Modified gravity models, Massive (bi-)gravity

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Lunch seminar

YITP, December 17, 2014

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Introduction – Revolution

- 2011 Nobel Prize: discovery of acceleration at large scales
- What drives it, dark energy, accounts for 68% of the total matter distribution
- What is it?

Possibilities

- Cosmological constant
- New matter sector (quintessence, etc.)
- New gravity sector (Deviations from GR)
- New gravity and matter sector (Extra-dims)
- More?
- Only experiments will decide

f(R) gravity

[Capozziello: IJMP 2002; ADF, Tsujikawa: LRR 2010]

- Phenomenological model $\mathscr{L}_{GR} = f(R)$
- Working toy models appeared: $f' > 0, f'' > 0, f(0) = 0$

[Hu et al 2007] $$\frac{f}{M_P^2} = R - \mu R_c [(R/R_c)^{2n} / (1 + (R/R_c)^{2n})]$$

[Starobinsky 2007] $$\frac{f}{M_P^2} = R - \mu R_c [1 - (1 + R^2/R_c^2)^n]$$

[Tsujikawa 2008] $$\frac{f}{M_P^2} = R - \mu \tanh(R/R_c)$$

Scalar-tensor theory approach

- Equivalent to the theory described by

$$S=\int d^4x\sqrt{-g}\left[f(\varphi)+(R-\varphi)f_{,\varphi}\right]$$

- Important mapping: f(R) is a scalar tensor theory
- 1 extra scalar field
- Non-minimally coupled to gravity
- Chameleon mechanism

General modifications

- Other theories of gravity [Nojiri et al 2005]

$$\mathscr{L}_{GR} = f(R,G) \rightarrow f(\lambda,\phi) + \frac{\partial f}{\partial \lambda}(R-\lambda) + \frac{\partial f}{\partial \phi}(G-\phi),$$

- GB-R gravity:
  - A ghost always exist [ADF, Tanaka 2010]
  - Need to tune the theory to make it massive
- Lesson to learn

dRGT massive gravity

[de Rham, Gabadadze, Tolley: PRL 2011]

- Introducing 4 new scalar fields: Stuckelberg fields
- Then 4 sc dof, 4 vct dof, 2 Gws dof + 4 SF dof
- Unitary gauge (remove 4 SF dof): 4 sc , 4 vct, 2 Gws dof
- Constraints kill 2 sc dof and 2 vect dof: 2+2+2=6 dof
- dRGT kills one mode, the BD ghost. Finally only 5 dof.

No stable FLRW solutions

- FLRW background allowed [E. Gumrukcuoglu, C. Lin, S. Mukohyama: JCAP 2011]
- Late de Sitter solutions exist
- But no stable FLRW exists: one of the 5 dof is ghost
  [ADF, E. Gumrukcuoglu, S. Mukohyama: PRL 2012]
- Inhomogeneity? Anisotropies? [D'Amico et al: PRD 2011]
  [E. Gumrukcuoglu, C. Lin, S. Mukohyama: JCAP 2011. ADF, EG, SM: JCAP 2012]
- Something else? Introducing other fields: a quasidilaton scalar field
  [ADF, Mukohyama: PLB 2013][See also Huang, Piao, Zhou: PRD 2012]

Bigravity

[Hassan, Rosen: JHEP 2012]

- Promote fiducial metric to a dynamical component
- Introduce for it a new Ricci scalar
- Degrees of freedom in the 3+1 decomposition:
  - Total: (4 sc + 4 vt + 2GW) · 2
  - Gauge: 2 sc + 2 vt
  - Constraints: (2 sc + 2 vt) · 2 + 1 no-BD-ghost
  - Finally: T-G-C => 1 sc + 2 vt + 4 GW

Bimetric Lagrangian

- For the two metrics

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu, \quad d\tilde{s}^2 = \tilde{g}_{\mu\nu} dx^\mu dx^\nu,$$

- Introduce a ghost free action

$$\mathcal{L} = \sqrt{-g}\left[M_G^2\left(\frac{R}{2} - m^2 \sum_{n=0}^{4} c_n V_n(Y^\mu{}_\nu)\right) + \mathcal{L}_m\right] + \frac{\kappa M_G^2}{2}\sqrt{-\tilde{g}}\,\tilde{R}$$

where

$$Y^\mu{}_\nu = \sqrt{g^{\mu\alpha}\tilde{g}_{\alpha\nu}},$$

$$[Y^n] = Tr(Y^n), \quad V_0 = 1, \quad V_1 = [Y],$$

$$V_2 = [Y]^2 - [Y^2], \quad V_3 = [Y]^3 - 3[Y][Y^2] + 2[Y^3],$$

$$V_4 = [Y]^4 - 6[Y]^2[Y^2] + 8[Y][Y^3] + 3[Y^2]^2 - 6[Y^4].$$

Phenomenology [ADF, Nakamura, Tanaka: PTEP 14]

- Assume FLRW ansatz $ds^2 = a^2(-dt^2 + d\vec{x}^2)$, $d\tilde{s}^2 = \tilde{a}^2(-\tilde{c}^2 dt^2 + d\vec{x}^2)$
- Two branches $\Gamma(\xi)(\tilde{c}\, a H - \dot{\tilde{a}}/\tilde{a}) = 0$, $\Gamma = c_1 \xi + 4 c_2 \xi^2 + 6 c_3 \xi^3$

  $[\xi = \tilde{a}/a, \quad H = \dot{a}/a^2]$
- Physical branch: $\tilde{c} = \dot{\tilde{a}}/(\tilde{a}\, a H)$
- GR evolution: $3H^2 = \frac{\varrho_m}{\tilde{M}_G^2}$, $\xi \approx \xi_c$, $\tilde{M}_G^2 = M_G^2(1 + \kappa \xi_c^2)$, $\tilde{c} \approx 1$, $\frac{\varrho_m}{M_G^2 m^2} \ll 1$,
- Vainshtein mechanism $\nabla^2 v \approx -\frac{\varrho_m}{\tilde{M}_G^2}$ if $\frac{d \ln \Gamma}{d \ln \xi} \gg 1$,
- Gravitons oscillations

$$\mu_1^2 = 0, \quad \mu_2^2 = \frac{(1 + \kappa \xi_c^2)\Gamma_c m^2}{\kappa \xi_c^2}$$

Conclusions

- Dark Energy/Gravity: active field of research
- What is gravity?
- Yet, a field to investigate
- Can the graviton (or one of them) be massive?
- Experimental and theoretical research is needed