The future of dark energy measurements

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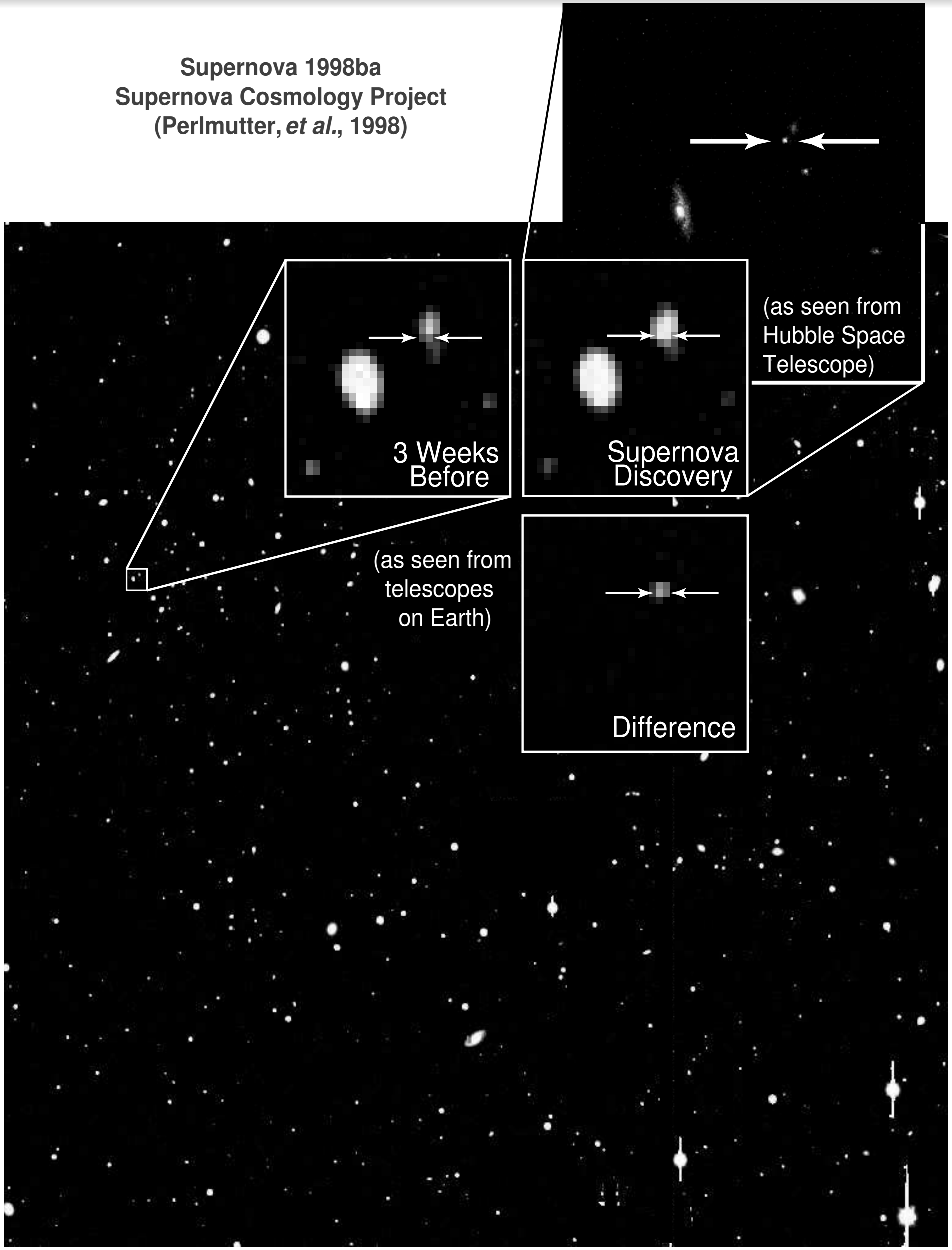
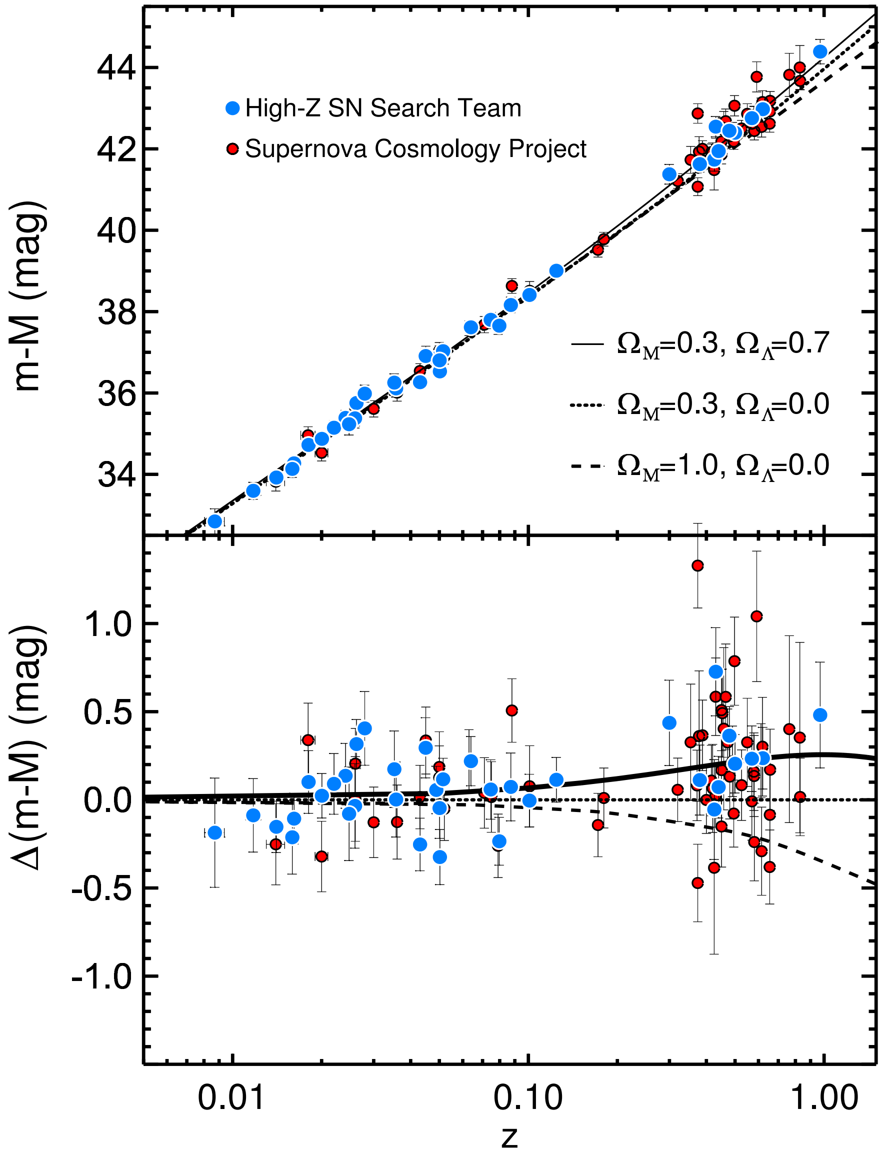
Type Ia Supernovae



SN Ia Hubble diagram



$$m(z) = \log\left[H_0 d_L(z)\right] + \mathcal{M}$$

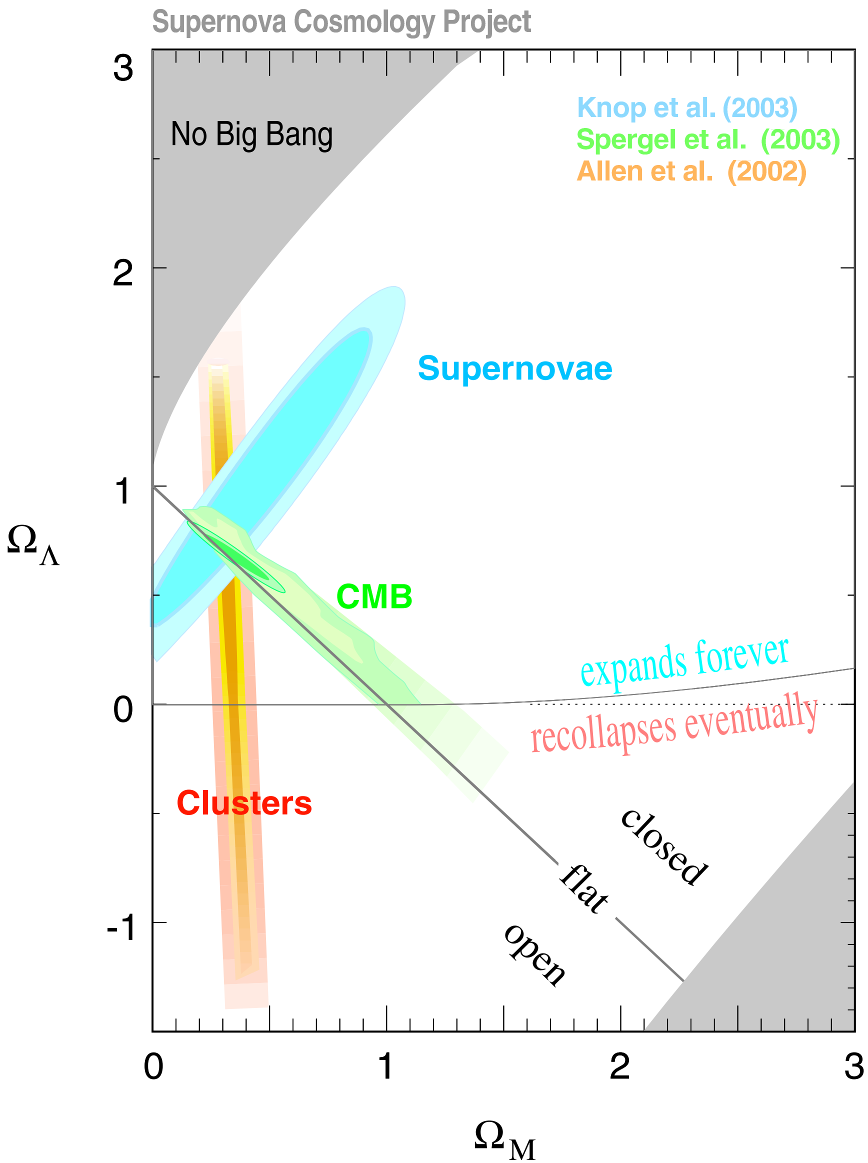
where

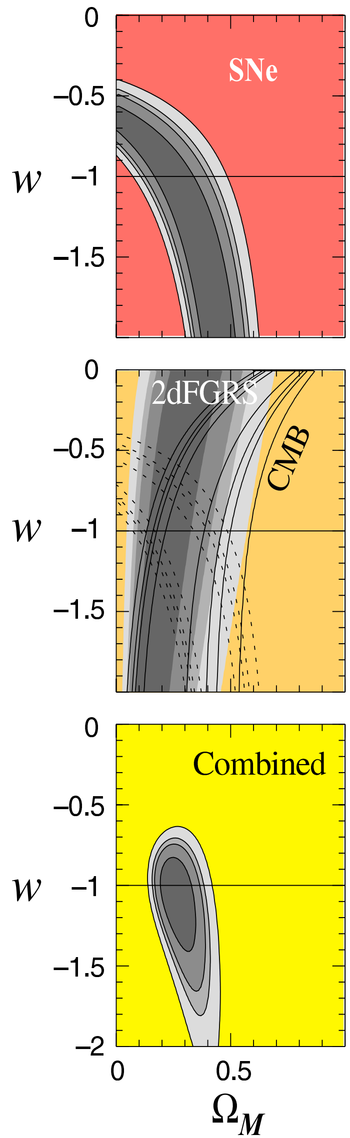
$$\mathcal{M} = M - 5\log\left(H_0\,\frac{\mathrm{Mpc}}{c}\right) + 25$$

Parameterizing Dark Energy

- $\Omega_{DE} \equiv \dfrac{\rho_{DE}(z=0)}{\rho_{\rm crit}(z=0)}, \qquad w \equiv \dfrac{p_{DE}}{\rho_{DE}}$
- $H^2(z) = H_0^2\left[\Omega_M(1+z)^3 + \Omega_{DE}\,(1+z)^{3(1+w)}\,\right]$ (flat)
- $d_L(z) = (1+z)\displaystyle\int_0^z \frac{dz'}{H(z')}$
- $\dfrac{\ddot{a}}{a} = -\dfrac{4\pi G}{3}(\rho_M + \rho_{DE} + 3p_{DE})$

Current Supernova Constraints





Supernova Cosmology Project
Knop *et al.* (2003)

Assuming constant w

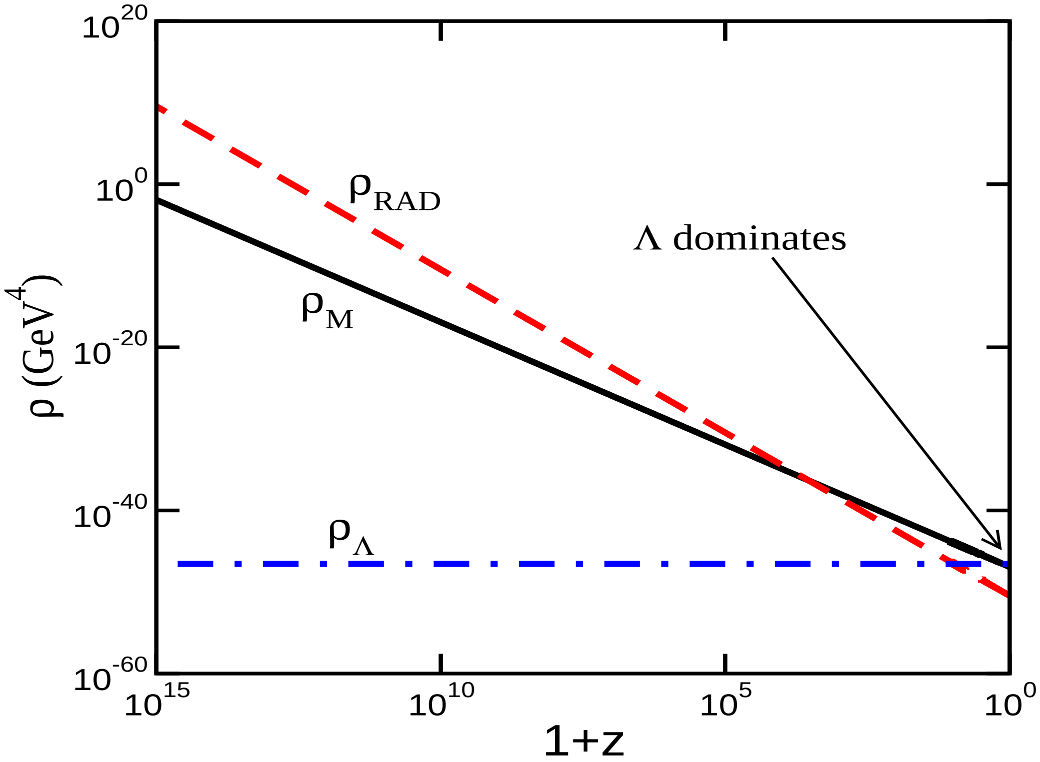
With limits from;
2dFGRS (Hawkins et al. 2002)
and CMB (Bennet et al. 2003, Spergel et al. 2003)

$$w = -1.05^{+0.15}_{-0.20} \text{ (statistical)}$$
$$\pm 0.09 \text{ (systematic)}$$

Fine-Tuning Problems I: "Why Now ?"

DE is important only at $z \lesssim 2$, since

$$\rho_{DE}/\rho_M \approx \frac{\Omega_{DE}}{\Omega_M}(1+z)^{3w} \qquad \text{and} \qquad w \lesssim -0.8$$



Fine-Tuning Problems II: “Why so small ?”

- Refers to the vacuum energy, $\rho_\Lambda \equiv \dfrac{\Lambda}{8\pi G}$.

  (recall $G_{\mu\nu} + \mathbf{\Lambda}\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$)

- $\rho_\Lambda \;\simeq\; (10^{-3}\,\mathrm{eV})^4 \;<<<\; (M_{\mathrm{PL}} = 10^{+19}\,\mathrm{GeV})^4$

- $\Rightarrow$ 50 – 120 orders of magnitude discrepancy!

Wish List

- Goals:
  - Measure Ω_{DE}, w
  - Measure $w(z)$ – equivalently, $\rho_{DE}(z)$
  - Measure any clustering of DE

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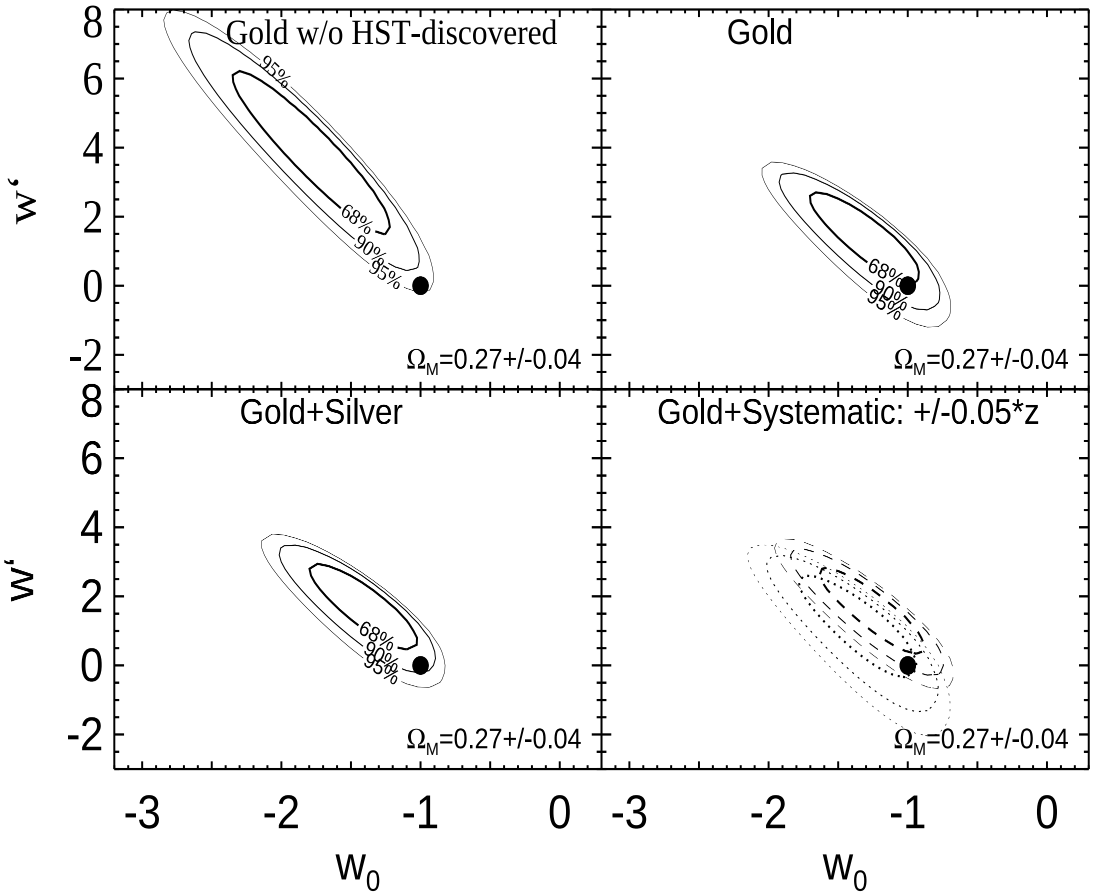
- Goals:
  - Measure Ω_{DE}, w
  - Measure $w(z)$ – equivalently, $\rho_{DE}(z)$
  - Measure any clustering of DE
- Difficulties:

$$r(z) = \int_0^z \frac{dz'}{H(z')}$$

$$H^2(z) = H_0^2 \left[\Omega_M (1+z)^3 + \Omega_{DE} \exp\left(3 \int_0^z (1 + \mathbf{w}(\mathbf{z}'))d\ln(1+z')\right)\right]$$

DE is smooth on scales $\ll H_0^{-1}$

Assuming $w(z) = w_0 + w'z$

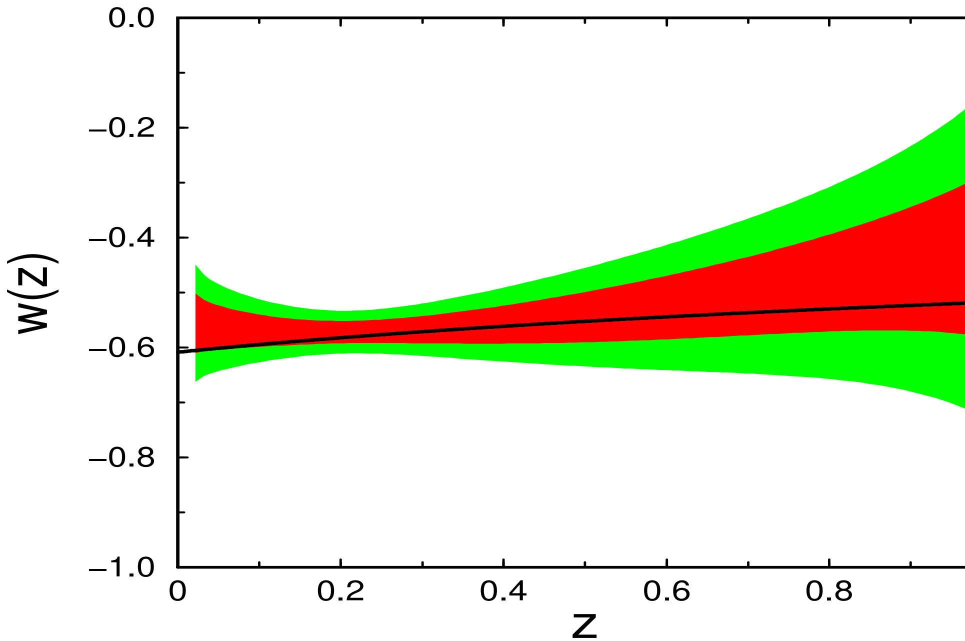


Riess et al. 2004

Direct reconstruction of $w(z)$ (or $\rho(z)$)

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

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

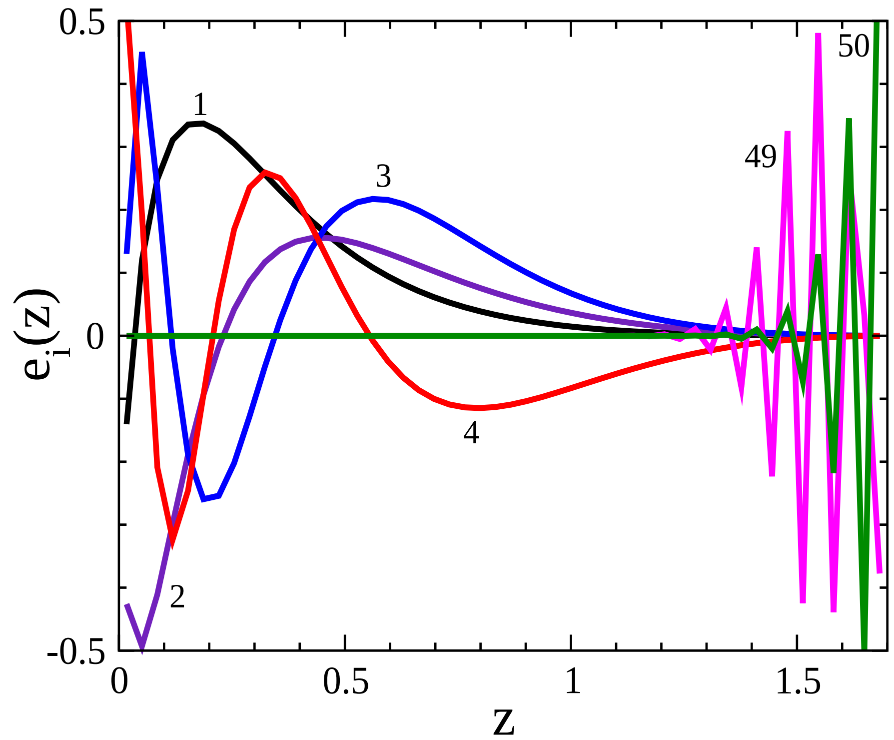


Huterer and Turner 1999; Chiba and Nakamura 1999, Weller & Albrecht 2002

Principal Components of Dark Energy

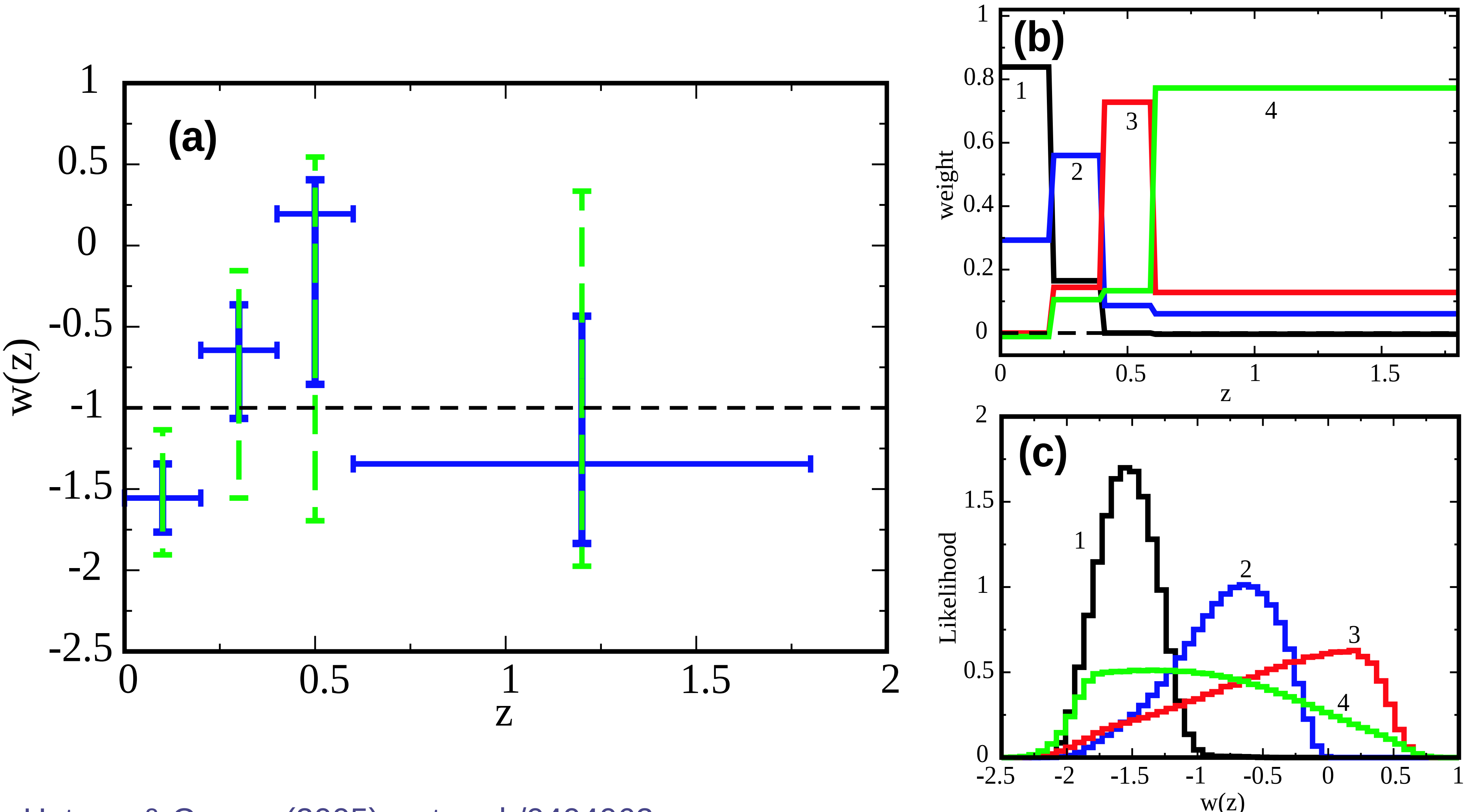
Consider a general description of w (say, w_i in 50 redshift bins at $z \in [0, 1.7]$)

- Compute the covariance matrix for w_i (assuming some SN survey)
- Diagonalize the covariance matrix. Get best, worst measured linear combinations of w_i's.
- $w(z) = \sum_{i=1}^{50} \alpha_i e_i(z)$



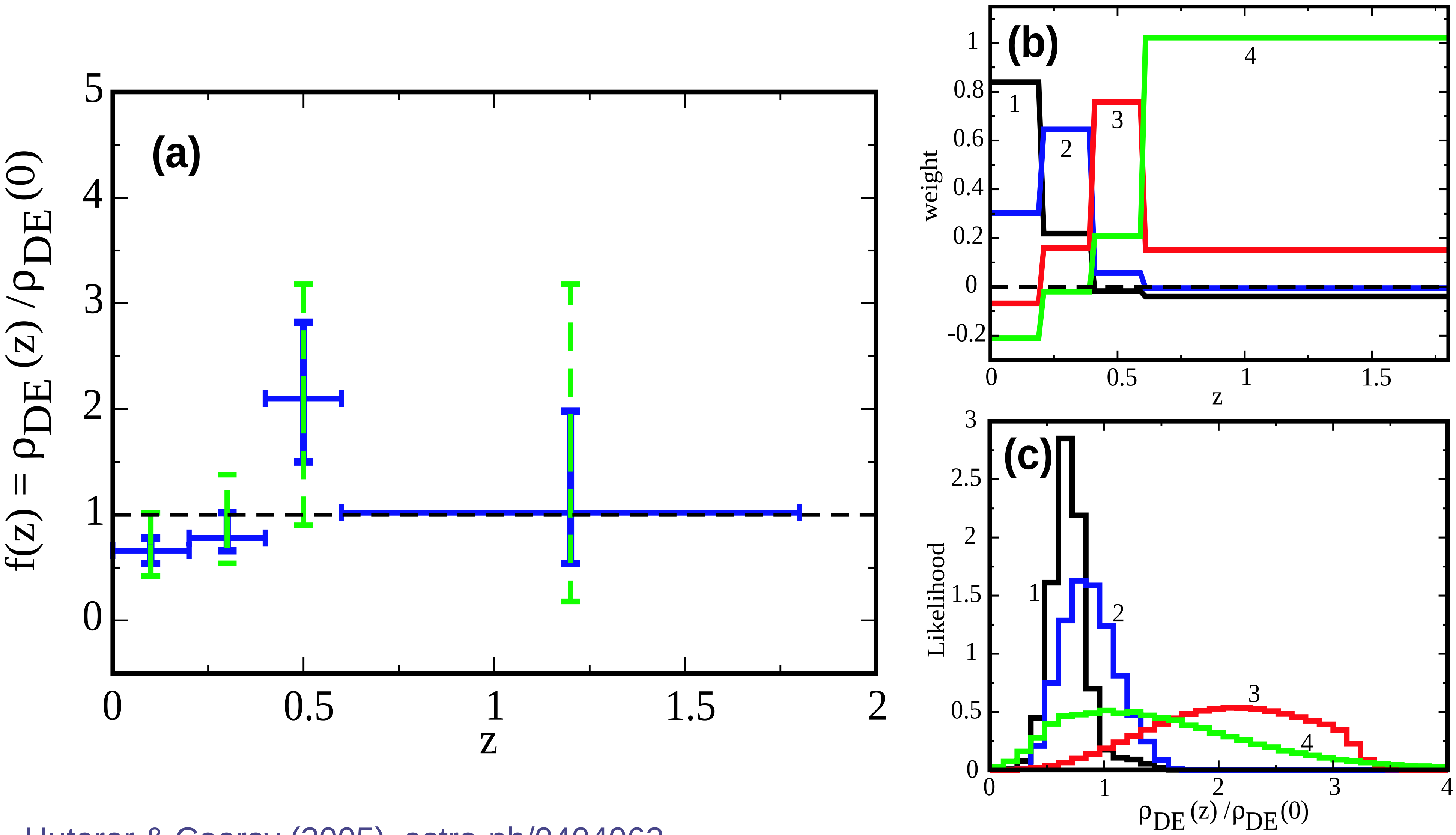
Huterer & Starkman 2003

Uncorrelated band powers of $w(z)$



Huterer & Cooray (2005), astro-ph/0404062

Uncorrelated band powers of $\rho_{\rm DE}(z)/\rho_{\rm DE}(0)$



Huterer & Cooray (2005), astro-ph/0404062

The central question:

Is $w(z) = -1$?

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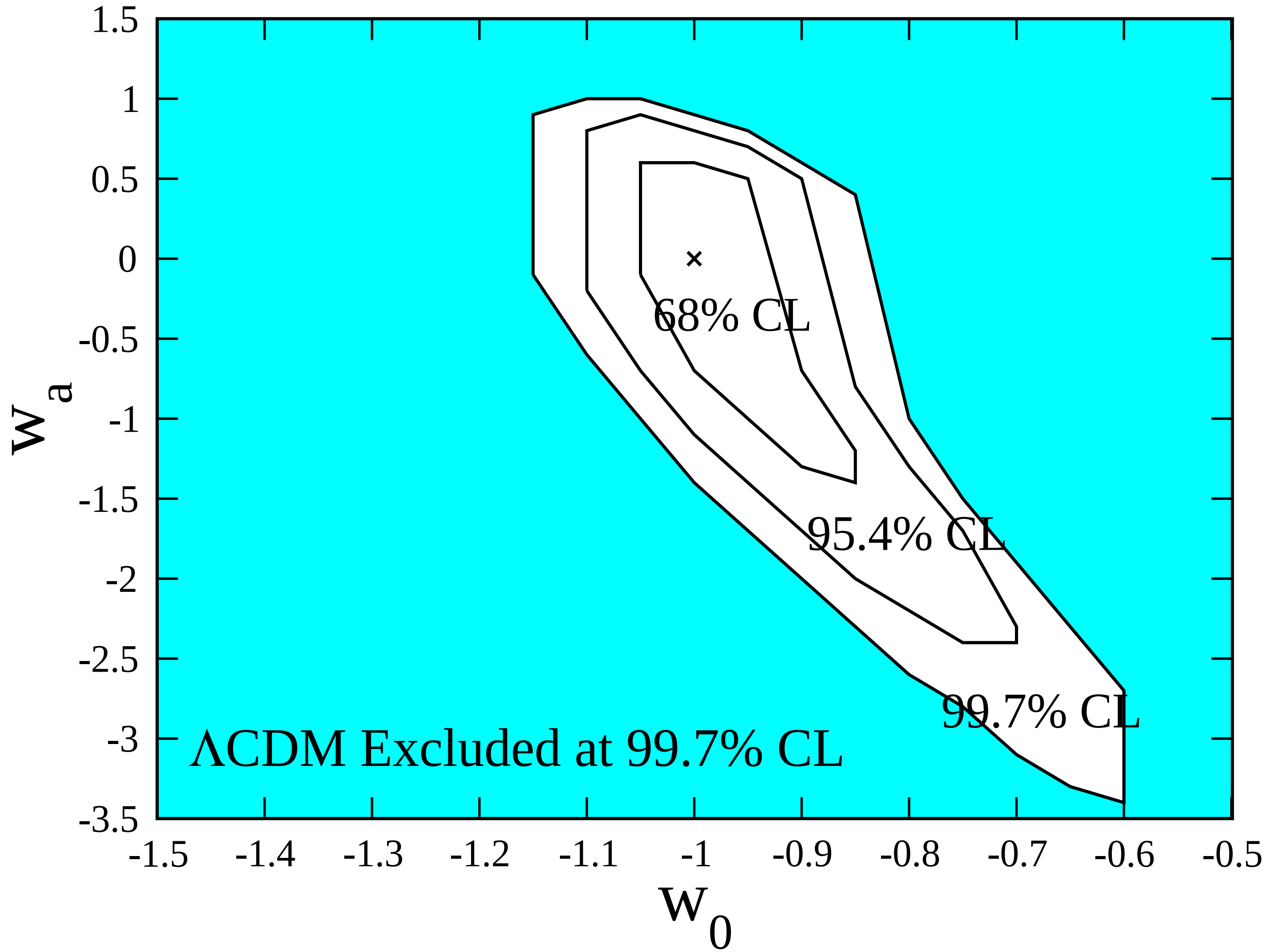
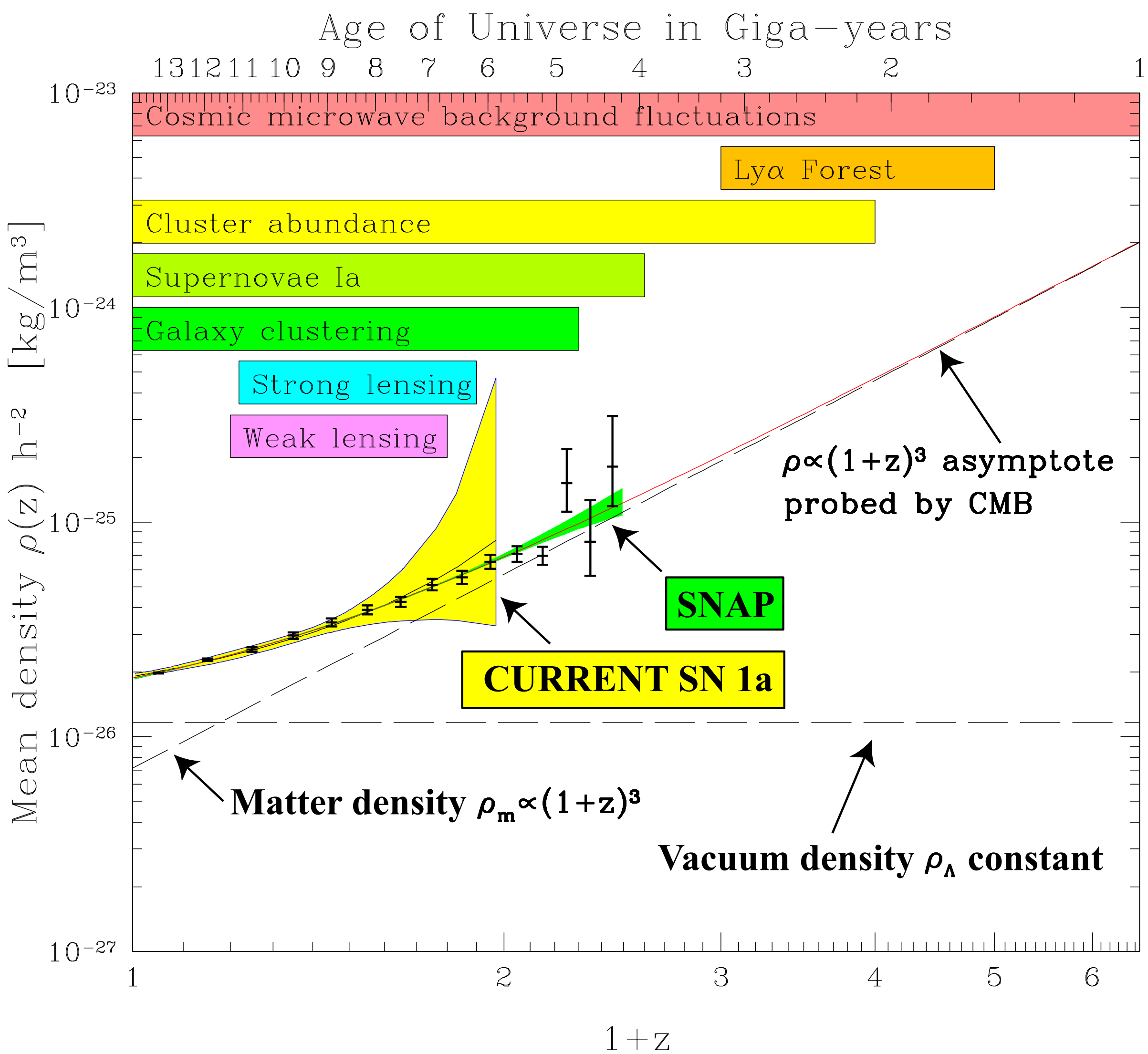


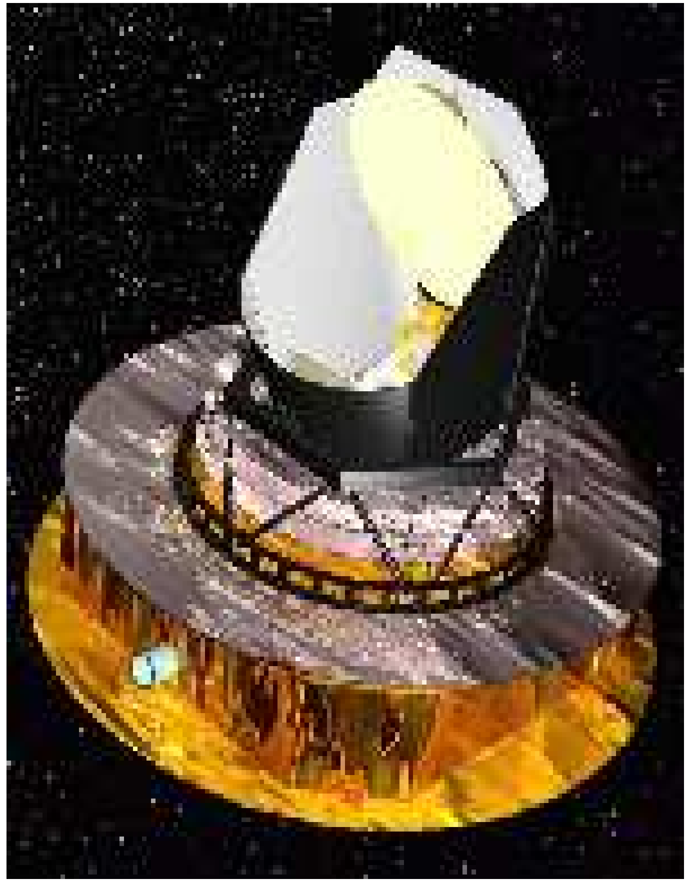
NB. This test is not parameter-dependent.

Cosmological Tests of Dark Energy

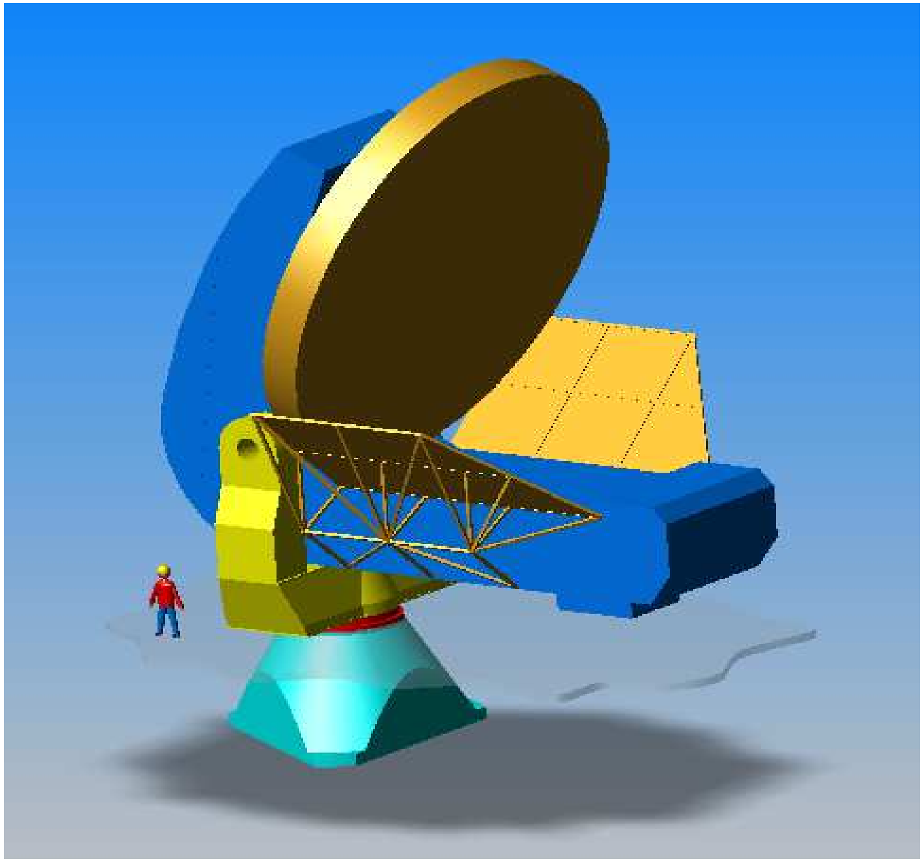


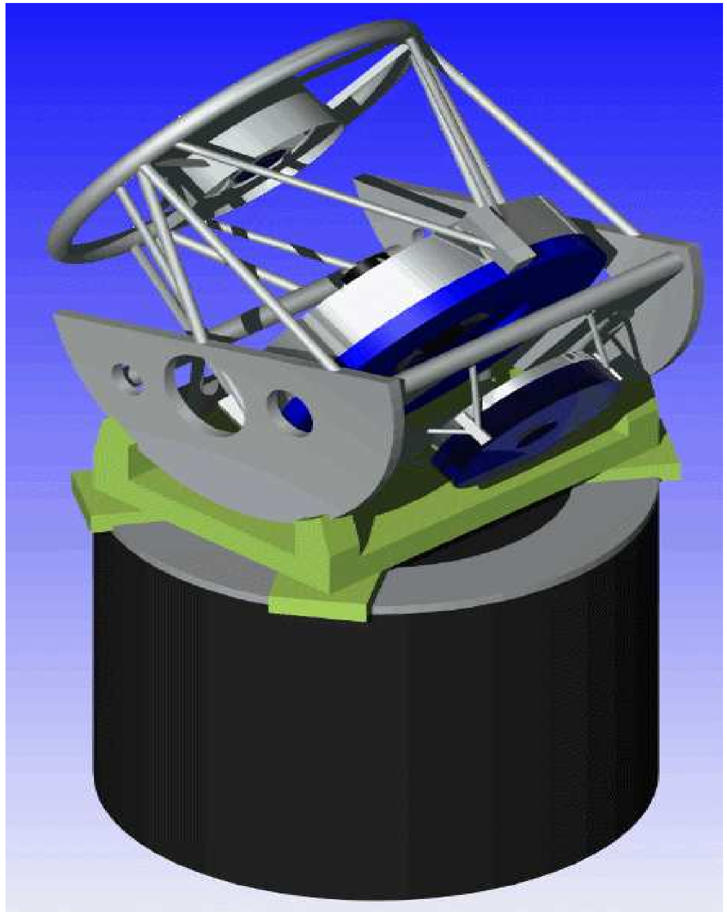
Tegmark 2001

Space: SNAP, WMAP, Planck

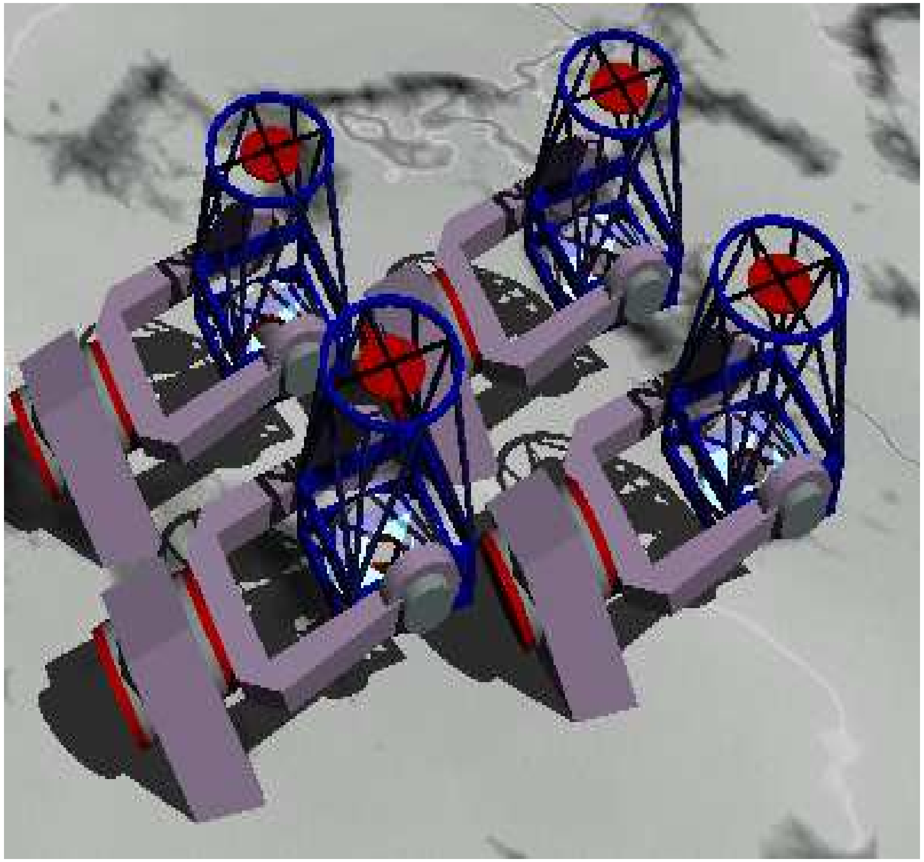


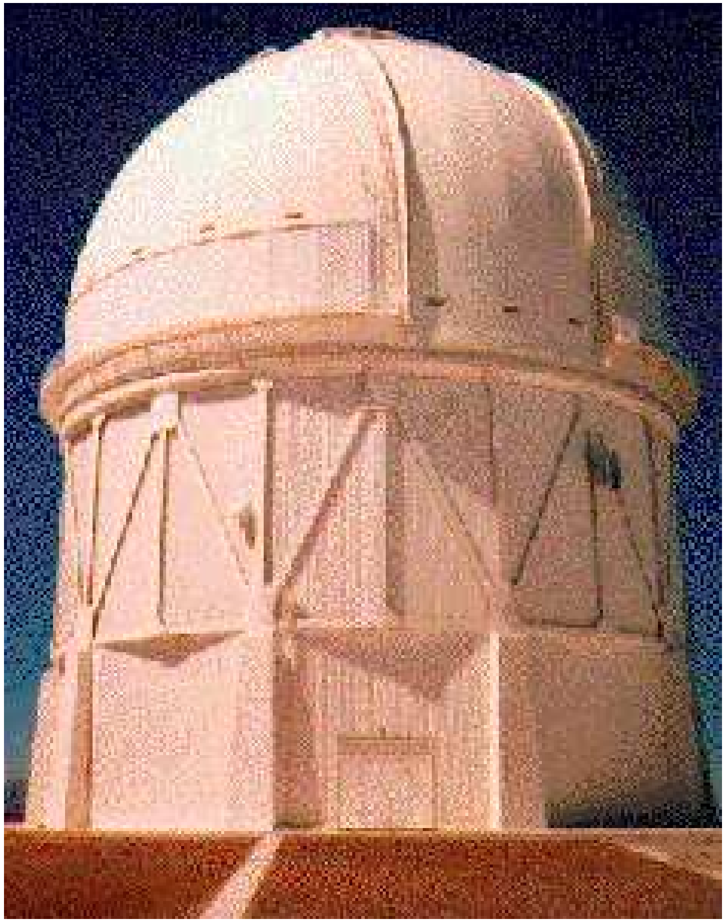
Ground: SPT, LSST





Ground: Pan-STARRS, DES

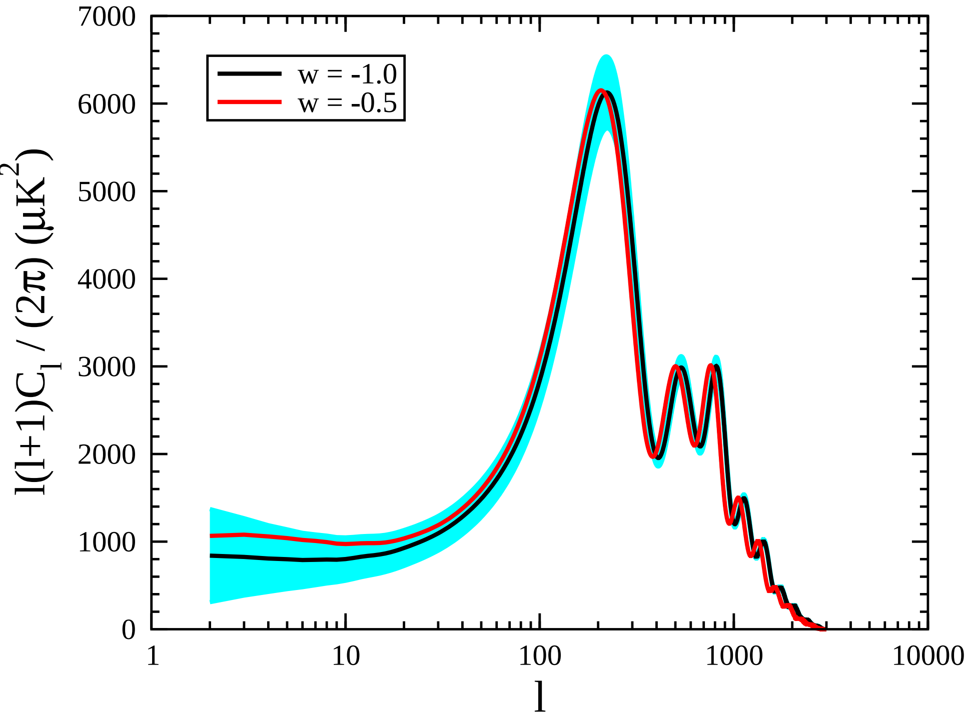




CMB Sensitivity to Dark Energy

Peak locations are sensitive to dark energy (but not much):

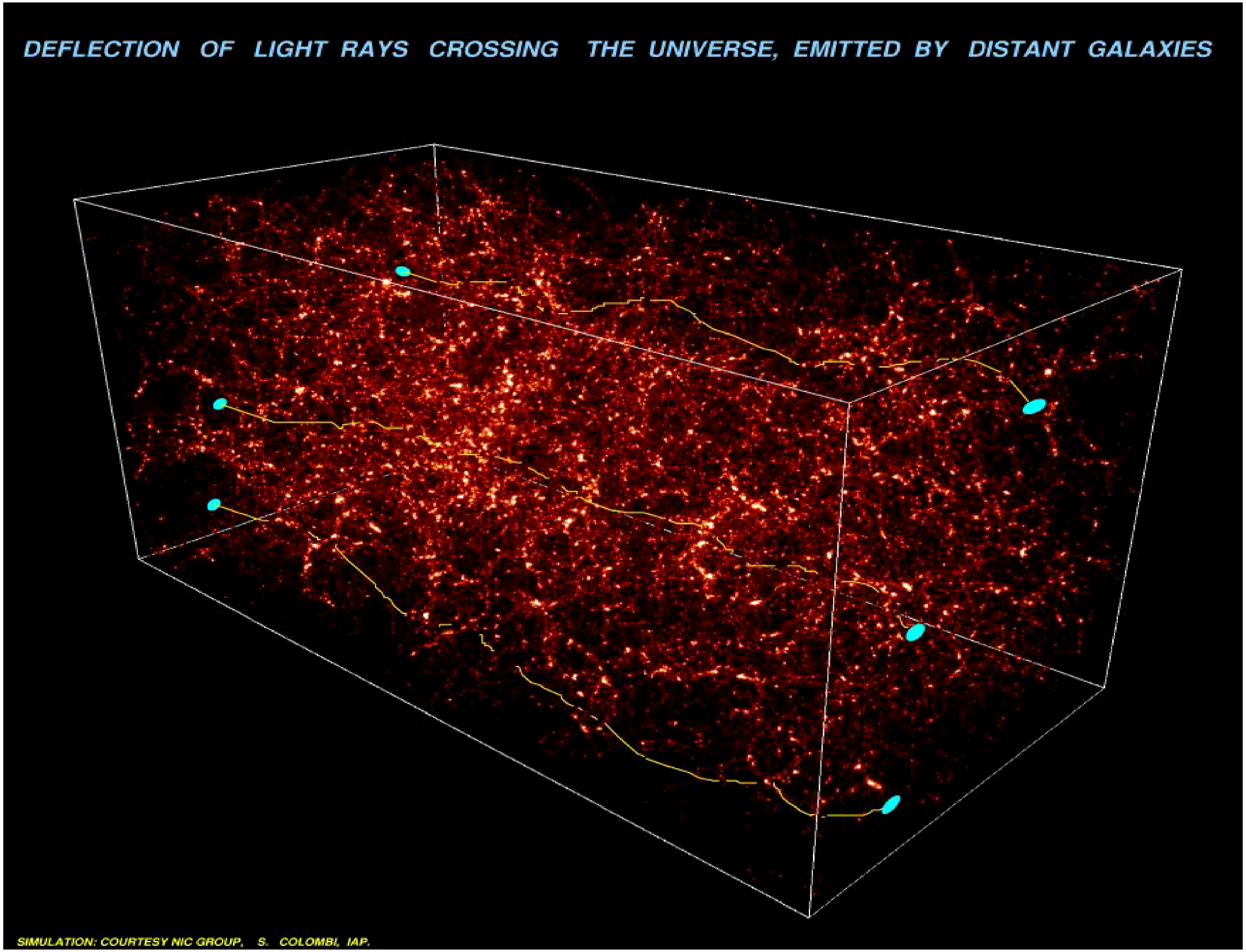
$$\frac{\Delta l_1}{l_1} = -0.084\Delta w - 0.23\frac{\Delta\Omega_M h^2}{\Omega_M h^2} + 0.09\frac{\Delta\Omega_B h^2}{\Omega_B h^2} + 0.089\frac{\Delta\Omega_M}{\Omega_M} - 1.25\frac{\Delta\Omega_{\rm TOT}}{\Omega_{\rm TOT}}$$



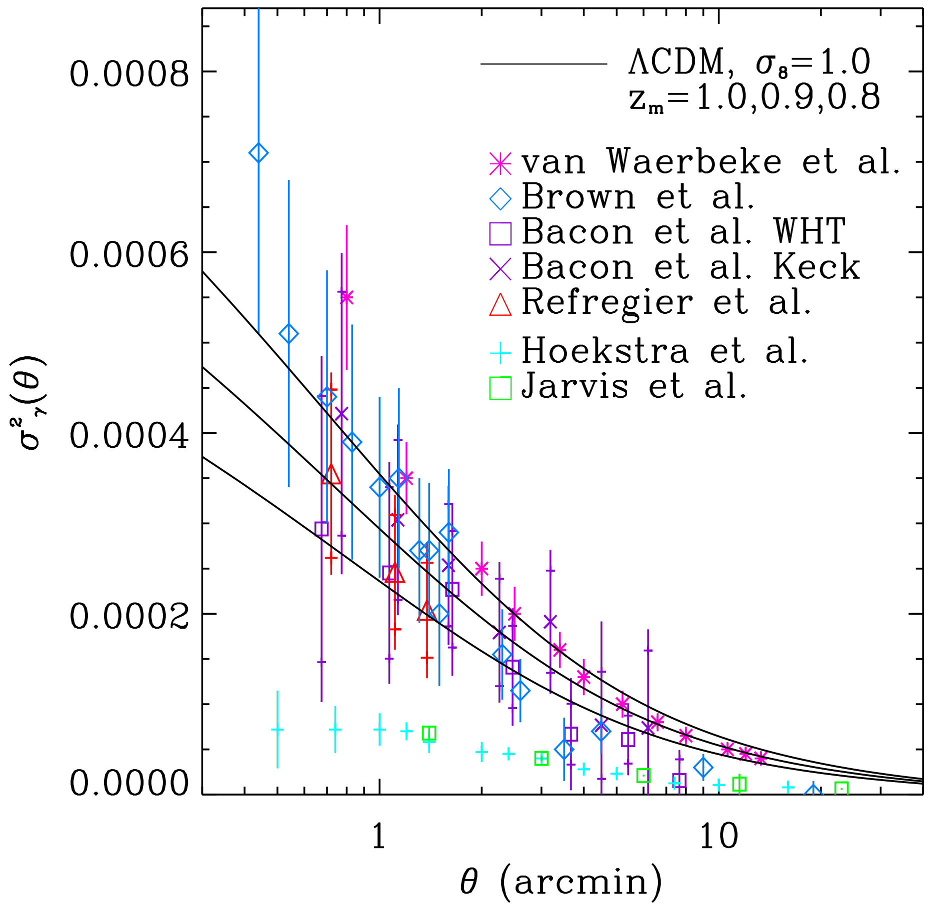
- Same as measurement of $d_A(z \approx 1000)$ *with* $\Omega_M h^2$ *fixed*, to $\sim 3\%$ (WMAP), $\sim 0.5\%$ (Planck)
- End up constraining: $\mathcal{D} \equiv \Omega_M - 0.28(1+w)$

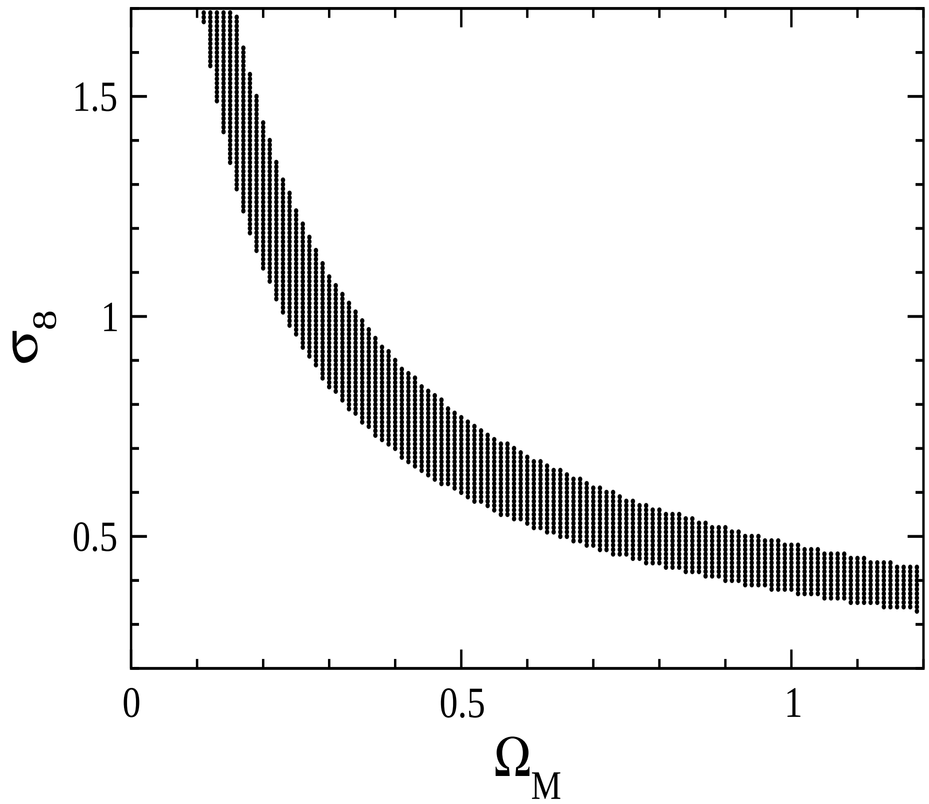
Huterer & Turner 2001, Hu et al. 2001, Frieman et al. 2003

Weak Gravitational Lensing



Current Data and Constraints

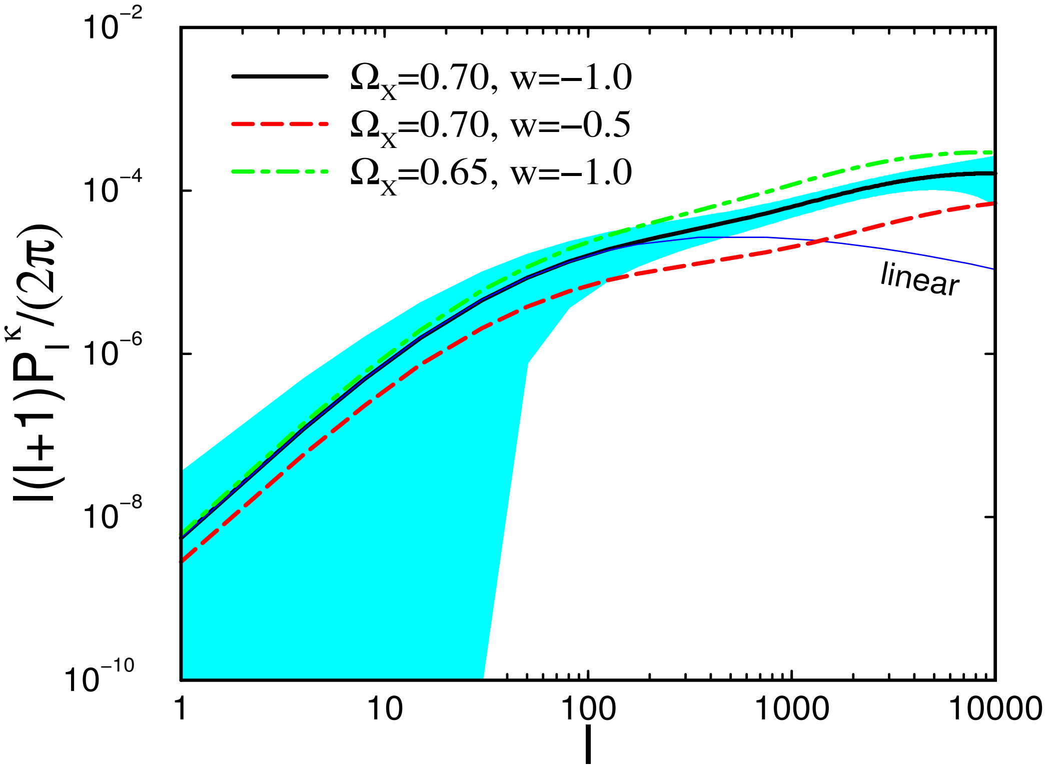


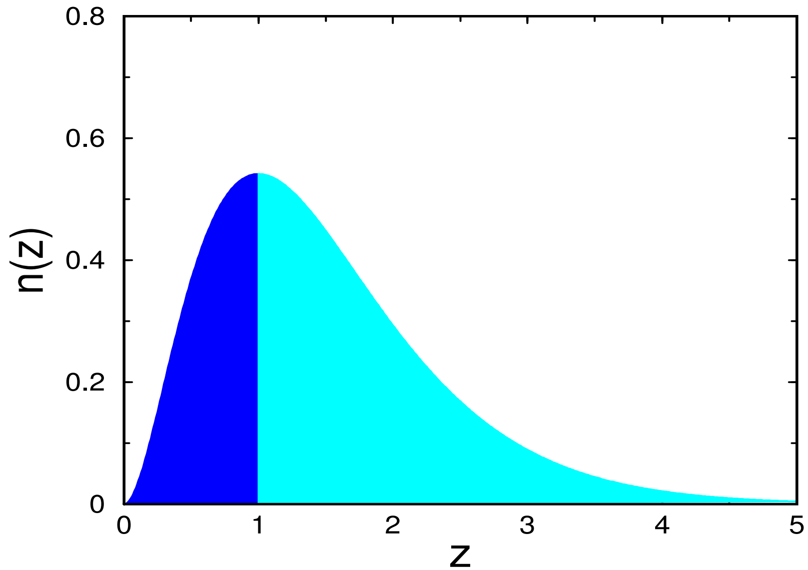


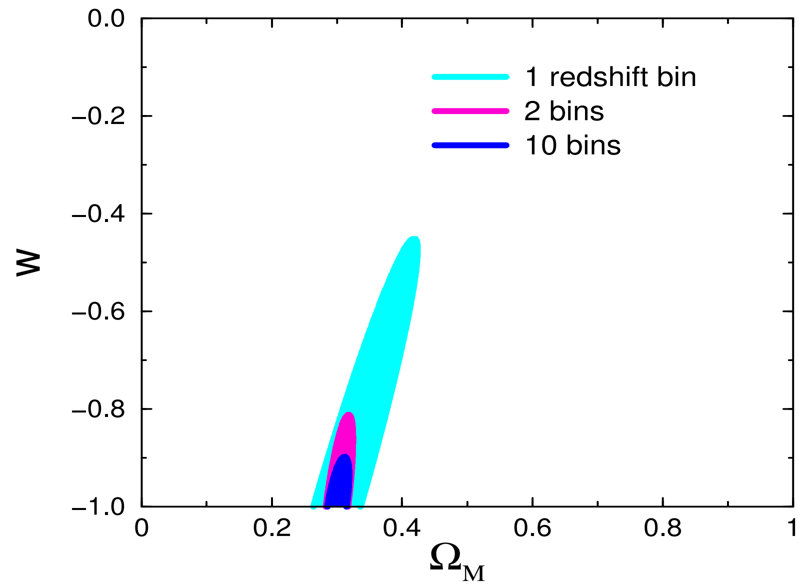
Refregier 2003, Bacon et al. 2003

Weak Lensing and DE

$$P_{ij}^{\kappa}(\ell) = \int_0^{\infty} dz \, \frac{W_i(z)\, W_j(z)}{r(z)^2\, H(z)} \, P\left(\frac{\ell}{r(z)}, z\right)$$





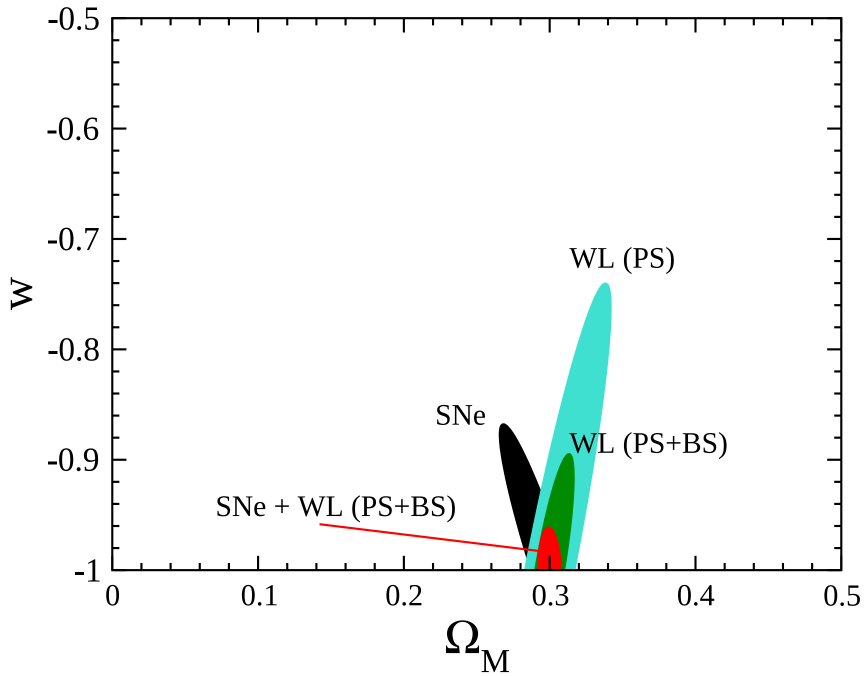


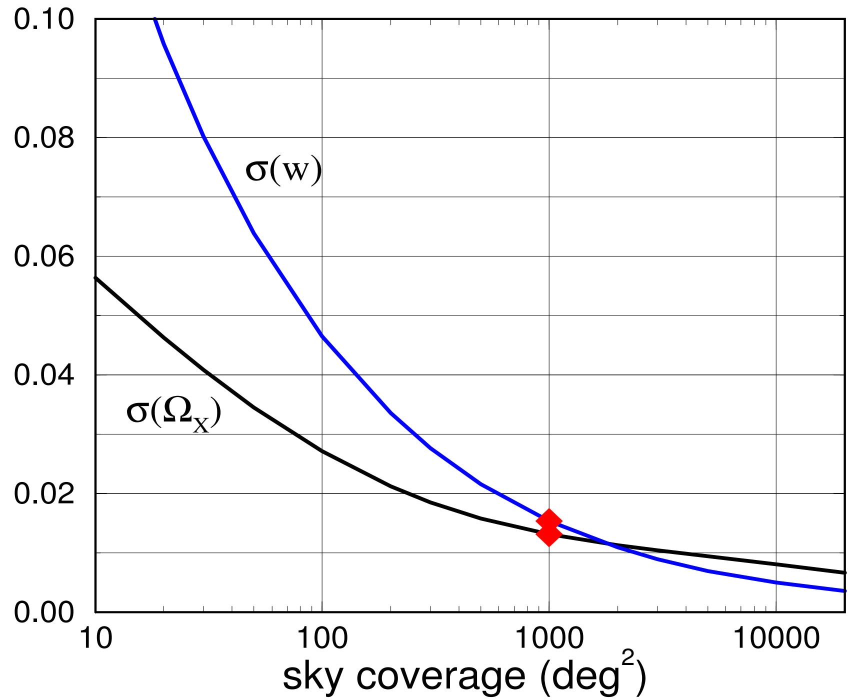
Hu 1999, Hui 1999, Huterer 2002, Refregier et al. 2003

Weak Lensing Systematics

Why work on this?

- The most powerful experiments (SNAP, and especially LSST) are likely to hit the systematic floor.
- Work on WL systematics is singled out as one of top priorities by various panels (e.g. SAGENAP)





Experimental systematics in WL

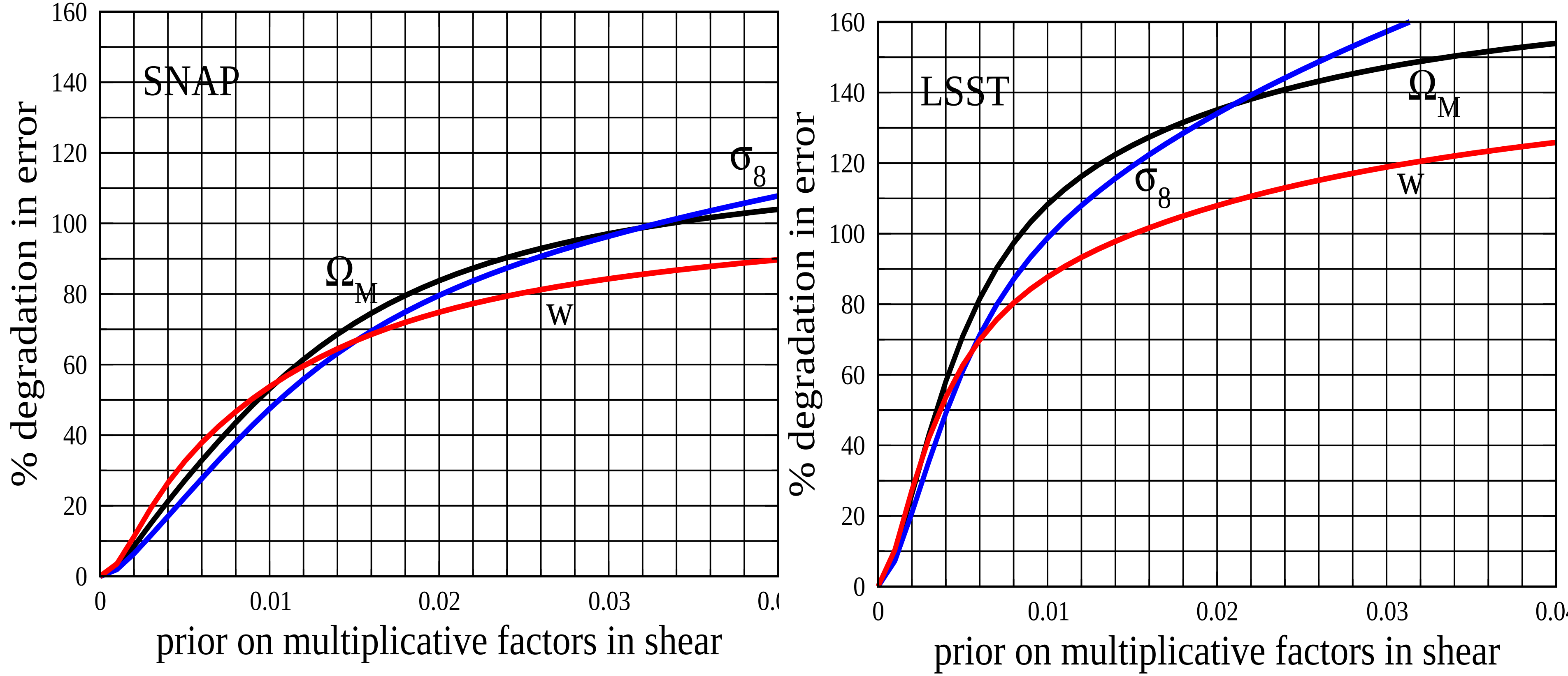
Our approach:

- Define and impose requirements on several generic types of error (i.e. multiplicative, additive, and redshift error)
- One can then use these to drive requirements on experiment-specific sources of the systematics (number of filters, depth of survey/galaxy size, atmosphere,...)

$$\hat{\gamma}(z_s) = \gamma\left(z_s + \delta z_p\right) \times \left[1 + f\left(z_s\right)\right] + \gamma_{\rm add}(z_s)$$

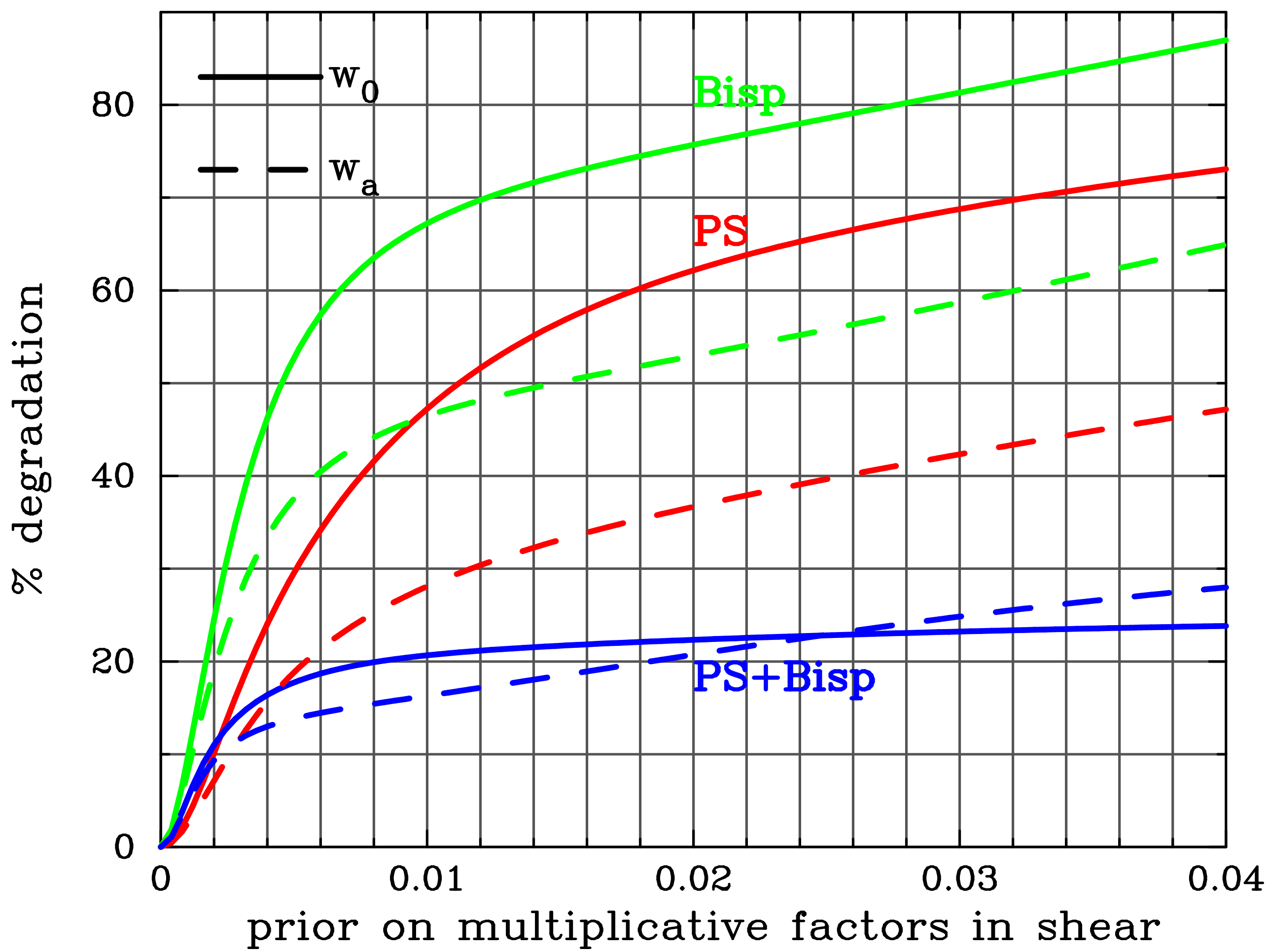
Huterer, Takada, Bernstein, Jain (2005)

Degradations due to multiplicative errors



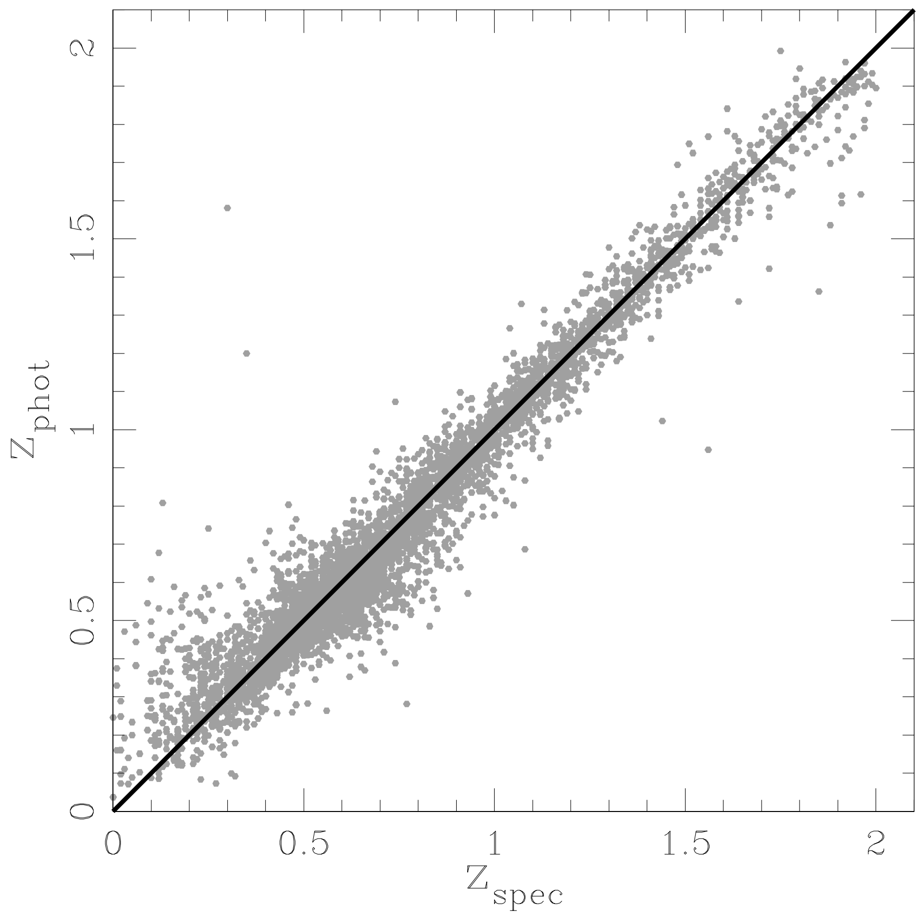
So, $\lesssim 1\%$ RELATIVE (but coherent) error in shear calibration is required.

PS+BS self-calibration



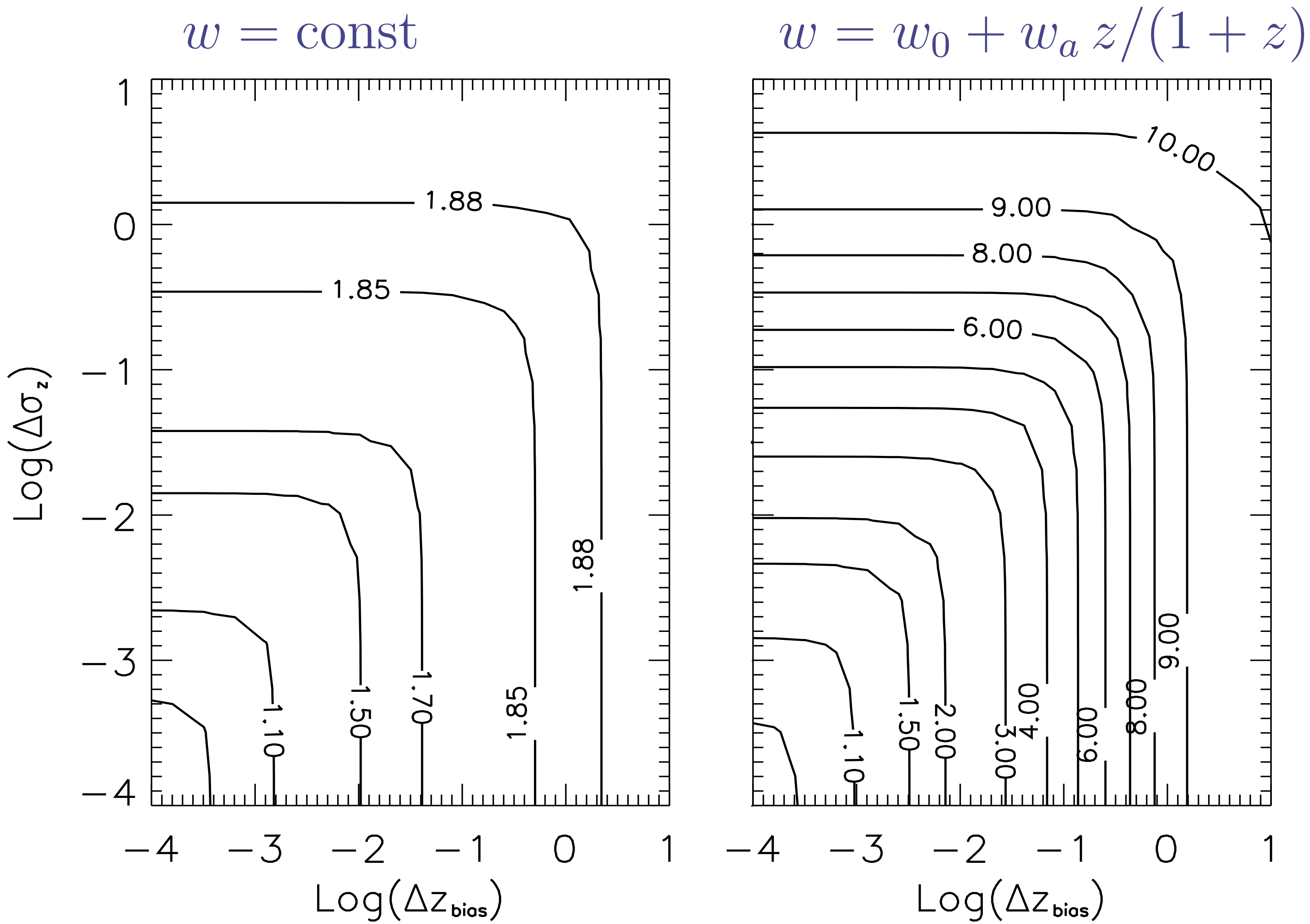
Huterer, Takada, Bernstein, Jain (2005)

Photometric Redshifts and Their Errors



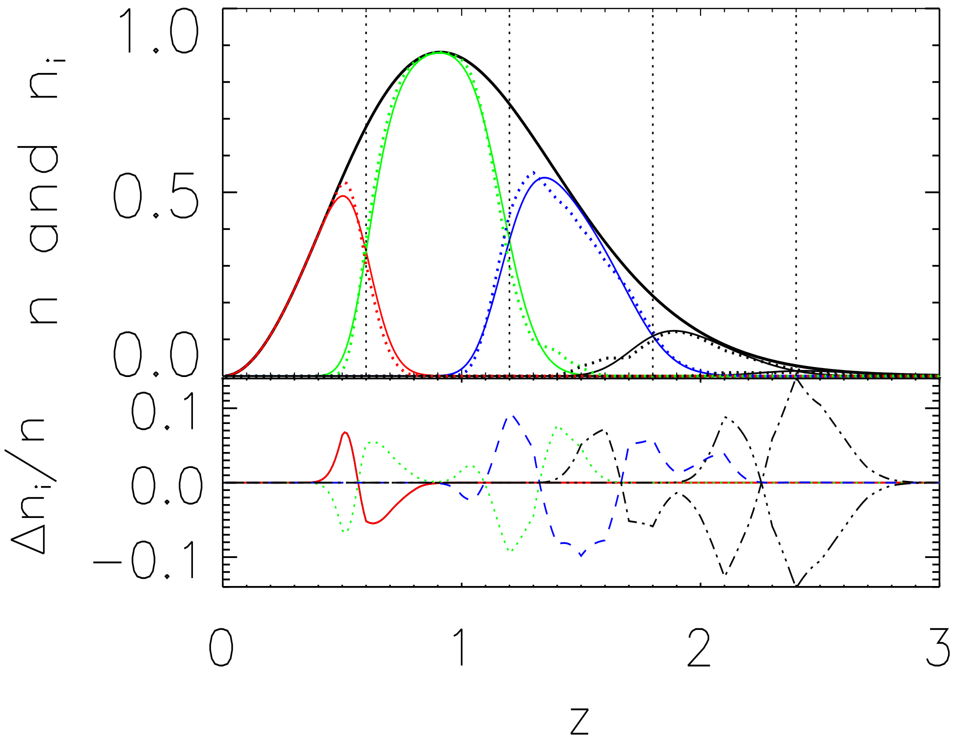
Cunha, Lima, Oyaizu et al. (2005)

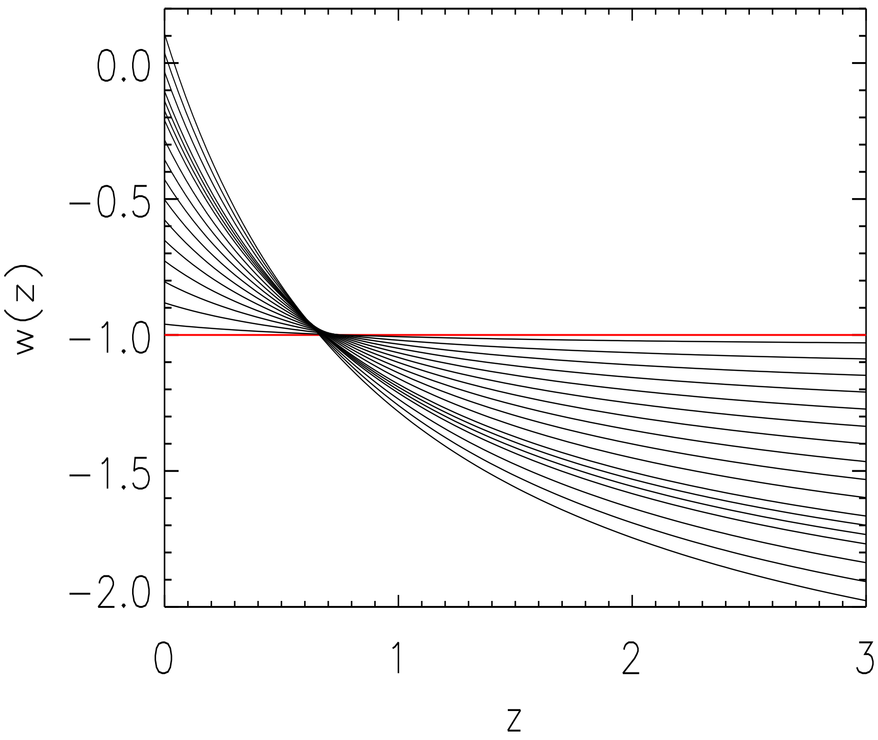
Degradations due to redshift errors



Ma, Hu & Huterer (2005)

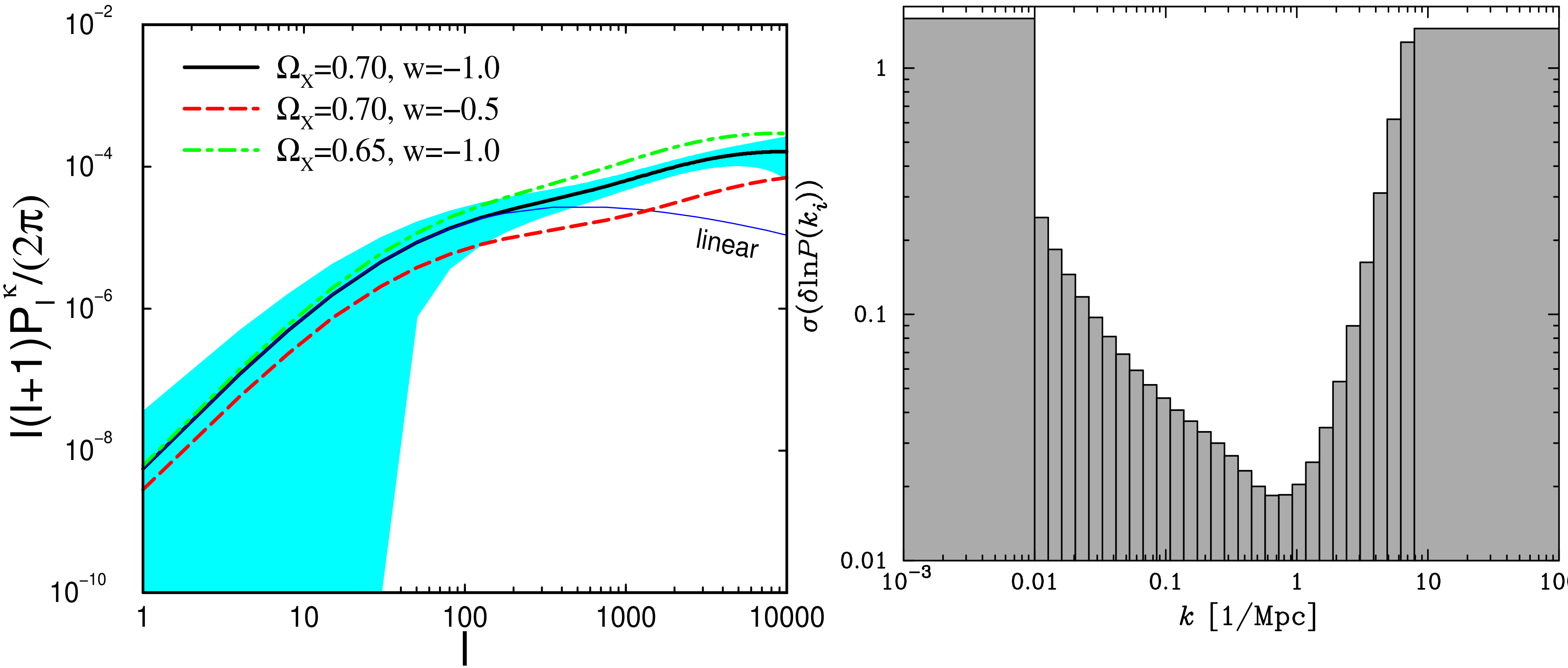
Degeneracies with redshift errors





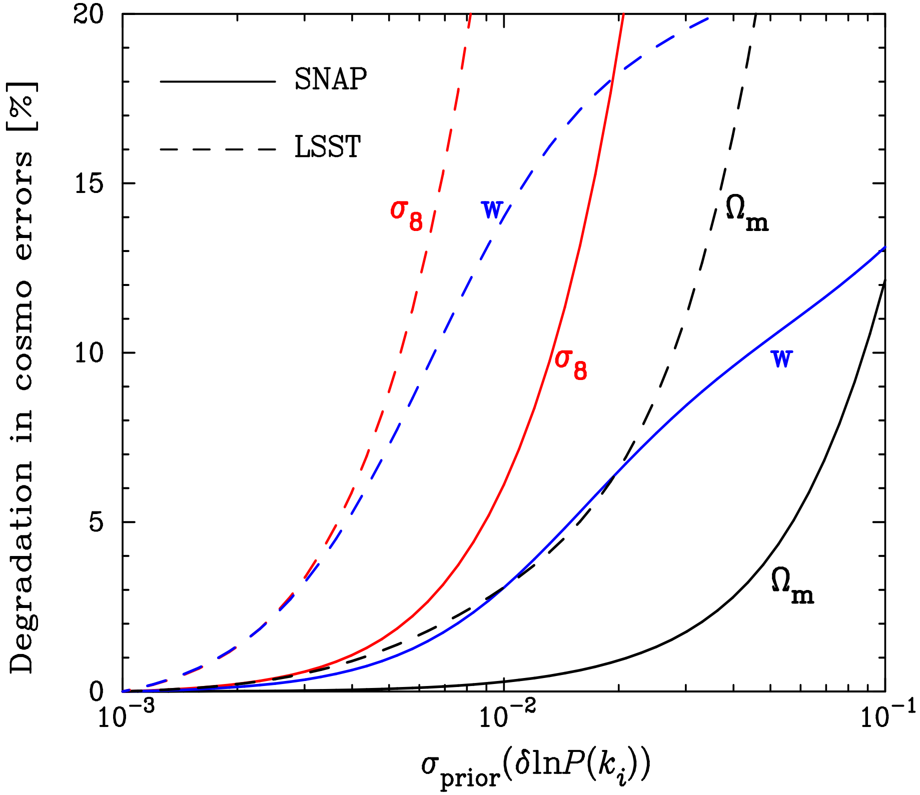
Ma, Hu & Huterer (2005)

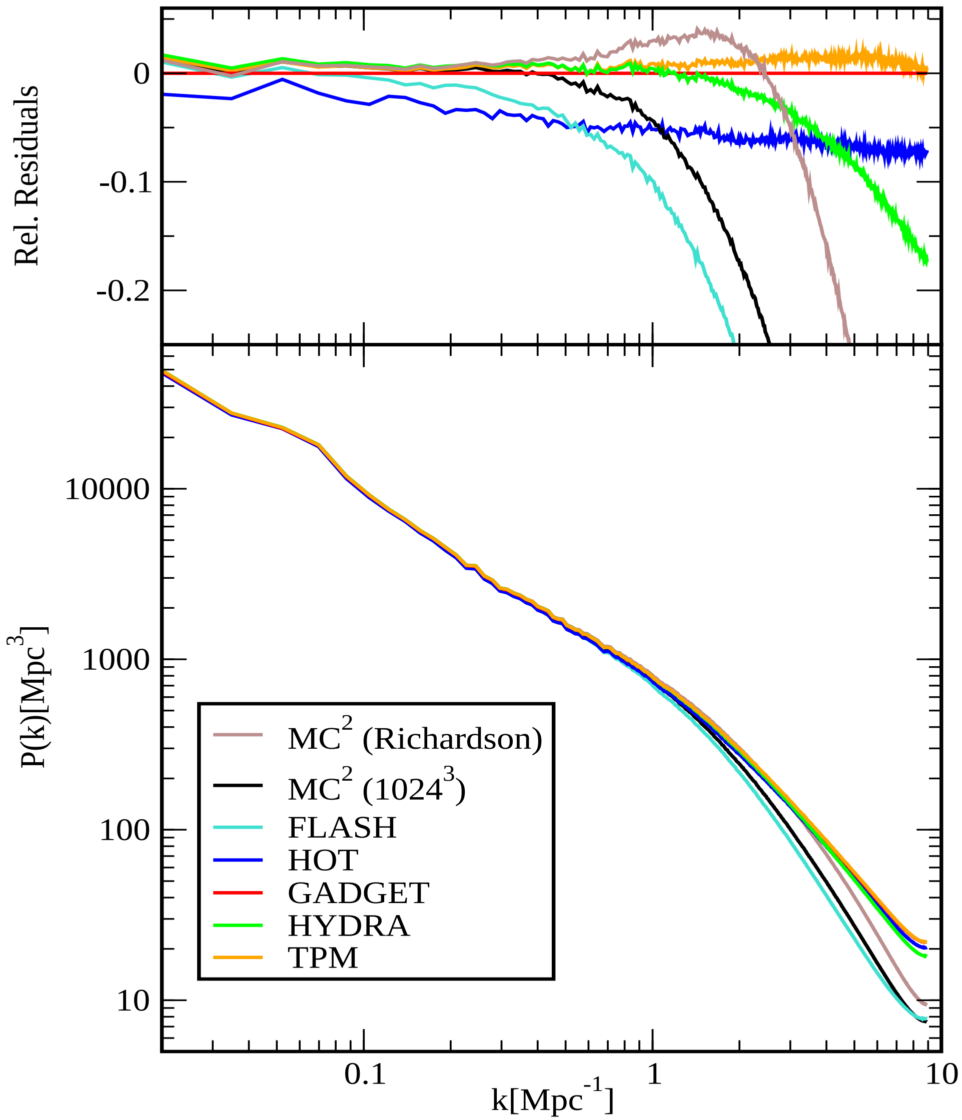
Theoretical systematics in WL



Huterer & Takada, astro-ph/0412142

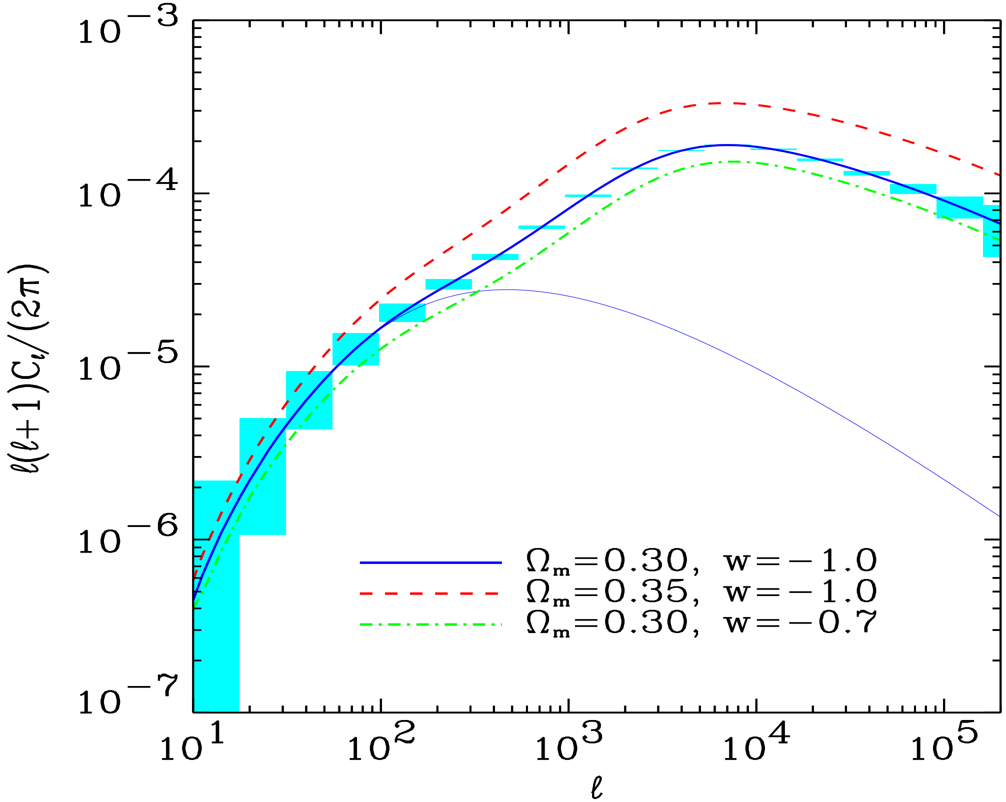
Required calibration of $P(k)$





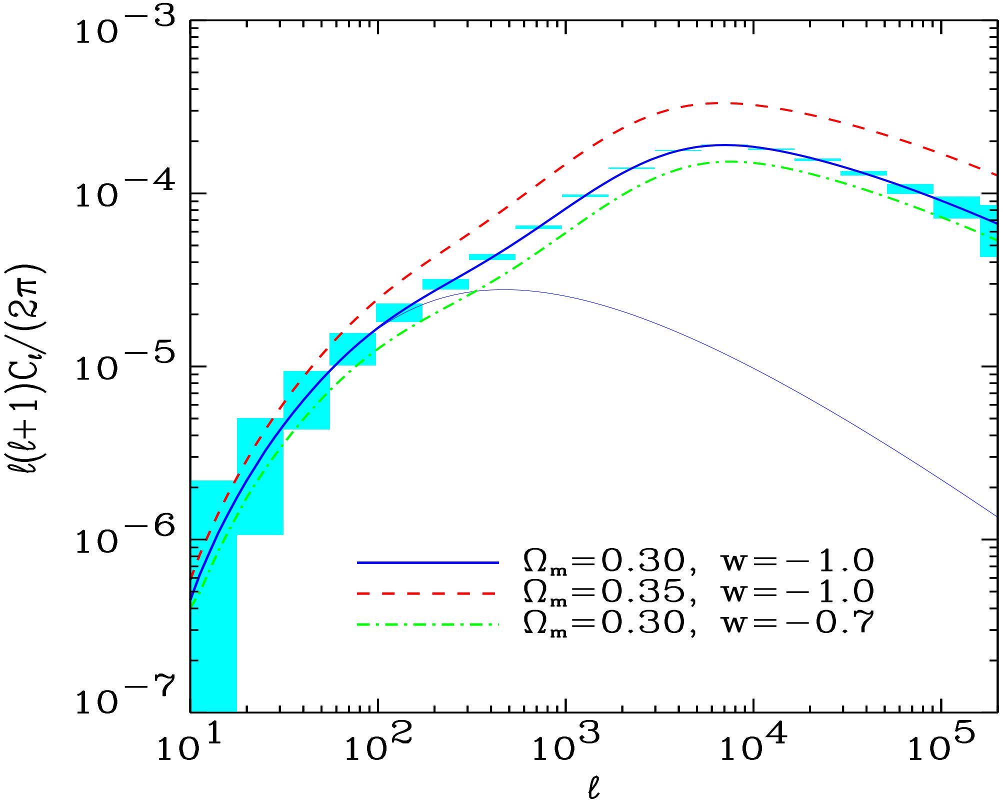
Huterer & Takada, astro-ph/0412142; Heitmann et al. 2004

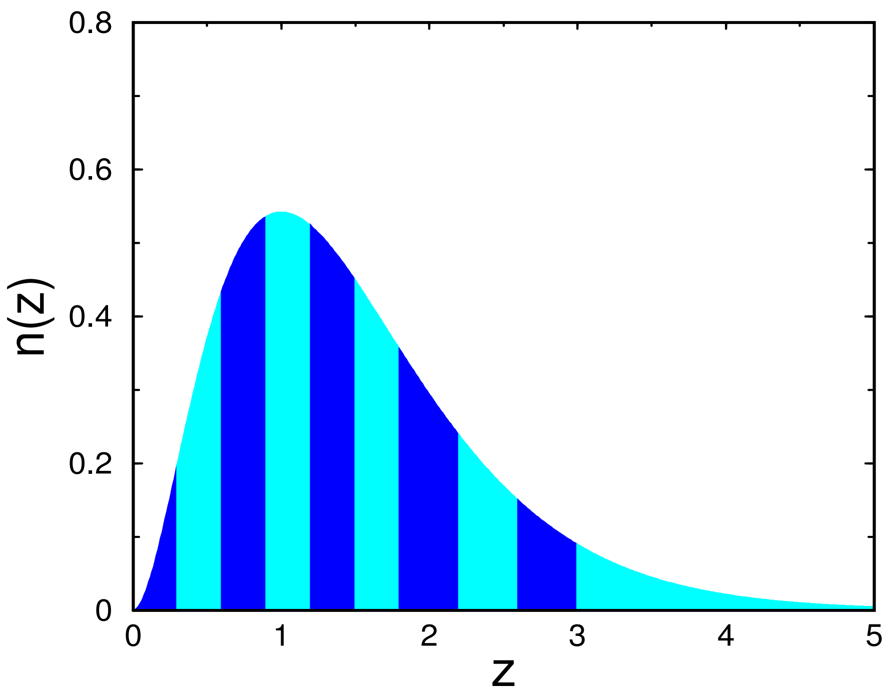
WL systematic control: Nonlinear Power



Need to run a suite of N-body simulations in (Ω_M, σ_8, n, w, m_ν,...)

Nulling Tomography with WL





Huterer & White, astro-ph/0501451

Nulling Tomography: cutting in k

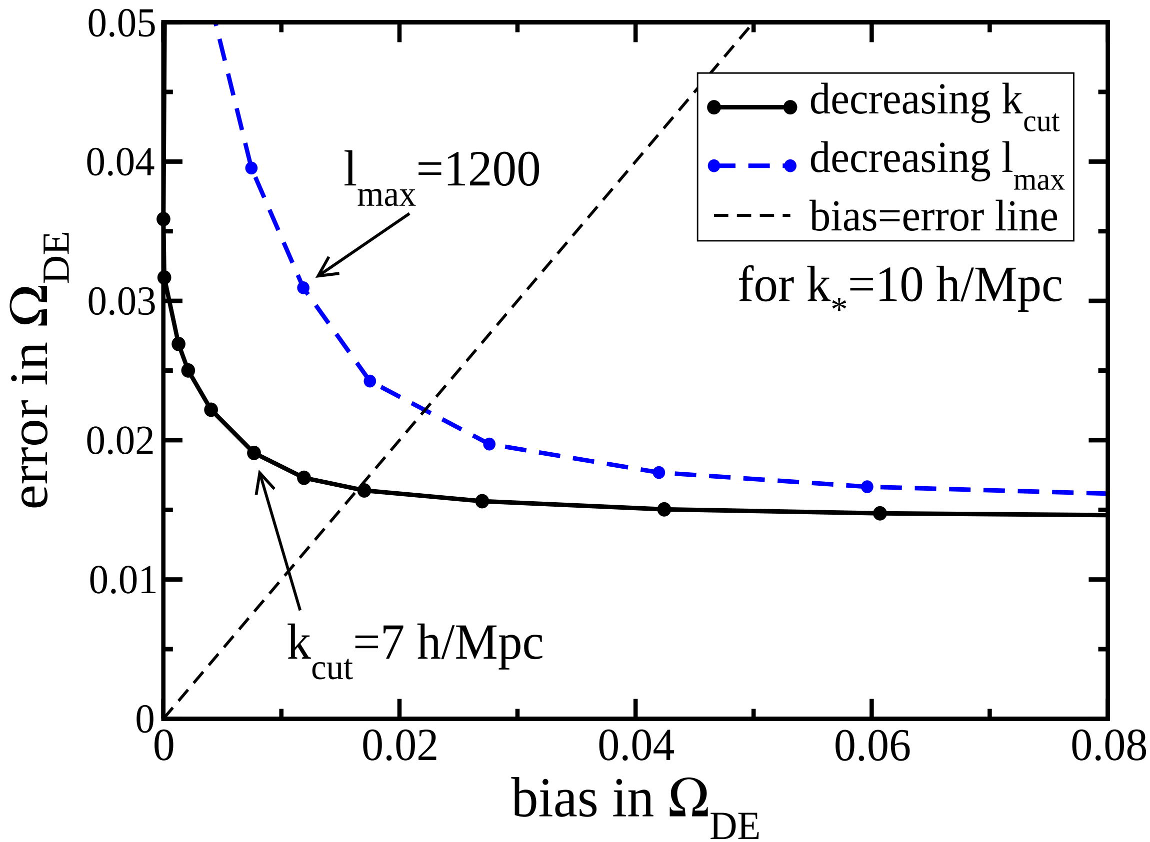
$$
\begin{aligned}
C_i^\kappa(\ell) &= \int_0^\infty dz\, \frac{W_1(z)\, W_2(z)}{r(z)^2\, H(z)}\, P\left(\frac{\ell}{r(z)}, z\right), \\
&\simeq \sum_{k=1}^{N_{\rm planes}} \tilde{W}_{ik}
\end{aligned}
$$

(i denotes a **pair** of redshift bins)

$$
\widetilde{\mathbf{W}} = \begin{pmatrix} \tilde{W}_{11} & \tilde{W}_{12} & \tilde{W}_{13} & \dots & \tilde{W}_{1N_P} \\ \tilde{W}_{21} & \tilde{W}_{22} & \tilde{W}_{23} & \dots & \tilde{W}_{2N_P} \\ \tilde{W}_{31} & \tilde{W}_{32} & \tilde{W}_{33} & \dots & \tilde{W}_{3N_P} \\ \vdots & \vdots & \vdots & \vdots & \vdots \end{pmatrix} \sim \begin{pmatrix} \mathcal{W}_{11} & \mathcal{W}_{12} & \mathcal{W}_{13} & \dots & \mathcal{W}_{1N_P} \\ 0 & \mathcal{W}_{22} & \mathcal{W}_{23} & \dots & \mathcal{W}_{2N_P} \\ 0 & 0 & \mathcal{W}_{33} & \dots & \mathcal{W}_{3N_P} \\ \vdots & \vdots & \vdots & \vdots & \vdots \end{pmatrix}
$$

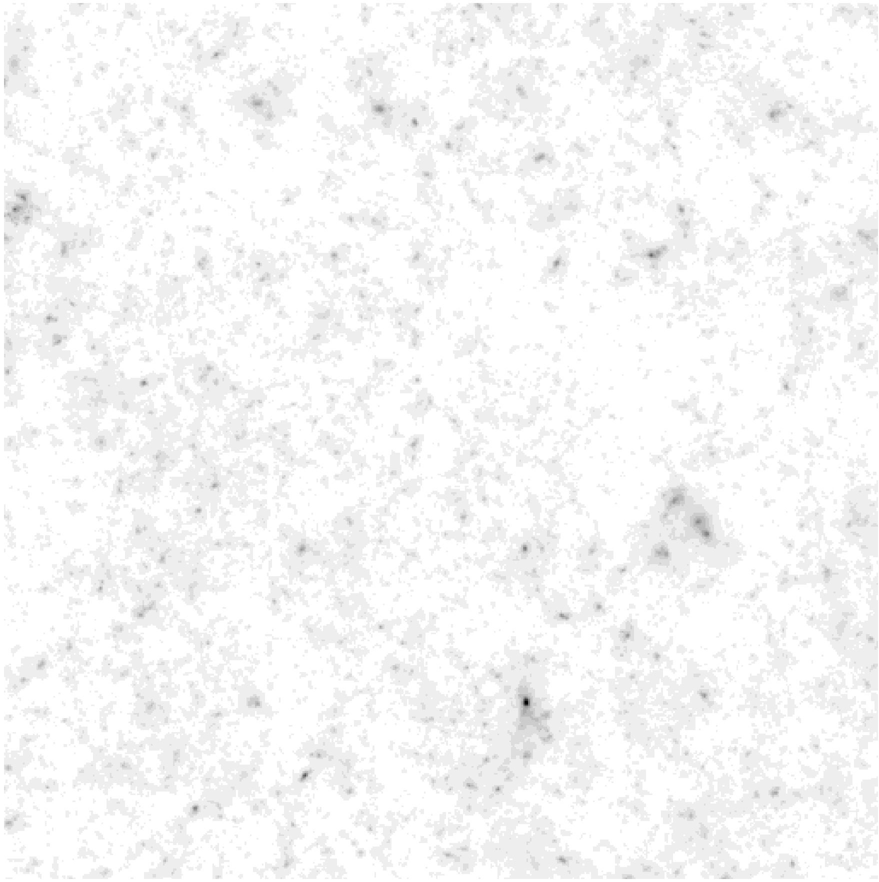
Nulling Tomography: cutting in k

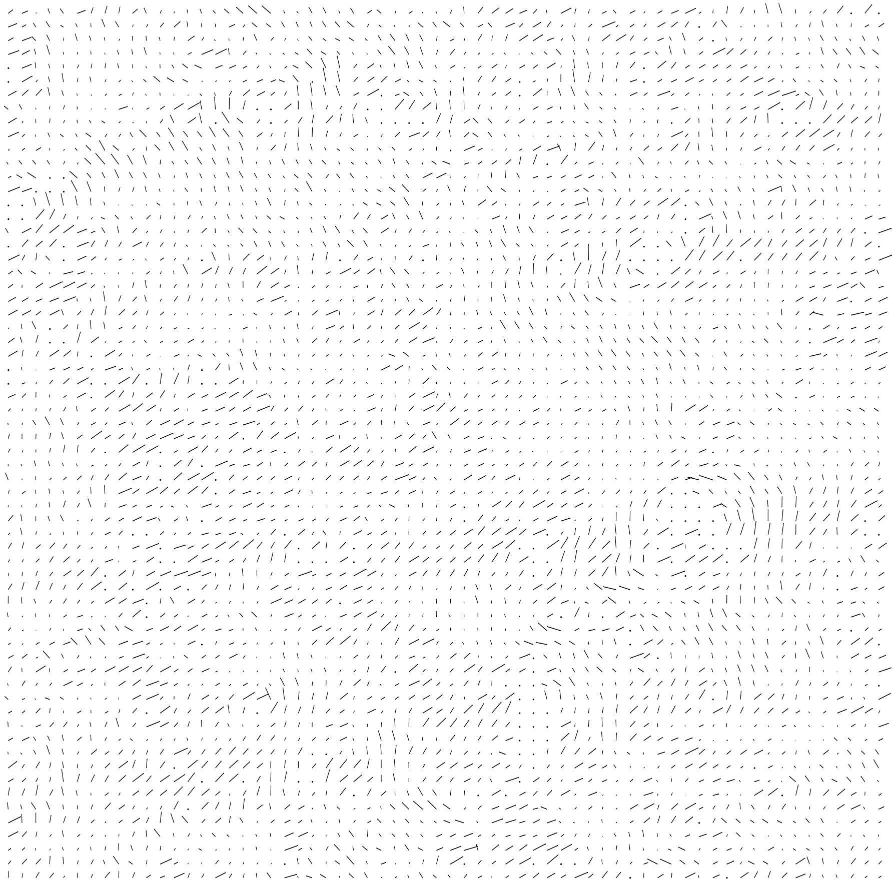
$$P(k,z) = P^{\rm true}(k,z)\left[1+\left(\frac{k}{k_*}\right)^3\right]$$



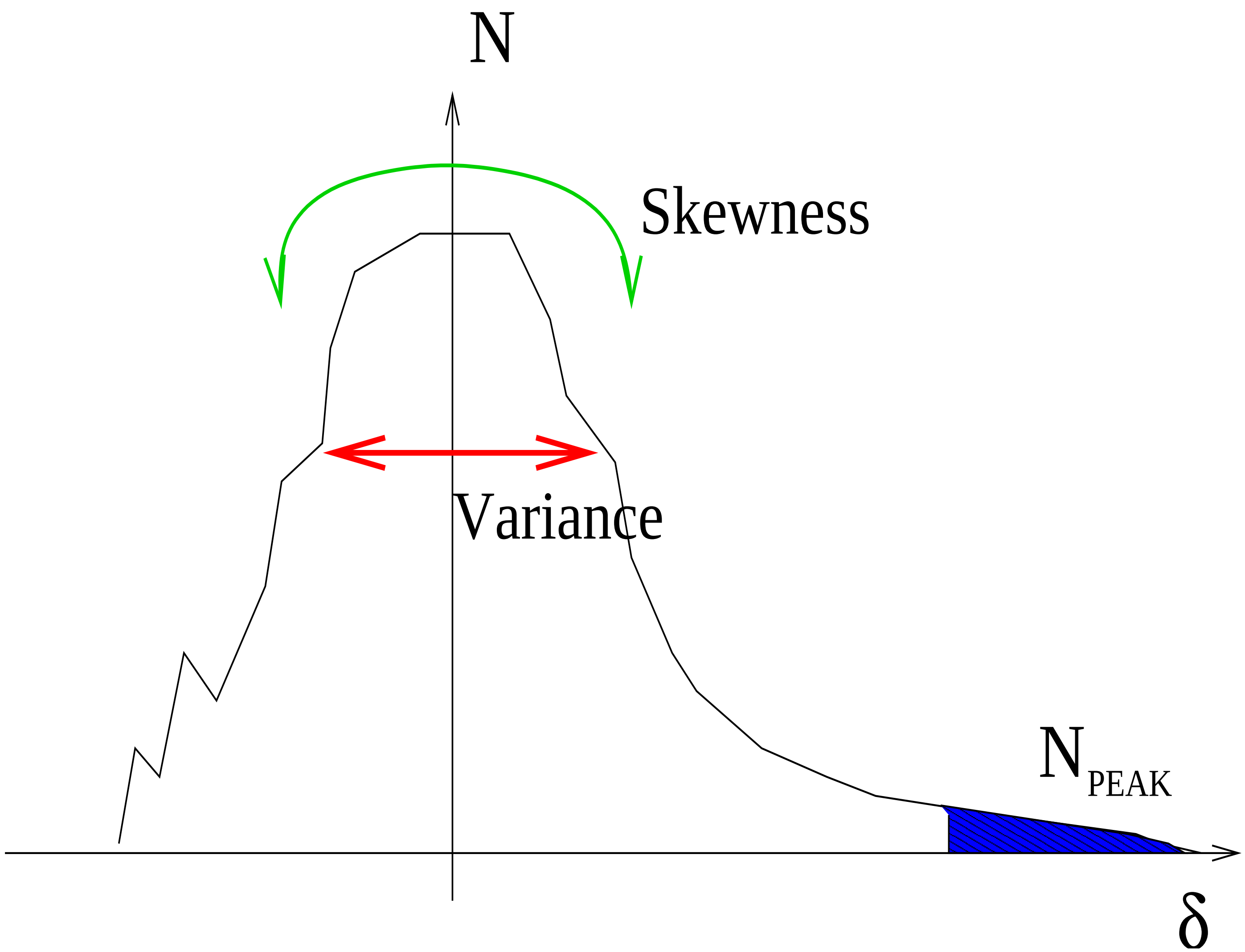
Huterer & White, astro-ph/0501451

Extracting information from WL surveys





Vale and White 2003


N
Skewness
Variance
N_{PEAK}
δ

Conclusions

- Dark energy constraints are getting better, although our understanding of it is not.
- Whether or not $w(z) = -1$ is shaping up as a central question.
- Identification and control of systematics, both experimental and theoretical, is crucial. More powerful experiments have more stringent systematic requirements.
- Bright prospects with ongoing and upcoming SNe, weak lensing, SZ, CMB surveys.