Title: Axions: an ideal cosmological probe of fundamental physics

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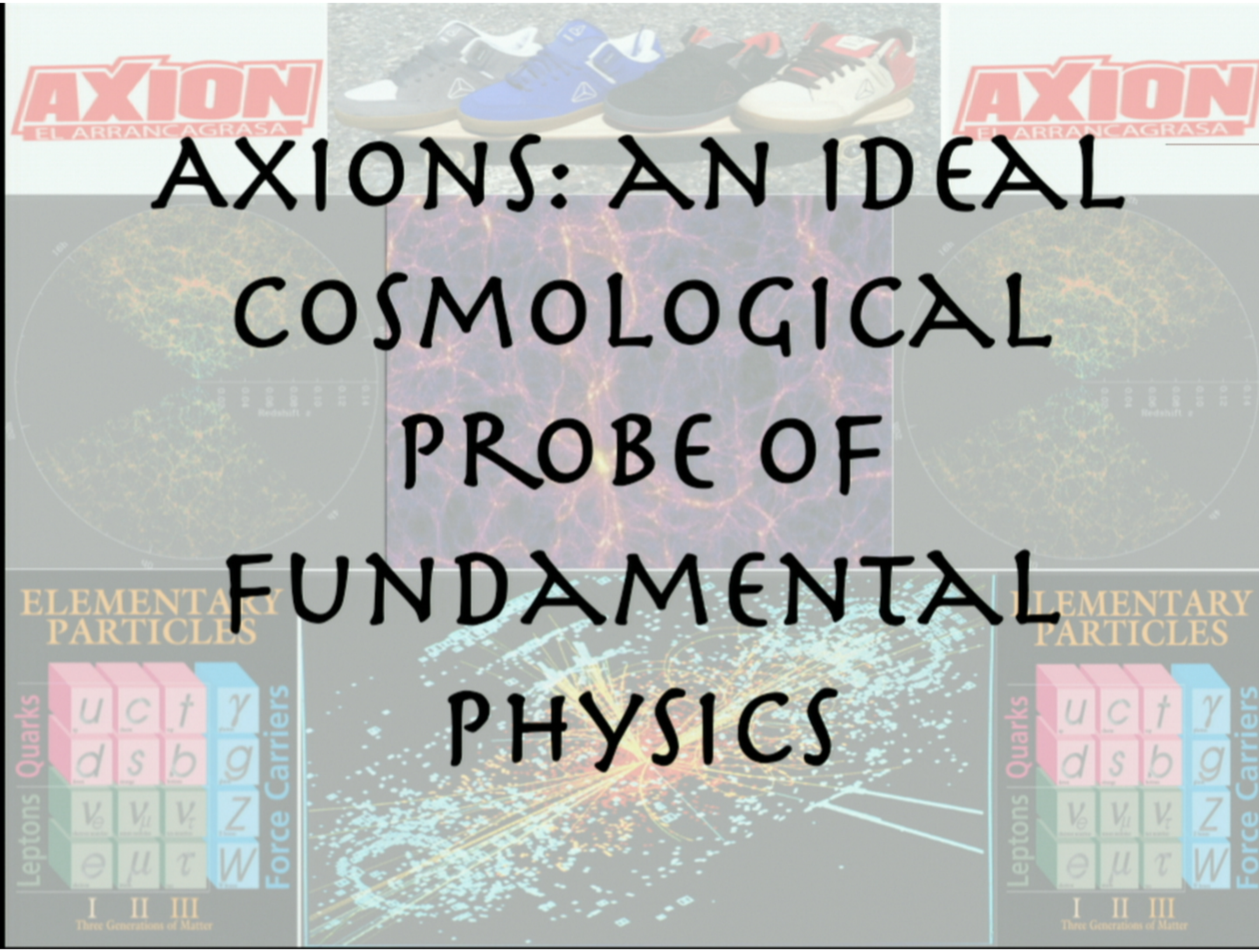
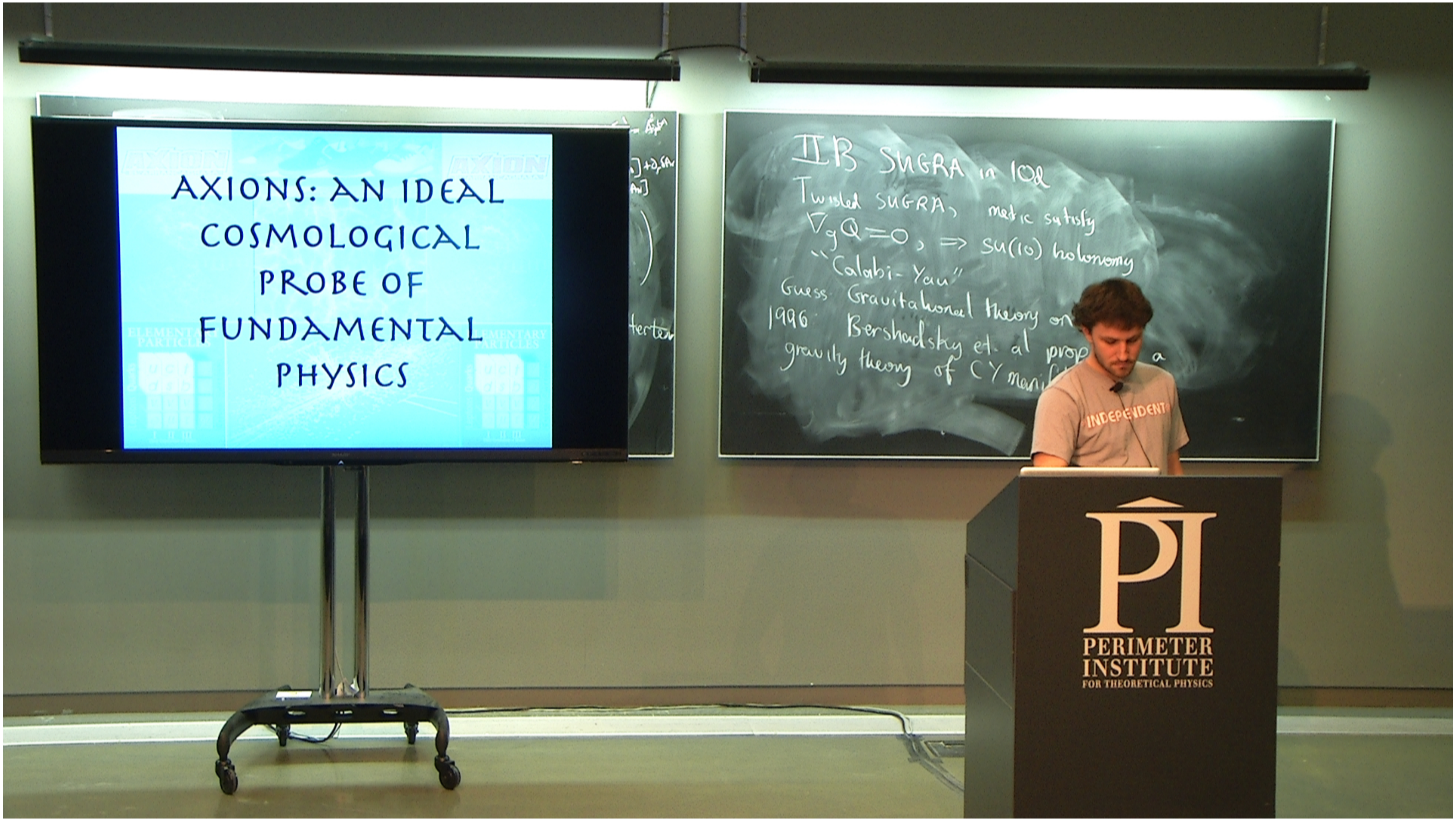
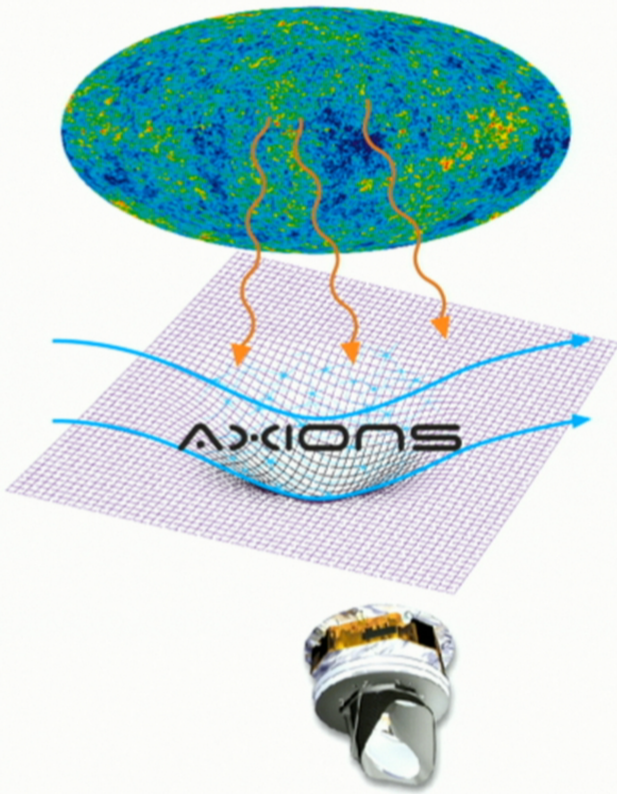
Abstract:

AXIONS: AN IDEAL COSMOLOGICAL PROBE OF FUNDAMENTAL PHYSICS




AXIONS: AN IDEAL COSMOLOGICAL PROBE OF FUNDAMENTAL PHYSICS
IIB SUGRA in 10d
Twisted SUGRA,
"Calabi-Yau"
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS
INDEPENDENT

A SEARCH FOR ULTRA-LIGHT AXIONS
USING PRECISION COSMOLOGICAL DATA



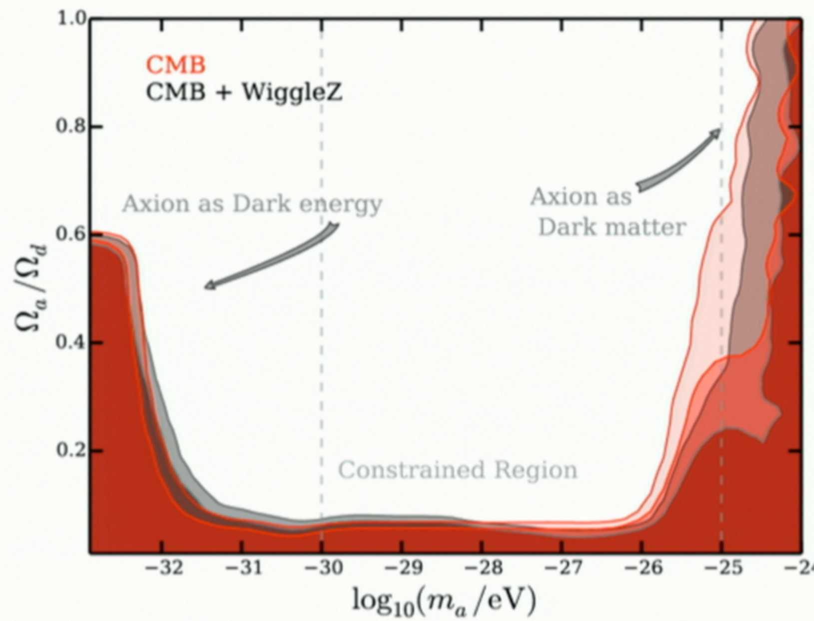


Image: Ela Secara

Collaborators





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

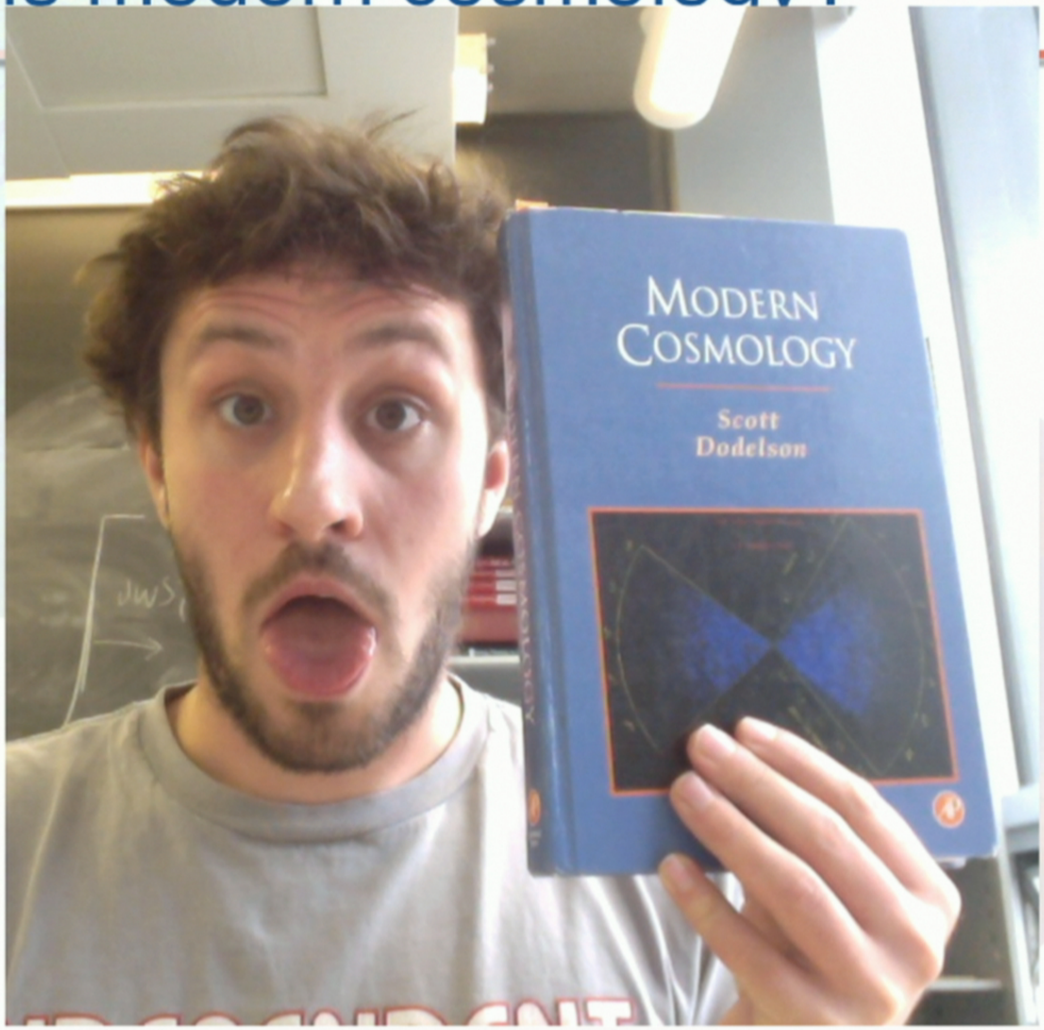
Using the CMB and large scale structure

Brandon Bozek, Joseph Silk & Rosemary Wyse
arXiv:1409.3544

Using high-z galaxies and reionisation

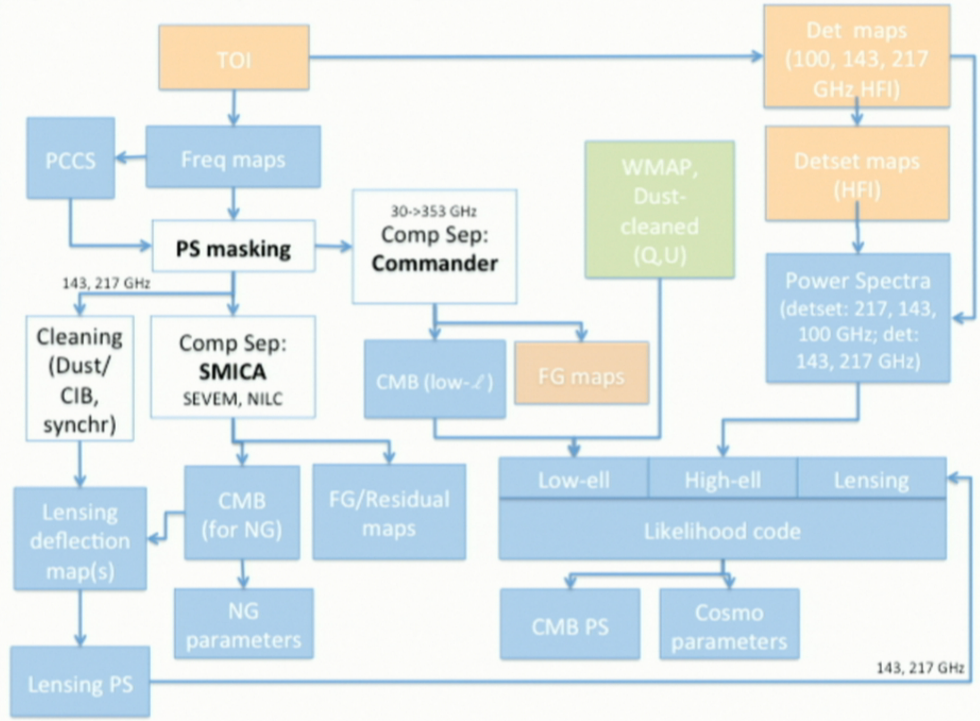
What is modern cosmology?

What is modern cosmology?



What is modern cosmology?

Case study: the LCDM model and Planck.
- Boltzman code (CAMB) + MCMC (cosmomc) Lewis and Challinor (2002)
- CMB temperature power spectrum Planck collaboration (2013)



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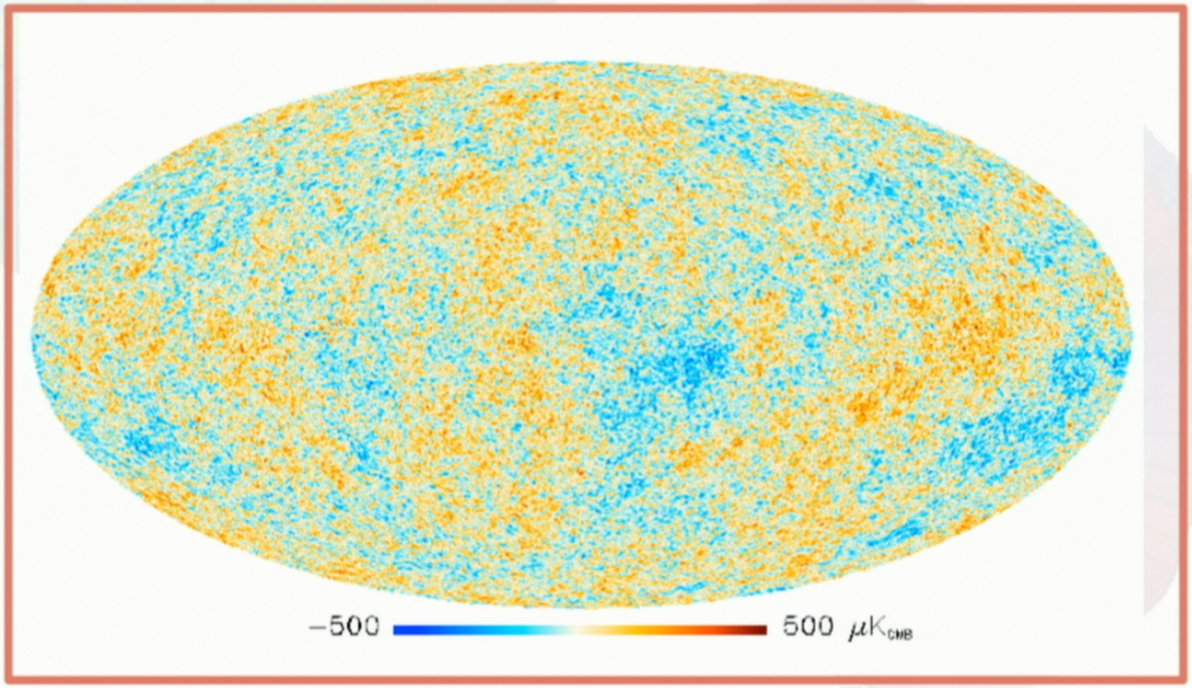

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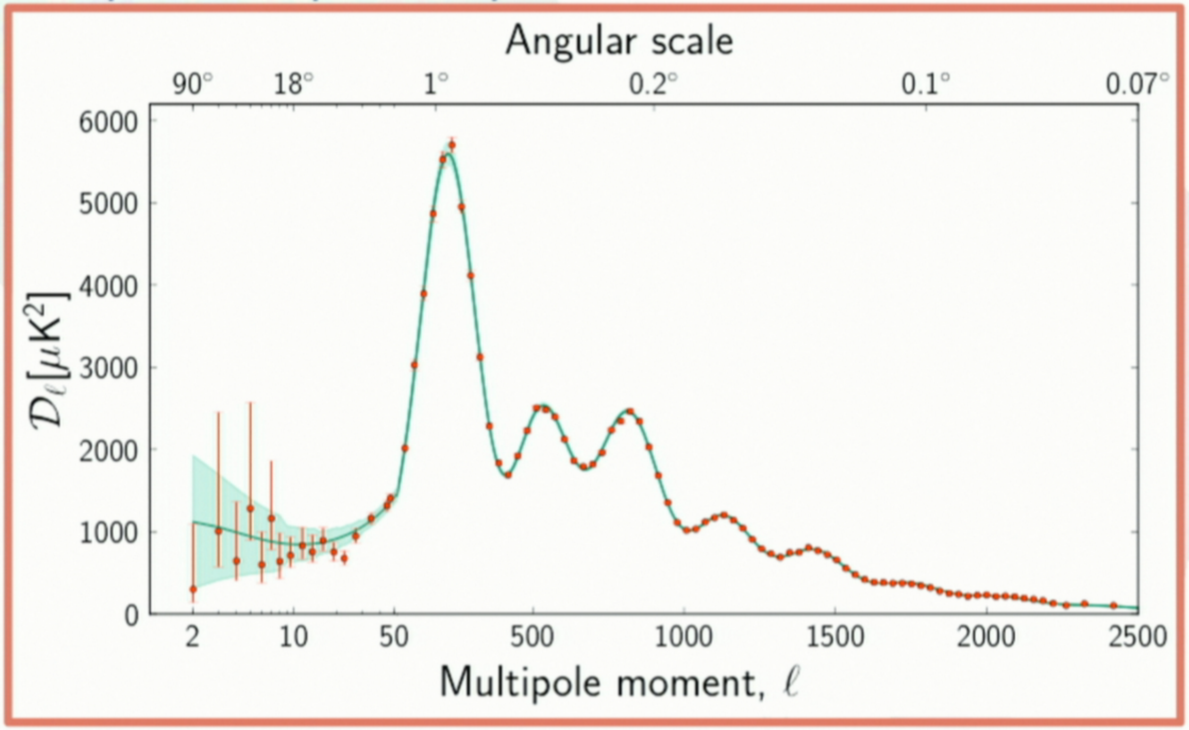

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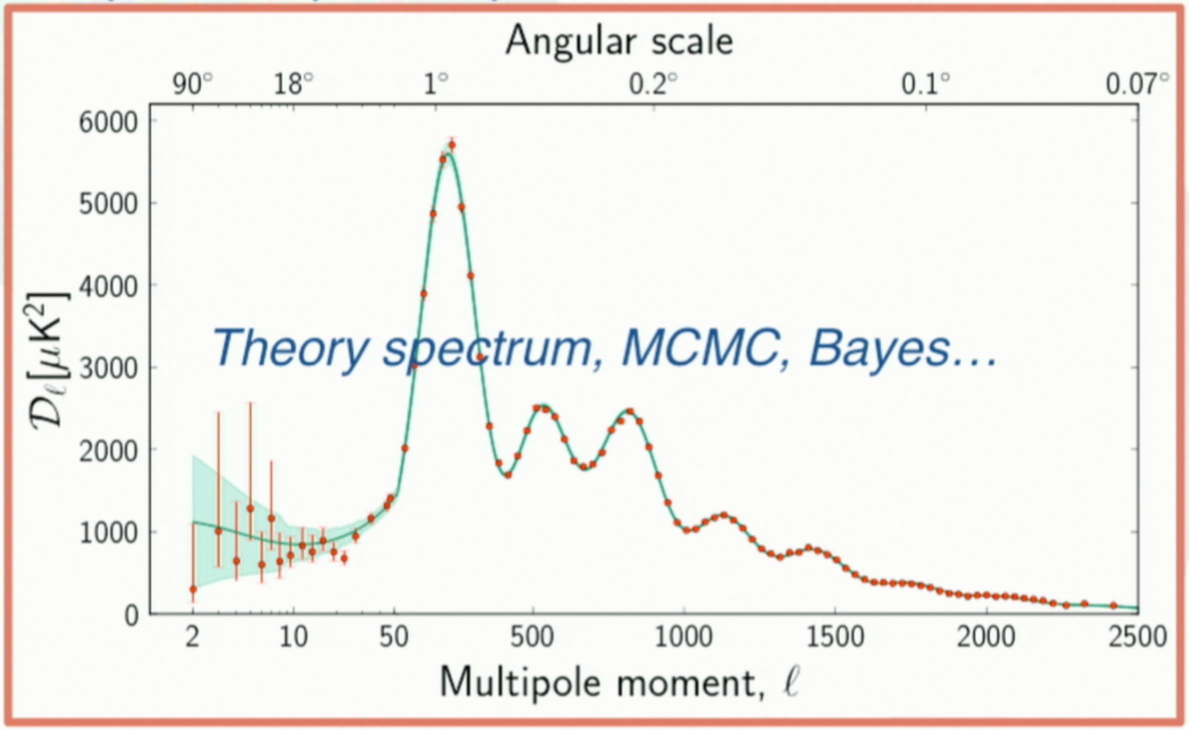

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Parameter	*Planck* (CMB+lensing) Best fit	*Planck* (CMB+lensing) 68 % limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

Cosmology and fundamental physics

Central problems:

- ✧ Cosmology is statistics.
- ✧ Model dependence.

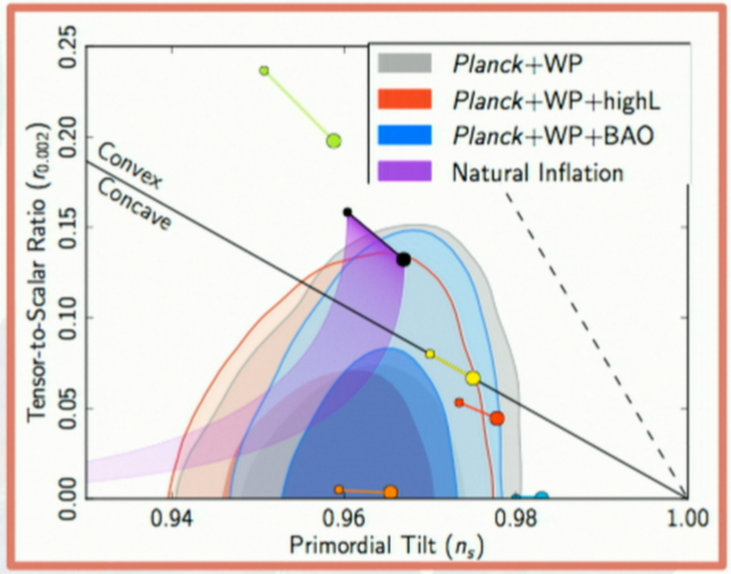
To really learn about fundamental physics with cosmology, the models must be clear and general, with few steps between theory and physical effect.*

[* i.e. extract parameters with a clear (high energy-) physical meaning]

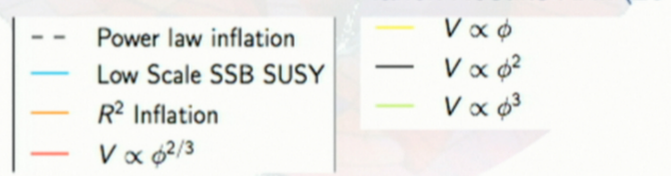
Cosmology and fundamental physics

Inflation: cosmology made big promises. But have we delivered?

- Some new physics definitely needed. ✔
- Certain models are ruled out. ✔
- Many very different models consistent (e.g. inflation vs cyclic). ✗
- Tensors necessary for model selection. ✗
- Range of models and interpretations vast. ✗
- Predictions in eternal inflation ???



Planck Results XXII (2013)



Cosmology and fundamental physics

Inflation: cosmology made big promises. But have we delivered?

My very scientific assessment: NO

(or at least not yet…)

Cosmology and fundamental physics

Massive neutrinos: a particle-cosmology success story!

- We know neutrinos have mass:

$$\sum m_\nu > 0.06 \text{ eV}$$

(oscillation experiments)
Forero et al (2012)

- CMB + LSS close to this sensitivity:

$$\sum m_\nu < 0.23 \text{ eV}$$

(Planck+WP+highL+BAO)
Planck Results XVI (2013)

- May even resolve hierarchy with e.g. *Euclid.* de Bernardis et al (2009)
- Neutrinos can play an important role in resolving cosmological tensions. e.g. Beutler et al (2014)
- Can constrain other properties, e.g. additional species, sterile mass. Hints for keV WDM from small scales?

Cosmology and fundamental physics

Massive n… story!

- We kno…

…on experiments)

Forero et al (2012)

- CMB + L…

…/P+highL+BAO)

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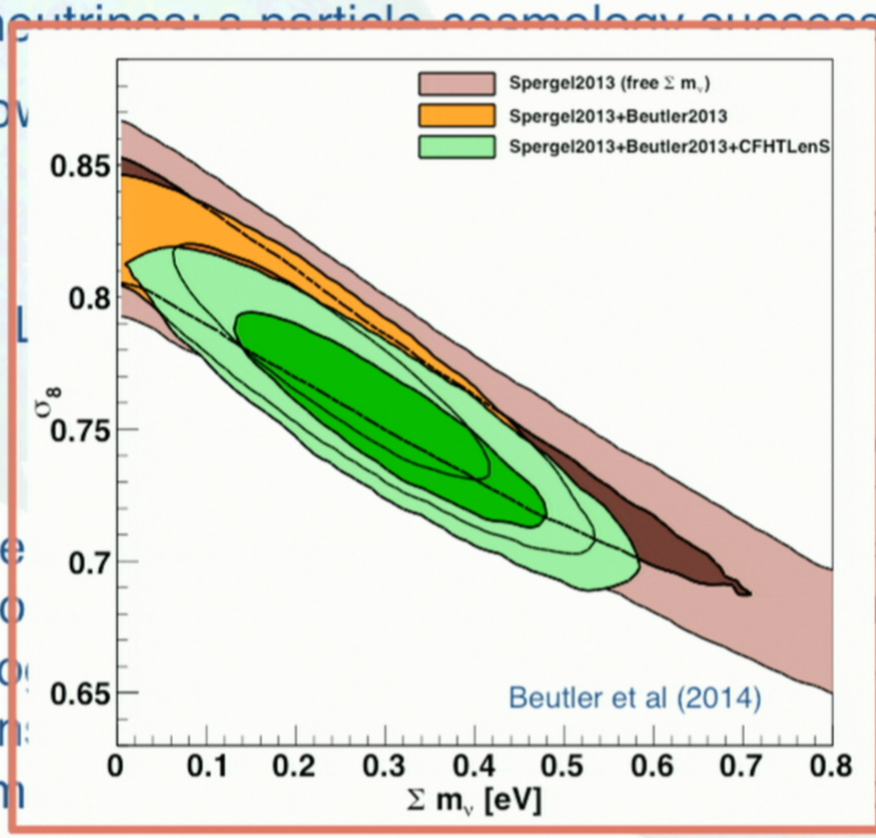


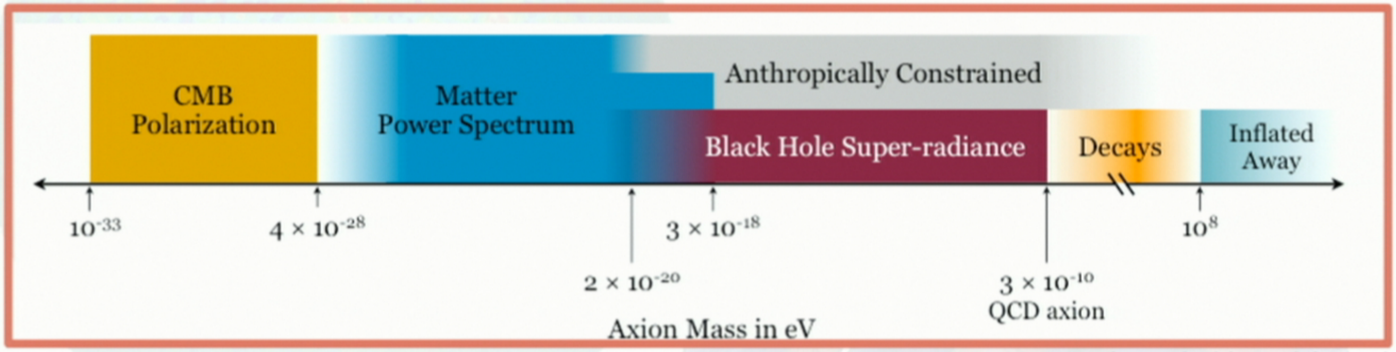
- May eve…
- Neutrin… …ng cosmolo…

…g. Beutler et al (2014)

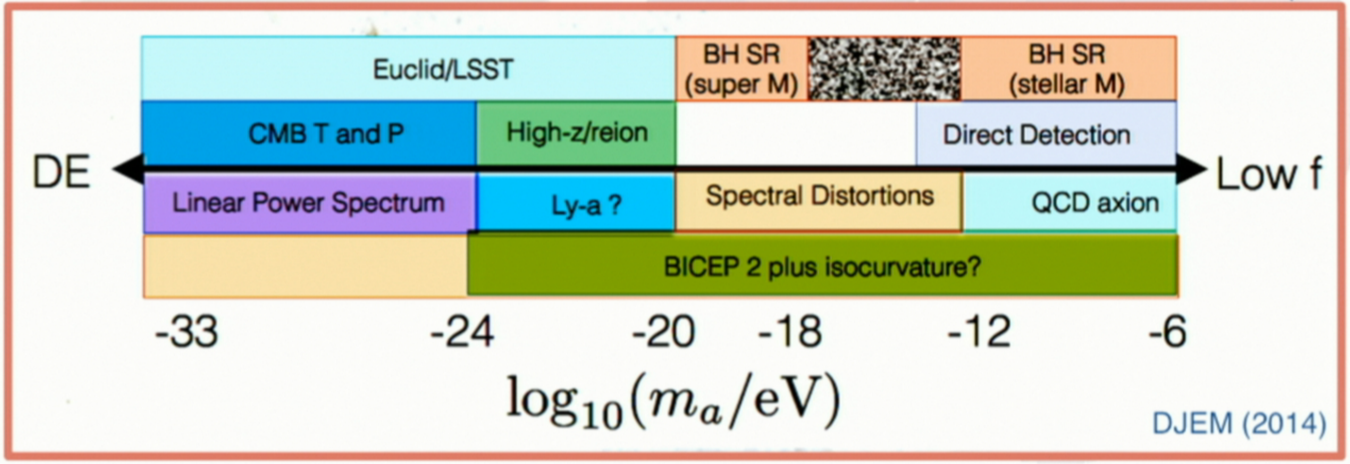
- Can con… …species, sterile m… …ales?

Cosmology and fundamental physics

Ultra-light axions (ULAs), like ν's, will prove a success story.



Arvanitaki et al (2009)



Outline

- Introduction to axion cosmology.
- Precision constraints.
- Small scales and more.
- Relation to Planck-scale physics.

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)

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

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

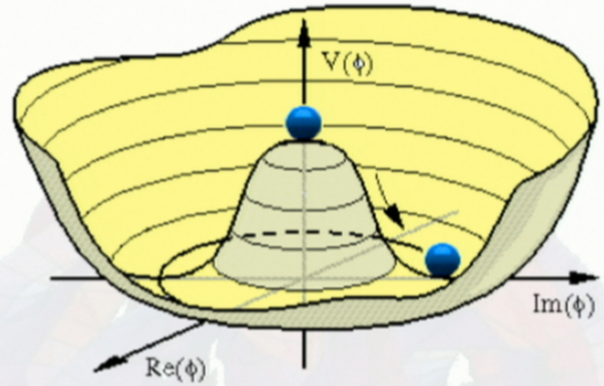
e.g. Svrcek & Witten (2006)
Arvanitaki et al (2010)

[* 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.



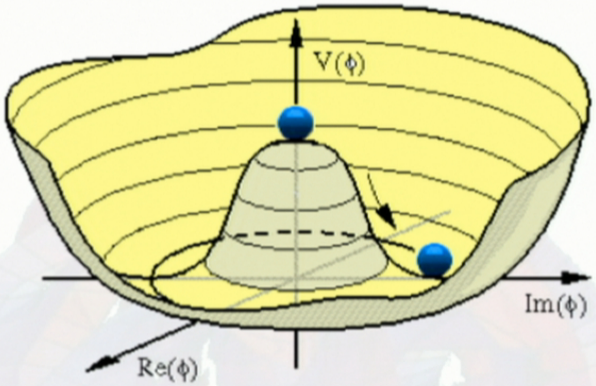
http://www.hep.ph.ic.ac.uk/cms/physics/higgs.ht

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.



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

$$\ddot{\phi} + \boxed{3H}\dot{\phi} + m_a^2\phi = 0$$

Hubble friction
→ Freezes field

Misalignment production

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

Energy density as function of field → relic abundance.

$$\rho = \frac{1}{2}(\dot{\phi}^2 + m_a^2 \phi^2)$$

$$\Omega_{\rm a} = \left[\frac{a^{-2}}{2}\dot{\phi}_0^2 + \frac{m_a^2}{2}\phi_0^2\right]_{m_a=3H} a_{\rm osc}^3/\rho_{\rm crit}$$

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$$\rho = \frac{1}{2}(\dot{\phi}^2 + m_a^2\phi^2)$$

$$\Omega_a = \begin{cases} \frac{1}{6}(9\Omega_r)^{3/4}\left(\frac{m_a}{H_0}\right)^{1/2}\left(\frac{\phi_{0,i}}{M_{pl}}\right)^2 \text{if } a_{\rm osc} < a_{\rm eq} \\ \frac{9}{6}\Omega_m\left(\frac{\phi_{0,i}}{M_{pl}}\right)^2 \text{ if } a_{\rm eq} < a_{\rm osc} \lesssim 1\,, \\ \frac{1}{6}\left(\frac{m_a}{H_0}\right)^2\left(\frac{\phi_{0,i}}{M_{pl}}\right)^2 \text{ if } a_{\rm osc} \gtrsim 1\,, \end{cases}$$

Initial conditions related to Planck-scale physics

Modeling perturbations

Axion mass fixes a scale. Fundamentally, de Broglie.
Sound-speed in fluid. “Jeans” scale in structure formation.

Uncertainty $\lambda_{\rm dB} = \dfrac{1}{mv}$ Recede with Hubble flow $v_{\rm H} = Hr$

Localisation only possible on large scales $r \gtrsim (mH)^{-1/2}$

c.f. CDM and QCD axion cluster on all cosmological scales

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+

=

Modeling perturbations

Axion mass fixes a scale. Fundamentally, de Broglie.
Sound-speed in fluid. “Jeans” scale in structure formation.

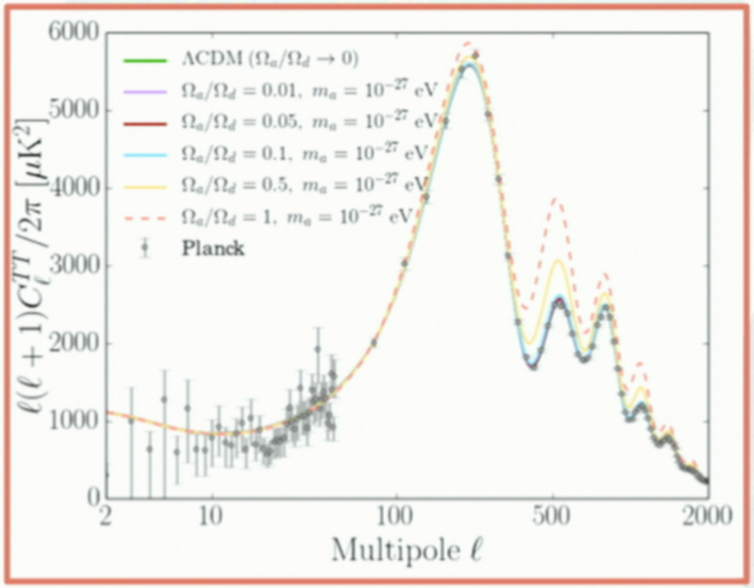
$$10^{-33}\ \mathrm{eV} \lesssim m_a \lesssim 10^{-20}\ \mathrm{eV}$$

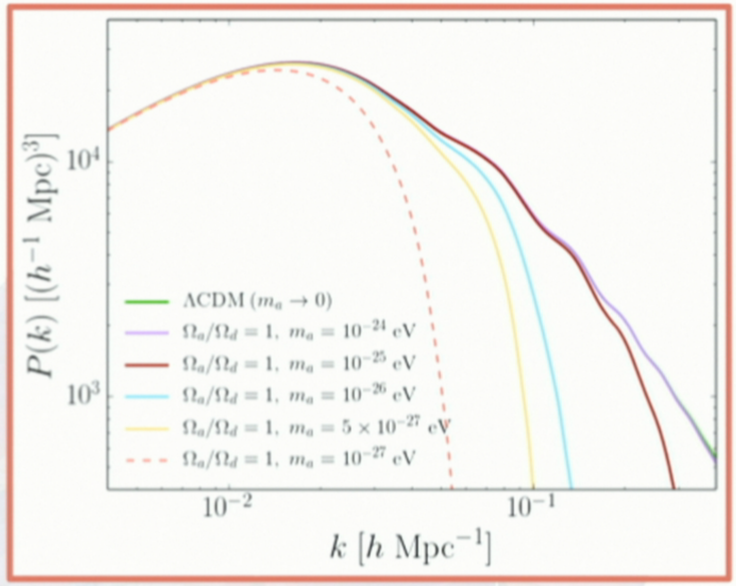
~ Gpc^{-1}, size of visible universe

~ kpc^{-1}, size of dwarf galaxy

Cosmological observables

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

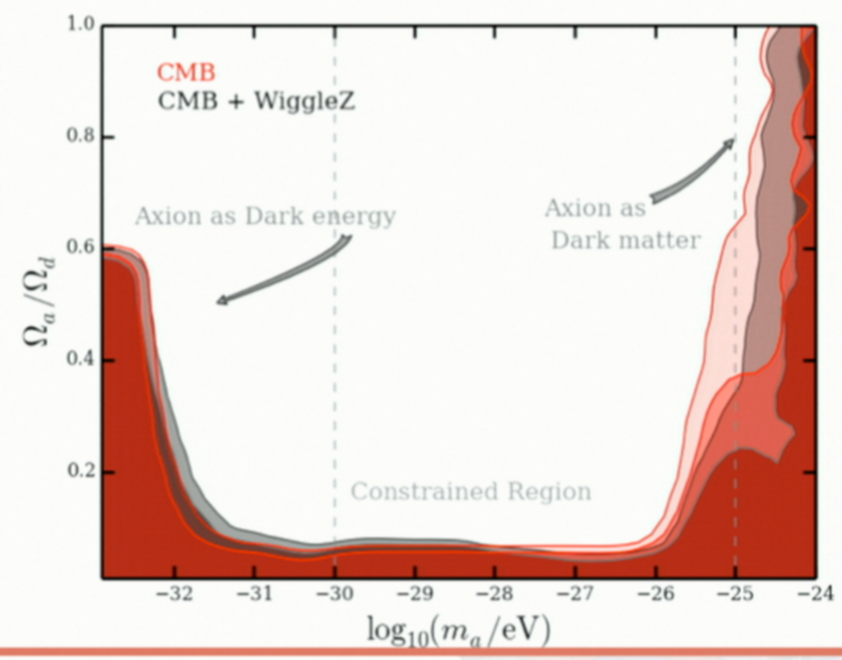




CMB temperature: variation of density. Expansion rate changes peak heights.

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

Precision constraints



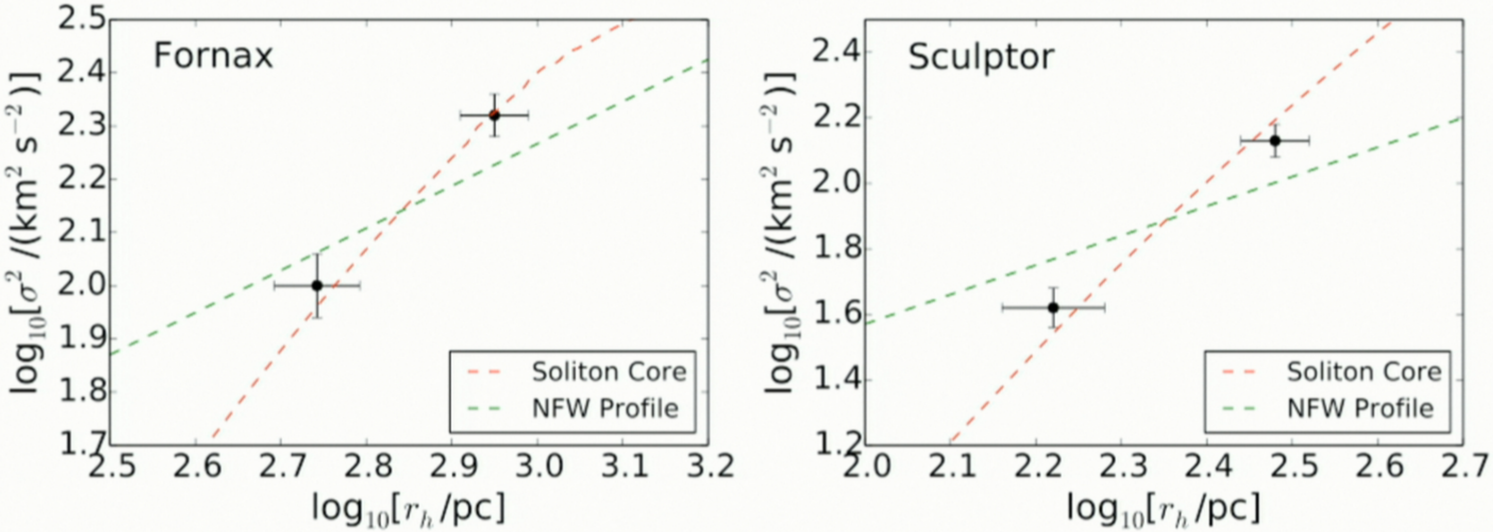
$\Omega_a/\Omega_d < 0.05$ (marginalised over all other parameters)

Why light axions?

Ongoing work with PI summer student 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 uncertainty.

Linear modes used, but need to push into this regime.

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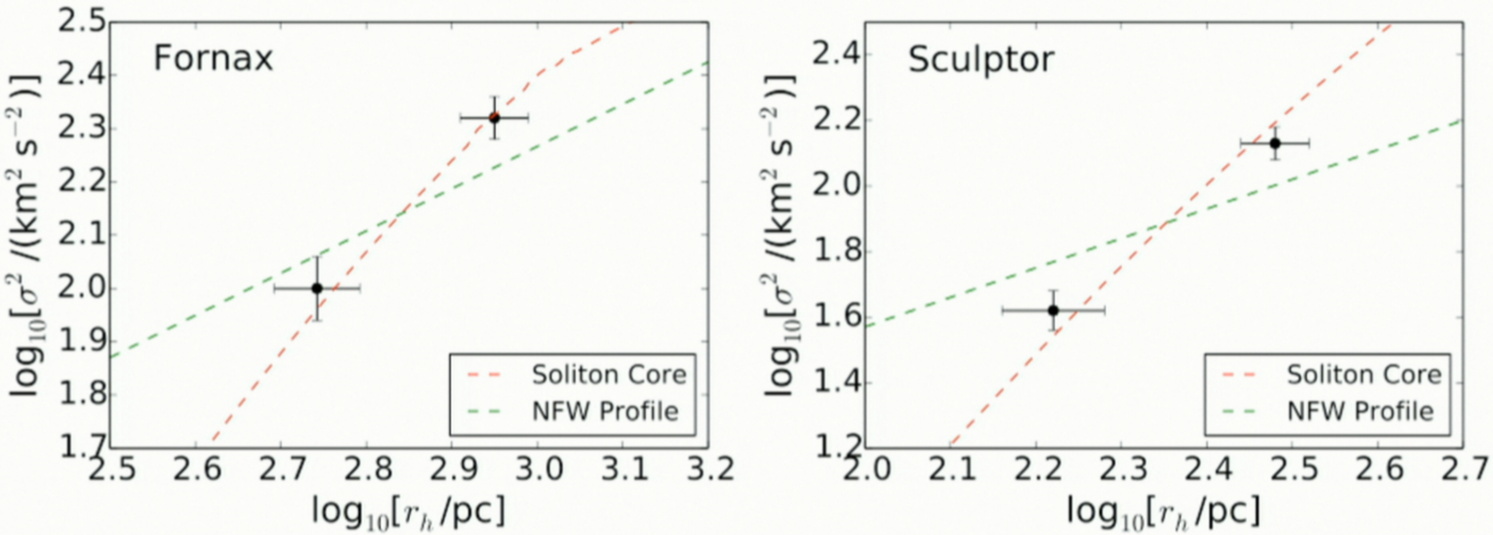

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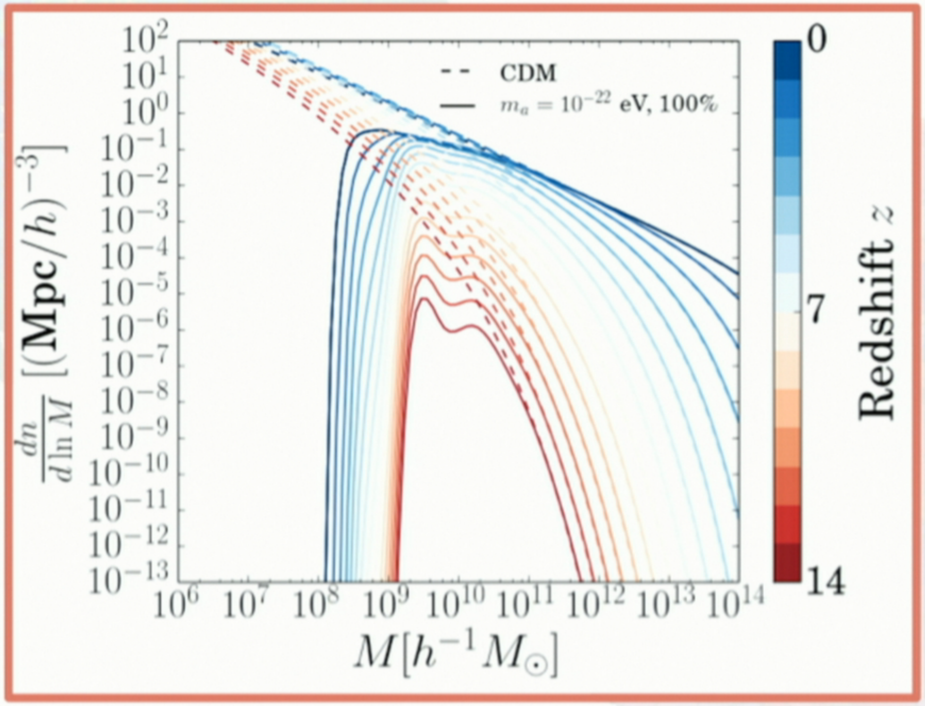
Halo formation at high redshift

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)

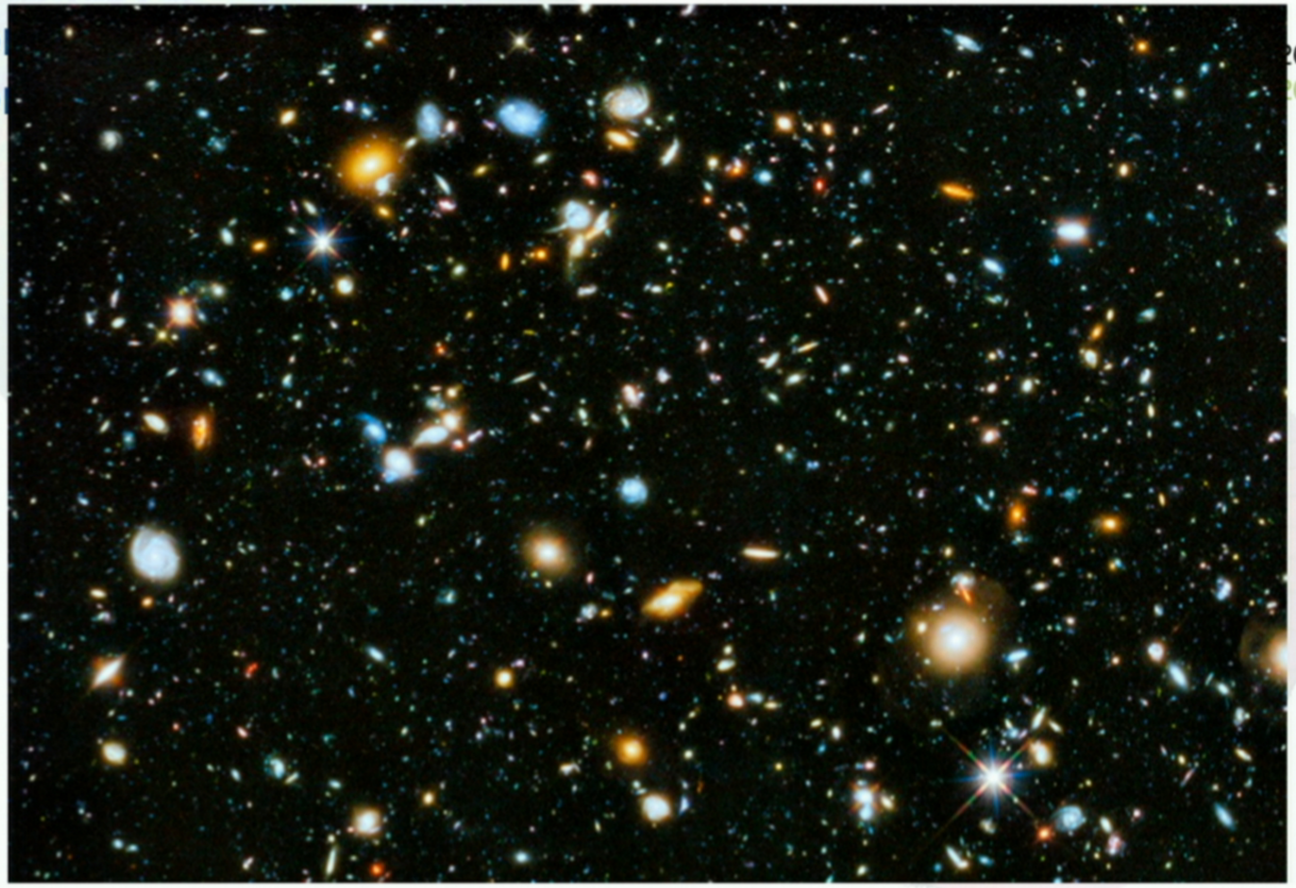
Hubble and James Webb

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

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

Hubble and James Webb

Co 2014)
Co 2006)



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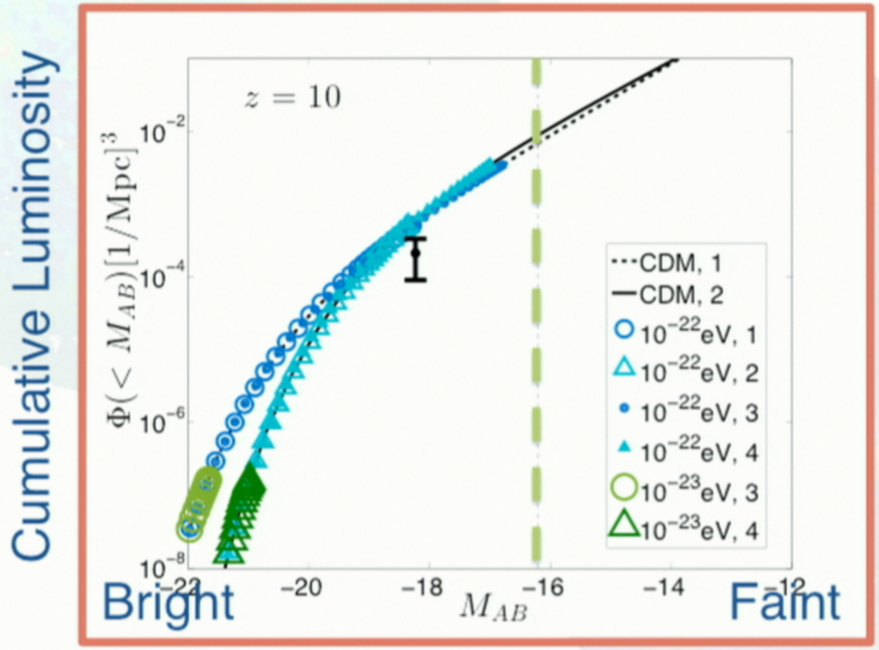
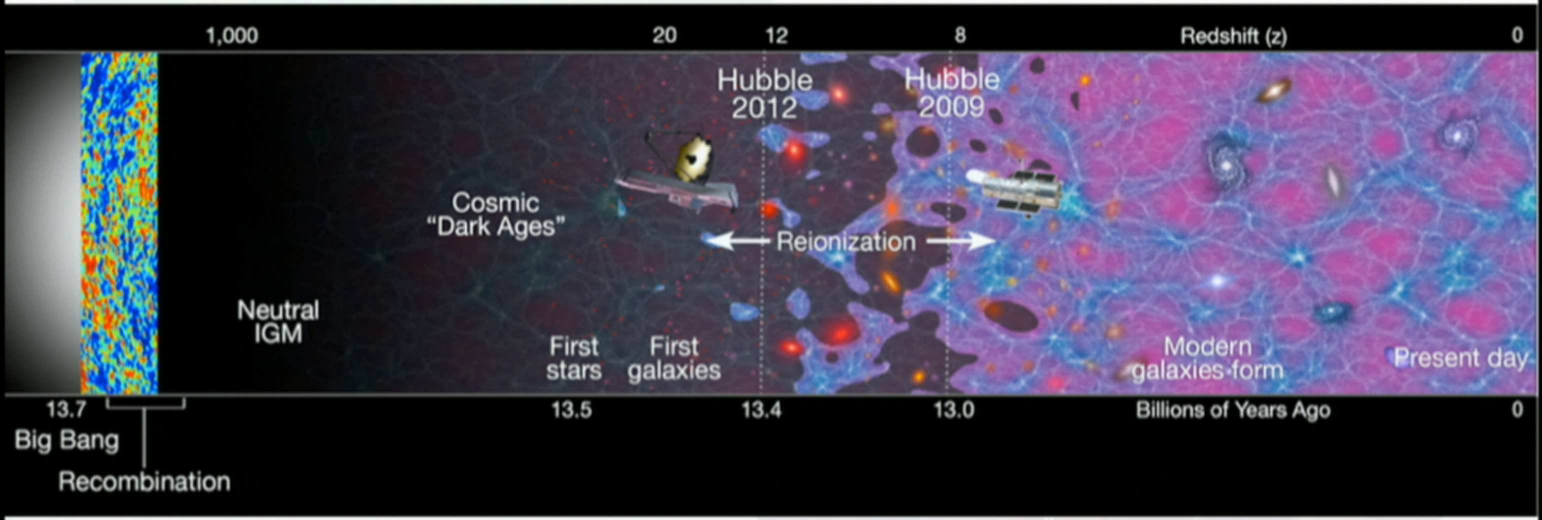


HUDF data
z=6,7,8,10
JWST z=13

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

Cosmic reionisation

Galaxies at high-z reionise the Universe.



Credit: NASA/ESA from caltech.edu

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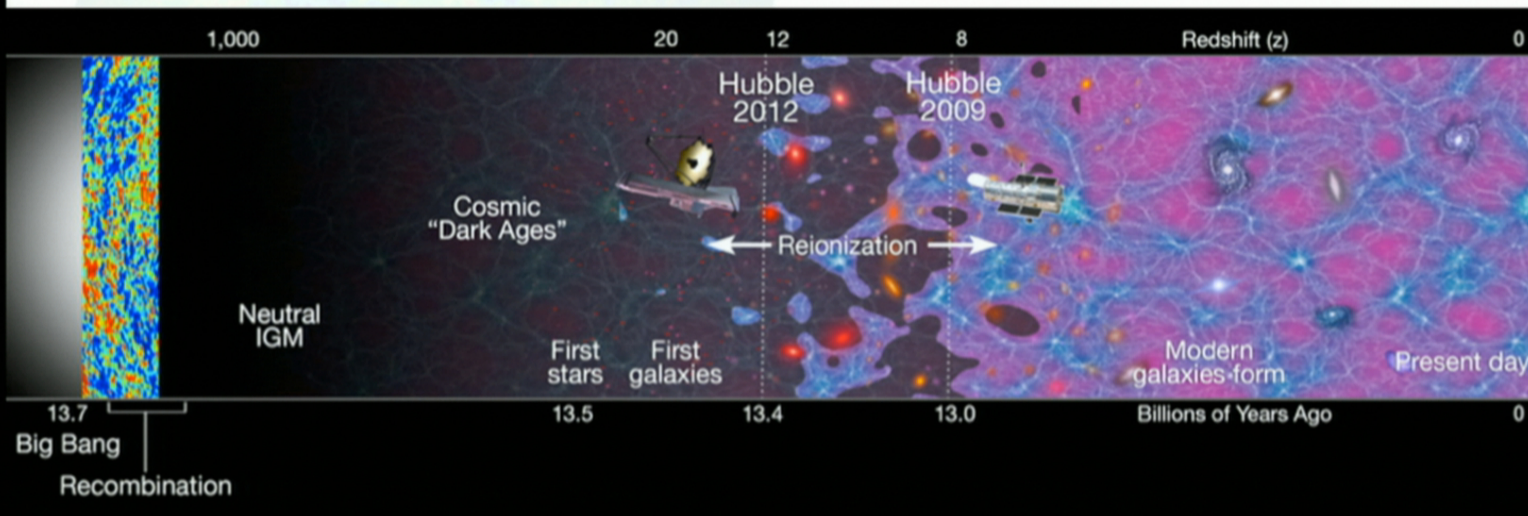
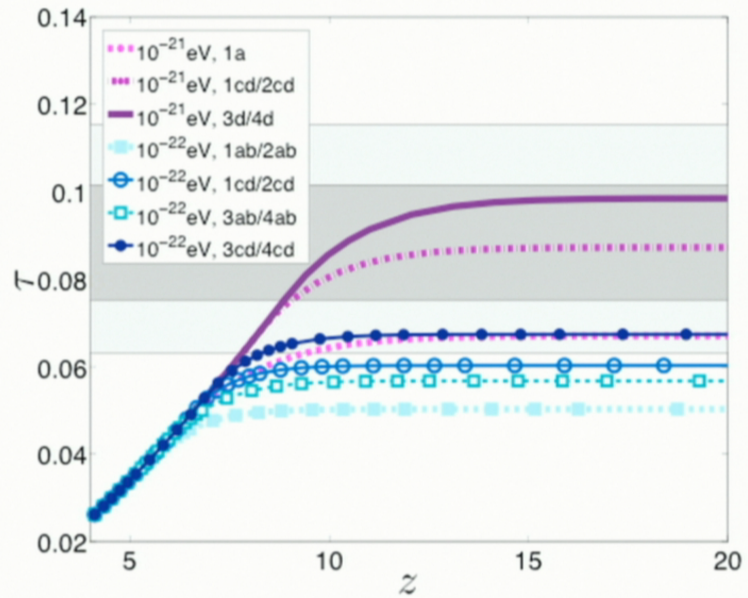


Credit: NASA/ESA from caltech.edu

Cosmic reionisation

Galaxies at high-z reionise the Universe.
Optical depth to CMB, τ, measured using polarisation.

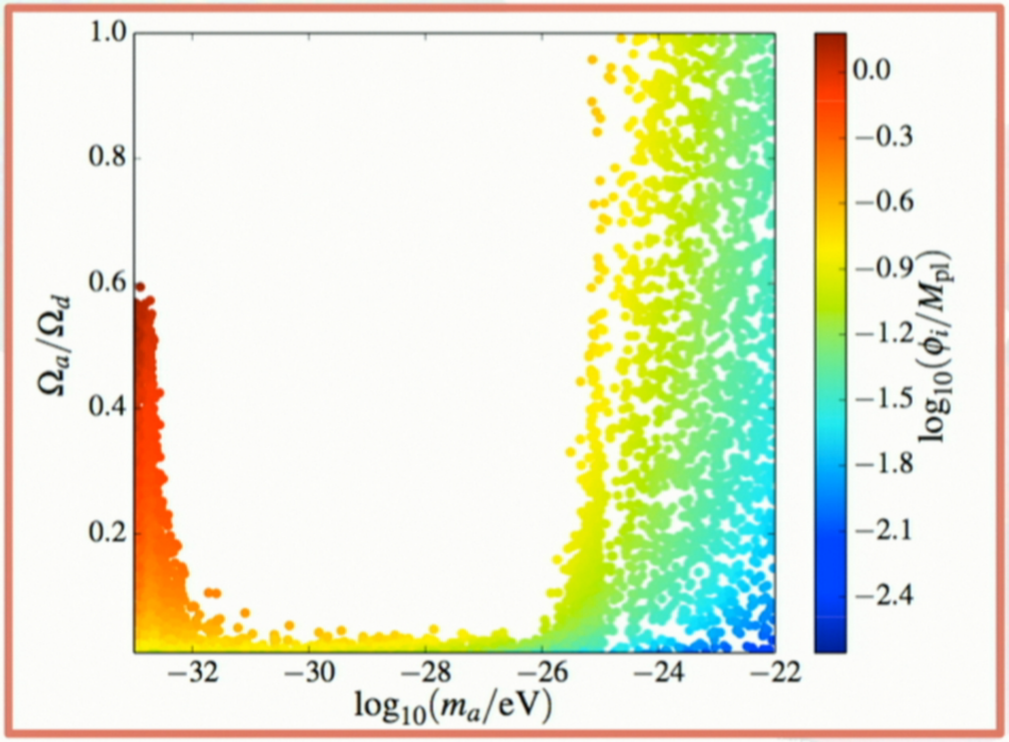
- Band: WMAP
- Planck December: rumoured down.
- AdvACT 2015: kSZ measure duration.



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

Planck (ish)-scale physics

Relic abundance gives constraints on effective decay const.
Consistent with simplest picture & “weak gravity conjecture”
Arkani-Hamed et al (2007)



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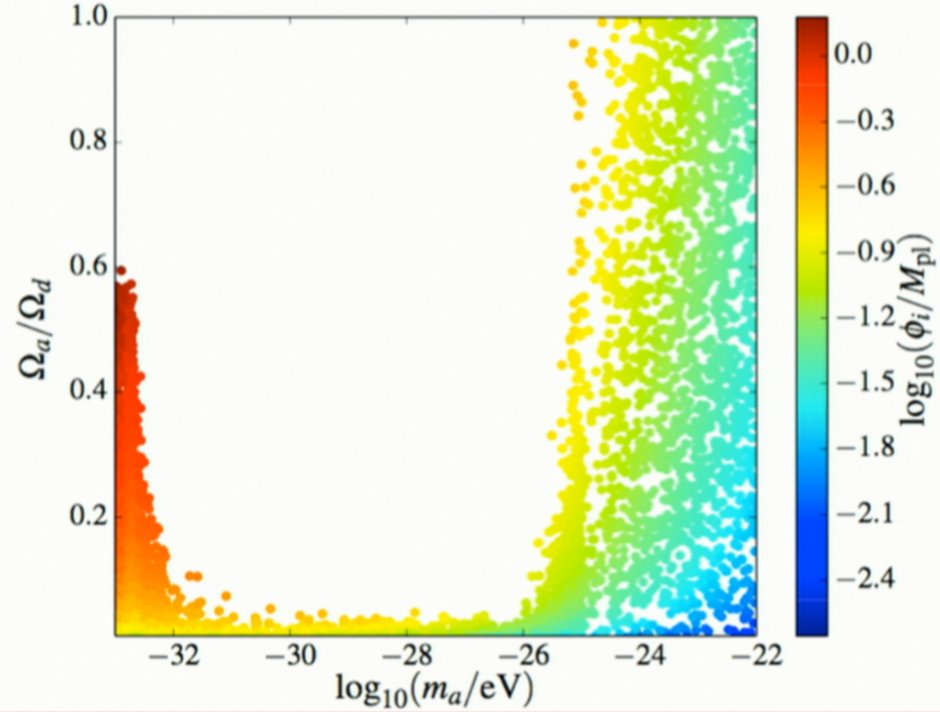
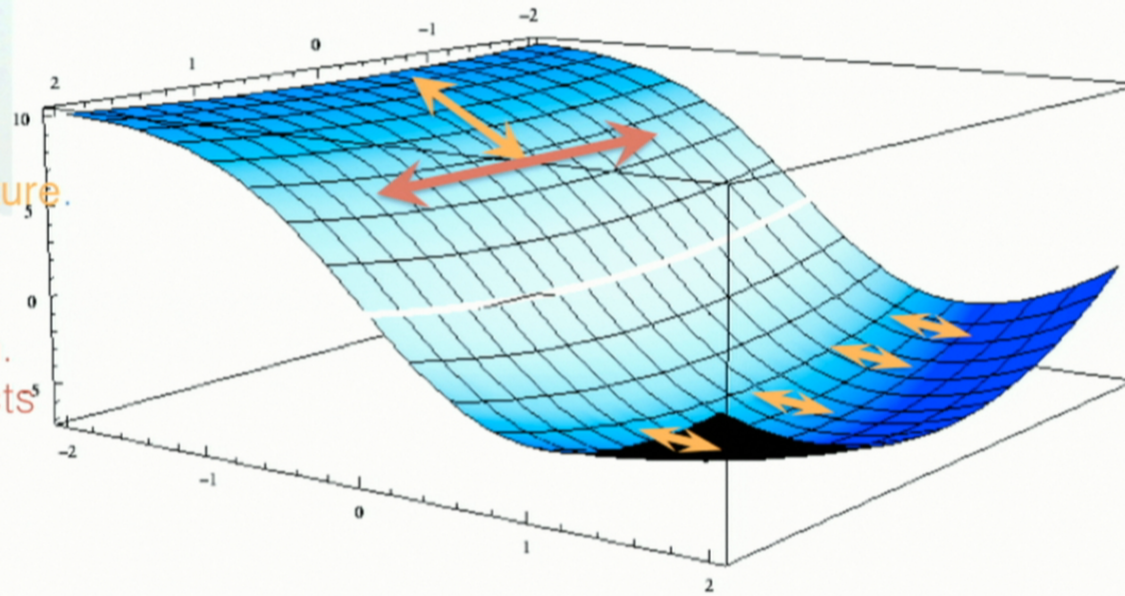


Isocurvature and inflation

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

Inflaton ~ clock.
Fluctuations delay reheating → curvature.

Axion ~ spectator.
Massless → frozen.
Late universe effects



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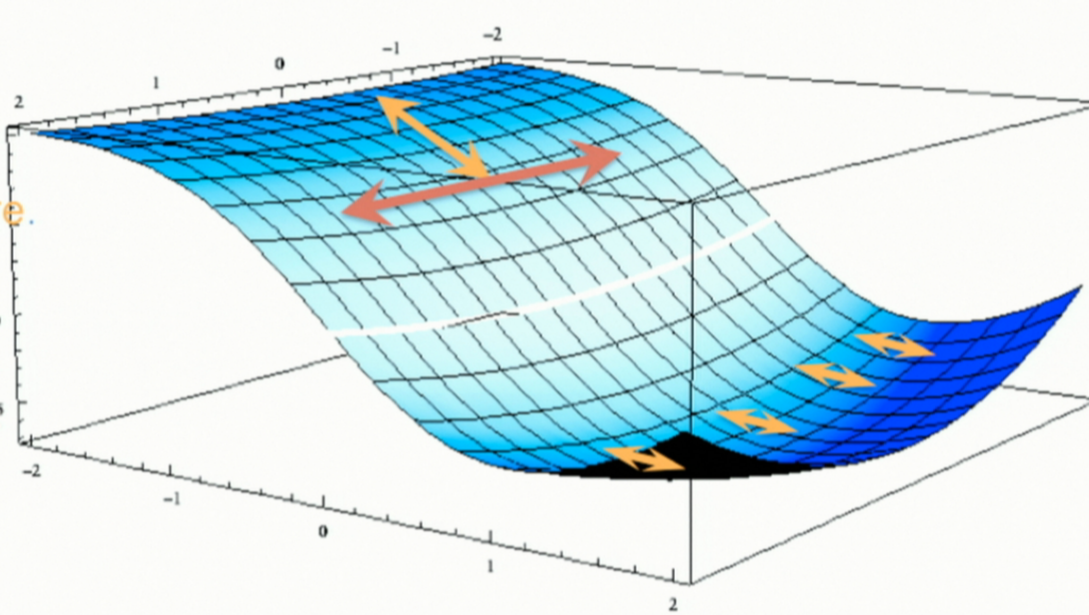

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$$r \lesssim 0.2 \Rightarrow H_I \lesssim 10^{14}\ \mathrm{GeV}$$

e.g. Planck, WMAP

[QCD axion, all the DM]

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

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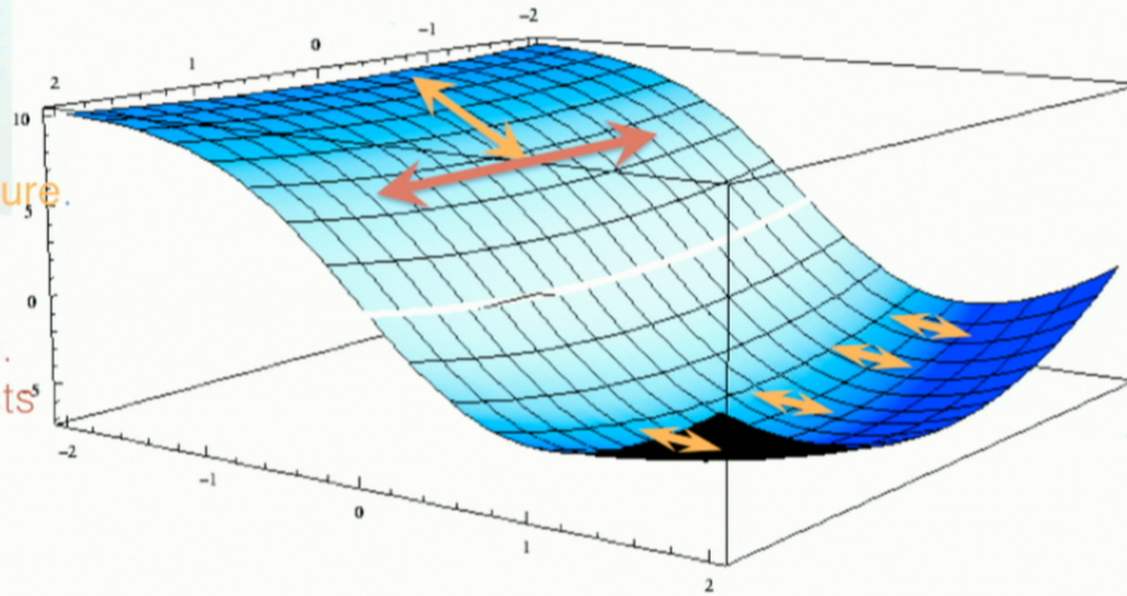

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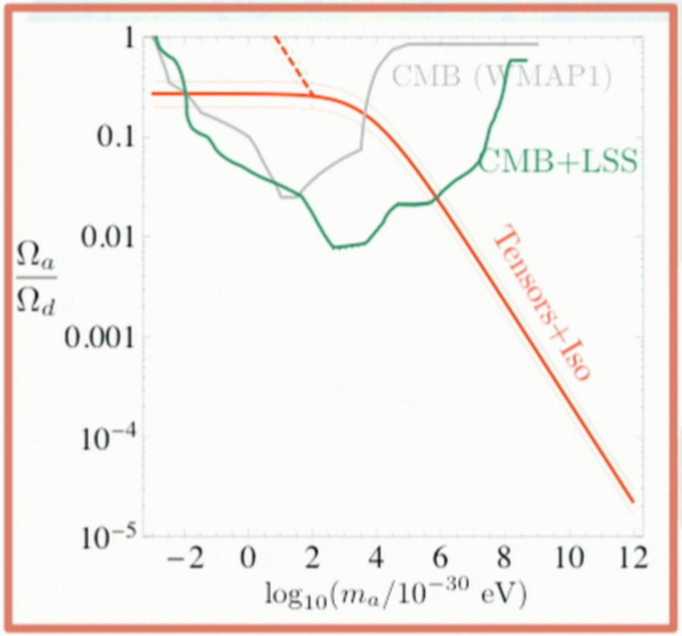
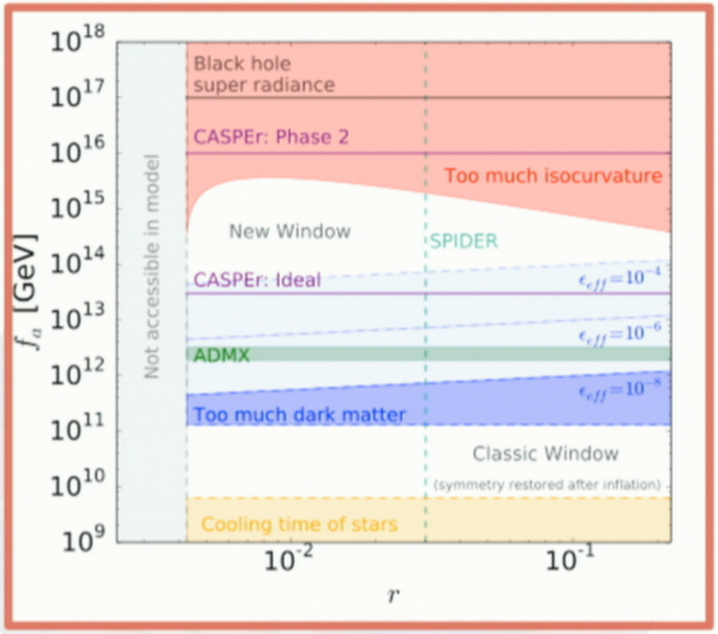
If axions are the Dark Matter, perturbation modes in the CMB probe the early universe in the "desert."

Isocurvature and inflation

We can use complementary probes to check inflation.



DJEM et al (2014)



Fairbairn, Hogan, DJEM (2014)

Light axion DM: small-scales and BICEP2.

Detecting the QCD axion: CASPEr and Spider.

Isocurvature and inflation

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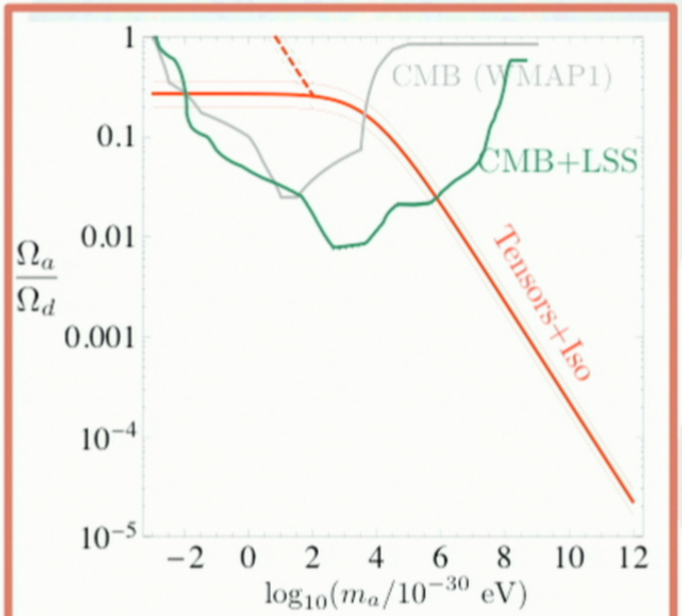
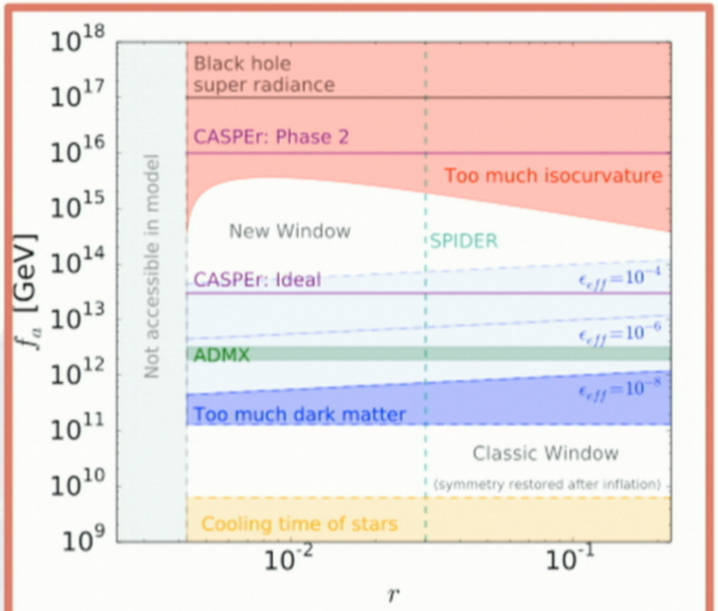


DJEM et al (2014)



Fairbairn, Hogan, DJEM (2014)

Light axion DM: small-scales and BICEP2.

Detecting the QCD axion: CASPEr and Spider.

Concluding remarks

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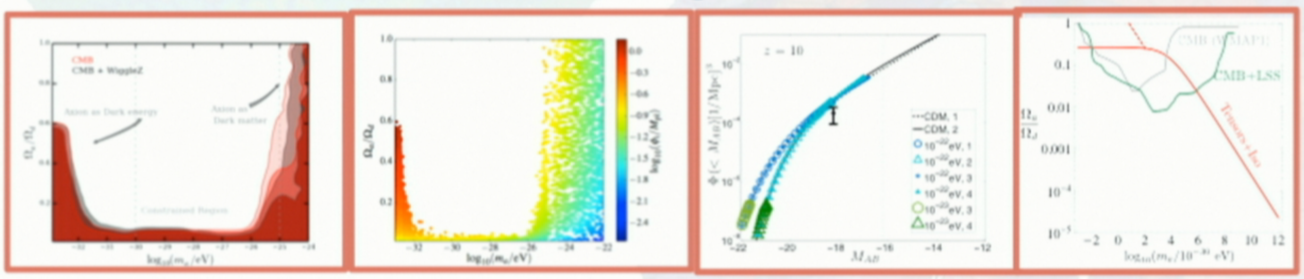

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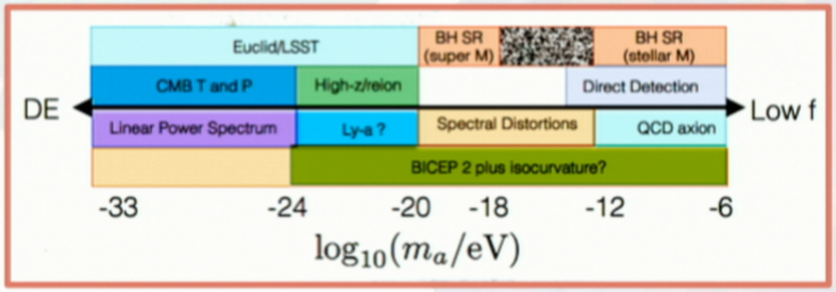

✧ What next? Complementary probes e.g.
(i) JWST high-z galaxies & AdvACT kSZ: close in on mass.
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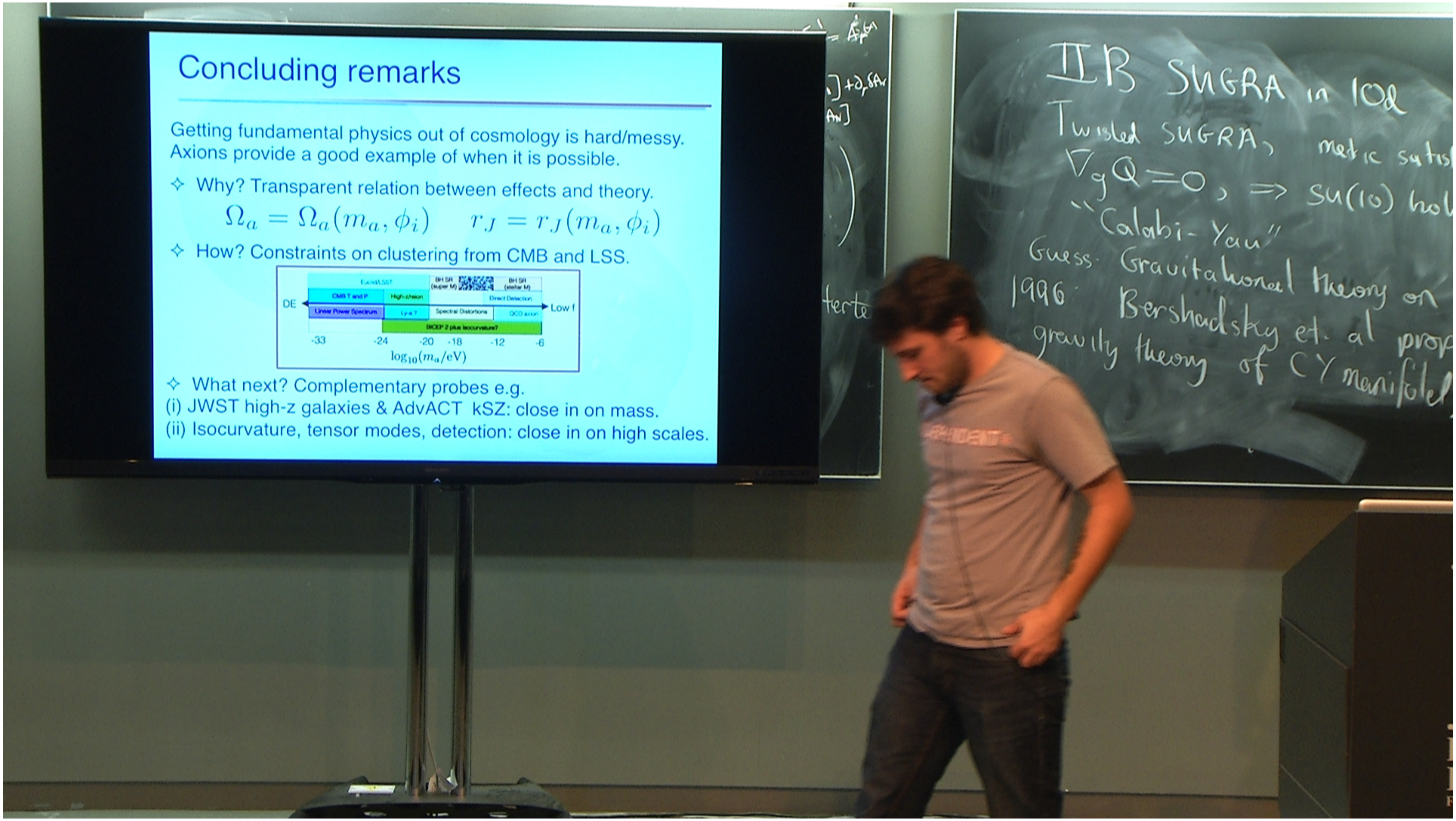
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DE
Low f
CMB T and P
Linear Power Spectrum
Spectral Distortions
Direct Detection
BICEP 2 plus isocurvature?
-33
-24
-20
-18
-12
-6
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IIB SUGRA in 10d
Twisted SUGRA,
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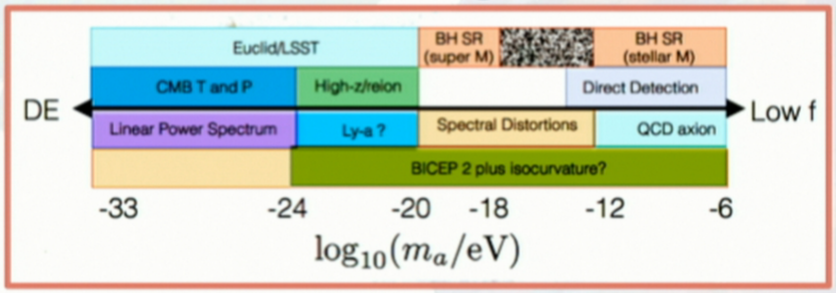

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EXIT