Constraining Dark Energy with the Cosmic Microwave Background

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Outline

1) Large Scale Cosmic Microwave Anisotropies

2a) Scalar Field Dark Energy

2b) Generalised Dark Energy Perturbations

3) Parameter Constraints

Large Scale Cosmic Microwave Anisotropies

$$C_l = 4\pi \int \frac{dk}{k} P_\chi \left| \Delta_l(k,\eta_0)^2 \right|$$

initial power

transfer function

large scales: $\Delta_l(k,\eta_0) = \Delta_l^{LSS}(k) + \Delta^{ISW}(k)$

ordinary Sachs − Wolfe;
from Last Scattering Surface

Integrated Sachs − Wolfe
effect (ISW).

ISW: $$\Delta_l^{ISW}(k) = 2\int d\eta\, e^{-\tau(\eta)} \phi' \, j_l[k(\eta-\eta_0)]$$

Poisson equation: $$k^2 \phi' = -4\pi G \frac{d}{d\eta}\left[a^2\left(\overline{\delta\rho_m} + \overline{\delta\rho_{de}}\right)\right]$$

(in rest frame of total energy)

Matter Domination: $\delta\rho_m \sim a^{-2}$ $\Rightarrow$ No ISW !

Presence of Λ or Dark Energy component: PRESENCE of ISW !

even in case of Λ where no perturbations are in the dark energy component (background evolution different) !

Perturbations in the Dark Energy Component

a) Scalar Fields:

assume: equation of state factor w is constant
(otherwise Martin Kunz)

use scalar
field to compute
perturbations

$$V(\varphi) \equiv \frac{1-w}{2}\rho_{de}$$

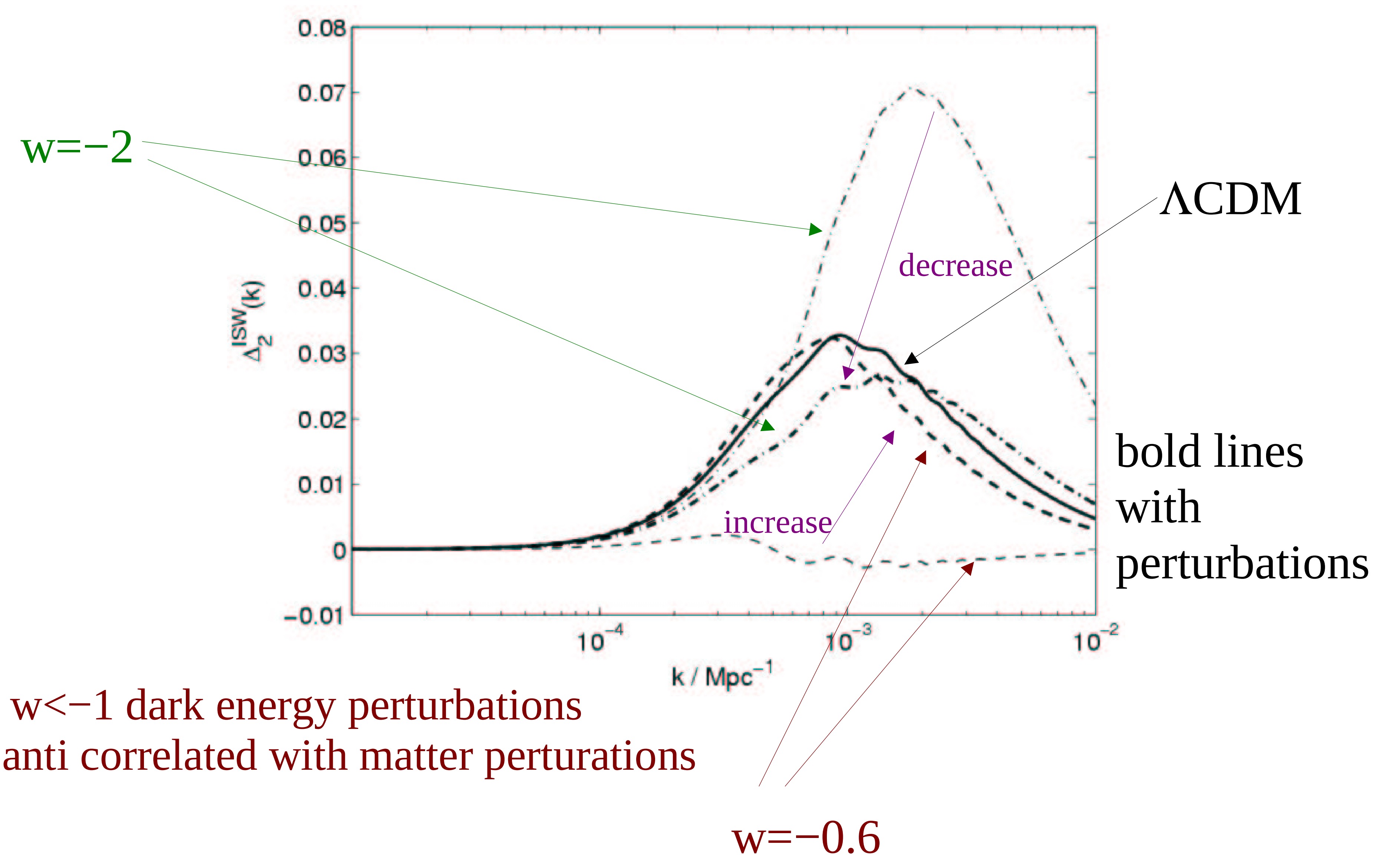
$$\dot{\varphi}^2 \equiv \pm(1+w)\rho_{de}$$

$$\delta\rho_{de} = \pm\dot{\varphi}\,\delta\dot{\varphi} + V_{,\varphi}\,\delta\varphi \pm A\dot{\varphi}^2$$

$$\delta\rho_{de} = \pm\dot{\varphi}\,\delta\dot{\varphi} - V_{,\varphi}\,\delta\varphi \pm A\dot{\varphi}^2$$

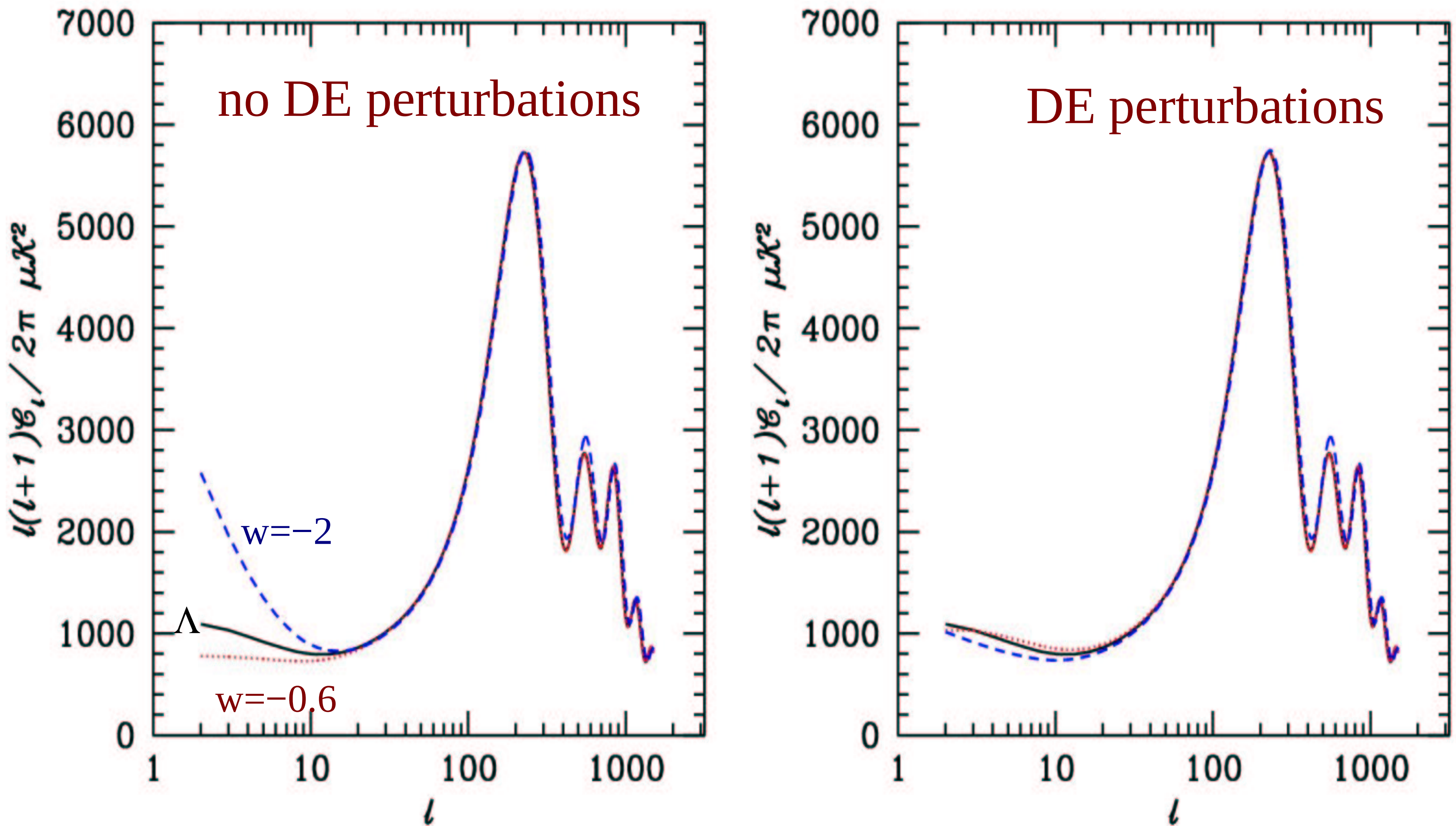
$\pm$: w>−1 and w<−1 !

Contribution to quadrupole from ISW



For w<−1 dark energy perturbations
are anti correlated with matter perturations

No Perturbation vs. perturbation



small scale CMB anisotropy in flat universe mainly depends on physical baryon and matter densities and angular diameter distance:

$$d_A \propto \int \left[\Omega_m (1+z)^3 + \Omega_{de} (1+z)^{3(1+w)} \right]^{-1/2}$$

Degeneracy on small scales

b) Generalised Dark Energy Perturbations

Fluid approach − not via scalar field:
(constant w !)

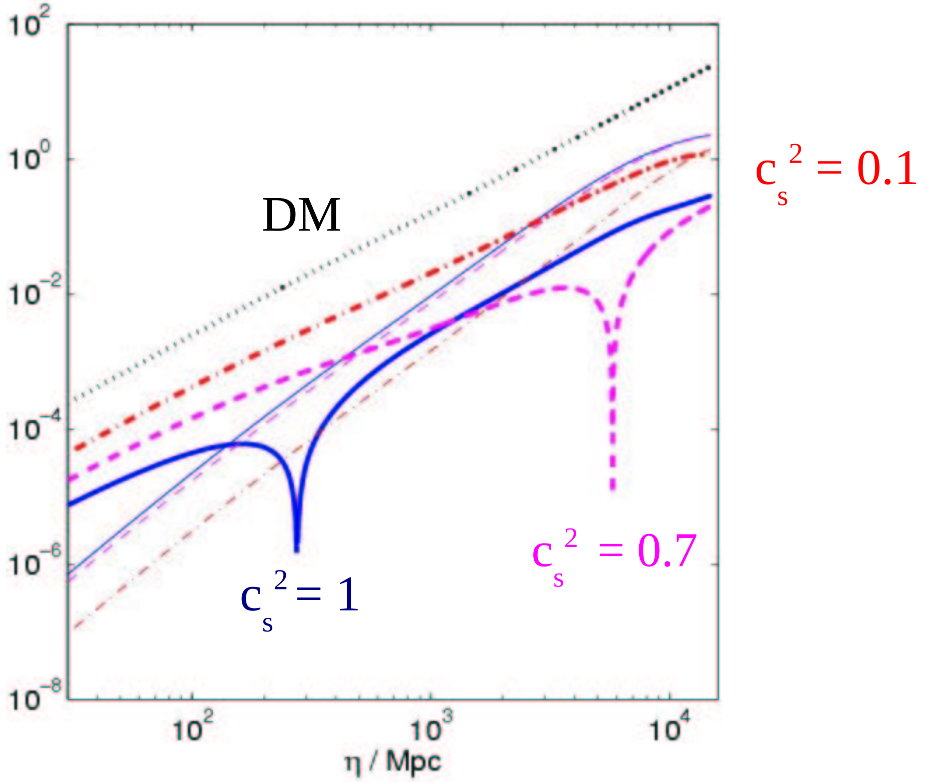
$$\delta' + 3H(c_s^2 - w)(\delta + 3H(1+w)v/k) + (1+w)kv = -3(1+w)h'$$

$$v' + H(1-3c_s^2)v + kA = kc_s^2\delta/(1+w)$$

note: H conformal Hubble, δ fractional perturbation, v velocity,
h=δa/a (with local scale factor) and need to specify
sound speed: $c_s^2 = \delta p/\delta\rho$

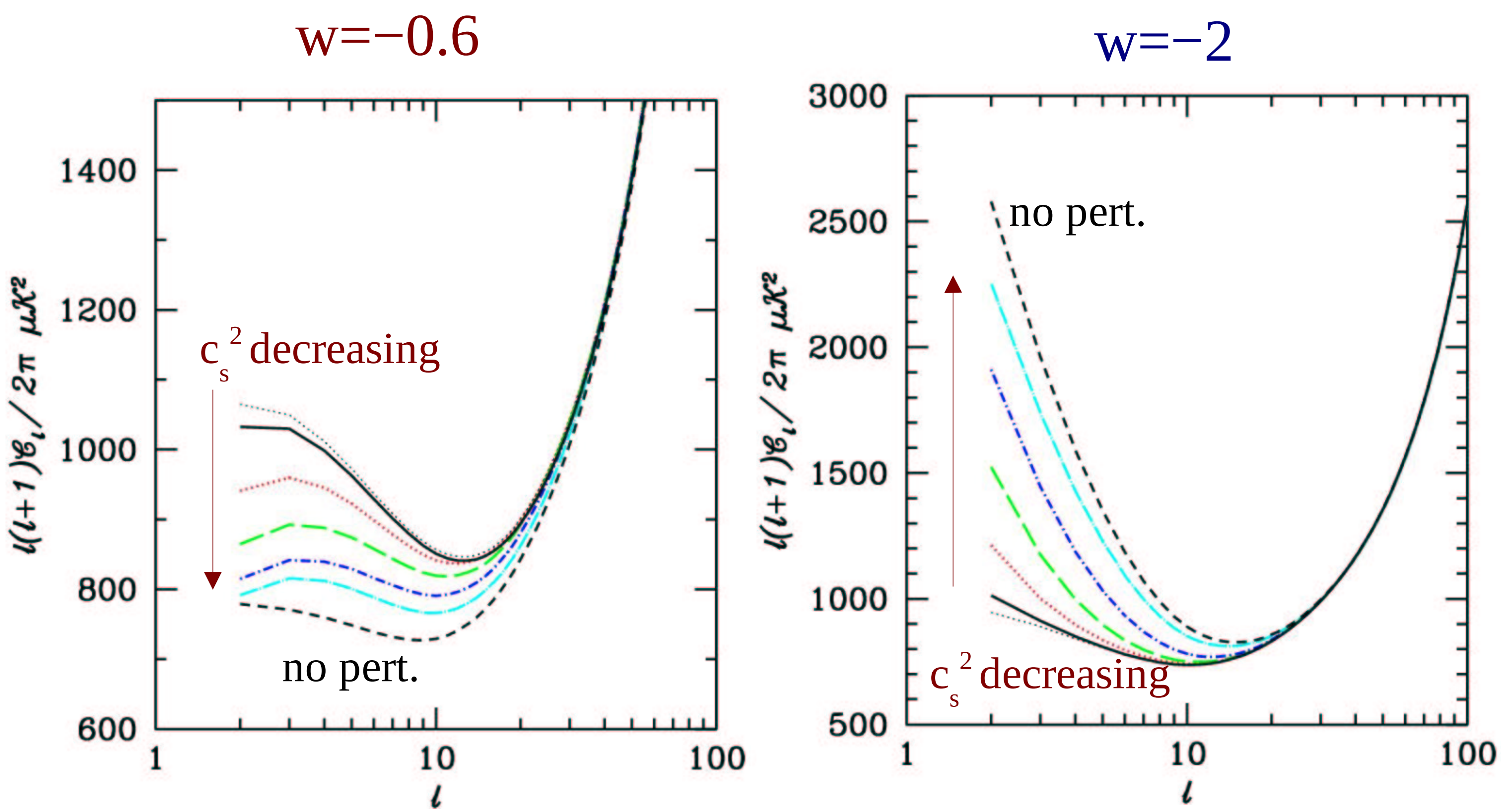
Frame comoving with scalar field dark energy: $c_s^2 = 1$
In general arbitrary parameter (like in k−essence models).

The Evolution of Perturbations



w=−0.6

CMB anisotropies for different sound speeds



$c_s^2 = 5.0, 1.0, 0.2, 0.05, 0.01, 0.0$

Note: $c_s^2 = 0$ is NOT no pertrubations !

Parameter Constraints

(COSMOMC; Lewis & Bridle)

variation of six non−dark energy parameters: baryon density $\Omega_b h^2$, cold dark matter density $\Omega_c h^2$, ratio of the sound horizon at last scattering to the angular diameter distance at last scattering θ, the damping of small scale fluctuations due to reionization $Z=e^{-2\tau}$, amplitude of fluctuations A_s , spectral index n_s .

Dark Energy parameters w and $-3 < \log c_s^2 < 2$.

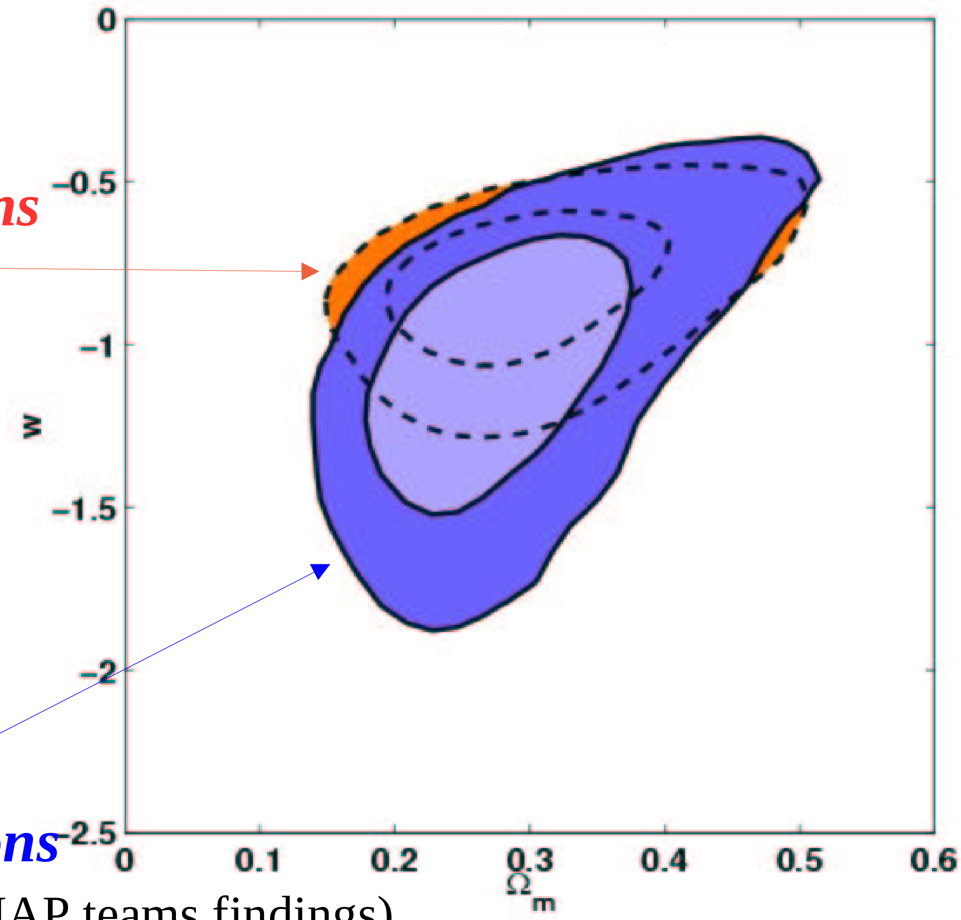
Priors from Hubble Key Project (Freedman et al.): $H_0 = (72\pm8)$ km/s/Mpc

BBN (Burles et al.): $\Omega_b h^2 = 0.022 \pm 0.002$

Use WMAP, CBI and ACBAR as CMB data

Analysis with scalar field ($c_s^2 = 1$) dark energy

no perturbations

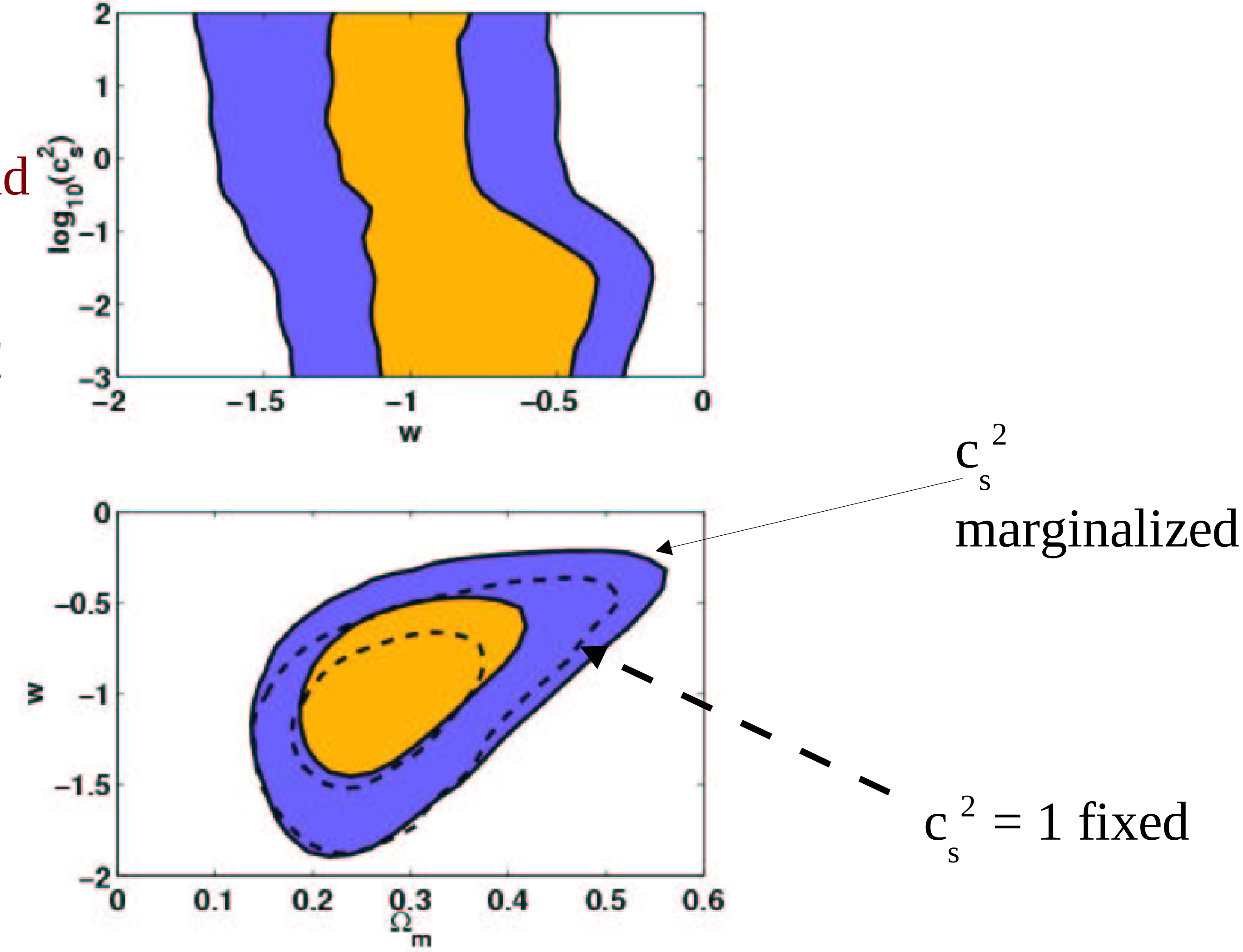


with perturbations

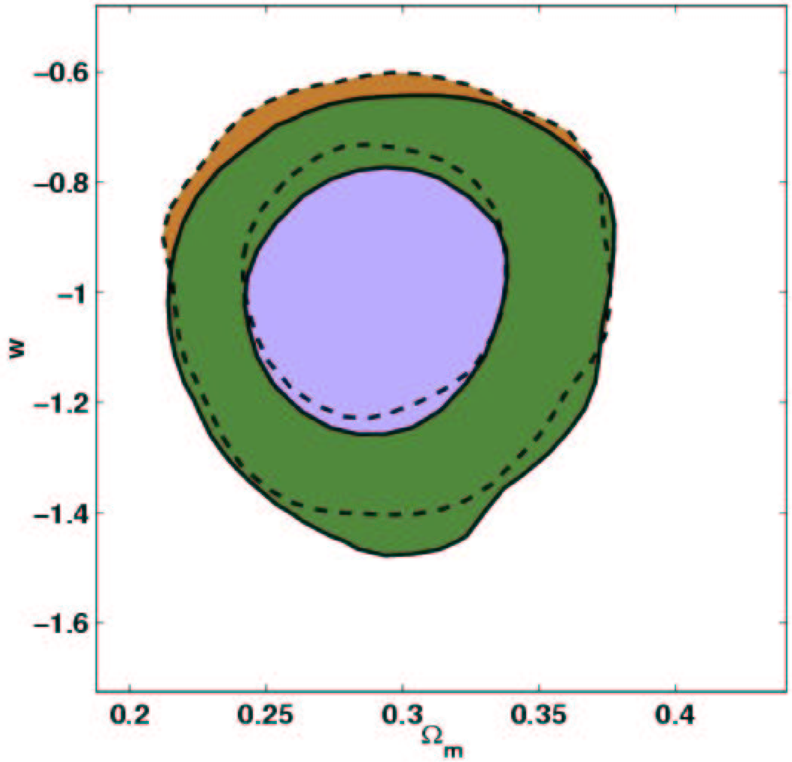
(consistent with WMAP teams findings)

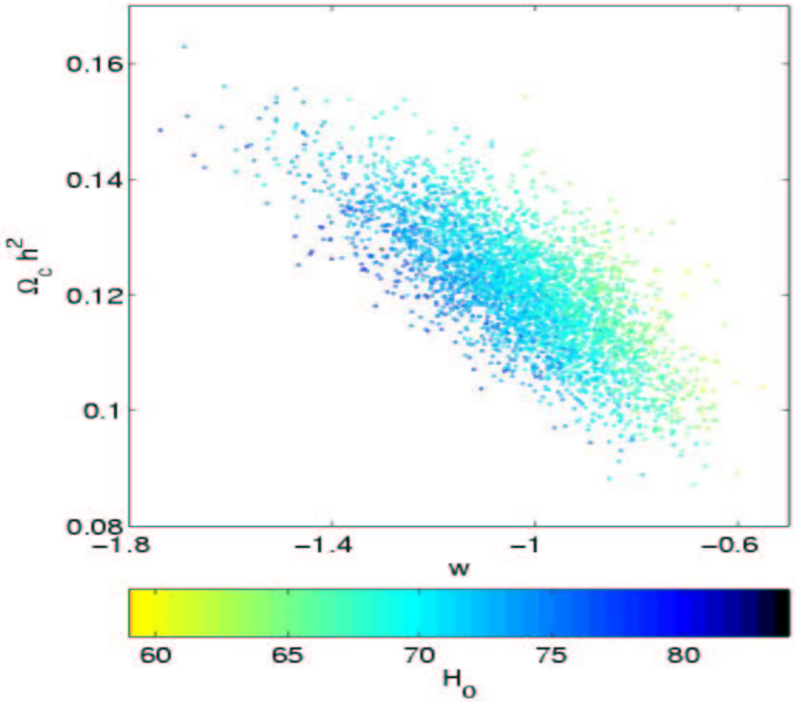
Analysis with c_s^2 varying

no constraints on sound speed; slight preference of low sound speeds for w>−1 ! Compare with Olivier Dore's talk tomorrow !



Final combined analysis: Including Supernovae Cosmology Project (Perlmutter et al.) and 2dF galaxy redshift survey date (Percival et al.)





Conclusions

- Essential to include perturbations for a consistent description of dark energy contribution to CMB !
- Generalisation to dark energy fluids with arbitrary sound speed
- With current data no constraint on sound speed; but see Dore's talk − cross correlation to large scale power spectra.
- What about varying w ? See Kunz's talk !
- $-1.37 < w < -0.74$ (95%)