Gravitation modifiée à grande distance et tests dans le système solaire

Gilles Esposito-Farèse, $\mathcal{G}\mathbb{R}\varepsilon\mathbb{C}\mathcal{O}$, IAP

et

Peter Wolf, LNE-SYRTE

10 avril 2008

Modified gravity at large distances and solar-system tests

J.-P. Bruneton and **G. Esposito-Farèse**

$\mathcal{G}\mathbb{R}\varepsilon\mathbb{C}\mathcal{O}$, Institut d'Astrophysique de Paris

Phys. Rev. D 76 (2007) 124012

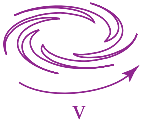
Discussions with L. Blanchet, C. Deffayet, B. Fort, G. Mamon, Y. Mellier, M. Milgrom, R. Sanders, J.-P. Uzan, R. Woodard, *etc.*

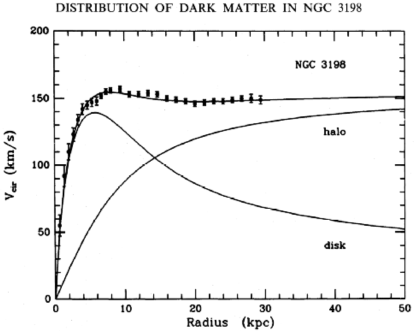
April 10th, 2008

Dark matter and galaxy rotation curves

$\exists$ evidences for dark matter:

- $\Omega_\Lambda \approx 0.7$ (SNIa) and $\Omega_\Lambda + \Omega_m \approx 1$ (CMB) $\Rightarrow$ $\Omega_m \approx 0.3$, at least $10\times$ greater than estimates of baryonic matter.
- Rotation curves of galaxies and clusters: almost rigid bodies





- $\exists$ many theoretical candidates for dark matter (e.g. from SUSY)
- Numerical simulations of structure formation are successful while incorporating (noninteracting, pressureless) dark matter

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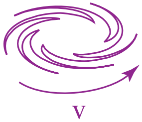

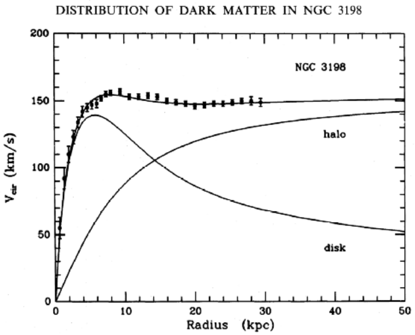

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Milgrom's MOND proposal [1983]

MOdified Newtonian Dynamics
for small accelerations (i.e., at large distances)

$$a = a_N = \frac{GM}{r^2} \quad \text{if } a > a_0 \approx 1.2 \times 10^{-10}\,\text{m.s}^{-2}$$

$$a = \sqrt{a_0 a_N} = \frac{\sqrt{GMa_0}}{r} \quad \text{if } a < a_0$$

- Automatically recovers the Tully-Fisher law [1977]

$$v_\infty^4 \propto M_{\text{baryonic}}$$

- Superbly accounts for galaxy rotation curves
  (but clusters still require some dark matter)
  [Sanders & McGaugh, Ann. Rev. Astron. Astrophys. **40** (2002) 263]

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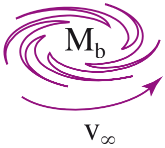

Consistent field theories of MOND?

- *A priori* easy to predict a force $\propto 1/r$:
  If $V(\varphi) = -2a^2 e^{-b\varphi}$, unbounded by below
  then $\Delta\varphi = V'(\varphi) \Rightarrow \varphi = (2/b)\ln(abr)$.

  Constant coefficient $2/b$ instead of $\sqrt{M}$.

  Some papers write actions which depend on the galaxy mass M
  $\Rightarrow$ They are actually using a different theory for each galaxy!

- Stability
  Full Hamiltonian should be bounded by below:
  no tachyon ($m^2 \geq 0$), no ghost ($E_{\text{kinetic}} \geq 0$)

- Well-posed Cauchy problem
  Hyperbolic field equations

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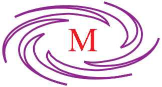

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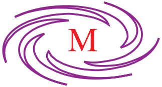

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  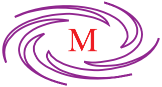

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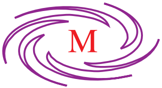

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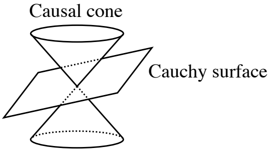

Most promising framework

Relativistic AQUAdratic Lagrangians
[Bekenstein (TeVeS), Milgrom, Sanders]

$$S = \frac{c^3}{16\pi G}\int d^4x\sqrt{-g}\Big\{R - 2f(\partial_\mu\varphi\partial^\mu\varphi)\Big\}$$
$$+S_{\text{matter}}\Big[\text{matter}\,;\ \tilde{g}_{\mu\nu} \equiv A^2(\varphi)g_{\mu\nu} + B(\varphi)U_\mu U_\nu\Big]$$

- A "k-essence" kinetic term can yield the $\frac{\sqrt{GMa_0}}{r}$ MOND force
- Matter coupled to the scalar field
- "Disformal" term (almost) necessary to predict enough lensing

Consistency conditions on $f(\partial_\mu\varphi\partial^\mu\varphi)$

Hyperbolicity of the field equations + Hamiltonian bounded by below

- $\forall x, \quad f'(x) > 0$
- $\forall x, \quad 2\,x f''(x) + f'(x) > 0$

N.B.: If $f''(x) > 0$, the scalar field propagates faster than gravitons, but still causally
$\Rightarrow$ no need to impose $f''(x) \leq 0$

These conditions become much more complicated *within matter*

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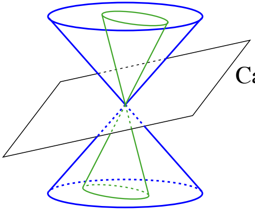

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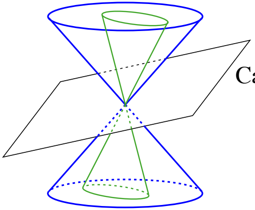

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Difficulties of such models

- Complicated Lagrangians (unnatural)
- Fine tuning (≈ fit rather than predictive models):
  Possible to predict different lensing and rotation curves
- Discontinuities: can be cured

- In TeVeS [Bekenstein], gravitons & scalar are slower than photons
  ⇒ gravi-Cerenkov radiation suppresses high-energy cosmic rays [Moore *et al.*]
  Solution: Accept slower photons than gravitons

- ∃ preferred frame (ether) where vector $U_\mu = (1, 0, 0, 0)$
  Maybe not too problematic if U_μ is dynamical
- Vector contribution to Hamiltonian unbounded by below [Clayton] ⇒ unstable model

- Post-Newtonian tests very constraining

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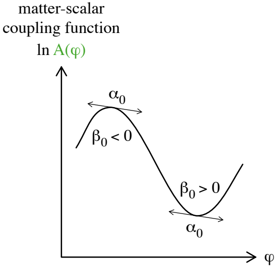
- Solar-system tests ⇒ matter *a priori* weakly coupled to φ
- TeVeS *tuned* to pass them even for strong matter-scalar coupling
- Binary-pulsar tests ⇒ matter must be weakly coupled to φ



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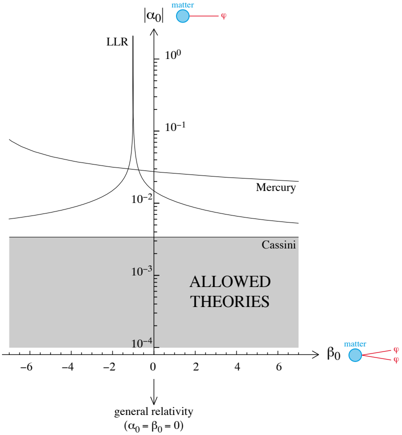

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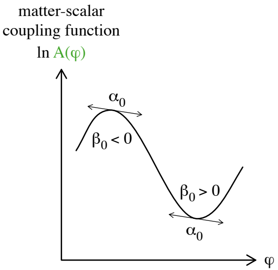

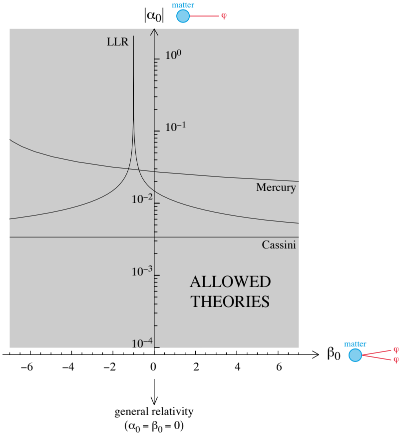

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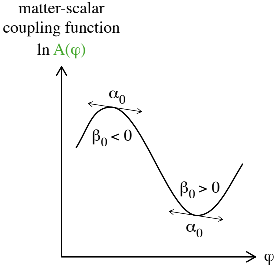

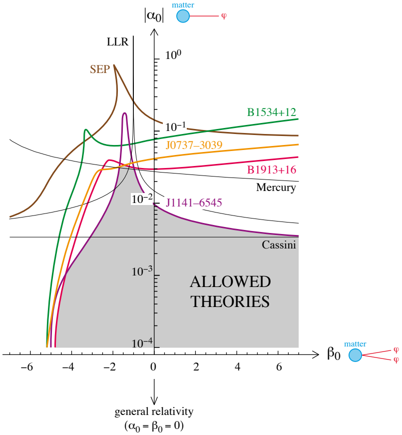

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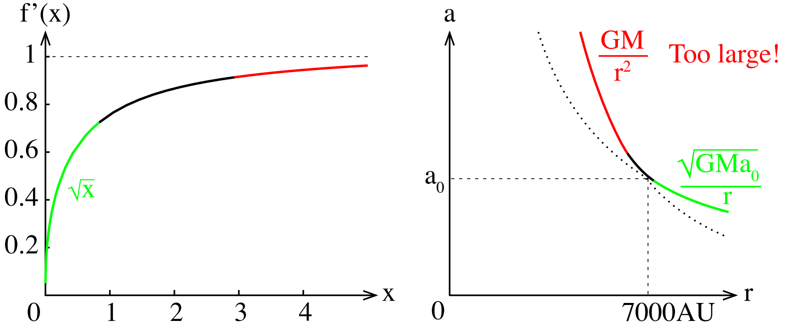

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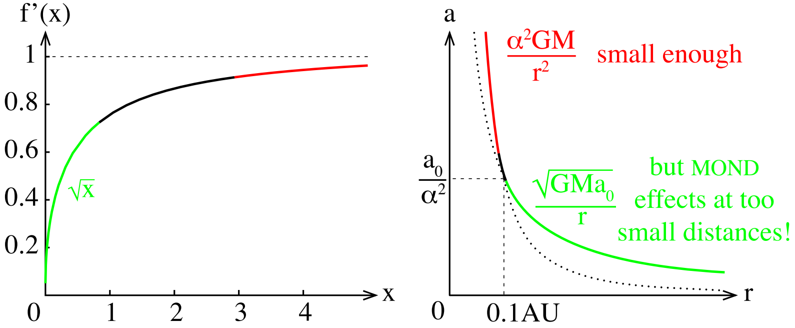

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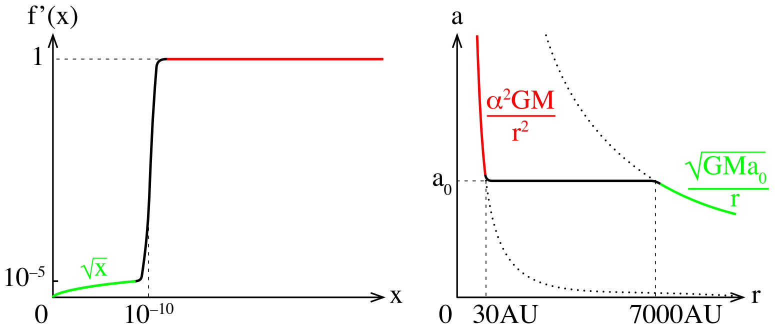

Quite unnatural! (and not far from being experimentally ruled out)

New simpler models?

Nonminimal metric coupling

$$S = \frac{c^3}{16\pi G}\int d^4x\sqrt{-g}\,R \qquad \text{pure G.R. in vacuum}$$

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Can reproduce MOND, but Ostrogradski [1850] $\Rightarrow$ unstable within matter

Nonminimal scalar-tensor model

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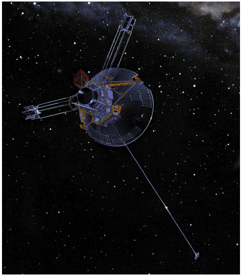
Pioneer 10 & 11 anomaly

- Extra acceleration $\sim 8.5 \times 10^{-10}\,\text{m.s}^{-2}$ towards the Sun between 30 and 70 AU
- Simpler problem than galaxy rotation curves ($M_\text{dark} \propto \sqrt{M_\text{baryon}}$), because we do not know how this acceleration is related to $M_\odot$
- $\Rightarrow$ *several* stable & well-posed solutions



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- $\lambda \approx \alpha^3 (10^{-4}\text{m})^2$ to *fit* Pioneer anomaly

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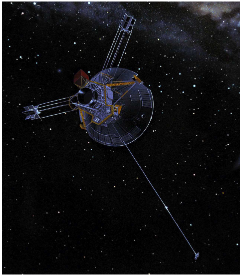

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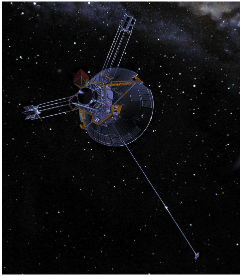
- $\Rightarrow$ *several* stable & well-posed solutions



Nonminimal scalar-tensor model

$$S = \frac{c^3}{16\pi G}\int d^4x\sqrt{-g}\left\{R - 2\,\partial_\mu\varphi\partial^\mu\varphi\right\} \quad \text{Brans-Dicke in vacuum}$$

$$+\, S_{\rm matter}\left[\text{matter}\ ;\ \tilde{g}_{\mu\nu} \equiv e^{2\alpha\varphi} g_{\mu\nu} - \lambda\,\frac{\partial_\mu\varphi\partial_\nu\varphi}{\varphi^5}\right]$$

- $\alpha^2 < 10^{-5}$ to pass solar-system & binary-pulsar tests
- $\lambda \approx \alpha^3 (10^{-4}\mathrm{m})^2$ to *fit* Pioneer anomaly

Conclusions

A consistent field theory should satisfy different kinds of constraints:

- Mathematical: stability, well-posedness of the Cauchy problem, no discontinuous nor adynamical field
- Experimental: solar-system & binary-pulsar tests, galaxy rotation curves, gravitational lensing by “dark matter” haloes, CMB
- Esthetical: natural model, rather than fine-tuned *fit* of data

Best present candidate: TeVeS [Bekenstein–Sanders], but it has still some mathematical *and* experimental difficulties

∃ simpler models, useful to exhibit the generic difficulties of all MOND-like field theories

By-product of our study: a consistent class of models for the Pioneer anomaly (but *not* natural!)

Nonlocal models? [Work in progress with Cédric Deffayet & Richard Woodard]

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