Testing General Relativity using the growth rate of structure

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- **Aim**: Place tight constraints on the growth rate of clustering
  $\rightarrow$ Test GR on extragalactic scales
- **How?** Compare theory with recent growth history results(2dFGRS, SDSS- LRG, VIMOS-VLT deep Survey, Wiggle Z) using a standard likelihood analysis

Basilakos S. & Pouri A., 2012, MNRAS, arXiv:1202.1637

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Cosmological Models

1. ΛCDM (spatially flat, Dark Energy Component)

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2. Dvali- Gabadadze- Porrati(DGP) model: the accelerated expansion of the universe can be explained by a modification of the gravitational interaction in which gravity becomes weak at cosmological scales owing to the fact that our 4D brane survives into an extra dimensional manifold (Deffayet, Dvali& Cabadadze 2002)

Theoretical Background

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Theoretical Background

Dark Energy

Observationally assuming a matter dominated and spatially flat Universe we get:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 > \frac{8\pi G}{3}\rho_m \rightarrow \begin{cases} \frac{8\pi G_{eff}}{3}\rho_m \\ \frac{8\pi G}{3}(\rho_m + \rho_Q) \end{cases}$$

1. Modification of GR
2. New fields in Nature

Theoretical Background

The Background Evolution

$$\frac{\mathrm{H}^2(\alpha)}{\mathrm{H}_0^2} \equiv \mathrm{E}^2(\alpha) = \Omega_{mo} a^{-3} + \Omega_{DE} e^{3\int_a^1 [1+w(y)] d\ln y}$$

$$P(a) = w(a)\rho(a) \qquad w(a) = \frac{-1-\frac{2}{3}\frac{d\ln E}{da}}{1-\Omega_m(a)}$$

$$\Omega_m(a) = \frac{\Omega_{mo} a^{-3}}{\mathrm{E}^2(\alpha)}$$

Equivalent Equations

$$\frac{\mathrm{H}^2(\alpha)}{\mathrm{H}_0^2} \equiv \mathrm{E}^2(\alpha) = \Omega_{mo} a^{-3} + \Delta H^2$$

$$w(a) = -1 - \frac{1}{3}\frac{d\ln \Delta H^2}{d\ln a}$$

The Background Evolution

- Λ Cosmology

$$\Delta H^2 = \Omega_\Lambda = 1 - \Omega_m$$
$$w(a) = -1$$

- DGP Gravity

$$\Delta H^2 = 2\Omega_{bw} + 2\sqrt{\Omega_{bw}}\sqrt{\Omega_{mo}a^{-3} + \Omega_{bw}}$$
$$\Omega_{bw} = \frac{(1-\Omega_m)^2}{4}$$
$$w(a) = -\frac{1}{1+\Omega_m(a)}$$
$$G_{eff}(a) = G_N Q(a)$$
$$Q(a) = \frac{2+4\Omega_m^2(a)}{3+3\Omega_m^2(a)}$$

Using cosmology to test gravity

- It is well tested that General Relativity is valid in small scales. Testing GR in extragalactic distances remains an open argument.
- The dark energy component slows the growth of inhomogeneities in the total matter (baryons and dark matter). Using linear perturbation theory in the co- moving context (mass conservation, Euler equation, Poisson equation and Friedmann equation) we get the differential equation that governs the evolution of matter perturbations:

$$\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G_{eff}\rho_m\delta_m \rightarrow \delta_m \propto D(t)$$

where:

- $H(z)$: expansion rate kinematics
- G_{eff}: Law of gravity

Using cosmology to test gravity

For any type of DE, an efficient parametrization of the matter perturbations is based on the growth rate of structure f(a) originally introduced by Peebles(1993)

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

$$D(a) \simeq \exp\left[\int_1^a \frac{\Omega_m^{\gamma}(a)}{a} da\right]$$

γ: growth index

Theoretical Background

Constant Growth Index Versus Gravity

Performing a 1st Taylor Expansion around $\Omega_m(a) = 1$ we find that the asymptotic value of the growth index to the lowest order becomes:

GR

$$Q(a) = 1$$

$$\gamma_{GR} \simeq \frac{3(w-1)}{6w-5}$$

$$\gamma_{\Lambda} \simeq \frac{6}{11}$$

Silveira & Waga (1994), Wang & Steinhardt (1998), Linder (2004), Nesseris & Perivolaropoulos (2008)

Theoretical Background

DGP

$$Q(a) = \frac{2 + 4\Omega_m^2(a)}{3 + 3\Omega_m^2(a)}$$

$$\gamma_{DGP} \simeq \frac{11}{16}$$

Linder (2004), Linder & Cahn (2007), Gong (2008)

If the derived (from growth data) value of γ shows scale or time dependence or it is inconsistent with $6/11$ then this will be a hint that the nature of DE reflects in the physics of gravity.

Data already used to test GR on cosmological scales

- Weak gravitational lensing data (CFHTLS: Hu et al. 2008, COSMOS: Nassey et al. 2007)
- Redshift Distortions in the galaxy power spectrum (Linder 2008, Guzzo et al. 2008; Blake et al. 2011; Samushia et al. 2012; Hudson & Turnbull 2012)
- CMB temperature- galaxy cross correlation (Ho et al. 2008, Hirata et al 2008)
- X- ray luminous galaxy clusters using Chandra data (Rappeti et al. 2010)

The growth Rate Data

z	A_{obs}	Refs.
0.17	0.510 ± 0.060	Song & Percival 2009; Percival et al. 2004
0.35	0.440 ± 0.050	Song & Percival 2009; Tegmark et al. 2006
0.77	0.490 ± 0.180	Song & Percival 2009; Guzzo et al. 2008
0.25	0.351 ± 0.058	Samushia et al. 2012
0.37	0.460 ± 0.038	Samushia et al. 2012
0.22	0.420 ± 0.070	Blake et al. 2011
0.41	0.450 ± 0.040	Blake et al. 2011
0.60	0.430 ± 0.040	Blake et al. 2011
0.78	0.380 ± 0.040	Blake et al. 2011

The growth Rate Data

- $A_{obs}(z) = f\sigma_8 = b\sigma_{8,g}$: The combination of the parameter of the growth rate of structure and the rms fluctuations of the linear field (at 8Mpc) is available as a function of redshift.
- σ_8 is the rms fluctuations of the tracers (galaxies - using spheres of 8Mpc) measured directly from the galaxy redshift surveys.
- b: is the distortion of the power spectrum (Kaiser 1987) measured from the anisotropy of the correlation function.

Fitting models to the data

$$x^2 = \sum_{i=1}^{9} \left[\frac{A_{obs}(z_i) - A_{th}(z_i)}{\sigma_i} \right]^2$$

where

$$A_{th} = f\sigma_8 = \sigma_{8,0}\Omega_m^{\gamma}(z)D(z)$$
$$\sigma_{8,0} = 0.81$$

(WMAP7, Komatsu et al. 2011)

Results

- ΛCDM ($\Omega_m = 0.273$): the likelihood function peaks at $\gamma = 0.602 \pm 0.055$
- ΛCDM ($\gamma_\Lambda = 6/11$): the likelihood function peaks at $\Omega_m = 0.243 \pm 0.034$

Hudson M. & Turnbull S., 2012 (arXiv:1203.4814) using almost the same data found that: $\gamma = 0.619 \pm 0.054$

- DGP gravity ($\Omega_m = 0.273$): we find $\gamma = 0.503 \pm 0.06$
- DGP gravity ($\gamma_{DGP} = 11/16$): we find a rather large value of the dimensionless matter density $\Omega_m = 0.38 \pm 0.042$

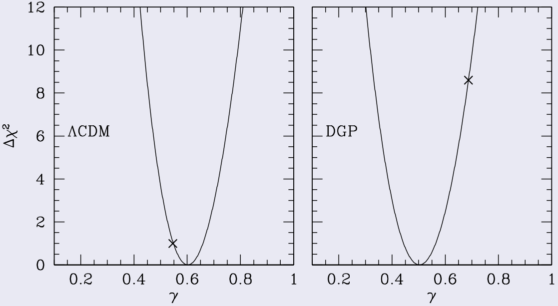
Comparison with other studies

- ΛCDM $\gamma = 0.602 \pm 0.055$
  - Di Porto & Amendola (2008) found $\gamma = 0.6^{+0.4}_{-0.3}$
  - Nesseris & Perivolaropoulos (2008): $\gamma = 0.67^{+0.2}_{-0.17}$
  - Gong (2008): $\gamma = 0.64^{+0.17}_{-0.15}$
- DGP gravity $\gamma = 0.503 \pm 0.06$
  - Gong (2008): $\gamma = 0.55^{+0.14}_{-0.13}$
  - Wei (2008): $\gamma = 0.438^{+0.13}_{-0.11}$
  - Dosset et al. (2010): $\gamma = 0.55^{+0.14}_{-0.13}$

Results

Variance around the best fit

- ΛCDM
- DGP



Conclusions

- We utilize the recent growth data provided by the 2dFGRS, SDSS-LRG, VVDS and Wiggle-Z galaxy surveys in order to constrain the growth index.
- We have achieved to place the most stringent constraints on the value of the growth index.

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END
THANK YOU