Testing Gravity in the Cosmos
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- First qualitatively complete parameterization of modified gravity acceleration models
- First complete study of specific models $f(R)$ and DGP
- First cosmological simulations of modified gravity compatible with solar system
- Collaborators:
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  - Wenjuan Fang
  - Dragan Huterer
  - Marcos Lima
  - Michael Mortonson
  - Hiro Oyaizu
  - Fabian Schmidt
  - Hiranya Peiris
  - Iggy Sawicki
  - Yong-Seon Song
  - Amol Upadhye
  - Sheng Wang
Incomplete Geometry or Energy?

- General relativity says **Gravity = Geometry**

- And **Geometry = Matter-Energy**

- Could the **missing energy** required by **acceleration** be an **incomplete** description of how **matter determines geometry**?
Parameterizing Acceleration

● **Cosmic acceleration**, like the cosmological constant, can either be viewed as arising from

Missing, or **dark energy**, with $w \equiv \frac{p}{\rho} < -1/3$

**Modification of gravity** on large scales

\[
G_{\mu\nu} = 8\pi G \left( T_{\mu\nu}^M + T_{\mu\nu}^{DE} \right)
\]

\[
F(g_{\mu\nu}) + G_{\mu\nu} = 8\pi G T_{\mu\nu}^M
\]

● Proof of principle models for both exist: **quintessence**, **k-essence**; **DGP braneworld acceleration**, $f(R)$ modified action

● Compelling **models** for either explanation lacking

● Study models as **illustrative toy models** whose features can be generalized
Three Regimes

- Three regimes defined by $\gamma = -\Phi/\Psi$ BUT with different dynamics
- Examples $f(R)$ and DGP braneworld acceleration
- Parameterized Post-Friedmann description

- Non-linear regime follows a halo paradigm but a full parameterization still lacking and theoretical, examples few: $f(R)$ now fully worked
Three Regimes

- Fully worked $f(R)$ and DGP examples show 3 regimes
- **Superhorizon** regime: $\zeta = \text{const.}, g(a)$
- **Linear** regime - closure $\leftrightarrow$ “smooth” dark energy density:

$$\nabla^2 (\Phi - \Psi)/2 = -4\pi G a^2 \Delta \rho$$

\[ g(a, x) \leftrightarrow g(a, k) \]

$G$ can be promoted to $G(a), G(a, k)$ but...

- **Non-linear** regime:

$$\nabla^2 (\Phi - \Psi)/2 = -4\pi G a^2 \Delta \rho$$

$$\nabla^2 \Psi = 4\pi G a^2 \Delta \rho + \frac{1}{2} \nabla^2 \phi$$

with non-linearity in the **field equation**

$$\nabla^2 \phi = g_{\text{lin}}(a) a^2 (8\pi G \Delta \rho - N[\phi])$$
DGP Braneworld Acceleration

- **Braneworld acceleration** (Dvali, Gabadadze & Porrati 2000)

\[ S = \int d^5 x \sqrt{-g} \left[ \frac{(5) R}{2\kappa^2} + \delta(\chi) \left( \frac{(4) R}{2\mu^2} + \mathcal{L}_m \right) \right] \]

with crossover scale \( r_c = \frac{\kappa^2}{2\mu^2} \)

- Influence of bulk through **Weyl tensor anisotropy** - solve master equation in bulk (Deffayet 2001)

- Matter still **minimally coupled** and conserved

- Exhibits the 3 regimes of modified gravity

- **Weyl tensor anisotropy** dominated conserved curvature regime \( r > r_c \) (Sawicki, Song, Hu 2006; Cardoso et al 2007)

- **Brane bending** scalar tensor regime \( r_* < r < r_c \) (Lue, Soćimirro, Starkman 2004; Koyama & Maartens 2006)

- **Strong coupling** General Relativistic regime \( r < r_* = \left( \frac{r_c r_g}{2} \right)^{1/3} \)

where \( r_g = 2GM \) (Dvali 2006)
Modified Action $f(R)$ Model

- $R$: Ricci scalar or “curvature”
- $f(R)$: modified action (Starobinsky 1980; Carroll et al 2004)

$$S = \int d^4x \sqrt{-g} \left[ \frac{R + f(R)}{16\pi G} + \mathcal{L}_m \right]$$

- $f_R \equiv df/dR$: additional propagating scalar degree of freedom (metric variation)
- $f_{RR} \equiv d^2 f/dR^2$: Compton wavelength of $f_R$ squared, inverse mass squared
- $B$: Compton wavelength of $f_R$ squared in units of the Hubble length

$$B \equiv \frac{f_{RR}}{1 + f_R} R' \frac{H}{H'}$$

- $' \equiv d/d \ln a$: scale factor as time coordinate
DGP CMB Large-Angle Excess

- Extra dimension modify gravity on large scales
- 4D universe bending into extra dimension alters gravitational redshifts in cosmic microwave background
Environment Dependent Force

- For large background field, gradients in the scalar prevent the chameleon from appearing.

![Image showing density, potential, and field variations with different values of $f_{R0}$](image)

Enhanced abundance of rare dark matter halos (clusters) with extra force.