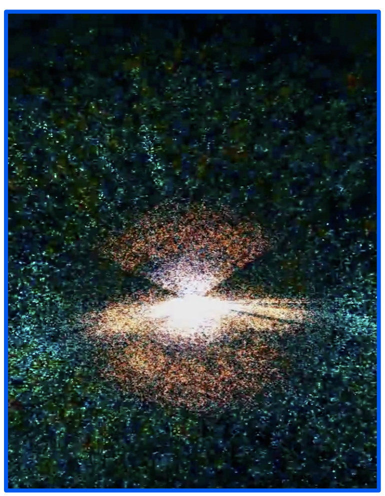
Physics of Cosmic Acceleration

3. Dark Energy as Gravity

Eric Linder

II Tiomno School (Rio 2012)

UC Berkeley & Berkeley Lab
Institute for the Early Universe, Korea



Expansion History

Observations that map out expansion history a(t), or w(a), tell us about the fundamental physics of dark energy.

Alterations to Friedmann framework → *w(a)*

Suppose we admit our ignorance:

$$H^2 = (8\pi/3)\,\rho_m + \delta H^2(a)$$

gravitational extensions
or high energy physics

Effective equation of state:

$$w(a) = -1 - (1/3)\, d\mathit{ln}\,(\delta H^2) \,/\, d\mathit{ln}\, a$$

Modifications of the expansion history are equivalent to time variation w(a). ***Period.***

ISW Potentials and Acceleration

The Integrated Sachs Wolfe (ISW) has been claimed to be a direct probe of acceleration. **Is it?**

Newtonian gravitational potential ϕ stays constant during matter domination.

$$\nabla^2\phi \to (k/a)^2\phi = 4\pi G\,\delta\rho_{\rm tot} \approx 4\pi G\rho_{\rm m}(\delta\rho/\rho)_{\rm m}$$

For matter domination, $\delta \sim a$, so $\phi \sim$ const.
ISW arises from $\dot{\phi}$ so no effect in matter domination.

ISW only shows breakdown of matter domination, *not* acceleration. (If other perturbations important then also not matter dominated.)

What about gravity? ISW actually depends on $(\dot{\phi}+\dot{\psi})/2$ ...

The Direction of Gravity

Cosmic acceleration: Gravity is pulling *out* not down!

Is gravity (G_{Newton}) constant, or strengthening, or weakening with time?

Does gravity govern the growth of large scale structure exactly as it does for cosmic expansion, or are there more degrees of freedom?

Effect of gravity on light (strong/weak lensing).

Does gravity behave the same on all scales?

Dark energy motivates us to ask "what happens when gravity no longer points down?".

Reality Check

Cosmic gravity desperately needs to be tested.
Why?

1) Because we can.

2) Because of the long extrapolation of GR from small scales to cosmic scales, from high curvature to low curvature.

3) GR + Attractive Matter fails to predict acceleration in the cosmic expansion.

4) GR + Attractive Matter fails to explain growth and clustering of galaxy structures.

First two cosmic tests failed – explore diligently!

see P.J.E. Peebles astro-ph/0208037 for inspiration

Cosmological Framework

Comparing cosmic **expansion history** vs. cosmic **growth history** is one of the major tests of the cosmological framework.

If do *not* simultaneously fit then deviation in one biases the other, e.g. looks like non-GR or non-Λ.

Approach 1: Separate out the expansion influence on the growth – **gravitational growth index** γ.

Approach 2: Parametrize equations of motion, i.e. Poisson equation and lensing equation – **gravity functions** $G_{\text{matter}}(k,a)$, $G_{\text{light}}(k,a)$.

Physics of Growth

Growth $g(a)=(\delta\rho/\rho)/a$ depends purely on the expansion history $H(z)$ -- *and* gravity theory.

$$g'' + [5 + \tfrac{1}{2}\frac{d\ln H^2}{d\ln a}]g'a^{-1} + [3 + \tfrac{1}{2}\frac{d\ln H^2}{d\ln a} - \tfrac{3}{2}G\,\Omega_m(a)]\,ga^{-2} = 0$$

Expansion effects via $w(z)$, but *separate* effects of gravity on growth.

$$\boxed{g(a) = \exp\{\int_0^a d\ln a\,[\Omega_m(a)^\gamma - 1]\}}$$

Linder 2005

Growth index γ is valid parameter to describe modified gravity. Accurate to 0.1% in numerics.

Similar to Peebles 1980 (γ=0.6) and Wang & Steinhardt 1998 (constant w).

Violating Matter Domination

Gravitational growth index γ depended on early matter domination. Need calibration parameter for growth, just like for SN (low z) and BAO (high z) distances.

$$g(a) = g_* \exp\{ \int_0^a d\ln a\, [\Omega_m(a)^\gamma - 1] \}$$

Linder 2009
0901.0918

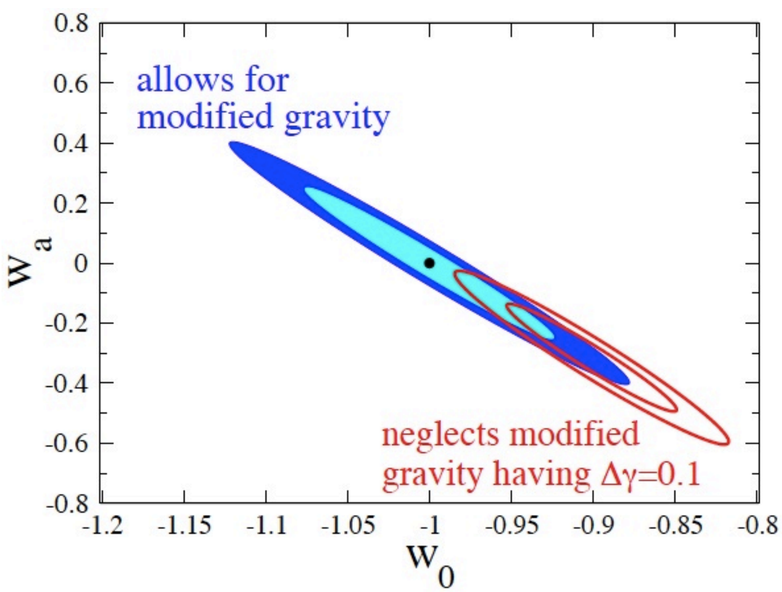
g_* is nearly constant, single parameter, handles early time deviations: modGR, early DE, early acceleration. *Separate* from γ, w; accurate to 0.1%.

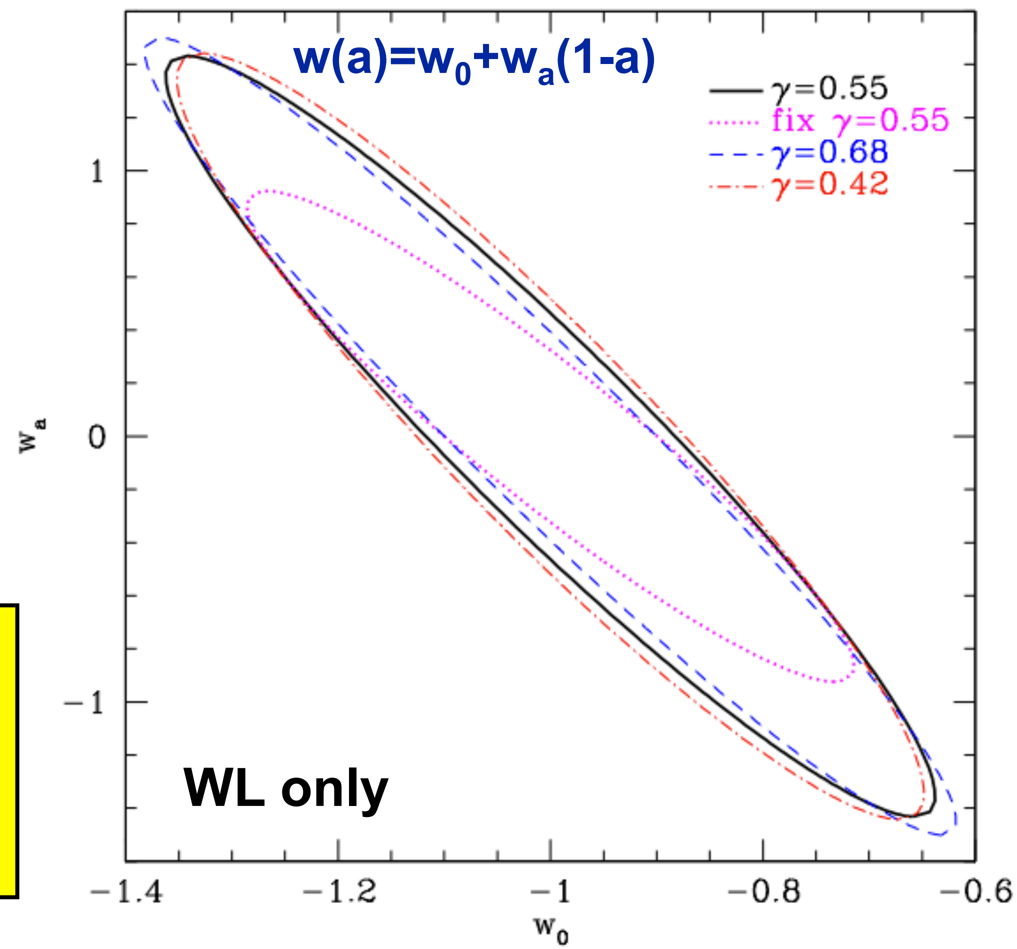
Beyond the Standard Model 3 **simultaneous fit to $\{\Omega_m, w_0, w_a, \gamma, g_*\}$. Next generation data can test $\sigma(\Omega_e)=0.005$, $\Delta G_{early}/G=1.4\%$, $\Delta \ln a=1.7\%$.**

Cosmological Framework

Allow parameters to describe growth separate from expansion, e.g. gravitational growth index γ. Otherwise bias $\Delta w_a \sim 8\Delta\gamma$

$$f = \frac{d\ln D}{d\ln a} \sim \Omega_m(a)^\gamma$$

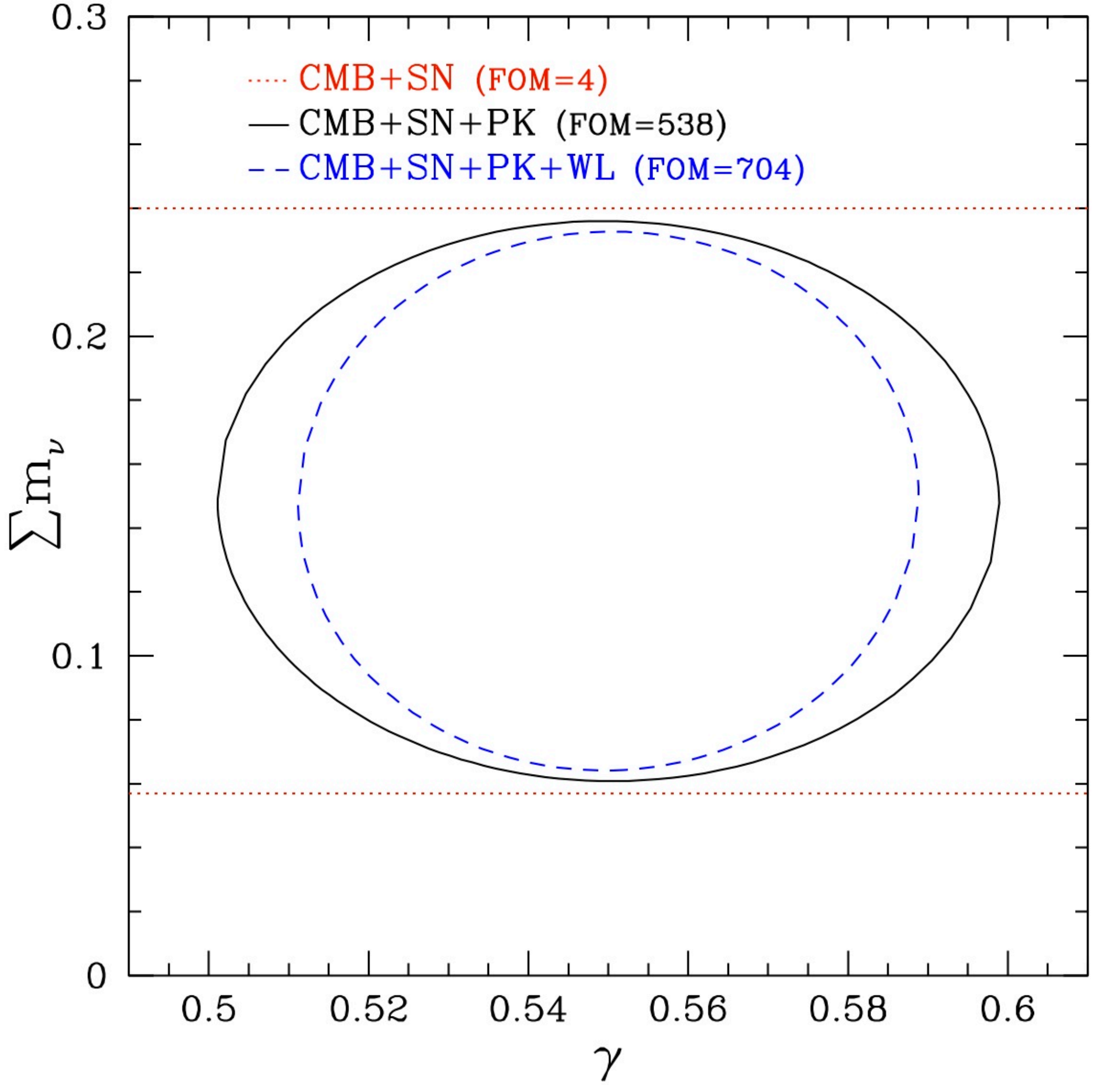




Fit simultaneously; good distinction from equation of state.

5 Year Realization (Cosmology 2017)

CMB lensing also probes gravity.
CMBlens+BOSS+DES can get $\sigma(\gamma)=0.026$ by ~2017!



Fit for vanilla +

- w_0, w_a
- m_ν
- γ

Das & Linder 2012

Beyond GR Functions

Test gravity in model independent way.

Gravity and growth: $\nabla^2\phi = 4\pi G\, a^2\, \delta\rho$

Gravity and acceleration: $-\vec{\nabla}\psi = \ddot{x}$

Are ϕ and ψ the same? (yes, in GR)

Tie to observations via modified Poisson equations:

$$\nabla^2(\phi+\psi) \;=\; 8\pi G_N\, a^2\, \delta\rho \times G_{\rm light}$$
$$\nabla^2\psi \;=\; 4\pi G_N\, a^2\, \delta\rho \times G_{\rm matter}$$

G_{light} tests how light responds to gravity: central to lensing and integrated Sachs-Wolfe.

G_{matter} tests how matter responds to gravity: central to growth and velocities (γ is closely related).

Notation

xkcd.com/927

2 x 2 x 2 Gravity

Bin in k and z:

Model independent "2 x 2 x 2 gravity"

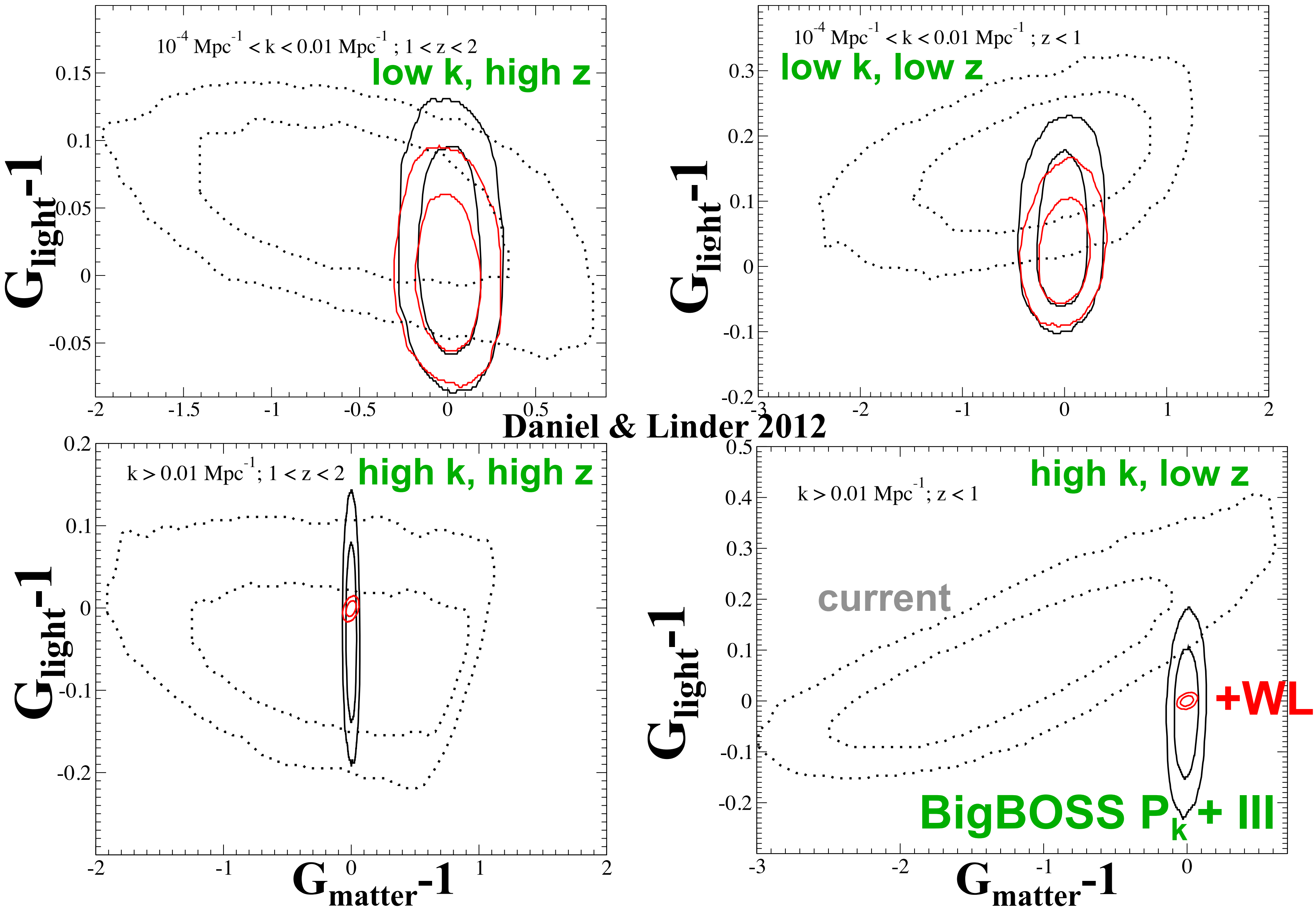
Why bin?

1) Model independent.

2) Cannot constrain >2 PCA with strong S/N (N bins gives $2N^2$ parameters, $N^2(2N^2+1)$ correlations).

3) a^s form gives bias: value of s runs with redshift so fixing s puts CMB, WL in tension. Data insufficient to constrain s.

Next Generation Leverage



5-10% test of 8 parameters of model-independent gravity.

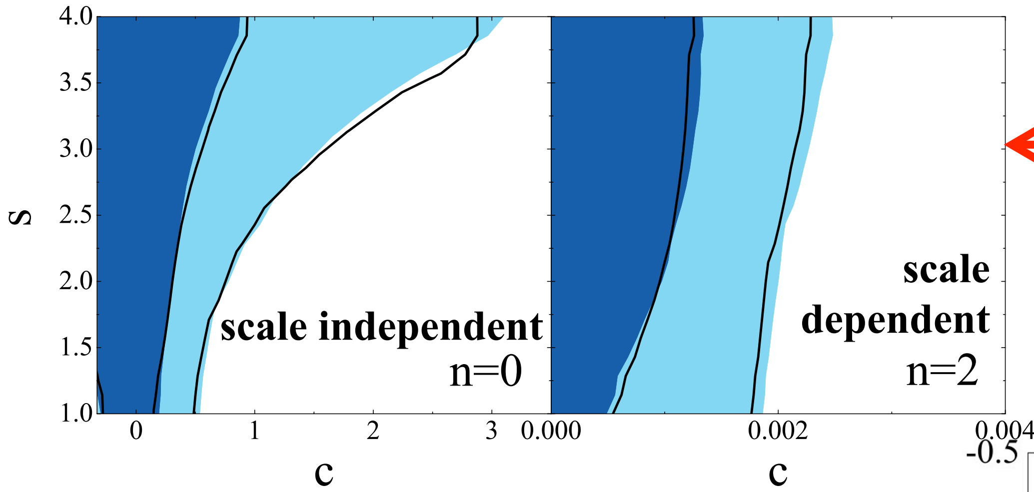
Scale and Time Dependence

Padé approximant weights high/low z fairly.

$$G_{\rm matter} = 1 + \frac{c a^s (k/H_0)^n}{1 + 3|c| a^s (k/H_0)^n}$$

Zhao+ 1109.1846

Accurate to ~1% for f(R) and DGP gravity.

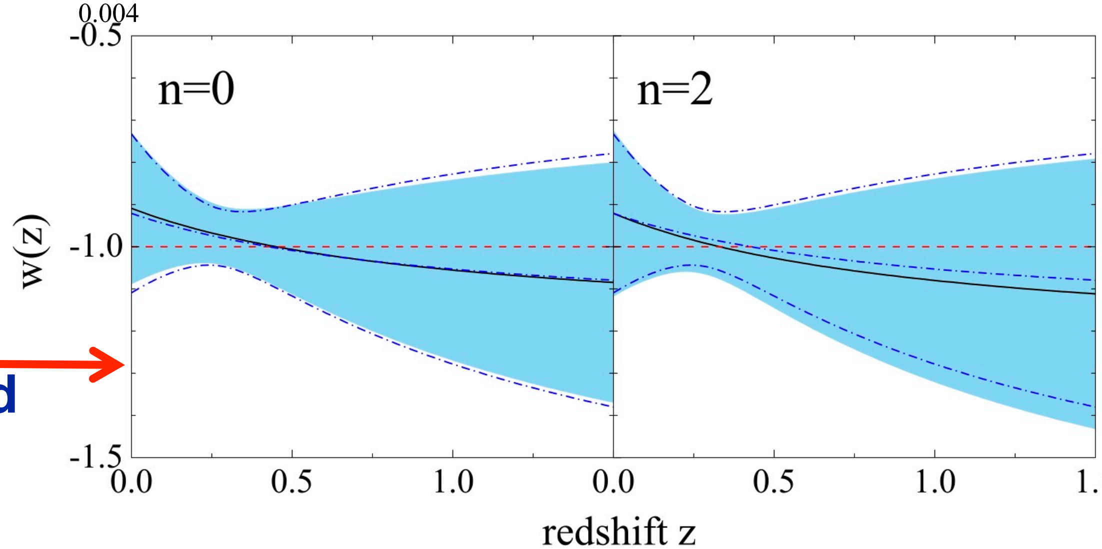


Shaded – fix to Λ ; Outline – fit w_0, w_a

Gravity fit unaffected by expansion fit.

Outline – fix to GR ; Shaded – fit gravity c,s

Expansion fit unaffected by gravity fit.



Types of Gravity

Gravity beyond general relativity must still approach GR in the early universe and the solar systems.

3 classes of achieving this have been identified.

Khoury 2010

Dimensional reduction [DGP] – GR restored below Vainshtein scale $r_\star(M)$.

Strong coupling [f(R), scalar/tensor] – field mass becomes large near large density and freezes out.

Symmetron – field decouples as symmetry forces vanishing VEV.

On cosmic scales, first and third similar so just consider DGP and f(R).

Paths of Gravity

Scalar field dark energy (and Λ) have problems with **naturalness** of potential and high energy physics corrections.

Can avoid *both* problems by having a purely **geometric** object with no potential.

Galileon fields arise as geometric objects from higher dimensions and have shift symmetry protection.

Nicolis+ 2009, Deffayet+ 2009

They also have **screening** (Vainshtein), satisfying GR on small scales.

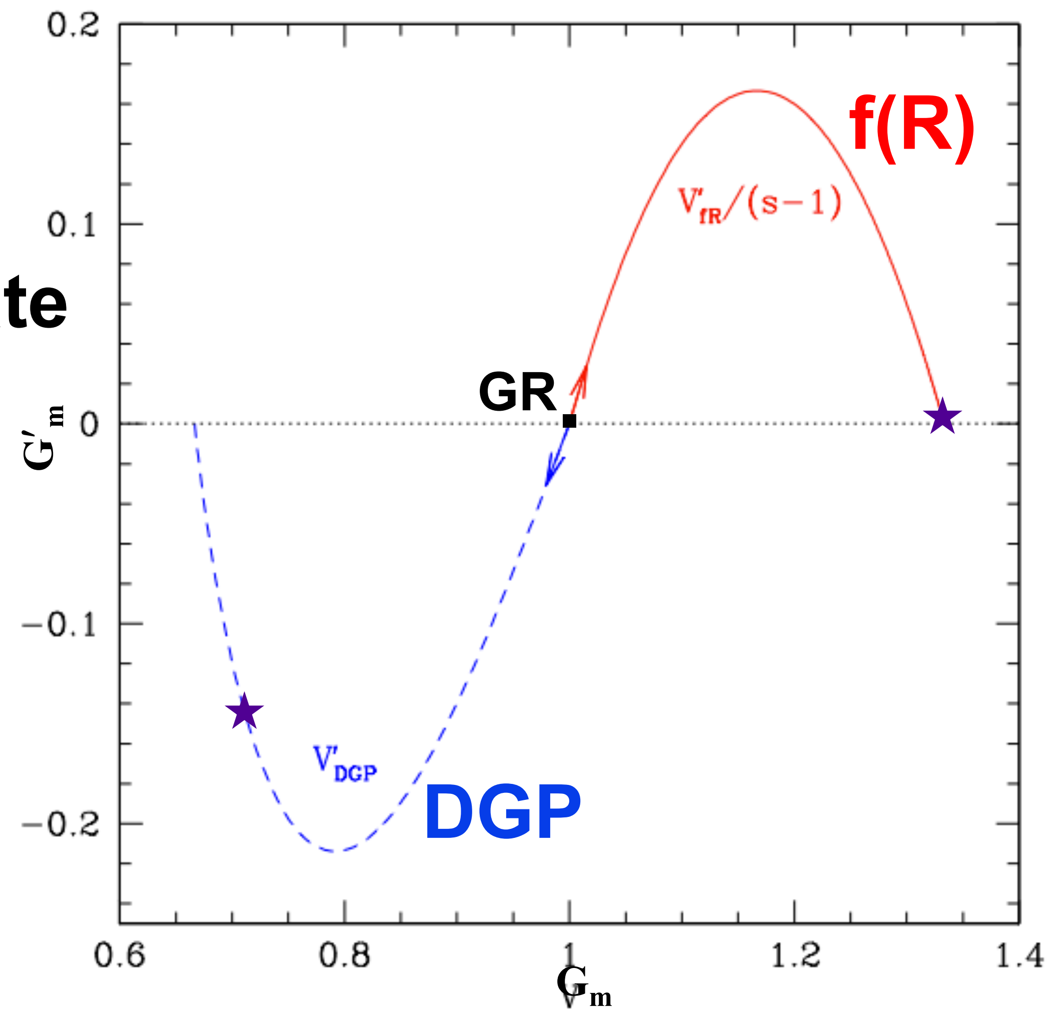
The Direction of Gravity

Understanding whether gravity weakens or strengthens (or is constant) with time is a key clue to the physics of extended gravity.

Look at G_{matter}-G'_{matter}

These theories separate in phase space.

Today, ΔG_m~±0.3 so gravity requirement is 3σ measure requires $\sigma(G_m)$~0.1.



Linder 2011

Galileon Gravity

Scalar field π with shift symmetry $\pi \rightarrow \pi + c$, derivative self coupling, guaranteeing 2nd order field equations.

$$S = \int d^4x \sqrt{-g} \left[\left(1 + 2c_0 \frac{\pi}{M_{\rm pl}}\right) \frac{M_{\rm pl}^2 R}{2} - \frac{c_2}{2}(\partial\pi)^2 - \frac{c_3}{M^3}(\partial\pi)^2 \Box\pi - \frac{c_4 \mathcal{L}_4}{2} - \frac{c_5 \mathcal{L}_5}{2} - \frac{M_{\rm pl}}{M^3} c_G G^{\mu\nu} \partial_\mu \pi \partial_\nu \pi - \mathcal{L}_{\rm m} \right]$$

GR

Linear coupling

Derivative coupling

Standard Galileon

Coupled Galileons ruled ~out by Appleby & Linder 1112.1981 **due to instabilities.**

Expansion & Gravity

Solve for background expansion and for linear perturbations – field evolution and gravity evolution.

$$\bar{\nabla}^2\phi = \frac{4\pi a^2 G_{\rm eff}^{(\phi)}\rho_{\rm m}}{H_0^2}\delta_{\rm m}$$

$$\bar{\nabla}^2\psi = \frac{4\pi a^2 \overbrace{G_{\rm eff}^{(\psi)}}^{G_{\rm matter}}\rho_{\rm m}}{H_0^2}\delta_{\rm m}$$

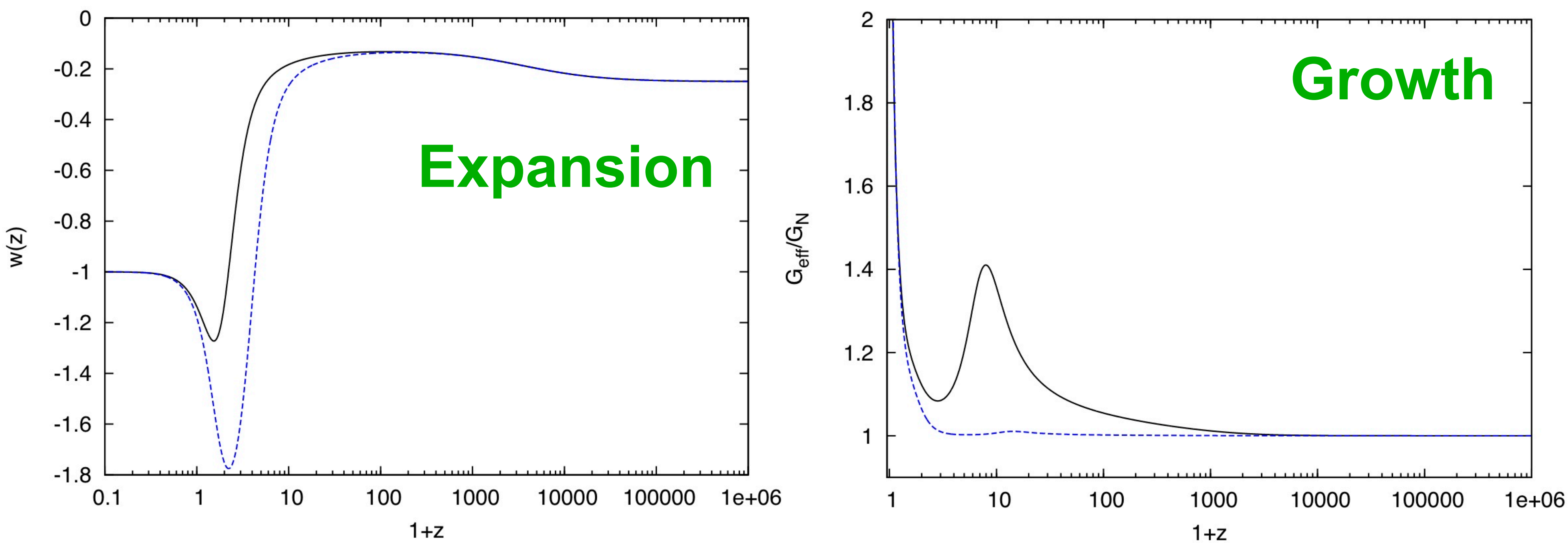
$$\bar{\nabla}^2(\psi+\phi) = \frac{8\pi a^2 \overbrace{G_{\rm eff}^{(\psi+\phi)}}^{G_{\rm light}}\rho_{\rm m}}{H_0^2}\delta_{\rm m}$$

Modified Poisson equations. Can study "paths of gravity" evolution of G(a).

Theory constrained by no-ghost condition and stability $c_s^2>0$.

Data vs Gravity

Galileon cosmology has early time tracker solutions (no fine tuning) and late time de Sitter attractor (slip=0). Beautiful class of theories!



But Appleby & Linder 1204.4314 **rule out Standard Galileon with $\Delta\chi^2_{LCDM}$>30 from current data. Data kill entire class of gravity!**

Beyond Einstein Gravity

Expansion is not the only determiner of growth of massive structure. "The Direction of Gravity"

Anisotropic Stress/Gravitational Slip

Metric fluctuations:

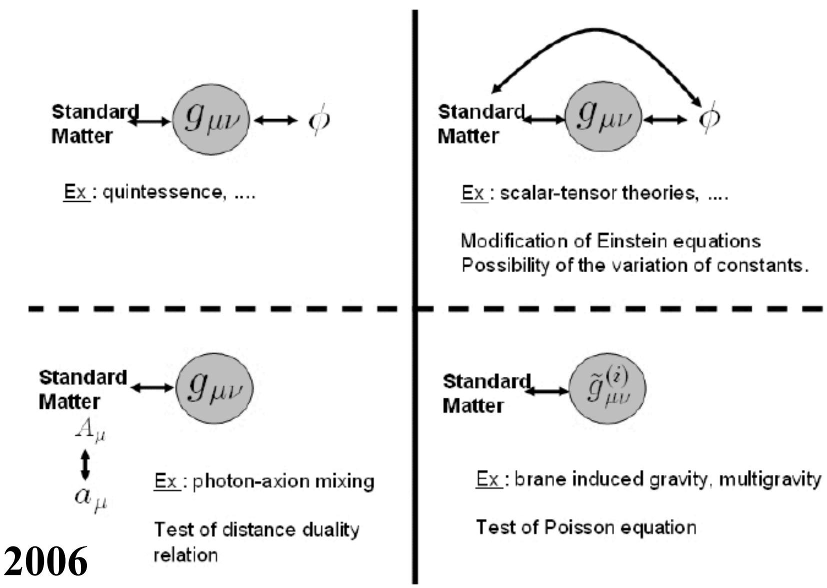
Poisson equations

Euler equation

Energy-momentum:

Continuity equation

$$\begin{tikzcd} \phi \arrow[r] \arrow[d] & \psi \arrow[d] \\ \delta \arrow[r] & v \end{tikzcd}$$



Uzan 2006

Need to know:

Expansion
DE perturbations
Couplings
Gravity

Theoretical Thoughts

Is a gravity explanation better than a scalar field explanation for dark energy?

It can be equally bad: arbitrariness of f(R) vs V(ϕ).

It usually does not solve the Λ problem
(except self-tuning fields see Charmousis+ 2011, Appleby+ 2012**)**

It may have fundamental geometric origins from higher dimensions.

It can be protected against radiative corrections.

Screening mechanisms give extra handles for tests.

Some are distinct from Λ and so can be ruled out!

The "B" word

Is acceleration caused by inhomogeneity?
There are many reasons and long history to say no.

Math – Expansion is not a number H but a 3x3 matrix H_{ij}. Hard to change diagonal by O(1) but offdiagonal by $<10^{-5}$.

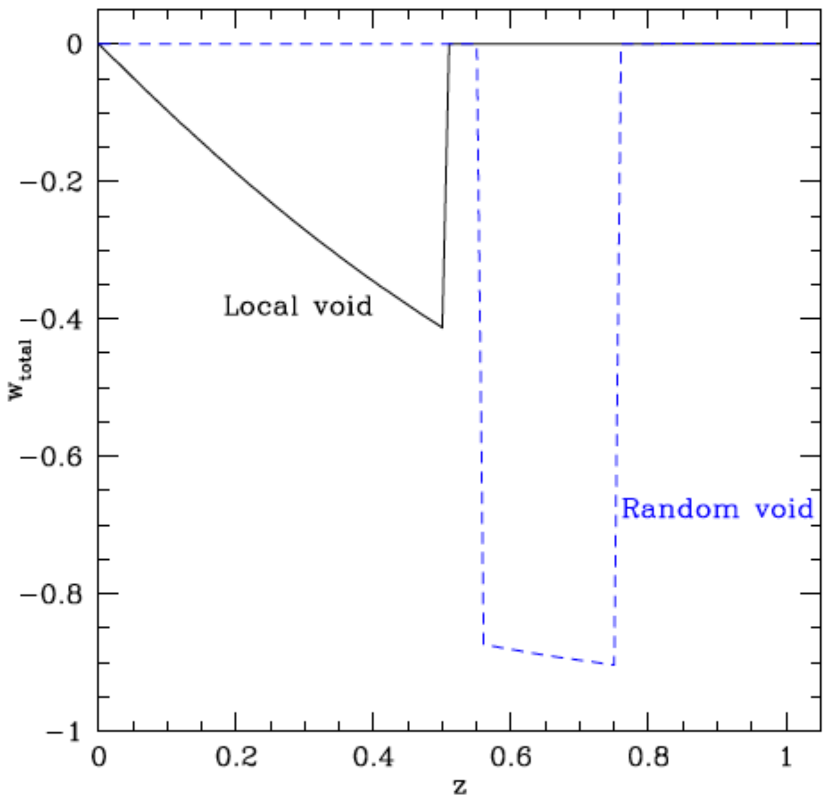
Physics – Chandrasekhar addressed this in 1940s: "mean field theory/two length scale formalism". Define size of potential (not density!) by ε^2, length by $\kappa=HL$. Geodesics change (dynamics) by ε^2/κ. If $\varepsilon^2/\kappa\sim 1$ then galaxies move at speed of light! See Jacobs, Linder, Wagoner 1992, 1993.

Data – WiggleZ direct measure of homogeneity 1205.6812, kSZ measures velocity from density inhomogeneity 1009.3967

The “B” word

Supernovae just measure line of sight so easy to confuse acceleration with them alone. Must satisfy many other constraints: growth, velocity, CMB.

Global void



Mirage; void must be huge

Local clumps

Raychaudhuri eq implies

$$\Omega_m(z) = 1 + 3w_{\rm tot}(z) \quad ; \quad \alpha(z) = \frac{1+w_{\rm tot}}{1+3w_{\rm tot}} ,$$

Cannot achieve acceleration with positive energy density.

0801.2968

Fundamental Scale

Exercise 3.1: Put a fundamental scale in the Friedmann equation for H(a), say as a power law $\delta H^2=(H/r_c)^n$. What is w(a) and the early/late time behavior?

For resources on dark energy as gravity, see

Jain & Khoury 2010, *Cosmological Tests of Gravity*
http://arxiv.org/abs/1004.3294 and the references cited therein.