Dark energy or modified gravity?

a proof of concept of a robust observational test
using weak lensing and redshift distortions

Reina Reyes
Princeton University

Jim Gunn (Princeton), Rachel Mandelbaum (Princeton),
Uroš Seljak (LBNL/UC Berkeley), Lucas Lombriser (U Zurich),
Robert E. Smith (U Zurich)

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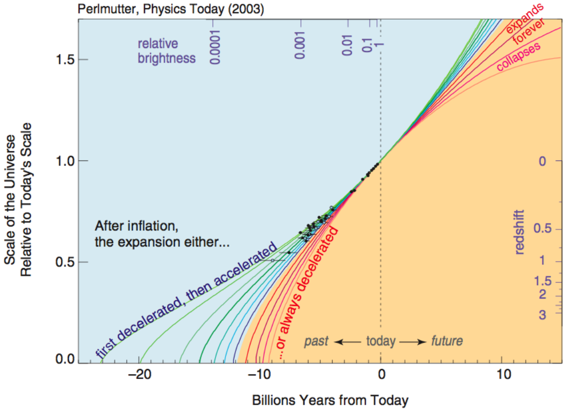
Outline

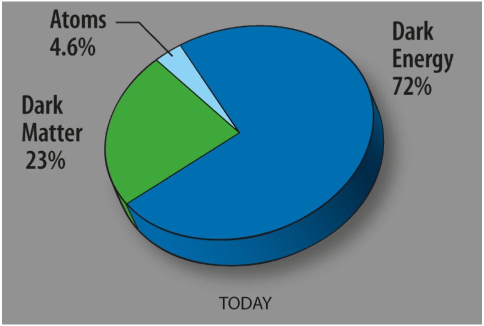
- Background
- Problem: Dark energy or modified gravity?
- Theoretical formalism
- Observations
  - Redshift distortions
  - Weak gravitational lensing
  - Galaxy clustering
- Probe of gravity E_G
- Current and future constraints

Background

SN observations show that the Universe is undergoing accelerated expansion!



Background



(image courtesy of WMAP/NASA)

We don't know what the dark energy is. [fine-tuning problem]

We don't even know what the dark matter is (yet).

Can we distinguish between the two?

Dark energy or modified gravity?

Can we distinguish between the two?

$$\begin{aligned} \text{add energy density} &: \quad G_{\mu\nu} = 8\pi G[T_{\mu\nu}(\text{matter}) + T_{\mu\nu}(\text{dark})] \\ \text{modify gravity} &: \quad G_{\mu\nu} + f(g_{\mu\nu}) = 8\pi G T_{\mu\nu}(\text{matter}) \end{aligned}$$

No, if we only use expansion history.
Yes, if we use growth of structure.

Does GR break down on large scales?

Dark energy or modified gravity?

Does GR break down on large scales?

- Table-top experiments test ∼mm scales
- Solar system experiments test ∼AU scales

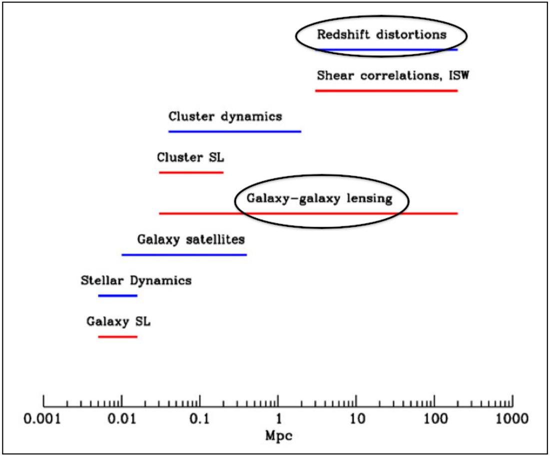
Parameterized Post-Newtonian (PPN) formalism:

$$ds^2 = -(1 + 2\Psi - 2\beta_{\rm PPN}\Psi^2)dt^2 + (1 - 2\gamma_{\rm PPN}\Psi)d\vec{x}^2.$$

$\rightarrow \gamma_{\rm PPN} - 1 \approx 10^{-5}$ (Doppler tracking of Cassini spacecraft)

Does GR break down on large scales?

- Astrophysical observations test ∼kpc–100 Mpc scales



(Jain & Khoury 2010)

Theoretical Formalism

Parametrization of modified gravity:

- **Ratio of scalar potentials** $\eta \equiv \Phi/\Psi$
- **Effective gravitational constant** $G_{\rm eff}$

Theoretical Formalism

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  Gravitational metric in Newtonian gauge:

$$ds^2 = -(1 + 2\Psi)dt^2 + (1 - 2\Phi)a^2(t)d\vec{x}^2$$

  In GR, $\eta = 1$ in the absence of anisotropic stresses, but in MoG theories, $\eta \neq 1$ in general.
- **Effective gravitational constant** $G_{\rm eff}$

Theoretical Formalism

Parametrization of modified gravity:

- **Ratio of scalar potentials** $\eta \equiv \Phi/\Psi$
- **Effective gravitational constant** $G_{\rm eff}$
  Analog to Poisson equation:

$$-k^2\Phi(a,\mathbf{k}) = 4\pi a^2 G_{\rm eff}(k)\bar{\rho}\delta(a,\mathbf{k}),$$

$\rightarrow$ linear growth factor $D = \delta/\delta_i$ is sensitive to $G_{\rm eff}/\eta$

Theoretical Formalism

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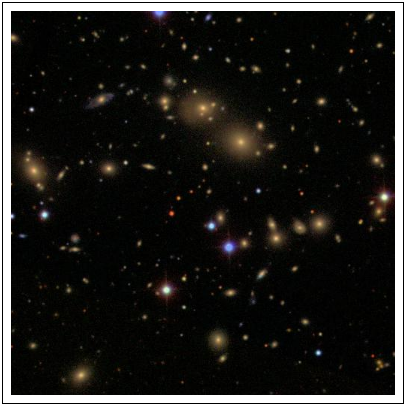
Sample parameterizations:

theory	η	$G_{\rm eff}/G$
GR+ΛCDM	1	1
Flat DGP	$\frac{1-1/(3\beta_{\rm DGP})}{1+1/(3\beta_{\rm DGP})}$	1
$f(R)$	1	$(1 + df/dR)^{-1}$
TeVeS	–	–

Observations

Objective: Constrain modified gravity using SDSS data.

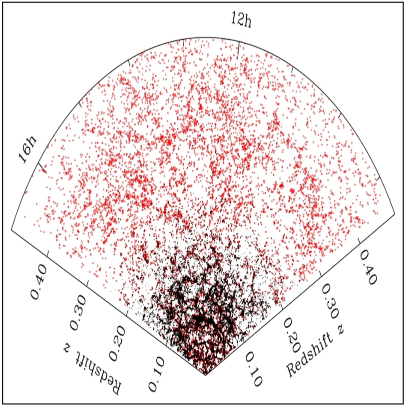


(SDSS Skyserver image)

- Redshift distortions
- Weak lensing
- Galaxy clustering

$\rightarrow$ Probe of gravity E_G (Zhang et al. 2007)

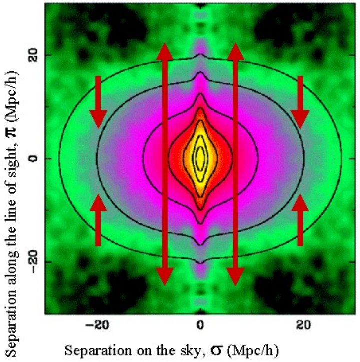
Observations: LRG sample



(courtesy of Michael Blanton)

- LRG color-magnitude cuts by Eisenstein et al. (2001)
- $-23.2 < M_g < -21.2$ mag (k-corrected to $z = 0.3$)
- 70,205 LRGs from DR6
- 5,215 sq. deg
- $1.0\ h^{-3}\ \mathrm{Gpc}^3$
- $\langle z \rangle = 0.32$ (0.16–0.48)

Observations: Redshift distortions

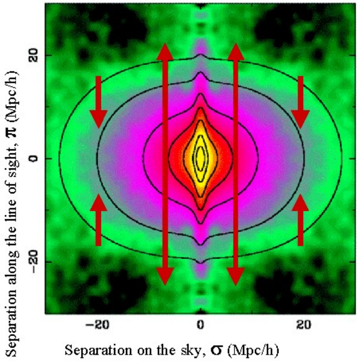


(2dF galaxy redshift survey team)

Correlation function $\xi(\pi, \sigma)$:

- small-scale stretching: random velocity dispersions in clusters (finger-of-God effect)
- large-scale squashing: infall into matter concentrations $\rightarrow$ redshift distortion parameter β

Observations: Redshift distortions

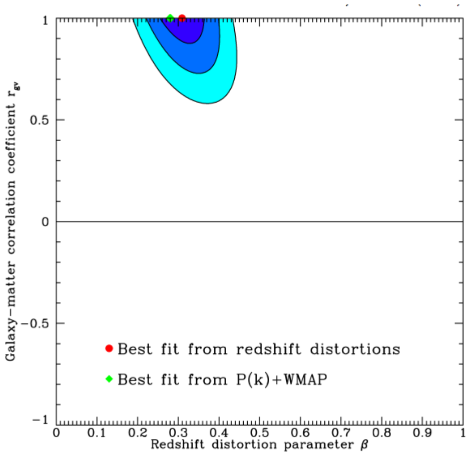


(2dF galaxy redshift survey team)

Redshift distortion parameter:

- $\beta = f/b$, where b is galaxy bias and $f \equiv d(\ln D)/d(\ln a)$.
- $f(z) \approx [\Omega_m(z)]^\gamma$ is the growth factor
- γ is sensitive to modified gravity:
  - $\gamma \approx 0.55$ (ΛCDM)
  - $\gamma \approx 0.68$ (DGP)

Observations: Redshift distortions



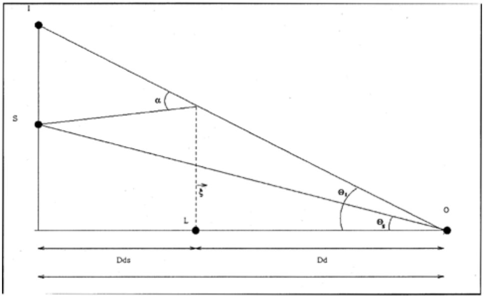
Tegmark et al. (2006)

Fits to the power spectra of 58,000 SDSS DR4 LRGs:

$$P_{\rm gv}(k) = \beta r_{\rm gv} P_{\rm gg}(k)$$
$$P_{\rm vv}(k) = \beta^2 P_{\rm gg}(k)$$

$\rightarrow \beta = 0.309 \pm 0.035$ at $z = 0.3$ and scales $k = 0.01 - 0.09 h/\mathrm{Mpc}$

Observations: Weak gravitational lensing

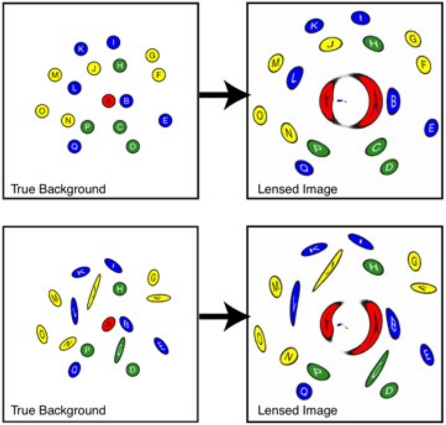


Light is bent by gravity. The deflection angle $\vec{\alpha}$ depends on the lensing potential:

$$\alpha_i = -\int \partial_i(\Psi + \Phi)ds.$$

$\rightarrow$ lensing is sensitive to $(1+\eta)\Psi$.

Observations: Weak gravitational lensing



Galaxy images are distorted due to the bending of light by intervening matter.

- Strong lensing: multiple images, arcs, rings
- Weak lensing: distortions small compared to original shape

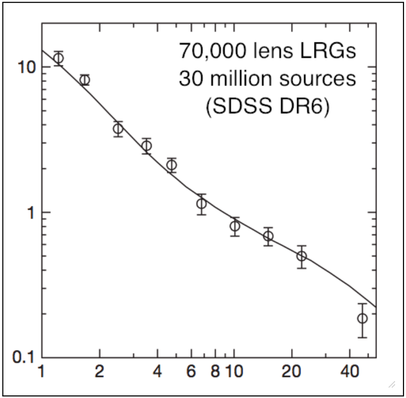
Observations: Weak gravitational lensing

Galaxy-galaxy lensing:

- correlation of shear of background galaxies with mass of foreground galaxies
- stacking over many galaxies yields good S/N
- measures the **surface mass density contrast**

$$\Delta\Sigma_{\rm gm} \equiv \bar{\Sigma}(< R) - \Sigma(R)$$
$$= \Sigma_{\rm crit} \times \gamma_t(R)$$

$\Delta\Sigma_{\rm gm}(R)$ $(hM_\odot {\rm pc}^{-2})$



$R(h^{-1}{\rm Mpc})$

Observations: Galaxy clustering

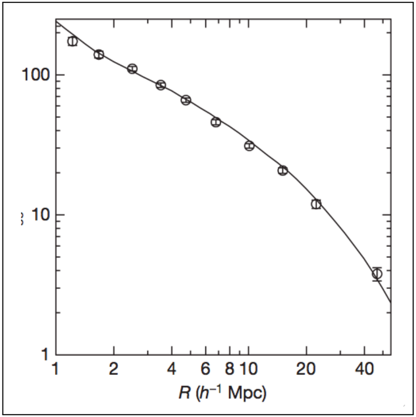
2-point correlation function:

$[1 + \xi_{gg}(r)]dV$ is the probability of finding two galaxies a distance r apart over that for a random distribution.

Projected 2-point correlation function:

$$w_{gg}(R) = \int \xi_{gg}(\sqrt{R^2 + \chi^2})d\chi$$

$w_{gg}(R)$ $(h^{-1}\text{Mpc})$



$R(h^{-1}\text{Mpc})$

Probe of gravity E_G

A model-independent, robust probe of gravity (Zhang et al. 2007):

$$E_G \sim \frac{\text{(gravitational lensing)}}{\text{(structure growth)(galaxy clustering)}}$$

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$$E_G \propto \frac{1}{b^{-1}} \frac{bA^2}{b^2 A^2}$$

$\rightarrow$ insensitive to nuisance parameters, b and A

Probe of gravity E_G

To remove the contribution from small scales, we define the ADSD $\Upsilon_{\rm gm}$:

$$\Upsilon_{\rm gm}(R) \equiv \Delta\Sigma_{\rm gm}(R) - \left(\frac{R_0}{R}\right)^2 \Delta\Sigma_{\rm gm}(R_0)$$

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$$= \frac{2}{R^2}\int_{R_0}^{R} dR' R' \Sigma_{\rm gm}(R') - \Sigma_{\rm gm}(R) + \left(\frac{R_0}{R}\right)^2 \Sigma_{\rm gm}(R_0)$$

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$\Upsilon_{\rm gg}(R)$ is defined similarly:

$$\Upsilon_{\rm gg}(R) \equiv \rho_{\rm c}\left[\frac{2}{R^2}\int_{R_0}^{R} dR' R' w_{\rm gg}(R') - w_{\rm gg}(R) + \left(\frac{R_0}{R}\right)^2 w_{\rm gg}(R_0)\right]$$

Probe of gravity E_G

Operationally:

$$E_G(R) = \frac{1}{\beta} \frac{\Upsilon_{\mathrm{gm}}(R)}{\Upsilon_{\mathrm{gg}}(R)}$$

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In GR+ΛCDM, this simplifies to:

$$E_G = \frac{\Omega_{\rm m,0}}{f(z)} \approx \frac{\Omega_{\rm m,0}}{[\Omega_{\rm m}(z)]^{0.55}}$$

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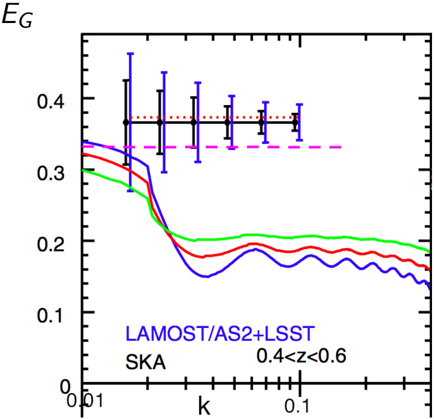
$$\rightarrow E_G = \frac{(0.25 \pm 0.018)}{(0.43)^{0.55}} = 0.41 \pm 0.03$$

Probe of gravity E_G

Predictions for $z = 0.32$	
theory	E_G
GR+ΛCDM	0.41 ± 0.03
DGP	0.4
$f(R)$	$0.328 - 0.365$
TeVeS	0.22

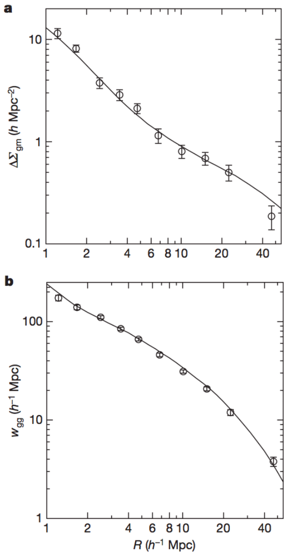


(Zhang et al. 2007)

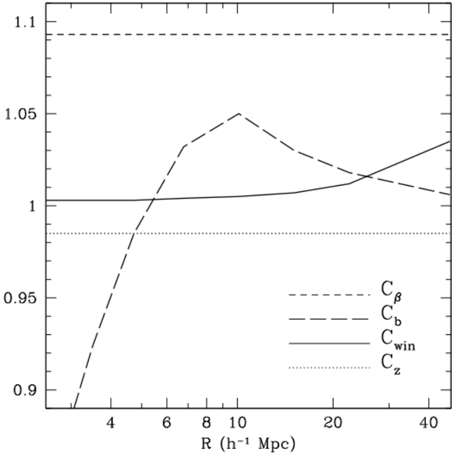
Corrections to E_G

Mock galaxy catalogs:

- 8 Zurich horizon simulations (Smith et al. 2009)
  - $1500h^{-1}$Mpc box
  - $N_p = 750^3$ DM particles
  - $M_{DM} = 5.6 \times 10^{11} h^{-1} M_\odot$
- N-body code GADGET-II
- FoF halo finder ($b = 0.2$)
- Mock galaxies assigned to haloes via HOD model that best matches the observed $\Delta\Sigma_{gm}$ and w_{gg}.

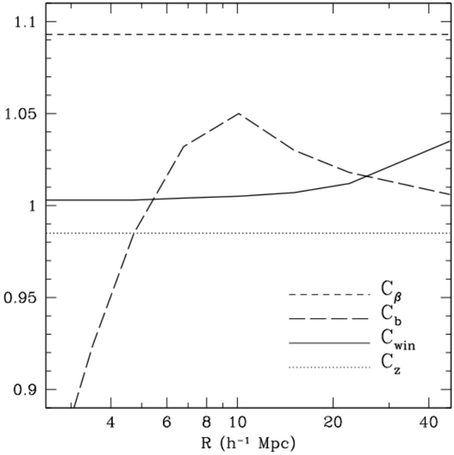


Corrections to E_G



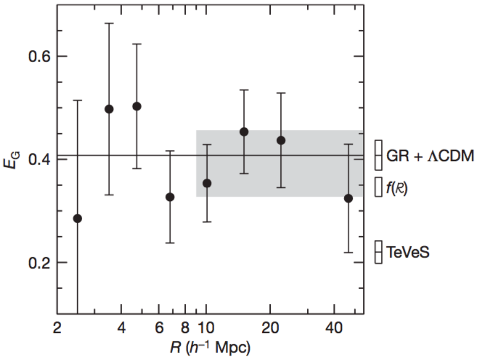
- $C_\beta = 1.09$ corrects for the over-estimation in β due to effect of FOG compression
- C_b corrects for the scale-dependence of galaxy bias

Corrections to E_G



- $C_{\rm win}$ corrects for the difference in the lensing and clustering window functions
- C_z corrects for the lower effective redshift of the lensing signal

Current constraints: E_G



$$\langle \mathbf{E_G} \rangle = \mathbf{0.392 \pm 0.065} \text{ at } z = 0.32 \text{ and } R = 10h^{-1} - 50h^{-1}\text{Mpc}$$

$\rightarrow$ TeVeS model is ruled out by $> 2.5\sigma$.

Future constraints: DES, LSST

Imaging survey parameters

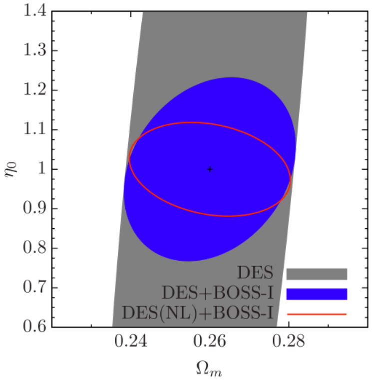
	$f_{\rm sky}$	$n_{\rm g}^{\rm 2d}$	z_0	$\langle z \rangle$
SDSS DR6	∼5000	1.5	–	0.1
DES	5000	15	0.46	0.7
Stage-IV	20000	30	0.8	1.2

Spectroscopic survey parameters

	$f_{\rm sky}$	$z_{\rm min}$	$z_{\rm max}$	V_s	$\bar{n}_{\rm g}$	$n_{\rm g}^{\rm 2d}$
SDSS DR6	∼5000	0.16	0.48	3	2.4×10^{-5}	0.004
BOSS-I	10000	0.1	0.7	15.5	1.1×10^{-4}	0.05
BOSS-II	20000	0.1	1.1	90	1.1×10^{-4}	0.14

(Guzik, Jain & Takada 2010)

Future constraints: DES, LSST



Guzik, Jain & Takada (2010)

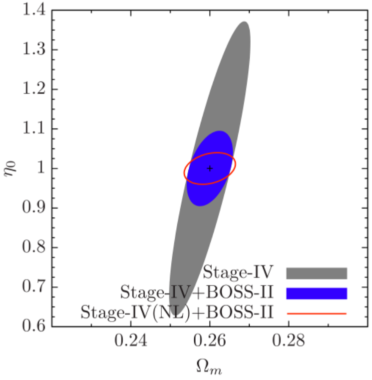
Constraints on η:

- imaging $\rightarrow C_{\kappa\kappa}(l)$, $C_{g\kappa}(l)$
- spectroscopy $\rightarrow P_{gv}(k)$
- CMB prior from Planck, b as free parameter

careful sample selection
$\rightarrow$ error reduced by factor of 8

$\sigma(\eta) = 0.11$ (DES)

Future constraints: DES, LSST



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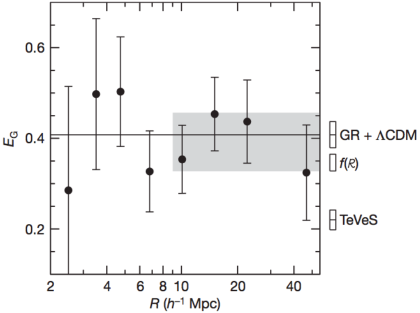
$\sigma(\eta) = 0.11$ (DES)
$\sigma(\eta) = 0.06$ (LSST)

Summary

Objective achieved: Constrain modified gravity using SDSS data.



(**R. Reyes** et al. 2010, Nature, 464, 256)

- Developed observational techniques to deal with theoretical difficulties
- Obtained first constraints on E_G on tens of Mpc scales
- Proof of concept for future datasets from DES, HSC, LSST, etc.