Cosmic Axion Background from the Primordial Bath

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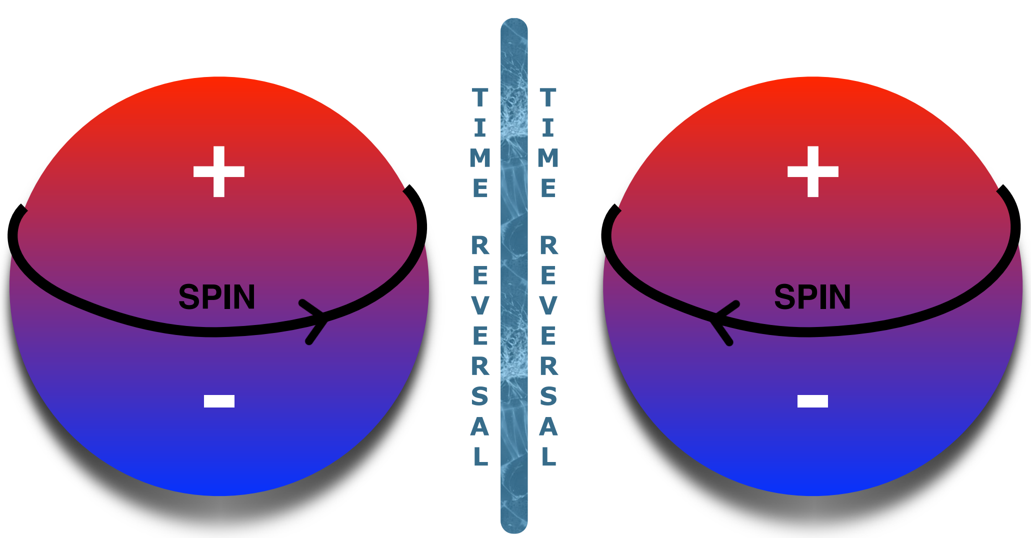
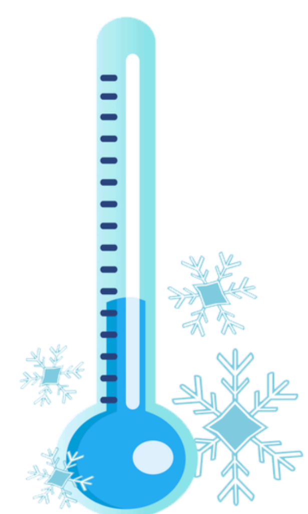
Karlsruhe Institute of Technology (KIT) — 10 October 2024

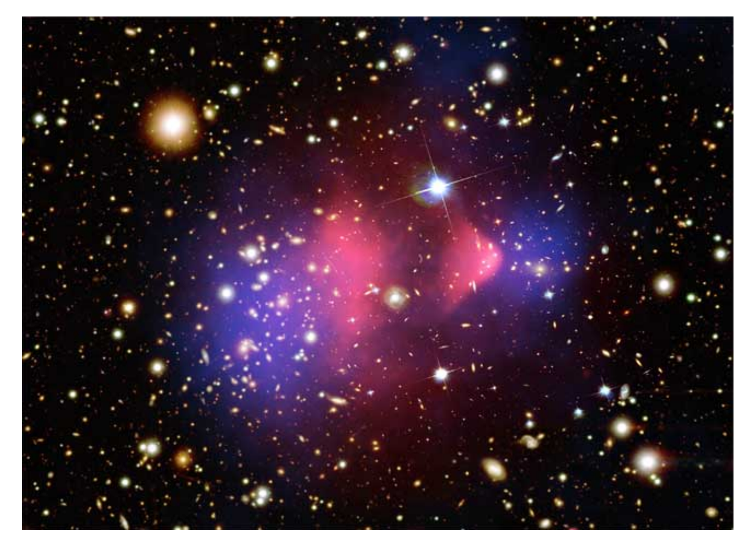
Virtues of the QCD Axion

Strong CP

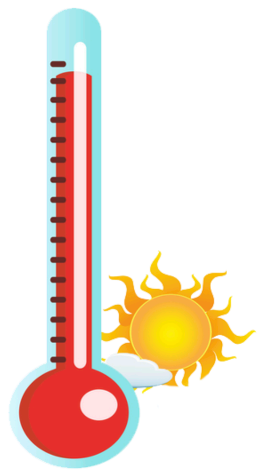


Cold Dark Matter

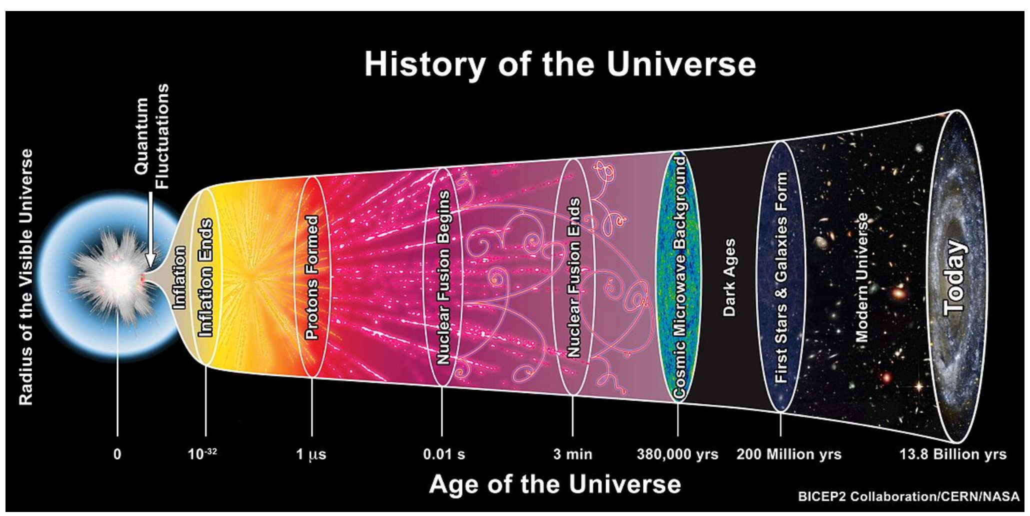




Plan for today: Hot Axions



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

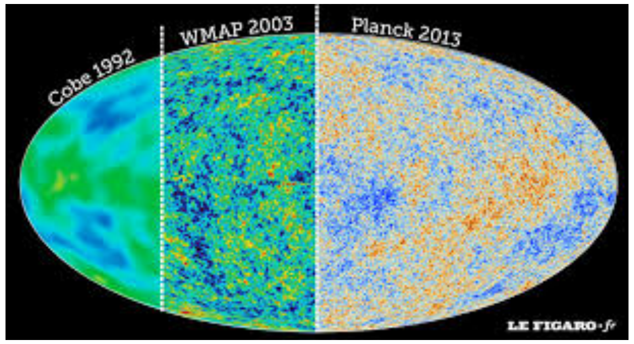


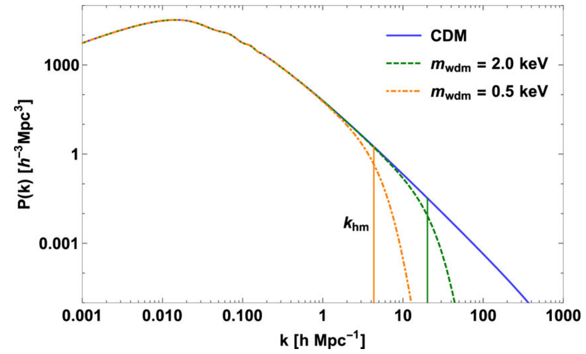
1. Production

Processes with particles from the primordial thermal bath

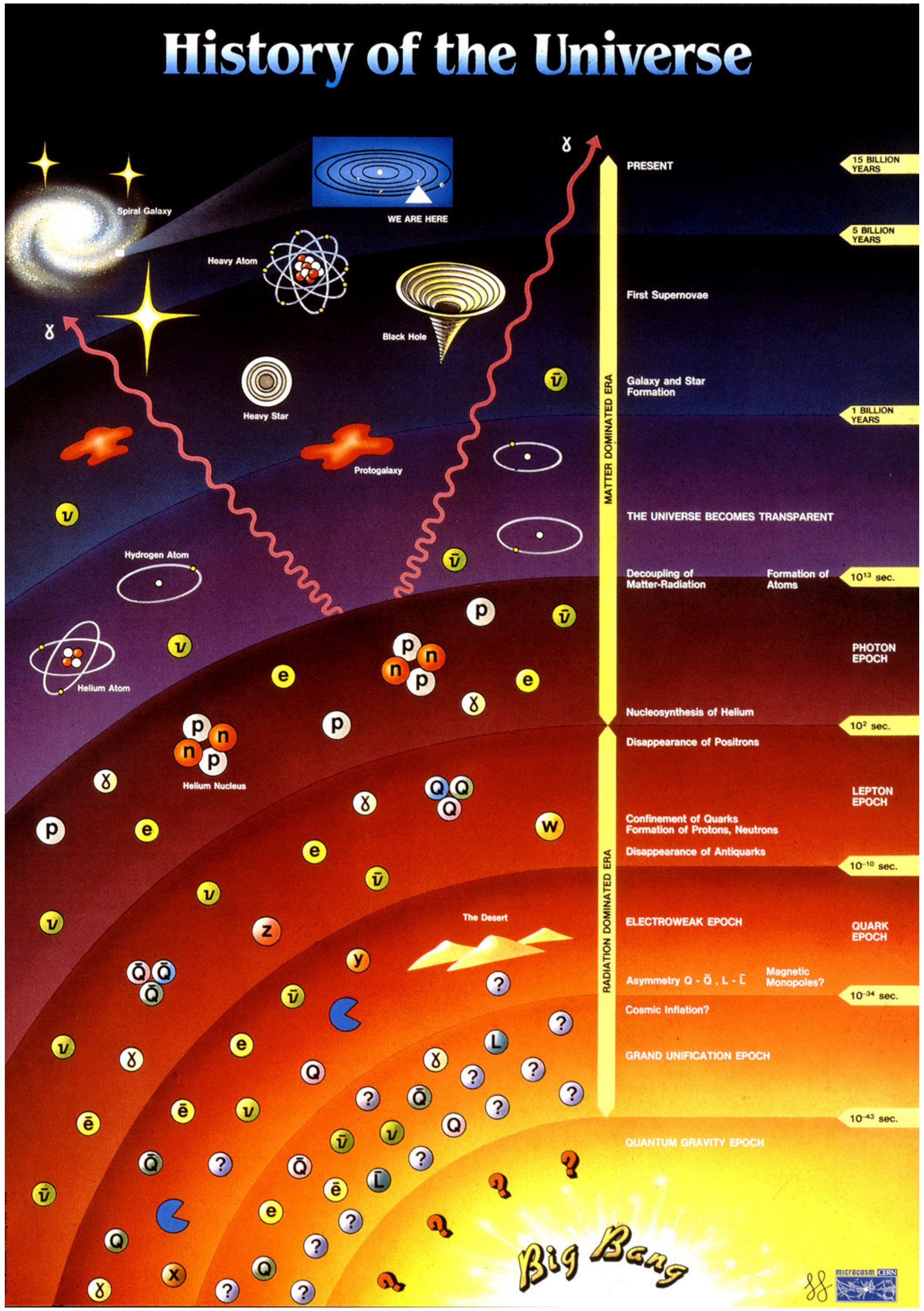
2. Signals

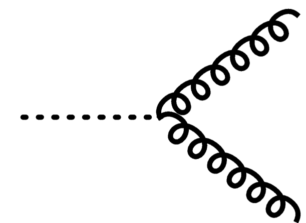
Dark radiation or warm dark matter



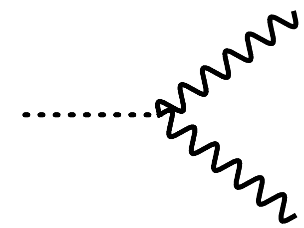


Unavoidable Thermal Production

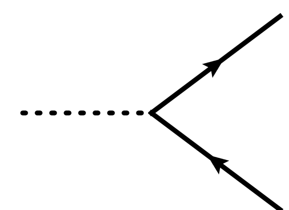




$$\frac{\alpha_s}{8\pi}\frac{a}{f_a}G^{\mu\nu}\widetilde{G}_{\mu\nu}$$



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



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

Scatterings and/or decays of thermal bath particles (axion energy $\gg m_a$, i.e. "hot")

Observable Effects

Dark Radiation

Additional radiation at:

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

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

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

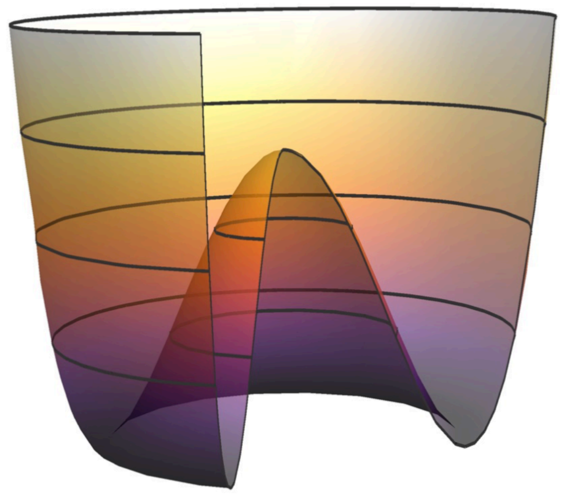
Warm Dark Matter

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

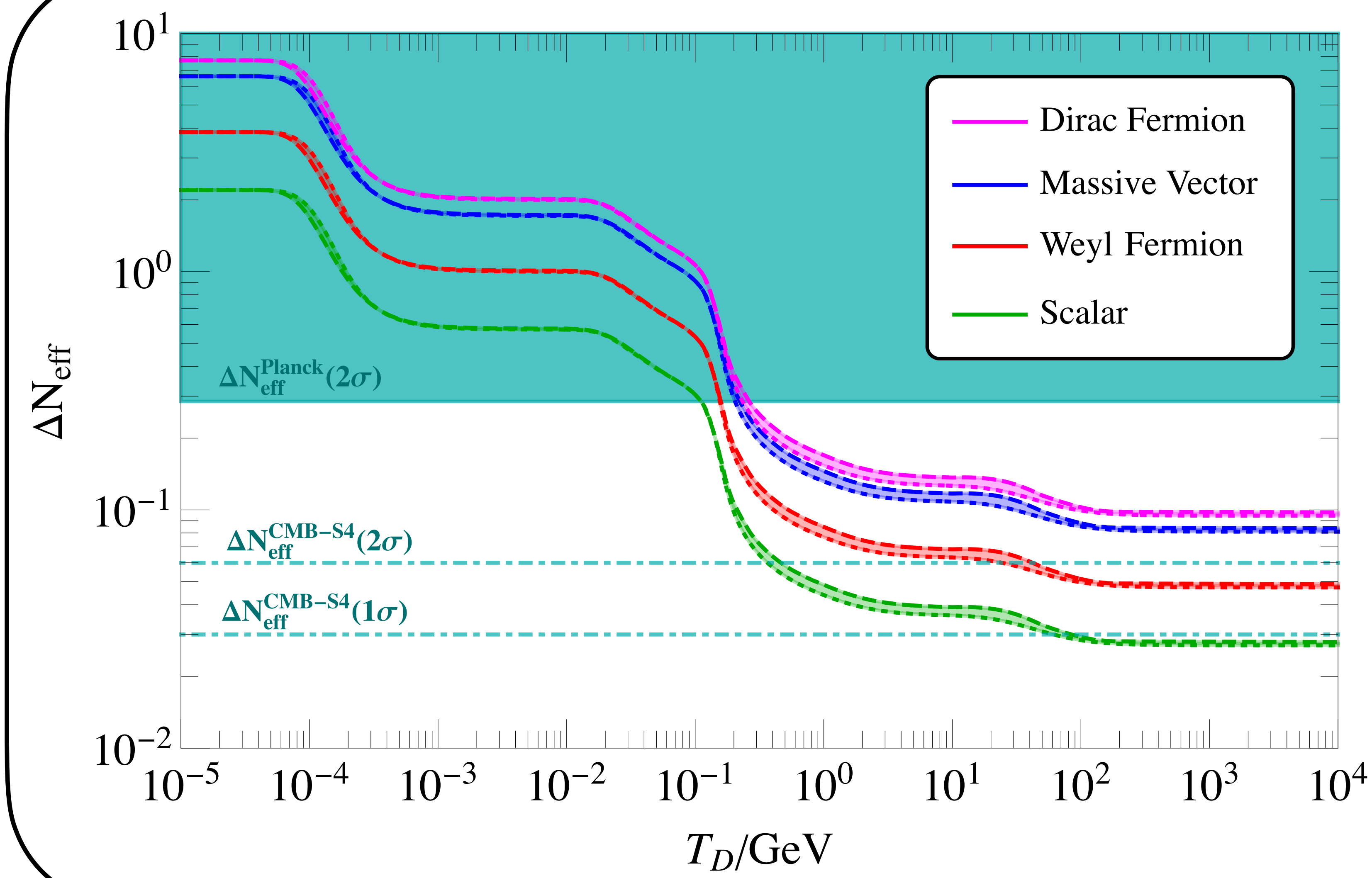
$$m_a \simeq \Lambda_X^2 / f_X$$

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

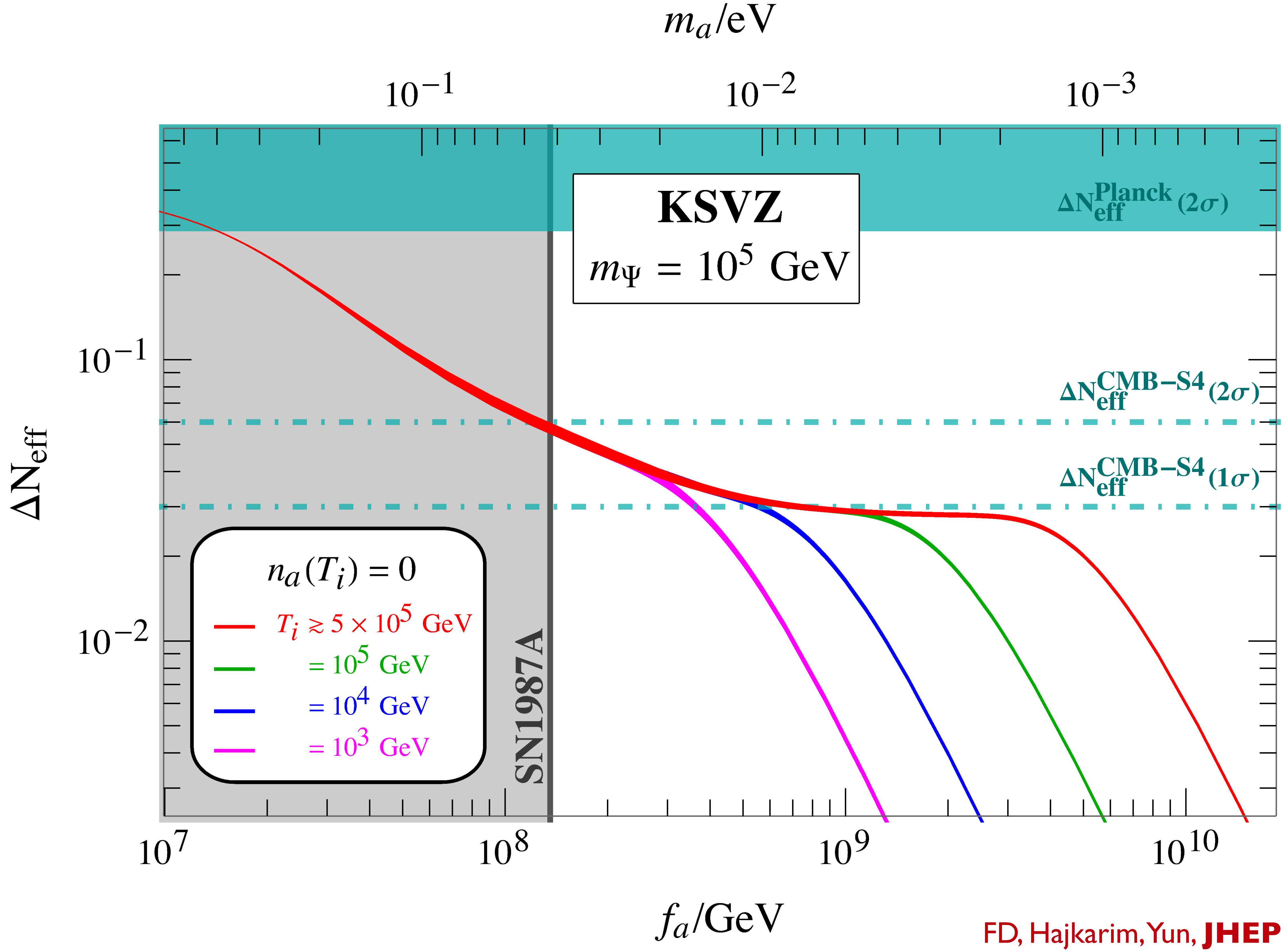
- Assume they thermalize at early times
- Estimate the decoupling temperature from $\Gamma(T_D) = H(T_D)$

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)

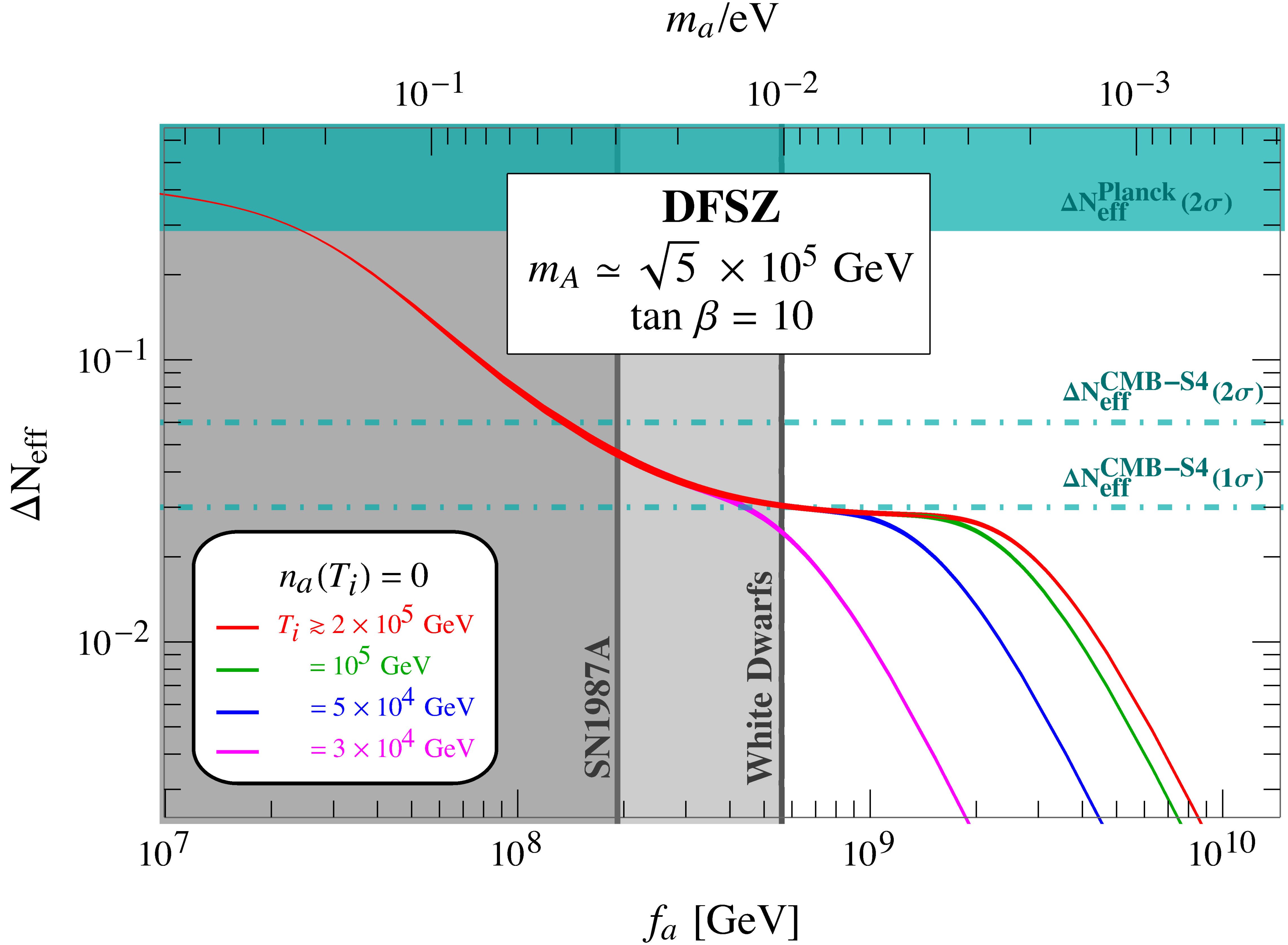
KSVZ Axion



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

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

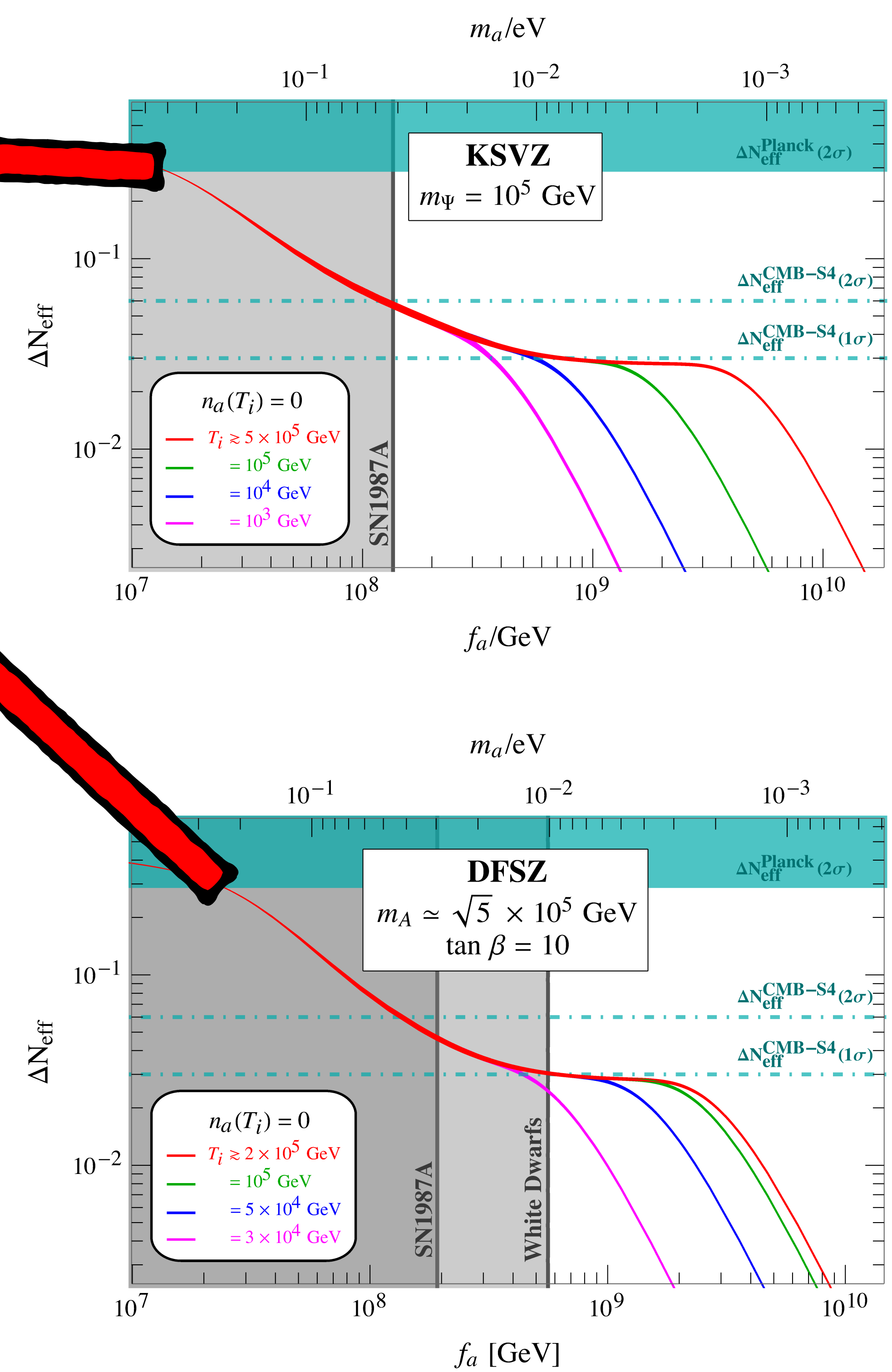
DFSZ Axion



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

Finite QCD Axion Mass Effects?

Planck: tension with astrophysics and axion mass non-negligible



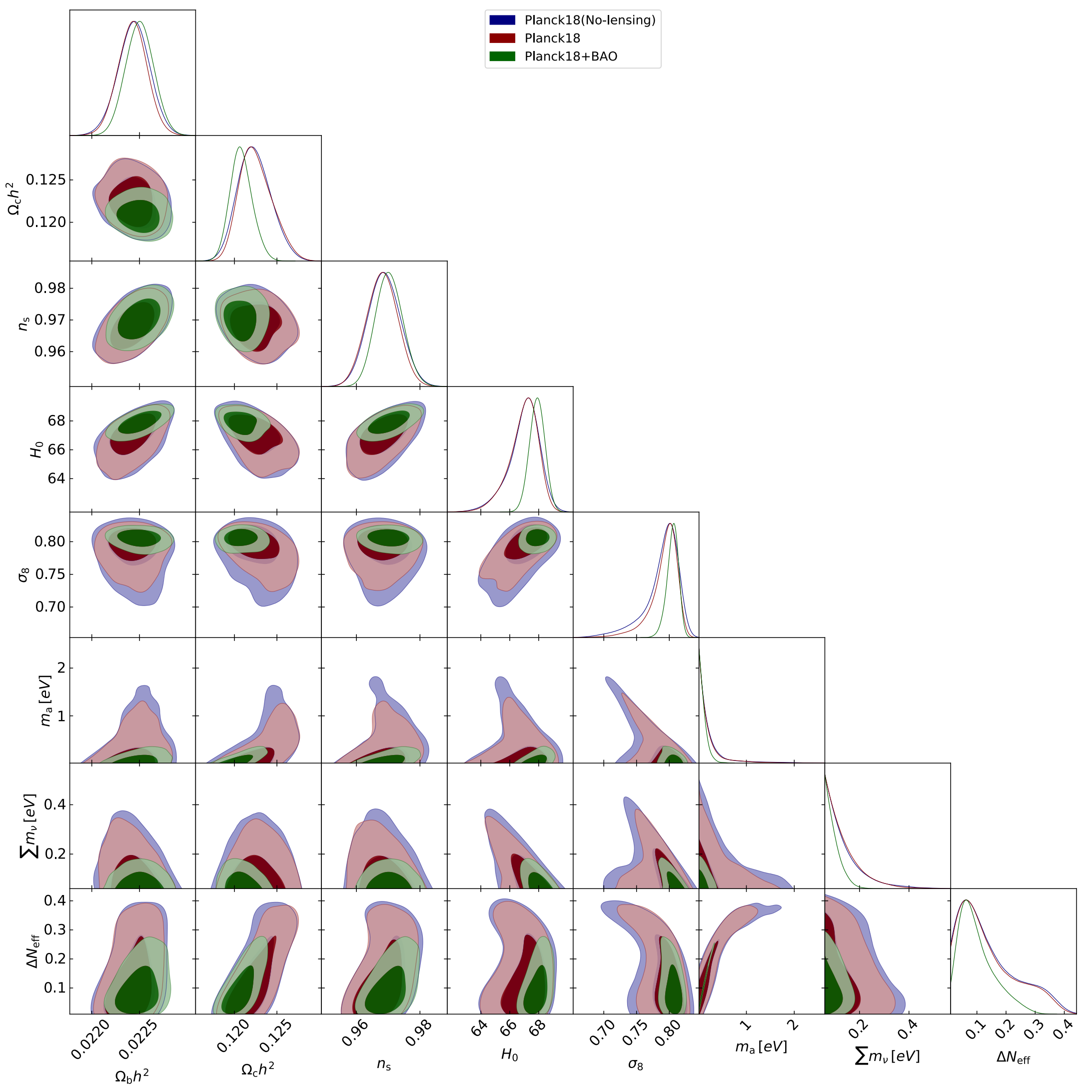
FD, Hajkarim, Yun, **JHEP 10 (2021)**

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)**

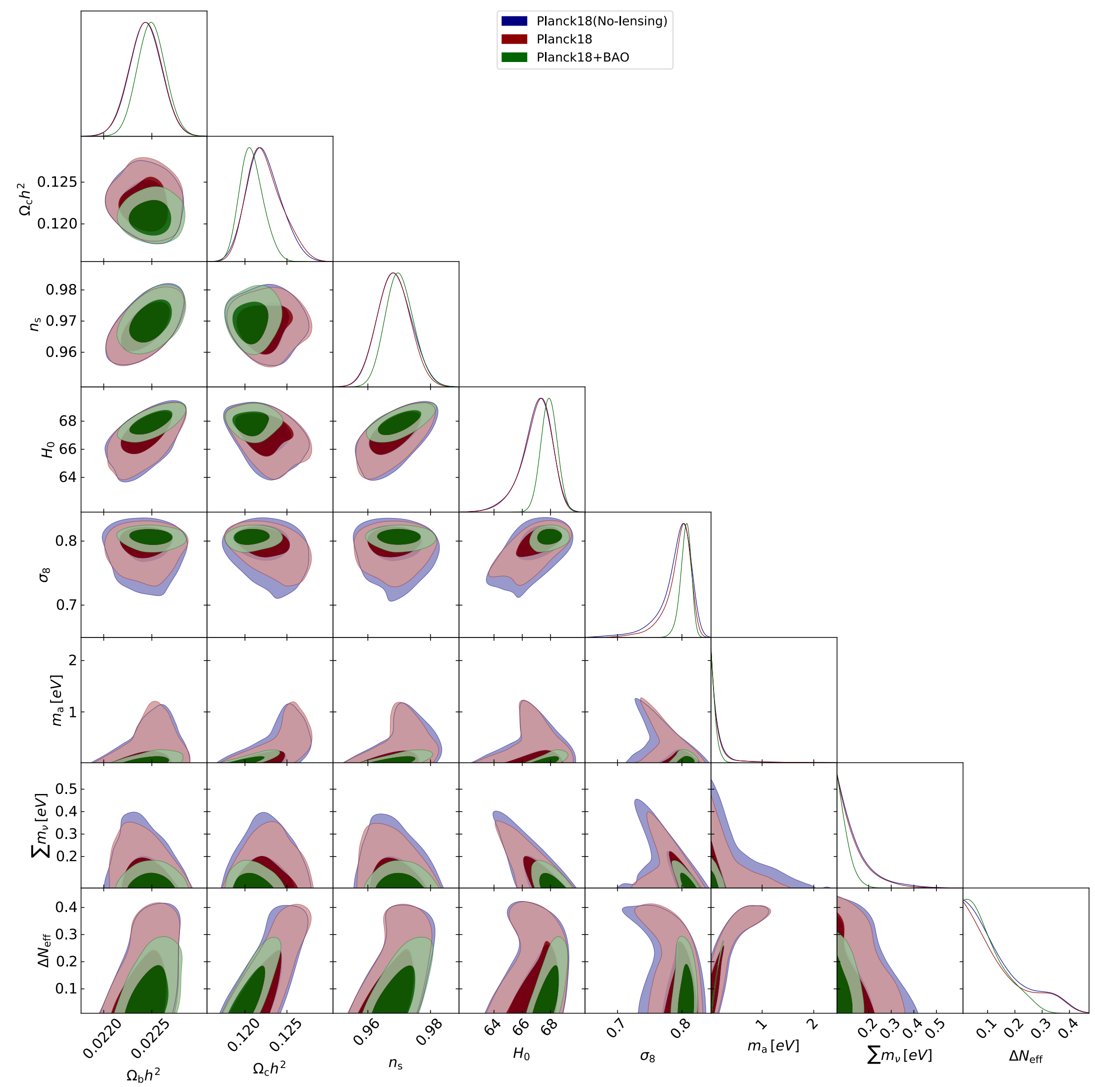
Axion Mass Bound

KSVZ



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

DFSZ



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

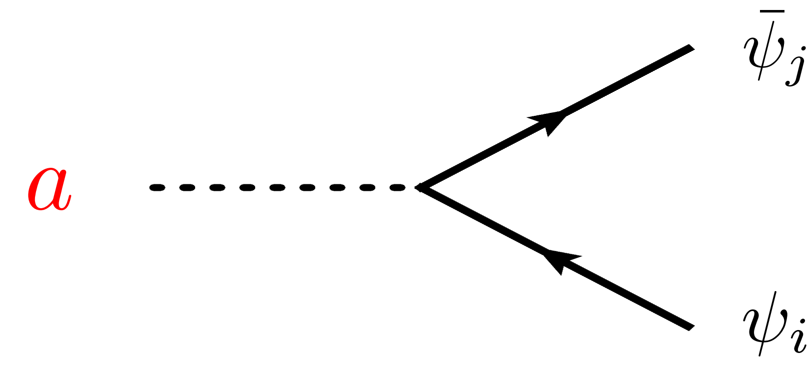
FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, **JCAP 09 (2022)**

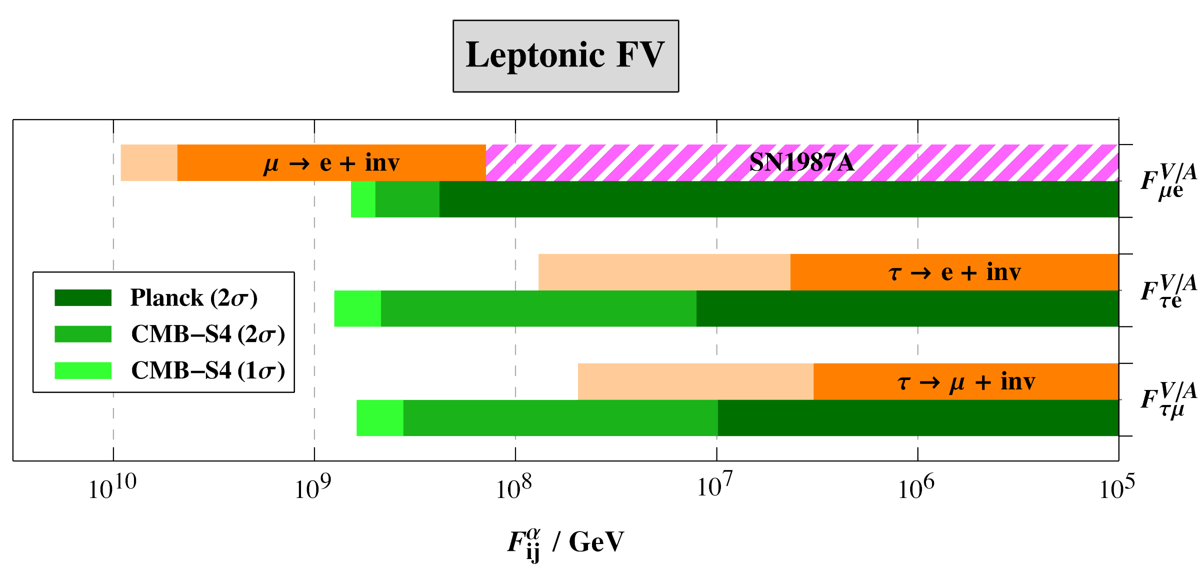
A Minor Variation: FV Axions

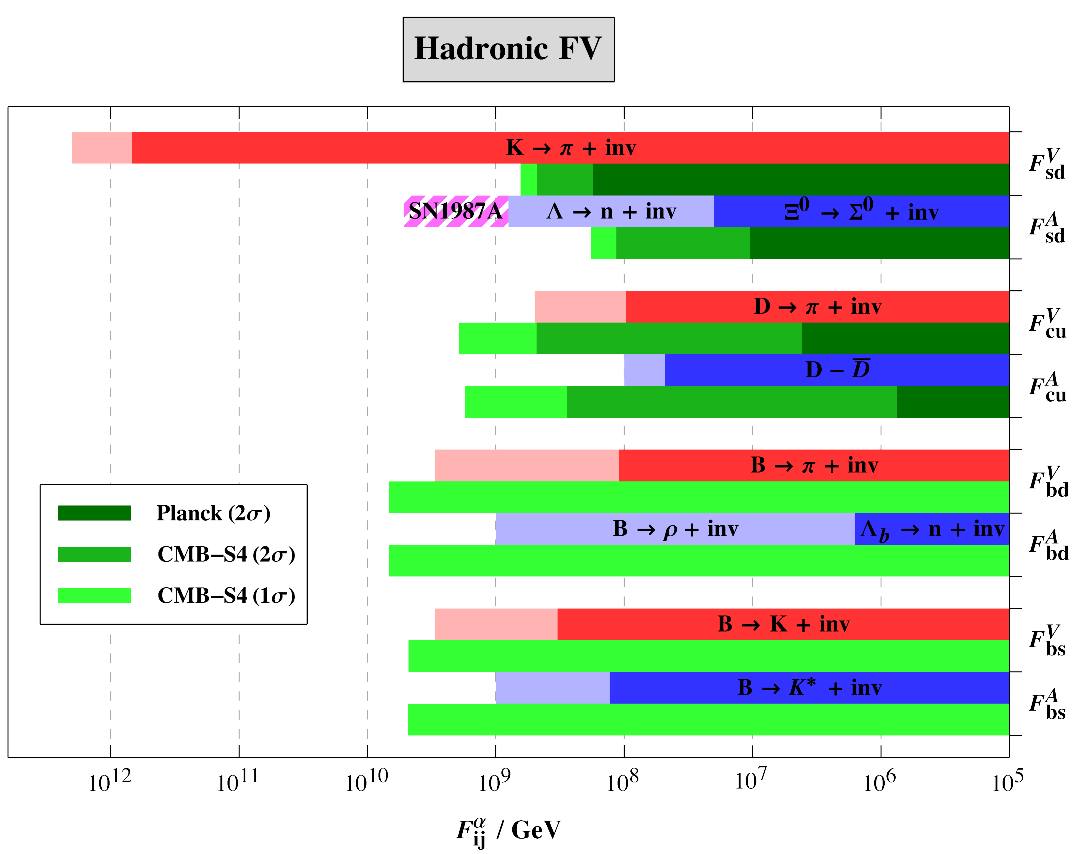
Target of several terrestrial experiments

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)**

Back to the Phase-Space

Model-independent analysis:

generic production of a light X

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

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

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

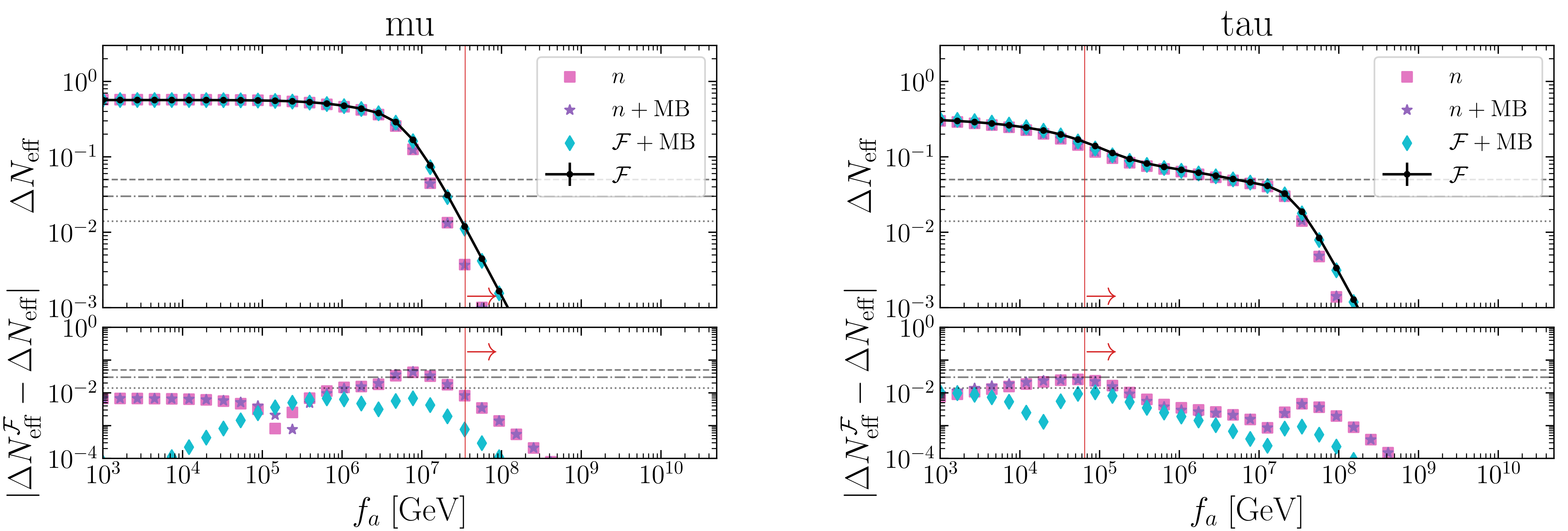
<u>Spectral distortions detectable in the future!</u>

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

Axion-Fermion Interactions

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

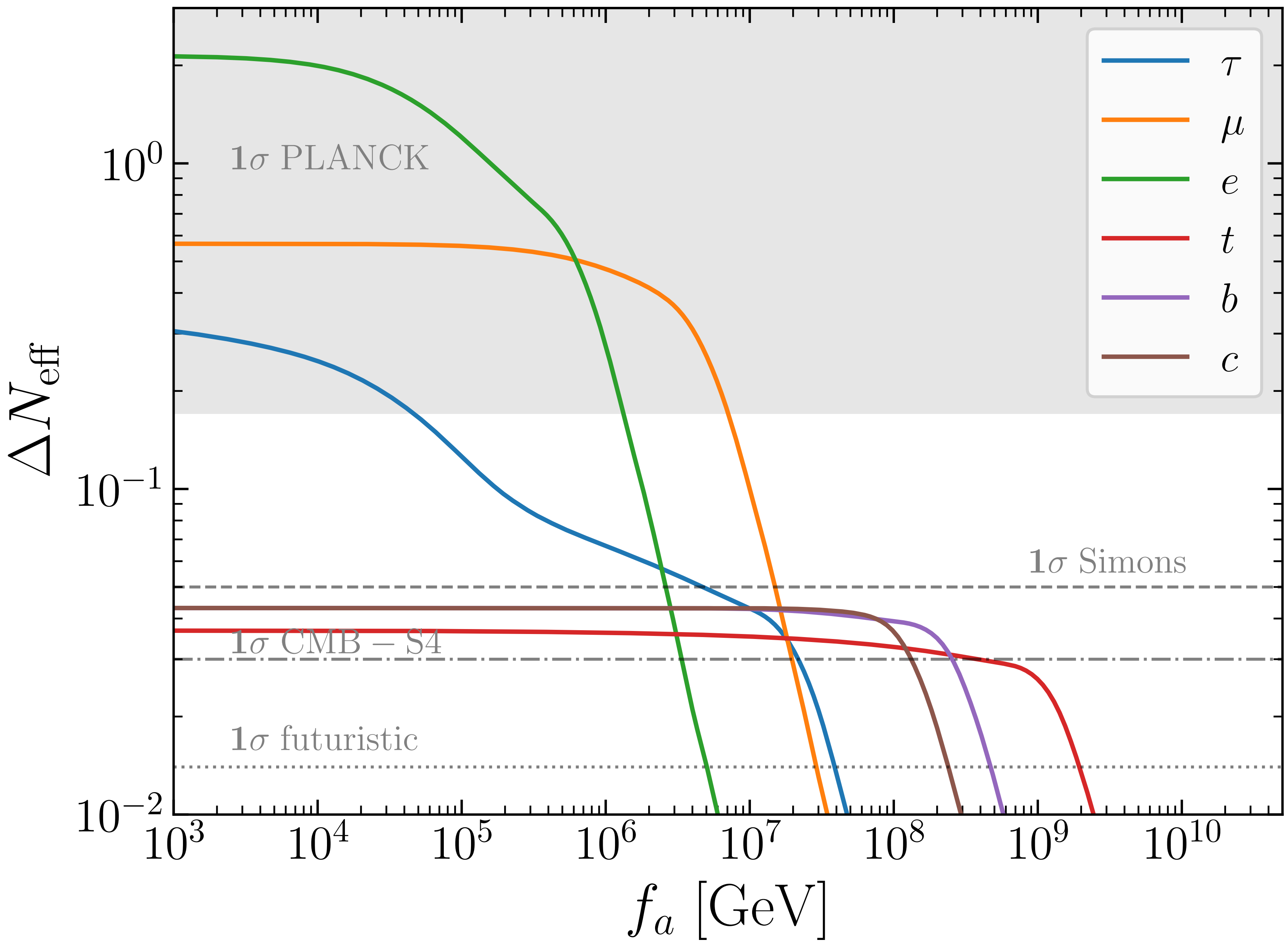
PRELIMINARY

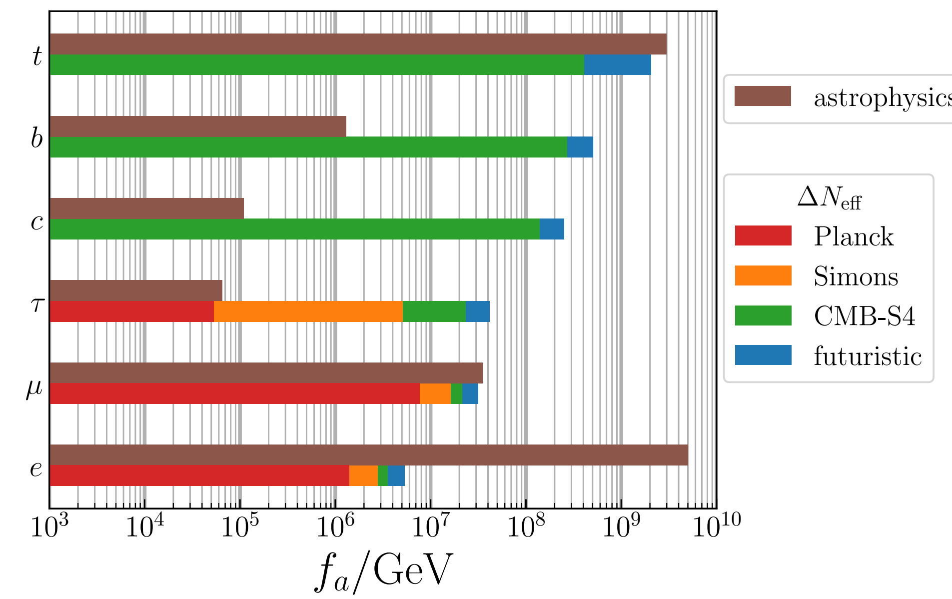


<u>Difference detectable in the future!</u>

FD, Lenoci, **in preparation**

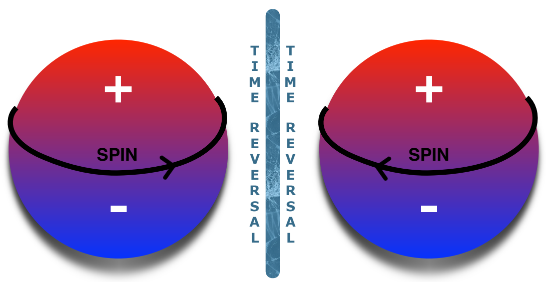
Axion-Fermion Interactions





FD, Lenoci, **in preparation**

Outlook



Peccei-Quinn Mechanism and the QCD Axion

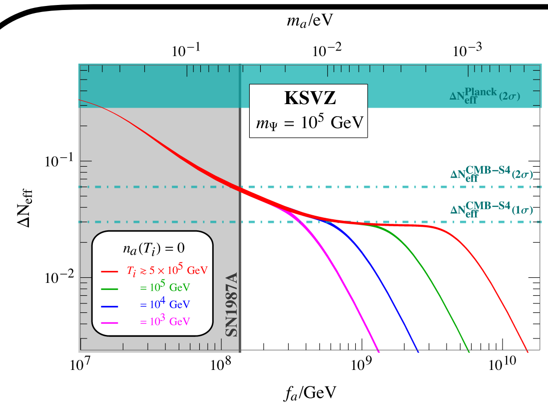
Motivated and testable scenario rich of cosmological consequences

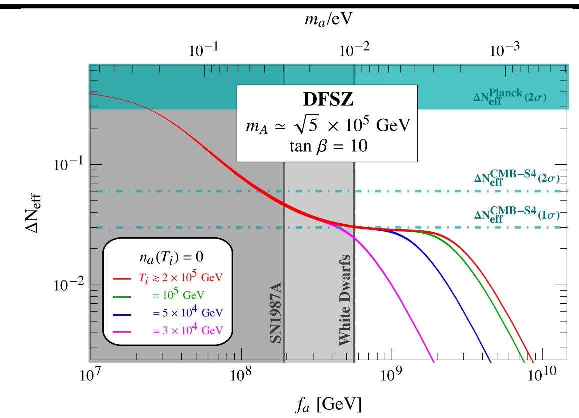
Thermal Axions

Complementary to other probes of the PQ mechanism

Distinct signatures of ALPs coupled to standard model particles

Outlook



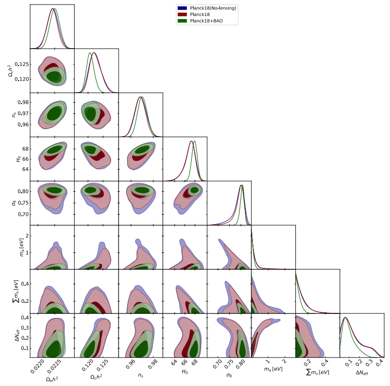


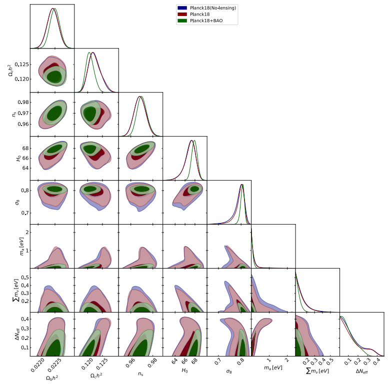
ΔN_{eff} tracking the number density

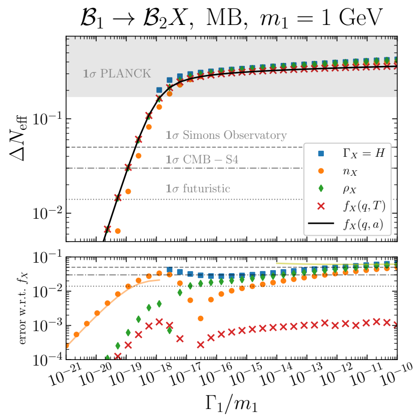
FD, Hajkarim, Yun, **JHEP 10 (2021)**
FD, Hajkarim, Yun, **Phys.Rev.Lett. 128 (2022)**

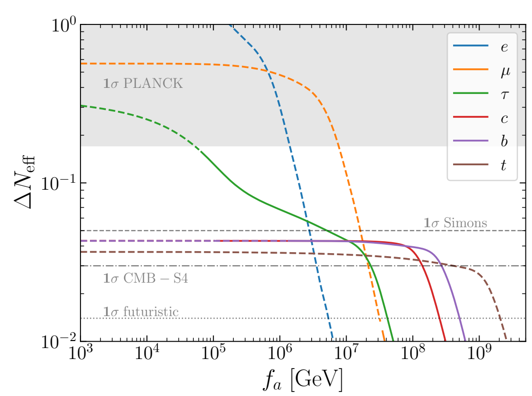
FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, **JCAP 09 (2022)**

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
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Mena, Renzi, Yun, **JCAP 09 (2022)**

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mass bo

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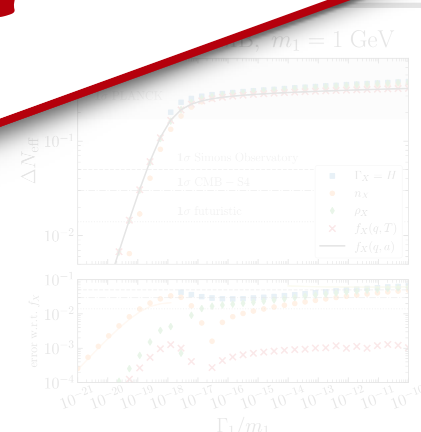

Importance of a
phase space analysis

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