QFT of Large Field Inflation

Nemanja Kaloper

UC Davis

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(skip some blah-blah-bah)

Due to the large number of positions to be filled, applications will be evaluated starting October 10, 2014. To ensure full consideration, applications should be received by this date. The positions will remain open and applications will be accepted until the search is complete. Applications should be submitted online via the job listing PMUFAC2014 on http://www.mathjobs.org, and should include a cover letter, CV, publication list, research and teaching statements, and letters of recommendation from at least four references.

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Large field inflation: bottom up (from the top down!)

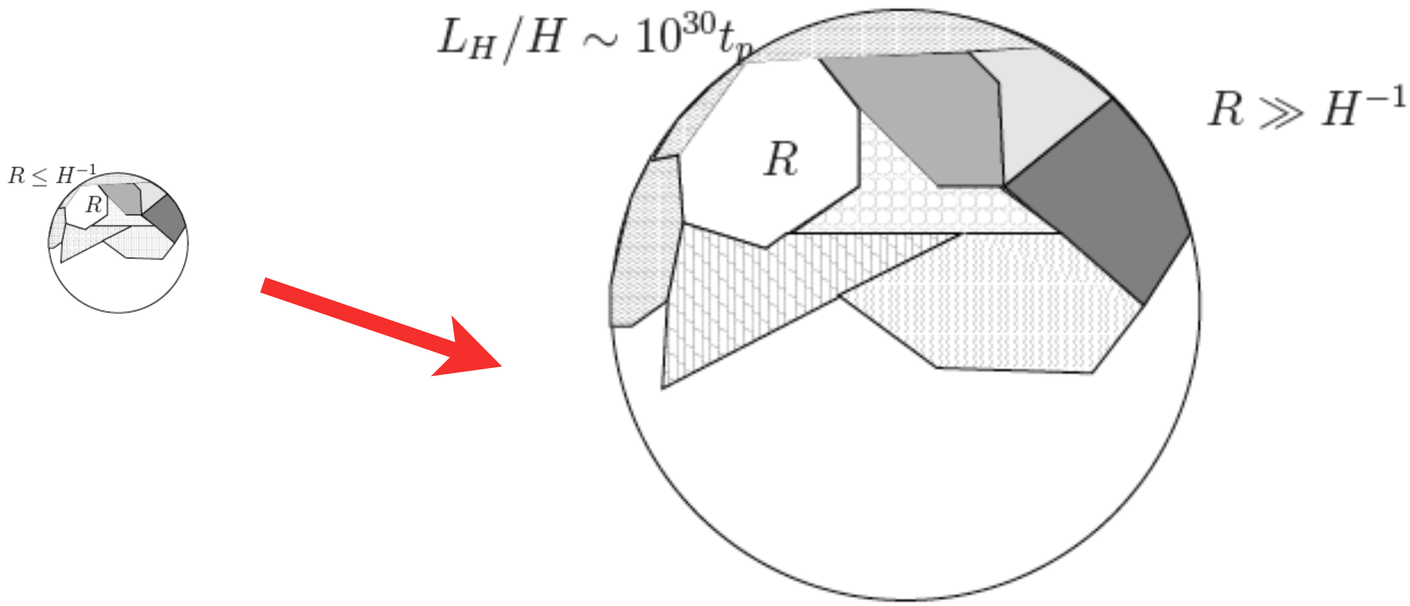
- Freese, Freeman, Olinto, Adams, Bond (1993)
- Kim, Nilles, Peloso, Dimopoulos, Kachru, McGreevy, Wacker, Silverstein, Westphal, McAllister, NK, Sorbo, Lawrence, Schlaer, Berg, Pajer, Sjors, D'Amico, Kleban, Palti, Weigand, Grimm, Marchesano, Shiu, Uranga, Czerny, Higaki, Kobayashi, Takahashi, Nakayama, Yanagida, Blumenhagen, Plauschinn, Hebecker, Kraus, Witkowski, Ibanez, Valenzuela, Quevedo, Ben-Dayan, Pedro, Lust, Wrase, Csaki, Terning, Serra, …
- IMPORTANT PRECURSORS: Julia, Toulouse (1979); Quevedo, Trugenberger (1996); … and …
- Aurilia and Spallucci: 1991 - a real inflationary idea!

Large field inflation: bottom up (from the top down!)

- Not interested in *how*, but instead, in *why*?
- Many different inflation candidates now thanks to some older and a lot of new interesting work.
- Axial and conformal “axions”: shift symmetry?
- Sudden ***Flood of Theories***: necessity a mother of invention, wisdom after the fact it’s great assistant.
- A tempting conjecture: an “equivalence class” of inflatons: explicit models somewhat detail-dependent, but is there a hidden underlying dynamics which is the same??? Could your favorite model and your least favorite model really be *related*?…

Whence inflation?

- Cosmological problems: inflation to the rescue!



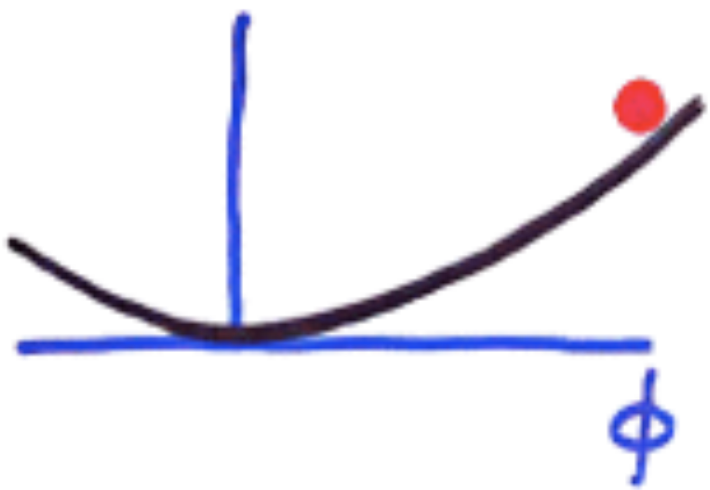
- Blow up the cosmic balloon REALLY FAST! That will get flatten it, and enlarge the homogeneous patches

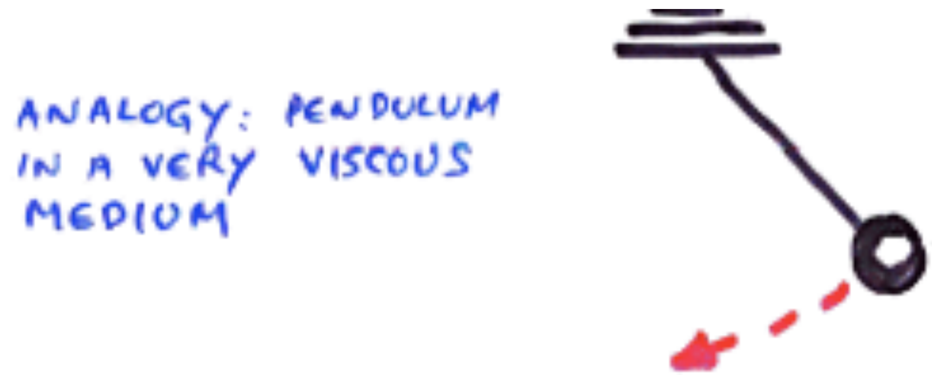
- Solves the problems if the superexpansion blows the balloon by

$$M_{Pl}/milli\ eV \sim 10^{30}$$

Ecce Inflaton: hence Inflation!

Inflation is brief, but not too brief: need expansion by O(30) orders of magnitude. The potential must be flat to yield this.





flatness of $V(\phi)$ means $V'(\phi) \ll V(\phi)/M_P$

but restoring force must be small too: $V''(\phi) \ll V(\phi)/M_P^2$

What's the big deal?

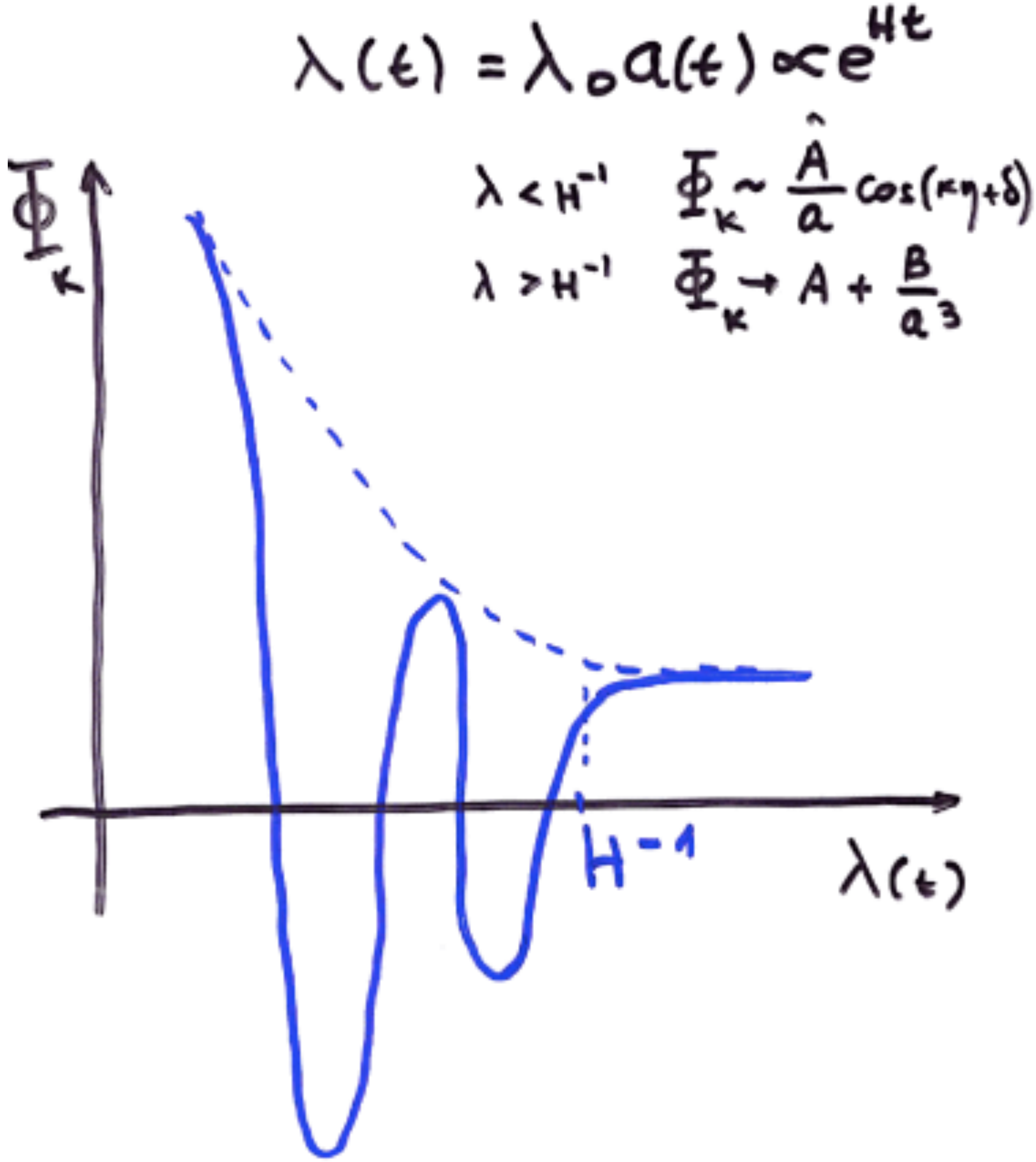
Linde: 1980's: take any polynomial; eg just a parabola, $m^2\phi^2/2$

Now 'just' take $\phi \gg M_{Pl}$ and keep $m \ll M_{Pl}$ and use the fact that far far away the potential looks flat! Indeed,

$$\frac{\partial_\phi V}{V/M_{Pl}} = \frac{M_{Pl}}{\phi}, \quad \frac{\partial_\phi^2 V}{V/M_{Pl}^2} = \frac{M_{Pl}^2}{\phi^2}$$

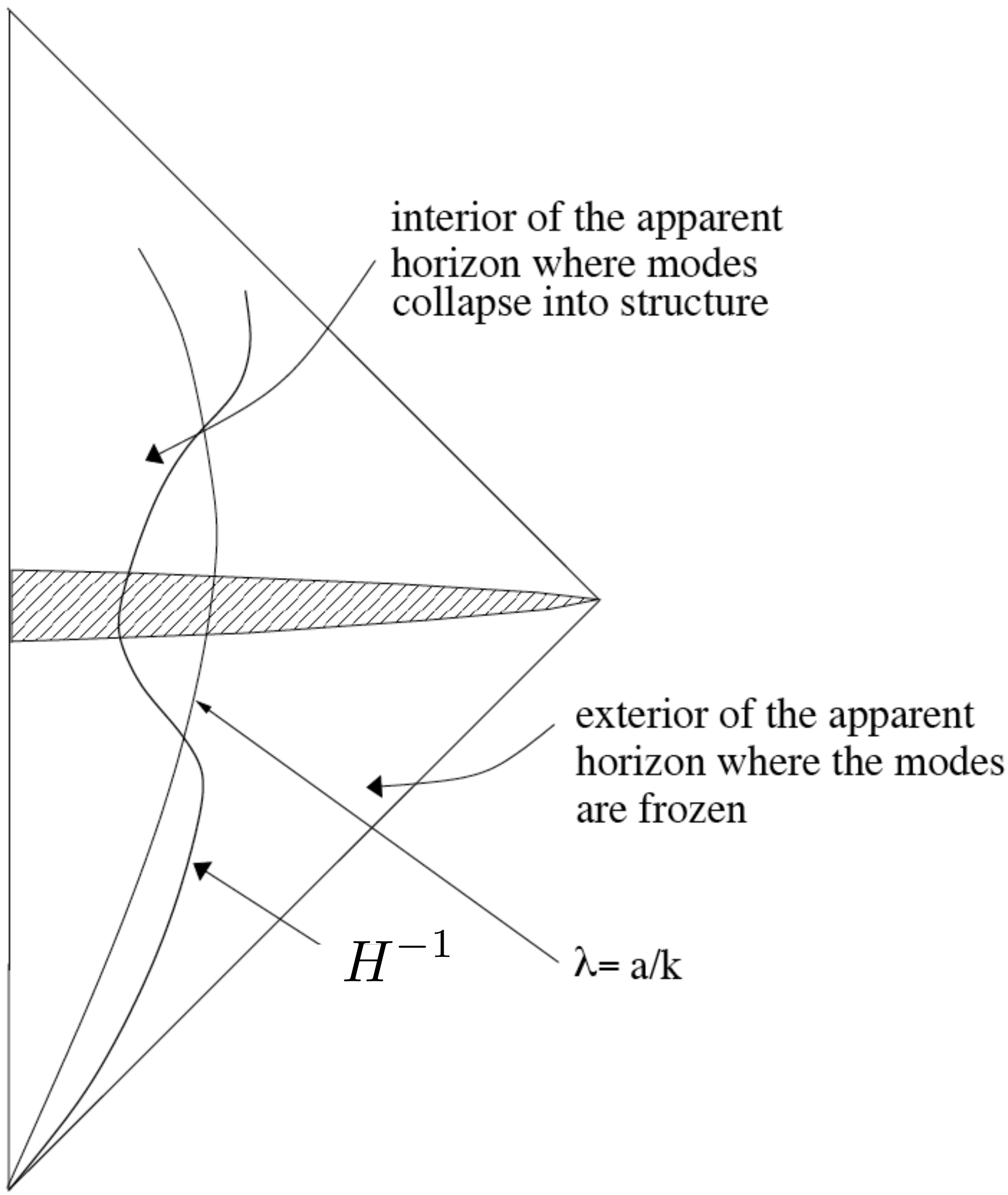
and done we are! Better yet: our pendula (scalars+tensors), while overdamped, do NOT stay put like in classical physics. They tremble, due to the uncertainty principle! The mode eq is "Schrodinger eq", manifest when we set $\phi = \varphi e^{ikx}/a$

$$\varphi'' + (k^2 - \frac{a''}{a})\varphi = 0$$



The quantum tremors gravitate and produce their 'Newtonian potential' - scalar and tensor: wiggles in space time geometry are FROZEN - constant - until much after inlfation ends. Their amplitude is almost independent of when they froze - ie of their wavelength - so they are nearly scale-invariant and Gaussian!

Enter BICEP2: if right, it *de facto* verifies this picture *and* picks the scale of inflation to be GUT scale



SO, ARE WE DONE?! This did not seem to be very difficult at all; we (i.e., Linde) just needed to be clever a bit, and voila, it all came out on a silver platter…

EASY DOES IT:

Radiative corrections could deform the inflationary potential

Even if we write a theory with a classically flat potential for some scalar inflaton, this field cannot ignore the rest of the world: inflation must end, the universe must be repopulated: the field driving inflation MUST couple to other stuff!!!

Due to quantum corrections these couplings are NOT inert: they could change the potential dramatically and spoil inflation badly !!

This suggests sensitivity of inflation to unknown, new physics!

(Really???)

Many have even claimed this is terminally deadly...

Eg: Lyth, *Phys.Rev.Lett. 78 (1997) 1861-1863*

(this is the paper we all quote for the `Lyth bound'... but: read it carefully: it is really a rally against large field inflation…)

The conclusion is that a model of inflation giving a detectable r will probably live in uncharted territory, where there is as yet no theoretical guidance as to the form of the potential. There is no particular reason to invoke the usually-considered forms $V \simeq A \pm B\phi^p$, though of course one should still test such forms against observation by measuring both r and the spectral index of the density perturbation [1].

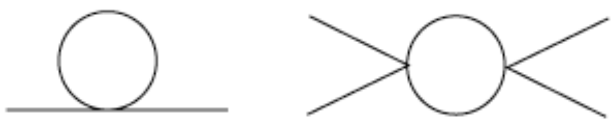
and...

Turning the viewpoint around, it is fair to say that there is at present a considerable theoretical prejudice against the likelyhood of such an observation.

But this prejudice is abject nonsense!!! And not only just because we might be seeing primordial tensors...

But because quantum effects often DO NOT mess things up!

1) Self-interacting scalars: no, even though the daisy diagrams look dangerous: they seem to yield corrections which individually look terrible, like



etc $$= (-1)^n \lambda^n \phi^4 (\frac{\phi}{M})^{2n-4}$$

BUT: they **alternate** and resum to log corrections:

$$\lambda \phi^4 (1 + c \ln(\frac{\phi}{M}))$$

2) Graviton loops: no, since they - as in induced gravity - yield finite potential and Planck mass renormalizations that go like

$$(\frac{\partial_\phi^2 V}{M_{Pl}^2} + \frac{V}{M_{Pl}^4}) V \qquad \partial_\phi^2 V R$$

which are small in the inflationary regime; the reason for these terms is that the couplings are proportional to energies and momenta, and so are small when the energies are below the Planck scale!

Why? The answer seems to be a (APPROXIMATE!!!) shift symmetry..

Invariance under $\varphi \to \varphi + c$; exact s.s. implies $V(\phi)$=const; not inflation! It needs variable $V(\phi)$ to end; so $V'(\phi)$ breaks shift symmetry, but radiative corrections are proportional only to the breaking terms, going as some derivatives of $V'(\phi)$. A flat potential stays flat even with the corrections included, if the worst breaking comes from $V'(\phi)$. *If matter couplings are derivative, the inflaton is immune to loop corrections. NO PROBLEM EVER WITH LOOP CORRECTIONS-AND NO FANCY STUFF NEEDED!*

Does it mean, there is no problem at all? NO! But: the problem is no worse than the usual radiative mass instability of a scalar which couples by relevant or marginal operators to some heavy physics - just like the Higgs mass instability.

So the point is: can we generate the mass by evading strong shift symmetry breaking?

But this should remain small even when we look at nonperturbative corrections.

QFT of 'constants'

$$S_{4form} = -\frac{1}{48}\int F_{\mu\nu\varrho\lambda} F^{\mu\nu\varrho\lambda}\, d^4x \qquad F_{\mu\nu\varrho\lambda} = \partial_{[\mu} A_{\nu\varrho\lambda]}$$

tensor structure in 4d $\Rightarrow F_{\mu\nu\varrho\lambda} = q(x^\alpha)\, \varepsilon_{\mu\nu\varrho\lambda}$

equations of motion $D^\mu F_{\mu\nu\varrho\lambda} = 0 \Rightarrow q(x^\alpha)$ = constant

(this is why particle physicists tended to ignore 4-forms: trivial *LOCAL* dynamics)

Sources for the 4-form: membranes:

$$S_{brane} \ni \frac{e}{6}\int d^3\xi \sqrt{\gamma} e^{abc} \partial_a x^\mu \partial_b x^\nu \partial_c x^\lambda A_{\mu\nu\lambda}$$

Basically boring (except that it gives the a framework for ignoring the cosmological constant problem (not alone any more... see eg papers by C.P. Burgess et al and arXiv:1309.6562, arXiv:1406.0711 for alternatives (NK & Padilla))

Let's make it interesting; consider:

$$\mathcal{S}_{bulk} = \int d^4x \sqrt{g} \Big(\frac{M_{Pl}^2}{2} R - \frac{1}{2} (\nabla \phi)^2 - \frac{1}{48} F_{\mu\nu\lambda\sigma}^2 + \frac{\mu\phi}{24} \frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}} F_{\mu\nu\lambda\sigma} + \ldots \Big)$$

Di Vecchia and Veneziano; Quevedo and Trugenberger; Dvali and Vilenkin; NK & Sorbo; NK, Lawrence & Sorbo.

Action invariant under (perturbative!) shift symmetry:

under $\phi \to \phi + c$, $\mathcal{L} \to \mathcal{L} + c\, \mu\, \varepsilon^{\mu\nu\varrho\lambda} F_{\mu\nu\varrho\lambda}/24$

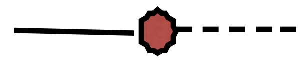
So we have the protection...

Mixing fields and constants

Think of it as flavor oscillations: we have the scalar propagator, 4-form propagator and scalar-form vertex:

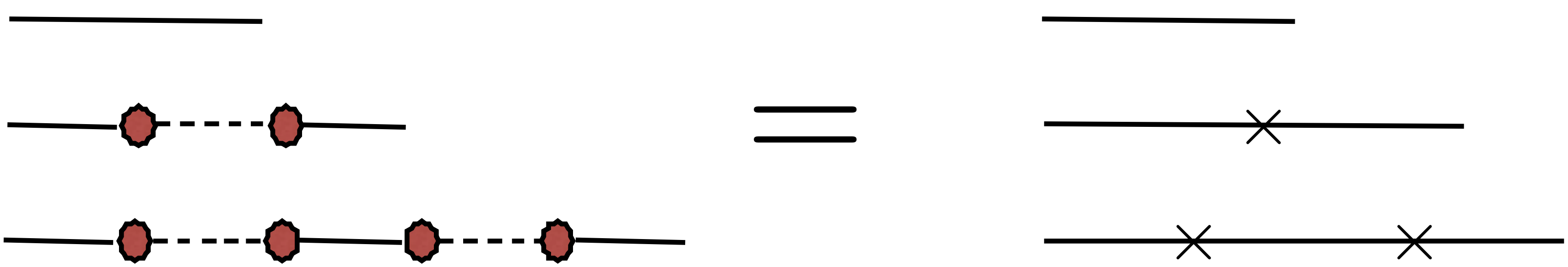
$$\frac{1}{p^2}$$

$$1$$



$$\mu$$

So we have a very simple sum of propagators



$$\frac{1}{p^2}+\frac{1}{p^2}\mu^2\frac{1}{p^2}+\frac{1}{p^2}\mu^2\frac{1}{p^2}\mu^2\frac{1}{p^2}+\ldots=\frac{1}{p^2-\mu^2}$$

This is just a MASS TERM

Mass & symmetries manifest!

- Mass term

$$V = \frac{1}{2}\left(q + \mu\phi\right)^2$$

- Shift symmetry

$$\phi \to \phi + \phi_0 \qquad\qquad q \to q - \phi_0/\mu$$

- Mass is radiatively stable; symmetry is broken spontaneously once background q is picked, as a boundary condition.
- Value of q can still change, by membrane emission

$$\Delta q|_{\vec{n}} = e$$

Note: it is as if the axion is effectively `gauging' the shift symmetry of the non-propagating field *q* which `eats' the axion and becomes propagating (massive)!

Mass as charge

- 11D SUGRA (assume volume moduli stabilized as BP)

$$S_{11D\ forms} = M_{11}^9 \int *F \wedge F + M_{11}^9 \int A \wedge F \wedge F$$

- Truncate on $M_4 \times T^3 \times T^4$

$$A_{\mu\nu\lambda}(x^\mu) \qquad \phi = A_{abc}(x^\mu) \qquad A_{ijk}(y^i)$$

- This yields QUANTIZED MASS!

$$S_{4D forms} = -\int d^4x\sqrt{g}\Big(\frac{1}{2}(\partial\phi)^2 + \frac{1}{48}\sum_a (F^a_{\mu\nu\lambda\sigma})^2 + \frac{\mu\phi}{24}\frac{e^{\mu\nu\lambda\sigma}}{\sqrt{g}}F_{\mu\nu\lambda\sigma}\Big)$$

$$\mu = n\mu_0 \qquad \mu_0 = 2\pi V_3 M_{11}^3 \Big(\frac{M_{11}}{M_{Pl}}\Big)^2 M_{11}$$

many people have rederived the model from string theory post-BICEP2; let's just see not how, but WHY that works

Naturalness issues and shift breaking

In string theory the axion is a zero mode of a form on a compact space. Its shift symmetry is a *large* gauge transformation of the field ϕ. It is broken to a discrete symmetry by the periodicity of ϕ (set by boundary conditions reflecting the compactness of the internal space, and given by the period $f_\phi < M_{Pl}$).

This is still OK with the ϕ F mixing, that remans invariant under ***discrete shifts*** which control pertubative corrections (ensuring they are small).

This helps *greatly* with non-perturbative corrections, since it i) implies that they will be periodic in ϕ with the same period f_ϕ and ii) keeps their dimensionless control parameters small even when gravity is turned on (since at short distances gauge symmetry kicks back in).

The potential \`unstable' to discharge of membranes. But when mebrane tension is GUT scale, the probability is exponentially exponentially tiny and the potential stays put, while inflaton stays on the same branch. Similar to (same as?) unwinding inlfation of D'Amico and Kleban.

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Instanton constributions to V

$$V_{inst} = \lambda_{d,inst}^4 \sum_n e^{-(n-1)c'S} \cos(\frac{n\phi}{f_\phi}) \simeq \lambda_{d,inst}^4 \sum_n \Big(\frac{\lambda_{d,inst}}{\lambda_{uv,inst}}\Big)^{4(n-1)} \cos(\frac{n\phi}{f_\phi}) \ll \frac{\mu^2\phi^2}{2}$$

- Crucial for the `naturalness' of the mechanism:
  - Mass dominated by the random 4-form fluxes. In the weak coupling, the instanton potential $\sim cos(\phi/f)$ coming from a gauge theory into which the axion reheats is not needed for the mass generation. With strong couplings the potential is resummed to a polynomial (Witten, LGT), but is ***bounded***!
  - The instanton contribution must be smaller than the 4-form one!
- Pick a ϕ so it won't couple to a theory that goes strong at too high a scale; then the instantons yield small (and potentially interesting) bumps… like in chain inflation, or in multiple inflation. This can also lead to nongaussianities through coherent amplifications and used to address anomalies.
- Similar suppression for gravitational instantons, with $f << M_P$

Skip

Moduli corrections

Gauge (and shift symmetry) invariant terms, after dim red:

$$\delta\mathcal{L} = c\frac{\Psi}{M_{Pl}}F^2 + \ldots$$

Stabilizing the moduli with mass M, this shifts them by:

$$\delta\Psi \sim c\frac{F^2}{M^2 M_{Pl}} \sim c\frac{\mu^2\phi^2}{M^2 M_{Pl}}$$

This corrects the scalar potential by $M^2\delta\Psi^2$

$$V_{corr} = V(\phi)\left(1 + \frac{c^2}{2}\frac{V(\phi)}{M^2 M_{Pl}^2}\right) \simeq V(\phi)\left(1 + \frac{c^2}{2}\frac{H^2}{M^2}\right)$$

OK as long as *M* > *H*

Higher order shift-symmetry invariant terms

Gauge (and shift symmetry) invariant terms:

$$S_{\phi F} = \int d^{4+d}x\sqrt{g}\Big(-F^2 + (\partial\phi)^2 + \mu\phi\epsilon F + \ldots + \frac{F^{2n}}{M^{(4+d)(n-1)}} + \ldots\Big)$$

After dimensional reduction and stabilization of moduli:

$$\begin{aligned} S_{\phi F} &= \int d^4x\sqrt{g}\Big(-V_d F^2 + V_d(\partial\phi)^2 + \mu V_d\phi\epsilon F + \ldots + V_d\frac{F^{2n}}{M^{(4+d)(n-1)}} + \ldots\Big) \\ &= \int d^4x\sqrt{g}\Big(-\tilde{F}^2 + (\partial\tilde{\phi})^2 + \mu\tilde{\phi}\epsilon\tilde{F} + \ldots + \frac{\tilde{F}^{2n}}{(V_d M^{4+d})^{n-1}} + \ldots\Big) \end{aligned}$$

So the higher corrections are suppressed by $V^d M^{4+d} = \Lambda_F^4 \sim M_{GUT}^4$

$$V_{eff} = \frac{\mu^2\phi^2}{2}\Big(1 + \sum c_n \frac{\mu^2\phi^2}{\Lambda_F^4}\Big)!!!$$

CMB and corrections: Chaotic Evil

These corrections are very interesting since they can leave imprint in the CMB (NK, Lawrence, 2014): when $\Lambda_F^4 \sim M_{GUT}^4$

$$V_{eff} = \frac{\mu^2\phi^2}{2} + \frac{\lambda_4}{4}\phi^4$$

where $\lambda_4 = 4c(\frac{\mu}{M_{GUT}})^4 \sim 10^{-13}$

So:

$$\mathcal{P}_T^{(4)} = \frac{4\mu^2}{3\pi^2 M_{Pl}^2}\mathcal{N}\left(1 + 3c\frac{\mathcal{N}}{21}\right) \sim r\mathcal{P}_S^{(4)}(1+9c)$$

Thus for c<0.1 this could even enhance the tensor signal!
Similar conclusions - with more detail - also follow from higher order terms.
This effect is similar to other corrections considered by McAllister et al.

Dungeons and dragons: Chaotic Evil character tends to have no respect for rules, other people's lives, or anything but their own desires, which are typically selfish and cruel…

Conformal 'Axion' (aka Dilaton)

Csaki, NK, Serra, Terning

Is shift symmetry necessarily a gauge theory remnant? Maybe not… Consider a theory which is SCALE invariant:

$$\mathcal{L} = \sqrt{-g}\left[\tilde{\xi}\Phi^2 R - \frac{1}{2}(\nabla\Phi)^2 - V(\Phi)\right] + \Delta\mathcal{L}(g_{\mu\nu}, \Phi) + \mathcal{L}_M(g_{\mu\nu}, \Phi, \Psi)$$

Now, break scale symmetry - controllably, but parameterize it by an explicit breaking parameter and canonically normalize the Goldstone mode

$$\mathcal{L} = \sqrt{-g}\left[\frac{M_{Pl}^2}{2}R - \frac{1}{2}(\nabla\varphi)^2 - V(\varphi)\right] + \Delta\mathcal{L}\left(\Omega^2(\varphi)g_{\mu\nu}, \Phi(\varphi)\right) + \mathcal{L}_M\left(\Omega^2(\varphi)g_{\mu\nu}, \Phi(\varphi), \Psi\right)$$

So: $V(\varphi) = \frac{M_{Pl}^4}{4\tilde{\xi}^2}\frac{V(\Phi(\varphi))}{\Phi^4(\varphi)}$ $\quad\quad$ $\Phi(\varphi) = \langle\Phi\rangle \exp\left(\frac{\sqrt{\xi}\varphi}{M_{Pl}}\right)$

If breaking is small, $\varphi \to \bar{\varphi} = \varphi + \frac{M_{Pl}}{\sqrt{\xi}}\lambda$ is an approximate shift symmetry!

This field is light since it is the Goldstone of the (weakly) broken scale symmetry

B. Bellazzini, C. Csaki, J. Hubisz, J. Serra and J. Terning

F. Coradeschi, P. Lodone, D. Pappadopulo, R. Rattazzi and L. Vitale

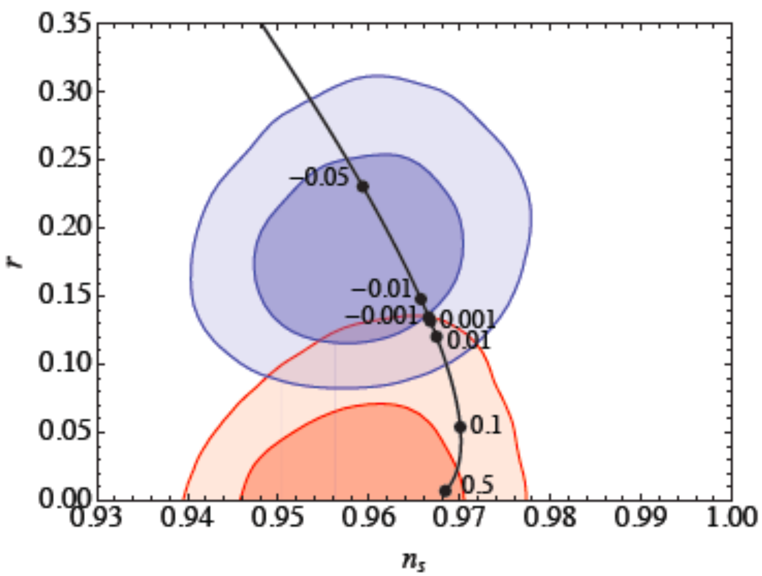
More on dilatons

A simple example of weak breaking, with e anomalous dimension of the scaling breaking operator: $V(\Phi) = \Phi^4 \left(\alpha + \beta \Phi^{-\epsilon}\right)^2$ so the Goldstone potential is

$$V(\varphi) = \frac{M_{Pl}^4}{4} \frac{\alpha^2}{\tilde{\xi}^2} \left(1 - e^{-\epsilon\sqrt{\xi}\varphi/M_{Pl}}\right)^2$$

Starobinsky!!! But it makes sense now… Quadratic gravity is an avatar of a weakly broken scaling symmetry!

Quadratic term must dominate in order to ensure scaling symmetry; breaking is induced by the Einstein term (eg induced gravity); but then shift symmetry and large field range follow automatically!



Many more examples exist…

Reheating

Consider the coupling

$$\delta\mathcal{L} = \frac{\phi}{f_\phi} Tr\Big(G^* G\Big) \quad \text{or} \quad \delta\mathcal{L} = \frac{\phi}{f_\phi} Tr(G^2)$$

Reheating temperature: $T_R \simeq \sqrt{\Gamma_{\phi GG} M_{Pl}}$

Decay rate: $\Gamma_{\phi GG} \simeq \frac{\mu^3}{f_\phi^2}$

Thus:

$$T_R \simeq \frac{\sqrt{\mu M_{Pl}}}{f_\phi}\mu \quad \text{this is easily} \quad \gg MeV$$

So when $f_\phi > \sqrt{\mu M_{Pl}}$ reheating temperature will be lower than the inflaton mass, and that will generically help avoid reproduction of undesired long lived relics.

PGW

r related to the inflaton displacement during inflation

(in single-field inflation)

$$\frac{\Delta\phi}{M_P} \sim \int H\, dt \sqrt{r/8}$$

and using $H\,\Delta t \sim 60$,

$$\boldsymbol{\Delta\phi \sim M_P\, (r/0.01)^{1/2}}$$

Observable tensor modes typically related to a planckian excursion of inflaton; they are within the range of the Planck satellite; and its data are currently analyzed, to be released (early?) in 2013. This can be falsified by Planck... Or, maybe even confirmed?

Enter BICEP2 (+ Keck Array + BICEP3 + ...)

Summary

- Inflation is a simple way of explaining the origin of the universe, its dynamics fully consistent with local QFT.
- There is an issue of UV sensitivity - naturalness - and its paradigmatic implications.
- Shift symmetries: a key for constructing inflationary models.
- String theory provides useful means for controlling corrections; it is tricky, but possible to have viable low energy models.
- Inflatons can be pseudoscalars and can be scalars. (Parity in the sky???)
- The ideas are experimentally predictive: so falsifiable... Soon we should know more. Patience!