Disentangling cosmological signatures from weak lensing systematics

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Cosmic geometry: Expansion history constraints

**Standard candles**

**Standard rulers**

Figure 8

(a) Constraints upon $\Omega_0$ and $\Omega_0/\Lambda_0$ in the consensus model (cosmological constant/cold dark matter model) using baryon acoustic oscillations (BAO), cosmic microwave background (CMB), and supernovae (SNe) measurements. (b) Constraints upon $\Omega_0$ and constant $w$ in the fiducial dark energy model using the same data sets. Reproduced from Kowalski et al. (2008).

Regarding Sandage’s two numbers, $H_0$ and $q_0$, Table 1 reflects both good agreement with and a smaller uncertainty than the direct $H_0$ measurement based upon the extragalactic distance scale, $H_0 = 72 \pm 8$ km/s/Mpc (Freedman et al. 2001). However, the parameter values in Table 1 are predicated on the correctness of the CDM paradigm for structure formation. The entries for $q_0$ in Table 1 are derived from the other parameters using Equation 6. Direct determinations of $q_0$ require either ultraprecise distances to objects at low redshift or precise distances to objects at moderate redshift. The former are still beyond reach, whereas for the latter the $H_0/q_0$ expansion is not valid.

If we go beyond the restrictive assumptions of these two models, allowing both curvature and $w$ to be free parameters, then the parameter values shift slightly and the errors increase, as expected. In this case, combining WMAP, SDSS, 2dFGRS (Two-Degree-Field Galaxy Redshift Survey), and SNe Ia data, Spergel et al. (2007) yield $w = -0.98 \pm 0.12$ and $\Omega_0 = 0.26 \pm 0.16 - 0.15$, whereas WMAP + SDSS only bounds $H_0$ to the range 61 – 84 km/s/Mpc at 95% confidence (Tegmark et al. 2006), comparable to the accuracy of the HST Key Project measurement (Freedman et al. 2001). Once we abandon the assumption that $w = -1$, there are no strong theoretical reasons for restricting our attention to constant $w$. A widely used and simple form that accommodates evolution is $w = w_0 + (1 - a)w_a$ (see Section 6). Future surveys with greater reach than that of present experiments will aim to constrain models in which $\Omega_0$, $\Omega_0/\Lambda_0$, $w_0$, and $w_a$ are all free parameters (see Section 8). We note that the current observational constraints on such models are quite...
Understanding cosmic acceleration

Cosmic acceleration = a modification of Einstein’s equations

\[ G_{\mu\nu} = 8\pi G T_{\mu\nu} \]

Broad aim = Distinguish which sector: modified gravity, \(\Lambda\) or a new type of matter?

Deviations from GR?

\(\Lambda\)?

Inhomogeneous universe?

New matter? interactions?

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How might we modify gravity?

- Active area of research, many different options, no solutions (yet)
- Scalar tensor gravity = simple models we can model effects for

\[
S = \int d^4x \sqrt{-g} \frac{1}{16\pi G} R.
\]

\[
S = \int d^4x \sqrt{-g} \frac{1}{16\pi G} (R + f_2(R)).
\]

\[
S = \int d^4x \sqrt{-g} \frac{1}{16\pi G} f_1(\phi) R.
\]

\[
S = \int d^5x \sqrt{-g^{(5)}} \frac{1}{16\pi G^{(5)}} R^{(5)}.
\]
Modifications to GR

- Alter Friedmann and acceleration equations at late times

\[ stuff f + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + 3P_m) \]

e.g. f(R) gravity

\[-H^2 f_R + \frac{a^2}{6} f + \frac{3}{2} H \dot{f}_R + \frac{1}{2} f_R + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) \]

e.g. DGP gravity

\[-\frac{\dot{H}}{r_c} + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) \]
Weak field tests of gravity

- Terrestrial and Solar System
  - Lab tests on mm scales
  - Lunar and planetary ranging

- Galactic
  - Galactic rotation curves and velocity dispersions
  - Satellite galaxy dynamics

- Intergalactic and Cluster
  - Galaxy lensing and peculiar motions
  - Cluster dynamical, X-ray & lensing mass estimates

- Cosmological
  - Late times: comparing lensing, peculiar velocity, galaxy position, ISW correlations
  - Early times: BBN, CMB peaks
The inhomogeneous universe: Metric and Matter

- Perturbed metric \( ds^2 = -(1 + 2\psi)dt^2 + a^2(1 - 2\phi)dx^2 \)
- Modified Einstein’s equations relate matter and metric perturbations
  - Poisson equation: How space responds to local density
    \[ k^2 \phi = -4\pi G a^2 \sum_j \rho_j \Delta_j \]
  - Relate two potentials
    \[ k^2 \psi = k^2 \phi - \text{shear stresses} \]
    Typically shear negligible at late times \( \phi \approx \psi \)
Changing the relationship between $\phi$ and $\psi$

- Aim to describe phenomenological properties common to theories

- A modification to Poisson’s equation, $Q$

  \[ k^2 \phi = -4\pi G Q a^2 \rho \Delta \]

  $Q \neq 1$: can be mimicked by additional (dark energy?) perturbations, or modified dark matter evolution

- An inequality between Newton’s potentials, $R$

  \[ \psi = R \phi \]

  $R \neq 1$: not easily mimicked.
  - potential smoking gun for modified gravity?
  - Significant stresses exceptionally hard to create in non-relativistic fluids e.g. DM and dark energy.
A modified growth model – Theoretical examples

- DGP: Scale independent modifications

- $f(R)$ gravity: scale dependent modifications

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Tying theory to observations

- **Galaxy positions and motions**
  - trace non-relativistic matter
  - Measure $\psi \sim QR$
  - Biasing of tracer (galaxy) issue
    \[
    \delta_g = b \delta_m
    \]

- **Weak lensing and CMB**
  - trace relativistic (photon path)
  - Sensitive to $(\phi+\psi) \sim Q(1+R)$ and time derivs
  - No bias (but plenty of systematics...)

- **Complementarity of tracers key to testing gravity**

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Correlating datasets

- 2-point correlation between observables $X$ and $Y = \delta_g, \theta, G, l, T_{\text{CMB}}$

\[
C_l^{X_iY_j} = \int_0^{\chi_{\text{max}}} \frac{d\chi}{\chi^2} W_X^i(\chi) W_Y^j(\chi) S_X(k_l, \chi) S_Y(k_{\ell}, \chi)
\]

Window function
- $i^{th}$ photo-z bin
- Instrument sensitivity & expansion history $w(z), H(z)…$

Source function
- $k=1/\chi$
- Large scale structure growth history $Q(z), R(z)…$

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Putting it all in the mix

- A “smoking gun” for GR on cosmic scales (Zhang et al PRL 2007)

\[ E_G \sim \frac{\text{galaxy position-lensing correlation } (C_{l}^{gG})}{\text{redshift space – galaxy position correlation } (C_{l}^{g\Theta})} \]

- Contrasts relativistic and non-relativistic tracers => \( R \neq 1 \)?
  - Lensing: \( G \sim \phi + \psi \sim Q(1+R) \),
  - Galaxy position and motion: \( g, \Theta \sim \psi \sim QR \)

- Independent of galaxy bias and initial conditions

\[
\frac{C_{l}^{gG}}{C_{l}^{g\Theta}} \sim \frac{b \sigma_8^2}{b \sigma_8^2}
\]
Vital proof of principle with SDSS LRG data

Figure 2 | Comparison of observational constraints with predictions from GR and viable modified gravity theories. Estimates of $E_G(R)$ are shown with $1\sigma$ error bars (s.d.) including the statistical error on the measurement of $1$ (filled circles). The grey shaded region indicates the $1\sigma$ envelope of the mean $E_G$ over scales $R = 10^{-50} h^{-1}$ Mpc, where the systematic effects are least important (see Supplementary Information). The horizontal line shows the mean prediction of the GR+$\Lambda$CDM model, $E_G = 0/0$, for the effective redshift of the measurement, $z = 0.32$. On the right side of the panel, labelled vertical bars show the predicted ranges from three different gravity theories: (i) GR+$\Lambda$CDM ($E_G = 0.408 \pm 0.029$), (ii) a class of cosmologically interesting models in $f(R)$ theory with Compton wavelength parameters $B_0 = 0.001 \pm 0.1$ ($E_G = 0.328 \pm 0.365$), and (iii) a TeVeS model designed to match existing cosmological data and to produce a significant enhancement of the growth factor ($E_G = 0.22$, shown with a nominal error bar of 10 per cent for clarity).
Galaxy positions

- Photometric redshifts locate galaxies in 3D (angular+redshift) space
  - Calibrate galaxy spectral energy densities (SED) – brightness vs frequency --against spectroscopic test set or templates

- Tomography
  - split galaxies into redshift bins
  - X-correlations between z bins useful for disentangling systematics and cosmology
Weak lensing distortions

- 2D map on the sky of galaxy ellipticities

\[ \epsilon^i(\theta) = \gamma^i_G(\theta) + \gamma^i_I(\theta) + \epsilon^i_{\text{rnd}}(\theta). \]

- Correlation in ellipticities measured statistically

- Random ellipticities (noise, randomly oriented galaxies) not an issue

- Correlated alignments (instrumental & astrophysical) need to be disentangled from cosmological shear

Credit: Williamson, Oluseyi, Roe 2007

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Astrophysical systematic: Intrinsic alignments

- Galaxies align in the potential gradient of their host halo

\[
\langle \epsilon^i \epsilon^j \rangle = \langle \gamma_G \gamma_G^i \rangle + \langle \gamma_G \gamma_I^j \rangle + \langle \gamma_I \gamma_G^i \rangle + \langle \gamma_I \gamma_I^j \rangle
\]

Correlation:
- Observed
- Cosmological (GG)
- Intrinsic (II)

GI shear (anti) correlation

Credit: Benjamin Joachimi, iCosmo

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Cross correlations and tomography help mitigate astrophysical systematics.

Plots of $C_l^{X_i Y_i}$ and $C_l^{X_5 Y_i}$

- GG and GI extended in $z$
- II strongly peaked at same $z$
- GI extra info about IAs
Cross-correlations can break theory degeneracies

Plots of $C^X_i Y_i$ and $C^X_5 Y_i$

MG in cross-z spectra, IA z dependent signature

Laszlo, RB, Kirk, Bridle, 2011
Forecasting: what you put in = what you get out

- FoM/Fisher insightful but

- Model dependent – e.g. w0/wa or functions of z?

- Systematic errors difficult but important!
  - Instrumental e.g. calibration uncertainties
    - Internal cross-checks: inter-filter, concurrent & repetition ≠ redundancy
  - Modeling: e.g. Photo z modeling errors, nonlinearity
    - Access to ground based facilities,
    - Training sets, simulation suites
  - Astrophysical: e.g. IAs, Hα z distribution, galaxy bias, baryonic effects
    - At what scale should one truncate the analysis?
    - Analytical modeling, gridded k & z bins, simulations?

- Buyer beware: risky to compare FoM unless apples-for-apples treatment
Assumptions about bias and IA model

Number of k and \( z \) bins for bias & IA nuisance parameters

Laszlo, RB, Kirk, Bridle, 2011
Assumptions about non-linear scales

Laszlo, RB, Kirk, Bridle, 2011
Cross-checks (and theory/simulations) are key to realizing tantalizing weak lensing science!

• “The WFIRST multiband approach to weak gravitational lensing is more robust than Euclid’s single very broad band, which is potentially vulnerable to galaxy color gradients. Because WFIRST measures lensing in three passbands, its data can be internally cross-correlated to help mitigate systematic measurement error. Since the WFIRST approach to weak gravitational lensing measurement appears to be more robust, it may produce better constraints on dark energy properties.”

• “Euclid’s and WFIRST’s measurements are not duplicative and the combinations will be more powerful than any single measurement. Combining WFIRST with Euclid and with ground-based data sets, such as that expected from LSST, should further enable astronomers to address the systematic challenges that previous ground-based weak gravitational lensing measurements have experienced. These combined data sets will likely overcome systematic limitations and realize the full potential of this powerful technique.”