Unitarity and the Vainshtein Mechanism

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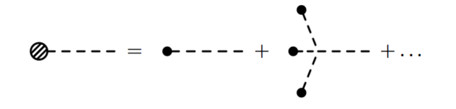
- Robustness of GR $\longrightarrow$ modifications of gravity require new propagating degrees of freedom
- Solar system tests $\longrightarrow$ new degrees of freedom must be screened
- Screening mechanisms are best understood by studying the scalar fluctuations φ
- At quadratic order

$$\delta\mathcal{L} = -\frac{1}{2}Z^{\mu\nu}[\bar{\varphi}]\partial_\mu\delta\varphi\partial_\nu\delta\varphi - \frac{1}{2}M^2[\bar{\varphi}]\delta\varphi^2 + \frac{1}{M_{pl}}\delta\varphi\delta T$$

- Vainshtein screening is realised in the full theory by irrelevant operators suppressed by a scale $\Lambda \ll M_{pl}$

$$\mathcal{L} \sim (\partial\phi)^2 + \frac{(\partial\phi)^2\Box\phi}{\Lambda^3} + \frac{(\partial\phi)^4}{\Lambda^4} + \ldots$$

- Breakdown of classical perturbation theory at r_V



- Perturbative unitarity breaks down at $\Lambda \longrightarrow$ restore unitarity with new heavy degrees of freedom

- Is there a way to trust the theory beyond Λ? $\longrightarrow \Lambda_{env} \sim Z^n\Lambda$

$$\delta\mathcal{L} = -\frac{1}{2}(\partial\delta\varphi)^2 + \frac{(\partial\delta\varphi)^2\Box\delta\varphi}{Z^{\frac{3}{2}}\Lambda^3}$$

- Consider massive gravity *(de Rham, Gabadadze, Tolley, 2011)*

$$\Lambda_3 \sim (m^2 M_{pl})^{\frac{1}{3}} \sim 1/(1000km)$$

- In the presence of an environment with Vainshtein screening (*Burrage, Kaloper, Padilla, 2013)*

$$\Lambda_{env} \sim \frac{1}{m}\left(\frac{m}{H_0}\right)^{1/6}$$

- Including environmental effects $\longrightarrow$ increases strong coupling scale by orders of magnitude

- *Can we really trust the classical dynamics to distance scales* $\sim 1/\Lambda_{env}$*?*

- Consider a UV complete theory

$$\mathcal{L} \sim (\partial\rho)^2 + \rho^2(\partial\alpha)^2 - \lambda(\rho^2 - \eta^2)^2$$

- Massive field, $M^2 = \lambda\eta^2$, and a massless goldstone boson
- Integrating out the heavy mode $\longrightarrow$ tower of irrelevant operators for the phase, α

$$\mathcal{L} \sim \eta^2 \left[(\partial\alpha)^2 + \frac{(\partial\alpha)^4}{M^2} + \mathcal{O}\left(\frac{\partial^6}{M^4}\right) \right]$$

- In the truncated theory loops become important at $\Lambda \sim \lambda^{1/4}\eta$

- Common Vainshtein mechanism is incompatible with a positive co efficient for the $(\partial\alpha)^4$ term

$$\mathcal{L} \sim (\partial\alpha)^2 - (\partial\alpha)^4 \longrightarrow \text{accomodates usual Vainshtein}$$

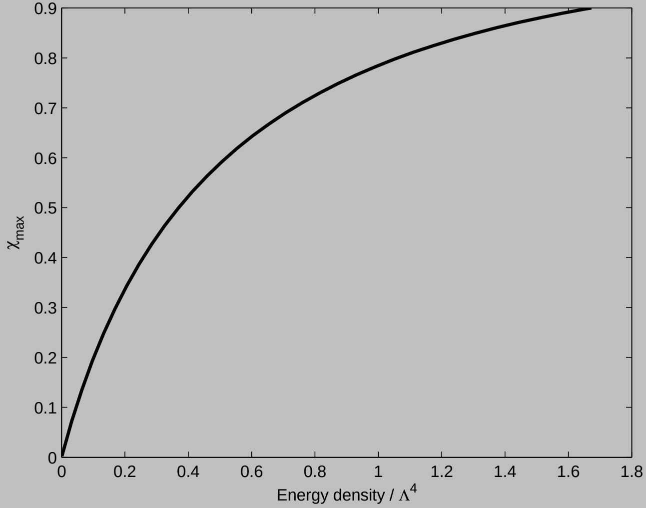
- Negative coefficient in the low energy EFT $\longrightarrow$ unstable UV theory *(A. Adams et al., 2006)*
- Vainshtein mechanism is just large Z factors!
- Solution: use time dependence!

- Excite the phase from its trivial vacuum to one of constant energy density, $\mathcal{E} > 0$

$$\mathcal{E} = \eta^2 \left(\dot{\alpha}^2 + \frac{3}{4M^2} \dot{\alpha}^4 \right)$$

- For which values of $\mathcal{E}$ is the truncation valid?
- Compare classical dynamics for a range of $\mathcal{E}$ using

$$\chi = \left| \frac{\dot{\alpha}_{UV} - \dot{\alpha}_{IR}}{\dot{\alpha}_{UV} + \dot{\alpha}_{IR}} \right|$$



0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
χmax
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Energy density / Λ4

Conclusion

- Vainshtein screening $\longrightarrow$ very low cut off!
- Modified gravities will be strongly affected by new operators somewhere between r_V and Λ
- True cut off for massive gravity $\Lambda \sim 1/1000km$
- Calculations inside $1/\Lambda$ can't be trusted
- For the example considered we require operators of the form *(Burgess, Williams, 2014)*

$$\frac{\partial^6}{M^4} \sim \frac{c}{M^4} \partial_\sigma \phi \partial^\nu \phi \partial_\mu \partial_\nu \phi \partial^\mu \partial^\sigma \phi$$

- Similar results apply to a low energy theory completed into a SU(2) Higgs model