Watching Galaxies Fall: structure formation in the universe as a probe of gravity

David Parkinson
University of Queensland
Summary

• Introduction
  • Modified gravity - why change a good thing?

• Theory of Structure formation
  • Motion of matter, galaxies as test particles
  • Motion of light, photons as test particles

• Cosmological data
  • Redshift-Space distortions (WiggleZ, BOSS, 2dFLenS)
  • Weak gravitational lensing (CFHTLenS, KiDS, DES)

• Beyond potentials - fifth forces
  • Deterministic and stochastic velocity bias

• Conclusions
Testing gravity

- The expansion of the Universe is accelerating
- The simplest explanation of a cosmological constant is problematic
- Vacuum energy calculations imply cosmological constant is $10^{120}$ times larger than its measured value - too small
- Coincidence problem - why is density of matter ($1/a^3$) so close to density of dark energy (~constant) today?
Cosmological Constant
Problem

- Why is the energy density of the vacuum so small?
- Alternatively we can ask, why does the vacuum energy gravitate so little?
  - “The effective Newton constant becomes very small at large length scales, so that sources with immense wavelengths and periods -- such as the vacuum energy-- produce minuscule curvature” (Arkani-Hamed, Dimopoulos, Dvali, Gabadadze)
  - Similar to the manner in which long wavelength excitations beyond the Debye sphere are screened by the effective photon mass in a plasma.
Modified Gravity

- Consider this as a change in the theory of gravity at large scales
- Can be either:
  - gravity gets weaker on large scales, owing to extra-dimension effects (Dvali-Gabadadze-Porrati model)
  - graviton has (induced) mass, meaning it does not propagate in the expected manner on large scales (massive gravity)
- Theories like this predict existence of extra degrees of freedom
  - The scalar degrees of freedom will affect the generation and propagation of gravitational instabilities
Theory of Structure Formation
Tracing structure

- Our observable universe is filled with structure, on all scales
- It’s only visible through galaxies
  - The relation between distribution of galaxies and matter is given by the ‘bias’
- Galaxies here are functioning as test particles - tracing out the gravitational field
Radiation domination
Redshift: 3700
Age: 100 kyr

Matter domination
Surface of last scattering

Matter-radiation equality
Redshift: 1090
Age: 400 kyr

Acceleration domination

10^9

0.67
7.3 Gyr

0.33
9.8 Gyr

Matter-Dark Energy equality

Acceleration begins

7.3 Gyr

9.8 Gyr

Big Bang

Time

Today
Post-recombination: Perturbation theory

- Metric:
  \[ ds^2 = -(1 + 2\Psi)dt^2 + a^2(1 + 2\Phi)dx^2 \]

- The force equation for matter is
  \[ \frac{d\theta_m}{dt} = -2H\theta_m - \frac{\partial^2}{a^2}\Psi \]

- The perturbation equation is
  \[ \frac{d\delta_m}{dt} = -\theta_m - \dot\Phi \]

- From these we derive the growth equation
  \[ \ddot\delta = 2H\theta - \frac{k^2}{a^2}\Psi \]
Einstein Gravity

• Here the Newtonian potential $\phi$ is given by the Poisson equation
  $$-k^2 \Phi = 8\pi G \frac{a^2}{2} \left( \rho \delta + 3H(\rho + p) \frac{a^2}{k^2} \theta \right),$$

• If we assume no anisotropic stress, $\phi = -\Psi$ and so we can complete the system (assuming matter domination, and sub-horizon scales)
  $$\ddot{\delta} = -2H \dot{\delta} + 4\pi G \rho \delta$$

• In the completely matter dominated limit, $\delta \sim a$

• In the quasi-static limit, the growth of matter fluctuations can be written as
  $$\frac{d \ln \delta}{d \ln a} \equiv f = -\frac{\theta_m}{H \delta_m}$$
Modified Gravities

- Single fluctuation generated by Newtonian potential $\Psi$
  \[
  \delta_m(k) = T^\delta_m(k) \Phi_*(k)
  \]
  \[
  \theta_m(k) = T^\theta_m(k) \Phi_*(k)
  \]
- Transfer function $T(k)$: describes how initial metric fluctuation is reprocessed into a late-time configuration of the species
- Growth rate now has a more general form
  \[
  f_{\text{eff}}(k) \equiv -\frac{T^\theta_m(k)}{T^\delta_m(k)}
  \]
- Deterministic bias
  \[
  \langle \delta_m \theta_m \rangle = -f_{\text{eff}} \langle \delta_m \delta_m \rangle
  \]
  \[
  \langle \theta_m \theta_m \rangle = f_{\text{eff}}^2 \langle \delta_m \delta_m \rangle.
  \]
Massless particle motion: gravitational lensing

- The motions of photons are also perturbed by the local gravitational potential.
- This is manifested as gravitational lensing.
- The ellipticities of galaxy shapes become correlated with the matter density, integrated over the whole photon trajectory.
null condition states

\[ k^\mu k_\mu = 0 \]

Thin lens approximation gives

\[ \frac{d^2 x^i}{d\lambda_s} + 2\mathcal{H} \frac{d\eta}{d\lambda_s} \frac{dx^i}{d\lambda_s} - (\Phi_{,x^i} - \Psi_{,x^i}) \left( \frac{d\eta}{d\lambda_s} \right)^2 \]

Finally we compute deflection equation

\[ \frac{d^2 x^i}{dr^2} = \Phi_{,x^i} - \Psi_{,x^i} \]

Difference between potentials is lensing potential, and deflection is sourced by spatial gradient of lensing potential
Cosmological Data
Redshift-space distortions

- The motions of galaxies are perturbed by the local gravitational field.
- The Power spectrum/correlation function in the line of sight is distorted relative to the transverse direction.
- Assuming these motions are generated by matter perturbations, we can measure the growth of structure.
Multipole power spectra

- Density and velocity divergence have different angular dependence
- Use Power spectra decomposed into Legendre polynomials (Cole, Fisher and Weinberg 1994)

\[ P(k, \mu) = \sum_{\ell=0}^{\infty} P_\ell(k) L_\ell(\mu) \]

- Orthogonality of the Legendre polynomials leads to the relation

\[ P_\ell = \frac{2\ell + 1}{2} \int_{-1}^{+1} d\mu P^s(k, \mu) L_\ell(\mu) \]
2dFlens - Results

Blake et al (2016)
Growth history

- Growth rate ($f$) and amplitude of fluctuations ($\sigma_8$) sourced by both gravitational force and expansion rate.
- Need to fit for both simultaneously, so some degeneracy with BAO signal.

Alam et al 2016
Peculiar velocities

- Data from the Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006) Tully-Fisher Survey (2MTF; Masters 2008) covers most of the sky, and uses 2018 galaxies to measure the bulk flow.
- Numerical simulation for the same sky, and select from the same redshift distribution
- $f(R)$ gravity predicts a larger bulk flow velocity than $\Lambda$CDM

$z_{\text{observed}} \approx z_{\text{cosmological}} + z_{\text{peculiar}}$

Seiler and Parkinson (2016)
Peculiar velocity power spectra

- Can measure power spectra of velocities
- No galaxy bias
- Use to measure deviations from gravitational force law on different scales

Lensing Data

- Lensing convergence power spectra
  \[ P_{\kappa}^{ij}(\ell) = \int_0^{r_H} dr \frac{q_i(r)q_j(r)}{[f_\kappa(r)]^2} P_\delta \left( \frac{\ell}{f_\kappa(r)}, r \right) \]

- Tomographic angular two-point shear correlation function
  \[ \xi^{ij}_\pm(\theta) = \frac{1}{2\pi} \int d\ell \ell P_{\kappa}^{ij}(\ell) J_{0,4}(\ell\theta) \]
Parameter constraints

Joudaki et al 2016
Fifth forces
Fifth forces

(With Seery and Burrage)

Metric: \( ds^2 = -(1 + 2\Psi)dt^2 + a^2(1 + 2\Phi)dx^2 \)

The force equations for matter and radiation are

\[
\frac{d\theta_m}{dt} = -2H\theta_m - \frac{\partial^2}{a^2}\Psi + F_{5r}
\]

\[
\frac{d\theta_r}{dt} = -H\theta_r - \frac{\partial^2}{a^2}\Psi - \frac{1}{4} \frac{\partial^2}{a^2}\delta_r + F_{5m}
\]

Perturbation equations

\[
\frac{d\delta_m}{dt} = -\theta_m - 3\dot{\Phi} + j_{5m}
\]

\[
\frac{d\delta_r}{dt} = -\frac{4}{3} \theta_r - 4\dot{\Phi} + j_{5r}
\]
Stochastic bias

• Several primordial perturbations:
  • fifth force mediated by scalar field ($\Phi$) that also has its own fluctuations
  $$\delta_m(k) = T^\delta_m(k)\Phi_*(k) + T^\delta_\phi(k)\phi_*(k)$$
  $$\theta_m(k) = T^\theta_m(k)\Phi_*(k) + T^\theta_\phi(k)\phi_*(k).$$
  • Relation between growth and density has now changed
  $$\theta_m = -f_{\text{eff}}\delta_m + \frac{W}{T^\delta_m}$$
  • Here $W$ is a Wronskian-like function which measures the correlation of $\delta$ and $\theta$
New correlation functions

- The correlation functions now satisfy

\[
\langle \theta \delta \rangle_k = \langle \delta \delta \rangle_k \left( -f_{\text{eff}}^\Phi(k) + \frac{f_{\text{eff}}^\Phi(k) - f^\phi(k)}{1 + \rho(k)} \right)
\]

\[
\langle \theta \theta \rangle_k = \langle \delta \theta \rangle_k \left( -f_{\text{eff}}^\Phi(k) + \frac{f_{\text{eff}}^\Phi(k) - f^\phi(k)}{1 + \sigma(k)} \right)
\]

\[
= \langle \delta \delta \rangle_k \left( -f_{\text{eff}}^\Phi(k) + \frac{f_{\text{eff}}^\Phi(k) - f^\phi(k)}{1 + \rho(k)} \right)
\]

- If we measure \( \langle \delta_m \delta_m \rangle, \langle \delta_m \theta_m \rangle \) and \( \langle \theta_m \theta_m \rangle \), and do not see complete correlation between \( \delta \) and \( \theta \), we have gone beyond \( f_{\text{eff}} \) as a test of modified gravity.
Example: Galileons

- Galileons are scalar fields that are invariant under shifts in the field value

\[ \pi \rightarrow \pi + c + b_\mu x^\mu \]

- Only 5 possible Lagrangians that give 2nd order equations of motion and are ghost free

\[
\begin{align*}
\mathcal{L}_1 &= M^3 \pi \\
\mathcal{L}_2 &= (\nabla \pi)^2 \\
\mathcal{L}_3 &= (\Box \pi)(\nabla \pi)^2 / M^3 \\
\mathcal{L}_4 &= (\nabla \pi)^2 [2(\Box \pi)^2 - 2\pi_{;\mu \nu} \pi^{;\mu \nu} - R(\nabla \pi)^2 / 2] / M^6 \\
\mathcal{L}_5 &= (\nabla \pi)^2 [(\Box \pi)^3 - 3(\Box \pi) \pi_{;\mu \nu} \pi^{;\mu \nu} + 2\pi^{;\mu} \pi^{;\nu} \pi^{;\rho} - 6\pi_{;\mu} \pi^{;\mu} \pi^{;\nu} G_{\nu \rho}] / M^9
\end{align*}
\]
Coupling to matter

- We expect a coupling of the Galileon field (for example) to matter

\[ T_\phi = -\frac{1}{2\Lambda} \left( 1 + \frac{\phi}{\Lambda} \right)^{-1} T_m \]

- The field starts small, and remains small during the evolution of the universe

- The perturbation of the field can grow, and will grow quickly at late times through the coupling to the matter perturbation
  
  - While the Galileon fluctuation will be smaller than the matter perturbation at matter-radiation decoupling, it can grow and become very large today.

- This is stochastic bias, where structures can form without presence of standard ‘Newtonian’ potential generated by the presence of matter
Screening mechanisms

• If the gravity is different, we can test it on lab or solar system scales
  • e.g. fifth force effect, or scale-dependent $G_{\text{Newton}}$
• Three “screening mechanisms” save the theories

\[ L \supset -\frac{1}{2} Z(\phi_0)(\partial \delta \phi)^2 - \frac{1}{2} m^2(\phi_0)\delta \phi^2 + \left(\frac{\beta(\phi)}{m_P}\right)\delta \phi \delta T \]

• Vainshtein mechanism: higher-order corrections (cubic and above) recover GR on scales smaller than Vainshtein radius (DGP, Galileon)
• Chameleon mechanism: mass of field large enough to suppress range of fifth force (f(R) theories)
• Symmteron mechanism: direct coupling to stress-energy tensor (T) is small
Equal Galileon and Newtonian potentials

Relevant Galileon potentials

Marginal Galileon potentials

Irrelevant Galileon potentials
Lensing

- Fifth forces: cannot distinguish between strength of coupling and size of field fluctuations
- Need to measure size of metric fluctuations independently
- A conformal coupling induces no change in the lensing potential
  - Photons only feel Newtonian potential
- However, matter formation (that sources the lensing potential) still influenced by fifth forces
- Considering only Galileon actions up to $L_3$ (which we are), there is no anisotropic stress, so $\phi = -\Psi$
- Cross-correlation of lensing with RSD will determine strength of stochastic bias
Conclusions

- Structure formation tests of gravity effectively measure force law on largest scales.
- The growth rate f gives the correlation between density and velocity statistics of galaxies.
- Lensing power spectrum gives correlation between induced ellipticity and density of matter.
- If fifth forces become important at late times, the density and velocity (or velocity and lensing) perturbations may no longer be perfectly correlated.
  - Galileons are an example of this behaviour, as the fluctuations in the field grow at late times and become a new source of structure formation, leading to \textit{stochastic bias}.
- Cross-correlation of lensing and RSD data will provide direct measurement of stochastic bias effect.
Thank you
2dFLens

- Spectroscopic survey, providing follow-up of lensing galaxies from KiDS survey

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