The Direction of Gravity

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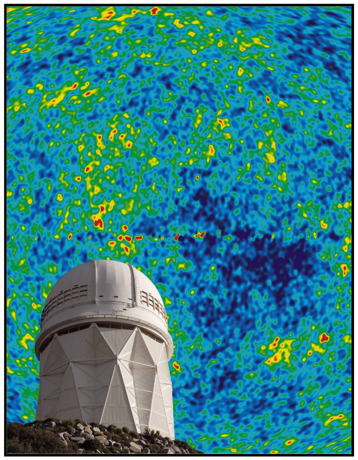


The Direction of Gravity

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?".

Higher Dimensional Data

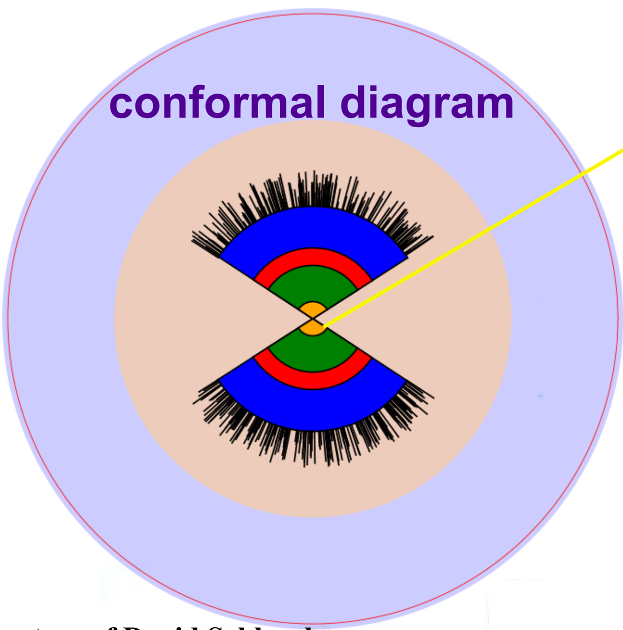
Cosmological Revolution:

From 2D to 3D – CMB anisotropies to tomographic surveys of density/velocity field.

Data, Data, Data

As wonderful as the CMB is, it is 2-dimensional. The number of modes giving information is *l(l+1)* or ~10 million.
BOSS (SDSS III) will map 400,000 linear modes.
BigBOSS/Euclid will map 15 million linear modes.

N. Padmanabhan



SDSS I, II, 2dF

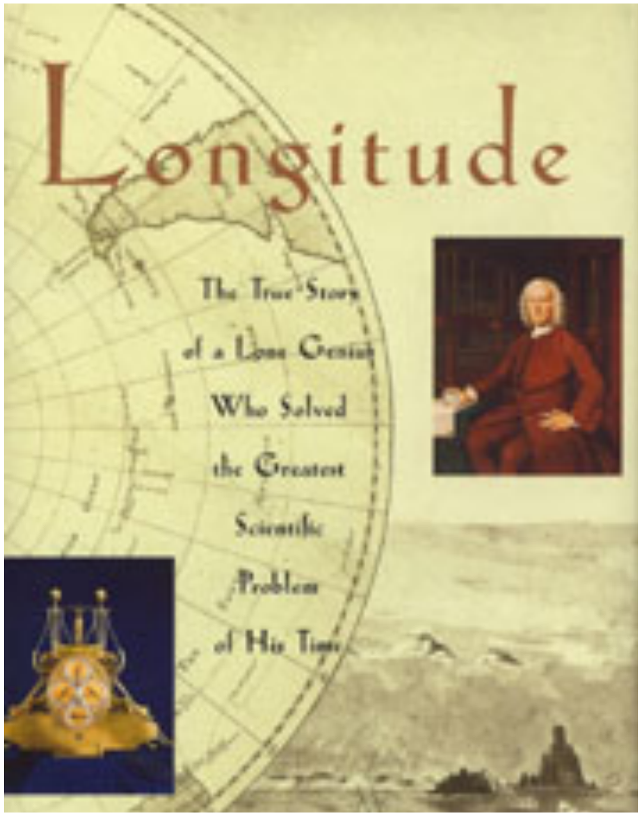
BOSS (SDSS III)

BigBOSS
18 million galaxies
z=0.2-1.5
600,000 QSOs
z=1.8-3

Maps of
density
velocity
gravity

courtesy of David Schlegel

“Greatest Scientific Problem”



“When I’m playful I use the meridians of longitude and parallels of latitude for a seine, drag the Atlantic Ocean for whales.”

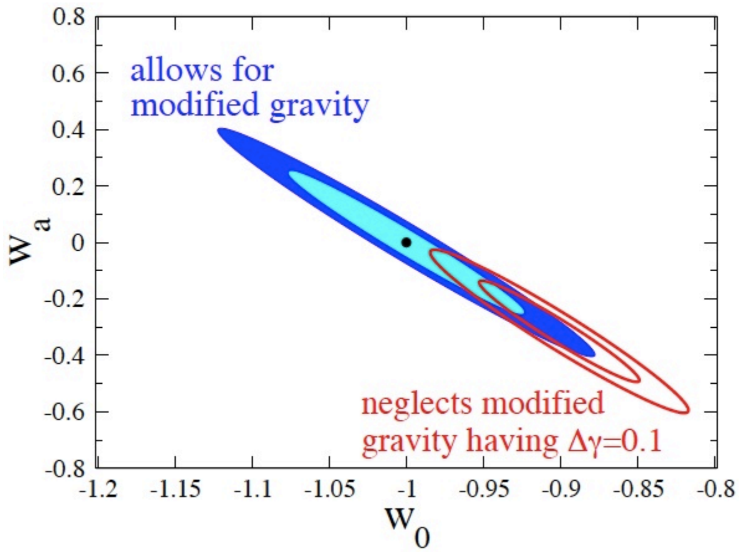
– Mark Twain, *Life on the Mississippi*

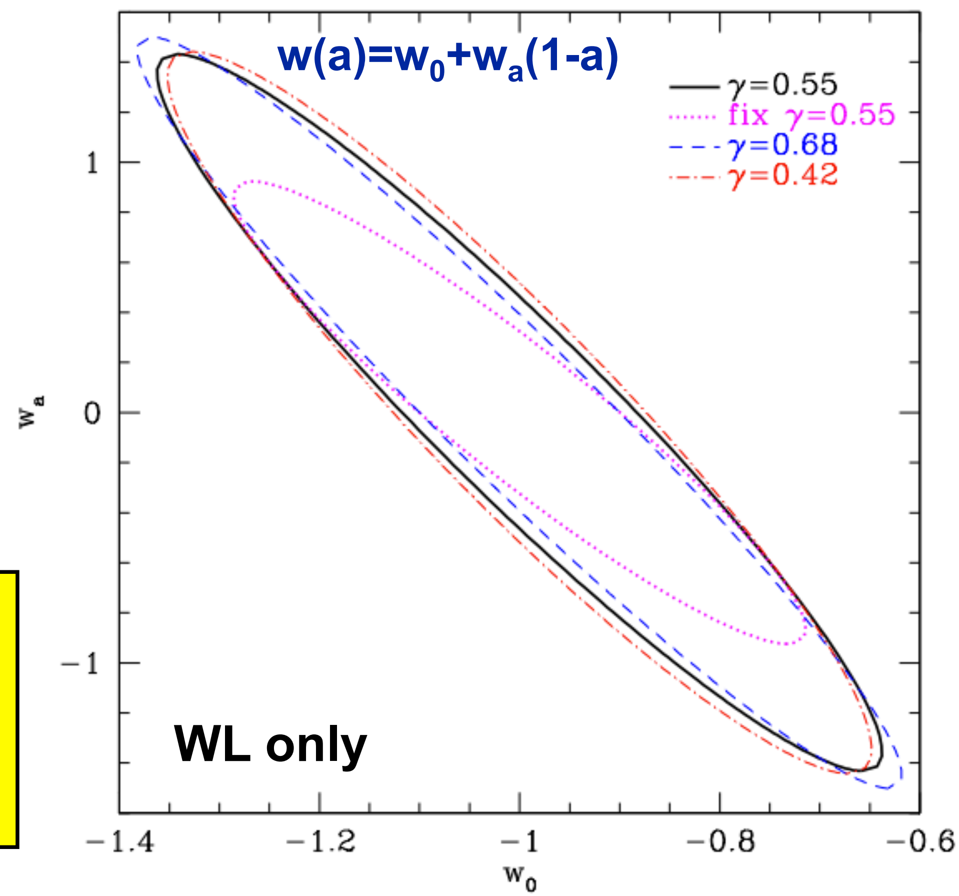
Cosmological Framework

Allow parameters to describe growth separate from expansion, e.g. gravitational growth index γ.

Otherwise bias $\Delta w_a \sim 8\Delta\gamma$

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

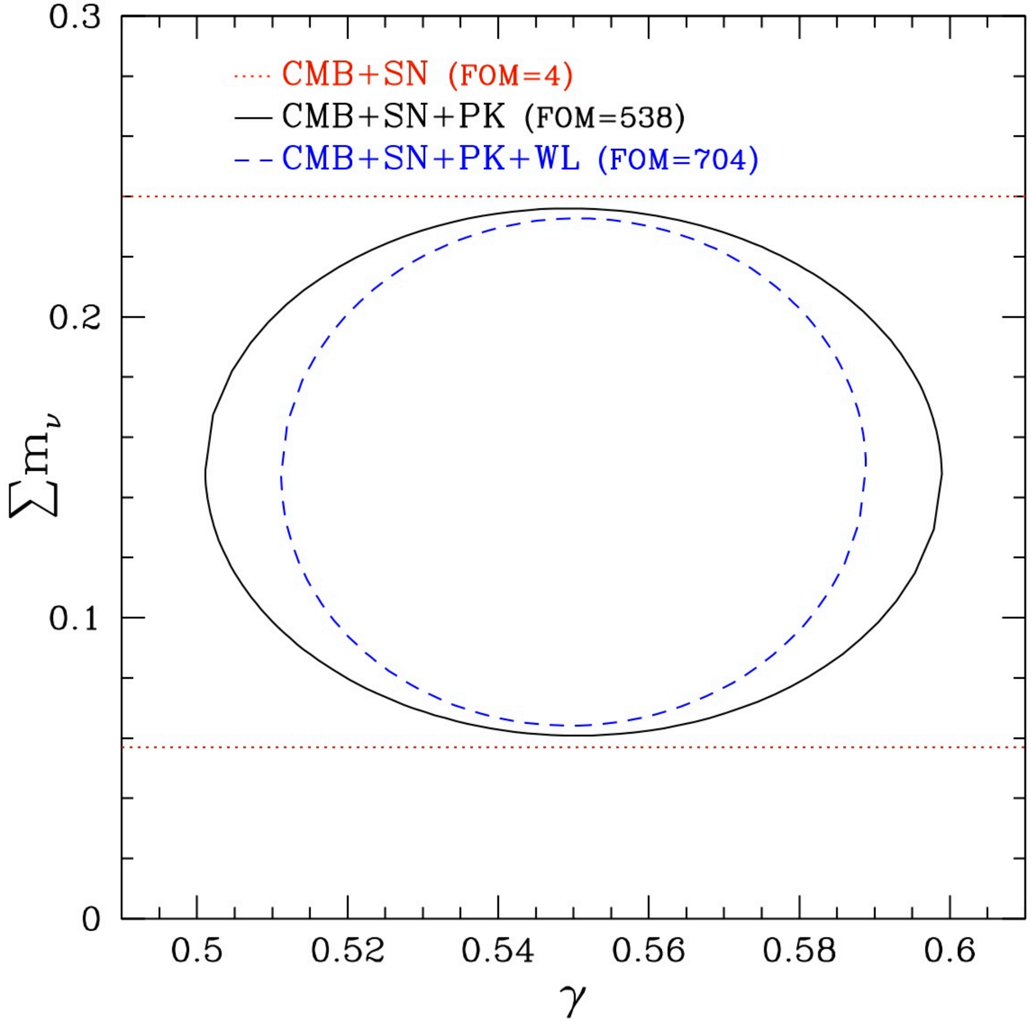




Fit simultaneously; good distinction from equation of state.

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:

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

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).

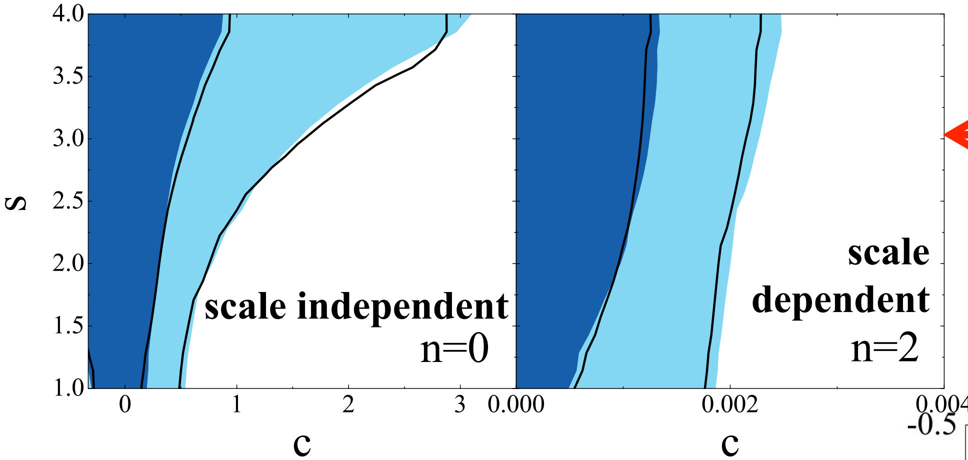
Scale and Time Dependence

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.

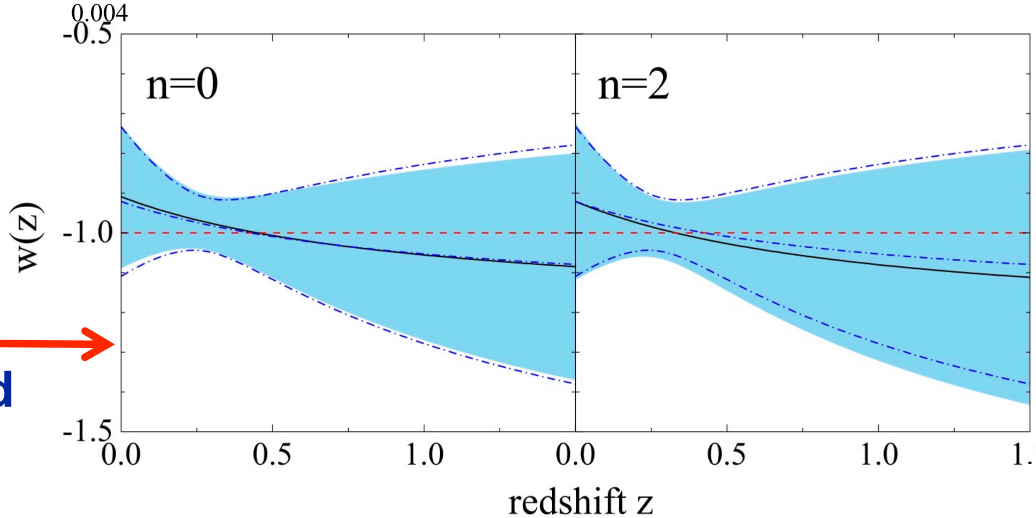


Shaded – fix to Λ ; Outline – fit w_0, w_a

Gravity fit unaffected by expansion fit.

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

Expansion fit unaffected by gravity fit.



2 x 2 x 2 Gravity

Bin in k and z:

Model independent "2 x 2 x 2 gravity"

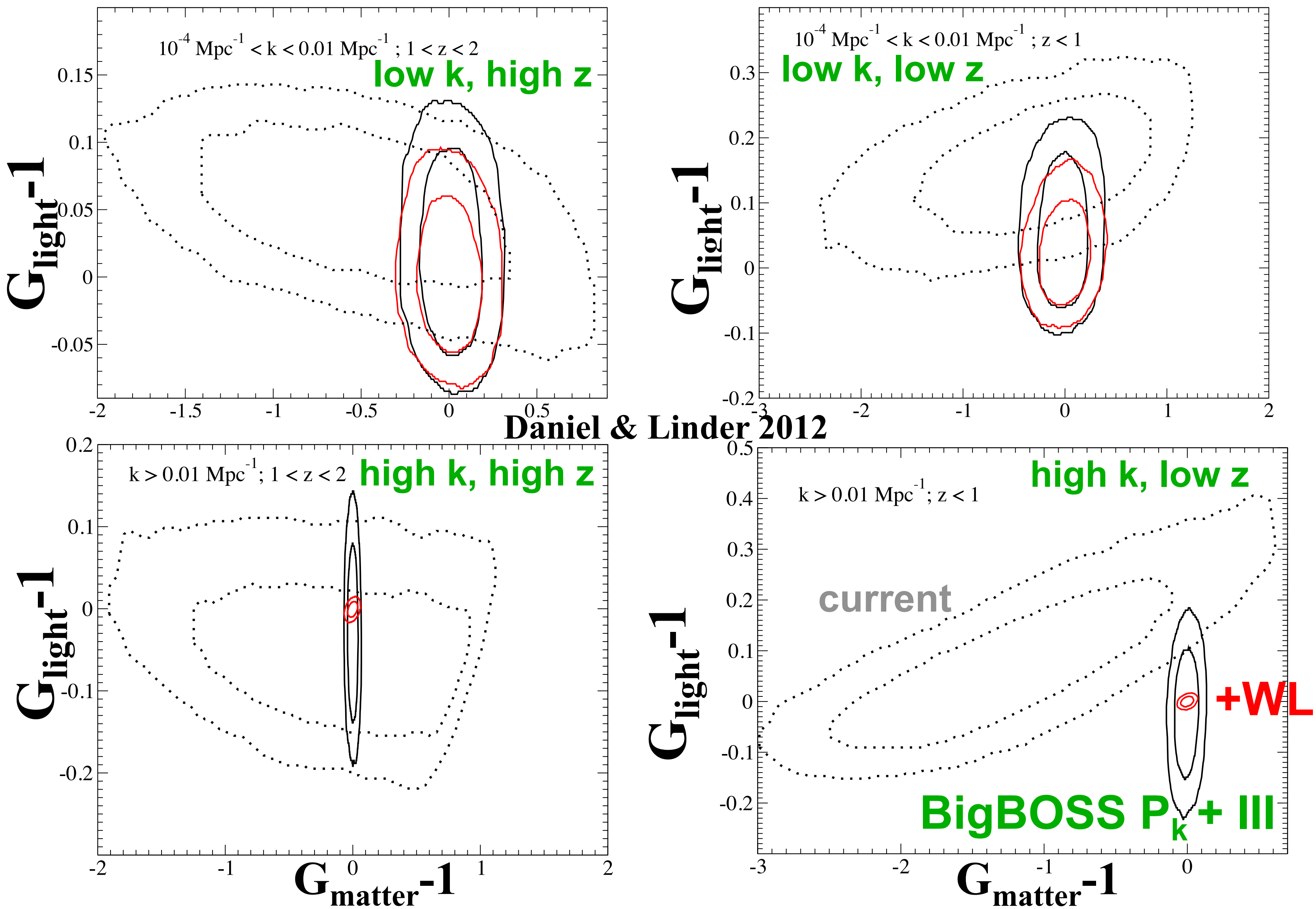
Why bin?

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.

The Direction of Gravity

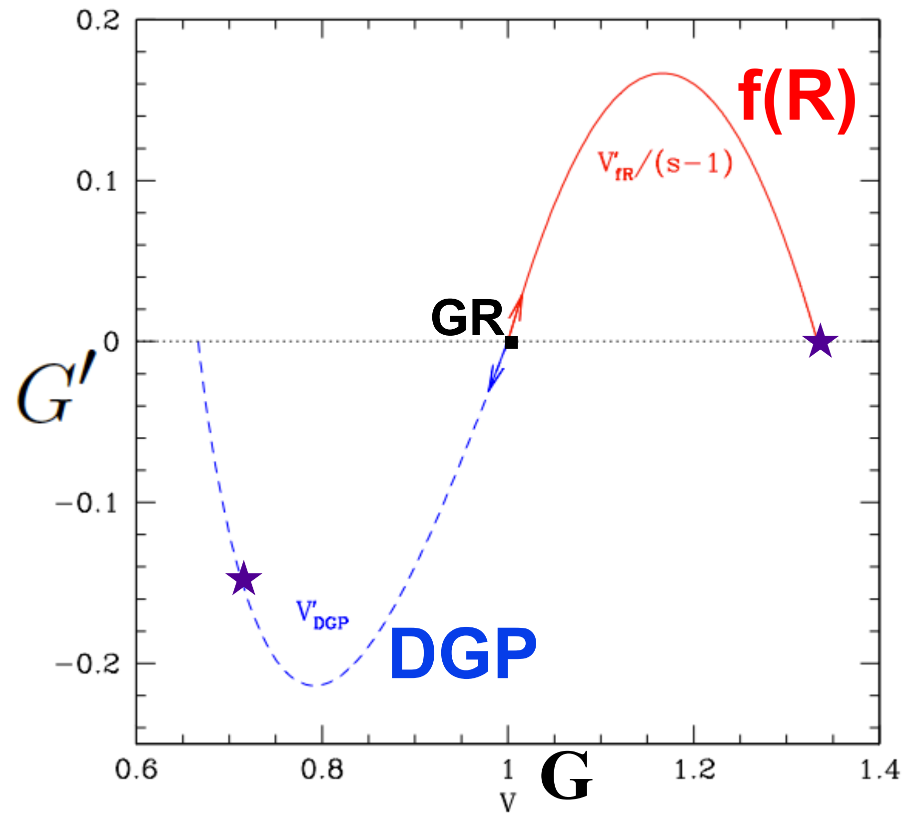
Scalar field dark energy (and Λ) have problems with **naturalness** of potential and high energy corrections.

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 (like DGP).

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

Nicolis+ 2009, Deffayet+ 2009



Galileon Gravity

Scalar field π with shift symmetry $\pi \to \pi+c$, 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

Standard Galileon

Derivative coupling

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.

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

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

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

$G_{\rm matter}$

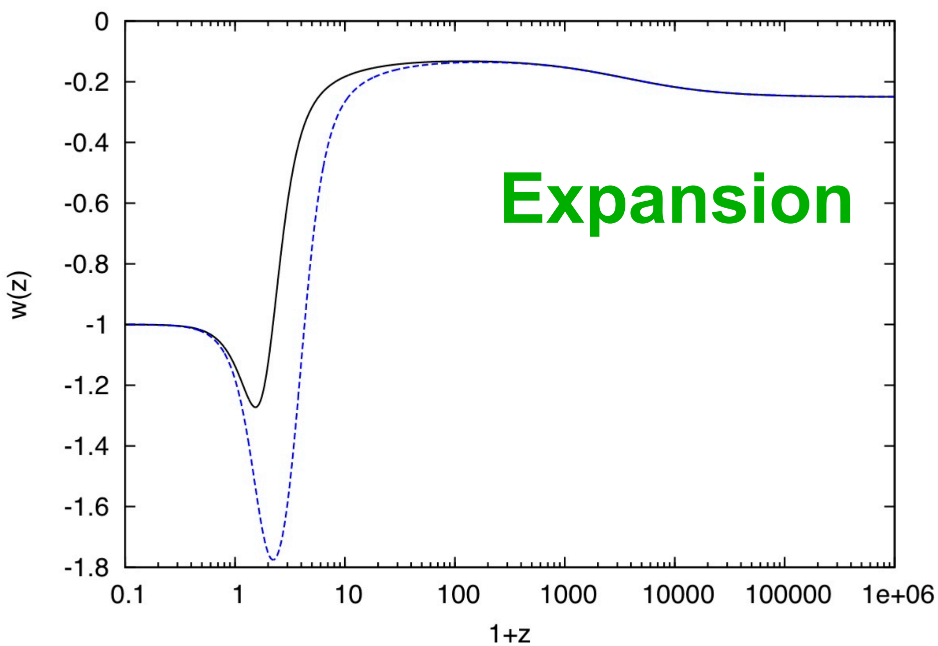
$G_{\rm light}$

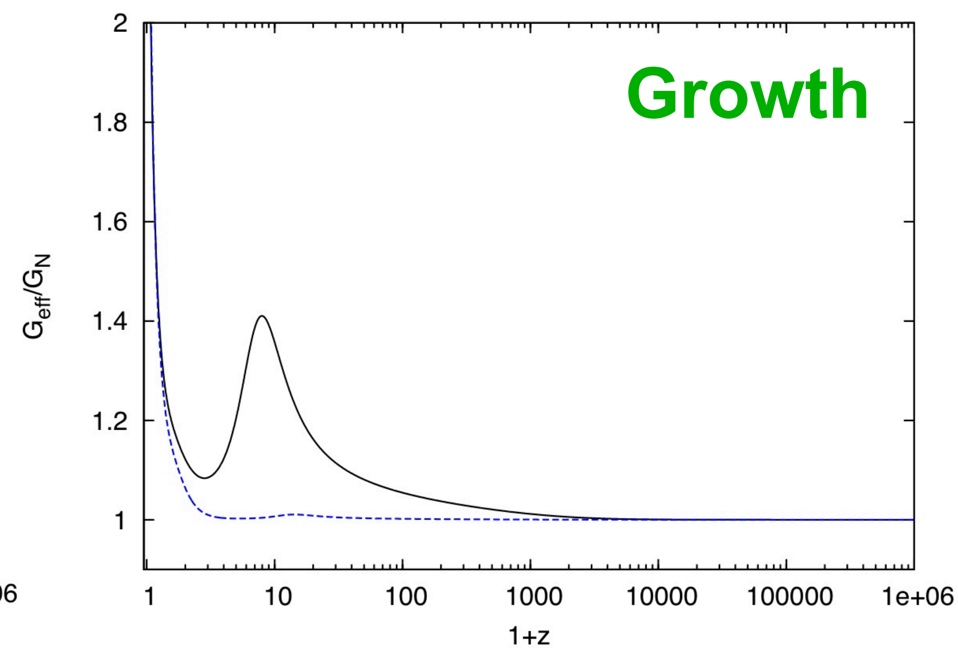
Modified Poisson equations. Can study "paths of gravity" evolution of G(a).

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!**

Weirder Gravity (and Λ)

From Horndeski general scalar-tensor theory,
Charmousis+ 2011 **found "Fab 4" unique self tuning terms.**
Appleby, De Felice, Linder 2012 **promote to nonlinear, mixed function.**

$$f\left(c_2 g^{\mu\nu}\phi_\mu\phi_\nu + c_G G^{\mu\nu}\phi_\mu\phi_\nu\right)$$

"Fab 5 Freddy"

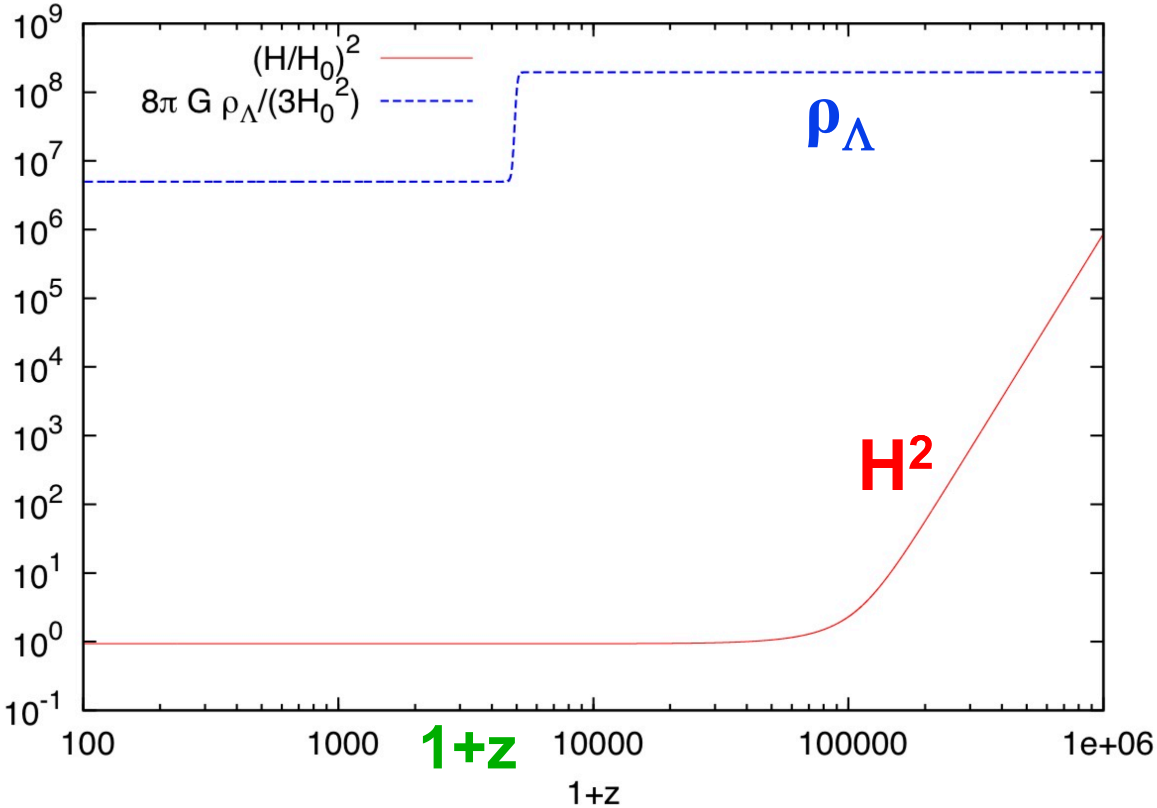
Noncanonical, nonlinear kinetic "hip-hop" gravity

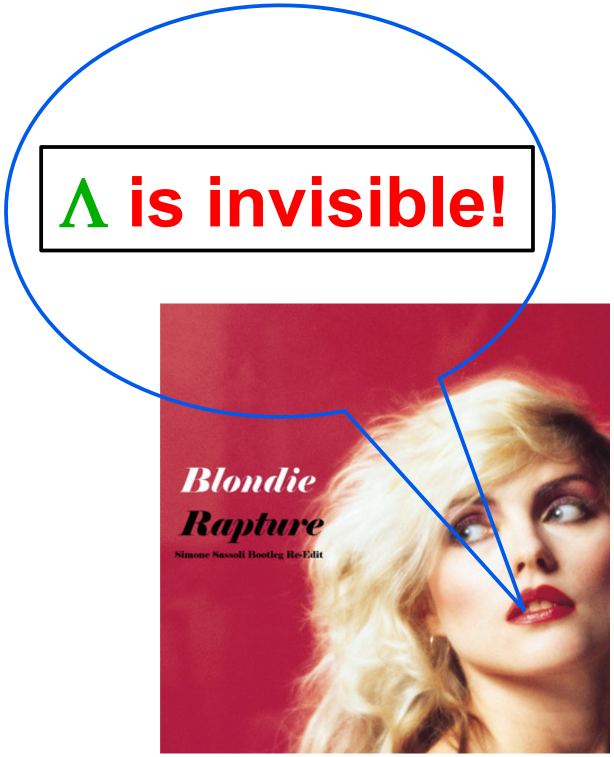
"Fab 5 Freddy told me everybody's fly" – Blondie, *Rapture*

Fab 5 Freddy

Fab 5 Freddy indeed accelerates, and has tracker, dS attractor, no extra dof! – and self tuning.

ϕ dynamically adjusts to cancel Λ, even thru phase transition.





Summary

2D to 3D mapping of cosmic structure is major advance. Galaxy redshift + CMB lensing: $\sigma(\gamma)=0.026$

Measure growth history. Comparison with expansion history opens window on gravity physics. w(a) alone not enough (especially if w~-1): G_{matter}, G_{light}. Don't fix w_0, w_a, GR, m_ν etc!

Data already powerful enough to put Galileon gravity on trial.

Model independent approach: 2 x 2 x 2 gravity. 5-10% measures possible with next generation.

Lots of interesting theory still to explore!