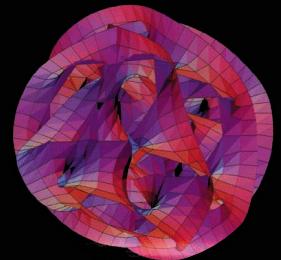
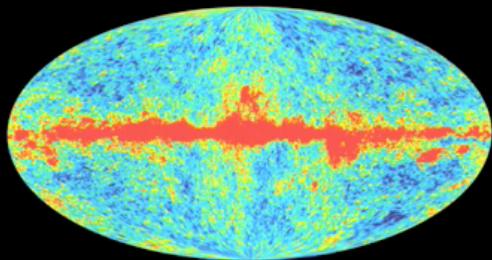


COSMOLOGICAL TESTS OF ULTRA-LIGHT AXIONS AND CMB-S4



DANIEL GRIN
HAVERFORD COLLEGE

Collabs: R.Hložek, D.J. E. Marsh, P.Ferreira, J. Dunkley, E. Calabrese, R.Allison



arXiv:1607.08208

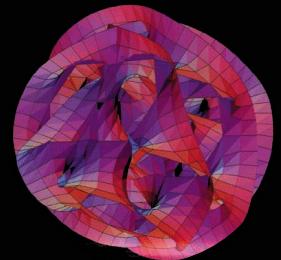
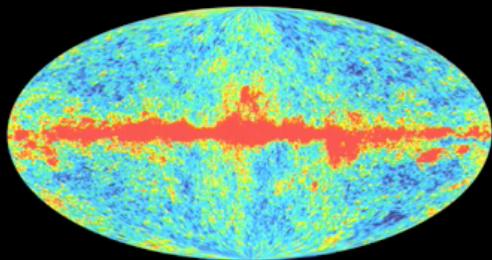
CMB-S4 Science Book: 1610.02743

arXiv:1410.2896, Phys. Rev. D 91, 103512 (2015)

arXiv:1403.4216, Phys. Rev. Lett. 113, 011801 (2014)

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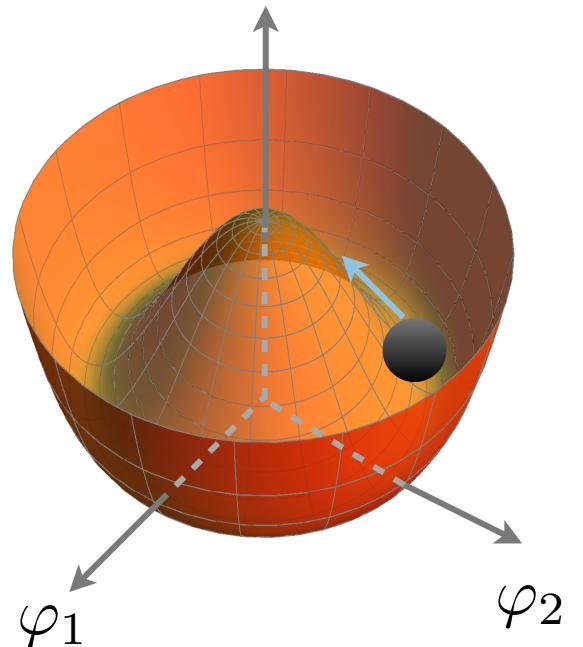
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WHAT ARE AXIONS?



New scalar with global symmetry!

$$\mathcal{L}_{\text{CPV}} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_a} g^2 G\tilde{G}$$

$$\theta < 10^{-10}$$

* Erases strong-interaction's CP-violation

* Light

$$m_a \sim 10^{-5} \text{ eV or } 10^{-33} \text{ eV} < m_a < 10^{-18} \text{ eV}$$

* Axions as DE

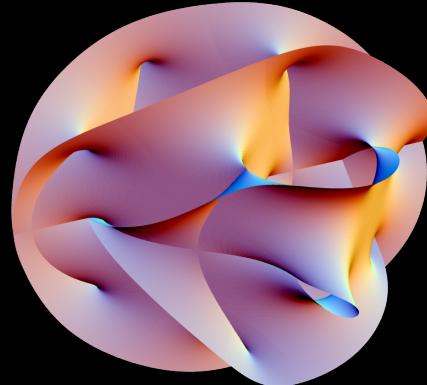
$$m_a < 10^{-27} \text{ eV}$$

* Axions as DM

$$m_a > 10^{-27} \text{ eV}$$

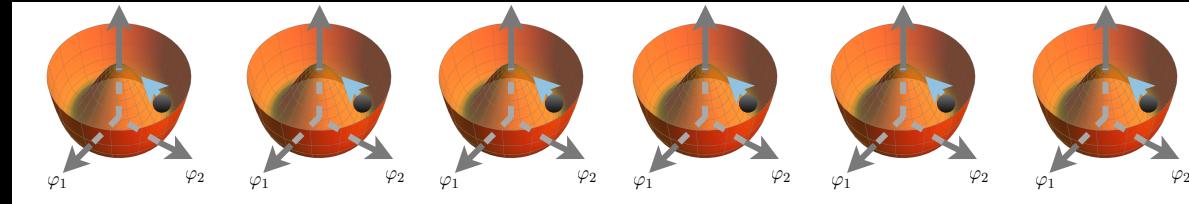
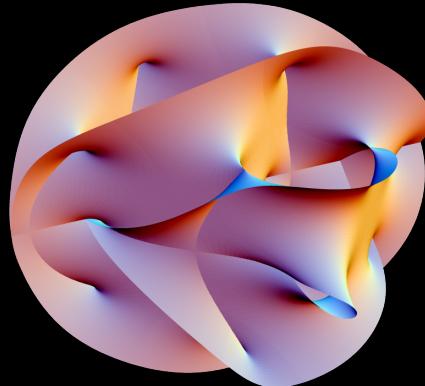
ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

- * In string theory, extra dimensions compactified: Calabi-Yau manifolds



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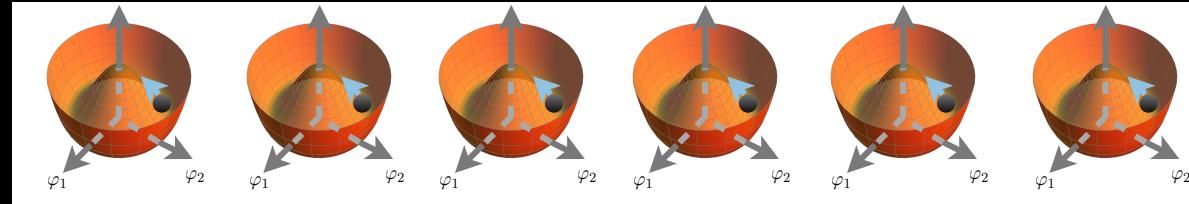
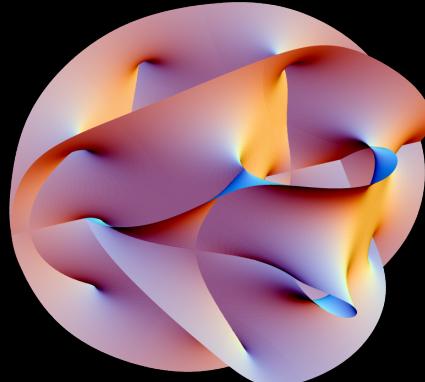


+....

*Hundreds of scalars
with approx shift symmetry*

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

- * In string theory, extra dimensions compactified: Calabi-Yau manifolds



+....

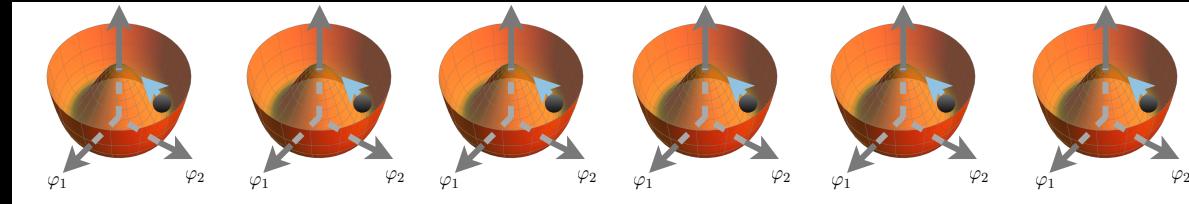
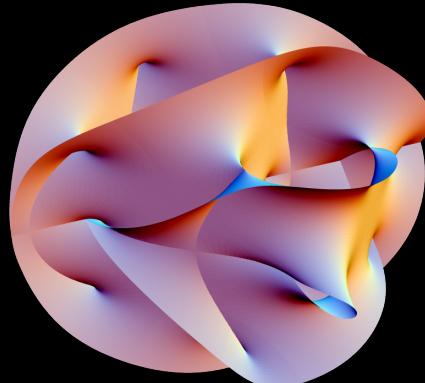
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Many axions

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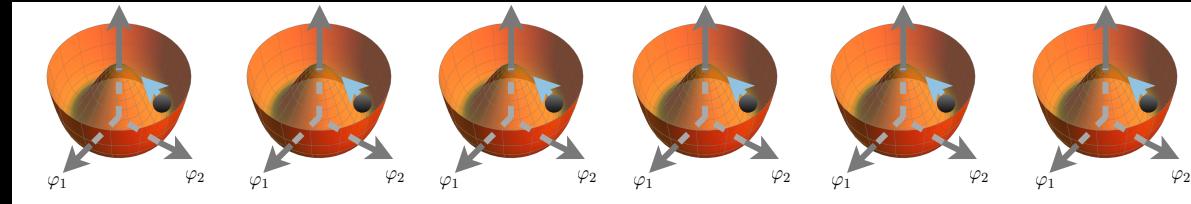
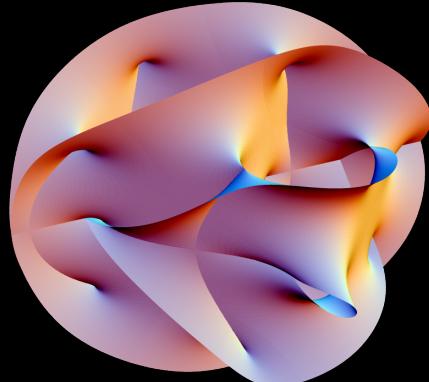
Many axions

- * Mass acquired non-perturbatively (instantons, D-Branes)

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\text{Volume}}$$

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

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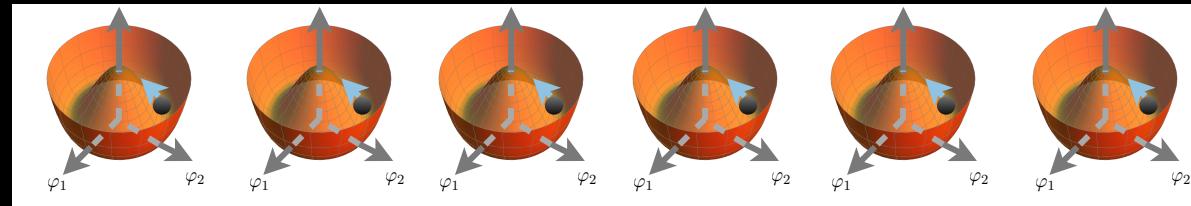
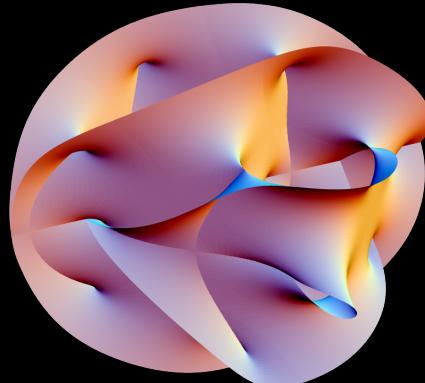
- * Mass acquired non-perturbatively (instantons, D-Branes)

**Scale of new
ultra-violet physics**

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\text{Volume}}$$

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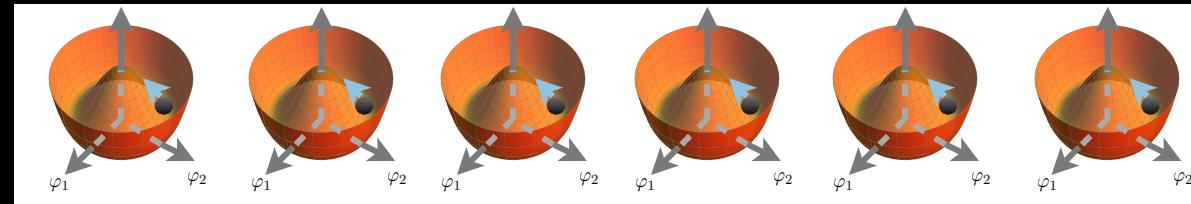
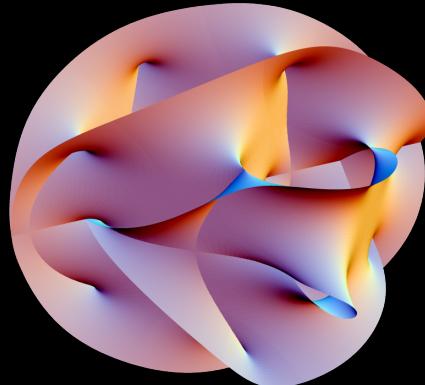
Scale of extra dimensions

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\text{Volume}}$$

in Planck units

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

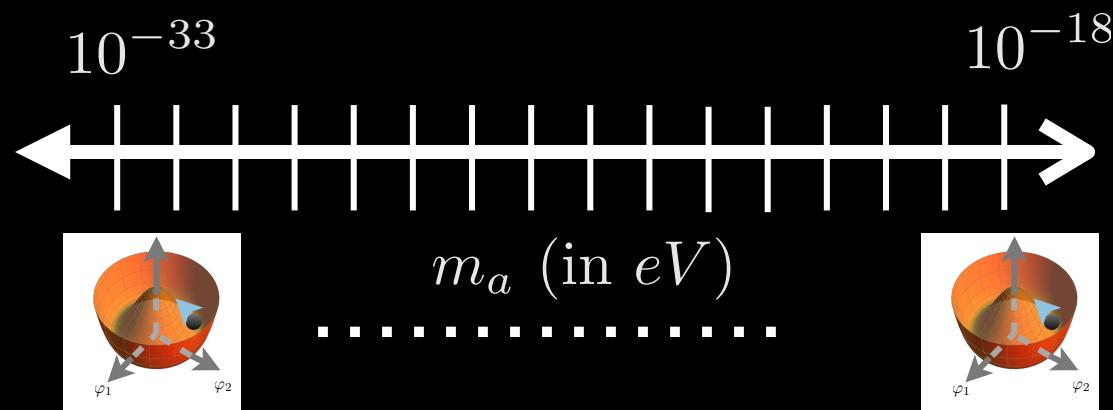
- * In string theory, extra dimensions compactified: Calabi-Yau manifolds



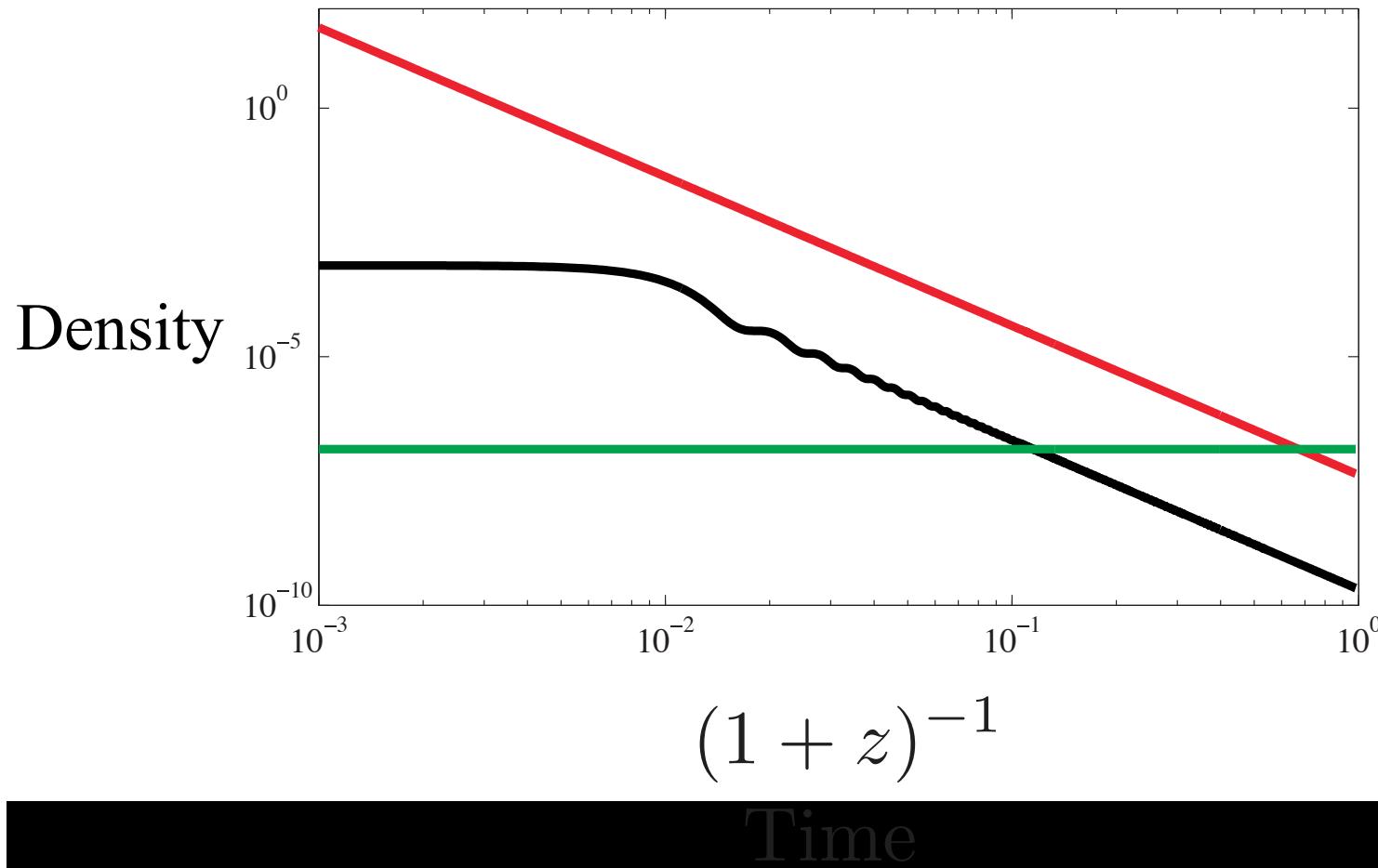
10

Axiverse! Arvanitaki+ 2009

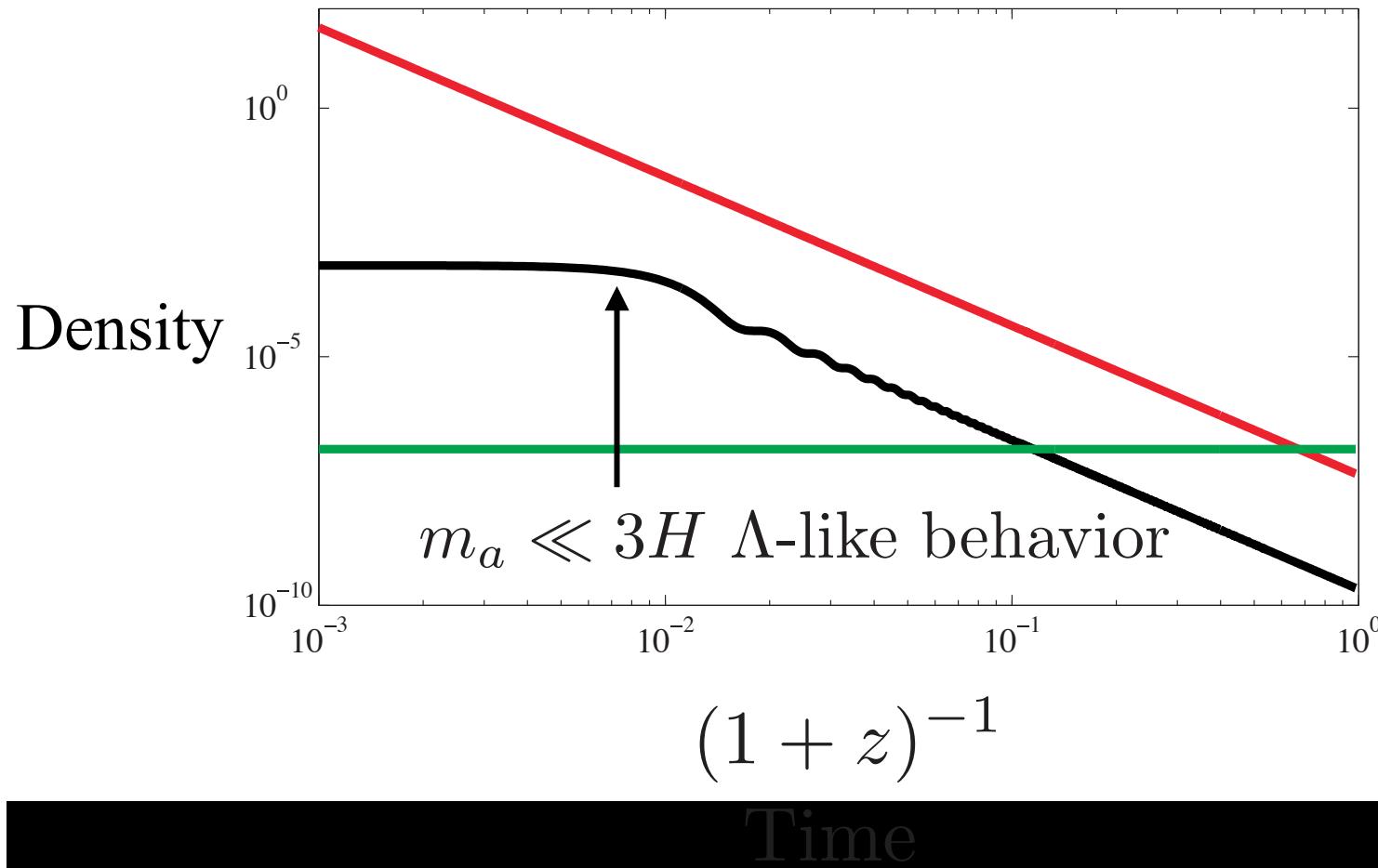
Witten and Srvcek (2006), Acharya et al. (2010), Cicoli (2012)



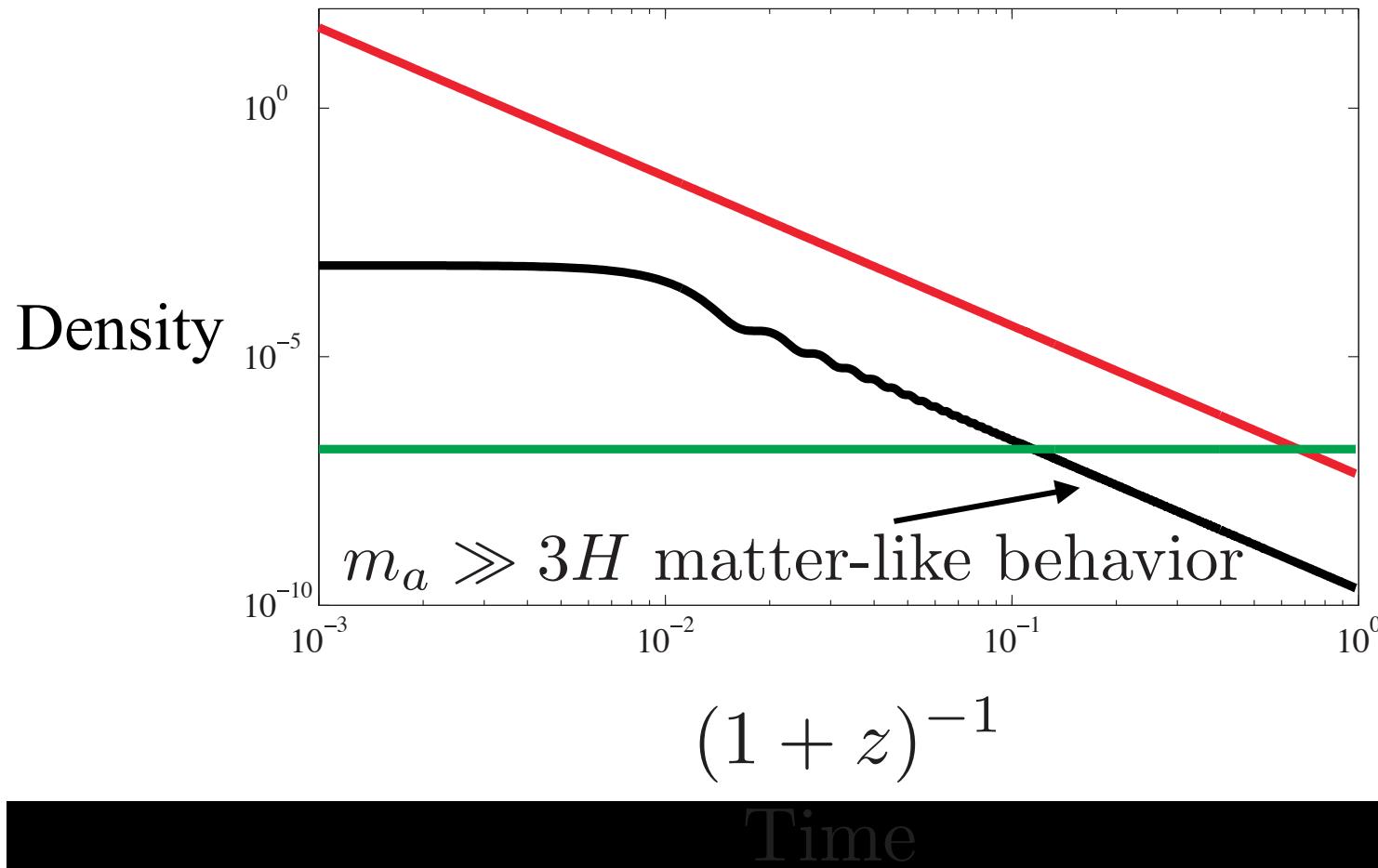
COSMOLOGY OF ULTRA-LIGHT AXIONS: DARK MATTER AND DARK ENERGY CANDIDATES



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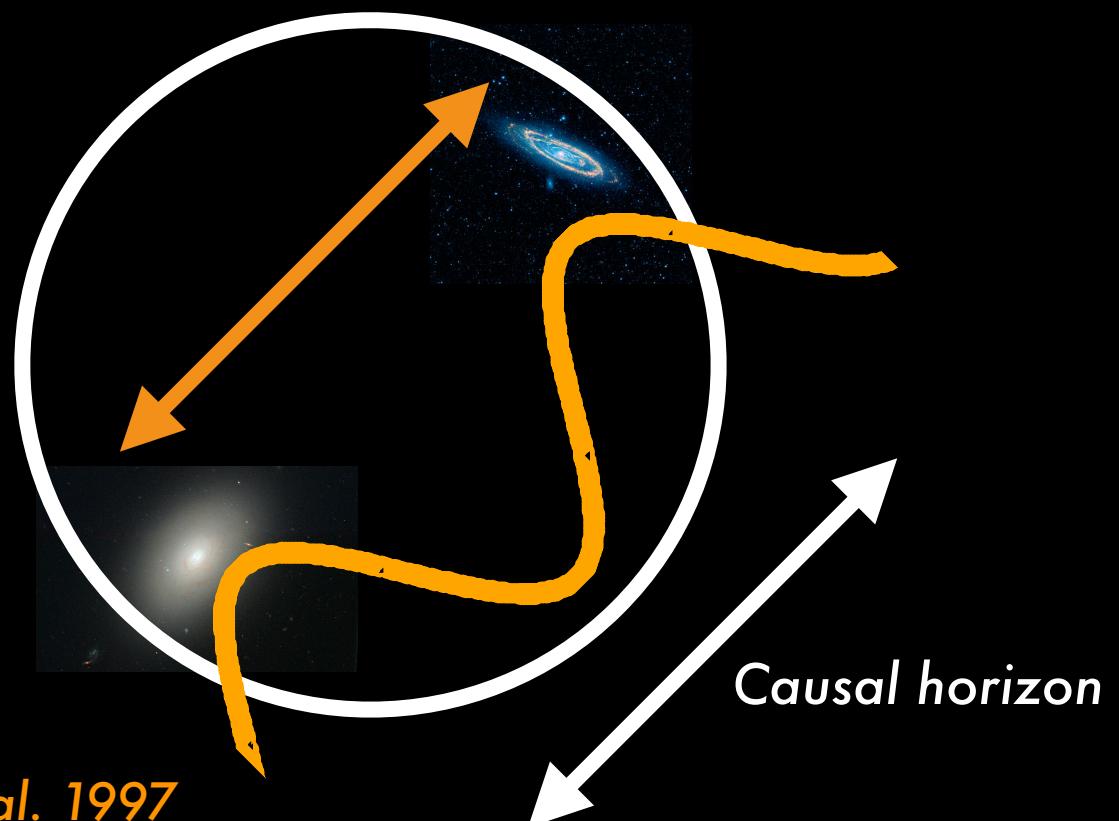
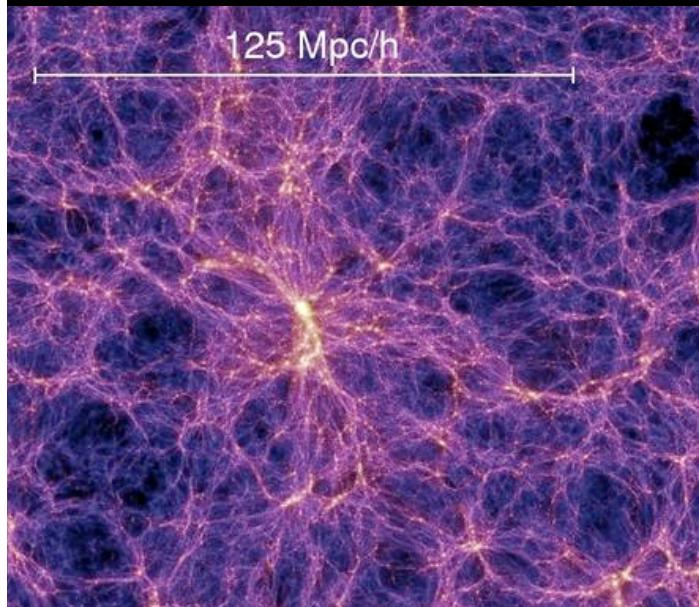


COSMOLOGY OF ULTRA-LIGHT AXIONS: DARK MATTER AND DARK ENERGY CANDIDATES



COSMOLOGY OF ULTRA-LIGHT AXIONS: DARK MATTER AND DARK ENERGY CANDIDATES

*Scale corresponding to
typical galaxy separation today*



Frieman et al 1995, Coble et al. 1997

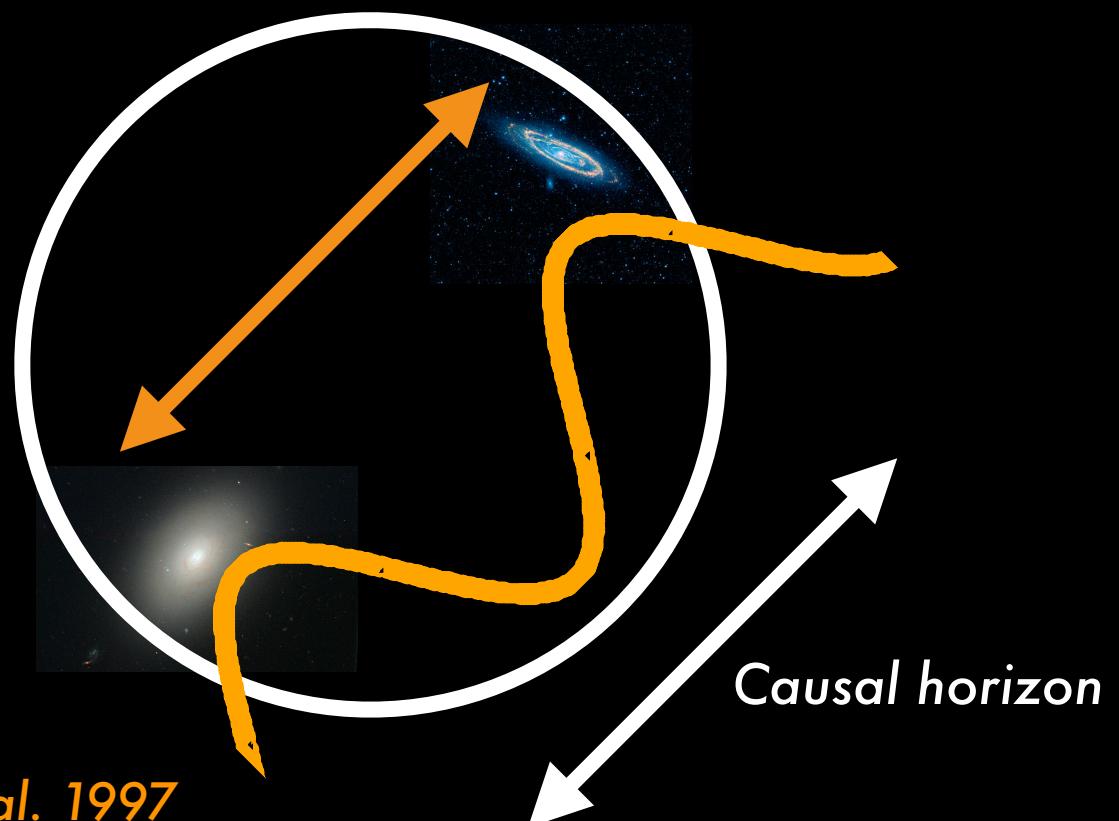
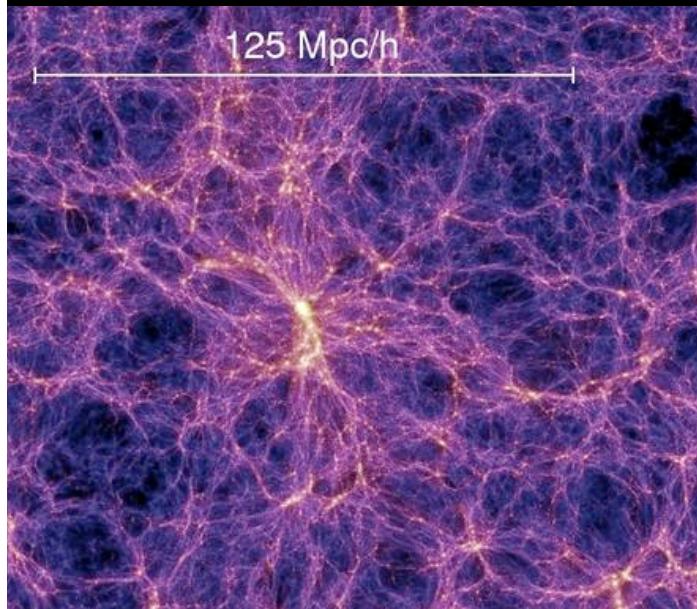
ULA as dark energy with specific $w(z)$

$$m_a \lesssim 10^{-27} \text{ eV}$$

ULA matter behavior starts too late for struct. formation

COSMOLOGY OF ULTRA-LIGHT AXIONS: DARK MATTER AND DARK ENERGY CANDIDATES

*Scale corresponding to
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Frieman et al 1995, Coble et al. 1997

ULA as dark matter

$$m_a \gtrsim 10^{-27} \text{ eV}$$

ULA matter behavior starts in time for struct. formation

GROWTH OF ULA PERTURBATIONS

* Perturbed Klein-Gordon + Gravity

$$\ddot{\delta\phi} + 2\mathcal{H}\dot{\delta\phi} + (k^2 + m_a^2 a^2)\delta\phi = 4\dot{\Psi}\phi_0 - \Psi a^2 m_a^2 \phi_0$$

* Axionic Jeans Scale is macroscopic [in contrast to QCD axion]:

$$\lambda_J = 2.4 h^{-1/2} \left(\frac{m}{10^{-25} \text{ eV}} \right)^{-1/2} \text{ Mpc}$$

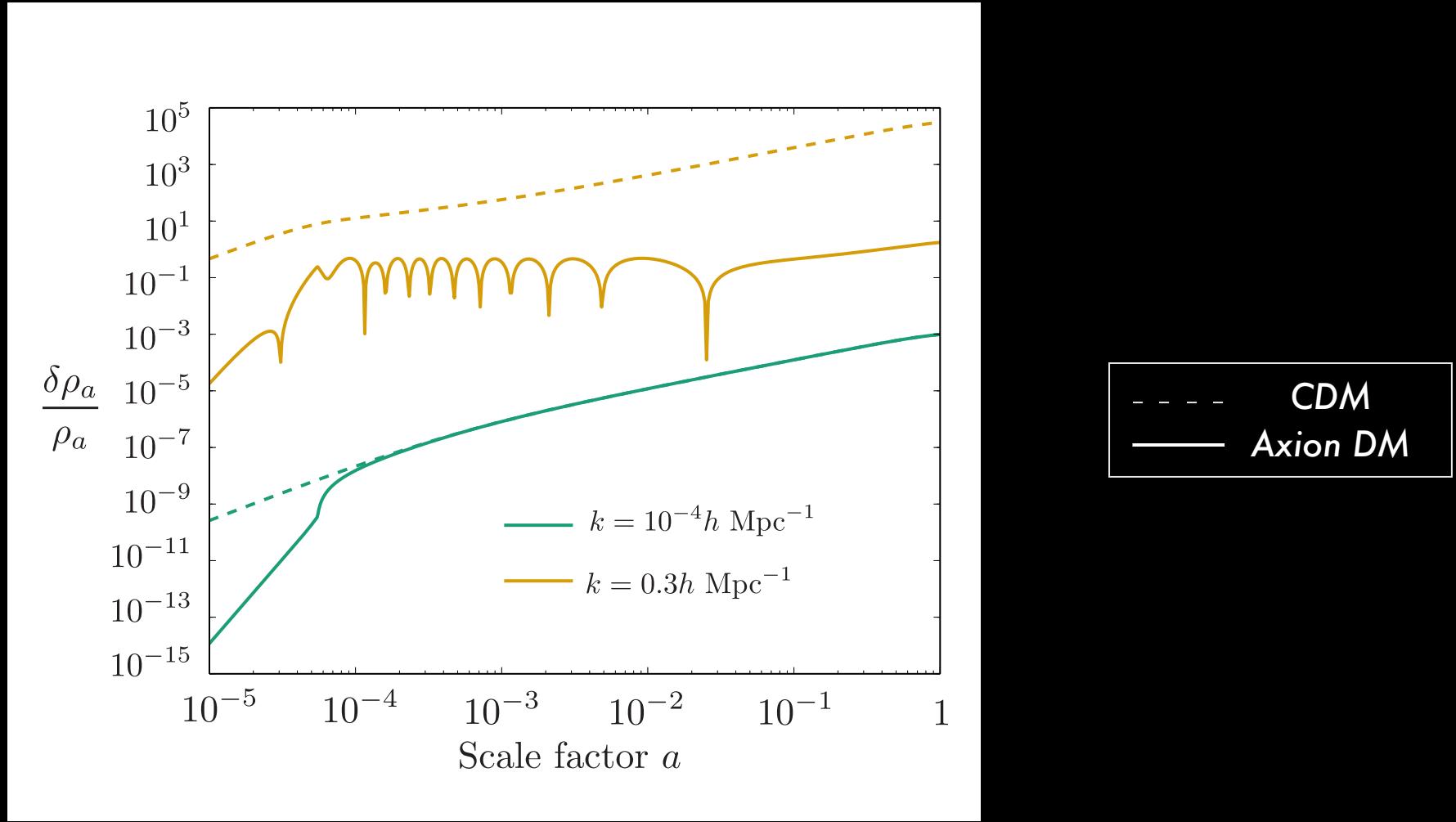
* Computing observables is expensive for $m \gg 3\mathcal{H}$:

- * Coherent oscillation time scale $\Delta\eta \sim (ma)^{-1} \ll \Delta\eta_{\text{CMB}}$
- * WKB approximation

$$\delta\phi = A_c \Delta_c(k, \eta) \cos(m\eta) + A_s \Delta_s(k, \eta) \sin(m\eta)$$

$$c_a^2 = \frac{\delta P}{\delta\rho} = \frac{k^2/(4m^2 a^2)}{1 + k^2/(4m^2 a^2)}$$

GROWTH OF ULA PERTURBATIONS

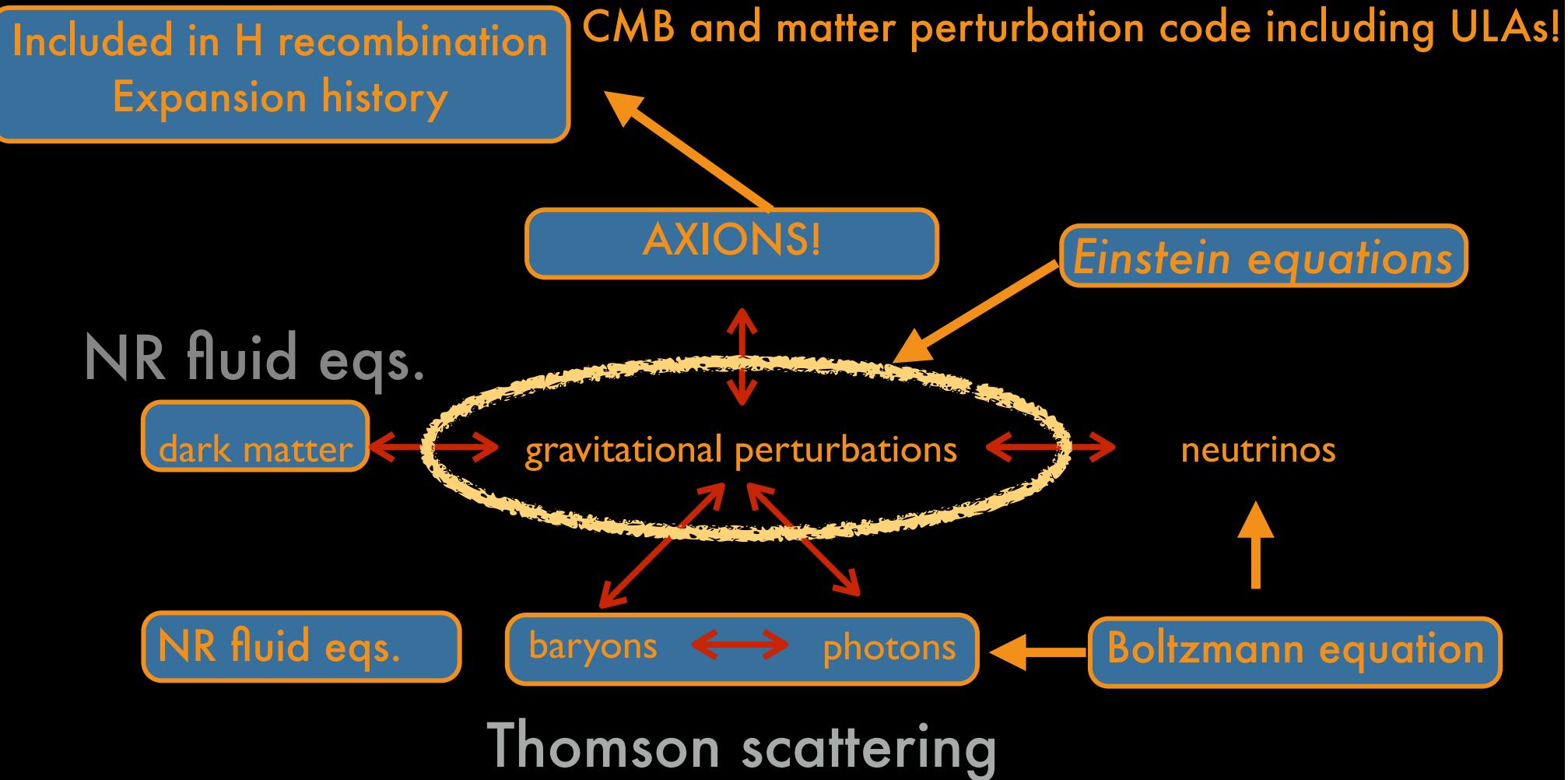


* Modes with $k \gg k_J \sim \sqrt{m\mathcal{H}}$ oscillate instead of growing

AXIONCAMB

Code by Grin et al. 2013, based on CAMB (A. Lewis)

<http://github.com/dgrin1/axionCAMB>

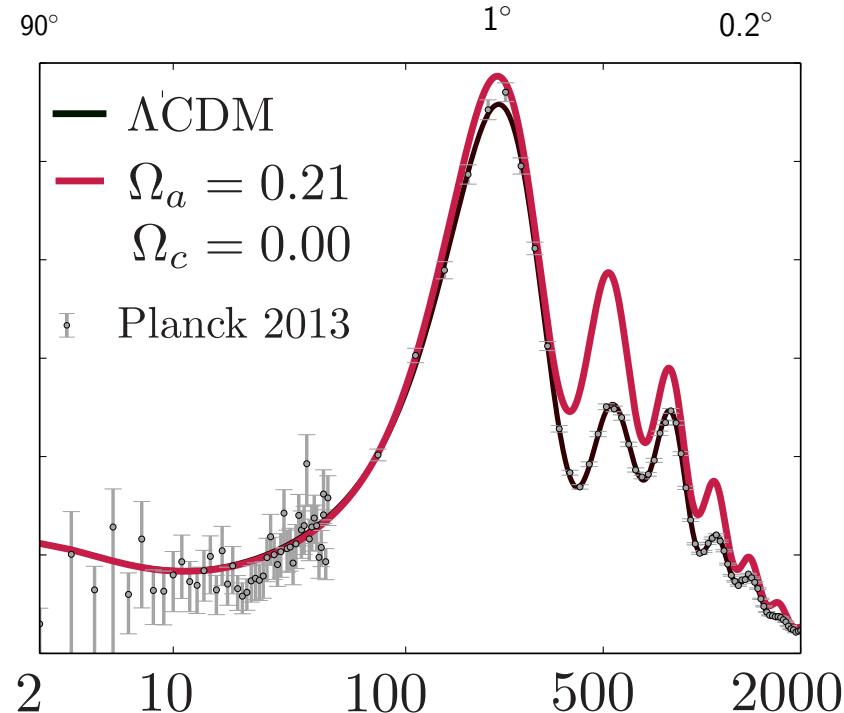


ULA of any mass is self-consistently followed from DE to DM regime

CMB OBSERVABLES

$$m_a = 10^{-27} \text{ eV}$$

Angular scale

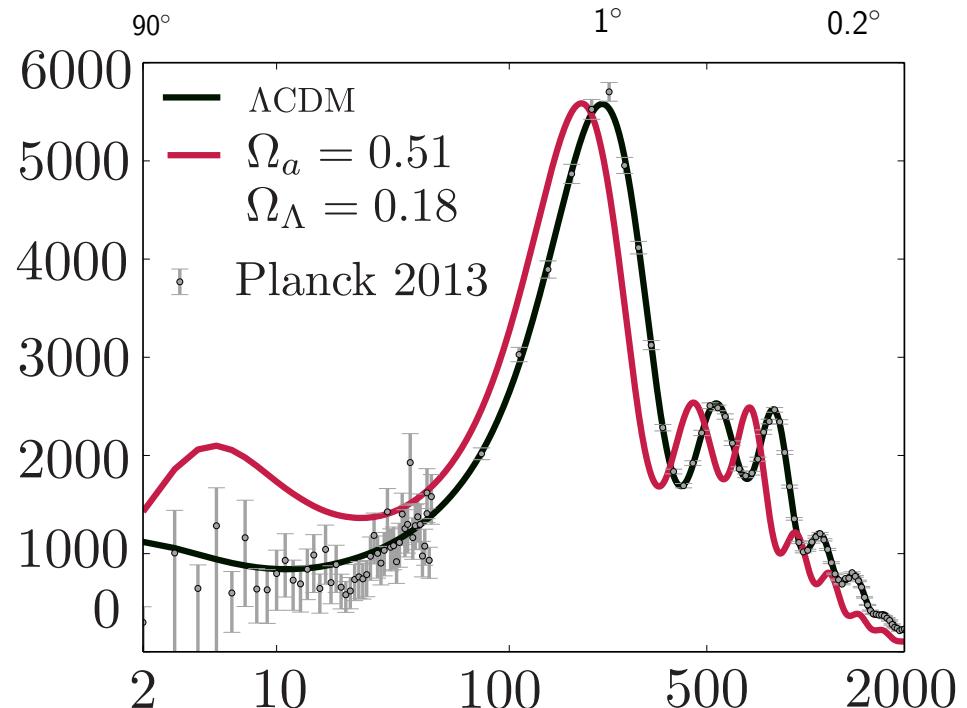


Dramatic changes to observables can result

CMB OBSERVABLES

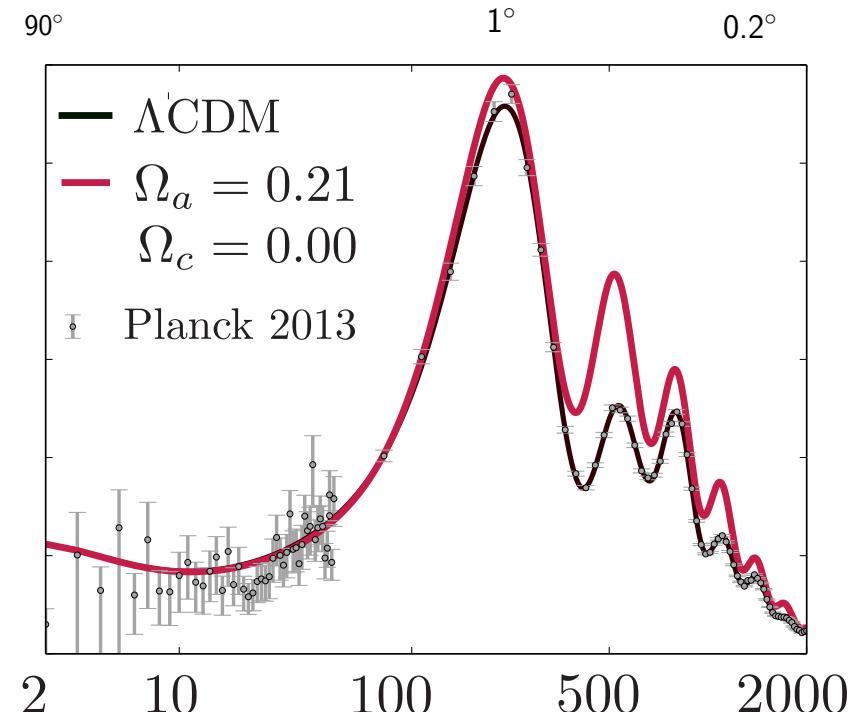
$$m_a = 10^{-32} \text{ eV}$$

Angular scale



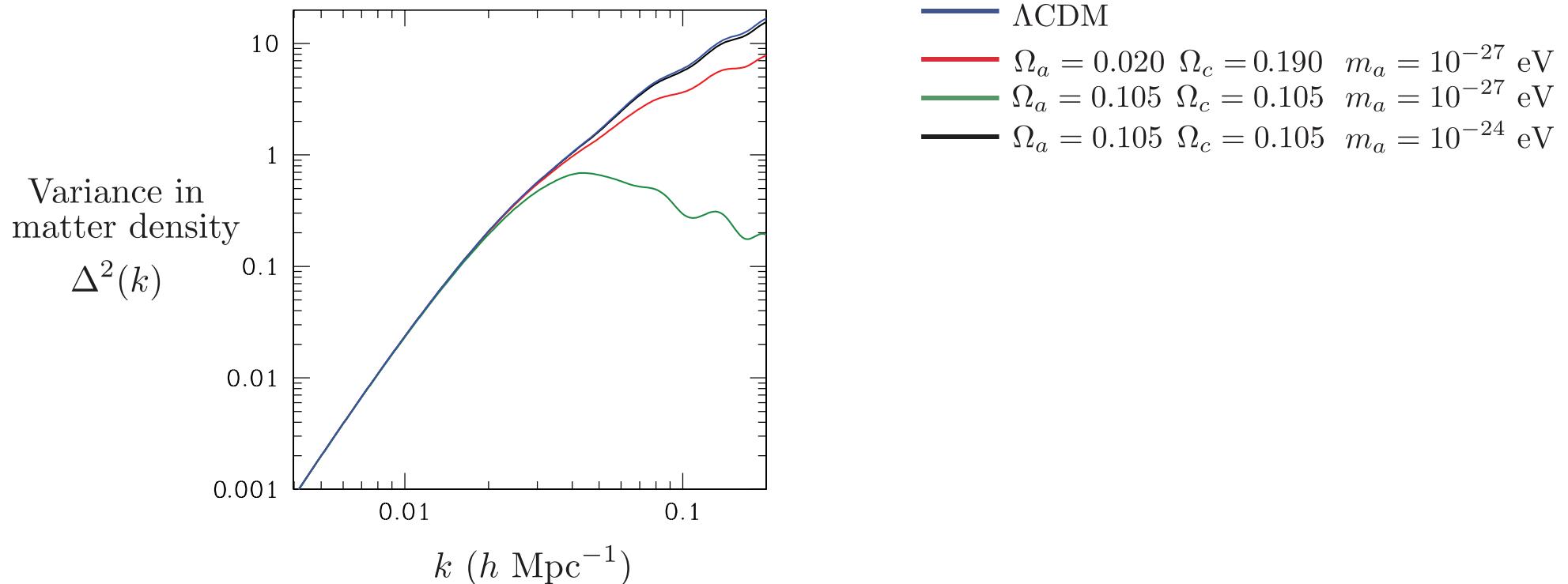
$$m_a = 10^{-27} \text{ eV}$$

Angular scale



Dramatic changes to observables can result

Matter power spectrum for ULA (in DM regime)

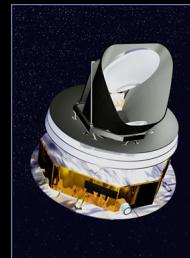
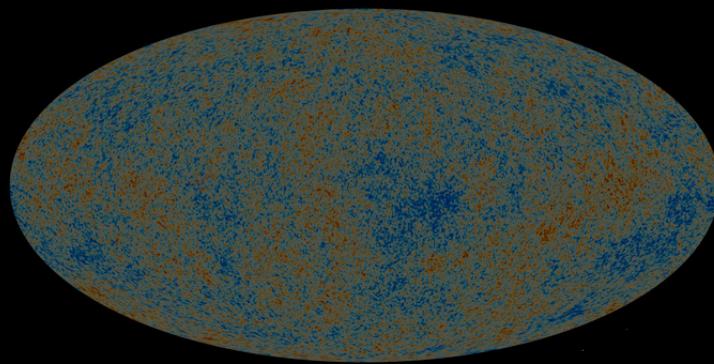


* Suppression grows with $\frac{\Omega_a}{\Omega_a + \Omega_c}$

* DM perturbation growth severely suppressed if $k > k_J \simeq \sqrt{m\mathcal{H}}$

Matter power spectrum for ULA (in DM regime)

DATA + ANALYSIS



*Planck 2013 temperature anisotropy power spectra (+SPT+ACT)

*Cosmic variance limited to $\ell \sim 1500$

*WiggleZ galaxy survey (linear scales only $k \lesssim 0.2h \text{ Mpc}^{-1}$)

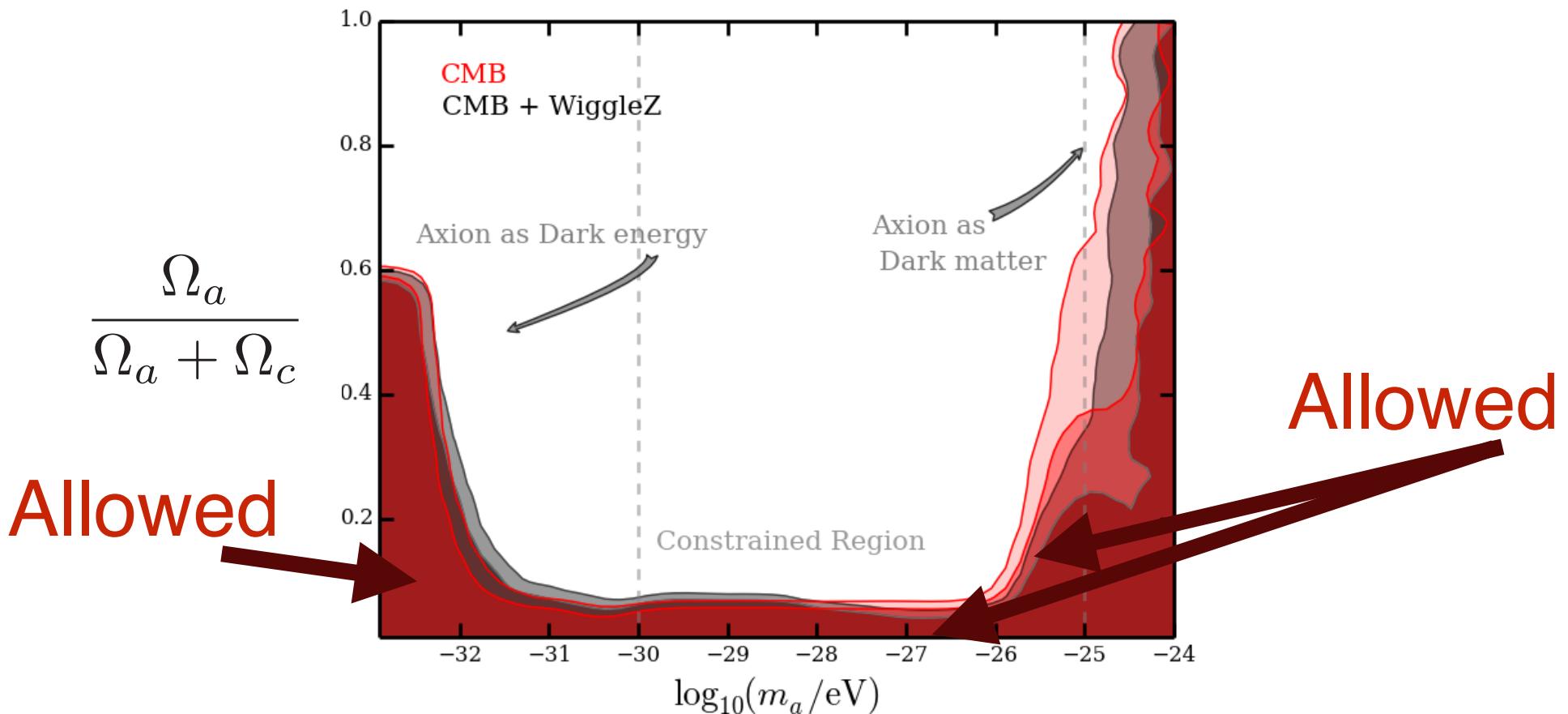


*240,000 emission line galaxies at $z < 1$

*3.9 m Anglo-Australian Telescope (AAT)

*Nested sampling, MCMC, vary $m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\text{reion}}$

CONSTRAINTS



* Interesting constraints over 7 orders of magnitude in mass:

Thanks to AXIONCAMB and MULTINEST

* ULAs highly constrained if $10^{-32} \text{ eV} \lesssim m_a \lesssim 10^{-25.5} \text{ eV}$

* ULAs are viable DM/DE candidates in linear theory outside ``belly'' 11

CMB-S4



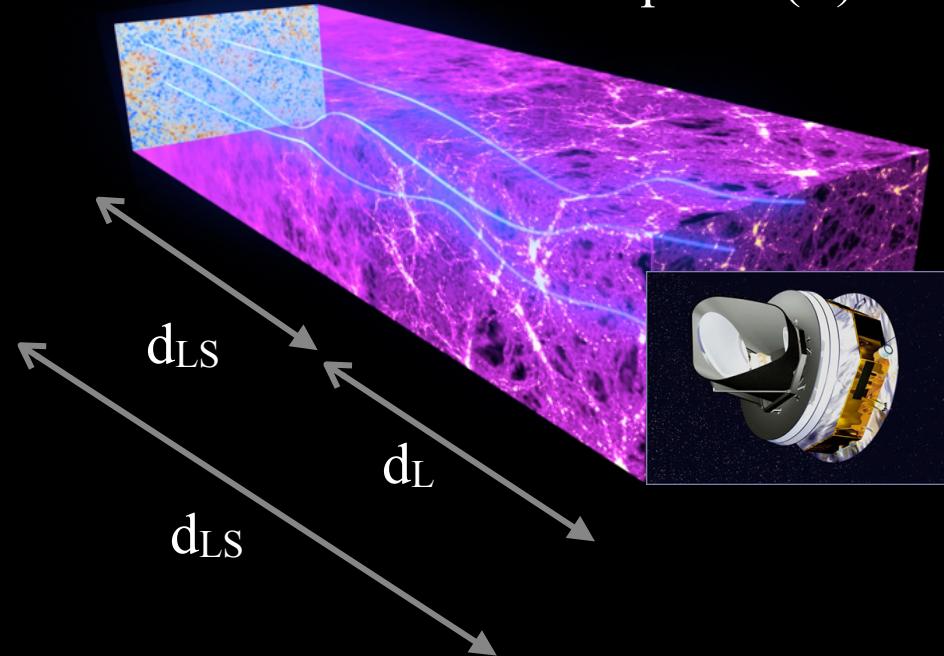
- * Next gen. CMB ground-based expt. concept
 - * ~1 arcmin beam
 - * 1 μK arcmin noise level
 - * ~500,000 detectors
 - * Location, sky coverage TBD

From CMB-S4 Science book.... arXiv: 1610.02743

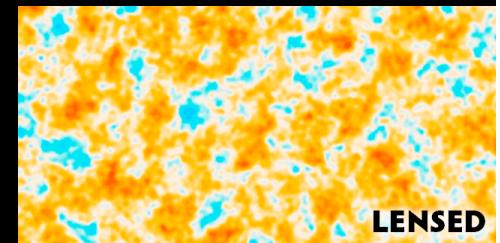
CMB LENSING

Source Plane (S)

Lens plane (L)



A slice of (dark matter) life at $z \sim 1$

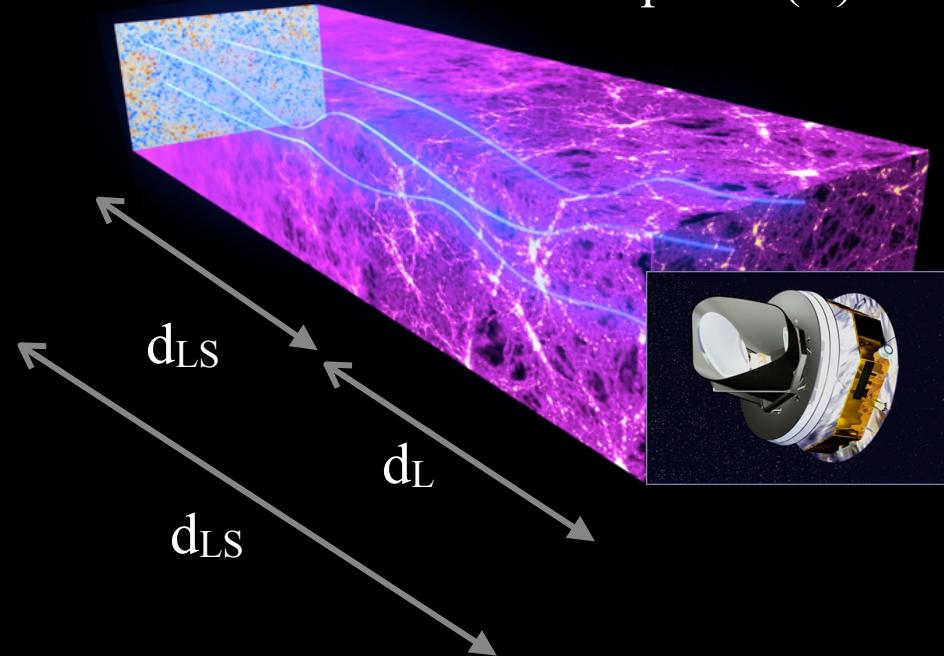


$$\vec{\alpha} = \nabla_{\vec{\theta}} \left\{ \int \left(\frac{d_{LS}}{d_L d_S} \right) \Phi \left[d(\eta) \vec{\theta}, \eta \right] d\eta \right\}$$

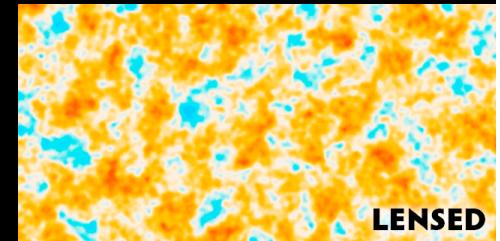
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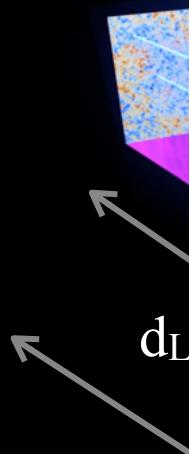
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CMB LENSING

Source

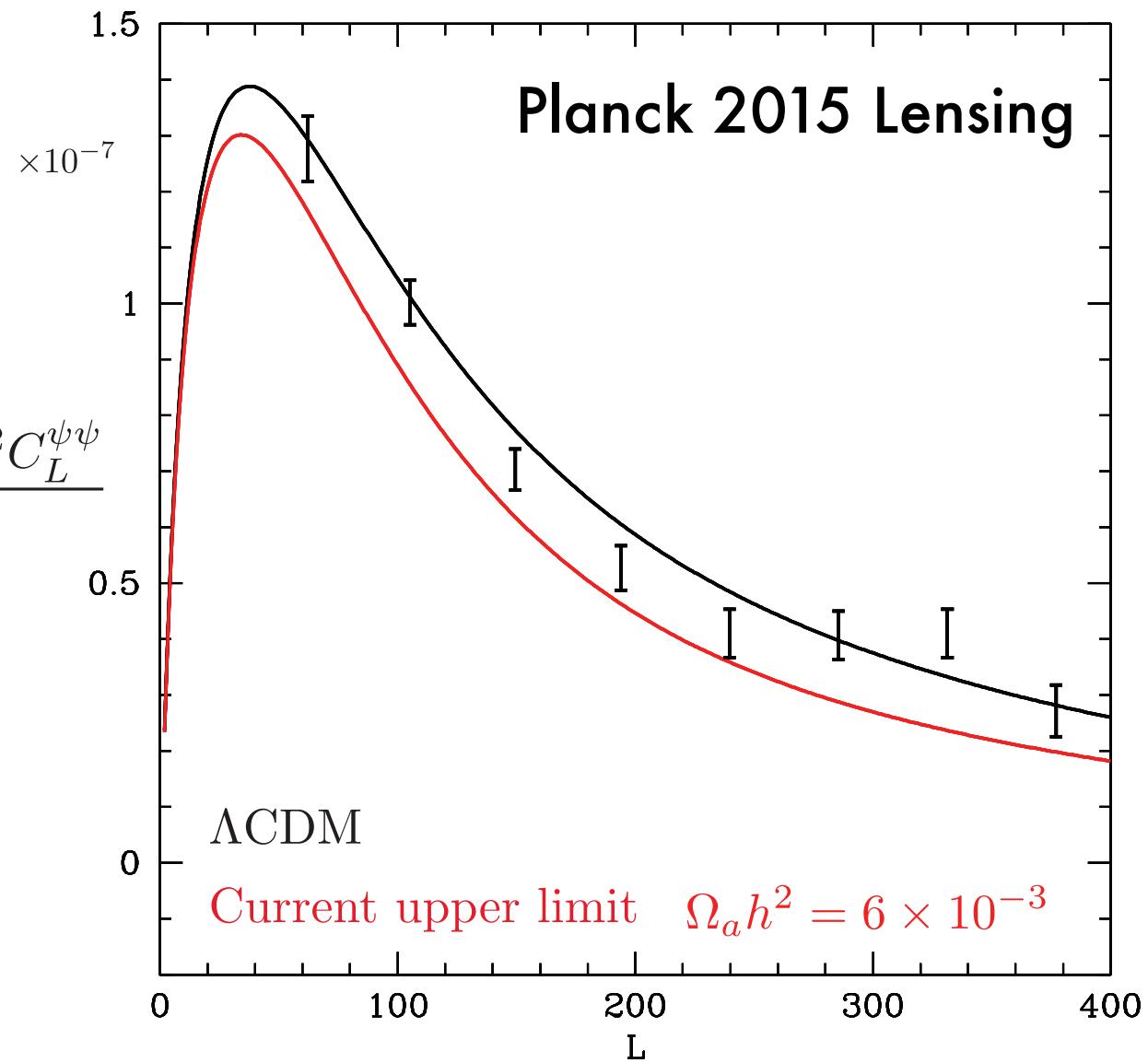


$$d \frac{[L(L+1)]^2 C_L^{\psi\psi}}{2\pi}$$

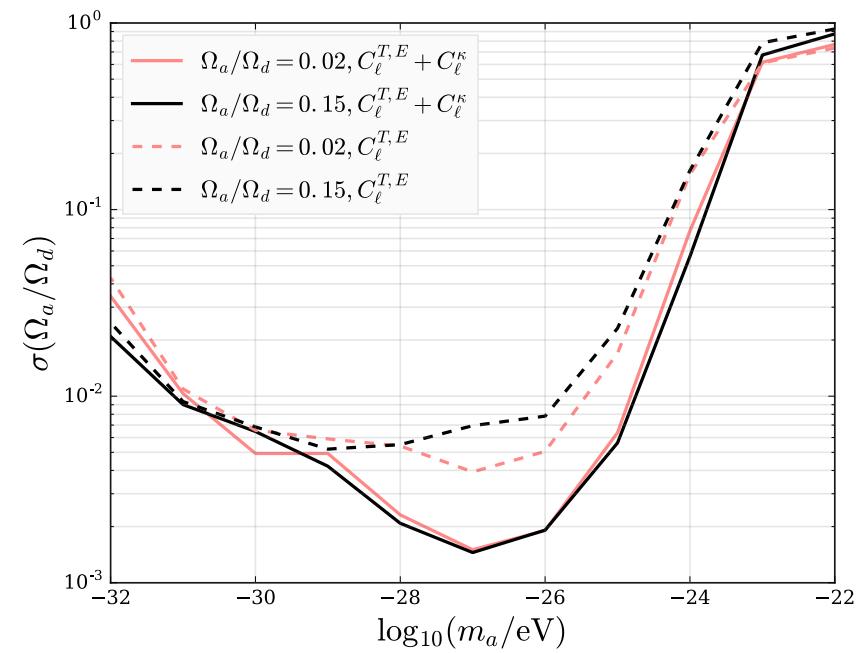
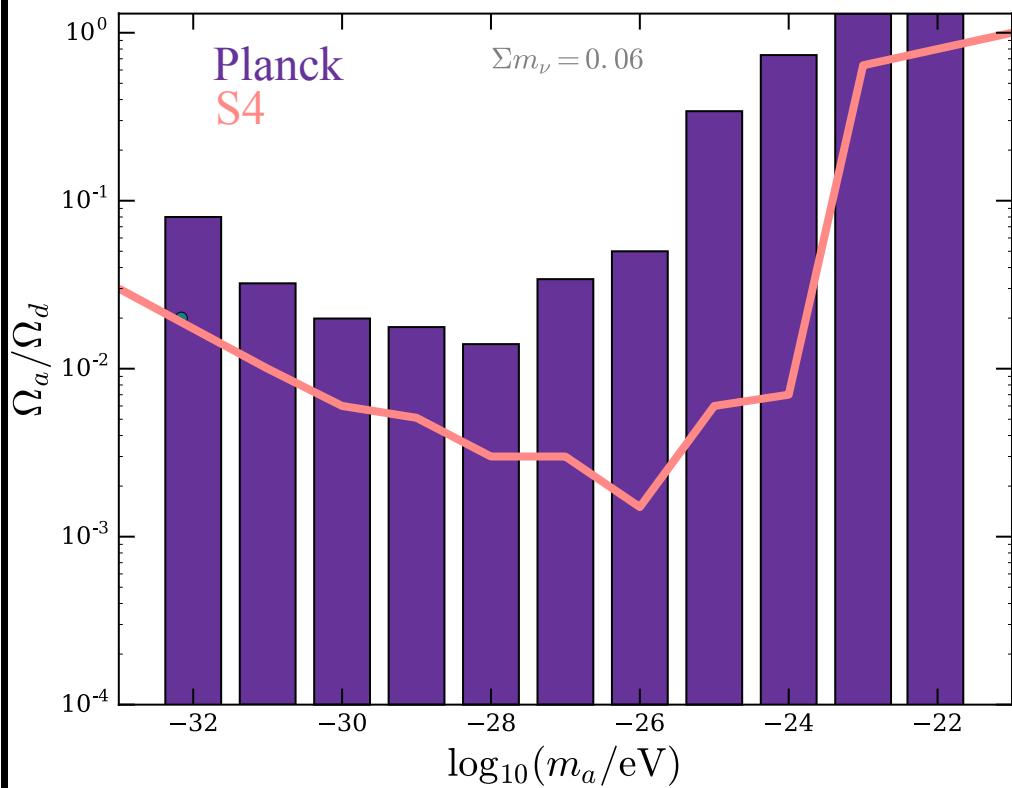
ULA saturating TT-only limits falsifiable at 4.5σ

$z \sim 1$

LENSED



S4-CAST FOR LENSING AND ULAS



Fisher forecast using OxFISH code—OOM
improvement driven by lensing

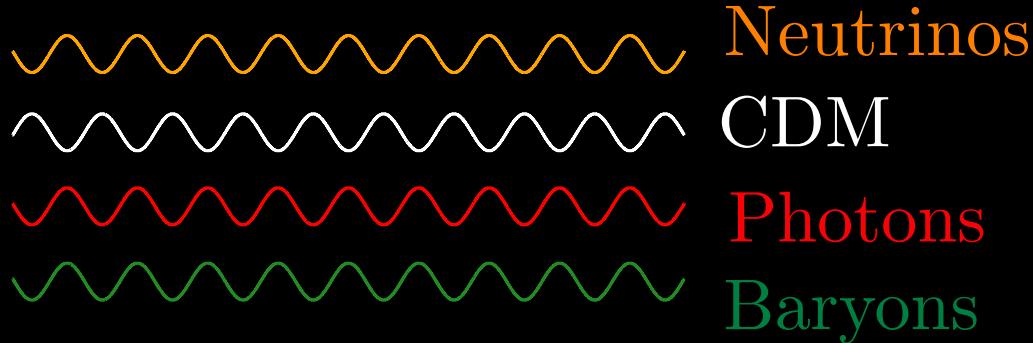
AXIONS AND ISOCURVATURE

- * Quantum zero-point flcuts. in axion field

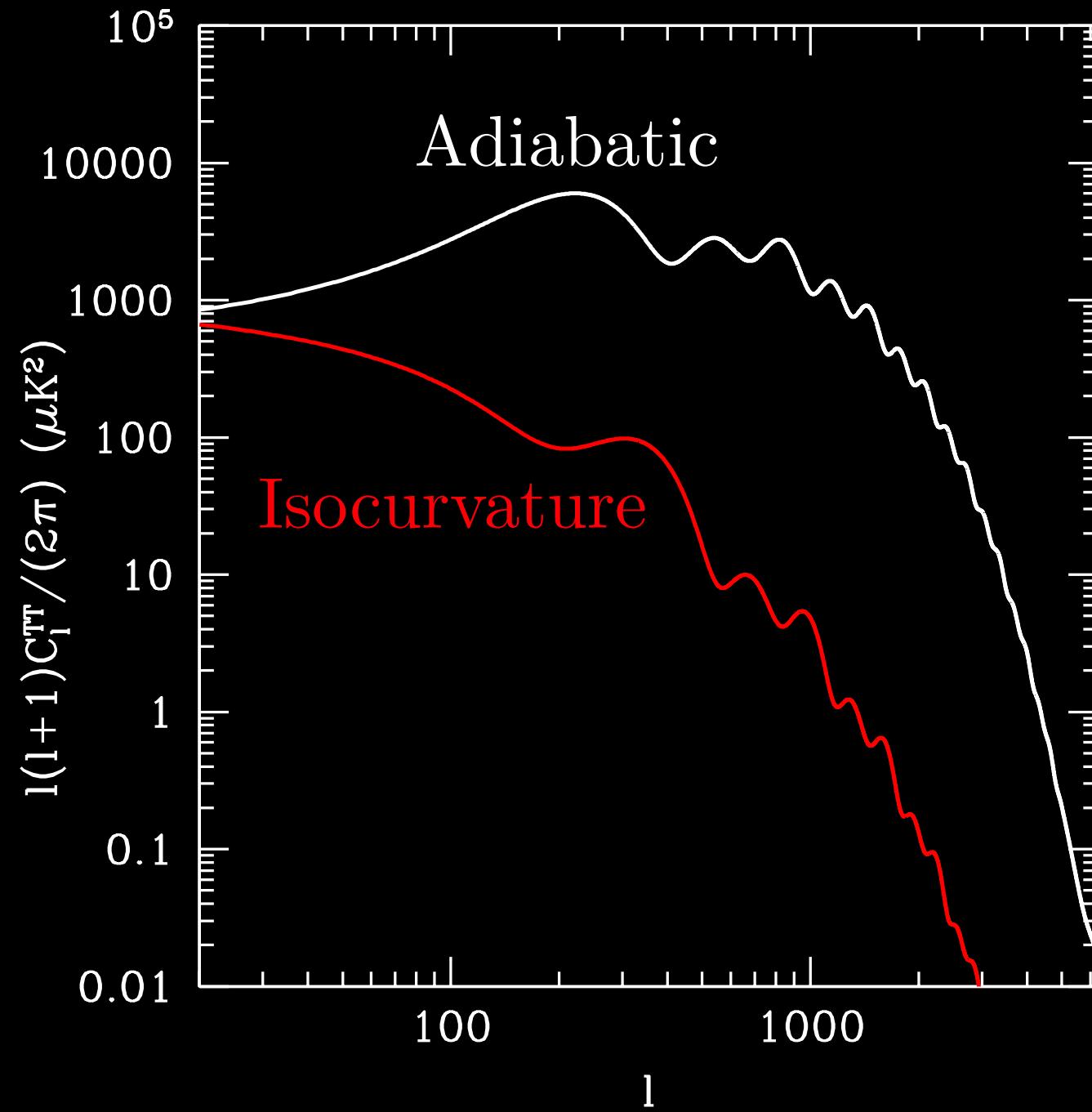
$$\sqrt{\langle a^2 \rangle} = \frac{H_I}{2\pi}$$

- * Subdominant species seed isocurvature fluctuations

$$\Phi \propto \left(\frac{\delta \rho_a}{\rho_a} \right) \left(\frac{\rho_a}{\rho_{\text{total}}} \right) \ll 10^{-5}$$

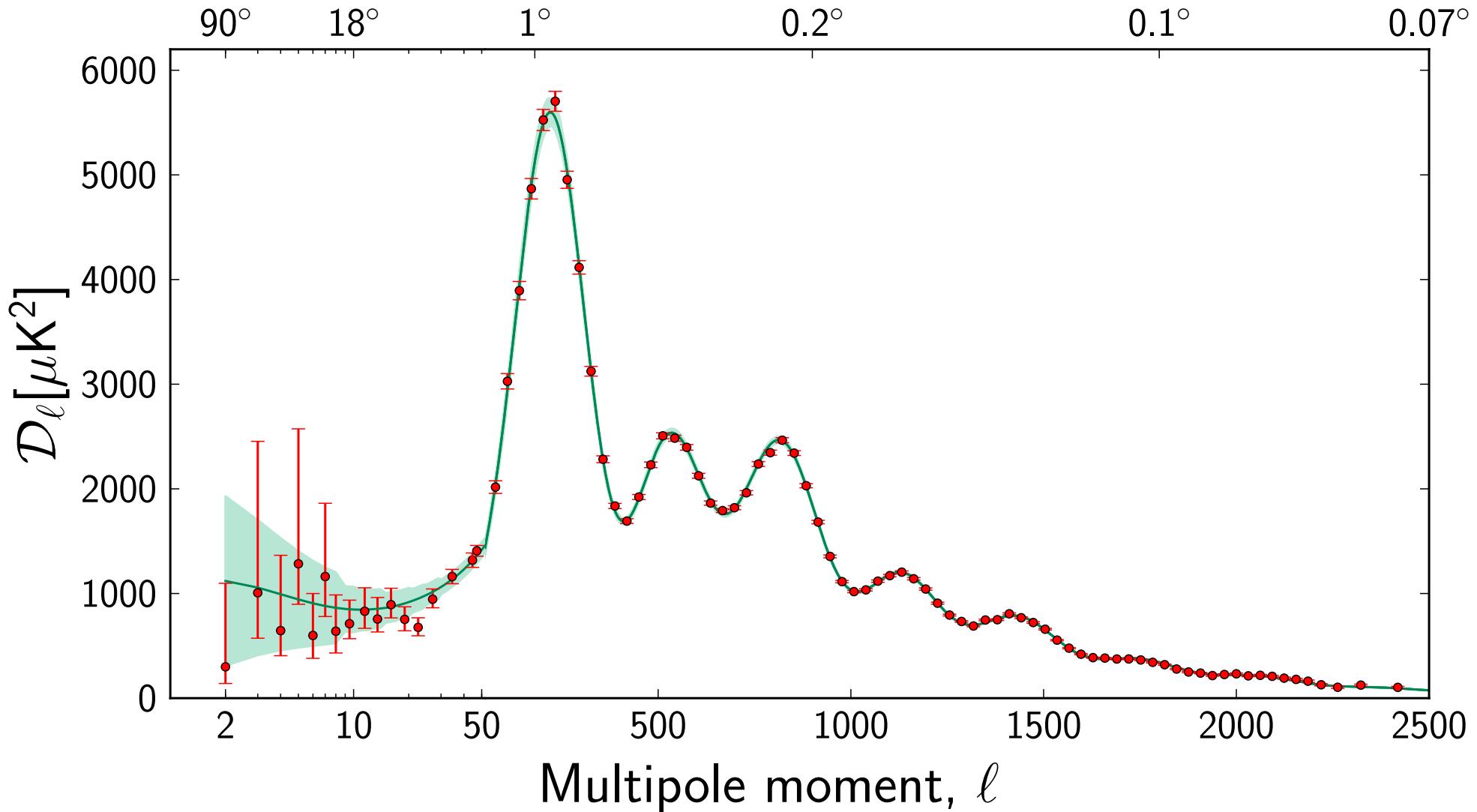


AXIONS AND ISOCURVATURE



AXIONS AND ISOCURVATURE

Angular scale



AXIONS AND ISOCURVATURE

Implications for measuring the scale of primordial inflation

$$m_a \gtrsim 10^{-26} \text{ eV}$$

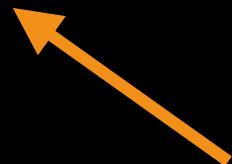
$$4 \times 10^{-8} \text{ eV} \gtrsim m_a \gtrsim 4 \times 10^{-11} \text{ eV}$$

$$4 \times 10^{-4} \text{ eV} \gtrsim m_a \gtrsim 4 \times 10^{-5} \text{ eV}$$

$$H_I \lesssim 10^{13.5} \text{ GeV}$$

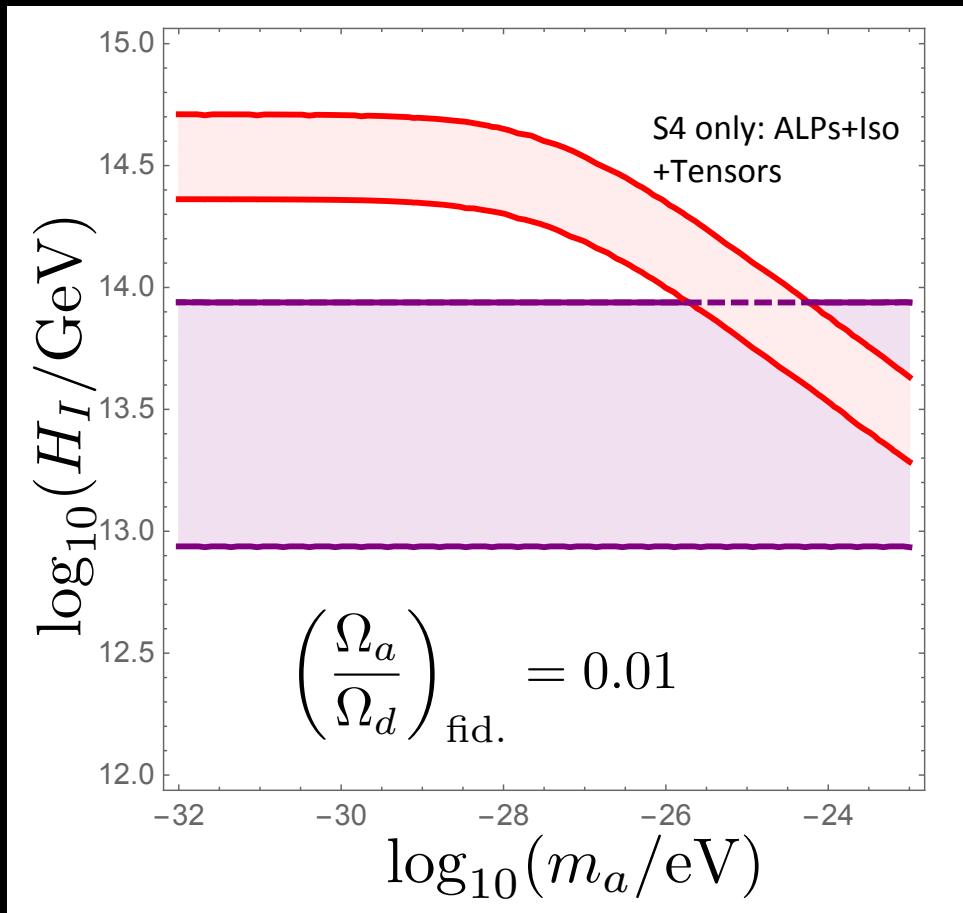
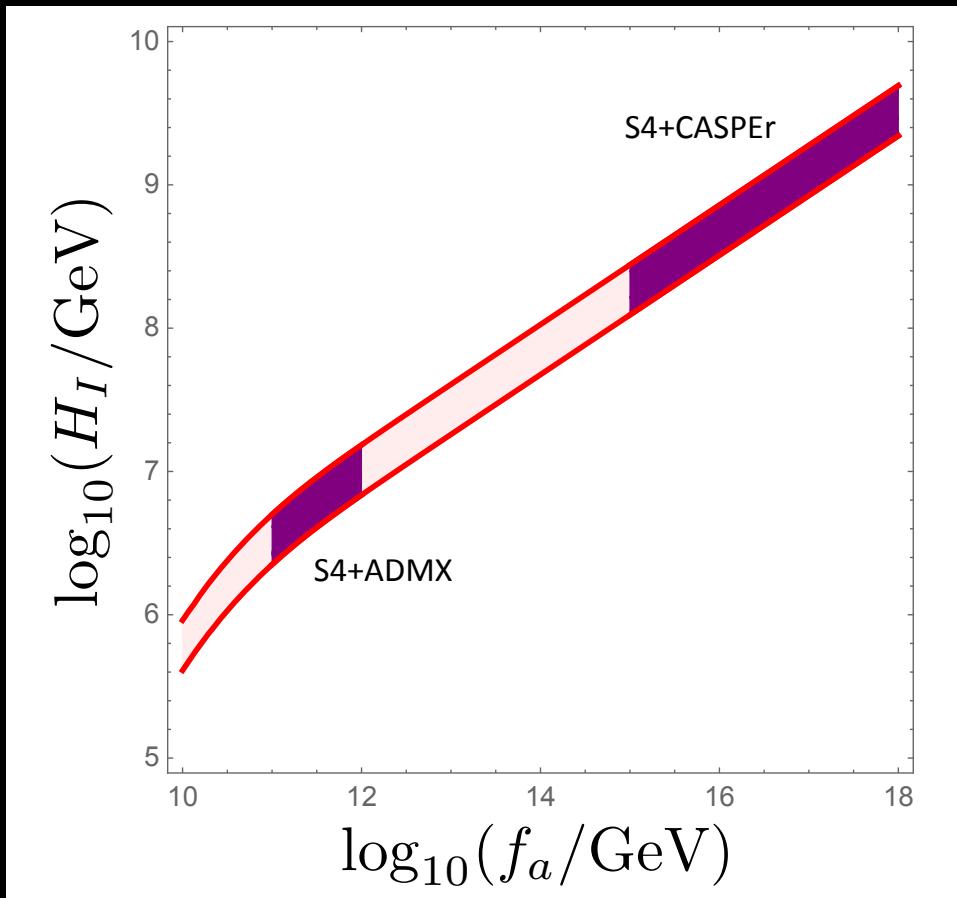
$$10^8 \text{ GeV} \lesssim H_I \lesssim 10^{10} \text{ GeV}$$

$$10^6 \text{ GeV} \lesssim H_I \lesssim 10^7 \text{ GeV}$$

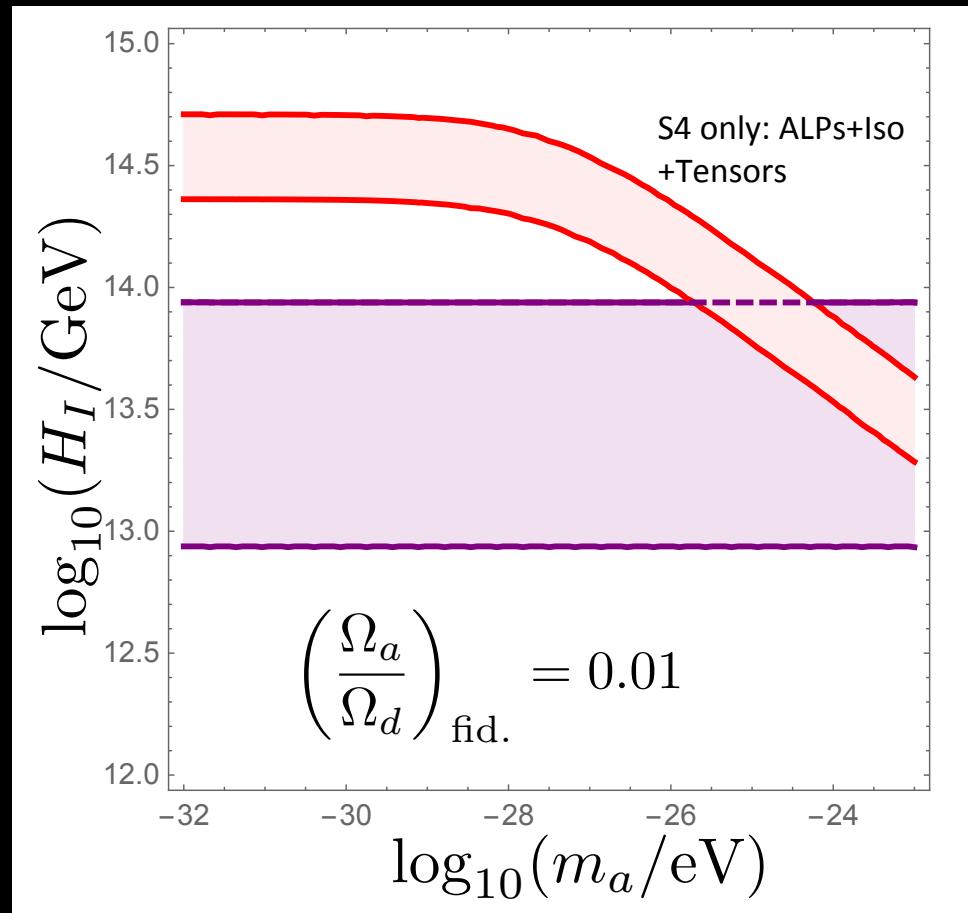
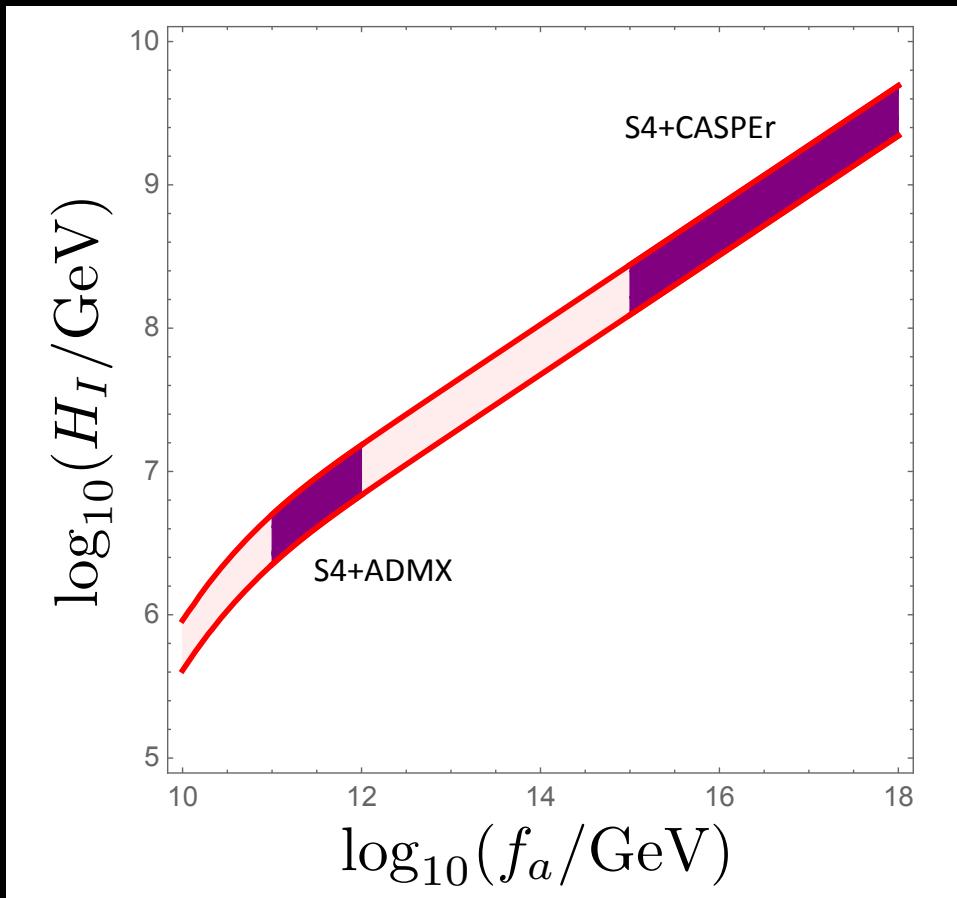


Could be probed by ADMX/CASPER (ongoing/upcoming axion search experiments)

HIGH-ENERGY COSMOLOGY WITH AXION ISOCURVATURE



HIGH-ENERGY COSMOLOGY WITH AXION ISOCURVATURE



The observational/experimental horizon for axion dark matter/dark energy tests is bright!