Current Issues in the Theory of Inflation

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Outline

- Why inflation? (Mainly, to solve fine tuning problems)
- Is inflation itself fine-tuned? (If so, what's the point?)
  - tuned initial conditions?
  - tuning in the model (scalar potential)
- Eternal inflation and its discontents
  - measure problem: everything happens infinitely many times
  - predictions, anyway
- Large tensors and super-Planckian field range (problematic?)
- Fundamental physics of inflation (what is it?)

Why inflation?

Because, fine-tuning…

The universe is very flat - the observational constraint is:

(radius of observable universe)/(radius of curvature) < 0.1

The universe is very homogeneous - on large scales the rms deviation from the average density is

$\delta\rho/\rho \sim 0.00002$

Both these numbers are much, much smaller than they “should” be

Cosmic evolution

- Both that ratio of radii and the density contrast increase with time, and the universe is very old (**t_{now}/1s ~ 10^{17}**)
- The radius of observable universe (**1/H**) goes as **t**, while radius of curvature goes as **$a(t) \sim t^{2/3}$** (matter domination)
- Hence, the radius of curvature in the early universe must have been very, very large - why?
- Hint: that ratio increases unless **$a(t) \sim t^p$** with **$p>1$** (accelerated expansion)

Flatness and horizon

- Inflation (accelerated expansion) lasting more than **~60** efolds produces regions as big or larger than the observable universe today that are flat and homogeneous, by hugely increasing **a(t)** while **1/H** is nearly constant

- Not *exactly* homogeneous - quantum fluctuations produce a nearly (but not quite) scale invariant spectrum of nearly Gaussian density perturbations (in most models, the normalized size of non-Gaussianity is **~10^{-4}** or smaller)

- 30+ years and three satellites and many other experiments on, this is perfectly consistent with observation

Tuned initial conditions?

- At the time it begins, inflation requires the energy to be mostly scalar potential energy, not radiation, matter, curvature, gradient energy, or anything else
- In particular, one needs ~homogeneity and ~isotropy over a few (inflationary) Hubble volumes
- Given that inflation is supposed to explain the ~homogeneity and ~isotropy over the single Hubble volume we observe today, does it help?

Numerical cosmology

- Homogeneity and isotropy over a Hubble volume are required *when* inflation begins, but not necessarily *before* it begins
- A radiation/matter dominated expanding universe will condense into clumps and voids, and inflation may begin in these voids (which by the way still have almost O(1) perturbations, and not scale invariant or Gaussian)
- Simulations show this is in fact what happens: overdense regions collapse into black holes, while underdense regions dilute and (often) eventually undergo inflation

East+Kleban+Senatore+Linde, in progress

Entropy

- Some have argued that inflation solves no fine-tuning problems, because their favorite measure on the probability of its initial conditions says it's very unlikely
- For example, the entropy during inflation is vastly lower than the entropy today, so if all states are equally probable…
- However, this conflates two different issues: the arrow of time problem (why the entropy was low in the early universe) and the horizon and flatness problems
- Inflation solves the latter, but not the former

Tuned potential?

- At least in simple models, the potential $\mathbf{V(\phi)}$ must obey slow-roll conditions, e.g.

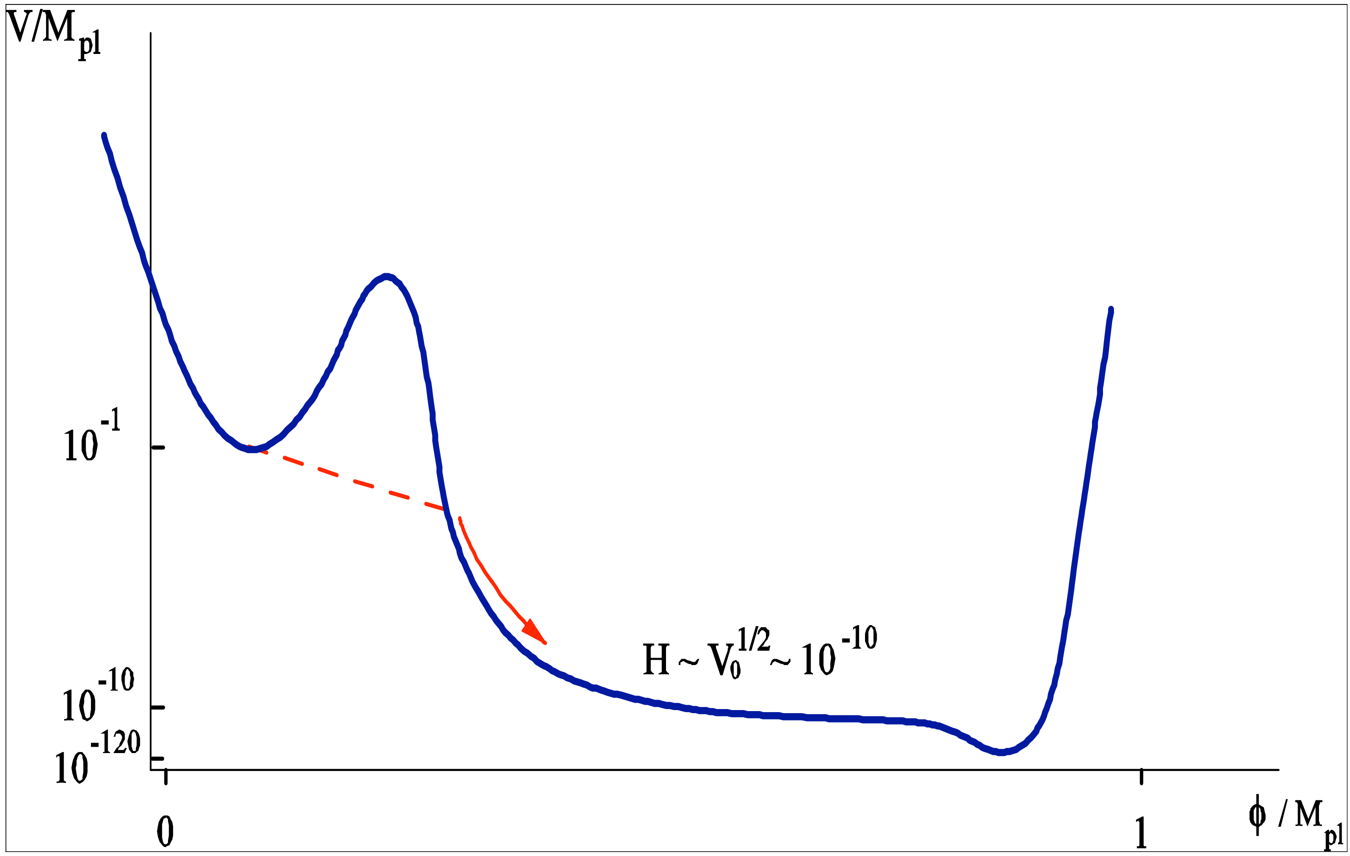
$$\mathbf{M_{Pl}\,(dV/d\phi)\,/\,V \ll 1}$$

- Putting in data, for $\boldsymbol{\lambda\phi^4}$ one needs $\boldsymbol{\lambda \sim 10^{-8}}$
- This is certainly a tuning, how severe depends on your prior
- It's hard to say more about this without a microscopic theory
- Note that these conditions (slow roll, small $\boldsymbol{\lambda}$) are preserved under loop corrections (including gravity loops), because there is a softly broken shift symmetry $\boldsymbol{\phi \to \phi + C}$

Eternal Inflation

- Consider a model with a false vacuum (a metastable phase with positive vacuum energy) and a true vacuum (a stable phase with zero or small vacuum energy)

- The false vacuum is metastable due to tunneling; bubbles of lower energy will nucleate



Rates

- There is a rate **Γ** (# per time per volume) of bubble nucleation
- If $\mathbf{\Gamma < H^4}$, less than one bubble will nucleate per Hubble time per Hubble volume
- In one Hubble time, an initial volume grows by x $\mathbf{2.7^3}$
- So even if the bubble took up an entire Hubble volume, there's usually still some expanding false vacuum left over
- It's a population with birth rate > death rate - the population grows eternally, even though every individual dies

Measures

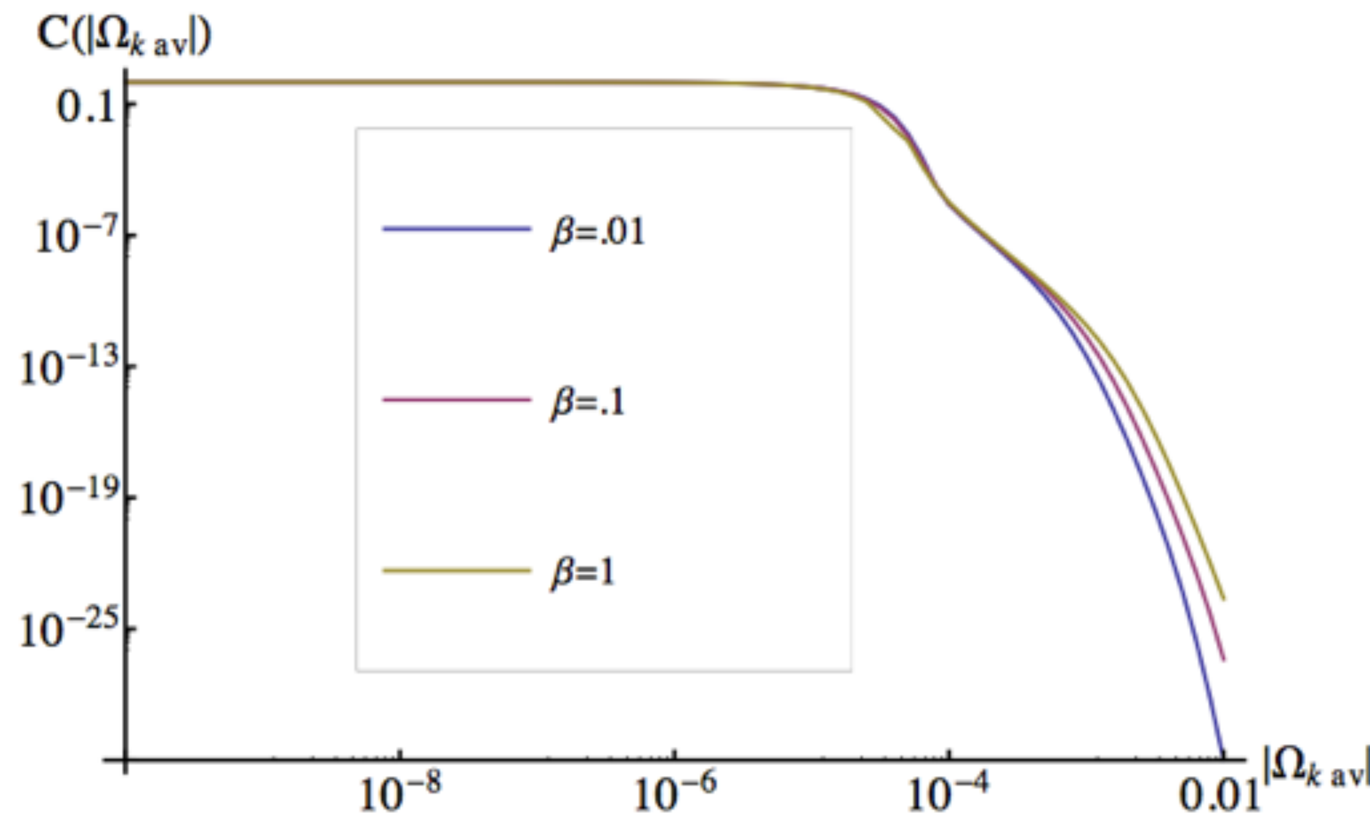
- Slow-roll inflation can also be eternal, if the slope of the potential is small enough
- Inflation seems to “like” to go on forever, just by the nature of exponential growth
- This means infinitely many bubbles/regions appear of every possible type (a “multiverse”) - so to make frequentist predictions, one needs some kind of cutoff or measure
- Naive cutoffs lead to disasters (in an exponentially growing population, everyone should expect to be young, and to live just before the apocalypse), but apparently successful ones do exist

Can we test eternal inflation?

- Eternal inflation is eternal, so it gets rid of all prior curvature

- However bubble nucleation produces universes with **negative** (open) spatial curvature

- Hence, an observation of **positive** (closed) curvature would **falsify** eternal inflation in our past, while an observation of **negative** (open) curvature would **confirm** a prediction of it (this multiverse **is** testable!)

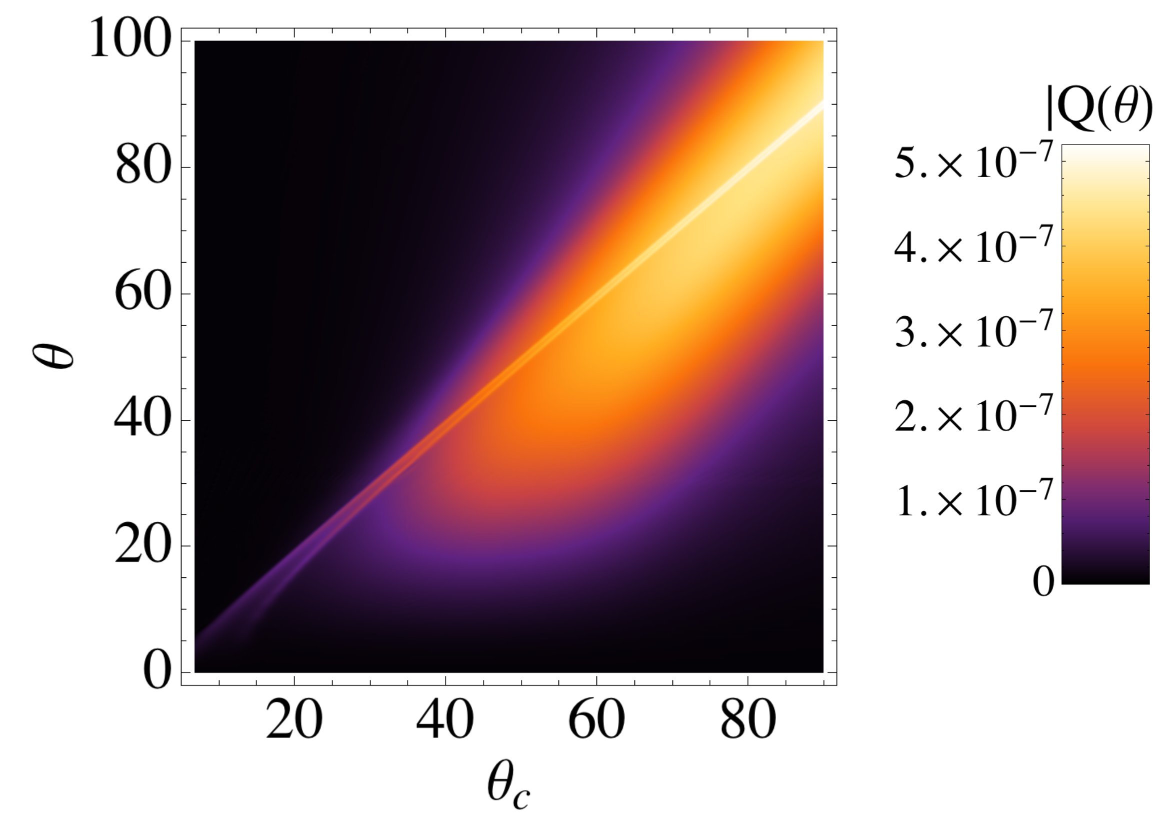


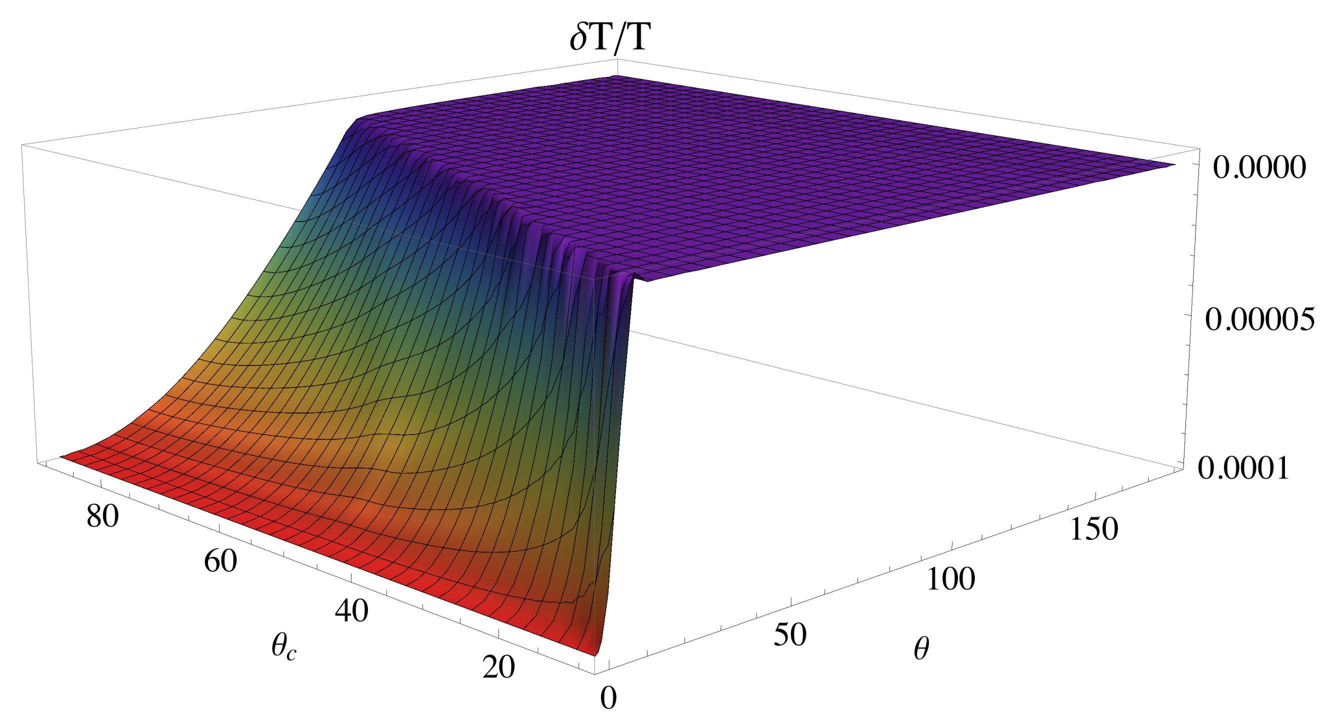
Kleban+Schillo
Guth+Nomura

Chang+Kleban+Levi, Sigurdson, Czech…

Cosmic bubble collisions

- Another prediction is that bubbles sometimes collide with each other
- These collisions produce very distinct patterns in the CMB and large-scale structure
- No other known mechanism can produce such patterns, so observing them would strongly favor eternal inflation (and the "multiverse")





Tensors

- It's not only the (scalar) inflaton that quantum fluctuates during inflation - the metric does, too
- This produces "tensor" perturbations that manifest themselves as B-mode polarization in the CMB
- The (observed) scalar power is $\mathbf{P_s \sim few*10^{-10}}$, while the (theoretical) tensor power is $\mathbf{P_h \sim (H/M_{Pl})^2}$, and the ratio is called $\mathbf{r = P_h/P_s < 0.1}$ (some forecasts predict $\sigma_r \sim 2*10^{-4}$)

Peiris, …

- Since $\mathbf{H^2 \sim V/M_{Pl}^2}$, tensor power is a direct measure of the energy scale of inflation (with some caveats)

Senatore, Silverstein, Zaldarriaga, Mirbabayi, …

Superplanckian field range

- "Large" tensor power also indicates that the inflaton field vev changed during inflation by $\sim M_{Pl}$:

  $\Delta\phi/M_{Pl} \sim .5\ (r/0.1)^{1/2}$ (Lyth "bound")

- This could be a problem: if there are operators in the Lagrangian like $O(1)*\phi^4(\phi/M_{Pl})^n$, they would spoil inflation (for instance, $M_{Pl}\ V' / V \sim 1$)

- However, perturbative field theory and gravity corrections cannot generate such terms if they are not present in the classical theory

Beyond perturbation theory

- Non-perturbative gravitational effects are expected to break all global symmetries and generate these terms

- However, the coefficient may not be O(1) but $\mathbf{e^{-S}}$, where **S** is the action for a gravitational instanton

- It turns out that **S** is very sensitive to corrections at the quantum gravity scale, and hence these NP corrections might be negligible (for example, large Gauss-Bonnet term with the right sign)

- To really answer this, one really needs a microscopic theory including both inflation and quantum gravity

Planckian accelerator

- The energy scale of inflation was certainly far above anything we can access on earth
- So the physics of inflation is extremely important and interesting, because it constitutes a probe of ultra high energy physics
- To learn from it, we need to build and test fundamental models

The fundamentals of inflation

- Some parameters characterizing inflation - for example, the scalar power and tilt - have been measured very accurately
- This has killed off many models, but many remain
- In addition, all or nearly all are effective field theories
- We need more than that (more detail, not more models)

The landscape

- String theory - and, independently, the observation of very small acceleration today - predict(s) the existence of a very large landscape of metastable phases

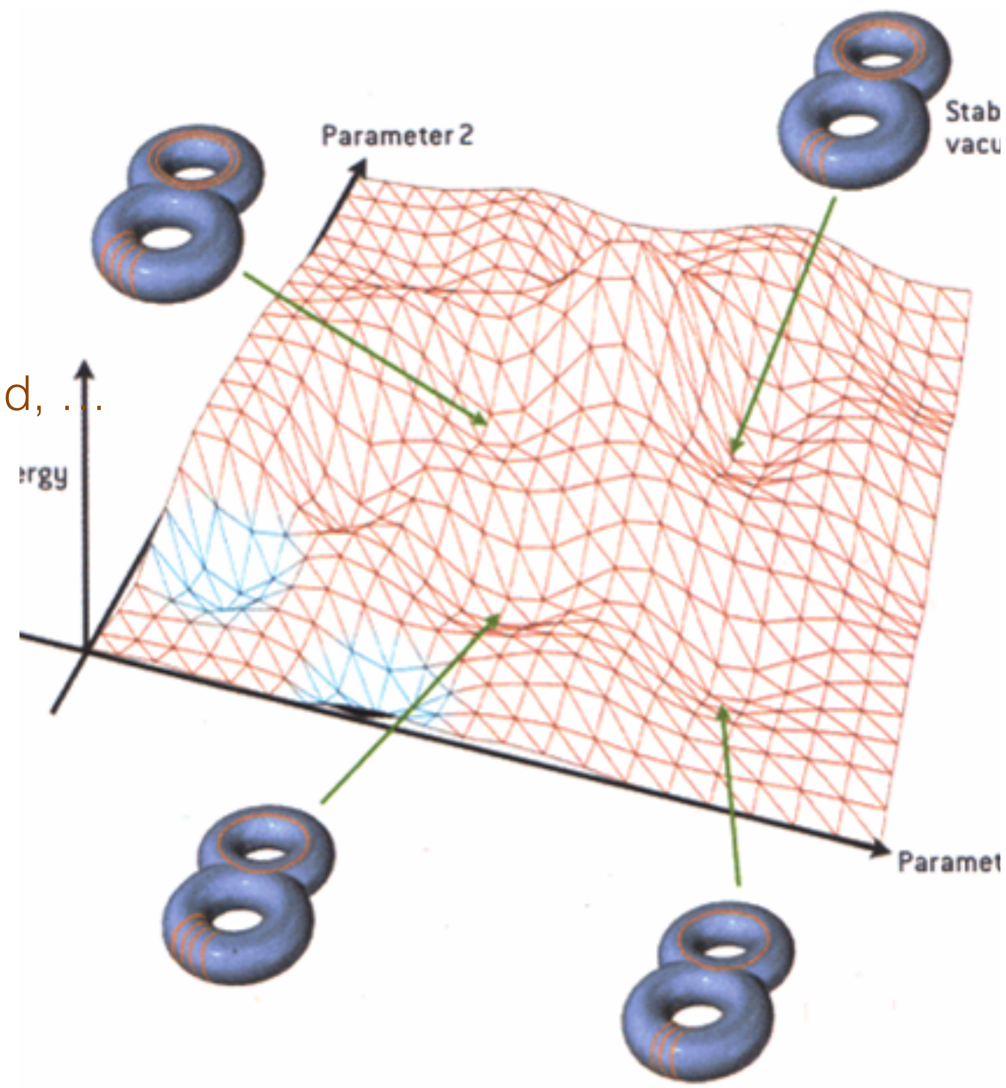
Weinberg, Bousso+Polchinski, Susskind, ...

- We are nothing special, so there should be many bubble nucleations in our past, with at least the most recent followed by slow roll inflation

- If you model the landscape as a random potential for **N** scalar fields, inflation following a bubble nucleation (or at a random point) is extraordinarily unlikely:

$$P \sim \exp(-c\, N^2), \quad c \sim 0.5$$

Yang



"The Landscape" (Picture from *Scientific American*)

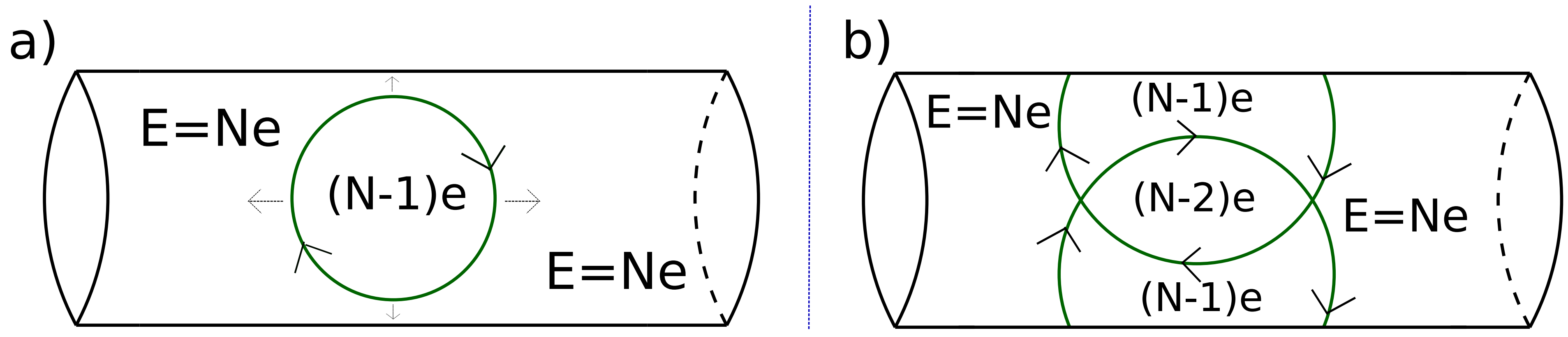
Unwinding inflation

- One needs some non-trivial structure in the landscape - inflation should happen after tunneling for a dynamical reason, or because of some structure, not randomly
- In my view this is a very interesting clue (particularly in that it connects current acceleration with past acceleration)
- There is a prototype of how this can happen - “unwinding inflation”, a model relying on the presence of compact extra dimensions, where the vacuum energy of the parent false vacuum gradually decreases after tunneling, eventually reheating in a low (vacuum) energy state

MK Krishnayengar Porrati
D'Amico Gobbetti MK Schillo

Flux cascade

- Charged brane nucleation initiates a cascading discharge of vacuum energy as the bubble expands around compact directions - many units of flux discharge, one for each "wind" or "wrap" of the bubble



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

- Reheating happens when most or all vacuum energy is gone

Summary

- Inflation really does solve the fine-tuning problems of cosmology
- It predicts a distinctive spectrum of density perturbations, now definitively confirmed observationally
- Eternal inflation remains very confusing, but some predictions can be made anyway
- Inflation was very high energy, and studying it provides a unique opportunity for fundamental physics