Testing the laws of gravity with cosmological data

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Our current model of cosmology

- We have a superbly detailed picture of the early Universe [e.g. CMB, nucleosynthesis]

- We have a model for the evolution of the Universe that matches a range of cosmological data

- This model invokes 3 new pieces of physics: inflation, dark matter and dark energy
Our current model of cosmology

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![Plot of dark energy and matter density](image)
Dark energy: evidence

- Supernovae cosmology

![Supernovae cosmology graph](image)

- Distribution of galaxies

![Distribution of galaxies](image)

- CMB

![CMB image](image)
Dark energy: is it vacuum energy?

A cosmological constant matches the data so far, but its amplitude is inexplicable.
Cosmology: the optimistic viewpoint!

- Dark matter and energy show that our understanding of physics is incomplete.
- Astronomy can provide fundamental physical insights into quantum theory, gravity, and particle physics.
- We are working in the breakthrough era where new data should be revolutionary!
Cosmology: the pessimistic viewpoint!

- How do we know that dark energy is a solvable problem?

- Unclear if we need better observations or better theories?

- Survey data needed to investigate cosmological questions are often very bad for other astronomical goals
The dark energy puzzle

**Dark energy** : what do we (think we) know?

- Assuming an FRW metric ...

- Dark energy **smoothly fills space** with a roughly constant energy density

- Dark energy **dominates the Universe today** but is insignificant at high redshift

- Dark energy propels the cosmos into a phase of accelerating expansion
Dark energy : what don’t we know?

- Physically, is it a manifestation of gravity or matter-energy?

- Why now? - why does dark energy become important billions of years after the Big Bang?

- If dark energy is vacuum energy, how can we explain its magnitude?

- How are our deductions about dark energy affected by inhomogeneity?
Tests of large-scale gravity

- Can tests of G.R. be extended to cosmic scales?
  And can that yield insight into dark energy?
Tests of large-scale gravity

• In a homogeneous Universe it would be tricky to distinguish the origin of dark energy

• However, the Universe is clumpy, which creates a rich variety of observable signatures we can explore in the gravitational sector!
First signature: peculiar velocities of galaxies
Measuring velocities of individual galaxies

- Simultaneous measurements of distance $D$ and redshift $z$
- Use **standard candle** (supernovae, fundamental plane, ...)

\[ v_{\text{peculiar}} = c \, z - H_0 \, D \]

[Small print: this equation is not exact!]
Measuring correlated galaxy velocities

- Even without velocity measurements, can detect via redshift-space distortion in galaxy redshift surveys.

![Graph showing line-of-sight offset versus projected offset with labels for observer, infalling galaxies, virialized motions, and coherent flows.](image-url)
Second signature: gravitational lensing

Due to a series of gravitational lenses, all the stars we observe over there...

Galaxies randomly distributed
Slight alignment

PATH OF LIGHT AROUND DARK MATTER
DISTANT UNIVERSE
OBSERVED SKY
Summary of new results I will present

- Tests based on **individual peculiar velocity measurements** from the 6dF Galaxy Survey

- Tests based on **measurements of correlated velocities** (redshift-space distortion) from galaxy redshift surveys

- Tests based on **weak gravitational lensing** of background galaxies in new deep imaging surveys

- In particular, we will compare with “the standard cosmological model”
Summary of new results I will present

• Tests based on individual peculiar velocity measurements from the 6dF Galaxy Survey

• Tests based on measurements of correlated velocities (redshift-space distortion) from galaxy redshift surveys

• Tests based on weak gravitational lensing of background galaxies in new deep imaging surveys

• In particular, we will compare with predictions based on a perturbed FRW metric of General Relativity in a Lambda-CDM Universe with matter density predicted by the Cosmic Microwave Background radiation
The cosmic growth rate
The cosmic growth rate

• A useful statistic for comparing data and models is the cosmic growth rate, $f$, which predicts the amplitude of velocities in this perturbation theory.

• In the “standard model”, this is a scale-independent quantity which varies with redshift in a predictable way.

[ Some equations for those who are interested ! ]

\[
\begin{align*}
  f &= \frac{d \ln G}{d \ln a} \\
  \delta(a) &= G(a) \delta(1) \\
  a &= \frac{1}{1 + z} \\
  \theta(k) &= -f \delta(k) \\
  \theta &\propto \vec{\nabla} \cdot \vec{v}
\end{align*}
\]
(1) Peculiar velocity measurements

- **6dF Galaxy Survey** is a large southern-sky redshift survey.
- 9,000 peculiar velocity measurements using fundamental plane distances [biggest existing sample]
- We measure the velocity power spectrum which is proportional to the growth rate.
- Credit to Andrew Johnson!
Technical interlude!

- Write down the likelihood of the observed radial velocities $v_i$ in terms of the covariance $C_v$

$$L = \frac{1}{\sqrt{2\pi |C_v|}} \exp \left( -\frac{1}{2} \sum_{ij} v_i (C_v^{-1})_{ij} v_j \right)$$

- Covariance matrix depends on the velocity power spectrum $P_v(k)$ and the errors in the data

- [noting that our analysis here is in Fourier space]

- We do Monte Carlo Markov Chain fit for amplitude of $P_v(k)$ in $k$-bins, i.e. growth rate in $k$-bins
Results from our velocity fits

• Here is our result: consistency with the prediction with particular sensitivity to large scales

![Graph showing data points for different wavenumbers and velocities: 6dFGSv + low-z SNe, low-z SNe, 6dFGSv. The graph includes labels for 300 Mpc/h, 100 Mpc/h, and 50 Mpc/h.]
(2) Redshift-space distortions

- Redshift-space distortion allows galaxy redshift surveys to measure the growth rate of structure.
The WiggleZ Dark Energy Survey

- 1000 sq deg, $0.2 < z < 1.0$
- 200,000 redshifts
- blue star-forming galaxies
- Aug 2006 - Jan 2011
Southern sky surveys

6dFGS (purple), 2dFGRS (blue), MGC (navy), GAMA (cyan), 2SLAQ-LRG (green), WiggleZ (yellow), 2SLAQ-QSO (orange), 2QZ (red); the celestial sphere is at z=1.
WiggleZ: redshift-space distortion results

$k_{\parallel} [h \text{ Mpc}^{-1}]$

$k_{\perp} [h \text{ Mpc}^{-1}]$

$log_{10}(\text{Power Spectrum Amplitude} [h^{-3} \text{ Mpc}^3])
Redshift surveys: fits for the growth rate
(3) Comparison with gravitational lensing

Observations on the sky

Source galaxies: measure lensing of their light!

Lens galaxies tracing density ripples: measure their velocities!
Technical interlude!

- Sensitive to theories of gravity in complementary ways

- General perturbations to FRW metric:

  \[ ds^2 = [1 + 2\psi(x, t)] dt^2 - a^2(t) [1 - 2\phi(x, t)] dx^2 \]

- \((\psi, \phi)\) are metric gravitational potentials, identical in General Relativity but can differ in general theories

- Relativistic particles (e.g. light rays for lensing) collect equal contributions and are sensitive to \((\psi + \phi)\)

- Non-relativistic particles (e.g. galaxies infalling into clusters) experience the Newtonian potential \(\psi\)
Gravitational lensing: data

- Need overlapping galaxy redshift and lensing surveys!
Gravitational lensing: data

- Redshift distribution of lenses!
Gravitational lensing: our measurement

Measurement [scale] = \frac{Amplitude of lensing [scale]}{Amplitude of velocities [scale]}

Prediction = \frac{Matter density}{Cosmic growth rate}

![Graph showing the relationship between gravitational slip and redshift.](image-url)
Technical interlude (1)!

- Measure cross-correlations between source shapes from CFHTLS / RCS2 (to $r \sim 25$) and lenses from WiggleZ / BOSS (covering $0.15 < z < 0.7$)

- Total overlap area = 483 deg$^2$

- Shape measurements using “lensfit” give shape density of 14 arcmin$^{-2}$ [CFHTLS] and 6 arcmin$^{-2}$ [RCS2]

- Source photometric redshift catalogue using BPZ

- Battery of systematic tests of shear measurements, results blinded
Technical interlude (2)!

- \( E_G(R) \) statistic?

\[
E_G(R) = \frac{1}{\beta} \frac{\gamma_{gm}(R, R_0)}{\gamma_{gg}(R, R_0)}
\]

- Lens-source cross-correlation:

\[
\gamma_{gm}(R, R_0) = \Delta \Sigma(R) - \frac{R_0^2}{R^2} \Delta \Sigma(R_0)
\]

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

- Lens-lens auto-correlation:

\[
\gamma_{gg}(R, R_0) = \rho_c \left[ \frac{2}{R^2} \int_{R_0}^{R} R' w_p(R') dR' - w_p(R) + \frac{R_0^2}{R^2} w_p(R_0) \right]
\]
Gravitational lensing: results

- Galaxy-galaxy lensing measurements

![Graphs showing galaxy-galaxy lensing measurements](image-url)
Gravitational lensing: results

- Clustering measurements of the lenses
Gravitational lensing: results

• Is $E_G$ scale-independent, and what is its value?

![Graph 1: 0.15 < z < 0.43](image1)

![Graph 2: 0.43 < z < 0.70](image2)

- **Reyes et al. (2010)**
- **Standard model**
We find the “gravitational slip” $E_G$ is independent of scale with amplitude consistent with the standard model.
Future projects: TAIPAN

- Deeper southern sky survey at the UKST, expanding the 6dFGS redshift/velocity sample by a factor of 5
- 1% measurement of Hubble constant using baryon acoustic peak as a standard ruler
- 5% measurement of local growth rate from velocities
Future projects: ASKAP

- WALLABY survey will measure galaxy velocities through Tully-Fisher relation
Future projects: gravitational lensing

- Data will increase by order of magnitude over next few years
Apparent existence of dark energy motivates new tests of large-scale gravitational physics

Two observable signatures are non-relativistic galaxy velocities and relativistic lensing of light

We have performed new measurements using the latest galaxy redshift, velocity and lensing surveys

General Relativity + cosmological constant + perturbed FRW metric models remain a good fit

The quest to understand dark energy continues!