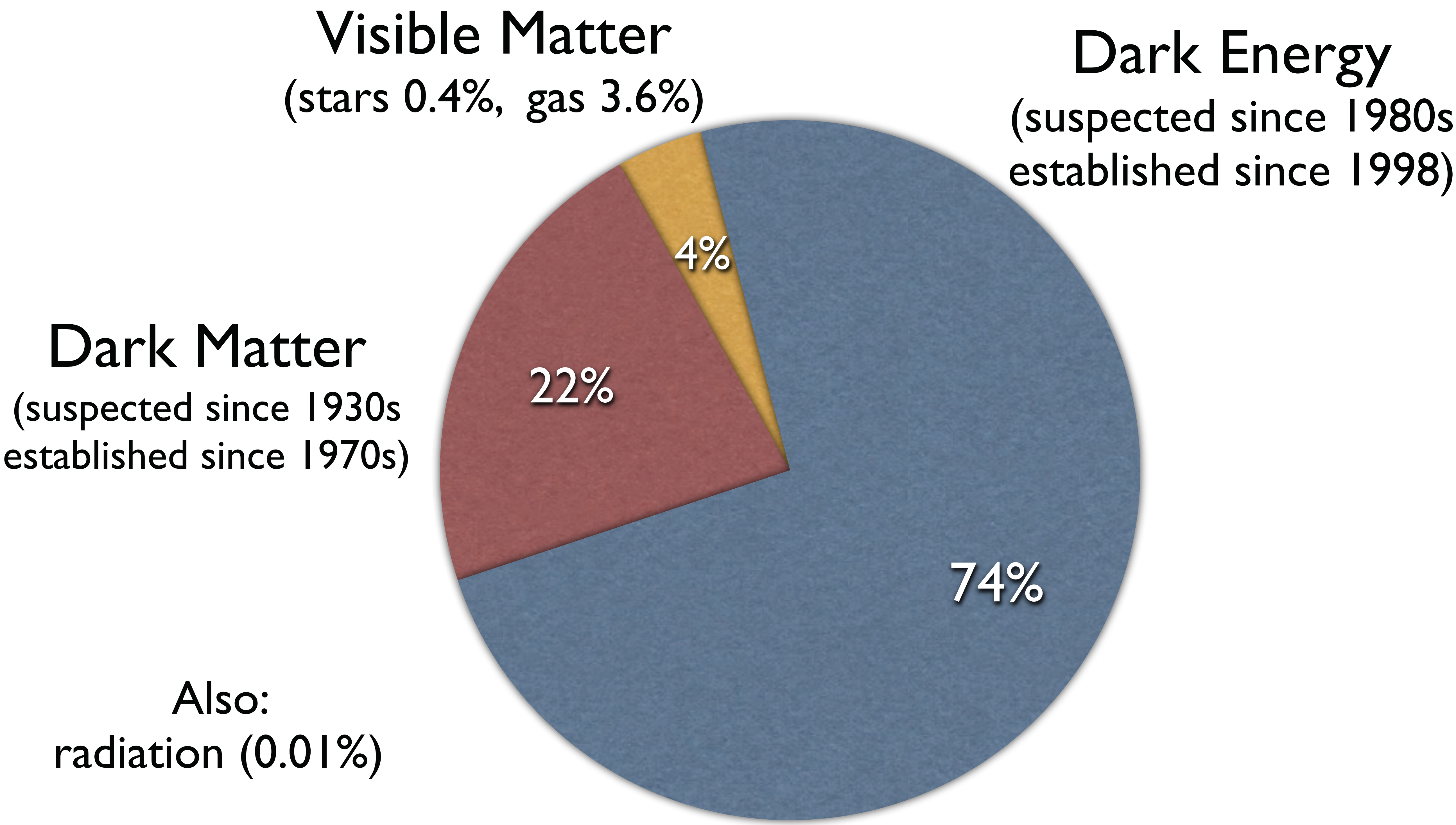
How to Falsify a Dark Energy Paradigm

Dragan Huterer
Physics Department
University of Michigan

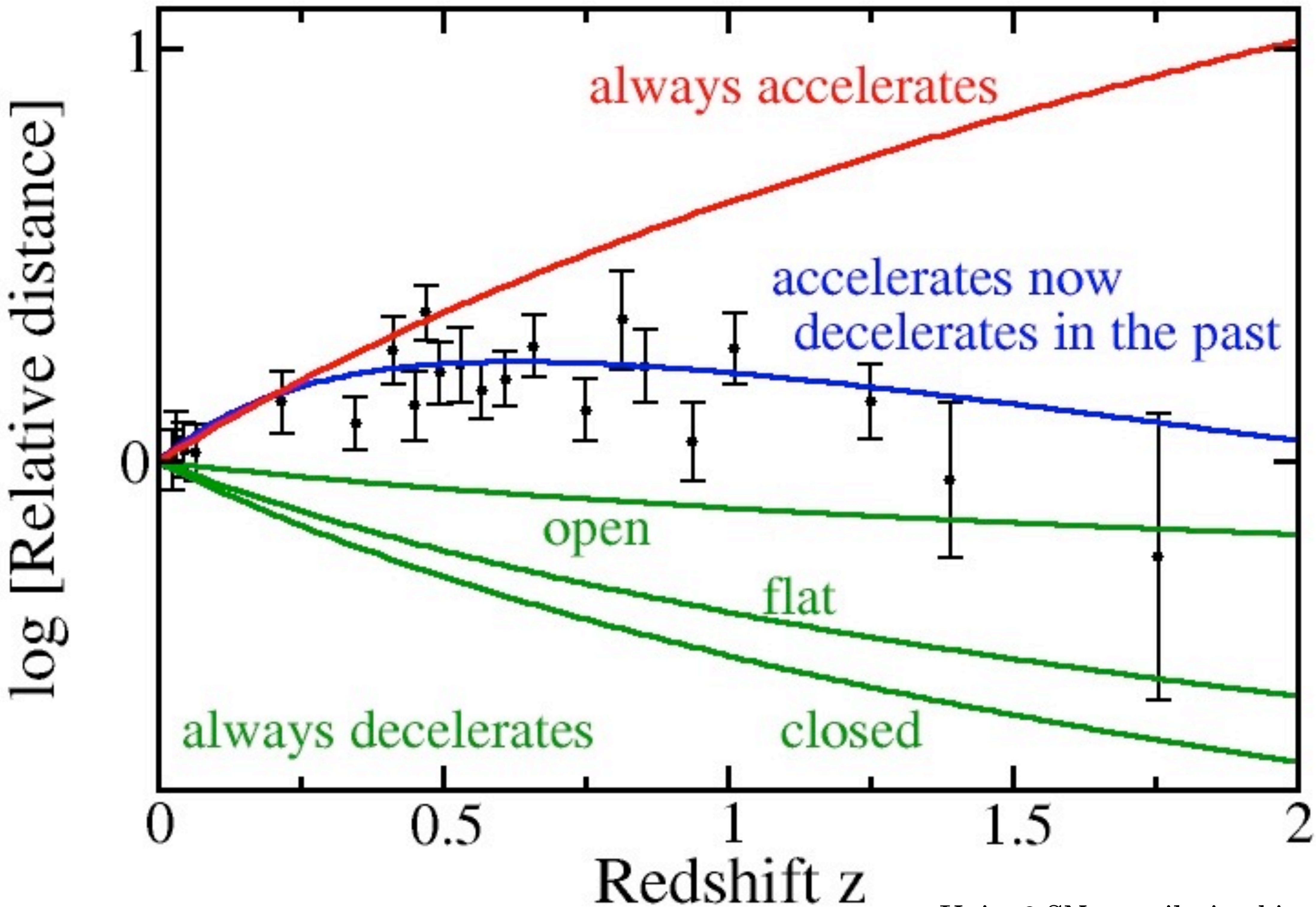
[On sabbatical at MPA and Excellence Cluster, Jan-Aug 2015]

Key Collaborators:
Eduardo Ruiz, Dan Shafer (grad students, Michigan)

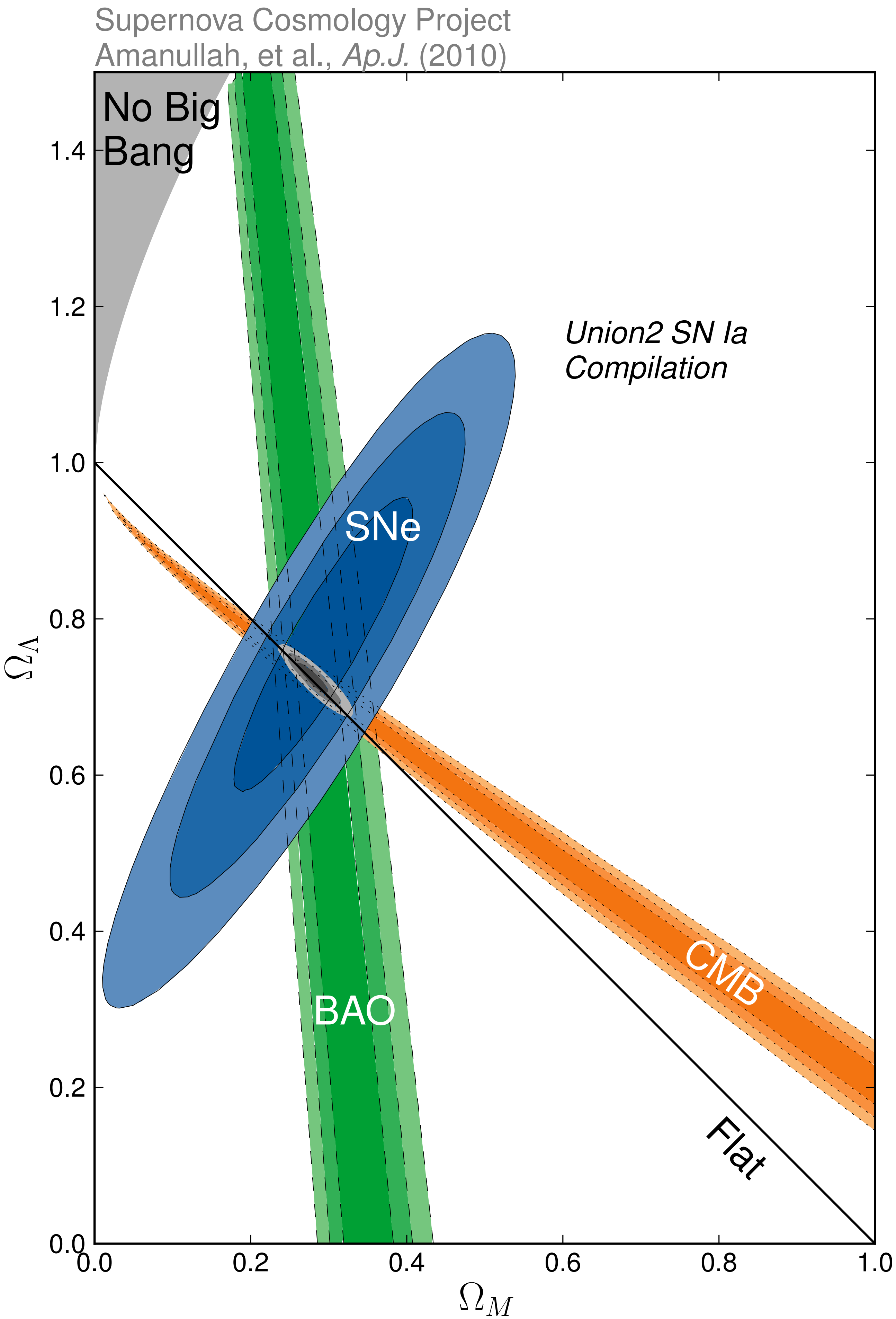
Makeup of universe today

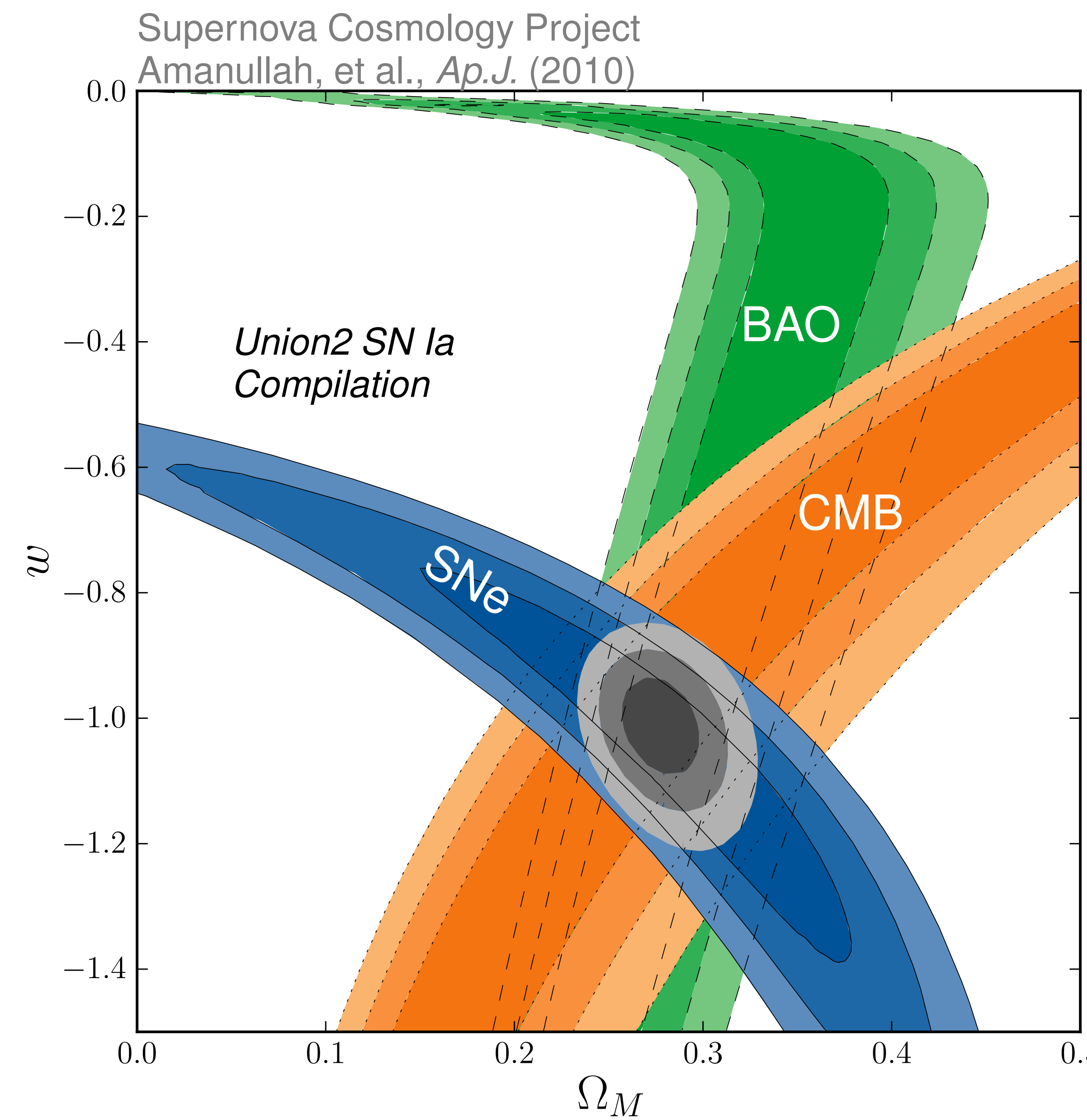


Evidence for Dark energy from type Ia Supernovae



Union2 SN compilation binned in redshift

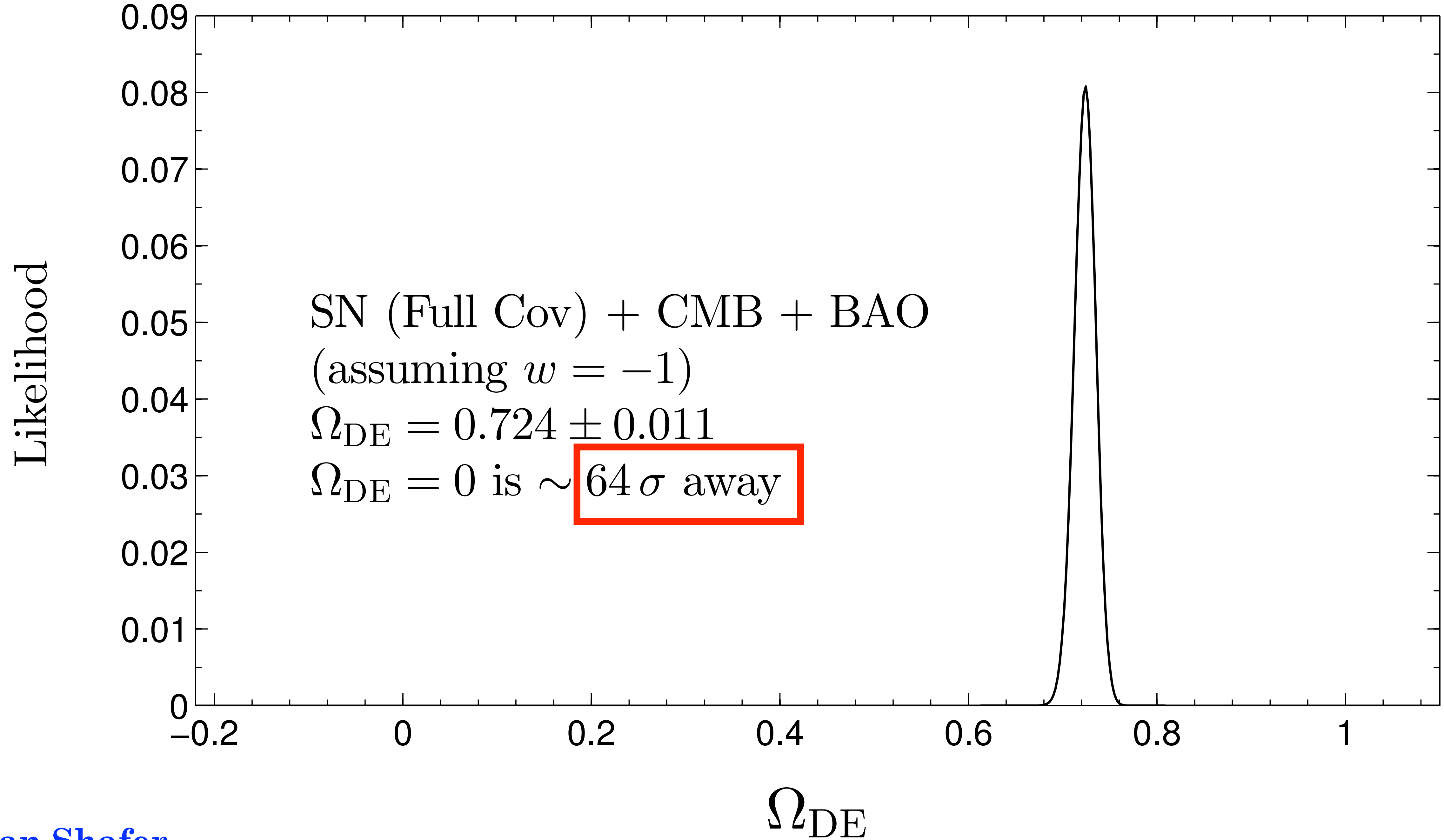




$$\Omega_{\rm DE} \equiv \frac{\rho_{\rm DE}}{\rho_{\rm crit}}$$

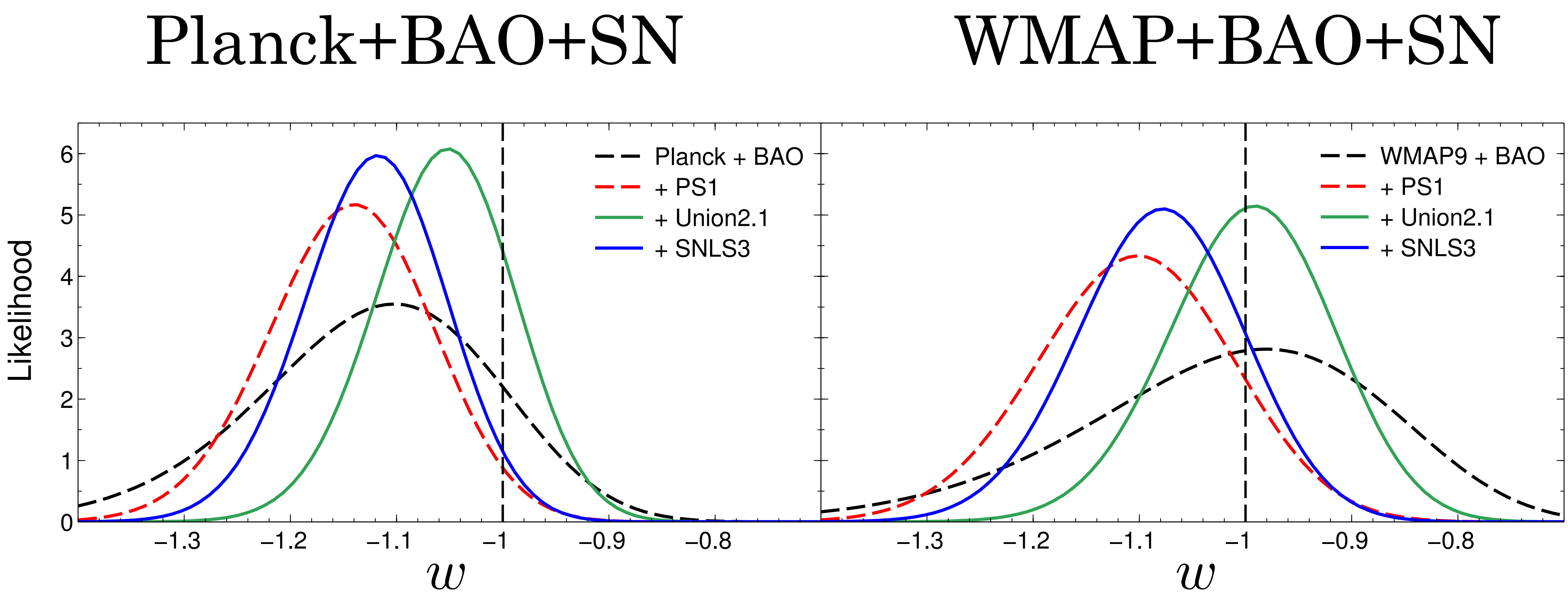
$$w \equiv \frac{p_{\rm DE}}{\rho_{\rm DE}}$$

Current evidence for dark energy is impressively strong



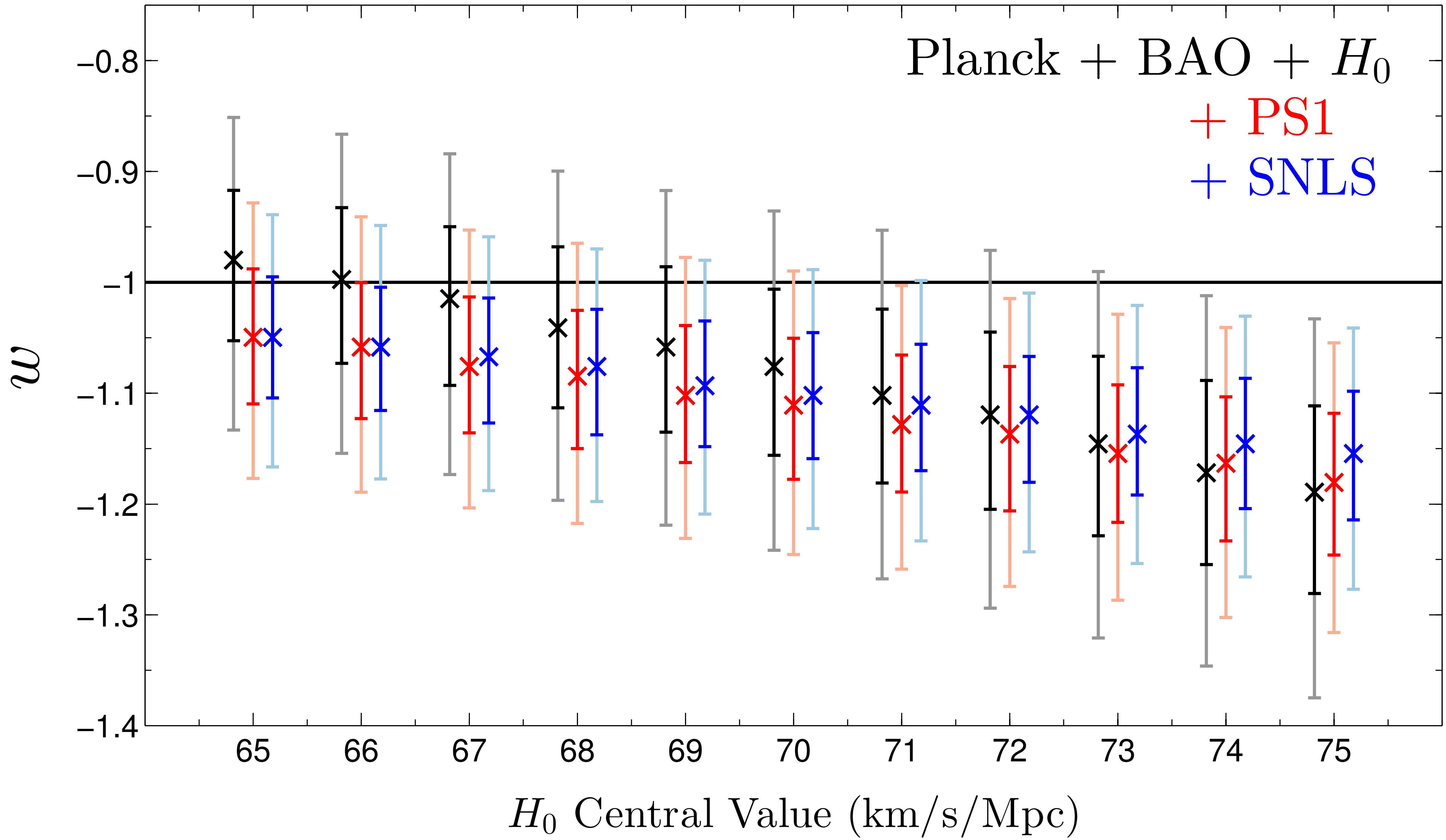
Dan Shafer

Hints that w < –1??



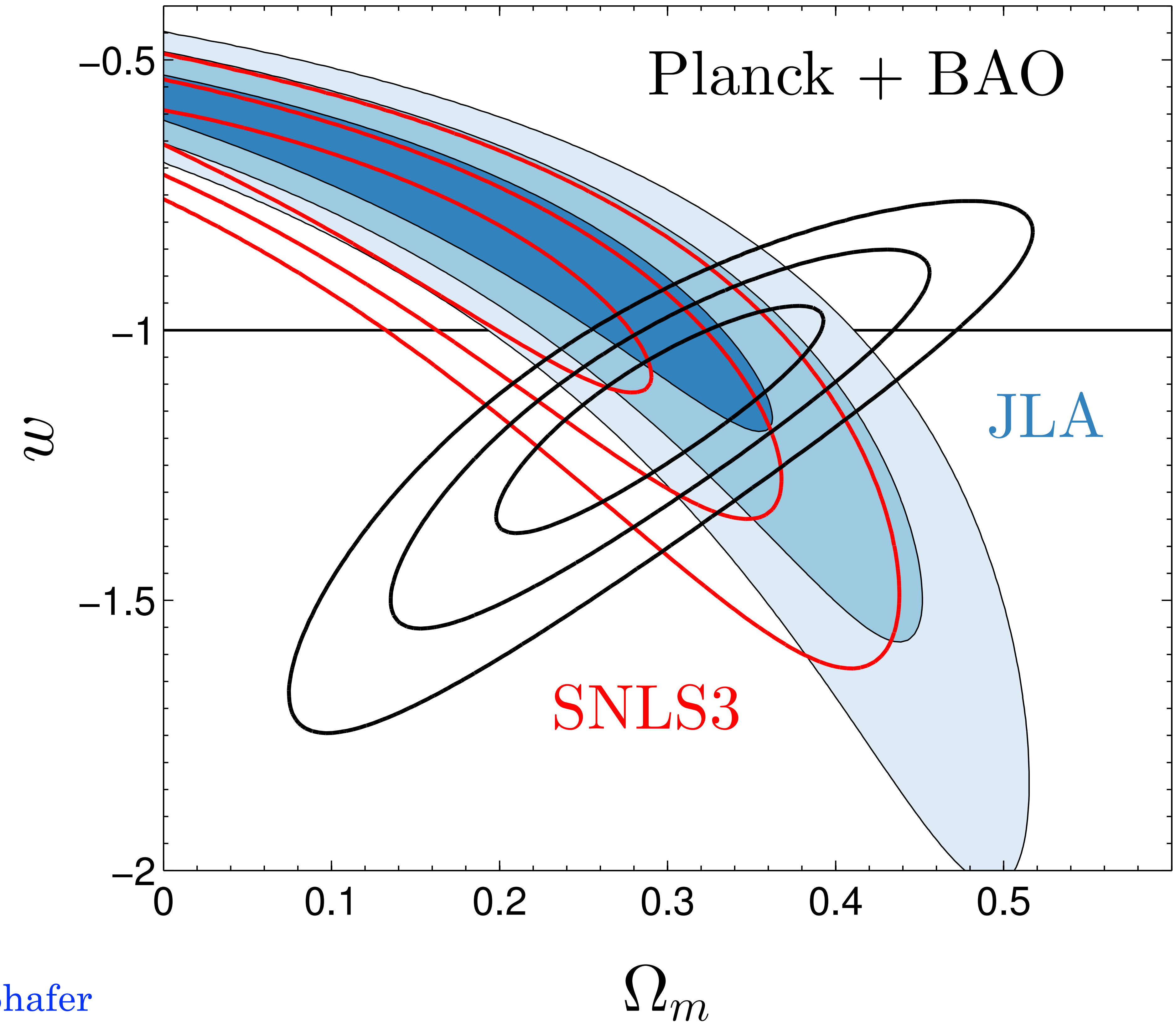
Shafer & Huterer, 1312.1688

Only if $H_0 \gtrsim 71$ *and* Planck assumed



Shafer & Huterer, 1312.1688

SN datasets and dark energy constraints

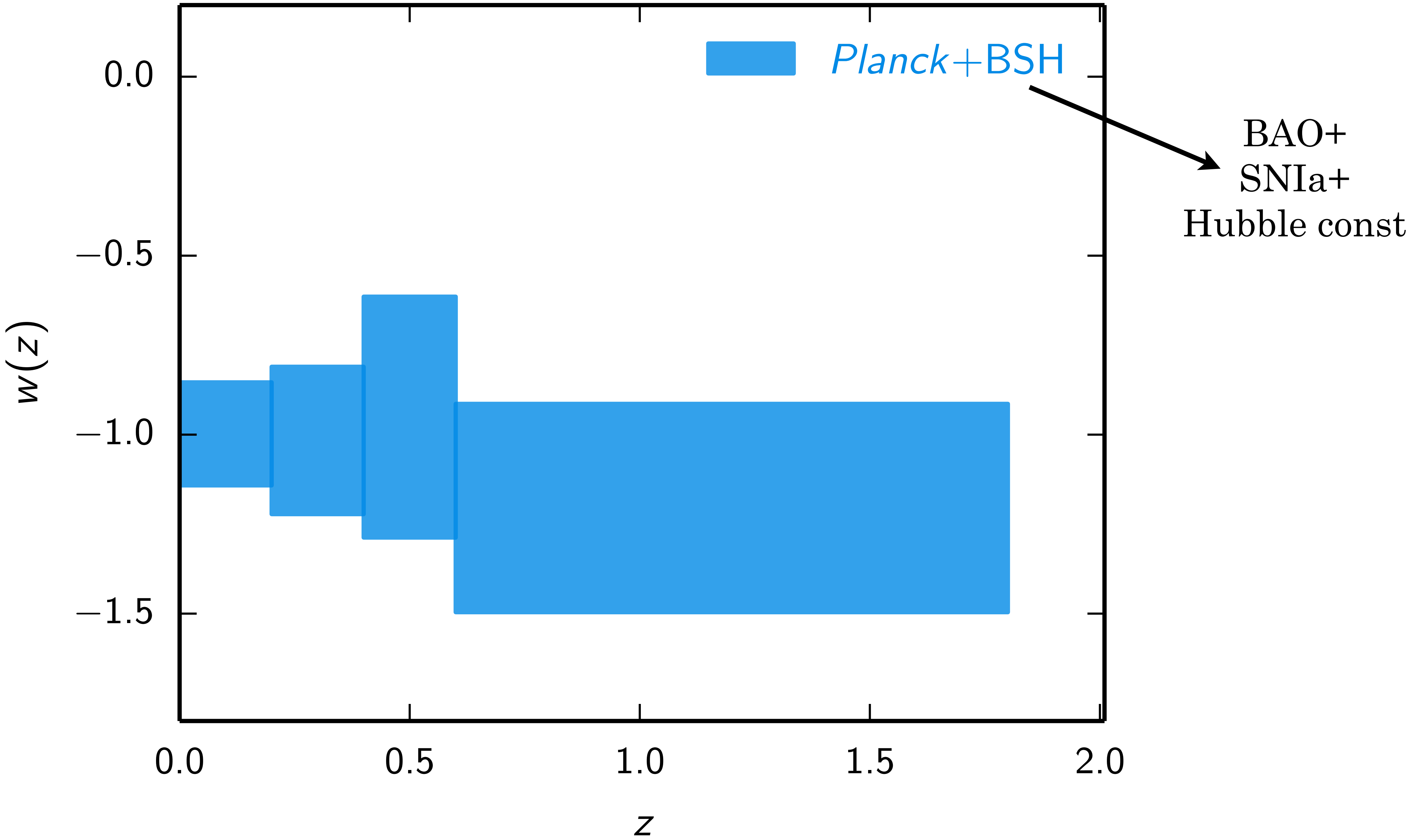


Dan Shafer

Big questions

1. Is DE something other than vacuum energy?
2. Does GR self-consistently describe cosmic acceleration?

Current constraints on w(z): largely from geometrical measures



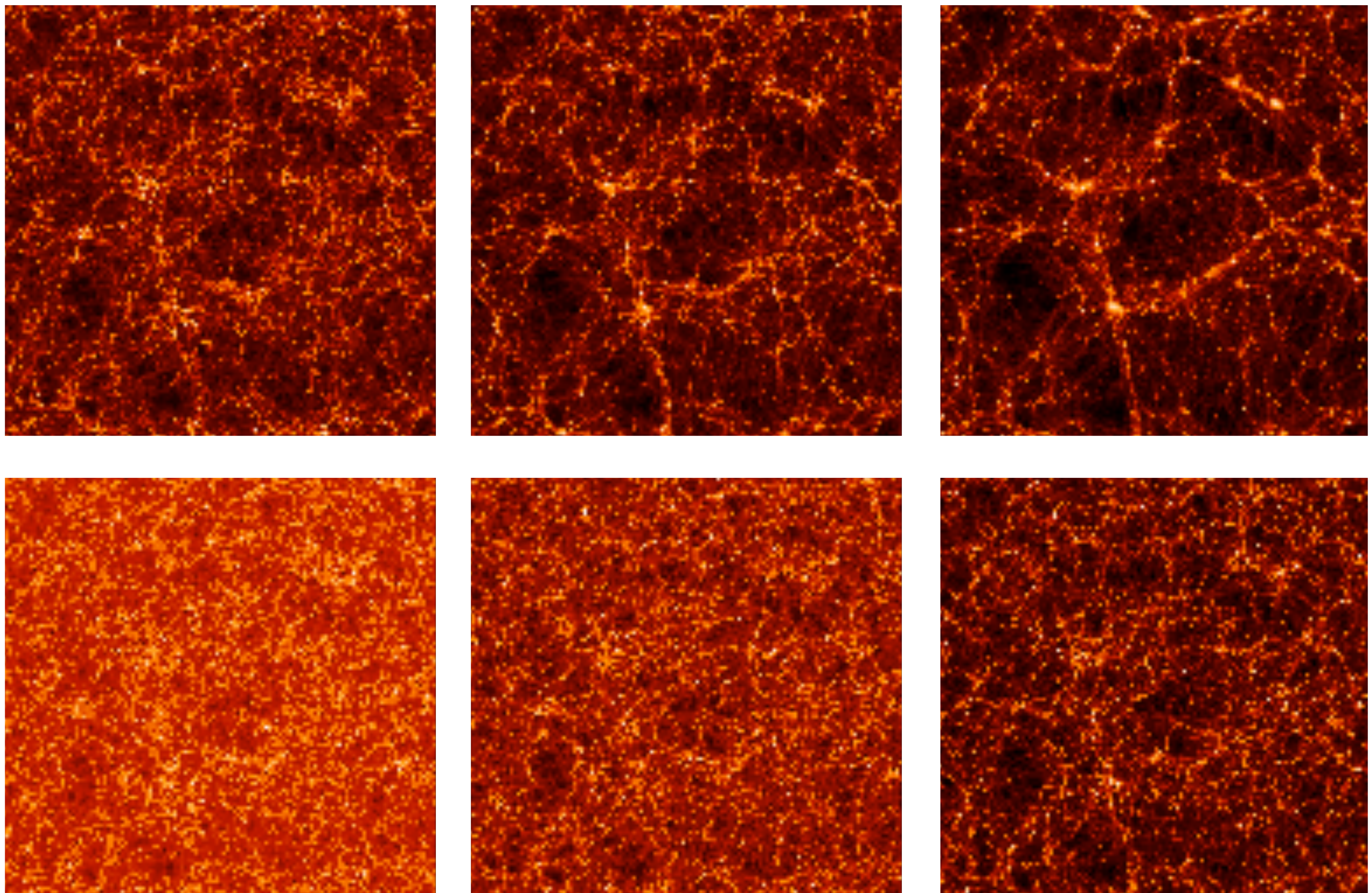
Planck XIV, "Dark Energy and Modified Gravity", arXiv:1502.01590

Remainder of talk

Part I: testing DE with geometry and growth

Part II: making predictions for DE observables

Dark Energy suppresses the growth of density fluctuations



Huterer et al, Snowmass report, 1309.5385

The Virgo Consortium (1996)

Idea: compare geometry and growth

e.g. Wang, Hui, May & Haiman 2007

Our approach:

Double the standard DE parameter space

($\Omega_M = 1 - \Omega_{DE}$ and w):

$\Rightarrow \Omega_M^{geom}, w^{geom}$ $\Omega_M^{grow}, w^{grow}$

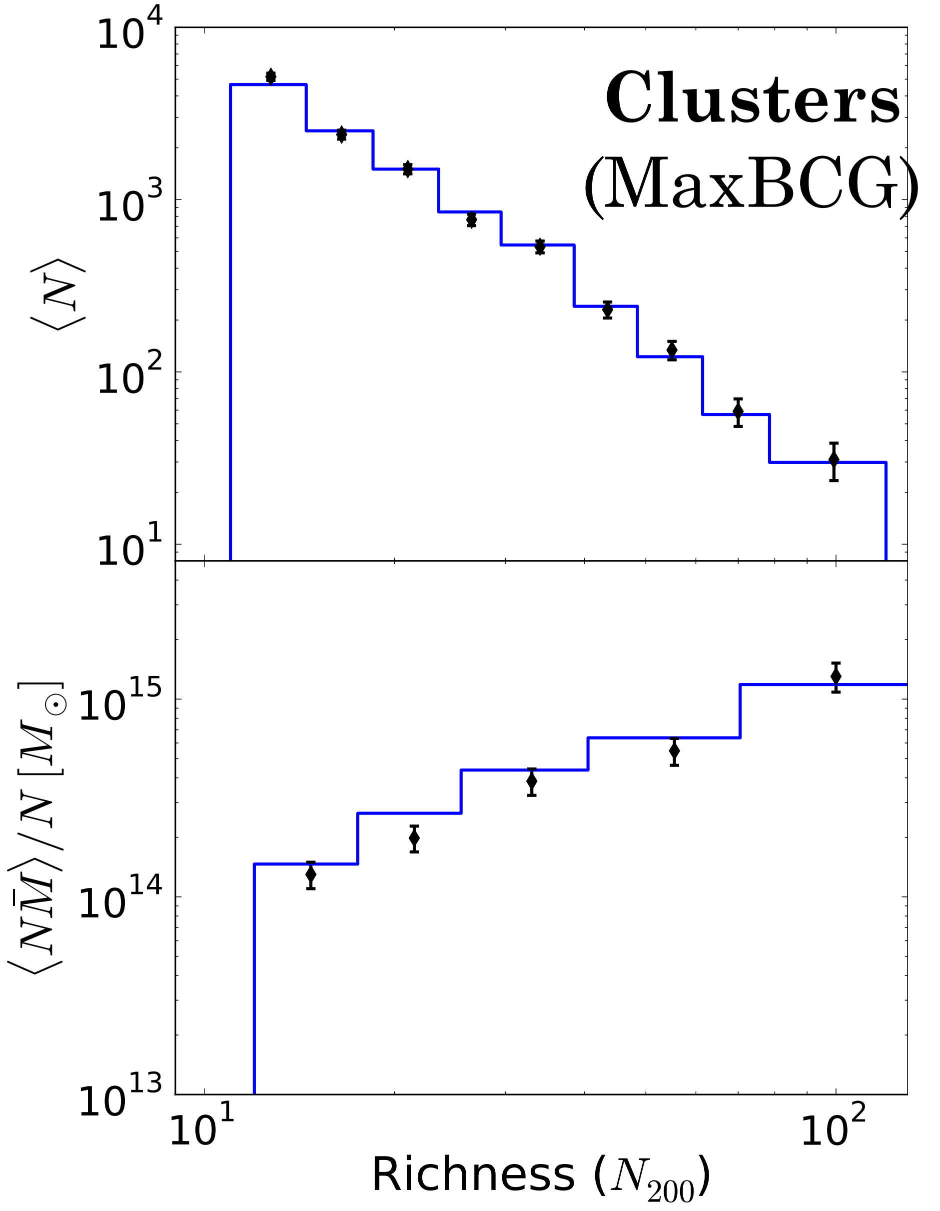
[In addition to other:

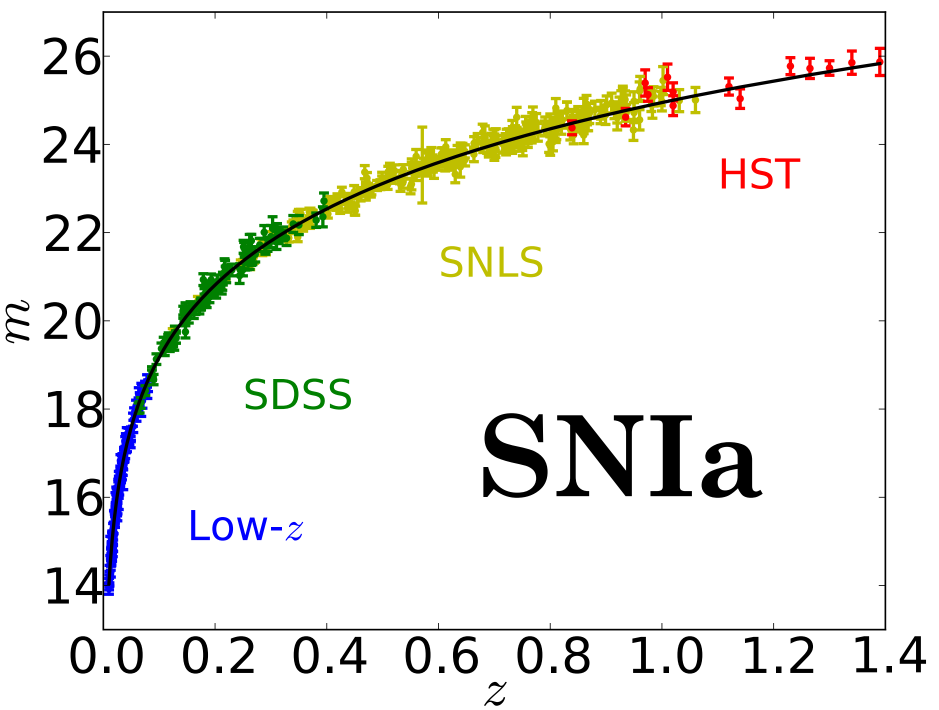
standard parameters: $\Omega_M h^2$ $\Omega_B h^2$, n_s, A)

nuisance parameters: probe-dependent]

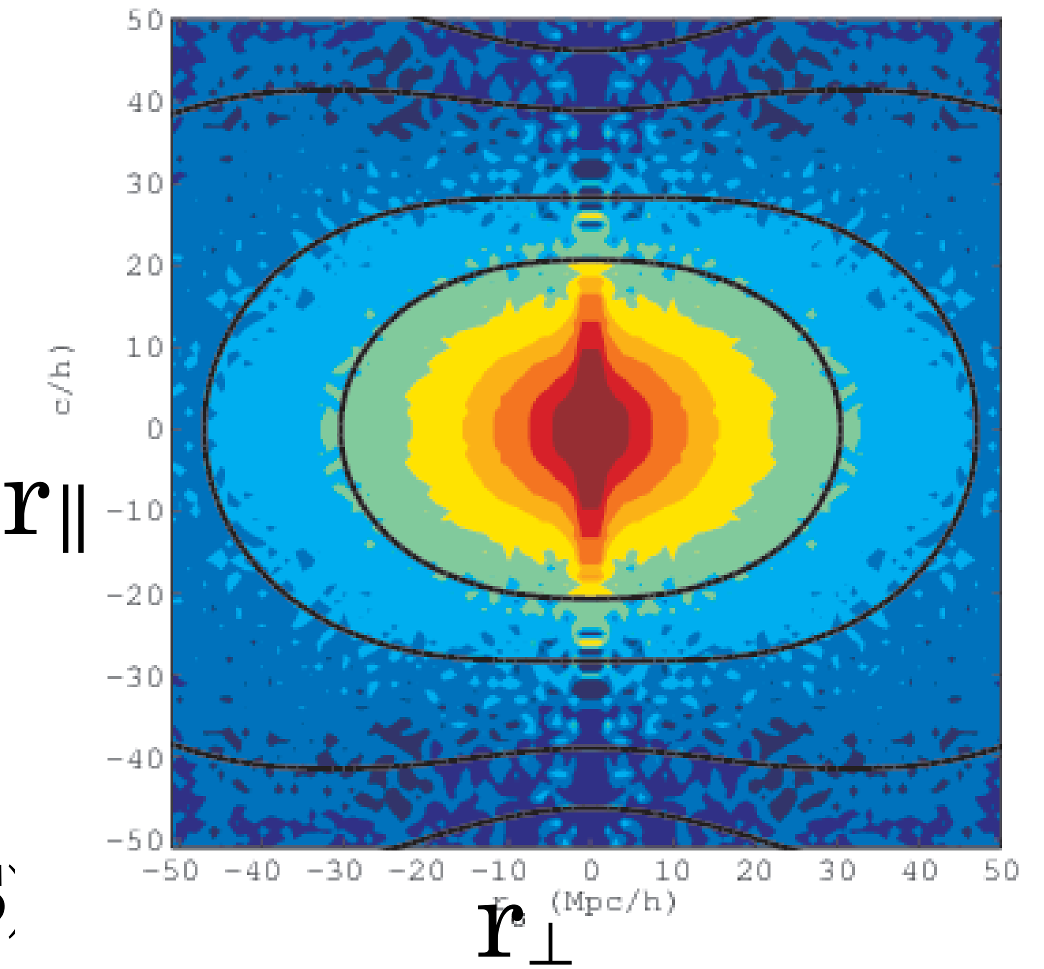
Ruiz & Huterer, arXiv:1410.5832

(Current) Data used





RSD



CMB (Planck peak location)

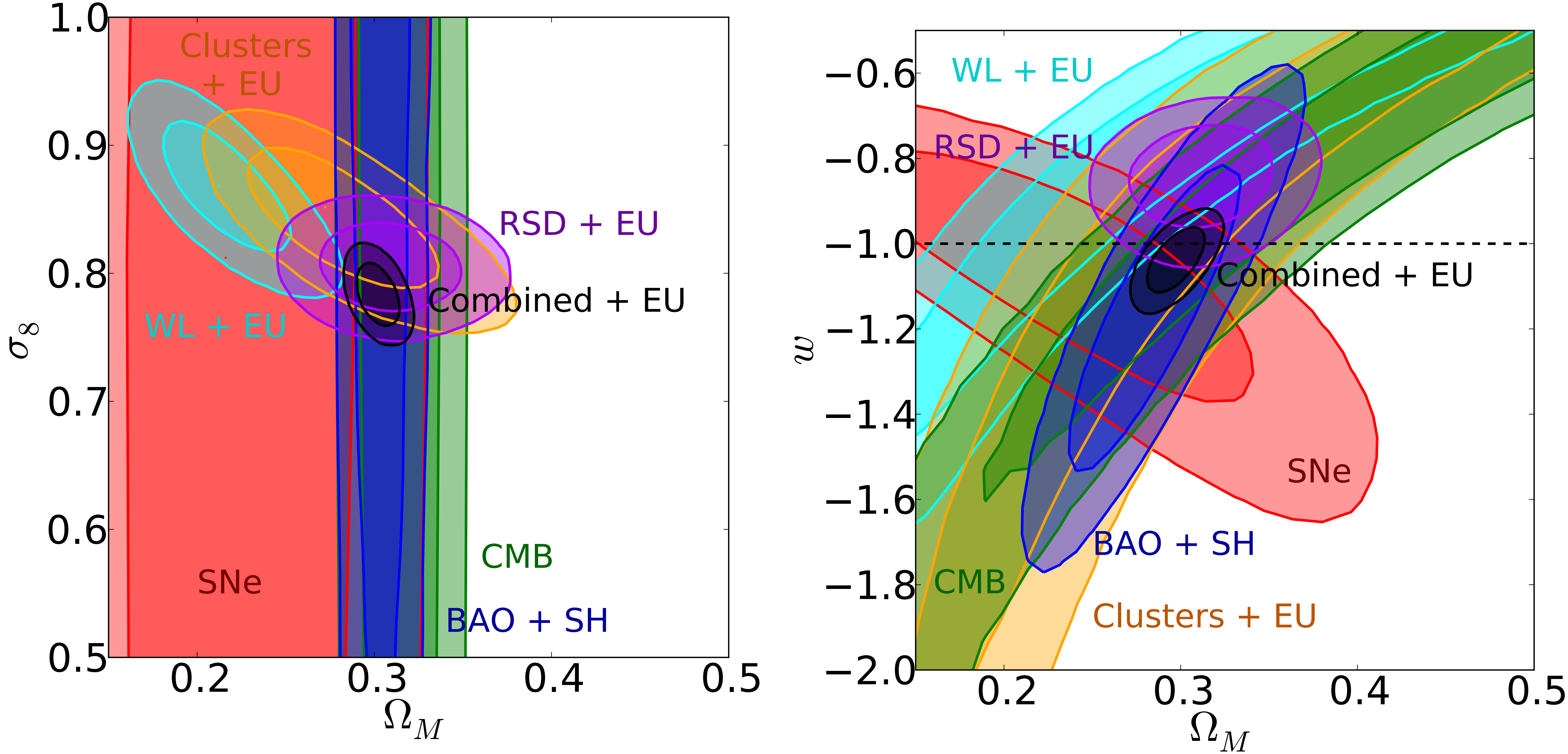
Weak Lensing (CFHTLens)

BAO (6dF, SDSS LRG, BOSS CMASS)

Sensitivity to geometry and growth

Cosmological Probe	Geometry	Growth
SN Ia	$H_0 D_L(z)$	—
BAO	$\left(\frac{D_A^2(z)}{H(z)}\right)^{1/3} / r_s(z_d)$	—
CMB peak loc.	$R \propto \sqrt{\Omega_m H_0^2}\, D_A(z_*)$	—
Cluster counts	$\frac{dV}{dz}$	$\frac{dn}{dM}$
Weak lens 2pt	$\frac{r^2(z)}{H(z)} W_i(z) W_j(z)$	$P\left(k = \frac{\ell}{r(z)}\right)$
RSD	$F(z) \propto D_A(z) H(z)$	$f(z)\sigma_8(z)$

Standard parameter spaces

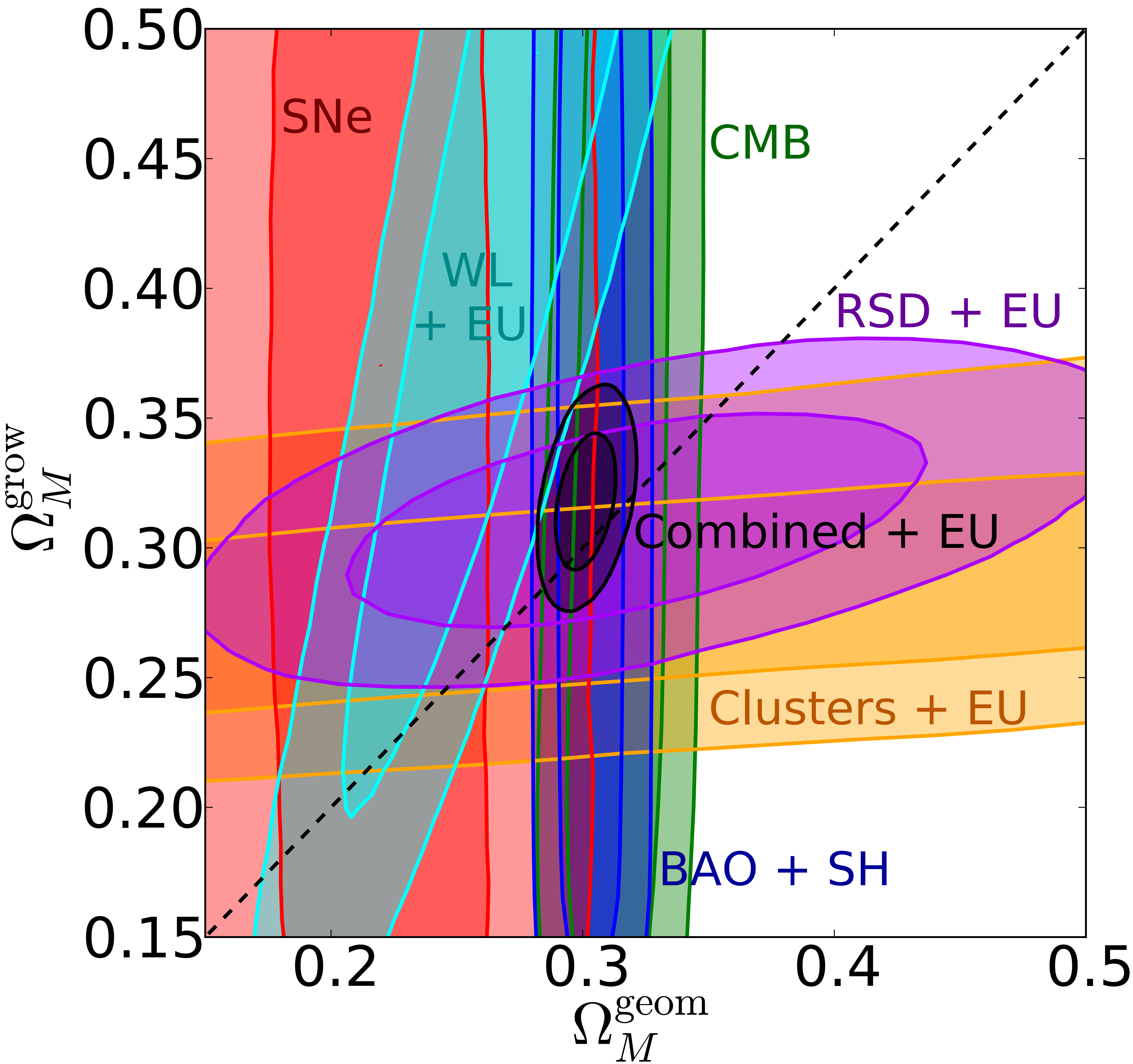


EU = Early Universe prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$, n_s, A)

SH = Sound Horizon prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$)

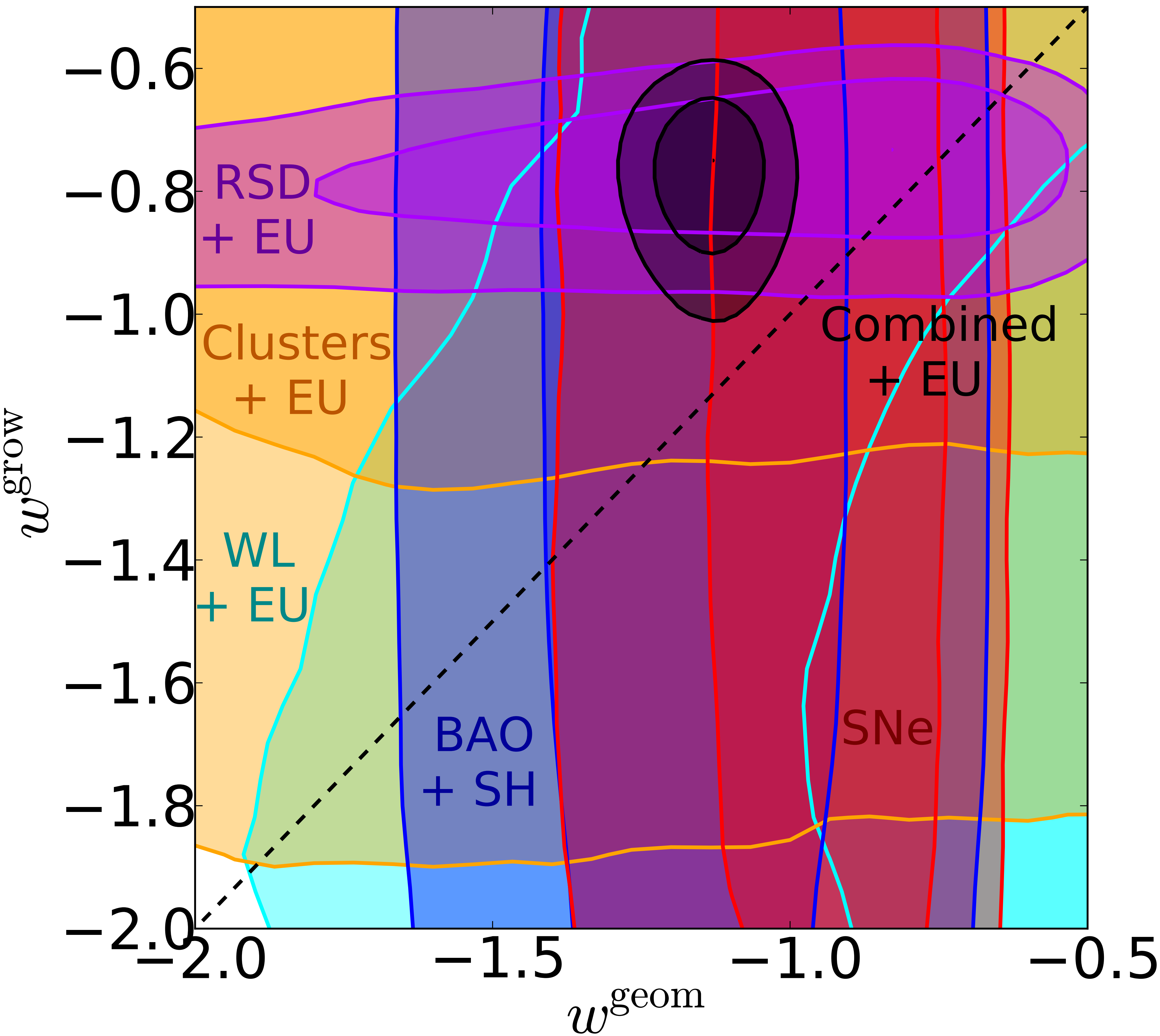
Ruiz & Huterer, arXiv:1410.5832

Omega matter: geometry vs. growth



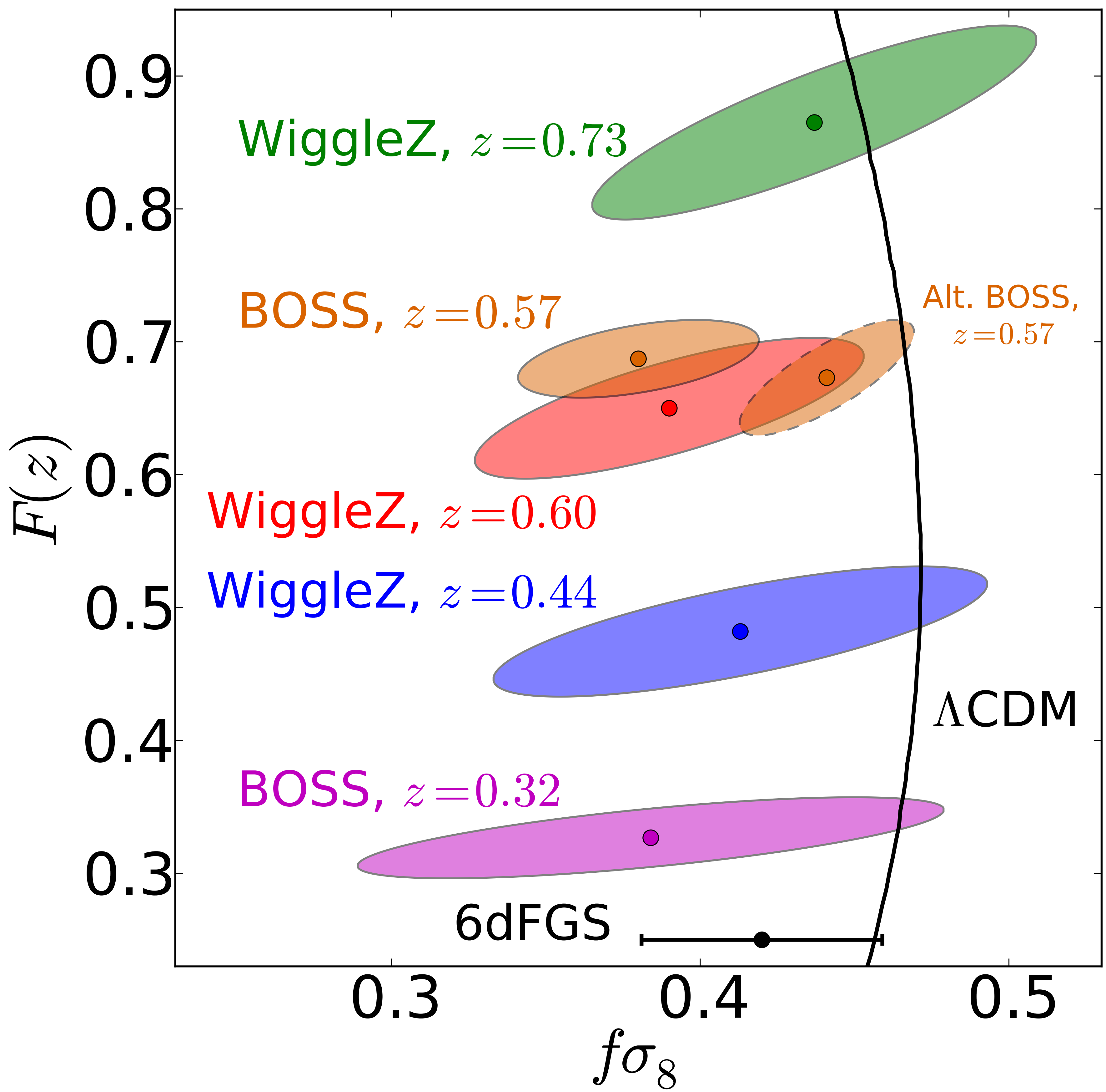
* SN not the recalibrated JLA compilation - need to update; will move Ω_M^{grow} up

w (eq of state of DE): geometry vs. growth

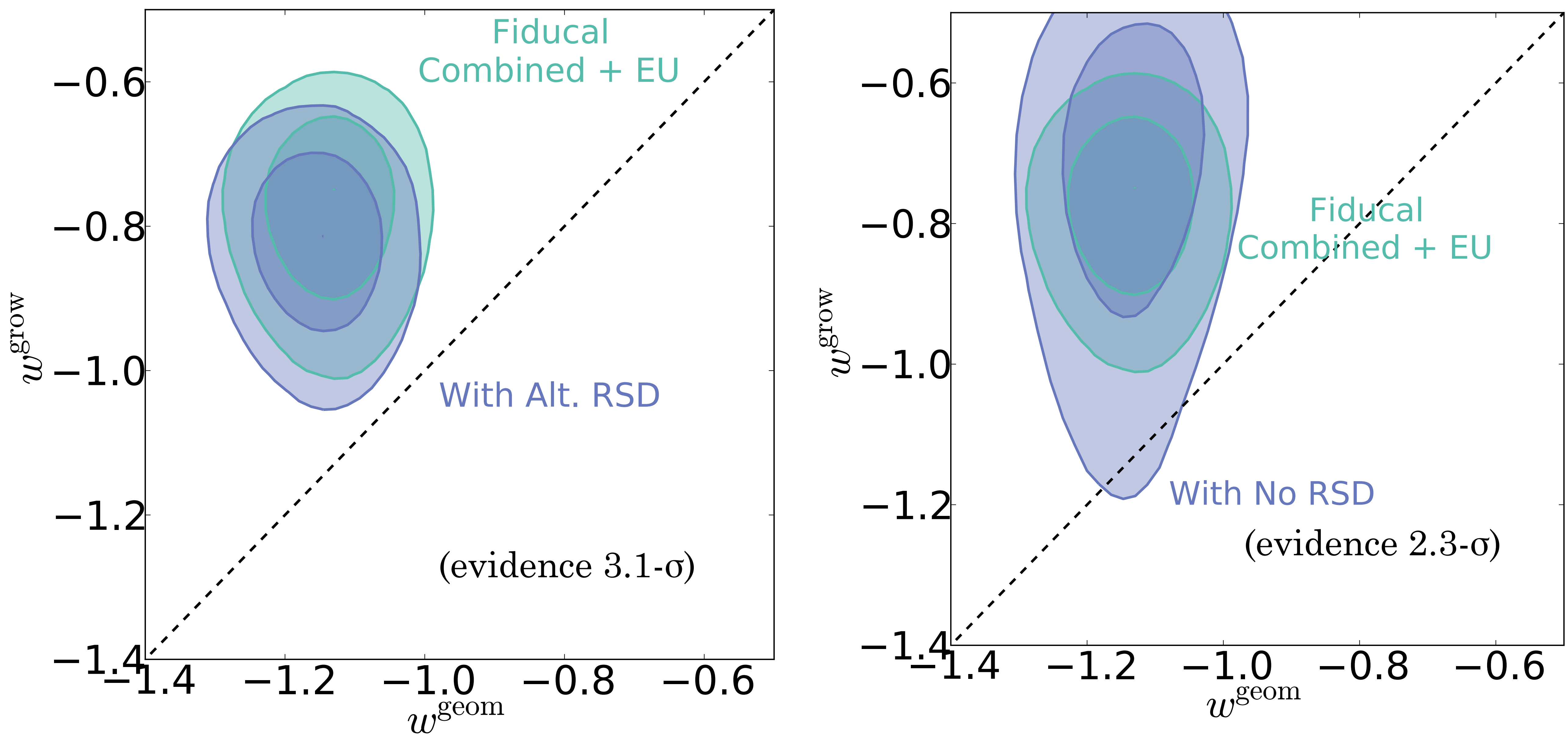


Evidence for $w^{\text{grow}} > w^{\text{geom}}$:
3.3-σ

Redshift Space Distortion data



RSD prefer $w^{\mathrm{grow}} > -1$ (slower growth than in LCDM)



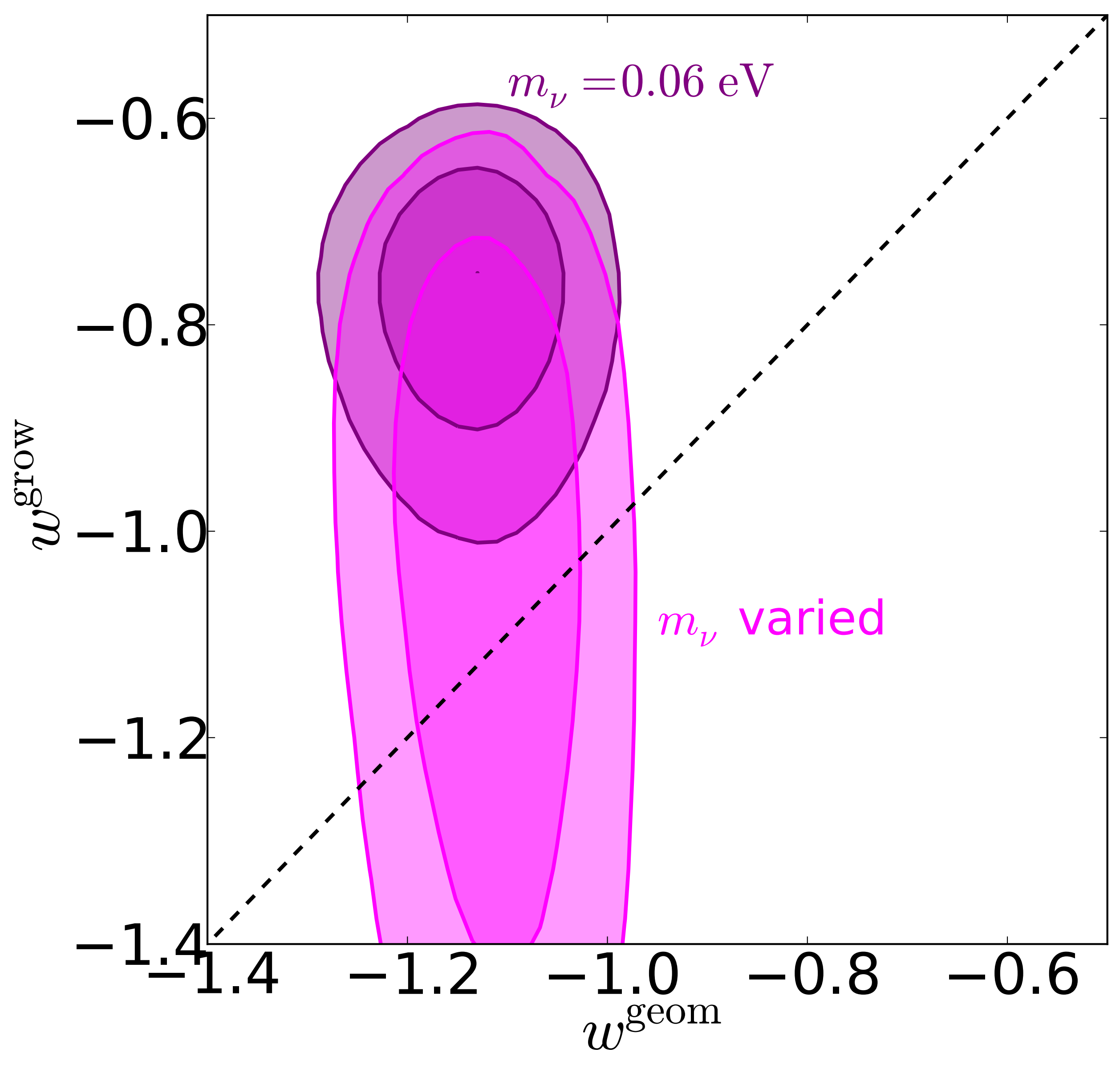
All growth probes (i.e. also clusters, WL) show preference for a slowed growth

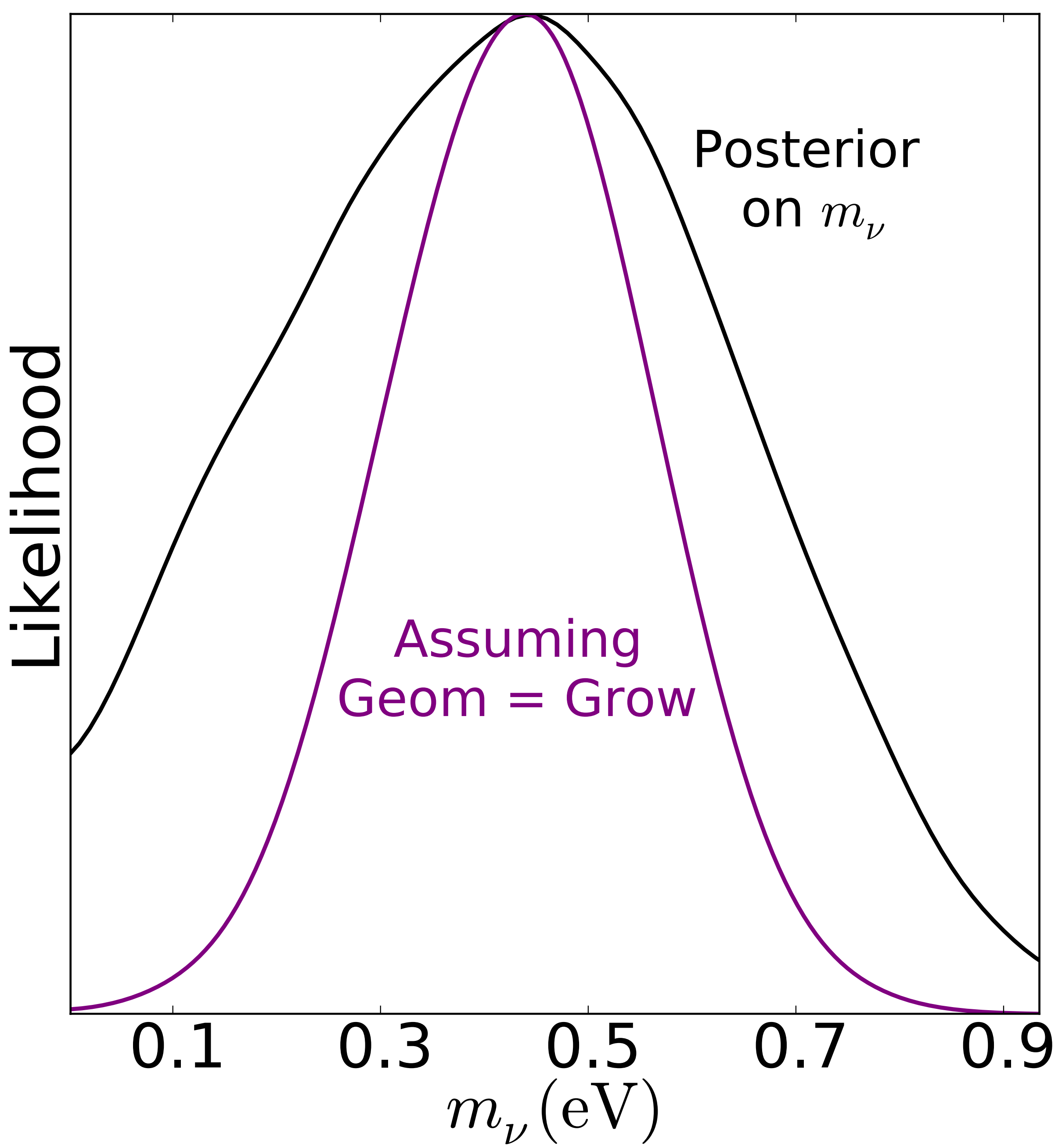
"Are there cracks in the Cosmic Egg?"

Michael Turner, Aspen, summer 2014

see also e.g. M. Costanzi et al, arXiv:1407.8338, S. Bocquet et al, arXiv:1407.2942

(Pretty high) neutrino mass can relieve the tension





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Remainder of talk

Part I: testing DE with geometry and growth

Part II: making predictions for DE observables

Falsifying DE Paradigms

Underlying Philosophy:

- For any given class of DE models, current data predict the possible range in fundamental cosmological functions D(z), H(z), G(z), etc …
- … which therefore provide ‘target’ quantities (in redshift) for ruling out classes of DE models with upcoming data

Mortonson, Hu & Huterer, 2009-2011

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

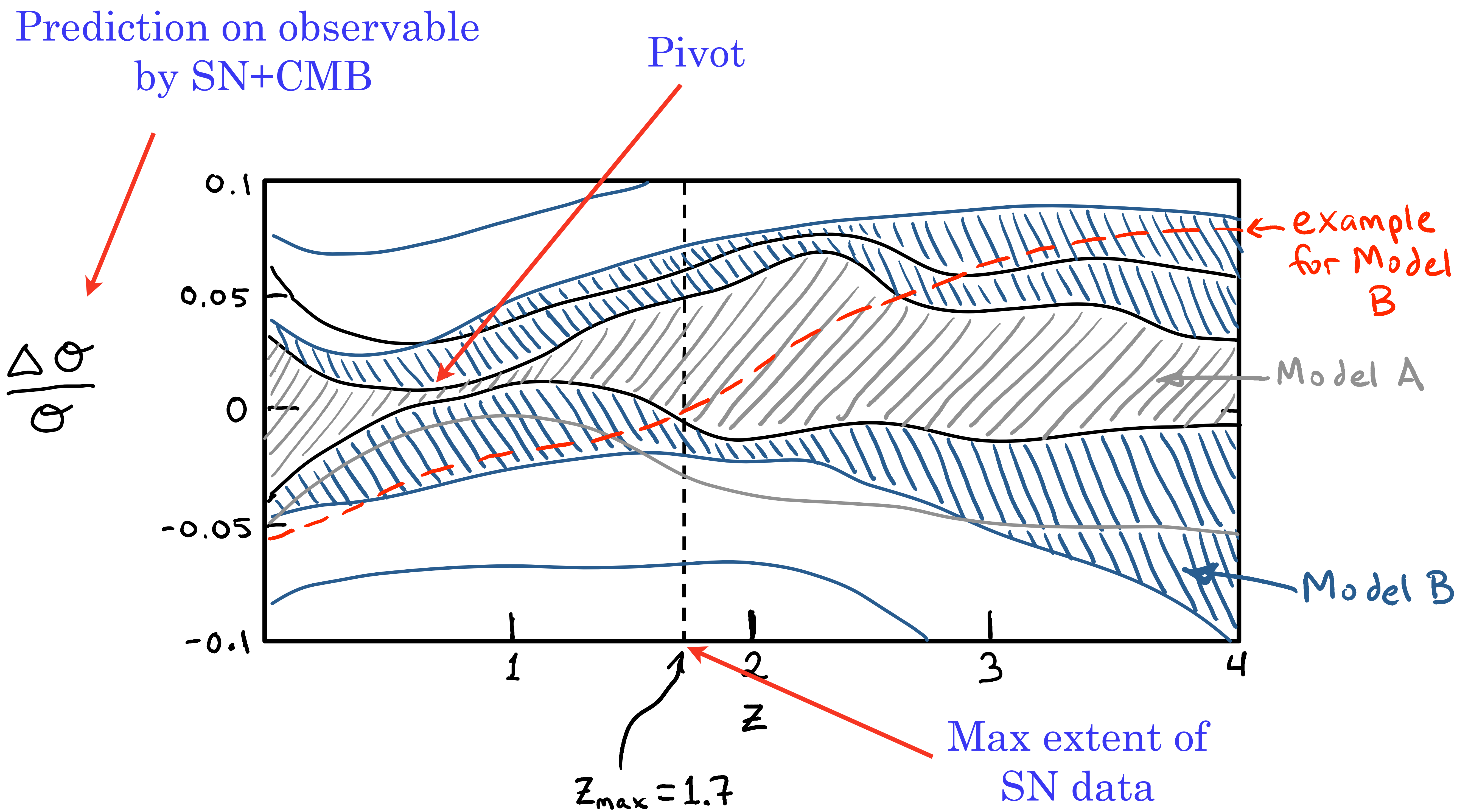
(current = Union2 SN + WMAP + $BAO_{z=0.35}$ + H_0
future = Planck + Space DE)

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 γ(z), f(z))

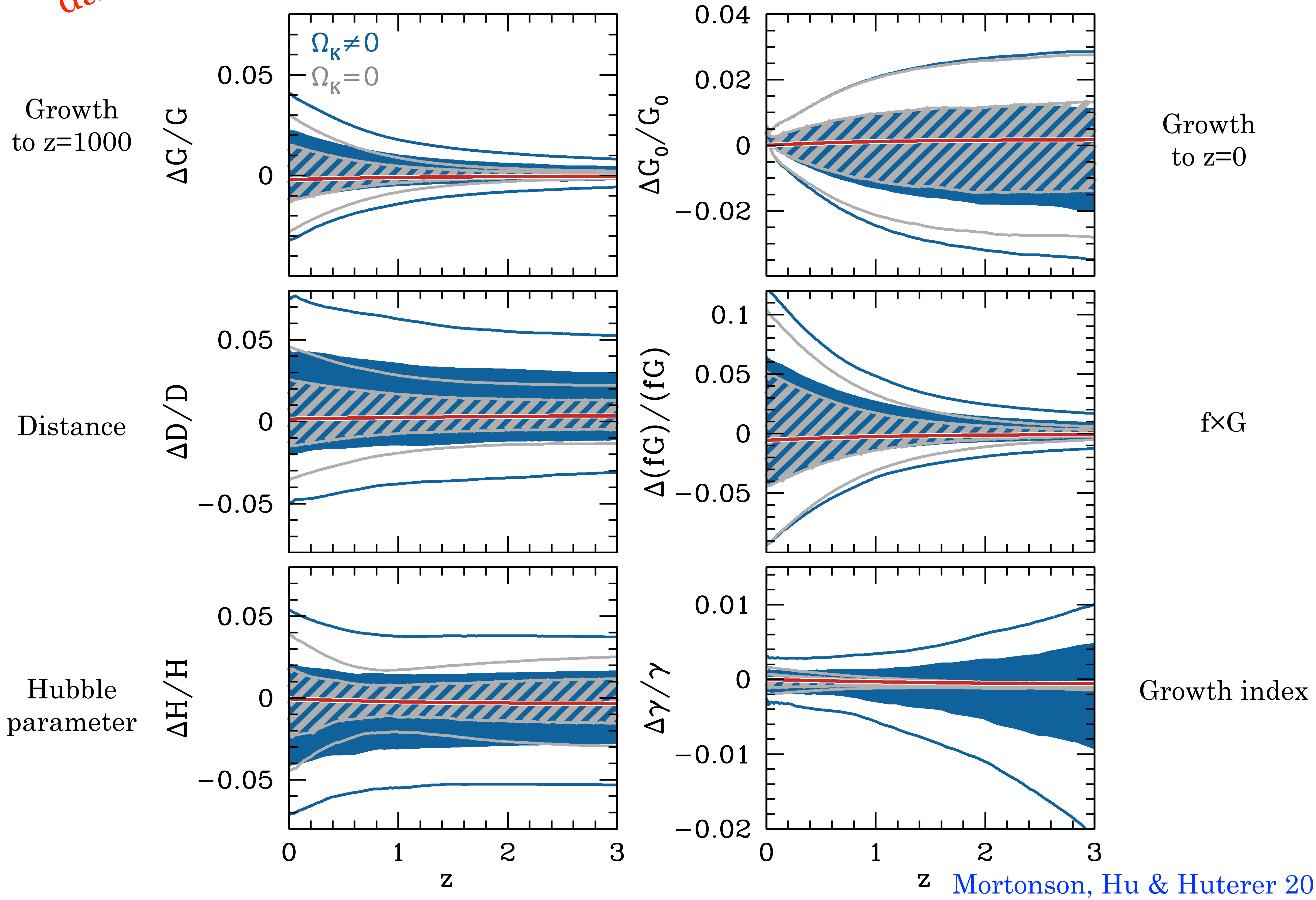
Structure of graphs to follow



Sketch by M. Mortonson

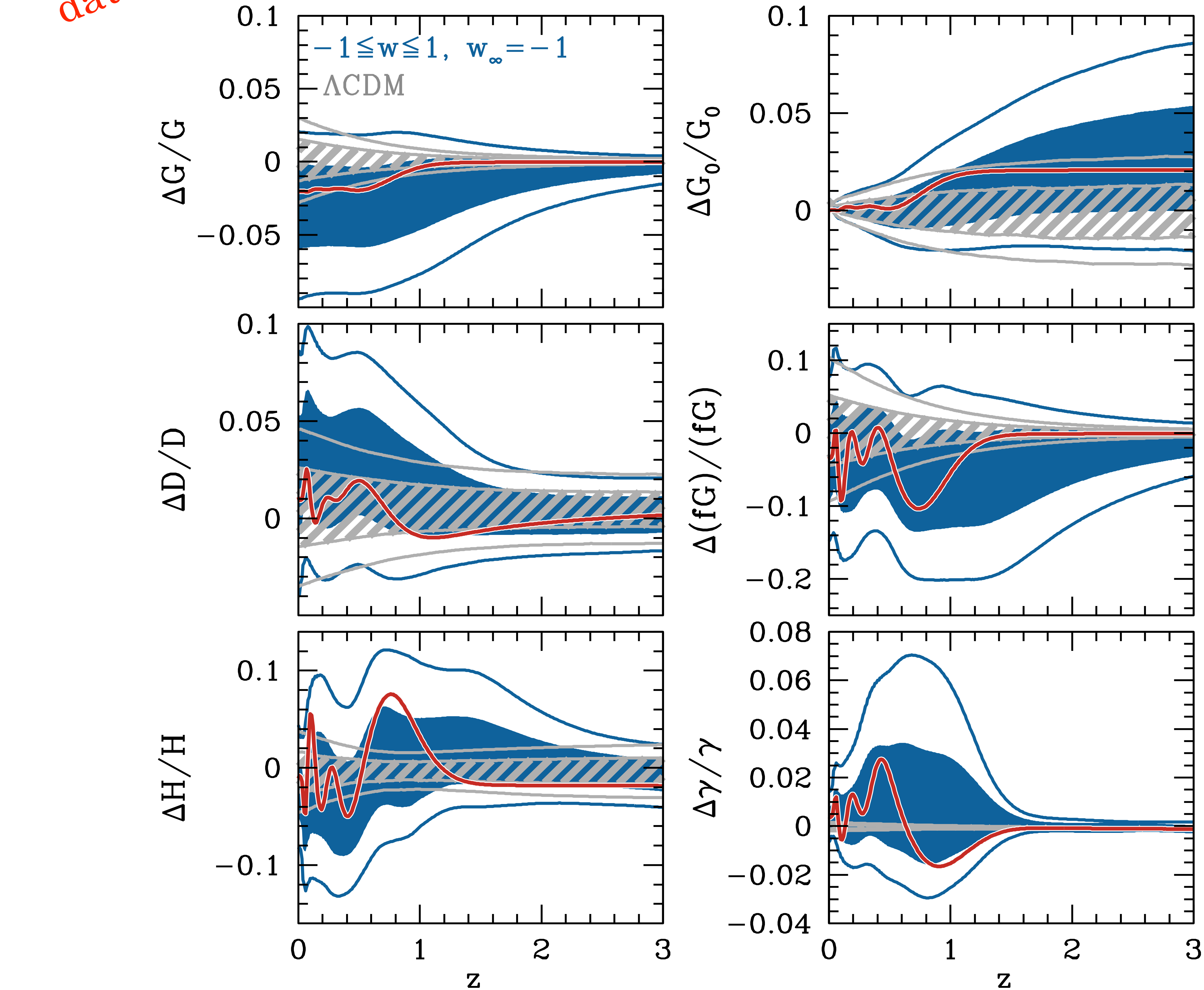
Current data

LCDM predictions - flat or curved



Mortonson, Hu & Huterer 2010

Quintessence predictions (flat, no Early DE)

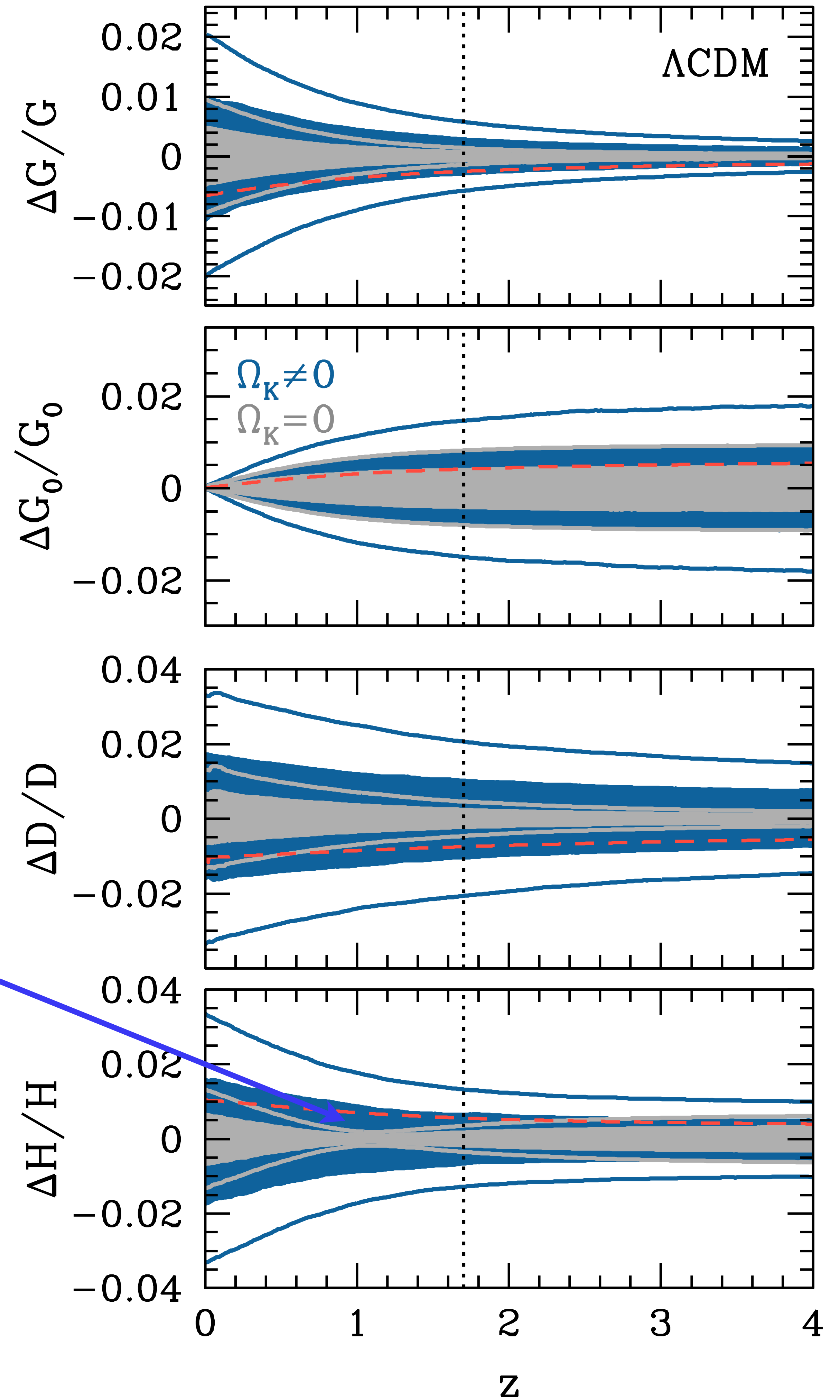


Future data

LCDM predictions (flat or curved)

Grey: flat
Blue: curved

D, G to <1% everywhere
H(z=1) to 0.1% for flat LCDM



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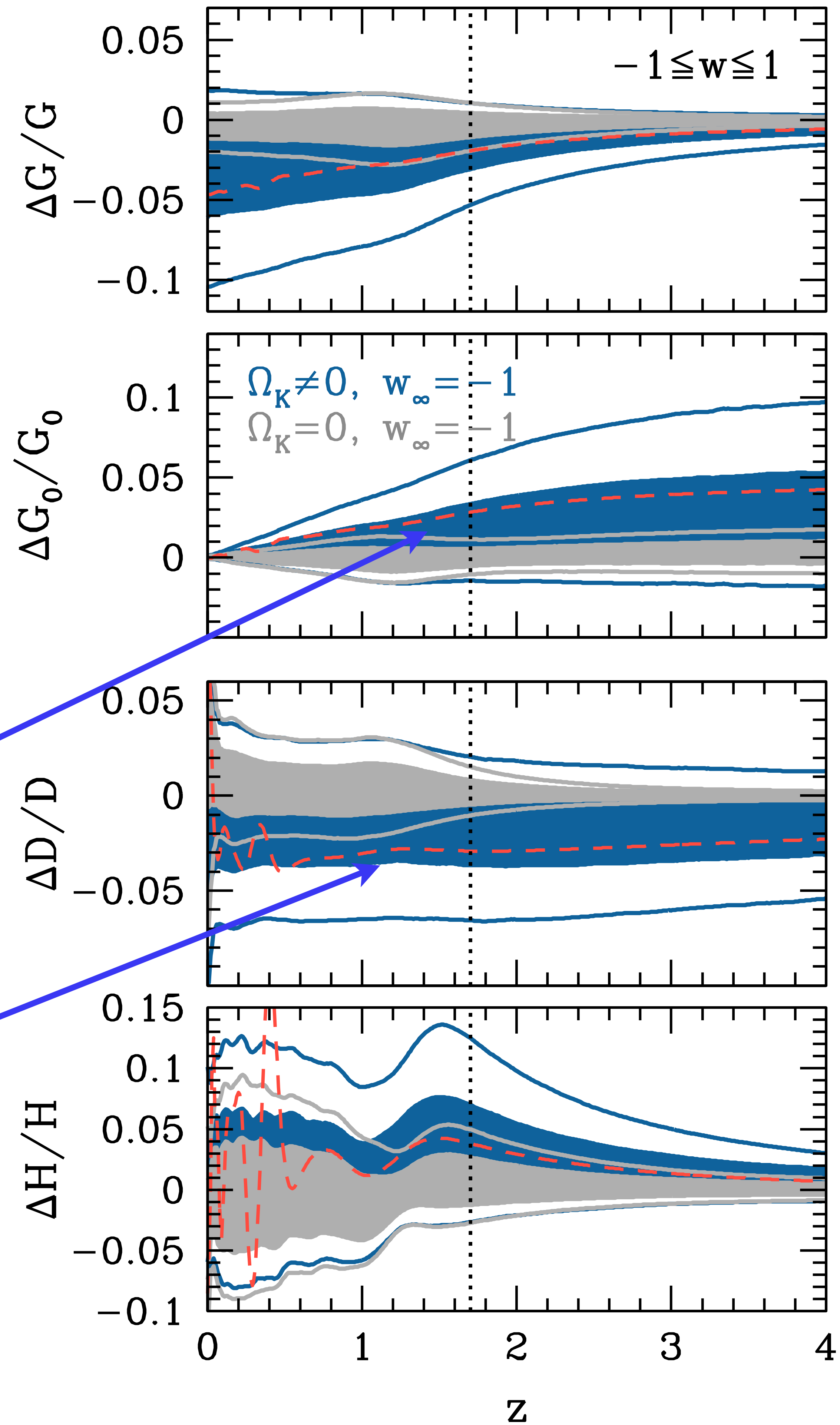


Smoking Gun of curvature:

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

Therefore:

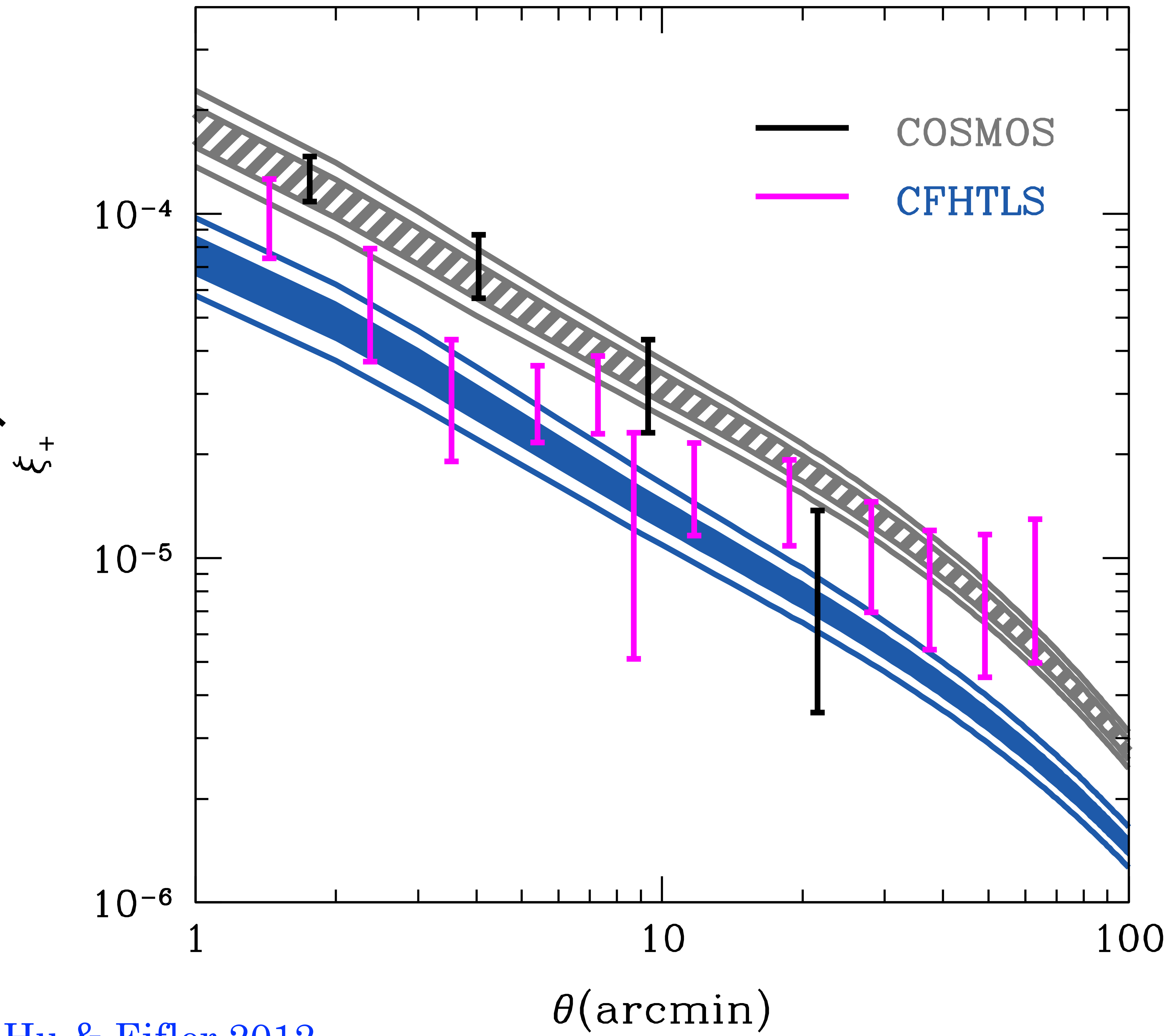
Whole classes of DE models
are highly falsifiable

Therefore:

Whole classes of DE models are highly falsifiable

Straightforward to make predictions for actually observable quantities for a given survey, given the class of DE models

Two-pt function of shear in real space



Vanderveld, Mortonson, Hu & Eifler 2012

Dark Energy Survey Instrument (**DESI**)

- Huge spectroscopic survey on Mayall telescope (Arizona)
- ~5000 fibres, ~15,000 sqdeg, ~20 million spectra
- LRG in $0 < z < 1$, ELG in $0 < z < 1.5$, QSO $2.2 < z < 3.5$
- Great for **dark energy** (RSD, BAO)
- Great for primordial non-Gaussianity - $P(k, z)$, bispectrum...
- Start ~2018, funding DOE + institutions

Conclusions

- So far, all measurements are in excellent agreement with Lambda (i.e. $w = -1$)...
- ...despite occasional alarms to the contrary:
  - Planck + BAO + SN + high H_0^{local}
- Separating growth from geometry is a good way to get a) constraints b) insights into DE constraints; it now indicates a 3-sigma growth ≠ geometry discrepancy
- We now have accurate, tight predictions for D(z), G(z), H(z) and the observable quantities for each class of DE models ⇒ way to rule them out.

EXTRA SLIDES

To shed light on dark energy: search for 'something else' in the data

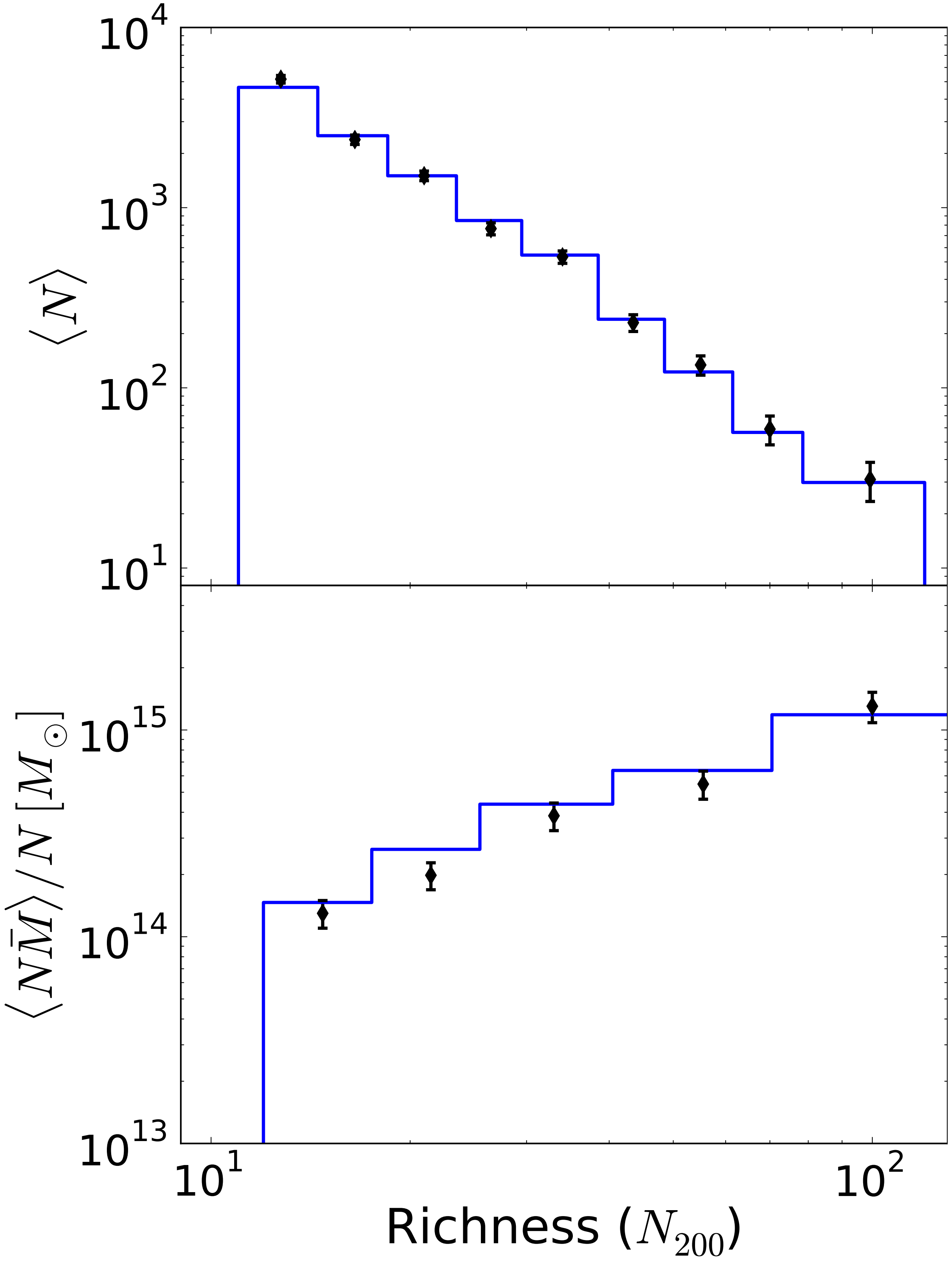
- Variation of eq. of state w → (none yet)
- Clustering of DE → (super hard)
- DM-DE interactions → (none yet)
- Early dark energy → (none yet)
- Modified gravity (MG) → (none yet)

BAO data

Survey	z_{eff}	Parameter	Measurement
6dFGS [33]	0.106	r_s/D_V	0.336 ± 0.015
SDSS LRG [34]	0.35	D_V/r_s	8.88 ± 0.17
BOSS CMASS [35]	0.57	D_V/r_s	13.67 ± 0.22

TABLE III. BAO data measurements used here, together with the effective redshift for the corresponding galaxy sample.

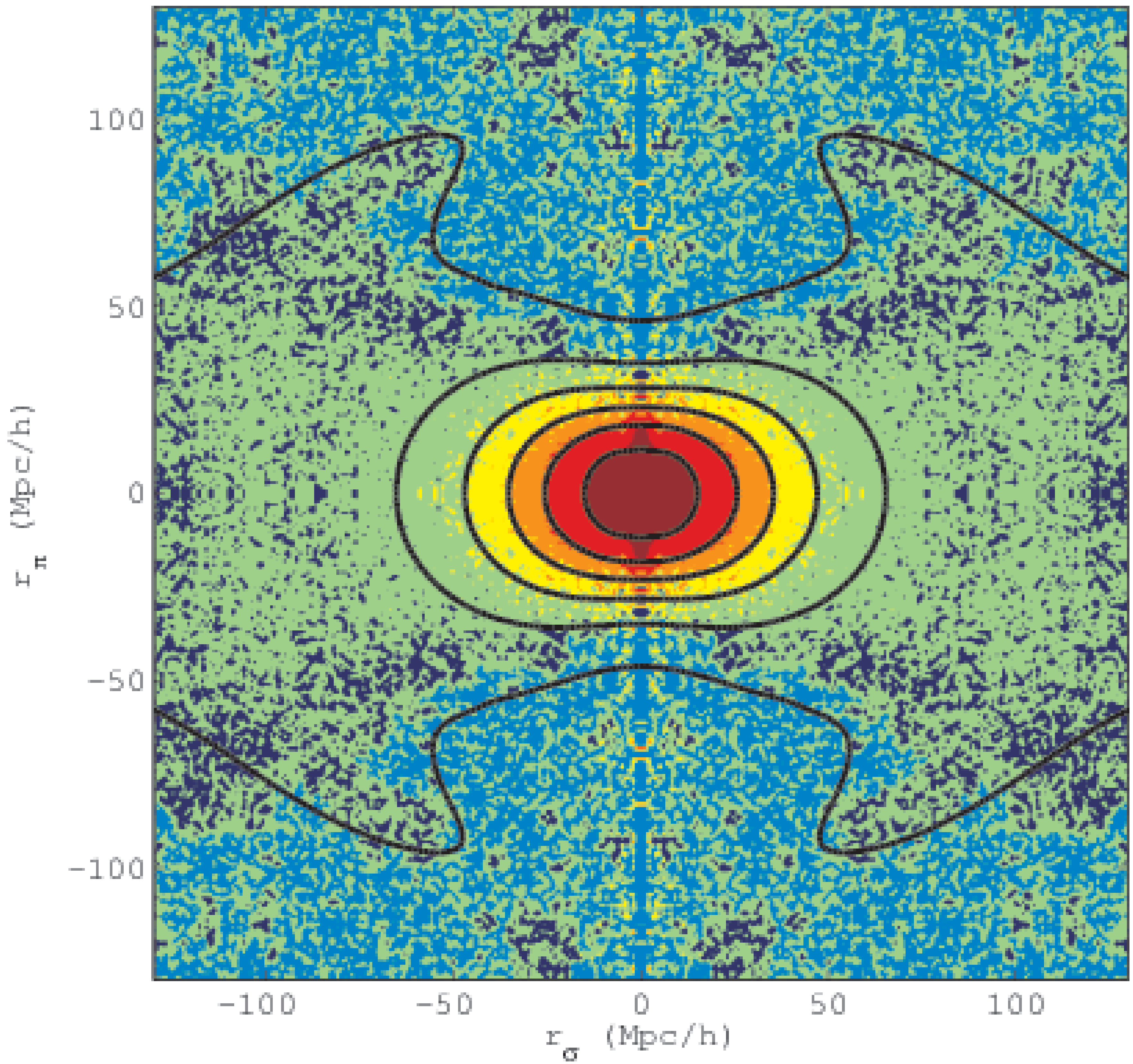
Cluster data



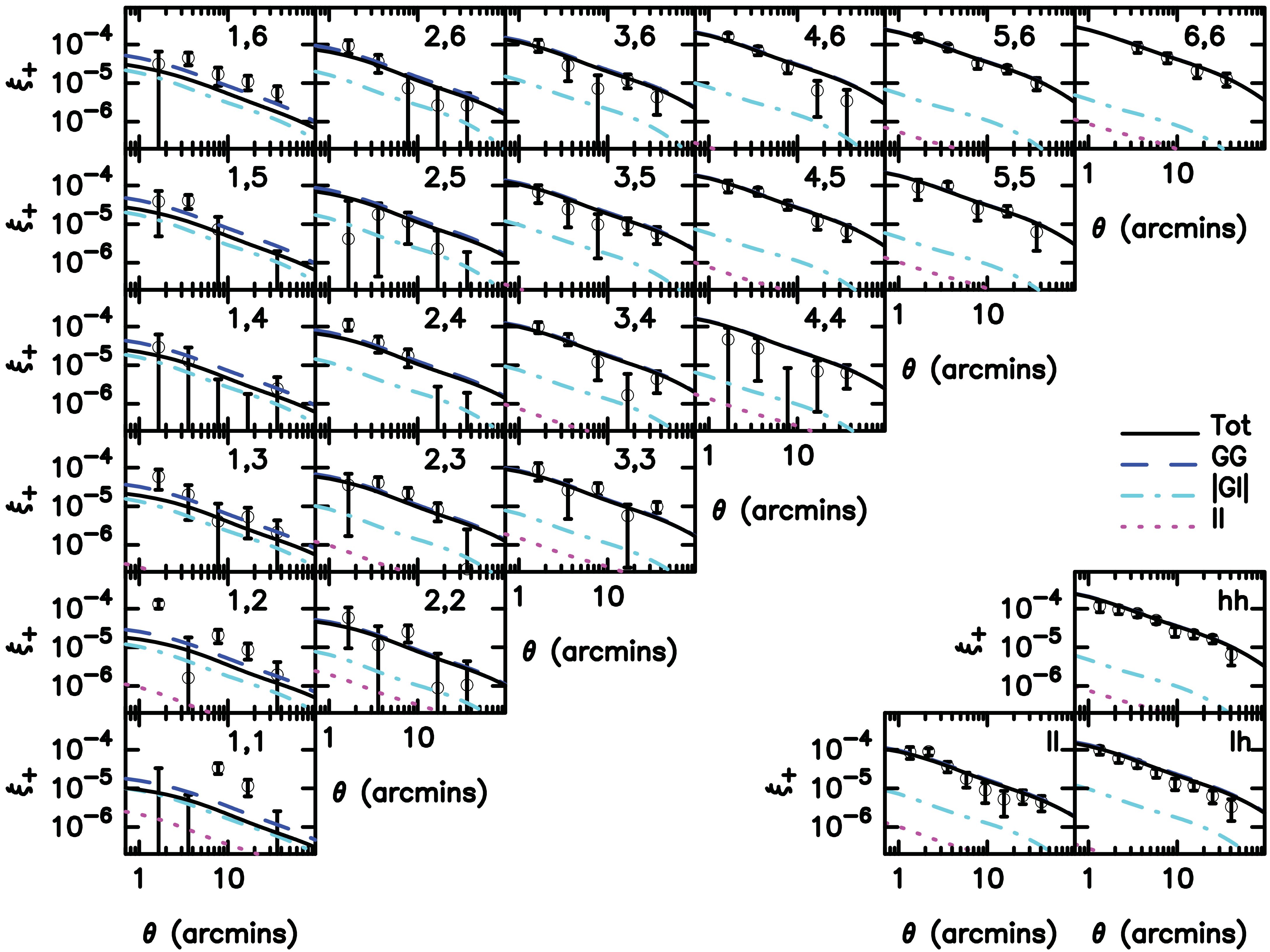
Richness bin	No. of Clusters	$\langle M_{200b} \rangle [10^{14} M_\odot]$
12-17	5651	1.298
18-25	2269	1.983
26-40	1021	3.846
41-70	353	5.475
71+	55	13.03

TABLE IX. Mean mass (and their number) of clusters with a richness within the given bin.

RSD (BOSS paper)



Measured 2-pt correlation func from CFHTLens

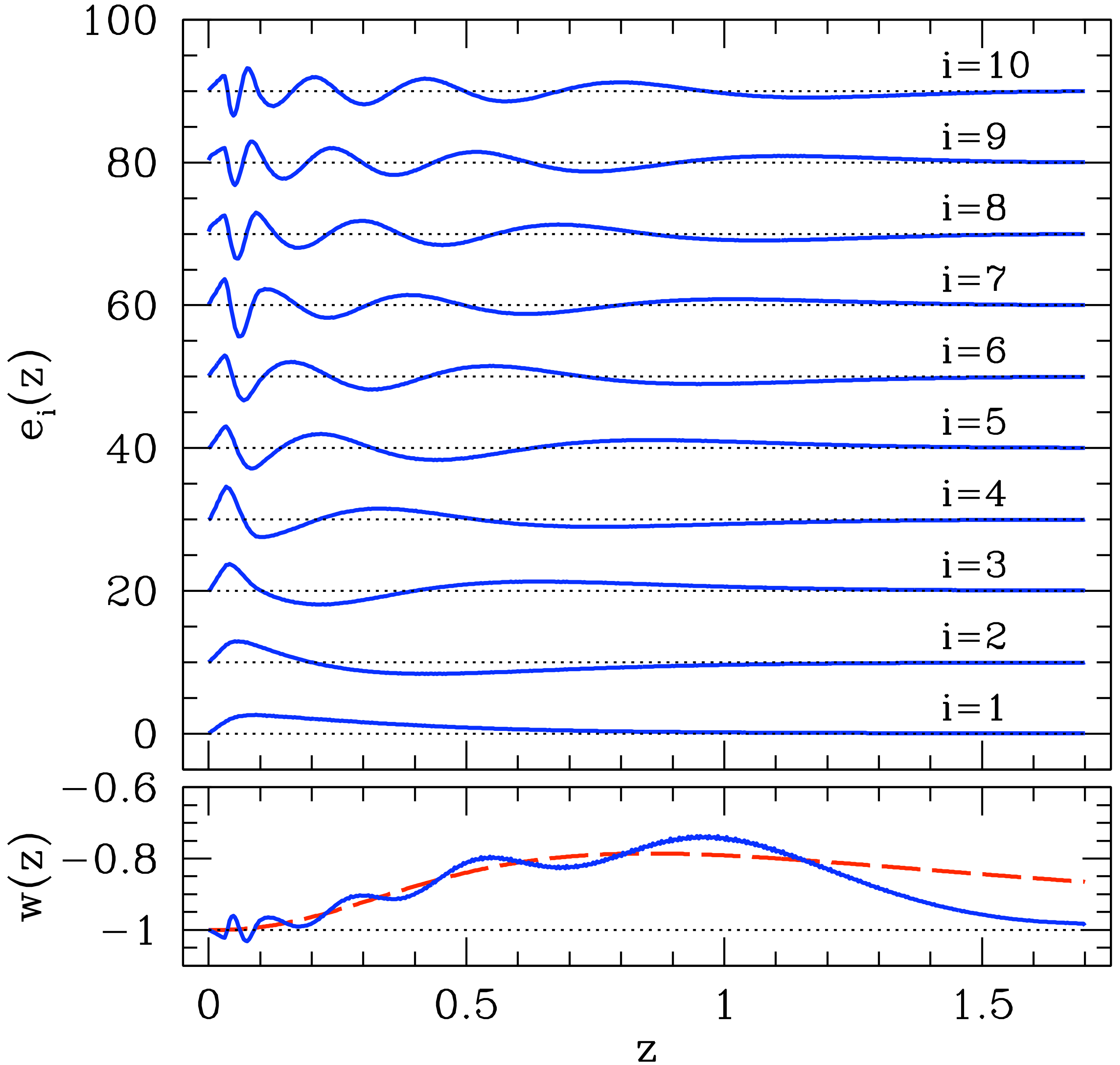


Parameter	Unsplit, $w=-1$	Unsplit, w free	Split, $w=-1$	Split, w free
Ω_M $\Omega_M^{\rm geom}$	0.303 ± 0.008	0.299 ± 0.010	0.302 ± 0.008	0.283 ± 0.011
Ω_M $\Omega_M^{\rm grow}$			0.321 ± 0.017	0.311 ± 0.017
$\Omega_M h^2$	0.140 ± 0.001	0.141 ± 0.002	0.140 ± 0.001	0.142 ± 0.002
$\Omega_b h^2$	0.0221 ± 0.0002	0.0220 ± 0.0003	0.0221 ± 0.0002	0.0221 ± 0.0003
w $w^{\rm geom}$	—	-1.03 ± 0.05	—	-1.13 ± 0.06
w $w^{\rm grow}$			—	-0.77 ± 0.08
$10^9 A$	1.95 ± 0.09	1.91 ± 0.10	1.96 ± 0.09	2.17 ± 0.13
n_s	0.961 ± 0.005	0.959 ± 0.006	0.962 ± 0.005	0.961 ± 0.006
σ_8	0.786 ± 0.015	0.788 ± 0.016	0.782 ± 0.016	0.771 ± 0.017
h	0.680 ± 0.006	0.687 ± 0.012	0.661 ± 0.017	0.677 ± 0.018
α_s	1.44 ± 0.11	1.44 ± 0.11	1.44 ± 0.11	1.44 ± 0.11
β_c	3.26 ± 0.11	3.26 ± 0.11	3.26 ± 0.11	3.27 ± 0.11
$\ln(N\|M_1)$	2.36 ± 0.06	2.37 ± 0.06	2.29 ± 0.08	2.33 ± 0.08
$\ln(N\|M_2)$	4.15 ± 0.09	4.16 ± 0.09	4.09 ± 0.11	4.15 ± 0.11
σ_{NM}	0.359 ± 0.057	0.357 ± 0.057	0.378 ± 0.059	0.367 ± 0.060
β	1.041 ± 0.050	1.045 ± 0.051	1.018 ± 0.054	1.036 ± 0.055
σ_{MN}	0.462 ± 0.081	0.459 ± 0.082	0.486 ± 0.085	0.464 ± 0.084

Modeling 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

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):

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

$$G = D_1/a$$

Methodology

1. Start with the parameter set:

$$\Omega_{\mathrm{M}}, \Omega_{\mathrm{K}}, H_0, w(z), w_\infty$$ (early DE eq of state)

2. Pre-compute PCs of w(z) based on future data

3. Using either the current data
   or future (SNAP+Planck) data...

4. ...employ the likelihood machine...

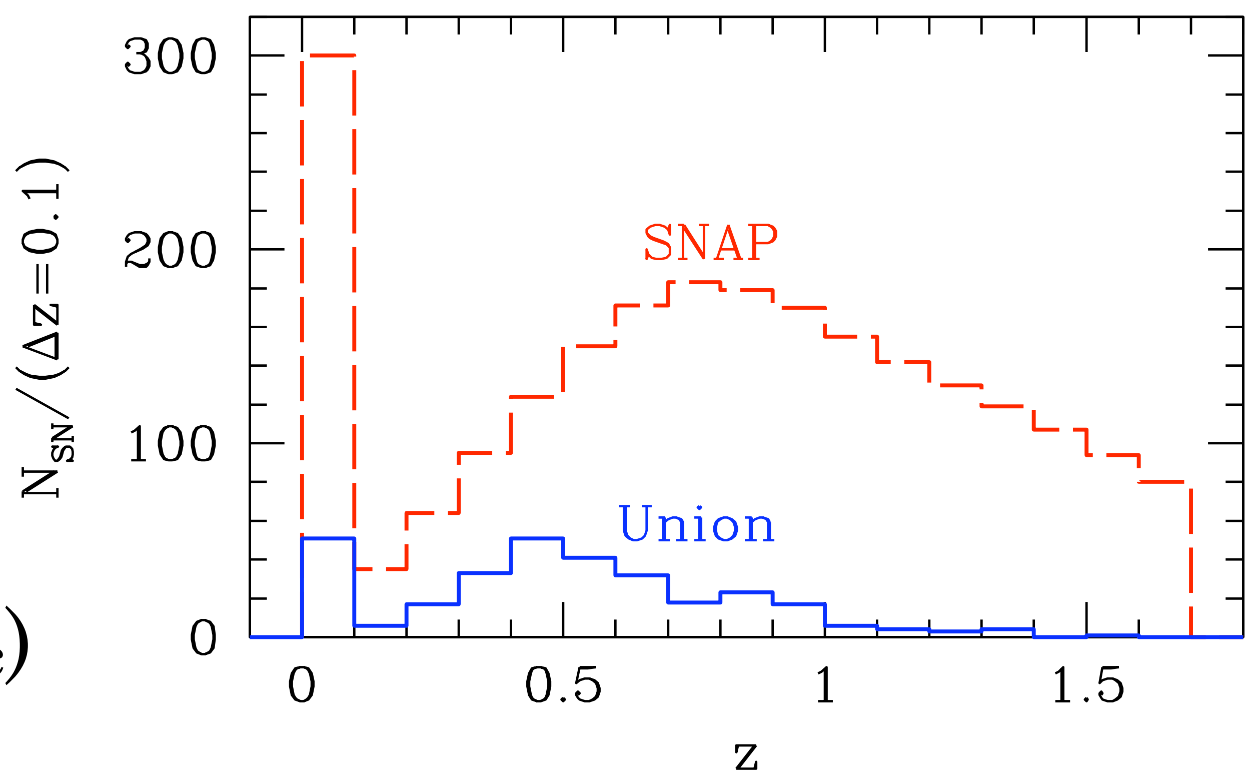
Markov Chain Monte Carlo likelihood calculation,
between ~2 and ~15 parameters constrained

5. .... and compute predictions for D(z), G(z), H(z) etc

Predictions from Future Data

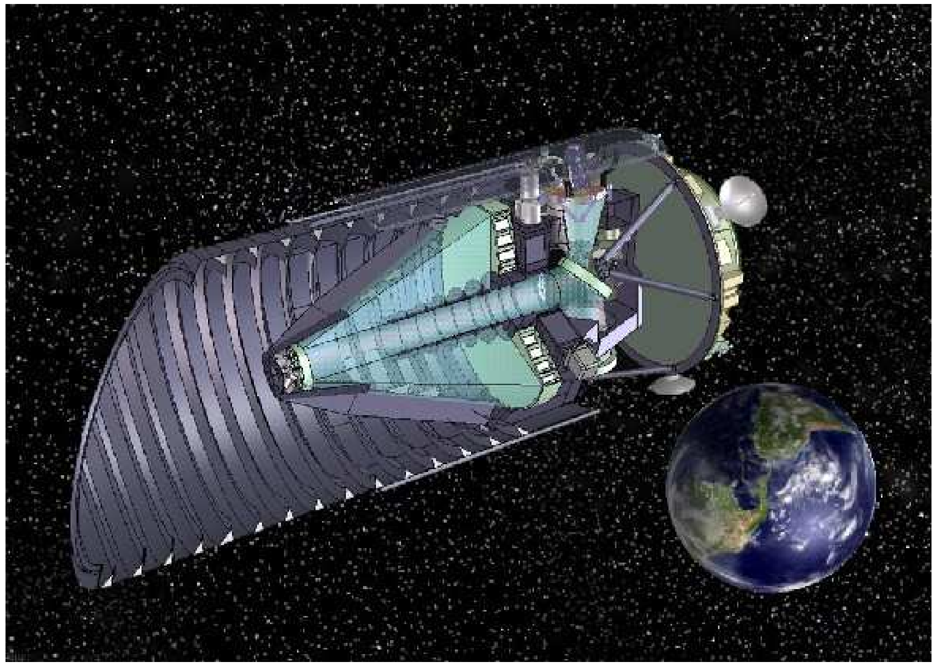
Assumed "data":

1. SNAP 2000 SNe, 0.1<z<1.7 (plus 300 low-z SNe); converted into distances
2. Planck info on $\Omega_m h^2$ and $D_A(z_{rec})$

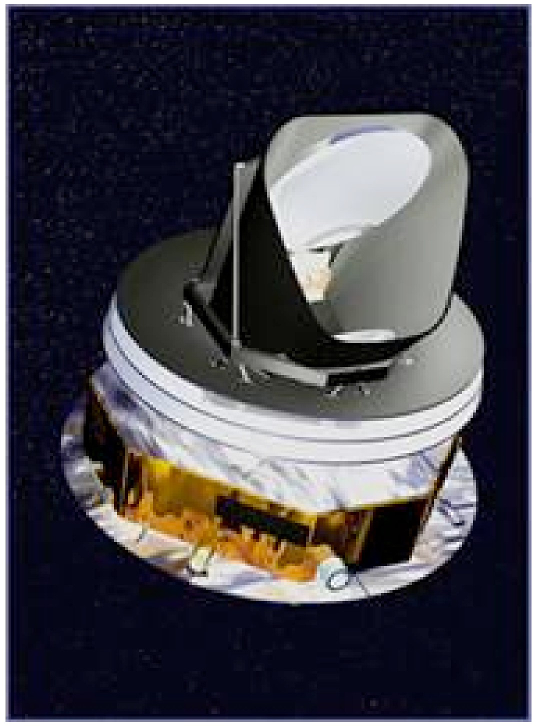


$$\sigma_\alpha^2 = \left(\frac{0.1}{\Delta z_{\rm sub}}\right)\left[\frac{0.15^2}{N_\alpha} + 0.02^2\left(\frac{1+z}{2.7}\right)^2\right]$$

Dead

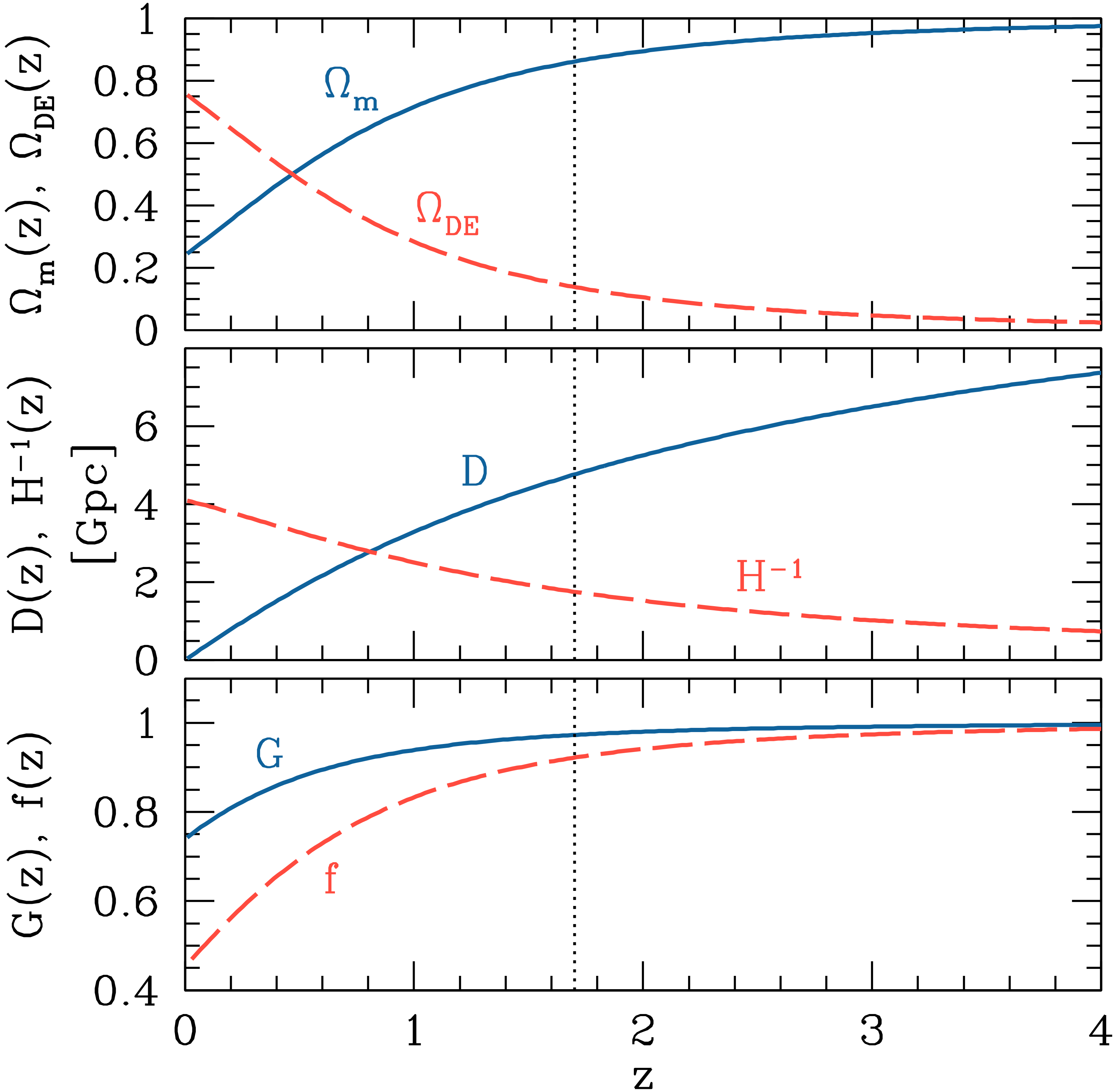


Alive



Predictions below shown around: fiducial model

Cosmological "observable" functions



Matter and DE energy density (relative to critical)

D = distance
H = expansion rate

G = growth of density fluctuations (ignore f)

Modeling of Early DE

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

de Putter & Linder 2008

Modeling of modified Gravity

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

Linder 2005

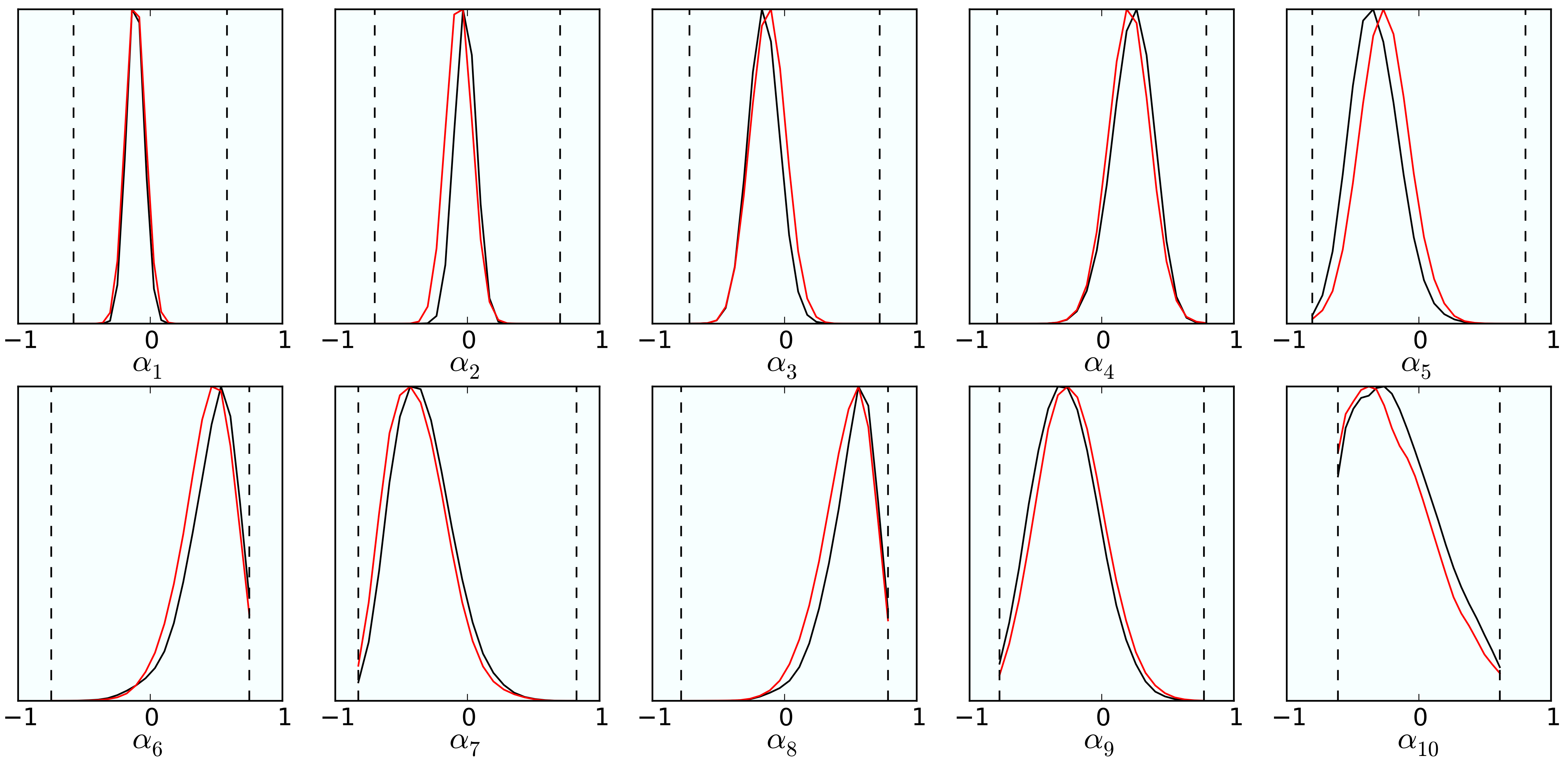
In *principal*, constraints are good...

(components....)

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

α_i = PC amplitude

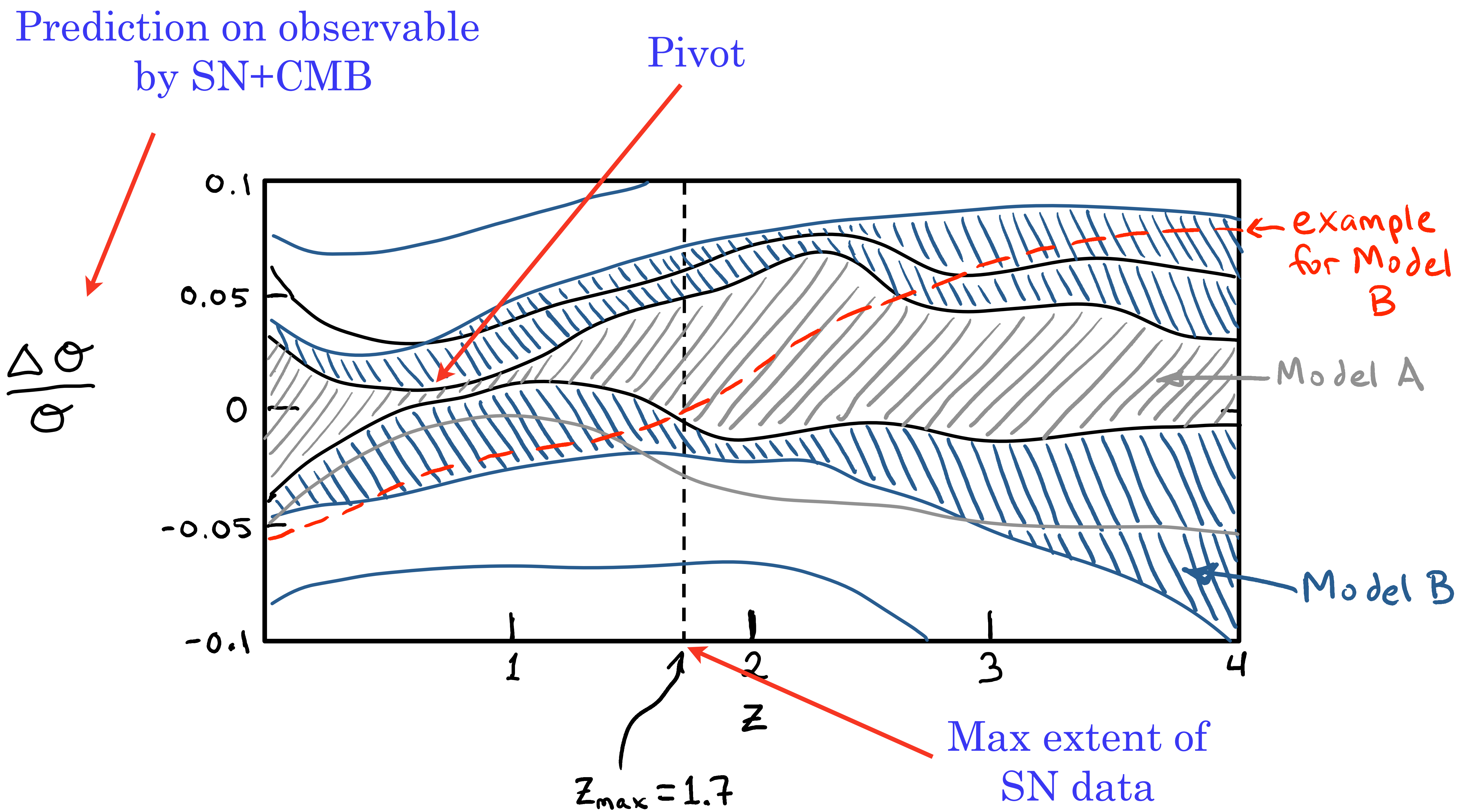
$e_i(z)$ = PC shape



Ruiz, Shafer, Huterer & Conley 2012

Red = with SN systematics

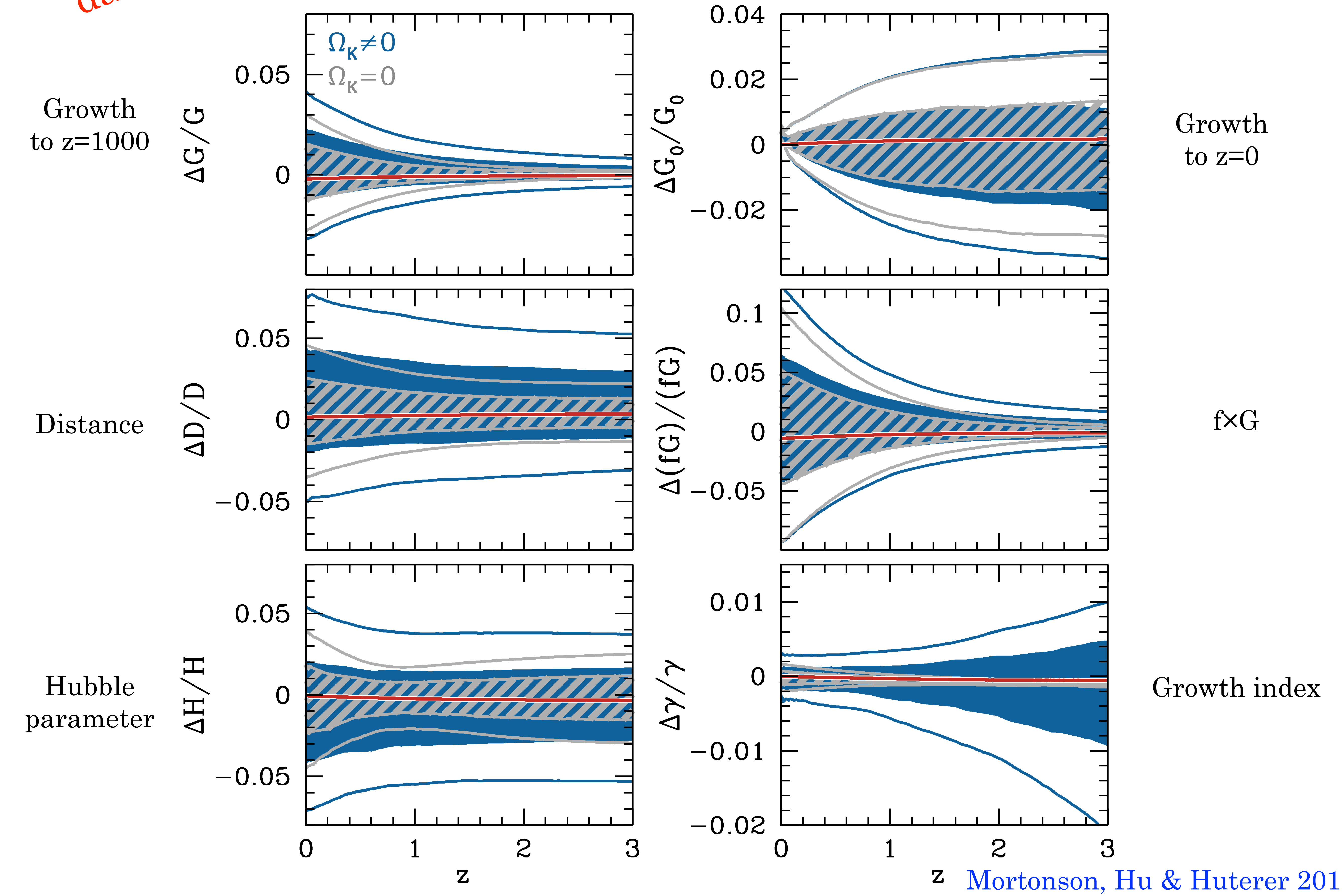
Structure of graphs to follow



Sketch by M. Mortonson

LCDM predictions - flat or curved

Current data



Mortonson, Hu & Huterer 2010

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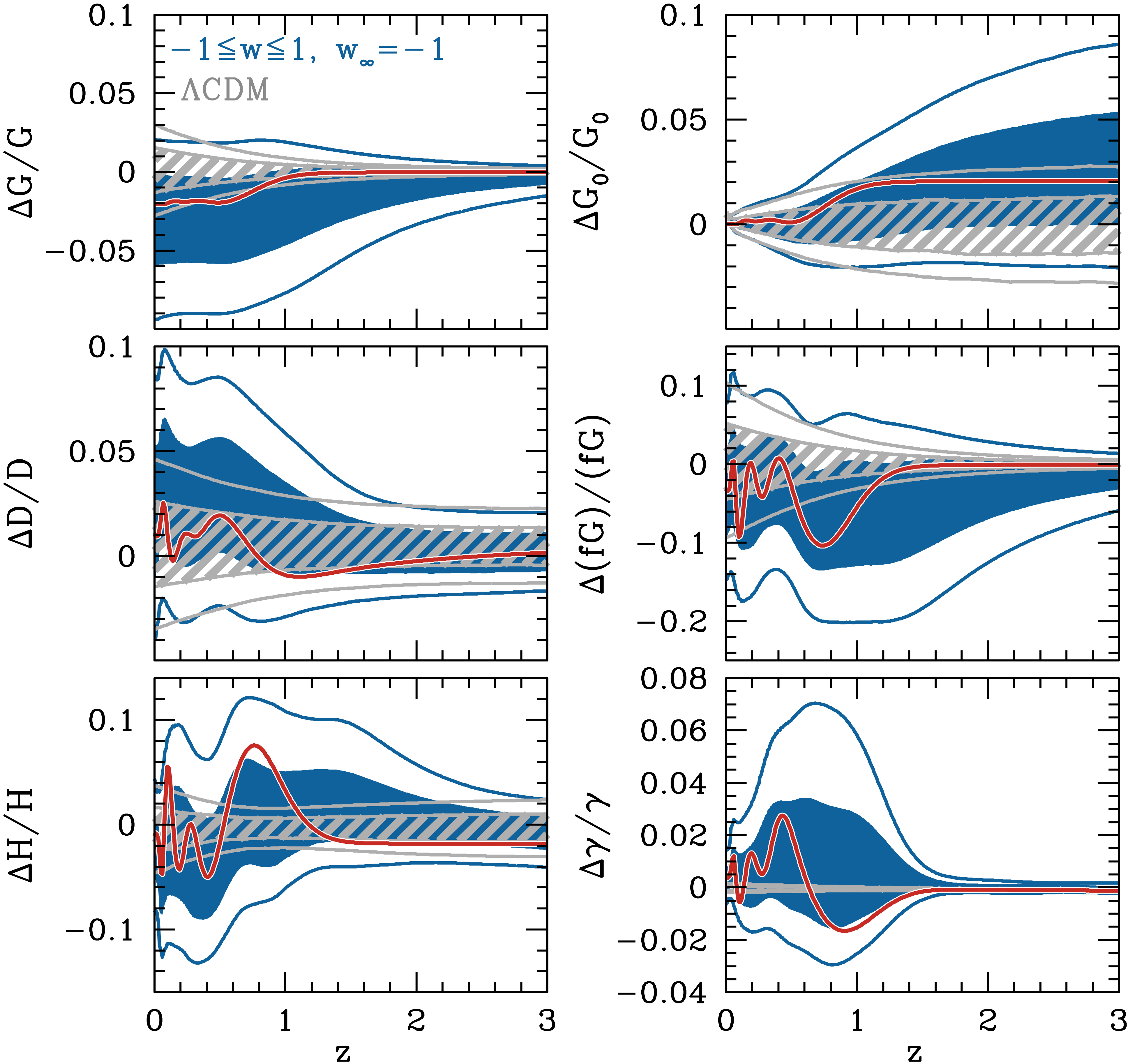

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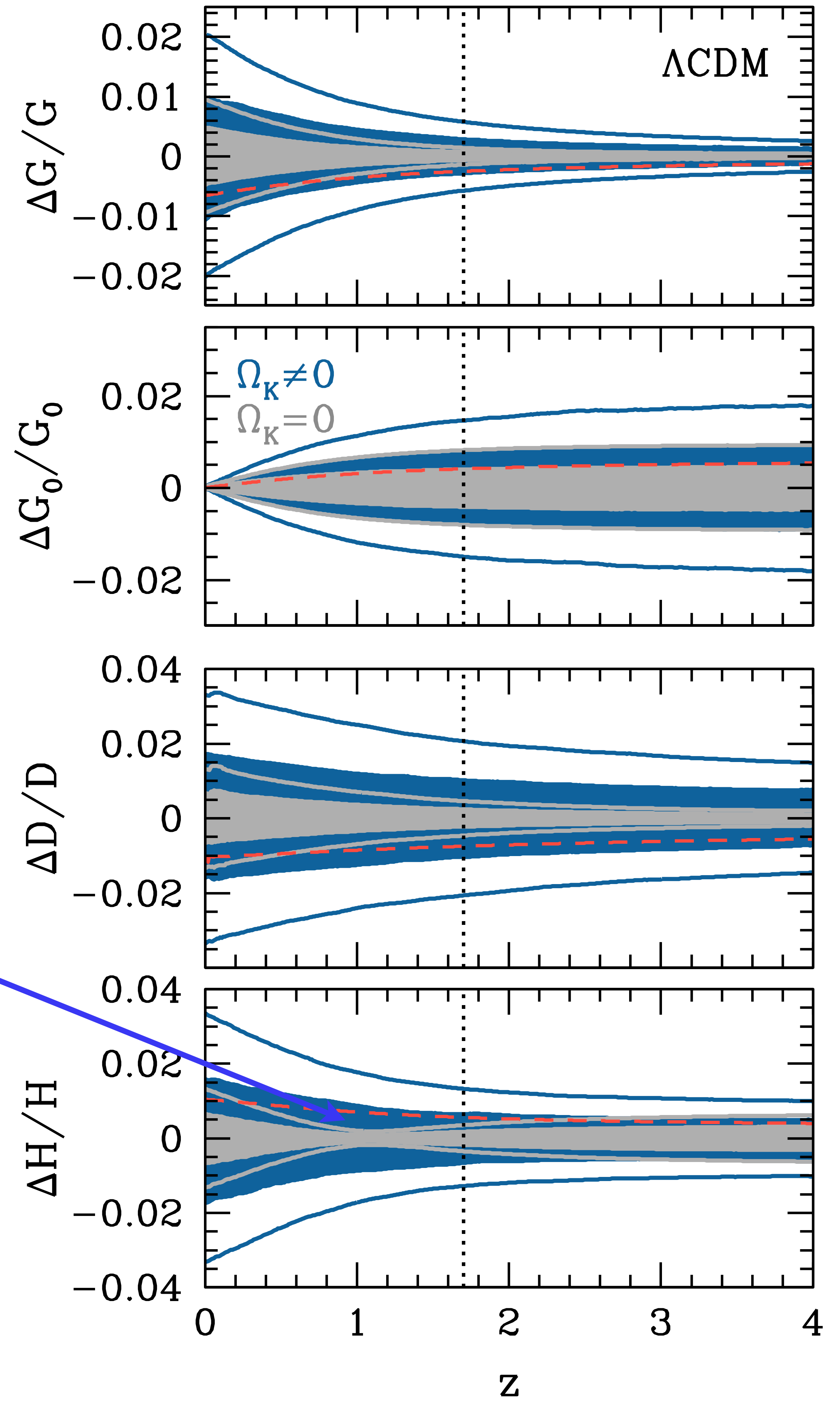

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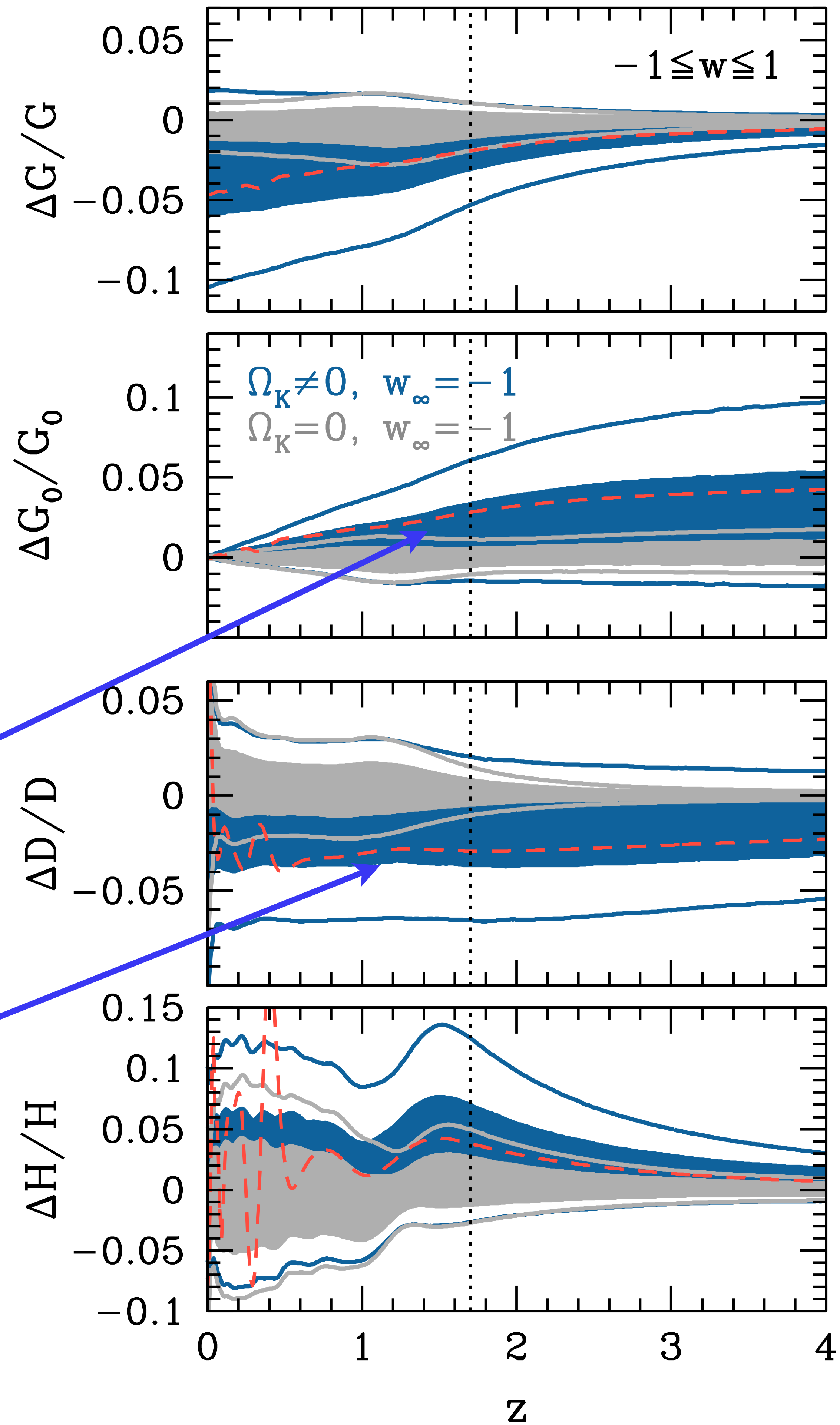

Smoking Gun of curvature:

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2. Negative const offset in D