AXIONS AND COSMOLOGY

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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

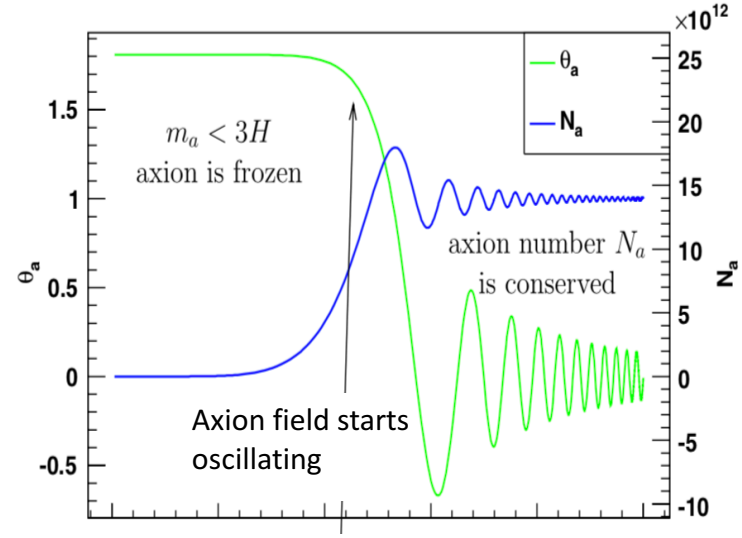
Axions as Dark Matter

- Axions produced via misalignment behave as cold dark matter once the field starts oscillating around the minimum:

$$\ddot{\theta} + 3H\dot{\theta}_a + m_a^2(T)\sin\theta_a = 0,$$

Given the PQ scale f_a, the present energy density Ω_{mis} of misalignment axions can be computed given:

- the initial misalignment angle θ_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:

$$\Omega_a = \Omega_{\rm mis} + \Omega_{\rm dec} \equiv \Omega_{\rm mis}(1 + \alpha_{\rm dec})$$

Computation of α_{dec} requires numerical simulations of the PQ phase transitions. Values quoted in the literature range from 0.16 to 186.

- Ω_{CDM} is one of the best known parameters of the SCM (1% precision). It represents an upper bound for Ω_a. Corresponding lower limits on m_a are in the ~few x 10μeV 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. θ_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, θ_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)

$$H_I < 2.7 \times 10^{-5} M_{\rm Pl} \qquad \text{(95\% CL)}$$

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

$$\beta_{\rm iso} < 0.038 \qquad \text{(95\% CL)}$$

Axion parameter space

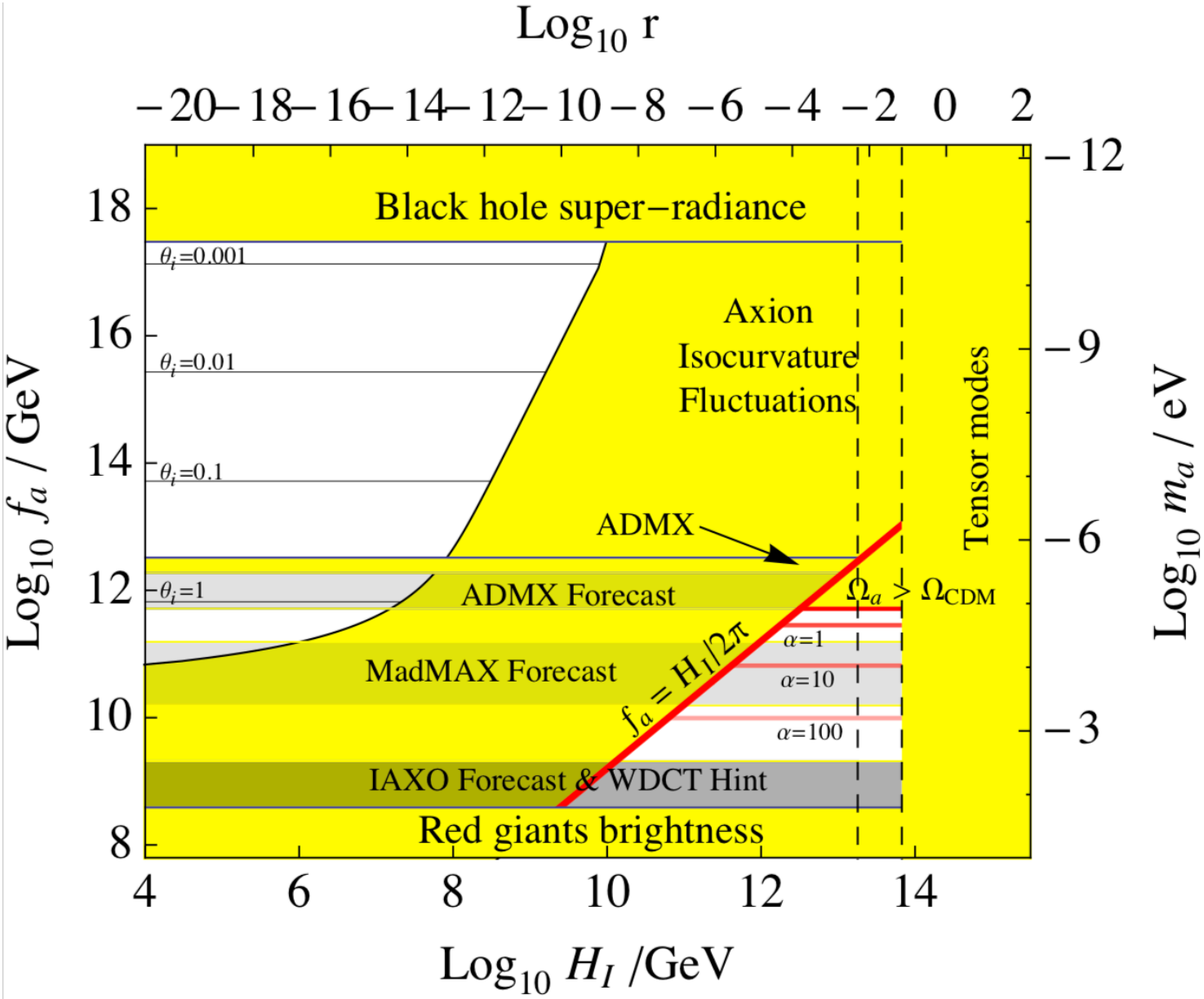


Image credit: L. Visinelli (see Visinelli & Gondolo PRD 2009, PRL 2014)

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_{eff}
- Present observations are consistent with no exotic radiation components:

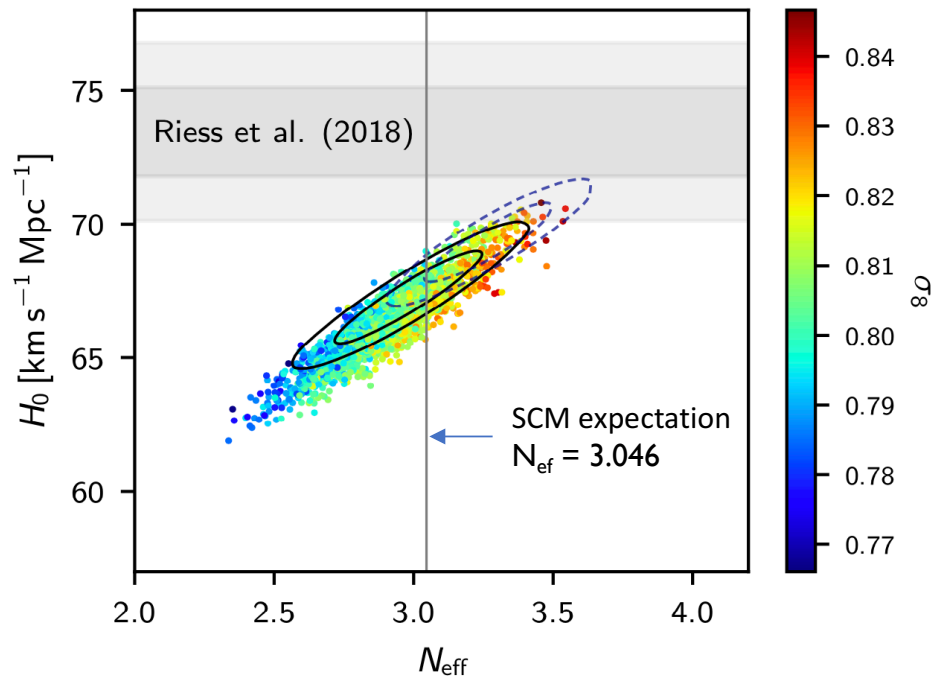
  N_{eff} = 2.99 +/- 0.34 @95%CL

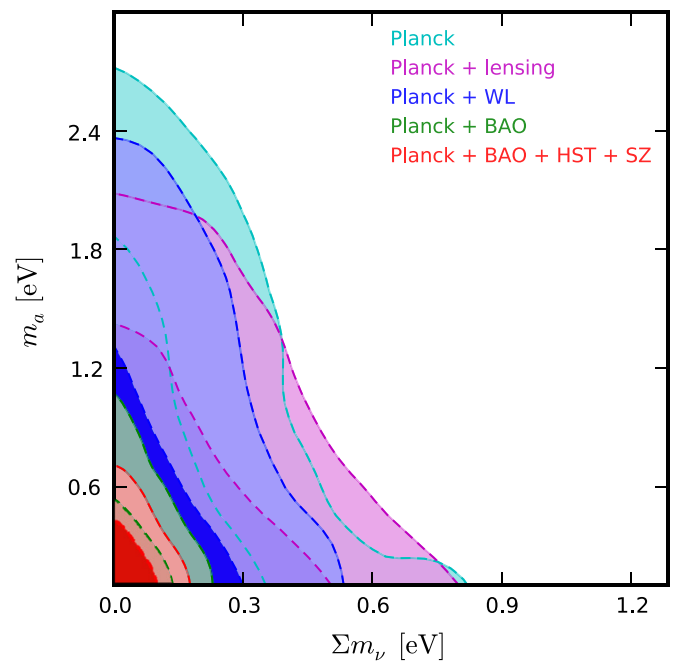
(Planck 2018 VI)

- At late times, hot axions would suppress structure formation in a similar way to what neutrinos do

  m_a < 1.7 eV @95% CL

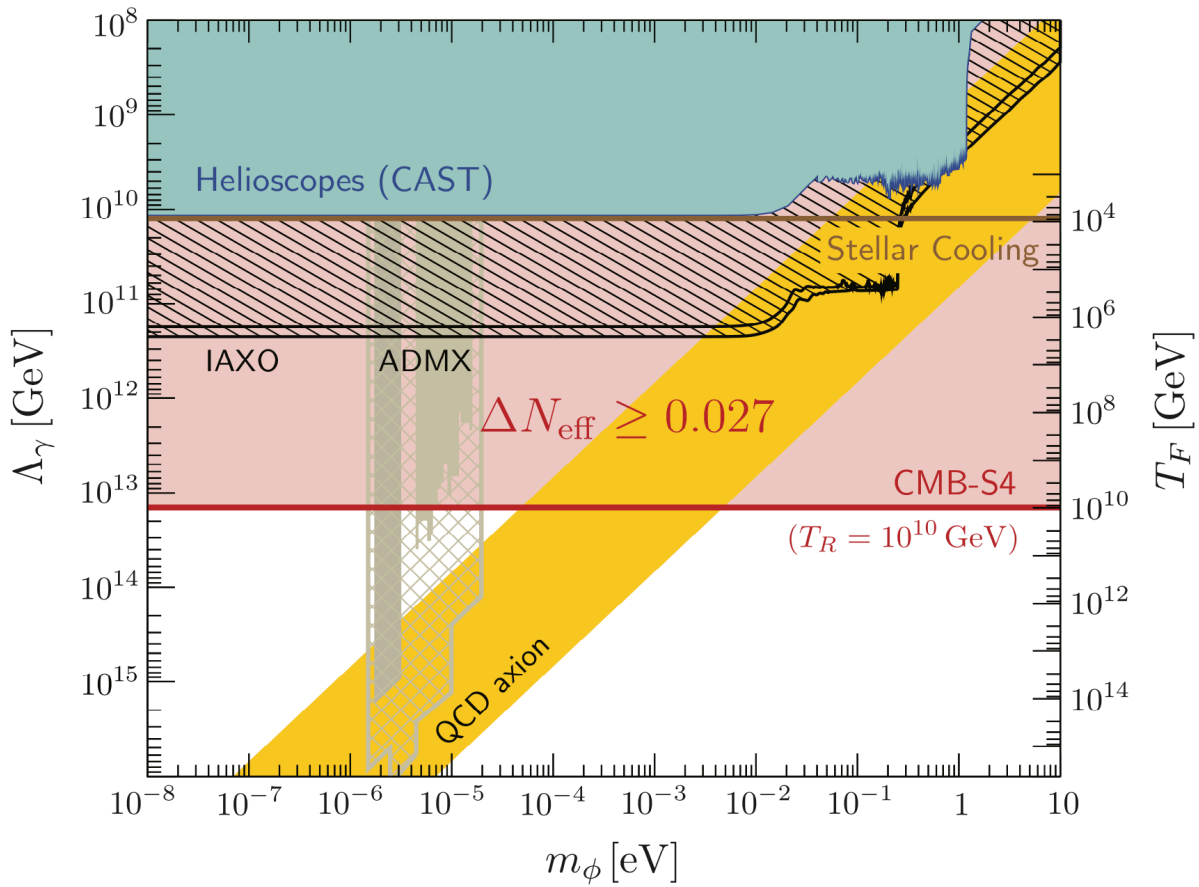
  (Di Valentino et al 2016, uses Planck 2015 data)





Axions as Dark Radiation

- Future CMB experiments are expected to reach a 1σ sensitivity on N_{eff} of ~0.2
- This would allow to detect thermal relics up to arbitrarily high decoupling temperatures (Baumann, Green,Wallisch 2017)

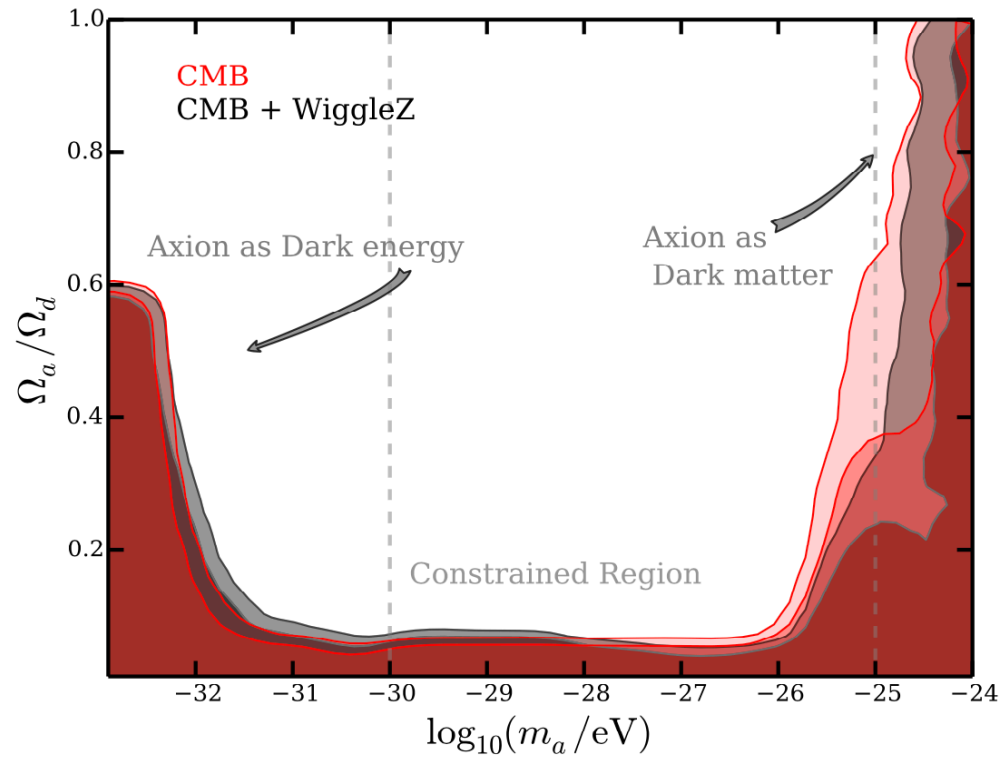


- In the future, a EUCLID-like survey together with Planck data could detect m_a ~ 0.15 eV with high significance (Archidiacono et al., 2015

Ultralight axions

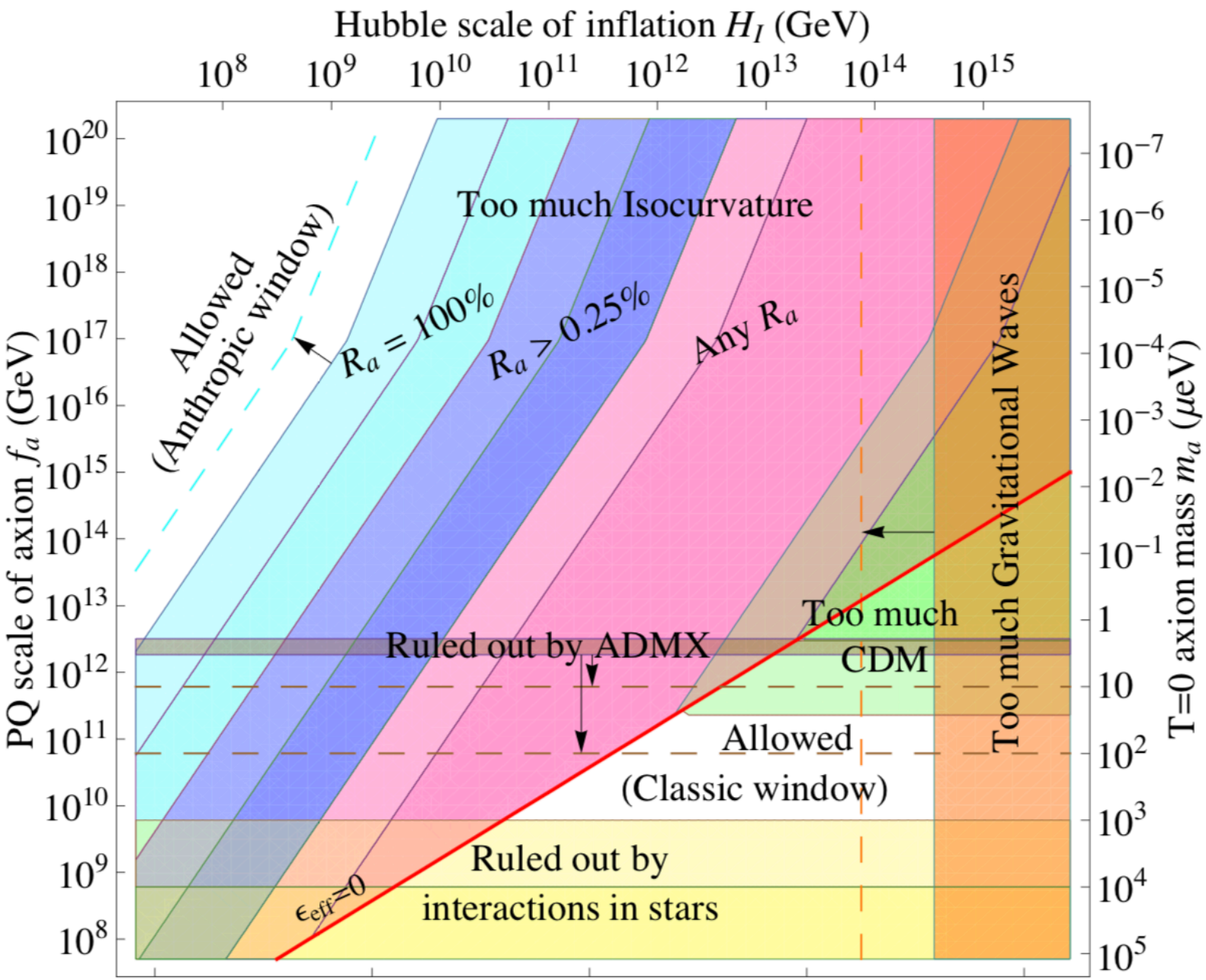
The cosmological phenomenology of axions in the mass range [10^{-33} – 10^{-18}] eV (ultralight axions, or ULAs) is somehow different

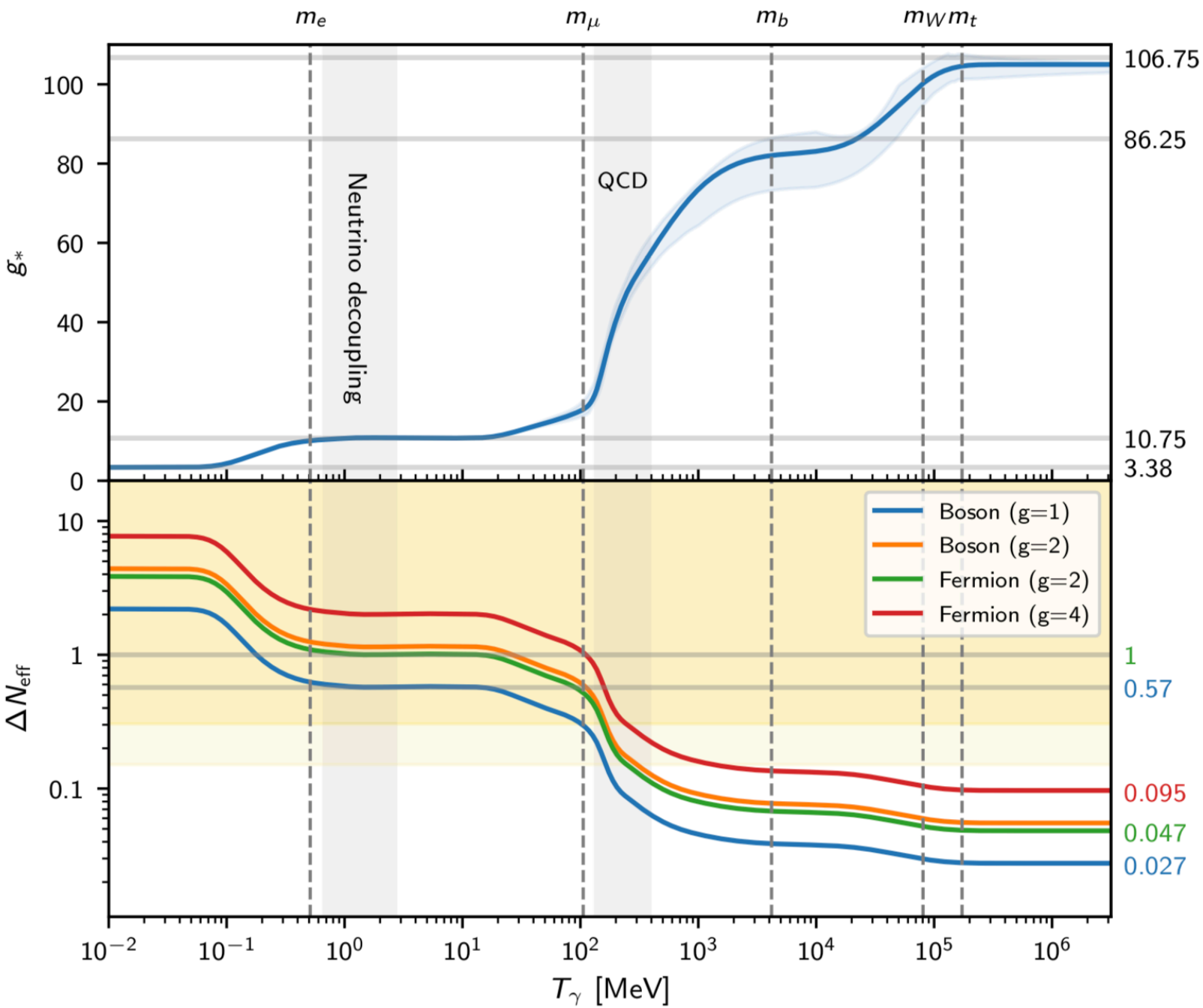
- They can drive the present expansion of the Universe, acting as a quintessence field
- They can drive inflation
- They have a peculiar effect on structure formation ("fuzzy dark matter")



Hlozek et al.,
PRD 2015

ADDITIONAL SLIDES


Hubble scale of inflation H_I (GeV)
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
PQ scale of axion f_a (GeV)
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^9
10^8
T=0 axion mass m_a (μeV)
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
10^3
10^4
10^5
Allowed
(Anthropic window)
Too much Isocurvature
$R_a = 100\%$
$R_a > 0.25\%$
Any R_a
Too much Gravitational Waves
Too much
CDM
Ruled out by ADMX
Allowed
(Classic window)
Ruled out by
interactions in stars
$\epsilon_{eff}=0$


m_e
m_μ
m_b
$m_W m_t$
106.75
86.25
10.75
3.38
Neutrino decoupling
QCD
g_*
Boson (g=1)
Boson (g=2)
Fermion (g=2)
Fermion (g=4)
$\Delta N_{\rm eff}$
1
0.57
0.095
0.047
0.027
T_γ [MeV]