2dFLENSS: Testing Gravity on Cosmic Scales

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Agenda Part 1

- **Introduction: Modified Gravity, Weak Lensing, Redshift Space Distortions.**
- \( E_g \) Test of Gravity: Current Data \((\text{RCSLenS}+\text{CFHTLenS})/(\text{WiggleZ} + \text{BOSS})\).  
- **2dFLenS Galaxy Redshift Survey:** Properties and Expected Constraints on Modified Gravity.
Cosmic acceleration

Universe accelerates

Cosmological constant, DE, or MG?

Expansion: SNe, BAO
Growth: WL, RSD

Critical for understanding MG
Perturbed Einstein: Metric Potentials

Newtonian gauge, (small) scalar perturbations:

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

Non-relativistic Particles: \( \psi \) \hspace{1cm} \text{Newtonian}

Relativistic Particles: \( \psi + \phi \)

Standard GR + no anisotropic stress: \( \psi = \phi \)

Poisson Equation:

\[ \nabla^2 \psi = \nabla^2 \phi = 4\pi G a^2 \sum \rho_i \Delta_i \]

Ma & Bertschinger 1995
Perturbed Einstein Equations

General Relativity

\[ k^2 \phi = -4\pi G a^2 \sum \rho_i \Delta_i \]

\[ \psi - \phi = -12\pi G a^2 \sum \rho_i (1 + w_i) \frac{\sigma_i}{k^2} \]

Modified Gravity

\[ k^2 \phi = -4\pi G_Q a^2 \sum \rho_i \Delta_i \]

\[ \psi = R \phi \]

In general: \( Q(k,a), R(k,a) \)
How to probe MG?

1) Weak Gravitational Lensing

Gravitational lensing magnifies (convergence=$\kappa$) and distorts shape (shear=$\gamma$) of galaxies. In weak lensing limit: $|\gamma|, |\kappa| << 1$.

$$\kappa = \frac{1}{2} \int_0^\chi_s \nabla^2 (\psi + \phi) W(\chi, \chi_s) d\chi$$

B. Jain (www.hep.upenn.edu/~bjain/lensing.html)

$C_{\kappa\kappa}(l), C_{\kappa g}(l)$
How to probe MG?

2) Peculiar Velocities

\[ \theta \equiv \nabla \cdot \mathbf{v} / H \]

\[ = -\dot{\delta} / H = -f \delta \]

\[ f = d \ln D / d \ln a \]

\[ P_s^g(k) = \left[ P_g(k) + 2u^2 P_{g\theta}(k) + u^4 P_{\theta}(k) \right] F \left( \frac{k^2 u^2 \sigma_v^2}{H^2(z)} \right) \]

Kaiser 1987
Dodelson 2003
Introduction: Modified Gravity, Weak Lensing, Redshift Space Distortions.

Eg Test of Gravity: Current Data (RCSLenS+CFHTLenS)/(WiggleZ + BOSS).

The unbiased minimum variance estimator of $E_G$ is given by

$$
\hat{E}_G = \frac{C_{\kappa g}(l, \Delta l)}{3H_0^2 a^{-1} \sum_{\alpha} f_{\alpha}(l, \Delta l) P_{\alpha}^{(1)}}
$$

Achieved by correlating lens galaxies to both surrounding velocity field using RSD ($\theta g$) and shear of background galaxies using galaxy-lensing ($kg$).

Does not depend on bias or on initial matter fluctuations. Sensitive to MG via Growth Rate ($\psi$) and Poisson Eqn ($\psi, \phi$).
Rephrase $E_G$ into more easily observable quantities (3 vs 2), and replace $P_{g\theta}$ with $\beta P_{gg}$:

$$E_G(R) = \frac{1}{\beta} \frac{\Upsilon_{gm}(R, R_0)}{\Upsilon_{gg}(R, R_0)}$$

Lens-Source correlation:

$$\Upsilon_{gm}(R, R_0) = \Delta \Sigma(R) - \frac{R_0^2}{R^2} \Delta \Sigma(R_0)$$

$$\Delta \Sigma(R) = \sum_{\text{pairs}} \text{[weights]} \gamma_t(\theta) \Sigma_c(z_s, z_l)$$

Lens-Lens correlation:

$$\Upsilon_{gg}(R, R_0) = \rho_c \left[ \frac{2}{R^2} \int_{R_0}^{R} R' w_p(R') \, dR' - w_p(R) + \frac{R_0^2}{R^2} w_p(R_0) \right]$$

Reyes et al. 2010
Blake et al. 2014, in prep
**First Measurement of $E_G$: SDSS**

\[ E_G = \frac{\nabla^2(\psi + \phi)}{3H_0^2a^{-1}f\delta} \]

\[ \psi = R\phi \]

\[ \nabla^2\phi = \frac{3}{2}\Omega_mH_0^2Qa^{-1}\delta \]

**$\Lambda CDM$ ($Q = 1$, $R = 1$):**

\[ E_G = \frac{\Omega_m}{f} \]

**$f(R)$:** $Q = (1+f_R)^{-1}$, $R = 1$

**Flat DGP:** $Q = 1$

\[ R = \frac{[1-1/3\beta_{DGP}]}{[1+1/3\beta_{DGP}]} \]
Current Lensing and RSD Surveys

Need overlapping galaxy redshift and lensing surveys

BOSS

Dec. 60

50

40

30

20

10

0

-10

-20

RA

BOSS DR10 NGP

WiggleZ

Dec. 60

50

40

30

20

10

0

-10

-20

R.A

CFHTLenS

155 deg^2

z_m = 0.7

n = 1.1 arcmin^{-2}

BOSS DR10 SGP

RCSLenS

700 deg^2

z_m = 0.6

n = 6 arcmin^{-2}

Blake, SJ, et al 2014, in prep
Measuring $E_G$: scale dependence

For this particular blinding, $E_G$ is found independent of scale with amplitude consistent with standard model

$\Lambda$CDM: $E_G = \Omega_m/f$

Figure 15. The annular differential surface density statistic for the galaxy-mass cross-correlation, $\Upsilon_{gm}(R, R_0)$, measured for the different combinations of lens-source datasets assuming $R_0 = 1.5 h^{-1}$ Mpc. We also plot the best-fitting model for each cross-correlation using both $\omega_p(R)$ and $\Delta\Sigma(R)$ measurements. The error bars are derived from the catalogues. The horizontal dotted line marks $\Upsilon_{gm} = 0$. 

Figure 16. $E_G(R)$ measurements in two independent redshift bins $0.15 < z < 0.43$ and $0.43 < z < 0.70$, after combining the results from the different cross-correlations. In the former case, the measurements of Reyes et al. (2010) are plotted as the open circles for comparison. The horizontal solid lines are the prediction of standard gravity, $E_G = \Omega_m/f$, for our fiducial model $\Omega_m = 0.27$. The horizontal dotted lines indicate the 1-$\sigma$ variation that would result given $\Delta\Omega_m = 0.02$, which is indicative of both the WMAP and Planck error in determining this parameter.

As a cross-check of the methodology we performed the same fits to the $\Delta\Sigma(R)$ measurements from the mock catalogues for all the combinations of source-lens datasets, using the full-survey realizations including masks. The average parameter measurement across the realizations is $\sigma_8 = 0.80 \pm 0.03$ with average value of $\chi^2$/dof = 50.5/47, compared to the input parameter value $\sigma_8 = 0.826$. The slight offset of the fit to lower values than the input is due to the artificial reduction in the clustering amplitude of high-bias mocks constructed via Equation 35, as discussed in Section 5. For $b = 1$ mocks we recover the input cosmology within the statistical error in the mean.

Future work will perform a full cosmological parameter analysis.
Measuring $E_G$: redshift dependence

Reyes et al. (2010) [SDSS]
Our study (low--z bin)
Our study (high--z bin)

Blake, SJ, et al 2014, in prep
Introduction: Modified Gravity, Weak Lensing, Redshift Space Distortions.

Eg Test of Gravity: Current Data (RCSLenS+CFHTLenS)/(WiggleZ + BOSS).

2dFLenS at the AAT in NSW
2dFLens at the AAT in NSW
2dFLenS - AAT Galaxy Redshift Survey

**PHASE 1)**
1000 Deg² (250 NGP, 750 SGP), 130,000 Gals

**PHASE 2)**
4100 Deg², 400,000 Gals

KiDS:
1500 Deg²
z_m = 0.65
N = 9 Arcmin⁻²

**Locations of current spectroscopic and lensing surveys**
- 2dFLenS
- BOSS
- WiggleZ
- GAMA

**2dFLenS Proposal Document**

I) 50 AAT nights over 3 semesters (14B/15A/15B)
II) 100 AAT nights over 4 yrs (16B/17B/18B/19B)
2dFLensS: Properties

Executive committee: C. Blake (PI, Swinburne), F. Abdalla (UCL/DES), C. Heymans (Edinburgh/KiDS), C. Lidman (AAO/OzDES), D. Parkinson (Queensland)

Institutions: Swinburne, AAO, ANU, Bonn, Edinburgh, Leiden, Melbourne, Queensland, UCL

350 spectra per pointing: 280 galaxy lenses (bright LRGs for $0.2 < z < 0.7$), 50 photo-z calibrators ($0.7 < z < 1.0$), 20 other science. On average 10 fields/night.
Total 130,000 spectra.

Priority of phase 1 is follow-up of KiDS (best existing cosmic shear dataset), covering 1500 deg$^2$ (1.5 yrs).
In phase 2, priority turns to DES (partial overlap with KiDS), covering 5000 deg$^2$ (4 yrs).
Order of mag increase in overlap compared to today!
Constraints on MG via $E_G$

- SDSS (Reyes et al. 2010) [5215 deg$^2$]
- CFHTLS/RCS2–BOSS/WGZ [483 deg$^2$]
- KiDS–BOSS current [110 deg$^2$]
- KiDS–GAMA current [109 deg$^2$]
- KiDS–GAMA final [180 deg$^2$]
- KiDS–2dFLenS phase 1 [1500 deg$^2$]
- KiDS/DES–2dFLenS phase 2 [5125 deg$^2$]

$\langle E_G \rangle (R > 10 \, h^{-1} \, \text{Mpc})$

$z$

C. Blake, private comm.
**2dFLenS forecast**

**Phase 1 of 2dFLenS produces factor 4 improvements w.r.t. either current overlapping surveys or WL alone.**

\[
Q = Q_0 a^s \\
R = R_0 a^s \\
s = 3
\]

- Current overlapping surveys \([480 \text{ deg}^2]\) \(\text{FoM}_{\text{MG}} = 0.3\)
- KiDS lensing only \([1500 \text{ deg}^2]\) \(\text{FoM}_{\text{MG}} = 0.1\)
- 2dFLenS phase 1 \([1500 \text{ deg}^2]\) \(\text{FoM}_{\text{MG}} = 1.1\)
- DES lensing only \([5000 \text{ deg}^2]\) \(\text{FoM}_{\text{MG}} = 0.3\)
- 2dFLenS phase 2 \([5000 \text{ deg}^2]\) \(\text{FoM}_{\text{MG}} = 3.6\)

- General Relativity + \(\Lambda\)CDM
**2dFLenS: Additional Benefits**

*WL limited by calibration of photo-z. Require ~0.1% accuracy in mean z of each photo-z bin. Achieved by cross-corr. source sample with overlapping spec. survey containing 5000 gals per Δz = 0.1 bin (Newman 2008). Lens sample allows calibrating z < 0.7. Additionally 0.7 < z < 1.0.*

Overlapping surveys enable range of **other science**.

i) **1000s of clusters with DES. spec-z of central galaxies required for cosmology.**

ii) **~1000 strong lenses with KiDS and DES. z-confirmation to understand their geometry and facilitate follow-up by 8m class telescopes.**

**Aside from MG:** Use \{ξ+, ξ-, γ, ξ0, ξ2\} for dark energy, curvature, neutrino mass, sterile neutrinos, etc.
Conclusions

- **Apparent existence of “dark energy” compels us to test laws of gravity across scales of universe in multiple ways. A powerful combination of two observables, gravitational lensing and galaxy velocities, may help pin down physics of gravity.**

- **The $E_g$ test of gravity, probing relation between metric potentials, is carried out for CFHTLenS +RCSLenS with WiggleZ+BOSS, to higher $z$ than before ($z < 0.7$), at 20% level.**

- **World’s leading imaging surveys, KiDS and DES, are covering the south without wide-area spectroscopic follow-up. Use of 2dFLens at AAT over 6 years (starting Autumn 2014) will remedy this situation, and allows for significant improvement in our potential to probe gravity via growth of structure.**
Thanks for listening.