Particle Physics from Cosmology

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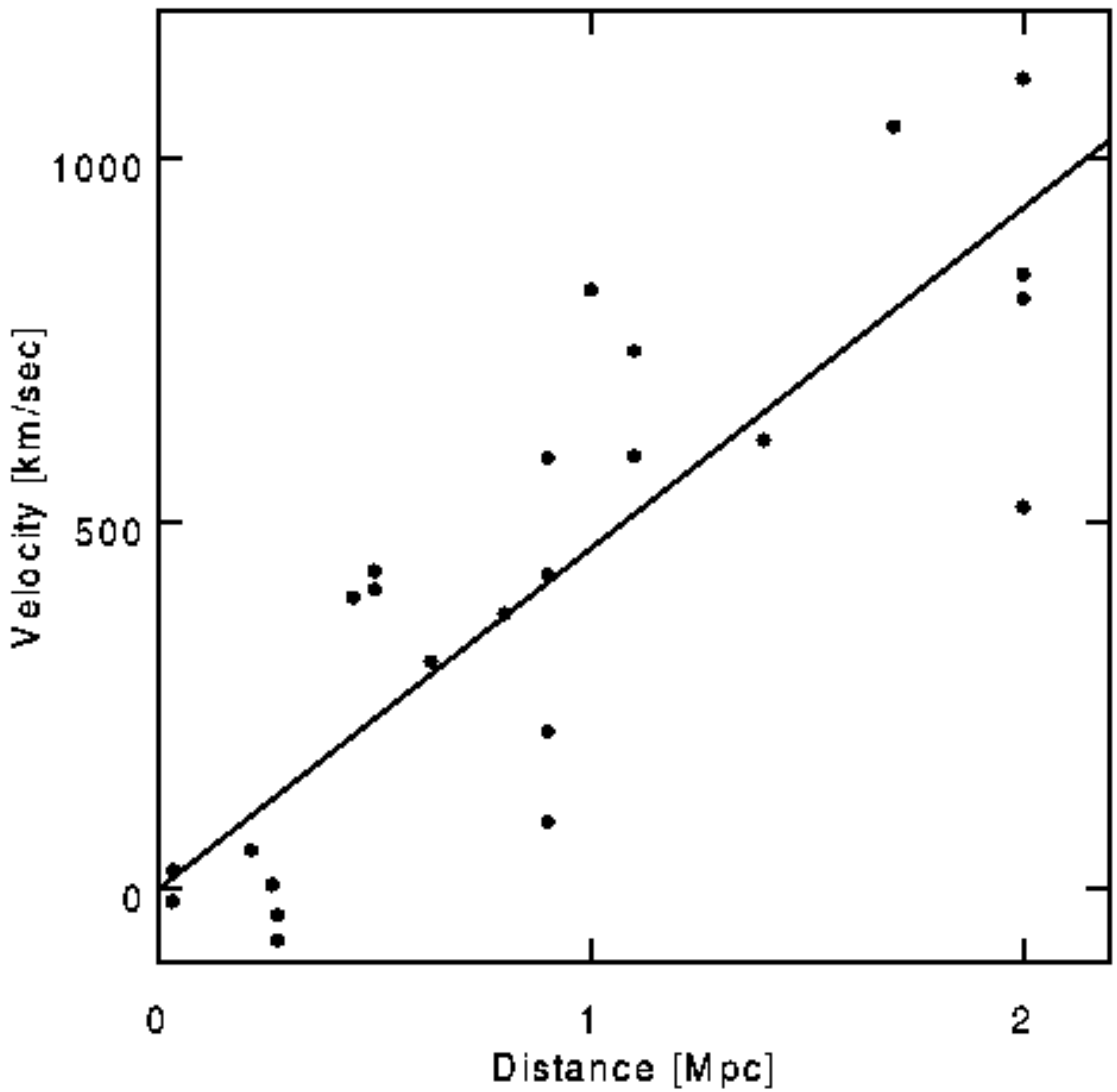
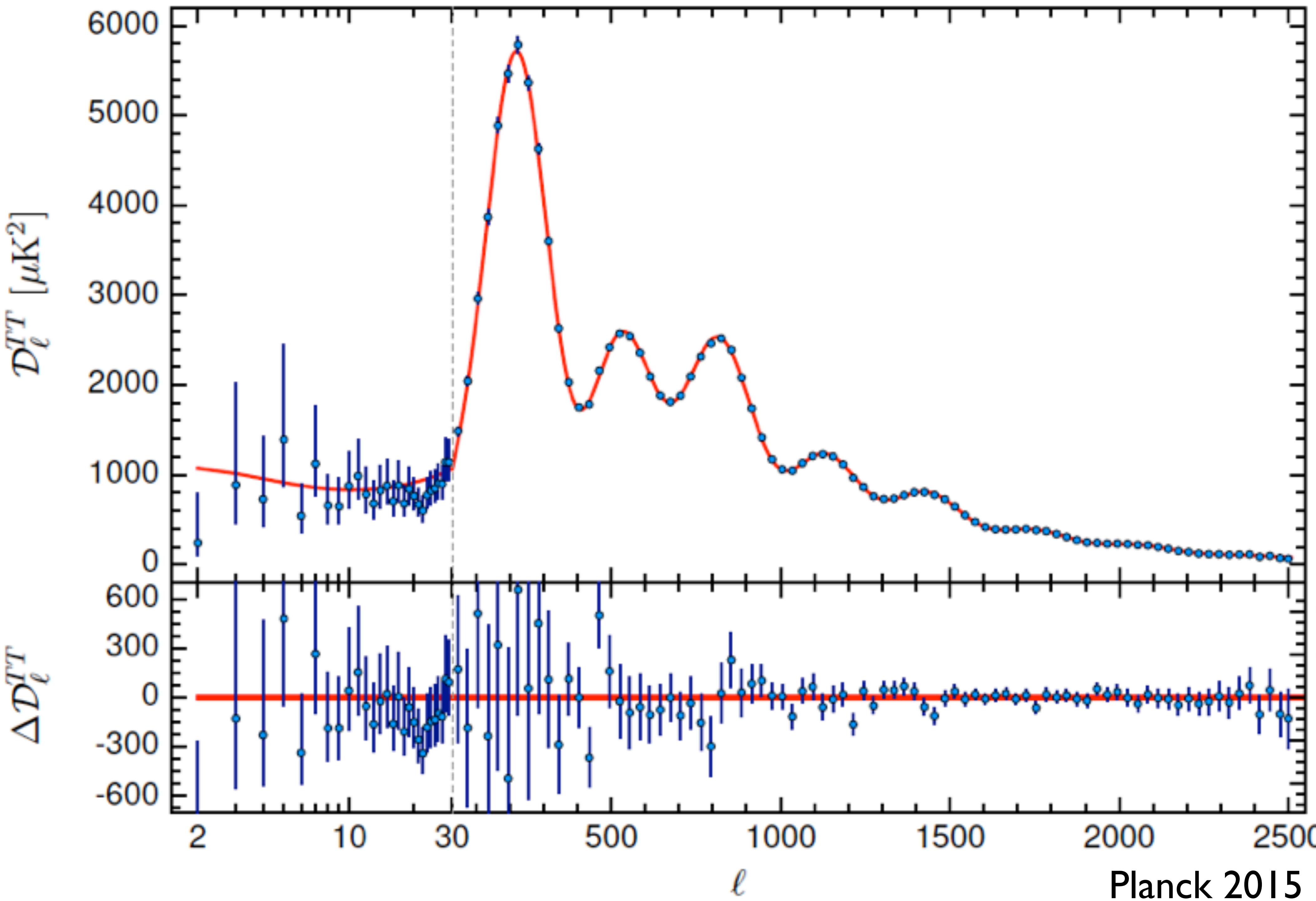
Erice 2015

Precision cosmology then ...



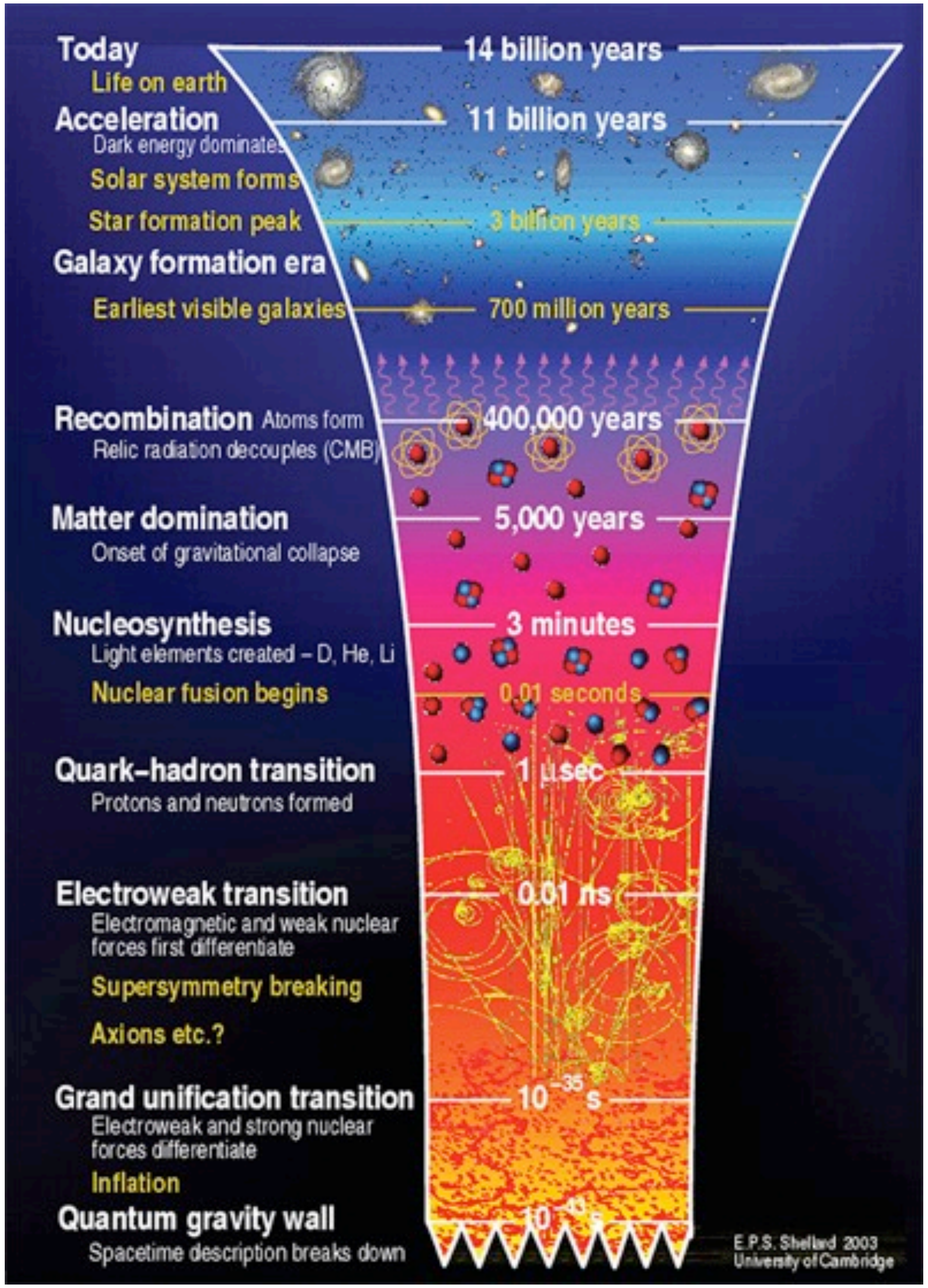
Hubble 1929

Precision cosmology now ...



Planck 2015

The Universe as a particle accelerator



Desiderata for a particle physicist

- 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)- next lecture

Outline

- The background
- Linear theory
- Inflation
- Dark energy
- Relativistic particles
- Inconsistencies

Background cosmology: FRW equations

$$ds^2 = -dt^2 + a^2(t)\gamma_{ij}dx^i dx^j$$

physical time — metric of 3-space

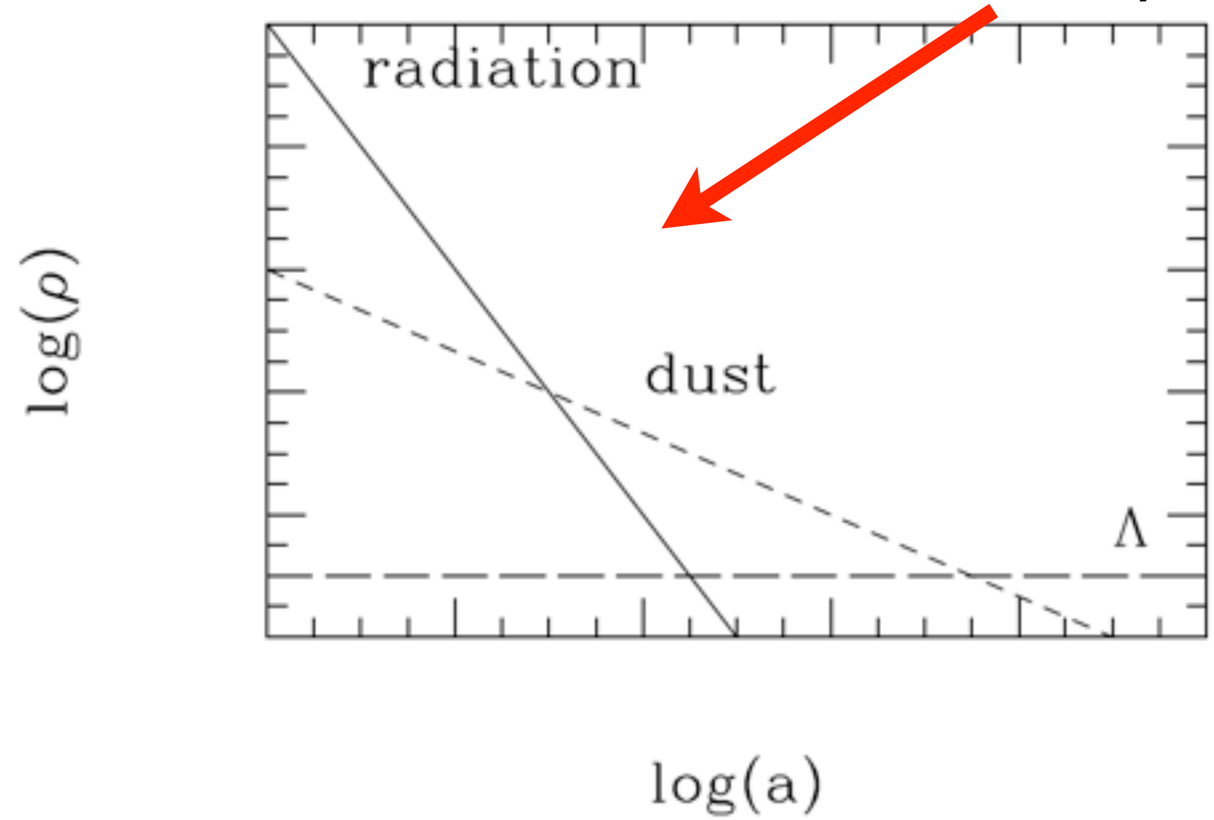
curvature of 3-space

$$G_{\alpha\beta} = 8\pi G T_{\alpha\beta} \longrightarrow H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - k$$

density

Conservation of energy-momentum

$$\nabla^\mu T_{\mu\nu} = 0$$



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

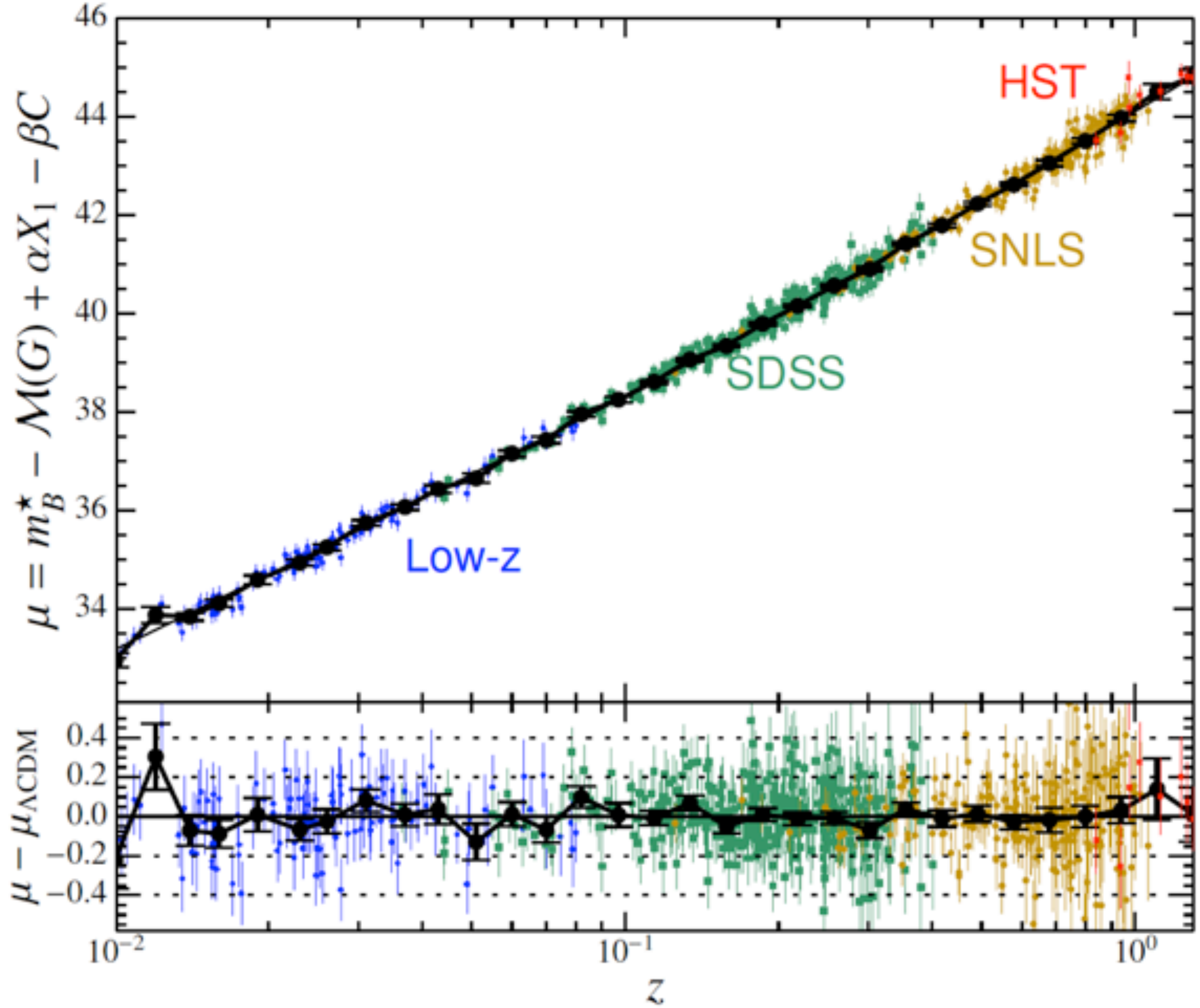
Angular diameter distance: $D_A = \frac{D_L}{(1+z)^2}$

Background cosmology: measure distances

Measure $z, D_L(z)$

or $z, D_A(z)$

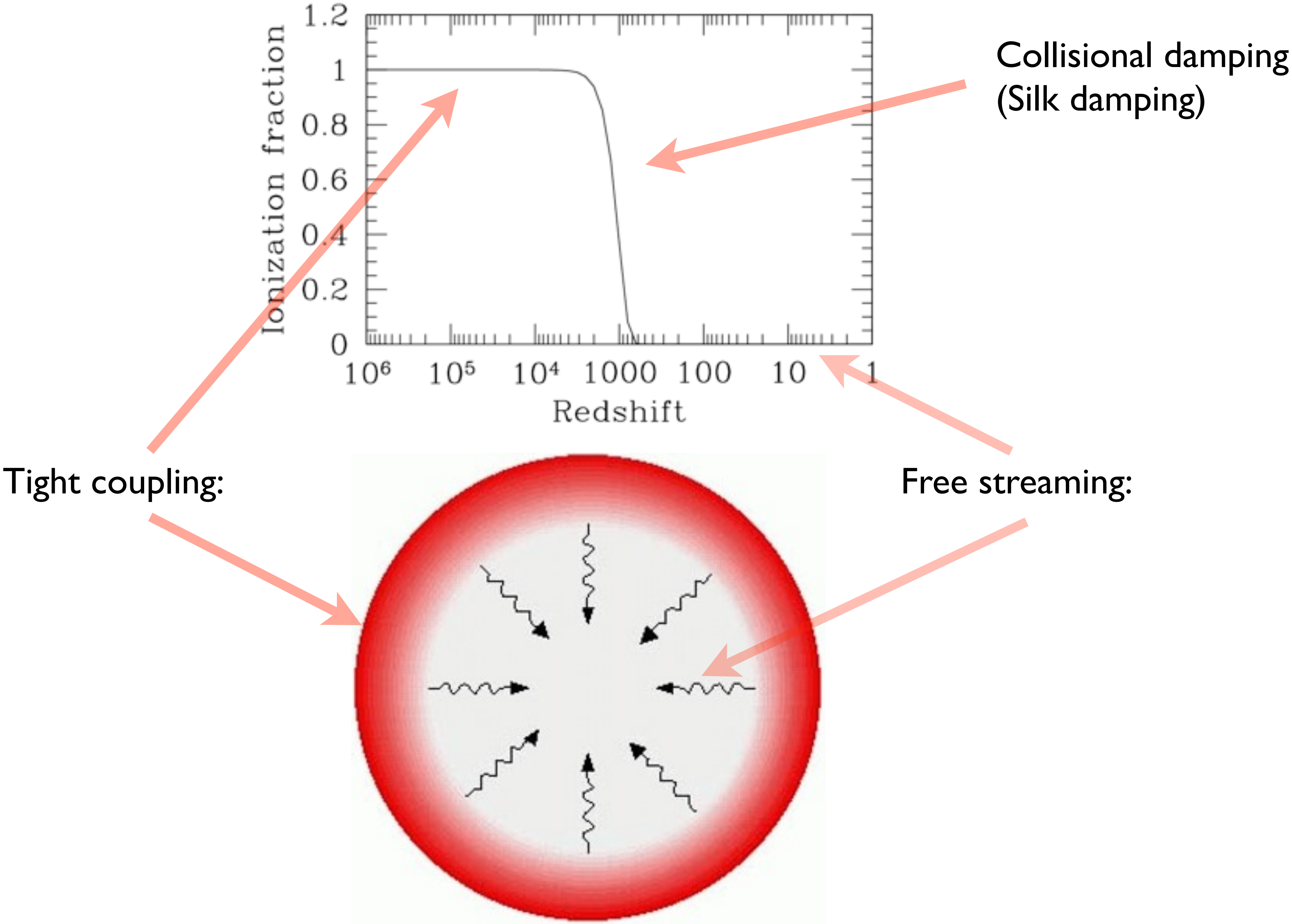
$$\mathcal{M} \propto -\log D_L$$



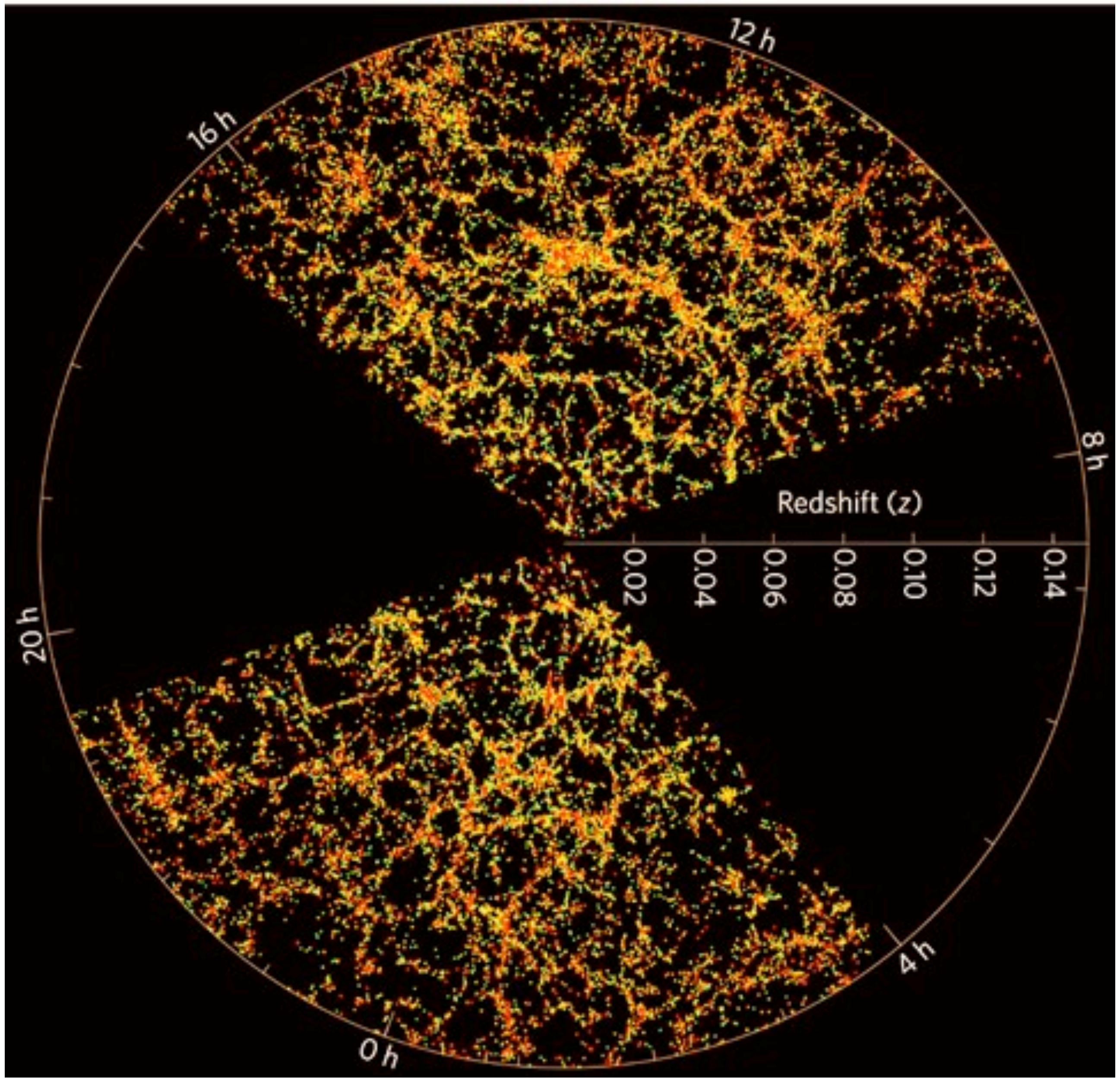
$$1 + z = \frac{1}{a}$$

Betoule et al (2014)

Background cosmology: CMB



Large scale structure: cosmic web



SDSS

Linear Perturbation Theory

Perturbed metric (in conformal time now)

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

Perturbed Einstein field equations

$$2(\Delta + 3\kappa)\Phi - 6\mathcal{H}(\Phi' + \mathcal{H}\Psi) = 8\pi G a^2 \sum_i \rho_i \delta_i$$

$$2(\Phi' + \mathcal{H}\Psi) = 8\pi G a^2 \sum_i (\rho_i + P_i)\theta_i$$

$$\Phi'' + \mathcal{H}\Psi' + 2\mathcal{H}\Phi' + \left(2\mathcal{H}' + \mathcal{H}^2 + \frac{1}{3}\Delta\right)\Psi - (\frac{1}{3}\Delta + \kappa)\Phi = 4\pi G a^2 \sum_i \delta P_i$$

$$\Phi - \Psi = 8\pi G a^2 \sum_i (\rho_i + P_i)\Sigma_i$$

Linear Perturbation Theory

Perturbed metric (in conformal time now)

$$ds^2 = a^2(\tau)\left[-(1+2\Psi)d\tau^2 + (1-\ldots \right]$$

Perturbed Einstein field equations

$$2(\Delta+3\kappa)\Phi - \ldots\Psi) = 8\pi G a^2 \sum_i \rho_i \delta_i$$

$$\ldots 2(\Phi' + \mathcal{H}\Psi) = 8\pi G a^2 \sum_i (\rho_i + P_i)\theta_i$$

$$\Phi'' + \ldots + \left(2\mathcal{H}' + \mathcal{H}^2 + \frac{1}{3}\Delta\right)\Psi - (\frac{1}{3}\Delta + \kappa)\Phi = 4\pi G a^2 \sum_i \delta P_i$$

$$\Phi - \Psi = 8\pi G a^2 \sum_i (\rho_i + P_i)\Sigma_i$$

Linear Theory = Fourier Transform

Linear Perturbation Theory

Energy-momentum conservation (no shear):

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$$

density contrast

$$\begin{aligned}
\delta' &= -(1+w)(\theta - 3\Phi') - 3\mathcal{H}\left(\frac{\delta P}{\delta \rho} - w\right)\delta \\
\theta' &= -\mathcal{H}(1-3w)\theta - \frac{w'}{1+w}\theta + \frac{\delta P/\delta\rho}{1+w}k^2\delta + k^2\Psi
\end{aligned}$$

velocity divergence

Examples:

dust:

$$\begin{aligned}
\delta' &= -(\theta - 3\Phi') \\
\theta' &= -\mathcal{H}\theta + k^2\Psi
\end{aligned}$$

radiation:

$$\begin{aligned}
\delta' &= -\frac{4}{3}(\theta - 3\Phi') \\
\theta' &= +\frac{1}{4}k^2\delta + k^2\Psi
\end{aligned}$$

Linear Perturbation Theory

Aside: Newtonian theory

sound speed → $c_s^2 = \frac{\nabla \delta P}{\nabla \delta \rho}$

$$\delta_k'' + \frac{a'}{a}\delta_k' + (c_s^2 k^2 - 4\pi G \rho a^2)\delta_k = 0$$

expansion/dilution　　pressure/reaction　　gravity/collapse

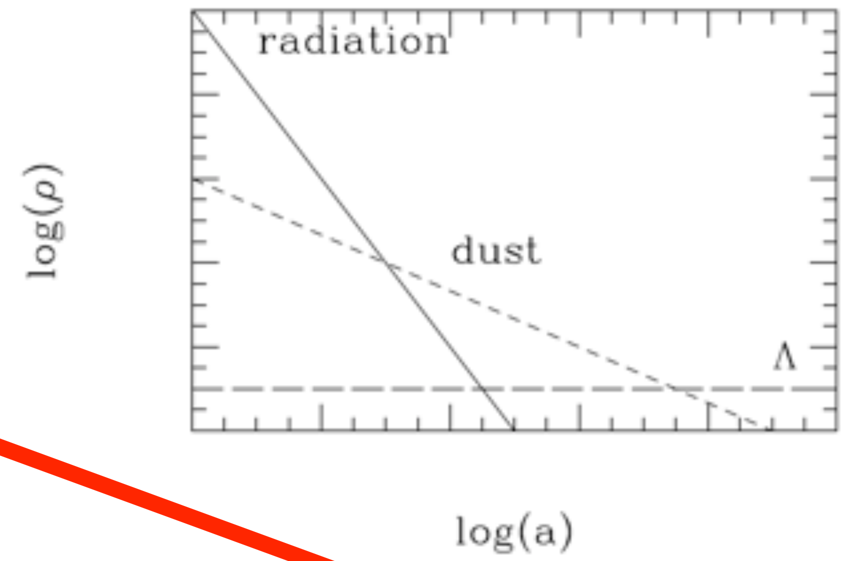
Jeans length:

$$\lambda_J = c_s \left(\frac{\pi}{G\rho_0}\right)^{\frac{1}{2}}$$

$$c_s^2 \sim (K_B T)/(M)$$

→ $$\lambda_J = \left(\frac{\pi K_B T}{G M \rho_0}\right)^{1/2}$$

Linear Perturbations: evolution



Scale factor: $a \propto \quad \tau, \quad \tau^2, \quad \frac{1}{|\tau_\infty - \tau|}$

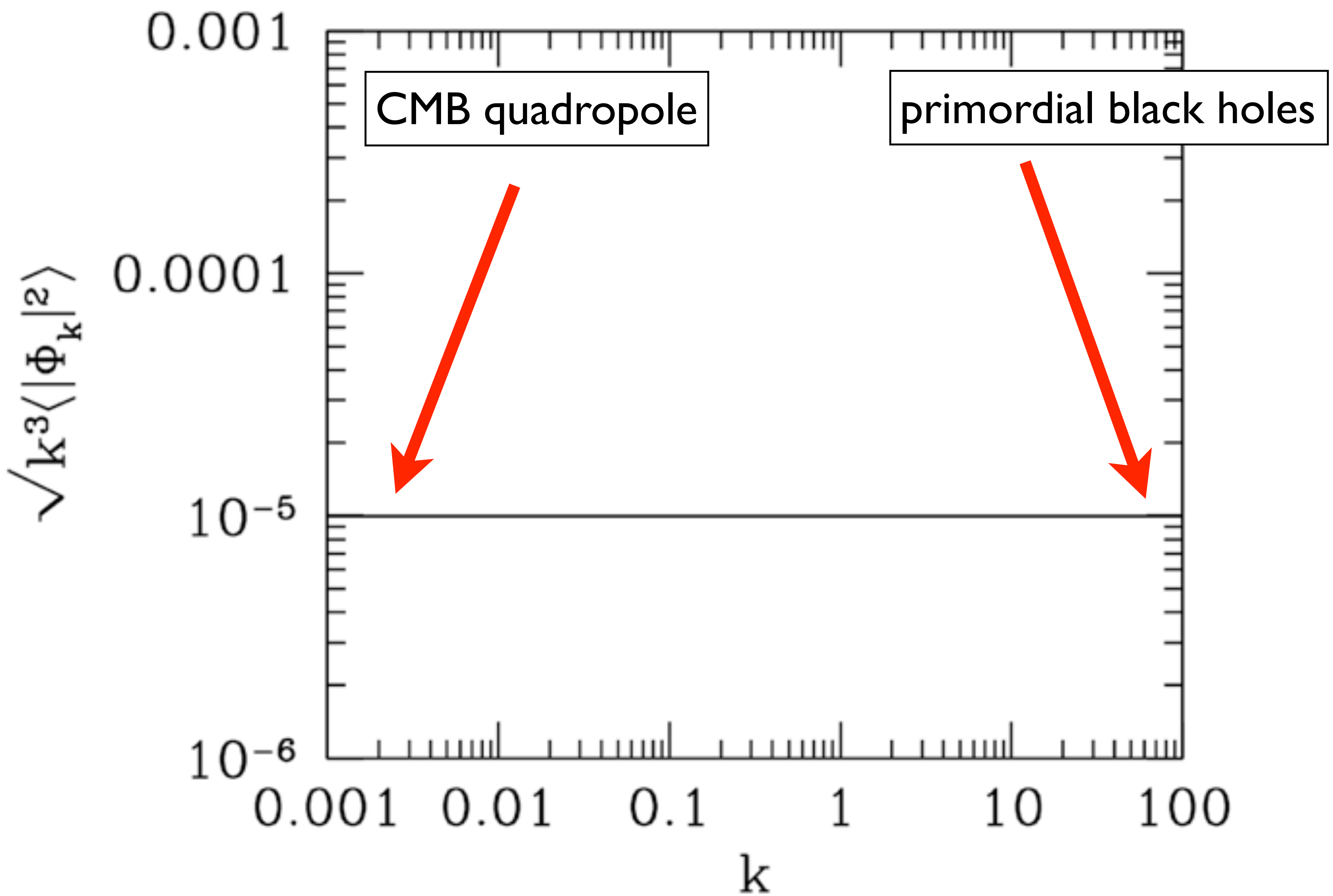
radiation era | matter era | Λ era

dust: $\delta \propto \log \tau$ | $\delta \propto \tau^2$ | $\delta \propto \text{constant}$

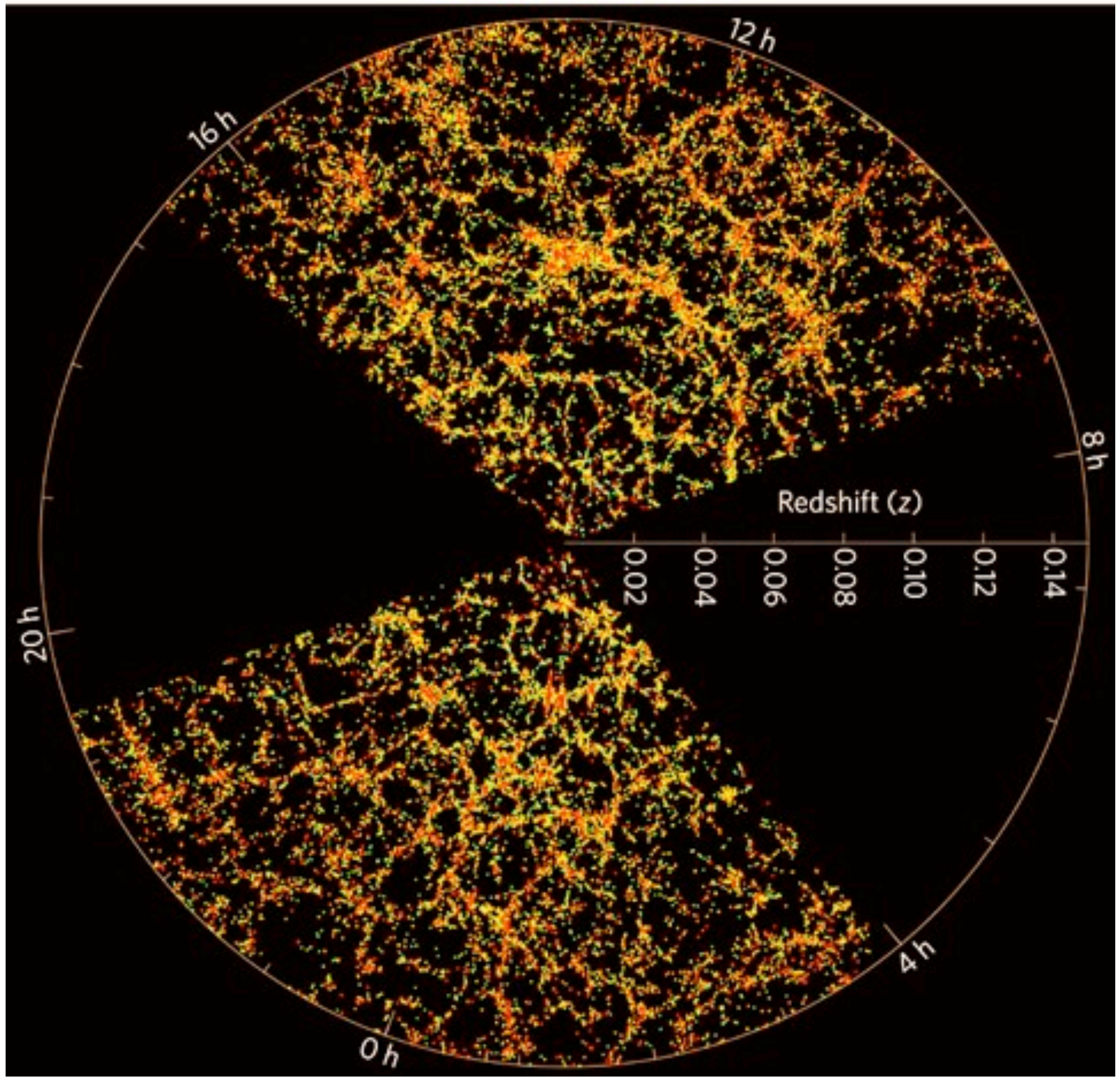
baryons: $\delta \propto \frac{1}{\sqrt{k\tau}} \cos\left(\frac{k\tau}{\sqrt{3}}\right)$ | $\delta \propto \tau^2$ | $\delta \propto \text{constant}$

Linear Perturbations: initial conditions

Peebles-Harrison-Zel'dovich spectrum (1970)



Large scale structure: cosmic web



SDSS

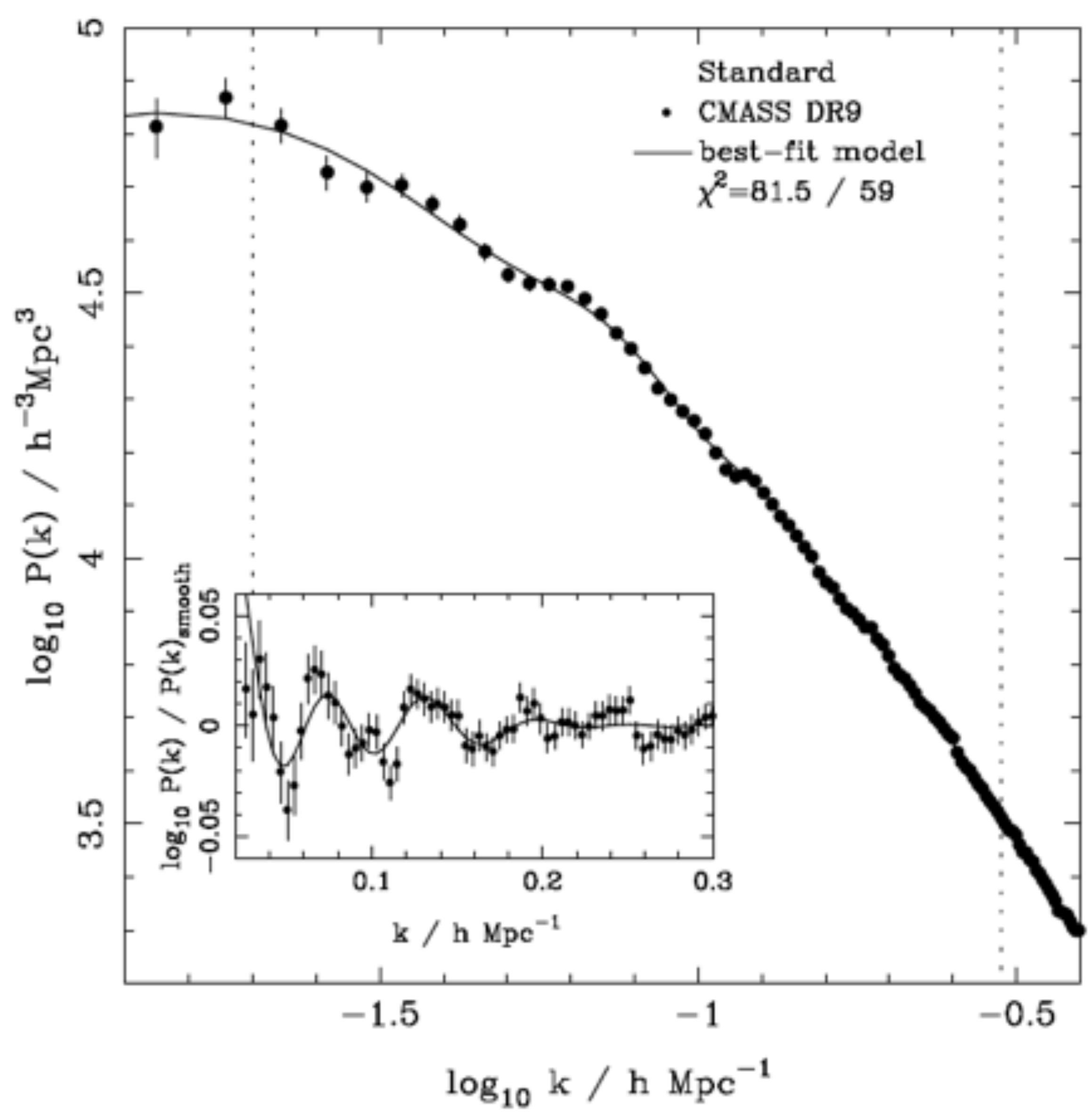
Large scale structure: cosmic web

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$$

density contrast

$$\langle \delta^*(\mathbf{k})\delta(\mathbf{k}')\rangle \equiv (2\pi)^2 P(k)\delta^3(\mathbf{k} - \mathbf{k}')$$

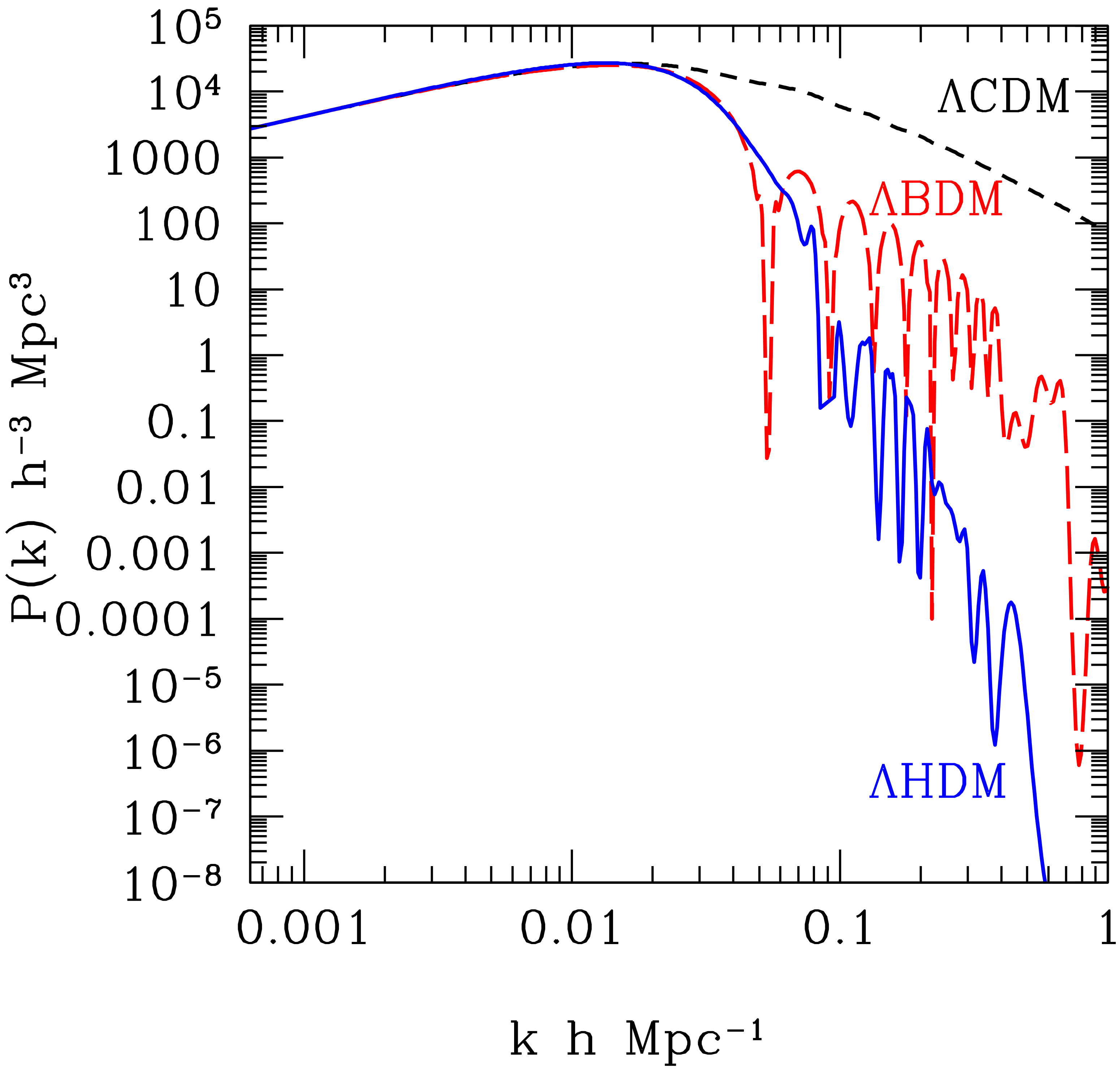
power spectrum



$$\left(\frac{\delta M}{\bar{M}}\right)^2 (R) \sim k^3 P(k)_{k=2\pi/R}$$

mass variance

Large scale structure: cosmic web



Large scale structure: CMB

Intrinisic $\rho_\gamma = \sigma T^4 \rightarrow \frac{\delta T}{T} = \frac{1}{4}\frac{\delta\rho_\gamma}{\rho_\gamma}$

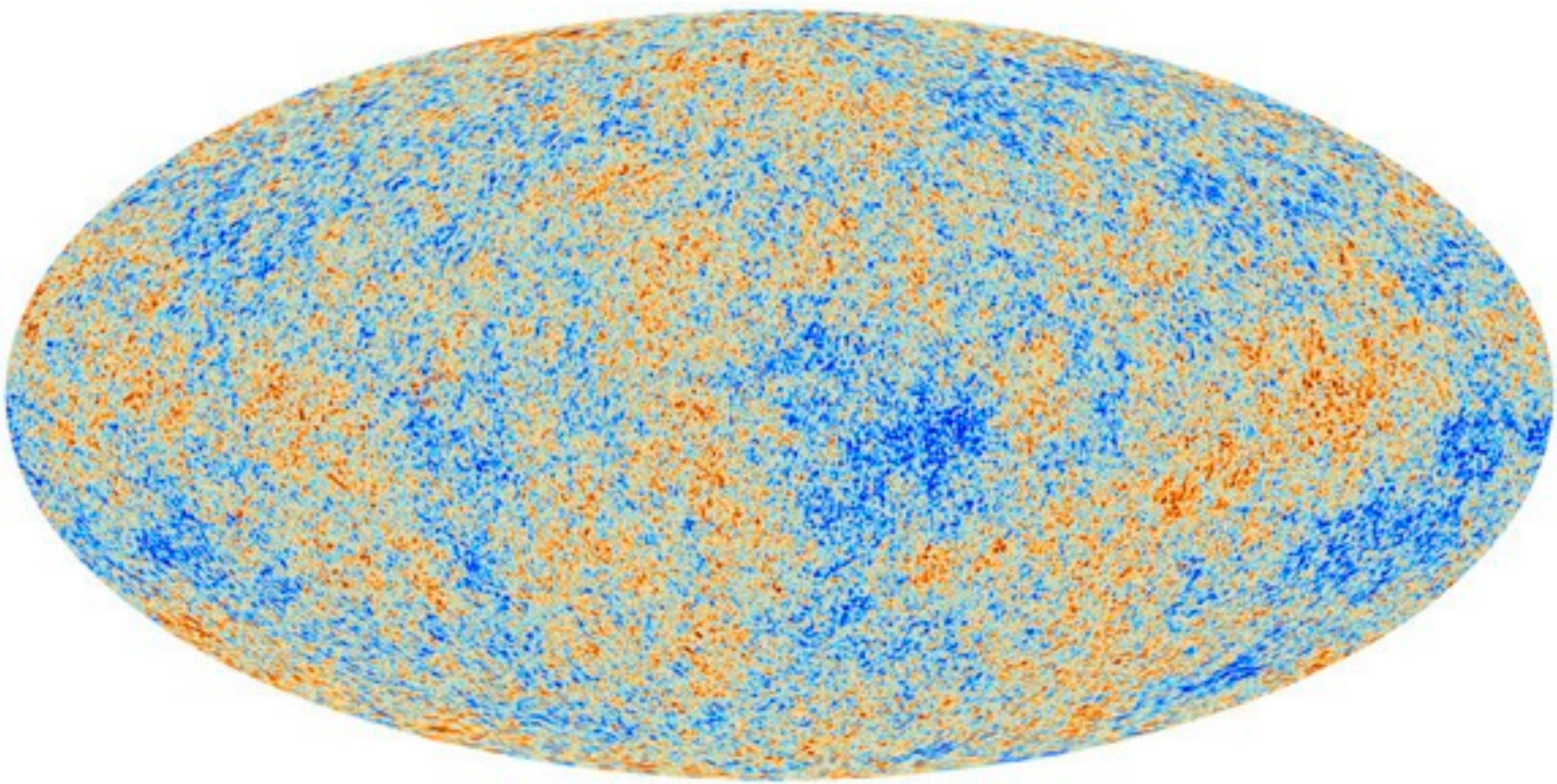
Doppler $\rightarrow \frac{\delta T}{T} = -\vec{v}_B \cdot \vec{n}$

Sachs-Wolfe $\frac{\delta T}{T} = -\Phi$

gravitational redshift

Integrated Sachs-Wolfe $\frac{\delta T}{T} = -2\int_{\tau_*}^{\tau_0} d\tau \Phi'$

Large scale structure: CMB



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Large scale structure: CMB

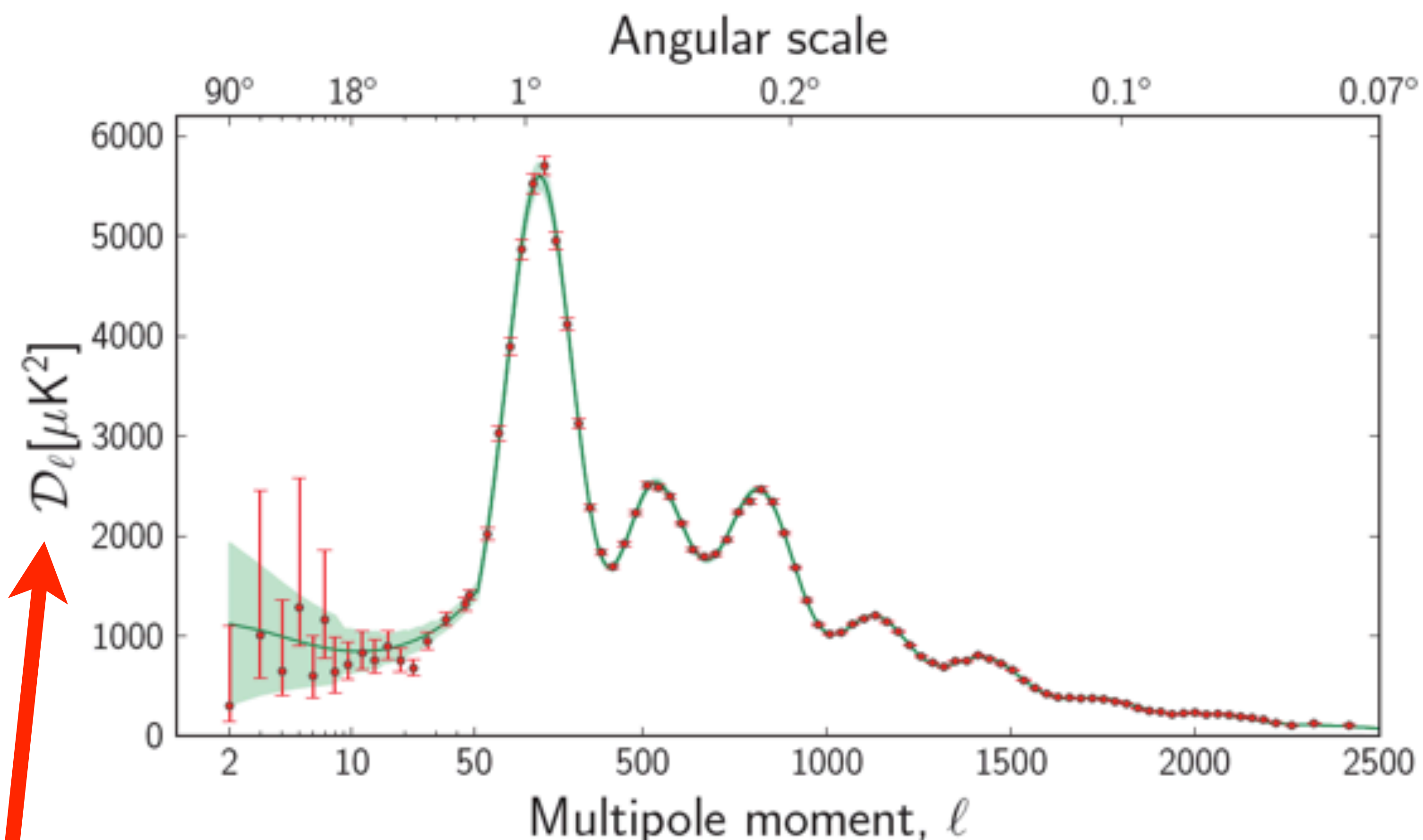
Angular power spectrum
of the CMB

$$\frac{\delta T}{T}(\mathbf{n}) = \frac{T(\mathbf{n}) - \bar{T}}{\bar{T}}$$

CMB anisotropies

$$\frac{\delta T}{T}(\mathbf{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\mathbf{n})$$

spherical harmonic transform

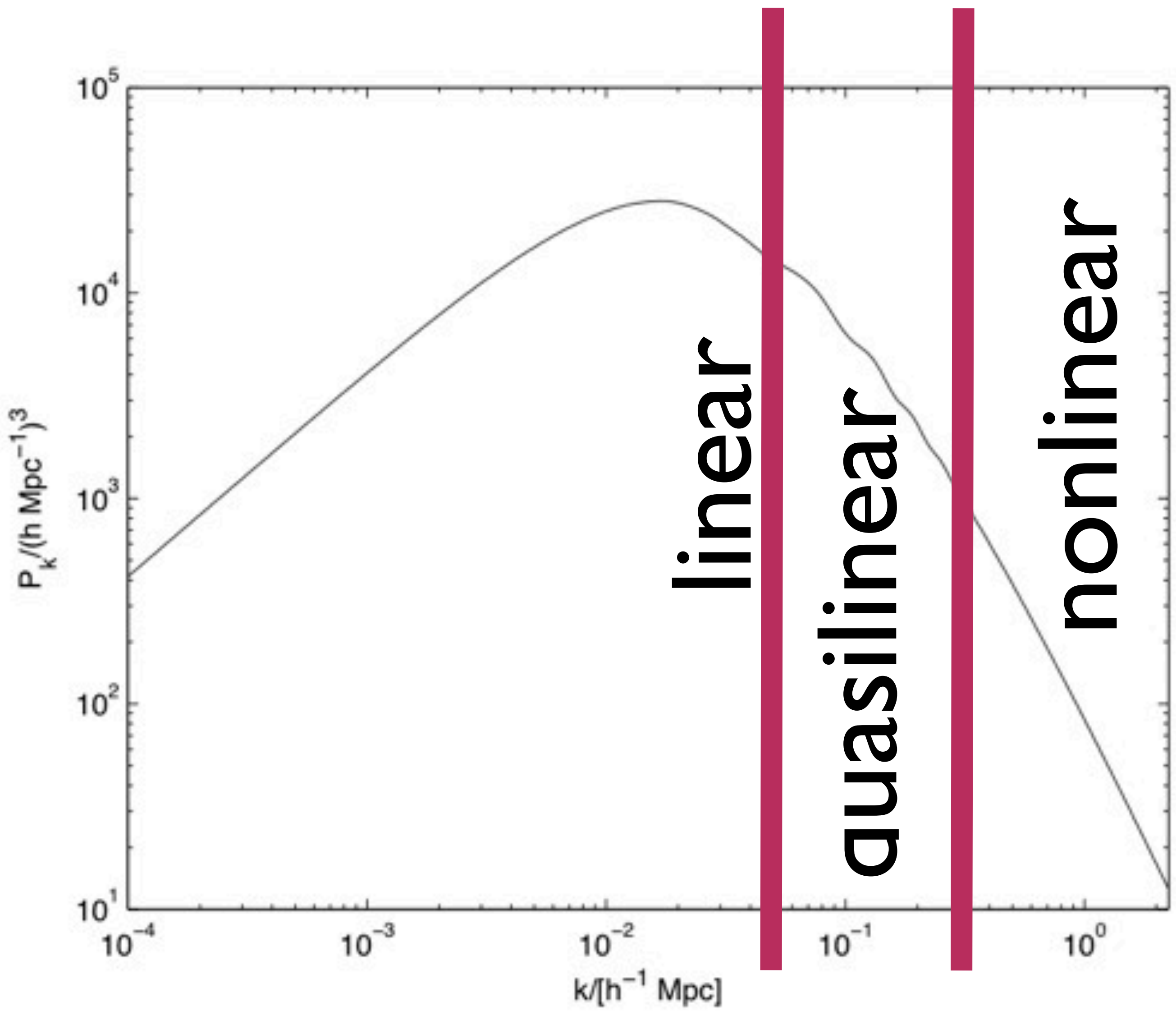


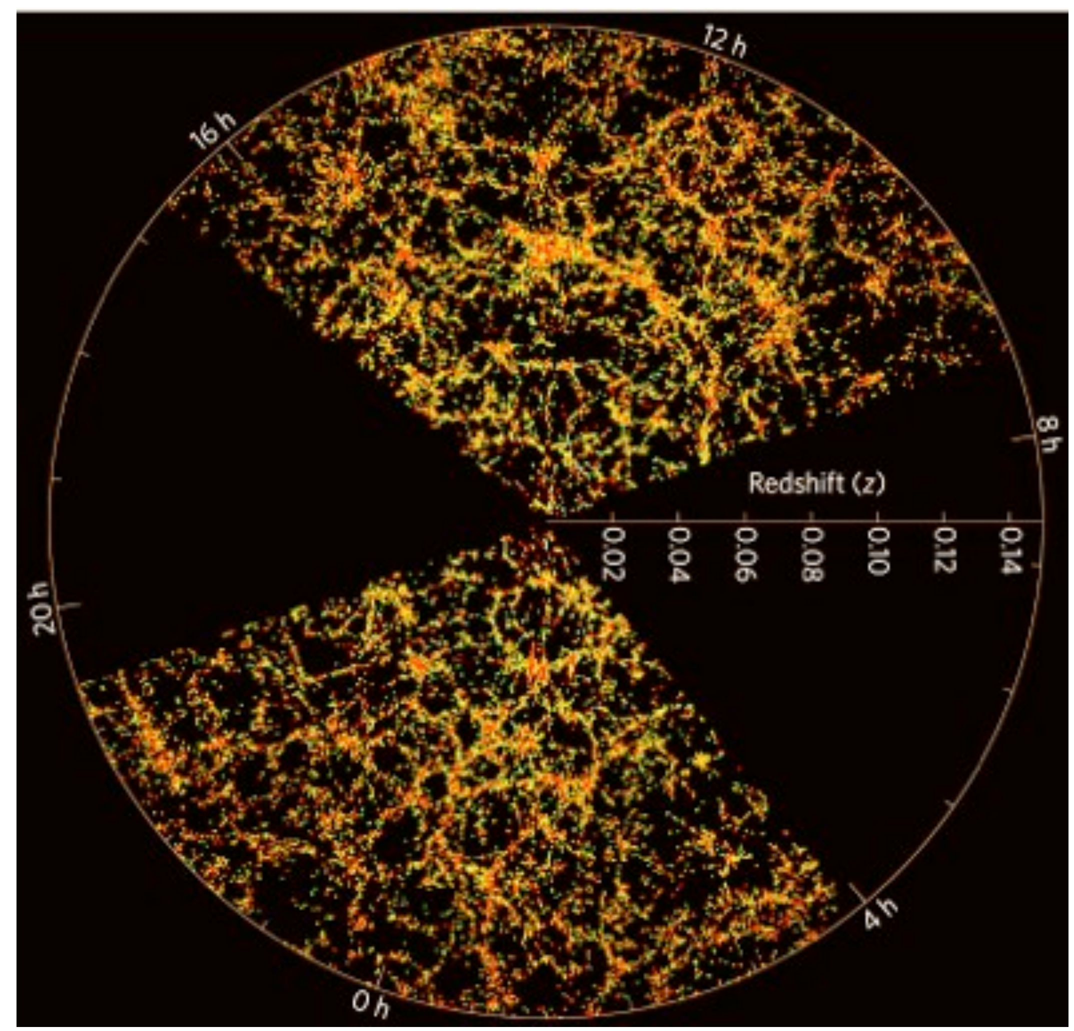
angular power spectrum

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

Planck
2013

From linear to non-linear physics.

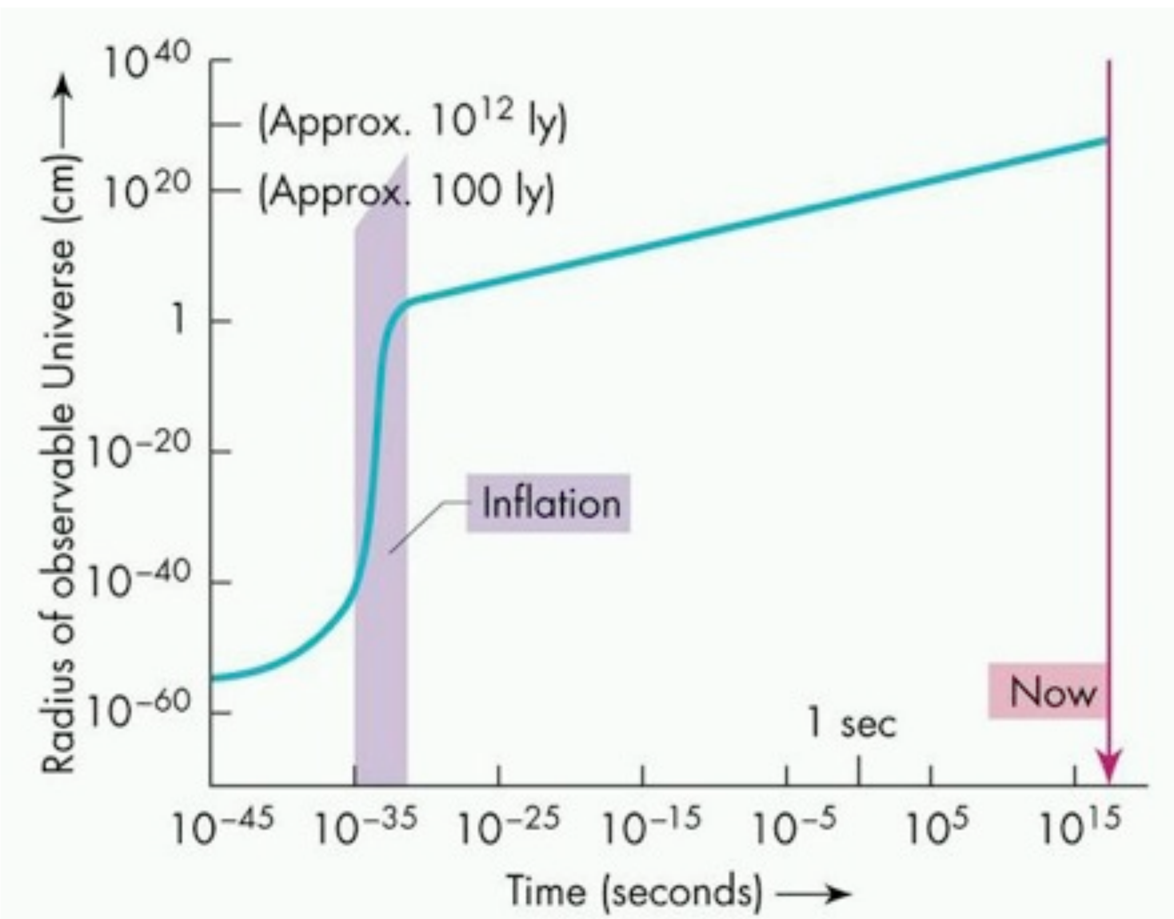


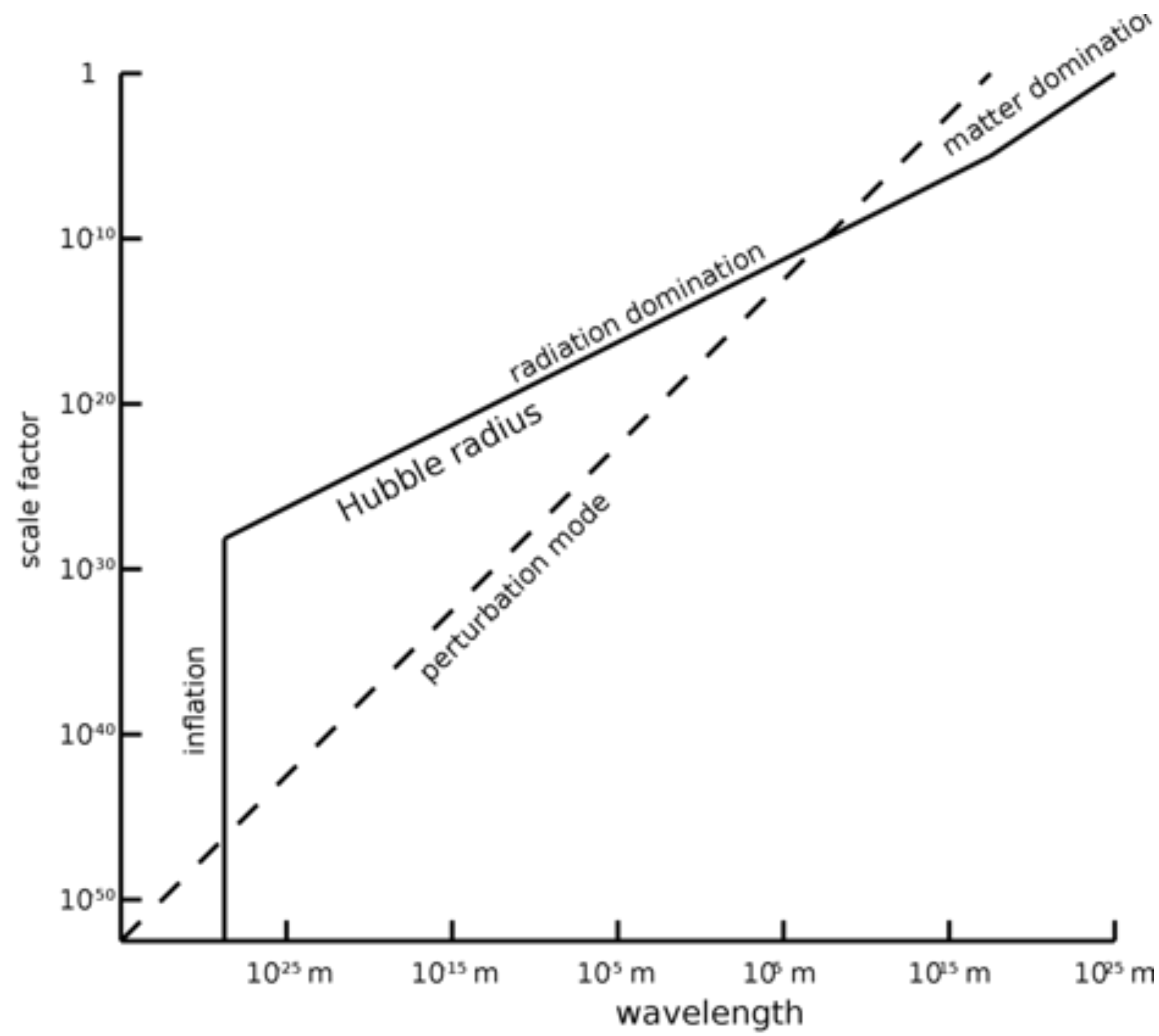


Inflation

Initial Conditions: Inflation

Inflation (1980)

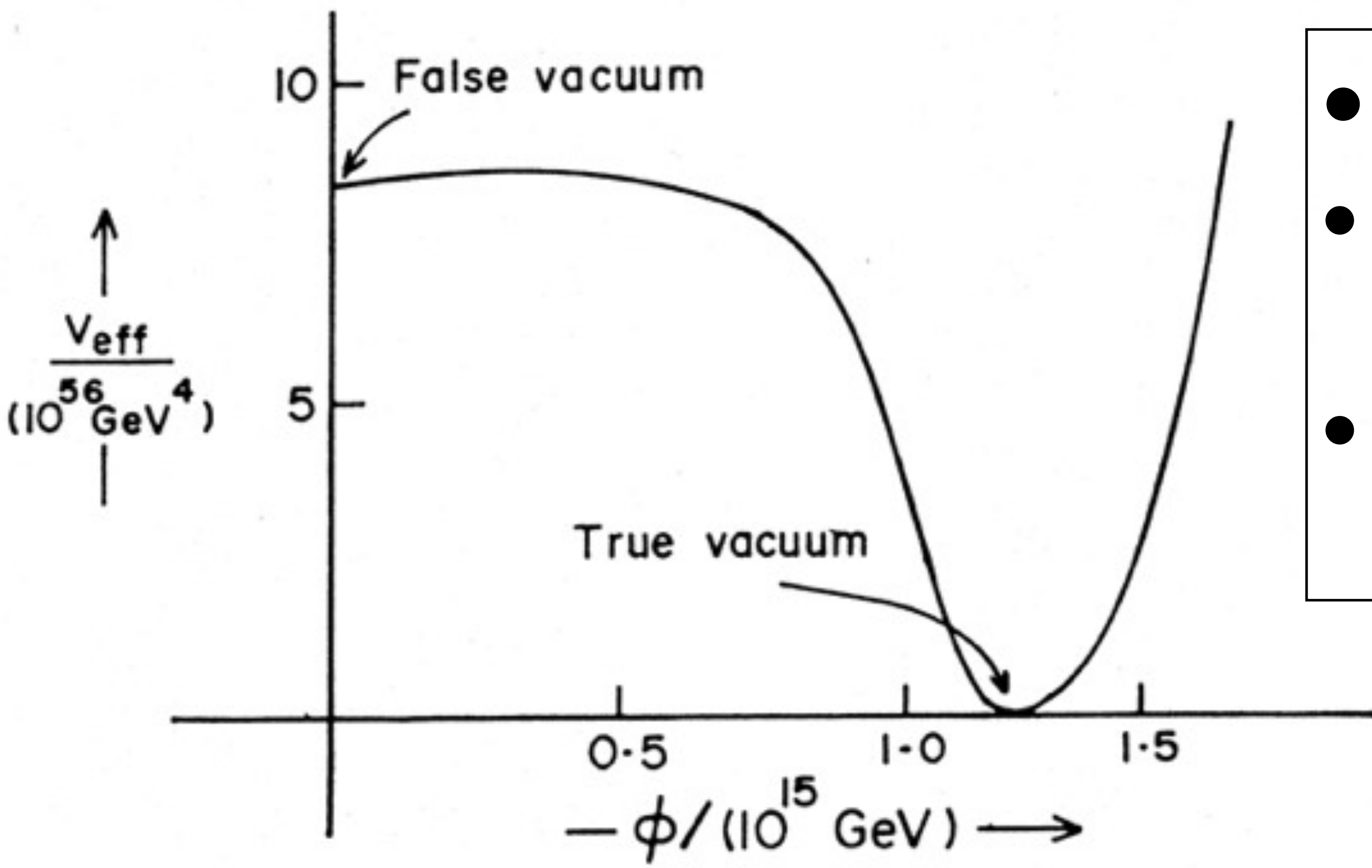




http://www.astro.umass.edu/~myun

Initial Conditions: Inflation

Cosmological scalar fields: $V(\phi) = \sum_n \lambda_n M^{4-n} \phi^n$



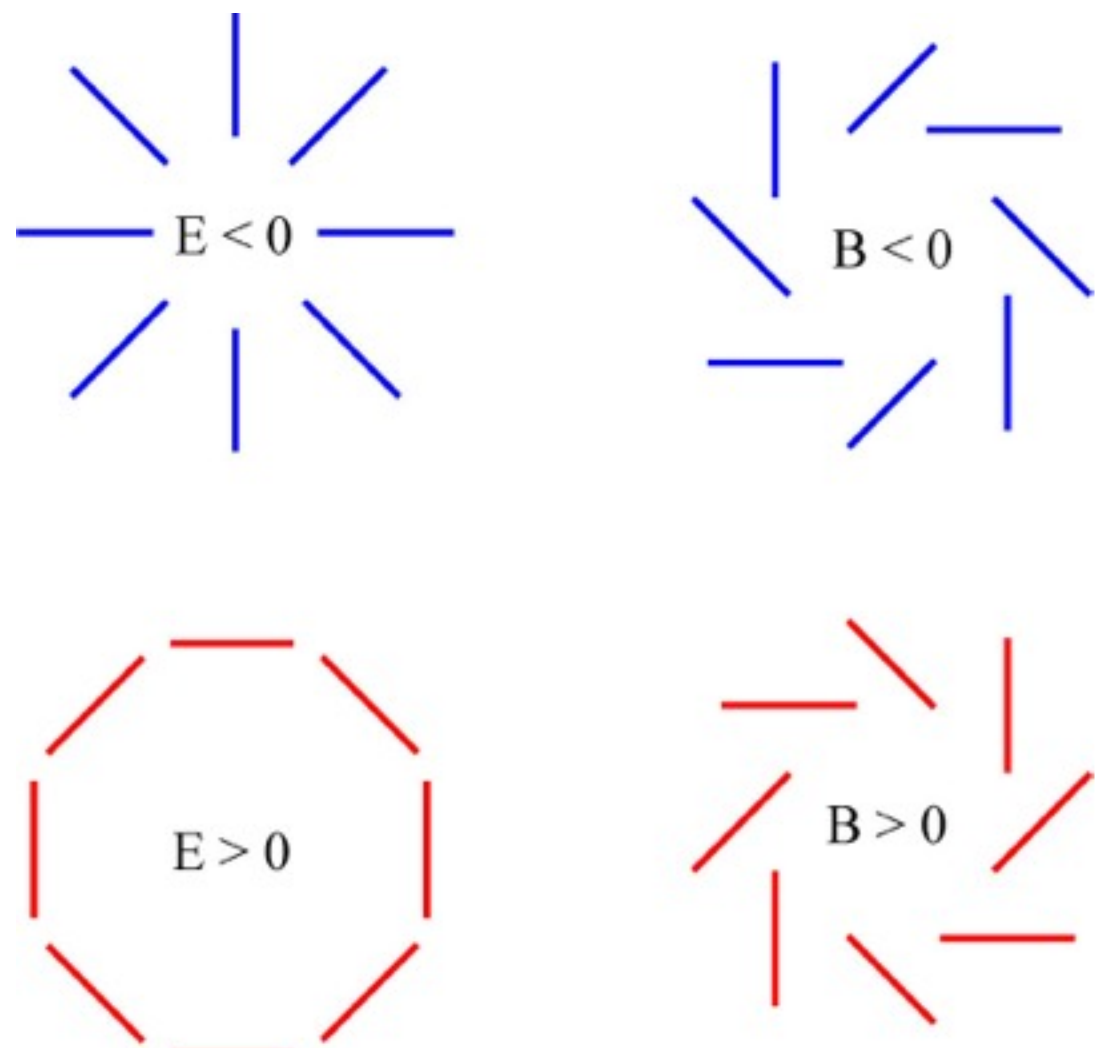
- Only 3 observables
- Constrain a very small piece of the potential
- Huge degeneracy between models

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

Initial Conditions: Inflation

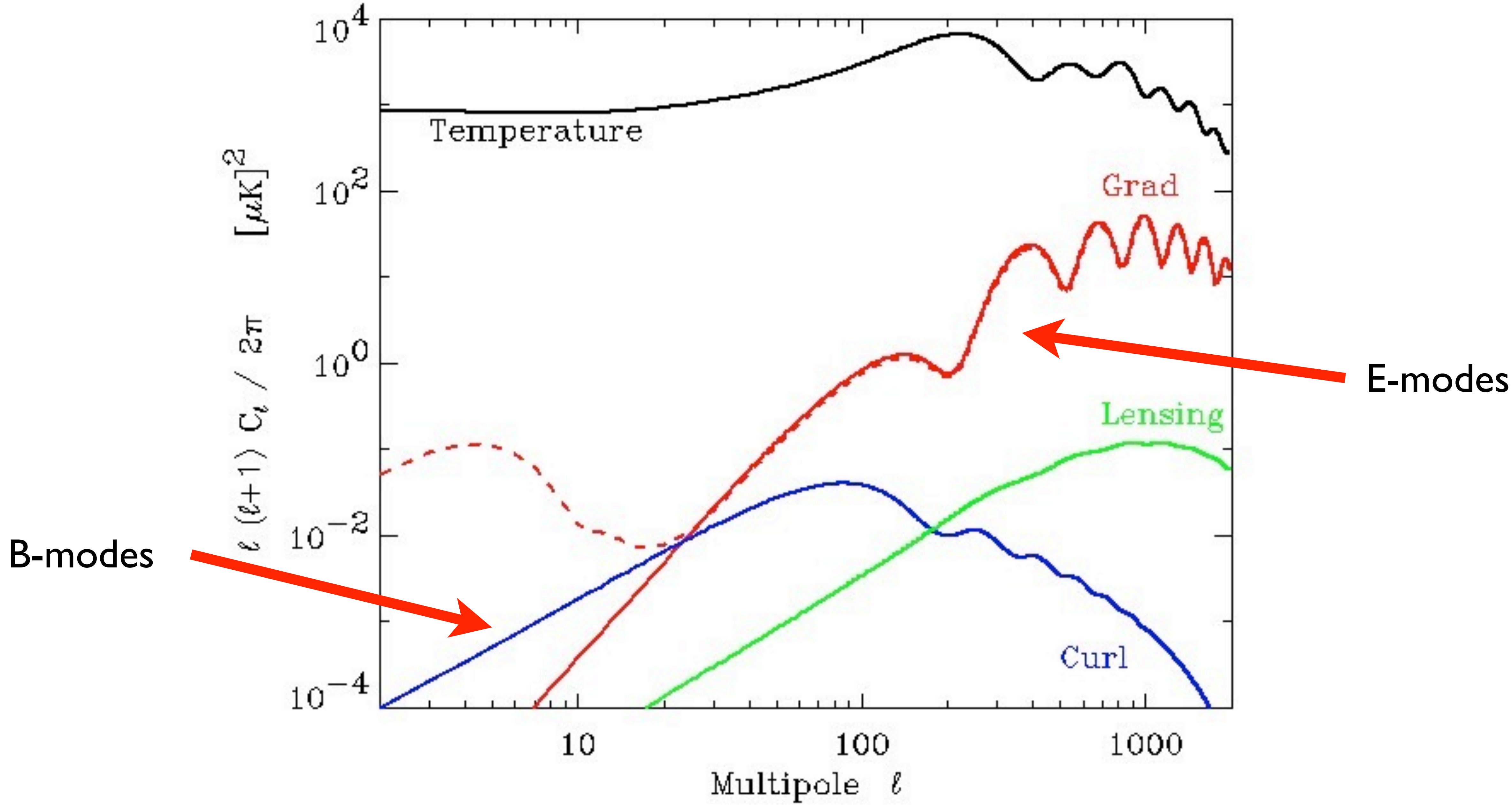
E and B modes of polarization

Sourced by scalars



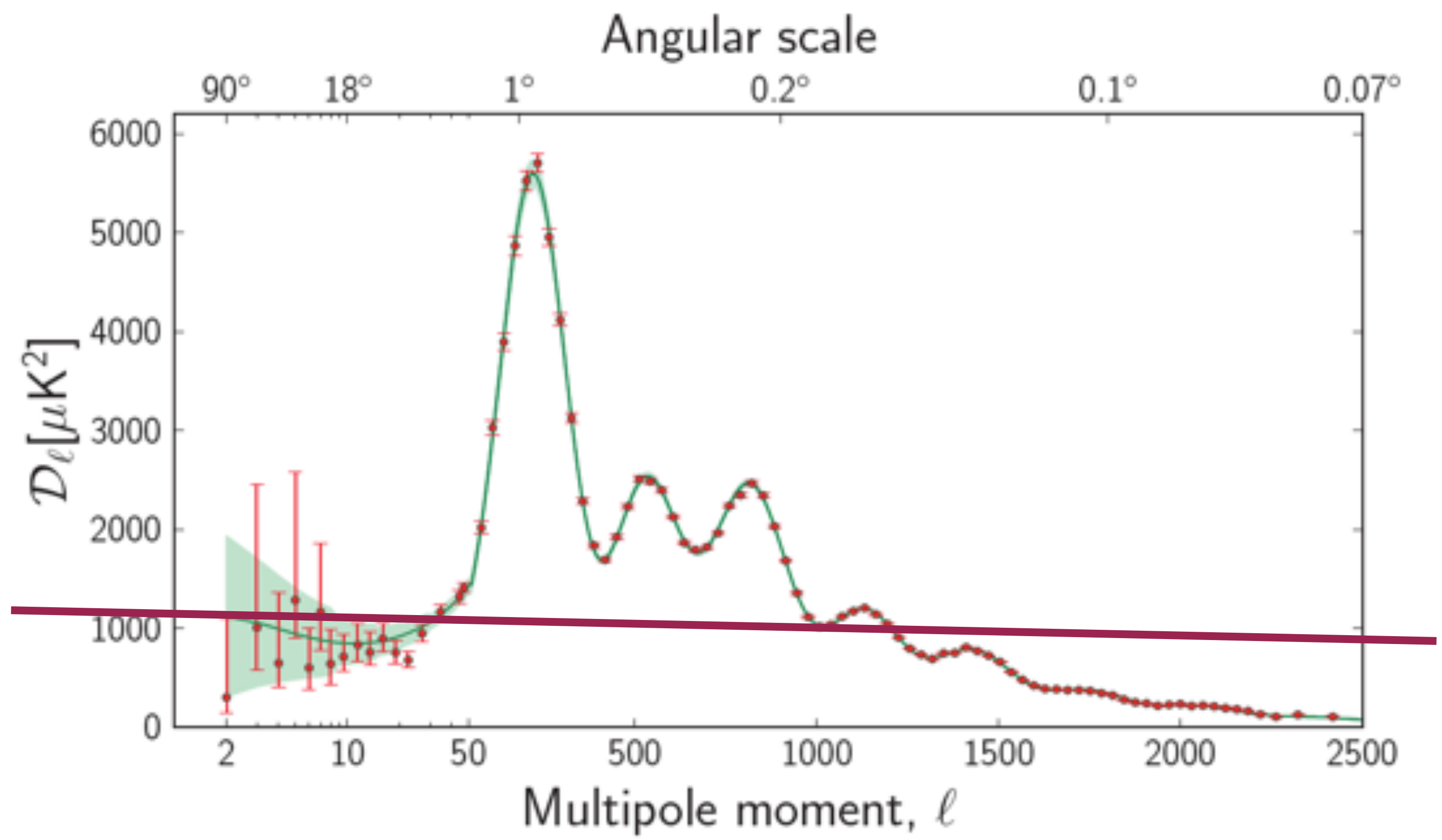
Sourced by tensors

Initial Conditions: Inflation



Initial Conditions: Inflation

Primordial Tilt



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5-sigma away from scale invariance

$$n_s = 0.9585 \pm 0.0070$$

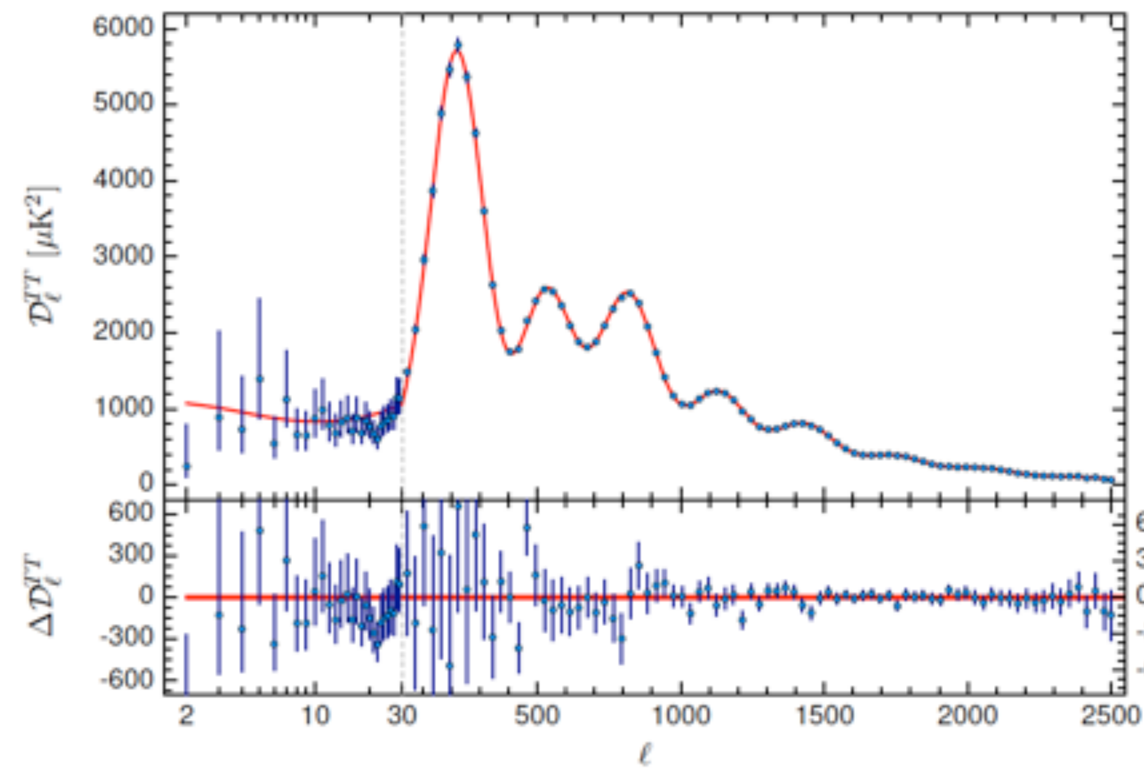
No running of spectral tilt

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

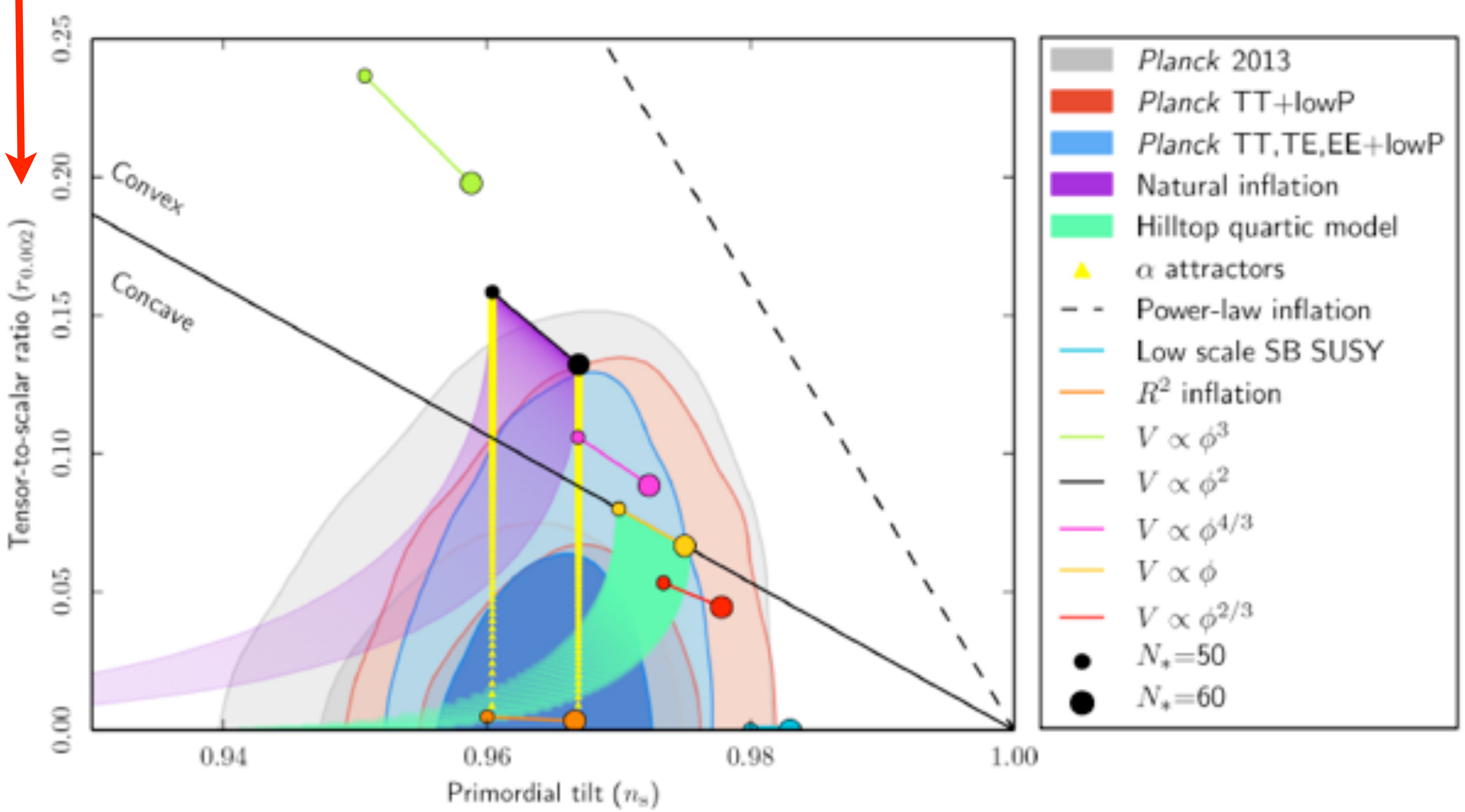
Upper bound on tensor modes

$$r < 0.11$$

Initial Conditions: Inflation



Primordial Gravitational Waves



Inflationary model	$\Delta\chi^2$		$\ln B_{0X}$	
	$w_{int} = 0$	$w_{int} \neq 0$	$w_{int} = 0$	$w_{int} \neq 0$
$R + R^2/(6M^2)$	+0.8	+0.3	...	+0.7
$n = 2/3$	+6.5	+3.5	−2.4	−2.3
$n = 1$	+6.2	+5.5	−2.1	−1.9
$n = 4/3$	+6.4	+5.5	−2.6	−2.4
$n = 2$	+8.6	+8.1	−4.7	−4.6
$n = 3$	+22.8	+21.7	−11.6	−11.4
$n = 4$	+43.3	+41.7	−23.3	−22.7
Natural	+7.2	+6.5	−2.4	−2.3
Hilltop ($p = 2$)	+4.4	+3.9	−2.6	−2.4
Hilltop ($p = 4$)	+3.7	+3.3	−2.8	−2.6
Double well	+5.5	+5.3	−3.1	−2.3
Brane inflation ($p = 2$)	+3.0	+2.3	−0.7	−0.9
Brane inflation ($p = 4$)	+2.8	+2.3	−0.4	−0.6
Exponential inflation	+0.8	+0.3	−0.7	−0.9
SB SUSY	+0.7	+0.4	−2.2	−1.7
Supersymmetric α-model	+0.7	+0.1	−1.8	−2.0
Superconformal ($m = 1$)	+0.9	+0.8	−2.3	−2.2
Superconformal ($m \neq 1$)	+0.7	+0.5	−2.4	−2.6

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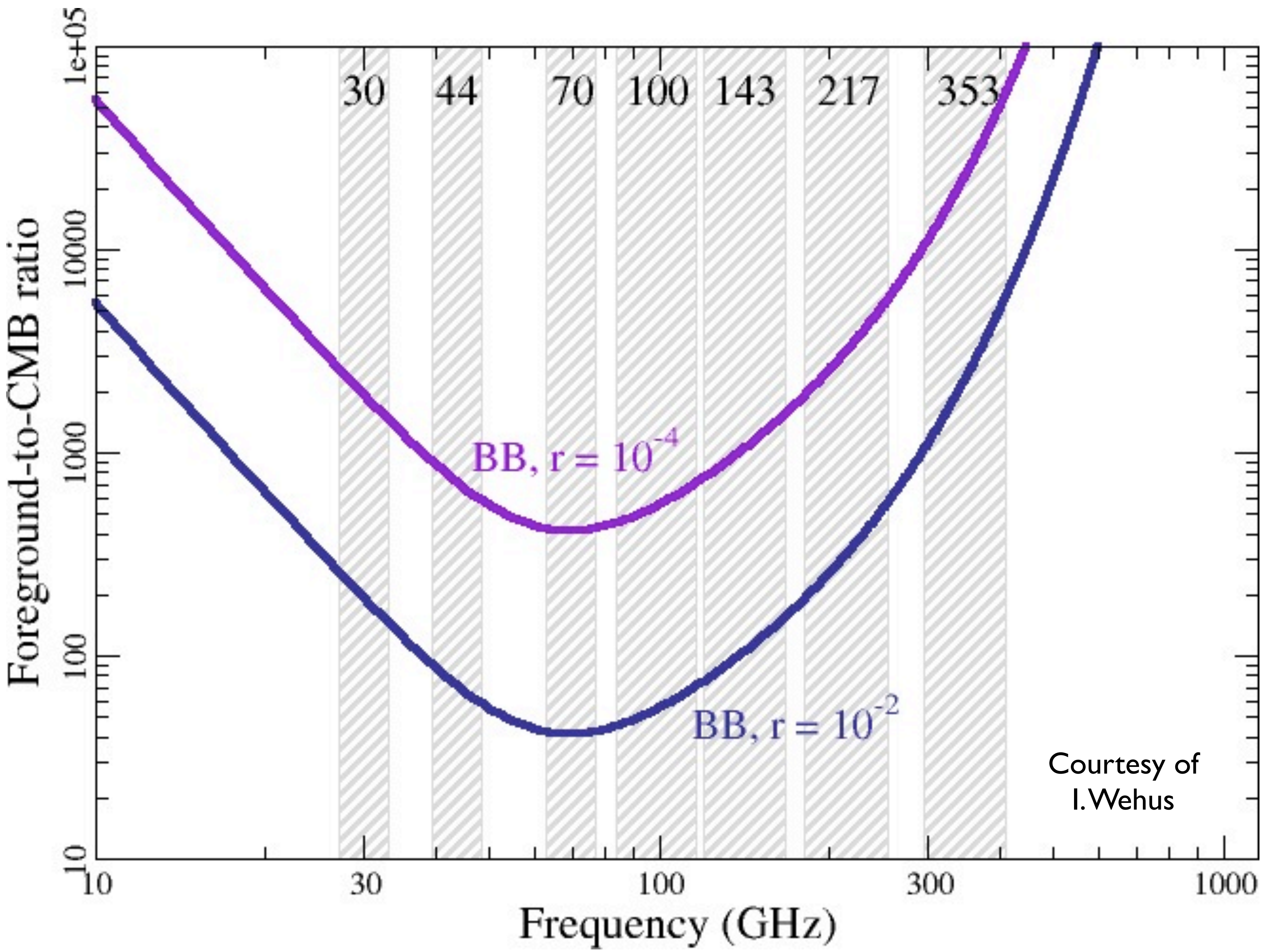


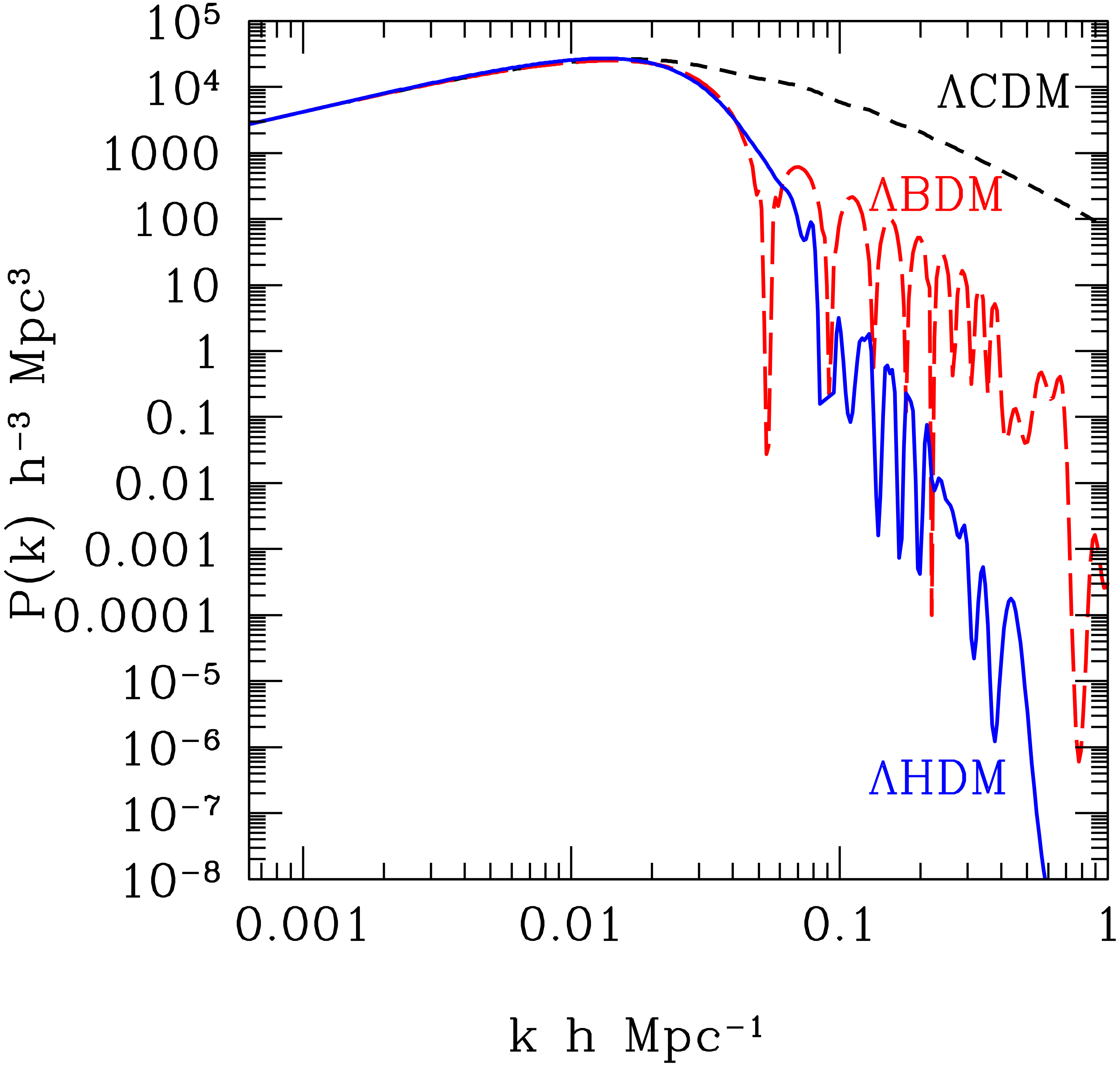
Foreground-to-CMB ratio
Frequency (GHz)
30
44
70
100
143
217
353
BB, r = 10^-4
BB, r = 10^-2
1e+05
10000
1000
100
10
10
30
100
300
1000
Courtesy of
I. Wehus

Initial Conditions: Inflation

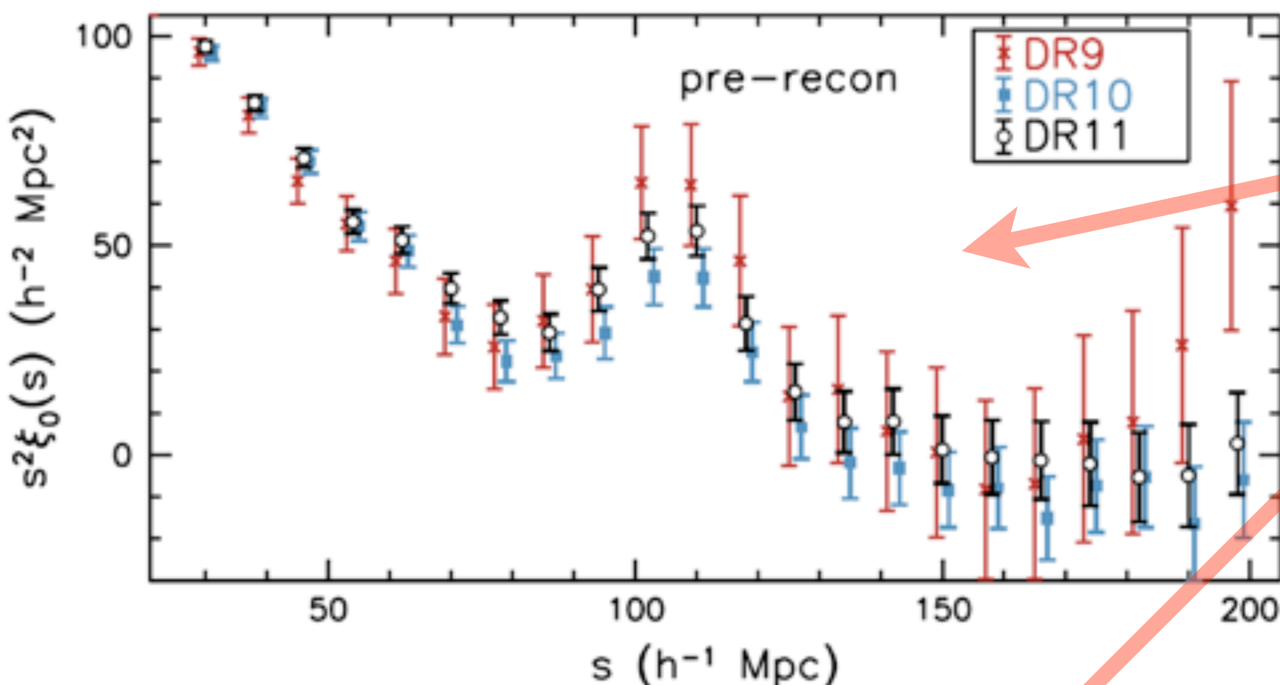
- Inflation fits the data.
- It is possible to look at higher order correlators- non-Gaussianity.
- There is an overabundance of possible models.
- There is a model for any possible value of the data.

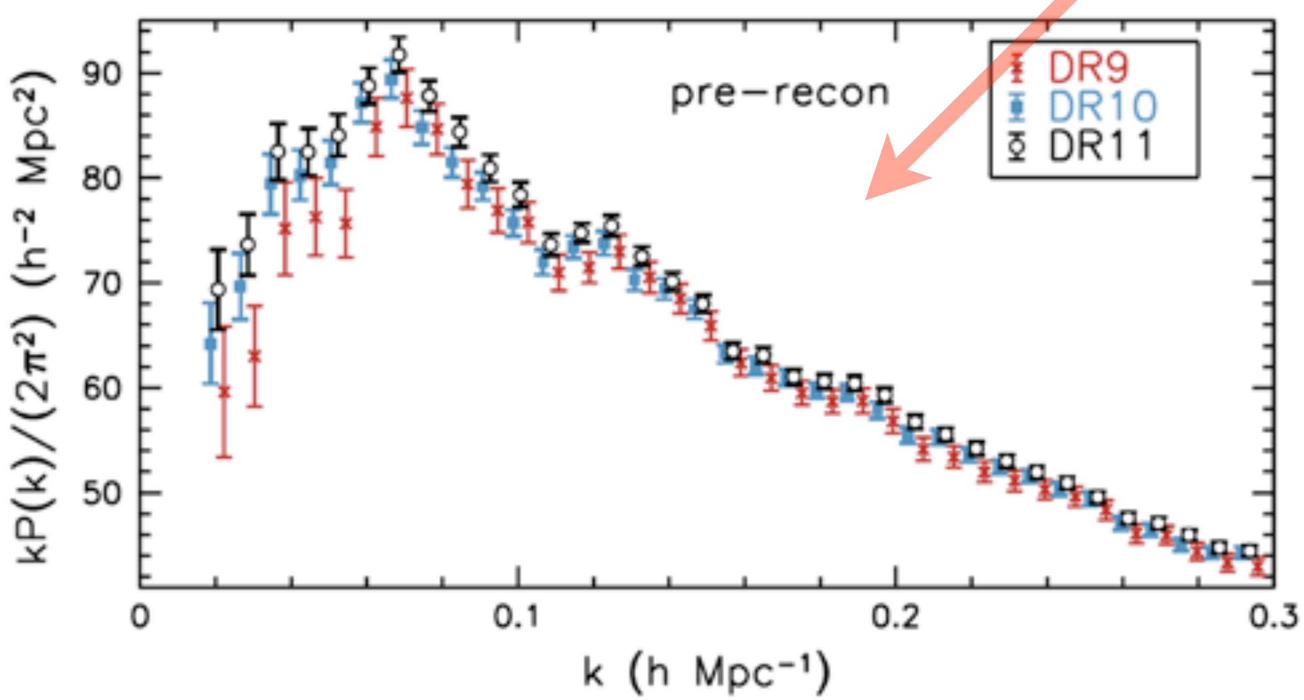
Dark Energy

Dark Energy: BAO

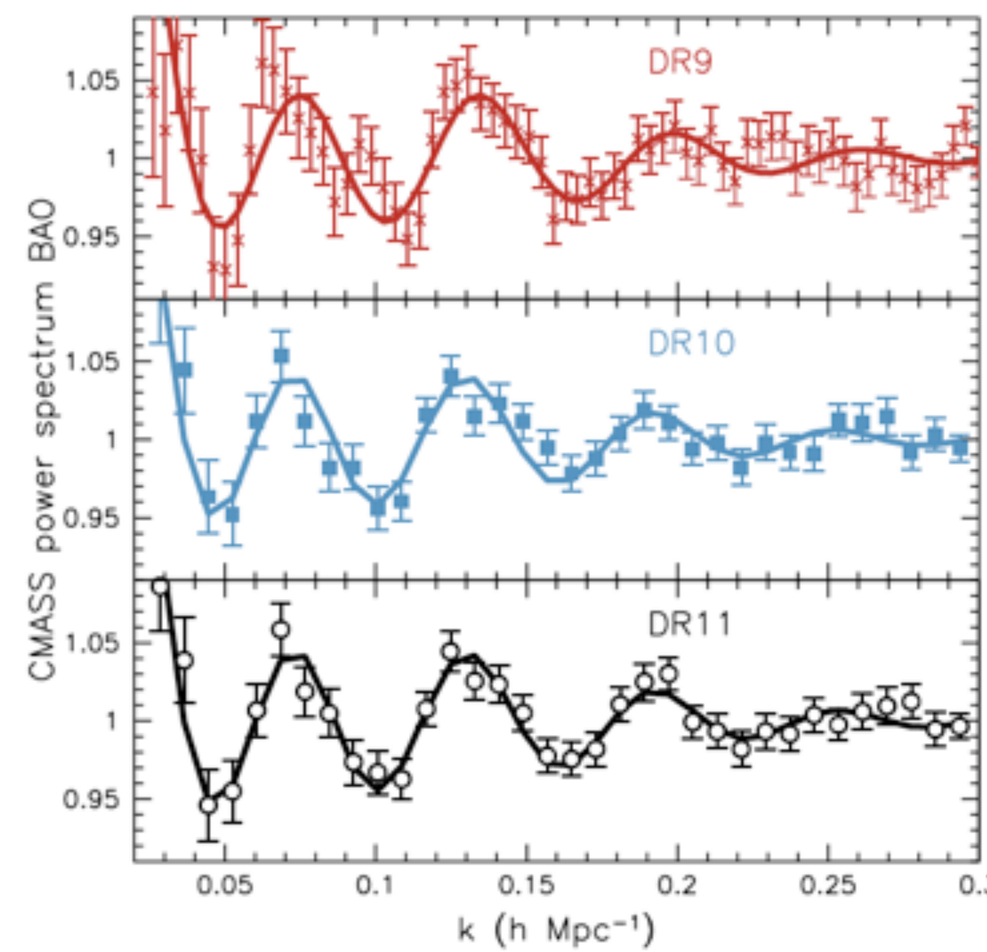


Dark Energy: BAO





Sound horizon at recombination r_s



BOSS, Anderson et al 2013.

* Baryon Acoustic Oscillations

Background cosmology: parameters

Hubble parameter

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

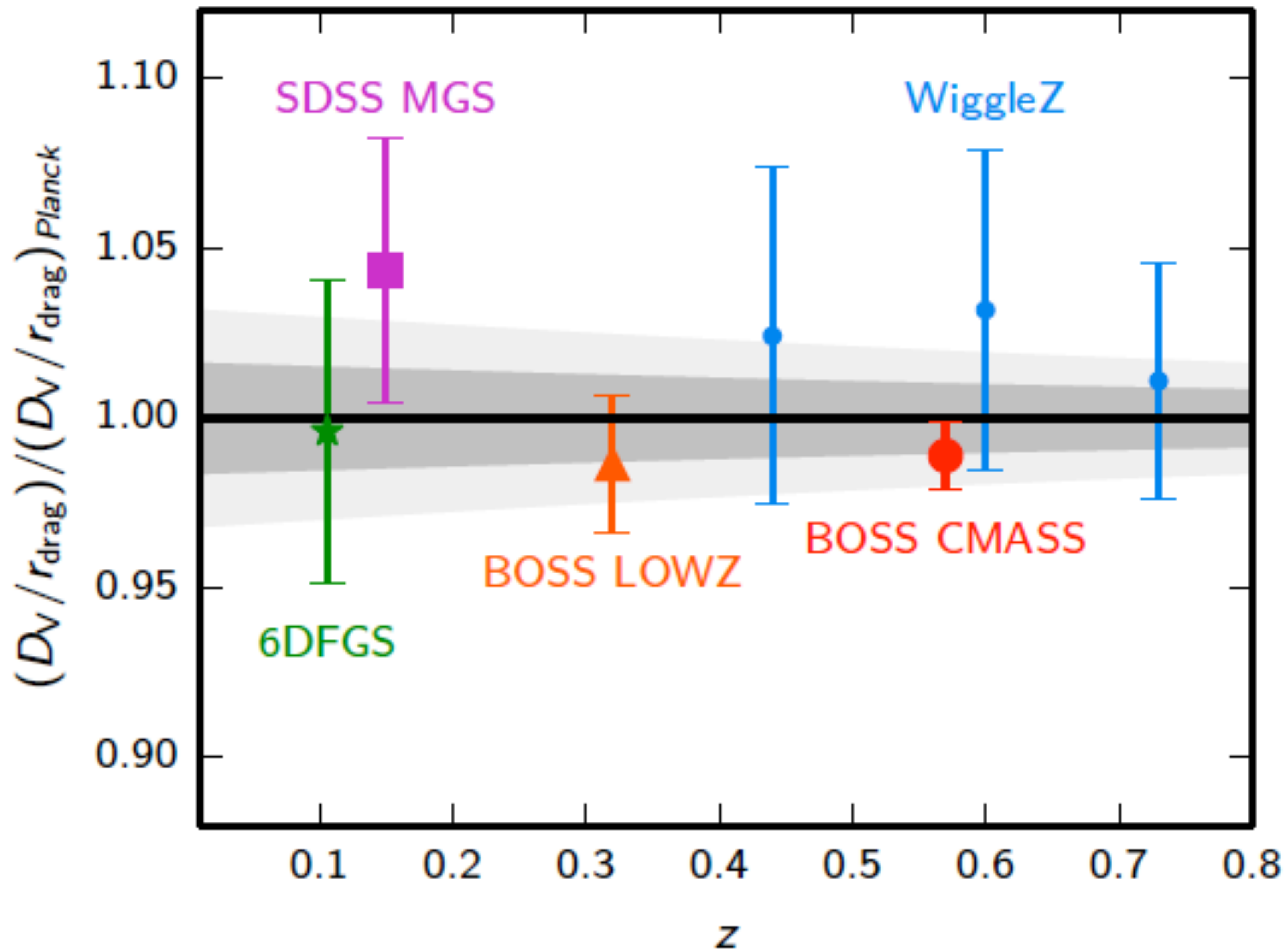
Critical density $\rho_c = 1.9 \times 10^{-26} h^2 \mathrm{kgm}^{-3}$ $\quad P_{DE} = w\rho_{DE}$

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

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: $D_A = \dfrac{D_L}{(1+z)^2}$

Dark Energy: BAO



$$D_{\mathrm{V}}(z) = \left[(1+z)^2 D_{\mathrm{A}}^2(z) \frac{cz}{H(z)}\right] .$$

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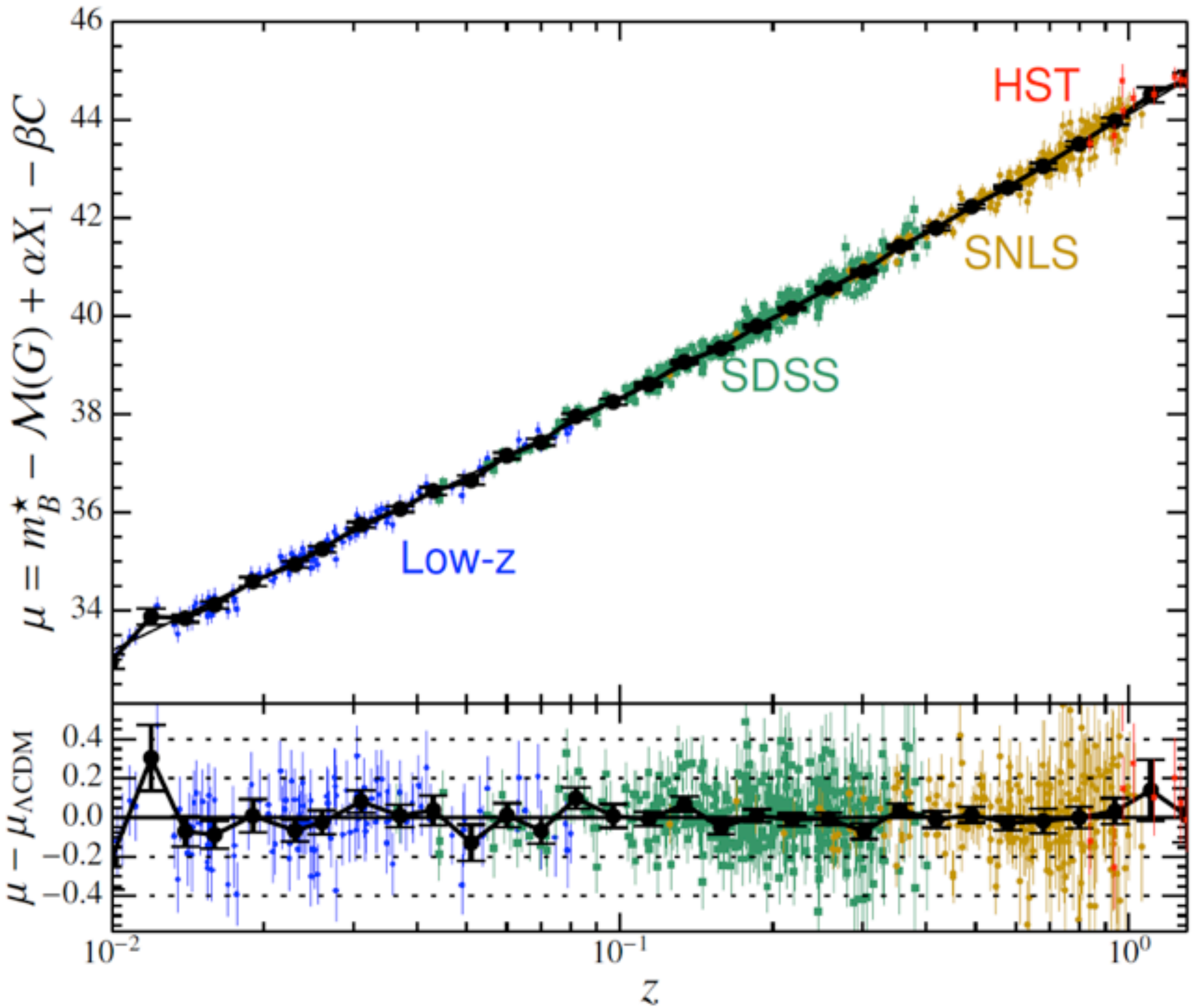
Dark Energy: Supernovae Ia

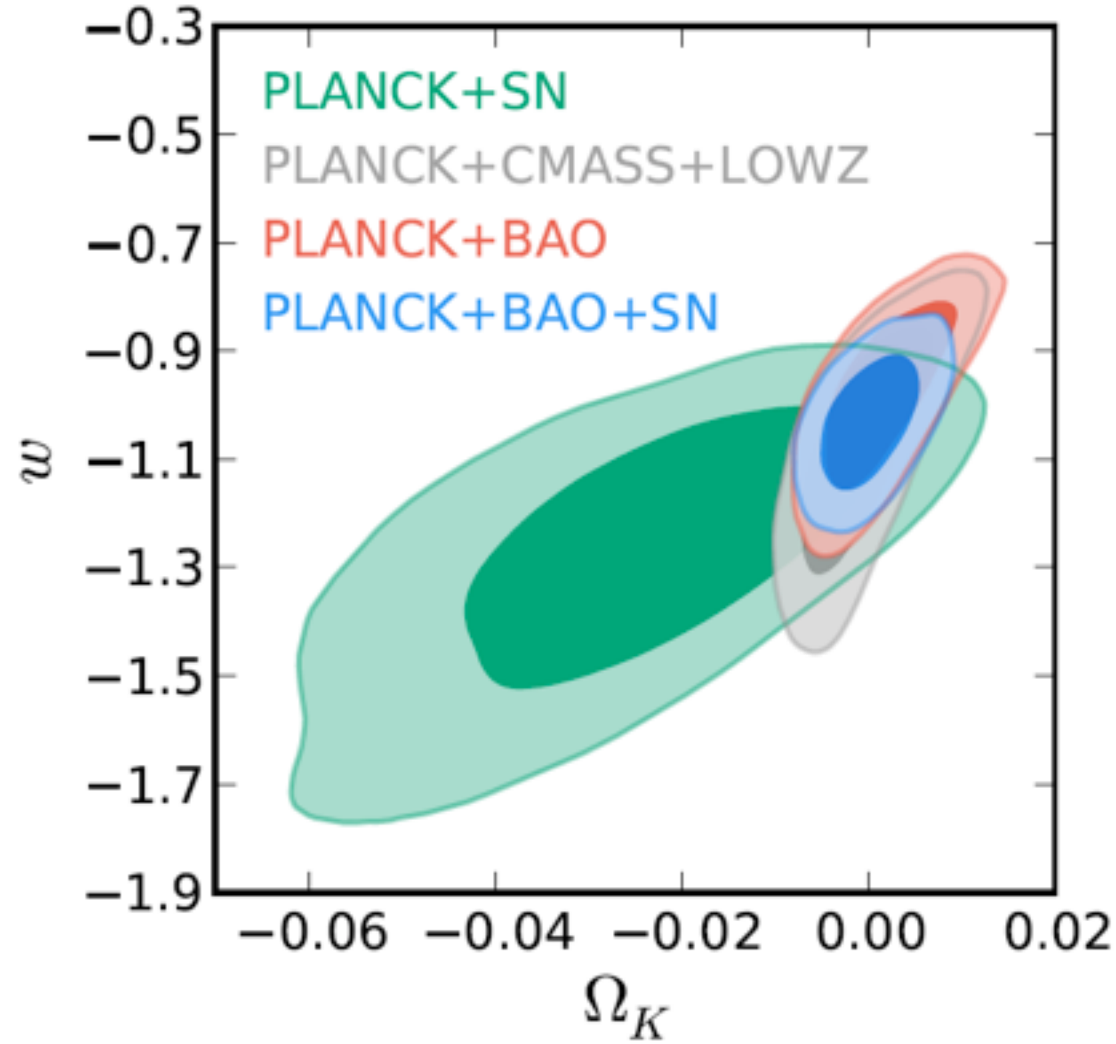


Betoule et al (2014)

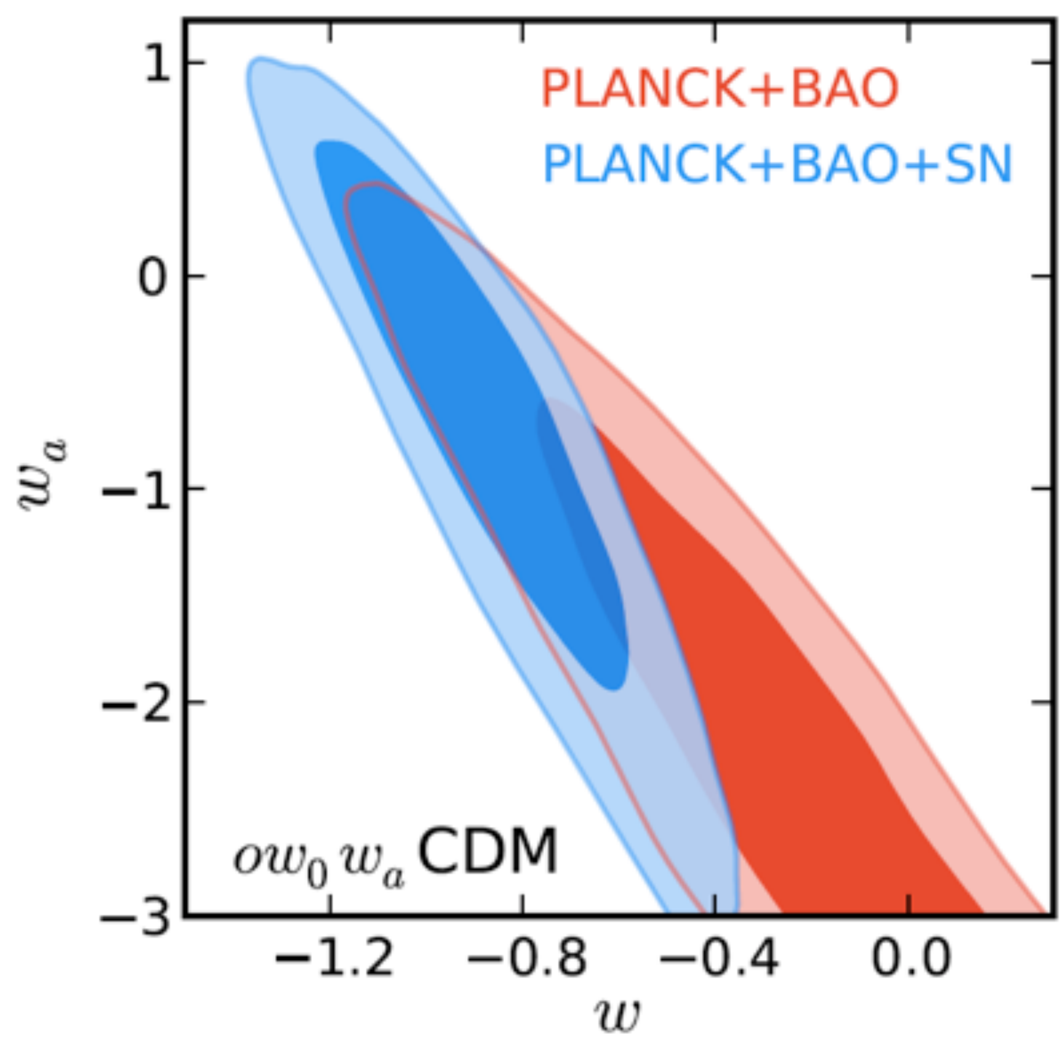
Dark Energy: CMB+SN+BAO

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

test of curvature



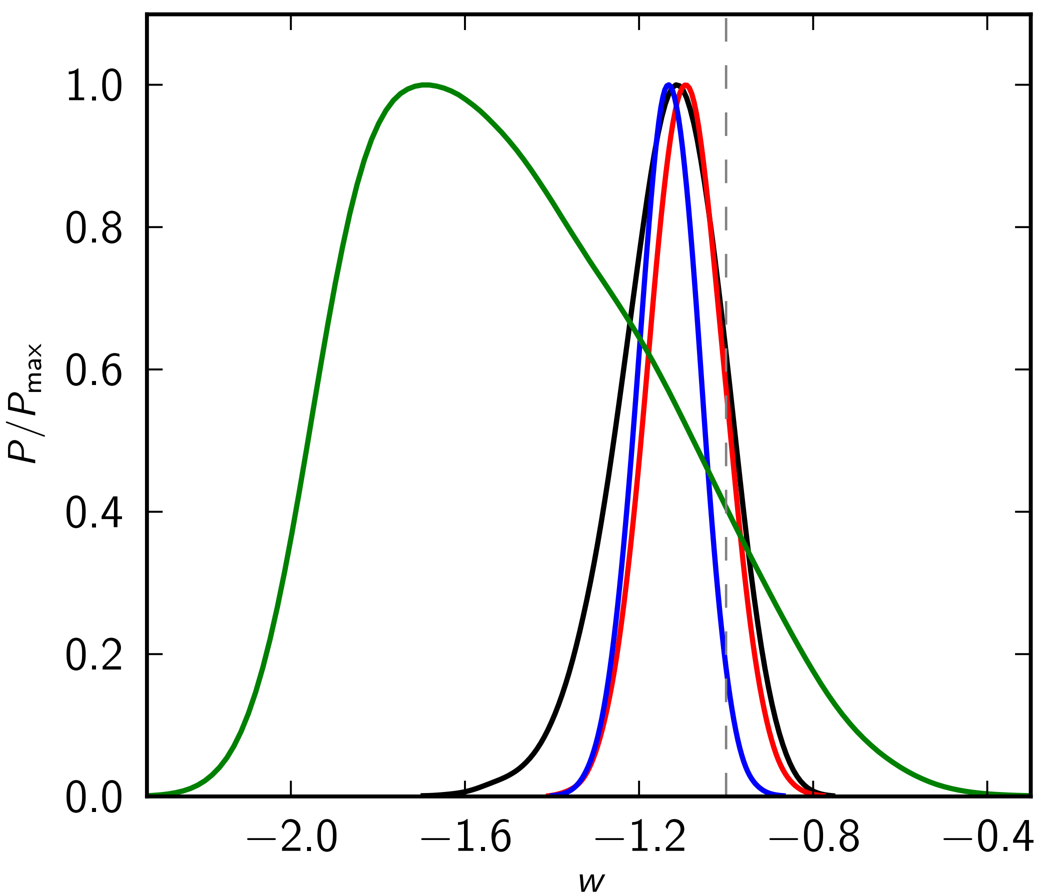
time evolution of equation of state



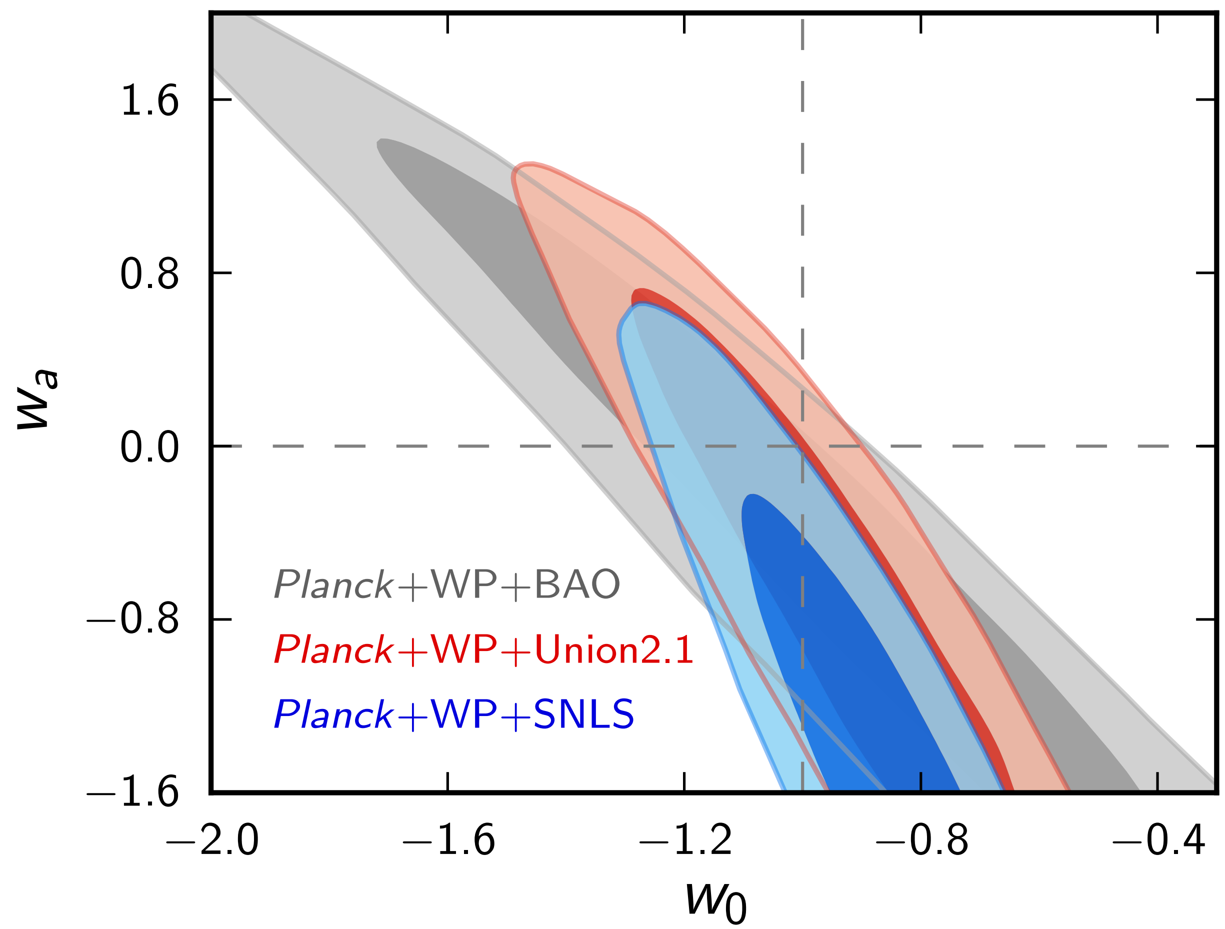
Anderson et al 2013

Dark Energy: CMB+SN+BAO

$w = \text{constant}$

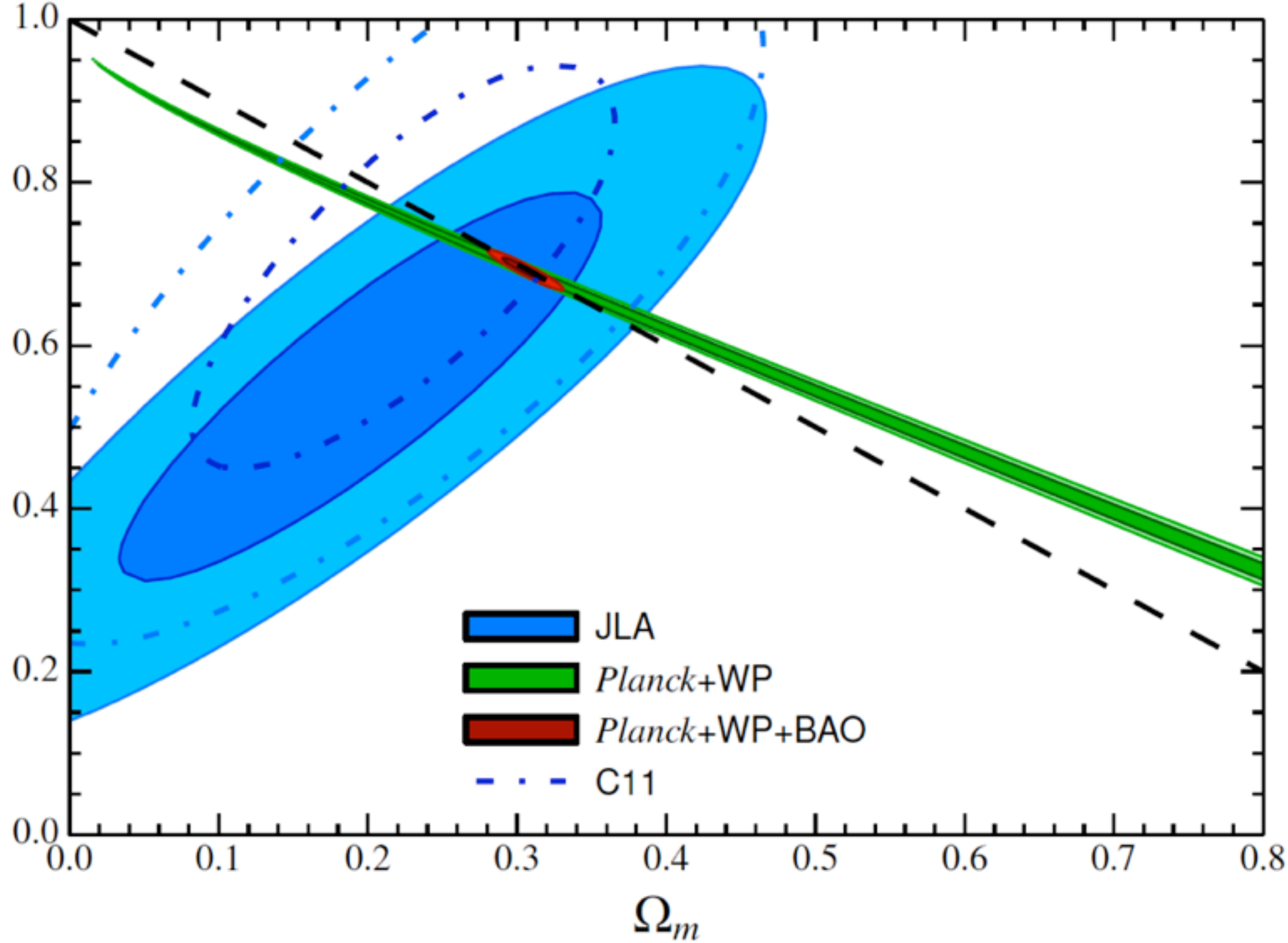


$w = w_0 + w_a(1 - a)$



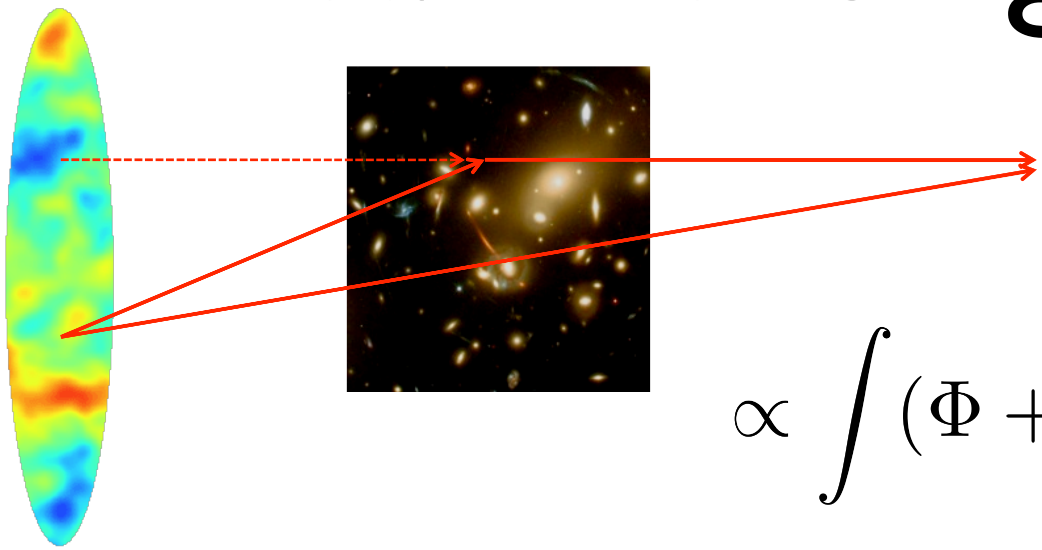
$$w = -1.13 \pm 0.12 \quad (68\% \text{ Planck} + \text{WMAP} + \text{BAO})$$

Dark Energy: CMB+SN+BAO

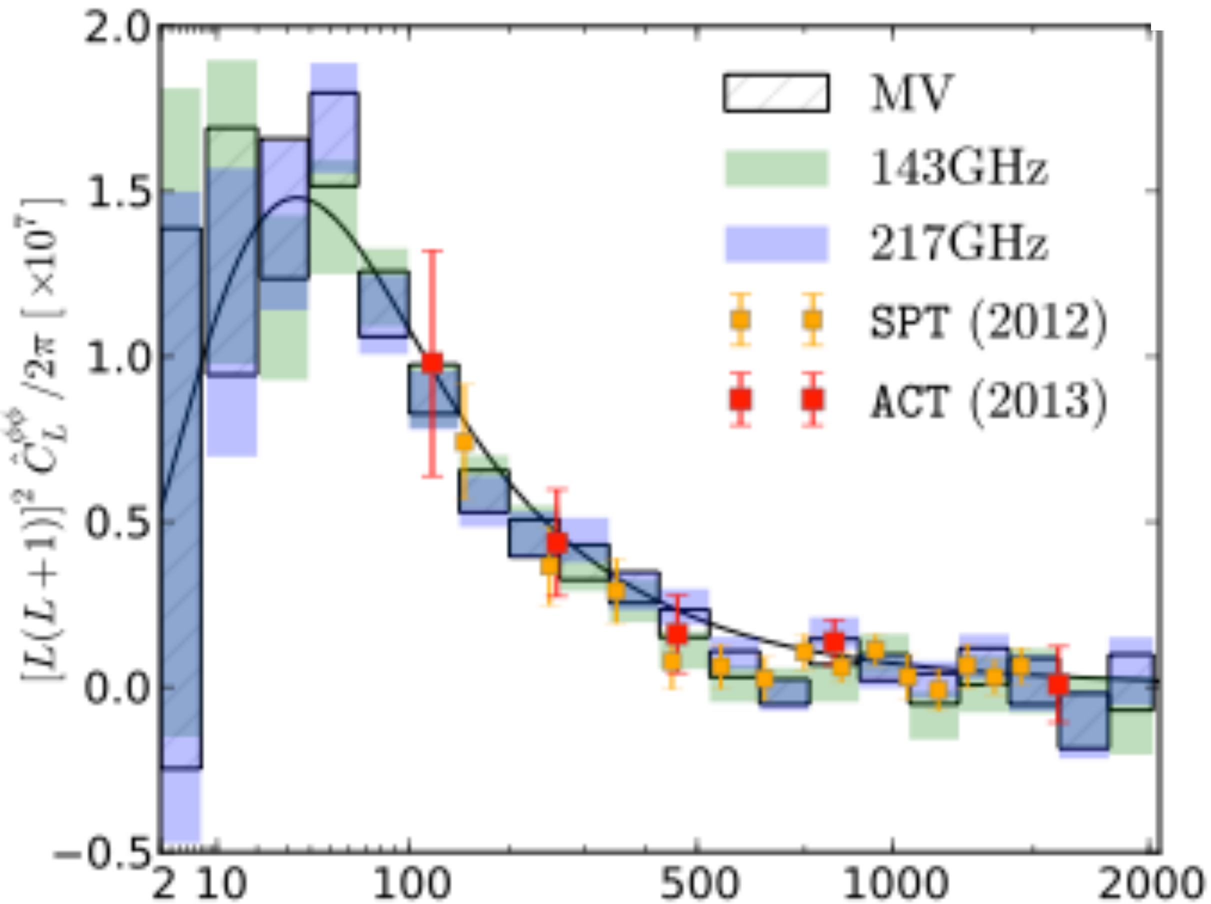


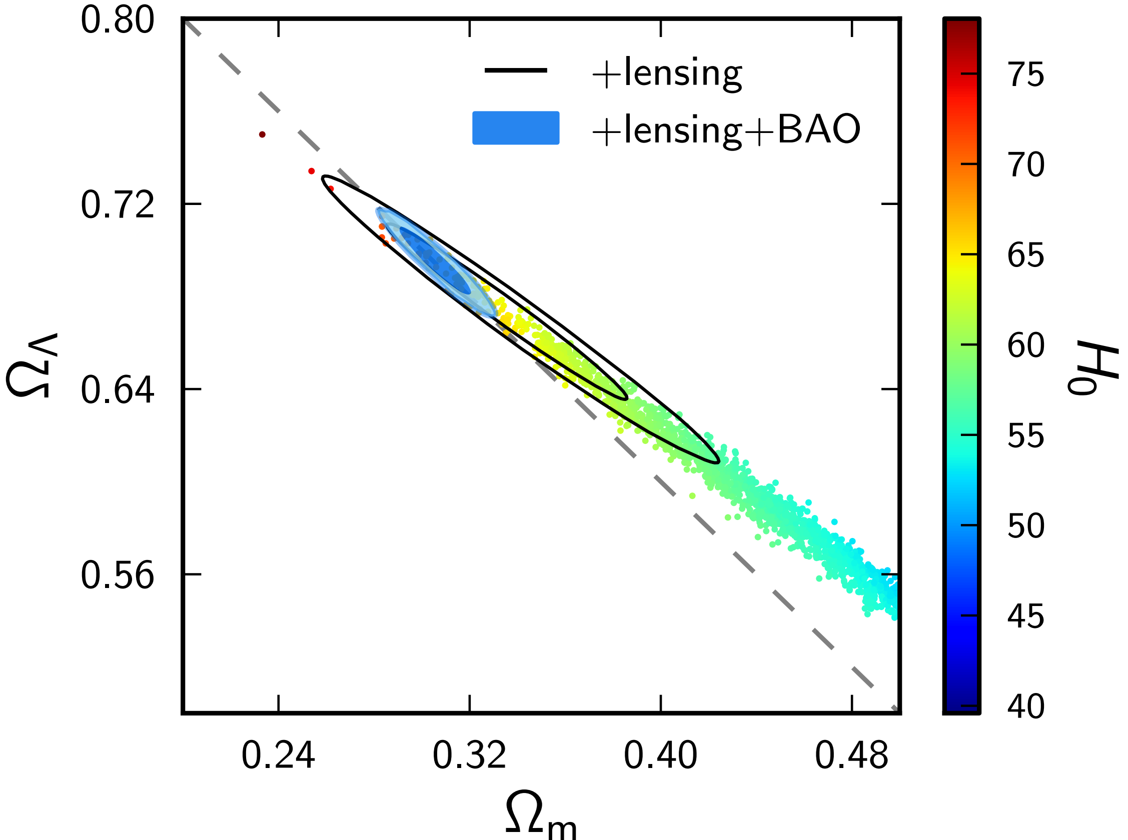
Dark Energy: CMB Weak Lensing

Measure curvature and Λ from CMB alone!



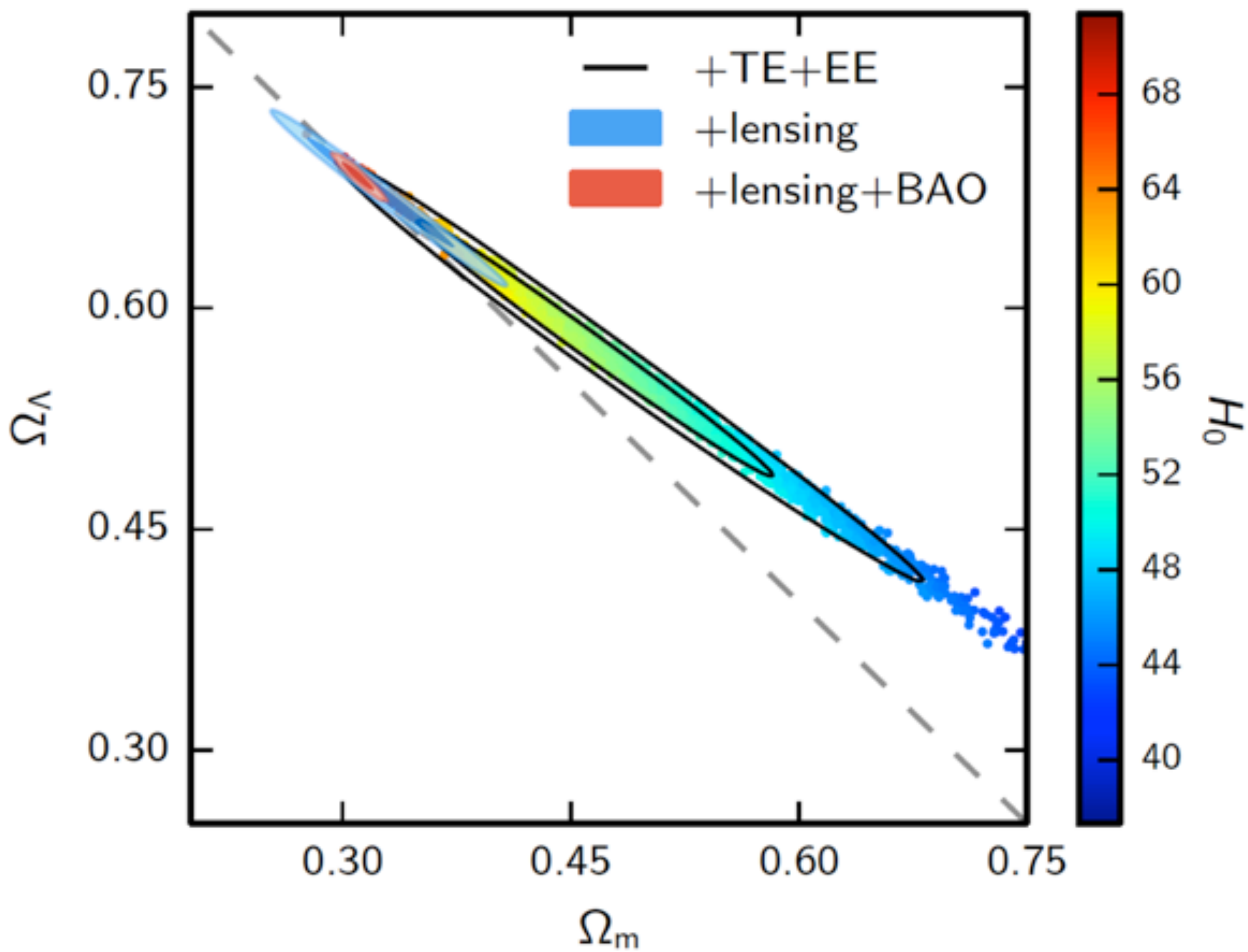
$$\propto \int (\Phi + \Psi) d\eta$$





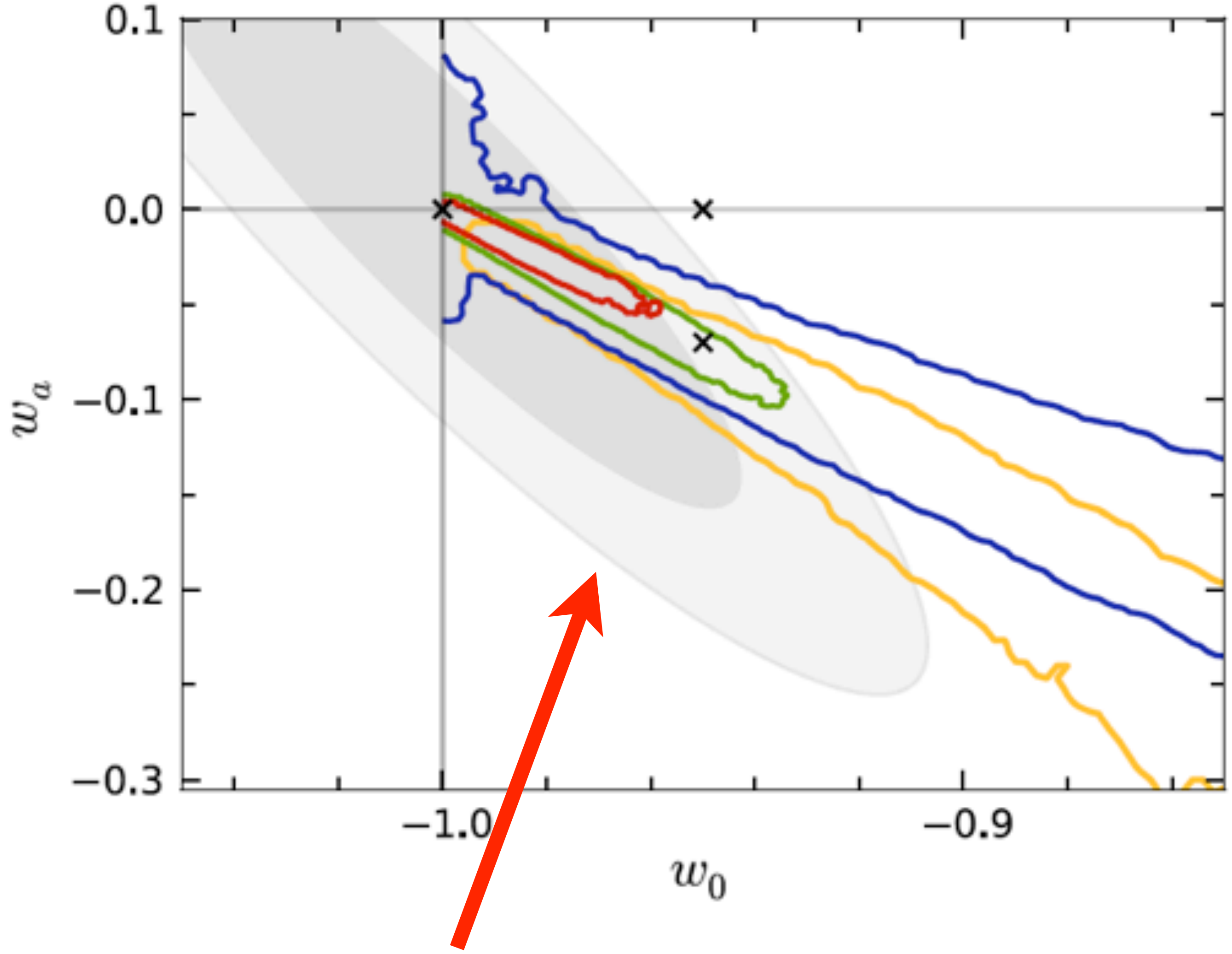
Planck 2013

Dark Energy: CMB Weak Lensing



$$\Omega_k = -0.005^{+0.016}_{-0.017}$$

Dark Energy: model discrimination



Forecast precision of Stage IV survey

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

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

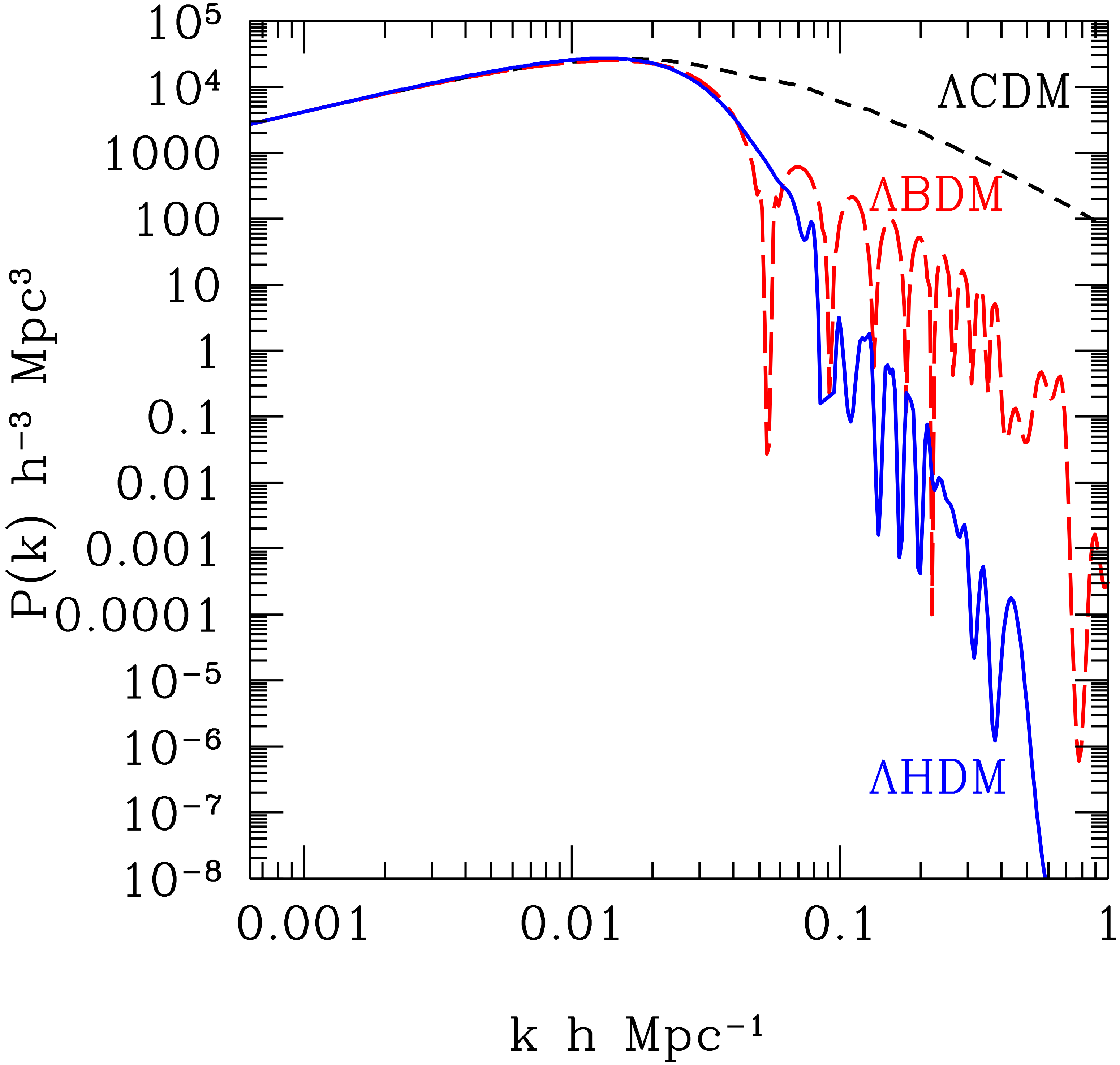
Model	$b_n(\phi)$	c_n	$n_{\min}$	$f(\phi)$	ϕ_i
Kac	ϕ^n	1	1	0	$[-1, 1]$
Weyl	ϕ^n	$1/\sqrt{n!}$	1	0	$[-1, 1]$
Monomial	0	...	...	ϕ^N	[0,4]
EFT	ϕ^n	$(\epsilon_F)^n$	p_E	$\xi_2 \epsilon_F^2 \phi^2 + \xi_4 \epsilon_F^4 \phi^4$	$[-\epsilon_F^{-1}, \epsilon_F^{-1}]$
Axion	$\cos(n \epsilon_F \phi)$	$(\epsilon_{NP})^{n-1}$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

Marsh et al (2014)

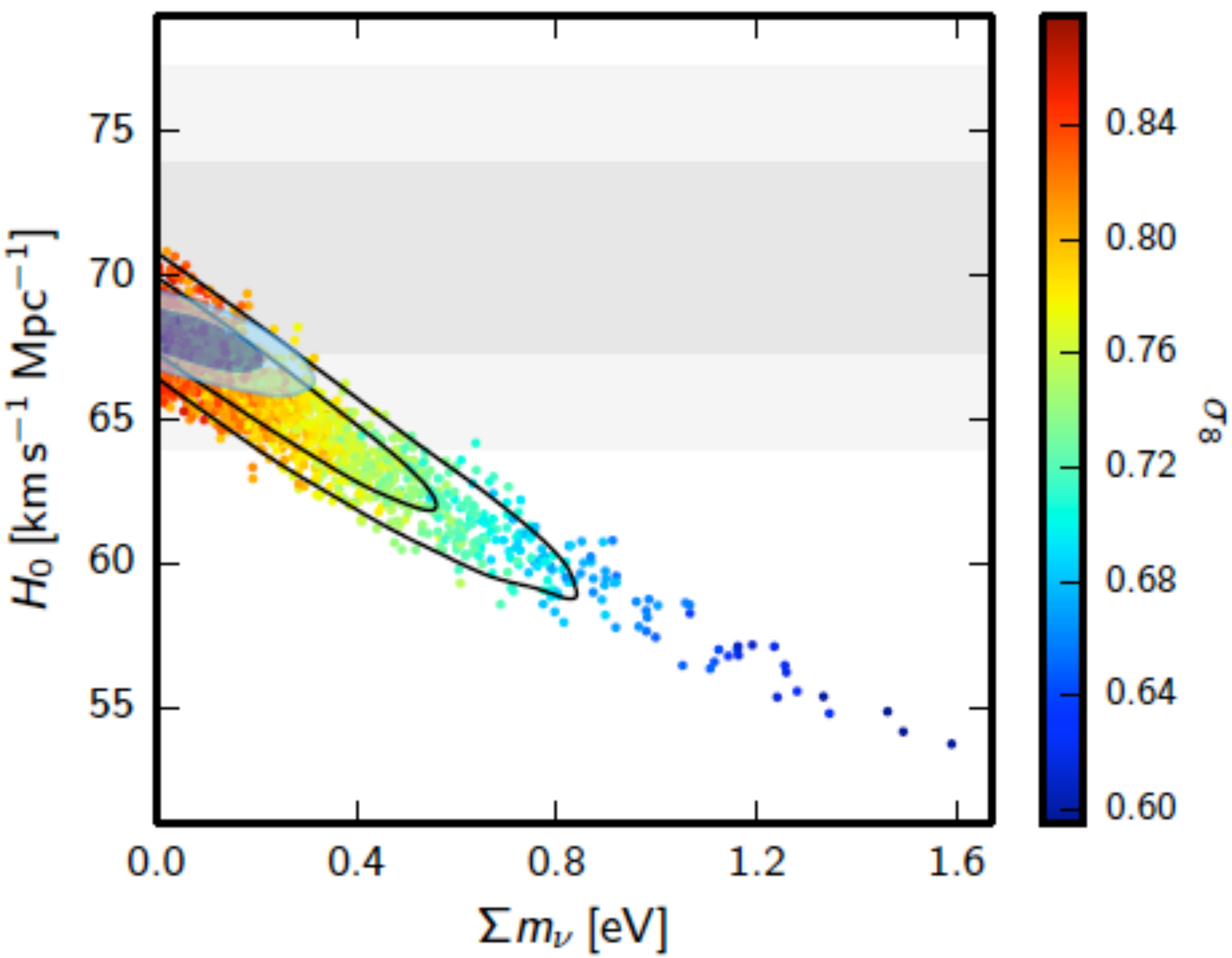
Dark Energy: model discrimination

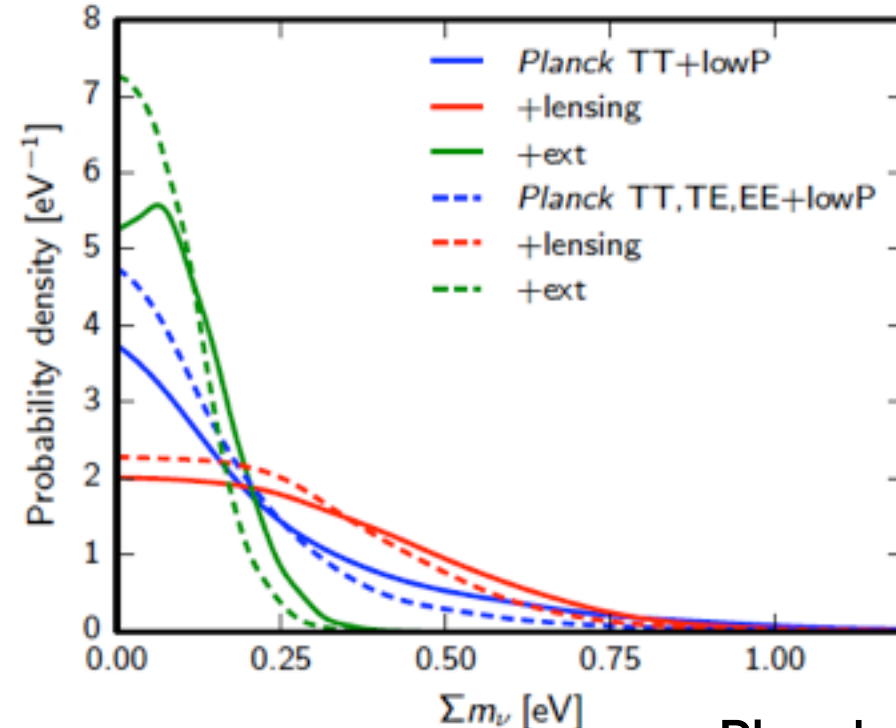
- Overwhelming evidence for dark energy.
- Different probes are orthogonal.
- Modest constraints on the equation of state.
- Will it be possible to discriminate between models?

Ultra light fields: Neutrinos

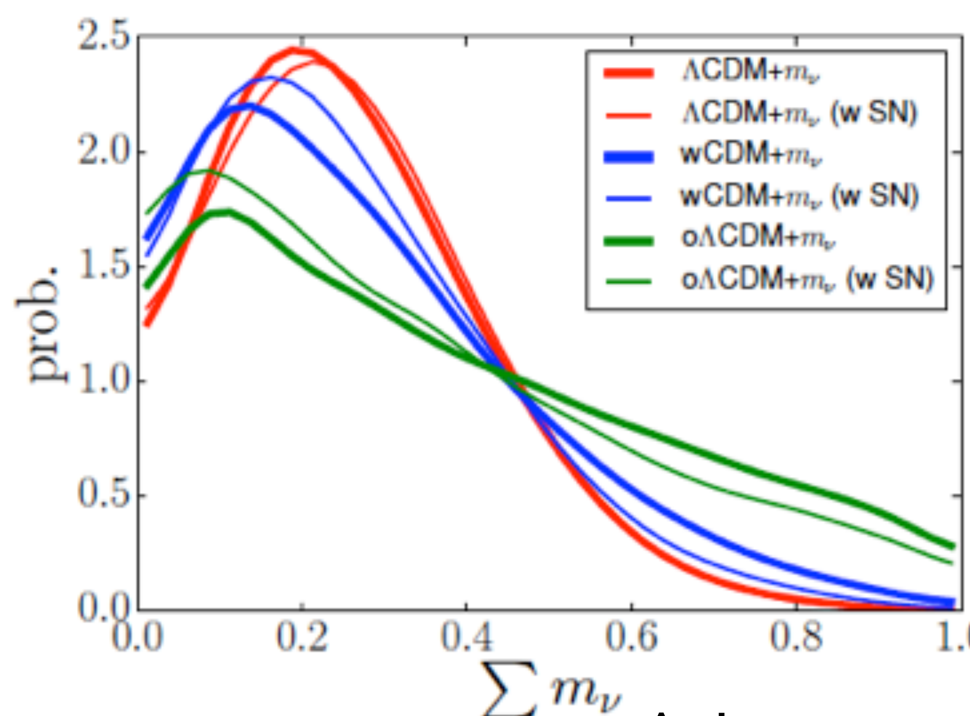


Ultra light fields: Neutrinos (mass)



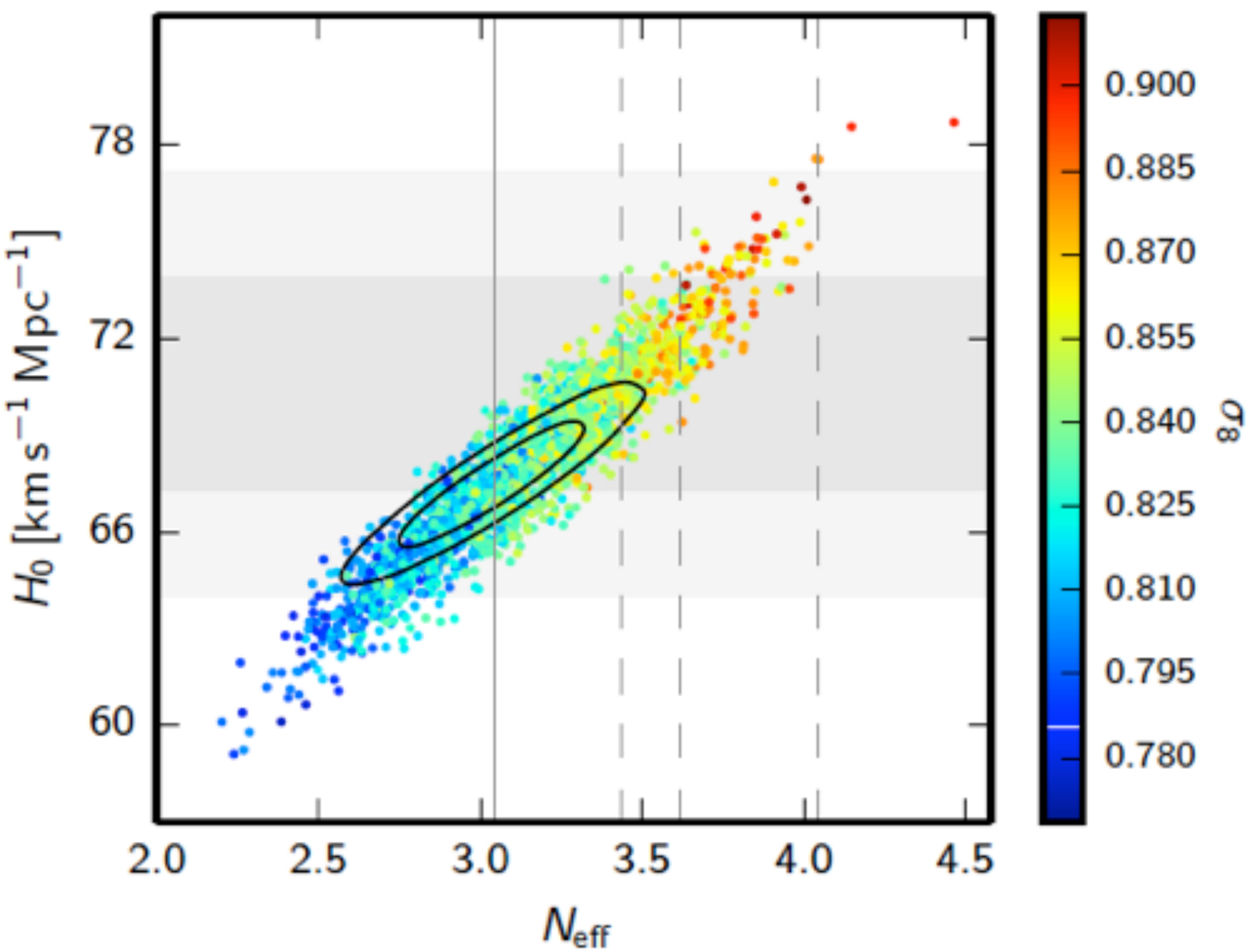


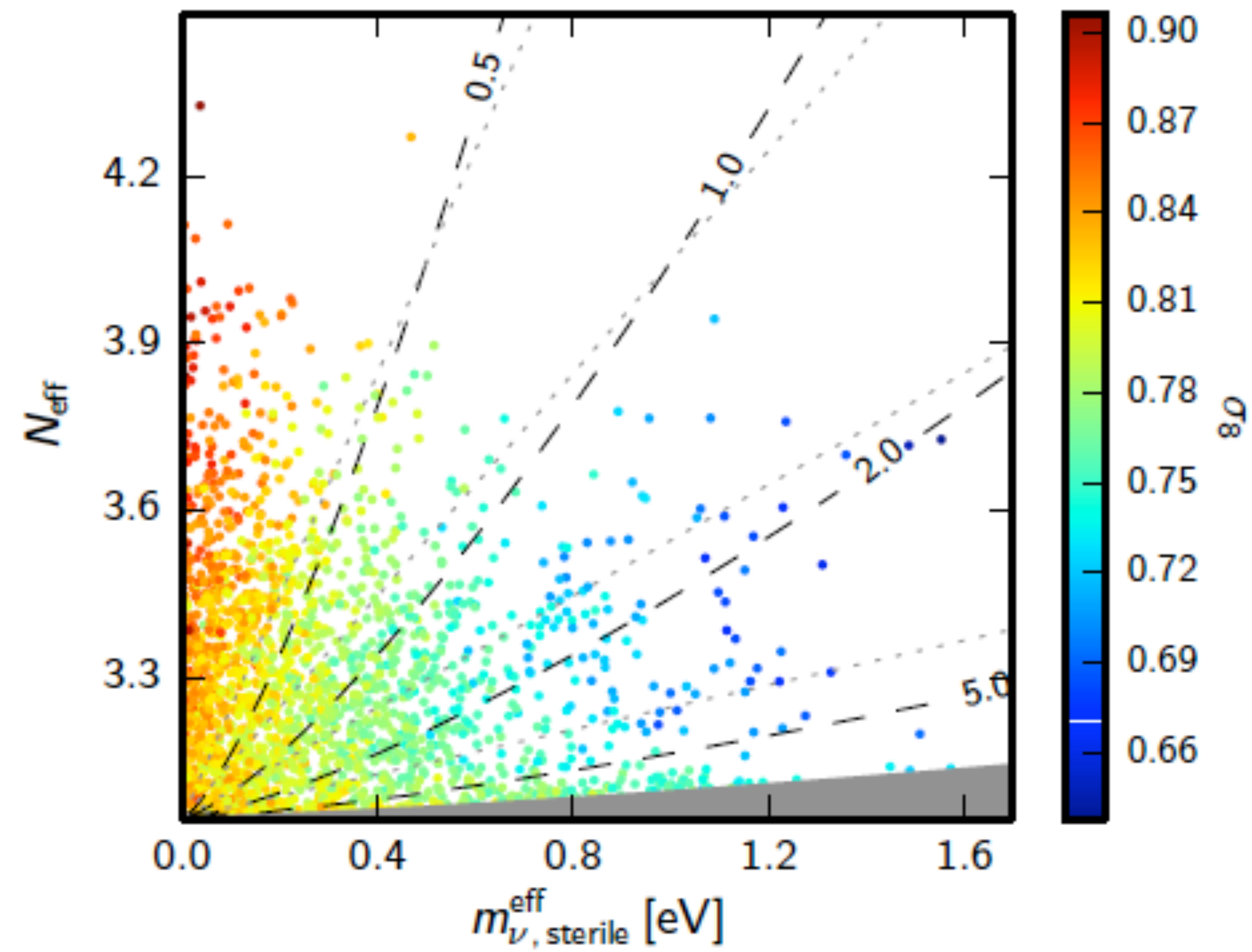
Planck 2015



Aubourg et al (2014)

Ultra light fields: Neutrinos (number)

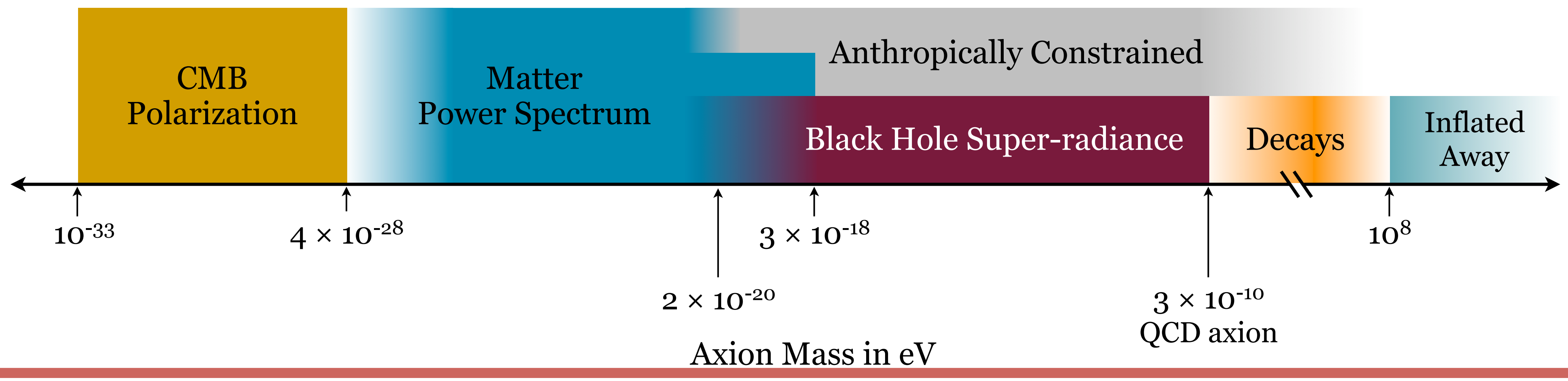




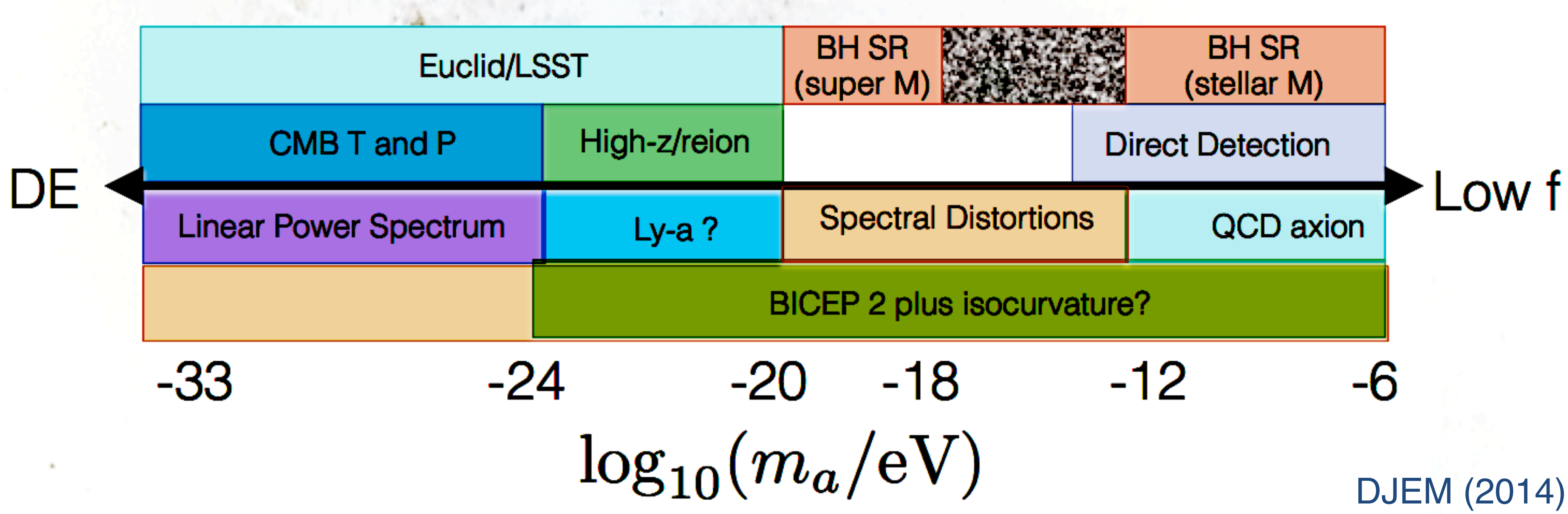
Planck 2015

$$\rho = N_{\rm eff}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma$$

Ultra light fields: ultra-light axions

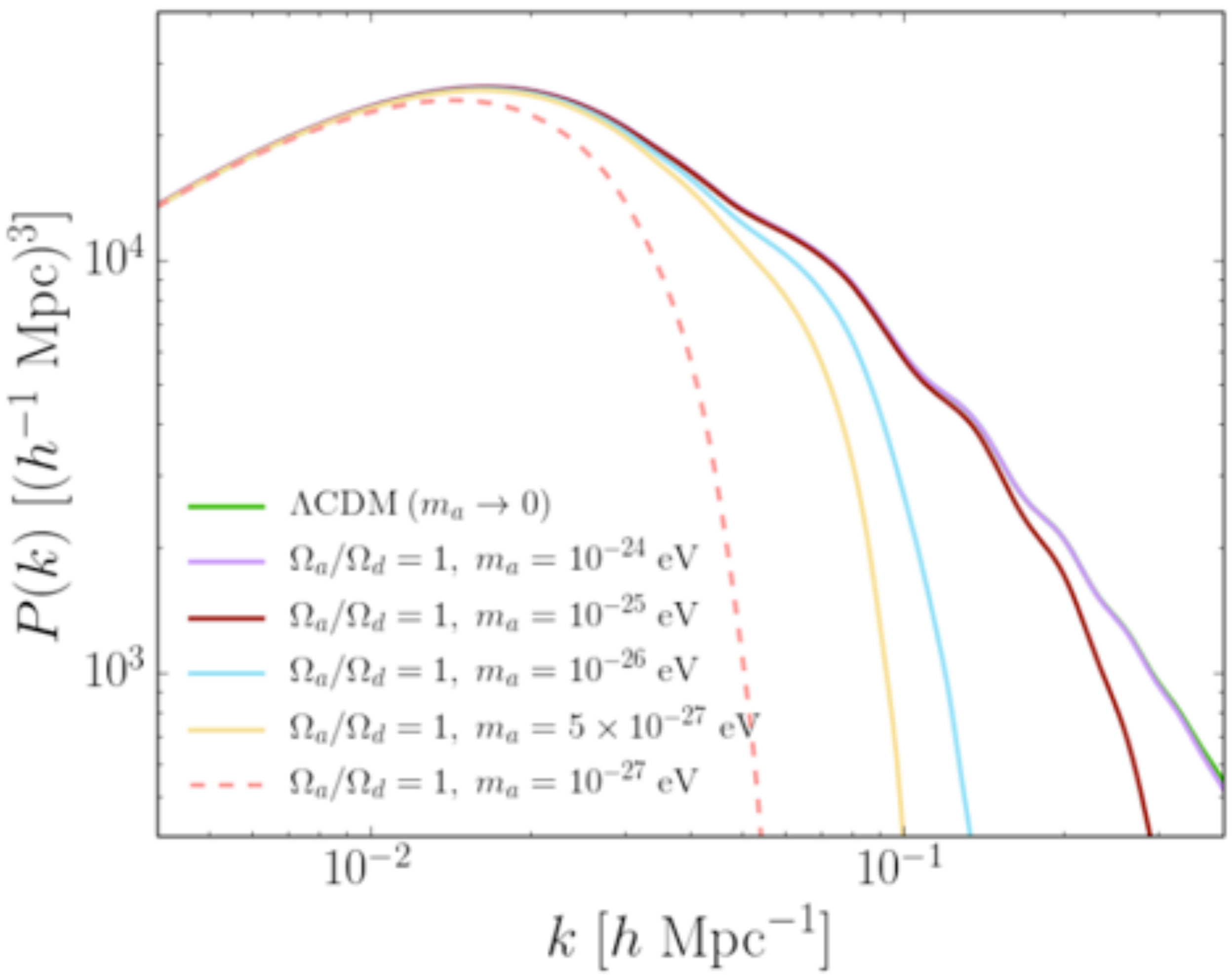


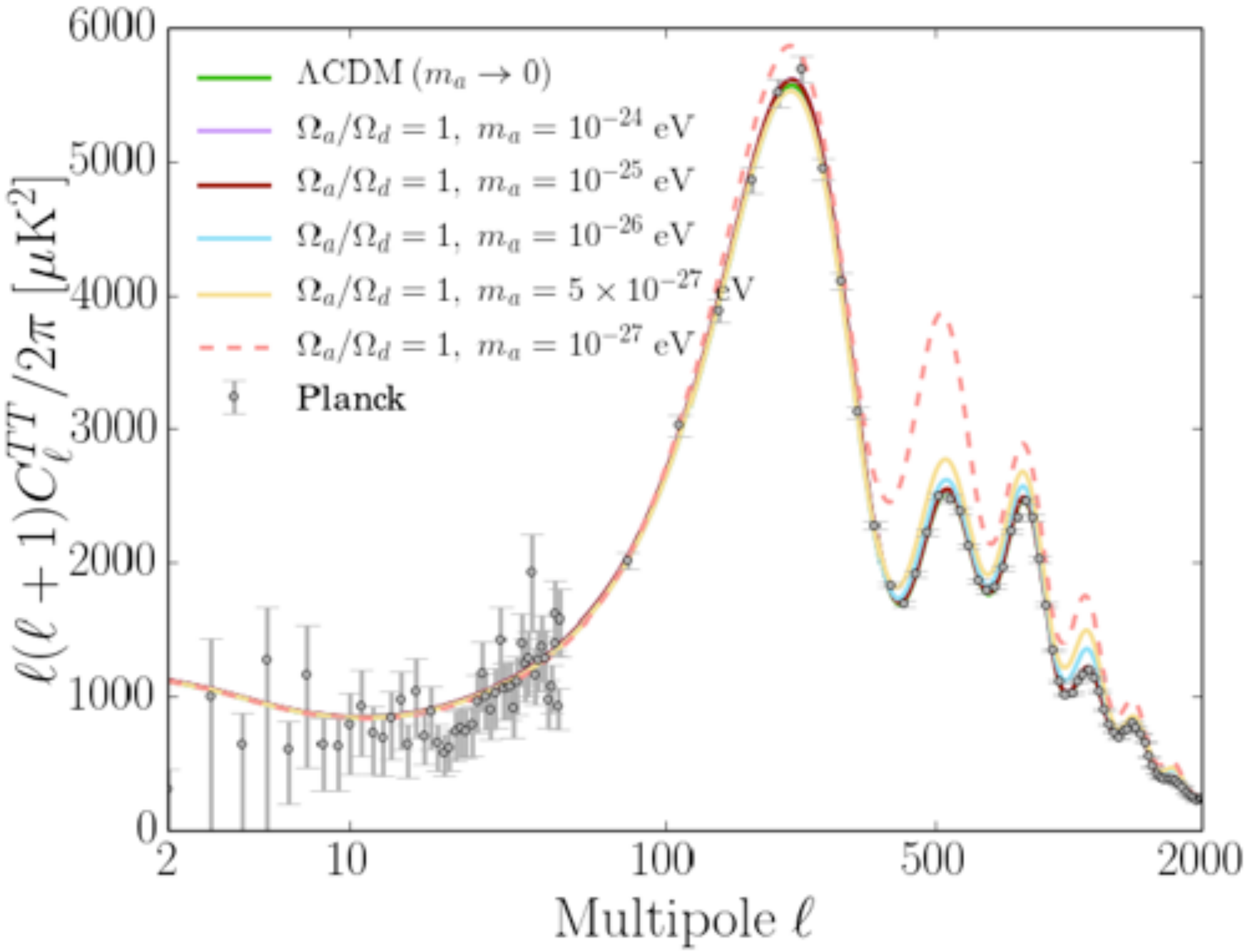
Arvanitaki et al (2009)



DJEM (2014)

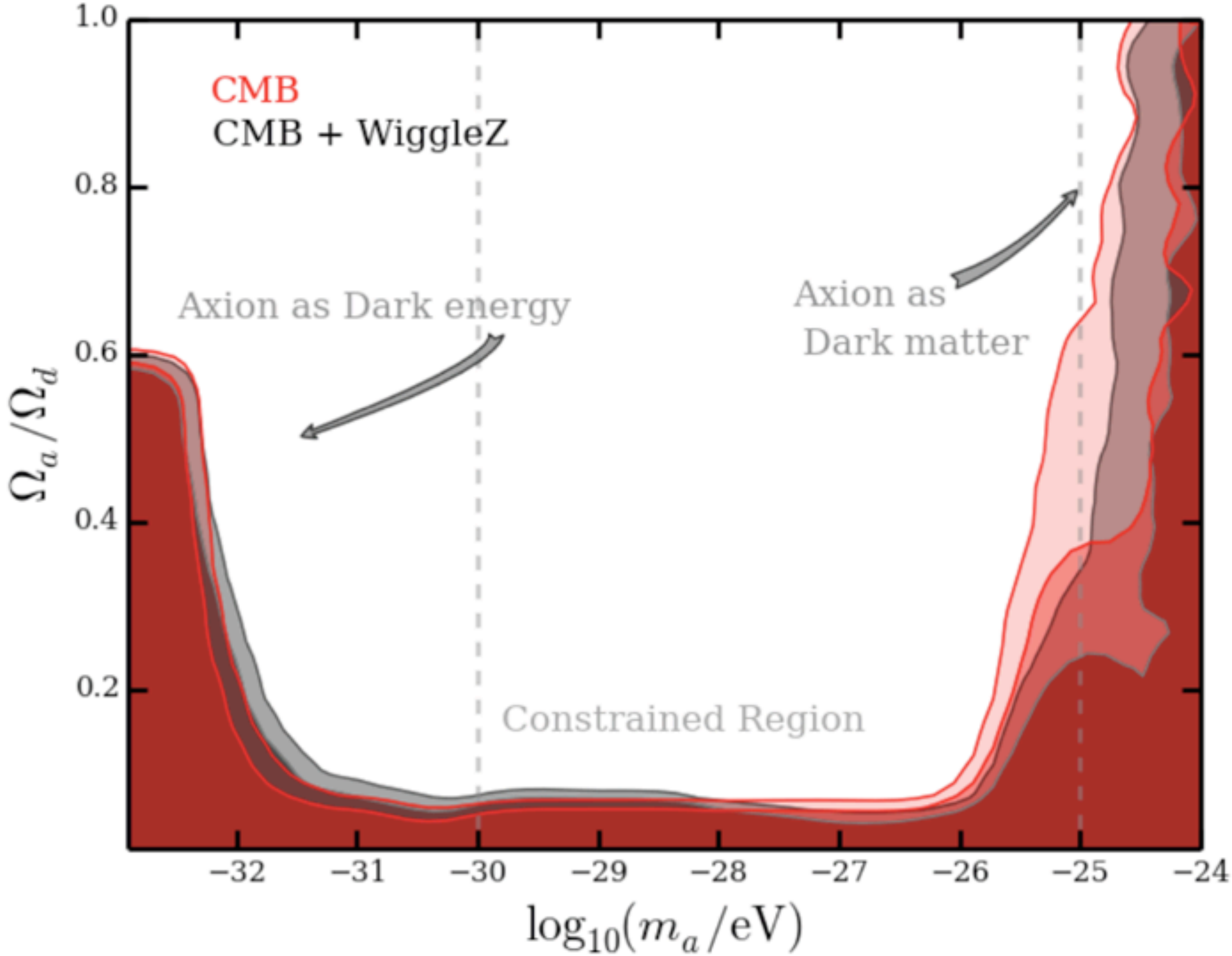
Ultra light fields: ultra-light axions





Marsh et al (2014)

Ultra light fields: ultra-light axions

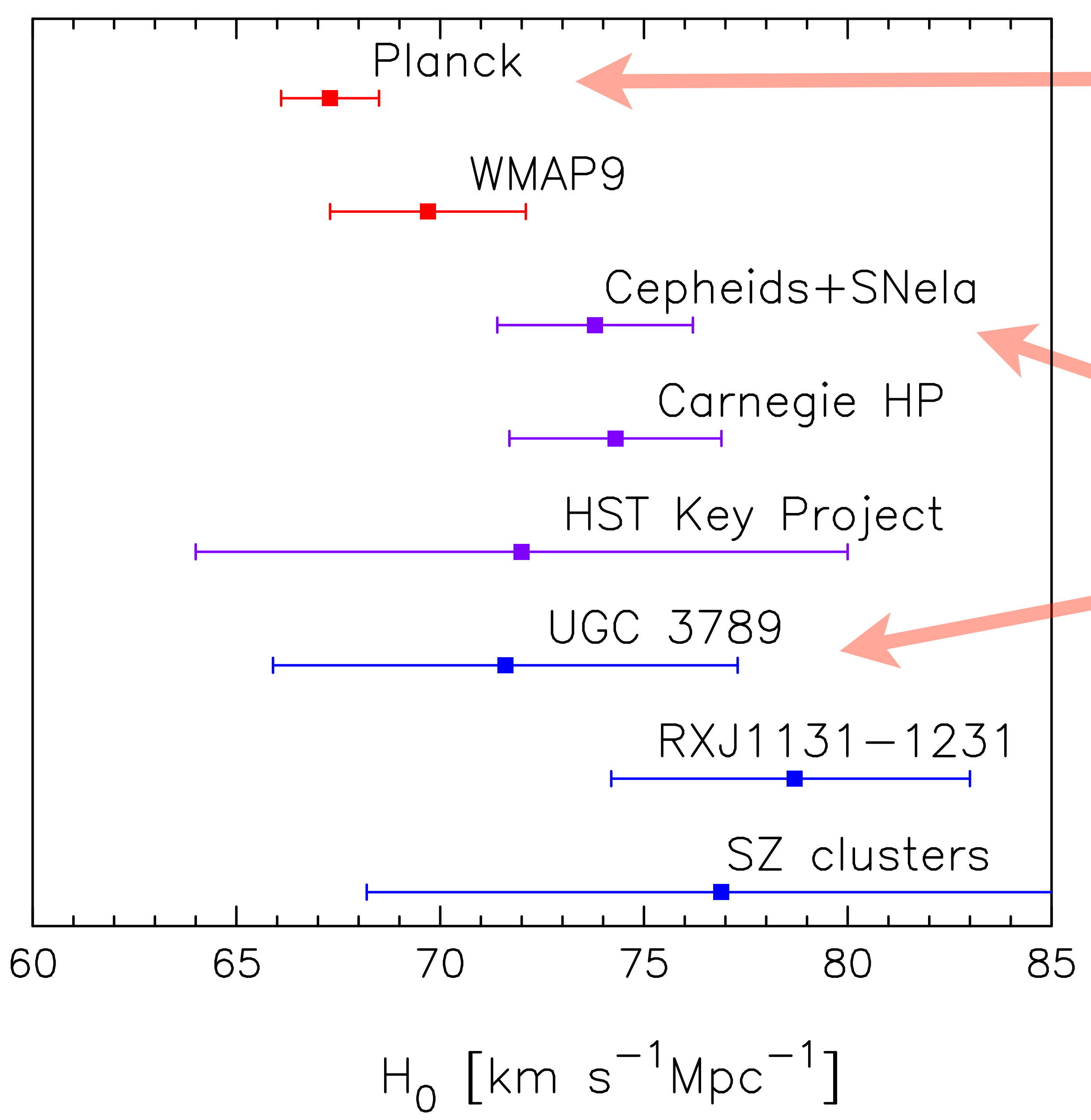


Marsh et al (2014)

Ultra light fields

- Strong effects from ultra-relativistic fields.
- Tight constraints on fundamental parameters.
- Most promising route in the near future.

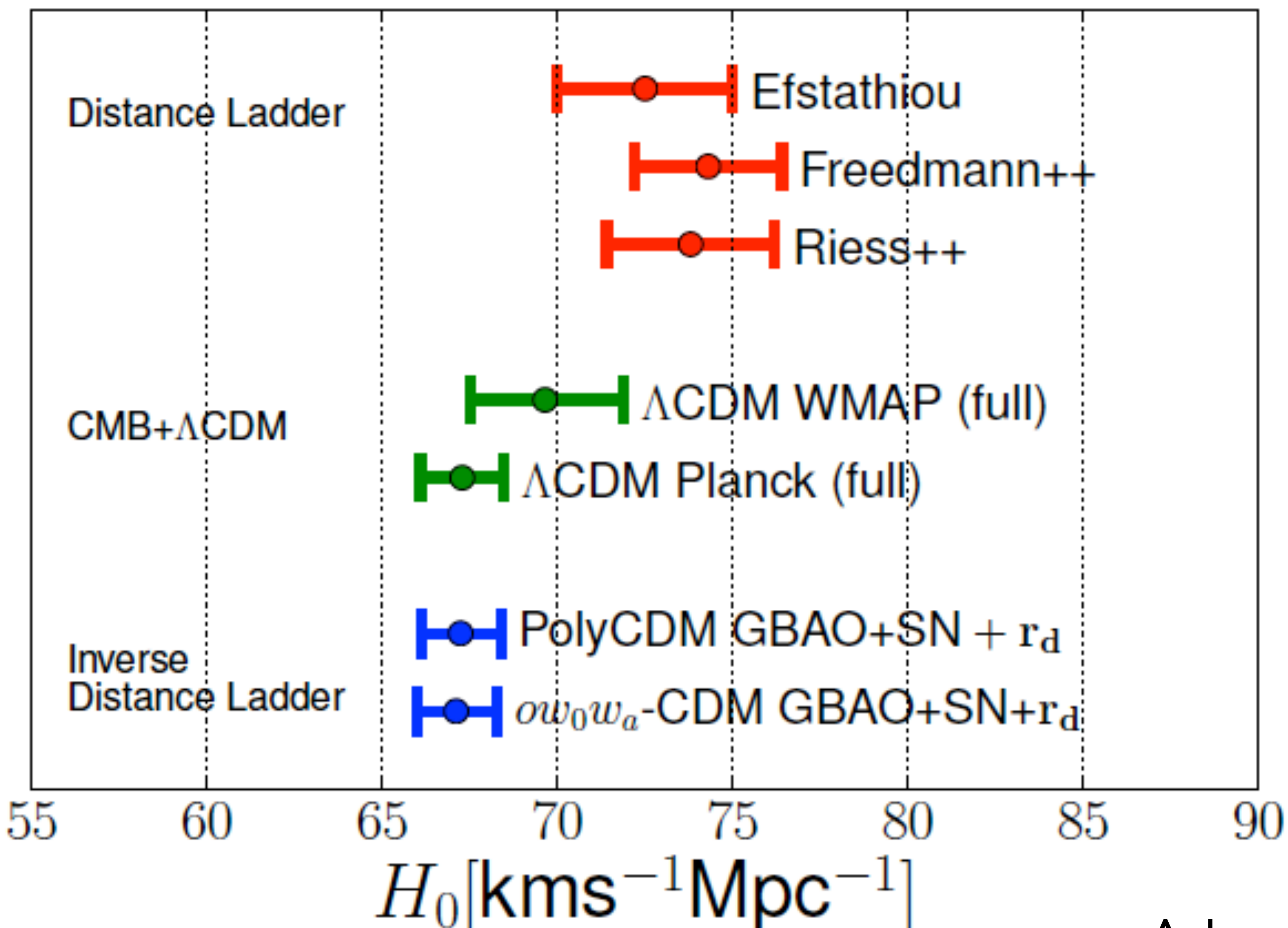
Inconsistencies: Hubble Constant



Mild tension with the CMB

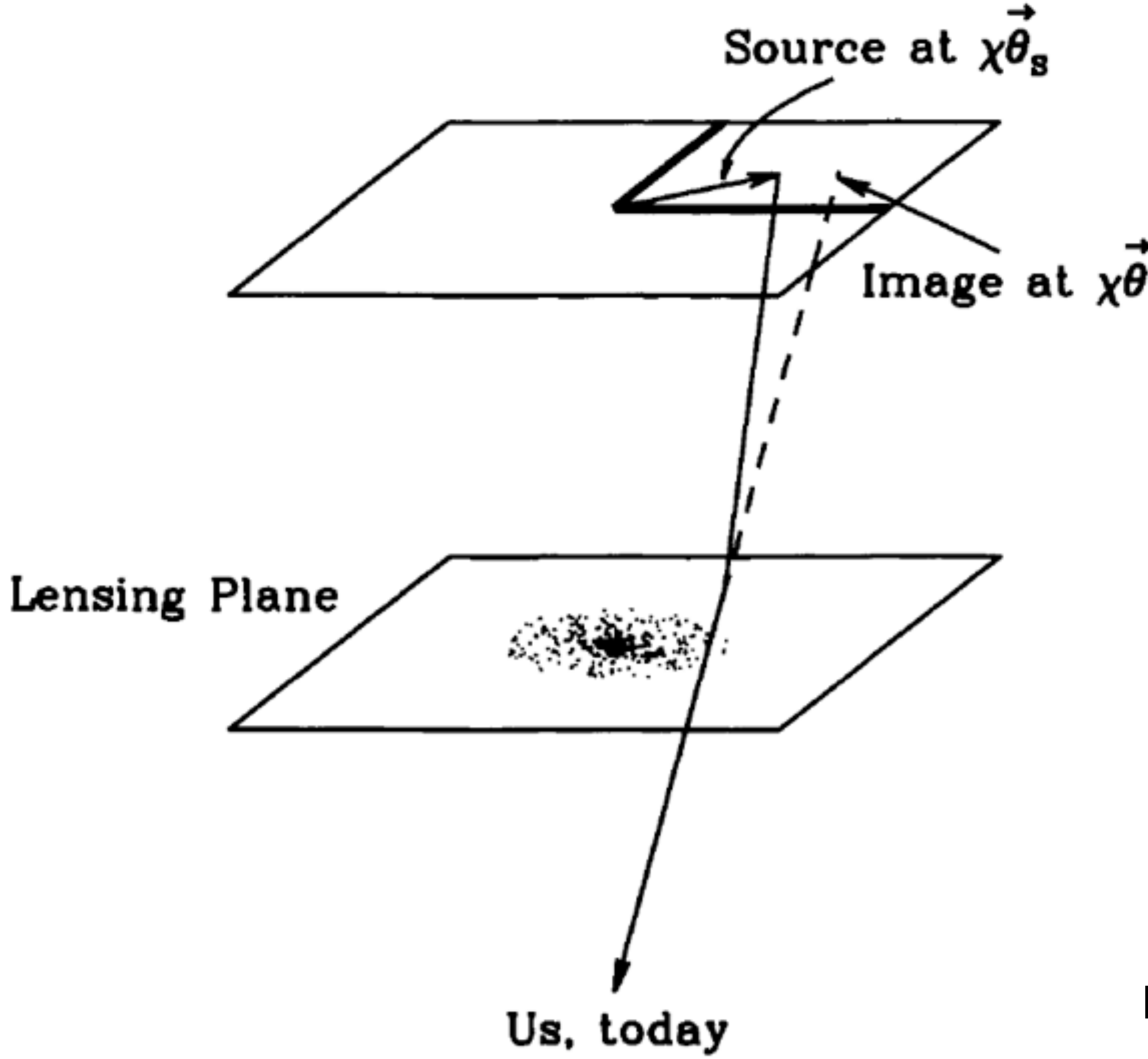
NGC4258 and UGC at 50 Mpc have been revised down

Inconsistencies: Hubble Constant



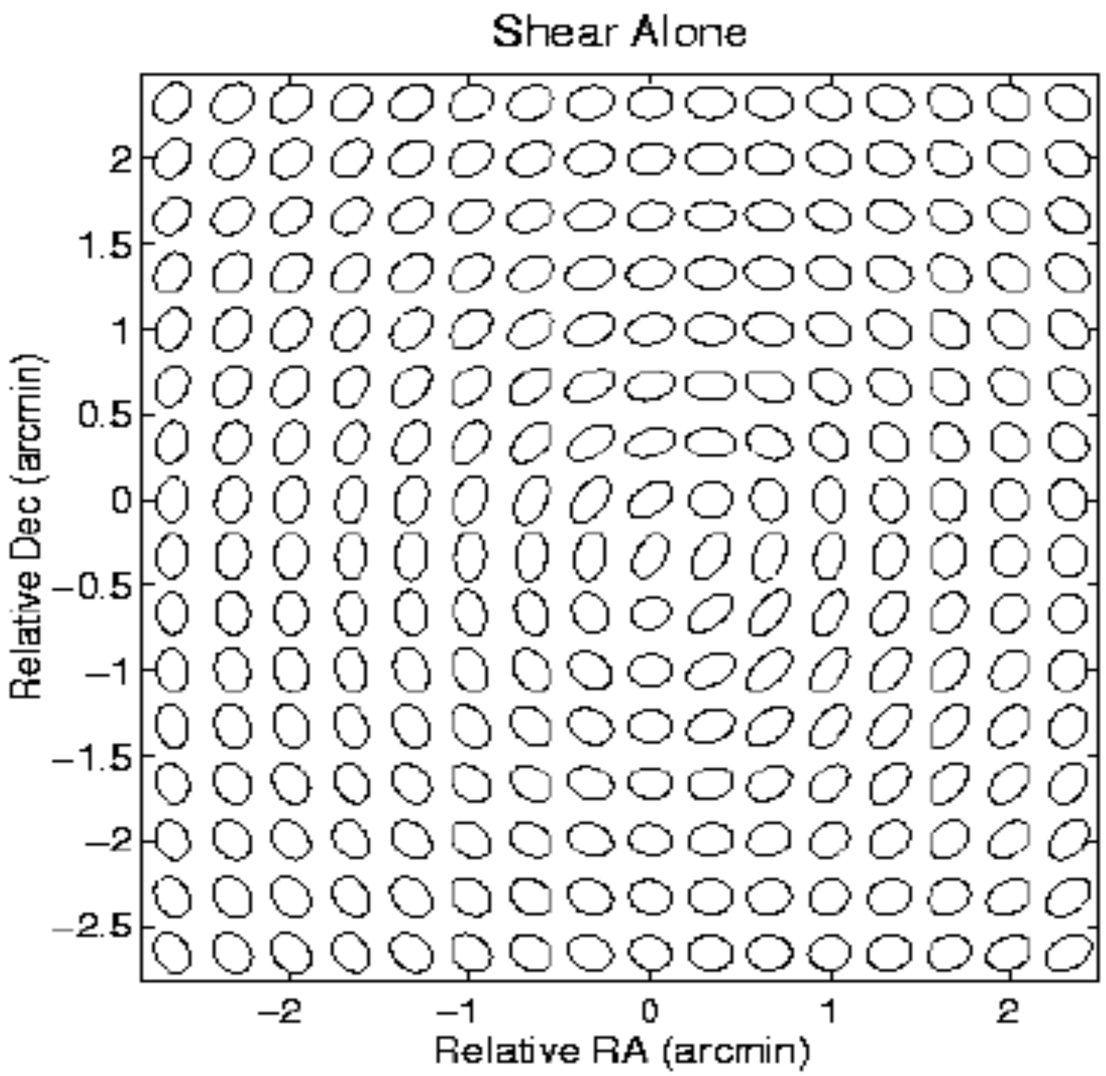
Aubourg 2014

Inconsistencies: Weak Lensing



Dodelson (2003)

Inconsistencies: Weak Lensing



distortion tensor

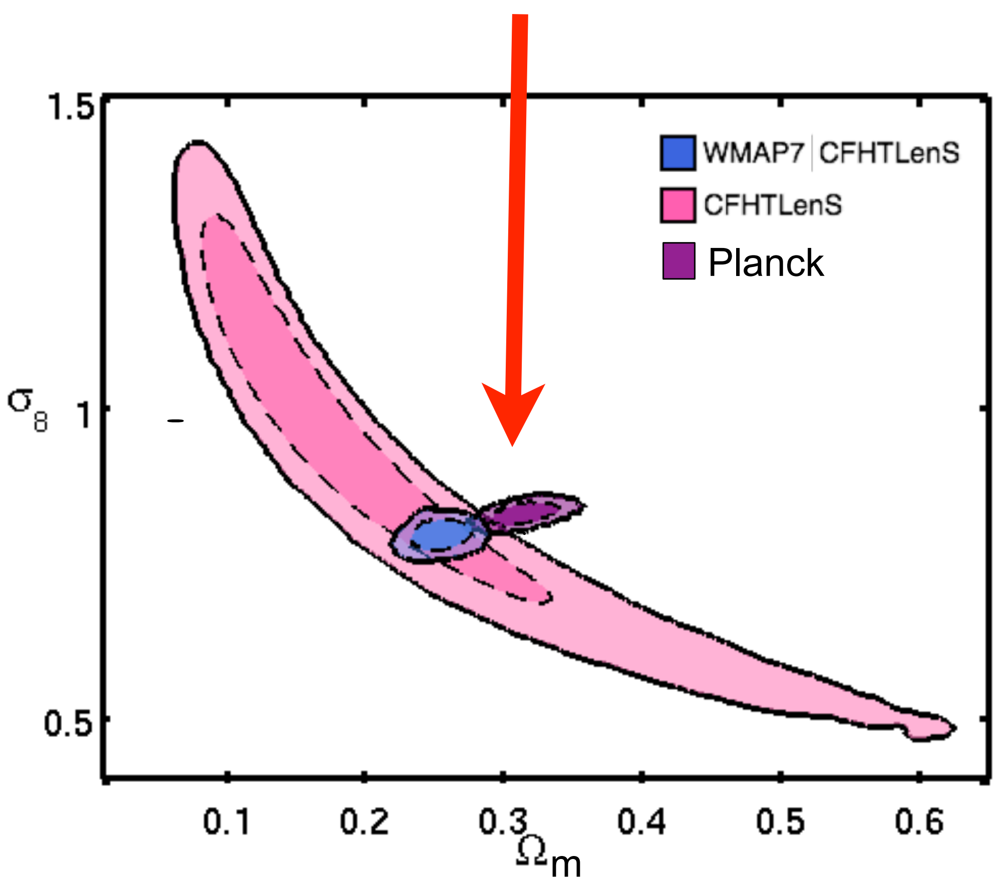
$$\psi_{ij}(\vec{\theta}) = \frac{1}{2}\int_0^{\chi_\infty} d\chi \partial_i \partial_j [\Psi + \Psi](\vec{x}(\chi)) g(\chi)$$

$$g(\chi) = 2\chi \int_\chi^{\chi_\infty} d\chi' \left(1 - \frac{\chi}{\chi'}\right) W(\chi')$$

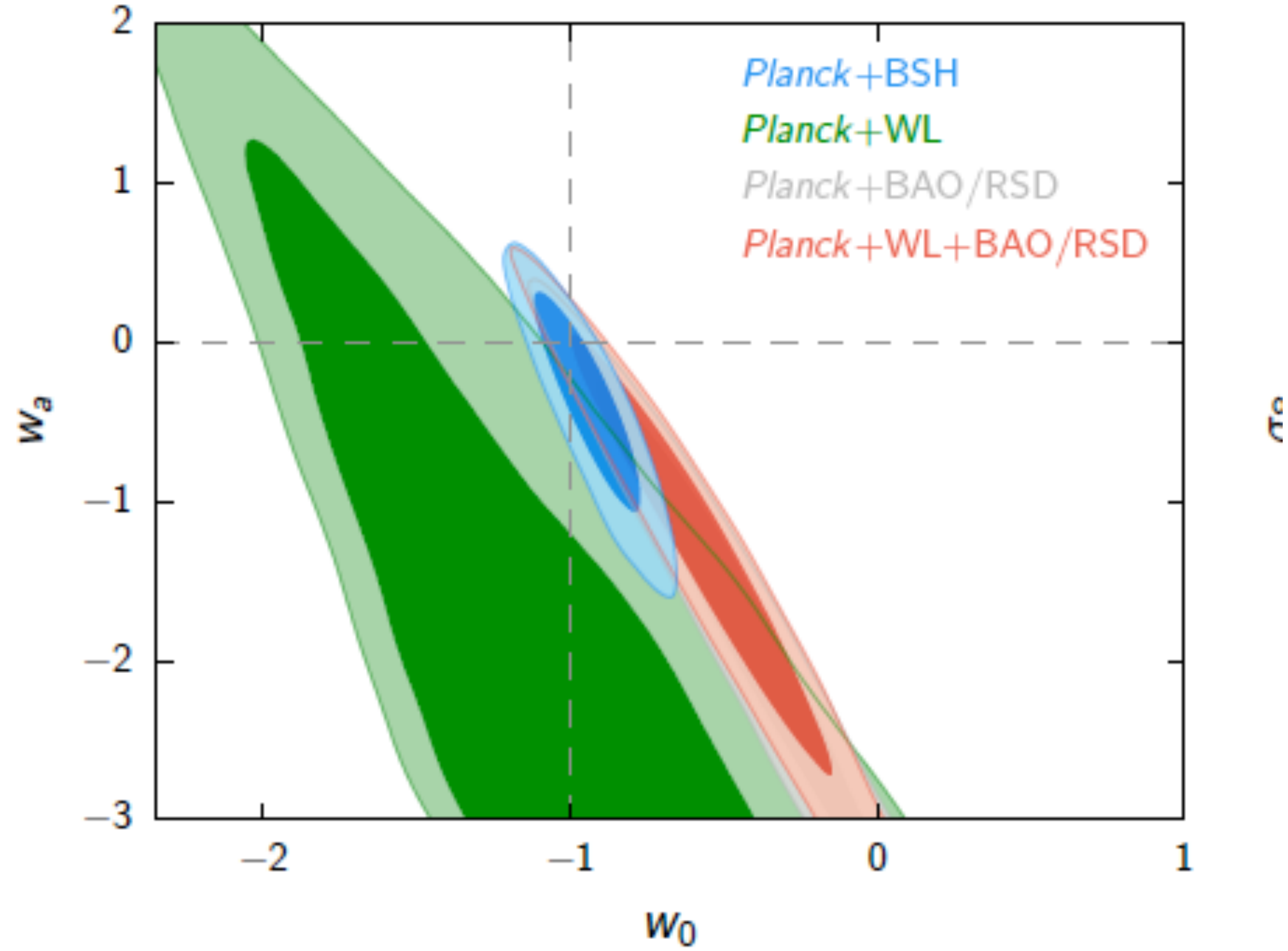
source distribution

Inconsistencies: Weak Lensing

Mild inconsistency
with Planck



CFHTLens Heymans et al 2013



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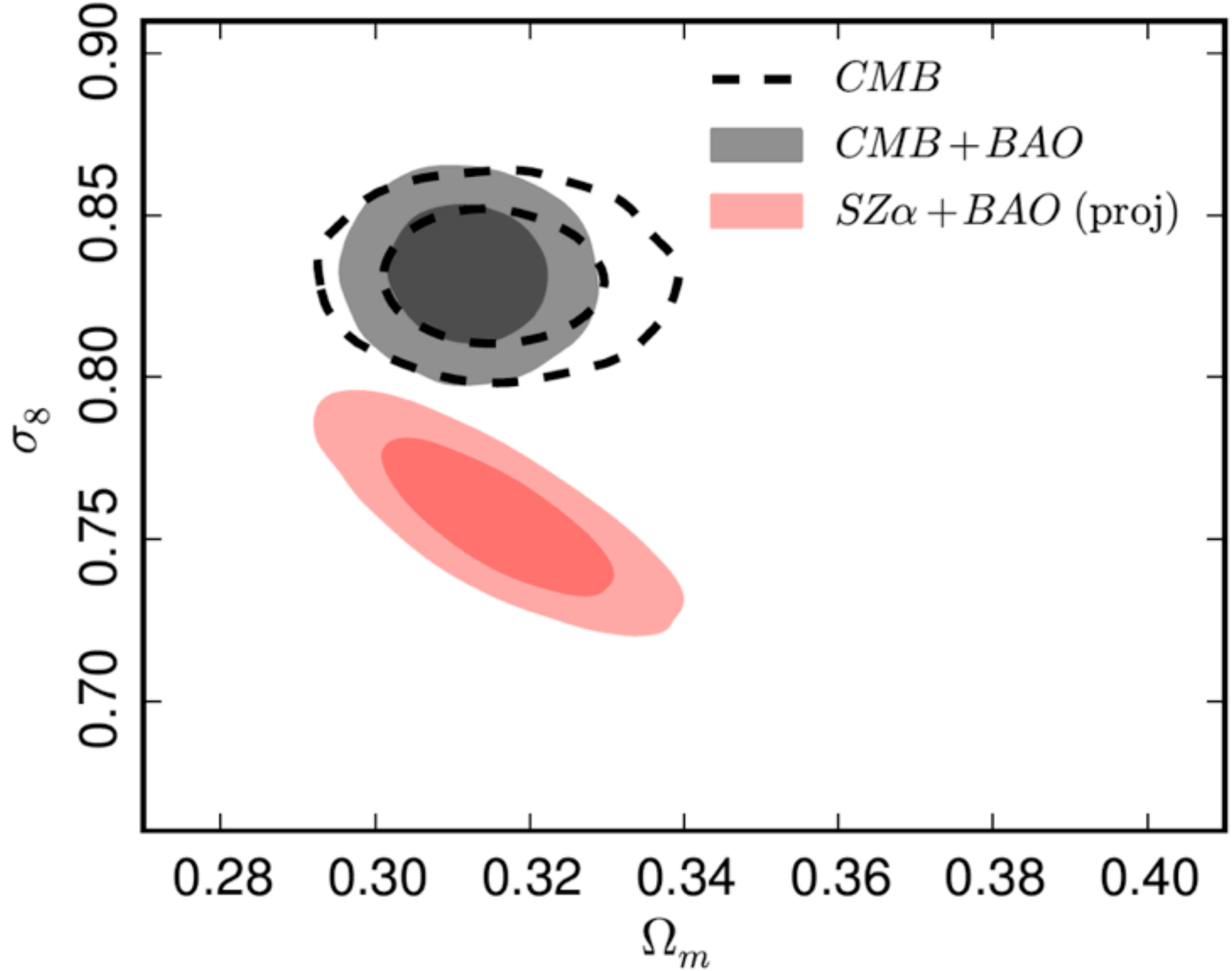
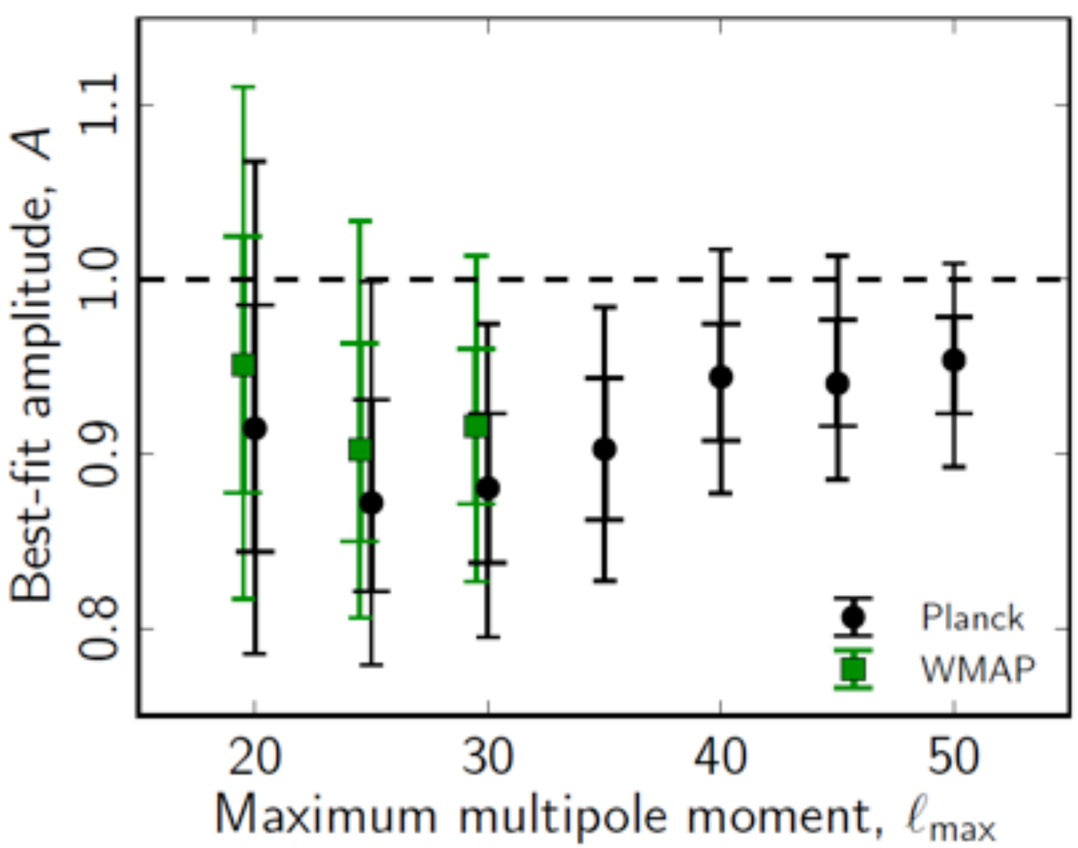
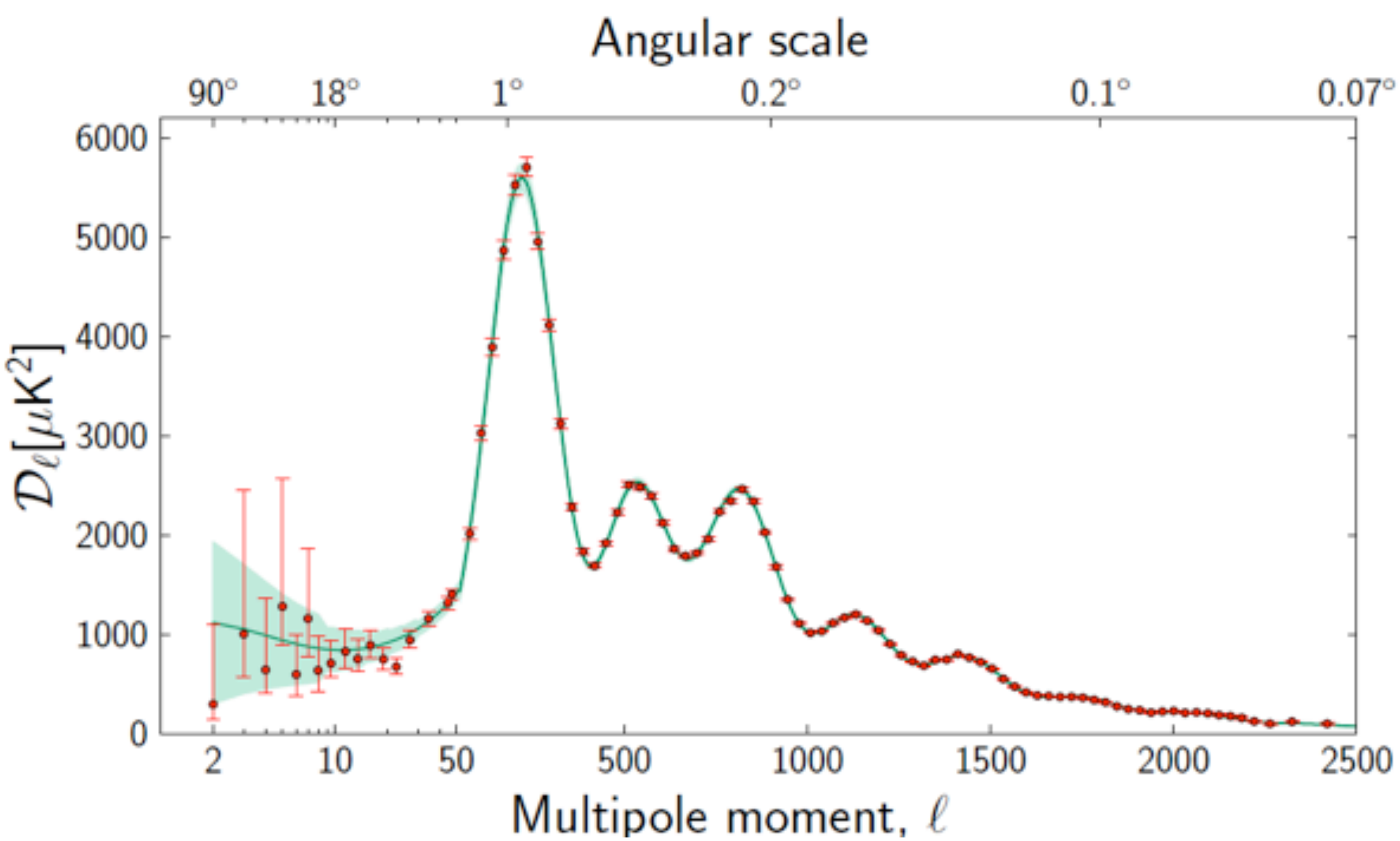
Inconsistencies: Cluster counts



Planck 2015

Inconsistencies: large angles CMB





Particle Physics from Cosmology

- Simple flat ΛCDM model still fits (most) data.
- Strong constraints on ultralight fields.
- Some constraints of inflation- are they fundamental?
- Some constraints DE behaviour - are they fundamental?
- Some inconsistencies- do we need better data?