# Prospects for Observing the Multiverse

## Fundamental Questions in Cosmology
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# First - what is the multiverse?

- High energy phases are generically unstable, and eventually decay - either gradually or suddenly - to other phases
- But coupled to gravity, such phases **inflate** rapidly and reproduce themselves
- Hence if decays are not too rapid, result is an exponentially growing universe populated by **all** phases: the eternally inflating "multiverse"

Guth, Linde, Vilenkin,...

- Difficult to avoid, since QM predicts that anything not forbidden will take place

Brown+Dahlen 11

# String landscape

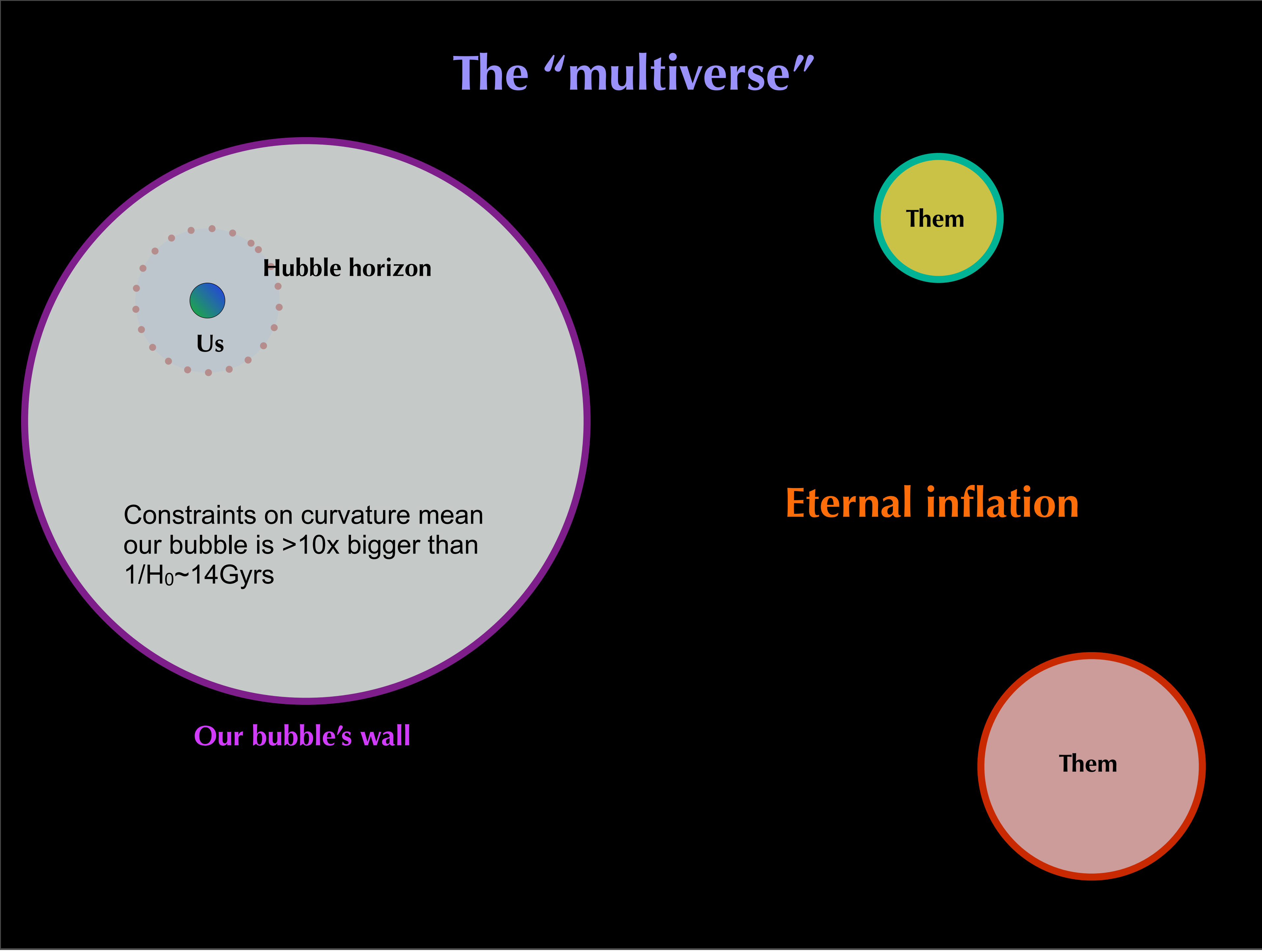
Bousso, Polchinski, Susskind, Kachru, Kallosh, Linde, Trivedi,...

- String theory seems to have very many metastable eternally inflating phases
- Sufficiently large numbers can explain (or at least account for) the cosmological constant

  Weinberg 87
- But even one eternally inflating phase suffices to create a multiverse; it is perhaps implausible that no such phase exists
- If so, implications are profound: among them is that the cosmological principle is **false** - our universe is extremely inhomogeneous and anisotropic on (very) large scales

# Consistent with observation?

- Our Hubble volume **is** homogeneous and isotropic (on scales of order the Hubble length)
- To create such a big smooth region, a relatively long (~60+ efolds) period of ordinary inflation must have taken place after our part of the multiverse emerged from its parent phase
- If not, we could see the edges of our bubble more directly
- Hence, most signatures of the multiverse are encoded in long wavelength effects - too long to be observable unless slow-roll was relatively short


The "multiverse"
Hubble horizon
Us
Them
Constraints on curvature mean our bubble is >10x bigger than $1/H_0$~14Gyrs
Eternal inflation
Our bubble's wall
Them

# How to observe the multiverse

- Traces of the state **before** slow-roll inflation (relics)
  - Requires short inflation, because all initial state effects inflate away exponentially
  - Signals are mostly on large scales
- Physics active **during** slow-roll inflation
  - Limited by inflationary energy scale
  - Less direct
  - Survives long inflation, much more data (signals persist on short scales)

# 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 (similar 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

# Curvature

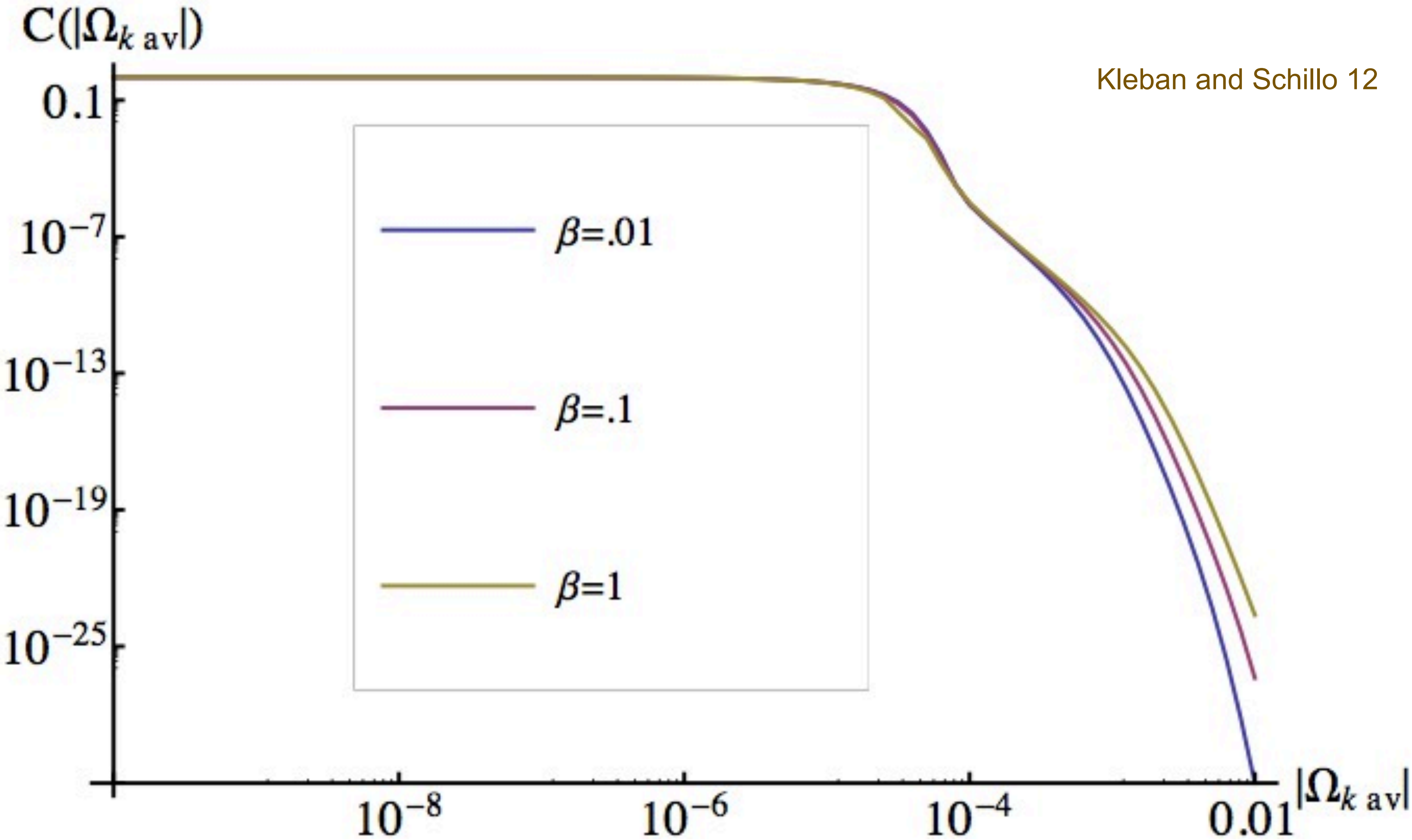
- Since each bubble contains an **open** FRW cosmology with negative spatial curvature:
  - If $\Omega_k<0$ (closed), this picture of the landscape is **falsified** (all types of eternal inflation are falsified)
  - If $\Omega_k>0$ (open), a landscape prediction is **confirmed** (and slow-roll eternal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

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

# Slow roll eternal inflation

- Another possibility is that the parent phase is not meta-stable, but actually unstable - so that the vacuum energy gradually decays
- If the decay is slow enough, quantum fluctuations ensure that even though every Hubble region eventually decays, regions of parent phase remain and continue to inflate
- These same fluctuations mean that parent phase is characterized by O(1) density perturbations, and has no well-defined spatial curvature
- Those must be on large scales, so need 60+ efolds of ordinary slow-roll inflation after exit, just as before
- Curvature and quadrupole receive equal contributions from these O(1) perturbations (Grishchuk-Zel′dovich)

# Spatial curvature can falsify eternal inflation/multiverse



# 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

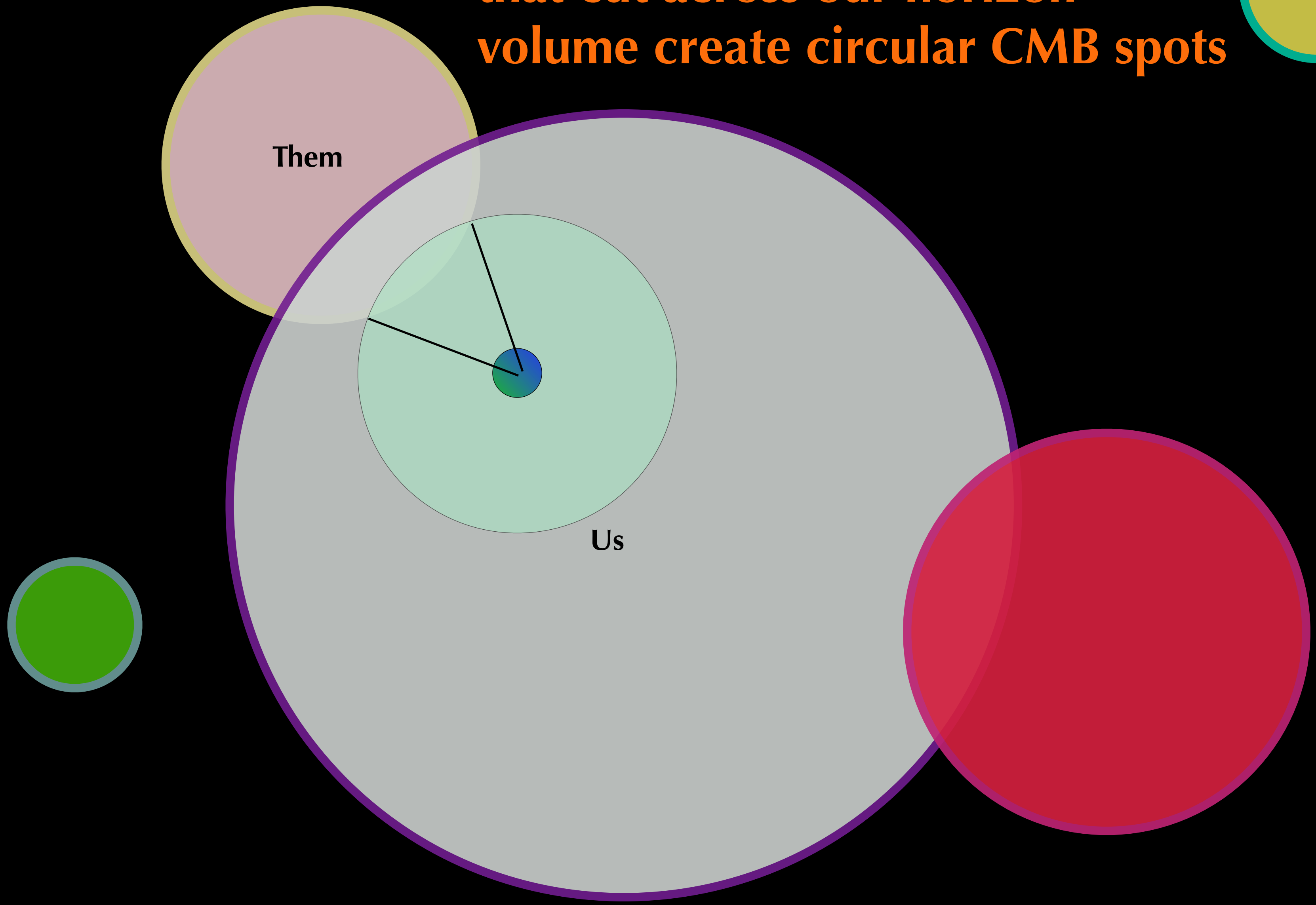
Garriga Guth Vilenkin 07
Freivogel Horowitz Shenker 07

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

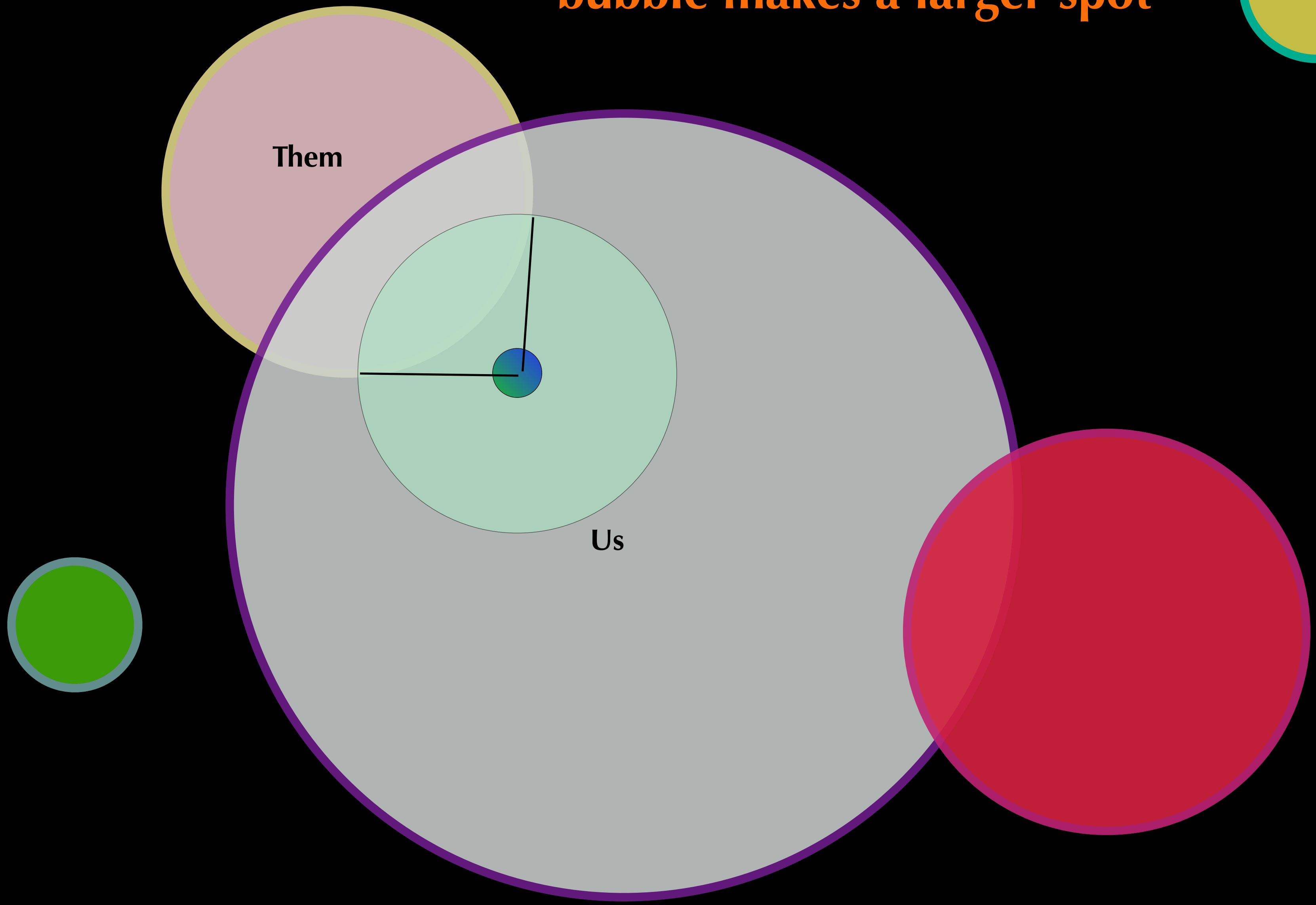
Chang, Kleban, Levi 07
Kleban, Levi, Sigurdson 11
Freivogel, Nicolis, Kleban, Sigurdson 09

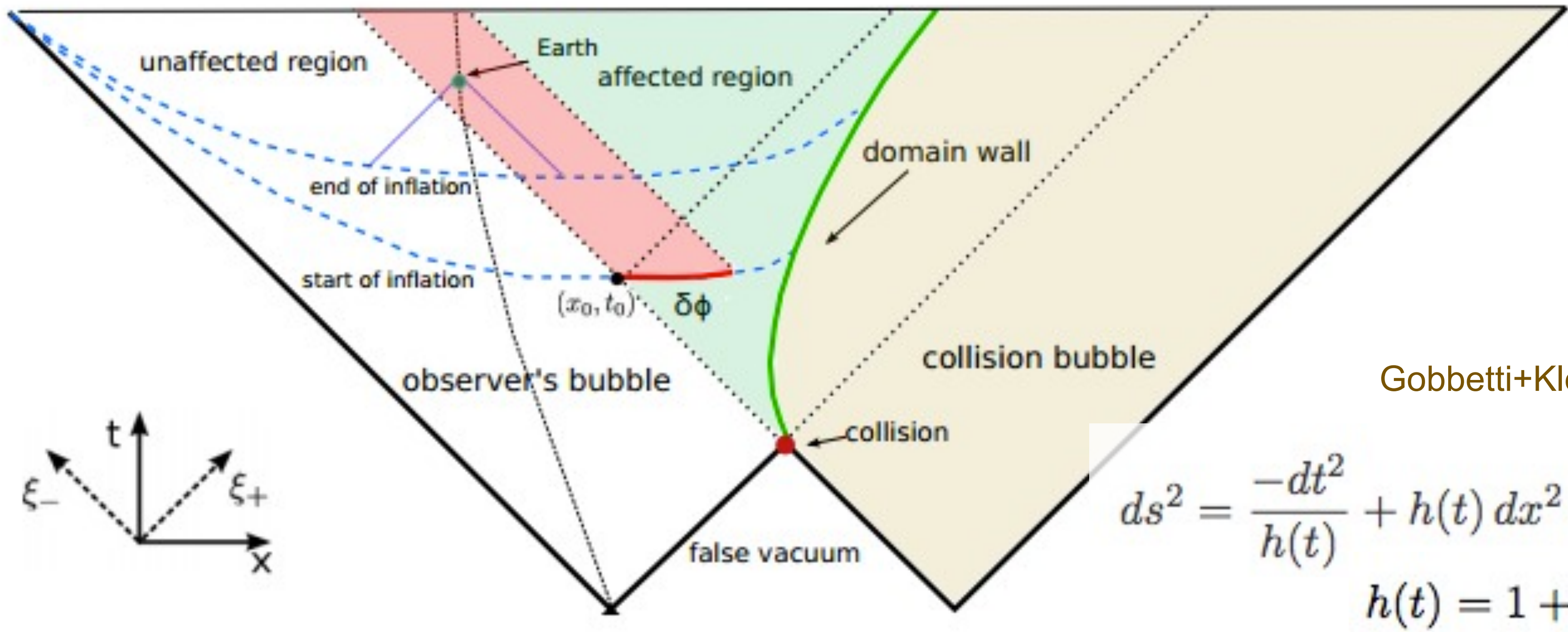
- Zero detections indicates somewhat longer than minimal inflation, or slow false-vacuum decay rate

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



# A larger/closer collision bubble makes a larger spot






Gobbetti+Kleban 12

$$ds^2 = \frac{-dt^2}{h(t)} + h(t)\,dx^2 + t^2 dH_2^2$$
$$h(t) = 1 + (H_i t)^2,$$

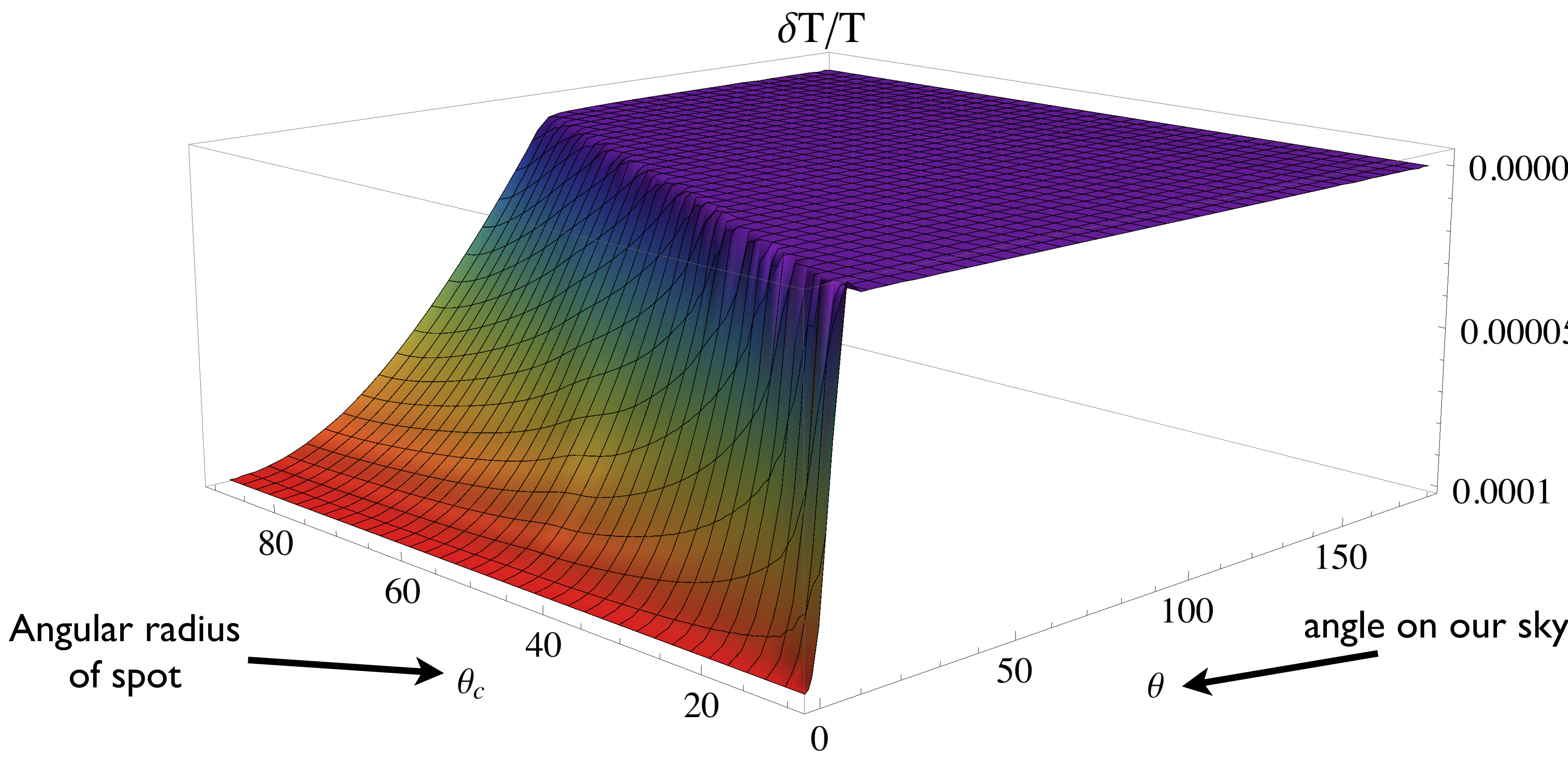
$$\delta\phi(x,\eta_0) = \sum_{n=0}^{\infty} c_n (x-x_0)^n \theta(x-x_0)$$

$$\begin{aligned}\delta\phi(x,\eta) = \sum_{n=0}^{\infty} c_n (-)^{n+1} n! \Bigg[ e^{\xi_+/\eta_0} - \sum_{m=0}^{n} \frac{1}{m!}\left(\frac{\xi_+}{\eta_0}\right)^m \\ - \frac{\eta}{\eta_0}\left( e^{\xi_+/\eta_0} - \sum_{m=0}^{n} \frac{1}{(m-1)!}\left(\frac{\xi_+}{\eta_0}\right)^{(m-1)}\right)\Bigg]\theta(\xi_+) \\ \approx \sum_{n=0}^{\infty} c_n (-)^{n+1} n! \left[ e^{\xi_+/\eta_0} - \sum_{m=0}^{n} \frac{1}{m!}\left(\frac{\xi_+}{\eta_0}\right)^m\right]\theta(\xi_+),\end{aligned}$$

Bubble collisions preserve a lot of symmetry, which can be used to find analytic solutions for the curvature perturbation at the end of inflation given an arbitrary initial perturbation created by the collision

The leading effect post-inflation is a **gradient (dipole)** in affected region

# CMB temperature from a bubble collision




The perturbation can then be evolved numerically to predict CMB T

Kleban, Levi, Sigurdson 11

# No detection - at least so far

Osborne+Senatore+Smith 13
McEwen+Feeney+Johnson+Peiris 12

- Data searches (using WMAP7 temperature data) have not found significant evidence for collisions
- However, all searches have focused on collisions with wakes that cut across our horizon volume, even though these are more rare by a factor of $\sqrt{\Omega_k} < .1$

Freivogel+Kleban +Nicolis+Sigurdson 09

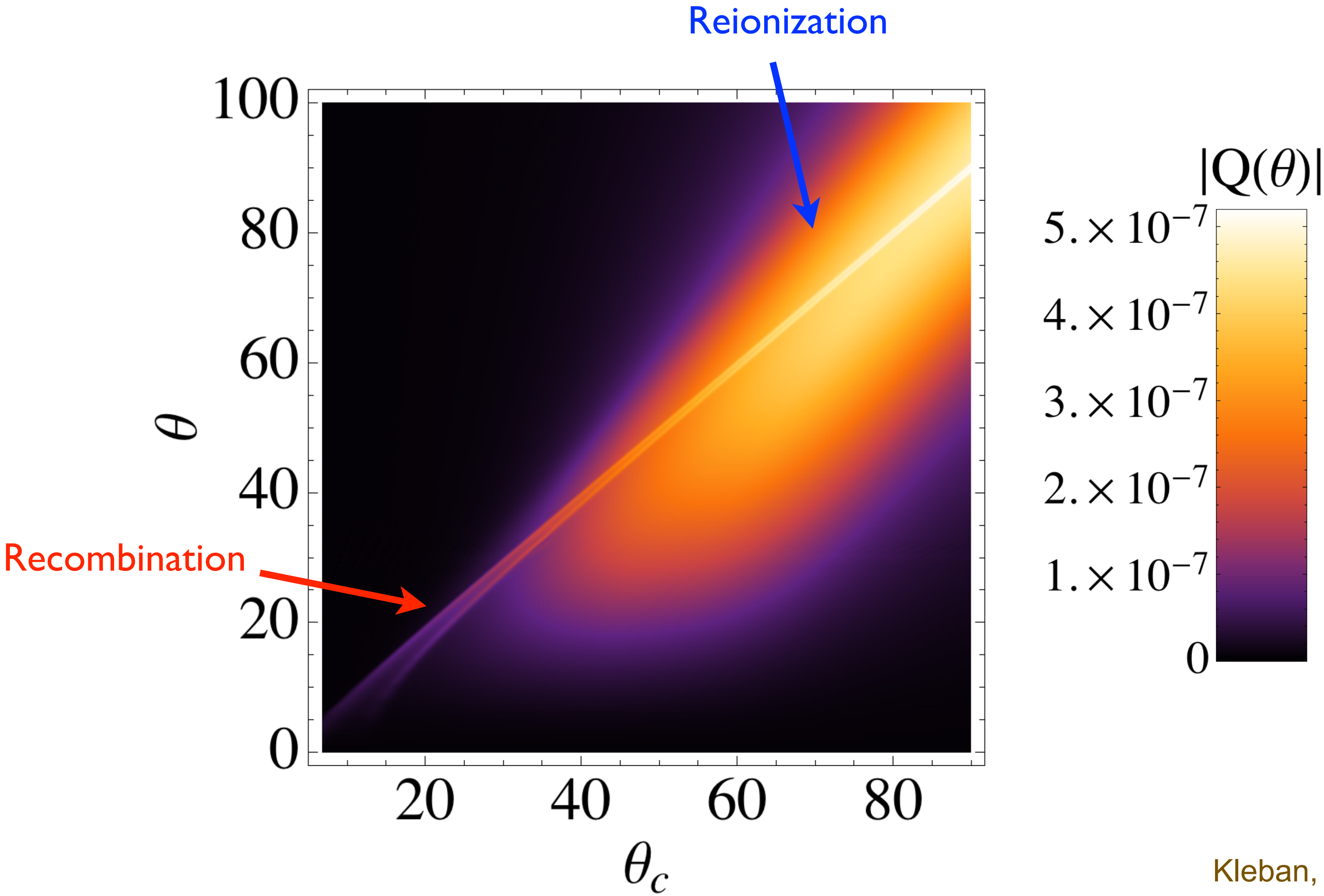
- There is a reason for this - edges are easier to detect than smooth signals, and wakes that entirely cover our horizon mostly produce just a dipole
- Still, collisions should affect all fields, and generically create gradients with varying strengths - which is potentially observable

Kleban+Gobbetti 12

# Polarization

- Large scale features like a cosmic wake produce characteristic features in polarization data
- Because collisions do not have a chirality, the signal is purely E-mode
- The fact that there is no significant detection in temperature reduces the chance that polarization can provide a significant detection
- On the other hand polarization is most sensitive for large bubbles, which are most common

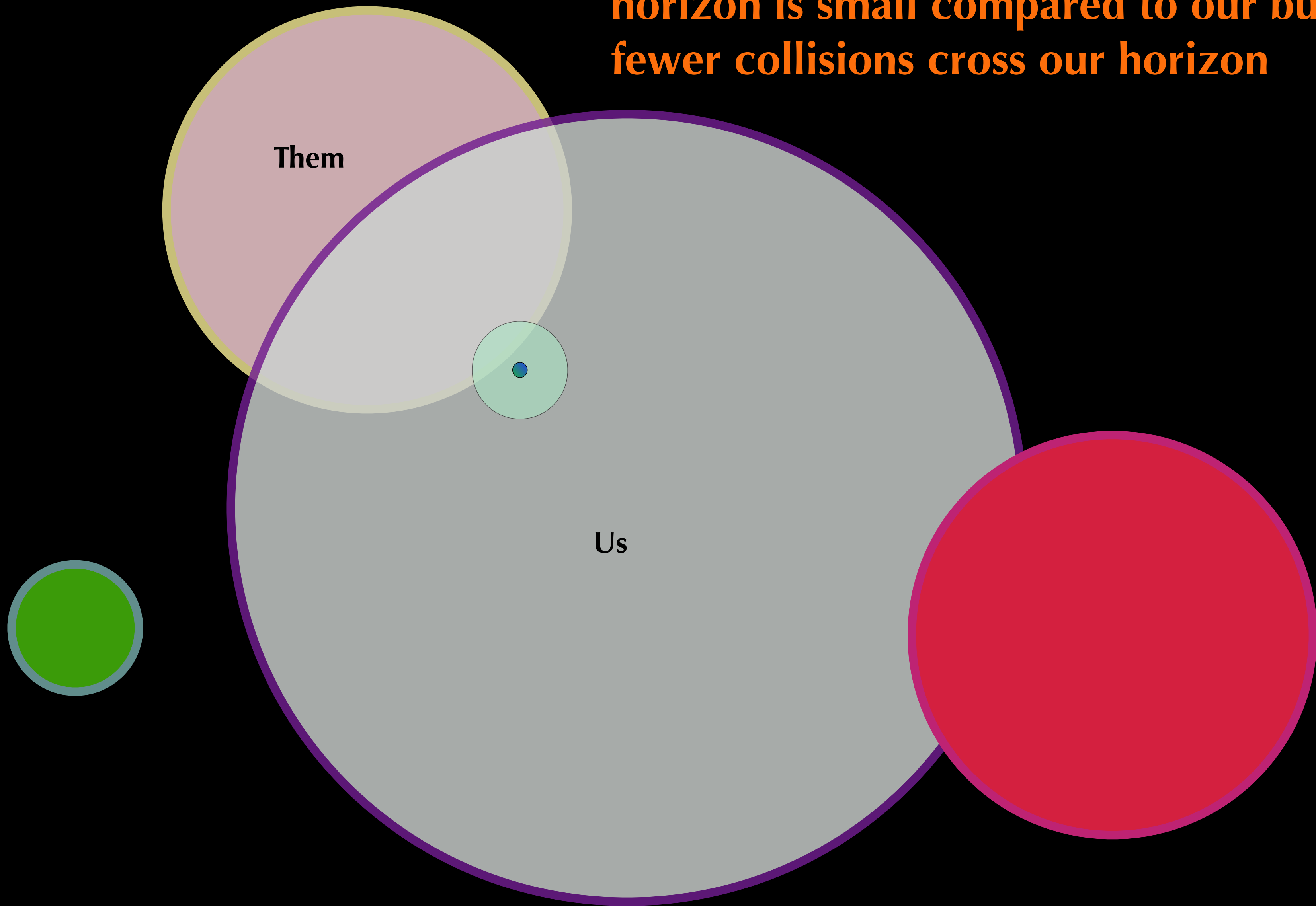
# Polarization



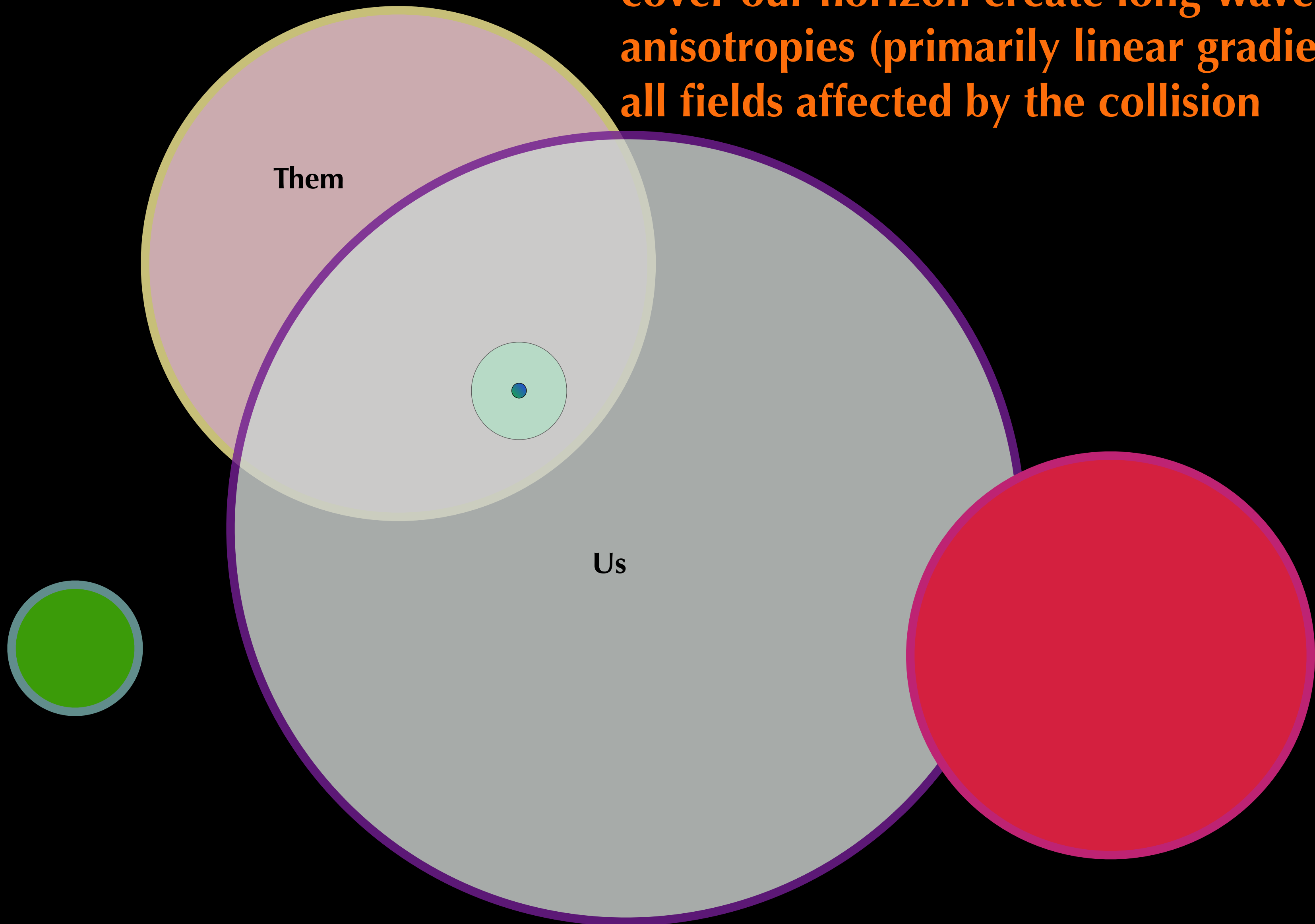

Kleban, Levi, Sigurdson 11

- 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 create long-wavelength anisotropies (primarily linear gradients) in all fields affected by the collision



# Low-l anomalies?

- Planck (and WMAP) found a number of "anomalies" at low l, including an overall **lack of power** and a hemispherical **power asymmetry**
- These are not very significant, and may simply be fluctuations
- Still, low l is precisely where one expects traces of the pre-inflationary state
- Could they be traces of a non-trivial initial state, or of the multiverse?

# Anomalies?

Freivogel, Kleban, Rodriguez-Martinez,Susskind 05

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

Dai+Jeong+Kamionkowski+Chluba 13

# Unwinding inflation

D'Amico+Gobbetti+Kleban+Schillo 12

- Still, it is possible to both suppress power at low l and generate a hemispherical power asymmetry
- Guido D'Amico will describe a new "slow-roll" inflation model called unwinding inflation tomorrow
- Part of the density perturbations in that model arise from particle production, and there is a second field that suppresses the amount of produced particles when it is non-zero
- A gradient in that field therefore both suppresses power and generates a hemispherical asymmetry - without producing a large quadrupole

# Correlated anisotropies

- Even in this model there is *some* effect on very low l temperature modes (l=2,3,4,5): particle production is a source of "friction" for the inflaton, and changes N
- The preferred axis of the power asymmetry is imprinted on these very low l moments
- In a coordinate system aligned with the power asymmetry the $a_{l0}$s are selected out
- What form this takes and whether it is large enough to be observable/ruled out is under study
- Not unique to this model - gradients in a field that affects the inflaton will generically produce such anisotropic effects along the same axis

# Physics during inflation

# String landscape

- As we've seen, if there is a multiverse there must have been ~60+ efolds of inflation following the decay of our parent vacuum
- Hence, such decays must at least occasionally be followed by significant amounts of slow-roll inflation
- But analyses of random scalar landscapes indicate that such slow-roll phases are extremely rare
- This is because n fields require >n tunings to inflate
- Other models of inflation in string theory require initial conditions that are not produced by tunneling

Aazami+Easther 05, McAllister+Easther 05...
...Yang 12, Pedro+Westphal 13

# Inflation in the landscape

- If inflation after tunneling is unlikely to happen by chance in a large landscape, then it must have happened by some non-random mechanism
- If the false-vacuum eternally inflating phase can decay in a way that **generically** leads to slow-roll, might be strongly favored
- Unwinding inflation (bubble collisions in compact extra dimensions) is precisely such a mechanism

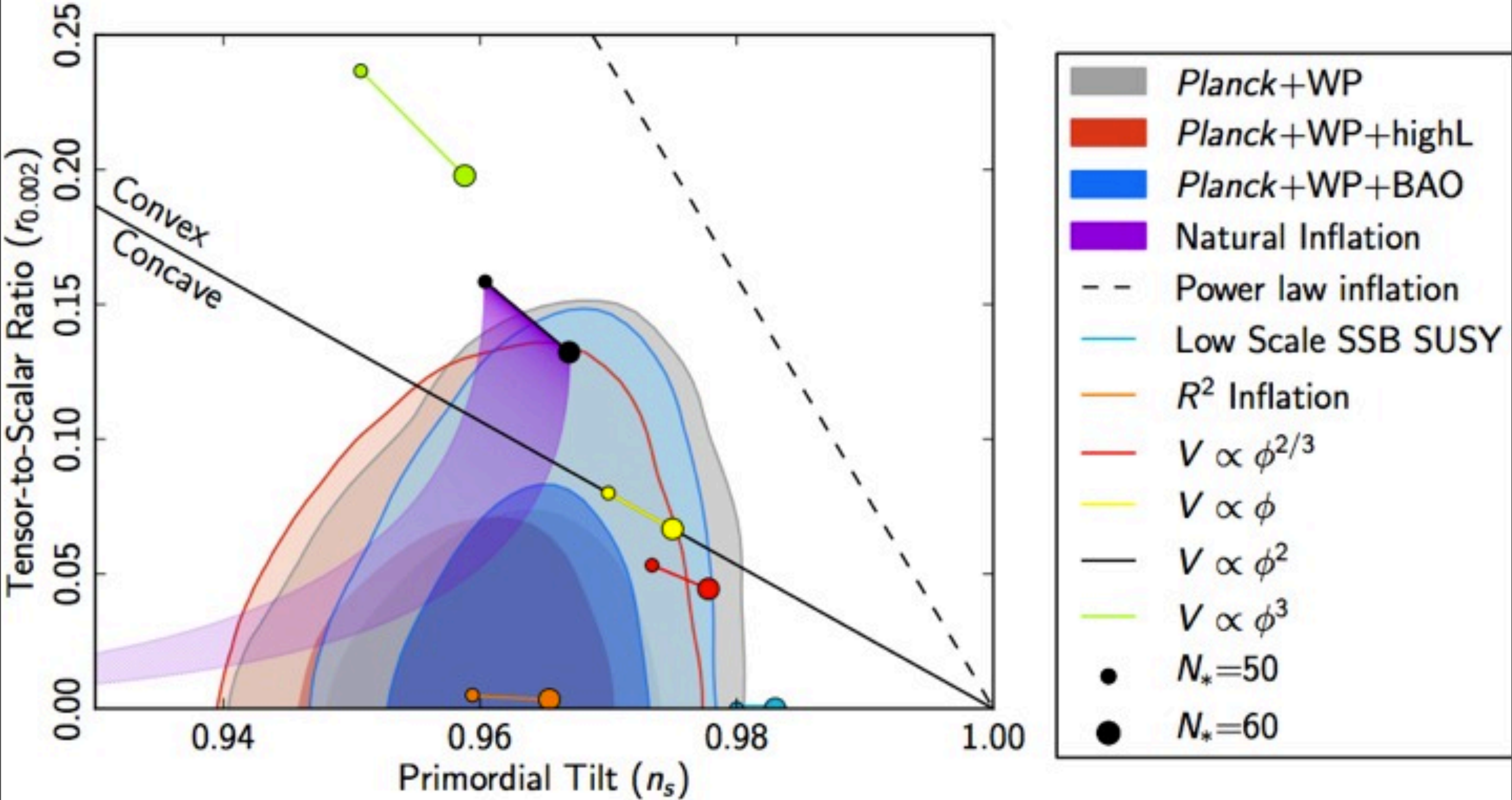
D'Amico+Gobbetti +Kleban+Schillo 12

- Reminiscent of old inflation in that the vacuum energy during inflation is the same vacuum energy as in the meta-stable parent vacuum - but decreases slowly, like slow roll, and reheats isotropically

Brown 08

# Signatures?

- Predictions are roughly similar to $m^2\varphi^2$, but with some flattening of the potential and with $c_s<1$
- The tilt $n_s$-1 and r are not in any tension with data, but at least one of r and $f_{NL,eq}$ will be detected soon if these constraints are improved
- Predicts oscillations in the power spectrum, and several flavors of non-Gaussianity
- Given the right initial conditions it can help account for the low-l anomalies, and this would help determine its parameters and sharpen these predictions




Planck collaboration 13

# Beyond the CMB?

- Future observations could provide much more information:
  - large field galaxy surveys
  - lensing
  - gravity waves
  - 21 cm and other precision tests of density
  - cosmic neutrino background
  - surprises, like cosmic strings or other present-day relics
- Bubble collisions for example perturb LSS, produce a lensing signal, and could be detected in several of these channels

# Major uncertainty: “measure problem”

- Infinite universes are very confusing - especially exponentially growing ones

Dyson+Kleban+Susskind 02
Albrecht+Sorbo 04....

- 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, Guth, Freivogel,
Page, Vilenkin, Yang,...

# Future

- Much of what I have discussed requires “luck” to observe
- But there are perhaps many such possibilities, most of which haven’t been thought of yet
- While it is possible we will never learn if the multiverse exists, there is a real possibility of detecting it - or falsifying it
- In my view, cosmology is still in its infancy - we still cannot answer many of the most basic questions about our universe
- Many surprises in store?