COSMIC ACCELERATION: THEORETICAL CHALLENGES

Snowmass on the Mississippi,   July 30, 2013

The universe is accelerating!

The most important theoretical question associated with Cosmic Acceleration is DOES IT IMPLY NEW PHYSICS?

At present theoretical physics has no convincing explanation of the origin of cosmic acceleration

To test the physics of cosmic acceleration we must develop theoretical models, alternatives to Lambda CDM to test against current observational data

Implications of New physics in the Dark Energy Sector would have drastic implications for high energy physics

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New physics responsible for Dark Energy?
-> New Degrees of Freedom

Theorem: Cosmological constant is the `unique' large distance modification to GR that does not introduce any new degrees of freedom

Dynamical Models of Dark Energy or Modified Gravity will be distinguished by new degrees of freedom

= new particles - new fields - new gravitational waves - new forces - new dynamics

New degrees of freedom must necessarily by incredibly light!

$$m_{\rm d.e.} \leq 10^{-33} eV$$

$$m_{\rm d.e.} = \text{Hubble rate} = 1/\text{Age of universe}$$

If new degrees of freedom are MINIMALLY coupled to gravity - we call the model DARK ENERGY

If new degrees of freedom are NON-MINIMALLY coupled to gravity - we call the model MODIFIED GRAVITY

What is NOVEL about modified gravity theories - is that the extra dynamical degrees of freedom have dynamics at cosmological scales, they are very light

Interactions of new d.o.f.

Imagine a scalar

$$\phi = \phi_b + \delta\phi$$

coupled to the energy density

$$\rho = \rho_b + \delta\rho$$

Generic form of equation of motion for perturbations

$$Z(\phi_b, \rho_b)\left[\frac{d^2\delta\phi}{dt^2} - c_s^2\frac{d^2\delta\phi}{dx^2}\right] + m^2(\phi_b, \rho_b)\delta\phi = \beta(\phi_b, \rho_b)G_{\text{Newton}}\delta\rho$$

kinetic term

gradient term

mass term

coupling to matter

TESTS

Fifth Forces (solar system)

Equivalence Principle Tests etc.

Binary Pulsar Timing

Nucleosynthesis/Cosmology

Variation of fundamental constants

New gravitational degrees of freedom that couple to matter (MODIFIED GRAVITY) are highly constrained

Need some kind of screening mechanism to hide extra d.o.f.

Fifth force constraints: screening

$$F \approx \frac{M_a M_b G}{r^2} \frac{\beta^2(\phi_b, \rho_b)}{\sqrt{Z}(\phi_b, \rho_b) c_s(\phi_b, \rho_b)} \exp(-m(\phi_b, \rho_b) r)$$

To ensure fifth forces are small

$$\frac{\beta^2(\phi_b, \rho_b)}{\sqrt{Z(\phi_b, \rho_b)} c_s(\phi_b, \rho_b)} \exp(-m(\phi_b, \rho_b) r)$$

Only three independent possibilities!

(a) Coupling is small $\beta(\phi_b, \rho_b) \ll 1$

(b) Mass is large $m(\phi_n, \rho_b) \gg \frac{1}{r_{exp}}$

(c) Kinetic term is large $Z(\phi_b, \rho_b) \gg 1$

Example of Screening: Vainshtein effect

$$Z = 1 + \frac{\rho}{\Lambda^3 M_{\rm Pl}} \qquad \Lambda^3 \sim m^2 M_{\rm Pl}$$

Allow in the action Irrelevant kinetic operators

$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda^3} \Box\phi(\partial\phi)^2 + \frac{\phi}{M_{\rm pl}}\rho \right)$$

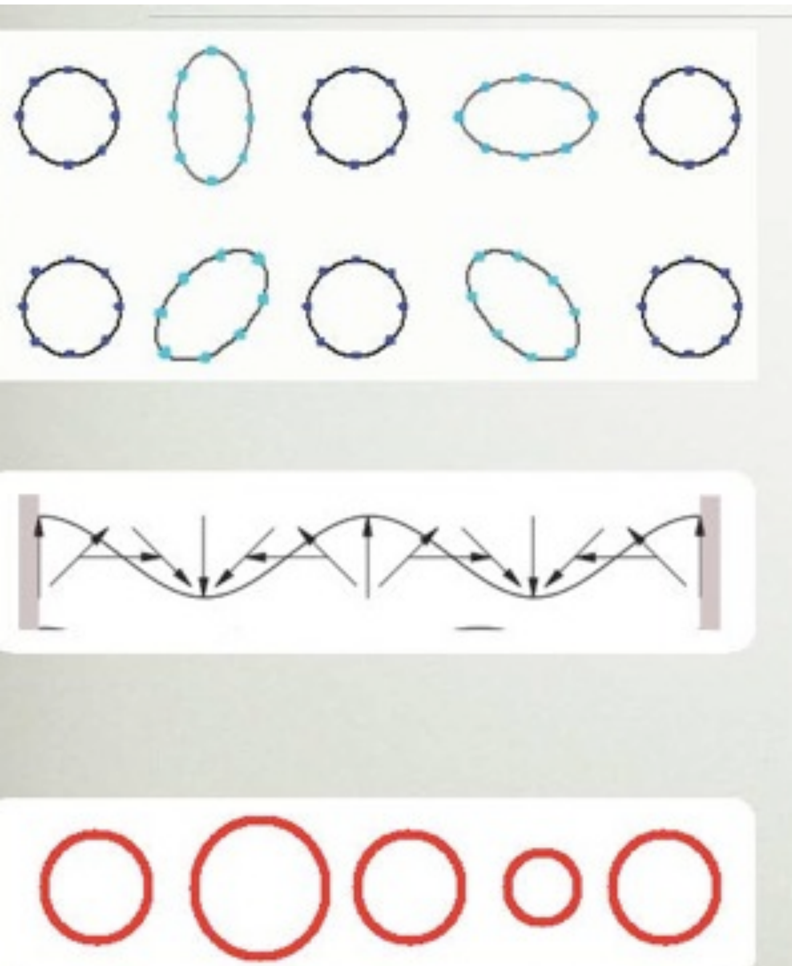
Expanding around background solution, generates large kinetic term

schematically: $\Box\phi \sim \dfrac{\rho}{M_{\rm pl}}$ $\qquad Z \approx 1 + \dfrac{\rho}{\Lambda^3 M_{\rm Pl}}$

$Z(\phi_b, \rho_b) \gg 1$ *when* $\rho_b \gg \Lambda^3 M_{\rm Pl} \sim m^2 M_{\rm Pl}^2$

Example:
Massive Gravity leads a scalar (helicity zero) field

Massive spin-2 field, has 5 dof



$$h_{\mu\nu} \sim \frac{G_N}{\Box_4 - m^2}\left(T_{\mu\nu} - \frac{1}{3}g_{\mu\nu}T\right)$$

tensor

$$\left(\text{in GR its } h_{\mu\nu} \sim \frac{G_N}{\Box_4}\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right)\right)$$

$$\boxed{2 \oplus 1 \oplus 2}$$

vector

$$\boxed{h_{\mu\nu} = h'_{\mu\nu} + \pi\eta_{\mu\nu}}$$

scalar

New scalar degree of freedom that couples to the trace of the stress energy momentum tensor

Vainshtein effect

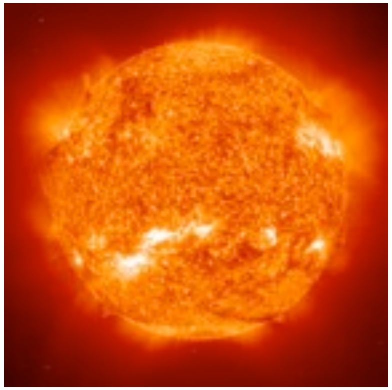
Characteristic radius from source
- Vainshtein radius

Screened region $r \ll r_V$ $Z \gg 1$

$$r_V = (r_s m^{-2})^{1/3} \qquad \Lambda^3 \sim m^2 M_{\rm Pl}$$

Weak coupling region $r \gg r_V$ $Z \sim 1$

For Sun



$$m^{-1} \sim 4000 Mpc$$

$$r_s \sim 3km$$

$$r_V \sim 250pc$$

Known nonlinear theory
Ghost-free
Massive Gravity

$$S = \frac{M_{\rm Pl}^2}{2} \int d^4x \sqrt{-g} \left(R - \frac{1}{4} m^2 U(g,f) \right)$$

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Theoretical Challenges, open questions

- Do any of these models actually improve on the old cosmological constant problem?
- To what extend do the predictions of these models differ from LCDM ?
  most focus on the existence of extra scalars - leads to fifth forces, new gravitational radiation, new dynamics
- How many of these models are simultaneously able to satisfy solar system and astrophysical tests and give interesting cosmological dynamics ?
- Do there exist natural models of chameleon/f(R), Brans Dicke/massive gravity etc. that are stable under quantum corrections?
- To what extend to dark energy/modified gravity models modify early universe physics
- Einstein gravity is stable in the sense that it satisfies positive energy theorems - modifications to gravity may induce instabilities, ghosts, tachyons, gradient instabilities - how many of these models are sufficiently stable to be plausible frameworks for cosmology ? CONSISTENCY ISSUES!

END

Other Screening Mechanisms

Making the coupling small universally

$$\beta(\phi_b, \rho_b) \ll 1$$

Theoretical Models:

Quintessence and its multifarious generalizations!!!

Canonical Example: Scalar field with no direct coupling to matter

$$S = \int d^4x\sqrt{-g}\left(\frac{M_{\rm pl}^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi)\right) + S_{\rm m}$$

These are the *Vanilla* models of Dynamical Dark Energy

Dark energy contributes to the background evolution, and plays an indirect role in perturbations, additional isocurvature modes

Making the coupling small environmentally

$$\beta(\phi_b, \rho_b) \ll 1$$

Theoretical Models:

Symmetron

Khoury and Hinterbichler 2010

Consider a scalar with

1. Symmetry
2. Symmetry breaking potential
3. Non-minimal coupling to matter density

example $$S = \int d^4x\sqrt{-g}\left(-\frac{1}{2}(\partial\phi)^2 - \frac{1}{4}\lambda\phi^4 + \frac{1}{2}\mu^2\phi^2 + \mathcal{L}_M(g_{\mu\nu}(1+\phi^2/M^2))\right)$$

Z2 symmetry

$$\phi \to -\phi$$

Broken symmetry vev

$$\phi^2 = \mu^2/\lambda$$

Symmetron - effective potential

$$\boxed{S = \int d^4x\sqrt{-g}\left(-\frac{1}{2}(\partial\phi)^2 - \frac{1}{4}\lambda\phi^4 + \frac{1}{2}\mu^2\phi^2 + \mathcal{L}_M(g_{\mu\nu}(1+\phi^2/M^2))\right)}$$

As a result of non-minimal coupling, effective potential is

$$V_{\text{eff}}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{1}{4}\lambda\phi^4 \qquad \beta \sim \frac{\phi M_{\text{PL}}}{M^2}$$

At low densities symmetry broken, coupling large

$$\rho < \mu^2 M^2 \qquad \phi \sim \mu^2/\lambda \qquad \beta \sim \frac{\mu^2 M_{\text{Pl}}}{\lambda M^2}$$

At high densities symmetry recovered, coupling small

$$\rho > \mu^2 M^2 \qquad \phi \sim 0 \qquad \beta \sim 0$$

$$M \leq 10^{-3} M_{\text{Pl}} \qquad \mu^{-1} \sim Mpc$$

Making mass large environmentally

Theoretical Models: Chameleon, Generalized Branes-Dicke models, f(R)

starts with same idea:

$$m(\phi_n, \rho_b) \gg \frac{1}{r_{exp}}$$

Khoury and Weltman, 2003

$$S_{\rm cham} = \int d^4x\sqrt{-g}\left(\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right) + S_{\rm matter}\left[g\ e^{2\beta\phi/M_{\rm Pl}}\right]$$

$$V_{\rm eff}(\phi) = V(\phi) + \rho\, e^{\beta\phi/M_{\rm Pl}}$$

$$m_{\rm eff}^2 = V_{,\phi\phi}(\phi_{\rm min}) + \frac{\beta^2}{M_{\rm Pl}^2}\rho\, e^{\beta\phi/M_{\rm Pl}}$$

Chameleon effect

$$\boxed{m_{\text{eff}}^2 = V_{,\phi\phi}(\phi_{\text{min}}) + \frac{\beta^2}{M_{\text{Pl}}^2}\rho\, e^{\beta\phi/M_{\text{Pl}}}}$$

Conditions necessary for chameleon mechanism to take place: $\beta > 0$

Balance	Stability	*m* increase with density
$V_{,\phi} < 0$	$V_{,\phi\phi} > 0$	$V_{,\phi\phi\phi} < 0$

easy to satisfy, e.g. $\boxed{V(\phi) \sim \frac{M^{4+n}}{\phi^n}}$

To satisfy fifth force $\boxed{M < 1meV}$

Making the kinetic term large environmentally

$$Z(\phi_b, \rho_b) \gg 1$$

Theoretical Models:

Vainshtein (or kinetic chameleon) mechanism:

Massive Gravity, DGP, Cascading Gravity, Galileon models and their generalizations!

Mechanism relies on a nontrivial reorganization of effective field theory to allow for large kinetic terms - arguably only natural in the context of massive gravity/DGP/Cascading