Improved Cosmological Constraints on Axion–Lepton Interactions

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Based on **Physics of the Dark Universe 52 (2026) 102335 [arxiv:2511.14864]**

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Axions: Motivation

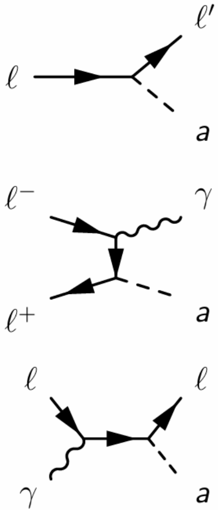
- The **QCD axion** solves the **strong CP problem**. More generally, **axion-like particles (ALPs)** are pseudo-Nambu-Goldstone bosons of broken global $U(1)$ symmetries, generic in string compactifications and in flavour models.
- Production in the early universe: **non-thermal** (misalignment, topological defects) or **thermal** (scatterings and decays) $\Rightarrow$ **here we focus on the thermal population**.
- Mass m_a and decay constant f are treated as **independent** (no QCD axion mass-coupling relation).

What kind of axions do we consider?

Interaction Lagrangian:

$$\boxed{\mathcal{L}_{\text{int}}^{(a)} = \frac{\partial_\mu a}{2f}\,\bar{\ell}_i \gamma^\mu \left(C_{ij}^V + C_{ij}^A \gamma_5\right) \ell_j \,,}$$

We consider both **lepton flavor-conserving (LFC)** and **flavor-violating (LFV)** couplings. From this we expect production via both scatterings and decays.



Our Approach

- These channels **do not** preserve kinetic equilibrium (elastic rates are $1/f^4$ suppressed) $\Rightarrow$ axions are **not** in equilibrium.

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$$\dot{n}_a + 3Hn_a = \int \frac{d^3p}{(2\pi)^3\, E}\, \mathcal{C}[f_a]$$

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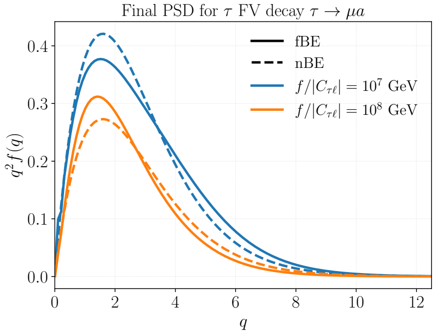
- We solve the **full** Boltzmann equation for $f_a(x, q)$ (**fBE**, see **[2410.18186]**) and include **axion mass effects**:

$$E\left(\partial_t f_a - H\, p\, \partial_p f_a\right) = \mathcal{C}[f_a]$$



Axion phase space from τ decays: fBE vs. nBE.

Cosmological behaviour

Cosmological behaviour

- Light axions ($\lesssim 0.3$ eV) act as **Dark Radiation** at CMB emission and contribute to $\Delta N_{\rm eff}$:

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

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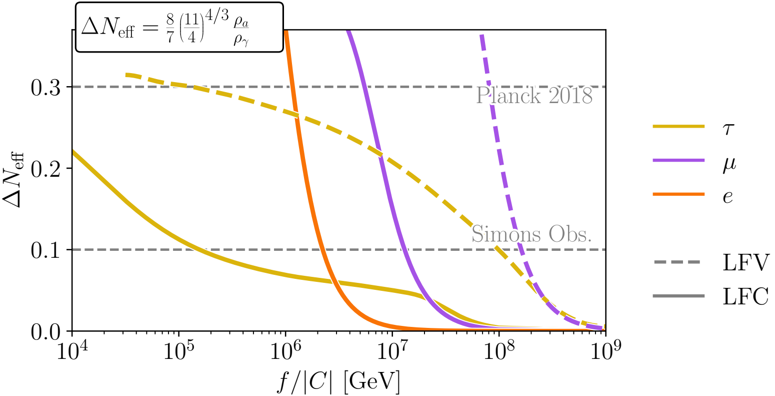
- Intermediate regime: axions behave as **Hot Dark Matter**.

ΔN_{eff} in the massless limit



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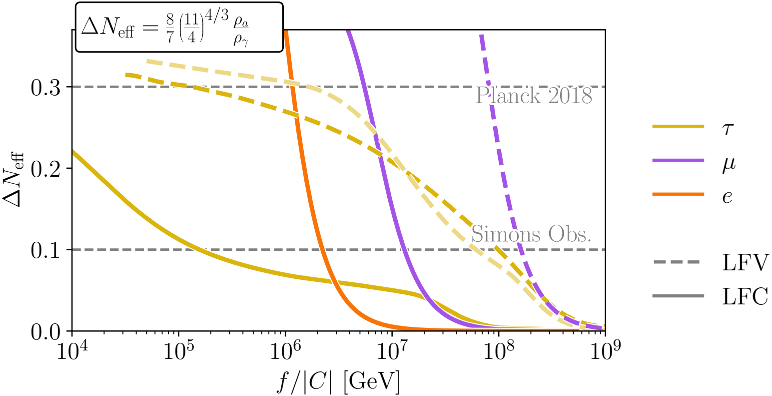
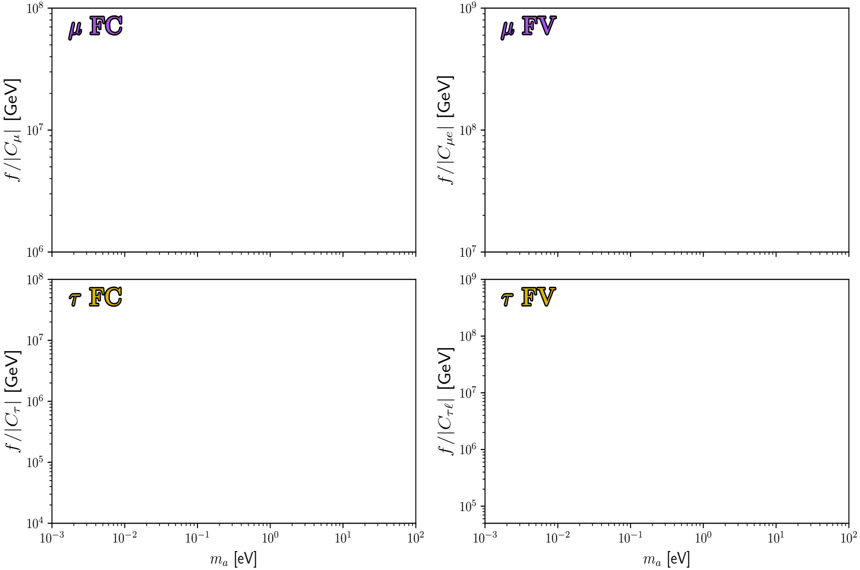


Faded curve: number-density-only treatment (equilibrium + Maxwell-Boltzmann).

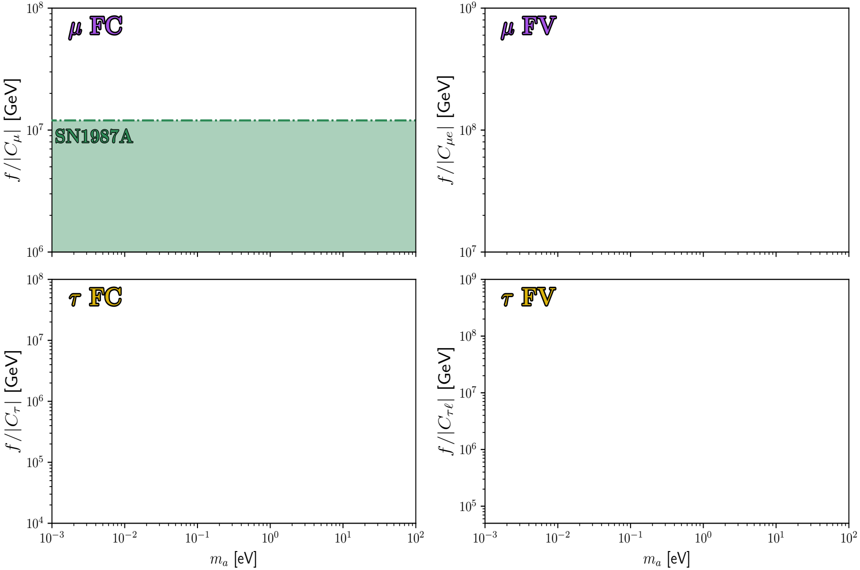
Cosmological Analysis

- We solve the full Boltzmann equations for $f_a(q)$ and import their fits into `CLASS` as new `ncdm` species.
- We use `MontePython` and run MCMC to obtain posteriors.
- Datasets used: **Planck 2018 TT,EE,TE w/ lensing + DESI DR2**.
- We run a grid of m_a values and vary the coupling strength $f/|C|$ (and the six ΛCDM parameters + $\sum m_\nu$) to obtain 95% C.L. limits in the $(m_a, f/|C|)$ plane.

Results: Step by step

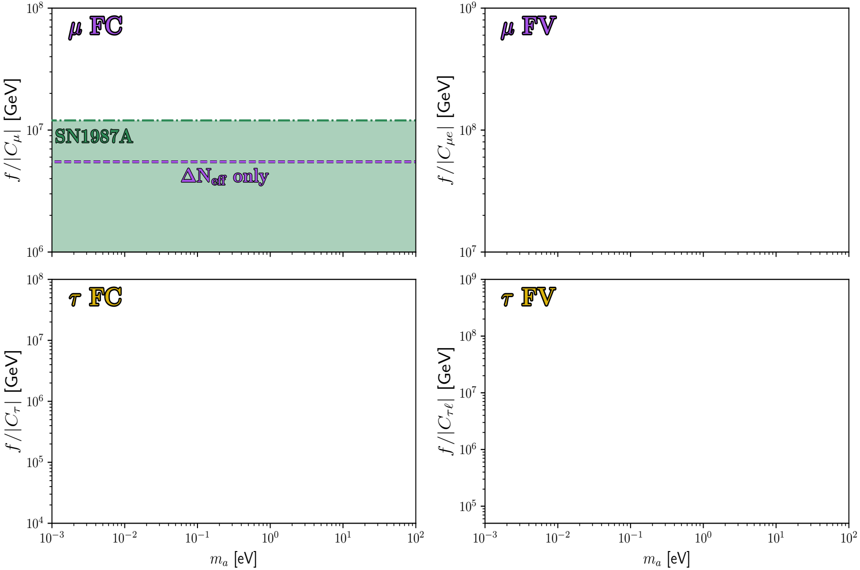


Results: Non-cosmological constraints

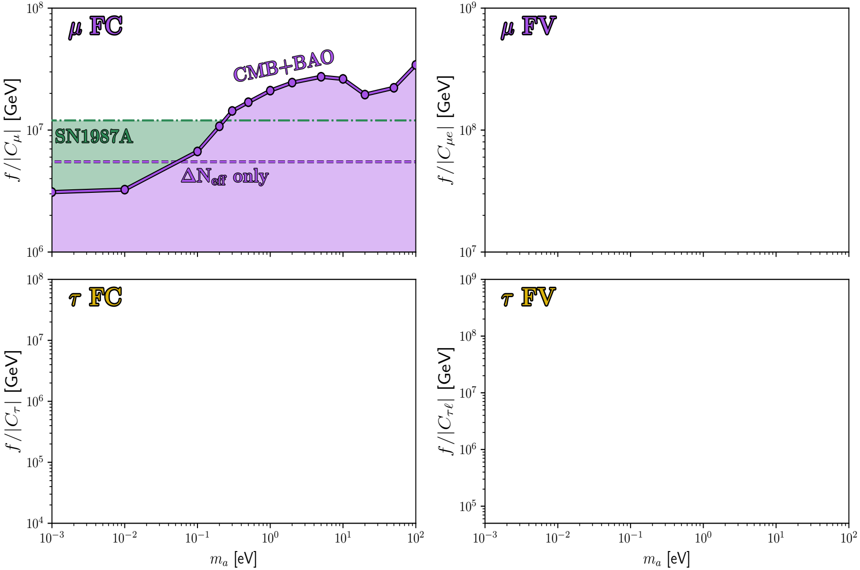


[Caputo et al. 2017; Belle-II collab. 2023; Jodidio et al. 1986; TWIST collab. 2015]

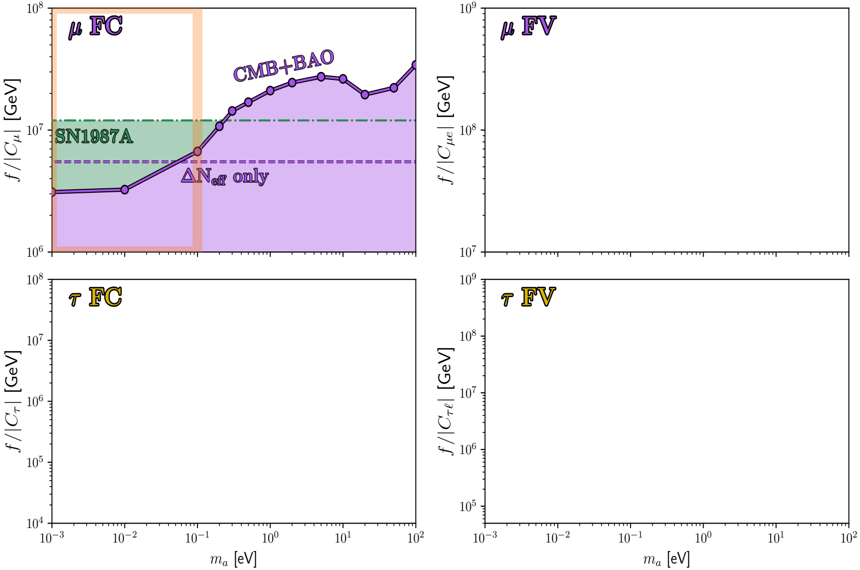
Results: $\Delta N_{\rm eff}$ Only



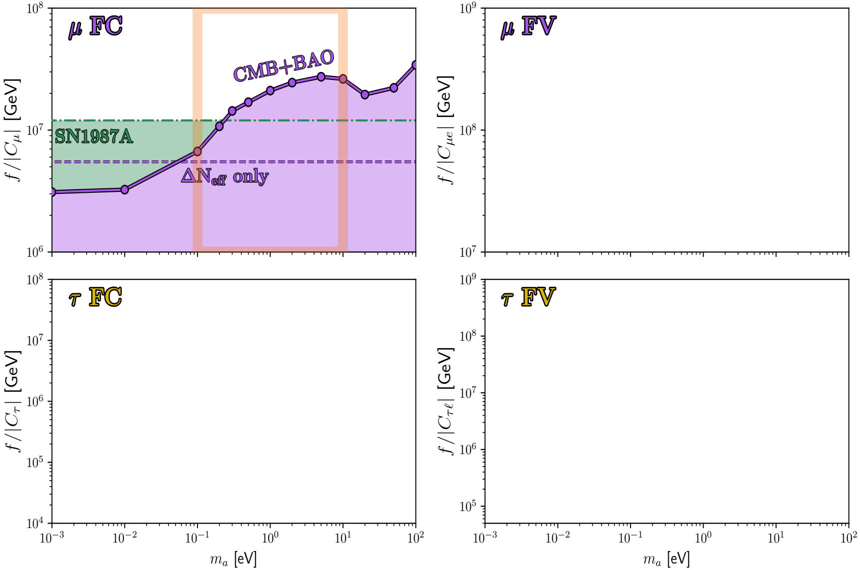
Results: CMB + BAO



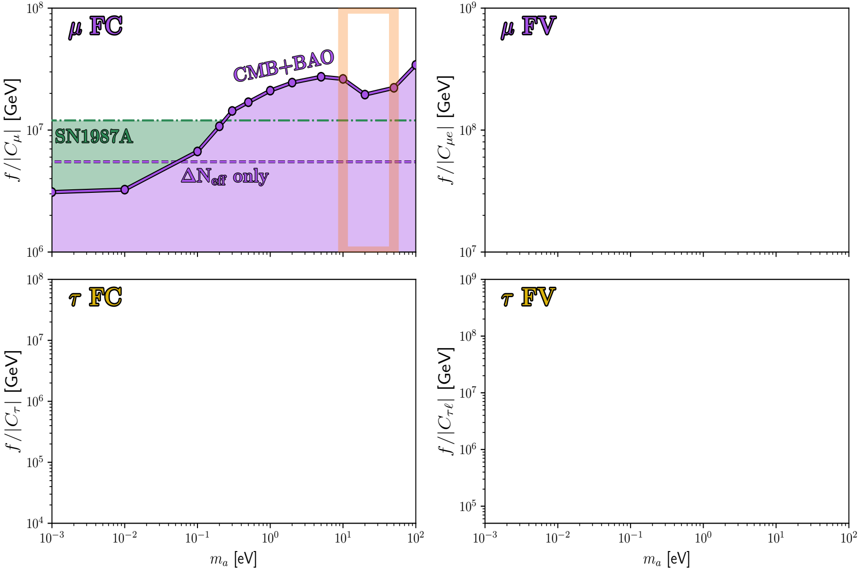
Results: Dark Radiation



Results: Mass Matters



Results: Non-relativistic axions



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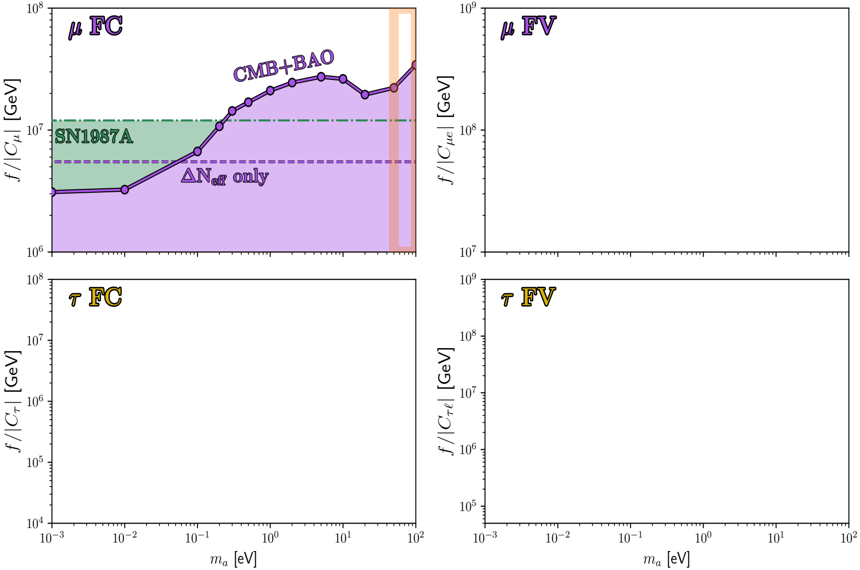
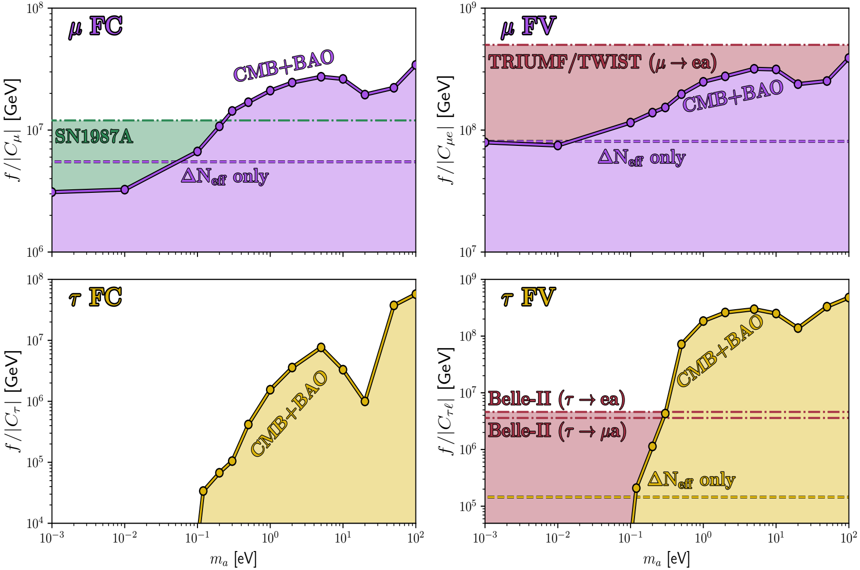


Results: All channels



Summary:

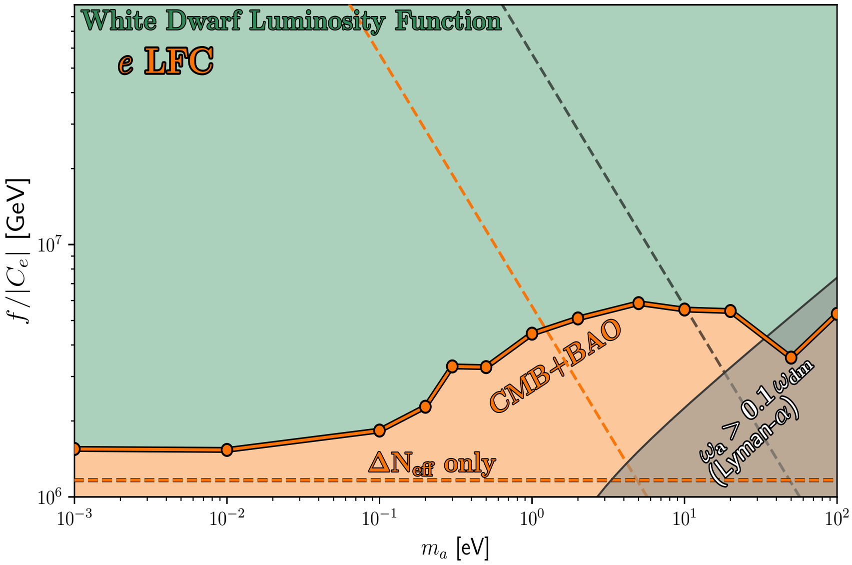
We obtained new cosmological constraints on thermally produced axions by:

- solving the full Boltzmann eq.
- including their mass effects on cosmology
- For μ FC and τ FV the cosmological constraints are stronger than non-cosmological ones for massive axions by up to a few orders of magnitude.
- For τ FC the cosmological constraints are the only relevant ones.
- See [2511.14864] for more details.

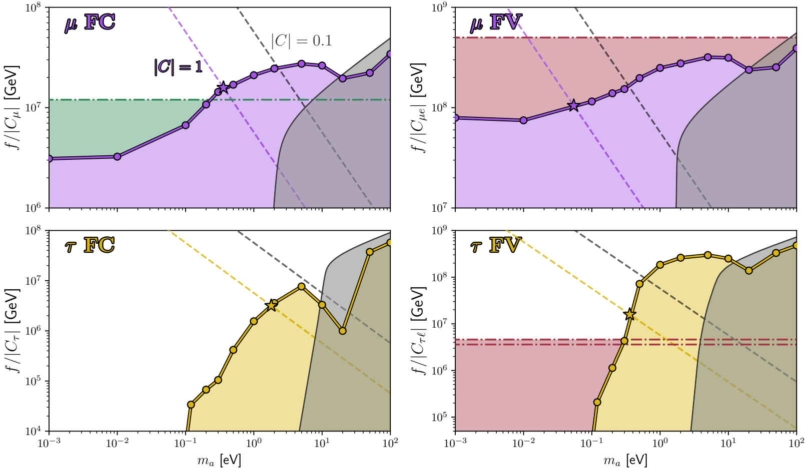
Thank You!

Backups

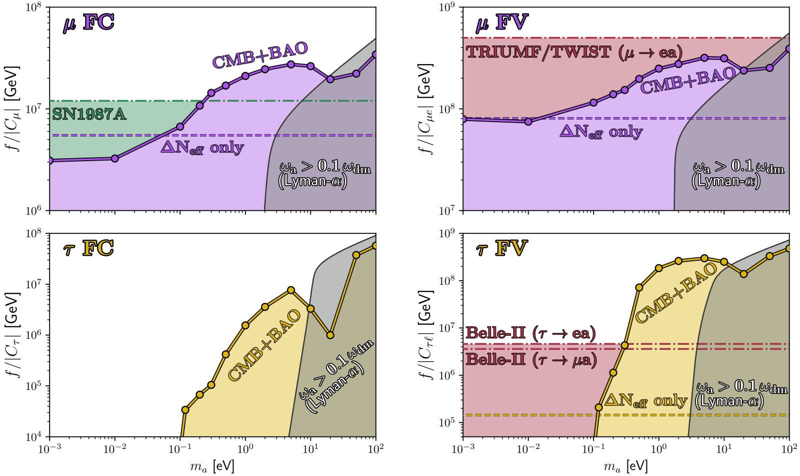
e LFC plot w/ QCD lines



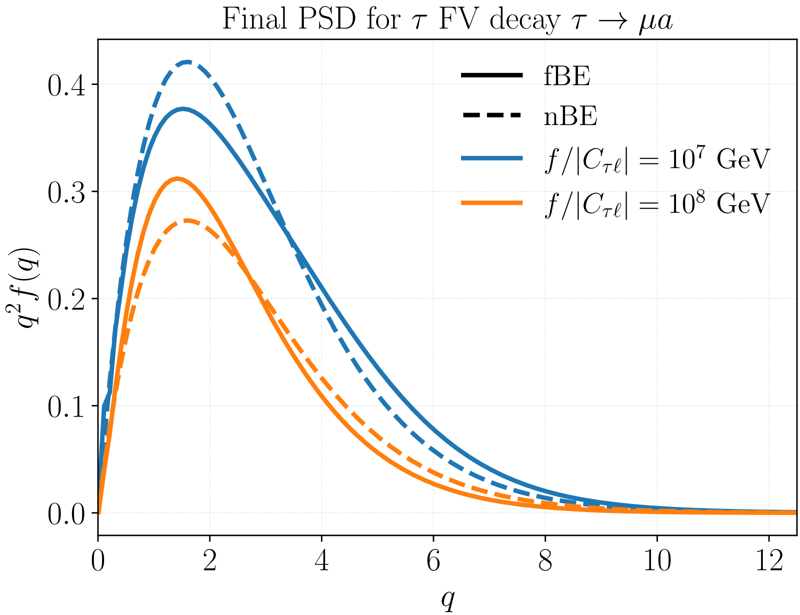
All channels with QCD lines



Lyman-α proxy



PSD example



Final PSD for τ FV decay $\tau \to \mu a$
fBE
nBE
$f/|C_{\tau\ell}| = 10^7$ GeV
$f/|C_{\tau\ell}| = 10^8$ GeV
$q^2 f(q)$
q
0.0
0.1
0.2
0.3
0.4
0
2
4
6
8
10
12