New Constraints on Dark Energy

Moriond, La Thuile, 30 Marzo, 2004

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The evidence for Dark Energy relies on Cosmic Complementarity

SN-Ia:

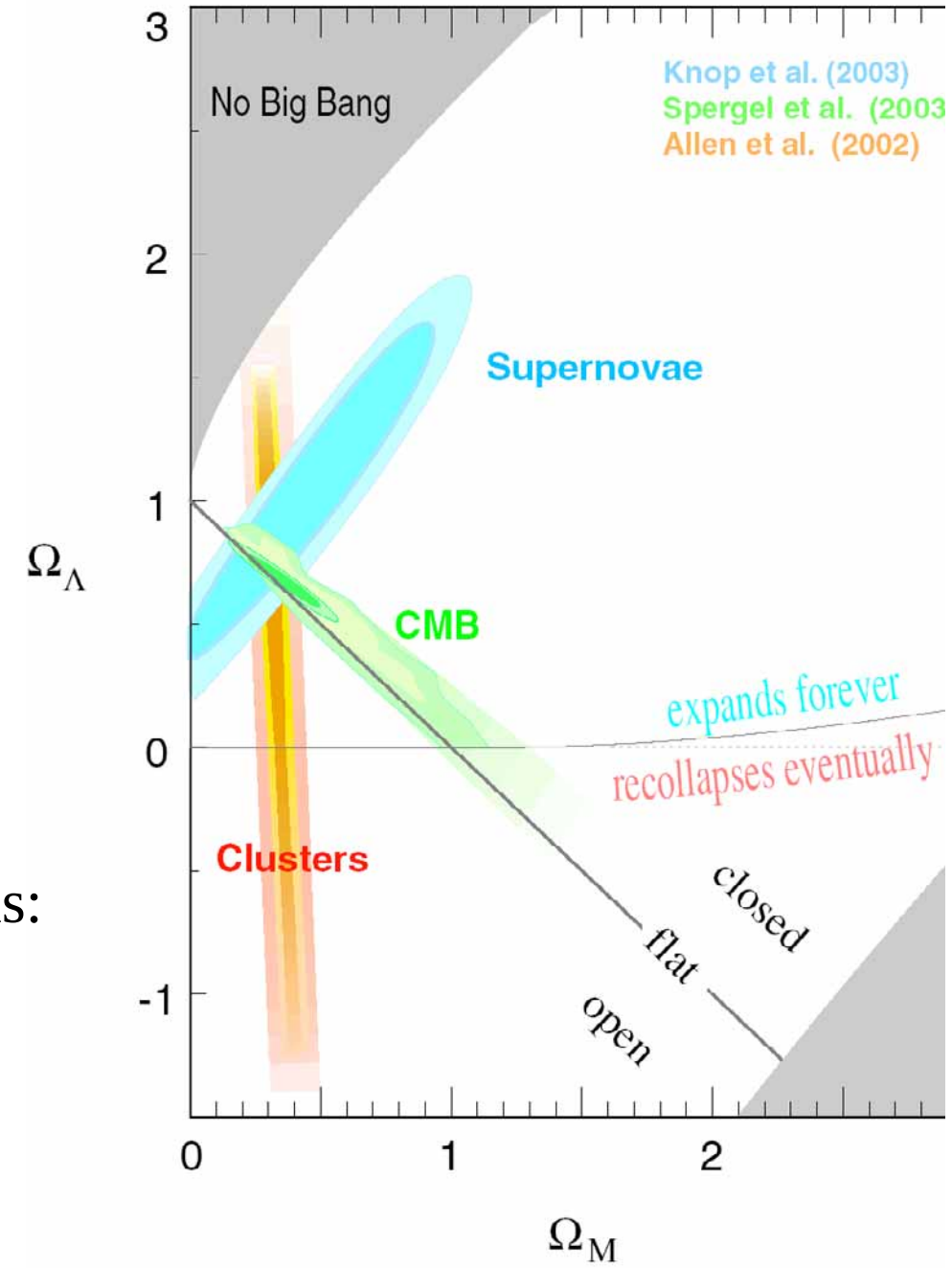
$$\Omega_\Lambda \approx 1.4\Omega_M + 0.2$$

CMB:

$$\Omega_\Lambda \approx 1 - \Omega_M$$

Several astronomical observations:

$$\Omega_M \approx 0.3$$



$$\Omega_\Lambda = 0.73 \pm 0.04$$

A zero cosmological constant is ruled out at about 18σ
Dark Energy is REAL !

General predictions for scalar field models:

The equation of state parameter is redshift-dependent and its effective value can be different from –1.

$$w_\phi \equiv w_\phi(z) \neq -1$$

$$w_{eff} = \int w_\phi(z)\Omega_\phi(z)dz \,/ \int \Omega_\phi(z)dz \neq -1$$

Can the equation of state be w < -1 ?

Fluids with w<-1 violate the 'weak energy condition'

$$p + \rho \geq 0$$

resulting in a faster-than-exponential expansion for the universe and in a cosmic 'Big Rip'.

$$a(t) \approx a(t_{eq}) \left[(1+w) \frac{t}{t_{eq}} - w \right]^{2/3(1+w)} , w < -1$$

$$a(t) \to \infty$$
$$\rho(t) \to \infty$$

as

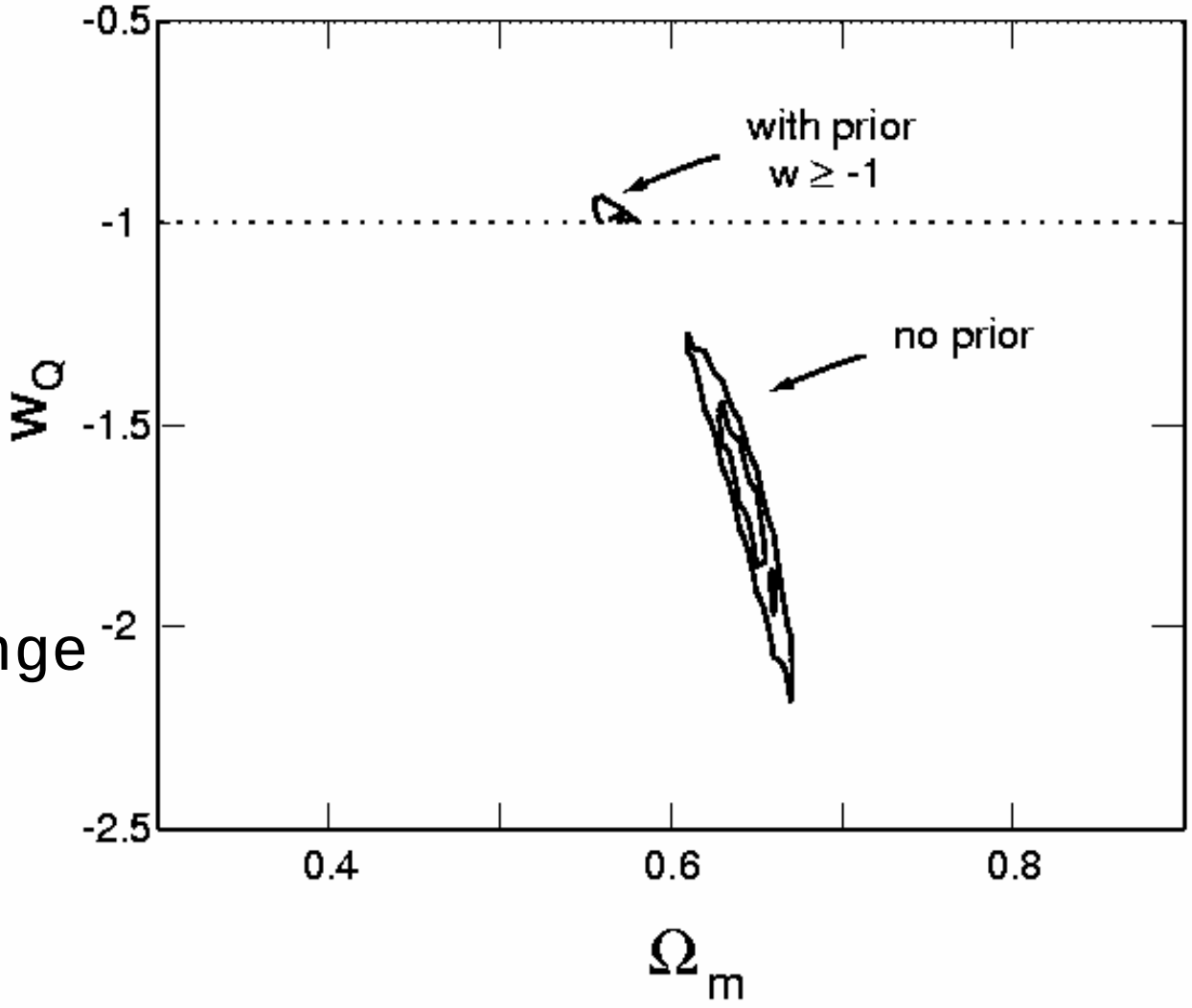
$$t \to t_{BR} = \left(\frac{w}{1+w} \right) t_{EQ}$$

However we don't measure w(z) directly !

$$w_\phi(z) > -1$$

$$w_{eff} \approx \int w_\phi(z)\, f(z) dz < -1$$

Maor et al., 2002
Toy model with
w(z) always >-1.
w assumed
constant in
the SN-Ia analysis
can yield
w <-1.
(Anyway very strange
model...)



Assuming w as constant with redshift in the analysis has the following advantages:

- Simplicity.

- If w is not –1 then we have evidence for a dark energy component different from a cosmological constant.

- If w<-1 then this may be an indication for phantom models or that the ‘true’ w varies strongly with redshift.

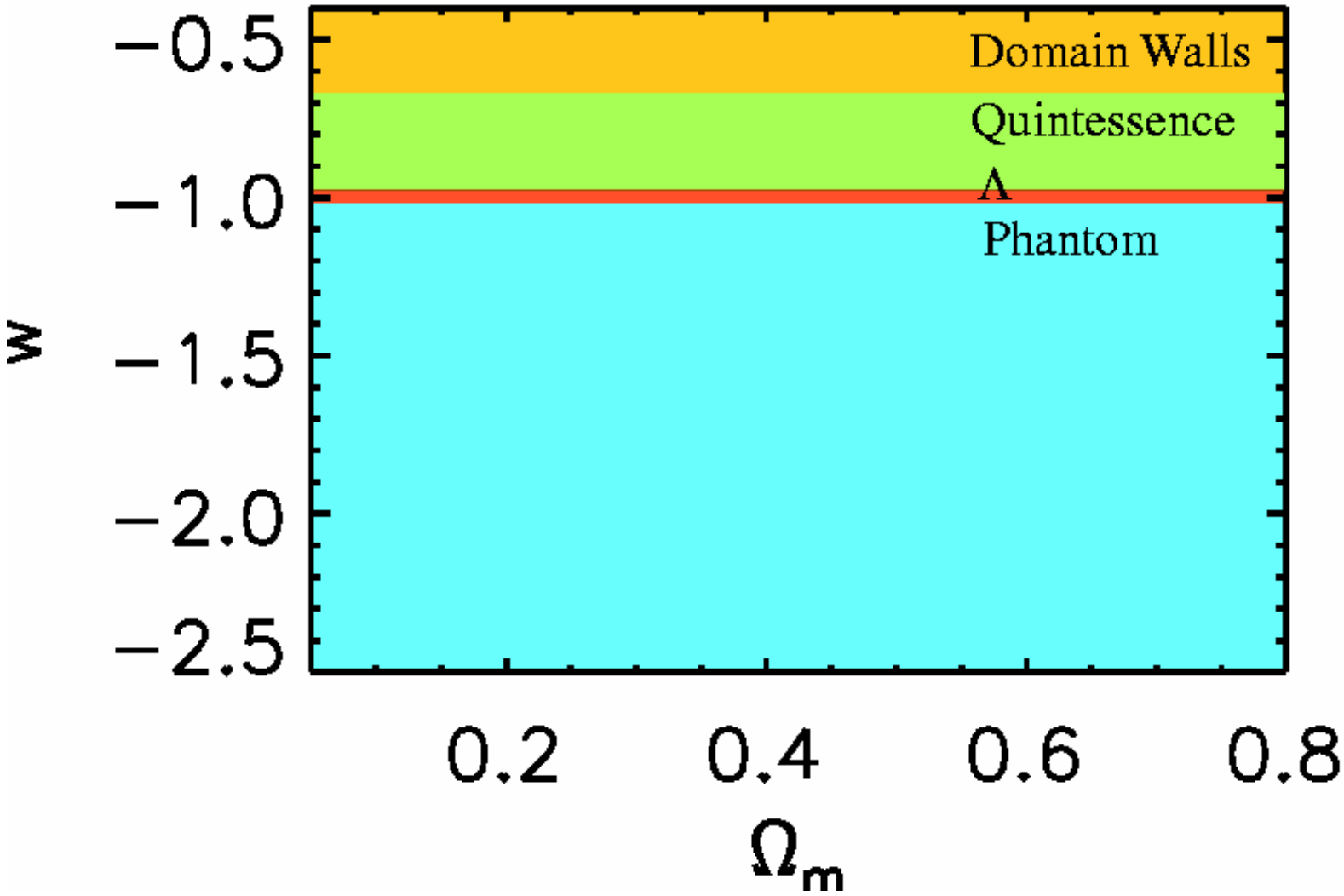
- If constrains on w from different datasets are not compatible between them this may be an indication for redshift dependence of w.

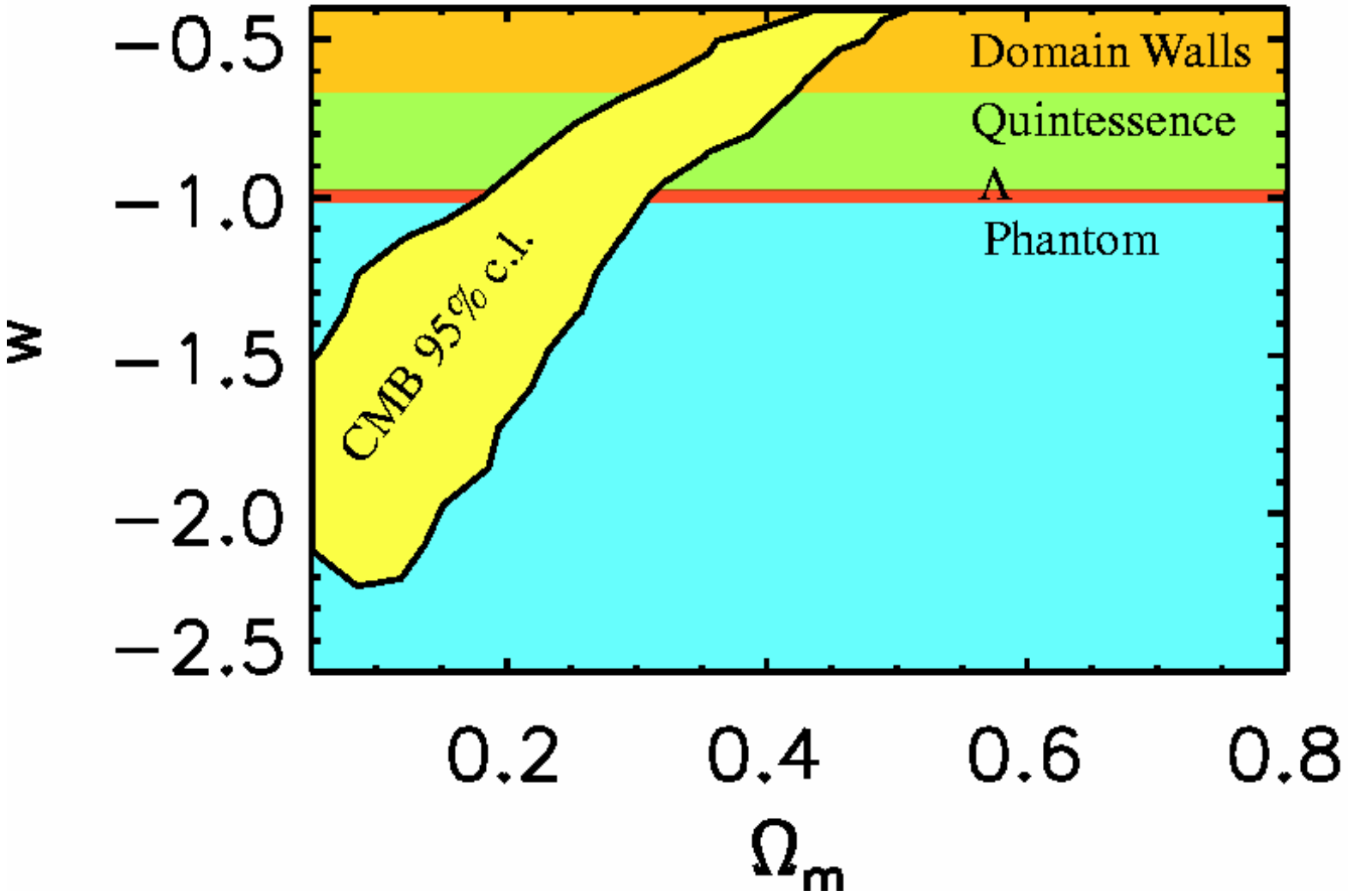
However, with the increasing precision of the datasets, studies with w(z) have been made.

$w_X(z) = w_0 + w_1 z$ Valid only for SN-Ia

$X(z) \equiv \rho_X(z) / \rho_X(0)$ Wang et al.

Statefinder Sahni et al.


−0.5
−1.0
−1.5
−2.0
−2.5
w
Domain Walls
Quintessence
Λ
Phantom
0.2
0.4
0.6
0.8
Ωm


−0.5
−1.0
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−2.0
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w
0.2
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0.6
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Ω_m
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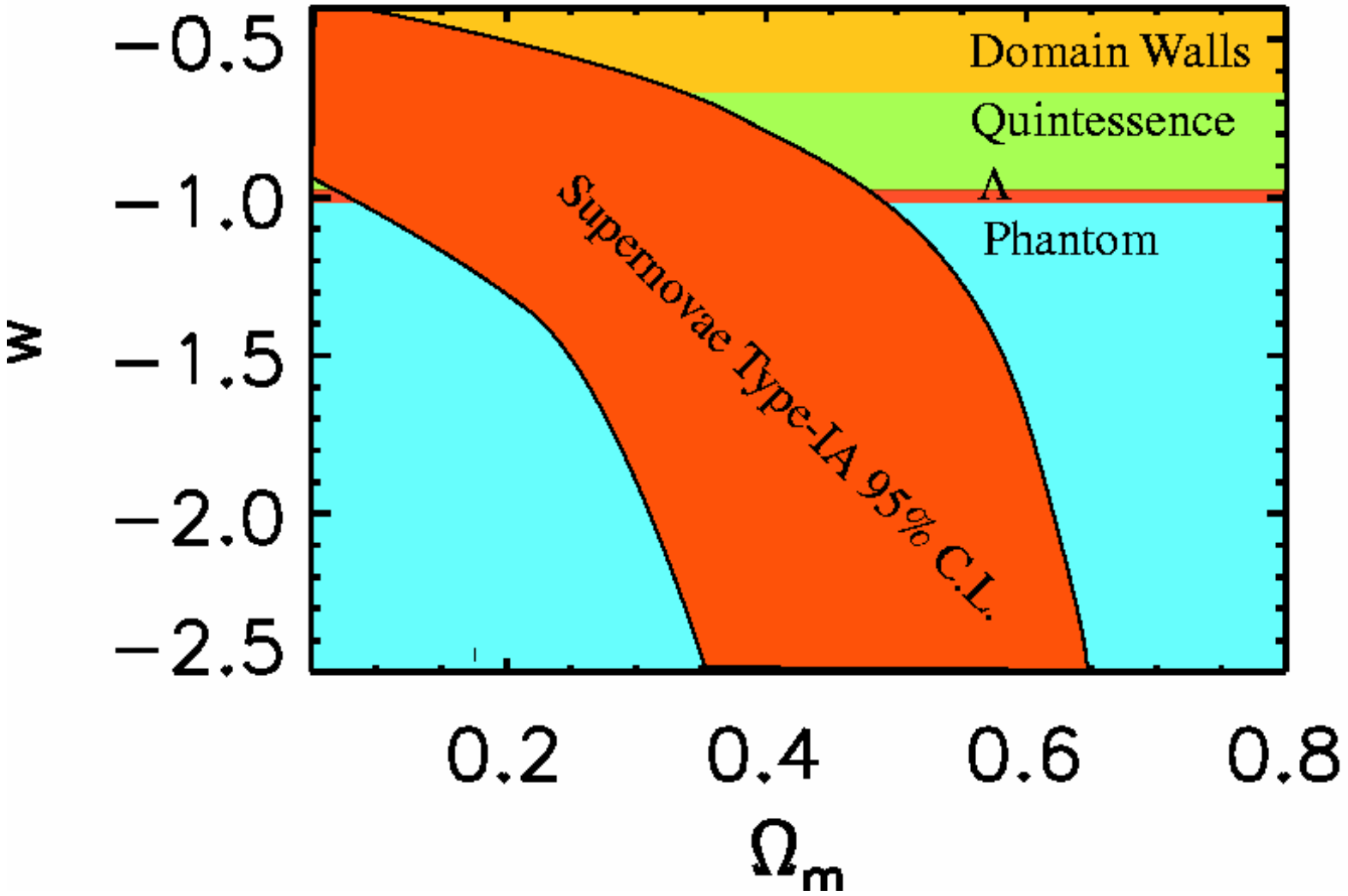
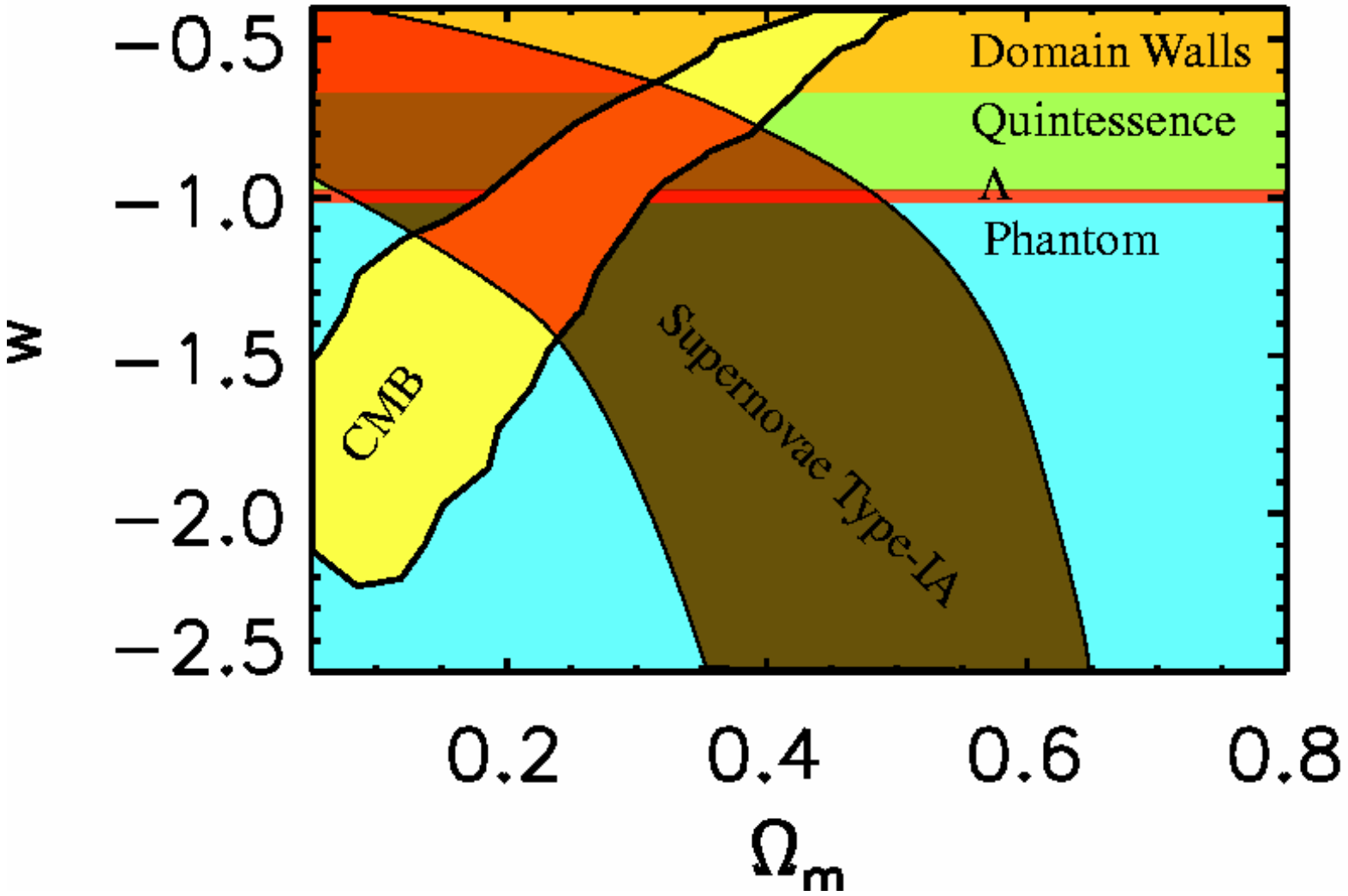
Phantom
CMB 95% c.l.


−0.5
−1.0
−1.5
−2.0
−2.5
w
0.2
0.4
0.6
0.8
Ω_m
Domain Walls
Quintessence
Λ
Phantom
Supernovae Type-IA 95% C.L.

From CMB+SN-IA: Domain Walls are ruled out.

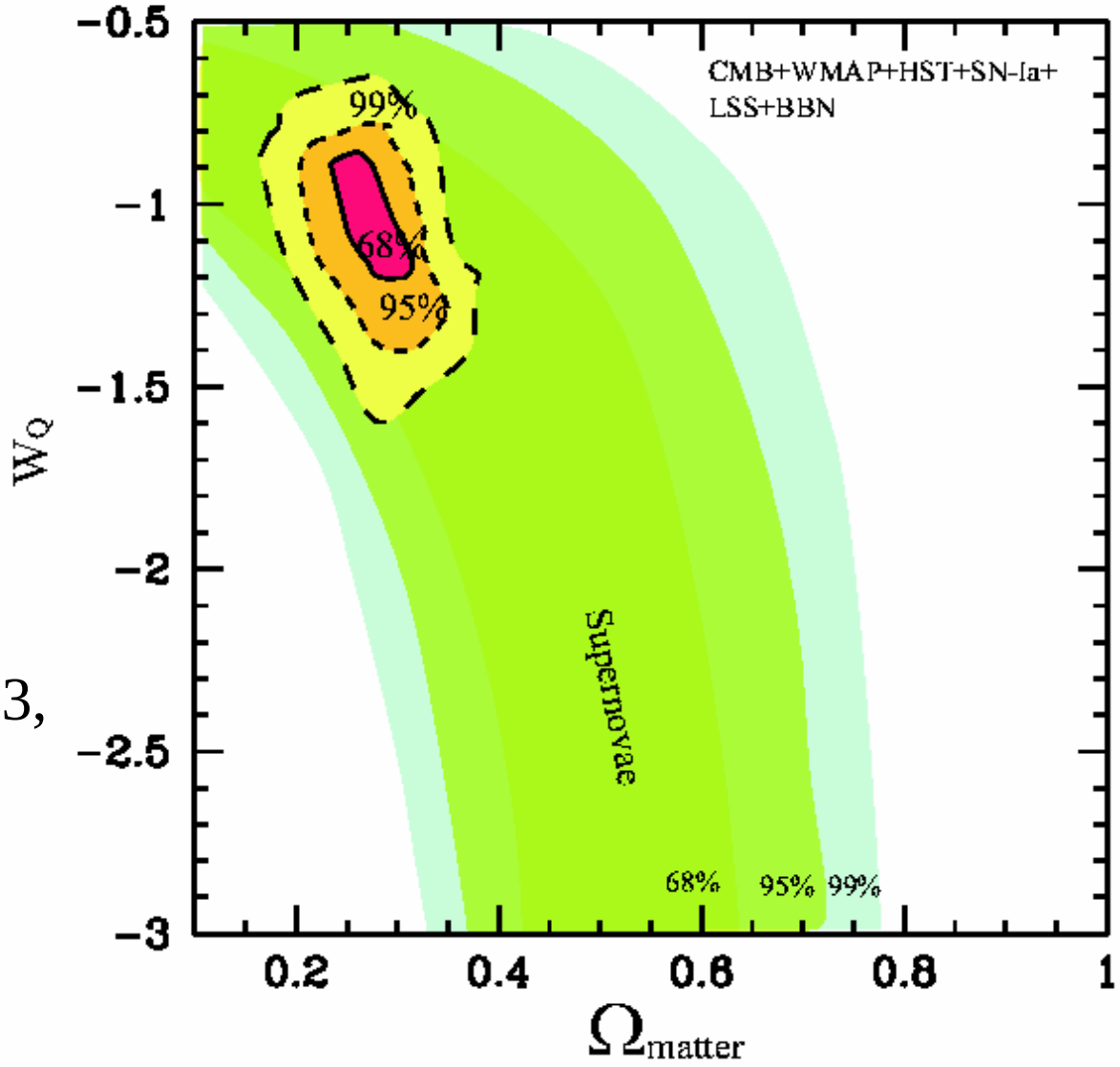


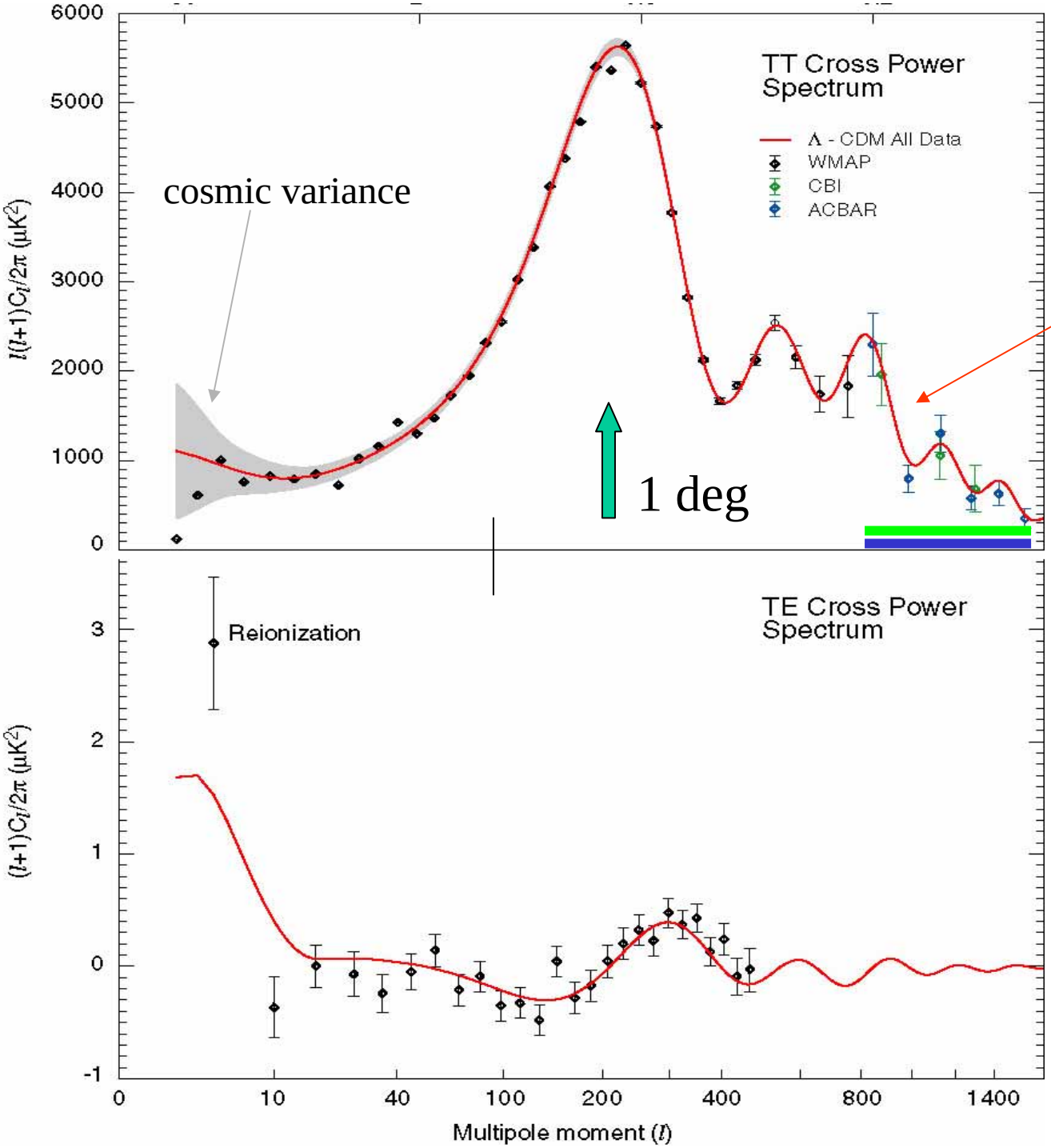
Combined Analysis:
-1.38 < wx < -0.81

Best Fit:
$w = -1.04, \chi^2 = 1471/1370$

Melchiorri et al.
Phys.Rev. D68 (2003)
043509

(similar results in
Lewis and Weller 2003,
Caldwell and Doran 2003,
Spergel et al. 2003)





Best Fit Model

$\Omega_{cdm} = 0.24$

$\Omega_b = 0.04$

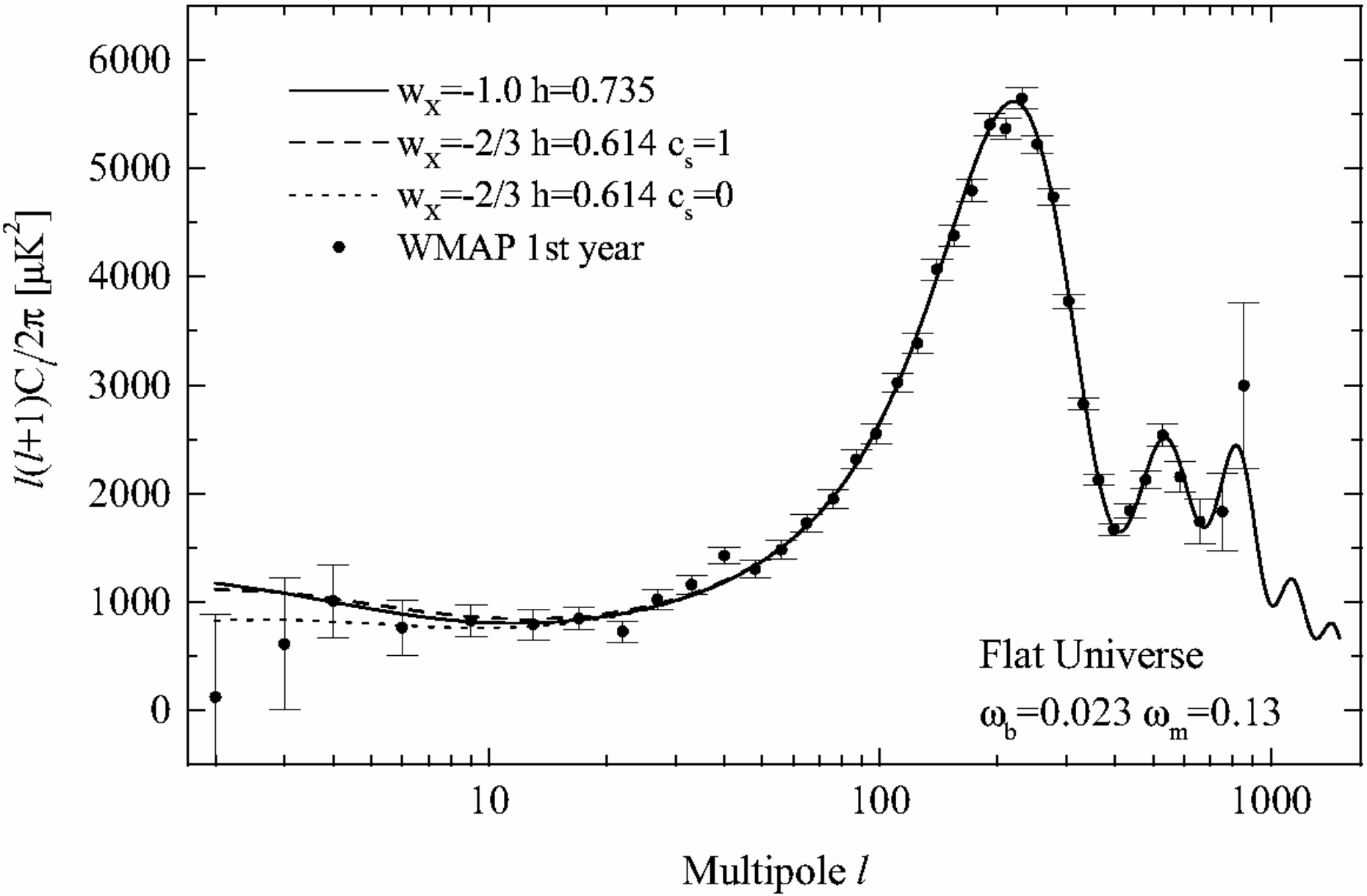
$h = 0.735$

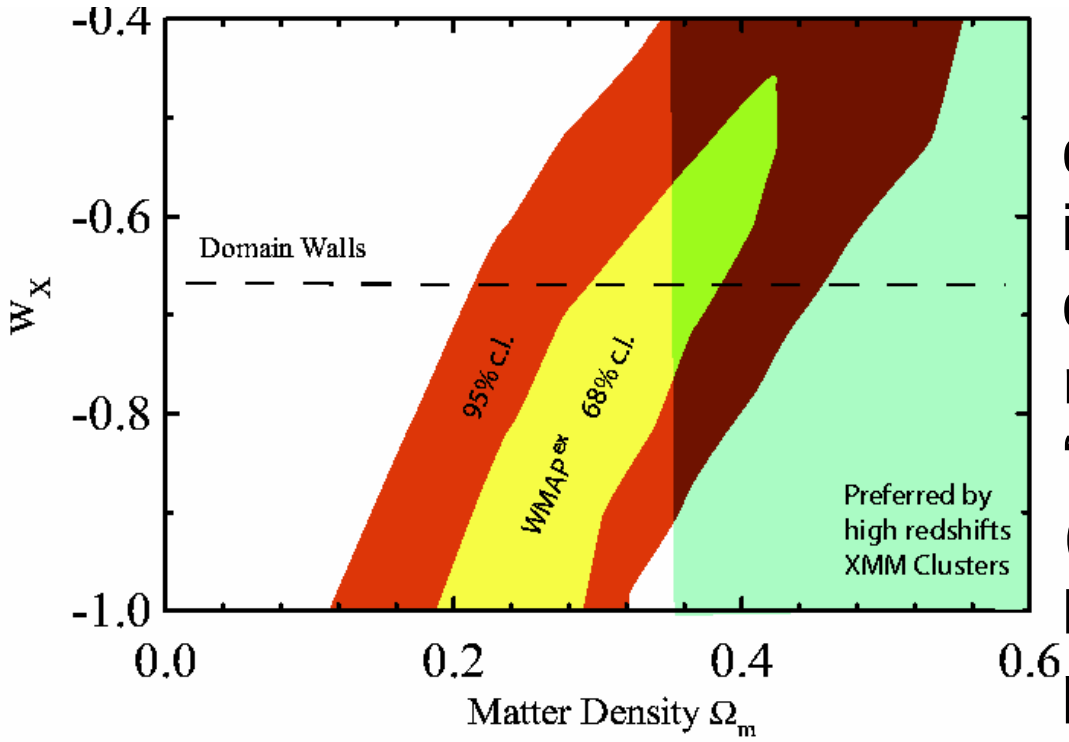
$\tau = 0.10$

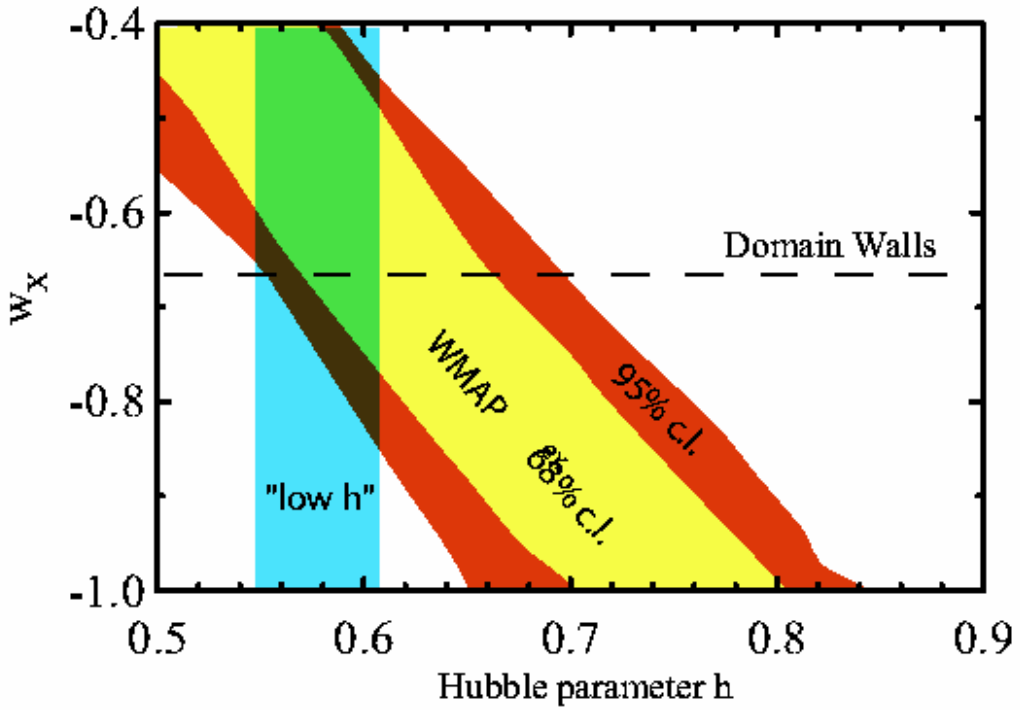
$n_S = 0.97$

$\Omega_\Lambda = 0.71$

Spergel et al, 2003


6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ [μK^2]
w_x=-1.0 h=0.735
w_x=-2/3 h=0.614 c_s=1
w_x=-2/3 h=0.614 c_s=0
WMAP 1st year
Flat Universe
ω_b=0.023 ω_m=0.13
10
100
1000
Multipole l





If we combine the CMB data with results indicating 'high' matter density (like high redshift clusters) and a 'low' Hubble constant (like SZ) then Domain Walls are preferred !

(see Conversi et al, 2004, in press).

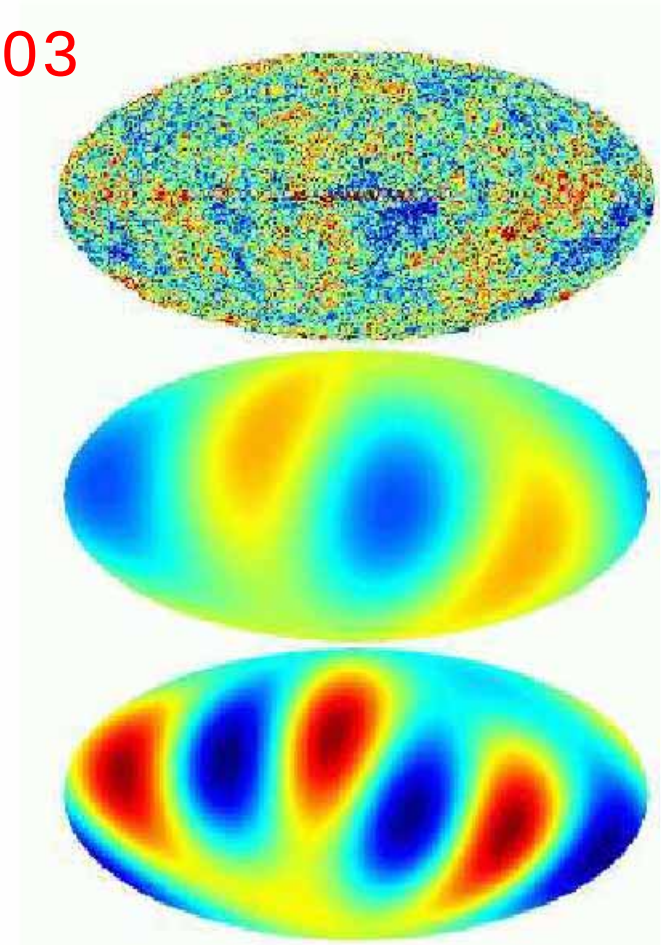
Dark Energy – Low Quadrupole connection

de Oliveira-Costa et al., 2003

Quadrupole anomalous at 1-in-20 level by being low.

Octupole anomalous at 1-in-20 by being very planar.

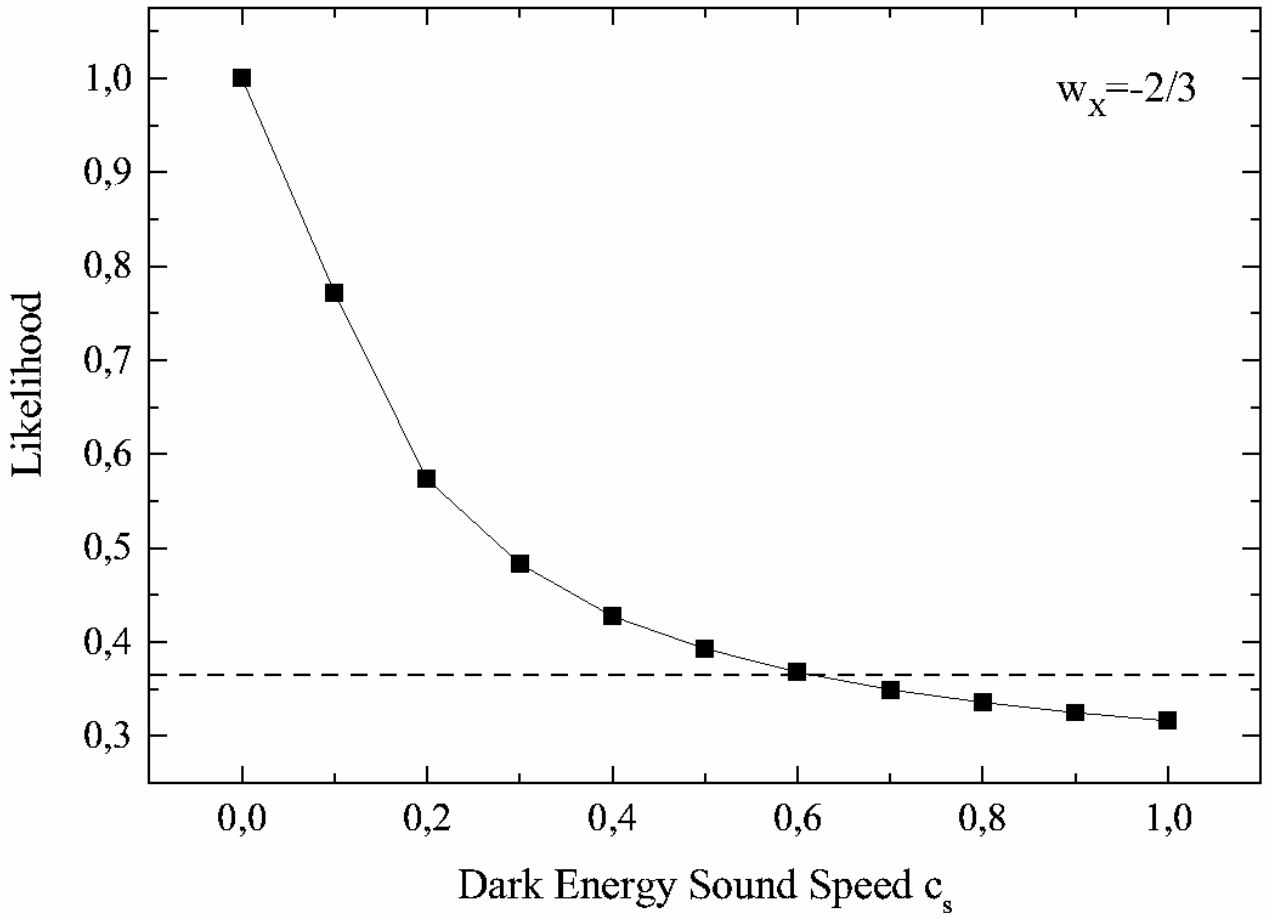
Alignement between Octupole and Quadrupole is anomalous at 1-in-60.



Is the low CMB Quadrupole related to the Dark Energy problem ?

Correlations between the quadrupole and the local dipole and the ecliptic plane are present (Schwarz et al. 2004) so is conceivable that the problem is due to a systematic or to foreground contamination.
However, if the explanation is cosmological then the answer must be in the dark energy otherways we have a new cosmic coincidence problem.

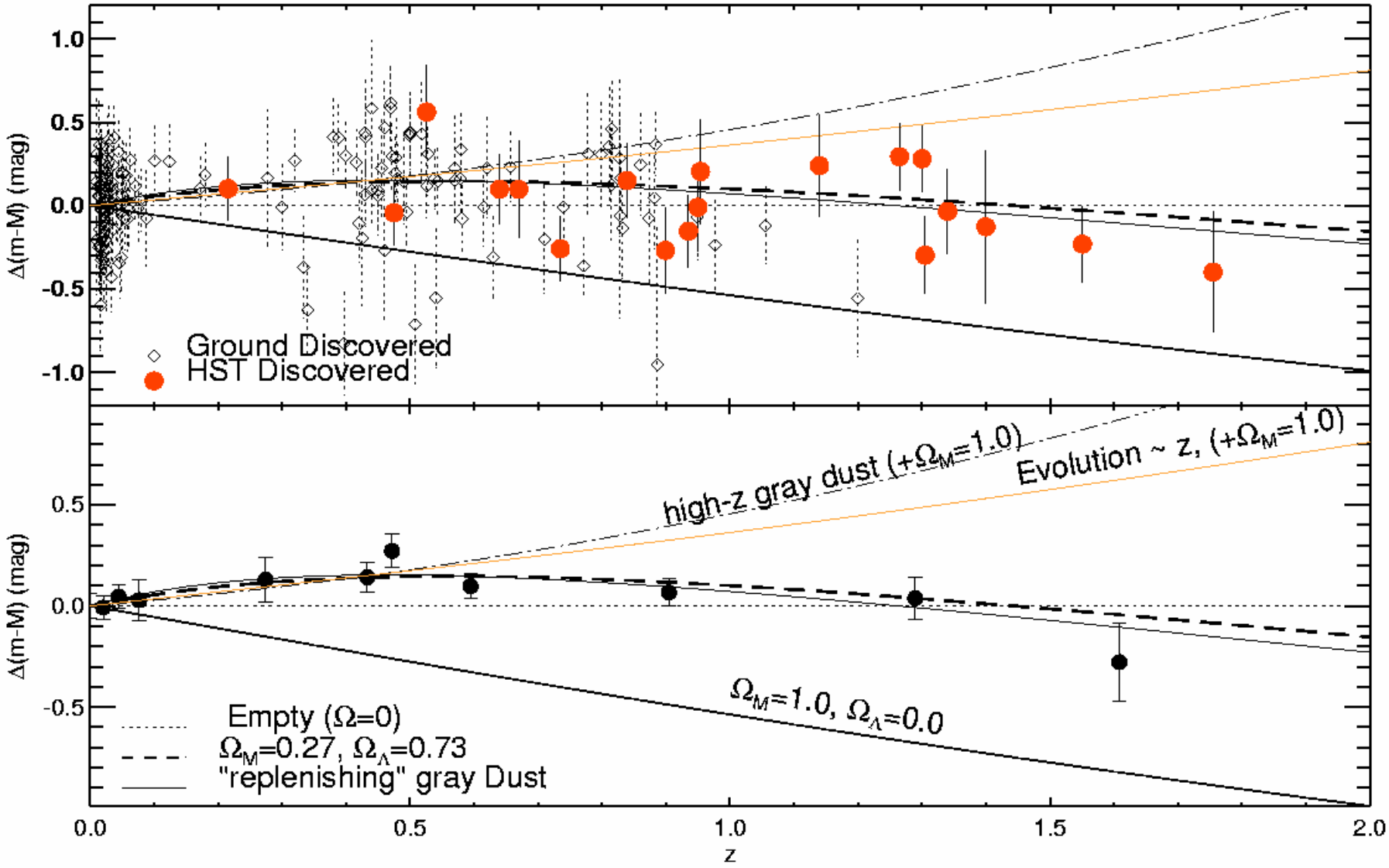
The late time action of a dark energy component, through the integrate Sachs-Wolfe effect, produce large angle CMB anisotropies correlated with density fluctuations at $z<2$.
Recent studies (Boughn and Crittenden, Nolta et al, Scranton et al.,Ashfordi et al,...) show indications for these expected correlations.

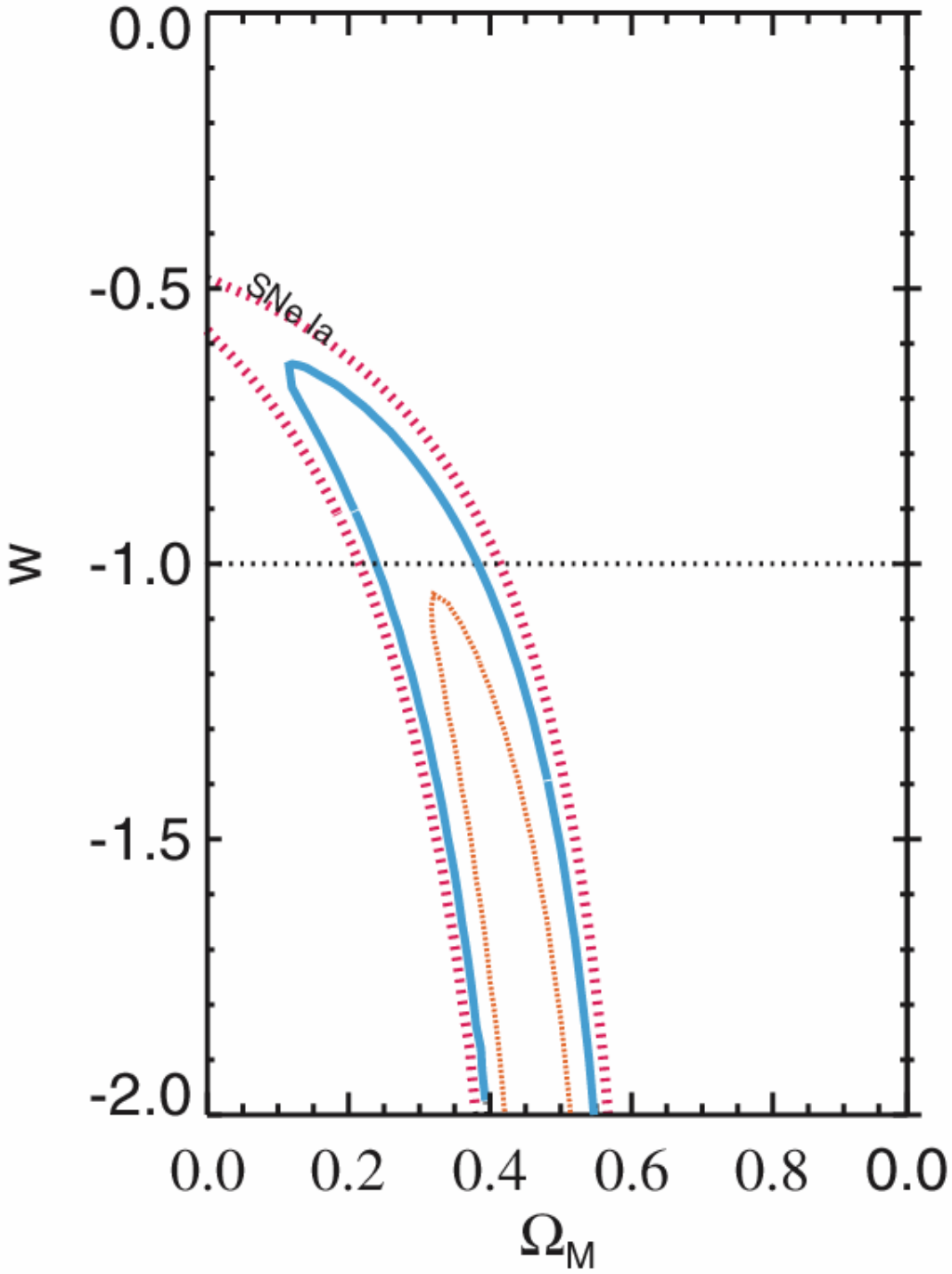


Lowering the dark energy sound speed suppresses the large angle anisotropies if w different from –1
(see Weller and Lewis 2003, Conversi et al. 2004).

New Supernovae Results !

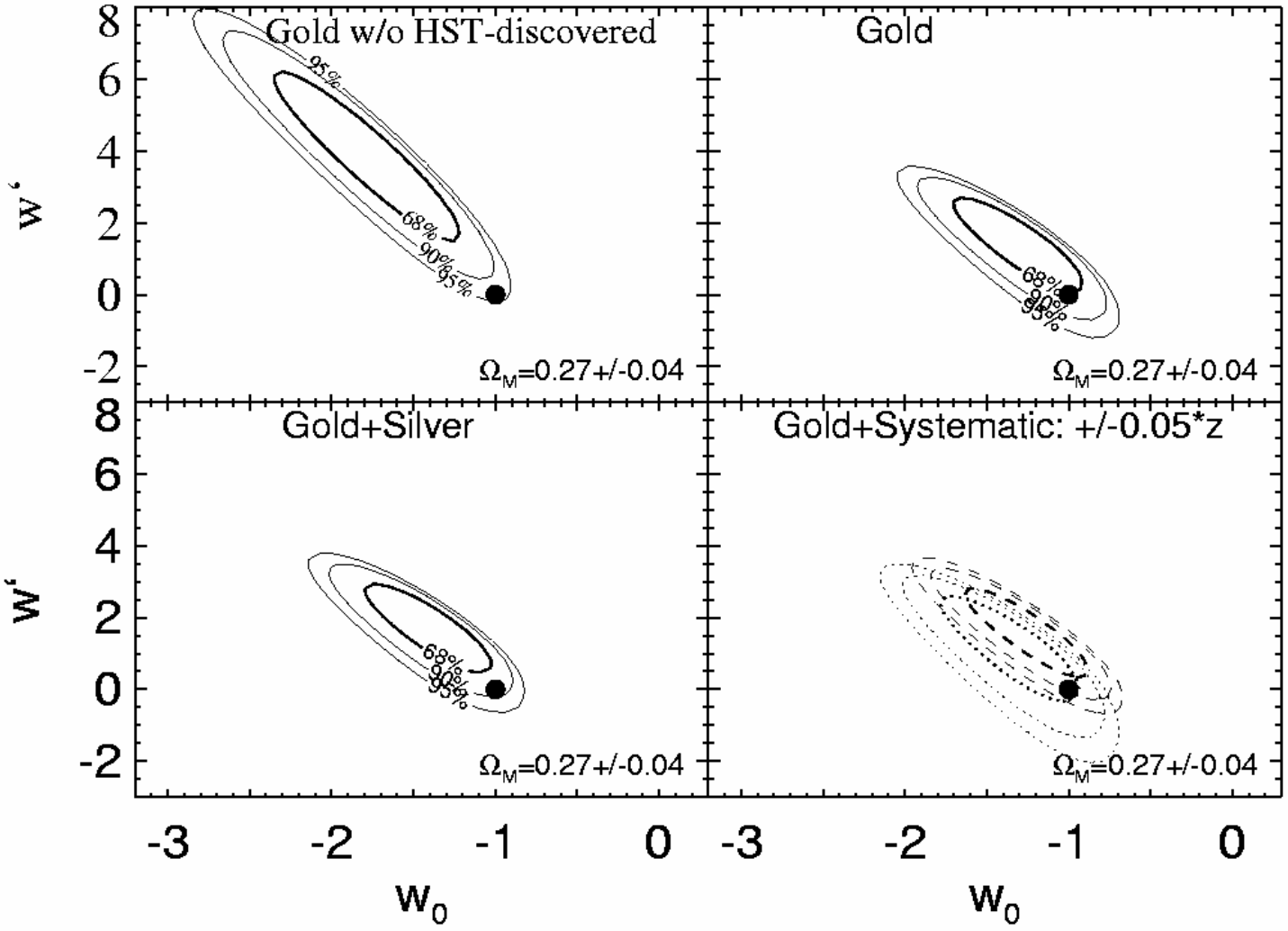
Riess et al., astro-ph/0402512
16 Type Ia supernovae (SNe Ia) discovered with the Hubble Space Telescope during the course of the GOODS ACS Treasury program (see talk by M. Giavalisco soon).6 of the 7 highest-redshift SNe Ia known !


Δ(m-M) (mag)
1.0
0.5
0.0
-0.5
-1.0
Ground Discovered
HST Discovered
high-z gray dust (+Ω_M=1.0)
Evolution ~ z, (+Ω_M=1.0)
Ω_M=1.0, Ω_Λ=0.0
Empty (Ω=0)
Ω_M=0.27, Ω_Λ=0.73
"replenishing" gray Dust
0.0
0.5
1.0
1.5
2.0
z

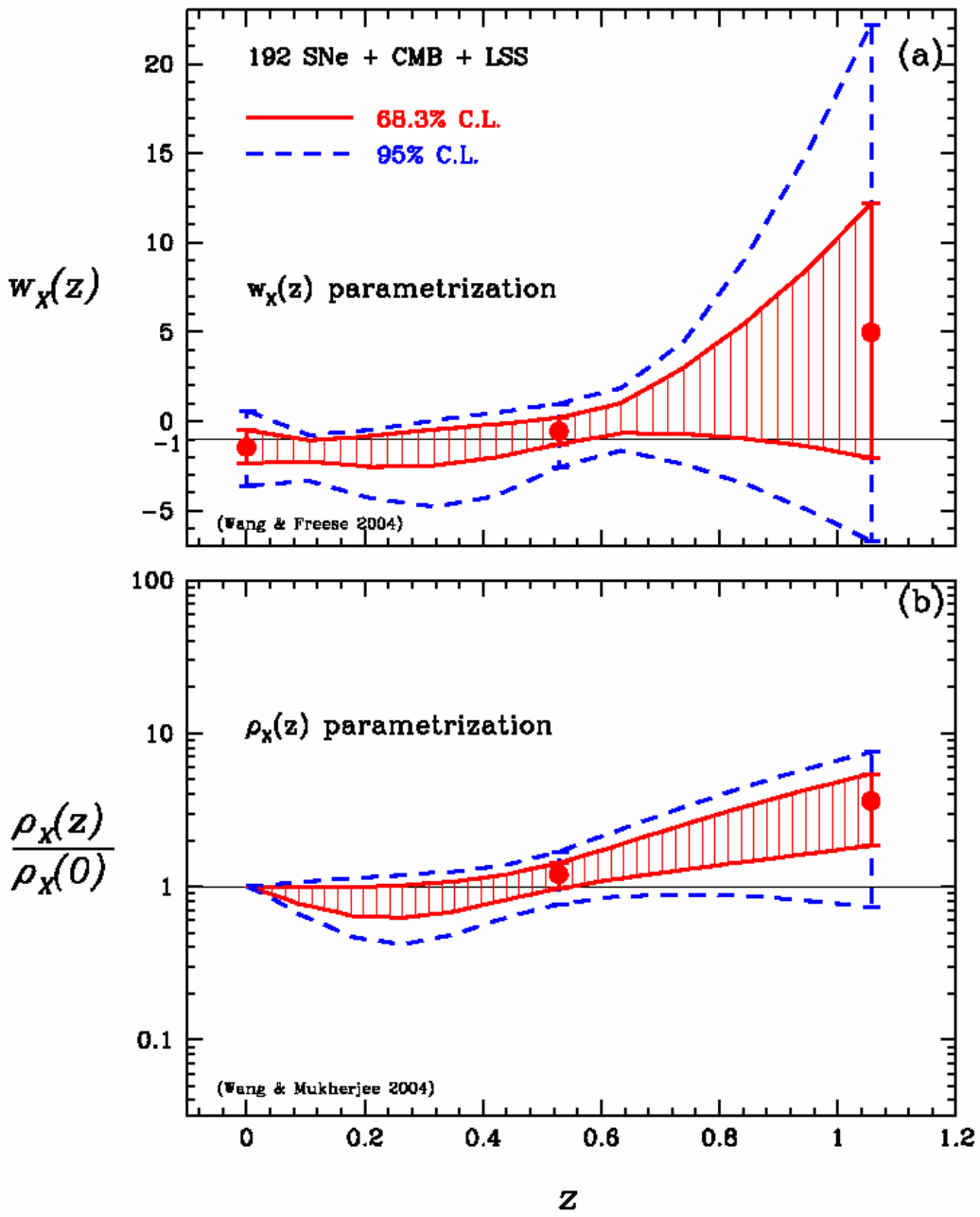


Results (SN-Ia alone):
w < -0.6 at 95%
w=-1 consistent with the data
w<-1 preferred

Evidence for a variation in w from SN-Ia ?



Riess et al., astro-ph/0402512, see also Alam et al (2003), and Wang et al (2003).



Y. Wang and K. Freese, astro-ph/0402208, 2004

Conclusions

- The presence of Dark Energy is now well established.
- Several theoretical candidates are available.
- A cosmological constant is consistent in between 2 sigmas with all datasets.
- Phantom models ($w_x<-1$) are preffered by SN-Ia data and by combined CMB+SN-Ia analyses.
- Hints for w_x (z) with w increasing with redshift.
- Models with w_x >-0.8 are ruled out at 95% c.l. unless systematics are present in SN-Ia.
- CMB+"Low h" and "High matter" analysis are consistent with $w_x>-2/3$.

Lineweaver et al., astro-ph/9610133, 1997, see also Moriond 1997 conference proceedings:

"A standard flat Λ model with Ω_λ=0.7 and Ω_0 =0.3 is fully consistent with CMB data. However the SNIa results (Perlmutter et al. 1997) rule it out, $-0.28 < \Omega_\lambda < 0.34$"