Karlsruhe Institute of Technology

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

Cosmological and astrophysical constraints on decaying axion-like particles

Felix Kahlhoefer

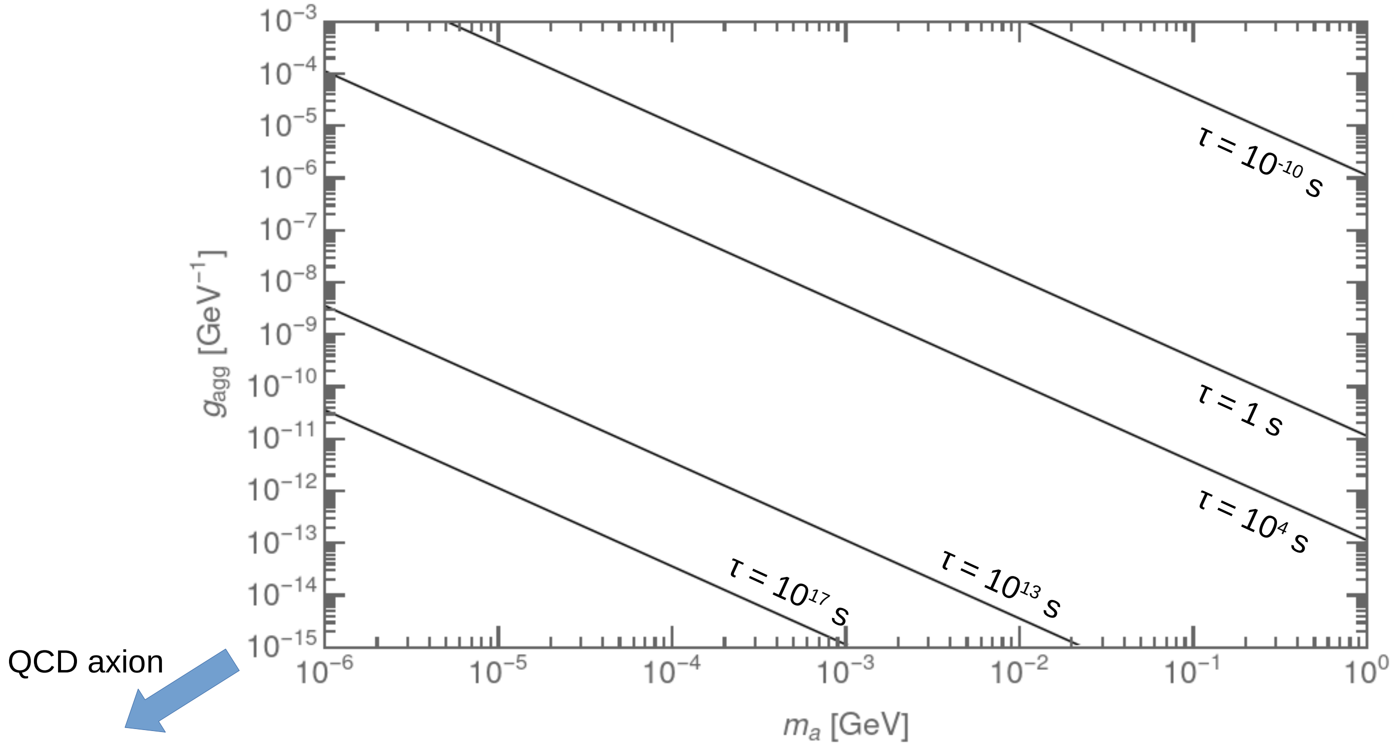
PASCOS, Max Planck Institute for Nuclear Physics, Heidelberg, 28 July 2022

Based on **arXiv:2205.13549**
with Csaba Balázs, Tomás E. Gonzalo, Will Handley, Sebastian Hoof, David J.E. Marsh, Pat Scott and Patrick Stöcker

Goldstone bosons

- Strong motivation for new light states: **Goldstone's theorem**
  - Spontaneous breaking of an (approximate) global symmetry → Goldstone bosons
  - Underlying symmetry protects mass, so they are naturally light (or even massless)
  - Interactions with SM particles are suppressed by the scale of symmetry breaking
  - Common explanation for small mass and small couplings!
- These so-called **axion-like particles (ALPs)** occur in many SM extensions
  - Solutions to the strong CP problem — Weinberg (1978), Wilzcek (1978)
  - String compactifications — Arvanitaki et al., arXiv:0905.4720, Cicoli et al., arXiv:1206.0819
  - Supersymmetry breaking — Bellazzini et al., arXiv:1702.02152
  - Relaxion mechanism — Graham et al., arXiv:1504.07551, Flacke et al., arXiv:1610.02025

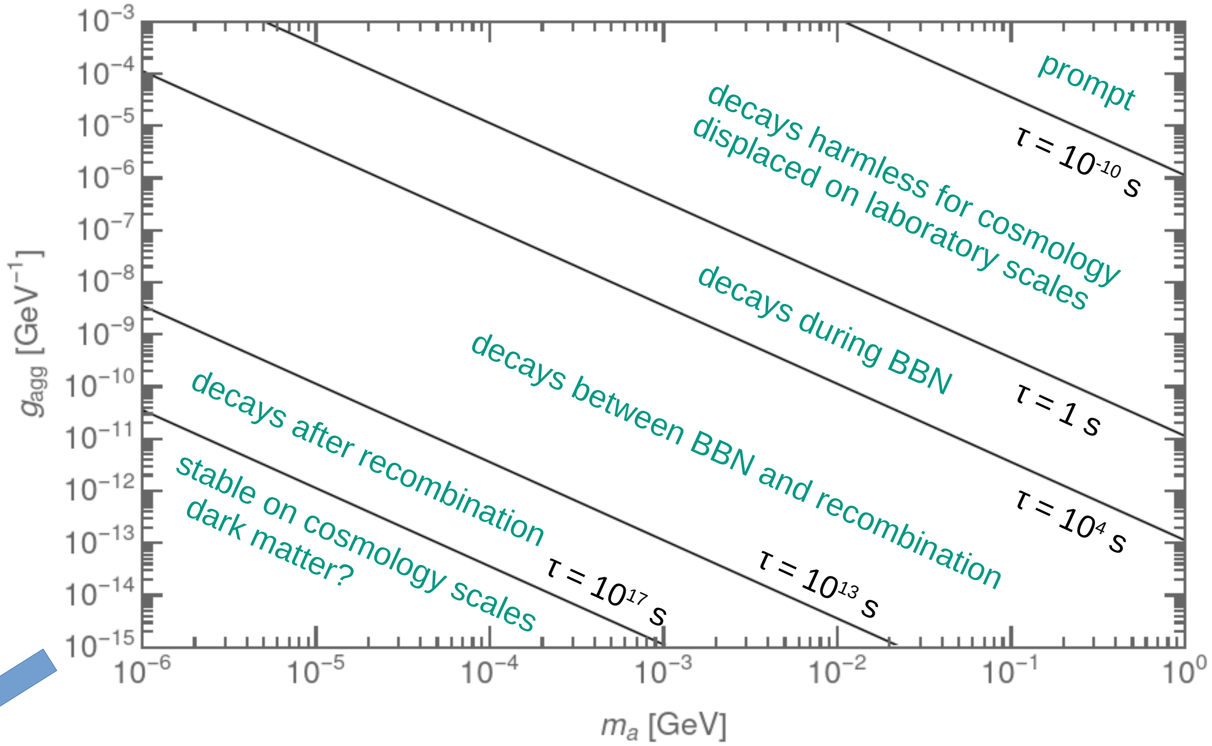
Parameter space for ALP-photon couplings



$$\Gamma_a = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Parameter space for ALP-photon couplings

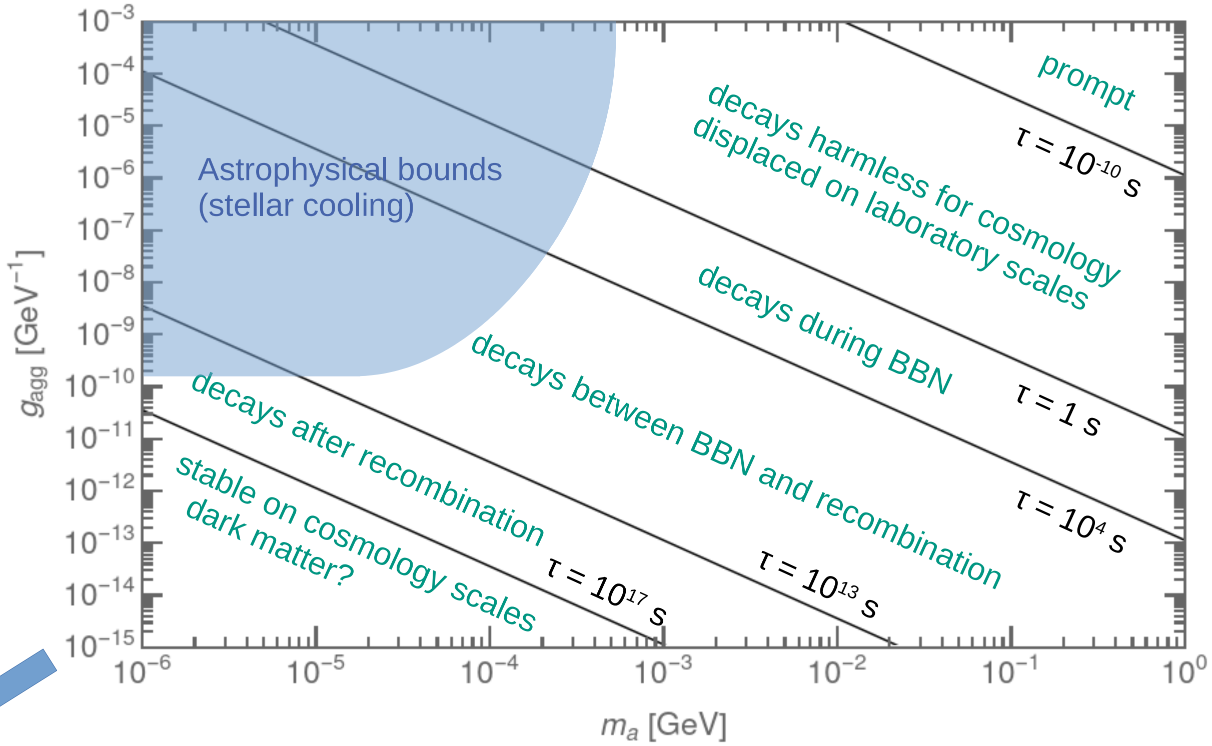


$$\Gamma_a = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

QCD axion

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Parameter space for ALP-photon couplings

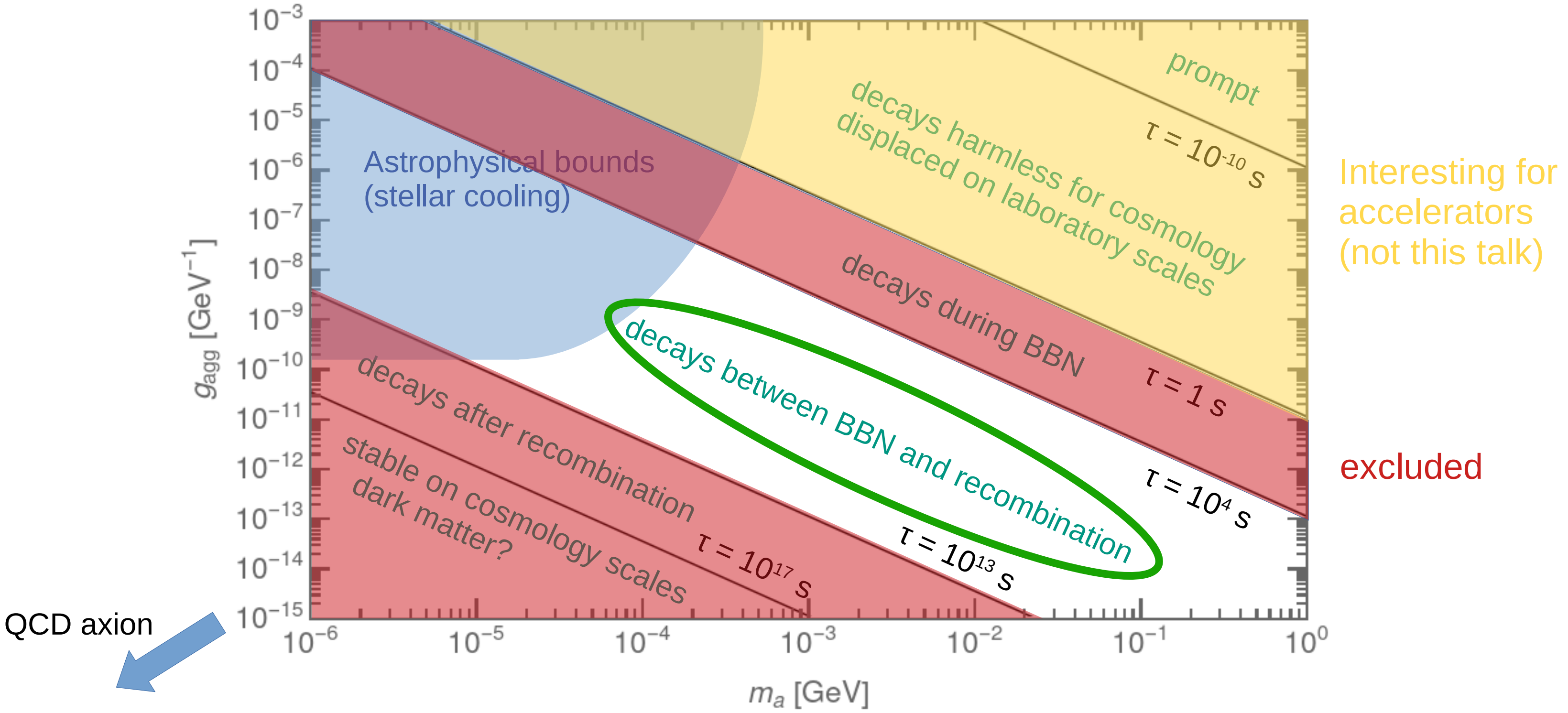


$$\Gamma_a = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

QCD axion

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Parameter space for ALP-photon couplings

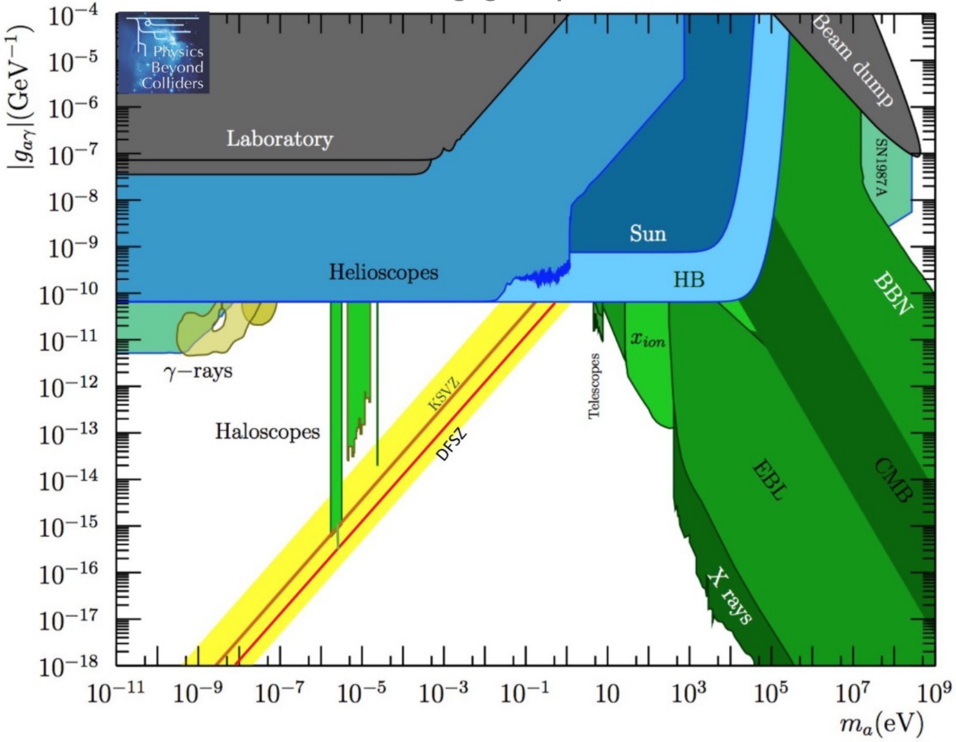


Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Cosmological constraints on ALPs

- **Standard lore:**
  - Parameter space corresponding to 1 s < τ < 10^{17} s fully excluded by cosmological constraints
  - Important **implicit assumption**: ALPs are in thermal equilibrium in the early universe
  - How robust is this assumption?

PBC BSM working group, arXiv:1901.09966

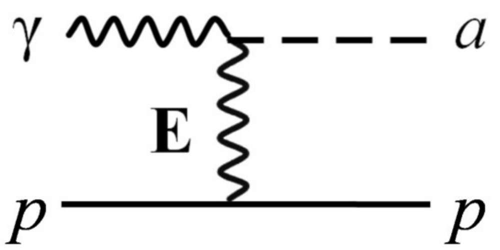


Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Thermal equilibrium

- ALPs thermalise through the Primakoff process
- **Interaction rate:** $\Gamma_p \sim \alpha\, T^3\, g_{agg}^2$
- Thermalisation if $\Gamma_p > H \sim T^2 / M_{pl}$

  $\rightarrow \quad T > \alpha / (M_{pl}\, g_{agg}^2)$



- For low reheating temperature, this condition may never be satisfied

Example: For $g_{agg} = 10^{-15}$ GeV no thermalisation occurs for $T_R < 50$ GeV

Depta et al., arXiv:2002.08370

ALP production beyond equilibrium

- **Low T_R:** ALP abundance set by non-equilibrium processes
  - *Realignment mechanism* (depends on unknown initial misalignment angle θ_a)

    → Resulting ALP abundance essentially free parameter
  - *Freeze-in production* (calculable as function of T_R, g_{agg} and m_a)

    → Lower bound on reheating temperature (T_R > 5 MeV) sets lower bound on ALP abundance
- ALP abundance may be suppressed by many orders of magnitude (compared to equilibrium) but cannot be arbitrarily small

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Cosmological constraints

- ALP decays inject energy into electron-photon plasma

  → Even ALPs that constitute a tiny fraction of the energy density of the universe may be tested by cosmological observations

  - Modifications of N_{eff} and η_b
  - Delay of recombination
  - CMB spectral distortions
  - Primordial element abundances

- Additional constraints (independent of ALP abundance) from SN1987A

Public code https://github.com/marie-lecroq/ALP-fluence-calculation
based on Jaeckel et al., arXiv:1702.02964

CMB spectral distortions (SDs)

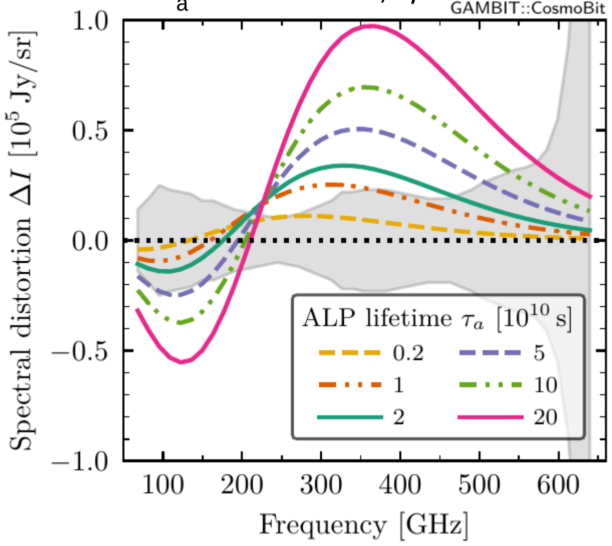
- If the ALPs decay shortly before recombination, the injected energy may not be fully thermalised

  → Imprint on the spectral shape of the CMB

- Best constraints on spectral distortions (from COBE/FIRAS) over 25 years old

- Much stronger constraints could be obtained with future satellites (“PIXIE”)

m_a = 100 MeV, ξ = 5 x 10^{-4}



For likelihood calculation, see Lucca et al., arXiv:1910.04619

Need for global fits

Karlsruhe Institute of Technology

Emmy Noether-Programm DFG Deutsche Forschungsgemeinschaft

- Need to combine variety of numerical codes

MicrOMEGAs CLASS Monte Python AlterBBN ACROPOLIS

- Want to also vary ΛCDM parameters → need to include BAO & SNIa data
- Want to also include other constraints → SN1987A, HB stars, neutron lifetime

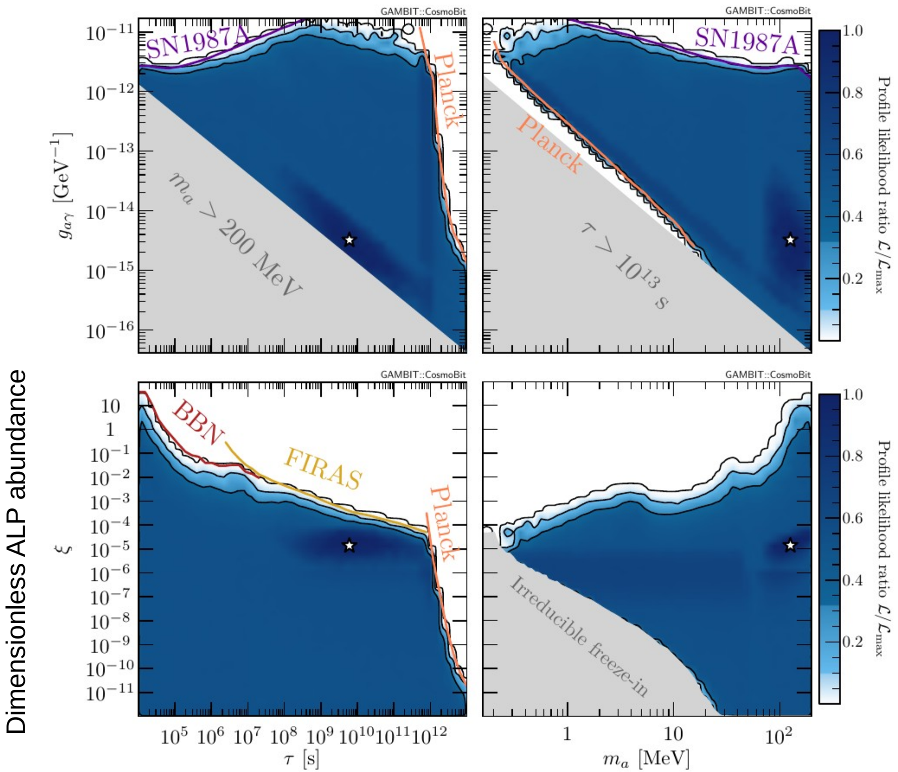
→ Challenging parameter scans!

→ Perfect for the **CosmoBit** module of the Global And Modular BSM Inference Tool **GAMBIT**

Renk, FK et al., arXiv:2009.03286

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Frequentist scan: Results

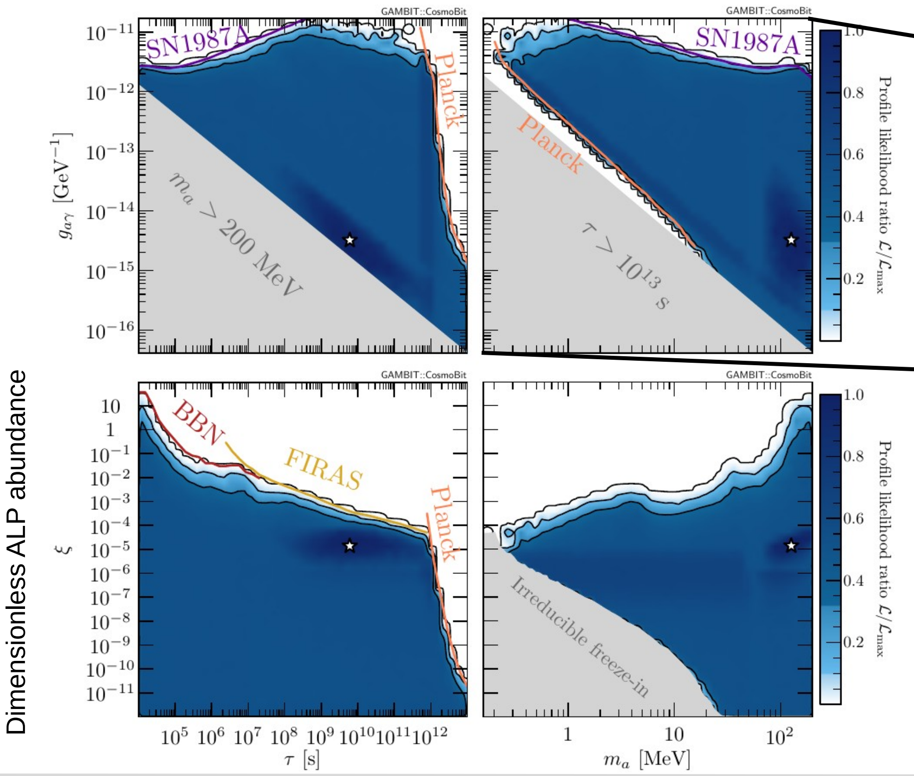


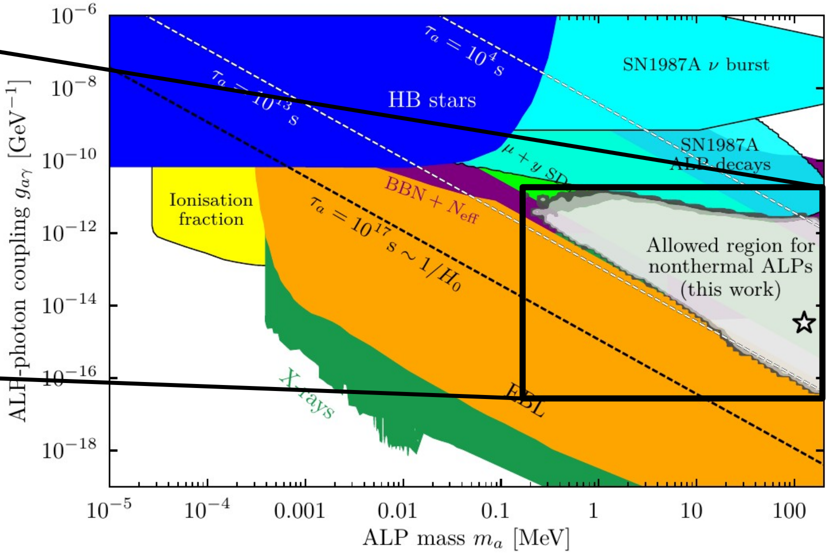
- blue: high likelihood ↔ allowed
- white: low likelihood ↔ excluded
- grey: not explored by scan
- white star: best-fit point

- Key points:
  - Different cosmological probes constrain different ranges of τ
  - SN1987A excludes large $g_{a\gamma\gamma}$

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Frequentist scan: Results

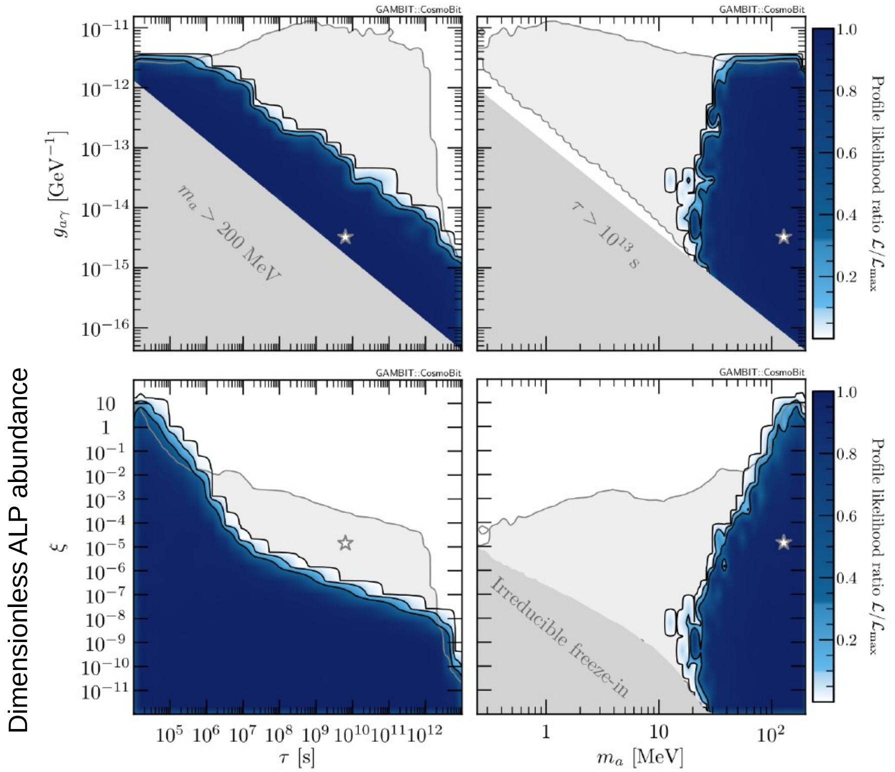




- Viable parameter space found in region previously assumed to be excluded

PIXIE forecasts

- Future satellite missions like PIXIE may substantially improve sensitivity to spectral distortions
- Upper bounds on g_{agg} may be improved by orders of magnitude for 10^6 s < τ < 10^{12} s
- Lower bound on m_a strengthened by two orders of magnitude
- Best-fit point from previous scan would lead to clear discovery



Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Conclusions

- Decaying (MeV-scale) axion-like particles have wide range of implications for particle physics and cosmology
- For 10^4 s < τ < 10^{13} s ALPs produced in the early universe decay between BBN and CMB
- Strongly excluded for thermally produced ALPs
- Global fit reveals viable parameter space for non-thermal ALPs (freeze-in & misalignment production)
- Promising strategy: future spectral distortion missions (PIXIE)