Dark Energy, Modified Gravity
and
The Accelerating Universe

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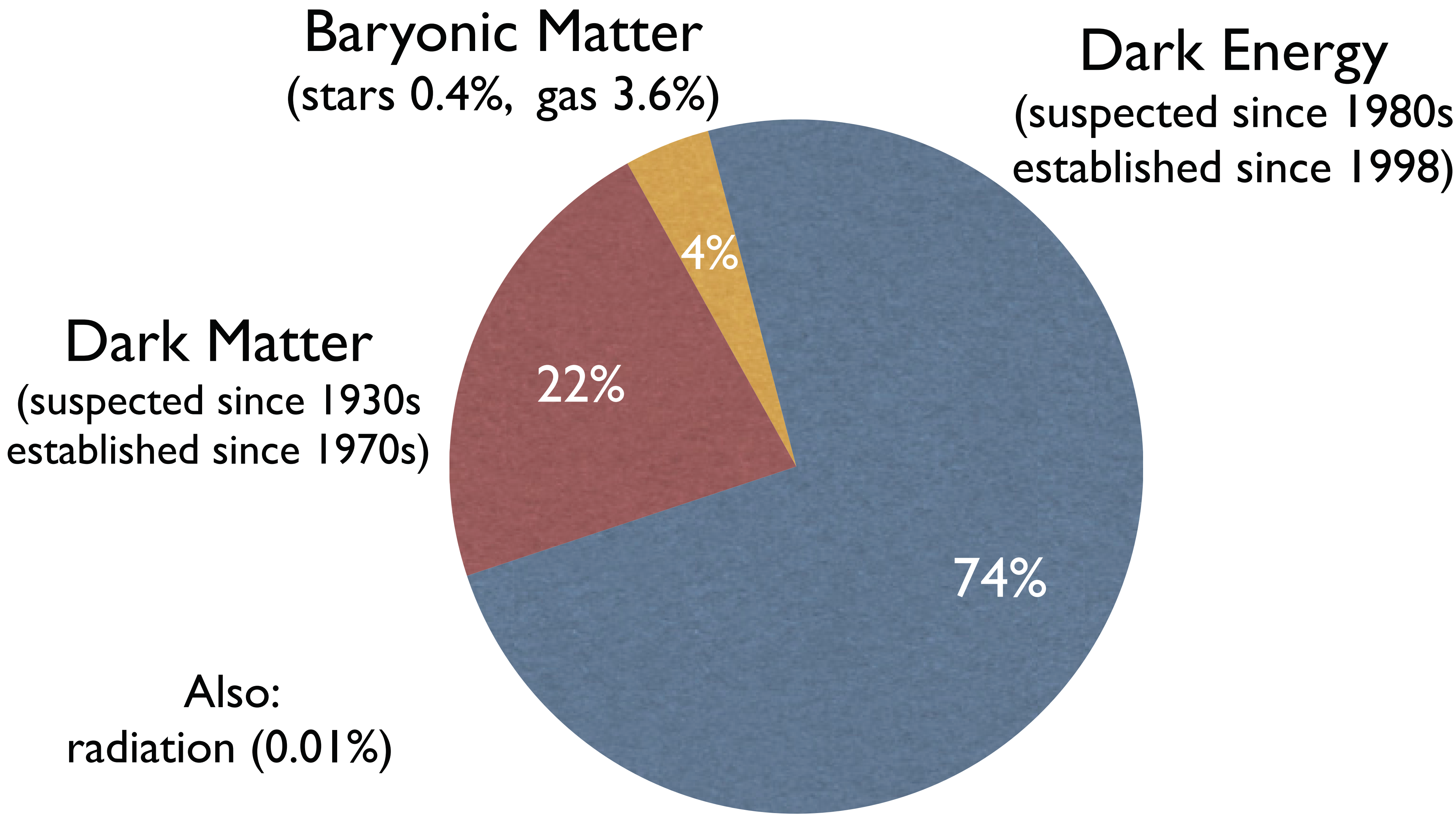
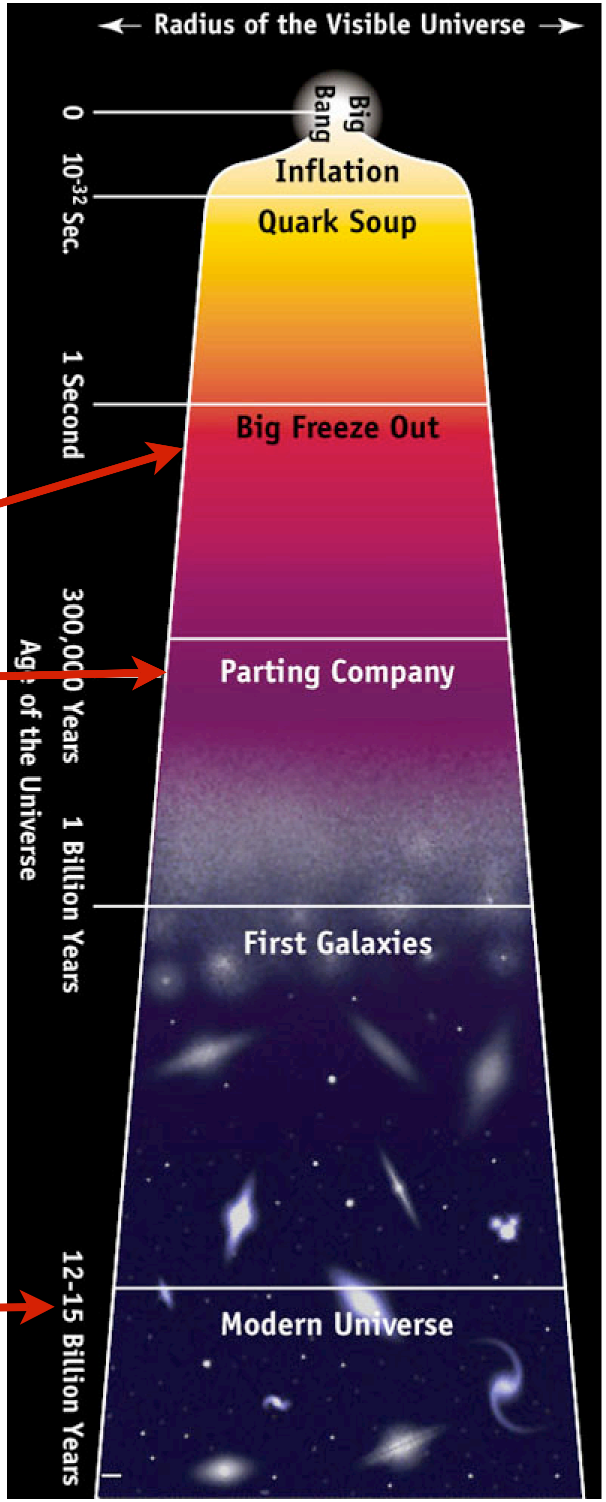
Makeup of universe today



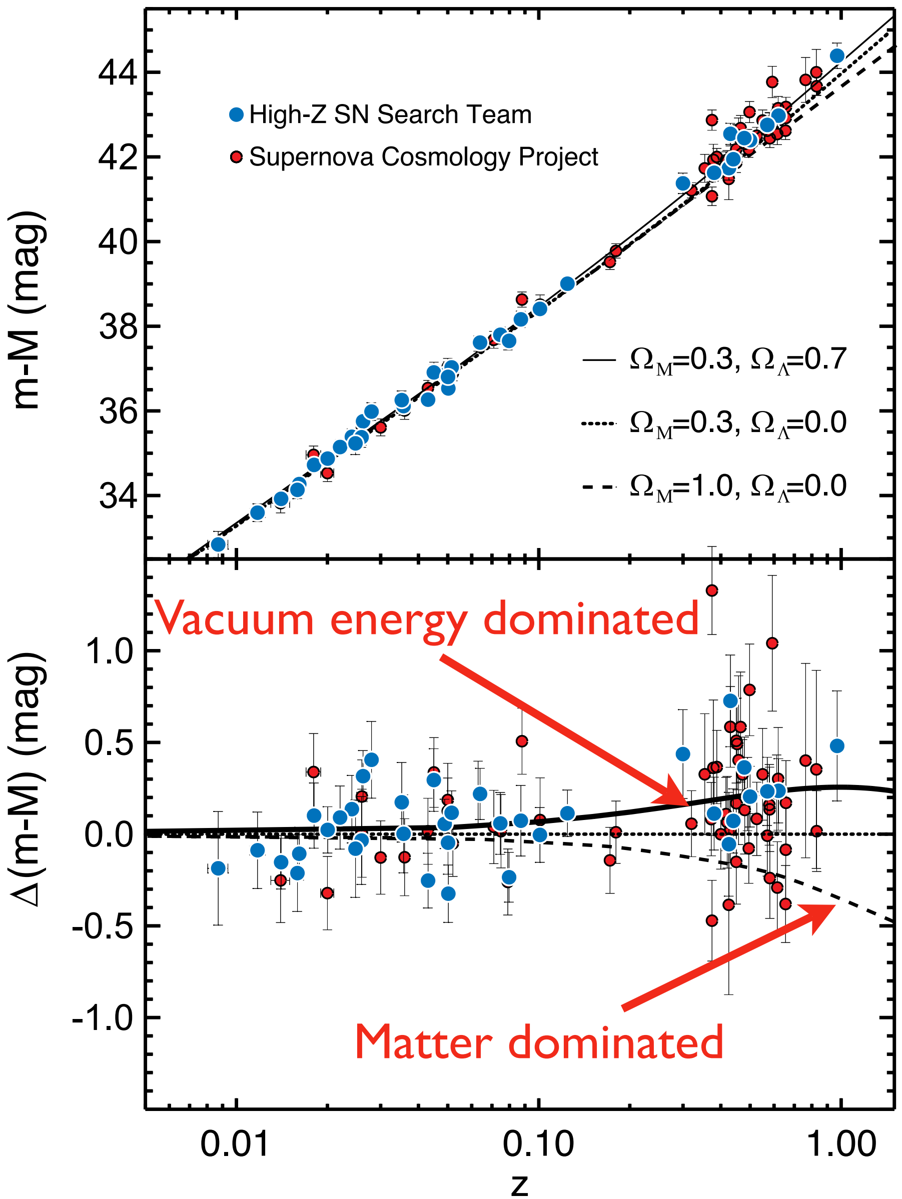
Some of the early history of the Universe is actually understood better!

Physics quite well understood

95% of contents only phenomenologically described



DE status ~8 years after discovery



Measurements much better, LCDM still a good fit

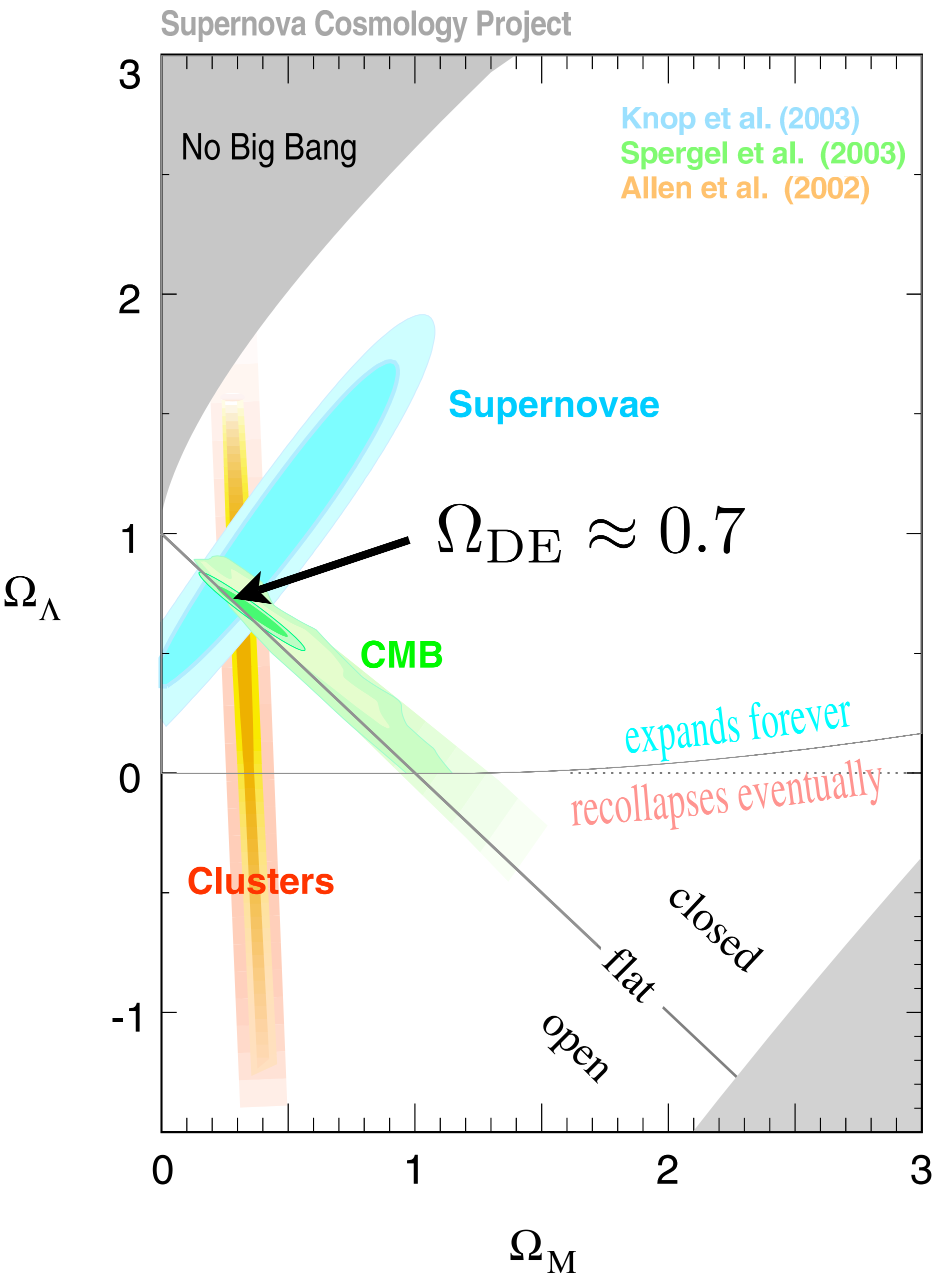
Strong indirect (non-SNa Ia) evidence for DE from CMB+LSS

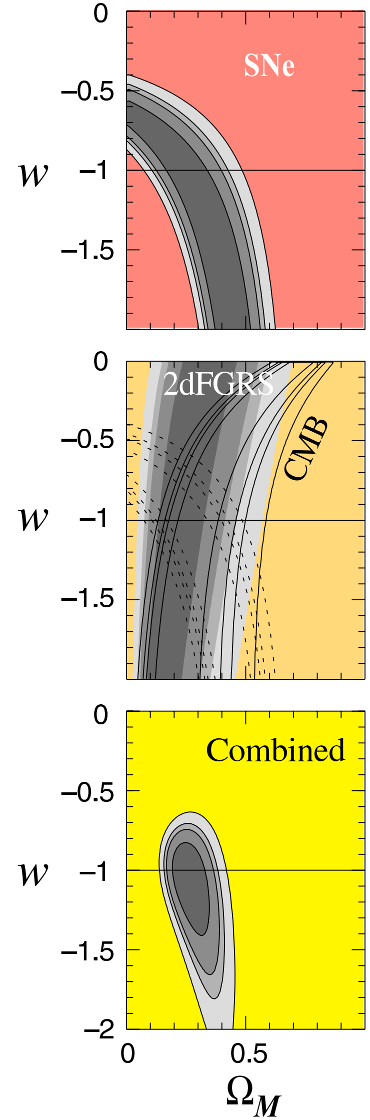
Physical mechanism responsible completely unknown

A lot of work on modified gravity proposals and observational signatures

Riess et al 1998; Perlmutter et al 1999

Current constraints





Supernova Cosmology Project
Knop *et al.* (2003)

Assuming constant w

With limits from;
2dFGRS (Hawkins et al. 2002)
and CMB (Bennet et al. 2003,
Spergel et al. 2003)

$w = -1.05\ ^{+0.15}_{-0.20}$ (statistical)
± 0.09 (systematic)

What if gravity deviates from GR?

For example:

$$H^2 - F(H) = \frac{8\pi G}{3}\rho, \qquad \text{or} \qquad H^2 = \frac{8\pi G}{3}\left(\rho + \frac{3F(H)}{8\pi G}\right)$$

Modified gravity

Dark energy

Modified gravity proposals

- Introduce modifications to GR (typically near horizon scale) to explain the observed acceleration of the universe
- Make sure Solar System tests are passed (can be hard)
- Constrain the MG theory using the cosmological data
- Try to distinguish MG vs. “standard” DE (can be hard!)

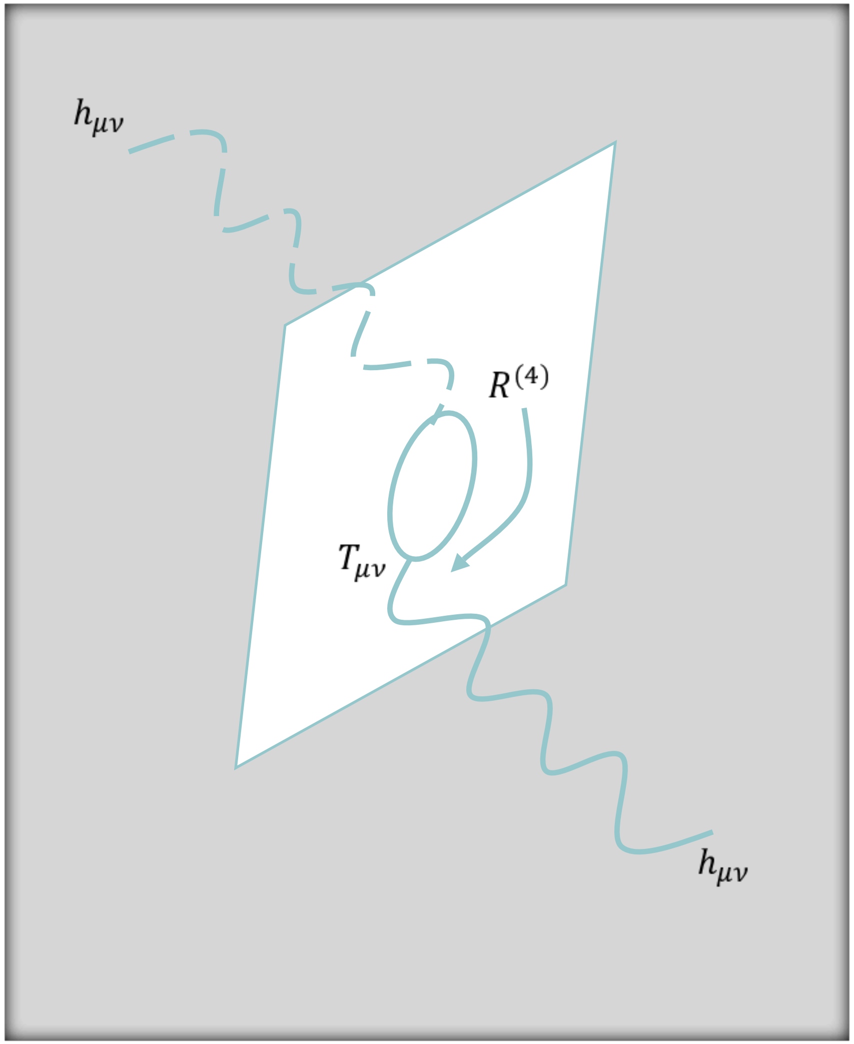
Example: f(R) gravity

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g}\,[R + f(R)]$$

- Einstein equations are now 4th order
- Two classes
  - $f_{RR}<0$ (never Matter Dominated, long range forces)
  - $f_{RR}>0$ (MD in the past, can evade Solar system tests)

Carroll, Duvvuri, Trodden, Turner 2005; Mena, Santiago & Weller 2006; Navarro & van Acoleyen 2006; Song, Hu & Sawicki 2006; many others....

Example: DGP braneworld theory



Credit: Iggy Sawicki

- 1 extra dimension ("bulk") in which only gravity propagates
- matter lives on the "brane"
- weakening of gravity at large distances = appearance of DE

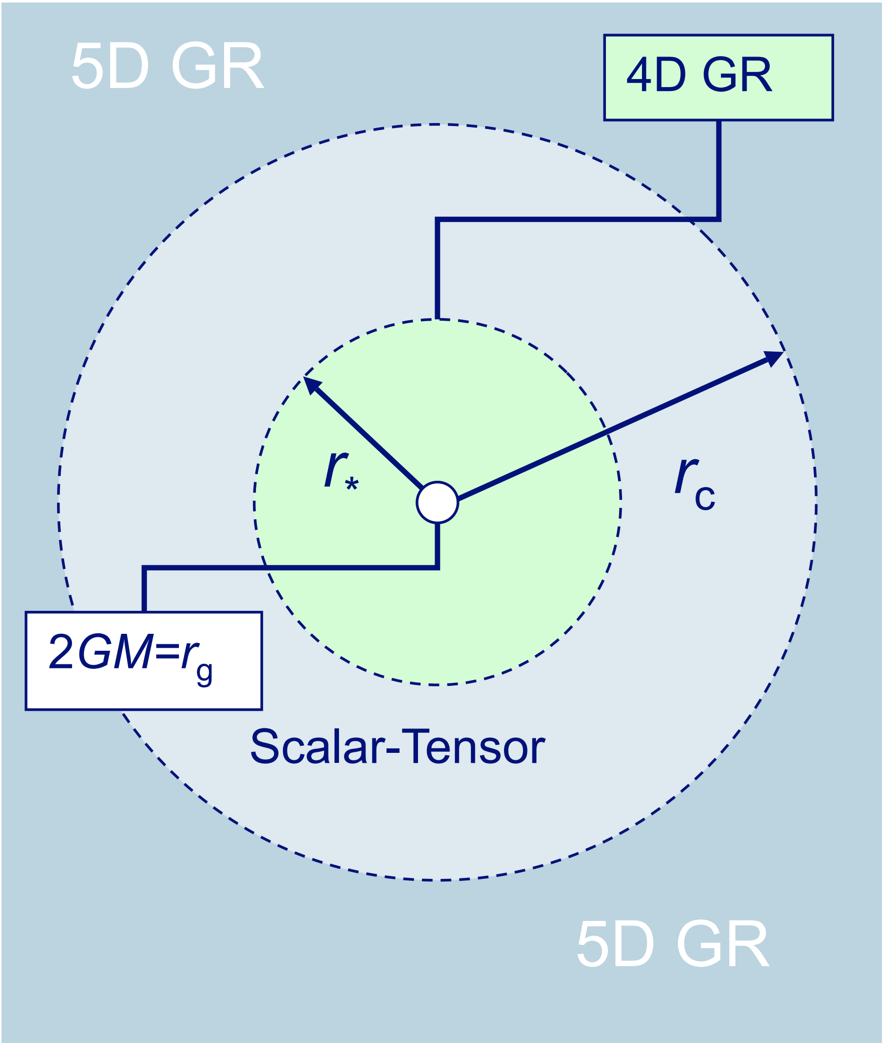
Dvali, Gabadadze & Porrati 2000; Deffayet 2001

The structure of DGP

$$H^2 - \frac{H}{r_c} = \frac{8\pi G}{3}\rho$$

r_c is a free parameter (to be consistent with observation, $r_c \sim 1/H_0$)

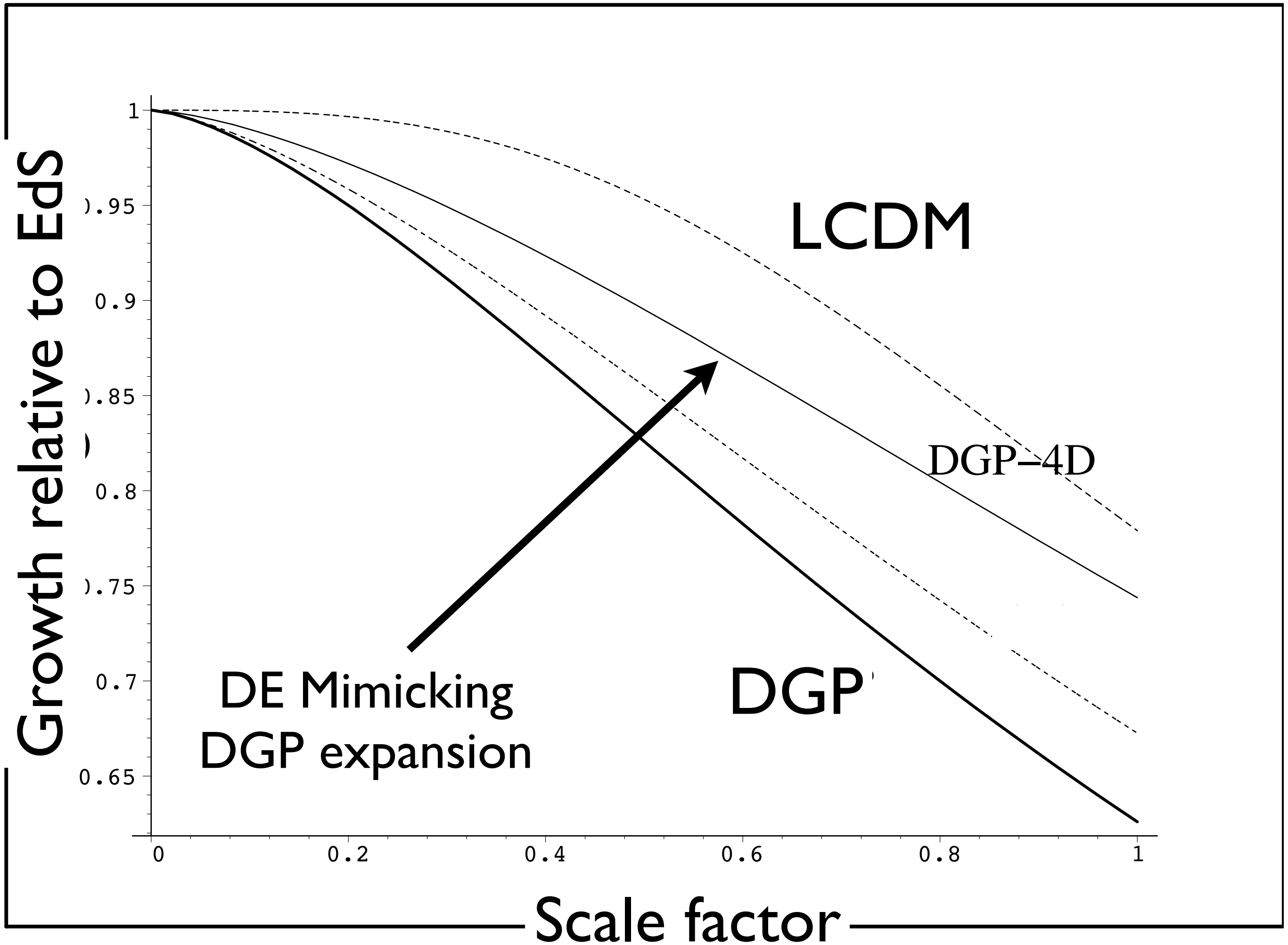
New scale $r_* = \left(r_g r_c^2\right)^{1/3}$



Credit: Iggy Sawicki

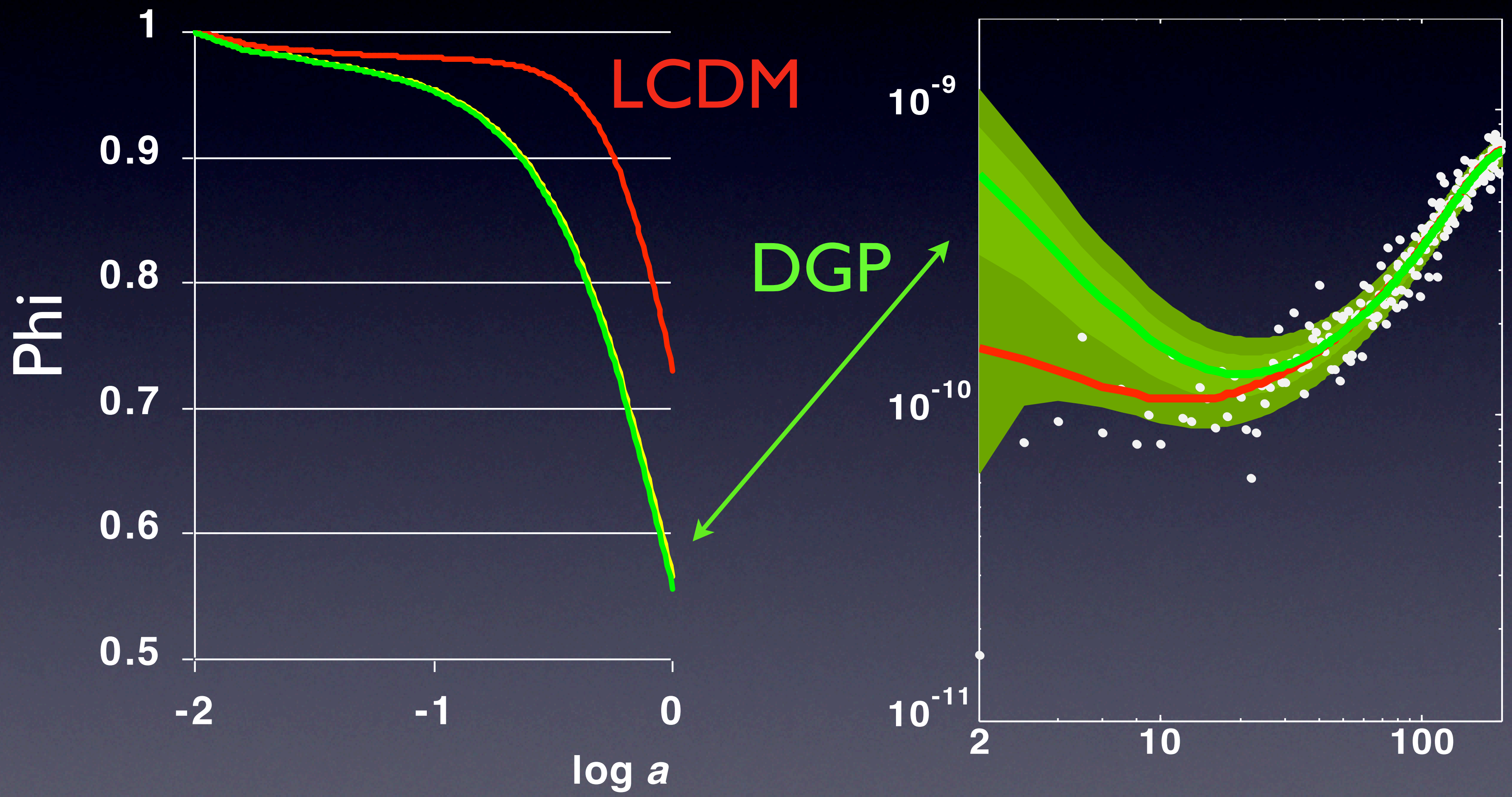
Dvali, Gabadadze & Porrati 2000; Deffayet 2001

DGP linear growth



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

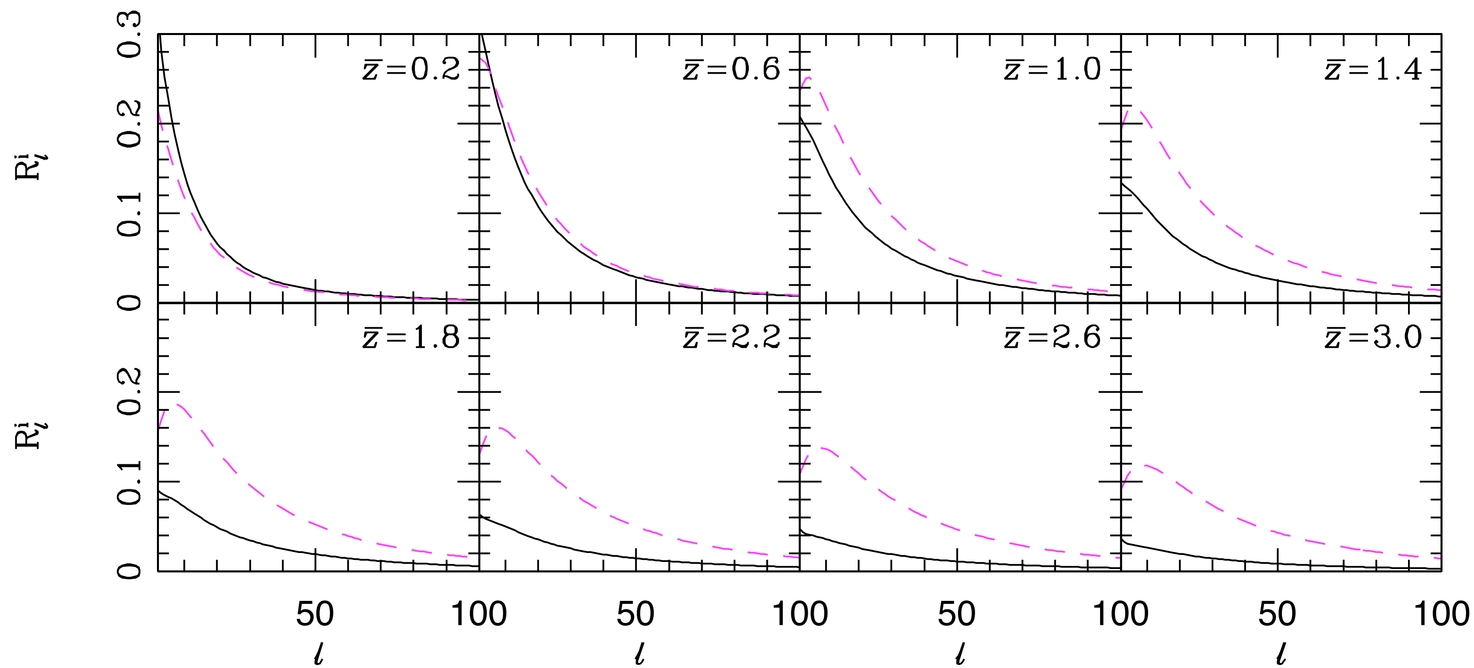
ISW in DGP



Song, Sawicki, & Hu 2007

So DGP is (almost) ruled out

- Disfavored at a few sigma from distances (SNe etc)
- Disfavored at a few more sigma from CMB ISW
- Decisive rule-out will come from ISW cross-correlation at high z:



Song, Sawicki, & Hu 2007

Dark Energy or Modified Gravity?

- A given DE and modified gravity models may both fit the expansion history data very well
- But they will predict different structure formation history, i.e. deviation from $\ddot{\delta} + 2H\dot{\delta} - 4\pi\rho_M\delta = 0$

- In standard GR, H(z) determines distances and growth of structure

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

- So check if this is true by measuring separately

Distances

(a.k.a. kinematic probes)

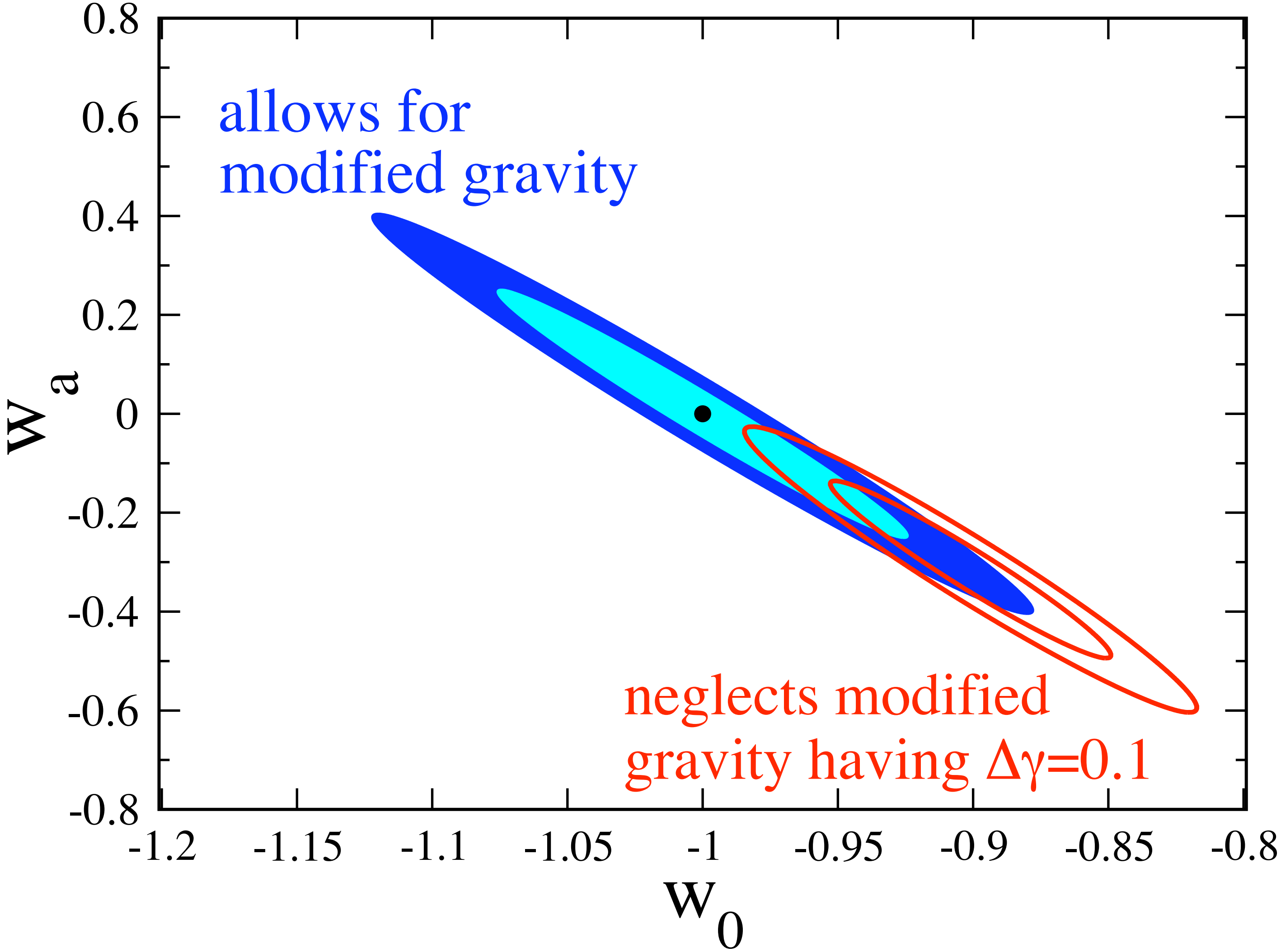
(a.k.a. 0^{th} order cosmology)

Growth

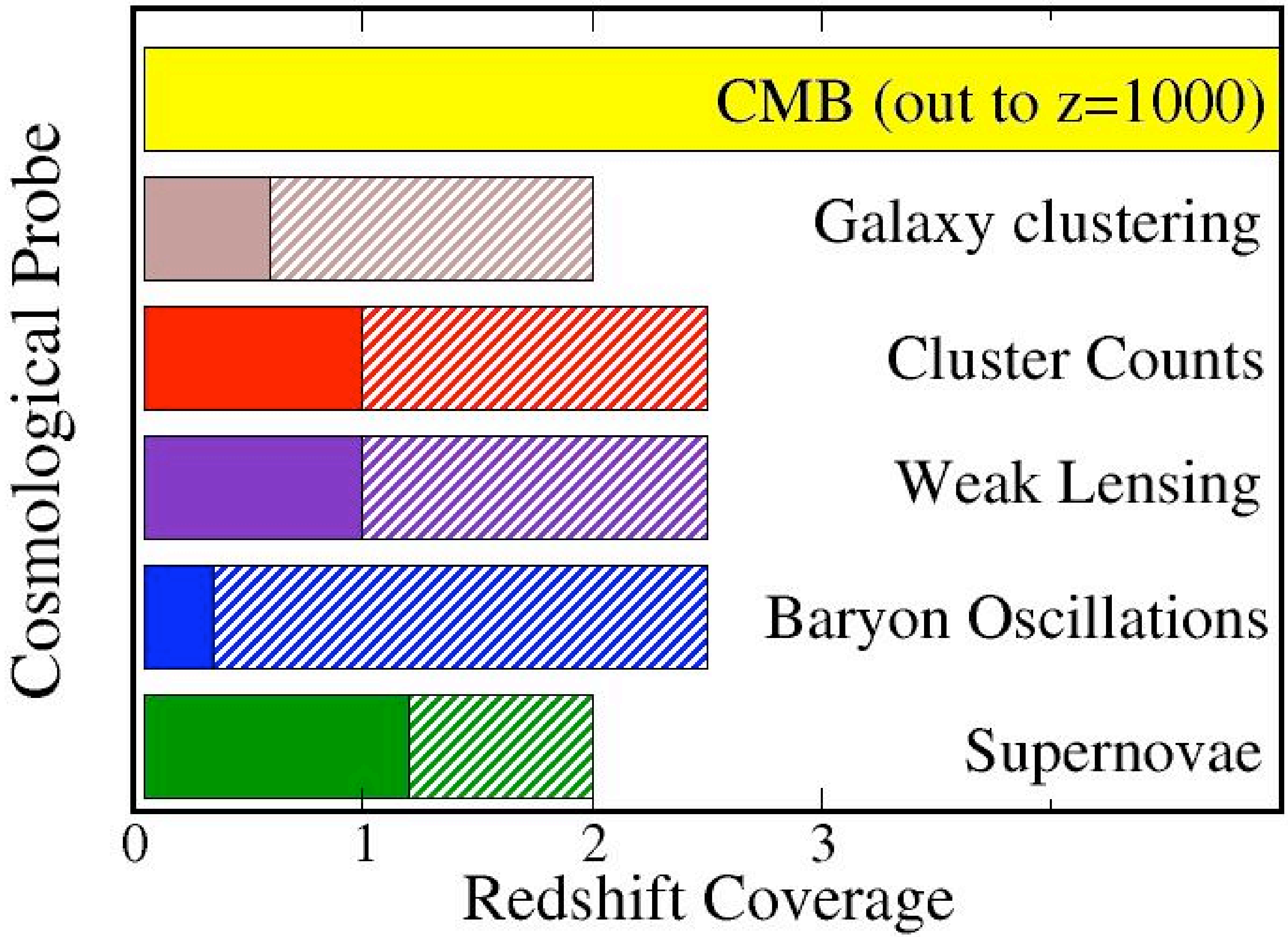
(a.k.a. dynamical probes)

(a.k.a. 1^{st} order cosmology)

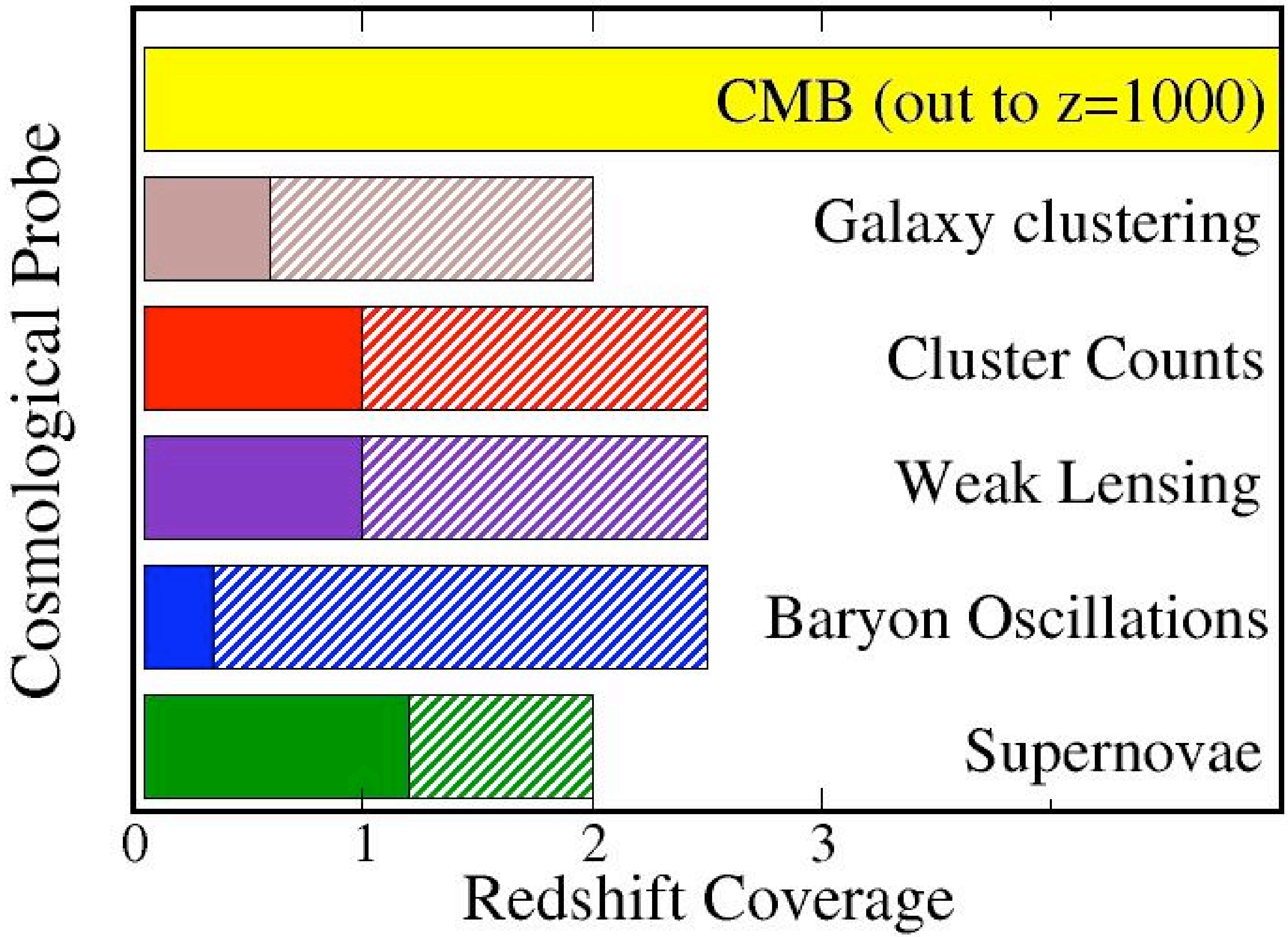
Price of ignorance of MG



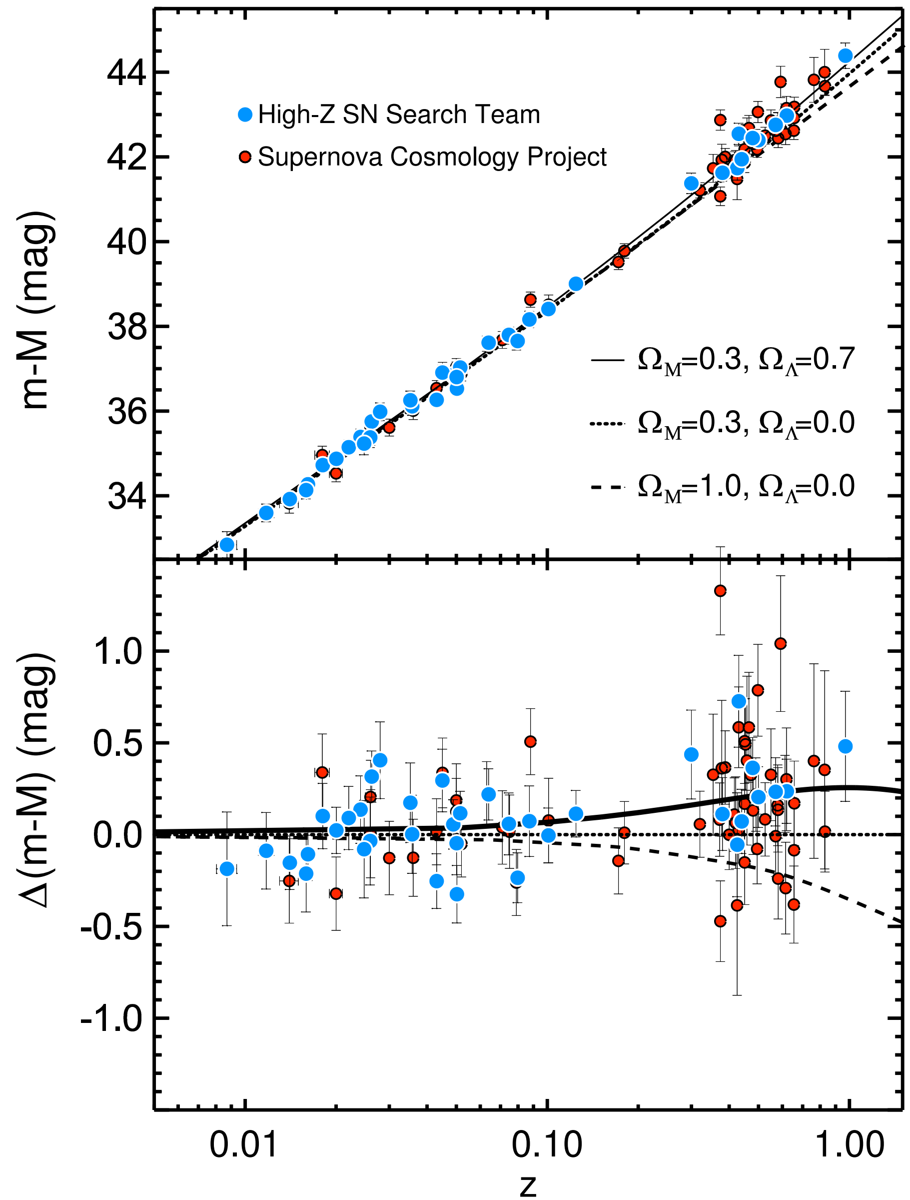
Huterer & Linder, astro-ph/0608681


CMB (out to z=1000)
Galaxy clustering
Cluster Counts
Weak Lensing
Baryon Oscillations
Supernovae
Cosmological Probe
0
1
2
3
Redshift Coverage

Cosmological Probes of Dark Energy (and Modified Gravity)



Kinematic probes: SNe Ia

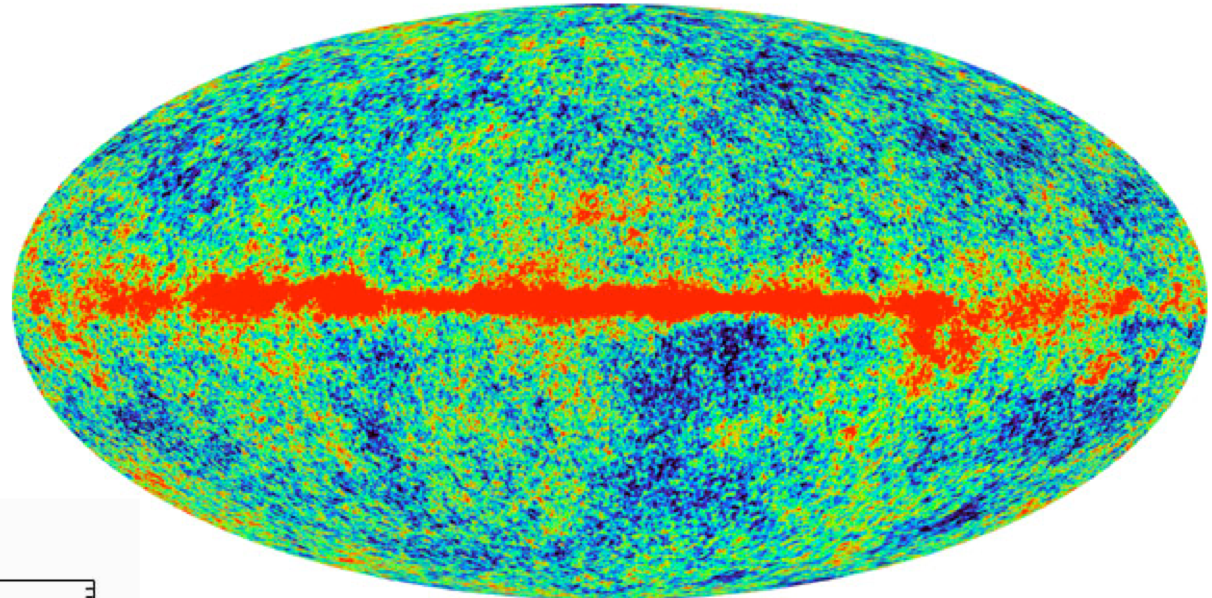


- Get pure (luminosity) distances

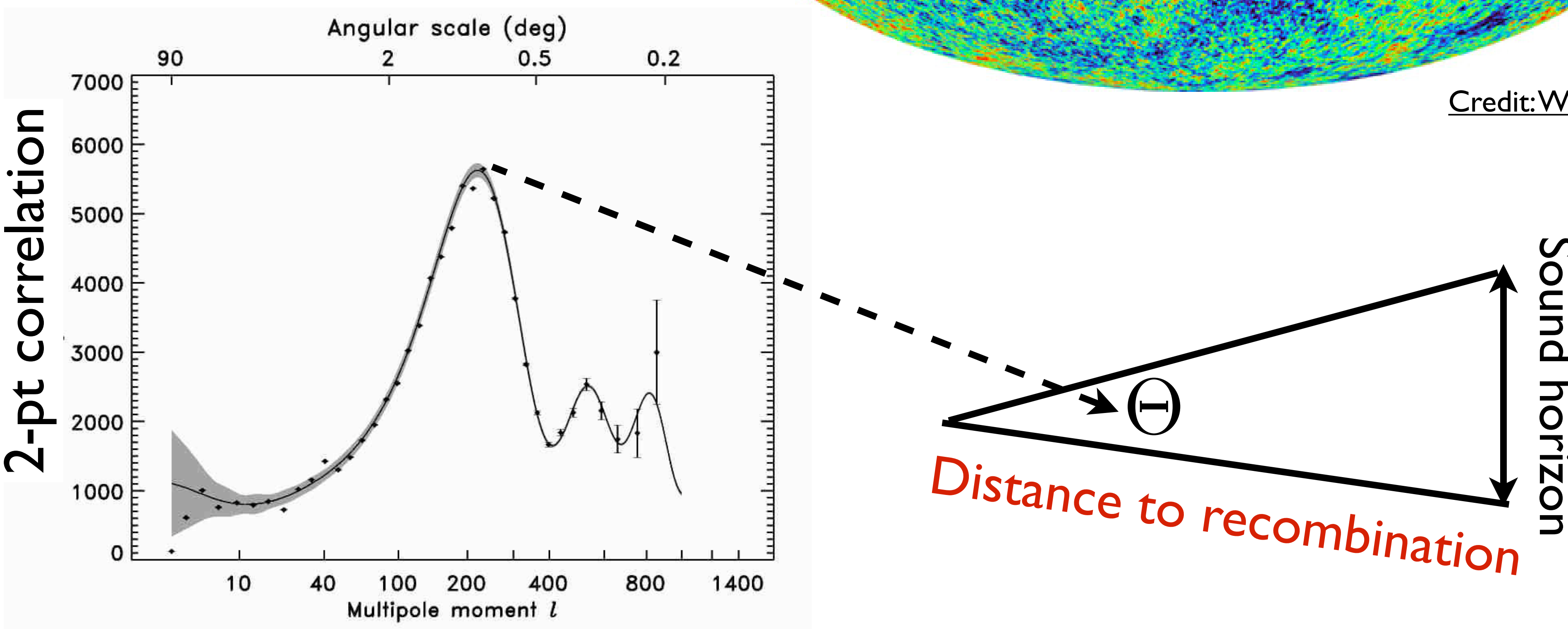
Kinematic probes: CMB and BAO

$$T = 2.726\,\mathrm{K}$$

$$\frac{\delta T}{T} \approx 10^{-5}$$



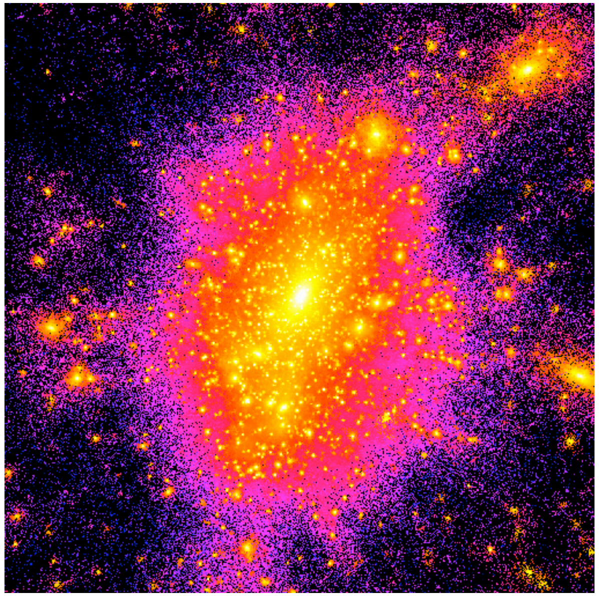
Credit: WMAP team



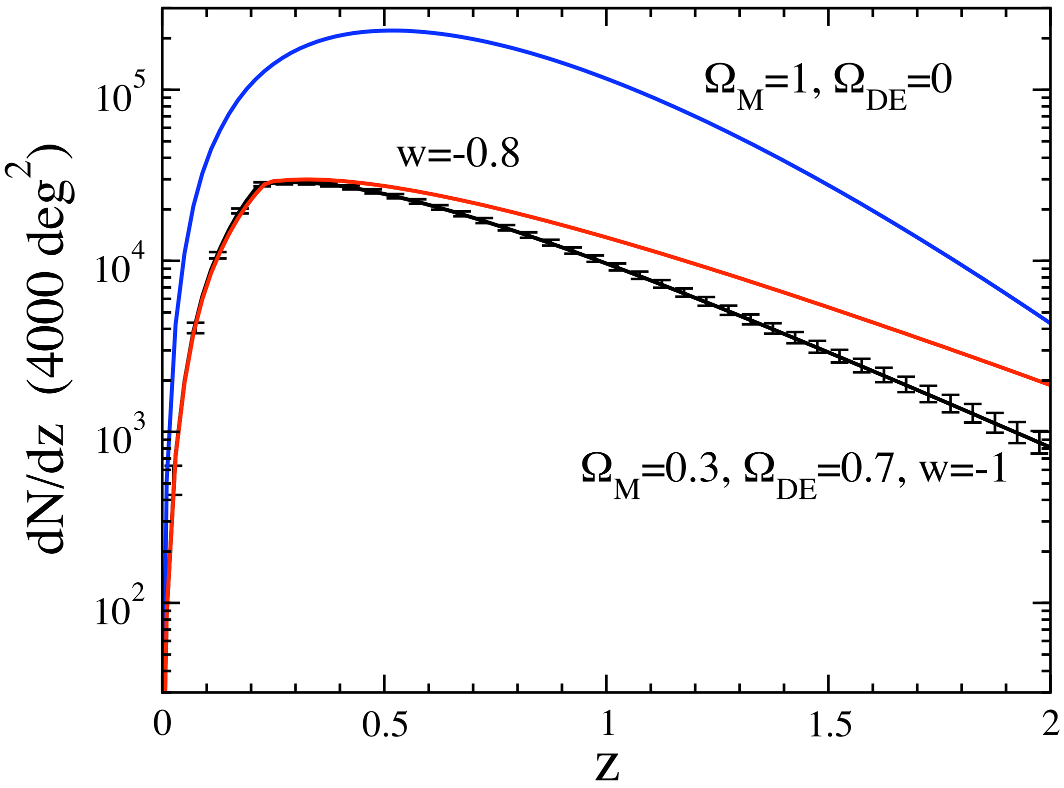
Bennett et al 2003 (WMAP collaboration)

Structure formation probes: Galaxy cluster counts

$$\frac{d^2 N}{d\Omega\, dz} = n(z)\, \frac{r(z)^2}{H(z)}$$



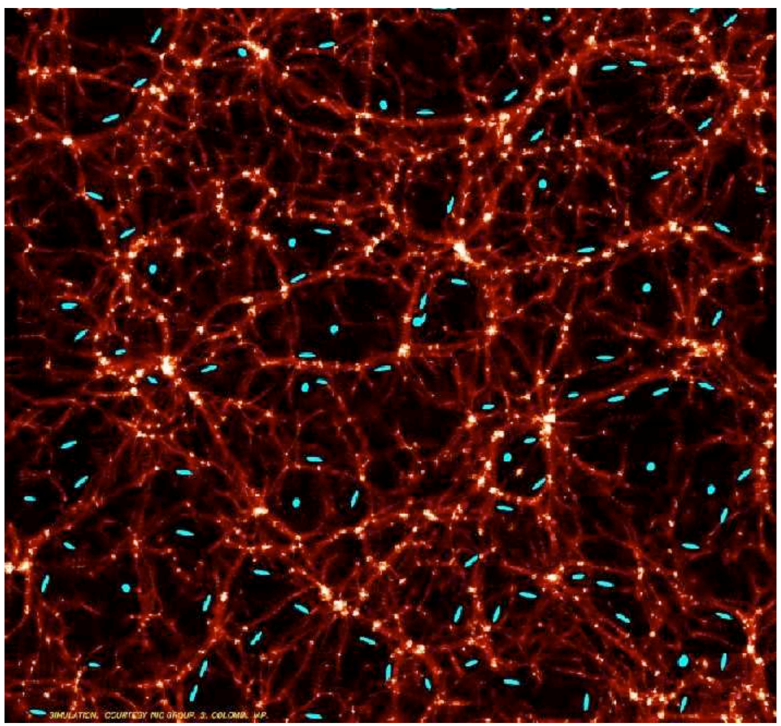
Credit: Quinn, Barnes, Babul, Gibson



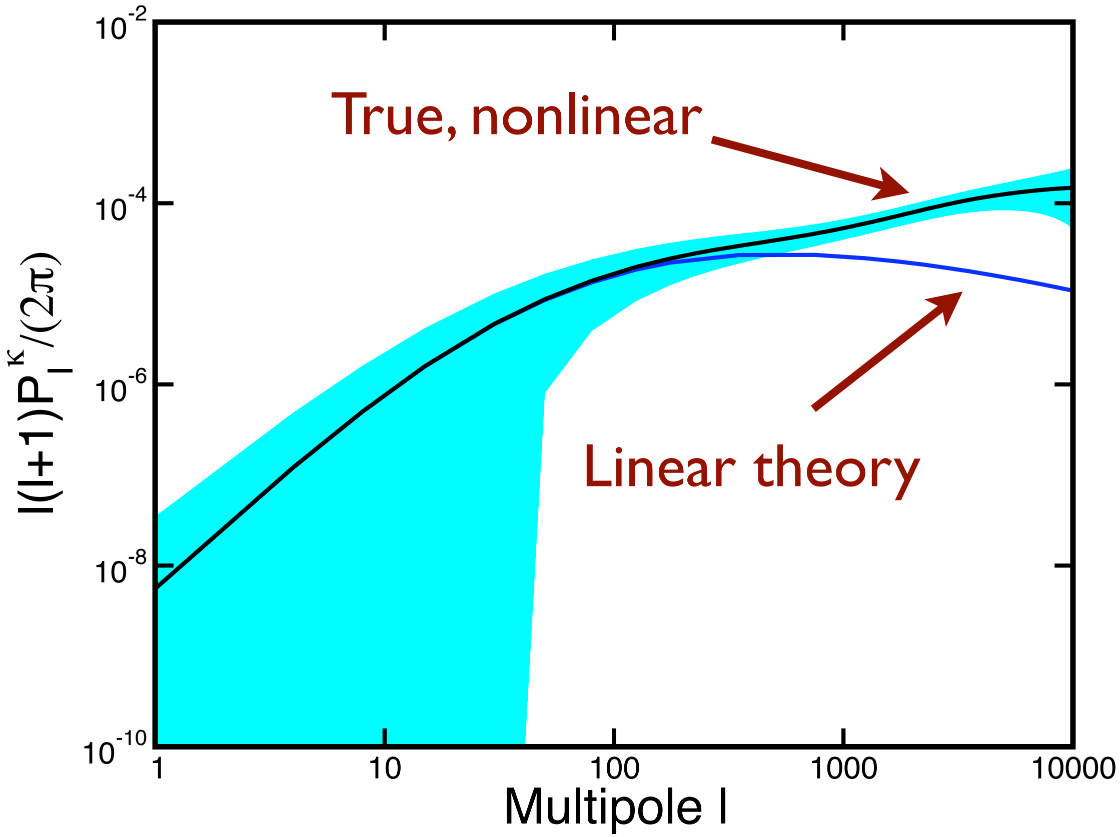
- Essentially fully in the nonlinear regime (scales ~1 Mpc)

Structure formation probes: Weak Gravitational Lensing

$$P_{\text{shear}} \simeq \int_0^\infty W(r) P_{\text{matter}}(r)\,dr$$



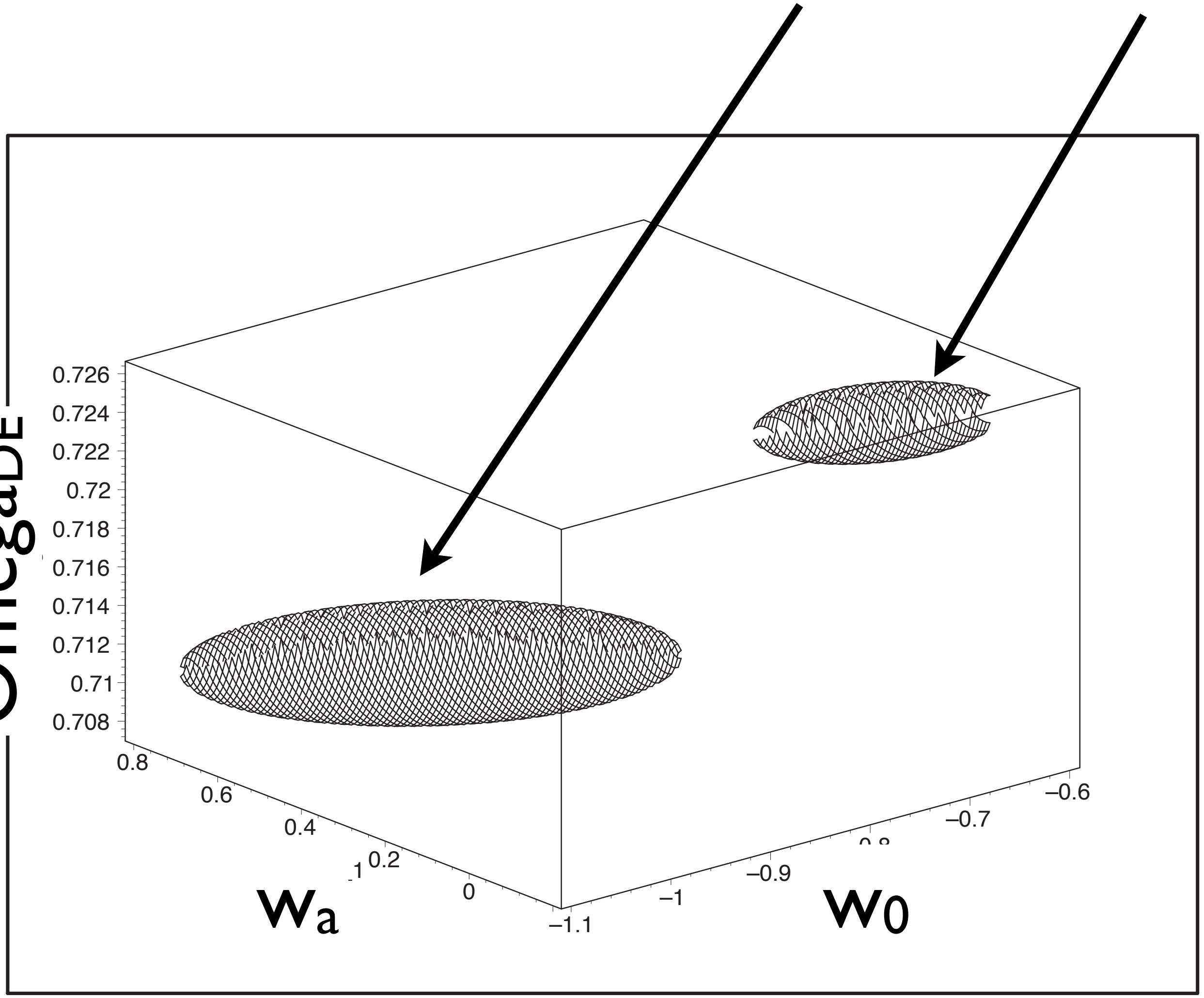
Credit: Colombi & Mellier



- Mostly in the nonlinear regime (scales ~10 arcmin, or ~1 Mpc)

More general approach

Measure the DE parameters from distances and growth separately

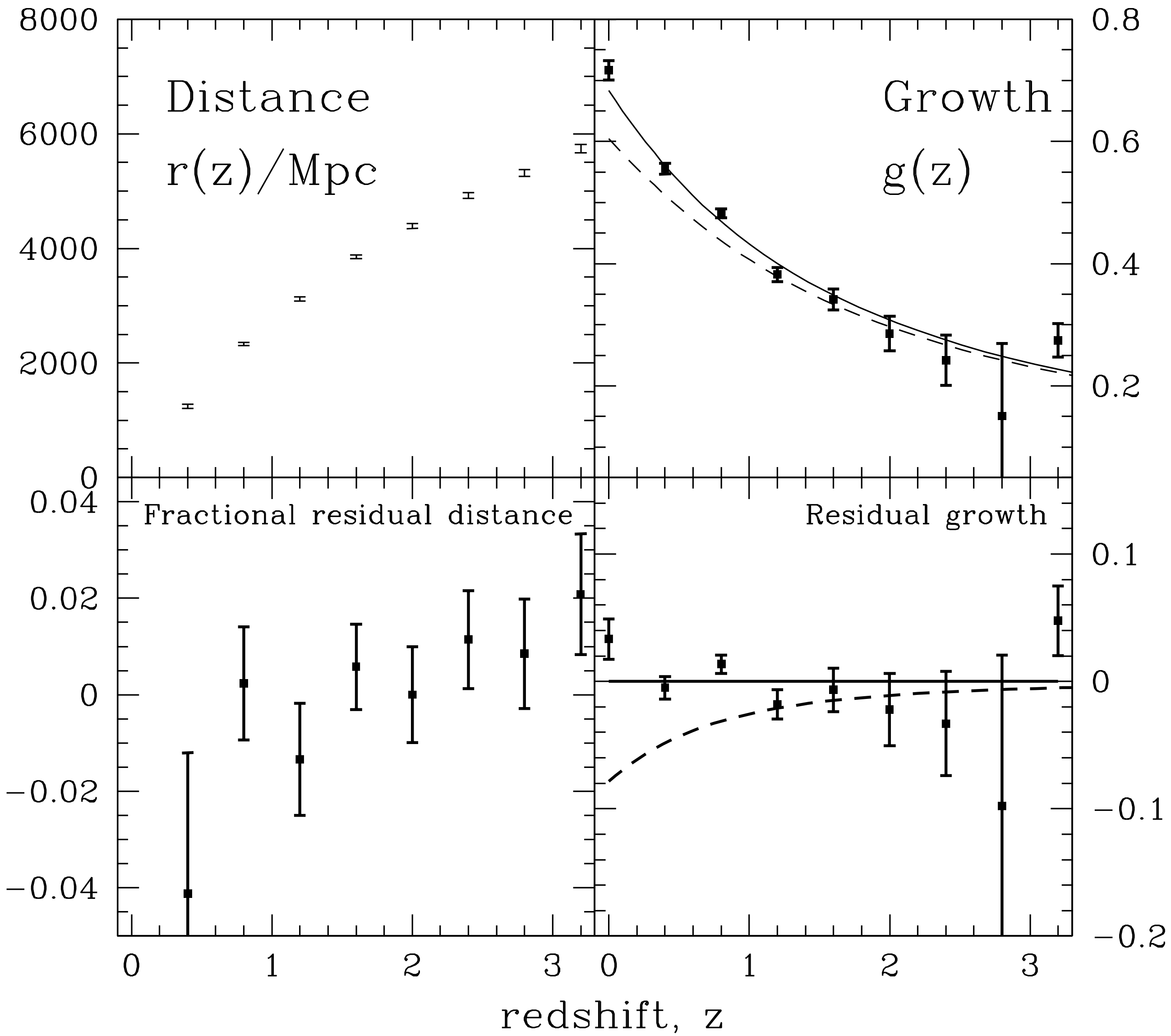


Ishak, Upadhye and Spergel 2006; others...

Still more general approach:

measure functions r(z) and g(z)

see if they are consistent



Knox, Song & Tyson 2005

Minimalist Modified Gravity vs. DE

Describe deviations from GR via a single new parameter

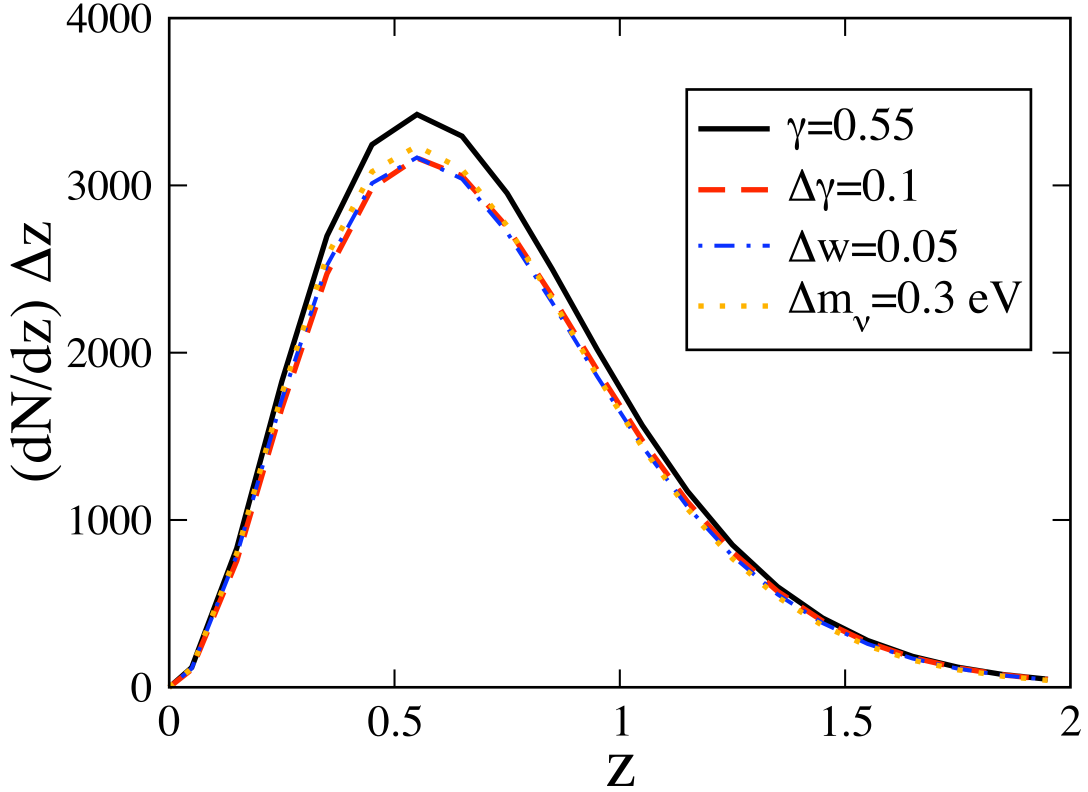
$$g(a) \equiv \frac{\delta}{a} = \exp\left[\int_0^a d\ln a[\Omega_M(a)^\gamma - 1]\right]$$

Excellent fit to standard DE growth function with

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

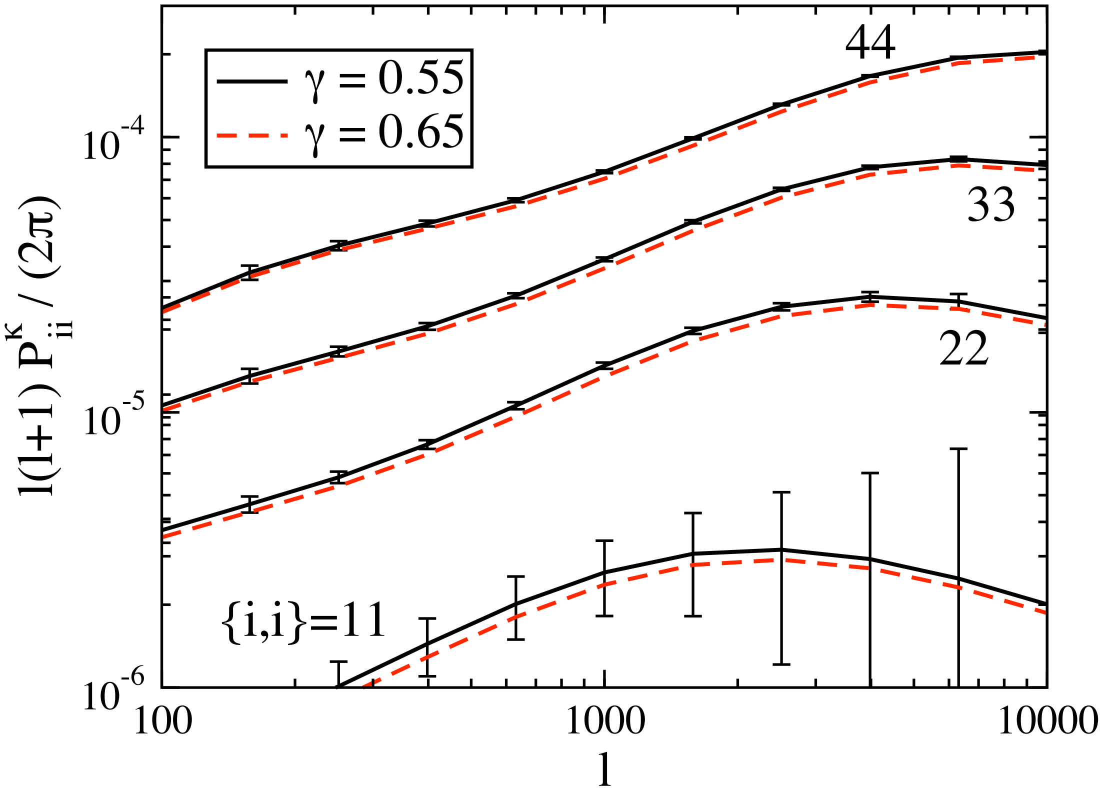
Also fits the DGP braneworld theory with $\Delta\gamma = 0.13$

Huterer & Linder, astro-ph/0608681
see also Linder & Cahn, astro-ph/0701317



Cluster counts

Weak lensing tomography



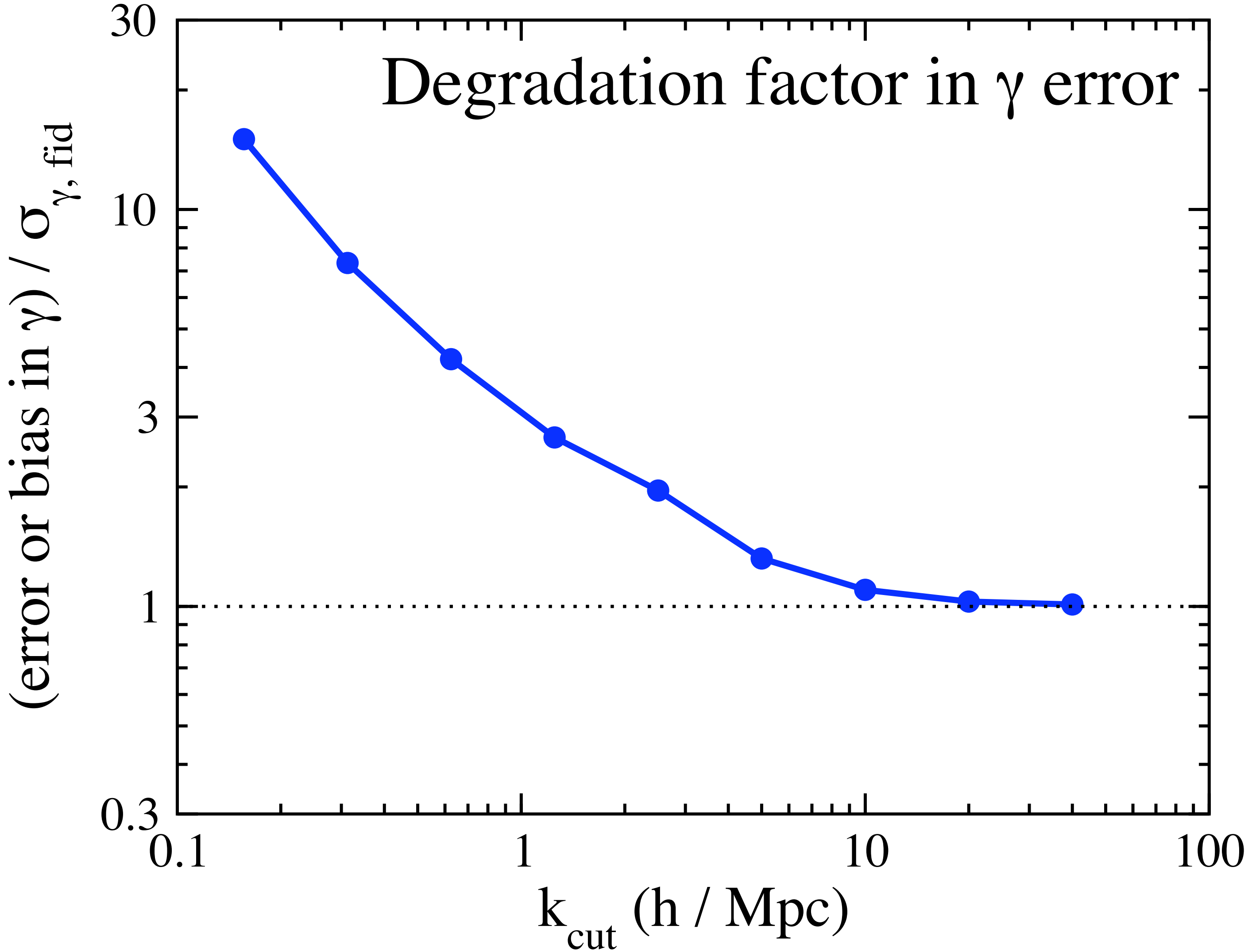
Constraints on the growth index

	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

Recall, for DGP $\Delta\gamma = 0.13$

Huterer & Linder, astro-ph/0608681

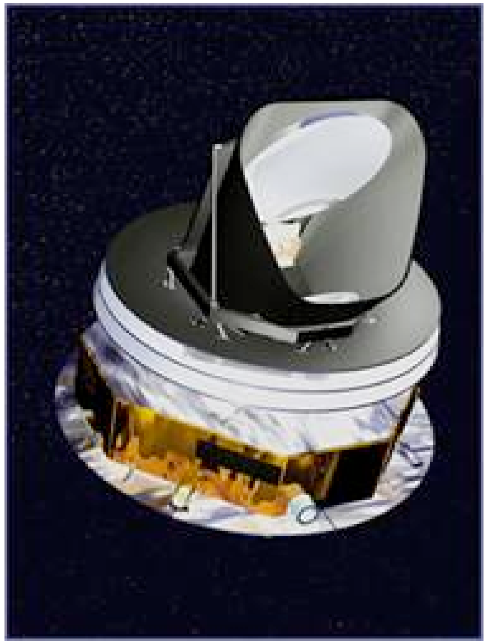
Discarding the small-scale info in weak lensing



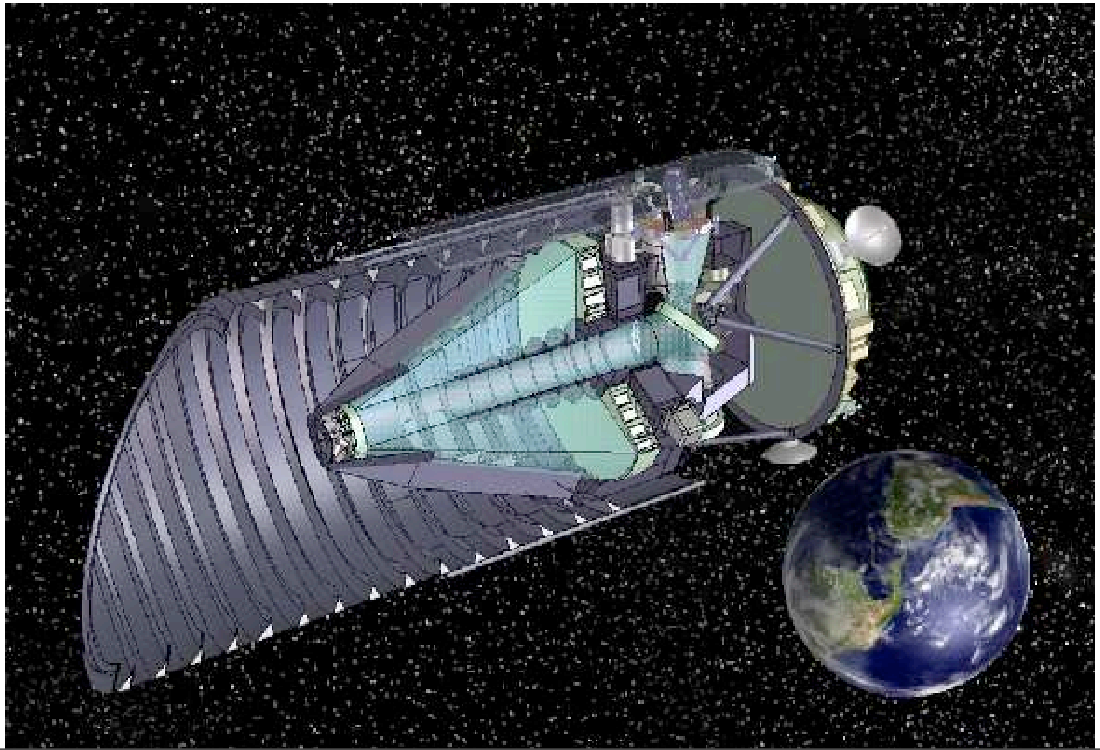
Using the Nulling Tomography of weak lensing (Huterer & White 2005)

South Pole Telescope

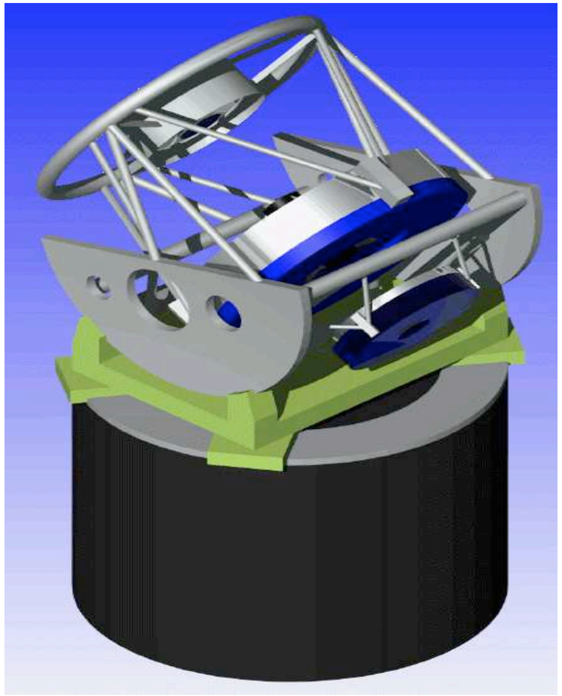
Planck



Supernova/Acceleration Probe



LSST



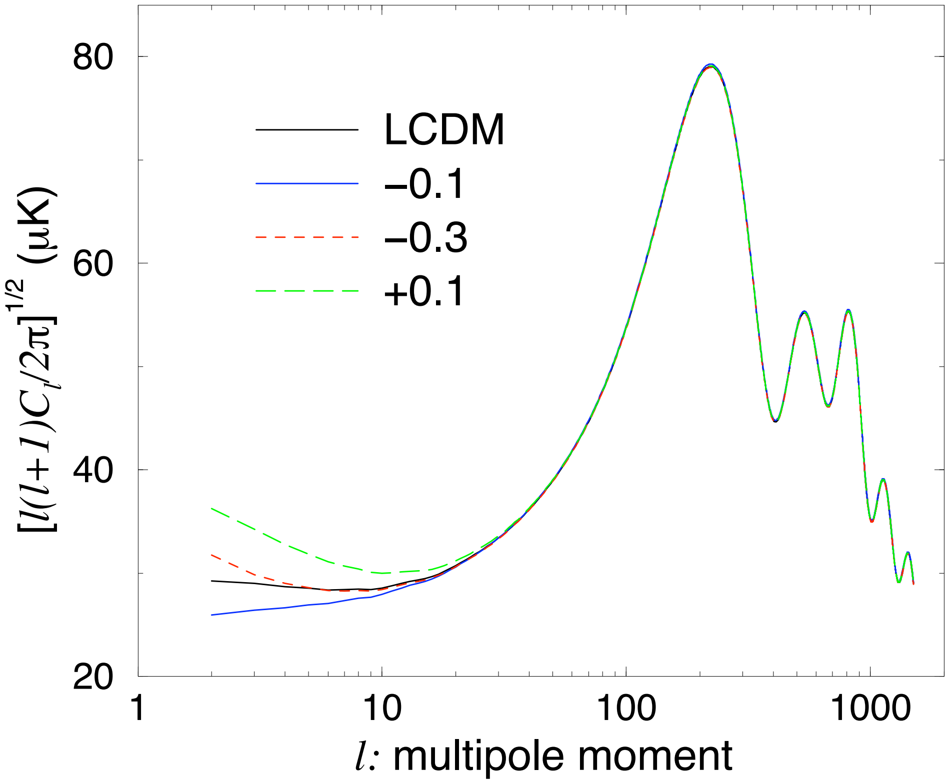
Conclusions

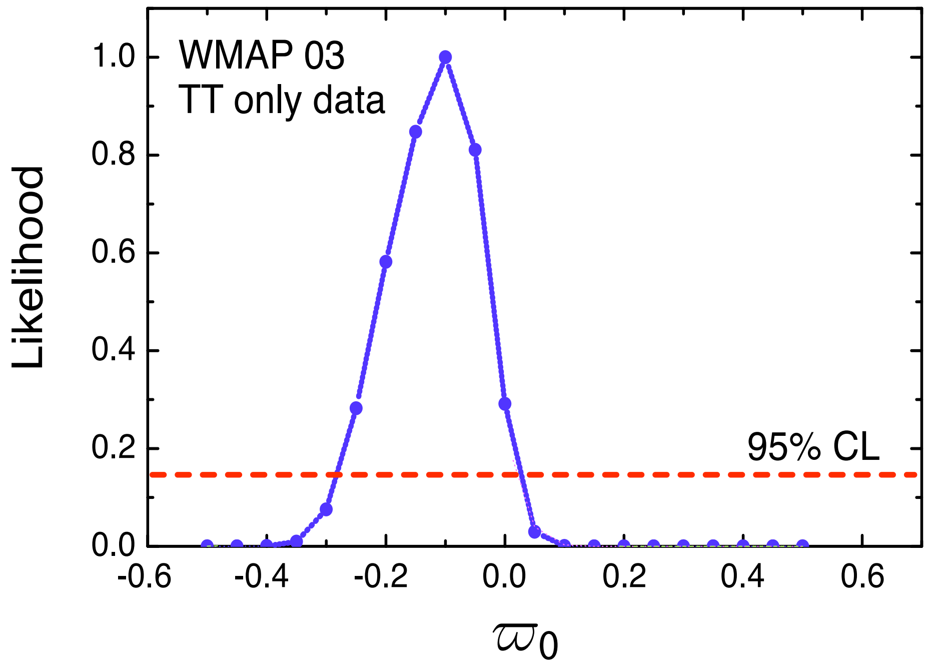
- distinguishing dark energy from modified gravity is becoming one of the key goals of cosmology in years to come
- assuming nonlinear clustering that follows the usual prescription even with MG, we find that future probes can achieve very interesting constraints on this parameter
- restriction to linear scales severely degrades the errors, but well worth pursuing
- ambitious, general approach: measure functions r(z) and g(z), check if they are consistent
- minimalistic approach: measure a single parameter that describes departures between DE and MG
- bright future with upcoming powerful surveys

Physically motivated MG parametrization

$$ds^2 = a^2(\tau)\left[-(1+2\psi)d\tau^2 + (1-2\phi)d\vec{x}^2\right]$$

$\psi = (1+\varpi)\phi$ and assume $\varpi = \varpi_0 \dfrac{\rho_{DE}}{\rho_M}$

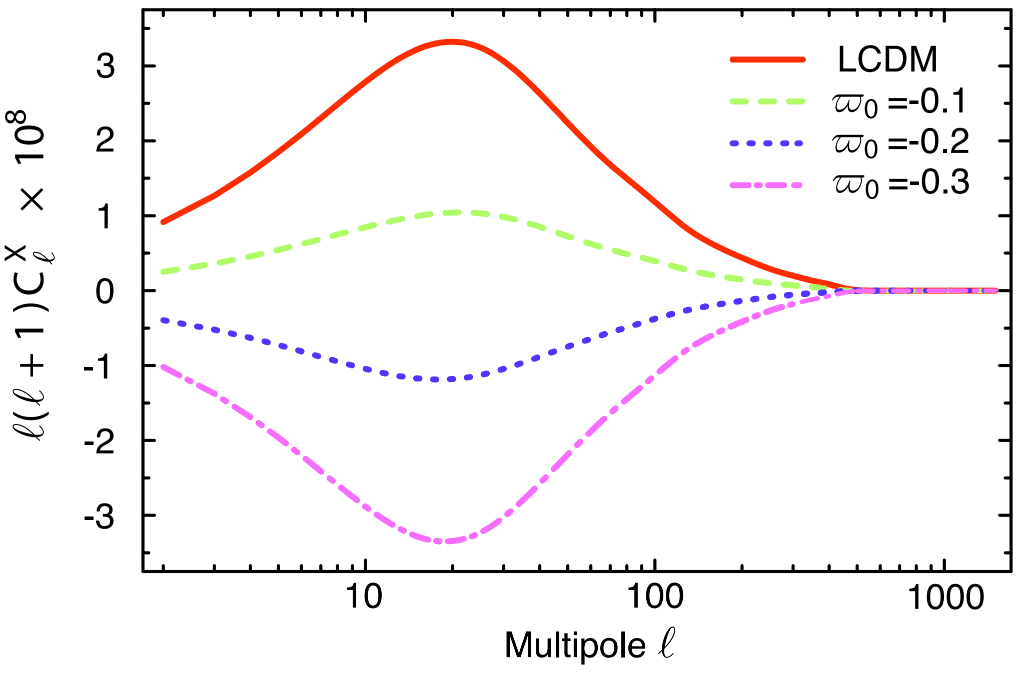




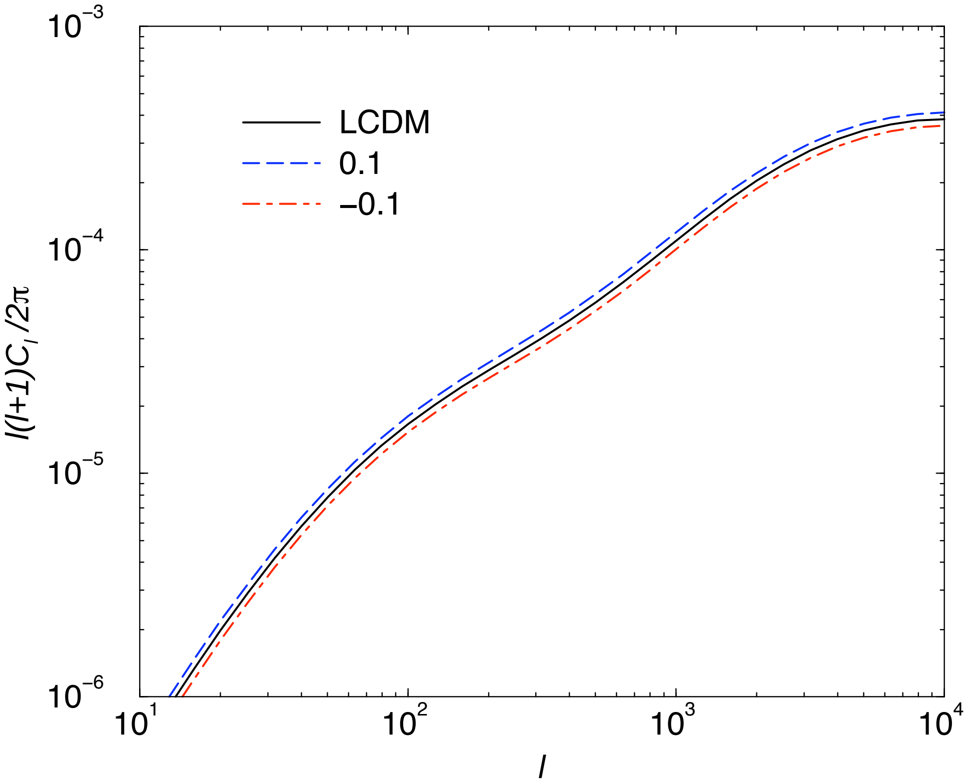
Caldwell, Cooray & Melchiorri, astro-ph/0703375

Physically motivated MG parametrization

CMB-galaxy cross-correlation



Weak lensing power spectrum



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