Lambda or Dark Energy or Modified Gravity?

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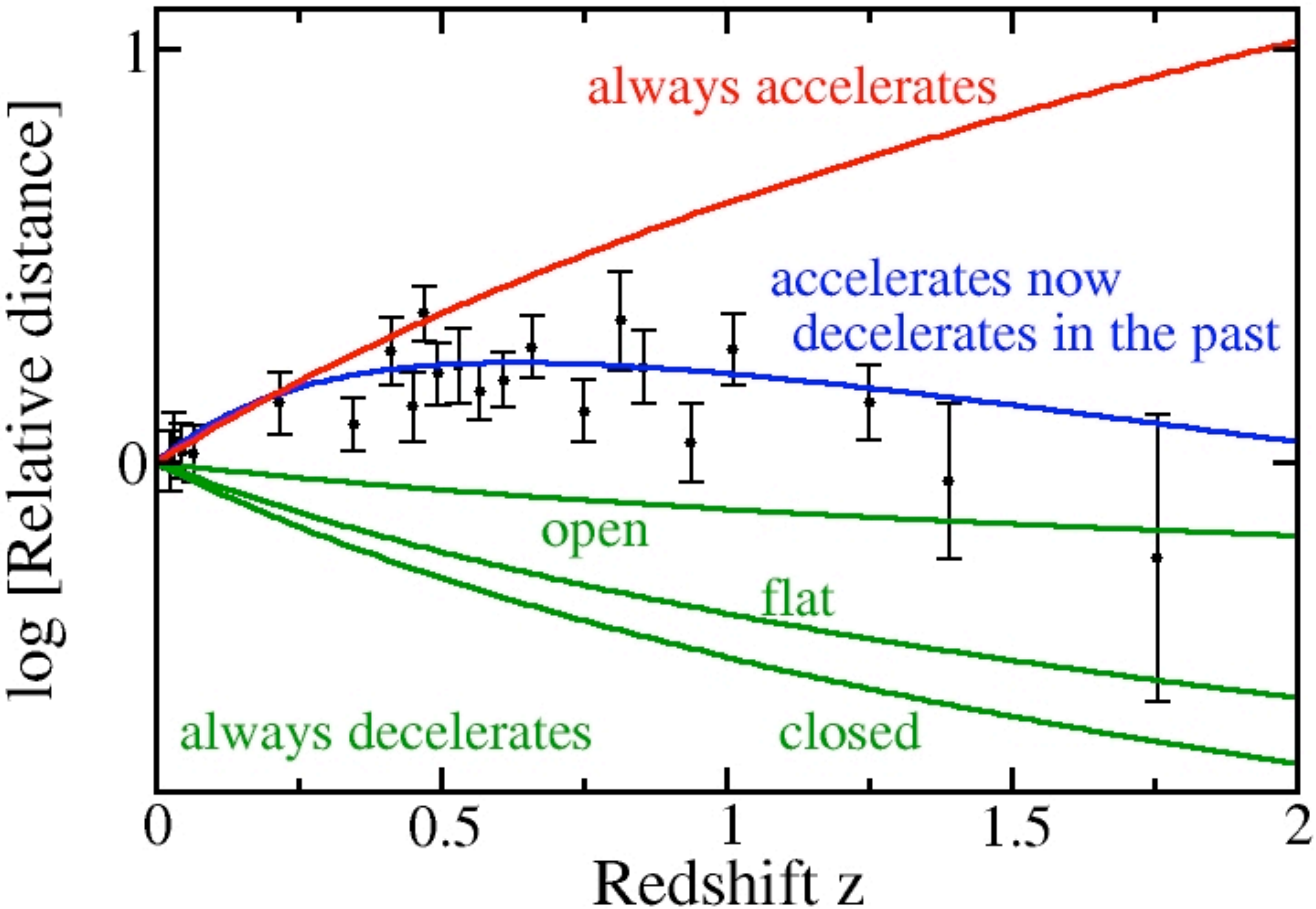
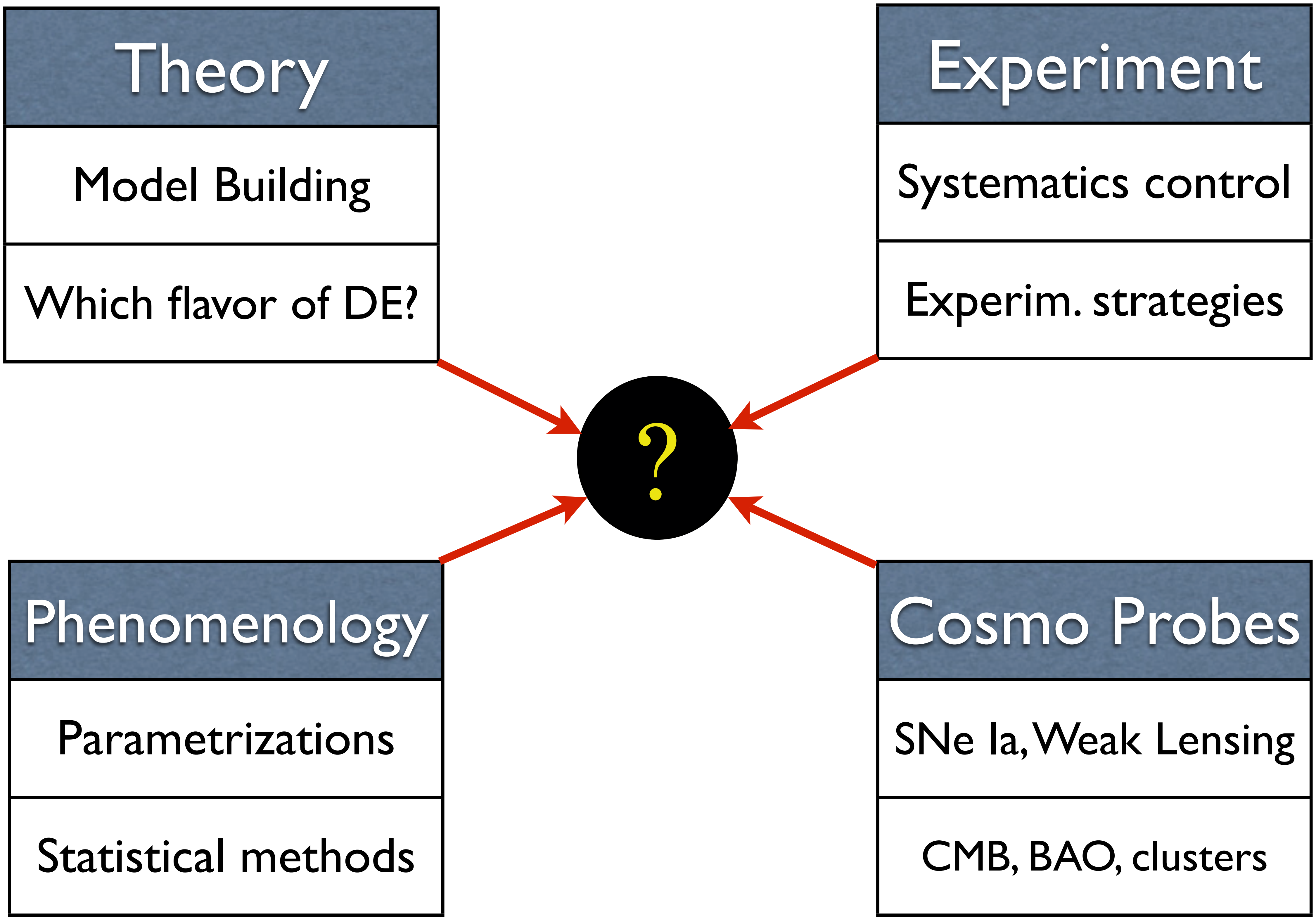
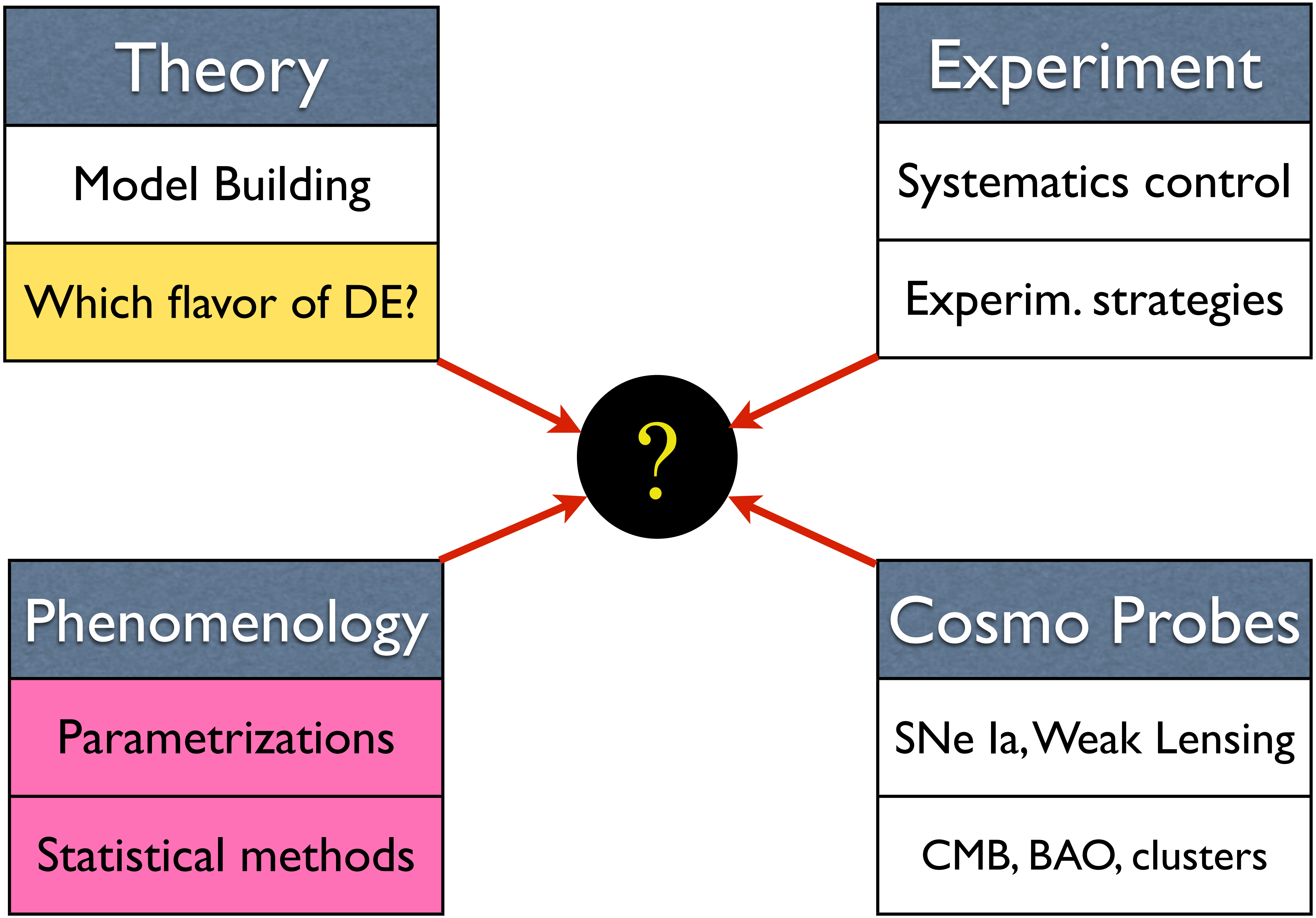
Evidence for Dark Energy




Theory
Model Building
Which flavor of DE?
Experiment
Systematics control
Experim. strategies
?
Phenomenology
Parametrizations
Statistical methods
Cosmo Probes
SNe Ia, Weak Lensing
CMB, BAO, clusters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Dark Energy constraints: Status circa spring 2008

- Very strong indication that the universe is accelerating
- Flat LCDM is an excellent fit to all data
- Interest in constraining alternatives to LCDM is gaining momentum

Which alternative (if any) should be pursued?

What I overheard various prominent theorists say:

- Lambda is "the only model that makes any sense"
- Lambda "doesn't make any sense"
- Modified gravity models are "a complete nonsense" but (my own model) is "promising"
- w is -1, and we are "wasting our time" searching for deviations

Two approaches

1) Develop framework to robustly determine implications of a given class of DE models

- What constraints are obtained on w(z), rho(z) within this class? On w0 and wa?
- Does the class of models itself significantly limit the range of DE histories?
- Is it worth spending $$$ for future experiments if “all reasonable non-Lambda models may have already been ruled out”?

Two approaches

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2) Develop framework to determine optimal observational strategies to distinguish between explanations for the acceleration

- Lambda or dw/dz, or curvature, or modified gravity... given current data, what do we do to find out?

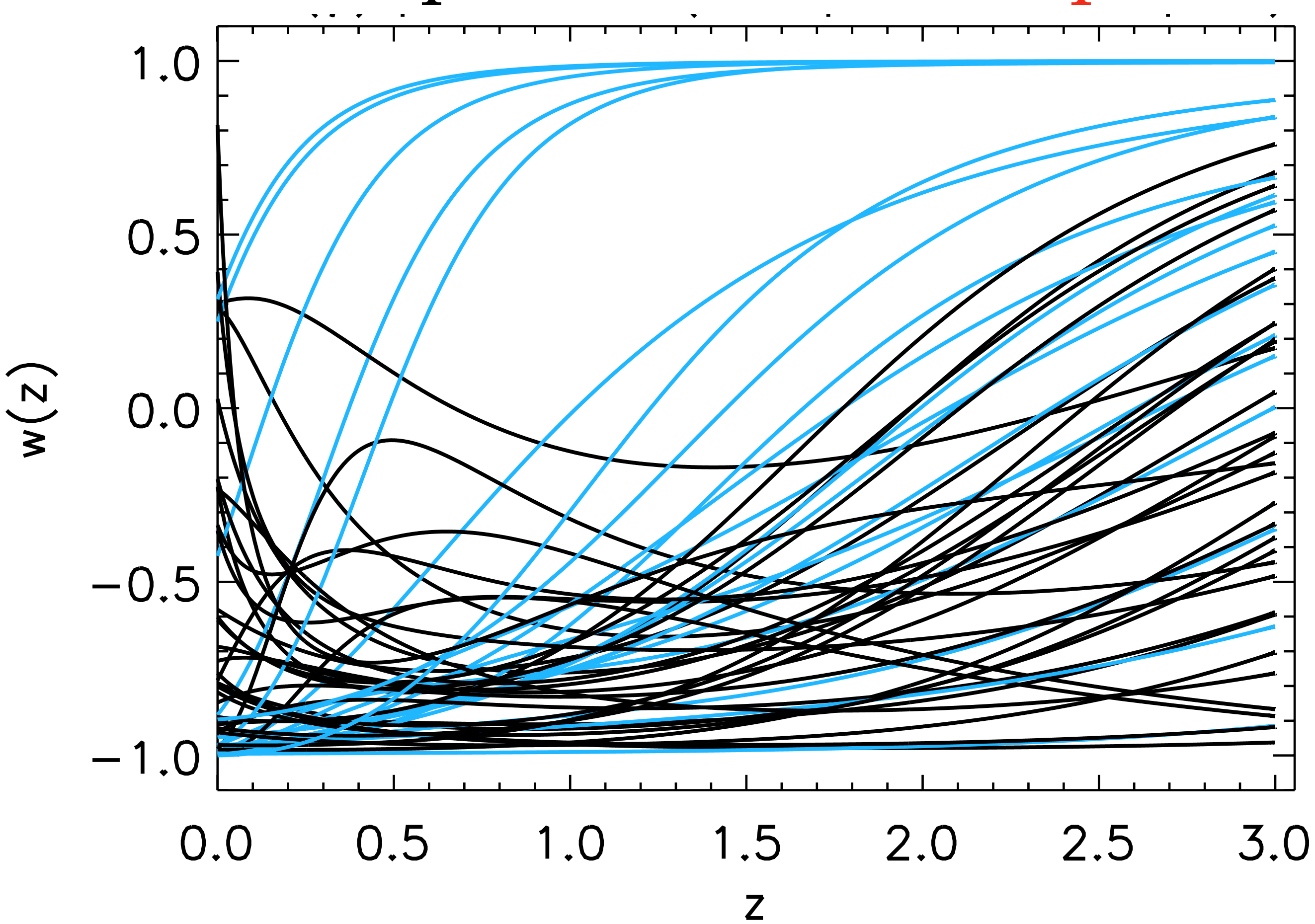
Example of 1:
Scan through quintessence models

Adopting to DE the flow-equation formalism from inflation:

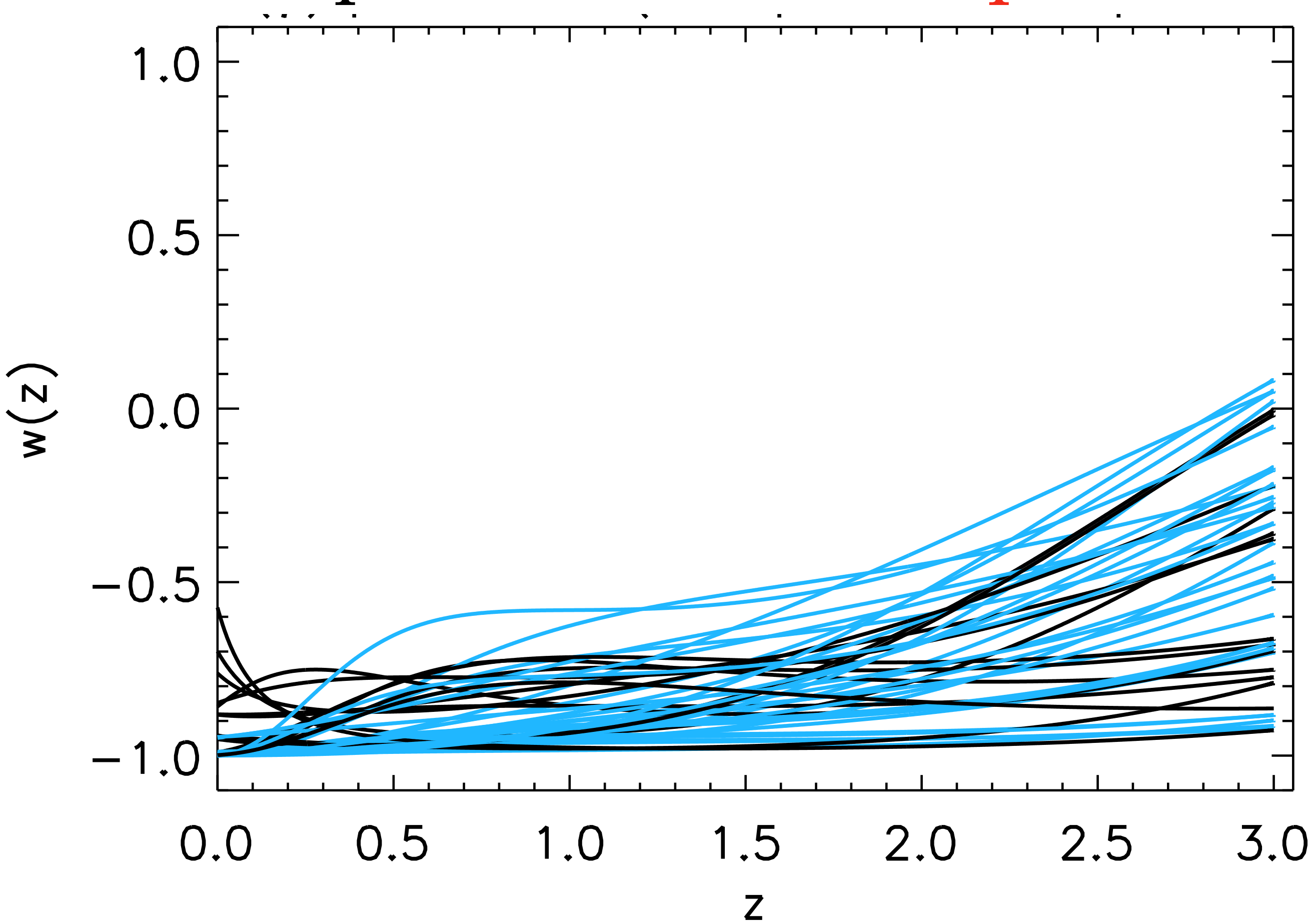
Scan all (sample millions) of models, and ICs, within a general paradigm - e.g. quintessence with polynomial potentials

$$w(z) = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$$

sample DE models in prior

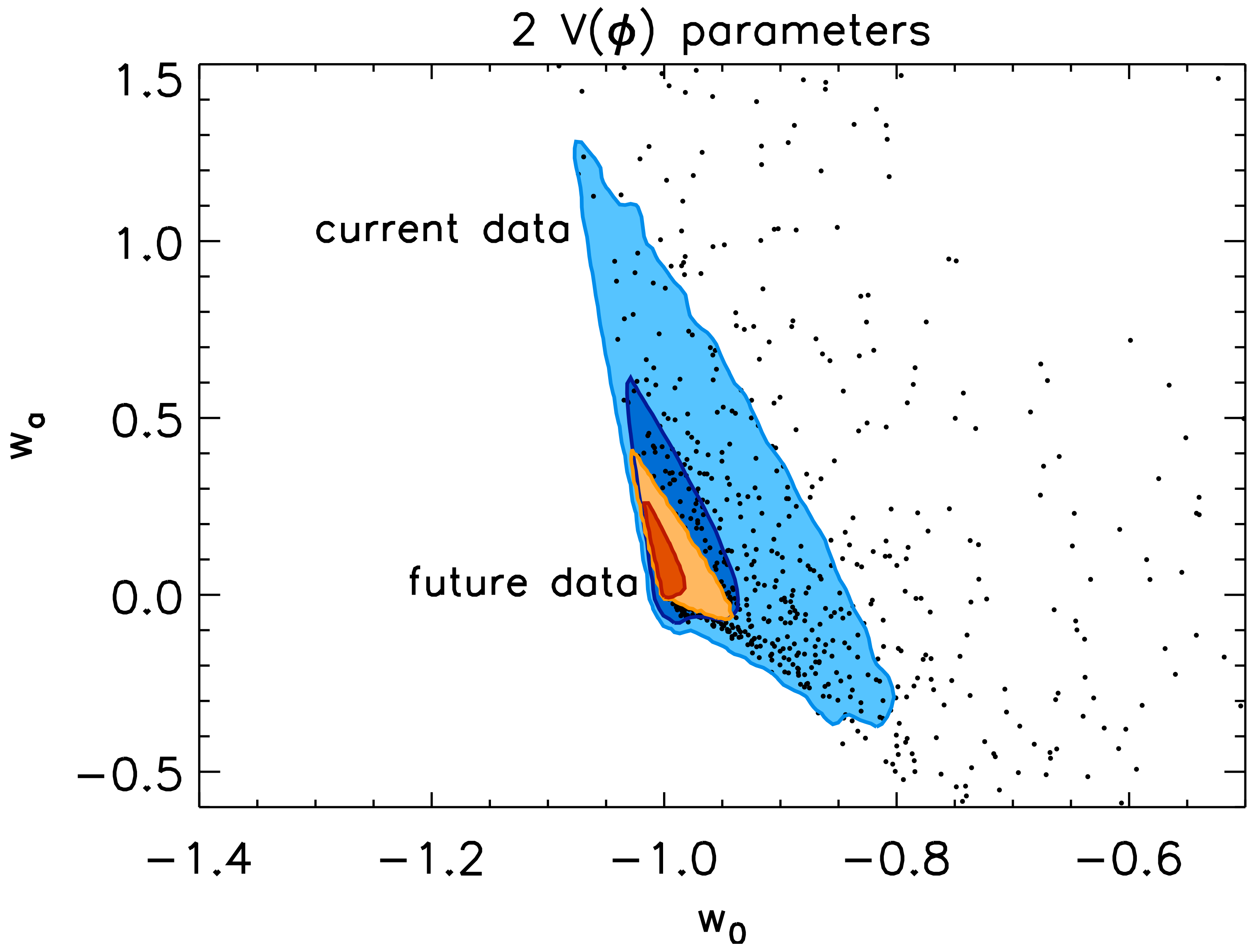


sample DE models in posterior



Huterer & Peiris, astro-ph/0610427

Scan through quintessence models



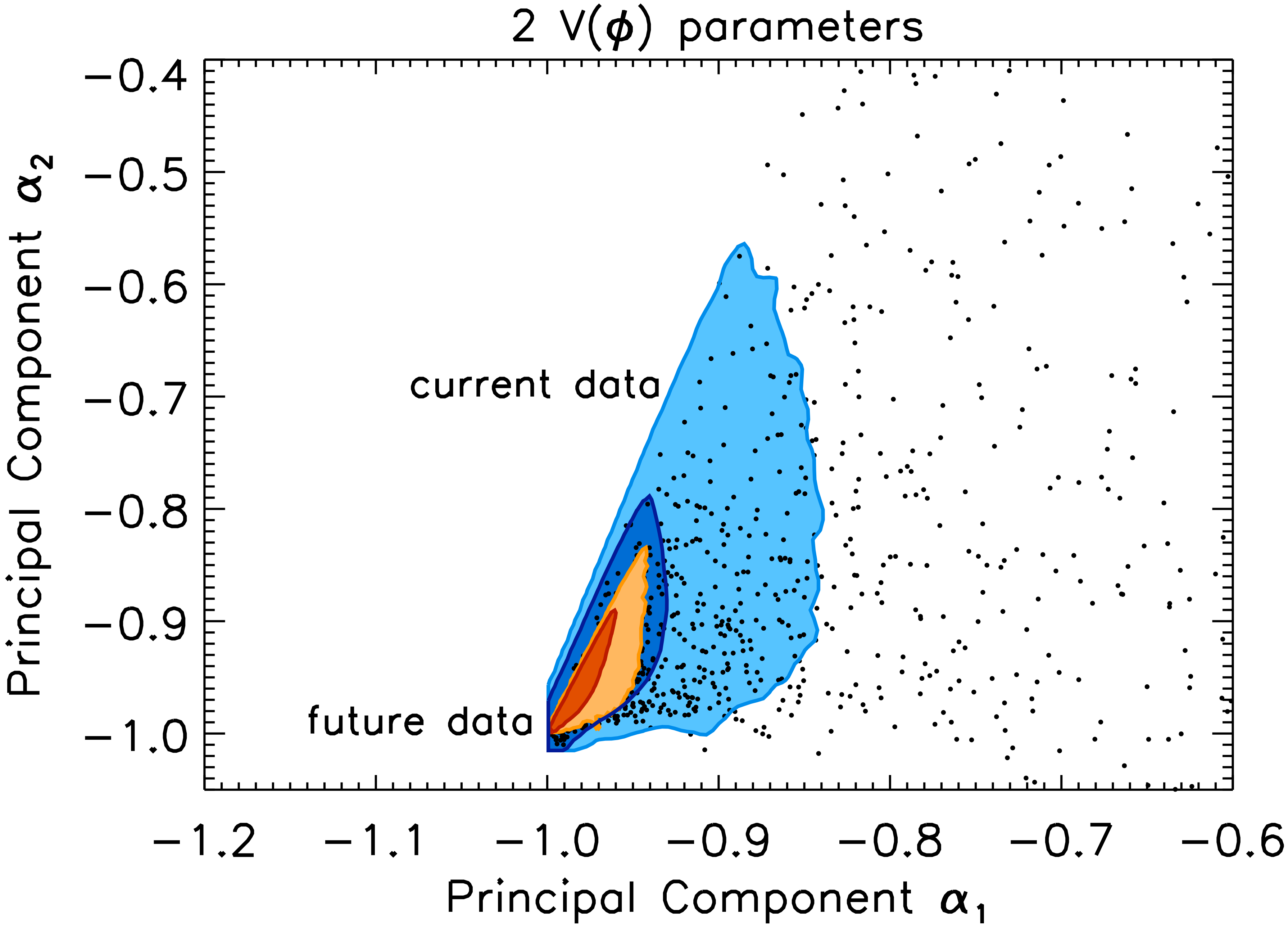
$$w(z) = w_0 + w_a \frac{z}{1+z}$$

Also allows straightforward computation and constraints on the principal components, phase-space flows, figures of merit....

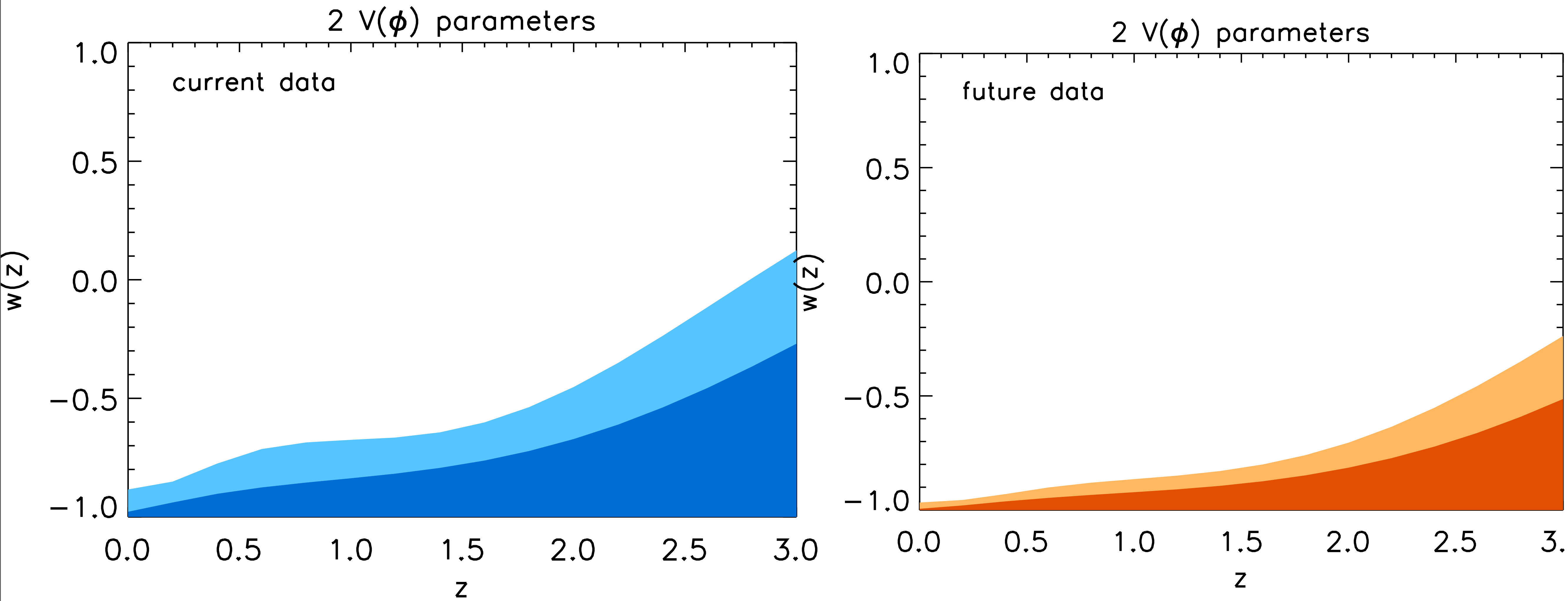
Huterer & Peiris, astro-ph/0610427

Principal components of w(z)

$$\alpha_i = \int_0^\infty w(z)\, e_i(z)\, dz$$

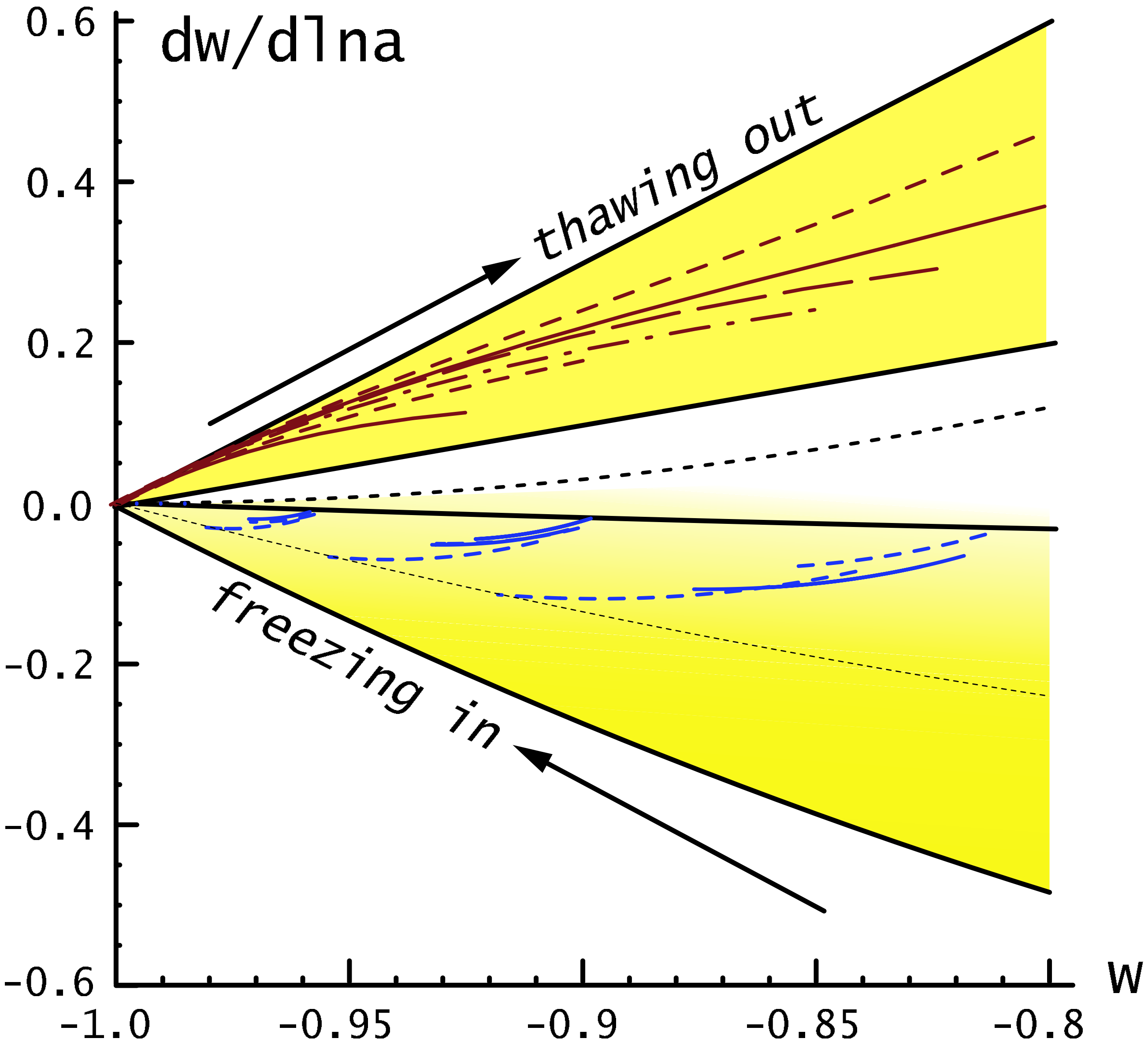


Reconstruction of w(z)



N.B. This scalar-field-model reconstruction is much more stable than the general "non-parametric" reconstruction

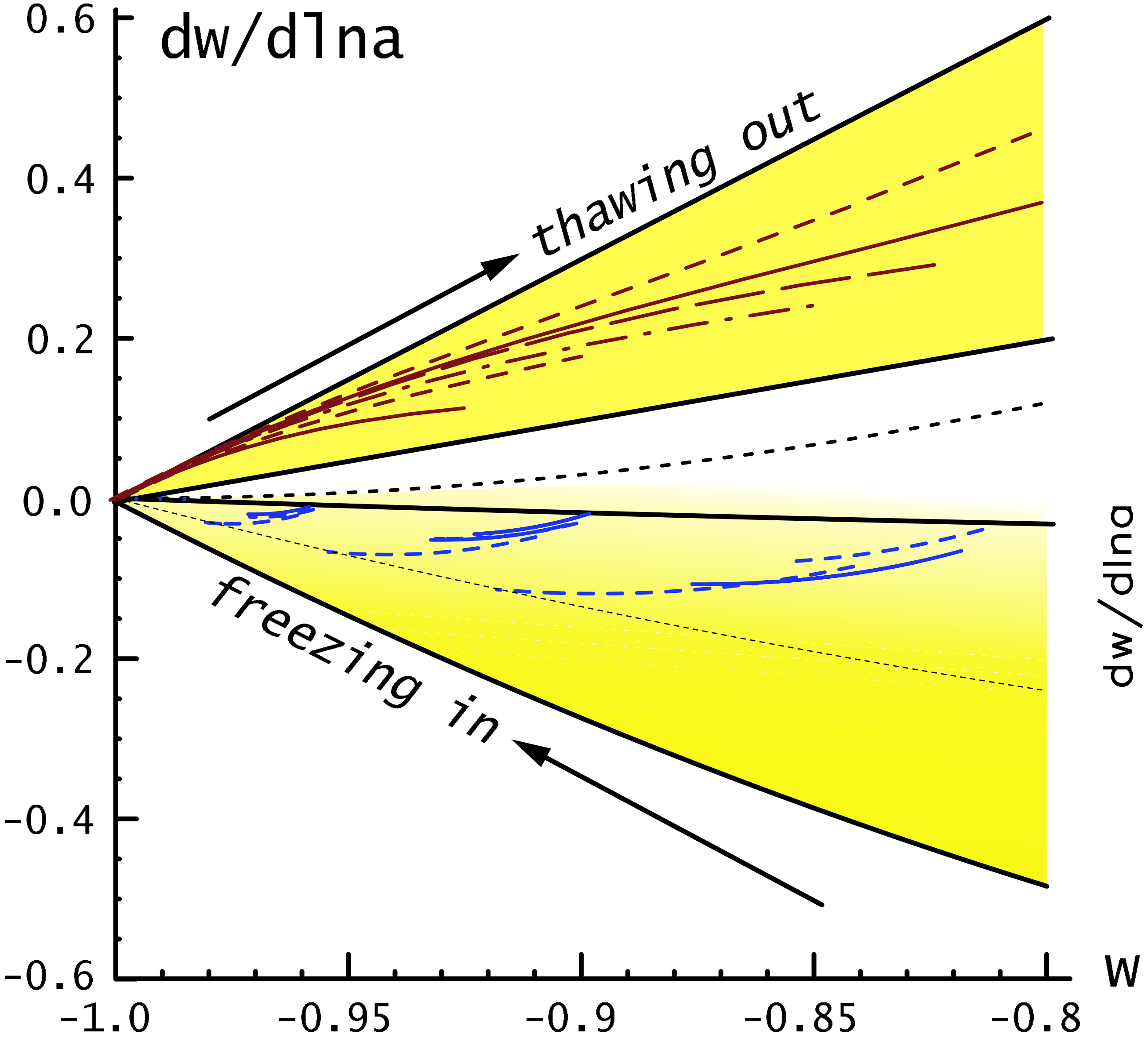
Generic behavior of scalar fields (?)



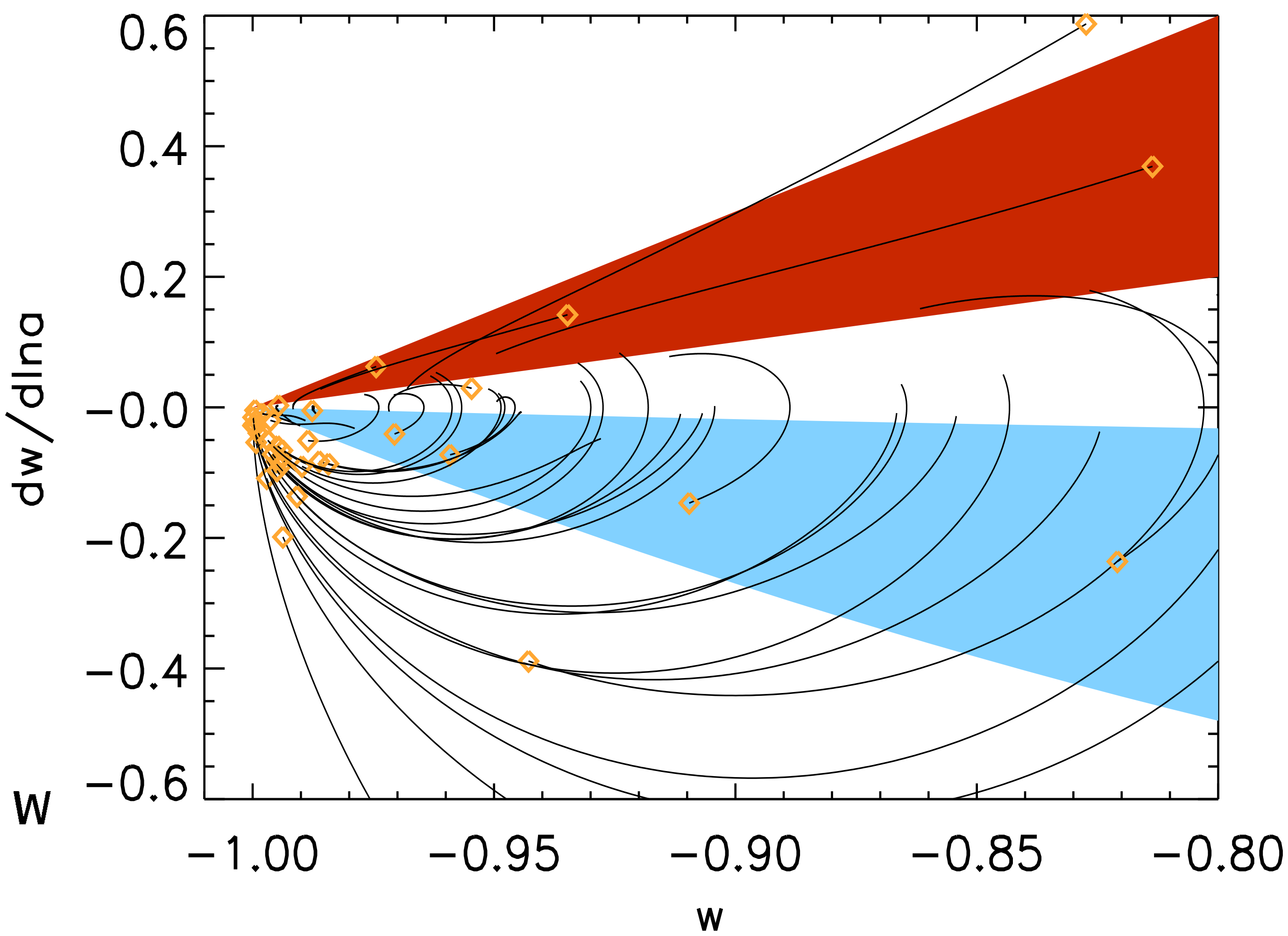
- Do scalar field models follow the freezing/ thawing behavior?
- The claim was based on specific scalar field models

Caldwell & Linder 2005

Generic behavior of scalar fields (?)



More general models do NOT cleanly fall into freezing/thawing



Caldwell & Linder 2005

Huterer & Peiris, astro-ph/0610427

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
- so far, there hardly exist any well-defined MG theories with specific cosmological predictions (except perhaps Dvali-Gabadadze-Porrati braneworld theory)
- 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!)

Two approaches for DE vs. MG

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

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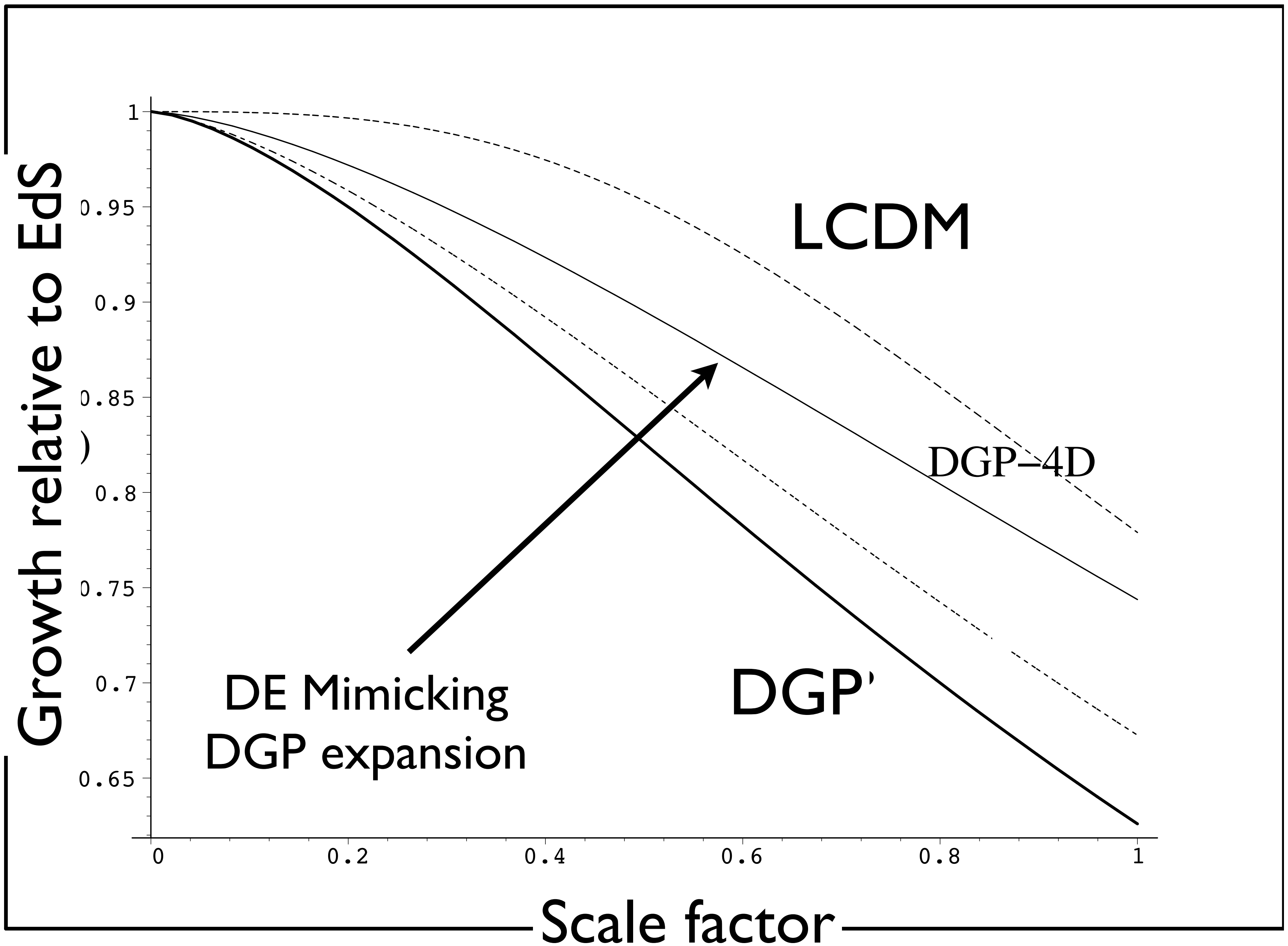
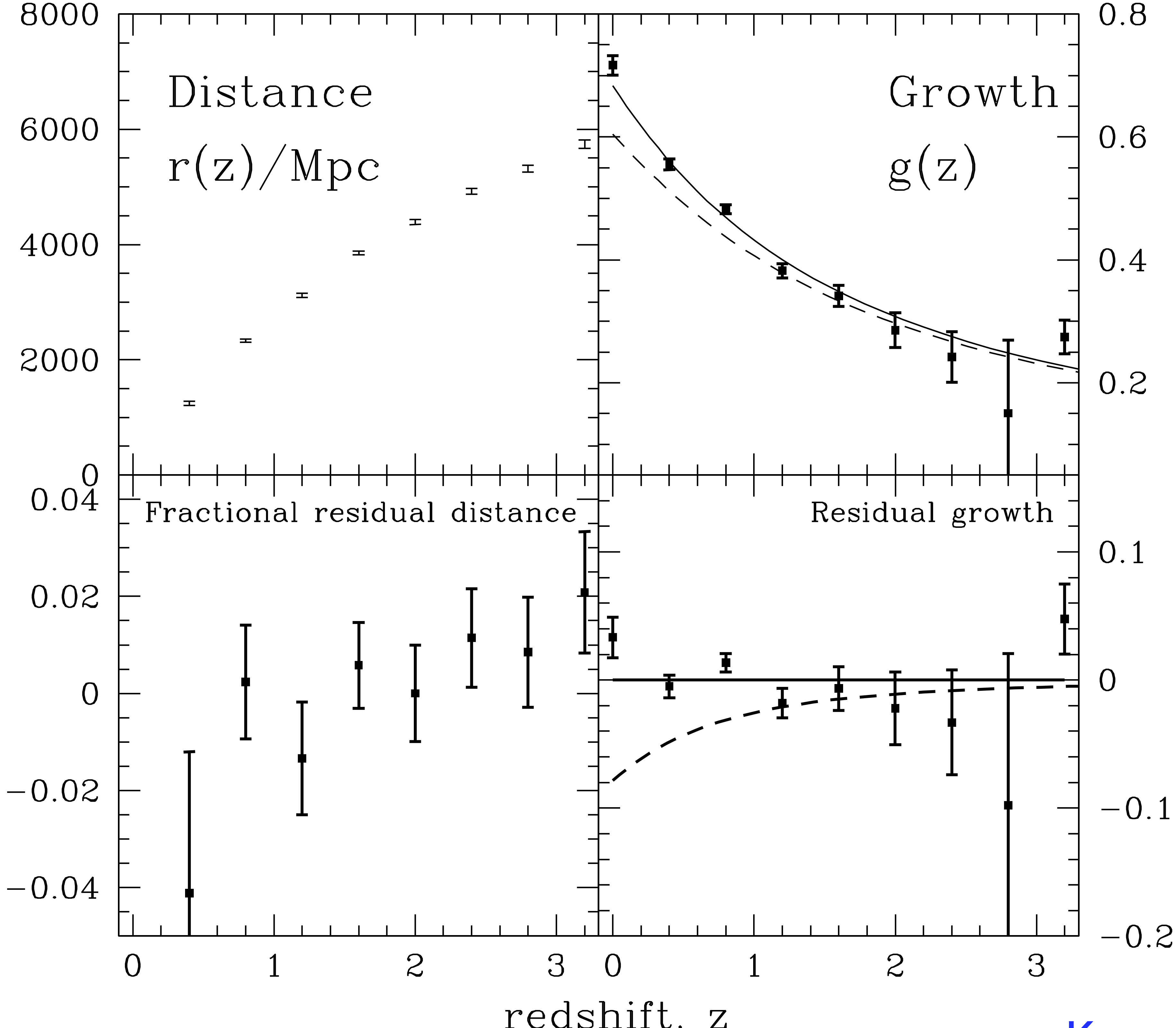
2. Parametrize the expansion and growth history separately; check consistency

DGP linear growth



Lue, Scoccimarro & Starkman; Koyama & Maartens; Sawicki, Song & Hu

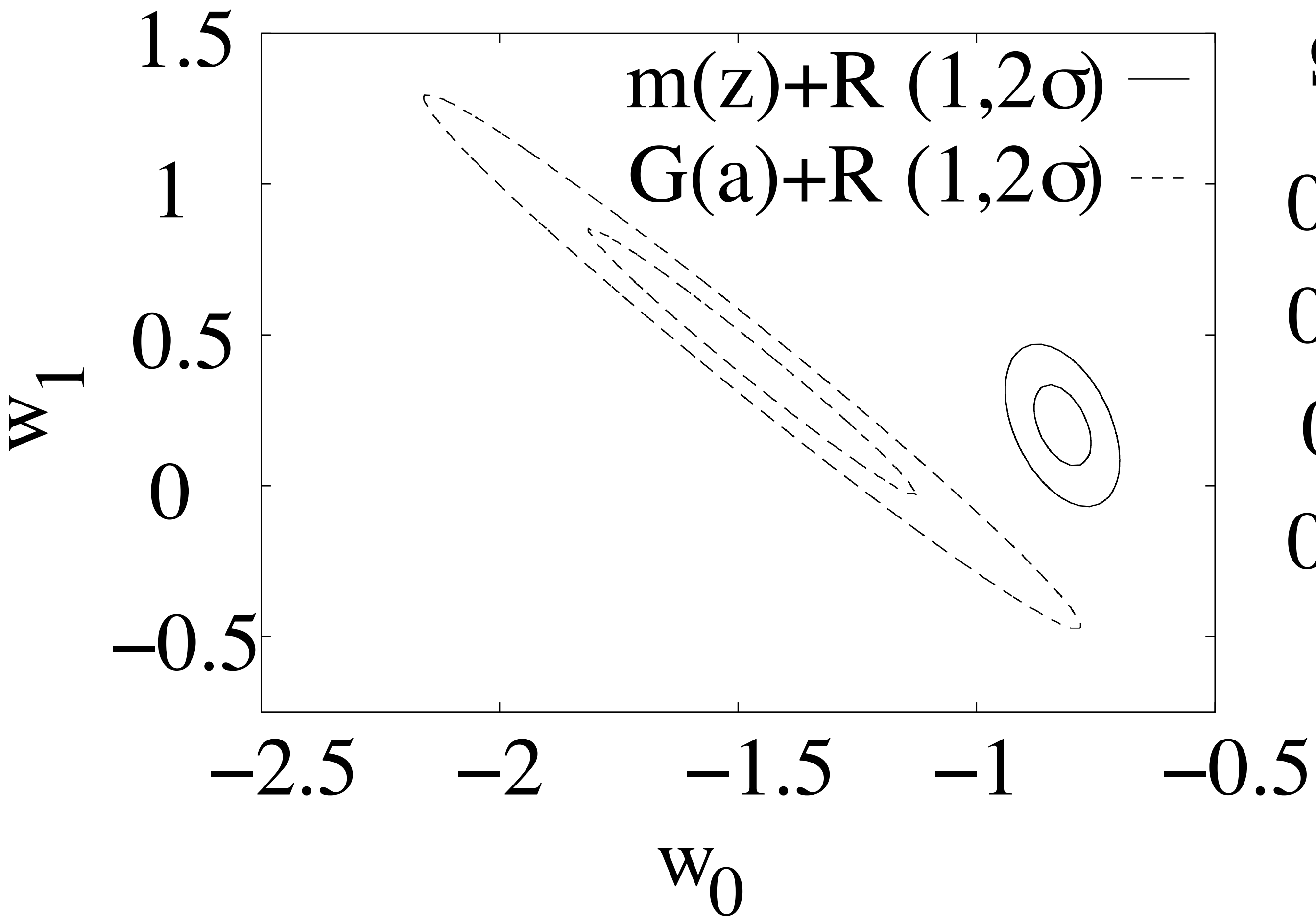
Strategy I: distance (z), growth(z) separately

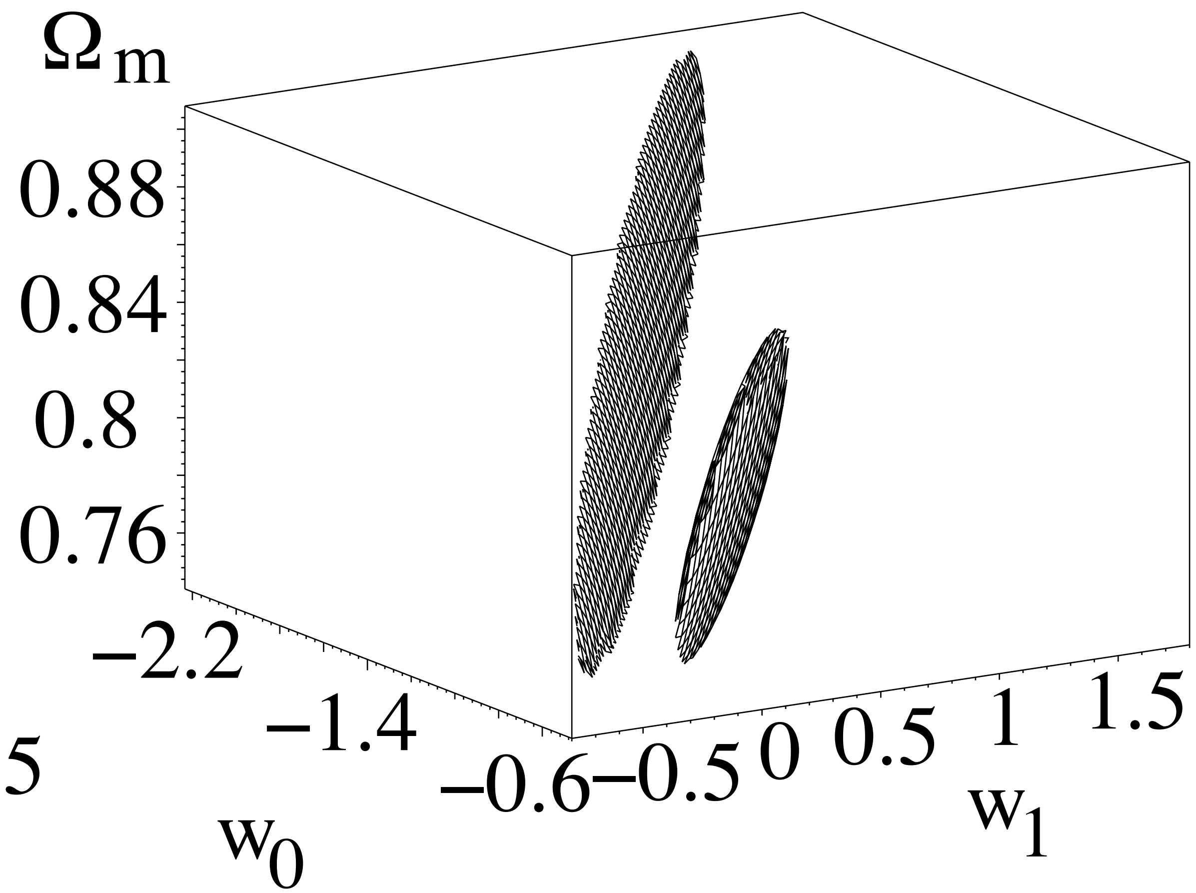


Measure r(z), g(z), see if they agree

Knox, Song & Tyson 2005

Strategy II: (O_m, w_0, w_a) separately



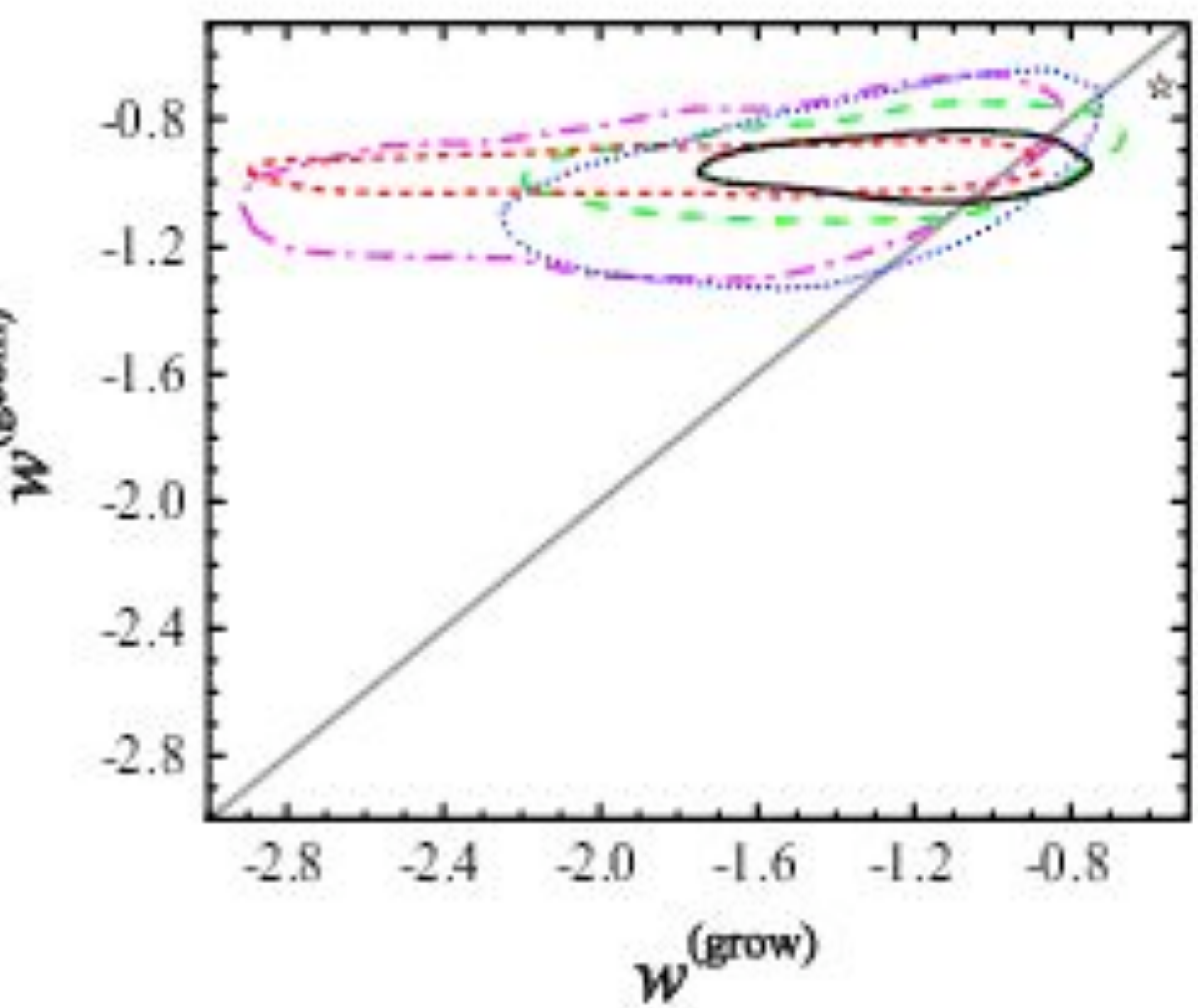


Measure w0 and w1 for growth and distance, see if they agree

Ishak, Upadhye & Spergel 2005, others...

Strategy II.5: w separately, real data

(w from distances)



(w from growth)

Nice work, but current constraints are weak

Wang, Hui, Morgan & Haiman, 2005

Strategy III: “Minimalist Modified Gravity”

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

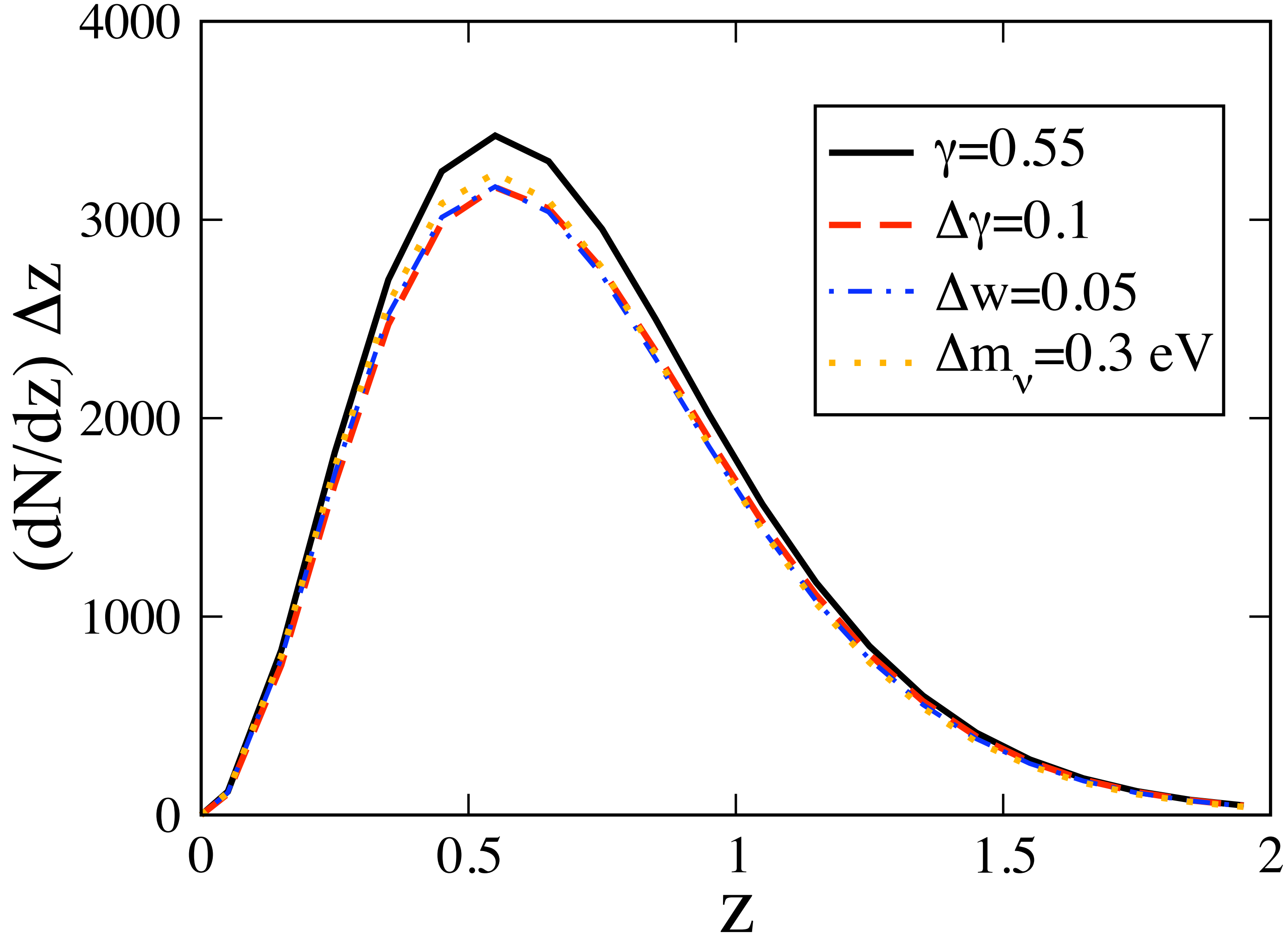
Excellent fit to standard DE cosmology with

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

Linder 2005

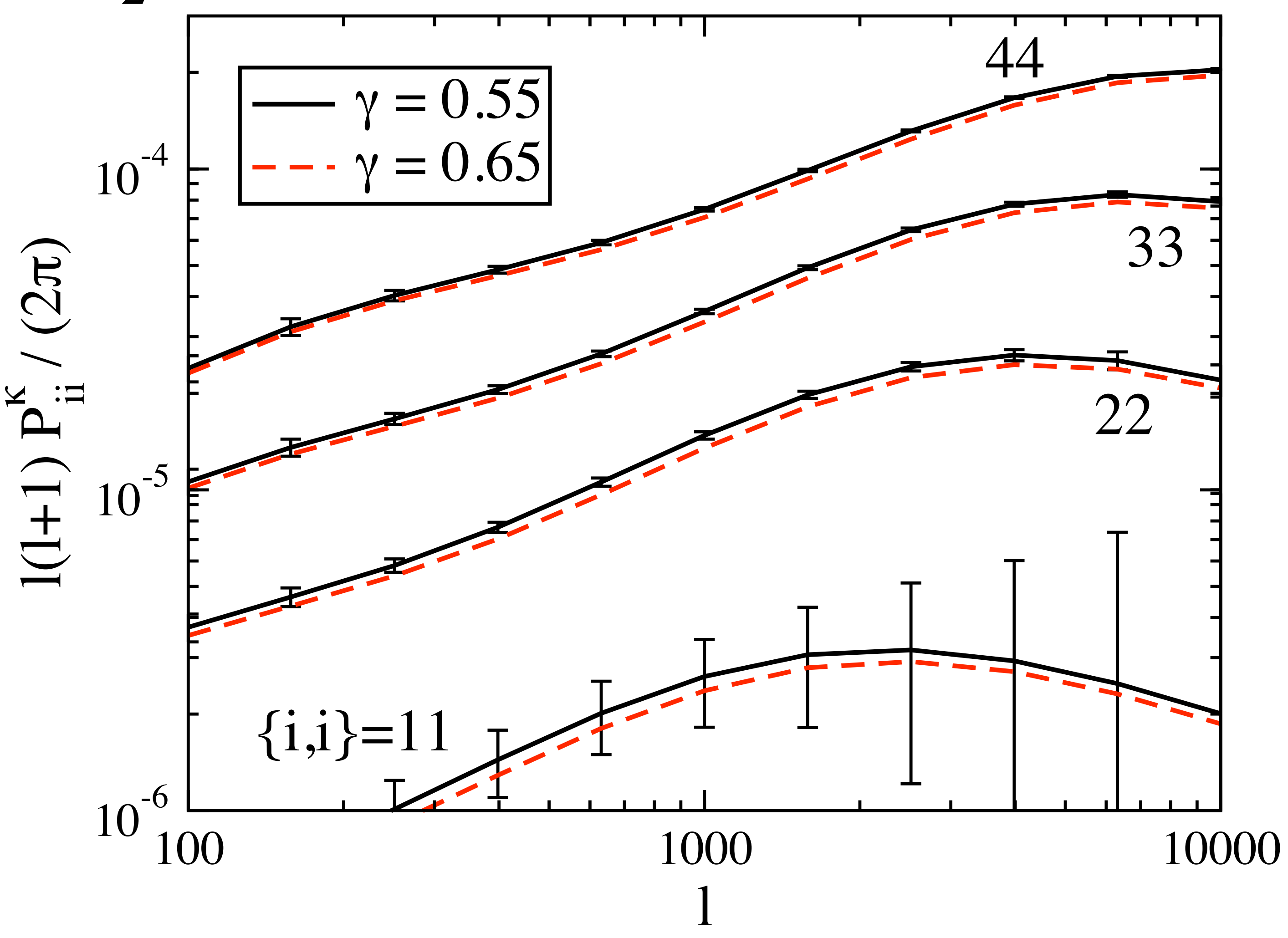
- Gamma is a new parameter - the growth index - and we should measure it!
- E.g. fits DGP with value different from GR by $\Delta\gamma = 0.13$
- For a moment, let us assume that the usual prescription for the nonlinear power spectrum is unchanged
- Apply to weak lensing and number counts; SNe and CMB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

Huterer & Linder, astro-ph/0608681



Cluster counts

Weak lensing tomography



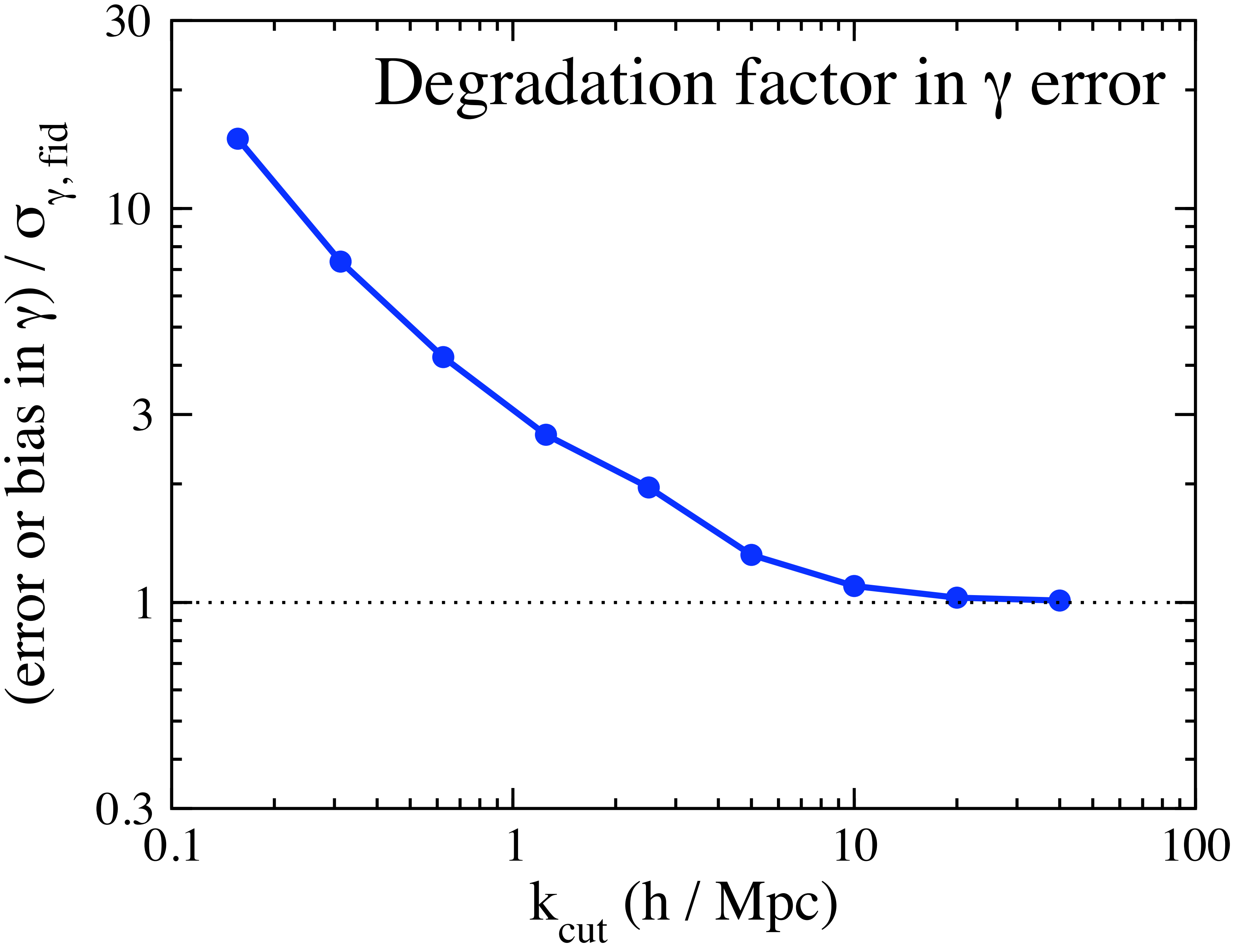
Constraints on the growth index

	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



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

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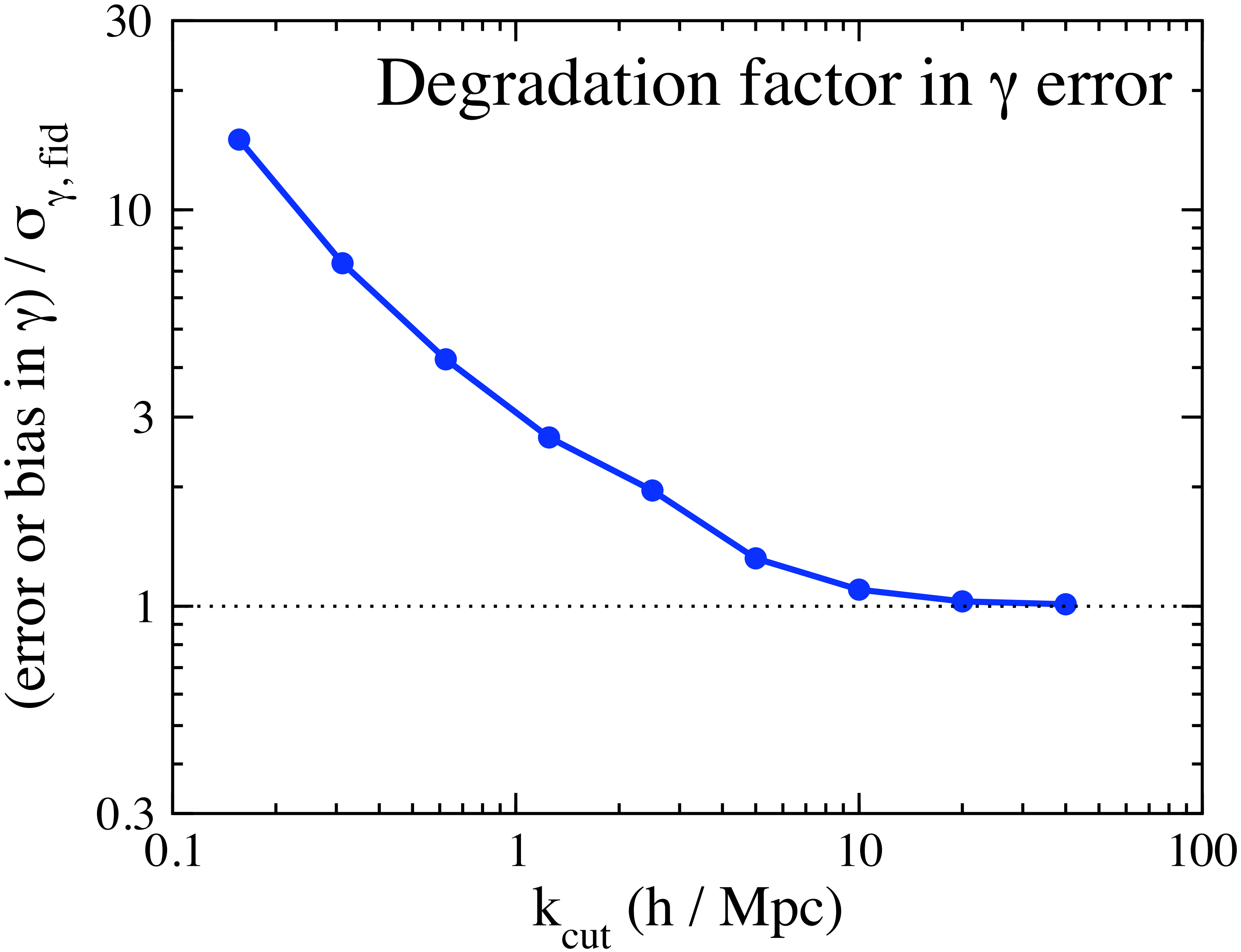
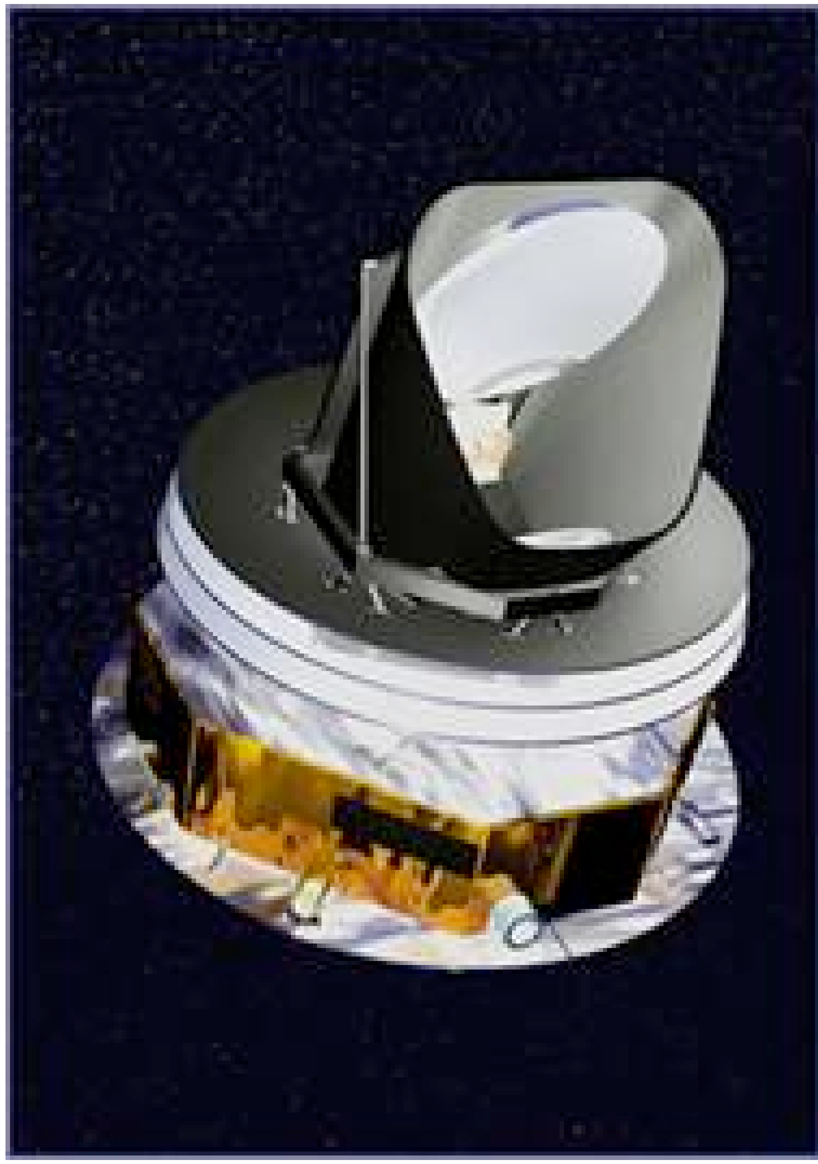


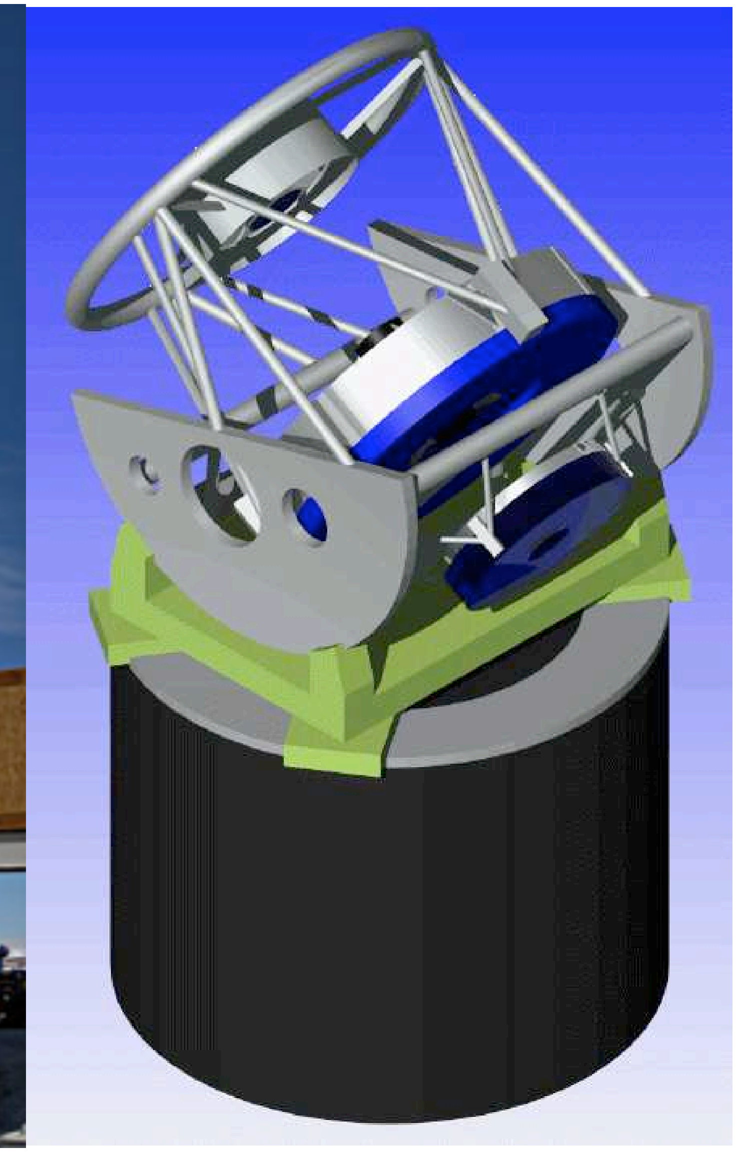
- Clearly, errors increase dramatically as you keep only linear scales
- For MG, it's hard to trust NL scales
- But for testing w(z) GR models, using NL scales may be possible

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

Upcoming Experiments

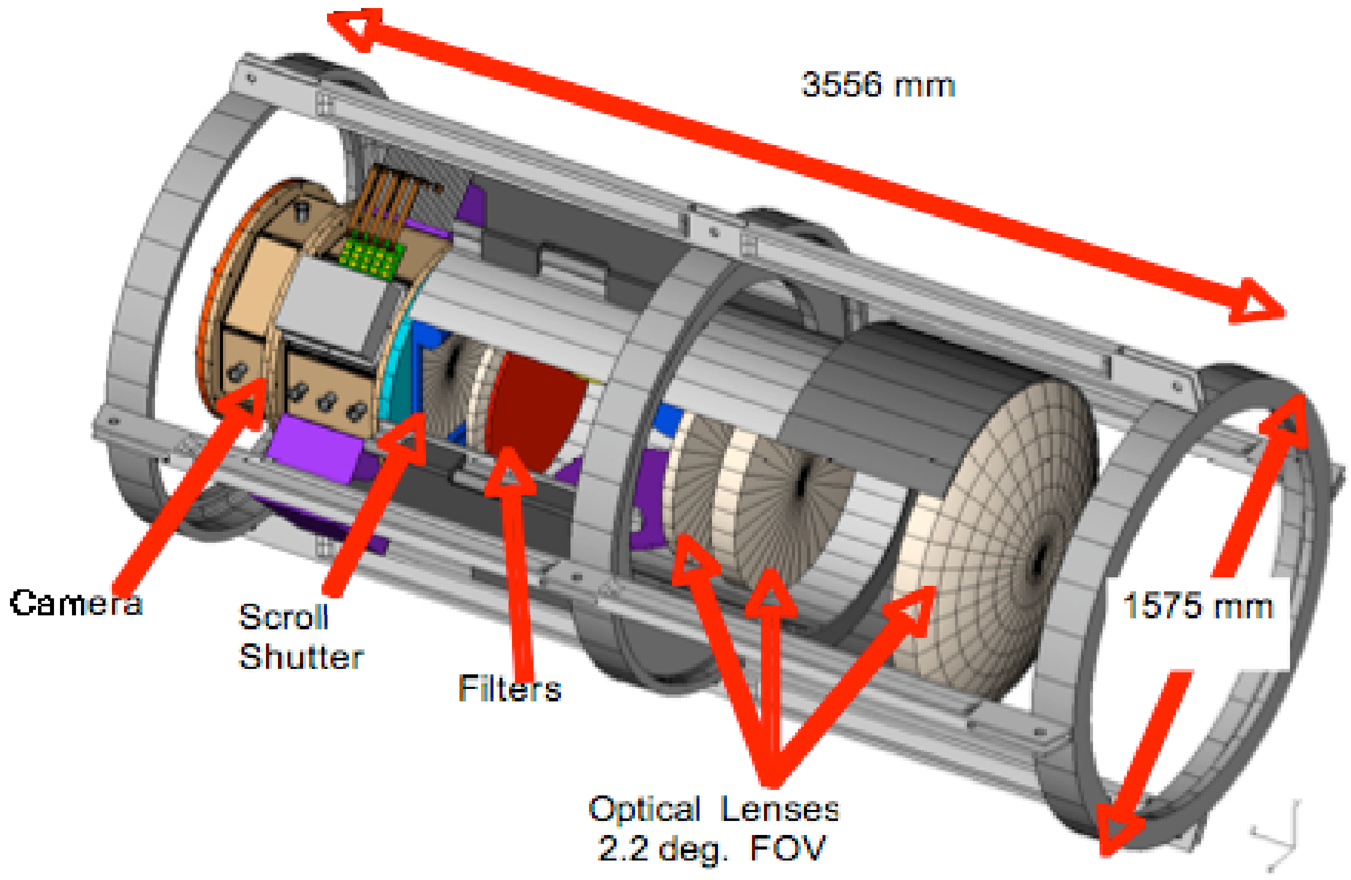
Planck | SPT (also ACT) | LSST





Lots and lots of data coming our way

Dark Energy Survey

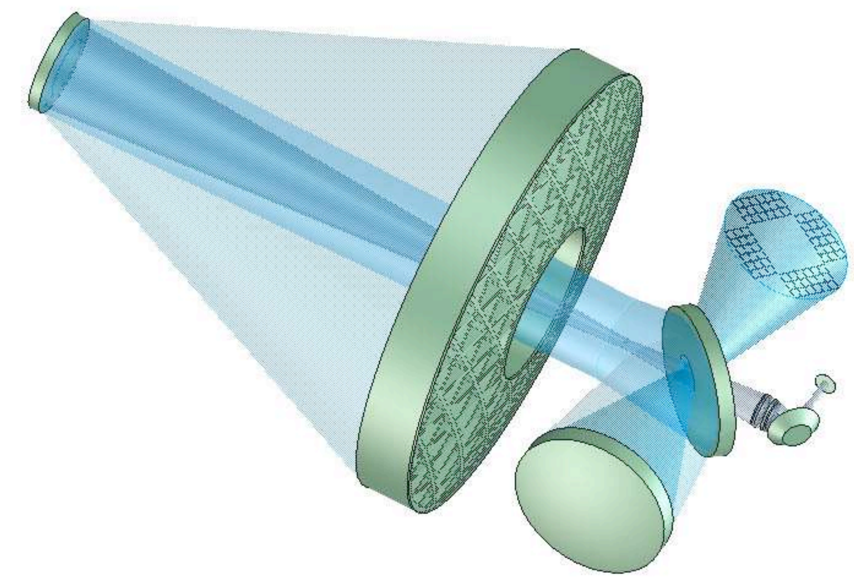


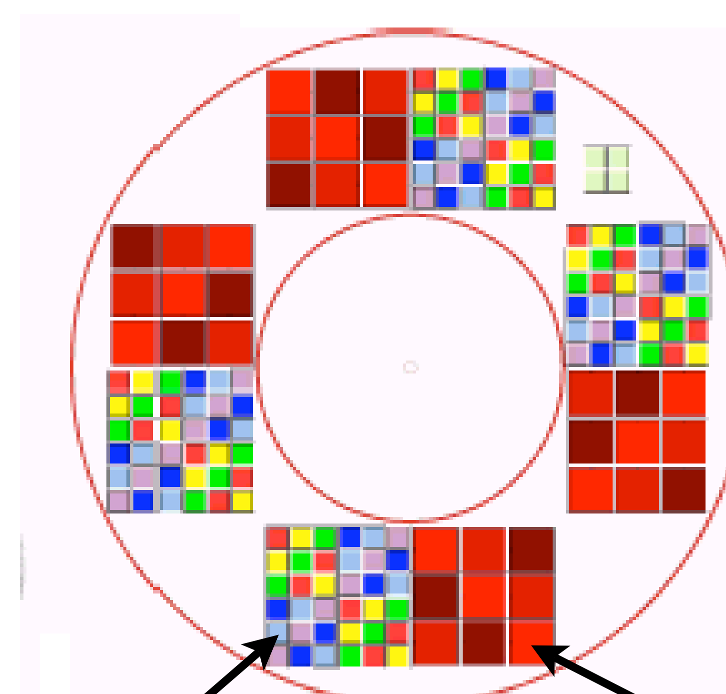
Blanco 4m telescope in Chile

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

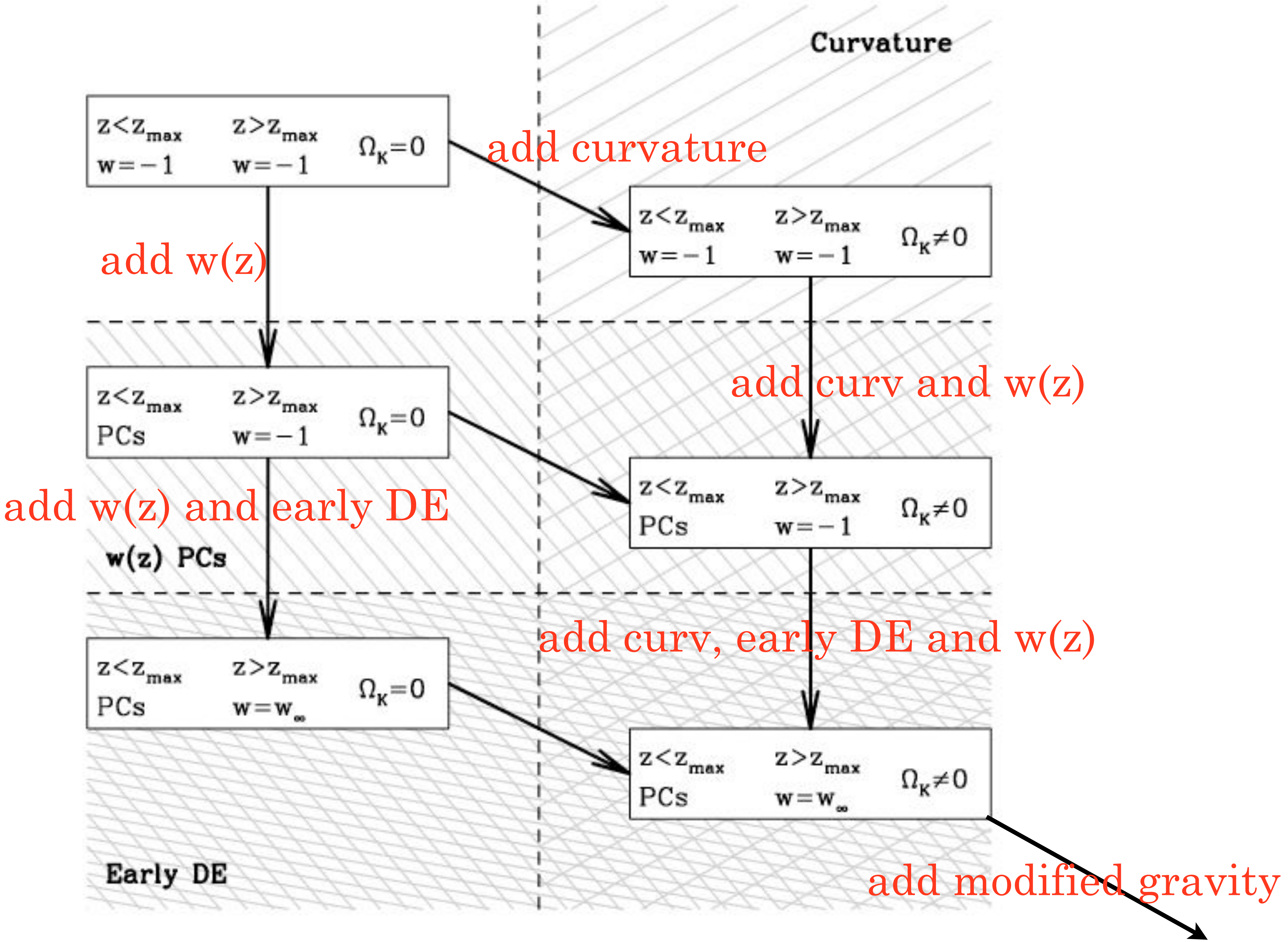




Unprecedented SNa Ia dataset; excellent systematic control
Weak Lensing power spectrum, bispectrum, cosmography
Number counts of clusters
Galaxy distribution; geometrical tests
Strong Lensing, Type II supernovae
A variety of other cosmology and astrophysics

What 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?
- Alternatives:
  - w(z)
  - early DE
  - curvature != 0
  - clustered DE
  - modified gravity
  - more than one of the above
  - ……



Mortonson, Hu & Huterer, in preparation

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 models to test, but still can do general tests within, and beyond, GR
- We need (and will be getting) a combination of experiments that are
  - ground and space probes,
  - expansion and growth probes,
  - linear and nonlinear theory
- Systematics control will be the key to utilizing these data

Open Questions and Issues

- Can we please get some reasonable, non-ruled-out, testable models of dark energy?
- What accuracy on growth(z) do we need? How do we get it?
- What is the best way to use non- and quasi-linear scales? (Perturbation theory, simulations...) What accuracy do we need/can we get, and out to what k?
- Should we push precision measurements to z of a few? (NB some constraints are already available) Or is it more worthwhile to invest more money into lower-z ($z<2$)?