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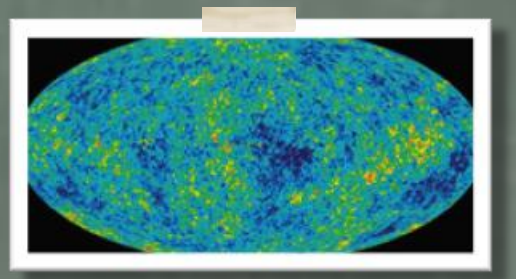
Effective Field Theory in Cosmology

Clues for cosmology from fundamental physics



Outline

- Motivation and Overview
- Effective field theories throughout physics
  - Decoupling and 'naturalness' issues
- Quantum effects in gravity: Fighting the 'split brain'
  - Living with gravity's non-renormalizability
  - Naturalness issues
- Relevance to cosmology
  - A brief cold shower
  - Inflation, Dark matter and Dark energy

4. A (personal) effective take on cosmology

- Good news and a cold shower
- Inflation
- Dark matter
- Dark energy

4.1 Some good news

- What do people really do when they make a cosmological model?
  - Make up some theory
  - Solve the theory's classical equations for a cosmological solution
  - Perhaps compute perturbations about this solution, such as to compute primordial fluctuations
- Good news:
  - Since the energy scales are small compared with M_p, classical approximation is usually good,
  - Also (for inflation) quantum fluctuations of order H/M_p can be small enough to be sensible, yet large enough to be observable

4.1 Two Cold Showers

§ Trans-planckianism

§ Emergence and Lorentz invariance

4.1 Two Cold Showers

- Trans-planckianism
  - Less concrete version: Since we don't understand quantum gravity (at short distances), how do we know that trans-Planckian physics decouples from long-wavelength physics?
- Cannot answer for sure without knowing the physics above the Planck scale. But:
  - Trans-planckian physics appears to decouple in string theory.
  - Proponents of theories where decoupling fails must also explain why any understanding of cosmology is possible at all (ie they are admitting to an uncontrolled theoretical error)

4.1 Two Cold Showers

- § Trans-planckianism (cosmological exceptionalism)
  - More precise version: Isn't cosmology a unique situation for which insights from EFTs in other areas do not apply?
    - In particular: doesn't inflation (or Hawking radiation) violate decoupling by stretching initially short-wavelength modes out to longer distances?
- § Descent of modes from high energy is not special to gravity:
  - similar effects can also happen in other time-dependent settings (like the collapse of Landau levels $E = n\,\omega$ with $\omega \propto B$ when magnetic field B is turned off).
  - Normally the appearance of such states has no low-energy effects, so long as the time dependence is adiabatic.

4.1 Two Cold Showers

- Effective field theory can only capture adiabatic evolution in the full theory (this is the main new condition for its validity)
  - When thinking about solutions to field equations a more useful way to think about integrating out a heavy field at tree level is as evaluating the action with the heavy field at its vacuum solution (as an adiabatic function of the light fields)

4.1 Two Cold Showers

§ Effective field theory can only capture adiabatic evolution in the full theory (this is the main new condition for its validity)

– For example, for the theory:

$$L = \dot{\varphi}^2 + \dot{\psi}^2 - M^2\psi^2 - g\,\varphi^2\psi$$

Feynman tree graphs give

$$L_{eff} = \dot{\varphi}^2 - \frac{g^2}{2M^2}\,\varphi^4 + \cdots$$

4.1 Two Cold Showers

§ Effective field theory can only capture adiabatic evolution in the full theory (this is the main new condition for its validity)

– Field equations for heavy field in the full theory:

$$\ddot{\psi} + M^2\psi = -\frac{g}{2}\varphi^2$$

have solutions

$$\psi = -\frac{g}{2M^2}\varphi^2 + \cdots$$

and so another way to think about L_{eff} (at tree level) is

$$L_{eff}(\varphi) = L(\varphi, \psi(\varphi))$$

4.1 Two Cold Showers

§ This makes it clear that classical solutions of the effective theory agree - order by order in $1/M$ - with those of the full theory

– But more general solutions for $\psi(\varphi)$ also exist

$$\ddot{\psi} + M^2\psi = -\frac{g}{2}\varphi^2$$

has general solution

$$\psi = \sum_{k=\mp} c_k e^{ikMt} - \frac{g}{2M^2}\varphi^2 + \cdots$$

and so equations of motion of the EFT only agree with those with $c_k = 0$: that is, the adiabatic solutions of the full theory: $\dot{\psi}/\psi \ll M$

A Cold Shower

- Emergent Lorentz invariance: can Lorentz invariance be emergent as an 'accidental' symmetry at low energies, if it is not present at high energies
  - Could they be like Baryon-number conservation, which emerges as an accidental symmetry in GUTs only in the limit $M \to \infty$?

$$L_{eff} = L_{sm} - \frac{g^2}{2M^2} qqq\ell + \cdots$$

A Cold Shower

- Possibly, but Lorentz invariance is not as easy to hide at long distances as is Baryon invariance:
  - Very hard to keep Lorentz-violating interactions from arising unsuppressed by powers of $1/M$
  - For example effective interactions that give $\dot{\varphi}^2$ and $(\nabla\varphi)^2$ different coefficients are usually not ruled out by other symmetries, and arise for all particle types with dimensionless coefficients
  - Constraints on such interactions, which give different particles different maximum speeds, require them to be small (sometimes smaller than $\sim 10^{-20}$)

4.2 Inflation

§ Classical Approximation

§ Very light vs cosmologically light scalars

4.2 Inflation

- Testing the classical approximation:
  - Usually slow-roll inflationary models are well within the classical regime, since the scalar energy scale is small compared with M_p
  - Quantum fluctuations are small but potentially observable

- Not all models are equally under control (so must check on a model-by-model basis)

4.2 Inflation

§ Models that inflate based on higher-curvature interactions:

$$L \approx M_p^2 R + \zeta R^2 + \cdots$$

– inflates with $R = H^2 = M_p{}^2/\zeta$

– gives right primordial density fluctuations if $\zeta \sim 10^8$.

4.2 Inflation

§ What seems suspicious is that successive terms in the curvature expansion are equal size (and not because the first term was particularly small)

- Should the dimensionless part of the coefficient of the R^3 term be order 1 or order ζ^2?
- Naively multiple insertions of R^2 interaction into loops shows that the low energy approximation requires $\zeta Q^2/M_p{}^2$ be small, and in particular be small for $Q \sim H$
- Time dependence is $a(t) \sim e^{Ht}$ with $H \sim M_p/\sqrt{\zeta}$ seems hard to understand as agreeing with full theory order by order in $1/M$

4.2 Inflation

§ Light, and cosmologically light, scalars

- It is generically hard to have scalar masses (and φ^3 coupling) smaller than high-energy scale: $m \ll M$
- Cosmological applications require more: since they require $m \ll H \sim M^2/M_p$
- Sensitive to "Planck Slop":

$$L_{eff} = V_0 - \frac{V_0}{{M_p}^2}\,\varphi^2 + \cdots$$

4.2 Inflation

§ Opportunities:

- Because it is hard, but not impossible, to have scalars this light (eg almost goldstone bosons, supersymmetric scalars or extra-dimensional moduli) they are an opportunity: focus on those models for which such scalars are natural
- Since Planck slop can be important, it is worth exploring sensible underlying theories (like string theory) to see if they can avoid producing it
  - Can be done, and tend to find many scalars, of which more than one becomes cosmologically light if one does. New signals & mechanisms?

4.3 Dark matter

- Dark matter vs modified gravity:
  - Since the evidence for dark matter and dark energy is all based on how they gravitate, it seems much more attractive to modify gravity than to postulate two kinds of new stuff
- True, but the devil is in the details:
  - Notoriously difficult to sensibly modify gravity at long distances, due to the delicate consistency between quantum mechanics and special relativity
  - No extant proposals account for all of the evidence for Dark matter
  - By contrast particle/scalar dark matter candidates are easy

4.4 Dark energy

§ Extremely light scalars

w Leo van Nierop

idea: hep-th/0304256, hep-ph/0404135

mechanism: 1012.2638; 1101.0152; 1108.0345

some implications: 1103.4556; 1108.2553

§ The cosmological constant problem

- Normally these are regarded as two independent bad things;
- I claim the second implies the first (and may make wimp dark matter unlikely, among a host of other observable predictions).

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4.4 Dark energy

- The cosmological constant problem
  - Is very difficult because it requires modifying properties of how light particles, like electrons, gravitate without ruining the success of our non-gravitational understanding of these particles
  - Party line is that there is no known solution, so it cannot yet be used to distinguish among proposals

- My claim:
  - A solution exists if there are two extra dimensions, as large as they can be (micron sized),
  - that are also supersymmetric

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4.4 Dark energy

§ Doubling down

- There is no evidence yet for extra dimensions, let alone large ones.
- There is no evidence yet that supersymmetry plays a role in nature

"...when you have eliminated the impossible, whatever remains, however improbable, must be the truth." ~ A. Conan Doyle

4.4 Dark energy

§ Why can extra dimensions help?

The CC Problem in essence:

Einstein's equations make a lorentz-invariant vacuum energy (which is generically large) an obstruction to a close-to-flat spacetime (which we see around us in cosmology)

$$T_{\mu\nu} = \lambda \, g_{\mu\nu}$$

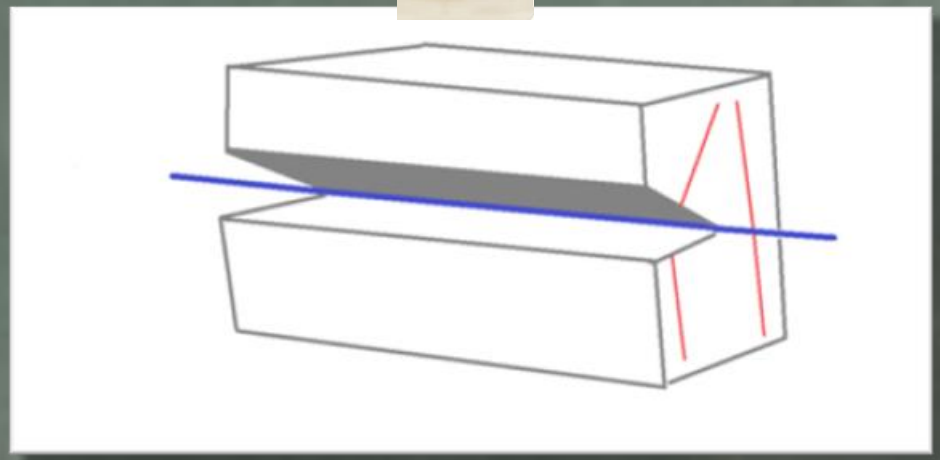
$$G_{\mu\nu} = 8\pi G \, T_{\mu\nu}$$

But this need not be true if there are more than 4 dimensions!!

4.4 Dark energy

§ Why can extra dimensions help?

— Need not be lorentz invariant in the extra dimensions
— Vacuum energy might curve the extra dimensions, rather than the ones we see in cosmology (like the gravity field of a cosmic string)

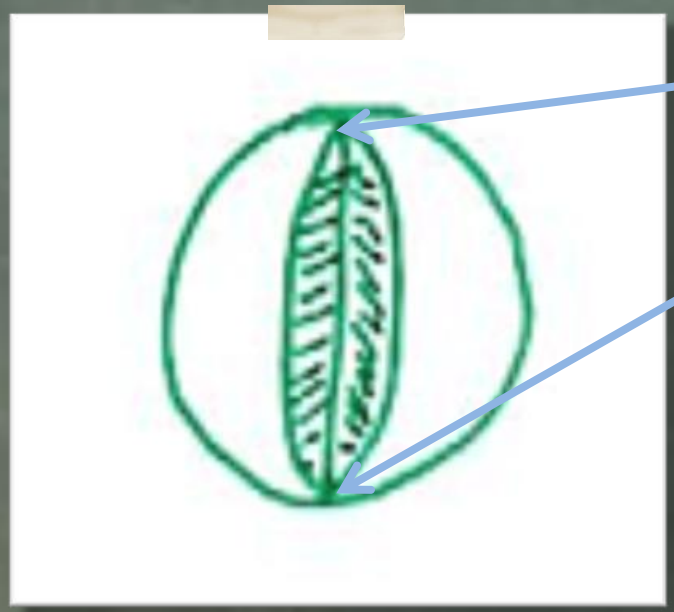


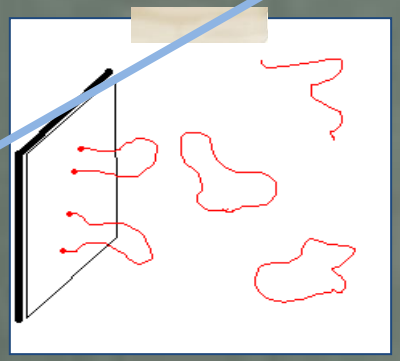
4.4 Dark energy

§ A higher-dimensional ana

— Similar (classical) examp
4D source (or brane) situ
ball and related solutions)

Notice: this framework manages to modify how things on the brane gravitate without strongly modifying other interactions





Particles can be localized on surfaces (branes or defects)

Gravity cannot be similarly localized

4.4 Dark energy

§ A higher-dimensional analog:

— Why is the brane flat despite there being tensions on the branes?

$$R = -2\kappa^2 \sum T_i \;\; \delta^2(x_i)$$

$$\text{4D cc} = \sum T_i + \frac{1}{2\kappa^2}\int d^2x \; R$$

$$= 0 \;\; \text{for all } T_i$$

4.4 Dark energy

§ A higher-dimensional ana

— Classical bulk adjusts to ca
— Quantum bulk effects are

Remarkably: this is possible if they are smaller than 45 μm and ordinary particles are stuck on branes

Requires:

- radius as large as micron size (cc size)

4.4 Dark energy

§ A higher-dimensional ana

— Classical bulk adjusts to ca
— Quantum bulk effects are

Remarkably: this is consistent with the electroweak hierarchy if precisely two dimensions are this large, since $M_p = M_g{}^2 r$

Requires:

- radius as large as micron size (cc size)
- at most two dimensions

4.4 Dark energy

§ A higher-dimensional ana

— Classical bulk adjusts to ca

— Quantum bulk effects are

Otherwise bulk cannot respond to branes.

Technical difficulty: bulk fields diverge at brane positions

Requires:

- radius as large as micron size (cc size)
- at most two dimensions
- back-reaction of the branes

4.4 Dark energy

§ A higher-dimensional ana

— Classical bulk adjusts to ca

— Quantum bulk effects are

For several reasons, including forbidding a cosmological constant in higher dimensions

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2\kappa^2}\, g^{MN}\left[R_{MN} + \partial_M\phi\,\partial_N\phi\right] - \frac{1}{4}\, e^{-\phi}\, F_{MN}F^{MN} - \frac{2g^2}{\kappa^4}\, e^{\phi}$$

- at most two dimensions
- back-reaction of the branes
- supersymmetry in the extra dimensions

4.4 Dark energy

§ A higher-dimensional ana

— Classical bulk adjusts to ca
— Quantum bulk effects are

Otherwise the extra-dimensional adjustments are obstructed by flux quantization

Requires:

- radius as large as micron size (cc size)
- at most two dimensions
- back-reaction of the branes
- supersymmetry in the extra dimensions
- flux localizable on the branes

4.4 Dark energy

§ The upshot:

— A sufficient condition for a classically flat brane is the absence of brane couplings to the dilaton (a 6D scalar related to the graviton by 6D supersymmetry)

— This condition is stable against arbitrary brane loops (and this is why the electron doesn't bite us)

— Bulk loops are suppressed by supersymmetry, leading to a generic contribution that is of Kaluza-Klein size: $1/r^4$

4.4 Dark energy

§ Many striking observational signatures:

— Deviation of Newton's law (crossover to $1/r^4$ from $1/r^2$ at micron distances (present limits are around 45 microns)
— Missing energy at the LHC and astrophysics (existing bounds require $M_g > 10\ TeV$
— Excited string states (or Quantum Gravity) at the LHC
✓ — Probably a vanilla Standard Model Higgs
✓ — Low energy supersymmetry without superpartners for ordinary particles (no selectron, squarks, etc)
— Very light Brans-Dicke-like scalar and quintessence cosmology
— Sterile neutrinos?

4.4 Dark energy

§ What's the catch?

— Weinberg's no-go theorem
— Didn't we see all this fail before in 5 dimensions?
— What about Nima's general argument against extra dimensions?
— What stops proton decay?
— How is inflation possible?
— Aren't long-range Brans-Dicke-like scalars already ruled out?
— Don't constraints already force the cc to be smaller than $1/r^4$?
— Etc.....

Cosmology summary

- Effective field theories organize how to think about how high-energy physics might effect cosmology
  - If an EFT then some options are more likely than others
  - If not an EFT must get control some other way over quantum and classical corrections

- Differing levels of guidance for inflation, dark matter and dark energy
  - Cosmological constant problem is a key clue, and supersymmetric extra dimensions seem the only way around it

Conclusions

- If you have a theory of quantum gravity, use it effectively!
  - Observable consequences are at low energies, and all implications (desired and undesired) most efficiently identified with an EFT
  - Justify the domain of validity of the classical approximation
- Naturalness issues identify when special features are required of the low-energy world.
  - Cases that need care include light scalars, lorentz violating effects, and so on
- Lowering the gravity scale allows novel ways to suppress quantum effects through powers of M_g / M_p
  - Extra dimensions may be just around the corner…

Muchas gracias!!