Title: Lessons from QuantumLand

Date: Apr 11, 2015 09:00 AM

URL: http://pirsa.org/15040111

Abstract: Theories with large kinetic interactions have very relevant phenomenological applications in cosmology, in particular in the context of cosmic acceleration. Their Effective Field Theory (EFT) description relies on the so-called Vainshtein effect being operative. When incorporated at the quantum level, this mechanism ensures the validity of the theory in a non-trivial way. I will discuss how to estimate the regime of validity of such EFTs on the basis of computing the quantum corrections to the classical theory. I will point out how some lessons learned from the study of quantum effects in these theories might help us to tackle the significance of superluminalities and revisit what properties a healthy EFT should have.

"**superluminal**" —faster than the speed of light

–a cosmologist gets nervous
–a field theorist gets intrigued

Raquel H Ribeiro

“**superluminal**” —faster than the speed of light

–cosmologist’s strategy: no, I’ll always impose $c_s<1$ or $c_s=1$
–field theorist’s strategy: hmmm, what does it tell us about the fundamental physics of the theory?

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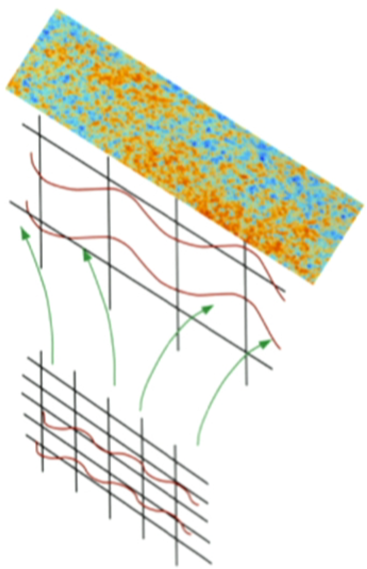
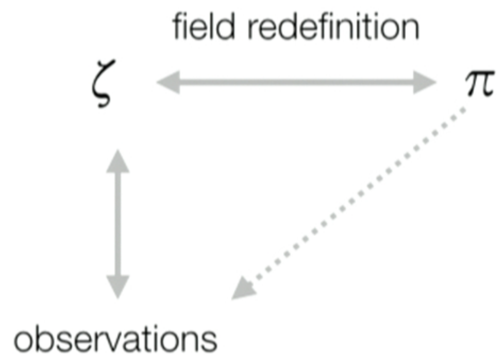
perturbation theory in data-driven cosmology

- the preferred language is effective field theory





cosmological data gives gives direct access to the perturbations, rather than the background

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fundamental principles

Adams et al.
hep-th/0602178

- causality
- unitarity
- naturalness

bottom-up approach

superluminalities? can the theory propagate viable phenomenology?

Warning: this talk is an exploration of ideas

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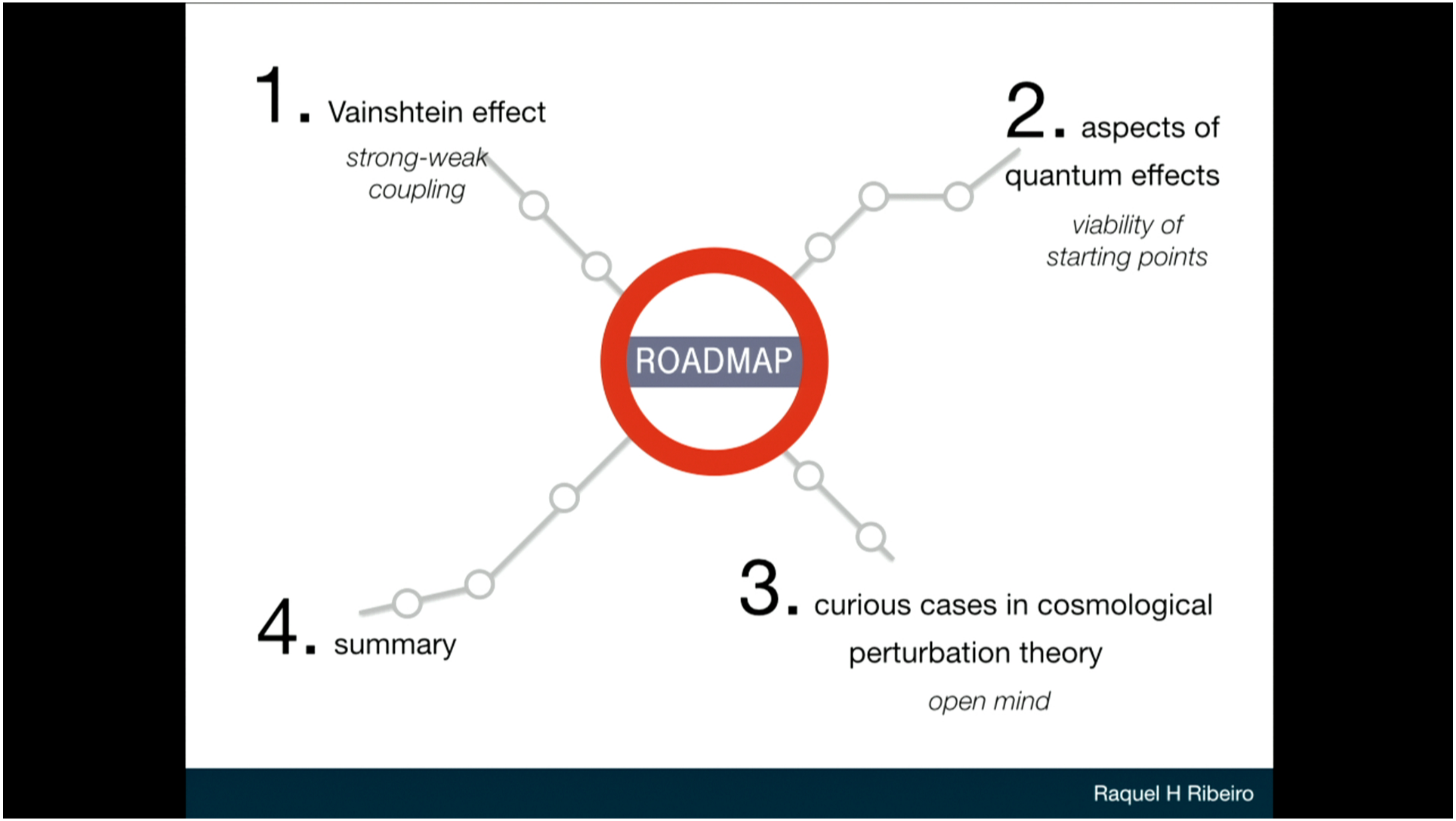
1. Vainshtein effect
strong-weak coupling
2. aspects of quantum effects
viability of starting points
ROADMAP
3. curious cases in cosmological perturbation theory
open mind
4. summary
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- non-standard theories, where **certain** irrelevant operators become important
- the kinetic term of quantum fluctuations receives **important** corrections from the background. symbolically using the background field method:

$$Z^{\mu\nu}\,\partial_\mu\delta\phi\,\partial_\nu\delta\phi \;\sim\; \big(1+f(\text{large background})\big)(\partial\delta\phi)^2$$

- **typical examples:**
  - P(X) where $X=-(\partial\phi)^2/\Lambda^4$ (endowed with the shift symmetry)
  - galileons (endowed with Galilean symmetry + extra hidden symmetry)

Nicolis, Rattazzi & Trincherini   Hinterbichler & Joyce

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Vainshtein effect in massless P(X) theories

- **start** with a generic P(X) theory and use the background field method

- write the action in terms of the kinetic matrix

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

$$Z^{\mu\nu}[\phi_0] = 2P'(X)\delta^{\mu\nu} - \frac{4}{\Lambda^4}P''(X)\,\partial^\mu\phi_0\partial^\nu\phi_0$$

- symbolically, if $Z \gg 1$ then interactions are rather large and redress intuition from standard EFT rules

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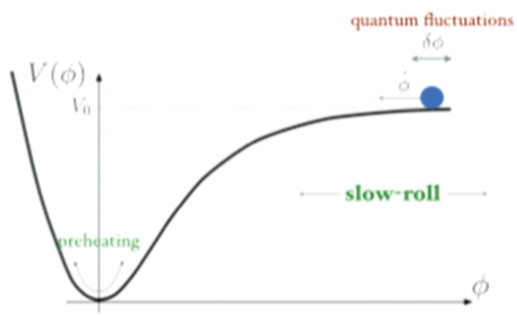
early universe

case study: DBI inflation



As the field rolls down the potential, it quantum-mechanically fluctuates.

Consider a homogeneous scalar field.

Silverstein & Tong
hep-th/0310221

Consider a specific class of P(X) models: Dirac—Born—Infeld [DBI] theories

$$\mathscr{L}_{\rm DBI} = \Lambda^4 P(X) = -\Lambda^4 \sqrt{1-X} + \Lambda^4 \qquad X = \frac{\dot\phi^2}{\Lambda^4}$$

In the strongly coupled regime, we have $|X| \lesssim 1$ and $\gamma \equiv \frac{1}{\sqrt{1-X}} \gtrsim 1$

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screening and superluminalities in P(X) theories

- the action for perturbations is

$$S^{(2)} = -\frac{1}{2} Z^{\mu\nu}\, \partial_\mu \delta\phi\, \partial_\nu \delta\phi$$

- focusing on the radial direction, we find

$$Z^{tt} \sim P_{,X}$$
$$Z^{rr} \sim P_{,X} + 2X\, P_{,XX}$$

- superluminalities can arise as a consequence of stability requirements

$$c_r^2 = 1 + 2X \frac{P_{,XX}}{P_{,X}} \quad \text{generically } > 1$$

for example, review by Joyce et al.

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screening in galileons

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

coupling the cubic galileon to **matter**:

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

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

Split the field into background + perturbation.

Consider spherically symmetric background solutions and compute the kinetic matrix.

$$Z^{\mu\nu}[\phi_0] \sim \delta^{\mu\nu} + \left(\frac{\Box\phi_0}{\Lambda^3}\delta^{\mu\nu} - \frac{\partial^\mu\partial^\nu\phi_0}{\Lambda^3} \right)$$

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superluminalities peekaboo

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

- there is a hierarchy between the different eigenvalues of Z:

$$c_r^2 \sim 1 + \frac{\phi_0'/r}{\Lambda^3}$$

- presence of superluminalities is tied to having effective screening:

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

- the effect is relevant for short-distance physics

$$r_\star \equiv \frac{1}{\Lambda}\left(\frac{M}{4\pi M_{\rm Pl}}\right)^{1/3}$$ divides between Newtonian and modified gravity is called the Vainshtein radius

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redressed strong coupling scale

case study: cubic galileon

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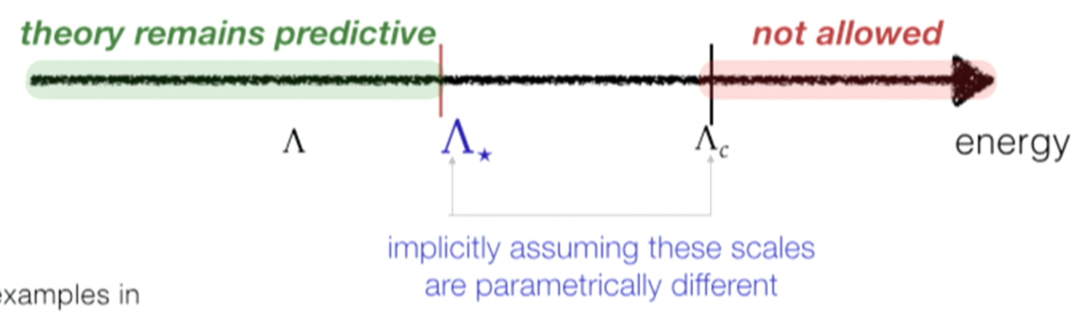
- if interactions are large, $\Box\phi \gg \Lambda^3$: $\Lambda_\star = \sqrt{Z}\Lambda \gg \Lambda$
- perturbative unitarity does not break at Λ, and we can use the EFT description beyond that scale



specific examples in
Aydemir et al. arXiv:1203.5153

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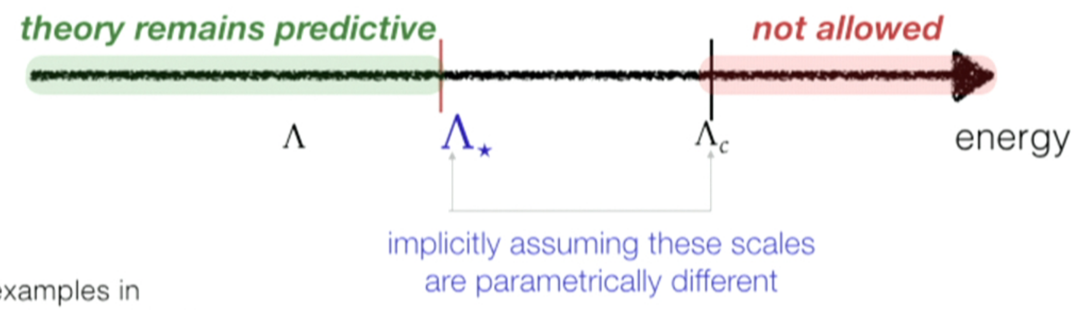

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2
aspects of quantum effects

are the irrelevant operators safe under quantum corrections?
&
usefulness of computing objects such as the one-loop effective action

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to get an insight on how quantum fluctuations affect the theory, we can use the one-loop effective action

$$e^{-\Gamma^{1\text{-loop}}[\phi]} = \int \mathscr{D}\left[\delta\phi\right] \, \exp^{-\frac{1}{2}\delta\phi\left(\frac{\delta^2 S_E[\phi]}{\delta\phi^2}\right)\delta\phi}$$

↓

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

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UV-divergences are organised as a Seeley—DeWitt expansion

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

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repackaging quantum corrections at 1-loop

cf. Burgess & London
hep-ph/9203216

- if we focus on log divergences and use dimensional regularisation

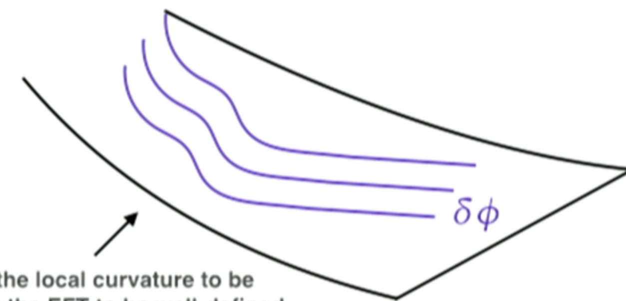
$$\Gamma^{\log}_{1-\text{loop}} \sim \int \mathrm{d}^4 x \, \sqrt{g_{\text{eff}}} \left\{ R^2 + 2 R_{\mu\nu} R^{\mu\nu} \right\}$$

generalisation of the Coleman—Weinberg potential

de Rham & RHR
arXiv:1405.5213

$$\sqrt{g_{\text{eff}}} \, |R^2[g_{\text{eff}}]| \ll \Lambda^4 \, P(X)$$

original Lagrangian



want the local curvature to be small for the EFT to be well-defined

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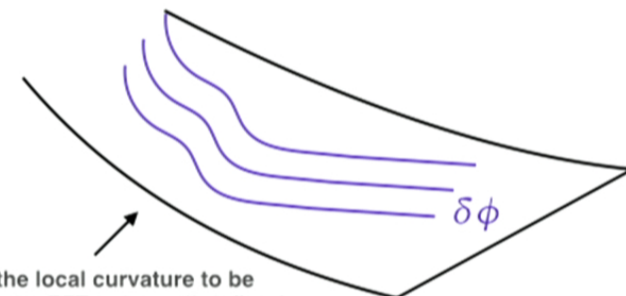

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early universe

DBI inflation: theory and data constraints

de Rham & RHR
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$$\mathscr{L}_{\rm DBI} = -\Lambda^4\sqrt{1-X} + \Lambda^4 \simeq \frac{1}{2}\dot{\phi}^2 + \frac{1}{8}\frac{\dot{\phi}^4}{\Lambda^4} + \cdots$$

popular statement in the literature: in DBI the speed of the field is allowed to be large provided the acceleration is small

Can we be a bit more precise?

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$$|\mathscr{L}_{\rm classical}| \gg |\mathscr{L}_{1-\rm loop}| \longrightarrow \frac{\ddot{\phi}_0}{\Lambda^3} \ll \gamma^{-3} \sim \mathcal{O}(10^{-3})$$

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late universe

kinetic/Vainshtein screening

Vainshtein PLB39 (1972)
Babichev & Deffayet arXiv:1304.7240
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- *the induced operators generate **ghosts***
- *consider the example* $\mathscr{L} = -\frac{1}{2}(\partial\phi)^2 + \frac{\lambda}{\Lambda^4}(\partial\phi)^4$

© *Alice in Quantumland* by Robert Gilmore

de Rham & RHR
arXiv:1405.5213

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coupling to high-energy sectors

Consider a two-field model $\mathscr{L}_{2-\text{field}} = \Lambda^4 P(X) - \frac{1}{2}(\partial\chi)^2 - \frac{1}{2}M^2\chi^2 - \frac{g}{2\Lambda^2}(\partial\phi)^2\chi^2$

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If we focus on the log divergences, we find overwhelming sensitivity to new physics (recall that **$M \sim \Lambda_c$**):

$$\mathscr{L}^{1-\text{loop}}_{\log} = -\frac{g}{8\Lambda^2}\left\{M^2(\partial\phi)^2 + g\frac{(\partial\phi)^4}{\Lambda^2}\right\}\log\left(\frac{k^2+M^2}{\mu^2}\right)$$

- *one-loop corrections **correct** the classical operators*

"If no mistake have you made, yet losing you are… a different game you should play"
Master Yoda

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insight through ERG methods

de Rham & RHR
arXiv:1405.5213

- *the main tool is the Wetterich equation:*

$$\frac{\partial P_\kappa(X)}{\partial \kappa} = \frac{1}{2}\mathrm{Tr}\left[\frac{\partial_\kappa R_\kappa}{R_\kappa + Z_\kappa^{\mu\nu}\partial_\mu\partial_\nu}\right] \quad \text{with} \quad R_\kappa = \mathscr{Z}_\kappa(\kappa^2 + \Box)\,\Theta(\Box + \kappa^2)$$

Litim hep-th/0005245

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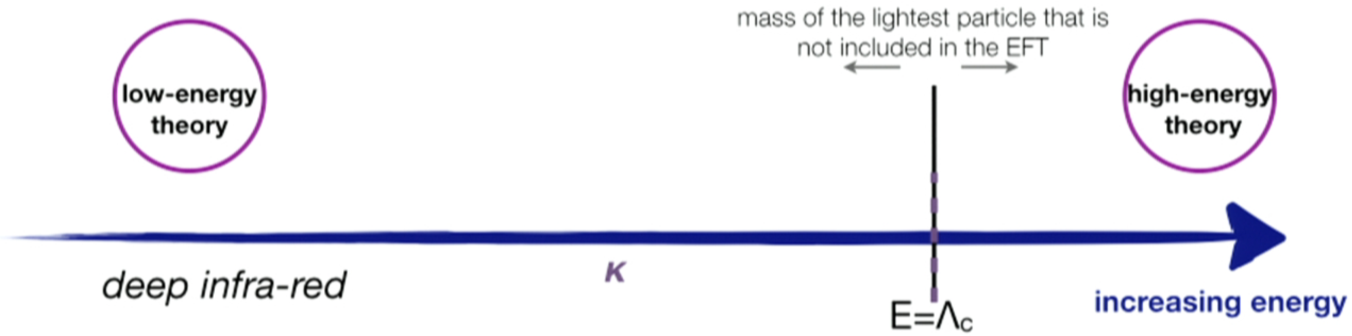

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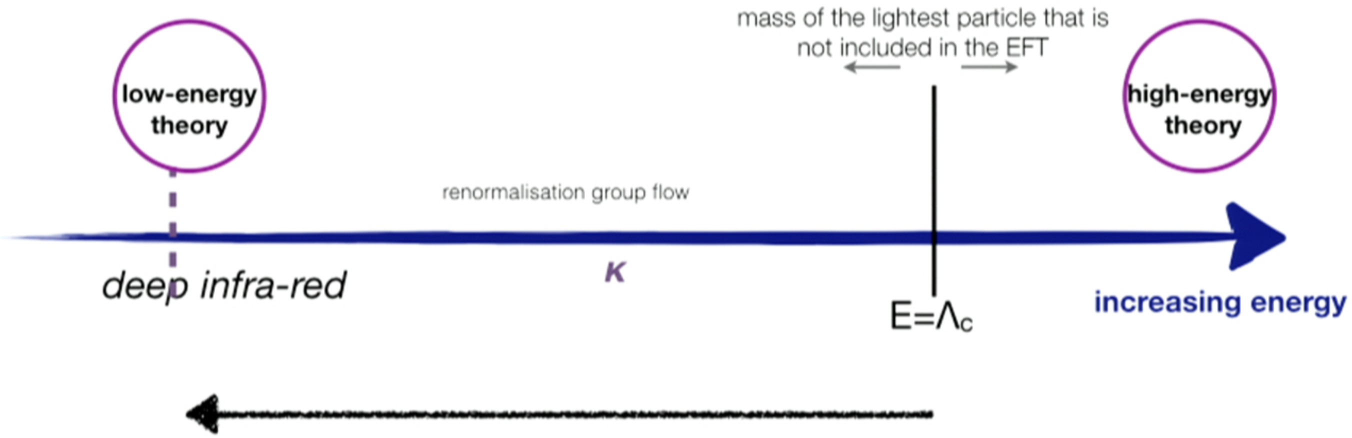

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arXiv:1405.5213

- not all the regimes are understood though

- estimates deep inside the Vainhstein radius based on the exact renormalisation group indicate the worst divergence appears as

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- **suggests UV sensitivity can be ameliorated by a quantum-mechanical analogue of the Vainshtein screening**

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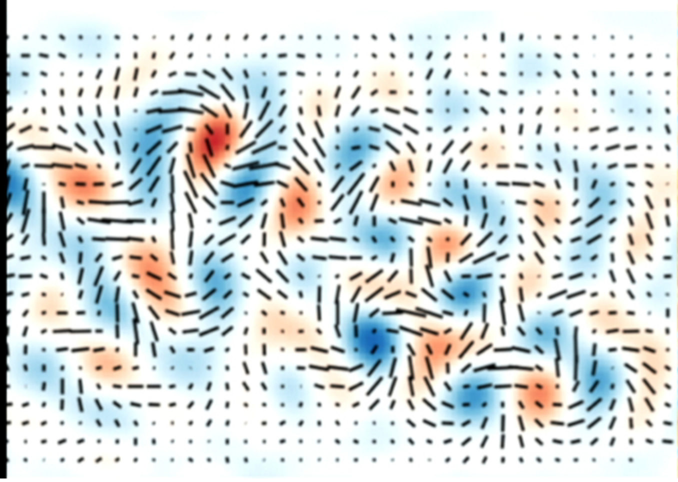
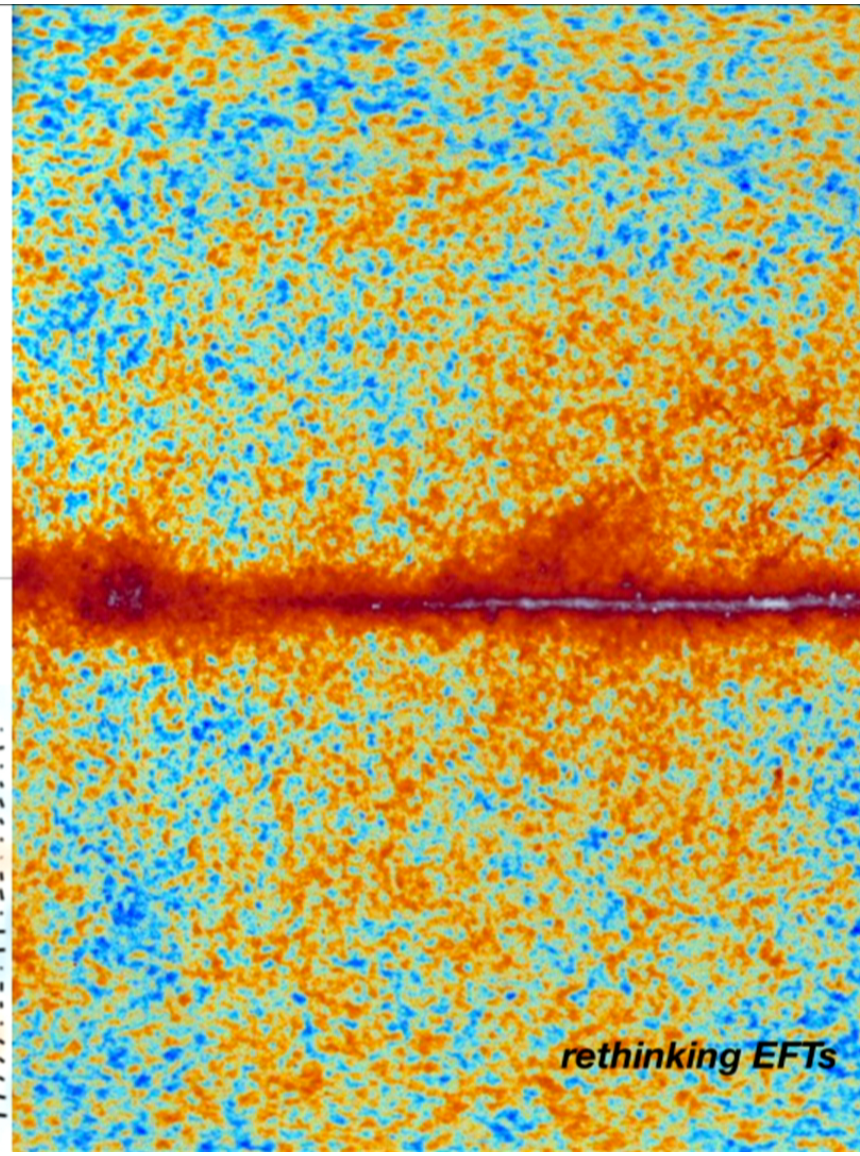
3

a curious case in cosmology





cosmological perturbation theory

remaining agnostic about the background

- the EFT of ζ contains the following cubic interactions

$$S_\zeta^{(3)} = \int \mathrm{d}^3x\,\mathrm{d}t\,a^3\left\{\Lambda_1\dot{\zeta}^3 + \Lambda_2\zeta\dot{\zeta}^2 + \frac{\Lambda_3}{a^2}\zeta(\partial_i\zeta)^2 \;\; + \Lambda_4\dot{\zeta}\partial_i\zeta\partial^i\partial^{-2}\dot{\zeta} + \Lambda_5\partial^2\zeta(\partial_i\partial^{-2}\dot{\zeta})^2\right\} + S_{\text{boundary}}$$

- to next-order in slow-roll, the EFT in π is

$$S_\pi^{(3)} = \int \mathrm{d}^3x\,\mathrm{d}t\,a^3\left\{C_1\dot{\pi}^3 + \frac{C_2}{a^2}\dot{\pi}(\partial_i\pi)^2 + C_3\pi\dot{\pi}^2 + \frac{C_4}{a^2}\pi(\partial_i\pi)^2 + C_5\dot{\pi}\partial_i\pi\partial^i\partial^{-2}\dot{\pi}\right\} + S_{\text{boundary}}$$

traditional rules of low-energy EFT: *identify the low energy dof and write down all the local operators which are compatible with the underlying symmetries*

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- to next-order in slow-roll, the EFT in π is

$$S_\pi^{(3)} = \int \mathrm{d}^3x\,\mathrm{d}t\,a^3 \left\{ C_1 \dot\pi^3 + \frac{C_2}{a^2}\dot\pi(\partial_i\pi)^2 + C_3 \pi\dot\pi^2 + \frac{C_4}{a^2}\pi(\partial_i\pi)^2 + C_5 \dot\pi \partial_i \pi \partial^i \partial^{-2}\dot\pi \right\} + S_{\text{boundary}}$$

traditional rules of low-energy EFT: *identify the low energy dof and write down all the local operators which are compatible with the underlying symmetries*

Raquel H Ribeiro

looking closer—where do ∂^{-2} come from?

- in ADM variables, the metric is

$$ds^2 = -N^2 dt^2 + h_{ij}\,(dx^i + N^i\,dt)\,(dx^j + N^j\,dt)$$

- when we solve for the lapse and the shift we introduce some hints at non-locality

$$N = 1 + \frac{\dot{\zeta}}{H} + \cdots \qquad N_i = \partial_i\left(-\frac{\zeta}{H} + \frac{a^2\,\Sigma(\text{bckg})}{H^2}\,\partial^{-2}\dot{\zeta}\right)$$

- plugging into the action generates those non-local-looking operators

the trouble appears because these EFTs are fundamentally gravitational

causality is not violated

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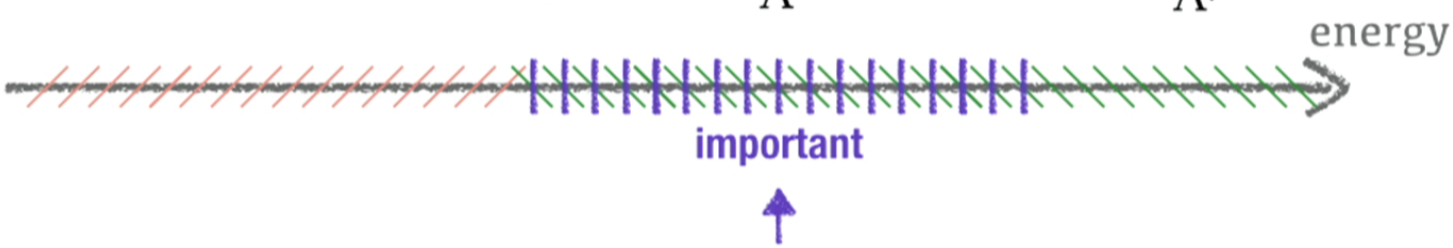
EFTs with active Vainshtein screening

Consider a field theory with at most 2nd order derivatives acting on the fields

relevant | irrelevant

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



reorganised EFT built on a hierarchy between (different orders in) derivatives

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

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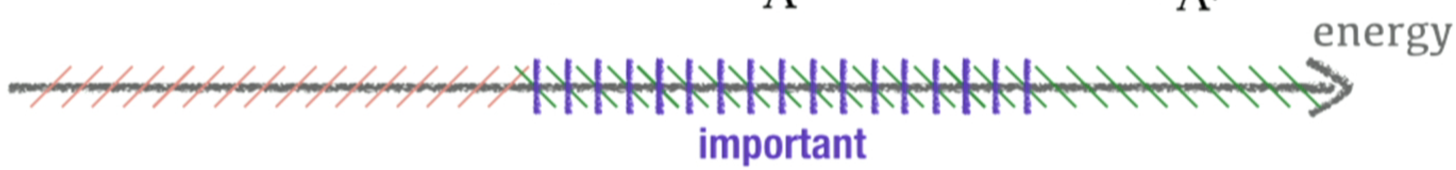

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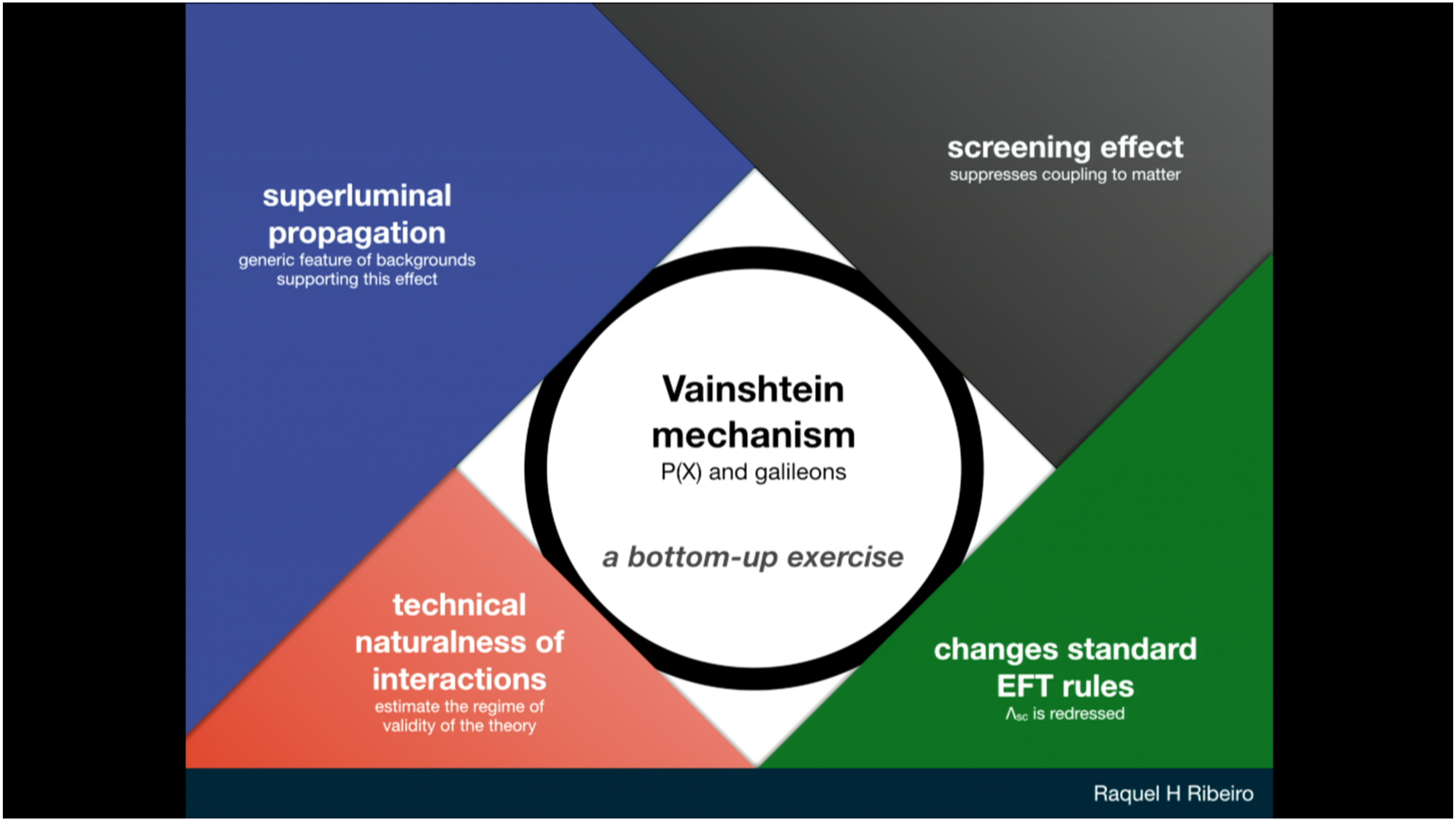
superluminal propagation
generic feature of backgrounds supporting this effect
screening effect
suppresses coupling to matter
Vainshtein mechanism
P(X) and galileons
a bottom-up exercise
technical naturalness of interactions
estimate the regime of validity of the theory
changes standard EFT rules
Λsc is redressed
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