Title: Cosmological tests of gravity: Unpacking degeneracies - Danielle Leonard

Date: Jul 21, 2015 11:00 AM

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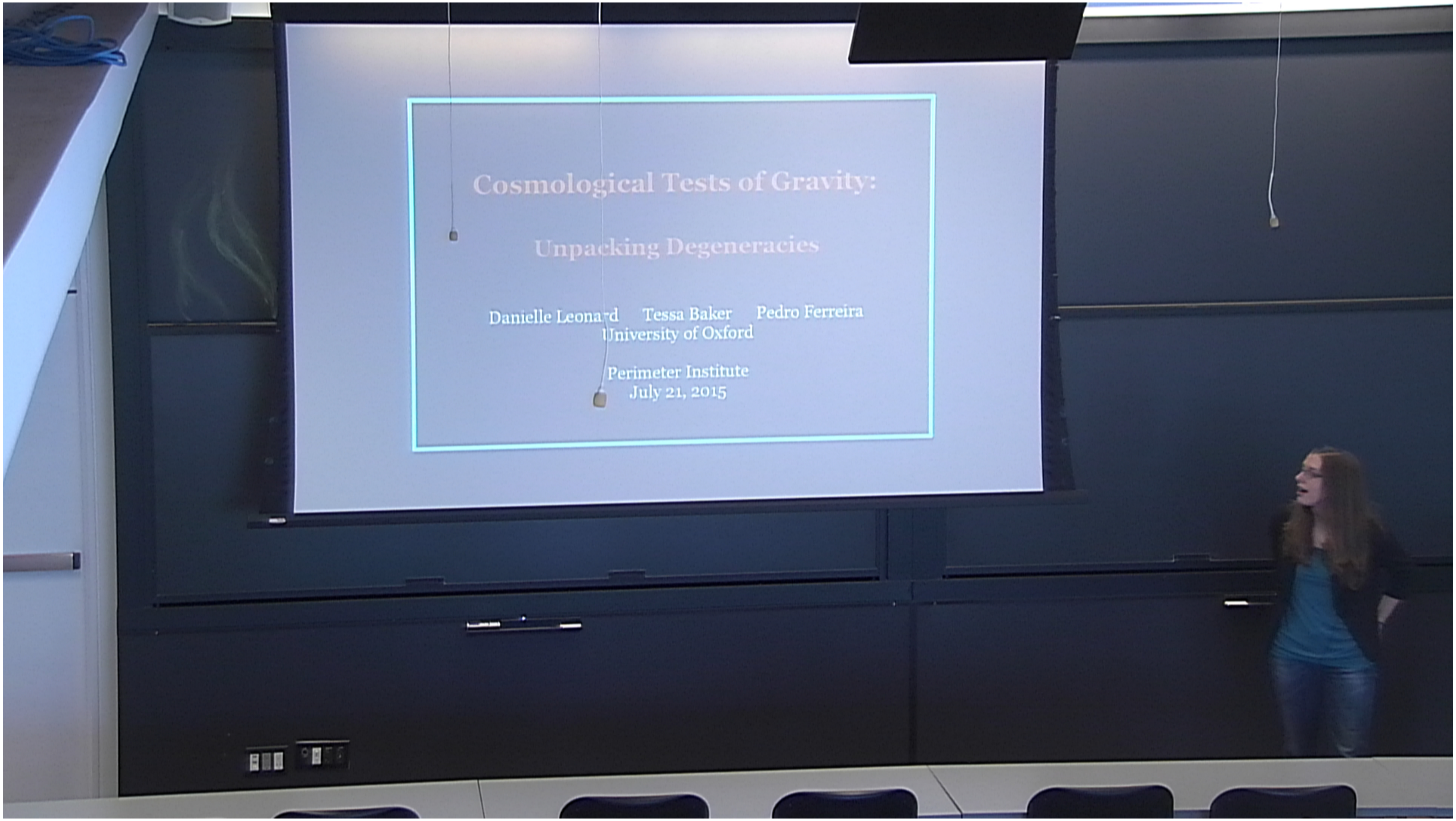
Abstract: <p>Current and near-future cosmological surveys can provide powerful tests of gravity on the largest scales. However, in order to extract this information, it is essential to understand the host of parameter degeneracies which may arise. I present two approaches towards this goal, with a focus on the use of weak gravitational lensing measurements in combination with other probes. First, I discuss a novel expression for a weak lensing power spectrum under alternative theories of gravity. Obtained by considering small deviations from GR, this expression separates various physical effects of modifications to GR, thus allowing a quantitative understanding of degeneracies between gravitational parameters. Second, I present an investigation into the theoretical uncertainty inherent to the popular gravity-testing statistic E_G. By improving our understanding of the theoretical value of E_G, we can use it to make more robust statements about the viability of alternative theories of gravity on cosmological scales.</p>


Cosmological Tests of Gravity:
Unpacking Degeneracies
Danielle Leonard Tessa Baker Pedro Ferreira
University of Oxford
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Outline

- Introduction and motivation
- A linear response approach
- E_G and degeneracies
- Summary and conclusions

Why consider (cosmological) alternatives to GR?

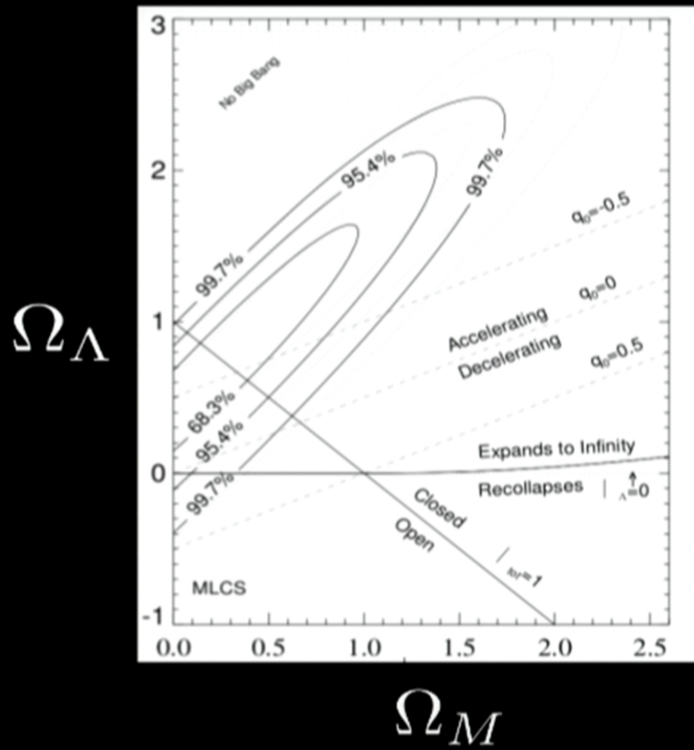

Figure: Riess et. al. 1998, 9805201

Introduction & Motivation

Why consider (cosmological) alternatives to GR?

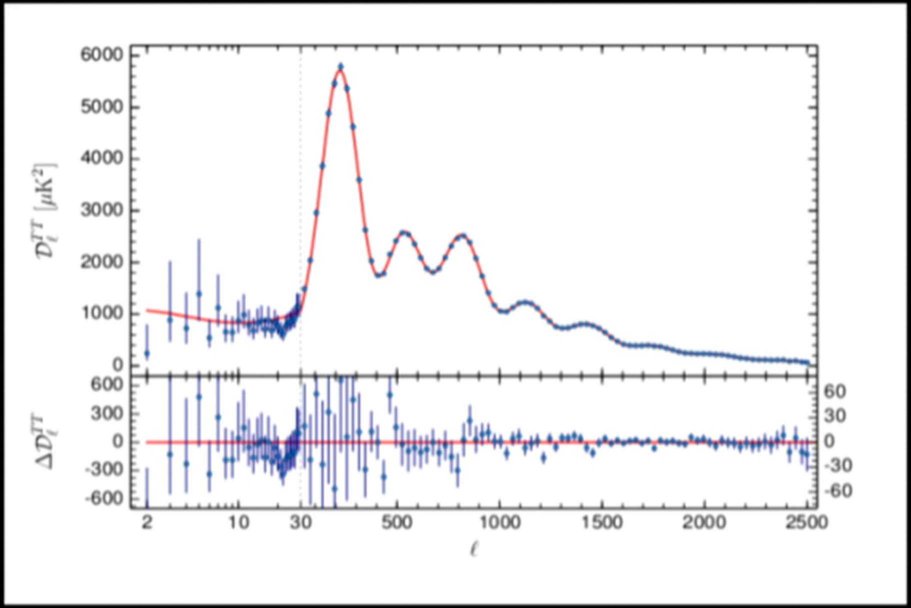

Figure: Planck Collaboration 2015, 1502.01589

Cosmological tests of gravity

- Weak gravitational lensing

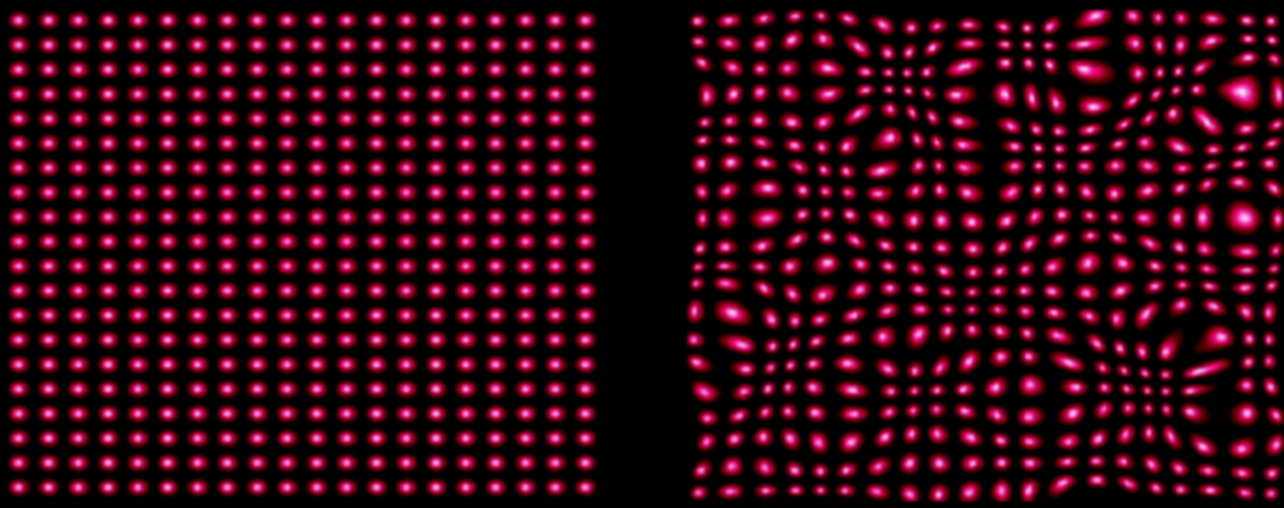

Image: iCosmo group (http://gravitationallensing.pbworks.com)

Introduction & Motivation

Cosmological tests of gravity

- Weak gravitational lensing
- Redshift space distortions

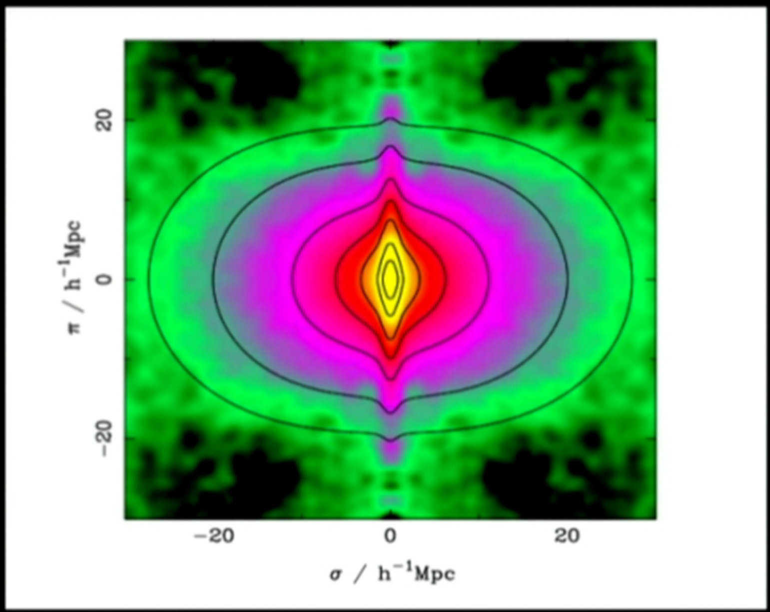

Figure: Peacock et. al. 2001, 0103143

Introduction & Motivation

Cosmological tests of gravity

- Weak gravitational lensing
- Redshift space distortions
- Baryon Acoustic Oscillations

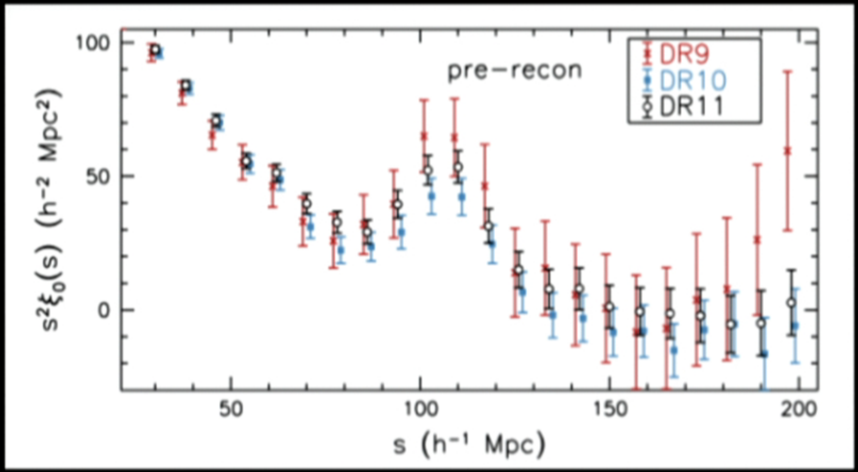

Figure: Anderson et. al. 2013, 1312.4877

Degeneracies:

When more than one physical effect has the same observational effect.

E. g. : In galaxy lensing: dark matter halo mass and gravitational properties.

A Linear Response Approach

Leonard et. al. 2015, astro-ph /1501.03509
Baker et. al. 2013, astro-ph/1310.1086

A Linear Response Approach

Parameterizing Gravity

The Quasi-static Approximation:

- Valid at significantly sub-horizon scales (k >> H).
- Allows us to drop time derivatives in gravitational equations of motion.
- Allows most cosmologically viable theories of gravity to be parameterized in a simple form.

Parameterizing Gravity

The Quasi-static Approximation:

• Allows most cosmologically viable theories of gravity to be parameterized in a simple form.

Valid for (e. g.):

- f(R)
- Brans-Dicke
- DGP

Proceed with caution (e. g.):

- Massive gravity

A Linear Response Approach

Parameterizing Gravity

$$2\nabla^2\Psi = 8\pi G a^2(1+\delta\mu(a,k))\bar{\rho}_M\Delta_M$$

$$\frac{\Phi}{\Psi} = 1+\delta\gamma(a,k)$$

A Linear Response Approach

Parameterizing Gravity

$$2\nabla^2\Psi = 8\pi G a^2(1+\delta\mu(a,k))\bar{\rho}_M \Delta_M$$

$$\frac{\Phi}{\Psi} = 1 + \delta\gamma(a,k) \qquad w(a) = -1 + \beta(a)$$

$$\Sigma(a,k) = \delta\mu(a,k) + \frac{1}{2}\delta\gamma(a,k)$$

$$\bar{\mu}(a,k) = \delta\mu(a,k) - \delta\gamma(a,k)$$

A Linear Response Approach

Parameterizing Gravity

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A Linear Response Approach

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A Linear Response Approach

Convergence in Modified Gravity

$$P_\kappa^{i,j}(\ell) = \int_{-\infty}^{0} d\mathrm{x}\, \frac{9}{16} \frac{g_i(\mathrm{x}) g_j(\mathrm{x})}{\chi_{\mathrm{GR}}(\mathrm{x})^2} P_M^{\mathrm{GR}}(k)\, D_{\mathrm{GR}}^2(\mathrm{x}) \mathcal{H}_{\mathrm{GR}}^3(\mathrm{x}) \Omega_M^{\mathrm{GR}}(\mathrm{x})^2$$

$$\times \left(1 + 2\Sigma(\mathrm{x},k) + 2\delta_\Delta(\mathrm{x},k) + \frac{3}{2} u(\mathrm{x}) \left[1 - \Omega_M^{GR}(\mathrm{x})\right] + \left(\frac{\partial \ln \left(g_i(\chi(\mathrm{x}))/\chi(\mathrm{x})^3\right)}{\partial \ln \chi(\mathrm{x})} \right.\right.$$

$$\left.\left. + \frac{\partial \ln \left(g_j(\chi(\mathrm{x}))/\chi(\mathrm{x})^3\right)}{\partial \ln \chi(\mathrm{x})} - \frac{\partial \ln (P_M^0(k)/k^4)}{\partial \ln k} \right) \Bigg|_{\chi_{\mathrm{GR}}(\mathrm{x})} \frac{\delta \chi(\mathrm{x})}{\chi_{\mathrm{GR}}(\mathrm{x})} \right)$$

$$\mathrm{x} = \ln(a) \qquad k = \frac{\ell}{\chi(\mathrm{x})}$$

A Linear Response Approach

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A Linear Response Approach

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$$\mathrm{x} = \ln(a) \qquad k = \frac{\ell}{\chi(\mathrm{x})}$$

A Linear Response Approach

Degeneracy Directions

Scale-independent $\bar{\mu}$ & Σ, $\beta = 0$

Redshift Space Distortions: Constrain only $\bar{\mu}(\mathrm{X})$

Weak Lensing:

$$\delta S_\kappa(\mathrm{X}) = 2\Sigma(\mathrm{X}) + 2\delta_\Delta(\mathrm{X})$$

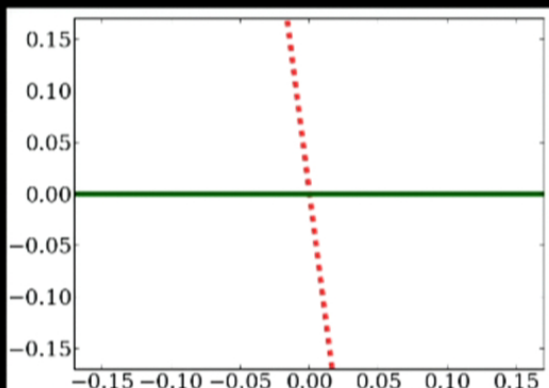
$$= 2\Sigma(x) + 3\int_{-\infty}^{\mathrm{X}} d\mathrm{x}'\bar{\mu}(\mathrm{x}')I(\mathrm{x},\mathrm{x}')\Omega_M^{GR}(\mathrm{x}')$$

A Linear Response Approach

Degeneracy Directions

Scale-independent $\bar{\mu}$ & Σ, $\beta = 0$

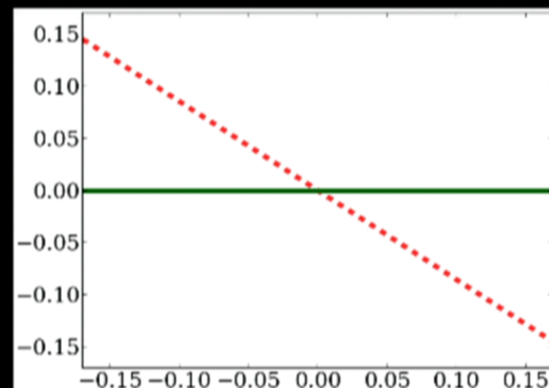
μ_0



Σ_0

$$\bar{\mu}(x)\,,\, \Sigma(x) \propto \frac{\Omega_\Lambda^{GR}(x)}{\Omega_\Lambda^{GR}(x=0)}$$

μ_0



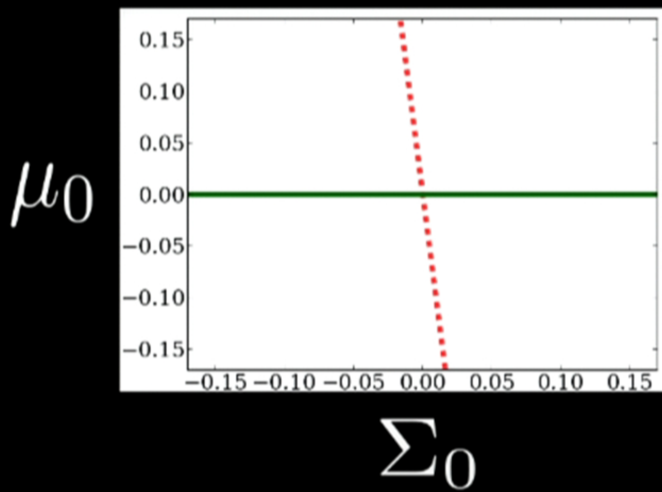
Σ_0

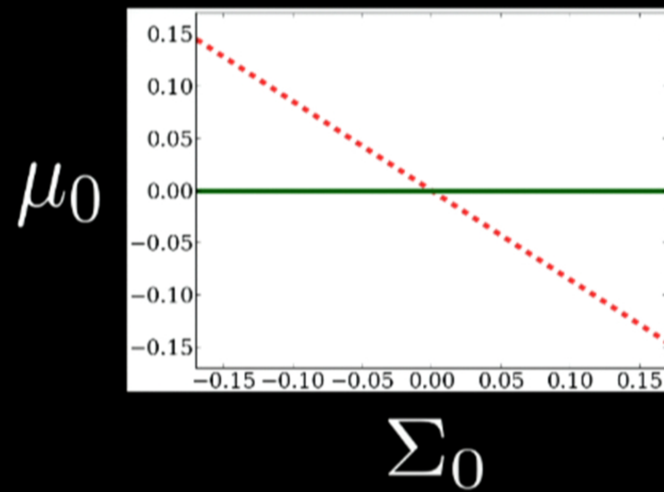
$$\bar{\mu}(x) = \mu_0\,,\, \Sigma(x) = \Sigma_0$$

A Linear Response Approach

Degeneracy Directions

Scale-independent $\bar{\mu}$ & Σ, $\beta = 0$





$$\bar{\mu}(x)\,,\ \Sigma(x) \propto \frac{\Omega_\Lambda^{GR}(x)}{\Omega_\Lambda^{GR}(x=0)}$$

$$\bar{\mu}(x) = \mu_0\,,\ \Sigma(x) = \Sigma_0$$

A Linear Response Approach

Degeneracies & Forecasting

Fisher forecasting methodology:

Likelihood

$$\mathcal{F}_{ab} = -\left\langle \frac{\partial^2 \ln \mathcal{L}}{\partial p_a \partial p_b} \right\rangle = C^{-1}_{ab}$$

Fisher matrix

Inverse covariance matrix

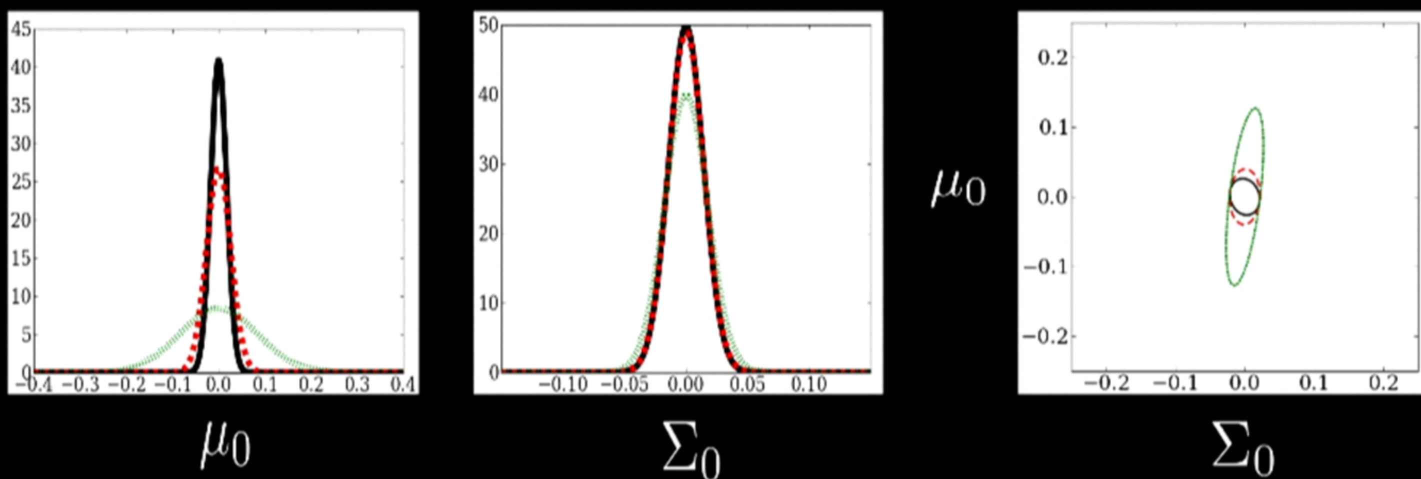
- For forecast parameter constraints: compute and invert the relevant sub-matrix of $\mathcal{F}_{ab}$.

A Linear Response Approach

Degeneracies & Forecasting

Consider a Dark Energy Task Force 4 Type Survey: $w_a = 0$

Gaussian posterior probability distributions: 68.3% confidence contours:



Black, solid: $w_0 = -1$

Red, dashed: $\sigma(w_0)_{BAO} = 1\%$

Green, dotted: $\sigma(w_0)_{BAO} = 5\%$

A Linear Response Approach

Degeneracies & Forecasting

Consider a Dark Energy Task Force 4 Type Survey: $w_a = 0$

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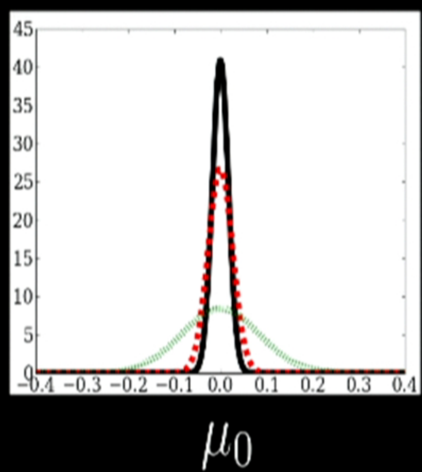

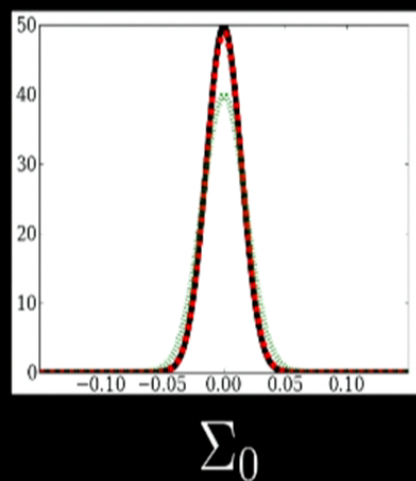

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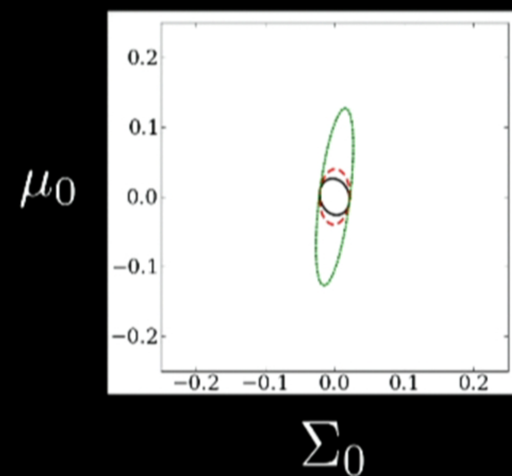

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A Linear Response Approach

Degeneracies & Scale-Dependence

Now consider scale-dependent $\bar{\mu}$ & $\Sigma,\ \beta = 0$

A Linear Response Approach

Degeneracies & Scale Dependence

Under the linear response approach, we get:

$$\bar{\mu}(\mathrm{x}, k) \approx -(\delta p_1(\mathrm{x}) + \delta p_4(\mathrm{x})) + k^2(-\delta p_2(\mathrm{x}) + 2\delta p_3(\mathrm{x}) - \delta p_5(\mathrm{x}))$$

$$\Sigma(\mathrm{x}, k) \approx -\left(\frac{\delta p_1(\mathrm{x})}{2} + \delta p_4(\mathrm{x})\right) + k^2\left(\frac{-\delta p_2(\mathrm{x})}{2} + \frac{3\delta p_3(\mathrm{x})}{2} - \delta p_5(\mathrm{x})\right)$$

$$p_i(\mathrm{x}) = 1 + \delta p_i(\mathrm{x})$$

Theoretical uncertainty and E_G

E_G : Original definition

P. Zhang et. al., 0704.1932

Galaxy-lensing cross spectrum (observable: shear)

$$\hat{E}_G = \frac{C_{\kappa g}(l, \Delta l)}{3H_0^2 a^{-1} \Sigma_\alpha f_\alpha(l, \Delta l) P_{vg}^\alpha}$$

E_G :Observational Definition

R. Reyes et. al., 1003.2185

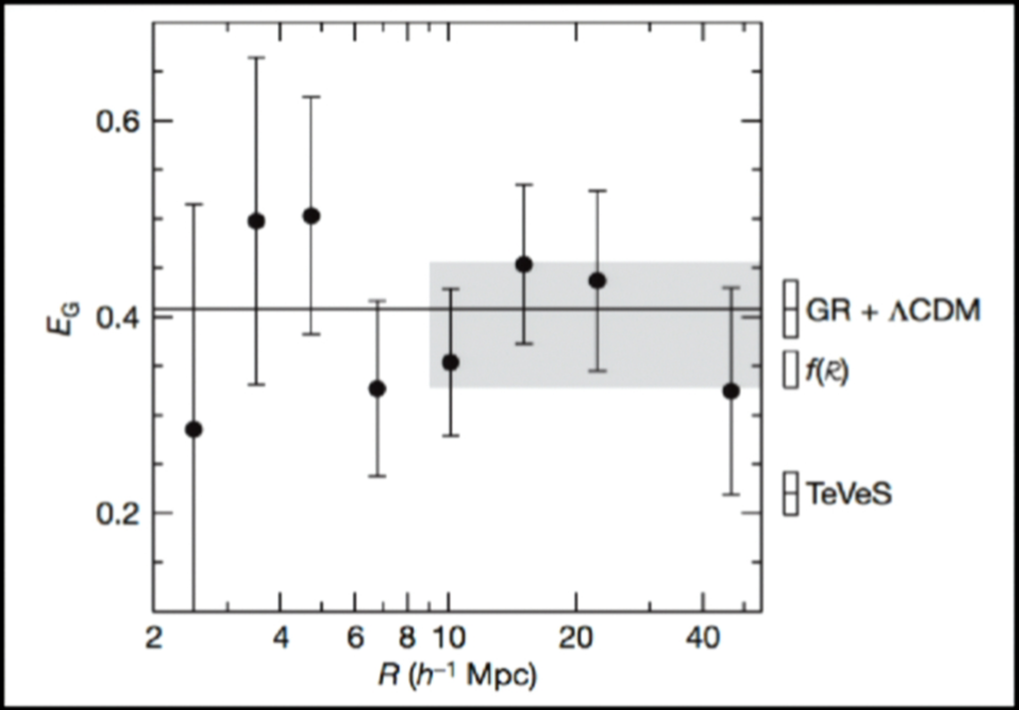
Galaxy – lensing cross correlation (small scales removed)

$$E_G(R) = \frac{\Upsilon_{gm}(R)}{\beta \Upsilon_{gg}(R)}$$

E_G **and degeneracies**

E_G :Current measurements

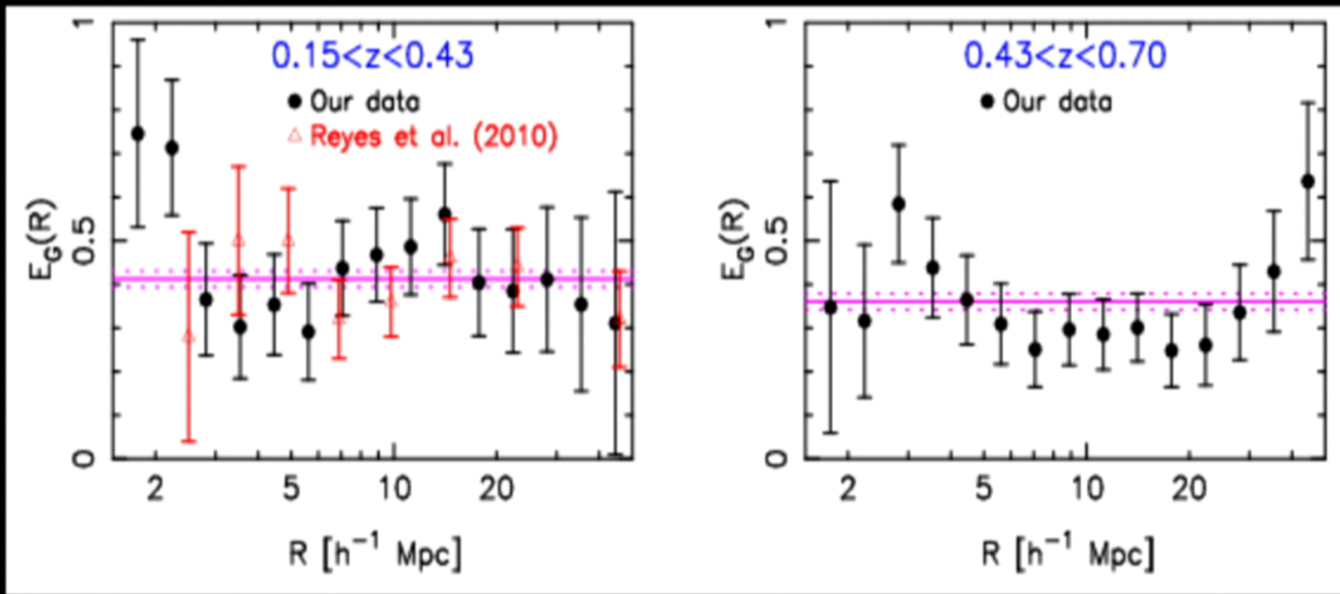
R. Reyes et. al., 1003.2185



E_G **and degeneracies**

E_G :Current measurements

C. Blake et. al., 1507.03086



Degeneracies: Non-gravitational parameters

$\Upsilon_{gm}(R)$ & $\Upsilon_{gg}(R)$ depend on:

$\frac{dn}{dz}$ = source redshift distribution

P = projection length

R_0 = minimum length scale included

$b(z,k)$ = galaxy bias

E_G **and degeneracies**

Degeneracies: Non-gravitational parameters

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$\frac{dn}{dz}$ = source redshift distribution

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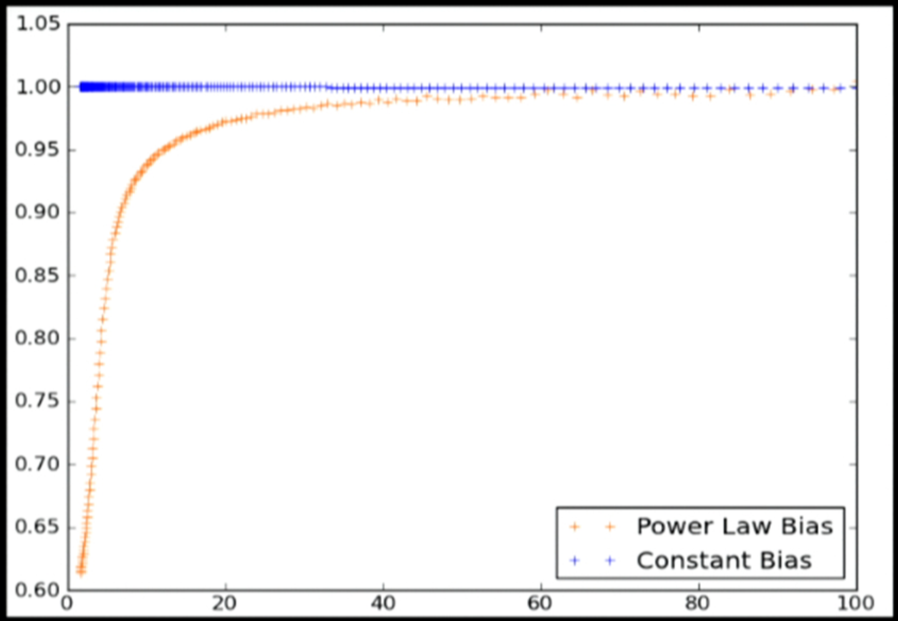
$b(z,k)$ = galaxy bias

E_G **and degeneracies**

Degeneracies: Scale-dependent galaxy bias

$$b(k) = b_0 + b_1 k^n$$

$$\frac{E_G}{E_G^{fid}}$$



R, Mpc /h

$b_0 = 1.09$

$b_1 = 0.66$

$n = 1.28$

Amendola et. al. 2015, 1502.13994

E_G **and degeneracies**

E_G :Observational Definition

P. Zhang et. al., 0704.1932
R. Reyes et. al., 1003.2185

Galaxy – lensing cross correlation (small scales removed)

$$E_G(R) = \frac{\Upsilon_{gm}(R)}{\beta \Upsilon_{gg}(R)} \sim \frac{\nabla^2(\Phi + \Psi)}{3H_0^2 a^{-1} f \delta}$$

Growth rate of structure over galaxy bias (on linear scales, w/ constant bias)

Projected galaxy-galaxy correlation (small scales removed)

Summary & Conclusions

- Analytic approaches can help us to grapple with parameter degeneracies.

- Taking a linear response approach:
  - shows that RSD+WL is robust to time-dependence of $\mu(x)$.
  - allows us to explain degeneracies in forecasts.

- Current work: degeneracies related to E_G may be important for future measurements.

- Future work: exploring degeneracies with basic cosmological parameters.

E_G **and degeneracies**

Degeneracies: Gravitational Parameters