Title: Observational Constraints on Gravitational Degrees of Freedom

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Abstract: TBA

The Phenomenology of Gravity

Simon DeDeo

KICP / University of Chicago
@ Perimeter Institute / U. Waterloo

12 August 2008

A Case For / Introduction To "Phenomenology" (with examples)

Kavli Institute
for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO

PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

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- Parsimony (*gratia* Alan Cooney, U. Arizona)

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Kavli Institute for Cosmological Physics at the University of Chicago

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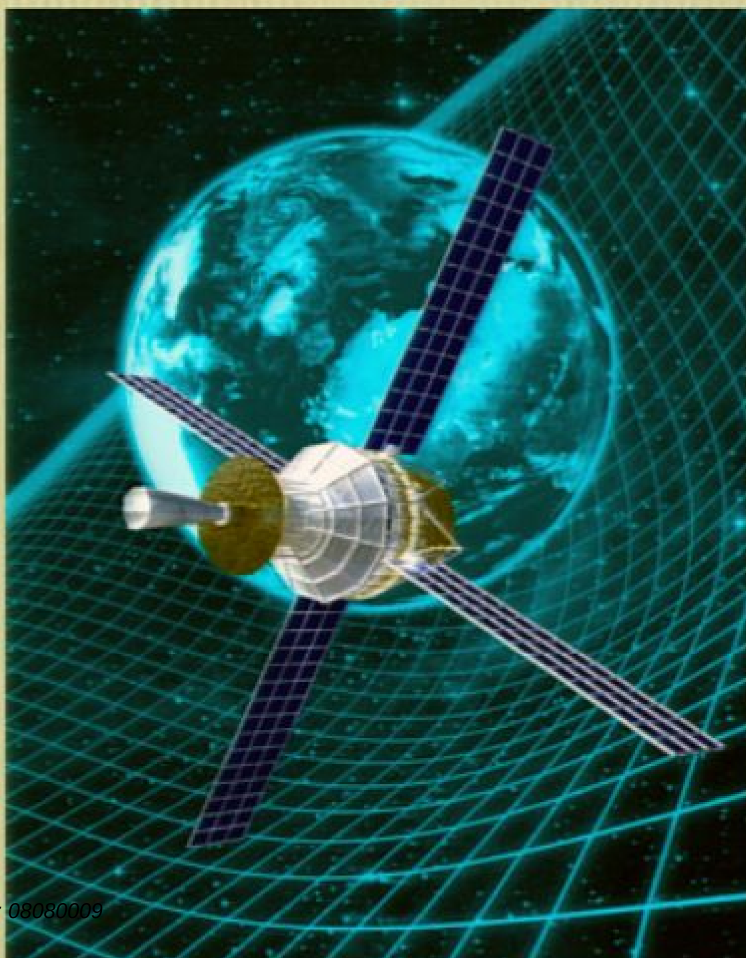
Example I.

Degrees of Freedom in Gravity

(work in collaboration with Alan Cooney & Dimitrios Psaltis @ U. Arizona)

"Parametrized Post-Newtonian"



Pioneered by Will and Nordvedt in the 1970s — a general "phenomenology" of solar system gravity

more than just "interoperability" — a deep assertion of physical principles

Newtonian gravity

$$g_{00} = -1 + 2U$$

$$U = \int \frac{\rho(x')}{|x - x'|} d^3x$$

"First order" post-Newtonian (in a particular gauge)

$$g_{00} = -1 + 2U + 2U^2$$

possible modifications . . .

$$g_{00} = -1 + 2U + 2\beta U^2 - 2\xi\Phi_W \cdots$$

$$\Phi_W = \int \frac{\rho'\rho''(x - x')}{|x - x'|^3} \cdot \left(\frac{x' - x''}{|x - x''|} - \frac{x - x''}{|x' - x''|}\right) d^3x' d^3x''$$

"Matter Dictatorship"

All possible modifications to the metric are functions of the matter/energy distribution and its velocity [& preferred frames]

$$\Phi_W = \int \frac{\rho' \rho'' (x - x')}{|x - x'|^3} \cdot \left(\frac{x' - x''}{|x - x''|} - \frac{x - x''}{|x' - x''|} \right) d^3x' d^3x''$$

$$\mathcal{A} = \int \frac{\rho' [v' \cdot (x - x')]^2}{|x - x'|^3} d^3x'$$

&c., &c.

not quite "no new degrees of freedom" — *e.g.*, Brans-Dickie theories can fit in, but not *f(R)* (in general)

PPN as Phenomenology

plus sides

$$A = \int \frac{\rho'[v' \cdot (x - x')]^2}{|x - x'|^3} d^3x'$$

"matter dictatorship" : parsimony without restriction
forms of dictatorship easy to cover (but see Alexander, 2008)

downsides (for cosmology &c.)

requires "post-Newtonian" conditions:
shallow potentials that fade at large distance
(but can adapt the gauge to cosmology)

too broad minded? : only "set of measure zero"

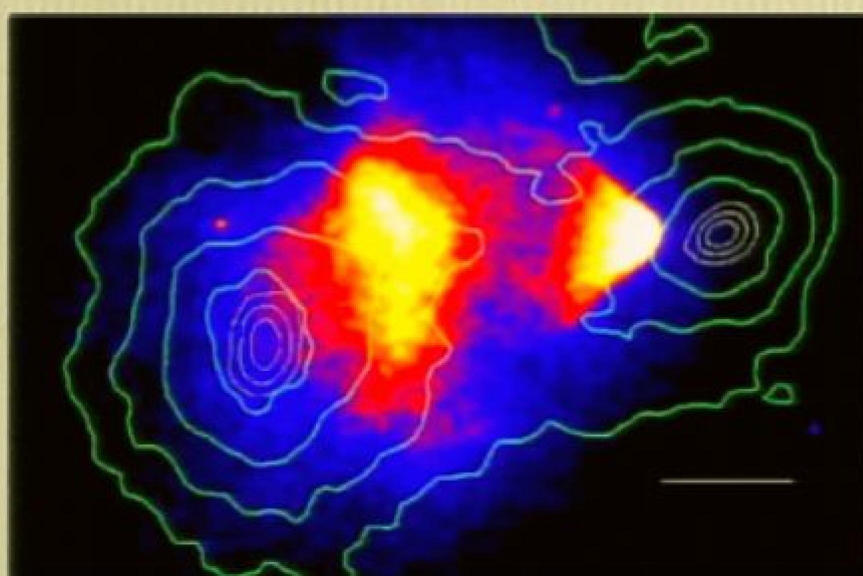
MONDS *vs.* Dark Matter

MOND has parsimony — one parameter "acceleration scale," but not relativistic

TeVeS has phenomenological parsimony — matter dictatorship[*], but not fundamentally so (new vector and scalar fields)

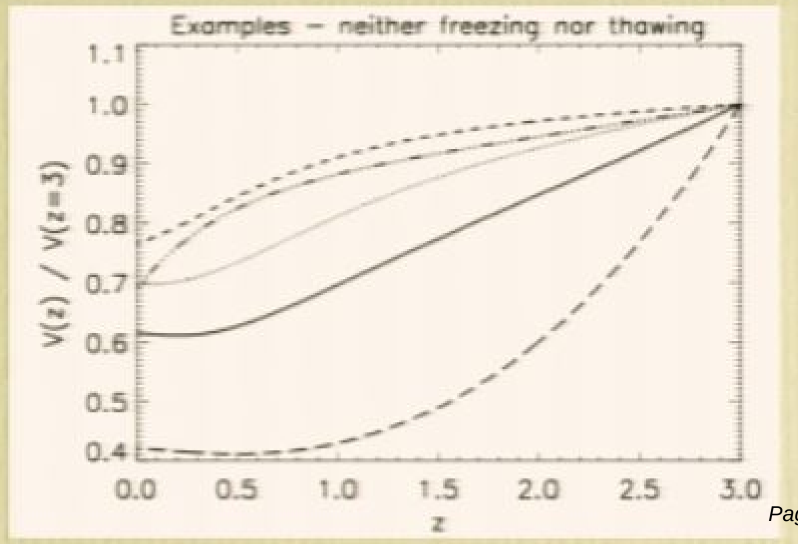
[*]. *caveat.* — only sort of.

observation ruled out (?) both — Clowe *et al.* 2006



The Age of Quintessence

- "in for a penny, in for a pound" — a newly cavalier attitude towards new degrees of freedom (but a time of great hope.)
- pick your *V(φ)*, find your E.O.M., discover great fundamental physics!
- where we are today:



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$$\int \sqrt{-g}[R + (\partial\phi)^2 + V(\phi) + \mathcal{L}_{\mathrm{matt}}]$$

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but! — as an "exact" theory, can be rewritten:

↓

$$\int \sqrt{-g}[R + (\partial\phi)^2 + \tilde{V}(\phi) + \mathcal{L}_{\rm matt}(\phi)]$$

$f(R)$ is the new V(φ)?

- Certainly new behaviors, with various clustering scales — looks in many ways like *k*-essence, which has non-trivial sound speeds. (See, *e.g.*, work by Sawicki & Hu.)

- One of the most interesting things in "classical cosmology" today

- But not *conceptually* distinct.

- Still new degrees of freedom!

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One "escape route"

Forget about it! — just parametrize w, the E.O.S. :
pick one you like, *e.g.*,

$$w(a) = w_0 + (1 - a)w_a$$

$$w(z) = w_0 + zw_1$$

nice for doing observational tests given the current data — but "so open-minded your brain falls out"? You are never sure what physics you are holding constant.

$w_a \lesssim 0.1$ means what, exactly? is it inconsistent with structure formation (*e.g.*)?
— you'll never know without a "real" model behind it.

Should we bite the bullet?

- Classical, local *f(R)* theories that are IR complete generically have new degrees of freedom, and are massless in cosmologically relevant regimes.
- Can we "do more with less"? Do the observations *require* new degrees? Is there a dark energy bullet cluster? [Not yet!]

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Modified Gravity

- Stay with Lagrangian formalism — retain, for free, general covariance (so no nasty MOND ⇒ *TeVeS* surprises.)

- But assume it is a *perturbative* approximation to a larger theory "we know not what" that fixes "we know not how" *fictional* extra degrees that appear perturbatively.

$$\mathcal{L} = \int \frac{1}{2}\dot{q}^2 + \alpha q(x+\delta x)q(x+\delta x')d^3x$$

second order UV non-local

$$= \int \frac{1}{2}\dot{q}^2 + \alpha \left[q + \frac{dq}{dx}\delta x + \frac{1}{2}\frac{d^2q}{dx^2}(\delta x)^2 + \cdots\right]\left[q + \frac{dq}{dx}\delta x' + \frac{1}{2}\frac{d^2q}{dx^2}(\delta x')^2 + \cdots\right]$$

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fictitious higher order local

The Formalism

- Adapt the "perturbative localization" of Woodard, Simon *et al.* — developed for the classic case of (UV) non-local theories.

deceptive "formalism overlap"

$$\int \sqrt{-g}[R + \frac{\mu^4}{R} + \cdots]$$

looks like a "standard" *f(R)* theory — but appearances are deceptive; here we write it in terms of an action, but only because it keeps us honest in spacetime symmetries

"Action is a heuristic"

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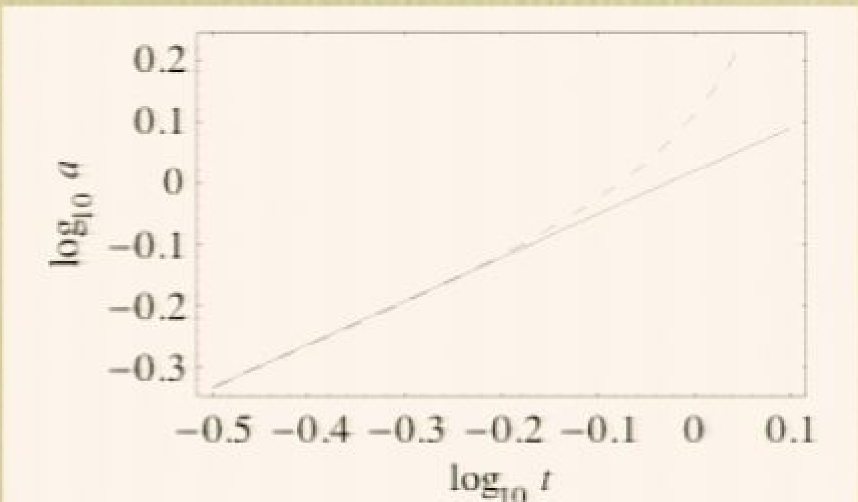

a self-consistent, accelerating universe with no new d.o.f.s

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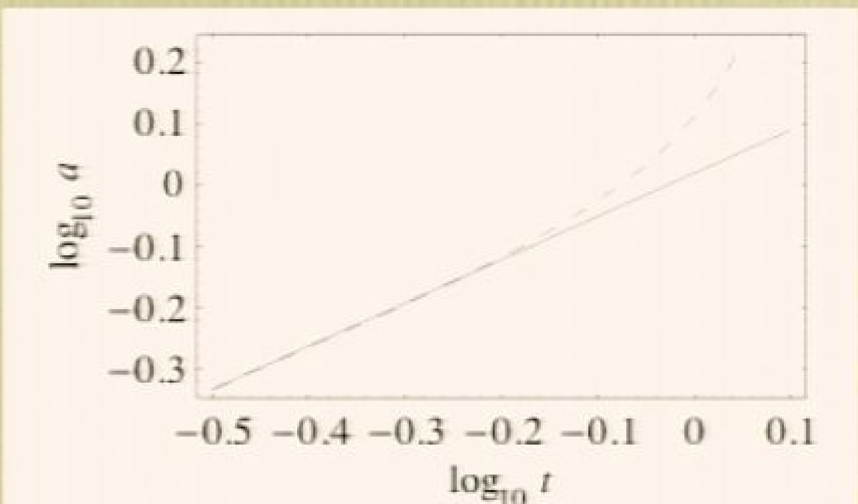

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Perturbative Validity?

control parameter for knowing when perturbative approximations break down : $R^2 \gg \mu^4$, or

$$H^4 \gg \frac{\mu^4}{36(1-q)^2}$$

i.e. — our solutions are valid even for "large" accelerations; (comes from the fact that H is not a scalar but rather gauge-dependent — Minkowski space can have large H!)

This Kind of Modified Gravity . . .

- has "interesting" behavior (*e.g.*, can produce reliable cosmic acceleration.)
- may imply a "bizarre" fundamental theory but will respect many important *empirical* features such as general covariance, gauge independence, &c.
- is not as wildly unconstrained as you might think . . .

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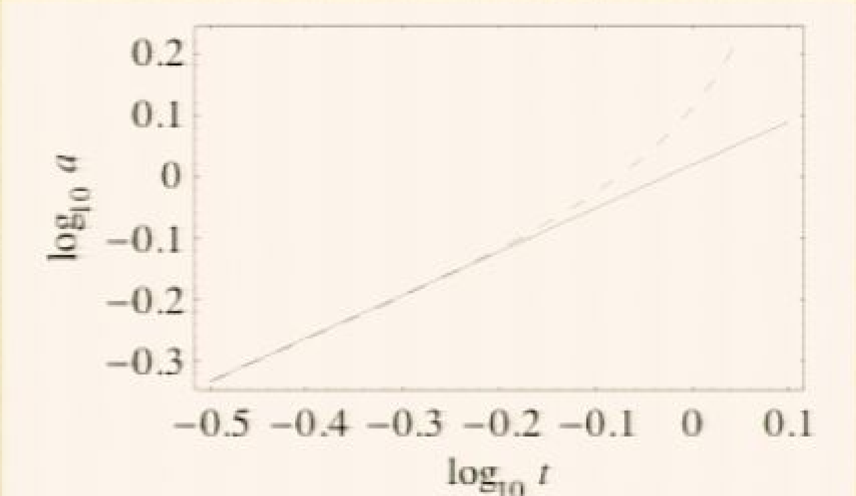

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Constraining Modified Gravity *simpliciter*

$$\int \sqrt{-g}[R + f(R, G_B) + \cdots]$$

(GB is the "Gauss-Bonnet" term — integral related to spacetime topology)

if f is an polynomial without a constant term,

$$w \leq -2$$

...ruled out by WMAP + Supernovae!

Taking the theory further

- homogenous expansion already a way to rule out entire classes of modified gravities quickly and powerfully.

$$\int \sqrt{-g}[R + f(R, R_{\mu\nu}R^{\mu\nu}, R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}) + \cdots]$$

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- the simplicity of the mathematics means that large classes can be ruled out quickly; homogenous expansion + structure formation constraints may well rule out such a massive class that we can answer (to a string theorist's delight)

"are new gravitational degrees of freedom necessary"?

Open Questions

- what fundamental theories lie beneath our perturbative approximations? Non-local theories are one obvious place to look, but the relationship is non-trivial because of our UV/IR exchange.

Open Questions

- Niayesh & Ghazal's work on Cuscutons & *Gravitational Aethers* — are their d.o.f.'s "frozen in the Cooney-DeDeo-Psaltis way"?

logically (but not physically?) independent ways to "freeze" apparent degrees of freedom:

- infinite speed-of-sound
- homogenous solution dies away
- "matter dictatorship"
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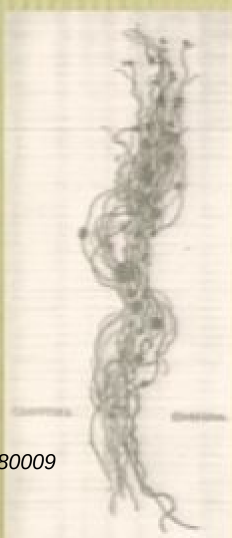

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Example II.

The Case of the Covariant Aether

(work in collaboration with Chanda Prescod-Weinstein @ P.I. & U. Waterloo)

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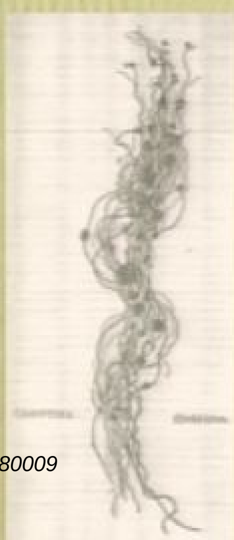

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