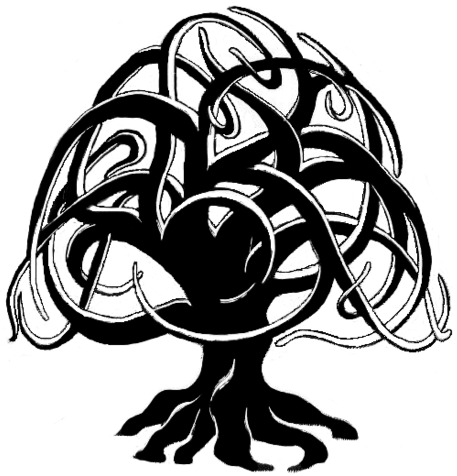
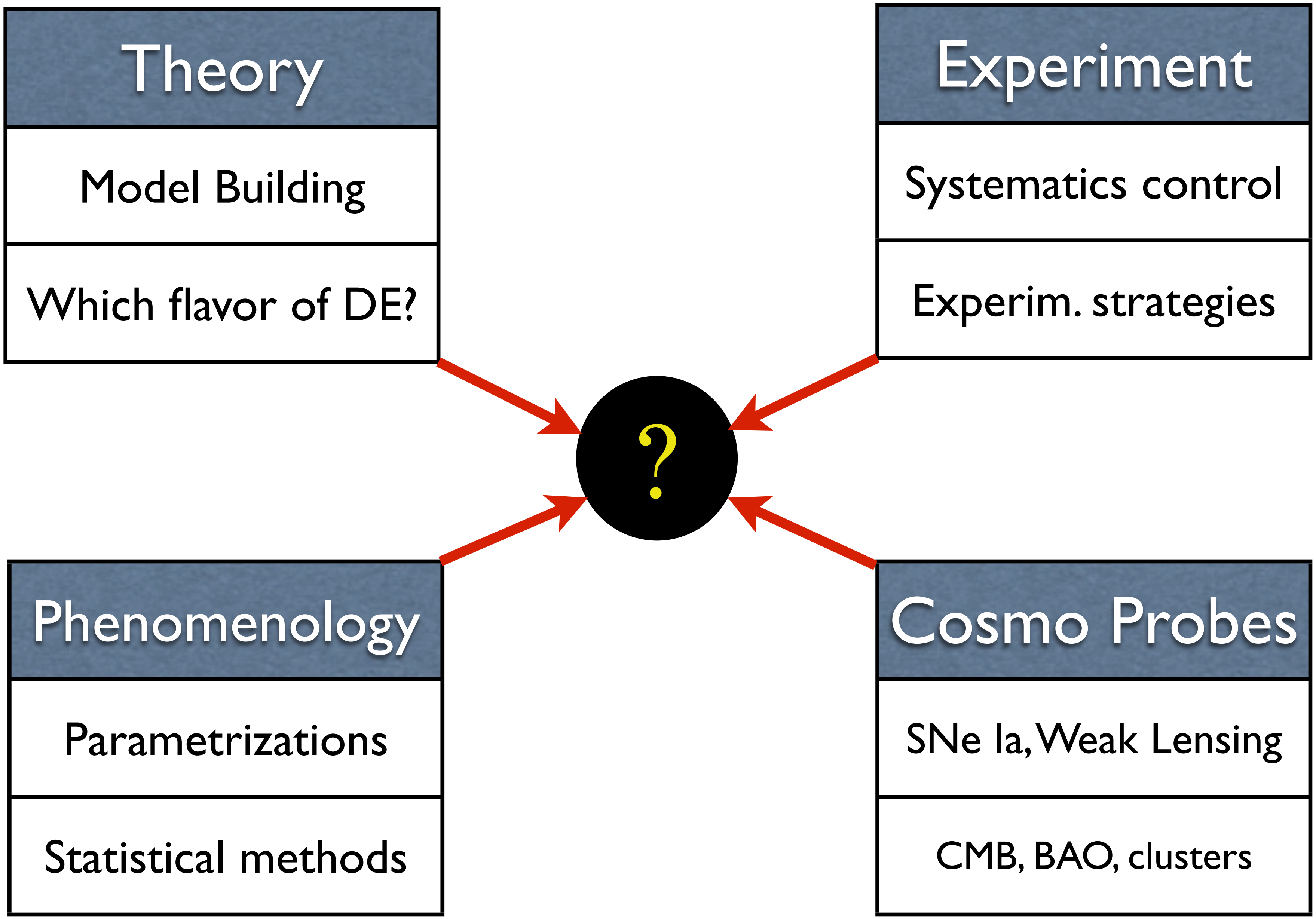
A Decision Tree for Dark Energy



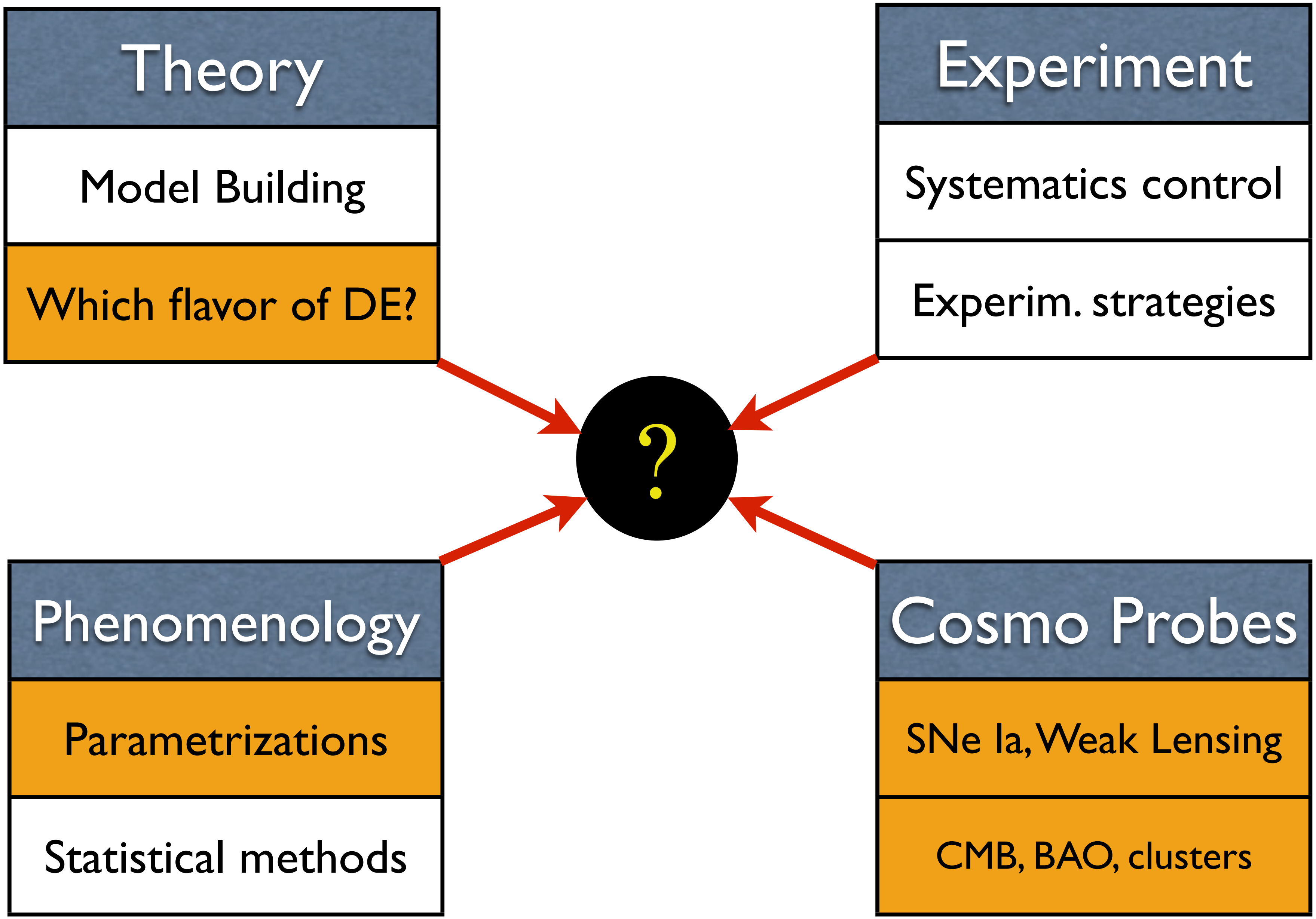
Dragan Huterer

Department of Physics
University of Michigan

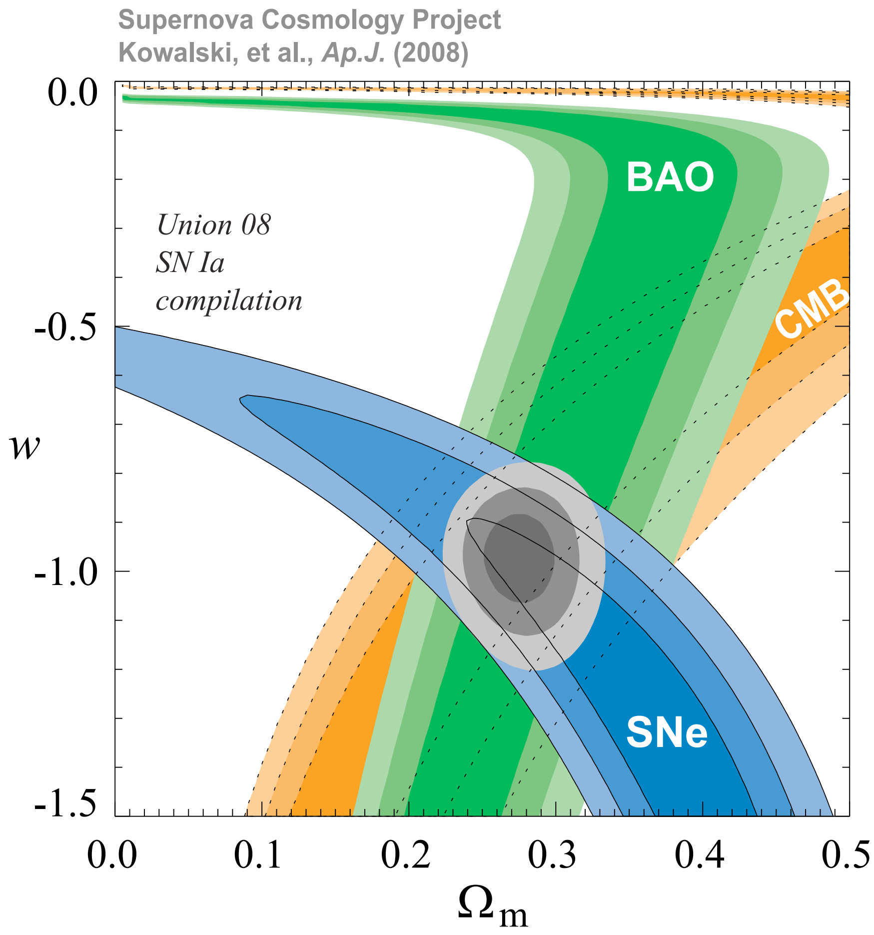
What next for Dark Energy?

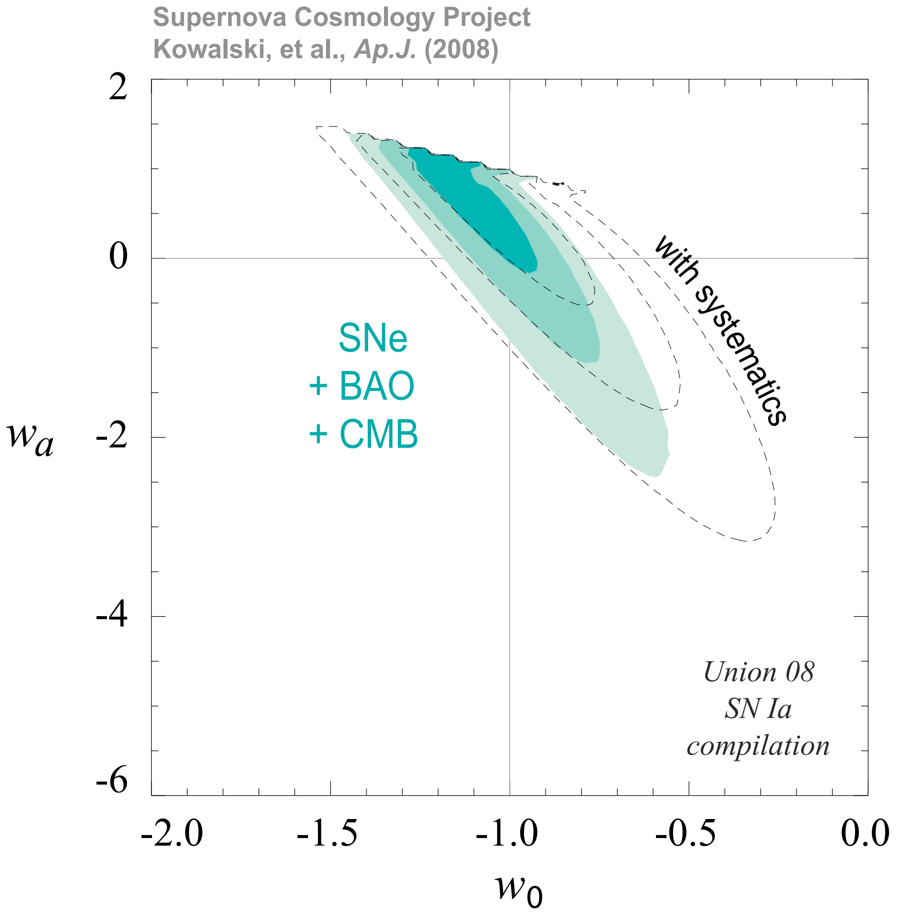


What next for Dark Energy?



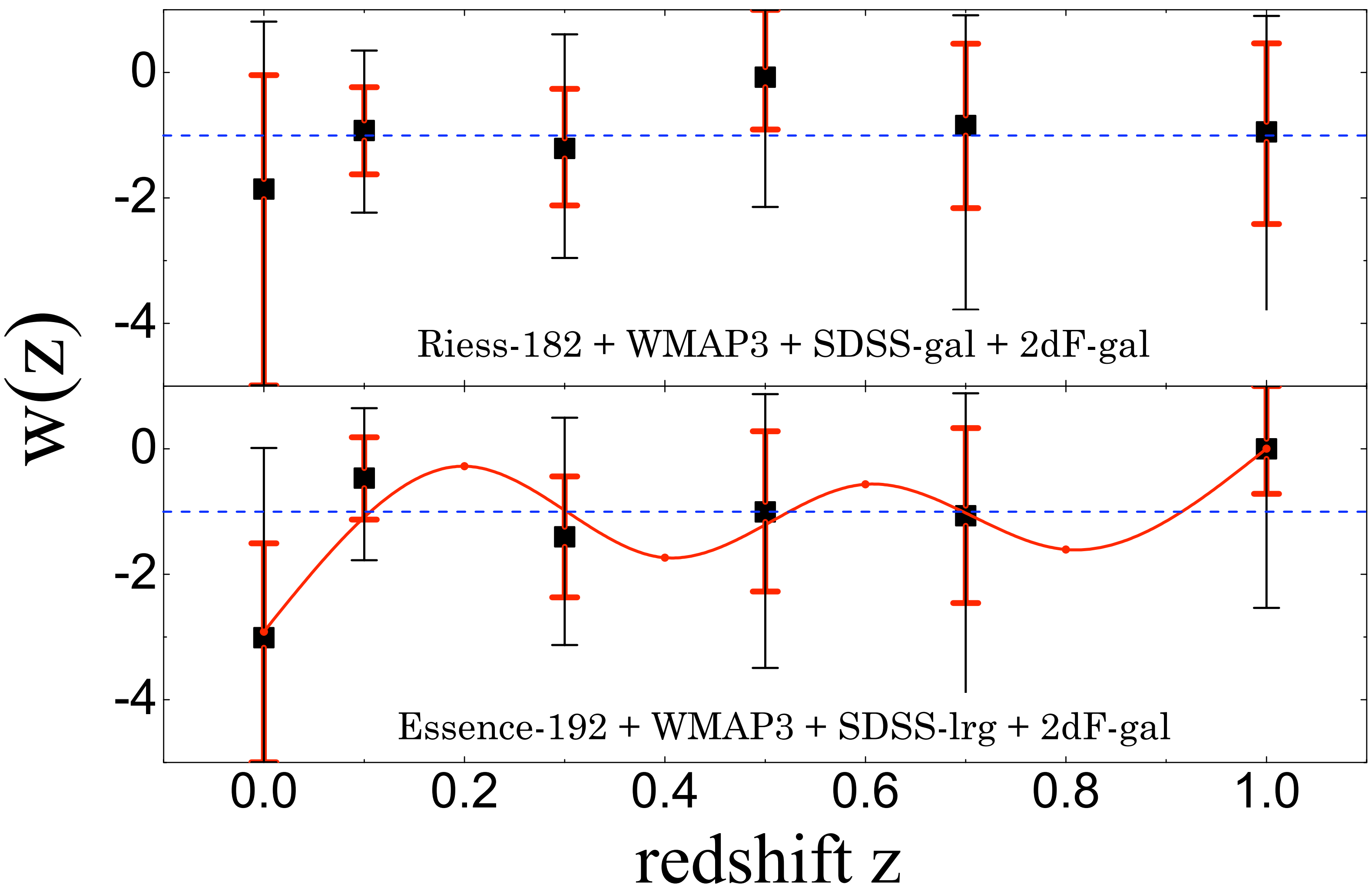
Dark Energy constraints: current status





Kowalski et al., arXiv:0804.4142

Dark Energy constraints: current status



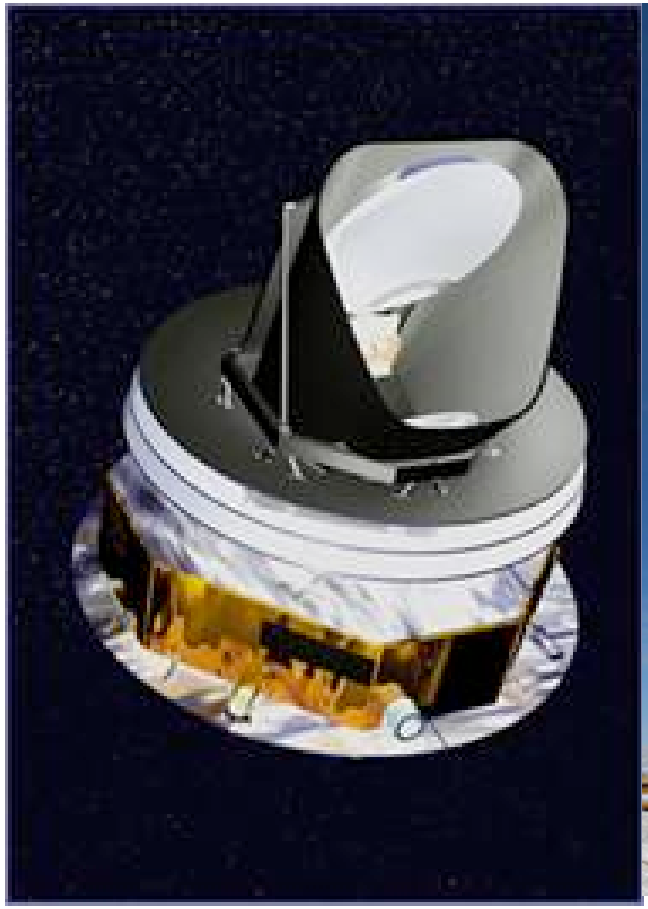
Zhao, Huterer & Zhang, arXiv:0712.2277

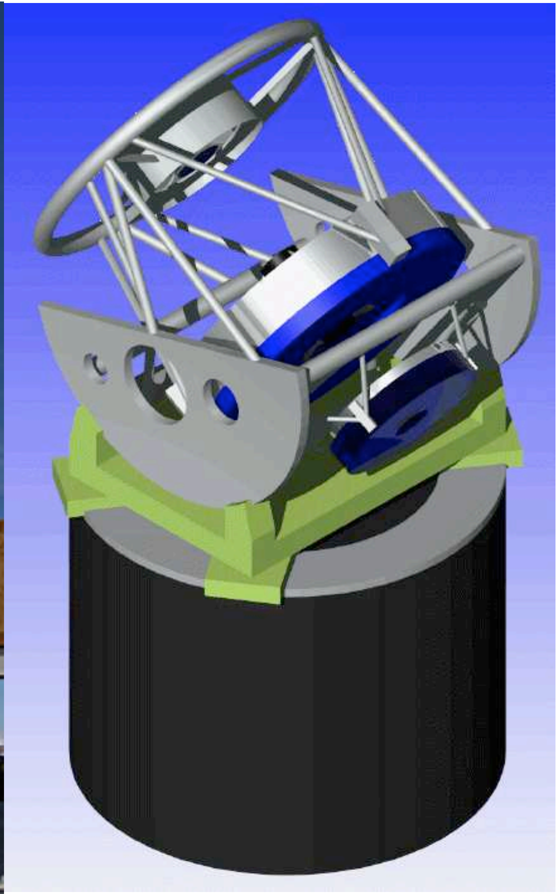
Upcoming Experiments

Planck

South Pole Telescope

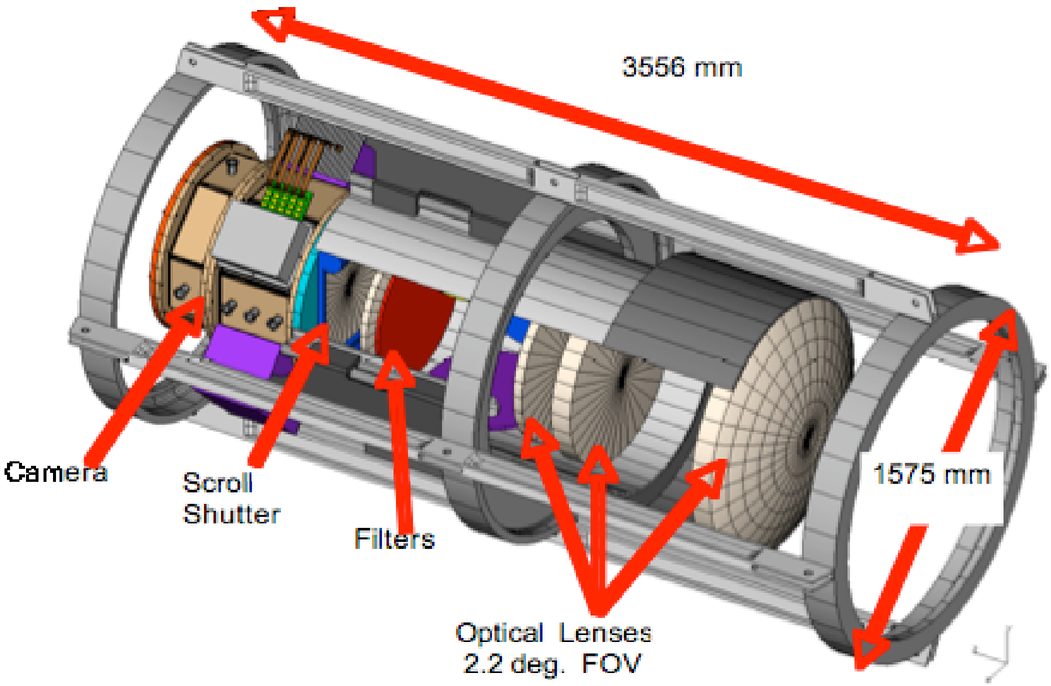
LSST





Lots and lots of data coming our way

Dark Energy Survey



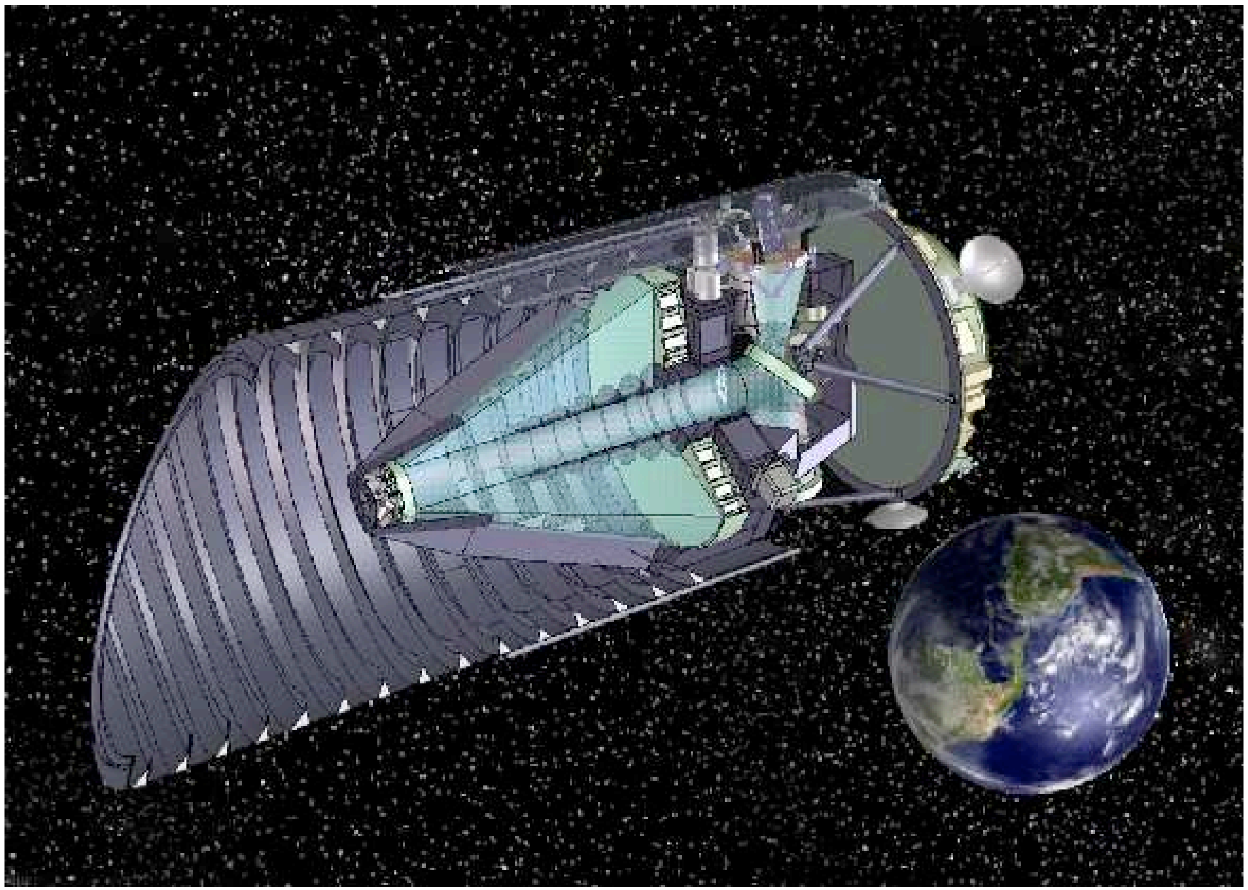
Blanco 4m telescope in Chile

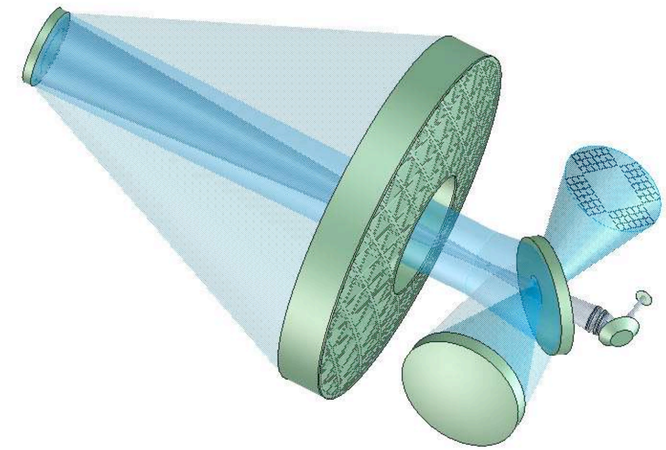
Four techniques to probe Dark Energy:

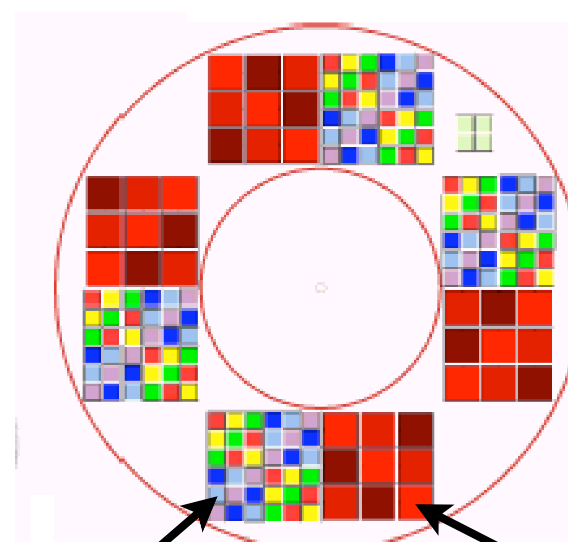
1. Number Counts of clusters
2. Weak Lensing
3. SNe Ia
4. Angular clustering of galaxies

SuperNova/Acceleration Probe

~2500 SNe at $0.1<z<1.7$





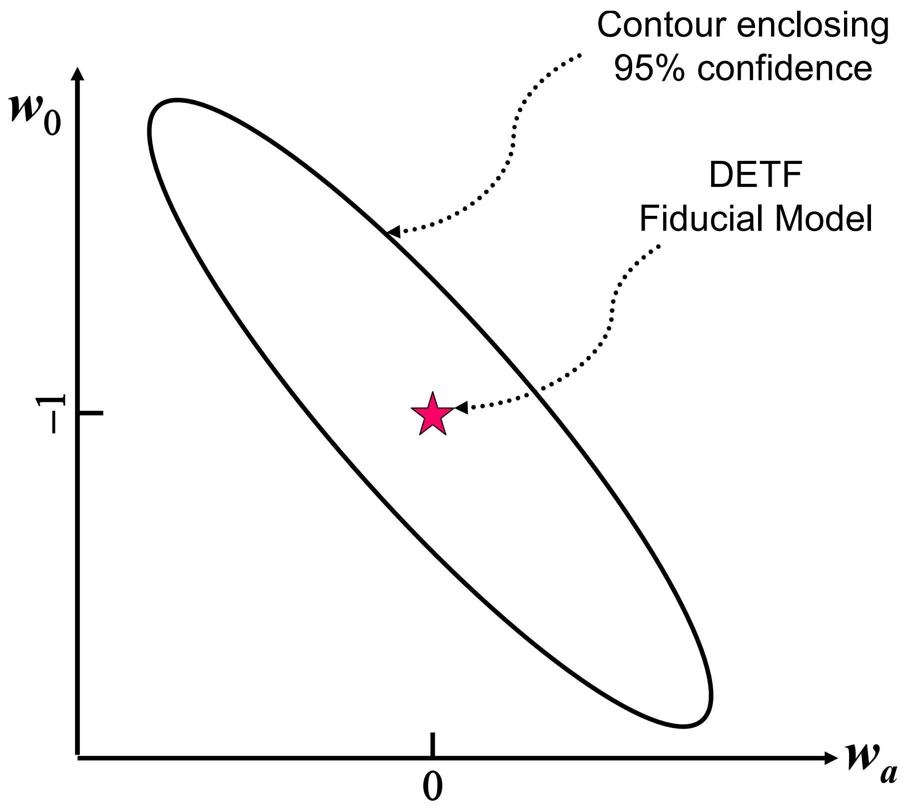


Visible (CCDs)

NIR (HgCdTe)

Measuring Properties of Dark Energy: the Figure of Merit

Currently accepted Figure of Merit



$$
\begin{aligned}
w(z) &= w_0 + w_a(1-a) \\
&= w_p + w_a(a_p - a) \\
\mathrm{FoM} &\equiv \frac{1}{\sigma(w_p)\times\sigma(w_a)}
\end{aligned}
$$

Huterer & Turner 2001; Albrecht et al 2006

DETF FoM - advantages and disadvantages

Pros:

- Captures not only w=const but also variation in w(z)
- (w0, wa) parametrization reasonable yet simple
- Easy to compute and intuitive

Cons:

- Probably fails with models with non-canonical 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

How to parametrize modified gravity

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,..

How to parametrize modified gravity

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

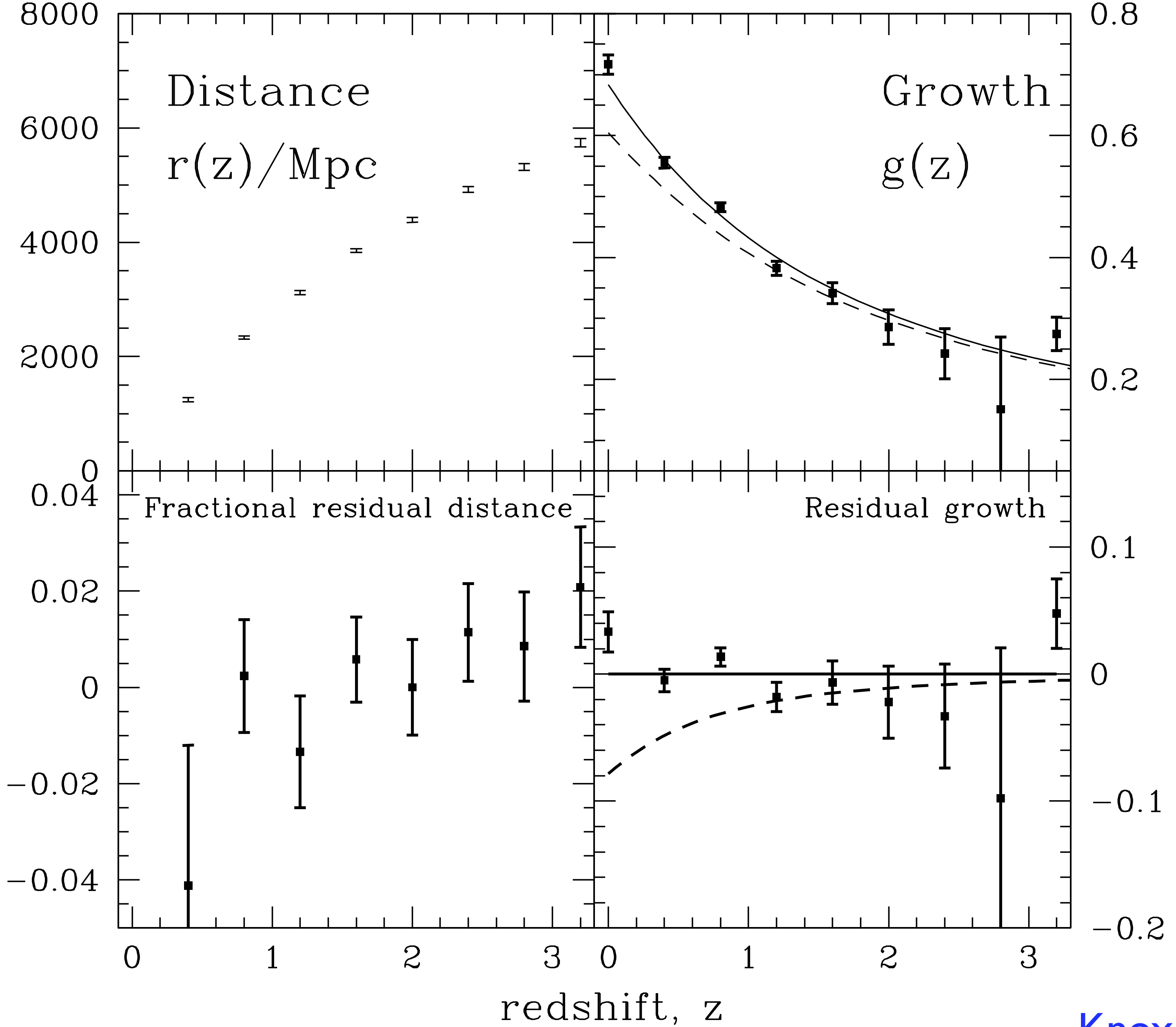
Beyond measuring w(z), we can ask...

Dark Energy or Modified Gravity?

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

- 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!)

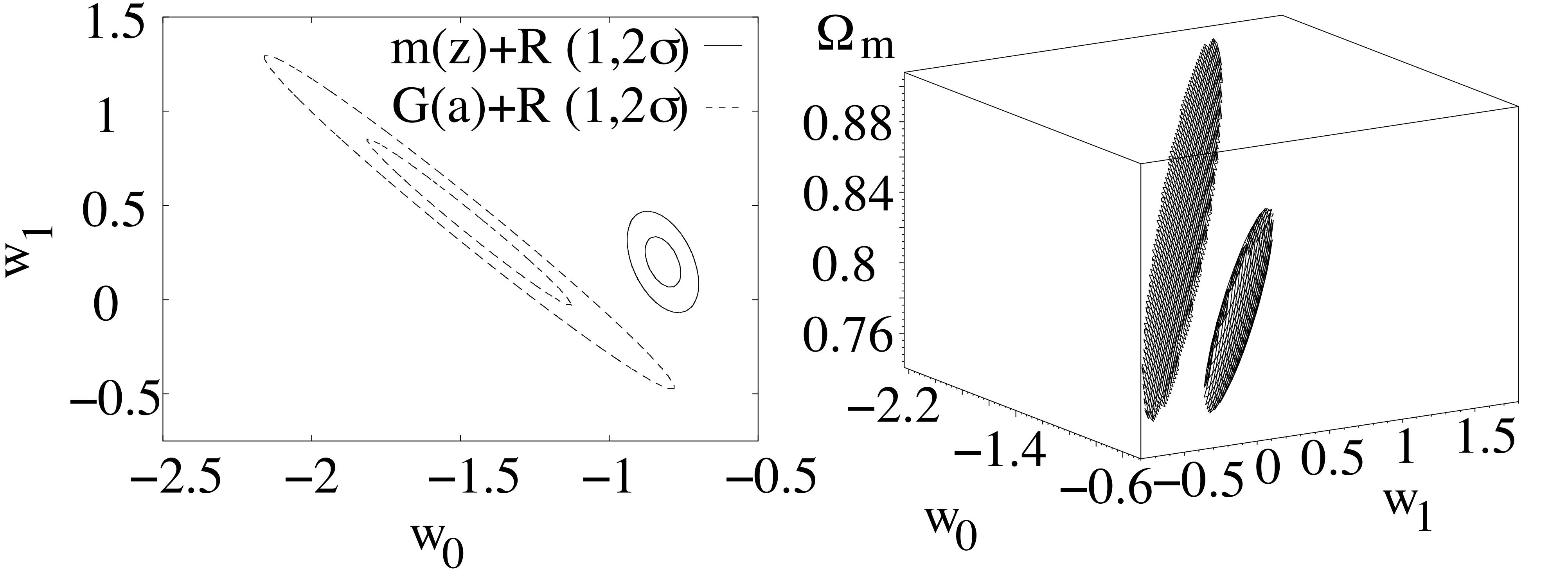
Strategy I: distance (z), growth(z) separately



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

Knox, Song & Tyson 2005

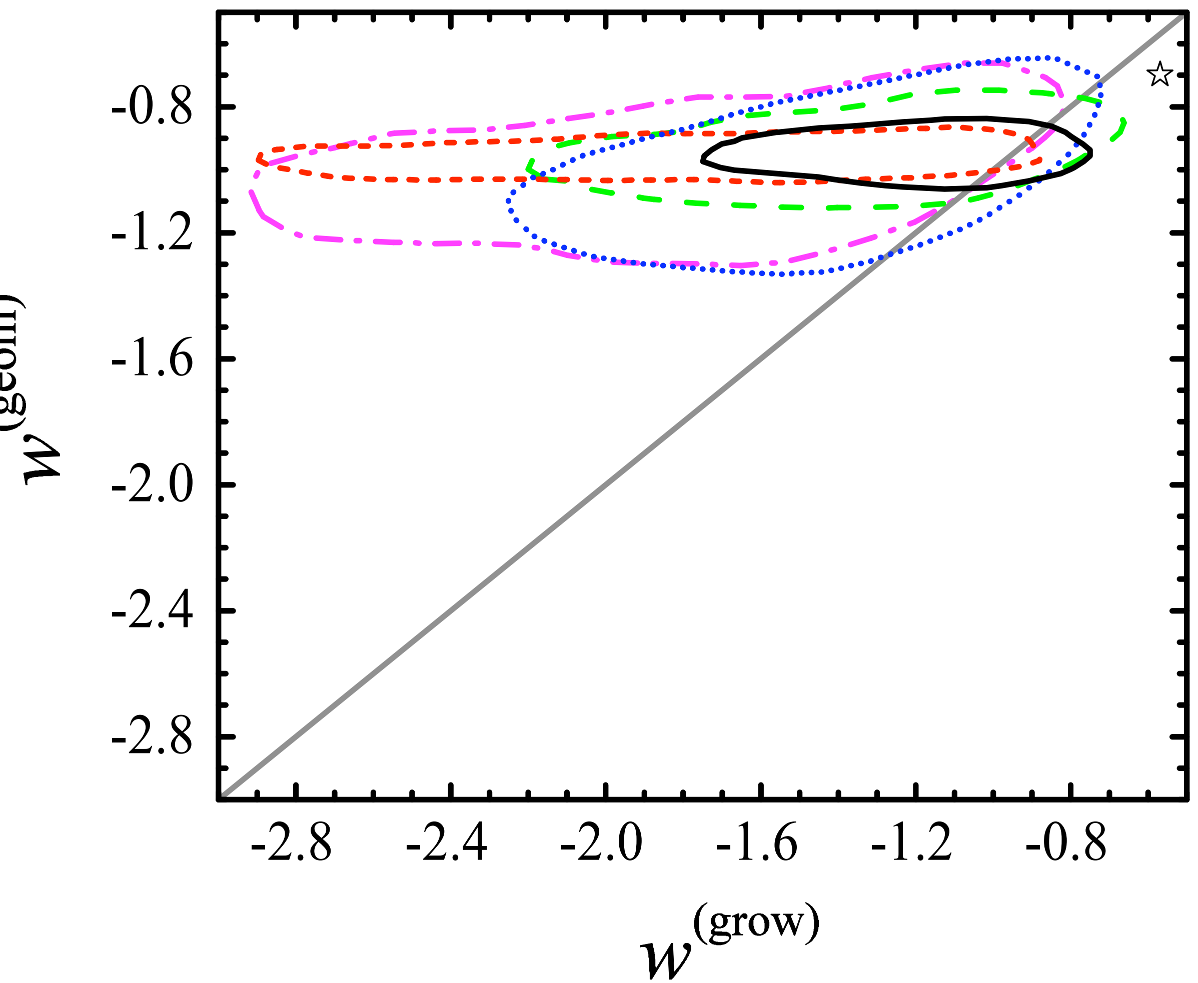
Strategy II: (Ω_m, w_0, w_a) separately



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"

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

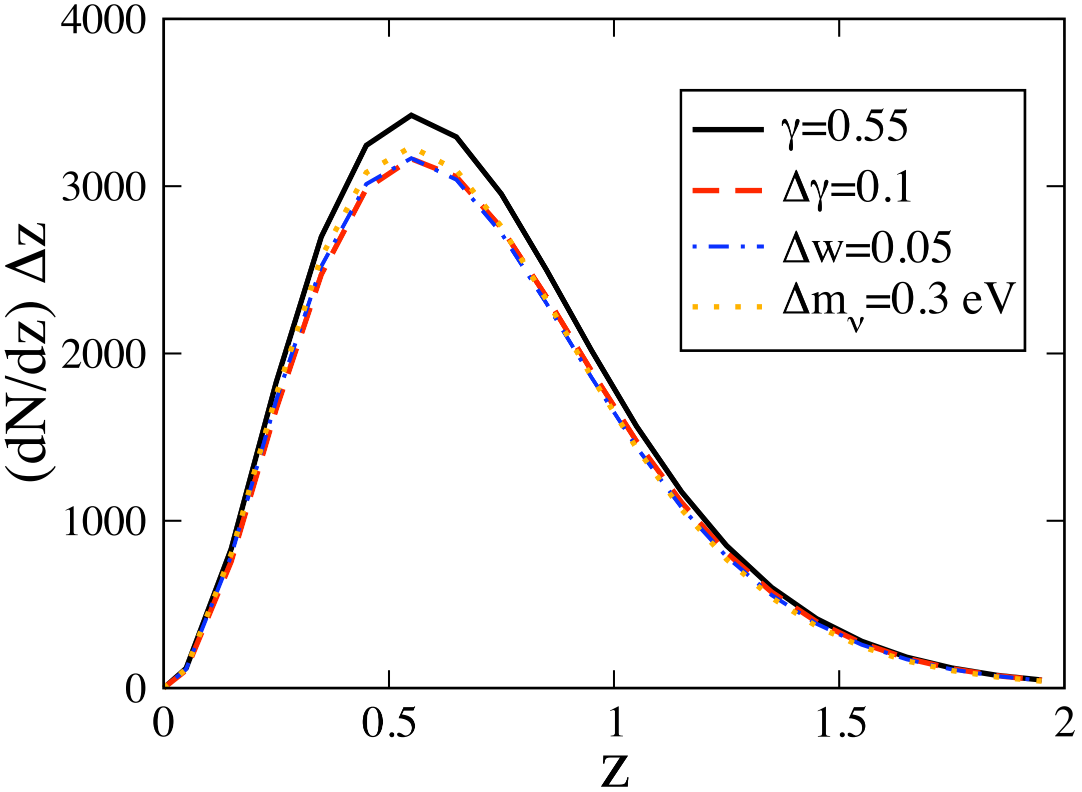
Excellent fit to standard DE cosmology with

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

Linder 2005

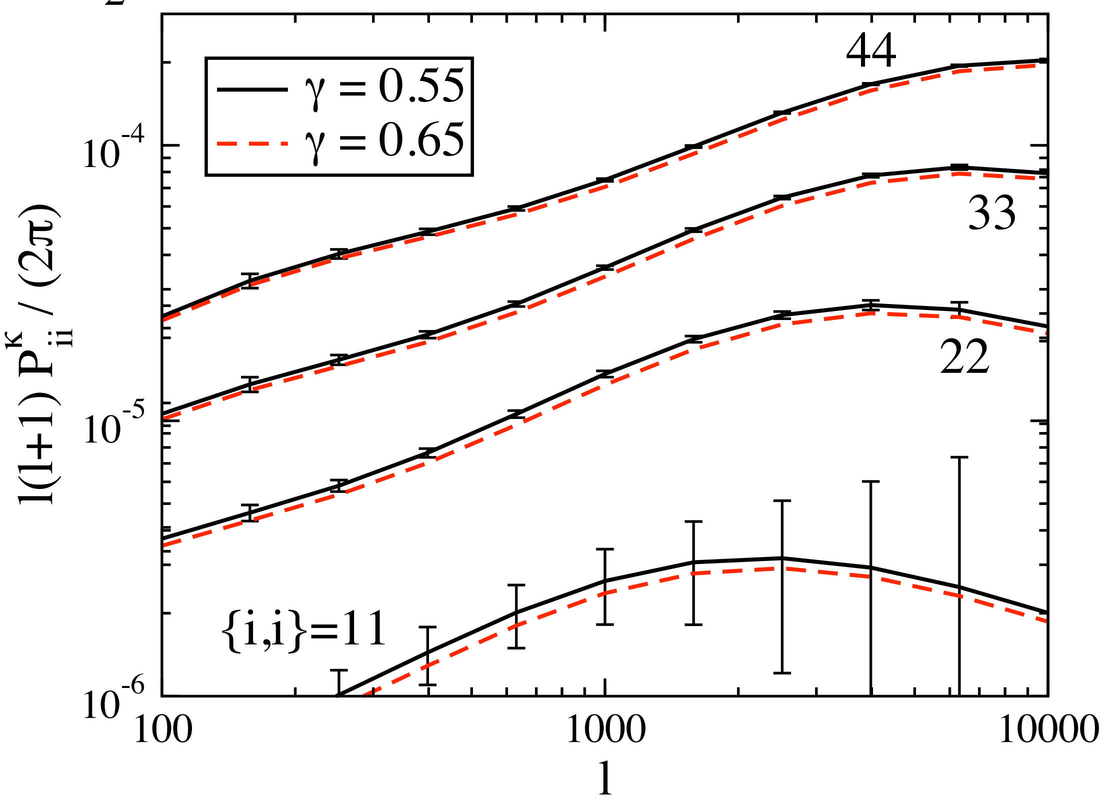
- Gamma is a new parameter - the growth index - and we should measure it!
- E.g. fits DGP with value different from GR by $\Delta\gamma = 0.13$
- Apply to weak lensing and number counts; SNe and CMB remain unaffected

Huterer & Linder, astro-ph/0608681



Cluster counts

Weak lensing tomography



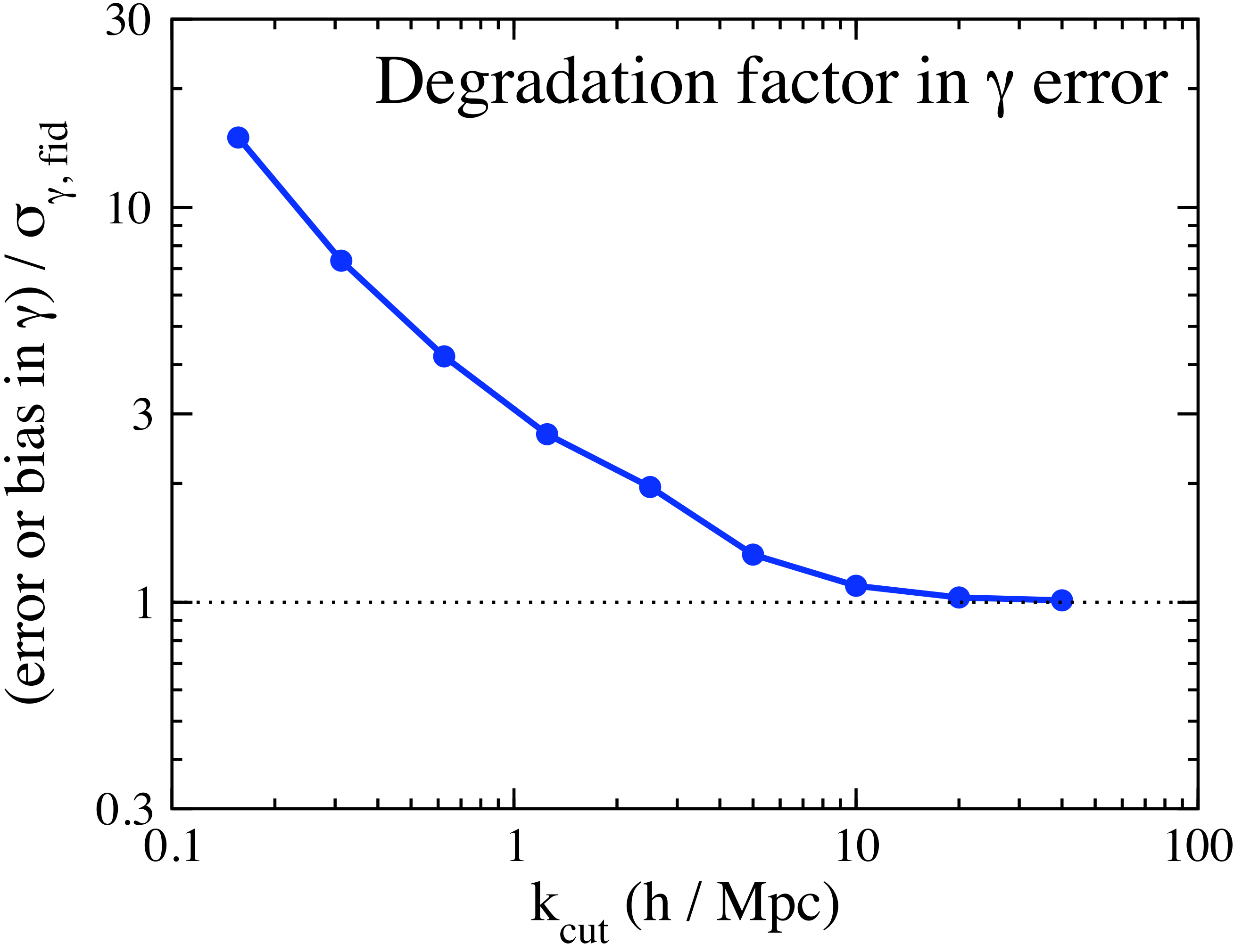
Constraints on the growth index

	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

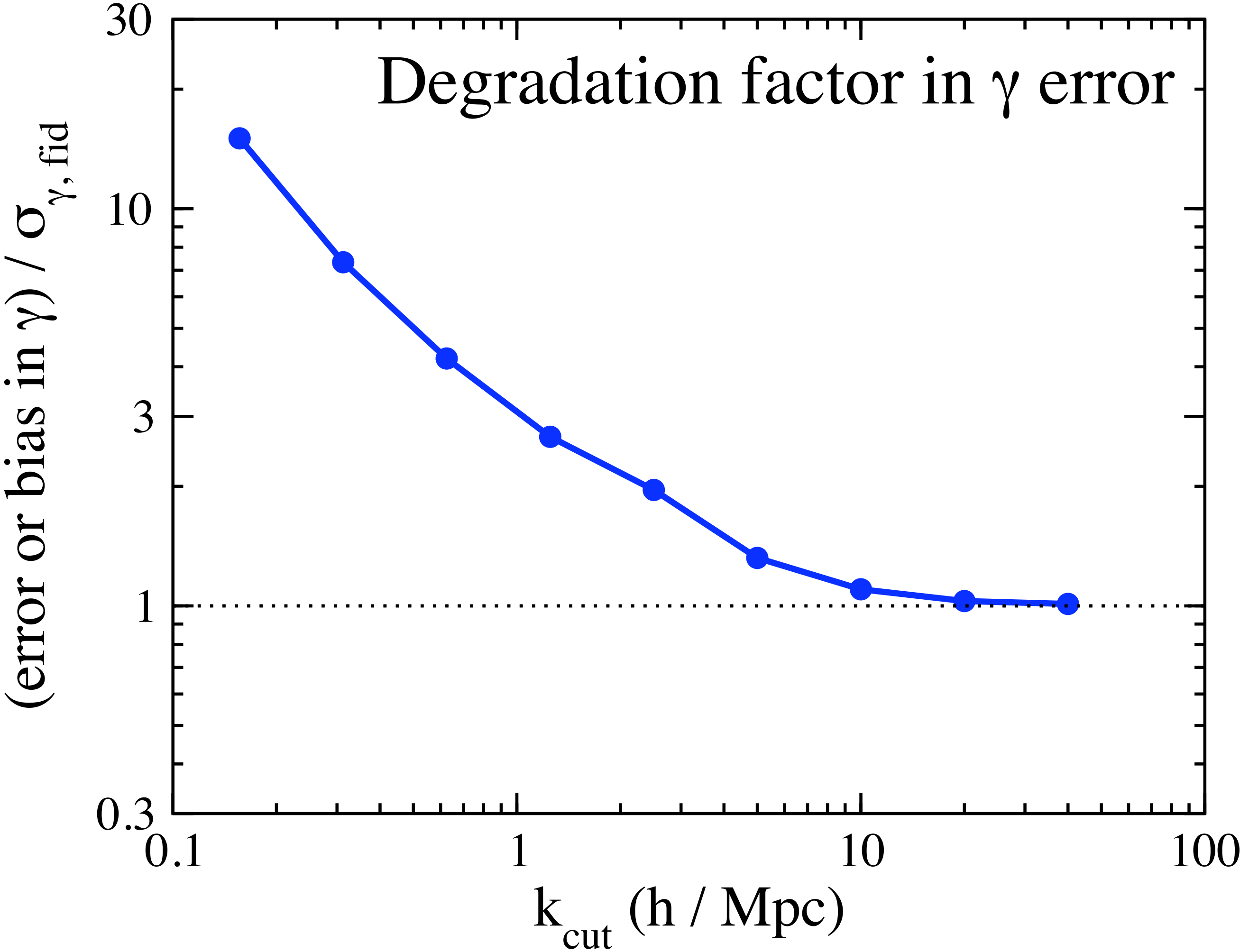
Huterer & Linder, astro-ph/0608681

Effects of discarding the small-scale info in weak lensing



Huterer & Linder 2007 (using the Nulling Tomography of weak lensing; Huterer & White 2005)

Effects of discarding the small-scale info in weak lensing

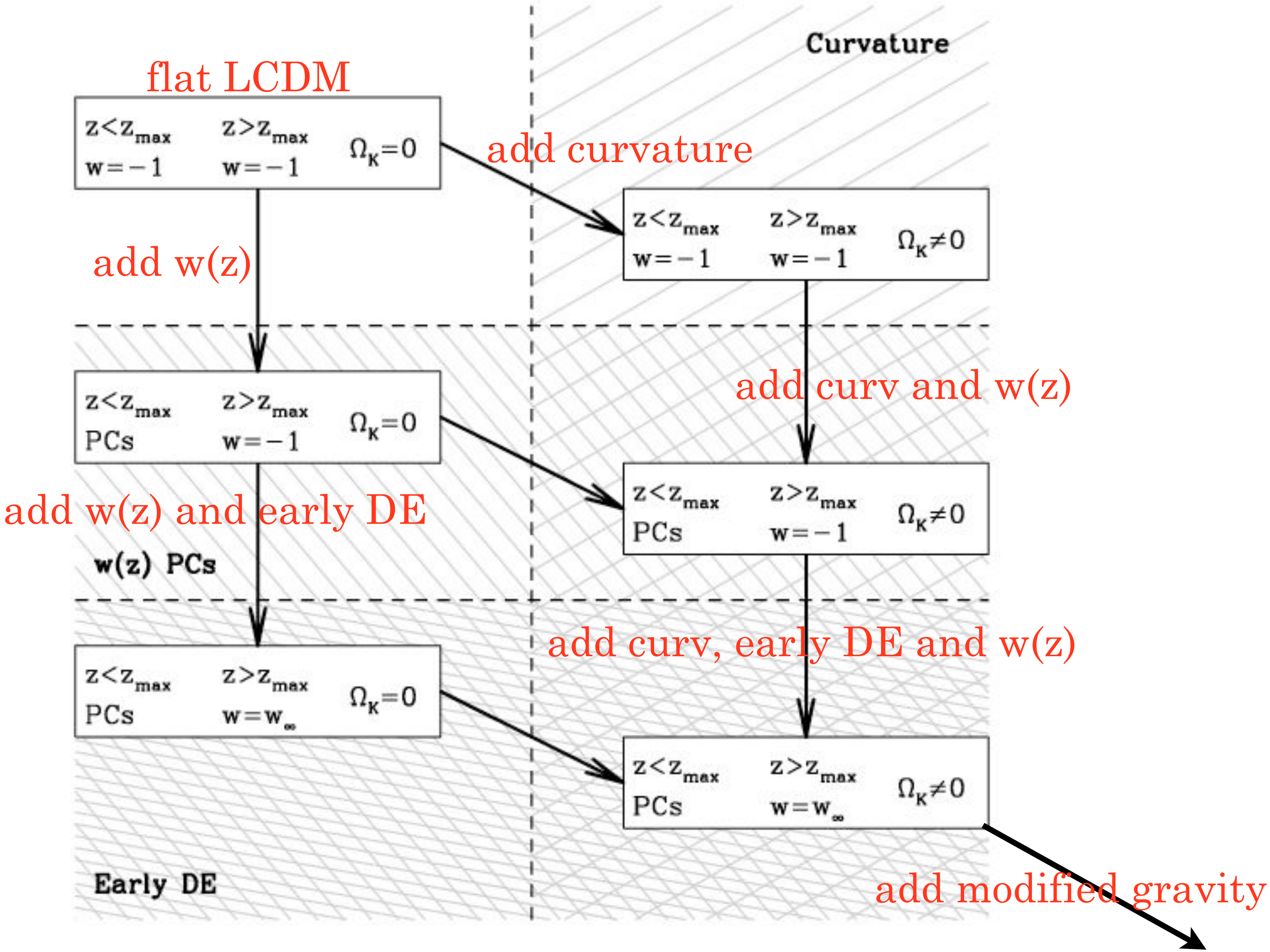


- Clearly, errors increase dramatically as you keep only linear scales
- For MG, it's hard to trust NL scales
- But for testing w(z) GR models, using NL scales may be possible

Huterer & Linder 2007 (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

Data and modeling of DE

Assumed data:

1. SNAP 2000 SNe, $0.1<z<1.7$
   (plus 300 low-z SNe)
2. Planck info on $O_m h^2$ and $D_A(z=1100)$

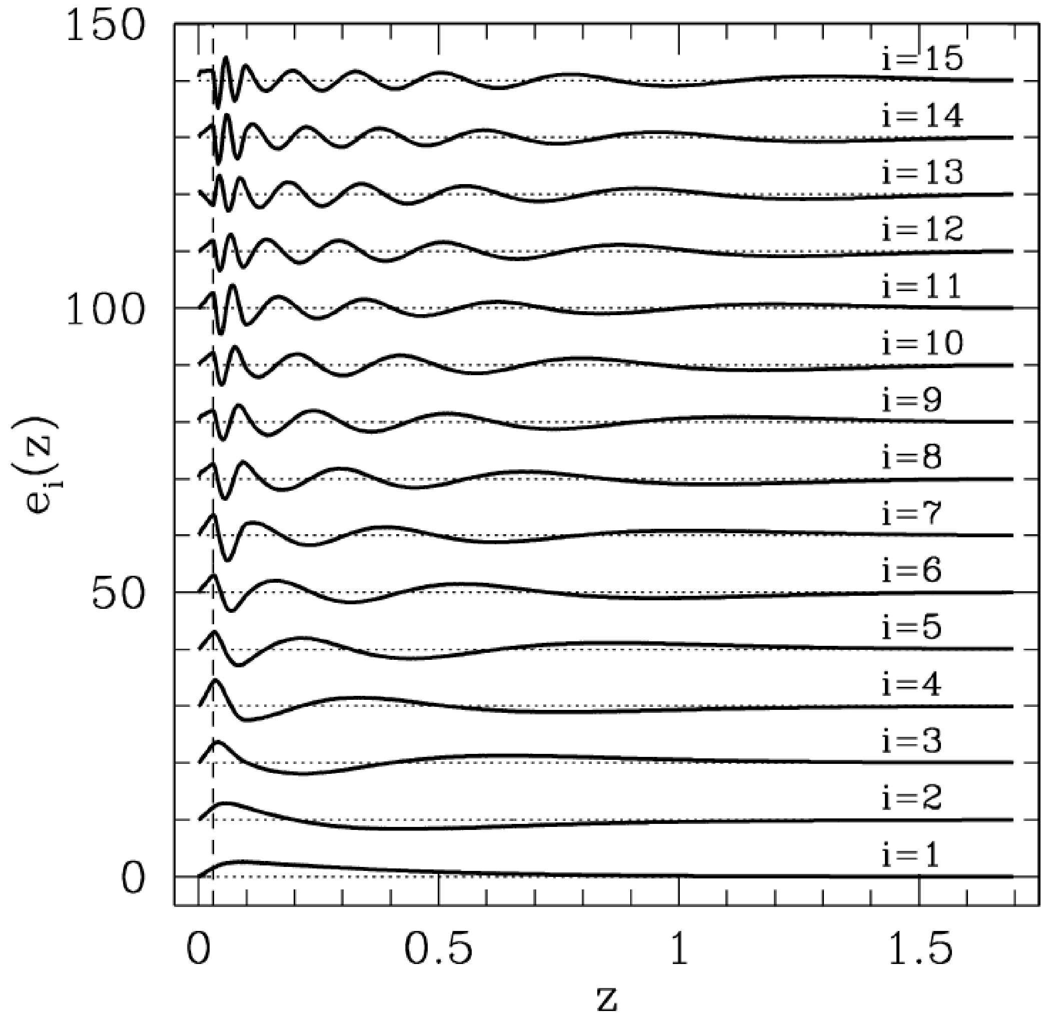
Analysis tool:

Markov Chain Monte Carlo likelihood calculation,
10-20 parameters constrained.

Data and modeling of DE

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

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



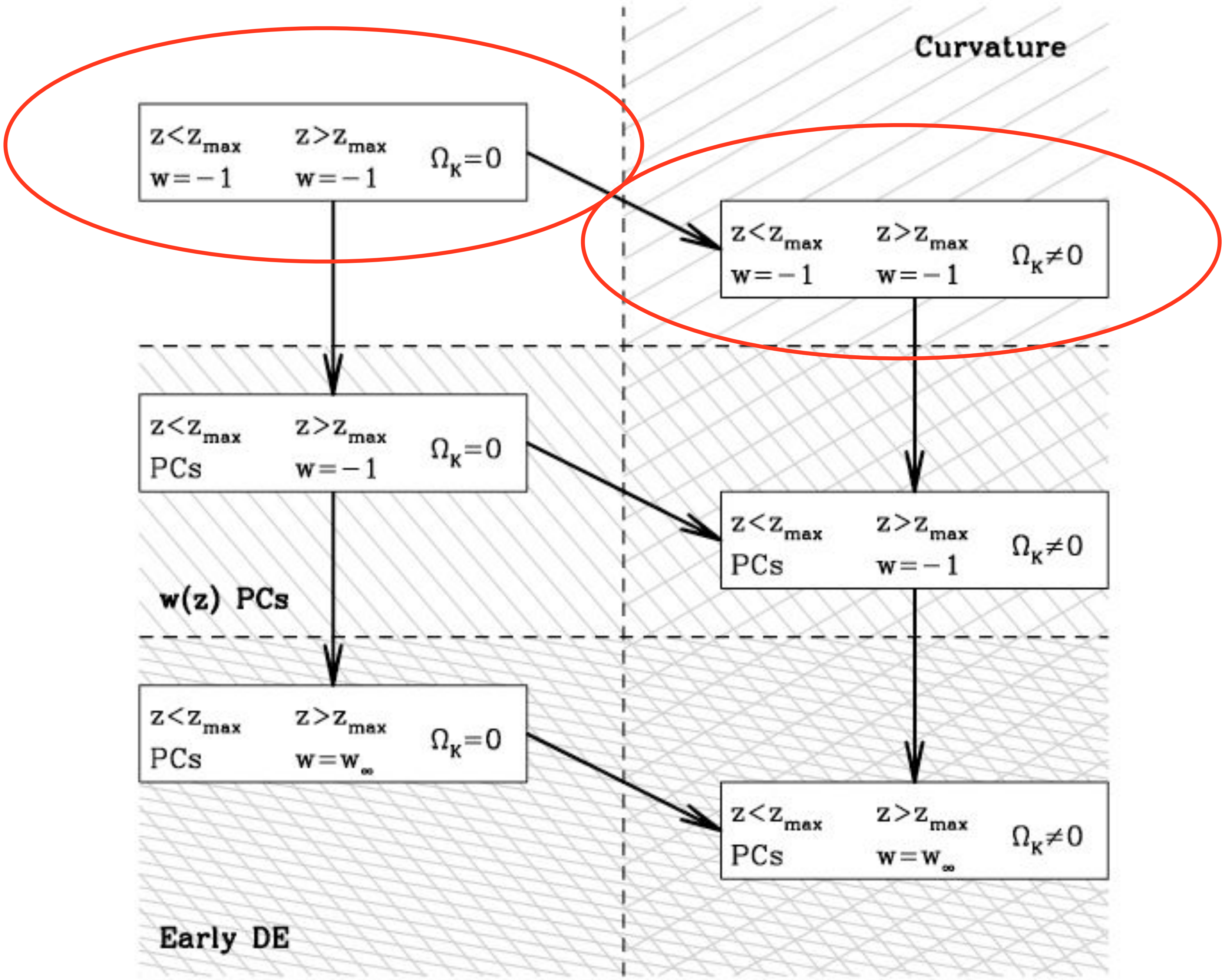
500 bins (so 500 PCs)
0.03<z<1.7
We use first ~15 PCs

Data and modeling of DE

Modeling of Early Dark Energy:

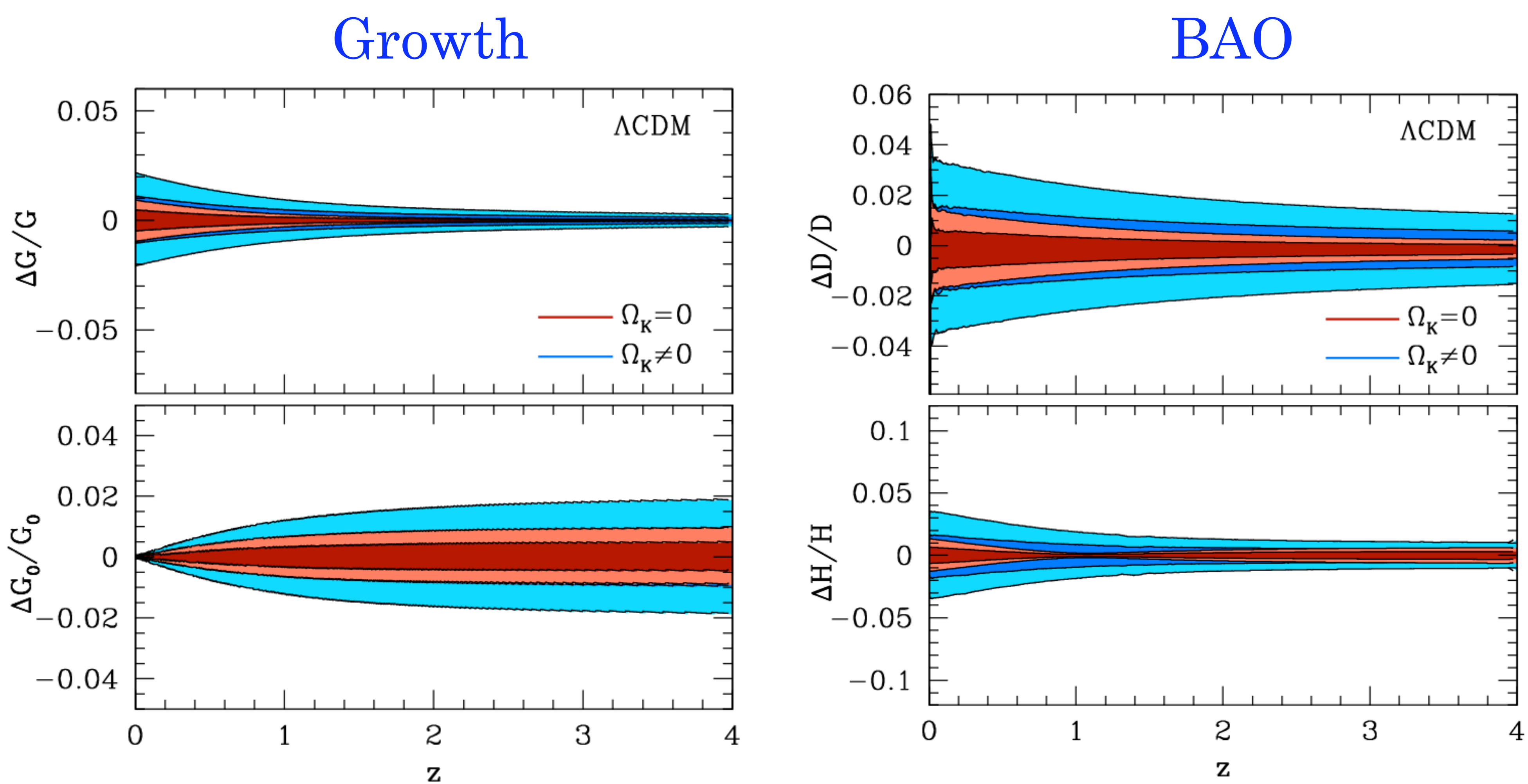
$$\rho_{\rm DE}(z > z_{\rm max}) = \rho_{\rm DE}(z_{\rm max}) \left(\frac{1+z}{1+z_{\rm max}} \right)^{3(1+w_\infty)}$$

LCDM predictions



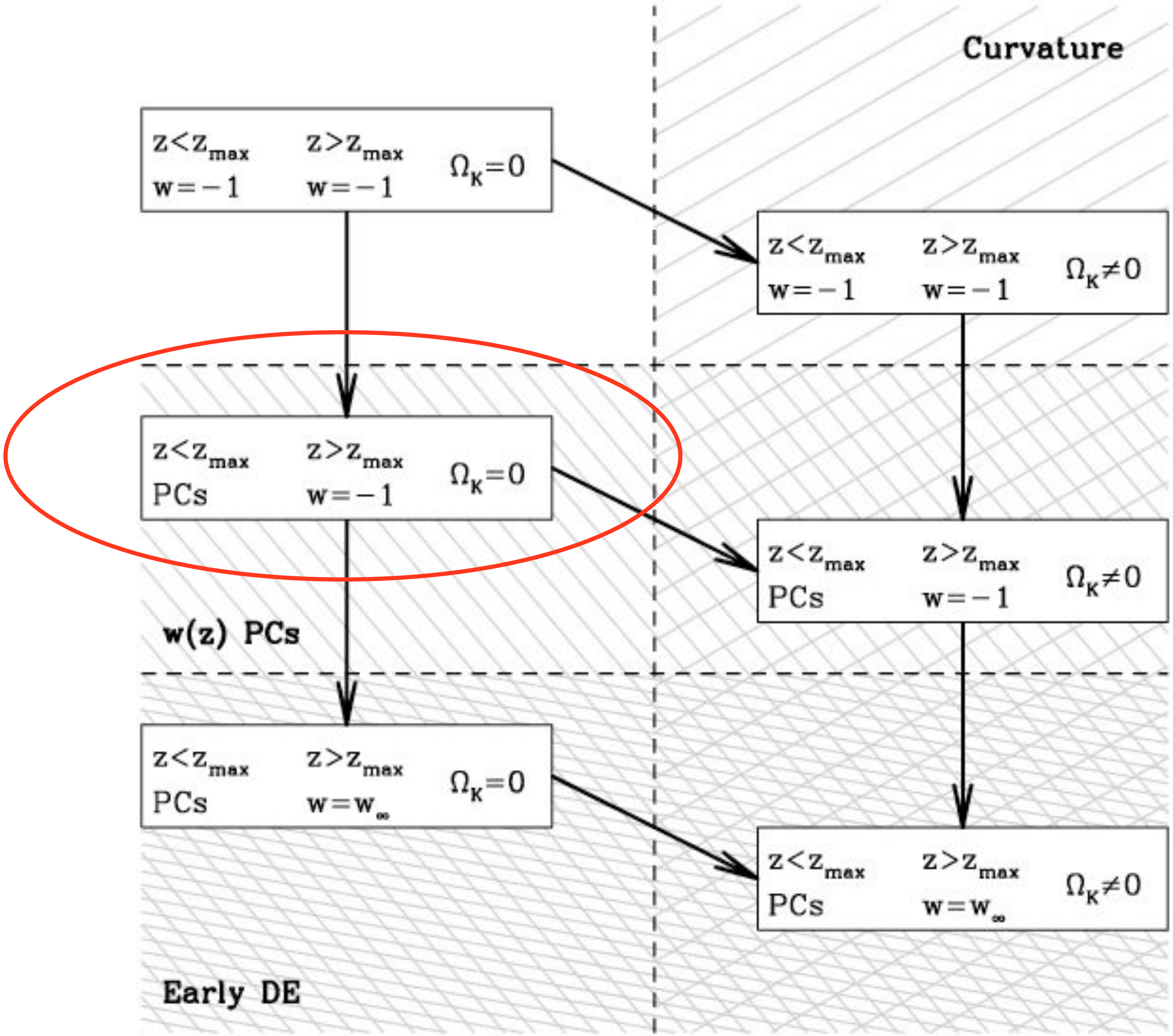
LCDM predictions (flat or curved)

Assuming SNAP SNe + Planck

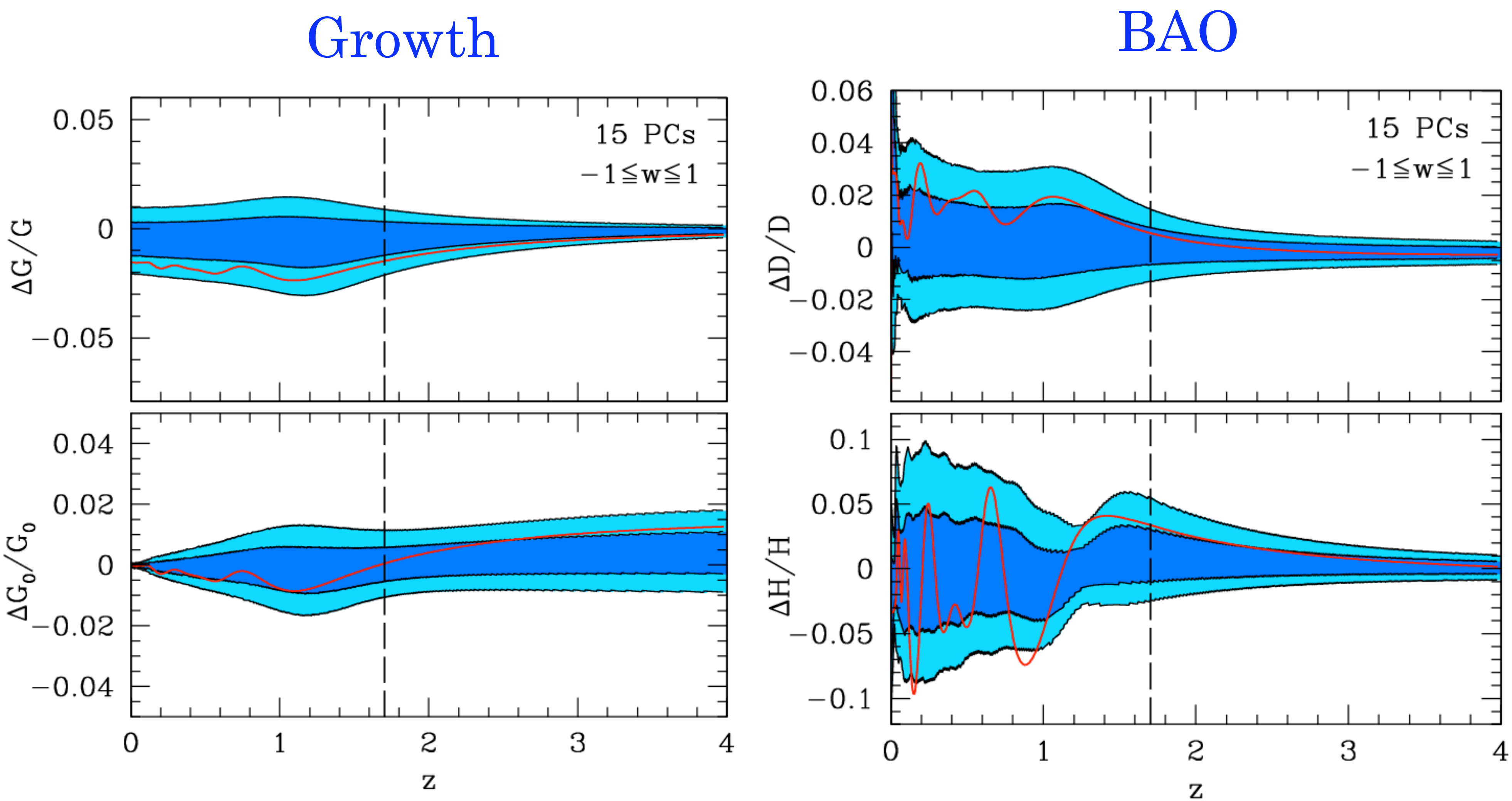


Mortonson, Hu & Huterer, in preparation

Flat, w(z) predictions

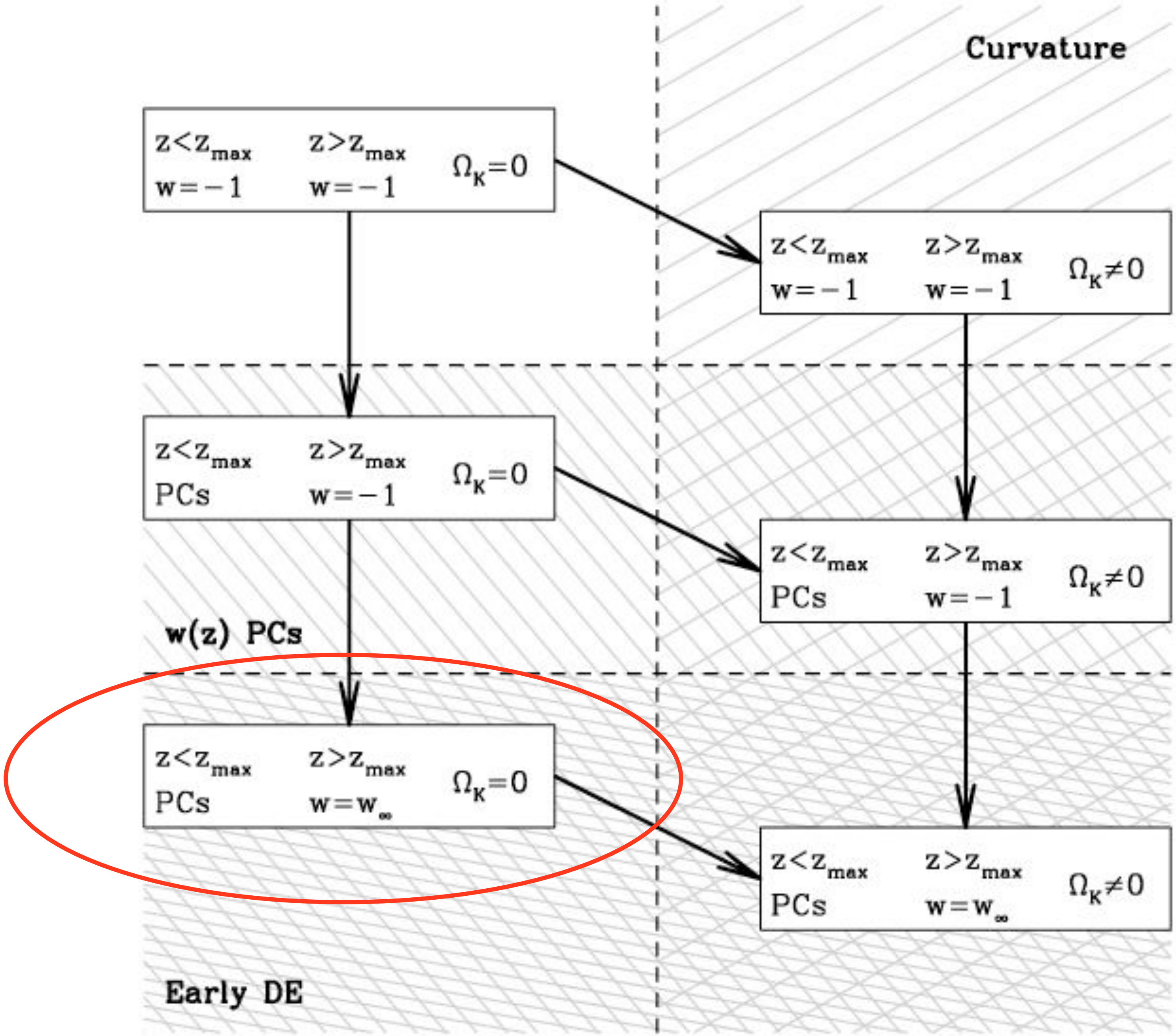


Flat, w(z) predictions

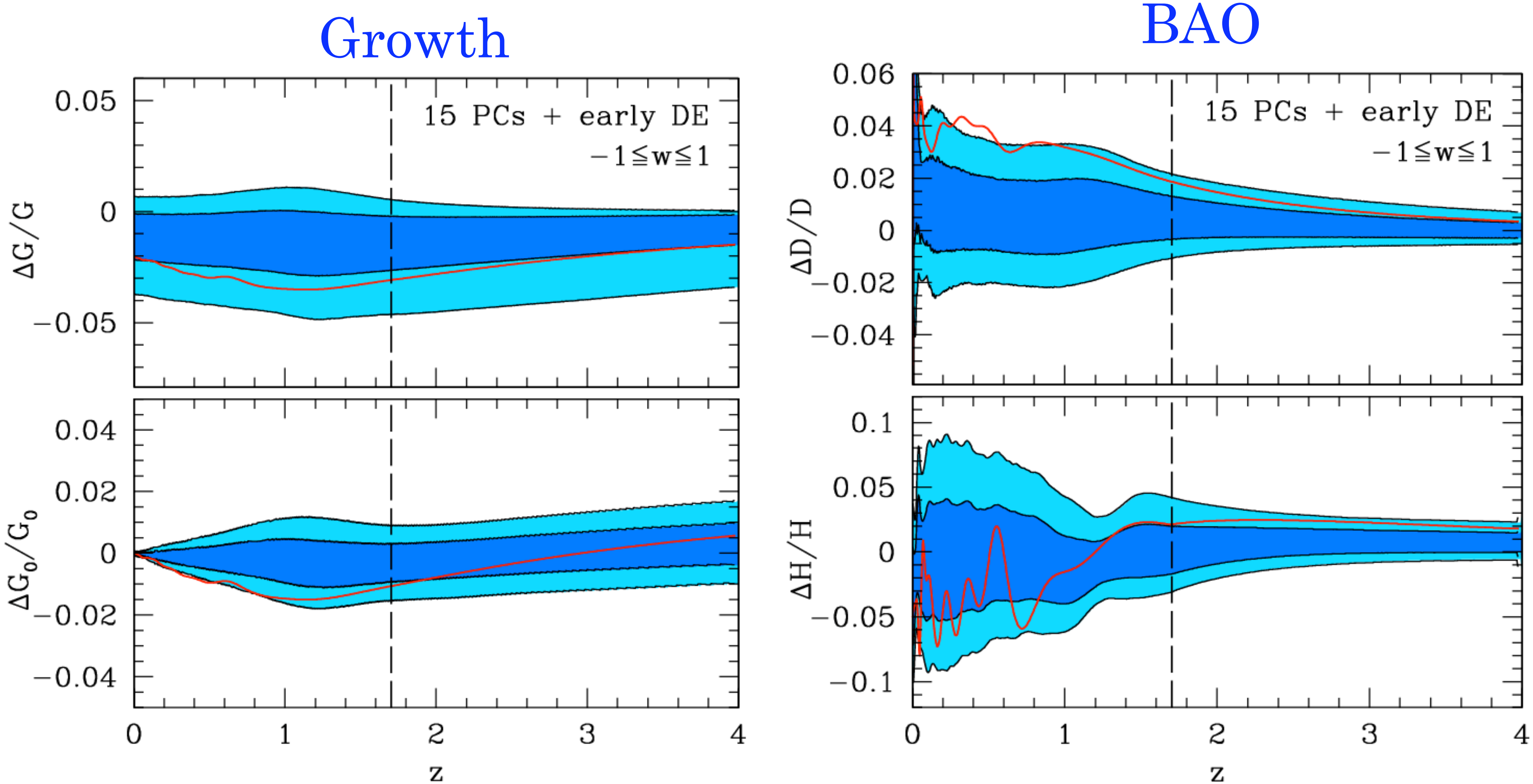


Mortonson, Hu & Huterer, in preparation

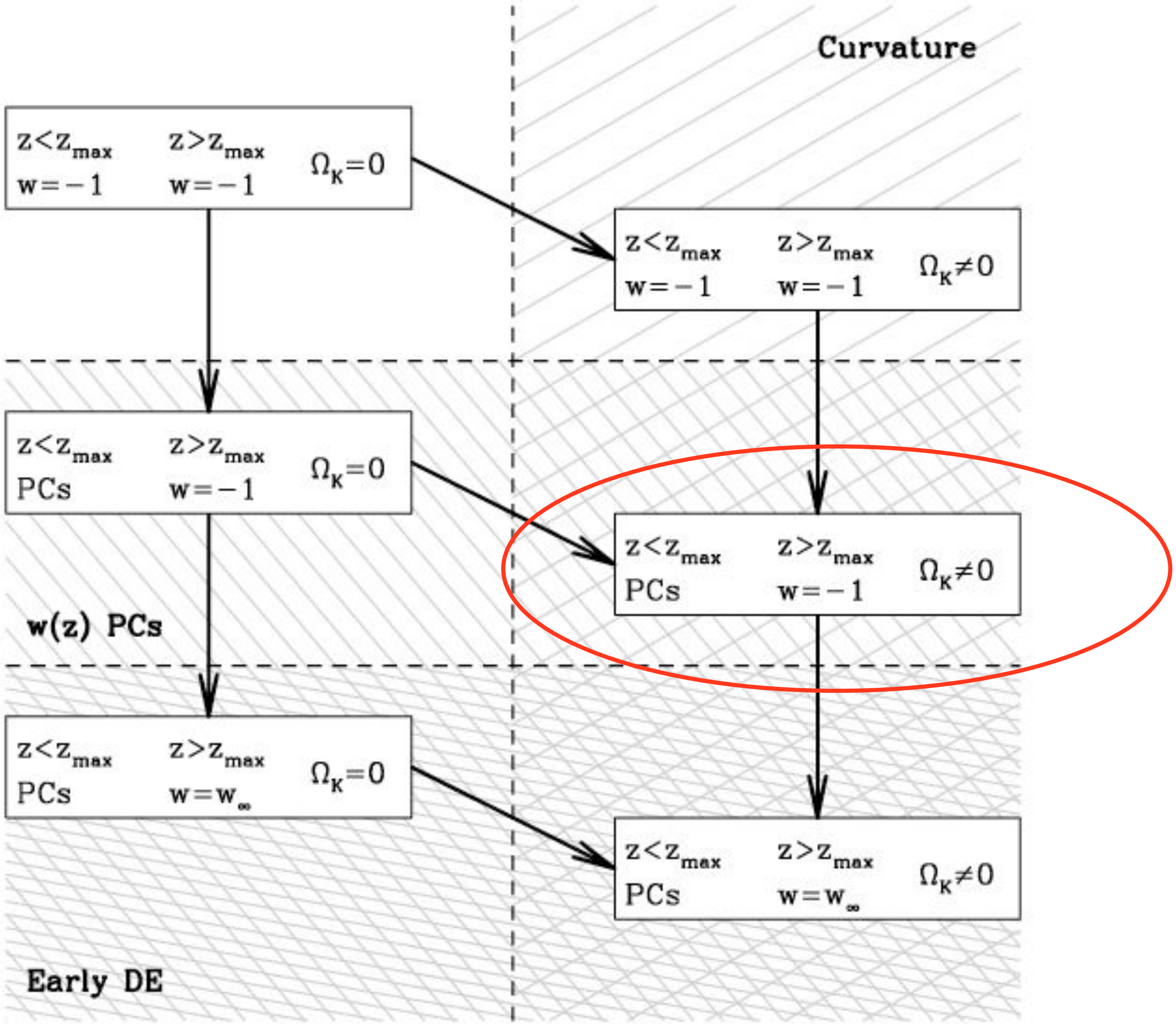
Early DE predictions



Early DE predictions

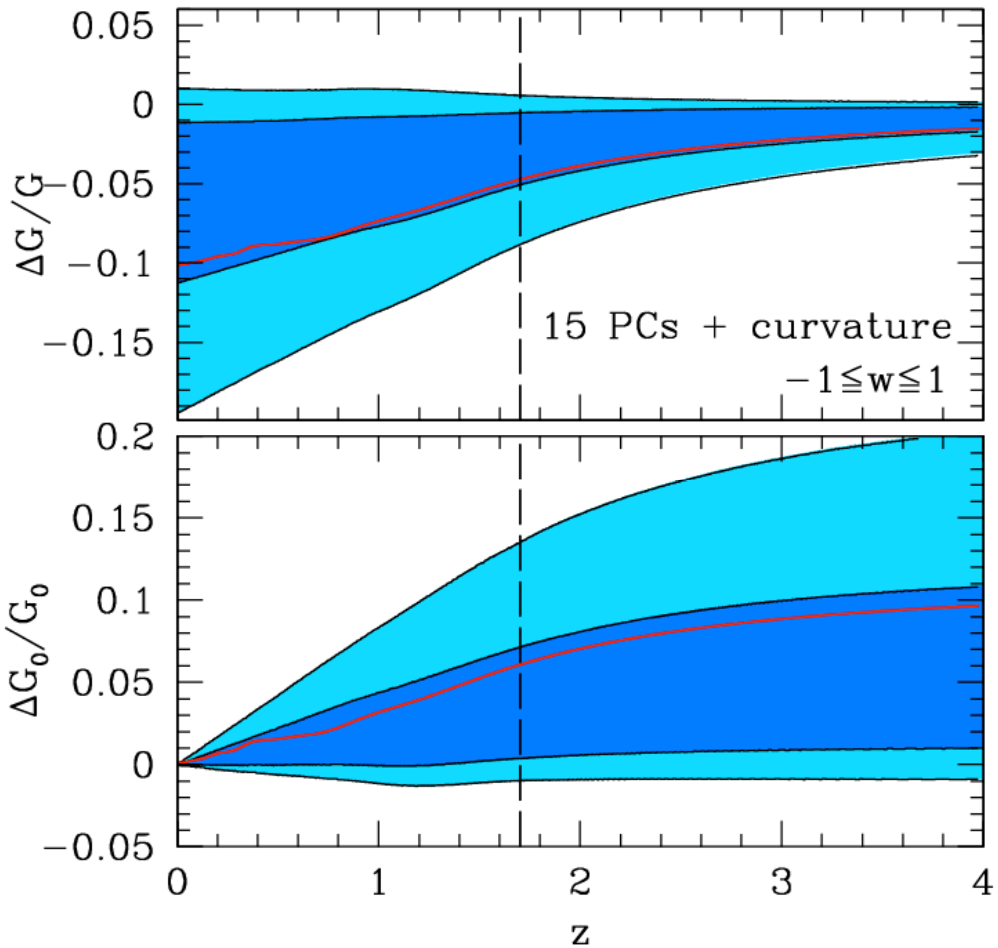


Curvature + w(z) predictions

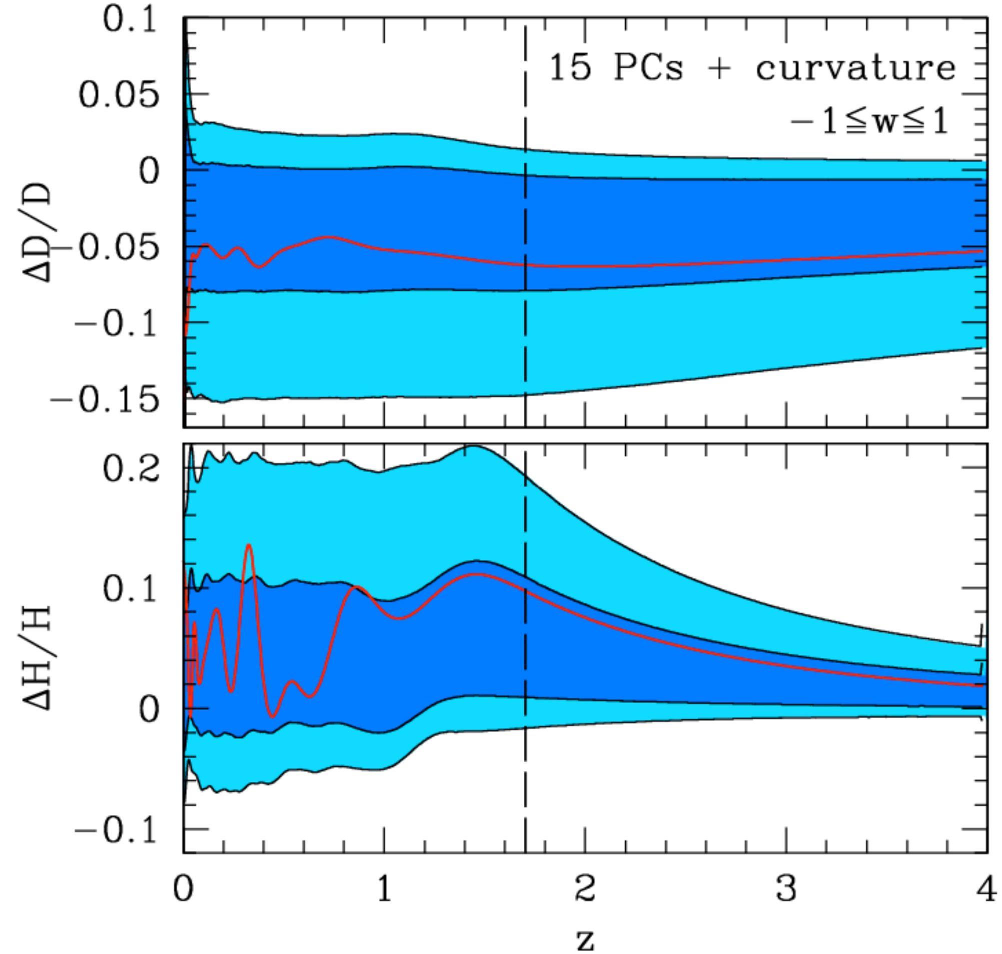


Curvature + w(z) predictions

Growth

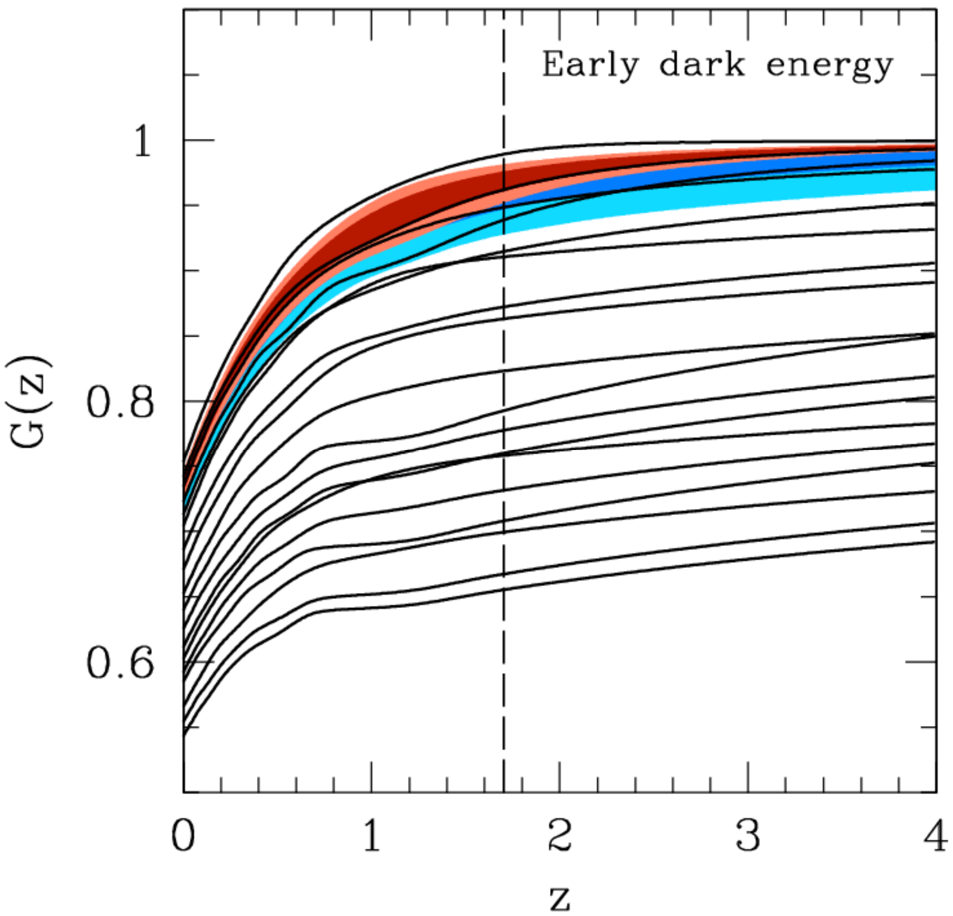


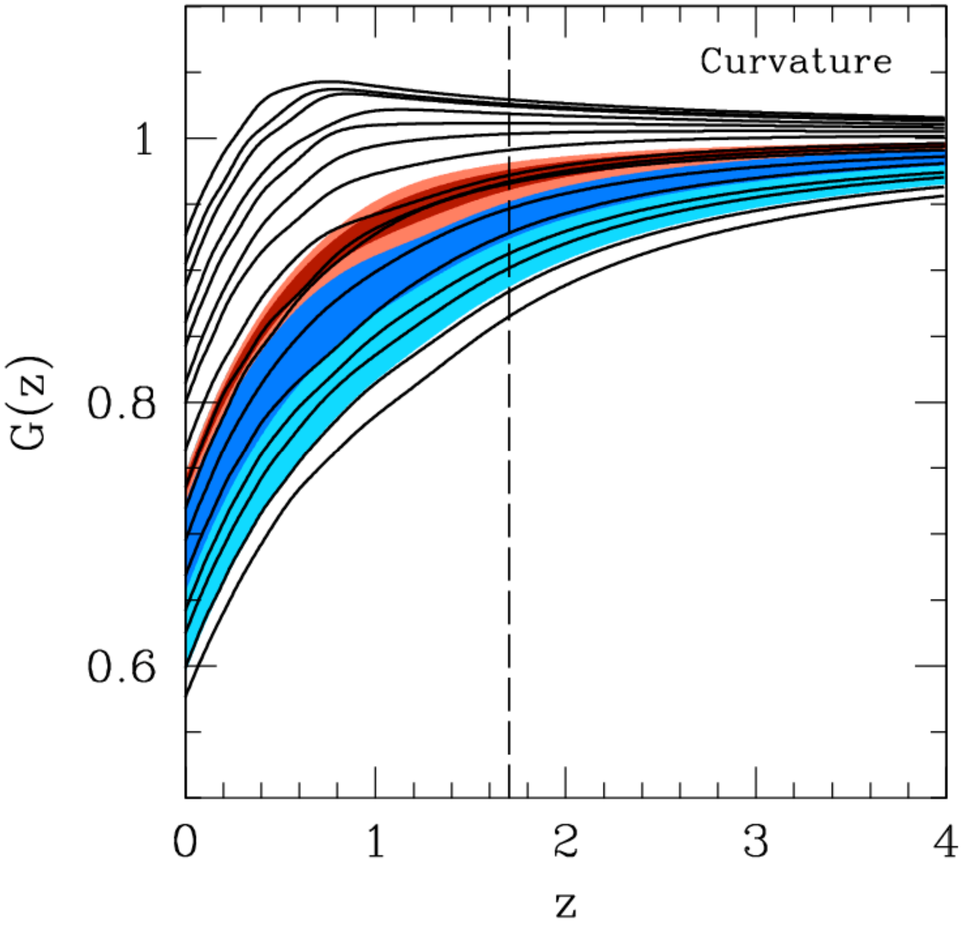
BAO



Curvature or early DE?

both cases with w(z) at low-z, no prior





Conclusions

- The interest is now shifting toward some of the most difficult tests of cosmology: probing the expansion and growth history of the universe
- Unfortunately, few if any good DE models to test, but still can do general tests within, and beyond, GR
- Understanding of nonlinear structure formation is a crucial theory systematic
- A (quantitative) "Decision Tree" for Dark Energy