AXIONS AND COSMOLOGY

Massimiliano Lattanzi
Istituto Nazionale di Fisica Nucleare- Sez. di Ferrara

XIIIth Quark Confinement and the Hadron Spectrum

Maynooth University, August 3rd, 2018
Axion production

A cosmological population of axions (and ALPs) can be produced through several mechanisms:

• Production from the thermal bath (e.g. through pion-pion scattering for QCD axions: $\pi + \pi \rightarrow \pi + a$)

• Decay of topological defects (TDs: cosmic strings and domain walls)

• Decay of a heavy particle (e.g. moduli; generic prediction of string and M-theory)

• Misalignment mechanism (very generic, basically works for all pNGBs; inherently non-thermal): coherent initial displacement of the axion field from its minimum
Axions as Dark Matter

- Axions produced via misalignment behave as cold dark matter once the field starts oscillating around the minimum:
  \[ \ddot{\theta} + 3H \dot{\theta} + m_a^2(T) \sin \theta = 0, \]

Given the PQ scale \( f_a \), the present energy density \( \Omega_{\text{mis}} \) of misalignment axions can be computed given:

- the initial misalignment angle \( \theta_i \) (if PQ symmetry is broken after inflation, see next slide). Free parameter (initial condition)
- the topological susceptibility \( \chi(T) = m_a^2(T) f_a^2 \). In principle, it can be computed from the lattice. However, no consensus in the literature (see GM’s talk)

- Axions from TDs decay are also cold, and their density is usually parameterized as:
  \[ \Omega_a = \Omega_{\text{mis}} + \Omega_{\text{dec}} \equiv \Omega_{\text{mis}}(1 + \alpha_{\text{dec}}) \]

Computation of \( \alpha_{\text{dec}} \) requires numerical simulations of the PQ phase transitions. Values quoted in the literature range from 0.16 to 186.

- \( \Omega_{\text{CDM}} \) is one of the best known parameters of the SCM (1% precision). It represents an upper bound for \( \Omega_a \). Corresponding lower limits on \( m_a \) are in the ~few \( \times 10 \mu\text{eV} \) ballpark.
Axions and Inflation

The PQ scale $f_a$ and the Hubble scale during inflation $H_i$ determine whether the PQ symmetry is broken or not during inflation:

- **pre-inflationary axion**, $f_a > H_i/2\pi$: the PQ symmetry is broken during inflation and not restored afterwards. $\theta_i$ is constant across the whole observable Universe, its value being a free parameter of the model. Isocurvature perturbations are produced.

- **post-inflationary axions**, $f_a < H_i/2\pi$: the PQ symmetry is broken after inflation, $\theta_i^2$ should be replaced by its spatial average. Topological defects are produced.

The Hubble constant during inflation is constrained by the non-observation of tensor modes in CMB experiments (Planck+BK14, see Planck 2018 X)

$$H_i < 2.7 \times 10^{-5} M_{Pl}$$

(95% CL)

The isocurvature fraction $\beta_{iso}$ (fraction of total power in isocurvature fluctuations) is also constrained by Planck:

$$\beta_{iso} < 0.038$$

(95% CL)
Axion parameter space

![Graph showing axion parameter space with various regions and markers such as ADMX, AXION, isocurvature fluctuations, and red giants brightness.](Image credit: L. Visinelli (see Visinelli & Gondolo PRD 2009, PRL 2014))
Axions as Dark Radiation

Axions produced by the thermal bath or through decay of heavy particles are ”hot” so they can only represent a subdominant fraction of the total matter content of the Universe

- At early times, they would contribute to the total radiation density, parametrized by the effective number of relativistic species (“neutrino families”) $N_{\text{eff}}$
- Present observations are consistent with no exotic radiation components: $N_{\text{eff}} = 2.99 \pm 0.34$ @95%CL (Planck 2018VI)
- At late times, hot axions would suppress structure formation in a similar way to what neutrinos do
  $m_a < 1.7 \text{ eV} @95\% \text{CL}$ (Di Valentino et al 2016, uses Planck 2015 data)
Axions as Dark Radiation

• Future CMB experiments are expected to reach a $1\sigma$ sensitivity on $N_{\text{eff}}$ of $\sim 0.2$

• This would allow to detect thermal relics up to arbitrarily high decoupling temperatures (Baumann, Green, Wallisch 2017)

• In the future, a EUCLID-like survey together with Planck data could detect $m_a \sim 0.15$ eV with high significance (Archidiacono et al., 2015)
Ultralight axions

The cosmological phenomenology of axions in the mass range \([10^{-33} \text{–} 10^{-18}]\) eV (ultralight axions, or ULAs) is somehow different

- They can drive the present expansion of the Universe, acting as a quintessence field
- They can drive inflation
- They have a peculiar effect on structure formation ("fuzzy dark matter")

Hlozek et al., PRD 2015
ADDITIONAL SLIDES