Long wavelength aspects of gravity

Austin Joyce
Center for Theoretical Physics
Columbia University

Testing Gravity 2017, Vancouver

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Outline

General organizing principles for approaching new IR gravitational physics

- Screening mechanisms
- Theoretical consistency
- Dark Energy vs. Modified Gravity

Soft theorems and gravity

- An often hidden assumption in cosmological soft theorems is about the underlying gravitational theory
- Soft theorems both as probes of gravity and as probes of new physics
- Connection to asymptotic symmetries

What can be said in general?

Refs.

Some background info can be found in

Beyond the Cosmological Standard Model

Austin Joyce,[a,b,*] Bhuvnesh Jain,[b,†] Justin Khoury[b,‡] and Mark Trodden[b,§]

[a] *Enrico Fermi Institute and Kavli Institute for Cosmological Physics University of Chicago, Chicago, IL 60637*

[b] *Center for Particle Cosmology, Department of Physics and Astronomy University of Pennsylvania, Philadelphia, PA 19104*

Abstract

After a decade and a half of research motivated by the accelerating universe, theory and experiment have a reached a certain level of maturity. The development of theoretical models beyond Λ or smooth dark energy, often called modified gravity, has led to broader insights into a path forward, and a host of observational and experimental tests have been developed. In this review we present the current state of the field and describe a framework for anticipating developments in the next decade. We identify the guiding principles for rigorous and consistent modifications of the standard model, and discuss the prospects for empirical tests.

We begin by reviewing recent attempts to consistently modify Einstein gravity in the infrared, focusing on the notion that additional degrees of freedom introduced by the modification must "screen" themselves from local tests of gravity. We categorize screening mechanisms into three broad classes: mechanisms which become active in regions of high Newtonian potential, those in which first derivatives of the field become important, and those for which second derivatives of the field are important. Examples of the first class, such as $f(R)$ gravity, employ the familiar chameleon or symmetron mechanisms, whereas examples of the last class are galileon and massive gravity theories, employing the Vainshtein mechanism. In each case, we describe the theories as effective theories and discuss prospects for completion in a more fundamental theory. We describe experimental tests of each class of theories, summarizing laboratory and solar system tests and describing in some detail astrophysical and cosmological tests. Finally, we discuss prospects for future tests which will be sensitive to different signatures of new physics in the gravitational sector.

The review is structured so that those parts that are more relevant to theorists *vs.* observers/experimentalists are clearly indicated, in the hope that this will serve as a useful reference for both audiences, as well as helping those interested in bridging the gap between them.

[*] ajoy@uchicago.edu
[†] bjain@physics.upenn.edu
[‡] jkhoury@sas.upenn.edu
[§] trodden@physics.upenn.edu

1407.0059

Dark Energy vs. Modified Gravity

Austin Joyce,[1] Lucas Lombriser,[2] and Fabian Schmidt[3]

[1] Enrico Fermi Institute and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637; email: ajoy@uchicago.edu

[2] Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, U.K.; email: llo@roe.ac.uk

[3] Max-Planck-Institute for Astrophysics, D-85748 Garching, Germany; email: fabians@mpa-garching.mpg.de

Ann. Rev. Nuc. Part. Sc. 2016. AA:1–29

Keywords

cosmology, dark energy, modified gravity, structure formation, large-scale structure

Abstract

Understanding the reason for the observed accelerated expansion of the Universe represents one of the fundamental open questions in physics. In cosmology, a classification has emerged among physical models for the acceleration, distinguishing between *Dark Energy* and *Modified Gravity*. In this review, we give a brief overview of models in both categories as well as their phenomenology and characteristic observable signatures in cosmology. We also introduce a rigorous distinction between Dark Energy and Modified Gravity based on the strong and weak equivalence principles.

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1601.06133

New degrees of freedom

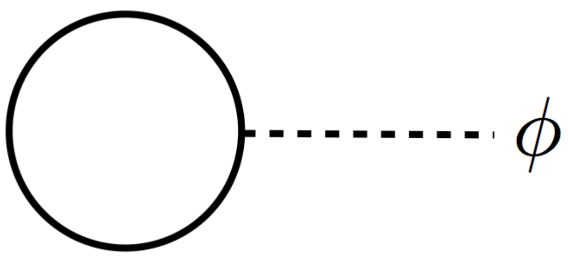
- Why? Einstein gravity is remarkably robust: it is the unique theory of a massless spin-2 field* Papapetrou 1948; Gupta 1952; Kraichnan 1955; Feyman 1962; Weinberg 1965; Deser 1970

- Modifications to Einstein gravity almost ubiquitously introduce *new* degrees of freedom—doing this consistently is *hard*

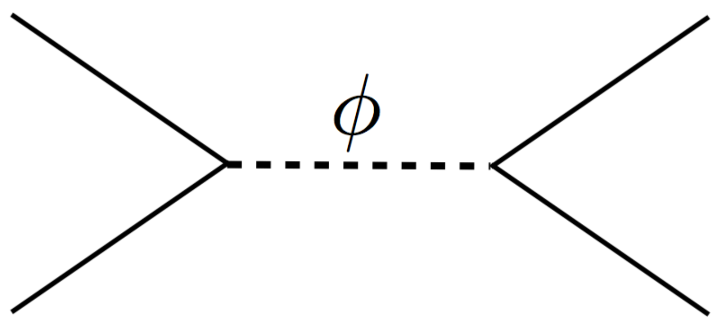
- In order for these new DOF to affect the present day CC, they must have a mass of order Hubble today

$$m \sim H_0$$

- To neutralize the CC, must couple to SM fields



- Unitarity implies that they mediate a force: $\Longrightarrow$



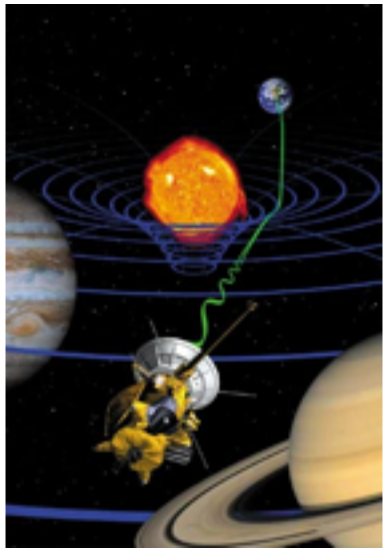
Screening

- 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

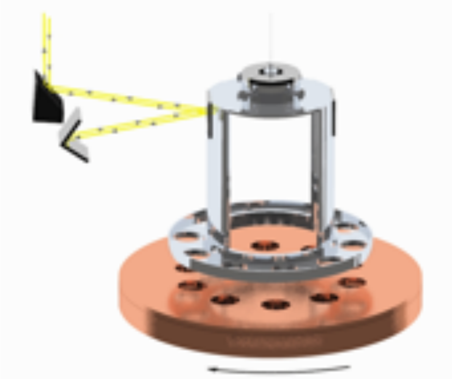
- Ways in which this can be accomplished are called *screening mechanisms*

- Could also just choose to couple very weakly to everything (dark energy)



Cassini (Shapiro time delay)

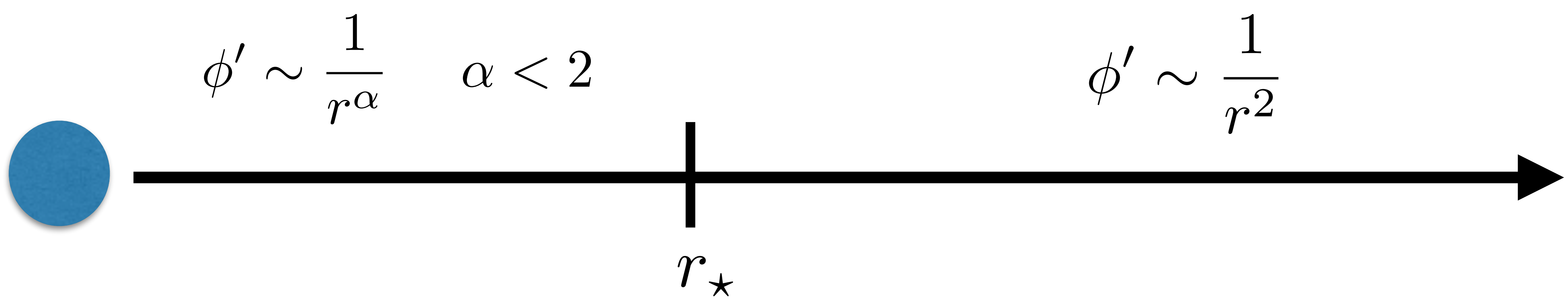
APOLLO (Nordtvedt effect)



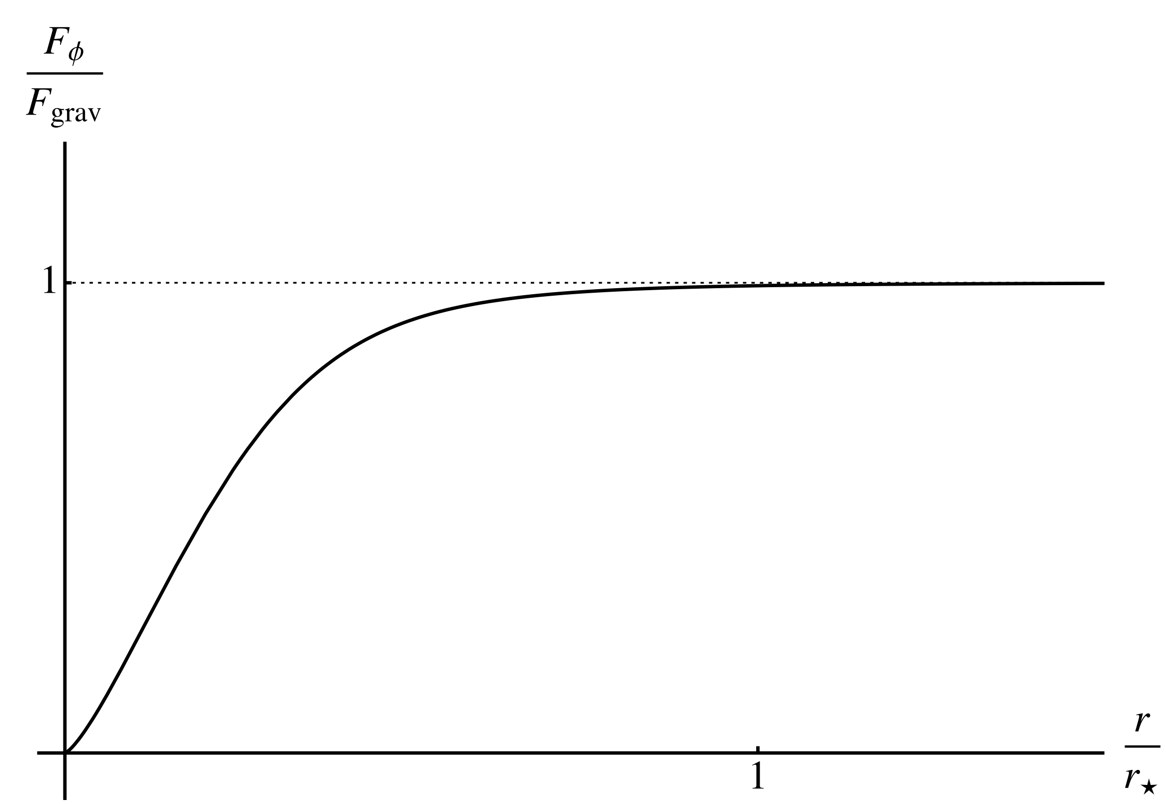
Eöt-Wash (Inverse square law)

Screening fifth forces

- Mechanisms to suppress effects of light degrees of freedom in local environment



- Ratio of fifth force strength to that of gravity drops off sharply



Screening

There are - roughly speaking - three ways to accomplish this

- **Screening by field nonlinearities**:

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

  Chameleon, Symmetron, Dilaton

- **Screening by large first derivatives**:

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

  K-mouflage, DBIonic screening

  characteristic scale: $r_\star \sim \frac{1}{\Lambda_{\rm s}}\left(\frac{M}{M_{\rm Pl}}\right)^{1/2}$

- **Screening by large second derivatives**:

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

  Vainshtein: Galileon, massive gravity

  characteristic scale: $r_{\rm v} \sim \frac{1}{\Lambda_{\rm s}}\left(\frac{M}{M_{\rm Pl}}\right)^{1/3}$

- Screening is typically very efficient: it is a bit of a challenge to find astrophysical objects that *aren't* screened

Double Screening

Gratia, Hu, AJ, Ribeiro 1604.00395

I have presented the above classification as exclusive, but there can be interesting interplay between different terms which want to screen

- Consider for example the theory

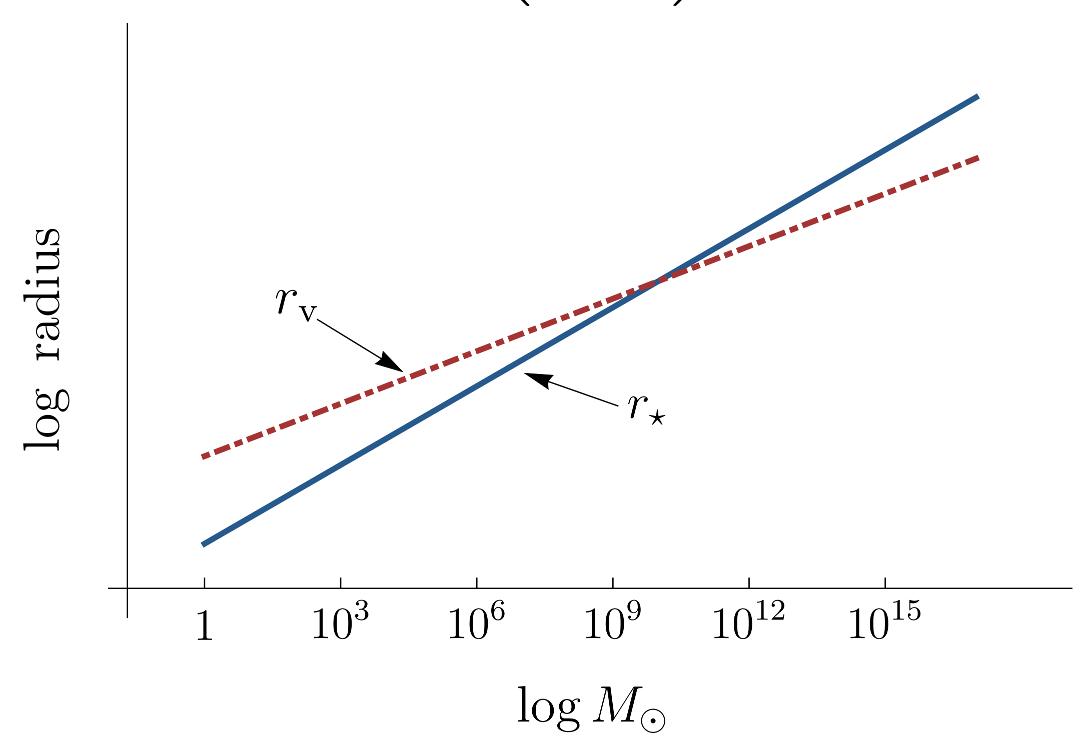
$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda_{\rm v}^3}\Box\phi(\partial\phi)^2 - \frac{1}{\Lambda_\star^4}(\partial\phi)^4 + \frac{g\phi}{M_{\rm Pl}}T$$

- Around a massive source there are two characteristic scales

$$r_\star \sim \frac{1}{\Lambda_\star}\left(\frac{M}{M_{\rm Pl}}\right)^{1/2} \qquad\qquad r_\star \sim \frac{1}{\Lambda_{\rm v}}\left(\frac{M}{M_{\rm Pl}}\right)^{1/3}$$

- They depend differently on the enclosed mass:

- Possibility for novel signatures



Dark Energy vs. Modified Gravity

AJ, Lombriser, Schmidt 1601.06133

A way to distinguish between the two is via the Strong Equivalence Principle

- SEP says: all test bodies gravitate in the same way (follow geodesics of the same metric) even including gravitational self-energy contributions. So, for example, a feather and a black hole fall along the same trajectory.

Call anything which satisfies the SEP Dark Energy and everything else Modified Gravity. Can think of this as a *definition*.

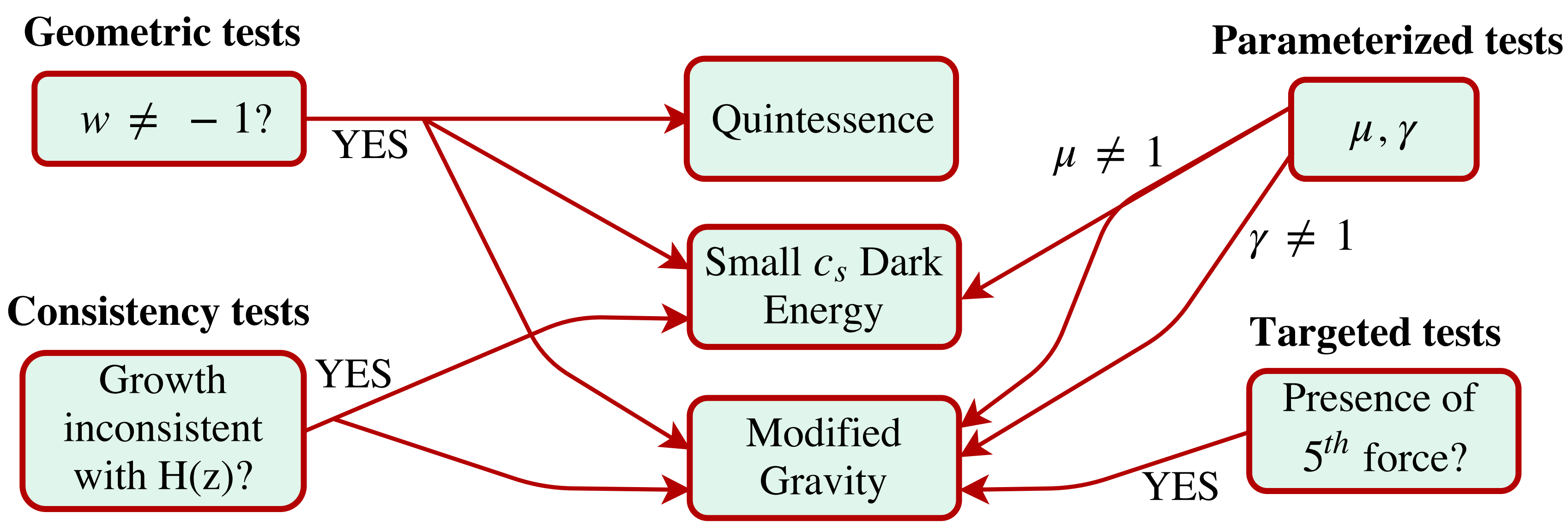
- Motivation comes from scalar tensor theories, can be cast in the form

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

- Assume all Ai are the same (WEP), then in models with A = 1, ϕ only affects visible matter through its stress energy, otherwise ϕ mediates a 5th force

Above definition extends this intuitive picture to more abstract settings

Is it possible to distinguish these things?



There are a few avenues through which we might hope to distinguish between MG, DE and Lambda

- Directly measure the expansion history, if we find that *w* is different from -1, or is changing in time, this rules out a CC
- Measure both the expansion history and growth of structure: in LCDM or in simple quintessence models, structure formation is fixed by the H(t); deviations from this imply either exotic DE or some kind of MG
- Directly parameterize deviations from GR and constrain these parameters (for example by comparing dynamical and lensing masses of objects)
- More targeted tests (lab searches, E_G ,…..)

Soft theorems

Soft theorems

- In the last few years, there has been a lot of progress in exploring cosmological correlators in the limit where one of the external particles is soft

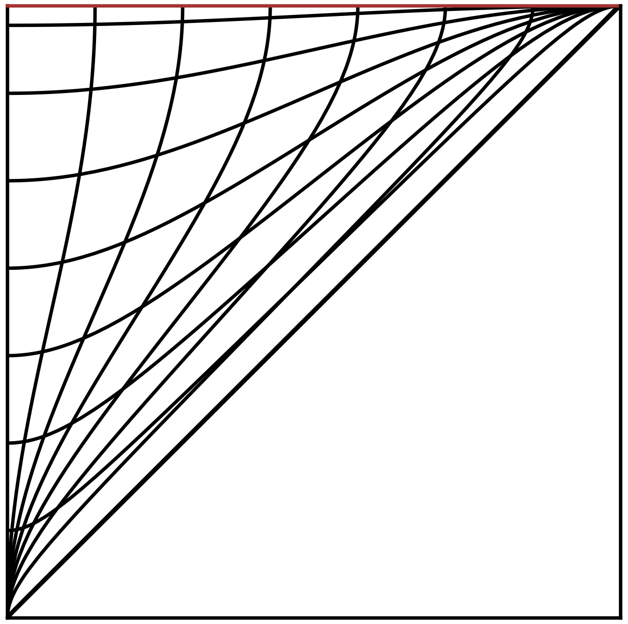
- These soft limits probe the underlying symmetry structure of a theory

My focus will be on soft limits of primordial correlators

- There has also been a lot of work on soft limits of LSS correlation functions, these also probe interesting physics—tests of the equivalence principle in particular

- There is a relationship between these cosmological soft theorems and asymptotic symmetries, which parallels the flat space scattering amplitude story

Inflation as SSB



Inflation ends - spacetime cannot be exact de Sitter

- EFT of inflation: Cheung, Creminelli, Fitzpatrick, Kaplan, Senatore 0709.0293

- There must be a *clock* telling inflation when to end - the inflaton is this clock. This picks out a preferred foliation of de Sitter, $\phi(t)$ is the order parameter

- Fluctuations of this clock $\rightsquigarrow$ fluctuations of the spatial slices

- What is the Nambu-Goldstone mode of this symmetry breaking? (curvature perturbation)

ζ is the Goldstone

- We are working in the context of a homogeneous FLRW background cosmology

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

- We now want to perturb both the metric and the scalar and study the perturbations

- In order to do this, we typically have to fix a gauge, a convenient choice is to use ADM variables

$$\mathrm{d}s^2 = -N^2\mathrm{d}t^2 + h_{ij}(\mathrm{d}x^i + N^i\mathrm{d}t)(\mathrm{d}x^j + N^j\mathrm{d}t)$$

  and fix the spatial metric to be $h_{ij} = a^2(t)e^{2\zeta}\left(e^{\gamma}\right)_{ij}$

  along with leaving the scalar unperturbed $\delta\phi = 0$

- Standard procedure: solve for lapse and shift, plug back in to the action to get an action for only ζ and γ

Residual symmetries

- Even after gauge-fixing, there are always residual "large gauge transformations" which act as genuine symmetries

$$h_{ij} = a^2(t)e^{2\zeta}\left(e^{\gamma}\right)_{ij}$$

- Setting the tensors to zero for the time being, there are residual diffs:

$$\xi^i = \lambda(t)x^i \qquad\qquad \xi^i = 2b^j(t)x_jx^i - \vec{x}^2b^i(t)$$

- These lead to a shift of ζ of the form:

$$\delta\zeta = \lambda(t)\left(1+\vec{x}\cdot\vec{\nabla}\right)\zeta \qquad\qquad \delta\zeta = 2\vec{b}(t)\cdot\vec{x} + \left(2\vec{b}(t)\cdot\vec{x}x^i - \vec{x}^2b^i(t)\right)\partial_i\zeta$$

these should be symmetries of the gauge-fixed action

From adiabatic modes to soft theorems

- Adiabatic modes are physical profiles that can be introduced by a diffeomorphism (restricts the residual symmetries)

- A local observer should not be able to tell whether or not they are in such a long-wavelength background

- A correlation function in the presence of a soft mode is related to a correlator without the soft mode, but in transformed coordinates

$$\langle \zeta(x_1) \cdots \zeta(x_n) \rangle_{\zeta_L} = \langle \zeta(\tilde{x}_1) \cdots \zeta(\tilde{x}_n) \rangle$$

- Leads to

$$\lim_{\vec{q} \to 0} \frac{1}{P_\zeta(q)} \langle \zeta_q \zeta_{k_1} \cdots \zeta_{k_N} \rangle' = \delta_D \langle \zeta_{k_1} \cdots \zeta_{k_N} \rangle' = -\left(3(N-1) + \sum_{a=1}^{N} \vec{k}_a \cdot \vec{\nabla}_{k_1} \right) \langle \zeta_{k_1} \cdots \zeta_{k_N} \rangle'$$

Soft limits in cosmology

- Require the following technical assumptions:
  - there is only a single clock (roughly, single field)
  - modes start in the Bunch-Davies vacuum
  - ζ goes to a constant at long wavelengths

- These relations are sharp null-tests, and violations of them can be striking signatures of new physics (example: Quasi-single field inflation)

$$\lim_{q\to 0}\frac{1}{P_\zeta(q)}\langle\zeta_q\zeta_k\zeta_k\rangle = -(n_s-1)P_\zeta(k)+\mathcal{O}\left[\left(\frac{q}{k}\right)^\Delta P_s(\cos\theta)\right] \qquad \Delta=\frac{3}{2}-\sqrt{\frac{9}{4}-\frac{m^2}{H^2}}$$

- Characteristic signature of new particles in the squeezed limit

- How general are these statements?

When is ζ constant?

Hu, AJ 1612.02454

- The curvature going to a constant in the long-wavelength limit holds in many situations beyond GR

- It is key to the inflationary consistency relations, and also to separate universe constructions—idea is that a local observer in a long-wavelength background sees an FRW universe w/ different parameters

- Many ways to phrase the result, but the simplest is that in comoving gauge (with flat spatial slices), the curvature evolves as

$$\zeta' = \delta N$$

so if the lapse perturbation is small compared to the curvature, the curvature will be conserved in the long wavelength limit

When is ζ constant?

Hu, AJ 1612.02454

- No equations of motion are needed to derive this statement—has a fully geometric characterization: if comoving and synchronous gauge approximately coincide, curvature will be conserved

- Newtonian gauge consequence of this statement:

$$\Phi'' - \Psi' - \frac{H''}{H'}\Phi' - \left(\frac{H'}{H} - \frac{H''}{H'}\right)\Psi = 0$$

This relation between the metric potentials is very general, a measurement of a deviation from this relationship would be striking

Asymptotic symmetries

Hinterbichler, AJ, Khoury 1609.09497

- Asymptotic symmetries: the group of diffeomorphisms which preserve the asymptotic structure of the theory (some boundary conditions)

  - *E.g.* in flat space for gravity, the asymptotic symmetry group is the set of all diffeomorphisms which preserve the structure at null infinity, form the BMS group

- The group that you get depends on the boundary conditions that you demand, there is no unique asymptotic symmetry group

- The adiabatic mode transformations in inflation are in one-to-one correspondence with the asymptotic symmetries of de Sitter space—this can be made very explicit in dS_3

Conclusions

- The infrared structure of gravity is quite rich: cosmic acceleration remains a puzzle, and soft limits of cosmological correlators contain a lot of information

- There is a set of general principles we can apply to characterize the space of possible new physics

- The behavior of soft limits is surprisingly universal—deviations from these relationships would signal interesting new physics

- There is an intriguing connection between soft theorems and asymptotic symmetries, which is worth investigating further