Title: Cosmology in Massive GravityLand

Date: Feb 10, 2015 11:00 AM

URL: http://pirsa.org/15020088

Abstract: <p>The last years have seen a renewed interest in theories of massive gravity. They represent an infra-red modification of gravity where the gravitational force weakens at very large scales. Heuristically, they provide the playground to understand a possible modification of GR which could potentially provide a dynamical solution to the cosmological constant problem. In this talk I will discuss a number of theoretical aspects of massive gravity theories, focusing on the relevance of the so-called Vainstein mechanism, both at the classical and the quantum level. I will also discuss how we can use cosmology from the early and late universe to constrain these theories. For example, what does the Cosmic Microwave Background Radiation know about the graviton mass?</p>

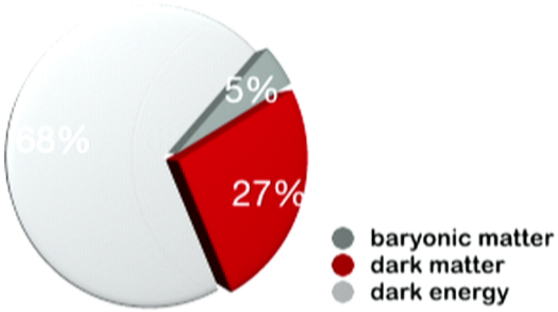
“The data is king. If what you’re working on has nothing to do with data, it’s not worth working on.”

David Lyth

Raquel H Ribeiro

ΛCDM — a phenomenological model

- ΛCDM seems a good fit to theoretical data
- but we don't really understand Λ!
- there's been much effort in developing infra-red modifications of gravity as a means to explain Λ

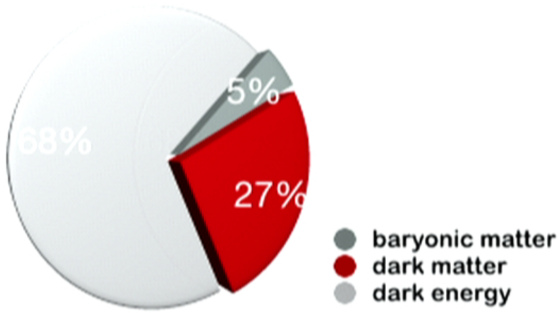


if the precision era has taught us anything, is that the theory needs to press on more boldly to catch up with observational precision.

Raquel H Ribeiro

ΛCDM — a phenomenological model

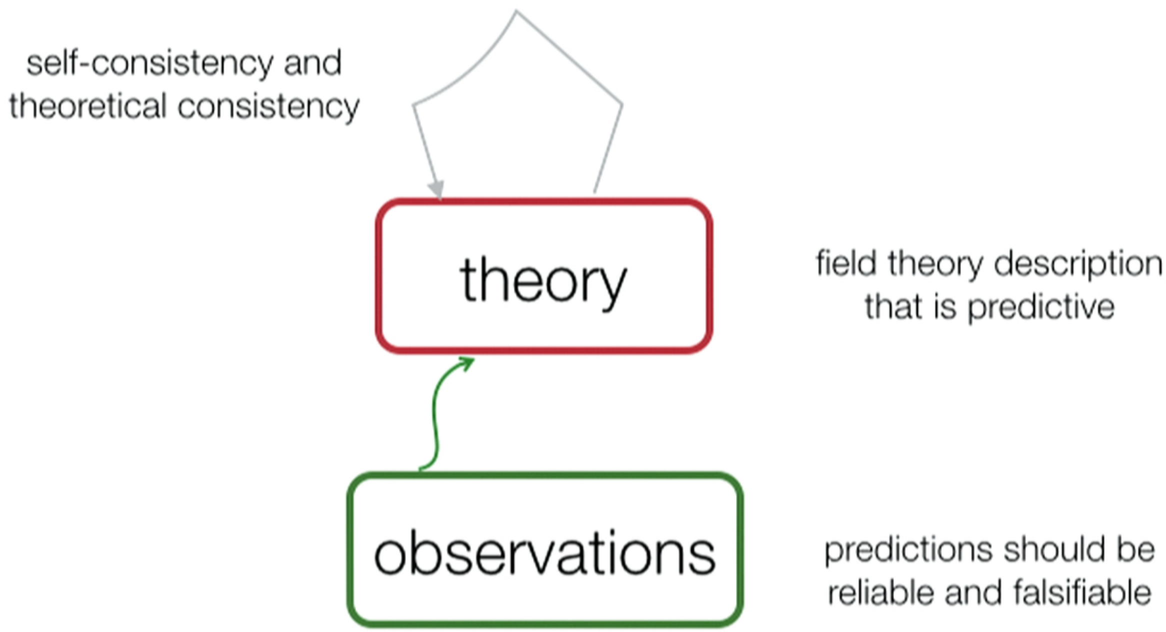
- ΛCDM seems a good fit to theoretical data
- but we don't really understand Λ!
- there's been much effort in developing infra-red modifications of gravity as a means to explain Λ



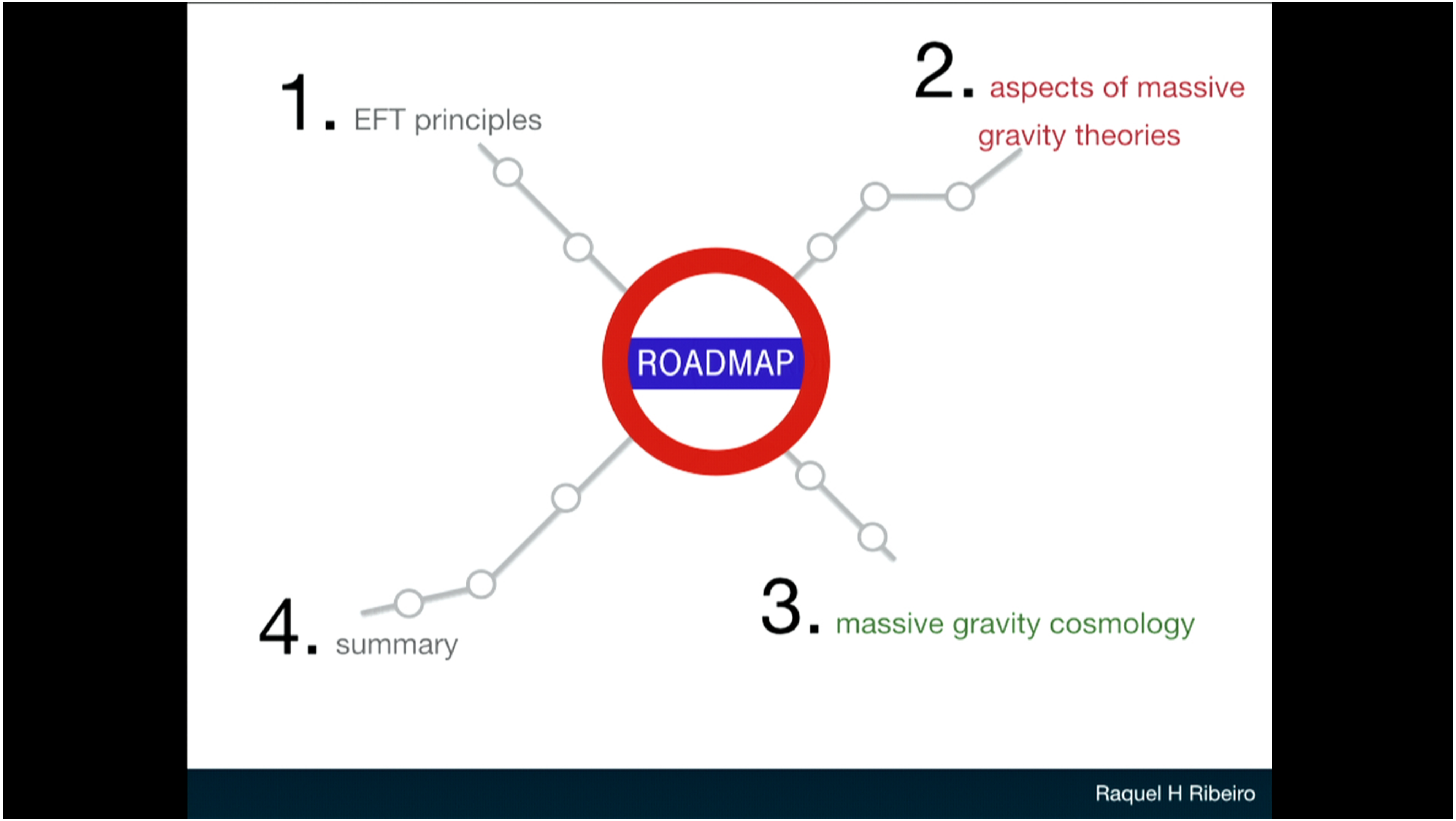
if the precision era has taught us anything, is that the theory needs to press on more boldly to catch up with observational precision.

Raquel H Ribeiro

gravity and cosmology—many unknowns



Raquel H Ribeiro



1. EFT principles
2. aspects of massive gravity theories
ROADMAP
3. massive gravity cosmology
4. summary
Raquel H Ribeiro

traditional principles of EFTs

- write a tower of interactions which are categorised by power counting

$$\mathscr{L}_{tEFT}(\phi) = \int \mathrm{d}^4 x \left\{ \mathscr{L}_{\text{low-energy}} + \sum_i c_i \frac{\mathscr{O}_\beta(\phi)}{\Lambda^\beta} \Lambda^4 \right\}$$

strong coupling scale

- interactions in *O* cannot be made large without the EFT running out of control
- we say these operators are irrelevant **and** unimportant
- they can be protected against large quantum effects if there exists *a* symmetry

Raquel H Ribeiro

traditional principles of EFTs

- write a tower of interactions which are categorised by power counting

$$\mathscr{L}_{tEFT}(\phi) = \int \mathrm{d}^4 x \left\{ \mathscr{L}_{\mathrm{low-energy}} + \sum_i c_i \frac{\mathscr{O}_\beta(\phi)}{\Lambda^\beta} \Lambda^4 \right\}$$

strong coupling scale

- interactions in *O* cannot be made large without the EFT running out of control

- we say these operators **are irrelevant and unimportant**

- **they can be protected against large quantum effects if there exists *a* symmetry**

new way of looking at EFTs: redressing effect

- EFTs like massive gravity rely **large derivative/kinetic interactions**

- Examples of scalar theories:
  - P(X) theories, where $X=-(\partial\phi)^2/\Lambda^4$ ➜ $P(X) \supseteq$ DBI, power-law models ~ $\Lambda^4 X^n$
  - the cubic galileon $S = \int d^4x \left\{ -\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda^3}\Box\phi(\partial\phi)^2 \right\}$

- Our interest is in theories which can exhibit a **Vainshtein/kinetic mechanism. This means large interactions.**

Raquel H Ribeiro

new way of looking at EFTs: redressing effect

- EFTs like massive gravity rely **large derivative/kinetic interactions**

- Examples of scalar theories:
  - P(X) theories, where $X=-(\partial\phi)^2/\Lambda^4$ ➜ P(X)⊇DBI, power-law models ~ $\Lambda^4 X^n$
  - the cubic galileon $S = \int d^4x \left\{ -\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda^3}\Box\phi(\partial\phi)^2 \right\}$

- Our interest is in theories which can exhibit a **Vainshtein/kinetic mechanism. This means large interactions.**

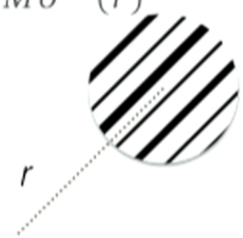
Raquel H Ribeiro

why are these theories special?

Defayet et al. hep-th/0106001
Nicolis & Rattazzi hep-th/0404159

case study: cubic galileon coupled to spherically distributed matter:

$$T = -M\delta^{(3)}(r)$$



$$S = \int d^4x \left\{ -\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda^3}\Box\phi(\partial\phi)^2 + \frac{\phi}{M_{\rm Pl}}T \right\}$$

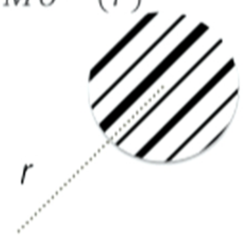
Raquel H Ribeiro

why are these theories special?

Defayet et al. hep-th/0106001
Nicolis & Rattazzi hep-th/0404159

case study: cubic galileon coupled to spherically distributed matter:

$T = -M\delta^{(3)}(r)$



$$S = \int \mathrm{d}^4x \left\{ -\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda^3}\Box\phi(\partial\phi)^2 + \frac{\phi}{M_{\mathrm{Pl}}}T \right\}$$

For large background sources and small enough distances:

$$F_\phi(r) \sim \phi'(r) \sim \sqrt{\frac{M\Lambda^3}{M_{\mathrm{Pl}}r}} \longrightarrow \Box\phi \gg \Lambda^3$$

$$r_\star \equiv \frac{1}{\Lambda}\left(\frac{M}{4\pi M_{\mathrm{Pl}}}\right)^{1/3}$$

Vainshtein radius

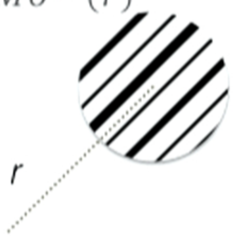
Raquel H Ribeiro

why are these theories special?

Defayet et al. hep-th/0106001
Nicolis & Rattazzi hep-th/0404159

case study: cubic galileon coupled to spherically distributed matter:

$$T = -M\delta^{(3)}(r) \qquad S = \int \mathrm{d}^4x \left\{ -\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda^3}\Box\phi(\partial\phi)^2 + \frac{\phi}{M_{\rm Pl}}T \right\}$$



For large background sources and small enough distances:

$$F_\phi(r) \sim \phi'(r) \sim \sqrt{\frac{M\Lambda^3}{M_{\rm Pl}r}} \longrightarrow \Box\phi \gg \Lambda^3$$

$$r_\star \equiv \frac{1}{\Lambda}\left(\frac{M}{4\pi M_{\rm Pl}}\right)^{1/3}$$

Vainshtein radius

Split the field into background+perturbations, & canonically normalise

$$\mathscr{L} \supseteq -\frac{1}{2}(\partial\delta\hat{\phi})^2 - \frac{1}{Z^{3/2}\Lambda^3}\Box(\delta\hat{\phi})(\partial\delta\hat{\phi})^2 + \cdots$$

with $Z \sim 1 + \frac{\Box\phi}{\Lambda^3} \gg 1$

Raquel H Ribeiro

redressed strong coupling scale

$$S = \int d^4x \left\{ -\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda^3}\Box\phi(\partial\phi)^2 + \frac{\phi}{M_{\rm Pl}}T \right\}$$

- if interactions are large, $\Box\phi \gg \Lambda^3$ then the strong coupling scale is redressed

$$\Lambda_\star = \sqrt{Z}\Lambda \gg \Lambda$$

environmentally dependent

- perturbative unitarity does not break at Λ, and we can trust the EFT description beyond that scale

specific examples in
Aydemir et al. arXiv:1203.5153

Raquel H Ribeiro

EFTs for large derivative interactions

These EFTs are perfectly well-defined around E~Λ.

relevant | **irrelevant**

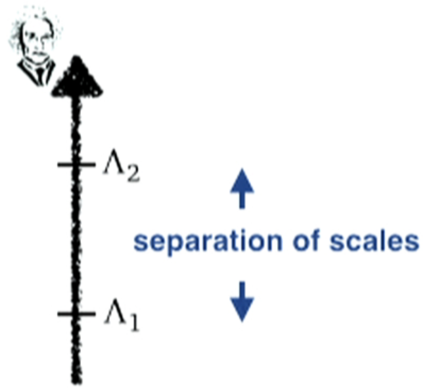
$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{low-energy}} + \sum \frac{f_\alpha(\partial\phi, \partial^2\phi)}{\Lambda^\alpha}\,\Lambda^4 + \sum \frac{\mathcal{O}_\beta}{\Lambda^\beta}\,\Lambda^4$$

Within the EFT unifying framework, there is no distinction between classical or quantum mechanical origin of the operators.

Raquel H Ribeiro

organised EFTs: traditional and novel

traditional EFTs



$$\mathscr{L}_{\text{int}} \sim c_1 \frac{\phi^6}{\Lambda^2} + c_2 \frac{\phi^8}{\Lambda^4}$$

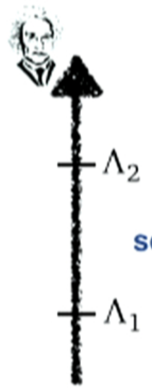
$$\downarrow \qquad \downarrow$$

$$\Lambda_1 \qquad \Lambda_2$$

Raquel H Ribeiro

organised EFTs: traditional and novel

traditional EFTs



separation of scales

$$\mathscr{L}_{\rm int} \sim c_1 \frac{\phi^6}{\Lambda^2} + c_2 \frac{\phi^8}{\Lambda^4}$$

$\downarrow$ Λ_1 $\quad$ $\downarrow$ Λ_2

reorganised EFTs

example: galileon-type interactions

hierarchy of derivatives

$$\mathscr{L}_{\rm int} \sim c_3 (\partial\phi)^2 \frac{\Box\phi}{\Lambda^3} + c_5 \frac{\Box^2\phi}{\Lambda}$$

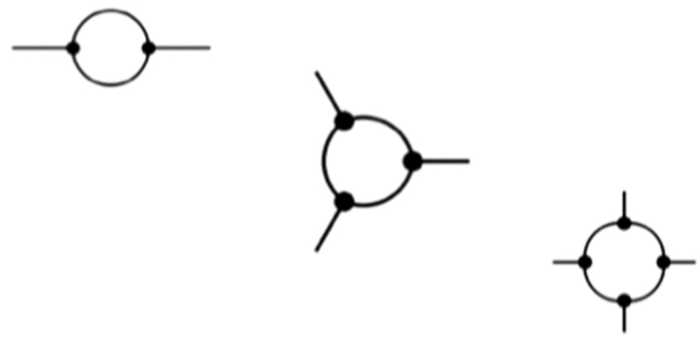
$\frac{\Box\phi}{\Lambda^3}$ $\downarrow$ not suppressed

$\frac{\Box^2\phi}{\Lambda}$ $\downarrow$ suppressed

Raquel H Ribeiro

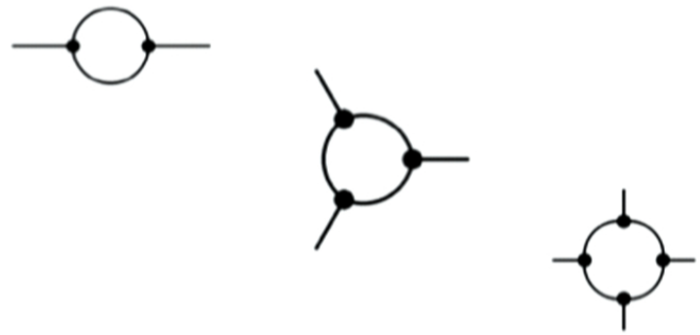
2

does mGR survive
quantum corrections?



2

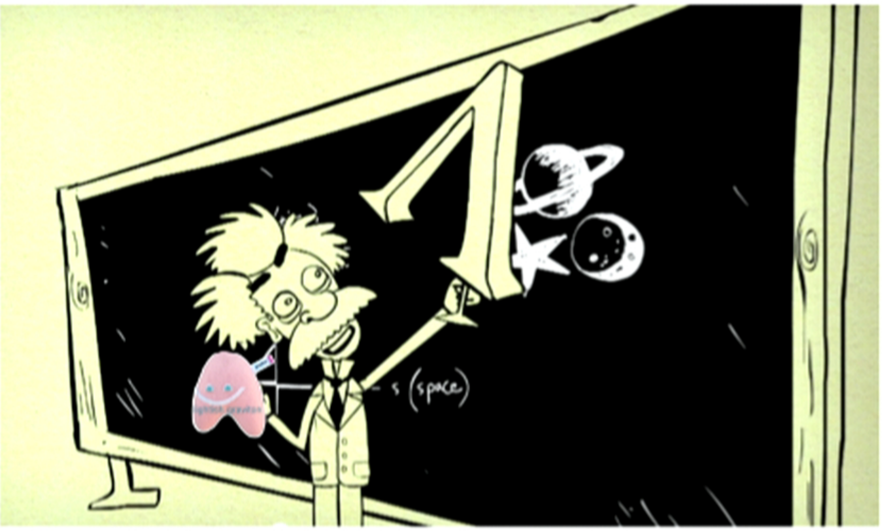
does mGR survive quantum corrections?



Raquel H Ribeiro

why are quantum corrections relevant?

This is a spectacular problem!

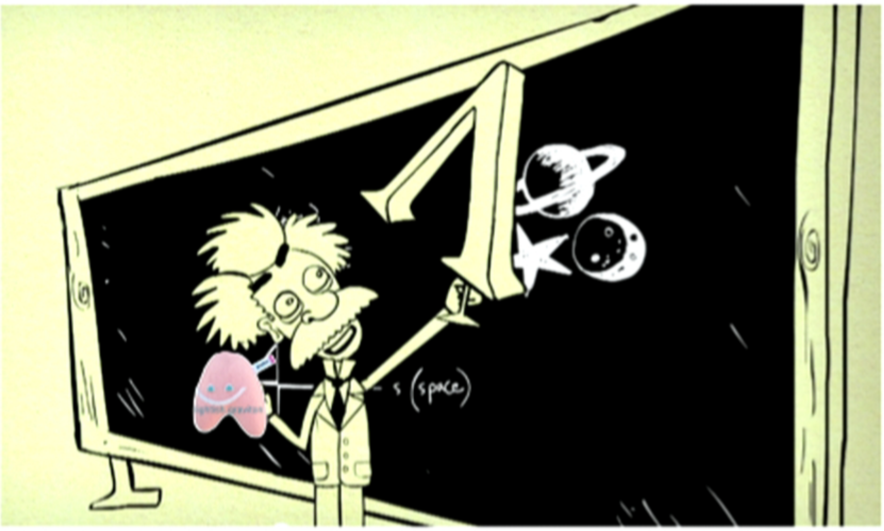


credit: open university, hacked by RHR

Raquel H Ribeiro

why are quantum corrections relevant?

This is a spectacular problem!



credit: open university, hacked by RHR

Raquel H Ribeiro

quantum corrections can ruin the EFT

- technically unnatural: if they change the coefficients of the existing operators
- if they generate relevant & important operators, destabilising the potential

Pick up a theory. We can determine its **regime of validity** at one-loop by requiring

$$|\mathscr{L}_{\text{classical}}| \gg |\mathscr{L}_{\text{one-loop}}|$$

The EFT is built out of classical and quantum operators.

Raquel H Ribeiro

how to compute quantum corrections?

For simplicity, consider a scalar theory and compute the one-loop effective action.

1. Split the field into a background piece and perturbations $\phi = \phi_0 + \delta\phi$

2. Compute the **quadratic action for fluctuations**

$$\delta S = -\frac{1}{2}\int \mathrm{d}^4x \ \left\{ Z^{\mu\nu}[\phi_0]\, \partial_\mu \delta\phi \ \partial_\nu \delta\phi \right\}$$

3. Covariantise this.

$$\Gamma_{\text{1-loop}} = \frac{1}{2}\log\det\left\{ Z^{\mu\nu}[\phi_0]\, \nabla_\mu \nabla_\nu \right\} \qquad Z^{\mu\nu} = \sqrt{g_{\text{eff}}}\ g^{\mu\nu}_{\text{eff}}$$

Raquel H Ribeiro

the one-loop effective action

UV-divergences are organised as a Seeley—DeWitt expansion

- Barvinsky & Vilkovisky — Phys.Rept. 119 (1985) & Nucl.Phys. B333 (1990)
- Avramidi — arXiv:math-ph/0107018

now select the universal, physical log divergences *(throw away the power-laws)*

cf. Burgess & London
hep-ph/9203216

and use dimensional regularisation

$$\Gamma^{\log}_{1-\text{loop}} \sim \int \mathrm{d}^4x \, \sqrt{g_{\text{eff}}} \left\{ R^2 + 2 R_{\mu\nu} R^{\mu\nu} \right\}$$

these are all curvature quantities
built out of the effective metric

Raquel H Ribeiro

the one-loop effective action

UV-divergences are organised as a Seeley—DeWitt expansion

- Barvinsky & Vilkovisky — Phys.Rept. 119 (1985) & Nucl.Phys. B333 (1990)
- Avramidi — arXiv:math-ph/0107018

now select the universal, physical log divergences *(throw away the power-laws)*

cf. Burgess & London hep-ph/9203216

and use dimensional regularisation

$$\Gamma^{\log}_{1-\text{loop}} \sim \int \mathrm{d}^4x\, \sqrt{g_{\text{eff}}}\left\{ R^2 + 2R_{\mu\nu}R^{\mu\nu} \right\}$$

these are all curvature quantities built out of the effective metric

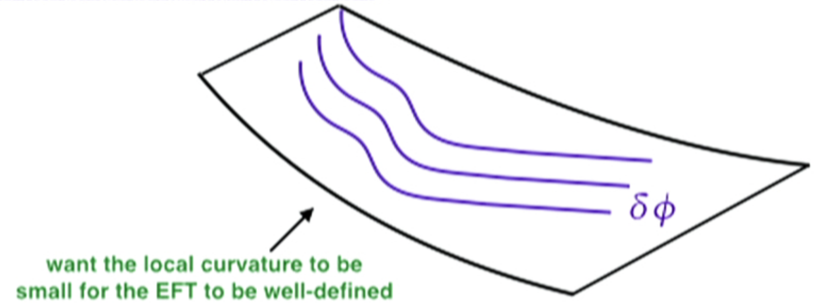
Raquel H Ribeiro

geometrical intuition

- when are these quantum corrections small?

$$\left|\sqrt{g_{\text{eff}}}\, R^2[g_{eff}]\right| \ll |\mathscr{L}_{\text{classical}}|$$

while $|Z^{\mu}{}_{\nu}| \gg 1$



- the stability of the EFT under quantum effects is determined by this condition for all theories **regardless** of invoking a special symmetry

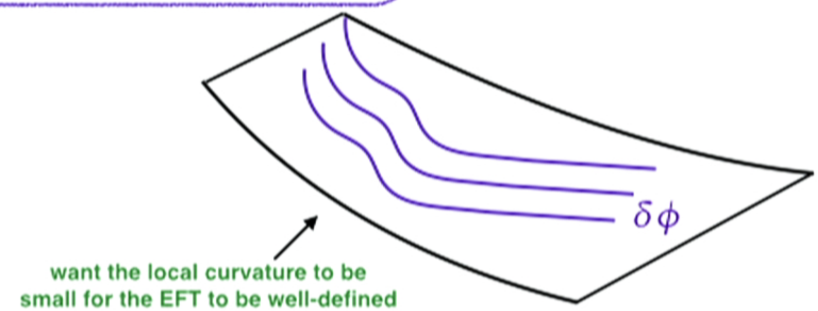
Raquel H Ribeiro

geometrical intuition

- when are these quantum corrections small?

$$\left|\sqrt{g_{\text{eff}}}\,R^2[g_{eff}]\right| \ll |\mathscr{L}_{\text{classical}}|$$

while $|Z^{\mu}{}_{\nu}| \gg 1$



- the stability of the EFT under quantum effects is determined by this condition for all theories **regardless** of invoking a special symmetry

case study

$$S = \int \mathrm{d}^4x \left\{ -\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda^3}\Box\phi(\partial\phi)^2 \right\}$$

- let us get back to the cubic galileon $Z \sim 1 + \frac{\Box\phi}{\Lambda^3}$
- so the effective metric will depend on second order derivatives of the fields (and will potentially have some constant terms as well). recall that:

$$g^{\mathrm{eff}}_{\mu\nu} = Z_{\mu\nu}\sqrt{g}$$

- so the logarithmic quantum effects we've calculated can only generate higher order derivative operators
- for quantum corrections do be under control, background configurations are such that

$$\phi \sim \Lambda \qquad \partial\phi \sim \Lambda^2 \qquad \partial^2\phi \sim \Lambda^3 \quad \text{but} \quad \partial^n\phi \sim \Lambda^{n+1} \quad \text{for} \quad n \geq 3$$

cf. Luty et al. hep-th/0303116
Nicolis & Rattazzi hep-th/0404159

Raquel H Ribeiro

case study

$$S = \int d^4x \left\{ -\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda^3}\Box\phi(\partial\phi)^2 \right\}$$

- let us get back to the cubic galileon $Z \sim 1 + \frac{\Box\phi}{\Lambda^3}$
- so the effective metric will depend on second order derivatives of the fields (and will potentially have some constant terms as well). recall that:

$$g^{\text{eff}}_{\mu\nu} = Z_{\mu\nu}\sqrt{g}$$

- so the logarithmic quantum effects we've calculated can only generate higher order derivative operators
- for quantum corrections do be under control, background configurations are such that

$$\phi \sim \Lambda \qquad \partial\phi \sim \Lambda^2 \qquad \partial^2\phi \sim \Lambda^3 \quad \text{but} \quad \partial^n\phi \sim \Lambda^{n+1} \quad \text{for} \quad n \geq 3$$

cf. Luty et al. hep-th/0303116
Nicolis & Rattazzi hep-th/0404159

Raquel H Ribeiro

case study

$$S = \int \mathrm{d}^4x \left\{ -\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda^3}\Box\phi(\partial\phi)^2 \right\}$$

- let us get back to the cubic galileon $Z \sim 1 + \frac{\Box\phi}{\Lambda^3}$
- so the effective metric will depend on second order derivatives of the fields (and will potentially have some constant terms as well). recall that:

$$g^{\text{eff}}_{\mu\nu} = Z_{\mu\nu}\sqrt{g}$$

- so the logarithmic quantum effects we've calculated can only generate higher order derivative operators
- for quantum corrections do be under control, background configurations are such that

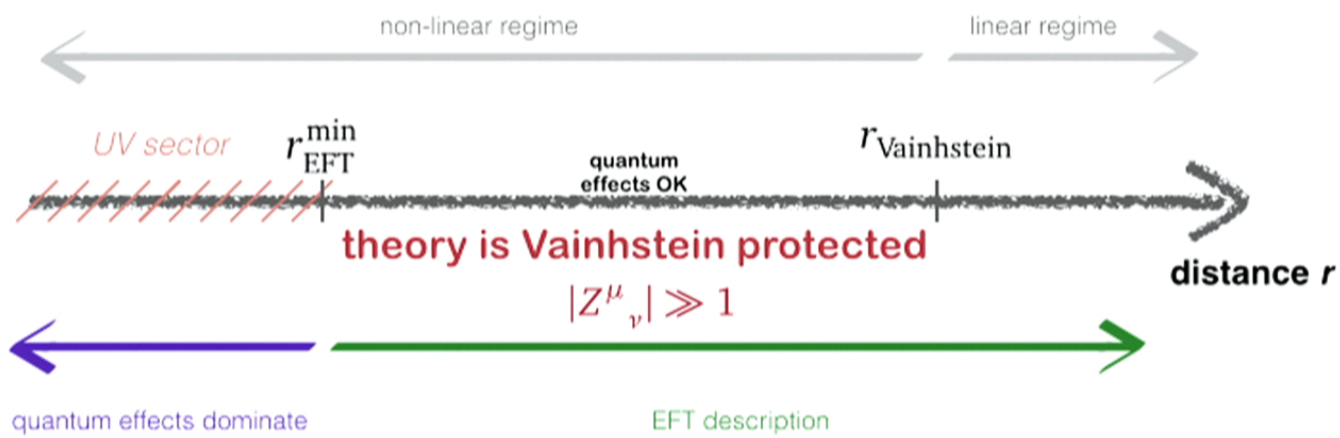
$$\phi \sim \Lambda \qquad \partial\phi \sim \Lambda^2 \qquad \partial^2\phi \sim \Lambda^3 \quad \text{but} \quad \partial^n\phi \sim \Lambda^{n+1} \quad \text{for} \quad n \geq 3$$

cf. Luty et al. hep-th/0303116
Nicolis & Rattazzi hep-th/0404159

Raquel H Ribeiro

dynamical regimes

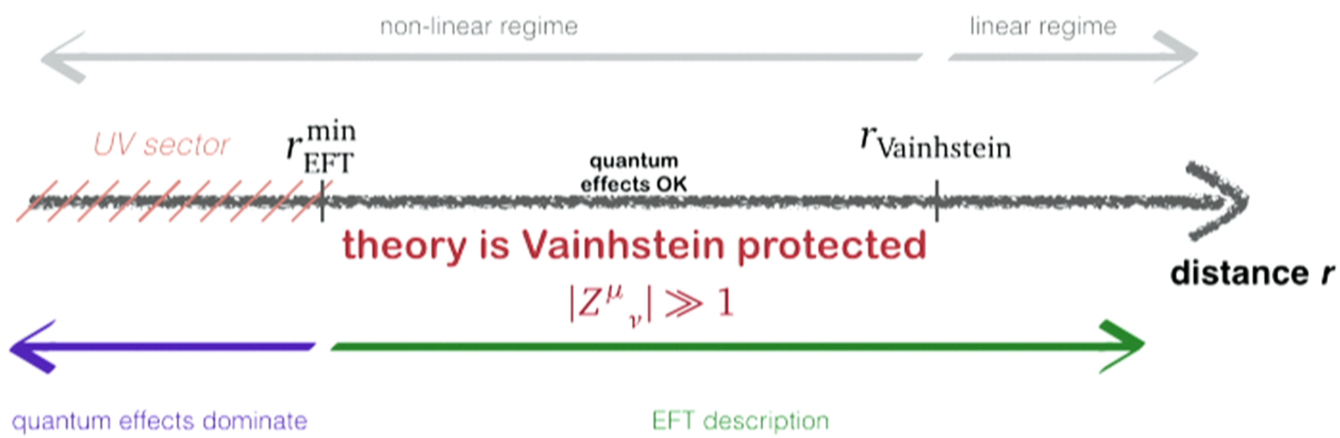
We see a Vainhstein screening effect at the quantum level



Raquel H Ribeiro

dynamical regimes

We see a Vainhstein screening effect at the quantum level



Raquel H Ribeiro

benefits of the one-loop effective action

- method is quite generic and accounts for all one-loop effects
- results are robust for all theories exhibiting the Vainhstein mechanism
- *it's still possible to do better using the DRGE and Wetterich equation*
- let's apply what we've learned to mGR

Raquel H Ribeiro

benefits of the one-loop effective action

- method is quite generic and accounts for all one-loop effects
- results are robust for all theories exhibiting the Vainhstein mechanism
- *it's still possible to do better using the DRGE and Wetterich equation*
- let's apply what we've learned to mGR

Raquel H Ribeiro

mGR action

dRGT [de Rham, Gabadadze & Tolley]
1007.0443 & 1011.1232

Interactions are **algebraically special** (very constrained) and ***ghost-free***

$$\mathcal{L}_{\rm mGR} = \frac{M_{\rm Pl}^2}{2}\sqrt{-g}\left(R[g] + \frac{m^2}{4}\sum_{n=0}^{4}\tilde{\alpha}_n \mathcal{U}_n[X]\right)$$

$$X^{\mu}{}_{\nu} \equiv \left(\sqrt{g^{-1}f}\right)^{\mu}{}_{\nu}$$

involves two metrics

To be precise, they are

$$\mathcal{U}_2 = [X]^2 - [X^2]$$

$$\mathcal{U}_3 = [X]^3 - 3[X][X^2] + 2[X^3]$$

$$\mathcal{U}_4 = [X]^4 - 6[X]^2[X^2] + 8[X^3][X] + 3[X^2]^2 - 6[X^4]$$

mGR encompasses a class of theories

Interactions are finite, algebraically special and ghost-free (classically)

$$\mathscr{L}_{\rm mGR} = \frac{M_g^2}{2}\left(\sqrt{-g}\,R[g] + \frac{M_f^2}{2\,M_g^2}\sqrt{-f}\,R[f] + \sqrt{-g}\,\frac{m^2}{4}\sum_{n=0}^{4}\tilde{\alpha}_n\,\mathscr{U}_n[X]\right)$$

$$X^\mu{}_\nu \equiv \left(\sqrt{g^{-1}f}\right)^\mu{}_\nu$$

In this class of theories there are two metrics, by construction:

- if $f_{\mu\nu}$ is fixed (Minkowski) , the theory is known as **massive gravity**.
- if $f_{\mu\nu}$ is dynamical, we call it **massive biGravity** and add the EH term

mGR encompasses a class of theories

Interactions are finite, algebraically special and ghost-free (classically)

$$\mathscr{L}_{\mathrm{mGR}} = \frac{M_g^2}{2}\left(\sqrt{-g}\,R[g] + \frac{M_f^2}{2\,M_g^2}\sqrt{-f}\,R[f] + \sqrt{-g}\,\frac{m^2}{4}\sum_{n=0}^{4}\tilde{\alpha}_n\,\mathscr{U}_n[X]\right)$$

$$X^{\mu}{}_{\nu} \equiv \left(\sqrt{g^{-1}f}\right)^{\mu}{}_{\nu}$$

In this class of theories there are two metrics, by construction:

- if $f_{\mu\nu}$ is fixed (Minkowski) , the theory is known as **massive gravity**.
- if $f_{\mu\nu}$ is dynamical, we call it **massive biGravity** and add the EH term

Raquel H Ribeiro

mGR corrected by quantum loops

eg. in dimensional regularisation

$\mathcal{A}^{(3\text{pt})} =$

$\sim m^4 \frac{h^3}{M_{\text{Pl}}^3} \sim \frac{(\partial^2\pi)^2}{M_{\text{Pl}}^2} \frac{\partial^2\pi_0}{\Lambda_3^3}$

$h \sim \partial^2\pi/m^2$

$\Lambda_3 \equiv (m^2 M_{\text{Pl}})^{1/3}$

making a theorist very nervous!

Raquel H Ribeiro

mGR corrected by quantum loops

eg. in dimensional regularisation

$\mathcal{A}^{(3\text{pt})} =$  $\sim m^4 \frac{h^3}{M_{\rm Pl}^3} \sim \frac{(\partial^2\pi)^2}{M_{\rm Pl}^2} \frac{\partial^2 \pi_0}{\Lambda_3^3}$

$h \sim \partial^2 \pi / m^2$

$\Lambda_3 \equiv (m^2 M_{\rm Pl})^{1/3}$

making a theorist very nervous!

Why? The detuning of the potential, on its own, is *not* worrisome.

For large background configurations however, where the Vainshtein mechanism is active, the mass of the induced ghost can be made arbitrarily small. This is bad!

Raquel H Ribeiro

riding with ghosts ***can be*** OK

The 1-loop effective action resums all these corrections

'Alice in QuantumLand'

$$\mathcal{L}^{1-\text{loop}}_{\text{quantum}} \sim m^4 \, \frac{1}{Z(h_0)} \, \frac{h^2}{M_{\text{Pl}}^2}$$

tensor object

Focusing on the helicity-0 mode again

$$\mathcal{L}^{1-\text{loop}}_{\text{quantum}} \sim \frac{1}{Z(h_0)} \, \frac{(\partial^2 \pi)^2}{M_{\text{Pl}}^2} \ll \mathcal{L}_{\text{classical}}$$

The graviton mass *m* and the interaction coefficients $\tilde{\alpha}_n$ are technically natural.

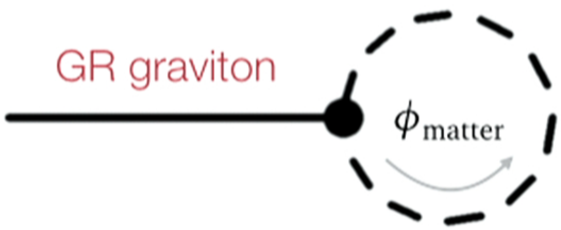
Raquel H Ribeiro

coupling mGR to matter

$$S_{\text{matter}} = \int \mathrm{d}^4x \sqrt{-g}\,\mathscr{L}_{\text{matter}}(g, \phi_{\text{matter}})$$

what types of coupling can we have? let's assume the minimal coupling and focus on the 1-point function, to start with.

Assume we couple GR with a matter sector.



Raquel H Ribeiro

coupling biGravity to matter

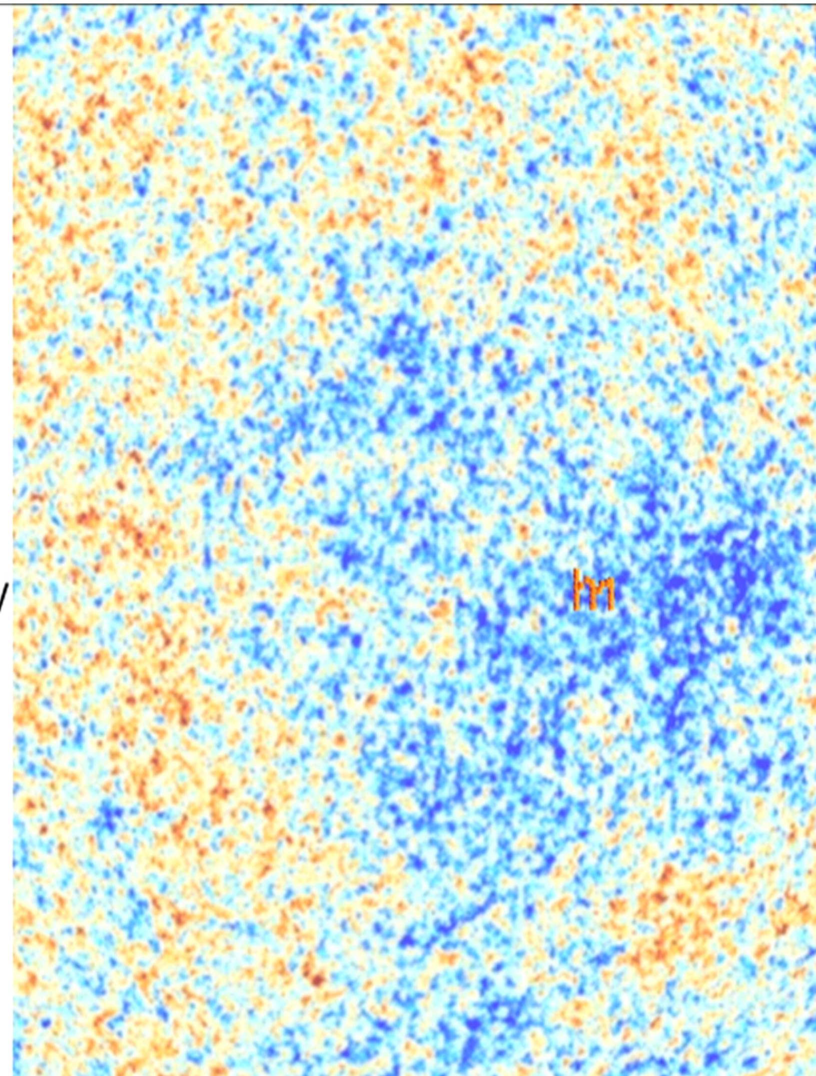
what types of coupling are sensible?

- only the metric **g** couples to the matter sector ⟶ $\Lambda[g] = \sqrt{g}$
- only the metric **f** couples to the matter sector ⟶ $\Lambda[f] = \sqrt{f}$

Raquel H Ribeiro

3

what does the CMBR know about the graviton **mass**?



Raquel H Ribeiro

cosmology in mGR

- cosmology is one of the motivations behind these theories
- absence of diffeomorphism invariance implies no spatially flat or closed FLRW solutions D'Amico et al.
- some solutions are known to exhibit instabilities (eg: infinitely strong coupling and gradient instabilities) or issues with the Higuchi bound

Massive Gravity Cosmology is still in its infancy

Raquel H Ribeiro

coupling biGravity to matter non-trivially

Does this coupling pass all the tests?

No, the ghost is excited on highly anisotropic backgrounds.

But on relatively smooth backgrounds, theory is perfectly well defined at $E \sim \Lambda_3$.

And, one-loop corrections do not introduce any ghost degree of freedom (though they do correct the graviton mass *m*).

Raquel H Ribeiro

coupling biGravity to matter non-trivially

Does this coupling pass all the tests?

No, the ghost is excited on highly anisotropic backgrounds.

But on relatively smooth backgrounds, theory is perfectly well defined at $E \sim \Lambda_3$.

And, one-loop corrections do not introduce any ghost degree of freedom (though they do correct the graviton mass *m*).

This theory has interesting phenomenological applications:

- with this non-minimal coupling, mGR *does* admit FLRW solutions. ***no more no-go***
- self-accelerated background probes no ghosts at $E \sim \Lambda_3$.

Raquel H Ribeiro

new coupling allows exact FLRW solutions

- Start with the action $\mathscr{L} = L_{\text{mGR}} + \mathscr{L}_\rho(g, \rho) + \mathscr{L}_\chi(g_{\text{eff}}, \chi)$

SM fields

a "dark" field

and choose $\mathrm{d}s_g^2 = -N(t)^2\mathrm{d}t^2 + a(t)^2\mathrm{d}\vec{x}^2$ and unitary gauge for the Stuckelberg fields.

Raquel H Ribeiro

new coupling allows exact FLRW solutions

- Start with the action $\mathscr{L} = L_{\rm mGR} + \mathscr{L}_\rho(g,\rho) + \mathscr{L}_\chi(g_{\rm eff},\chi)$

and choose $\mathrm{d}s_g^2 = -N(t)^2\mathrm{d}t^2 + a(t)^2\mathrm{d}\vec{x}^2$ and unitary gauge for the Stuckelberg fields.

- Within the decoupling limit and for a spatially homogeneous field χ_0 :

$$m^2 M_{\rm Pl}^2 (aN)^{-1}\partial_t(a^2 - a^3) = 2AB\,\tilde{a}^2 H\left(\frac{\dot{\chi}_0^2}{2\tilde{N}^2} - V(\chi_0)\right)$$

- We obtain a modified Friedmann equation:

$$3\,M_{\rm Pl}^2\,H^2 = \rho + \frac{m^2\,M_{\rm Pl}^2}{2\,B\,a^2}\left[5B + 2(A-6B)a - 3(A-2B)a^2\right] + 2A\left(\frac{\tilde{a}}{a}\right)^3 V(\chi_0)$$

Raquel H Ribeiro

new coupling allows exact FLRW solutions

- Start with the action $\mathscr{L} = L_{\mathrm{mGR}} + \mathscr{L}_\rho(g, \rho) + \mathscr{L}_\chi(g_{\mathrm{eff}}, \chi)$

and choose $\mathrm{d}s_g^2 = -N(t)^2\mathrm{d}t^2 + a(t)^2\mathrm{d}\vec{x}^2$ and unitary gauge for the Stuckelberg fields.

- Within the decoupling limit and for a spatially homogeneous field χ_0 :

$$m^2 M_{\mathrm{Pl}}^2 (aN)^{-1}\partial_t(a^2 - a^3) = 2AB\,\tilde{a}^2 H\left(\frac{\dot{\chi}_0^2}{2\tilde{N}^2} - V(\chi_0)\right)$$

- We obtain a modified Friedmann equation:

$$3\,M_{\mathrm{Pl}}^2\,H^2 = \rho + \frac{m^2\,M_{\mathrm{Pl}}^2}{2\,B\,a^2}\left[5B + 2(A-6B)a - 3(A-2B)a^2\right] + 2A\left(\frac{\tilde{a}}{a}\right)^3 V(\chi_0)$$

new coupling allows exact FLRW solutions

- Start with the action $\mathscr{L} = L_{\mathrm{mGR}} + \mathscr{L}_\rho(g,\rho) + \mathscr{L}_\chi(g_{\mathrm{eff}},\chi)$

and choose $\mathrm{d}s_g^2 = -N(t)^2\mathrm{d}t^2 + a(t)^2\mathrm{d}\vec{x}^2$ and unitary gauge for the Stuckelberg fields.

- Within the decoupling limit and for a spatially homogeneous field χ_0 :

$$m^2 M_{\mathrm{Pl}}^2 (aN)^{-1}\partial_t(a^2 - a^3) = 2AB\,\tilde{a}^2 H\left(\frac{\dot{\chi}_0^2}{2\tilde{N}^2} - V(\chi_0)\right)$$

- We obtain a modified Friedmann equation:

$$3M_{\mathrm{Pl}}^2 H^2 = \rho + \frac{m^2 M_{\mathrm{Pl}}^2}{2B\,a^2}\left[5B + 2(A-6B)a - 3(A-2B)a^2\right] + 2A\left(\frac{\tilde{a}}{a}\right)^3 V(\chi_0)$$

Raquel H Ribeiro

FLRW cosmology works

What does the CMBR know about the graviton mass?

Raquel H Ribeiro

Massive Gravity in the CMBR

- the helicity-2 mode is massive, so the dispersion relation for GWs changes
- the primordial spectrum of GWs is directly affected by the graviton mass

Raquel H Ribeiro

Massive Gravity in the CMBR

- the helicity-2 mode is massive, so the dispersion relation for GWs changes
- the primordial spectrum of GWs is directly affected by the graviton mass

Make the splitting $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ and compute the quadratic action:

$$S^{(2)}_{\text{tensors}} \sim M_{\text{Pl}}^2 \int \mathrm{d}^4 x \left[\dot{h}^{ij}\dot{h}_{ij} + \frac{h^{ij}}{a^2}\nabla^2 h_{ij} - m^2 f(\tilde{\alpha}_n)\, h^{ij} h_{ij} \right]$$

GR

Comoving momenta larger than the graviton mass are unaffected. Any changes in the tensor spectrum are only visible for low multipole number.

see also Dubovsky et al. 0907.1658

Raquel H Ribeiro

BiGravity in the CMBR

- In bigravity, we perturb both metrics $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ and $f_{\mu\nu} = \eta_{\mu\nu} + \ell_{\mu\nu}$

Focus on a regime where the **diagonalisation** can be done, and the action reads

$$S^{(2)}_{\text{tensors,biGrav}} \sim \int \mathrm{d}^4x \left[M_+^2 \left(\dot{v}_+^{ij} \dot{v}_{ij}^+ + \frac{v_+^{ij}}{a^2} \nabla^2 v_{ij}^+ \right) + M_-^2 \left(\dot{v}_-^{ij} \dot{v}_{ij}^- + \frac{v_-^{ij}}{a^2} \nabla^2 v_{ij}^- - m_{\text{eff}}^2 v_-^{ij} v_{ij}^- \right) \right]$$

massless mode (2 dof) *massive mode (5 dof)*

Raquel H Ribeiro

BiGravity in the CMBR

- In bigravity, we perturb both metrics $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ and $f_{\mu\nu} = \eta_{\mu\nu} + \ell_{\mu\nu}$

Focus on a regime where the **diagonalisation** can be done, and the action reads

$$S^{(2)}_{\text{tensors,biGrav}} \sim \int \mathrm{d}^4x \left[M_+^2 \left(\dot{v}_+^{ij}\dot{v}^+_{ij} + \frac{v_+^{ij}}{a^2}\nabla^2 v^+_{ij} \right) + M_-^2 \left(\dot{v}_-^{ij}\dot{v}^-_{ij} + \frac{v_-^{ij}}{a^2}\nabla^2 v^-_{ij} - m_{\text{eff}}^2 v_-^{ij} v^-_{ij} \right) \right]$$

massless mode (2 dof)   *massive mode (5 dof)*

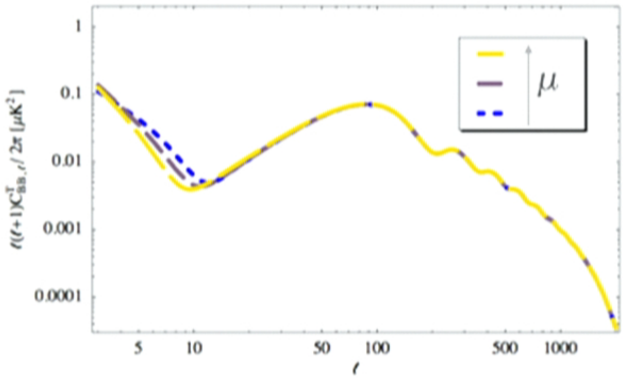
The tensor-to-scalar ratio in these theories is $r_{\text{BiGrav}} = r_{\text{GR}} + \varepsilon\, r_{\text{mGR}}$

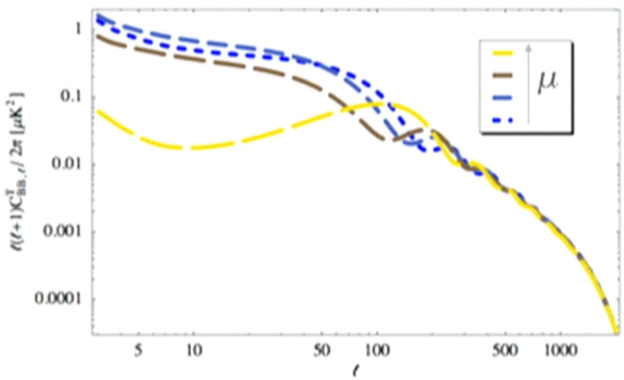
work in preparation

Raquel H Ribeiro


$\mathcal{L}_{DBI} \sim \Lambda^4 \sqrt{1-X}$

hints of a massive graviton in the CMBR





μ here is a placeholder for the mass of the massive tensor mode

if the graviton mass is very small, power spectrum is insensitive to that mass

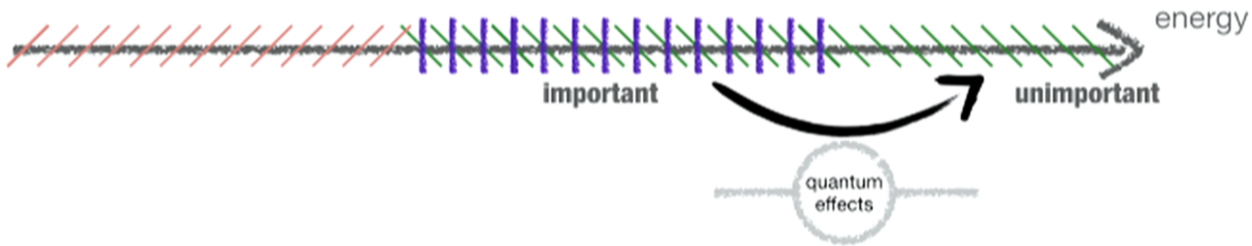
plots from Dubovsky et al. 0907.1658

Raquel H Ribeiro

EFTs as a preferred toolkit

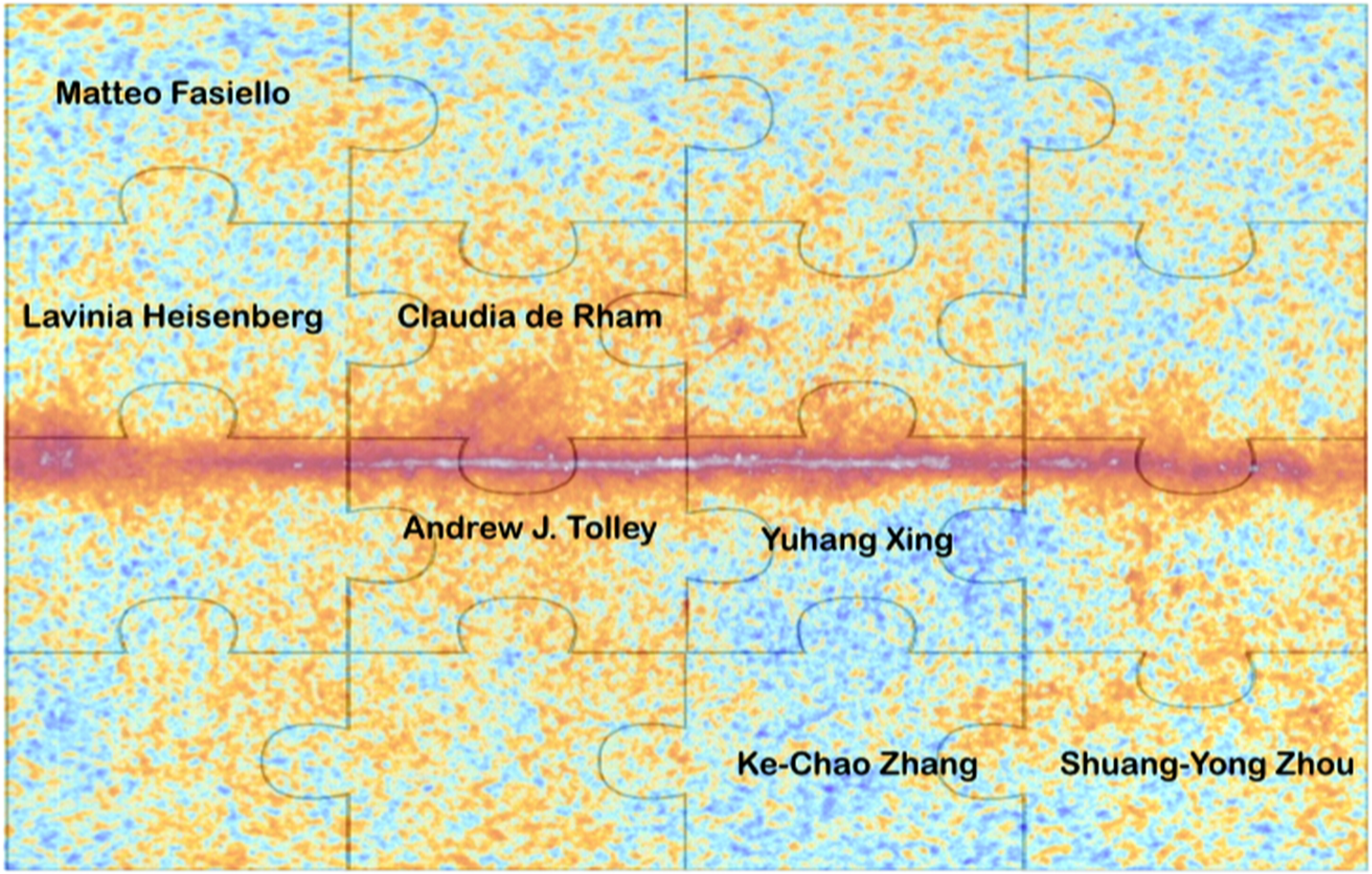
relevant irrelevant

$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\text{low-energy}} + \sum \frac{f_\alpha(\partial\phi, \partial^2\phi)}{\Lambda^\alpha}\,\Lambda^4 + \sum \frac{\mathscr{O}_\beta}{\Lambda^\beta}\,\Lambda^4$$



- notion of theory error becomes clearer
- **the range of scales of the EFT is defined**
- role of symmetry becomes more subtle
- applications to **all** theories exhibiting the Vainshtein mechanism (including galileons)

Raquel H Ribeiro



Raquel H Ribeiro

“the universe is made of stories, not of atoms”

Muriel Rukeyser

EFT principles in 1405.5213,
massive gravity considerations in 1307.7169, 1408.1678, 1409.3834
+ more to come soon