Weak Lensing Probes of Modified Gravity

Fabian Schmidt

with S. Dodelson, W. Hu, M. Liguori

Dep. of Astronomy / Kavli Institute for Cosmological Physics, University of Chicago

Cosmo 08, Madison, 8/25/08

Kavli Institute for Cosmological Physics AT THE UNIVERSITY OF CHICAGO

Fermilab

The Force behind the Acceleration

General Relativity

Geometry $\longleftrightarrow$ Energy-momentum

$$G_{\mu\nu} + \Lambda\, g_{\mu\nu} = 8\pi\, G\, T_{\mu\nu}$$

Left-hand side

Gravity (General Relativity) modified

Right-hand side

Energy content of Universe modified – *Dark Energy*.

Modifying Gravity

Gravity is well tested on *many scales*: from Solar System to Big Bang Nucleosynthesis.

- Gravity theory has to reduce to GR locally and in Early Universe.
- GR limit in high curvature regime
- Modifications at late times on large scales

Dark energy can mimic expansion history of modified gravity (or vice versa).
$\Longrightarrow$ Have to go beyond background universe to probe gravity

Modified Gravity on Large Scales

Cosmological metric:

$$ds^2 = -(1 + 2\Psi)dt^2 + a^2(t)(1 + 2\Phi)d\mathbf{x}^2$$

Effects of Modified Gravity:

- ***Growth of structure***
  - Cosmological potentials unequal: $\Phi(k, \eta) \neq -\Psi(k, \eta)$
  - Scale-dependent growth factor
- ***Poisson equation modified*** in some models

Caveat: Only ***linear evolution of modified gravity*** worked out so far.

Modified Gravity Models

Popular models considered here:

I. $f(R)$ ***gravity*** *Carroll et al. 2004*
- Potential decay reduced / delayed $\Rightarrow$ *stronger lensing*

II. ***DGP (braneworld) model*** *Dvali et al. 2000*
- Amplified potential decay $\Rightarrow$ *weakened lensing*

III. ***TeVeS model*** *Bekenstein 2004*
- No dark matter - *mimicked by vector field perturbations*

Weak Lensing

- ***Growth of lensing potential*** $\Phi_- \equiv (\Phi - \Psi)/2$ observable through *redshift evolution* of weak lensing correlations
- *Galaxy-shear correlation* tests ***matter–potential relation*** $\Rightarrow$ Poisson equation

Compare modified gravity predictions with ***GR + (smooth) DE models with same expansion history***

$\Rightarrow$ separate *growth/gravity* from *expansion history*

Restricting to linear scales: $\ell \lesssim 300$ at $z \gtrsim 1$

See *Knox et al. 2006; Jain & Zhang 2007; F.S. 2008*

Weak Lensing Correlations

Galaxy-shear correlation

$$C^{g\kappa}(\ell) = \int dz \frac{H(z)}{\chi^2(z)} b W_g(z) W_\kappa(z) \left[D_{\Phi_-}(k,z)\, D_m^2(k,z)\, k^2 P(k, z_m) \right]_{k = \frac{l+1/2}{\chi(z)}}$$

Depends on: *Well-constrained observables (SN / CMB).*

- Expansion history (geometry) $W_\kappa(z) \sim \chi(z)/\chi_s(\chi_s - \chi(z))$
- Matter power spectrum at early times $P(k, z_m)$

Caveat: galaxy bias $b \rightarrow$ e.g., consider $C^{g\kappa}/\sqrt{C^{gg}}$

Weak Lensing Correlations

Galaxy-shear correlation

$$C^{g\kappa}(\ell) = \int dz \frac{H(z)}{\chi^2(z)} b W_g(z) W_\kappa(z) \left[D_{\Phi_-}(k,z)\, D_m^2(k,z)\, k^2 P(k, z_m) \right]_{k = \frac{l+1/2}{\chi(z)}}$$

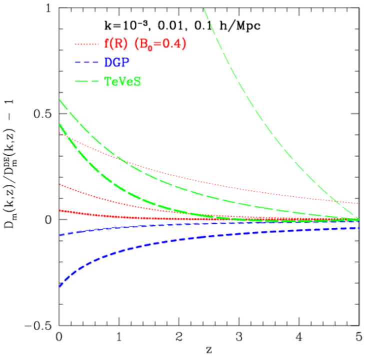
... also depends on:

- Linear growth of mode k (since z_m) $\quad D_m(k,z) \equiv \frac{\delta(k,z)}{\delta(k,z=z_m)}$
- Poisson equation $\quad D_{\Phi_-}(k,z) \equiv \frac{\Phi_-(k,z)}{\delta(k,z)}$

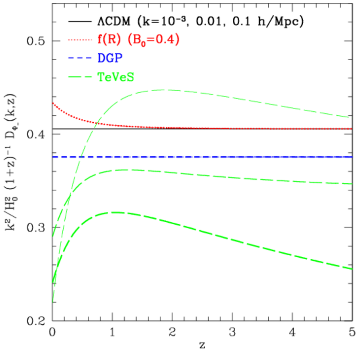
Probes of modified gravity

Weak Lensing in Modified Gravity

Linear growth: $D_m(k, z)$



Poisson equation: $D_{\Phi\_}(k, z)$



F.S. 2008

Assumed parameters

As expected for *LSST*:

- 50 galaxies / arcmin^2
- 20,600 sq. deg. ($f_{Sky} = 0.5$)
- Galaxy z distribution expected for $I < 27$ mag

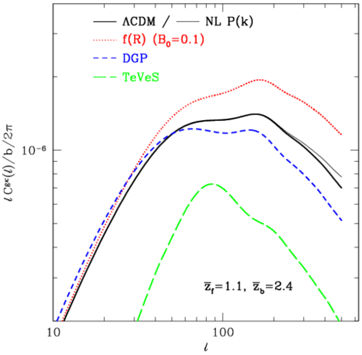
Redshift bins:

- 7 *foreground bins* with $\Delta z \approx 0.4$
- 1 *background bin* $z = 2...3$ (median $\bar{z} = 2.4$)

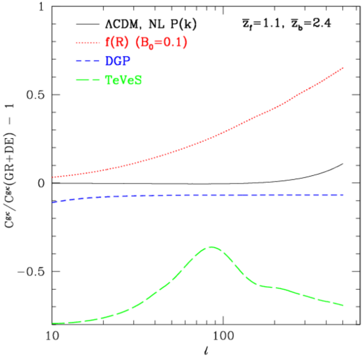
Similar results for *SNAP wide* survey parameters.

Galaxy-shear correlation: Scale Dependence

$\ell C^{g\kappa}(\ell)$ vs. ℓ for foreground galaxies at $\bar{z}_f = 1.1$

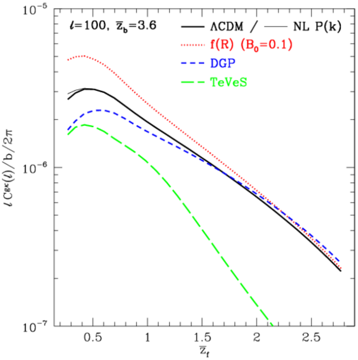


Deviation from GR+DE model with same $H(z)$

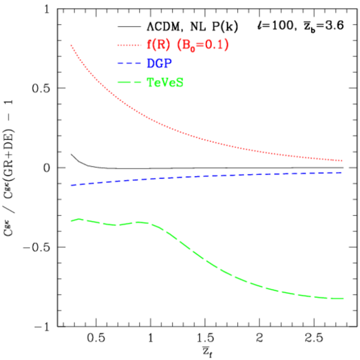


Galaxy-shear correlation: Redshift Evolution

$C^{g\kappa}(\ell = 100)$ for varying foreground redshifts

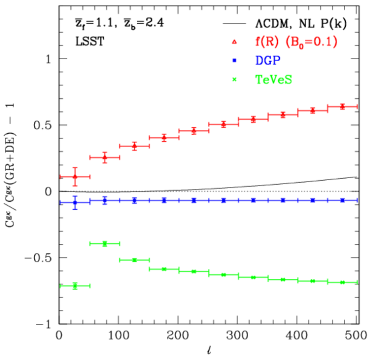


Deviation from GR+DE model with same $H(z)$

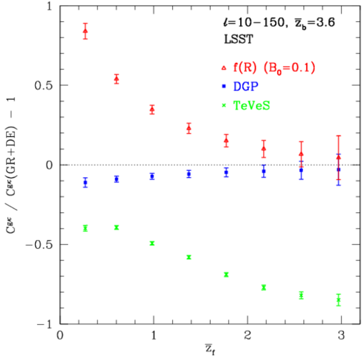


Modified Gravity constrainable with future surveys

Constraints on the deviation of galaxy-shear correlation from GR+DE: (similar results for shear-shear correlations)



vs ℓ for $\bar{z}_f = 1.1$



vs z_f for $\ell = 10 - 150$

Modified gravity and local tests

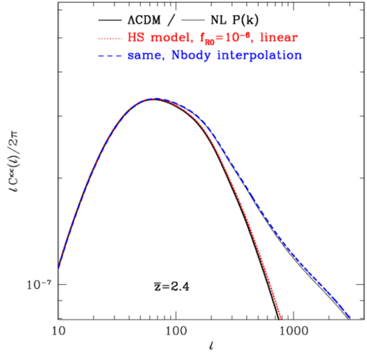
$f(R)$, *DGP*: how to satisfy Solar System constraints ?

- Non-linear mechanism to restore GR in high-density environments: *Chameleon effect* *Khoury & Weltman, 2004*
- *Not taken into account* in linear perturbation theory
- Cannot rely on fitting formulae based on GR simulations
- Have to solve full field equations together with dark matter dynamics

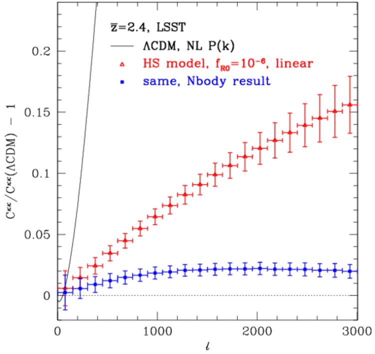
Has now been done: *Oyaizu, Lima, Hu, 2008*

Modified Gravity: non-linear lensing predictions

$C^{\kappa\kappa}(\ell)$ for ΛCDM and f(R)
(linear / full NL calculation)



Forecasted constraints
Huge S/N available at high ℓ



Background scalar field value today: $f_{R0} = 10^{-6}$

NL calculation: uses interpolation of Nbody power spectrum; work in progress...

Conclusions

- **Modified gravity is a *fundamental alternative*** to Dark Energy – but ***any expansion history*** can be produced by either alternative
- ***Growth of structure*** and ***matter-potential relation*** are key to probing gravity on cosmological scales.
- **Future surveys** like *SNAP, LSST* will be able to place stringent constraints on modified gravity.
- Understanding of **non-linear structure formation in modified gravity** crucial in order to extend constraints to smaller scales **(large S/N!)** – *work in progress*

References

S. M. Carroll et al.,
Phys. Rev. **D70**:043528 (2004)

G. Dvali, G Gabadadze, M. Porrati,
Phys. Lett. **B485**, 208 (2000)

J. D. Bekenstein,
Phys. Rev. **D70**:083509 (2004)

L. Knox, Y.-S. Song, J. A. Tyson,
Phys. Rev. **D74**:023512 (2006)

B. Jain, P. Zhang,
ArXiv:0709.2375 [astro-ph] (2007)

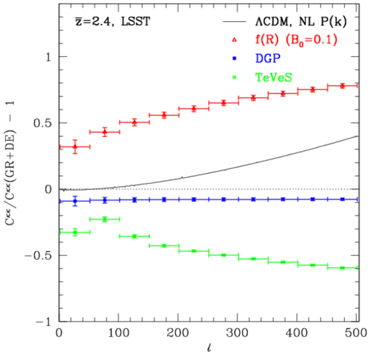
F. Schmidt,
Phys. Rev. **D78**:043002 (2008),
ArXiv:0805.4812

J. Khoury, A. Weltman,
Phys. Rev. **D69**:044026 (2004)

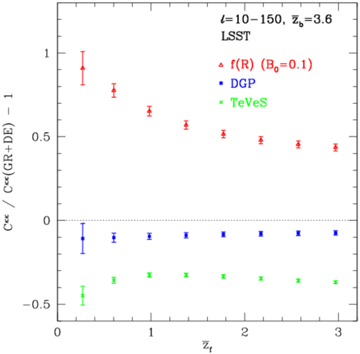
H. Oyaizu, M. V. Lima, W. Hu,
ArXiv:0807.2462 [astro-ph] (2008)

Modified Gravity constrainable with future surveys (II)

Same for shear-shear correlation:



vs ℓ for $\bar{z} = 3.6$



vs z_f for $\ell = 10 - 150$

Reduced galaxy-shear correlation

$$\frac{C^{g\kappa}(\ell)}{\sqrt{C^{gg}(\ell)}} \longrightarrow \sim$$ independent of galaxy bias

vs z_f for $\ell = 10 - 150$

LSST: