Title: Cosmic Bubble Collisions

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Abstract: TBA

Cosmic Bubble Collisions

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New York University

Based on

In progress: MK, Levi, Sigurdson; MK, Bovy and Dore; MK and Gobbetti

Polarizing Bubble Collisions, Czech, MK, Levi, Larjo, Sigurdson

When worlds collide, S. Chang, MK, T. Levi

Watching worlds collide, S. Chang, MK, T. Levi

Eternal Inflation, Bubble Collisions, and the Disintegration of the Persistence of Memory, B. Freivogel, MK, A. Nicolis, K. Sigurdson

Transitions Between de Sitter Minima, P. Batra, MK

Observational consequences of a landscape, B. Freivogel, MK, M. Rodriguez Martinez, L. Susskind

Bubble, Bubble, Flow, and Trouble: Large Scale Galaxy Flow from Cosmological Bubble Collisions, Larjo and Levi

Work by Hawking, Moss, Stewart, Guth, Linde, Weinberg^2, Garriga, Vilenkin, Bousso, Freivogel, Horowitz, Shenker, Aguirre, Johnson, Shomer, Tysanner

Hubble, bubble, toil and trouble!

- In the string landscape, ∃ many metastable phases with positive vacuum energy
- Regions of the universe that in these phases inflate, but also decay by first order transitions to other phases
- If total bubble nucleation rate in some phase is less than 1 per Hubble time per Hubble volume, have false-vacuum eternal inflation in that phase
- When it forms, each bubble contains a spatially infinite, homogeneous and isotropic open universe
- Presumably we are inside such a bubble
- But collisions with other bubbles are guaranteed to

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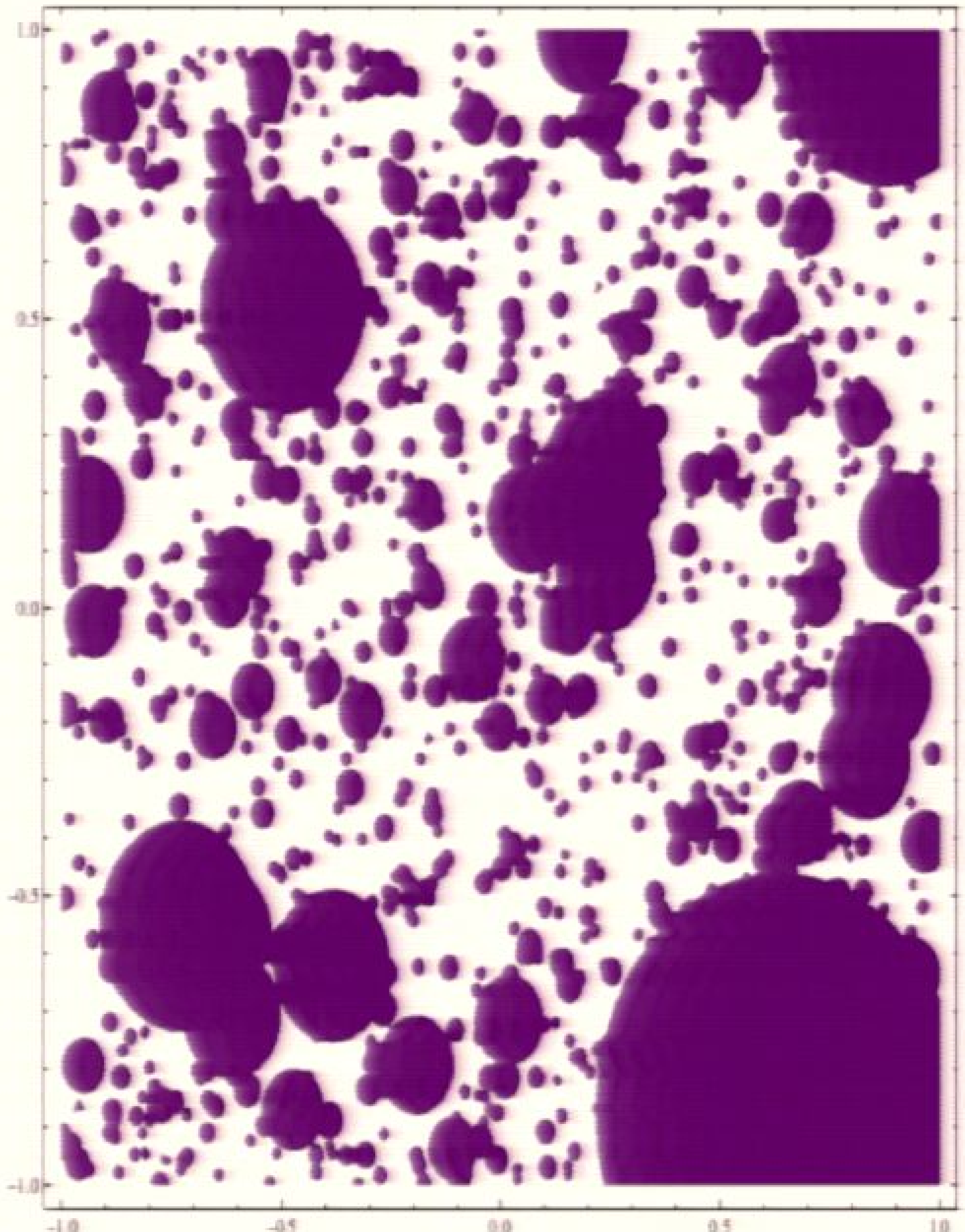
Bubble distribution at late times



Questions

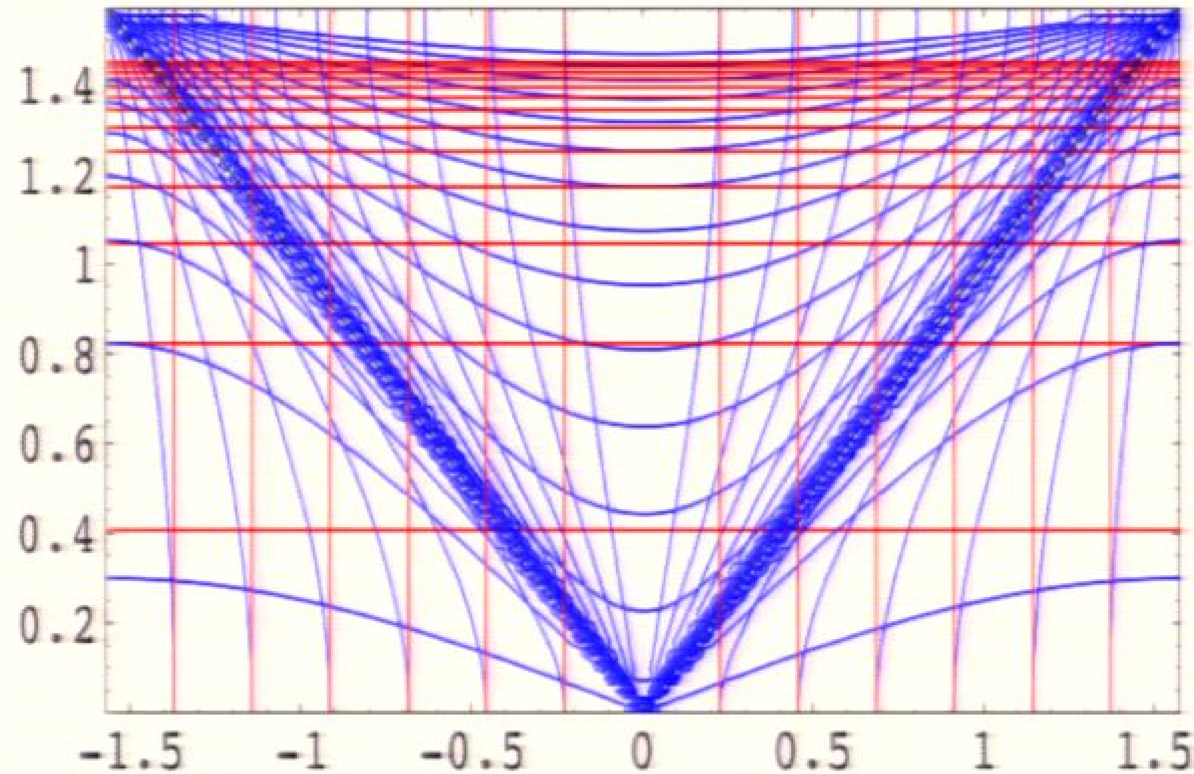
- How likely are we to observe bubbles?
  - exponentially small decay rates
  - slow-roll inflation
- What can we learn from them about VHEP?
  - Can we use them as a test of ST?
- What are their effects on cosmology?
  - bubble nucleation as big bang
  - collisions with other bubbles
- Are there any indications in current data?

False vacuum eternal inflation

- The expectation is that most of the universe is very rapidly inflating, with small regions occasionally bubbling off
- Since our observable universe is not rapidly inflating, we are in a bubble with small vacuum energy surrounded by false vacuum
- This picture has profound implications for the "big bang", early universe, and largest scales visible now

Instantons

- For instance: standard singularity theorems in general relativity imply that there should be a curvature singularity 13.7 Gyrs in our past
- Yet this is **not** the case if we live in a bubble, because the bubble is **regular** at t=a(t)=0 (no curvature singularity, just coordinate)
- The early universe is "non-generic" and has scalar potential energy (evading the theorems), and so is **non-singular**, which allows predictivity
- We could observe what came before the "big bang", and what exists outside the FRW region



Carter-Penrose diagram of bubble spacetime: particles moving at the speed of light are lines at 45 degrees, and one uses coordinates that cover the entire spacetime in a finite range

$$ds^2 = -dt^2 + a(t)^2 dH_3^2$$

$$\phi = \phi(t) \qquad \rho = \rho(t)$$

Generic features

- Key features come from SO(4) (Euclidean rotation) invariance of the instanton: isotropy and homogeneity (FRW), and negative spatial curvature (open & ∴ infinite volume)
- Very likely that the dominant decay instanton has this symmetry
- Other possibilities do exist, such as tunneling from 2+1-->3+1

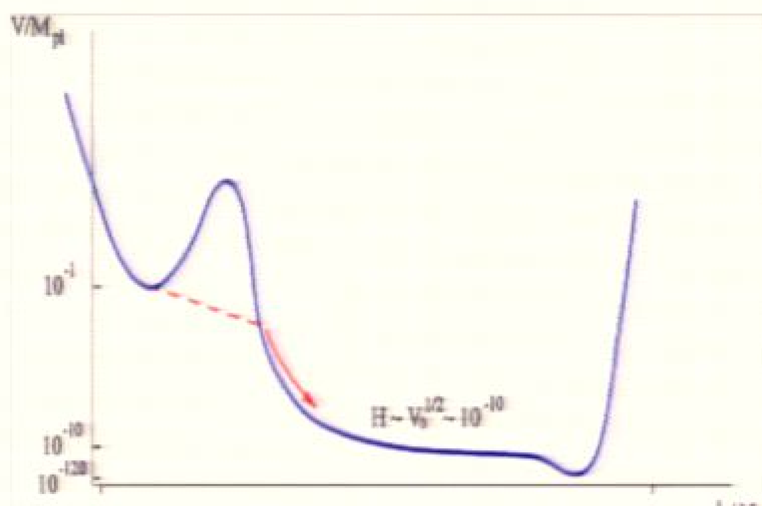
Graham, Harnik, Rajendran
Blanco-Pillado, Salem

Empty universe?

- If the instanton action is >>1 the bubble is very homogeneous; this and negative spatial curvature prevent structure formation
- Need a period of N efolds of standard slow roll inflation AFTER tunneling to reduce curvature and generate density perturbations
- Anthropic considerations (structure not exponentially rare) tell us N>60, roughly

Freivogel, MK, Rodriguez Martinez, Susskind

- But if N >> 60, the resulting universe will be almost indistinguishable from a flat universe.



Inflation

- This illustrates the most significant obstacle in all attempts to test VHEP with cosmology: inflation does an exponentially good job of hiding remnants of the big bang
- Can either look for effects generated during or after inflation, or
- Hope that inflation didn't last too much longer than was necessary to solve flatness problem
  - ∃ reasons to believe this may be likely
  - models which generate very large pre-inflation effects will be easiest to test

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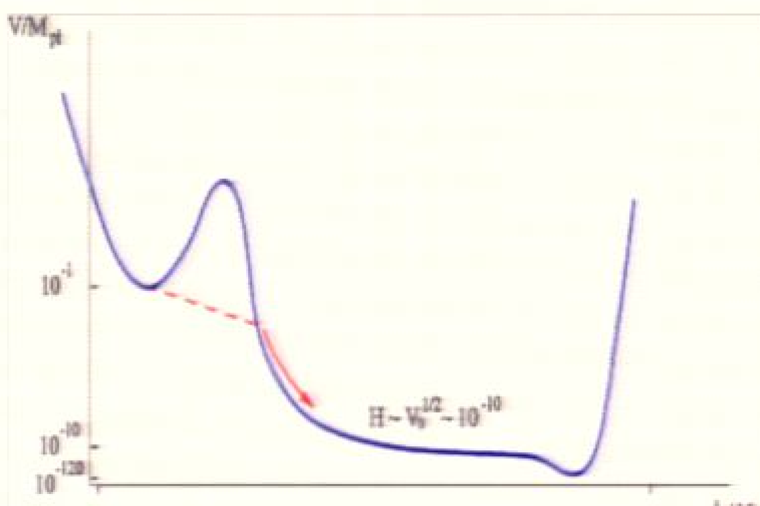

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Single bubble cosmology

Because of the symmetry of the instanton, the bubble universe has certain characteristic features:

- it is open (has negative spatial curvature), but cannot have large curvature anthropically
- it has a characteristic power spectrum of density perturbations at large scales

An observation of $\Omega_{\text{total}} > 1$ would **rule out** this model

An observation of the characteristic features in the power spectrum would provide strong support for it

The string theory landscape is **falsifiable** and **predictive***

B. Freivogel, MK, M. Rodriguez Martinez, L. Susskind

*(Caveat: too much inflation wipes out these signatures, and the effective field theory description is crucial)

Bubble collisions

- Consider an initial state in which the universe is homogeneous and in some positive vacuum energy inflating phase
- Randomly, bubbles will form via quantum tunneling
- If two are within a false-vacuum Hubble length, they will collide and form a domain wall
- This eventually produces infinite clusters, with statistics that are almost independent of the initial condition

Guth & Weinberg; Guth, Garriga, & Vilenkin

Probability and statistics

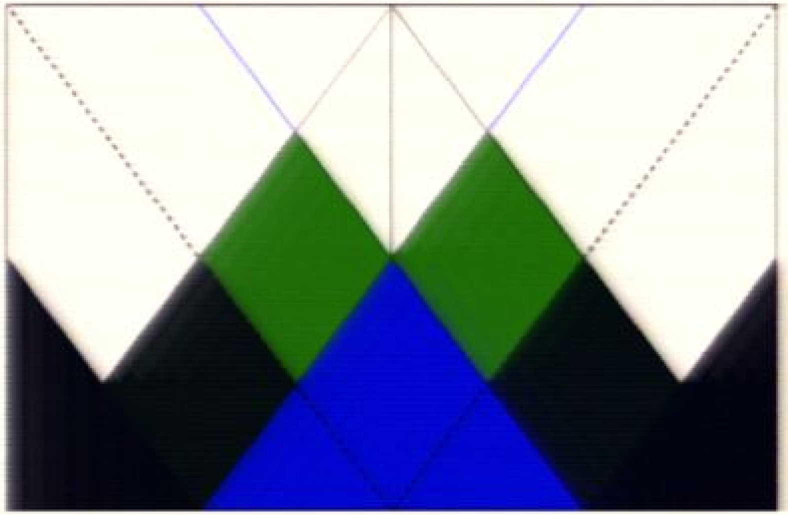
- How many bubbles should we expect there to be in our past lightcone today?
- How many of those could be observable?

Distribution

- One can determine this by studying the 4-volume in the past lightcone of an observer at finite time in a bubble containing a realistic cosmology.

Guth Weinberg; Garriga
Guth Vilenkin; Freivogel MK
Nicolis Sigurdson; Aguirre
Johnson...

- There are some very large dimensionless parameters involved, such as the ratio of the vacuum energy in the false vacuum to the one in the bubble.
- The infinite spatial volume inside a bubble leads to a significant subtlety
- One must be careful to take all of these into account



If a boundary condition is imposed at the dashed line (t=0 in a flat dS slice), only the light green 4-volume is relevant

The resulting distribution of collisions is clearly isotropic, but bubble observers boosted with respect to this frame do not agree - dS symmetry is broken by the BC surface

Garriga Guth Vilenkin

But this anisotropy is very small at late times for observers seeing a CMB sky rather than the full wall of their bubble

Freivogel MK Nicolis Sigurdson

So what's the answer?

$$\langle N \rangle \approx \frac{4\pi}{3}\gamma\frac{V_f}{V_i} = \frac{4\pi}{3}\Gamma R_i^2 R_f^2$$

Freivogel MK Nicolis Sigurdson

This is the decay rate Γ times a certain 4-volume: the surface area of the bubble by the start of inflation times the thickness of the false vacuum shell around it

Is N likely to be larger than 1?

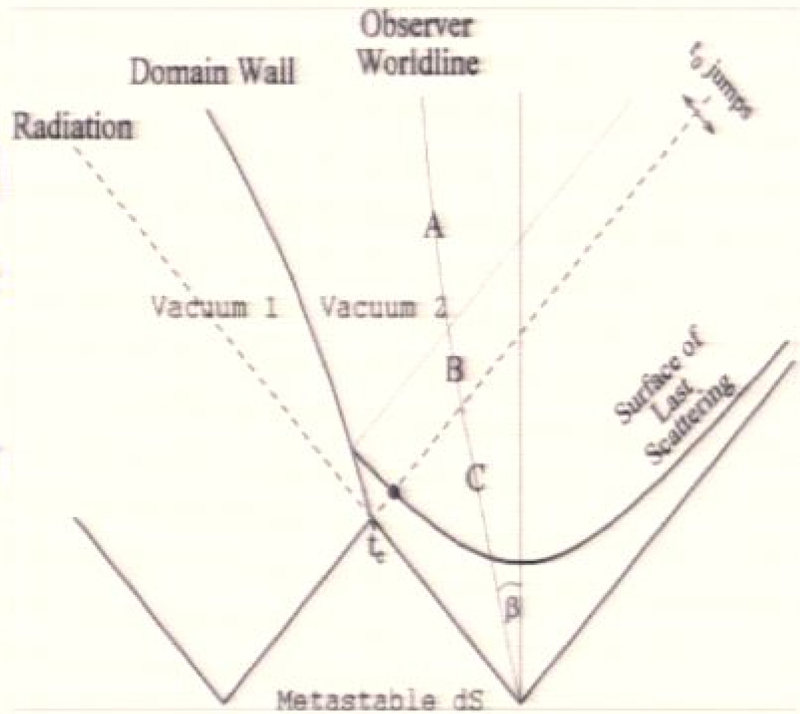
Maybe, for example if Vf is near the Planck scale (and recall fastest decay of parent is most important)

$$\frac{V_f}{V_i} \gtrsim 10^{12} \qquad \gamma > \exp(-S_f) \qquad S_f \sim \frac{M_P^4}{V_f}$$

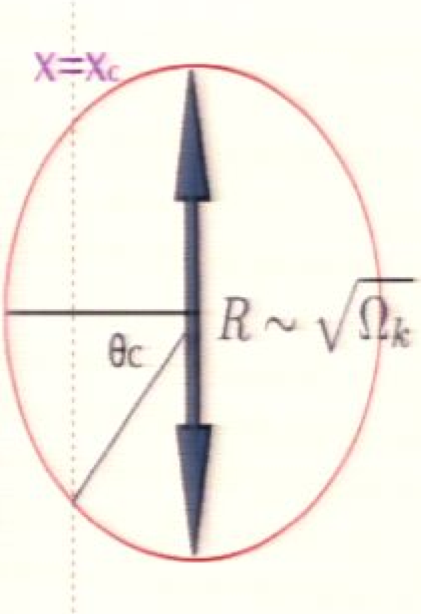
But are all those collisions really observable?

Collisions that occur too early will contain our entire CMB sky in their lightcone.

If they are very large they will be difficult to detect, because the observable universe will be approximately isotropic or dipolar



So we'd like to compute the expected number of collisions that are within our past lightcone AND intersect the observable part of the LSS



Inflation solves the curvature problem by expanding the universe so much that we can only see a small part of the full surface of last scattering - $\sqrt{\Omega_k}$ of it

Therefore if we require collisions to affect the part of the last scattering surface we can see, we should expect a factor of $\sqrt{\Omega_k}$

Because we are seeing only a small part of the LSS, the collision lightcone should be approximately planar, with random (flat distribution) location

The angular size distribution should be flat in $x_c \sim \cos(\theta_c)$

So now what's the answer?

It turns out that this has the simple effect of multiplying the distribution by the inverse radius of curvature today, in Hubble units:

$$N \sim \gamma \sqrt{\Omega_k(t)} (H_f^2 / H_i^2)$$

Freivogel MK Nicolis Sigurdson

Recall that

$$\sqrt{\Omega_k} \sim \exp\left(N_0 - N\right), \quad N_0 \sim 60$$

Long inflation (large N) "inflates away" the signal, as expected.

But the measure on N in string theory may favor minimal inflation, and the current constraints on curvature are relatively weak.

Conformal field theory?

These distributions are potentially relevant to observation, but they are also interesting for more theoretical reasons.

Consider the distribution of disks on the sky of an observation bubble at late times. Roughly, it is

$$dN = \Gamma(d\psi/sin^3\psi)d(\cos\theta)d\phi$$

(As an aside, this turns out to approximate the distribution of craters on the surface of the moon)

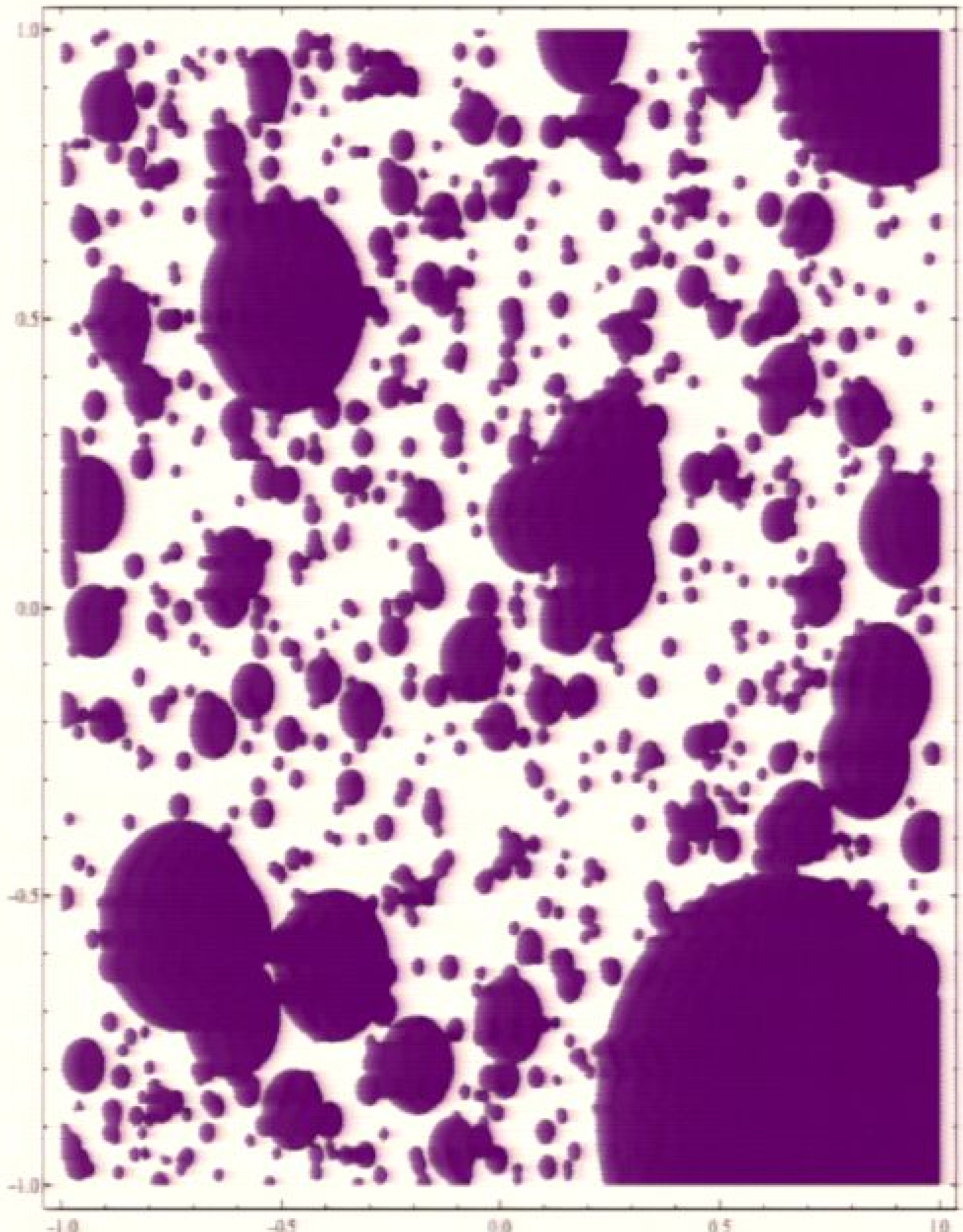
- To understand this distribution, project it stereographically onto a plane
- It becomes even simpler:

$$dN = \Gamma(dr/r^3)dxdy$$

B. Freivogel, MK

- This distribution described a fractal which is scale, rotation, and translation invariant - in fact it is invariant at least under global conformal transformations

Crater Percolation

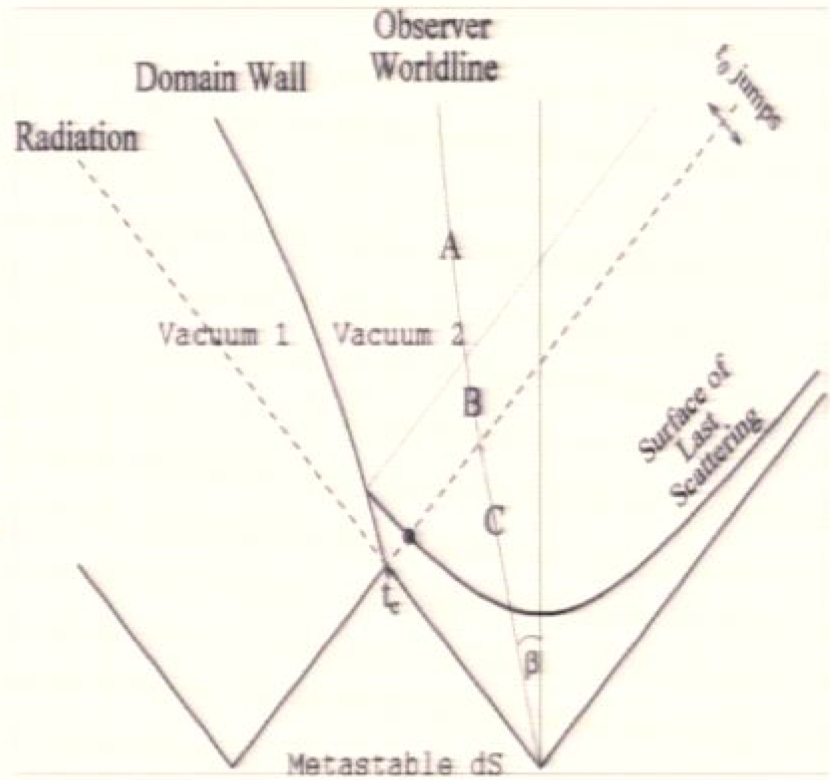


Two-bubble collisions

One can exploit the symmetry to find exact solutions under the assumption that the space is vacuum-energy dominated and the walls are thin, and solve for the trajectory of the domain walls.

Hawking, Moss,& Stewart; Freivogel, Horowitz,& Shenker

S. Chang, MK, T. Levi



Like the walls of the bubbles, these domain walls undergo constant acceleration.

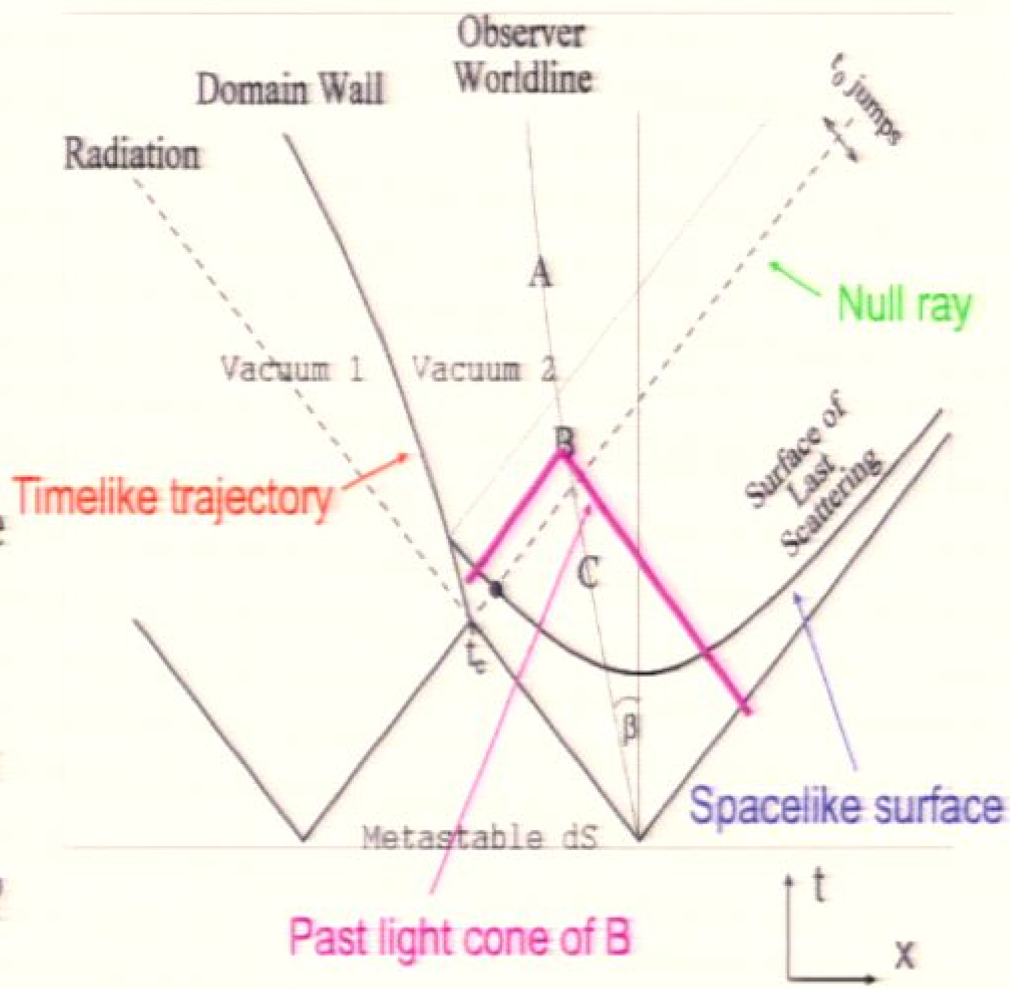
Some results

- The domain wall always accelerates away from the bubble with smaller Λ
- It sometimes accelerates towards the bubble with larger Λ, sometimes away (both are possible depending on the tension of the wall and the difference in Λs)
- A small positive Λ, such as the one we observe, therefore "protects" the bubble from catastrophic collisions with bubble with larger positive Λ S. Chang, MK, T. Levi
- We may also be safe from collisions with bubbles with negative Λ, due to the tension of the wall (BPS)

Freivogel, Horowitz,& Shenker; Cvetic Griffies

Observables

- Observer C is oblivious to the collision, as it is in her causal future
- Observer B lives in an **anisotropic** universe and may detect that in the CMB or LSS
- Observer A observes very large anisotropies
- Because of inflation the majority of observers are B or C
- Focus on case B - what are the signals of the collision in cosmology?



S. Chang, MK, T. Levi

Parametrizing the signal

- The signal is remarkably model-independent
- As we will see, this is because of
  - the large degree of symmetry of the bubbles
  - inflation, which irons out all but a leading effect
- The effect is circularly symmetric & described at leading order by 4 parameters:
  - location of the center (2)
  - angular radius of the affected region(1)
  - magnitude of temperature anomaly at the disk center (1)

- To fully characterize the effect of the collision requires a model and (probably) numerical simulations, but the leading order effect is almost model independent
- The collision is an O(1) perturbation to the inflaton at the time of curvature/potential energy equality
- At that time, expand the inflaton perturbation in a power series around the edge of the collision lightcone:

$$\delta\phi(x,\eta_i) = M(a_0 + a_1 x + a_2 x^2 + \ldots)\Theta(-x)$$

- In this expansion x=1 is the radius of curvature of the universe, and the radius of the earth's past lightcone is $|x| \sim \sqrt{\Omega_k} \ll 1$
- The next step is to evolve this initial perturbation to the end of inflation, and express it in terms of the comoving curvature ζ

Evolution of planar perturbations

- One can solve analytically and in full generality for the position-space evolution of inflaton perturbations with planar (or hyperbolic) symmetry
- The general solution (in slow roll or for a free field) is

$$\delta\phi(x,\eta) = f(\eta - x) - \eta f'(\eta - x) + g(\eta + x) - \eta g'(\eta + x)$$

Chang MK Levi

- Since the perturbation is zero outside the lightcone of the collision, only g can be non-zero
- But g is determined by the perturbation at any initial time (i.e. by the power series coefficients a_n)

The result is

$$\phi(\eta + x) \;=\; \sum_{n=0}^{+\infty} a_n (-)^{n+1} n! \left[e^{\eta+x)/\eta_i} - \sum_{m=0}^{n} \frac{1}{m!} \left(\frac{\eta + x}{\eta_i} \right)^m \right.$$
$$\left. - \frac{\eta}{\eta_i} \left(e^{(\eta+x)/\eta_i} - \sum_{m=0}^{n} \frac{1}{(m-1)!} \left(\frac{\eta + x}{\eta_i} \right)^{(m-1)} \right) \right]$$

After a few efolds, this simplifies dramatically

MK and Gobbetti

$$\sum_{n=0}^{+\infty} a_n (-)^{n+1} n! \left[e^{(\eta+x)/\eta_i} - \sum_{m=0}^{n} \frac{1}{m!} \left(\frac{\eta + x}{\eta_i} \right)^m \right]$$

MK and Gobbetti

Specializing to small x, it's very simple:

$$\delta\phi(x, \eta) = \frac{-a_0}{\eta_i} M x \Theta(-x)$$

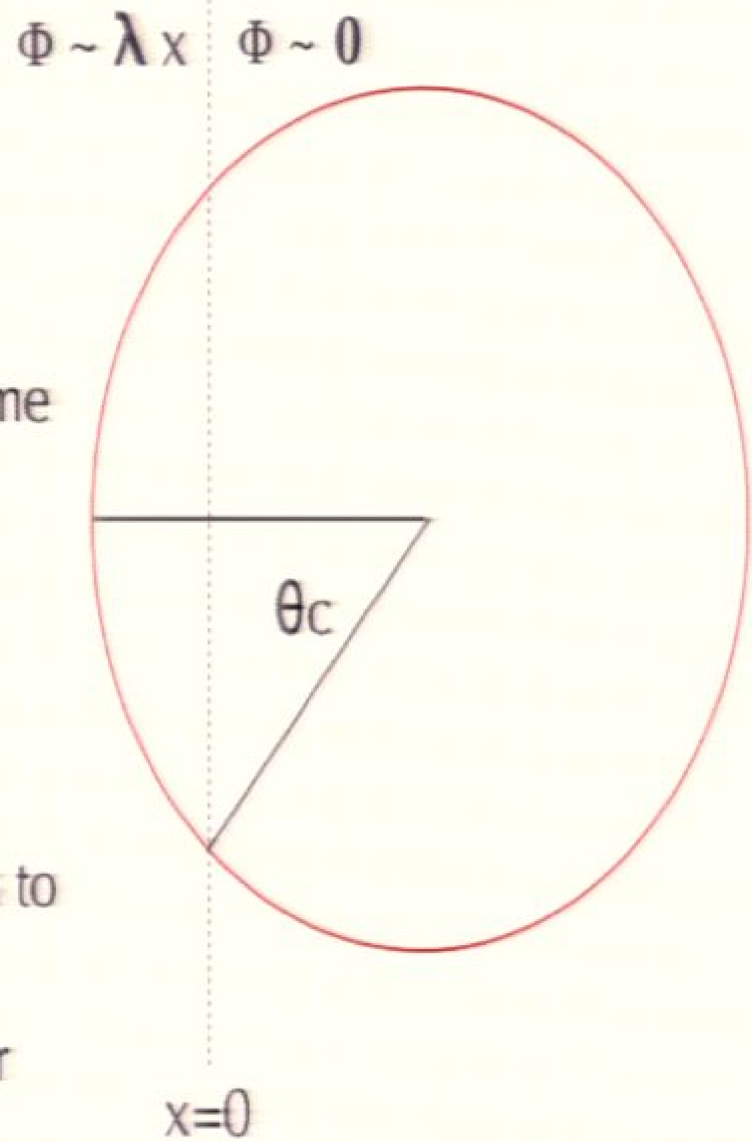
Chang MK Levi

Curvature perturbations

- To determine the effect on the CMB temperature, should convert inflaton perturbation into perturbation in Newtonian potential Φ or comoving curvature ζ
- Result is that Φ is proportional to $\delta\phi$ at end of inflation
- Through the Sachs-Wolfe effect, the CMB temperature today is proportional to Φ
- Note that a discontinuity Φ in corresponds to a very singular density distribution
- Instead, a discontinuity in Φ' is a delta function sheet

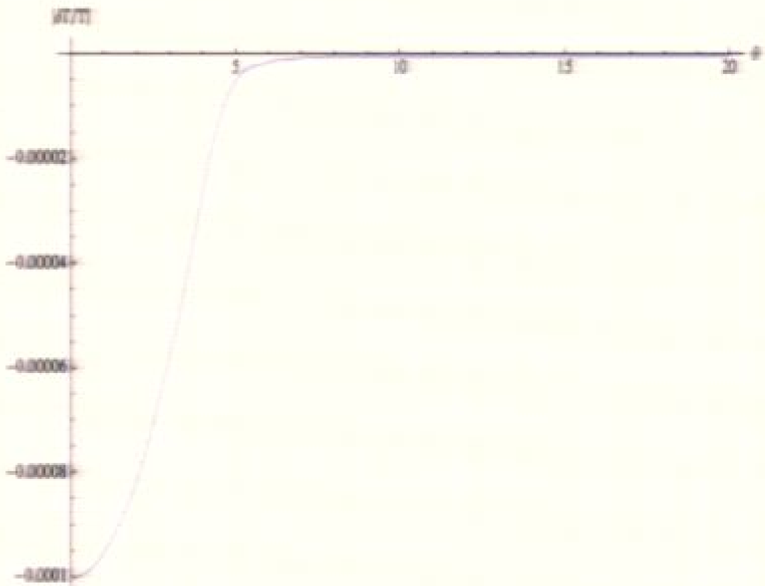
Effect on the reheating surface

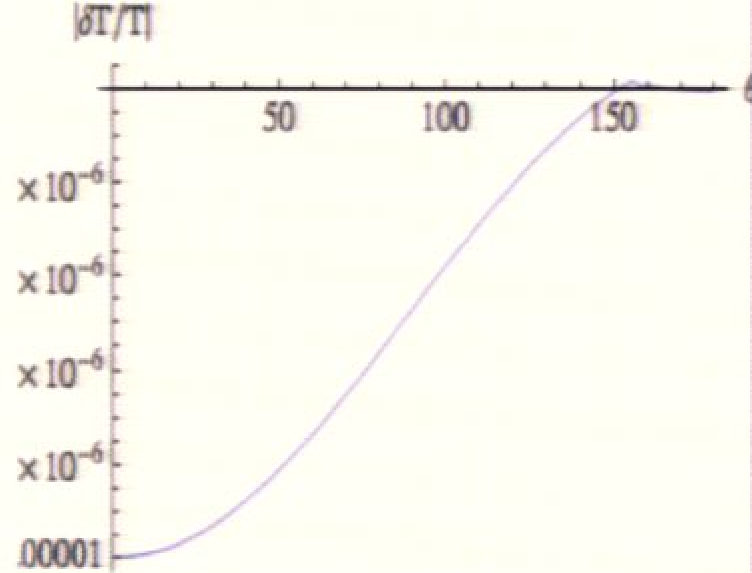
- The Newtonian potential to lowest order at reheating is $\Phi \sim \lambda x \theta(-x)$, where the $x=0$ plane is the edge of the collision lightcone at that time
- So for $x>0$, the reheating surface is unperturbed
- For $x<0$, there is a linear gradient
- A linear gradient corresponds to a dipole ($x \sim \cos\theta$), but here affects only a disk of angular radius θ on the CMB sky

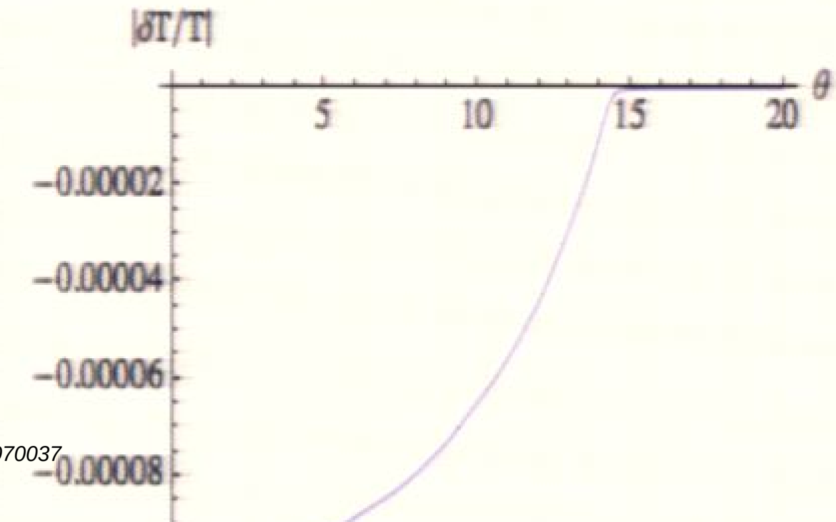


Chang, MK, Levi; MK, Levi, Sigurdson

CMB temperature anomaly





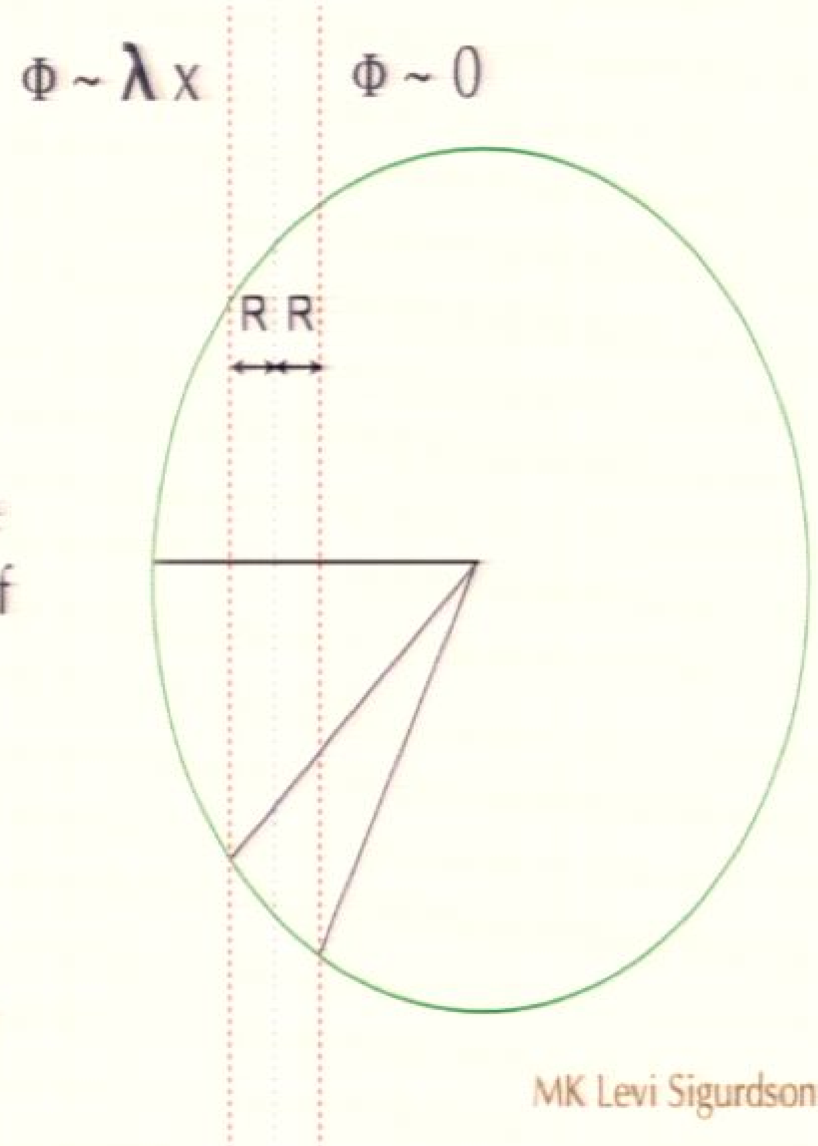


The effect is smooth, which makes it potentially hard to distinguish from a Gaussian random fluctuation if the amplitude is small

Can be either hot or cold

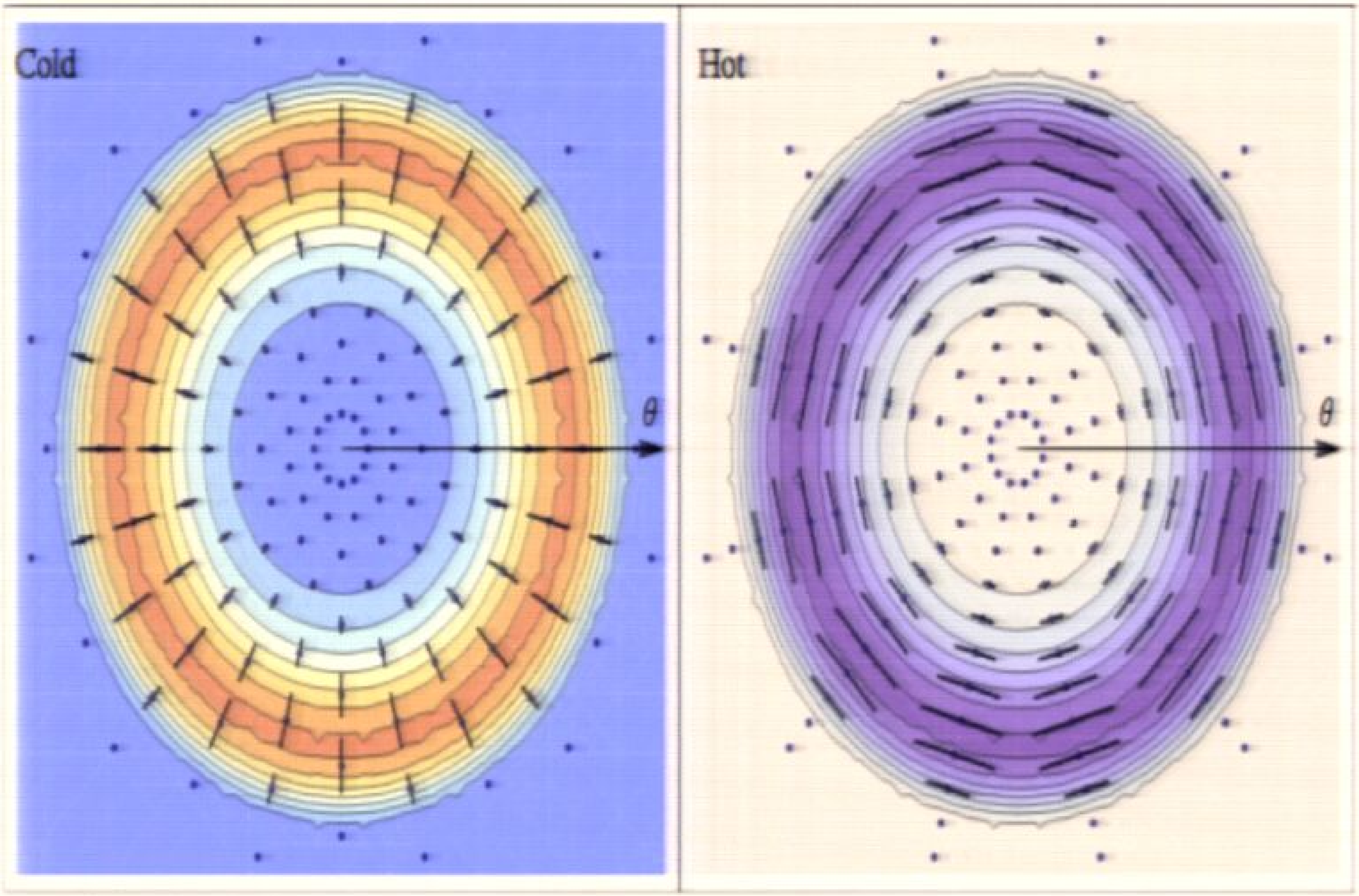
Last scattering

- $\Phi \sim \lambda x$ for $x<-R$
- $\Phi \sim 0$ for $x>R$
- For $-R<x<R$, Φ is some smooth function
- But first derivative is discontinuous at $x=-R$ and $x=R$
- CMB polarization is sensitive to the **quadrupole** moment of features on the LSS
- Therefore there will be **two** rings of large polarization, separated by an angular distance that follows trivially from this geometry



MK Levi Sigurdson

Polarization

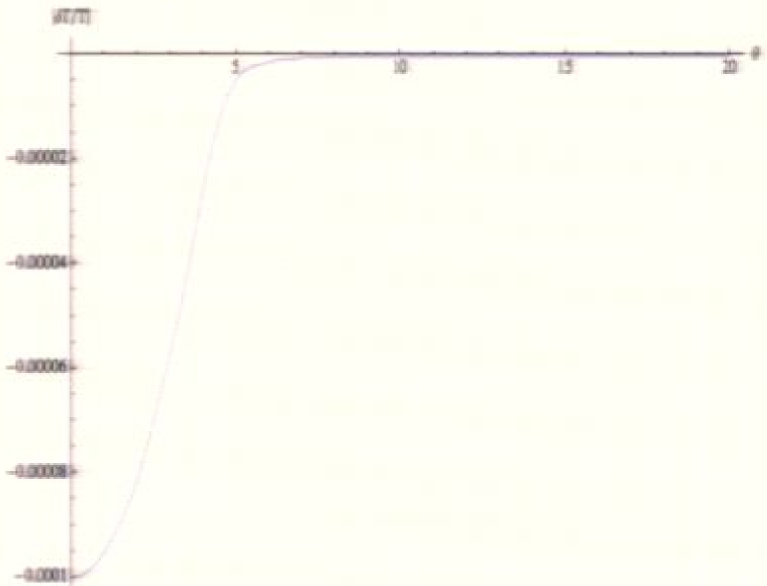


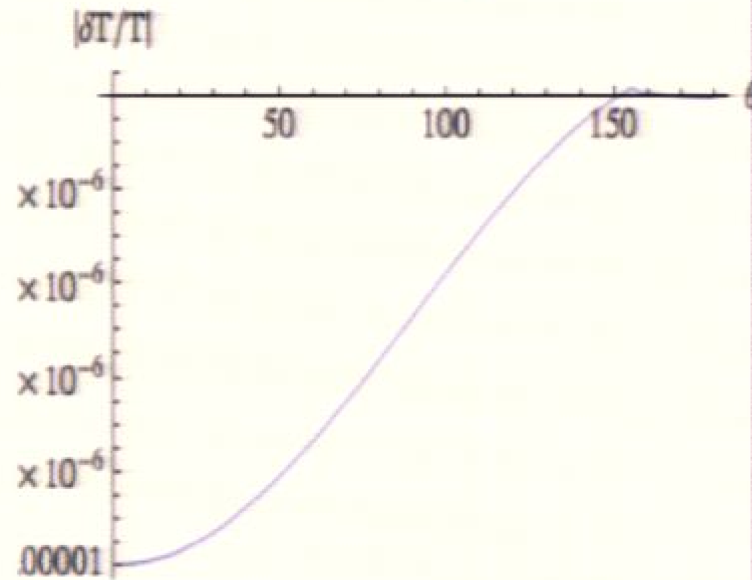
Czech, MK, Levi, Larjo, Sigurdson

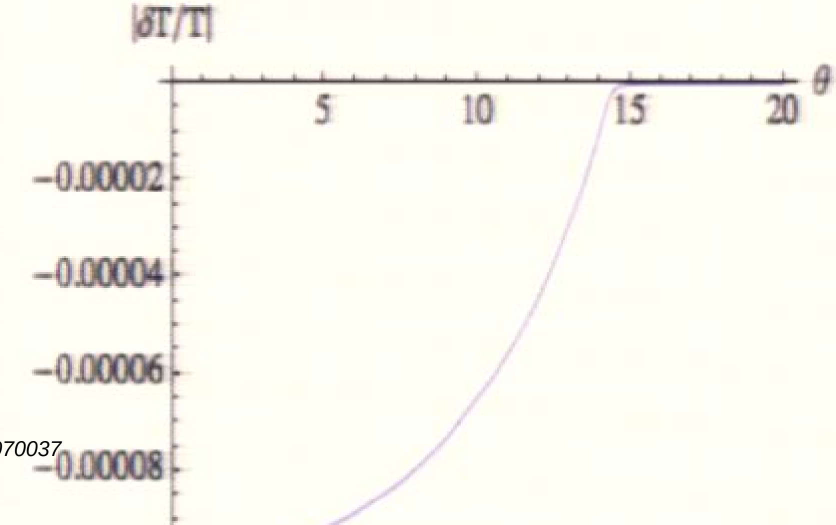
Figure 3. Polarization patterns around cold ($Q > 0$) and hot ($Q < 0$) spots.

Chang, MK, Levi; MK, Levi, Sigurdson

CMB temperature anomaly







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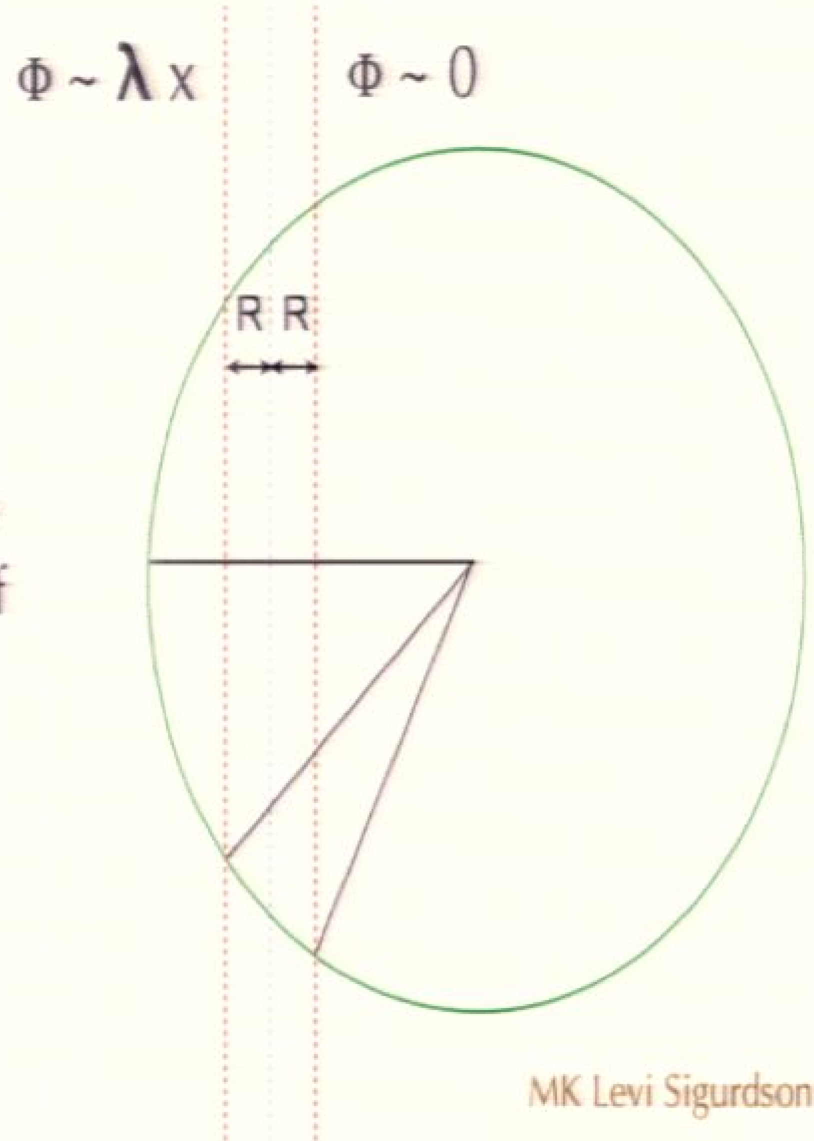

MK Levi Sigurdson

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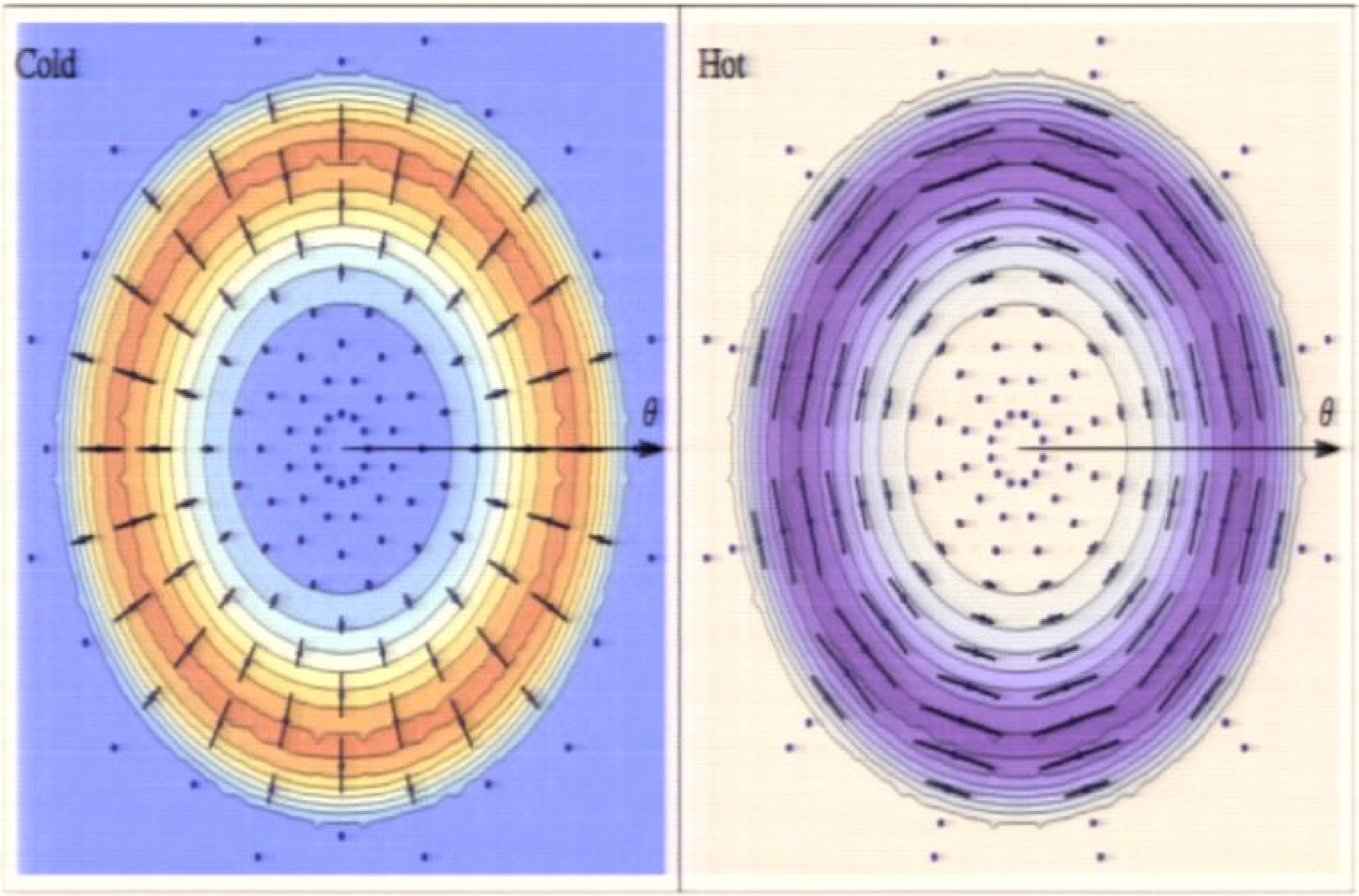
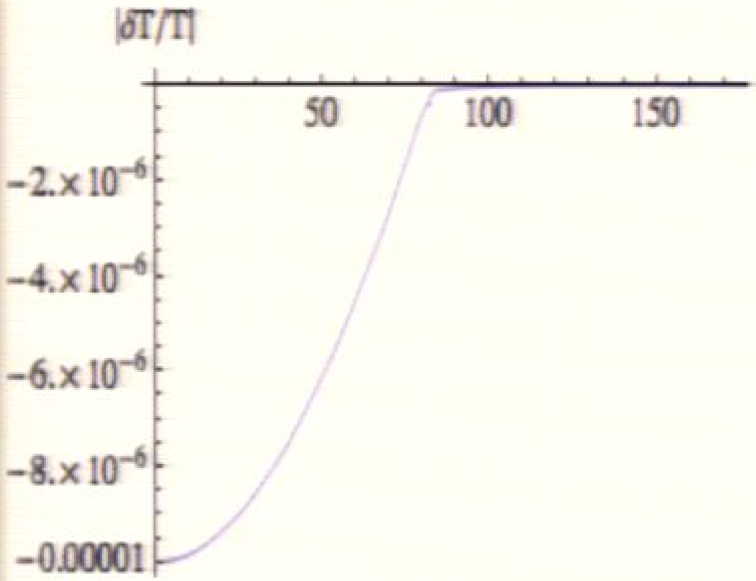
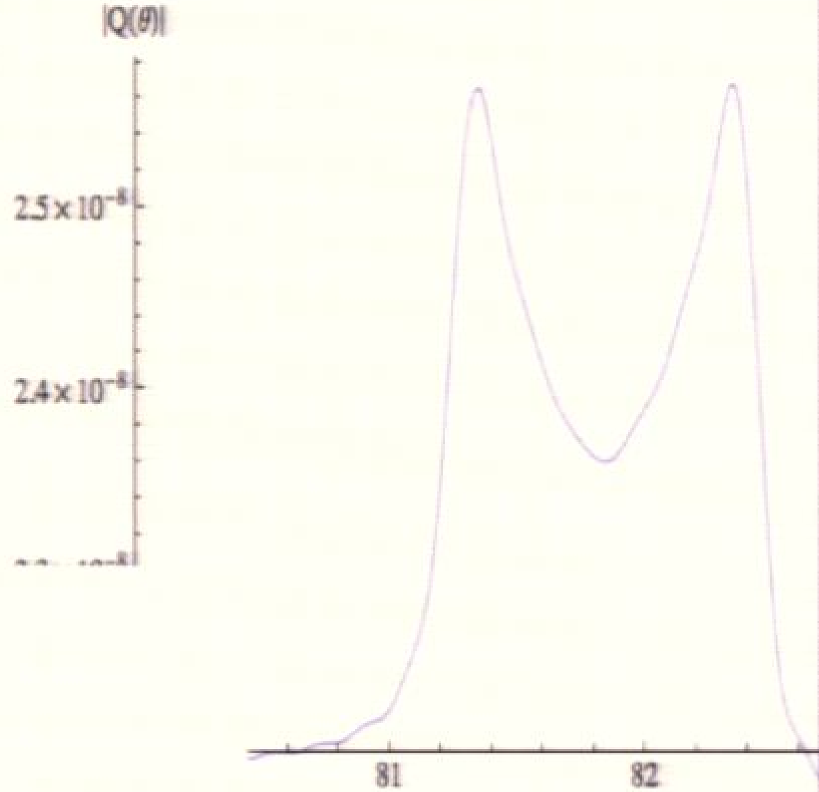


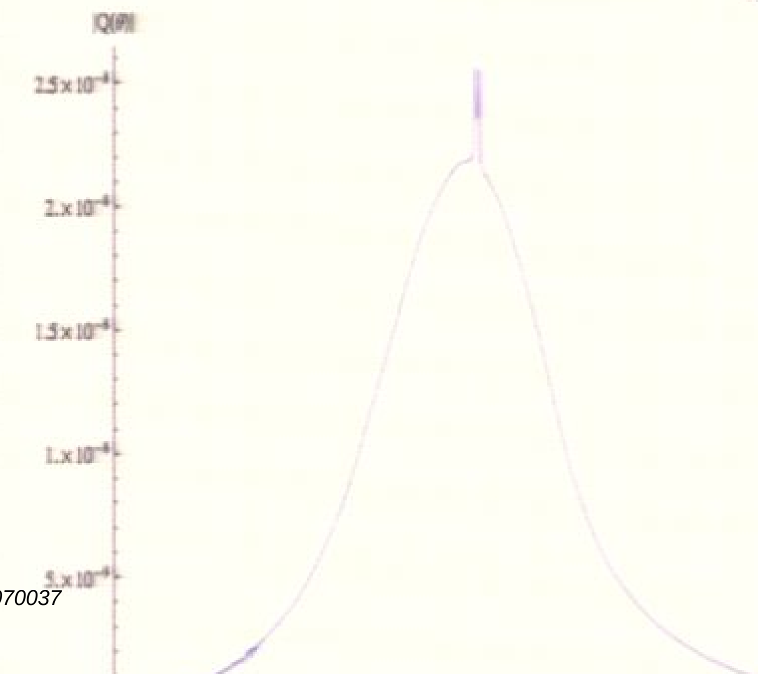
Czech, MK, Levi, Larjo, Sigurdson

Figure 3. Polarization patterns around cold ($Q > 0$) and hot ($Q < 0$) spots.

Yes, we CAMB!



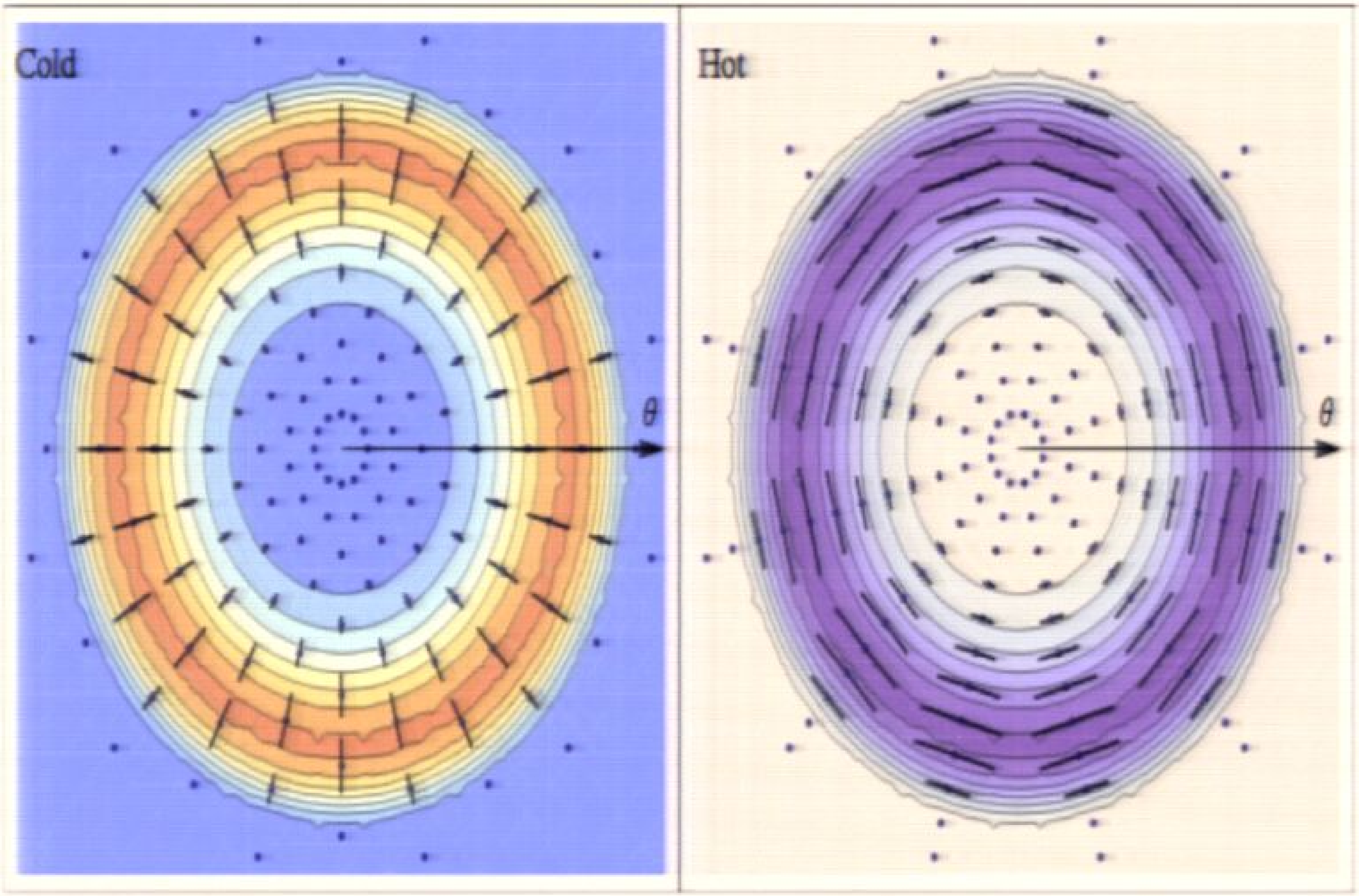




Note that these peaks are about 1.2 degrees apart (the acoustic horizon)

MK, Levi, Sigurdson, in progress

Polarization



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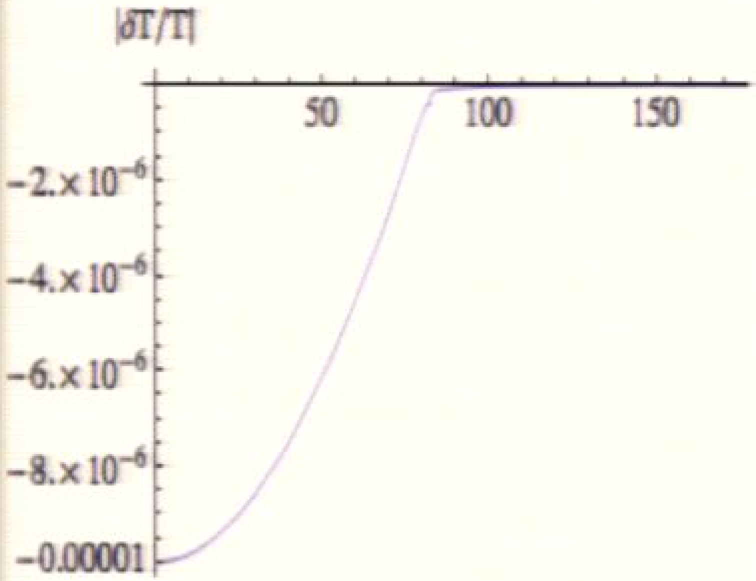

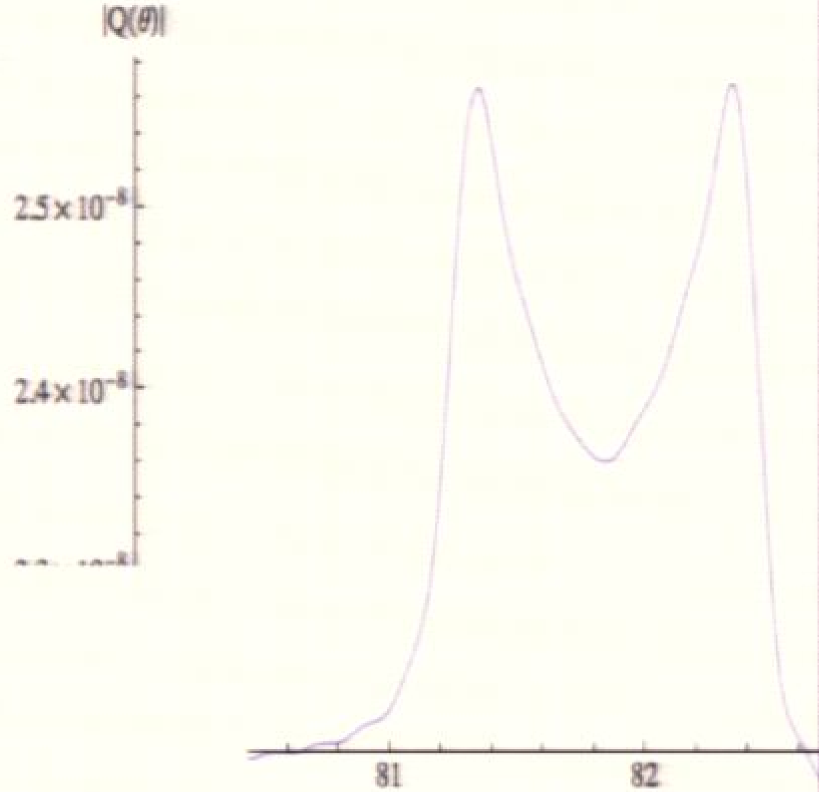

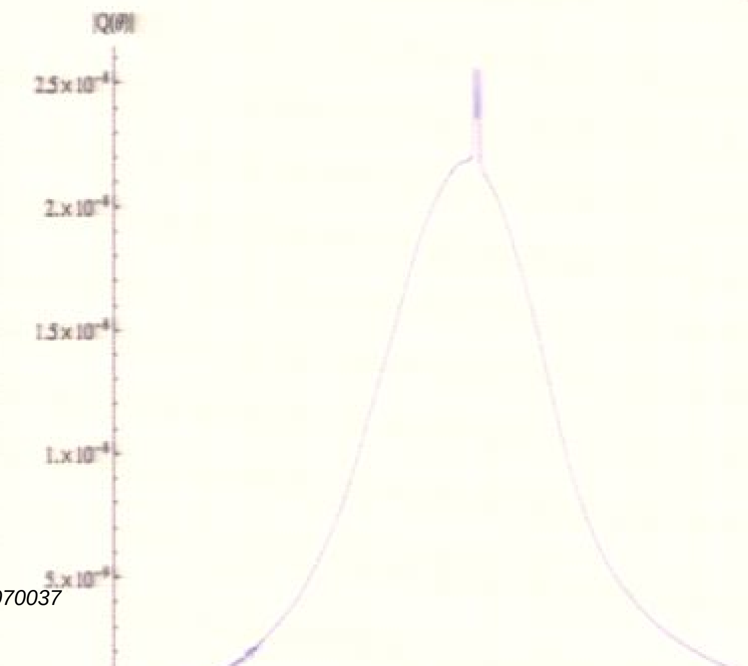

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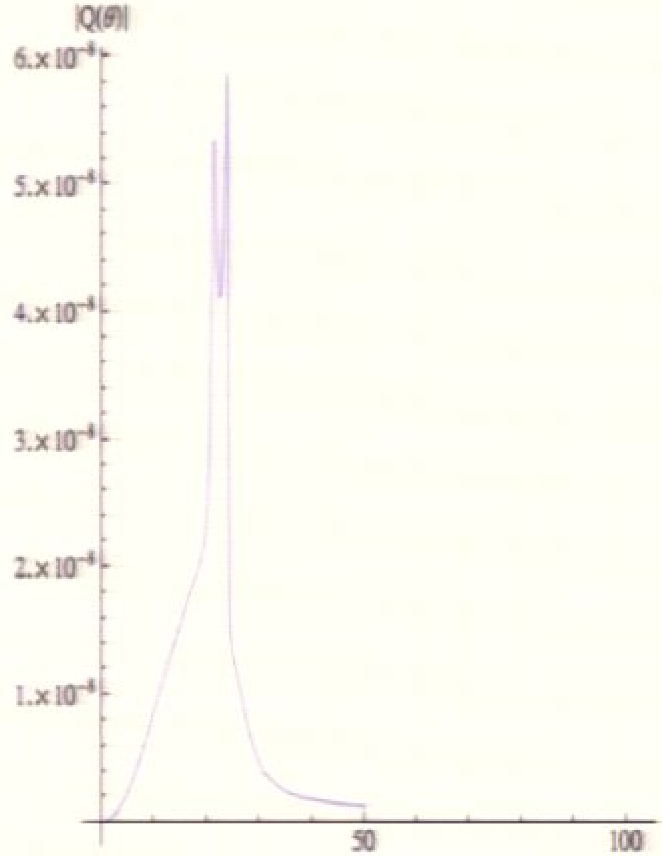
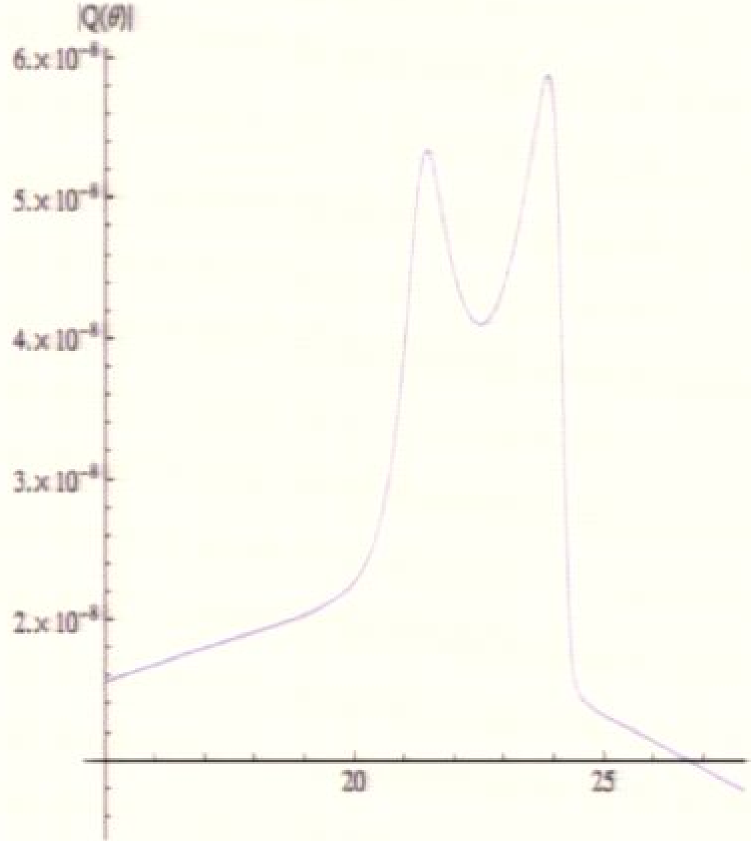
For smaller spots the peaks are farther apart....

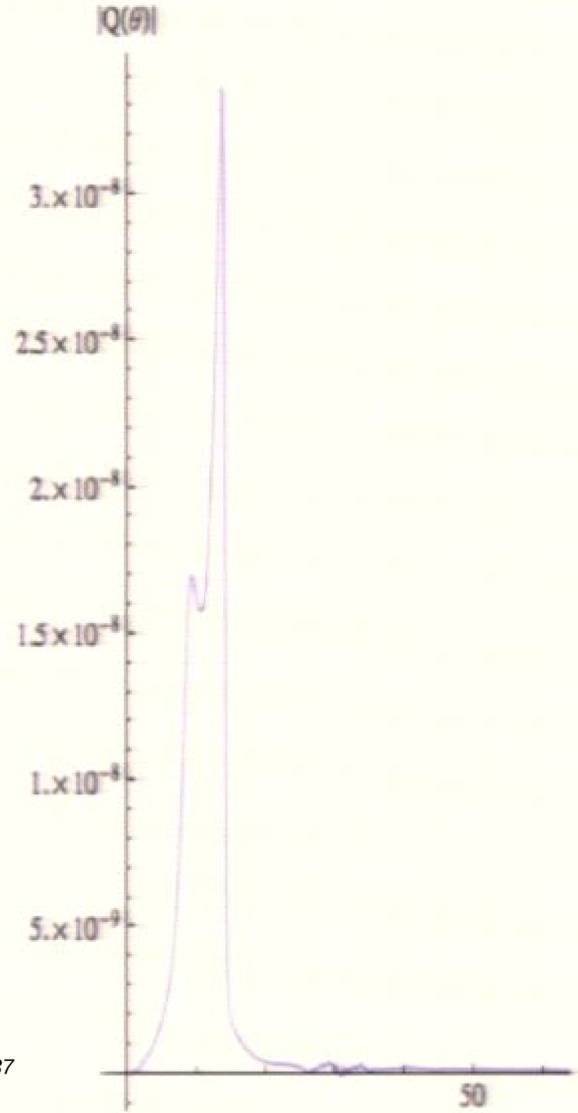


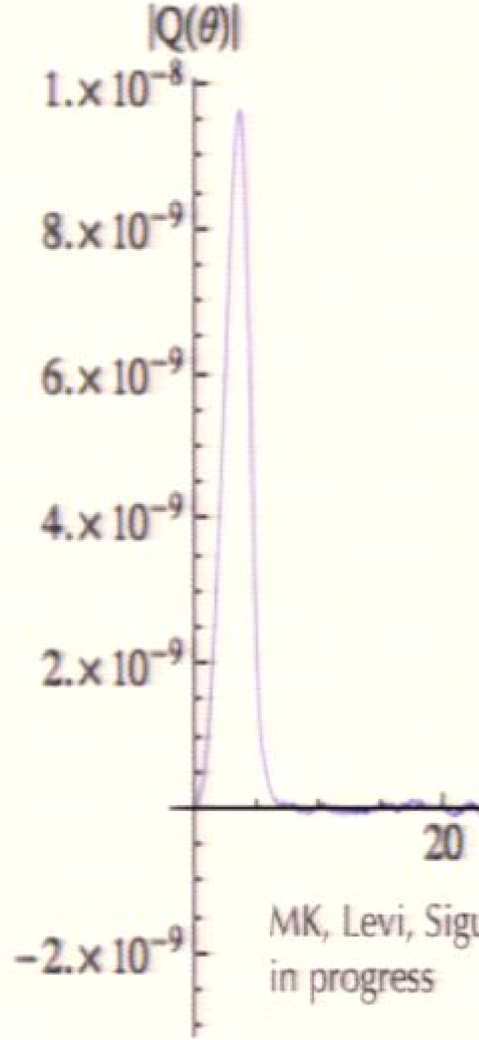


These are about 2.5 degrees apart

MK, Levi, Sigurdson, in progress

....and the inner peak disappears entirely when the disk is smaller than ~10 degrees





MK, Levi, Sigurdson, in progress

Other Signatures

- CMB temperature and polarization - Planck will test this
- Galaxies form differently inside the collision lightcone than outside, and therefore there is an angular dependence in large scale structure
- In particular, there is no longer a unique cosmic rest frame, and structure within the lightcone may not be at rest with respect to the CMB outside
- The wall itself may emit radiation, either gravitational or otherwise
- These could be tested with great precision in the future using 21cm data
- There are lensing signatures, but they are weak
- Taken together, we might be able to learn something significant about the other vacuum

"First Observational Tests of Eternal Inflation"?

- Using the CMB temperature prediction from 2008 (MK, Chang and Levi), Feeney, Johnson, Mortlock, and Peiris recently reported the detection of several (four) spots in the WMAP temperature data that are consistent with a bubble collision
- Polarization could provide a very strong test of their regions, and allow a much more sensitive search for more (sharp edges make such searches easier)

Comments

- I don't know a way to get a discontinuous jump in temperature at the edge (z_crit=0)
- Small (<10 degrees) disks are significantly less likely than larger ones

Conclusions

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- E-mode polarization *can* have sharp features

Parametrizing the signal

- The signal is remarkably model-independent
- As we will see, this is because of
  - the large degree of symmetry of the bubbles
  - inflation, which irons out all but a leading effect
- The effect is circularly symmetric & described at leading order by 4 parameters:
  - location of the center (2)
  - angular radius of the affected region(1)
  - magnitude of temperature anomaly at the disk center (1)

Probability and statistics

- How many bubbles should we expect there to be in our past lightcone today?
- How many of those could be observable?

Single bubble cosmology

Because of the symmetry of the instanton, the bubble universe has certain characteristic features:

- it is open (has negative spatial curvature), but cannot have large curvature anthropically
- it has a characteristic power spectrum of density perturbations at large scales

An observation of $\Omega_{\text{total}} > 1$ would **rule out** this model

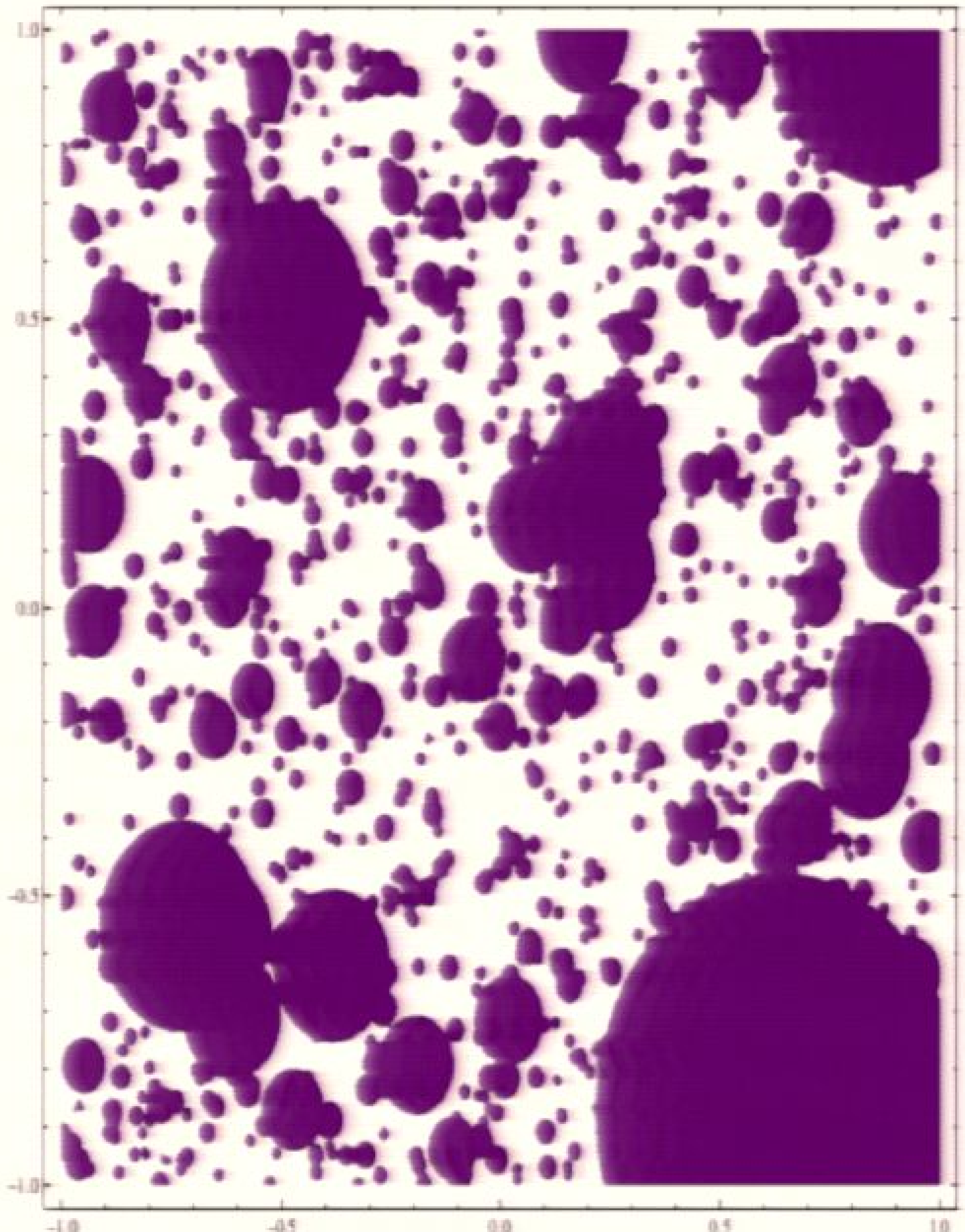
An observation of the characteristic features in the power spectrum would provide strong support for it

The string theory landscape is **falsifiable** and **predictive***

B. Freivogel, MK, M. Rodriguez Martinez, L. Susskind

*(Caveat: too much inflation wipes out these signatures, and the effective field theory description is crucial)

Crater Percolation



- To fully characterize the effect of the collision requires a model and (probably) numerical simulations, but the leading order effect is almost model independent
- The collision is an O(1) perturbation to the inflaton at the time of curvature/potential energy equality
- At that time, expand the inflaton perturbation in a power series around the edge of the collision lightcone:

$$\delta\phi(x, \eta_i) = M(a_0 + a_1 x + a_2 x^2 + \ldots)\Theta(-x)$$

- In this expansion x=1 is the radius of curvature of the universe, and the radius of the earth's past lightcone is $|x| \sim \sqrt{\Omega_k} \ll 1$
- The next step is to evolve this initial perturbation to the end of inflation, and express it in terms of the comoving curvature ζ

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