Figures of Merit for Dark Energy Measurements

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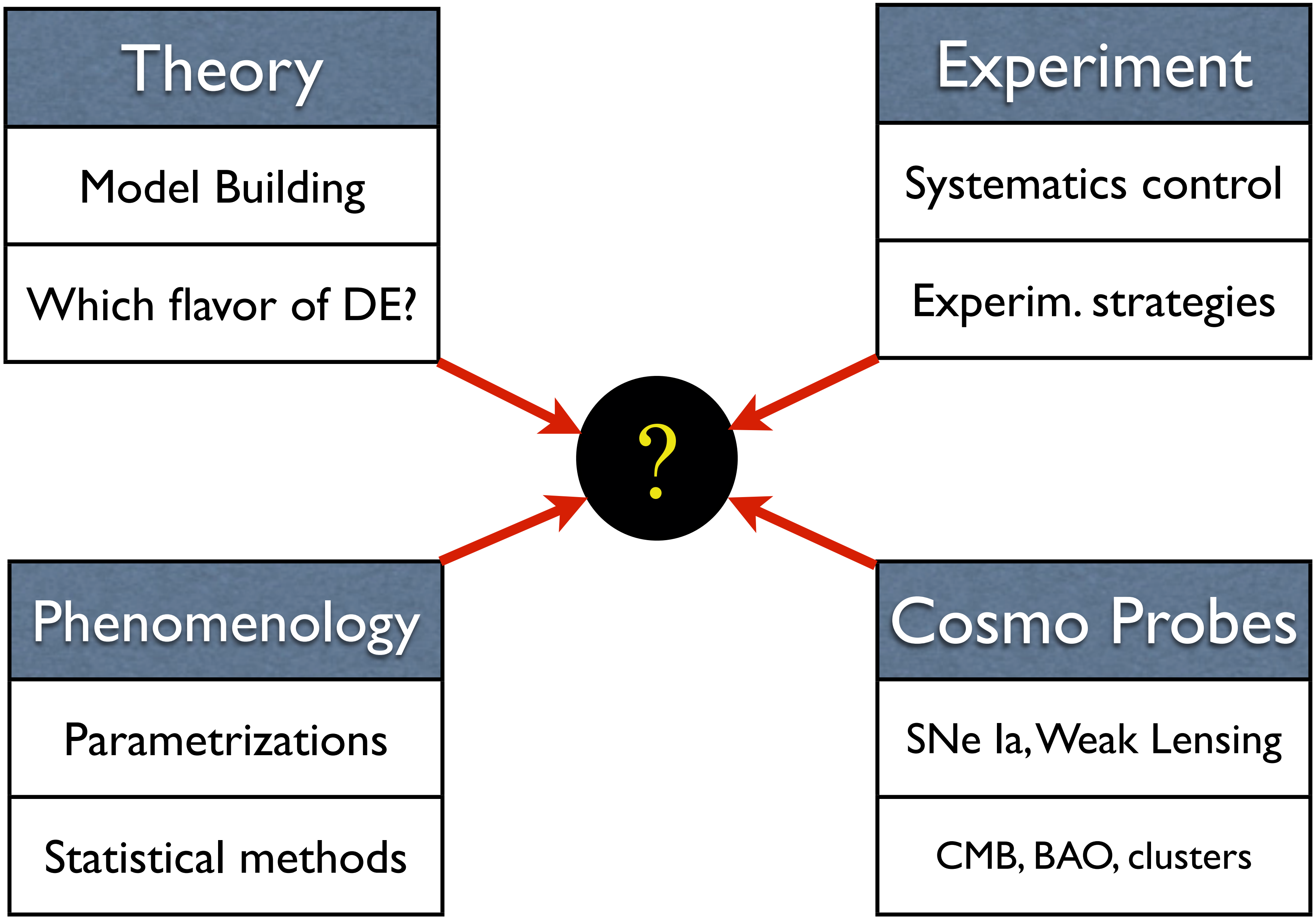
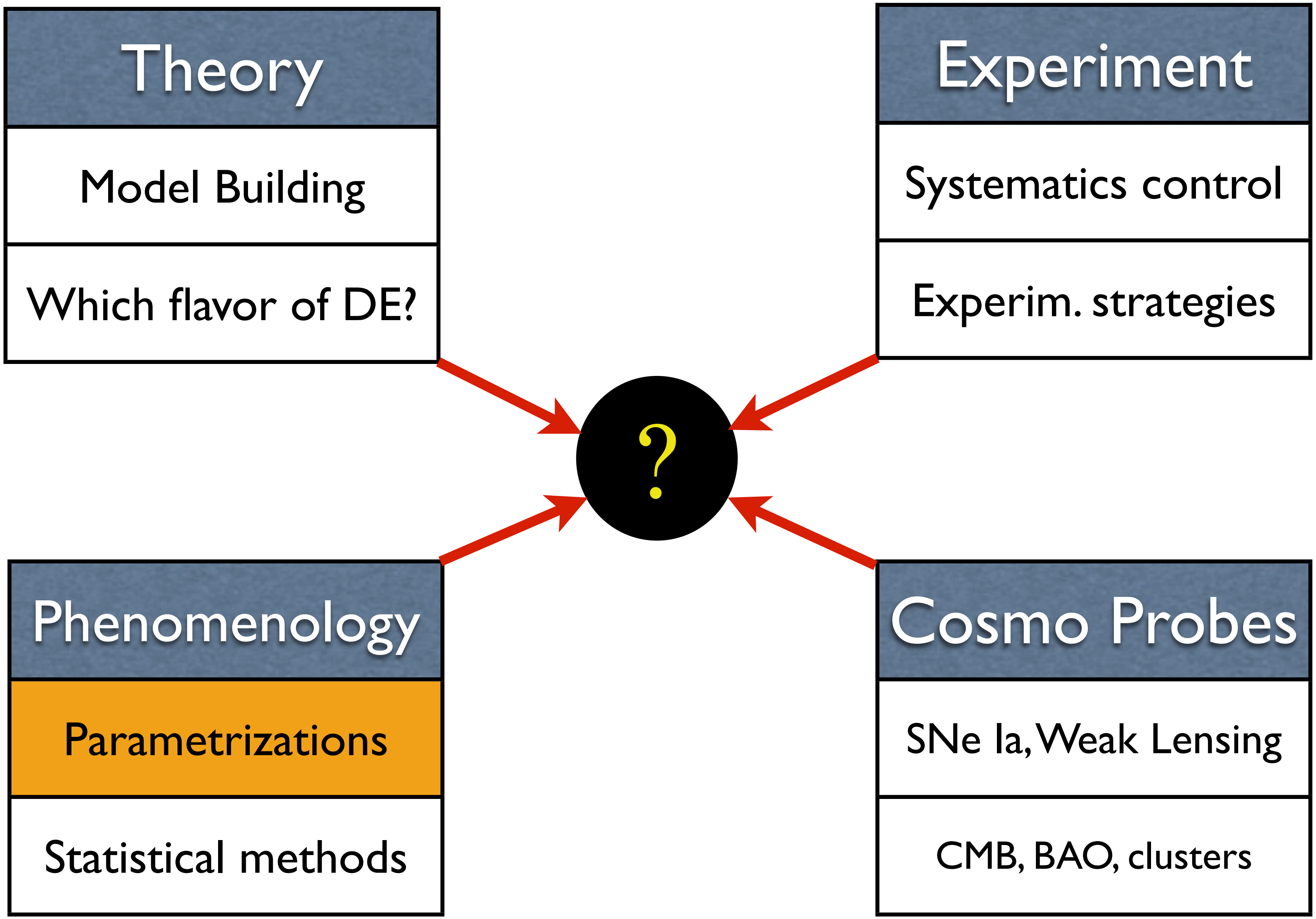
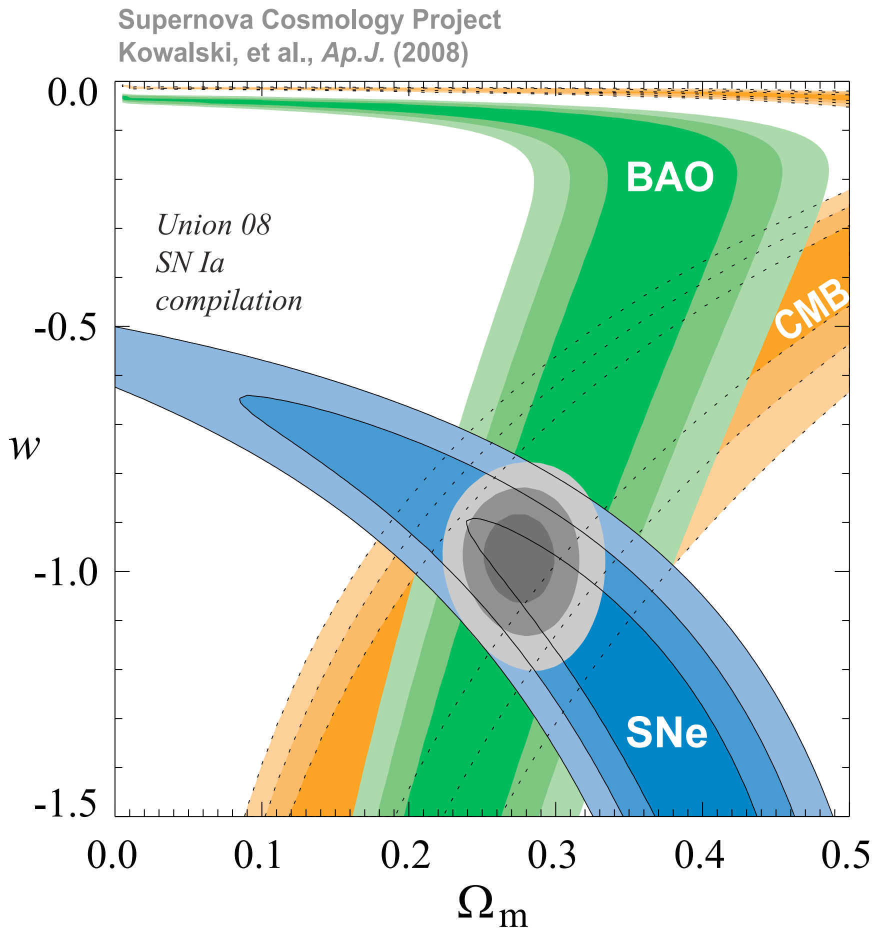
What next for Dark Energy?

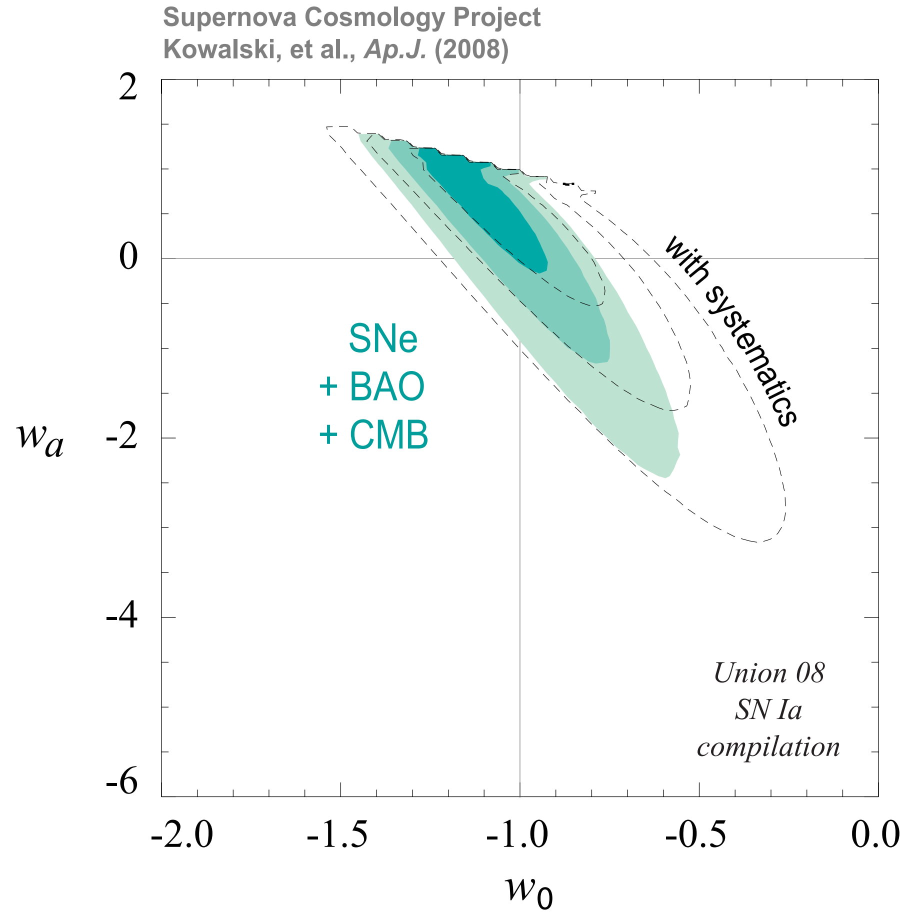


What next for Dark Energy?



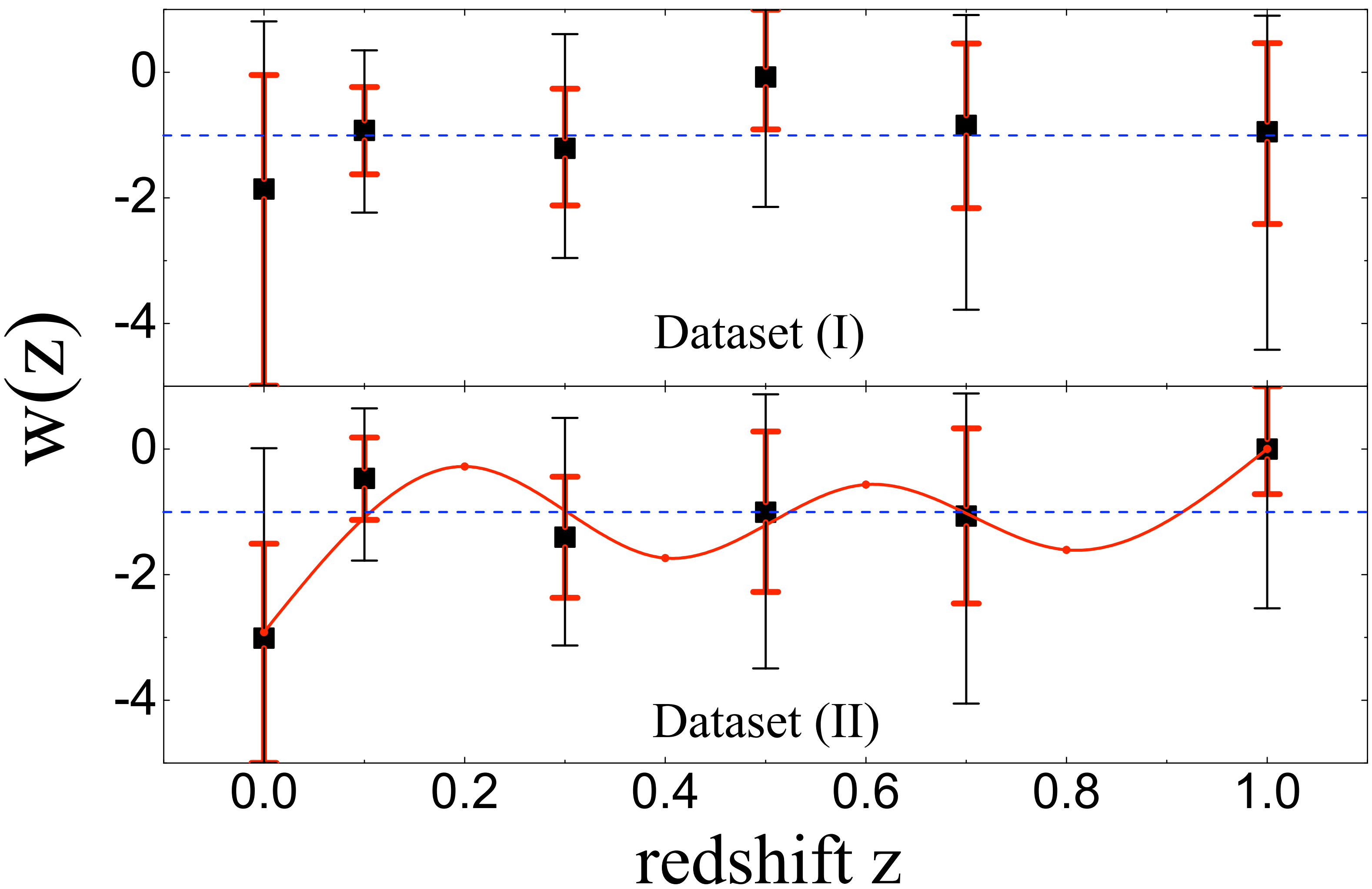
Dark Energy constraints: current status





Kowalski et al., arXiv:0804.4142

Dark Energy constraints: current status



Zhao, Huterer & Zhang, arXiv:0712.2277

Figure of Merit:
definition, history, current status

FoM: requirements

- FoM should show intrinsic power of any given cosmological probe OR individual experiment to measure the properties of DE
- FoM should be as robust as possible w.r.t. fiducial DE model
- Should try to intuitively capture quantities/concepts we like to measure (e.g. variation in time of w)
- It should clearly differentiate between experiments/probes in a way that agrees with overall assessment
- It should, ideally, be represented by one number!

In sum, finding a suitable FoM is neither easy nor is there a unique choice

Early work

"If we are using SNe Ia alone to determine the cosmological parameters, then we clearly want to minimize the area of the error ellipse. "

$$\text{volume of the ellipsoid} : V \propto \det(F)^{-1/2} \quad \text{where} \quad F \equiv \left\langle -\frac{\partial^2 L}{\partial p_i \partial p_j} \right\rangle$$

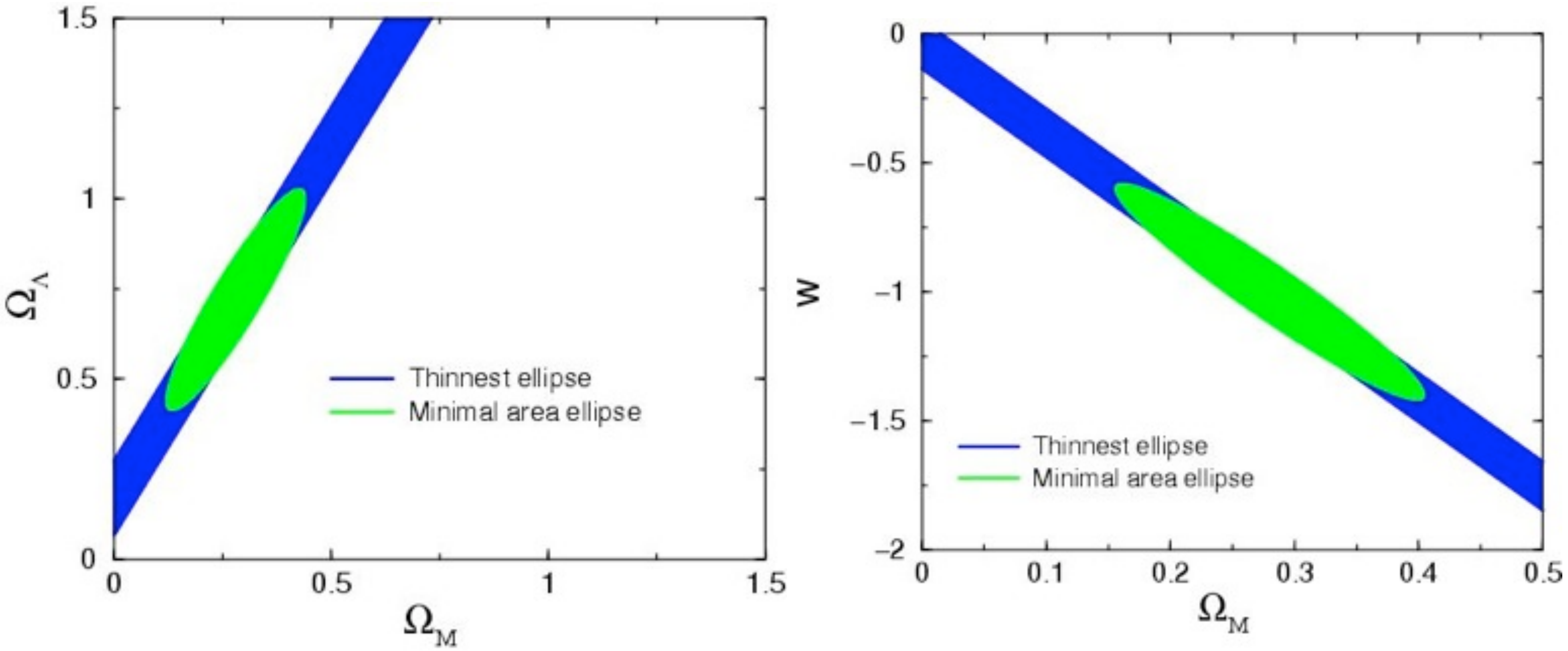
(Also showed how to get such a minimal-area/volume ellipse:
for N cosmological parameters, need SNe located at N discrete, specific locations in z)

However, clearly there are other possibilities, e.g.:

" SN measurements will also be combined with other methods to determine cosmological parameters. A good example of the symbiosis is combining CMB measurements with those of SNe." -> thinnest ellipse

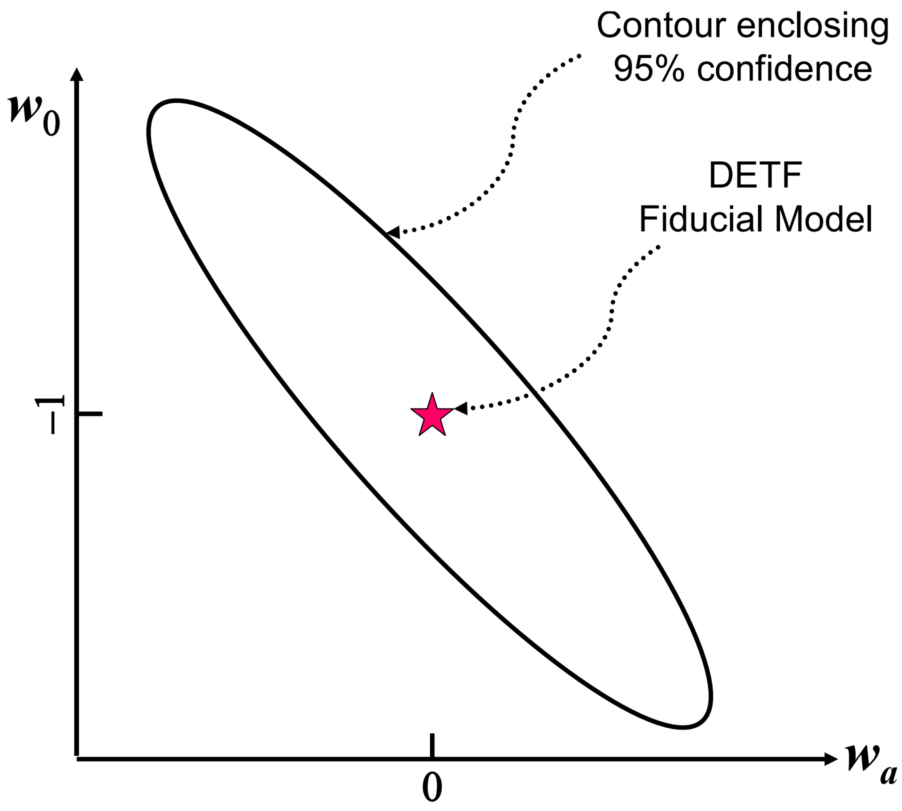
Huterer & Turner, PRD, 2001

Smallest ellipse, thinnest ellipse



Huterer & Turner, 2001

Currently accepted FoM: inverse area of ellipse in w_0-w_a plane



$$w(z) = w_0 + w_a(1-a)$$
$$= w_p + w_a(a_p - a)$$
$$\text{FoM} \equiv \frac{1}{\sigma(w_p) \times \sigma(w_a)}$$

DETF report; Albrecht et al 2006

DETF FoM - advantages and disadvantages

The currently accepted FoM is a very reasonable choice which captures essential ingredients and is easy to compute.

However, we should also be aware of its deficiencies:

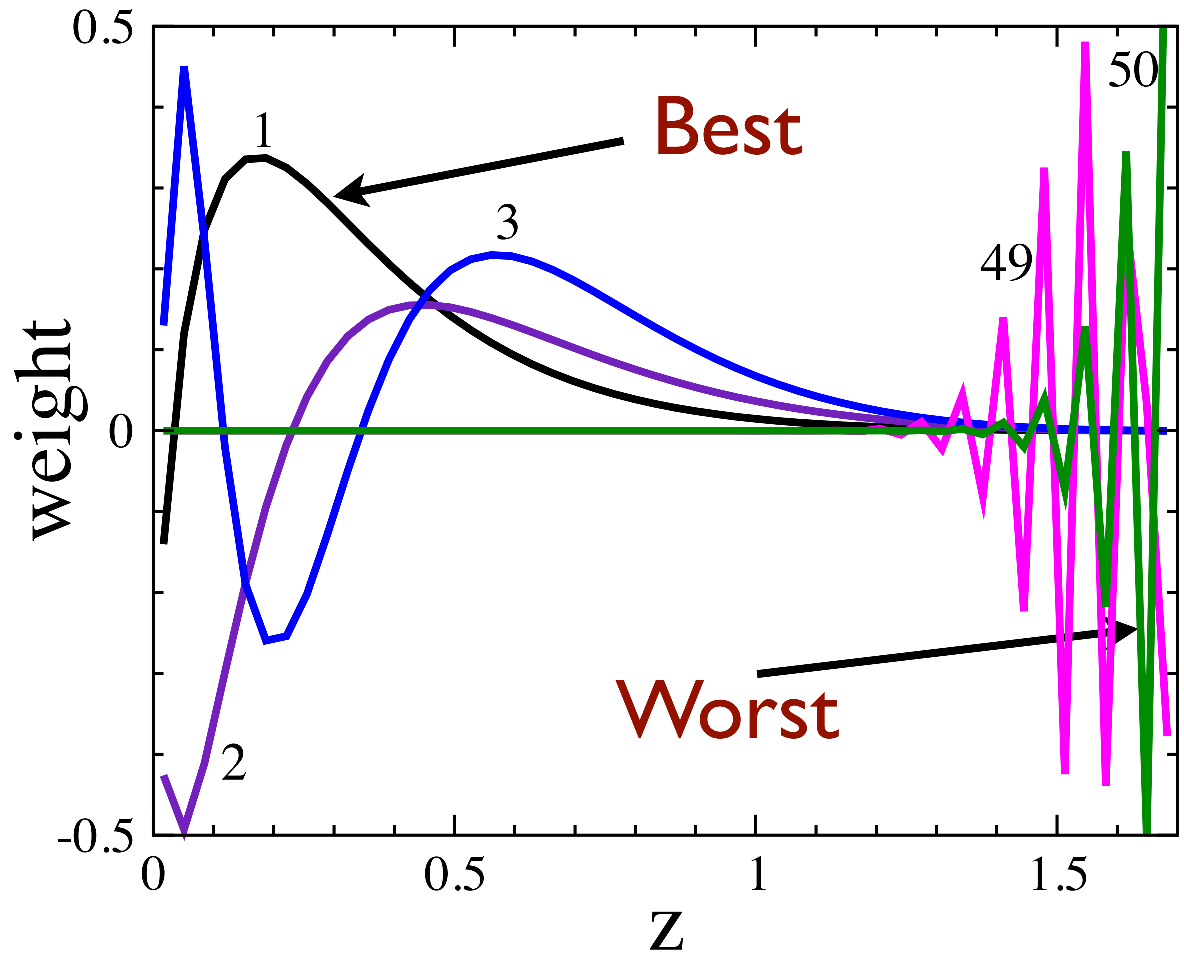
- DETF FoM probably fails to capture success at measuring models with non-canonical variations in w(z) at late times
- It definitely fails to capture success at measuring early DE
- It does not address anything about modified gravity vs. DE
- It doesn't account for clustering of DE
- It's not designed to measure deviations from LCDM

Other proposals/options for the dark energy FoM

Principal Components of $w(z)$

These are best-to-worst measured linear combinations of w(z)

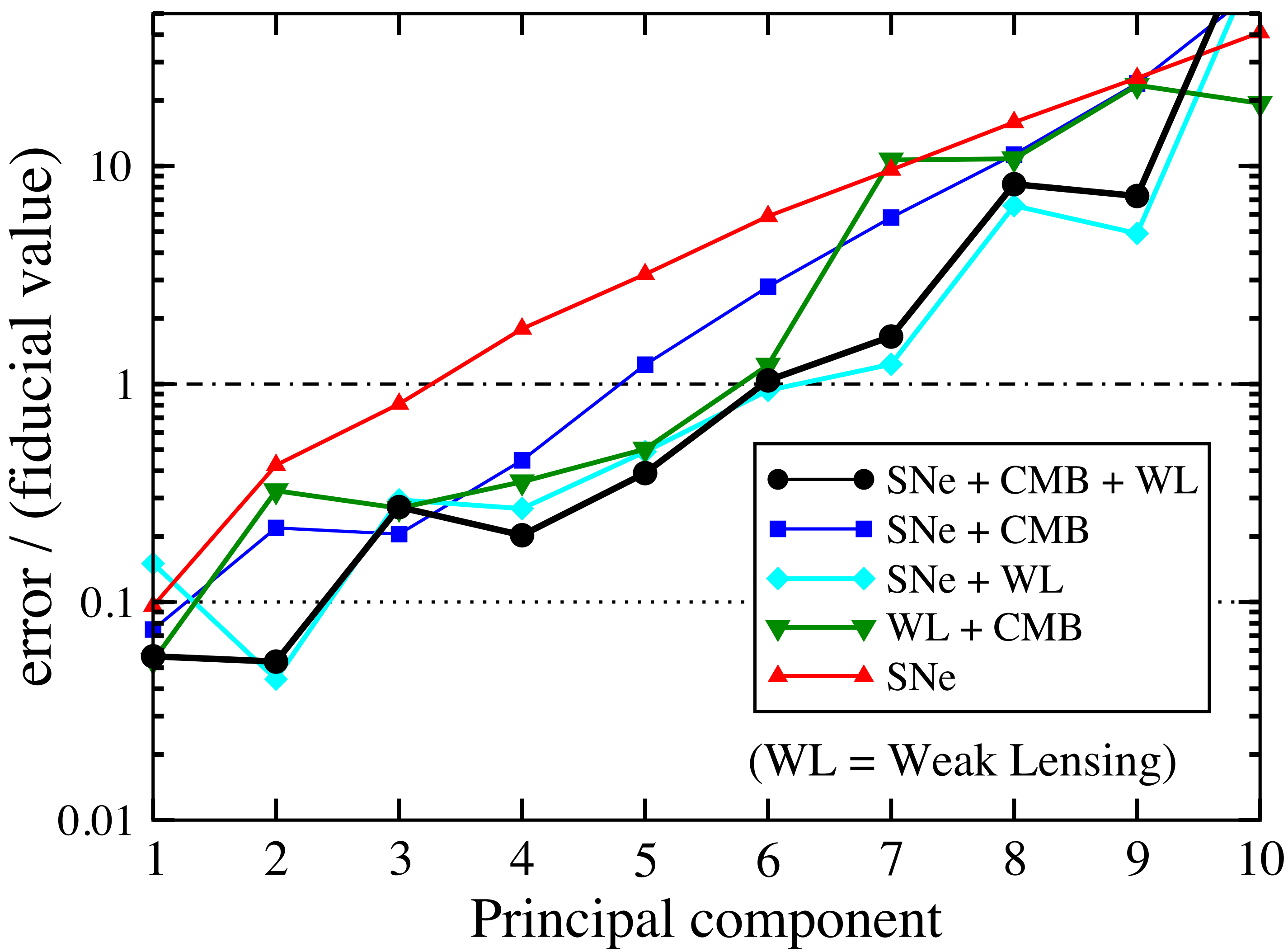
Uncorrelated by construction



- Shows where sensitivity of any given survey is greatest
- Used by various authors to study optimization of surveys
- Used to make model-(in)dependent statements about DE

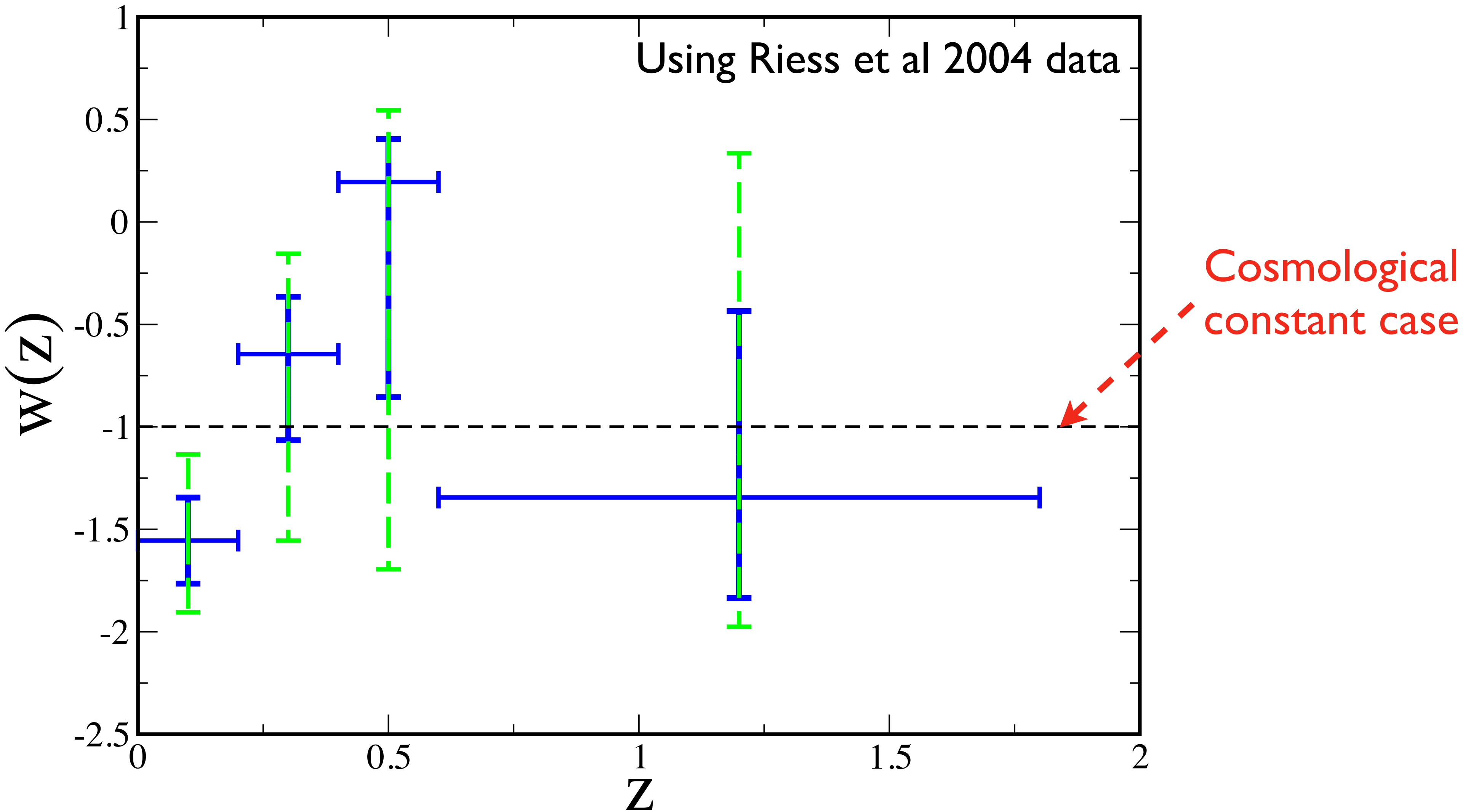
Huterer & Starkman 2003

Principal Components of $w(z)$



Linder & Huterer 2005

Uncorrelated measurements of Dark Energy evolution



Huterer & Cooray 2005

Other proposals for the FoM: using uncorrelated bandpowers

$$\mathrm{FoM} = \prod_{i=1}^{N_{\mathrm{bins}}} \frac{1}{\sigma(\tilde{w}_i)}$$

Albrecht & Bernstein 2006

$$\mathrm{FoM} = \left[\sum_{i=1}^{N_{\mathrm{bins}}} \frac{1}{\sigma^2(\tilde{w}_i)}\right]^{1/2}$$

Sullivan, Sarkar, Joudaki, Amblard, Holz & Cooray 2007

How to parametrize modified gravity

1. Parametrize the gravitational potentials (and/or other metric, stress tensor variables) - Song 2006, Kunz & Sapone 2006, Jain & Zhang 2007, Amin et al 2007, Caldwell et al 2007, Hu 2008

2. Parametrize the expansion and growth history separately; check consistency

Beyond measuring w(z), we can ask...

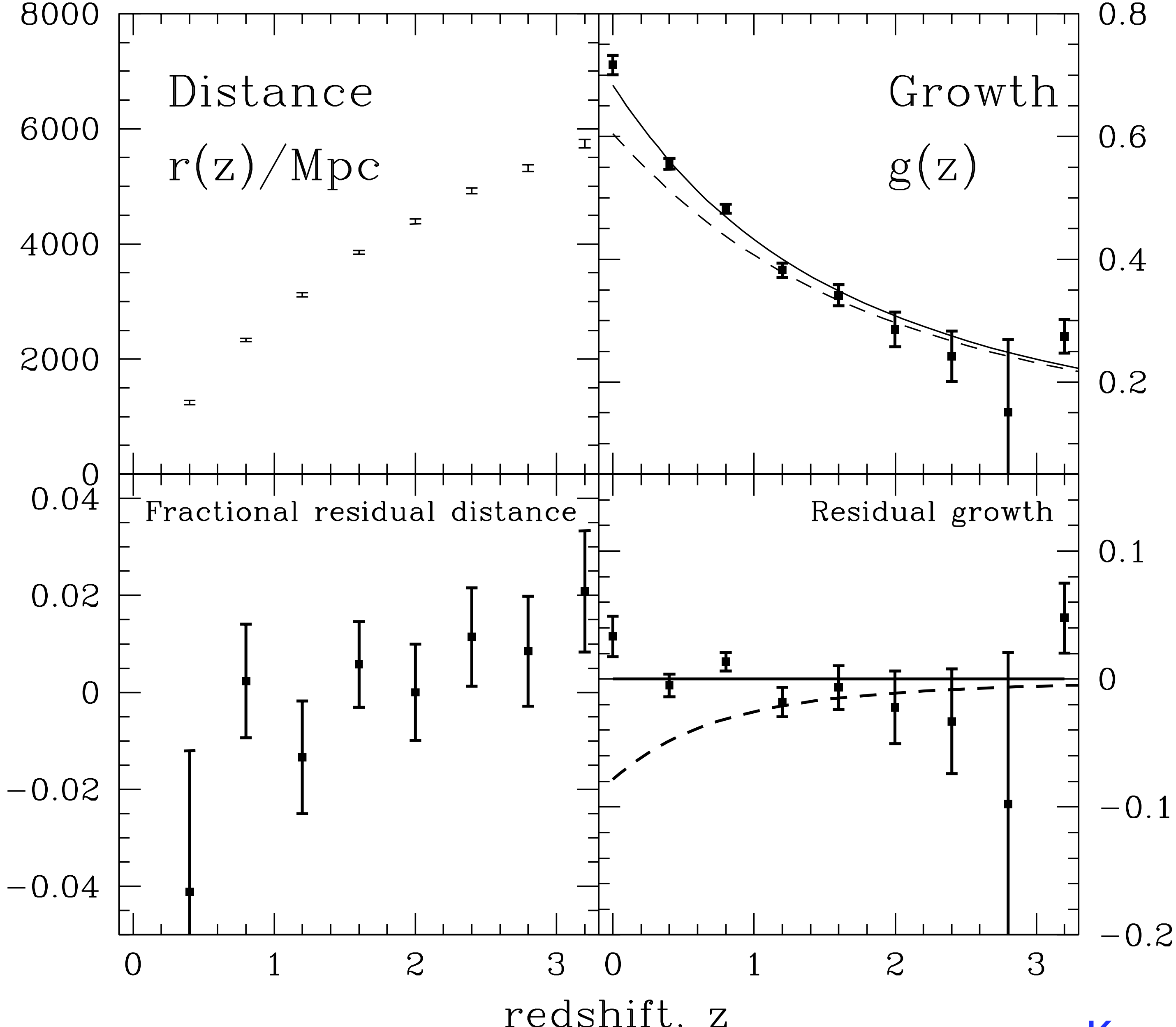
Dark Energy or Modified Gravity?

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

*Assuming smooth DE

- A given DE and modified gravity models may both fit the expansion history data very well
- But they will predict different structure formation history
- Linear growth is hard to compute even in fully well defined models for modified gravity (e.g. DGP)
- Nonlinear growth is much harder still to compute (c.f. this is a challenge even in GR!)

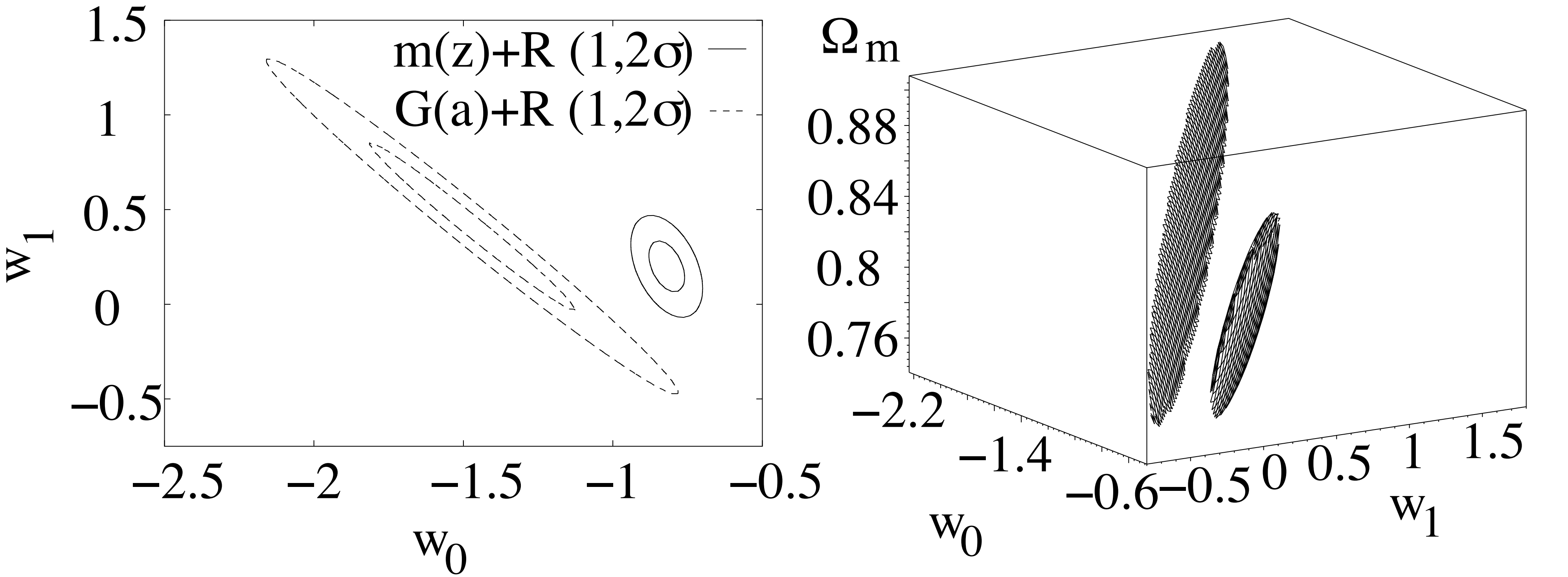
Strategy I: distance (z), growth(z) separately



Measure r(z), g(z), see if they agree

Knox, Song & Tyson 2005

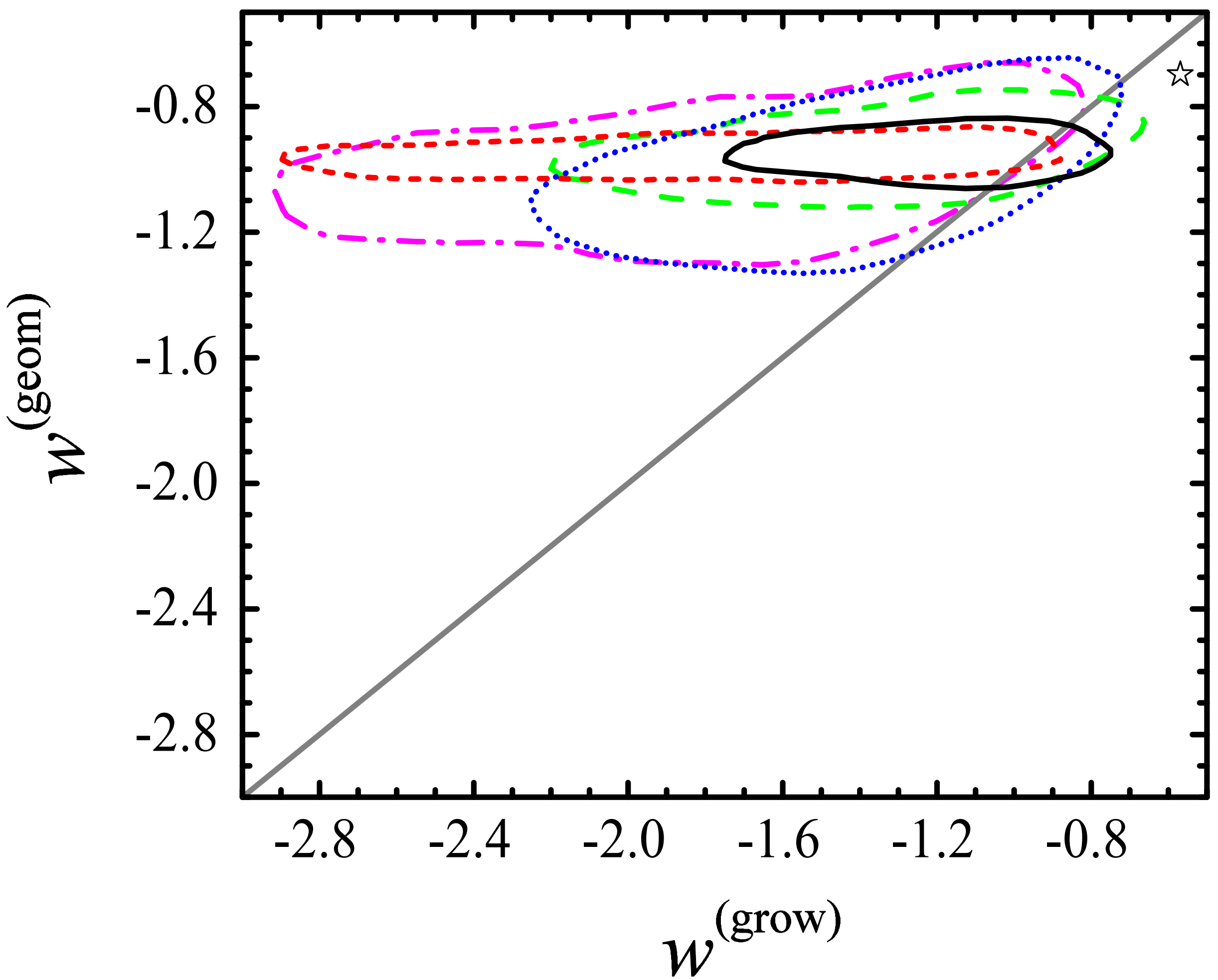
Strategy II: (O_m, w_0, w_a) separately



Measure w0 and w1 for growth and distance, see if they agree

Ishak, Upadhye & Spergel 2005, others...

Strategy II.5: w separately, real data



Nice work, but current constraints are weak

Wang, Hui, May & Haiman, 2007

Strategy III: “Minimalist Modified Gravity”

$$g(a) \equiv \frac{\delta}{a} = \exp\left[\int_0^a d\ln a[\Omega_M(a)^\gamma - 1]\right]$$

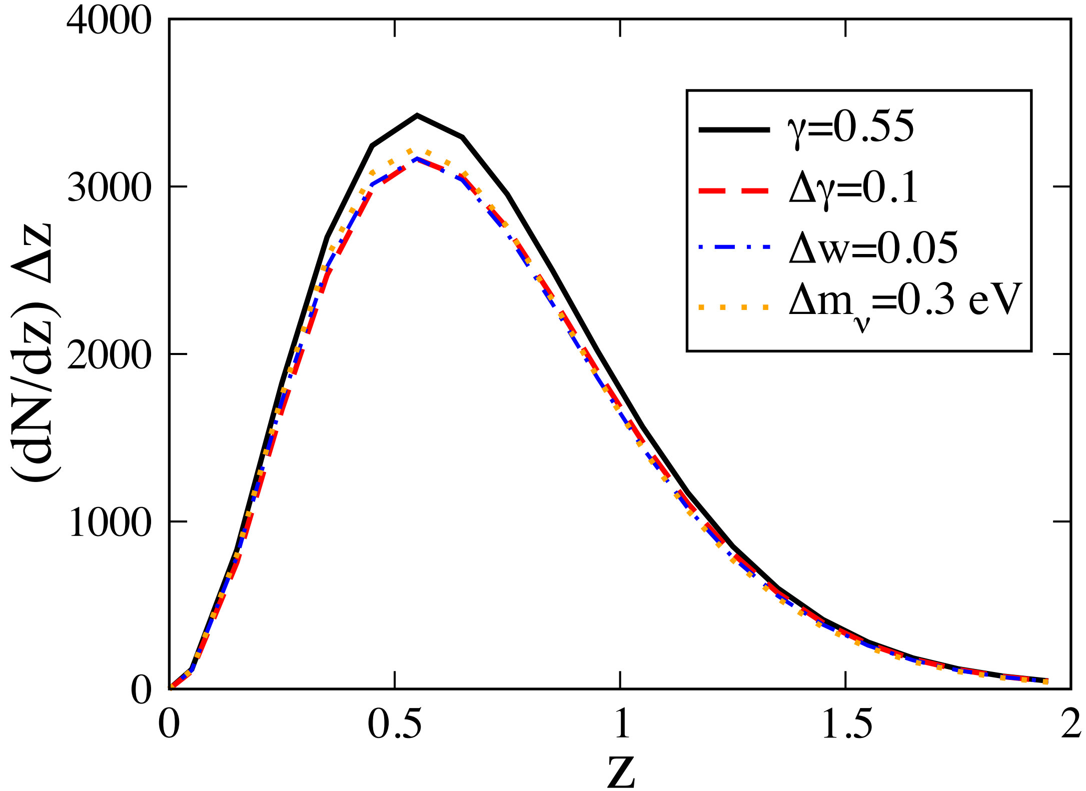
Excellent fit to standard DE cosmology with

$$\gamma = 0.55 + 0.05[1 + w(z = 1)]$$

Linder 2005

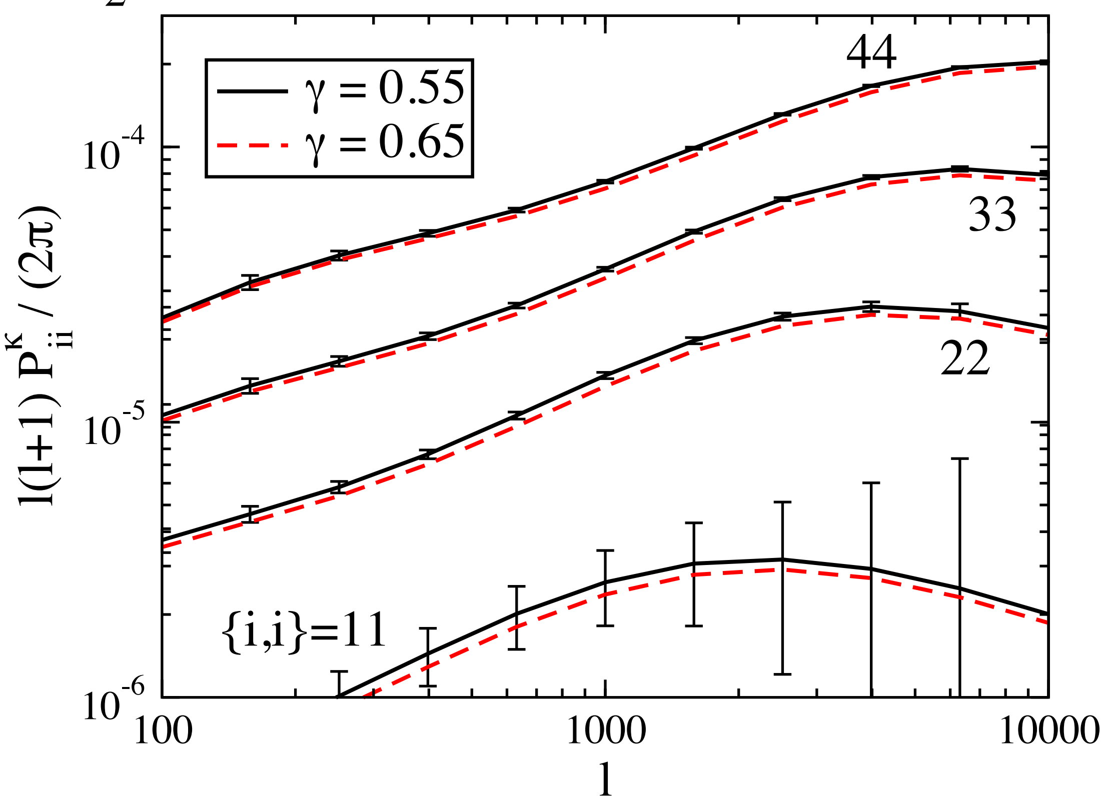
- Gamma is a new parameter - the growth index - and we should measure it!
- E.g. fits DGP with value different from GR by $\Delta\gamma = 0.13$
- For a moment, let us assume that the usual prescription for the nonlinear power spectrum is unchanged
- Apply to weak lensing and number counts; SNe and CMB remain unaffected

Huterer & Linder, astro-ph/0608681



Cluster counts

Weak lensing tomography



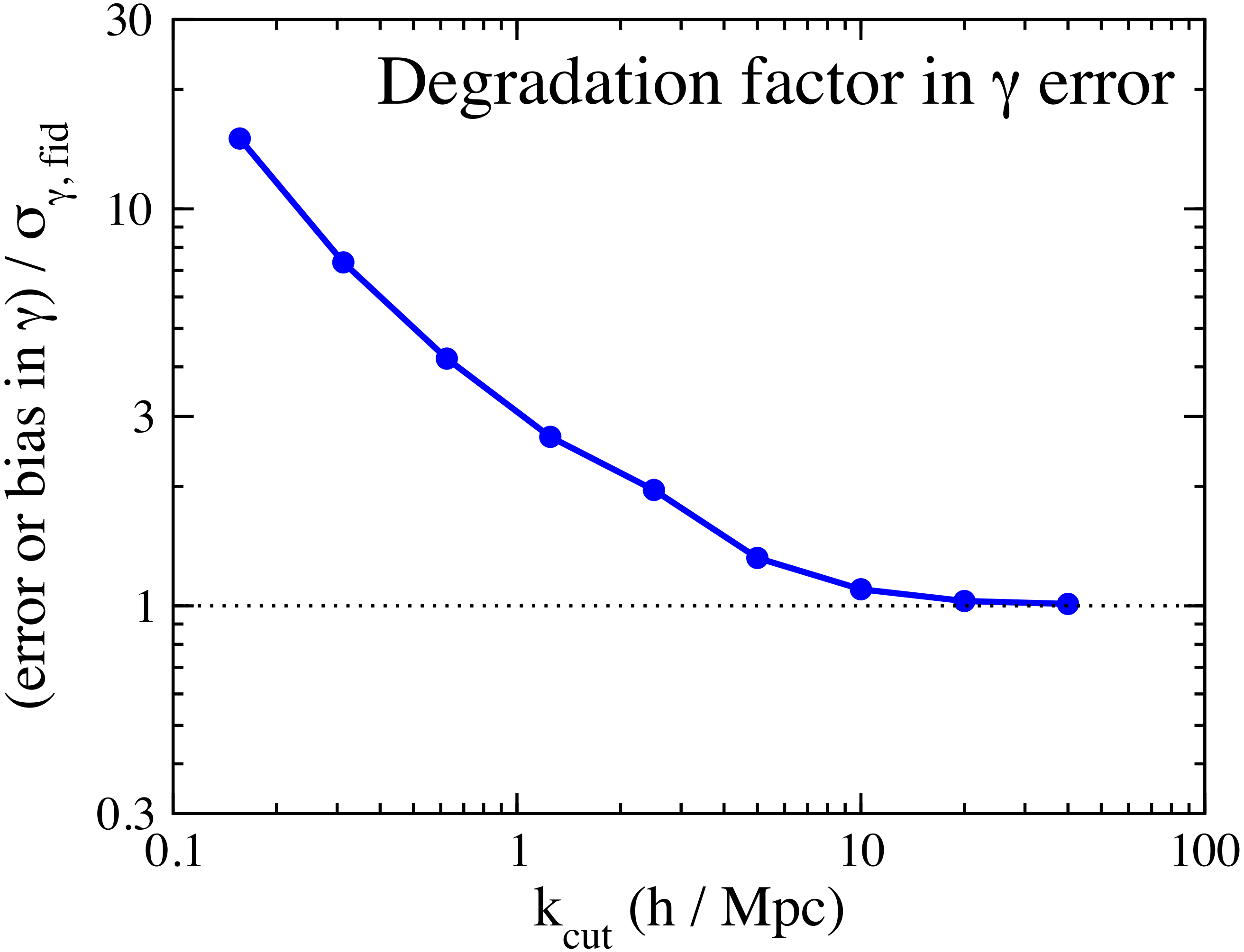
Constraints on the growth index

	sig(w_0)	sig(w_a)	sig(gamma)
WL	0.33	1.16	0.23
+SNE	0.06	0.28	0.10
+Planck	0.06	0.21	0.044
+Clusters	0.05	0.16	0.037

WL: 1000 sqdeg (SNAP)
SNe: 2800 SNe (SNAP)
Clusters: 4000 sqdeg (SPT), dN/dz only, but mass-obs relation exact
parameters: Ode, A, w0, wa, omhh, obhh, m_nu, gamma

Huterer & Linder, astro-ph/0608681

Effects of discarding the small-scale info in weak lensing

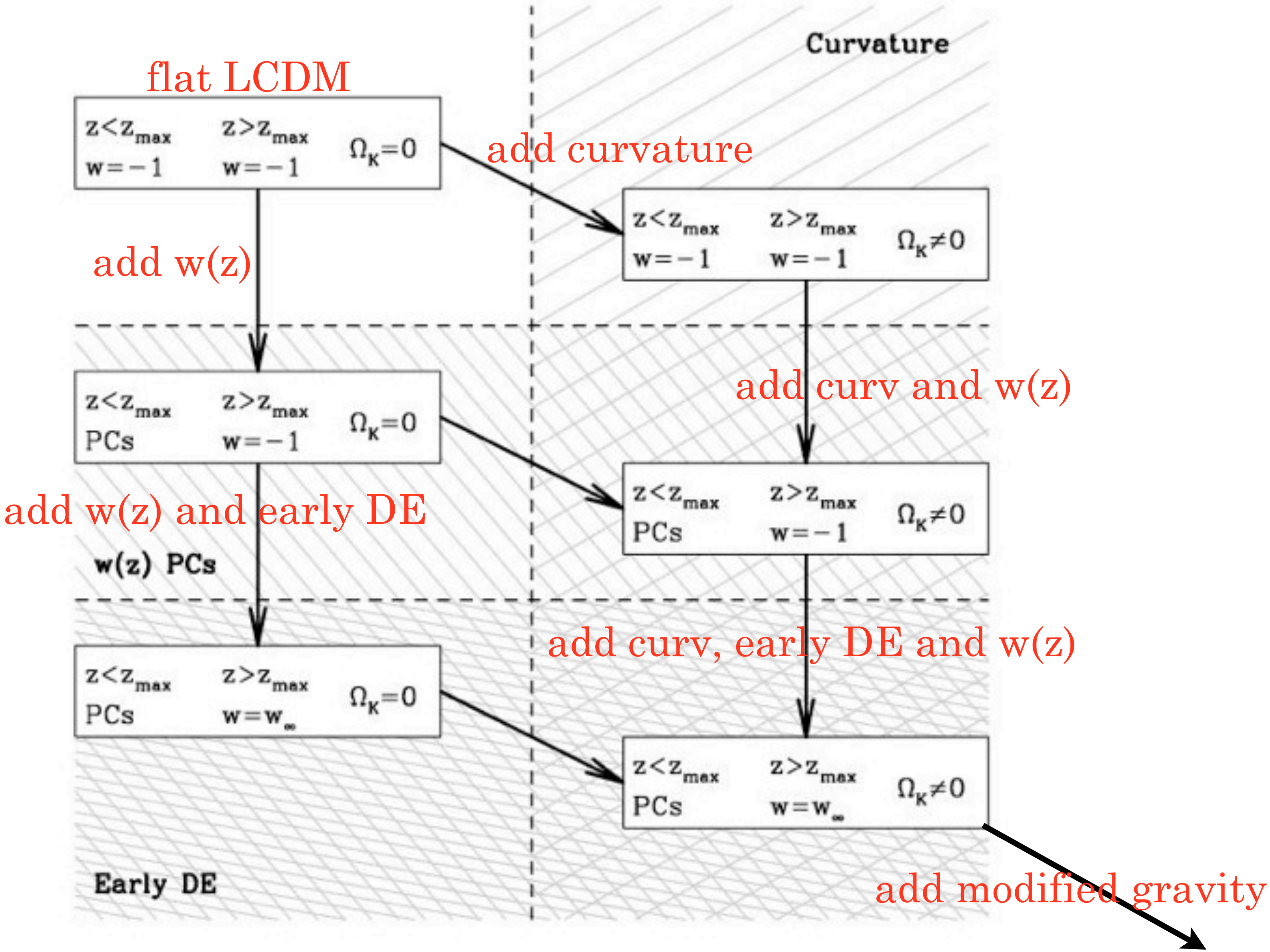


- Clearly, errors increase dramatically as you keep only linear scales
- For MG, it's hard to trust NL scales
- But for testing w(z) GR models, using NL scales may be possible

Using the Nulling Tomography of weak lensing (Huterer & White 2005)

We really need - a decision tree

- The data are now consistent with LCDM, but that may change
- If so, what observational strategies do we use to determine which violation of Occam's Razor has the nature served us?
- Possible alternatives:
    - w(z)
    - early DE
    - curvature != 0
    - clustered DE
    - modified gravity
    - more than one of the above
    - ......



Mortonson, Hu & Huterer, in preparation