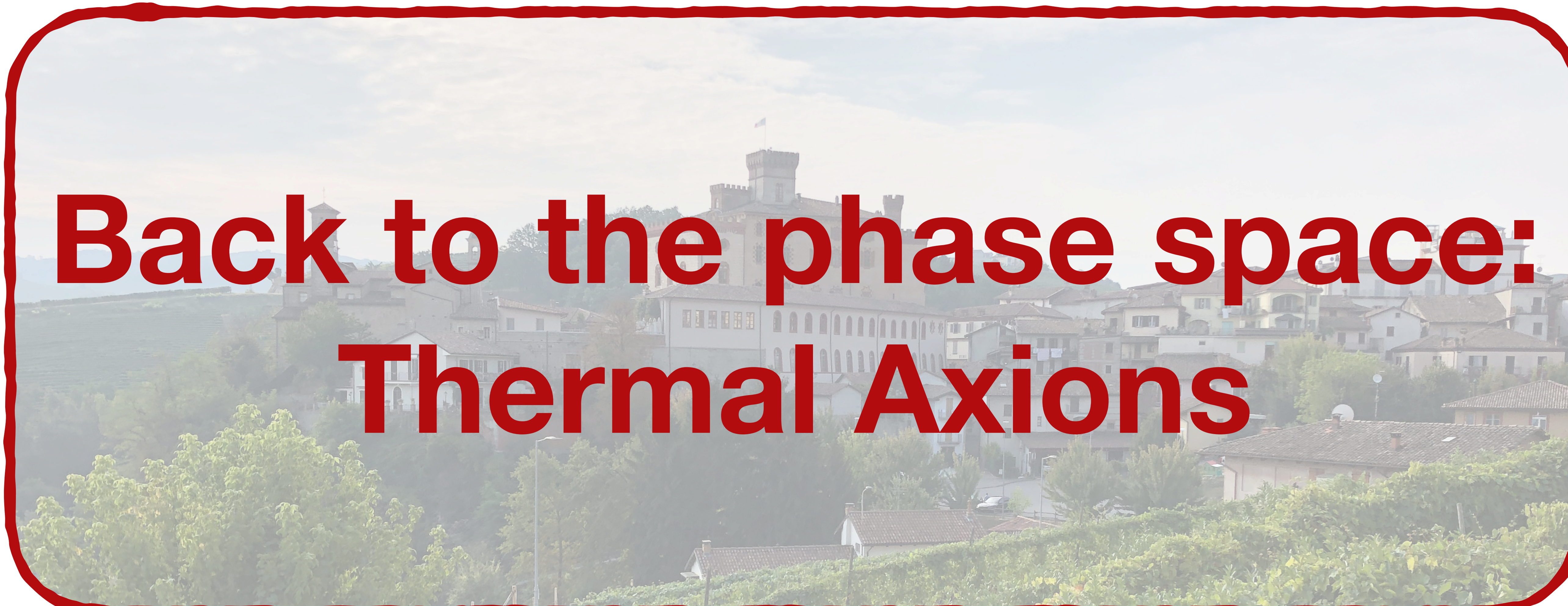

# Back to the phase space: Thermal Axions


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Università degli Studi di Padova

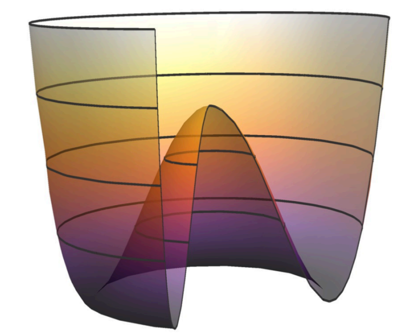
INFN Padova


Barolo Astroparticle Meeting (BAM): Axions in the sky! — 13 June 2024

# The QCD Axion and ALPs

## Ubiquitous in extension of the standard model

- QCD axions: global $U(1)_{PQ}$ symmetry spontaneously broken and color anomalous
- Pseudo-Nambu-Goldstone-bosons
- Axions in string theory



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

**QCD Axion**

$$m_a \simeq 5.7\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)\mu\text{eV}$$

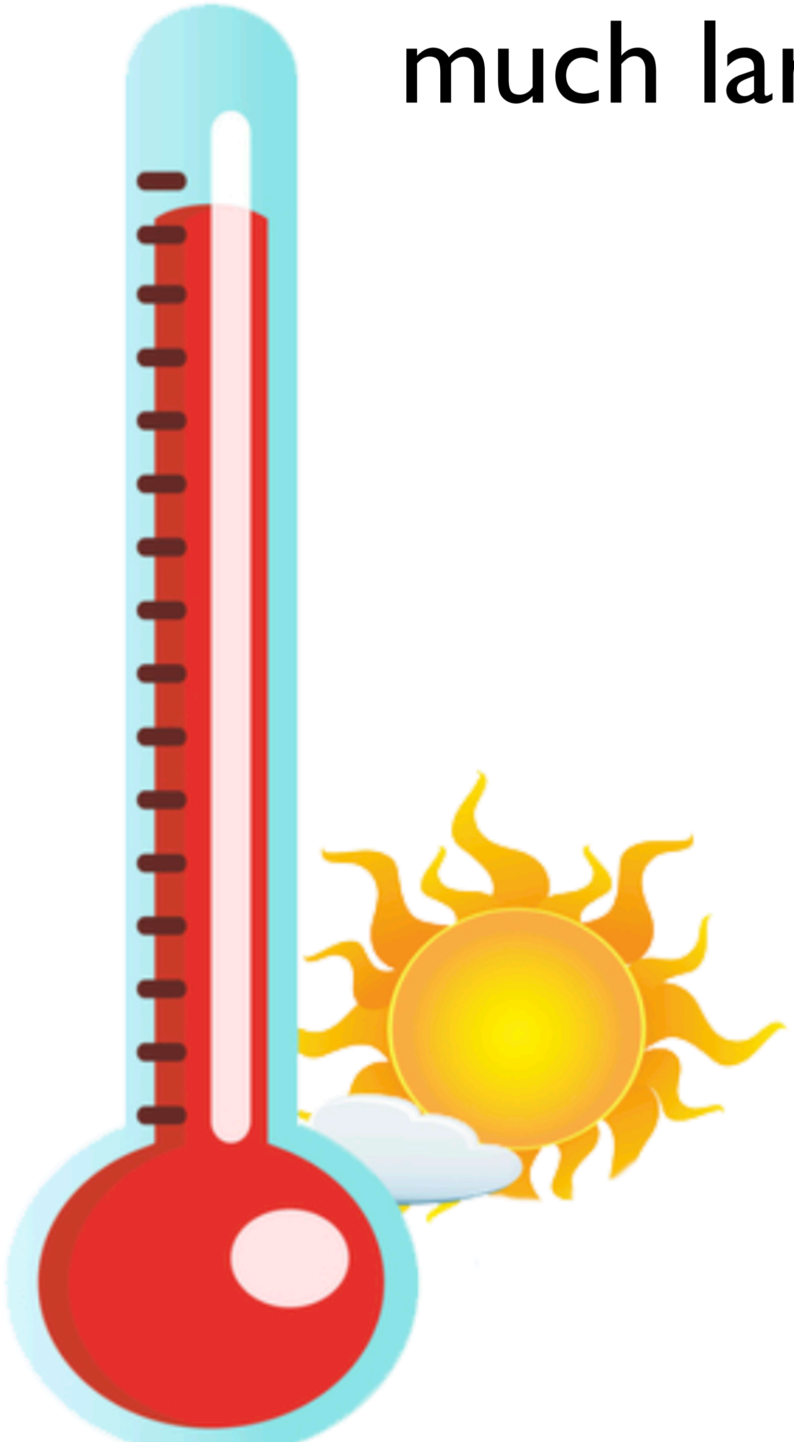
**Axion-like Particles**

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

Results in this talk mostly about the QCD axion
(easily generalized especially when the mass does not play any role)

# Hot Axions

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



Additional radiation at:

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

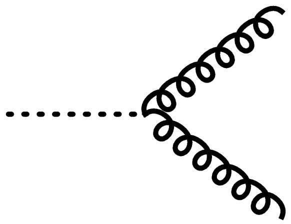
$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{\rm eff}\right]\rho_\gamma$$

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

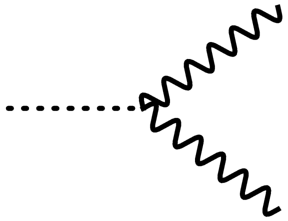
# Thermal Production

**<u>Unavoidable Production Source!</u>**

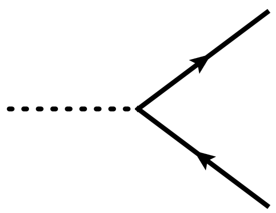
Scatterings and/or decays involving primordial thermal bath particles (axion energy ≫ $m_a$, i.e. "hot")



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



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



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

**<u>GOALS</u>:**

- Compute how many axions are produced in the early universe
- Quantify the resulting effect on cosmological observables

# How to Predict $\Delta N_{eff}$

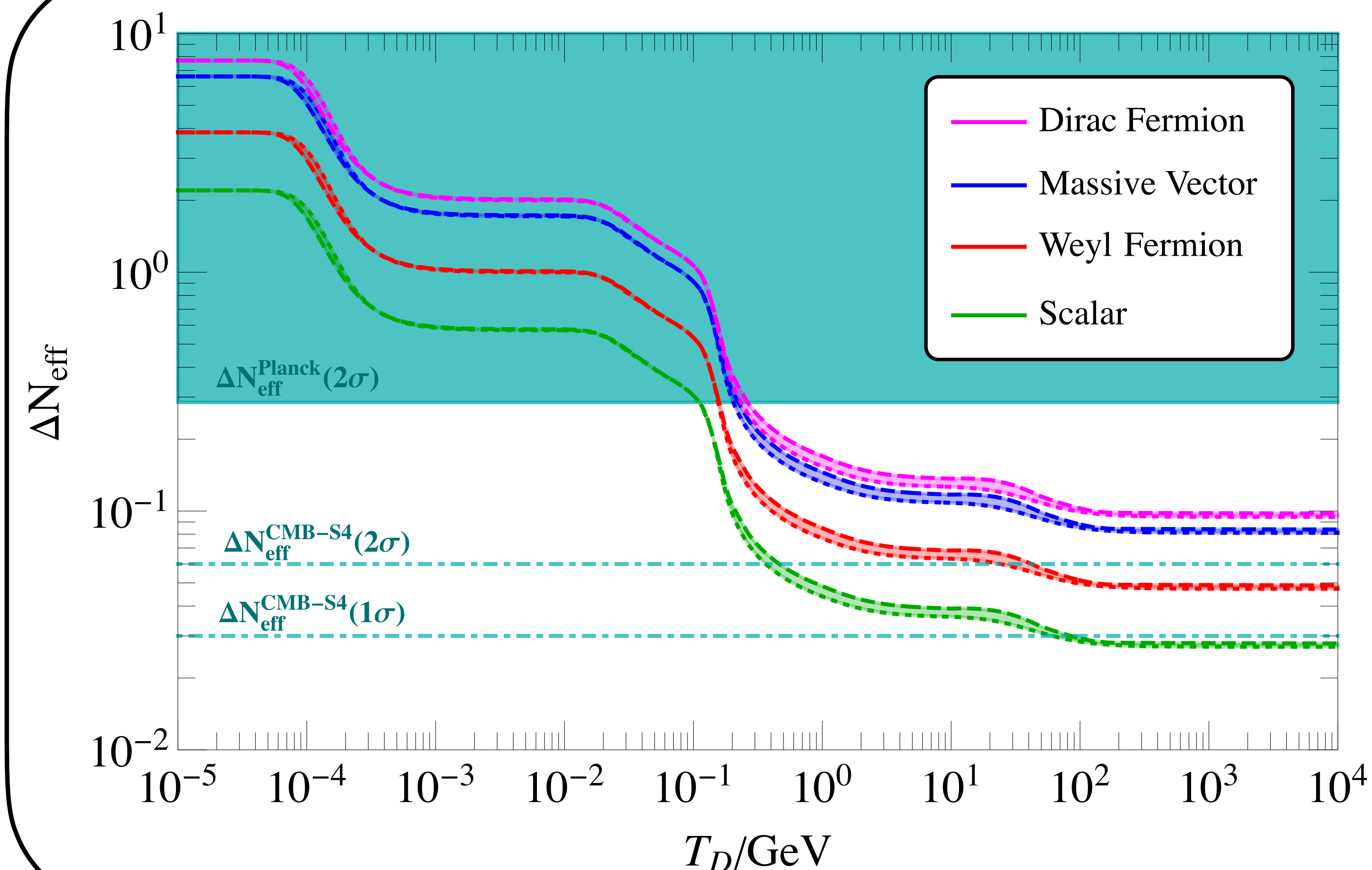
**$\Delta$Neff - I: Instantaneous decoupling**

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

# How to Predict $\Delta N_{eff}$

## <u>ΔNeff - I: Instantaneous decoupling</u>

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




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

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

# How to Predict $\Delta N_{eff}$

## $\Delta$Neff - I: Instantaneous decoupling

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

## $\Delta$Neff - II: Boltzmann equation for $n_a$

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

# How to Predict $\Delta N_{eff}$

## $\Delta$Neff - I: Instantaneous decoupling

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## $\Delta$Neff - II: Boltzmann equation for $n_a$

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

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

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

$\alpha = \text{Production processes}$

# How to Predict $\Delta N_{eff}$

## **$\Delta$Neff - I: Instantaneous decoupling**

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

## **$\Delta$Neff - 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 Thermal Axions

## Single Coupling Switched On

Axion coupled to 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)**
FD et al., **Phys.Rev.Lett. 128 (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 $\Psi$

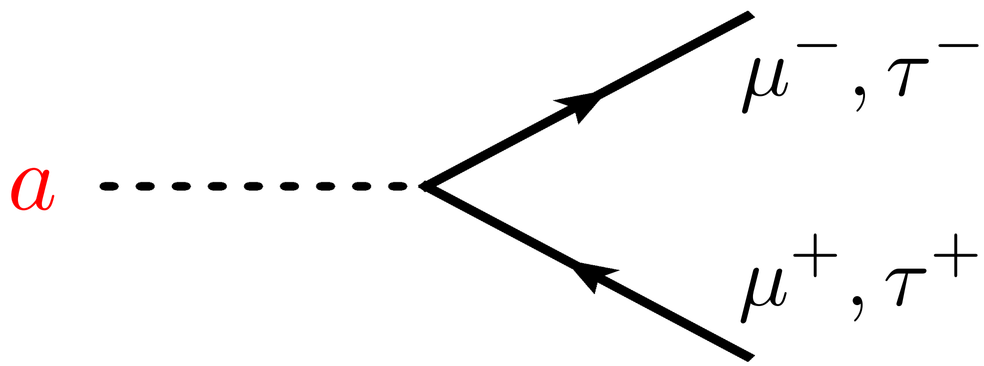
Kim, **PRL 43 (1979)**
Shifman, Vainshtein, Zakharov, **NPB 166 (1980)**

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

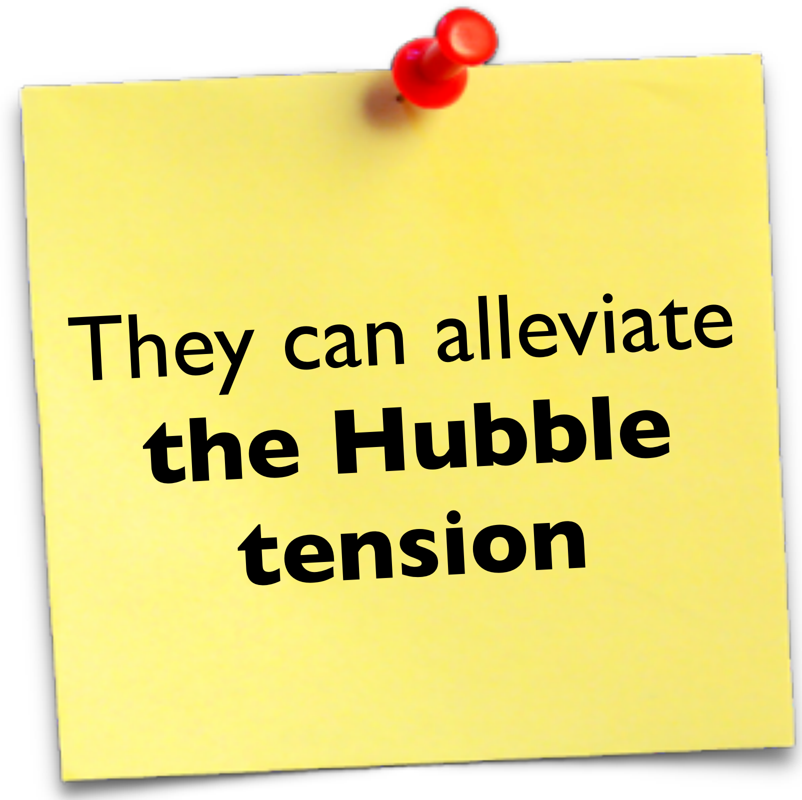
Zhitnitsky, **SJNP 31 (1980)**
Dine, Fischler, Srednicki, **PLB 104 (1981)**

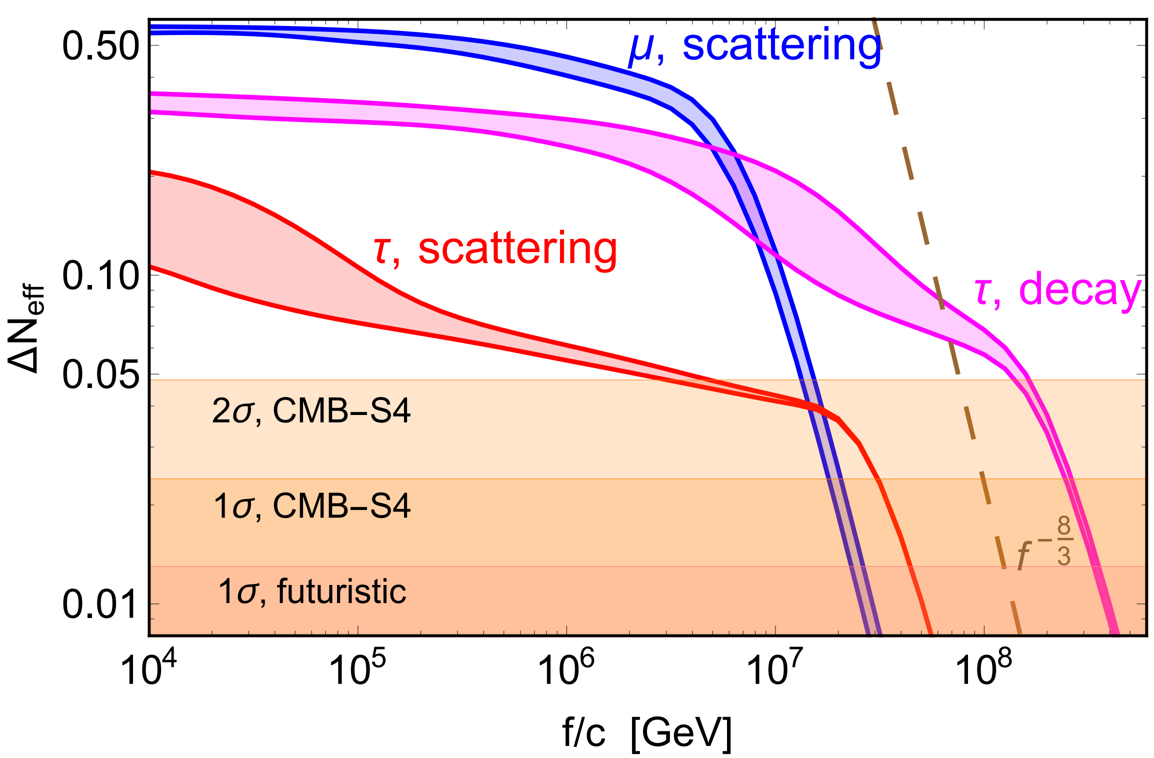
# A Leptophilic Axion

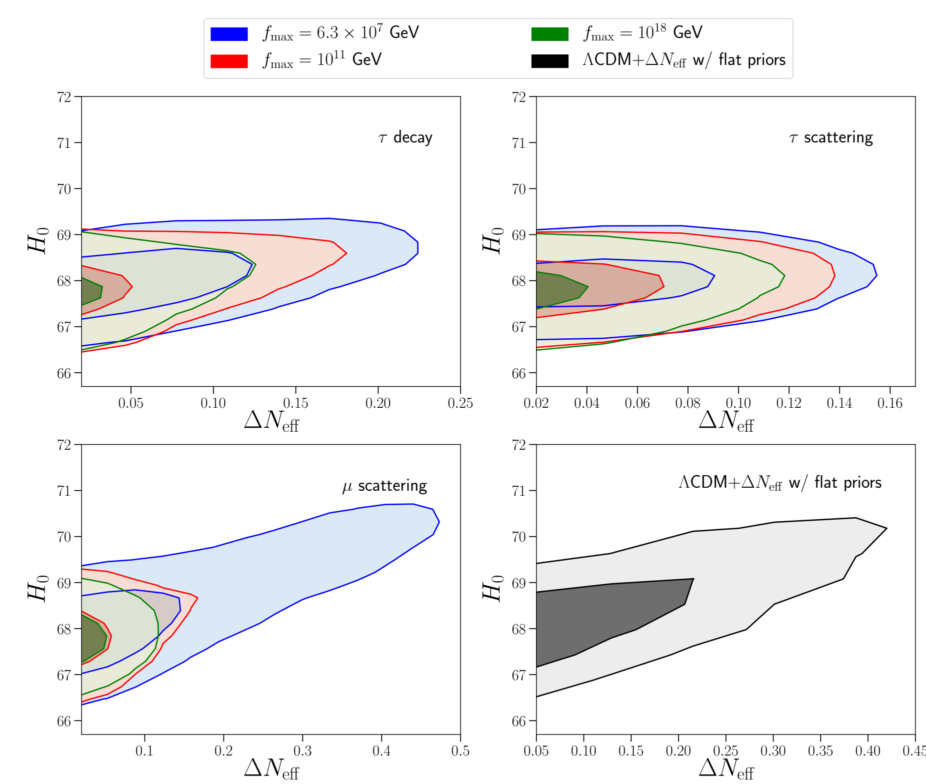
**Leptons**




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



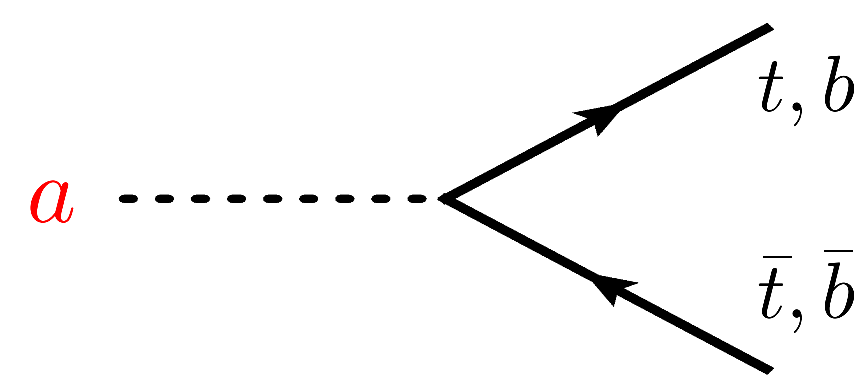



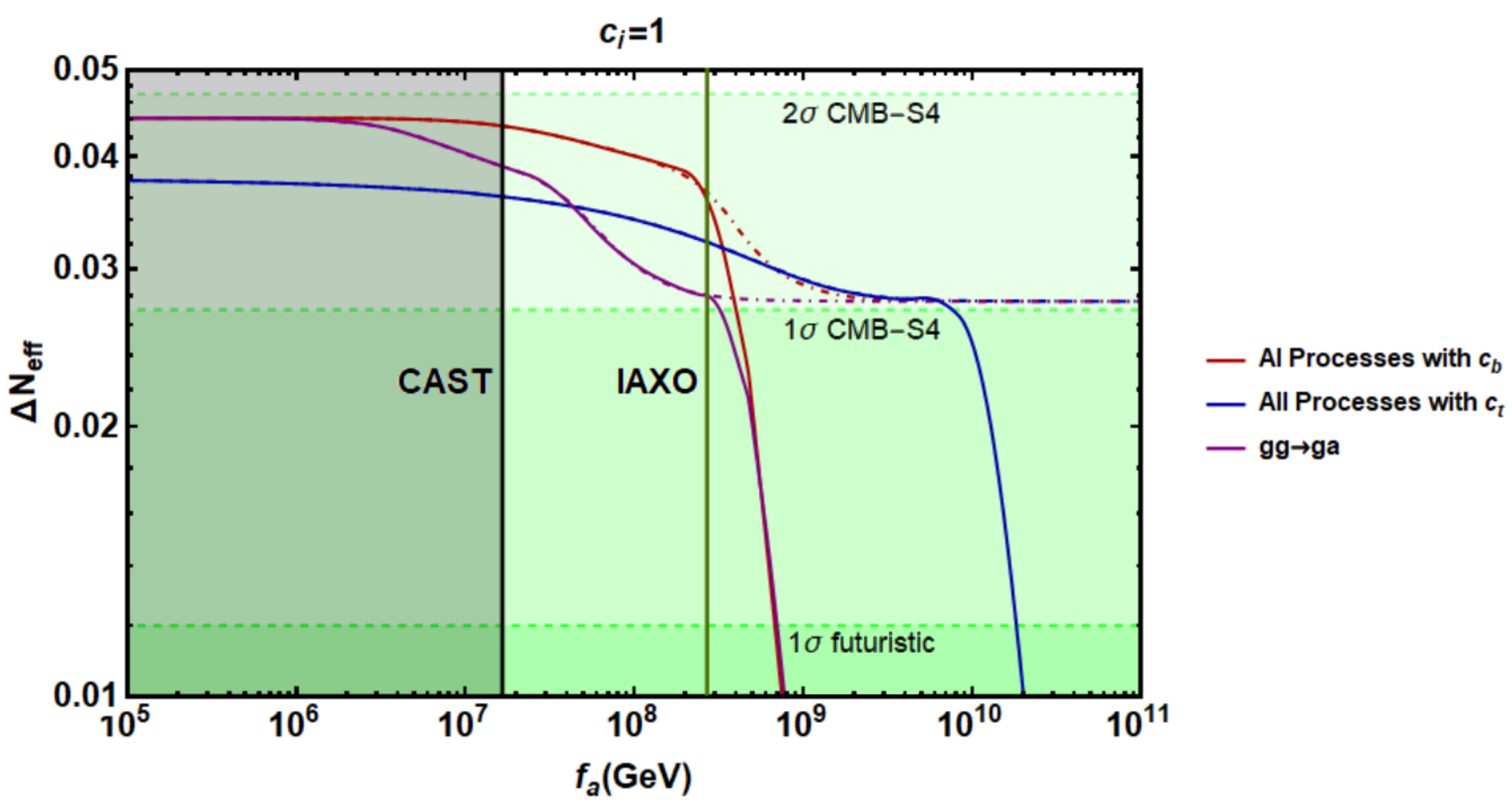
# Axion Coupled to Heavy Quarks

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

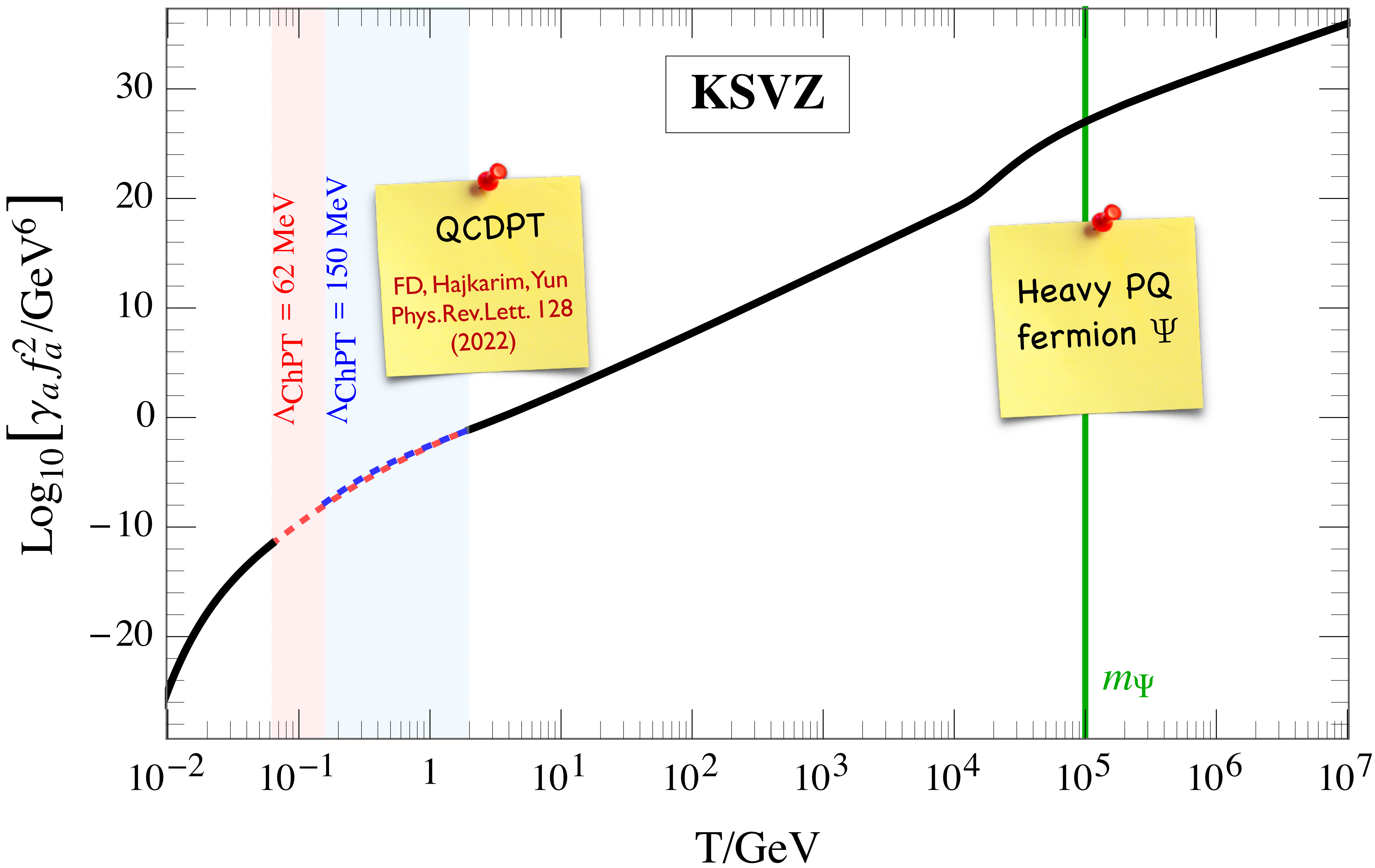
**3rd Gen. Quarks**




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

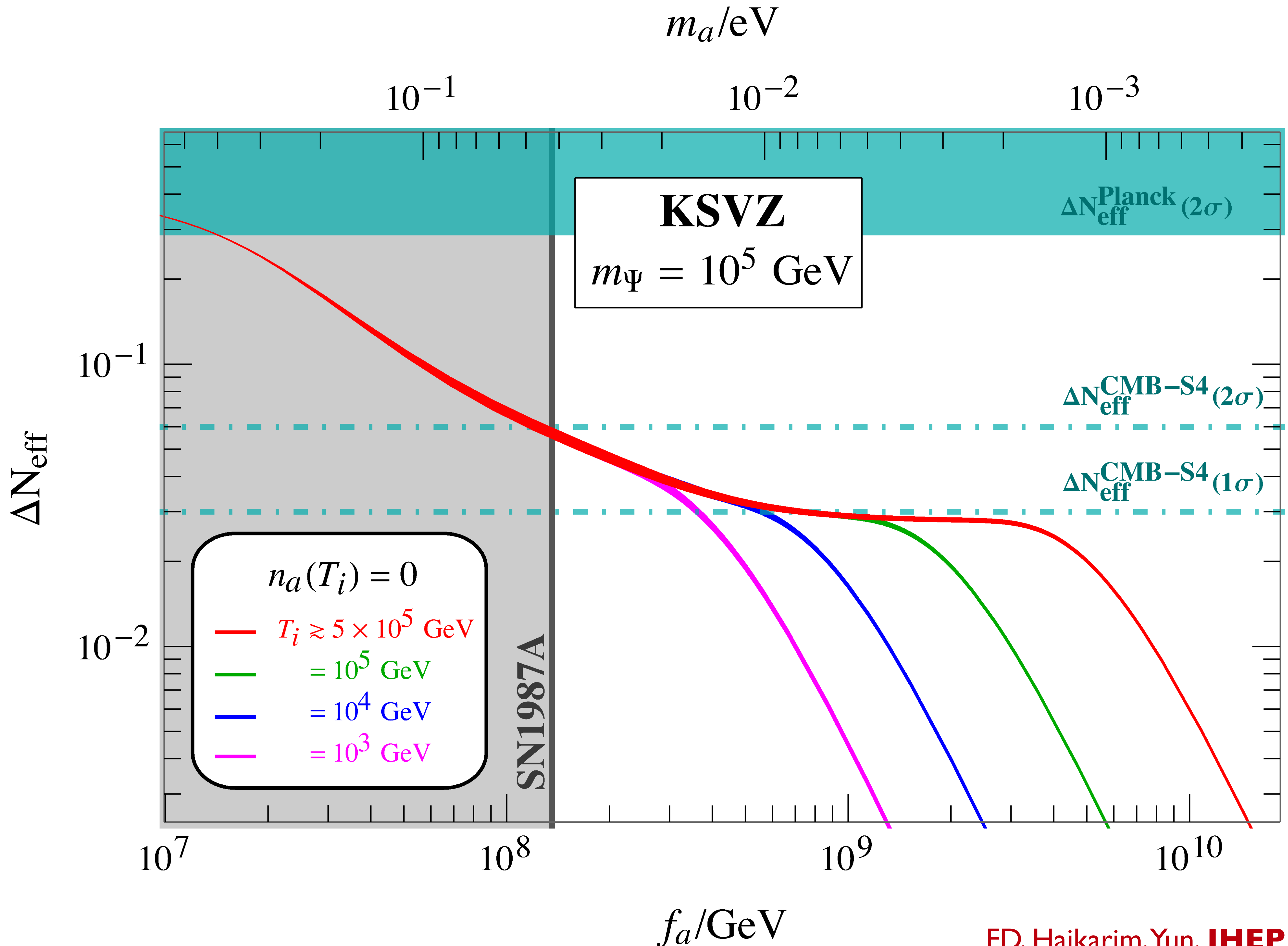


# KSVZ Axion — Production Rate




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

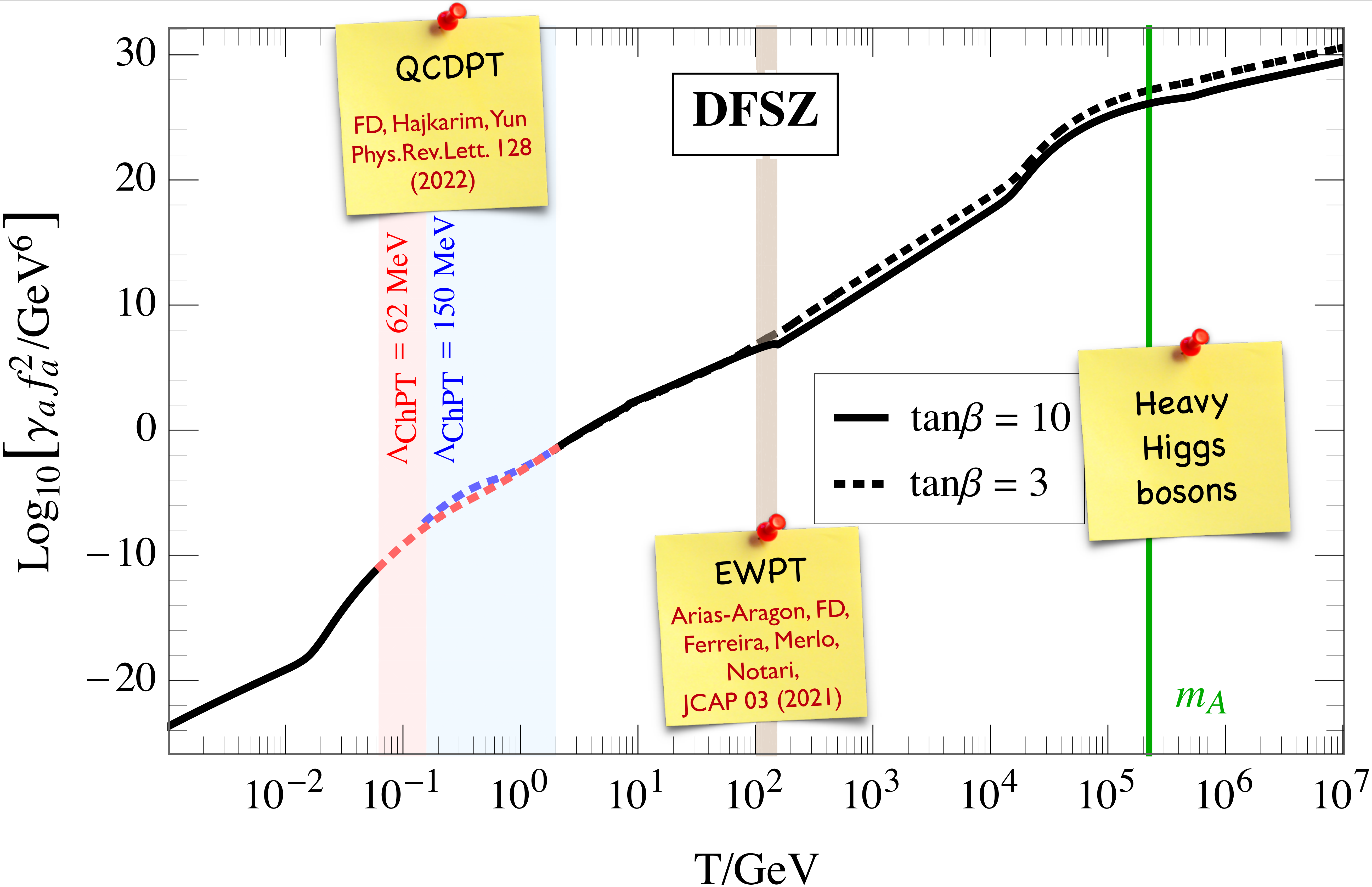
# KSVZ Axion — Results for $\Delta N_{eff}$




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

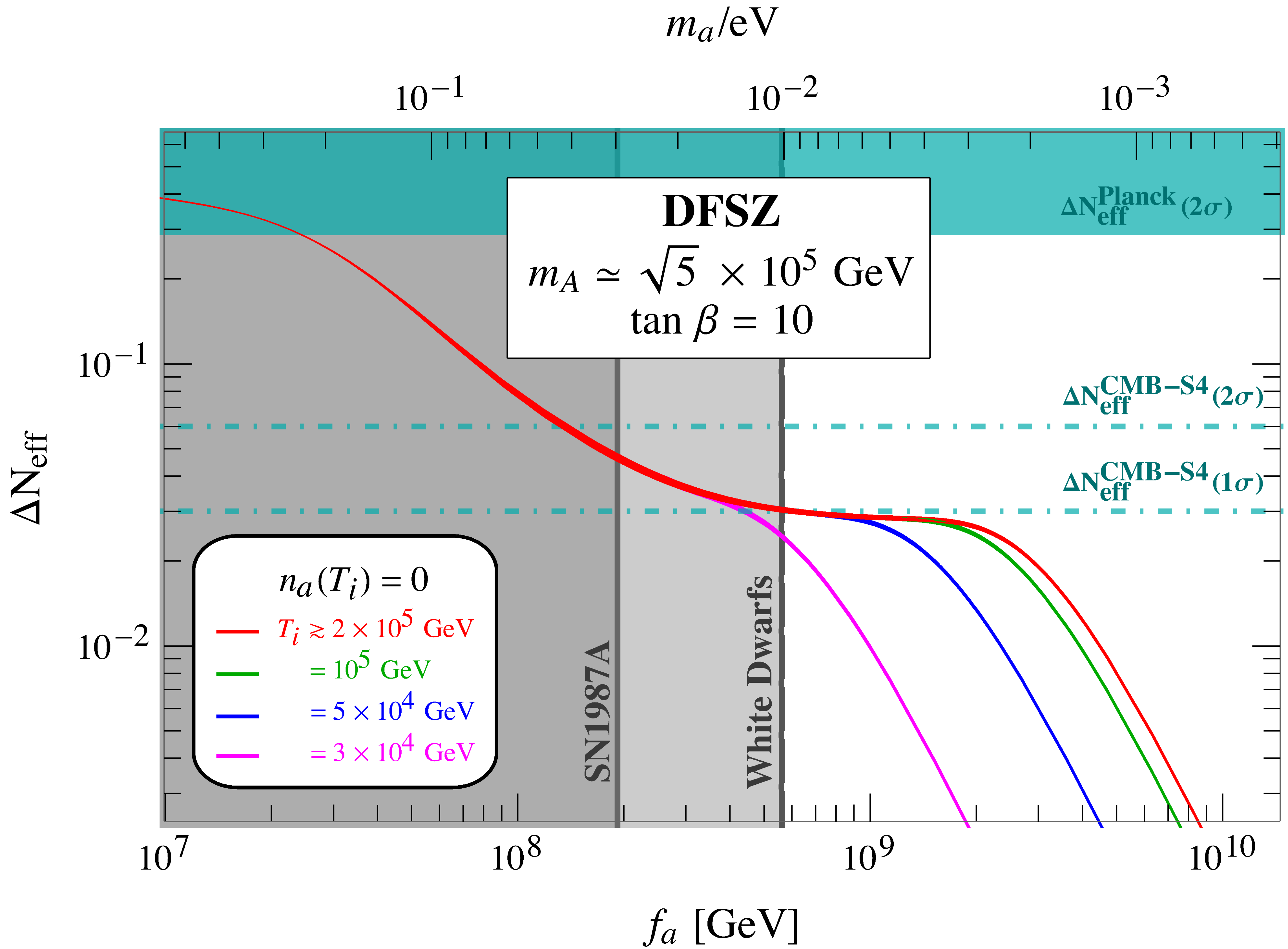
FD, Hajkarim, Yun, **Phys.Rev.Lett. 128 (2022)**

# DFSZ Axion — Production Rate




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

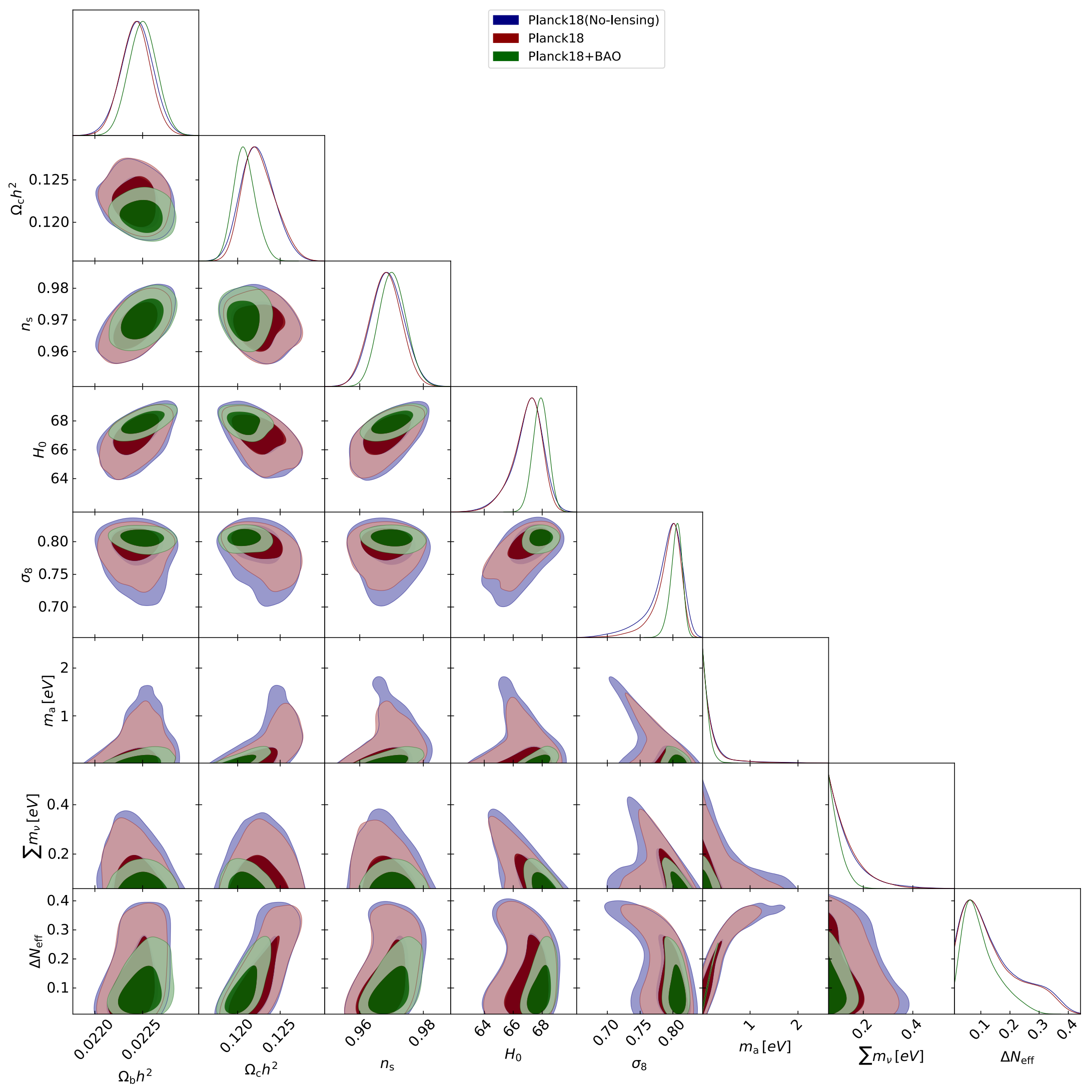
# DFSZ Axion — Results for $\Delta N_{eff}$




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

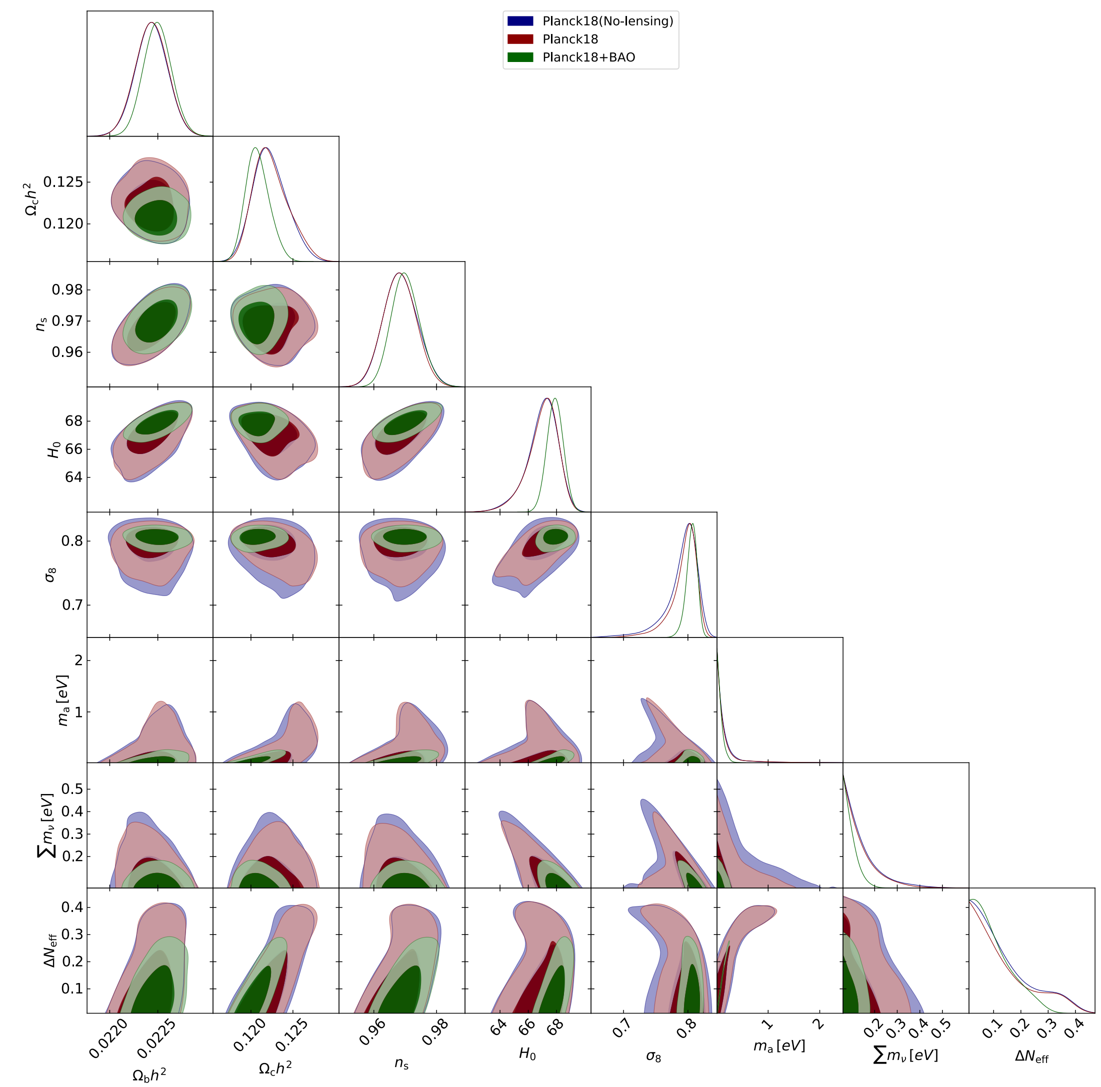
# Axion Mass Bound

## KSVZ




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

## DFSZ




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

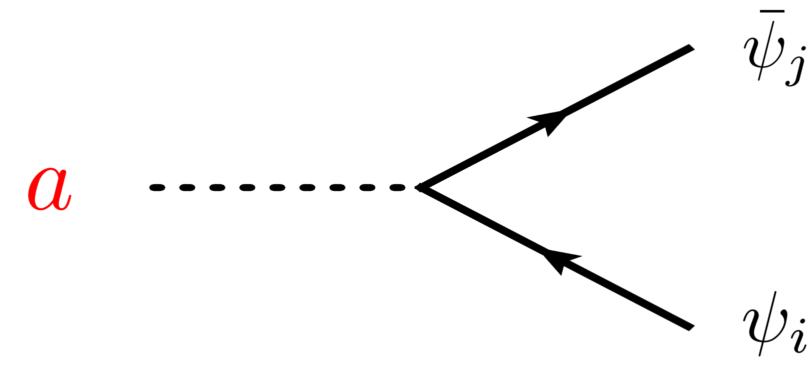
FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, **JCAP 09 (2022)**

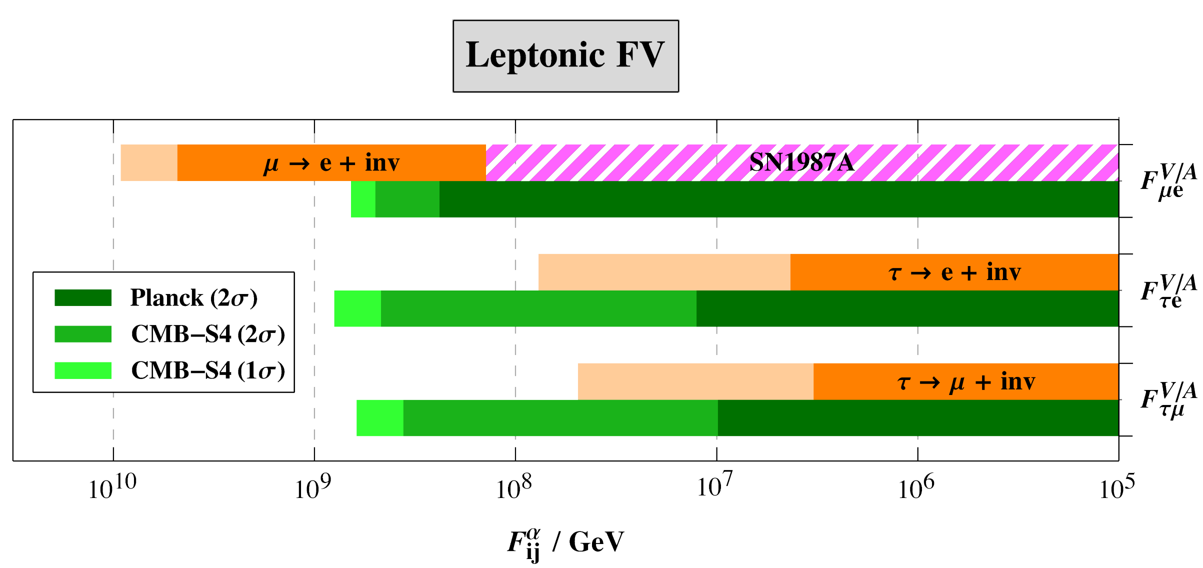
# A Minor Variation: FV Axions

Target of several terrestrial experiments

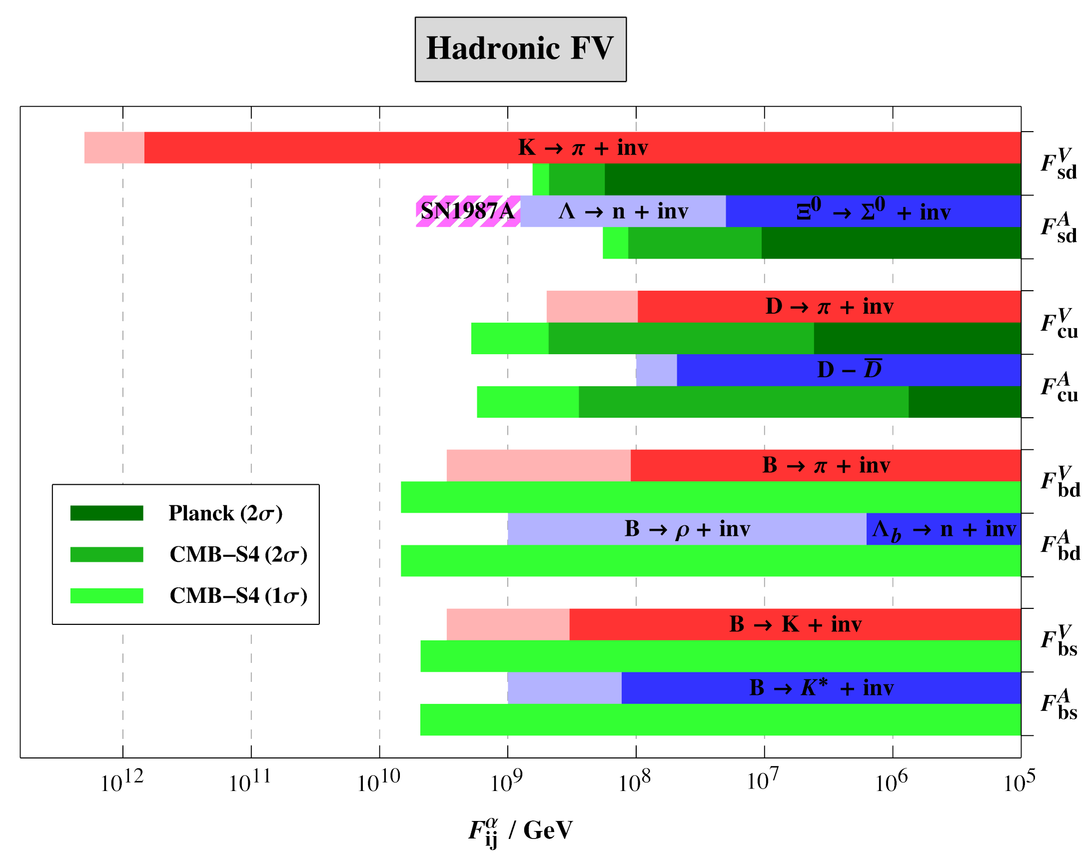
What about their role in the early universe?

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



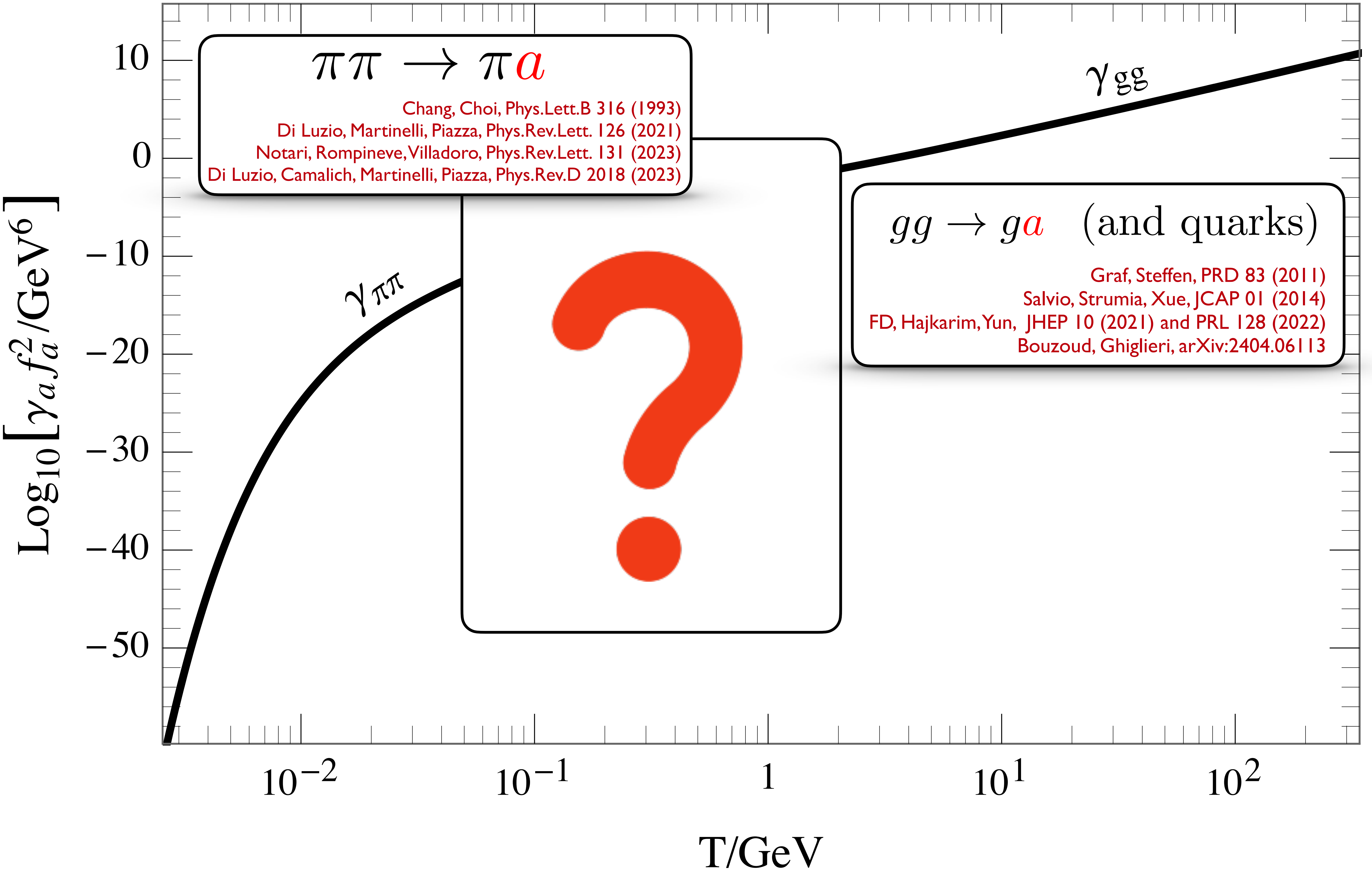




Current and future cosmological bounds competitive (or sometimes even better!) than terrestrial searches

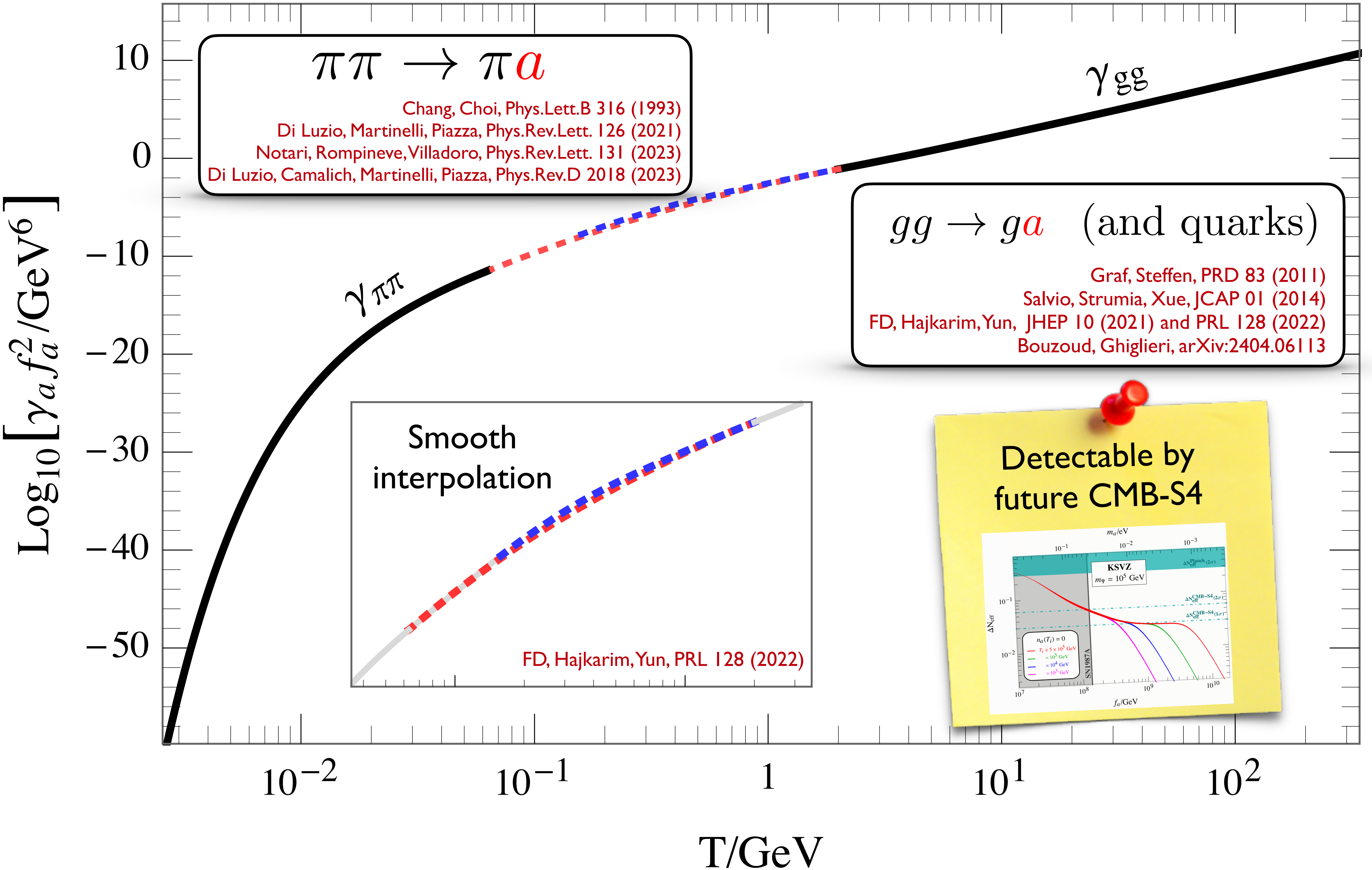



FD, Yun, **Phys.Rev.D 105 (2022)**

# 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. Cross sections with 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

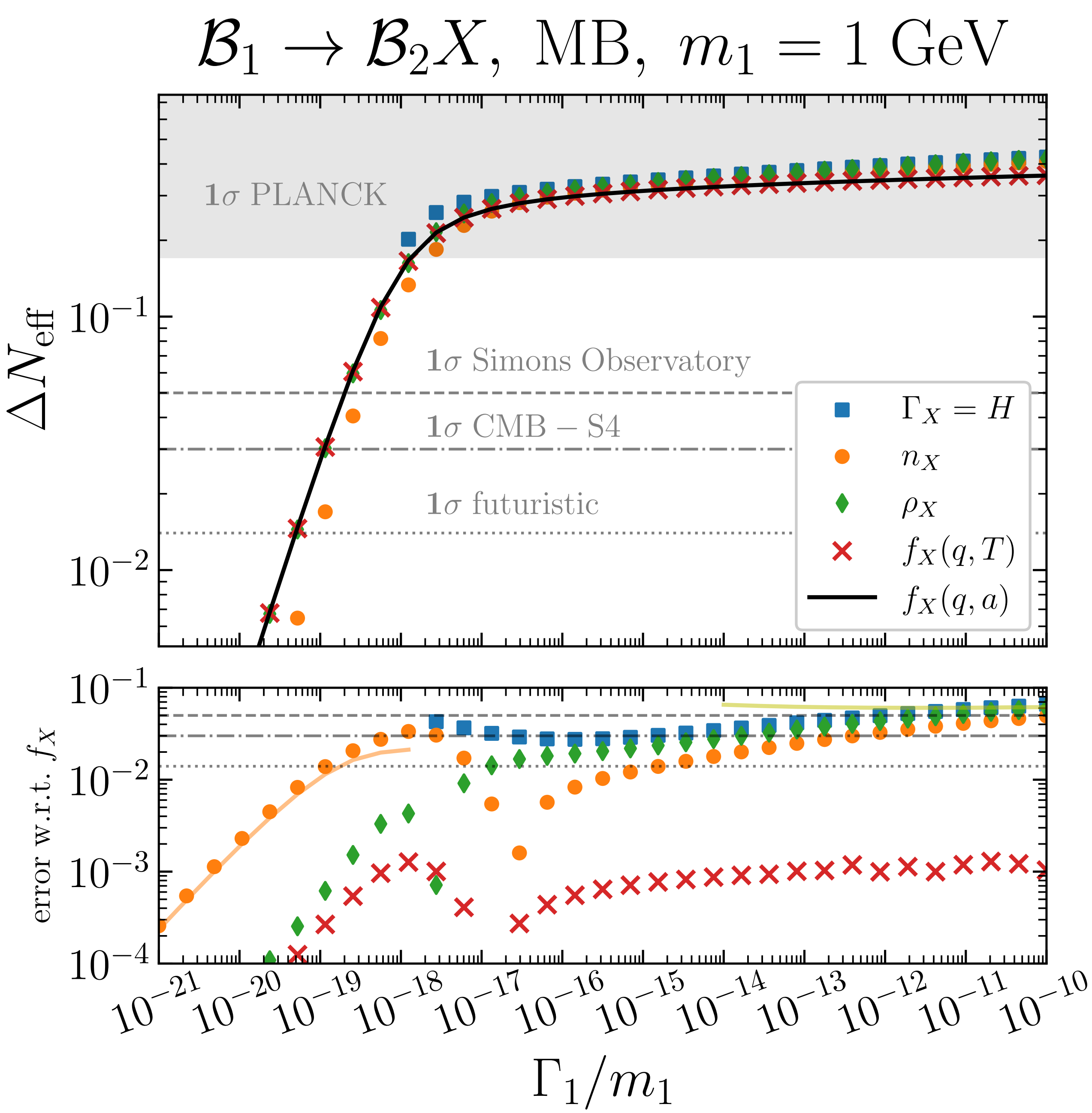
$$\mathcal{B}_1 \dots \mathcal{B}_n \to \mathcal{B}_{n+1} \dots \mathcal{B}_m \, X$$

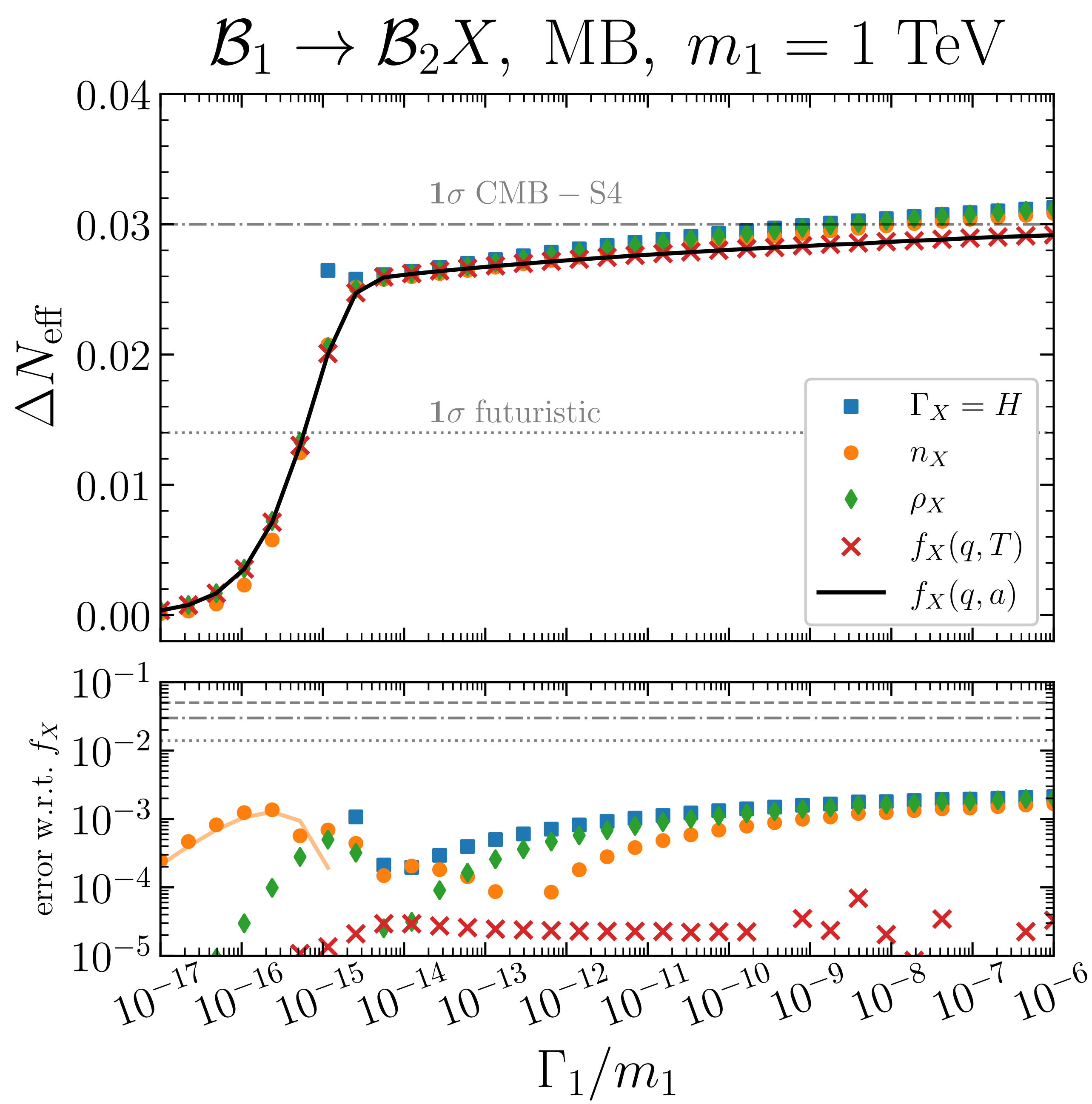
$$\frac{df_X(k,t)}{dt} = \left(1 - \frac{f_X(k,t)}{f_X^{\rm eq}(k,t)}\right) \mathcal{C}_{n\to mX}(k,t)$$

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

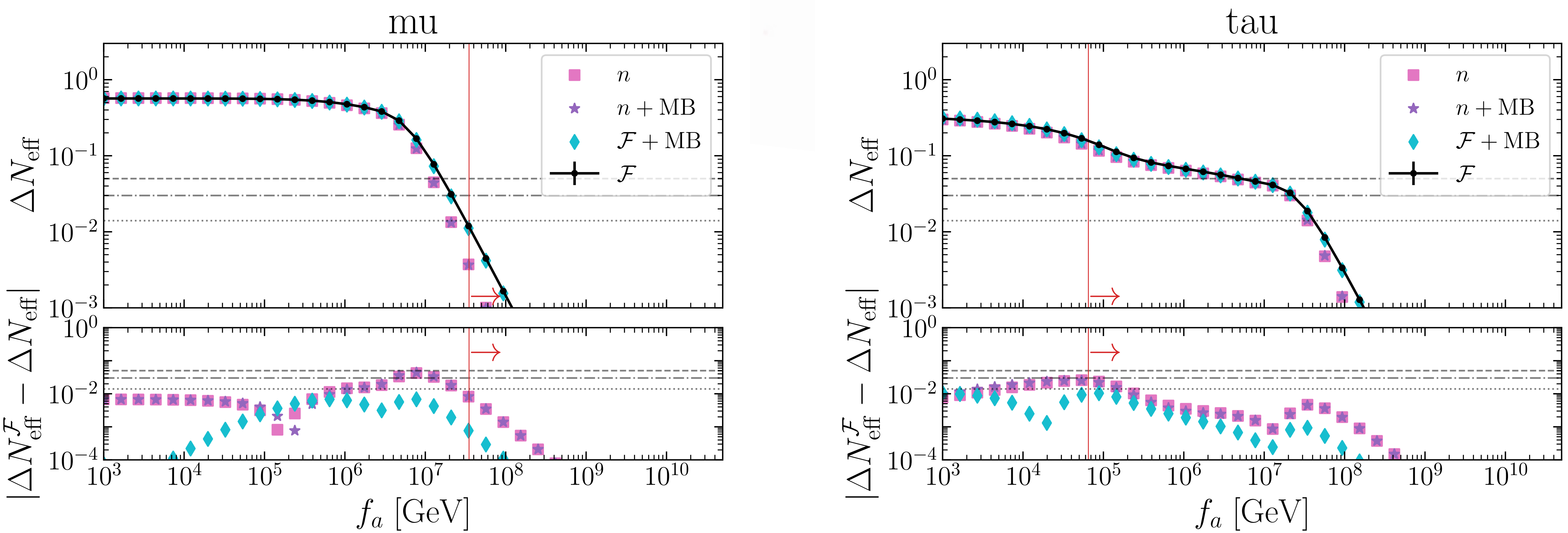
Baumann et al, **Phys.Rev.Lett. 117 (2016)**
Ferreira, Notari, **Phys.Rev.Lett. 120 (2018)**
FD et al, **JCAP 11 (2018)**
Arias-Aragón et al., **JCAP 11 (2020)**
Arias-Aragón et al., **JCAP 03 (2021)**
Green at al., **JCAP 02 (2022)**

<u>Will it change if we go back to the phase space?</u>

FD, Lenoci, **in preparation**

# Axion-Fermion Interactions

PRELIMINARY

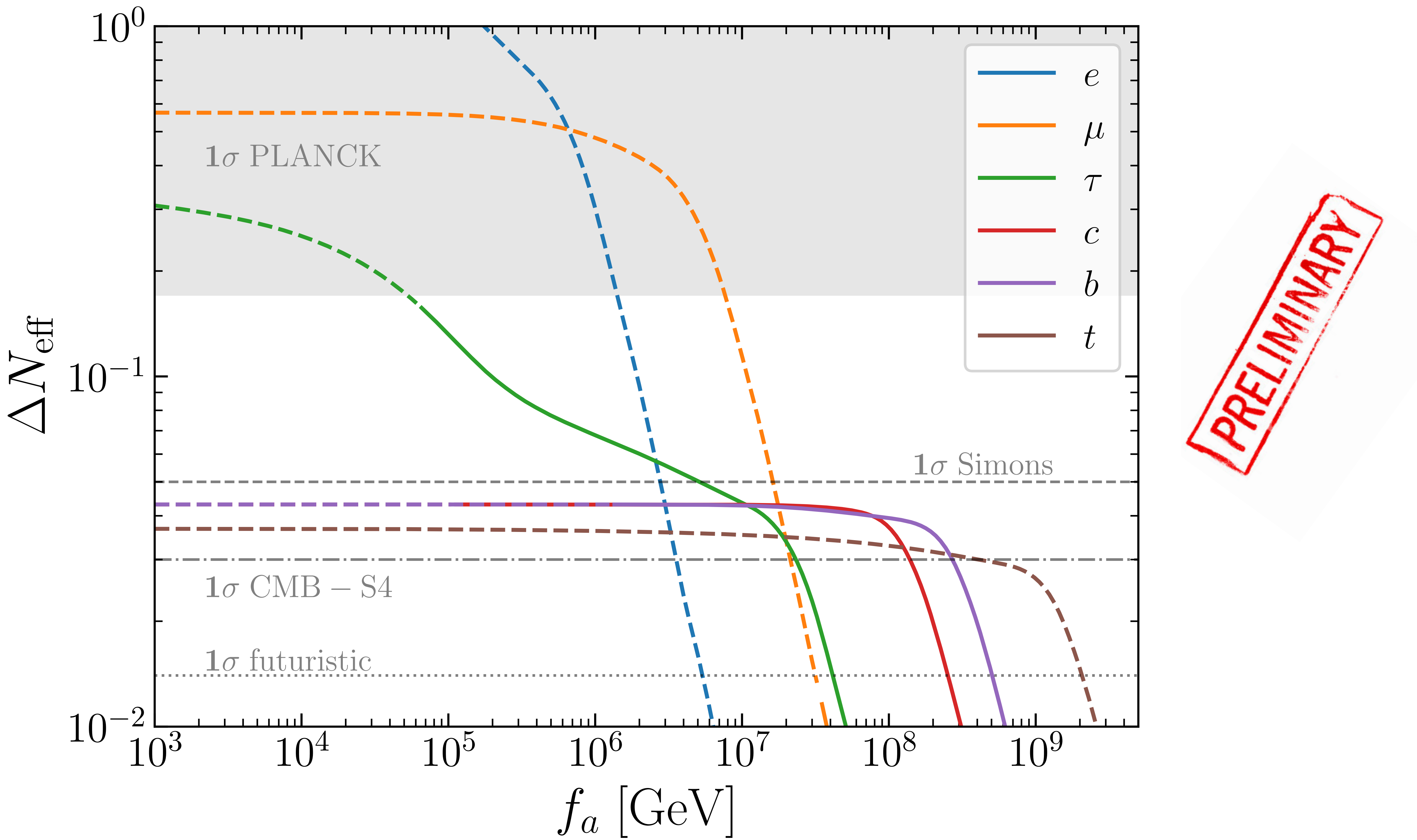



<u>Difference detectable by future CMB-S4 surveys!</u>

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

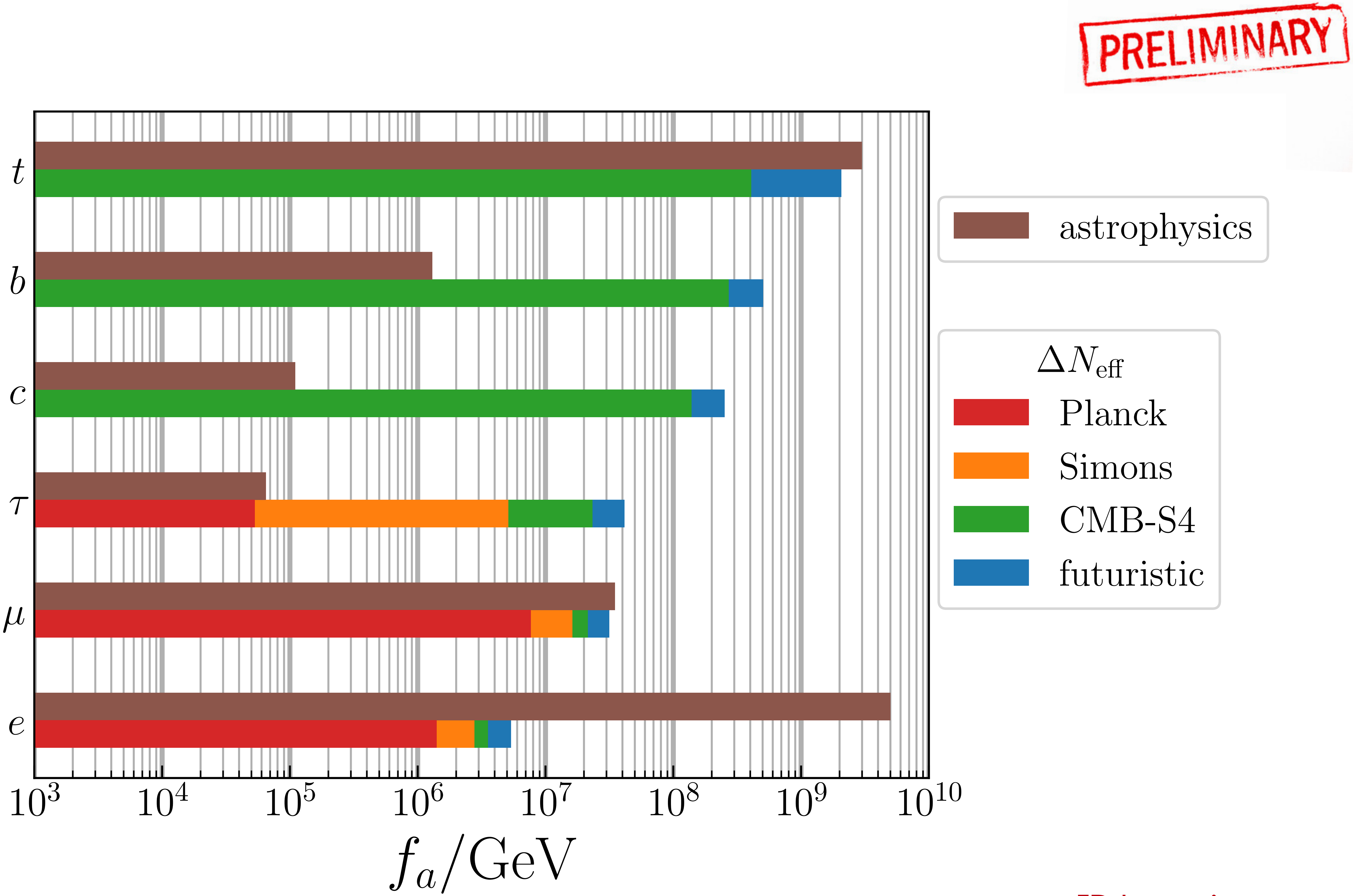
FD, Lenoci, **in preparation**

# Axion-Fermion Interactions



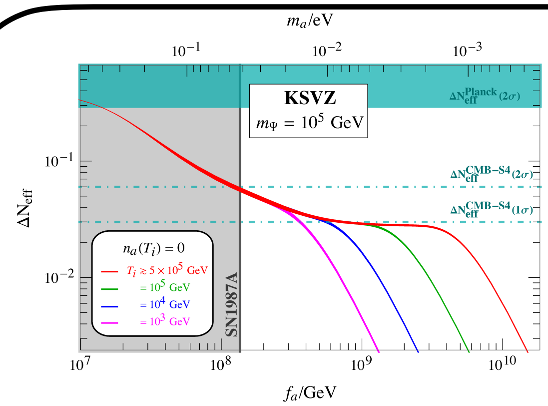

FD, Lenoci, **in preparation**

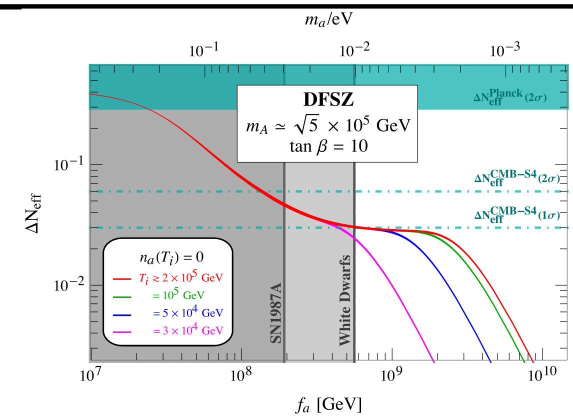
# Axion-Fermion Interactions




FD, Lenoci, **in preparation**

# The Way Back to the Phase Space



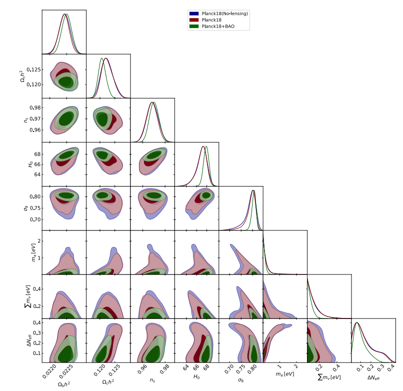

ΔN<sub></sub>

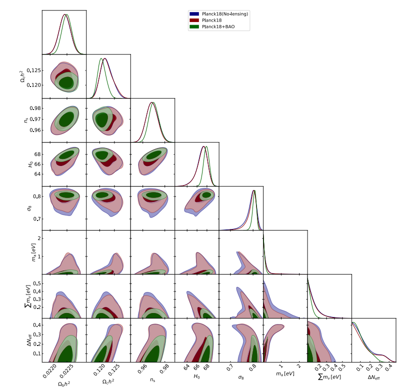
$\Delta N_{\rm eff}$ tracking the number density

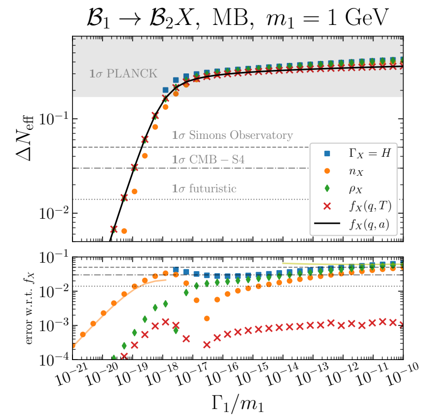
FD, Hajkarim, Yun, **JHEP 10 (2021)**
FD, Hajkarim, Yun, **Phys.Rev.Lett. 128 (2022)**

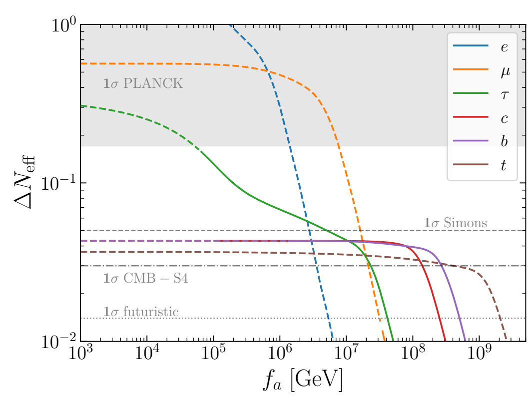
FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, **JCAP 09 (2022)**

Axion cosmological mass bound








Importance of a phase space analysis

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

# The Way Back to the Phase Space

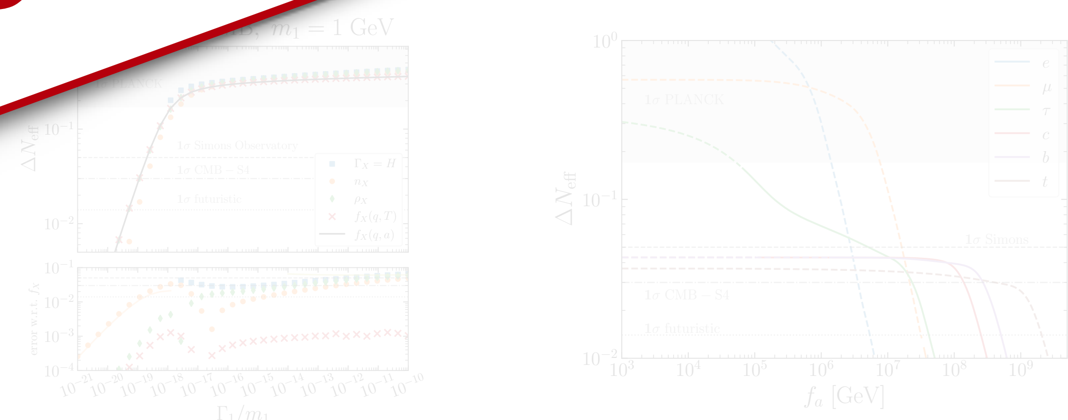


$\Delta N_{eff}$ tracking the number d[...]ity

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

Axion cosmological mass bo[...]

THANK YOU!



Importance of a phase space analysis

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