CMB Constraints on Fundamental Physics

Cosmology on the Beach, January 2011

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Lecture II

CMB & PARAMETERS

(Mostly Dark Energy)

Things we learned from lecture I

- Theory of CMB Temperature anisotropy was well established by 1995. No evidence of peaks in the angular spectrum at that time.
- This highly predictive theory motivated high accuracy measurements (Planck mission was approved and selected by ESA in 1996 !).
- Result: Success for the standard model based on passive and coherent perturbations. Textures and topological defects ruled out as the only mechanism of structure formation.
- Angular power spectrum can be described with few parameters: baryon density, CDM density, «Shift» parameter. This is what CMB can really measure.
- CMB does'nt measure total curvature. Results on Ω_{tot} may be biased towards larger values. Take CMB only contraints on curvature with grain of salt.

You need at least 15 parameters to fit an elephant.

How many parameters are needed to describe the CMB anisotropies ?

The standard cosmological model

- Assumes General Relativity, Inflation, Adiabatic and Scalar Perturbations, flat universe.

- Friedmann-Robertson-Walker (or Friedmann-Lemaitre) metric. Hubble Constant (+1)

$$H_0 = 100h\ km/s/Mpc$$

- 3 Energy components: Baryons, Cold Dark Matter, Cosmological Constant (+3). Flat Universe (-1).

$$\omega_b = \Omega_b h^2 \qquad \omega_{CDM} = \Omega_{CDM} h^2$$

- Initial conditions for perturbations given by Inflation: Adiabatic, nearly scale invariant initial power spectrum, only scalar perturbations. Two free parameters (+2): Amplitude and Spectral index.

$$P(k) \approx A_S \left(\frac{k}{k_0} \right)^{n_S}$$

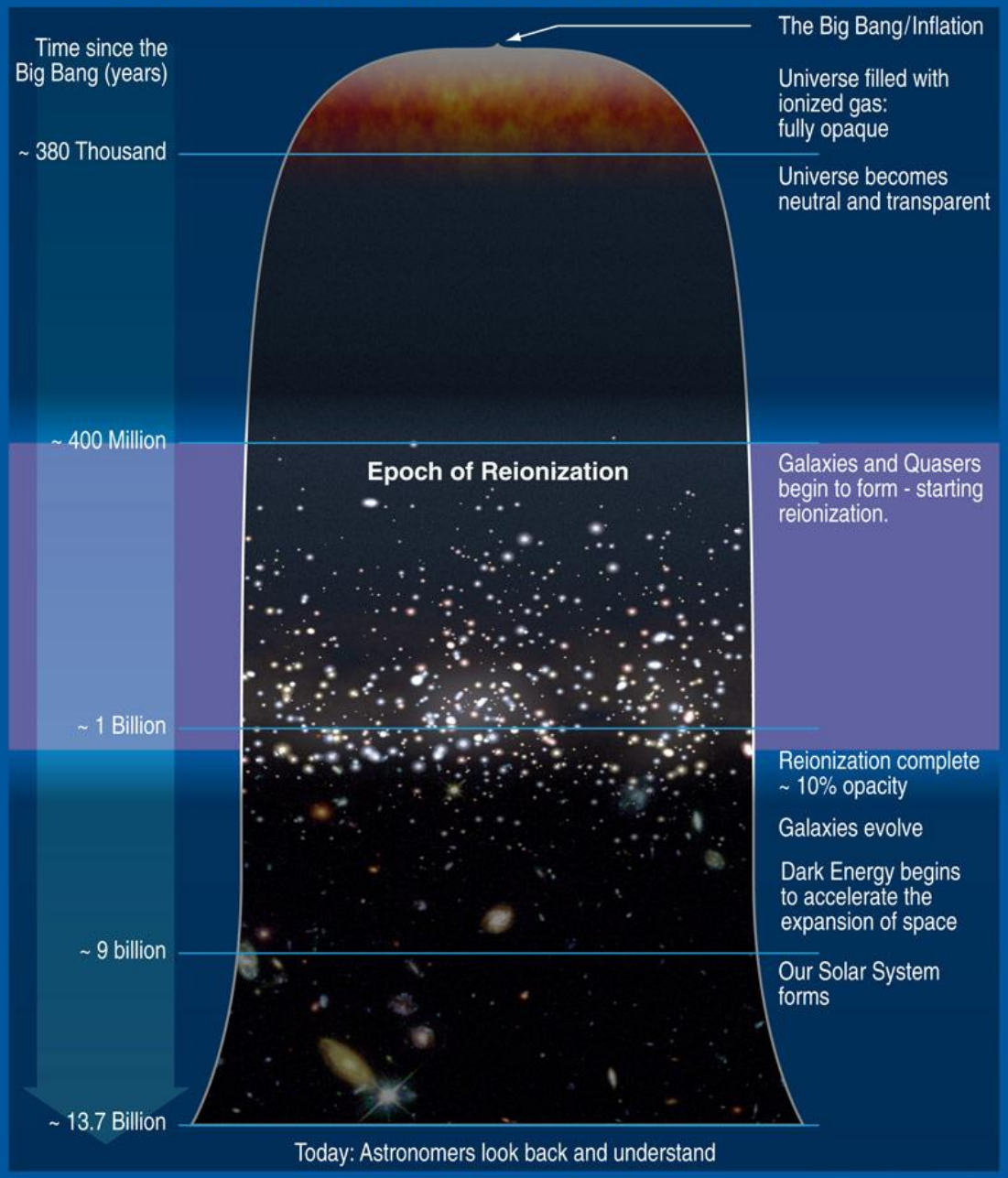
Pivot scale is usually fixed to:

$$k_0 = 0.002\ hMpc^{-1}$$

- Late universe reionization characterized with a single parameter(+1) : optical depth τ or reionization redshift z_r.

Total: 1+3-1+2+1= 6 parameters.

First Stars and Reionization Era



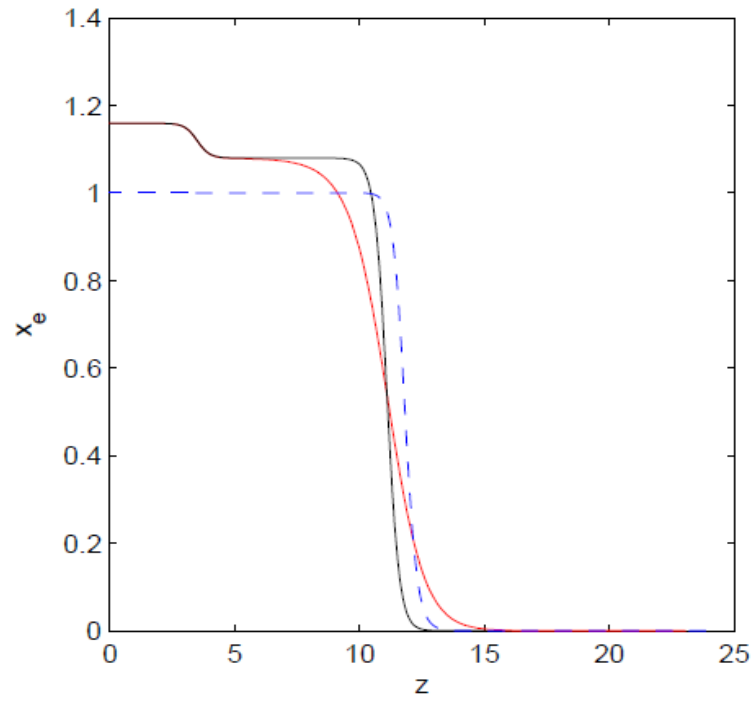
NASA/WMAP Science Team

The standard reionization model

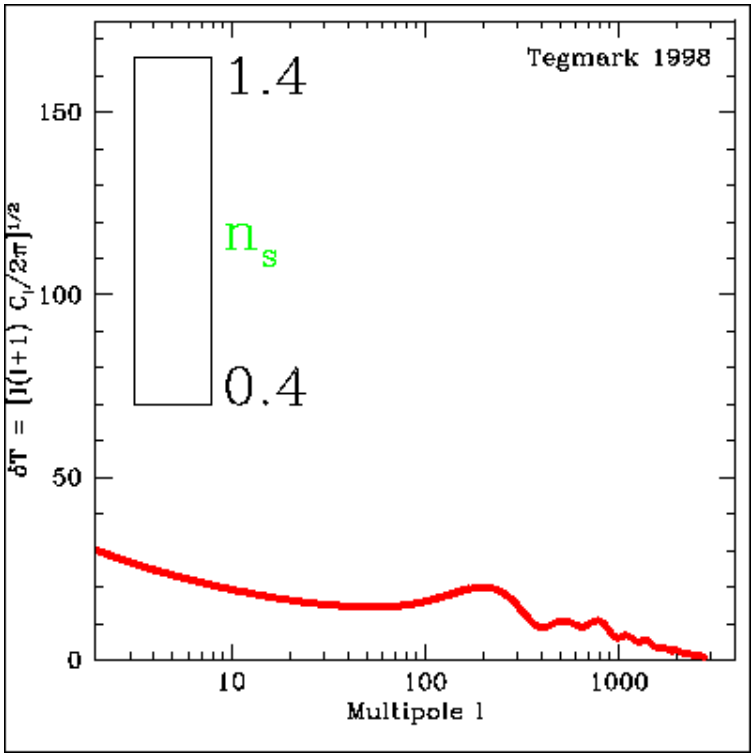
$$y(z_{re}) = (1 + z_{re})^{3/2}$$

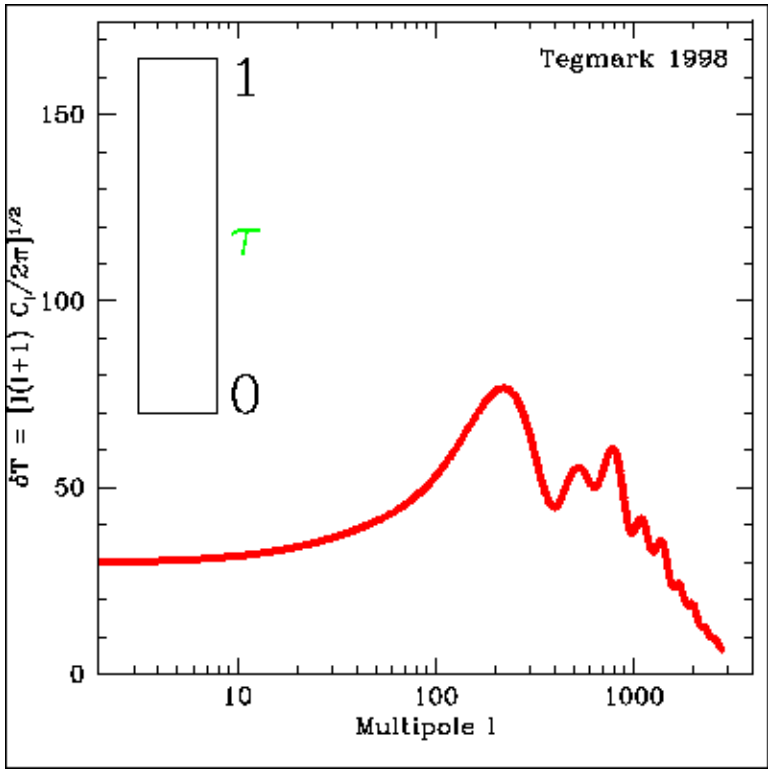
$$x_e(y) = \frac{f}{2}\left[1 + \tanh\left(\frac{y - y(z_{re})}{\Delta_y}\right)\right]$$

$$\tau = \int_0^{25} \frac{\sigma_T n_e x_e}{(1+z')H(z')} dz'$$

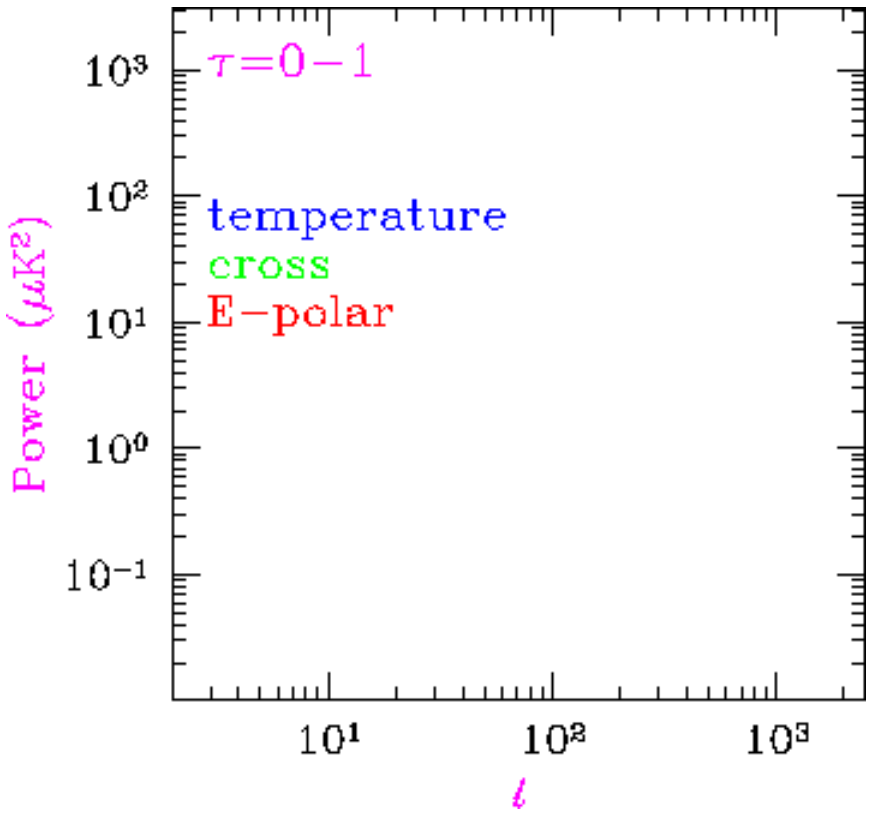


However, n is almost completely degenerate with the optical depth !





Measuring large scale CMB polarization can break this degeneracy.



WMAP7 constraints, Komatsu et al, 2010.

Class	Parameter	*WMAP* 7-year Mean[c]
Primary	$100\Omega_b h^2$	$2.249^{+0.056}_{-0.057}$
	$\Omega_c h^2$	0.1120 ± 0.0056
	Ω_Λ	$0.727^{+0.030}_{-0.029}$
	n_s	0.967 ± 0.014
	τ	0.088 ± 0.015
	$\Delta^2_{\mathcal{R}}(k_0)$[d]	$(2.43 \pm 0.11) \times 10^{-9}$
Derived	σ_8	$0.811^{+0.030}_{-0.031}$
	H_0	70.4 ± 2.5 km/s/Mpc
	Ω_b	0.0455 ± 0.0028
	Ω_c	0.228 ± 0.027
	$\Omega_m h^2$	$0.1345^{+0.0056}_{-0.0055}$
	$z_{\rm reion}$[e]	10.6 ± 1.2
	t_0[f]	13.77 ± 0.13 Gyr

Constraints on the spectral index can be affected by Model of reionization.

A more model independent parametrization of the reionization process based on principal components (Mortonson and Hu,2009) could change the results on n. See talk by Stefania Pandolfi tomorrow.

Dataset	Ionization	n (68% c.l.)	95% c.l.
WMAP7	sudden	0.965 ± 0.014	$n \leq 0.993$
CMB All	sudden	0.959 ± 0.013	$n \leq 0.984$
WMAP7	MH	0.993 ± 0.023	$n \leq 1.042$
CMB All	MH	0.975 ± 0.017	$n \leq 1.011$
CMB All+LRG-7	MH	0.966 ± 0.014	$n \leq 0.994$
CMB All+BAO	MH	0.965 ± 0.014	$n \leq 0.995$
CMB All+BAO	MH+$w(z)$	0.985 ± 0.018	$n \leq 1.025$
WMAP7	LWB	0.977 ± 0.018	$n \leq 1.01$
CMB All	LWB	0.963 ± 0.015	$n \leq 0.998$

S.Pandolfi et al, Phys.Rev.D81:123509,2010
S.Pandolfi et al, Phys.Rev.D82:123527,2010

WMAP7 constraints, Komatsu et al, 2010.

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	Ω_c	0.228 ± 0.027
	$\Omega_m h^2$	$0.1345^{+0.0056}_{-0.0055}$
	$z_{\rm reion}$[e]	10.6 ± 1.2
	t_0[f]	13.77 ± 0.13 Gyr

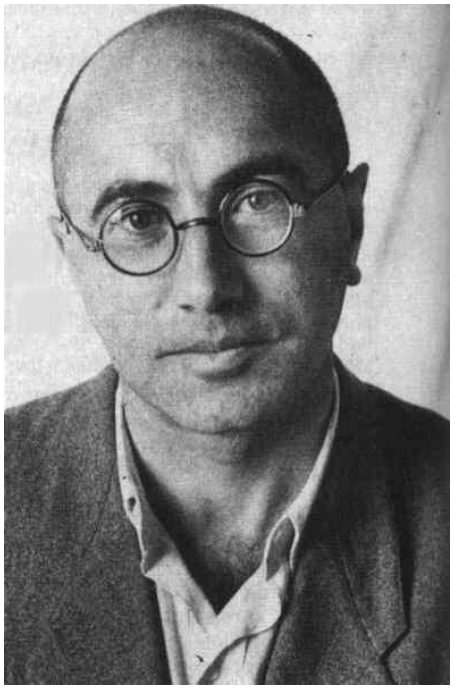
Friedmann Cosmological Model works only if:

$$\Omega_\Lambda = 0.73 \pm 0.03$$

A model without cosmological constant is now ruled out at more than 20 sigma!

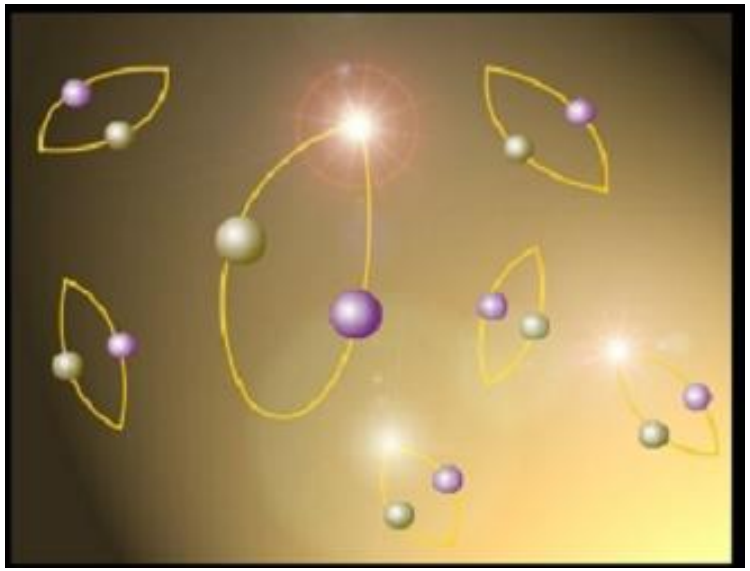
The problem of the Cosmological Constant

Already in 1968 Zeldovich noticed that the vacuum energy in particle physics could be a source for a cosmological constant.



Zeldovich

"The genie (Λ) has been let out of the bottle"



"A new field of activity arises, namely the determination of Λ"

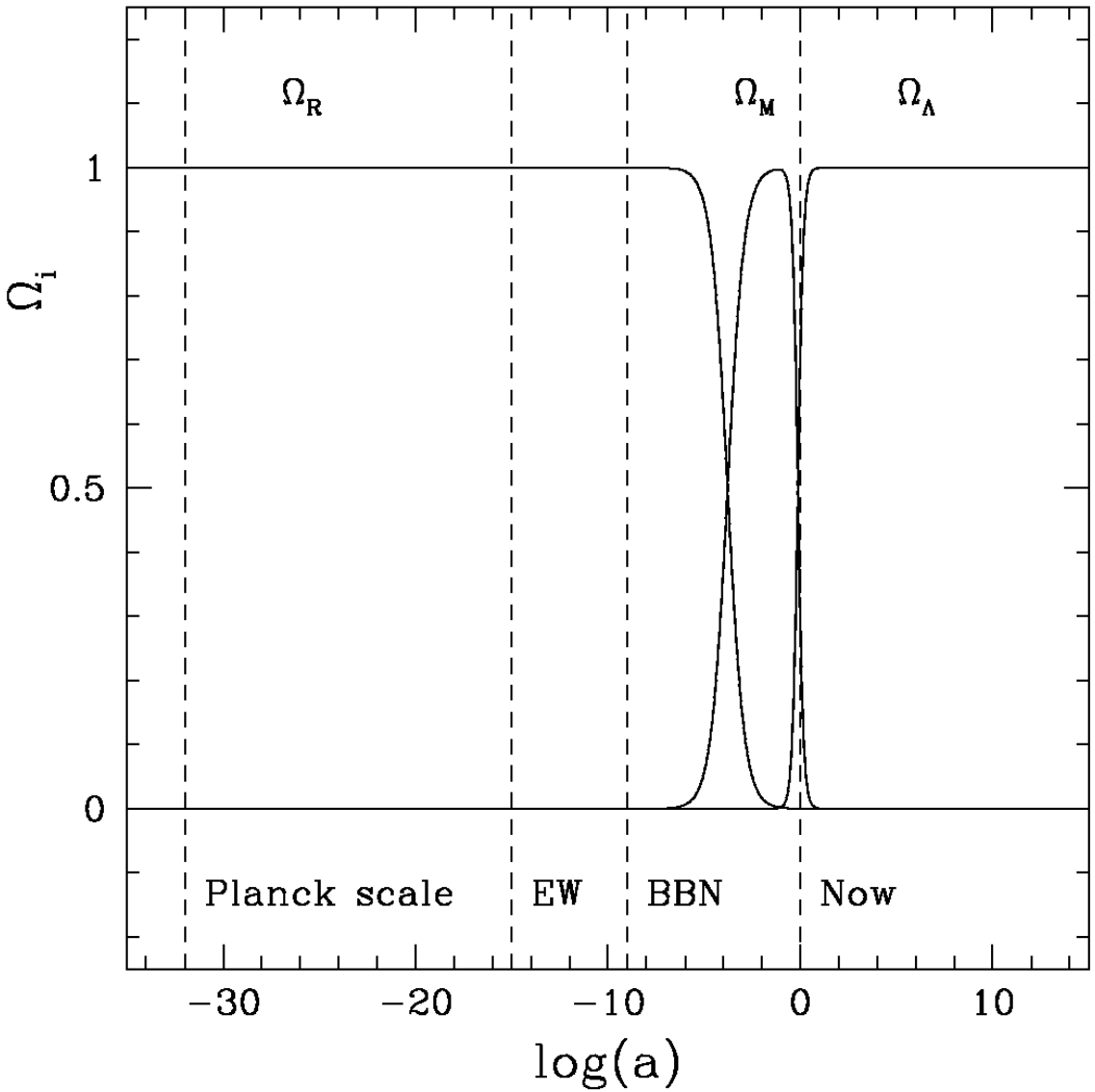
This anyway would lead to a great problem. The vacuum energy in particle physics is infinite. We may stop at Planck Scale but still we have a discrepancy of 120 orders of magnitude:

$$\rho_{vac} \approx \int_0^{M_P} \sqrt{k^2 + m^2}\, d^3k \approx M_p^4 \approx 10^{120} \rho_\Lambda$$

If we consider supersimmetry we go in the right direction but we are still 60 orders of magnitude away !

$$\rho_{vac} \approx \rho_{susy} \approx M_{susy}^4 \approx 10^{60} \rho_\Lambda$$

But there is a second problem, why the universe is accelerating Today ? ?



Why so small ? Why now ?

COSMOLOGICAL COSTANT vs "Something else"

$$\rho_\Lambda \equiv const$$

$$p_\Lambda = -\rho_\Lambda$$

$$\delta\rho_\Lambda = 0$$

Vs.

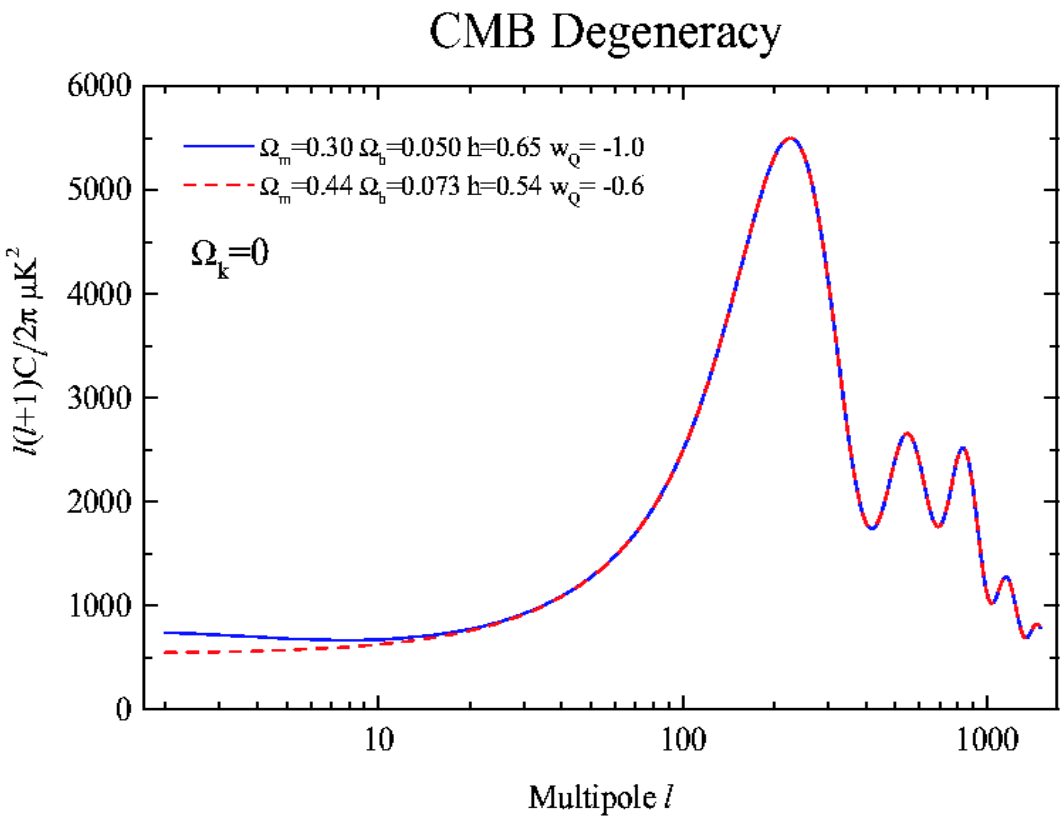
$$\rho_X(z) \equiv \rho_X(0)\exp\left(3\int_0^z dz' \frac{1+w(z')}{1+z'}\right)$$

$$p_X = w(z)\rho_X$$

$$\delta\rho_X \neq 0$$

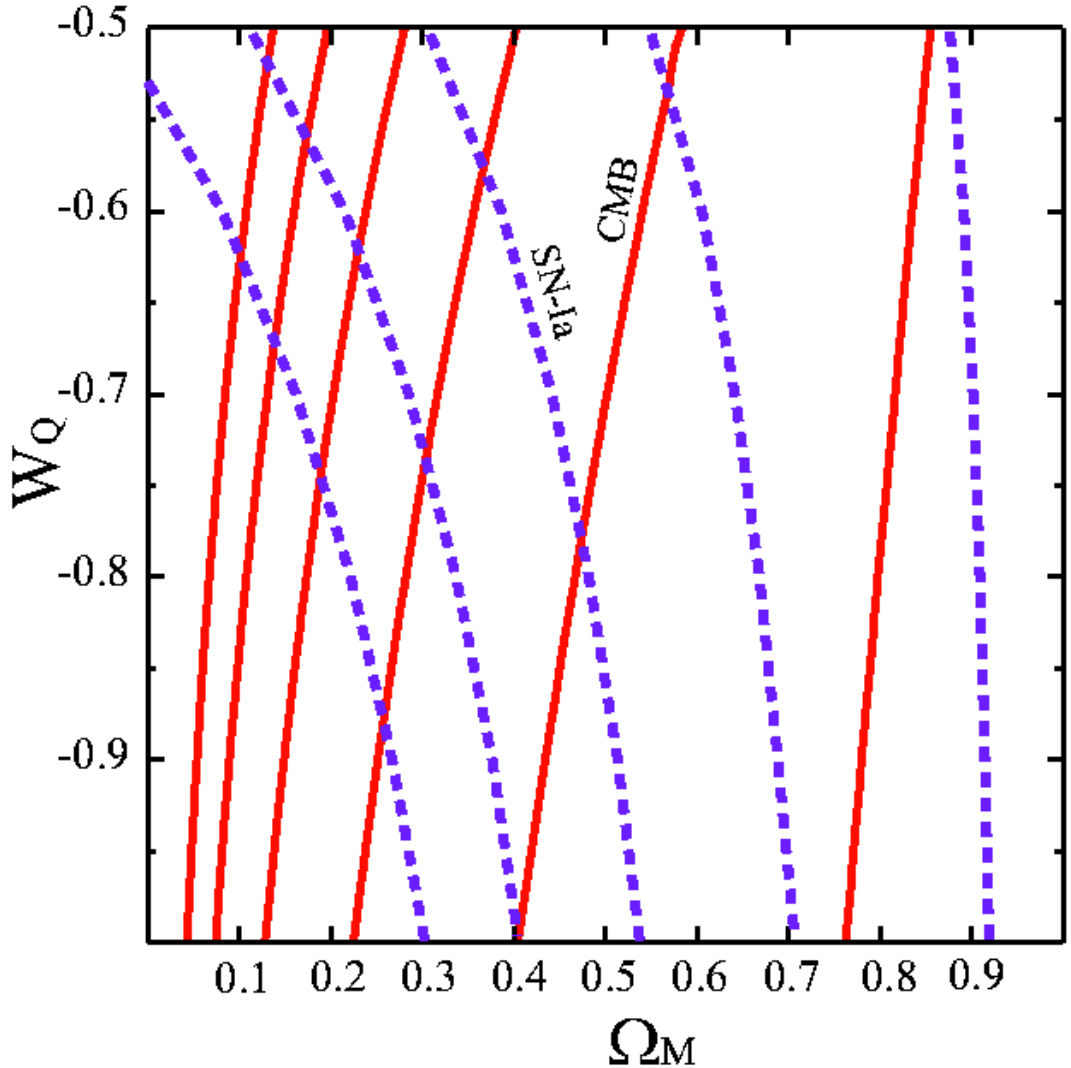
Dark Energy and the shift parameter

A variation in w changes
The angular diameter distance
At recombination and the
Shift parameter.
We have a degeneracy also
In the case of flat universes.

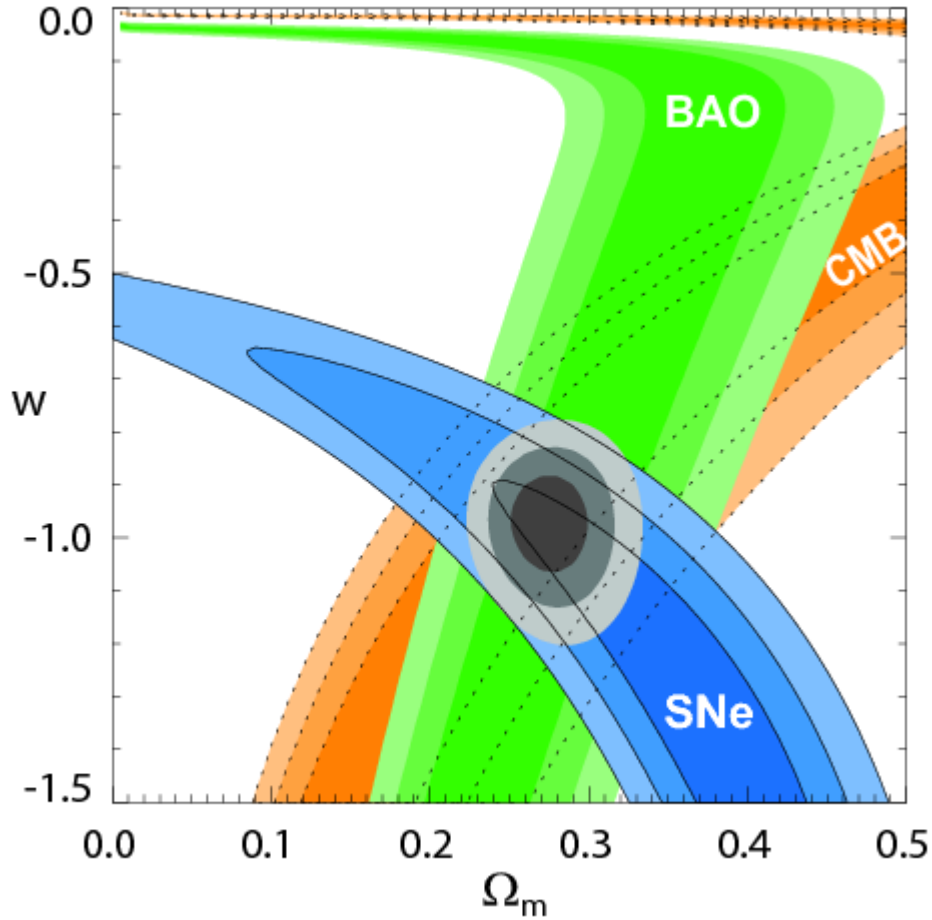


$$R = \frac{1}{\sqrt{\Omega_m}} \int_0^{z_{dec}} \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_Q (1+z)^{3(1+w_Q)}}}$$

Dark Energy and the shift parameter



Combining CMB and SN-Ia using the shift parameter



Kowalski et al, Astrophys.J.686:749-778,2008

CMB data is usually included in SN-Ia And BAO analysis by using the WMAP Constraint on the shift parameter.

WMAP constraints R

$$R = \frac{H_0}{\sqrt{\Omega_m}} \int_0^{z_{dec}} \frac{dz}{H(z)}$$

Constraints on the w-Ω_m plane are combined as independent datasets.

Is the CMB constraint on the shift parameter model independent ?

Model	R
ΛCDM	1.707 ± 0.025
wCDM ($c^2_{DE} = 1$)	1.710 ± 0.029
wCDM ($c^2_{DE} = 0$)	1.711 ± 0.025
ΛCDM $m_\nu > 0$	1.769 ± 0.040
ΛCDM $N_{eff} \neq 3$	1.714 ± 0.025
ΛCDM $\Omega_k \neq 0$	1.714 ± 0.024
$w(z)$CDM CPL ($c^2_{DE} = 1$)	1.710 ± 0.026
ΛCDM + tensor	1.670 ± 0.036
ΛCDM + running	1.742 ± 0.032
ΛCDM + running + tensor	1.708 ± 0.039
ΛCDM + features	1.708 ± 0.028

Corasaniti, Melchiorri, Phys.Rev.D77:103507,2008
Elgaroy, Multamaki, http://arxiv.org/abs/astro-ph/0702343

Dark Energy Perturbations

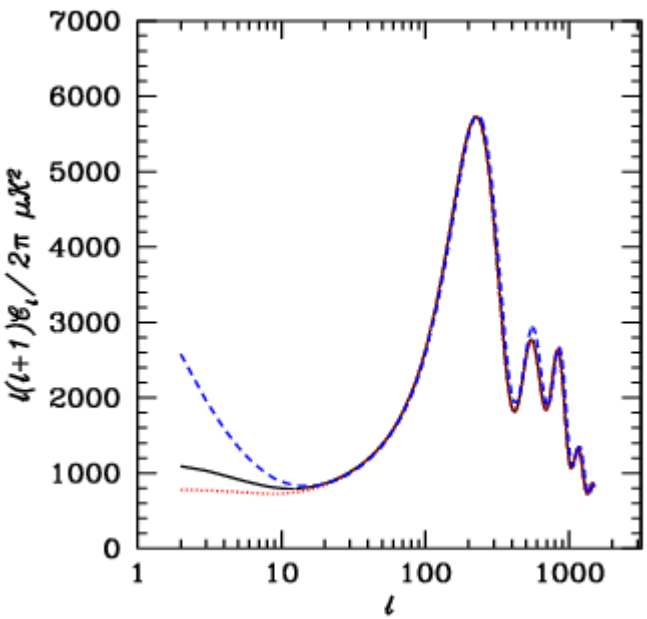
For a perfect fluid the speed of sound purely arises from adiabatic perturbations in the pressure, p, and energy density ρ and the adiabatic speed of sound is purely determined by the equation of state w:

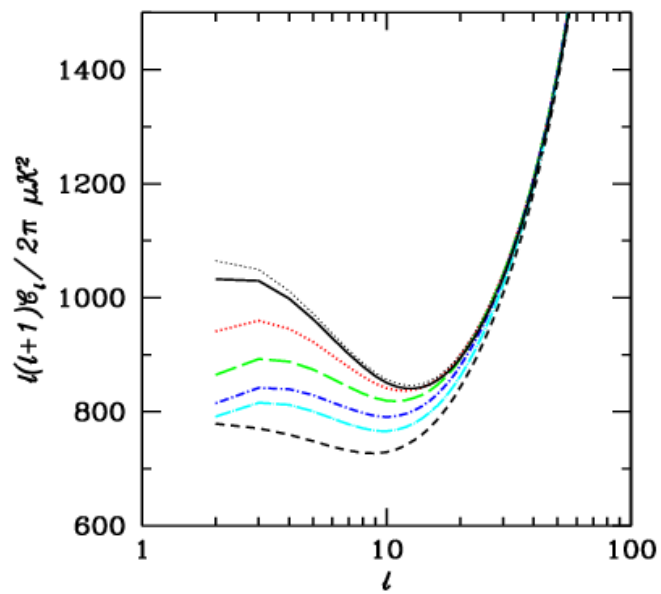
$$
\begin{aligned}
w_i &\equiv \frac{p_i}{\rho_i} \\
c_{ai}^2 &\equiv \frac{\dot{p}_i}{\dot{\rho}_i} = w_i - \frac{\dot{w}_i}{3\mathcal{H}(1+w_i)}
\end{aligned}
$$

In imperfect fluids, for example most scalar field or quintessence models, however, dissipative processes generate entropic perturbations in the fluid and this simple relation between background and the speed of sound breaks down.
This is usually parametrized by introducing the rest frame sound speed:

$$
\begin{aligned}
\dot{\delta} &= -(1+w)\left\{\left[k^2 + 9\mathcal{H}^2(\hat{c}_s^2 - c_a^2)\right]\frac{\theta}{k^2} + \frac{\dot{h}}{2}\right\} \\
&\quad -3\mathcal{H}(\hat{c}_s^2 - w)\delta \\
\frac{\dot{\theta}}{k^2} &= -\mathcal{H}(1-3\hat{c}_s^2)\frac{\theta}{k^2} + \frac{\hat{c}_s^2}{1+w}\delta\,.
\end{aligned}
$$

Dark Energy Perturbations

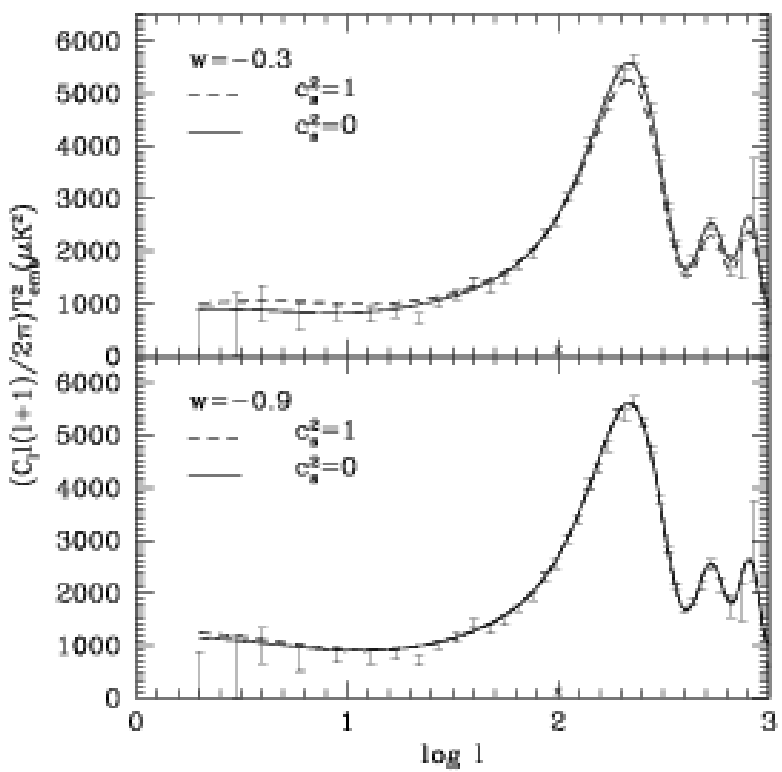


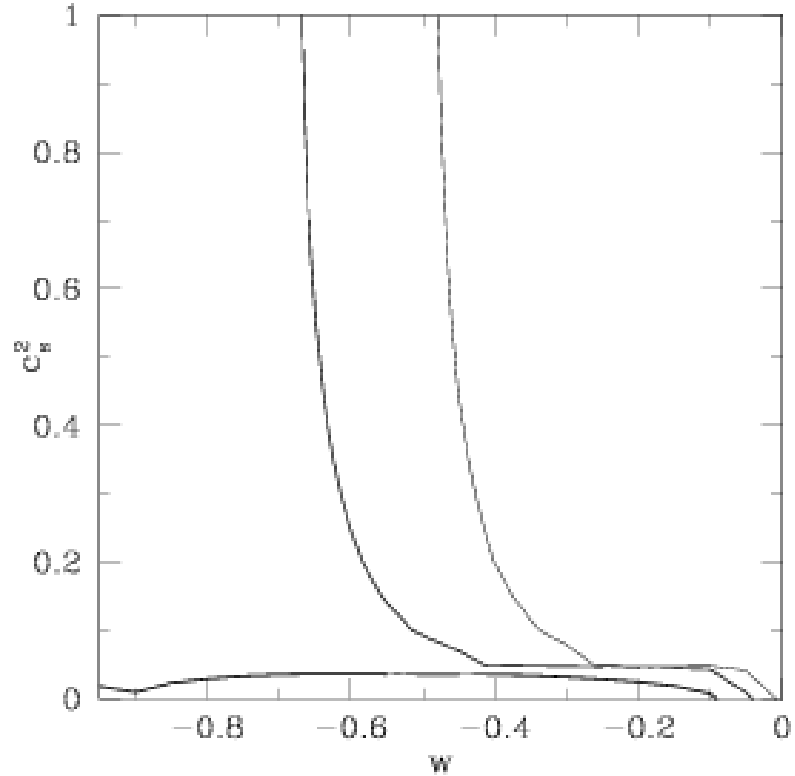


- Perturbations in the dark energy component must be included in order to avoid a too large ISW signal.
- Effects of variation in the sound speed are very small and substantially decrease for values of w closer to -1.

Weller, Lewis, Mon.Not.Roy.Astron.Soc.346:987-993,2003

Dark Energy Perturbations





CMB alone is essentially unable to constrain the dark energy sound speed.

Bean, Dore', Phys.Rev.D68:023515,2003

Integrated Sachs-Wolfe effect Part One

while most cmb anisotropies arise on the last scattering surface, some may be induced by passing through a time varying gravitational potential:

$$\frac{\delta T}{T} = -2\int d\tau\, \dot{\Phi}(\tau)$$

linear regime – integrated Sachs-Wolfe (ISW)

non-linear regime – Rees-Sciama effect

when does the linear potential change?

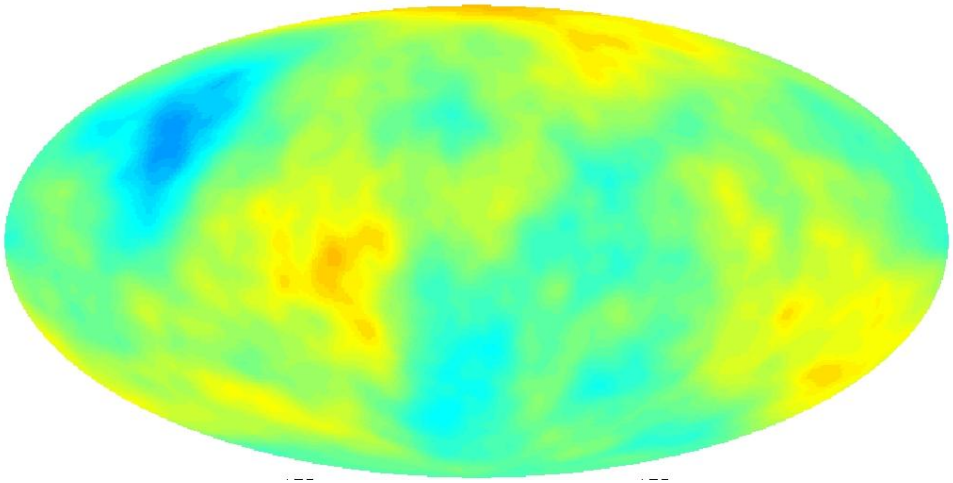
$$\nabla^2 \Phi = 4\pi G a^2 \overline{\rho}\, \delta$$

Poisson's equation

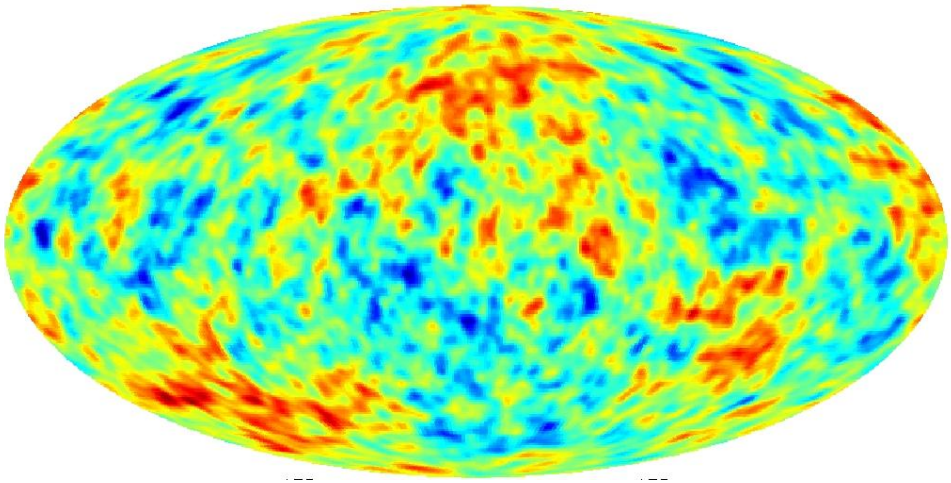
- constant during matter domination
- decays after curvature or dark energy come to dominate (z~1)

induces an additional, uncorrelated layer of large scale anisotropies

two independent maps

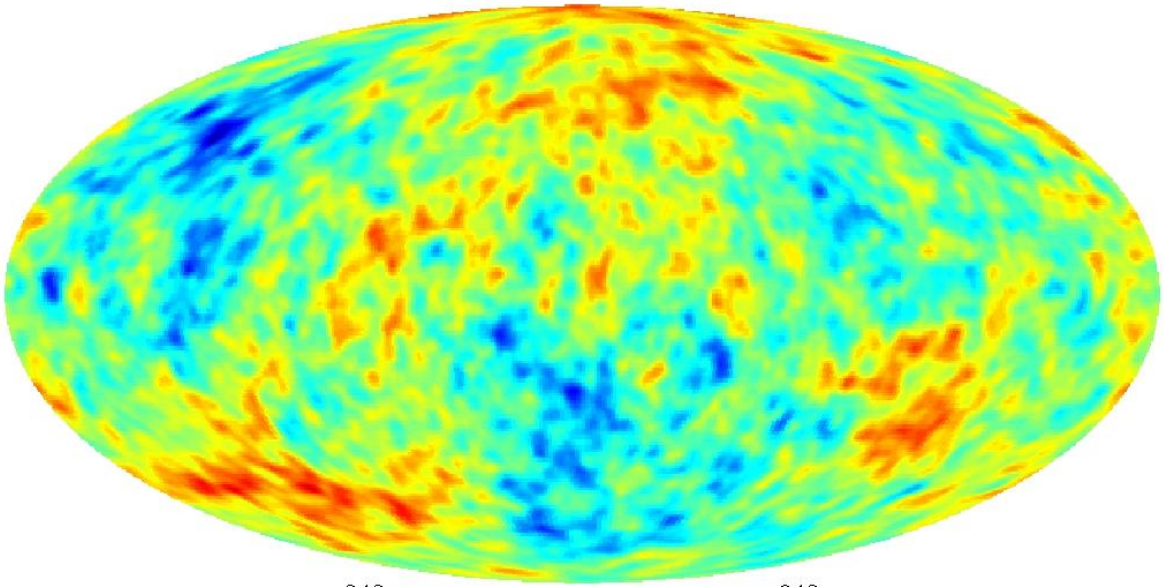


Integrated Sachs-Wolfe map
Mostly large angular features



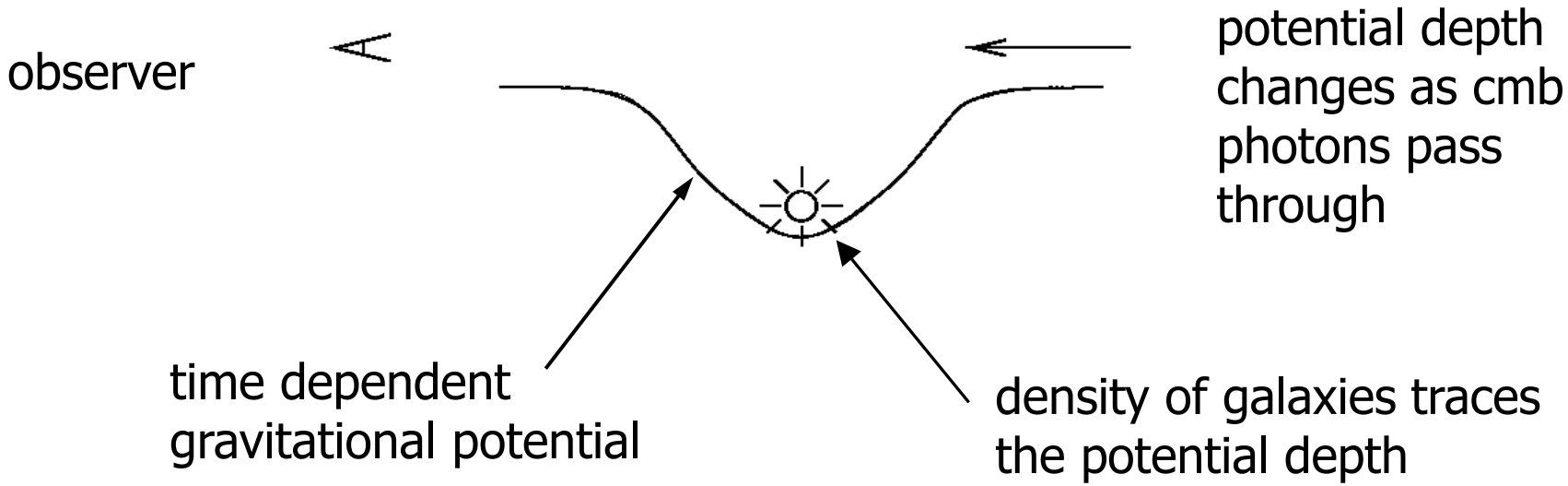
Early time map (z > 4)
Mostly from last scattering surface

Observed map is total of these, and has features of both (3 degree resolution)



compare with large scale structure

ISW fluctuations are correlated with the galaxy distribution!



since the decay happens slowly, we need to see galaxies at high redshifts (z~1)

- active galaxies (quasars, radio, or hard x-ray sources)
- possibility of accidental correlations means full sky needed

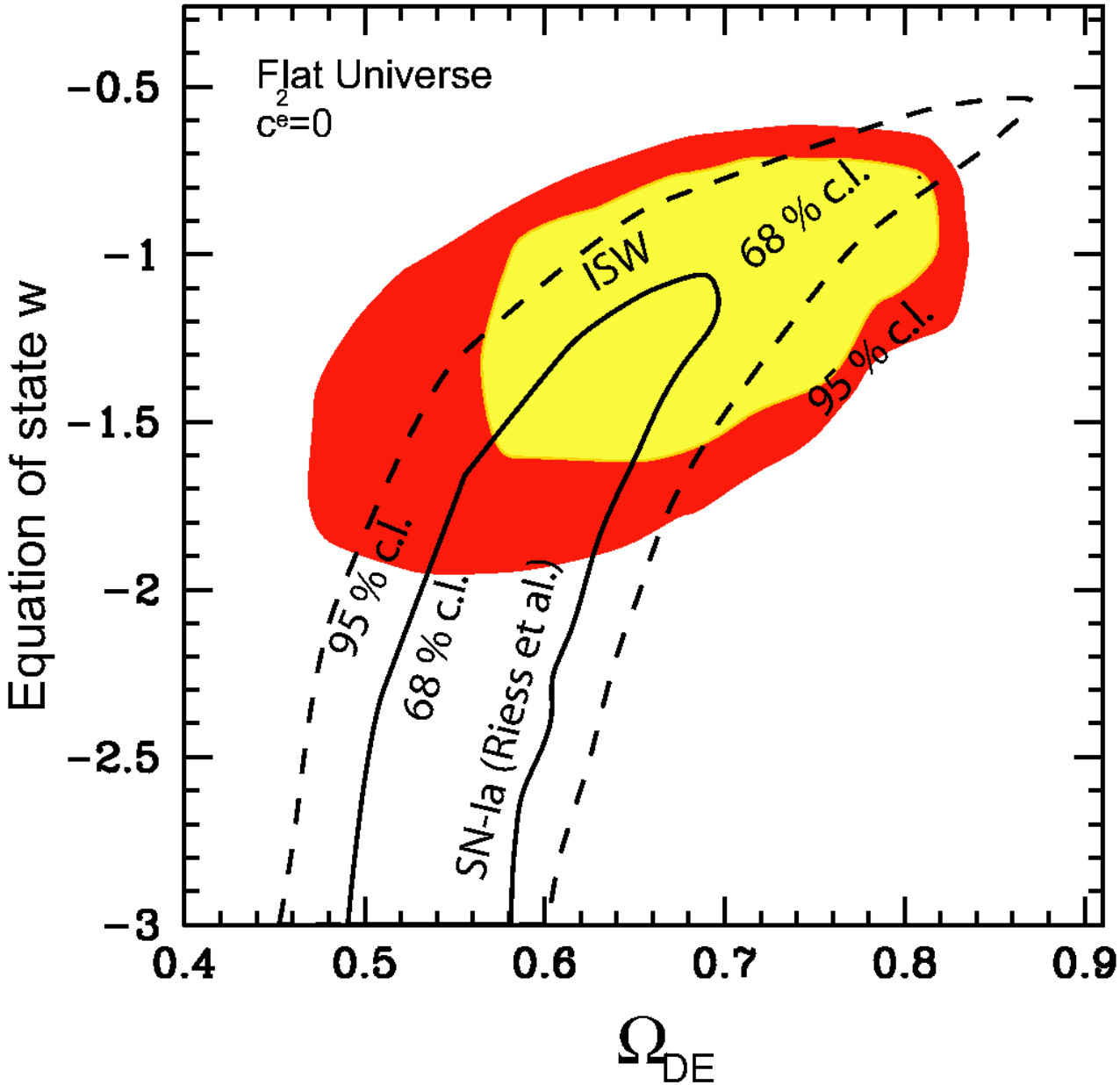
Current Observational Constraints

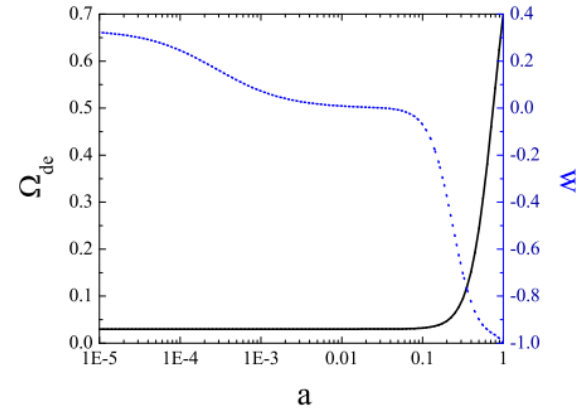
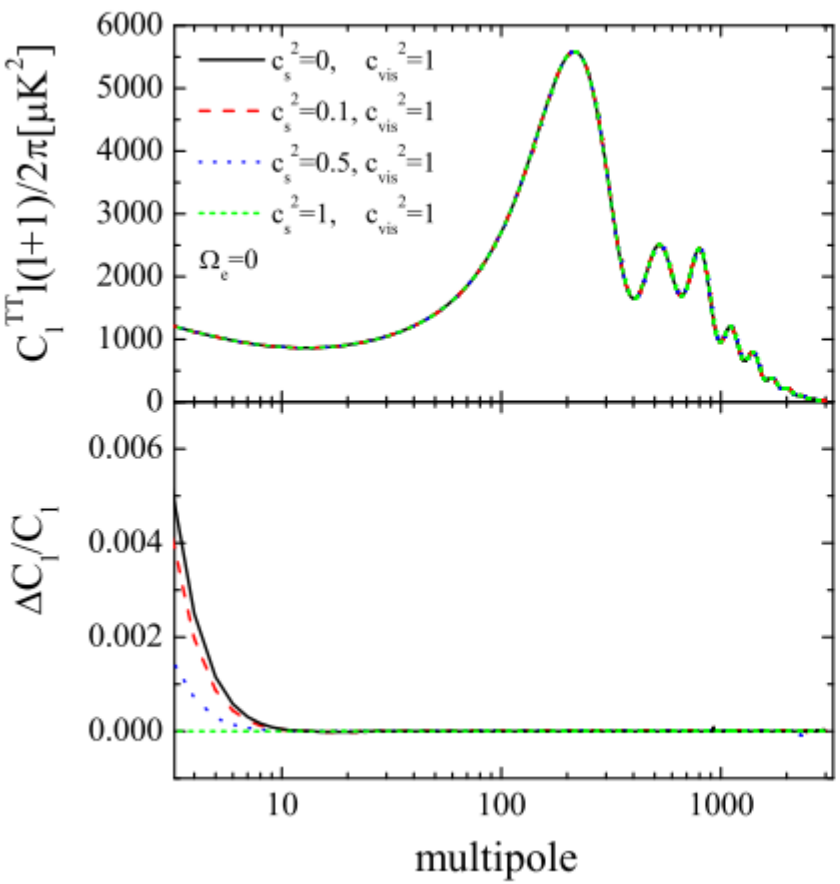
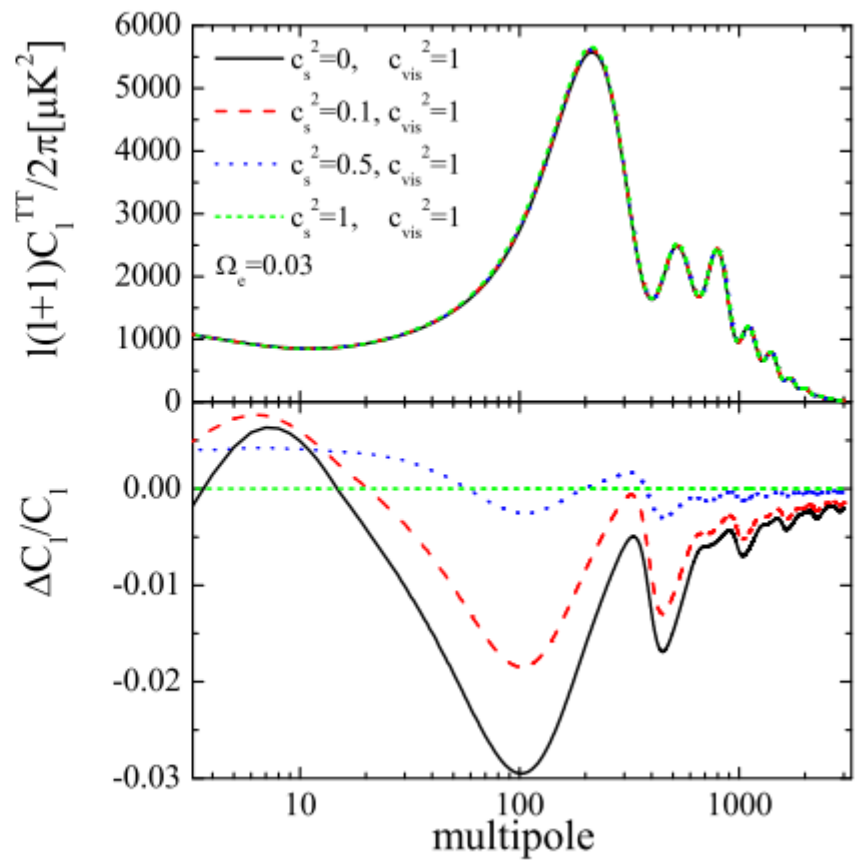
	5000 T-only Monte Carlos		5000 full Monte Carlos		JK - δ only		JK - δ and T	
catalogue	A	S/N	A	S/N	A	S/N	A	S/N
2MASS cut	1.22 ± 1.87	0.7σ	1.00 ± 1.96	0.5σ	0.66 ± 0.77	0.9σ	1.36 ± 1.10	1.2σ
SDSS	1.58 ± 0.70	2.2σ	1.48 ± 0.66	2.2σ	1.24 ± 0.42	3.0σ	1.59 ± 0.44	3.6σ
LRG	1.67 ± 0.76	2.2σ	1.73 ± 0.80	2.2σ	0.92 ± 0.50	1.8σ	1.22 ± 0.49	2.5σ
NVSS	1.12 ± 0.40	2.8σ	1.20 ± 0.37	3.3σ	0.68 ± 0.29	2.4σ	0.83 ± 0.27	3.1σ
HEAO	1.10 ± 0.41	2.7σ	1.22 ± 0.45	2.7σ	0.97 ± 0.26	3.7σ	1.00 ± 0.24	4.2σ
QSO	1.40 ± 0.53	2.6σ	1.33 ± 0.54	2.5σ	1.50 ± 0.58	2.6σ	1.33 ± 0.46	2.9σ
TOTAL	$\mathbf{1.02 \pm 0.23}$	$\mathbf{4.4\sigma}$	$\mathbf{1.24 \pm 0.27}$	$\mathbf{4.5\sigma}$	—	—	—	—

Giannantonio et al, '08
Ho et al, '08

Late ISW is detected at about 4 standard deviations.

Corasaniti, Giannantonio, AM, Phys.Rev. D71 (2005) 123521



ISW is sensitive
to dark energy perturbations
but also to w, etc.
Prospects for determining
The dark energy sound
Speed are not really
Promising....

Dark Energy can/must be more complicate than a constant with redshift w. In case of early dark energy perturbations have a larger impact on the CMB angular power spectrum.