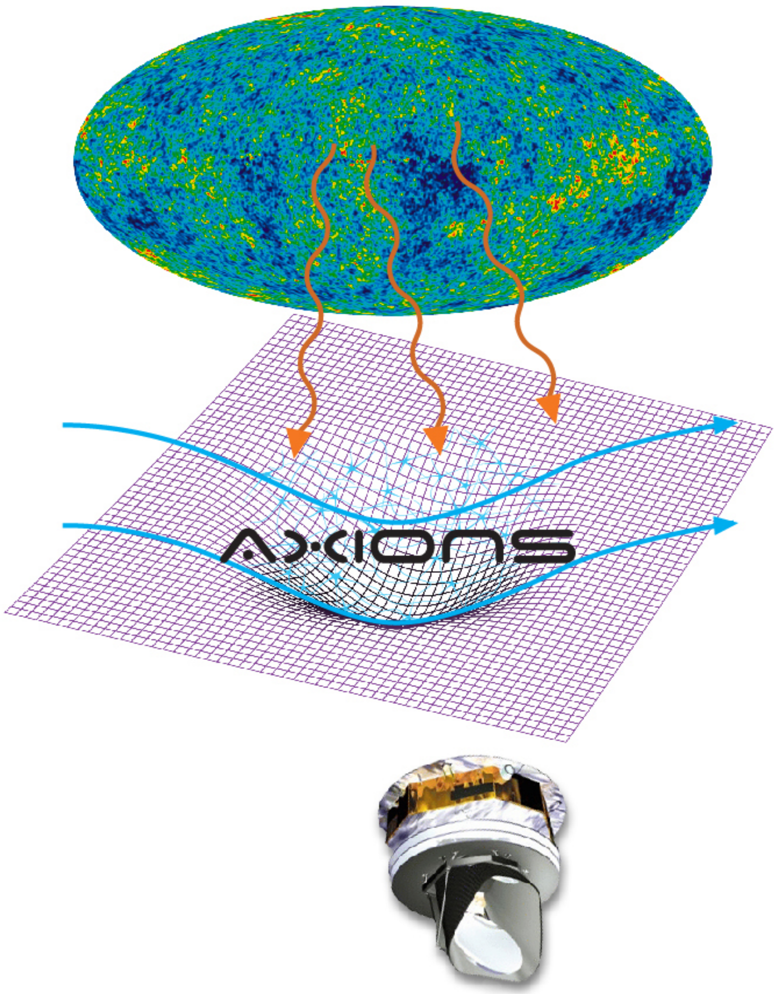
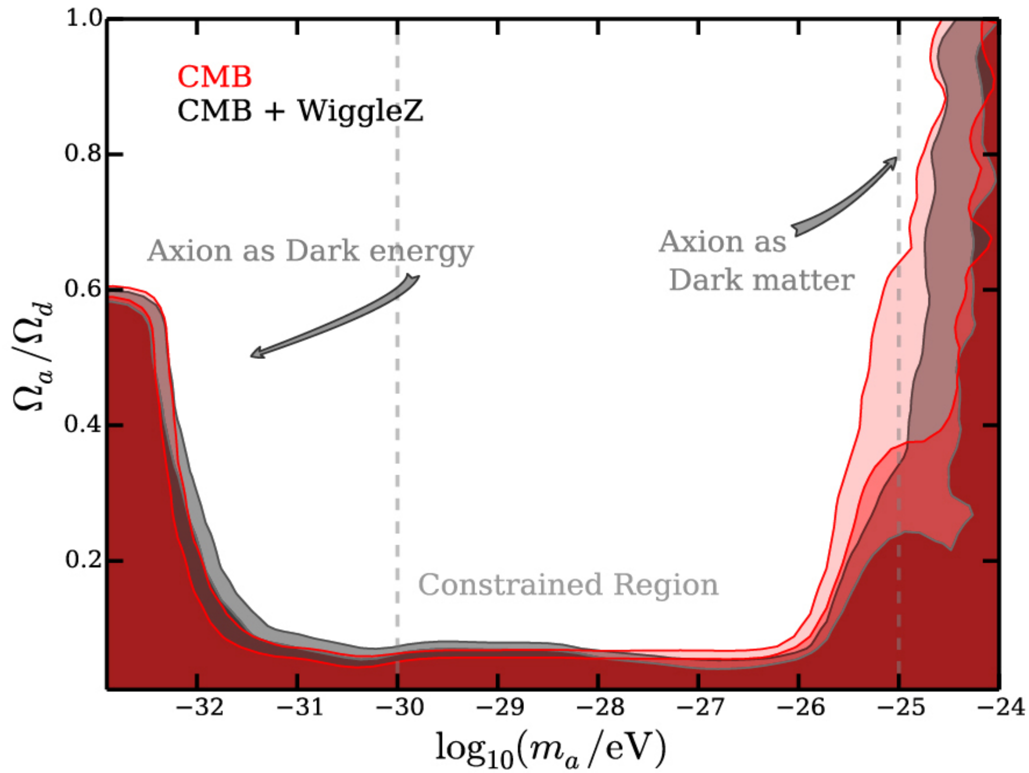
PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

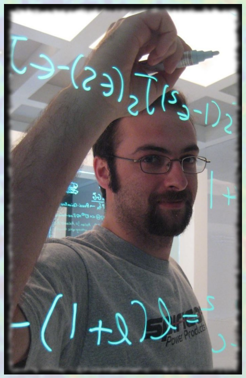
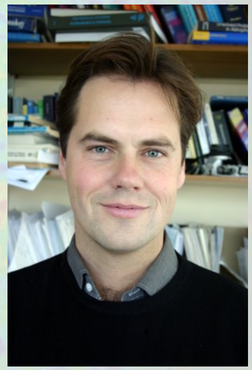
Google: Defining Gravity, Defying Gravity

A SEARCH FOR ULTRA-LIGHT AXIONS USING PRECISION COSMOLOGICAL DATA



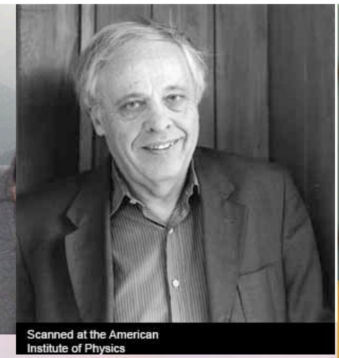


Collaborators

Renée Hlozek, Daniel Grin & Pedro Ferreira
arXiv:1410.2896
arXiv:1403.4216

Using the CMB and large scale structure

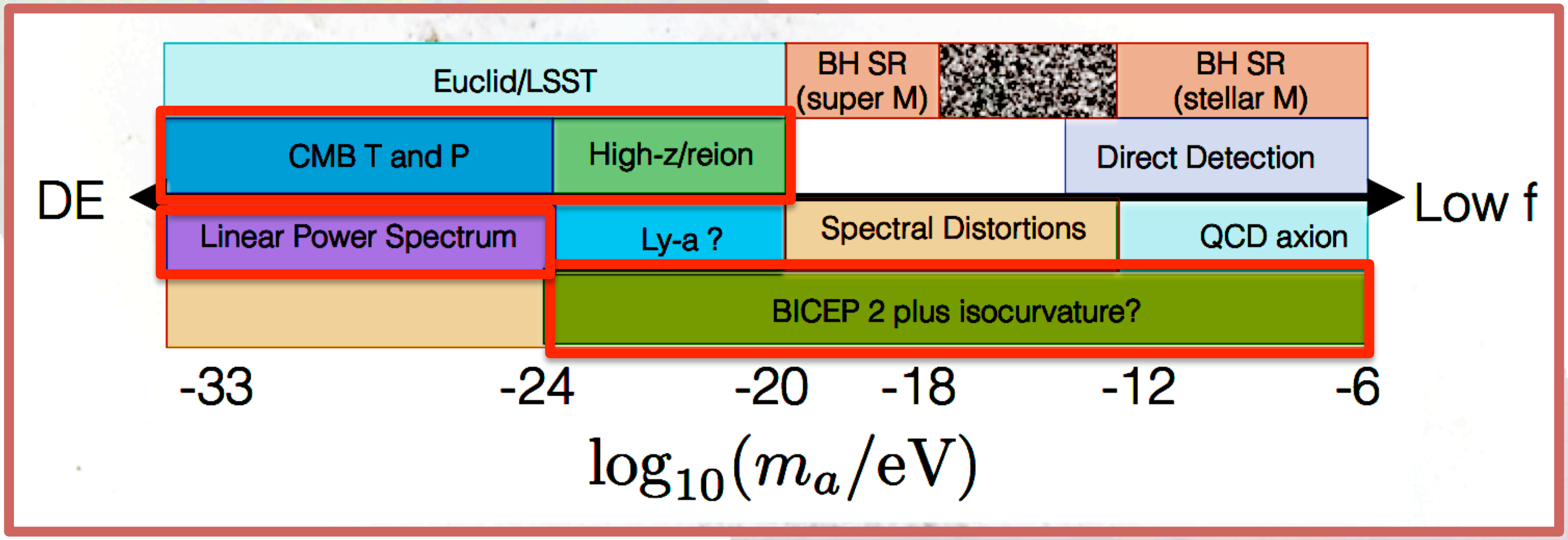
Brandon Bozek, Joseph Silk & Rosemary Wyse
arXiv:1409.3544

Using high-z galaxies and reionisation

Outline

- ✧ Introduction to axion cosmology.
- ✧ Precision constraints.
- ✧ Small scales and high redshifts.
- ✧ Using axion DM to probe inflation.

Masses and effects of axions



Introduction to axion cosmology

What are axions? "Normally" the QCD axion:

Peccei & Quinn; Weinberg; Wilczek, ('77, '78)

$$d_n \lesssim 2.9 \times 10^{-26}\ e\ \mathrm{cm} \Rightarrow m_a^2 \sim \Lambda_{\mathrm{QCD}}^4 / f_a^2$$

Solves strong CP- problem and passes astrophysical tests if:

Raffelt (2006)

$$10^9\ \mathrm{GeV} \lesssim f_a \lesssim 10^{17}\ \mathrm{GeV}$$

Arvanitaki et al (2010)

Generically: axions are ultra-light pseudo-scalar PNGBs.
Many axions may arise in string theory*, with log-dist masses.

See Burgess and Silverstein talks.

$$m_a^2 \sim \frac{\mu^4 e^{-c\mathrm{Vol}_p}}{f_a^2}$$

e.g. Svrcek & Witten (2006)
Arvanitaki et al (2010)

Two scales: one high, one low. Transparent link to theory.

[* and many other theories, e.g. SUGRA, extra dimensions, etc.]

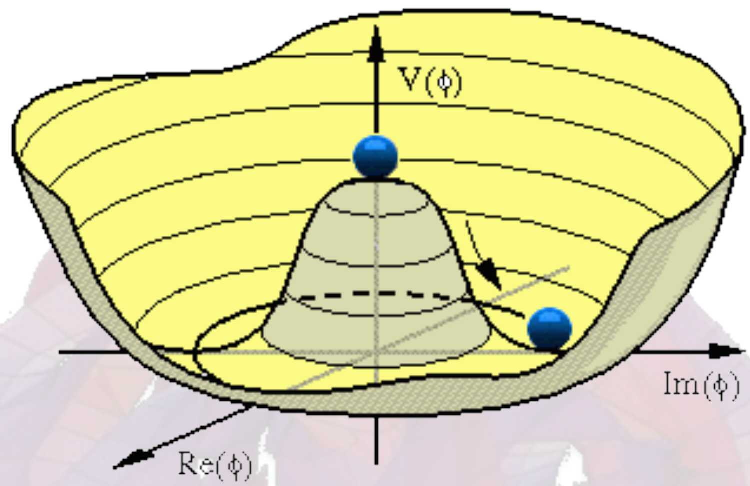
Introduction to axion cosmology

Evolution of the axion. High occupation no. → classical field.

Stage I: SSB at high scale f_a. Random displacement. PNGB.

Stage II: non-pert effects → mass. Friction → const. density.

Stage III: Oscillation energy scales with volume → matter.



http://www.hep.ph.ic.ac.uk/cms/physics/higgs.ht

Friction decreases with time

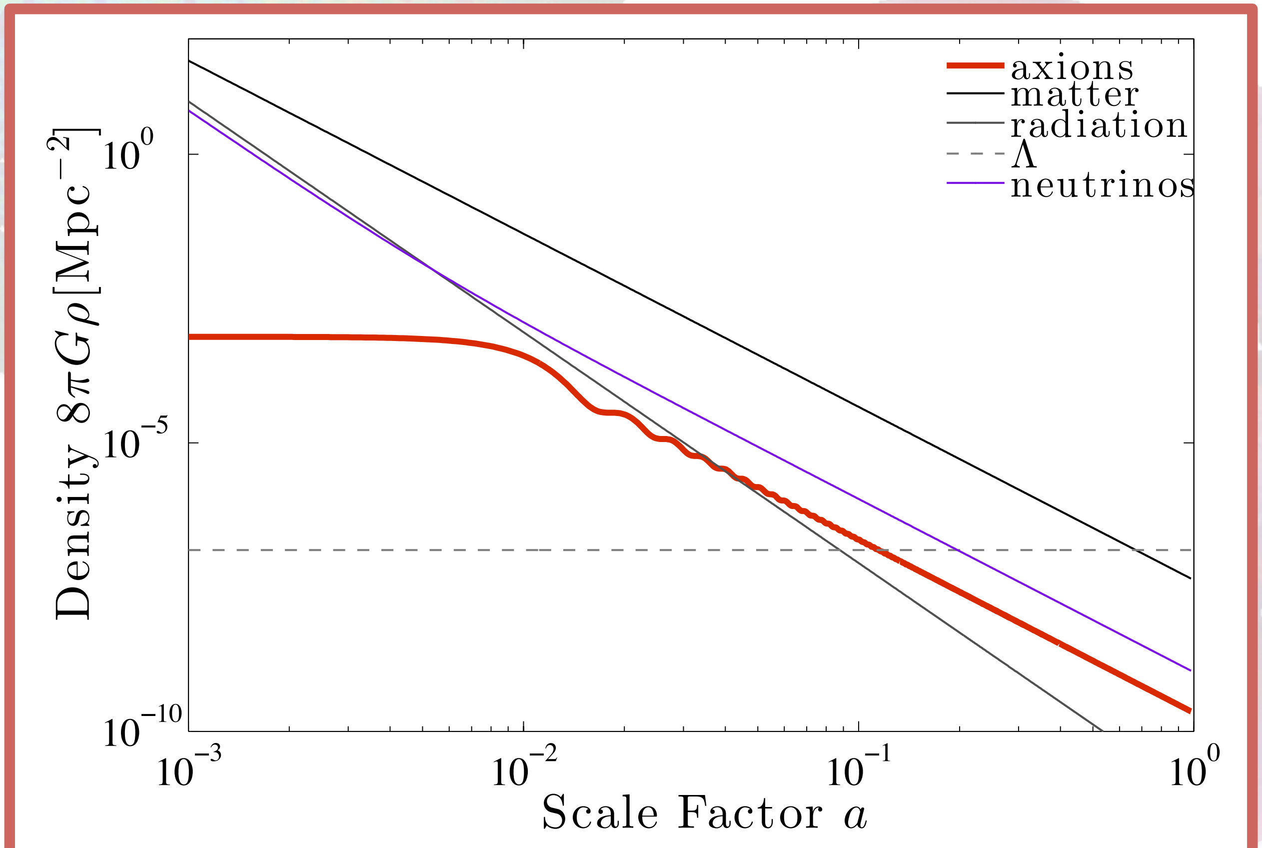
$$H_{\rm BBN} \sim 10^{-15}\ {\rm eV}$$

$$H_0 \sim 10^{-33}\ {\rm eV}$$

Misalignment production

Axion production is non-thermal: the misaligment-mechanism.

$$\Omega_a = \Omega_a(m_a, \phi_i)$$



Modeling perturbations

e.g. Hu (1998)

Modified version of CAMB & KG background: shoot for density.

$$\frac{\dot{P}}{\dot{\rho}} := c_{\rm ad}^2 = -1 + \frac{2m_a}{3\mathcal{H}}\sqrt{\frac{1-w_a}{1+w_a}}$$

Early times: compute w. Late times: set w=0 on average.
Perts: continuity + Euler with entropy perts. Effective fluid.

$$w_a\Gamma_a = (1-c_{\rm ad}^2)(\delta_a + 3\mathcal{H}u_a/k)$$

Eliminate. Rest frame solution. Boosts.

$$\frac{\delta P}{\delta\rho} := c_s^2$$

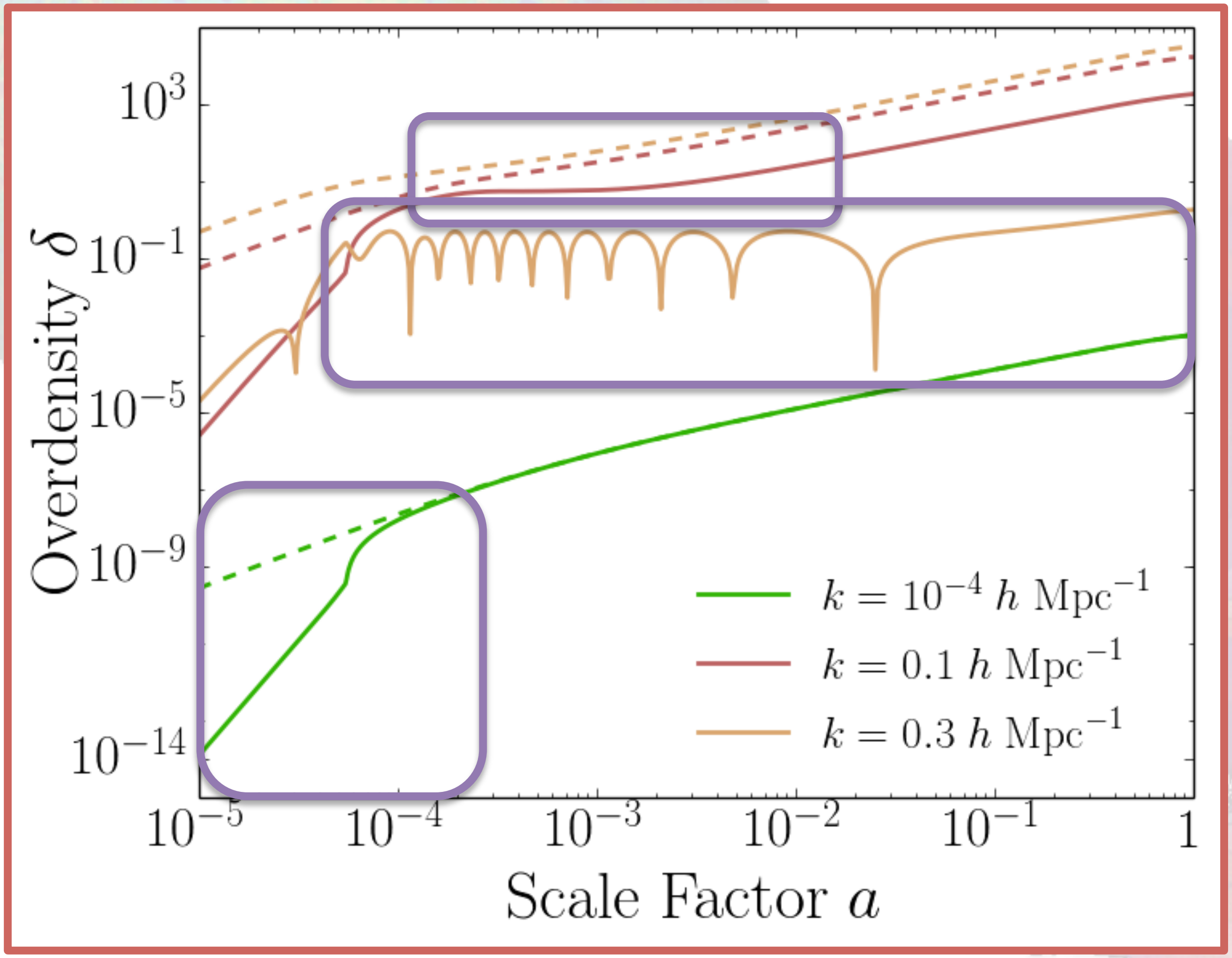
Solve and average oscillations.

$$\frac{k^2/4m_a^2a^2}{1+k^2/4m_a^2a^2}$$

e.g. Hwang & Noh (2009)

Suppression of Power

"Poster-child" effect of ultra-light scalar DM.

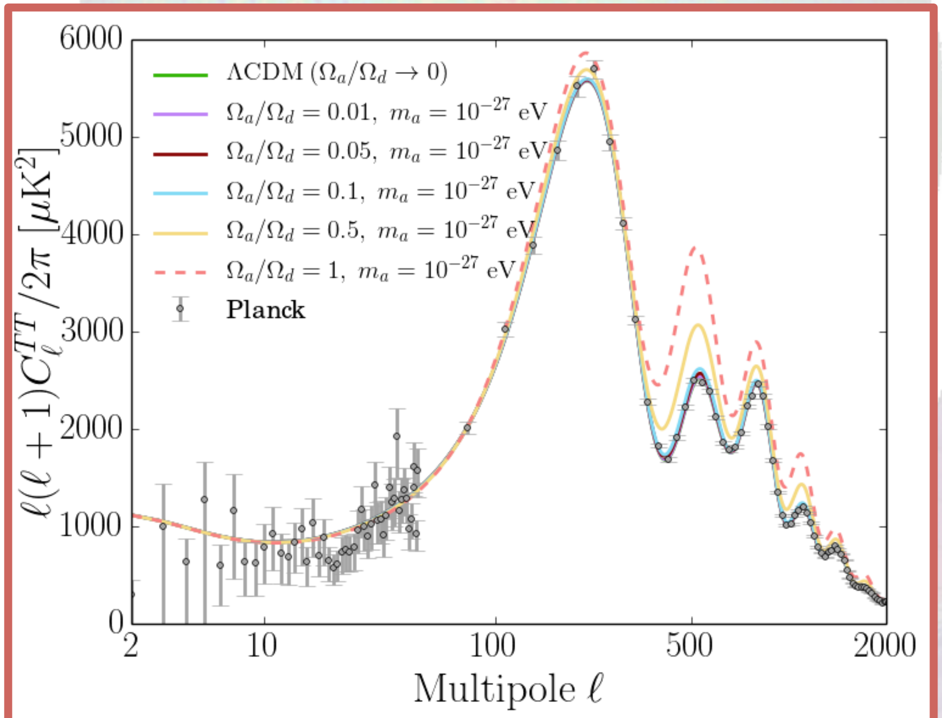


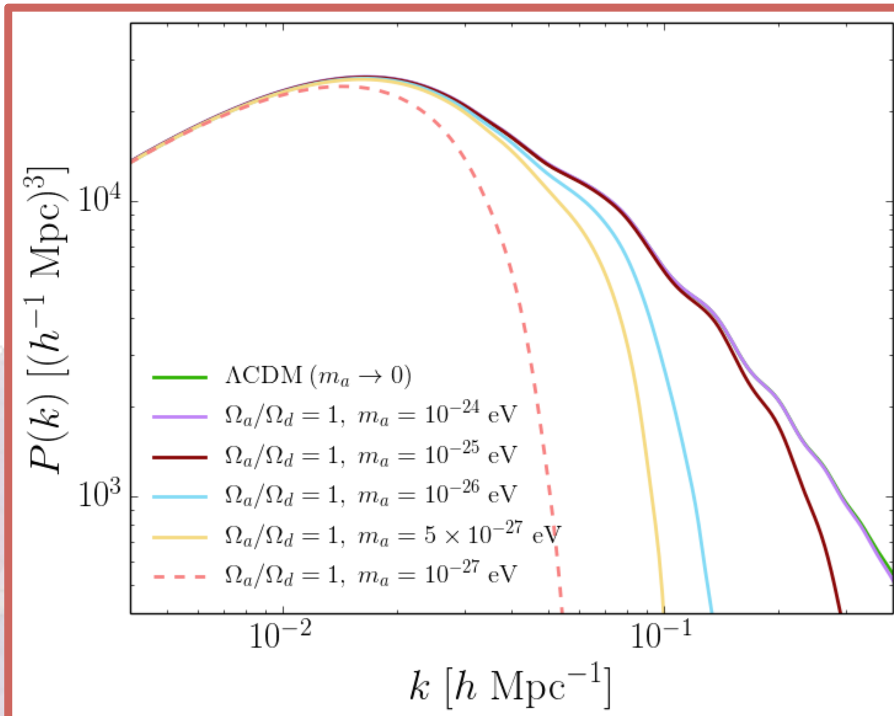
Large sound speed. Jeans

suppression distinct from WDM.

Cosmological observables

Magnitude of effect away from CDM fixed by mass and density.



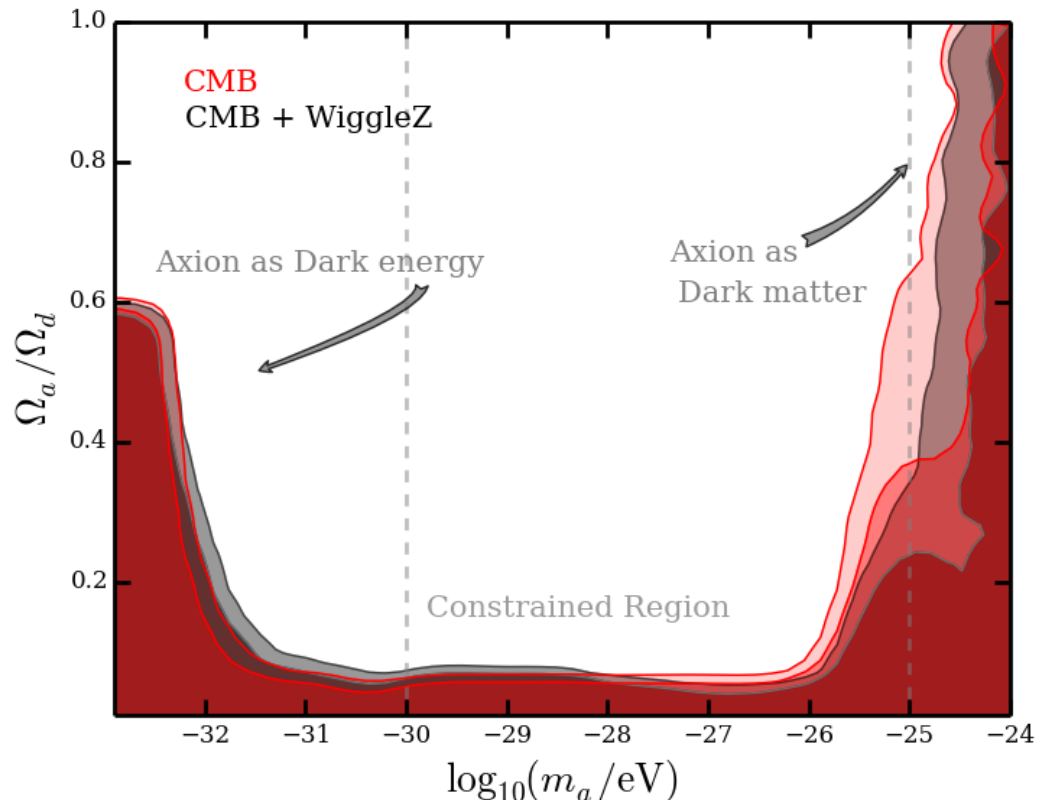


CMB temperature: variation of density. RD era exp. rate changes peak heights.

Galaxy survey: variation of mass. Larger mass clusters on smaller scales.

Precision constraints

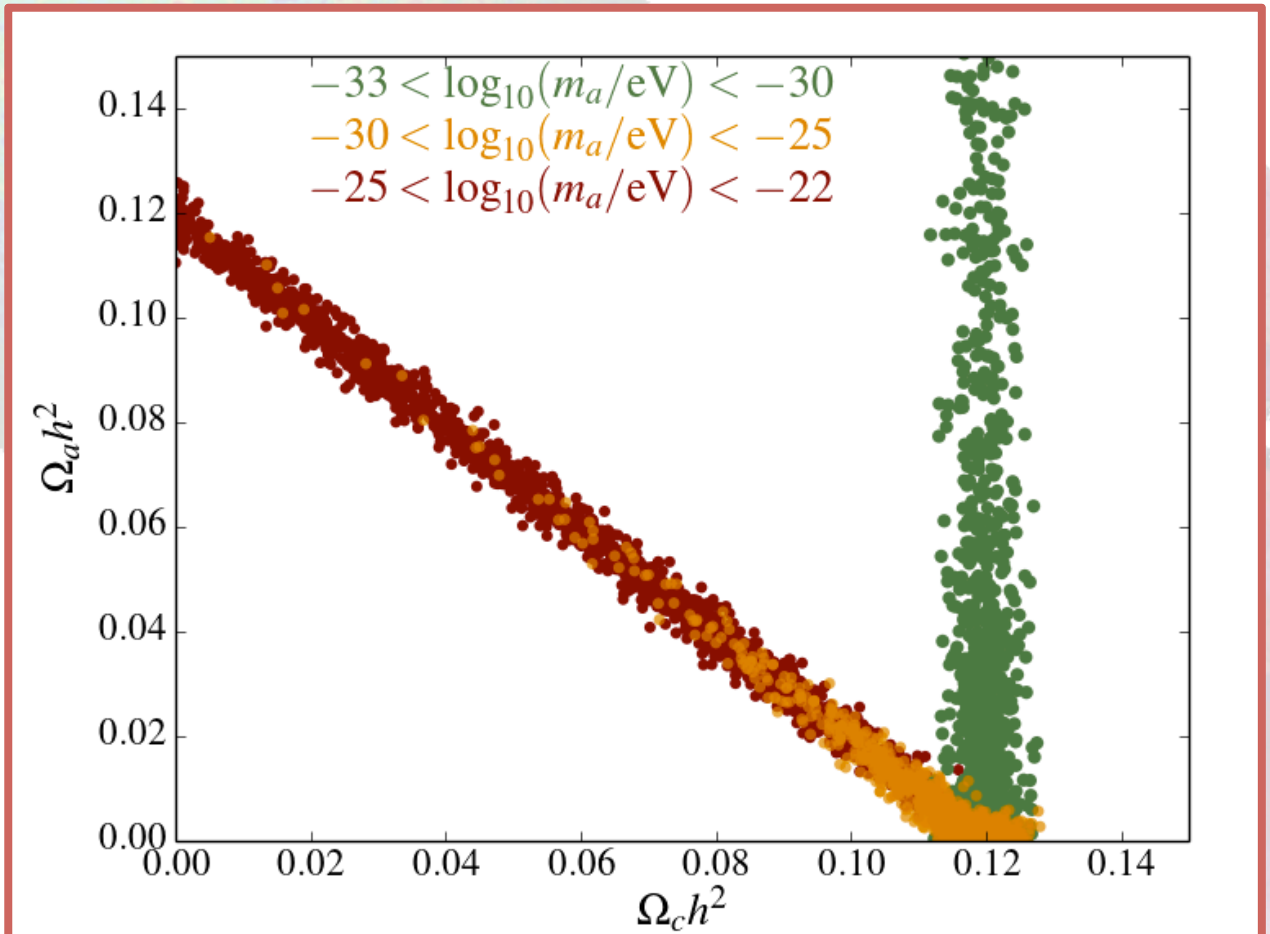
First the “money plot” summary:



$\Omega_a/\Omega_d < 0.05$ (marginalised over all other parameters)

Precision constraints

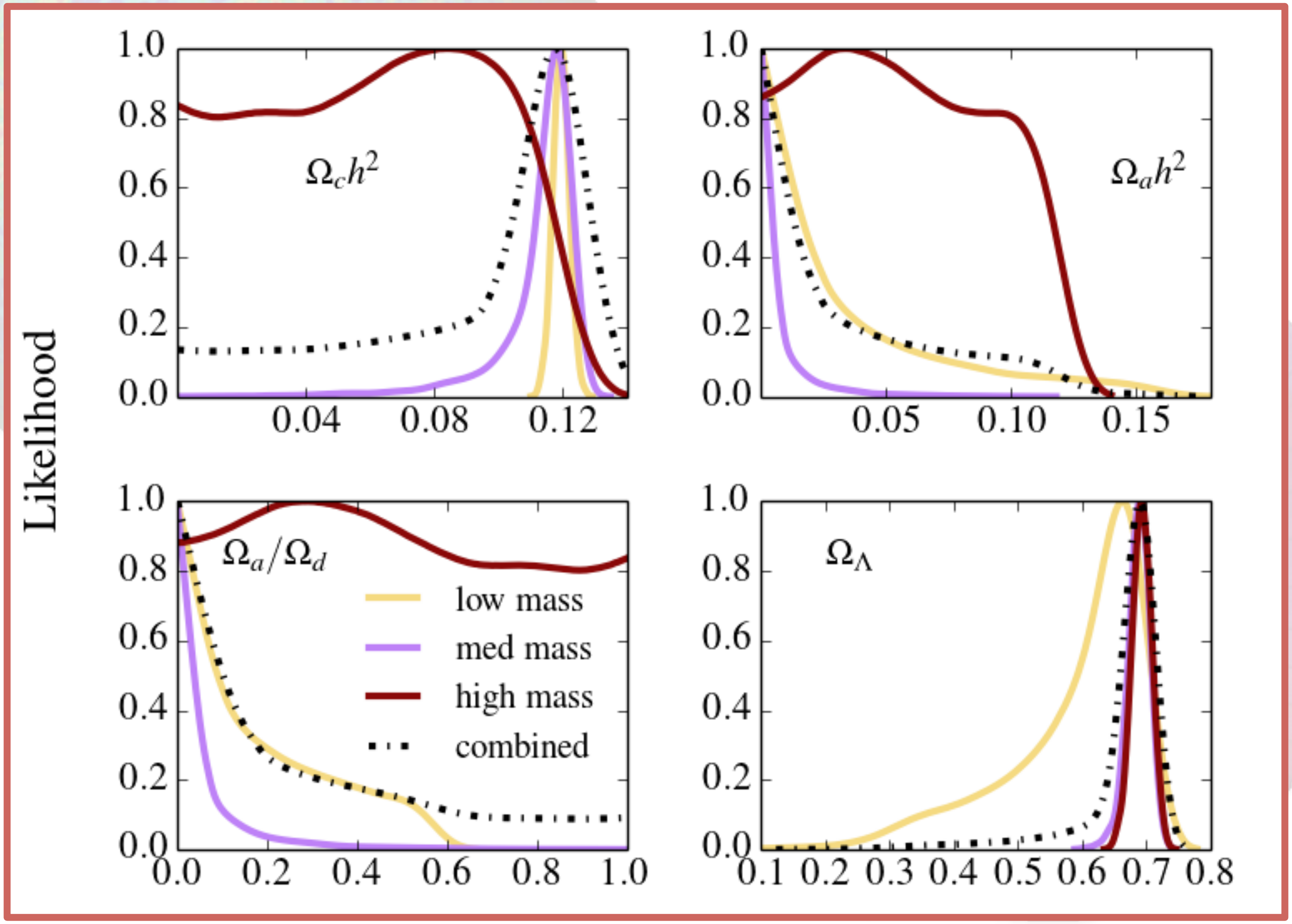
Complicated degeneracy structure. Use *Multinest* to sample.
"Stitch" prior regions with 2d importance sampling.



(Checked consistency against "quasi-frequentist" approach.)

Precision constraints

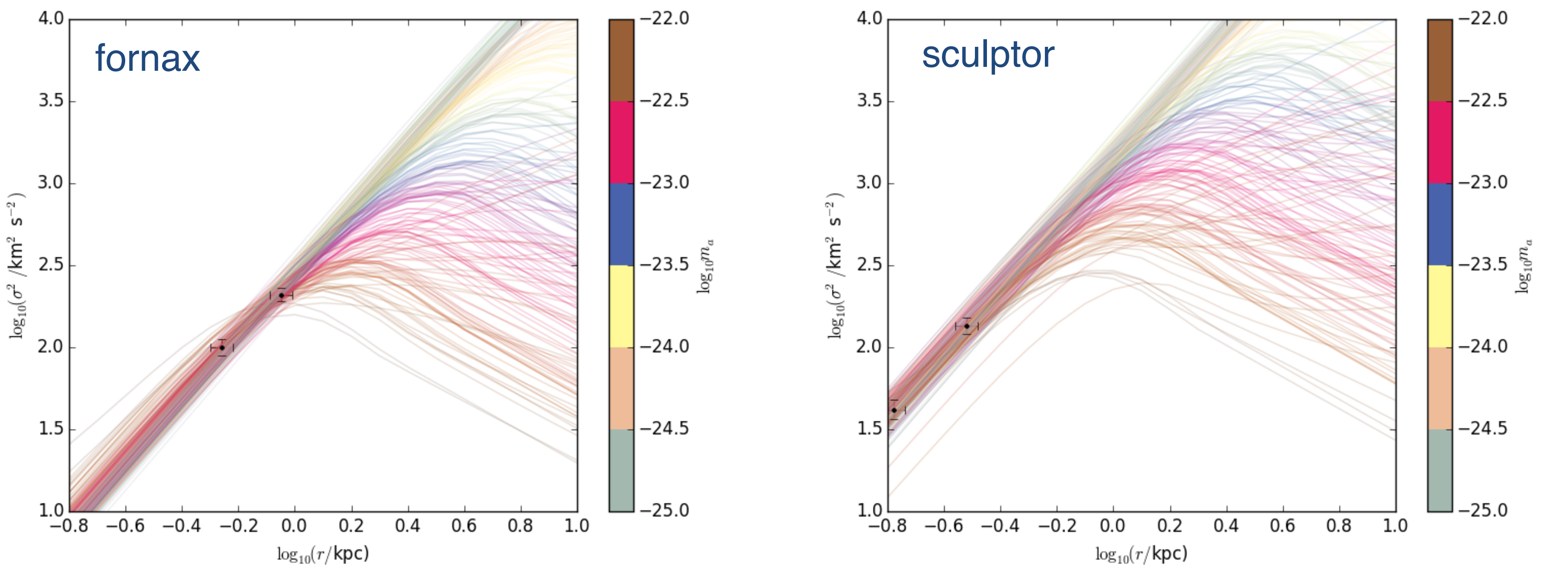
Degeneracies with CDM and Lambda separate key effects.



Why light axions?

Ongoing with Ana Pop
(see also Schive, Chiueh & Broadhurst 2014)

The "cusp-core" problem of standard CDM: e.g. Wyse & Gilmore (2008)



[Data: Walker & Penarrubia, 2011]

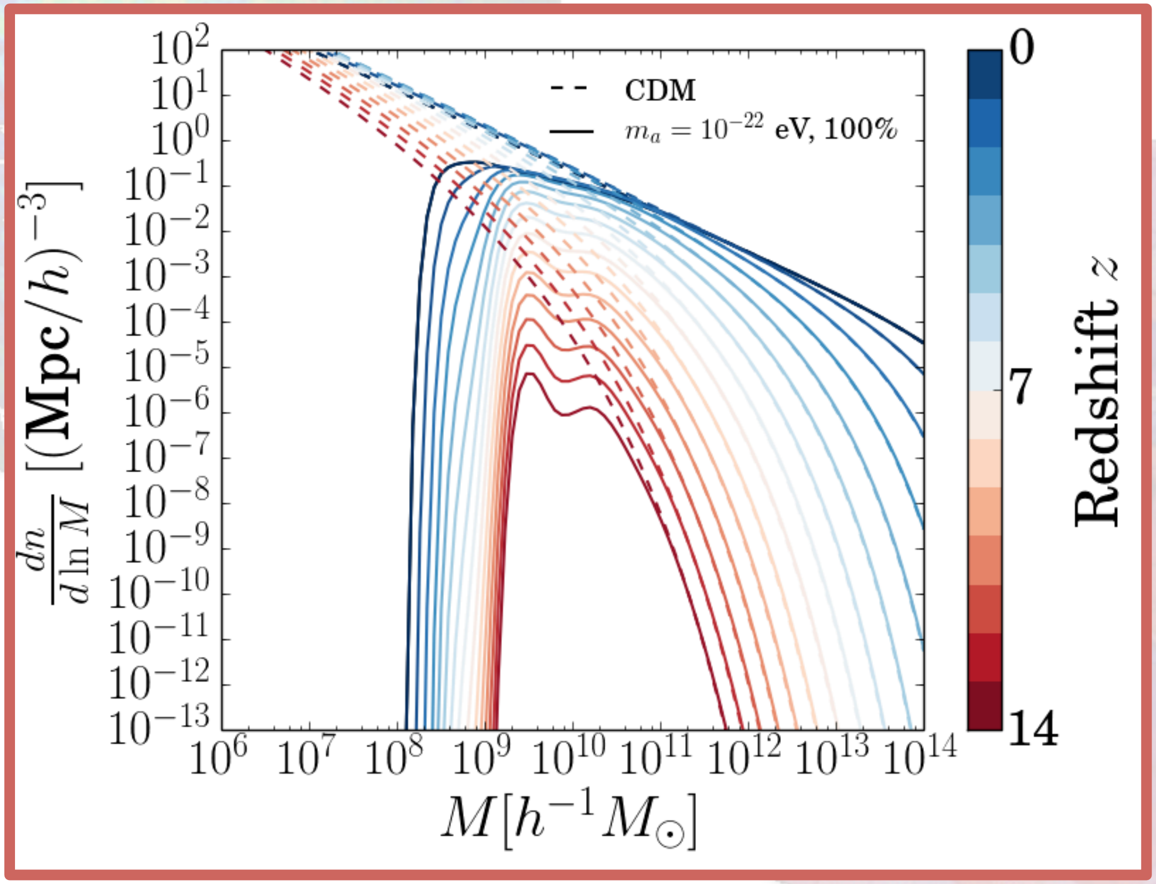
$$m_a \sim 10^{-22}\ \mathrm{eV}$$ → kpc cores from solitons.

Linear modes all used. Need other probes to push into this regime.

Halo formation at high redshift

CDM: structure formation is hierarchical. Press & Schechter (1977)

Axion de Broglie scale suppresses low mass and old objects.

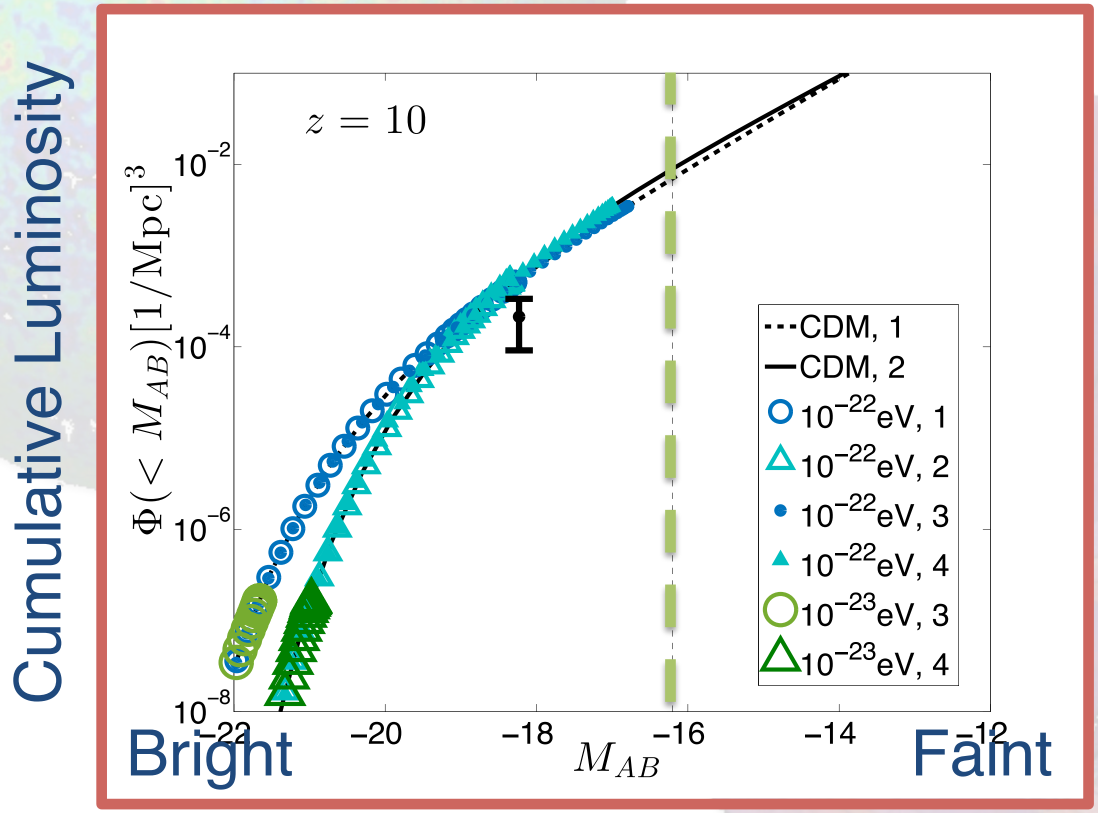


Halo mass function: Sheth & Tormen (2001), Marsh & Silk (2013)

Hubble and James Webb

Compute expected number of galaxies at high-z.
Compare to HUDF and predictions for JWST.

Bouwens et al (2014)
Windhorst et al (2006)



HUDF data
z=6,7,8,10
JWST z=13

HUDF excludes 10^{-23} eV at $>8\sigma$, JWST can reach 10^{-22} eV

Cosmic reionisation

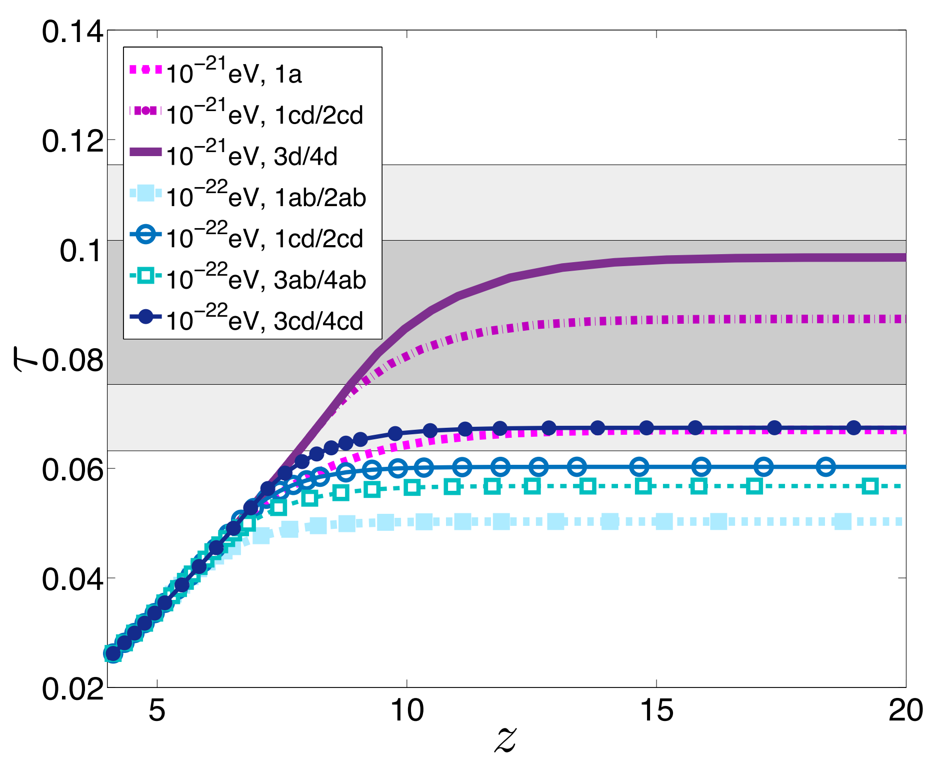
Galaxies at high-z reionise the Universe. Axions cut HMF. τ computed using abundance matching. Vary models.

- Band: WMAP
- Planck changes?
- AdvACT/SPT3G: kSZ measure duration.

Calabrese et al (2014), Holzapfel talk

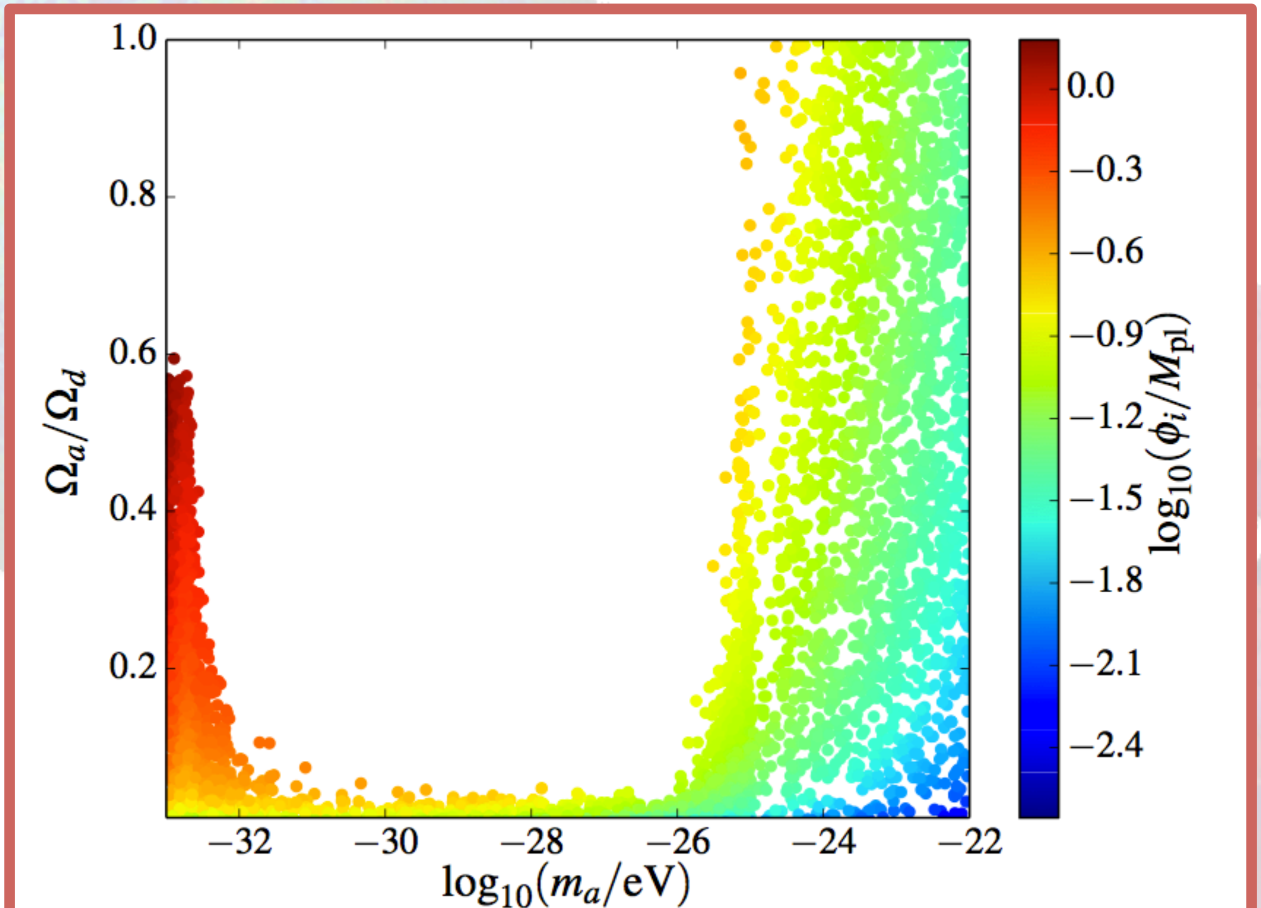
- 10^{-22} eV in tension currently. 10^{-21} eV reachable in future.

→ Axion dwarf core solution testable with reionisation.



Planck (ish)-scale physics

Relic abundance gives constraints on effective decay const.



What are the predictions from string theory?
Have we constrained any interesting models?

Isocurvature and inflation

Massless fields fluctuate → graviton/axion perts depend on H_I.
CMB constrains these modes → bounds on fractions r and α.

$$r \lesssim 0.2 \Rightarrow H_I \lesssim 10^{14}\ \mathrm{GeV}$$

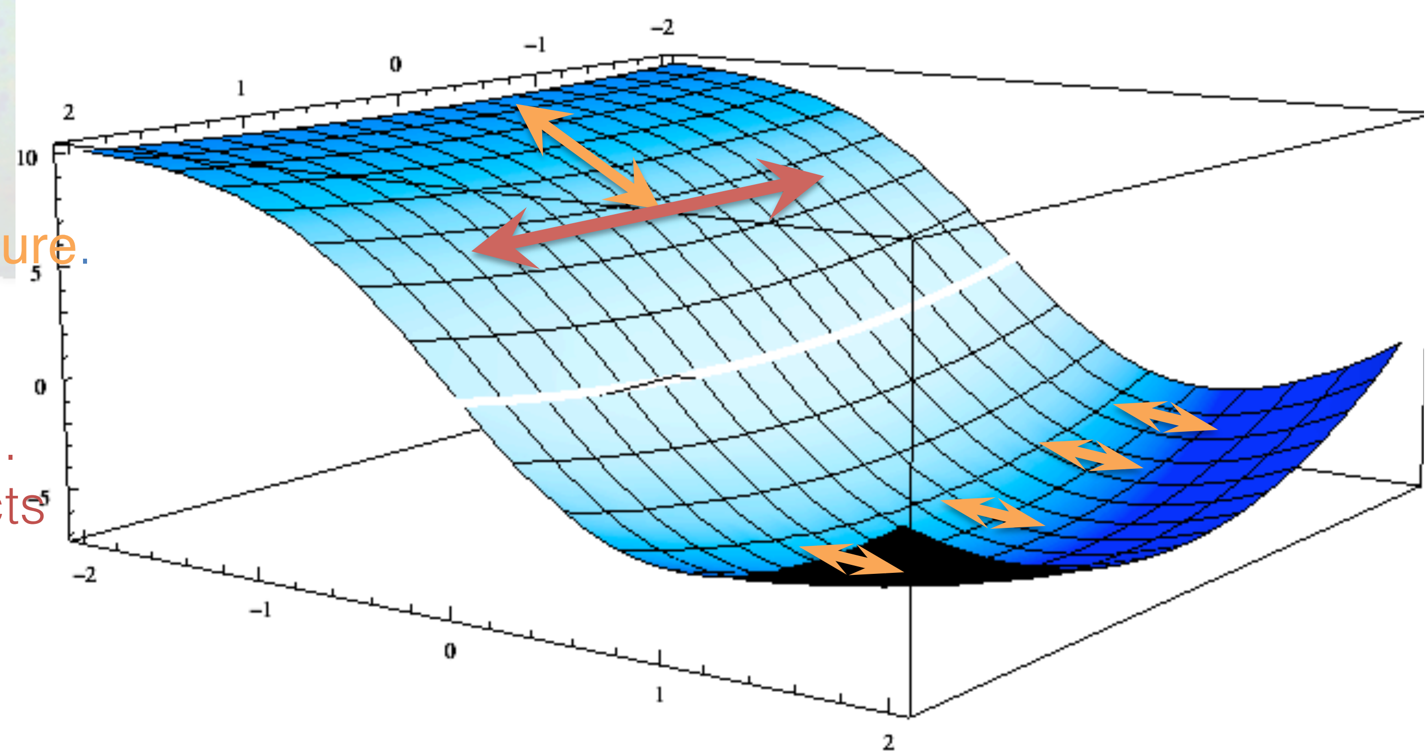
[QCD axion, all the DM]

$$\alpha \lesssim 0.05 \Rightarrow H_I \lesssim 10^{9}\ \mathrm{GeV}$$

e.g. Planck, WMAP

Inflaton ~ clock.
Fluctuations delay reheating → curvature.

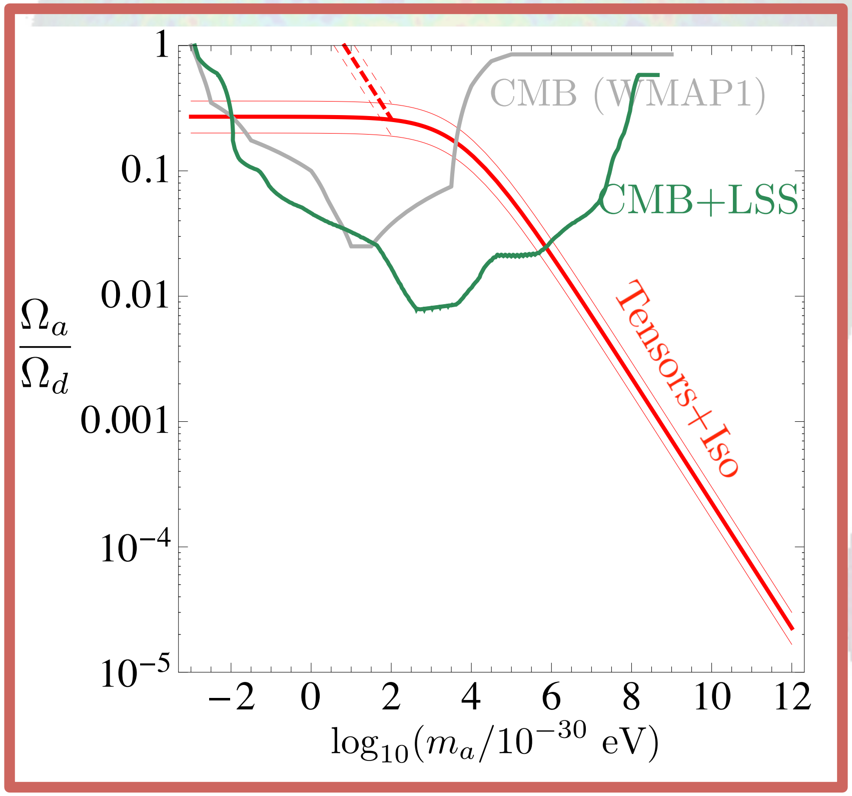
Axion ~ spectator.
Massless → frozen.
Late universe effects.



Using DM to test inflaiton

DJEM et al (2014)
Fairbairn, Hogan, DJEM (2014)

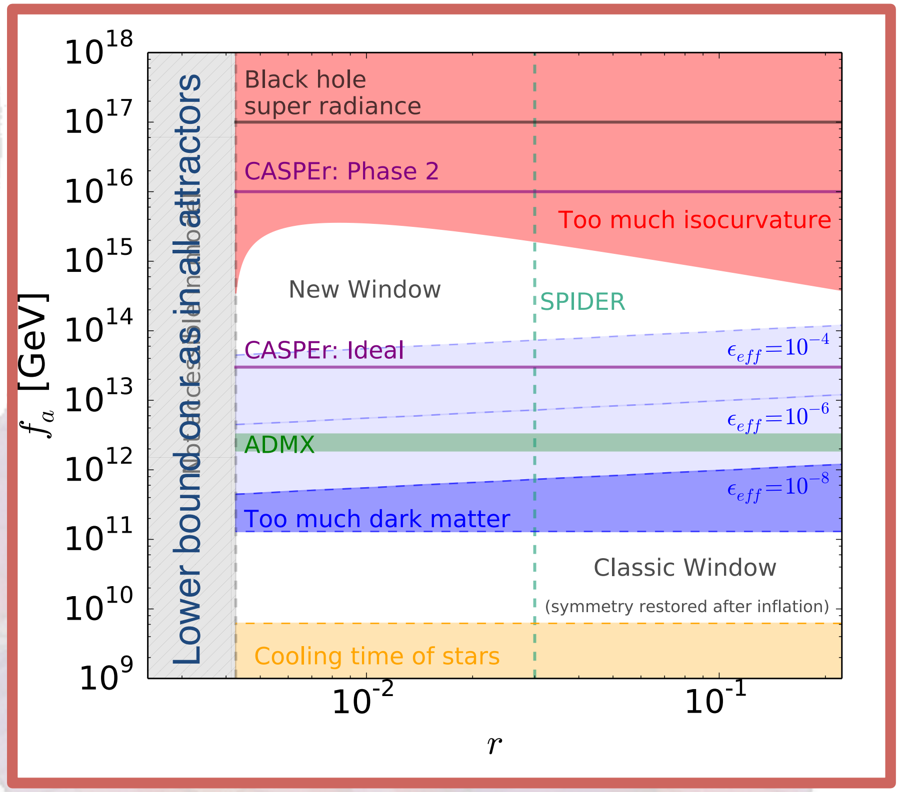
ULAs: structure formation



Dwarf cores mass forbids inf r. Imply synthetic?

See Sloth talk

QCD: direct detection



PQ inflaton attractor: CASPEr and Spider detections poss.

See Linde talk

Concluding remarks

If any searches, e.g.:

- CMB and LSS
- High-z galaxies
- Reionization
- Dwarf density profiles
- Direct detection
- …

(High-z galaxies, Reionization, Dwarf density profiles: complementary)

Reveal evidence of high f axions:

- cosmology - density
- QCD - coupling

Then:

tensors cannot be single-field slow-roll inflation