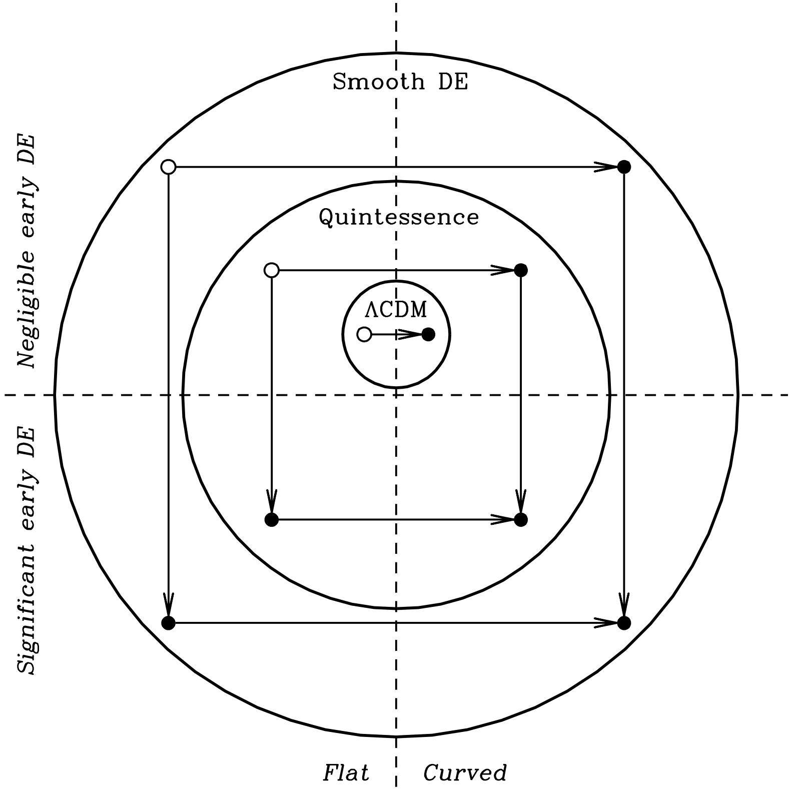
Falsifying Paradigms for Cosmic Acceleration

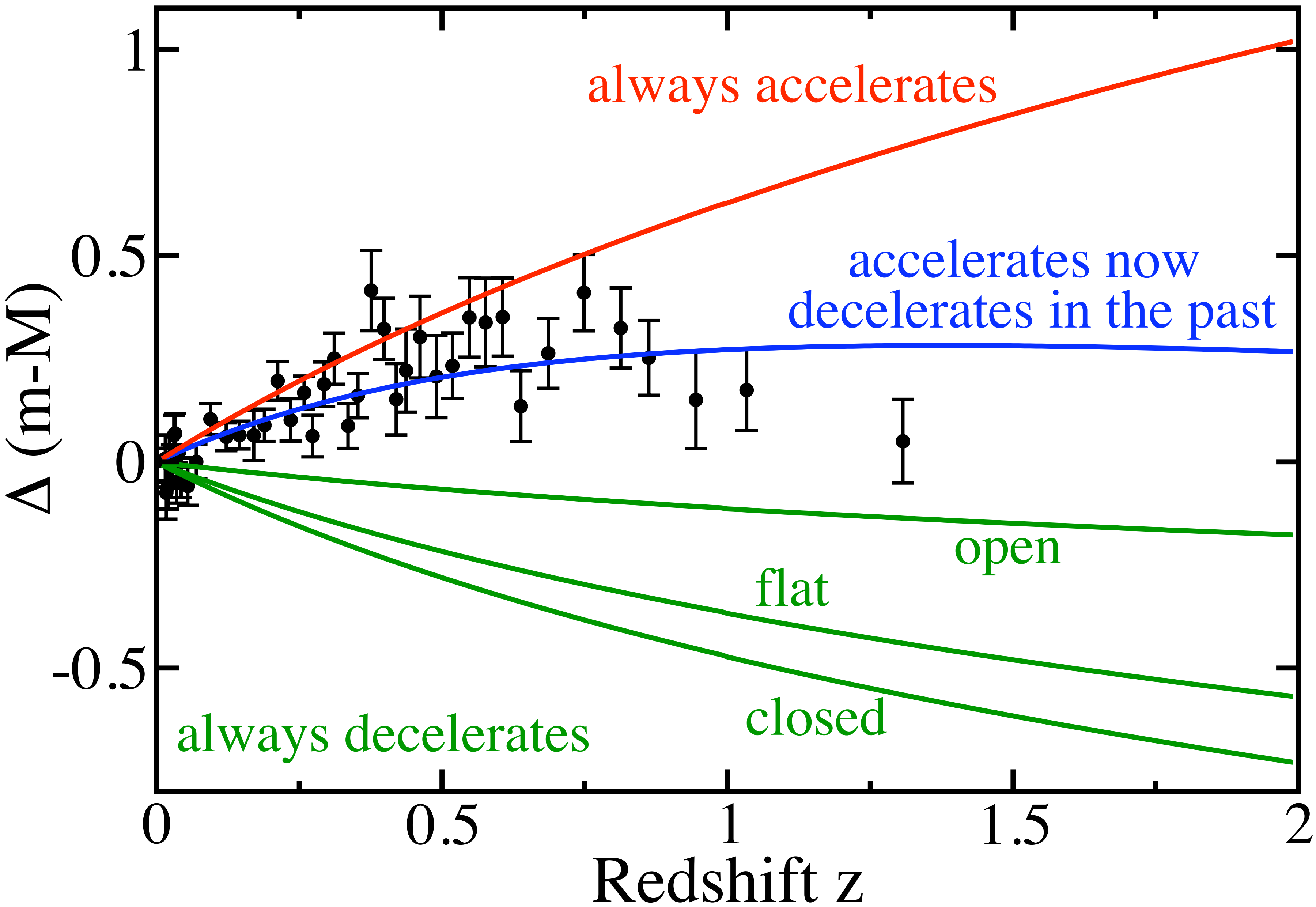
Dragan Huterer (University of Michigan)



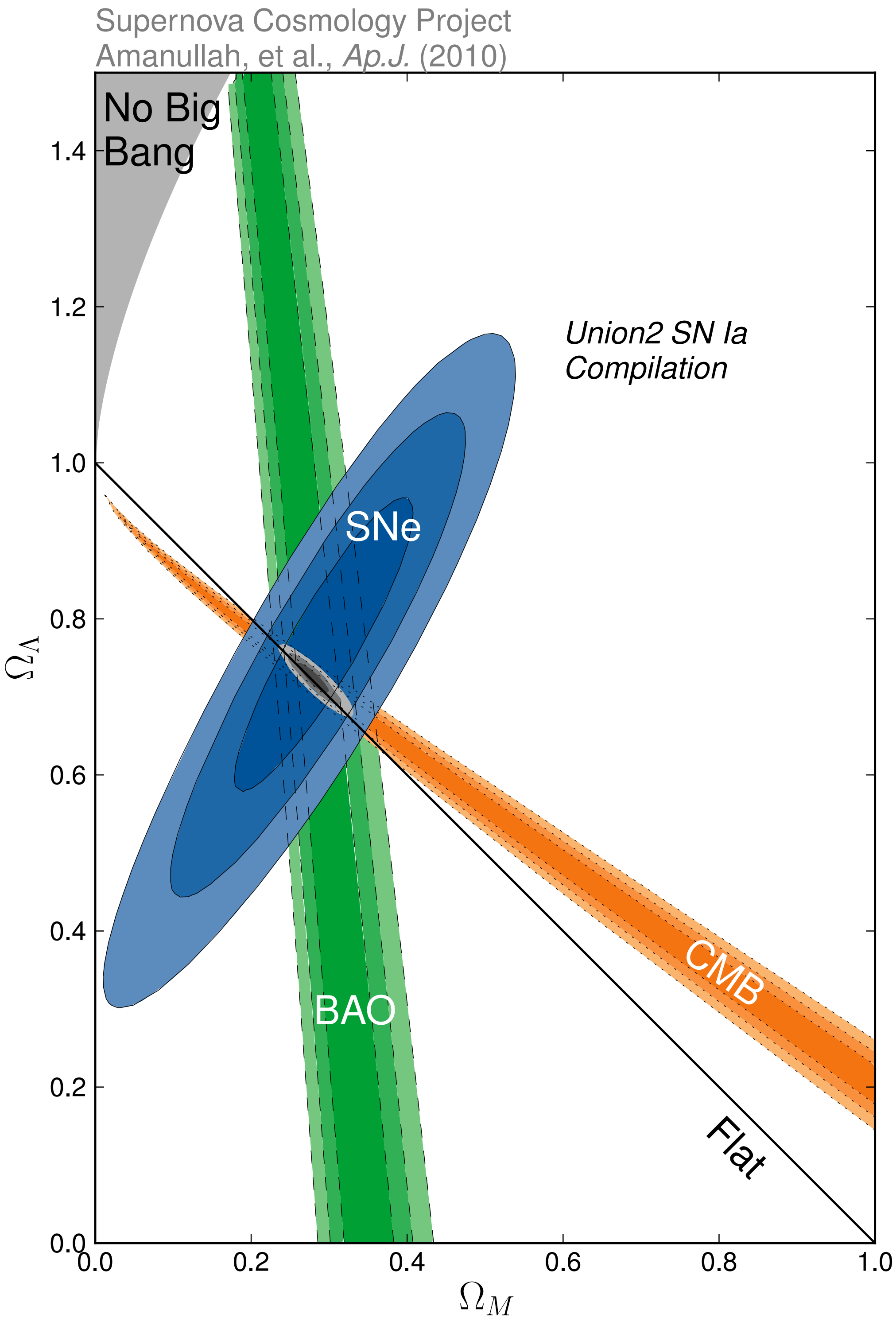
Mortonson, Hu & Huterer:

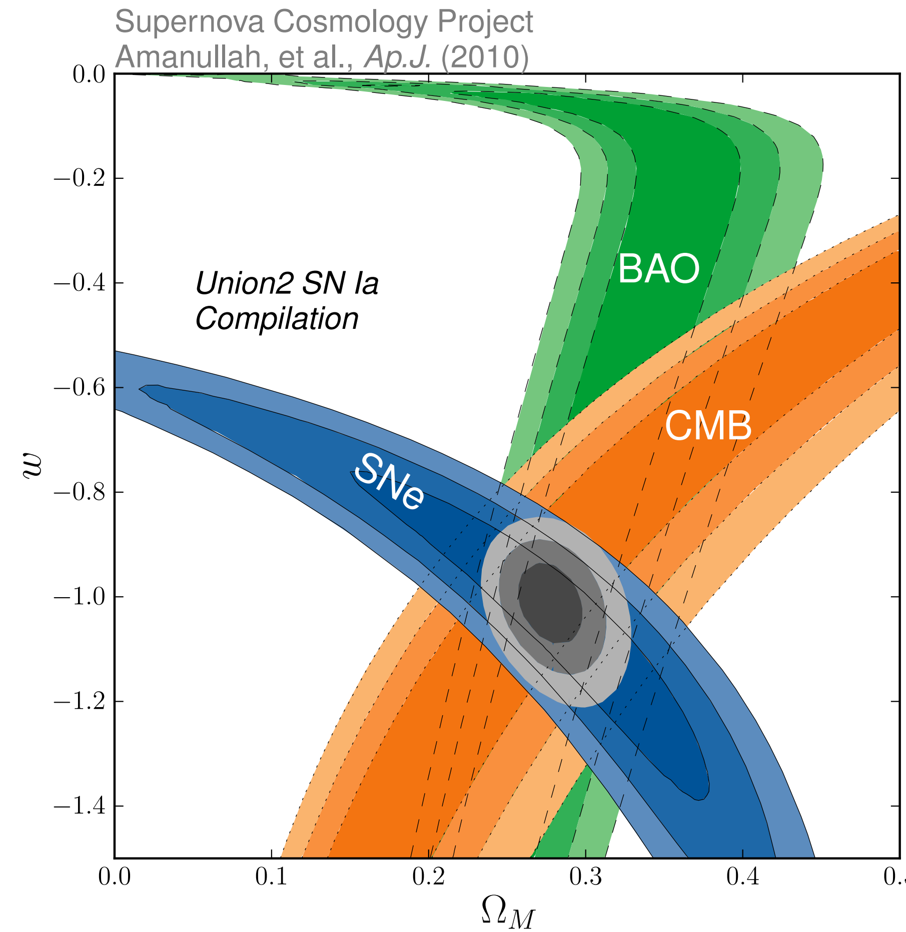
PRD, 79, 023004 (2009) - method, and future data ←
PRD, 80, 067301 (2009) - hiding DE transitions at low z
PRD, 81, 063007 (2010) - current data ←
PRD, 82, 063004 (2010) - Figures of Merit ←
PRD, 81, 023015 (2011) - 'Pink Elephant' clusters ←

This talk



Using Union2 SN data (Amanullah et al 2010) binned in redshift



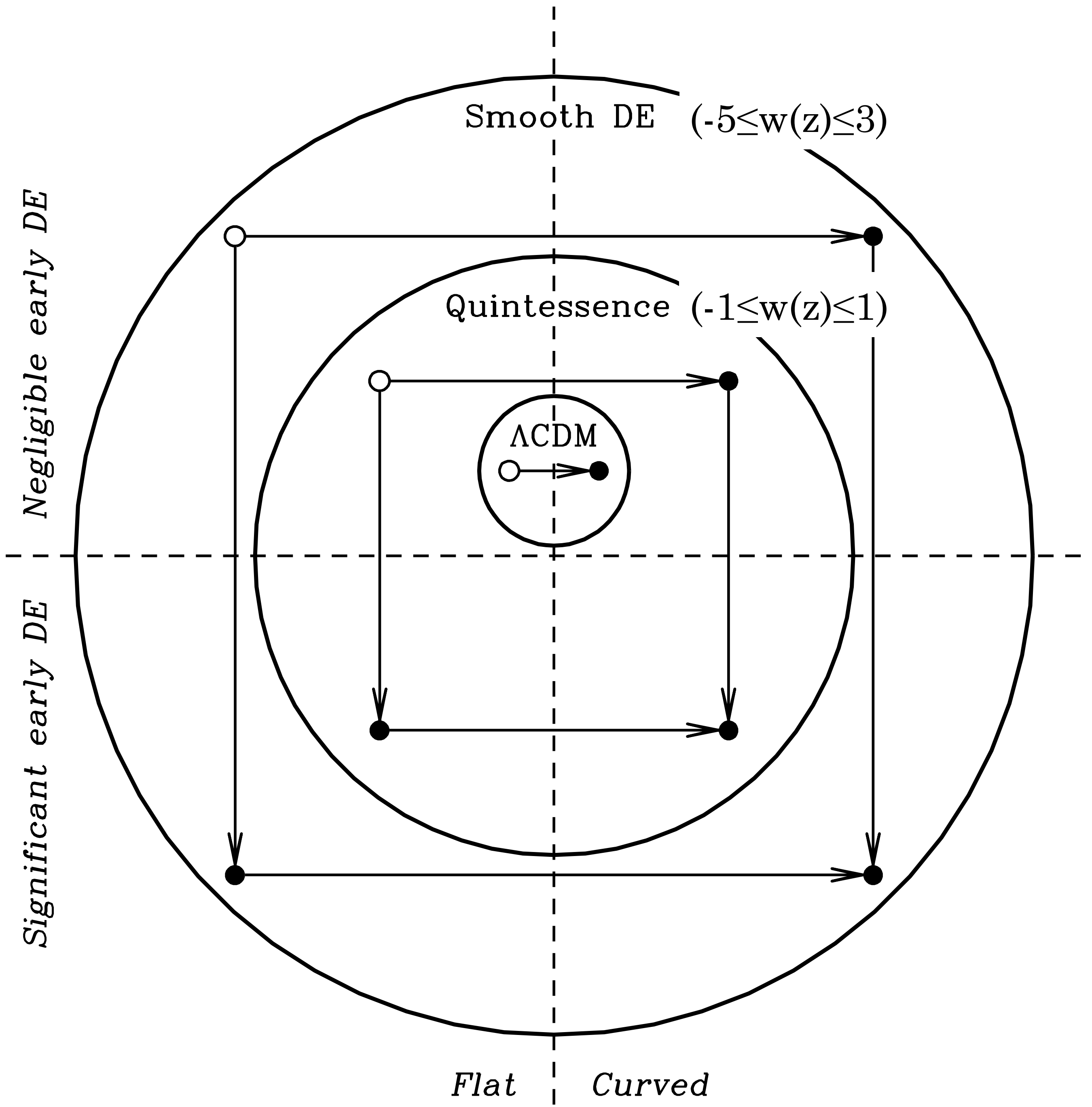


$$\rho_{\mathrm{DE}}(z) = \Omega_{\mathrm{DE}}\,\rho_{\mathrm{crit}}\,(1+z)^{3(1+w)}$$

Underlying Philosophy

- The data are now consistent with LCDM, but that may change.
- So, what observational strategies do we use to determine which violation of Occam's Razor has the nature served us?
- Possible alternatives: $w(z) \neq -1$, early DE, curvature $\neq 0$, modified gravity, more than one of the above (?!)
- Goal: to calculate predicted ranges in fundamental cosmological functions D(z), H(z), G(z), (and any other parameters/functions of interest), given current or future observations
- ... and therefore to provide 'target' quantities/redshifts for ruling out classes of DE models with upcoming data (BigBOSS, DES, LSST, space mission, ...)

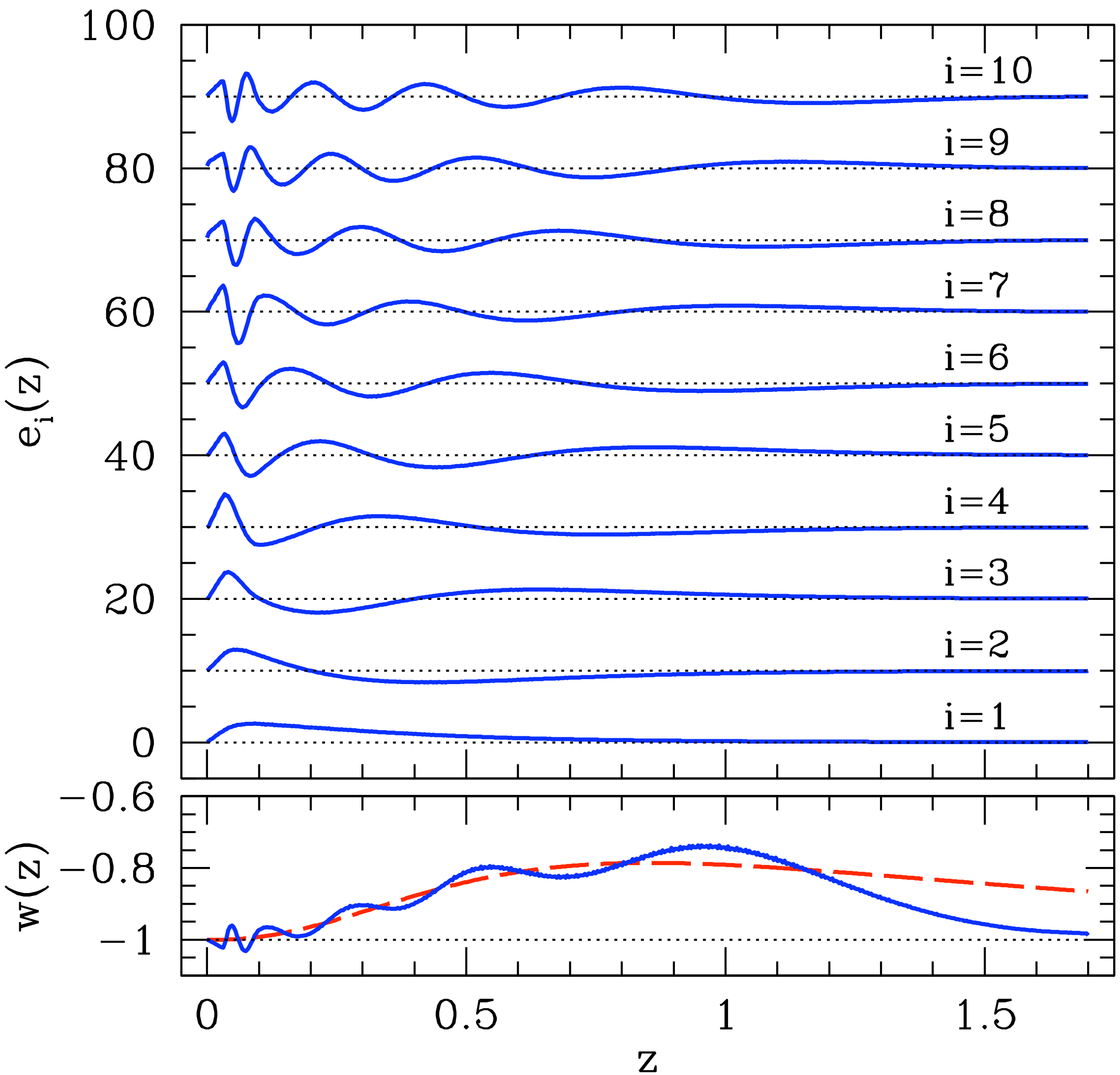
DE Models and their complexity



Modeling of DE

Modeling of low-z w(z):
Principal Components

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



500 bins (so 500 PCs)
0.03<z<1.7

We use first ~10 PCs;
(results converge 10→15)

Fit of a quintessence model with PCs

Modeling of Early DE

(de Putter & Linder 2008)

$$\rho_{\rm DE}(z > z_{\rm max}) = \rho_{\rm DE}(z_{\rm max}) \left(\frac{1+z}{1+z_{\rm max}}\right)^{3(1+w_\infty)}$$

Early DE - current constraints

- $\Omega_{DE}(z_{rec})$ <0.03 (CMB peaks; Doran, Robbers & Wetterich 2007)
- $\Omega_{DE}(z_{BBN})$<0.05 (BBN; Bean, Hansen & Melchiorri 2001)

Modeling of Modified Gravity

(Linder 2005)

$$G(a) = \exp\left(\int_0^a d\ln a' \, [\Omega_M^\gamma(a') - 1]\right)$$

Advantage: $\gamma \approx 0.55$ for any GR model (small corrections for $w(z) \neq -1$)

Advantage: extremely easy to implement

Disadvantage: actual MG growth may be scale-dependent

Methodology

1. Start with the parameter set:

$$\Omega_{\rm M}, \Omega_{\rm K}, H_0, w(z), w_\infty$$

2. Use either the current data or future data

3. Employ the likelihood machine

Markov Chain Monte Carlo likelihood calculation, between ~2 and ~15 parameters constrained

4. Compute predictions for D(z), G(z), H(z) (and γ(z), f(z))

Cosmological Functions

Expansion Rate (BAO):

$$H(z) = H_0 \left[\Omega_{\rm M}(1+z)^3 + \Omega_{\rm DE}\frac{\rho_{\rm DE}(z)}{\rho_{\rm DE}(0)} + \Omega_{\rm K}(1+z)^2\right]^{1/2}$$

Distance (SN, BAO, CMB):

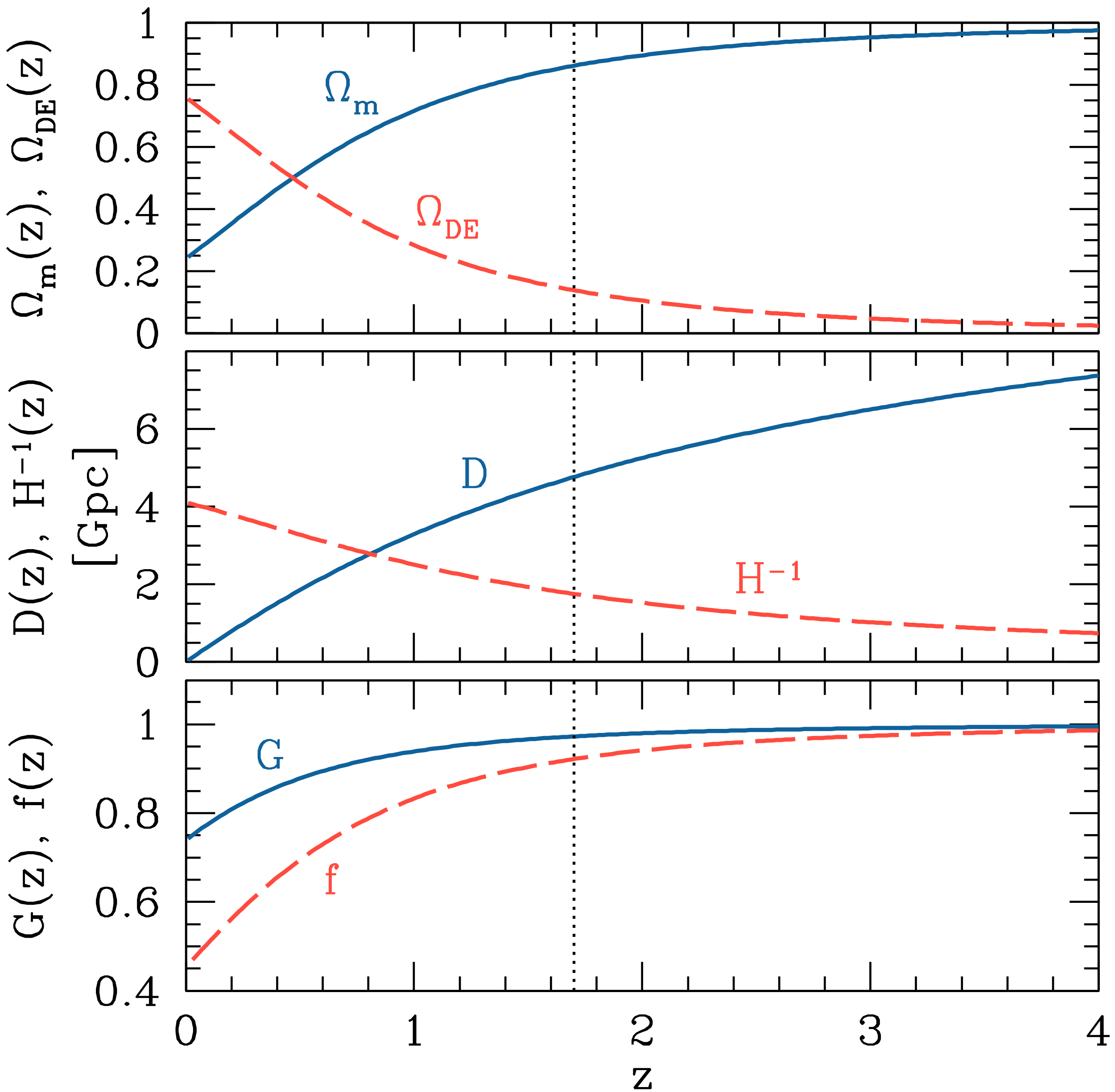
$$D(z) = \frac{1}{(|\Omega_{\rm K}|H_0^2)^{1/2}} S_{\rm K}\left[(|\Omega_{\rm K}|H_0^2)^{1/2}\int_0^z \frac{dz'}{H(z')}\right]$$

Growth (WL, clusters):

$$G'' + \left(4 + \frac{H'}{H}\right)G' + \left[3 + \frac{H'}{H} - \frac{3}{2}\Omega_{\rm M}(z)\right]G = 0$$

$$G = D_1/a$$

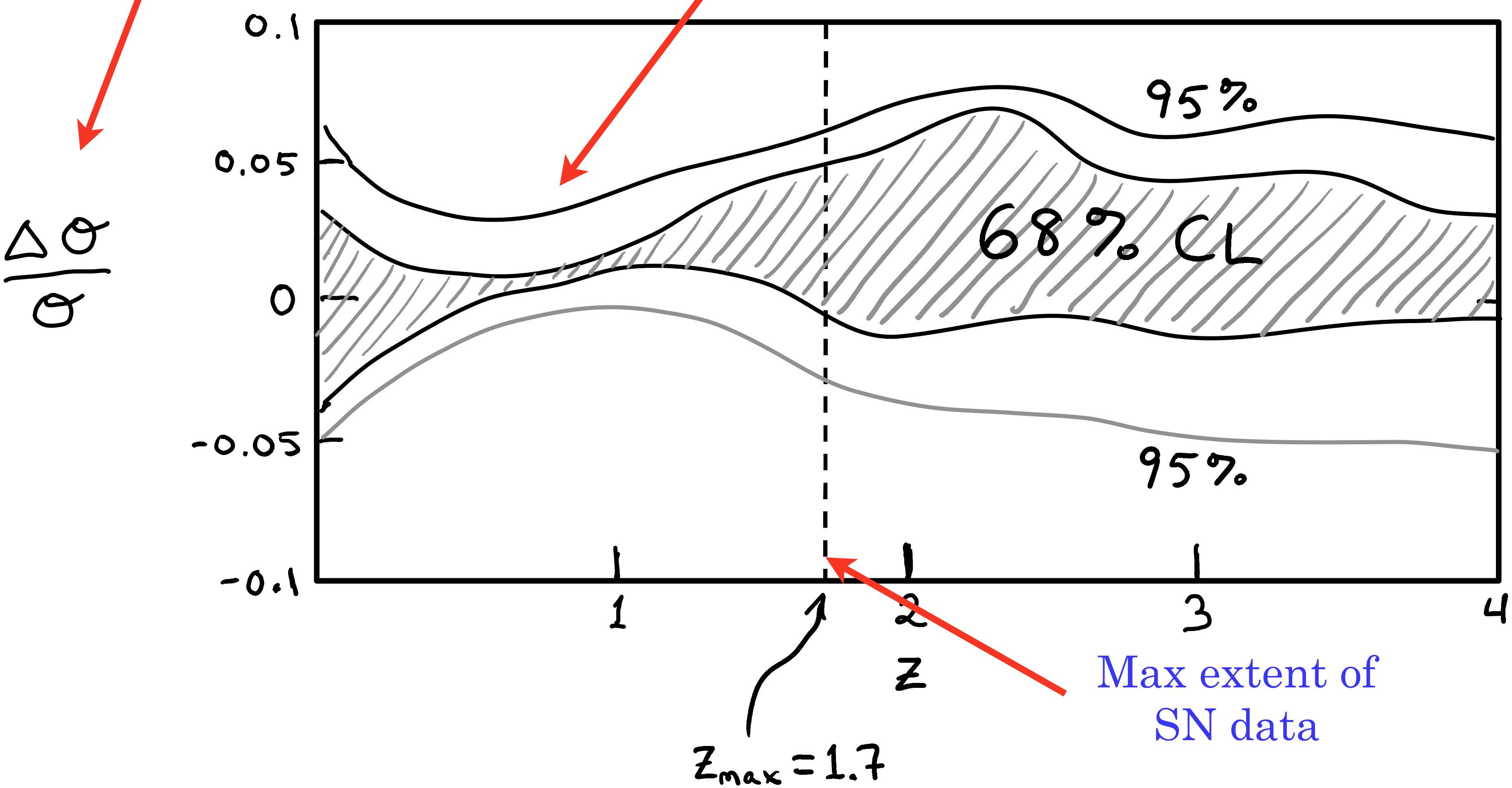
Cosmological Functions



Structure of graphs to follow

Prediction on observable (given data) by SNe+CMB (around fiducial, or best-fit)

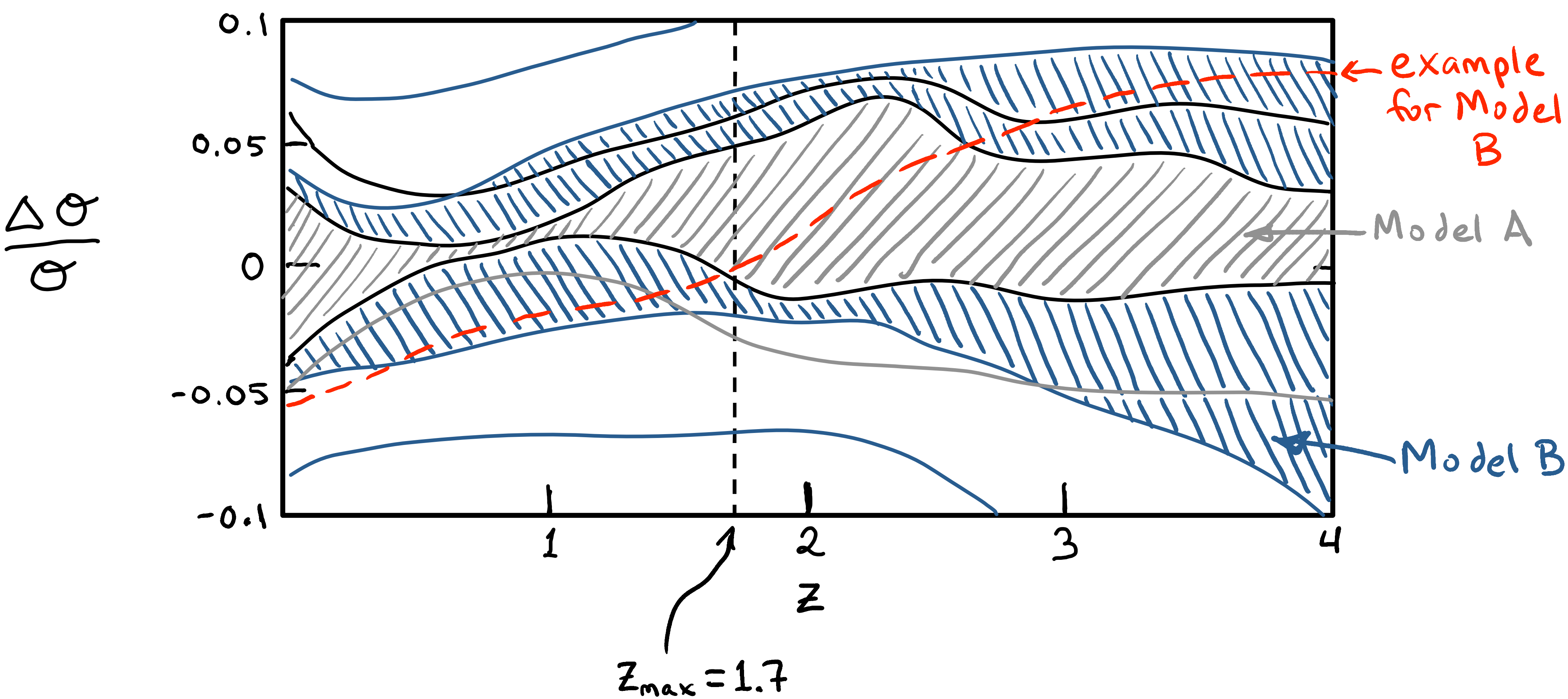
Pivot



Max extent of SN data

Sketch by M. Mortonson

Structure of graphs to follow

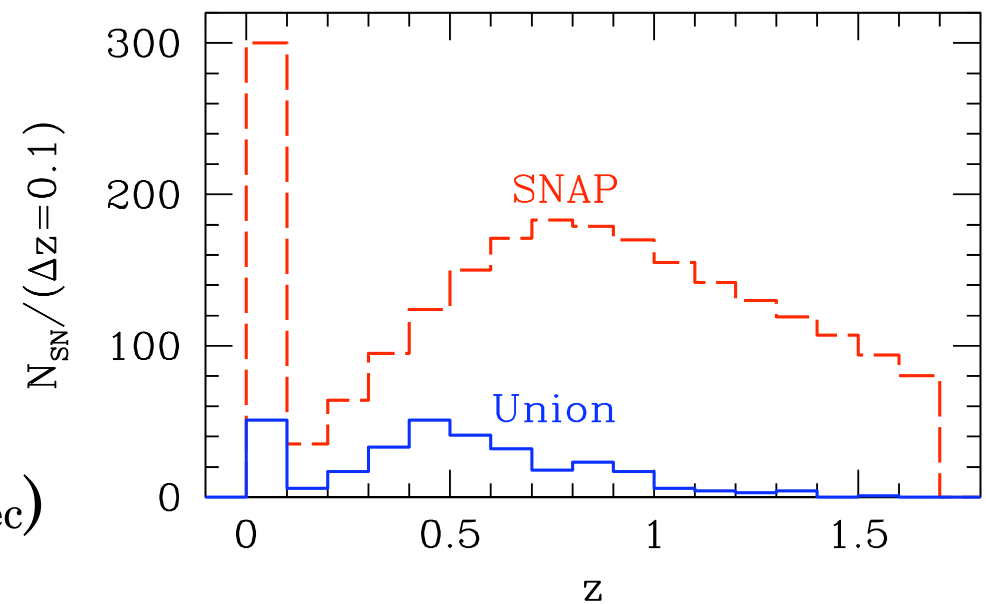


Sketch by M. Mortonson

Predictions from Future Data

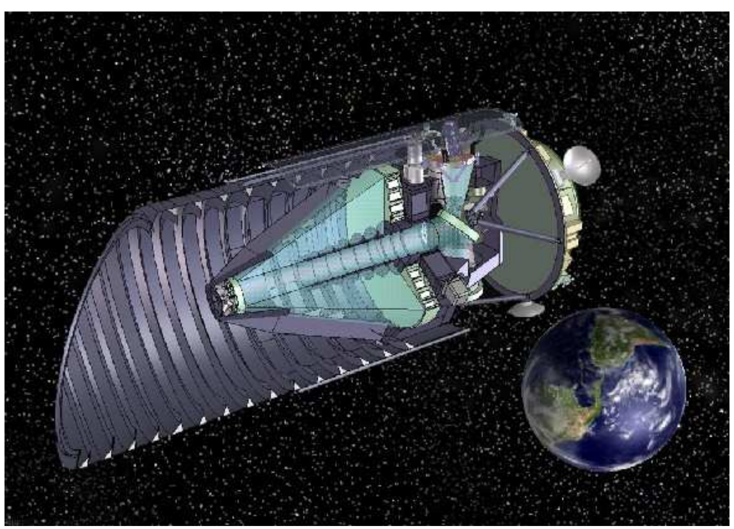
Assumed "data":

1. SNAP 2000 SNe, 0.1<z<1.7
   (plus 300 low-z SNe);
   converted into distances
2. Planck info on $\Omega_m h^2$ and $D_A(z_{rec})$



$$\sigma_\alpha^2 = \left(\frac{0.1}{\Delta z_{\rm sub}}\right)\left[\frac{0.15^2}{N_\alpha} + 0.02^2\left(\frac{1+z}{2.7}\right)^2\right]$$

Dead



Alive

Predictions below shown around: fiducial model

Future data

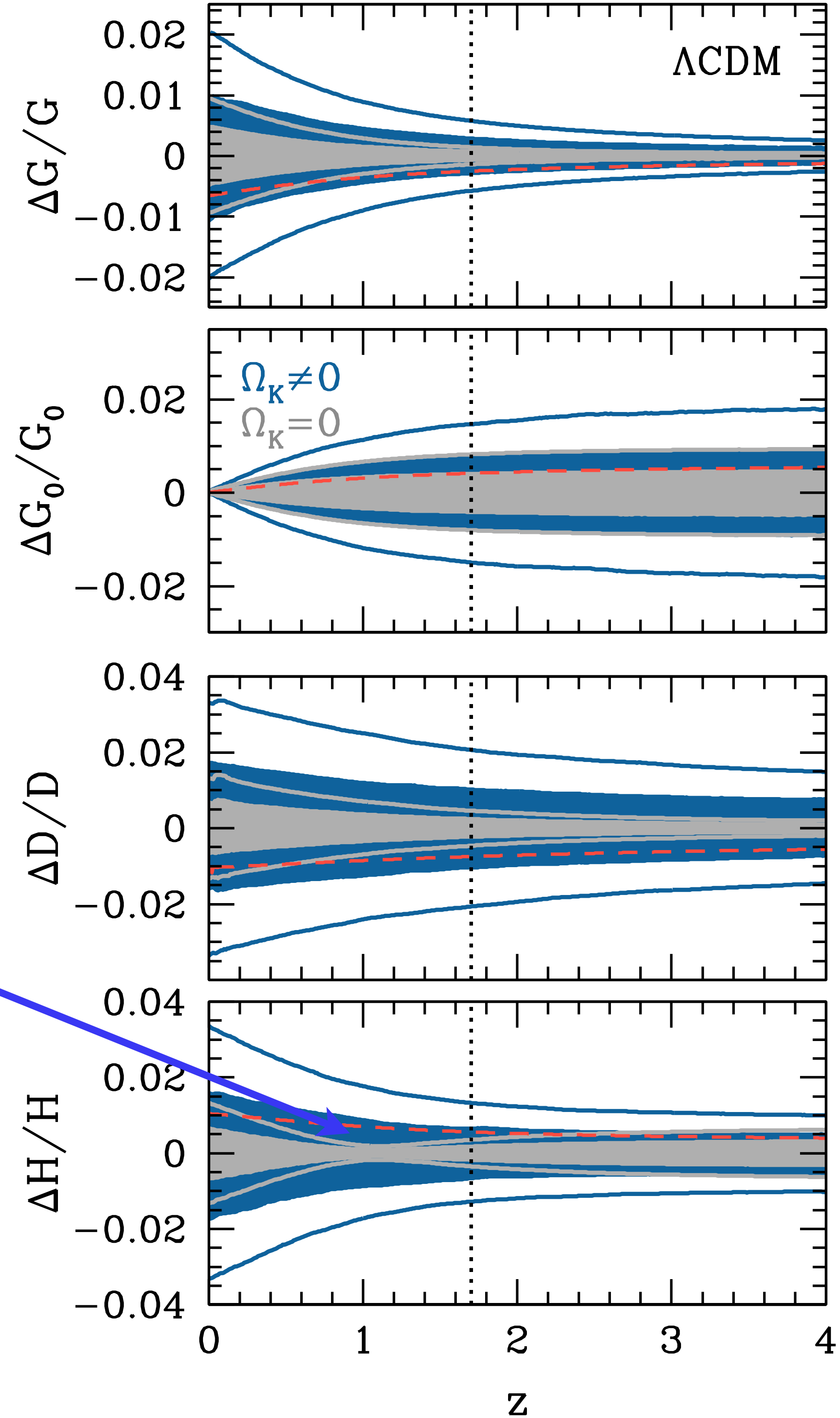
LCDM predictions (flat or curved)

Grey: flat

Blue: curved

D, G to <1% everywhere

H(z=1) to 0.1% for flat LCDM



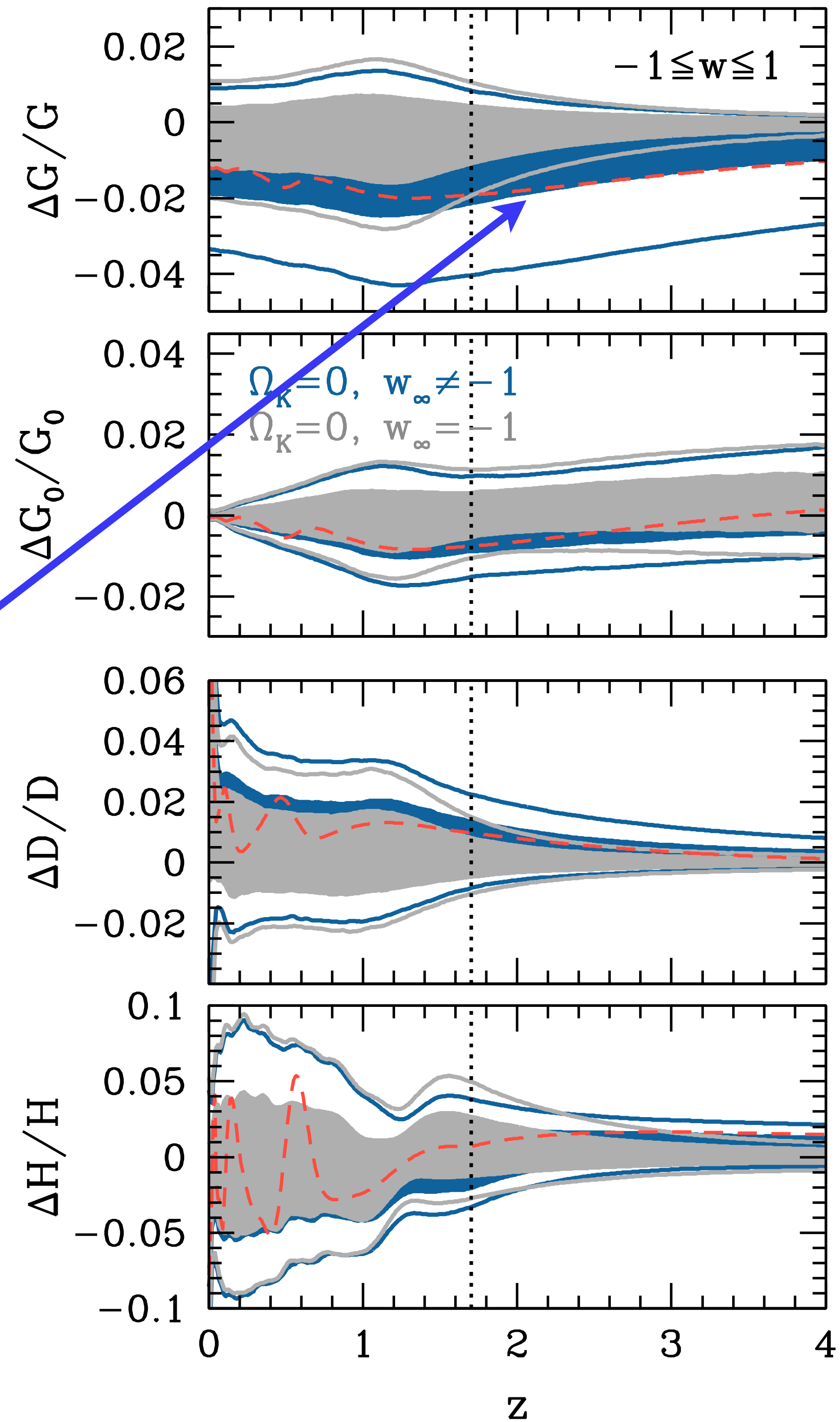
Future data

Quintessence predictions (flat)

Grey: no Early DE

Blue: with Early DE

Smoking Gun of EDE:
Uniform suppression in G

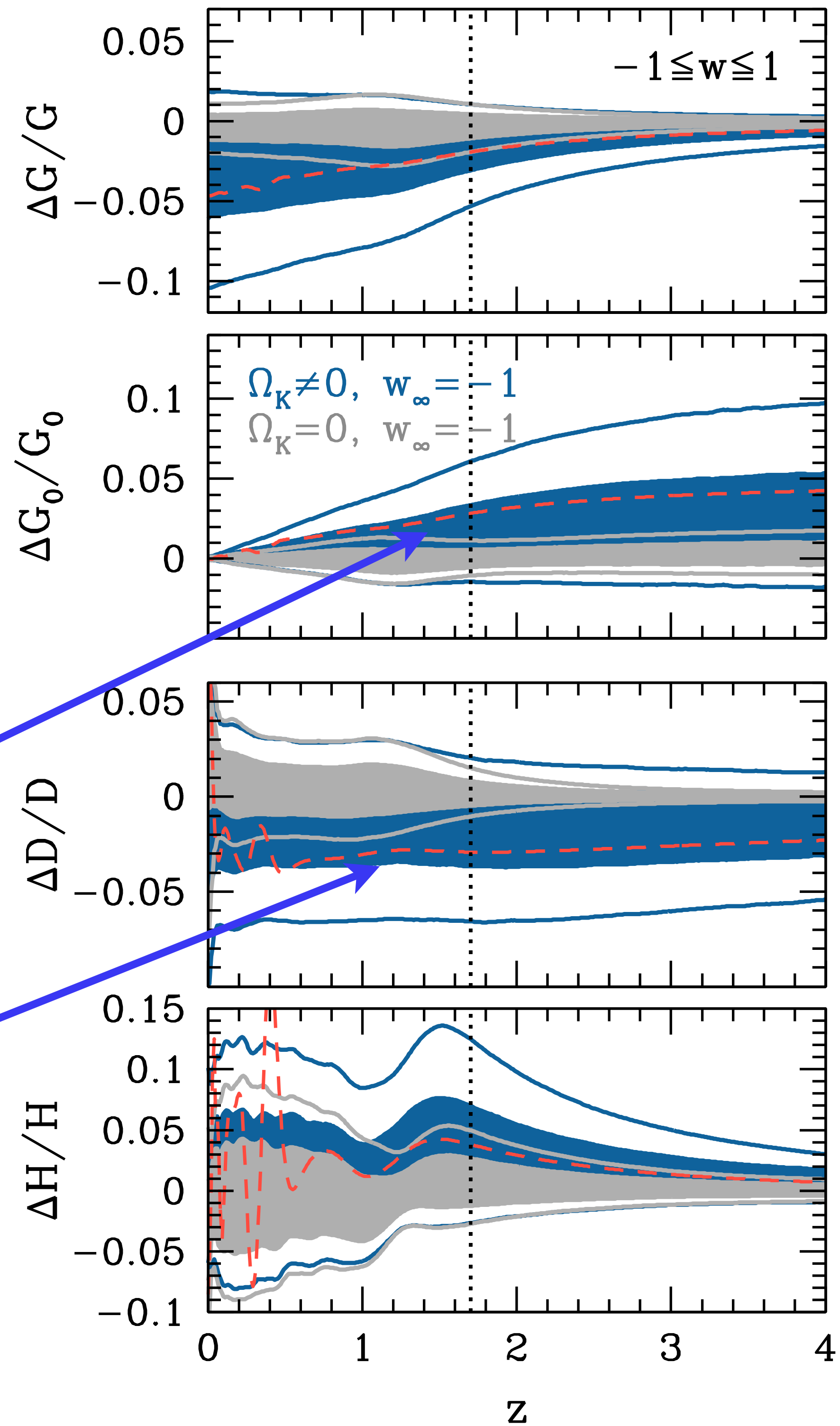


Future data

Quintessence predictions (no EDE)

Grey: flat

Blue: curved



Smoking Gun of curvature:

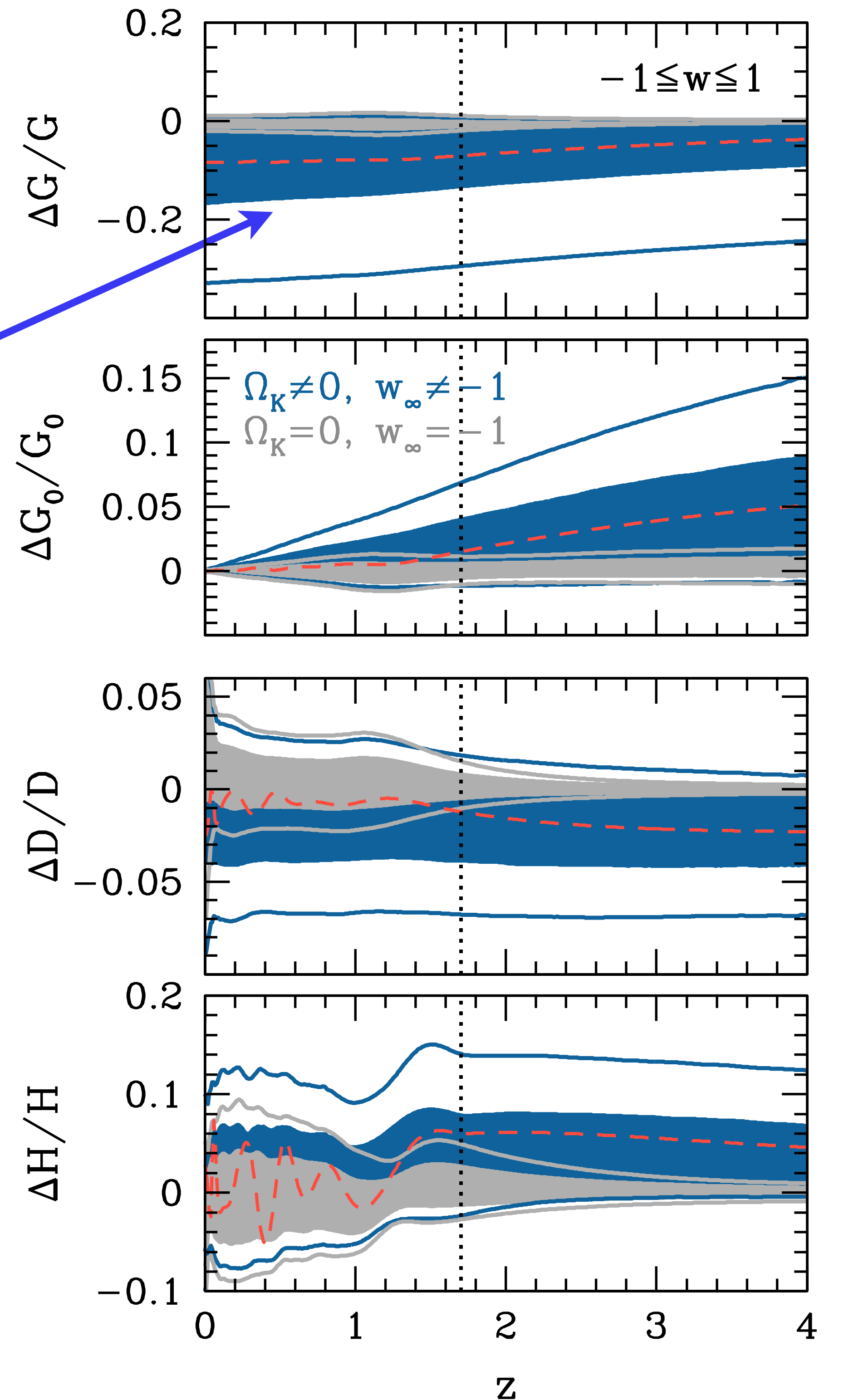
1. Shift in G_0
2. Negative const offset in D

Future data

Quintessence predictions

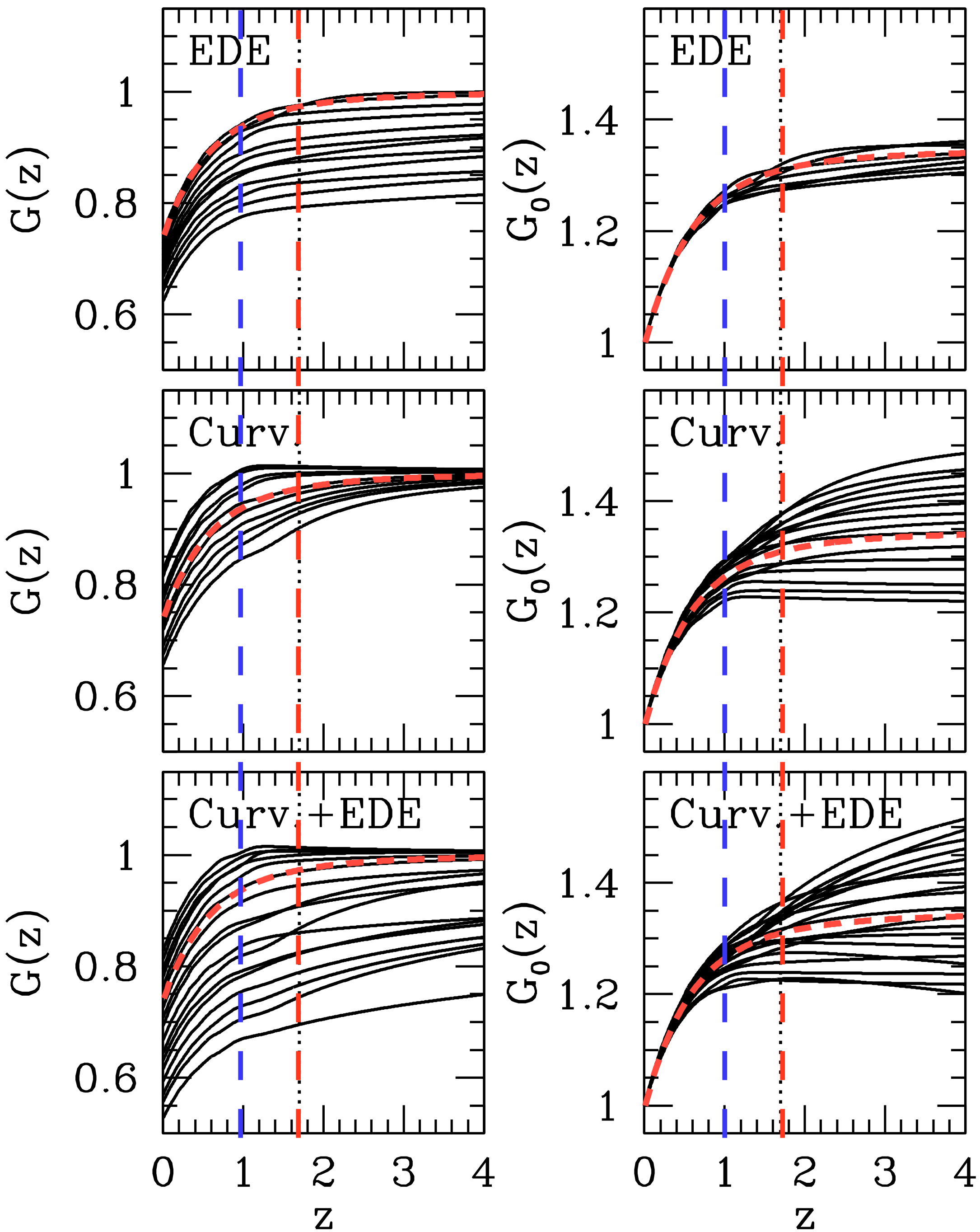
with curvature and EDE

Smoking Gun:
Large negative deviation in G



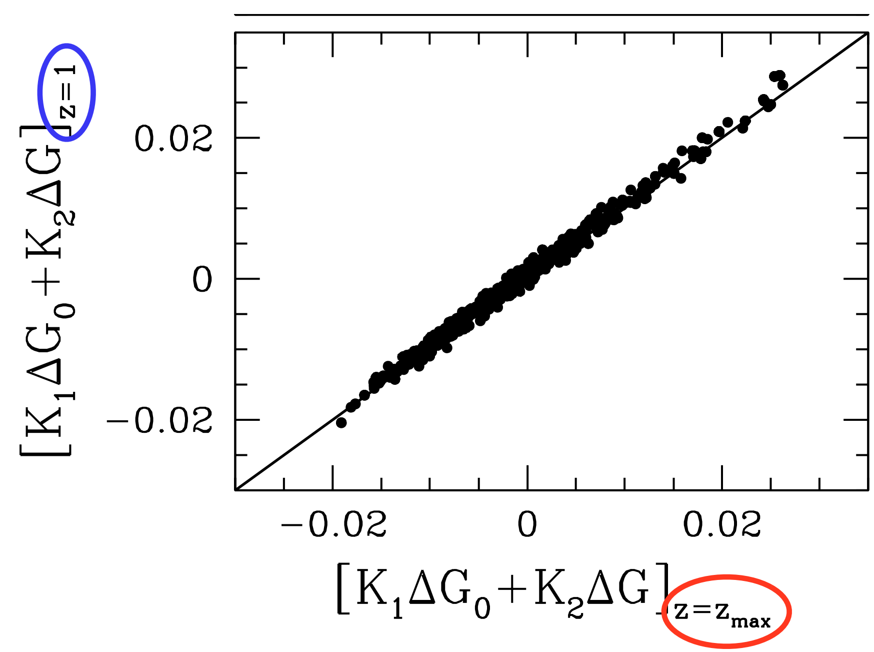
Note even in this general class,
firm predictions: e.g.,
G and D can't be >> LCDM value

Smooth DE with curvature and/or Early DE



Some quantities are accurately predicted even in very general classes of DE models

(e.g. specific linear combination of G_0 and G evaluated at z=1 vs $z=z_{max}$)

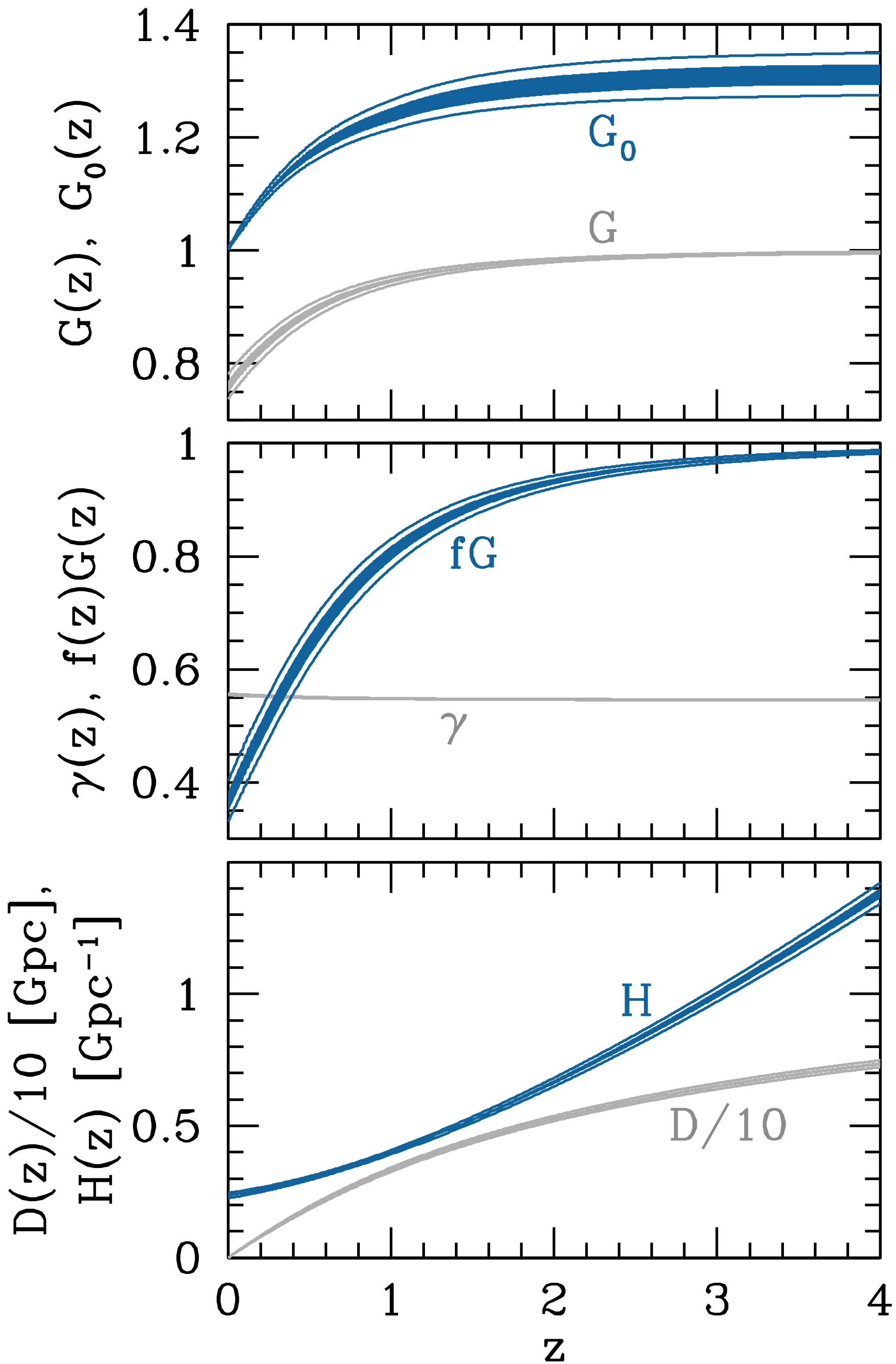


Predictions from **Current** Data

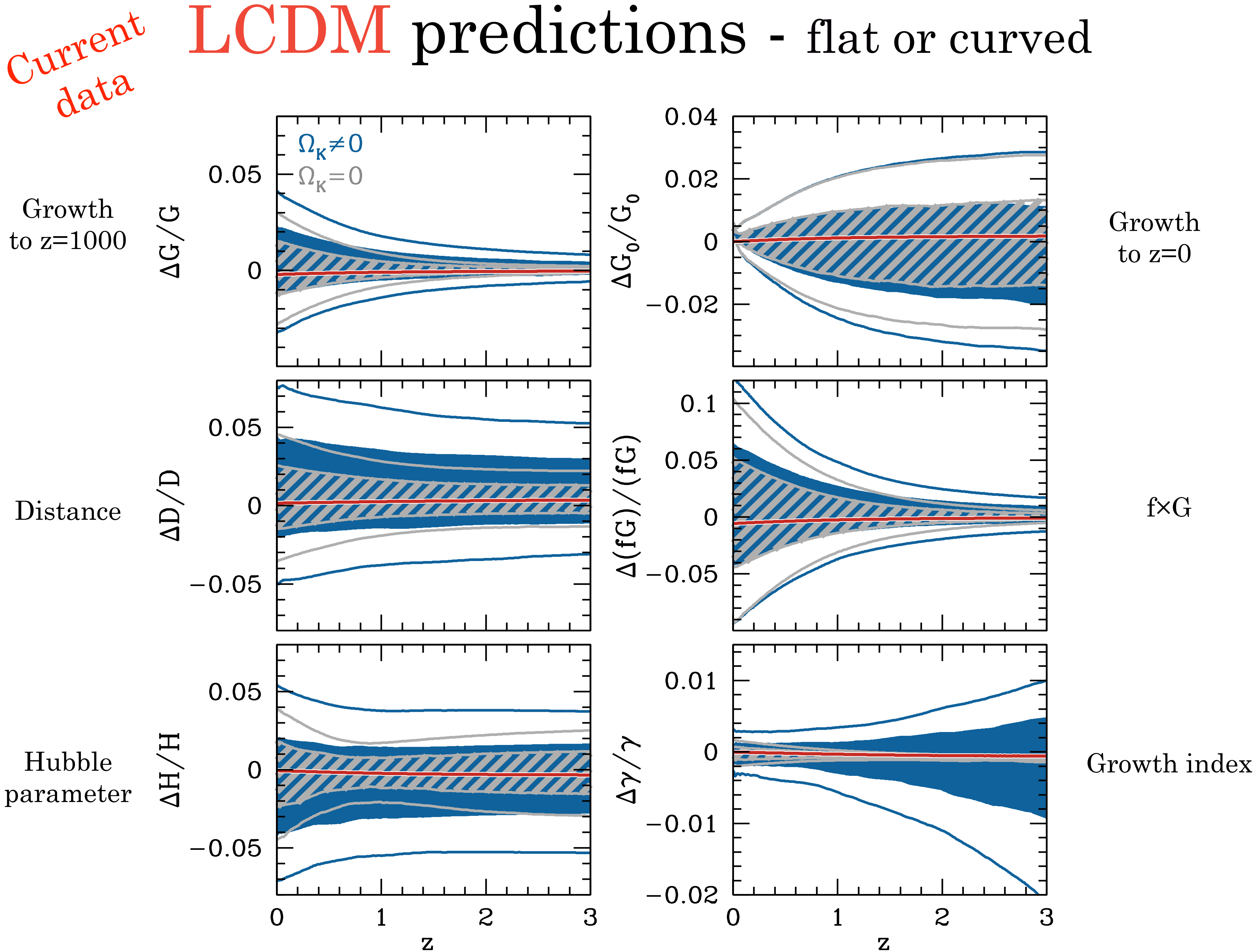
- SN Union compilation
- Full WMAP power spectrum
- $D_{BAO}(z=0.35)$ to ~3% from SDSS (adding 2dF $\Rightarrow$ little diff)
- H_0 from SHOES (Riess et al): (74±3.6) km/s/Mpc; apply at z=0.04

Predictions below shown around:
best-fit LCDM model

Current LCDM (flat, no early DE) predictions

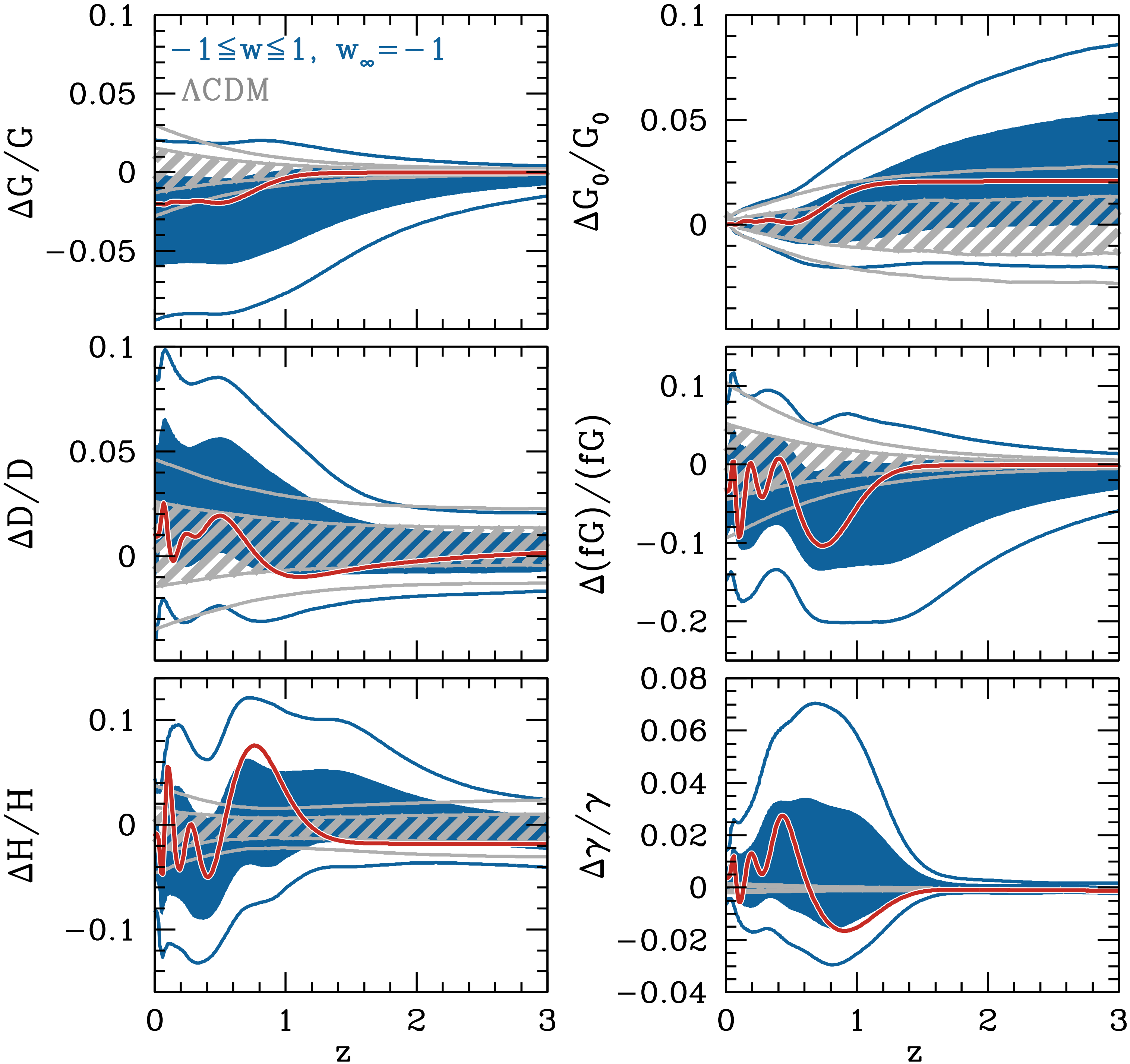


LCDM predictions - flat or curved

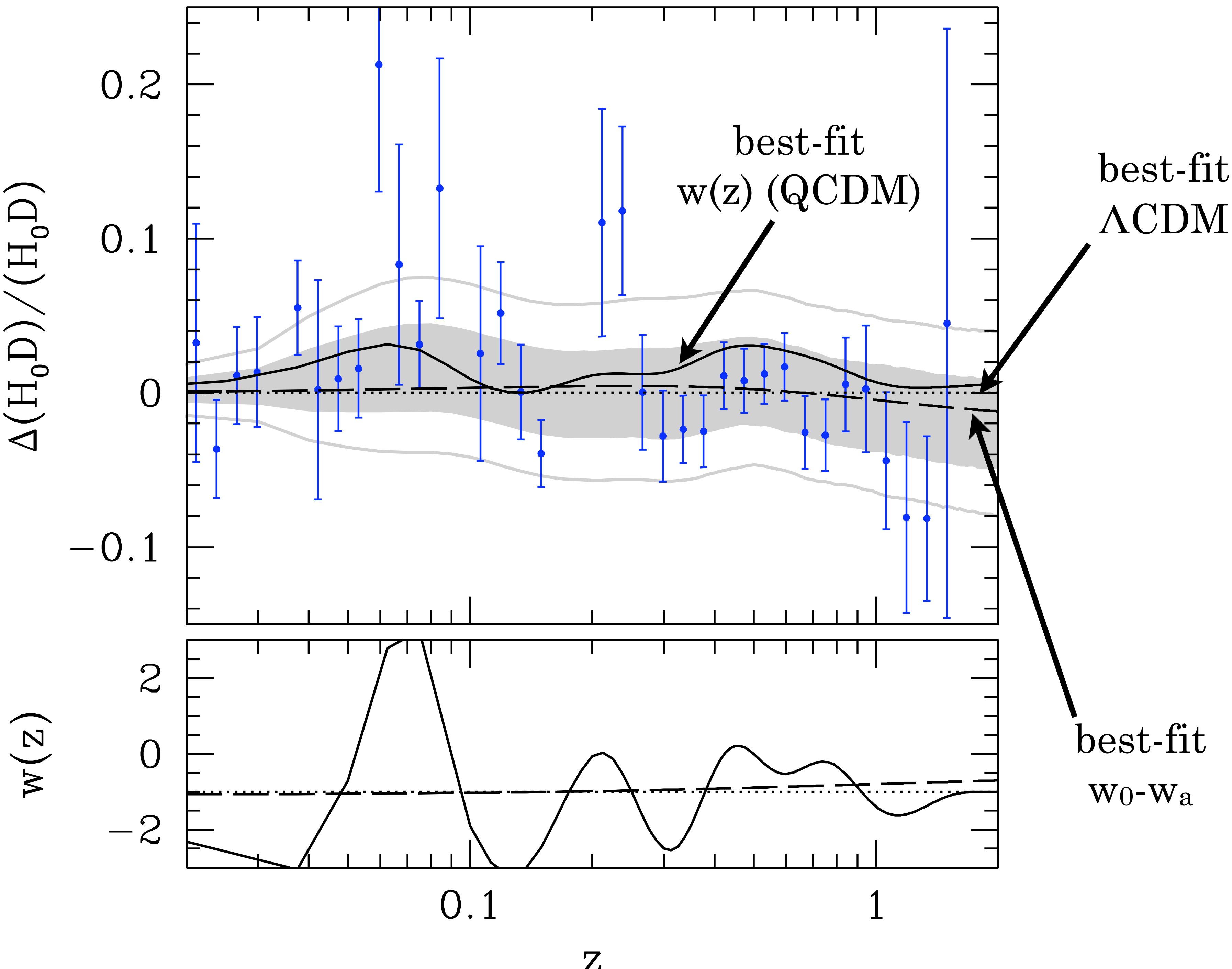


Current data

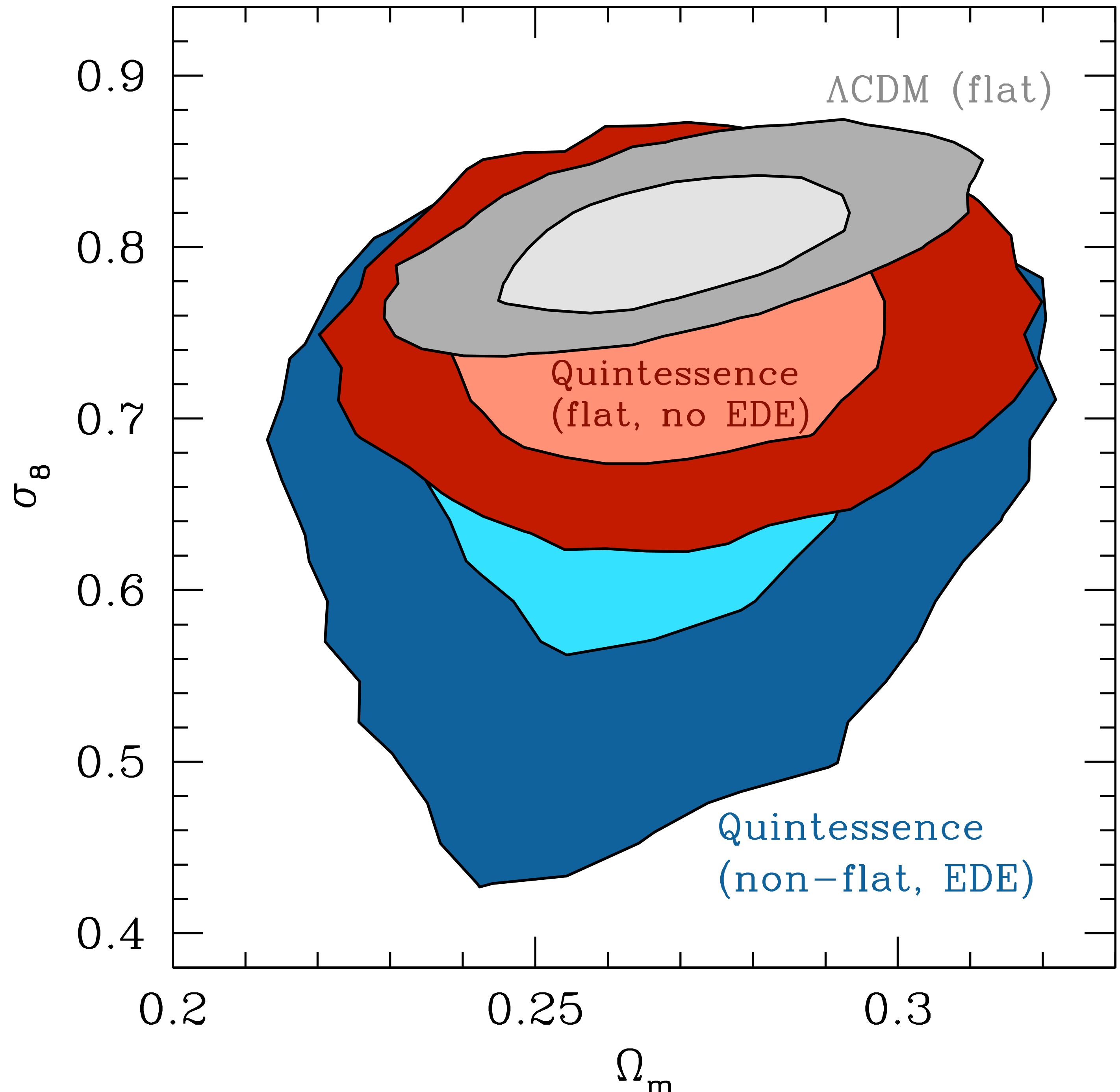
Quintessence predictions (flat, no Early DE)



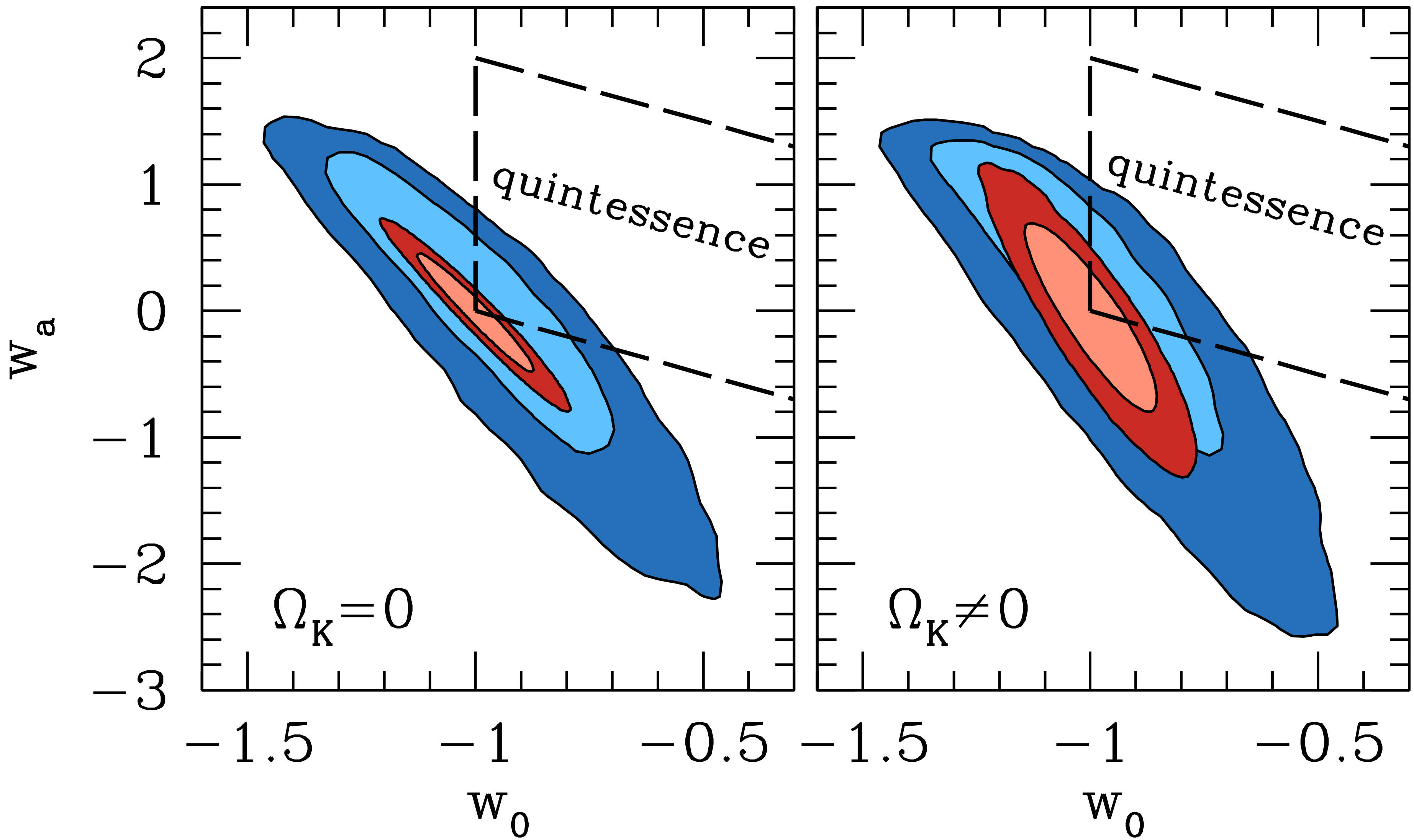
What current data (SN, mostly) prefer



From **current** data, projected down on Ω_M-σ_8



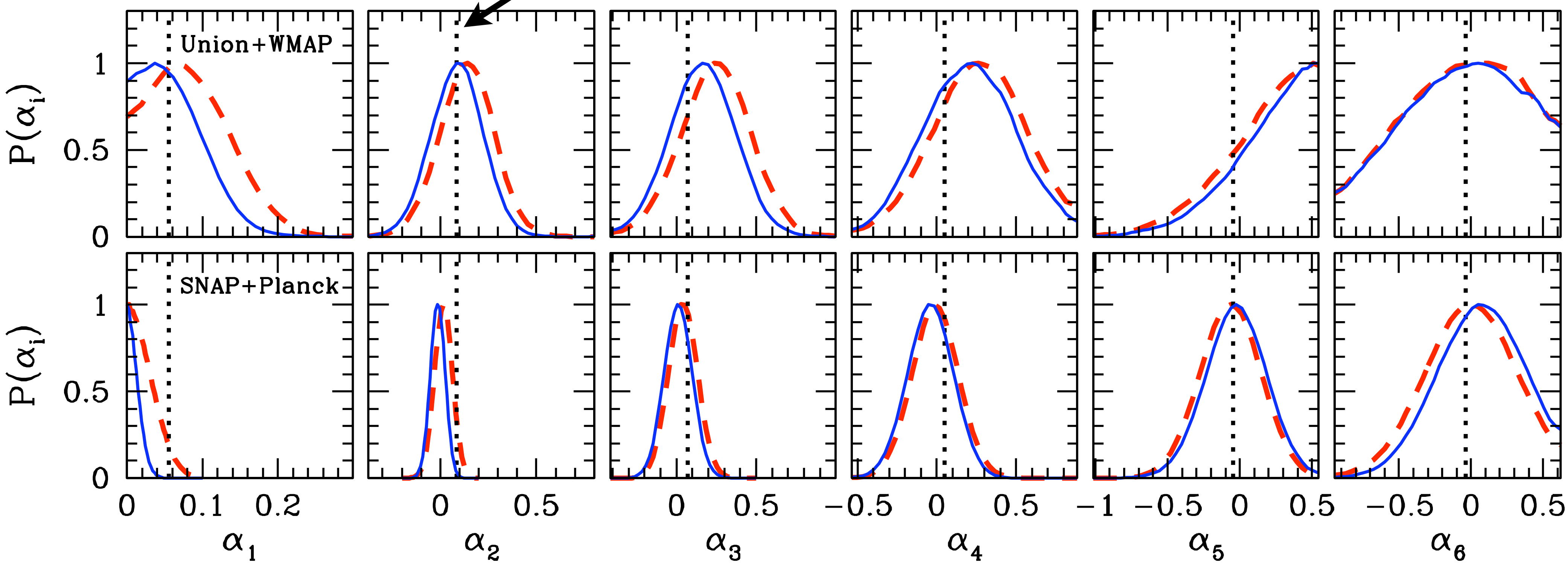
From **current** and **future** data,
projected down on w_0-w_a



In *principal*, constraints are good...
(components)

Top row:
Current Data

values for example quintessence model



Bottom Row:
Future Data
(assumes α_i=0)

Flat

Curved

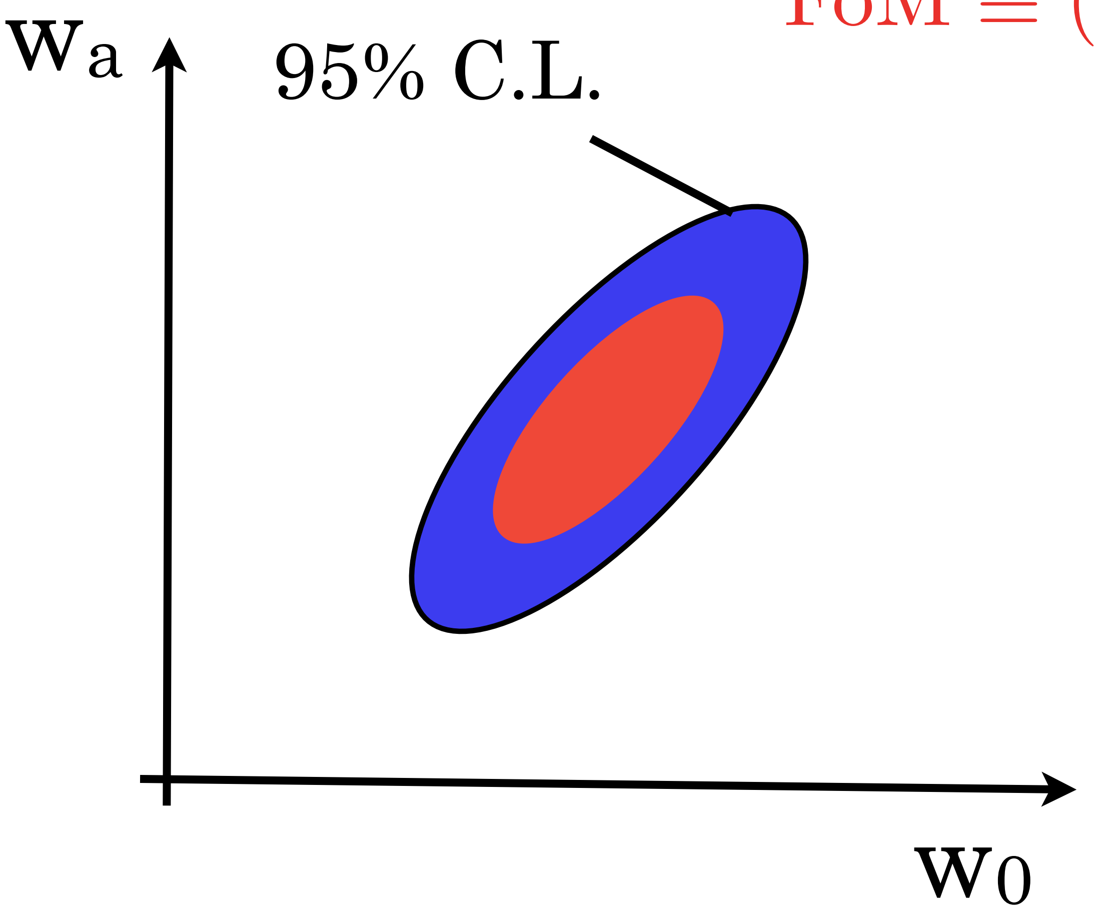
Figures of Merit (FoMs)

The most common choice:

area of the (95%) ellipse in the w_0-w_a plane

(DETF report 2006, Huterer & Turner 2001)

$$\mathrm{FoM} \equiv (\det \mathbf{C}_{\mathbf{w_0 w_a}})^{-1/2} \approx \frac{6.17\pi}{A_{95}}$$



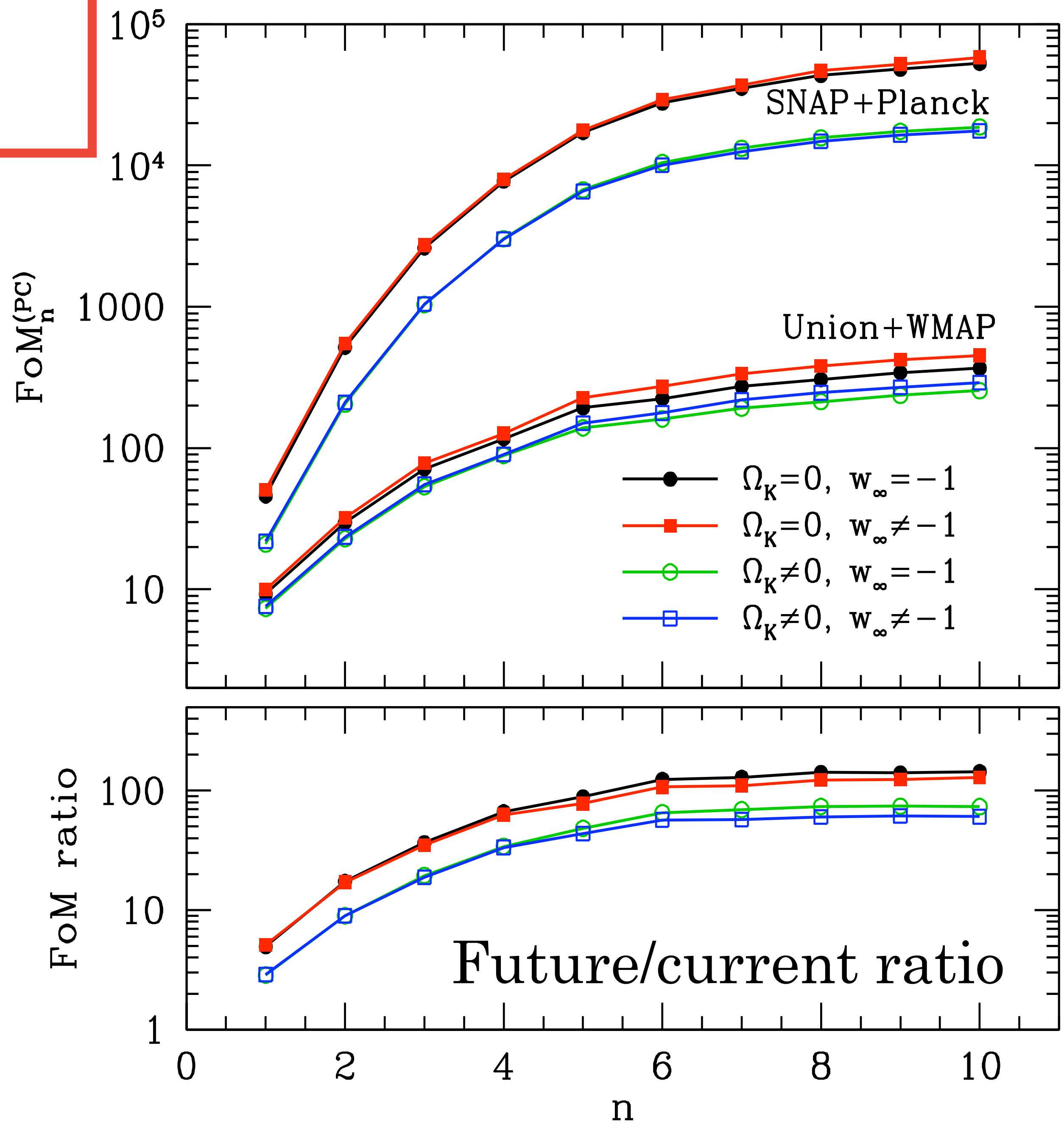
Or, simply:

$$\mathrm{FoM} \equiv \frac{1}{\sigma_{w_{\mathrm{pivot}}} \times \sigma_{w_a}}$$

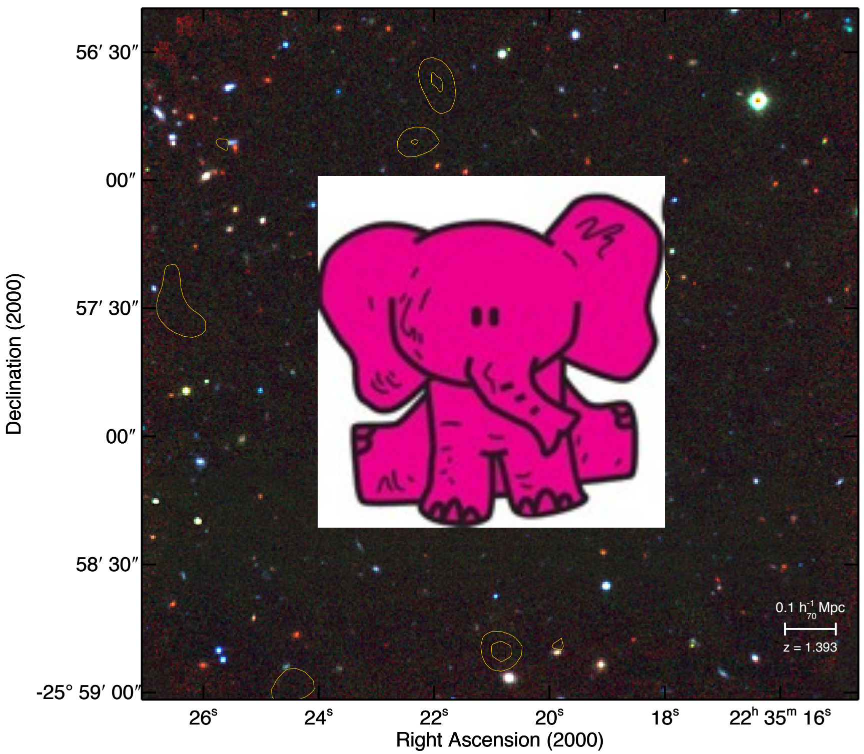
Generalizing FoM to many parameters - PCs of w(z)

$$\mathrm{FoM}_n^{(\mathrm{PC})} \equiv \left(\frac{\det \mathbf{C}_n}{\det \mathbf{C}_n^{(\mathrm{prior})}}\right)^{-1/2}$$

(proportional to volume of n-dim ellipsoid)



Falsifying LCDM and Quintessence with "pink elephant" clusters



Pink Elephant:

- any of various visual hallucinations sometimes experienced as a withdrawal symptom after sustained alcoholic drinking.

-Dictionary.com

Mortonson, Hu & Huterer: arXiv:1004.0236

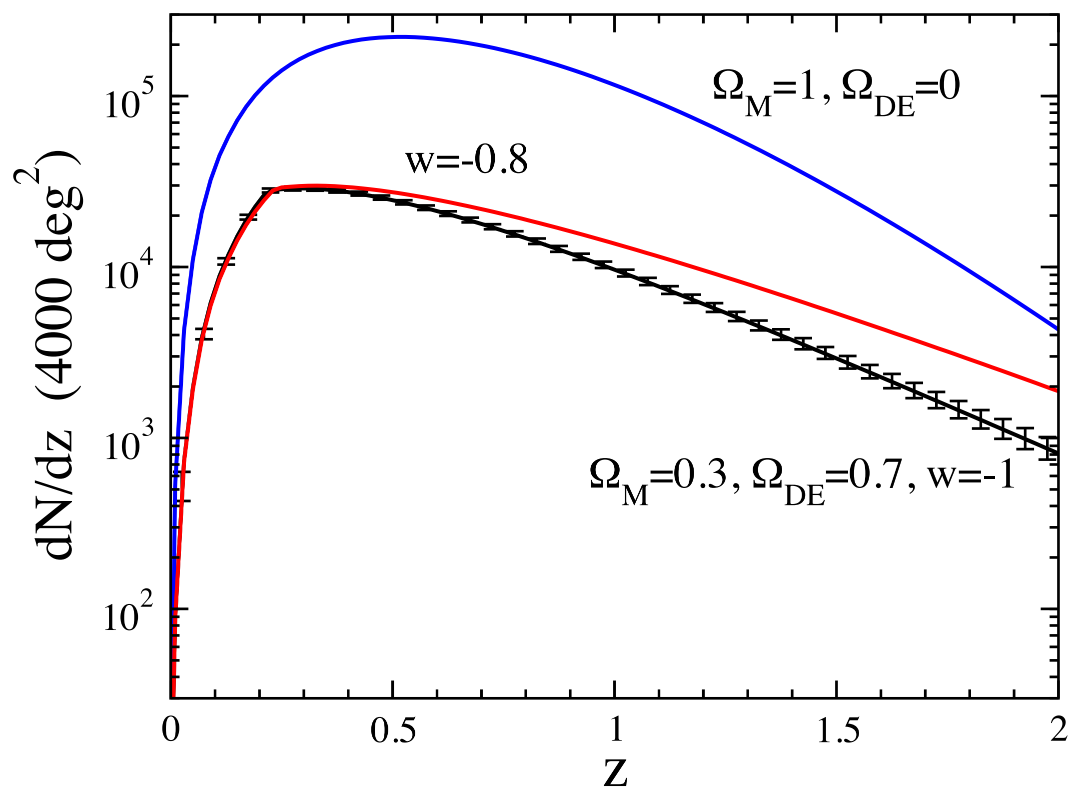
Cluster number counts: basics

mass function;
calibrated from simulations
to ~10% accuracy

$$\frac{d^2N}{d\Omega\, dz} = n(z)\, \frac{r(z)^2}{H(z)}$$

= dV / (dΩdz); exactly
predictable given
a cosmological model

observed



- Essentially fully in the nonlinear regime (scales ~few Mpc)

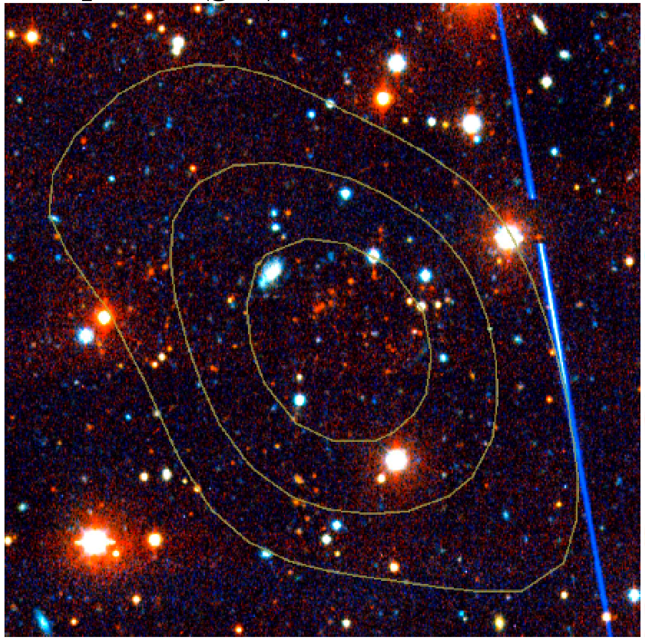
Pink elephant, candidate 1:
SPT-CL J0546-5345

Brodwin et al, arXiv:1006.5639

z=1.067

M ≈ (8±1)·10^{14} M_{sun}

optical (grz); contours are SZ



optical (ri)+IRAC; contours are X-ray

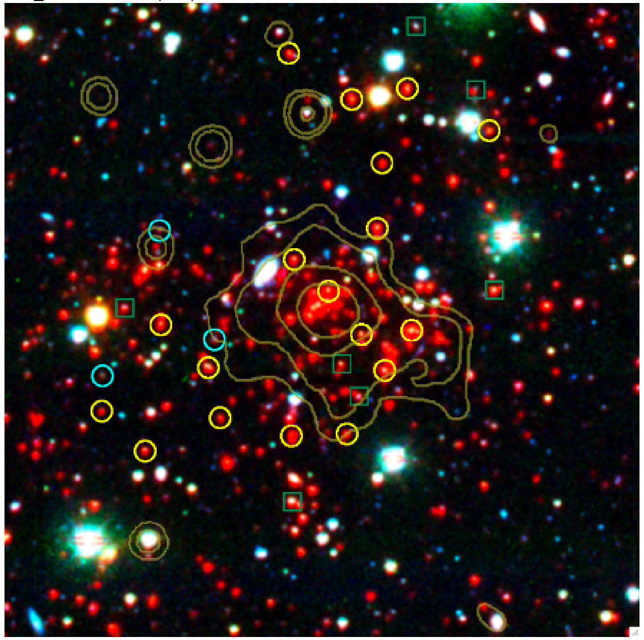


TABLE 2
Comparison of Mass Measurements for SPT-CL J0546-5345

Mass Type	Proxy	Measurement	Units	Mass Scaling Relation	M_{200} [a,b] (10^{14} $M_\odot$)
Dispersion	**Biweight**	1179^{+232}_{-167}	km/s	σ–M_{200} (Evrard et al. 2008)	$\mathbf{10.4^{+6.1}_{-4.4}}$
	Gapper	1170^{+240}_{-128}	km/s	σ–M_{200} (Evrard et al. 2008)	$10.1^{+6.2}_{-3.3}$
	Std Deviation	1138^{+205}_{-132}	km/s	σ–M_{200} (Evrard et al. 2008)	$9.3^{+5.0}_{-3.2}$
X-ray	$\boldsymbol{Y_X}$	5.3 ± 1.0	$\times 10^{14}$ $M_\odot$keV	Y_X–M_{500} (Vikhlinin et al. 2009)	$\mathbf{8.23 \pm 1.21}$
	T_X	$7.5^{+1.7}_{-1.1}$	keV	T_X–M_{500} (Vikhlinin et al. 2009)	8.11 ± 1.89
SZE	$\mathbf{Y_{SZ}}$	3.5 ± 0.6	$\times 10^{14}$ $M_\odot$keV	$Y_{SZ} - M_{500}$ (A10)	$\mathbf{7.19 \pm 1.51}$
	S/N at 150 GHz	7.69		$\xi - M_{500}$ (V10)	$5.03 \pm 1.13 \pm 0.77$
Richness	$\boldsymbol{N_{200}}$	80 ± 31	galaxies	$N_{200} - M_{200}$ (H10)	$\mathbf{8.5 \pm 5.7 \pm 2.5}$
	N_{gal}	66 ± 7	galaxies	$N_{gal} - M_{200}$ (H10)	$9.2 \pm 4.9 \pm 2.7$
Best	**Combined**				$\mathbf{7.95 \pm 0.92}$

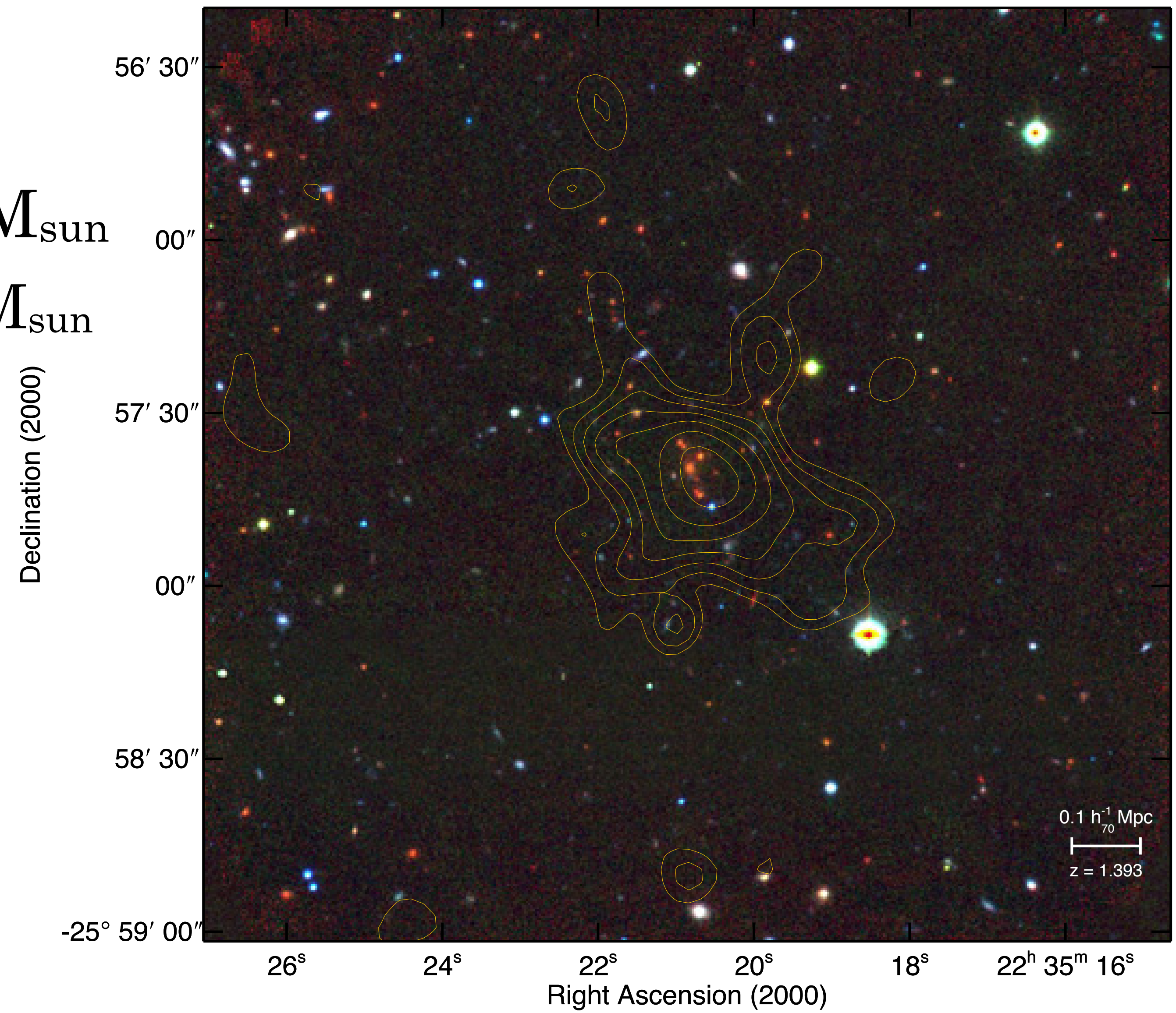
Pink elephant, candidate 2: XMMU J2235.3-2557

Mullis et al, 2005
Jee et al. 2008

$z=1.39$

$M_{x\text{-}ray} \approx (7.7 \pm 4) \cdot 10^{14}\, M_{sun}$

$M_{WL} \approx (8.5 \pm 1.7) \cdot 10^{14}\, M_{sun}$

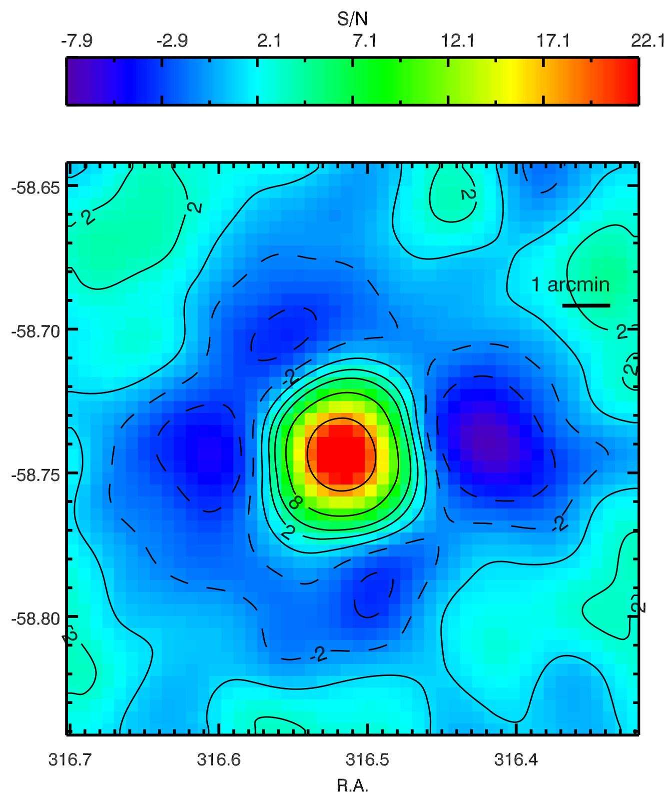


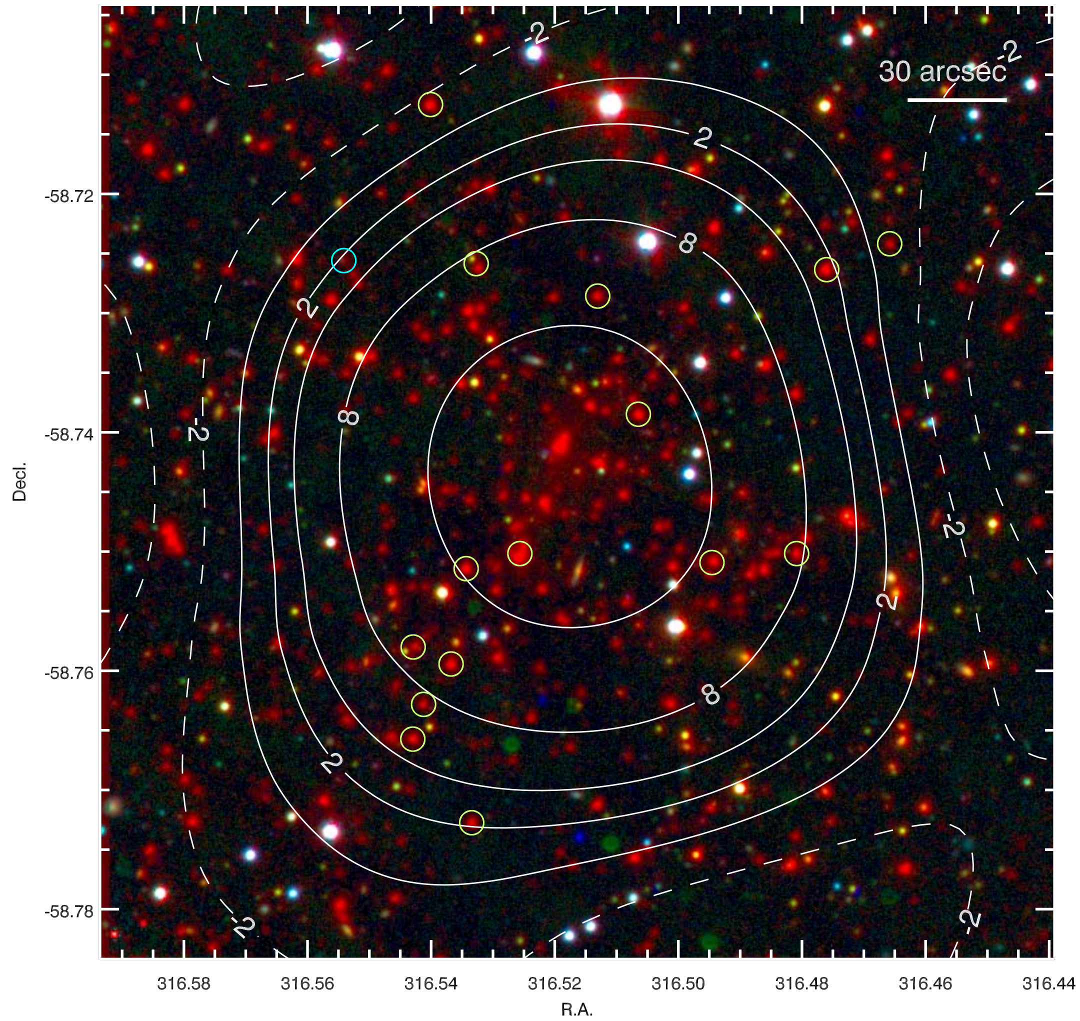
Pink elephant, candidate 3: SPT-CL J2106-5844

$z=1.132$

$M_{SZ+x\text{-}ray} \approx (1.27\pm0.21)\cdot 10^{15}\, M_{sun}$

Foley et al 2011
Williamson et al. 2011





Two sources of statistical uncertainty

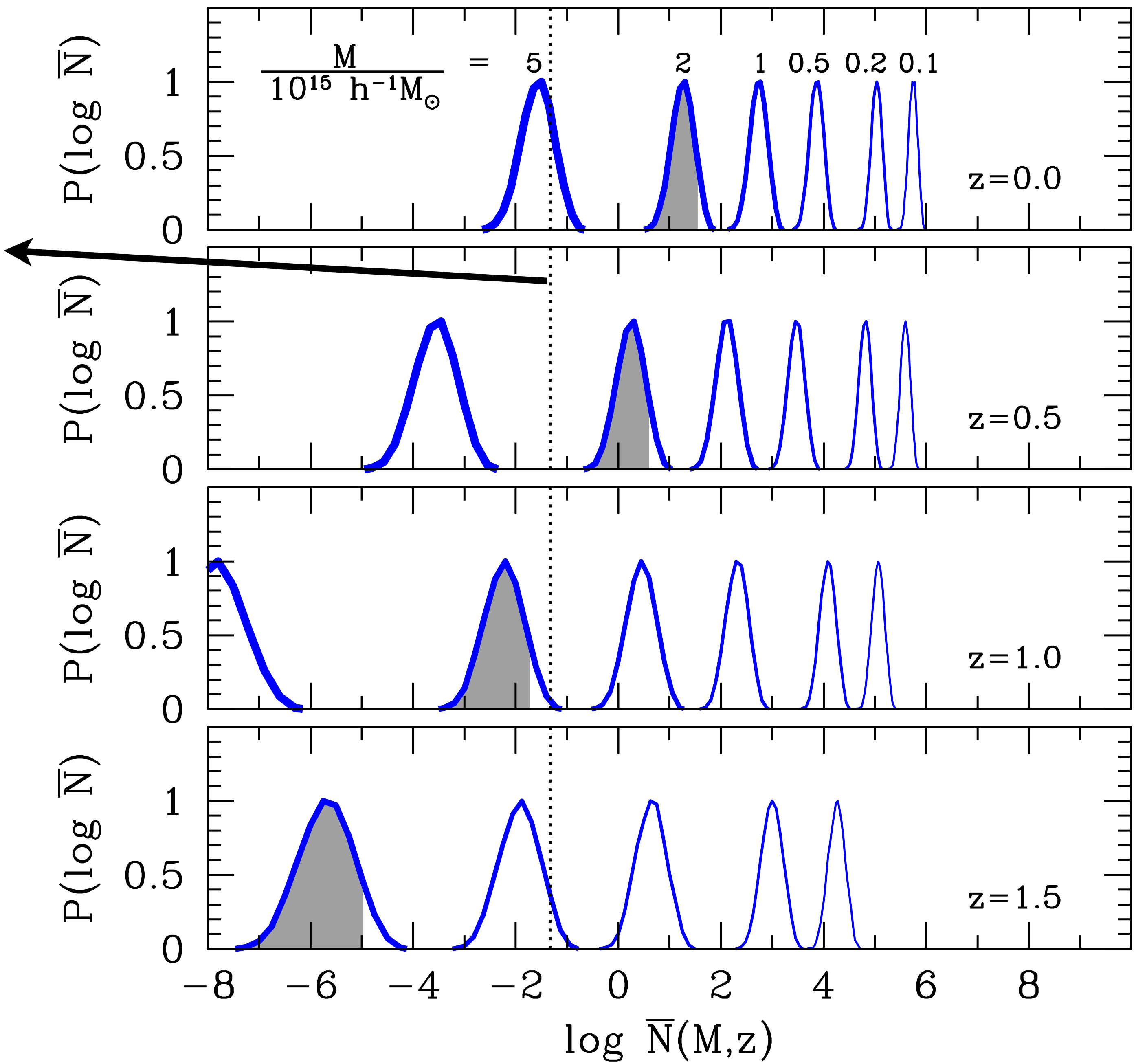
1. **Sample variance** - the Poisson noise in counting rare objects in a finite volume

2. **Parameter variance** - uncertainty due to fact that current data allow cosmological parameters to take a range of values

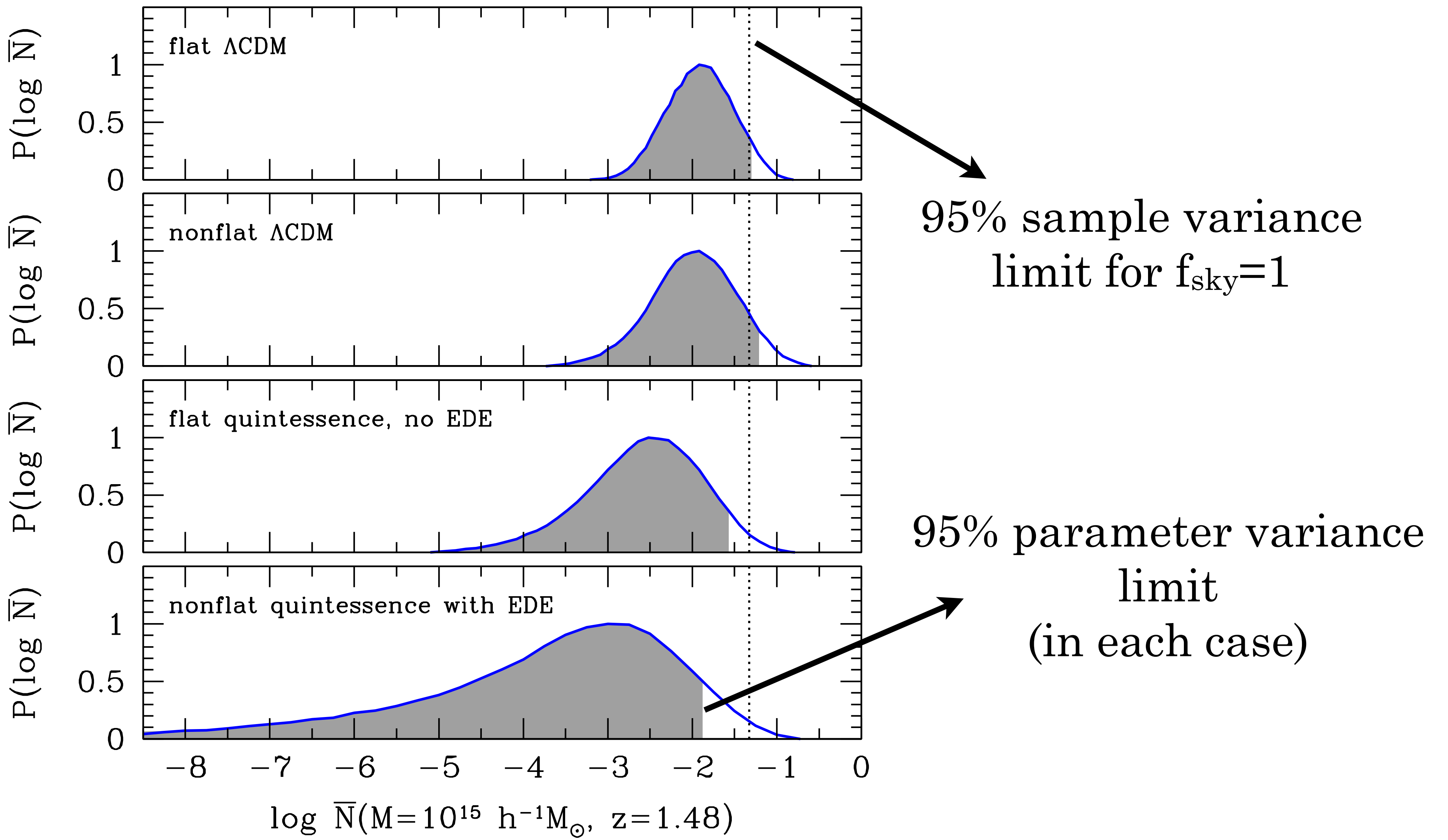
Parameter variance

(due to uncertainty in cosmo parameters)

95% sample variance limit for seeing ≥1 clusters (and for f_{sky}=1)



Predicted abundance for $M > 10^{15} h^{-1} M_{sun}$, $z > 1.48$



Rule out ΛCDM ⇒ automatically rule out quintessence

Eddington bias

A.S. Eddington, MNRAS, 1913

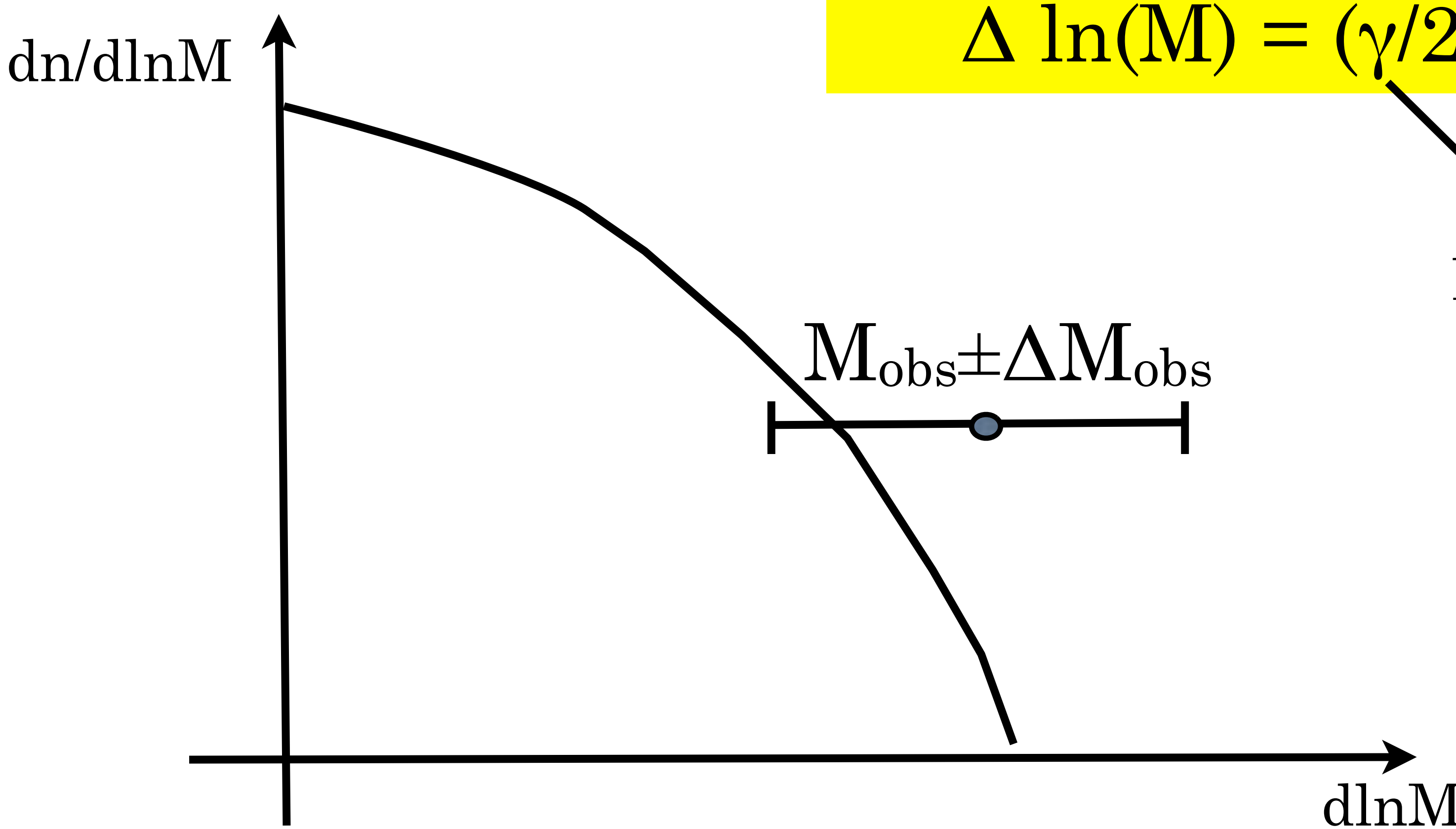
For a steeply falling mass function,

observed mass was more likely to be scattered into observed range from lower M than for higher M

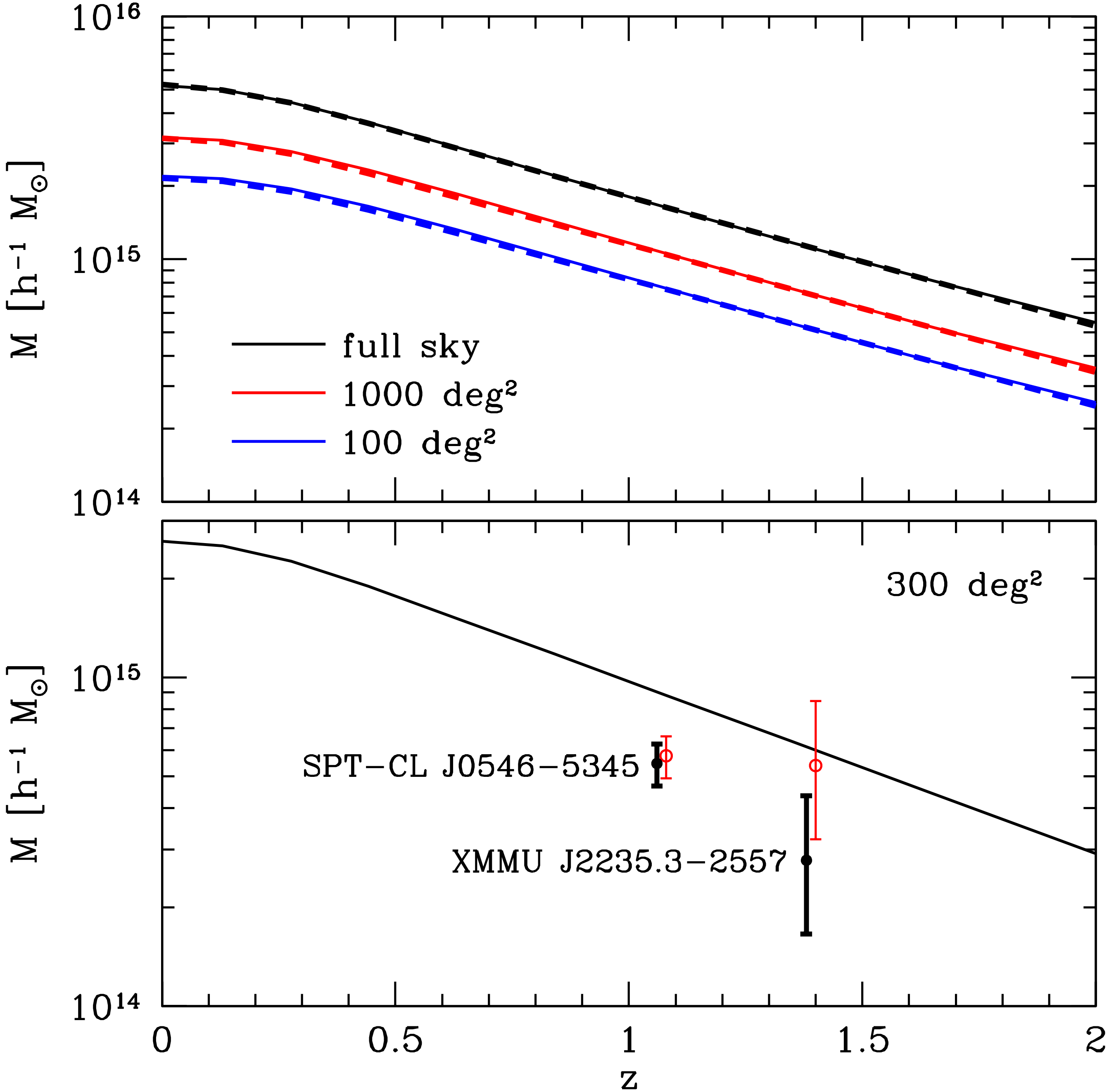
(≠ Malmquist bias: more luminous objects are more likely to scatter into the sample)

$$\Delta \ln(M) = (\gamma/2)\, \sigma_{\ln M}^2$$

γ → log slope of MF



Results for the two pink elephant clusters vs. predictions for LCDM



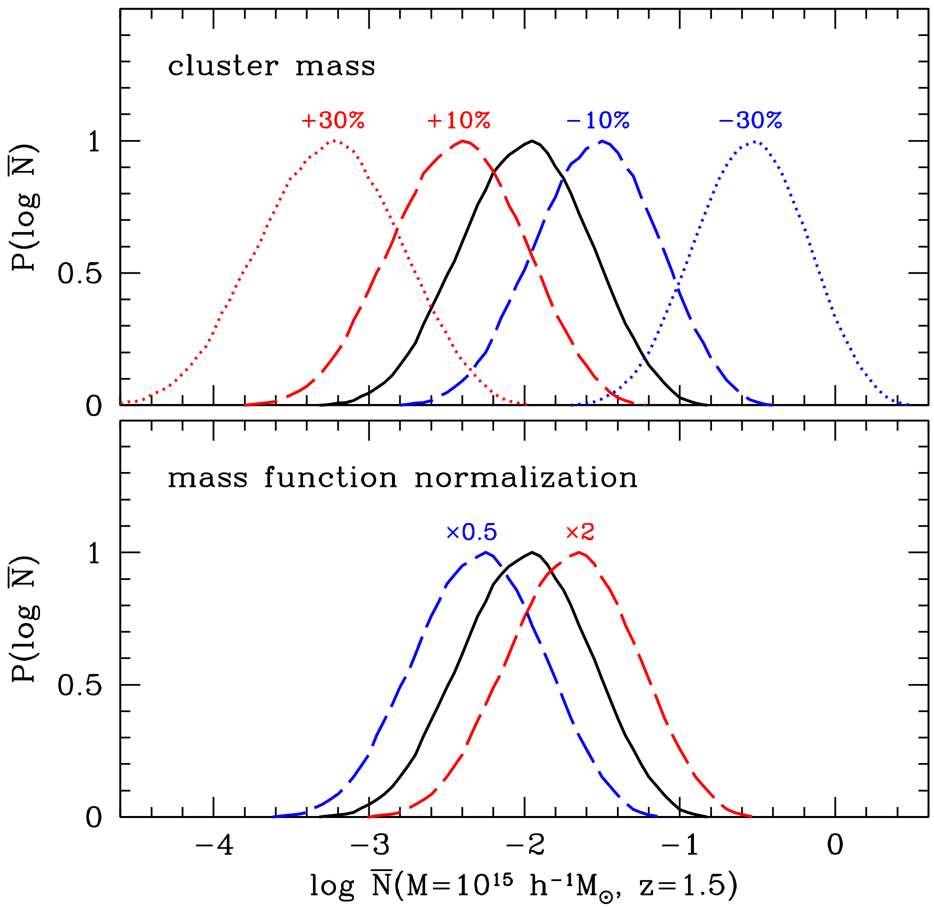
Shown limits: 95% both sample and parameter variance

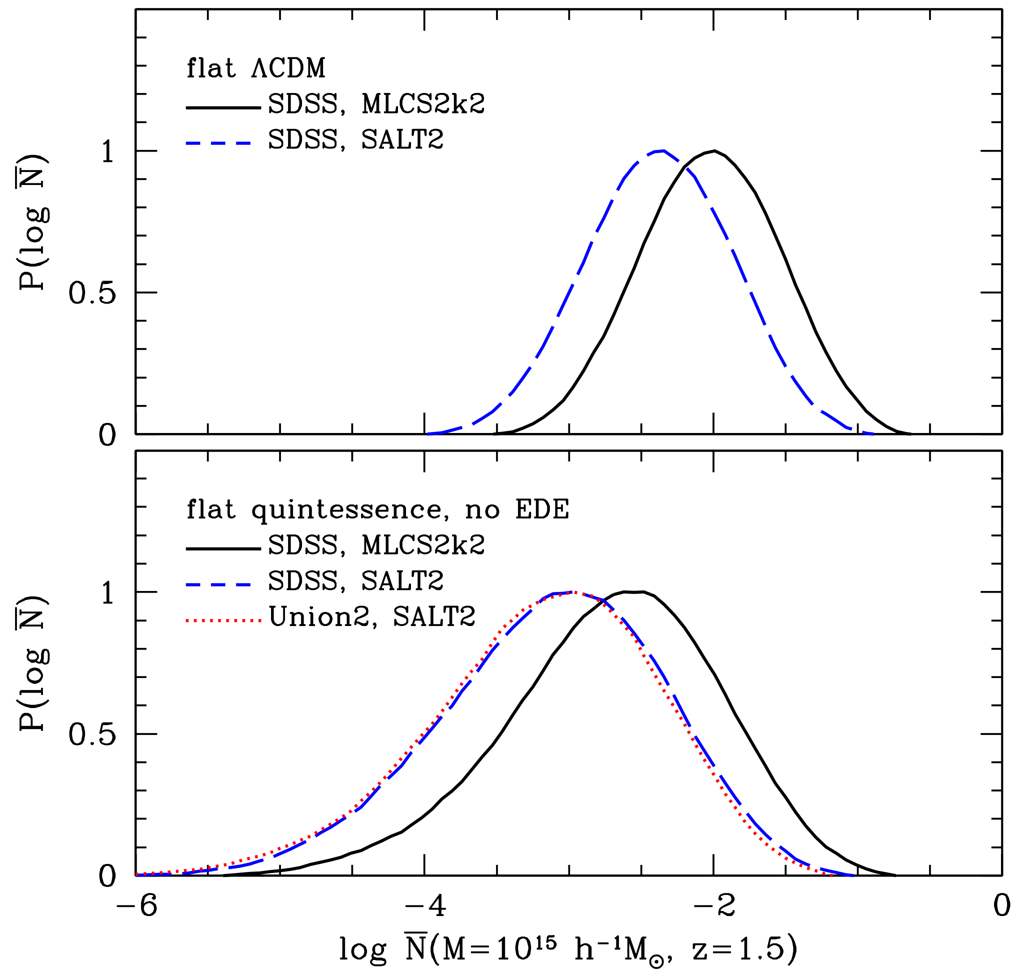
black error bars: masses corrected for **Eddington bias**

Systematic effects

Cluster mass

SN light-curve fitter (Lambda)





MF normalization

SN light-curve fitter (Quint)

Disagreement with previous work

Hoyle, Jimenez & Verde (2010), and
Cayon, Gordon & Silk (2010)
(partial agreement with Holz & Perlmutter (2010))

They find LCDM is ruled out at 2-4 sigma,
and we don't.
But they

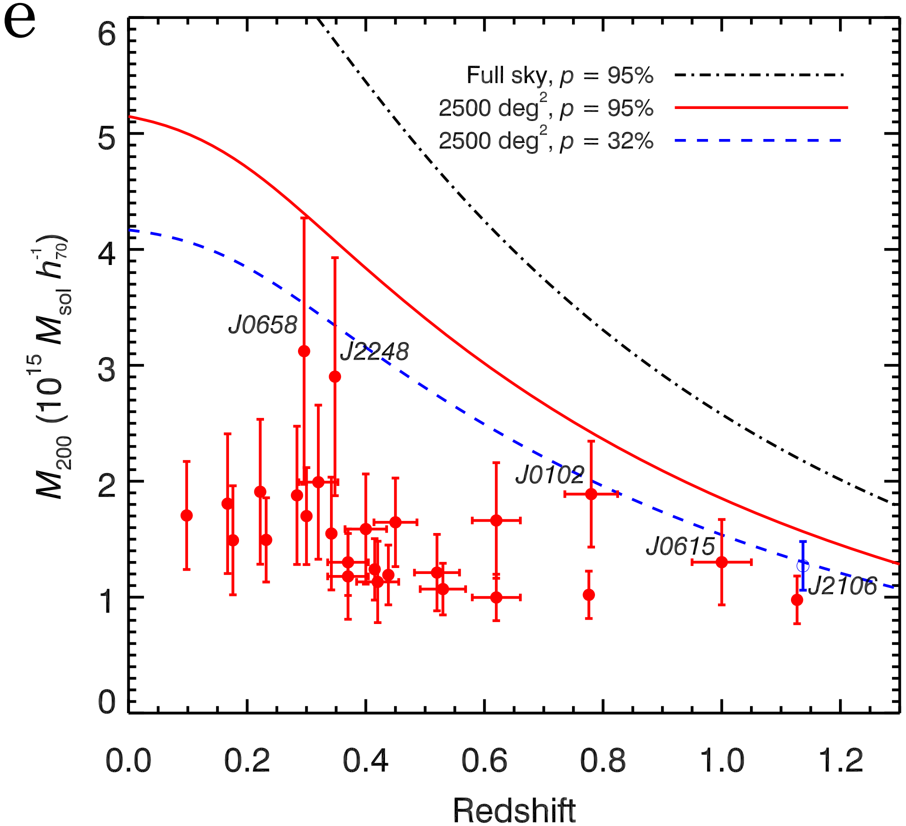
- ➡ Don't correct for Eddington bias
- ➡ Don't account for the parameter variance
- ➡ In some cases, use inappropriately small f_{sky}
- ➡ In some cases, use weird statistical methods

Potentially useful product of paper:

Fitting formulae to evaluate $N_{clusters}$ that rule out LCDM at a given

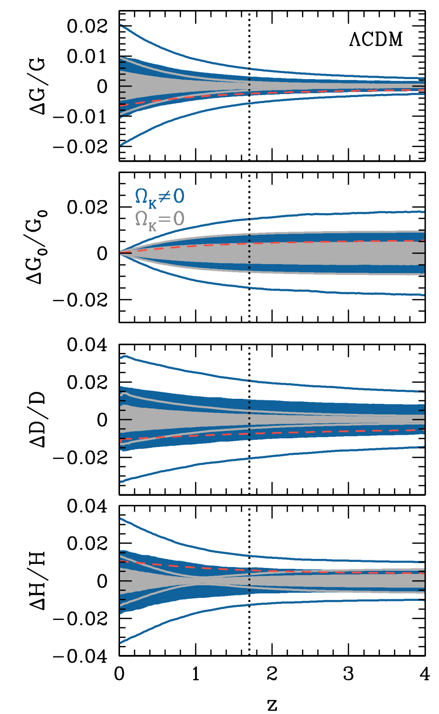
- ✓ mass and redshift
- ✓ sample variance confidence
- ✓ parameter variance confidence
- ✓ f_{sky}

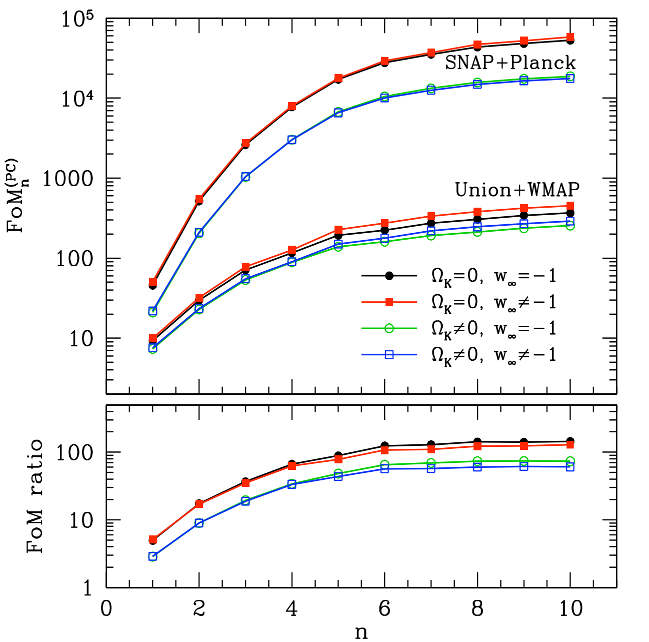
e.g. Williamson et al. 2011 (SPT)



Conclusions I: Falsifying DE

- Current (and, esp, future) data lead to strong predictions for D(z), G(z), H(z)
- Examples:
  - Flat LCDM: H(z=1) to 0.1%, D(z), G(z) to 1% everywhere
  - Quint: D(z), G(z) to 5%; one-sided deviations
  - Smooth DE: tight consistency relations can still be found
  - GR tests: γ to 5% (~0.02) even with arbitrary w(z)
- Total FoM=det(Cov)$^{-1/2}$ improvement of >100 in the future
- it's wise to keep eyes open for mode exotic DE (and measuring PCs 3, 4, 5, 6...)





Conclusions II: ‘Pink Elephants’

- It’s important to be careful about the various statistical, not just systematic, effects in analyzing the abundance of rare, massive and distant clusters
- In particular, we find that the following effects have major effect on their likelihood
  - Parameter variance (in addition to sample variance)
  - Fair assessment of f_{sky}
  - Eddington bias
- So far none of the detected clusters rules out any models (contrary to some claims in the literature)
- If an unusually massive/distant observed cluster observed tomorrow rules out LCDM, it will rule out quintessence at the same time