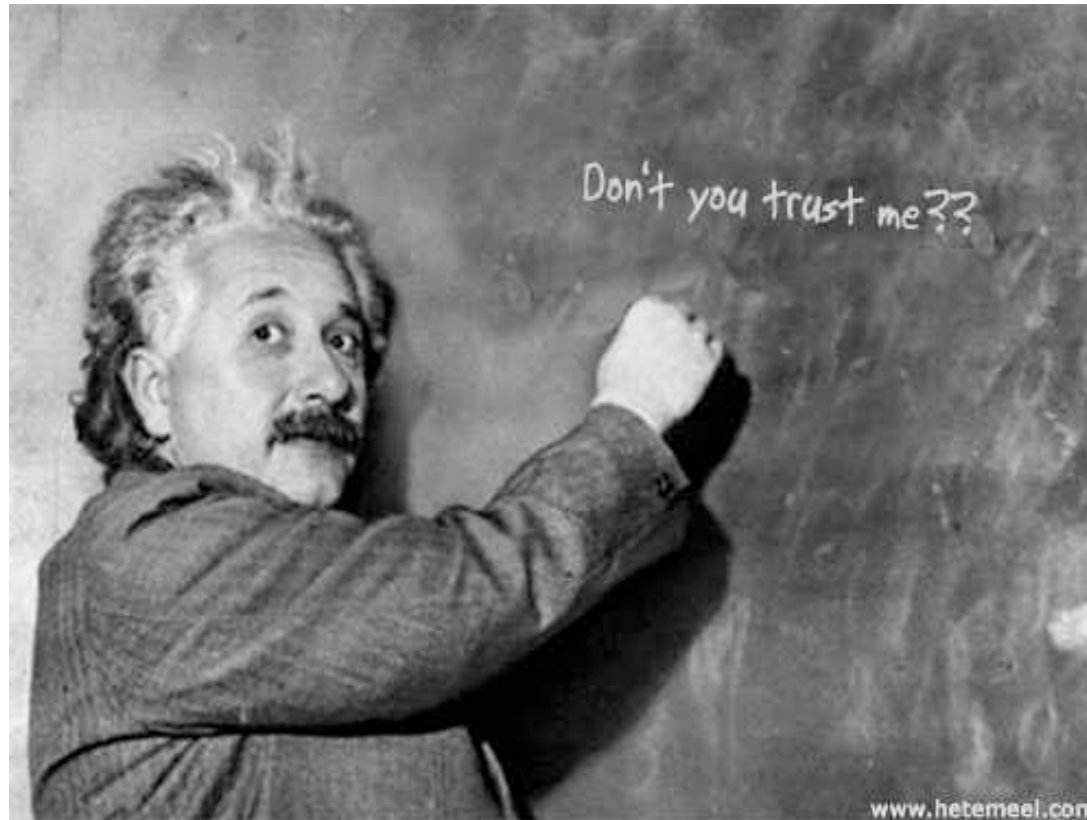


Modified Gravity: Fairy Godmother or Untamed Beast?



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Outline

- What is “modified gravity”?
- Motivations for modifying gravity
 - theoretical
 - observational
- Survey of pitfalls and potential problems

What is Modified Gravity?

- How do we decide if a given a modification of the laws of physics involves a modification of gravity? Perhaps ask which side of the Einstein equation is modified, or which term in action is modified:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$
$$S = \int d^4x \sqrt{-g} \frac{R}{16\pi G} + S_{\text{matter}}[g_{\mu\nu}, \Psi_{\text{matter}}]$$

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- This criterion is in fact ambiguous.

Example:

$$S = \int d^4x \sqrt{-g} \frac{R}{16\pi G} + S_{\text{matter}}[e^{\alpha(\Phi)} g_{\mu\nu}, \Psi_{\text{matter}}] - \int d^4x \sqrt{-g} \left[\frac{1}{2} (\nabla\Phi)^2 - V(\Phi) \right]$$

$$\bar{g}_{\mu\nu} \equiv e^{\alpha(\Phi)} g_{\mu\nu}, \quad \bar{\Phi} \equiv f(\Phi),$$

$$S = \int d^4x \sqrt{-\bar{g}} \left[\frac{\mathcal{A}(\bar{\Phi}) \bar{R}}{16\pi G} - \frac{1}{2} (\bar{\nabla}\bar{\Phi})^2 - \bar{V}(\bar{\Phi}) \right] + S_{\text{matter}}[\bar{g}_{\mu\nu}, \Psi_{\text{matter}}]$$

What is Modified Gravity (cont.)?

- How do we decide if a given a modification of the laws of physics involves a modification of gravity?
- Properties of gravity: (i) weak, (ii) long range (iii) universally coupled (iv) spin 2
- **Operational definition:** require corrections to long-range forces on all macroscopic bodies, eg in Solar System
- Do not require that interactions be spin 2 or that the number of dynamical degrees of freedom not be altered.

Levels of Description

1. Partial classical models

- For example, a prescription for linearized scalar cosmological perturbations in terms of two functions of k and a .
- MOND

2. Complete classical models, $S = \int d^4x \dots$

3. Weakly coupled effective field theories

4. "Natural", weakly coupled field theories

5. UV complete theories, eg string theory models

Motivations for Modifying Gravity

- Exploring diverse theories can expand our set of anticipated phenomenologies and suggest new observations and experiments
 - A 10% measurement of G in orbit (Chameleon theories)
 - Measure spacecraft orbits independently of planetary orbits (K-essence theories with matter coupling)

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- String theory has extra dimensions and fields
- Potential to solve theoretical problems
 - Hierarchy problem of particle physics (large extra dimensions, ADD)
 - Cosmological constant problem (degravitation)
 - Exorcise gravitational singularities??
- Phenomenological models of quantum gravity effects, e.g. violations of Lorentz invariance

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Motivations from Observations

- The Universe's expansion appears to be accelerating. Does this motivate modifying gravity?
 - Occam's razor favors a cosmological constant. "Dark energy is the cosmological constant until proven otherwise, for the same reason that the moon is not made of cheese until proven otherwise." (Bousso 2007)
 - Most modifications of gravity do not address the cosmological constant problem (exceptions: degravitation, SLEDs)
 - Dynamical models can address coincidence problem
 - Weinberg's (2008) attitude to quintessence models: better to compare data to a physically possible model (even if finely tuned) than no model at all.

Motivations from Observations (cont.)

- The gravitational potential in galaxies appears to be strongly correlated with the baryon density; “tail wagging the dog”
 - Motivated MOND and TeVeS
 - Bullet cluster observations (X-ray, lensing) show spatial separation between baryons and minimum of potential; disfavors modified gravity
 - Leaves open possibility of novel dark matter models whose ground state yields the MOND potential (eg Blanchet 2008)
- Other anomalous observations that are tentatively inconsistent with GR and Λ CDM:
 - Low power in CMB on large angular scales

Modified Gravity: Potential Pitfalls

1. Initial value formulation

- Example: Any Ricci flat metric, $\Phi = 1 / \sqrt{\xi}$ always a solution of

$$S = \int d^4x \sqrt{-g} \left[R - \frac{1}{2} (\nabla\Phi)^2 - \xi R\Phi^2 \right]$$

3. Strong coupling (loops)

4. Inapplicability of macroscopic field equations

5. Hamiltonian unbounded below (generic for higher derivative theories)

6. Instabilities: ghost, tachyonic, adiabatic

7. Singularities in formation of neutron stars

8. Superluminal effects

Consistency with Existing Data

- Solar System Tests: Lunar Laser Ranging, light deflection, time delay, limits on deviations from Kepler's law in outer
- Binary Pulsars: consistency of measured post-Keplerian parameters as well as decay rate.
- Equivalence principle tests
- Constraints on time variation of Newton's constant
- Nucleosynthesis
- Tidal stripping of dwarf galaxies constrains different Newton's constant for dark matter
- Cosmological data on large scales: CMB, lensing, power spectrum

Conclusion

- Modifying gravity is full of pitfalls, the benefits are not completely compelling
- An observation of time-dependence of acceleration would completely change the situation