Title: Watching Worlds Collide: Prospects for Observing Cosmic Bubble Collisions

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Abstract:

WATCHING WORLDS COLLIDE

Prospects for Observing Cosmic Bubble Collisions

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Outline

- Introduction and motivation
  - Cosmology and high energy physics
  - String landscape
  - Tunneling from a false vacuum
- Observation
  - Bubble cosmology
  - Two bubble collisions
  - Cosmological observables
- How many collisions?
  - Measure
  - Counting bubbles
- Conclusions

Based on

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

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

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

Transitions Between de Sitter Minima, P. Batra, MK

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

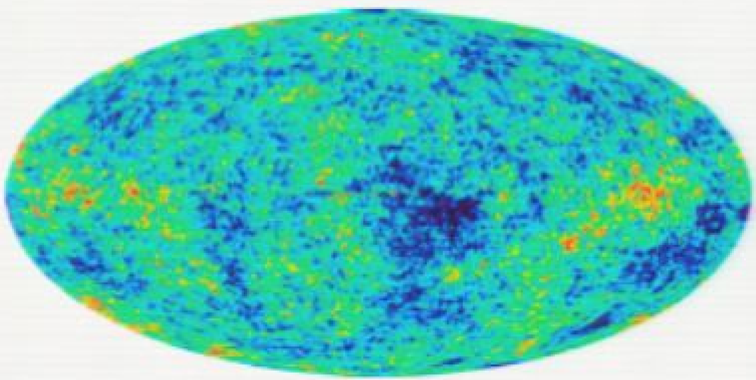
In progress: Zhang; Bovy and Dore; Larjo and Levi

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

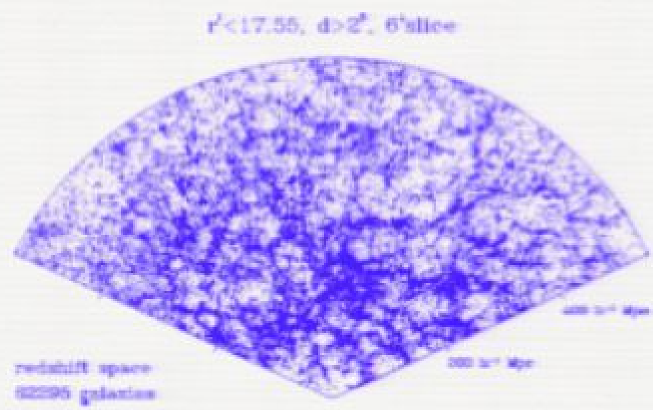
Introduction and motivation

Cosmology

With data from experiments like COBE, WMAP, SDSS, NVSS, upcoming 21cm experiments, cosmology has become a precision science



(WMAP)



(SDSS)

- The early universe had a very high energy density
- Shortly after the bang there was a phase of very rapid expansion, called inflation, which smoothed out any initial inhomogeneities

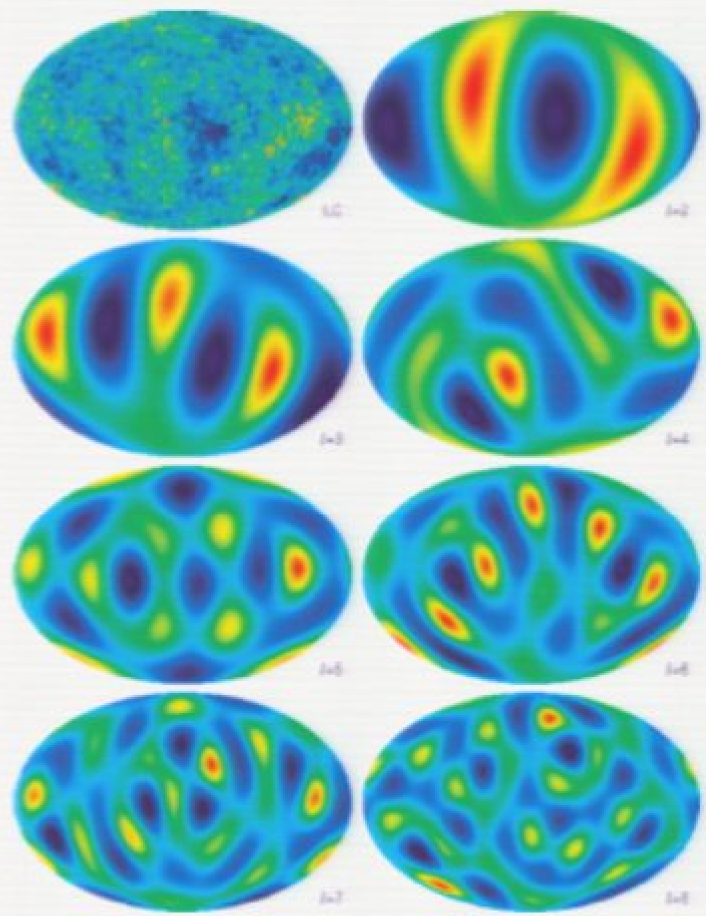
Inflation

Inflation serves two functions: it homogenizes the universe, and it creates nearly scale-invariant density perturbations via QM

It does both at very high energies, potentially leaving traces of high-scale physics

There are roughly two categories of HEP effects one can look for:

- effects on the spectrum of QM perturbations during inflation
- remnants of the initial state



Claim: the string theory landscape predicts a very special big bang, making it falsifiable and predictive.*

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*when taken with some strong assumptions about the landscape. Check with your doctor about side effects and interactions.

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Probably follows from 2): can be proven in field theory, true in examples incorporating backreaction

Given these assumptions, we live in an open universe with a very special type of “big bang”

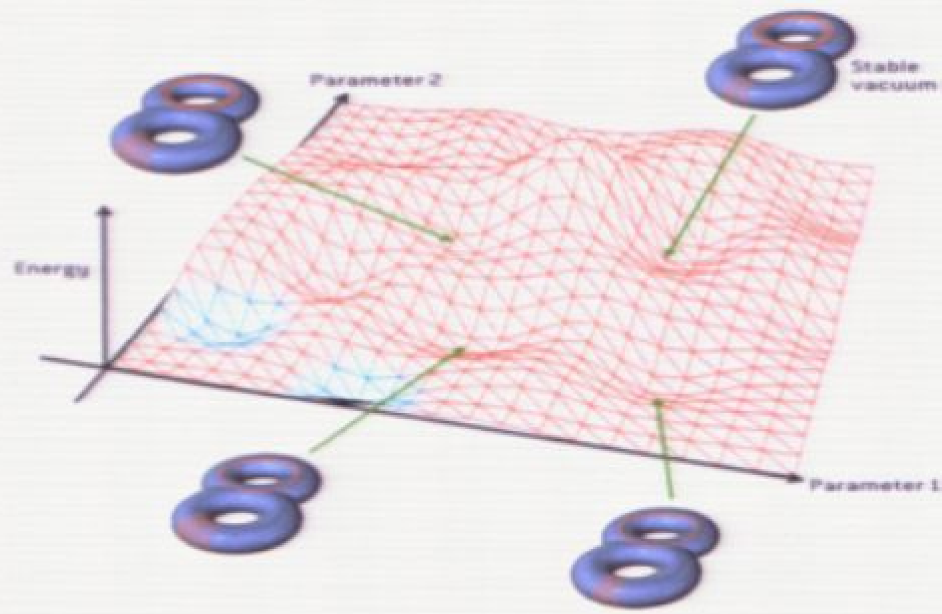
This leads immediately to a set of falsifiable predictions (which I will describe)

Other bubbles (besides the one we live in) will form and collide with ours with probability 1- eventually

I think this should be taken seriously - opportunities of this type are very hard to find

What kind of effective field theory to expect from ST?

- Many scalars (100s)
- MANY minima (10^100s)
- In each minimum, different vacuum energy
- Tunneling will create bubbles of different vacua

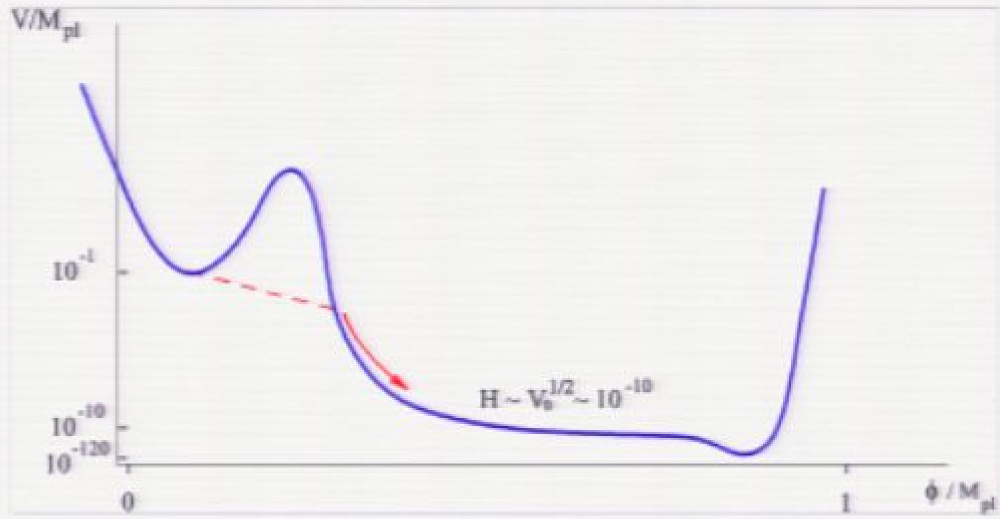


"The Landscape" (Picture from Scientific American)

In fact, any theory with extra dimensions will contain 4D scalars. If it's sufficiently complex to contain the standard model, it is likely to have many. Even purely 4D theories often have 1st order phase transitions described by a scalar order parameter.

Tunneling

- The false vacuum on the left is meta-stable, and can decay via tunneling
- The bubble that is produced is very homogeneous and has large negative curvature: prevents structure formation
- Need a period of N efolds of inflation inside
- If N >> 60, the resulting universe will be indistinguishable from a flat universe.



The instanton which creates such a bubble is a solution to the Euclidean equations of motion expanded around the false vacuum.

The solution is of form

$$ds_E^2 = d\psi^2 + a(\psi)^2(d\theta^2 + \sin^2\theta d\Omega_2^2)$$

$$\phi = \phi(\psi)$$

which has a manifest SO(4) invariance

Coleman-de Luccia

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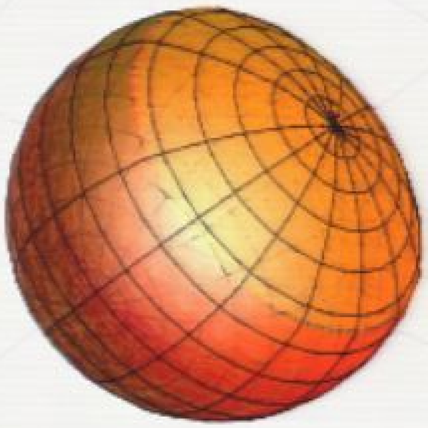
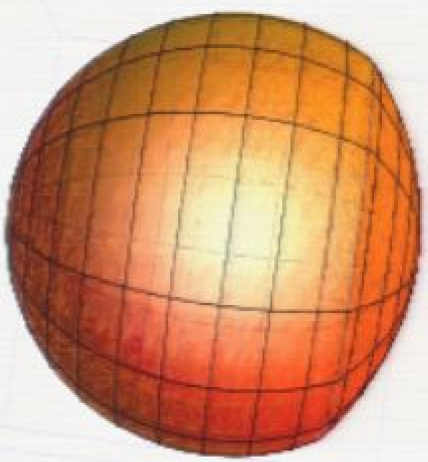




The radius of curvature is determined by the Euclidean "energy density", which depends on the scalar field and is a function of theta.

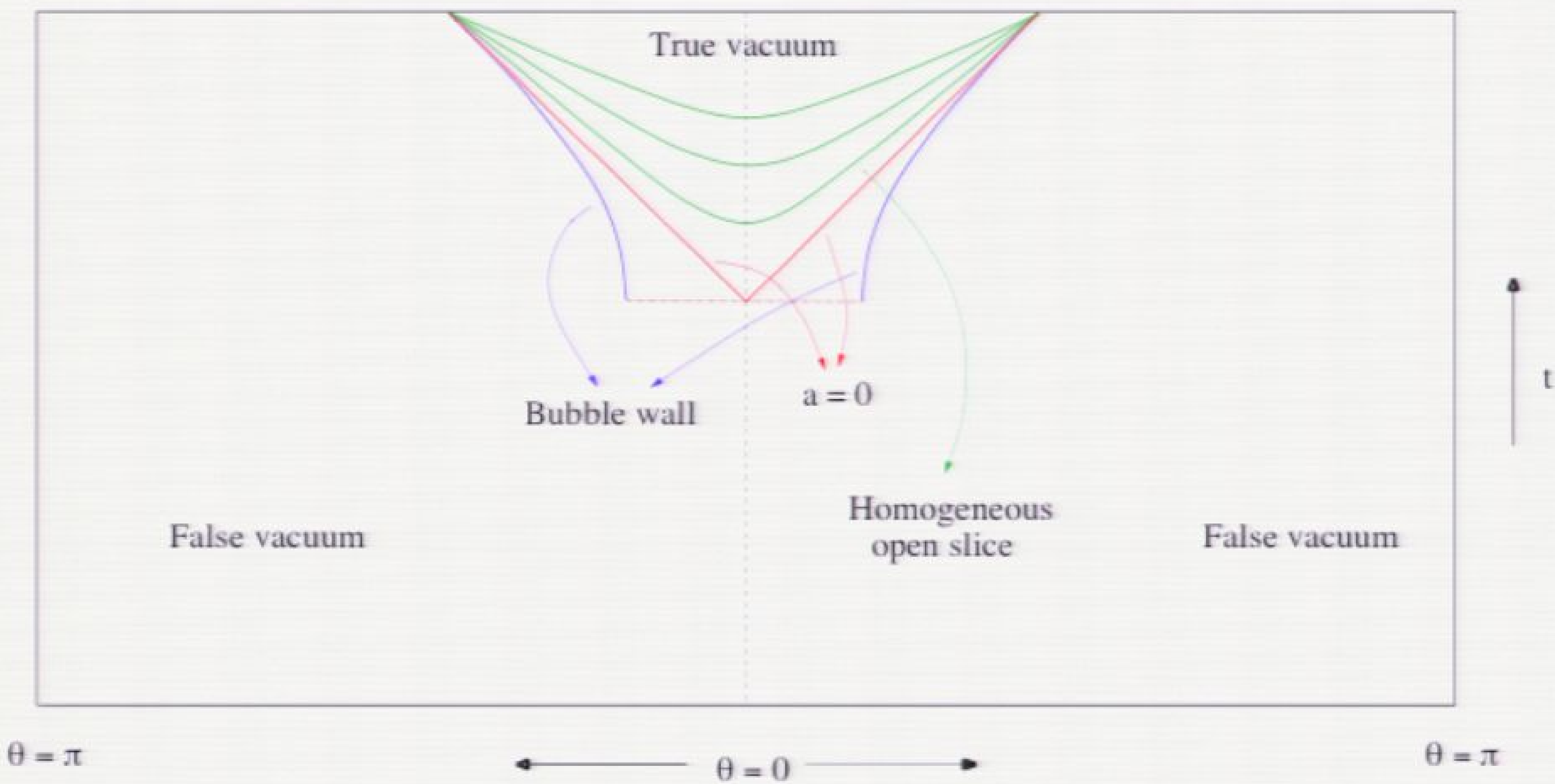
In the thin wall limit it changes suddenly at some theta - the wall of the bubble.

To find the Lorentzian solution resulting from the transition, we can analytically continue this solution:

$$ds_E^2 = d\psi^2 + a(\psi)^2(d\theta^2 + \sin^2\theta d\Omega_2^2)$$
$$\phi = \phi(\psi)$$

$$\rightarrow ds_M^2 = -dt^2 + a(t)^2(d\rho^2 + \cosh^2\rho d\Omega_2^2)$$
$$= -dt^2 + a(t)^2 dH_3^2$$
$$\phi = \phi(t)$$

This is an FRW open universe, with all the energy density initially stored in the scalar field



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

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

Introduction

Observation

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 particular power spectrum of density perturbations at large scales

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

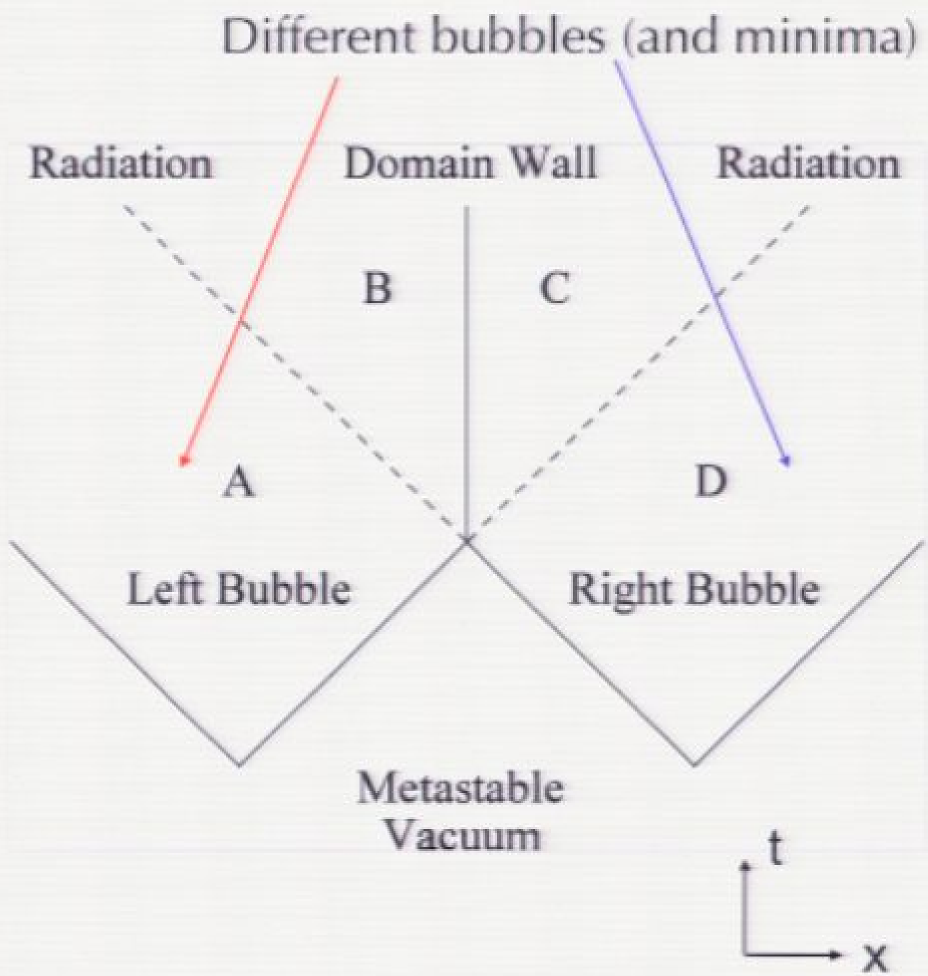
An observation of these characteristic features in the power spectrum would provide strong support for it

The model is **falsifiable** and **predictive**

(Caveat: too much inflation wipes out these signatures)

Collisions

- Inside the bubble, the space approaches either de Sitter, flat, or anti-de Sitter
- One can find exact, analytic solutions to Einstein's equations describing the collision of two such bubbles embedded in a false vacuum
- After the collision, both bubbles are perturbed by radiation emitted into their interior, and by the presence of the domain wall separating the two of them



Analytic Solutions

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

$$g(t) = 1 + \frac{t^2}{\ell^2} - \frac{t_0}{t}$$

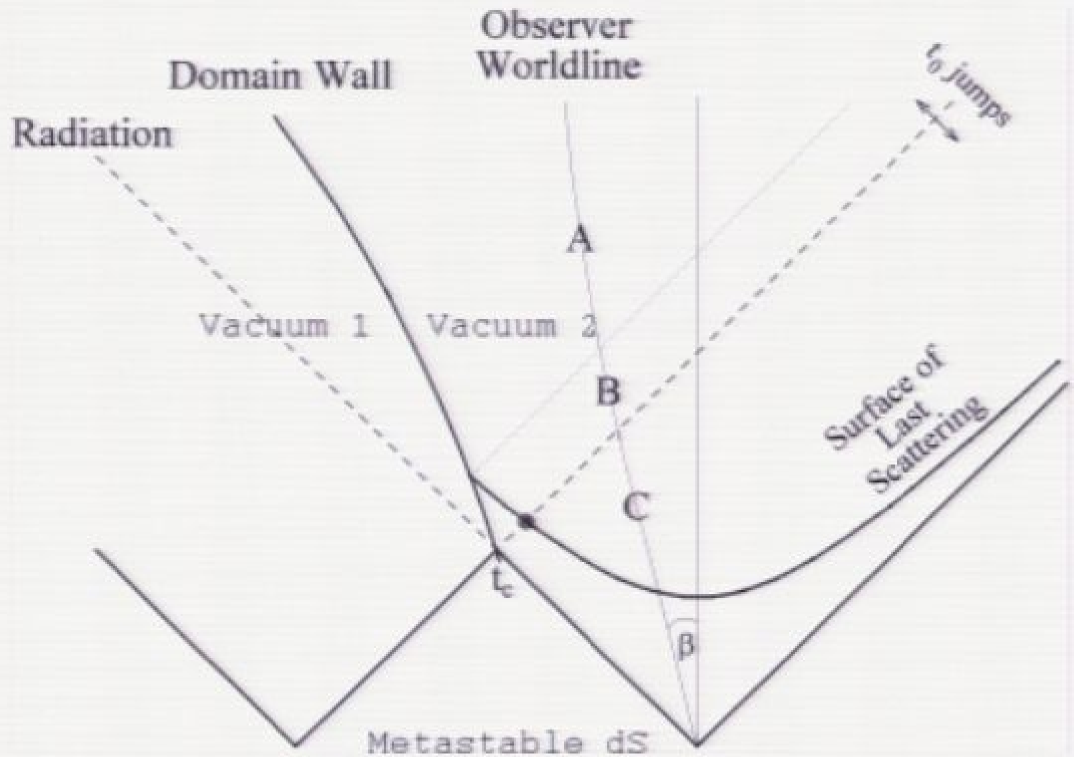
It is possible to find exact solutions because the bubble collision preserves an SO(2,1) group of isometries (which arises from the fact that the bubble walls accelerate at a constant rate).

By "gluing" pieces of these metrics one can find the full solution in the thin wall/shell limit, but we have exact solutions even far from that limit.

Analytic solutions

These solutions are exact in the approximation that the bulk is vacuum-energy dominated, and solve for the trajectory of the domain walls.

Like the walls of the bubbles, they undergo constant acceleration.



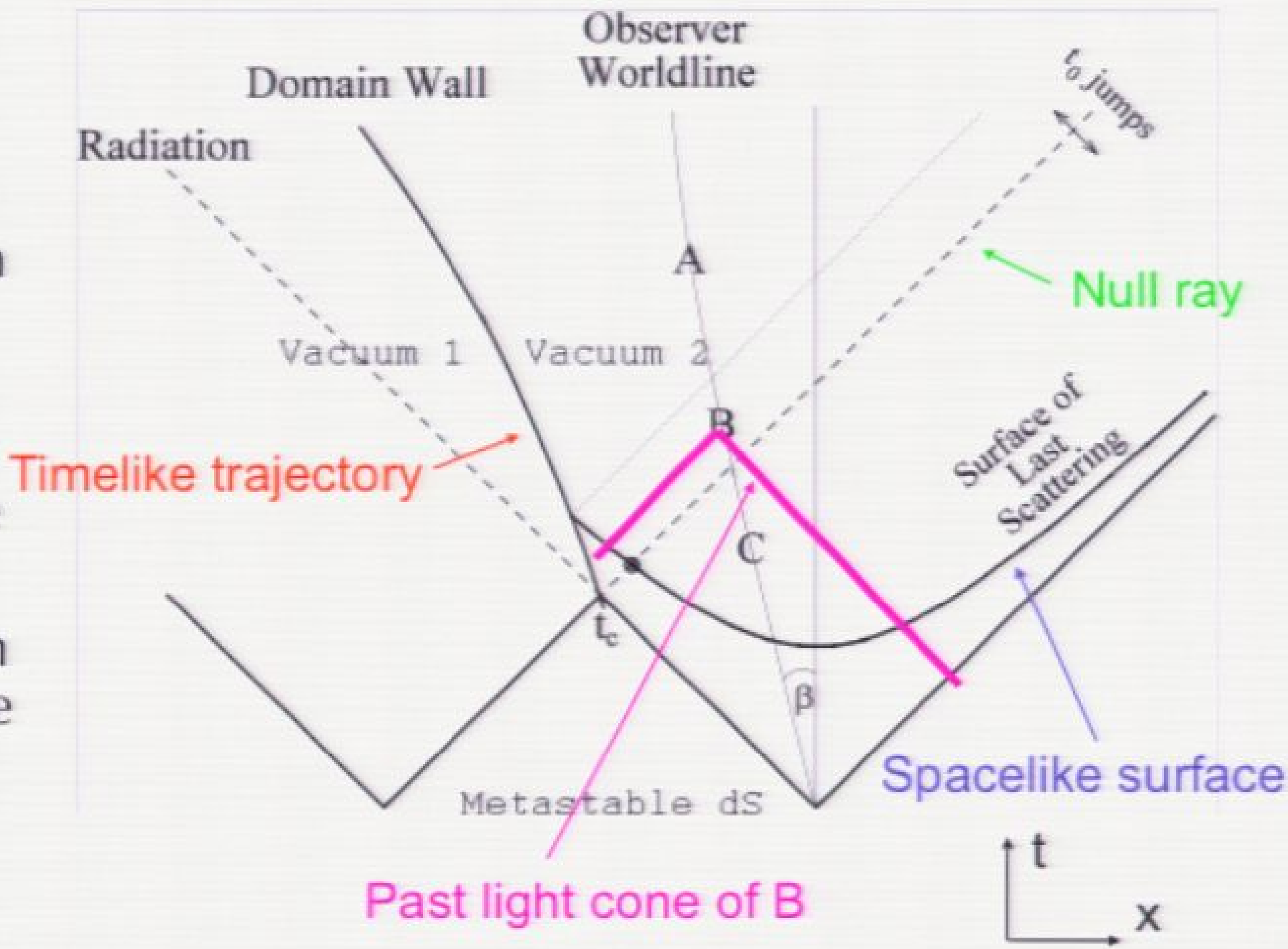
Some results

- The domain wall always moves away from the bubble with smaller Λ (conservation of energy)
- It sometimes moves 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, protects the bubble from catastrophic collisions with bubble with larger positive Λ
- We may also be safe from collisions with bubbles with negative Λ, due to the tension of the wall (BPS)

Freivogel Horowitz Shenker

Observables

- Observer C is oblivious to the collision
- Observer B will see anisotropic redshifts in the CMB
- Observer A will see the anisotropic redshifts and "see" the domain wall directly
- Can see radiation from collision along the line where t_0 jumps, and possibly throughout regions A and B.



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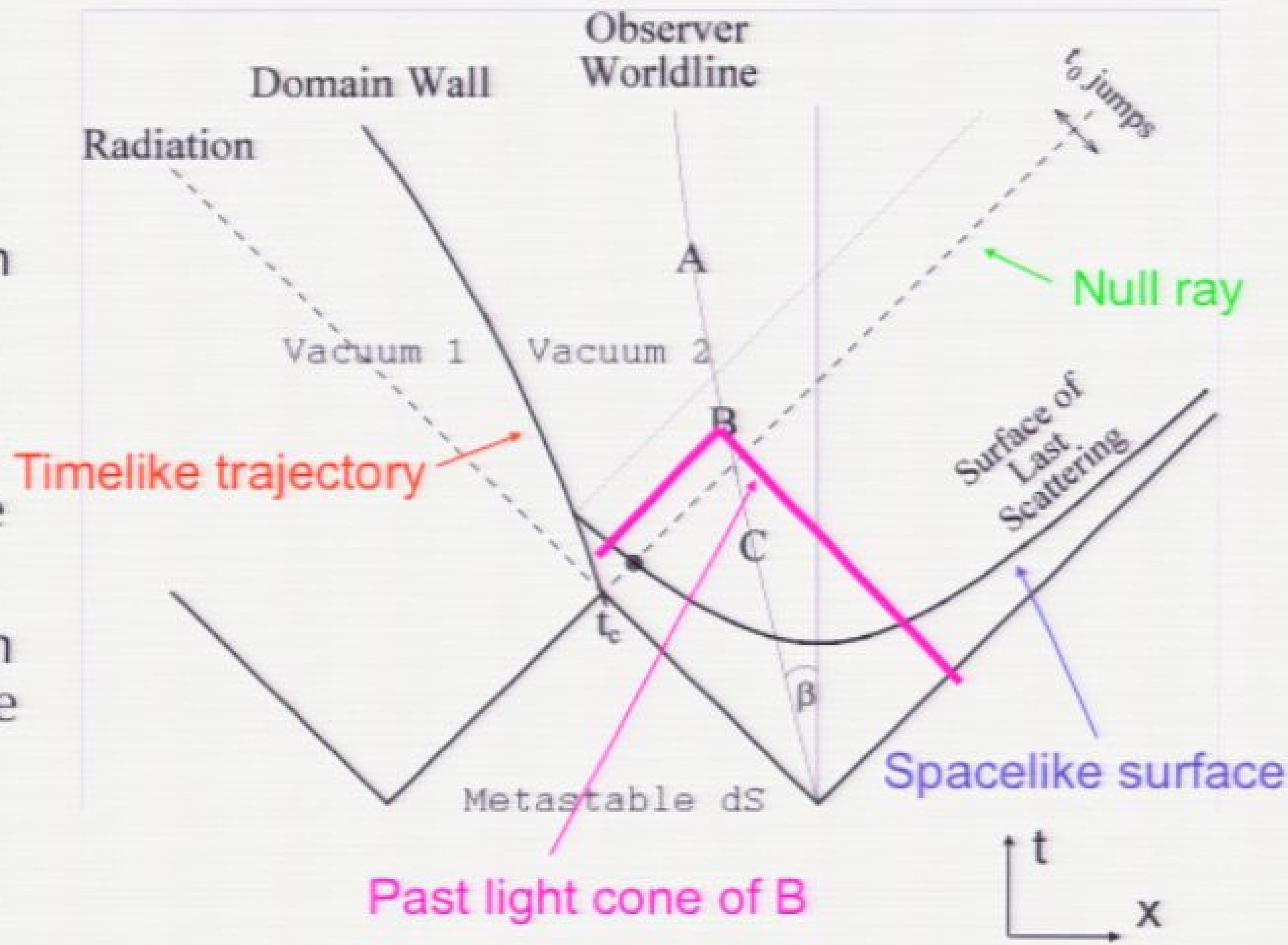

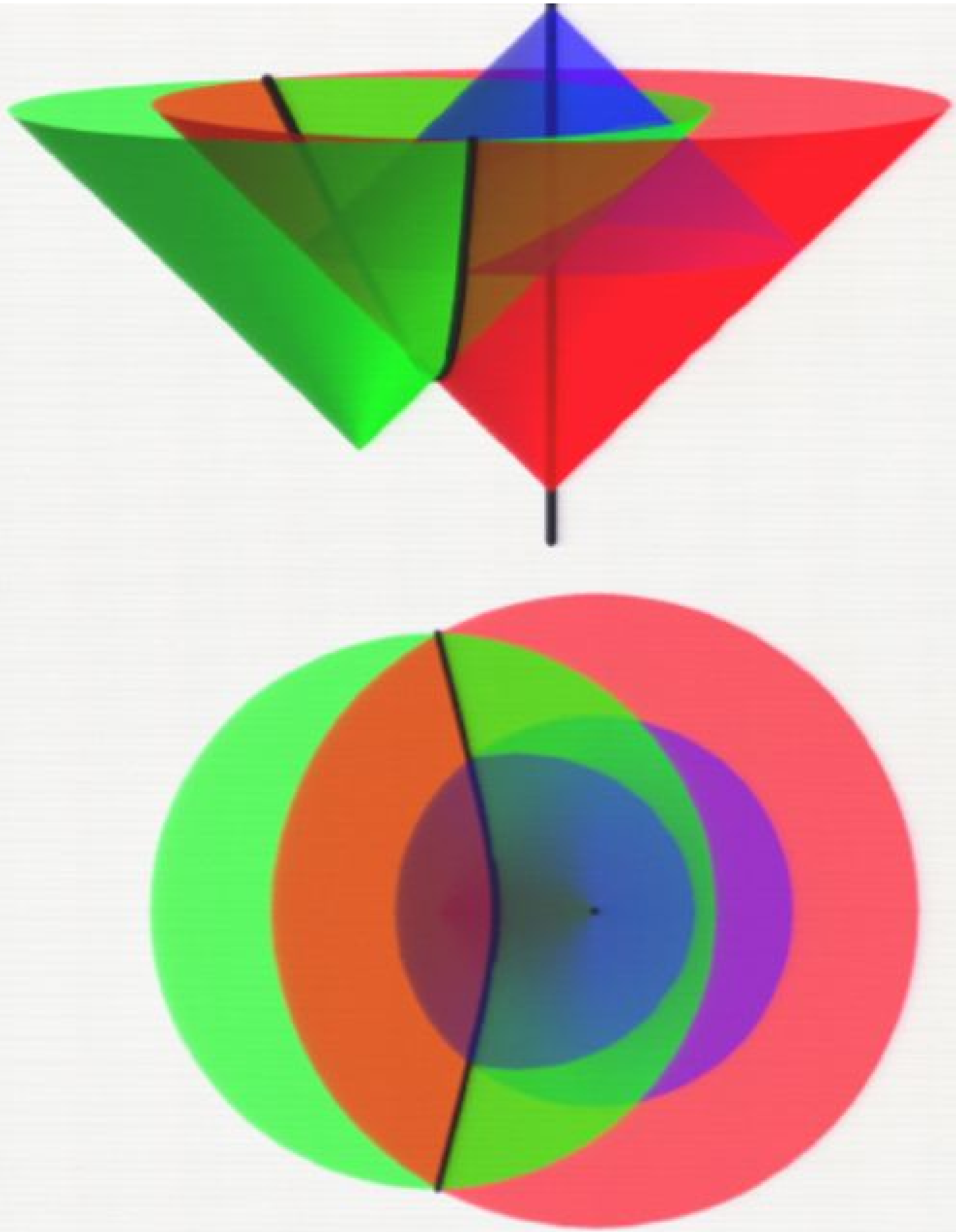

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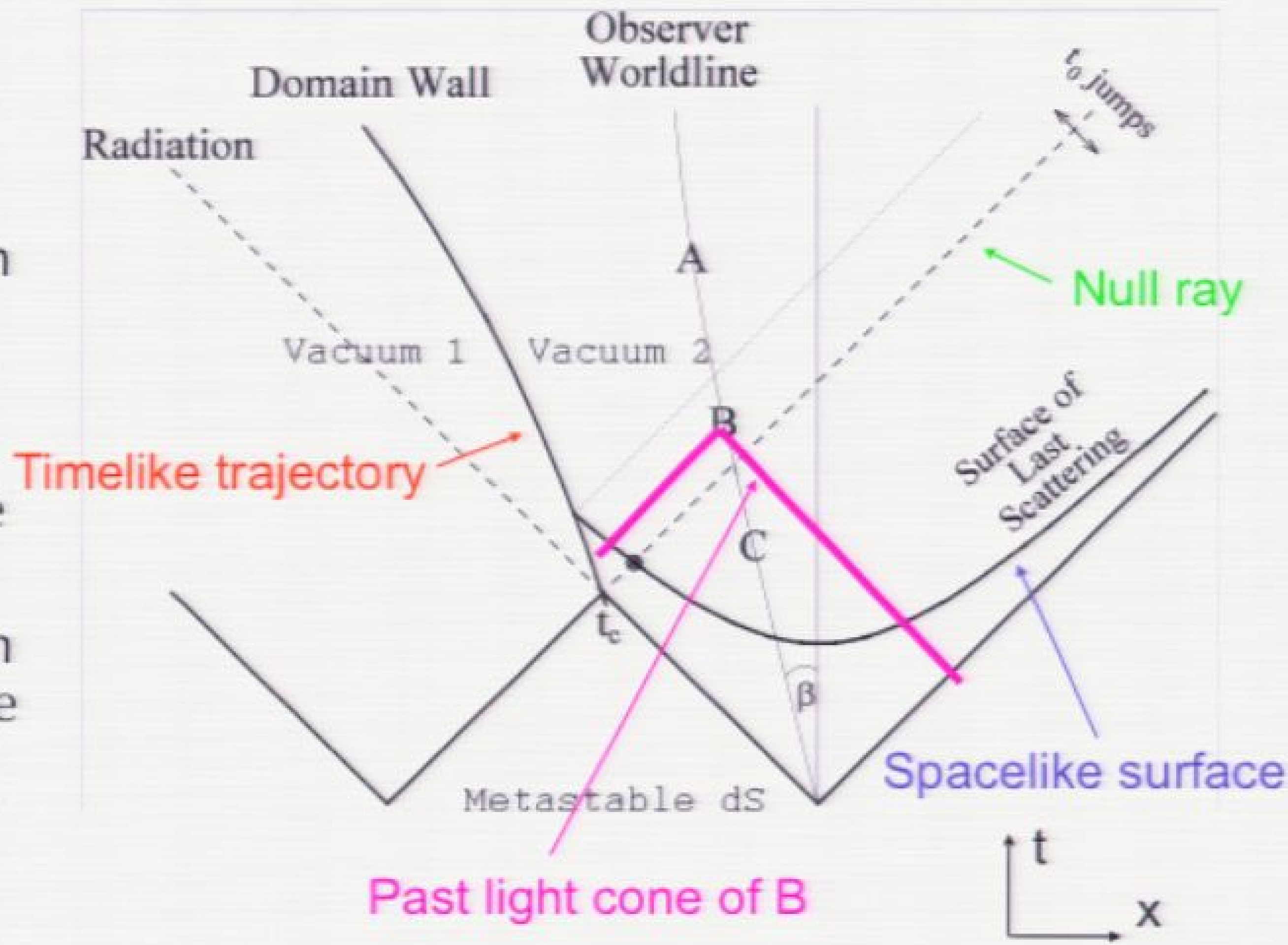
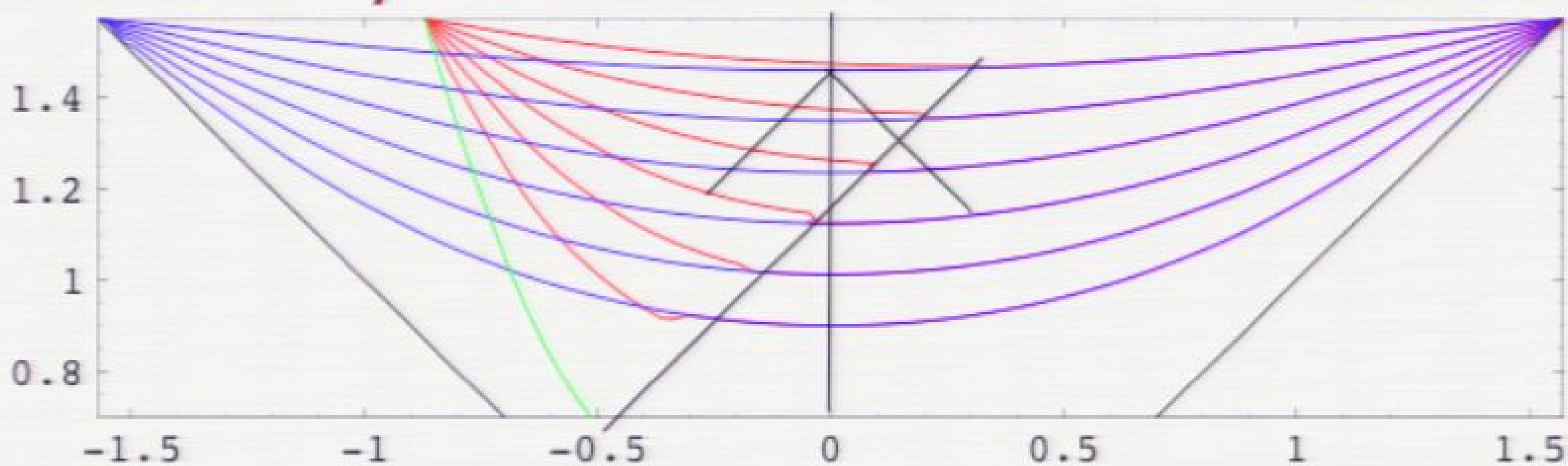
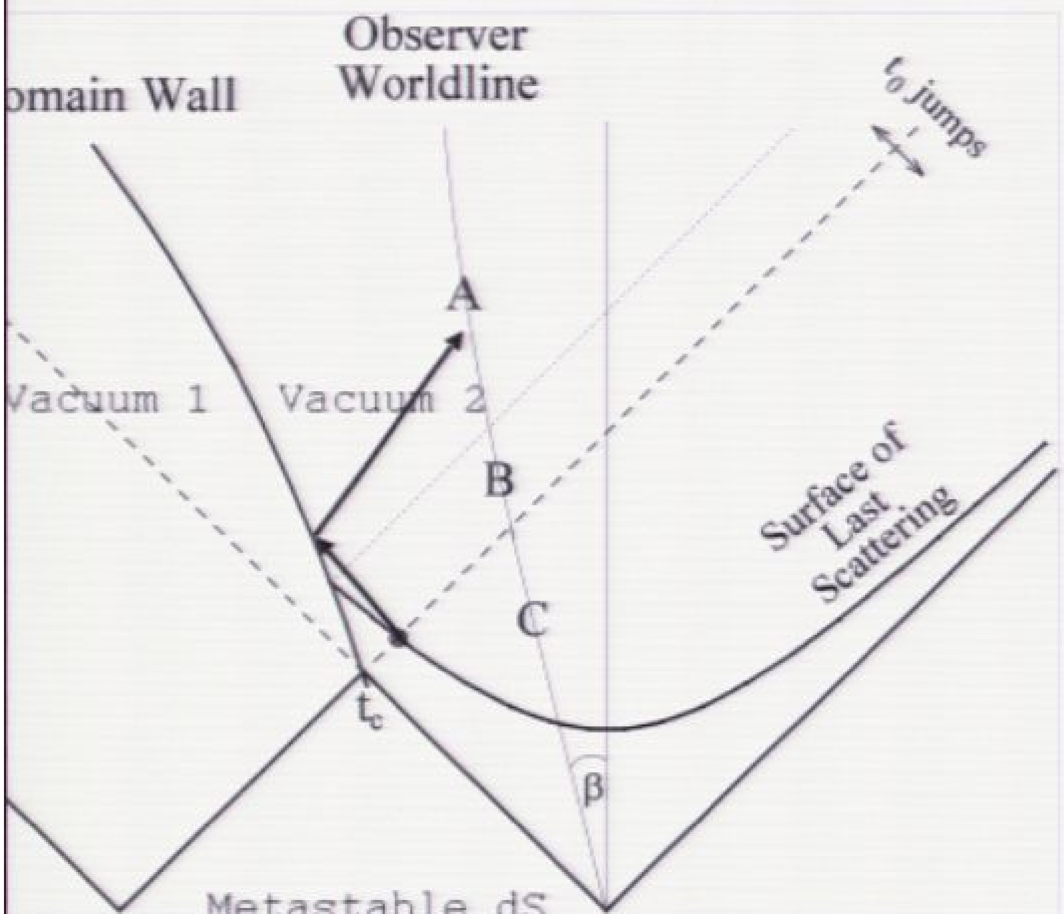


Asymmetric redshifts



- Photons from different directions travel through different metrics, and originate from a perturbed reheating surface.
- This leads to a differential redshift as a function of angle. Photons that last scatter inside the lightcone versus those outside divides the sky into two halves (disks) of some size.
- There is a preferred direction and dependence only on the angle towards it.
- One can learn something about the physics of the other bubble from the sign and radial dependence of the temperature shift.

Seeing the wall



- If the two vacua are different the domain wall will (probably) be a near perfect reflector for CMB photons
- Since the wall is moving, reflected photons will generically be Doppler shifted
- Will show up as a circular disc with temperature red (or blue) shifted. The doppler shift is a function of the radial distance from the center of the disc, and there is a sharp jump at the edge of the disc
- If very close to the wall (highly boosted) can see mirror images

Parameters

- There are a few parameters which are important for determining the observable signatures:
  - the separation distance between the bubbles at the time of their nucleation, which affects the time when an observer's worldline passes into the future lightcone of the collision
  - the boost of the observer towards or away from the collision
- There is the tension of the wall and the energy released, but these are calculable given the effective potential
- Both analytic and numerical work in progress to determine magnitude and type of effect

Other signatures

- 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 will not be at rest with respect to the CMB outside
- CMB polarization will be affected
- The wall itself may emit radiation, either gravitational or otherwise
- It remains to be see which of these effects is most important

Summary of Observables

- The anisotropy in a 2-bubble collision is of "l=0" type - i.e. it depends only on the angle from the preferred axis (and not on the azimuthal angle).
- CMB temperatures will be significantly affected (in a way which is easily calculable for part of the sky).
- If the domain wall cut off part of the last scattering surface, it would be very easy to see (unless it is small).
- Large scale structure statistics, polarization, and direct radiation from the wall are possibilities.
- Most of these quantities depend primarily on only two parameters: the bubble separation and the observer's boost.

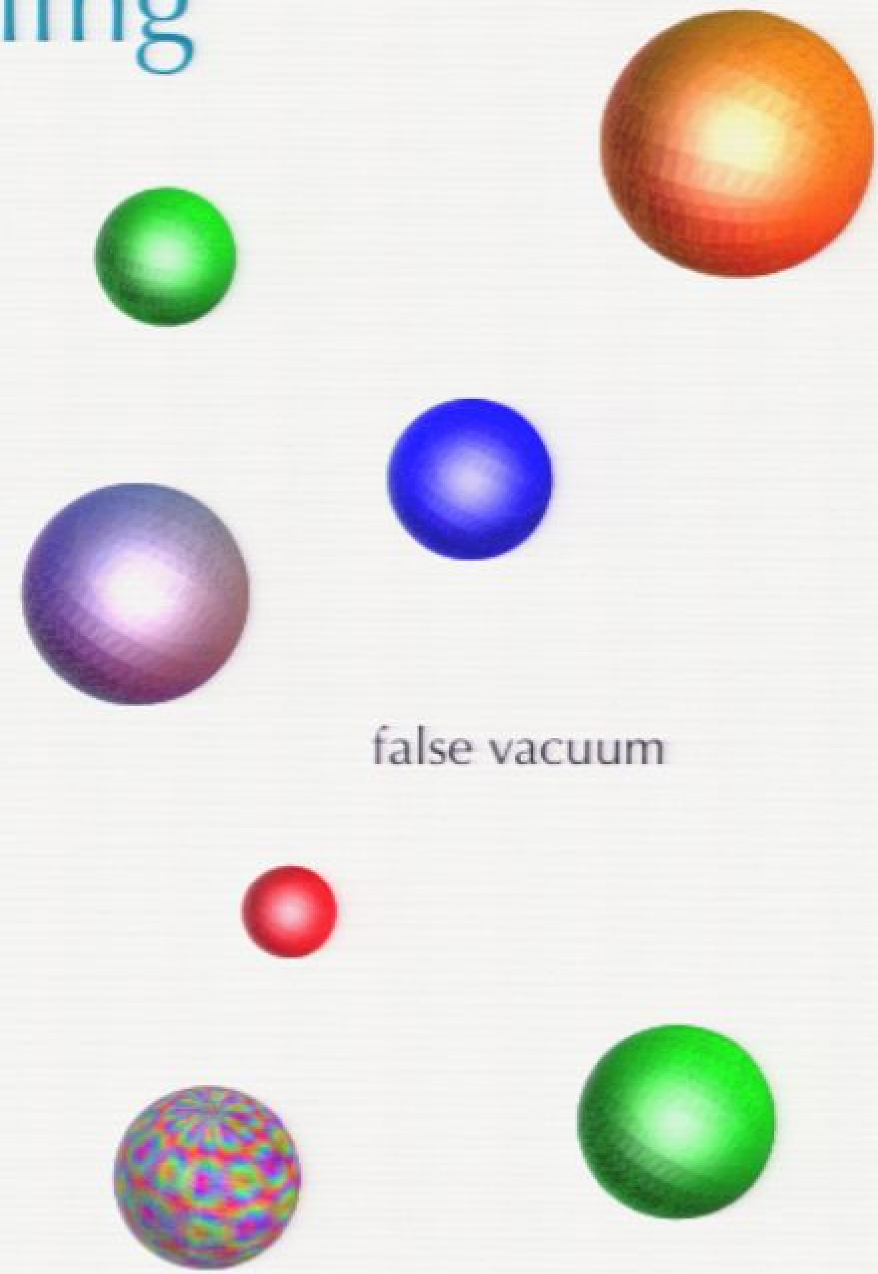
- Introduction and motivation

- Observation

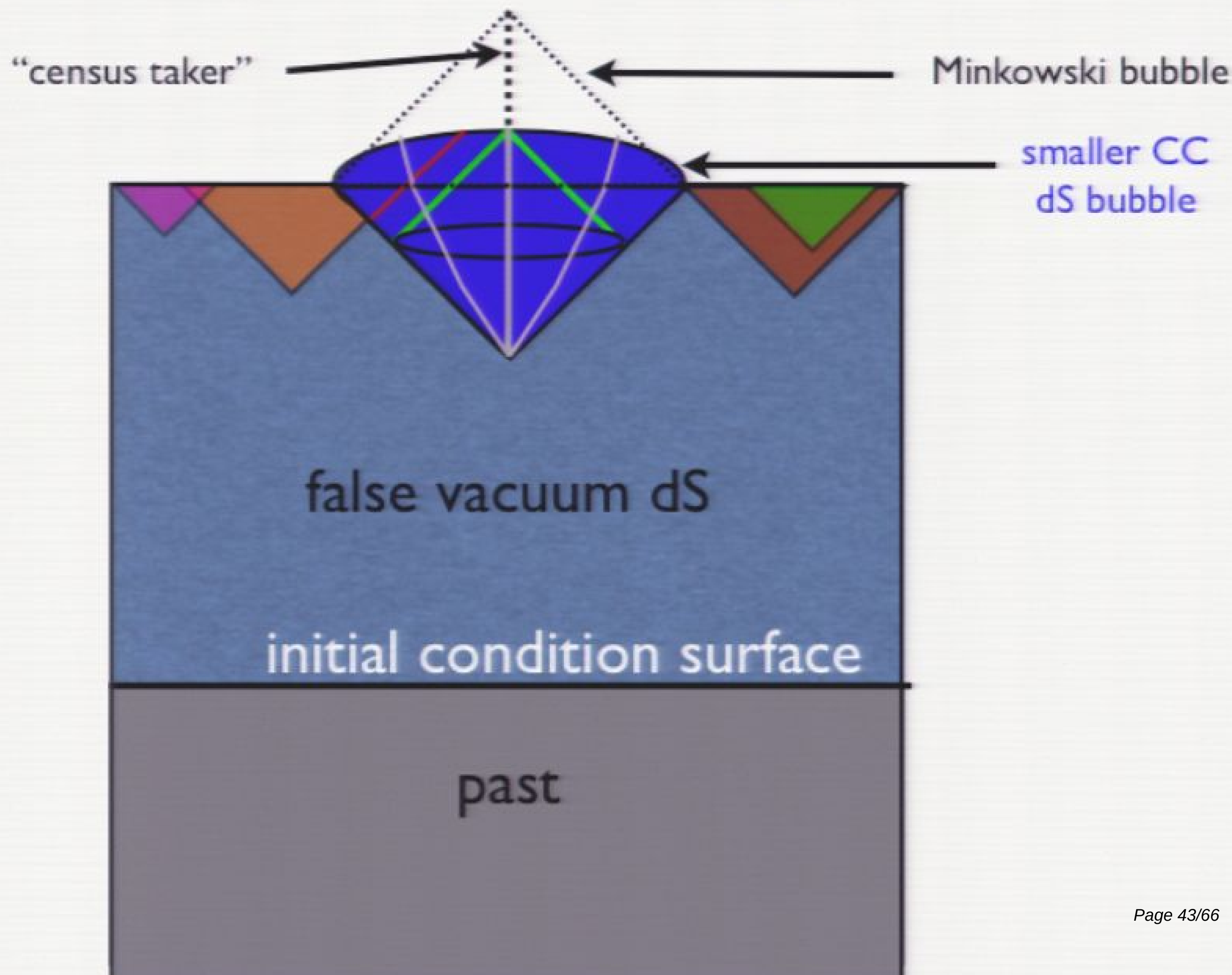
- How many collisions?

Bubbling

- If happens once, it happens many times… many bubbles form, most(?) with physics very different from ours
- How many should we expect in our past?
- If we see none, can we constrain some parameters of the landscape?

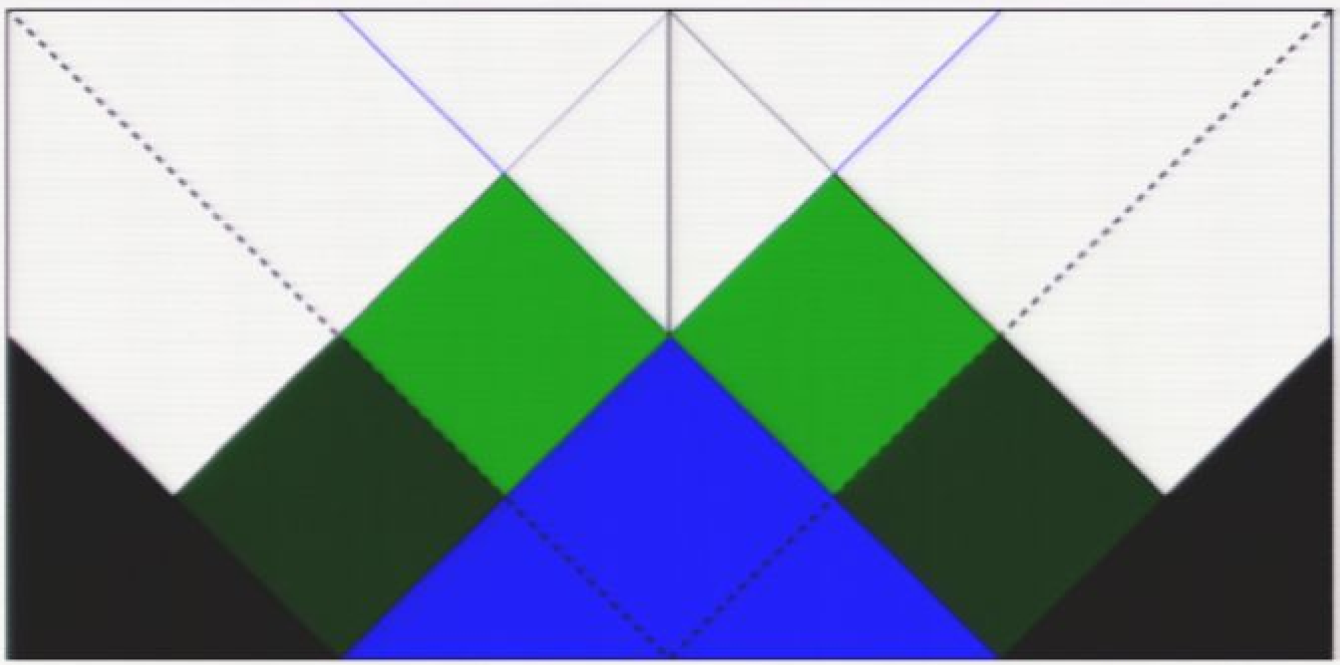


a conformal diagram



To count the expected number of bubbles in our past, we should compute the 4-volume in our past lightcone, and multiply it by the nucleation rate (per time per volume) of the bubbles.

Following Guth, Garriga, Vilenkin, let's exclude some of that volume with an initial condition, and treat the case of equal CCs inside and out.



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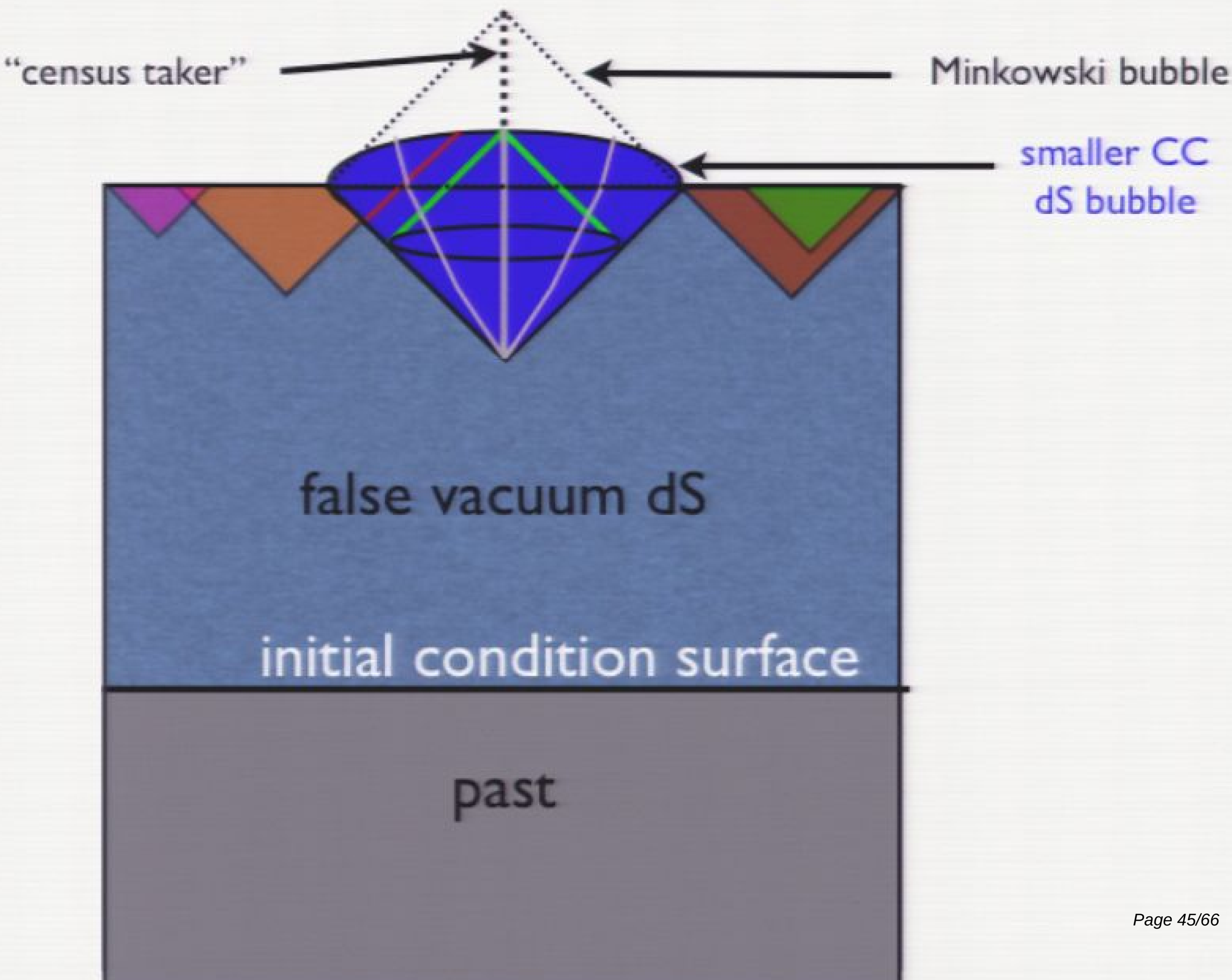

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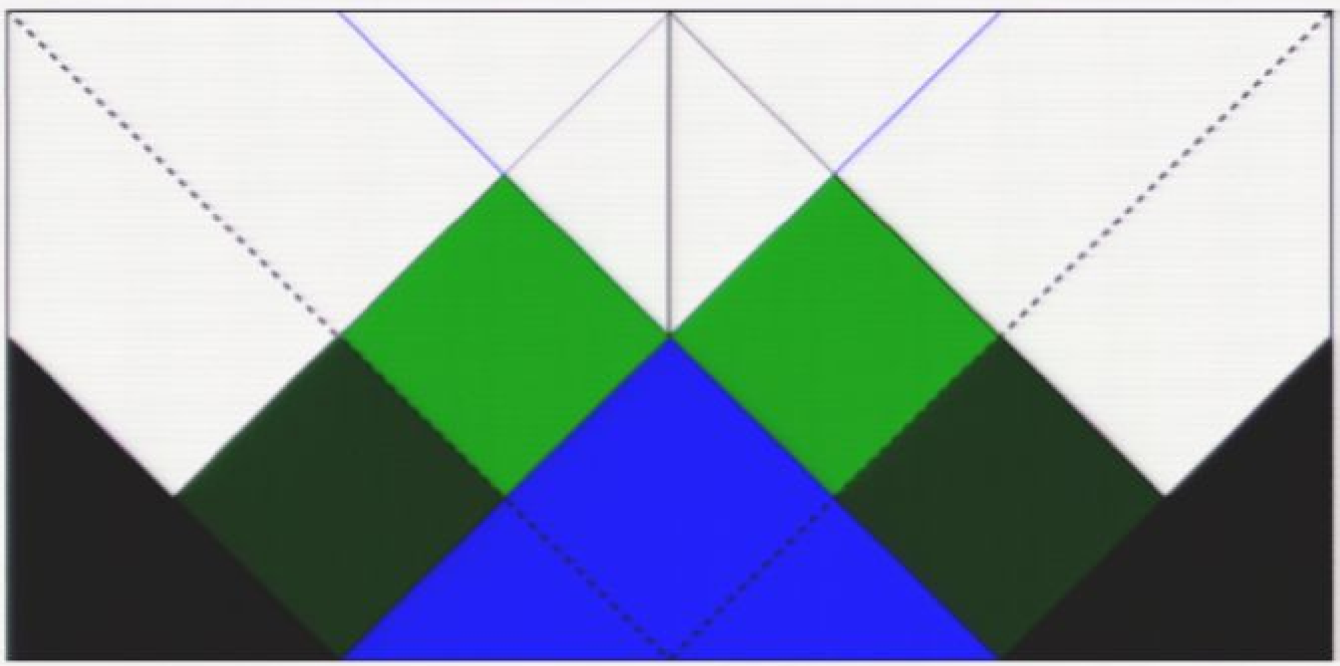

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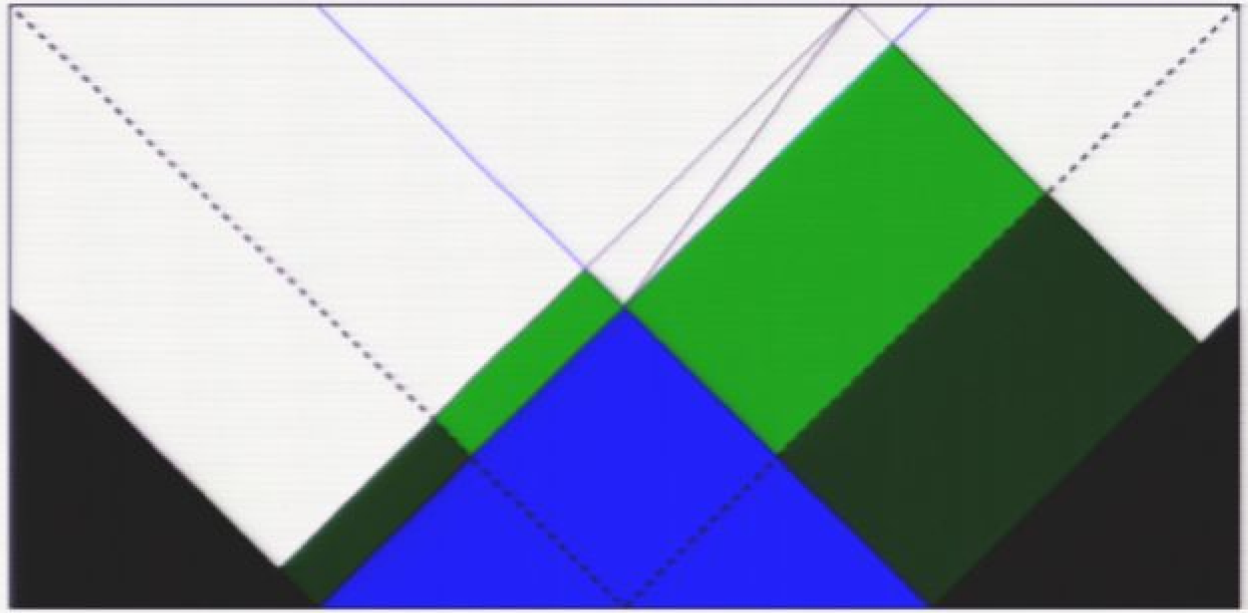
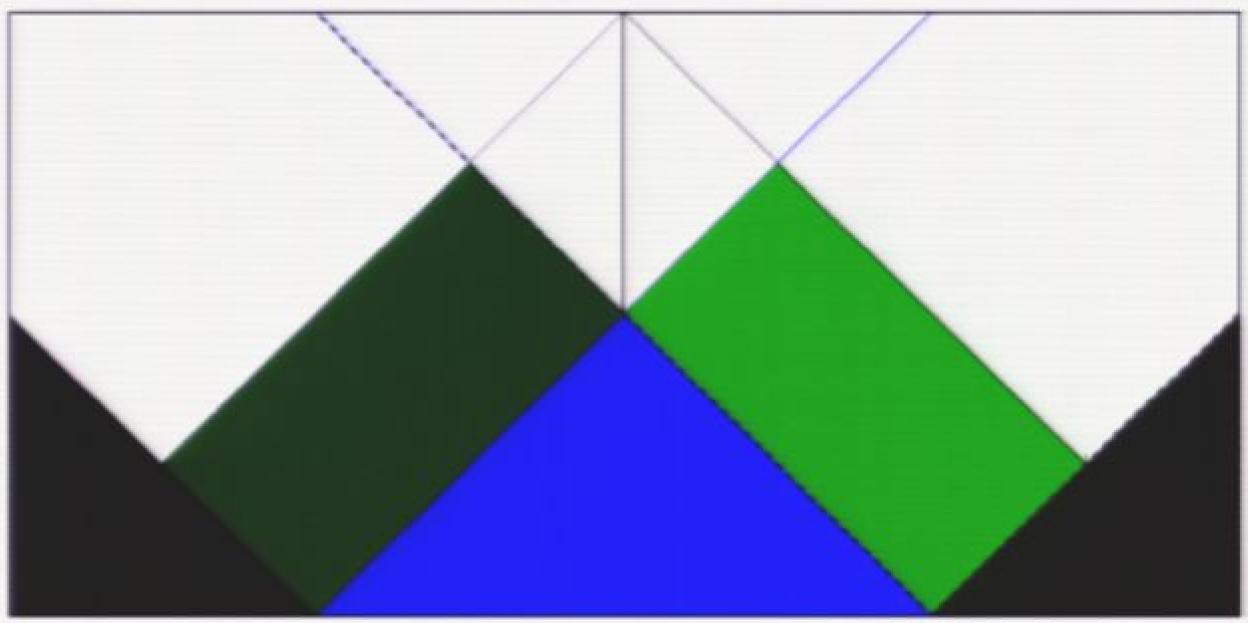
Inside the bubble, observers related by boosts around the nucleation point are equivalent (open FRW)



But the past volume available for nucleations is not invariant under these boosts, because of the initial condition surface



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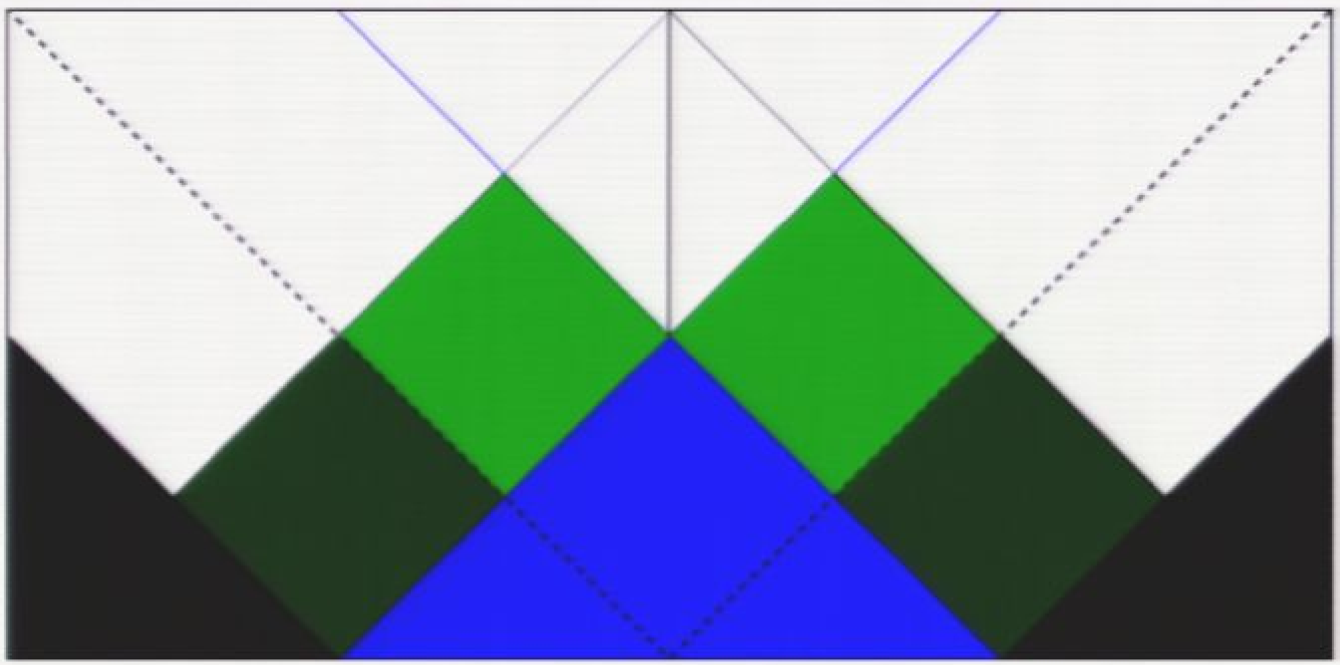

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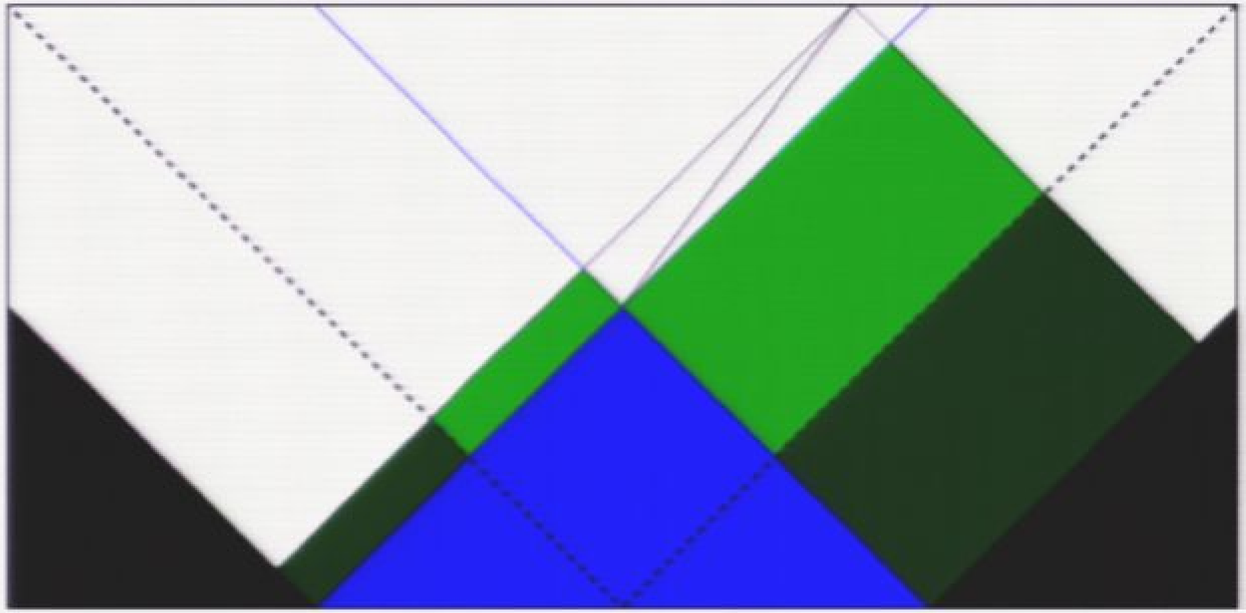

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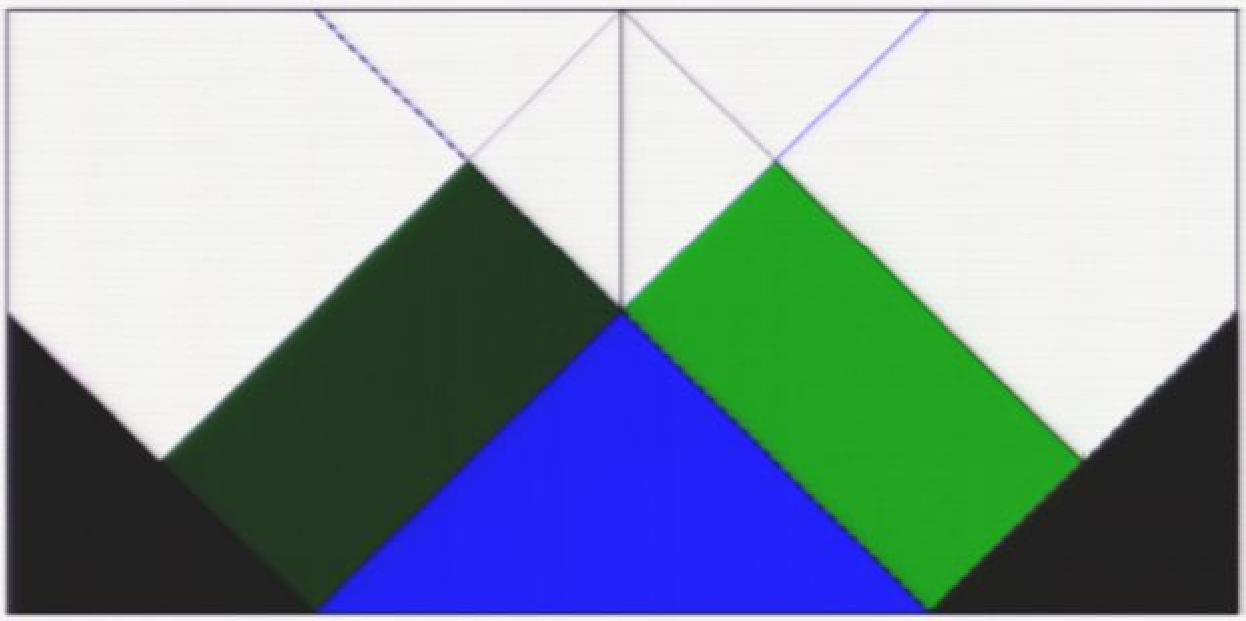

The persistence of memory

Therefore, the FRW symmetry SO(3,1) is badly broken by bubble collisions for all but a set of measure zero of observers. But there is a caveat - nearly all these collisions take place at early times, because an infinity of proper time fits into an infinitesimal conformal time interval. What few collisions there are at later times get more and more isotropic.

More importantly, the total volume available for bubble nucleations that affect the unboosted observer is only of order 1 in units of the false vacuum Hubble constant, which means the total number is of order the nucleation rate: small

It turns out that both of these conclusions change dramatically once we allow for a realistic cosmology inside the bubble

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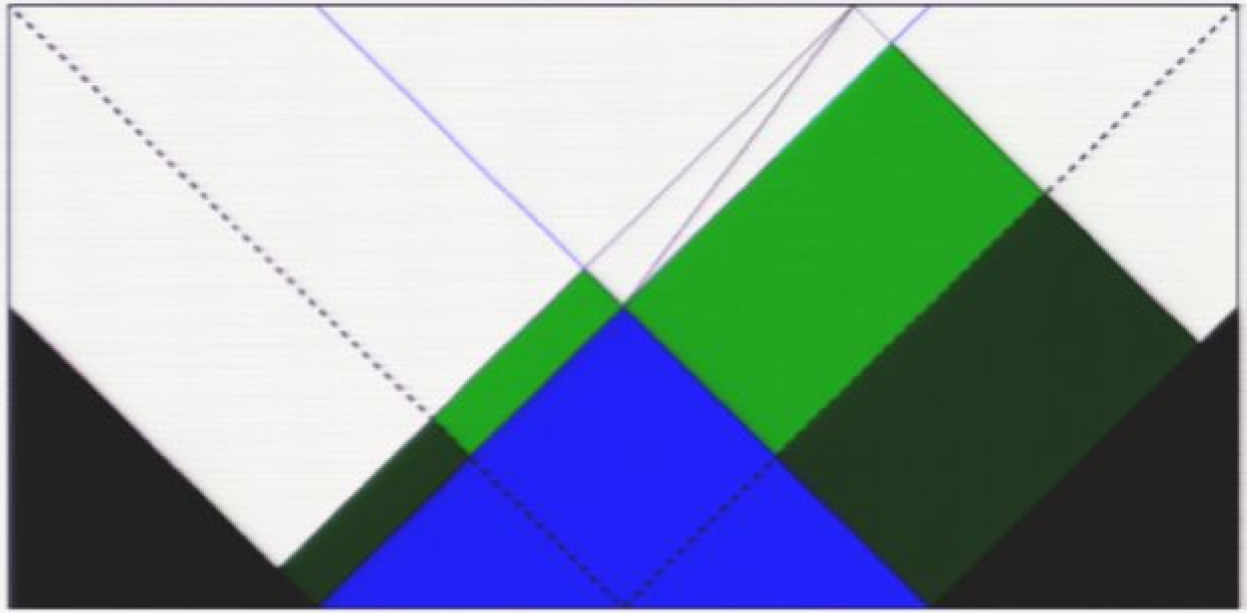

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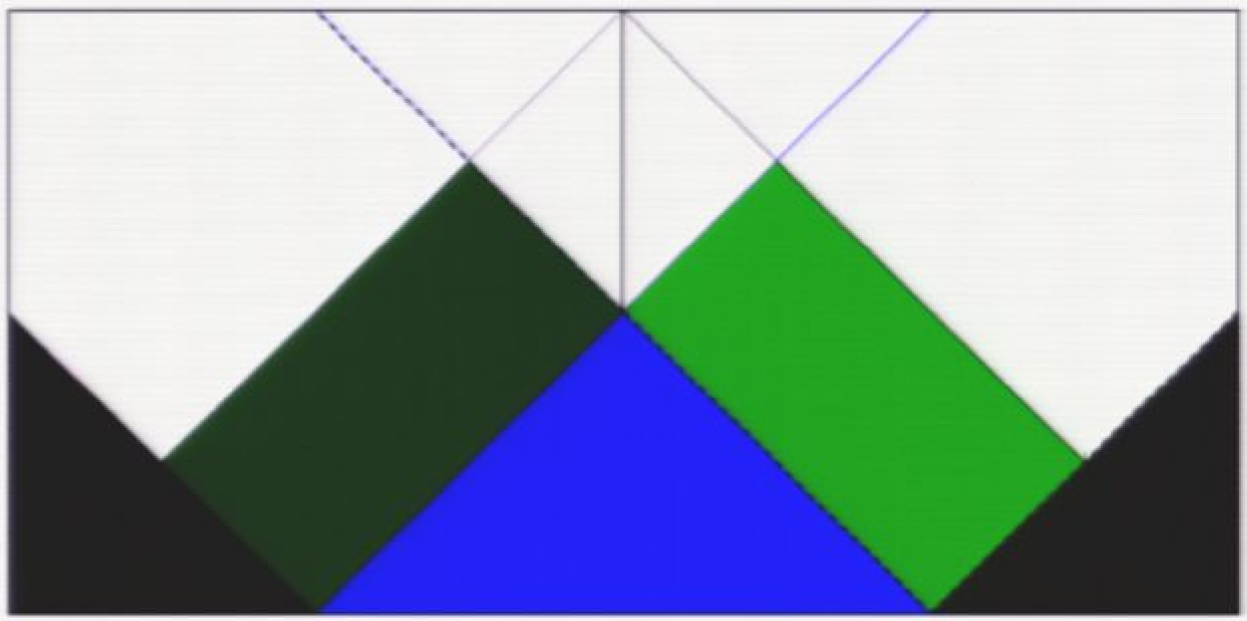

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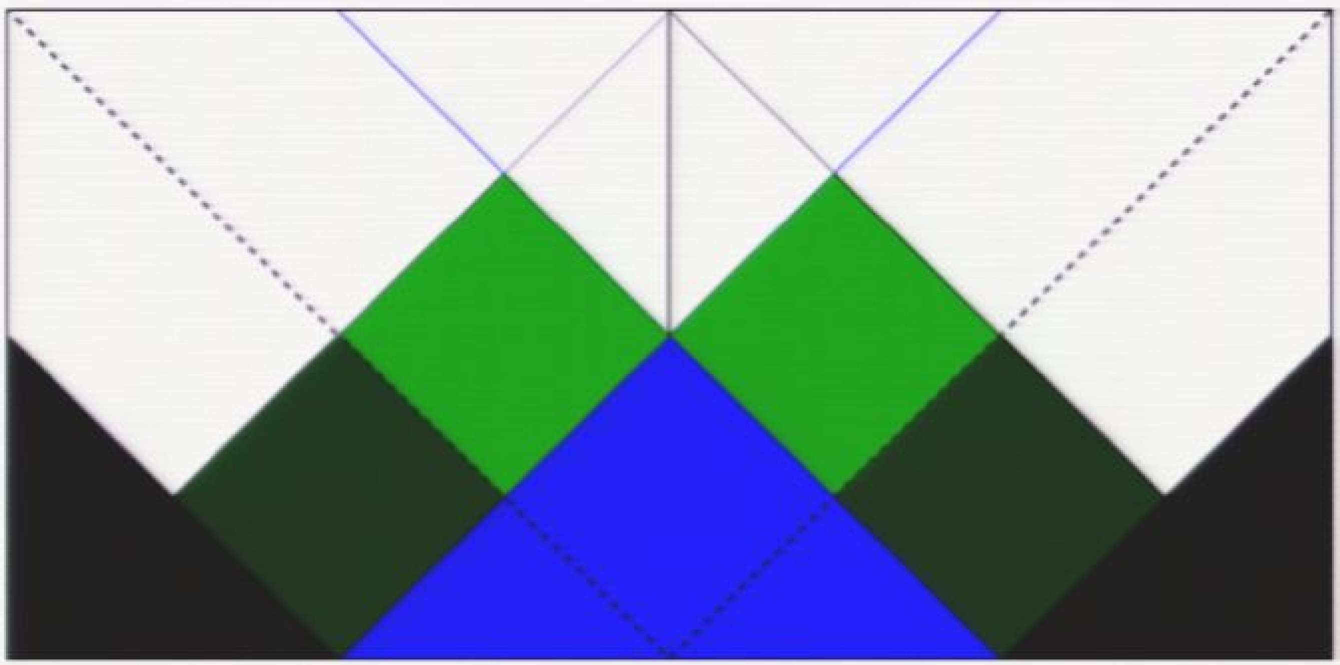

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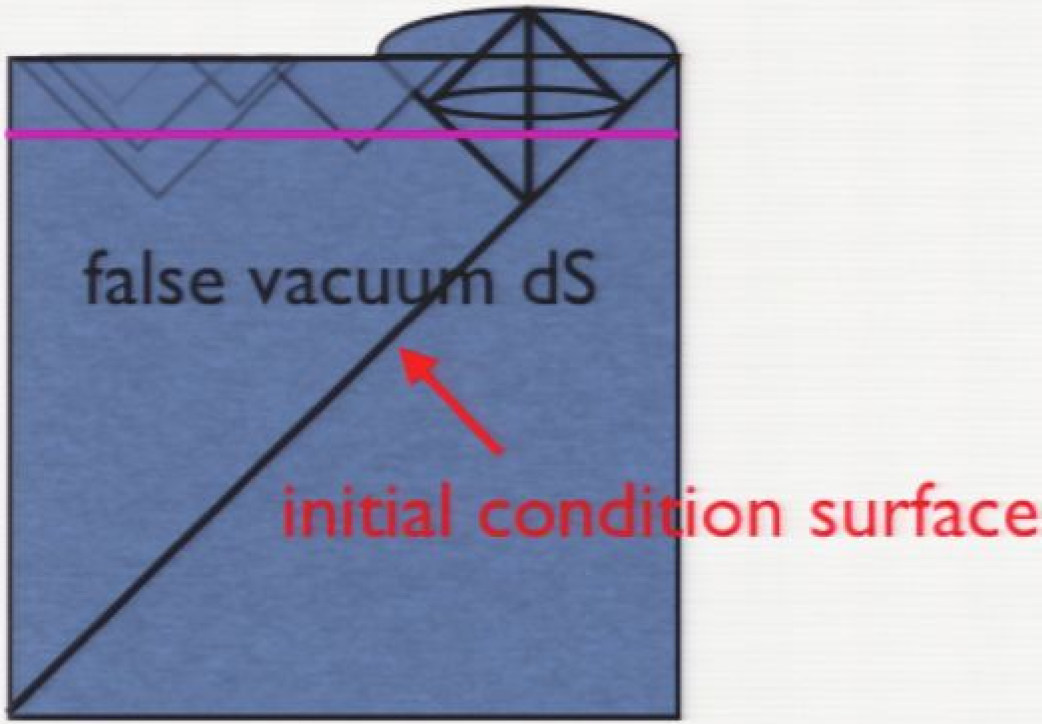
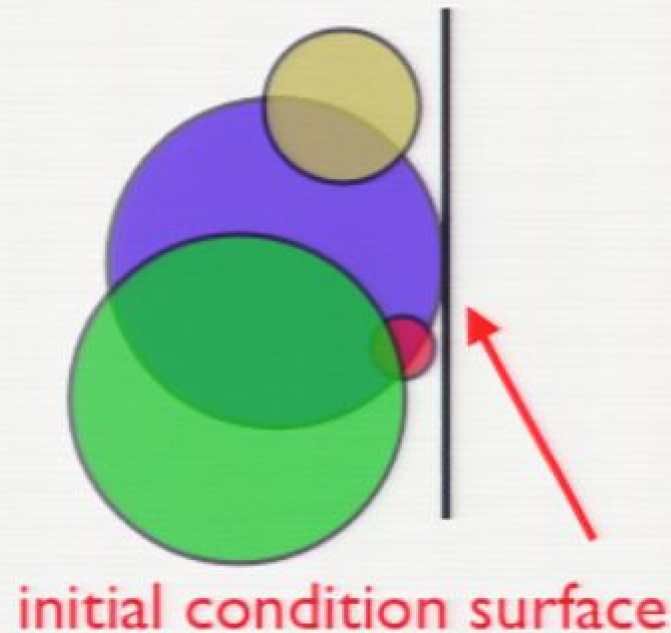
infinite boost

viewed from the side...



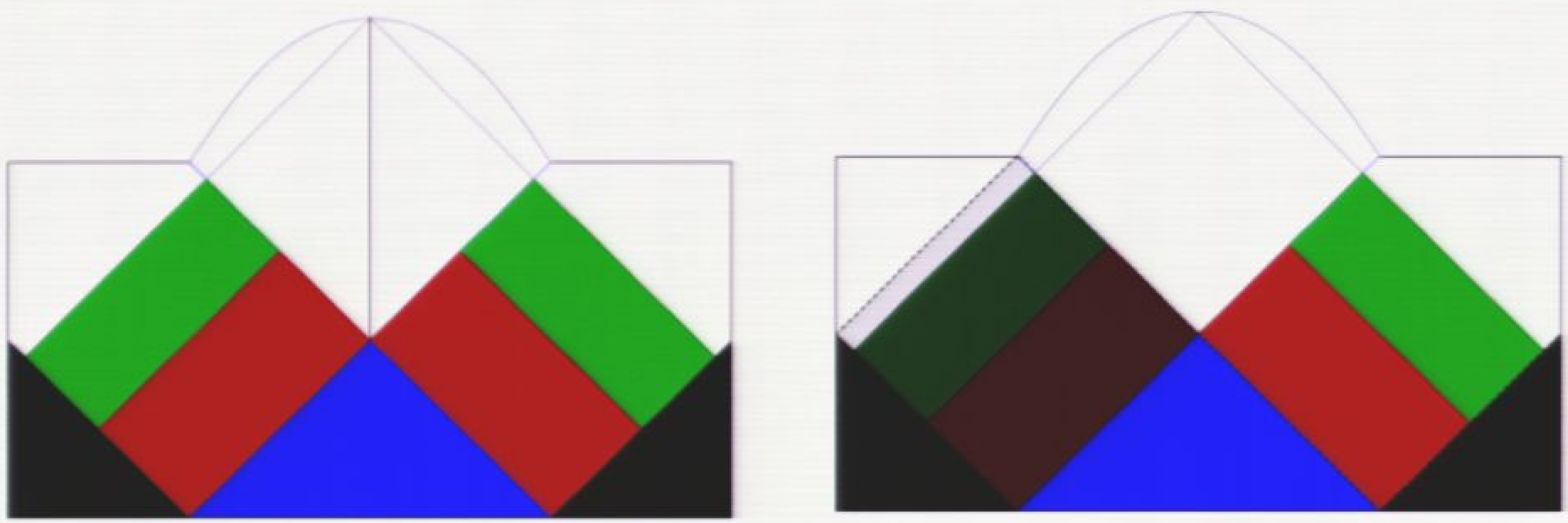
viewed from above...



Small bubbles - bubbles that collided with ours at late times - are hardly affected at all. The late-time distribution is nearly isotropic.

Our CC is very small - probably much smaller than our parent's. If so, the conformal diagram is very different.

Late bubbles, which are not significantly affected by the initial condition surface, may now be visible.



zero boost   infinite boost

Isotropy restored

The domain wall either accelerates away from our bubble, in which case it sweeps away a fraction of our volume, or it accelerates in and destroys an entire lightcone's worth. The later case is not interesting. The former case will remove only a part of the universe. But the part removed is the early part, where the anisotropy was significant.

This together with small CC inside the bubble removes nearly all of the anisotropy in the distribution.

More importantly, small vacuum energy means our bubble grows much larger (it's actually the Hubble constant during inflation that matters most). Because it's much larger, it is struck by many more collisions.

So what's the answer?

$$\boxed{N \approx \frac{4\pi}{3}\gamma\frac{V_f}{V_i}}$$

Is N likely to be larger than 1? Yes, for example if V_f is near the Planck scale:

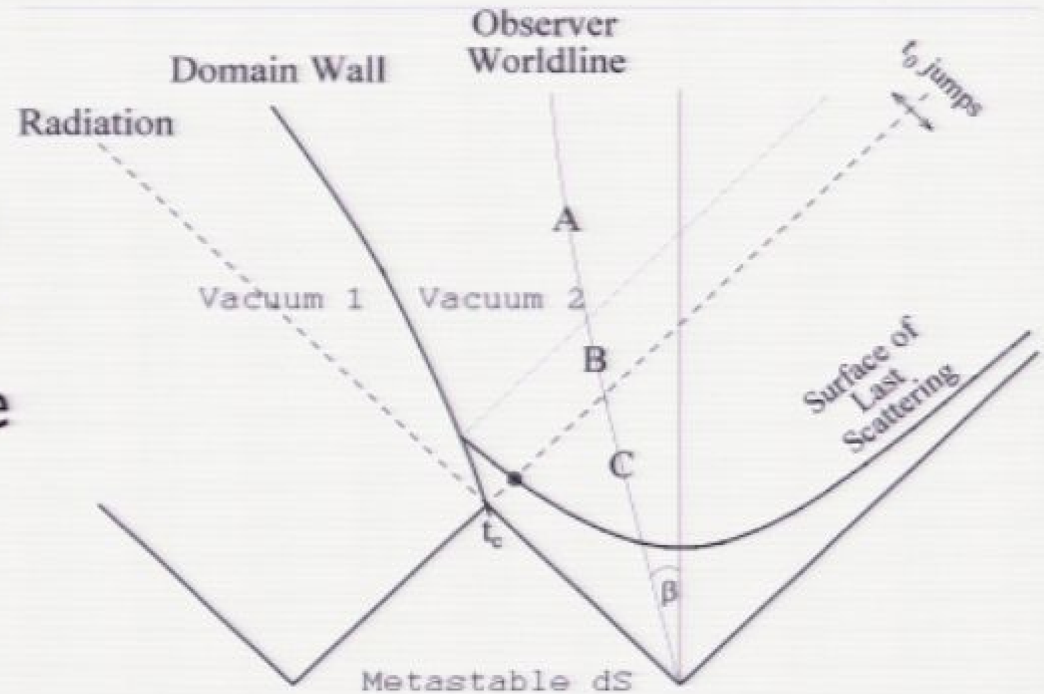
$$\frac{V_f}{V_i} \gtrsim 10^{12} \qquad \gamma > \exp(-S_f) \qquad S_f \sim \frac{M_P^4}{V_f}$$

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

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



So what's the answer now?

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

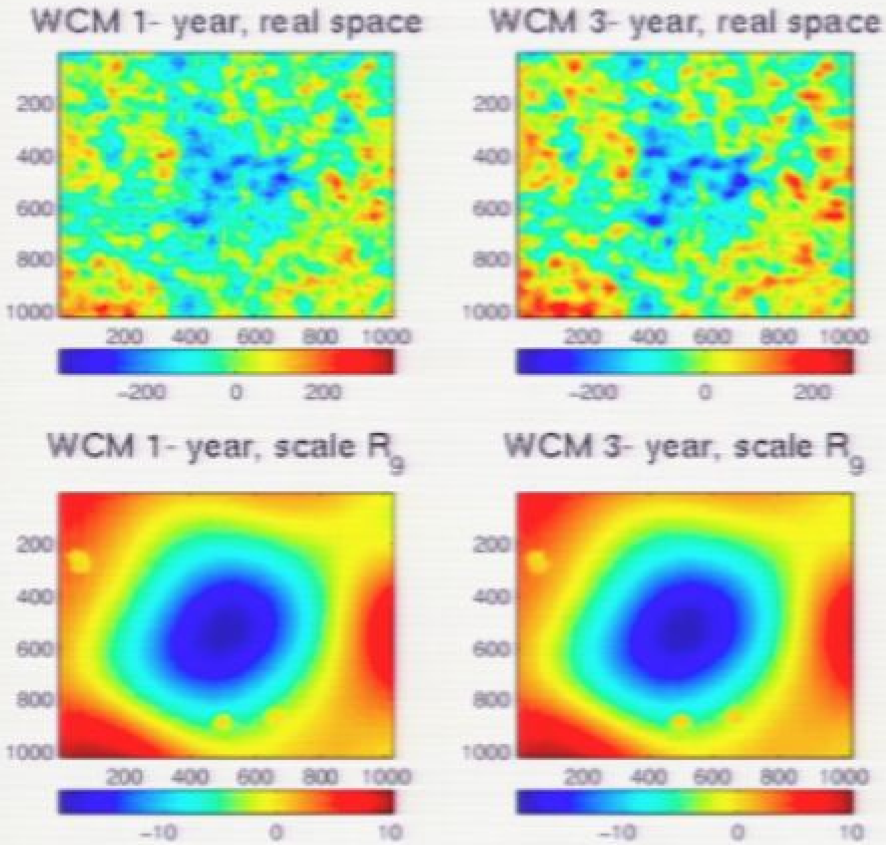
$$N \sim \gamma \sqrt{\Omega_k(t)} (H_f^2 / H_i^2)$$

Recall that

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

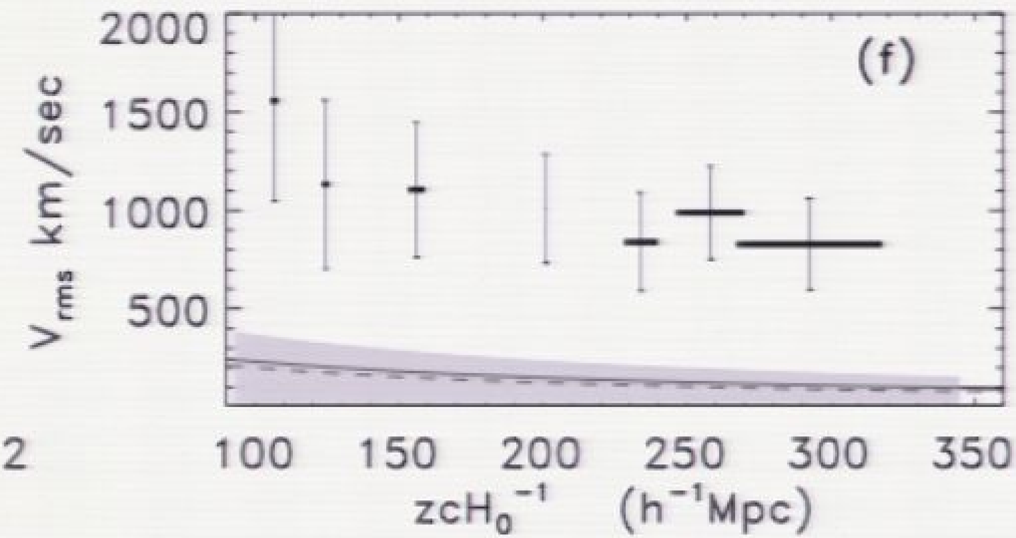
So long inflation (large N) inflates away the signal, as expected. Like every other pre-inflation state, long inflation hides it. But the measure on N in string theory may favor minimal inflation, and the current constraints on curvature are relatively weak.

Some interesting anomalies...



From *The non-gaussian cold spot in the 3-year wmap data.*

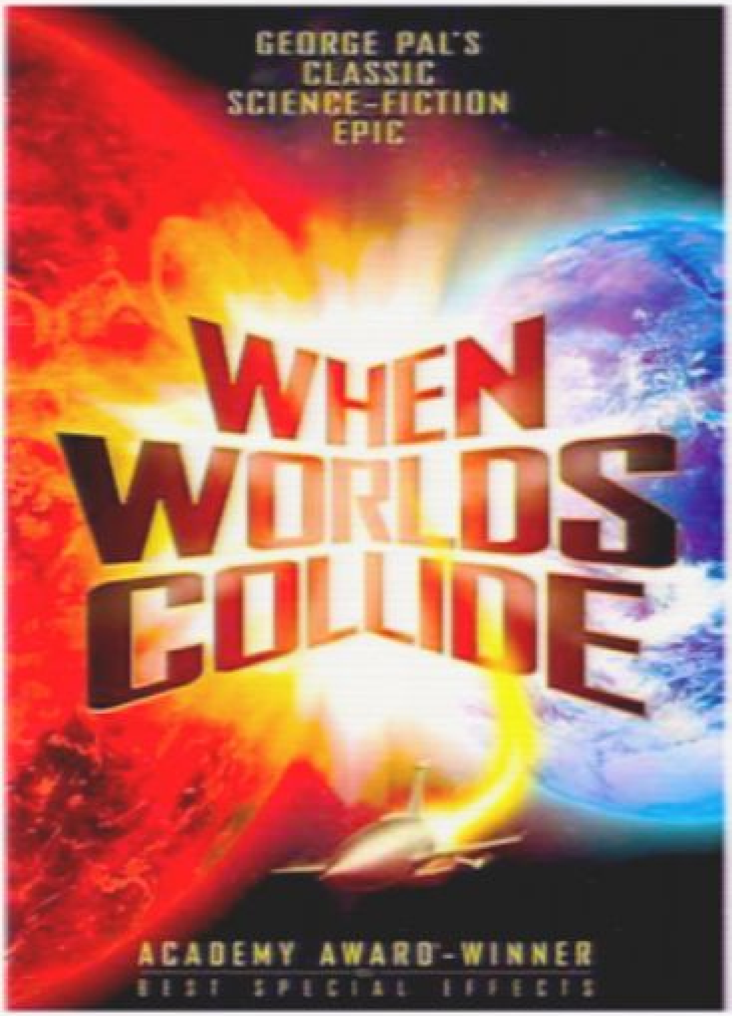
M. Cruz, L. Cayon , E. Martinez-Gonzalez, P. Vielva, J. Jin



From *A measurement of large-scale peculiar velocities of clusters of galaxies: results and cosmological implications.*

A. Kashlinsky, F. Atrio-Barandela, D. Kocevski, H. Ebeling

Conclusions and future directions

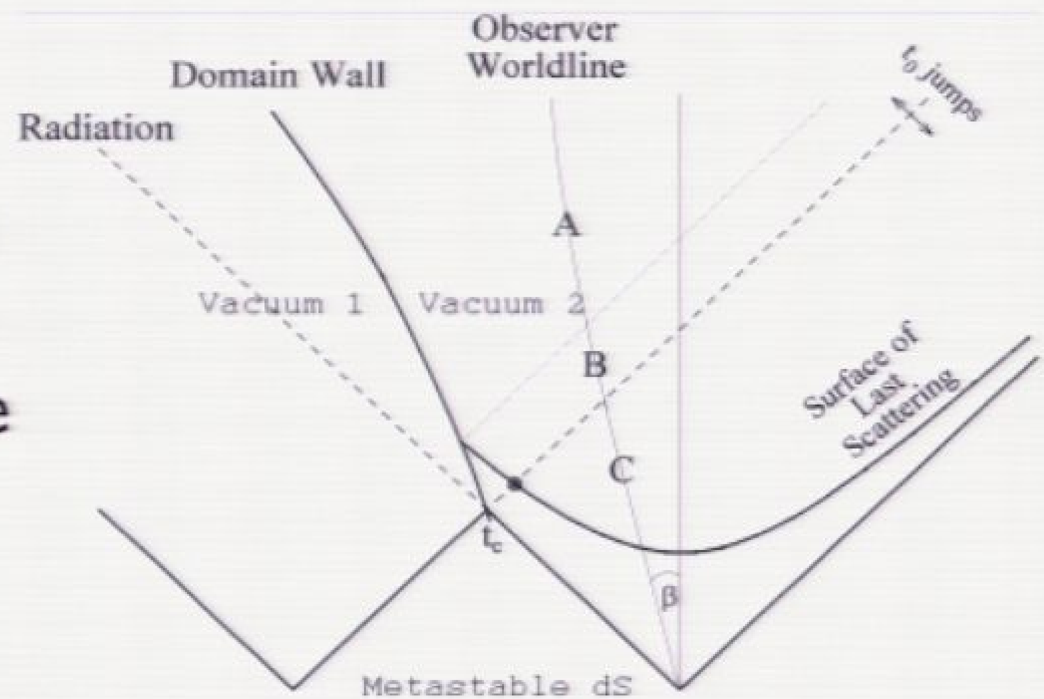


- Cosmology has unique potential as a probe of high energy physics and string theory
- Can study the dynamics of bubble collisions analytically
- The CMB, 21cm radiation, structure formation, etc. are affected in a specific way
- The expected number of observable collisions may be larger than one without any signficant fine-tuning, at least with short inflation
- Any connection to the "axis of evil" and/or the cold spot? Numerical study in progress...

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

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



Matthew Kleban

Tufts/CfA/MIT joint seminar

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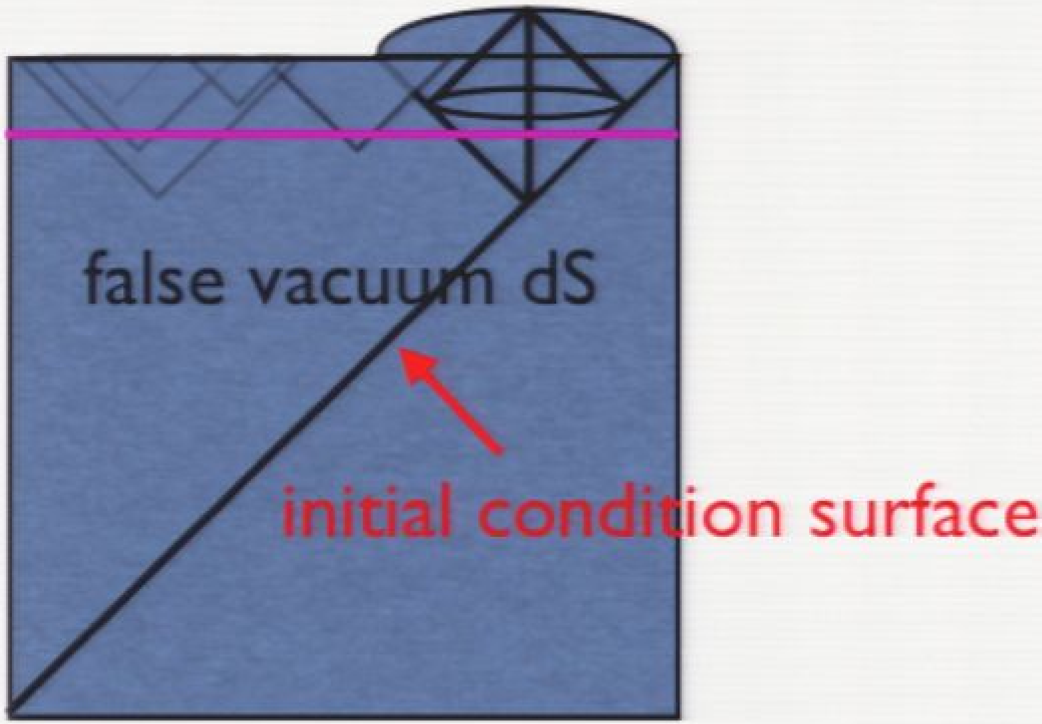
infinite boost

viewed from the side...

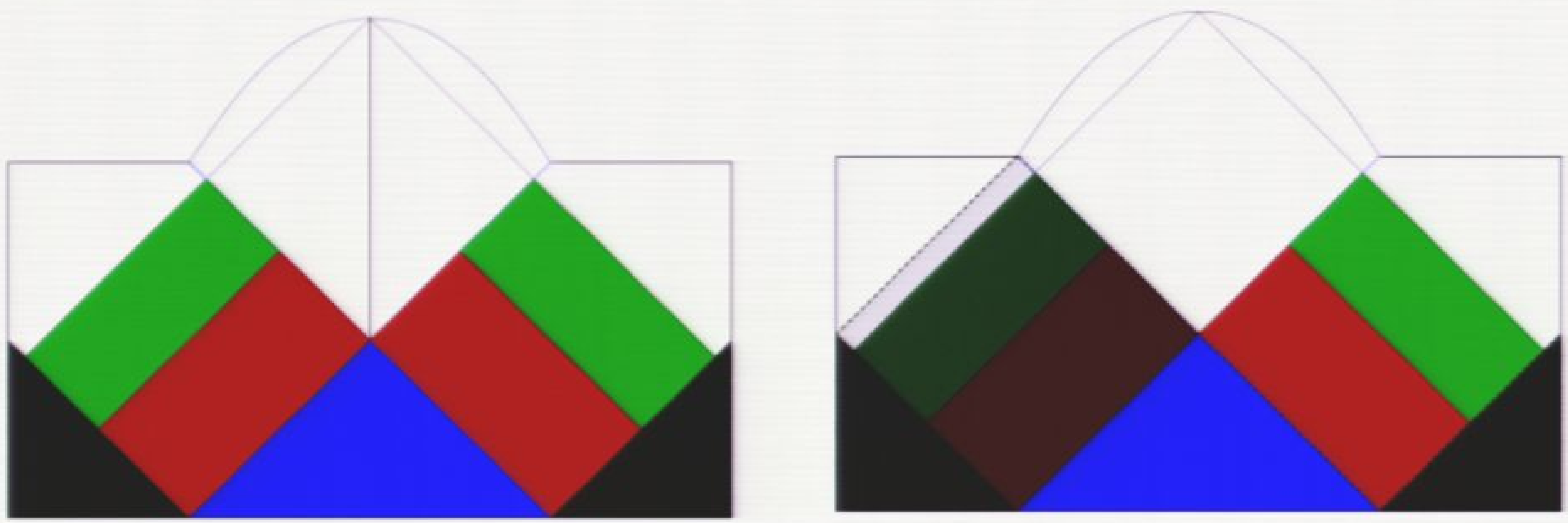


viewed from above...

Small bubbles - bubbles that collided with ours at late times - are hardly affected at all. The late-time distribution is nearly isotropic.

Our CC is very small - probably much smaller than our parent's. If so, the conformal diagram is very different.

Late bubbles, which are not significantly affected by the initial condition surface, may now be visible.



zero boost | infinite boost

17/7/2009

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