A breaking of the equivalence principle in the electromagnetic sector and its cosmological signatures

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Les rencontres de Moriond
24/03/2015
Why alternative theories of gravitation?

- Quantum theory of gravity:
  - GR: classic theory (non quantizable)
  - useful to study black holes and the Planck Era

- Unification of all fundamental interactions: unify Standard model of particles with gravitation

- Cosmological and galactic required the introduction of Dark Matter and Dark Energy: not directly observed so far ⇒ hints of a deviation from GR?

What are the observable signatures produced by modified gravity?
Einstein Equivalence Principle

Effects of gravitation \( \leftrightarrow \) Space-time geometry \( g_{\mu\nu} \)

Principle of “minimal coupling”\(^1\)

\[
S_{\text{mat}} = \int d^4x \sqrt{-g} \mathcal{L}_{\text{mat}}(g_{\mu\nu}, \Psi)
\]

metric theories of gravitation

\(^1\) C. Will, LRR, 17, 4, 2014
General Relativity

**Einstein Equivalence Principle**

Effects of gravitation \( g_{\mu\nu} \)  
Space-time geometry  

Principle of “minimal coupling”\(^1\)

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\]

metric theories of gravitation

**Einstein Field Equations**

Space-time geometry  
Energy/Matter content  

Can be derived from the action

\[
S_{\text{grav}} = \frac{1}{2\kappa} \int d^4 x \sqrt{-g} R
\]

determine the “form” of the metric depending on the matter/energy content

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\(^1\) C. Will, LRR, 17, 4, 2014
One way to break the EEP in scalar tensor theories

- Introduce a multiplicative coupling

\[ S_{\text{mat}} = \int d^4 x \sqrt{-g} h(\varphi) \mathcal{L}_{\text{mat}}(g_{\mu \nu}, \Psi) \]

motivated by…

- phenomenological low-energy limit of string theories

\[ S = \int d^4 x \sqrt{g} B(\Phi) \left\{ \frac{1}{\alpha'} [\hat{R} + 4\hat{\Delta} \Phi - 4(\nabla \Phi)^2] - \frac{k}{4} \hat{F}^2 - \bar{\Psi} \hat{D} \Psi + \ldots \right\} \]

- BSBM theory of varying \( \alpha \)

- “pressuron” field: TS theory with decoupling mechanism in region where the matter pressure is low

\[ \text{cfr O. Minazzoli’s talk and O. Minazzoli and A. Hees, PRD 88, 041504, 2013} \]
What are the cosmological signatures of a multiplicative coupling in the EM sector?

$$S_{EM} = -\frac{1}{4} \int d^4 x \sqrt{-g} h(\varphi) F_{\mu\nu} F^{\mu\nu} - q_i \int A_\mu dx_i^\mu$$

Rq.: - interaction EM/matter standard required by gauge invariance
    - GR and “standard” Brans-Dicke $h(\varphi) = 1$
Variation of the fine structure constant

- by identification in the action \( \alpha \propto 1/h(\varphi) \)
- easily linked to observations

\[
\frac{\Delta \alpha}{\alpha} = \frac{\alpha(z) - \alpha_0}{\alpha_0} = \frac{h(\varphi_0)}{h(\varphi)} - 1
\]

see J. Bekenstein, Phys. Rev. D 25, 1527, 1982
J.-P. Uzan, LRR 14, 2011
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Experimental constraints

- Clocks constraint: \( \frac{\dot{\alpha}}{\alpha} \bigg|_0 = (-2.4 \pm 2.3) \times 10^{-17} \text{yr}^{-1} \)
  from S. Bize’s talk (Monday)

- Quasar absorption lines: 2 datasets with \( z \) between 0.2 and 4.2
  - VLT (Chile): 154 data \( \Delta \alpha/\alpha = (2.08 \pm 1.24) \times 10^{-6} \)
  - Keck (Hawaai): 128 data \( \Delta \alpha/\alpha = (-5.7 \pm 1.1) \times 10^{-6} \)

- Improvements expected
  see for example J.C.A.P. Martins, GRG 2015
Maxwell equations

• Modified Maxwell equations
  \[ \nabla_\mu (h(\varphi) F^{\mu \nu}) = 0 \]

• Geometric Optic Approximation
  \[ A^\mu = \Re \left\{ (b^\mu + \varepsilon c^\mu + \ldots) e^{i\theta/\varepsilon} \right\} \]

  see Misner, Thorne, Wheeler, “Gravitation”

null geodesic

\[ k^\mu k_\mu = 0 \]

with \[ k_\mu = \partial_\mu \theta \]

non-conservation of the number of photons

\[ \dot{n} + 3Hn = -n \partial_t \ln h(\varphi(t)) \]

• Reciprocity relation holds but violation of distance duality relation

\[ \eta(z) = \frac{D_L(z)}{D_A(z)(1 + z)^2} = \sqrt{\frac{h(\varphi_0)}{h(\varphi(z))}} \]

see G. Ellis, GRG 39, 2007

see Basset and Kunz, PRD 69, 2004
Constraints on $\eta(z)$

• Data used:
  - $D_L(z)$: Supernovae Ia (Union 2.1)
  - $D_A(z)$: clusters of galaxies, BAO

<table>
<thead>
<tr>
<th>$\eta(z) = \eta_0$</th>
<th>$\eta_0 = 0.95 \pm 0.025$</th>
<th>[Laczos et al, JCAP 7, 2008]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta(z) = 1 + \eta_1$</td>
<td>$\eta_1 = 0.06 \pm 0.08$</td>
<td>[Holanda et al, JCAP 6, 2012]</td>
</tr>
<tr>
<td>$\eta(z) = 1 + \eta_2 \frac{z}{1+z}$</td>
<td>$\eta_2 = -0.07 \pm 0.12$</td>
<td>[Holanda et al, JCAP 6, 2012]</td>
</tr>
<tr>
<td>$\eta(z) = (1 + z)^\epsilon$</td>
<td>$\epsilon = 0.02 \pm 0.055$</td>
<td>[Holanda and Busti, Phys. Rev. D 89, 2014]</td>
</tr>
</tbody>
</table>

• Constraints at the order of $10^{-2}$
Evolution of CMB radiation

- CMB treated as a gaz of photons with a distribution function $f$ satisfying a Boltzmann equation

$$\mathcal{L} f(t, p) = p \frac{\partial f}{\partial t} - H p^2 \frac{\partial f}{\partial p} = C[f]$$

- Integration over momenta leads and use of geometric optics approximation

$$\dot{n} + 3Hn = \Psi = \frac{1}{\pi^2} \int pC[f]dp = -n\partial_t \ln h(\varphi)$$

$$\dot{\rho} + 4H\rho = C_x = \frac{1}{\pi^2} \int p^2 C[f]dp = -\rho\partial_t \ln h(\varphi)$$
Evolution of CMB radiation

• Distribution function $f$ parametrized by
  \[ f(t, p) = \frac{1}{e^{p/T} + \mu - 1} \]

• The temperature and the chemical potential depends on the cosmic evolution
Evolution of CMB radiation

- Distribution function $f$ parametrized by
  $$ f(t, p) = \frac{1}{e^{p/T+\mu} - 1} $$

- The temperature and the chemical potential depends on the cosmic evolution

- Perturbative solution at first order in the chemical potential

procedure from Sec. 8.2 of “The CMB”, R. Durrer, 2008

$$ T(z) = T_0 (1 + z) \left[ 0.88 + 0.12 \frac{h(\varphi_0)}{h(\varphi(z))} \right] $$

$$ \mu(z) = 0.47 \left[ 1 - \frac{h(\varphi(z_{CMB}))}{h(\varphi(z))} \right] $$
Constraints on CMB temperature

- Parametrization used: \( T(z) = T_0 (1 + z)^{1-\beta} \)

- Deviations from a Planckian spectrum parametrized by \( \mu \)

- Datas used
  - Sunyaev-Zel’dovich
  - molecular absorption lines

\[
\beta = 0.011 \pm 0.016 \quad \text{see Saro A., et al, MNRAS 440, 2610, 2014}
\]
\[
\beta = 0.016 \pm 0.012 \quad \text{see Luzzi G., et al, arXiv:1502.07858}
\]

- CMB observations with COBE/FIRAS

\[
|\mu| < 9 \times 10^{-5}
\]

A multiplicative coupling implies

- Temporal variation of $\alpha$
- Violation of the cosmic distance duality $\eta \neq 1$
- Modification of the $T_{\text{CMB}}$ evolution
- CMB non Planckian

see Hees A., Minazzoli O., Larena J., PRD, 2014
A multiplicative coupling implies

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All of these observables are intimately related

$$\frac{h(\phi_0)}{h(\phi(z))} = \eta^2(z) = \frac{\Delta \alpha(z)}{\alpha} + 1 = 8.33 \frac{T(z)}{T_0(1 + z)} - 7.33.$$  

$$\mu = 0.47 \left( 1 - \frac{1}{\eta^2(z_{CMB})} \right) = 0.47 \frac{\Delta \alpha(z_{CMB})}{\alpha} = 3.92 \left( \frac{T(z_{CMB})}{T_0(1 + z_{CMB})} - 1 \right)$$
1) Under the assumption that a “multiplicative” coupling holds (include GR and standard TS theories), use these relations to transform constraints on the variation of $\alpha$ into constraints on the other observables.

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$$\frac{h(\phi_0)}{h(\phi(z))} = \eta^2(z) = \frac{\Delta \alpha(z)}{\alpha} + 1 = 8.33 \frac{T(z)}{T_0(1 + z)} - 7.33.$$ 

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see Hees A., Minazzoli O., Larena J., PRD, 2014
Derived constraints from $\Delta \alpha$
assuming the multiplicative coupling

- Quasar absorption lines: 2 datasets with $z$ between 0.2 and 4.2
  - VLT (Chile): 154 data
  - Keck (Hawaii): 128 data

- Bayesian inversion of $\eta_i$ and $\beta$ from these data’s

<table>
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<tr>
<th>Parameter</th>
<th>Estimation $[\times 10^{-7}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VLT</td>
</tr>
<tr>
<td>$\eta_0 - 1$</td>
<td>$10 \pm 6$</td>
</tr>
<tr>
<td>$\eta_1$</td>
<td>$8.4 \pm 3.5$</td>
</tr>
<tr>
<td>$\eta_2$</td>
<td>$20 \pm 10$</td>
</tr>
<tr>
<td>$\eta_3$</td>
<td>$14 \pm 6$</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>$14 \pm 6$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$-3.3 \pm 1.5$</td>
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- clocks: one constraint at $z = 0$; only valid if no chameleon effect

5 orders of magnitude better than direct constraints

see Hees A., Minazzoli O., Larena J., PRD, 2014


see Khoury J., Weltman A., PRD/PRL, 2004
Objectives

2) Check the consistency of these relations using the different types of observations to “test” the multiplicative coupling

All of these observables are intimately related

\[
\frac{h(\phi_0)}{h(\phi(z))} = \eta^2(z) = \frac{\Delta \alpha(z)}{\alpha} + 1 = 8.33 \frac{T(z)}{T_0(1 + z)} - 7.33.
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\[
\mu = 0.47 \left( 1 - \frac{1}{\eta^2(z_{CMB})} \right) = 0.47 \frac{\Delta \alpha(z_{CMB})}{\alpha} = 3.92 \left( \frac{T(z_{CMB})}{T_0(1 + z_{CMB})} - 1 \right)
\]

• Estimation of \( h(\phi) \) with 3 different type of observations using Gaussian Processes: GaPP

for GaPP, see http://www.acgc.uct.ac.za/~seikel/GAPP/main.html
and M. Seikel et al, JCAP06, 036, 2012
Test of the multiplicative coupling

- Use: $D_L$ data from SNe Ia (Union 2.1)
- $D_A$ data from 25 galaxy clusters
- variation of $\alpha$ from Keck/VLT
- CMB temperature

from $\eta$

from $T_{CMB}$

- SKA will improve this by 1 order of magnitude
- constraint on $\phi$ related to the gravitation action $S_{grav}[g_{\mu\nu}, \phi]$


see for example Martins C.J.A.P. et al, PLB, 2015
A rescaling of the 4-potential

- a recent claim: in such theory, no CMB temperature-redshift modification.

- use of “rescaled” 4-potential

\[ a^\mu = \sqrt{h(\phi)} A^\mu \]
\[ f_{\mu\nu} = \sqrt{h(\phi)} F_{\mu\nu} \]

which leads to

\[ S_{EM} = -\frac{1}{4} \int d^4 x \sqrt{-g} f^{\mu\nu} f_{\mu\nu} - q_i \int (h(\phi))^{-1/2} a_\mu dx^\mu_i \]
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- standard EM propagation but... non standard interaction with matter

- in a complete modeling (emission, propagation, detection), both approaches give the same observables (current in an antenna, ...)

see Barrow J., Magueijo J., PRD, 2014

see Hees A., Minazzoli O., Larena J., GRG 2015
Conclusion

- A multiplicative coupling between a scalar field and EM implies a violation of the EEP which results in
  - Temporal variation of $\alpha$
  - Violation of the cosmic distance duality
  - Modification of the $T_{CMB}$ evolution
  - CMB non Planckian

  All of these observables are univoquely related

- Assuming the coupling holds: the constraints on the temporal variation of $\alpha$ can improve the constraints on other observables

- **Test of the coupling**: comparison of the different types of observations
  - Not so good constraints on $T_{CMB}$ and $D_A$ compare to $\alpha$

see Hees A., Minazzoli O., Larena J., PRD, 2014 and GRG 2015
BACKUP SLIDES
Two approaches

\[ S = -\frac{1}{4\mu_0 c} \int d^4x \sqrt{-g} e^{-2\Psi} f_{\mu\nu} f_{\mu\nu} \]

\[ -m_p c^2 \int d\tau_p + q_p \int a_\mu dx_\mu^\mu \]

\[ f_{\mu\nu} = \nabla_\mu a_\nu - \nabla_\nu a_\mu \]

\[ a_\mu \rightarrow a_\mu + \partial_\mu \chi, \]

\[ \dot{n} + \frac{3a}{a} n = 2n \dot{\Psi} \]

\[ A^\mu = e^{-\Psi} a^\mu \]

\[ S = -\frac{1}{4\mu_0 c} \int d^4x \sqrt{-g} F^{\mu\nu} F_{\mu\nu} \]

\[ -m_p c^2 \int d\tau_p + q_p \int e^{\Psi} A_\mu dx_\mu^\mu \]

\[ F_{\mu\nu} := e^{-\Psi} [\partial_\mu (e^{\Psi} A_\nu) - \partial_\nu (e^{\Psi} A_\mu)] \]

\[ A^\mu \rightarrow A^\mu + e^{-\Psi} \partial^\mu \chi \]

\[ \dot{N} + \frac{3a}{a} N = 0. \]

- but observables are the same! Effects on the propagation if using the left approach - same effects coming from the interaction if using the right

see Hees A., Minazzoli O., Larena J., arXiv:1409.7273
**Einstein Equivalence Principle**

- **Universality of Free Fall**
  - Lunar Laser Ranging (LLR): $10^{-13}$
  - Torsions Balance: $10^{-13}$
  - Macro vs “quantum object”: $10^{-9}$

  see A. Peters et al, Nature, 400, 849, 1999

for a review, see C. Will, LRR, 17, 4, 2014
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- Local Position Invariance
  - Gravitational redshift: $10^{-5}$
    
  - Are the constants of Nature really constant?
    \[ \frac{\dot{\alpha}}{\alpha} < 10^{-17} \text{ yr}^{-1} \]
    
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- **Local Position Invariance**
  - Gravitational redshift: $10^{-5}$


  - Are the constants of Nature really constant? $\frac{\dot{\alpha}}{\alpha} < 10^{-17}\text{ yr}^{-1}$


- **Local Lorentz Invariance**
  - Standard Model Extension (SME): a dedicated framework

  see A. Kostelecky, N. Russel, Rev. of Mod. Phys., 83/11, 2011
Boltzmann Equation (in FLRW)

- Identification of the “source term” with the Maxwell equation

\[
\dot{n} + 3Hn = \Psi = \frac{1}{\pi^2} \int pC[f] \, dp = -n\partial_t \ln h(\varphi)
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\dot{\rho} + 4H \rho = C_x = \frac{1}{\pi^2} \int p^2C[f] \, dp
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- Does not satisfy the “adiabaticity” condition defined by Lima

\[ \frac{C_x}{\Psi} \neq \frac{4\rho}{3n} \]

⇒ CMB spectrum cannot stay Planckian!
Boltzmann Equation (in FLRW)

- Identification of the “source term” with the Maxwell equation

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- Does not satisfy the “adiabaticity” condition defined by Lima

\[ \frac{C_x}{\Psi} \neq \frac{4\rho}{3n} \]

\[ \Rightarrow \text{CMB spectrum cannot stay Planckian!} \]

- Similar to what is found for disformal couplings


see C. van de Bruck et al, Phys. Rev. Letters 111, 161302, 2013
Derived constraints from $\mu$

assuming the multiplicative coupling

- **COBE/FIRAS constraint**
  
  \[ |\mu| < 9 \times 10^{-5} \]
  

- **Use the relation coming from the mult. coupling**
  
  \[ \mu = 0.47 \frac{\Delta \alpha(z_{\text{CMB}})}{\alpha} \]

- **Constraints on the variation of $\alpha$**
  
  \[ \left| \frac{\Delta \alpha(z_{\text{CMB}})}{\alpha} \right| < 1.91 \times 10^{-4} \]

I order of magnitude better than direct constraint

see Hees A., Minazzoli O., Larena J., arXiv:1406.6187
Prospective for SKA

- SKA will measure BAO and improve measurement of angular distances
- Simulations of SKA $D_A$ data with realistic uncertainties and use of current SNe Ia data
- Improvement by 1 order of magnitude and observations at higher redshift