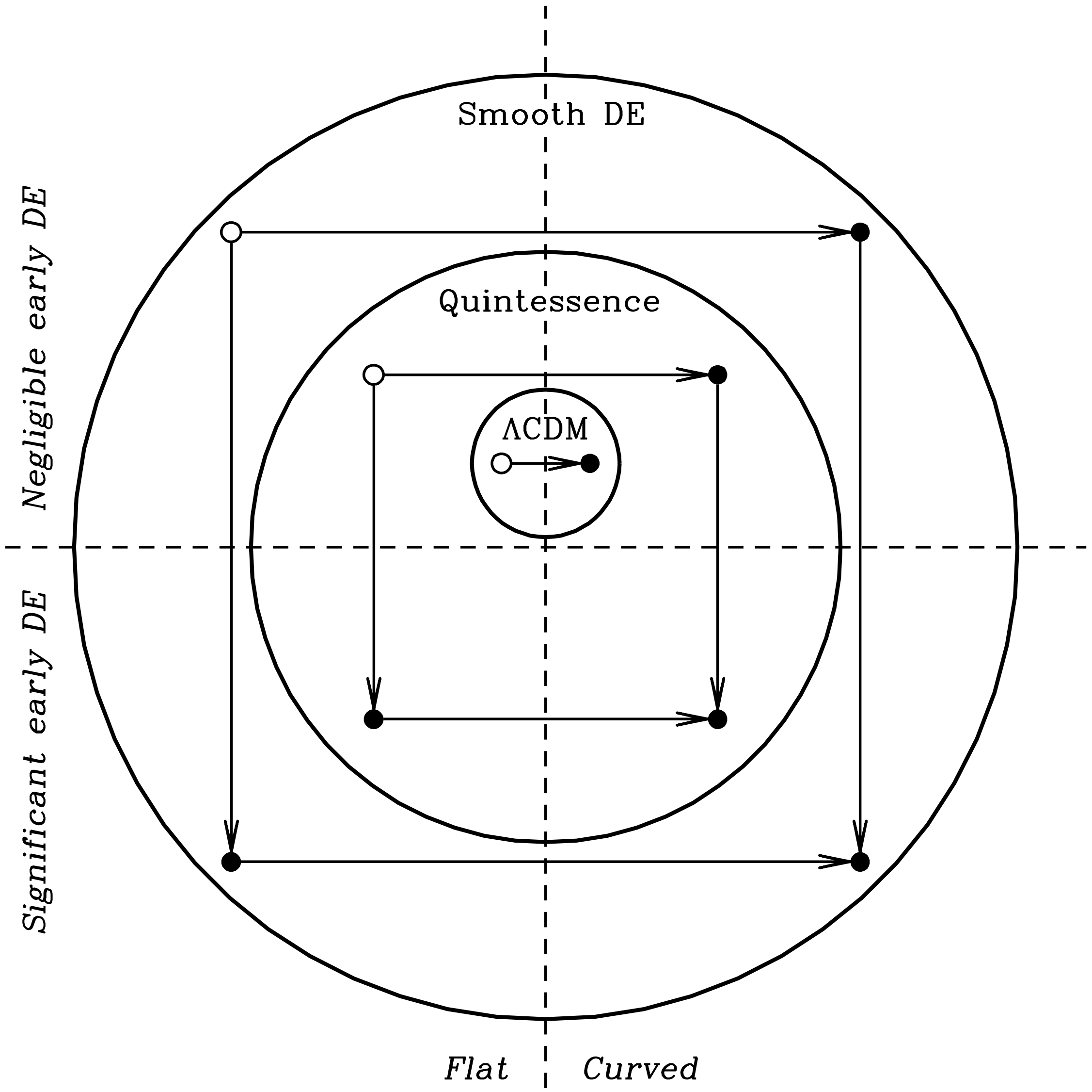
Falsifying Paradigms for Cosmic Acceleration in the Systematics-Dominated Era



Dragan Huterer (University of Michigan)

Collaborators:
Eduardo Ruiz, Dan Shafer (Michigan)
Hao-Yi (Heidi) Wu (Michigan)
Michael Mortonson (Ohio State), Wayne Hu (Chicago), Carlos Cunha (Stanford)

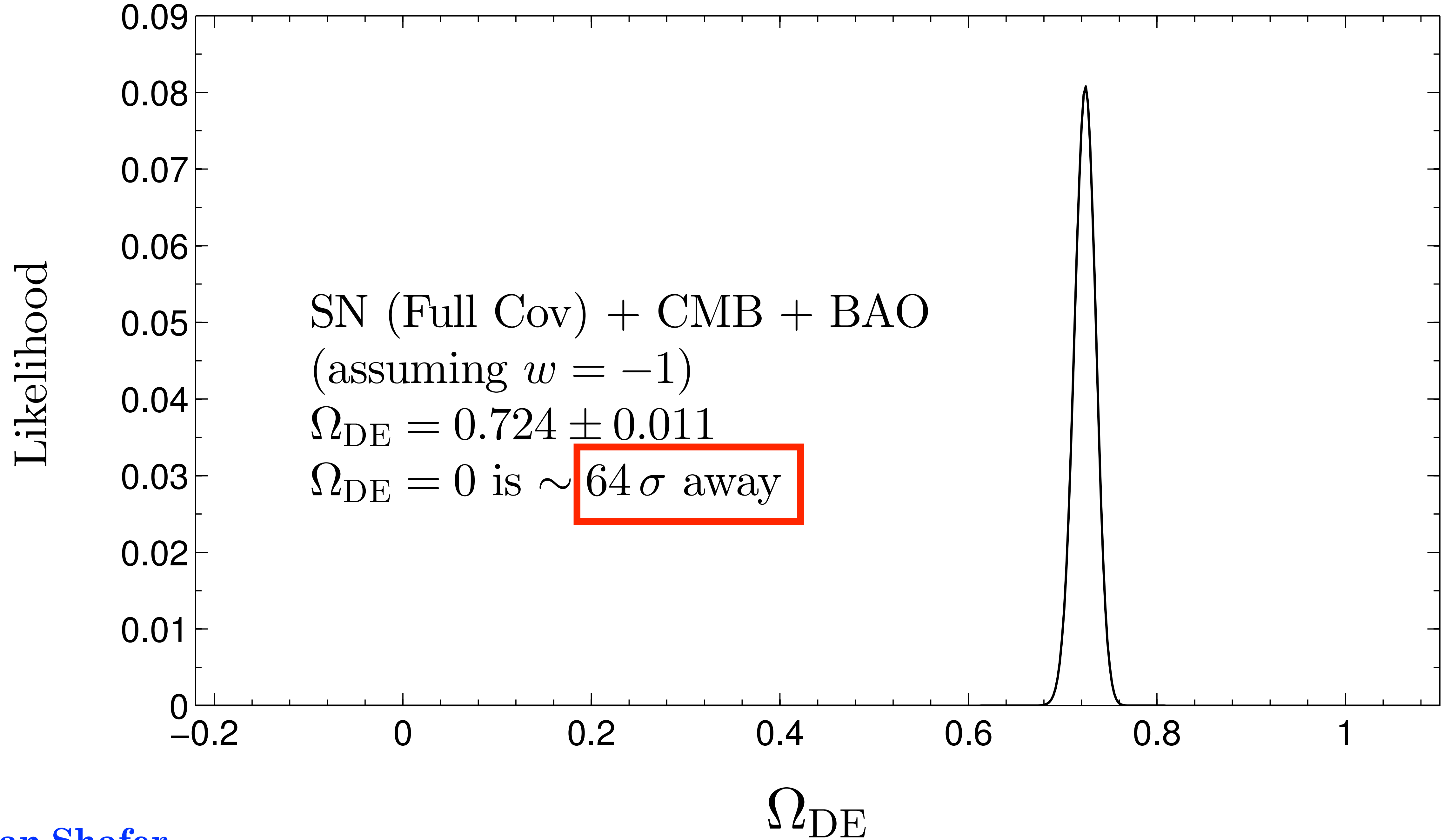
This talk

1. Systematic errors in DE probes: a worked example

2. Predictions of classes of DE models for D(z)/H(z)/G(z)

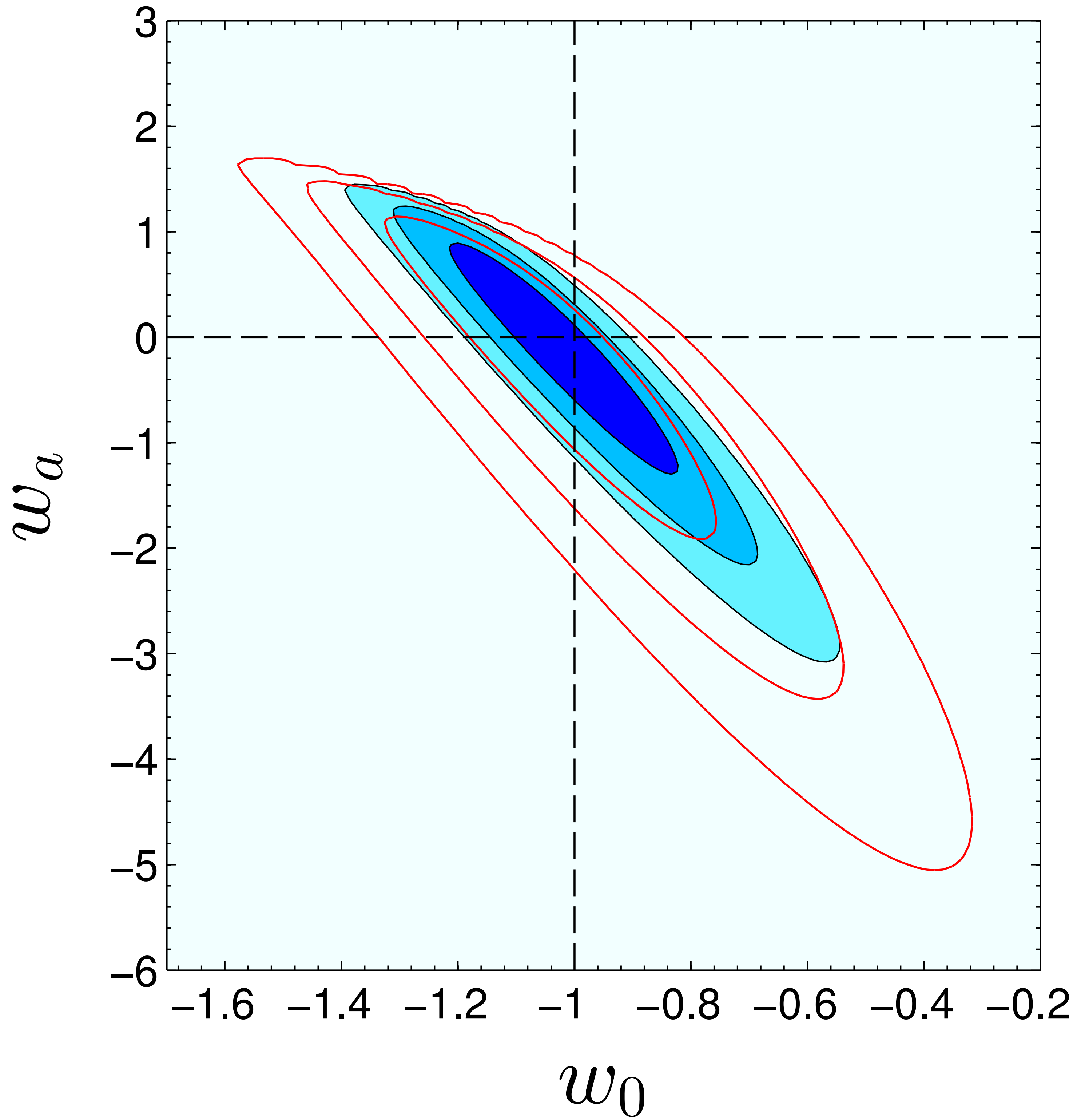
Current evidence for dark energy is impressively strong

Current evidence for dark energy is impressively strong



Dan Shafer

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



$$w(z) = w_0 + w_a\,(1-a)$$

Current
SN + BAO + CMB
constraints shown.

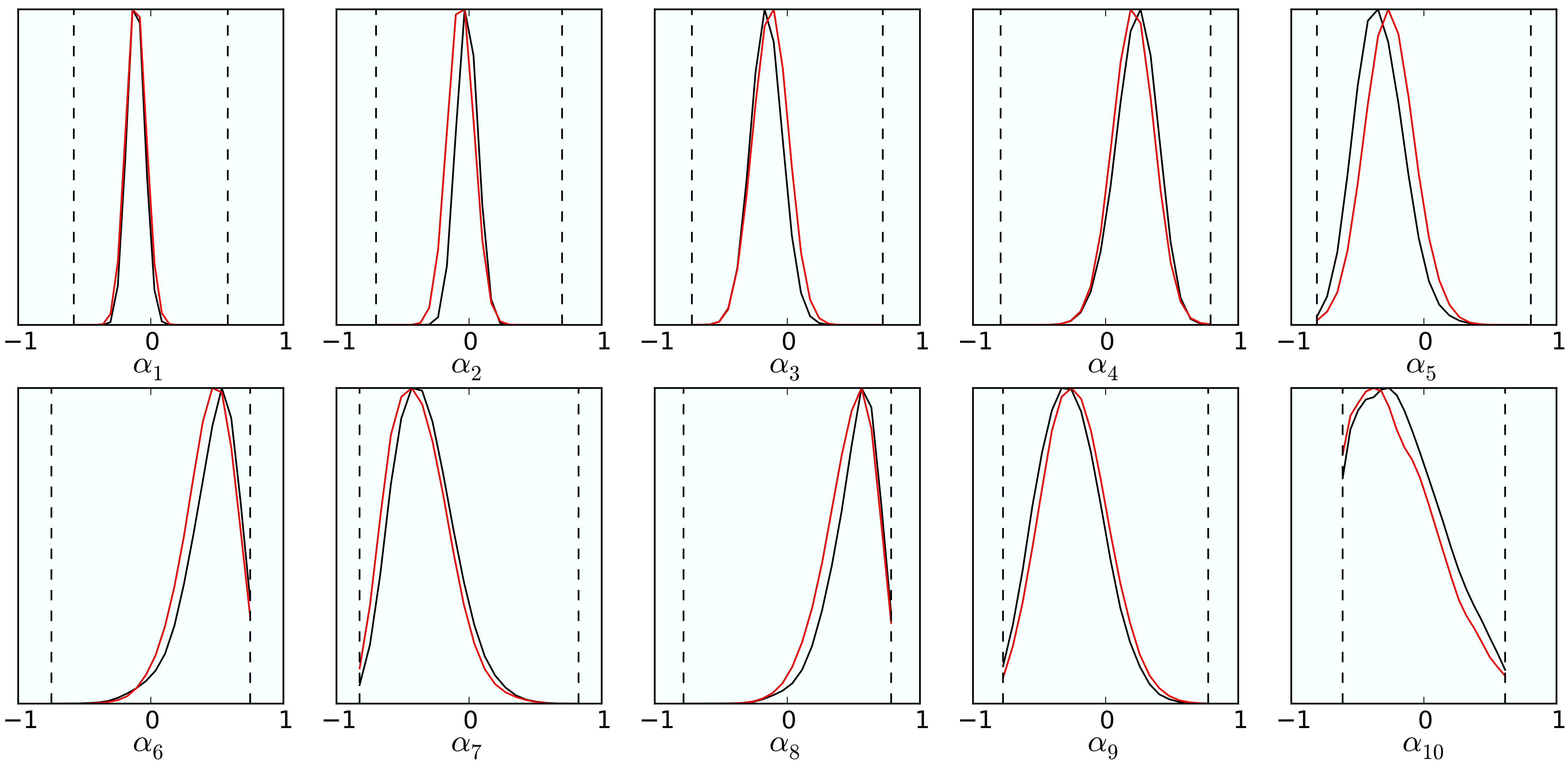
Red contours:
Includes SN
Cov + systematics

Ruiz, Shafer et al, 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



Ruiz, Shafer, Huterer & Conley, arXiv:1207.4781

Red = with SN systematics

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

Specifically for "big 4" probes of DE:

Supernovae: each SN provides info about DE; can choose a "golden subsample" to limit systematics

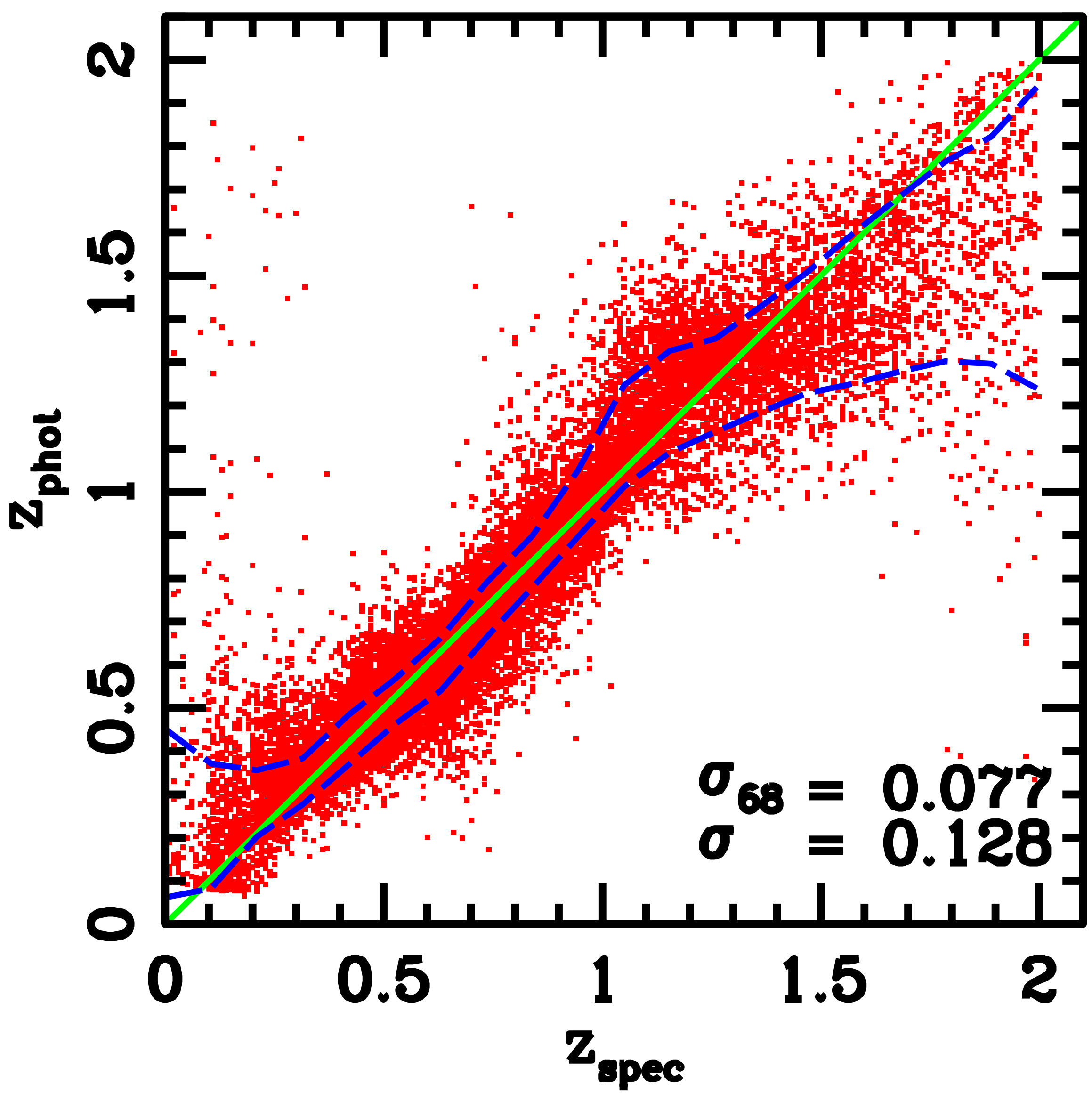
BAO: relatively systematics-free (additional info in RSD and P(k), but also additional systematics!)

Weak lensing: control of systematics most challenging, but great potential, esp in providing info on growth

Clusters: understanding mapping between observable luminosity/flux/N_{gal} and mass is crucial

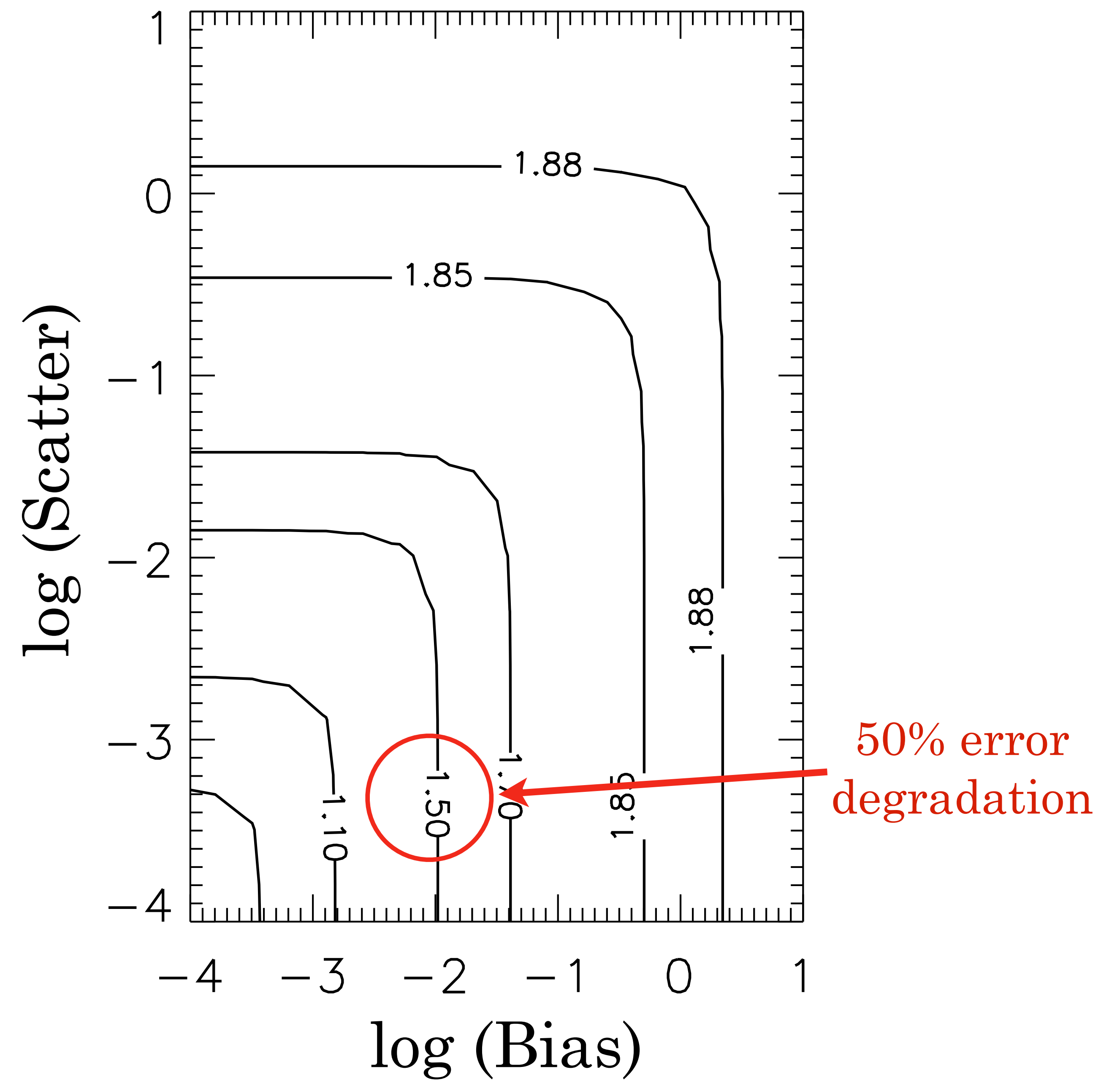
Poster child of systematics: photometric redshift errors

Example



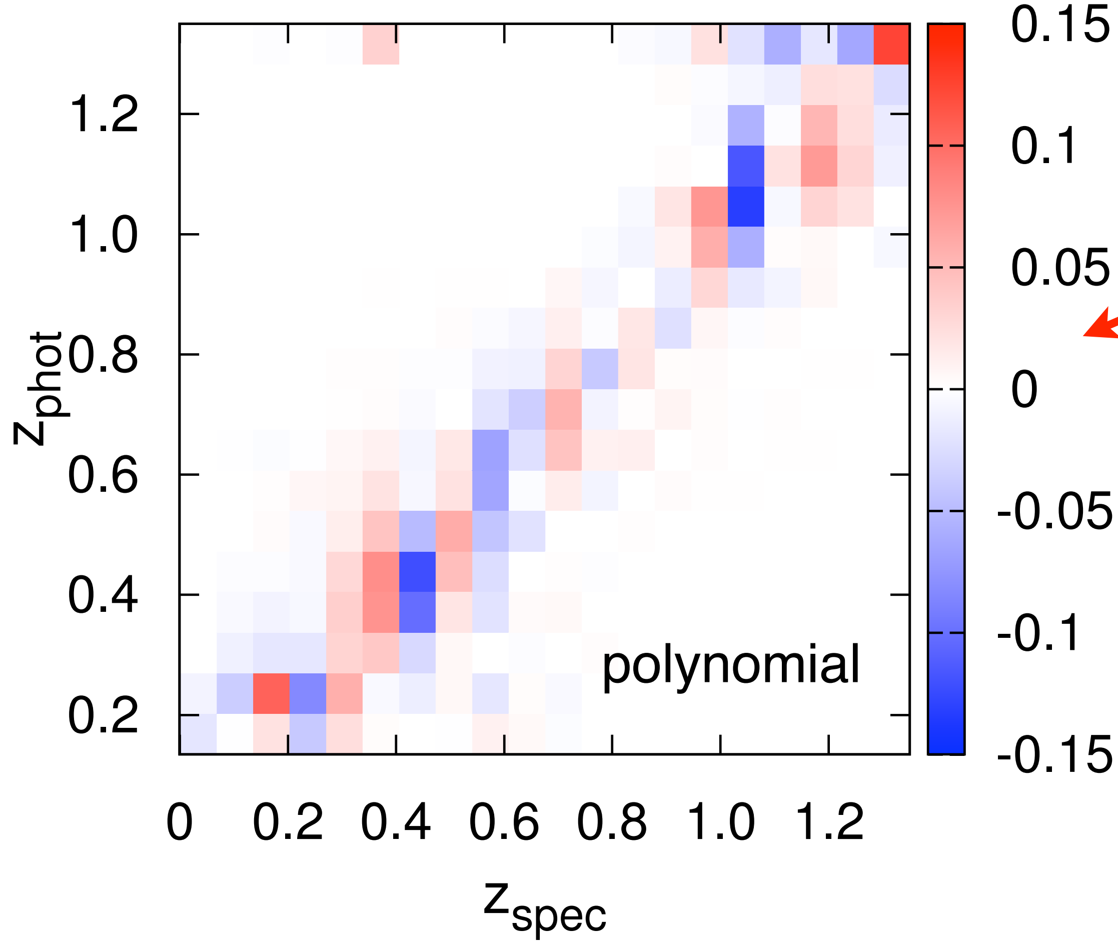
C. Cunha

Requirements

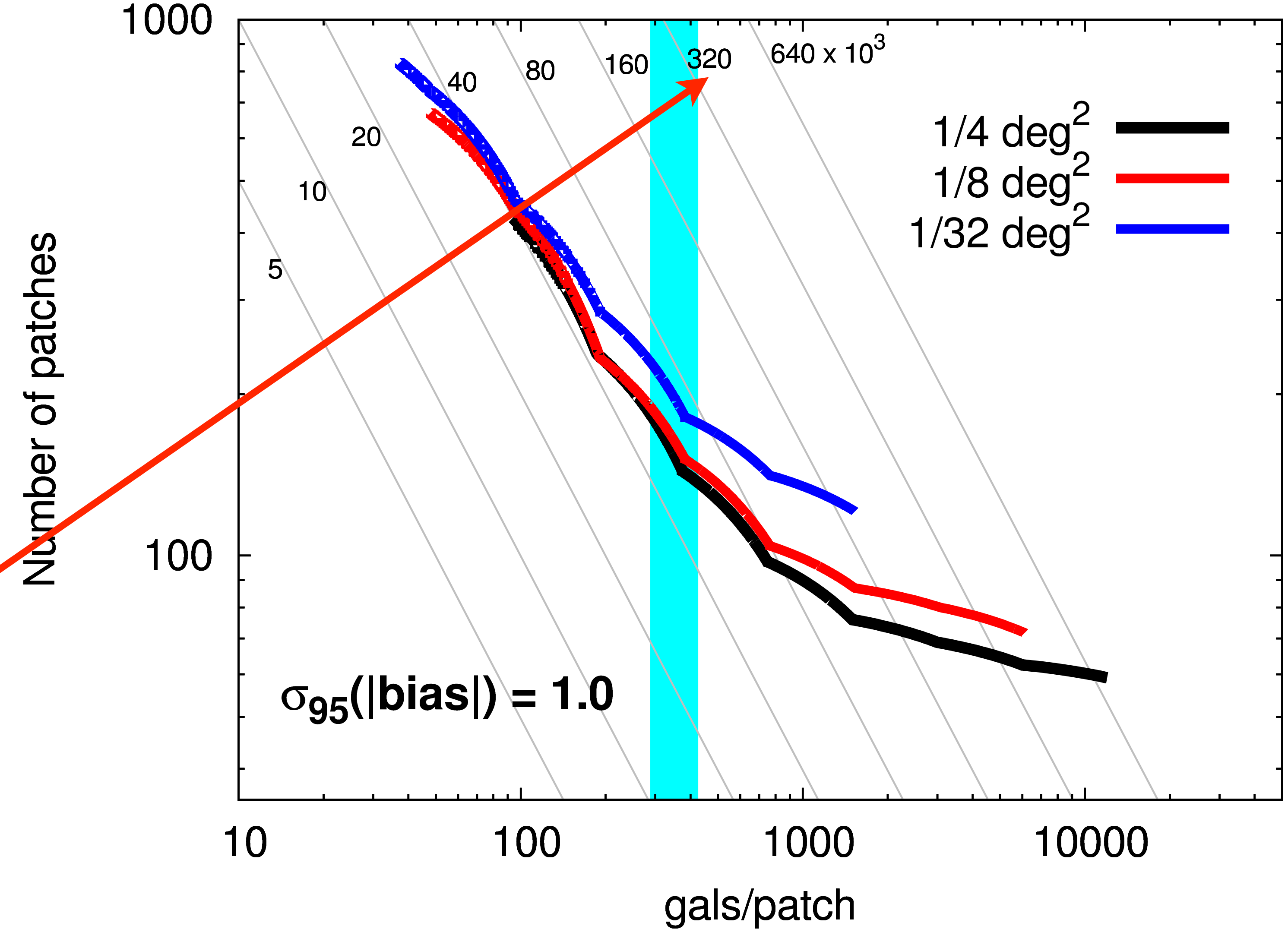


Ma, Hu & Huterer 2006

Note: scatter σ, or even σ(z) and bias(z), are NOT sufficient to describe effects of photo-z errors on DE



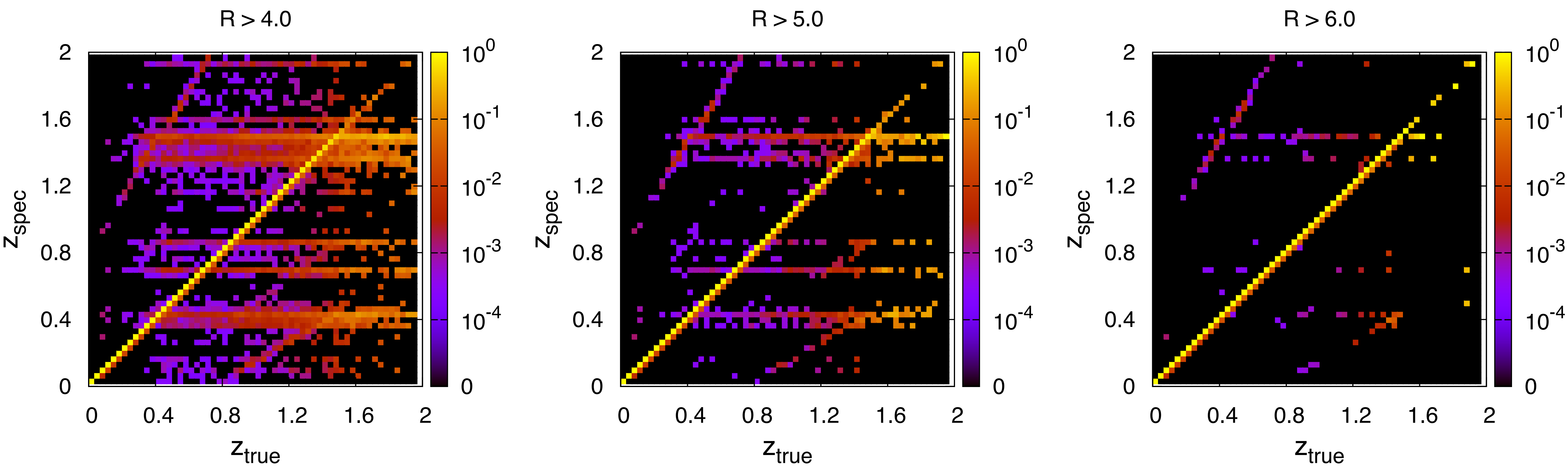
Need to consider the full $P(z_s \mid z_p)$: difference (true P – estimated P) generates cosmological biases



Only then can you derive survey requirements (here, size of spectroscopic follow-up)

Cunha, Huterer, et al, arXiv:1109.5691

Spectroscopic failures (shown below) lead to increased photo-z errors, and thus DE biases



Increasing quality threshold (R) of spectroscopic zs

Final requirement (based on end-to-end simulation):
must have <1% fraction of wrong spectroscopic redshifts

Cunha, Huterer et al, arXiv:1207.3347

Major photo-z challenge: get spectroscopic followup

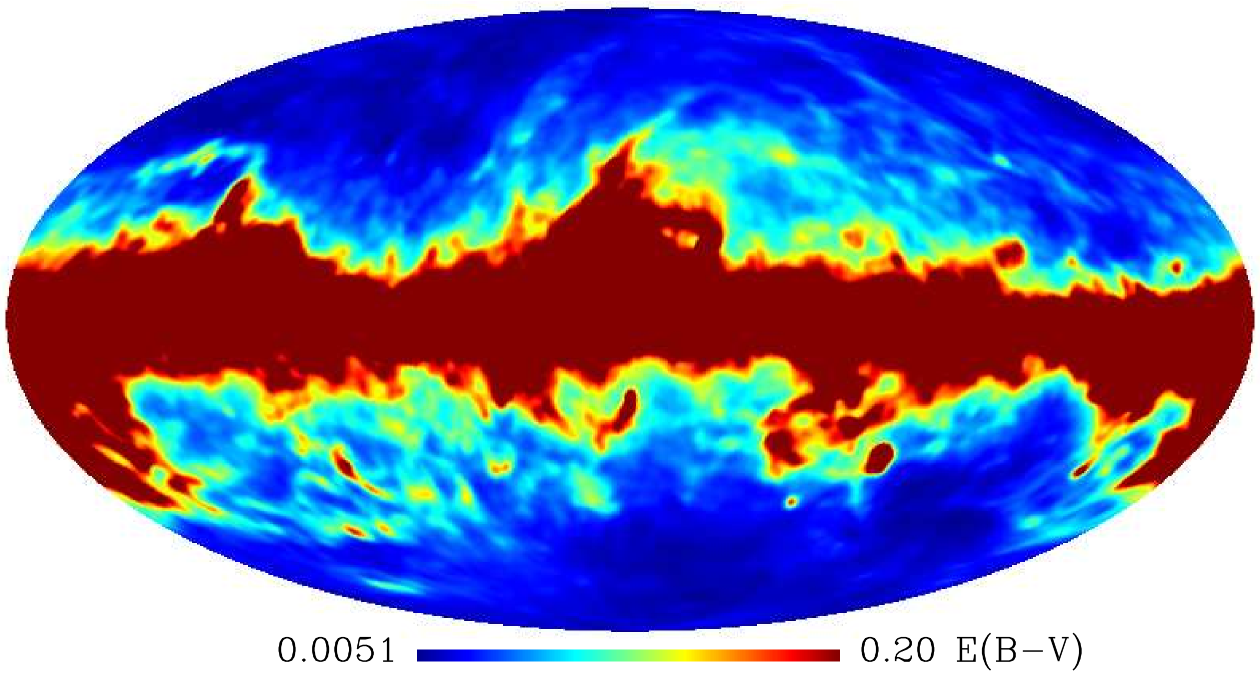
- with $O(10^6)$ spectra
- to depth of photometric sample (!)
- with <1% wrong redshifts

Major unsolved problem:

How to take into account dozens/hundreds of nuisance parameters describing systematic errors in the actual data analysis?

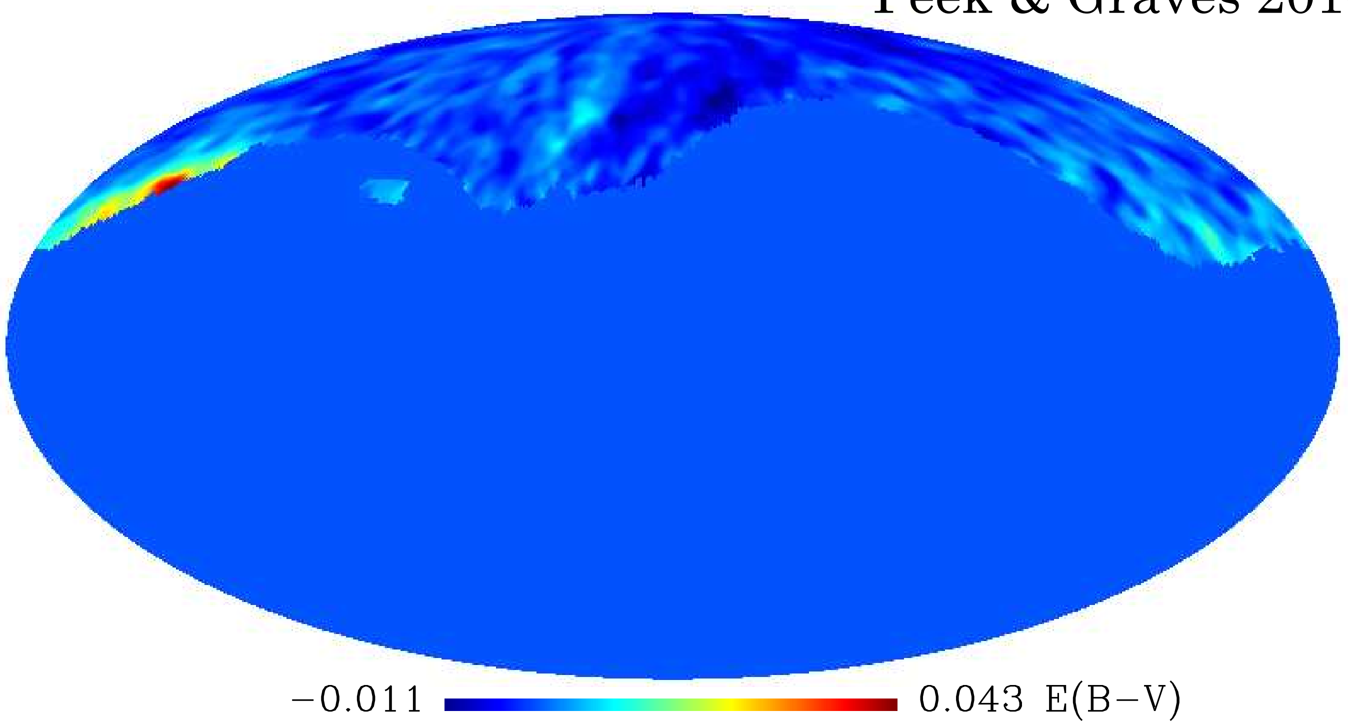
Example II: photometric calibration errors

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
- ......

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 et al, in preparation

Photometric Calibration systematics

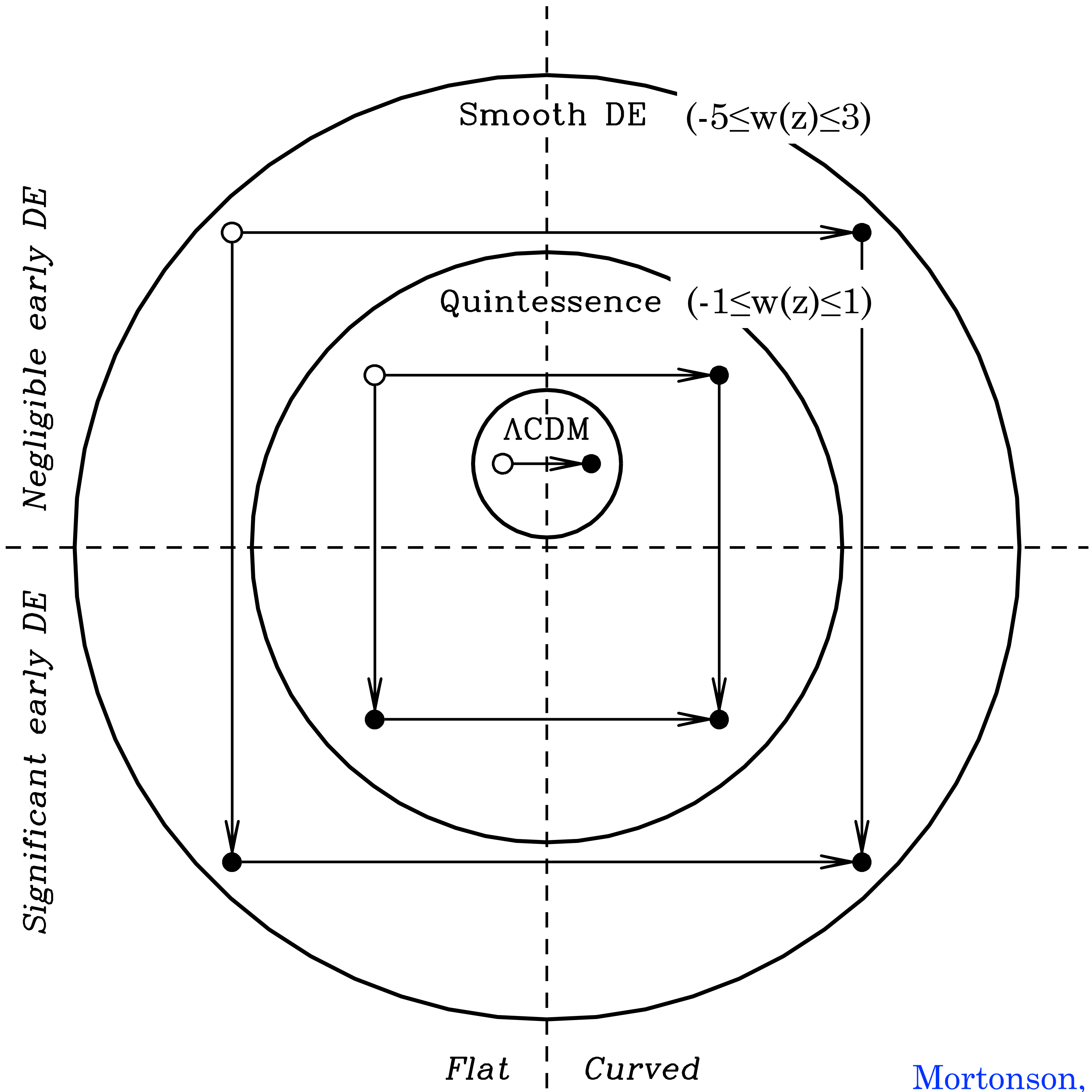
Summary of findings:

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

Falsifying paradigms for cosmic acceleration



Mortonson, Hu & Huterer 2010

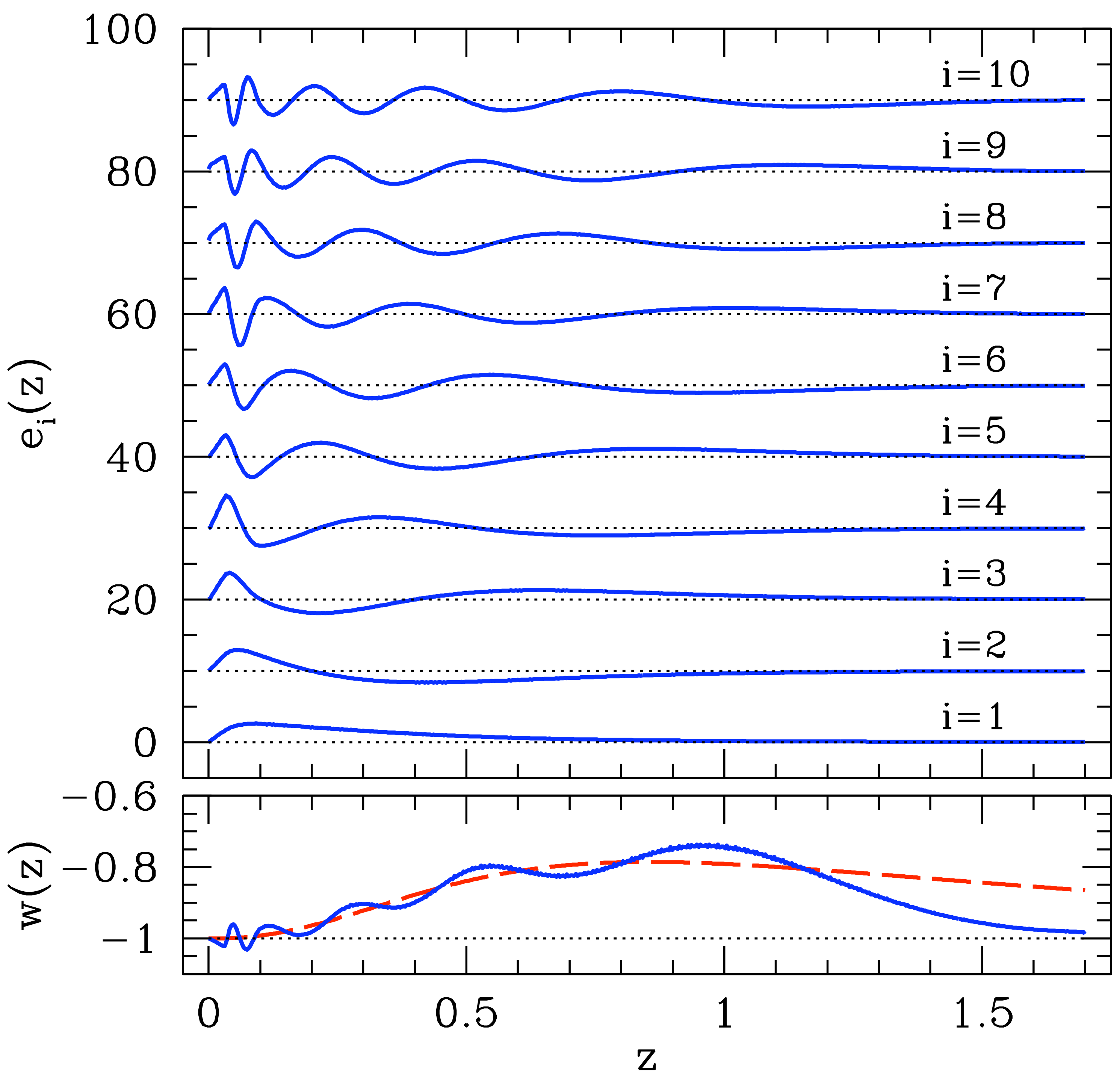
Falsifying paradigms - Underlying Philosophy

- 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, WFIRST, ...)

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

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

(current = Union2 SN + WMAP + $BAO_{z=0.35}$ + H_0
future = Planck + SNAP)

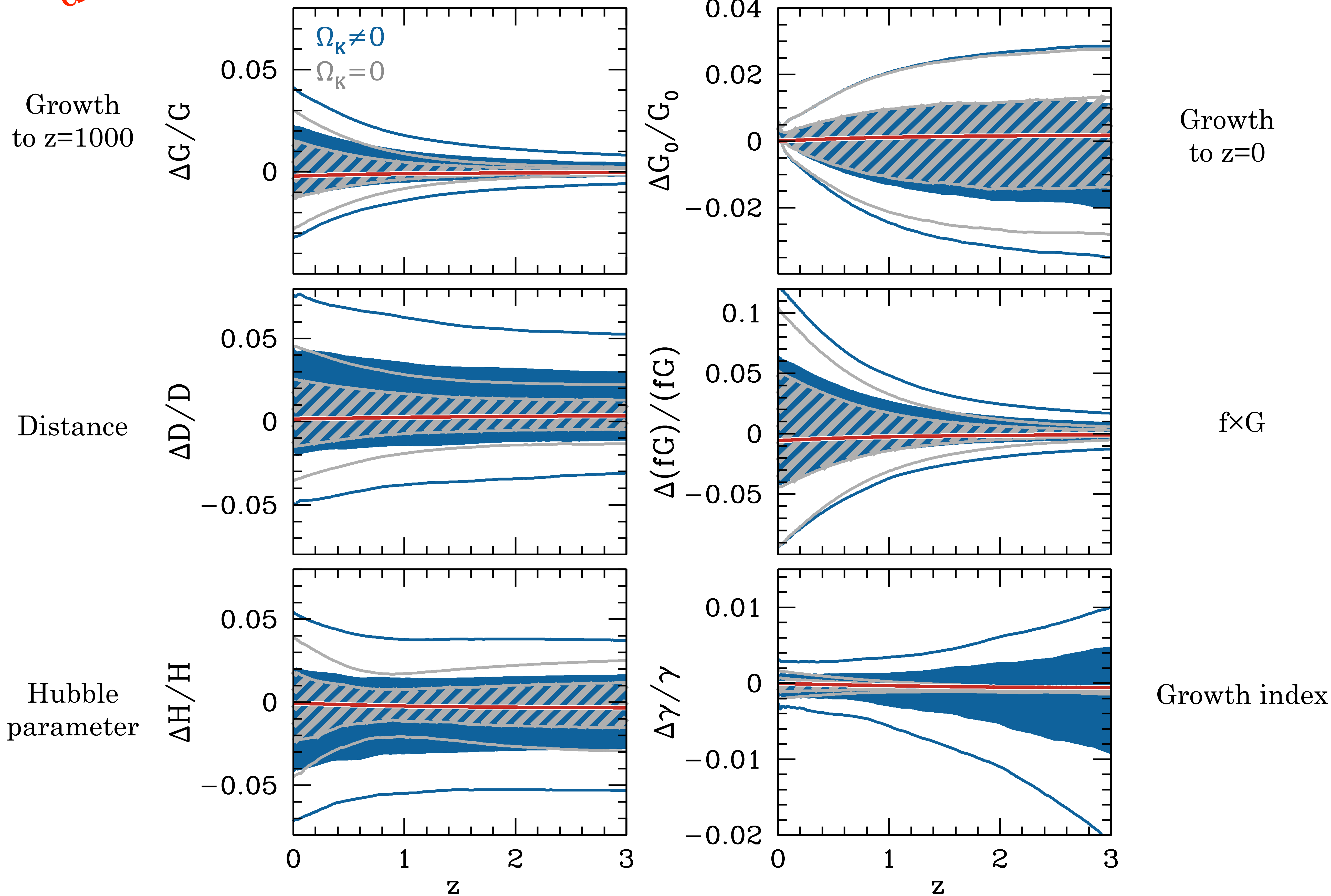
3. Employ the likelihood machine

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))

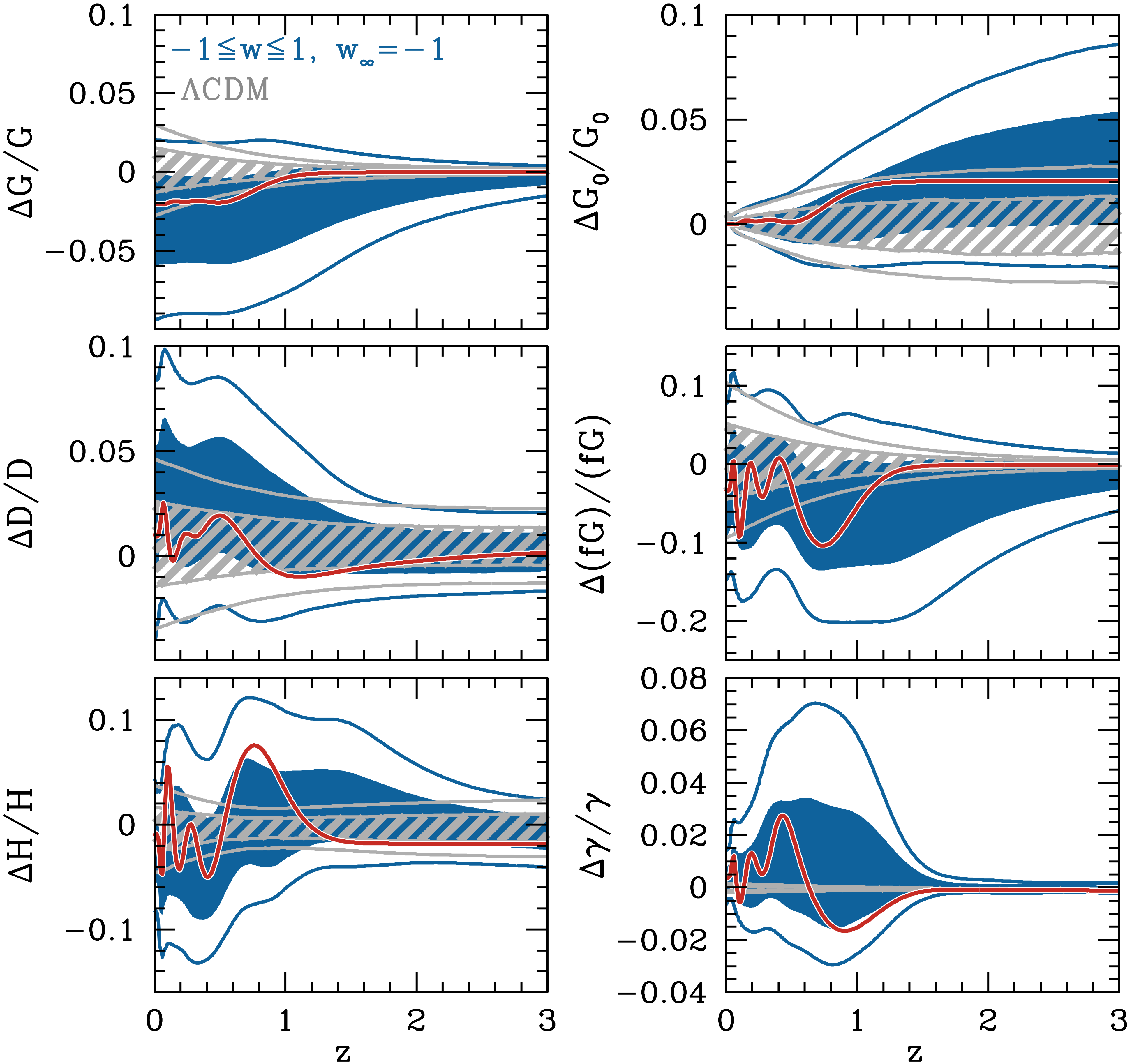
Mortonson, Hu & Huterer 2010

LCDM predictions - flat or curved



Quintessence predictions (flat, no Early DE)

Current data

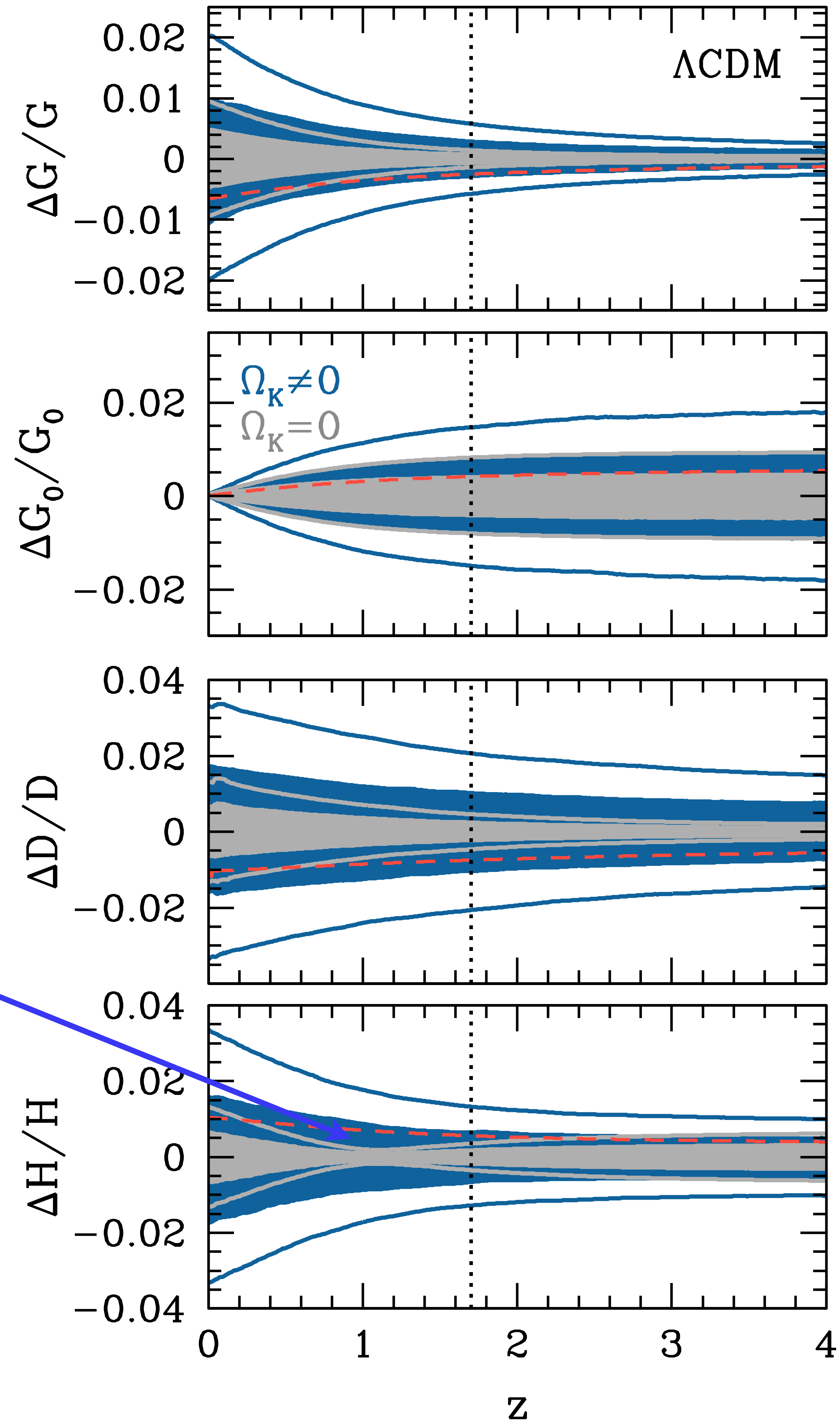


Future data

LCDM predictions (flat or curved)

Grey: flat
Blue: curved

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



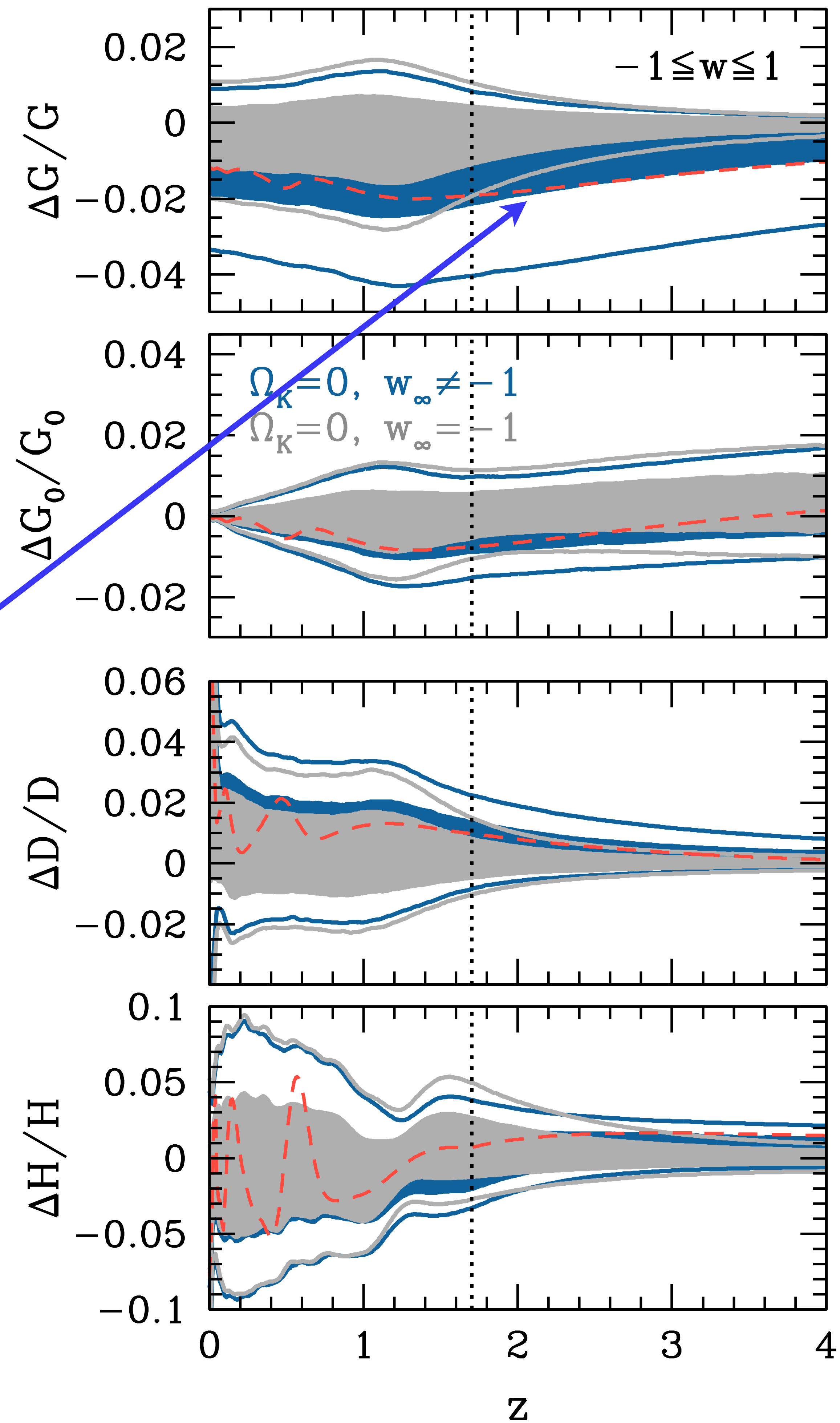
Future data

Quintessence predictions (flat)

Grey: no Early DE

Blue: with Early DE

Smoking Gun of EDE: Uniform suppression in G

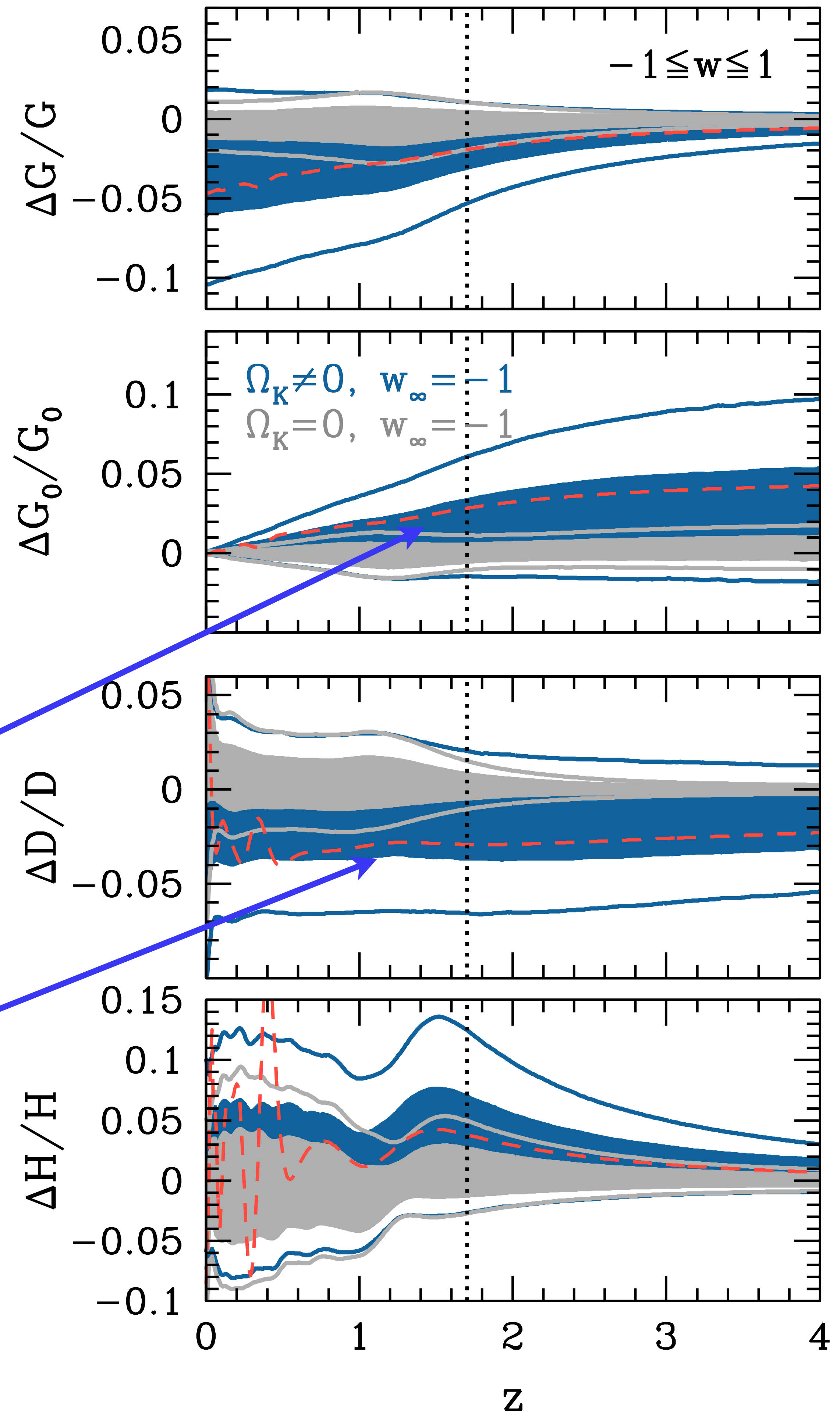


Future data

Quintessence predictions (no EDE)

Grey: flat

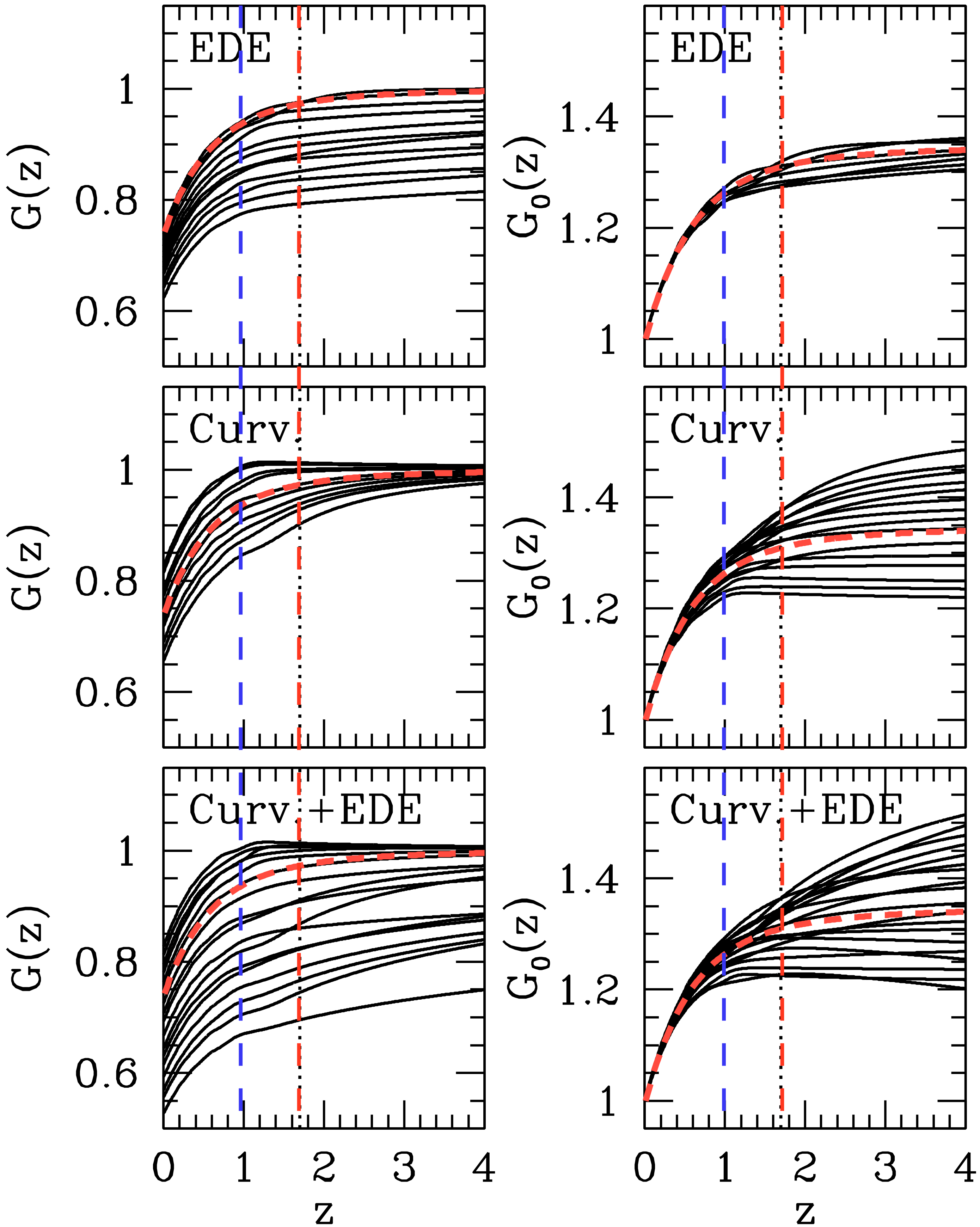
Blue: curved



Smoking Gun of curvature:

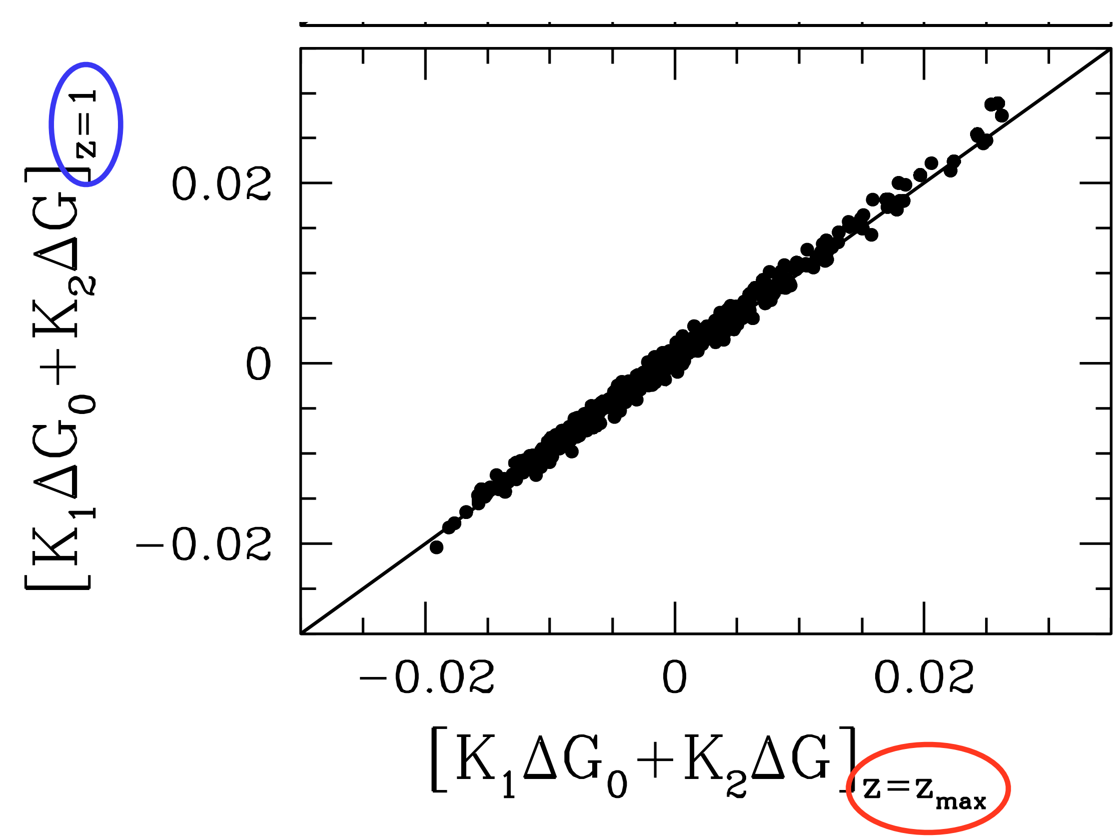
1. Shift in G_0
2. Negative const offset in D

Smooth DE with curvature and/or Early DE



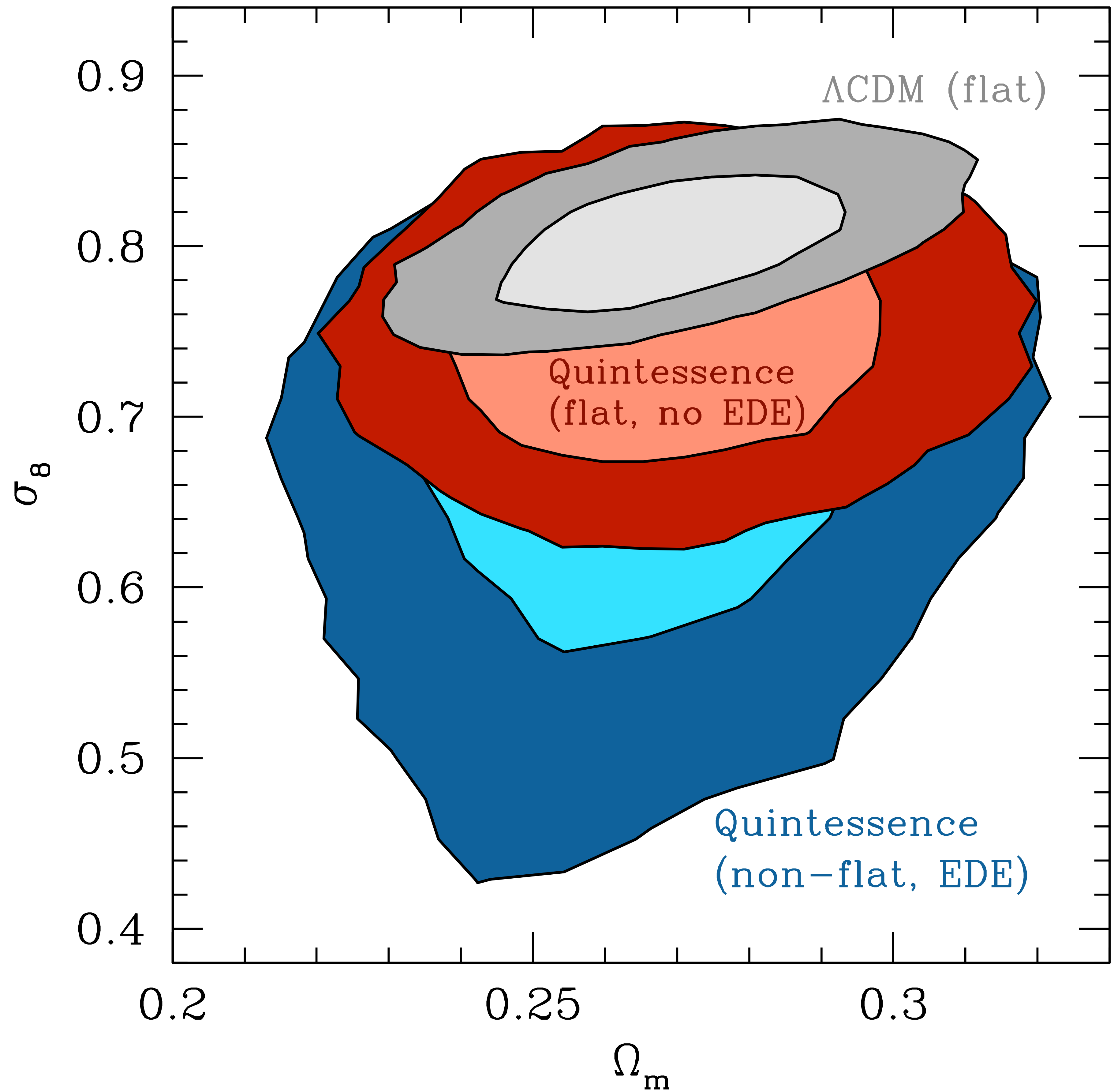
Some quantities are accurately predicted even in very general classes of DE models

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



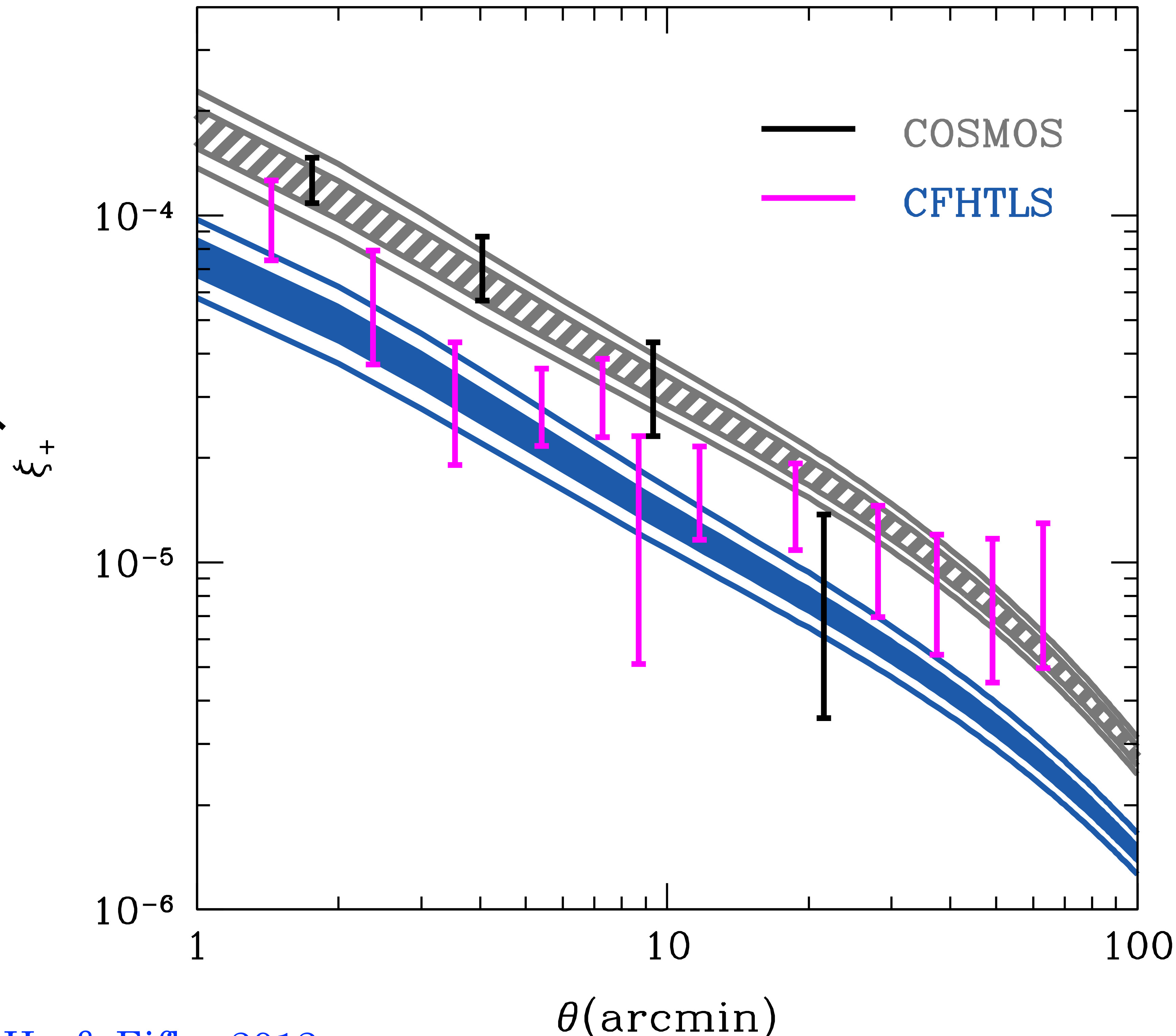
Mortonson, Hu & Huterer 2010

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



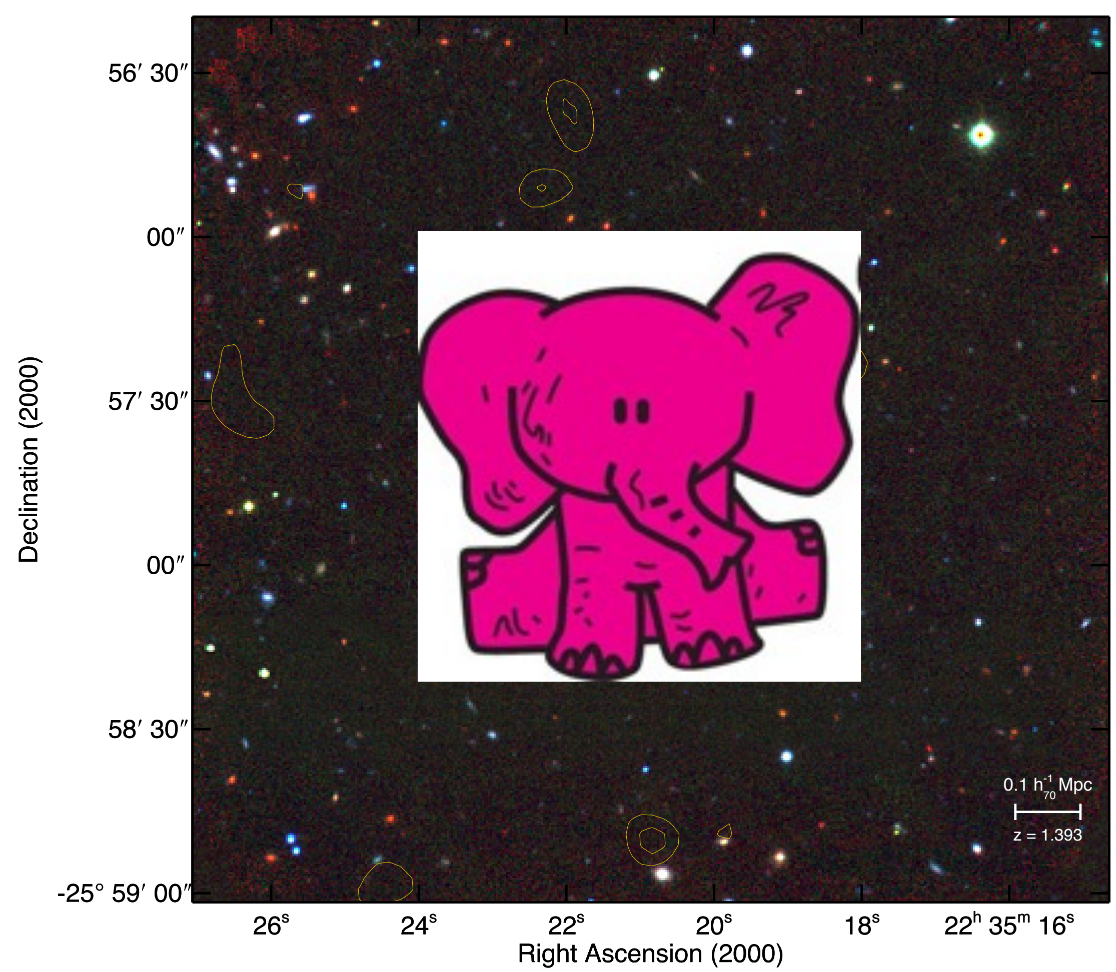
Straightforward to make predictions for actually observable quantities for a given survey, given the class of DE models

Two-pt function of shear in real space



Vanderveld, Mortonson, Hu & Eifler 2012

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, 2011

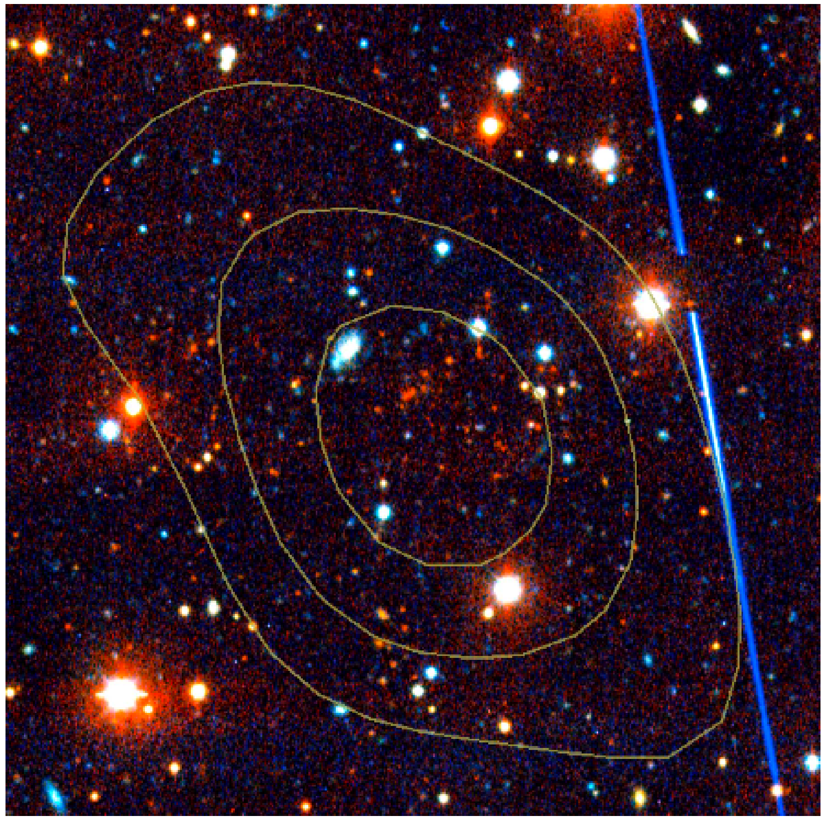
Pink elephant, candidate 1: SPT-CL J0546-5345

Brodwin et al, arXiv:1006.5639

z=1.067

$M \approx (8\pm1)\cdot10^{14}\,M_{sun}$

optical (grz); contours are SZ



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

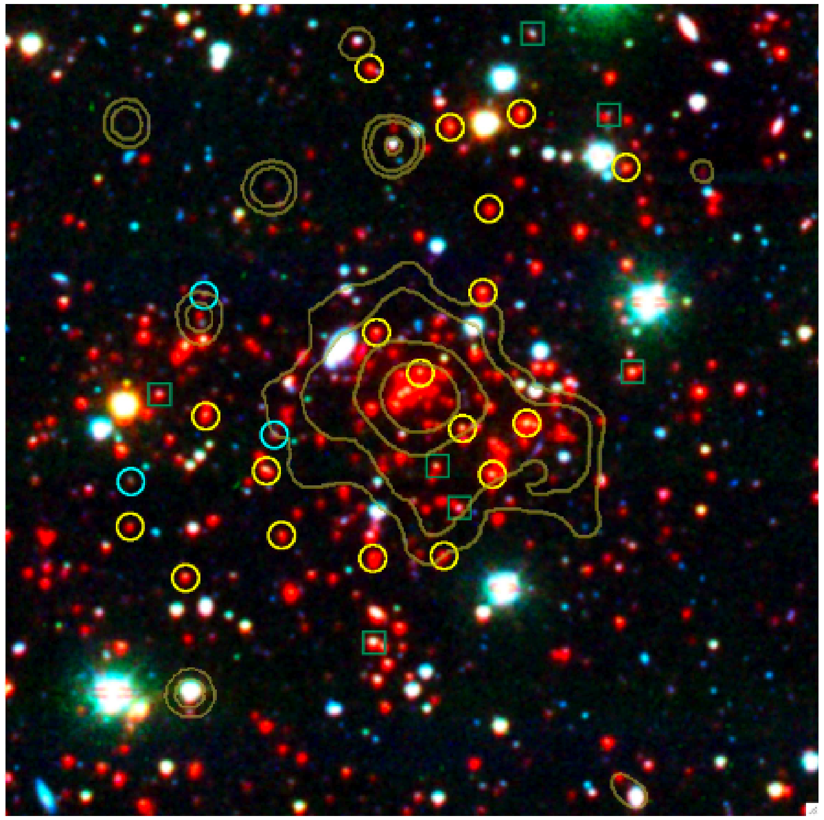


TABLE 2
Comparison of Mass Measurements for SPT-CL J0546-5345

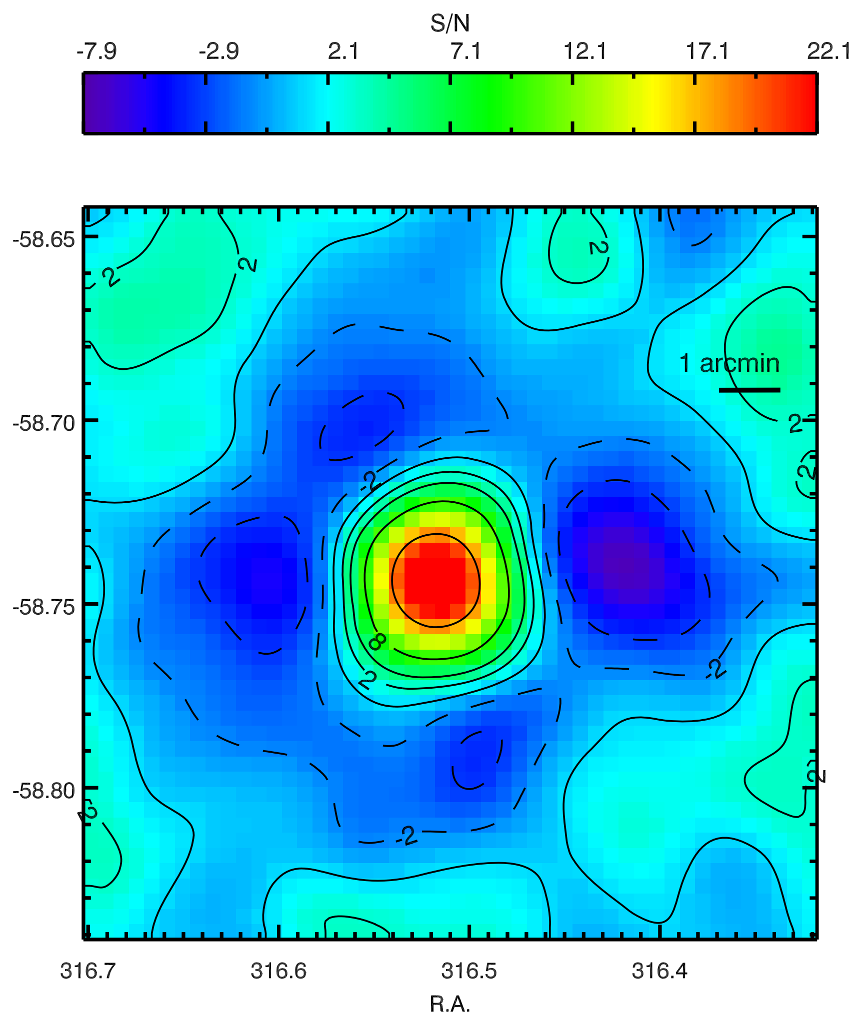
Mass Type	Proxy	Measurement	Units	Mass Scaling Relation	M_{200}[a,b] ($10^{14}\ M_\odot$)
Dispersion	**Biweight**	1179^{+232}_{-167}	km/s	σ–M_{200}(Evrard et al. 2008)	$\mathbf{10.4^{+6.1}_{-4.4}}$
	Gapper	1170^{+240}_{-128}	km/s	σ–M_{200} (Evrard et al. 2008)	$10.1^{+6.2}_{-3.3}$
	Std Deviation	1138^{+205}_{-132}	km/s	σ–M_{200} (Evrard et al. 2008)	$9.3^{+5.0}_{-3.2}$
X-ray	$\mathbf{Y_X}$	5.3 ± 1.0	$\times10^{14}\ M_\odot$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	$\times10^{14}\ M_\odot$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	$\mathbf{N_{200}}$	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**				$\mathbf{7.95 \pm 0.92}$

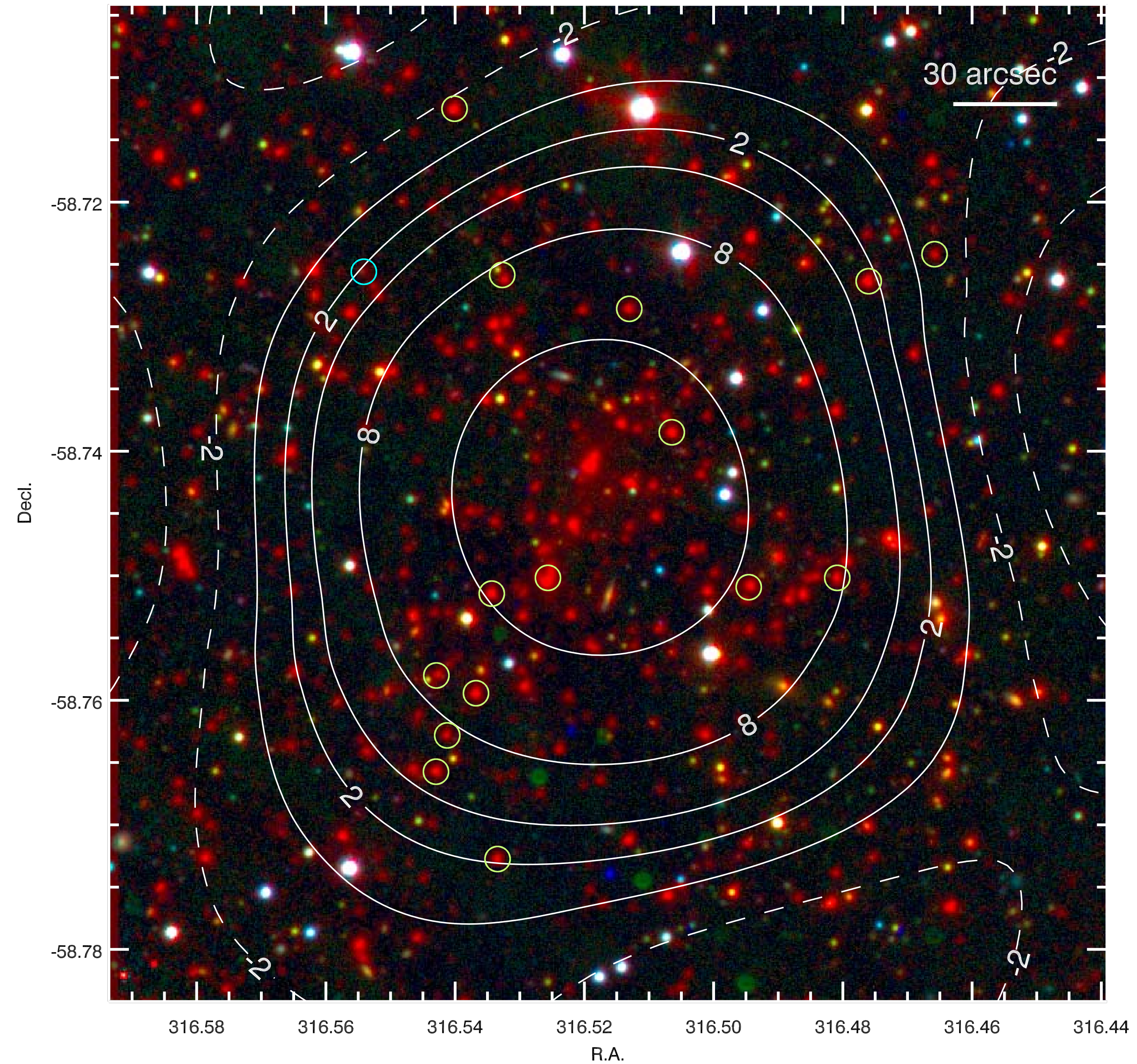
Pink elephant, candidate 2:
SPT-CL J2106-5844

z=1.132

$M_{SZ+x\text{-}ray} \approx (1.27\pm0.21)\cdot10^{15}\,M_{sun}$

Foley et al 2011
Williamson et al. 2011



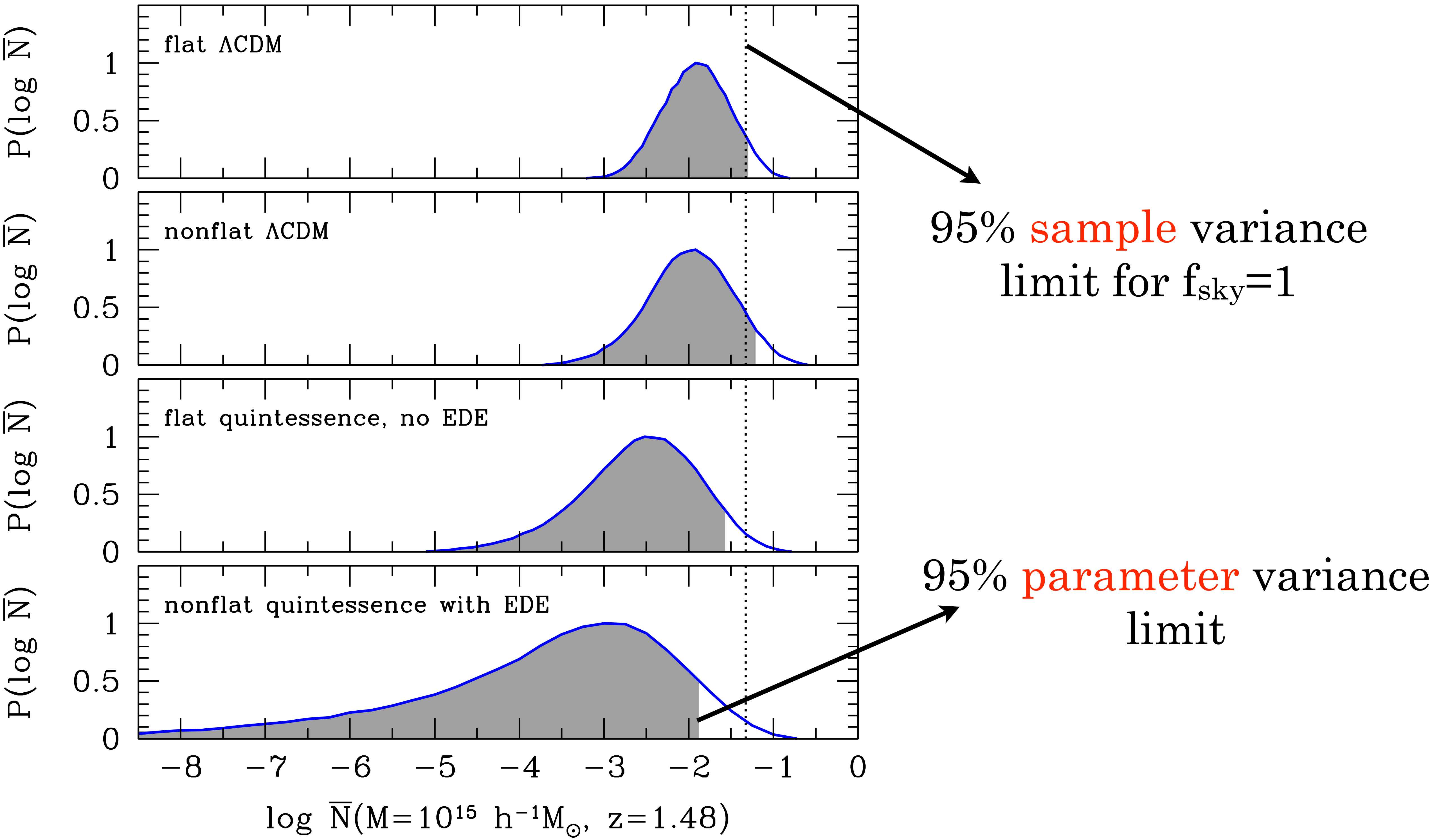


Two sources of statistical uncertainty

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

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



Rule out ΛCDM ⇒ automatically rule out quintessence

(then left with e.g. DM-DE coupled models; e,g, Pettorino & Baldi 2011)

Eddington bias

A.S. Eddington, MNRAS, 1913

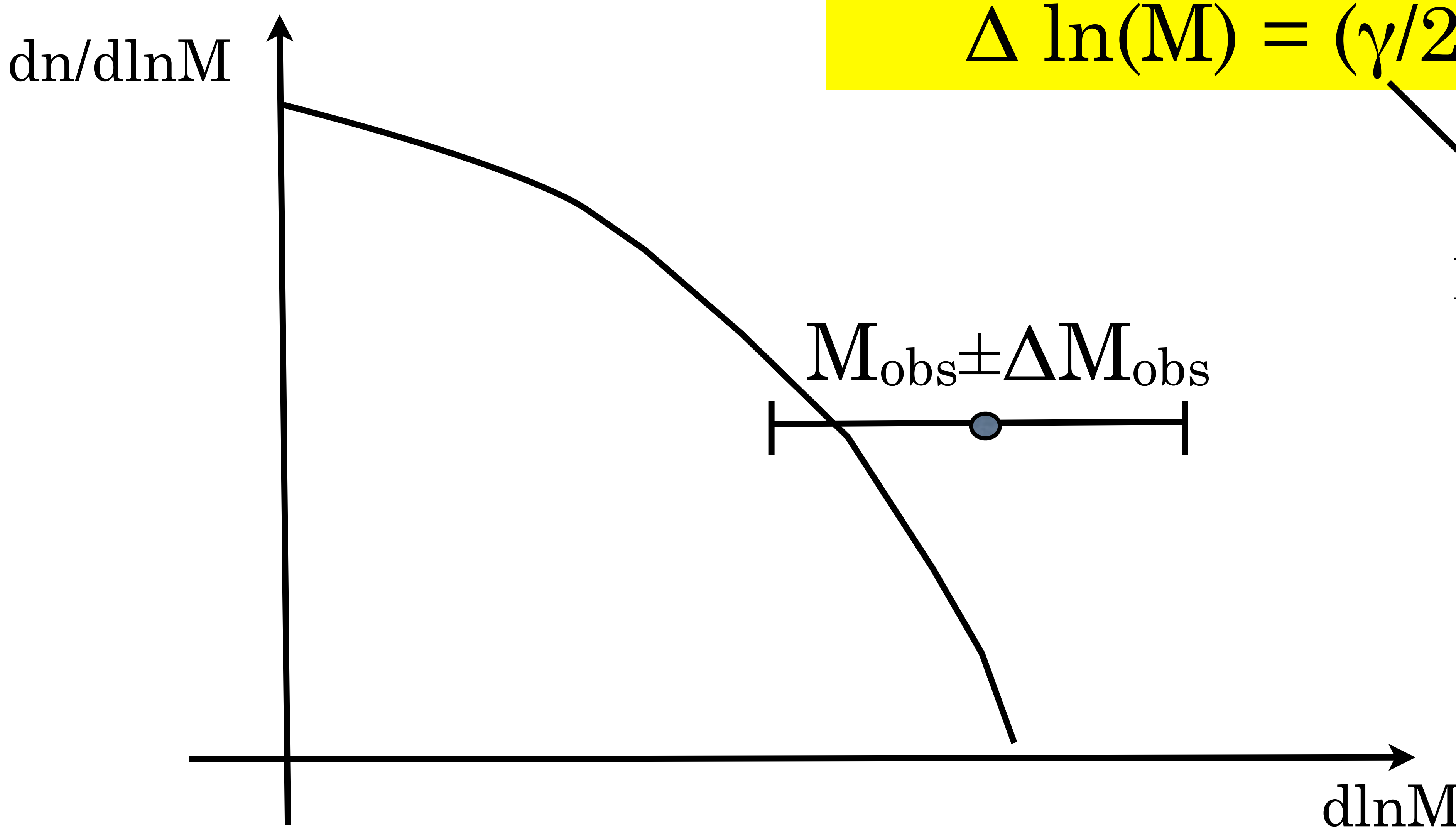
For a steeply falling mass function,

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

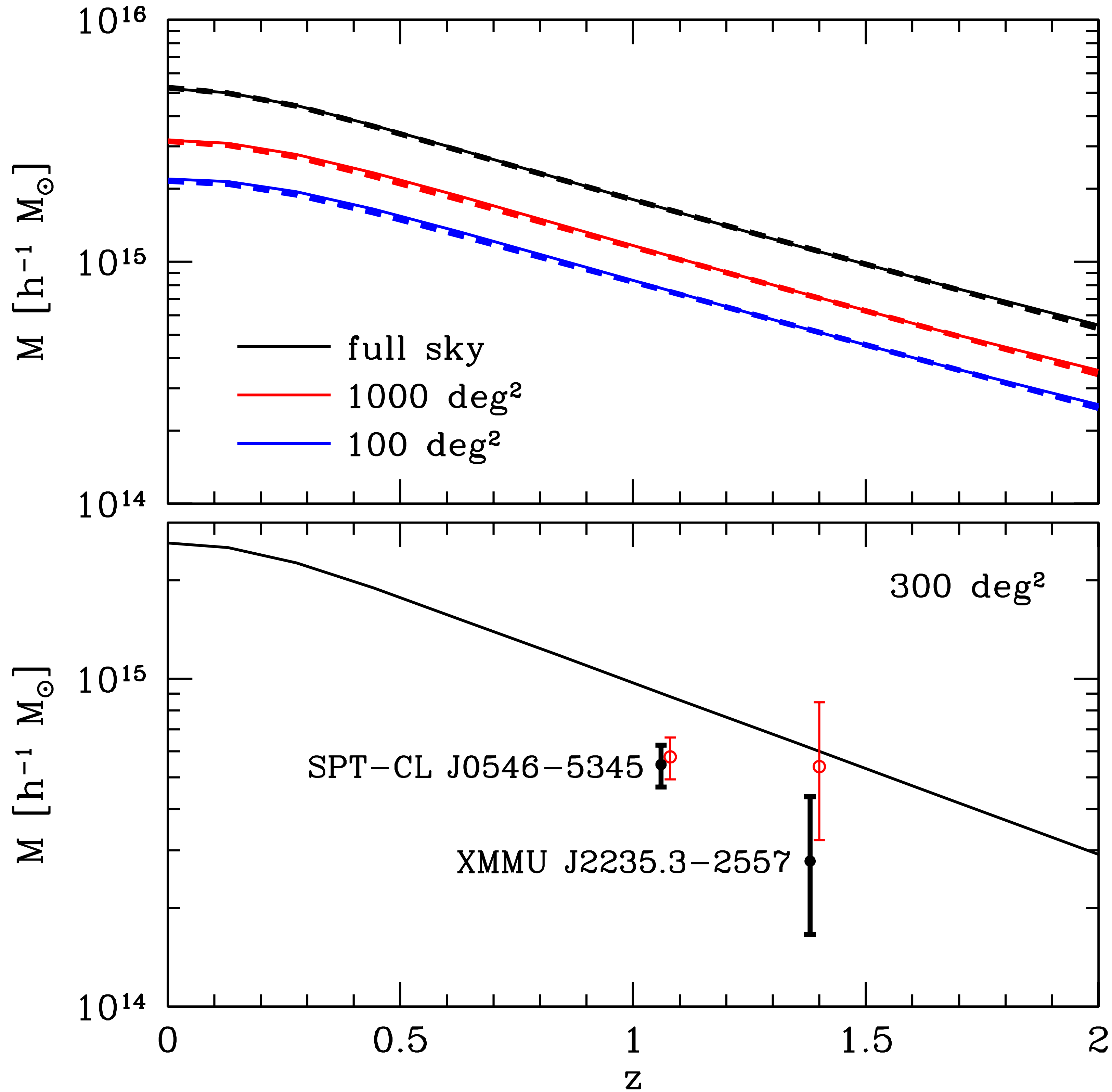
(≠ Malmquist bias: more luminous objects are more likely to scatter into the sample)

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

log slope of MF (is negative)



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



Shown limits: 95% both sample and parameter variance for finding one cluster with >M, >z

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

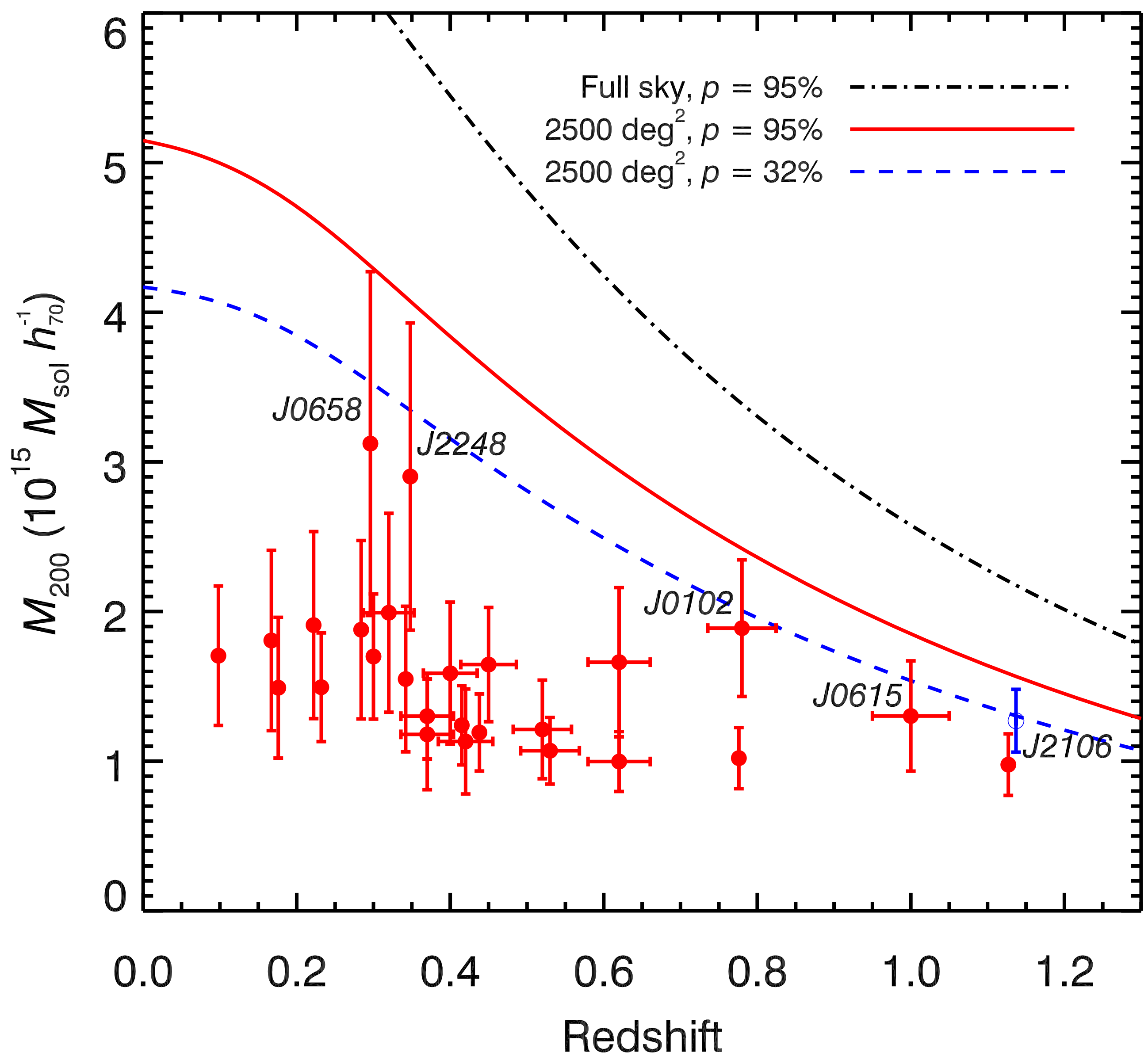
Mortonson, Hu & Huterer, 2011

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}

Williamson et al. 2011
(SPT)



Conclusions

- We are well into the systematics-dominated era of DE measurements.
- Example I: Photo-z errors.
- Example II: Photometric calibration errors.
- How do we quantify and treat these errors? Self-calibration is powerful, but can't self-calibrate everything.
- We have accurate, tight predictions for D(z), G(z), H(z) and the observable quantities for each class of DE models $\Rightarrow$ way to rule them out.