Improved Cosmological Constraints on Axion–Lepton Interactions

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Outline

1. **Introduction**: QCD axion, ALPs and motivation for lepton couplings
2. **Thermal axion production**: physical picture and Boltzmann equation
3. **Cosmological constraints**: why ΔN_{eff} is not enough, and our extended analysis
4. **Implications for the QCD axion**: standard and astrophobic scenarios
5. **Summary and outlook**: key takeaways and future directions

Introduction

The strong CP problem and the QCD axion

- The QCD Lagrangian admits a CP-violating term

$$\mathcal{L} \supset \theta \, \frac{g_s^2}{32\pi^2} \, G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu},$$

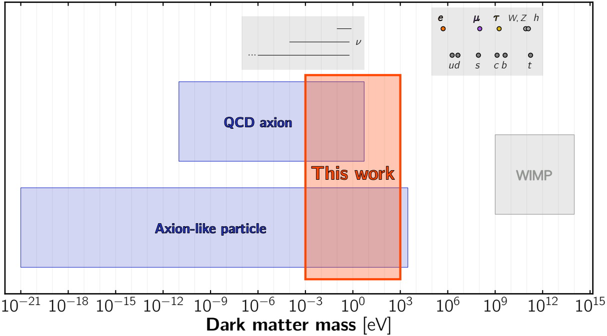
  yet neutron EDM measurements imply $|\theta| \lesssim 10^{-10}$. Why so small?
- **Peccei–Quinn solution:** promote $\theta \to a(x)/f$, a dynamical field of a broken $U(1)_{\mathrm{PQ}}$. Non-perturbative QCD generates the axion potential; $\langle a \rangle$ relaxes to zero.
- Mass linked to decay constant:

$$\boxed{m_a \approx 0.569 \left(\frac{10^7\,\mathrm{GeV}}{f} \right) \mathrm{eV}.}$$

- The axion is also a natural cold DM candidate via *misalignment* (separate from the production studied here).

Beyond the QCD axion: axion-like particles (ALPs)

- Any spontaneously broken approximate global symmetry produces a PNGB. For a generic **axion-like particle (ALP)**, m_a and f are **independent** parameters; mass can span many orders of magnitude.
- **This work:** model-independent cosmological constraints applicable to both QCD axions and ALPs, with focus on the eV mass range.



[Plot adapted from Ciaran O'Hare's GitHub repo cajohare/HowToMakeAPlot/code/DarkMatterLandscape.ipynb]

Axion–lepton interactions

Why lepton couplings?

- Axion-lepton couplings appear generically in well-motivated models:
  - **DFSZ-type**: flavor-conserving.
  - **PQ as flavor symmetry** (Davidson–Wali, Wilczek, “flaxion”, Calibbi et al.): flavor-violating.
  - **Astrophobic QCD axion**: flavor-violating.
- Existing cosmological constraints on these couplings use only $\Delta N_{\rm eff}$ *[Ghosh & Sachdeva 2020]*. Mass-dependent constraints exist only for axion–photon/gluon couplings *[Caloni et al. 2022]*.
- **This work:** model-independent constraints on axion–lepton couplings, including axion mass effects and the actual non-thermal distribution.

The effective Lagrangian

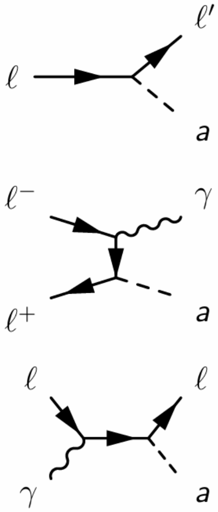
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 + \mathcal{L}_{\rm int}^{(a)}$$

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

$C_{ij}^{V,A}$ are vector/axial coupling matrices in flavor space.

- $i = j$: **LFC** (scatterings)
- $i \neq j$: **LFV** (decays)

We define $C_i \equiv C_{ii}^A$ and $C_{ij} \equiv \sqrt{|C_{ij}^A|^2 + |C_{ij}^V|^2}$.



Thermal production

Physical picture: thermal axion production

In the early universe plasma ($T \gtrsim m_\ell$), SM particles produce axions via the interactions just discussed.

Two production regimes:

- **Freeze-out** (large coupling): axions thermalize, then decouple once interaction rate drops below H.
- **Freeze-in** (small coupling): never reach equilibrium;

Three cosmological regimes:

- $m_a \lesssim 0.3$ eV: **Dark Radiation**

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

- Intermediate: **Warm DM**.
- $m_a \gtrsim \mathcal{O}(50)$ eV: **Cold DM**.

Why kinetic equilibrium fails

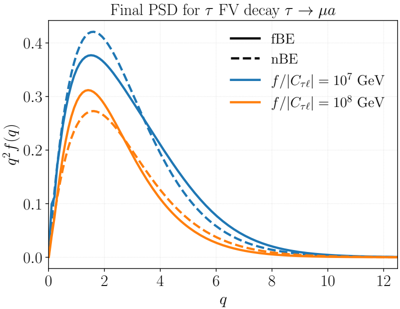
- The processes producing axions ($\ell\gamma \to \ell a$, $\ell^+\ell^- \to \gamma a$, $\ell_i \to \ell_j a$) change axion *number*; no efficient **elastic** channel exists to redistribute axion momenta.
- $\Rightarrow f_a(q)$ is generically **not** Bose–Einstein, especially in the freeze-in regime.
- **nBE** (number-density Boltzmann eq.): assume kinetic equilibrium → axions have B-E distribution, solve only for $n_a(T)$.
- **fBE** (full phase-space): solve for $f_a(x, q)$ directly. *[Badziak & Laletin, 2410.18186]*

The full Boltzmann equation

$$\tilde{H}(x)\left(x\partial_x - \tilde{g}\,q\partial_q\right) f_a(x,q) = \mathcal{C}[f_a]$$

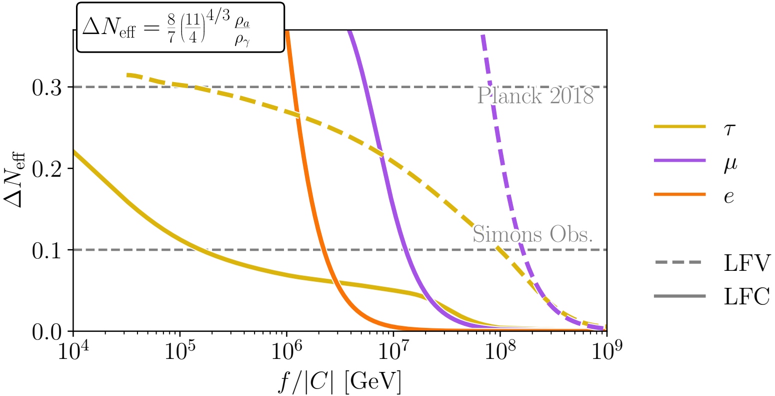
with $x = m/T$, $q = p/T$,
$\tilde{g} = -\frac{1}{3}\frac{d\ln h_s}{d\ln x}$, $\tilde{H} = H/(1+\tilde{g})$.

- $\mathcal{C}[f_a]$ encodes *all* processes (scatterings for LFC, decays for LFV).
- Numerical solution: $f_a(q)$ as a function of $f/|C|$ for one coupling at a time.
- See [2410.18186] for details!

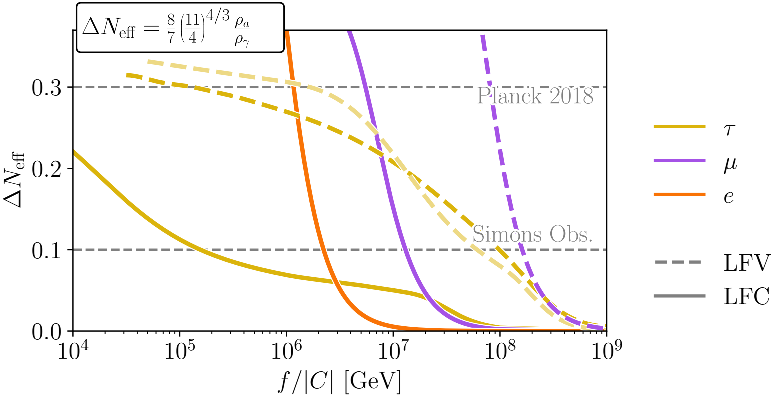


ΔN_{eff} and its limitations

ΔN_{eff} as a function of $f\,/\,|C|$



ΔN_{eff} as a function of $f\,/\,|C|$



When does ΔN_{eff} break down?

- The Planck bound $\Delta N_{\mathrm{eff}} \lesssim 0.3$ assumes axions are **ultra-relativistic at recombination**.
- Above $m_a \sim 0.1$ eV, axions are no longer ultra-relativistic at $T_{\mathrm{rec}} \approx 0.3$ eV. Their energy density gets an extra mass contribution:

$$\rho_a = \frac{g_a T^4}{2\pi^2} \int dq \sqrt{q^2 + \boxed{(m_a/T)^2}}\, q^2 f_a(q)$$

- $\Rightarrow$ A naive ΔN_{eff} bound **underestimates** the coupling constraint.
- For $m_a \gtrsim 10$ eV, axions also contribute to the matter budget and modify the CMB through structure formation.
- **Full cosmological analysis required, with m_a as a parameter.**

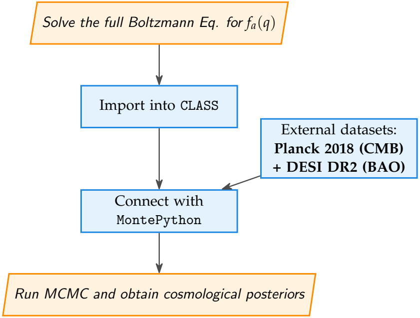
Cosmological analysis

Extended cosmological model

We work within ΛCDM extended by axions and massive neutrinos:

$$\boxed{\Lambda\text{CDM} + m_a + f/|C| + \sum m_\nu}$$

- Six baseline ΛCDM parameters: ω_b, $\omega_{\rm cdm}$, A_s, n_s, $\tau_{\rm reio}$, θ_s.
- Three massive neutrinos with $\sum m_\nu \geq 0.06$ eV.
- Axion parameters: m_a and $f/|C|$.
- Axions: non-cold DM species with custom $f_a(q)$.



Solve the full Boltzmann Eq. for $f_a(q)$

Import into `CLASS`

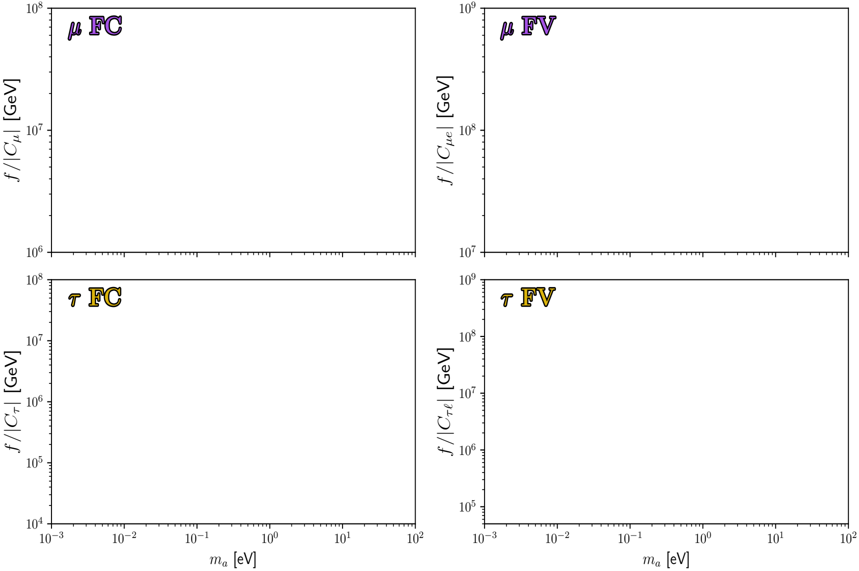
External datasets: **Planck 2018 (CMB) + DESI DR2 (BAO)**

Connect with `MontePython`

Run MCMC and obtain cosmological posteriors

Results

Building up the constraints



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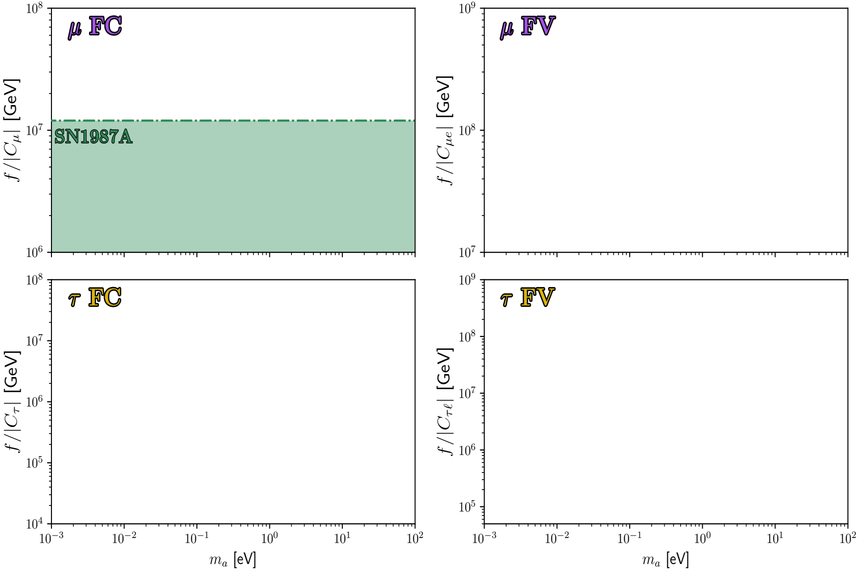

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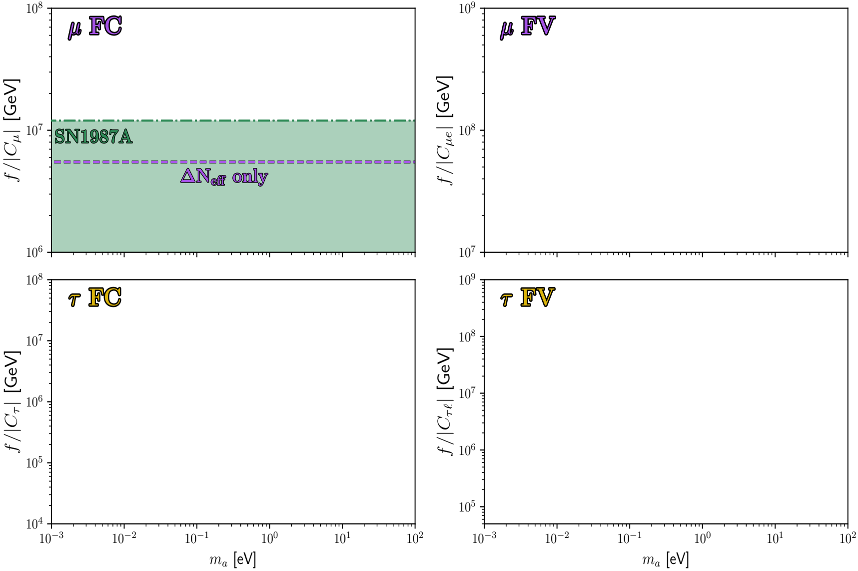

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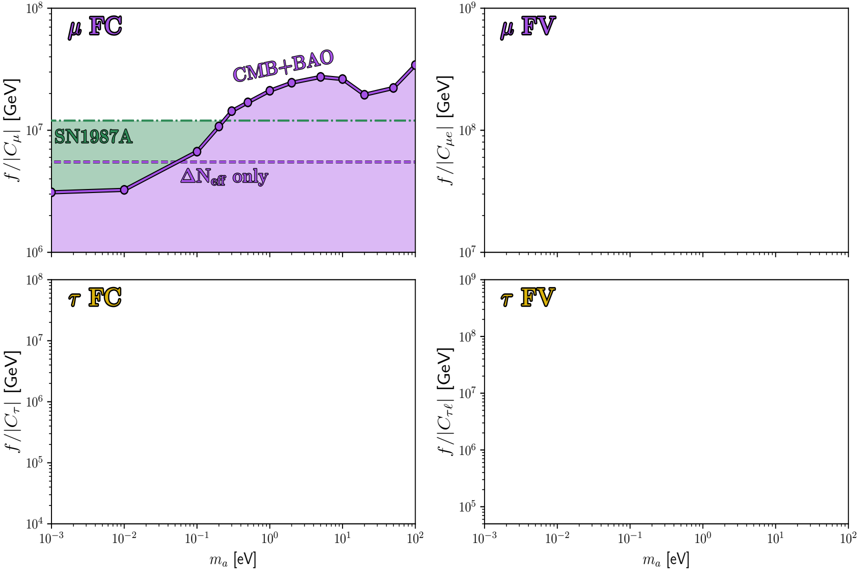

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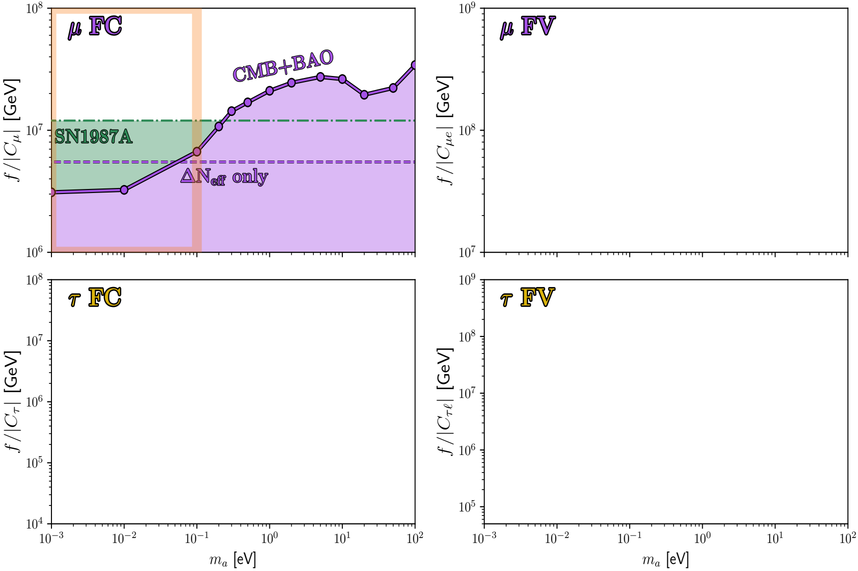

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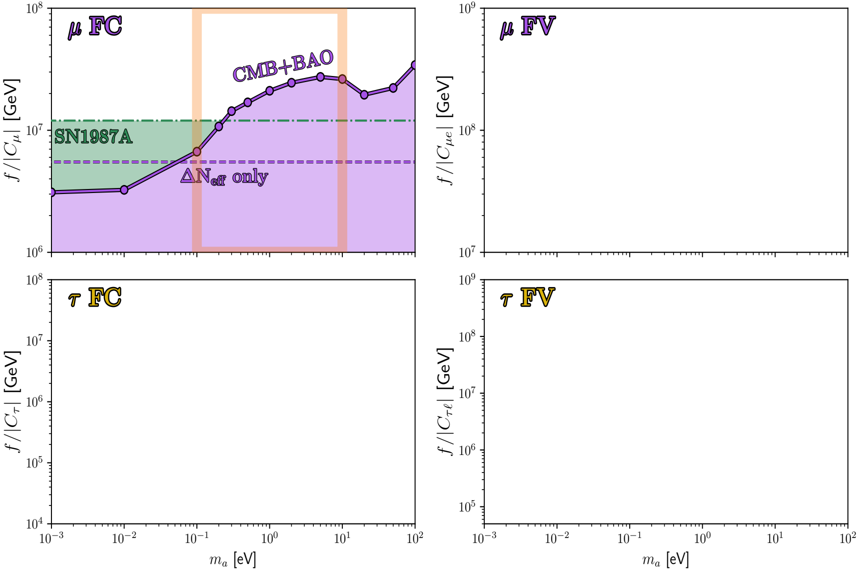

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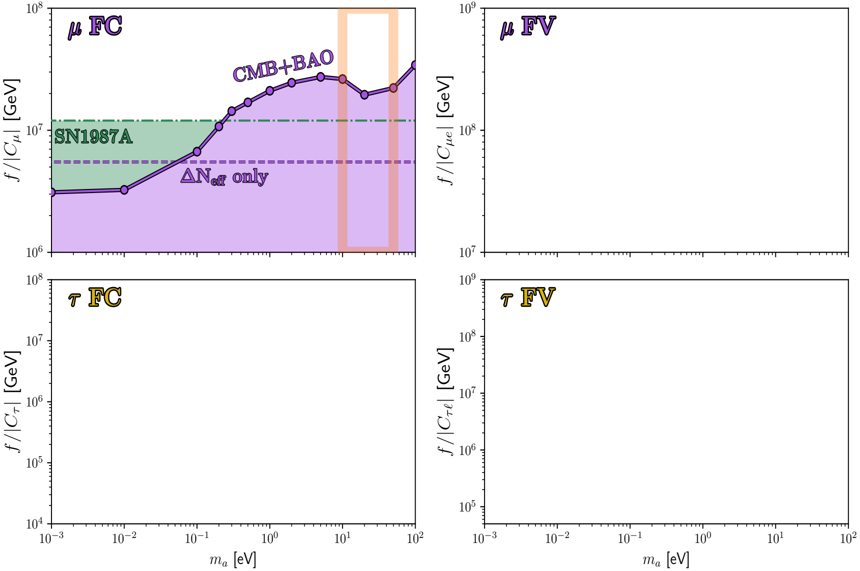

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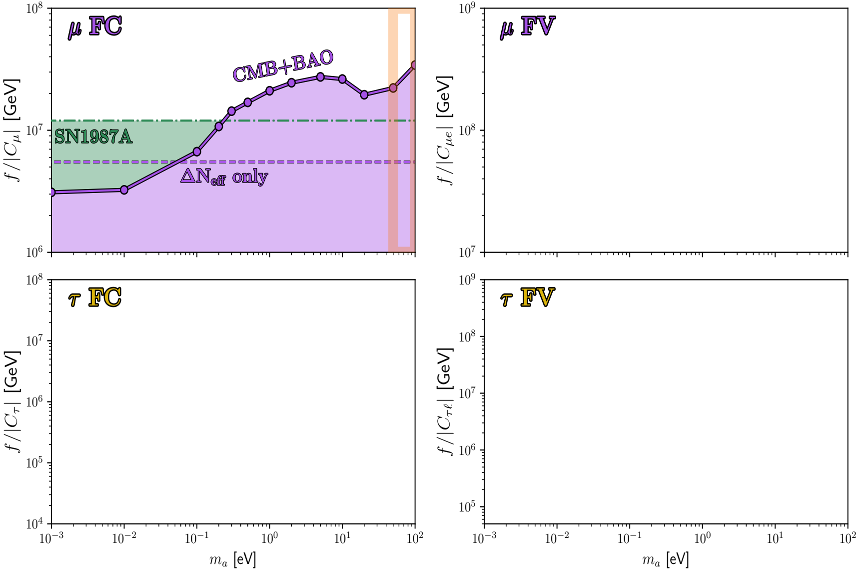

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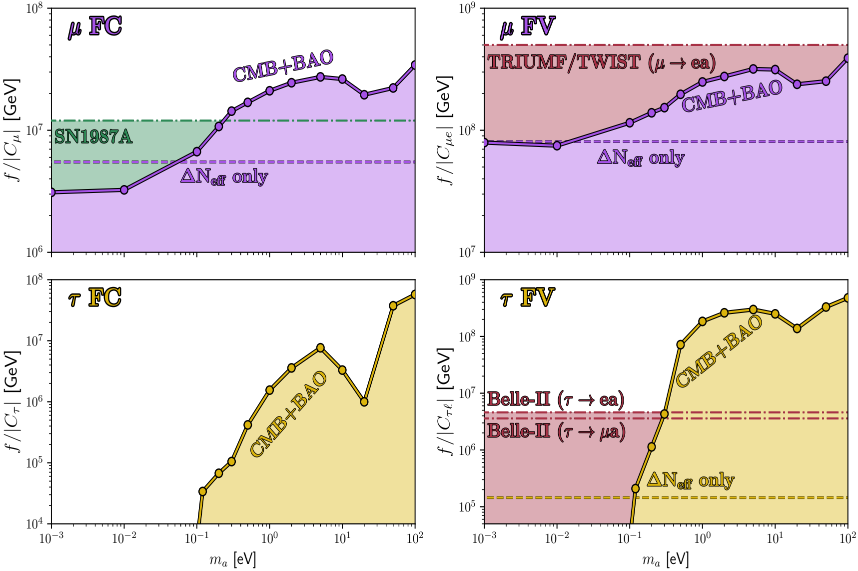


Warm DM regime

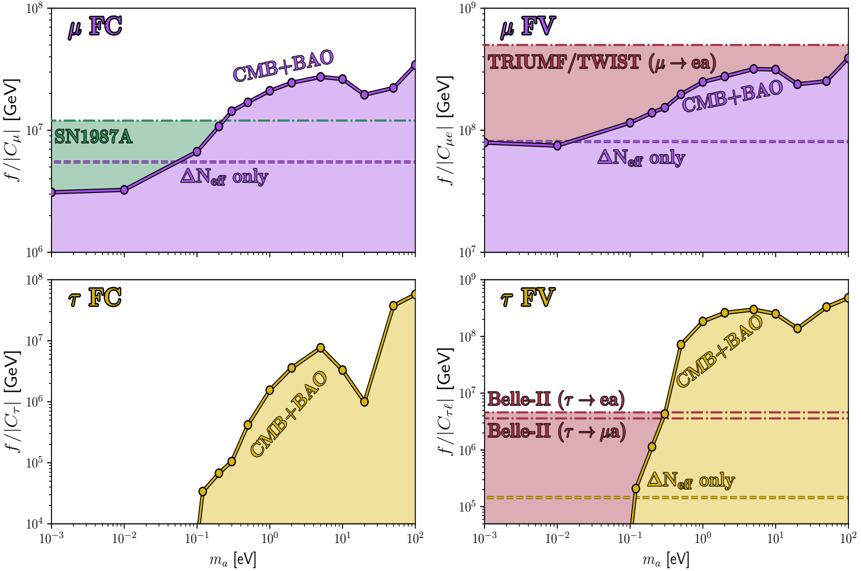
Beyond CMB+BAO: Ly-α forest

- Axions with $m_a \lesssim \mathcal{O}(10)$ keV affect **late-time** structure formation $\Rightarrow$ probed by Ly-α forest.
- From hydrodynamical simulations *[Baur et al. 2017, Garcia-Gallego et al. 2025]*:

  $$f_{\mathrm{wdm}} \equiv \omega_a / \omega_{\mathrm{dm}} \lesssim 0.1$$

  for m_a in the keV range.
- **Caveat:** we extrapolate from $\sim$keV results down to eV range. Conservative, but not based on dedicated simulations at these masses.

CMB+BAO+Ly-α forest



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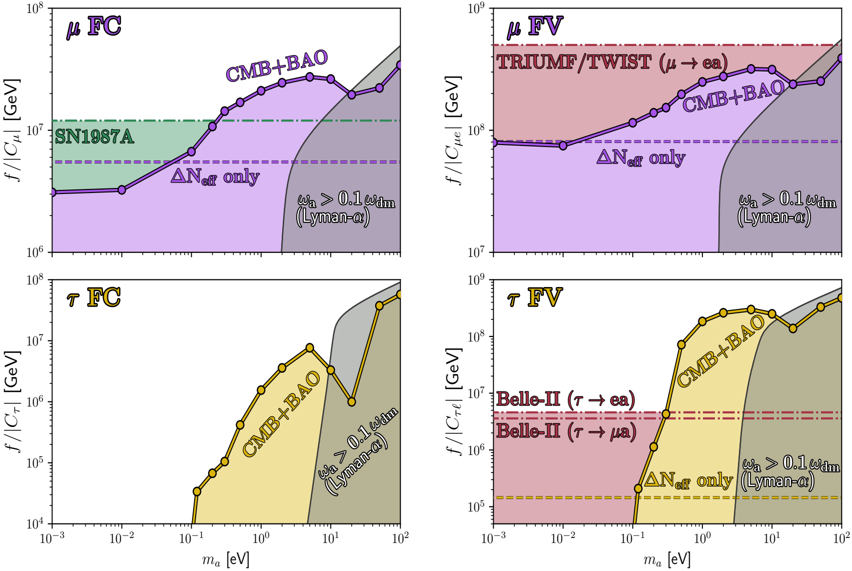


QCD axion implications

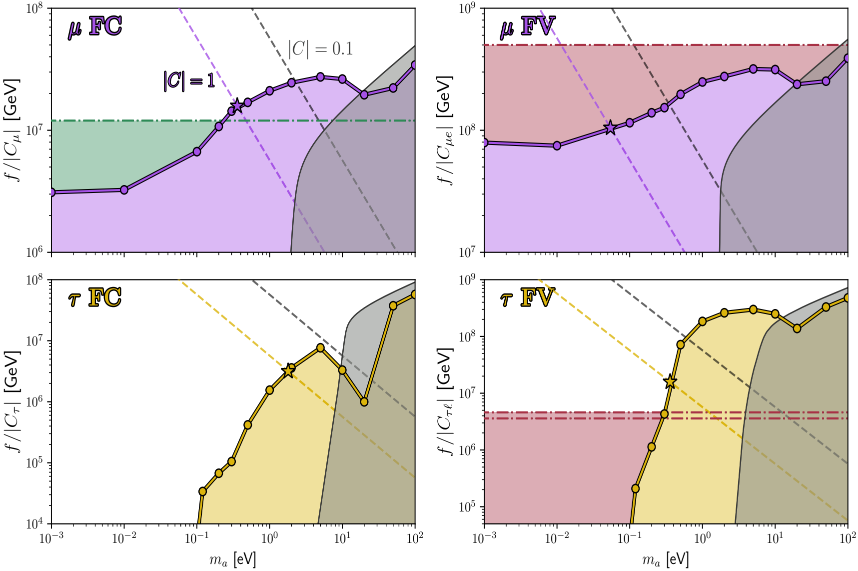
QCD axion: standard vs astrophobic

- QCD axion mass-decay-constant relation:

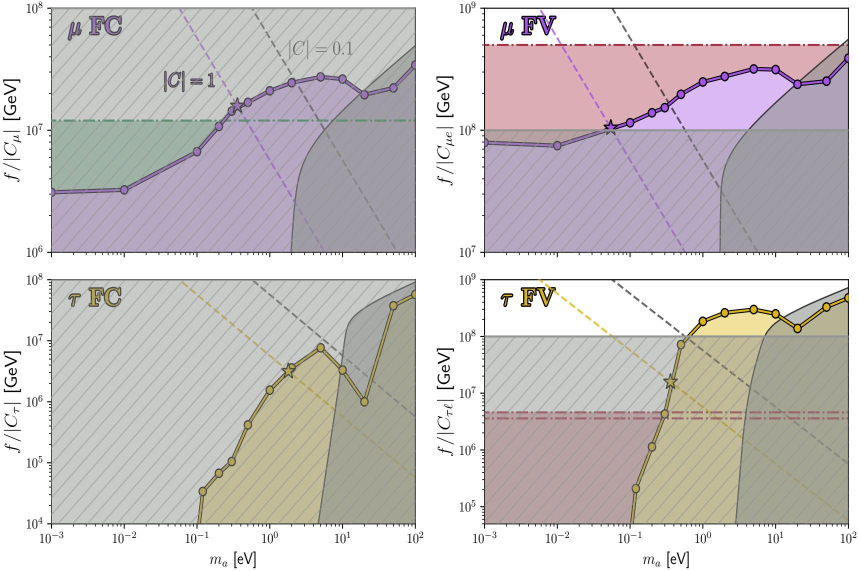
$$m_a \approx 0.569 \left(\frac{10^7\,\mathrm{GeV}}{f} \right) \mathrm{eV}$$

  fixes a diagonal line in $(m_a, f/|C|)$ for each $|C_\ell|$.
- **Standard QCD axion**: astrophysical bounds (SN1987A, stellar cooling) push $f \gtrsim$ few $\times 10^8$ GeV $\Rightarrow m_a \lesssim \mathcal{O}(10^{-2})$ eV.
- **Astrophobic QCD axion** *[Di Luzio et al. 2017; Badziak & Harigaya 2023; Badziak et al. 2024]*: suppress couplings to nucleons. Opens up $f \sim 10^6$ GeV, $m_a \sim \mathcal{O}(1)$ eV.

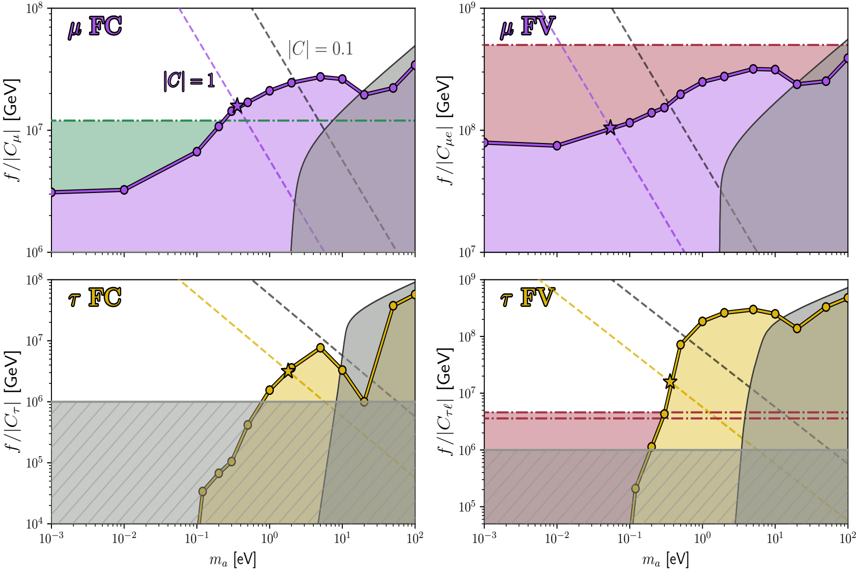
How to get constraints for the QCD axion



Standard QCD axion – excluded by astrophysics



Astrophobic QCD axion – cosmology leads



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- For $m_a \gtrsim 0.1$ eV, our bounds are the **strongest available** on:
  - LFC couplings to μ and τ
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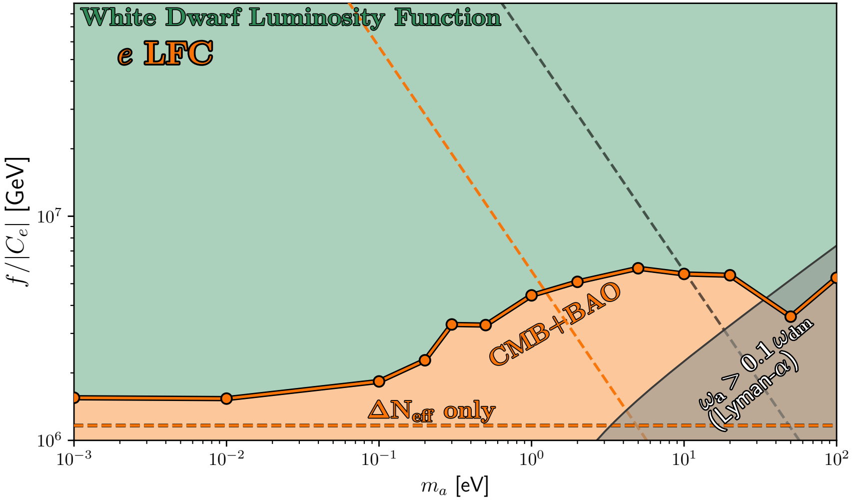
- **For astrophobic QCD axion models, cosmology now provides the leading constraint in the eV mass range.**
- **Outlook:** weak-lensing data + dedicated Ly-α simulations could tighten bounds by a factor of a few in the $m_a \gtrsim 1$ eV regime.

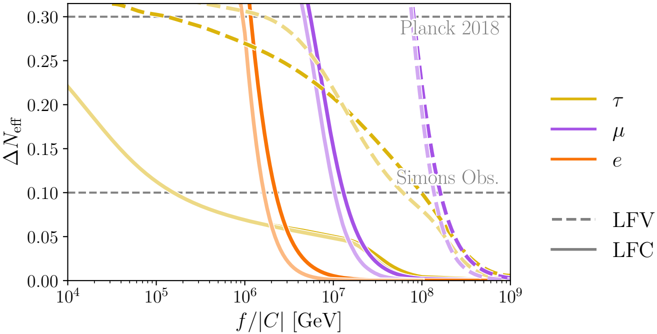
Thank You!

Backups

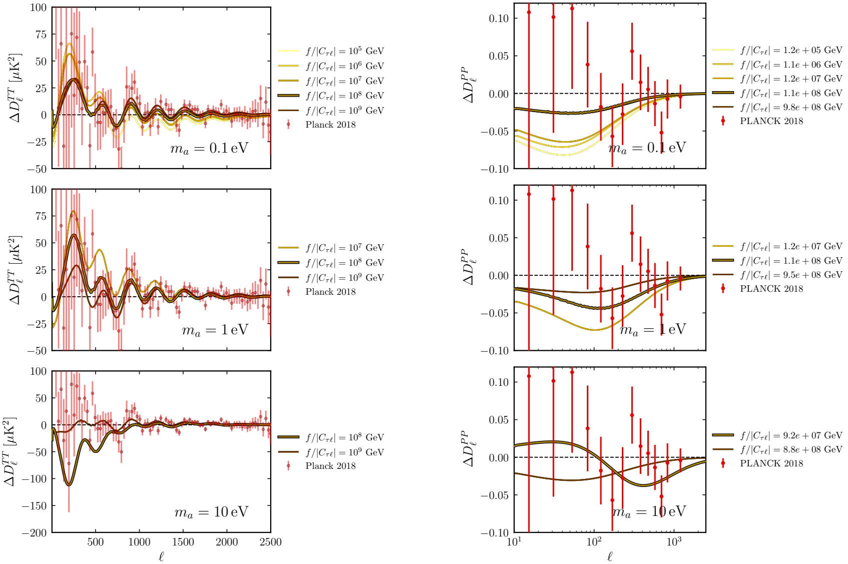
Backup: e LFC plot



Backup: ΔN_{eff}: fBE vs nBE



Backup: CMB power spectra



Backup: prior dependence