Testing for alternatives to a positive cosmological constant

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Cosmic geometry: Expansion history constraints

Standard candles

Standard rulers

Kowalski 2008

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Is it $\wedge$?

- Worth asking more questions to see if things are truly as they seem?
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

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

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

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

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

- Alter Friedmann and acceleration equations at late times

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

e.g. f(R) gravity

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

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
  - Pulsar timing

- **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

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The inhomogeneous universe: Matter

- Matter collects into clumps, and leaves voids: density fluctuations

\[ \delta(x, t) \equiv \frac{\rho(x, t)}{\bar{\rho}} \]

- Motion over and above the Hubble expansion: peculiar velocity fluctuations

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

- Conservation of energy and momentum relate evolution over time to potentials

\[ \dot{\delta} = -\theta + 3\dot{\phi} \quad \frac{1}{a} \frac{d(a\theta)}{d\tau} = k^2 \psi \]
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 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.
Distinct behavior on large and small scales

Large scale suppression of growth $Q, R > 1$

Small scale boosting of growth $Q, R > 1$
Tying theory to observations

- **Galaxy positions and motions**
  - trace non-relativistic matter
  - Measure $\psi \sim G_{\text{mat}} = Q RG_N$
  - Biasing of tracer (galaxy) issue
    \[ \delta_g = b\delta_m \]

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

- **Complementarity of tracers key to testing gravity**
A modified growth model - Theoretical examples

- **DGP: Scale independent modifications**

\[ \frac{G_{\text{light}}}{G_N} \]

\[ Q(1+R)/2 \]

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

\[ f(R) \]

- Hu and Sawicki '07
Correlating datasets

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

$$C_l^{X_i Y_j} = \int_0^{\chi_{\text{max}}} d\chi \frac{W^i_X(\chi) W^j_Y(\chi) S_X(k_l, \chi) S_Y(k_\ell, \chi)}{\chi^2}$$

- Window function
  - $i^{th}$ photo-z bin
- Source function
  - $k_l = l / \chi$
- Instrument sensitivity & expansion history
- Large scale structure growth history
- $w(z), \, H(z)\ldots$
- $Q(z), \, R(z)\ldots$

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Putting it all in the mix

• A “smoking gun” for GR on cosmic scales

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

• Contrasts relativistic and non-relativistic tracers \( \Rightarrow R \neq 1? \)
  - Lensing: \( G \sim \phi + \psi \sim Q(1+R) = \frac{G_{\text{light}}}{G_{N}} \)
  - Galaxy position and motion: \( g, \Theta \sim \psi \sim QR = \frac{G_{\text{mat}}}{G_{N}} \)

• Independent of galaxy bias and initial conditions

\[ \frac{C_{l}^{gG}}{C_{l}^{g\Theta}} \sim \frac{b}{b} \frac{\sigma_{8}^{2}}{\sigma_{8}^{2}} \]

Zhang, Liguori, RB, Dodelson PRL 2007
Distinguishing between modified gravity and $\Lambda$

$$E_g \sim \frac{C_l^{g\kappa}}{C_l^{g\Theta}}$$

- GR
- DGP
- $f(R)$
- TeVeS $K=0.1$
- TeVeS $K=0.09$
- TeVeS $K=0.08$
Vital proof of principle with SDSS LRG data

Reyes et al. Nature 2010
CMB temperature correlations

- CMB photons traveled through cosmic gravitational wells

- Sensitive to gravitational decay/growth
  - boost/decline in temperature
  - Integrated Sachs Wolfe “ISW”
    \[
    \frac{\Delta T}{T} \sim \dot{\phi} + \dot{\psi}
    \]

- Important on large scales

- Integrated effect but useful none the less
  - Cross-correlations help extract z dependence
Dissecting the CMB power spectrum

Multipole moment $l$

Angular Size

Temperature correlation ($\mu K^2$)

ISW
Light only covered these distances (~Gpc) recently
Initial conditions & late-time evolution

Acoustic peaks
$\gamma - e^-$ scattering at time CMB formed ($z=1100$)

Horizon at $z=1100$

Adapted from WMAP collaboration
Galaxy positions: photometric surveys

- 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

- Cross-correlations between z bins useful for disentangling systematics and cosmology

Credit: LSST Consortium

Stage IV
Galaxy motions: Redshift Space Distortions

- Spectroscopic survey (basis for BAO) contains rich clustering info

- "Redshift space distortions"

- 3D map of galaxy positions in redshift space
  \[ z_{\text{obs}} = z_{\text{cosmo}} + \frac{v_{\text{pec}}}{c} \]

- Small scales: Line of sight smearing from velocity dispersion in groups/clusters

- Large scales: Coherent infall compresses halo image in redshift space

The 2dF Galaxy Redshift Survey Team (2001)
Galaxy motions: Redshift Space Distortions

- Coherent peculiar motions of galaxies ($\Theta = \theta/aH$) can be statistically estimated from redshift space distortions

$$P_g^{obs}(k, z, \mu) = [P_{gg}(k, z) + 2\mu^2 P_{g\Theta}(k, z) + \mu^4 P_{\Theta\Theta}(k, z)] e^{-k^2\mu^2\sigma_v^2(z)}$$

- Complementary $\phi$ and $\psi$ dependence from lensing and ISW

$$\frac{d(a\theta)}{dt} = k^2\psi$$

- 1D velocity dispersion, simple statistic (Velocity equiv to $\sigma_8$)

$$\sigma_v^2(z) = \frac{1}{3(2\pi^2)} \int dk P_{\Theta\Theta}(k, z)$$

But aspiration to use all $z$, $k$ information tomographically

- Nonlinear effects can be significant - require numerical simulation (Kwan, Lewis and Linder 2011)
Galaxy shapes: Weak lensing distortions

- 2D map on the sky of galaxy ellipticities

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

- Correlation in ellipticities measured statistically

- Random ellipticities not an issue

- Correlated alignments need to be disentangled from cosmological shear

- Instrumental & astrophysical "contaminants"

Credit: Williamson, Oluseyi, Roe 2007

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Galaxy shapes: Intrinsic alignments

- Significant astrophysical systematic

- Galaxies align in the potential gradient of their host halo

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

Correlation:

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

GI shear (anti) correlation

Credit: Benjamin Joachimi, iCosmo
Cross correlations and tomography: help mitigate astrophysical systematics

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

Laszlo, RB, Kirk, Bridle, 2011
Cross-correlations and tomography: break degeneracy between systematics and theory

Plots of $C_{l}^{X_i Y_i}$ and $C_{l}^{X_5 Y_i}$

MG and IA have different $z$ dependent signatures

Laszlo, RB, Kirk, Bridle, 2011
Three groups of extra galactic observations for testing gravity

I: Background expansion
- CMB angular diameter distance
- Supernovae luminosity distance
- BAO angular/radial scale

II: Growth, up to some normalization
- Galaxy autocorrelations
- Galaxy - ISW x-correlation
- X-ray and SZ galaxy cluster measurements
- Ly-alpha measurements

III: Growth directly
- CMB ISW autocorrelation
- Weak lensing autocorrelation
- Peculiar velocity distribution/bulk flows

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Current constraints

- **Multiple data**
  - WMAP CMB,
  - SDSS LRG auto
  - SDSS-WMAP ISW cross correlation
  - COSMOS weak lensing,
  - Union SN1a

- **ISW + ISW-galaxy correlations drive constraints**

- **Principal degeneracy**
  - \((\phi+\psi)\) direction \(\sim Q(1+R)/2\)

- **“Figure of Merit”**
  - \(1/\text{error ellipse area}\)
  - MG FoM \(\sim 0.03\)
What about future surveys?

- Fisher matrix analysis = Inverse covariance (error) matrix
  \[ Cov_{ij}^{-1} = F_{ij} = \frac{\partial t_a}{\partial p_i} Cov_{ab}^{-1} \frac{\partial t_b}{\partial p_j} \]

- Assumed cosmology and parameterization
  \[ p = \{ \Omega_b h^2, \Omega_m h^2, \Omega_k, \tau, w_0, w_a, Q_0, Q_0(1 + R_0)/2, n_s, \Delta^2_R(k_0), + \text{systematic nuisance parameters} \} \]

- Datasets
  \[ t = \{ C_{\ell}^{TT}, C_{\ell}^{TE}, C_{\ell}^{EE}, C_{\ell}^{g1}, ..., C_{\ell}^{Eg1}, ...C_{\ell}^{g1g1}, C_{\ell}^{g1g2}, ..., C_{\ell}^{KN_{ph}KN_{ph}'} \} \]

- Survey specifications
  - near future (stage III) and end of decade (stage IV) surveys
  - Stage III = Planck CMB + DES-like imaging + BOSS spectroscopic surveys
  - Stage IV = Planck CMB + EUCLID-like imaging and spectroscopy
Forecasting: what you put in = what you get out

- Figures of merit / Fisher insightful but
- Model dependent - e.g. $w_0/w_a$ 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, $H\alpha z$ 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
Systematic assumptions matter

WFIRST (conservative)

+SN

312

450

180

+BAO

600

+WL

499

219

WFIRST (optimistic)

+SN

370

831

1209

496

+BAO

651

764

275

+RSD

275

+WL

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NASA WFIRST SDT Interim report 2011
Sensitivity to theory and systematics

95% confidence contours

- GR no IA
- GR with IA systematic error
- MG no IA
- MG with IA systematic error

Impact of cross-correlations: reducing systematics, breaking theory degeneracies

Assumptions about bias and IA model

Number of $k$ and $z$ bins for bias & IA nuisance parameters

*If* you understand non-linear scales they could make a big difference
Concluding thoughts

- **Growth history key to testing large scale, weak field gravity**
  - We can do more than measure $w$; important opportunity, not just a 2 for the price of 1.
  - Included in assessing upcoming missions. Not just piggy-back science.

- **Complementary techniques and datasets important to break cosmological and systematic degeneracies**
  - Multiple upcoming surveys DES, BOSS/BigBOSS, LSST, EUCLID, WFIRST

- **Systematics modeling essential in FoM calculations**
  - Characterization key to assessing relative strengths of different techniques/ survey specs.
  - Can significantly impact predictions (beware apples vs oranges)

- **Figures of merit (DE & MG) useful but constraining**
  - $\gamma$ or $f$ describe the LSS growth rate
  - $R$ and $Q$ contrast relativistic and NR tracers of gravity, closer tie to theory
  - Isolating $R\neq 1$ could be a smoking gun for MG.
  - Phenomenological form, a choice, but may not be the answer. Mapping to theory is a further significant effort.