CMB lensing:
Science Overview

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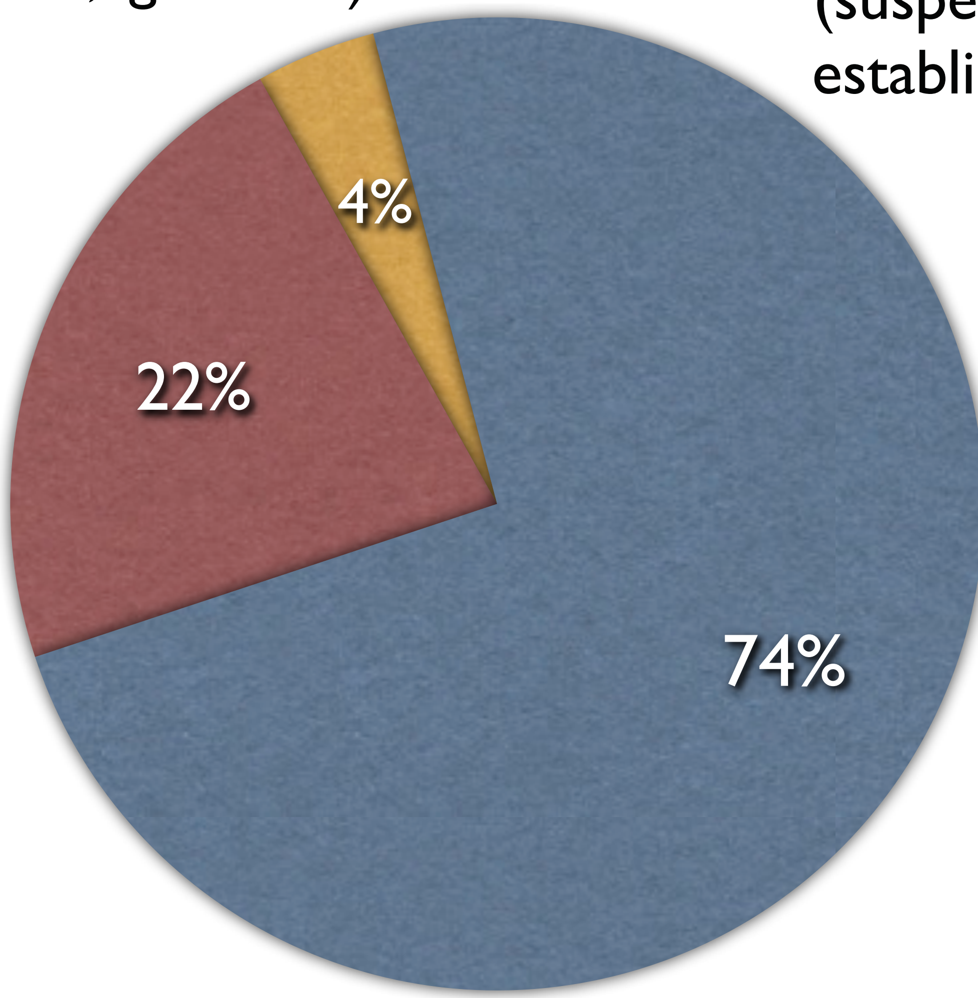
Makeup of universe today

Visible Matter
(stars 0.4%, gas 3.6%)

Dark Energy
(suspected since 1980s
established since 1998)

Dark Matter
(suspected since 1930s
established since 1970s)

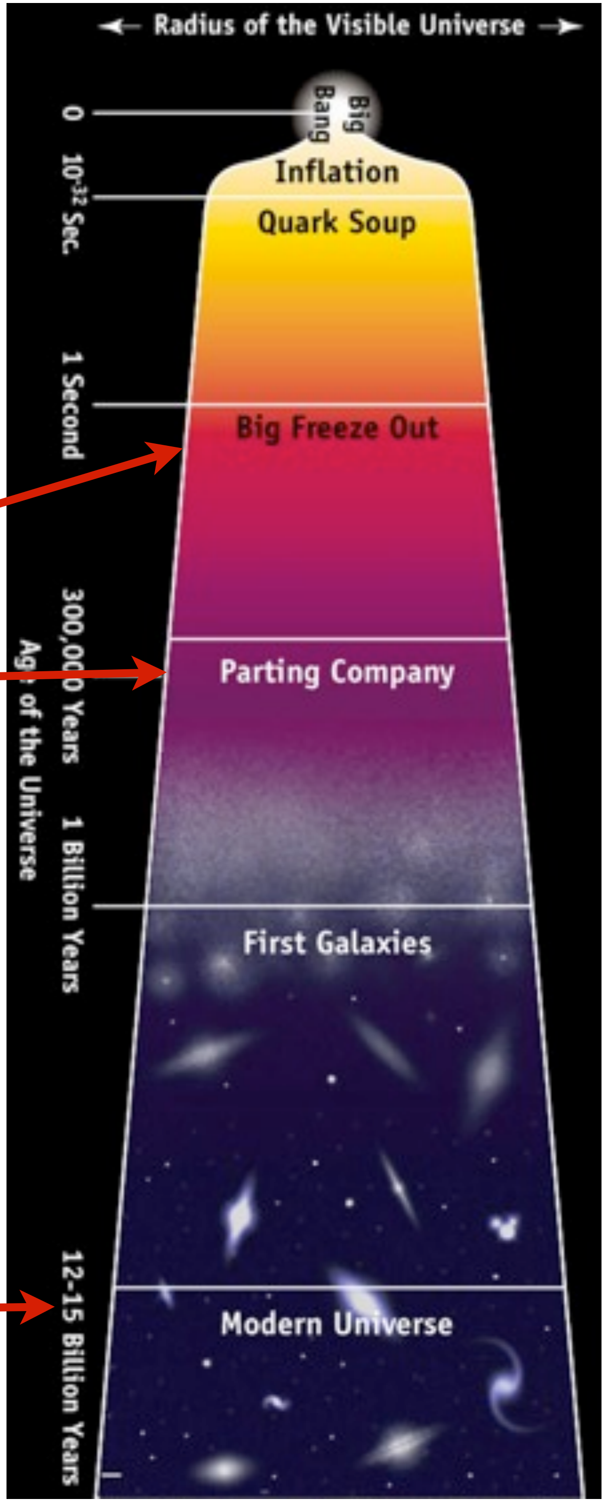


Also:
radiation (0.01%)

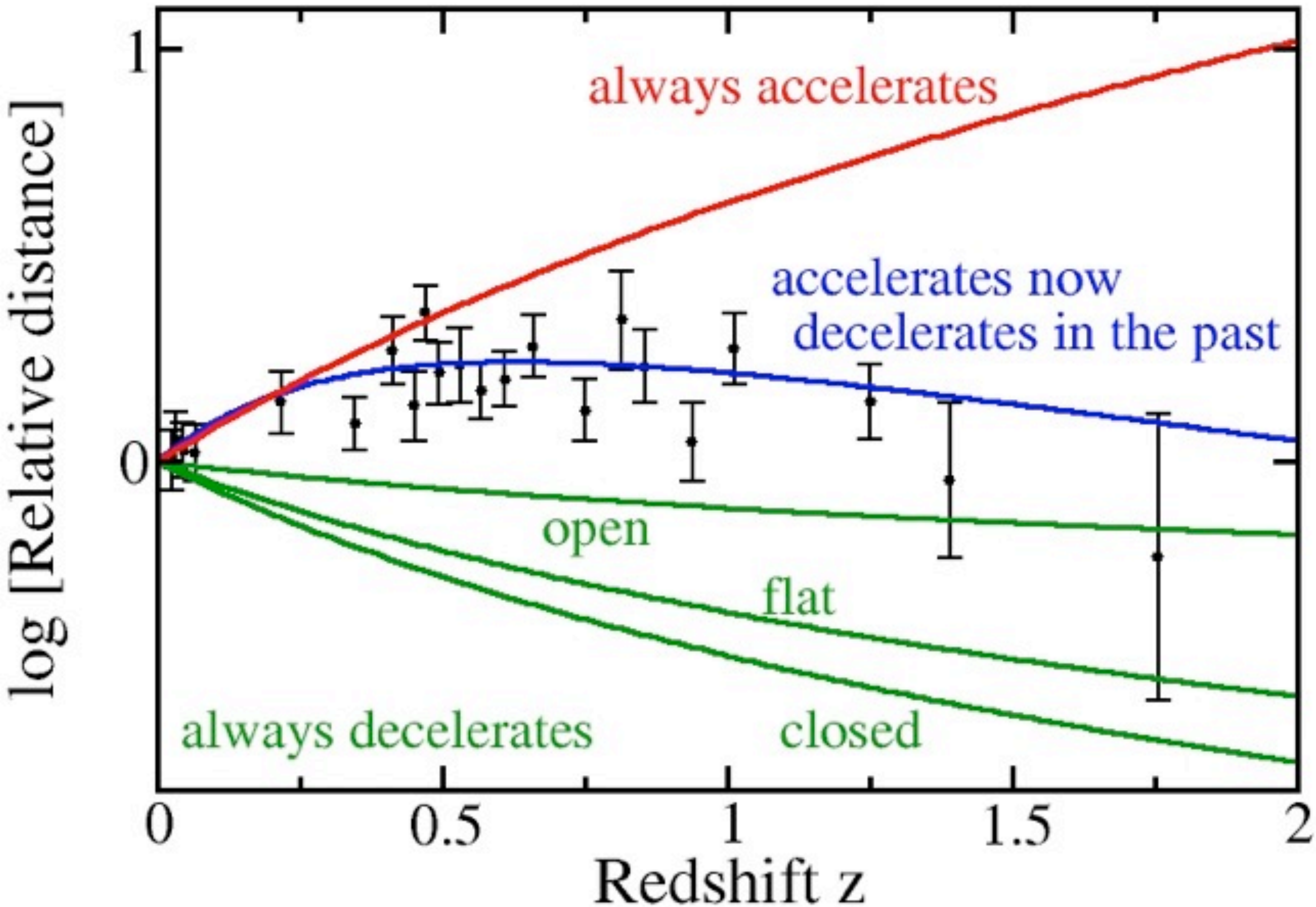
Some of the early history of the Universe is actually understood better!

Physics quite well understood

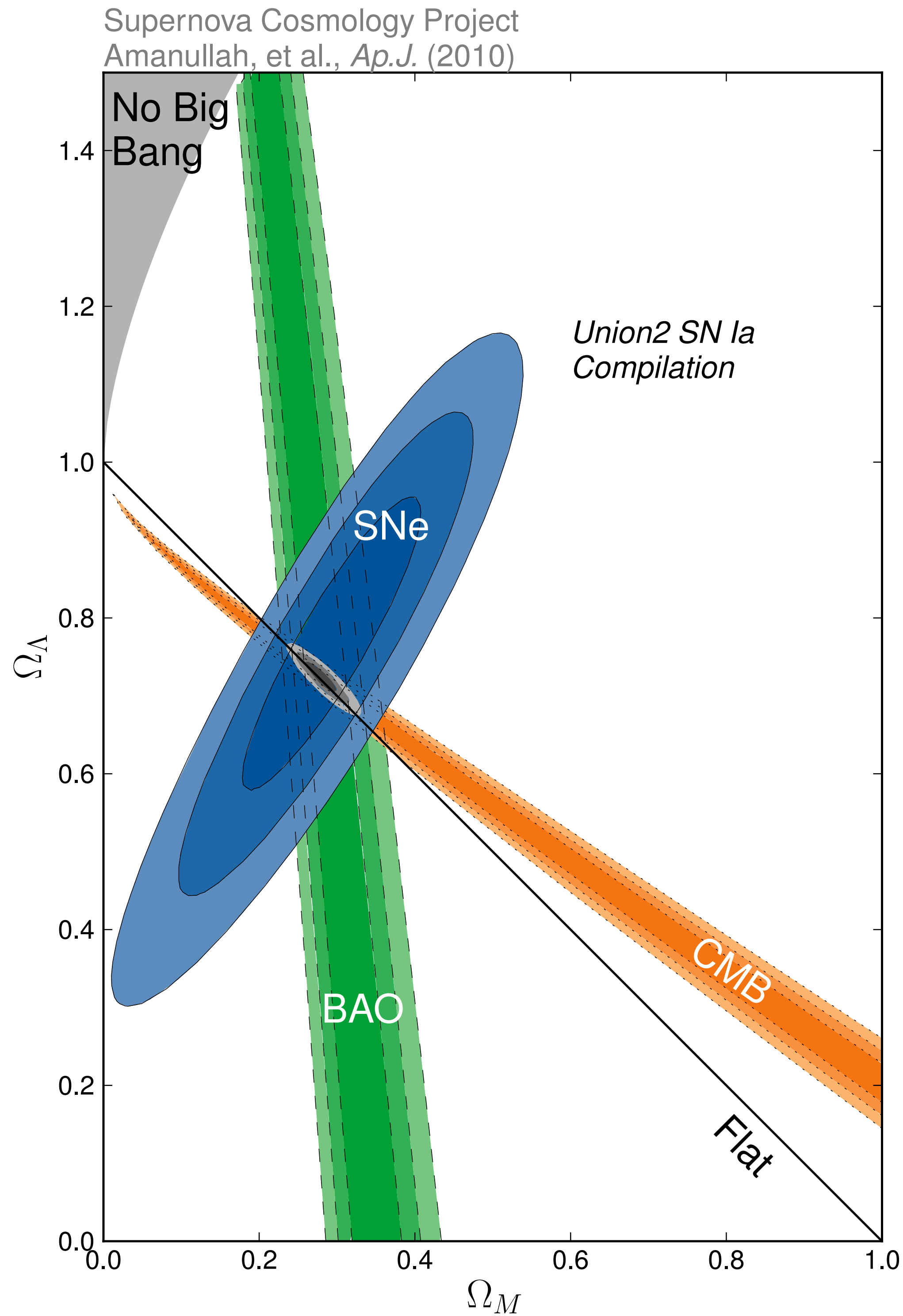
95% of contents only phenomenologically described

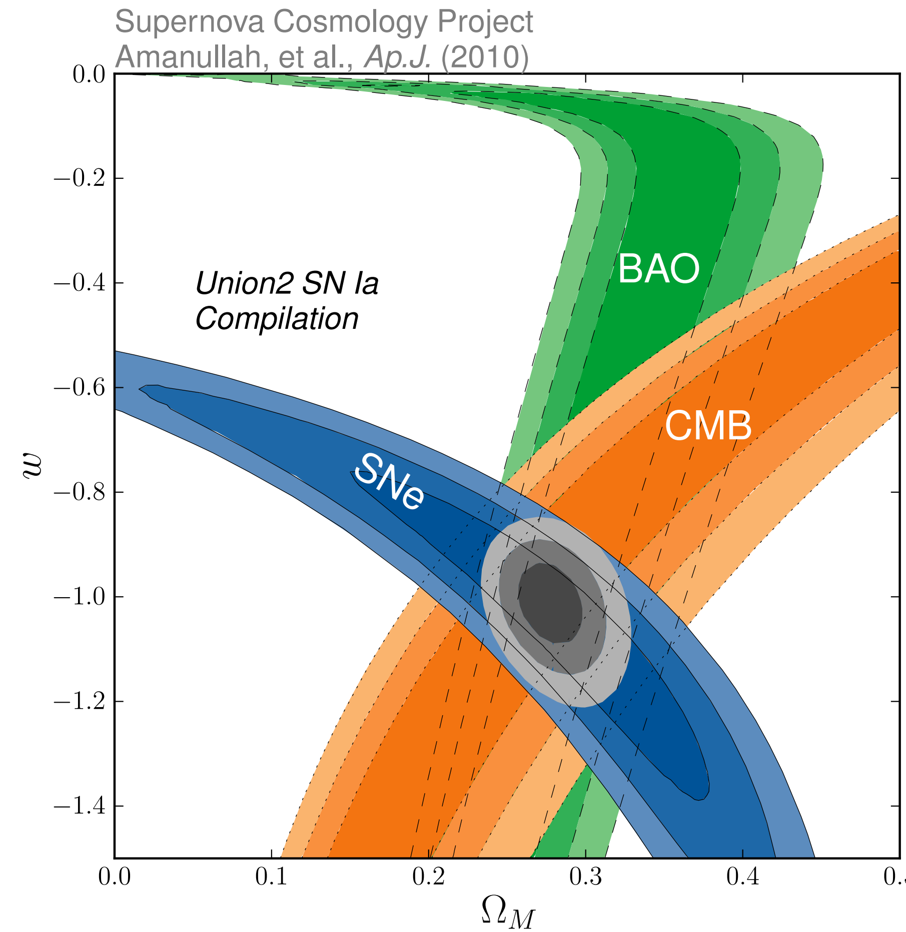


Evidence for Dark Energy from type Ia Supernovae



Union2 SN compilation binned in redshift

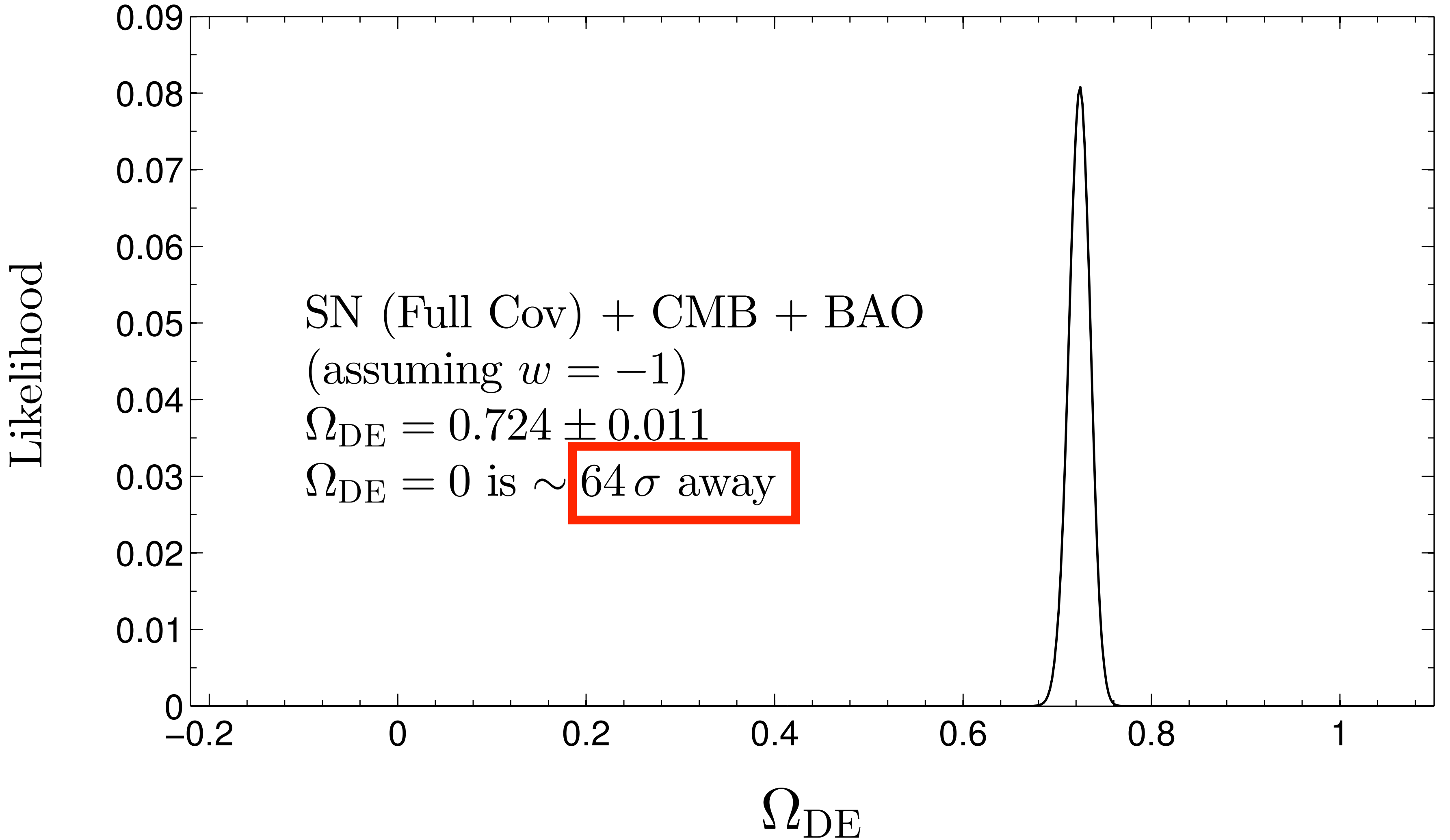




$$\Omega_{\mathrm{DE}} \equiv \frac{\rho_{\mathrm{DE}}}{\rho_{\mathrm{crit}}}$$

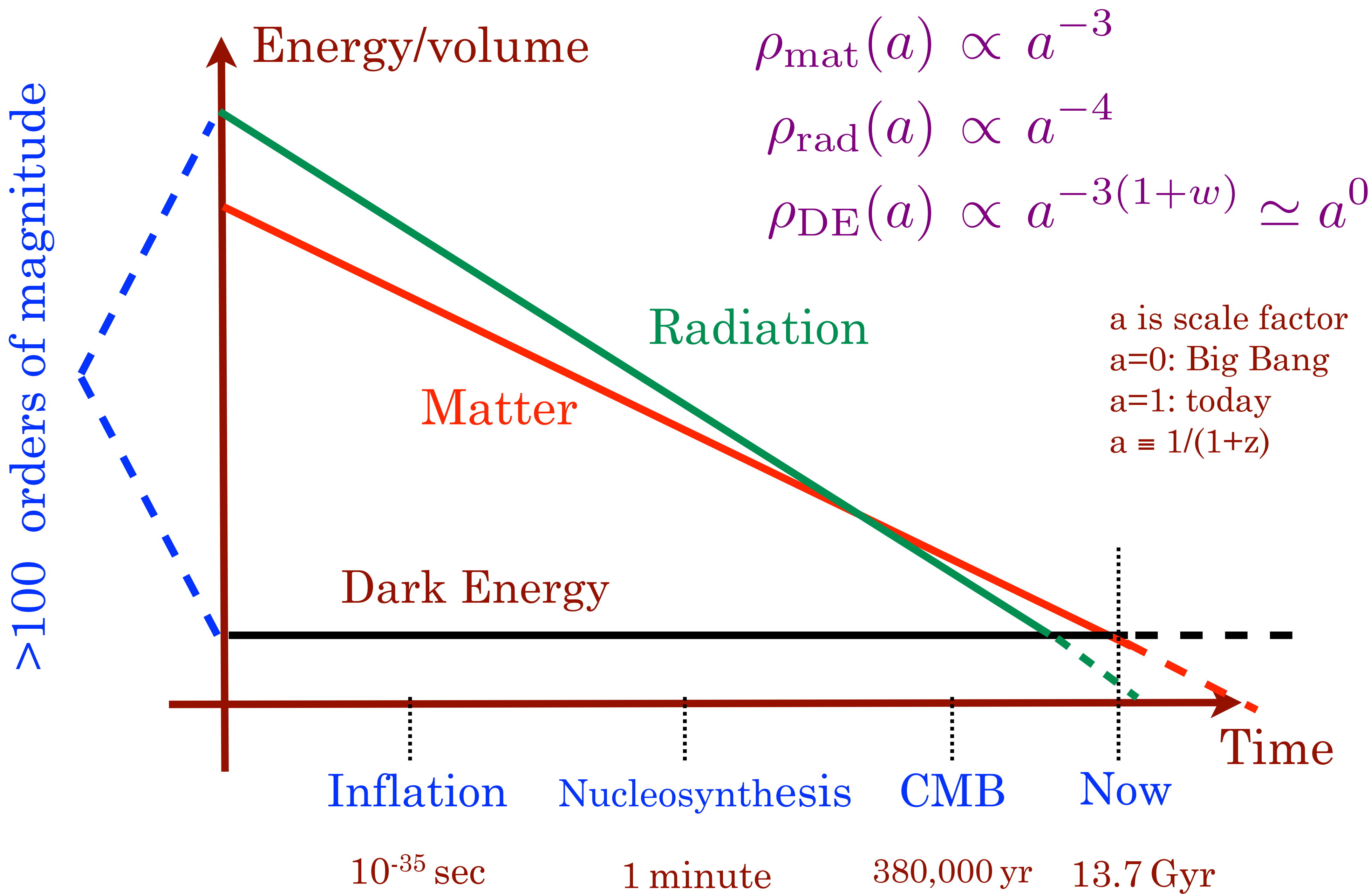
$$w \equiv \frac{p_{\mathrm{DE}}}{\rho_{\mathrm{DE}}}$$

Current evidence for dark energy is impressively strong



D. Shafer
(Michigan)

Coincidence problem



Cosmological constant problem

Vacuum Energy: QFT predicts it to be cutoff scale

$$\rho_{\mathrm{VAC}} = \frac{1}{2}\sum_{\mathrm{fields}} g_i \int_0^\infty \sqrt{k^2+m^2}\,\frac{d^3k}{(2\pi)^3} \simeq \sum_{\mathrm{fields}} \frac{g_i k_{\mathrm{max}}^4}{16\pi^2}$$

Measured: $(10^{-3}\mathrm{eV})^4$

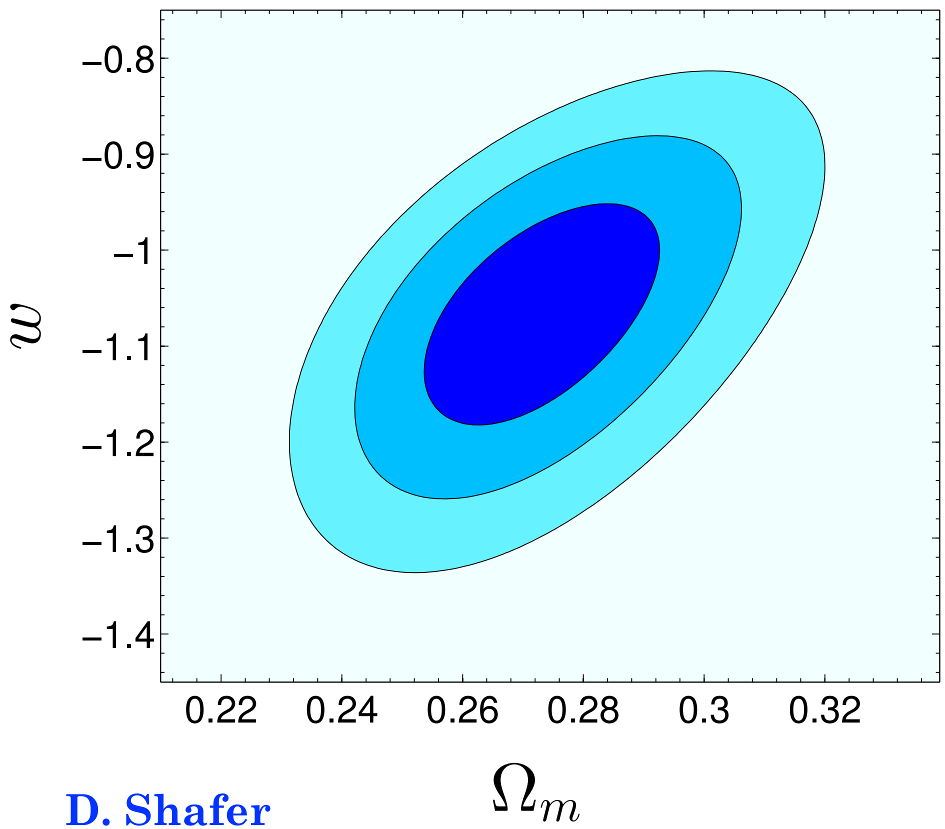
SUSY scale: $(1\,\mathrm{TeV})^4$

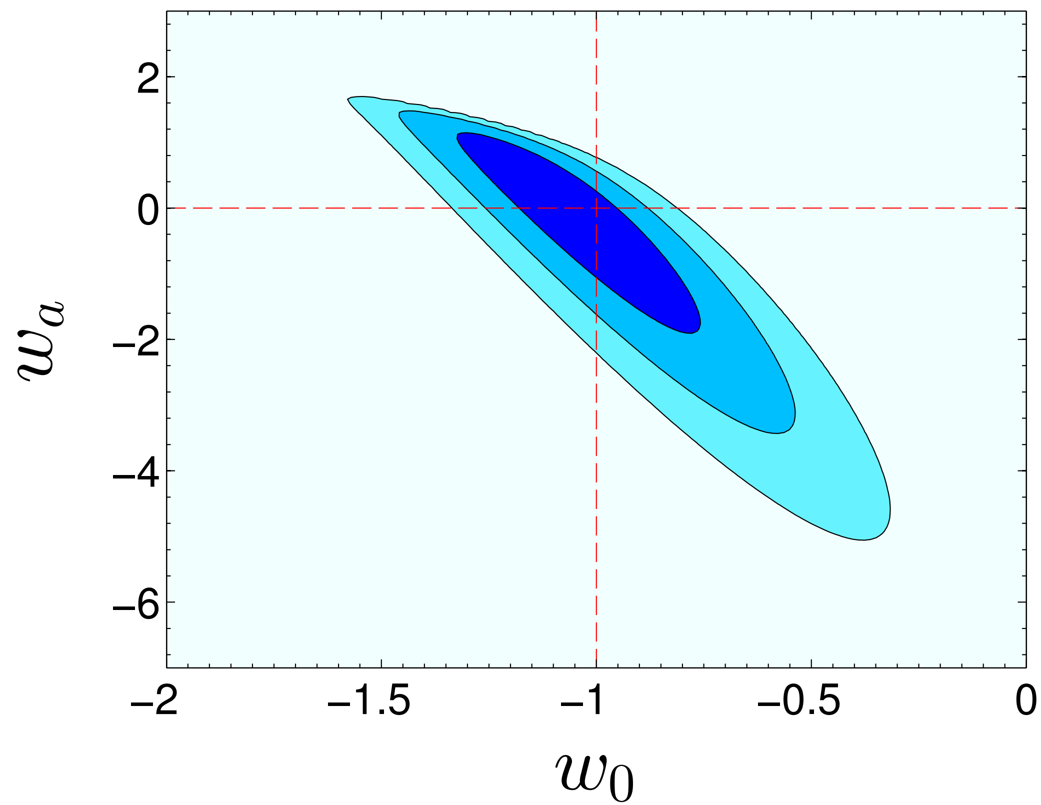
Planck scale: $(10^{19}\,\mathrm{GeV})^4$

60-120 orders of magnitude smaller than expected!

Since the discovery of acceleration, constraints have converged to w ≈ −1

SN + BAO + CMB





D. Shafer

But we can do much better; need:

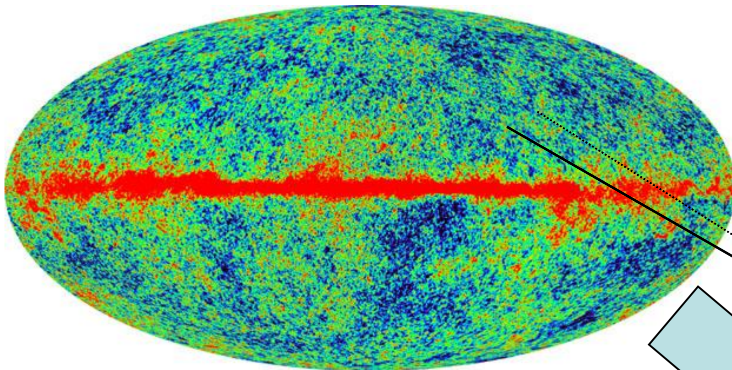
- Better mapping of expansion history
- Precision measurements of growth history.

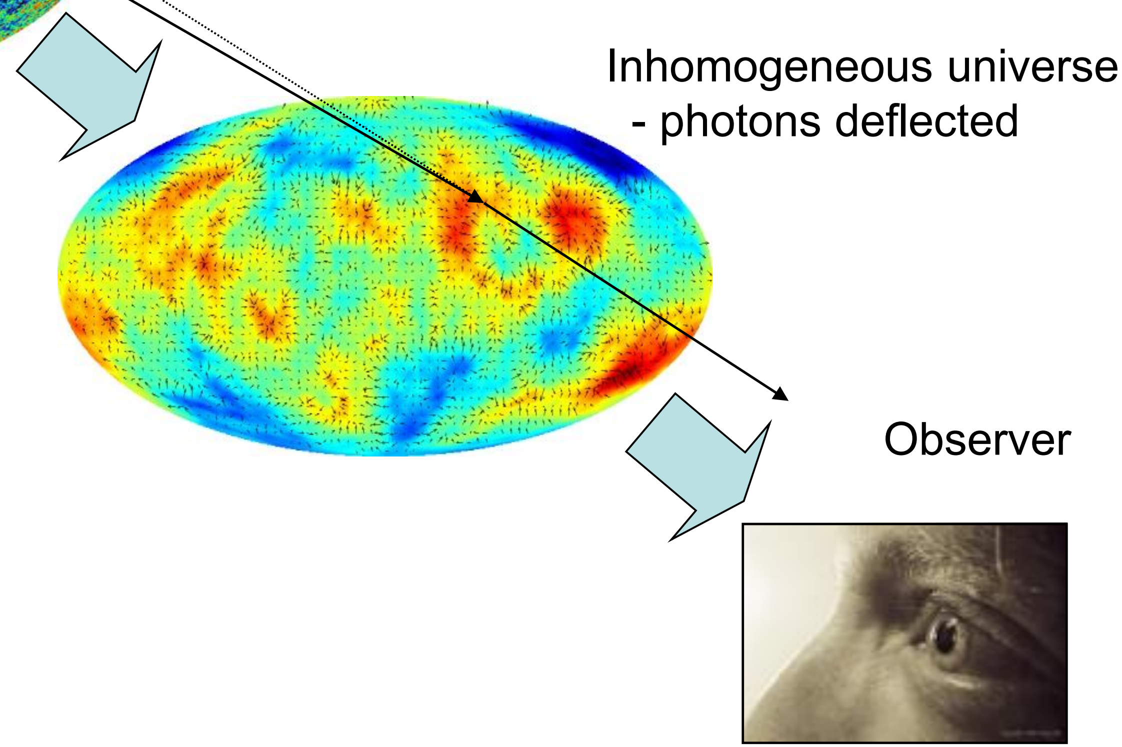
CMB lensing is related to some of the most exciting questions in cosmology:

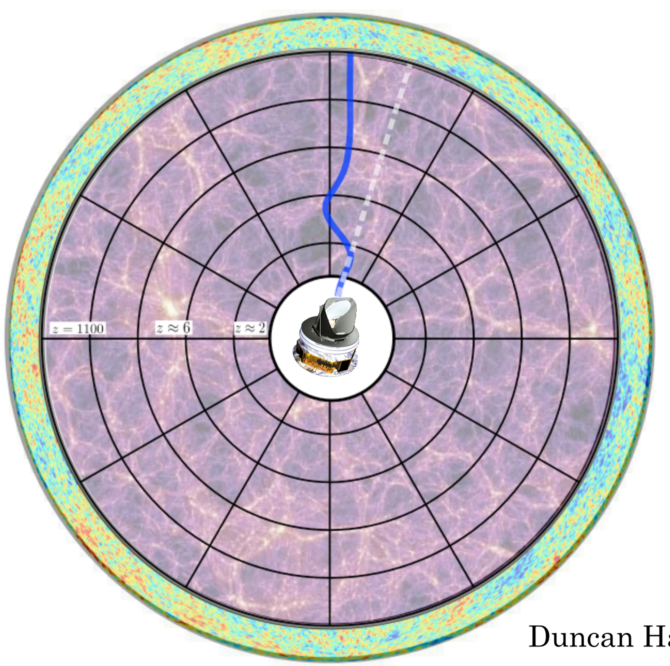
- What is the nature of dark energy? Does General Relativity require modifications?
- What is the neutrino mass hierarchy?
- What is the energy scale of inflation?

from Antony Lewis

CMB Lensing



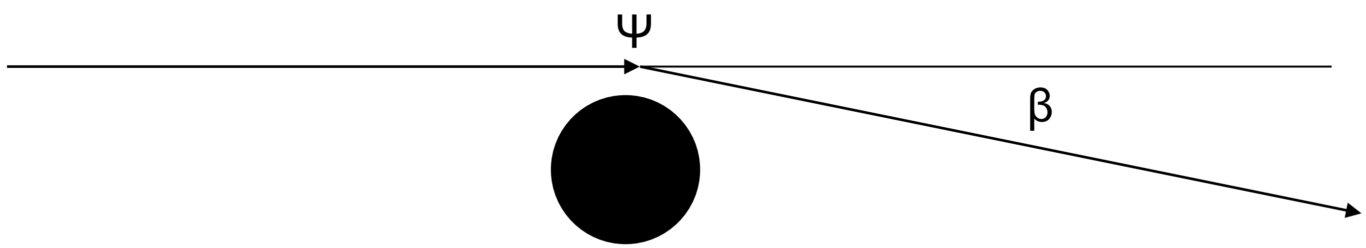




Duncan Hanson

from Antony Lewis

Lensing order of magnitudes



Newtonian argument: $\beta = 2\,\Psi$
General Relativity: $\beta = 4\,\Psi$ ($\beta \ll 1$)

Potentials linear and approx Gaussian: $\Psi \sim 2 \times 10^{-5}$

$\beta \sim 10^{-4}$

Characteristic size from peak of matter power spectrum ~ 300Mpc

Comoving distance to last scattering surface ~ 14000 MPc

⇒ pass through ~50 lumps ⇒ total deflection ~ $50^{1/2} \times 10^{-4}$

assume uncorrelated

~ 2 arcminutes

(neglects angular factors, correlation, etc.)

from Antony Lewis

So why does it matter?

- 2arcmin: ell ~ 3000

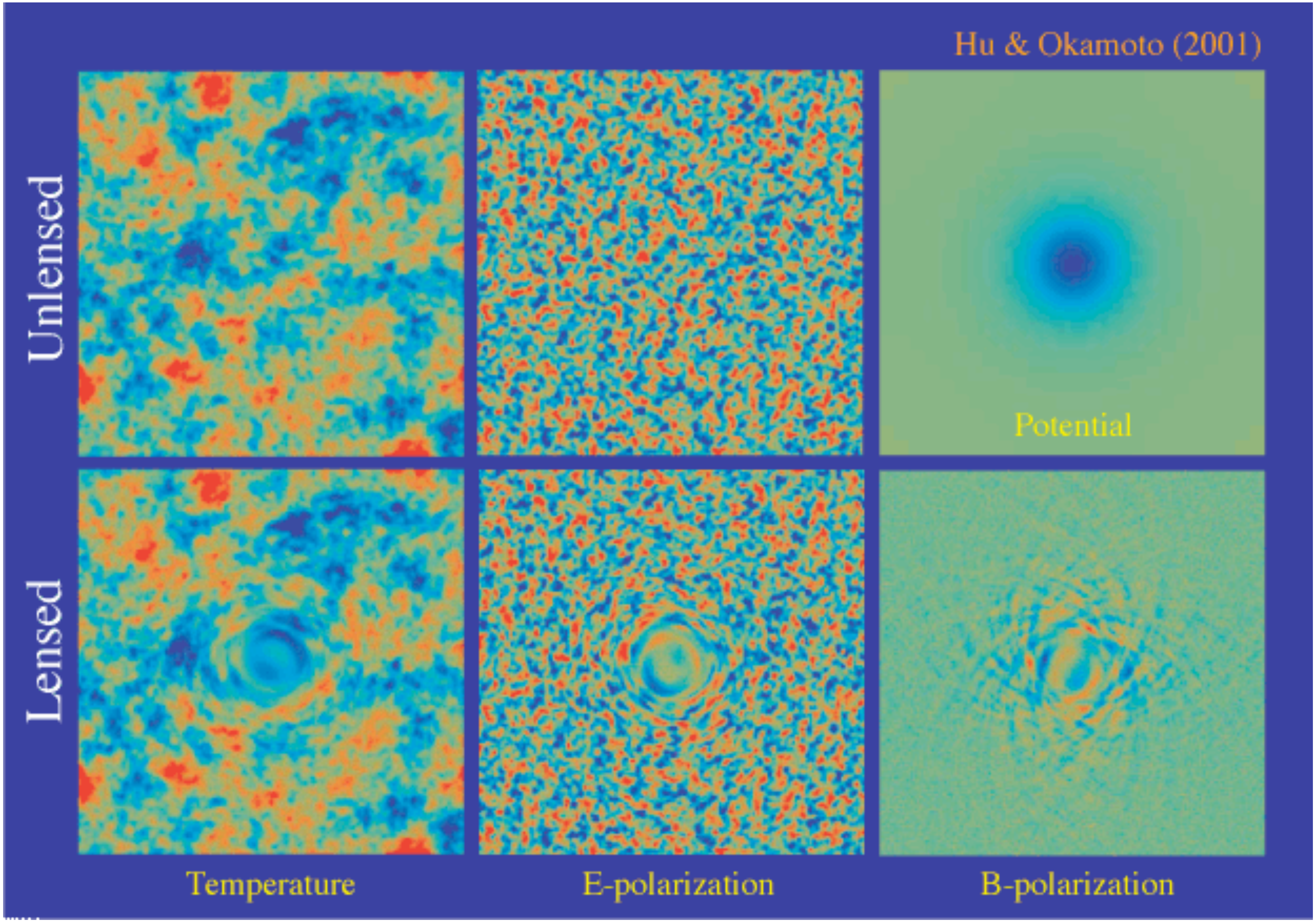
  - On small scales CMB is very smooth so lensing dominates the linear signal

- Deflection angles coherent over 300/(14000/2) ~ 2°

  - comparable to CMB scales

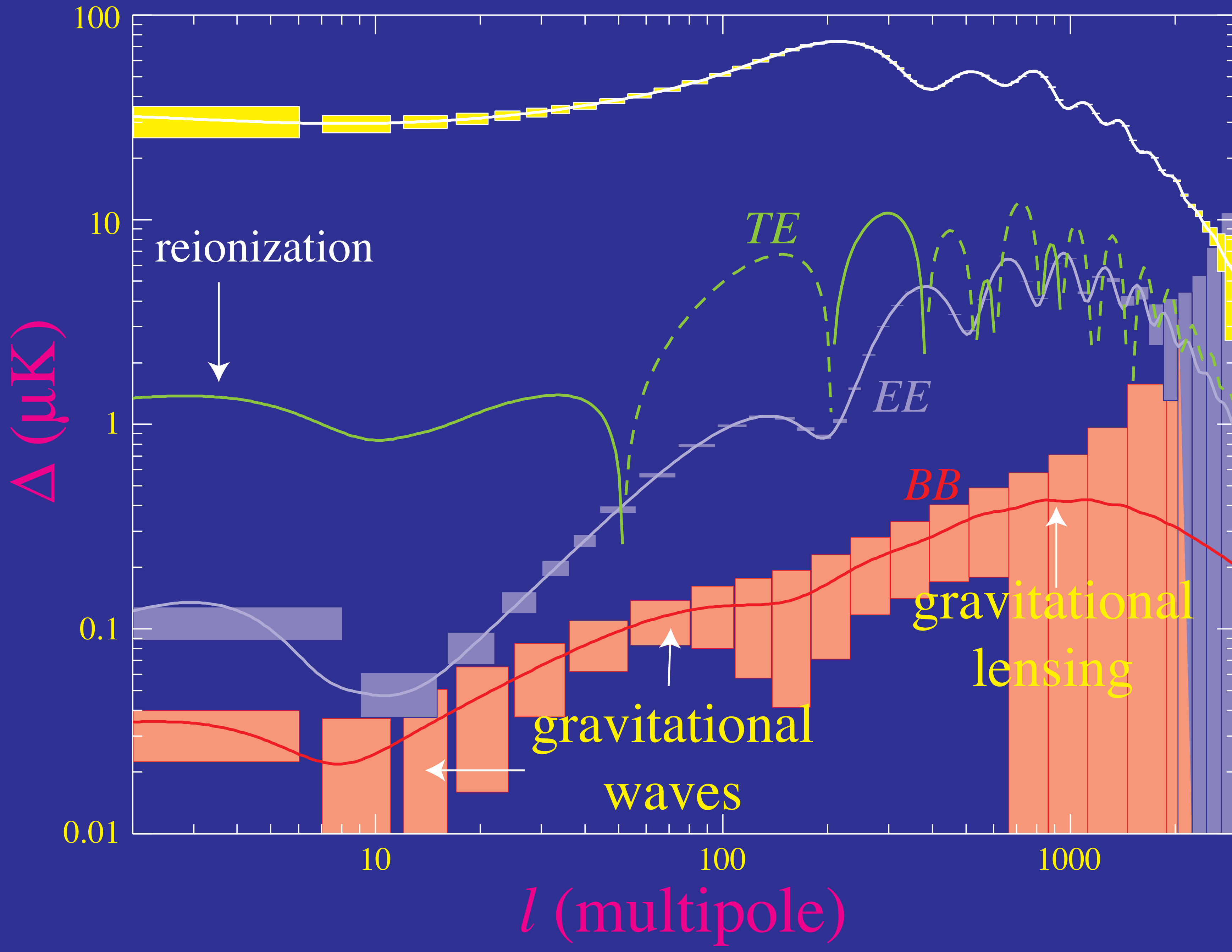
  - expect 2arcmin/60arcmin ~ 3% effect on main CMB acoustic peaks

Lensing effects on CMB observables

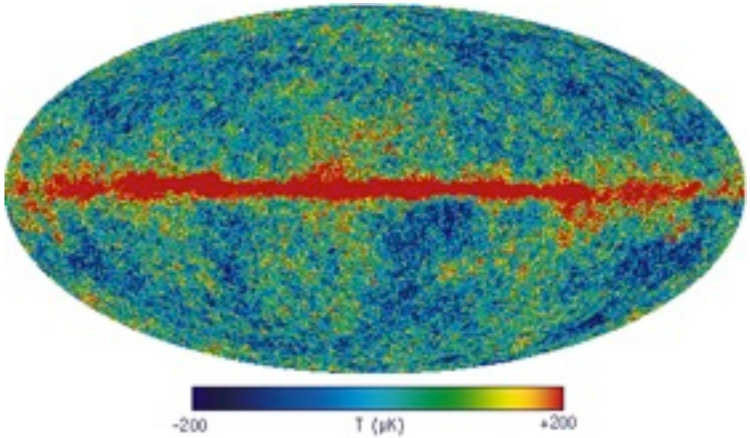


Temperature and Polarization Spectra

Wayne Hu

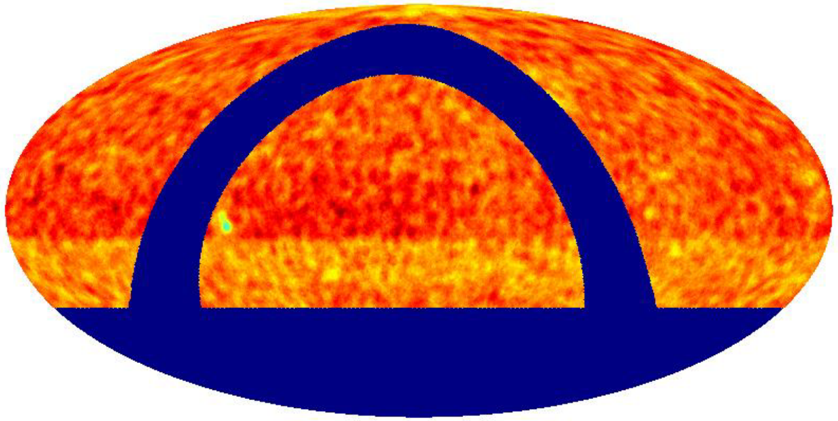


CMB Lensing detected!

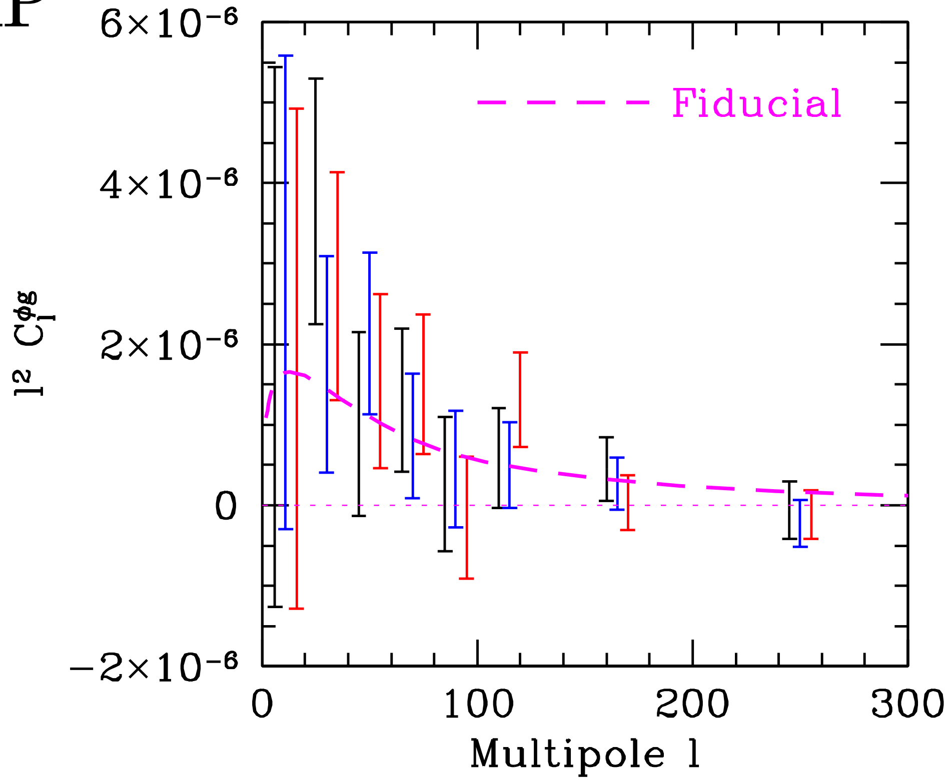


WMAP

X

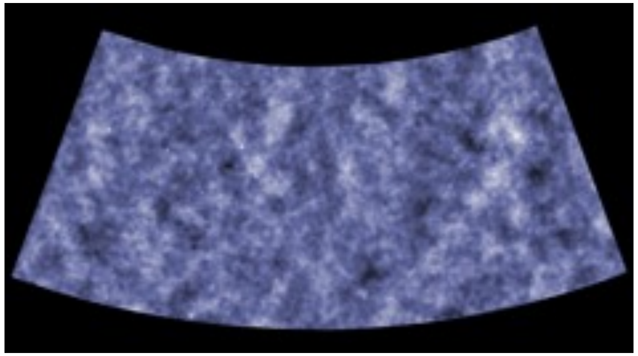


NVSS



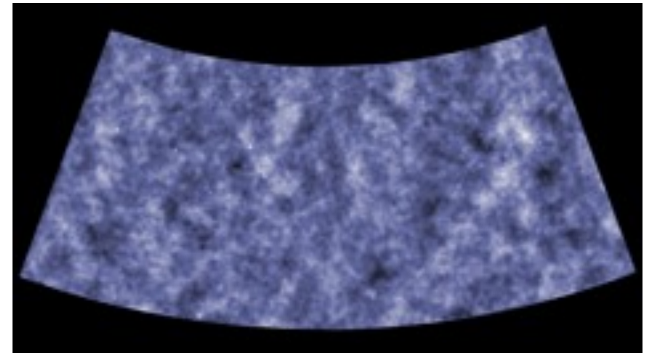
Smith, Zahn and Doré 2007 (also Hirata et al 2008)

CMB Lensing detected!

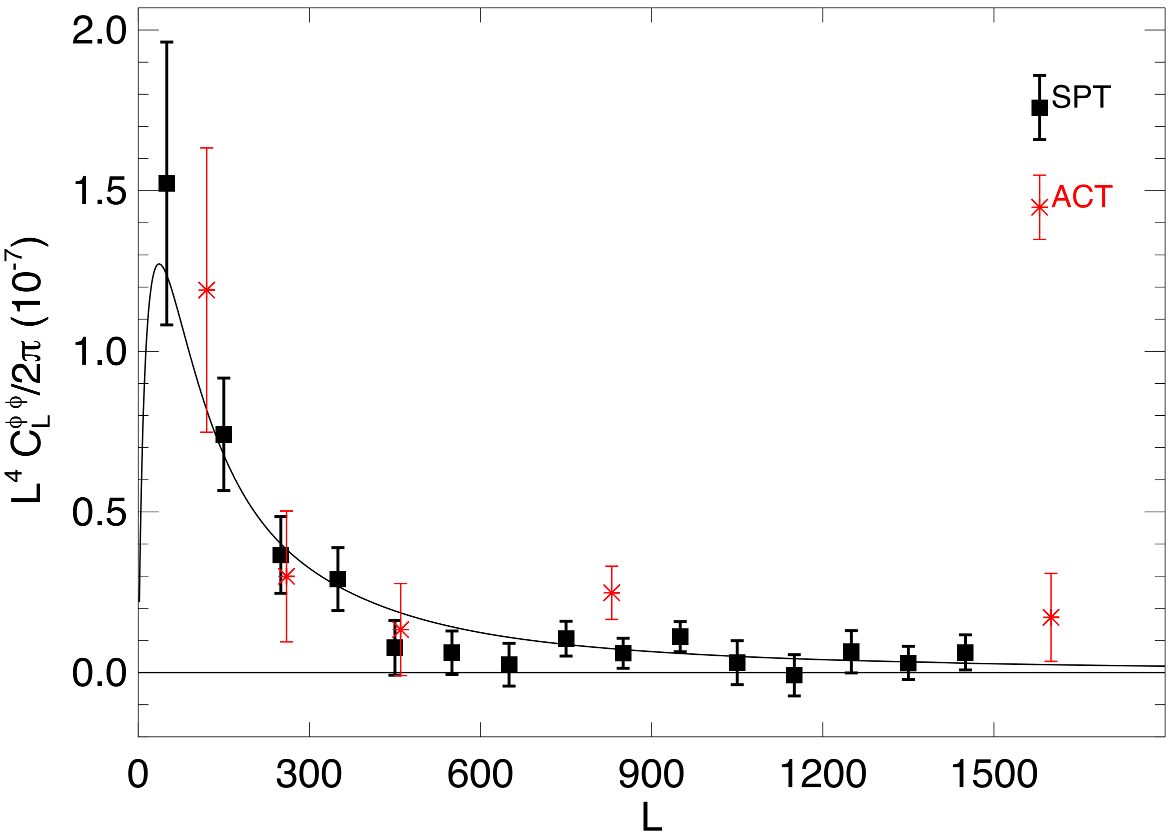


SPT/ACT

X

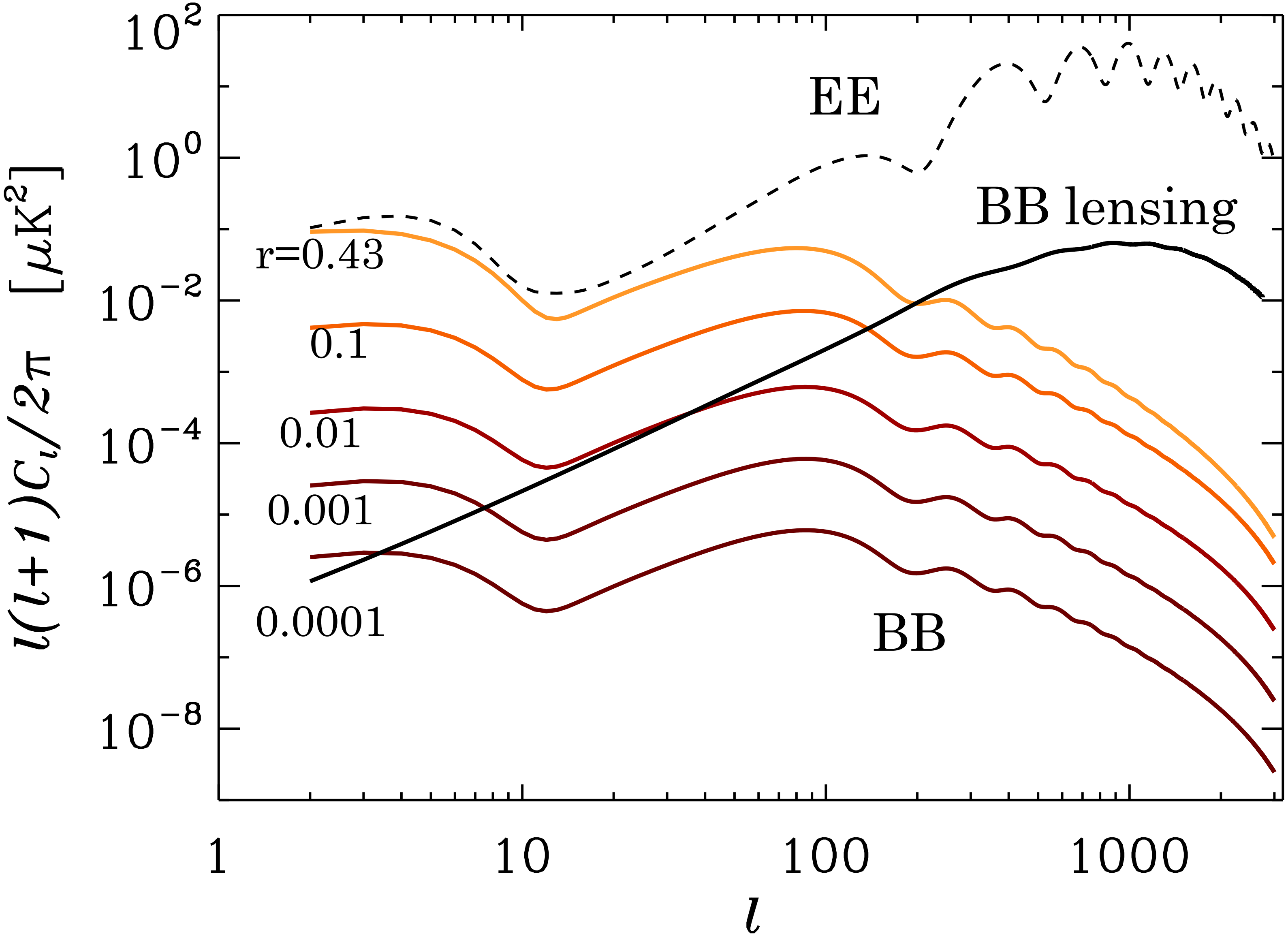


SPT/ACT



van Engelen et al

Das et al (2011; ACT; 4-sigma)
van Engelen et al (2012; SPT; 6-sigma)

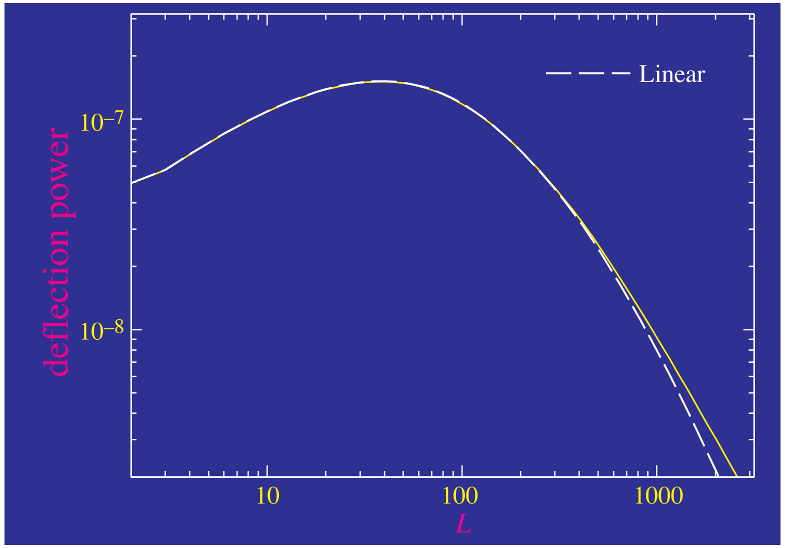


Smith et al, white paper, 2008

Lensing potential:

$$\phi(\widehat{\mathbf{n}}) = -2\int_0^{z_{\rm rec}} \frac{dz}{H(z)}\Psi(z, D(z)\widehat{\mathbf{n}})\left(\frac{D(z_{\rm rec})-D(z)}{D(z_{\rm rec})D(z)}\right)$$

Angular power of potential:

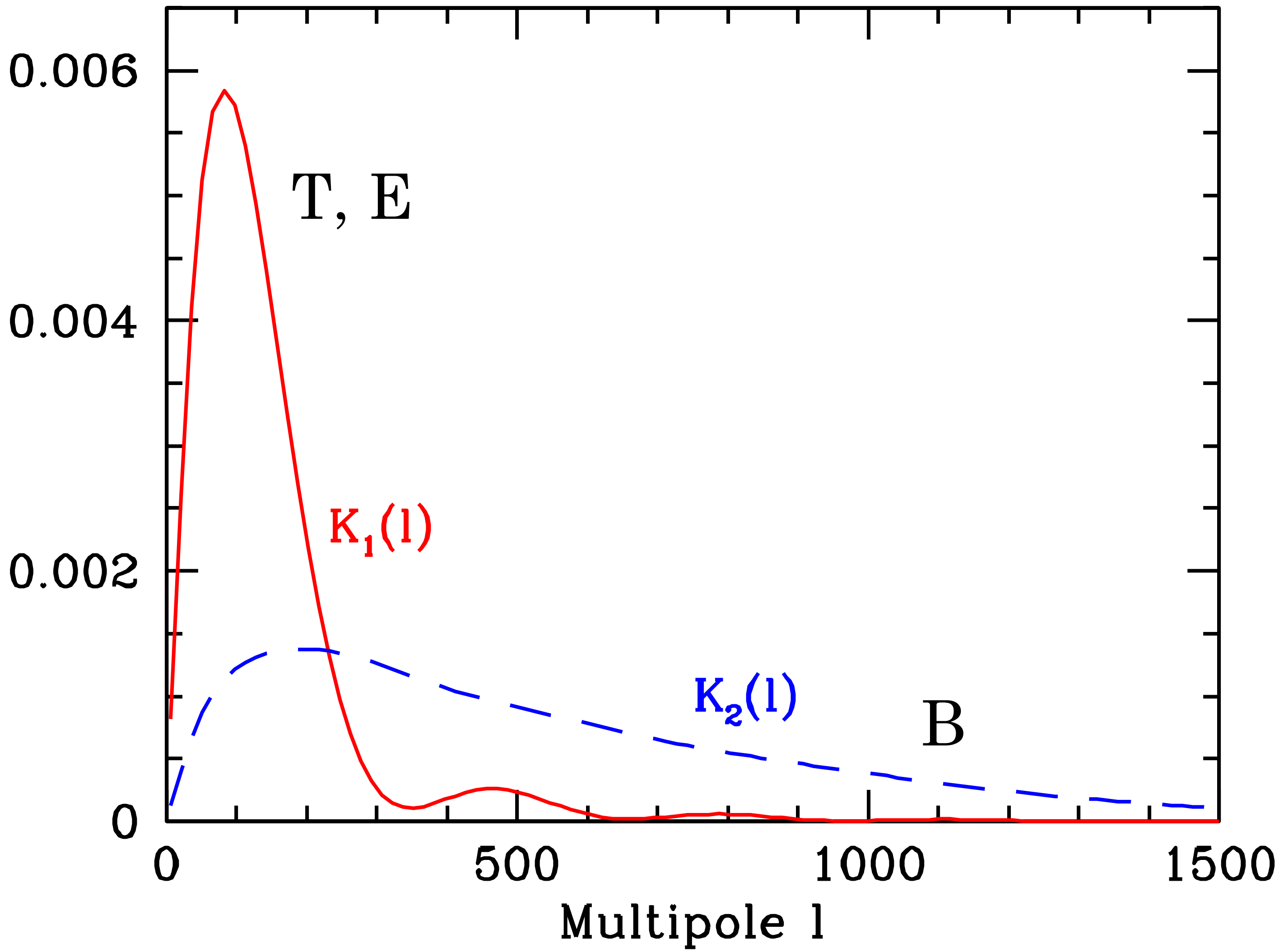


Wayne Hu

$$C_\ell^{\phi\phi} = \frac{8\pi^2}{\ell^3}\int_0^{z_{\rm rec}} \frac{dz}{H(z)} D(z)\left(\frac{D(z_{\rm rec})-D(z)}{D(z_{\rm rec})D(z)}\right)^2 P_\Psi(z, k=\ell/D(z))$$

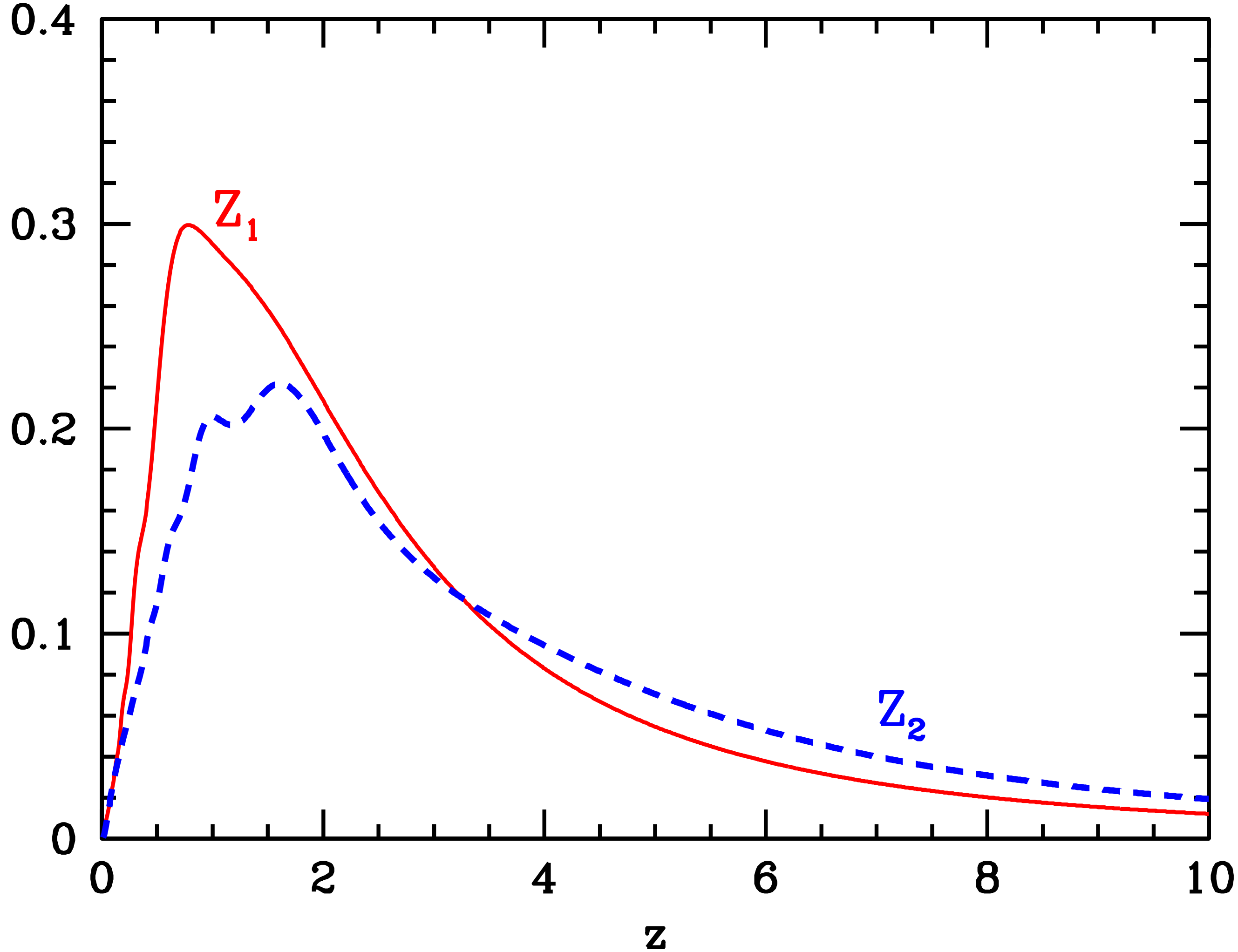
geometry | DM clustering

Principal components of observable potential power (in ℓ)



Smith, Hu and Kaplinghat 2006

Redshifts constrained by $\phi\phi$ power spectrum

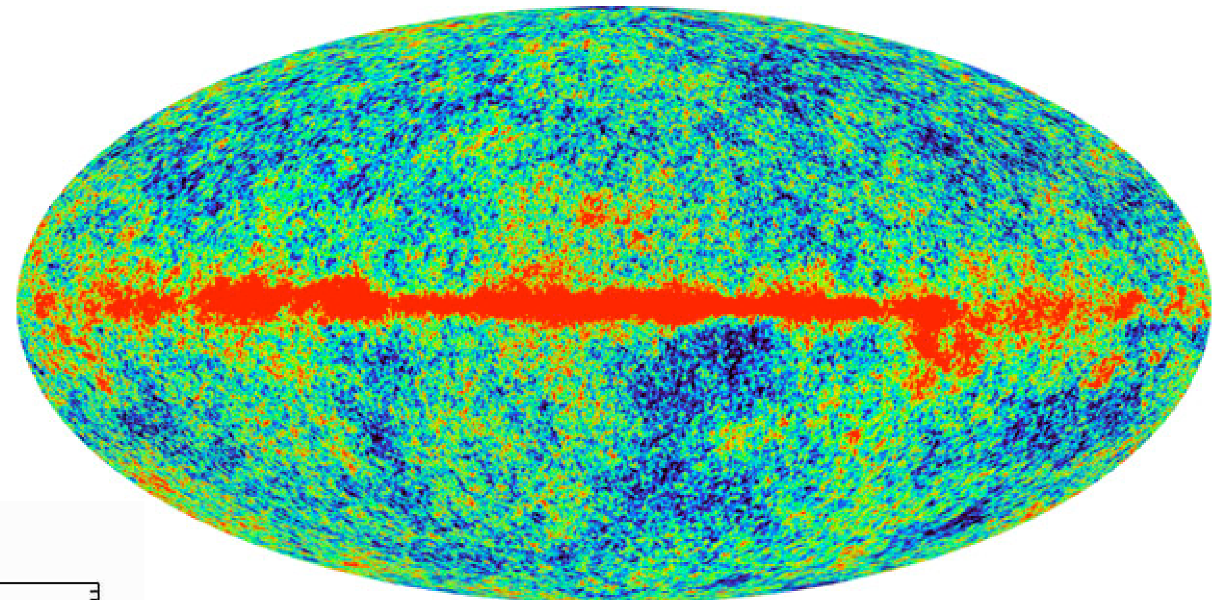


Smith, Hu and Kaplinghat 2006

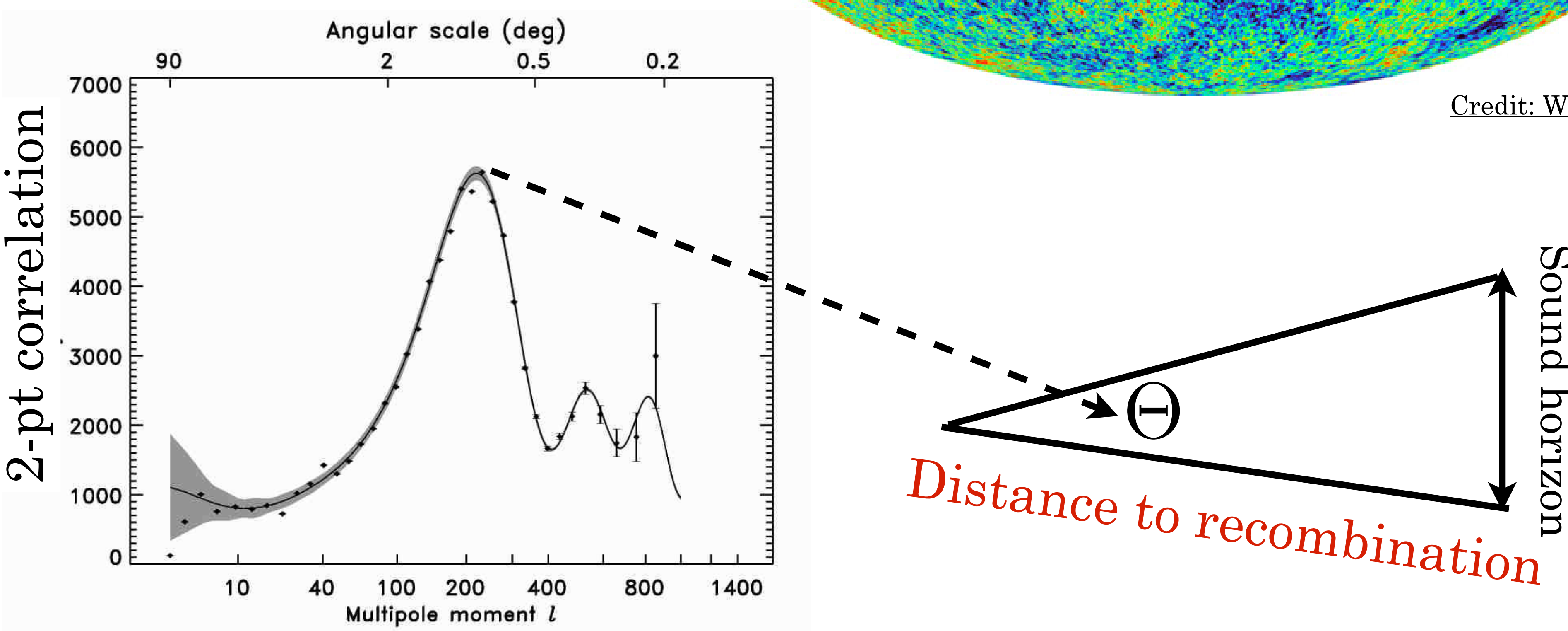
What is the relation between constraints on dark energy from CMB power spectrum (e.g. C^{TT}) and CMB lensing (e.g. $C^{\phi\phi}$) ?

CMB and Dark Energy

Dependence on DE:
1. Peaks' positions
2. ISW (low ell)



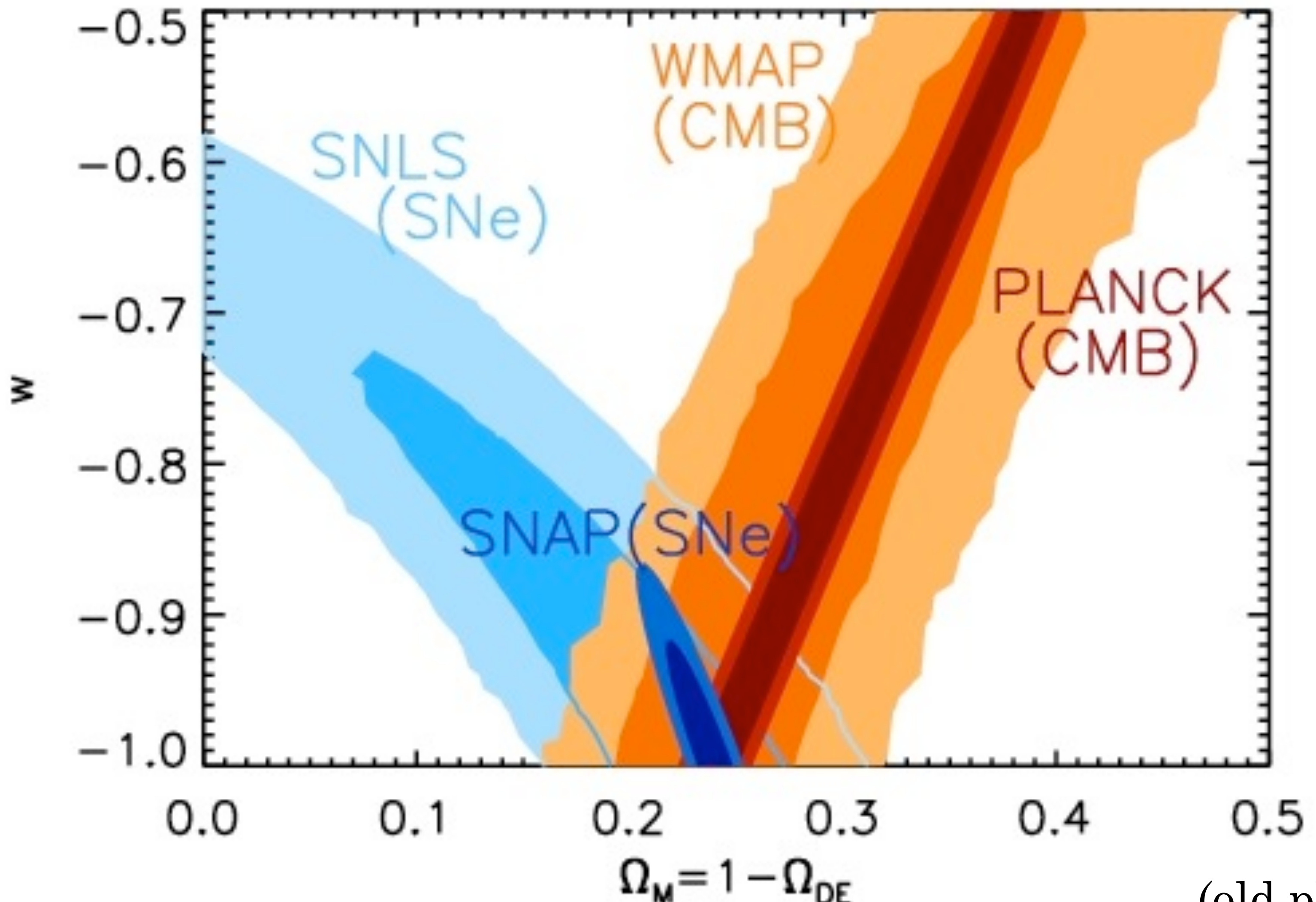
Credit: WMAP team



Bennett et al (WMAP collaboration)

CMB and Dark Energy

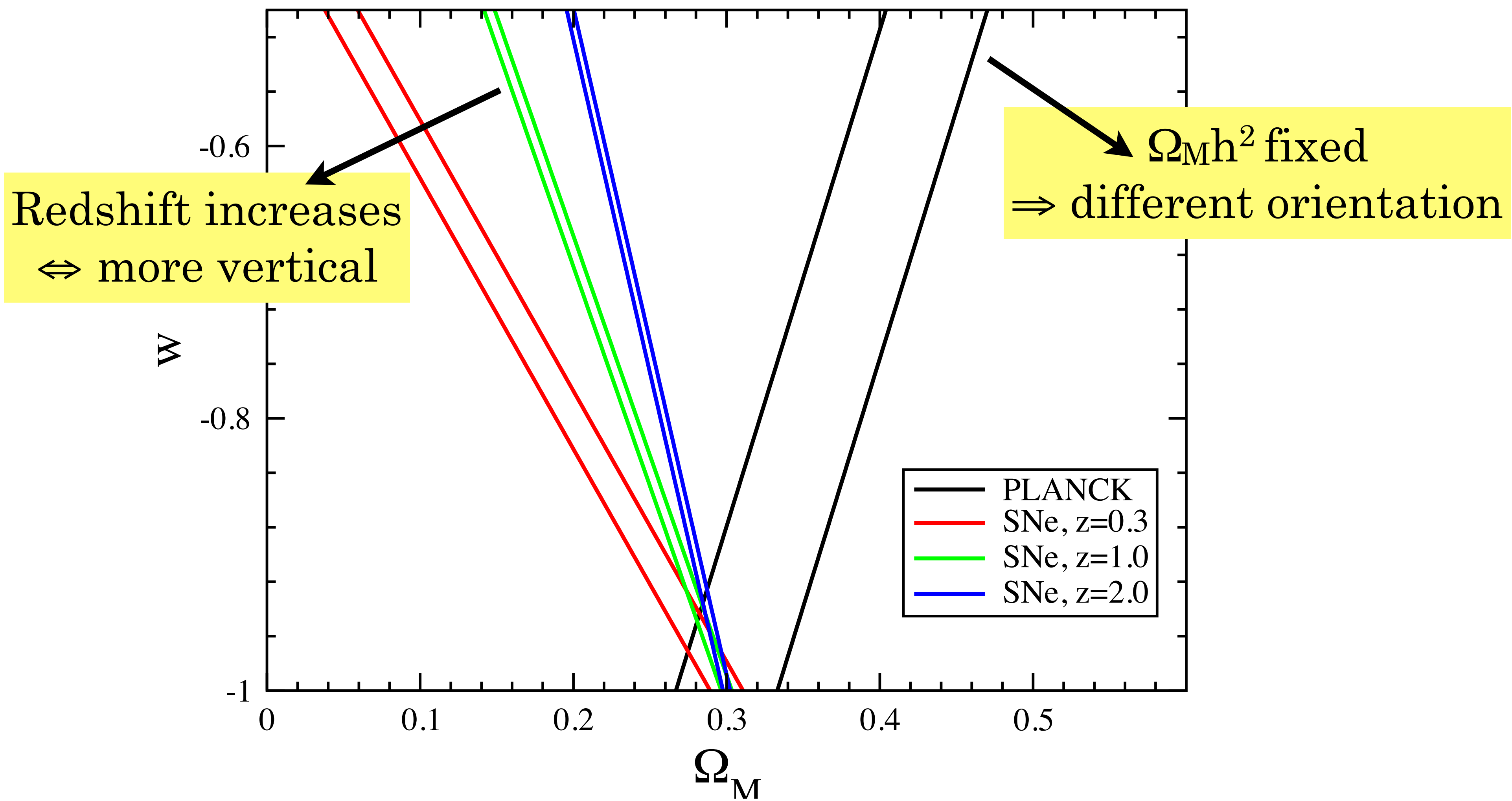
One* linear combination of DE parameters is measured by the CMB
(*ignoring ISW)



(old plot, sorry...)

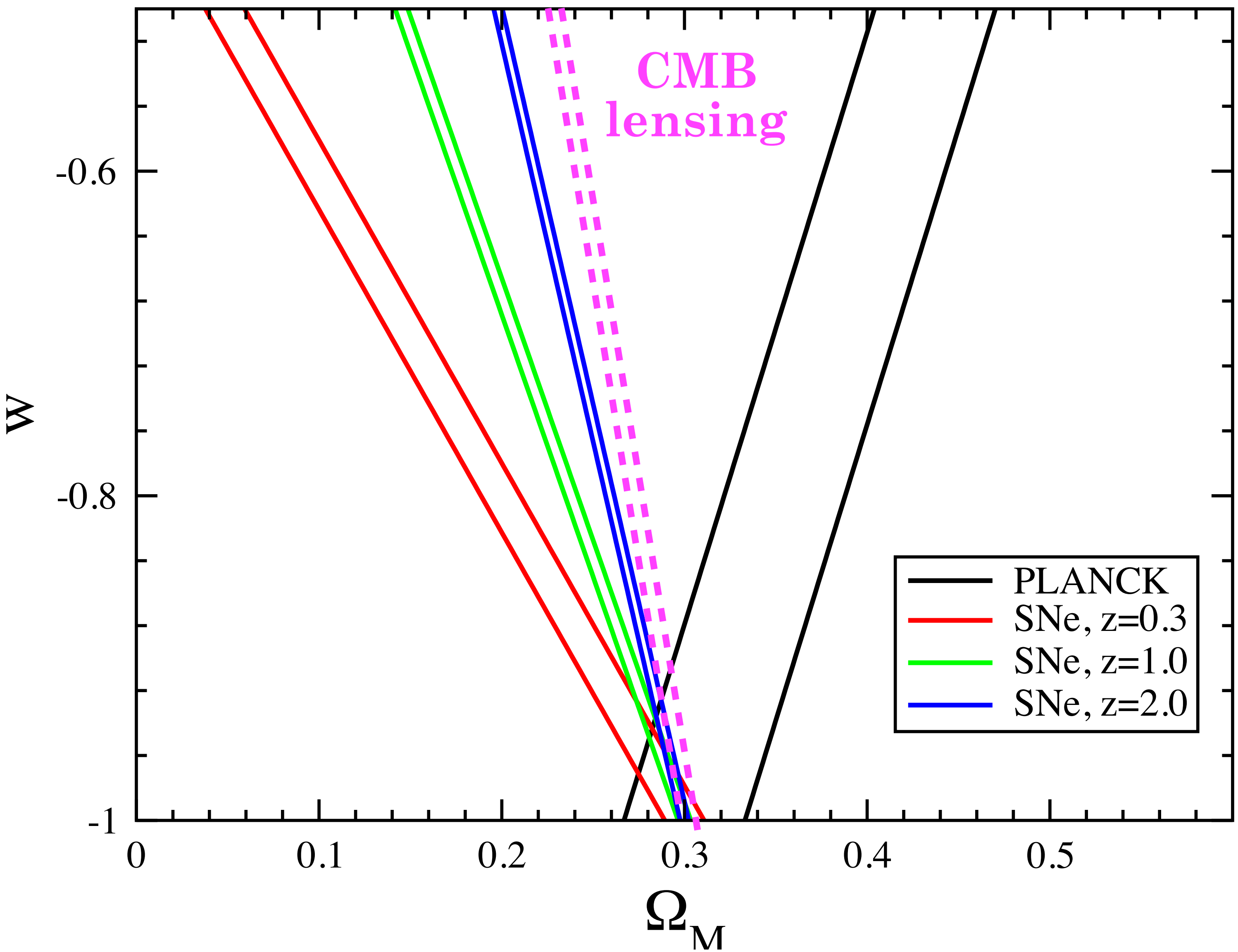
$D_A(z)$ with $\Omega_M h^2$ fixed is basically the "CMB shift parameter" R

$$R = \sqrt{\Omega_M h^2} \int_0^{z_*} \frac{dz'}{H_0 \sqrt{\Omega_M (1+z')^3 + (1-\Omega_M)(1+z')^{3(1+w)}}}$$



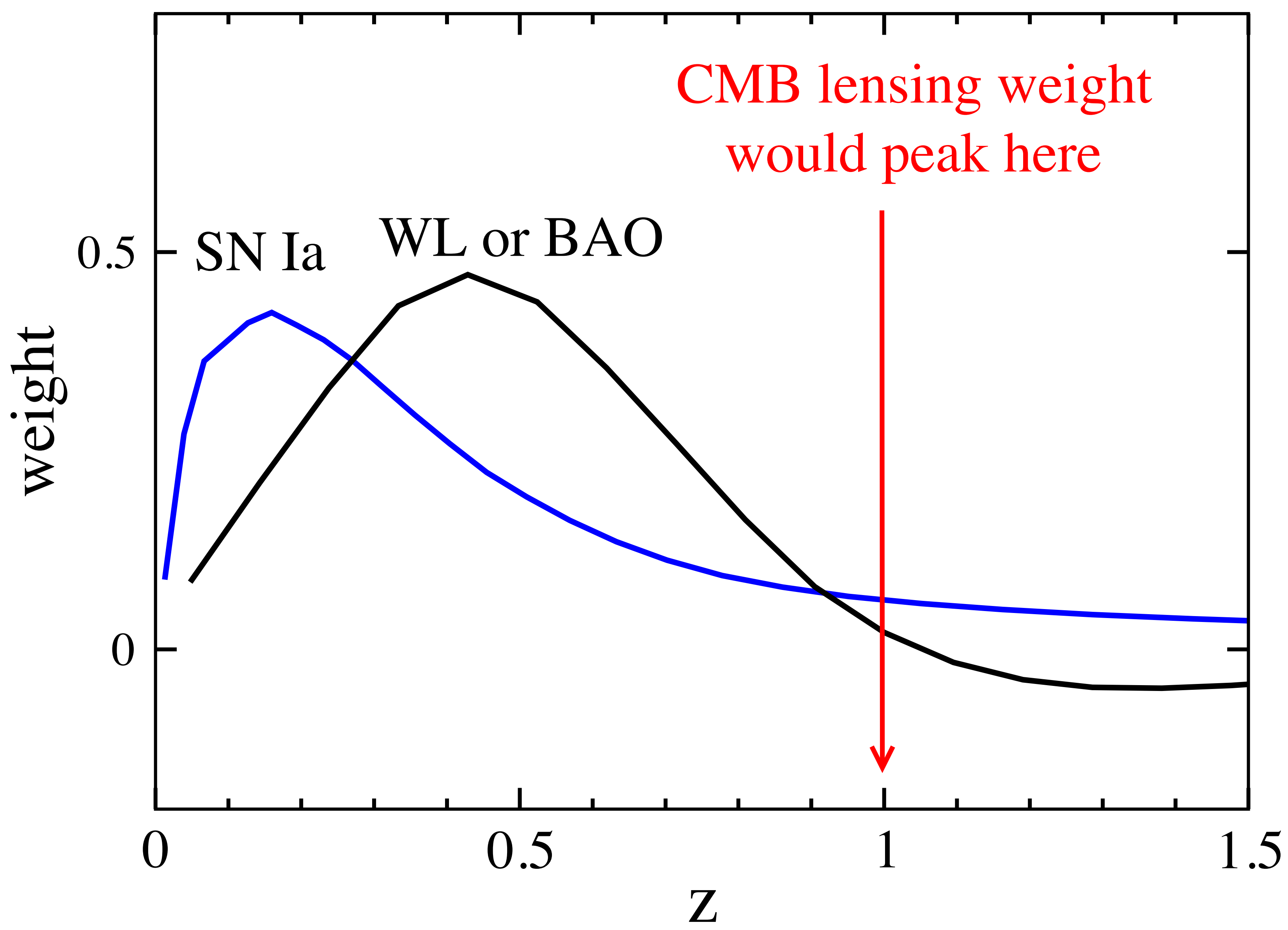
Frieman, Huterer, Linder & Turner 2003

CMB Lensing gives D_A(z~few)



[Recall, CMB lensing additionally carries info about power spectrum P(k)]

Redshifts where probes measure DE (i.e. w(z))



Parameter constraint forecasts: dark energy, early DE, neutrino mass

Model	Experiment	$\sigma(w_0)$	$\sigma(w_a)$	$\sigma(\Omega_e)$	$\sigma(\Sigma m_\nu)$ [eV]
ΛCDM	Planck	–	–	–	0.11
ΛCDM	CMBpol	–	–	–	0.036
w_0-w_a	Planck+SN	0.073	0.32	–	0.13
w_0-w_a	CMBpol+SN	0.066	0.25	–	0.041
w_0-Ω_e	Planck+SN	0.032	–	0.0041	0.15
w_0-Ω_e	CMBpol+SN	0.018	–	0.0019	0.047

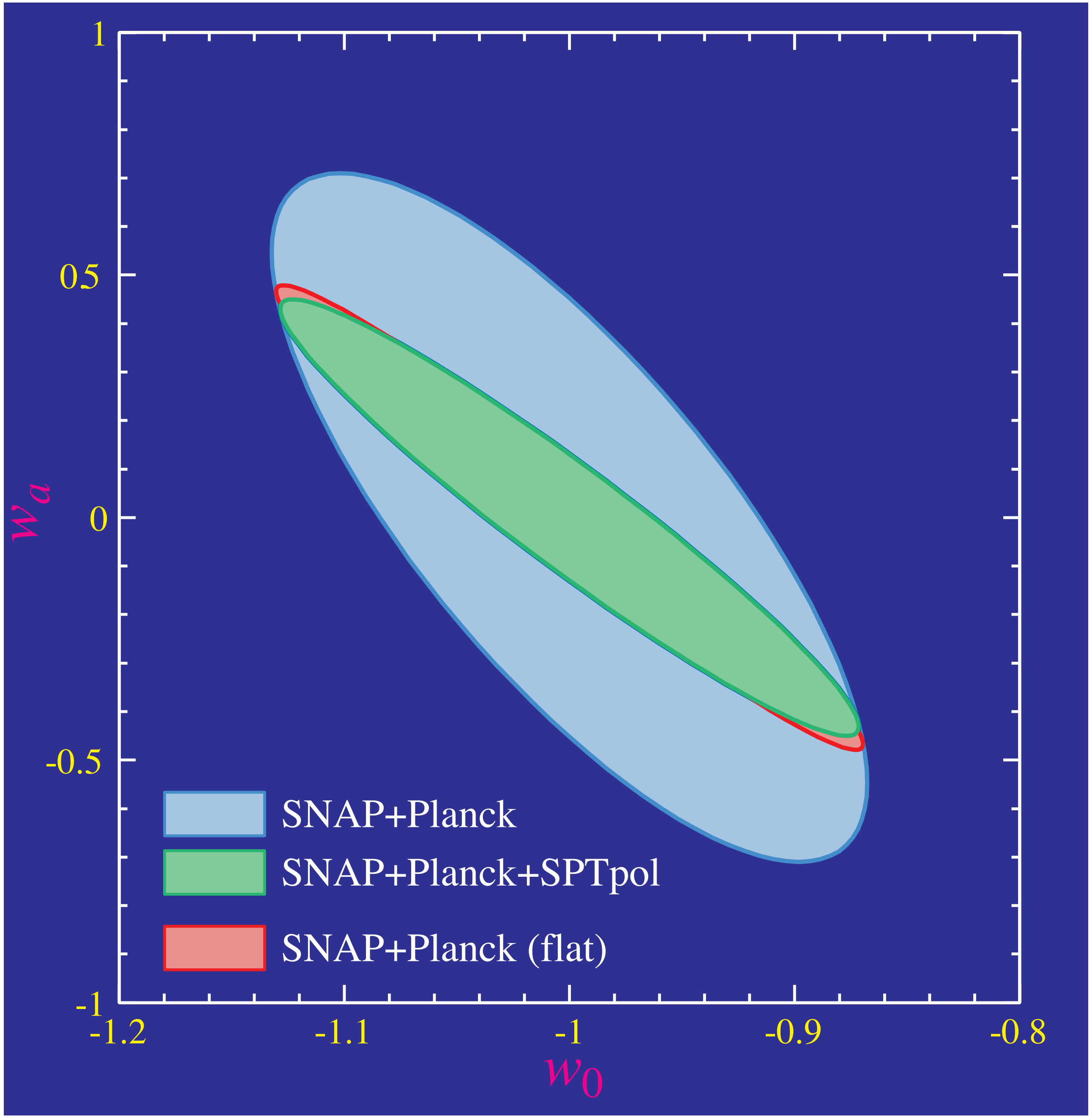
Future constraints with lensing:

- w_{pivot} to 0.02
- Ω_{early} to 0.002
- Σm_ν to 0.05

De Putter, Zahn and Linder 2009

Lensing breaks DE degeneracy with curvature:

$\sigma(w)_{\text{curved with lensing}} \approx \sigma(w)_{\text{flat without lensing}}$



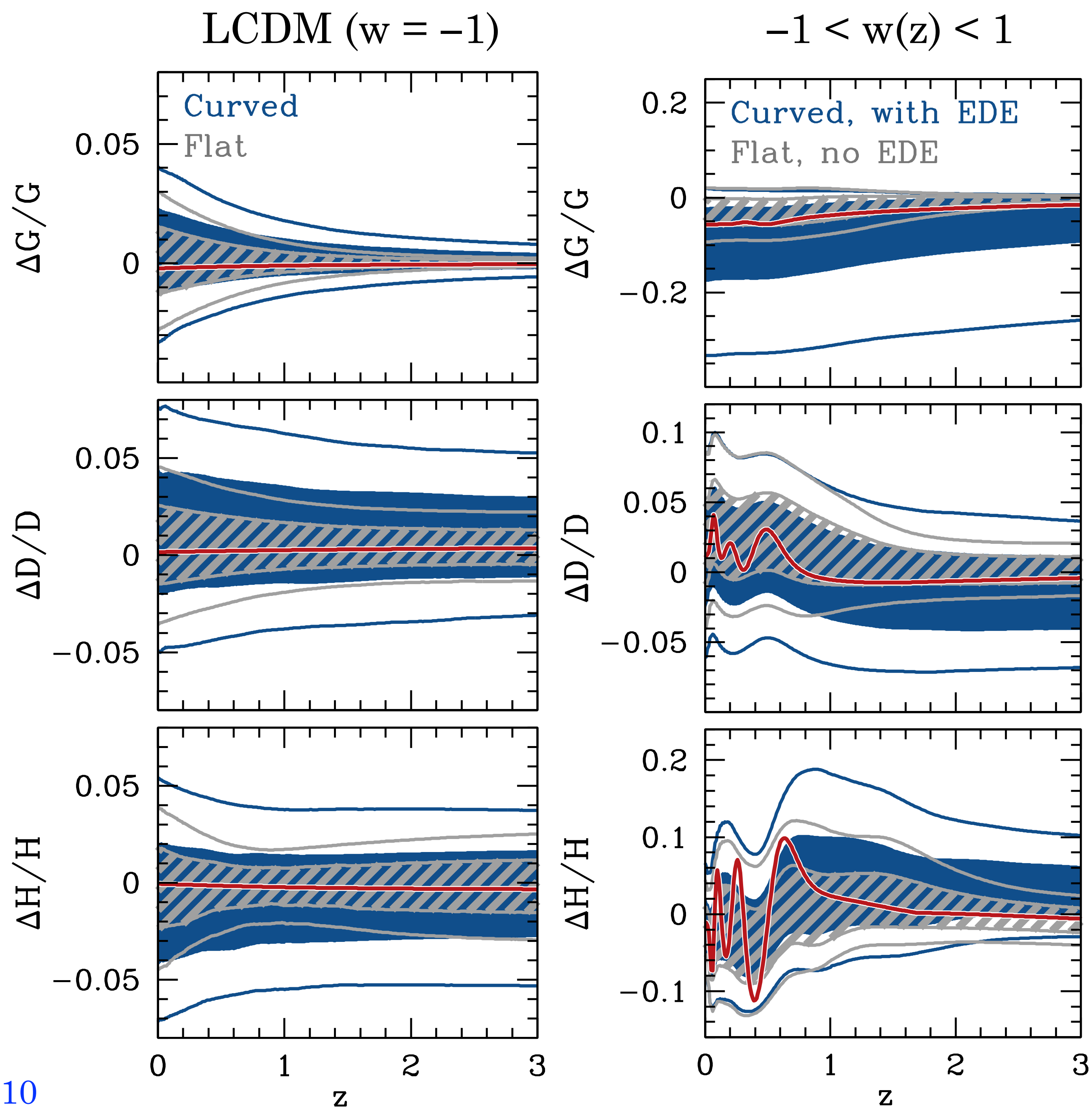
Hu, Huterer & Smith 2006

Falsifying general classes of DE models

Predictions on D/G/H
(68% and 95%)
from **current data**
(SN+CMB+BAO+H_0)

Allowed deviations
around best-fit
LCDM value shown

Red curve:
sample model
consistent with data



Mortonson, Hu & Huterer 2010

Conclusions - CMB lensing

- Is an important new probe of cosmology
- Provides measurement of $D_A(z)$, and $P(k, z)$, at $z\sim2$-3....
- ...and therefore helps in extending low-z lever arm on DE
- The (lensing) source is at exactly known redshift $z\approx1100$
- Helps break degeneracy between DE and curvature
- Helps improve constraints on sum of neutrino masses
- Probes the decelerating epoch; sensitive to surprises such as early dark energy (Ω_{early})