Beyond the Standard Model of cosmology

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The Standard Model: ΛCDM

We are in a somewhat strange time for cosmology

- All observational data is consistent with a simple phenomenological model

- But, at the same time, there are serious fundamental questions:
  - We don't know what Λ is
  - We don't know what the CDM is

- In fact, for the Λ part, it is even worse, we expect that it should be massively larger than its measured value
  - This is a problem of *naturalness*

Like the hierarchy problem

The situation in cosmology is somewhat analogous to the situation in particle physics

- The SM is consistent with all observed phenomena, and there are no clear energy scales to aim for

- One of the main motivators of BSM model-building is the Weak hierarchy problem — which is also one of naturalness

- The CC problem is actually *worse* though, the hierarchy problem is due to *new* particles posited to exist beyond the Weak scale. The CC is radiatively unstable accounting *only* for known particles

Overview

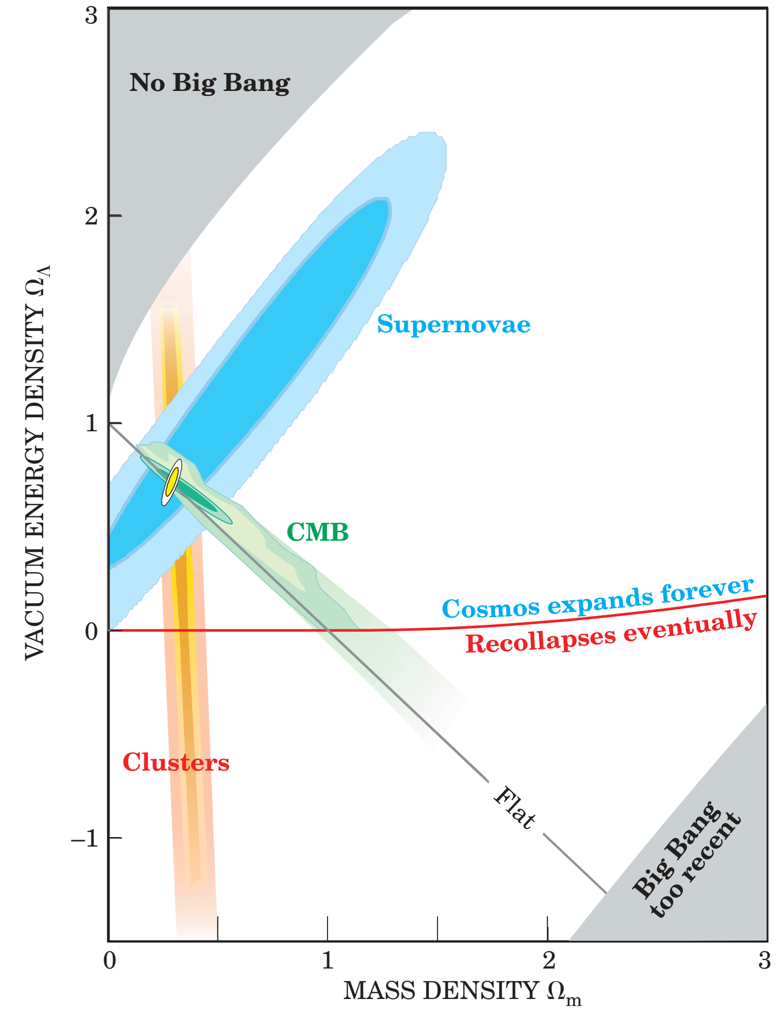
I will use the Cosmological Constant problem as motivation to explore "BSM" physics in the gravitational sector

- Problem & approaches (*un*like the hierarchy problem, the CC problem has no satisfactory solutions)
- I will focus particularly on the notion of introducing new degrees of freedom which interact with gravitational strength — often called modified gravity
- Often times these theories are interesting and worth thinking about on their own, divorced from the CC motivation
    - Does anything go? No! In addition to phenomenological constraints, I will discuss severe theoretical restrictions
- Goes towards the program of testing gravity on a variety of scales and in a variety of situations (huge extrapolation of scales to cosmological distances)

Most of what I will say can be found in:

AJ, Jain, Khoury, Trodden 1407.0059, *Physics Reports* (2015)

Cosmic acceleration



Perlmutter, *Physics Today* 2003

- On the largest scales, we can describe the universe as nearly homogeneous and isotropic, the geometry is well-approximated by

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a(t)^2 \mathrm{d}\vec{x}^2$$

- Background evolution is governed by the Friedmann equations (assuming a perfect fluid drives things)

$$3H^2 = \rho \qquad\qquad 3H^2 + 2\dot{H} = -P$$

- CMB, SN and LSS measurements indicate that the background expansion rate is increasing $(\ddot{a} > 0)$

- Requires component with $w < -1/3$. In fact, all the data is well-fit by something with $w = -1$ (CC) with $\Lambda_{\rm observed} \sim (\mathrm{meV})^4$

Theoretical expectation: Λ

- Estimate the contribution to the CC from SM fields: $\langle T_{\mu\nu}\rangle \sim -\langle\rho\rangle g_{\mu\nu}$

$$\langle\rho\rangle = \int_0^{\Lambda_{\mathrm{UV}}} \frac{\mathrm{d}^3k}{(2\pi)^3}\frac{1}{2}\hbar E_k \sim \int_0^{\Lambda_{\mathrm{UV}}} \mathrm{d}k\ k^2\sqrt{k^2+m^2} \sim \Lambda_{\mathrm{UV}}^4 + m^2\Lambda_{\mathrm{UV}}^2 - \frac{m^4}{2}\log\frac{\Lambda_{\mathrm{UV}}}{m}$$

- Let's be as conservative as possible: consider the logarithmic divergence — the contribution from the electron alone, leads to

$$\Lambda_{\mathrm{theory}} \sim (10^8\ \mathrm{meV})^4$$

- This is embarrassingly discrepant with the observed value already. Trusting things up to the Planck scale reproduces the famous factor of 10^{120}

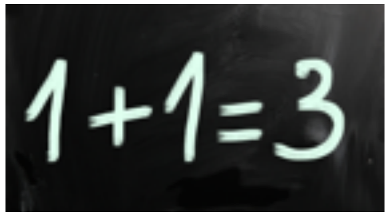
- The fact that this is a small number is not inherently a problem; the problem is that it is radiatively unstable (*e.g.*, we do not care the electron mass is small)

- This is a problem of naturalness, the value of the Cosmological Constant is extremely sensitive to the addition of new heavy states

Approaches to understanding this problem

- Maybe naturalness is not a good criterion; maybe things just happen to be tuned.

- Possibly we are calculating something incorrectly — something wrong with our understanding of QFT in curved space?



- Maybe the CC is selected from some distribution and is small for essentially anthropic reasons — larger values of CC would not allow structures to form. Relies on many assumptions

- New physics/new degrees of freedom in the gravitational sector?

The first thing you should try

- Maybe the cosmological constant is actually a field and some mechanism causes it to dynamically relax to a small value; or a conspiracy of field potentials causes the CC to be very small

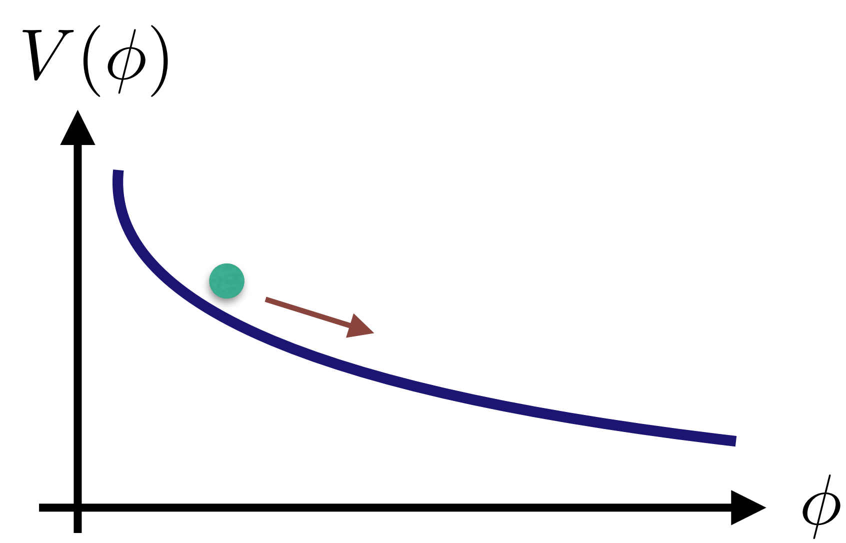
  Weinberg: Assume

  - Einstein gravity
  - $\phi_I = \text{const.} \qquad g_{\mu\nu} = \eta_{\mu\nu}$

  Then, this will always require fine tuning.

- Moving slightly away from this, you could imagine that the CC is still evolving

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) \qquad \Longrightarrow \qquad w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$



- This still suffers from roughly the same problems — still have to explain the overall scale of the potential *along with* its flatness

New degrees of freedom

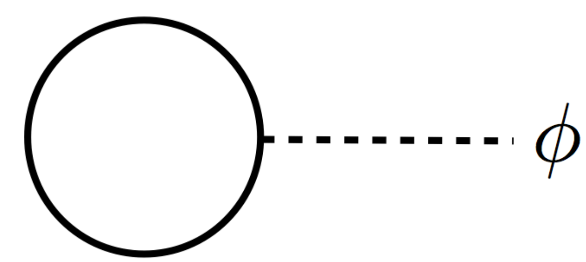
- Why? Einstein gravity is remarkably robust: it is the unique theory of a massless spin-2 field Papapetrou 1948; Gupta 1952; Kraichnan 1955; Feyman 1962; Weinberg 1965; Deser 1970

- Therefore, modifications to Einstein gravity almost ubiquitously introduce *new* degrees of freedom — we will see that doing this consistently is *hard*

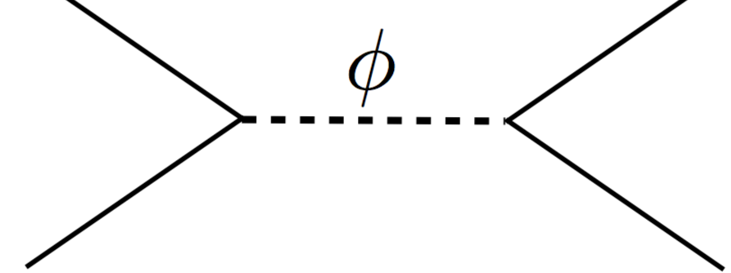
- In order for these new DOF to affect the present day CC, they must have a mass of order Hubble today

$$m \sim H_0$$

- To neutralize the CC, must couple to SM fields

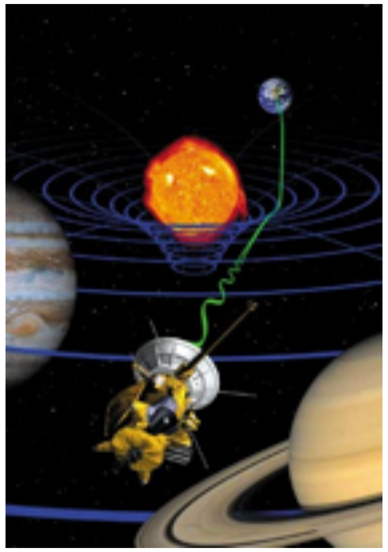


- Then, unitarity implies that they mediate a force: $\Longrightarrow$



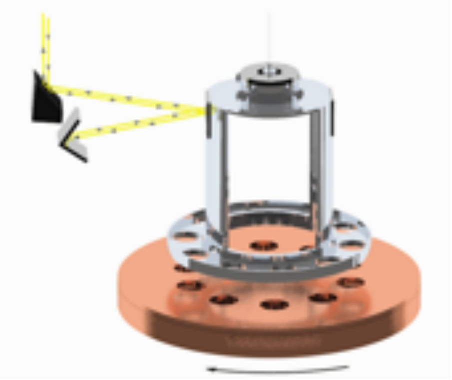
Screening

- Gravity is *extremely* well-tested in the lab & solar system
- No deviations from Einstein gravity — extra degrees of freedom must hide themselves in some way
- Ways in which this can be accomplished are called *screening mechanisms*
- Could also just choose to couple very weakly to everything (dark energy)



Cassini (Shapiro time delay)

APOLLO (Nordtvedt effect)



Eöt-Wash (Inverse square law)

How can forces be suppressed?

Consider a scalar field with a general action

$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, \partial\phi, \ldots)\partial_\mu\phi\partial_\nu\phi - V(\phi) + g(\phi)T^\mu_\mu$$

- The potential between two localized sources from $\phi = \bar{\phi} + \varphi$ is

$$V(r) \sim -\frac{g^2(\bar{\phi})}{Z(\bar{\phi})c_s(\bar{\phi})} \frac{\mathcal{M}e^{-m(\bar{\phi})r}}{r}$$

key is that the various quantities appearing here are *background dependent*

- Can suppress the force by making $m(\bar{\phi})$ *environmentally* large: Chameleon

- Also possible to make $g(\bar{\phi})$ environmentally small: symmetron

- Can also make $Z(\bar{\phi})$ environmentally large: kinetic/Vainshtein

A more phenomenological classification

We can group things in a different way:

- Screening by field nonlinearities:

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - M^4 V(\phi/M) + \frac{g\phi}{M_{\rm Pl}}T$$

when $\phi \gg M$ non-linearities in the potential and matter coupling can become important and suppress the force. Can also use $\Phi \gg \Phi_{\rm c}$

Heuristically, these mechanisms operate in regions of high Newtonian potential. Examples:

- Chameleon mechanism — Khoury, Weltman astro-ph/0309300
- Symmetron mechanism — Hinterbichler, Khoury 1001.4525
- Environmentally-dependent dilaton — Damour Polyakov hep-th/9401069; Brax, van de Bruck, Davis, Shaw 1005.3735

A more phenomenological classification

We can group things in a different way:

- Screening by large first derivatives

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{4\Lambda_{\rm s}^4}(\partial\phi)^4 + \frac{g\phi}{M_{\rm Pl}}T$$

when $\partial\phi \gg \Lambda_{\rm s}^2$ non-linearities in the derivative self-coupling can suppress the force. Can also use $\nabla\Phi > \Lambda^2$

Heuristically, these mechanisms operate in regions of large *acceleration*

- K-mouflage — Babichev, Deffayet, Ziour 0905.2943
- (D)BIonic screening — Burrage, Khoury 1403.6120

A more phenomenological classification

We can group things in a different way:

- Screening by large second derivatives

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda_s^3}\Box\phi(\partial\phi)^2 + \frac{g\phi}{M_{\rm Pl}}T$$

when $\partial\phi^2 \gg \Lambda_s^3$ non-linearities in the derivative self-coupling can suppress the force. Can also use $\nabla^2\Phi > \Lambda^3$

Heuristically, this mechanism operates in regions of large *curvature*

- Vainshtein — Vainshtein 1972; Deffayet, Dvali, Gabadadze, Vainshtein hep-th/0106001

- Most familiar in galileon theories — Luty, Porrati, Rattazzi hep-th/0303116
  Nicolis, Rattazzi hep-th/0404159
  Nicolis, Rattazzi, Trincherini 0811.2197

Guiding principles

When constructing models of new gravitational physics, constraints of theoretical consistency end up being extremely powerful

- The most convenient language to describe new physics is as effective field theories (this mode of thinking is beginning to pervade all of cosmology)

- Organizing principle here is simple: identify the degrees of freedom of interest, specify the symmetries and then write down all possible terms consistent with these specifications

- In order for this to be useful, there must be an expansion in some small parameter (typically in powers of $E/M \ll 1$) so that to a given level of precision we only need to keep track of a finite number of terms.

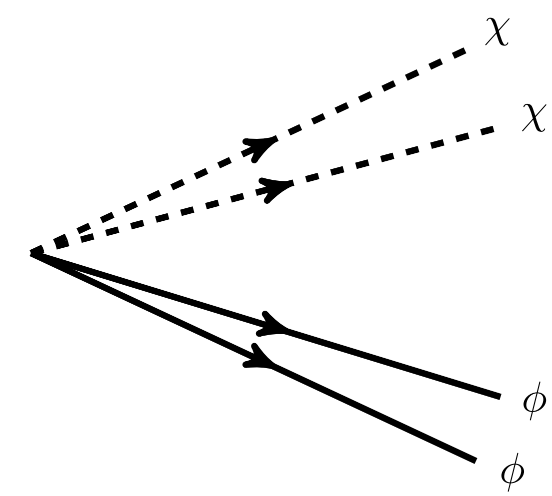
- If we try to describe physics near M, we need an infinite number of terms, and the EFT *breaks down,* signals DOF we have not tracked are becoming important

Theoretical consistency

Beyond having a well-defined power-counting expansion, there are other constraints on low-energy EFTs:

- Probably the most common (and most dangerous!) is the presence of ghosts - fields with wrong-sign kinetic terms

$$\mathcal{L} = \frac{1}{2}(\partial\chi)^2 - \frac{m^2}{2}\chi^2$$



these fields have *negative* kinetic energy — allows the vacuum to spontaneously decay

- Ghosts often arise from higher-derivative terms in the action. Example:

$$\mathcal{L} = -\frac{1}{2}(\partial\psi)^2 + \frac{1}{2\Lambda^2}(\Box\psi)^2 - V(\psi)$$

can introduce an auxiliary field to write this as

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\chi)^2 - \frac{\Lambda^2}{2}\chi^2 - V(\phi,\chi)$$

- In practice, most of the time demanding second-order equations of motion is enough keep ghosts from arising

Theoretical consistency

Having a ghost in the low-energy theory makes it not predictive. Other pathologies we do not want:

- Gradient instabilities; if the spatial gradient terms have wrong sign:

$$\mathcal{L} = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\vec{\nabla}\phi)^2$$

the free mode functions will be exponentially growing $\phi_k(t) \sim e^{\pm kt}$

- Tachyonic instabilities; fields with wrong sign mass terms

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 + \frac{m^2}{2}\phi^2$$

also have growing modes of the form $\phi(t) \sim e^{\pm mt}$ but these can be made sense of if we restrict to modes with $k \gg m^{-1}$

Vainshtein mechanism: galileons

Let's see in detail how large derivatives can screen fifth forces

- One particularly well-motivated example which has attracted a lot of recent attention - the galileon

- First appeared in a certain limit of the Dvali-Gabadadze-Porrati model

Dvali, Gabadadze, Porrati hep-th/0005016

Goon, Hinterbichler, Trodden1103.5745

$$S = M_5^3 \int \mathrm{d}^5 X \sqrt{-G} R_5 + M_{\rm Pl}^2 \int \mathrm{d}^4 x \sqrt{-g} R$$

- In an appropriate limit, the theory is well described by the scalar-tensor theory

Luty, Porrati, Rattazzi hep-th/0303116
Nicolis, Rattazzi hep-th/0404159

$$\Lambda \equiv \frac{M_5^3}{M_{\rm Pl}^2}$$

$$S = \int \mathrm{d}^4 x \frac{1}{4} h^{\mu\nu} \mathcal{E}^{\alpha\beta}_{\mu\nu} h_{\alpha\beta} - 3(\partial\phi)^2 - \frac{1}{\Lambda^3} \Box\phi (\partial\phi)^2$$

Galileons

This effective action has two interesting properties:

- Invariance under the shift symmetry $\phi \mapsto \phi + c + b_\mu x^\mu$
- Second-order equations of motion (despite higher derivatives in the action) - *no ghost in the theory*

Are there any other terms with these two properties? Yes

Nicolis, Rattazzi, Trincherini 0811.2197

- In *d* dimensions, there are *only* (*d*+1) terms with these properties

$$\mathcal{L}_n \sim \epsilon_{\mu_1 \cdots \mu_{n-1} \alpha_n \cdots \alpha_d} \epsilon^{\nu_1 \cdots \nu_{n-1} \alpha_n \cdots \alpha_d} \phi \partial_{\nu_1} \partial^{\mu_1} \phi \cdots \partial_{\nu_{n-1}} \partial^{\mu_{n-1}} \phi$$

in *d* = 4, they take the form

$$\mathcal{L}_2 \sim (\partial\phi)^2 \qquad \mathcal{L}_3 \sim (\partial\phi)^2 \Box\phi \qquad \mathcal{L}_4 \sim (\partial\phi)^2((\Box\phi)^2 - (\partial_\mu\partial_\nu\phi)^2)$$

$$\mathcal{L}_1 \sim \phi \qquad \mathcal{L}_5 \sim (\partial\phi)^2 \left((\Box\phi)^3 + 2(\partial_\mu\partial_\nu\phi)^3 - 3\Box\phi(\partial_\mu\partial_\nu\phi)^2\right)$$

Galileons

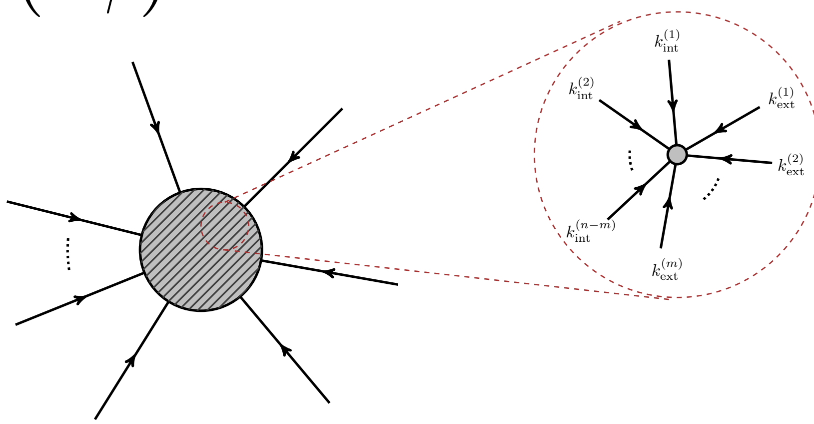
Galileons have many interesting properties:

- The (*n*+1)th galileon is the EOM of the *n*th term times $(\partial\phi)^2$

  Fairlie, Govaerts, Morozov hep-th/9110022

- They are not renormalized to any loop order

  Luty, Porrati, Rattazzi hep-th/0303116
  Hinterbichler, Trodden, Wesley 1008.1305

$\Gamma^{(n)} \sim$ 

- They appear as Wess-Zumino terms for broken spacetime symmetries - cohomologically nontrivial Goon, Hinterbichler, AJ, Trodden 1203.3191

- Can become classically non-linear without EFT breaking down — essence of the Vainshtein mechanism

- Admit an interesting duality that maps one galileon theory to one with different coefficients de Rham, Fasiello, Tolley 1308.2702

- Have been generalized in countless ways and applied to all corners of cosmology — inflation, solitons, NEC violation… has become a sort of "catch-all" phrase for derivatively coupled theories

Aside — higher shift symmetries

Hinterbichler, AJ 1404.4047

The galileon is invariant under the space time shift symmetry

$$\phi \longmapsto \phi + c + b_\mu x^\mu$$

A question you may want to ask: *can this be extended to higher order polynomials?*

$$\phi \longmapsto \phi + c^{(0)} + c^{(1)}_{\mu} x^\mu + c^{(2)}_{\mu\nu} x^\mu x^\nu + \cdots + c^{(N)}_{\mu_1\cdots\mu_N} x^{\mu_1}\cdots x^{\mu_N}$$

- Yes! It is possible to find the analogues of galileons for these extended shifts
- May be relevant for the study of higher-spin fields (galileon appears in spin-2)
- In condensed-matter contexts, symmetries of this type can stabilize exotic dispersion relations

$$\omega^2(\vec{k}) \sim a_2 \vec{k}^2 + a_4 \vec{k}^4 + \cdots$$

- Example, quadratic shift symmetry, 3 fields:

$$\mathcal{L}_3 \sim \epsilon_{i_1 i_2 k_3 \cdots k_D} \epsilon^{j_1 j_2 k_3 \cdots k_D} \nabla^2\phi \nabla_{j_1}\nabla^{i_1}\nabla_l \phi \nabla_{j_2}\nabla^{i_2}\nabla^l \phi$$

- For a special choice of parameters, the galileon actually has a quadratic shift symmetry of this type   Hinterbichler, AJ 1501.07600

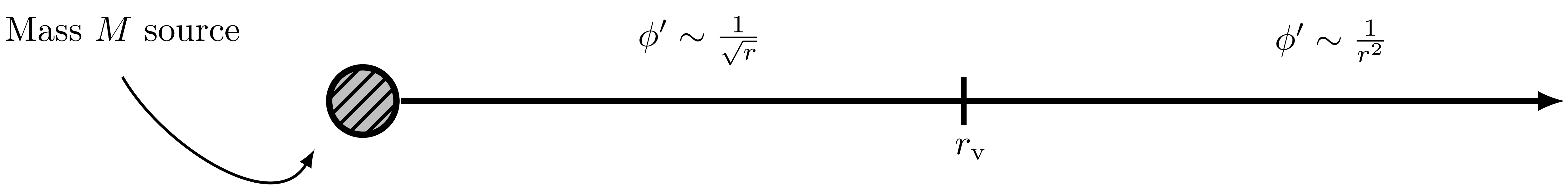
Screening in galileon theories

Let's consider the cubic galileon around a heavy source

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda^3}\Box\phi(\partial\phi)^2 - \frac{gM}{M_{\rm Pl}}\delta^{(3)}(x)$$

- There is a characteristic length scale where the interaction becomes important — the Vainshtein radius

$$r_{\rm V} \equiv \frac{1}{\Lambda}\left(\frac{gM}{M_{\rm Pl}}\right)^{1/3}$$



- Far from the source, the field has the normal Coulomb profile: $\phi' \sim \dfrac{1}{r^2}$
- However inside r_V the field profile goes as $\phi' \sim \dfrac{1}{\sqrt{r}}$

so that the force due to the galileon relative to that from gravity scales as

$$\left.\frac{F_\phi}{F_{\rm gravity}}\right|_{r \ll r_{\rm V}} \sim \left(\frac{r}{r_{\rm V}}\right)^{3/2} \ll 1$$

Galileon screening cont.

This is really a kinetic effect, to see this, expand $\phi = \bar{\phi} + \varphi$

$$\mathcal{L} = -\frac{1}{2} Z(\bar{\phi})^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi + \cdots + \frac{g\varphi}{M_{\rm Pl}} T$$

- Upon canonically-normalizing the field $\hat{\varphi} = \sqrt{Z}\varphi$

$$\mathcal{L} = -\frac{1}{2}(\partial\hat{\varphi})^2 + \cdots + \frac{g\hat{\varphi}}{\sqrt{Z} M_{\rm Pl}} T$$

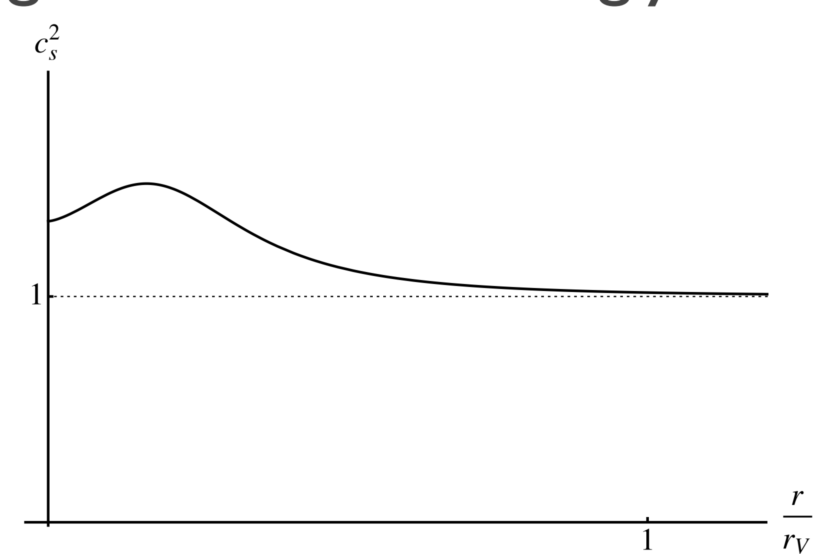
  we see that the "effective" coupling to matter is

$$\hat{g} \equiv \frac{g}{\sqrt{Z}}$$

- Around backgrounds where Z is large, the coupling to matter is strongly suppressed — another way to see screening

- A peculiarity: radial perturbations are superluminal

  (See Garrett's talk!)



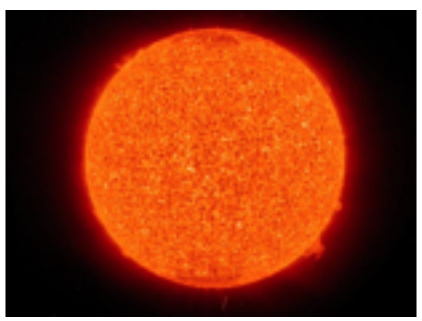
Vainshtein screening is very efficient

In order for the galileon to be relevant at cosmological scales, we must set

$$r_c \sim (\Lambda^{-3} M_{\rm Pl})^{1/2} \sim H_0^{-1}$$

this sets $\Lambda \sim 10^{-13}\ \text{eV} \sim 10^{7}\ \text{m}$

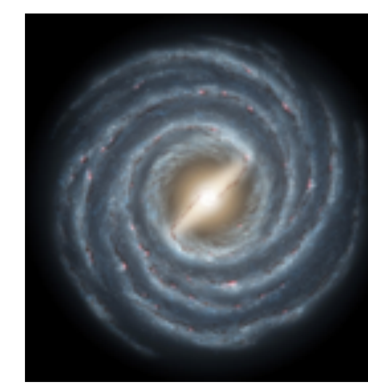
- Then, the Vainshtein radii of various objects are $\quad r_{\rm V} \equiv \frac{1}{\Lambda}\left(\frac{gM}{M_{\rm Pl}}\right)^{1/3}$



Sun

$$r_{\rm V} \sim 10^{19}\ \text{m} \sim .5\ \text{kpc}$$

$$r_{\rm V} \sim 10^{23}\ \text{m} \sim 10\ \text{Mpc}$$



Milky Way

- So, it is a bit of a challenge to find astrophysical objects that *aren't* screened

Massive gravity

In order to apply galileon theories to cosmology, we must covariantize, there are morally two approaches to this

- Standard minimal covariantization - this is actually ambiguous, non-minimal couplings required, leads to Horndeski theories

  Horndeski 1974
  Deffayet, Deser, Esposito-Farese 0906.1967

- Galileons appear naturally as the helicity 0 mode of a massive graviton

- Quite surprisingly, for a very long time it was not known how to write down a nonlinear theory of a massive spin-2

- Aside from the cosmological constant, this is an extremely interesting field-theoretic problem — part of a more general program to understand what the space of consistent field theories is

Massive gravity

- A massive graviton should have 5 polarizations (compare to 2 for a massless graviton)

Idea is to supplement Einstein-Hilbert term with all possible terms involving the metric perturbation

$$S = \frac{M_{\rm Pl}^2}{2}\int \mathrm{d}^4x\sqrt{-g}\left(R - \frac{m^2}{2}\mathcal{V}(g,h)\right) \qquad h_{\mu\nu} = g_{\mu\nu} - \eta_{\mu\nu}$$

- This obviously is not diffeomorphism invariant - tells us we are propagating more DOF than the 2 of Einstein gravity — Higgs phase of gravity?

Goon, Hinterbichler, AJ, Trodden, 1412.6098

- A generic choice of potential will propagate 6 DOF - too many for a massive graviton, the last DOF is a *ghost* Boulware, Deser 1972

- However, it is possible to carefully choose the interactions to cancel off this unwanted ghost

Stuckelberg trick

In order to isolate the DOF, it is useful to restore diffeomorphism invariance by performing the Stuckelberg replacement

$$h_{\mu\nu} \to \begin{cases} h_{\mu\nu} \\ \partial_{(\mu}A_{\nu)} \\ \partial_\mu\partial_\nu\phi \end{cases}$$

- Focus on the scalar sector; the naive scale suppressing the scalar interactions is

$$h_{\mu\nu} \sim \frac{1}{m^2 M_{\rm Pl}}\partial_\mu\partial_\nu\phi$$

but a general potential actually has scalar self-interactions suppressed by the lower scale $\Lambda_5 = (m^4 M_{\rm Pl})^{1/5}$ schematically of the form

$$\mathcal{L} \sim \frac{1}{\Lambda_5^5}(\partial^2\phi)^3$$

these higher-derivative terms propagate a ghost, this is the modern way to see the Boulware-Deser ghost

Arkani-Hamed, Georgi, Schwartz hep-th/0210184
Creminelli, Nicolis, Papucci, Trincherini hep-th/0505147

- It is actually possible to choose the form of the potential terms to cancel off these self interactions

de Rham, Gabadadze 10070443

Ghost free massive gravity

It turns out that we can cancel off scalar self interactions with lower scales so that the naive scale $\Lambda_3 = (m^2 M_{\rm Pl})^{1/3}$ is indeed the one that appears in the action

- In order to zoom in on this scale, we take the decoupling limit

$$m \to 0 \qquad\qquad M_{\rm Pl} \to \infty \qquad\qquad \Lambda_3 \quad \text{fixed}$$

- In this limit, after raising the cutoff, the scalar sector is precisely described by a galileon theory!

$$\mathcal{L} = -\frac{1}{4} h^{\mu\nu} \mathcal{E}^{\alpha\beta}_{\mu\nu} h_{\alpha\beta} - 6\mathcal{L}_2^{\rm gal}(\phi) + \frac{3(6c_3-1)}{2\Lambda_3^3}\mathcal{L}_3^{\rm gal}(\phi) - \frac{4}{\Lambda_3^6}\left[\frac{1}{4}(6c_3-1)^2 - 2(c_3+8d_5)\right]\mathcal{L}_4^{\rm gal}(\phi)$$
$$- \frac{15}{4\Lambda_3^9}(6c_3-1)(c_3+8d_5)\mathcal{L}_5^{\rm gal}(\phi) - \frac{(8d_5+c_3)}{\Lambda_3^6} h^{\mu\nu} X^{(3)}_{\mu\nu}(\phi)$$

- Details not important, but this tells us that many things we know are true in galileon theories (like screening) will also occur in massive gravity

dRGT massive gravity

de Rham, Gabadadze, Tolley 1011.232

We know that the galileons do not have ghosts, so we are tempted to trust the theory nonlinearly

- In fact, there is a re-organization of the potential terms that makes sense as a fully nonlinear theory beyond the strict decoupling limit we have explored

$$S = \frac{M_{\rm P}^2}{2}\int {\rm d}^4x\,\sqrt{-g}\left(R - \frac{m^2}{2}\mathcal{U}(g,\mathcal{K})\right) \qquad \mathcal{K}^\mu_\nu = \delta^\mu_\nu - \sqrt{\delta^\mu_\nu - H^\mu_\nu}$$

$$\mathcal{U}(g,\mathcal{K}) = \sum_{n=2}^{d} \alpha_n \mathcal{L}_n^{\rm TD}(\mathcal{K}) \qquad \begin{aligned} \mathcal{L}_2^{\rm TD}(\mathcal{K}) &= \langle\mathcal{K}\rangle^2 - \langle\mathcal{K}^2\rangle\ , \\ \mathcal{L}_3^{\rm TD}(\mathcal{K}) &= \langle\mathcal{K}\rangle^3 - 3\,\langle\mathcal{K}\rangle\,\langle\mathcal{K}^2\rangle + 2\langle\mathcal{K}^3\rangle\ , \\ \mathcal{L}_4^{\rm TD}(\mathcal{K}) &= \langle\mathcal{K}\rangle^4 - 6\,\langle\mathcal{K}\rangle^2\,\langle\mathcal{K}^2\rangle + 3\langle\mathcal{K}^2\rangle^2 + 8\,\langle\mathcal{K}\rangle\,\langle\mathcal{K}^3\rangle - 6\langle\mathcal{K}^4\rangle\ , \\ &\vdots \end{aligned}$$

- This theory has been proven to propagate *only* the 5 polarizations of a massive graviton   Hassan, Rosen 1106.3344

- These theories are intriguing because there is hope the CC can be related to the graviton mass, which is technically naturally small because diff invariance is restored as $m \to 0$

Partially massless gravity

It turns out that massive gravity is even more interesting on de Sitter space

$$\mathcal{L} = -\frac{1}{4}h\mathcal{E}h - \frac{m^2}{2}\left(h_{\mu\nu}^2 - h^2\right) + 3H^2\left(h_{\mu\nu}^2 - \frac{1}{2}h^2\right)$$

- For generic values of *m*, this action propagates 5 degrees of freedom
- At the special point $m^2 = 2H^2$ the theory develops a gauge symmetry

$$\delta h_{\mu\nu} = \left(\nabla_\mu\nabla_\nu + H^2 g_{\mu\nu}\right)\xi$$

which removes the scalar polarization, meaning the field only has 4 DOF

Deser, Nepomechie 1984

- This is very interesting because it has tied the cosmological constant to the mass of the graviton through a gauge symmetry — recall the graviton mass is technically natural
- The bad news: a nonlinear version of this theory appears not to exist

Deser, Sandora, Waldron 1301.5621; de Rham, Hinterbichler, Rosen, Tolley1302.0025, Joung, Li, Taronna1406.2335

- An even richer range of things can happen for higher spins, work underway to find interacting versions of these theories — stay tuned

Conclusions

- The cosmological constant problem still has no good solutions, but it has inspired a lot of work into exploring how new physics can appear in the gravitational sector

- In particular, any new physics must have some screening mechanism which hides it from local tests, these come in 3 distinct types

- Here I have presented situations where there is only one type of screening active at a time, it is reasonable to ask what happens when more than one type is present Gratia, Hu, AJ, Ribeiro to appear

- Of particular interest have been derivatively-coupled theories, which have a rich and interesting phenomenology — particularly galileon theories

- Going forward, it is interesting to look for situations where screening may be less efficient, these are opportunities to test these theories

- Partially massless high-spin theories are somewhat unexplored territory, many exciting things to learn