Fundamental Physics from Cosmology

Observations and Theoretical Challenges in Primordial Cosmology, KITP April 2013

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The universal microscope

- The universe expanded by huge factor between reheating and now, and during inflation
- Energy scale during inflation was naturally very high, $H \sim 10^{-5} * M_P \sim 10^{10}$*LHC energy
- Not far below the GUT/string scale
- Prior to inflation, at least naively there was arbitrarily high energy (singularity)
- A unique opportunity to study very high energy physics?

Three possibilities

- Traces of the **pre-inflationary** state (relics)
  - Not limited by inflationary energy scale
  - Requires short inflation, because all initial state effects inflate away exponentially
- Physics active **during** inflation
  - Limited by inflationary energy scale
  - Survives long inflation, much more data potential
- Theory constraints
  - Current/near future data might suffice
  - Requires a major theoretical advance

Pre-inflationary relics

Short inflation?

- There are reasons to believe inflation didn't last much longer than necessary to solve horizon/flatness
- For example, in a universe with too large negative curvature, structure cannot form
- With positive curvature, universe collapses as soon as curvature dominates
- If one fixes $\delta\rho/\rho$ to the observed value, >60 efolds are necessary to form structure (related to Weinberg's argument for the CC)

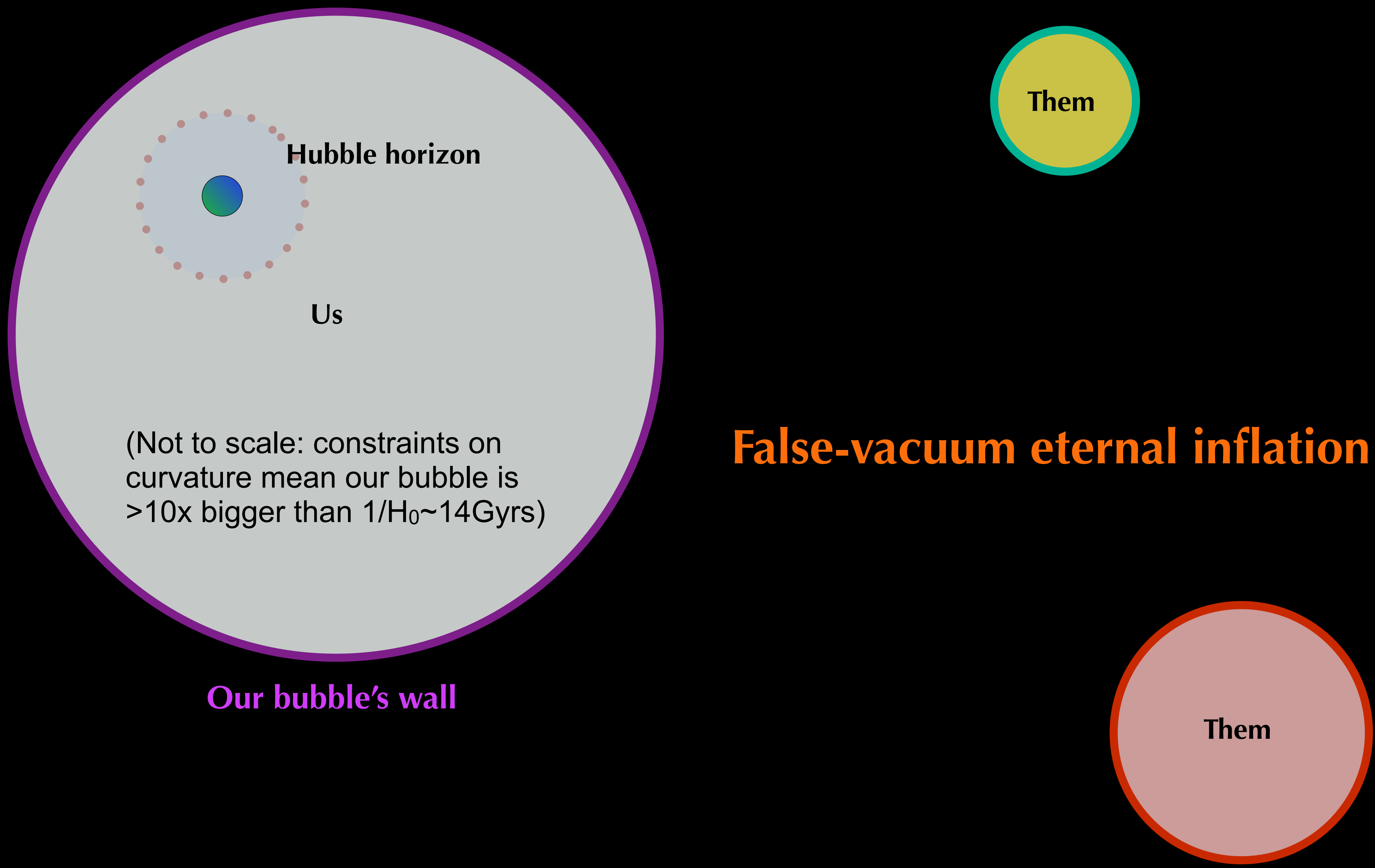
Freivogel, Kleban, Rodriguez-Martinez, Susskind 05

- If the probability of N efolds goes as N^{-p} with p>>1, N should be close to this limit and inflation was short

What could we observe?

- String theory predicts a landscape of metastable minima (false vacua) with positive vacuum energy
  - Since these regions inflate exponentially with extremely high Hubble constant, they presumably dominate the volume
  - We do not live there (anthropic?), so we live in a bubble that decayed from a rapidly inflating region
  - Each bubble contains an **open** FRW cosmology, with curvature radius ~ radius of the bubble - which means bubble must have inflated **after** it formed
  - All bubbles eventually collide with many others

False-vacuum eternal inflation

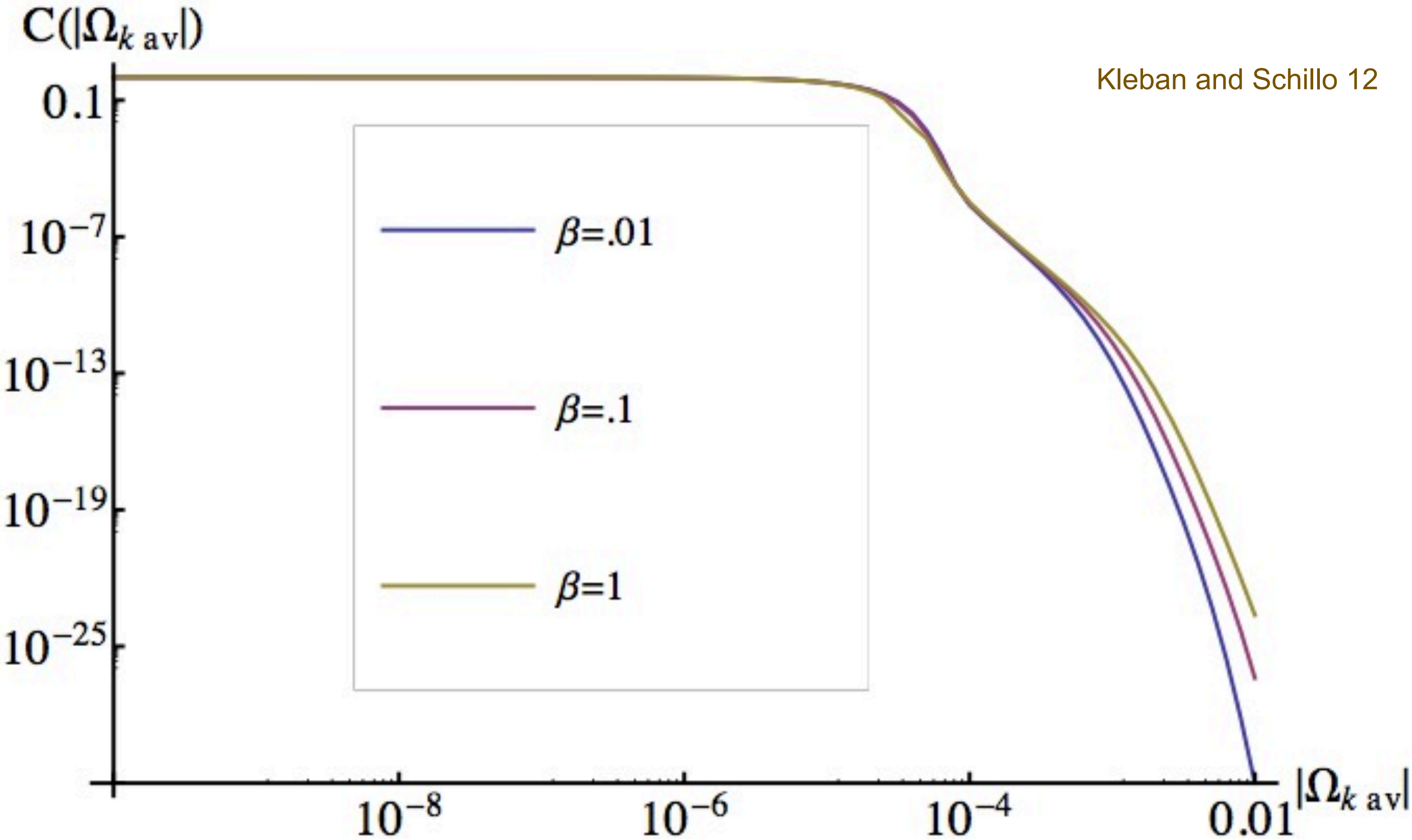


Curvature

- Since each bubble contains an FRW cosmology with negative spatial curvature:
  - If $\Omega_k<0$ (closed), this picture of the landscape is **falsified** (all types of eternal inflation are falsified)
  - If $\Omega_k>0$ (open), a landscape prediction is **confirmed** (and slow-roll eternal inflation is falsified)
  - If Ω_k is consistent with zero, slow-roll inflation was somewhat longer than required
- Constraining curvature is very important!

Freivogel+Kleban+Rodriguez-Martinez+Susskind 05, Batra +Kleban 07, Kleban+Schillo 12, Guth+Nomura 12

Spatial curvature falsifies (slow-roll) **eternal** inflation



Kleban and Schillo 12

Bubble collisions

- Our bubble will eventually collide with infinitely many others, but these collisions may or may not have occurred yet, or may not be visible

Garriga Guth Vilenkin 07
Freivogel Horowitz Shenker 07

- Each collision injects a huge pulse of energy into the early universe (before inflation) that propagates across the universe - a “cosmic wake”
- Cosmic wakes cut across our horizon volume create unique signals in the CMB and LSS

Chang, Kleban, Levi 07
Kleban, Levi, Sigurdson 11

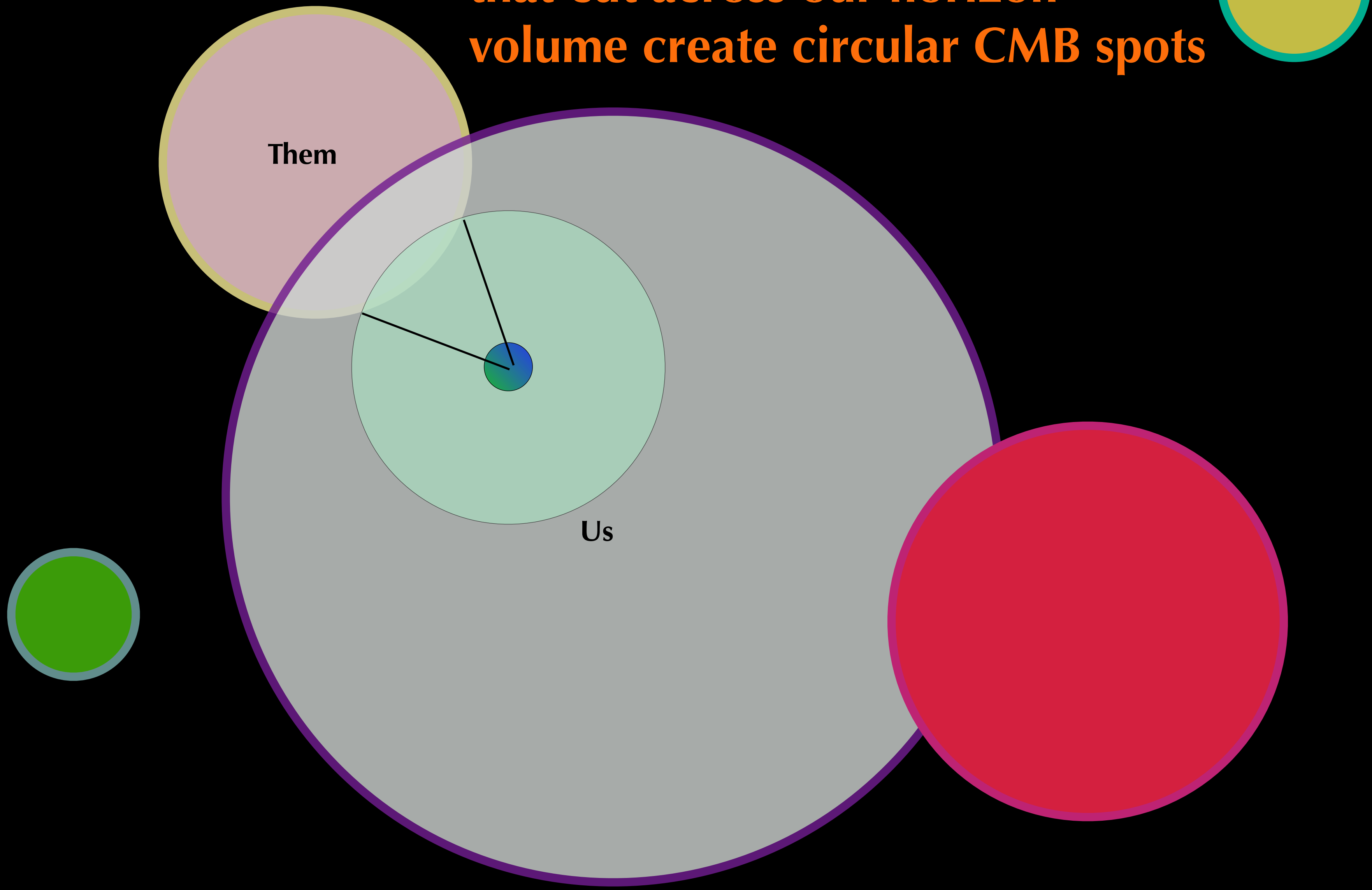
- Number and amplitude ~< $|\Omega_k|$

Freivogel, Nicolis, Kleban, Sigurdson 09

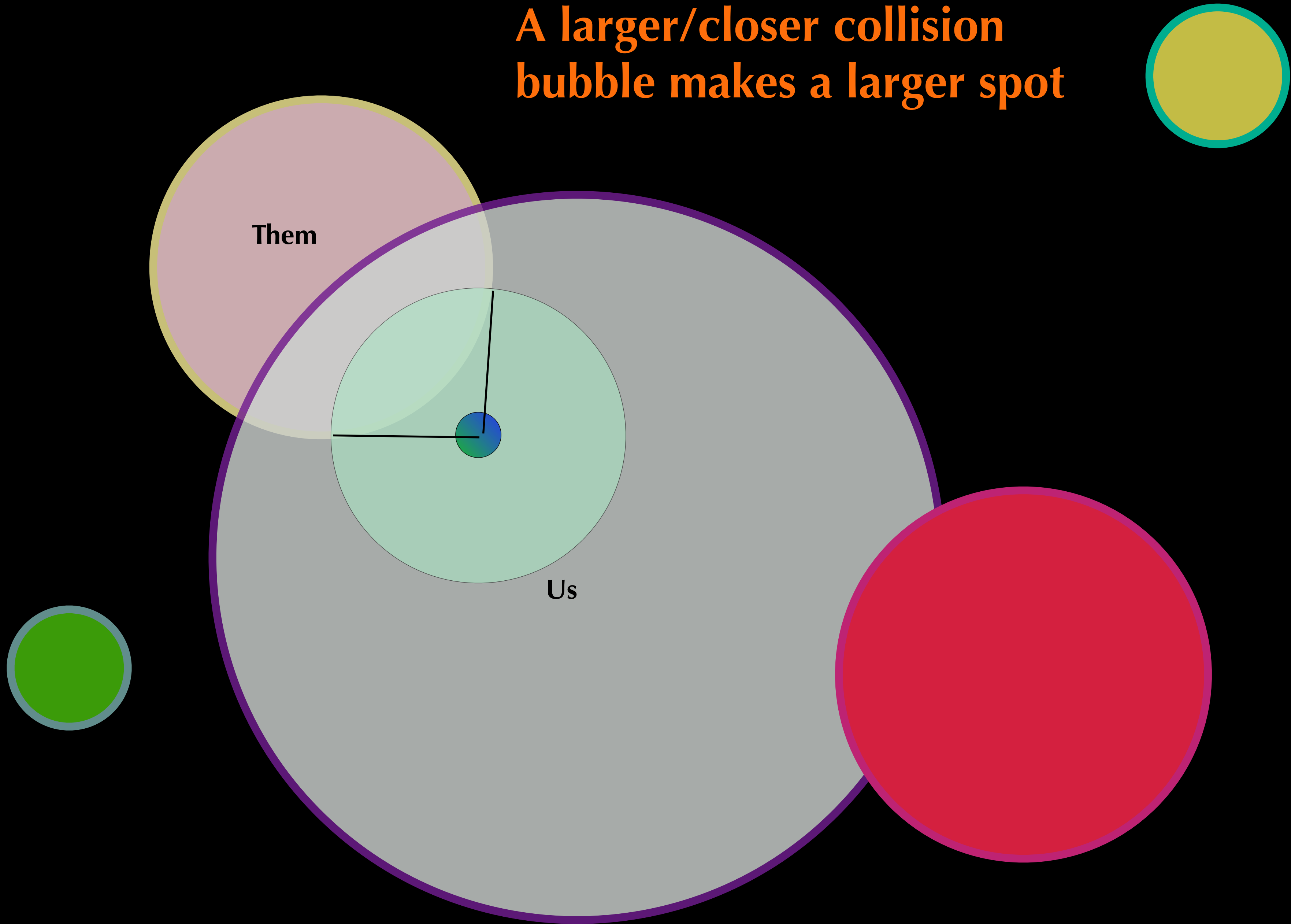
- Zero detections indicates somewhat longer than minimal inflation, or slow false-vacuum decay rate

Pre-inflationary relics

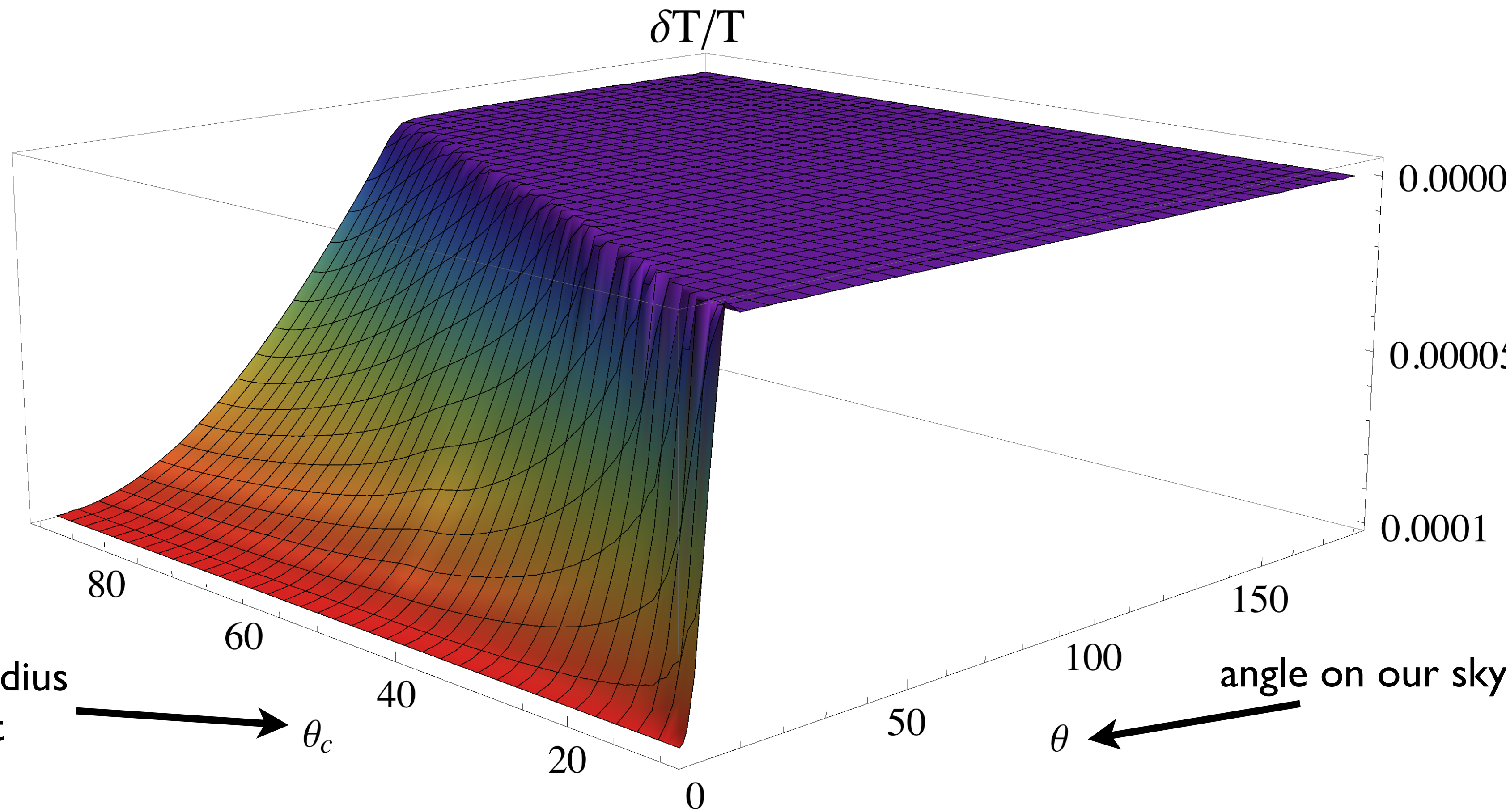
Edges of bubble collision wakes that cut across our horizon volume create circular CMB spots



A larger/closer collision bubble makes a larger spot

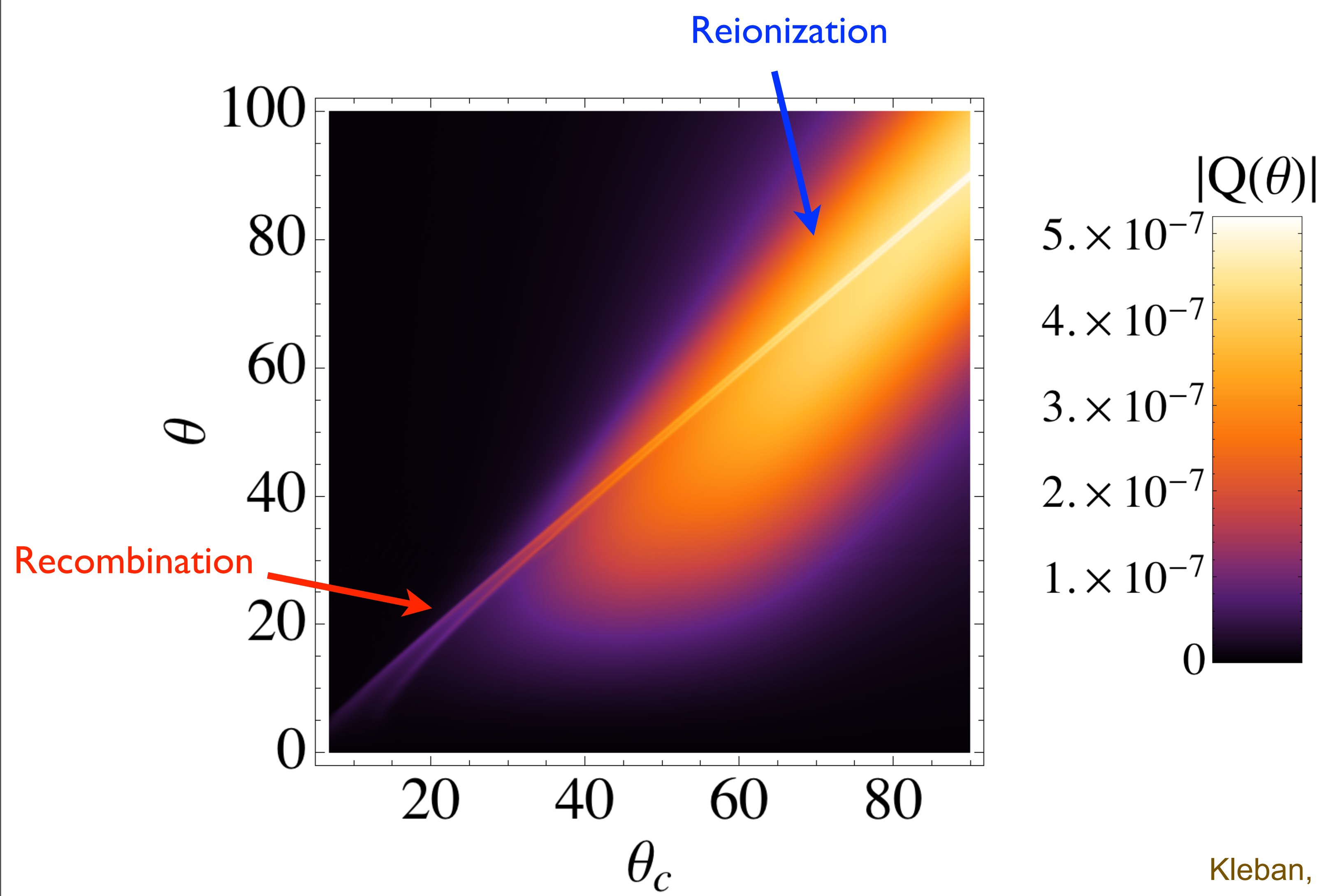


CMB temperature from a bubble collision



Kleban, Levi, Sigurdson 11

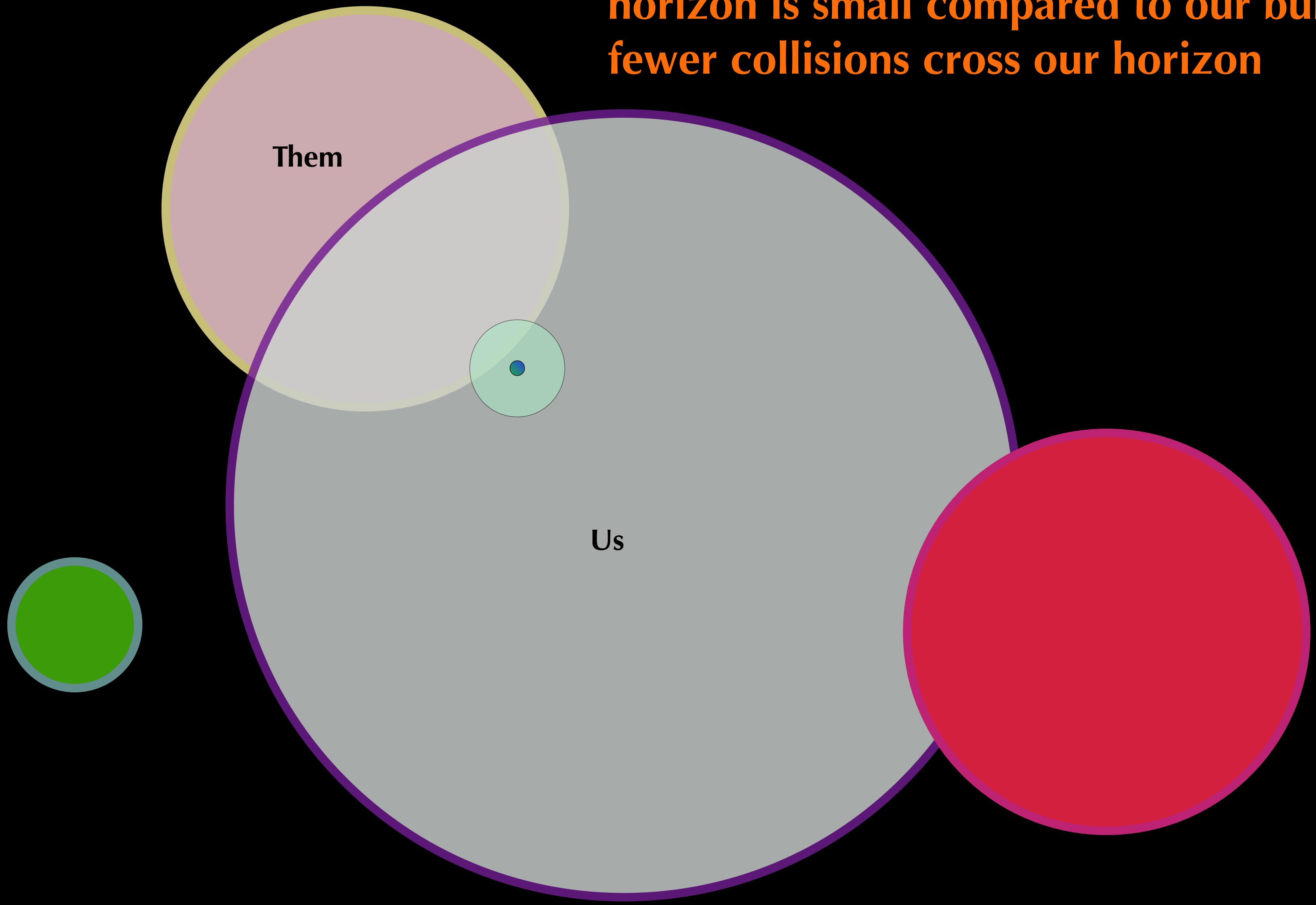
Polarization



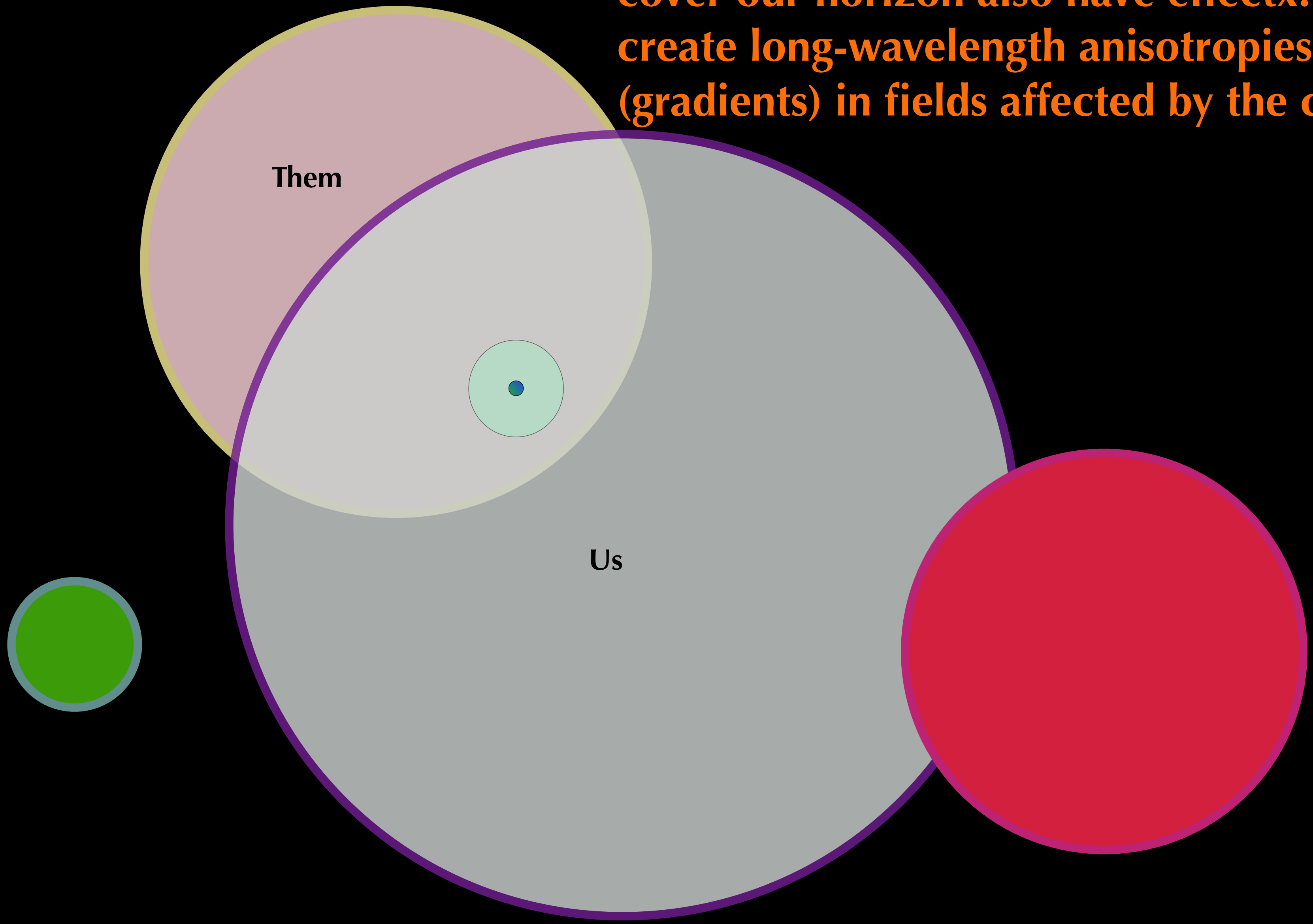
Kleban, Levi, Sigurdson 11

- Spots with $\theta_c \geq 12^\circ$ exhibit a double peak

If the spatial curvature is small, (our horizon is small compared to our bubble) fewer collisions cross our horizon



The more common wakes that entirely cover our horizon also have effectx: they create long-wavelength anisotropies (gradients) in fields affected by the collision



Low-l anomalies?

- Low scalar power is generic during the first phase (low l) of slow-roll inflation after a bubble forms

Freivogel, Kleban, Rodriguez-Martinez,Susskind 05

- Hemispherical power asymmetry is more complex: requires at least two fields, with different initial gradients
- Main effect of bubble collisions with wakes that encompass our entire horizon is to create superhorizon gradients in fields

Kleban+Gobbetti 12

- **Caution**: the 10^{-5} amplitude of the low-l (particularly l=2) modes severely constrains **all** anisotropic initial states
  - Any initial anisotropy must barely modulate the background/CMB monopole, else it will provide much too much l=2,3,4... power
- Still, these anomalies may provide an interesting clue, and can be explained by models with initial gradients for a second field
- Hopefully, candidate explanations make other predictions

High-scale effects during inflation

First, inflation itself...

- Inflation itself is a high-scale new physics phenomenon about which we know almost nothing, hence studying it is intrinsically interesting (for example the **running**!)
- This is particularly true for signatures that cannot be reproduced by the simplest single-field models
- For example, oscillations in the power spectrum would be a very interesting hint, as is NG (especially local or folded)

High-scale effects on the inflaton

- Consider a single inflaton field with potential energy sourcing Hubble constant H, coupled to physics at a higher scale M
- Integrating out massive fields will produce irrelevant operators in the effective field theory and corrections $(H/M)^2$

  Kaloper, Kleban, Lawrence, Shenker 02
- The utility of this is limited because these effects are small, and measuring them requires knowledge of the inflaton dynamics
- But an effective theory can be constructed systematically, and measuring its parameters may provide information about both inflaton and other fields

  Cheung, Creminelli, Fitzpatrick, Kaplan, Senatore 08

  Baumann, D'Amico, Green, Silverstein, Zaldarriaga...

Oscillations in power

- Predicted by monodromy inflation and by unwinding inflation (two large-field models in string theory)

Silverstein and Westphal + McAllister 08
D'Amico, Gobbetti, Kleban, Schillo 12

- The oscillations arise due to compact extra dimensions
- Their details can probe the geometry of extra dimensions - and the oscillations exist on all scales (unlike a feature or initial state)
- There are correlated signals as well, such as NG or gravity waves

Other possibilities

- (Persistent) particle production/dissipation **during** inflation (warm, trapped, dissipative, and unwinding inflation), folded NG?
- Gravity waves (B-modes or direct detection)
- Cosmic strings or other defects produced at reheating
- Exotica: "trans-Planckian" effects, α-vacua, Lorentz violation

Theory constraints

Theory constraints

Priors

- Perhaps theory will provide very strong priors
- Combined just with currently available data, this might be quite powerful
- For example, T. Hertog mentioned the no-boundary measure from quantum gravity, which can exponentially favor certain models

Rare inflation?

- Another possibility comes from the landscape
- There is evidence that slow-roll inflation is extremely rare in random scalar field landscapes (exponentially suppressed in number of fields, or number squared)

Yang 12, Pedro+Westphal 13, Battefeld^2 12

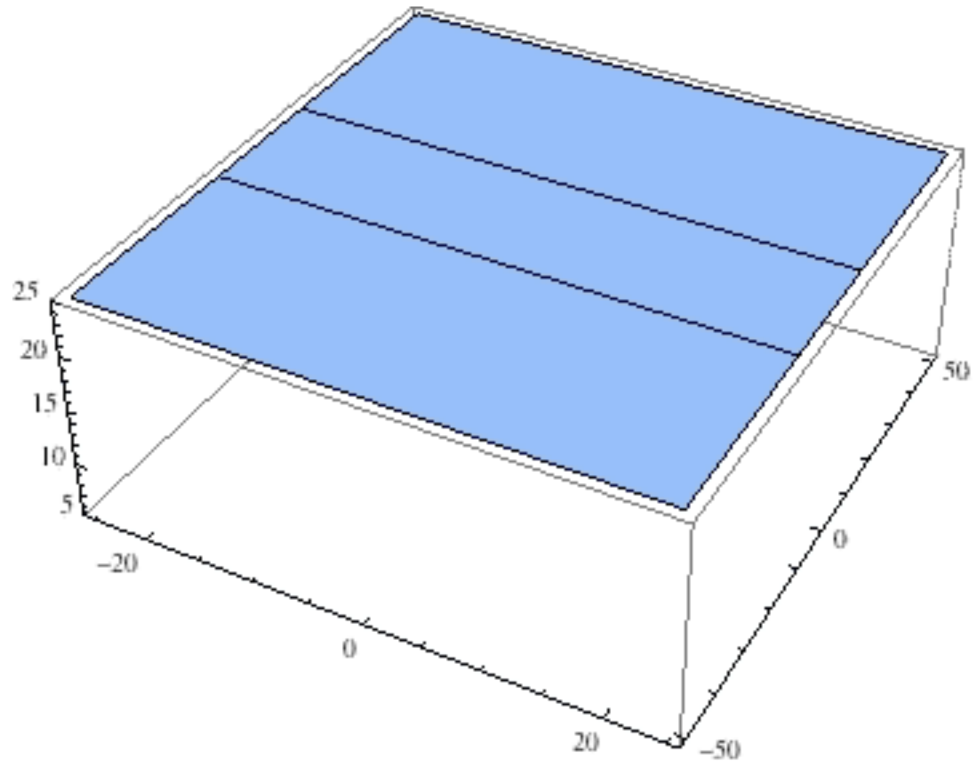
- Therefore tunneling from a false-vacuum may be very unlikely to be followed by a period of inflation
- If so, all evidence for inflation should be multiplied by an exponentially small prior, which entirely alters the picture (fine-tuned initial conditions might be more probable than slow roll)
- However, the string theory landscape is not random!

Brown 08

D'Amico, Gobbetti, Kleban, Schillo 12

Unwinding inflation

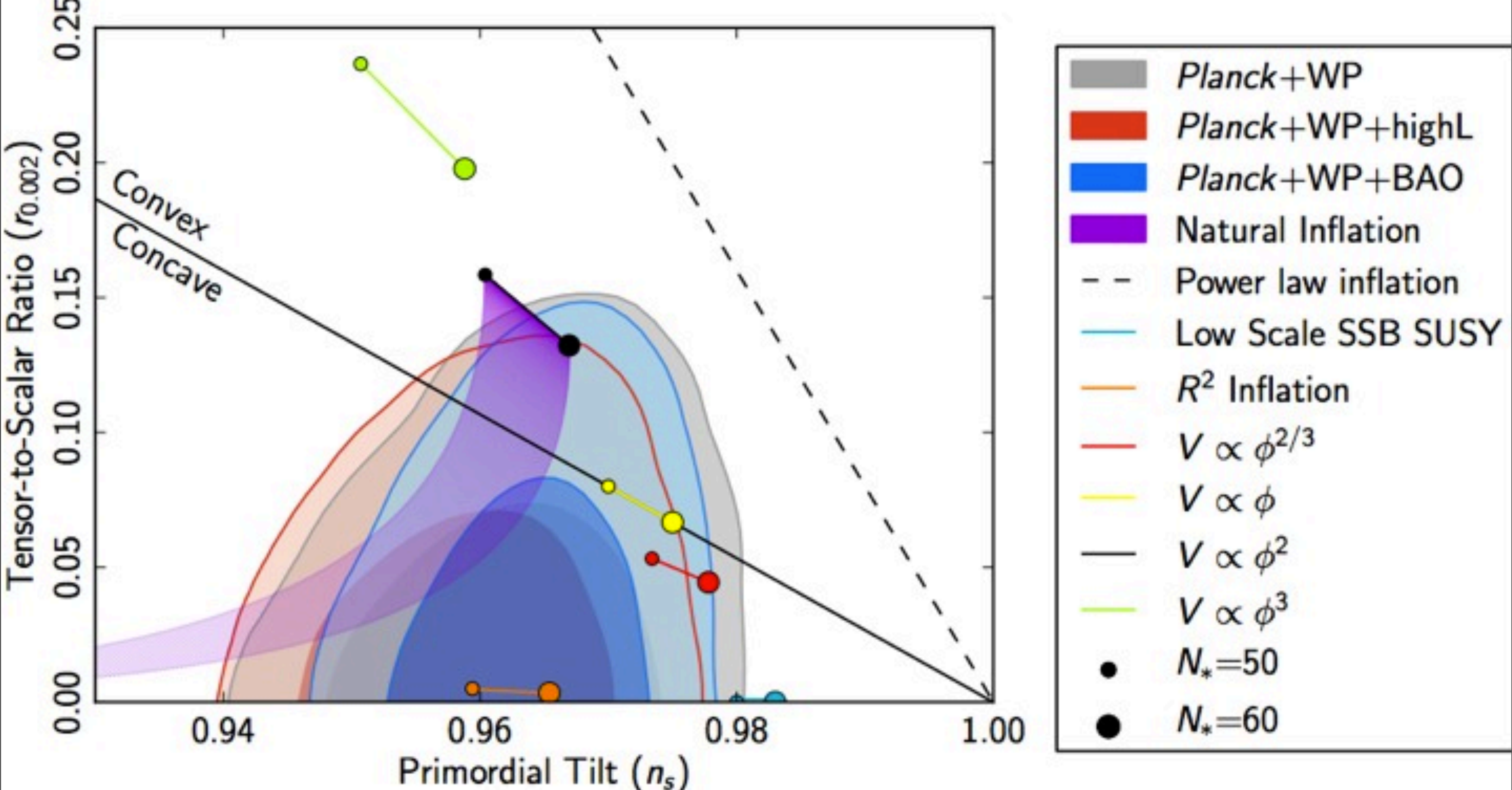
- In unwinding inflation slow-roll is the spontaneous decay ("unwinding") of electric flux that threads compact extra dimensions, and that powered false-vacuum eternal inflation prior to the decay
- Fluxes and compact dimensions are basic ingredients of the landscape, and meta-stable minima seem to be exponentially powerful attractors (the black region in my earlier plots)
- A major advantage of this type of slow roll is that it initiates spontaneously from such minima, with no tuning of initial conditions whatsoever: tunneling from this initial metastable state deposits the inflaton at rest directly onto a slow-roll plateau
- Furthermore, the existence and stability of the slow-roll plateau itself does not require multiple coincidences (instead, stability likely follows from the metastability of the parent minimum)
- Hence models like this might be exponentially preferred, again providing a sharp prior that could allow data to be leveraged much more efficiently



Theory constraints

Signatures?

- In addition to being potentially favored by initial conditions/ priors, unwinding inflation predicts both pre-inflationary relics and effects during inflation (oscillations and NG)
- Its predictions are roughly similar to $m^2\varphi^2$, but with cs<1 - so the tilt is consistent with data, and at least one of r and $f_{NL,eq}$ should be detected soon
- One possible relic is an initial gradient (produced either by a bubble collision or by a fluctuation around spherical shape in the bubble when it nucleated) in a field that modulates the level of string/particle production
- This could potentially account for both low power at low l and the hemispherical anomaly (work in progress)



Theory constraints

Major uncertainty: “measure problem”

- Inflation likes to be eternal, producing infinite volumes and all possibilities
- Infinite universes are very confusing - especially exponentially growing ones Dyson, Kleban, Susskind 02
- Even long-ish slow-roll can produce a huge number of present-day Hubble volumes with large variation in (inferred) parameters LoVerde, Nelson, Shandera 13
- It is very unclear how to make predictions in eternal inflation, but finding the correct answer (a non-perturbative definition of eternal inflation, for example) could dramatically alter the picture

Bousso, Freivogel, Yang,...

Future

- Much of what I have discussed requires "luck" to observe
- But there are many such possibilities, most of which probably haven't been thought of yet
- Data+theory may well converge on a specific model with multiple testable predictions
- We shouldn't forget that we have almost no idea what inflation was and why it happened, what dark matter is, what dark energy is
- We still have a lot of work to do: the most basic questions in cosmology remain unanswered

What can we learn?

- Cosmology may be the best opportunity we have to probe very high energy physics
- Inflation **is** unknown, very high energy physics
- Any information about the early universe is useful, but certain things would be extremely interesting
- Detection of certain relic signals - cosmic bubble collisions, for example - would revolutionize our understanding