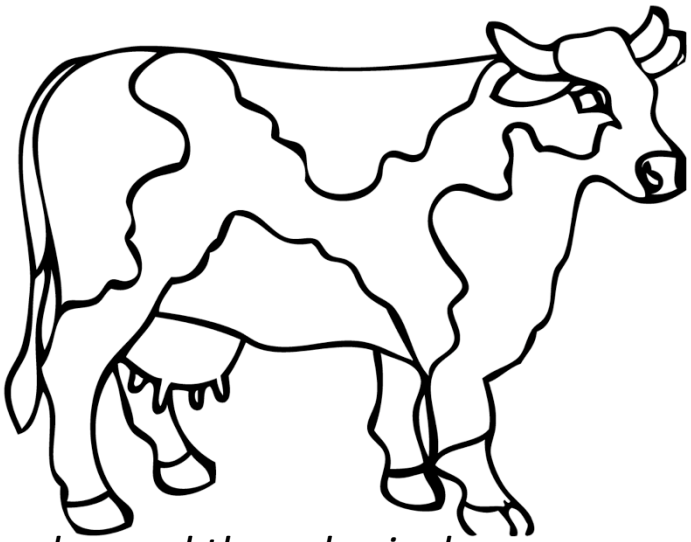
DARK ENERGY is the weirdest and most abundant stuff in the universe. It is causing the expansion of the universe to speed up, and the destiny of our universe rests in its hands. However, we don't know much about dark energy.

Dark energy is everywhere and is extremely diffuse–a cubic meter of dark energy contains only as much energy as a hydrogen atom–and it is not made of particles. Dark energy is like a continuous, extraordinarily elastic medium. Its elasticity leads to its defining and most spectacular feature: its gravity repels rather than attracts. For the first nine billion years after the big bang, the attractivegravity of matter caused the expansion of the universe to slow down. Five billion years ago, dark energy's repulsive gravity overcame matter's attractive gravity, leading to the accelerating universe.

Figuring out dark energy is high on the to-do lists of both astronomers and physicists. During the next 20 years, ground- and space-based telescopes will shed new light on dark energy and perhaps bring a few surprises too. I, for one, believe that dark energy is the most profound mystery in all of science and that cracking the dark-energy puzzle will lead to advances elsewhere, from understanding the birth of the universe to illuminating string theory.

Michael S. Turner, The University of Chicago

Perspectives on Dark Energy

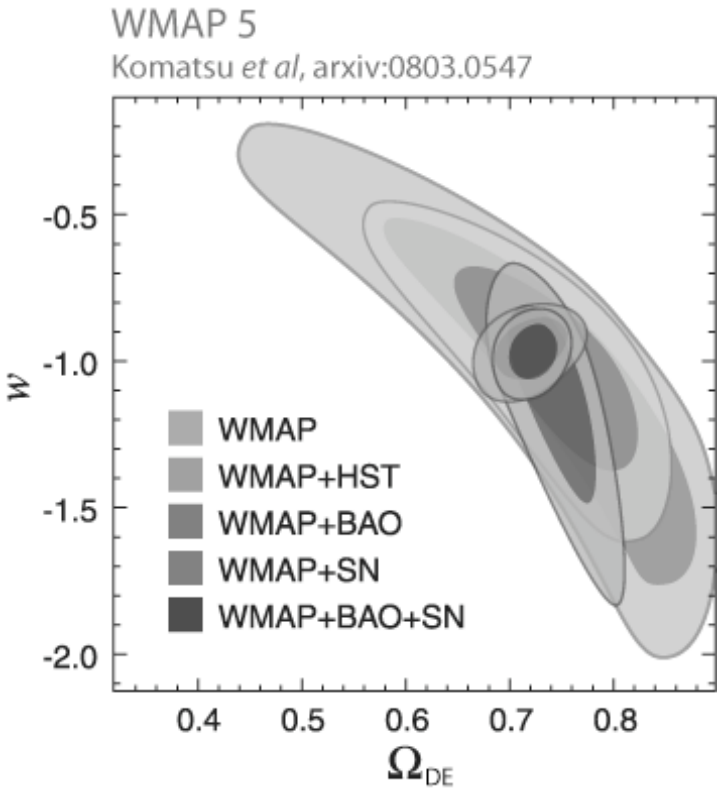


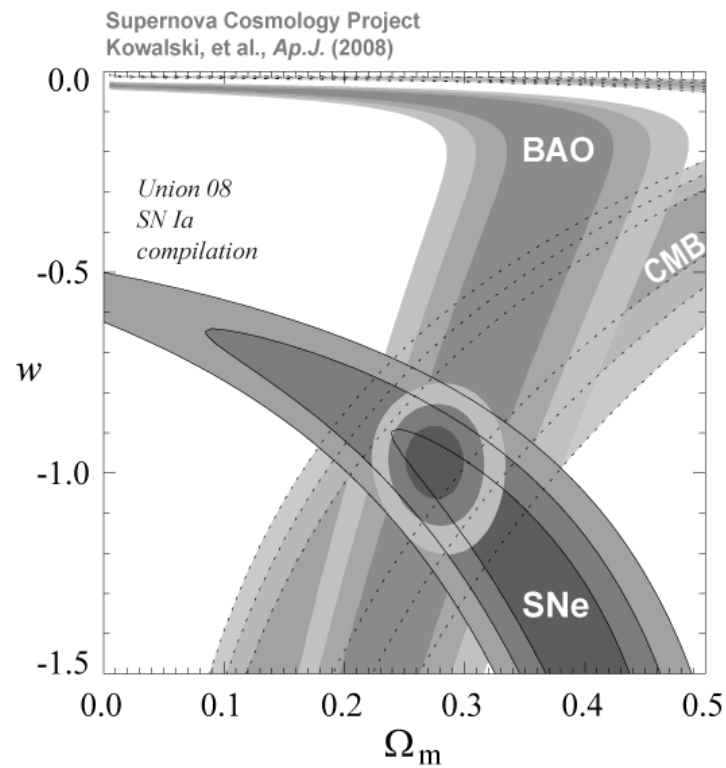
beyond the spherical cow

Robert Caldwell
Dartmouth College

Cos**moo** 2008
Madison, Wisconsin

Dark Energy Equation of State





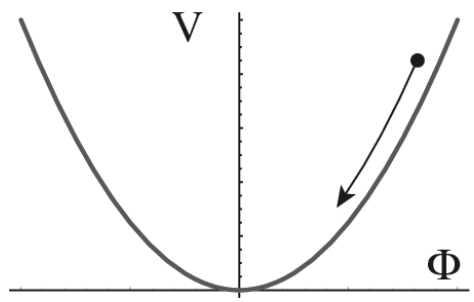
WMAP 5: Komatsu et al, arxiv:0803.0547

$$\Omega_m h^2 = 0.1369 \pm 0.0037 \qquad \Omega_\Lambda = 0.721 \pm 0.015$$

$$w = -0.984^{+0.065}_{-0.064} \qquad \Omega_k = -0.0046^{+0.0066}_{-0.0067}$$

Dynamical Dark Energy: Quintessence

attempt a classification of scalar field models

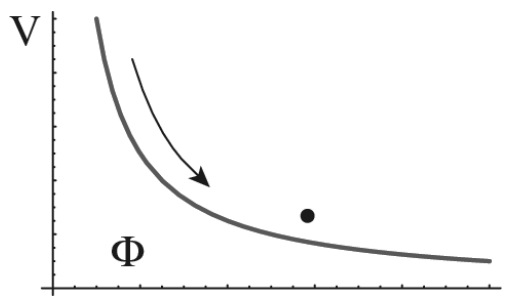


thawing

Field is critically damped until Hubble friction drops; ***w*** starts at -1 and grows larger

any field near minimum: V=V'=0

massive scalar, axion / pngb



freezing

Field decays until curvature of potential causes field to slow; ***w*** evolves towards -1

"tracker" / runaway or vacuumless field

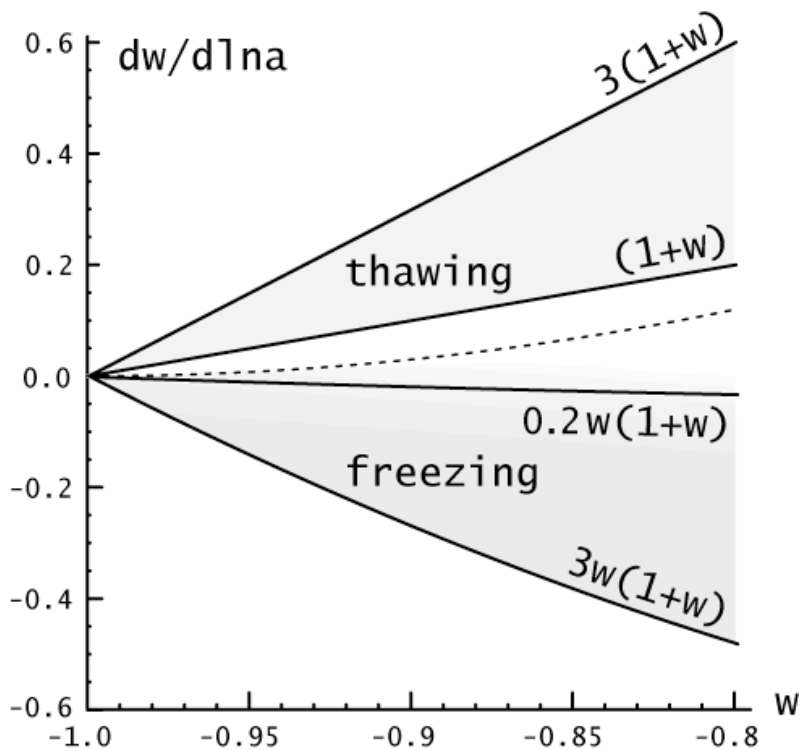
sticking point & glaciers

A simplistic view may help to understand the range of possibilities

Crittenden *et al*, PRL 98, 251301 (2007); Huterer & Peiris, PRD 75, 083503 (2007)

Dynamical Dark Energy: Quintessence

phase space domains



Caldwell & Linder, PRL 95, 141301 (2005)

$$\Omega_Q < 0.8$$

$$w < -0.8$$

$$\min(V) = 0$$

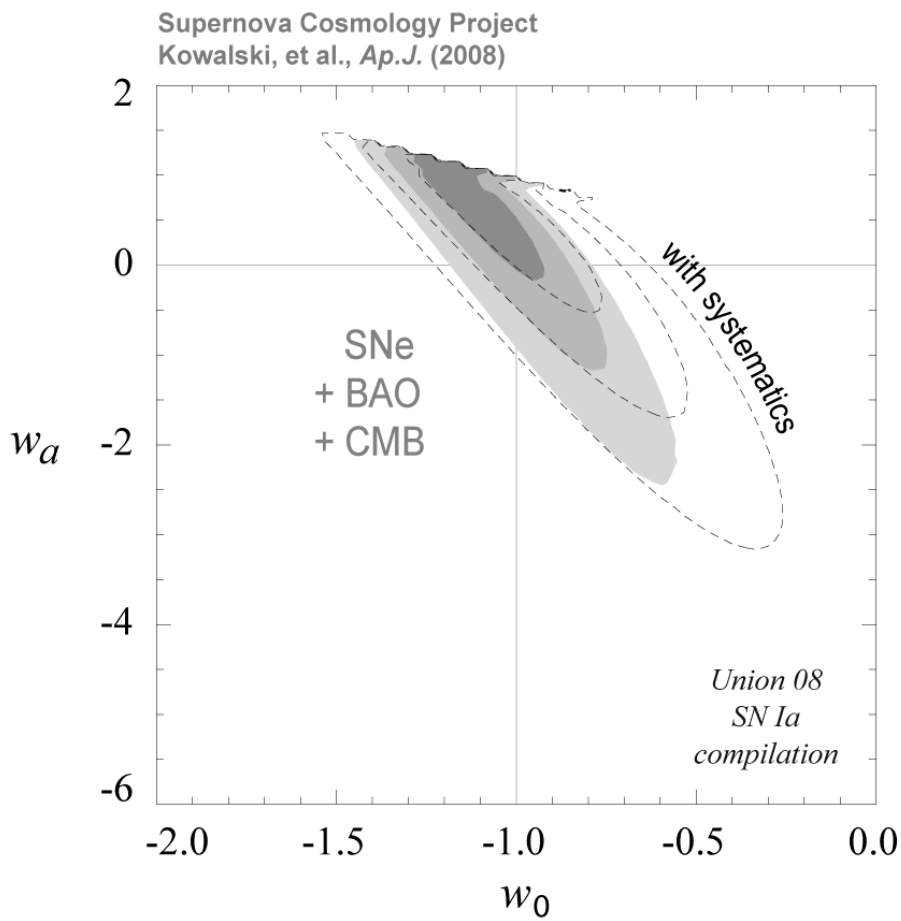
Attempt to identify a scale for dw/d*ln*a

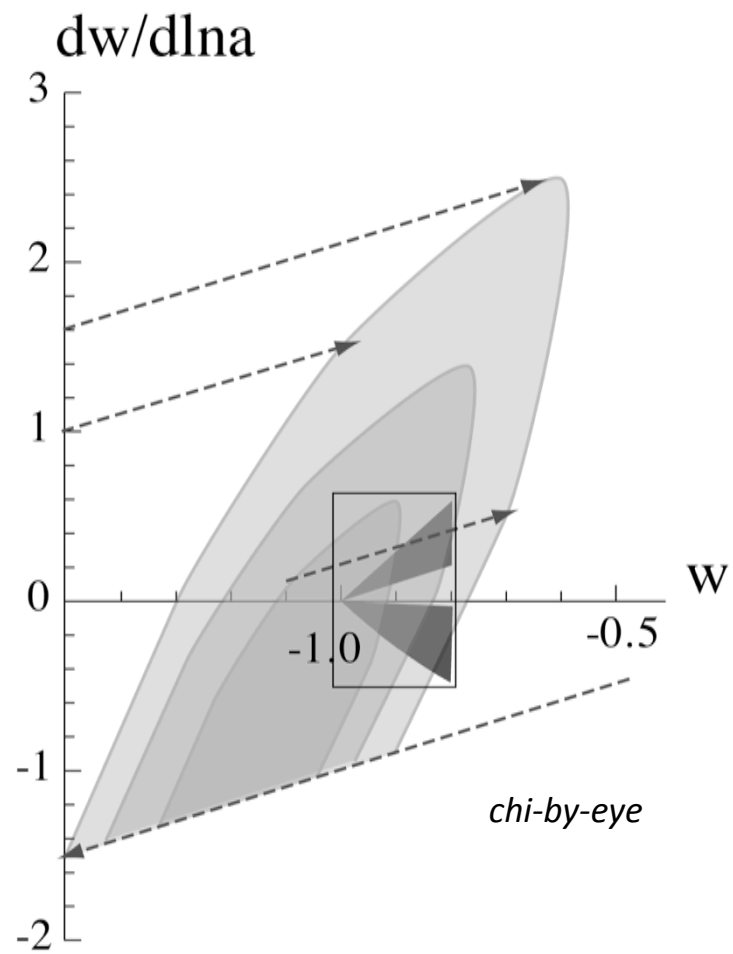
In practice, these may be difficult to distinguish

also see: Crittenden *et al*, PRL 98, 251301 (2007); Huterer & Peiris, PRD 75, 083503 (2007)

Dynamical Dark Energy

$$w(a) = w_0 + w_a(1-a)$$





w *perspectives on dark energy*

w=-1?
Simple parameterizations of w(z) may be susceptible to bias towards *w=-1.*

w>-1?
Binned distance data may be susceptible to bias towards *w>-1*.

w<-1?
Distance data may be susceptible to bias towards *w<-1*.

W

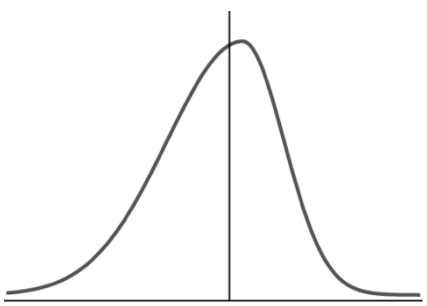
w<-1?

Distance data may be susceptible to bias towards *w<-1*.

$$r(z,w) = r|_{w_0} + (w - w_0)\frac{\partial r}{\partial w}|_{w_0} + \frac{1}{2}(w - w_0)^2 \frac{\partial^2 r}{\partial w^2}|_{w_0} + \ldots$$

$$\frac{\partial r}{\partial w},\ \frac{\partial^2 r}{\partial w^2} < 0$$

An increase in $w=w_0+\Delta$ produces more change in r than a decrease $w=w_0-\Delta$.



More change in r means poorer fit of model to data.

Symmetric errors on distance or magnitude will cause the likelihood $L(w)=\exp(-\chi^2[w]/2)$ to be skewed towards negative w: $\gamma_W<0$.

$$\langle w \rangle - w_{peak} \approx \frac{1}{2}\gamma_w \sigma_w,\ \langle w \rangle < w_0,\ w_{peak} > w_0$$

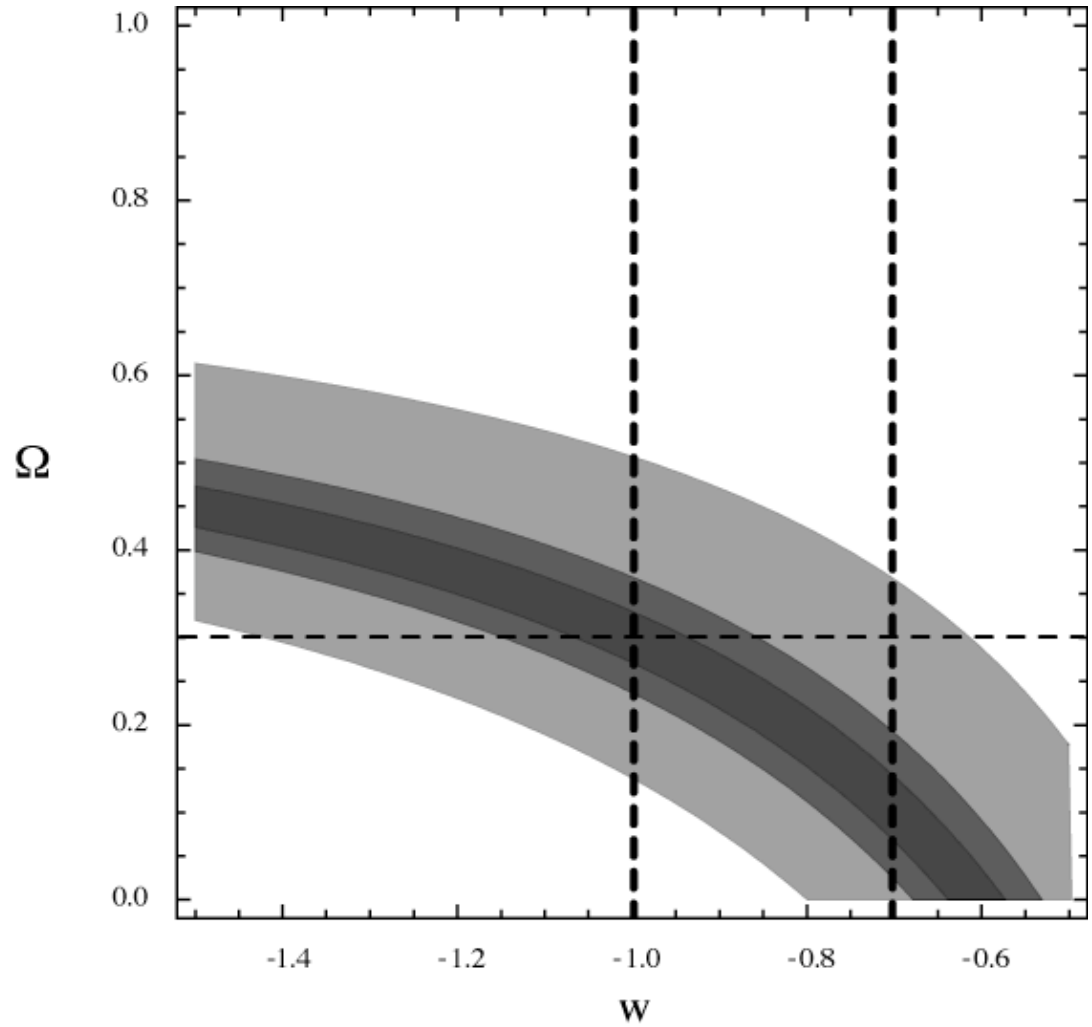
W **w<-1?**

Distance data may be susceptible to bias towards *w<-1*.

marginalize!

$$\langle w \rangle < w_0$$

$$w_0 < w_{peak}$$



W

w<-1?

Distance data may be susceptible to bias towards *w<-1*.

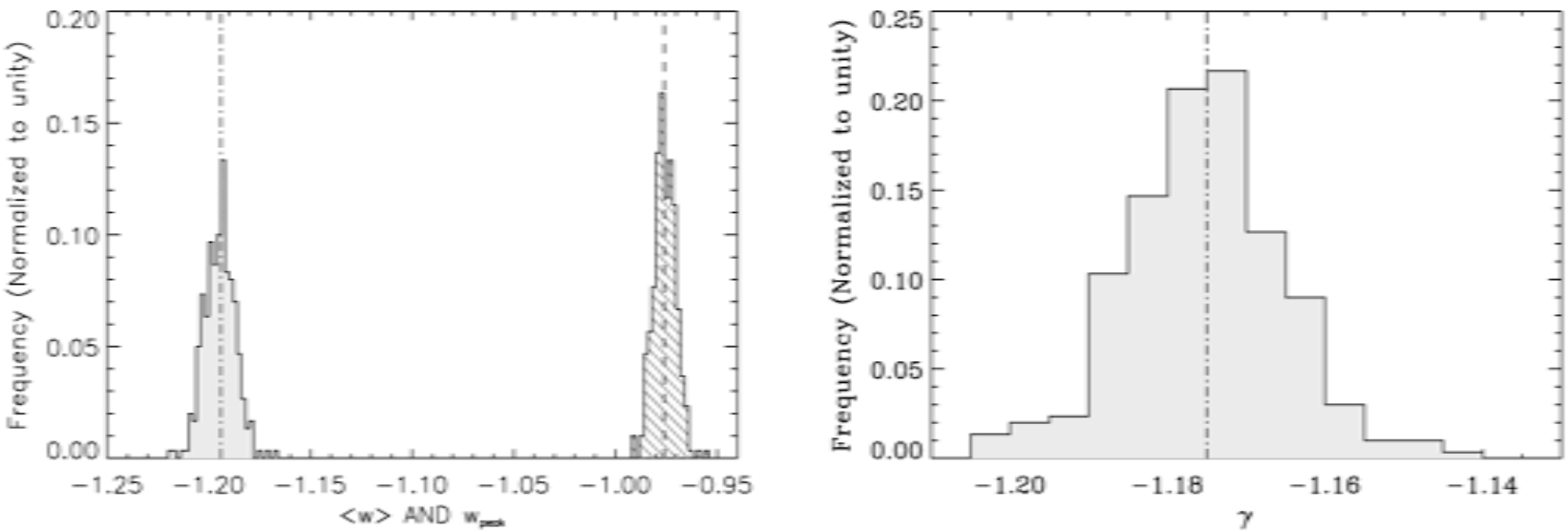
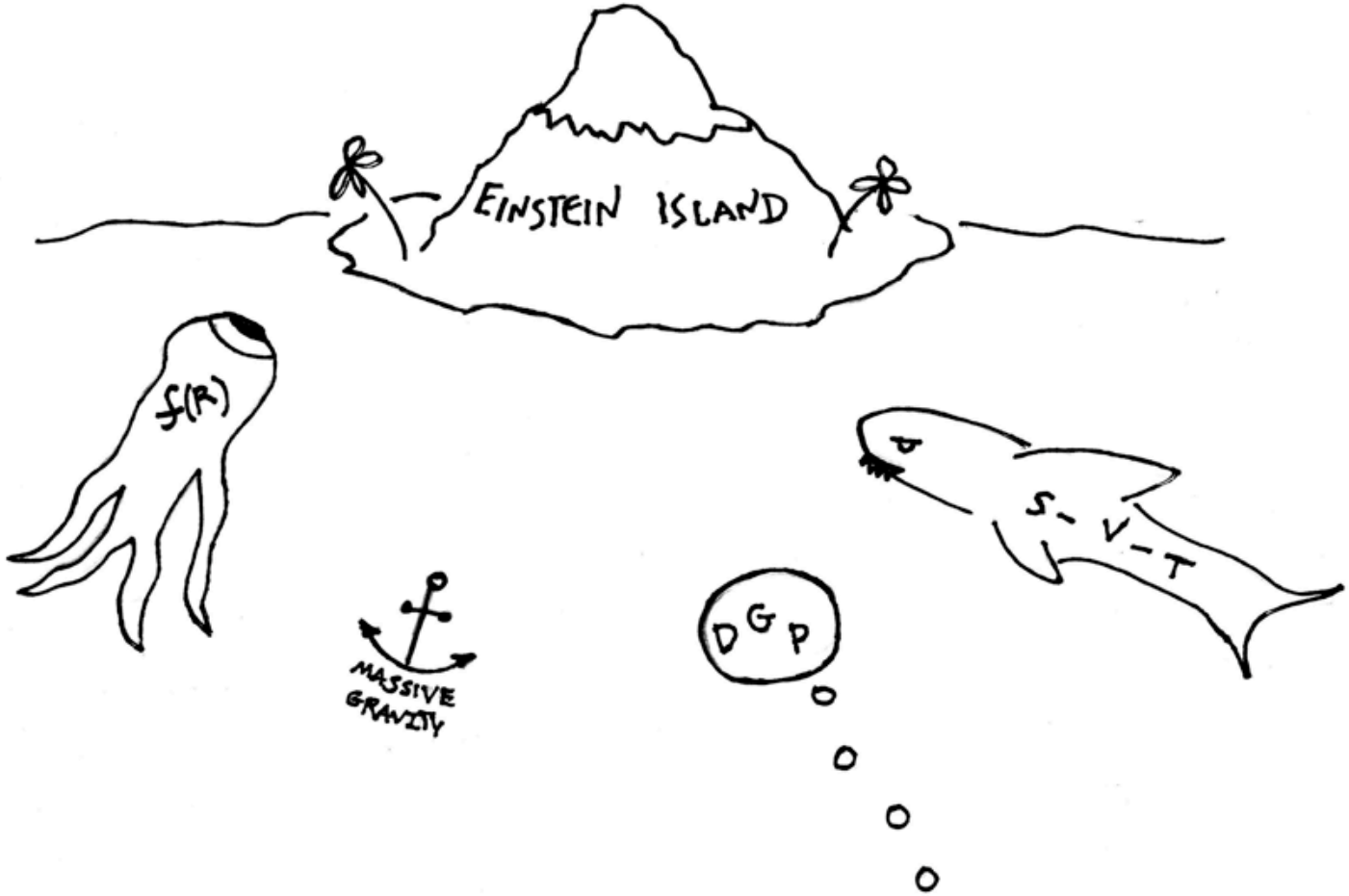


FIG. 2.— *Left panel:* The distribution of the expectation value of w and w_{peak} after 300 realizations using 2000 SN samples. The shaded histogram shows the distribution of $\langle w \rangle$ and the hatched histogram depicts the distribution of w_{peak}. *Right panel:* Histogram showing the distribution of the skewness after 300 realizations.

Sarkar, Cooray, Caldwell (in preparation, 2008)

Lost?

Is Dark Energy Phenomena due to New Gravitation?



Gravity?

Is dark energy due to new gravitational phenomena?

$$\boxed{3H^2 = 8\pi G\rho}$$

A problem of balance:
Not enough curvature per unit mass?

Consider a modulation in the strength of gravitation that produces dark energy phenomena consistent with LCDM.

Local and Global descriptions of spacetime curvature

$$ds^2 = -(1 - 2\frac{Gm}{r})dt^2 + (1 + 2\gamma\frac{Gm}{r})d\vec{x}^2$$

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

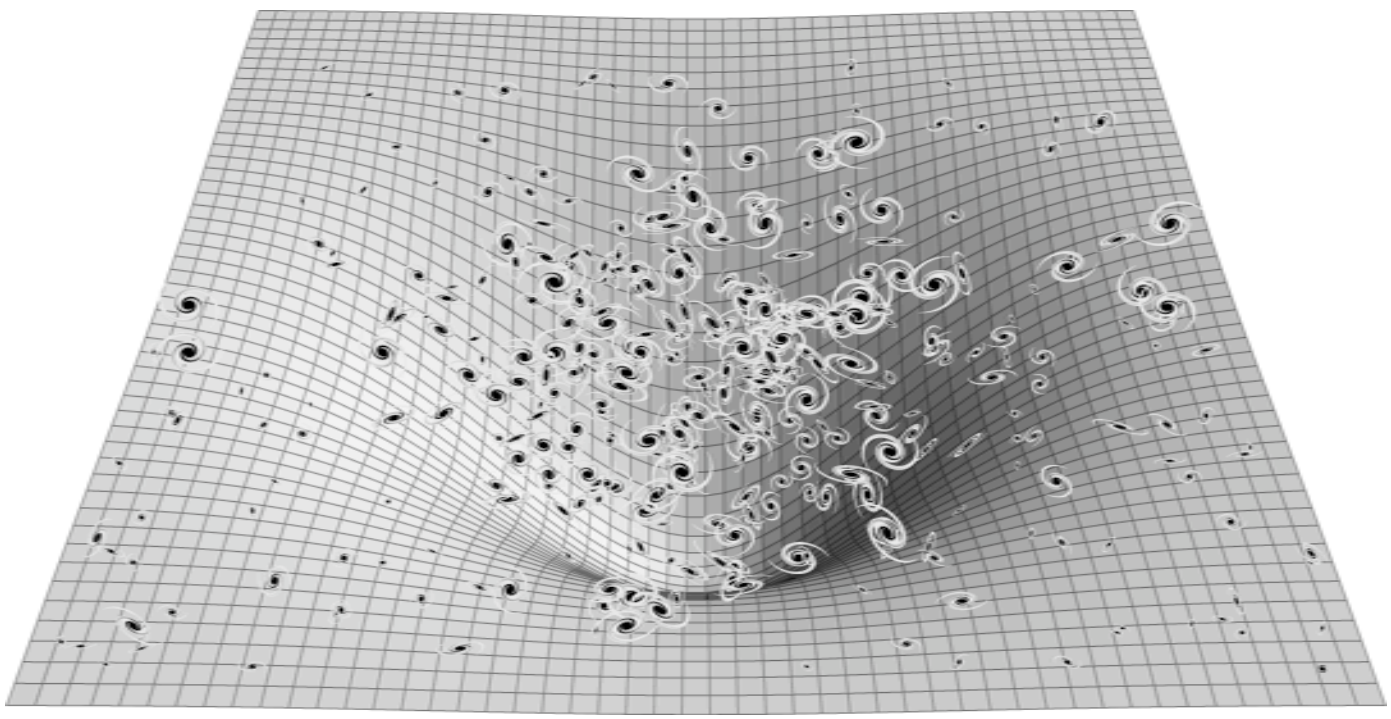
Consistent with a variety of gravitational theories!

Gravity?

Is dark energy due to new gravitational phenomena?

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

$$\phi \neq \psi : \quad \ddot{\vec{x}} = -\vec{\nabla}\psi, \quad \nabla^2\phi = 4\pi G\delta\rho$$



Gravity?

Build a phenomenological model to test for consistency

Consider a background expansion consistent with LCDM

Impose inequality between gravitational potentials

$$\psi \equiv (1+\varpi)\phi, \;\; \varpi = \varpi(t, \vec{x})$$

Toy model: dark energy domination causes gravitational "slip"

$$\varpi(t) = \varpi_0 \rho_{DE}/\rho_m(t)$$
$$\text{expect } \varpi_0 \sim \pm 1$$

busy!

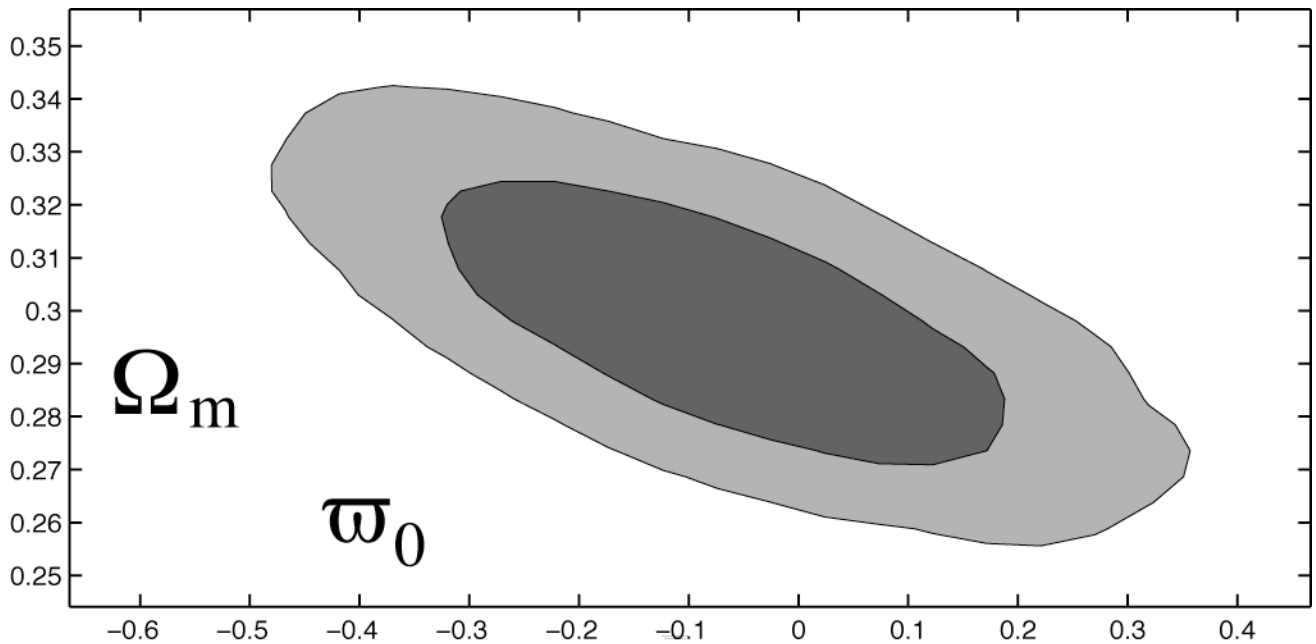
Caldwell, Cooray, Melchiorri, PRD 76, 023507 (2007)
Daniel et al, PRD 77, 103513 (2008)
Bertschinger, ApJ 648, 797 (2006)
Bertschinger & Zukin, PRD 78, 024015 (2008)
Hu & Sawicki, PRD 76, 104043 (2007)
Zhang et al, PRL 99, 141302 (2007) …

$$\varpi, \; \gamma, \; \eta, \; \Phi_\pm, \; \ldots$$

Gravity?

Build a phenomenological model to test for consistency

cmb: WMAP5 + ***sne***: Union + ***wl***: CFHTLS + ***isw***: SDSS x WMAP

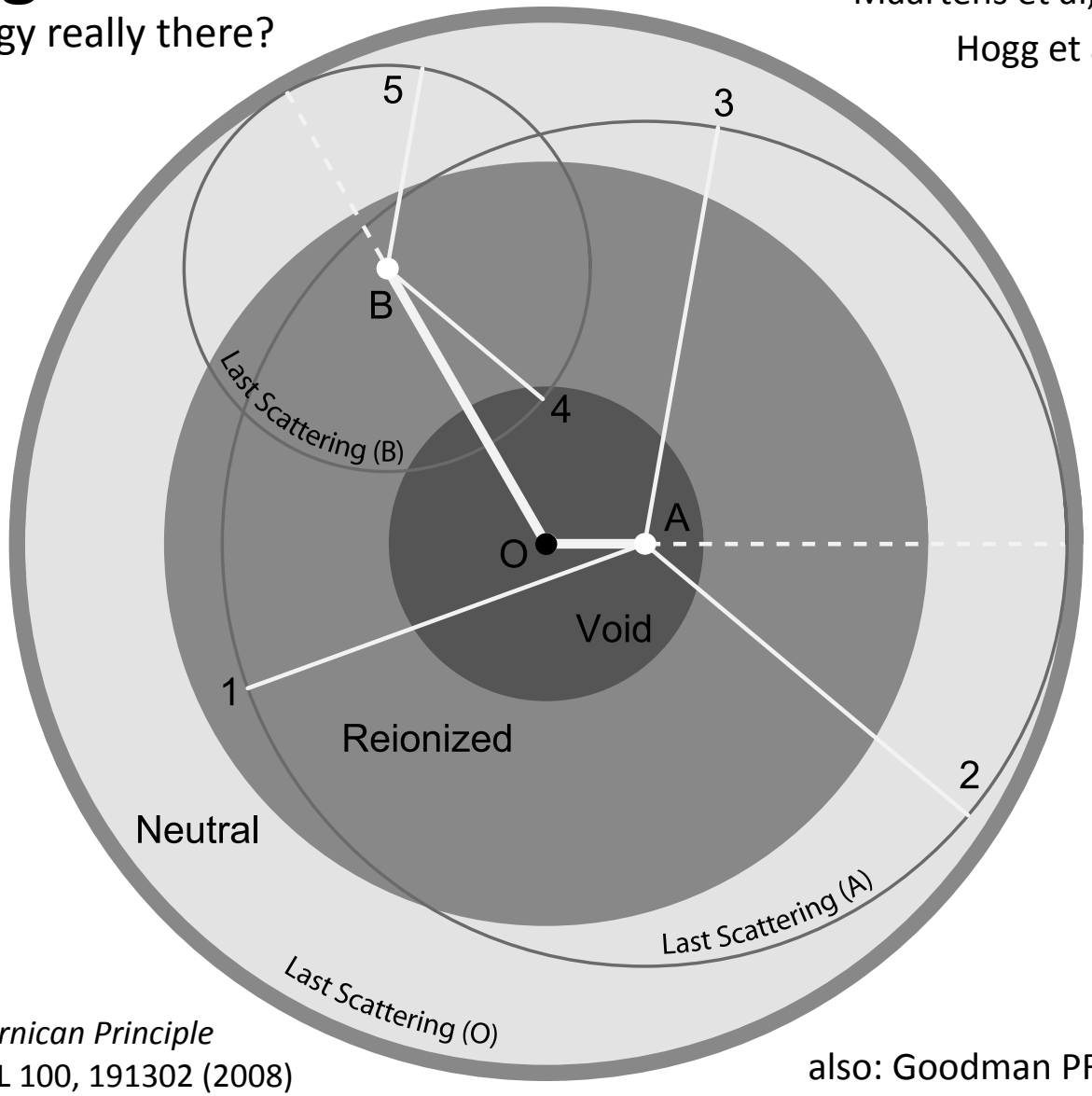


Daniel *et al* (in preparation, 2008)

A Mirage?

Is dark energy really there?

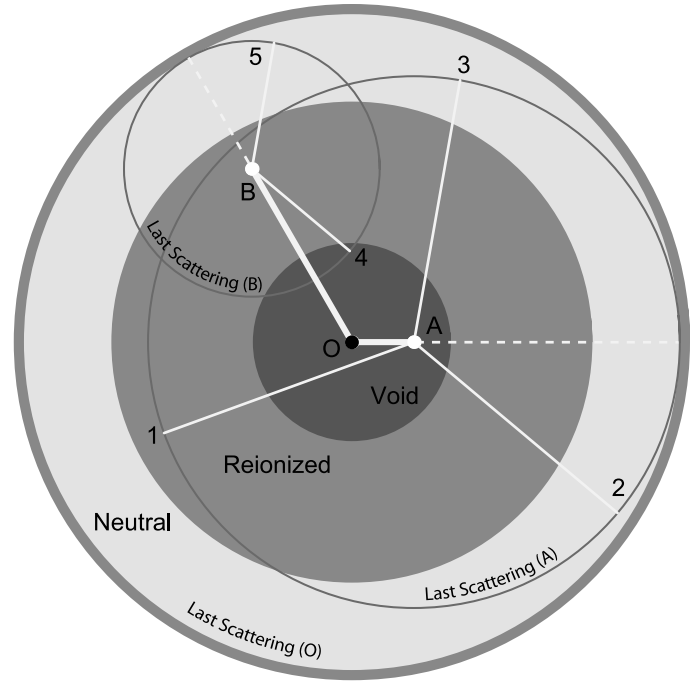
Evidence for our Robertson-Walker spacetime
Maartens et al, PRD 51, 1525 (1995)
Hogg et al, ApJ 624, 54 (2005)



A Test of the Copernican Principle
Stebbins & RC, PRL 100, 191302 (2008)

also: Goodman PRD 52, 1821 (1995)

u-distortion



A blackbody spectrum at temperature T mixed with a blackbody at temperature T+ΔT produces a *u*-distorted blackbody.

Stebbins, astro-ph/0703541

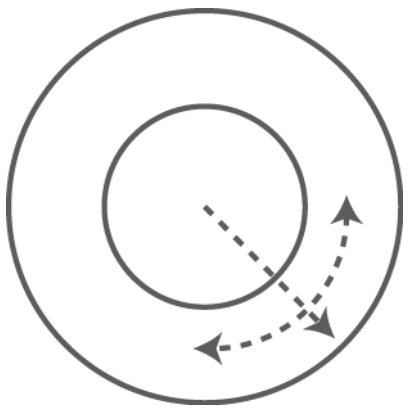
$$u[\hat{n}] = \frac{3}{16\pi}\int_0^\infty dz' \, \frac{d\tau}{dz'} \int d\hat{n}'(1 + (\hat{n}\cdot\hat{n}')^2)$$
$$\times \left(\frac{\Delta T}{T}[\hat{n},\hat{n},z] - \frac{\Delta T}{T}[\hat{n}',\hat{n},z]\right)^2$$

Degenerate with Compton y-distortion parameter: u = 2y

FIRAS: $y < 15 \times 10^{-6}$ (95%): Fixen et al, ApJ 473, 576 (1996)

Nonlinear Inhomogeneous Spacetime

$$ds^2 = -dt^2 + \frac{(\partial_r R)^2}{1 + k(r) r^2} dr^2 + R^2(t,r) d\Omega^2$$

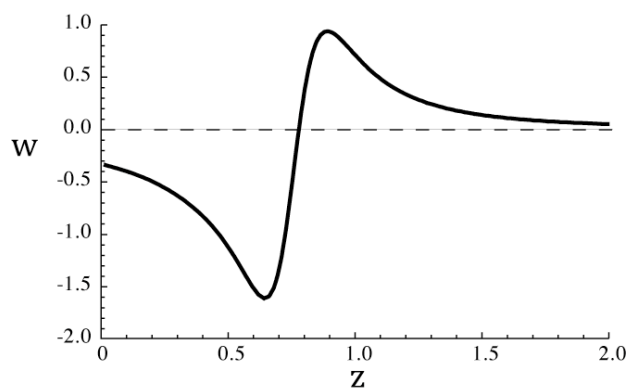


Lemaitre (1933), Tolman (1934), Bondi (1947)

(See Krasinski (1997) for more general inhomogeneous, perfect fluid models)

k(r): curvature function fixes the mass density profile

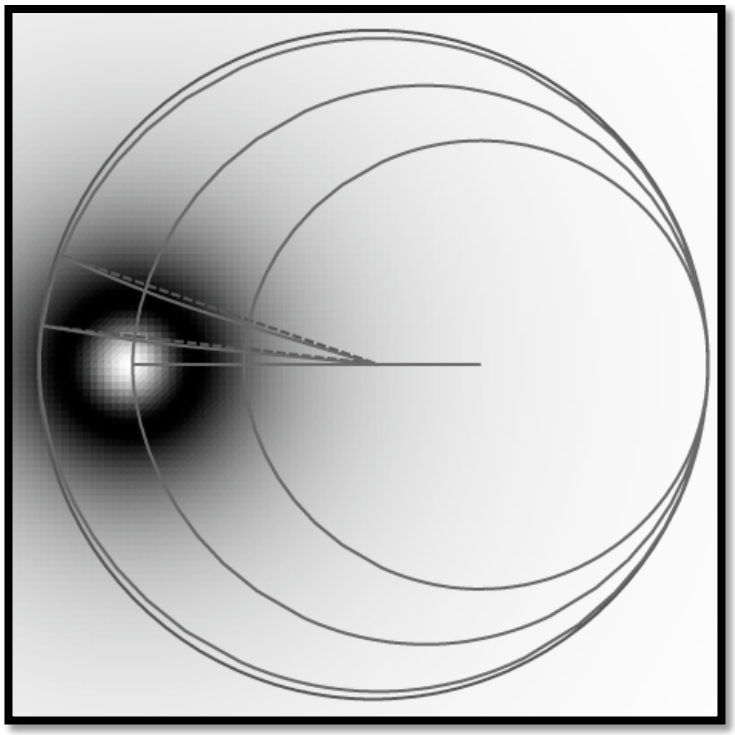
R(t,r): solve for the radially-dependent scale factor



$$\frac{k(r)}{H_0^2} = \frac{1 - \Omega_0}{1 + (r/r_0)^n}$$

Instructions: Garfinkle, CQG 23, 4811 (2006), Garcia-Bellido & Haugbolle, JCAP 0804:003 (2008)

Nonlinear Inhomogeneous Spacetime



Single-scattering recipe:

- Integrate the photon geodesic radially outward to the scattering site.

- Change direction and follow the photon to the last scattering surface.

- All gravitational effects are included – SW, ISW, Doppler, lensing deflection.

$$R(t,r) = a(t,r)r$$

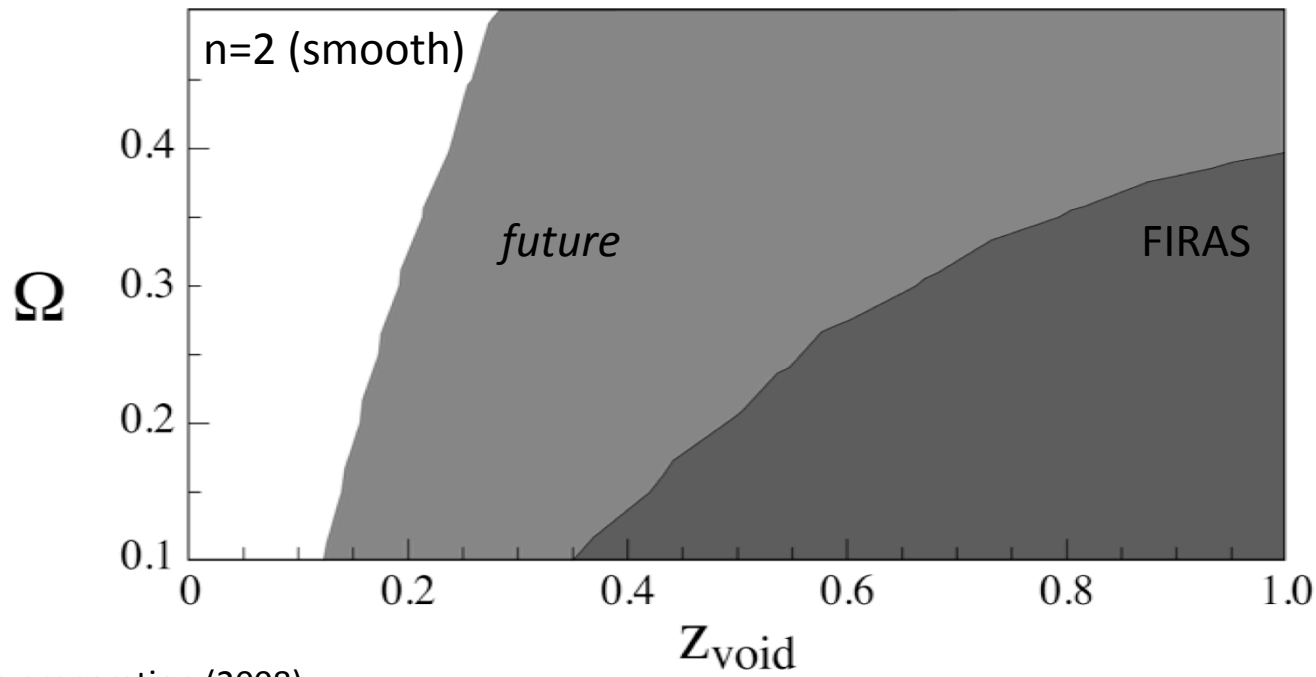
$$L = \frac{\ell}{(1+z)R},\ Q = 1 - \frac{\dot{R}R'}{R\dot{R}'}$$

$$\frac{dR}{dz} = \frac{R'}{\dot{R}'}\frac{\sqrt{1+kr^2}\sqrt{1-L^2} - \dot{R}}{(1+z)(1-L^2Q)}$$

$$\frac{da}{dz} = \frac{a'\sqrt{1+kr^2}\sqrt{1-L^2} - \dot{a}R'}{\dot{R}'(1+z)(1-L^2Q)}$$

Nonlinear Inhomogeneous Spacetime

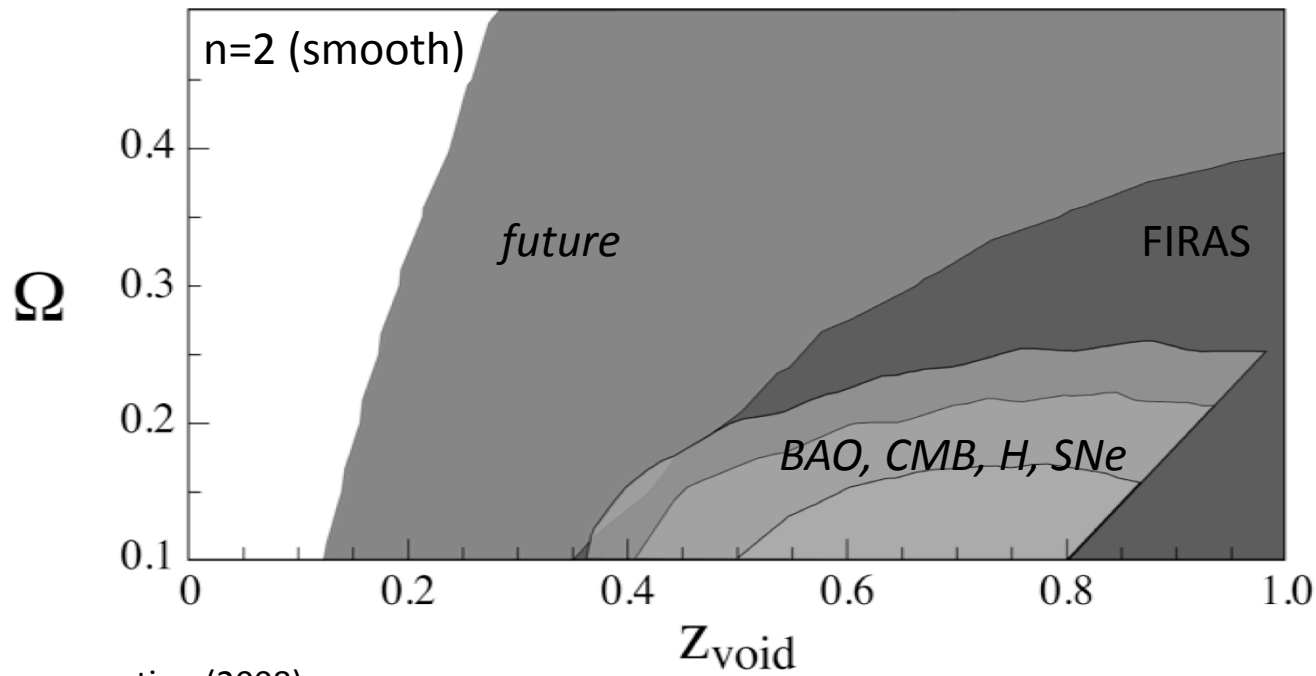
u-distortion rules out a wide range of parameters describing anti-Copernican, inhomogeneous cosmological models



Caldwell & Stebbins, in preparation (2008)

Nonlinear Inhomogeneous Spacetime

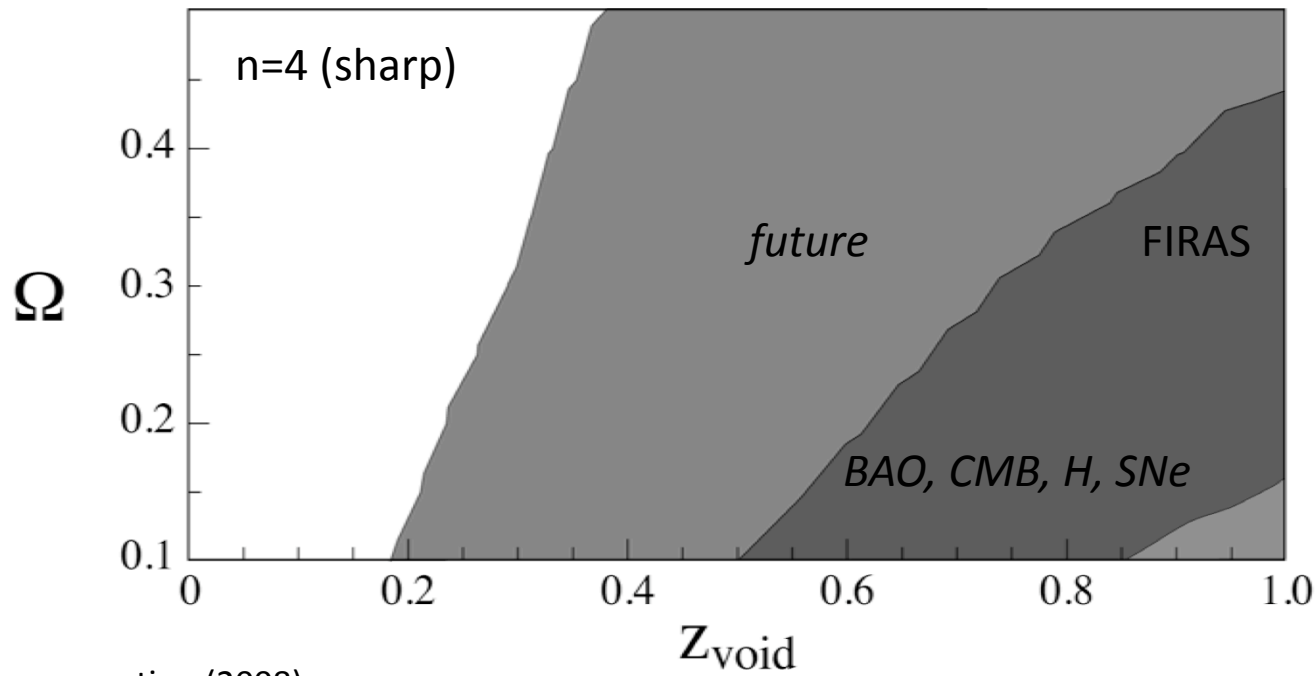
u-distortion rules out a wide range of parameters describing anti-Copernican alternatives to Dark Energy



Caldwell & Stebbins, in preparation (2008)

Nonlinear Inhomogeneous Spacetime

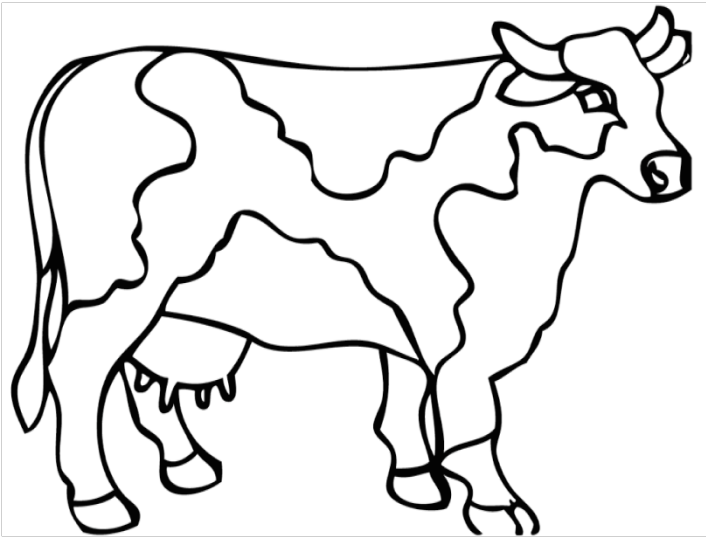
u-distortion rules out a wide range of parameters describing anti-Copernican alternatives to Dark Energy



Caldwell & Stebbins, in preparation (2008)

?

Λ



Q

ρ

G