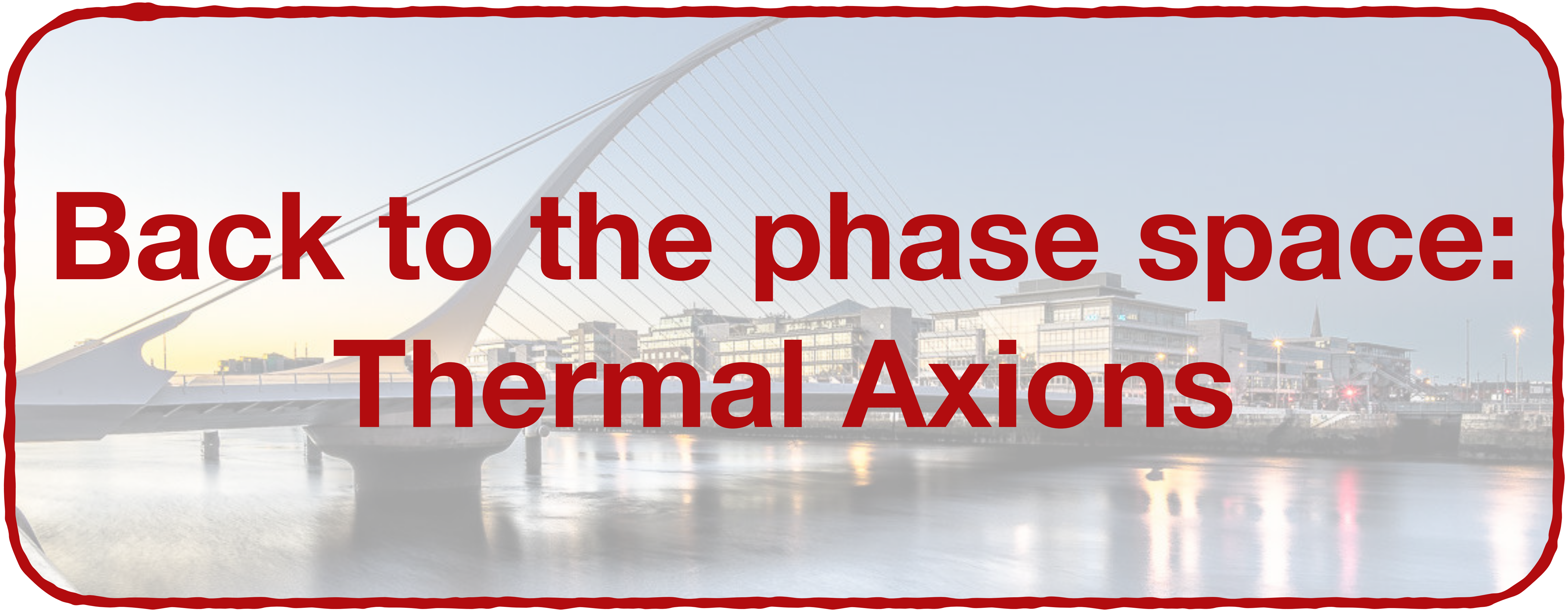
Back to the phase space: Thermal Axions



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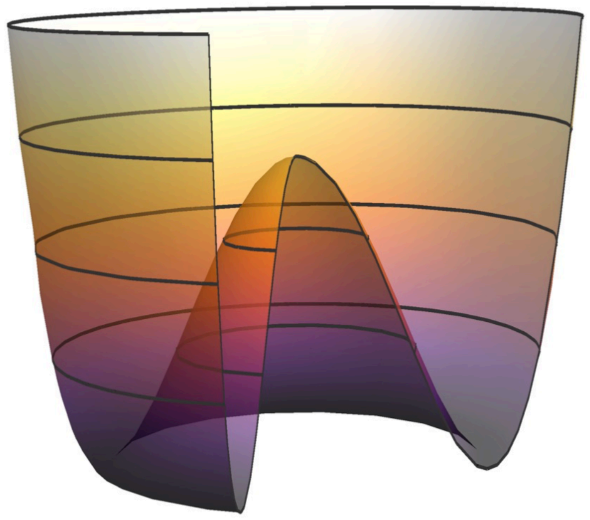
Cosmology, Astrophysics, Theory and Collider Higgs 2024 (CATCH22+2)
Dublin Institute for Advanced Studies (DIAS), 2 May 2024

The QCD Axion

New global $U(1)_{PQ}$ symmetry

- spontaneously broken at the scale f_a (with $f_a \gg$ weak scale)
- anomalous under strong interactions



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

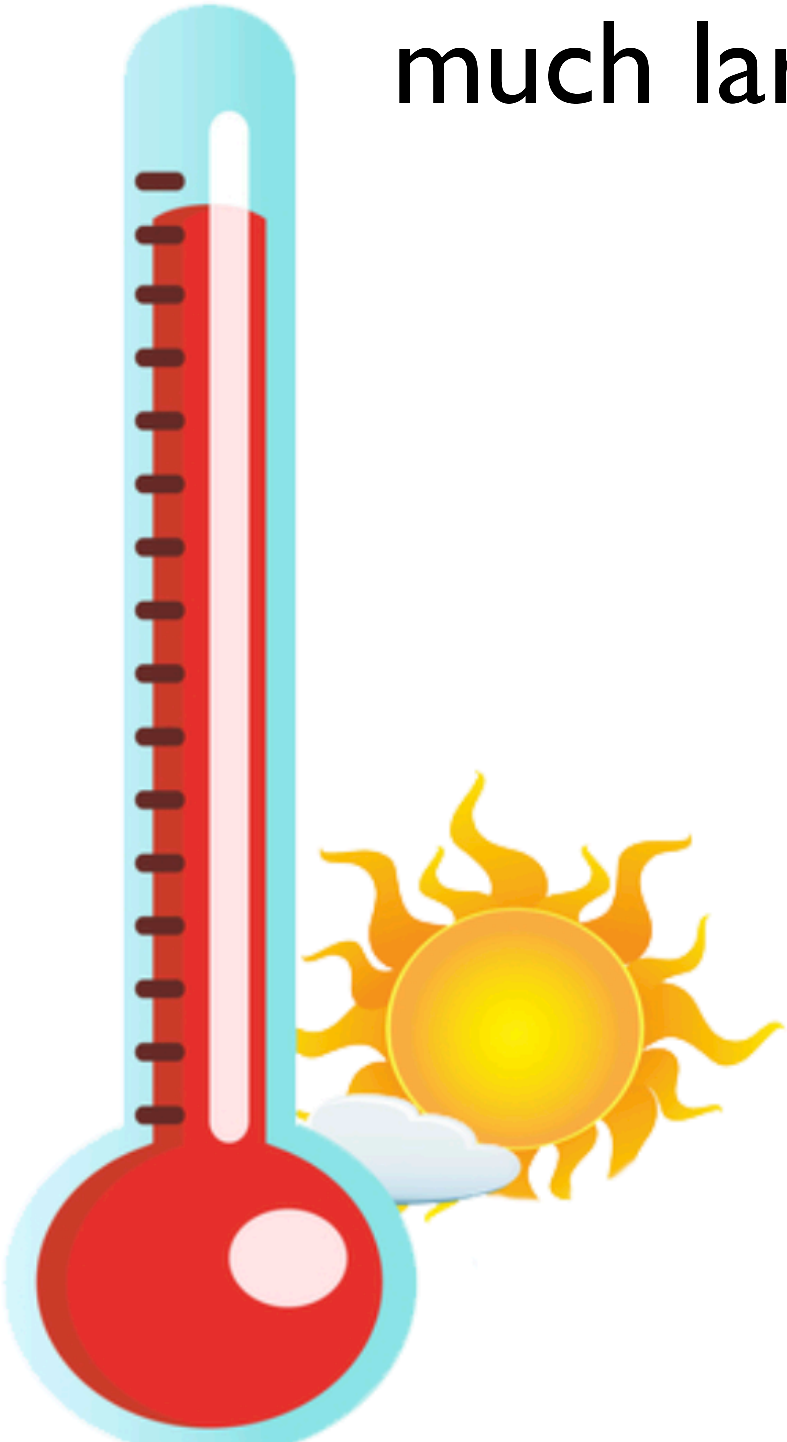
$$m_a \simeq 5.7\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)\mu\mathrm{eV}$$

Results in this talk mostly about the QCD axion

Easy to extend to ALPs (especially when the mass is negligible)

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)

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

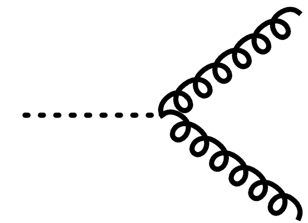
$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_a}{\rho_\gamma}$$

Thermal Production

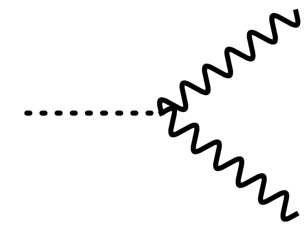
Scatterings and/or decays involving primordial thermal bath particles (axion energy ≫ m_a, i.e. “hot”)

<u>Unavoidable</u>

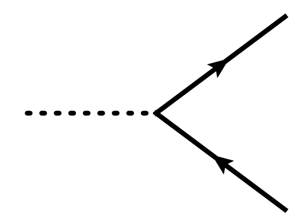
Production Source!



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



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



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

Thermal Production

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

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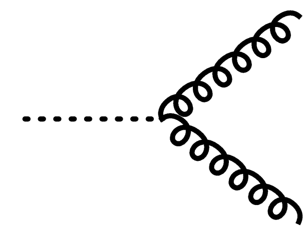

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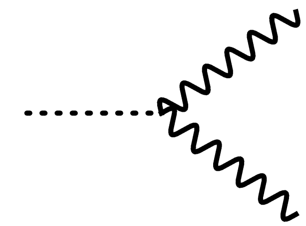

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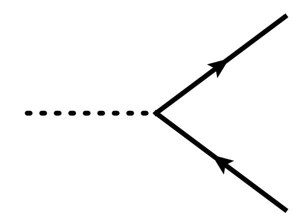


$$c_\psi\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$$

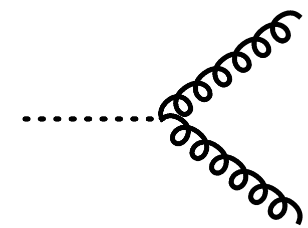
<u>Computing ΔNeff - I</u>
Instantaneous decoupling

- Assume they thermalize at early times
- Estimate the decoupling temperature, $\Gamma(T_D) = H(T_D)$, and the resulting $\Delta N_{\rm eff}$

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

Thermal Production

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



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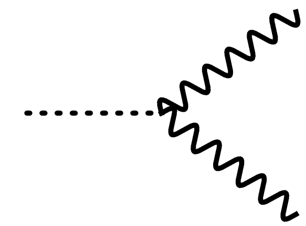

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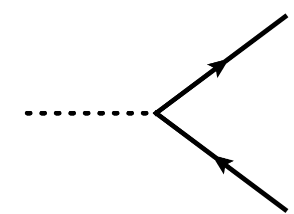

$$c_\psi\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$$

<u>Unavoidable</u>

Production Source!

<u>Computing ΔNeff - II</u>

Boltzmann equation for n_a

- Track the number density of axions
- Convert the asymptotic result to $\Delta N_{\rm eff}$ via the equilibrium distribution

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

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

Thermal Production

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)

<u>Computing ΔNeff - II</u>

Boltzmann equation for n_a

- Track the number density of axions
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$$\frac{dn_a}{dt} + 3Hn_a = \sum_\alpha \gamma_\alpha$$

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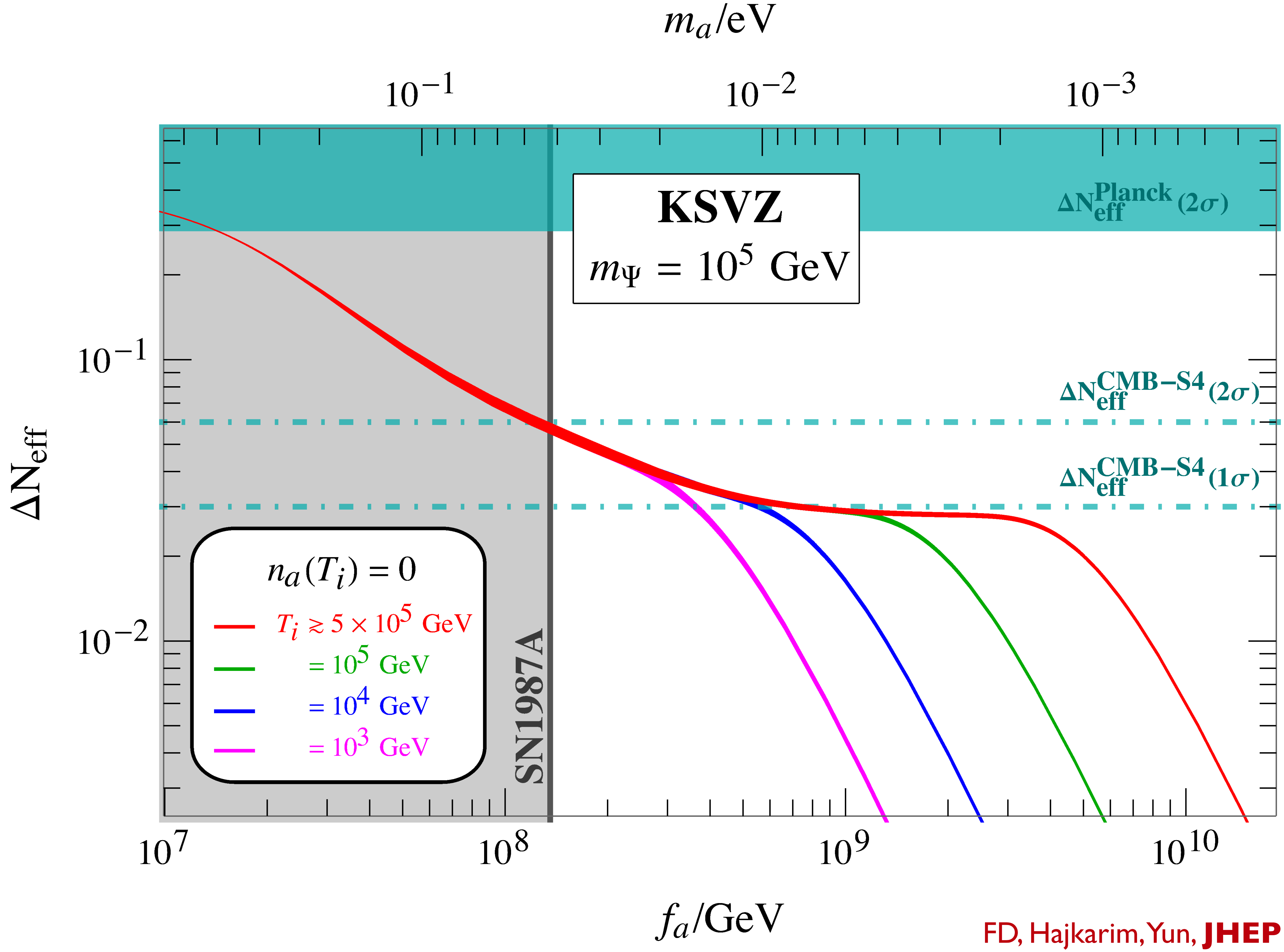
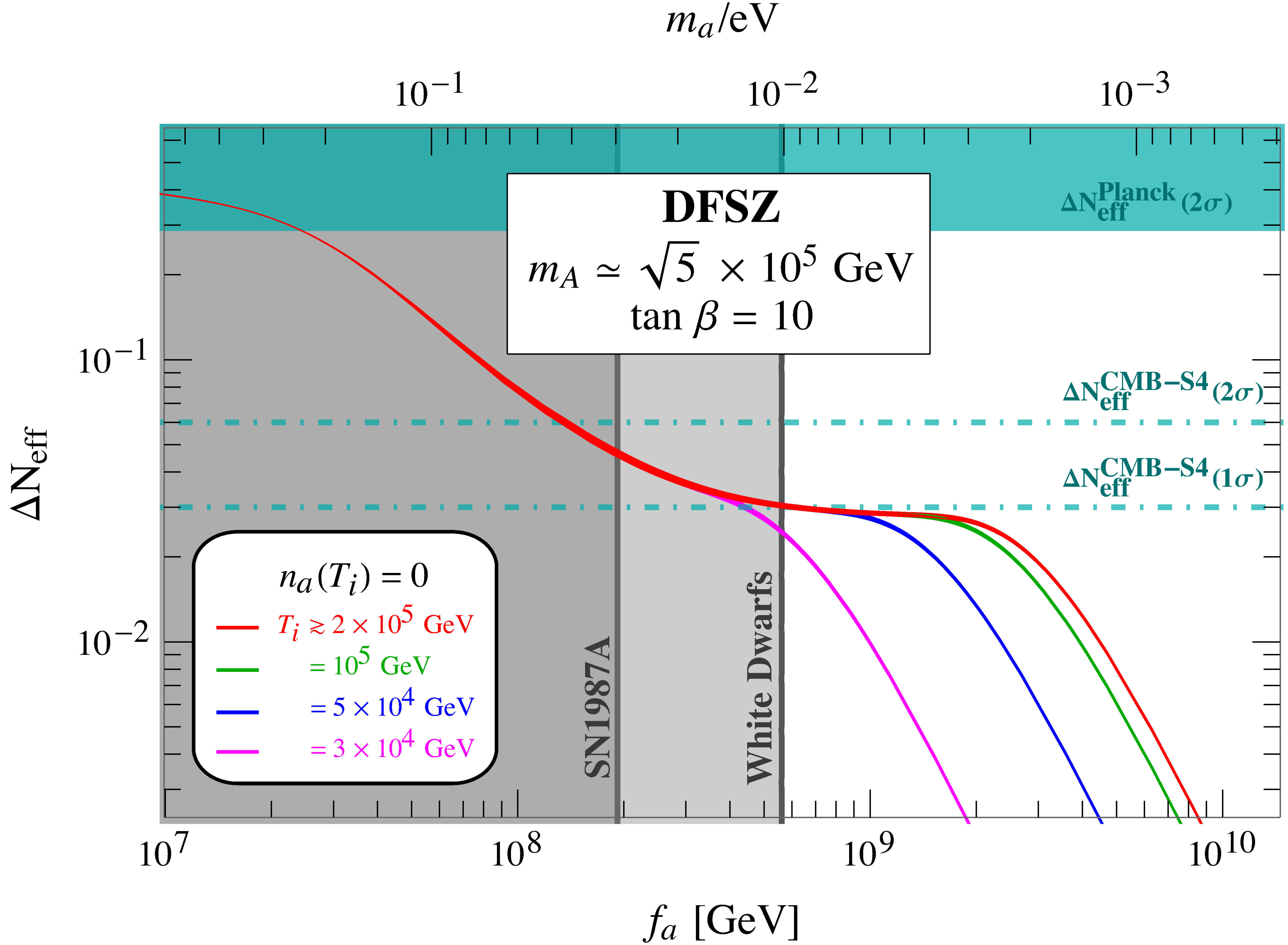
KSVZ Axion



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

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

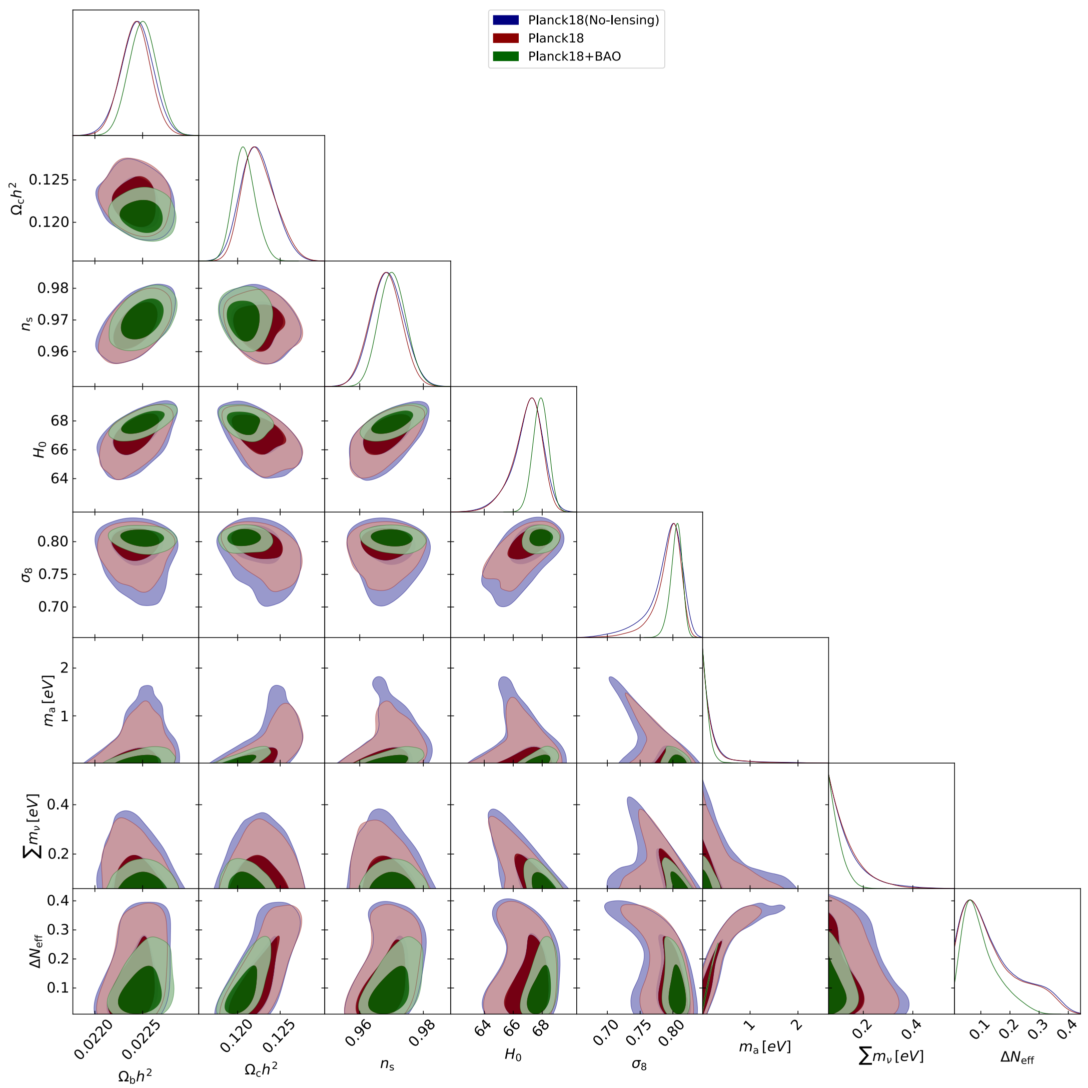
DFSZ Axion



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

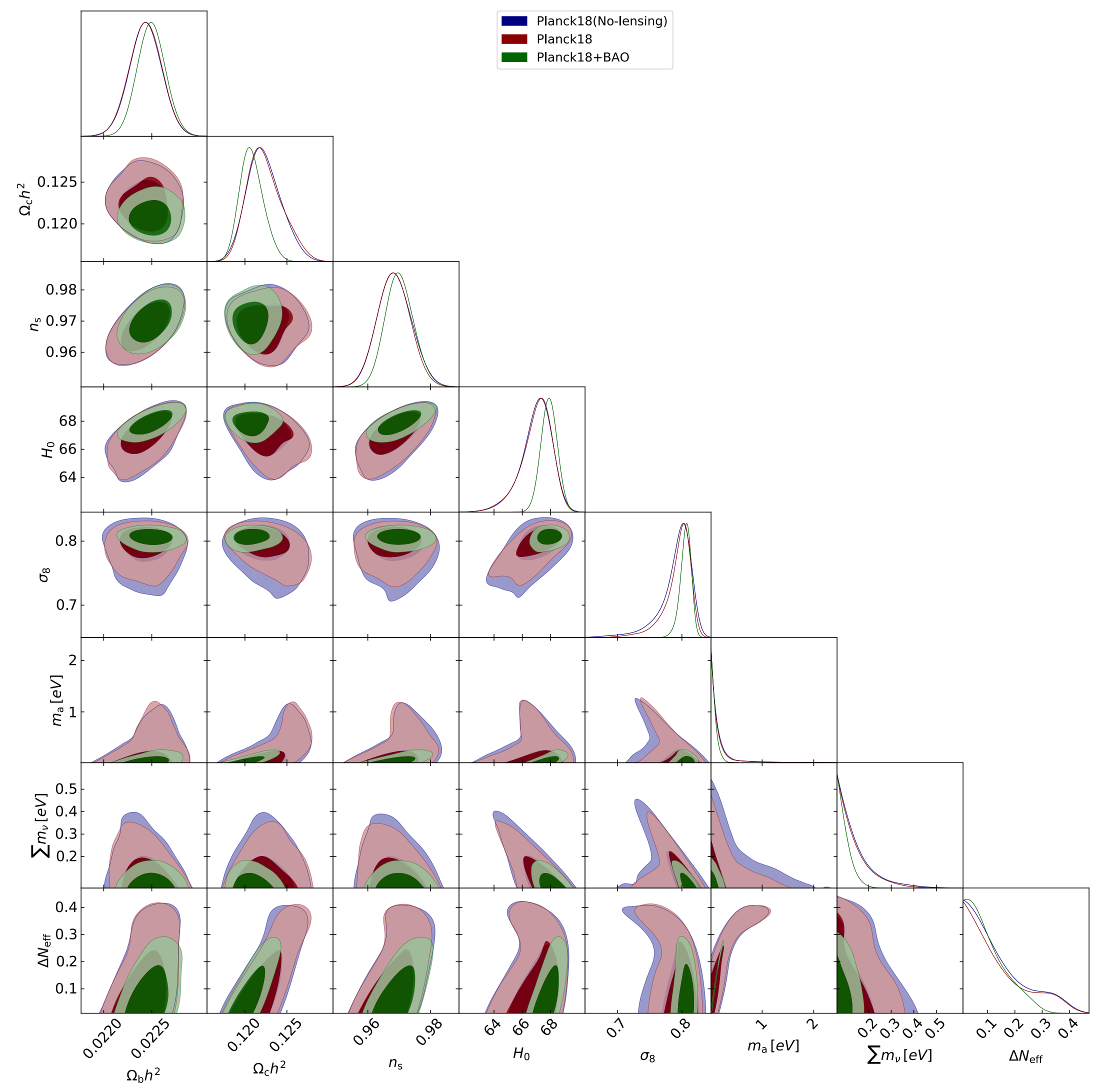
Axion Mass Bound

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)**

Back to the Phase-Space

Model-independent analysis:

generic production of a light X

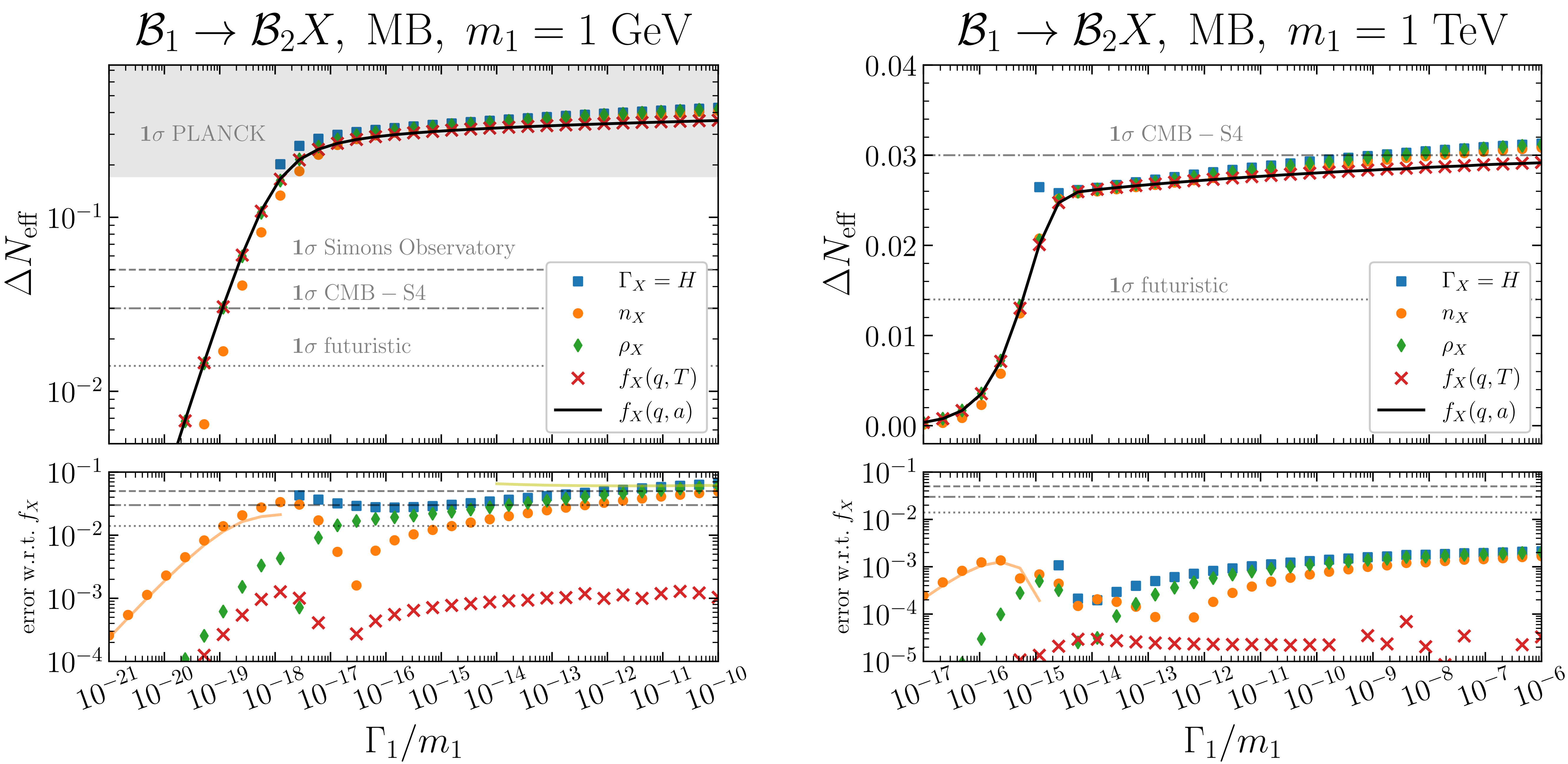
$$\mathcal{B}_1 \dots \mathcal{B}_n \to \mathcal{B}_{n+1} \dots \mathcal{B}_m \, X$$

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

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 ΔN_{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

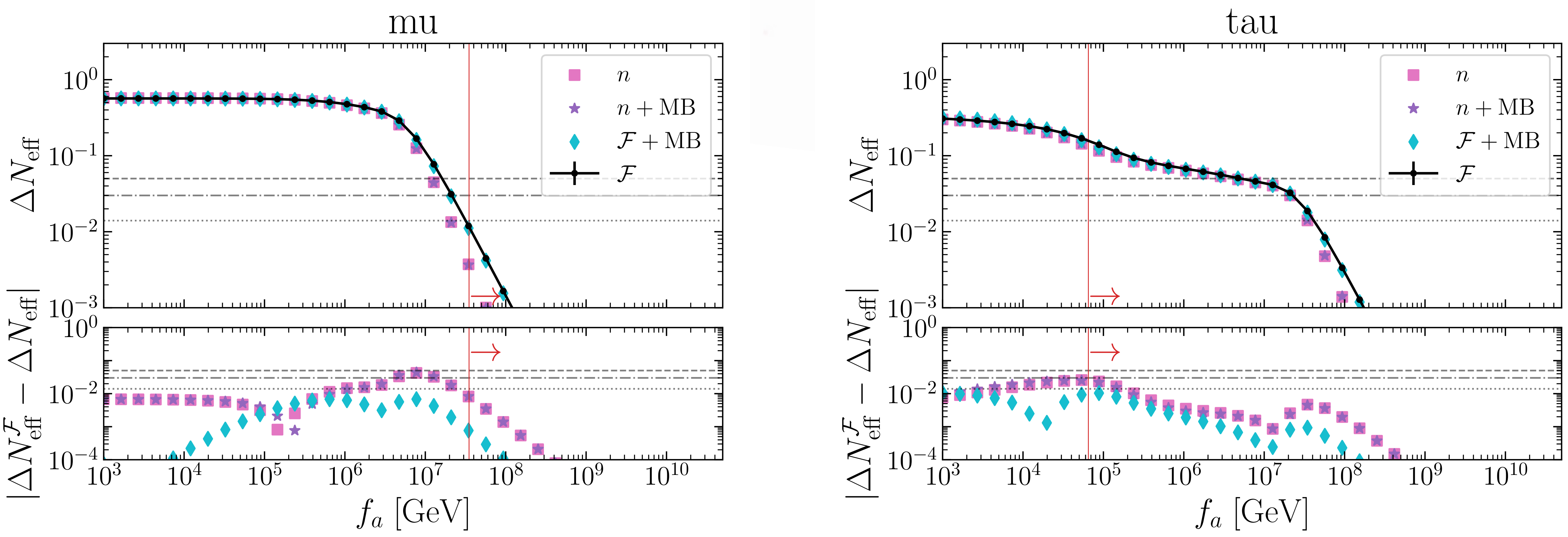
Baumann et al, Phys.Rev.Lett. 117 (2016)
Ferreira, Notari, Phys.Rev.Lett. 120 (2018)
FD et al, **JCAP 11 (2018)**
Arias-Aragón et al., **JCAP 11 (2020)**
Arias-Aragón et al., **JCAP 03 (2021)**
Green at al., JCAP 02 (2022)

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

FD, Lenoci, **in preparation**

Axion-Fermion Interactions

PRELIMINARY

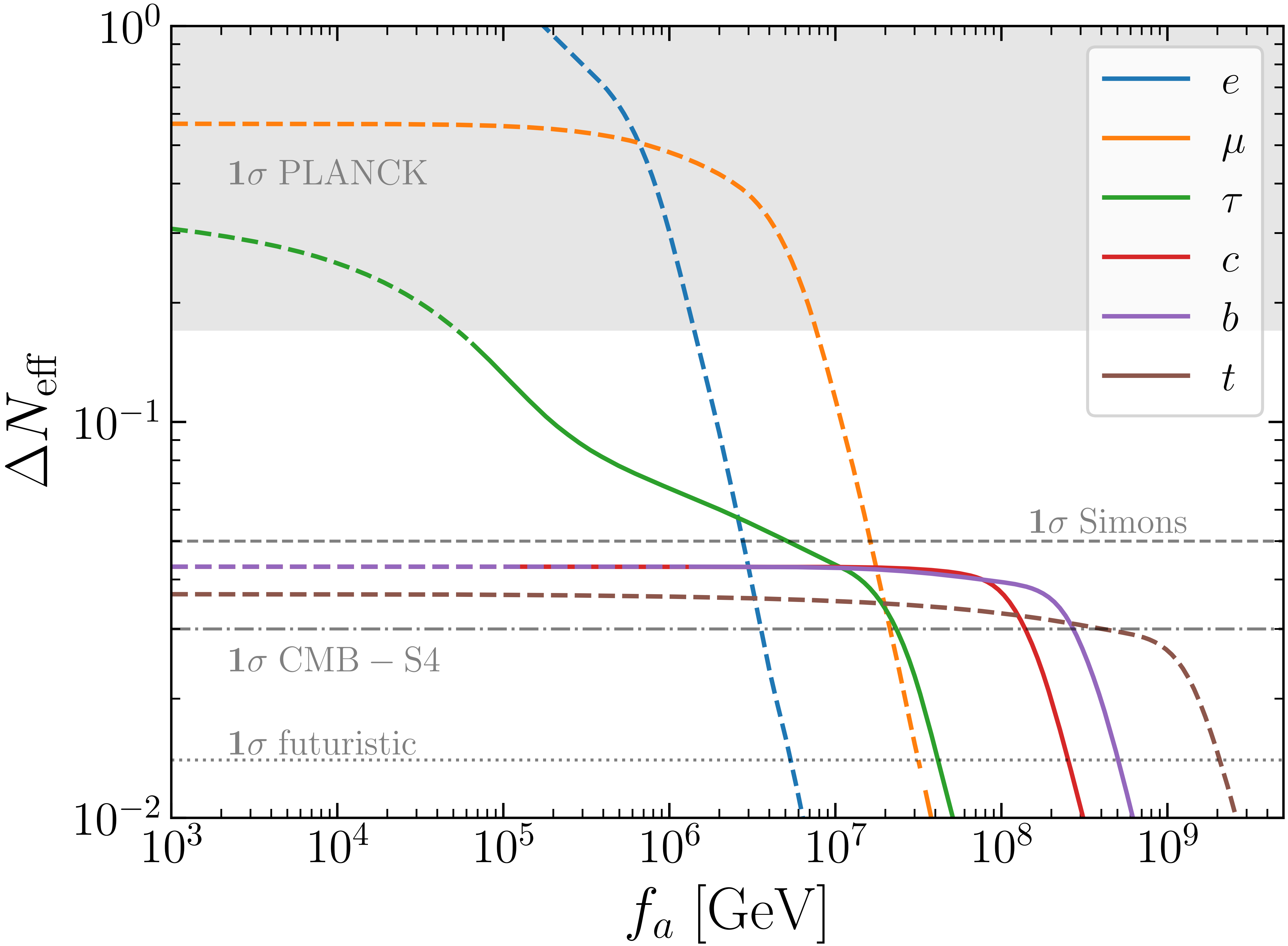


Difference detectable by future CMB-S4 surveys!

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

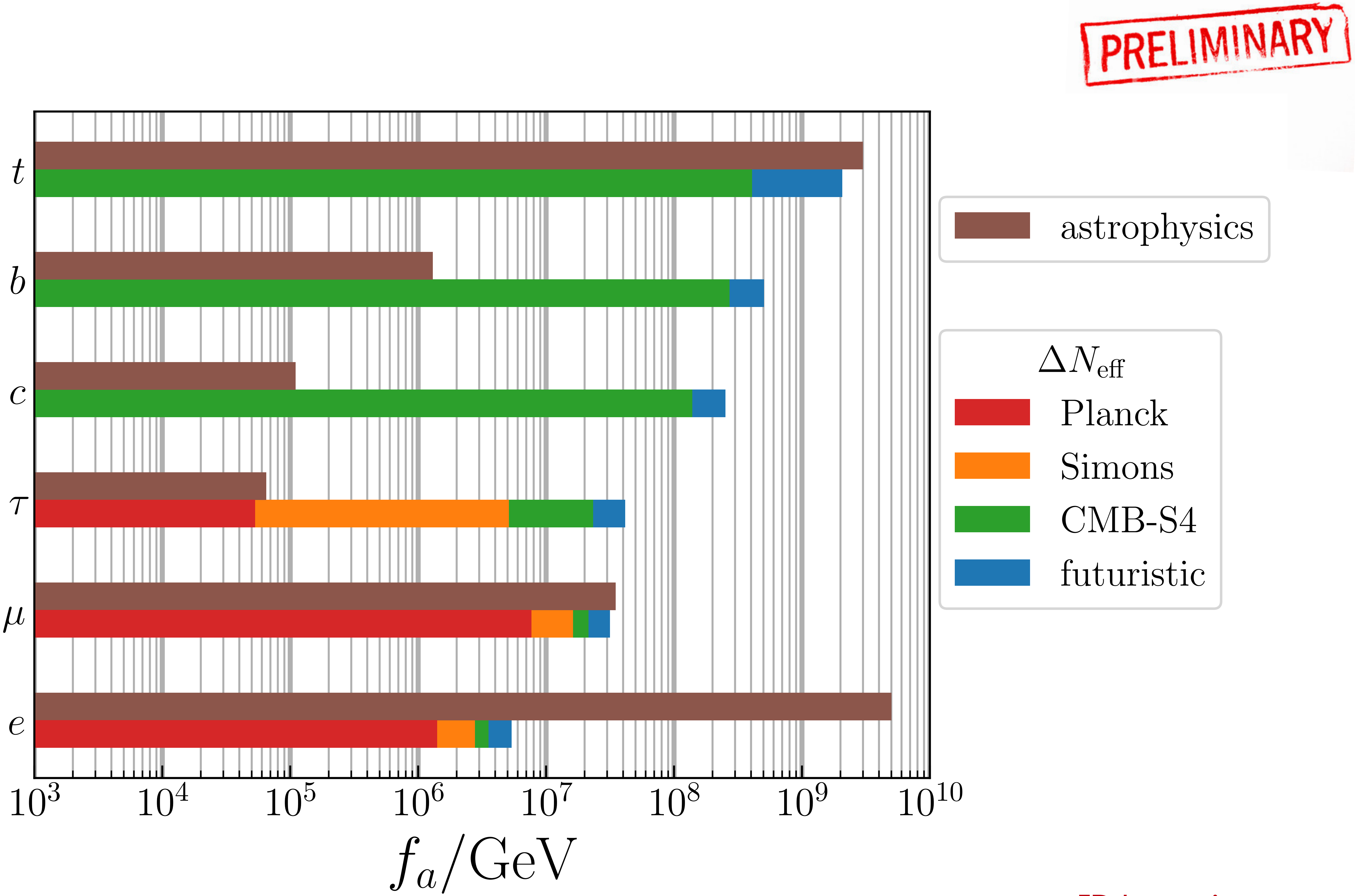
FD, Lenoci, **in preparation**

Axion-Fermion Interactions



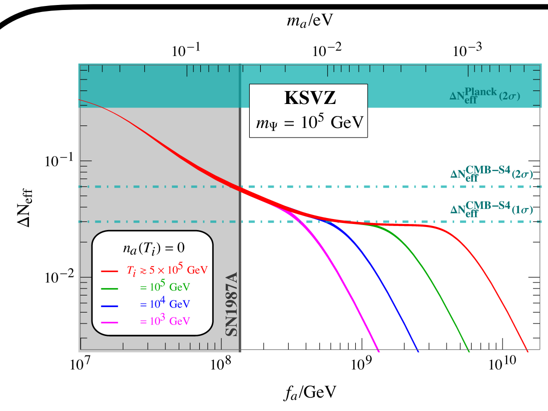
FD, Lenoci, **in preparation**

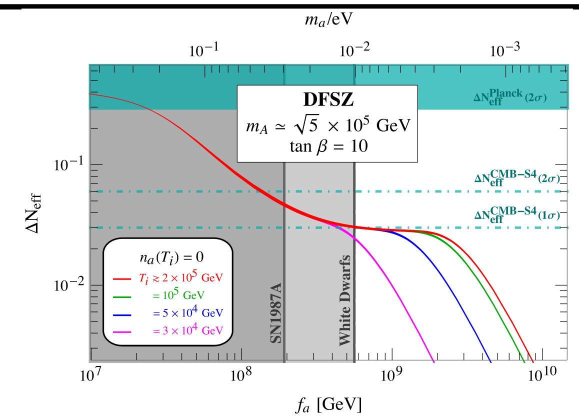
Axion-Fermion Interactions



FD, Lenoci, **in preparation**

The Way Back to the Phase Space



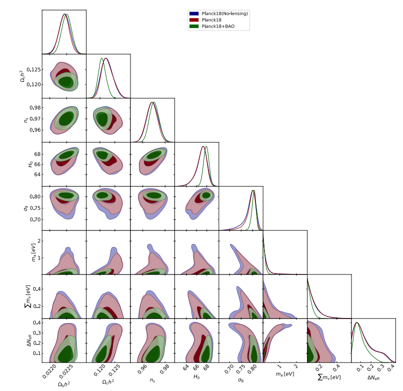


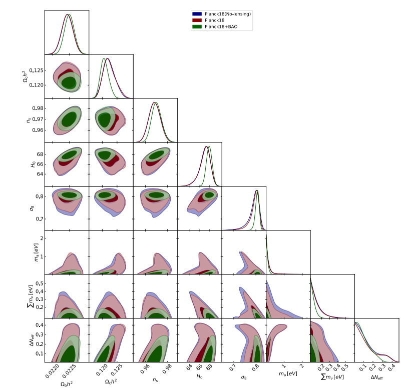
$\Delta N_{\rm eff}$ tracking the number density

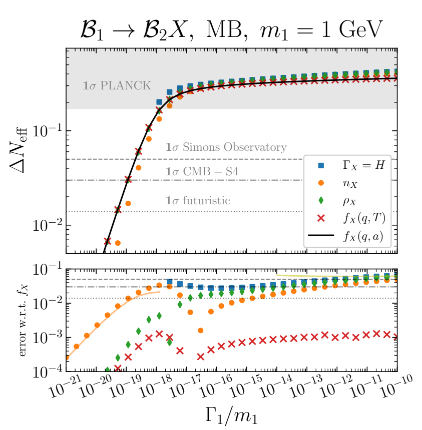
FD, Hajkarim, Yun, **JHEP 10 (2021)**
FD, Hajkarim, Yun, **Phys.Rev.Lett. 128 (2022)**

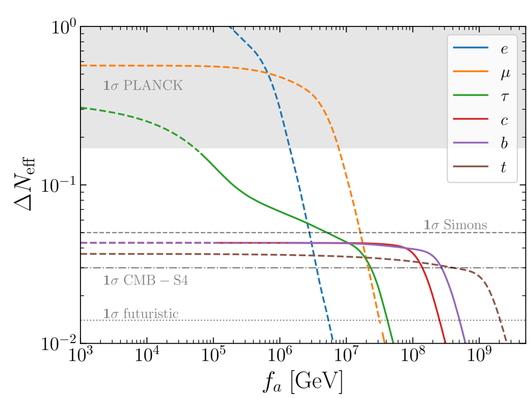
FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, **JCAP 09 (2022)**

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

ΔN_{eff} tracking the number de...ity

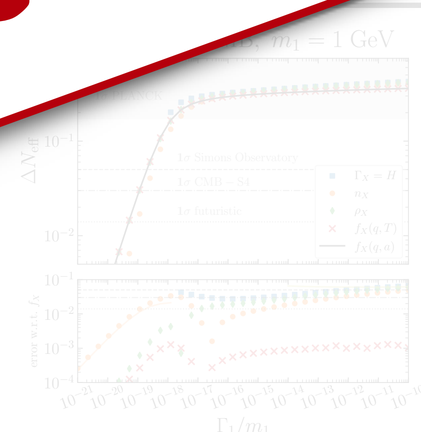
FD, H...

FD, Hajkari...

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**