Particle Physics from Cosmology

(November 2014)

Pedro G. Ferreira
University of Oxford

Desiderata...

- The inflationary era (what kind of fields, potentials, energy scales)
- Dark energy (what is it, what energy scales)
- Ultra-light fields (neutrinos, ultralight axions)
- The dark matter (what kind of dark matter particle, cross section)
- Gravity (what is it, precision tests)

Background cosmology: parameters

Hubble parameter $$H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \left[\frac{\Omega_M}{a^3} + \frac{\Omega_R}{a^4} + \frac{\Omega_K}{a^2} + \frac{\Omega_{DE}}{a^{3(1+w)}}\right]$$

critical density $\rho_c = 1.9 \times 10^{-26} h^2 \mathrm{kgm}^{-3}$ $\quad P_{DE} = w\rho_{DE}$

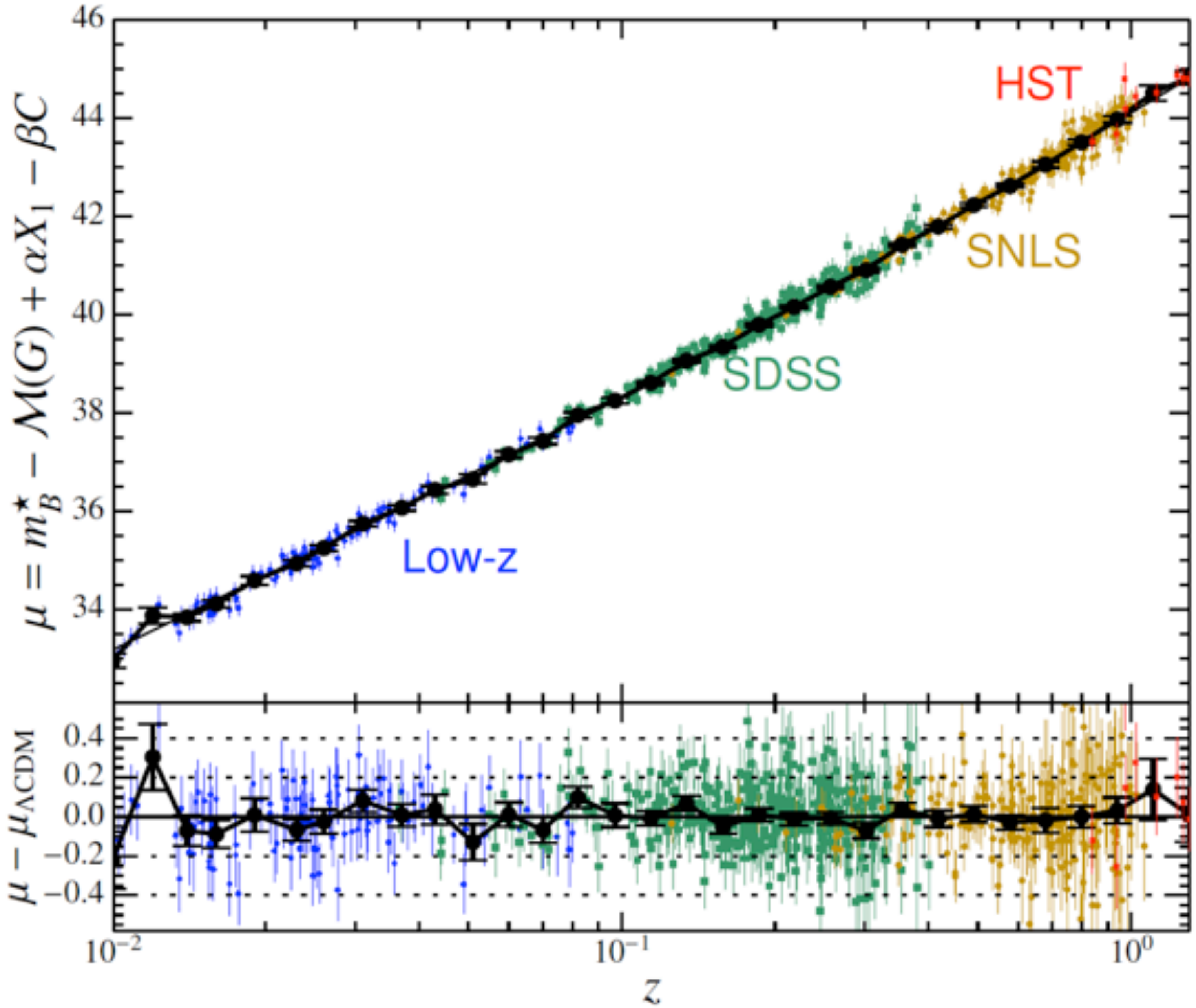
$$D_H = \frac{c}{H_0} = 3000\ h^{-1}\ \mathrm{Mpc} \qquad D_C = \int_t^{t_0} \frac{c\,dt'}{a(t')} = c\int_a^1 \frac{da}{a^2 H(a)}$$

Luminosity distance: $$D_L = (1+z)\begin{cases} \frac{D_H}{\sqrt{\Omega_k}} \sinh[\sqrt{\Omega_k} D_C/D_H] & \text{for } \Omega_k > 0 \\ D_C & \text{for } \Omega_k = 0 \\ \frac{D_H}{\sqrt{|\Omega_k|}} \sin[\sqrt{|\Omega_k|} D_C/D_H] & \text{for } \Omega_k < 0 \end{cases}$$

Angular diameter distance: $$D_A = \frac{D_L}{(1+z)^2}$$

Background cosmology: deceleration

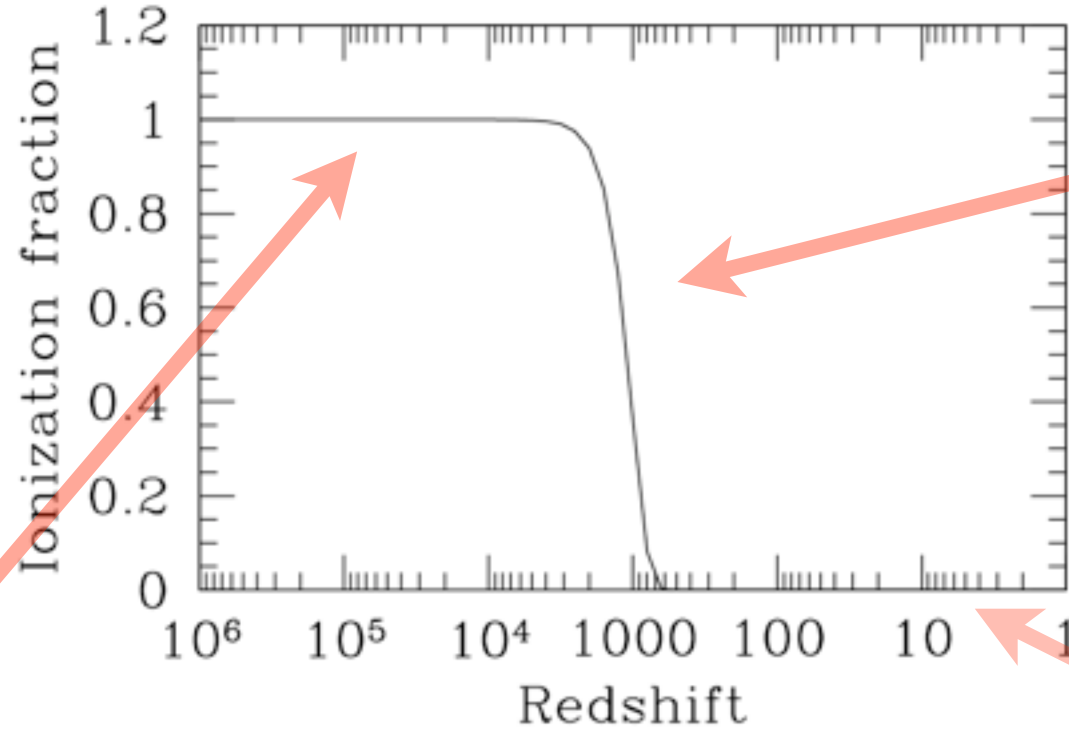
$$\mathcal{M} \propto -\log D_L$$



$$1 + z = \frac{1}{a}$$

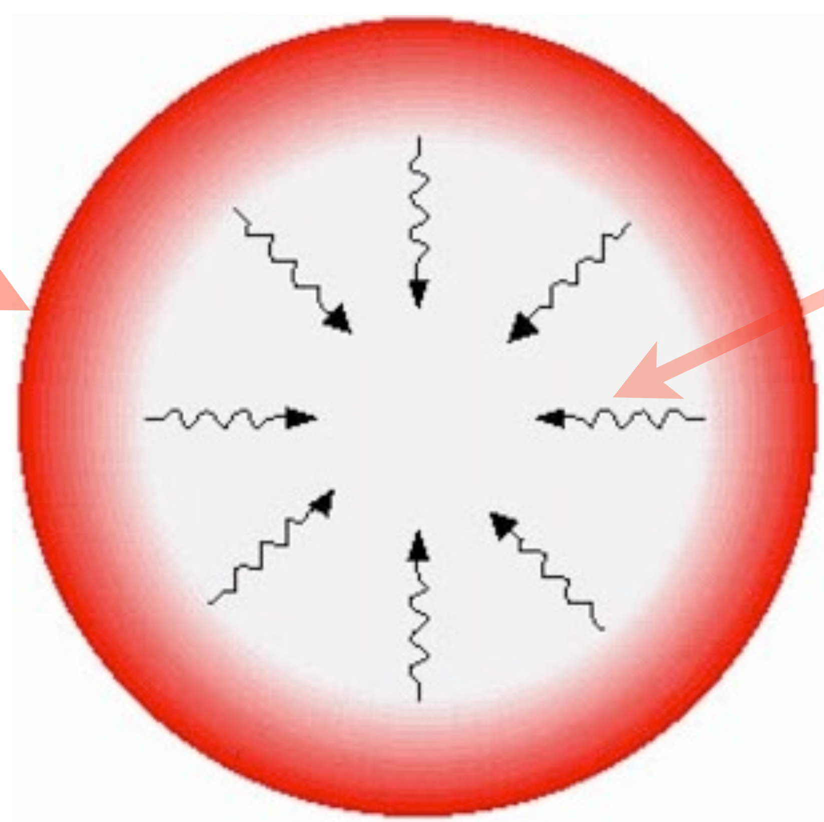
Betoule et al (2014)

Background cosmology: CMB



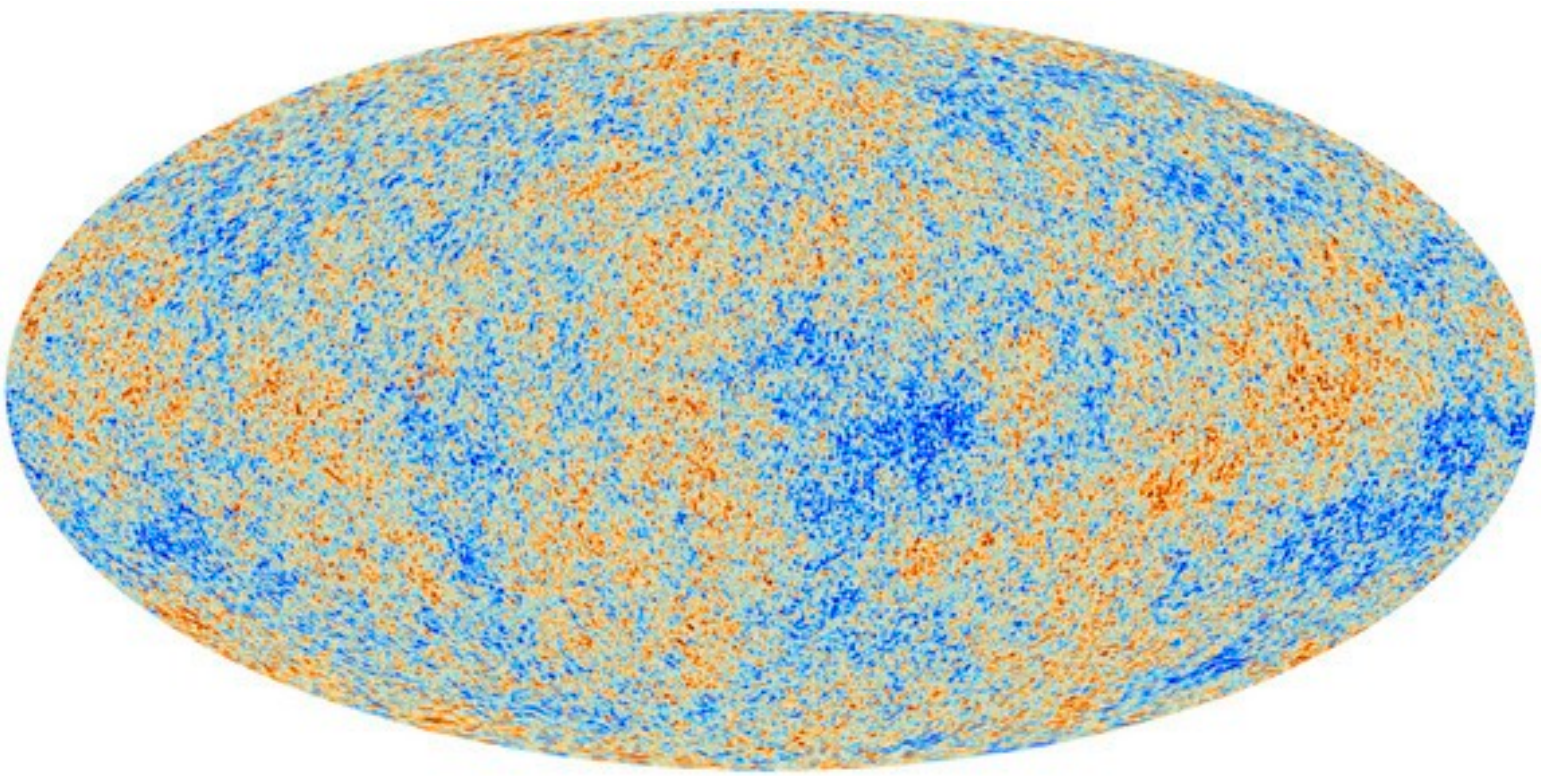
Collisional damping
(Silk damping)

Tight coupling:



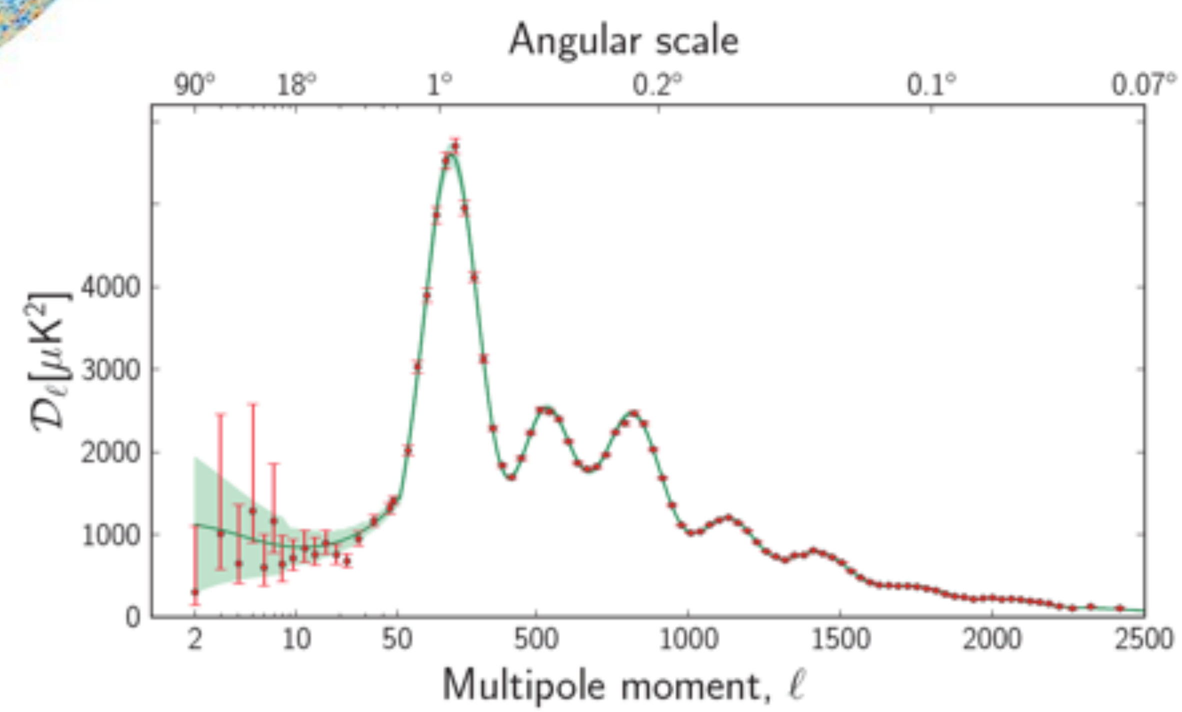
Free streaming:

Large scale structure: CMB



Planck

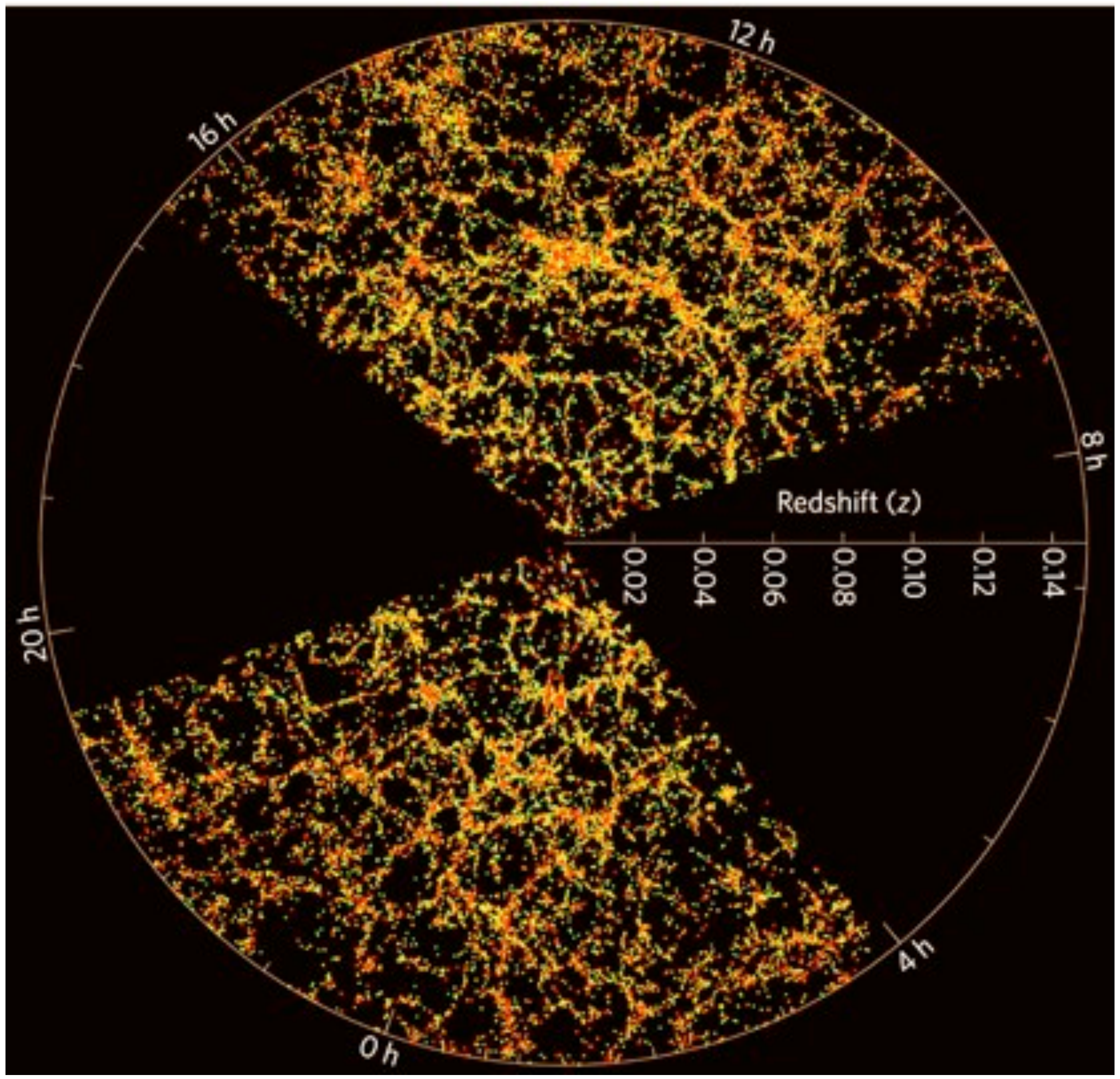
Angular power spectrum of the

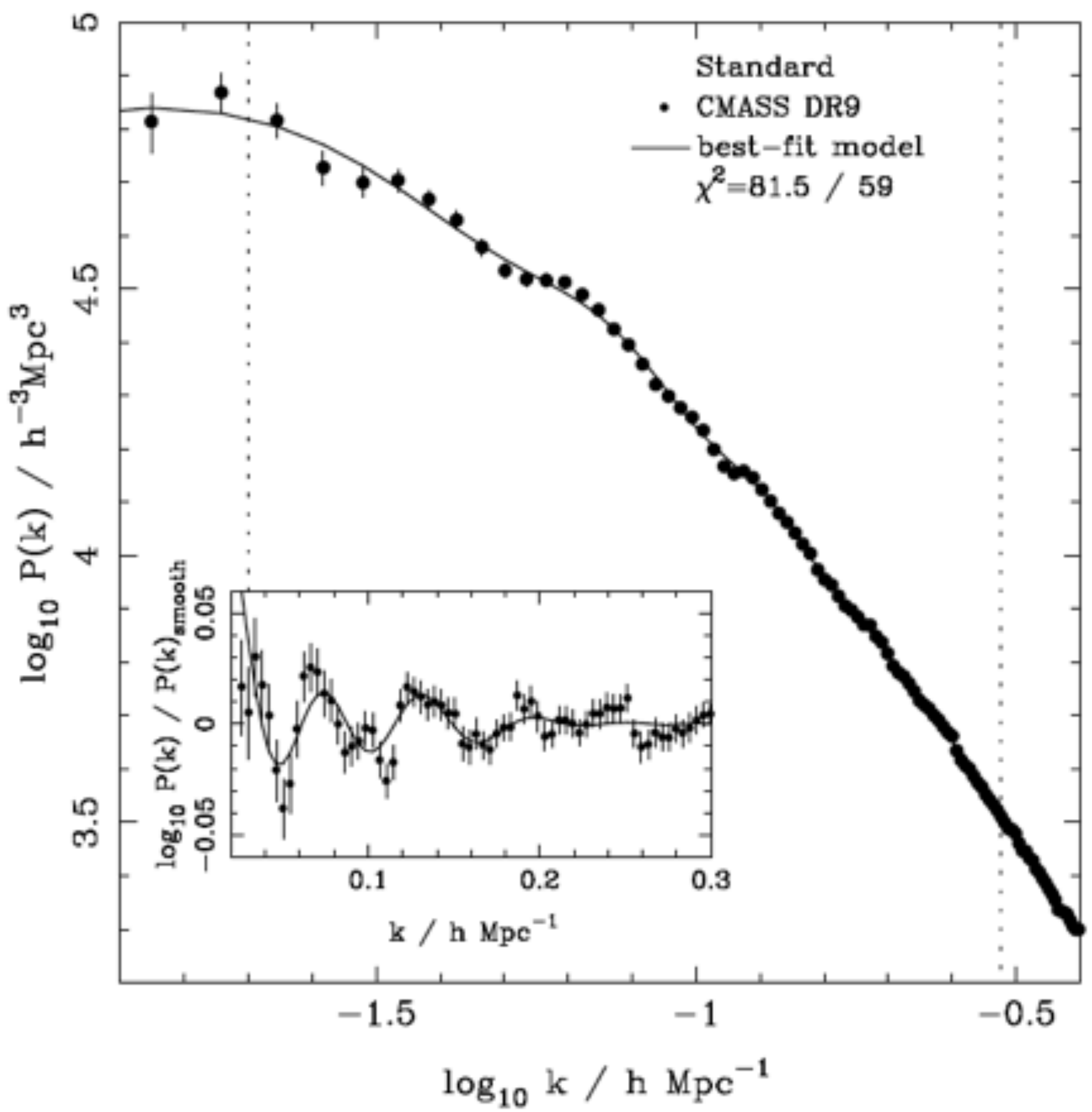


$$\mathcal{D}_\ell = \frac{\ell(\ell+1)C_\ell}{4\pi}$$

Planck 2013

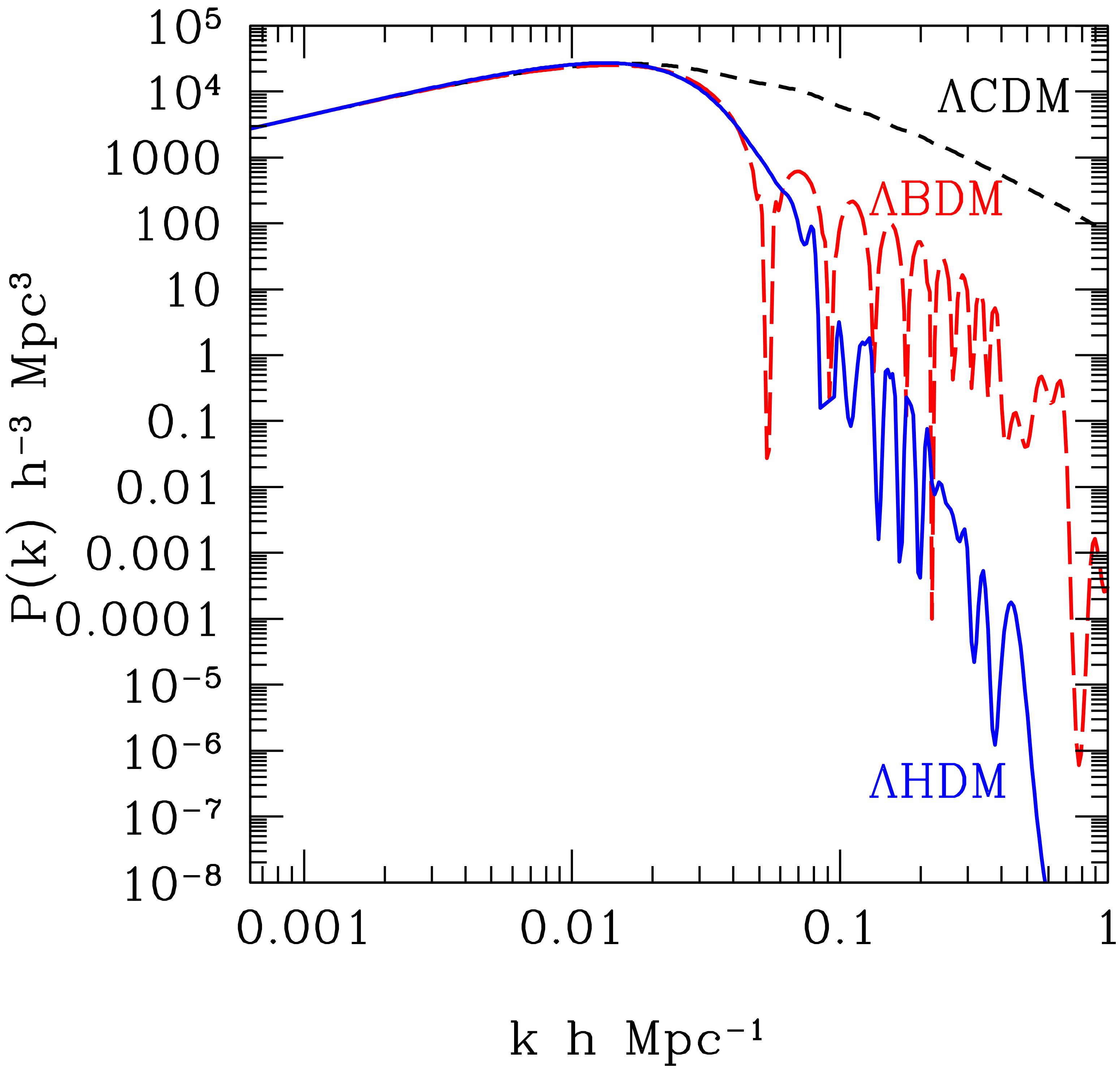
Large scale structure: cosmic web



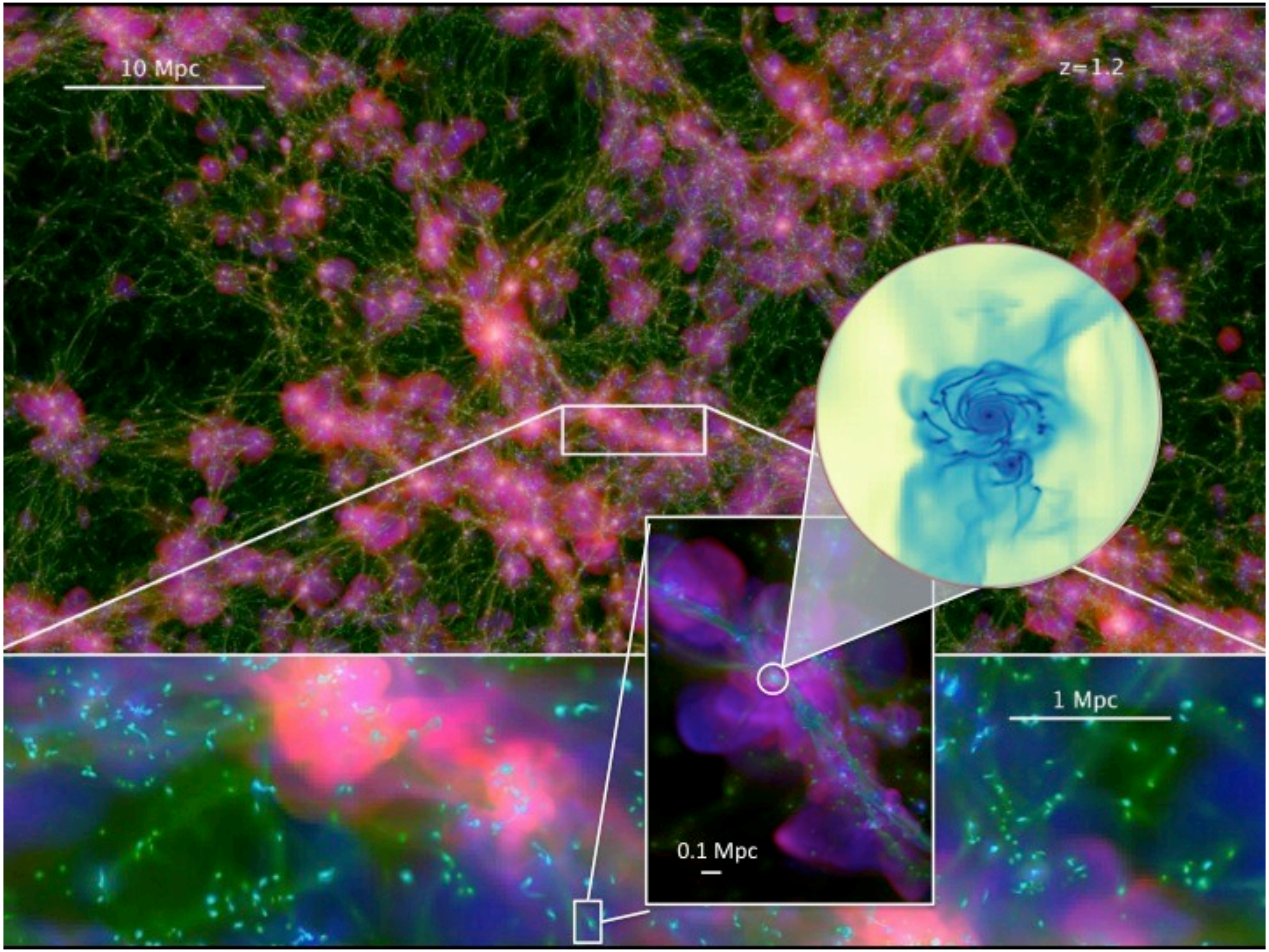


SDSS

Large scale structure: cosmic web



Linear versus non-linear

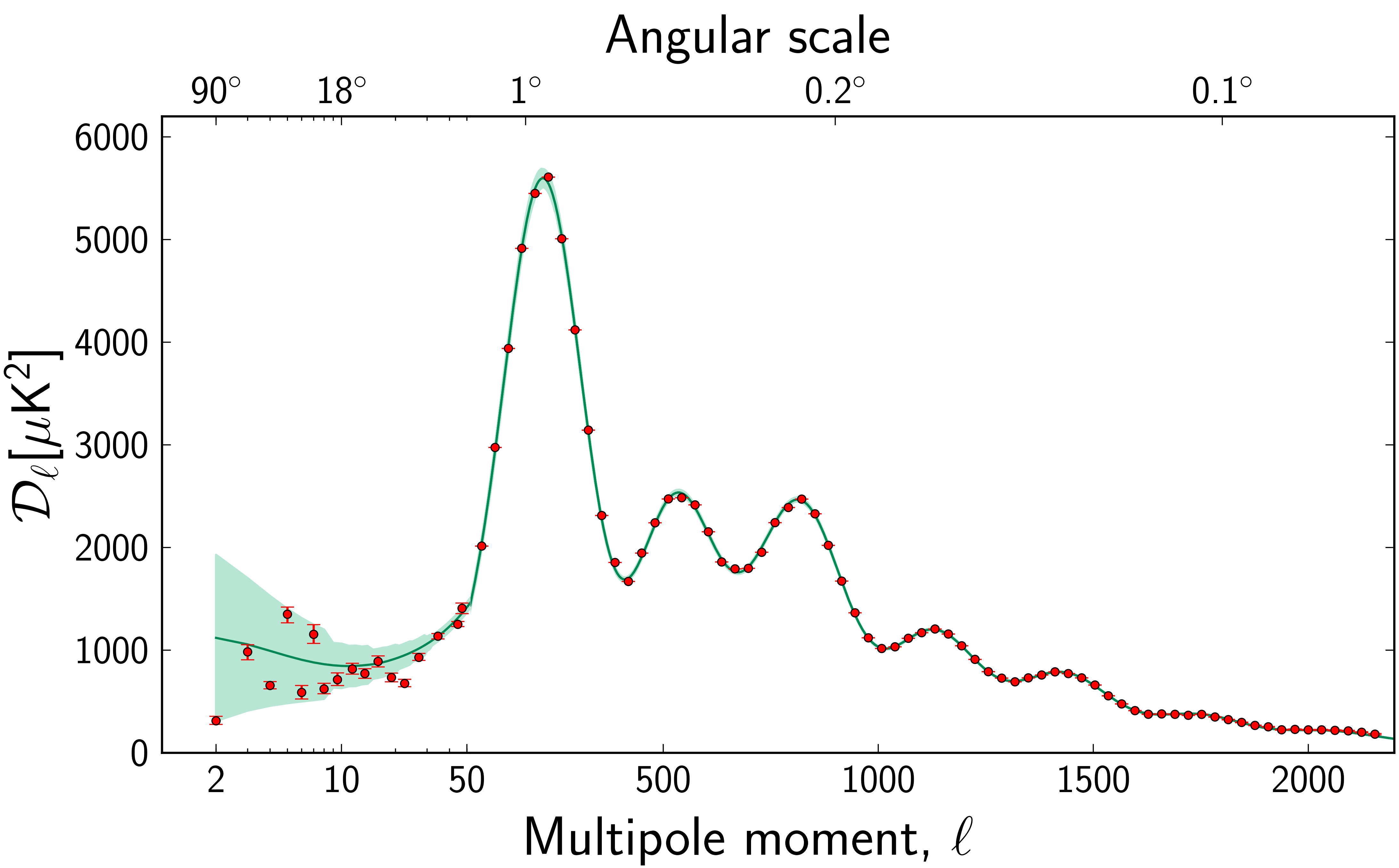


Courtesy of Devriendt & Slyz 2014

Data: the State of the Universe

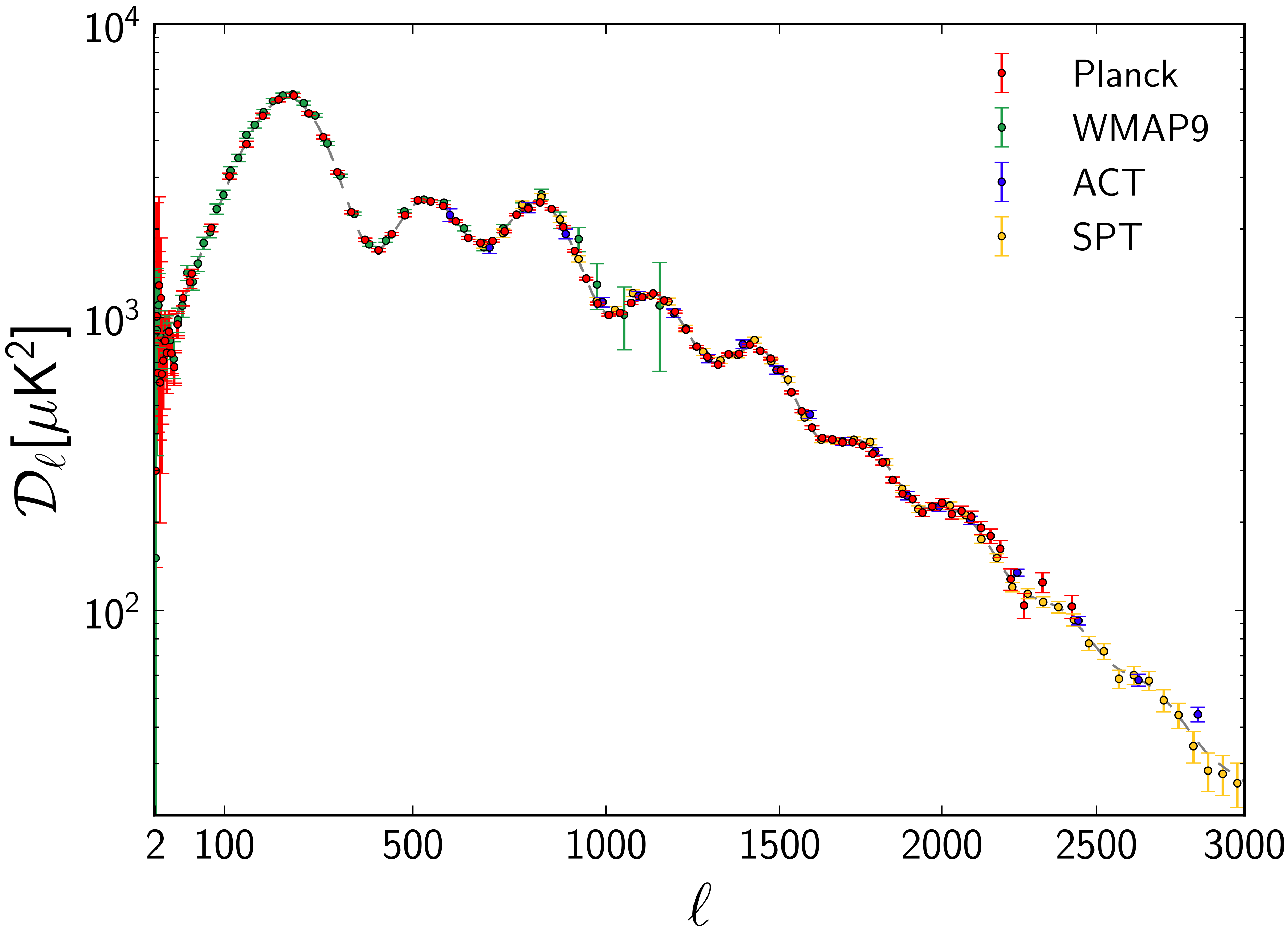
- Simple flat ΛCDM model still fits (most) data
- New data from Planck rules out array of possible deviations, strengthened with improved BAO.
- Some mild tensions between CMB and low redshift measures (clusters, H_0).
- Lensing (both galaxy and CMB) starting to play role in ‘best’ constraints. First measure of HI spectrum made.
- Little knowledge of DE behaviour; need future measurements.

Data: CMB



Planck collaboration 2013

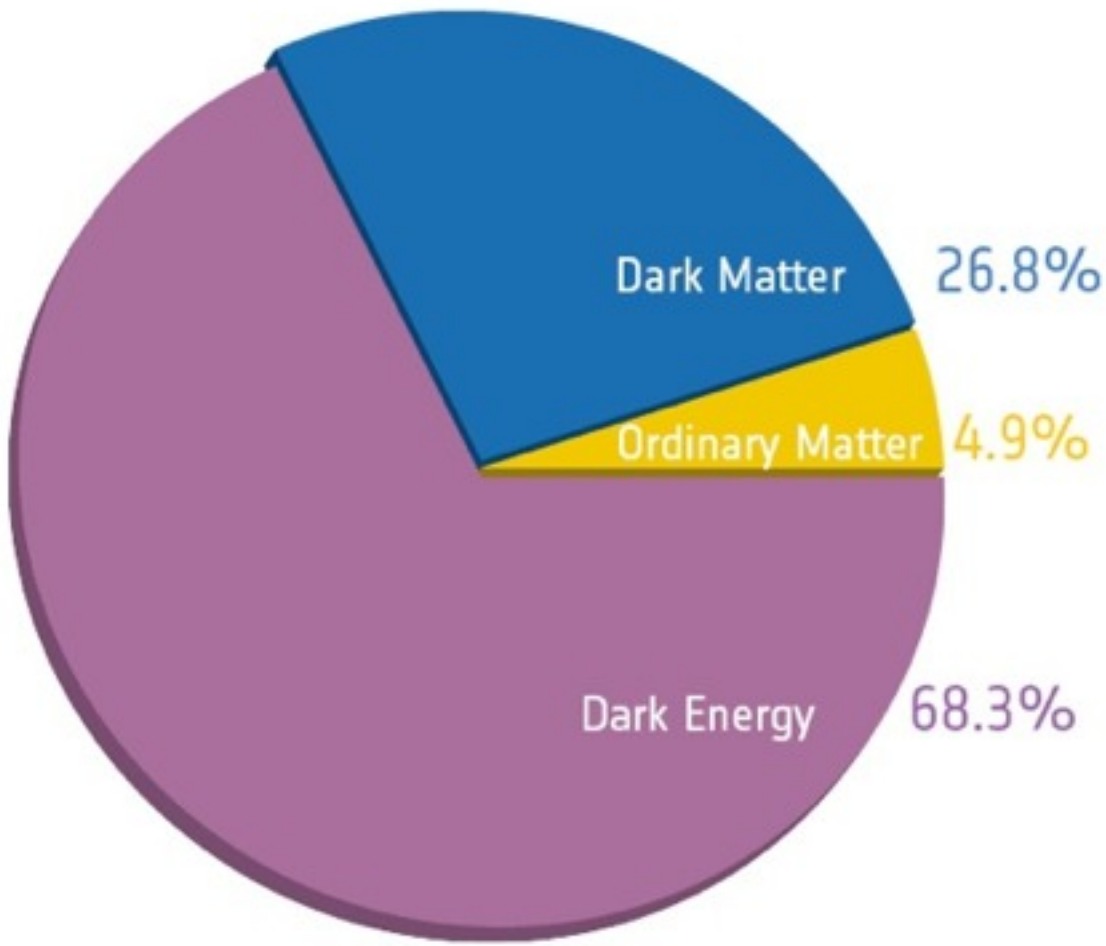
Data: CMB



Smaller scales probed by ACT and SPT

ΛCDM

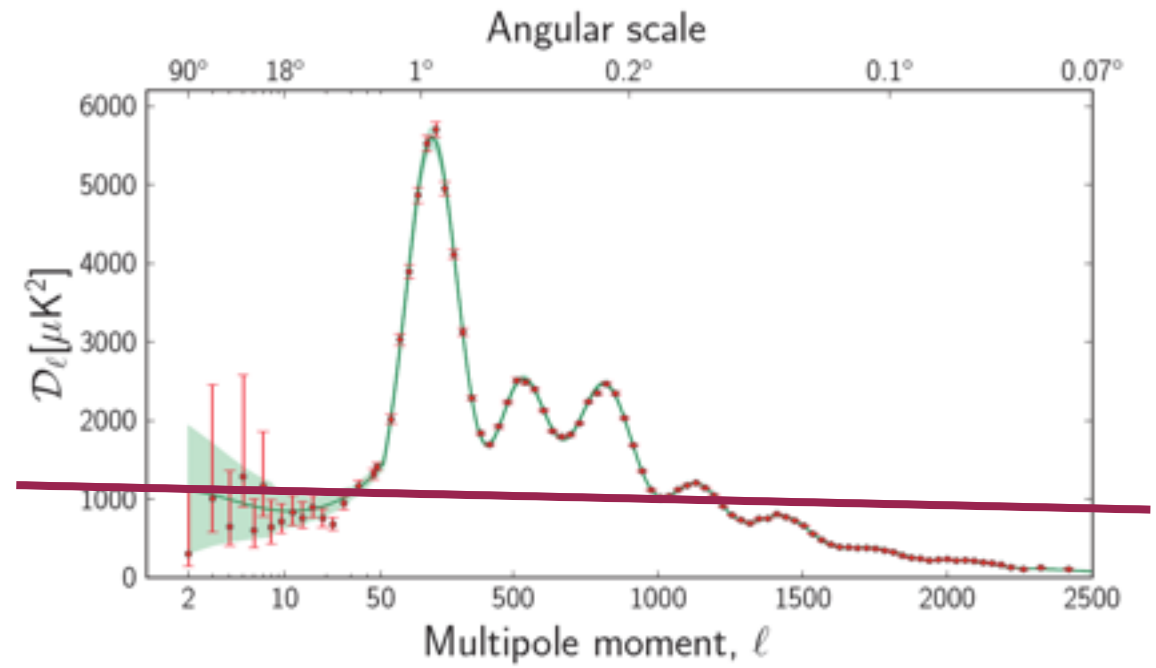
Parameter	Value (68%)
$\omega_b h^2$	0.02207 ± 0.0003
$\omega_c h^2$	0.1198 ± 0.0026
$100\theta_*$	1.04148 ± 0.00062
τ	0.091 ± 0.014
n_s	0.9585 ± 0.0070
H_0	67.3 ± 1.2
Ω_Λ	0.685 ± 0.017
σ_8	0.828 ± 0.012
$z_{\rm re}$	11.1 ± 1.1

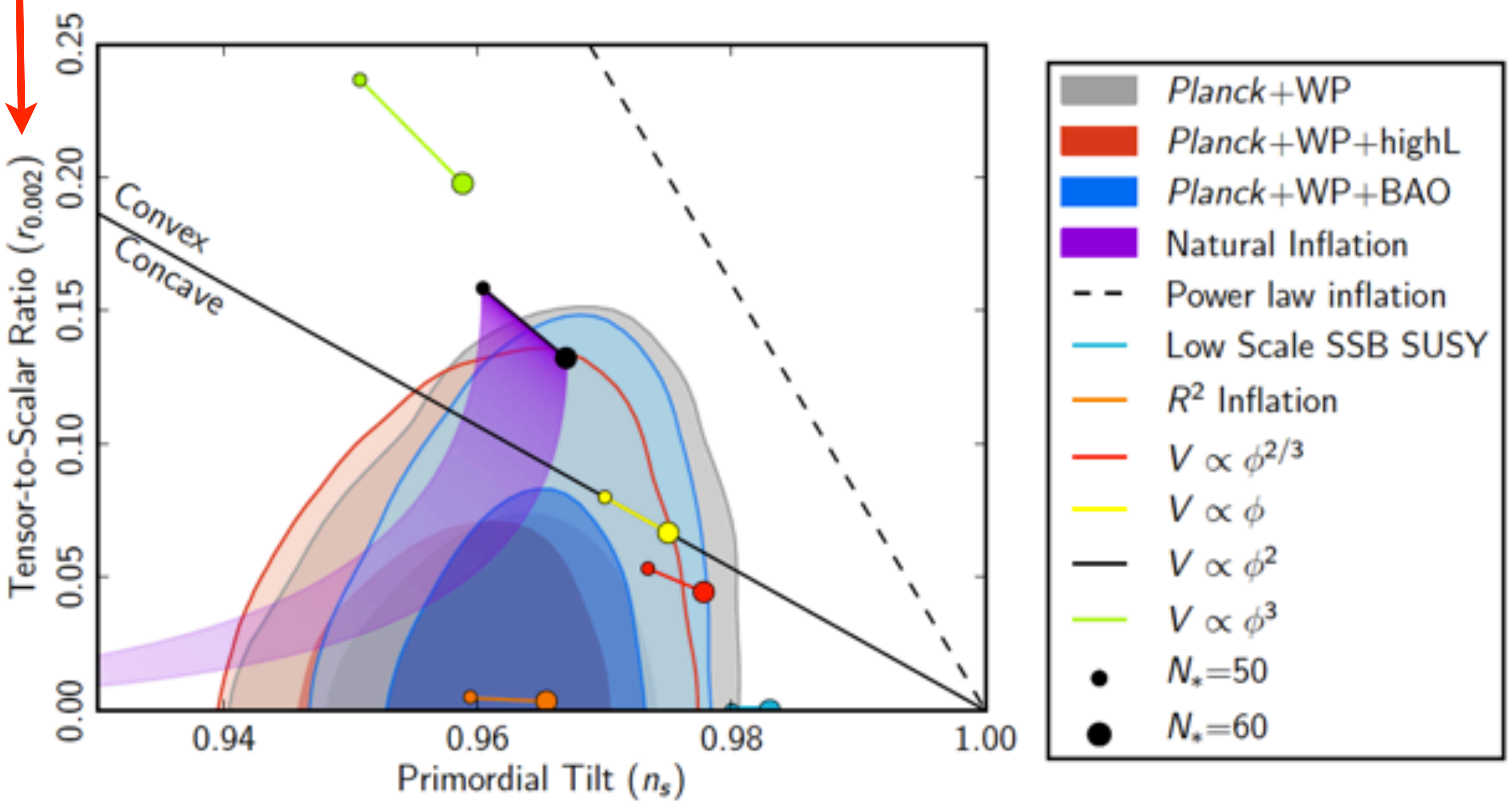


Initial Conditions: Inflation

Primordial Gravitational Waves

Primordial Tilt





Planck XXII

5-sigma away from scale invariance

$$n_s = 0.9585 \pm 0.0070$$

No running of spectral tilt

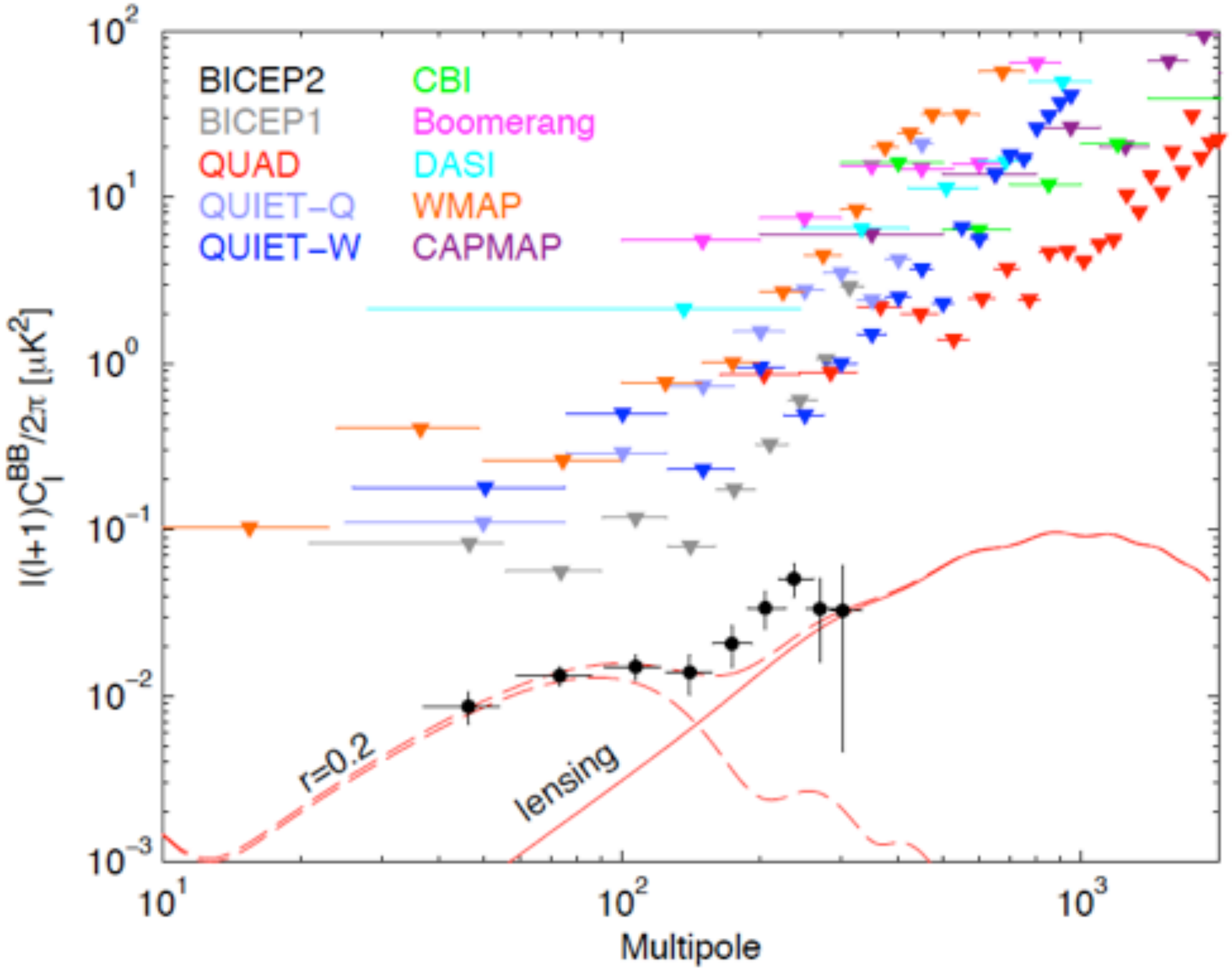
$$\frac{dn_s}{d\ln k} = -0.014 \pm 0.009$$

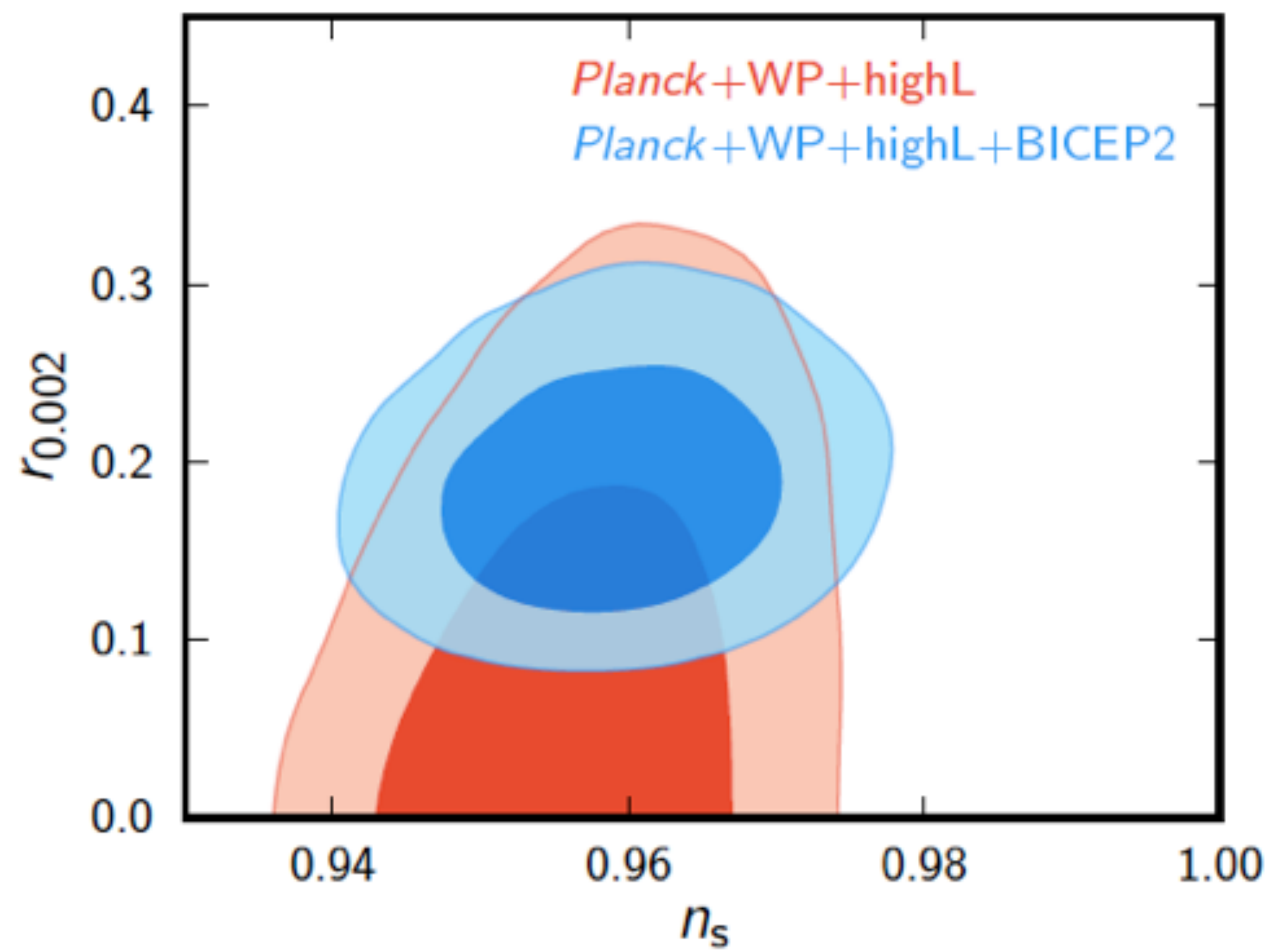
Upper bound on tensor

$$r < 0.11$$

$$E_{\rm inf} \equiv (3H^2 M_{\rm pl}^2)^{1/4} = 8 \times 10^{-3} \left(\frac{r}{0.1}\right)^{1/4} M_{\rm pl}$$

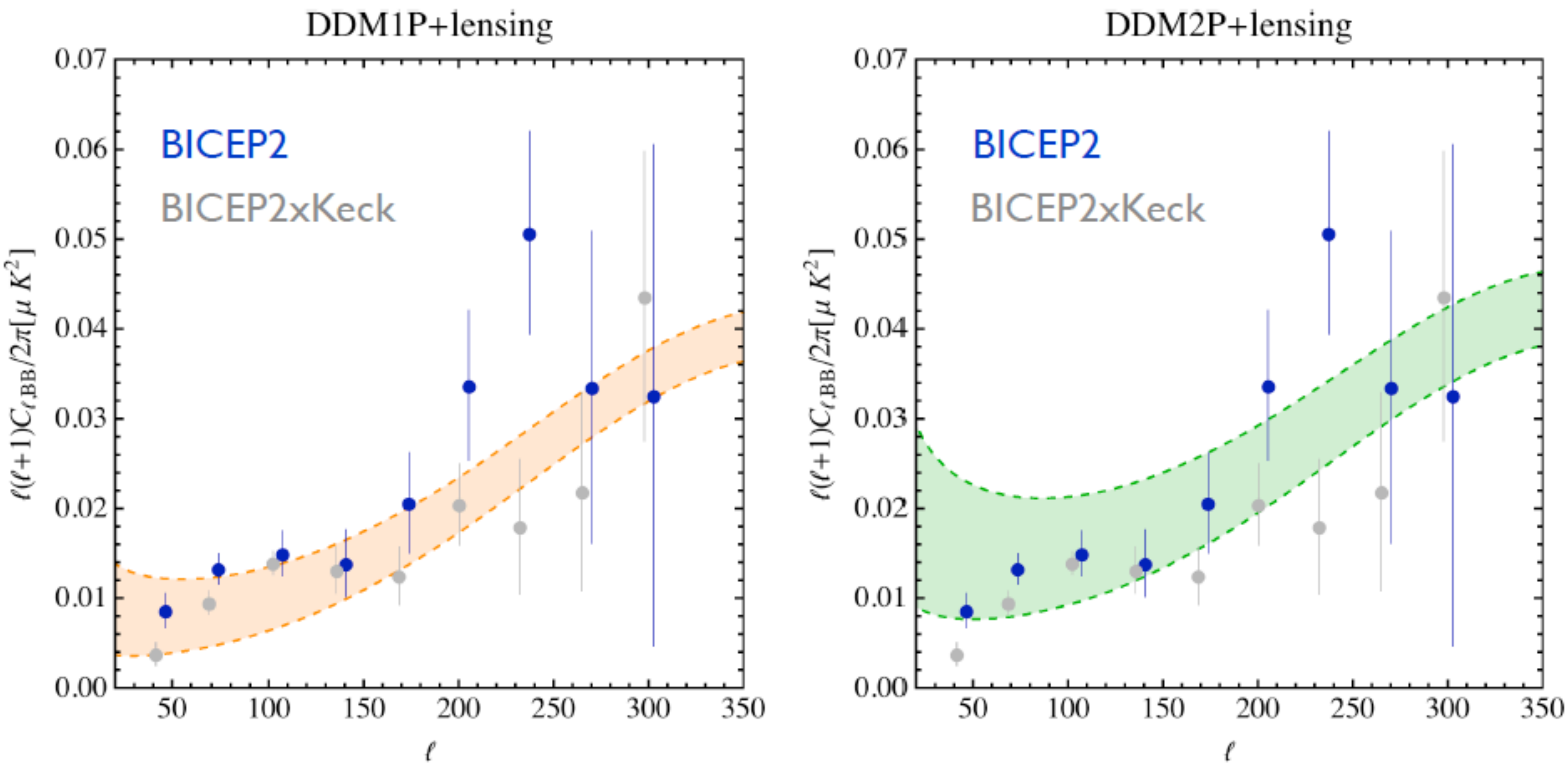
Initial Conditions: BICEP2





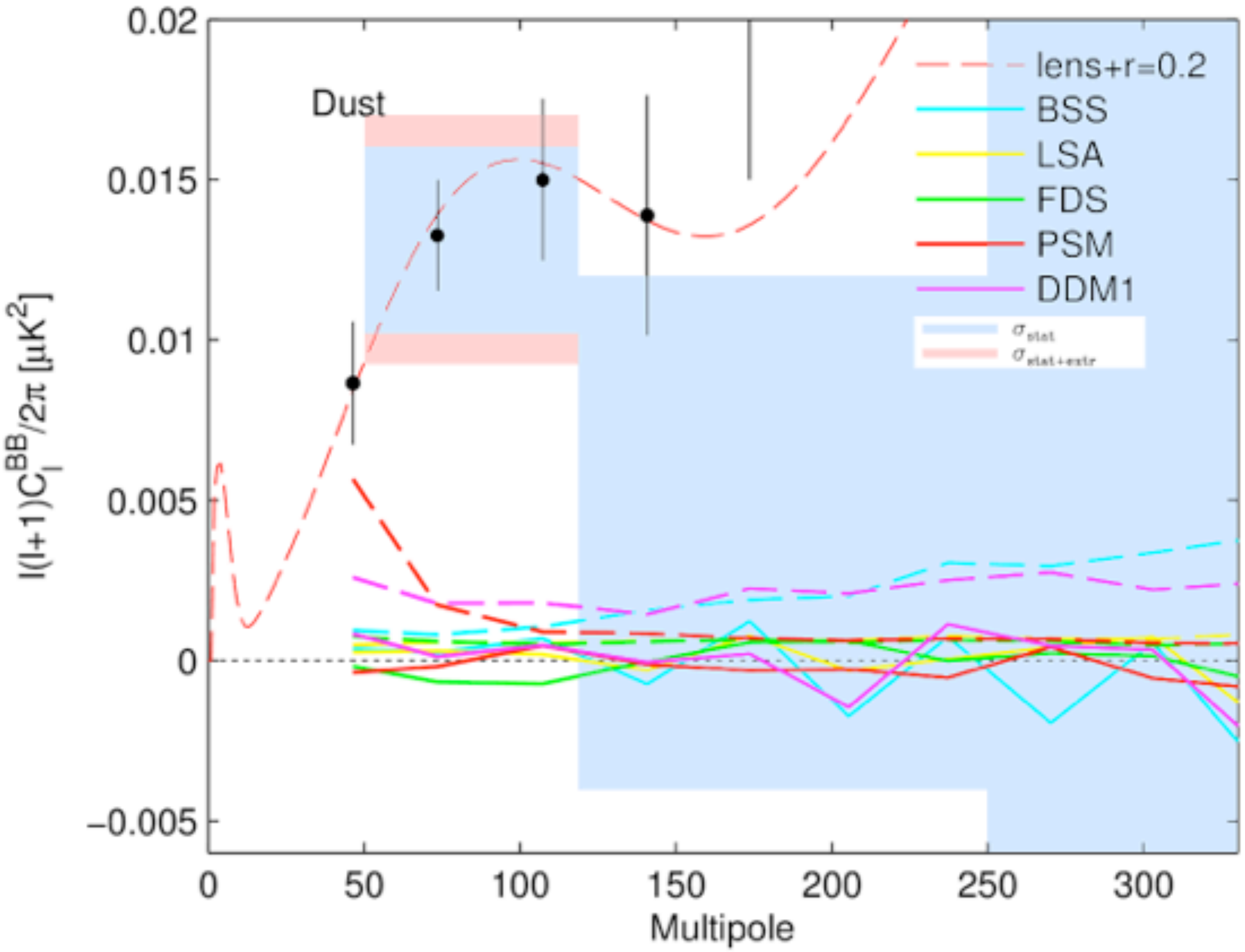
BICEP2

Initial Conditions: BICEP2



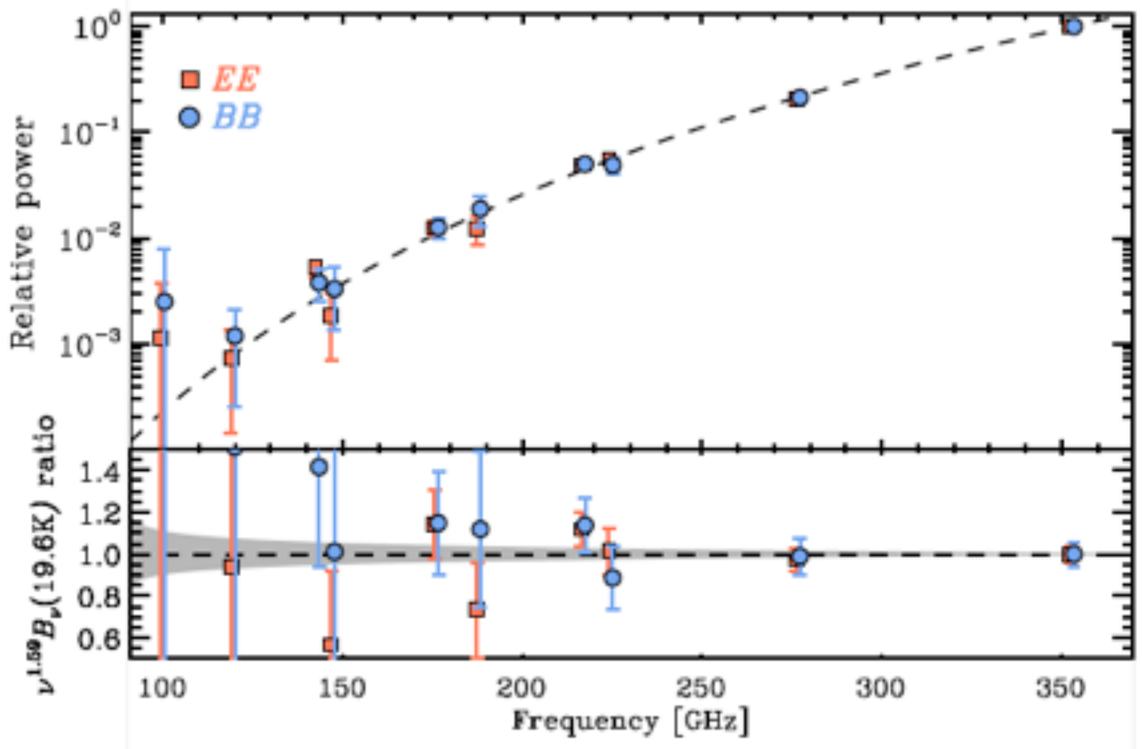
Flauger et al 2014

Initial Conditions: BICEP2

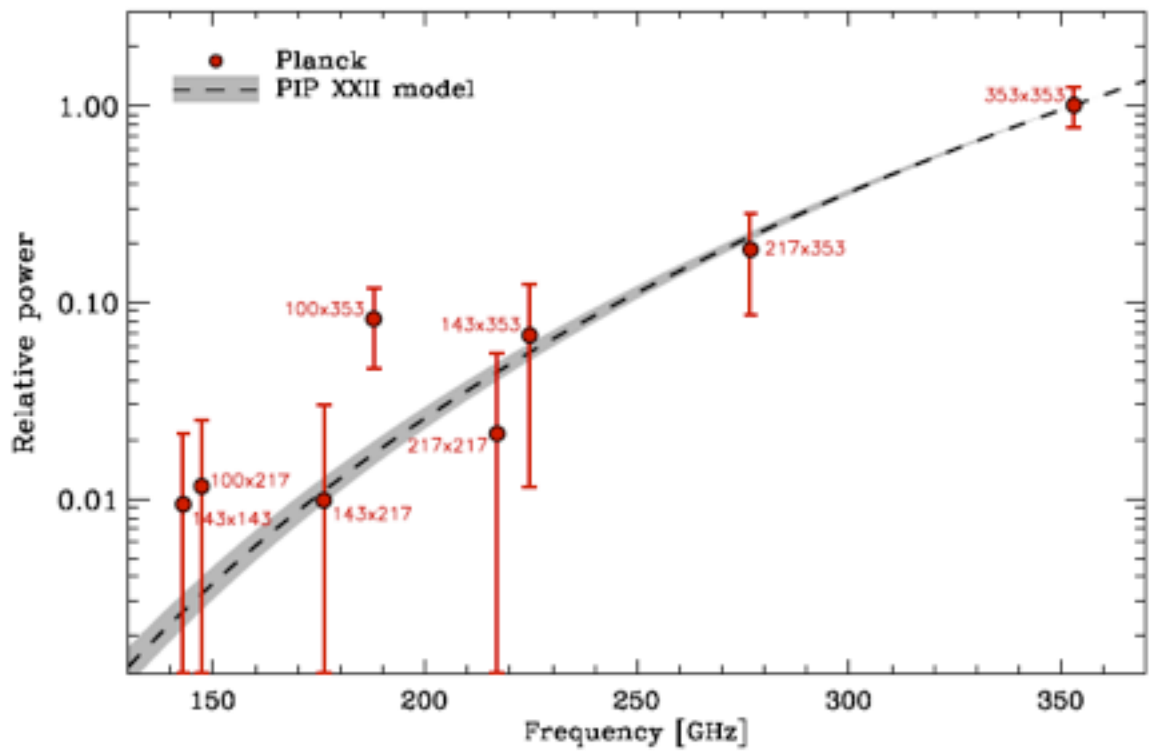


Planck XXX

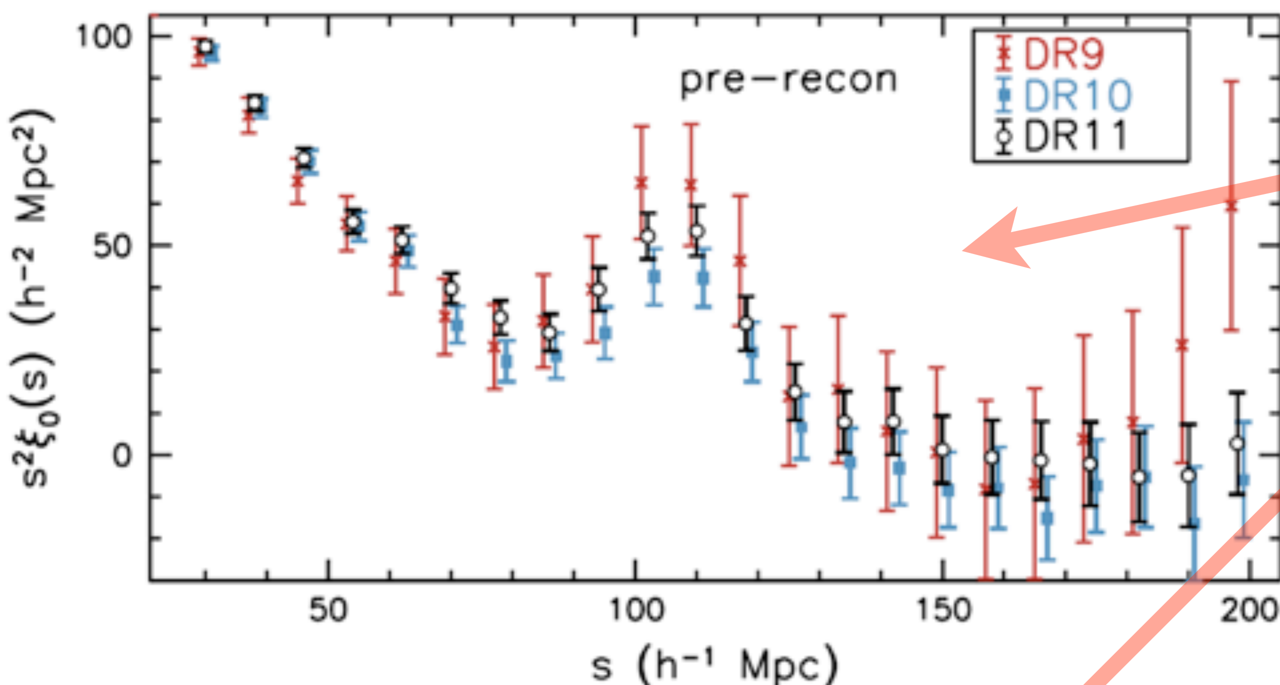
“full” sky extrapolation



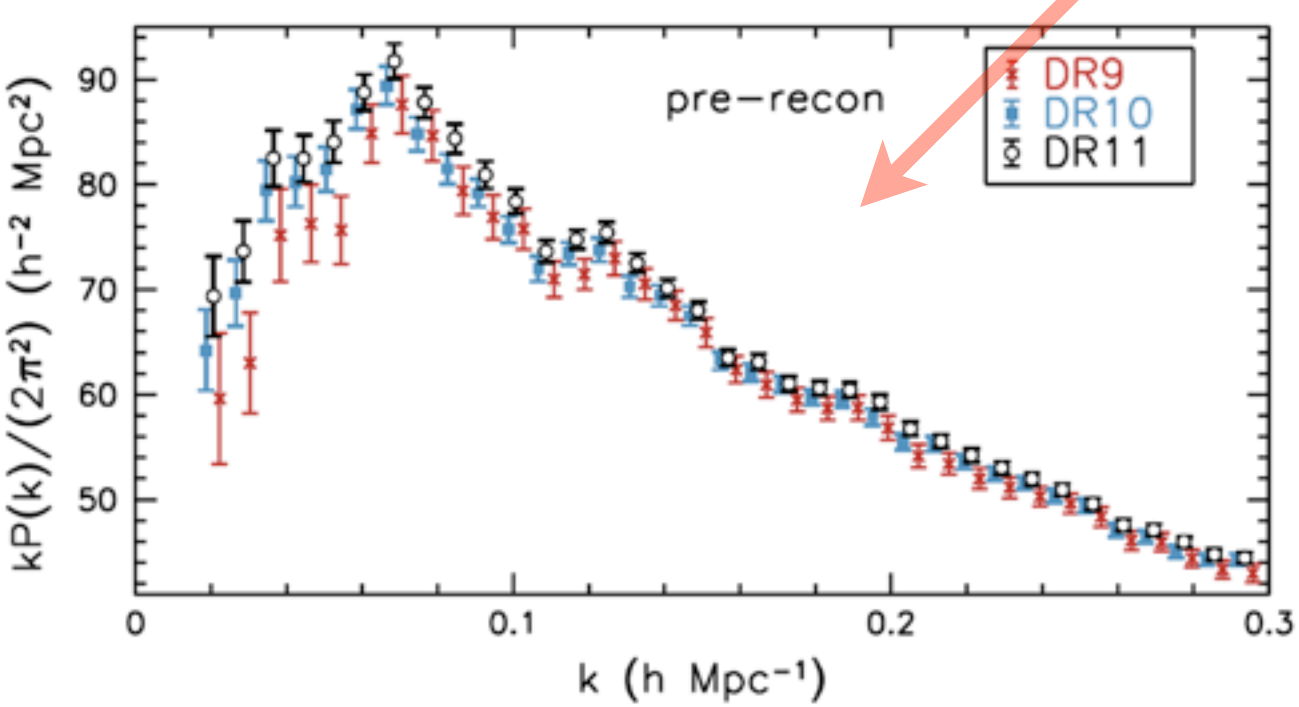
BICEP2 field extrapolation

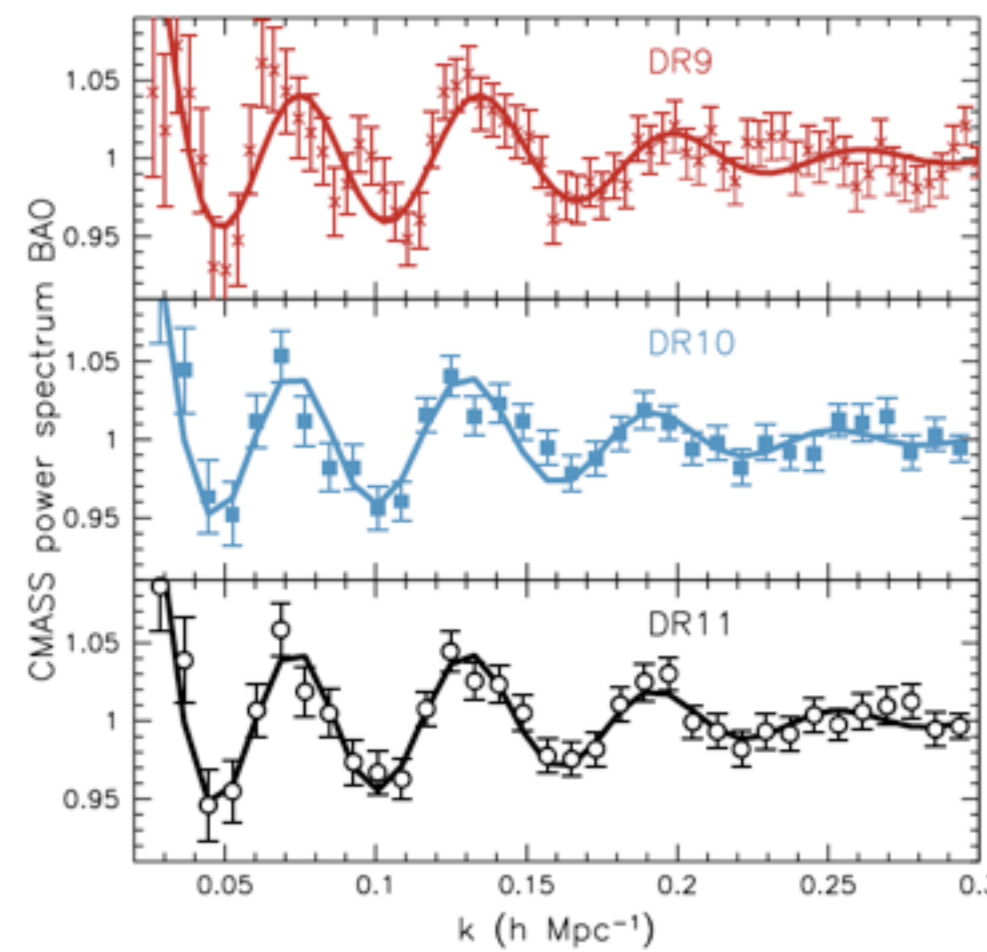


Dark Energy: BAO*



Sound horizon at recombination r_s

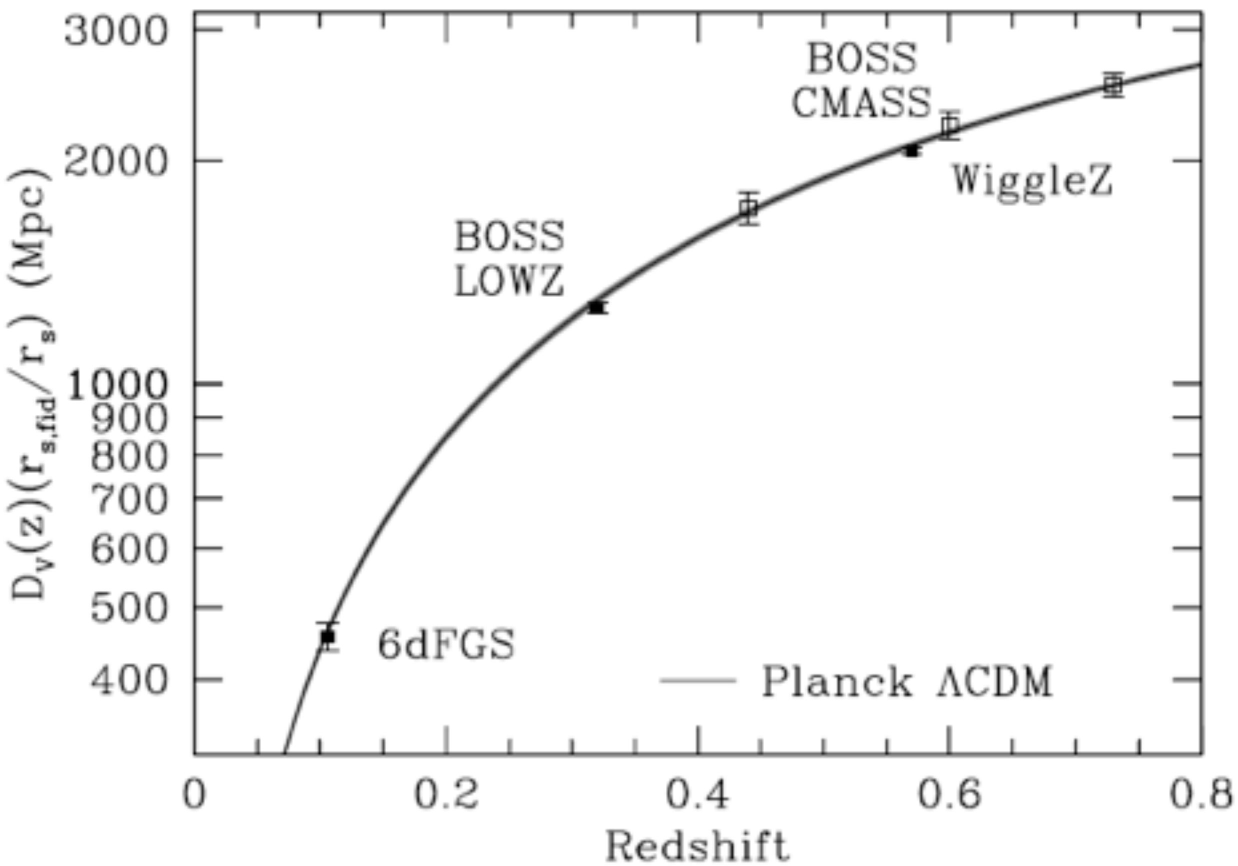


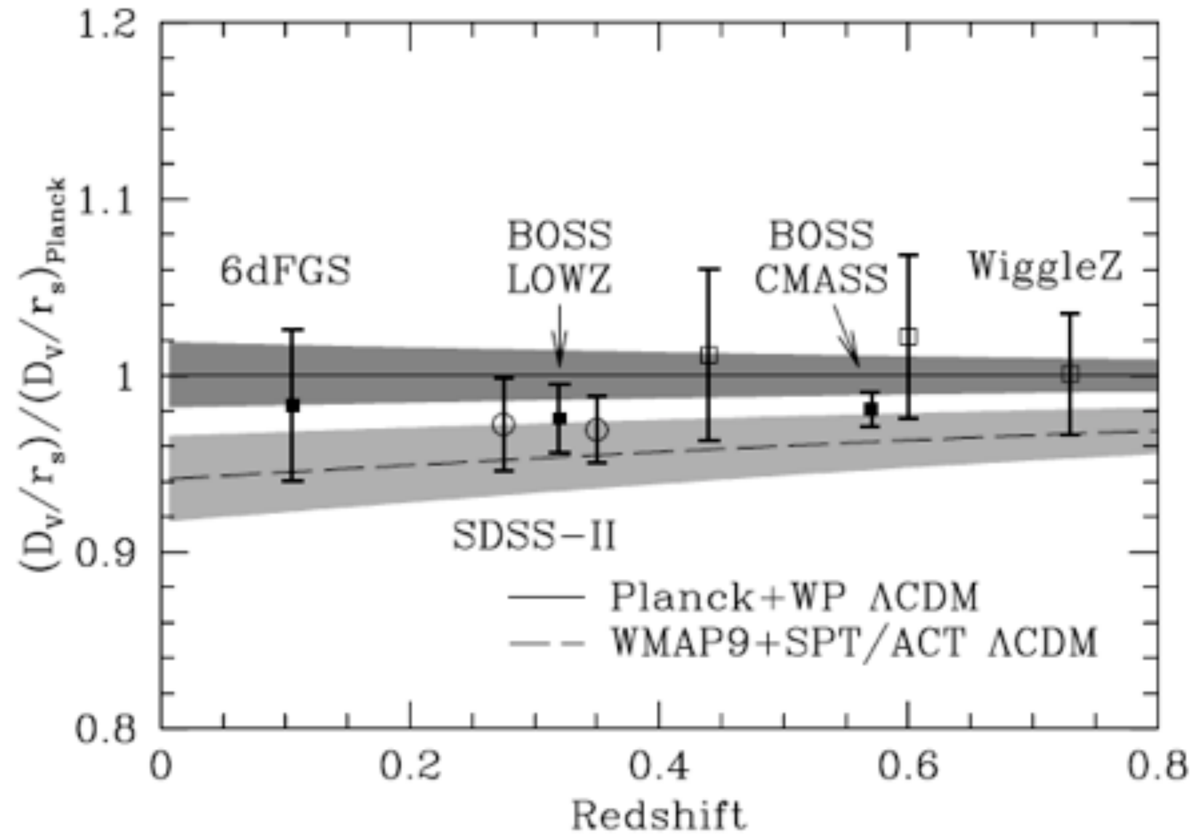


BOSS, Anderson et al 2013.

* Baryon Acoustic Oscillations

Data: Baryon Acoustic Oscillations

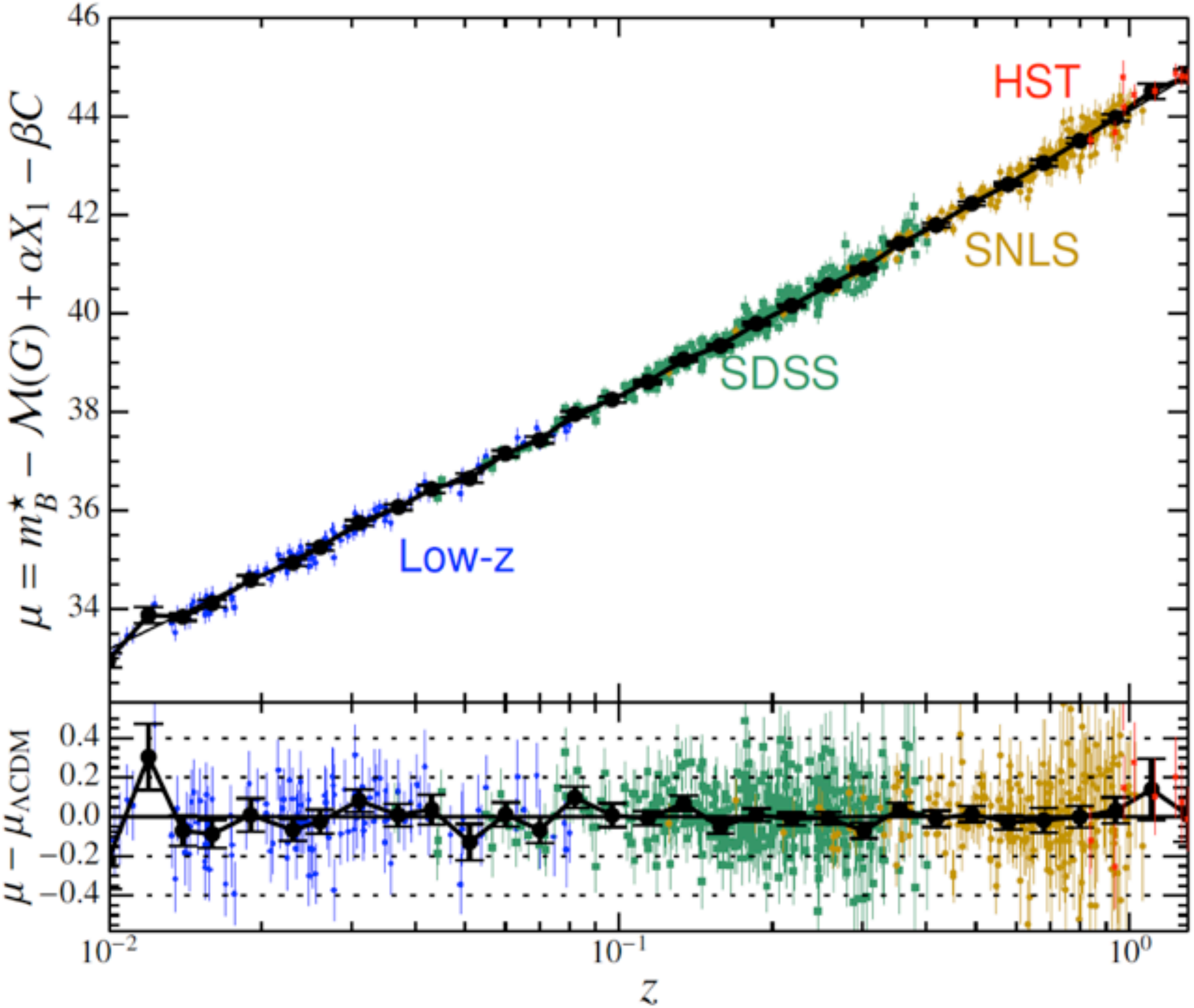




BOSS, Anderson et al 2013.

$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}.$$

Dark Energy: Supernovae Ia

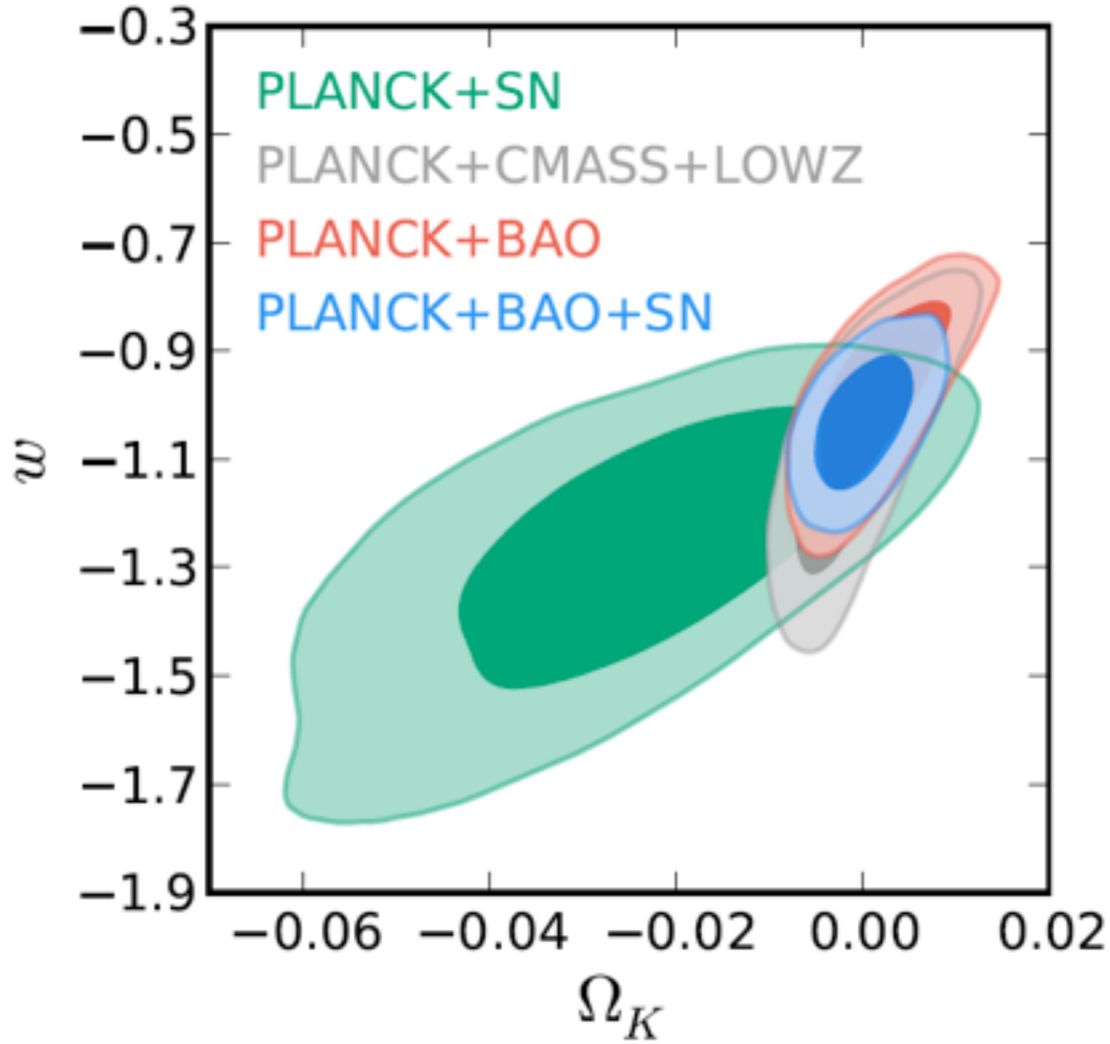


Betoule et al (2014)

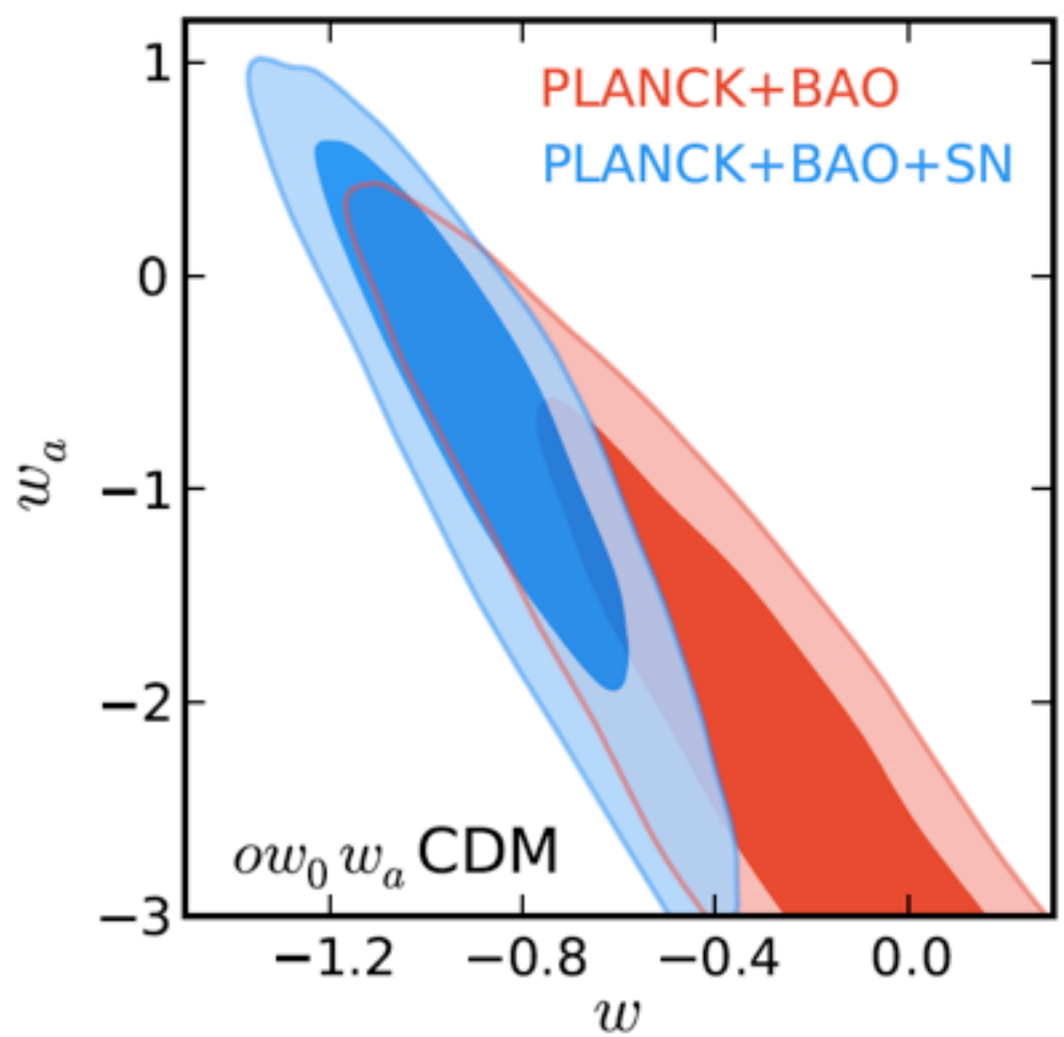
Dark Energy: CMB+SN+BAOs

$$w = w_0 + w_a(1 - a)$$

test of curvature



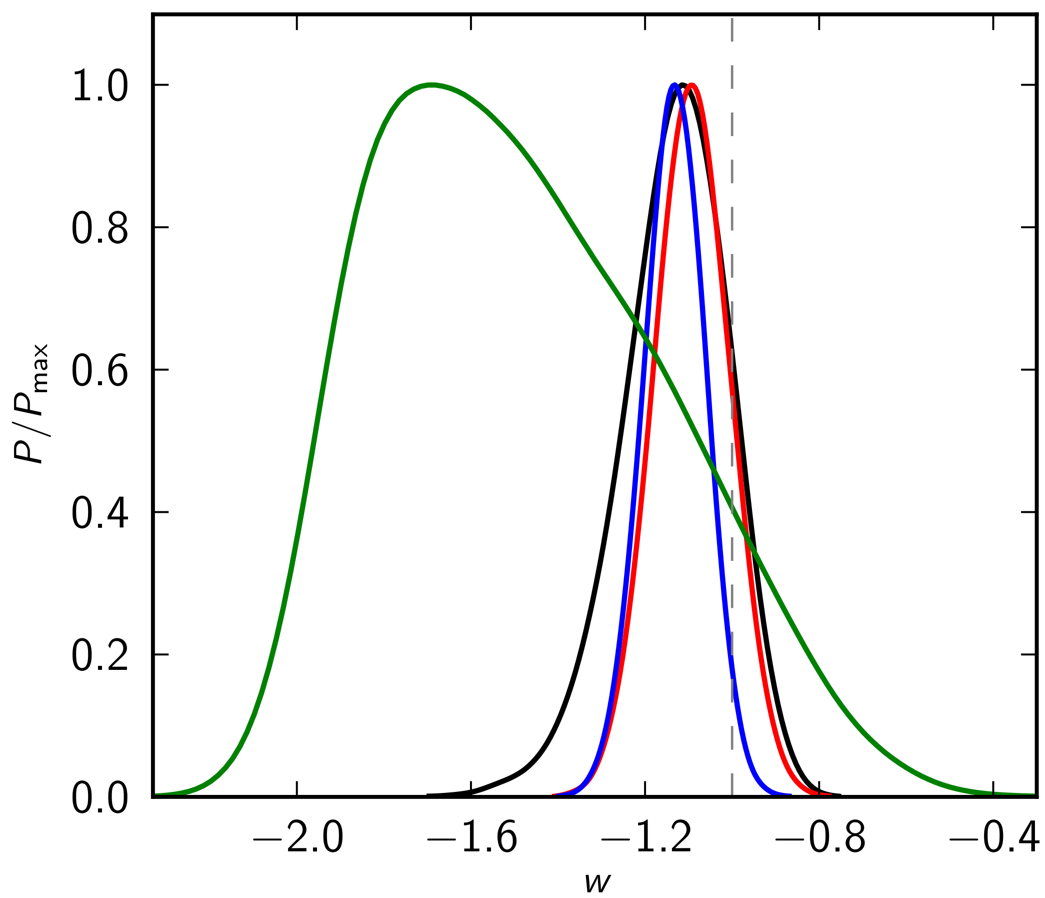
time evolution of equation of state



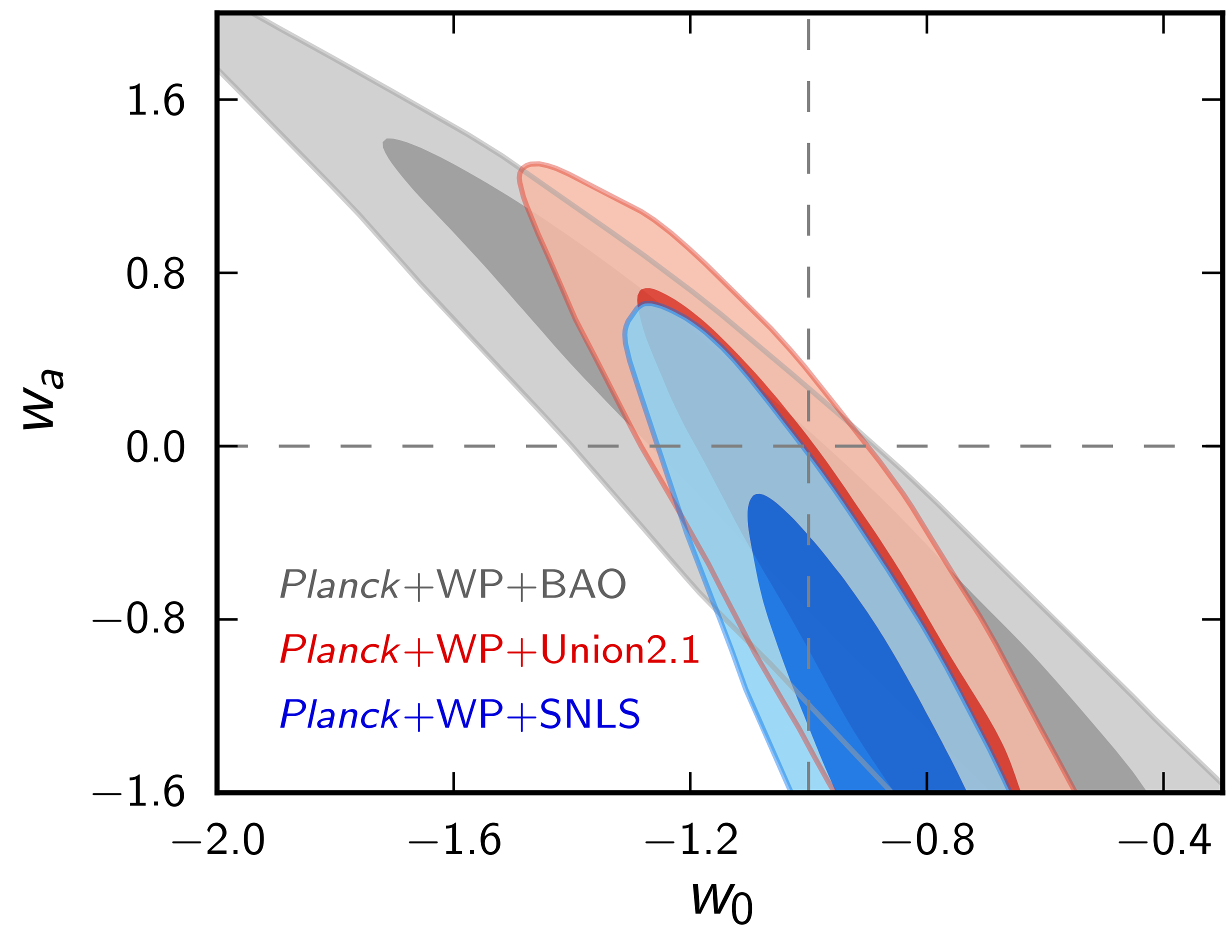
Anderson et al 2013

Dark Energy: CMB+SN+BAOs

$w = \text{constant}$

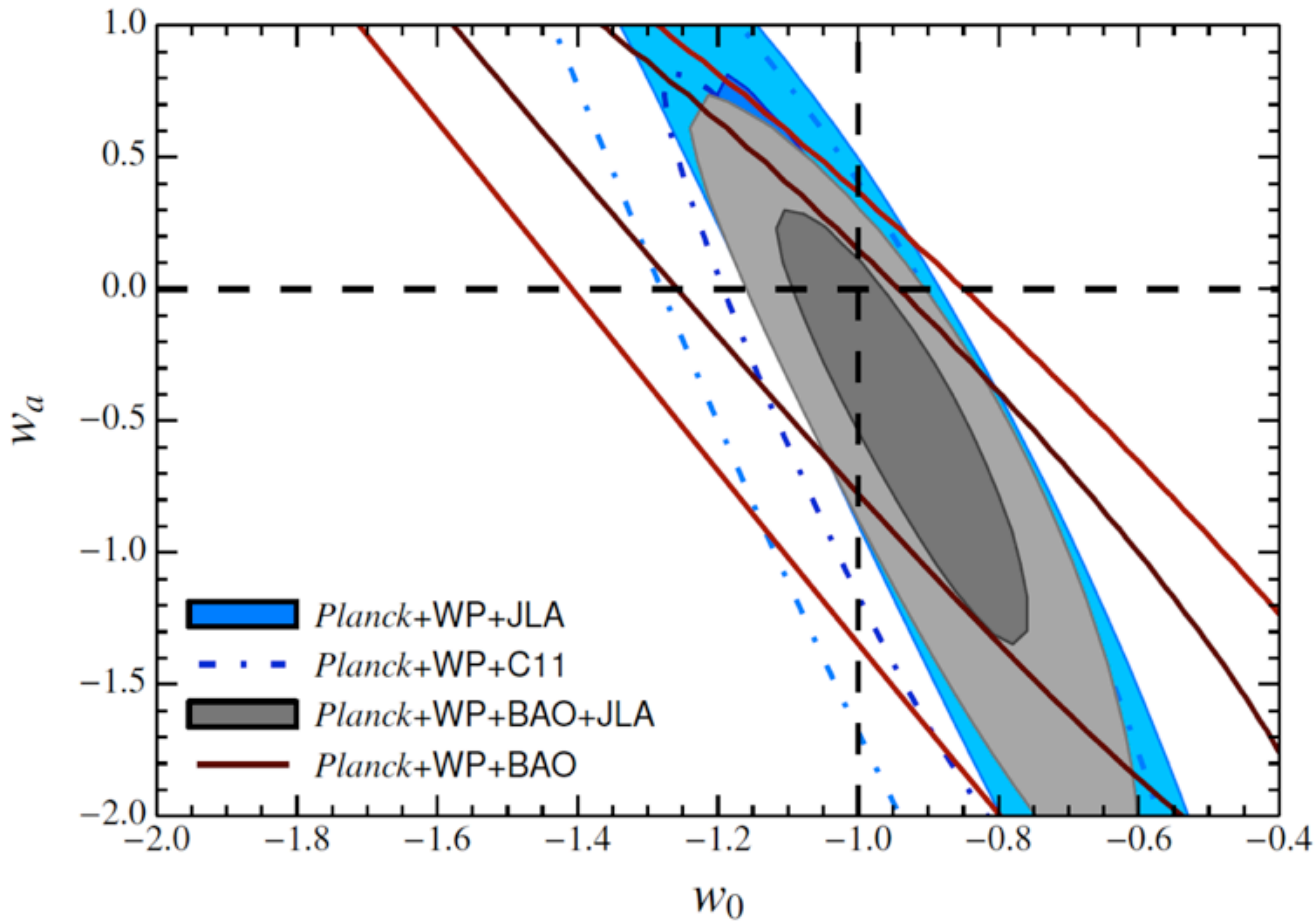


$w = w_0 + w_a(1 - a)$

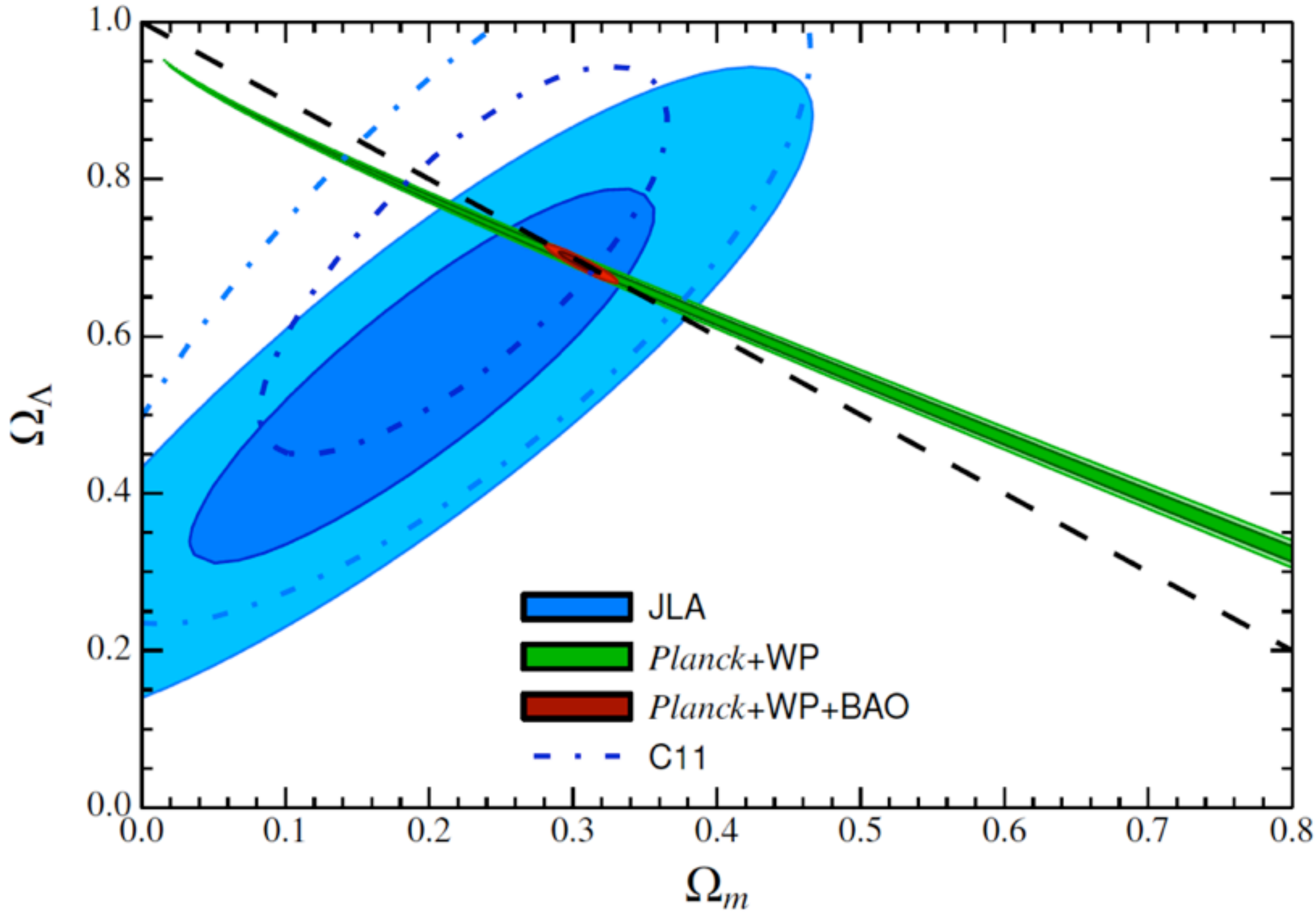


$$w = -1.13 \pm 0.12 \quad (68\% \text{ Planck} + \text{WMAP} + \text{BAO})$$

Dark Energy: CMB+SN+BAOs

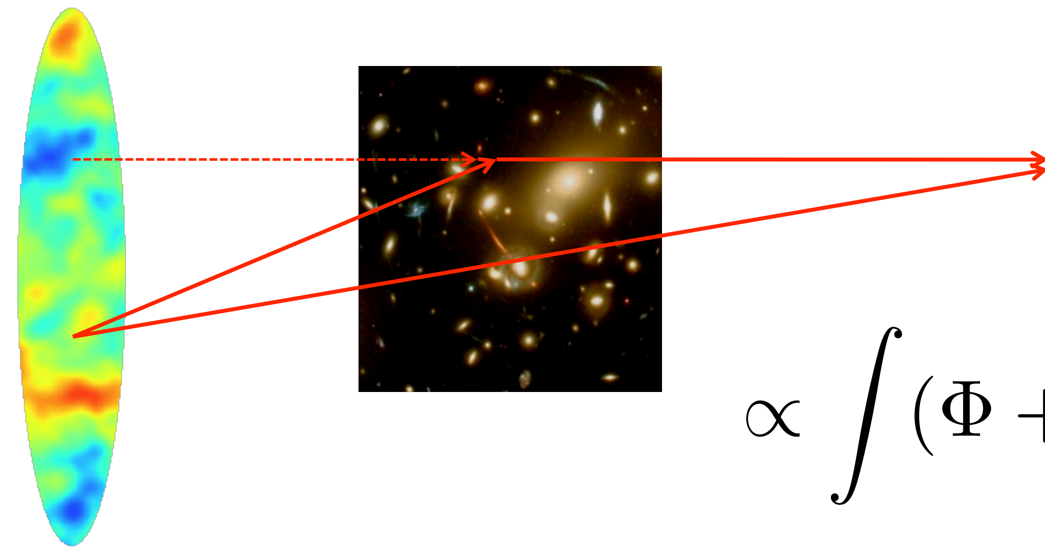


Dark Energy: CMB+BAOs *vs* SN

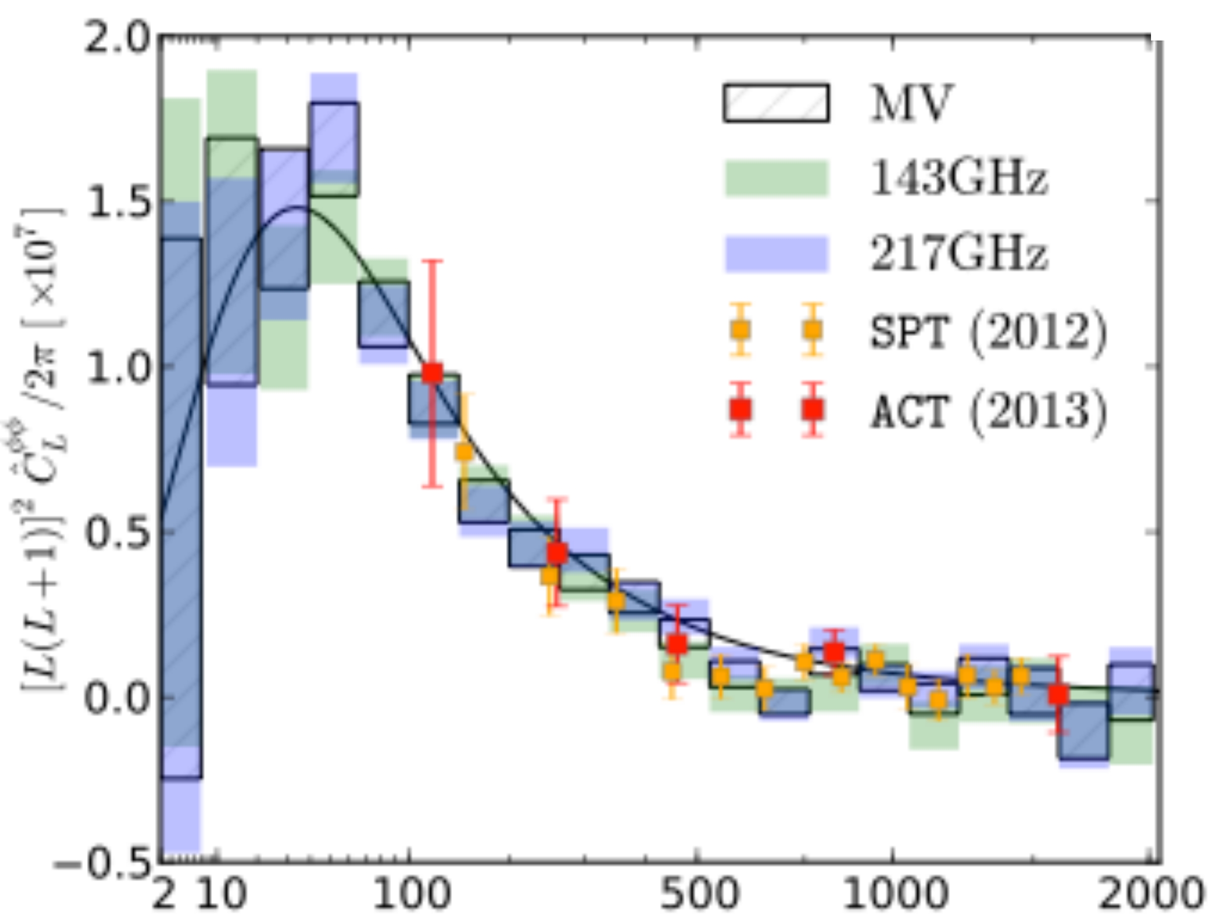


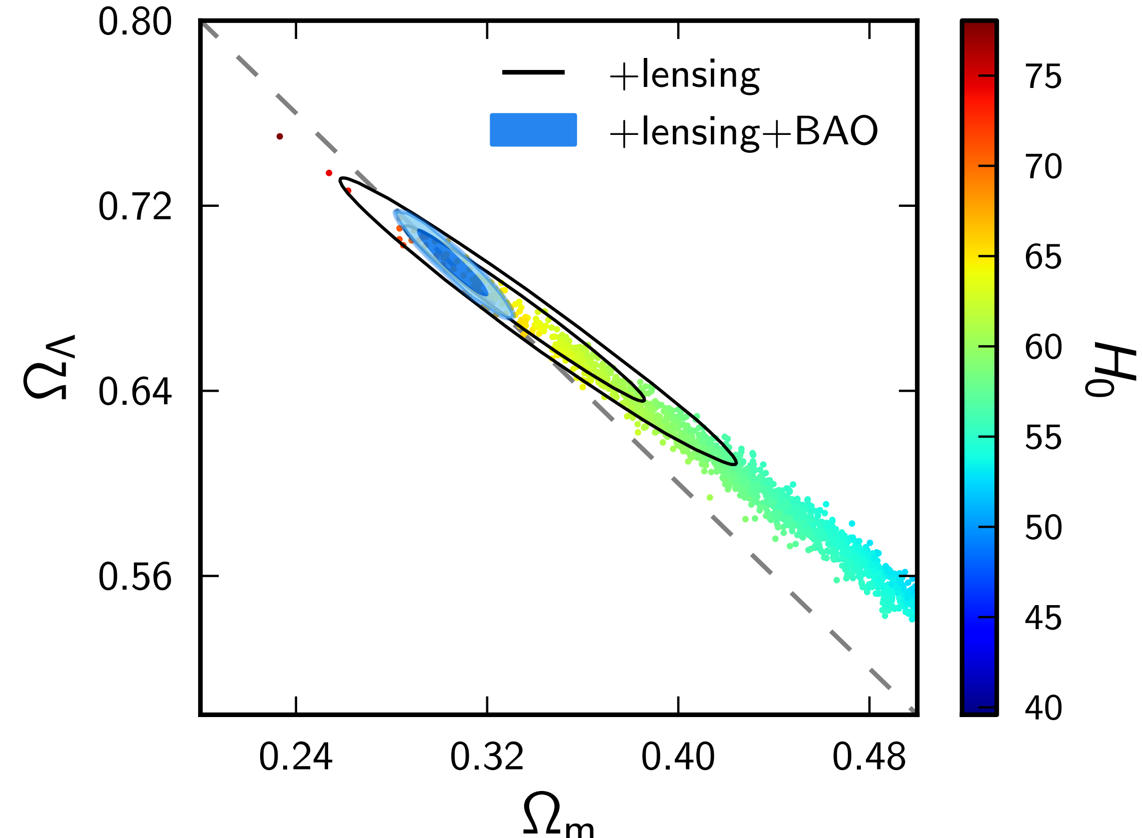
Dark Energy: CMB Weak Lensing

Measure curvature and Λ from CMB alone!



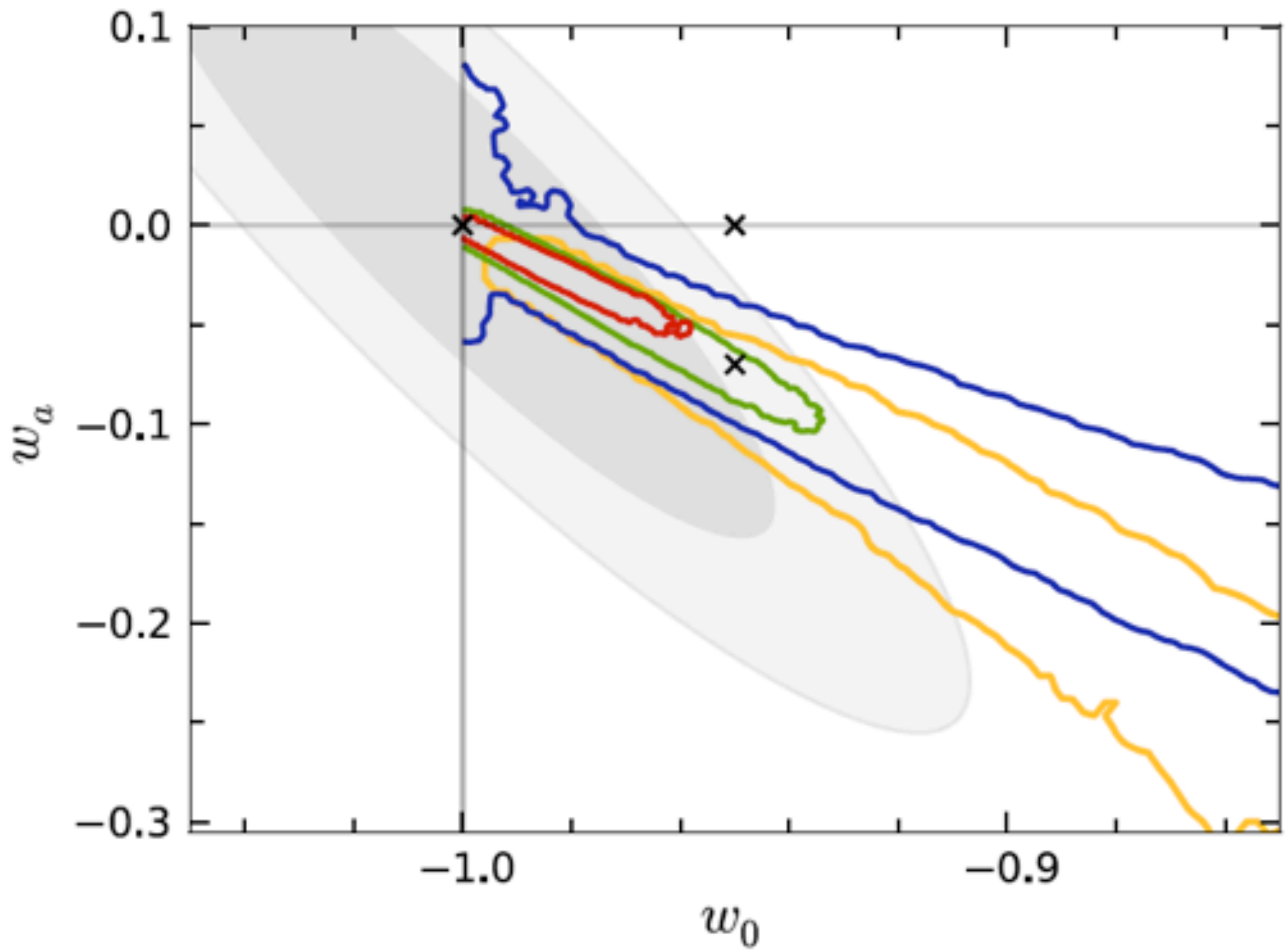
$$\propto \int (\Phi + \Psi)\, d\eta$$





Planck 2013

Dark Energy: model discrimination?



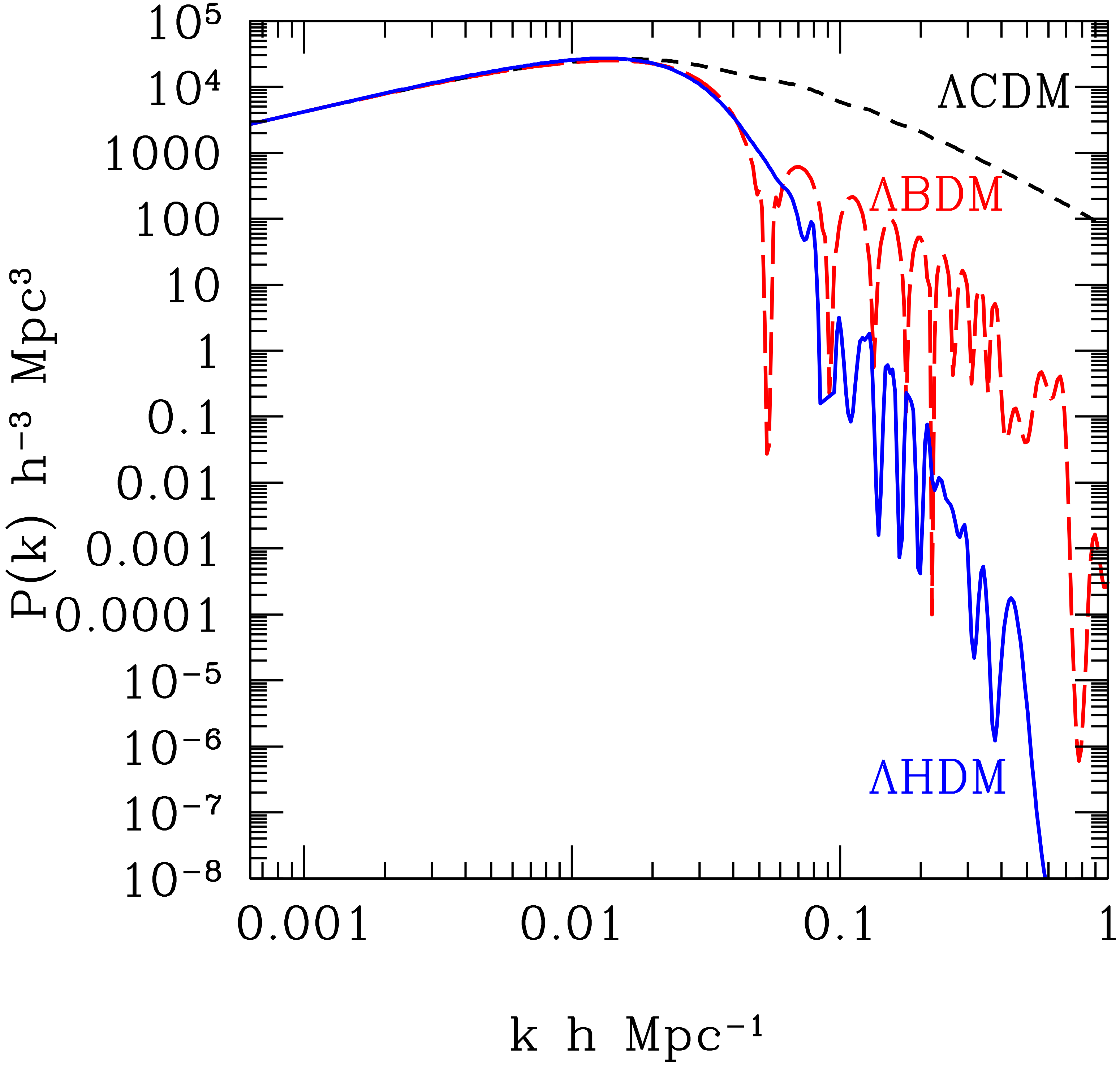
$$V(\phi) = AM_P^2 M_H^2 \mathcal{P}(\phi)$$

$$\mathcal{P}(\phi) = c_\Lambda \xi_\Lambda + f(\phi) + \sum_{n_{\min}}^{n_{\max}} c_n \xi_n b_n(\phi)$$

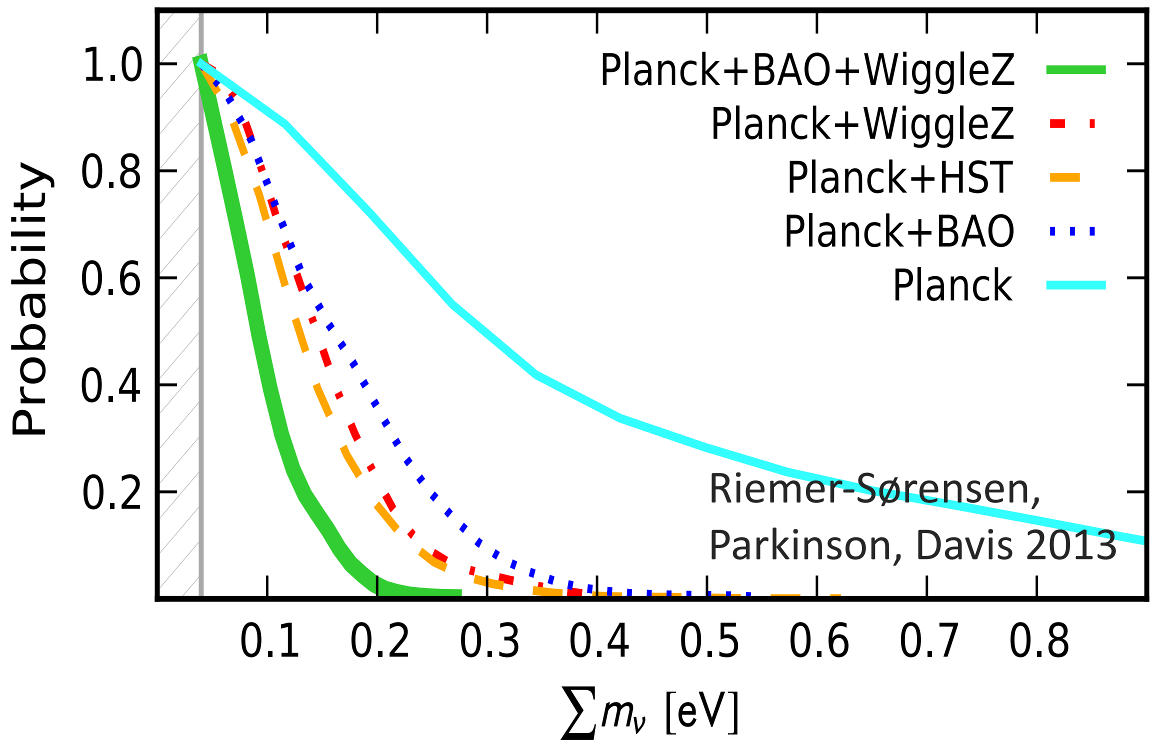
Model	$b_n(\phi)$	c_n	$n_{\min}$	$f(\phi)$	ϕ_i
Kac	ϕ^n	1	1	0	$[-1, 1]$
Weyl	ϕ^n	$1/\sqrt{n!}$	1	0	$[-1, 1]$
Monomial	0	$\cdots$	$\cdots$	ϕ^N	$[0,4]$
EFT	ϕ^n	$(\epsilon_{\rm F})^n$	p_E	$\xi_2\epsilon_{\rm F}^2\phi^2 + \xi_4\epsilon_{\rm F}^4\phi^4$	$[-\epsilon_{\rm F}^{-1}, \epsilon_{\rm F}^{-1}]$
Axion	$\cos(n\epsilon_{\rm F}\phi)$	$(\epsilon_{\rm NP})^{n-1}$	2	$1+\cos\epsilon_{\rm F}\phi$	$[-\frac{\pi}{\epsilon_{\rm F}}, \frac{\pi}{\epsilon_{\rm F}}]$
Modulus	$e^{\alpha(p_D-n)\phi}$	$(\epsilon_{\rm D})^n$	0	0	$[-1, 1]$

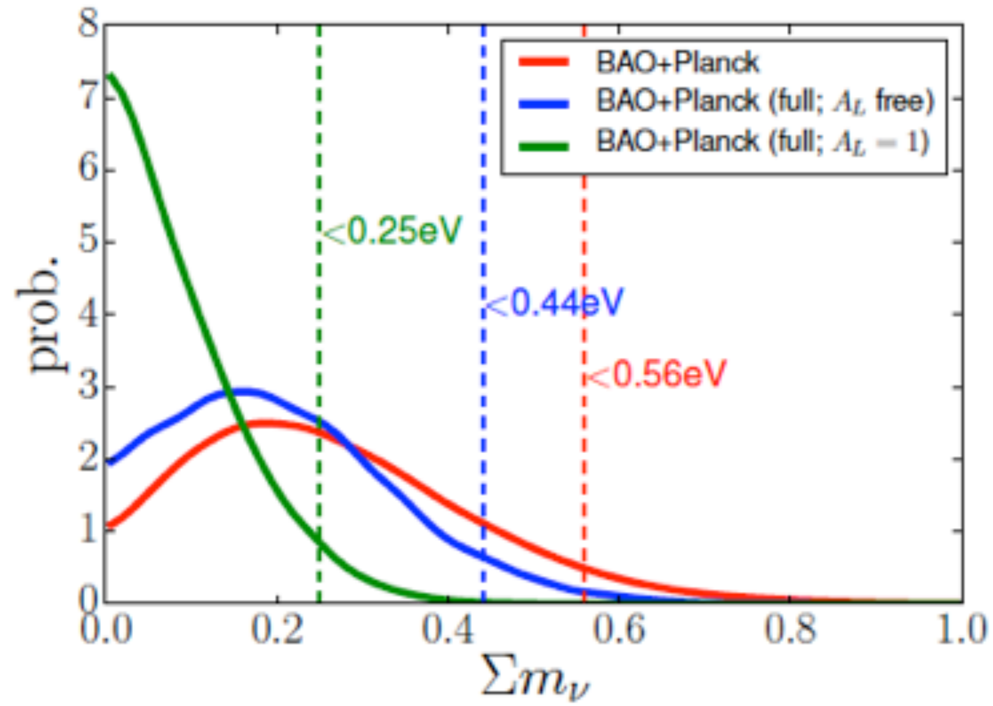
Marsh et al (2014)

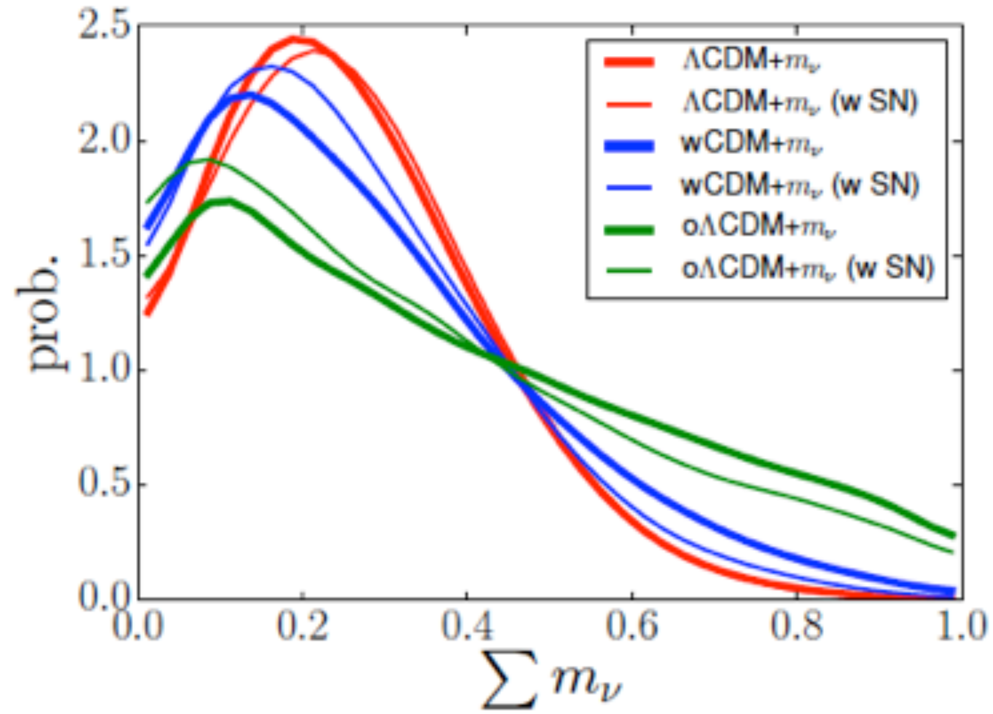
Ultra light fields: Neutrinos



Ultra light fields: Neutrinos

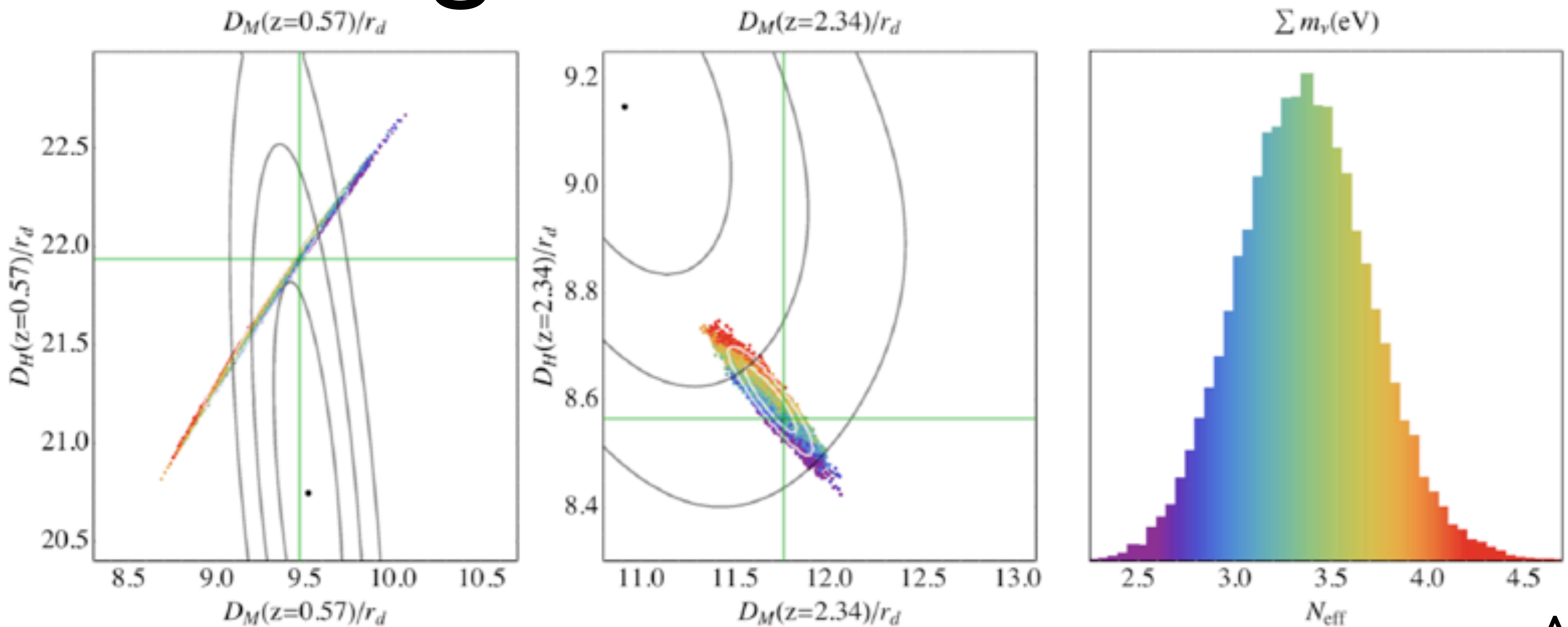




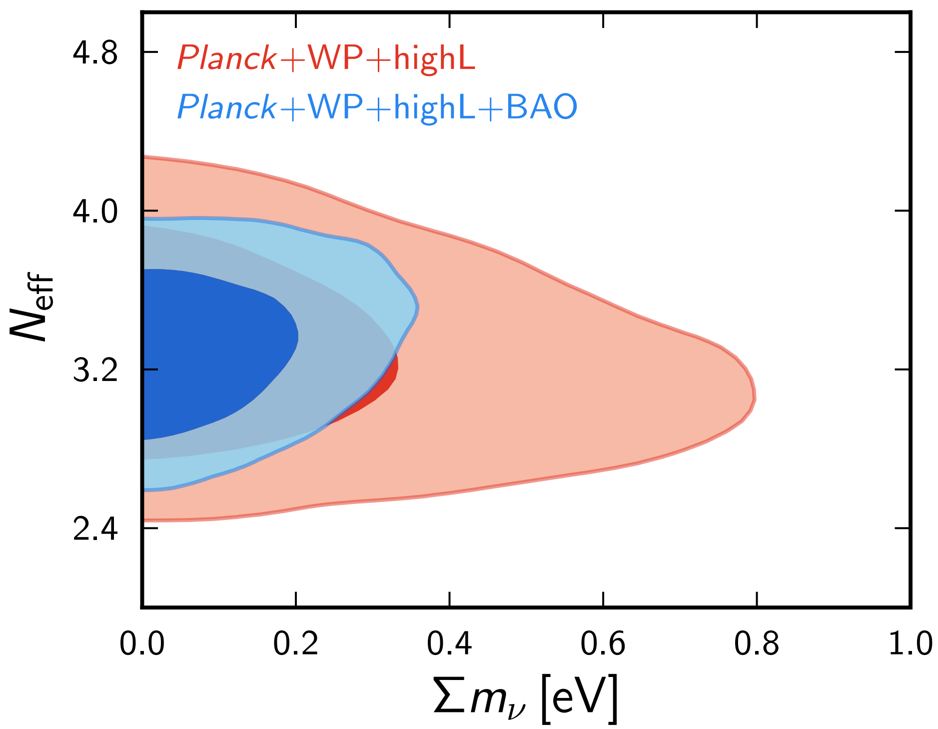


Aubourg et al (2014)

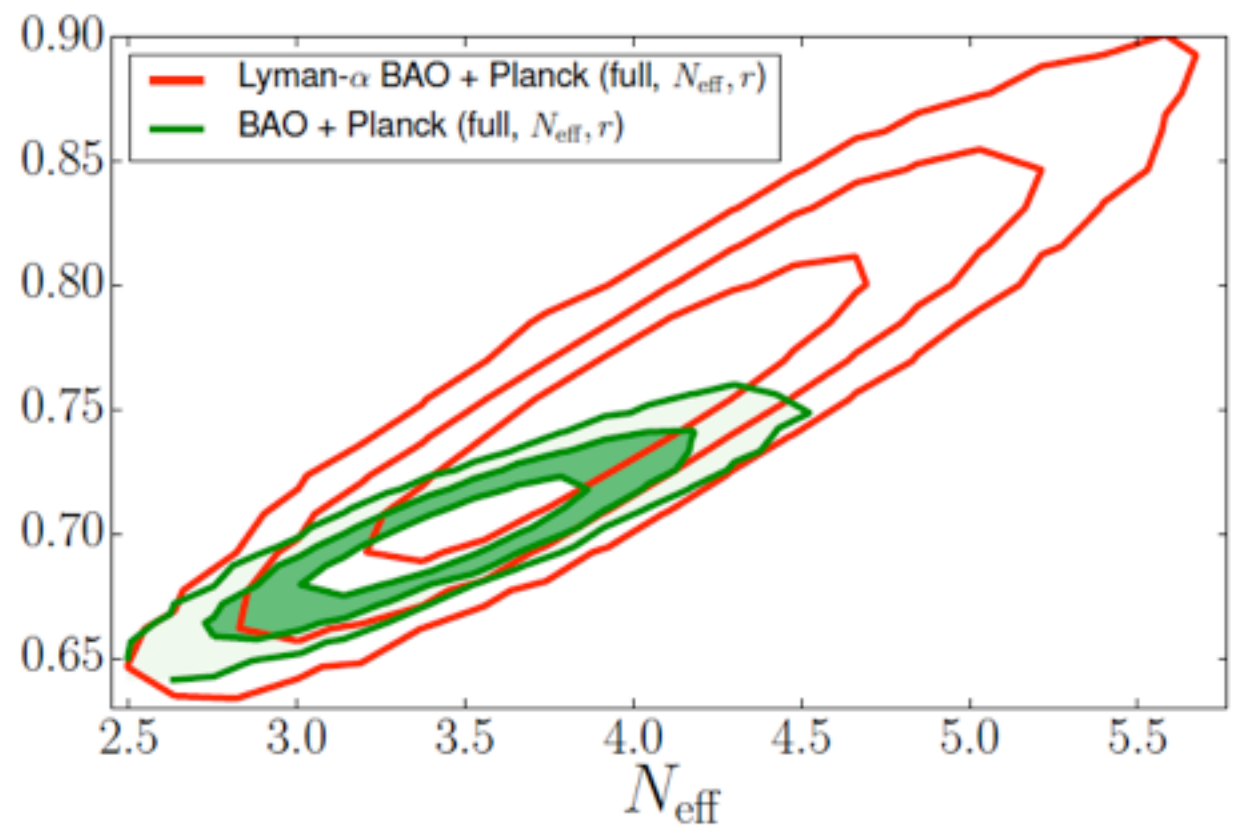
Ultra light fields: Neutrinos



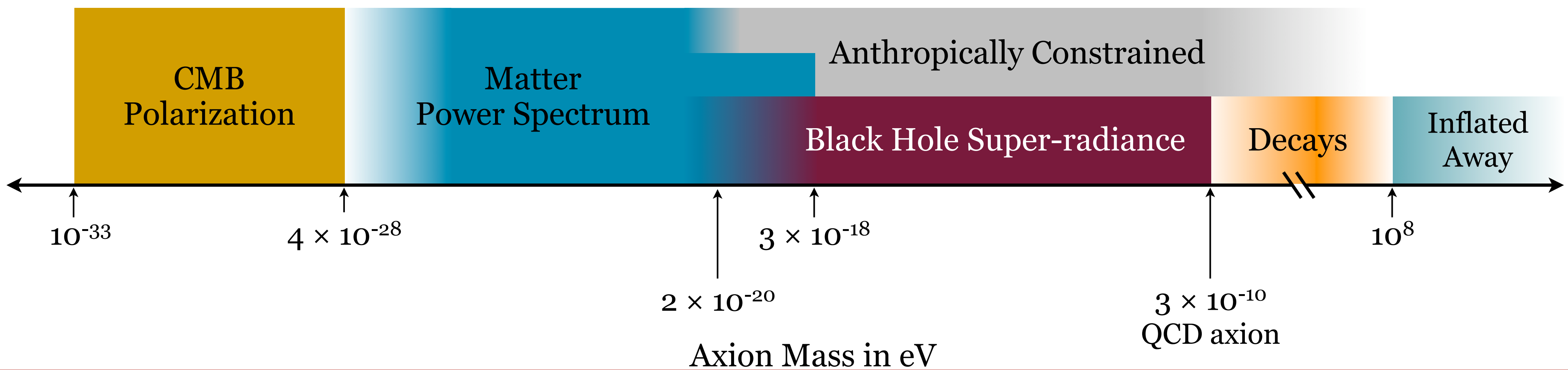
Aubourg et al (2014)



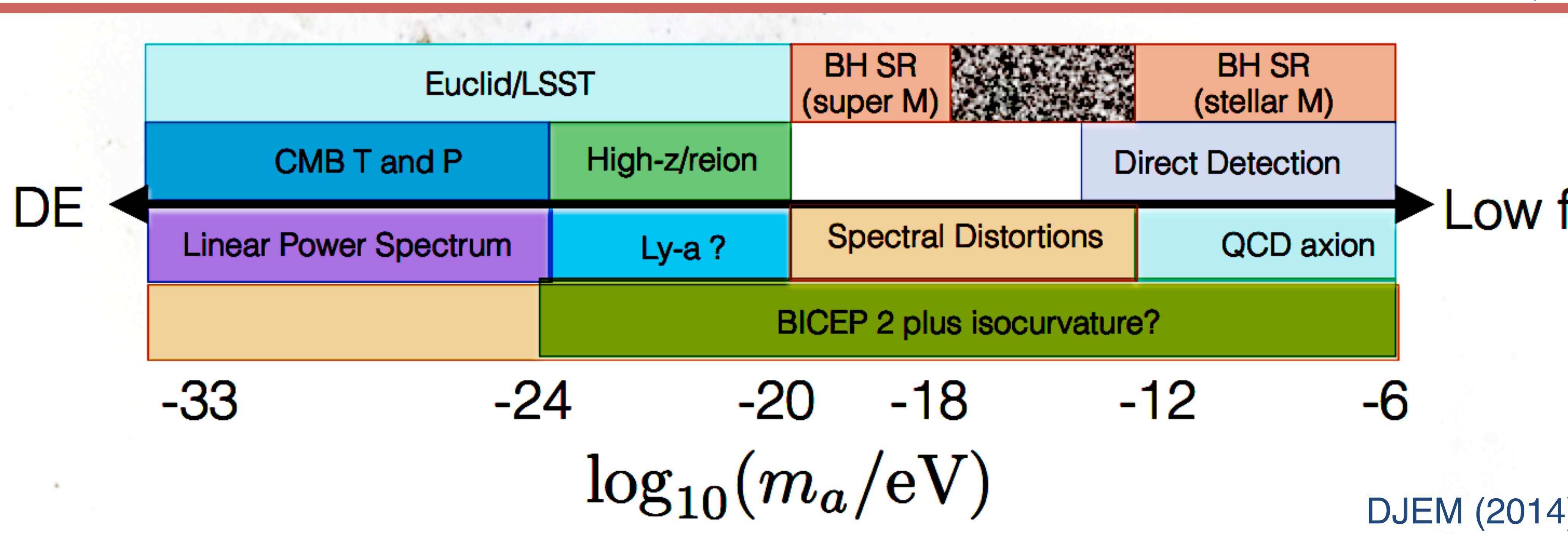
Planck 2013



Ultra light fields: ultra-light axions

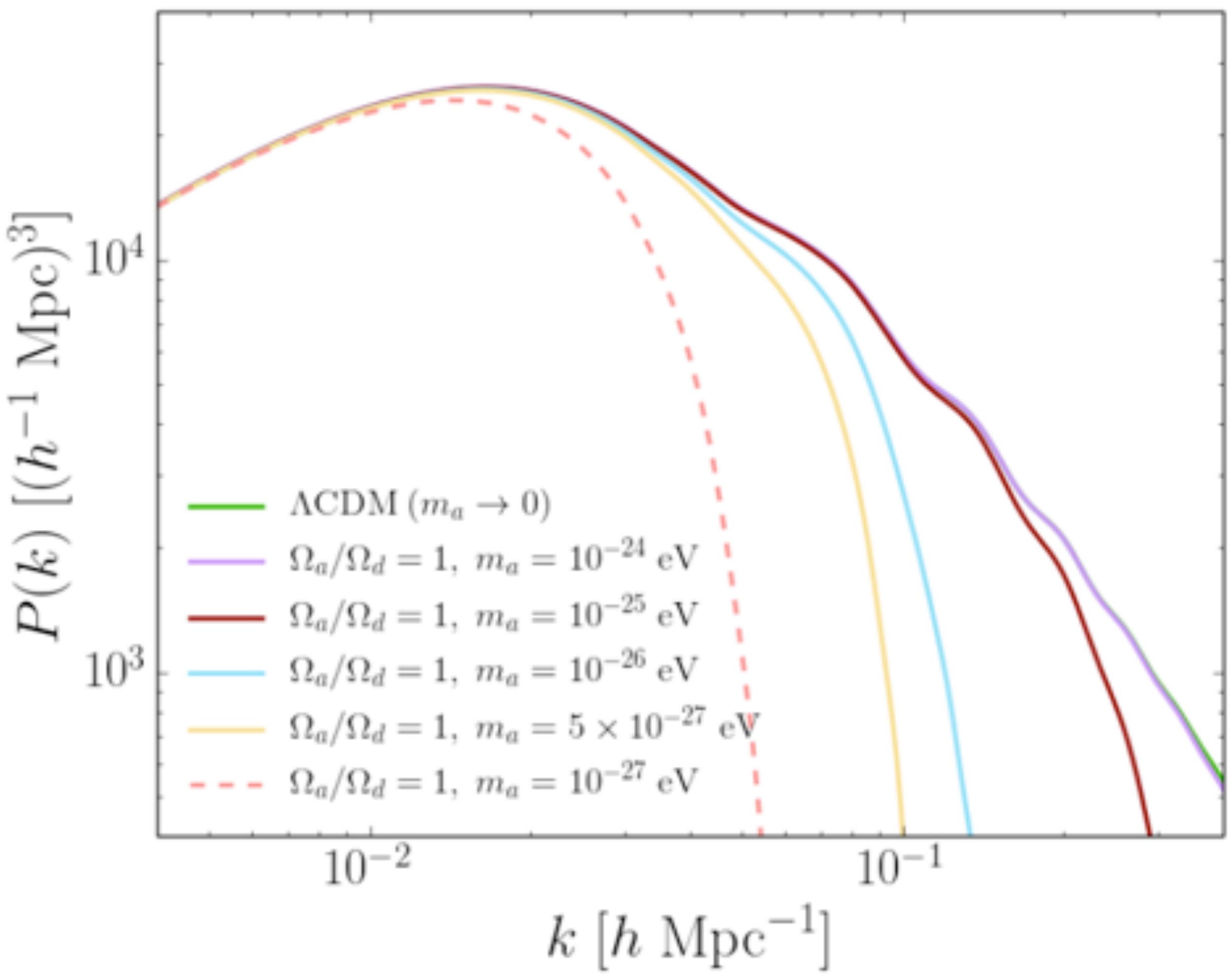


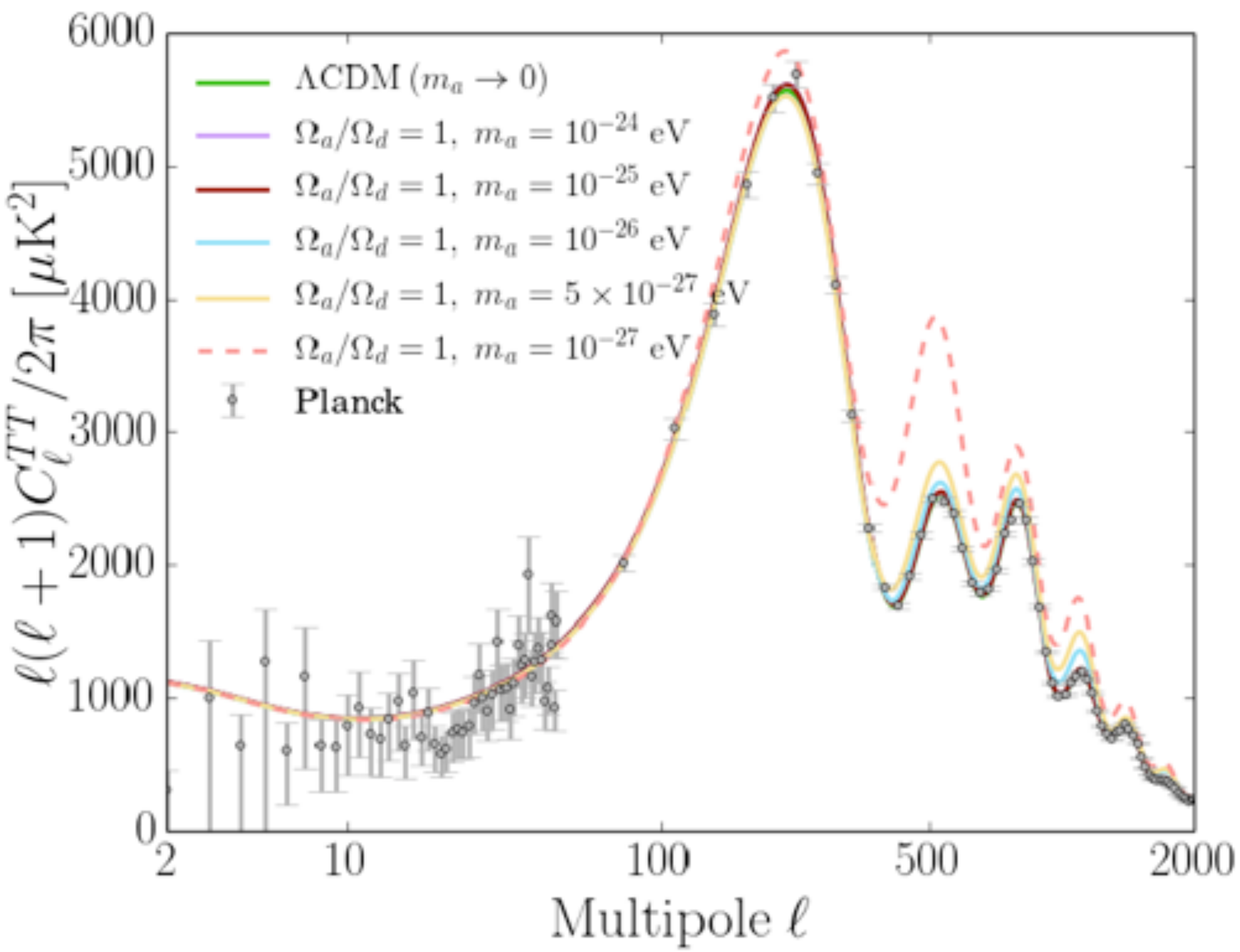
Arvanitaki et al (2009)



DJEM (2014)

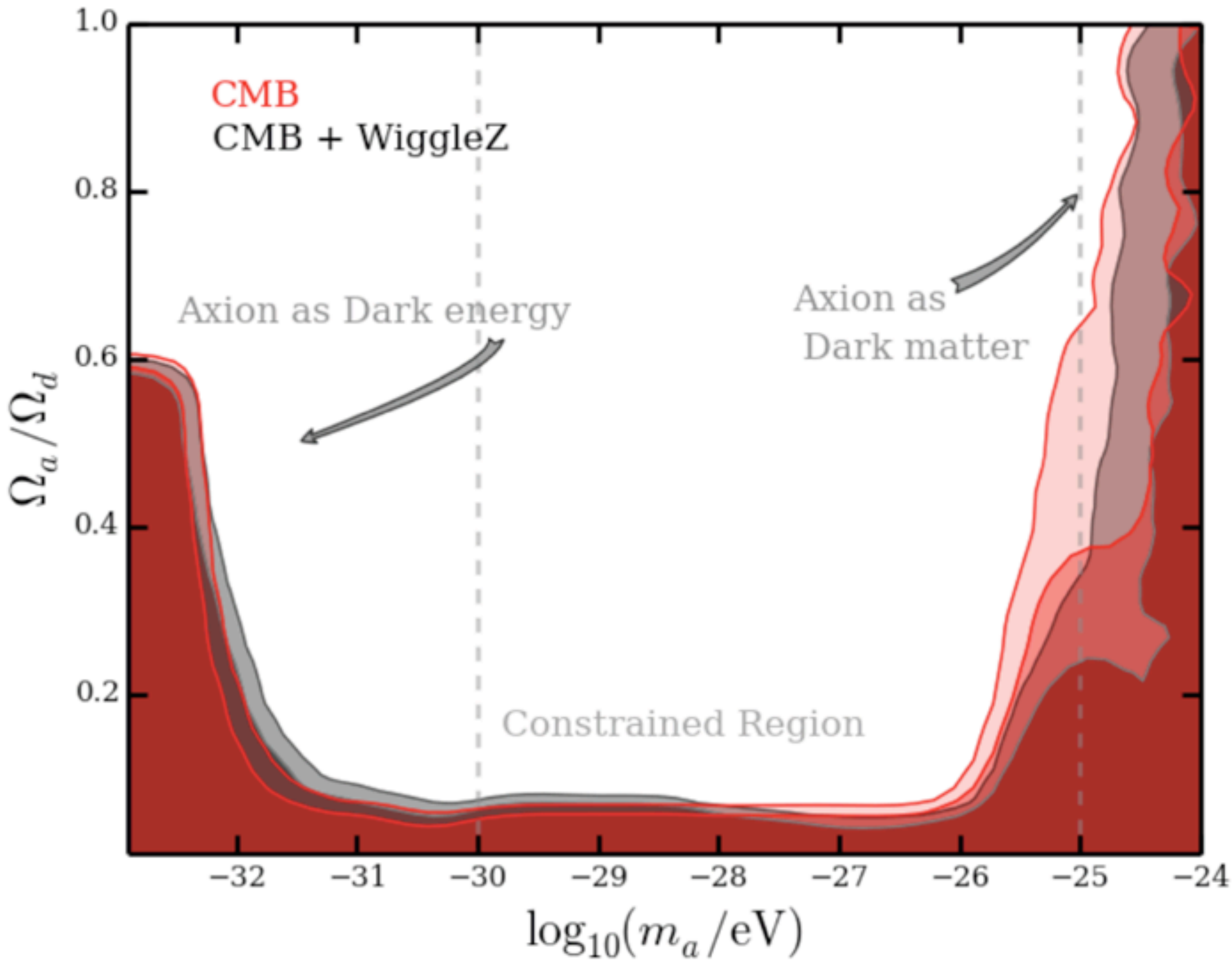
Ultra light fields: ultra-light axions





Marsh et al (2014)

Ultra light fields: ultra-light axions



Marsh et al (2014)

Gravity: quasi-static limit

- For a perturbed line element of the form:

$$ds^2 = a^2(\tau)[-(1+2\Phi)d\tau^2 + (1-2\Psi)\gamma_{ij}dx^i dx^j]$$

the equations of motion are:

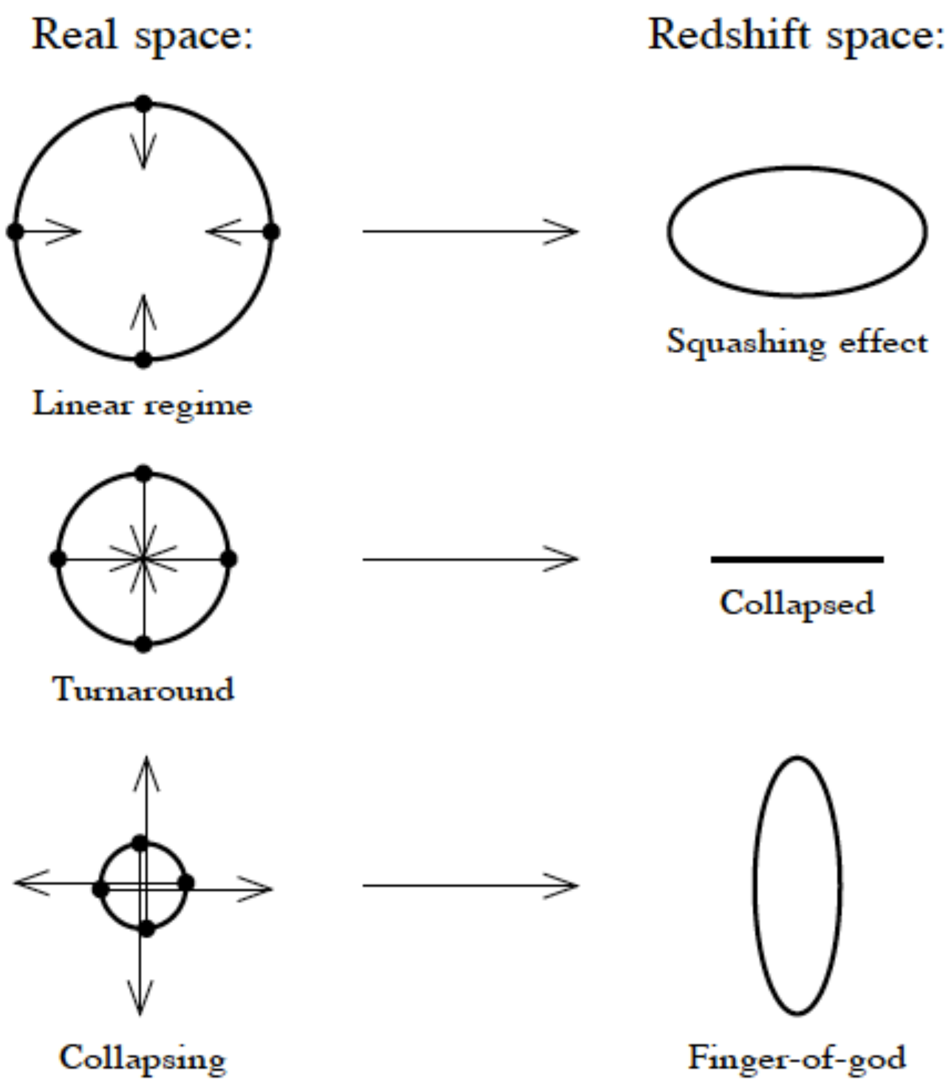
$$\frac{1}{a}\frac{d(a\mathbf{v})}{d\tau} = -\nabla\Phi$$ (non-relativistic particles)

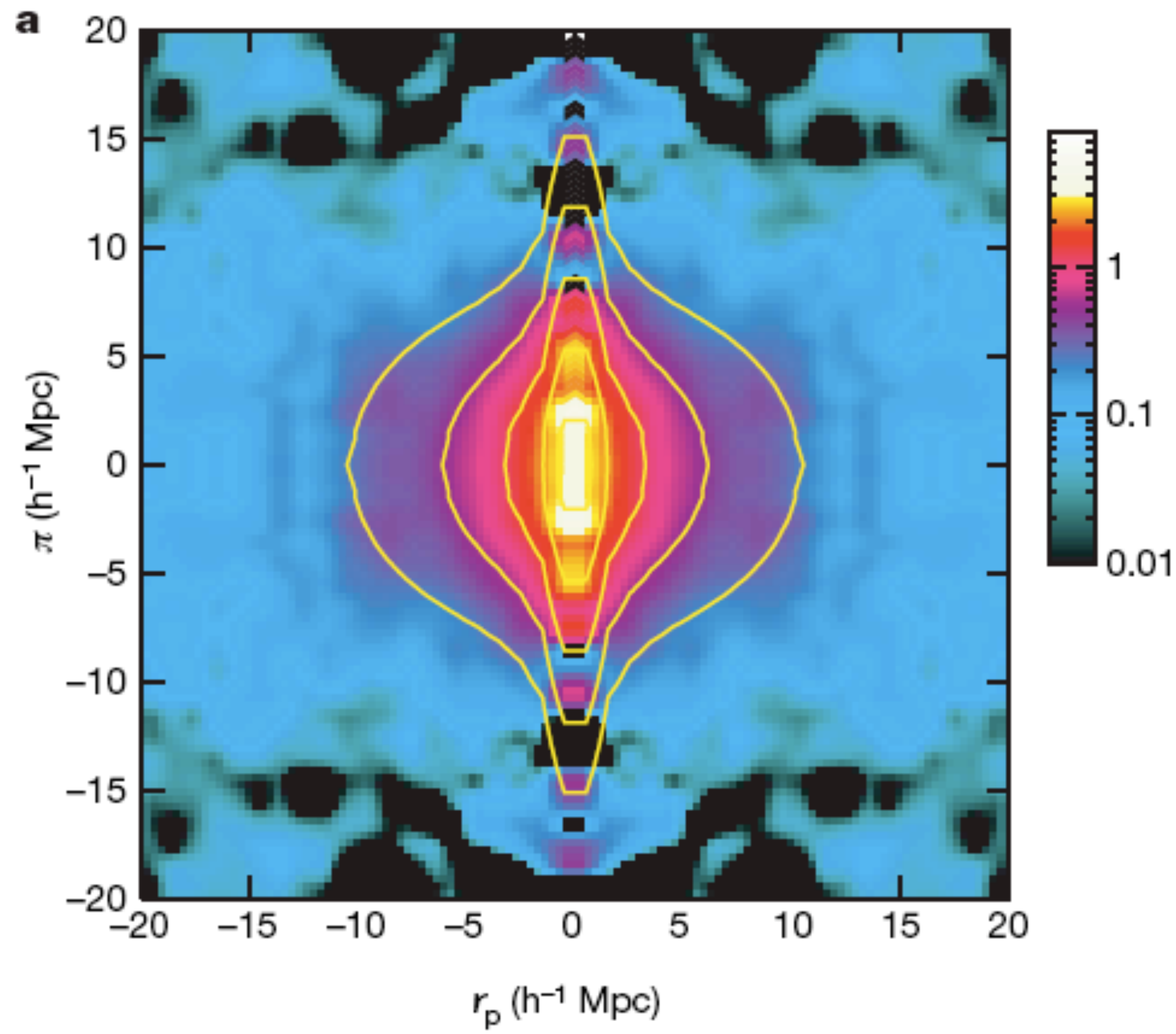
$$\frac{d\mathbf{v}}{d\tau} = -\nabla_\perp(\Phi+\Psi)$$ (relativistic particles)

$$-k^2\Phi = 4\pi G\mu a^2\rho\Delta$$

$$\gamma\Psi = \Phi$$

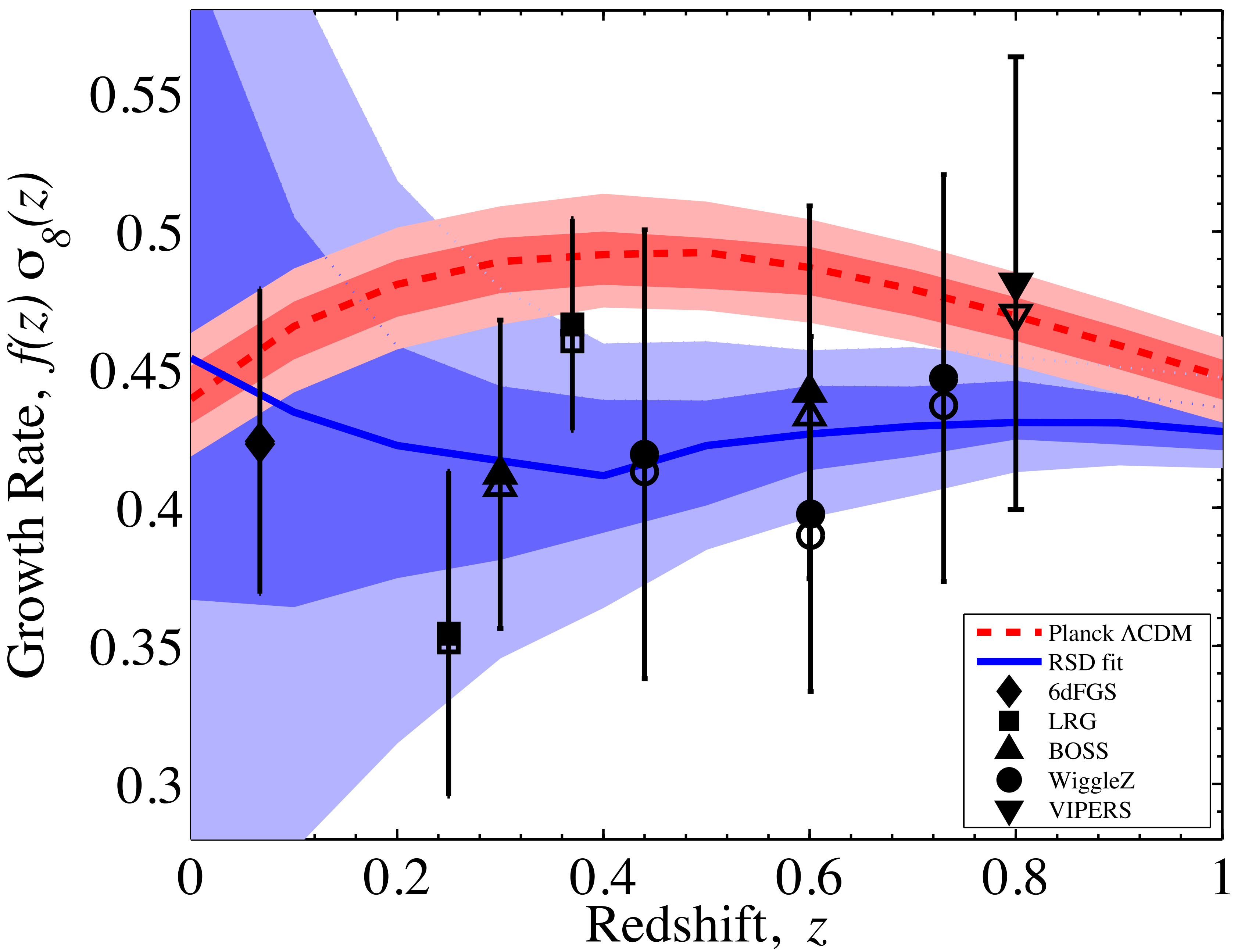
Gravity: Redshift space distortions





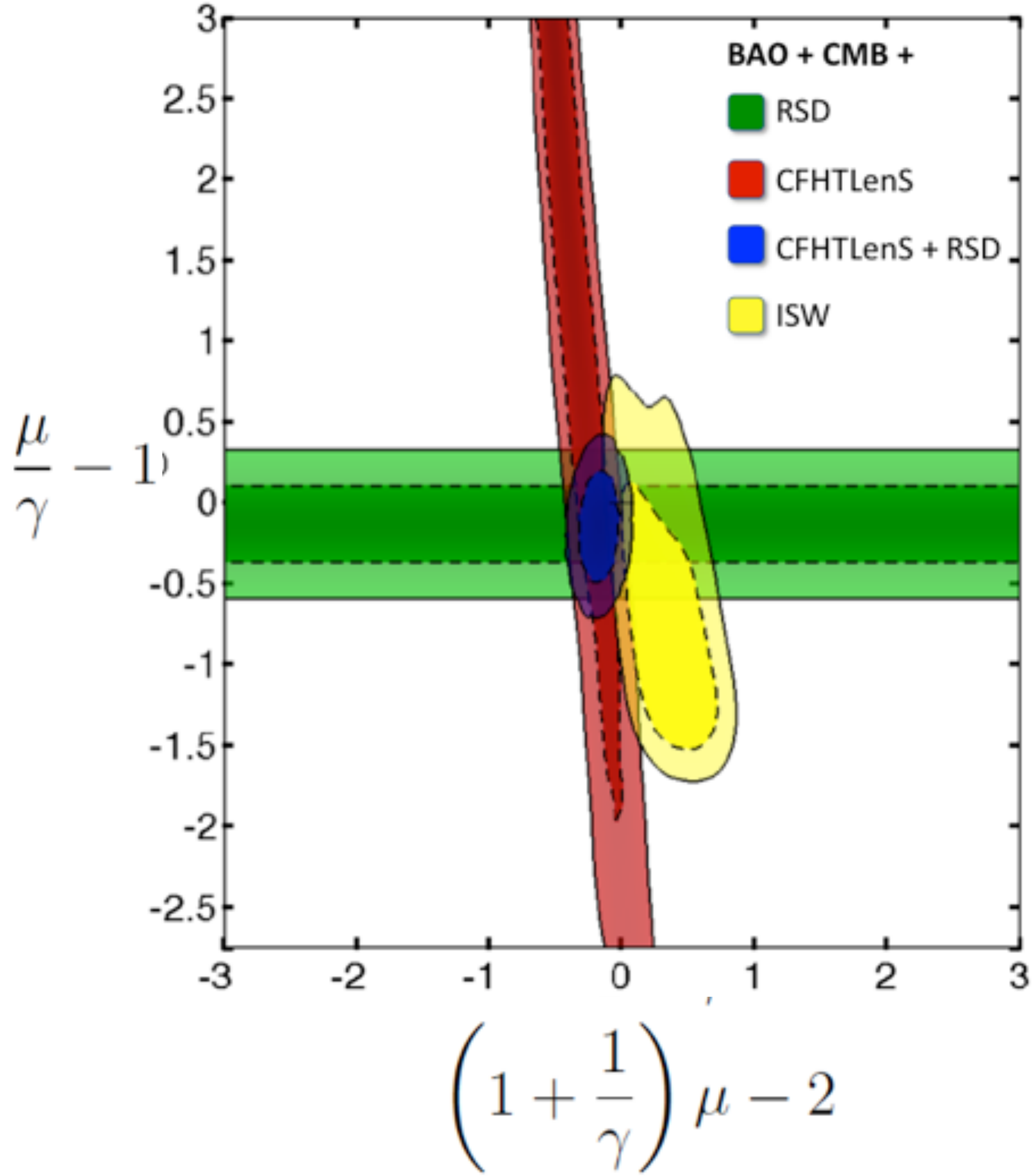
Guzzo et al 2008

Gravity: Redshift space distortions



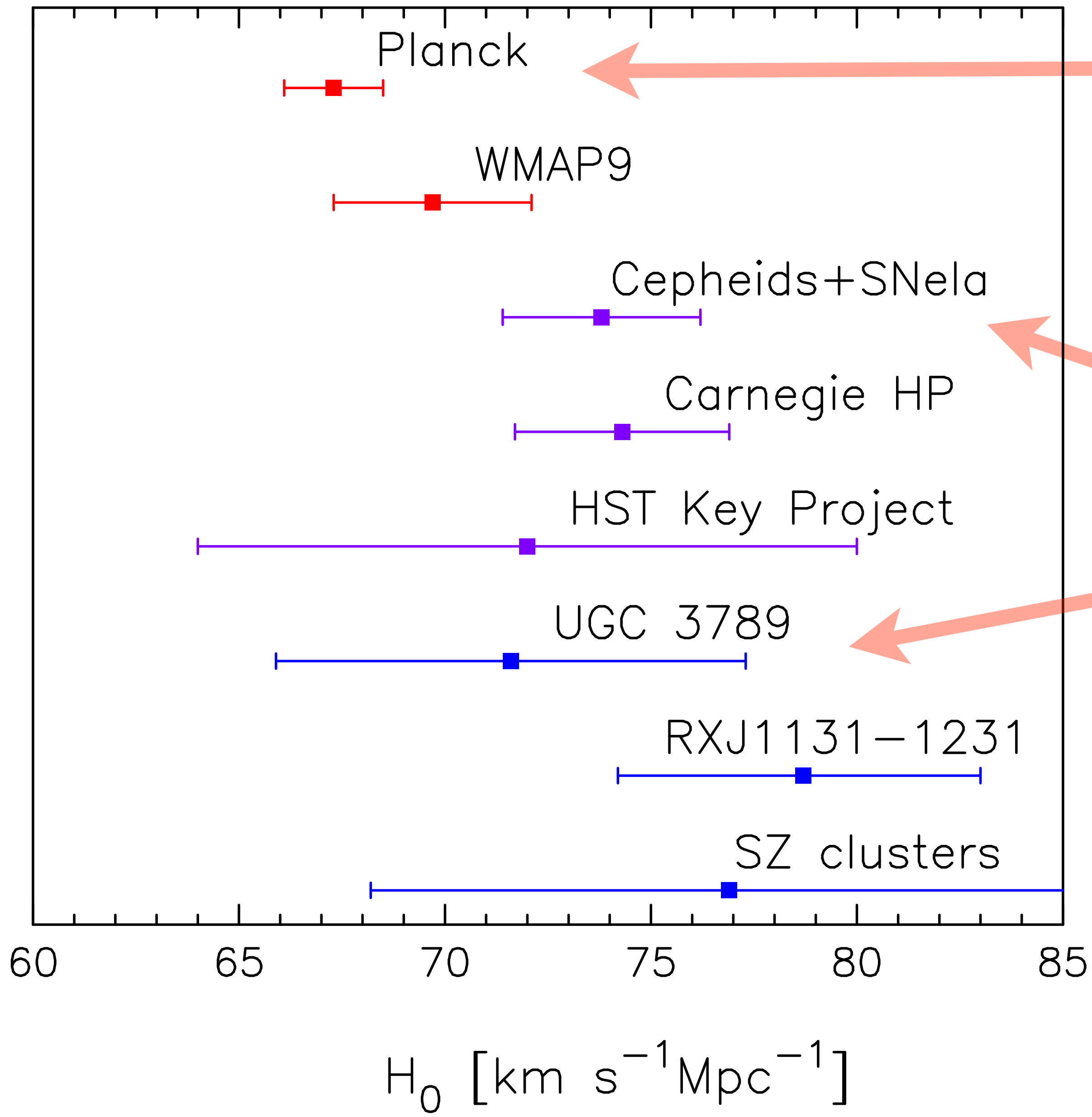
Macaulay et al
ArXiv:1303:6583

Gravity: RSDs and Lensing



Simpson et al 2012
(CFHTLens)

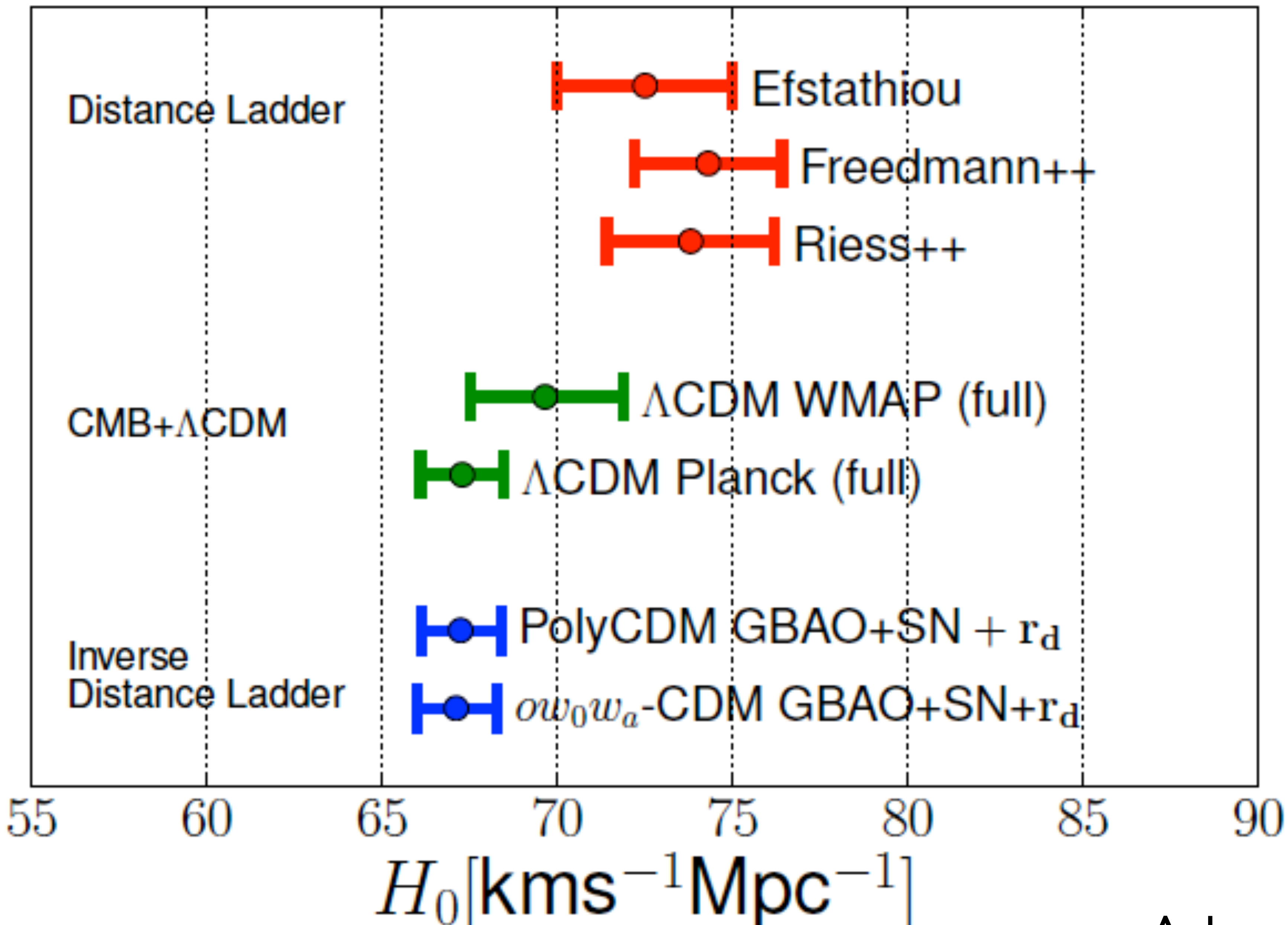
Inconsistencies: Hubble constant



Mild tension with the CMB

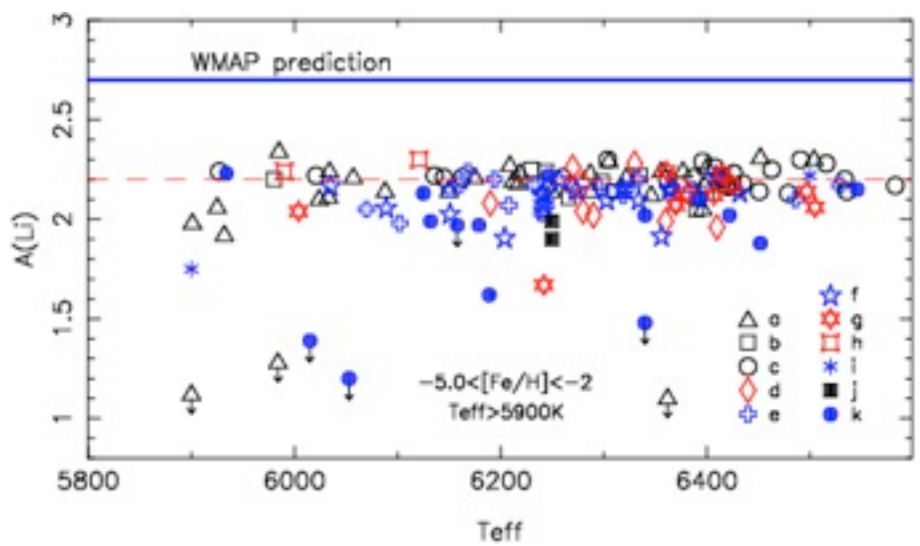
NGC4258 and UGC at 50 Mpc have been revised down

Inconsistencies: Hubble constant



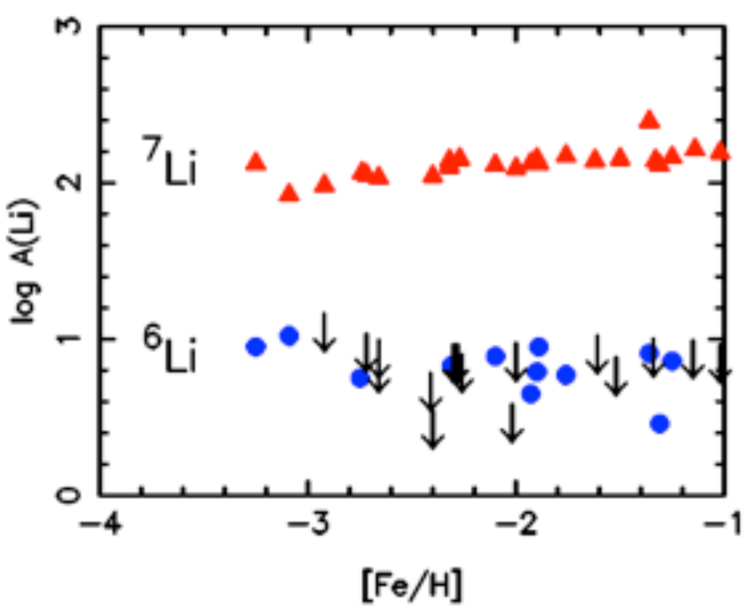
Aubourg 2014

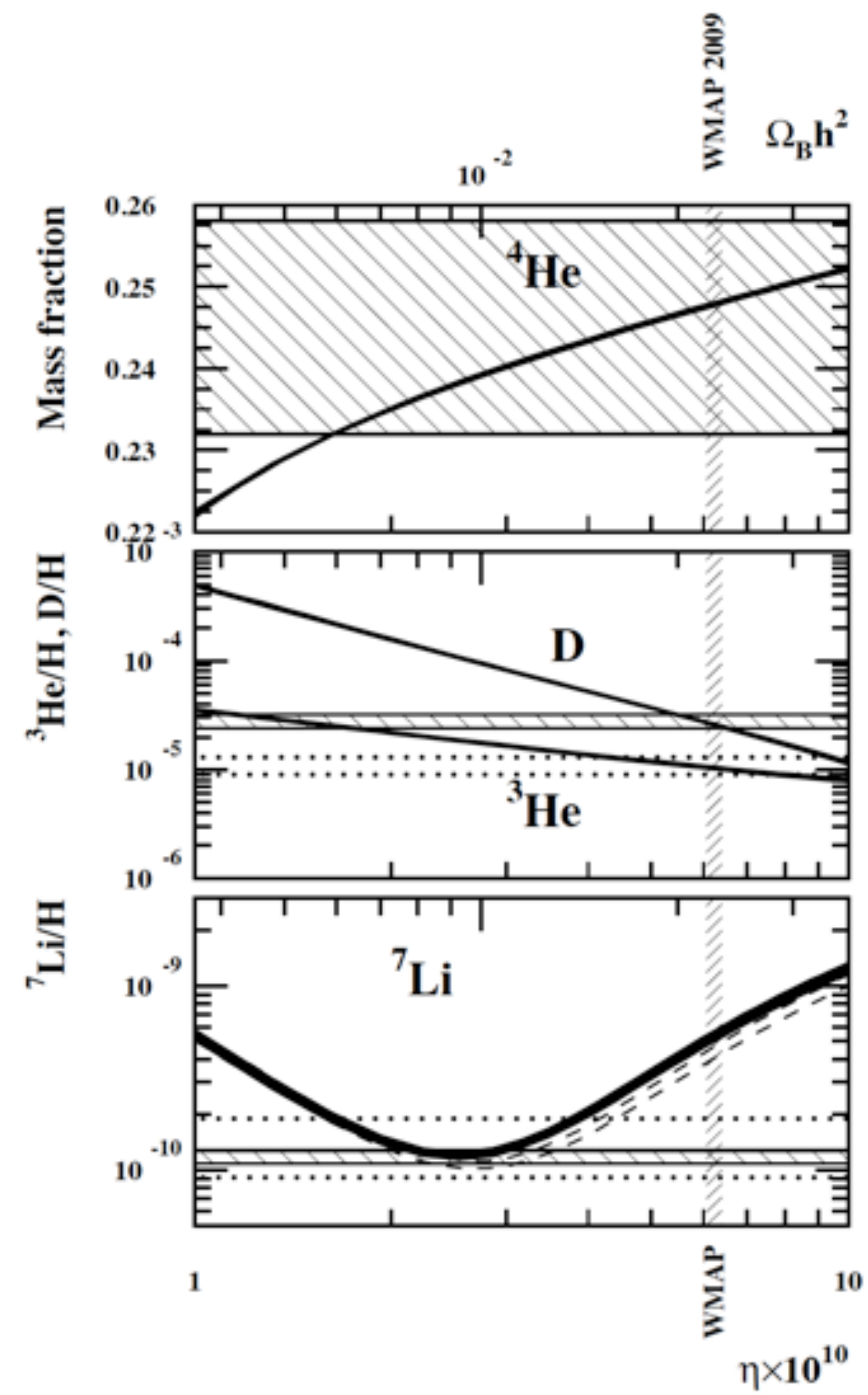
Inconsistencies: BBN and Lithium



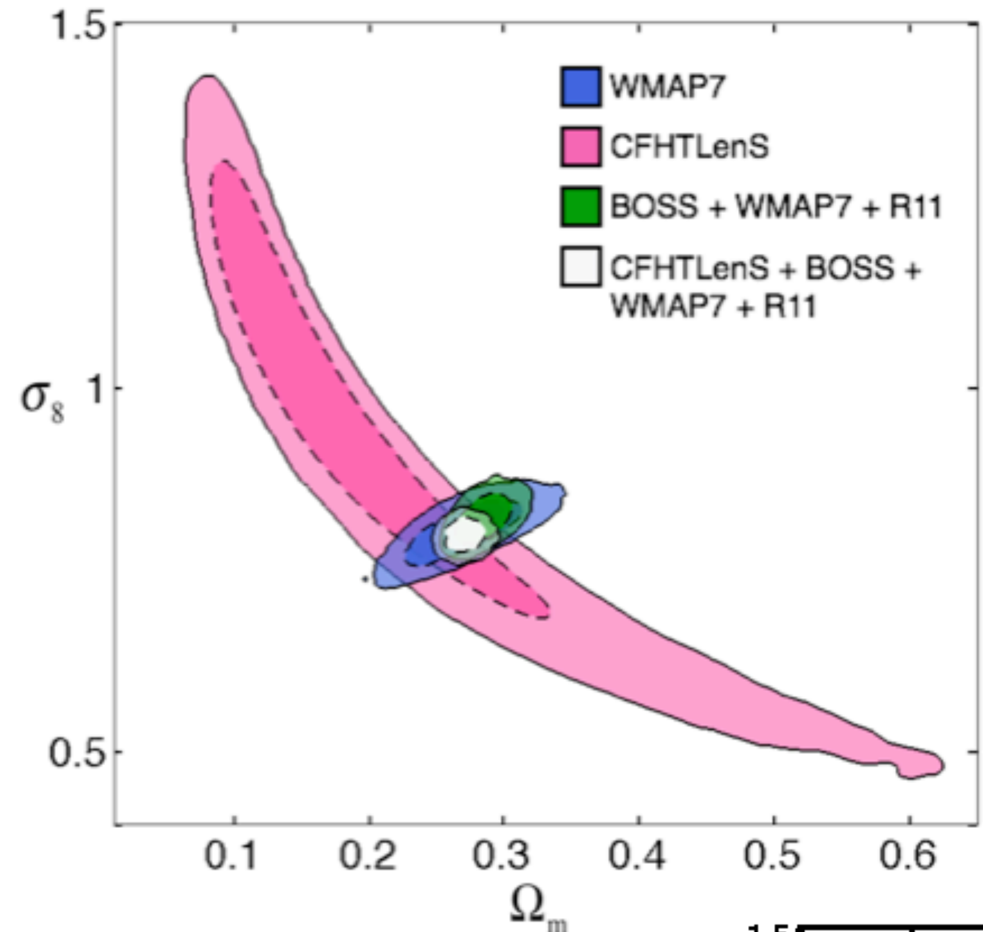
Dearth of Li 7 and abundance of Li 6.

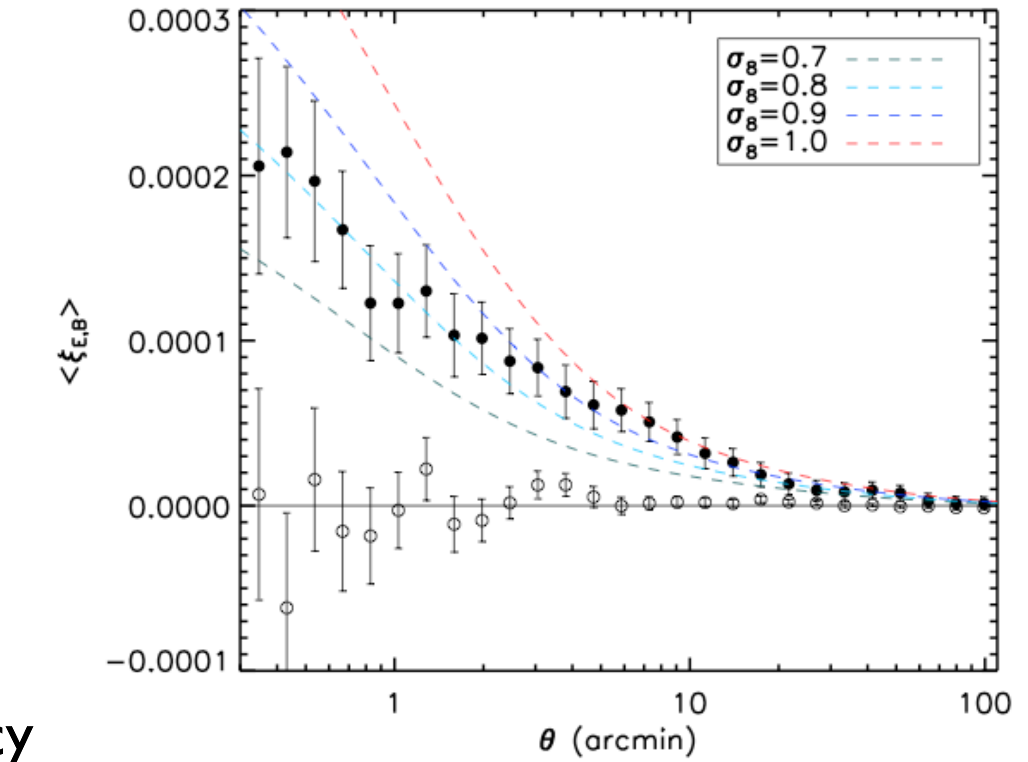
Spite et al (2012)





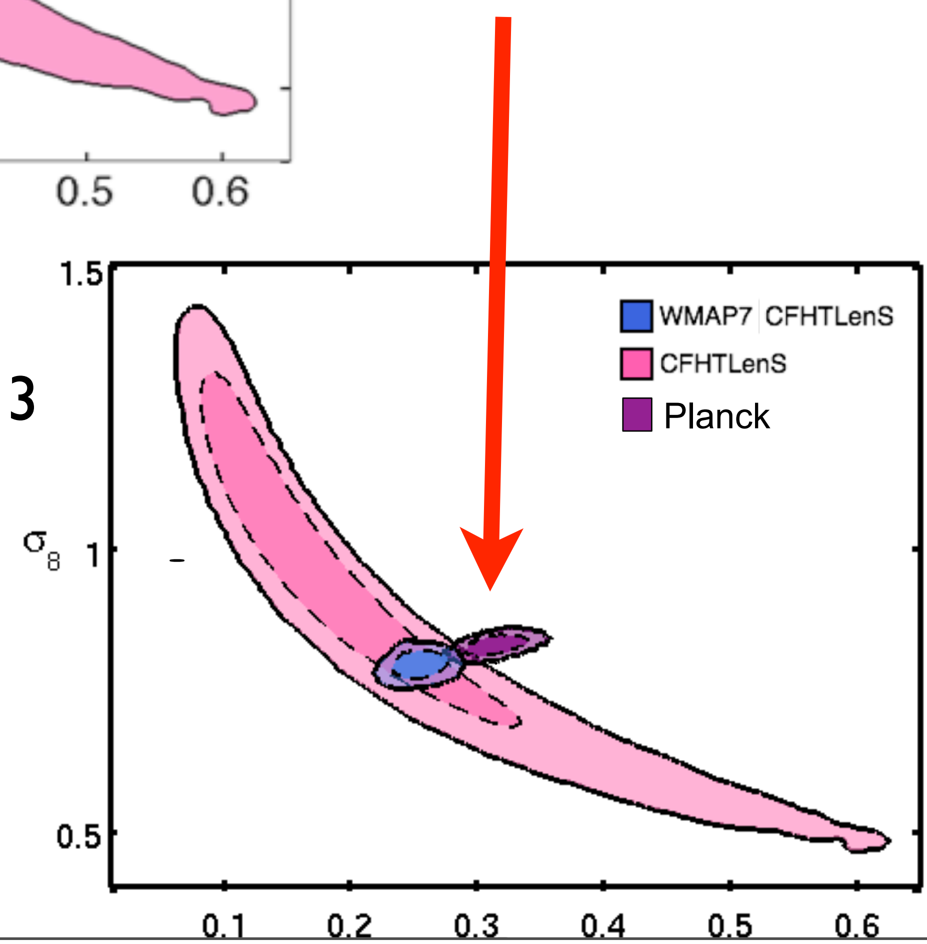
Inconsistencies: Weak Lensing

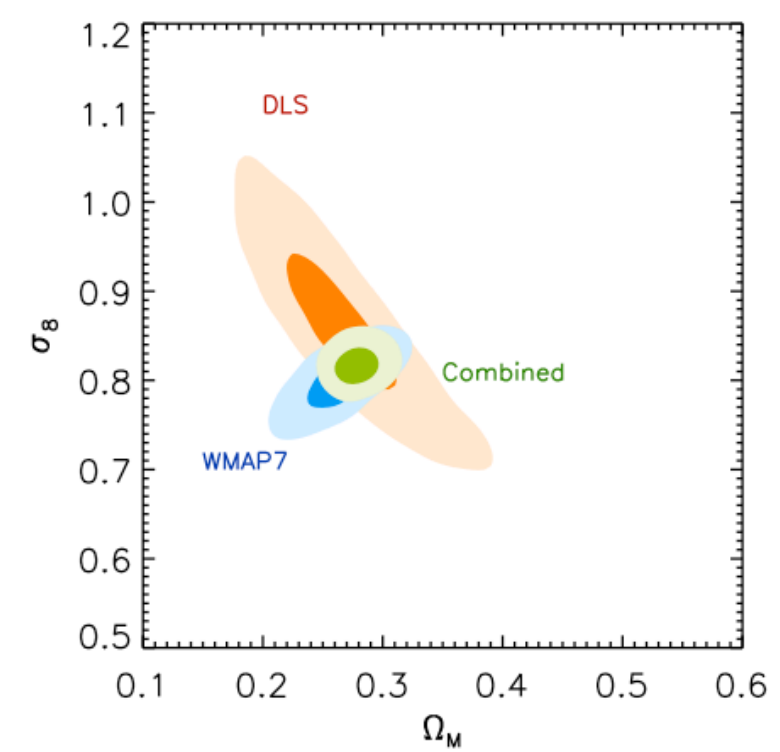




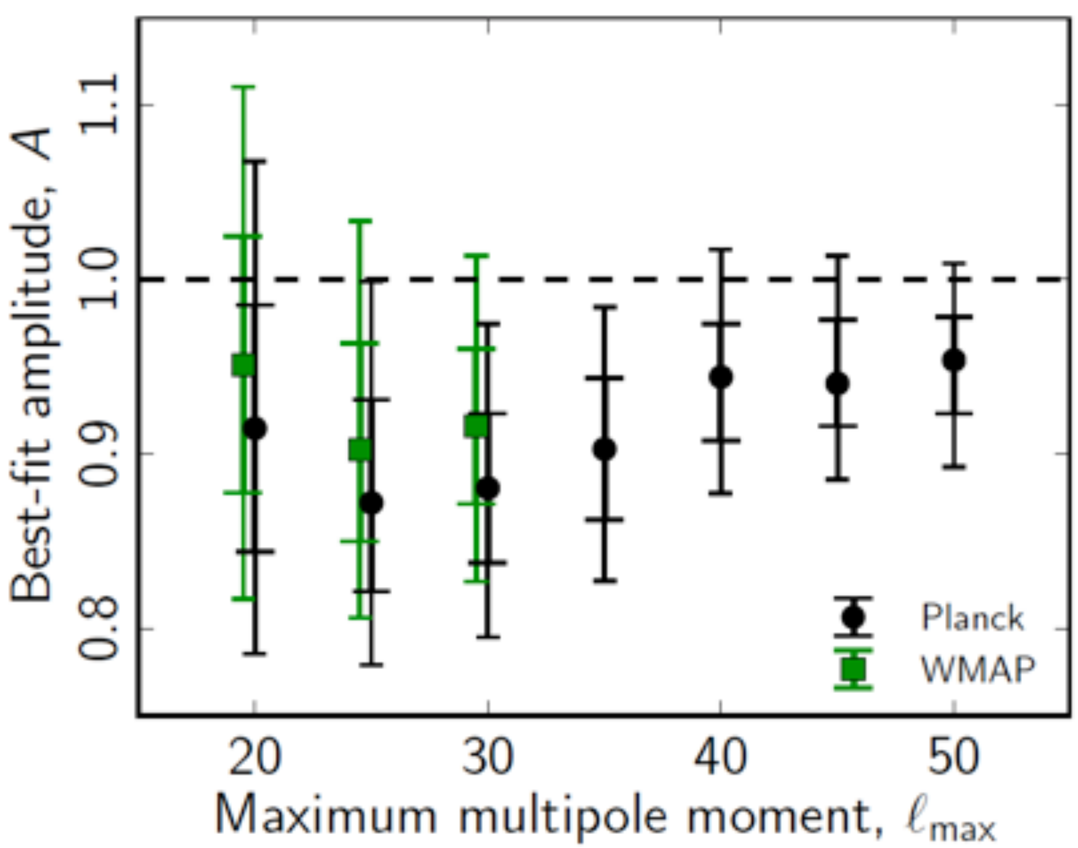
Mild inconsistency
with Planck

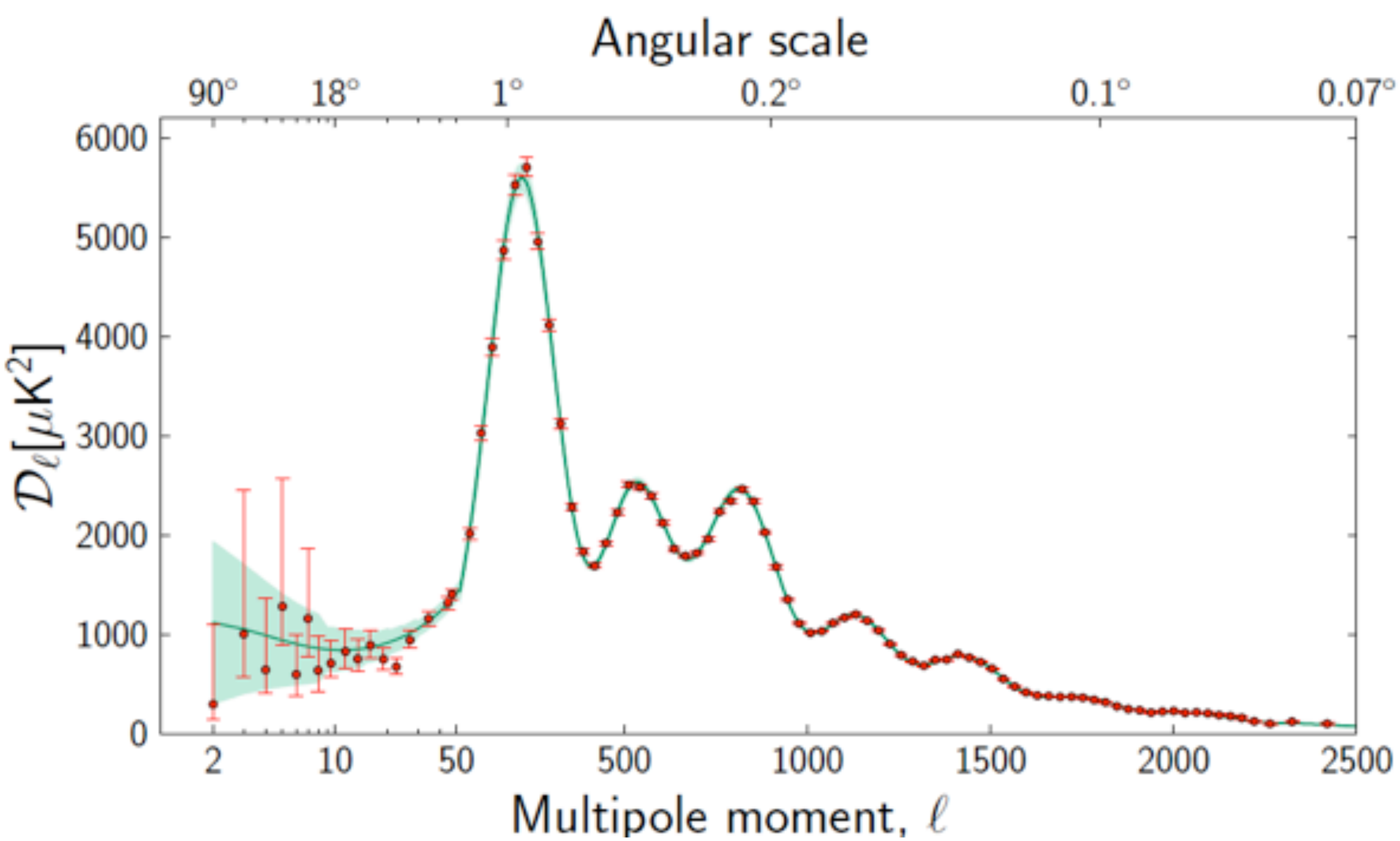
CFHTLens Heymans et al 2013





Inconsistencies: CMB large angles





Particle Physics from Cosmology

- Simple flat ΛCDM model still fits (most) data
- Strong constraints on ultralight fields
- Some constraints on inflation
- Little knowledge of DE behaviour.
- Weak constraints on gravity
- Some inconsistencies...