
What Could Dark Energy Be?

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Overview

- Motivations - background, and the problem of cosmic acceleration

- Some possible approaches:
 - The cosmological constant
 - Dynamical dark energy
 - Modified gravity

Note: I was fortunate enough to give a very similarly-titled talk 3 years ago at the SSI. Any of you who were there will find **many** similarities!

- What are the theoretical issues facing any dynamical approach?
Screening mechanisms, Connections to particle physics and field theory.

- An example: Galileons

- Discussion of Massive Gravity

- A few comments.

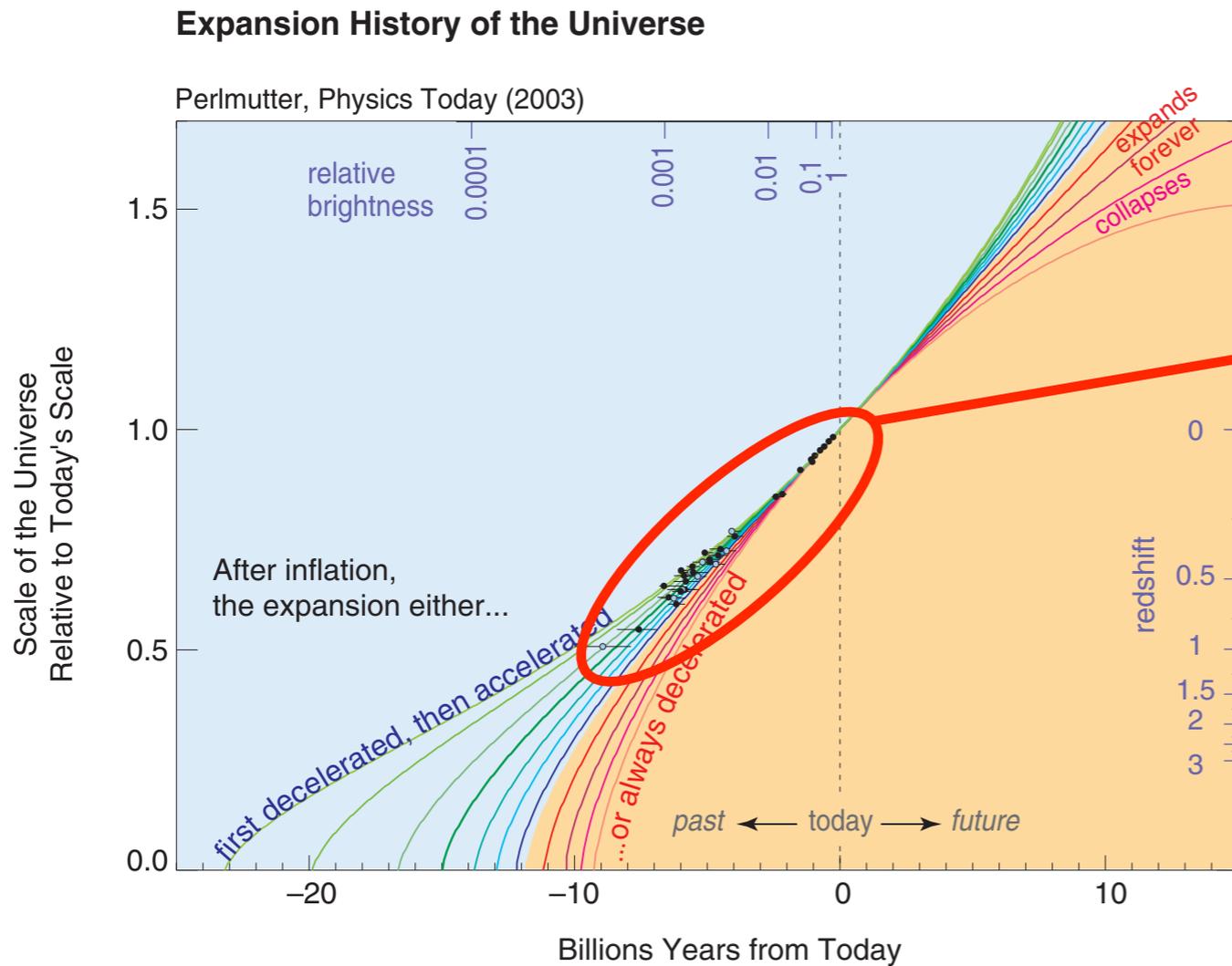
Try to explain how particle physicists think about these things. Older, but still hopefully useful reference for some of what I'll say

Beyond the Cosmological Standard Model
Bhuvnesh Jain, Austin Joyce, Justin Khoury and MT

Phys.Rept. **568** 1-98 (2015), [[arXiv:1407.0059](https://arxiv.org/abs/1407.0059)]

The Cosmic Expansion History

What does data tell us about the expansion rate?



We now know, partly through this data, that the universe is not only expanding ...

$$\dot{a} > 0$$

... but is accelerating!!

$$\ddot{a} > 0$$

If we trust GR then

$$\frac{\ddot{a}}{a} \propto -(\rho + 3p)$$

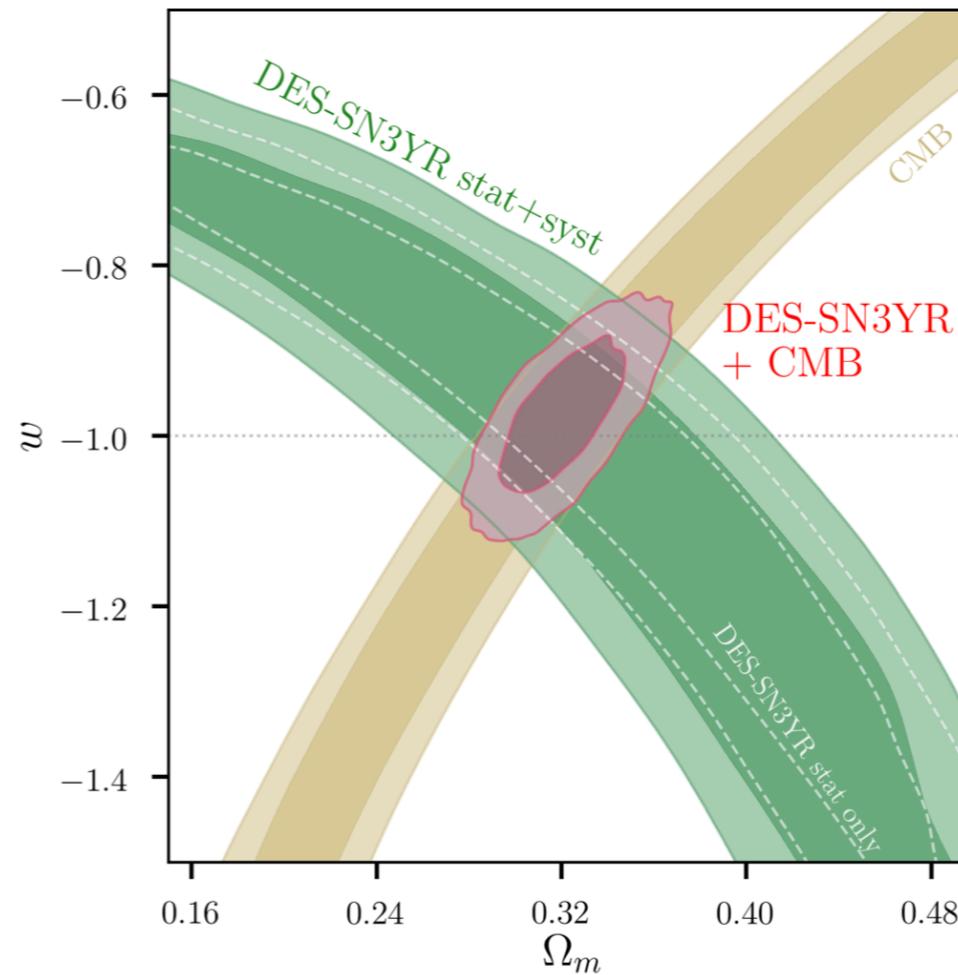
Then we infer that the universe must be dominated by some strange stuff with $p < -\rho/3$. We call this **dark energy!**

Cosmic Acceleration

$$\frac{\ddot{a}}{a} \propto -(\rho + 3p)$$

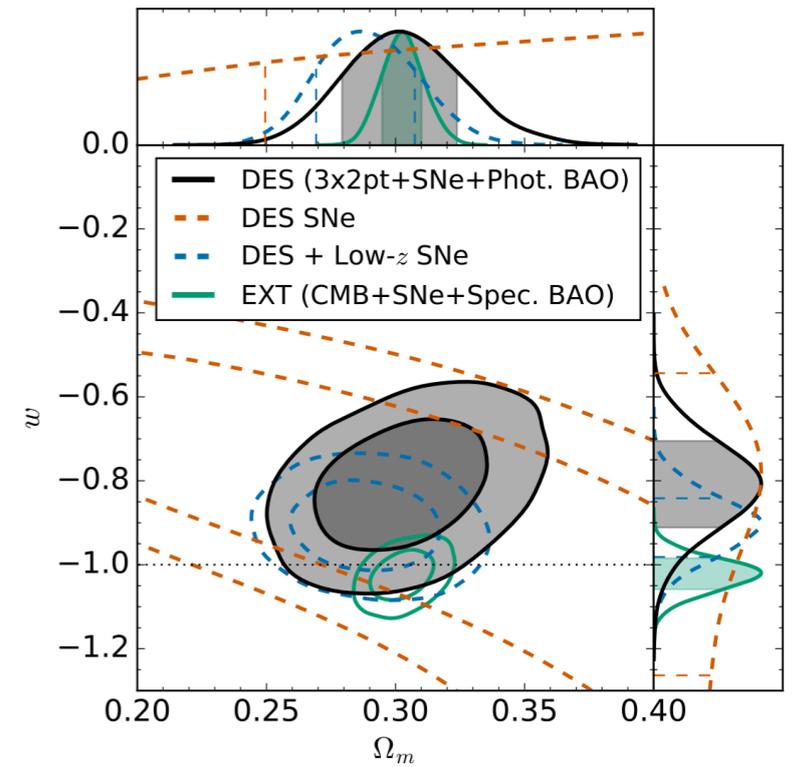
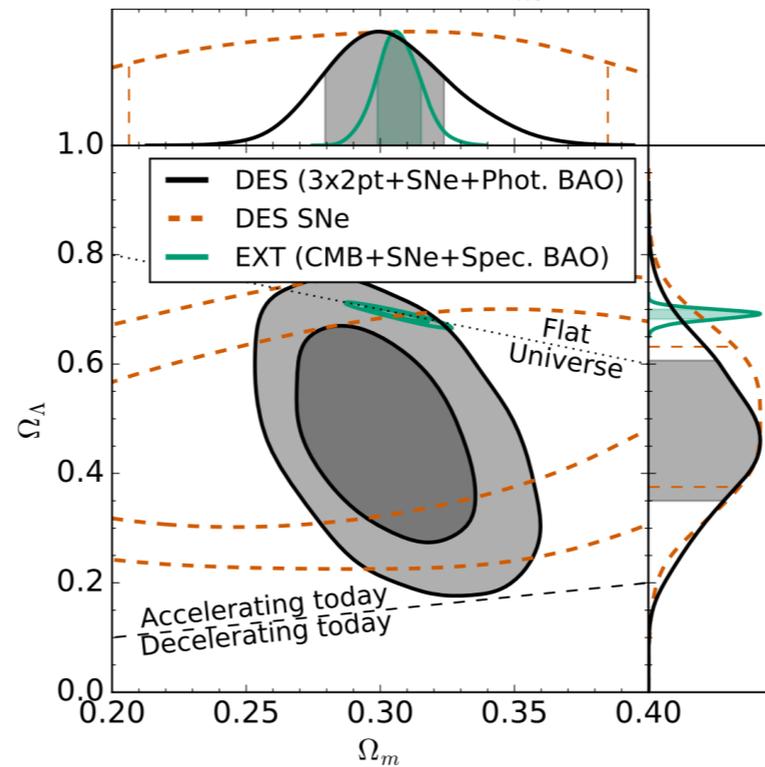
So, writing $p=w\rho$,
accelerating expansion
means $p < -\rho/3$ or

$$w < -1/3$$



$$w = -0.978 \pm 0.059$$

$$w = -1.02^{+0.03}_{-0.04}$$



DES Collaboration 2019

The Cosmological Constant

Vacuum is full of virtual particles carrying energy. Equivalence principle (Lorentz-Invariance) gives

$$\langle T_{\mu\nu} \rangle \sim -\langle \rho \rangle g_{\mu\nu}$$

A constant vacuum energy! How big? Quick & dirty estimate of size only by modeling SM fields as collection of independent harmonic oscillators and then summing over zero-point energies.

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

Most conservative estimate of cutoff: $\sim 1 \text{ TeV}$. Gives

$$\Lambda_{\text{theory}} \sim (\text{TeV})^4 \sim 10^{-60} M_{\text{Pl}}^4 \ll \Lambda_{\text{obs.}} \sim M_{\text{Pl}}^2 H_0^2 \sim 10^{-60} (\text{TeV})^4 \sim 10^{-120} M_{\text{Pl}}^4$$

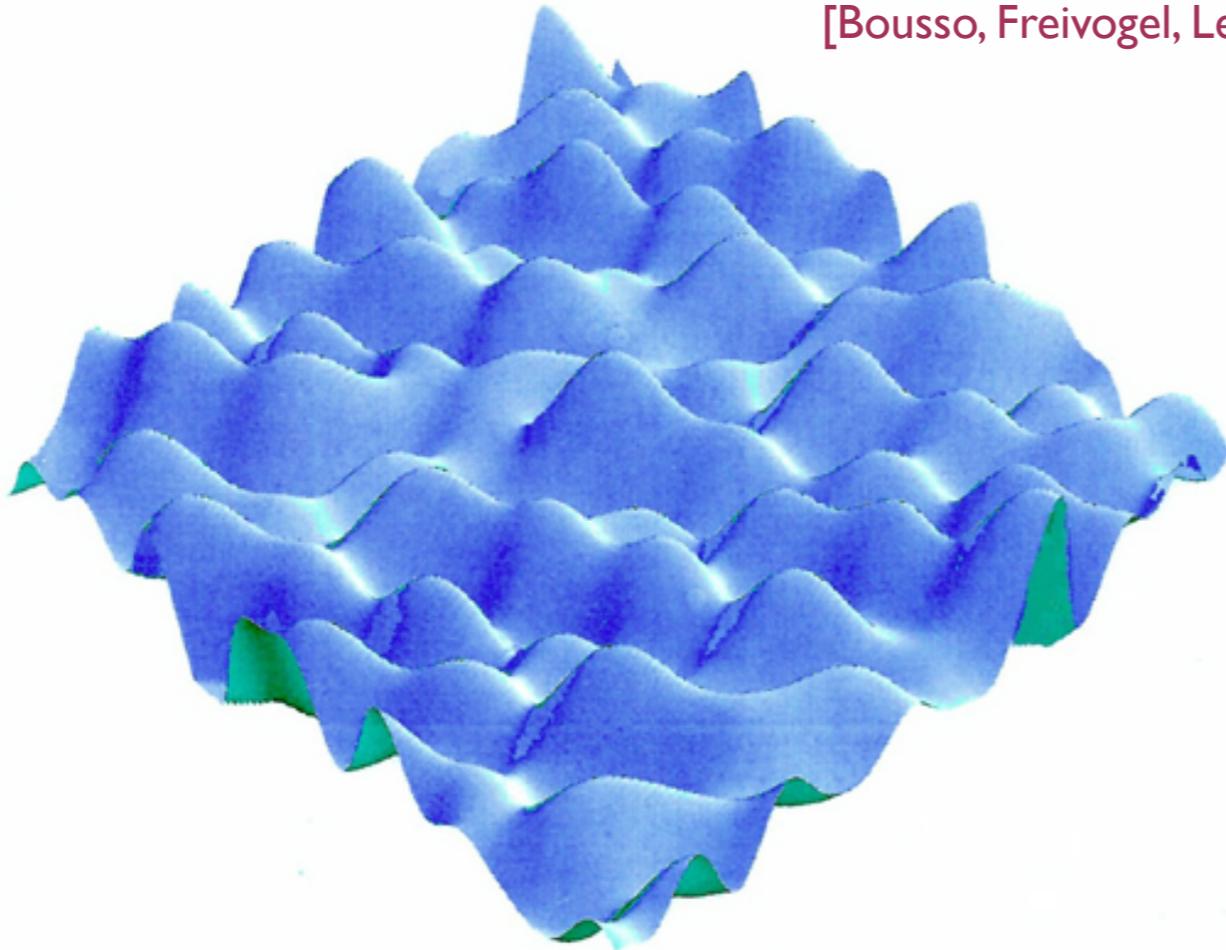
An enormous, and entirely unsolved problem in fundamental physics, made more pressing by the discovery of acceleration!

At this stage, fair to say we are almost completely stuck! - No known dynamical mechanism, and a no-go theorem (Weinberg) to be overcome.

Lambda, the Landscape & the Multiverse

Anthropics provide a logical possibility to explain this, but a necessary (not sufficient) requirement is a way to realize and populate many values. The string landscape, with eternal inflation, may provide a way to do this.

[Bousso, Freivogel, Leichenauer, ...; Vilenkin, Guth, Linde, Salem, ...]



[Image: SLIM FILMS. Looking for Life in the Multiverse, [A. Jenkins](#) & [G. Perez](#), Scientific American, December 2009]

An important step is understanding how to compute probabilities in such a spacetime

No currently accepted answer, but quite a bit of serious work going on. Too early to know if can make sense of this.

How to Think of This (or, at least, how I do)

A completely logical possibility - should be studied. Present interest relies on

- String theory (which may not be the correct theory)
- The string landscape (which might not be there)
- Eternal inflation in that landscape (which might not work)
- Perhaps a solution of the measure problem (which we do not have yet)

If dynamical understanding of CC is found, would be hard to accept this.

If DE is time or space dependent, would be hard to explain this way.

Worthwhile mapping out the space of alternative ideas.
Even though there are no compelling models yet, there is already theoretical progress and surprises.

Furthermore - the CC problem alone is an important motivating factor in quite a lot of theoretical work on these issues.

Dynamical Dark Energy

Once we allow dark energy to be dynamical, we are imagining that it is some kind of honest-to-goodness mass-energy component of the universe.

It isn't enough for a theorist to model matter as a perfect fluid with energy density ρ and pressure p (at least it shouldn't be enough at this stage!)

$$T_{\mu\nu} = (\rho + p)U_{\mu}U_{\nu} + pg_{\mu\nu}$$

Our only known way of describing such things, at a fundamental level is through quantum field theory, with a Lagrangian. e.g.

$$S_m = \int d^4x L_m[\phi, g_{\mu\nu}] \quad L_m = \frac{1}{2}g^{\mu\nu} (\partial_{\mu}\phi) \partial_{\nu}\phi - V(\phi)$$

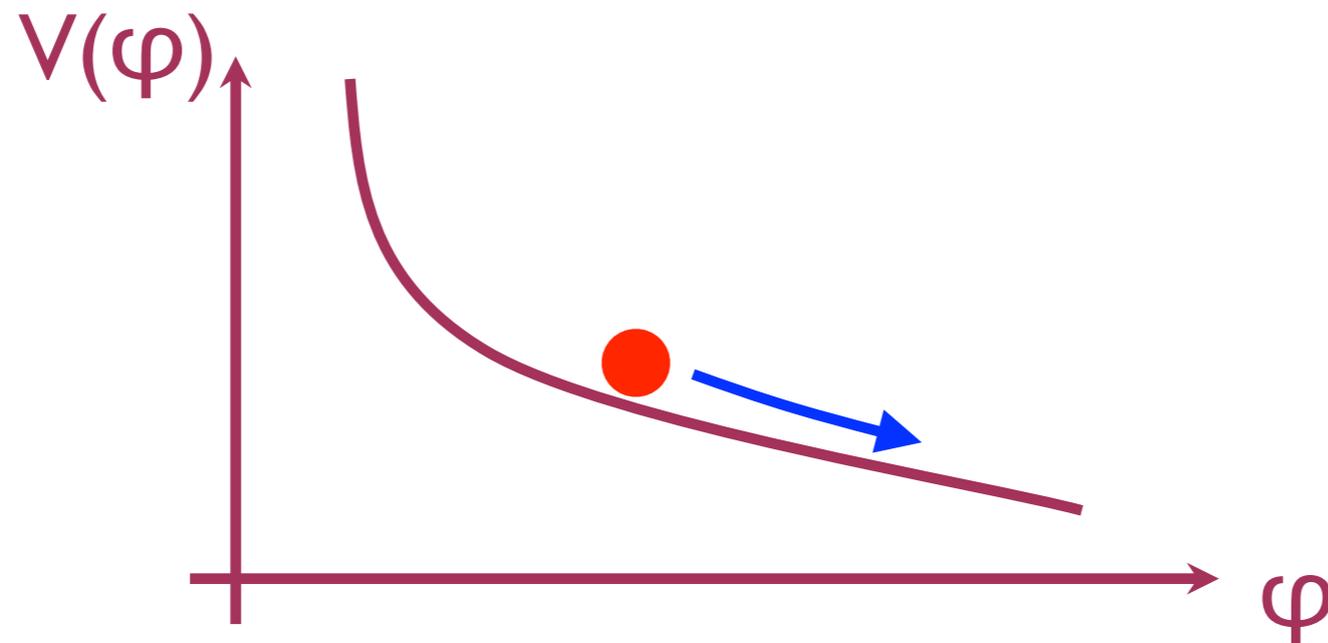
$$T_{\mu\nu} \equiv -\frac{2}{\sqrt{-g}} \frac{\delta S_m}{\delta g^{\mu\nu}} \quad R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi GT_{\mu\nu}$$

Dynamical Dark Energy

Maybe there's some principle that sets vacuum energy to zero. Then dark energy might be inflation at the other end of time.

(Essential differences - the overall scale; no minimum; no reheating)

Use scalar fields to source Einstein's equation - *Quintessence*.



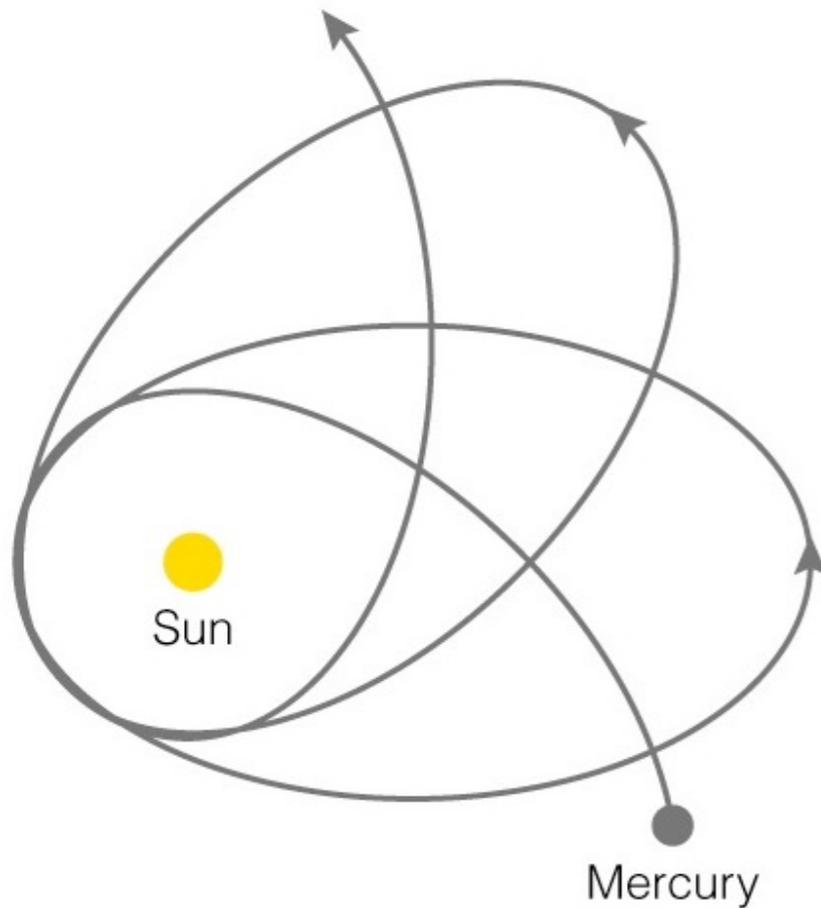
Small slope

$$\rho_\phi \approx V(\phi) \approx \text{constant}$$

$$w = - \left[\frac{2V(\phi) - \dot{\phi}^2}{2V(\phi) + \dot{\phi}^2} \right]$$

Another Possibility

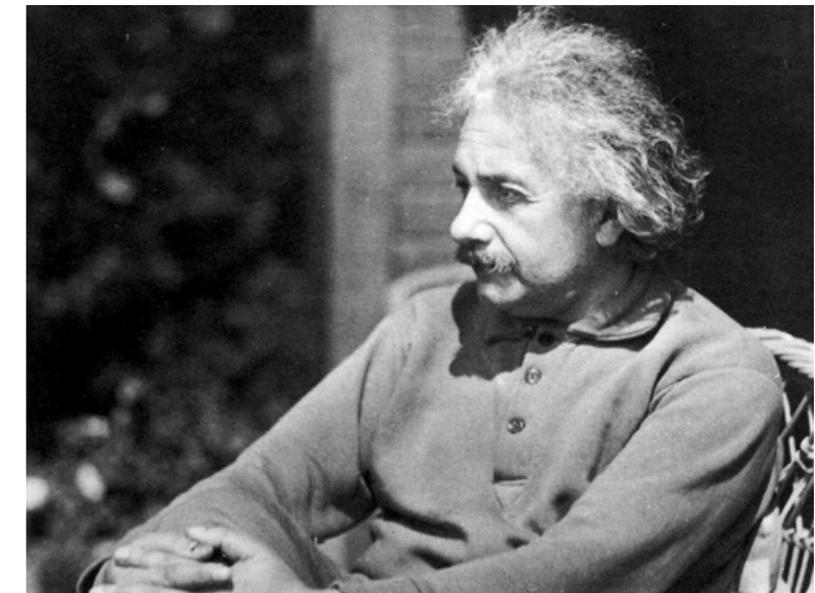
A related tale played out over 50 years over a century ago



Annales de l'Observatoire Impérial de Paris. Publiées par U. J. Leverrier, Directeur de l'Observatoire, tom. v. 4to, Paris, 1859.

This volume contains the theory and tables of *Mercury* by M. Leverrier; the discrepancy as regards the secular motion of the perihelion which is found to exist between theory and observation, led, as is well known, to the suggestion by M. Leverrier of the existence of a planet or group of small planets interior to *Mercury*. The volume contains also a memoir by M. Foucault, on the "Construction of Telescopes with Silvered

"[General Relativity] explains ... quantitatively ... the secular rotation of the orbit of Mercury, discovered by Le Verrier, ... without the need of any special hypothesis.", SPAW, Nov 18, 1915



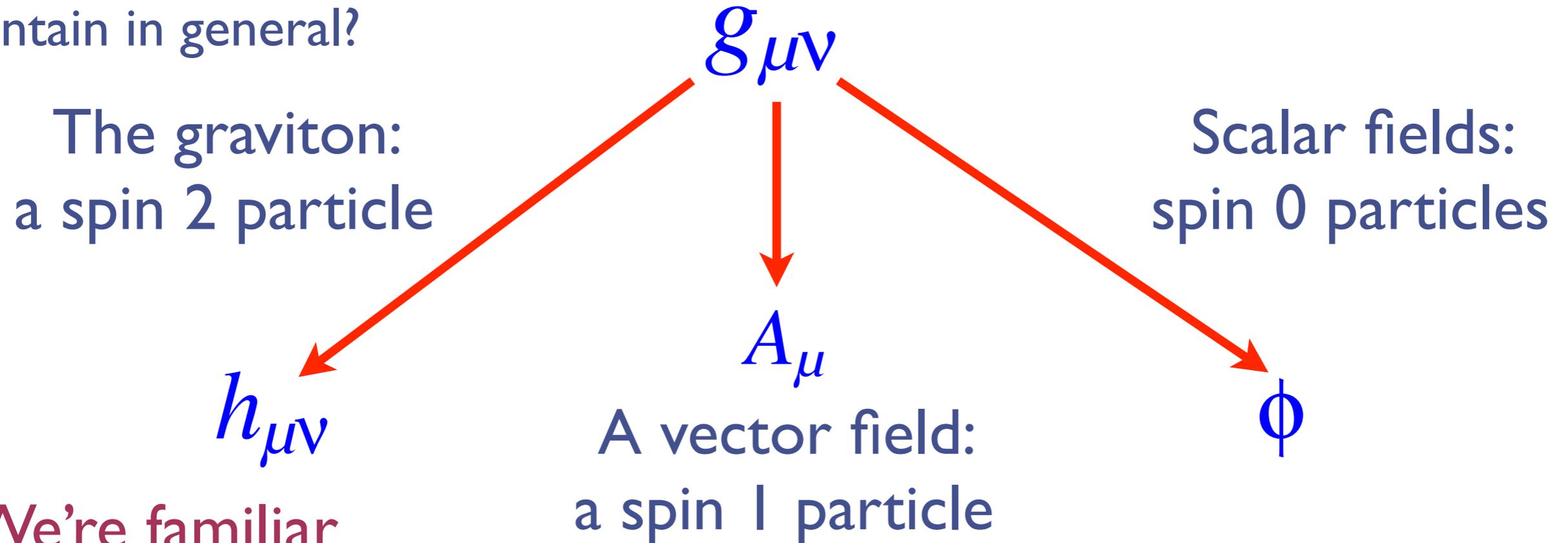
This leads to the question:

Could a similar story be unfolding today, with cosmic acceleration the canary in the mine, warning of the breakdown of gravity?

Modifying Gravity

Maybe cosmic acceleration is *entirely* due to corrections to GR!

One thing to understand is: what degrees of freedom does the metric $g_{\mu\nu}$ contain in general?



We're familiar with this.

These are less familiar.

GR pins vector A_{μ} and scalar ϕ fields, making non-dynamical, and leaving only familiar graviton $h_{\mu\nu}$

Almost any other action will free some of them up

e.g., $f(R)$ models
[Carroll, Duvvuri, M.T. & Turner, (2003)]

More interesting things also possible - massive gravity - see later

A common Language - EFT

How do theorists think about all this? In fact, whether dark energy or modified gravity, ultimately, around a background, it consists of a set of interacting fields in a Lagrangian. The Lagrangian contains 3 types of terms:

- **Kinetic Terms: e.g.**

$$\partial_\mu \phi \partial^\mu \phi \quad F_{\mu\nu} F^{\mu\nu} \quad i\bar{\psi} \gamma^\mu \partial_\mu \psi \quad h_{\mu\nu} \mathcal{E}^{\mu\nu;\alpha\beta} h_{\alpha\beta} \quad K(\partial_\mu \phi \partial^\mu \phi)$$

- **Self Interactions (a potential)**

$$V(\phi) \quad m^2 \phi^2 \quad \lambda \phi^4 \quad m\bar{\psi}\psi \quad m^2 h_{\mu\nu} h^{\mu\nu} \quad m^2 h^\mu{}_\mu h^\nu{}_\nu$$

- **Interactions with other fields (such as matter, baryonic or dark)**

$$\Phi \bar{\psi} \psi \quad A^\mu A_\mu \Phi^\dagger \Phi \quad e^{-\beta\phi/M_p} g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi \quad (h^\mu{}_\mu)^2 \phi^2 \quad \frac{1}{M_p} \pi T^\mu{}_\mu$$

Depending on the background, such terms might have functions in front of them that depend on time and/or space.

Many of the concerns of theorists can be expressed in this language

e.g. Weak Coupling

When we write down a classical theory, described by one of our Lagrangians, are usually implicitly assuming effects of higher order operators are small. Needs us to work below the strong coupling scale of the theory, so that quantum corrections, computed in perturbation theory, are small. We therefore need.

- The dimensionless quantities determining how higher order operators, with dimensionful couplings (irrelevant operators) affect the lower order physics be $\ll 1$ (or at least < 1)

$$\frac{E}{\Lambda} \ll 1 \quad (\text{Energy} \ll \text{cutoff})$$

But be careful - this is tricky! Remember that our kinetic terms, couplings and potentials all can have background-dependent functions in front of them, and even if the original parameters are small, these may make them large - the **strong coupling problem!** You can no longer trust the theory!

$$G(\chi) \partial_\mu \phi \partial^\mu \phi \longrightarrow f(t) \partial_\mu \phi \partial^\mu \phi \quad f(t) \rightarrow 0$$

e.g. Technical Naturalness

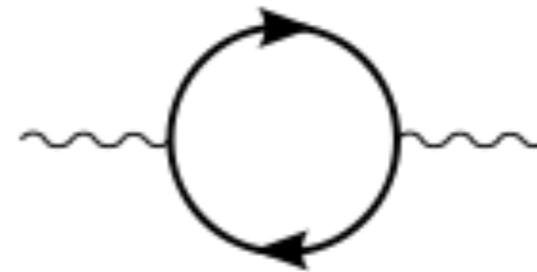
Even if your quantum mechanical corrections do not ruin your ability to trust your theory, any especially small couplings you need might be a problem.

- Suppose you need a very flat potential, or very small mass for some reason

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - \frac{1}{2}m^2\phi^2 - \lambda\phi^4 \quad m \sim H_0^{-1}$$

Then unless your theory has a special extra symmetry as you take m to zero, then quantum corrections will drive it up to the cutoff of your theory.

$$m_{\text{eff}}^2 \sim m^2 + \Lambda^2$$



- Without this, requires extreme fine tuning to keep the potential flat and mass scale ridiculously low - **challenge of technical naturalness.**

e.g. Ghost-Free

The Kinetic terms in the Lagrangian, around a given background, tell us, in a sense, whether the particles associated with the theory carry positive energy or not.

- Remember the Kinetic Terms: e.g.

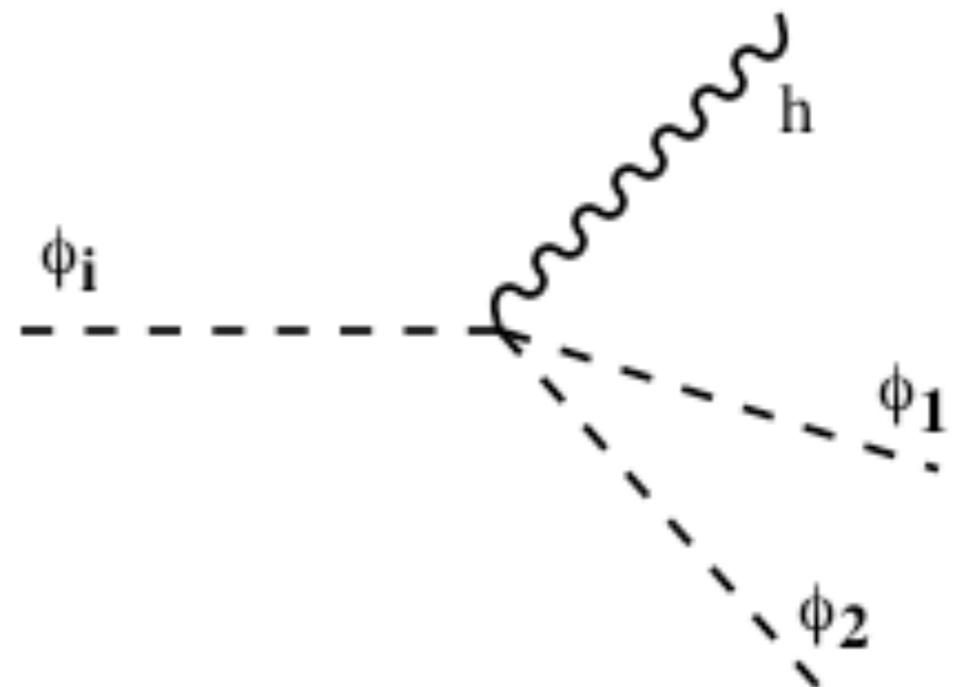
$$-\frac{f(\chi)}{2} K(\partial_\mu \partial^\mu \phi) \rightarrow F(t, x) \frac{1}{2} \dot{\phi}^2 - G(t, x) (\nabla \phi)^2$$

This sets the sign of the KE

- If the KE is negative then the theory has **ghosts!** This can be catastrophic!

If we were to take these seriously, they'd have negative energy!!

- Ordinary particles could decay into heavier particles plus ghosts
- Vacuum could fragment



(Carroll, Hoffman & M.T.,(2003); Cline, Jeon & Moore. (2004))

A Ghostly Example

The most obvious place this happens is when there are uncontrolled higher derivatives in the theory. A simple example illustrates this easily.

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

- Introduce an auxiliary field via

$$\mathcal{L} = -\frac{1}{2}(\partial\psi)^2 + \chi\Box\psi - \frac{\Lambda^2}{2}\chi^2 - V(\psi) \quad \text{w/ EOM} \quad \chi = \frac{\Box\psi}{\Lambda^2}$$

(easy to check that substituting this back in yields original Lagrangian)

- Now make a field redefinition $\psi = \phi - \chi$ and integrate by parts in action

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

A ghost, with mass at the cutoff (so might be OK in full theory, but not always true)

This is why, within GR, almost all attempts to get a sensible model of $w < -1$ have failed.

e.g. Superluminality ...

Crucial ingredient of Lorentz-invariant QFT: *microcausality*. Commutator of 2 local operators vanishes for spacelike separated points as operator statement

$$[\mathcal{O}_1(x), \mathcal{O}_2(y)] = 0 ; \quad \text{when} \quad (x - y)^2 > 0$$

Turns out, even if have superluminality, under right circumstances can still have a well-behaved theory, as far as causality is concerned. e.g.

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 + \frac{1}{\Lambda^3}\partial^2\phi(\partial\phi)^2 + \frac{1}{\Lambda^4}(\partial\phi)^4$$

- Expand about a background: $\phi = \bar{\phi} + \varphi$
- Causal structure set by effective metric

$$\mathcal{L} = -\frac{1}{2}G^{\mu\nu}(x, \bar{\phi}, \partial\bar{\phi}, \partial^2\bar{\phi}, \dots)\partial_\mu\varphi\partial_\nu\varphi + \dots$$

- If G globally hyperbolic, theory is perfectly causal, but *may* have directions in which perturbations propagate outside lightcone used to define theory. May or may not be a problem for the theory - remains to be seen.

But: there can still be worries here, such as analyticity of the S-matrix, ...

The Need for Screening in the EFT

Look at the general EFT of a scalar field conformally coupled to matter

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

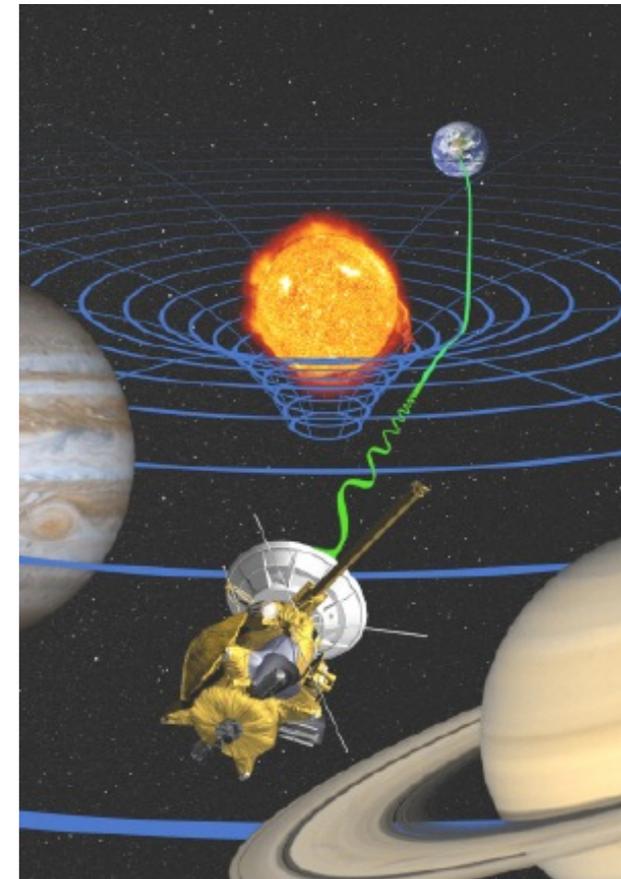
Specialize to a point source $T^\mu_\mu \rightarrow -\mathcal{M}\delta^3(\vec{x})$ and expand $\phi = \bar{\phi} + \varphi$

$$Z(\bar{\phi})\left(\ddot{\varphi} - c_s^2(\bar{\phi})\nabla^2\varphi\right) + m^2(\bar{\phi})\varphi = g(\bar{\phi})\mathcal{M}\delta^3(\vec{x})$$

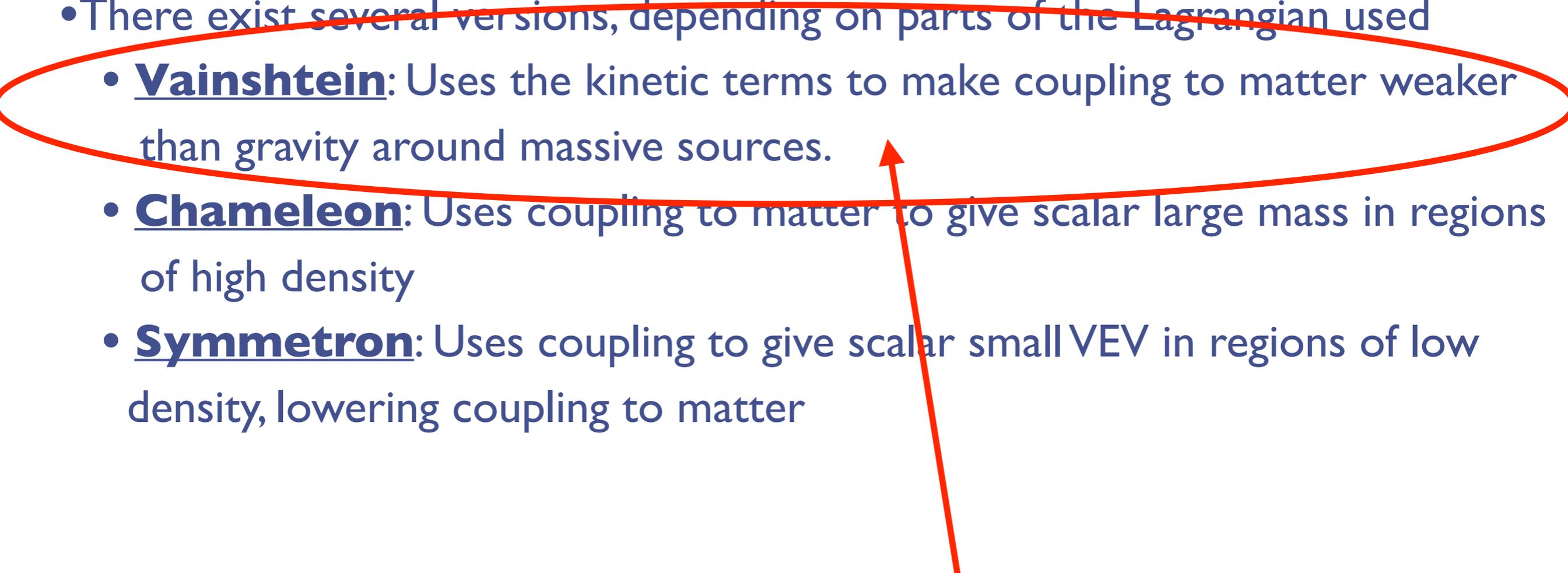
Expect background value set by other quantities; e.g. density or Newtonian potential. Neglecting spatial variation over scales of interest, static potential is

$$V(r) = -\frac{g^2(\bar{\phi})}{Z(\bar{\phi})c_s^2(\bar{\phi})} \frac{e^{-\frac{m(\bar{\phi})}{\sqrt{Z(\bar{\phi})c_s(\bar{\phi})}}r}}{4\pi r} \mathcal{M}$$

So, for light scalar, parameters $\mathcal{O}(1)$, have gravitational strength long range force, ruled out by local tests of GR! If we want workable model need to make this sufficiently weak in local environment, while allowing for significant deviations from GR on cosmological scales!



Remember the EFT classification of terms in a covariant Lagrangian

- There exist several versions, depending on parts of the Lagrangian used
 - **Vainshtein**: Uses the kinetic terms to make coupling to matter weaker than gravity around massive sources.
 - **Chameleon**: Uses coupling to matter to give scalar large mass in regions of high density
 - **Symmetron**: Uses coupling to give scalar small VEV in regions of low density, lowering coupling to matter
- 

I'll focus on this in a specific example, to illustrate some issues

Massive gravity

More recent concrete suggestion - consider massive gravity

- Fierz and Pauli showed how to write down a linearized version of this, but...

$$\propto m^2 (h^2 - h_{\mu\nu} h^{\mu\nu})$$

- ... thought all nonlinear completions exhibited the “Boulware-Deser ghost”.

Over last decade a counterexample has been found.

This is a very new, and potentially exciting development!

[de Rham, Gabadadze, Tolley (2011)]

$$\mathcal{L} = M_P^2 \sqrt{-g} (R + 2m^2 \mathcal{U}(g, f)) + \mathcal{L}_m$$

Proven to be ghost free, and investigations of the resulting cosmology - acceleration, degravitation, ... are underway, both in the full theory and in its decoupling limit - galileons!

(Also a limit of DGP)

[Hassan & Rosen(2011)]

Focus on Galileons (for now)

In a limit yields novel and fascinating 4d EFT that many of us have been studying. Symmetry: $\pi(x) \rightarrow \pi(x) + c + b_\mu x^\mu$

Relevant field referred to as the *Galileon*

(Nicolis, Rattazzi, & Trincherini 2009)

$$\mathcal{L}_1 = \pi \quad \mathcal{L}_2 = (\partial\pi)^2 \quad \mathcal{L}_3 = (\partial\pi)^2 \square\pi$$

$$\mathcal{L}_{n+1} = n\eta^{\mu_1\nu_1\mu_2\nu_2\cdots\mu_n\nu_n} (\partial_{\mu_1}\pi\partial_{\nu_1}\pi\partial_{\mu_2}\partial_{\nu_2}\pi\cdots\partial_{\mu_n}\partial_{\nu_n}\pi)$$

There is a separation of scales

- Allows for classical field configurations with order one nonlinearities, but quantum effects under control.
- So can study non-linear classical solutions.
- Some of these very important (Vainshtein screening)

We now understand that there are many variations on this that share its attractive properties (probe brane construction; coset construction)

The Vainshtein Effect

Consider, for example, the cubic galileon, coupled to matter

$$\mathcal{L} = -3(\partial\pi)^2 - \frac{1}{\Lambda^3}(\partial\pi)^2\Box\pi + \frac{1}{M_{Pl}}\pi T$$

Now look at spherical solutions around a point mass

$$\pi(r) = \begin{cases} \sim \Lambda^3 R_V^{3/2} \sqrt{r} + const. & r \ll R_V \\ \sim \Lambda^3 R_V^3 \frac{1}{r} & r \gg R_V \end{cases} \quad R_V \equiv \frac{1}{\Lambda} \left(\frac{M}{M_{Pl}} \right)^{1/3}$$

Looking at a test particle, strength of this force, compared to gravity, is then

$$\frac{F_\pi}{F_{\text{Newton}}} = \frac{\pi'(r)/M_{Pl}}{M/(M_{Pl}^2 r^2)} = \begin{cases} \sim \left(\frac{r}{R_V} \right)^{3/2} & R \ll R_V \\ \sim 1 & R \gg R_V \end{cases}$$

So forces much smaller than gravitational strength within the Vainshtein radius - hence safe from 5th force tests.

The Vainshtein Effect

Suppose we want to know the the field that a source generates within the Vainshtein radius of some large body (like the sun, or earth)

Perturbing the field and the source

yields
$$\pi = \pi_0 + \varphi, \quad T = T_0 + \delta T,$$

$$\mathcal{L} = -3(\partial\varphi)^2 + \frac{2}{\Lambda^3} \underbrace{(\partial_\mu\partial_\nu\pi_0 - \eta_{\mu\nu}\square\pi_0)}_{\sim \left(\frac{R_v}{r}\right)^{3/2}} \partial^\mu\varphi\partial^\nu\varphi - \frac{1}{\Lambda^3}(\partial\varphi)^2\square\varphi + \frac{1}{M_4}\varphi\delta T$$

Thus, if we canonically normalize the kinetic term of the perturbations, we raise the effective strong coupling scale, and, more importantly, heavily suppress the coupling to matter!

Regimes of Validity

The usual quantum regime
of a theory

The usual linear, classical
regime of a theory

$$r \ll \frac{1}{\Lambda}$$

$$\alpha_{cl} \sim \left(\frac{R_V}{r}\right)^{3/2} \gg 1$$

$$\alpha_q \sim \frac{1}{(r\Lambda)^2} \gg 1$$

$$\frac{1}{\Lambda} \ll r \ll R_V$$

$$\alpha_{cl} \sim \left(\frac{R_V}{r}\right)^{3/2} \gg 1$$

$$\alpha_q \sim \frac{1}{(r\Lambda)^2} \ll 1$$

$$r \gg R_V$$

$$\alpha_{cl} \sim \left(\frac{R_V}{r}\right)^3 \ll 1$$

$$\alpha_q \sim \frac{1}{(r\Lambda)^2} \ll 1$$

$$r \sim \frac{1}{\Lambda}$$

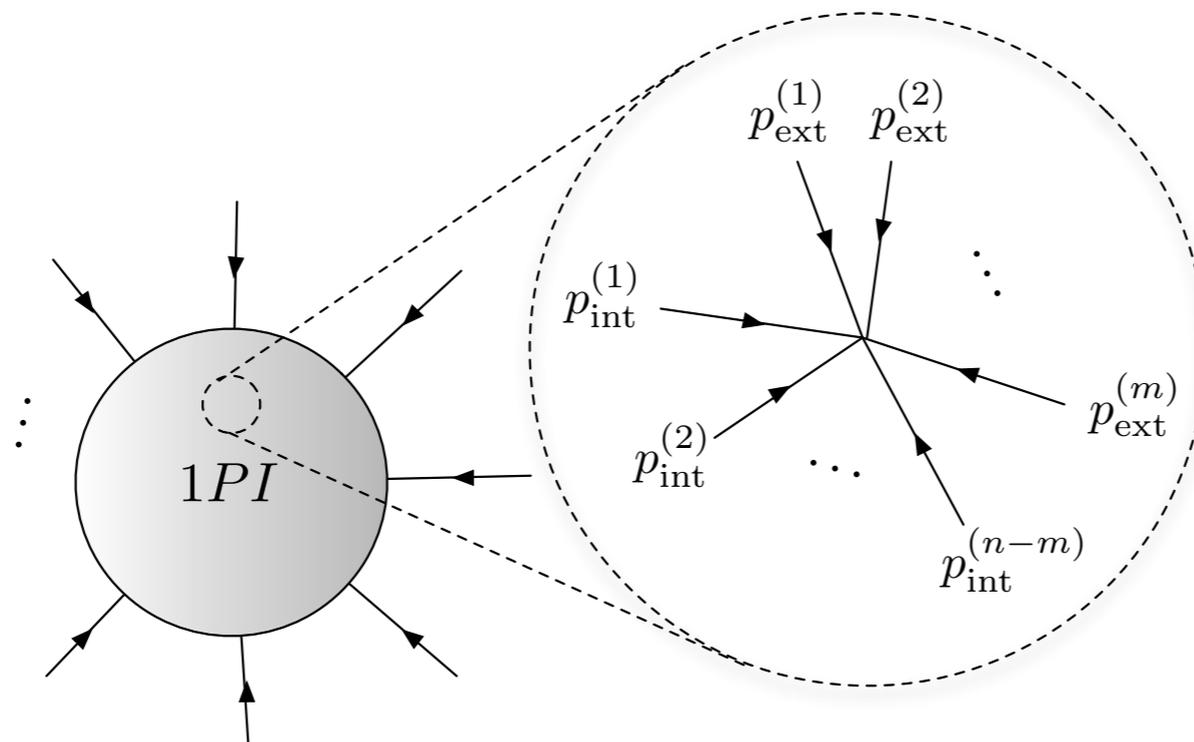
$$r \sim R_V$$

A new classical regime, with
order one nonlinearities

Nonrenormalization!

Amazingly terms of galilean form are nonrenormalized (c.f SUSY theories).
Possibly useful for particle physics & cosmology. We'll see.

Expand quantum effective action for the classical field about expectation value



The n-point contribution contains at least $2n$ powers of external momenta:
cannot renormalize Galilean term with only $2n-2$ derivatives.

Can show, just by computing Feynman diagrams, that at all loops in perturbation theory, for any number of fields, terms of the galilean form cannot receive new contributions.

[Luty, Porrati, Rattazzi (2003); Nicolis, Rattazzi (2004); Hinterbichler, M.T., Wesley, (2010);
Goon, Hinterbichler, Joyce and M.T., (2016)]

Can even add a mass term and remains technically natural

The Vainshtein Effect is Very Effective!

Fix r_c to make solutions cosmologically interesting - $4000 \text{ Mpc} = 10^{10} \text{ ly}$



sun

galaxy

galaxy cluster



$\sim 0.1 \text{ kpc} = 10^7 \text{ AU}$



$\sim \text{Mpc} \sim 30 \text{ galactic radii}$



$\sim 10 \text{ Mpc} \sim 10 \text{ virial radii}$

$$r^* = \left(\frac{2GM}{c^2} r_c^2 \right)^{1/3}$$

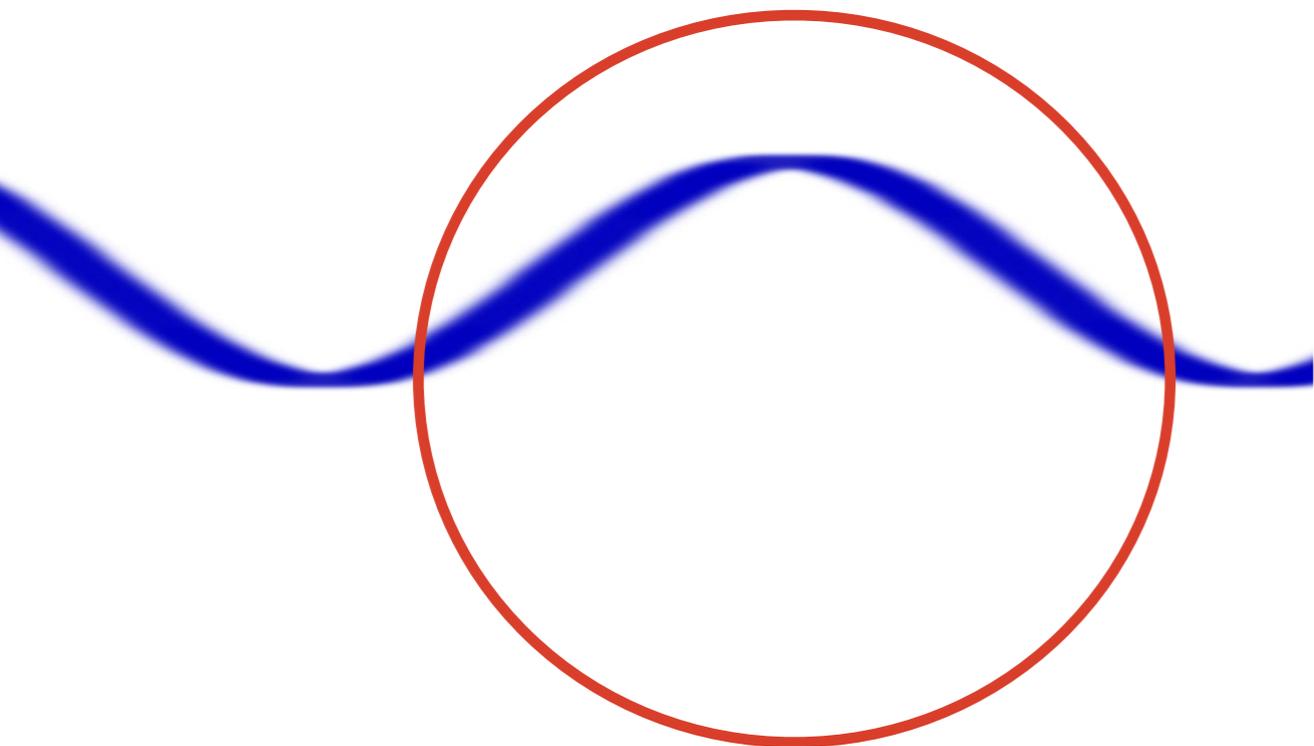
Cosmology in (e.g) Massive Gravity

Nontrivial modifications to gravity such as massive gravity hold the promise of being able to address new problems.

However, there are also new constraints. Perfect, homogeneous, isotropic solutions (the FRW solutions) do not exist in the simplest incarnation of massive gravity

Nevertheless, can find inhomogeneous cosmologies that behave just like FRW models over a given scale. This is set by the inverse graviton mass, which we need to be very large anyway.

[D'Amico et al. (2011)]

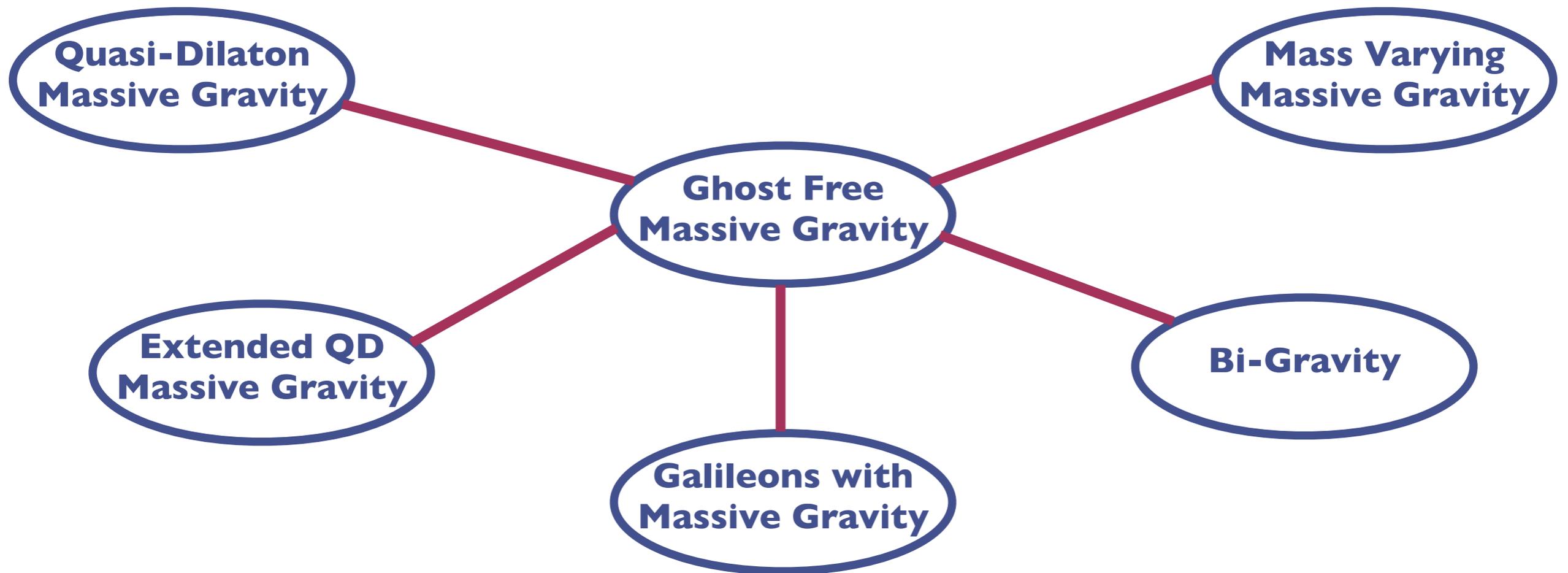


In each bubble the Vainshtein mechanism works, as it did in the solar system, and we approximately recover GR, and its (approximately) FRW solutions.

Some extensions can even relax this, although not fully developed yet. The deviations may be interesting.

Is Massive Gravity up to the Job?

- Minimal massive gravity has fascinating features, but faces some cosmological challenges. Solutions not small modifications of GR.
- This has led to searches for extensions.

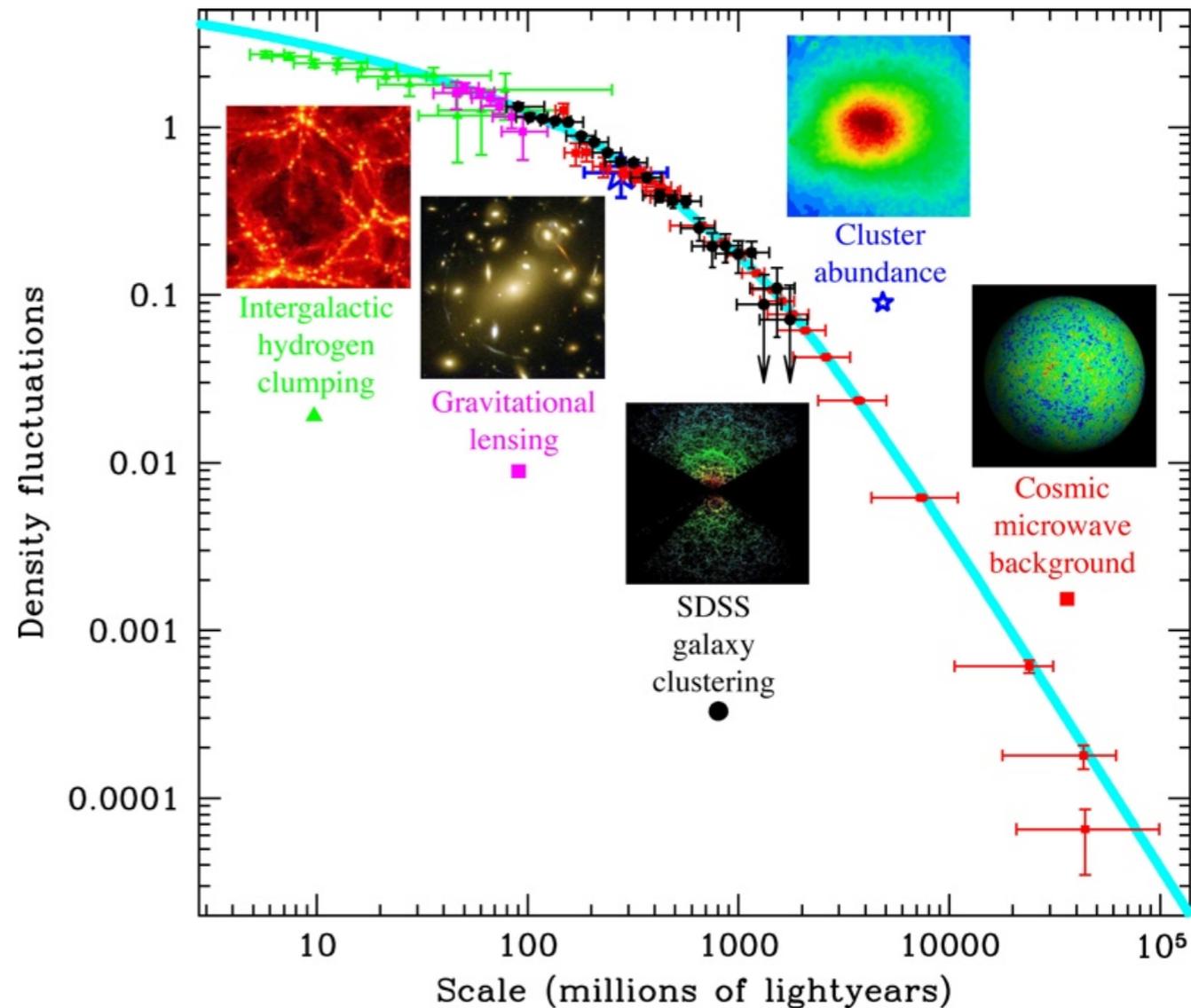


- But so far, results are mixed - no definitive model yet in which all calculations are under control.

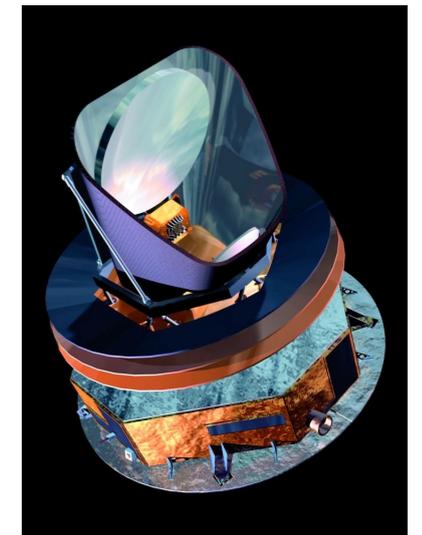
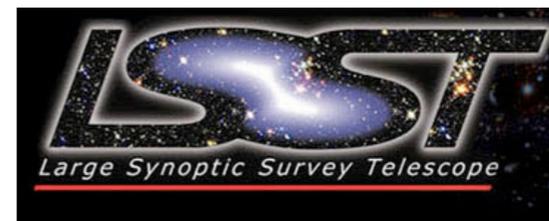
(Nice summary in Hinterbichler 1701.02873)

Can look for signals in, e.g., cosmology

- Weak gravitational lensing
- CMB lensing and the ISW effect
- Redshift space galaxy power spectra
- Combining lensing and dynamical cross-correlations
- The halos of galaxies and galaxy clusters
- You will have heard a lot of this from others.
- Very broadly: Gravity is behind the expansion history of the universe
- But it is also behind how matter clumps up - potentially different.
- This could help distinguish a CC from dark energy from other possibilities
- Much work remains here!



DARK ENERGY SURVEY



Analogy with Particle Physics

Particle Physics

New physics discovery relies on:

- increasing energy of collisions,
 - Allows access to new events that don't appear at lower E.
- increasing accelerator luminosity
 - e.g. produce more Higgs, and measure decay modes more accurately.
 - Can allow very rare decays to be discovered at statistically significant level.

Survey Cosmology

New physics discovery relies on:

- increasing redshift of detection,
 - Allows access to new events and objects absent at lower z .
- increasing number of objects
 - detecting more objects, allows more precise measurements of inhomogeneities.
 - Can allow different signatures in shape of power spectrum to be discovered at statistically significant level.

All allow access to **a lot of** new physics!

(“Cosmic Visions Dark Energy: Science,” arXiv:1604.07626 [astro-ph.CO].)
S. Dodelson, K. Heitmann, C. Hirata, K. Honscheid, A. Roodman, U. Seljak, A. Slosar and M.T.)

Now we have New Tools!



LIGO / VIRGO +DES, etc. are already bounding many of these ideas!

Theory space is about to get narrower. How much?

With a single event (GW170817 and GRB 170817A), huge regions of the modified gravity and related theory space were completely ruled out as solutions for cosmic acceleration.

As we measure more events, these constraints will get much tighter, or a spectacular discovery may be around the corner!



Constraints from from GW170817 and GRB 170817A

A number of relevant papers (particularly <https://arxiv.org/pdf/1710.06394.pdf>)

The landscape for scalar-tensor theories seems to be summarizable as:

$$\mathcal{L} = K(\phi, X) + G_3(\phi, X)\square\phi + G_4(\phi)R \quad X = -1/2(\partial\phi)^2$$

is OK, (G_3 term - trouble w/ ISW in some circumstances (e.g. cubic galileon)).

Anything higher i.e.

$$G_4(\phi, X) + G_{4,X} ((\square\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2) + G_5(\phi, X) \dots$$

is in trouble unless

- the scalar is non cosmological i.e. $\dot{\phi} \ll H_0 m_p$ (similarly other time derivatives)
- there is some sort of tuning between the functions
- there is a tuning in the initial conditions so that all time-derivatives cancel near the present time
- the theories lie in the beyond Horndeski class of theories that are conformally related to the Horndeski subset where $c_T = c$

Caveat: can be parameter tunings and certain initial conditions that give you a small subset of models that just get everything right. Not attractive though.

These Theories are Difficult

- What we're doing is laying out criteria that must be satisfied, by these theories, and others. But so far, it is important to note that, no entirely satisfactory understanding of acceleration exists in the controlled regime. Much more work is needed.
- Screening (particularly Vainshtein) is a very powerful effect - it is better than needed to recover local tests of gravity.
- Its behavior around different sources, and poorly-understood dynamics for t -dependent ones, mean there is much work to do.
- One might consider the uncertainties about sensible UV behavior to be very worrying, but there is serious work to be done to understand whether this is a feature or a bug.
- These ideas may ultimately fail, or require a different understanding of UV behavior to conventional field theories. A theoretical challenge

Summary

- Cosmic acceleration is one of our deepest problems, but also one for which data continues to flood in
- Theory faces serious questions posed by the data, even if a cosmological constant is the right answer. Many theorists are hard at work on this, using insights from cosmology, gravitation, and particle physics.
- In my opinion, we still seem far from a solution, despite some very interesting and challenging new ideas that may find uses beyond this question.
- Many ideas are being ruled out or tightly constrained by combined measurements from surveys and completely new types of measurements from LIGO.
- Serious models only need apply - theoretical consistency is a crucial question. We need (i) models in which the right questions can be asked and (ii) A thorough investigation of the answers.

Thank You!