Dark Energy Theory

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Overview

- Motivations - background, and the problem of cosmic acceleration

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

- 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.

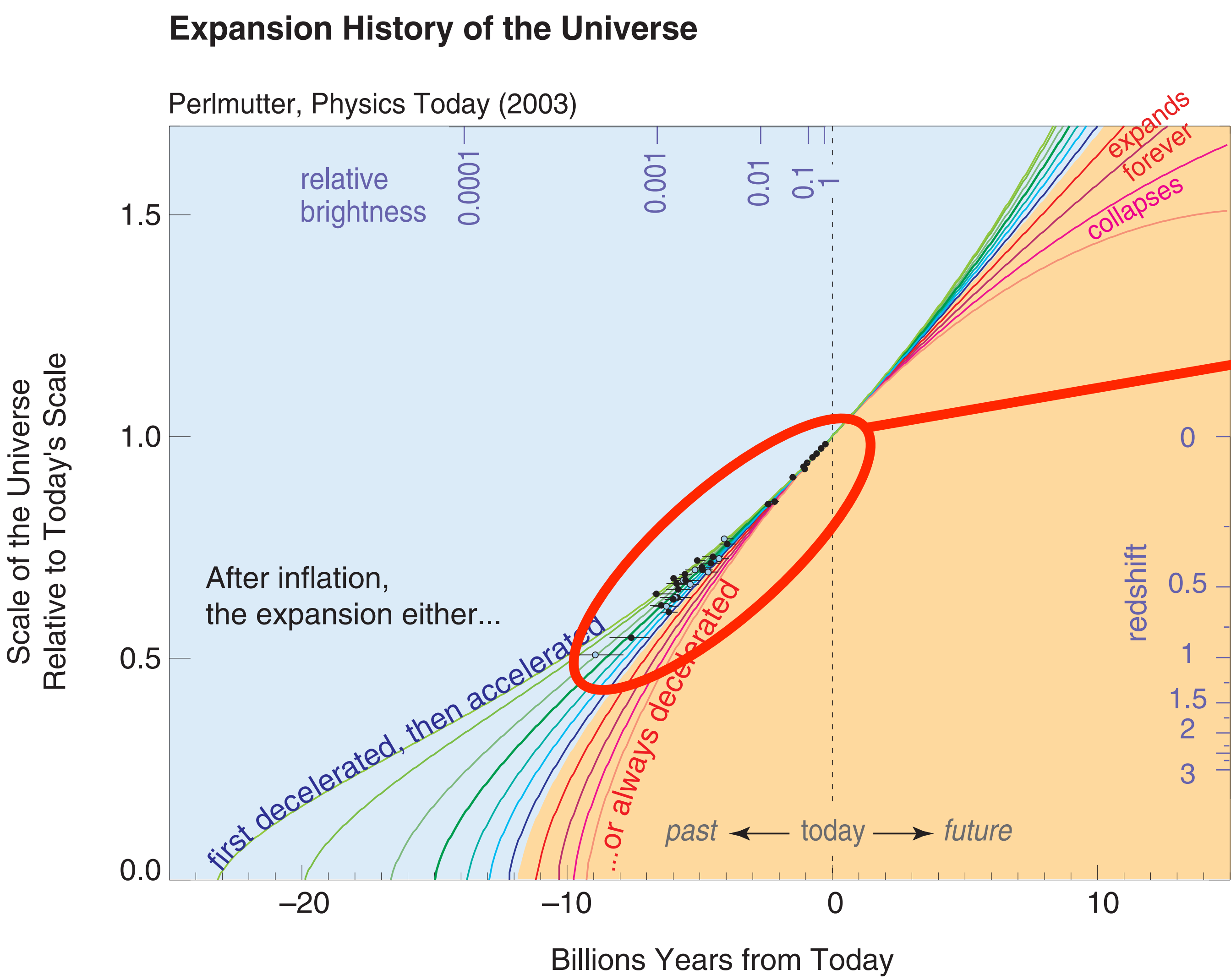
Try to explain how particle physicists think about these things. Useful (hopefully) reference for some of what I'll say

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

Phys.Rept. **568** 1-98 (2015), *[arXiv:1407.0059]*

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!**

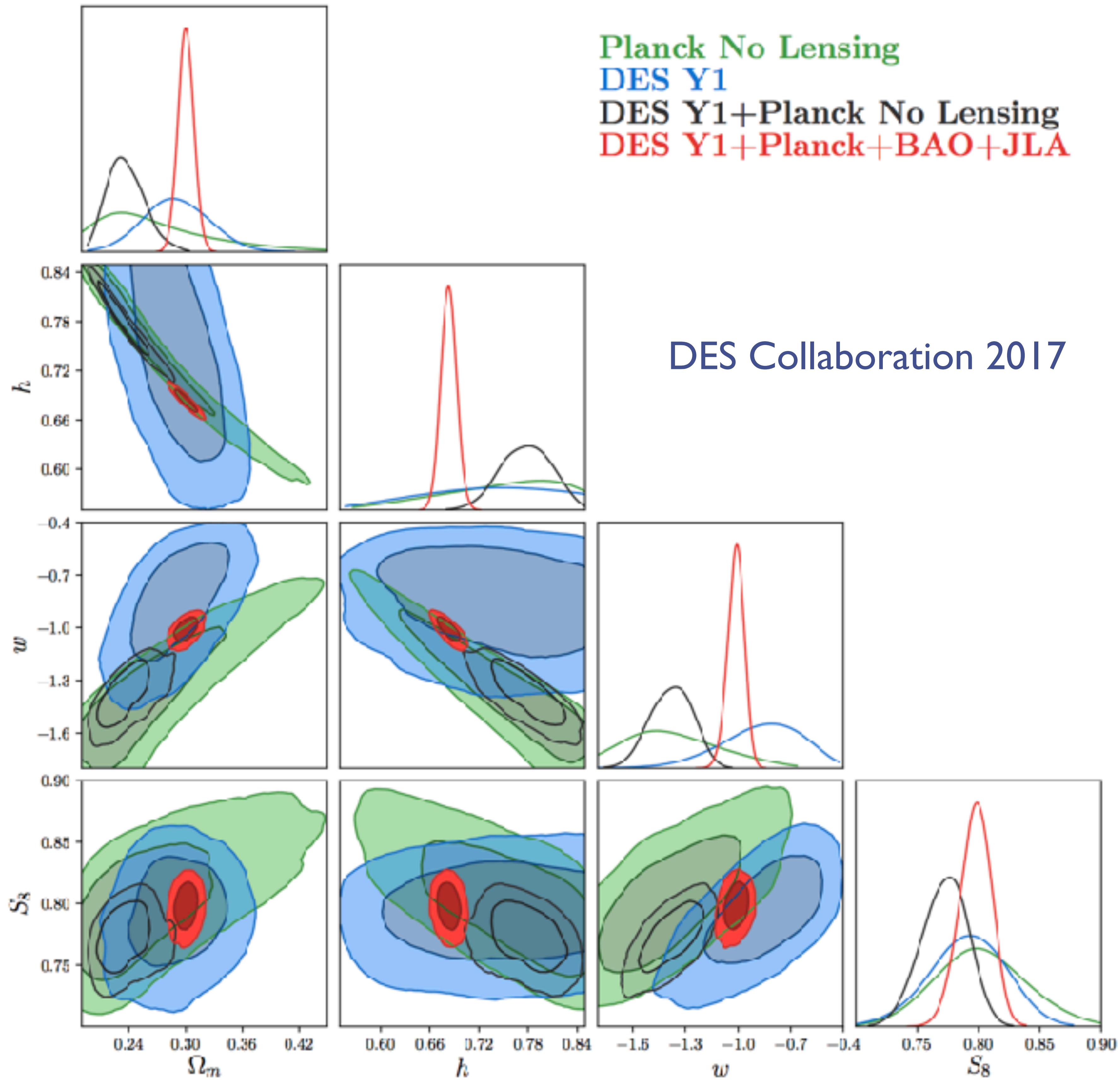
Cosmic Acceleration

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

So, writing p=wρ, accelerating expansion means p<-ρ/3 or

$$\boxed{w<-1/3}$$

$$w = -1.00^{+0.04}_{-0.05}$$



DES Collaboration 2017

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.

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

Most conservative estimate of cutoff: ~ 1 TeV. Gives

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

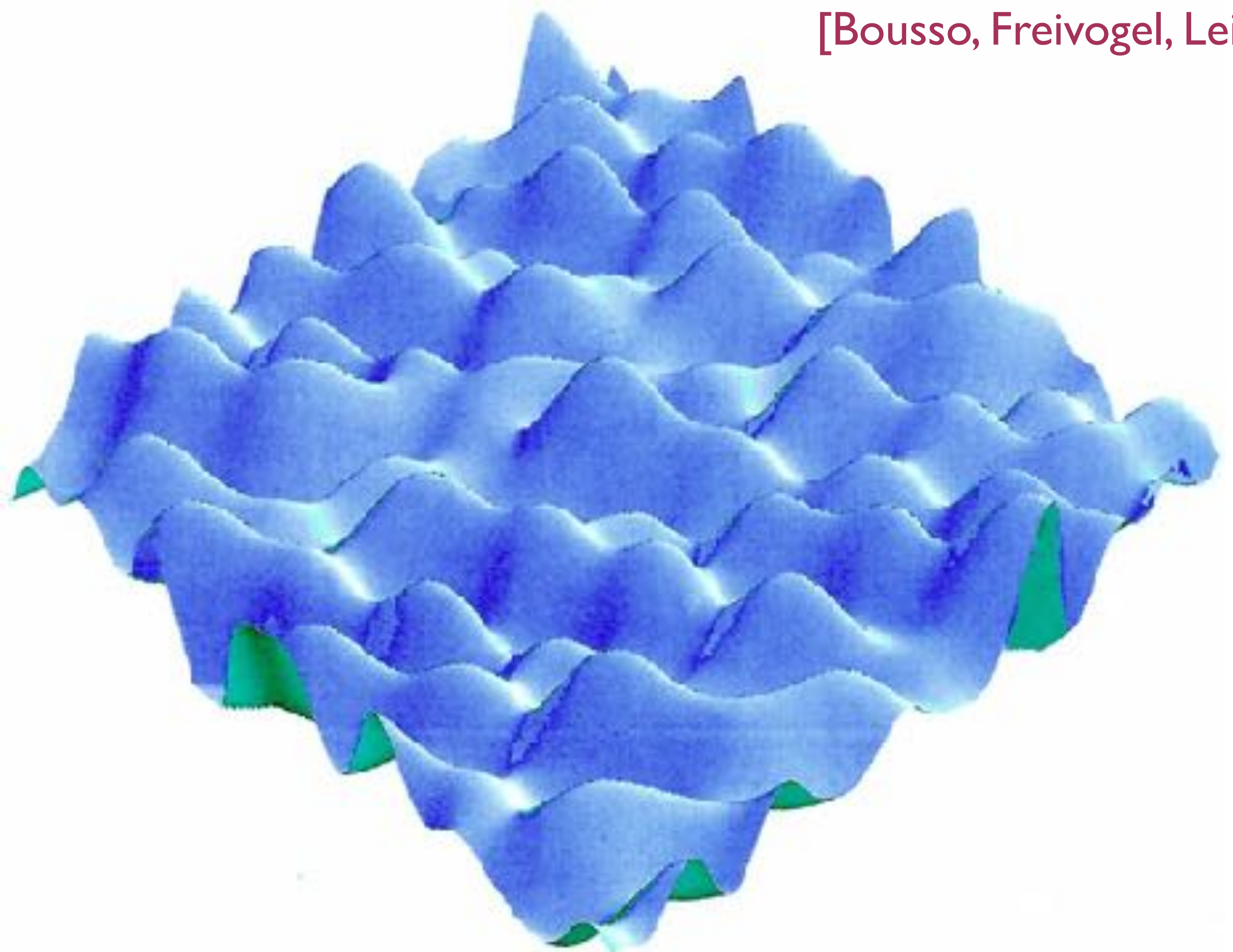
An enormous, and entirely unsolved problem in fundamental physics, made more pressing by the discovery of acceleration!

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 is 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!)

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

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

$$S_m = \int d^4x \, L_m[\phi, g_{\mu\nu}]$$

$$L_m = \frac{1}{2} g^{\mu\nu} \left(\partial_\mu \phi\right) \partial_\nu \phi - V(\phi)$$

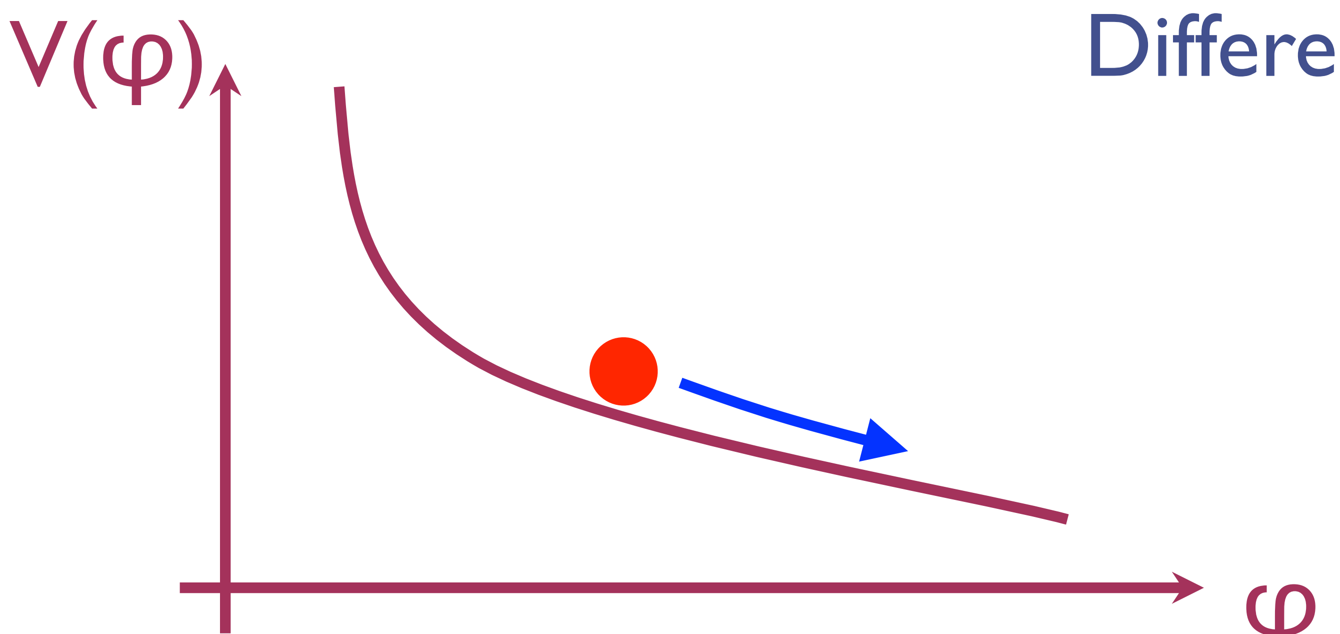
$$T_{\mu\nu} \equiv -\frac{2}{\sqrt{-g}} \frac{\delta S_m}{\delta g^{\mu\nu}}$$

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

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.

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



Difference: no minimum or reheating

$$L = \frac{1}{2}\left(\partial_\mu \phi\right)\partial^\mu \phi - V(\phi)$$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\nabla\phi)^2 + V(\phi)$$

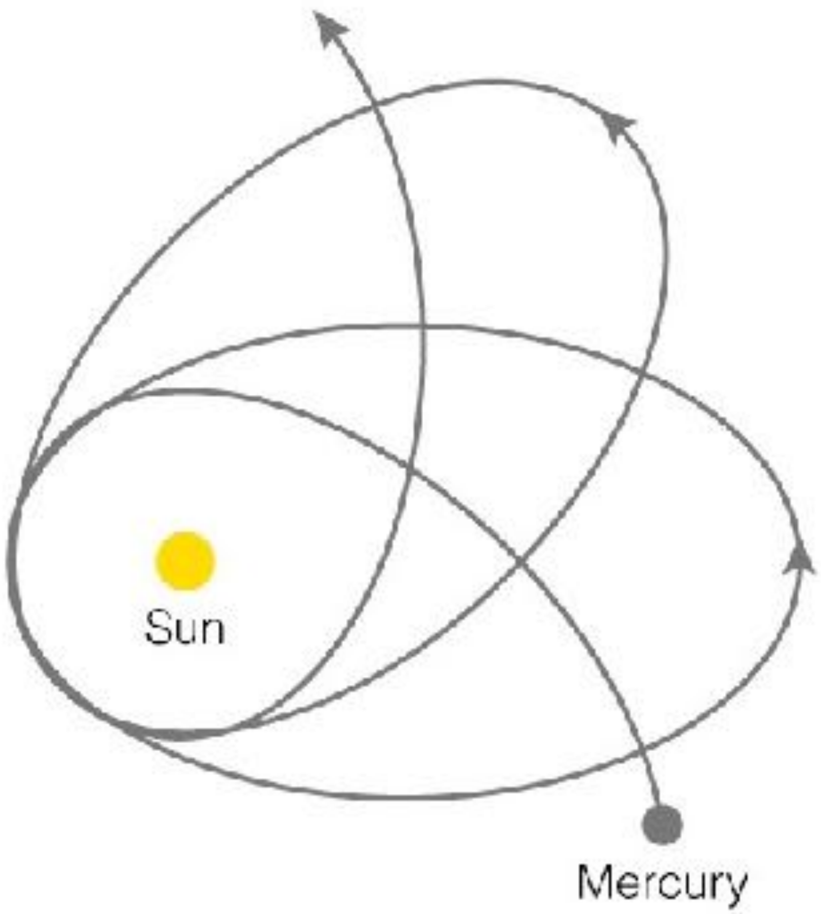
$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

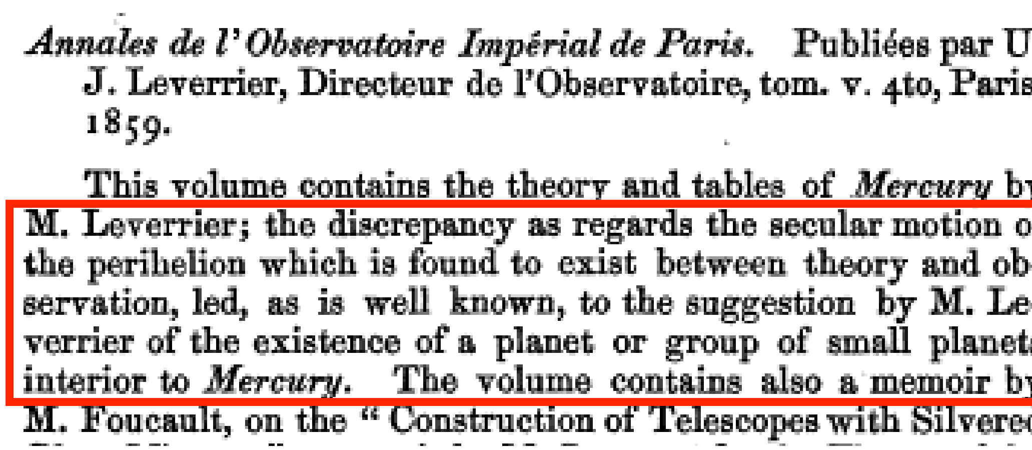
Small slope $\rho_\phi \approx V(\phi) \approx constant$

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

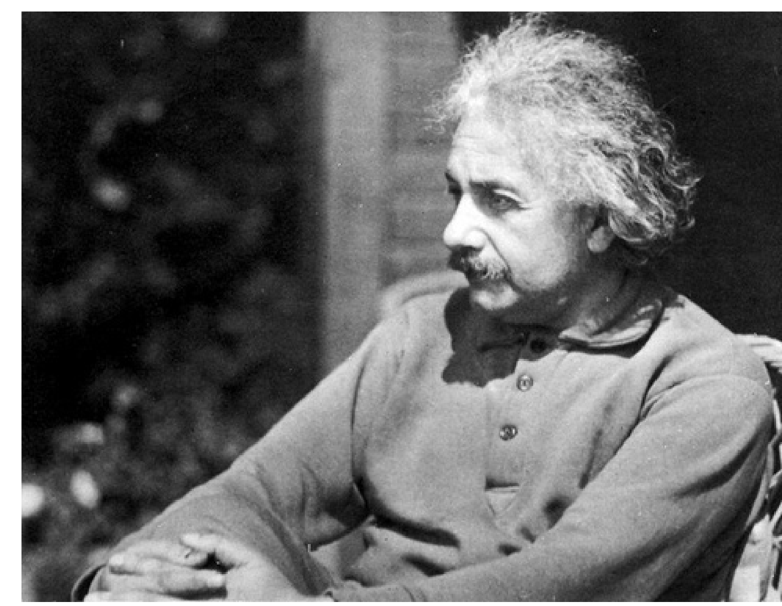
Another Possibility

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?

$$g_{\mu\nu}$$

The graviton:
a spin 2 particle

$$h_{\mu\nu}$$

We're familiar
with this.

$$A_\mu$$

A vector field:
a spin 1 particle

Scalar fields:
spin 0 particles

$$\phi$$

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.

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

- Self Interactions (a potential)

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

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

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

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 <<1 (or at least <1)

$$\frac{E}{\Lambda} << 1 \qquad \text{(Energy << cutoff)}$$

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!

$$G(\chi)\partial_\mu\phi\partial^\mu\phi \longrightarrow f(t)\partial_\mu\phi\partial^\mu\phi \qquad f(t) \to 0$$

e.g. Technical Naturalness

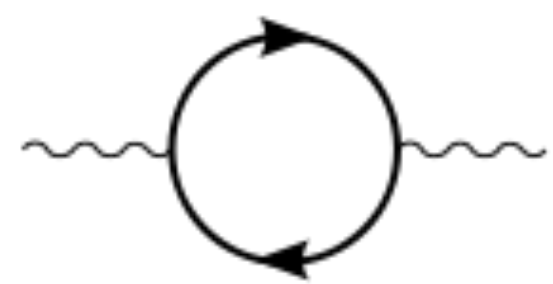
Even if your quantum mechanical corrections do not ruin your ability to trust your theory, any especially small couplings you need might be a problem.

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

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

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.

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



- 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.

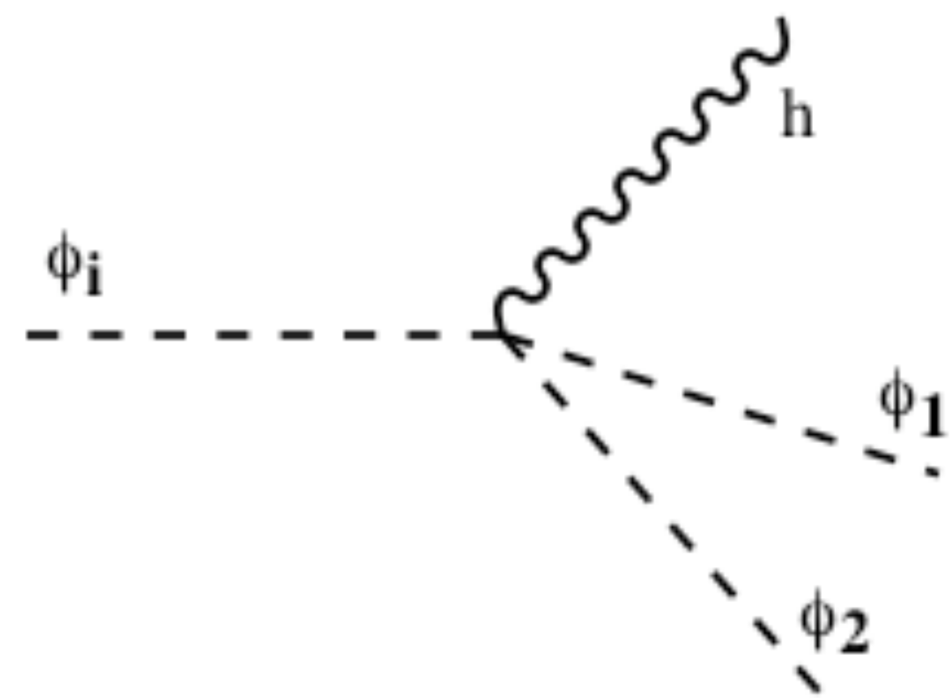
$$-\frac{f(\chi)}{2}K(\partial_\mu\partial^\mu\phi) \rightarrow F(t,x)\frac{1}{2}\dot{\phi}^2 - G(t,x)(\nabla\phi)^2$$

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

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

(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

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

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

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

- 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, …

… & (a little something for the aficionados) Analyticity

Theory may not have a Lorentz-Invariant UV completion! Sometimes can see from 2 to 2 scattering amplitude - related to superluminality: can think of propagation in G as sequence of scattering processes with background field

- Focus on 4-point amplitude $\mathcal{A}(s,t)$ expressed as fn of Mandelstam variables.

- Won't provide details here, but can use analyticity properties of this, with a little complex analysis gymnastics, plus the optical theorem to show

$$\frac{\partial^2}{\partial s^2}\mathcal{A}(s,0)\Big|_{s=0} = \frac{4}{\pi}\int_{s_*}^{\infty} ds\,\frac{\mathrm{Im}\mathcal{A}(s,0)}{s^3} \geq 0$$

So, in forward limit, amplitude must have +ve s^2 part. True for *any* L-I theory described by an S-matrix. Violation implies violation of L-I in the theory.

- There exist other consistency relations in a range of models. In general can conclude

(De Rham et al. (2017))

May have to have a non-Wilsonian, non-LI UV completion of the theory. Might be very challenging!!

A Toy Example

Consider a simple and benign-looking model, that is clearly LI

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

Can compute 2 to 2 scattering amplitude in field theory

$$\mathcal{A}_{2\to 2}(s,t) = \frac{\alpha}{2\Lambda^4}(s^2+t^2+u^2) = \frac{\alpha}{\Lambda^4}(s^2+t^2-st)$$

Take the forward limit t = 0:

$$\mathcal{A}_{2\to 2}(s,0) = \frac{\alpha}{\Lambda^4}s^2$$

So are not free to choose alpha<0 in a Lorentz-invariant theory with an analytic S-matrix. Note also that, in this theory alpha<0 is naively interesting because it exhibits screening. It *also* exhibits superluminality for that choice: Circumstantial evidence for connection between superluminality and analyticity - but not a proof.

The Need for Screening in the EFT

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

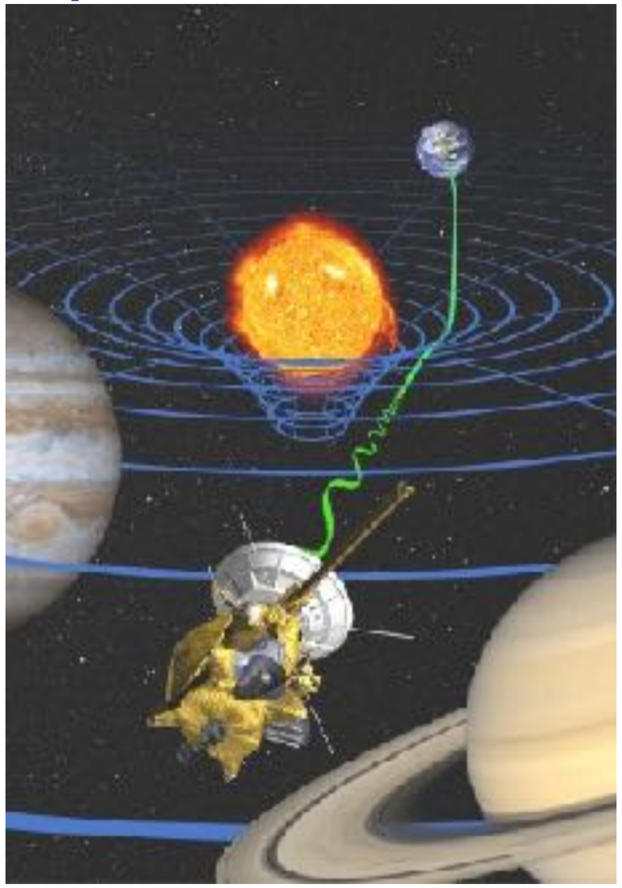
$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, \partial\phi, \ldots)\partial_\mu\phi\partial_\nu\phi - V(\phi) + g(\phi)T^\mu_\mu$$

Specialize to a point source $T^\mu_\mu \to -\mathcal{M}\delta^3(\vec{x})$ 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 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

Eg. The Chameleon Mechanism

Consider the following action:

$$S = \int d^4x\sqrt{-g}\left(\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right) + S_{\rm matter}\left[A^2(\phi)g_{\mu\nu},\psi\right]$$

Acceleration of test particle influenced by scalar field via

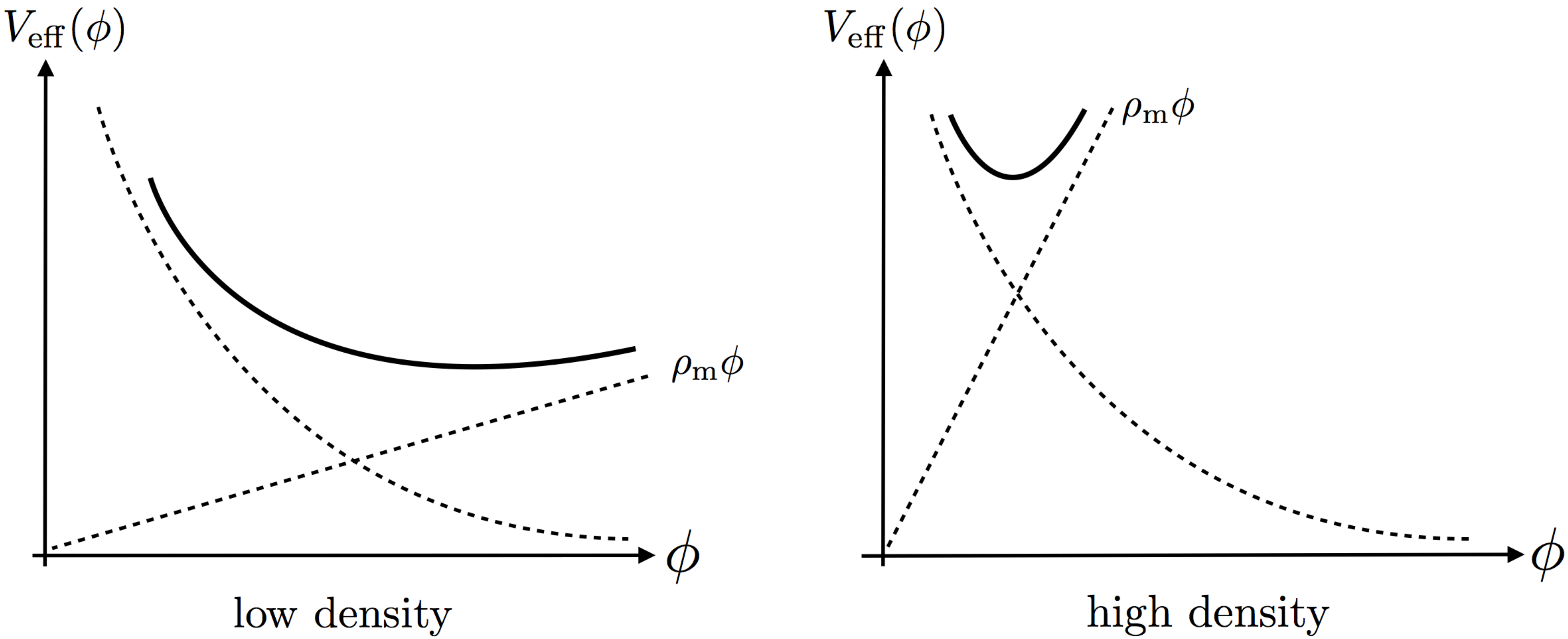
$$\vec{a} = -\vec{\nabla}\Phi - \frac{\mathrm{d}\ln A(\phi)}{\mathrm{d}\phi}\vec{\nabla}\phi = -\vec{\nabla}\Big(\Phi + \ln A(\phi)\Big)$$

Can choose V and A so that scalar propagates freely and mediates fifth force in regions of low Newtonian potential, but force shuts off in high density regions.

Equation of motion

$$\Box\phi = V_{\rm eff\ ,\phi}(\phi) \qquad \text{where} \qquad V_{\rm eff}(\phi) = V(\phi) + A(\phi)\rho$$

Matter density appears in effective potential allows suppression of force due to the scalar field is hidden in regions of high density.



General limitation of chameleon (& symmetron) - and any mechanism with screening condition set by local Newtonian potential: range of scalar-mediated force on cosmological scales is bounded. So have negligible effect on linear scales today, and so deviation from LCDM is negligible. Remain very interesting as way to hide light scalars suggested by e.g. string theory. But won't discuss too much more here, except for an example later. Focus on Vainshtein.

Massive gravity

Quite 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 few years 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: $\pi(x) \to \pi(x) + c + b_\mu x^\mu$

Relevant field referred to as the *Galileon*

(Nicolis, Rattazzi, & Trincherini 2009)

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

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

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

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

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

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

yields

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

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

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

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

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

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

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

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

The usual linear, classical regime of a theory

$$r \gg R_V$$

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

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

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

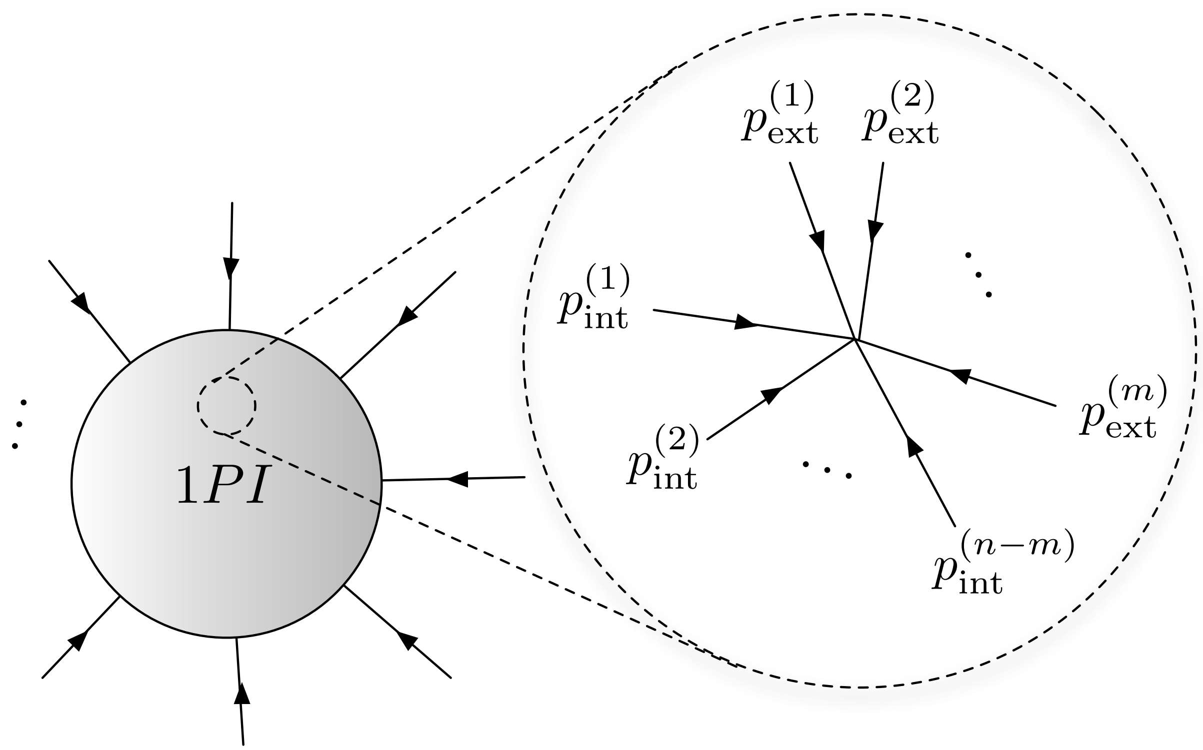
$$r \sim R_V$$

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, Ratazzi (2003); Nicolis, Rattazzi (2004); Hinterbichler, M.T., Wesley, (2010)]

Can even add a mass term and remains technically natural

New Perspective - the Coset Construction

- For those of you who are more mathematically inclined, there is a nice story here that may have implications for, among other things, better understanding the nonrenormalization theorems.

- Since the galilean symmetry in nonlinearly realized, can use the coset construction to build the effective theory. (We've also shown that one can do this for massive gravity!)

[Goon, Hinterbichler, Joyce & M.T., arxiv:1412.6098 [hep-th])

- Galileons are Wess-Zumino terms! In d dimensions are d-form potentials for (d+1)-forms which are non-trivial co-cycles in Lie algebra cohomology of full symmetry group relative to unbroken one. Slightly different stories for DBI and conformal Galileons.

[Goon, Hinterbichler, Joyce & M.T., arxiv:1203.3191 [hep-th])

The Vainshtein Effect is Very Effective!

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

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

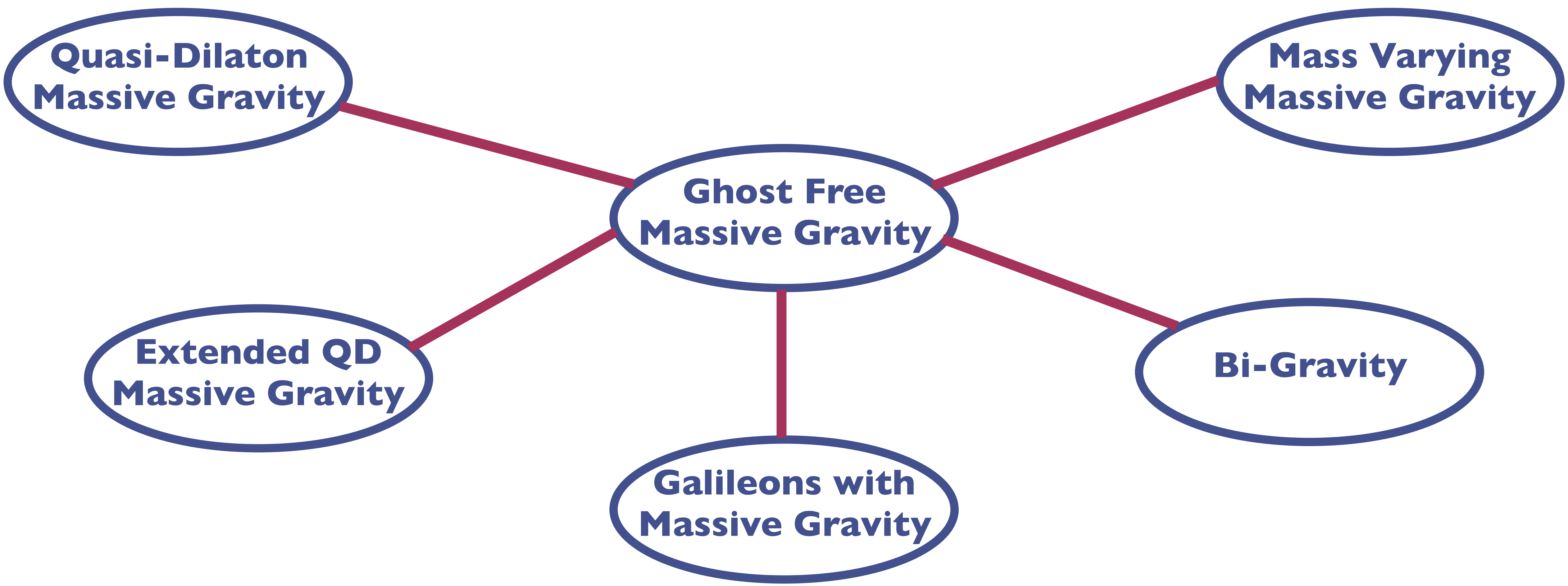
→ ~0.1 kpc = 10^7 AU

→ ~Mpc ~ 30 galactic radii

→ ~10 Mpc ~ 10 virial radii

Is Massive Gravity up to the Job?

- Minimal massive gravity has fascinating features, but faces some cosmological challenges. Solutions not small modifications of GR.
- No flat isotropic accelerating cosmologies. Open ones (w/ a strong coupling problem); or anisotropic ones (not yet analyzed in detail).
- This has led to searches for extensions.



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

Status of Massive Gravity Theories

- Just to give an idea of what has been going on …

	Flat Isotropic Cosmology	Anisotropic Cosmology	Strongly-Coupled Perturbations
dRGT Massive Gravity	NO	YES	YES
Mass Varying Massive Gravity	YES	YES	NO
Quasi-Dilaton Theory	YES	YES	SOME
Extended QD Theory	YES	YES	NO
Galileons w/ Massive Gravity	NO	?	YES
BiGravity	DEPENDS	ON	FORM

(Nice summary in Hinterbichler 1701.02873)

- Again: results are mixed - no definitive model yet in which all calculations are under control.

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

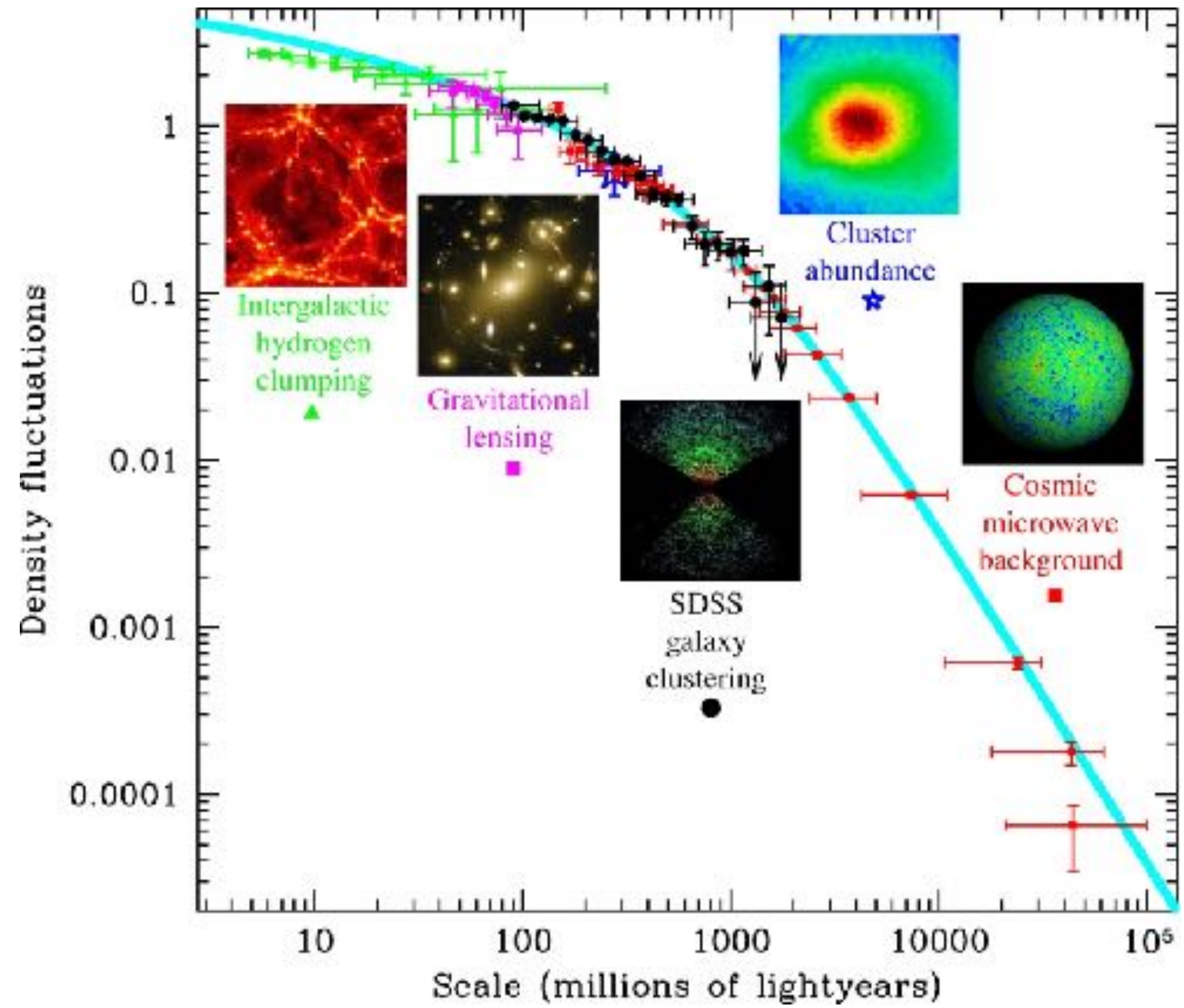
- You will have heard a lot of this from others.

- Very broadly: Gravity is behind the expansion history of the universe

- But it is also behind how matter clumps up - potentially different.

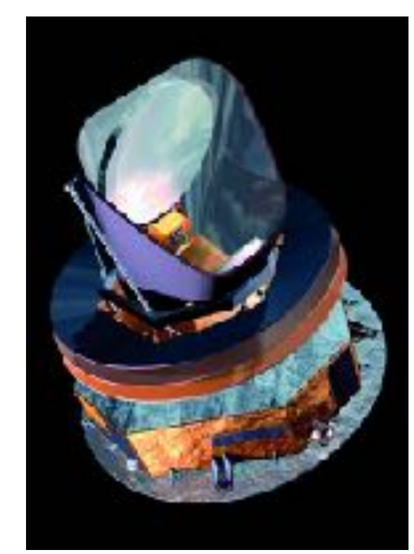
- This could help distinguish a CC from dark energy from other possibilities

- Much work remains here!



DARK ENERGY SURVEY

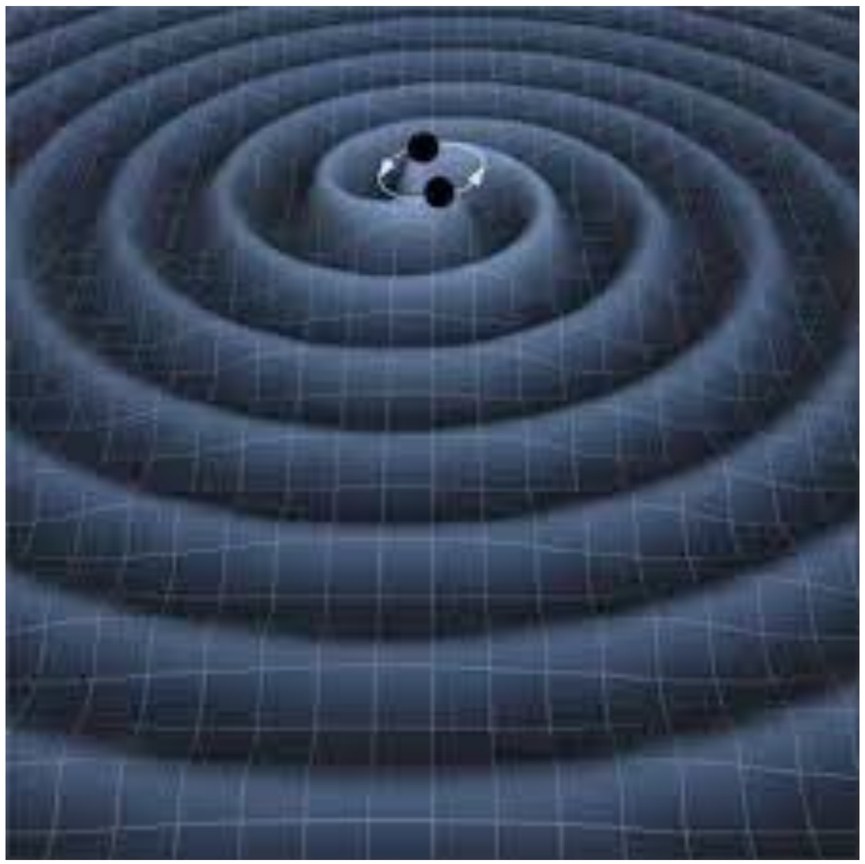
Large Synoptic Survey Telescope



A Final Topical Comment - Galileon Waves

[Chu & M.T.; (also de Rham & Tolley; Matas, de Rham & Tolley)]

- e.g. can construct Galileon retarded Green's function about background field of a central mass (& exact static Green's function)



- Have applied to radiation spectrum due to motion of n point masses gravitationally bound to central mass M.
- Have focused on the non-relativistic limit

Interesting surprise - direct consequence of structure of Galileon radial Green's function.

- In the high frequency limit ($\omega r_{\rm V} \gg l$), get anticipated Vainshtein screening of Galileon radiation at low multipole orders. BUT!
- At high enough multipoles, high frequency Galileon radiation enhanced!

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.
- Vainshtein screening 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: one of our deepest problems
- Questions posed by the data need to find a home in fundamental physics, even if a cosmological constant is the right answerand many theorists are hard at work on this. Requires particle physicists and cosmologists to work together.
- We still seem far from a solution in my opinion, but some very interesting ideas have been put forward in last few years.
- Many ideas (and a lot of ugly ones) being ruled out or tightly constrained by these measurements. And fascinating new theoretical ideas are emerging (even without acceleration)
- 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. (***Beware of theorists' ideas of likelihood.***)

Thank You!