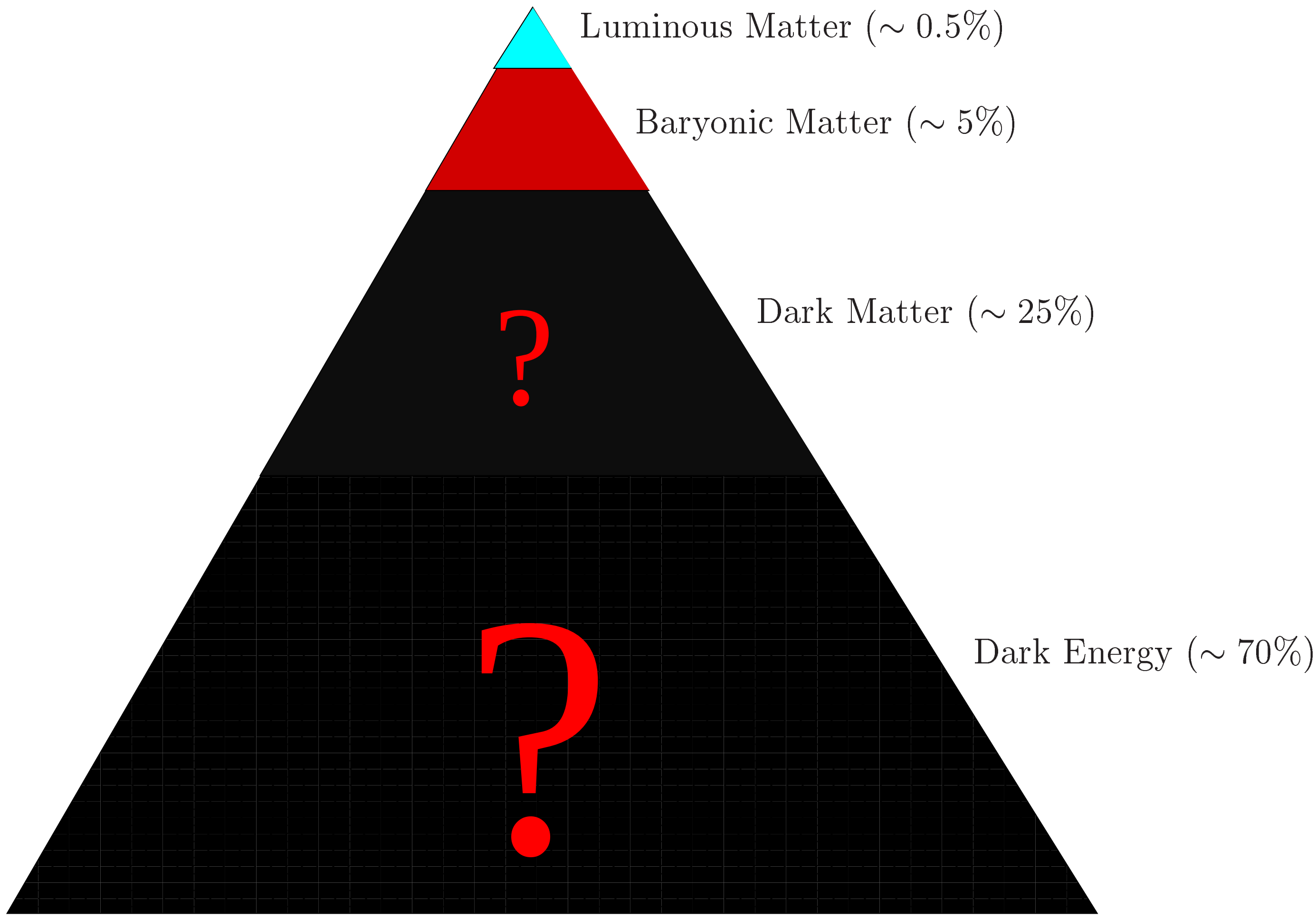
Cosmological Probes of Dark Energy*

Dragan Huterer (CWRU)

*also featured at

University of Chicago

13 - 16 December, 2001

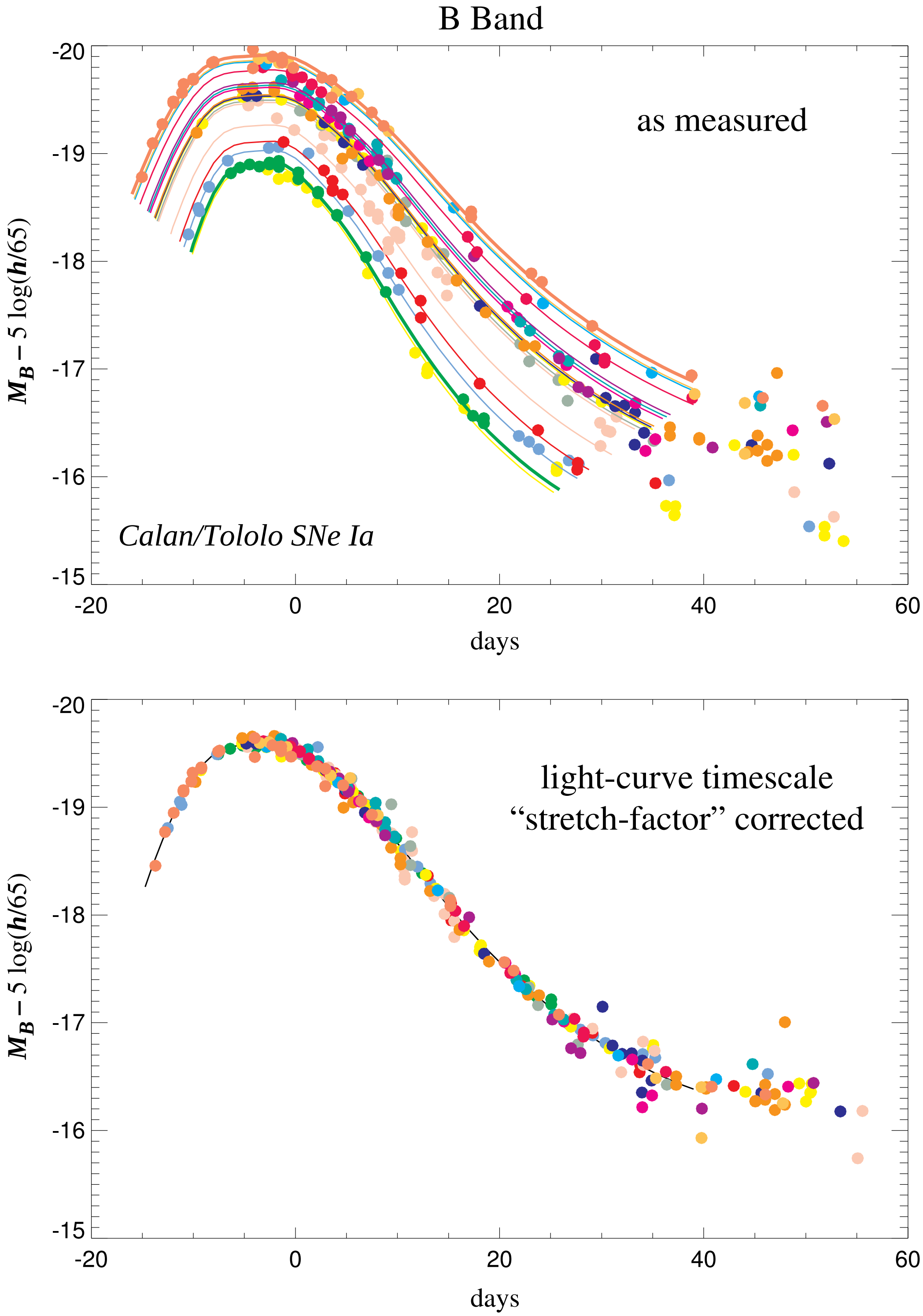


Evidence for dark energy:

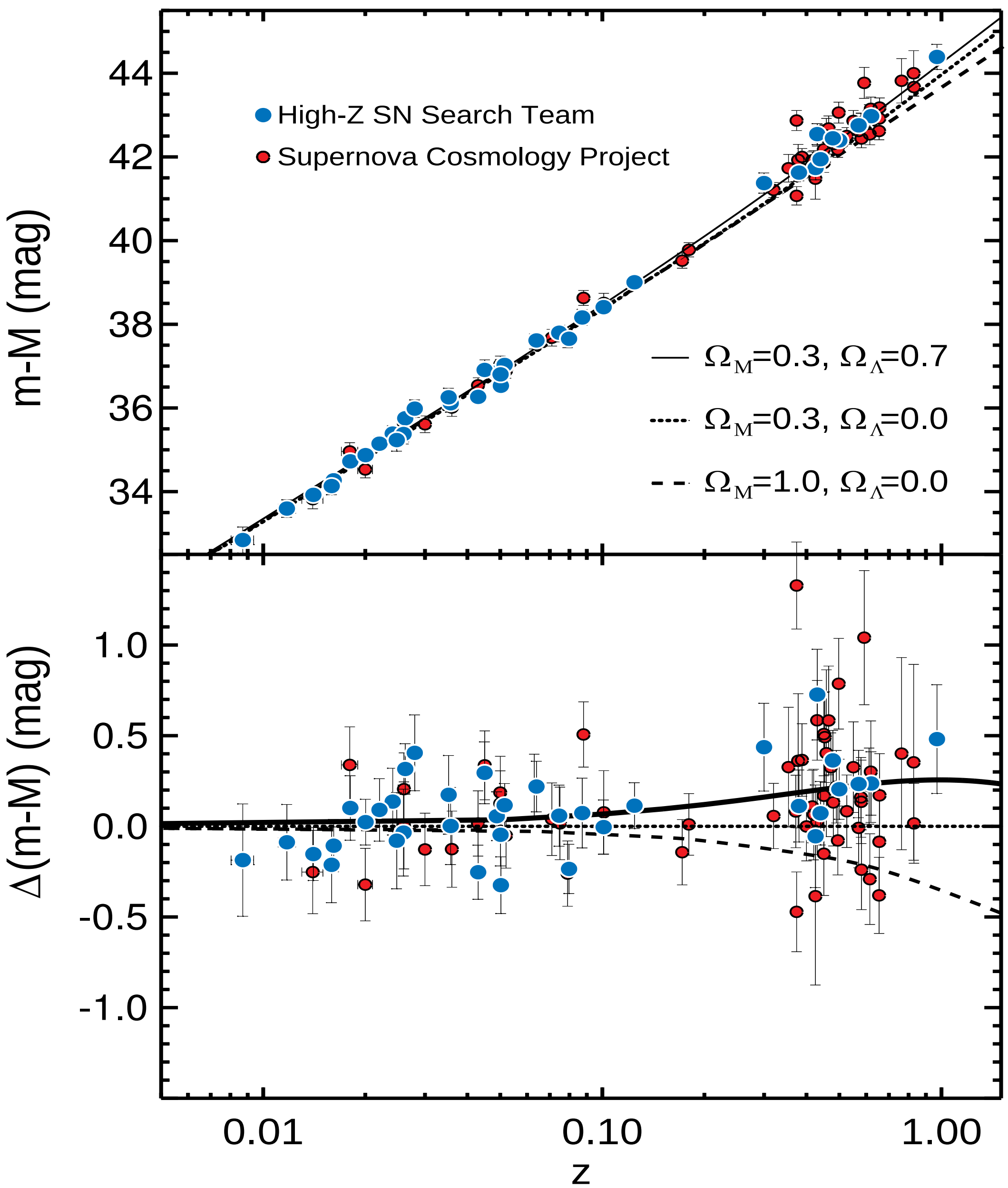
1) Structure formation: $\Omega_M \simeq 0.3 \pm 0.1$

2) CMB: $\Omega_{\rm TOT} \simeq 1.0 \pm 0.06$

3) Type Ia Supernovae: $0.8\,\Omega_M - 0.6\,\Omega_\Lambda = -0.2 \pm 0.1$



Kim, *et al.* (1997)



$$m = M + 5 \log \left(\frac{d_L(z, \Omega_M, \Omega_\Lambda, \ldots)}{10\,\mathrm{pc}} \right)$$

Parameterize with $\Omega_X = \rho_X/\rho_c$

$$w = \frac{p_X}{\rho_X}$$

then $H^2(z)/H_0^2 = \Omega_M(1+z)^3 + \Omega_X(1+z)^{3(1+w)}$

- $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_M + \rho_X + 3p_X)$

  $\Rightarrow$ Has (strongly) negative pressure

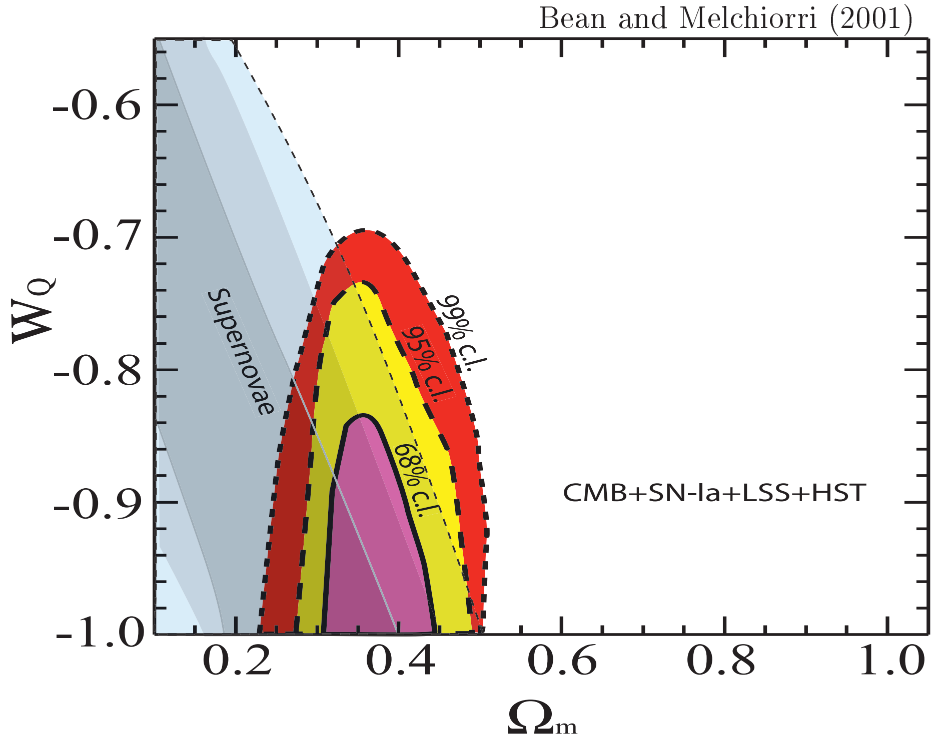
- Smooth - clusters only at $\lambda \sim \lambda_{\rm HOR}$ (if at all)

  $\Rightarrow$ cannot see it in galaxy surveys

- From observations: $-1 > w \gtrsim -0.6$

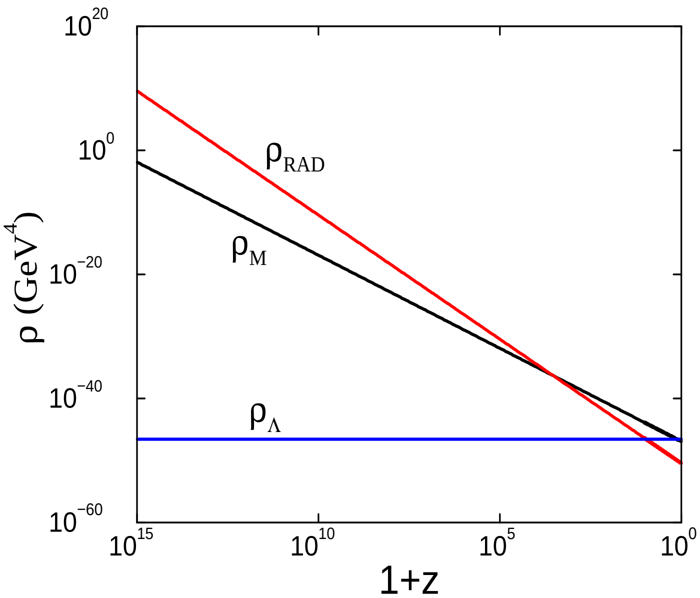
  $\Rightarrow$ important only at $z \lesssim 1$, since $\rho_X/\rho_M \propto (1+z)^{3w}$.

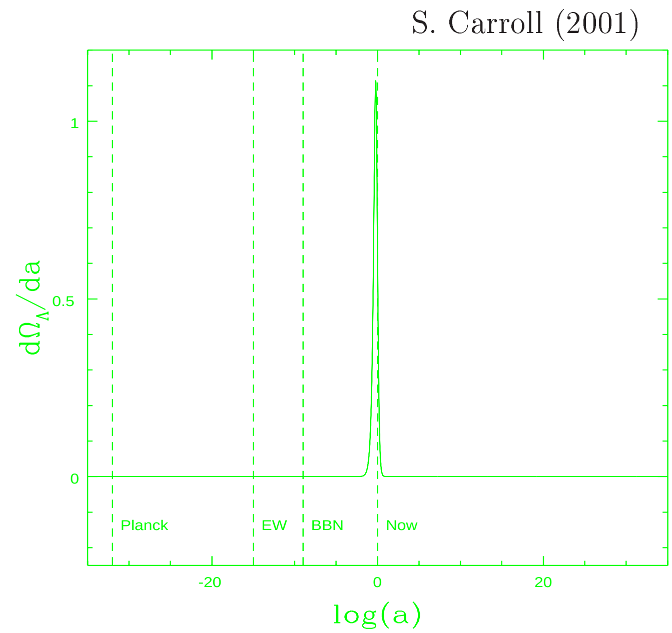
Bean and Melchiorri (2001)



Fine-Tuning Problems

1) "Why now?"





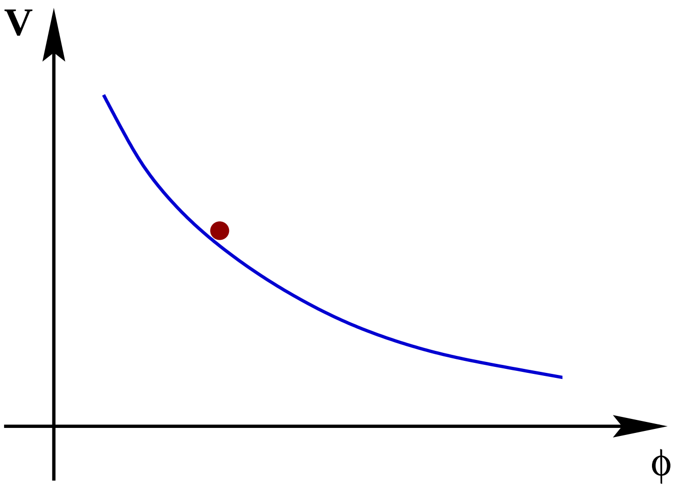
2) "Why so small?" (The Cosmological Constant, that is)

$$G_{\mu\nu} + \boldsymbol{\Lambda}\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

but

$$\rho_\Lambda \lesssim (10^{-3}\,\text{eV})^4 \lll (10^{+19}\,\text{GeV})^4$$

A candidate: Quintessence

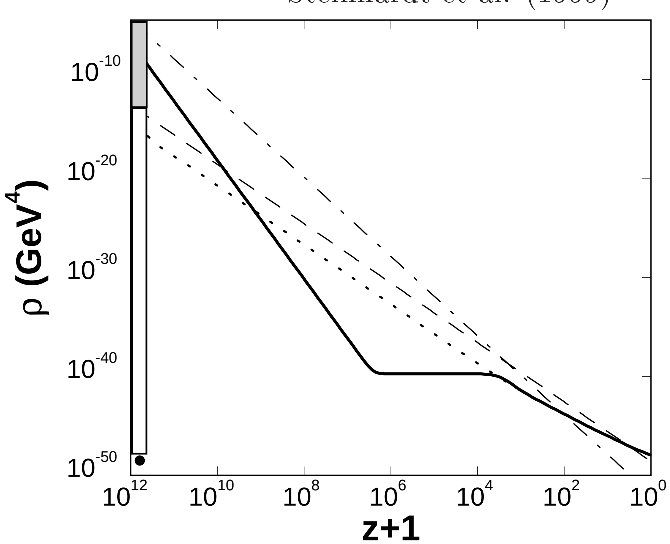


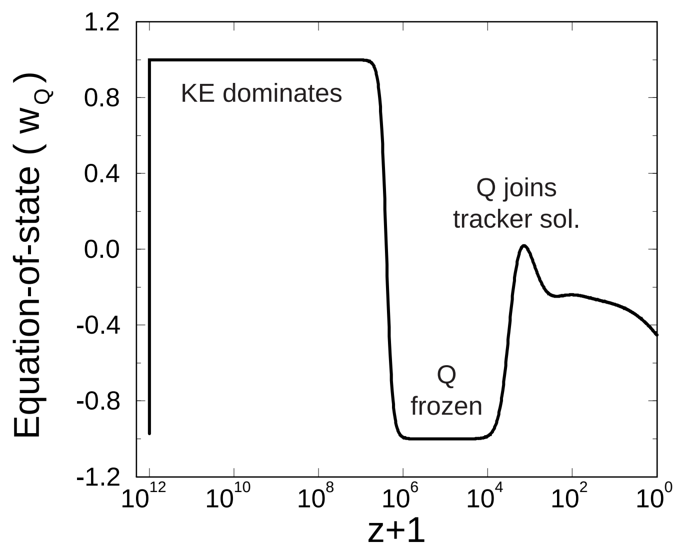
$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0$$

$$m_\phi \sim H_0 \sim 10^{-33} eV$$

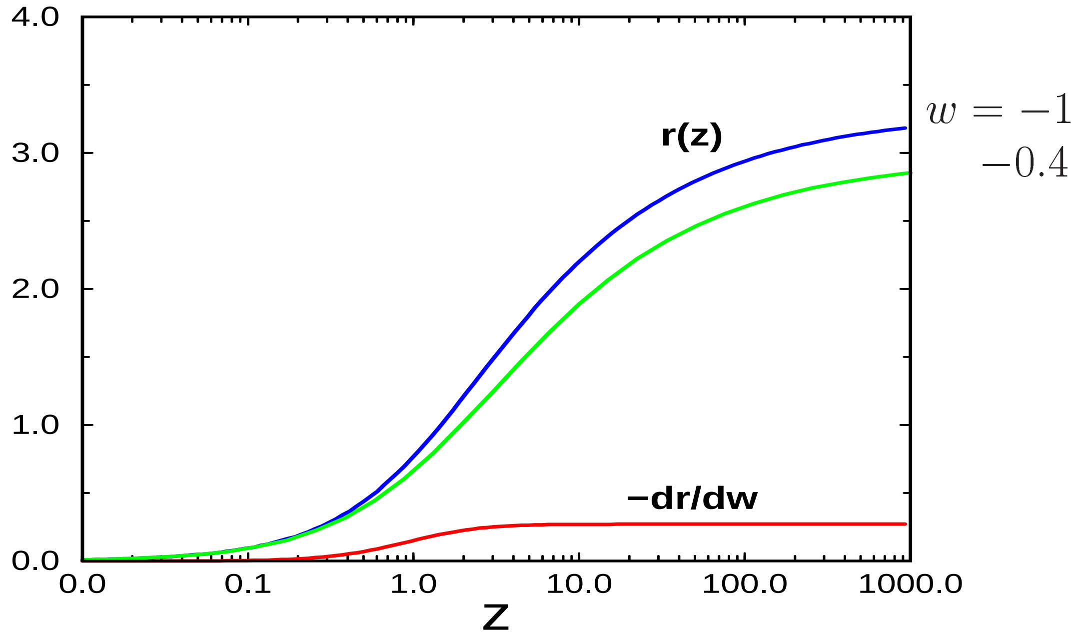
$$w = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$$

Steinhardt et al. (1999)

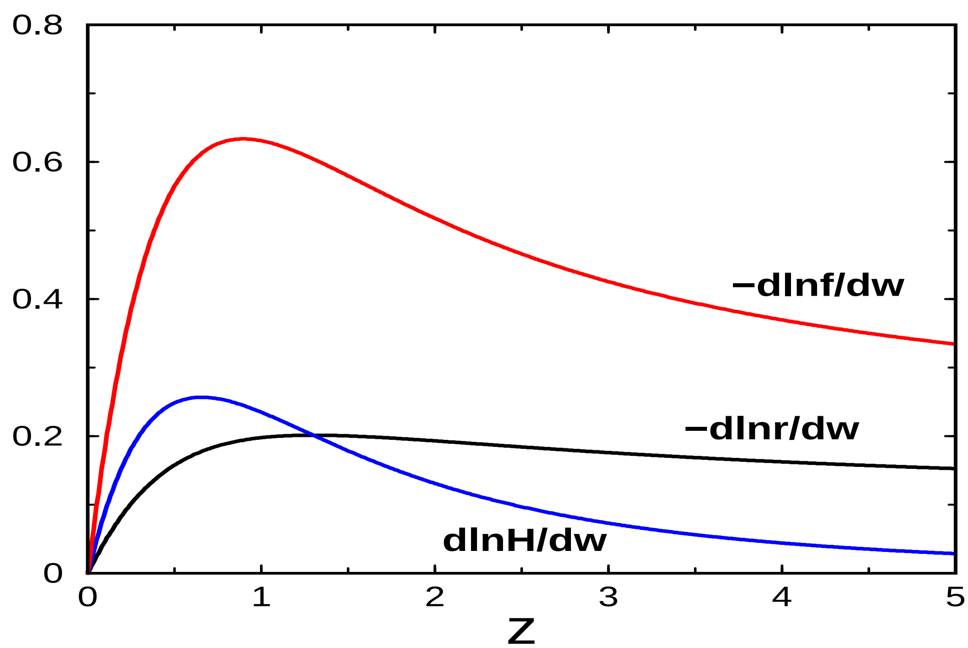




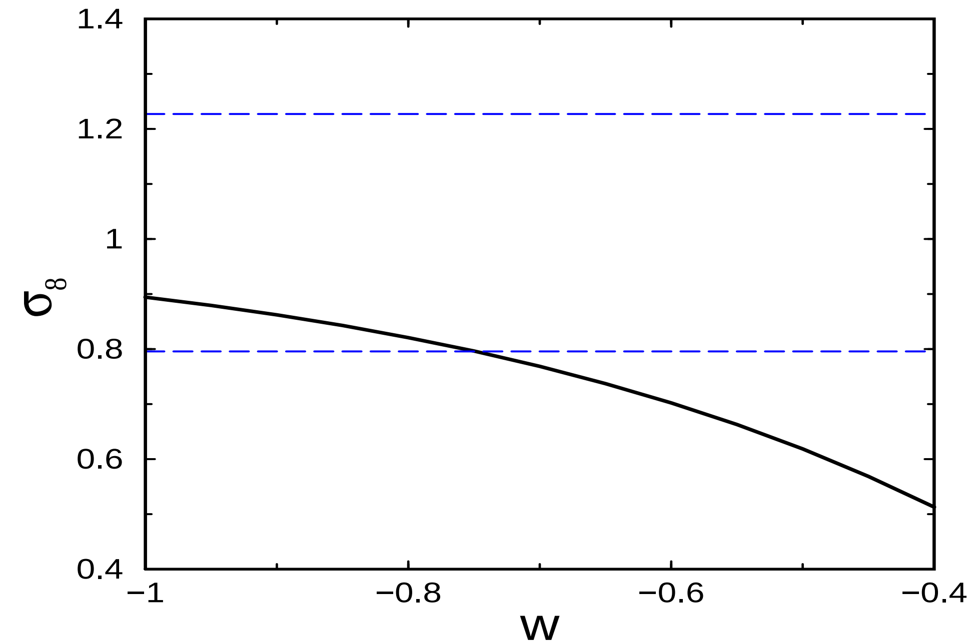
Kinematic Tests

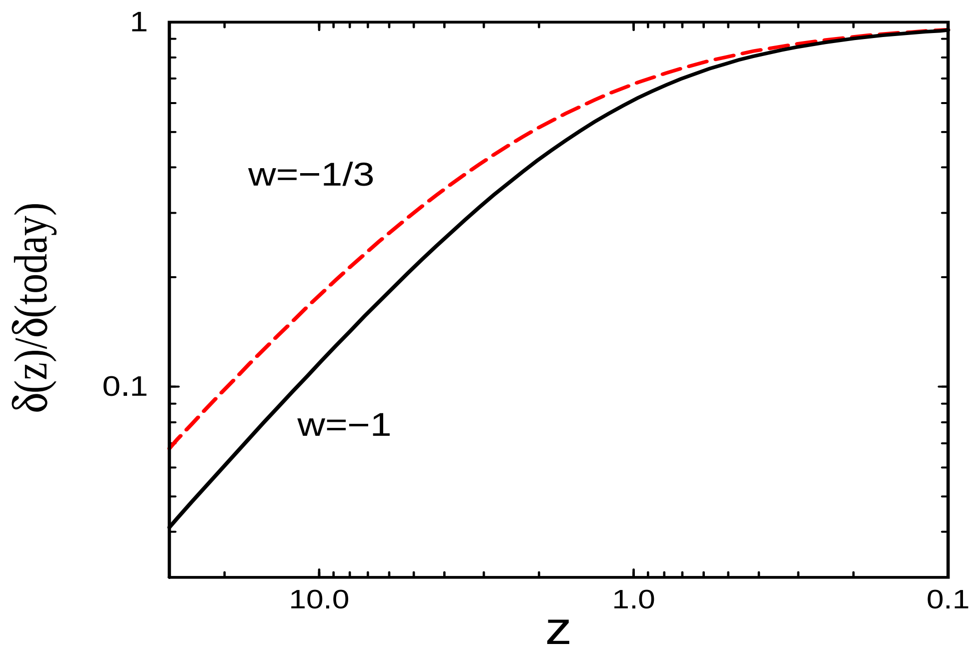


$$r(z) \to H_0^{-1}\left[z - \frac{3}{4}z^2 - \frac{3}{4}\Omega_X w z^2 + \cdots\right] \quad \text{for } z \ll 1$$



Growth of Density Perturbations

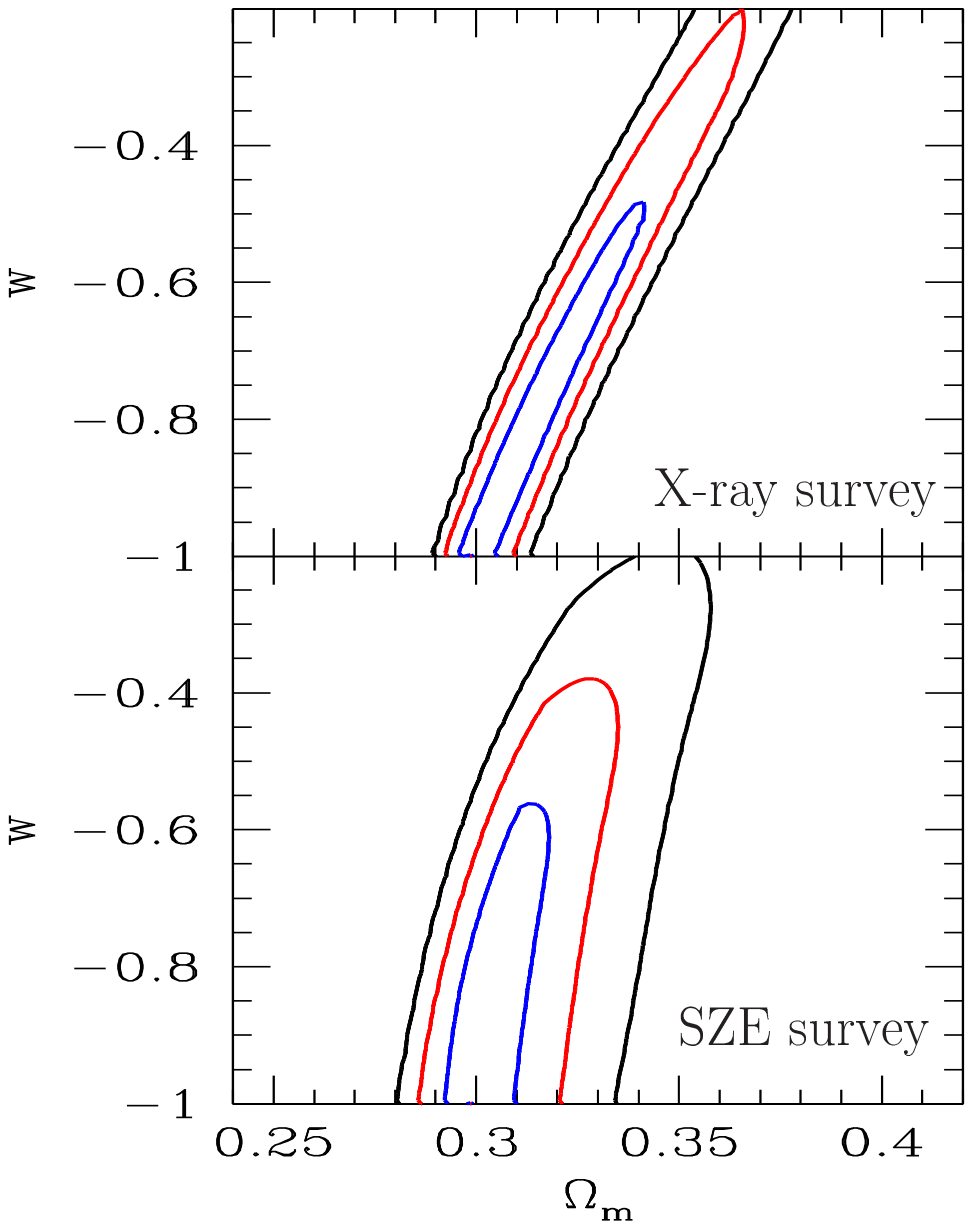




Galaxy Cluster Abundance

$$\frac{dN}{dz d\Omega}(z) = \left[\frac{dV}{dz d\Omega}(z) \int_{M_{\min}(z)}^{\infty} dM \frac{dn}{dM}\right]$$

Haiman, Mohr & Holder (2000)

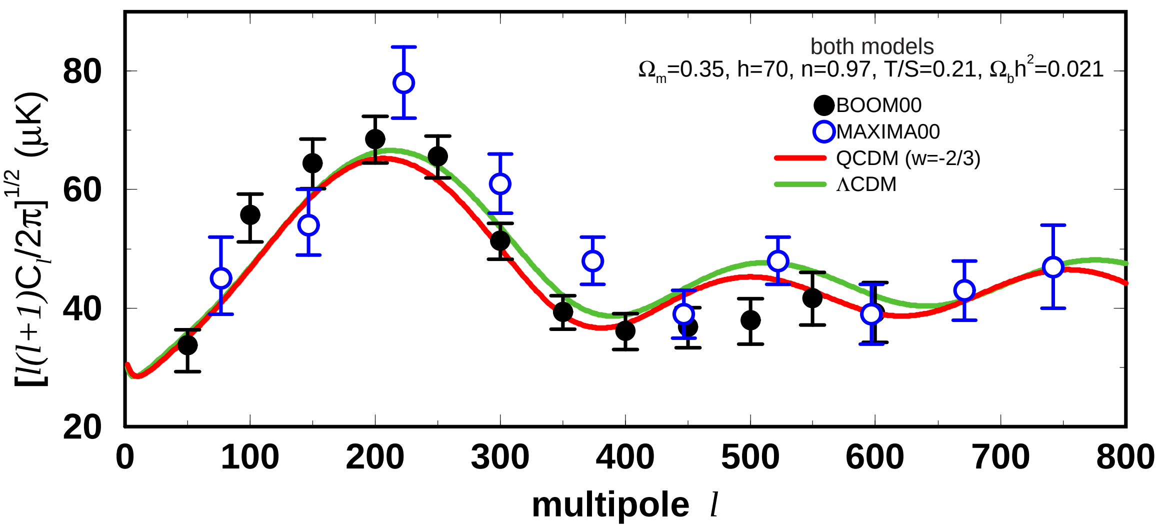


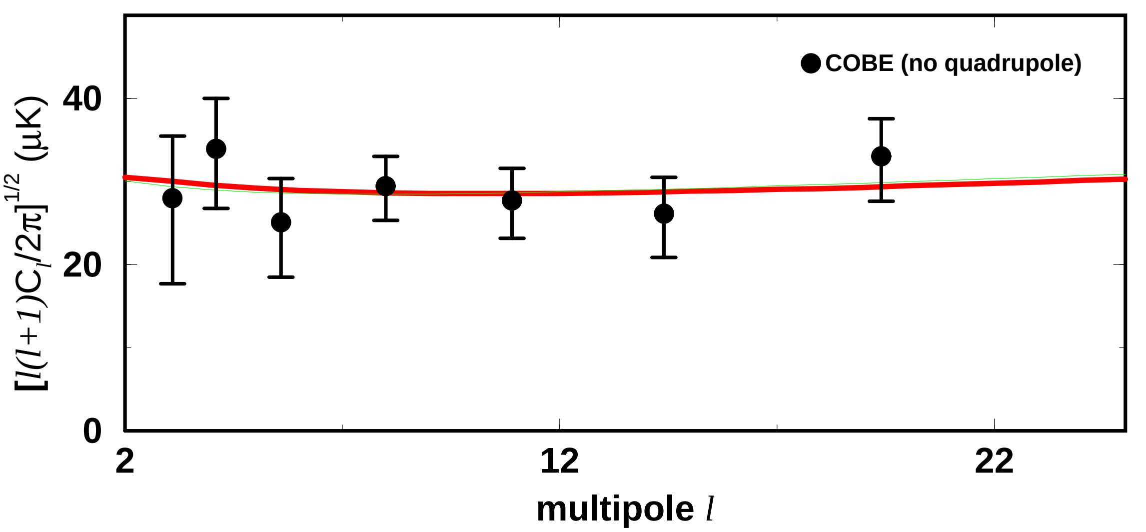
CMB and Dark Energy

Location of the first peak: $l_1 \approx \pi \frac{\eta_{LS}}{\eta_{SH}}$

$$\frac{\Delta l_1}{l_1} \approx \mathbf{-0.084\Delta w} - 0.45\frac{\Delta h}{h} + 0.09\frac{\Delta \Omega_B h^2}{\Omega_B h^2} - 0.14\frac{\Delta \Omega_M}{\Omega_M} - 1.25\frac{\Delta \Omega_0}{\Omega_0}$$

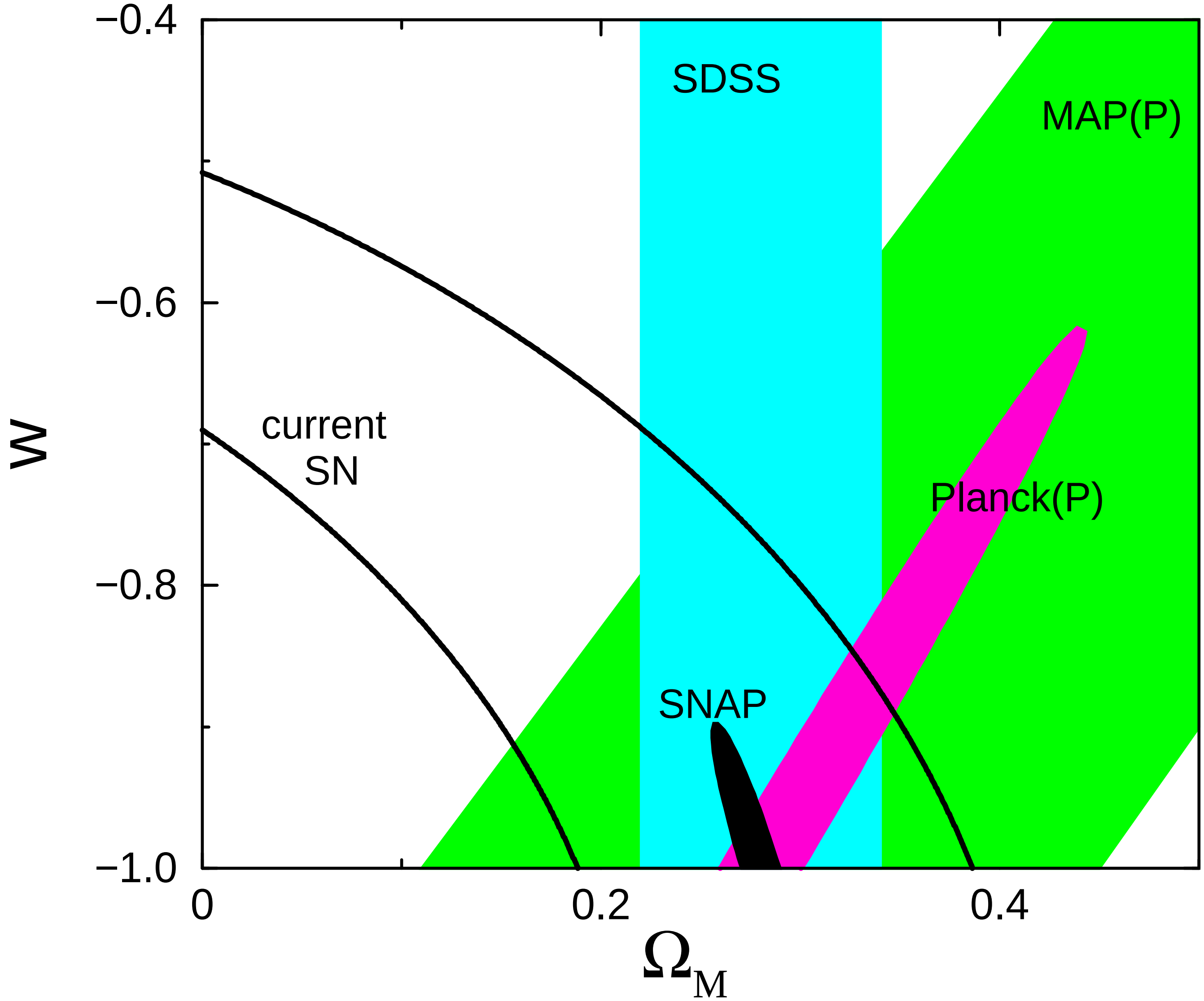
P. Steinhardt (2000)





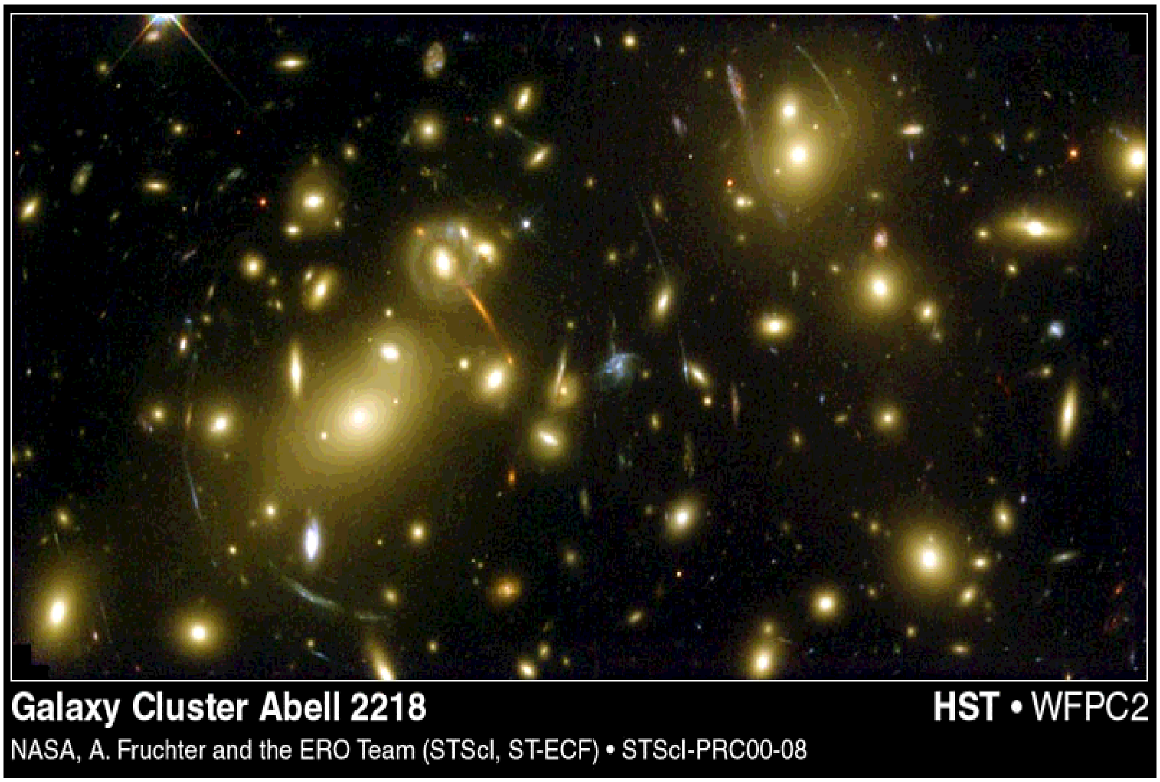
CMB provides a *single* measurement of the distance to LSS, therefore

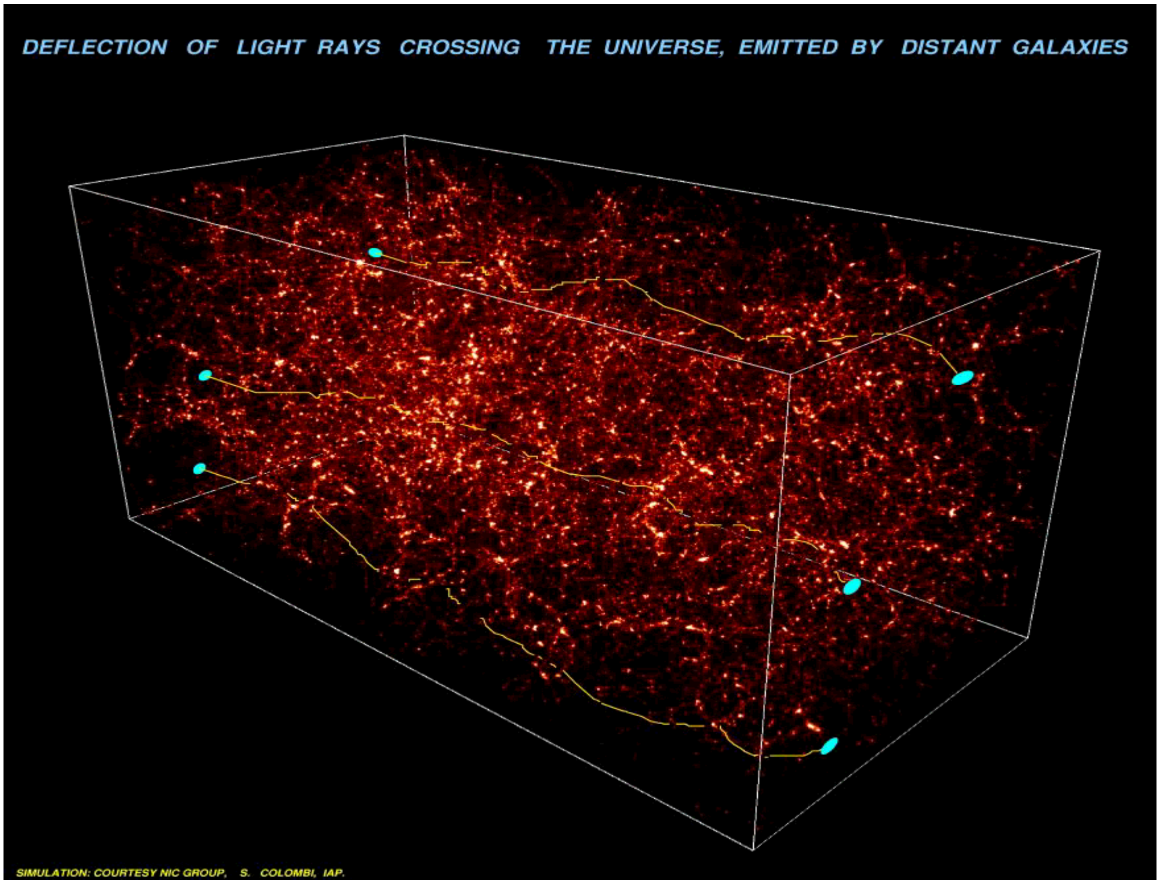
- Degeneracy in parameter estimation
- Only $w_{\rm eff}$ is probed

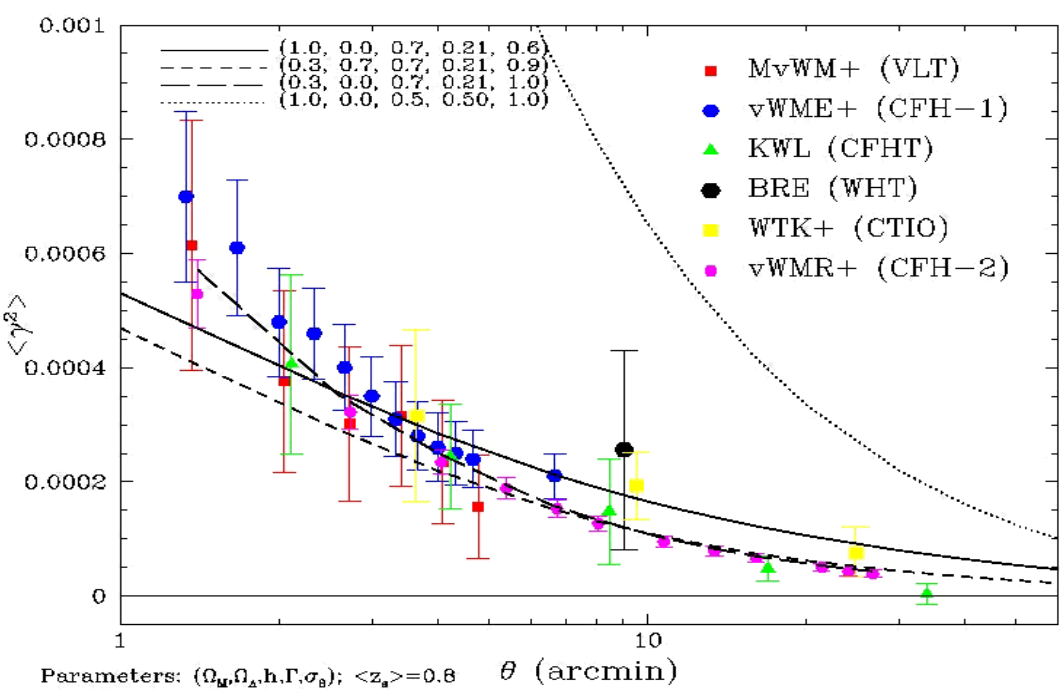


Weak Lensing and Dark Energy

(Huterer 2001)




DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES
SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

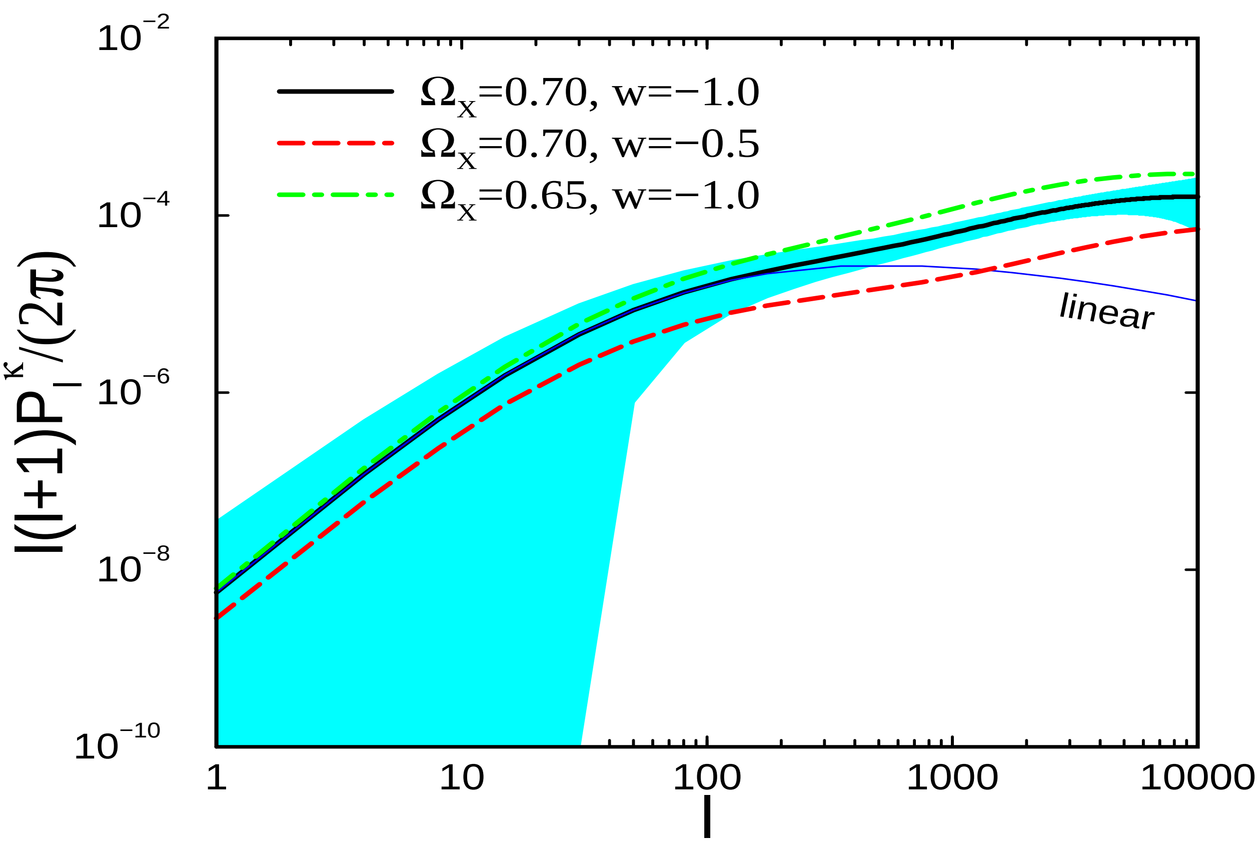

(1.0, 0.0, 0.7, 0.21, 0.6)
(0.3, 0.7, 0.7, 0.21, 0.9)
(0.3, 0.0, 0.7, 0.21, 1.0)
(1.0, 0.0, 0.5, 0.50, 1.0)
MvWM+ (VLT)
vWME+ (CFH−1)
KWL (CFHT)
BRE (WHT)
WTK+ (CTIO)
vWMR+ (CFH−2)
<γ²>
θ (arcmin)
Parameters: (Ω_M,Ω_Λ,h,Γ,σ_8); <z_s>=0.8

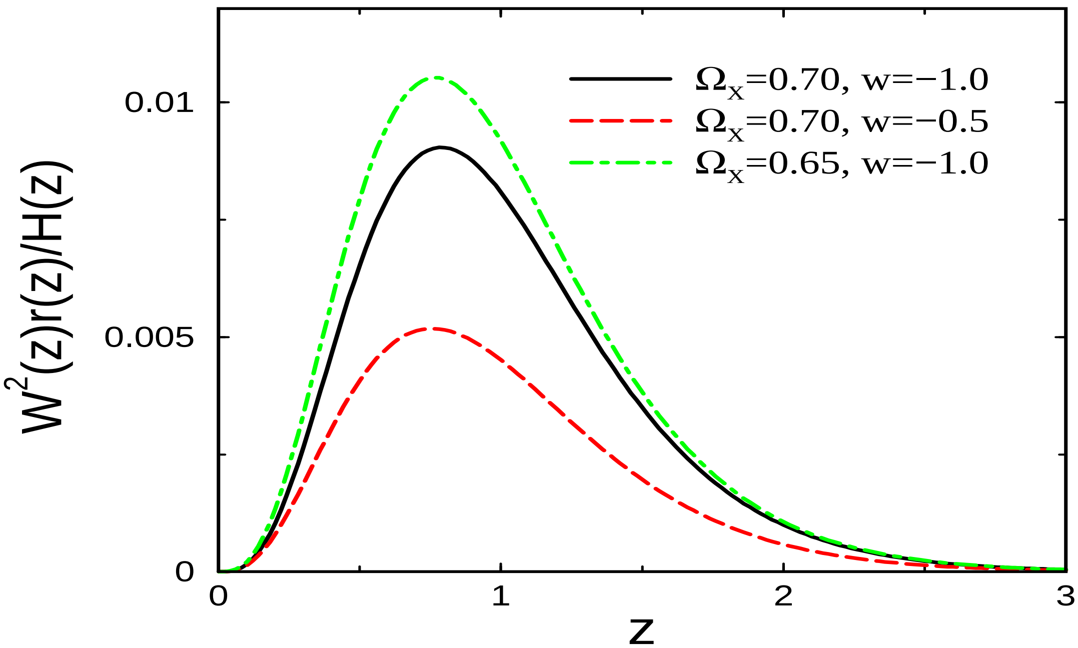
Power Spectrum of the Convergence

$$\kappa(\hat{\mathbf{n}}, \chi) = \int_0^{\chi} W(\chi')\, \delta(\chi')\, d\chi'$$

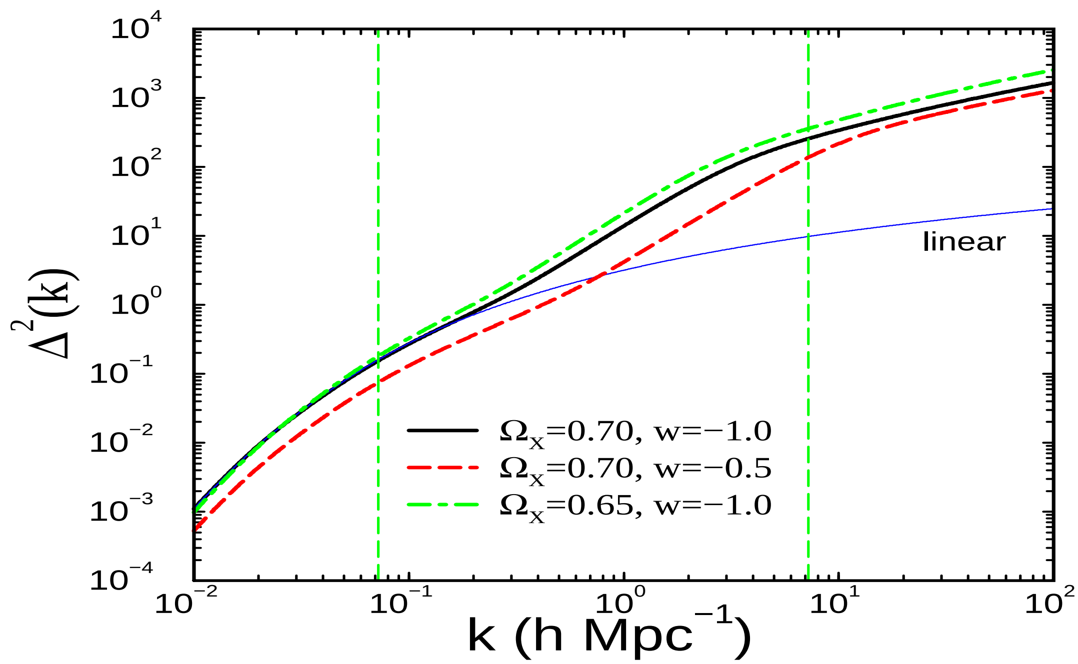
$$\langle \kappa_{lm} \kappa_{l'm'} \rangle = \delta_{l_1 l_2}\, \delta_{m_1 m_2}\, P_l^{\kappa}$$

$$P_l^{\kappa} = \frac{2\pi^2}{l^3} \int_0^{z_s} dz\, W_1(z)\, \Delta^2 \left(\frac{l}{r(z)}; z \right)$$





$$\Delta^2(k,z) = \delta_H^2 \left(\frac{k}{H_0}\right)^{n+3} T^2(k,z)\,\frac{D^2(z)}{D^2(0)}\,T_{NL}$$



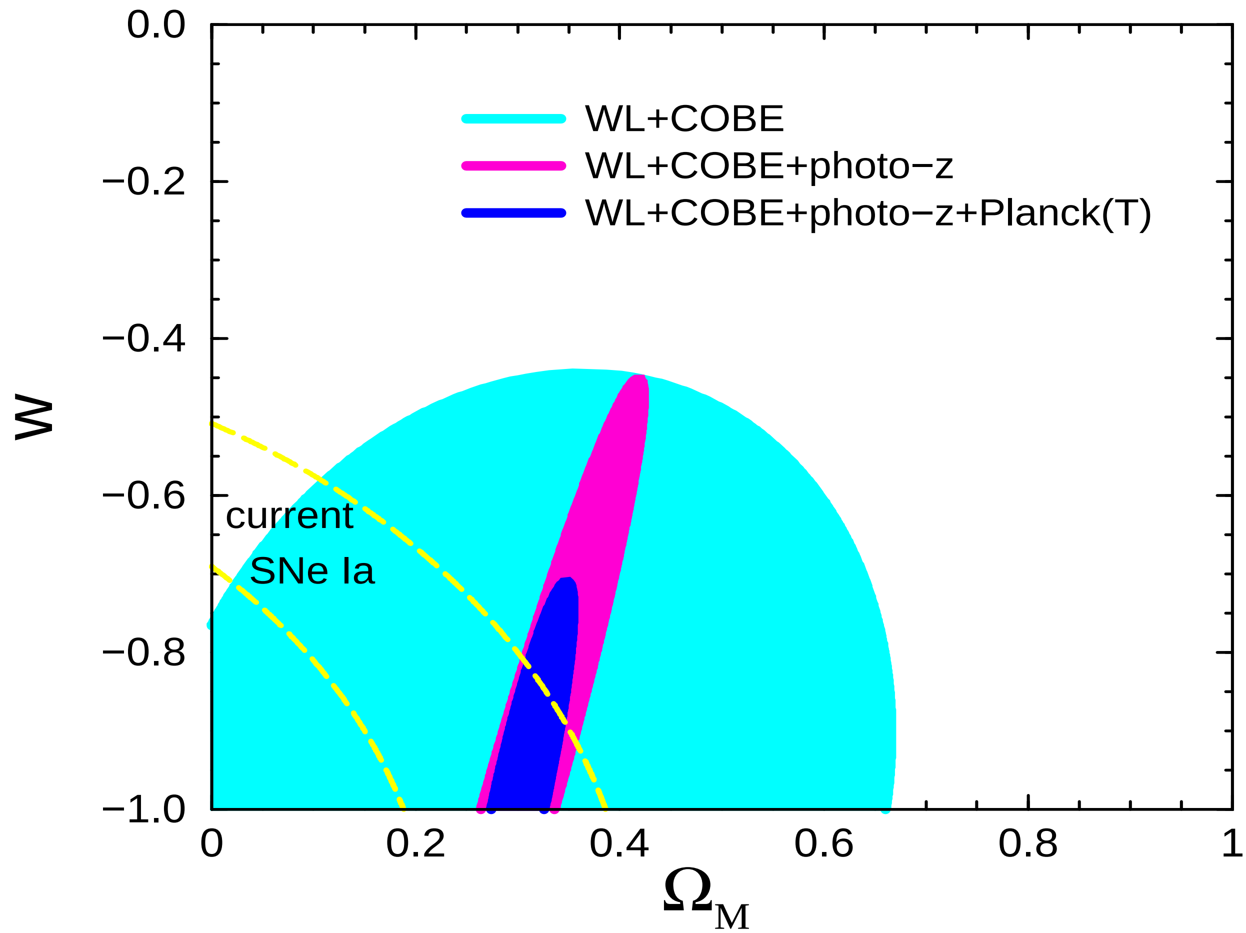
Parameters:

$$\delta_H \quad \Omega_X \quad w \quad \Omega_M h^2 \quad n_s \quad \Omega_B h^2 \quad m_\nu$$

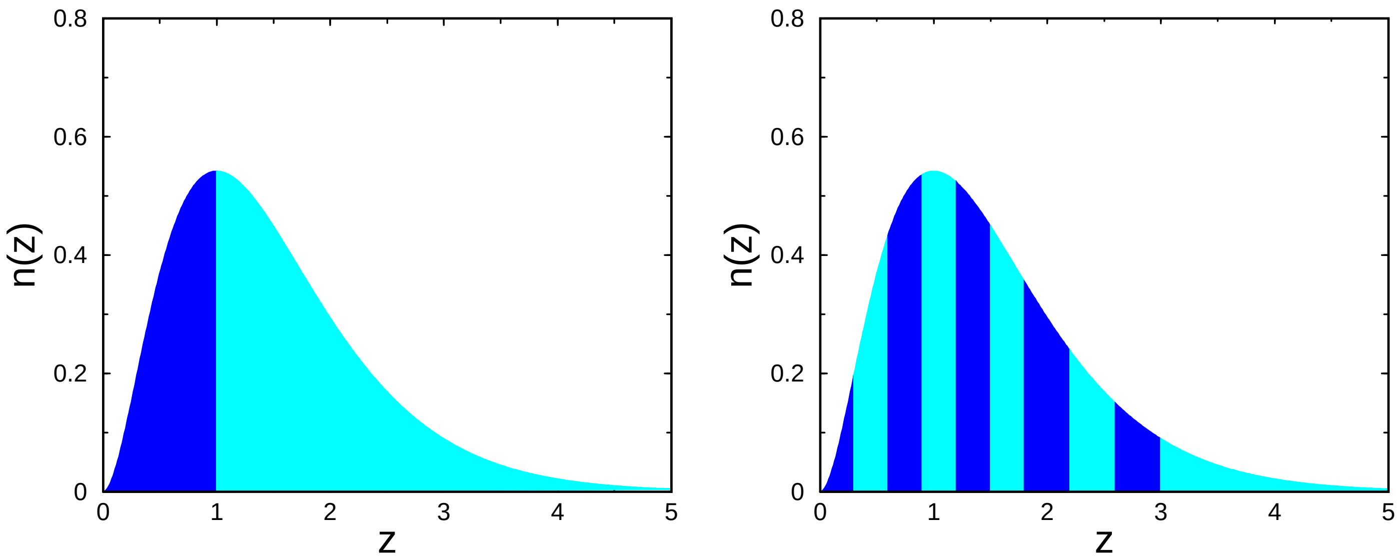
Fisher Matrix formalism:

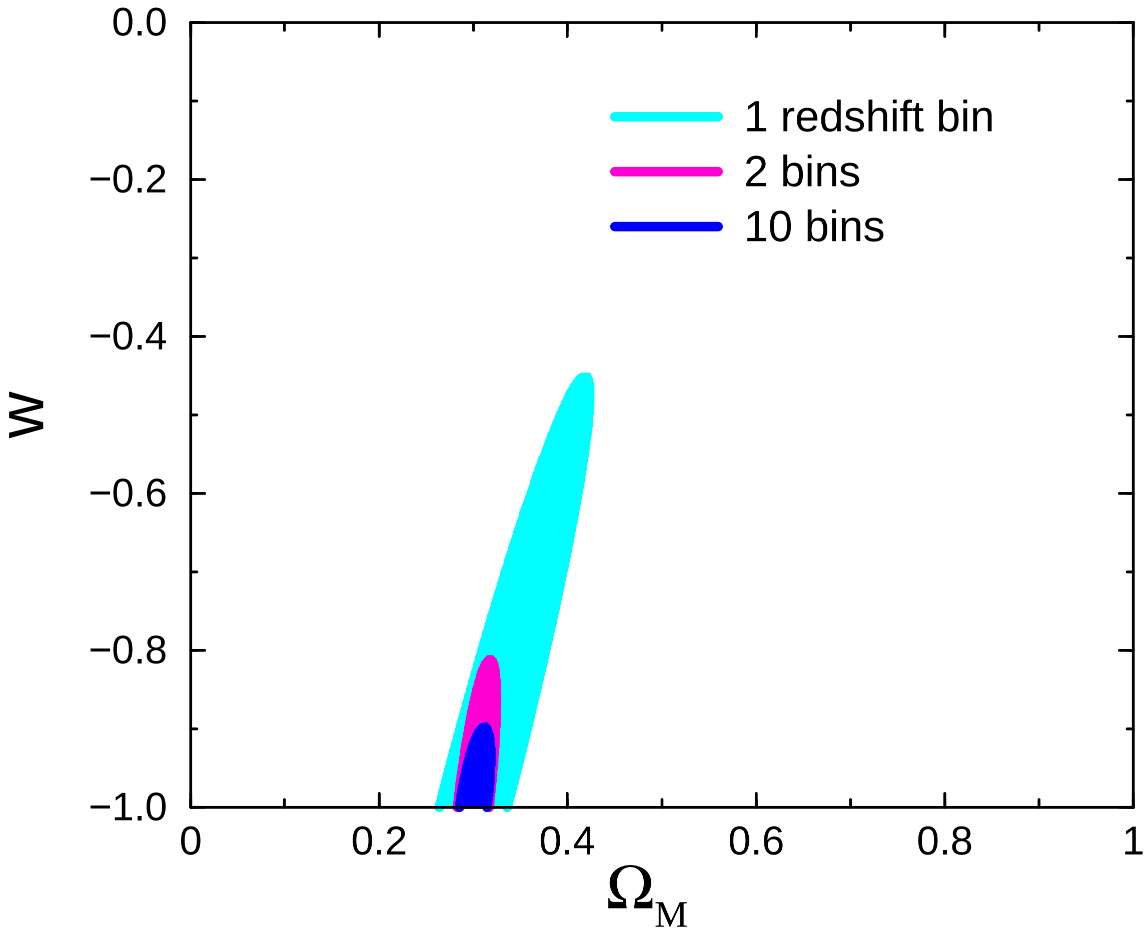
$$F_{ij} = -\left\langle \frac{\partial^2 \ln L}{\partial p_i \partial p_j} \right\rangle = \sum_l \frac{1}{(\Delta P_l^\kappa)^2} \frac{\partial P_l^\kappa}{\partial p_i} \frac{\partial P_l^\kappa}{\partial p_j}$$

Results:

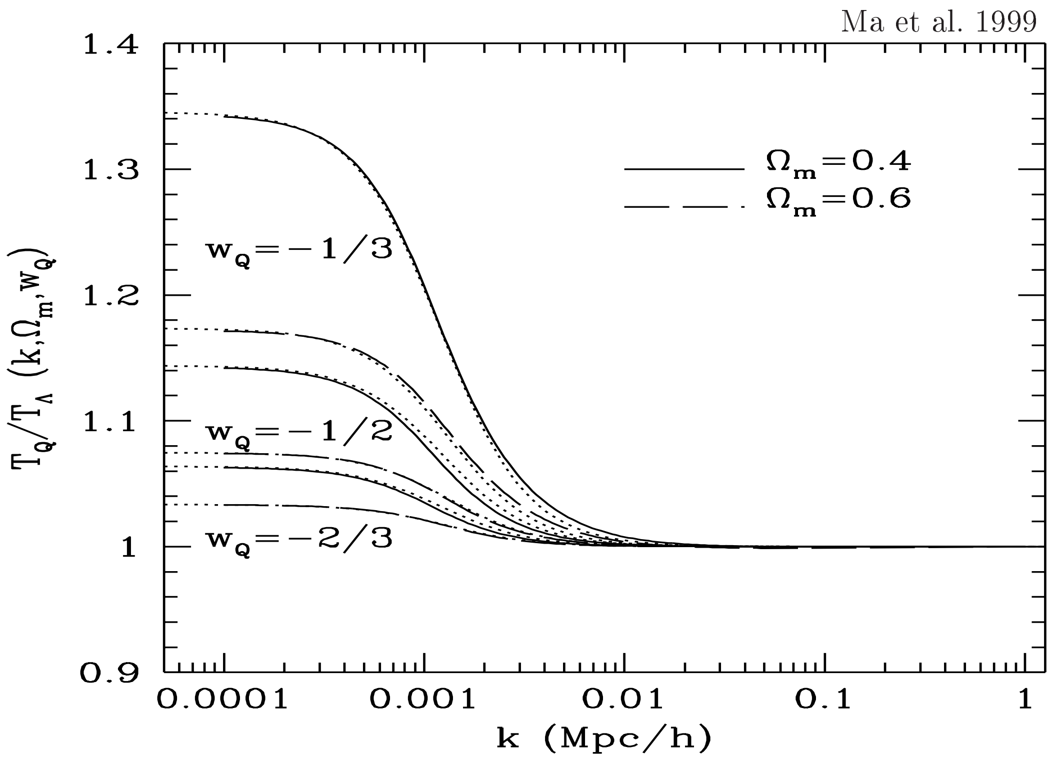


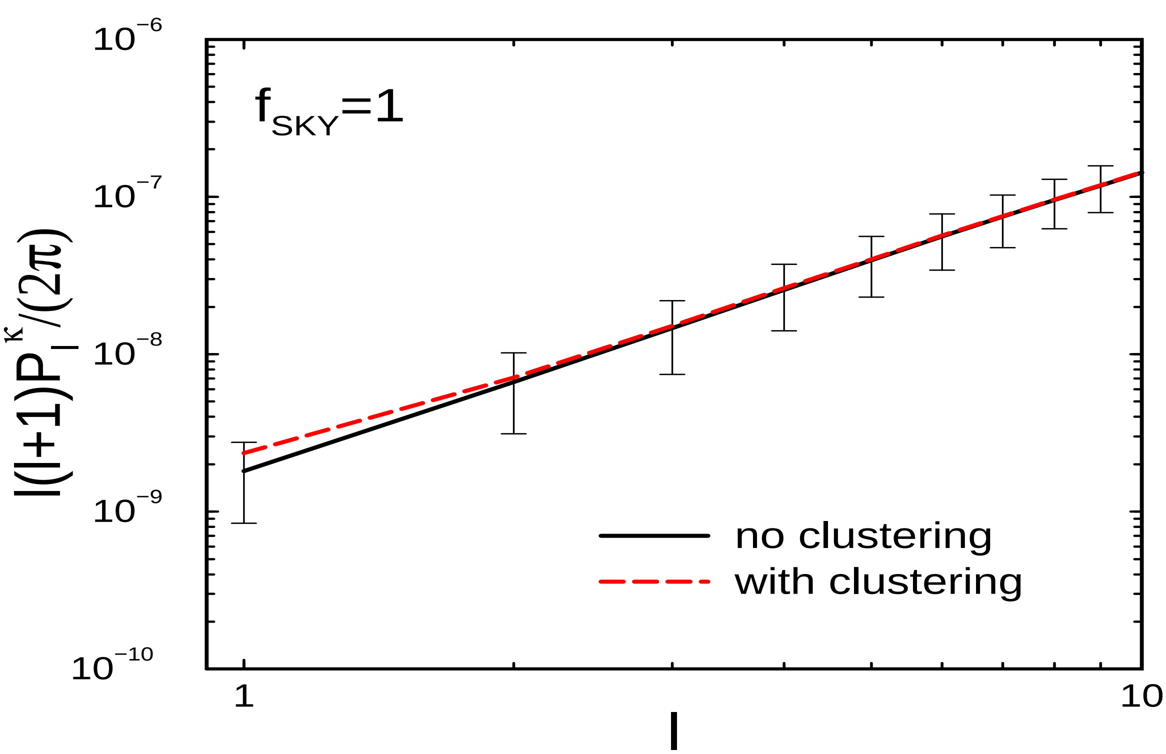
WL Tomography



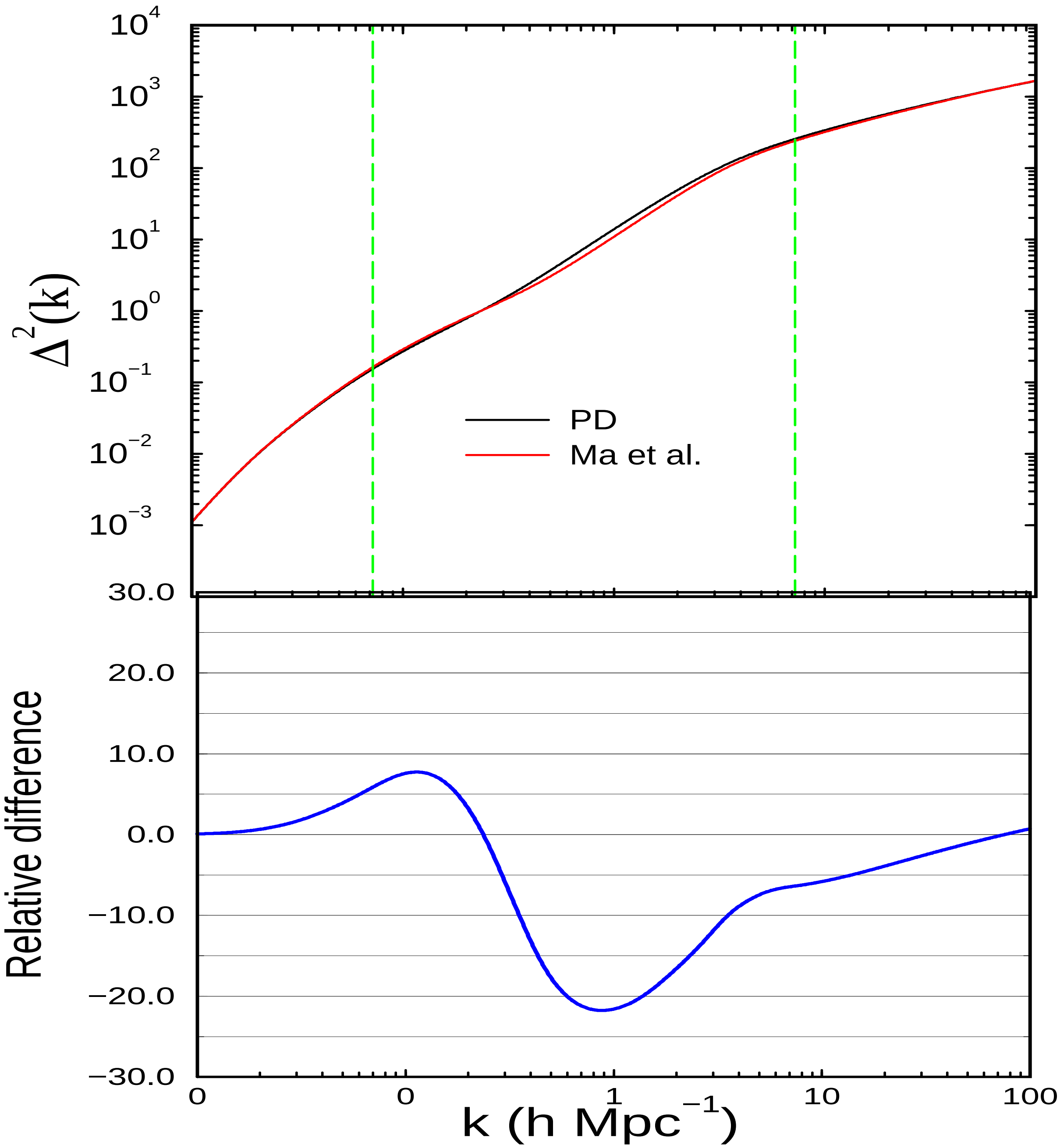


Can clustering of Dark Energy be seen in WL?





Biases: Non-linear Power Spectrum



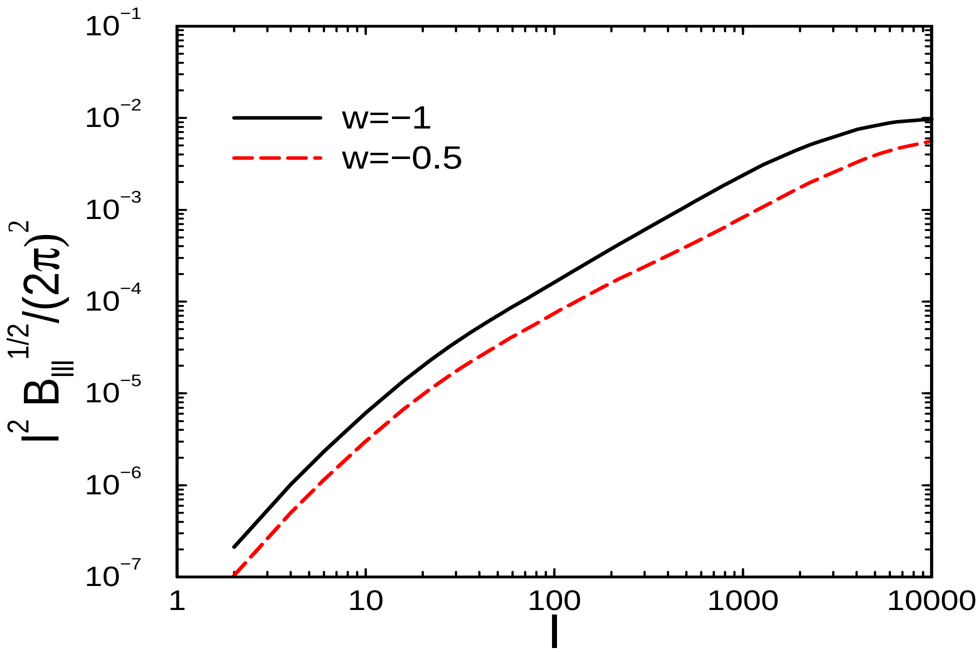
$$|\delta\Omega_X|/\sigma(\Omega_X) \sim 2.5$$

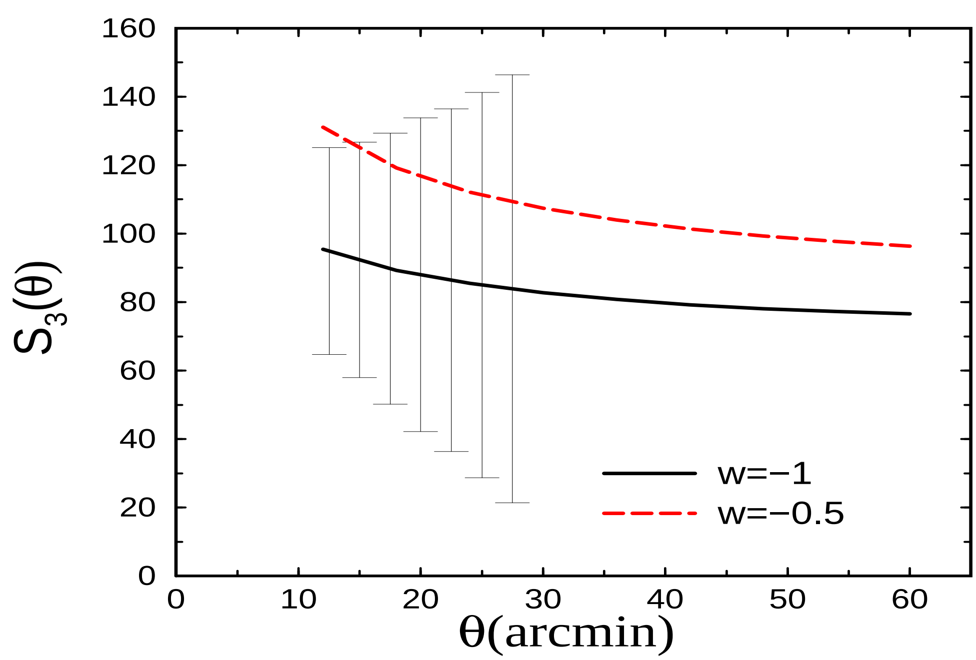
$$|\delta w|/\sigma(w) \sim 4.8$$

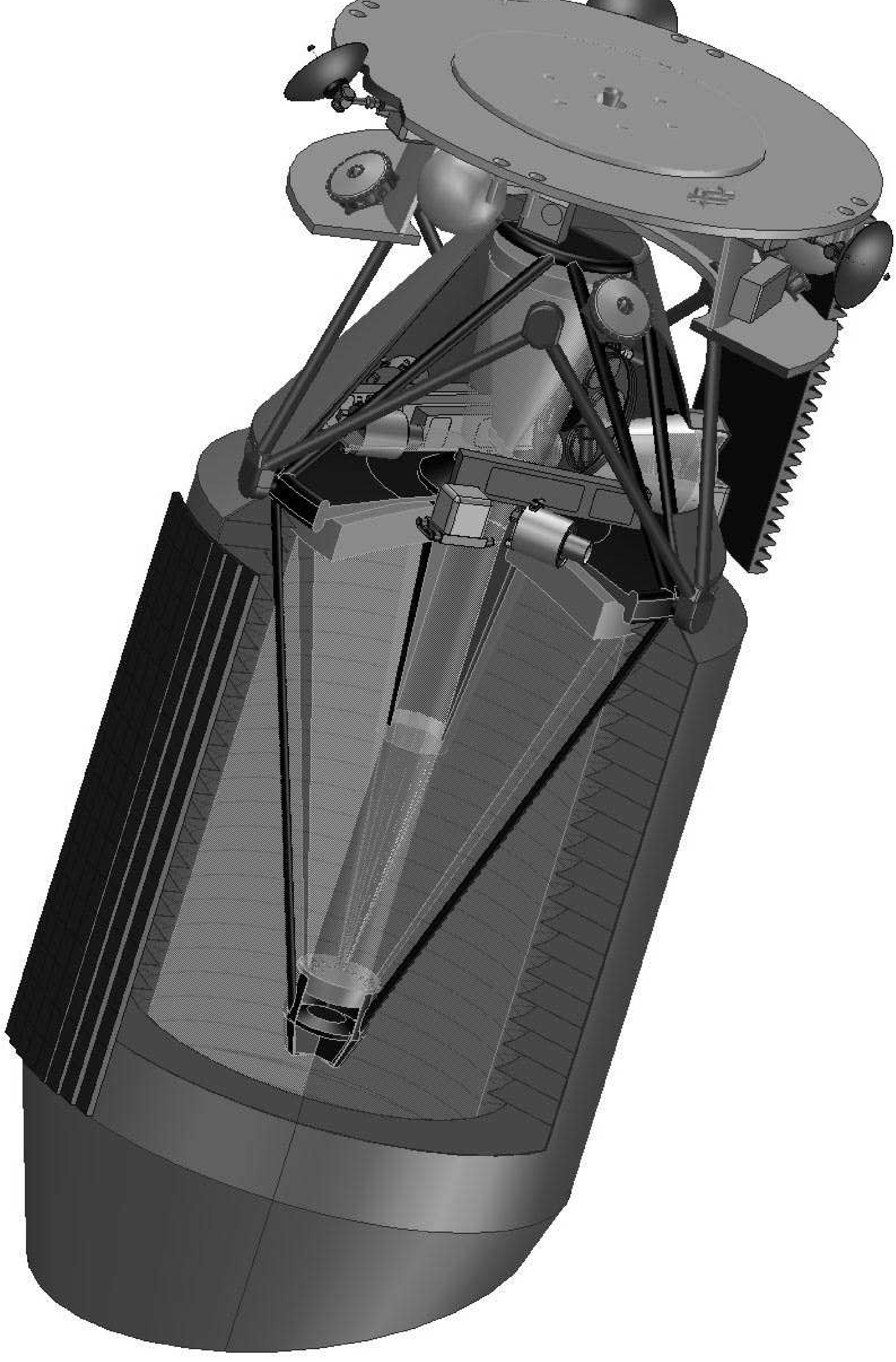
Bispectrum and Skewness

$$B^{\kappa}_{l_1 l_2 l_3} \propto \langle \kappa_{l_1 m_1} \kappa_{l_2 m_2} \kappa_{l_3 m_3} \rangle$$

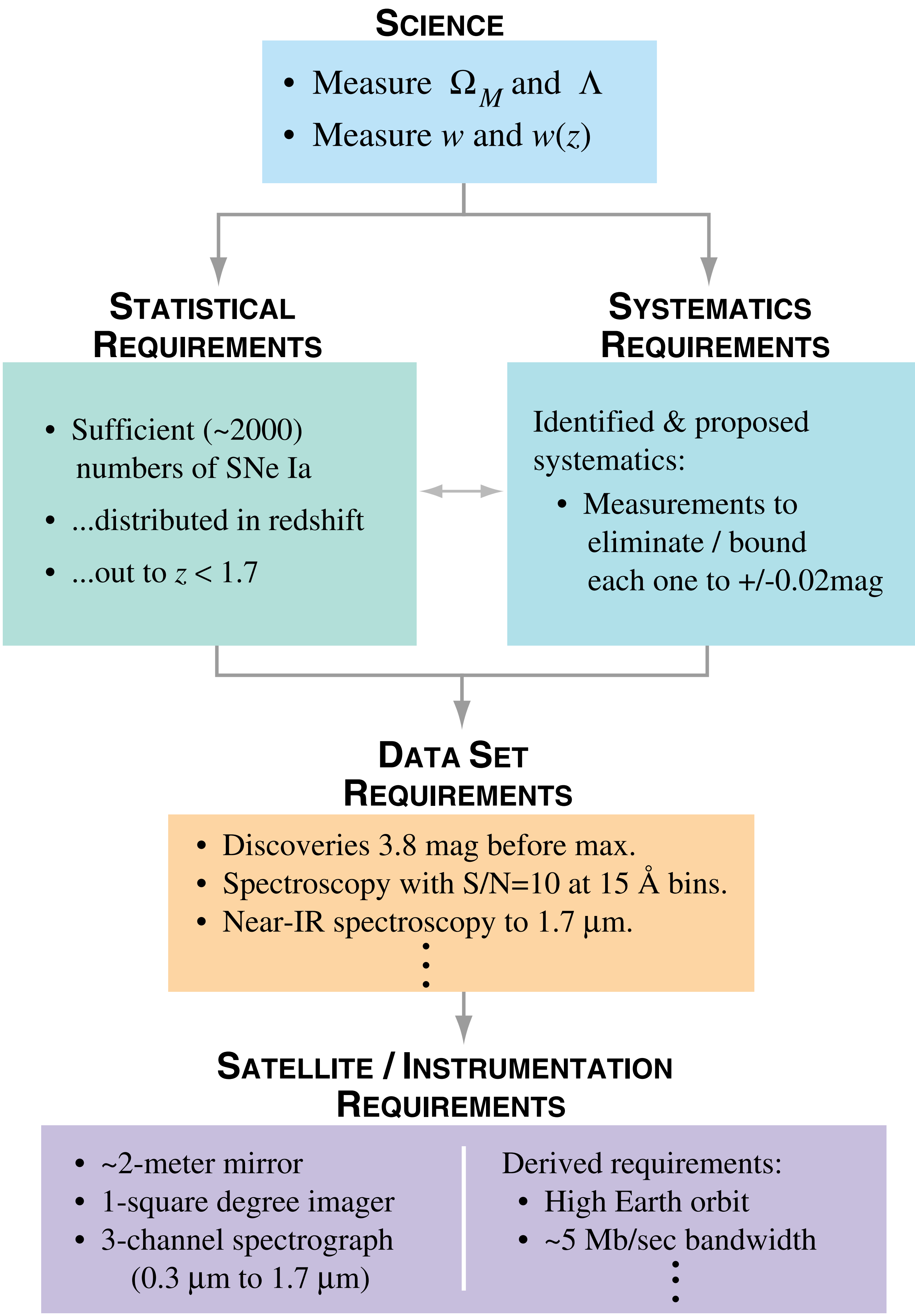
$$S_3(\theta) \propto \sum_{l_1 l_2 l_3} B^{\kappa}_{l_1 l_2 l_3} \mathcal{W}(l_1\theta)\mathcal{W}(l_2\theta)\mathcal{W}(l_3\theta)$$



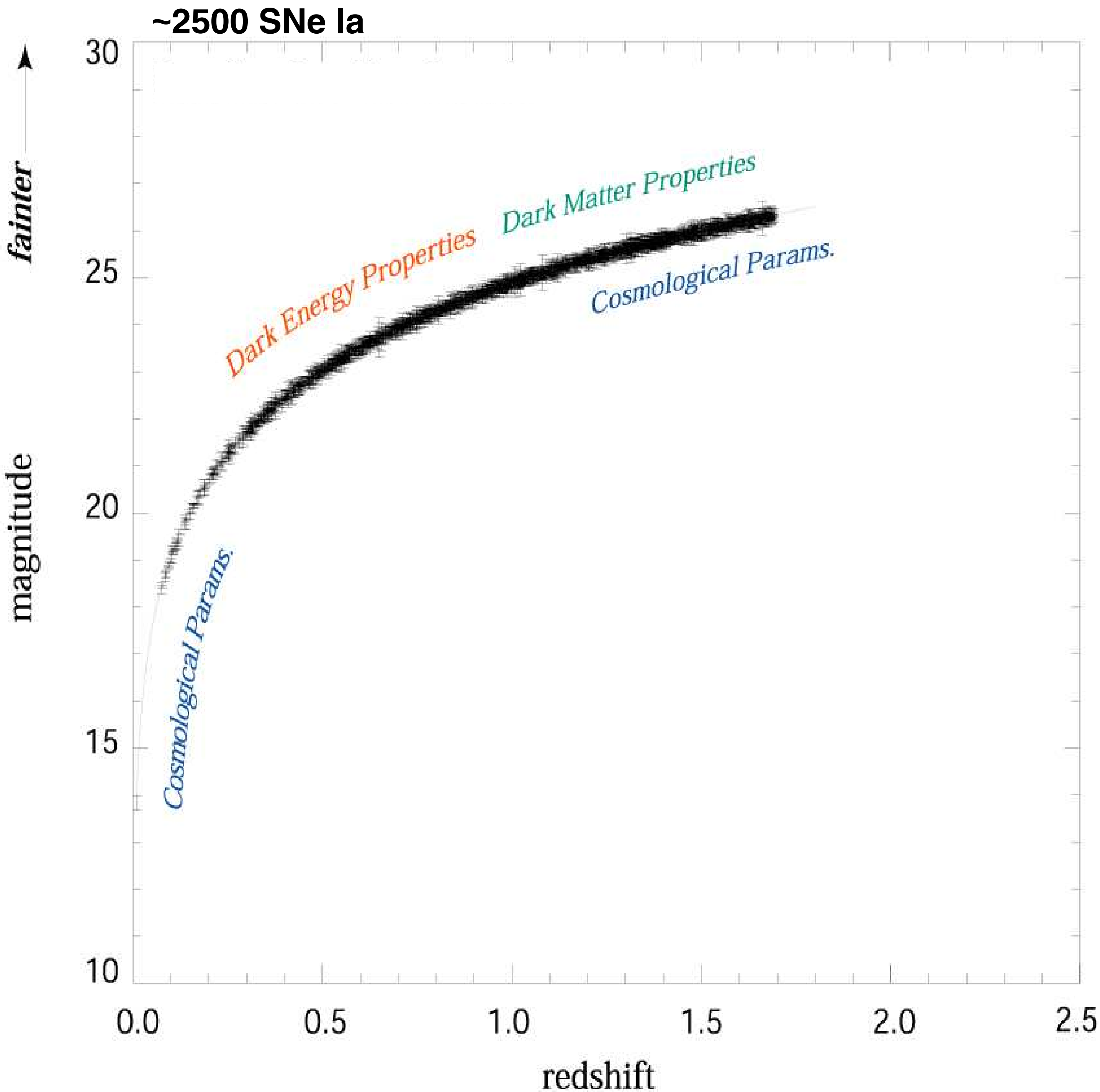


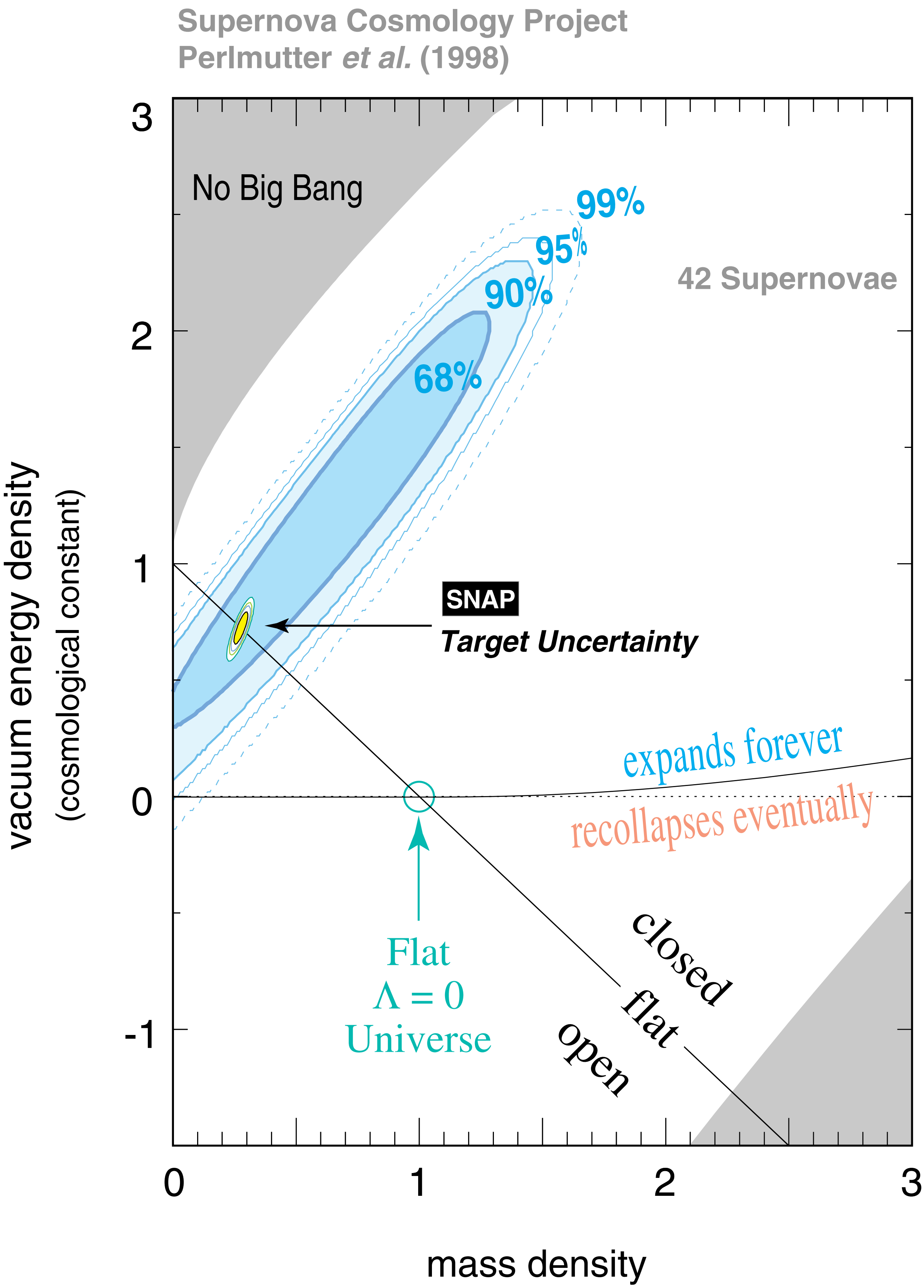


SNAP


SCIENCE
• Measure Ω_M and Λ
• Measure w and $w(z)$
STATISTICAL REQUIREMENTS
• Sufficient (~2000) numbers of SNe Ia
• ...distributed in redshift
• ...out to $z < 1.7$
SYSTEMATICS REQUIREMENTS
Identified & proposed systematics:
• Measurements to eliminate / bound each one to +/-0.02mag
DATA SET REQUIREMENTS
• Discoveries 3.8 mag before max.
• Spectroscopy with S/N=10 at 15 Å bins.
• Near-IR spectroscopy to 1.7 μm.
SATELLITE / INSTRUMENTATION REQUIREMENTS
• ~2-meter mirror
• 1-square degree imager
• 3-channel spectrograph (0.3 μm to 1.7 μm)
Derived requirements:
• High Earth orbit
• ~5 Mb/sec bandwidth

SNAP SuperNova Acceleration Probe

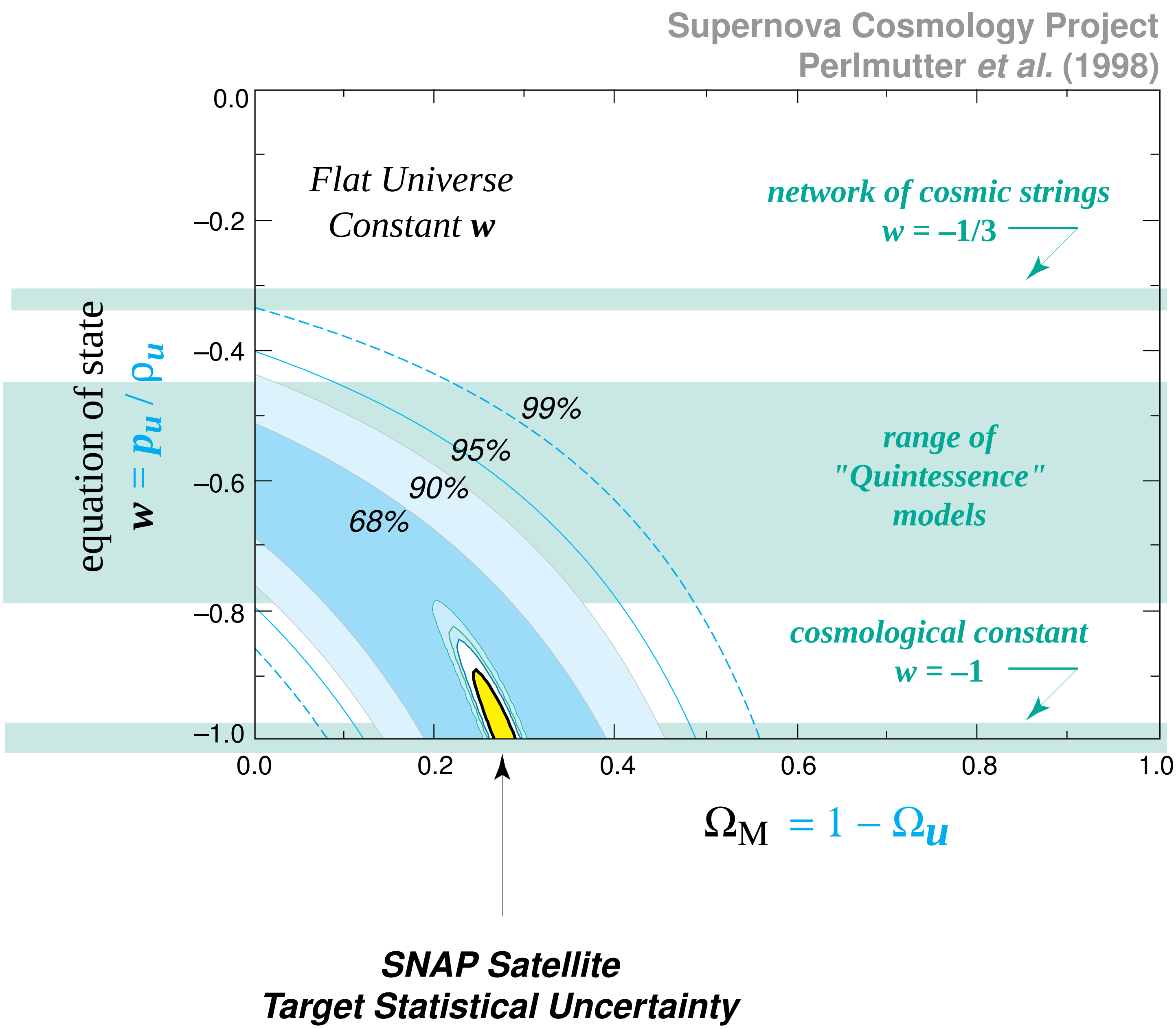




Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAP
Target Uncertainty
expands forever
recollapses eventually
closed
flat
open
Flat
Λ = 0
Universe
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

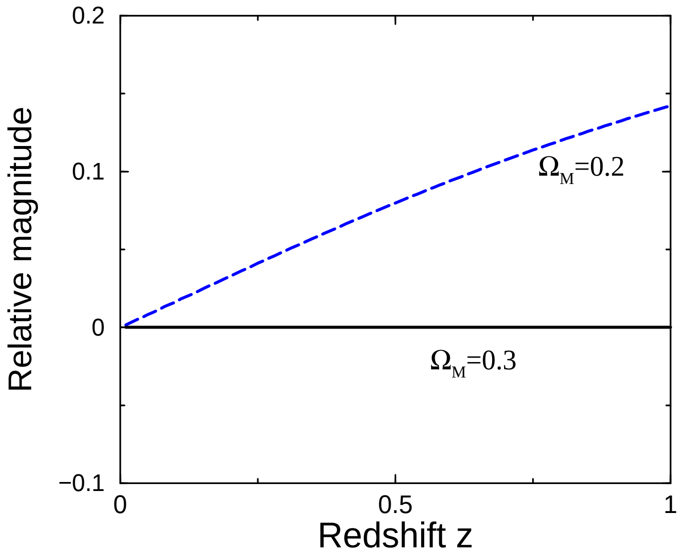
Dark Energy

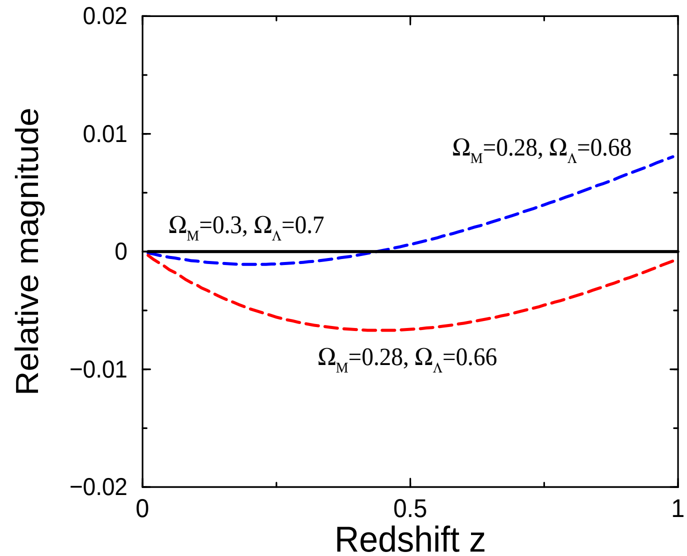
Unknown Component, Ω_u, of Energy Density

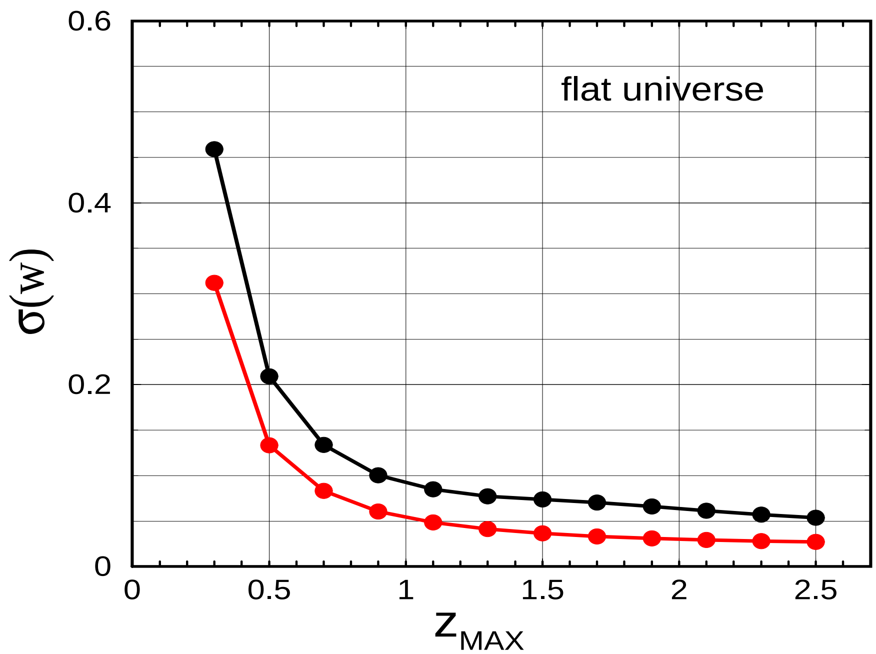


Strategies: Optimal Redshifts

(Huterer and Turner 2000)



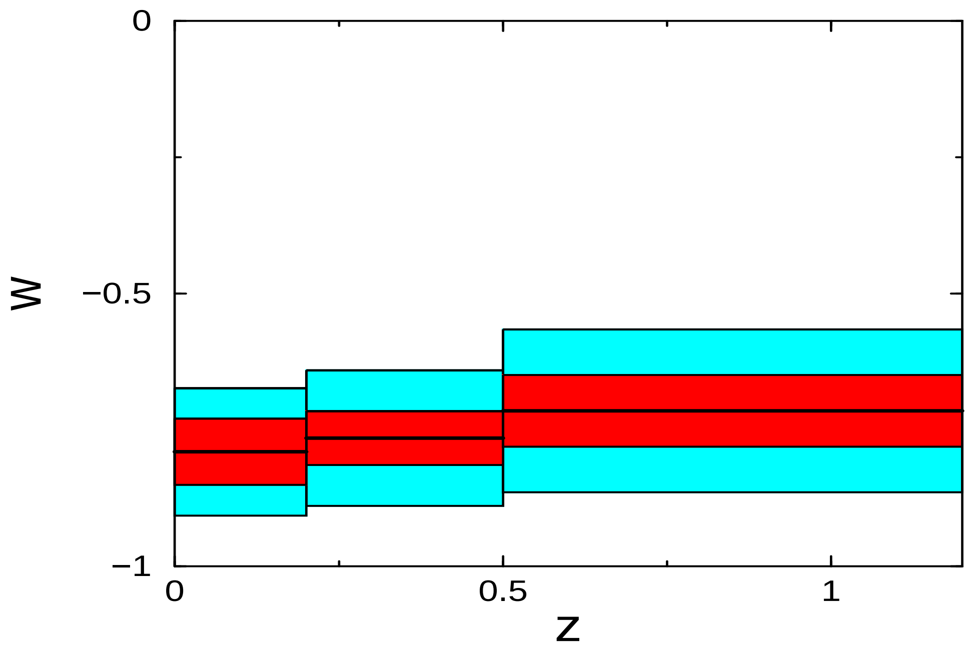




Beyond Constant w: Probing $w(z)$

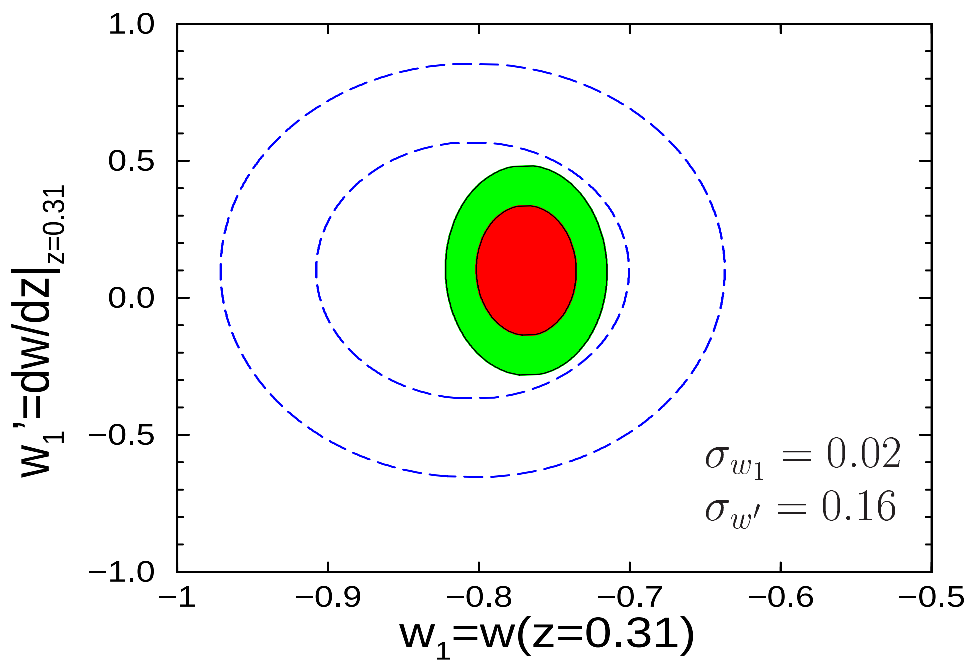
The difficulty:

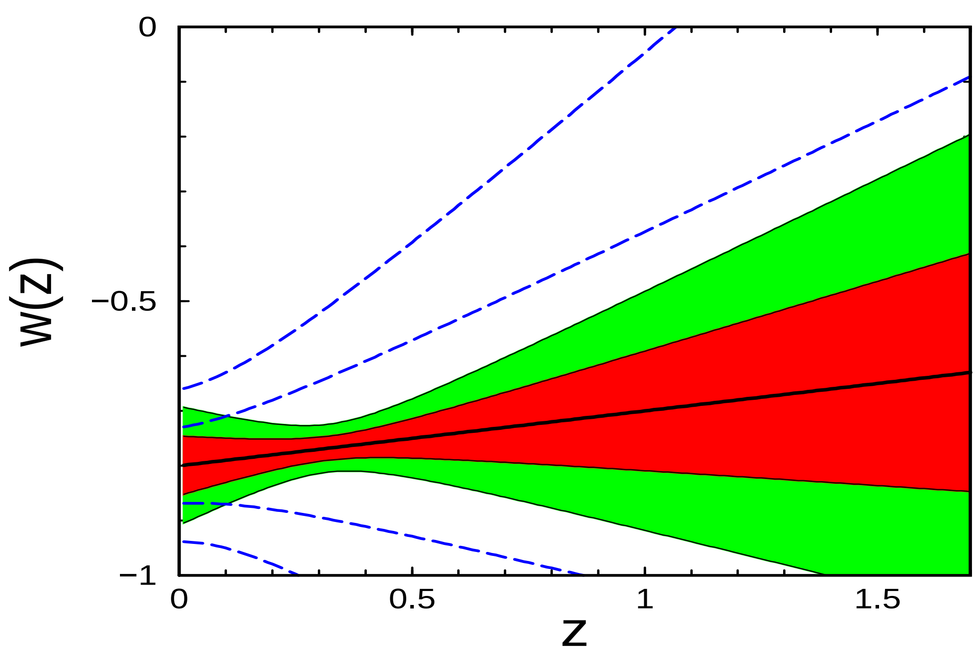
$$r(z) = \frac{1}{H_0}\int_0^z \frac{dz'}{\left\{\Omega_M(1+z')^3 + \Omega_X \exp[3\int_0^{z'}(1+\mathbf{w}(\mathbf{z''}))d\ln(1+z'')]\right\}^{1/2}}$$



Probing $w(z)$: $w = w_1 + w'(z - z_1)$

(Cooray and Huterer 1999)





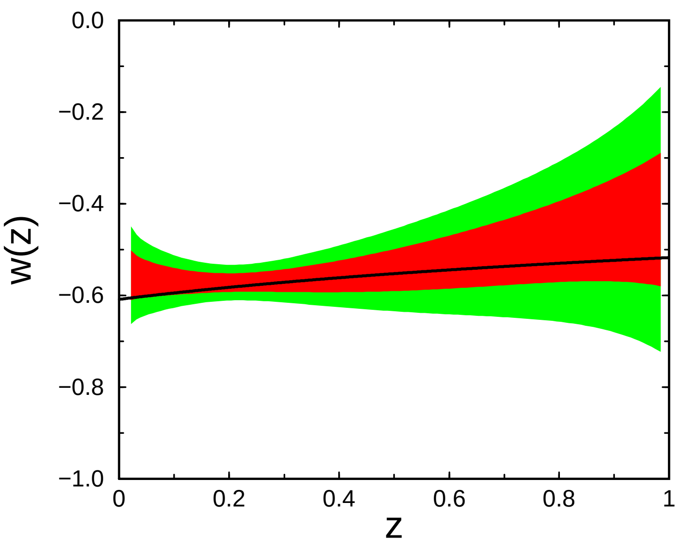
Probing $w(z)$: Reconstruction

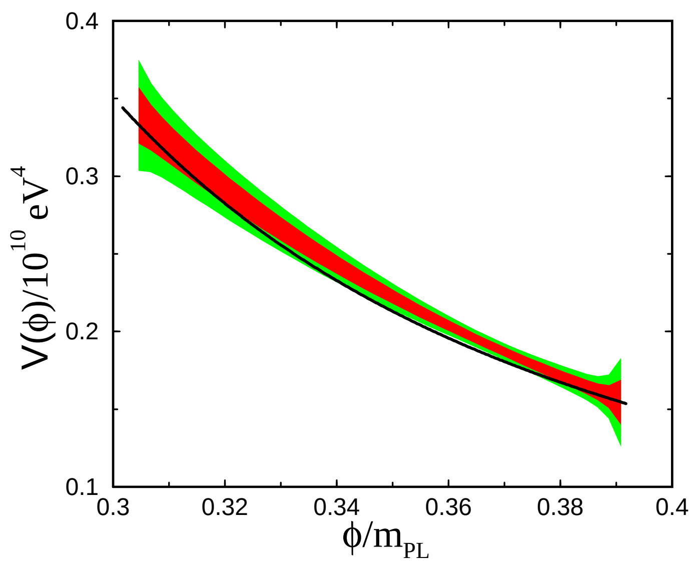
(Starobinsky 1998; Huterer and Turner 1999; Chiba and Nakamura 1999)

$$1 + w(z) = \frac{1+z}{3} \frac{3H_0^2\Omega_M(1+z)^2 + 2(d^2r/dz^2)/(dr/dz)^3}{H_0^2\Omega_M(1+z)^3 - (dr/dz)^{-2}}$$

$$V[r(z)] = \frac{1}{8\pi G}\left[\frac{3}{(dr/dz)^2} + (1+z)\frac{d^2r/dz^2}{(dr/dz)^3}\right] - \frac{3\Omega_M H_0^2(1+z)^3}{16\pi G}$$

$$\frac{d\phi}{dz} = \mp\frac{dr/dz}{1+z}\left[-\frac{1}{4\pi G}\frac{(1+z)d^2r/dz^2}{(dr/dz)^3} - \frac{3\Omega_M H_0^2(1+z)^3}{8\pi G}\right]^{1/2}$$





Good: Non-parametric (e.g., no assumptions about $w(z)$ needed)

Bad: The constraint upon $w(z)$ is relatively weak

Ugly: Need to fit $r(z)$ with a smooth curve first.

What next?

- Explore the acceleration using future powerful measurements:
  e.g., measure isotropy of expansion using SNAP.

- Work on optimization of proposed methods:
  e.g., weak lensing tomography.

- Combine various measurements in a clever way in order to get to w(z).

- But to understand dark energy, esp. if $w = -1$,
  major input will be needed from theory!