Dark Energy: Pedagogical Overview and Future Prospects

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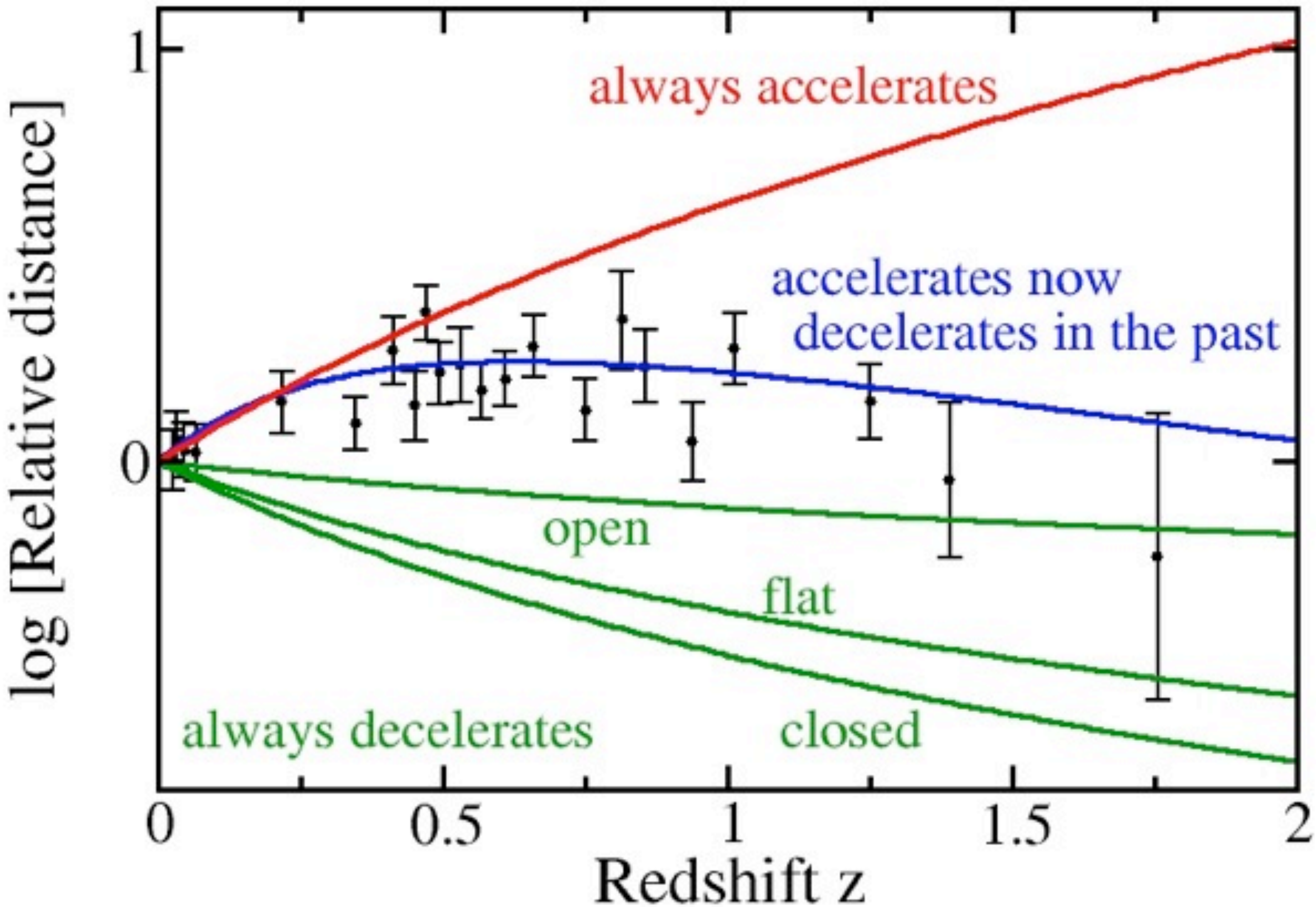
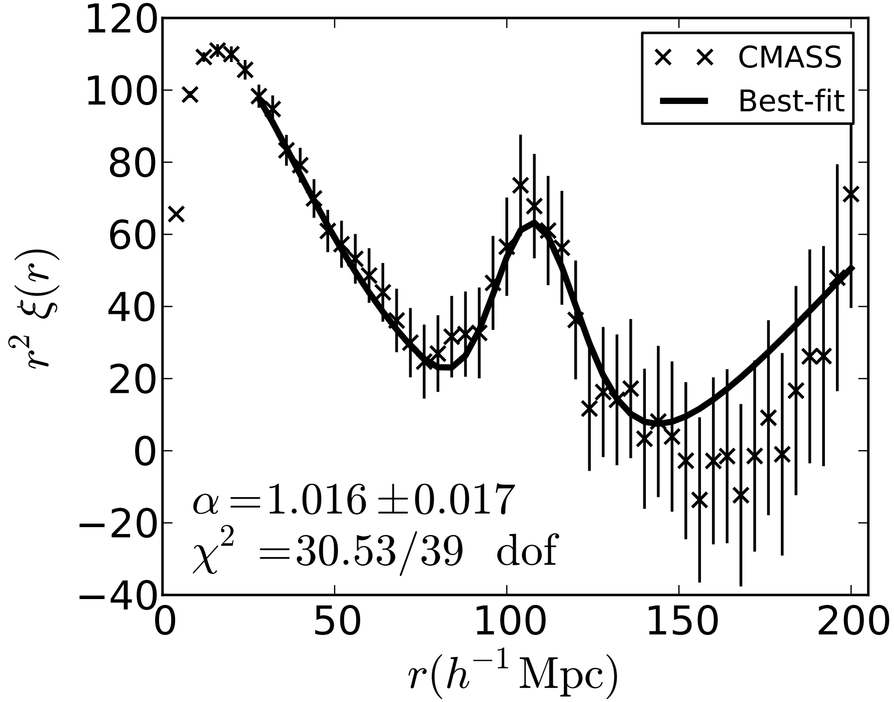
Supernova Hubble diagram (binned)

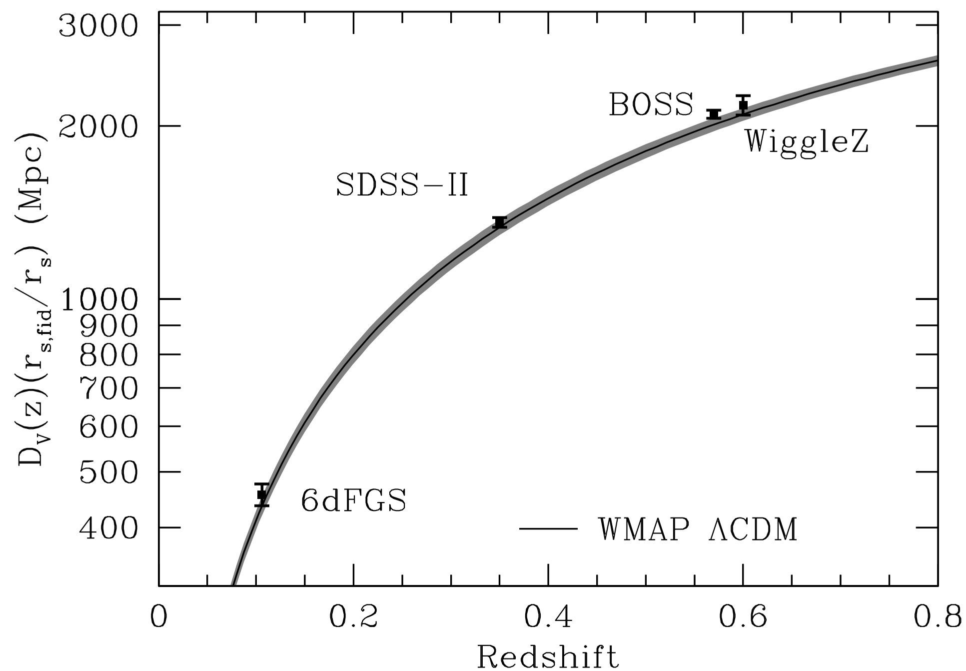


Frieman, Turner & Huterer, Ann. Rev. Astro. Astroph., 2008

Baryon Acoustic Oscillations



Anderson et al, 1203.6594 (BOSS)



sensitive to $D_V(z) \equiv \left[cz\,(1+z)^2 \,\frac{D_A^2(z)}{H(z)} \right]^{1/3}$

But, with separation of radial and angular modes,
can measure $D_A(z)$ and $H(z)$ separately

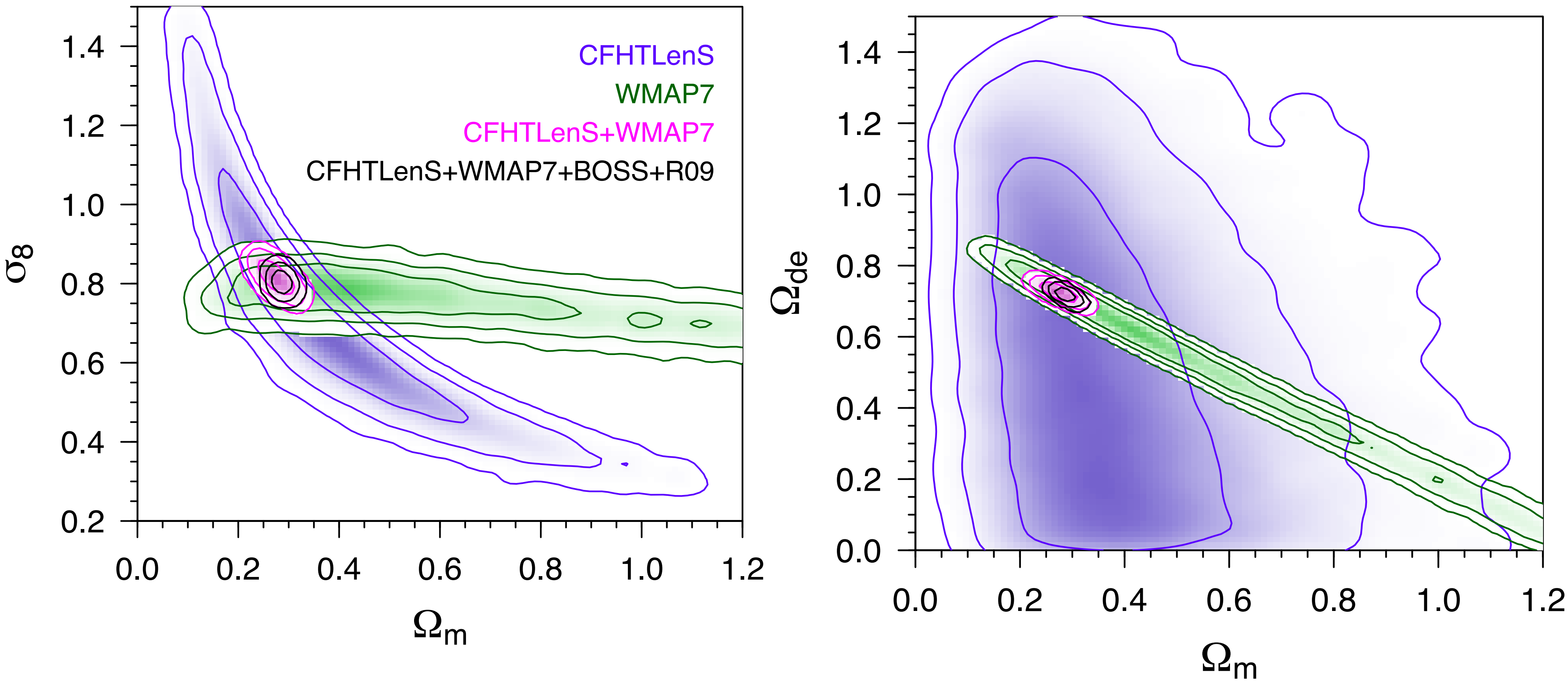
Weak Gravitational Lensing

Credit: NASA, ESA and R. Massey (Caltech)

Key advantage: measures distribution of matter, not light

Weak Gravitational Lensing current constraints on DE are weak

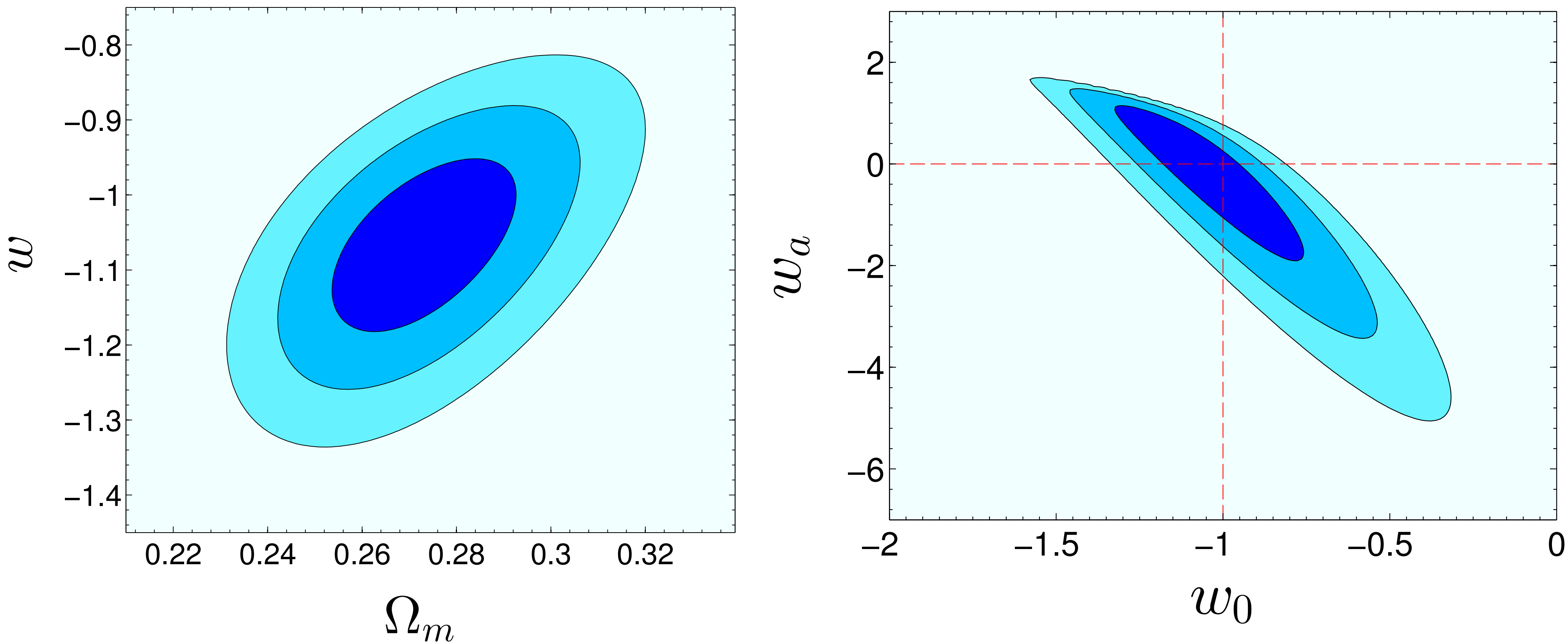
Kilbinger et al (CFHTLens), arXiv:1212.3338



... but WL still has a lot of promise! (no bias)

Since the discovery of acceleration, constraints have converged to w ≈ −1

SN + BAO + CMB(WMAP) data:



Ruiz, Shafer, Huterer & Conley, 1207.4781

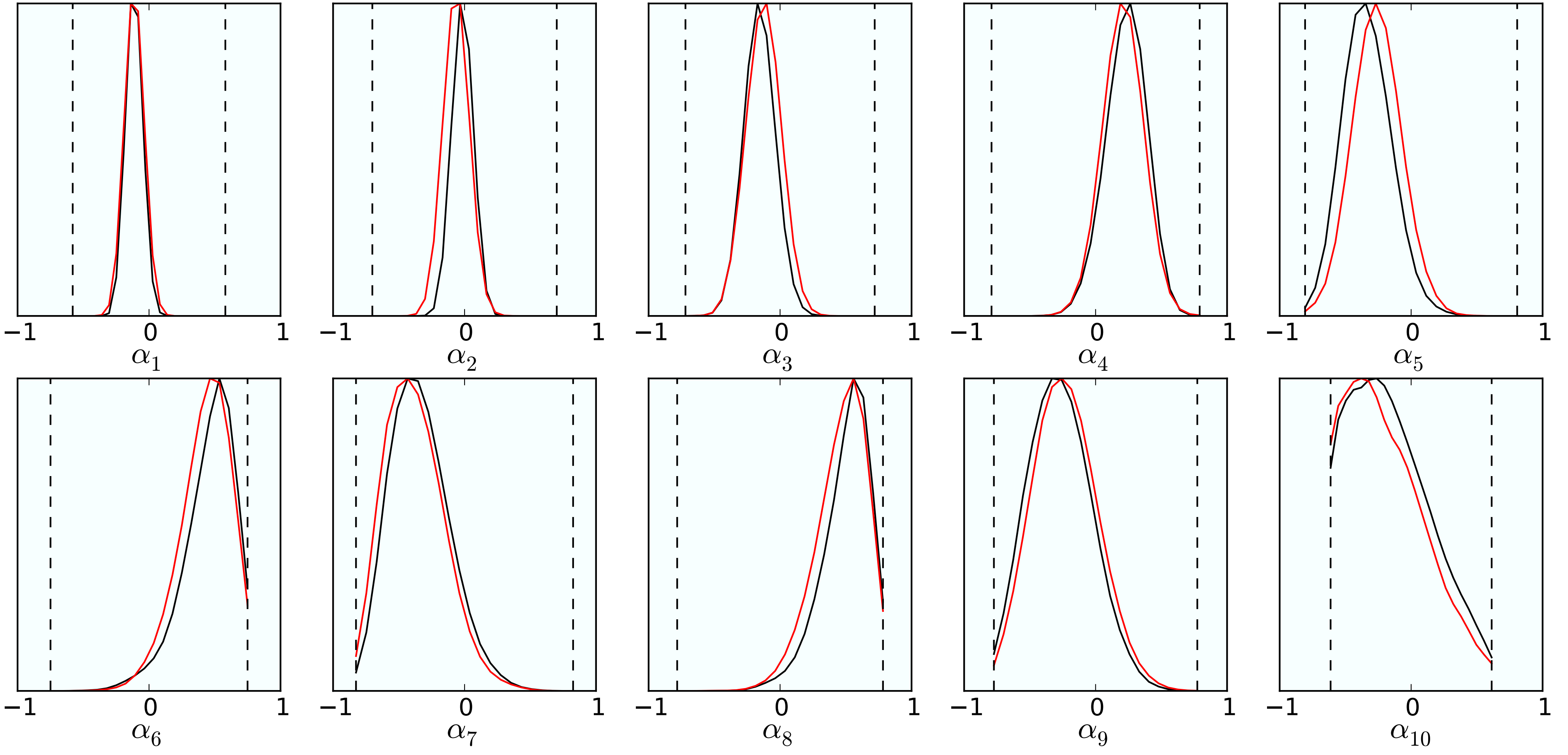
In *principal*, constraints are good...

(components)

$$w(z_j) = -1 + \sum_{i=1}^{N} \alpha_i e_i(z_j)$$

α_i = PC amplitude

$e_i(z)$ = PC shape



Red = with SN systematics

Ruiz, et al. 1207.4781

Systematic errors

- Already limiting factor in measurements
- Will definitely be limiting factor with future data
- Quantity of interest: (true sys. – estimated sys.) difference
- Self-calibration : measuring systematics internally from the survey -
  - e.g., parametrize systematics, solve internally for those parameters

Systematics summary for the "big four"

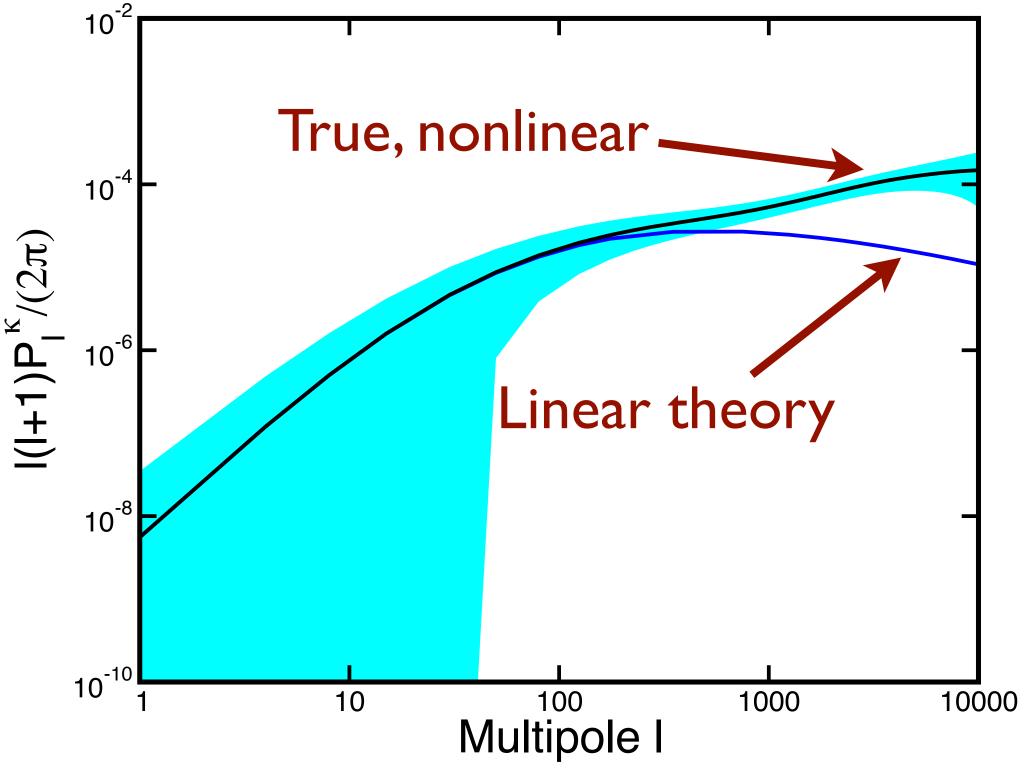
Table 2: Comparison of dark energy probes.

Method	Strengths	Weaknesses	Systematics
WL	growth+geometric, statistical power	CDM assumption	image quality, photo-z
SN	purely geometric, mature	standard candle assumption	evolution, dust
BAO	largely geometric, low systematics	large samples required	bias, non-linearity
CL	growth+geometric, X-ray+SZ+optical	CDM assumption	determining mass, selection function

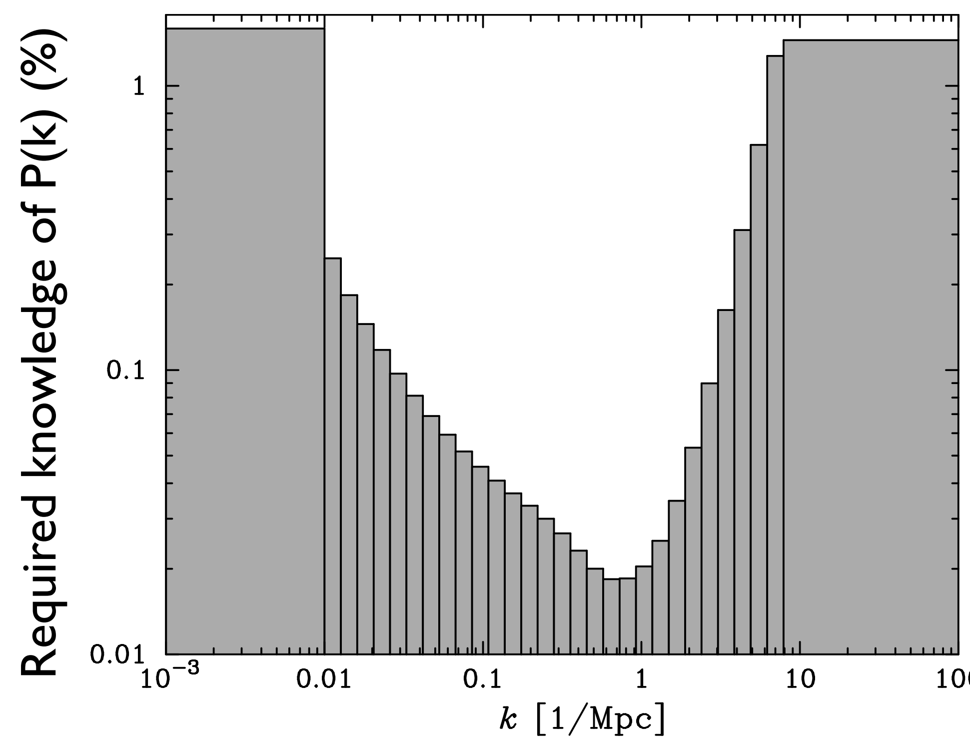
Frieman, Turner & Huterer, Ann. Rev. Astro. Astroph., 2008

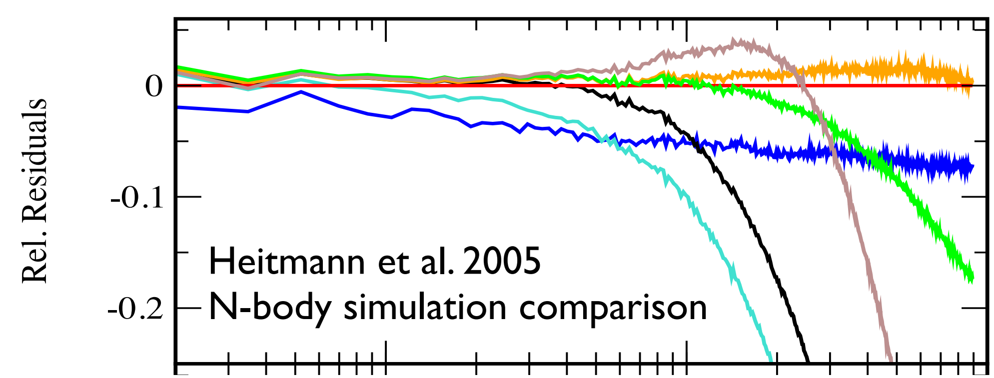
Example 1

Theory Systematics: calibrating the matter (and, later, gal) P(k) at large k



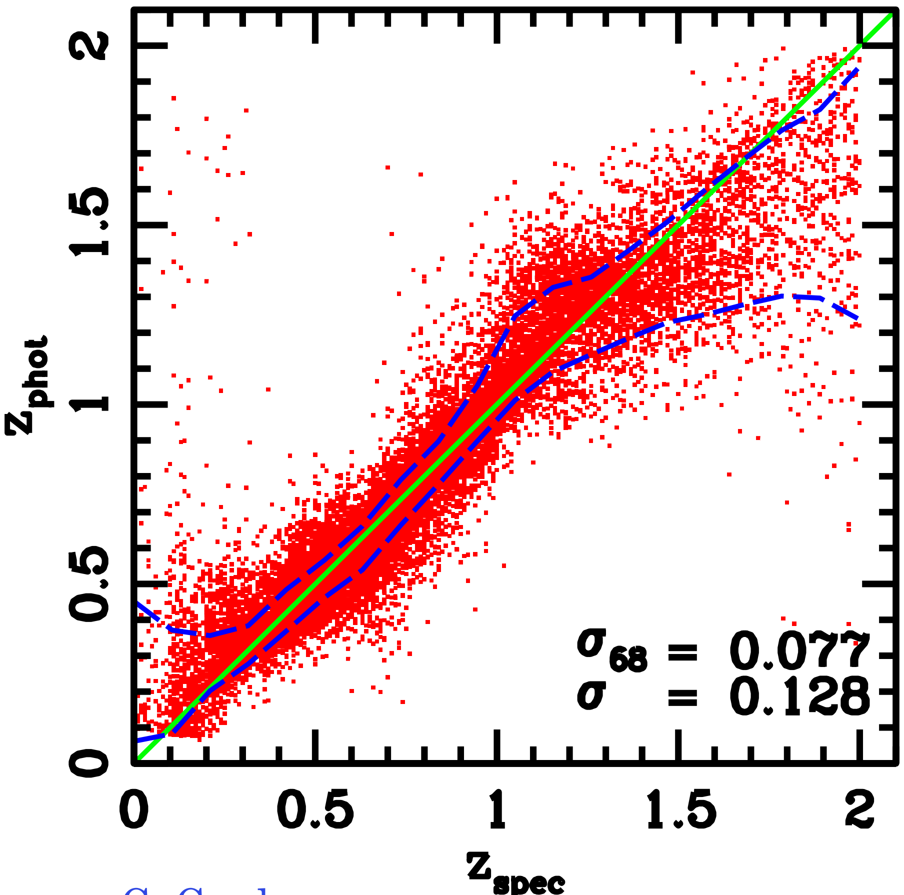
Huterer & Takada 2005





Example 2

Poster child of systematics: photometric redshift errors



C. Cunha

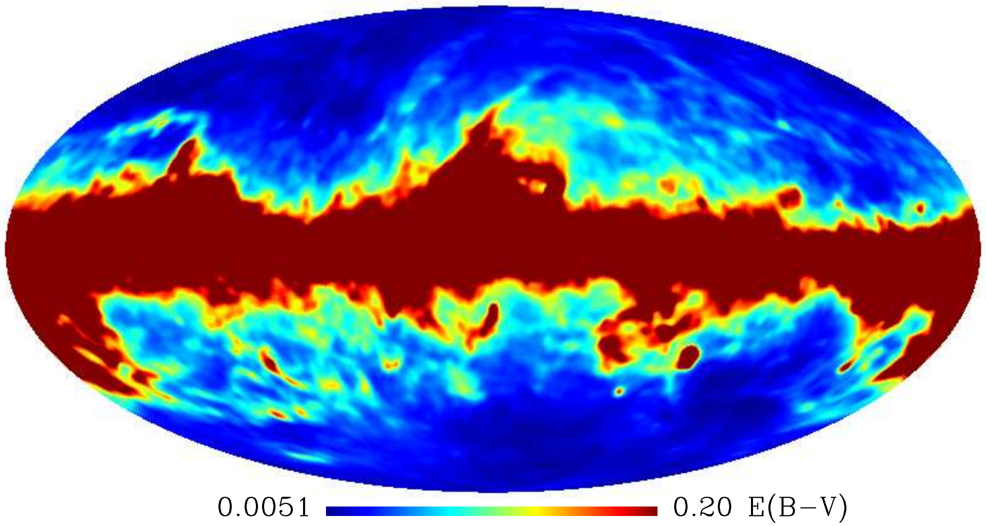
- Measure z_{phot} from colors
- Calibrate $P(z_{phot} | z_{spec})$ relation from spectroscopic follow-up
- Need accurate characterization of "islands", not just sigma_error of the "core" of distribution

- Major challenge: spectroscopic surveys typically much shallower than photometric

Example 3

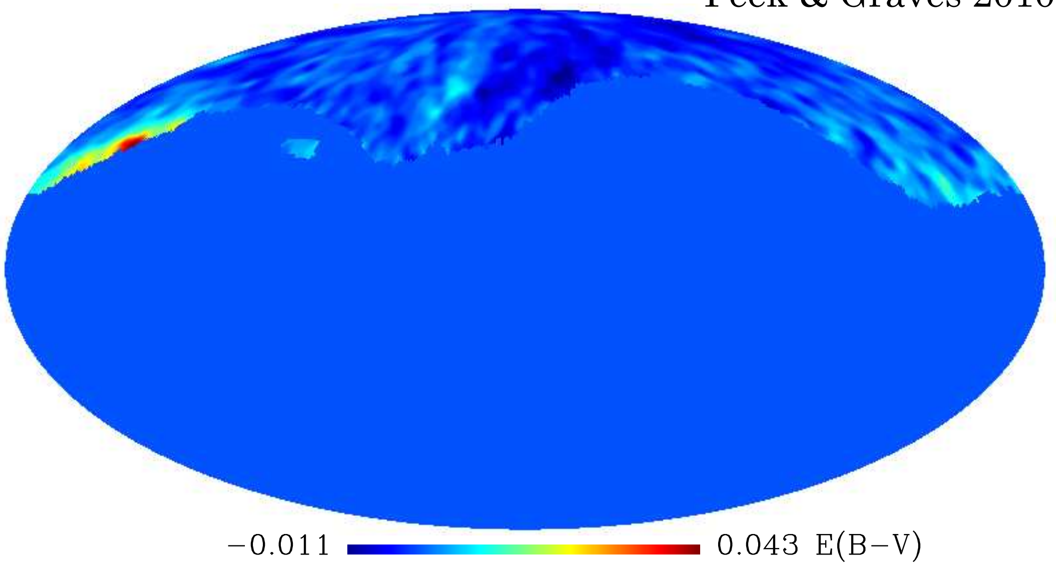
Photometric calibration errors

SFD Galactic dust extinction map



Correction to the extinction map

Peek & Graves 2010



Photometric calibration also can be due to:

- "seeing" and weather
- thickness of atmosphere
- instrumental effects
- need to avoid bright stars
- ....

Very generic!

How do calibration errors affect the measured galaxy angular power spectrum?

$t_{\ell m}$ – observed galaxy field
$c_{\ell m}$ – calibration (systematics) field
C_ℓ – true galaxy clustering power

Final result for the **observed** power spectrum is:

$$\langle t_{\ell m} t^*_{\ell' m'} \rangle = \frac{1}{(1+\epsilon)^2} \left\{ \underbrace{\delta_{mm'}\delta_{\ell\ell'} C_\ell}_{\text{isotropic}} + \underbrace{\left[U^{\ell\ell'}_{mm'} C_{\ell'} + (U^{\ell\ell'}_{mm'})^* C_\ell \right] + \sum_{\ell_2 m_2} U^{\ell_2 \ell}_{m_2 m} (U^{\ell_2 \ell'}_{m_2 m'})^* C_{\ell_2} + c_{\ell m} c^*_{\ell' m'}}_{\text{breaks statistical isotropy}} \right\}$$

Cancels effects of calibration monopole

True power

Calibration (biases)

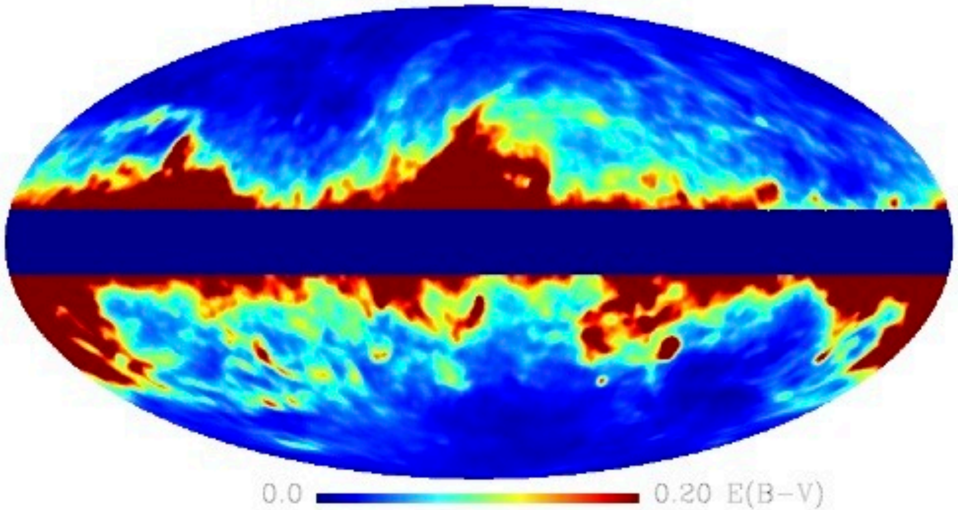
where $U^{\ell_2 \ell}_{m_2 m} \equiv \sum_{\ell_1 m_1} c_{\ell_1 m_1} R^{\ell_1 \ell_2 \ell}_{m_1 m_2 m}$

$$R^{\ell_1 \ell_2 \ell}_{m_1 m_2 m} \equiv (-1)^m \sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2\ell+1)}{4\pi}} \begin{pmatrix} \ell_1 & \ell_2 & \ell \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell_1 & \ell_2 & \ell \\ m_1 & m_2 & -m \end{pmatrix}$$

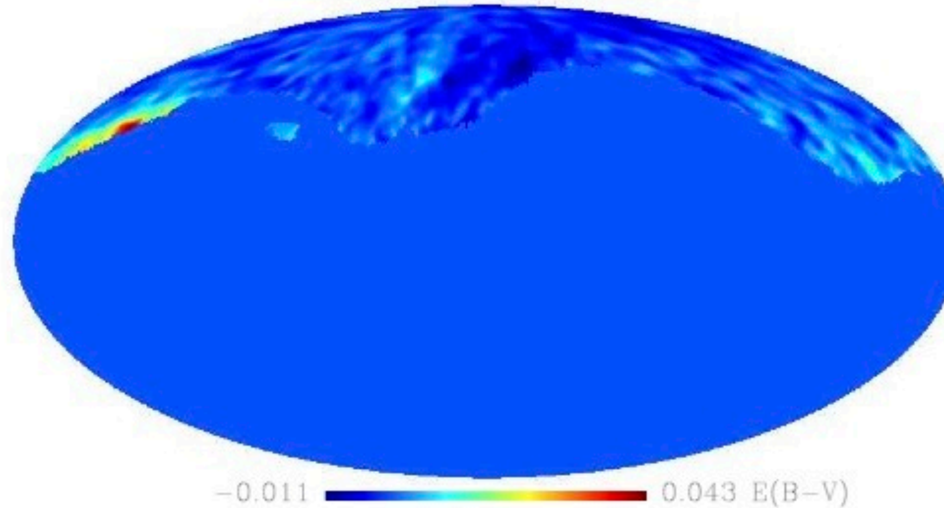
Huterer, Cunha & Fang, arXiv:1211:1015

Calibration bias: Worked Example 1

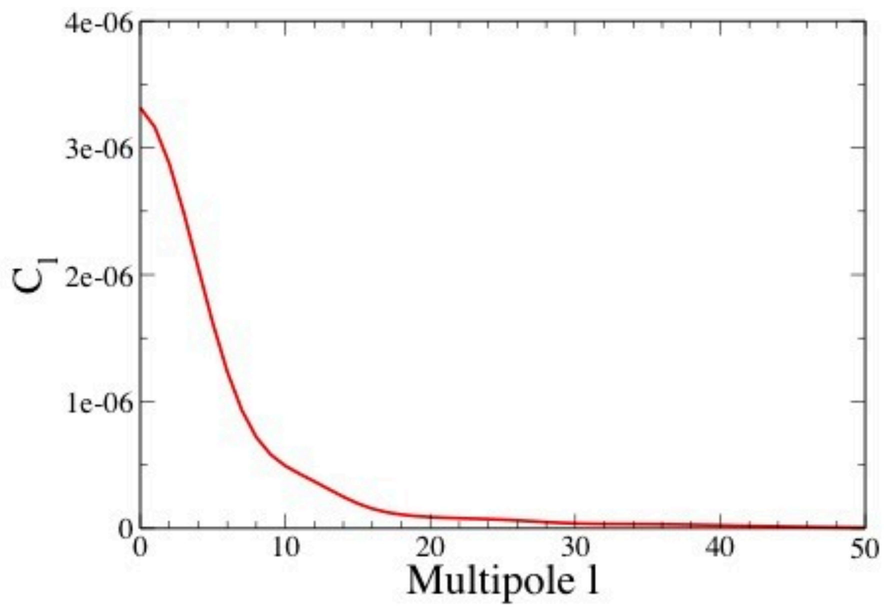
SFD dust map



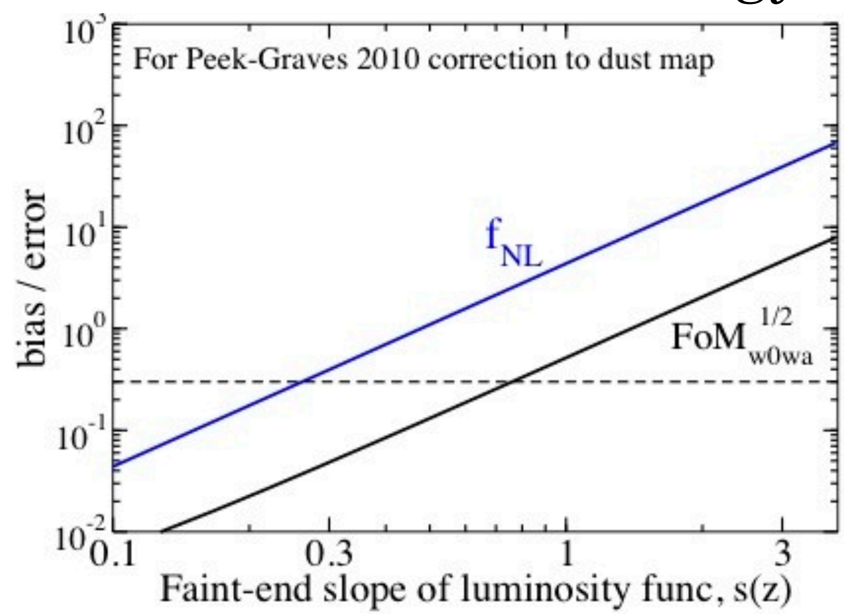
PG10 corrections to map



angular power of corrections



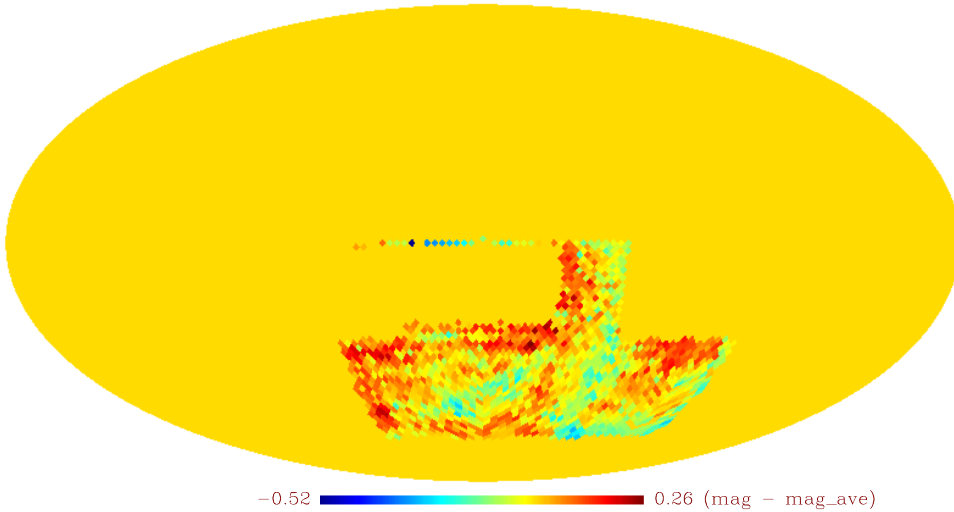
bias/error in cosmology

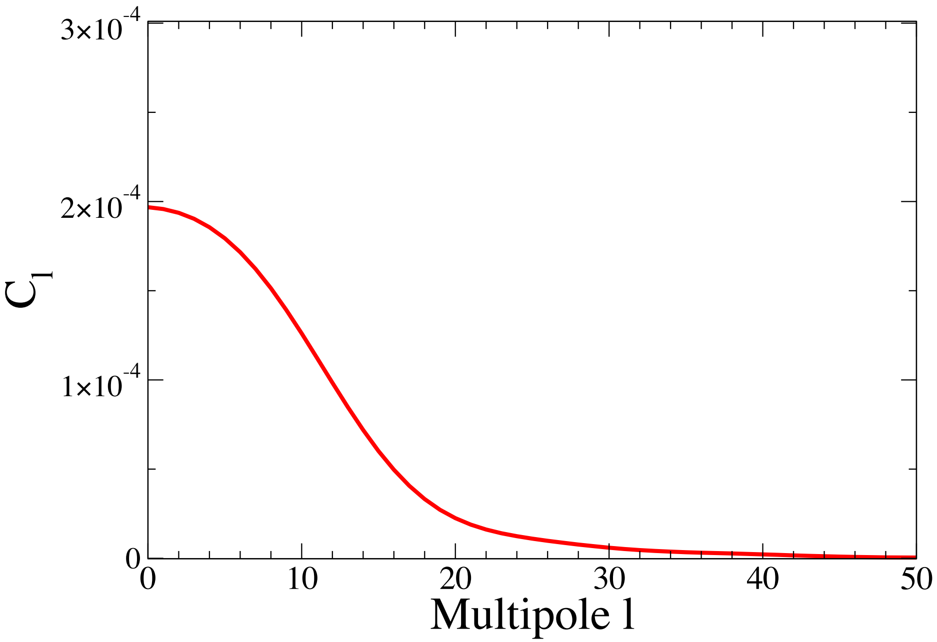


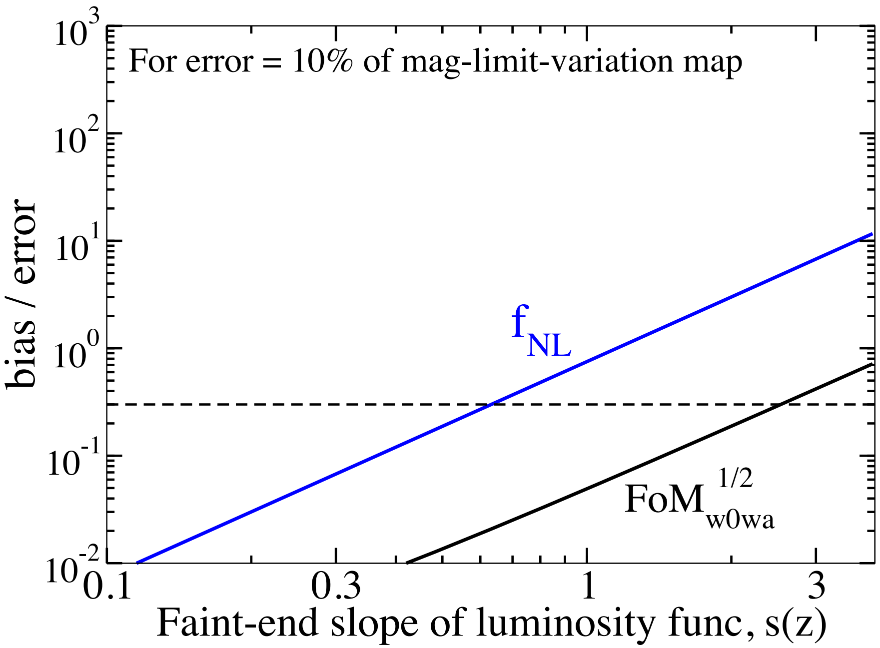
Huterer, Cunha & Fang, arXiv:1211:1015

Calibration bias: Worked Example 2

DES magnitude limit (J. Annis)







Photometric Calibration systematics

Summary of findings:

1. Calibration *breaks statistical isotropy* of LSS signal (obvious in retrospect)
2. *Large-angle* errors beyond the monopole - dipole, quadrupole, etc - are most damaging
3. Control at level $< 0.1\%$ might be required for DES-type survey and beyond

Recommendations of the "Rocky III" DOE/HEP report
(Albrecht et al, 2012)

1. Advanced wide-field spectroscopic survey in time frame roughly between DES and LSST (& Euclid/WFIRST)
   - Stage IV BAO/RSD information
   - Provide calibration data for systematic error mitigation to improve dark-energy constraints from photometric surveys like DES & LSST (in particular, helps WL & CL)

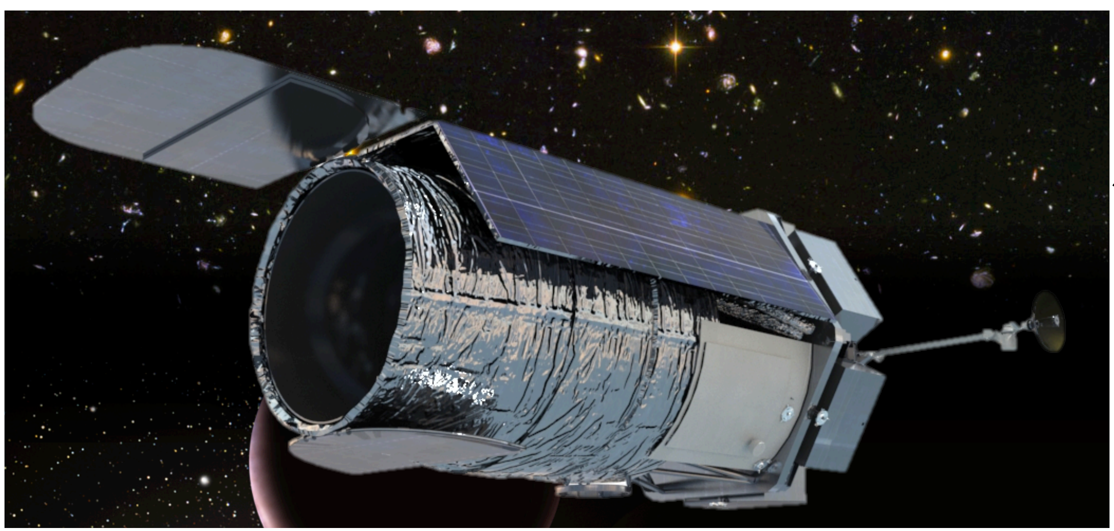
2. Advance SN technique to Stage IV
   - Clearest path: DOE participation in SNe at high-redshift from space (example: DOE-led modest upgrade to WFIRST)
   - Explore vigorously ground-based alternatives (R&D effort for near-IR technology and sky-line suppression)

3. Pilot studies to generate new ideas for the future
   - Deep spectroscopic calibration data needed for LSST. Pilot study to determine exact needs and how to meet them.
   - Pilot studies combining theory and targeted observations to chart an effective modified gravity program to study transition to modified gravity.

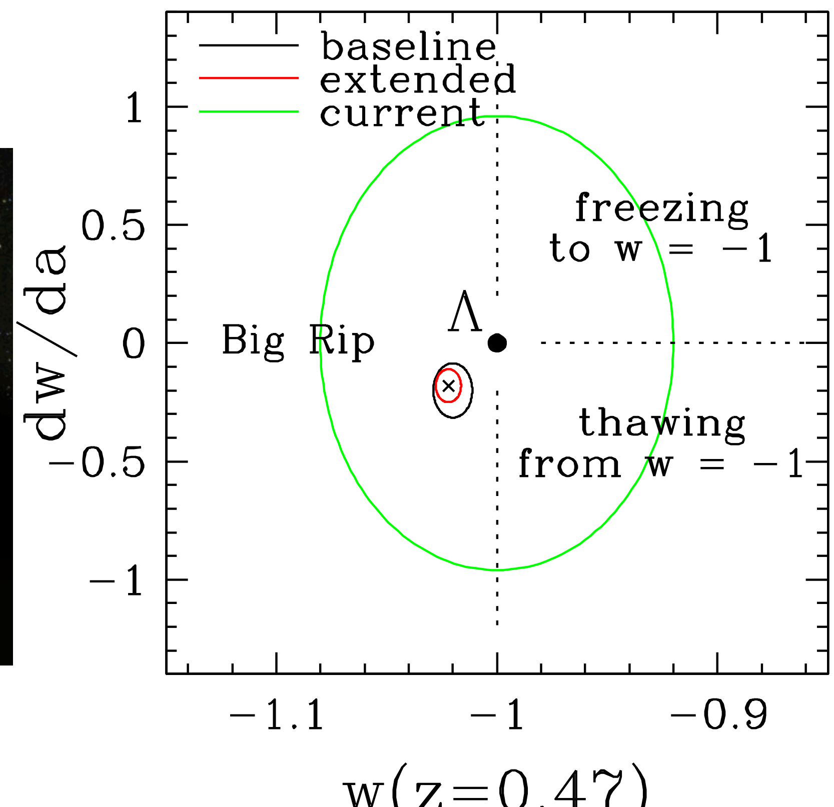
In the next 10-15 years, can expect measurements of:

- w (or w_{pivot}) to 0.01 (incl systematics)
- d(z), growth(z) in bins out to z=2-3
- parametric DE vs MG consistency tests

e.g. WFIRST



Spergel et al arXiv:1305.5422



Can we distinguish between DE and MG?

(Usual answer:) Yes; here is how:

- In standard GR, H(z) determines distances and growth of structure

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi\rho_M\delta = 0$$

- So check if this is true by measuring separately

Distances
(as known as kinematic probes)
(a.k.a. 0^{th} order cosmology)

Probed by SN Ia, BAO, CMB, weak lensing, cluster abundance

Growth
(a.k.a. dynamical probes)
(a.k.a. 1^{st} order cosmology)

Probed by galaxy clustering, weak lensing, cluster abundance

(Actually...) Not without assuming that DE has no e.g. anisotropic stress

$$G_{\mu\nu} + X_{\mu\nu} = 8\pi G T_{\mu\nu} \quad \text{vs.} \quad G_{\mu\nu} = 8\pi G T_{\mu\nu} - X_{\mu\nu}$$

What if gravity deviates from GR?

For example:

$$H^2 - F(H) = \frac{8\pi G}{3}\rho, \qquad \text{or} \qquad H^2 = \frac{8\pi G}{3}\left(\rho + \frac{3F(H)}{8\pi G}\right)$$

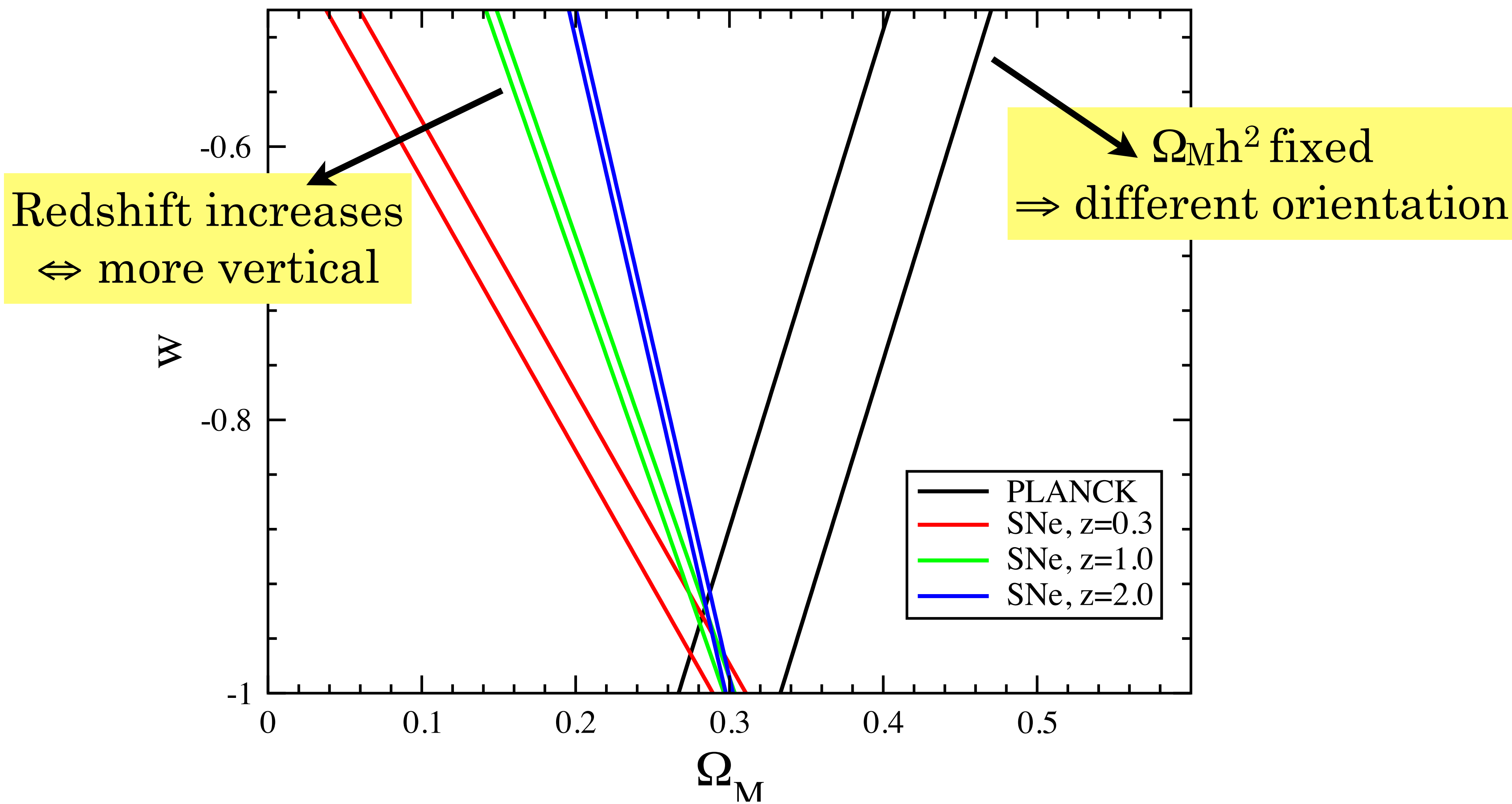
↓ Modified gravity

↓ Dark energy

Notice: there is no way to distinguish these two possibilities just by measuring expansion rate H(z)!

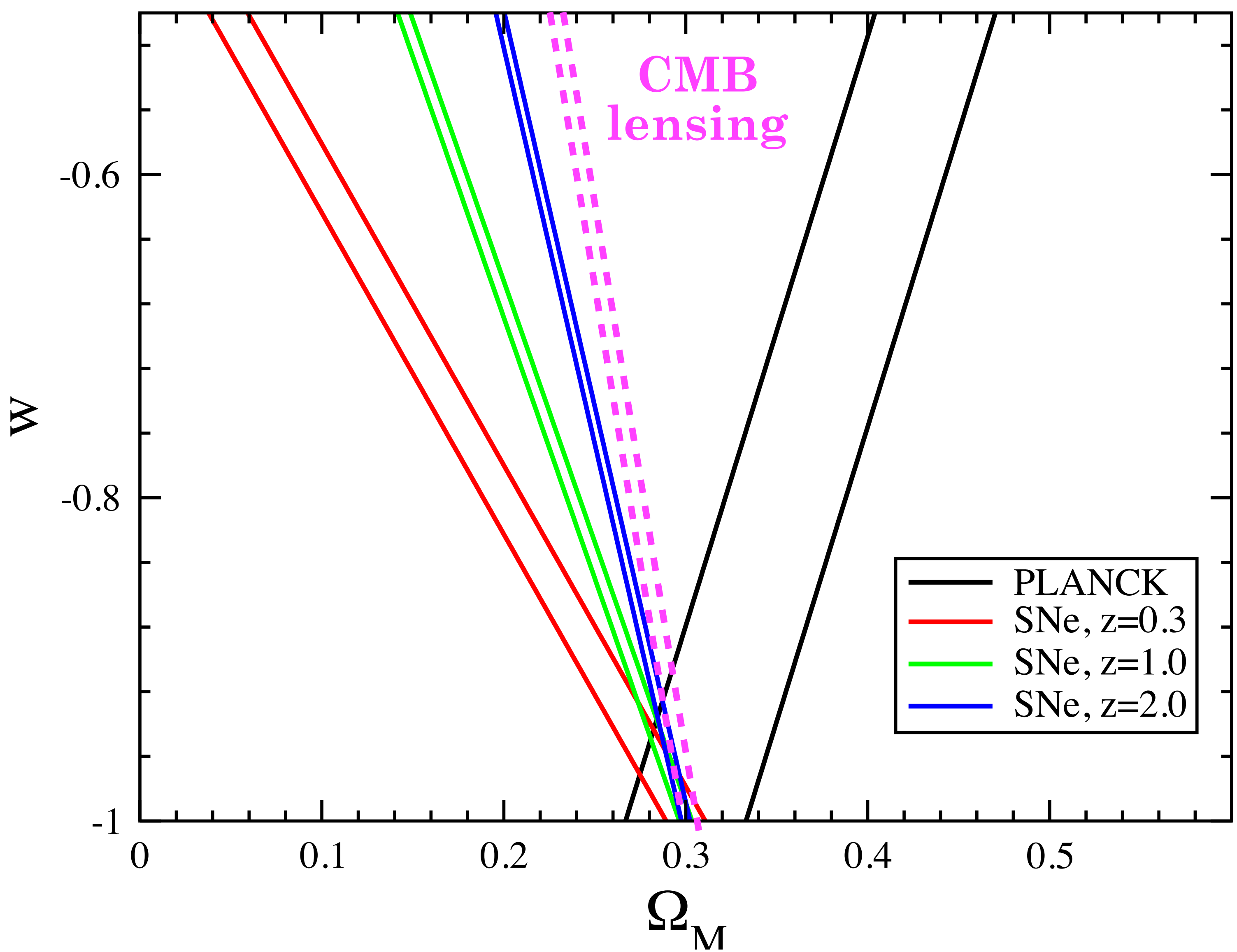
$D_A(z)$ with $\Omega_M h^2$ fixed is basically the "CMB shift parameter" R

$$R = \sqrt{\Omega_M h^2} \int_0^{z_*} \frac{dz'}{H_0 \sqrt{\Omega_M (1+z')^3 + (1-\Omega_M)(1+z')^{3(1+w)}}}$$



Frieman, Huterer, Linder & Turner 2003

CMB Lensing gives D_A(z~few)

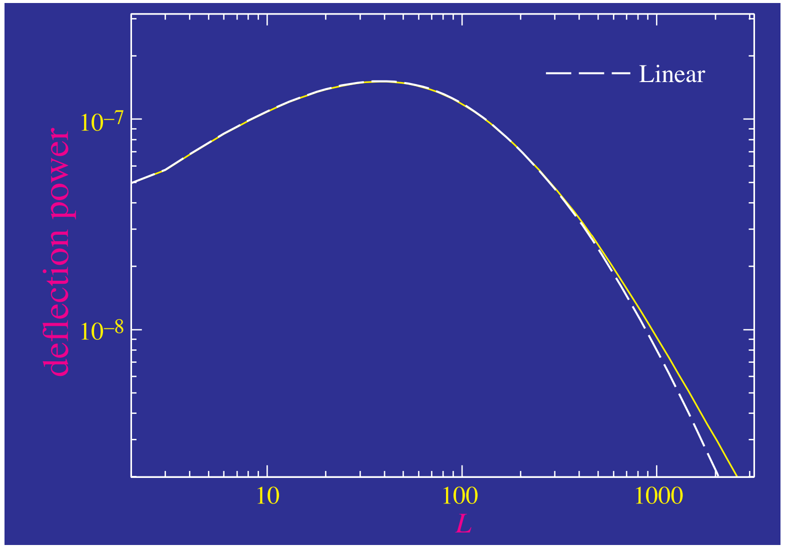


[Recall, CMB lensing additionally carries info about power spectrum P(k)]

Lensing potential:

$$\phi(\widehat{\mathbf{n}}) = -2\int_0^{z_{\rm rec}} \frac{dz}{H(z)}\Psi(z, D(z)\widehat{\mathbf{n}})\left(\frac{D(z_{\rm rec}) - D(z)}{D(z_{\rm rec})D(z)}\right)$$

Angular power of potential:

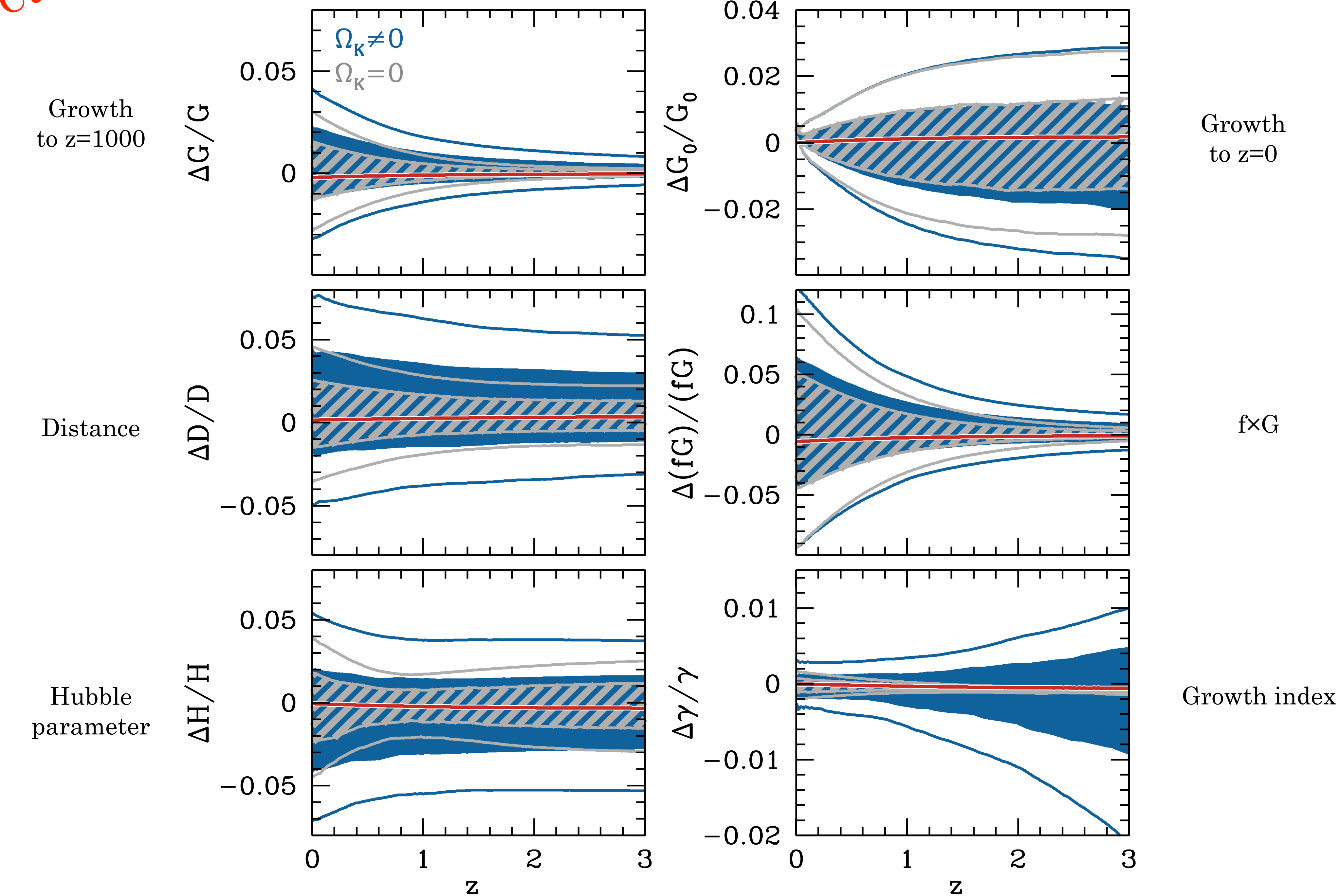


Wayne Hu

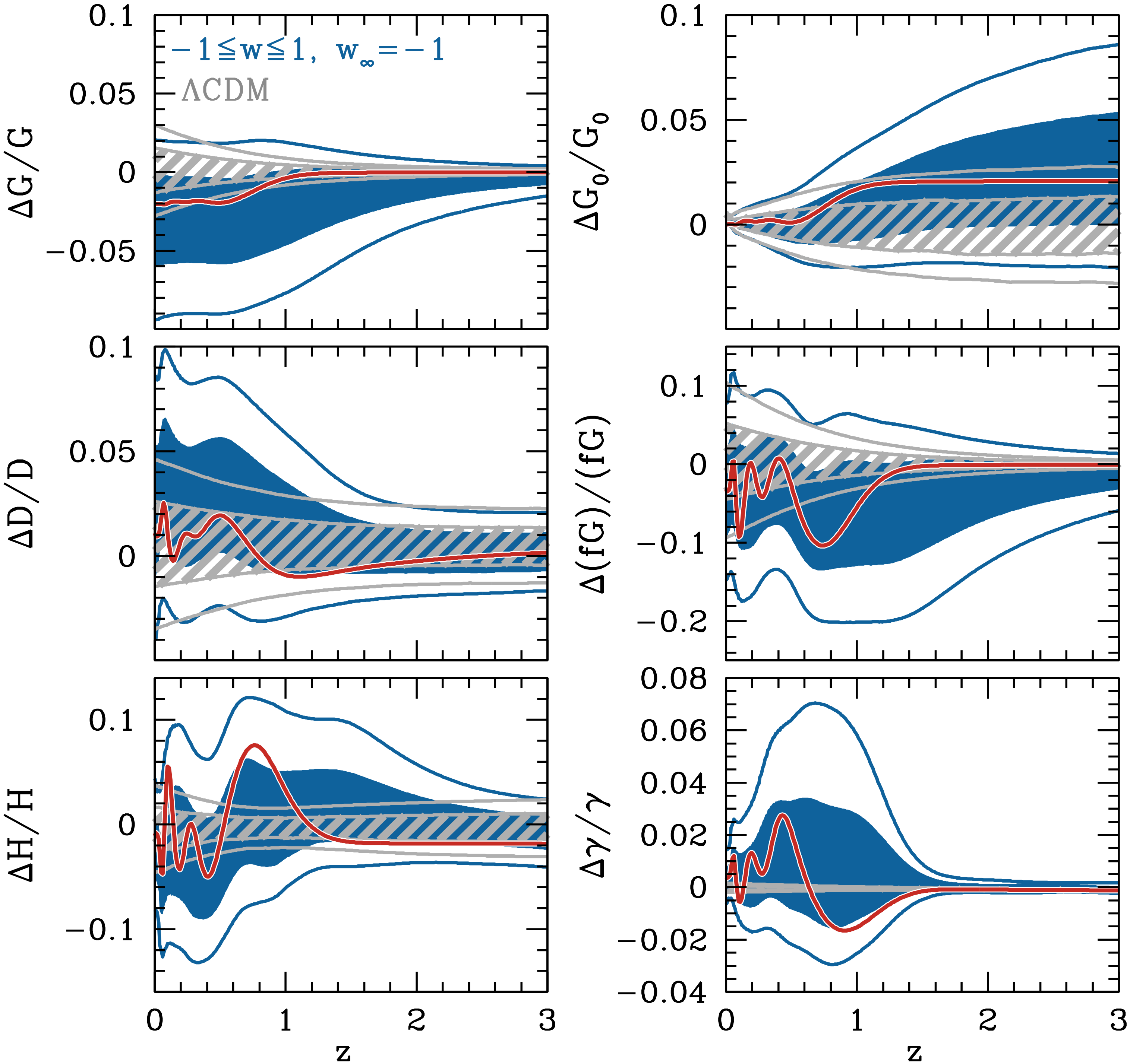
$$C_\ell^{\phi\phi} = \frac{8\pi^2}{\ell^3}\int_0^{z_{\rm rec}} \frac{dz}{H(z)} D(z)\left(\frac{D(z_{\rm rec}) - D(z)}{D(z_{\rm rec})D(z)}\right)^2 P_\Psi(z, k = \ell/D(z))$$

geometry DM clustering

Current data LCDM predictions - flat or curved



Quintessence predictions (flat, no Early DE)



Future data

LCDM predictions (flat or curved)

Grey: flat
Blue: curved

D, G to <1% everywhere
H(z=1) to 0.1% for flat LCDM