The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2419-5

Workshop on Large Scale Structure

30 July - 2 August, 2012

Falsifying LambdaCDM with clusters

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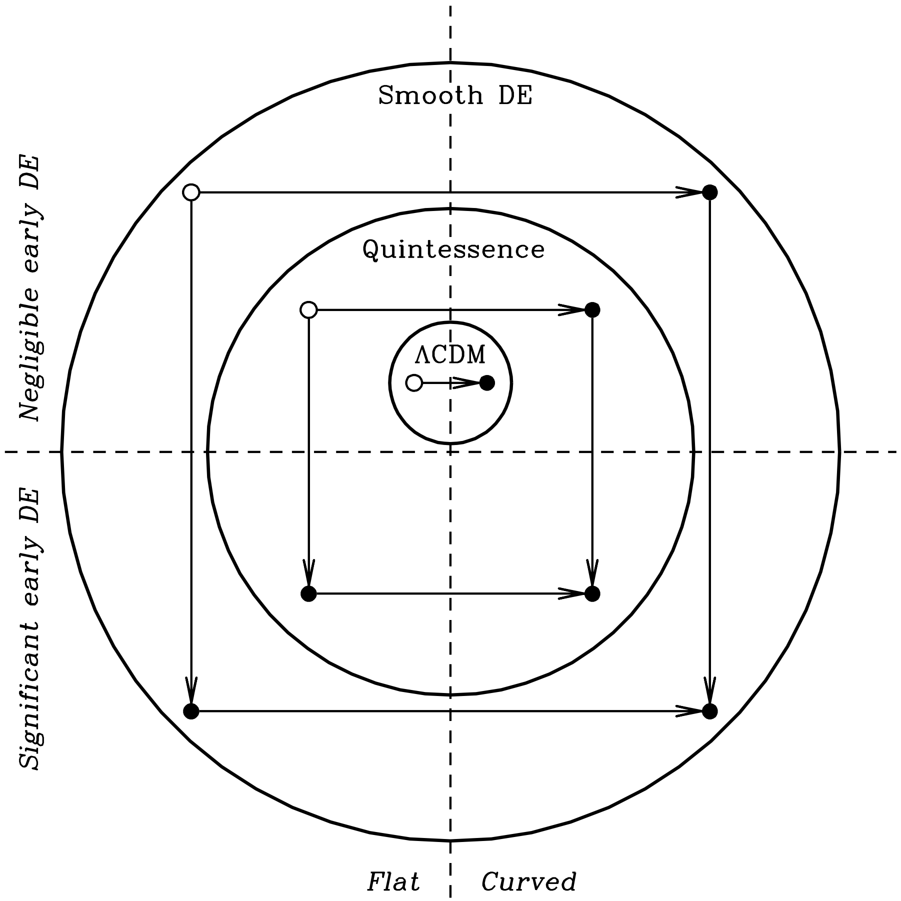
University of Michigan

Falsifying LCDM with Galaxy Clusters

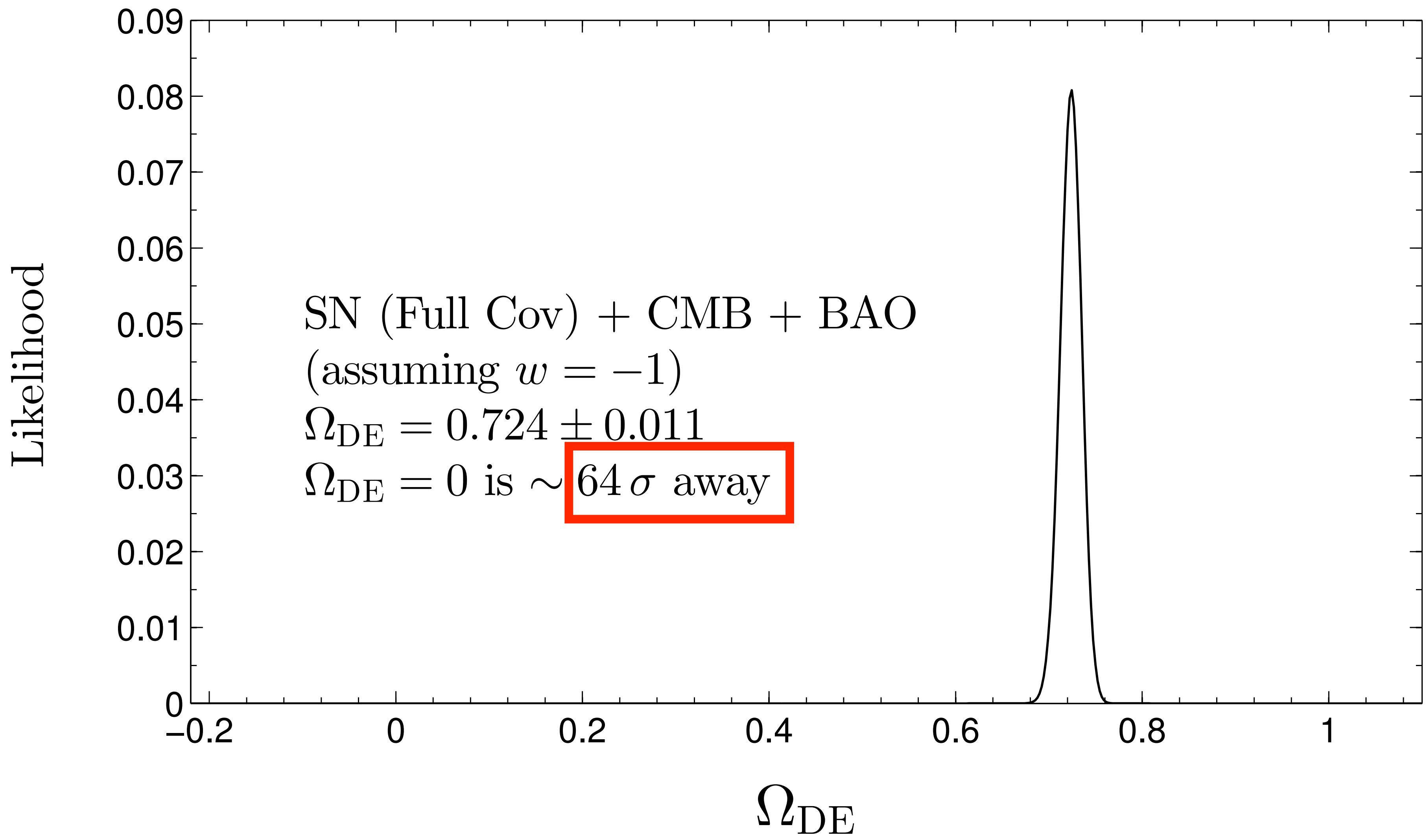
(and with future data in general)



Dragan Huterer (University of Michigan)

Collaborators:
Michael Mortonson (Ohio State), Wayne Hu (Chicago)
Eduardo Ruiz, Dan Shafer (Michigan)

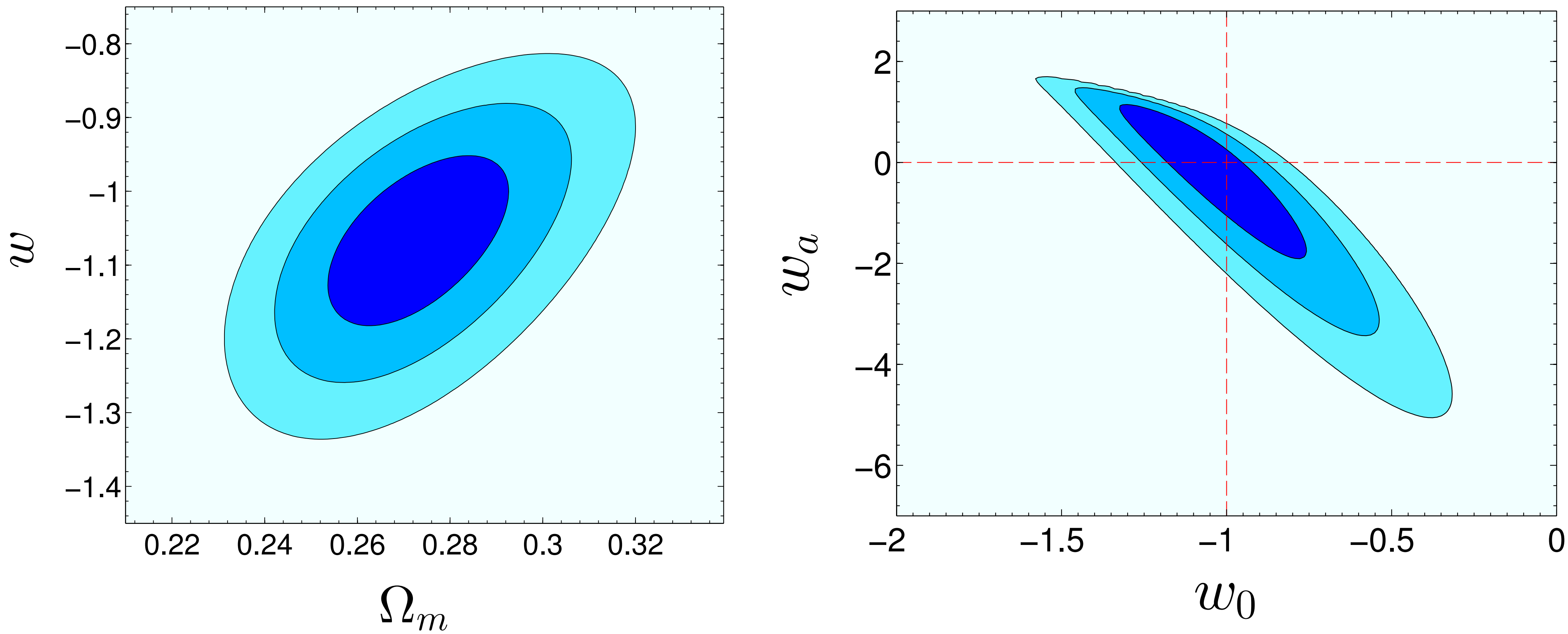
Current evidence for dark energy is impressively strong



Dan Shafer (Michigan)

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

SN + BAO + CMB

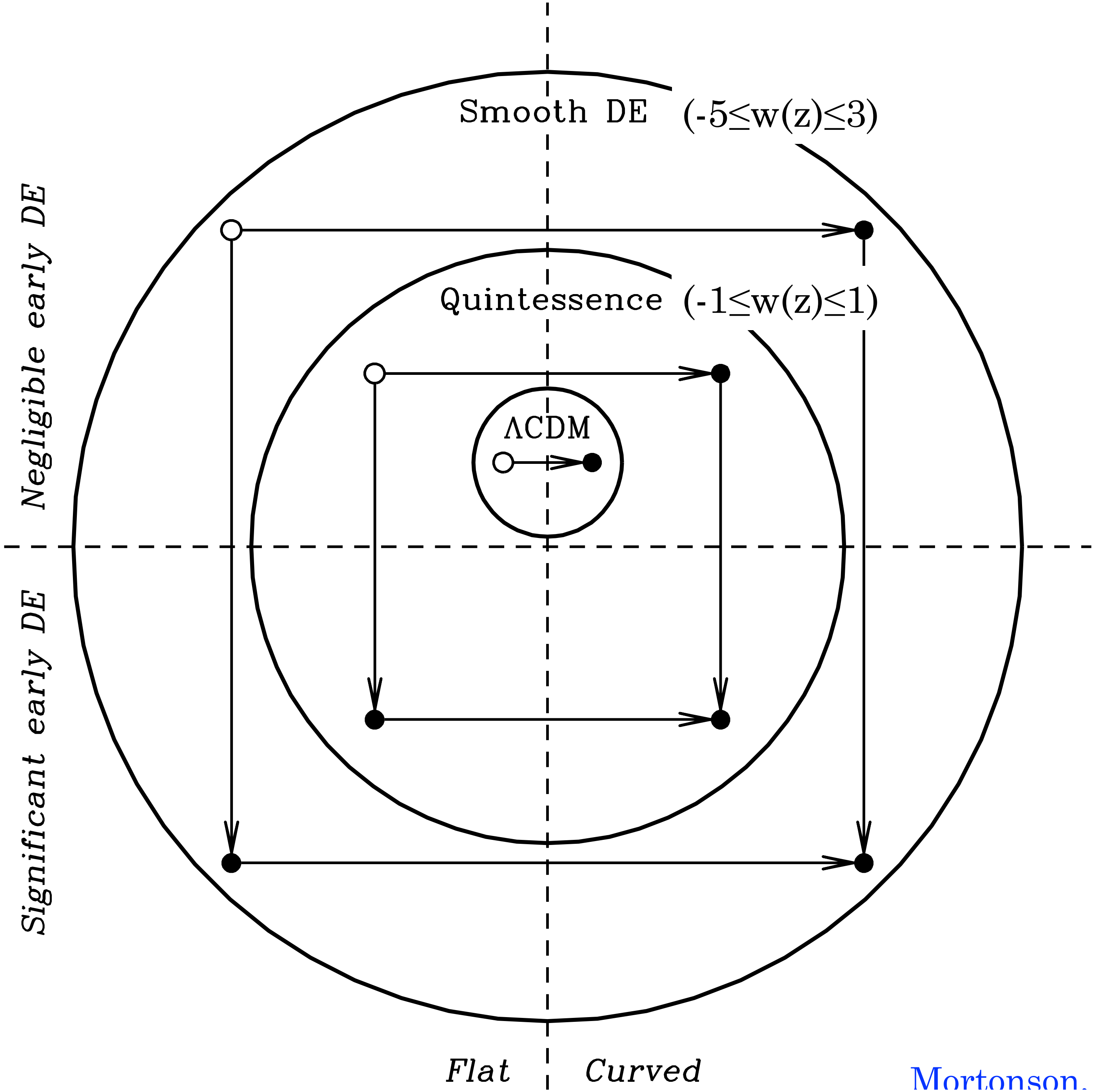


Ruiz, Shafer et al. 1206.4781

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, Euclid, ...)

DE Models and their complexity

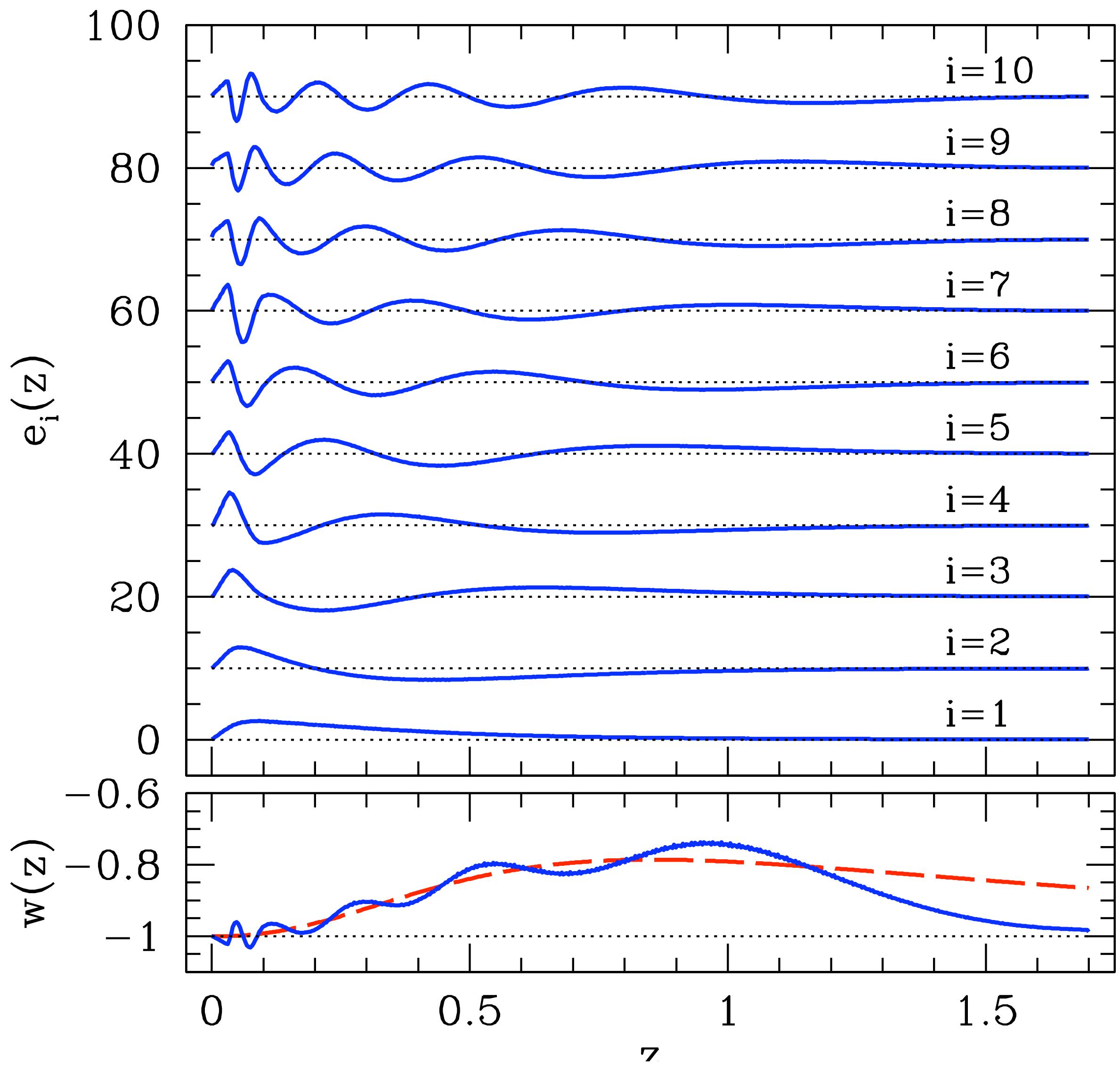


Mortonson, Hu & Huterer 2010

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 + WMAP + $BAO_{z=0.35}$ + H_0)

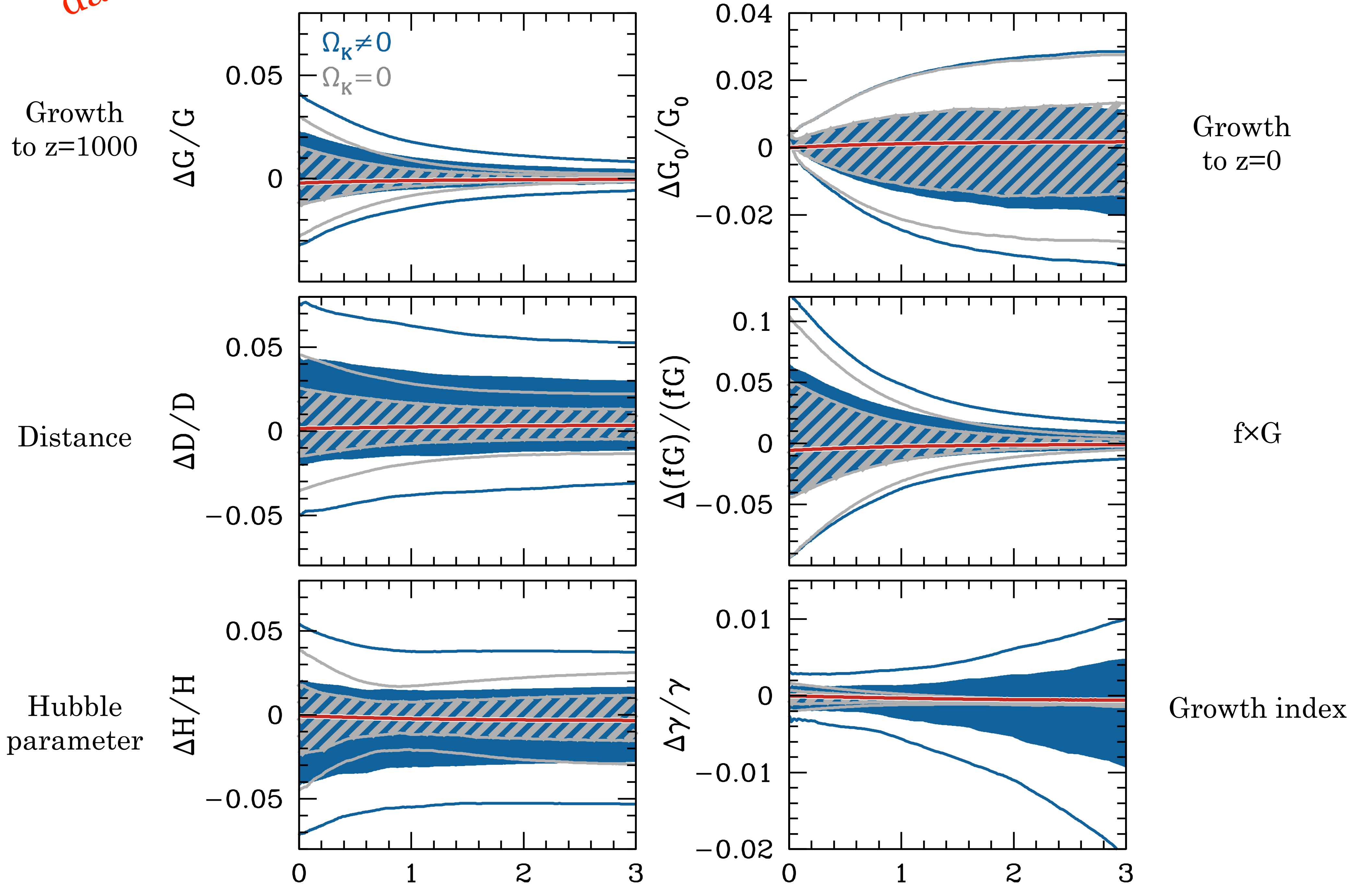
3. Employ the likelihood machine

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

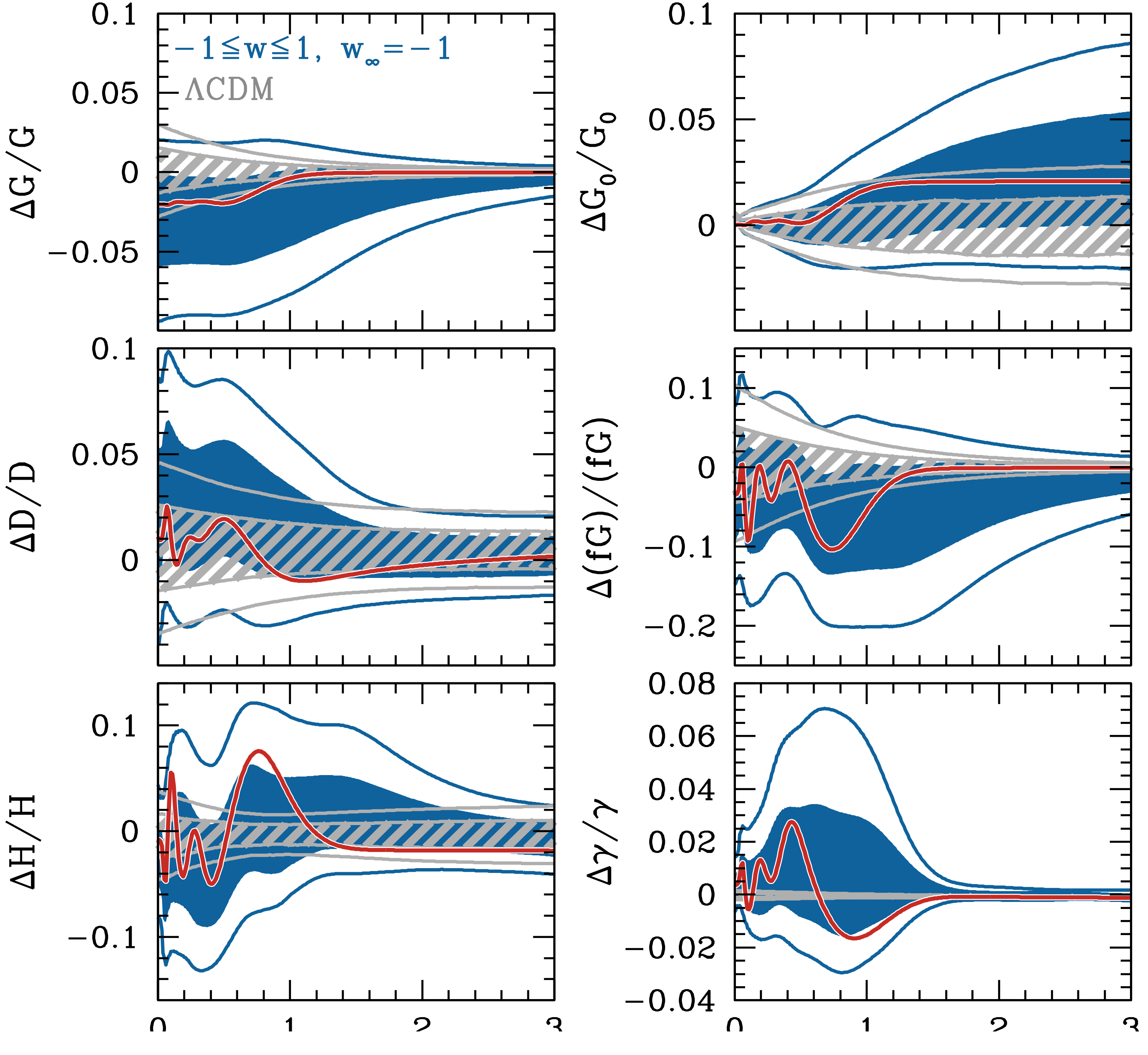
4. Compute predictions for D(z), G(z), H(z) (and $\gamma(z)$, f(z))

LCDM predictions - flat or curved

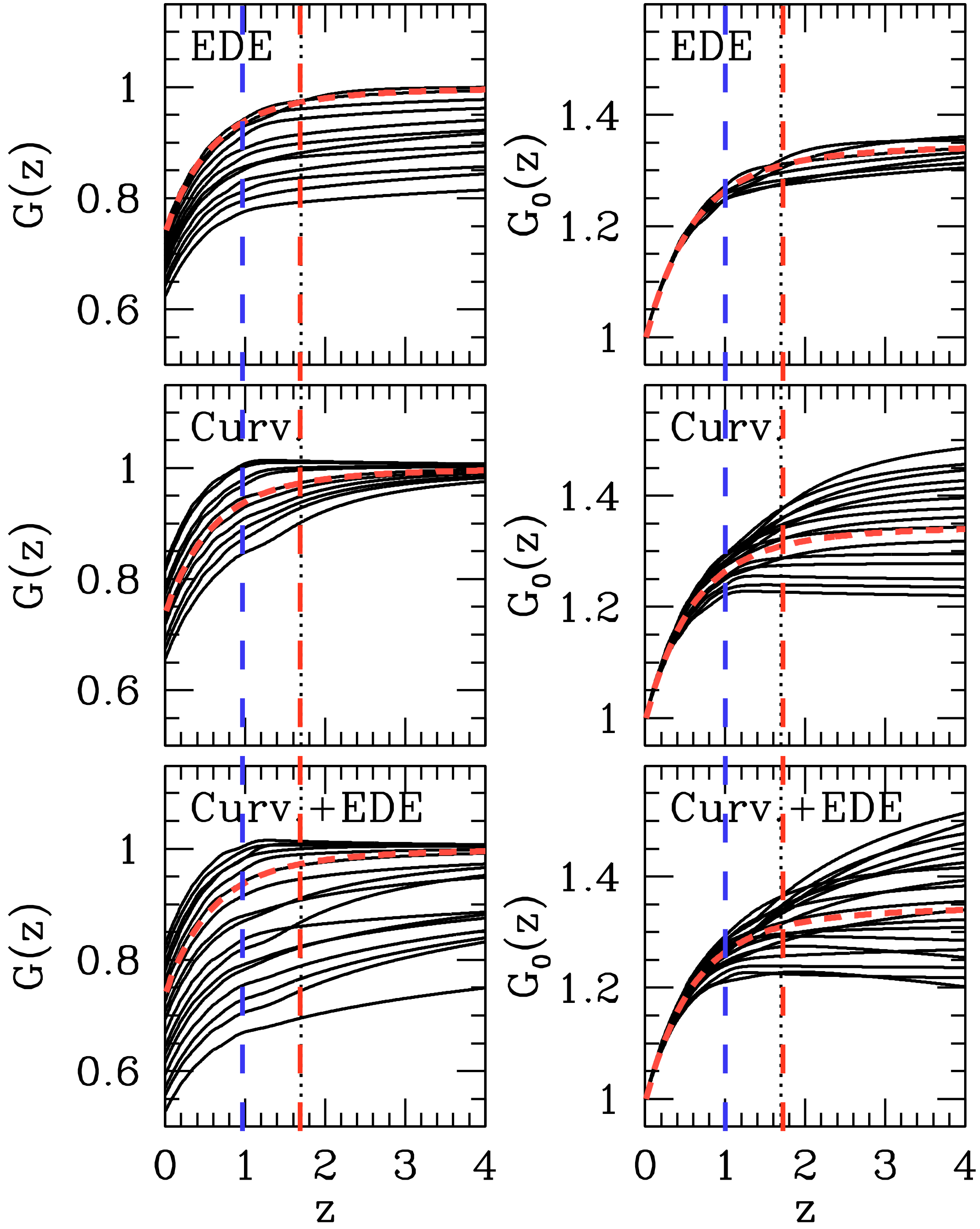
Current data



Current data Quintessence predictions (flat, no Early DE)

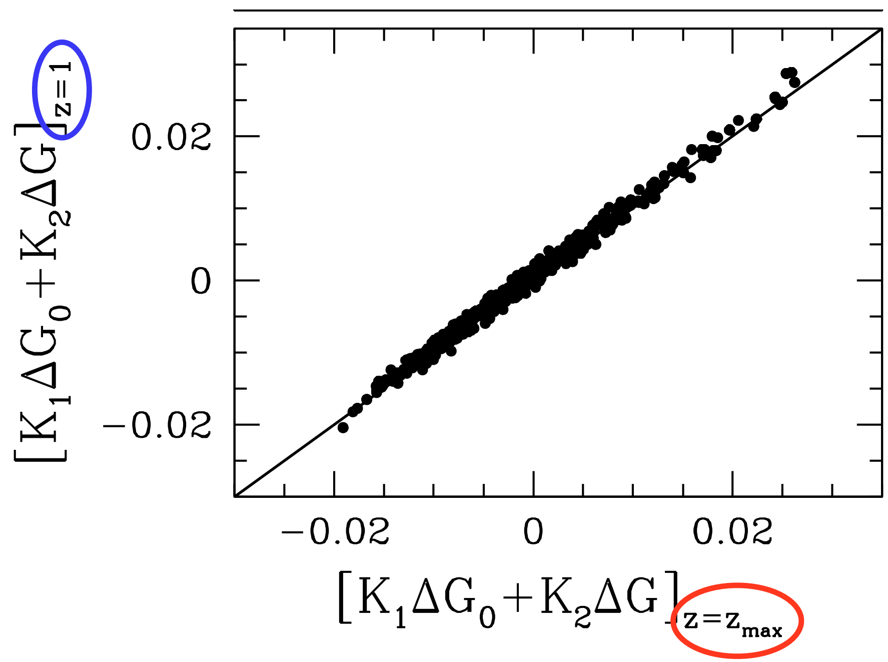


Smooth DE with curvature and/or Early DE

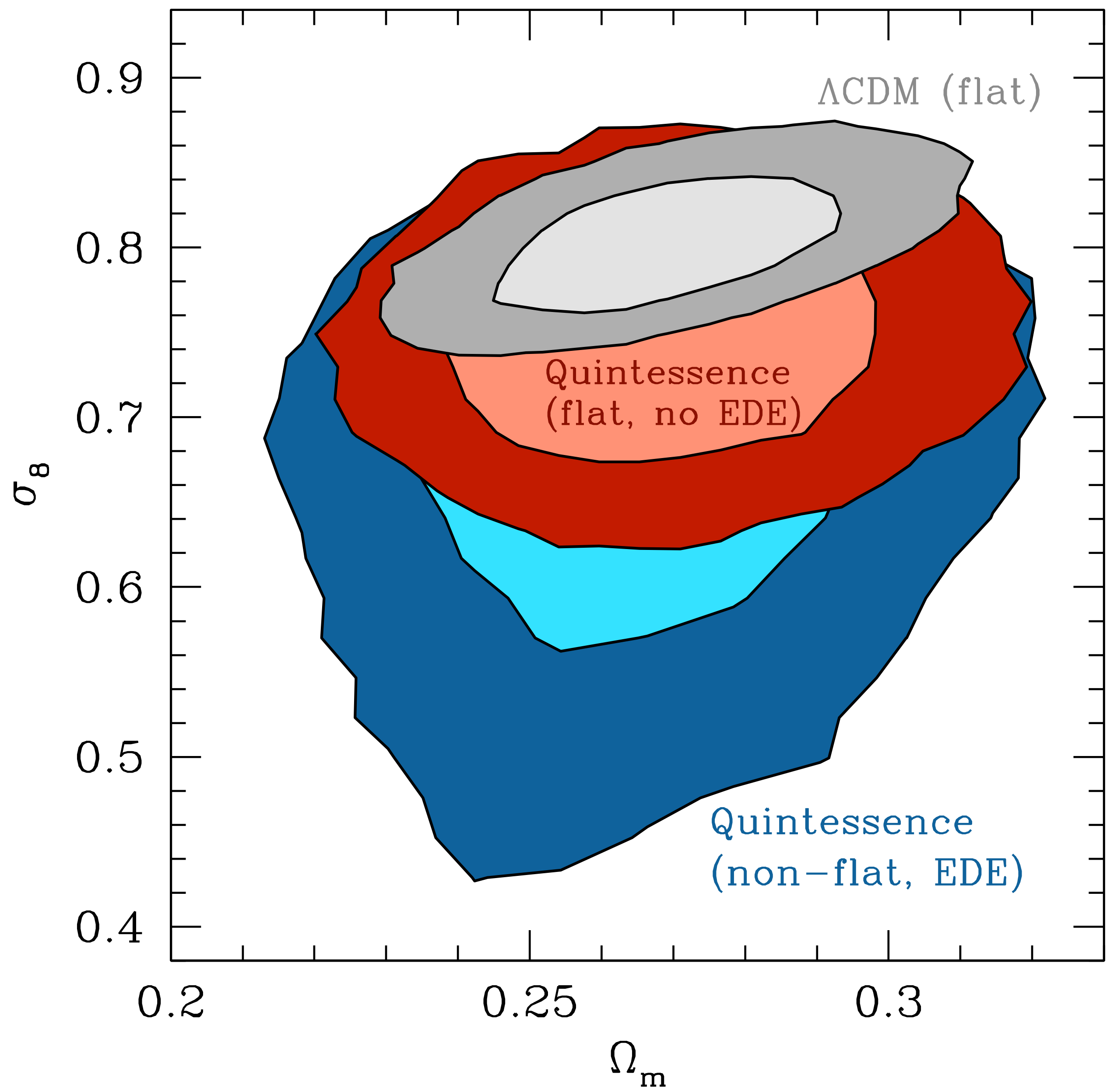


Some quantities are accurately predicted even in very general classes of DE models

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



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



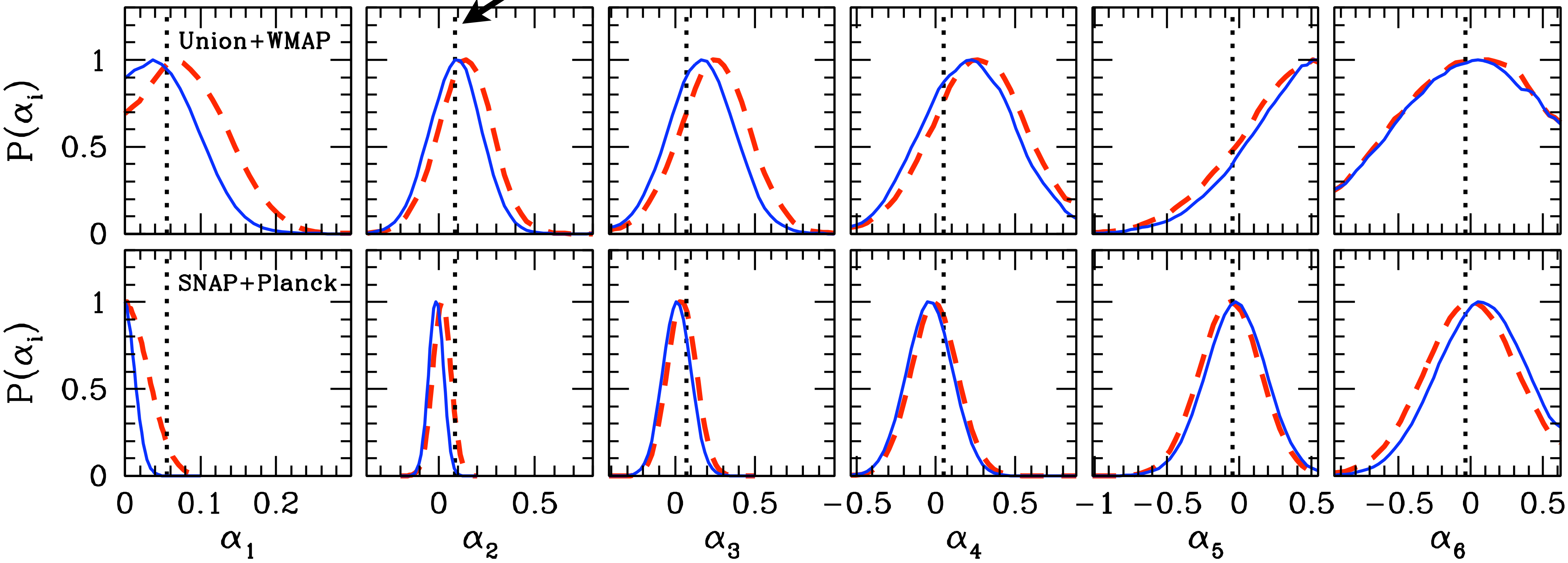
Mortonson, Hu & Huterer 2010

In *principal*, constraints are good...

(components)

values for example quintessence model

Top row:
Current Data



Bottom Row:
Future Data
(assumes $\alpha_i=0$)

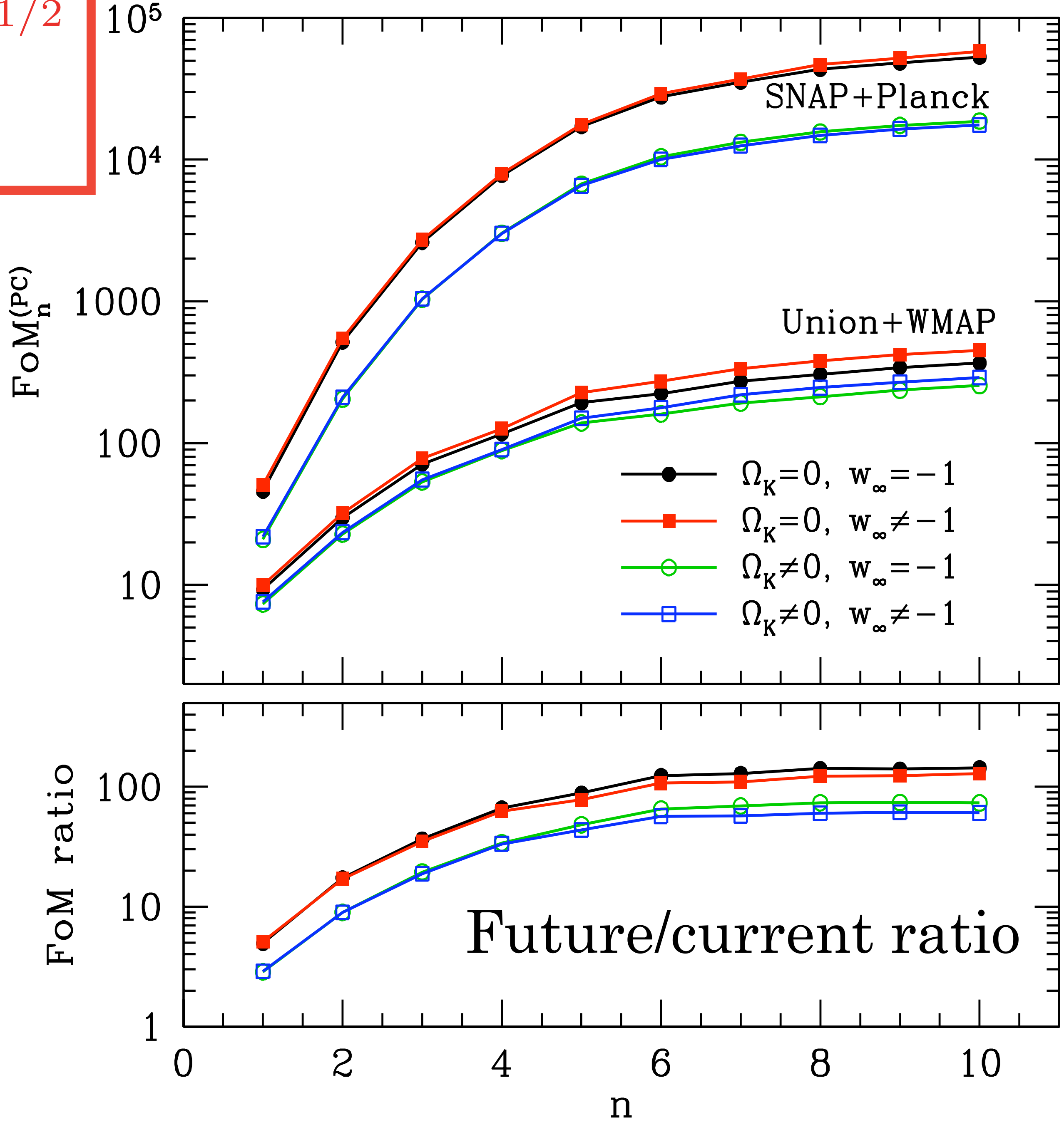
Flat

Curved

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

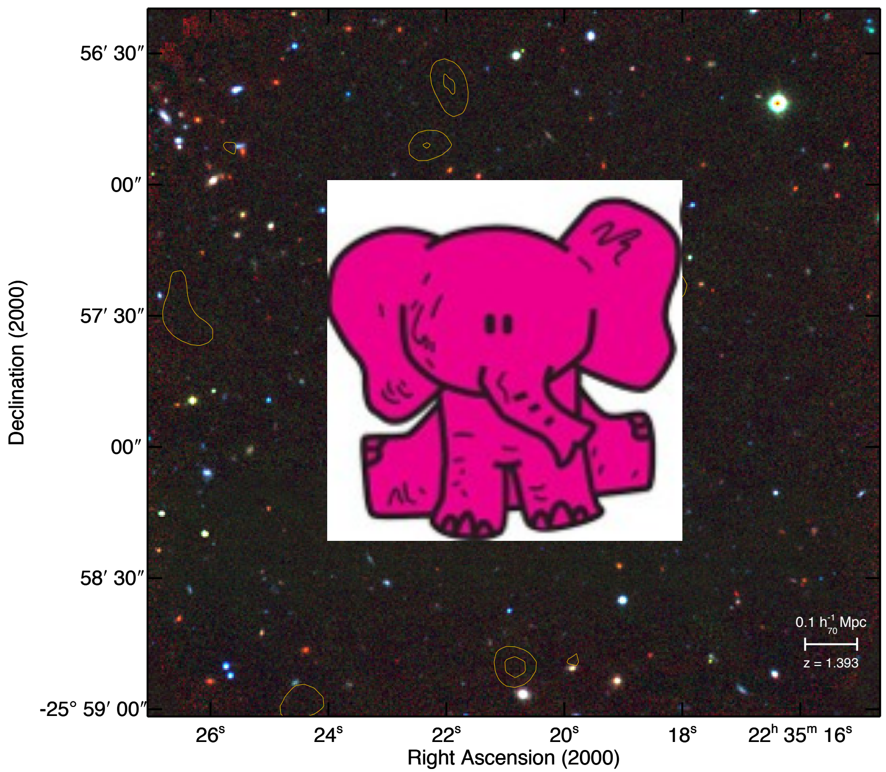
$$\mathrm{FoM}_n^{(\mathrm{PC})} \equiv \left(\frac{\det \mathbf{C}_n}{\det \mathbf{C}_n^{(\mathrm{prior})}} \right)^{-1/2}$$

(proportional to volume of n-dim ellipsoid)



Full SN systematics degrade this FoM by factor 2-3
(Ruiz et al, arXiv:1206.4781)

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

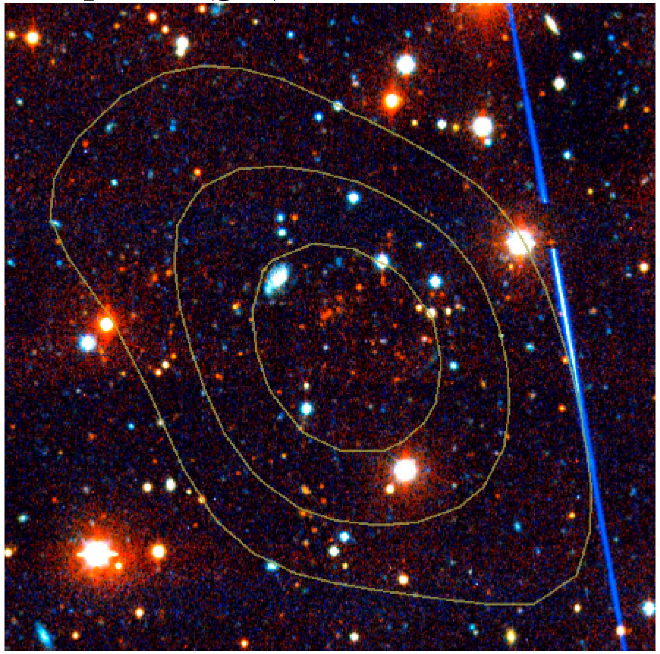
Pink elephant, candidate 1: SPT-CL J0546-5345

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

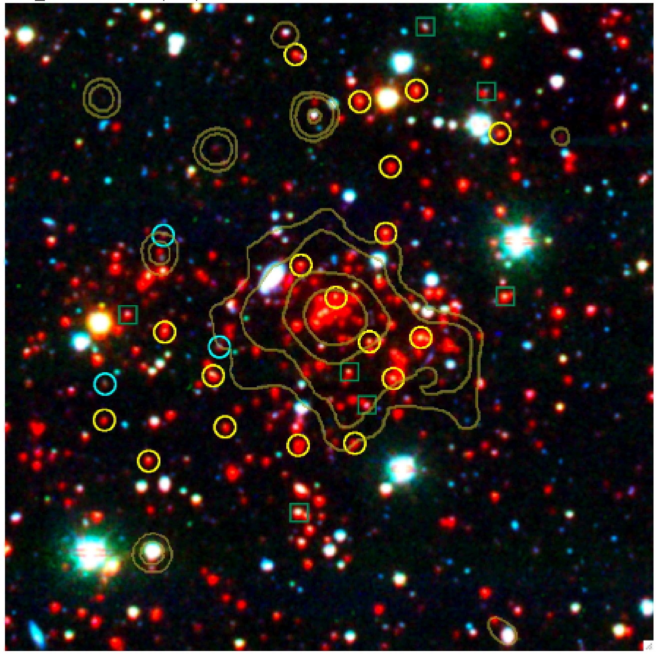


TABLE 2
Comparison of Mass Measurements for SPT-CL J0546-5345

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)	$9.2 \pm 4.9 \pm 2.7$

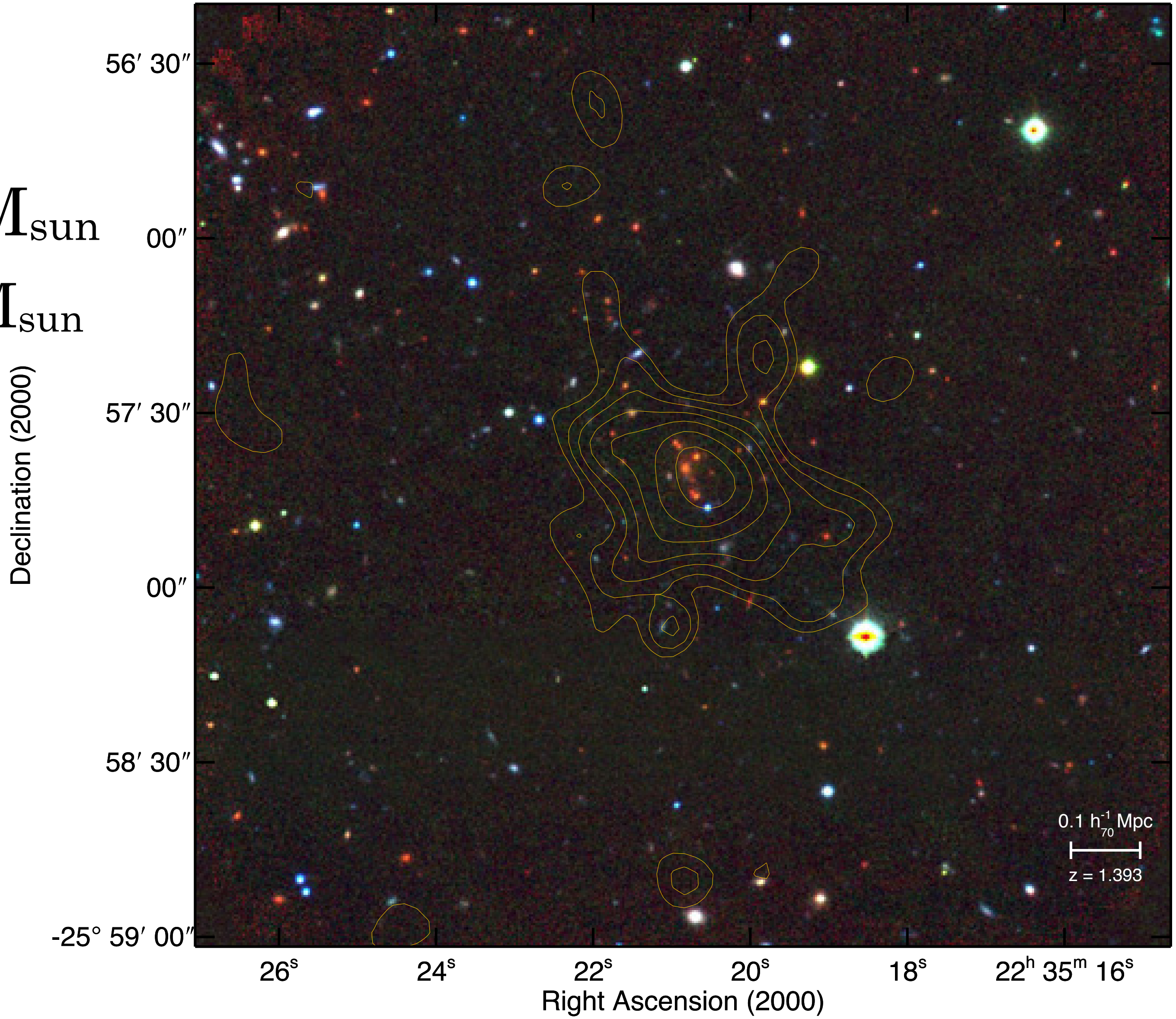
Pink elephant, candidate 2: XMMU J2235.3-2557

Mullis et al, 2005
Jee et al. 2008

$z=1.39$

$M_{x\text{-ray}} \approx (7.7\pm4)\cdot10^{14}\,M_{sun}$

$M_{WL} \approx (8.5\pm1.7)\cdot10^{14}\,M_{sun}$

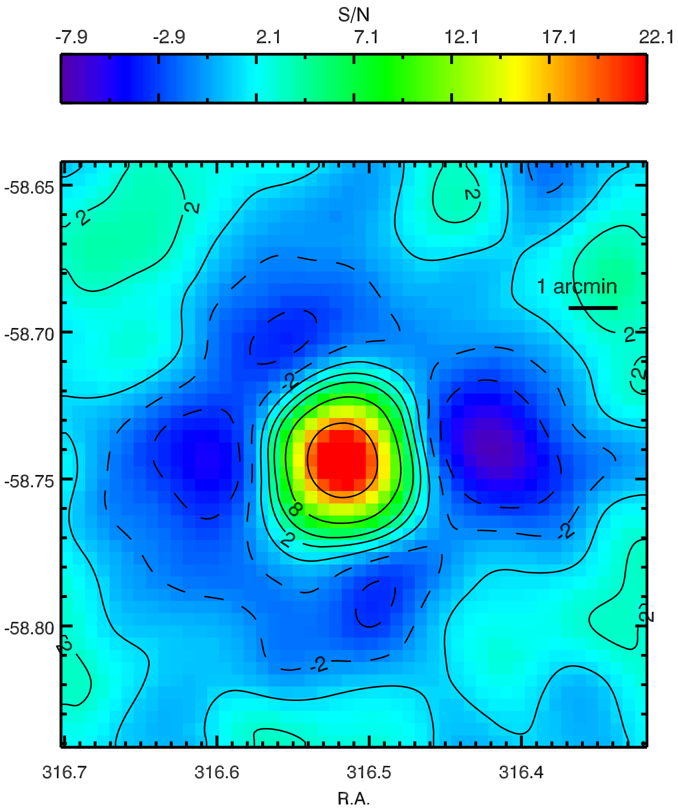


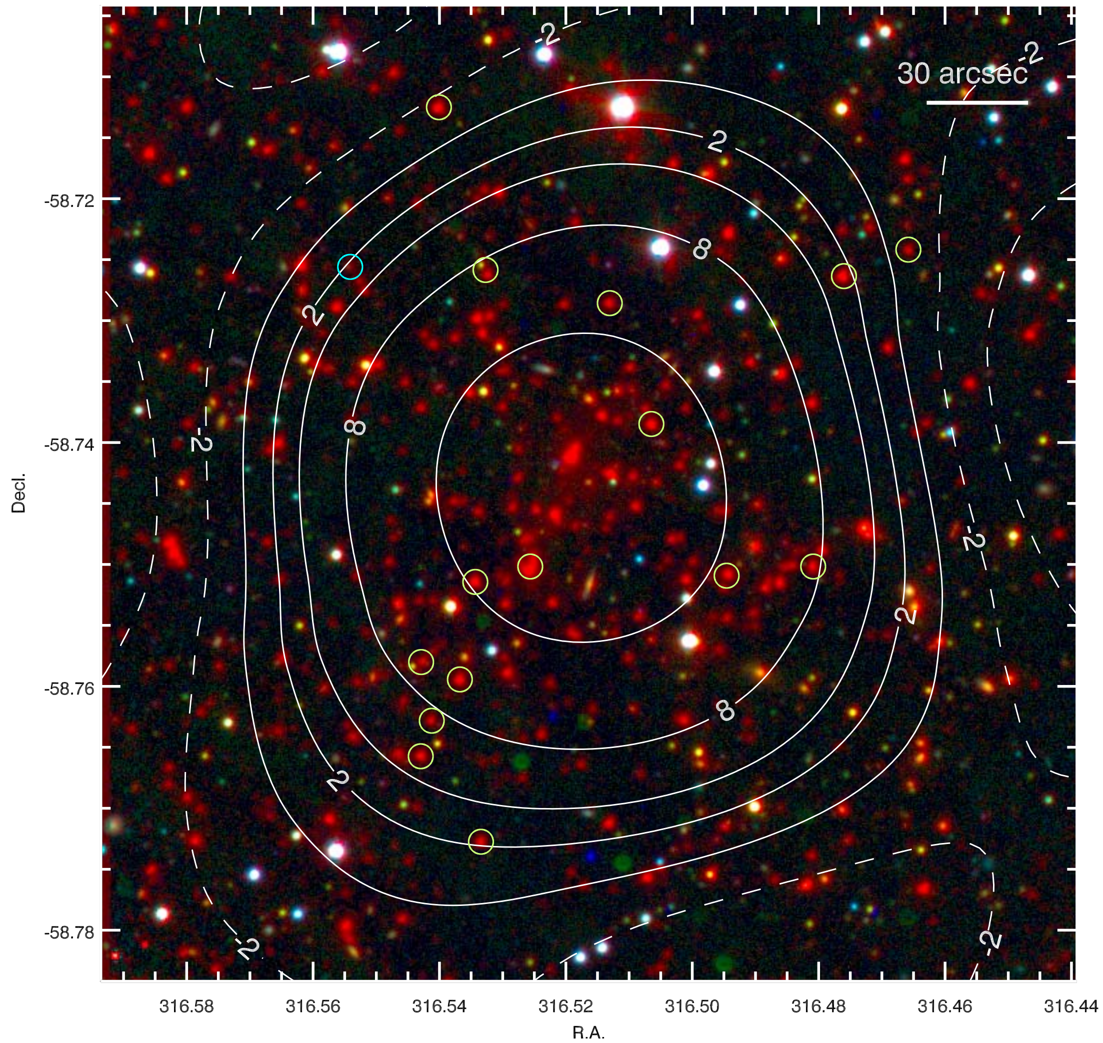
Pink elephant, candidate 3: SPT-CL J2106-5844

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

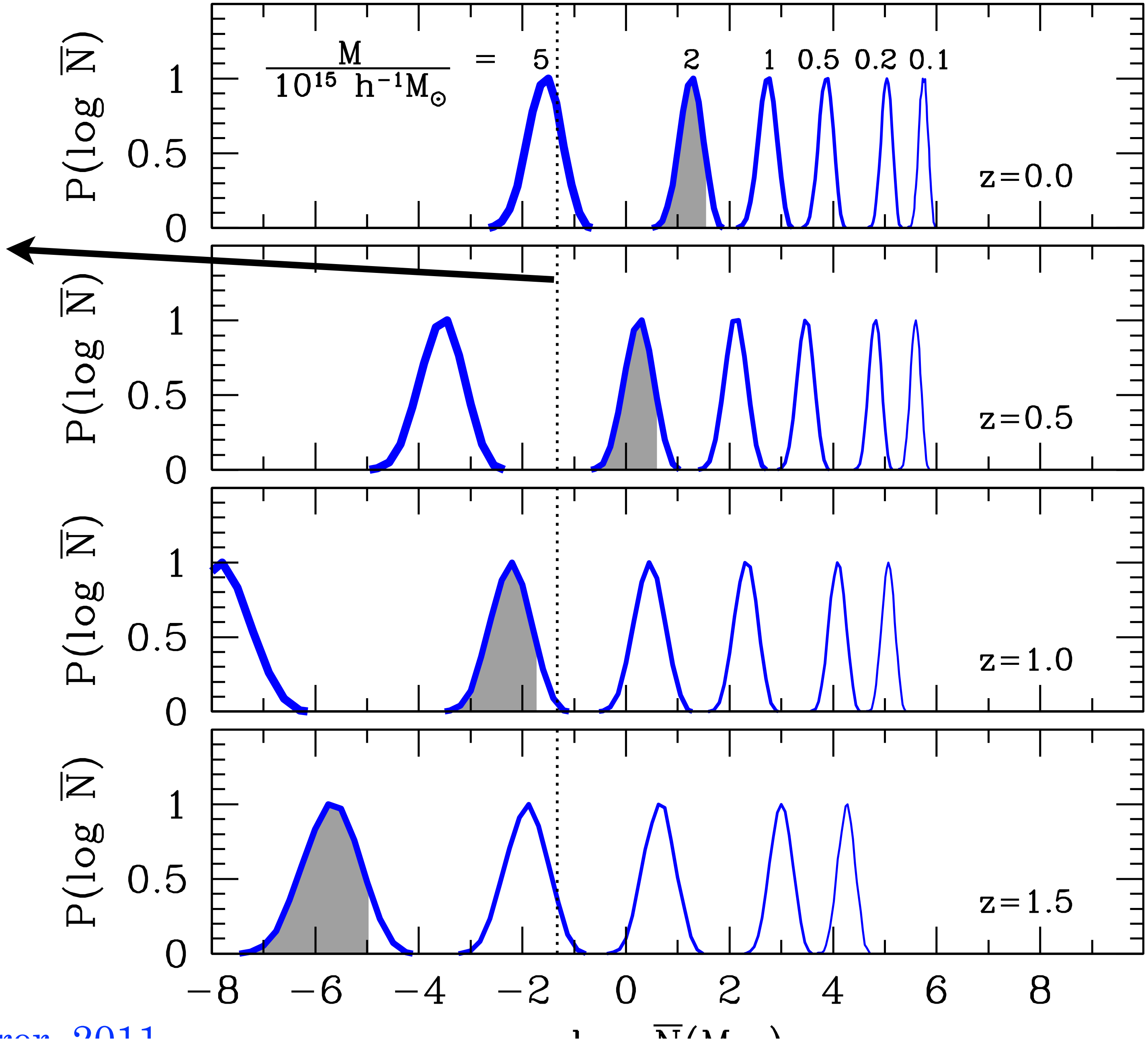
1. **Sample variance** - the Poisson noise in counting rare objects in a finite volume

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

Parameter variance

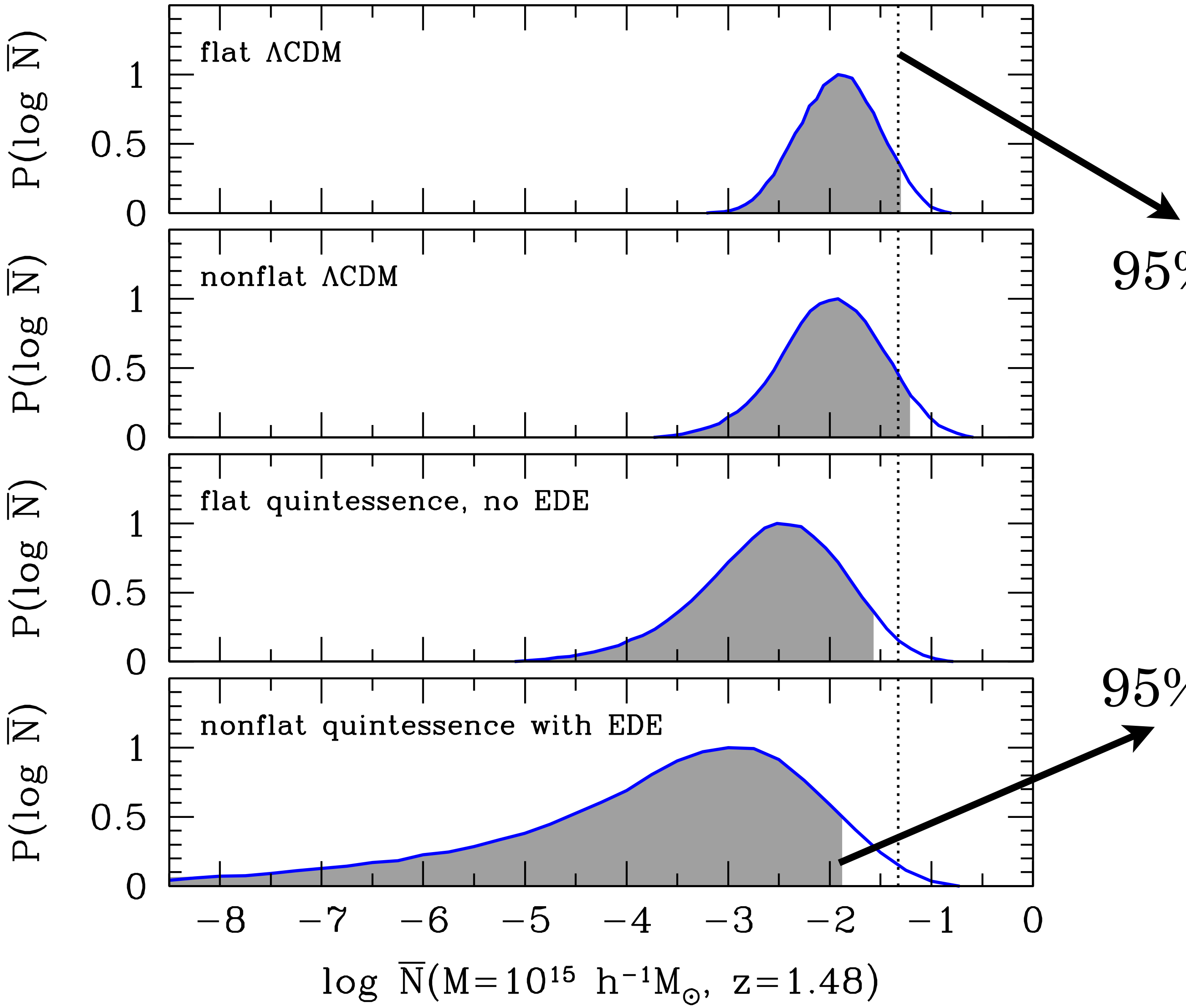
(due to uncertainty in cosmo parameters)

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



Mortonson, Hu & Huterer 2011

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



95% sample variance limit for f_{sky}=1

95% parameter variance limit

Rule out ΛCDM ⇒ automatically rule out quintessence

Eddington bias

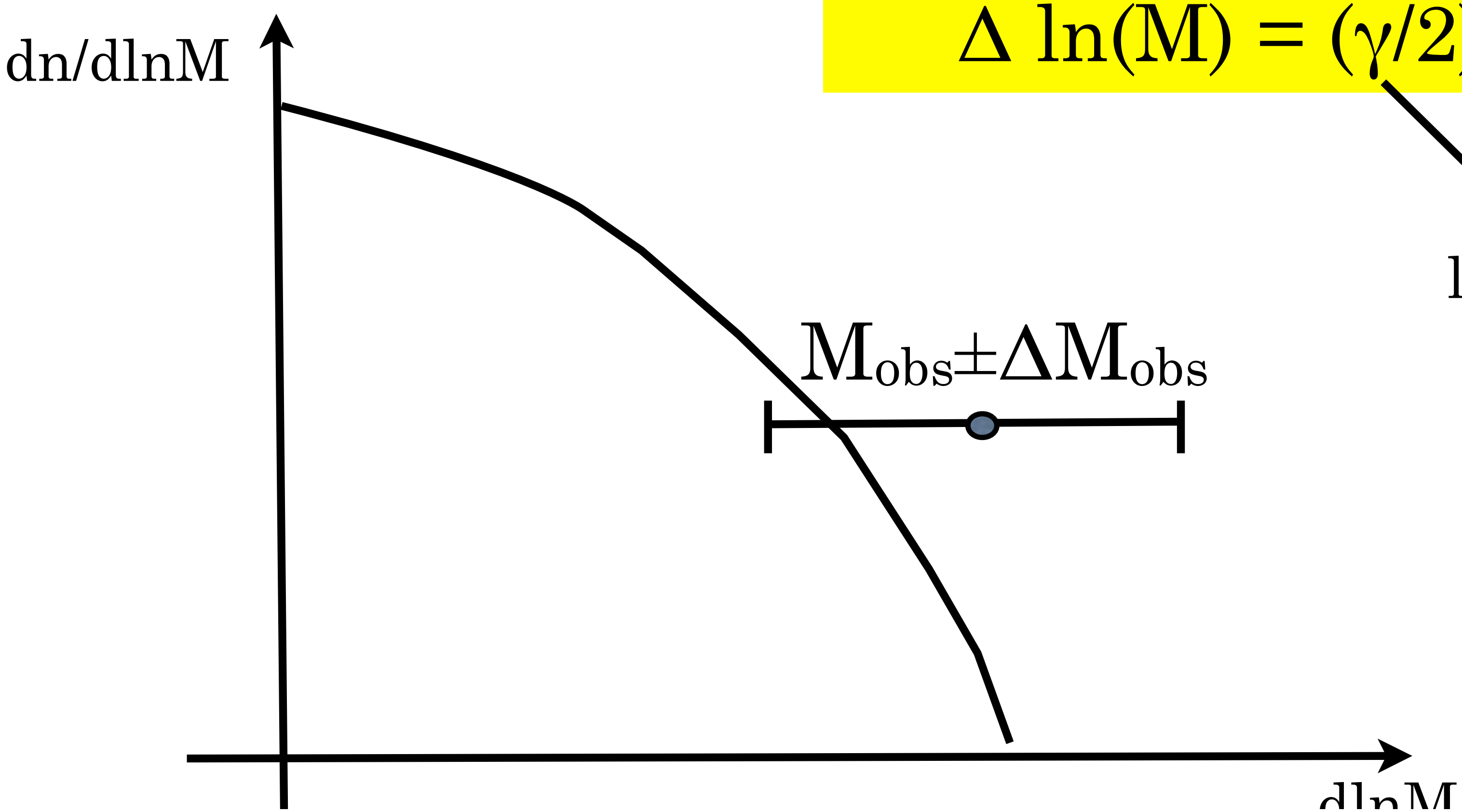
A.S. Eddington, MNRAS, 1913

For a steeply falling mass function,
observed mass was more likely to be scattered into observed range from lower M than for higher M

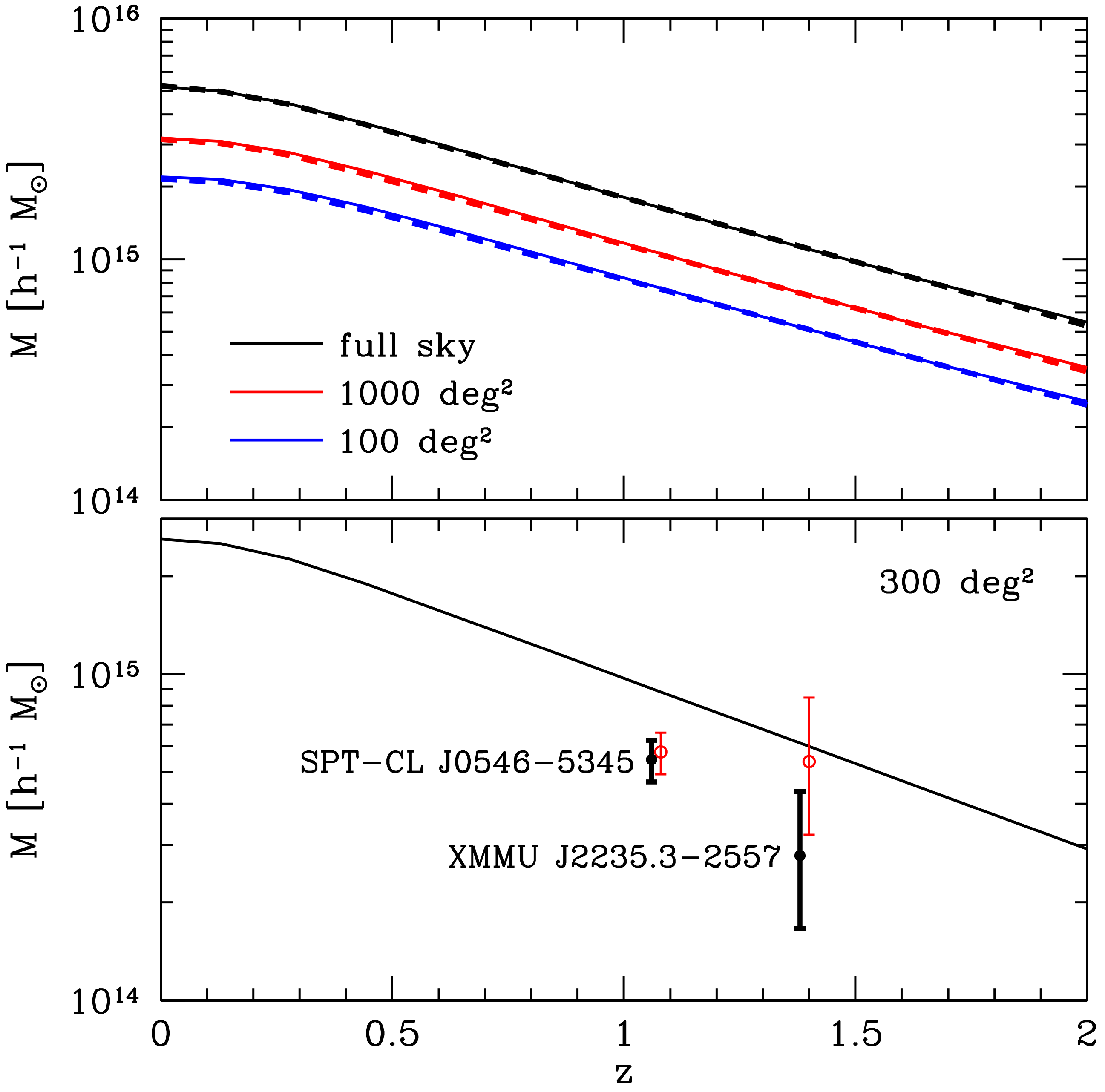
(≠ Malmquist bias: more luminous objects are more likely to scatter into the sample)

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

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

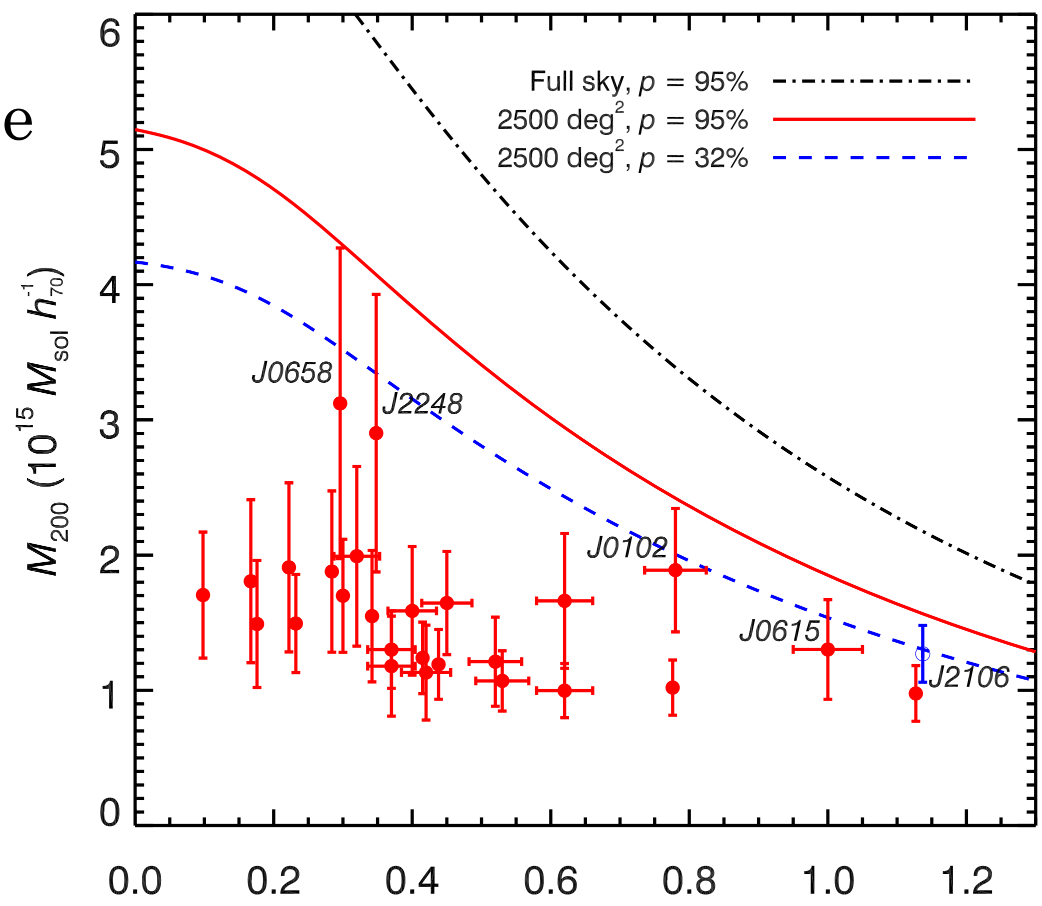
black error bars: masses corrected for **Eddington bias**

Potentially useful product of paper:

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

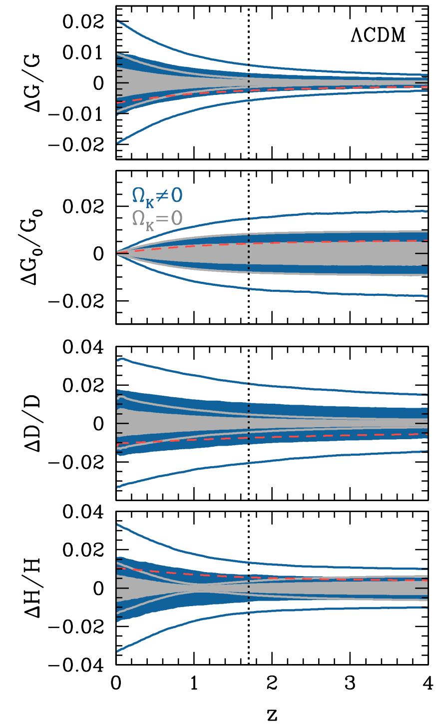
- ✓ mass and redshift
- ✓ sample variance confidence
- ✓ parameter variance confidence
- ✓ f_{sky}

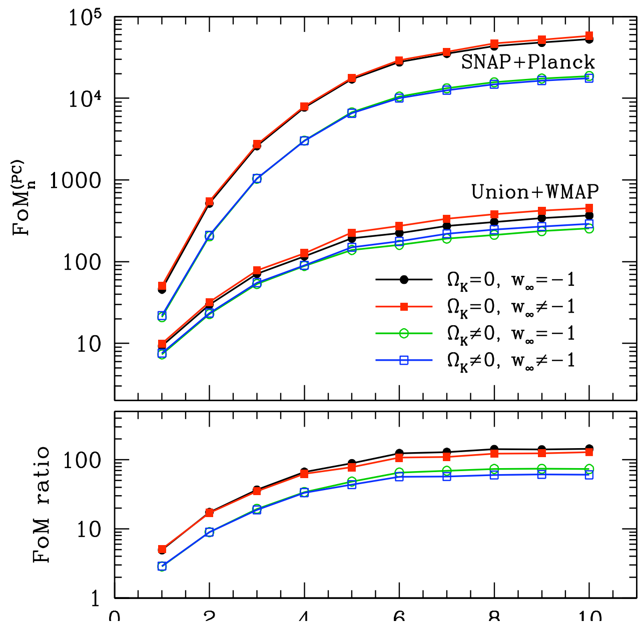
Williamson et al. 2011 (SPT)



Conclusions 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