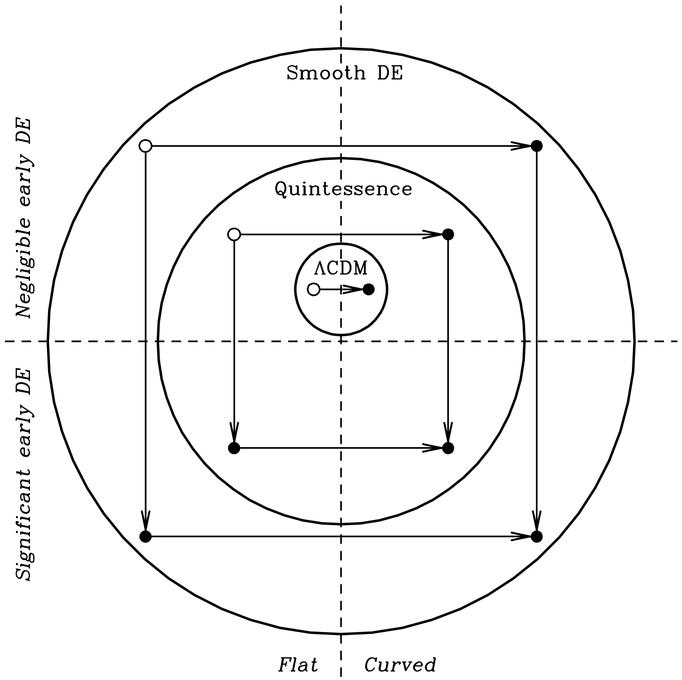
Falsifying Paradigms for Cosmic Acceleration



Dragan Huterer
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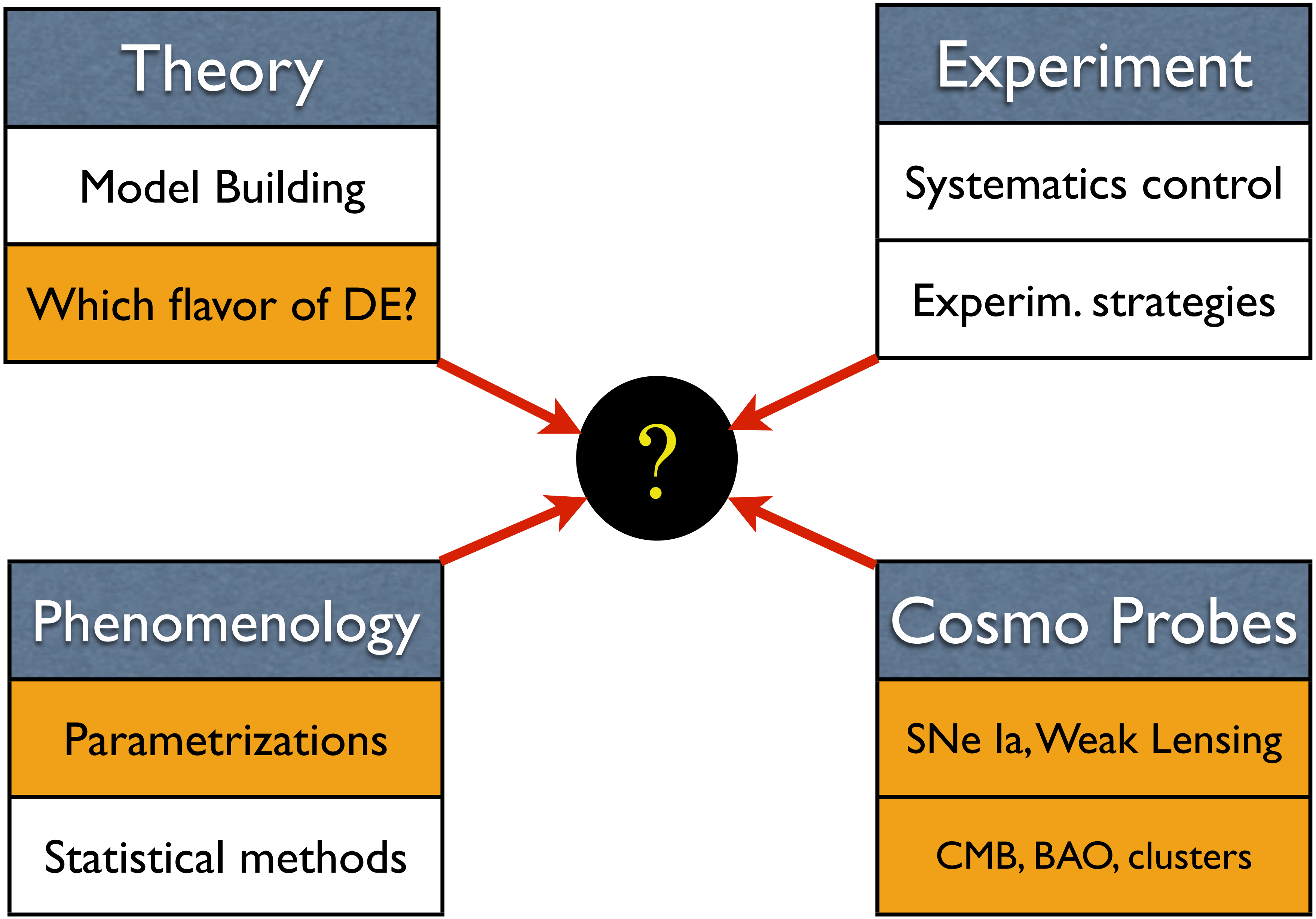
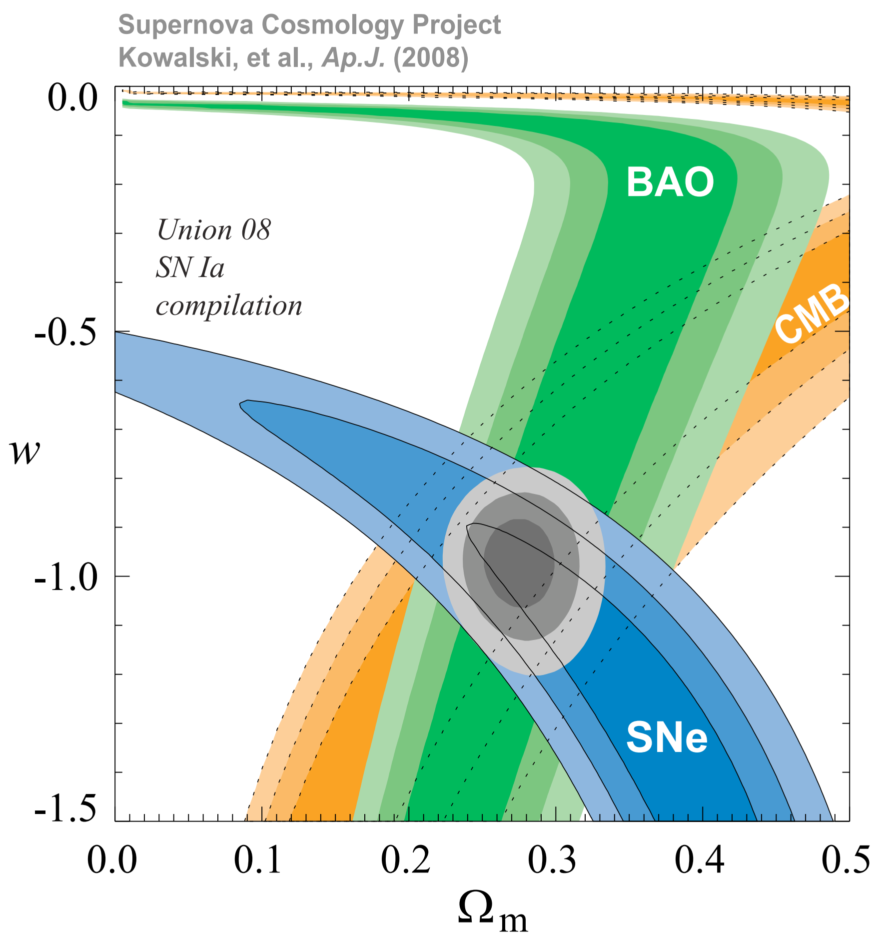
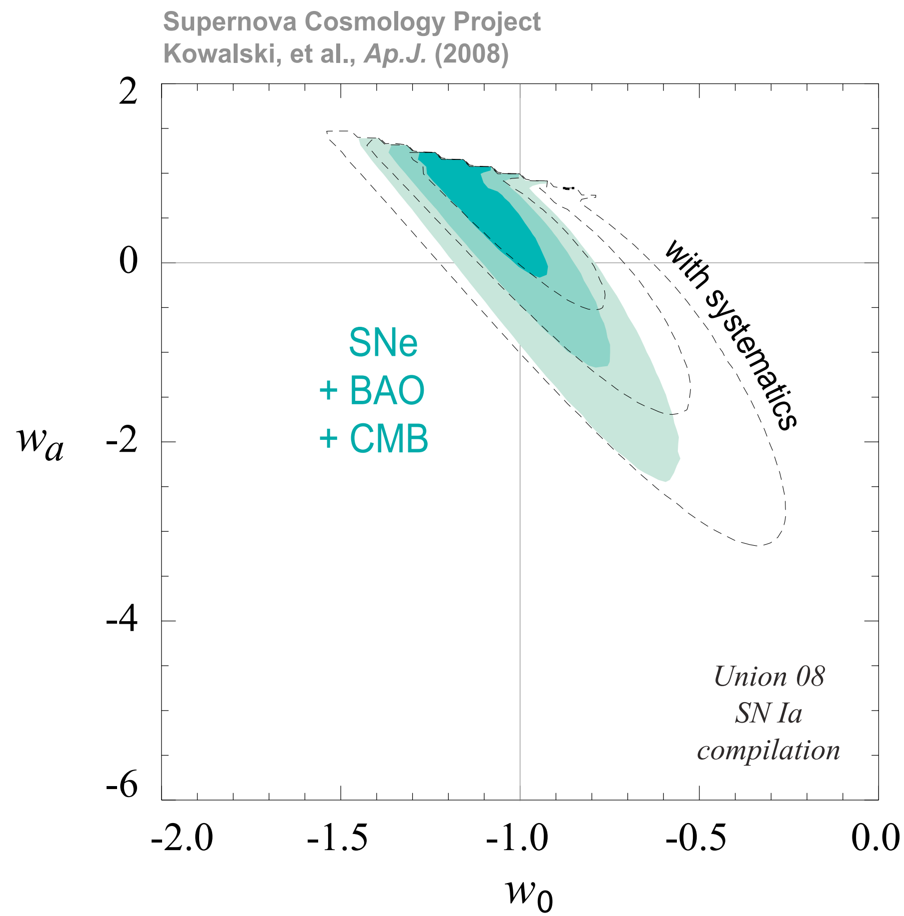
Mortonson, Hu & Huterer, arXiv:0810:1744 (PRD, in press)

What next for Dark Energy?



Dark Energy constraints: current status





Kowalski et al., arXiv:0804.4142

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
  - ……

Subject of this work

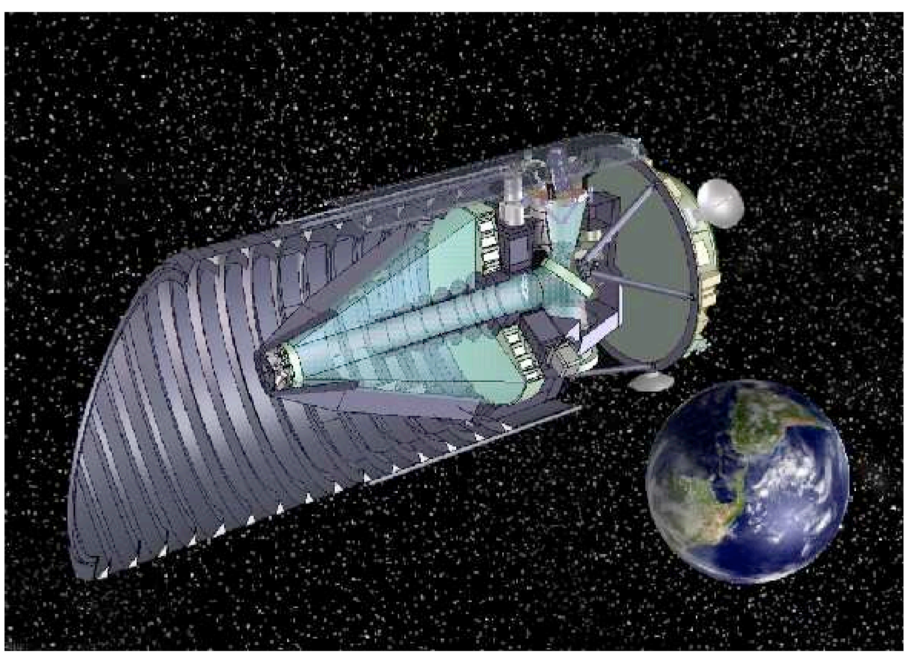
Data and modeling of DE

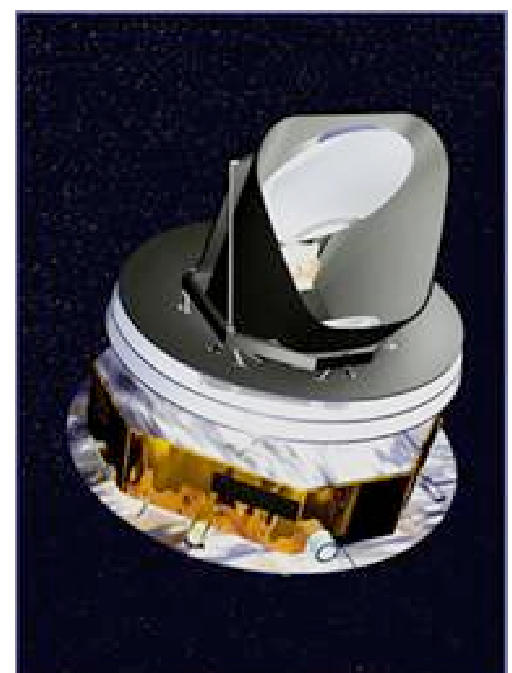
Assumed "data":

1. SNAP 2000 SNe, $0.1<z<1.7$ (plus 300 low-z SNe); converted into distances

$$\sigma_\alpha^2 = \left(\frac{0.1}{\Delta z_{\rm sub}}\right)\left[\frac{0.15^2}{N_\alpha} + 0.02^2\left(\frac{1+z}{2.7}\right)^2\right]$$

2. Planck info on $\Omega_m h^2$ and $D_A(z_{rec})$





Cosmological Functions

Expansion Rate (BAO):

$$H(z) = H_0 \left[\Omega_{\rm M}(1+z)^3 + \Omega_{\rm DE} \frac{\rho_{\rm DE}(z)}{\rho_{\rm DE}(0)} + \Omega_{\rm K}(1+z)^2 \right]^{1/2}$$

Distance (SN, BAO, CMB):

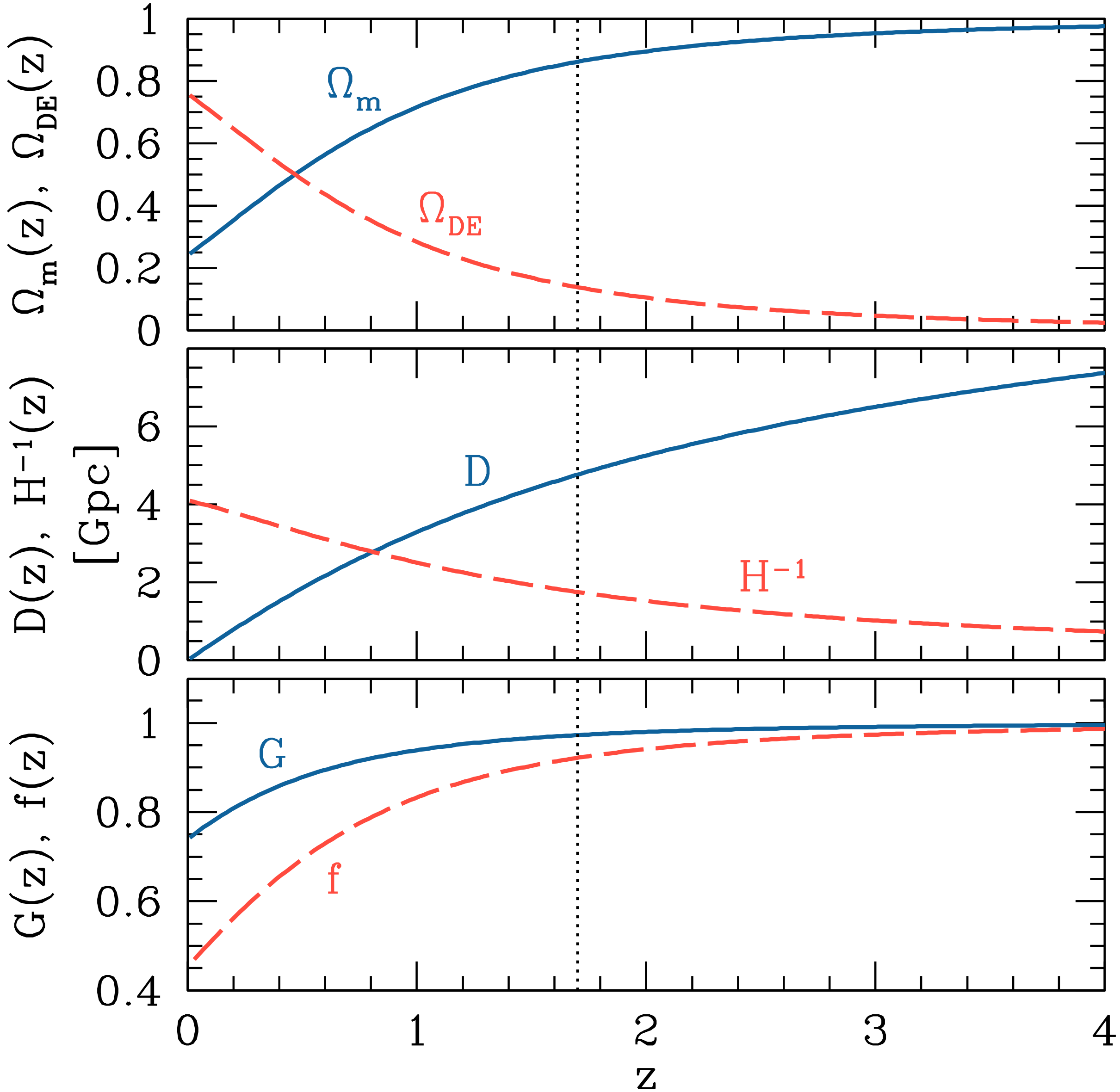
$$D(z) = \frac{1}{(|\Omega_{\rm K}|H_0^2)^{1/2}} S_{\rm K} \left[(|\Omega_{\rm K}|H_0^2)^{1/2} \int_0^z \frac{dz'}{H(z')} \right]$$

Growth (WL, clusters):

$$G'' + \left(4 + \frac{H'}{H}\right) G' + \left[3 + \frac{H'}{H} - \frac{3}{2}\Omega_{\rm M}(z)\right] G = 0$$

$$G = D_1/a$$

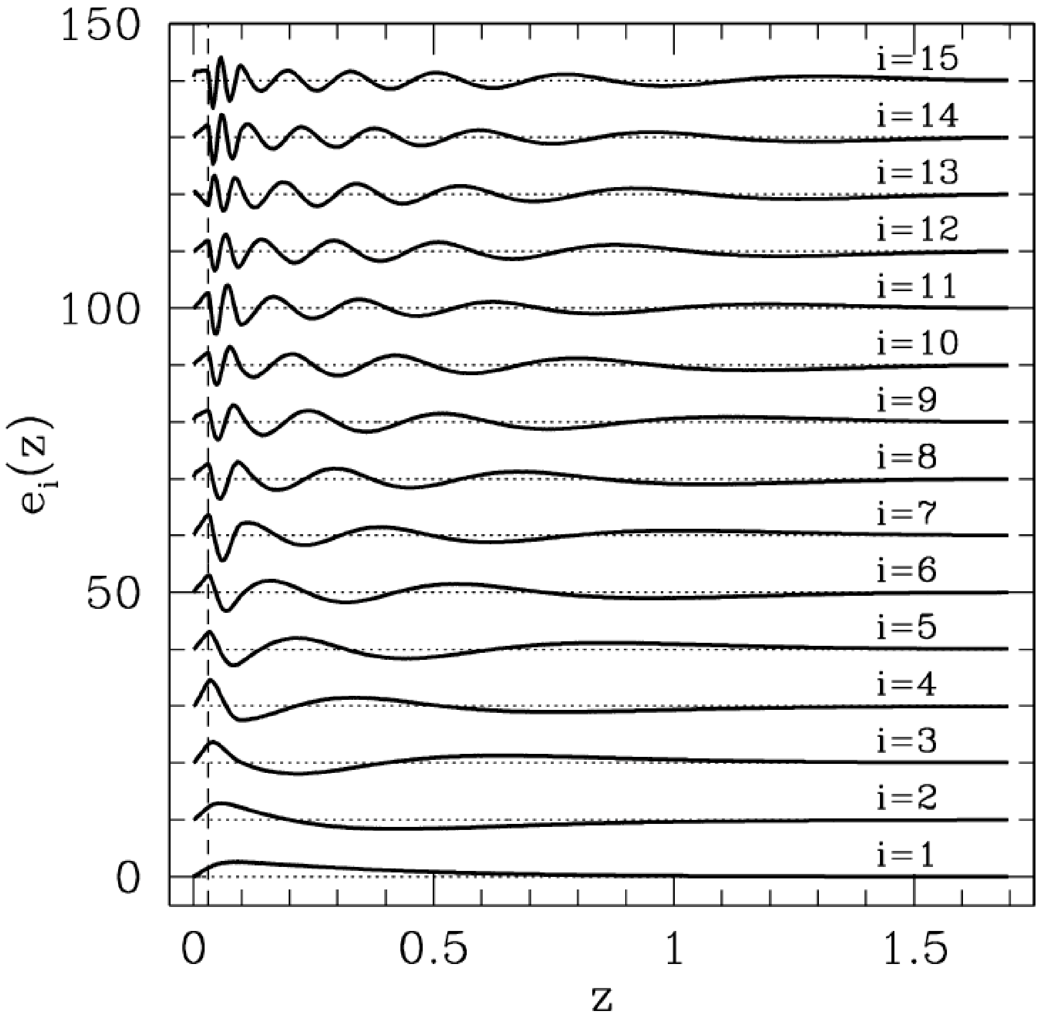
Cosmological Functions



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;
(results converge 10→15)

Not too dissimilar from parametrization employed in...

Findings of the
Joint Dark Energy Mission
Figure of Merit Science Working Group

Andreas Albrecht, Luca Amendola, Gary Bernstein, Douglas Clowe, Daniel Eisenstein,
Luigi Guzzo, Christopher Hirata, Dragan Huterer, Robert Kirshner, Edward Kolb, Robert Nichol
(Dated: Dec 7, 2008)

These are the findings of the Joint Dark Energy Mission (JDEM) Figure of Merit (FoM) Science Working Group (SWG), the FoMSWG. JDEM is a space mission planned by NASA and the DOE for launch in the 2016 time frame. The primary mission is to explore the nature of dark energy. In planning such a mission, it is necessary to have some idea of knowledge of dark energy in 2016, and a way to quantify the performance of the mission. In this paper we discuss these issues.

arXiv:0901:0721

http://jdem.gsfc.nasa.gov/fomswg.html

Modeling of Early DE

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

Early DE - current constraints

- $\Omega_{DE}(z_{rec})$ <0.03 (CMB peaks; Doran, Robbers & Wetterich 2007)
- $\Omega_{DE}(z_{BBN})$<0.05 (BBN; Bean, Hansen & Melchiorri 2001)

Procedure

1. Start with the parameter set:

$$\Omega_{\rm M}, \Omega_{\rm K}, H_0, w(z), w_\infty$$

2. Use the future data:

SNAP SNe data converted into distances

Planck CMB data as a distance, and its $\Omega_{\rm M}h^2$

also use H_0, $D_{\rm BAO}(z=0.35)$, and *weak* w(z) **priors**

everything centered on LCDM

3. Employ the likelihood machine:

Markov Chain Monte Carlo likelihood calculation,

~15-20 parameters constrained

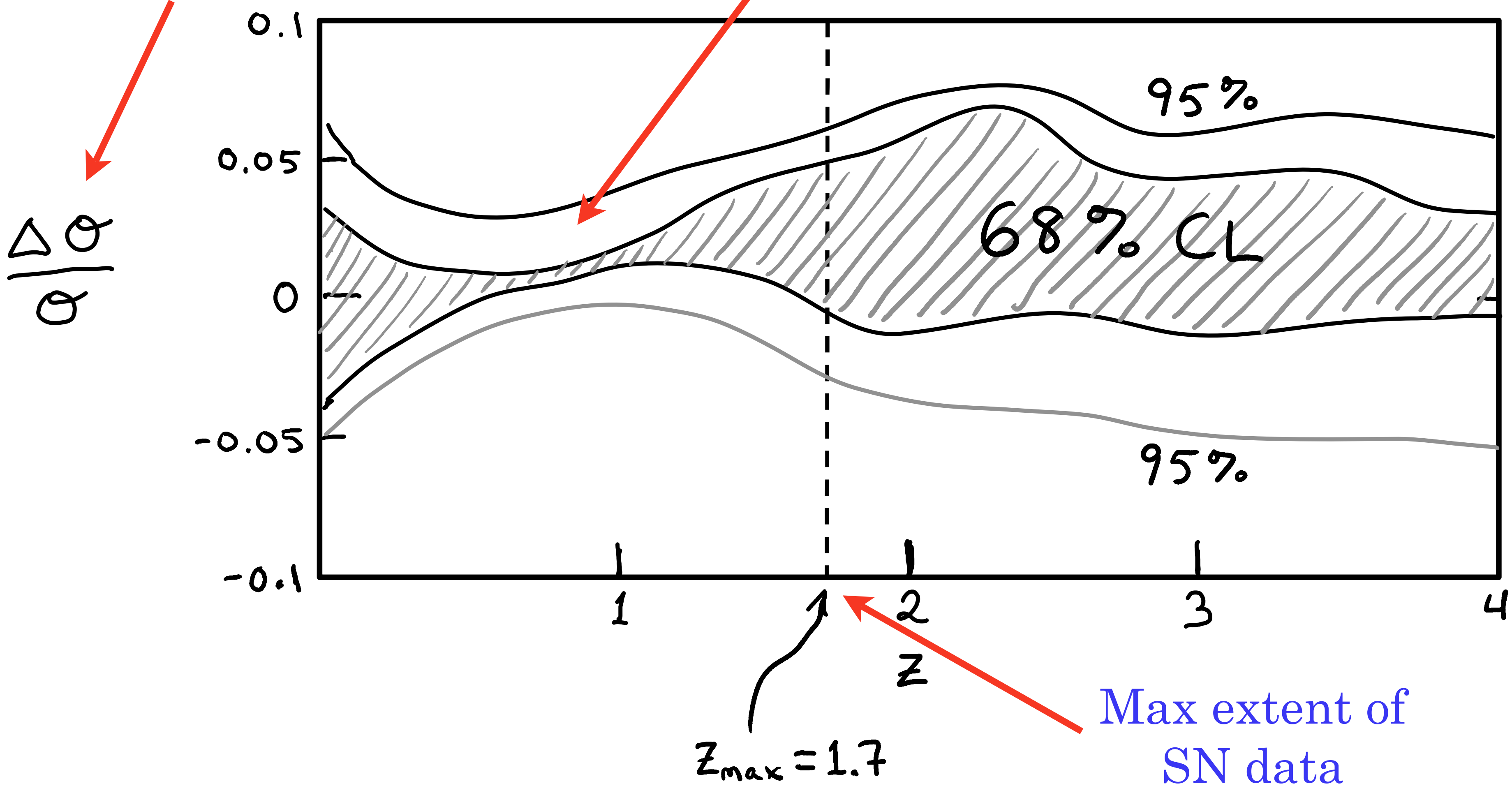
4. Compute predictions for D(z), G(z), H(z)

Read off these functions directly from the chains

Structure of graphs to follow

Prediction on observable by SNe+CMB

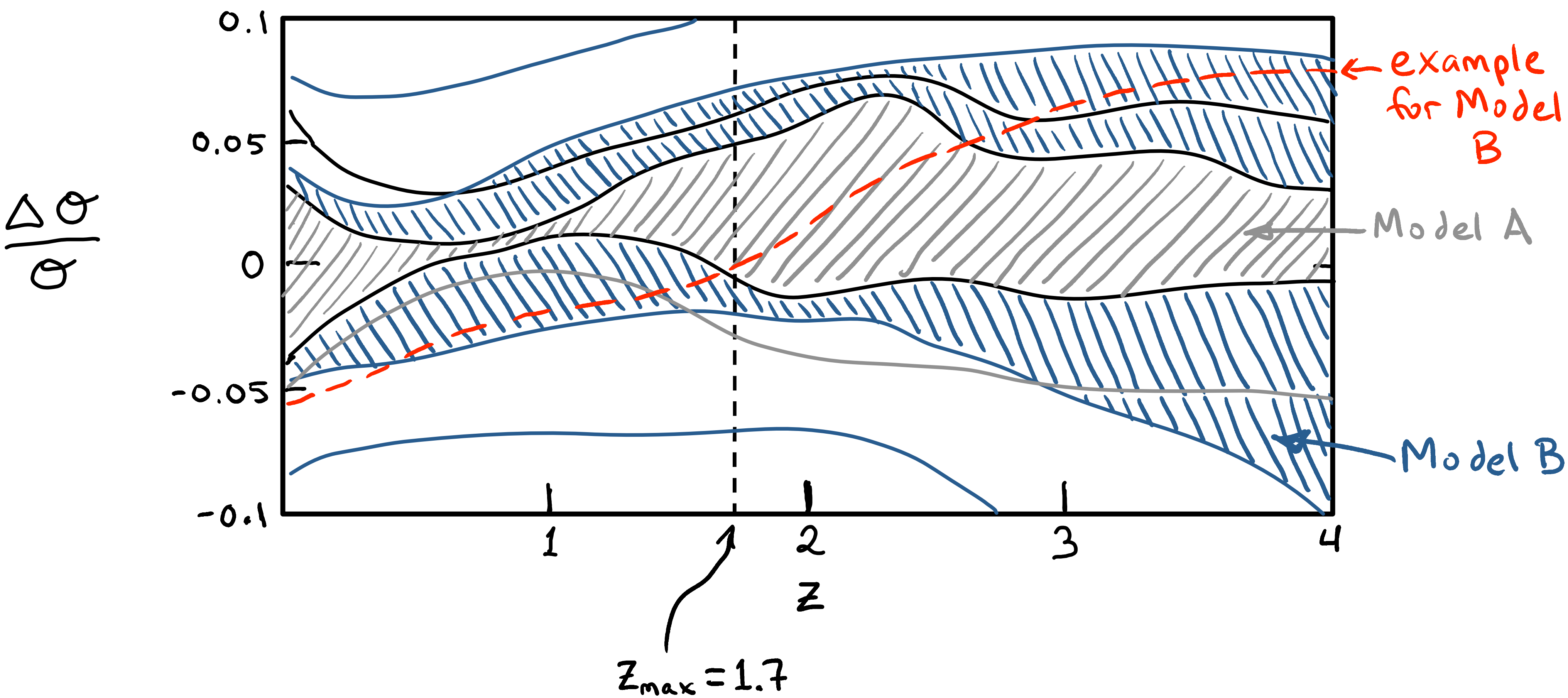
Pivot



Max extent of SN data

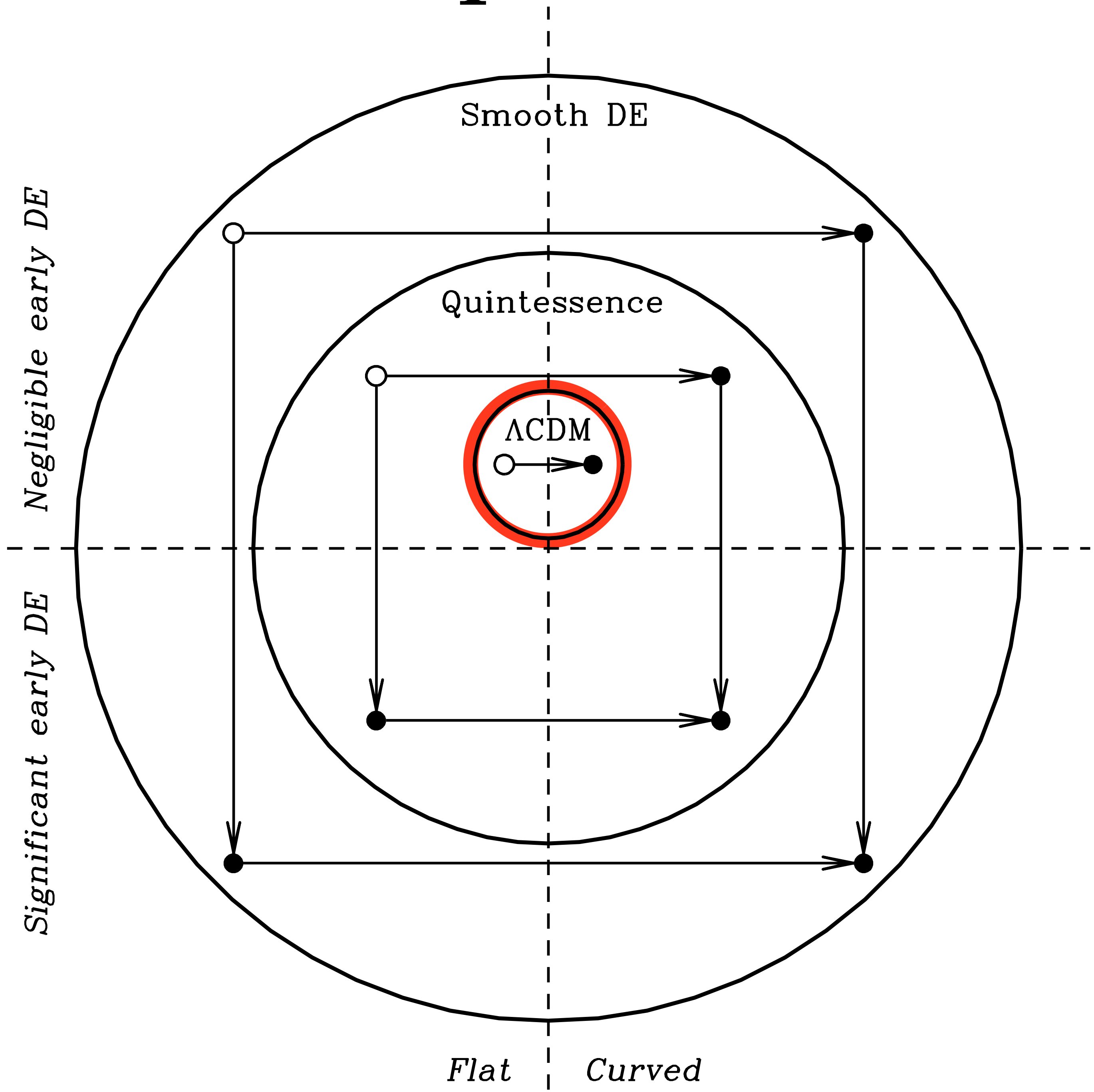
Sketch by M. Mortonson

Structure of graphs to follow



Sketch by M. Mortonson

LCDM predictions



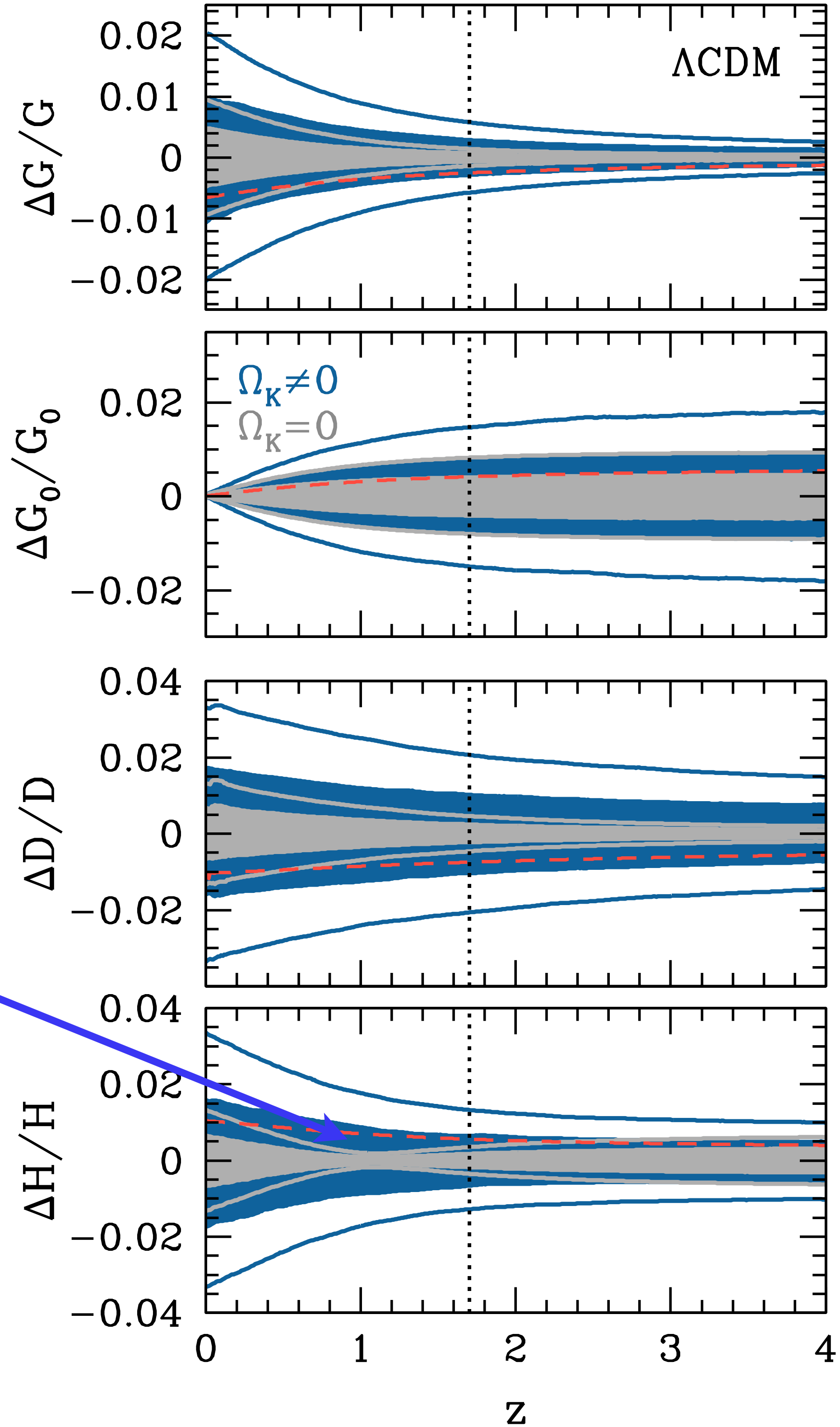
LCDM predictions (flat or curved)

Grey: flat

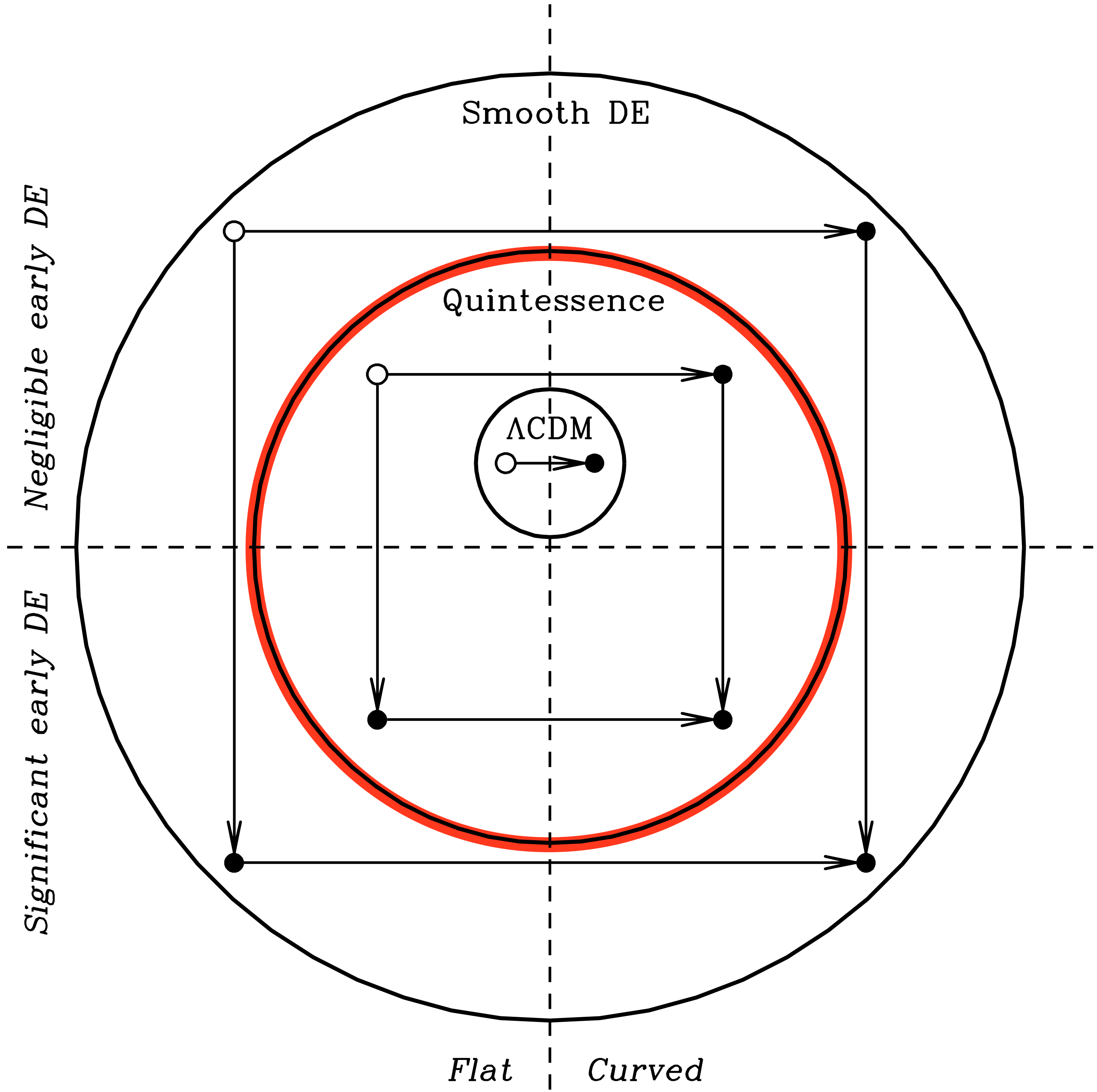
Blue: curved

D, G to <1% everywhere

H(z=1) to 0.1% for flat LCDM

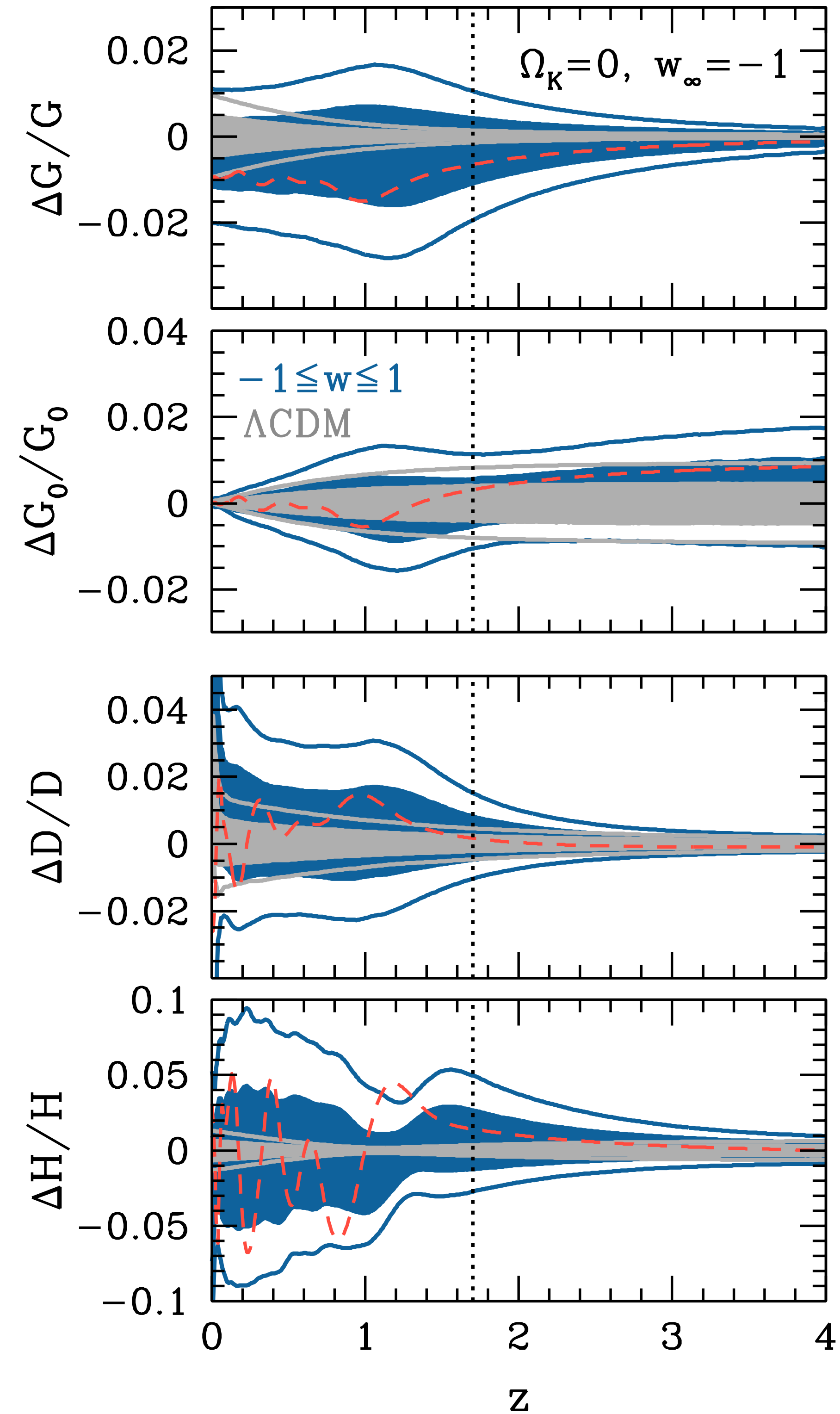


Quintessence (-1<w(z)<1) predictions



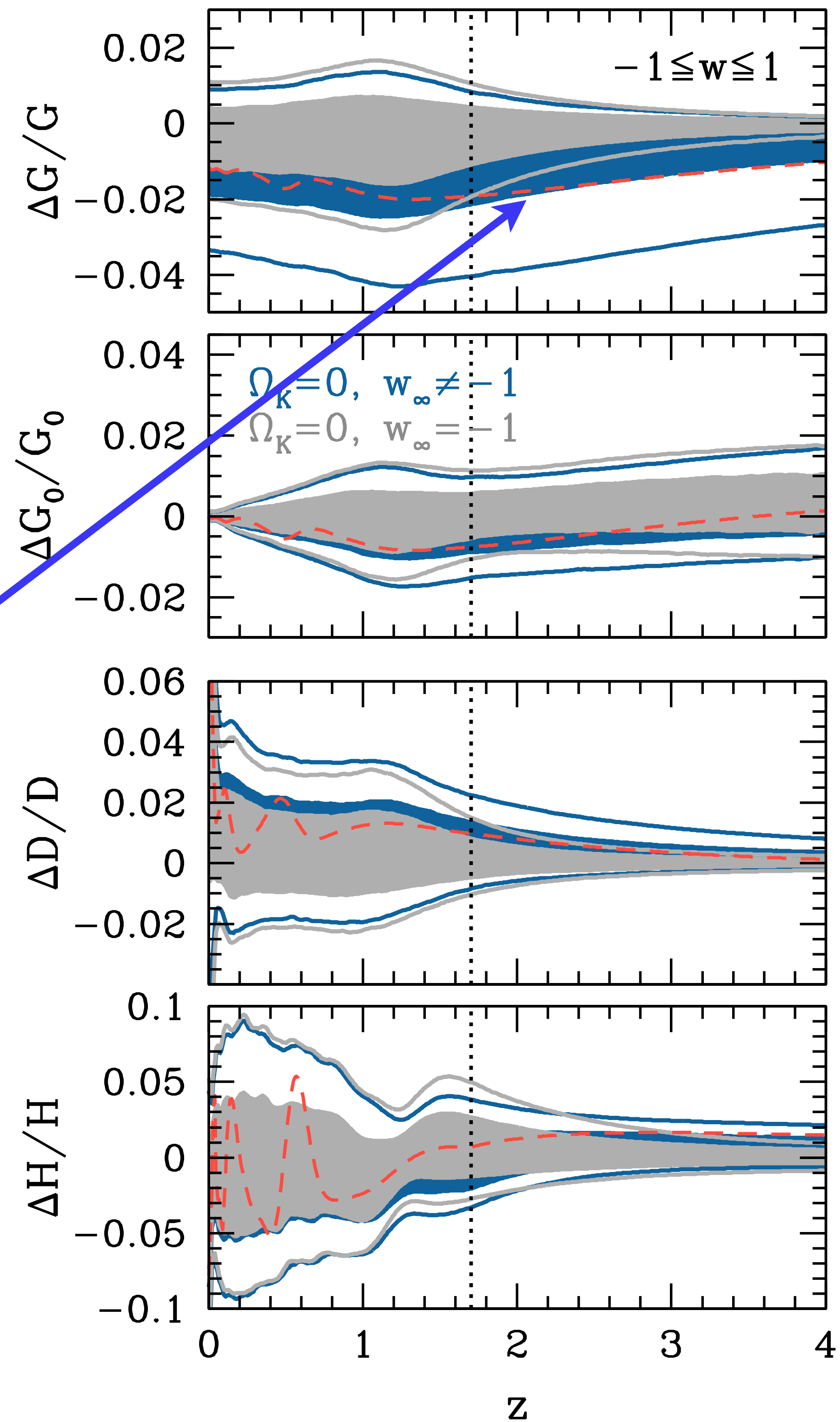
Quintessence predictions

flat, no Early DE



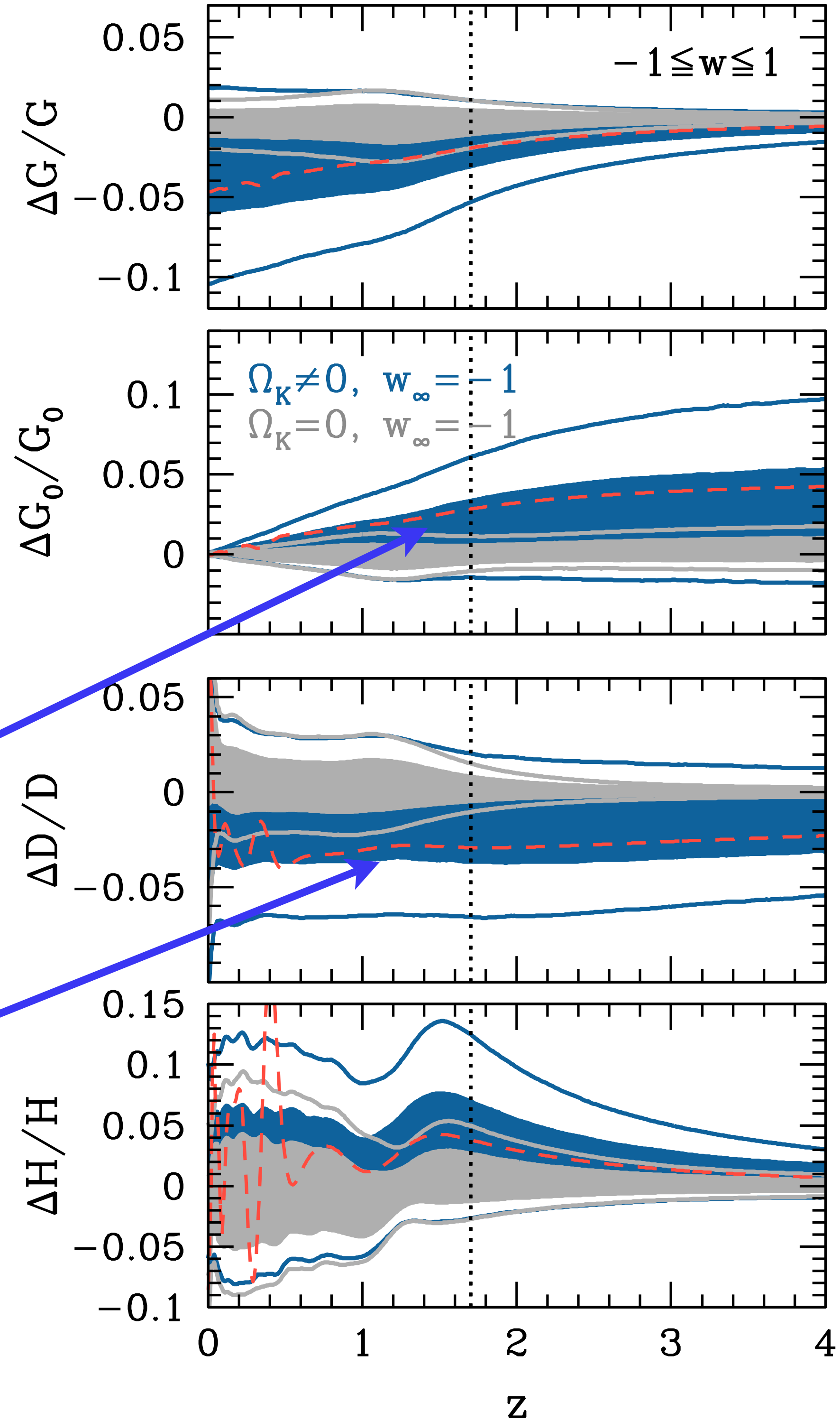
>>1 effective dof, so
"waist" at z=1 disappears

Quintessence predictions flat, with Early DE



Smoking Gun:
Uniform suppression in G

Quintessence predictions with curvature, no EDE



Smoking Gun:

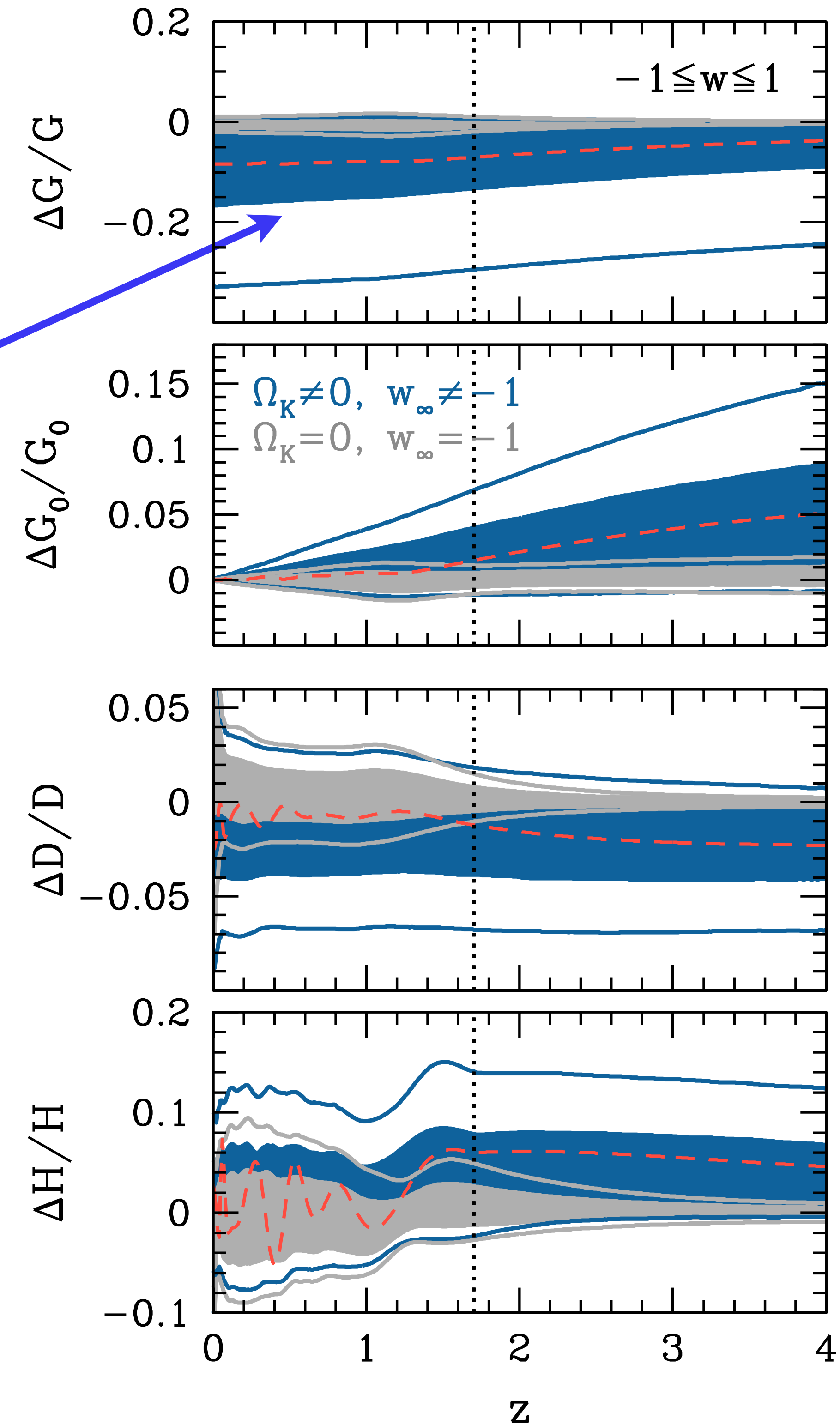
1. Shift in G_0
2. Negative const offset in D

Quintessence predictions

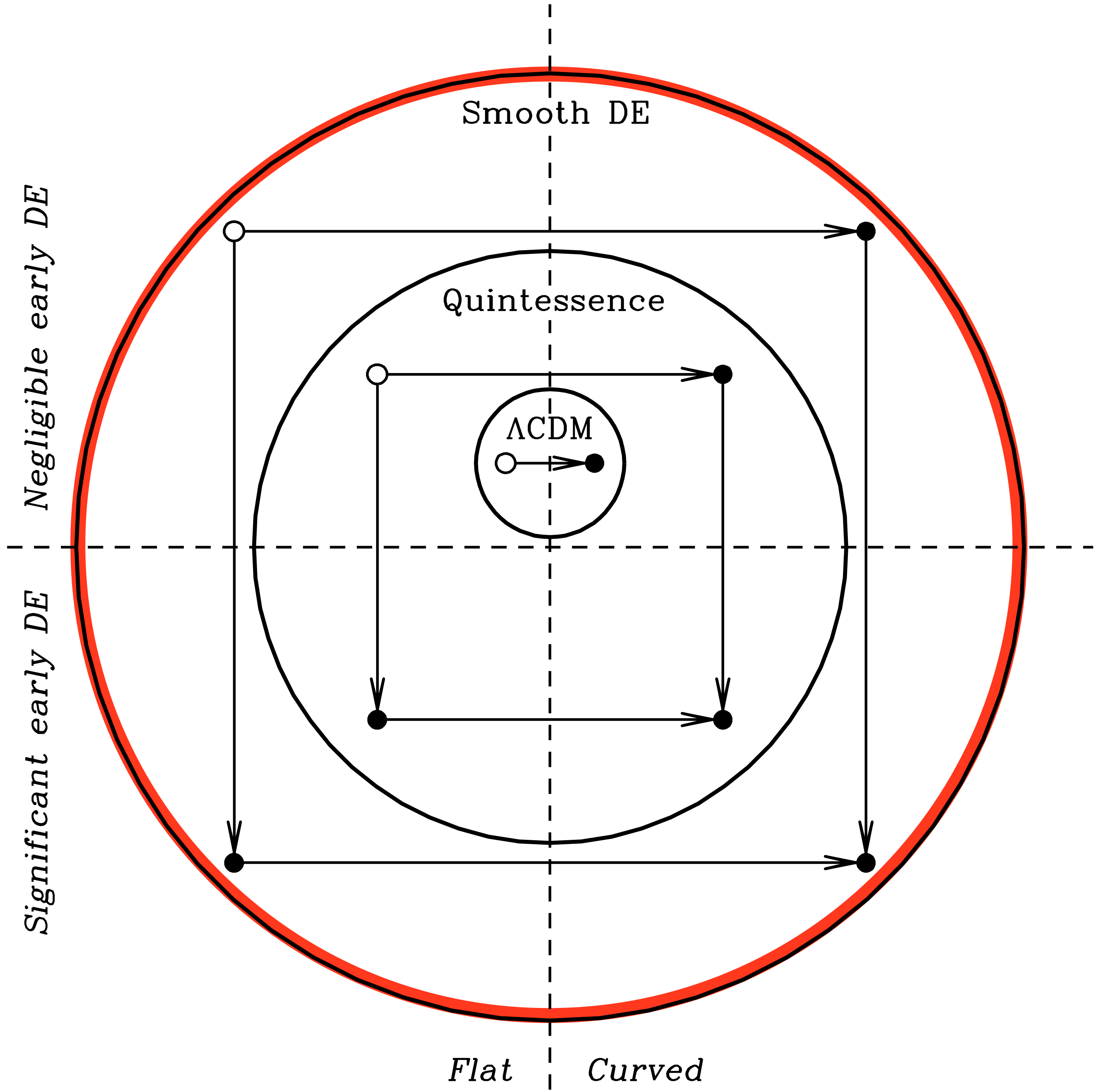
with curvature and EDE

Smoking Gun:
Large negative deviation in G

Note even in this general class,
firm predictions: e.g.,
G and D can't be >> LCDM value

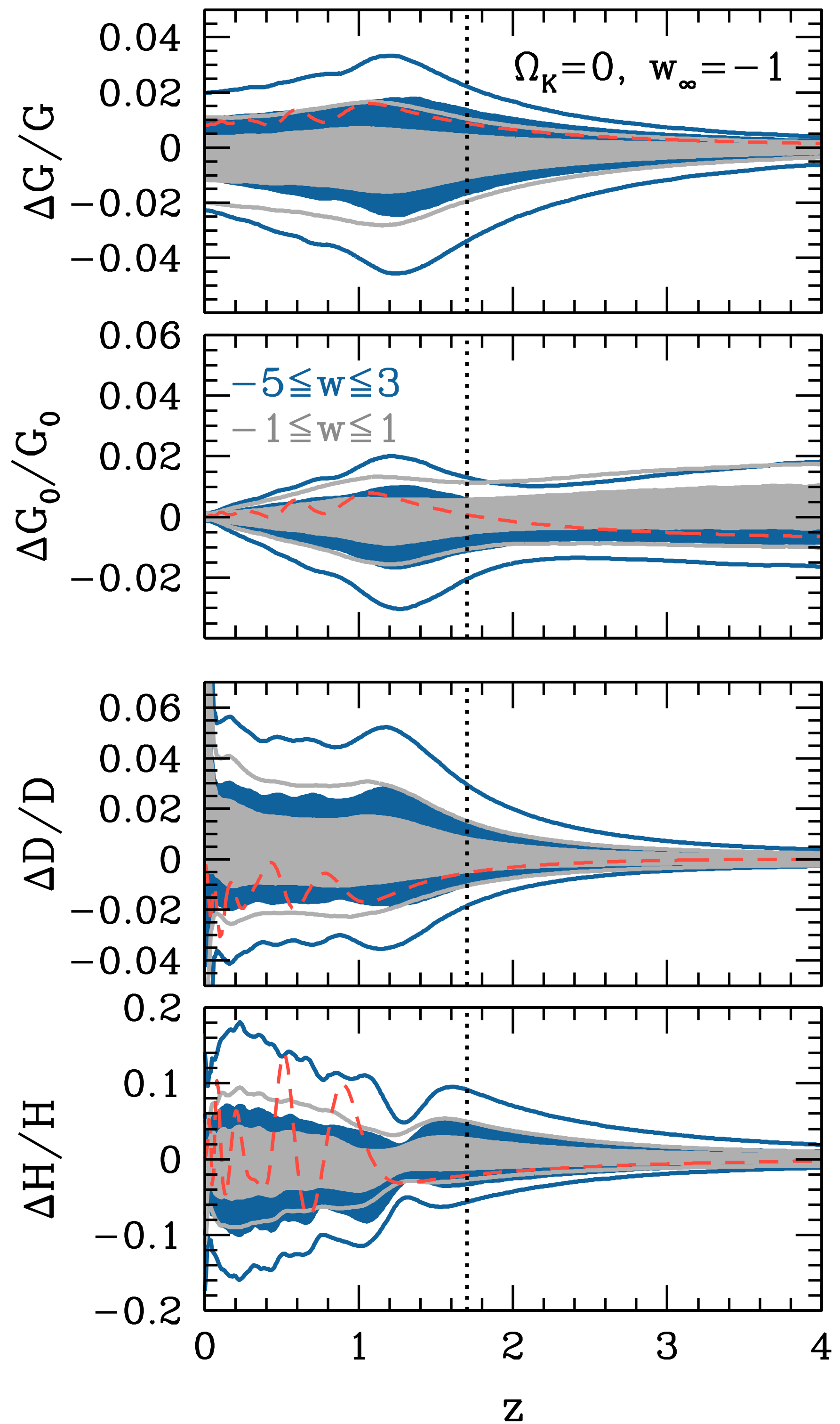


Smooth DE (-5<w(z)<3) predictions

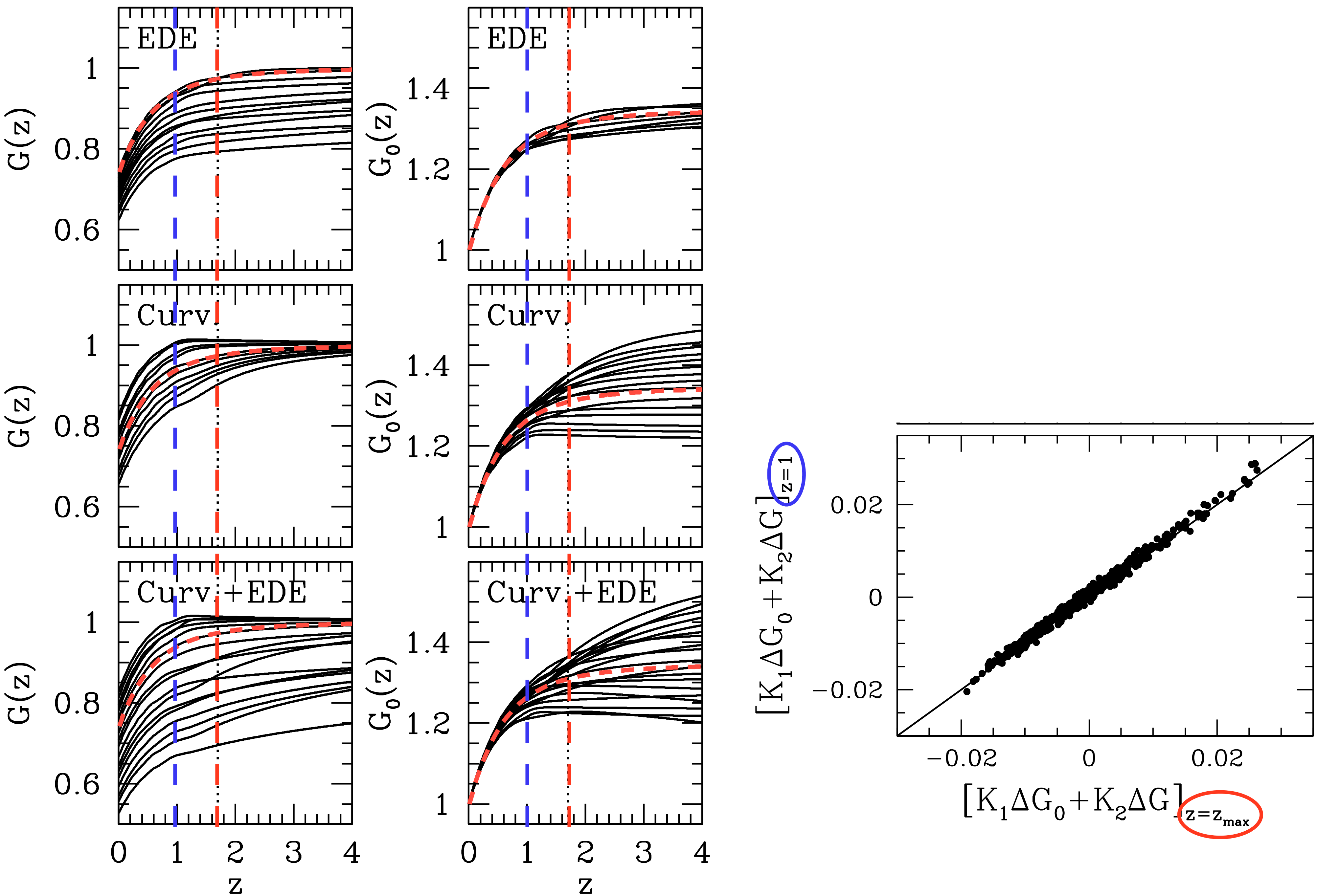


Smooth DE predictions

flat, no Early DE

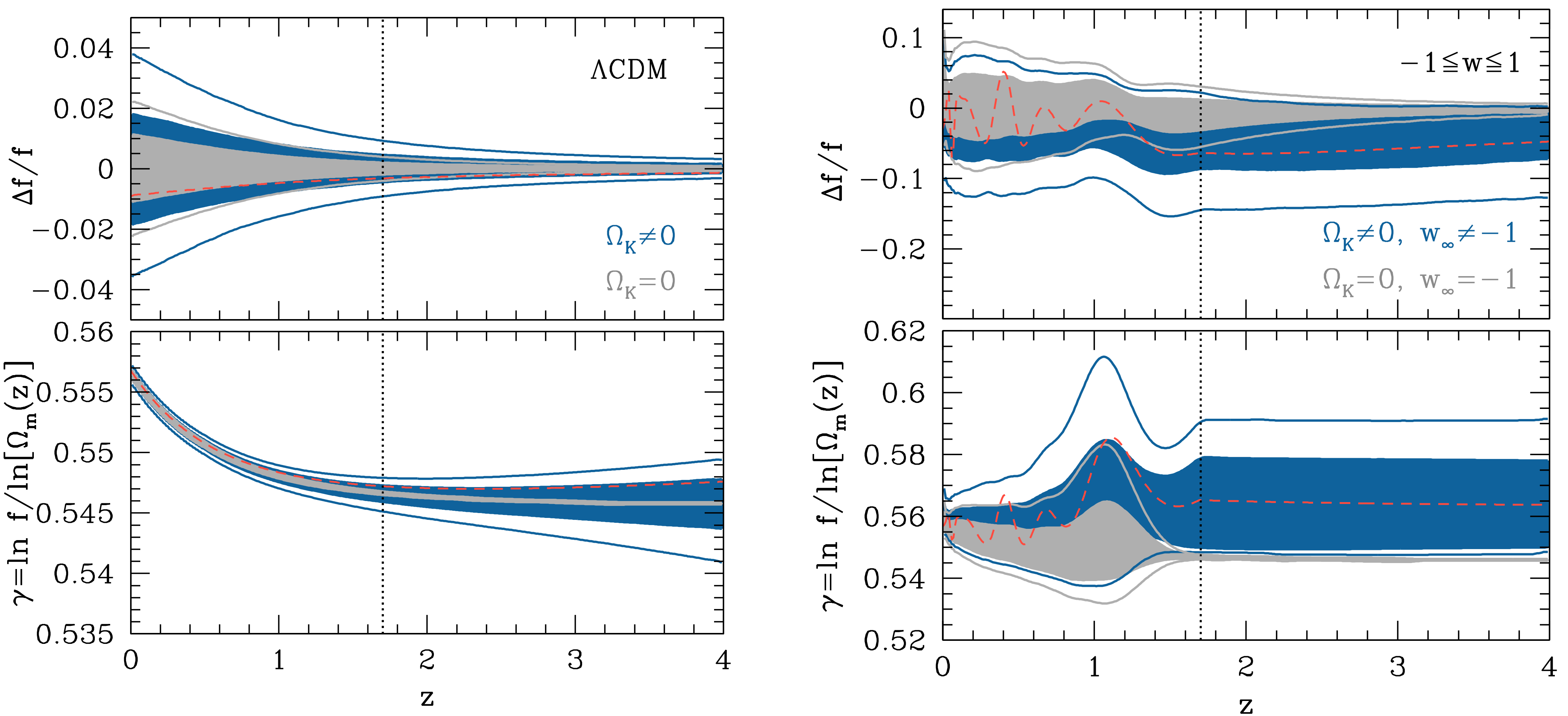


Smooth DE with curvature and/or Early DE



Modified Gravity

$$G(a) = \exp\left(\int_0^a d\ln a' \, [\Omega_M^\gamma(a') - 1]\right)$$



Conclusions

- Combined distance + growth data can falsify whole classes of dark energy models
  - LCDM
  - Quintessence (scalar field)
  - Smooth DE models
  - (modified gravity)
- Upcoming SN + Planck observations will impose strong predictions on growth and distance observables (1% in many interesting cases)
- Even in more general cases (e.g. smooth DE), stringent predictions from SNe+CMB that can be verified with BAO, WL, Cluster data

Examples of SNAP+Planck predictions

- Flat LCDM:
  - D(z), G(z) to 1% everywhere
  - H(z=1) to 0.1%
  - γ to 0.1% at all z
- Quintessence - with/out curvature or early DE
  - D(z), G(z) to <5%; one-sided deviations
- Smooth dark energy - with/out curvature or early DE:
  - Tight consistency relations (e.g. G(z=1) vs. G(z=1.7))
- General Relativity
  - γ to 5% (~0.02) even with arbitrary w(z)