(Super)Planckian Physics and Inflation

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Status and Future of Inflationary Theory, KICP
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What I'm **not** talking about

- Inflation expands the universe by a factor >~e^{60} in linear scale
- This inflates initially subPlanckian wavelengths to large, observable scales
- But the true physics of inflation is close to time-translation invariant (hence scale invariance), and high scale corrections are suppressed by powers of $H/M <\sim 10^{-5}$

Field ranges

- But there is another interesting superPlanckian issue
- If H/M >~ few*10^{-7}, the value of the inflaton field changed by a (reduced) Planck mass or more during the last ~60 efolds of slow roll, $\Delta\phi$ >~ M
- Such a large value of H also produces large tensor power via the usual mechanism of de Sitter quantum fluctuations
- If BICEP2 measured primordial gravity waves, the tensor/scalar power ratio r>~.1
- Standard dS fluctuations give r ~ $(10^5\,H/M)^2$, so r~.1 implies $\Delta\phi$ ~10*M

Lyth, Turner

- Does this constitute superPlanckian physics, with large (and very interesting and very hard to compute) quantum gravity corrections?

Possible loophole?

- Before addressing that, one way out is if gravity waves can be generated in some non-standard way during inflation, so large r does not imply large H/M

- Extra tensors can be produced, for instance, by coupling the inflaton to other fields, in such a way that while it rolls it produces stuff that then decays to or emits gravitons

- However, there is a no-go theorem being developed, the result of which is that any such mechanism produces more scalars than tensors, by a factor of ε^{-2}, so that $r \sim \varepsilon^2$

Mirbabayi Senatore Silverstein Zaldarriaga

- There are models that seem to evade this, but they are not beautiful (additional rolling scalar, many other fields)

SuperPlanckian vevs

- So, r>~.001 probably implies a O(1) change in the inflaton vev in Planck units during inflation (and we will know if this is true in the near future)
- Of course, gravity doesn't couple (directly) to the vev, it couples to stress-energy
- So long as the energy density is below Planck, the gravitational coupling is weak

Effective potential

- Indeed, one can compute the effects of graviton loops on the effective potential for the inflaton

Coleman-Weinberg, Smolin, Linde

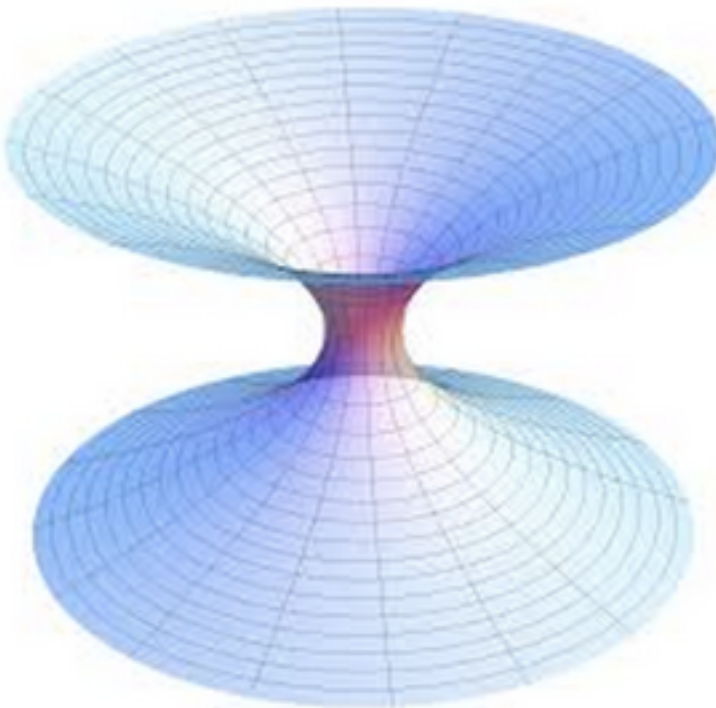
- They produce corrections like $V(1+V/M^4 + V''/M^2 + \ldots)$
- These are never large during inflation, when V/M^4 and V''/V are small
- So, there is no problem with superPlanckian field ranges in perturbation theory
- However there is still a potential issue

Hierarchy

- The mass of the inflaton must remain small for slow roll, but scalar masses get large corrections from loops
- Obvious candidate to protect the mass is an (approximate) shift symmetry $\phi \longrightarrow \phi + C$
- But we know that gravity breaks global symmetries (e.g. Hawking evaporation of black holes)
- So if not forbidden by symmetry, shouldn't we write all operators like $\Sigma_p\, \phi^{p+4}/M^p$ with O(1) coefficients?
- That really would destroy inflation, because all terms become larger than ϕ^4 when $\phi > M$ - so there are/were claims that large r is inconsistent, or at least incompatible with an EFT description of inflation

Wormholes!

- Assuming they are absent in the classical theory, such terms must be generated non-perturbatively
- The known NP effects in gravity do indeed produce terms like that, but not with O(1) coefficients - instead they are multiplied by e^{-S}, where S is the action for some instanton that eats the global charge (a wormhole)
- Turns out that S (for wormholes) is extremely sensitive to threshold corrections at or below the Planck scale, as well as various curvature corrections to Einstein



Kallosh, Linde, Linde, Susskind

For example…

- Adding a Gauss-Bonnet term ($R_{....}^2 - 4R_{..}^2 + R^2$) doesn't change Einstein's equations, because it's topological
- But it does change S, because a wormhole that eats global charge has a different topology than flat space
- In this way one can make S arbitrarily large without affecting experiments
- Another way is to have compact extra dimensions, where the wormhole throat never gets smaller than the extra dimension, making its action large, or by adding other higher curvature corrections

Weakest force

- Another possible worry is that, at least in some models, superPlanckian field ranges end up corresponding to a force that is weaker than gravity
- However, the "gravity is the weakest force" argument only clearly has weight for gauge forces

Arkani-Hamed, Motl, Nicolis, Vafa

- Furthermore there seem to be explicit models in string theory that accomplish this

Summary

- So far we have considered two distinct but related issues for inflation with superPlanckian field ranges

- Perturbative corrections to the mass, which can be controlled with a global symmetry

- Non-perturbative gravity corrections to the potential, which break that symmetry - but at least wormhole corrections can be made small in several ways (of course, it’s still possible some other NP effects are more important)

- So superPlanckian vevs probe some aspects of non-perturbative quantum gravity, but not very directly, and it doesn’t seem difficult to make the effects very small if you are not in pure Einstein

Models?

- In fact we have various models that produce superPlanckian vevs without any apparent issue
  - Monodromy inflation

    Silverstein, Westphal, McAllister, Flauger…
  - Unwinding inflation

    D'Amico, Gobbetti, MK, Schillo
  - Extranatural inflation

    Arkani-Hamed, Cheng, Creminelli, Randall
  - 4D effective models of Kaloper/Lawrence/Sorbo

What about naturalness?

- Are large field models less natural than small field models?
- If there is a landscape, we are in a bubble that formed in a first-order phase transition from a metastable parent phase, and then underwent slow roll inflation of some sort
- These transitions can generically initiate unwinding inflation (“creation myth”)
- Because the inflationary vacuum energy is that of the parent phase, it is naturally large, hence large field range
- Small field inflation might require much more tuning

Unwinding

- Consider a spacetime of the form $dS_4 x M$, where all moduli of M are stabilized (these had better exist, or we are in trouble!)

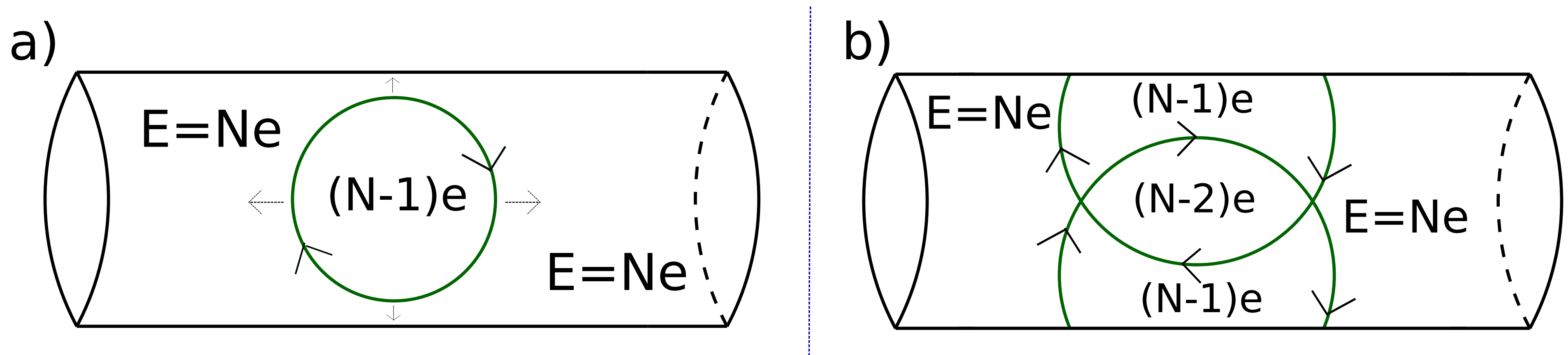
- There are several possible contributions to the vacuum energy of the dS, one of which is a flux F_p with $p>4$ that fills the dS and threads M

- Any spacetime like this is at best metastable, and one decay mode is to discharge one unit of F flux (F is quantized) via nucleation of a bubble of charged brane (higher form flux analog of Schwinger pair production)

MK Krishnayengar Porrati
D'Amico Gobbetti MK Schillo

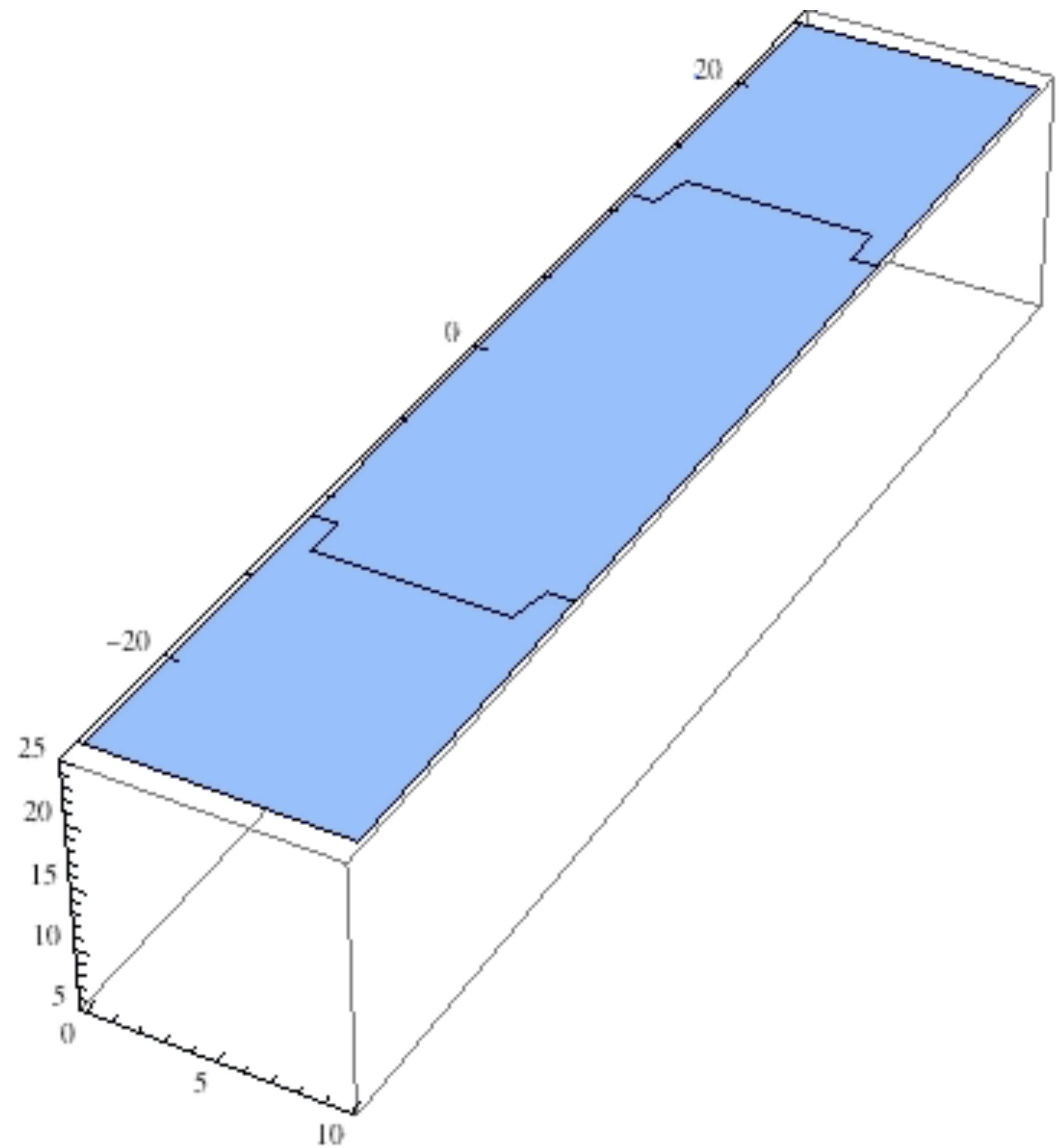
Flux cascade

- This can initiate a cascade as the bubble expands around the compact directions - many units of flux discharge



- Result is a homogeneous and isotropic **open** FRW cosmology dominated by gradually decreasing vacuum energy - slow roll (open) inflation, where the inflaton is the radius of the bubble

- In a sense this is a version of old inflation, since it is the false vacuum energy density that dominates during inflation



20
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10

Old inflation rejuvenated

Brown

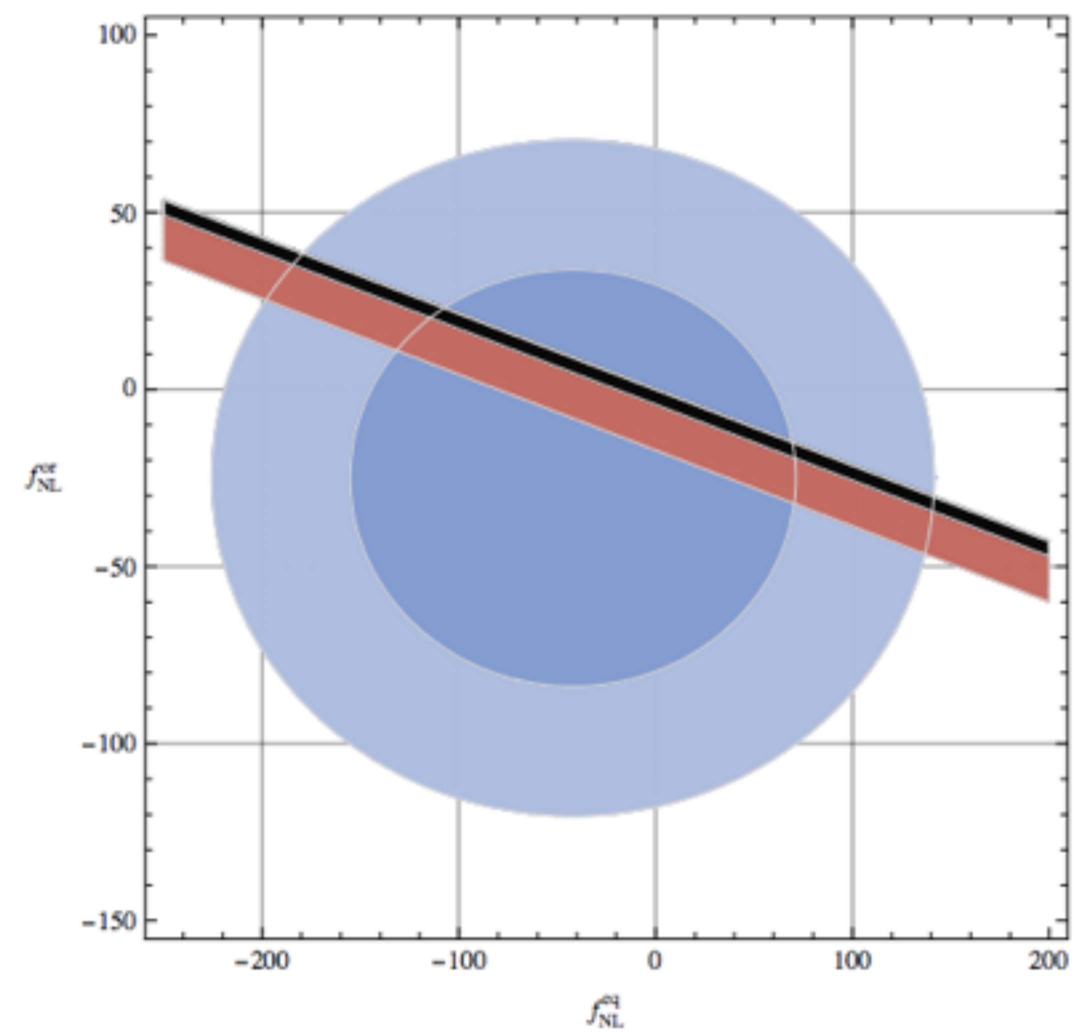
- Inflation ends when the flux is discharged and the brane annihilates with itself, reheating the universe
- $\Delta\phi = M$ (for the canonical 4D inflaton ϕ) corresponds to the discharge of a few units of flux (a few wraps around)
- Doesn't necessarily disturb the stabilization mechanism much, although it can and lead to flattening a la monodromy
- Most generic prediction (at current understanding) is that there is either detectable equilateral NG, or tensors, or both

Reheating?

- An interesting situation arises near the end of inflation
- The branes may "prematurely" annihilate in a Hubble-sized region before discharging all units of flux
- This possibility is realized by a random distribution of regions with different values of the flux at reheating
- I think these regions will collide and reduce the flux to zero everywhere, but there will be large perturbations on Hubble scales, and maybe gravitational waves

Does large r imply Gaussianity?

- Naively, large r makes detectable NG unlikely, because the easiest way to achieve large NG is to make c_s small ($f_{NL} \sim c_s^{-2}$), but this suppresses tensors ($r = 16\epsilon c_s$)
- But there is an operator (dot π)^3 in the cubic effective theory, and its coefficient is not constrained by large r and does not generate small c_s
- This operator predicts a very specific shape for NG, which can be large



D'Amico MK

High scales

- Anomalies in the CMB data are enhanced by large r, and hint at short inflation (Cora's talk)
- Various relics from the pre-inflationary state might be detectable
- I think **spatial curvature** should be our next target
    - if positive, it falsifies the landscape (or at least a parent vacuum) and slow roll eternal inflation in our immediate past
    - if negative, consistent with birth by tunneling, and rules out SREI
    - Only remaining very-large-scale observable that is far from cosmic variance limit

What’s next?

- If large r is confirmed, it’s a great situation for both theorists and observers
- SuperPlanckian field range is possible and controllable, but “on the edge of respectability”
- Non-perturbative quantum gravity effects are potentially detectable
- Very useful hint