Title: Eternal Inflation, Bubble Collisions, and the Disintegration of the Persistence of Memory

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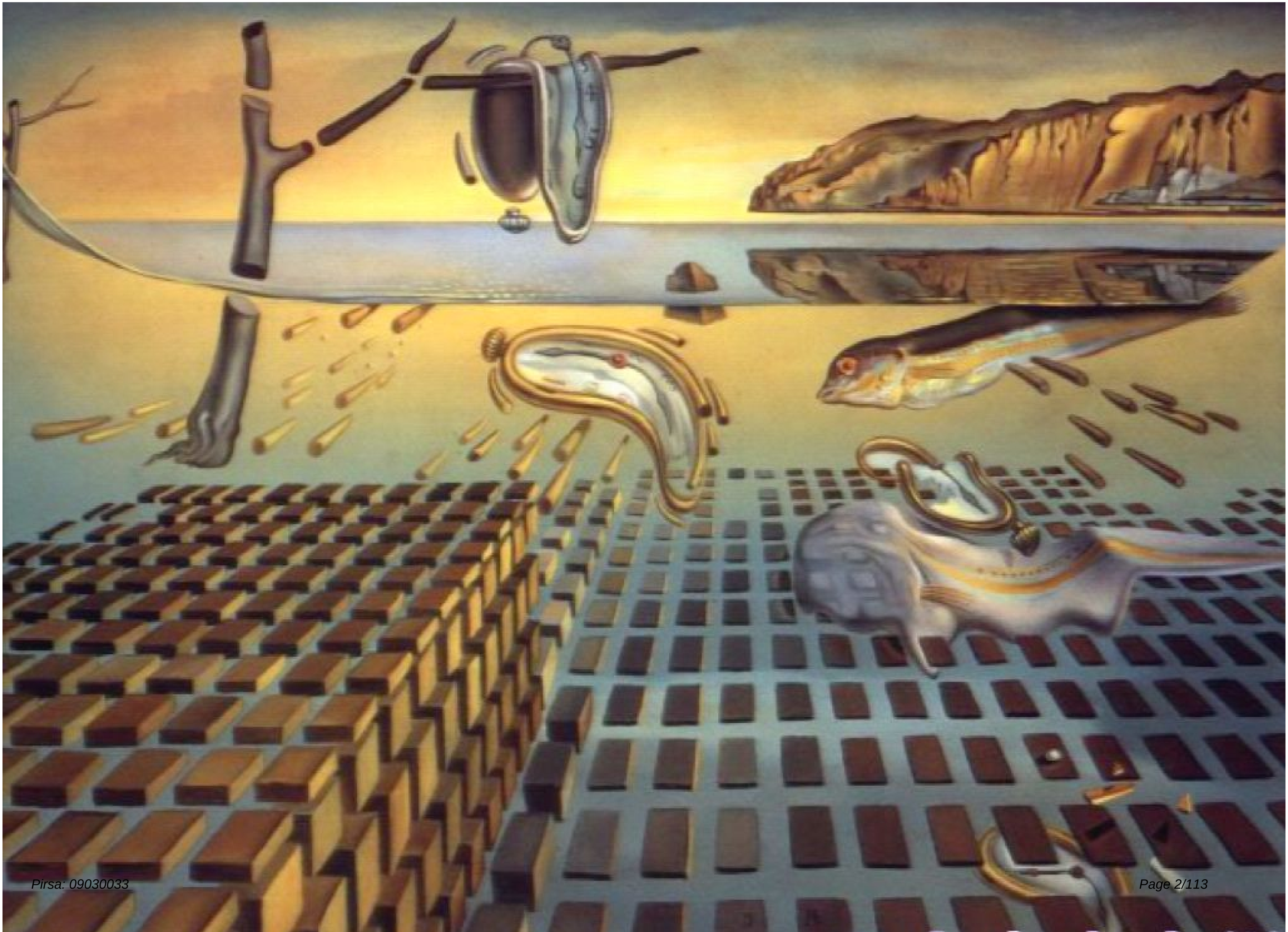
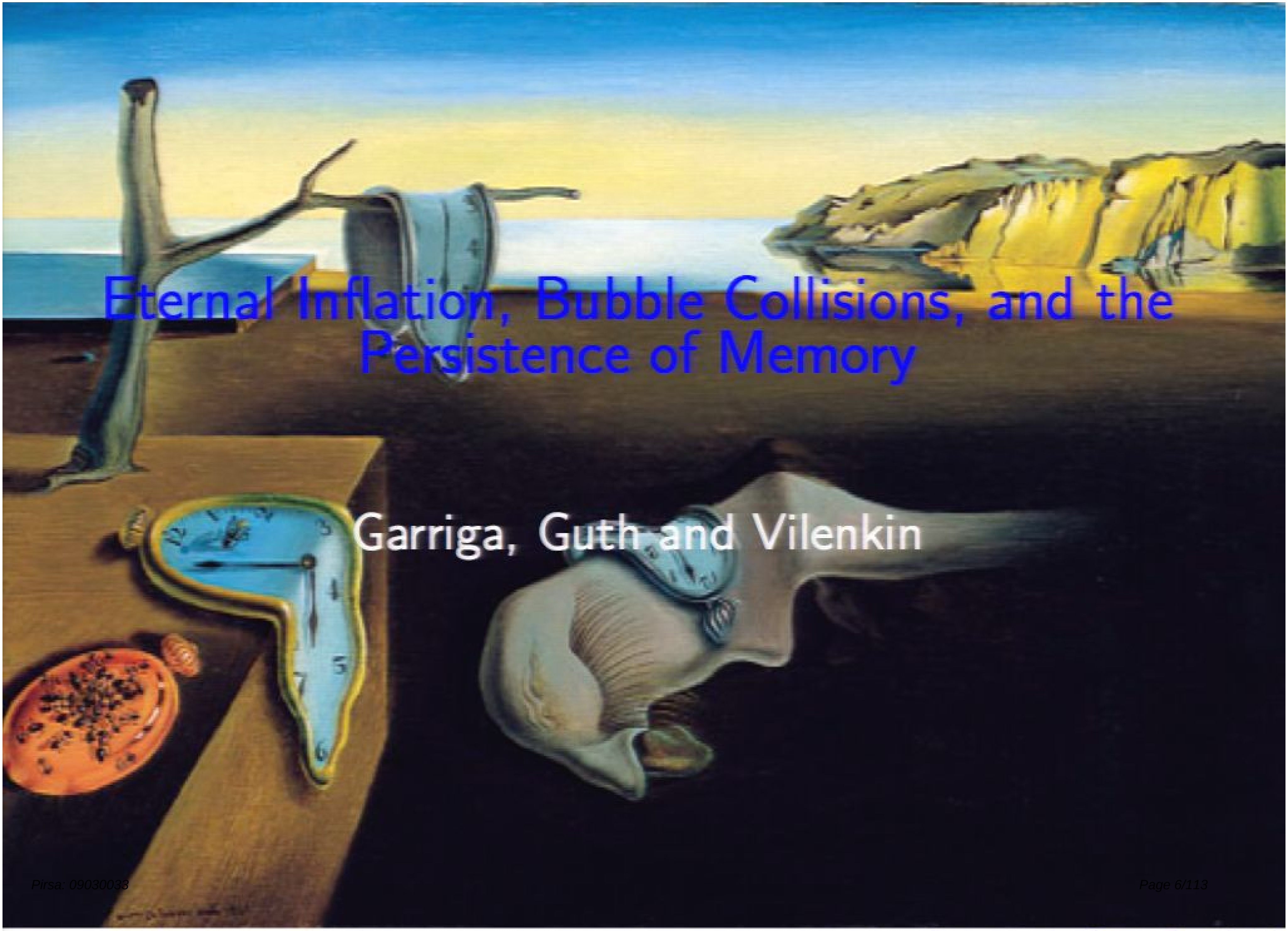
Abstract: I will compute the probability distribution for bubble collisions in an inflating false vacuum which decays by bubble nucleation. The number of collisions in our backward lightcone can be large in realistic models without tuning. In addition, we calculate the angular position and size distribution of the collisions on the cosmic microwave background sky.



Eternal Inflation, Bubble Collisions, and the Disintegration of the Persistence of Memory

Ben Freivogel, UC Berkeley
in collaboration with Matt Kleban, Alberto Nicolis, and Kris Sigurdson

Why the long title?



Eternal Inflation, Bubble Collisions, and the Persistence of Memory

Garriga, Guth and Vilenkin

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"My father today is Dr. Heisenberg."
-Salvador Dalí, *Anti-Matter Manifesto*

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My goal is to communicate to non-experts the motivations and context for our work and the main results. I will skip most of the computational details.

Please interrupt if something is confusing.

I would be happy to discuss the computational details after the talk.

Introduction

Slow roll inflation solves the flatness and horizon problems.

But what was happening before slow roll inflation started?

Are there observable consequences of that something?

(If you would like to substitute something else for "slow roll inflation" throughout the rest of the talk, feel free.)

Slow Roll Inflation

Exponential expansion of the universe while potential energy dominates,

$$ds^2 \approx -dt^2 + e^{2Ht} d\vec{x}^2 \ , \qquad H^2 \sim G_N V(\phi) \qquad (1)$$

Radius of curvature of reheating surface $\sim \exp N_e$, with $N_e \sim Ht$.
N_e is a polynomial function of the parameters in the potential.
For example, if $V = m^2\phi^2$ over a range $\Delta\phi$, then $N_e \sim G_N(\Delta\phi)^2$.

Really, slow roll inflation takes the log of the flatness and horizon problems.

The initial conditions problem

To assess the observability of how slow roll inflation began, we need a theory of initial conditions.
Not many candidates:

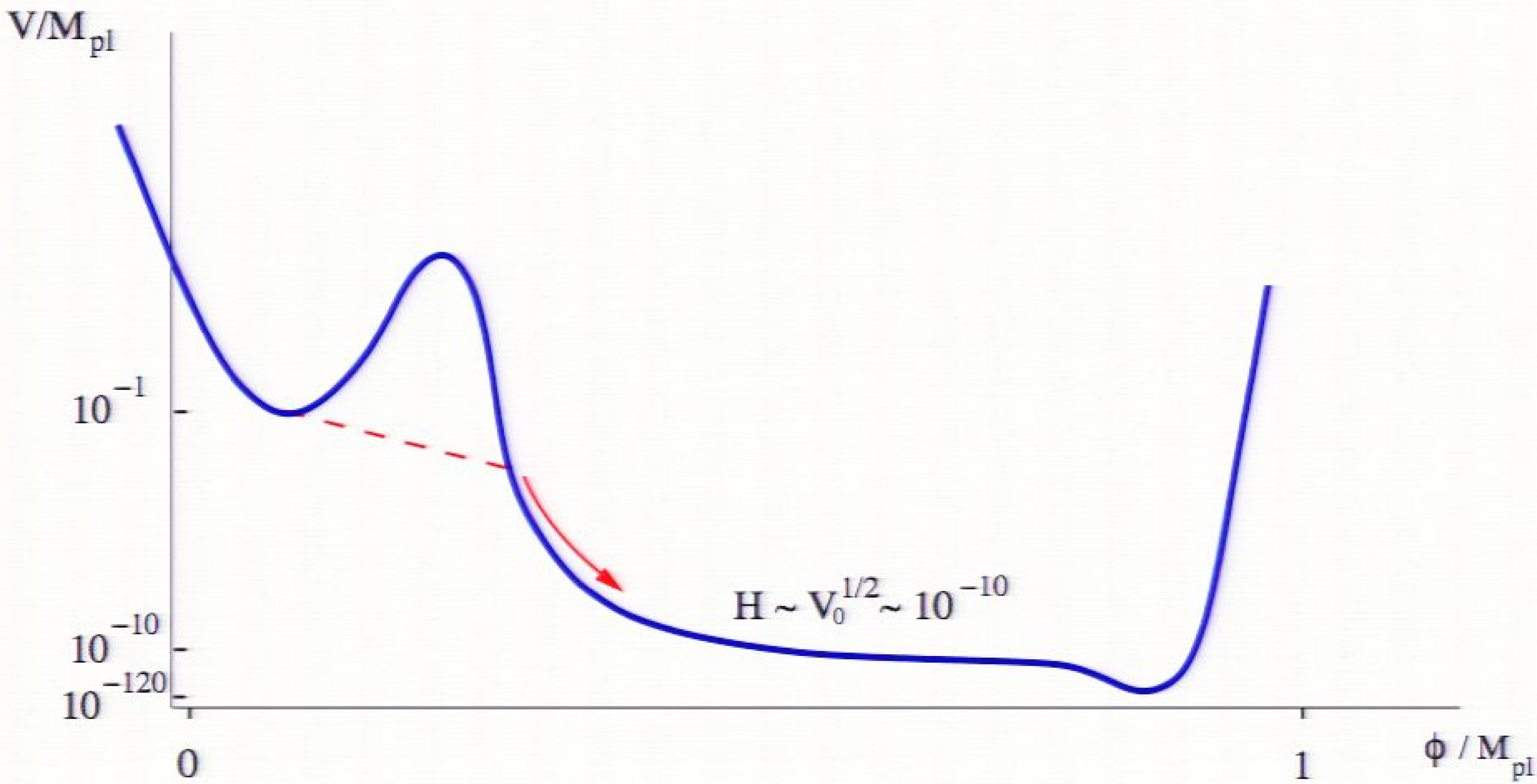
- No-boundary proposal (Hartle, Hawking, ...)
- Eternal Inflation

The no-boundary proposal

- Sign ambiguity in the exponent
- Not obviously well defined- Euclidean Quantum Gravity
- Perhaps in conflict with observation

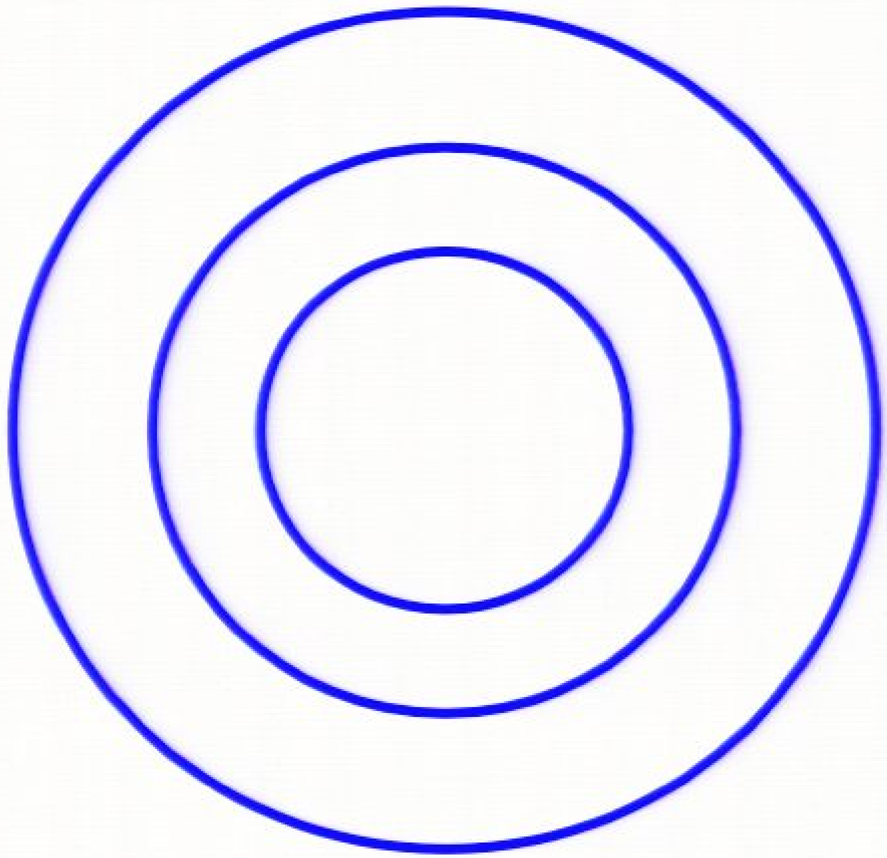
But what is the alternative?

Eternal Inflation



The false vacuum decays by bubble nucleation. (CDL)
The decay is nonperturbative.

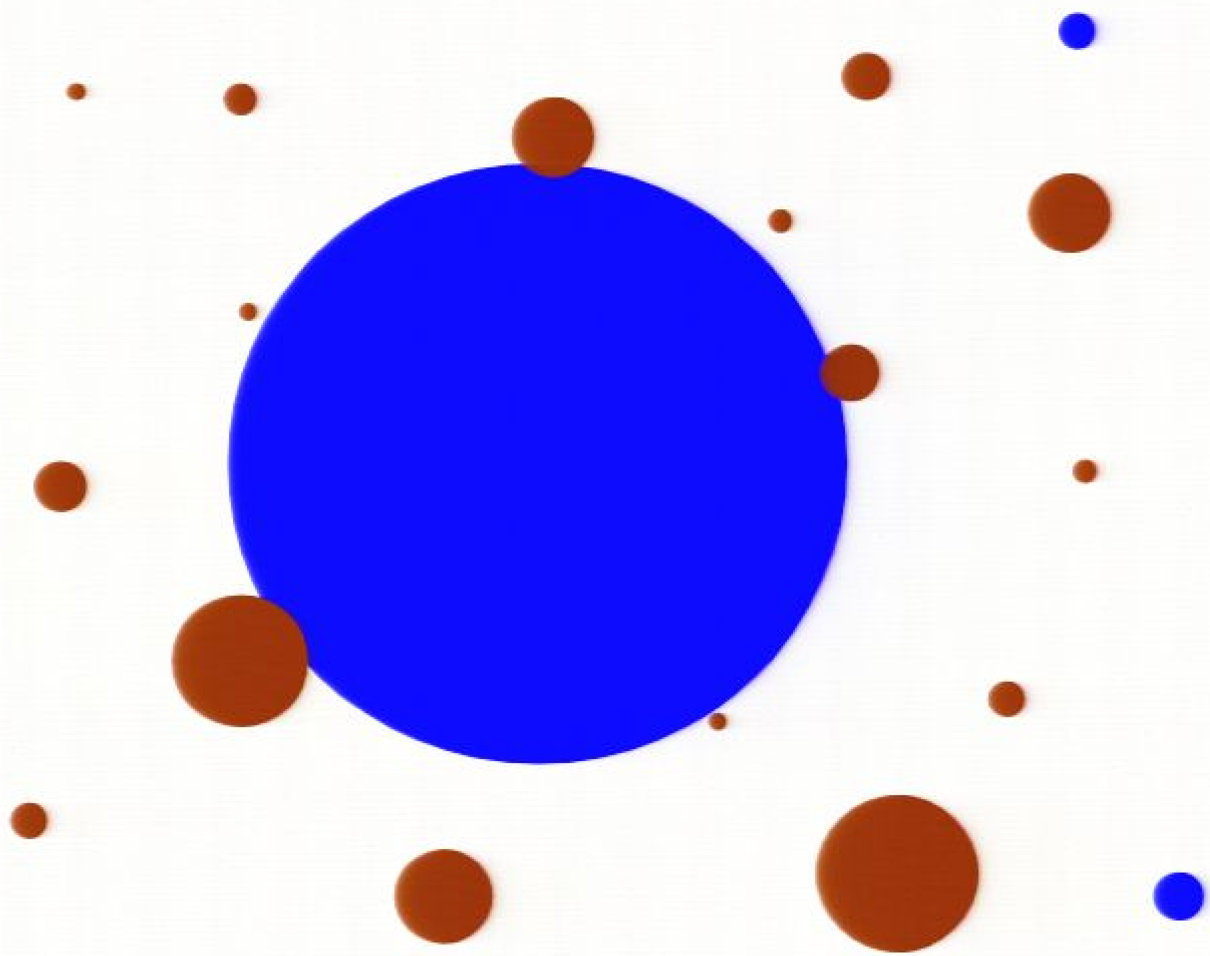
Eternal Inflation



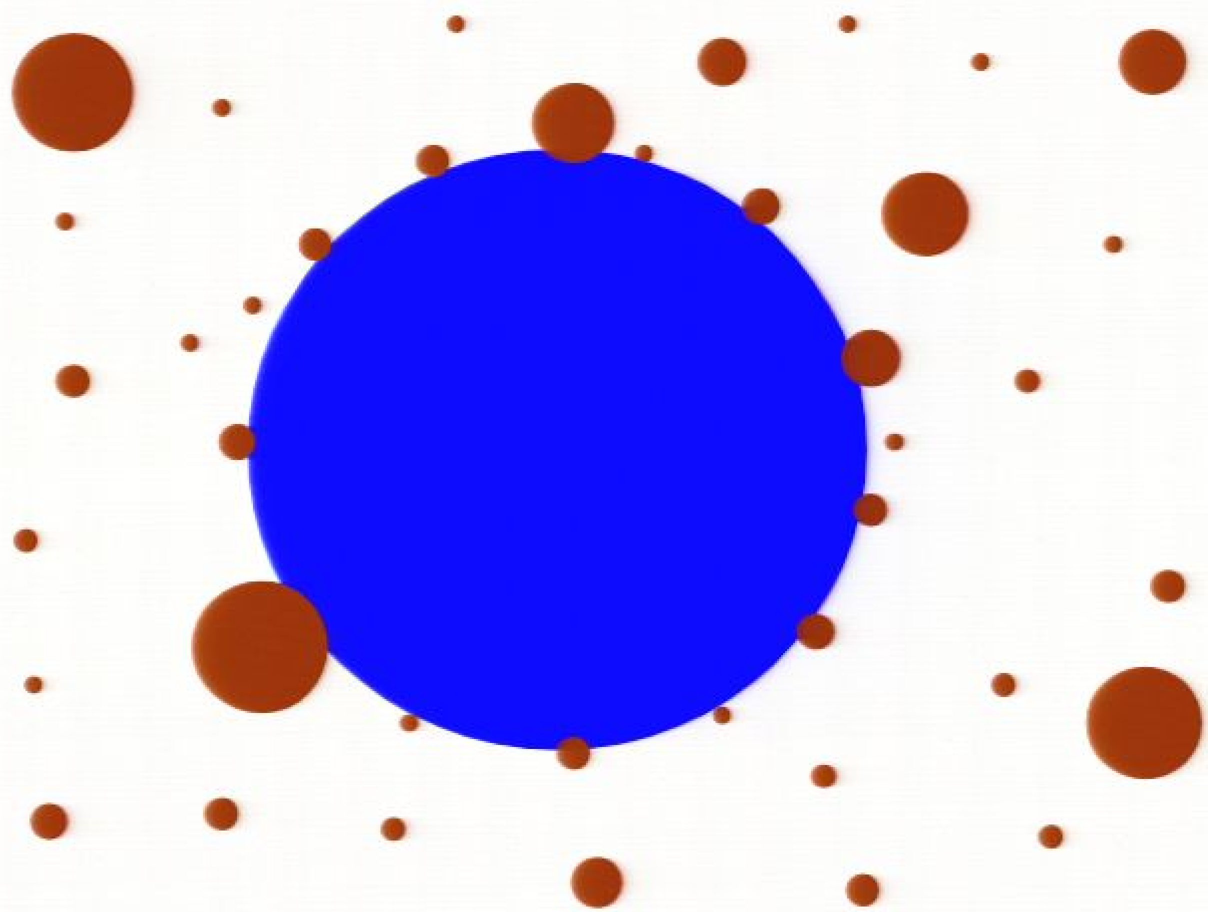
The bubbles expand into the false vacuum.

Eternal Inflation

But the false vacuum gains volume by exponential expansion faster than it loses volume to decays.



Eternal Inflation



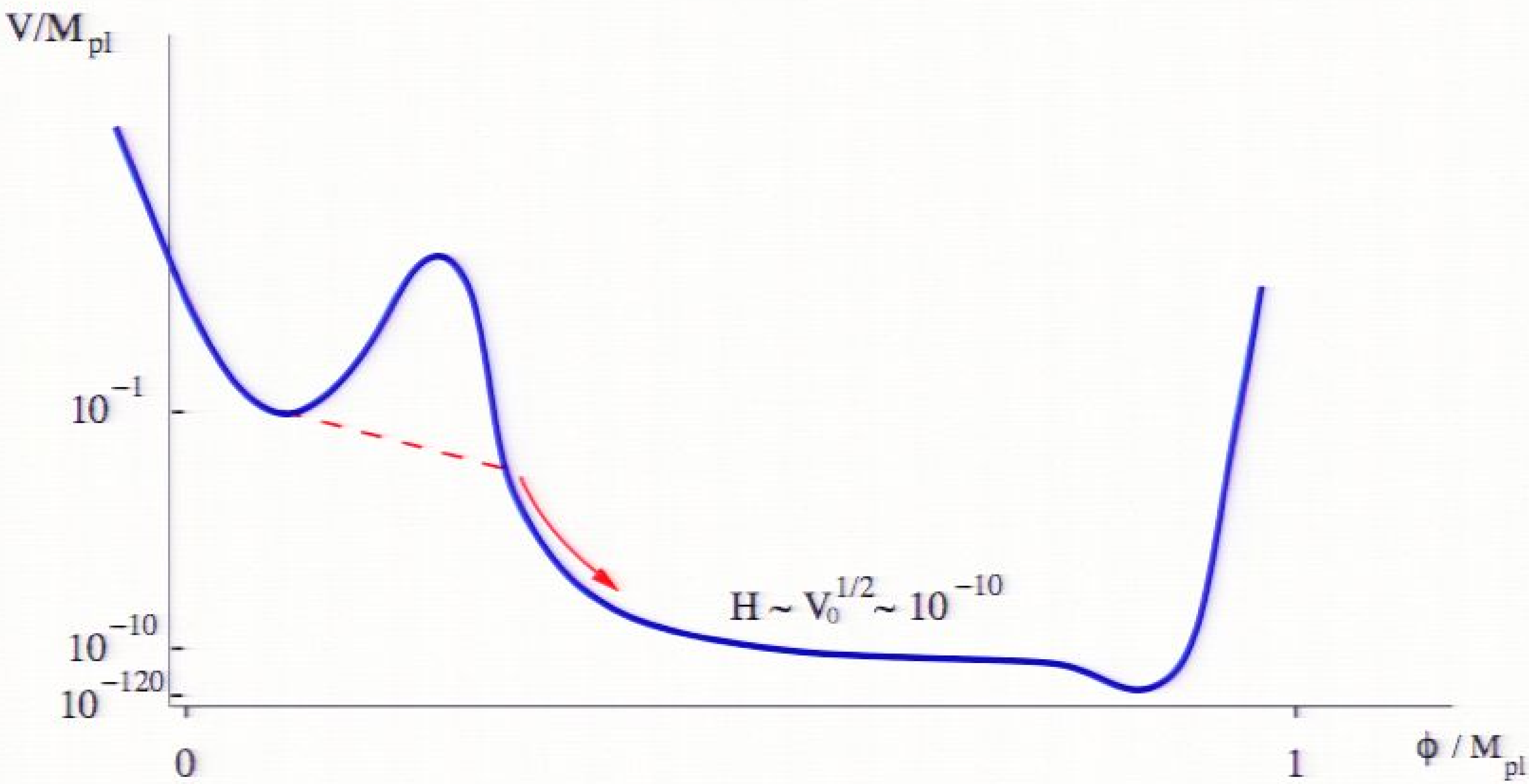
Eternal Inflation

- Starting from generic initial conditions, eternal inflation leads to attractor behavior.
- The late-time state does not remember the initial conditions.
- Rather than seeking a prescription for initial conditions, perhaps we just need to describe the attractor behavior.

(Not necessarily in conflict with the no-boundary proposal.)

However, there are ambiguities in characterizing the attractor behavior.
(Work to appear with Kleban on a dual conformal field theory description.)

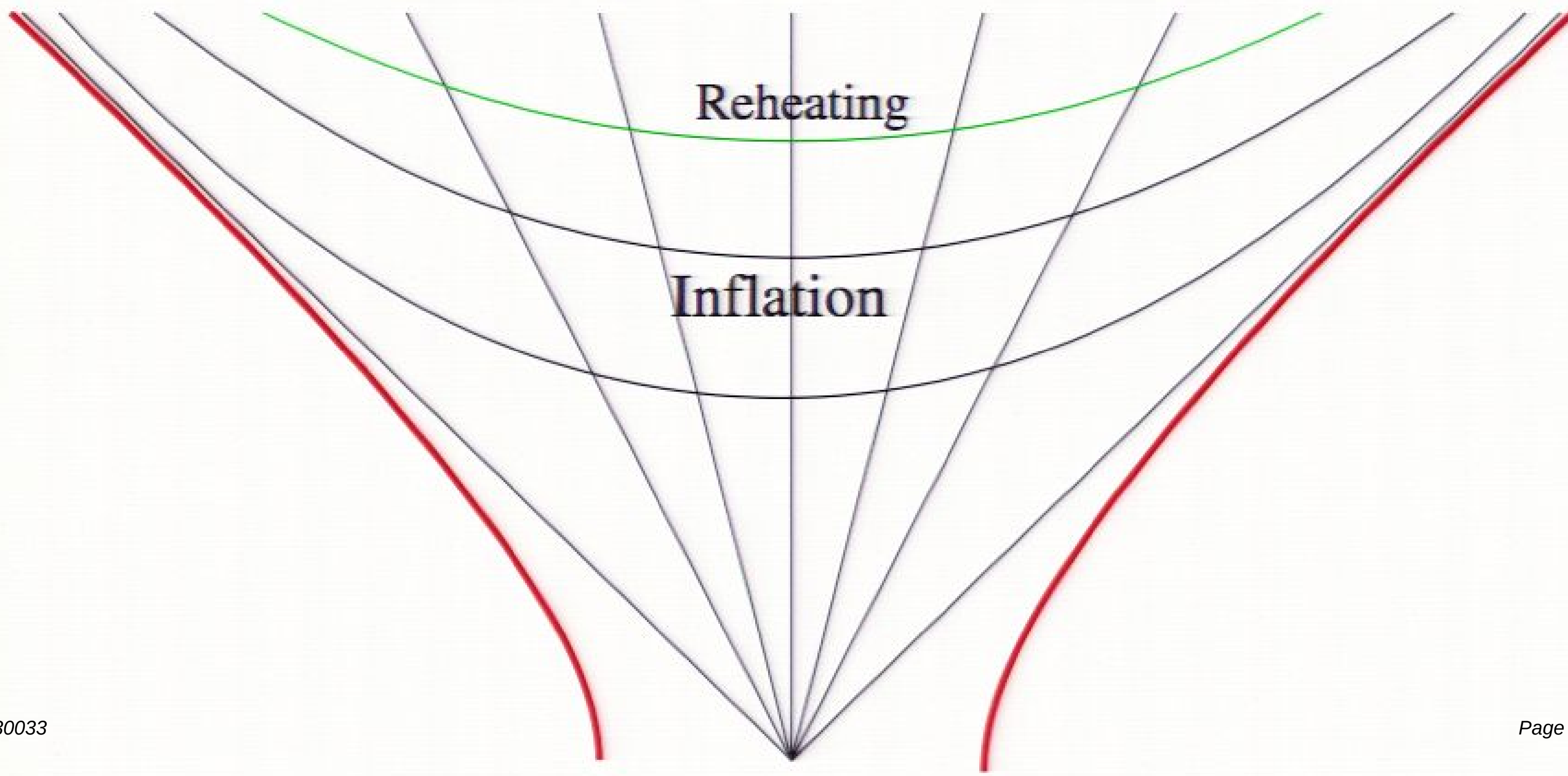
In this talk, I will assume that eternal inflation is the answer to the question: "What was happening *before* slow roll inflation began?"



Our universe inside a bubble

The domain wall accelerates with constant proper acceleration.
Inside the bubble is an infinite, open FRW universe.
$SO(3,1)$ symmetry is preserved.

$$ds^2 = -dt^2 + a^2(t) dH_3^2 = -dt^2 + a^2(t)\left(d\rho^2 + \sinh^2\rho \, d\Omega_2^2\right)$$



Observational consequences of living inside a bubble.

- Negative spatial curvature
- The fields are in a particular quantum state (Turok...) $\rightarrow$ Features in power spectrum at low ℓ
- Etc. (work in progress with Niemeyer on isocurvature)

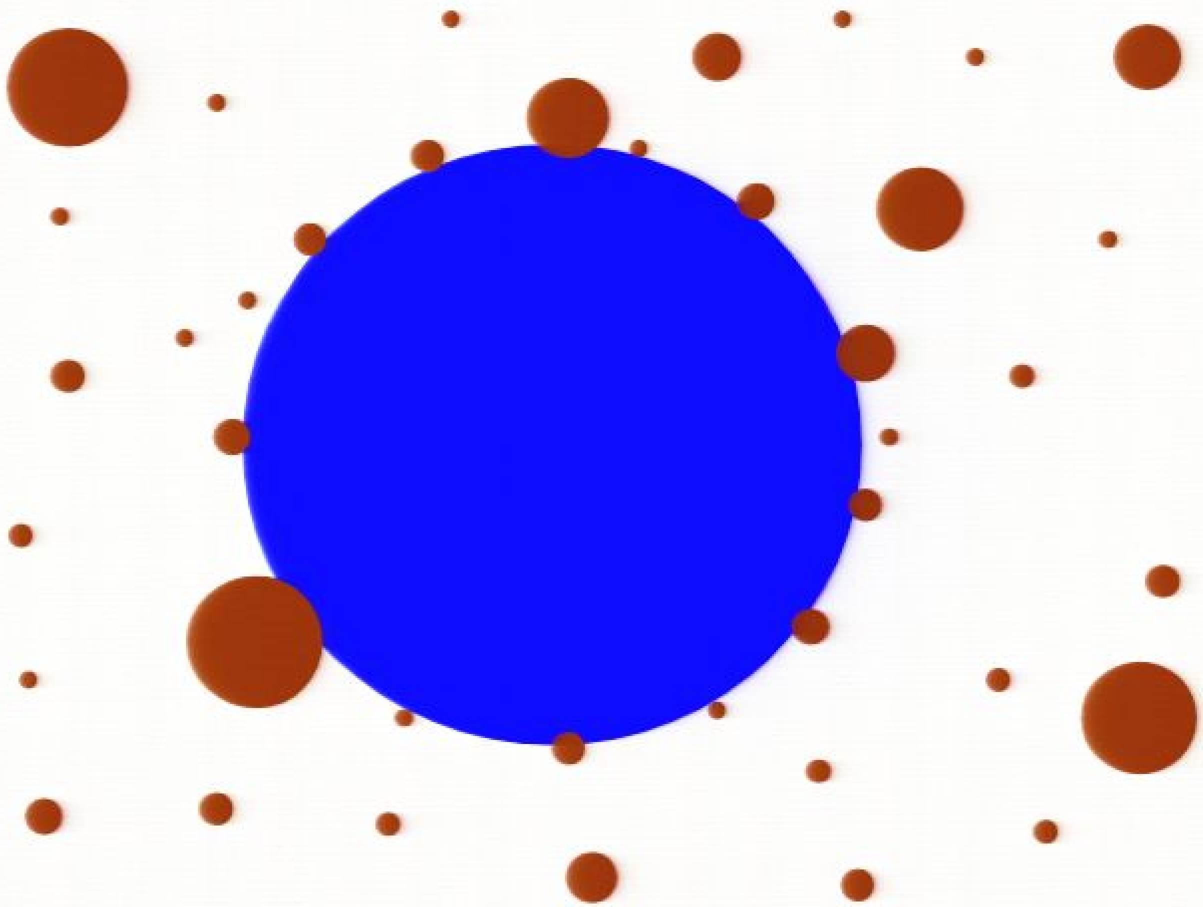
Too many efoldings of slow roll inflation will redshift all signals so that wavelengths are far bigger than the visible universe

But no reason to expect an excessive number of efoldings- requires tuning.
(BF, Kleban, Martinez, Susskind, 2005)

In this talk, focus on a distinctive possible signal: Bubble collisions

- Naively: Bubble nucleation is a nonperturbative process. Bubbles do not percolate, so collisions are rare.
- But Guth and Weinberg showed that every bubble collides with an INFINITE number of other bubbles
- Question: How many bubble collisions are in our backward lightcone?
- If we expect at least one, then we can go on to assess its observability.

Bubble Collisions



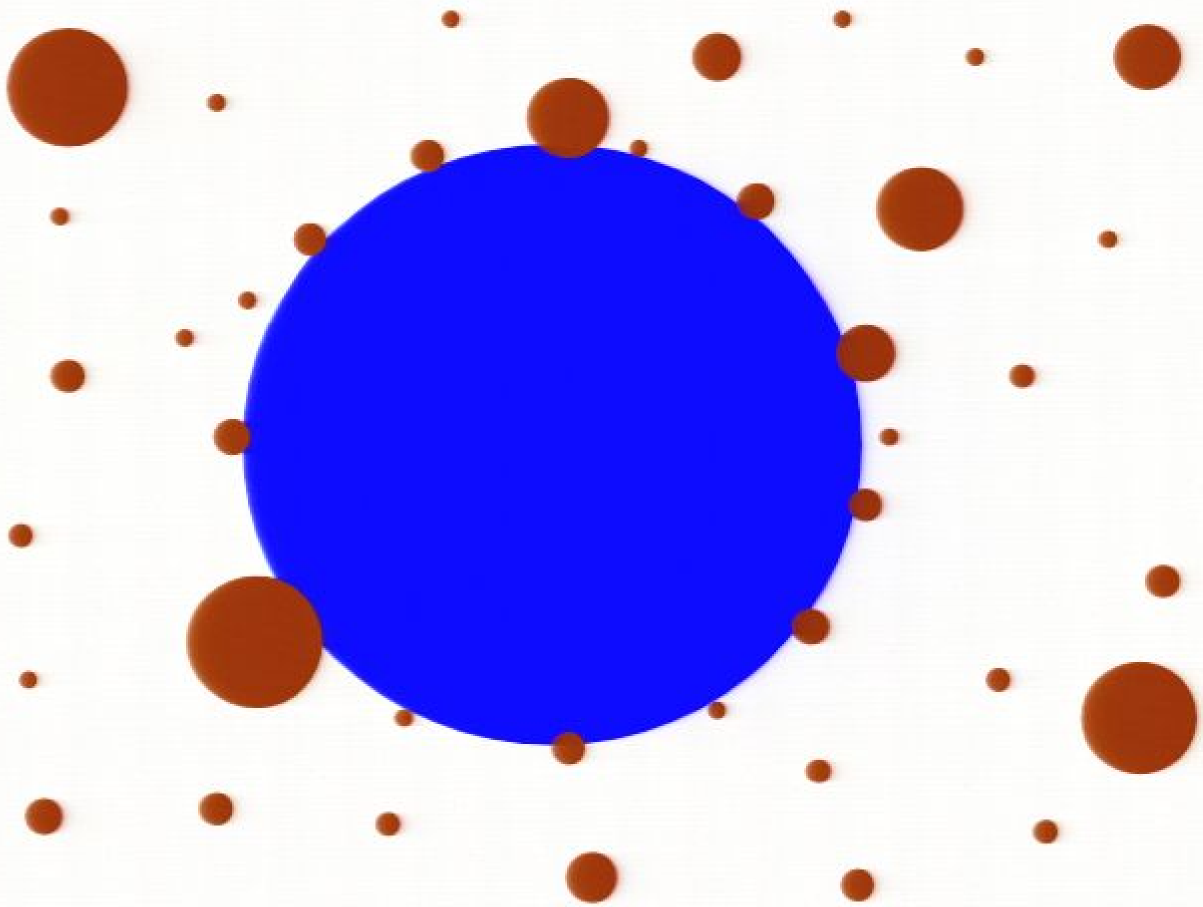
Outline

- Brief description of bubble collisions
- Review analysis of Garriga, Guth, and Vilenkin
- Our more general analysis →

$$N \sim \gamma \frac{V_f}{V_i} \quad (2)$$

V_f is the vacuum energy in the false vacuum outside our bubble.
V_i is the vacuum energy during slow roll inflation.
γ is the decay rate per Hubble 4-volume of the false vacuum.

Bubble Collisions



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Outline

- Observability? Easiest collisions to observe influence only part of the last scattering surface.

$$N_{LS} \sim N\sqrt{\Omega_k} \sim Ne^{-\Delta n} \tag{3}$$

  Δn is the number of efoldings beyond the current observational bound.
- Future Directions

Related Work

- Aguirre, Johnson, and Shomer (2007)
- Aguirre and Johnson (2007)
- Aguirre, Johnson, and Tysanner (2008)
- Dahlen, 2008
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Bubble collisions

Two bubbles collide along a spacelike surface, a two-dimensional hyperboloid H_2.

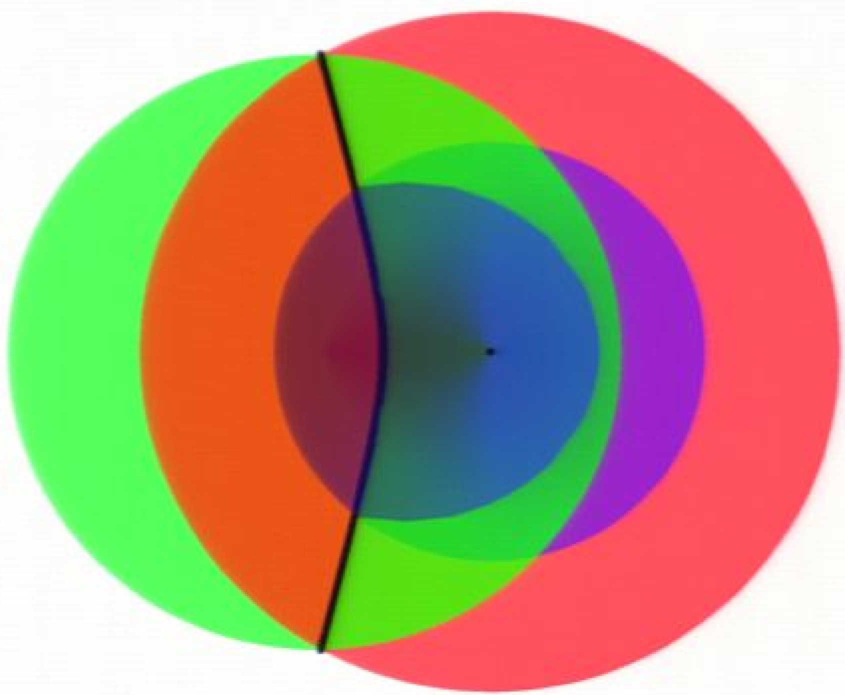
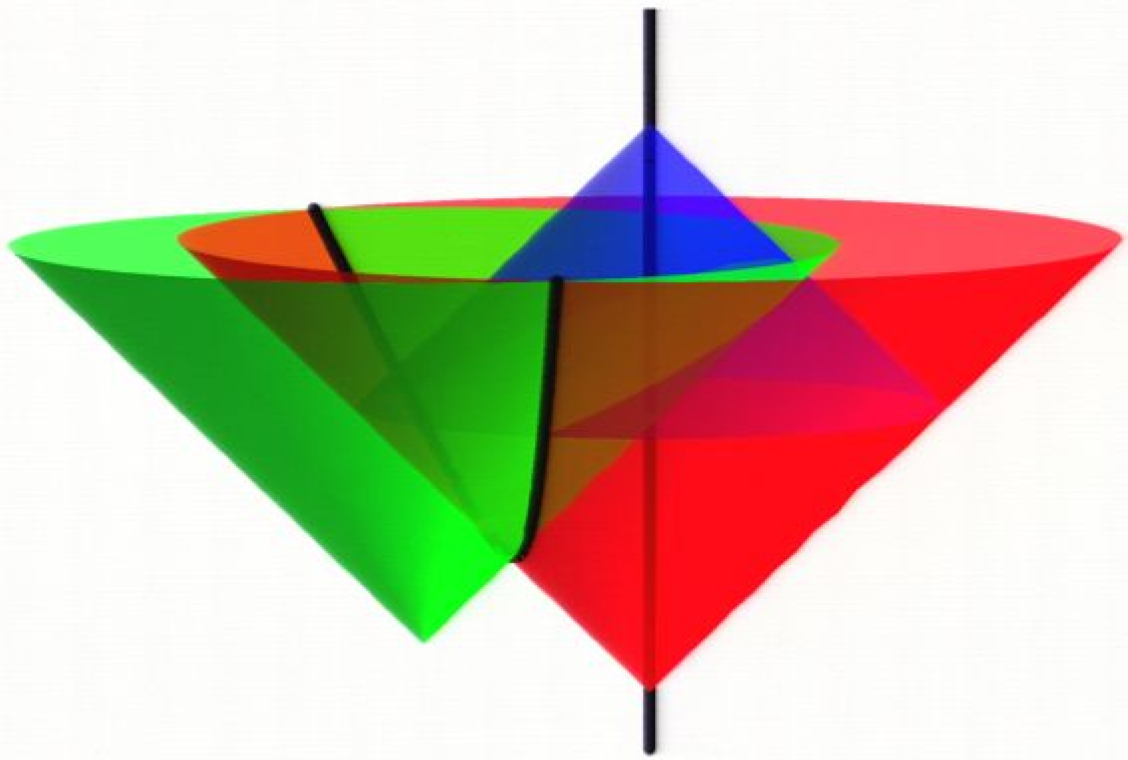


Figure: Top view of a collision

The collision affects part of our backward lightcone–
Disks on the sky.



Observational signatures: (Chang, Kleban, and Levi)
Much remains to be done.

I will focus mainly on describing the distribution of collisions and computing the total number.

Analysis of Garriga, Guth, and Vilenkin (GGV)

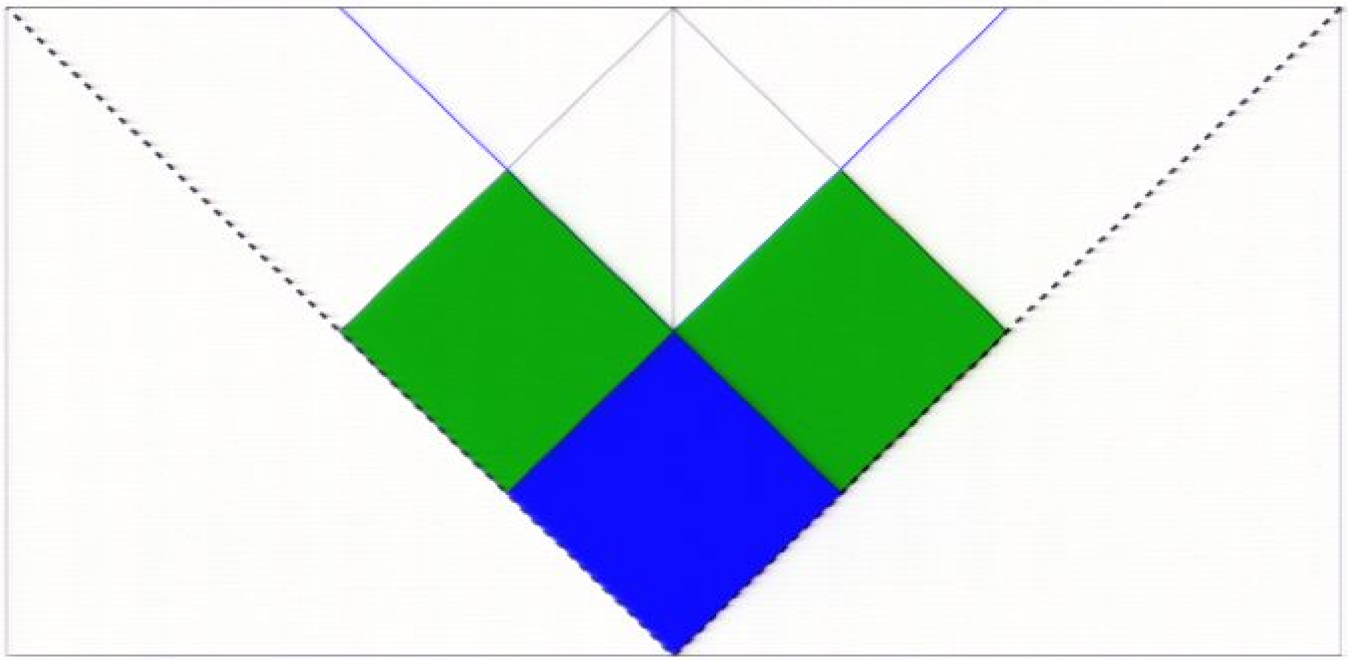
In analyzing the decay of a false vacuum, need to specify initial conditions.
At the semiclassical level, the simplest choice is to choose a spacelike surface on which the field is completely in the false vacuum.
GGV choose the surface $t = -\infty$ in the flat slicing of de Sitter space, in which the metric is

$$ds^2 = -dt^2 + H^{-2} e^{2Ht} d\vec{x}^2 \quad (4)$$

The details of this choice will not be important, but it has two reasonable properties:

- Our bubble nucleates an infinite time after the initial conditions surface.
- Only the "expanding half" of de Sitter space is included.

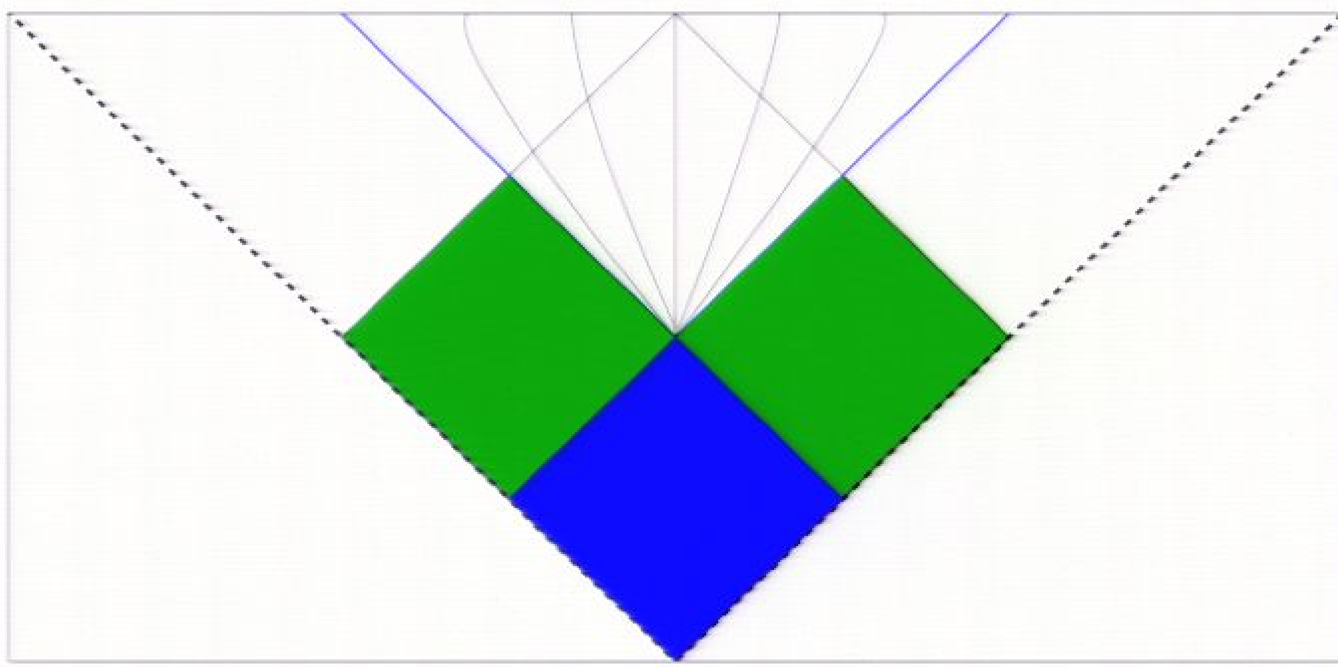
Consider observers who form in a bubble. How many collisions do they have in their backward lightcone?



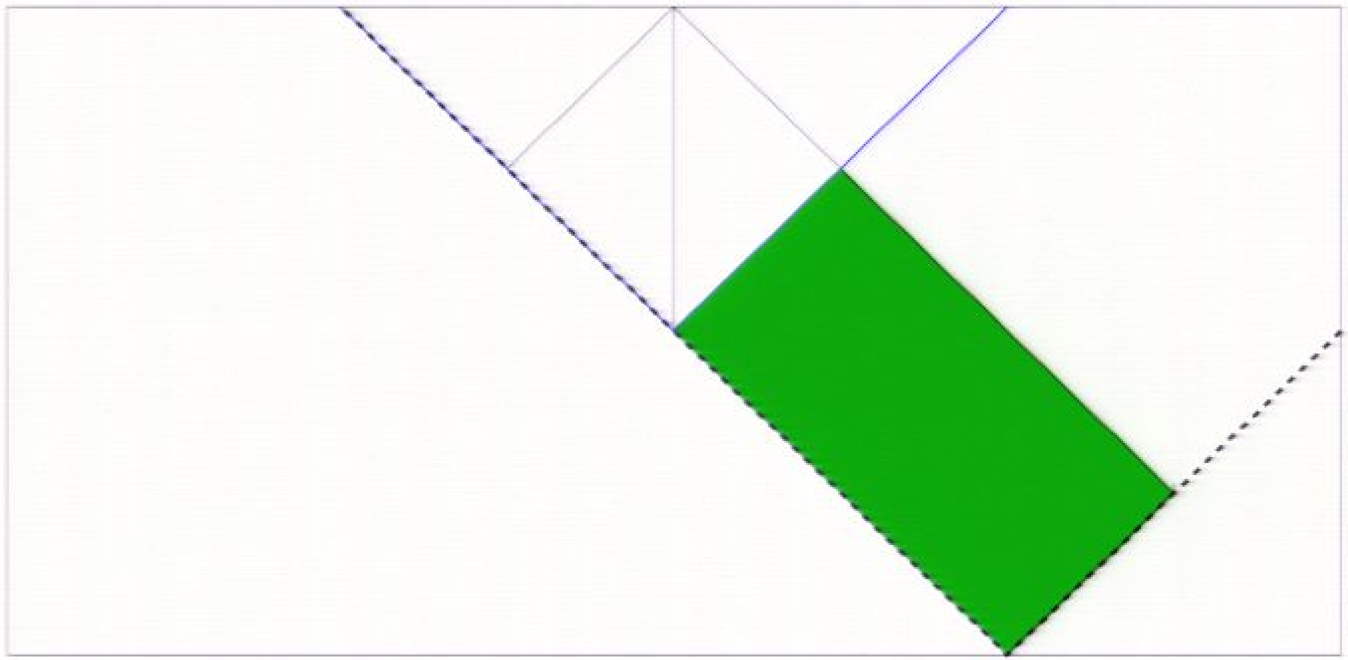
GGV use the approximation that the spacetime inside the bubble is undisturbed.
Four-volume of green region $\sim H_f^{-4}$

$$N \sim \gamma \ll 1 \quad (5)$$

In the approximation that bubble collisions can be ignored, each bubble contains an infinite open universe.
Let's compute the expected number of collisions in the backward lightcone of a different "observer."



Easier to analyze if we boost the observer back to the center:



The 4-volume depends on the boost. Minimized for a preferred "observer" at rest relative to the initial conditions surface.
$N \rightarrow \infty$ for highly boosted "observers."
Therefore, SO(3,1) symmetry is badly broken.
The distribution of collisions is highly anisotropic at large boost, even at late time inside the bubble.

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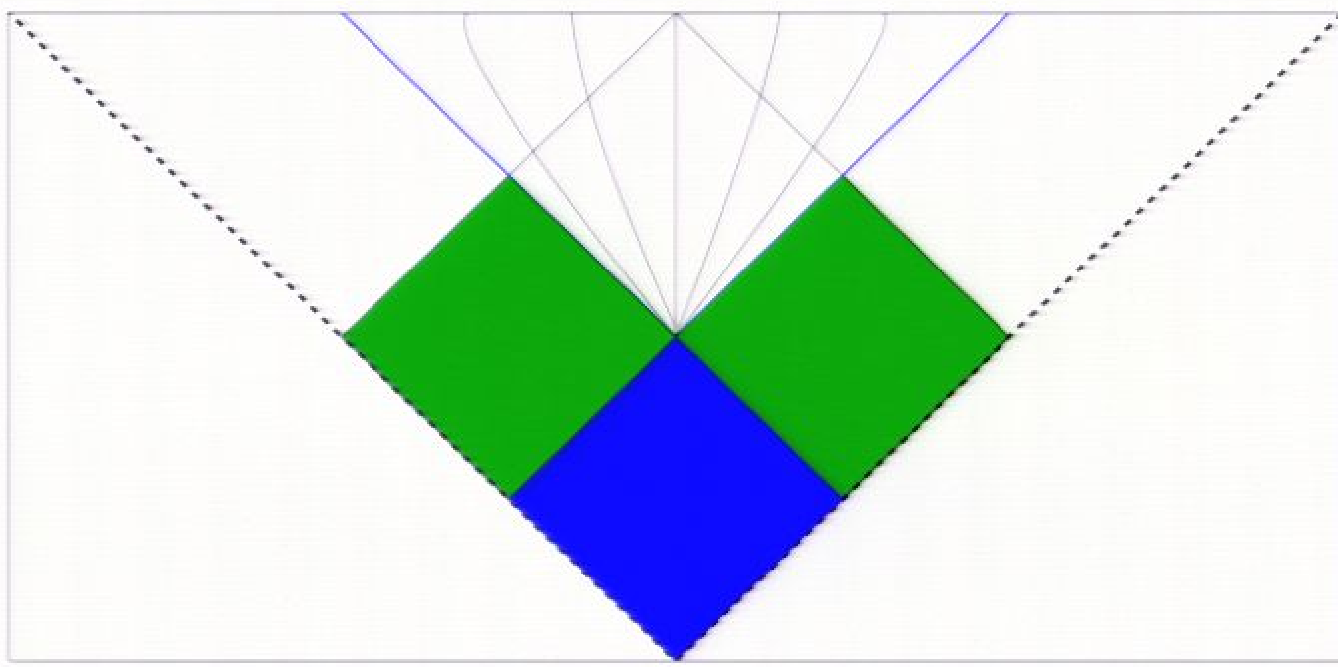

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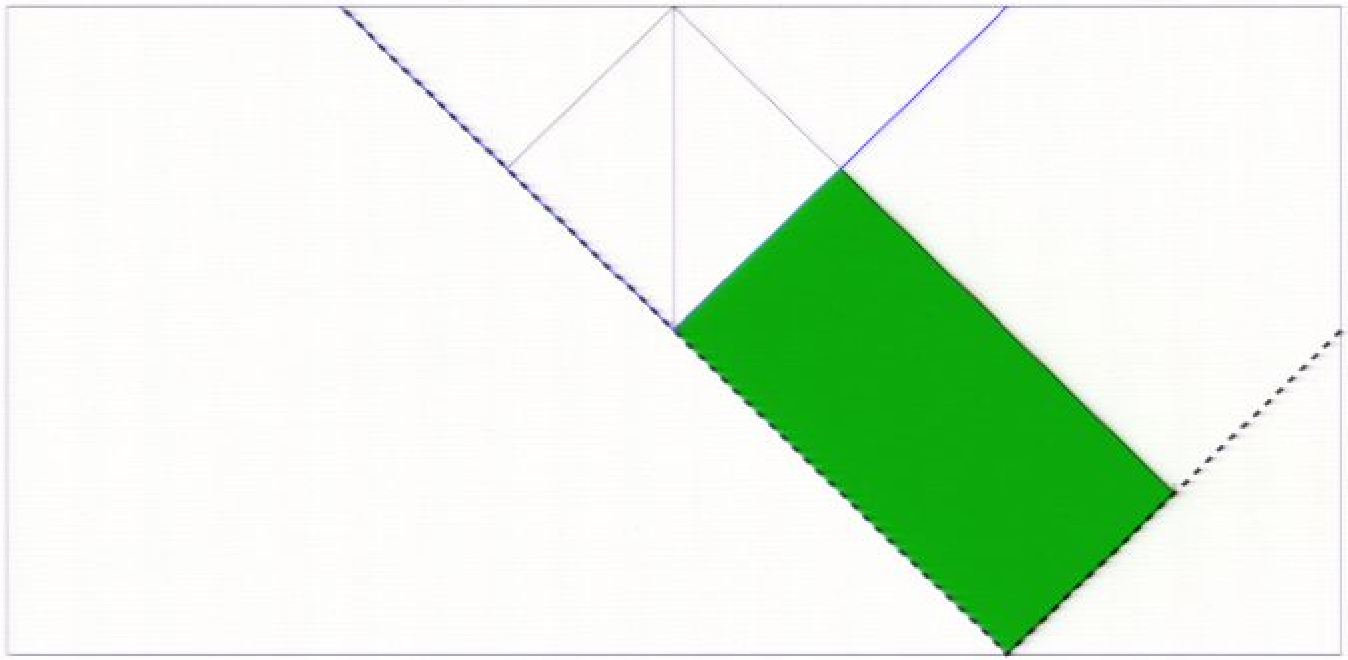

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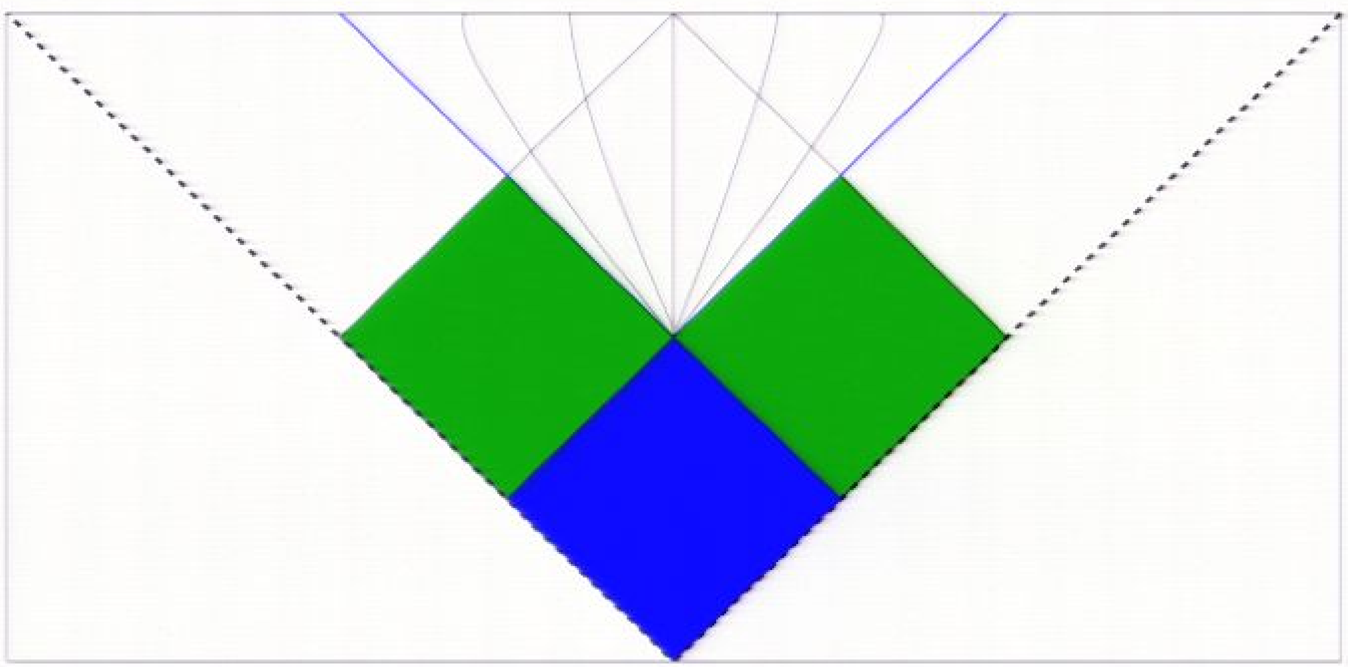

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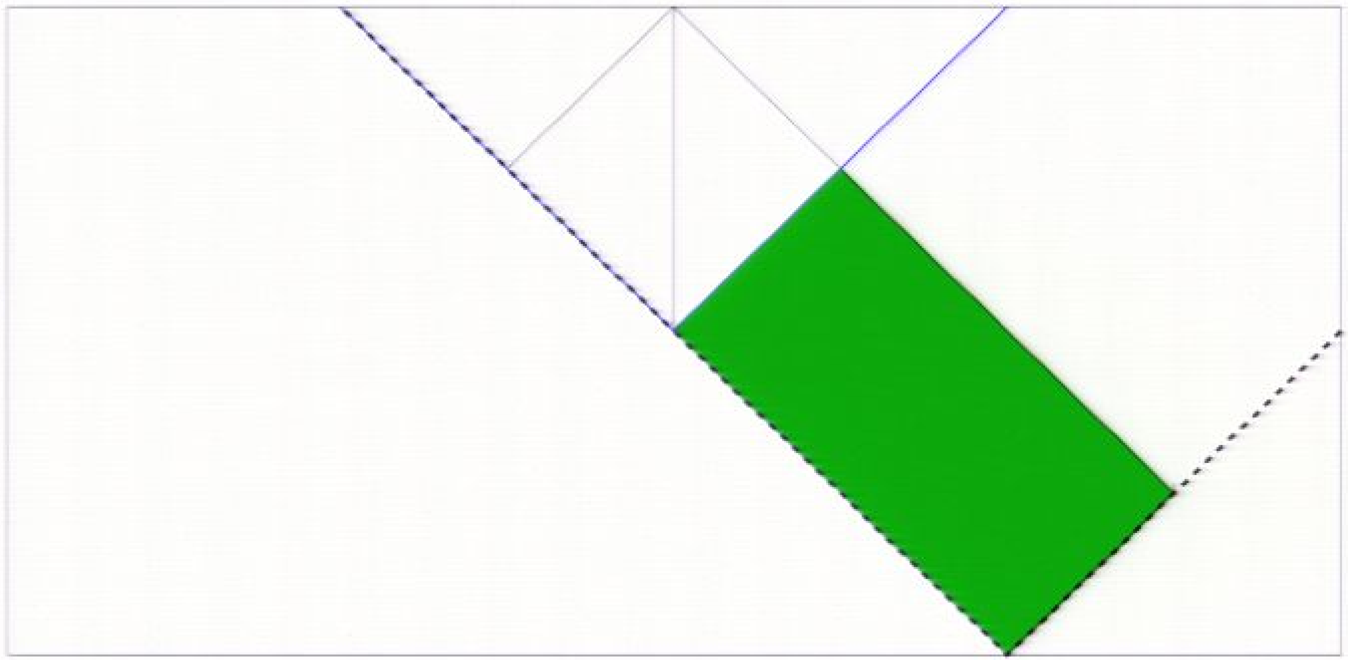

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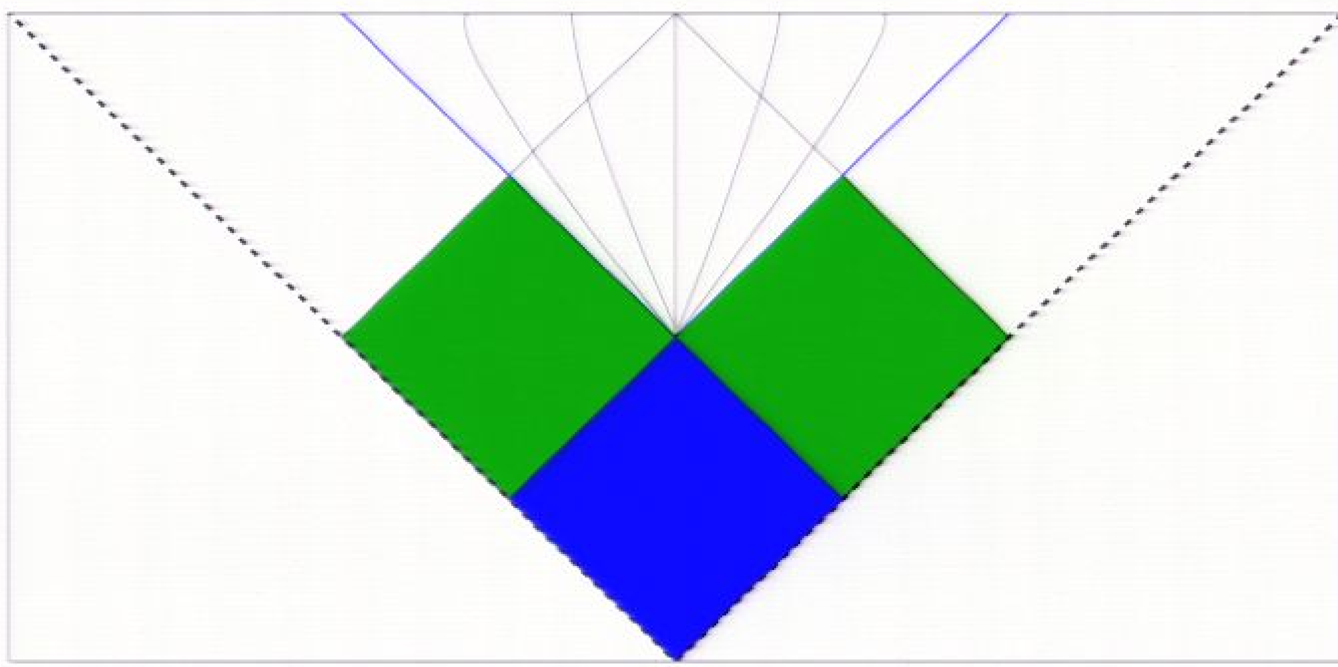

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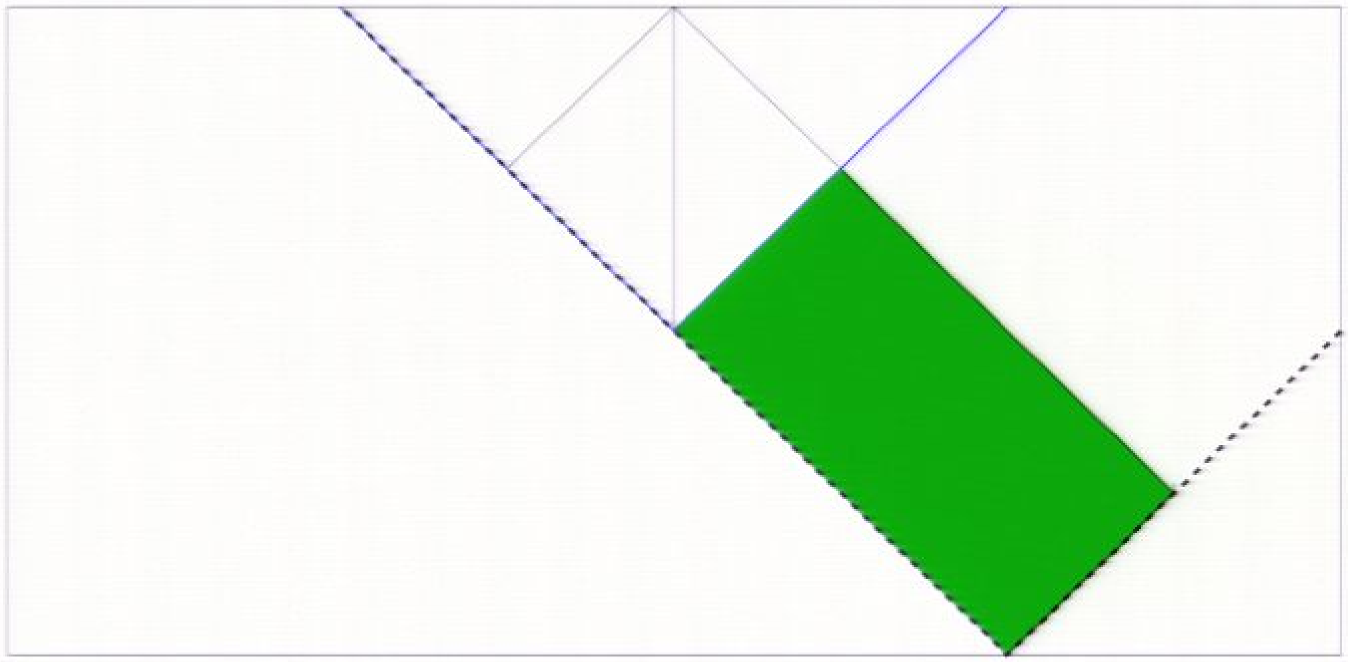

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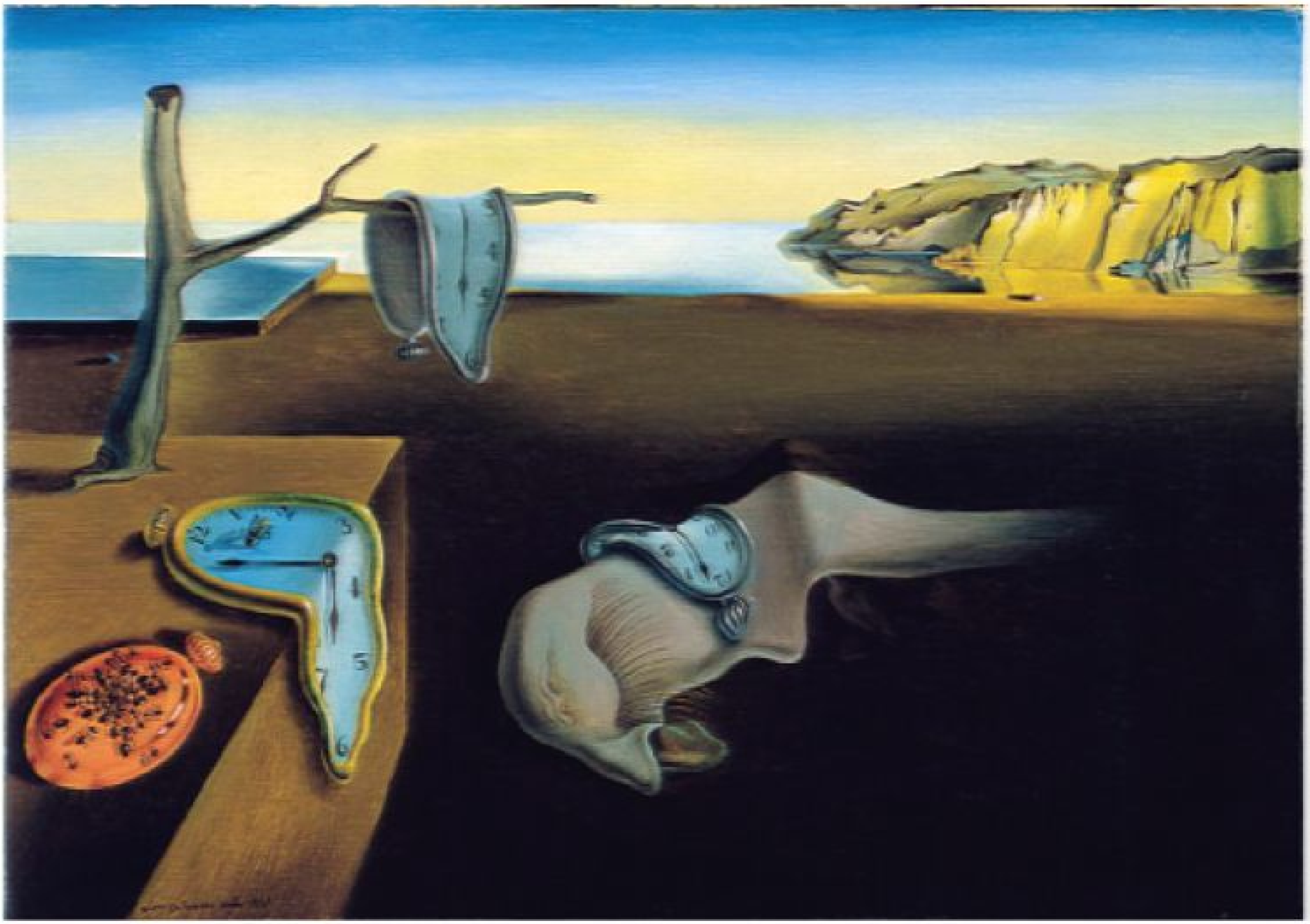
The Persistence of Memory

- Because $SO(3,1)$ is broken, predictions depend on our boost relative to the initial conditions surface.
  Need additional theory to predict where we are living.
- Need a model for what happens in the future lightcone of collisions.
  This will include allowing for a realistic cosmology inside the bubble.
- Focus on the conditional question:
  In regions where structure formation is not disrupted, what is the predicted distribution of bubble collisions?
- Will find a robust answer to this question, allowing us to avoid confronting the measure problem for now.

The Persistence of Memory



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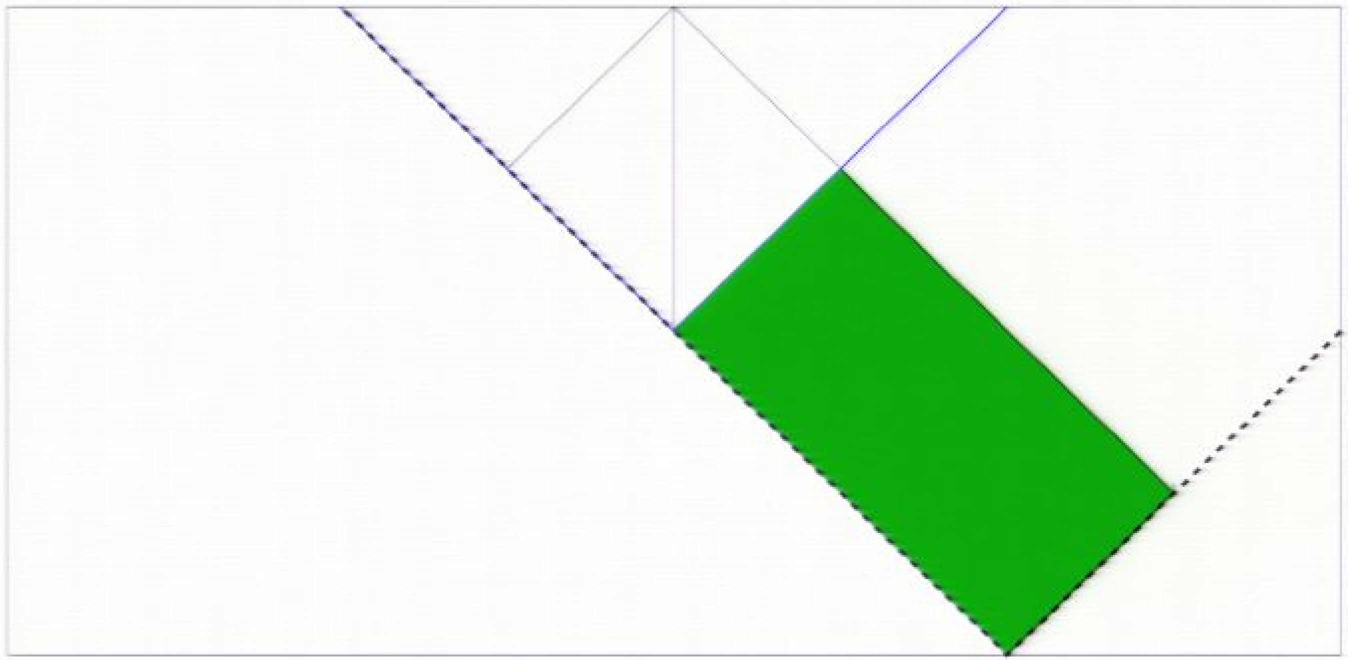

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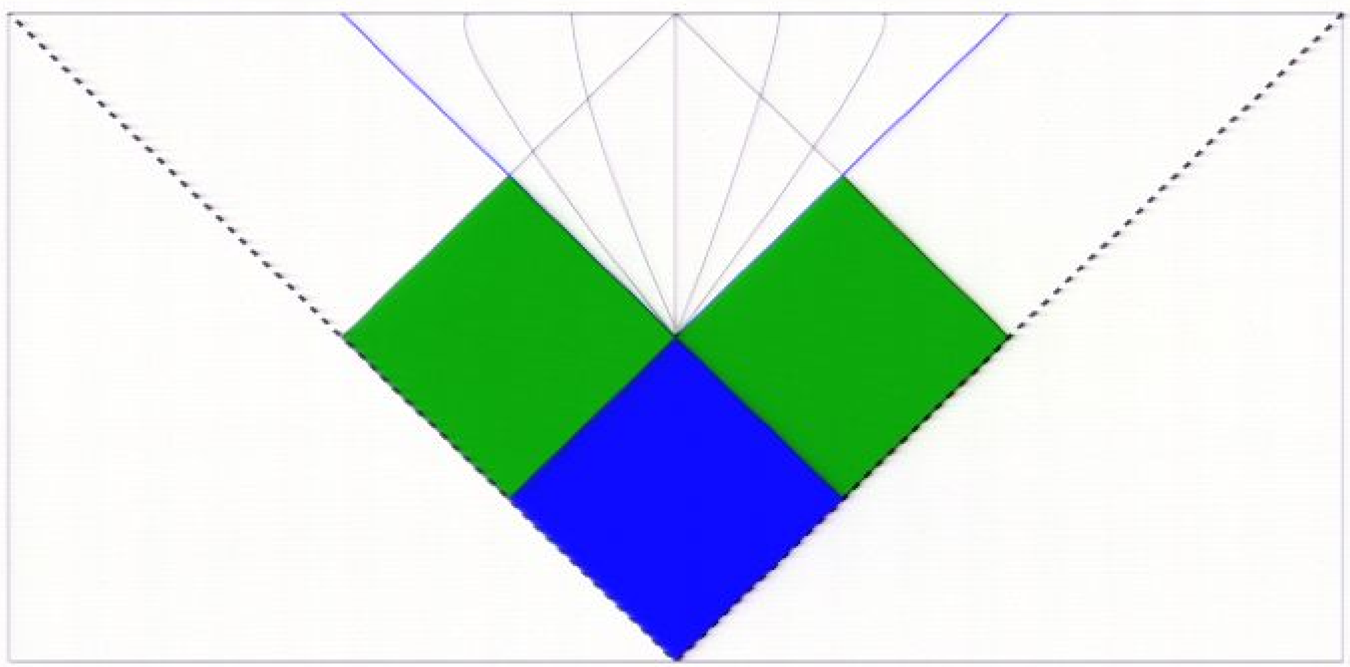

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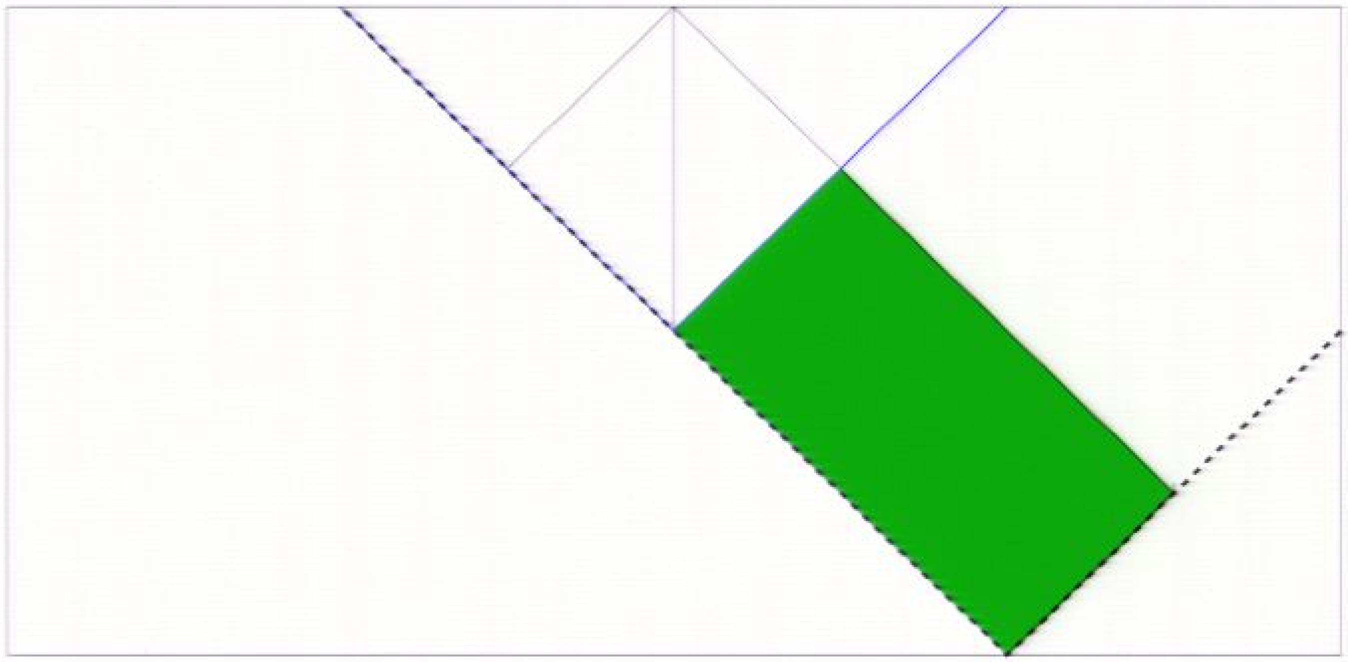

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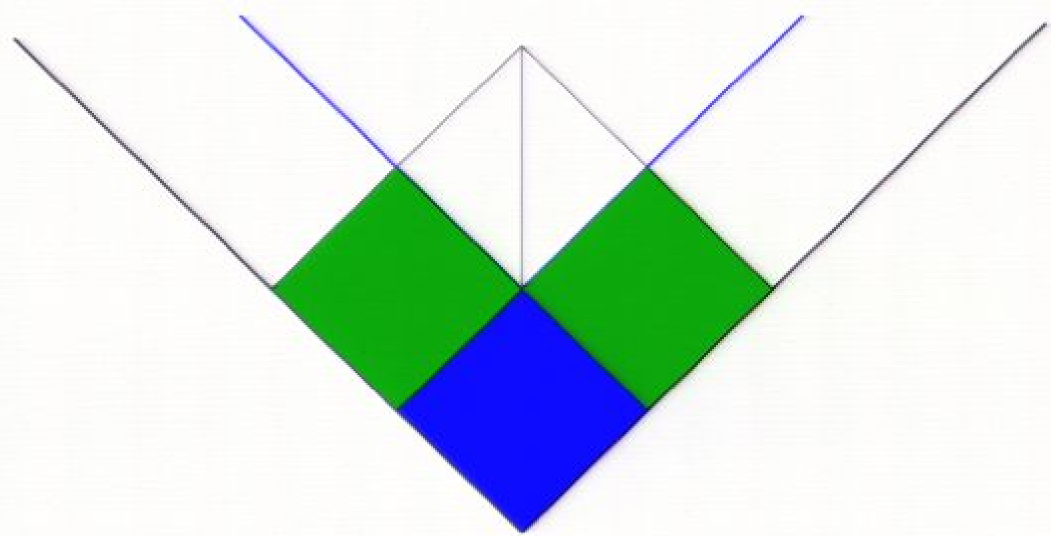
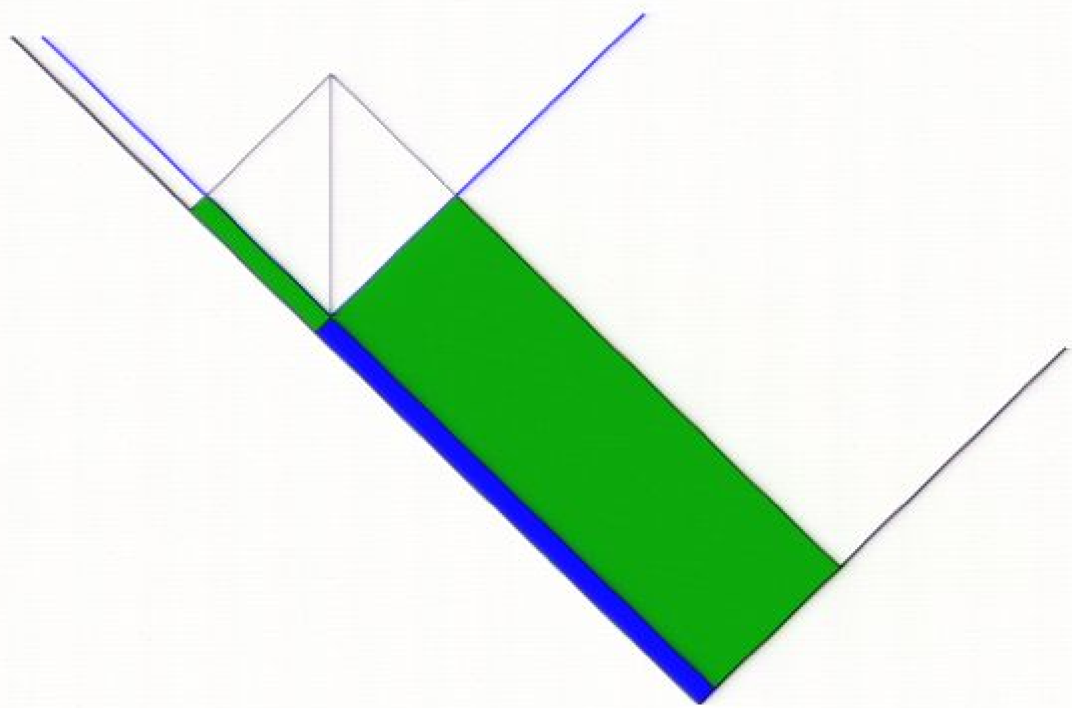
A flat-space model

We can write a model with all of the crucial features in Minkowski space.



A flat-space model

A boosted "observer" sees



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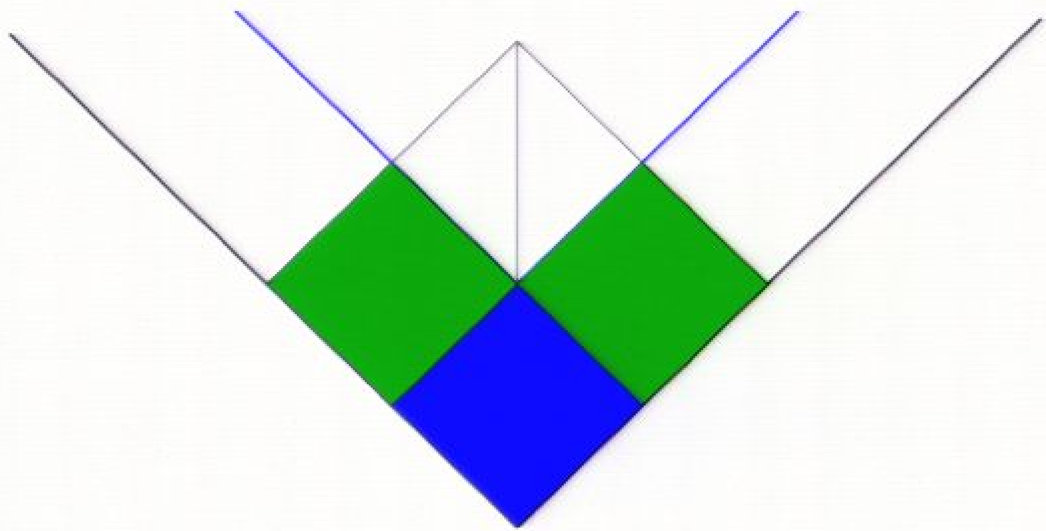

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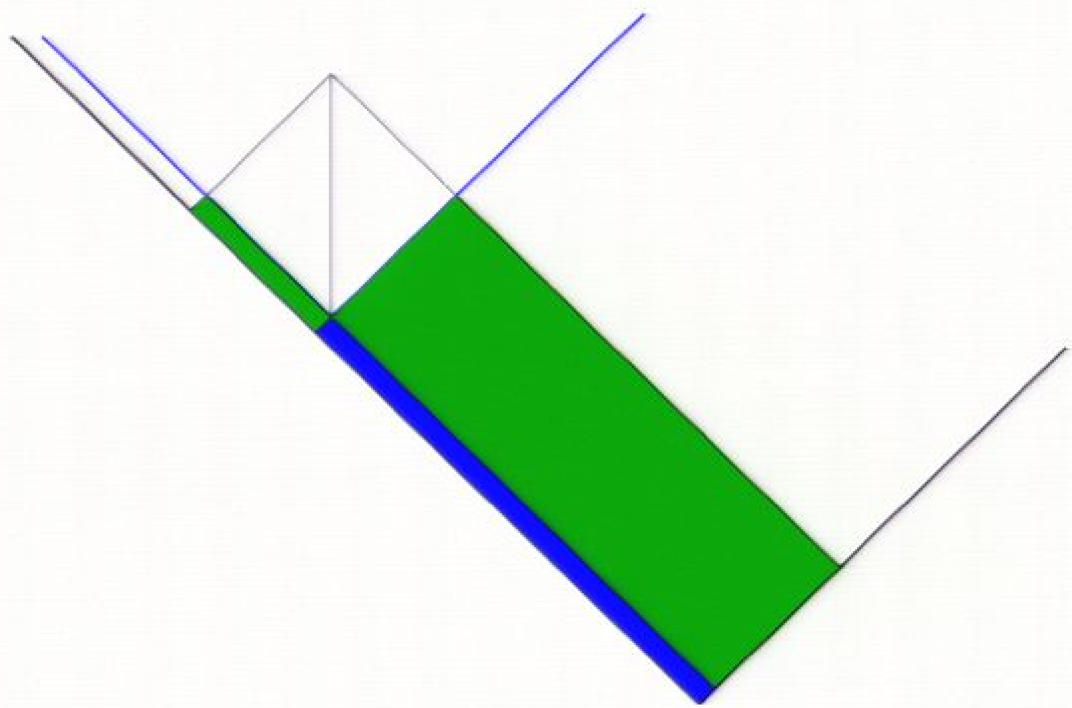
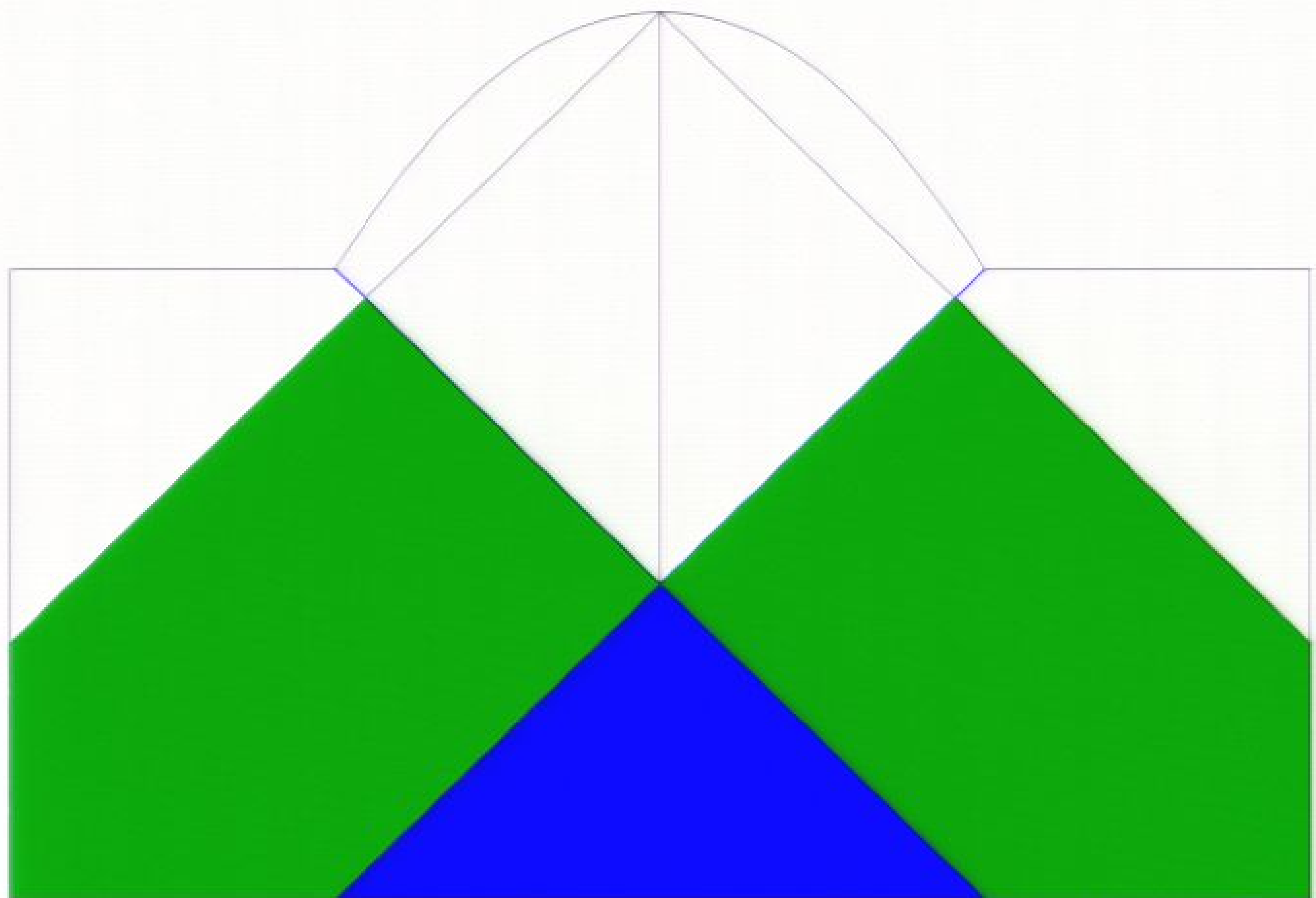
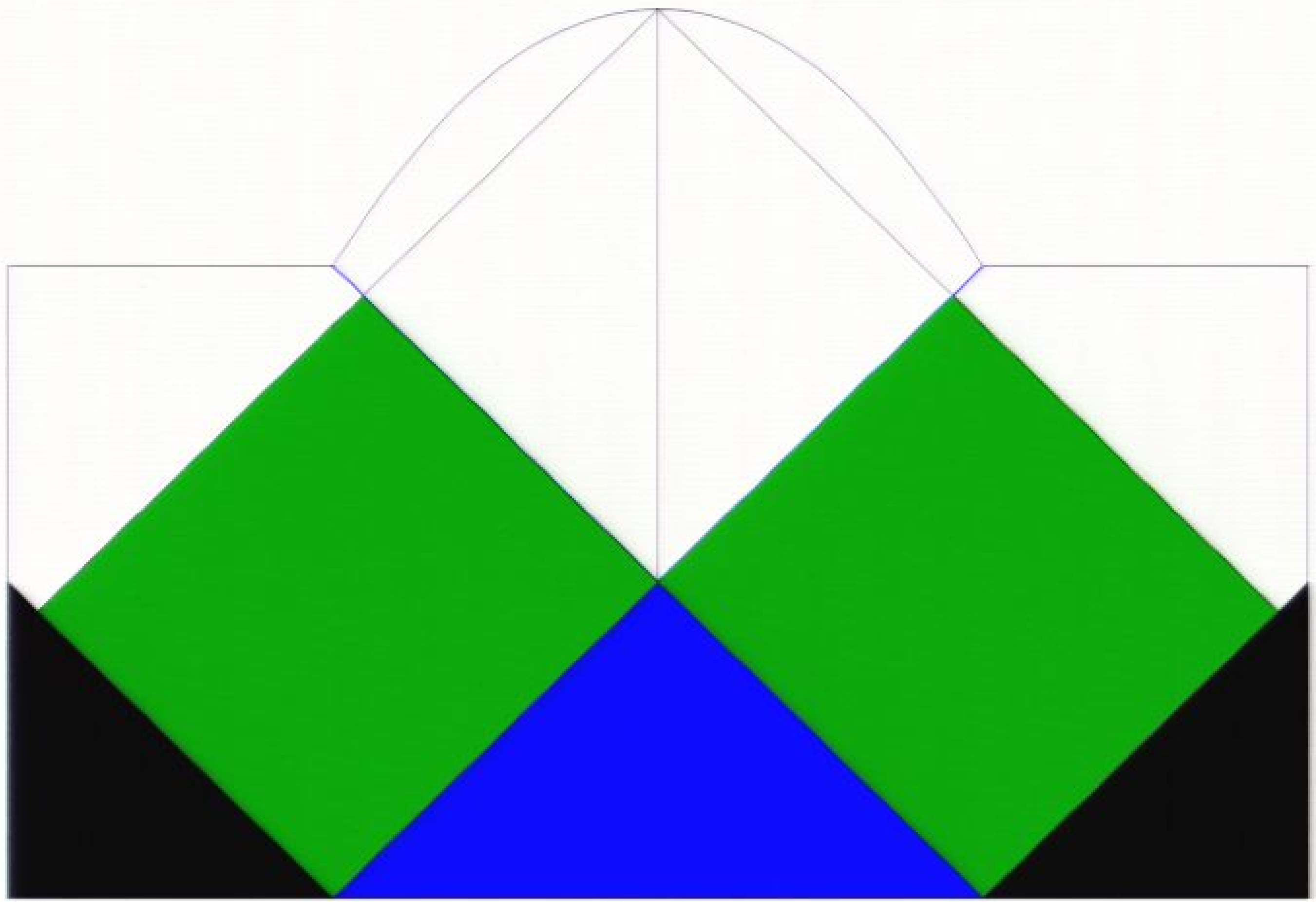


Calculate probability distribution for bubble collisions in our backward lightcone

Put in realistic cosmology from the beginning.
Gradually add in disruptive effects of collisions, and initial conditions surface.



Any initial conditions surface which keeps only the expanding part of the de Sitter space will eliminate the black regions, leaving the green 4-volume.
A particular surface will also remove part of the green region.



Coordinates outside the bubble

Coordinate system which covers the region where collision bubbles can nucleate:

$$ds^2 = H_f^{-2} \frac{1}{\cosh^2 \mathcal{X}} (d\mathcal{X}^2 + dS_3^2) \tag{6}$$

Collisions with different $\mathcal{X}$ are physically different.

Choosing coordinates on the de Sitter space:

$$ds^2 = H_f^{-2} \frac{1}{\cosh^2 \mathcal{X}} (d\mathcal{X}^2 - d\tau^2 + \cosh^2 \tau d\Omega_2^2) \tag{7}$$

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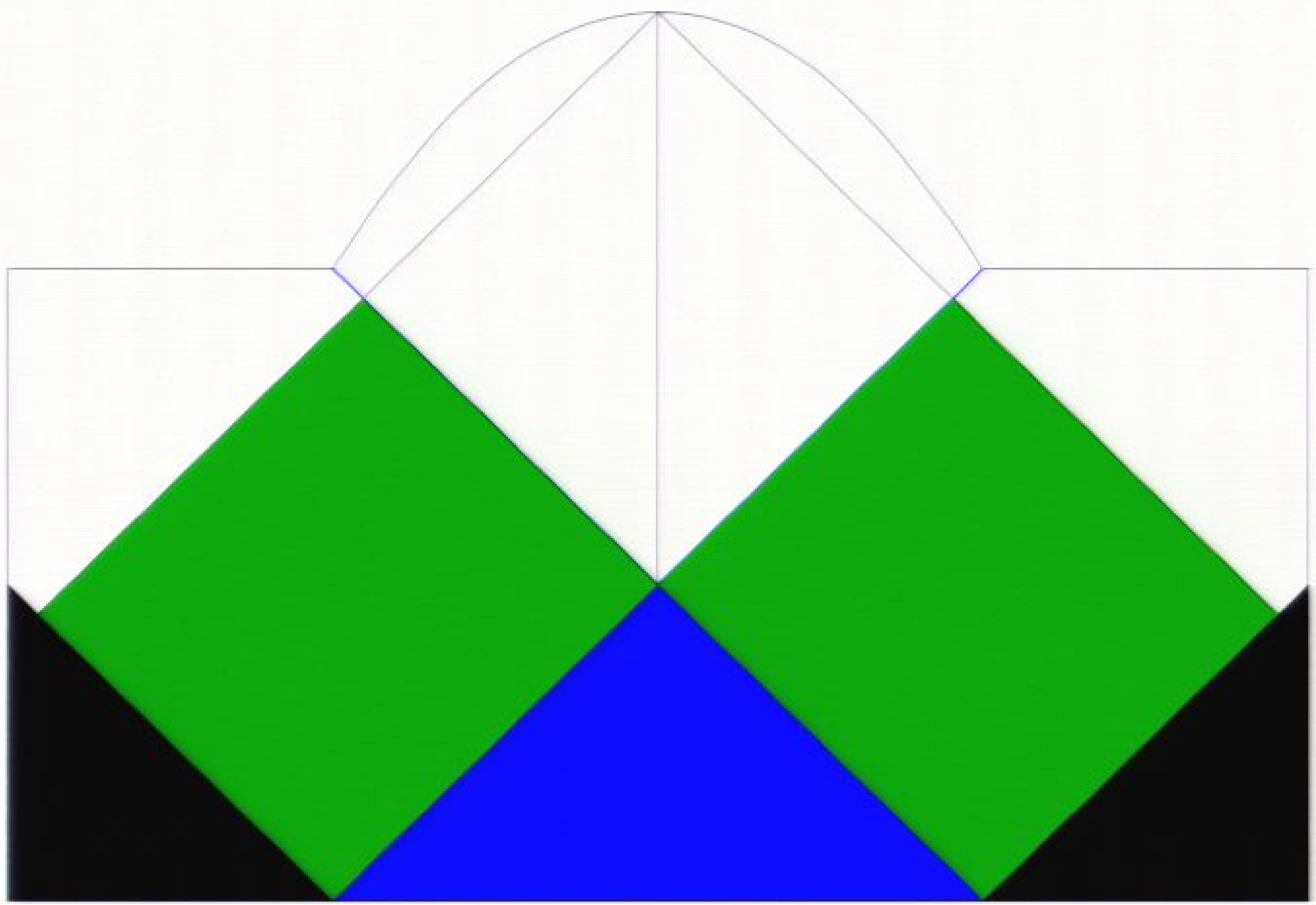

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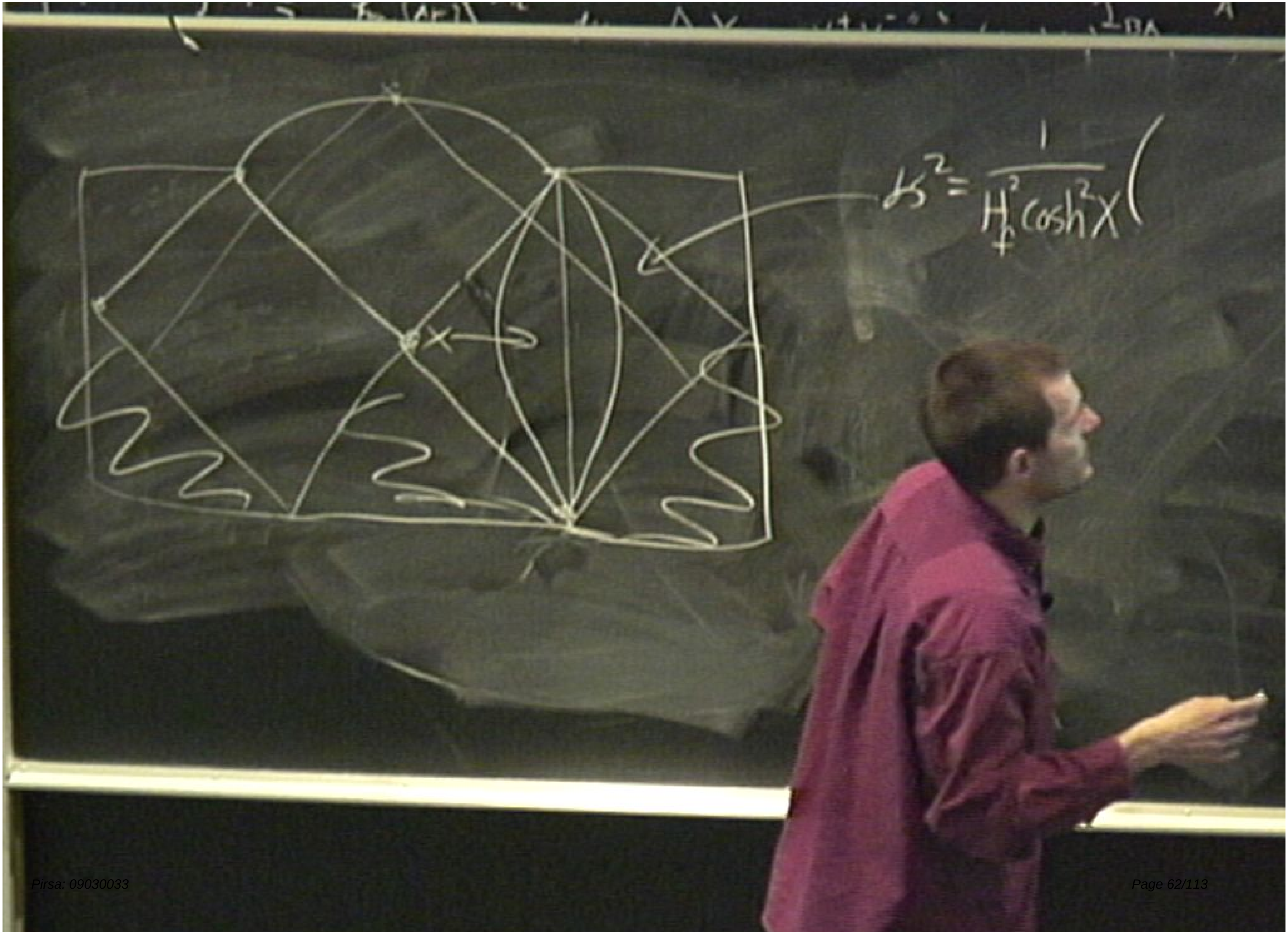
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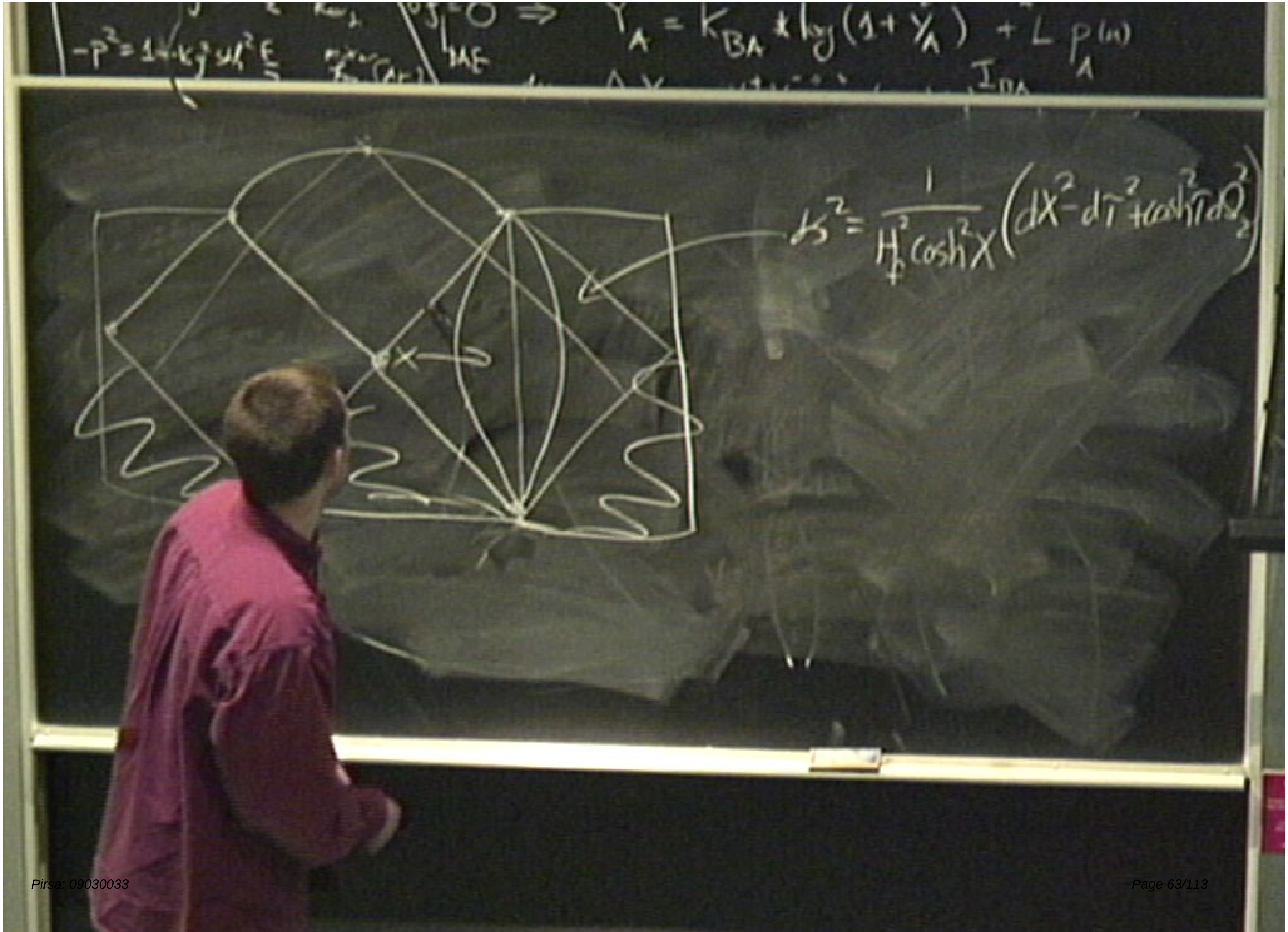

$ds^2 = \frac{1}{H_f^2 \cosh^2 X}\left(dX^2 - dT^2 + \cosh^2 T\, d\Omega_2^2\right)$

Distribution of Collisions

The probability to nucleate a bubble in an infinitesimal region is proportional to the 4-volume of that region,

$$dN = \gamma H_f^4 dV_4 = \gamma \frac{\cosh^2 \tau}{\cosh^4 \mathcal{X}} d\tau d\mathcal{X} d^2\Omega_2 \;\; (naive) \qquad (8)$$

Metric:

$$ds^2 = H_f^{-2} \frac{1}{\cosh^2 \mathcal{X}} (d\mathcal{X}^2 - d\tau^2 + \cosh^2 \tau d\Omega_2^2) \qquad (9)$$

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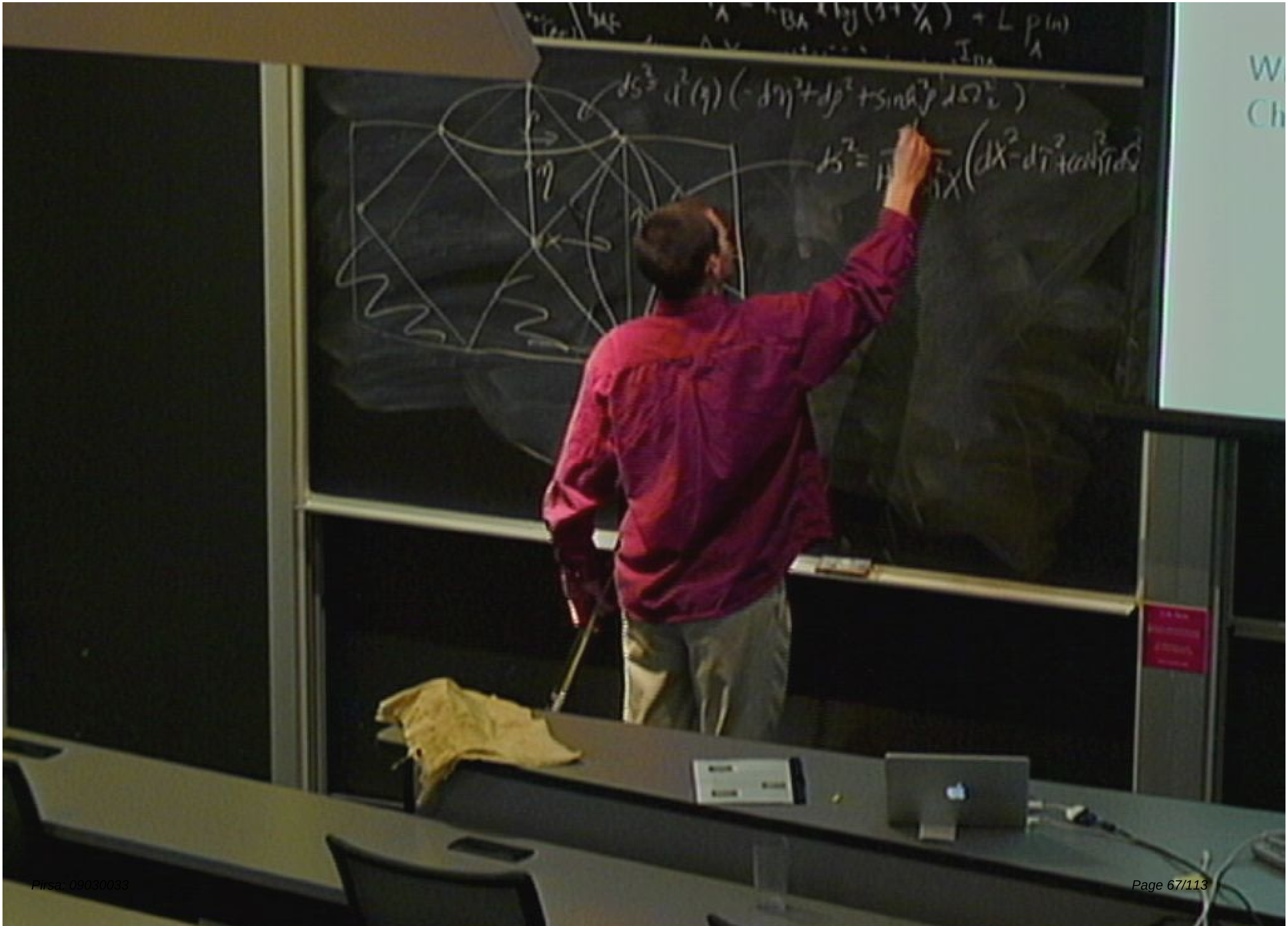
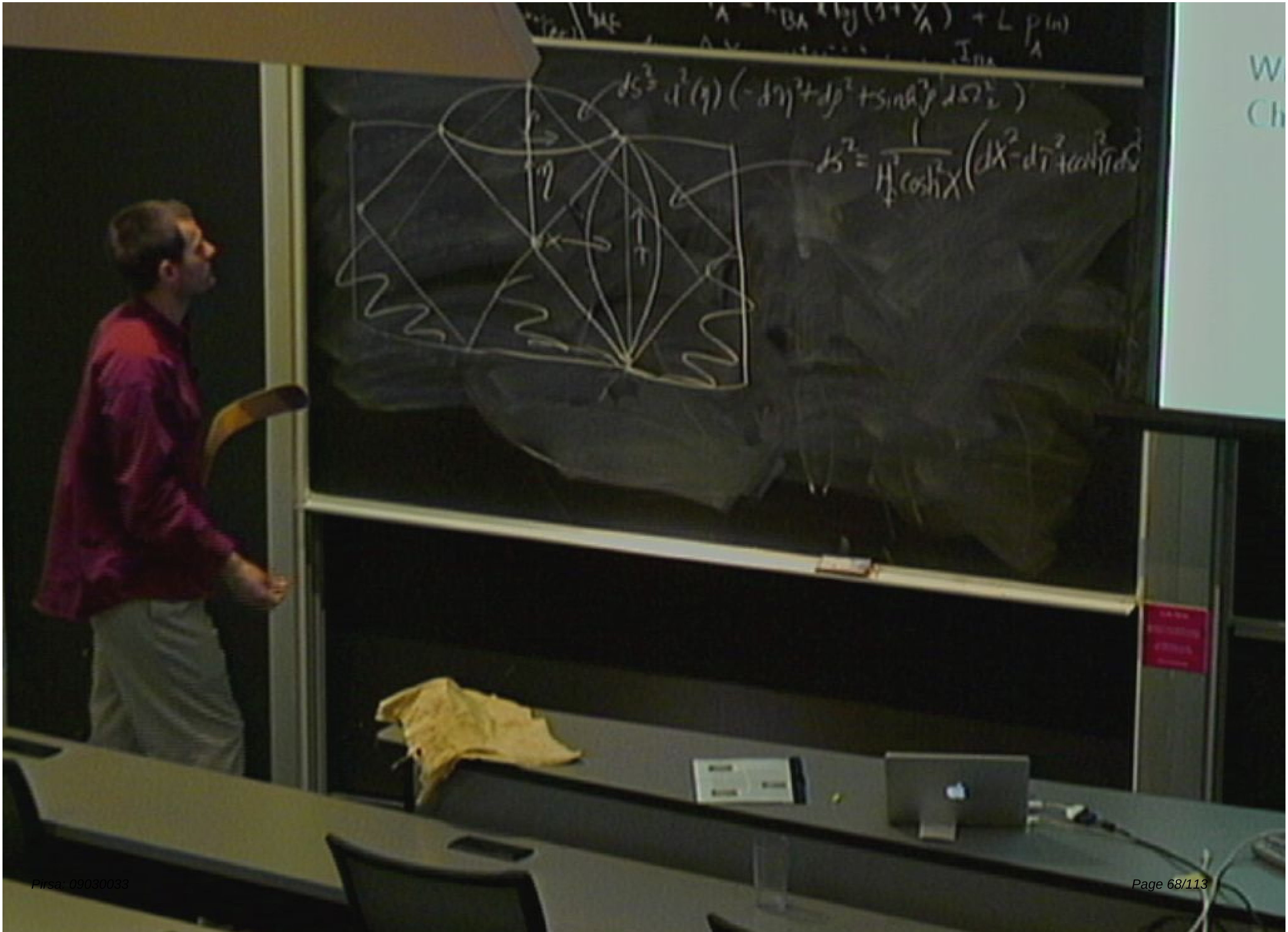
Coordinates inside the bubble

Inside the bubble, we want to keep the cosmology general. Before considering the effects of collisions, it is an open FRW universe.

$$ds^2 = a^2(\eta)(-d\eta^2 + d\rho^2 + \sinh^2 \rho d\Omega_2^2), \qquad (10)$$

Without loss of generality we focus on an observer at $\rho = 0$.
Choice of normalization: $\eta = 0$ corresponds to $t = H_f^{-1}$




ds² = a²(η) (−dη² + dρ² + sinh²ρ dΩ₂²)
ds² = 1/(H² cosh²X) (dX² − dτ² + cosh²τ dΩ²)

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Inside the bubble, we want to keep the cosmology general. Before considering the effects of collisions, it is an open FRW universe.

$$ds^2 = a^2(\eta)(-d\eta^2 + d\rho^2 + \sinh^2 \rho d\Omega_2^2), \qquad (10)$$

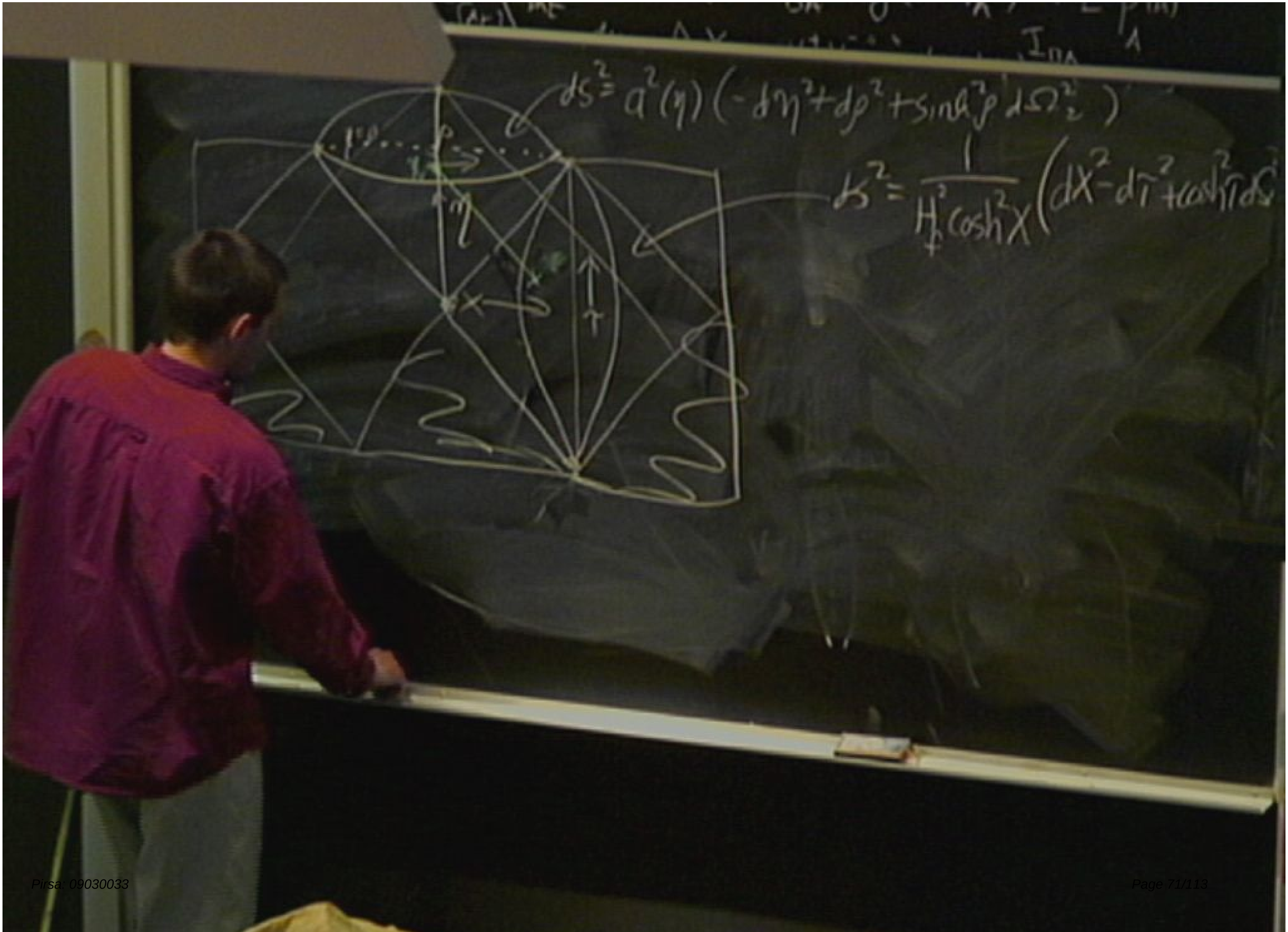
Without loss of generality we focus on an observer at $\rho = 0$. Choice of normalization: $\eta = 0$ corresponds to $t = H_f^{-1}$

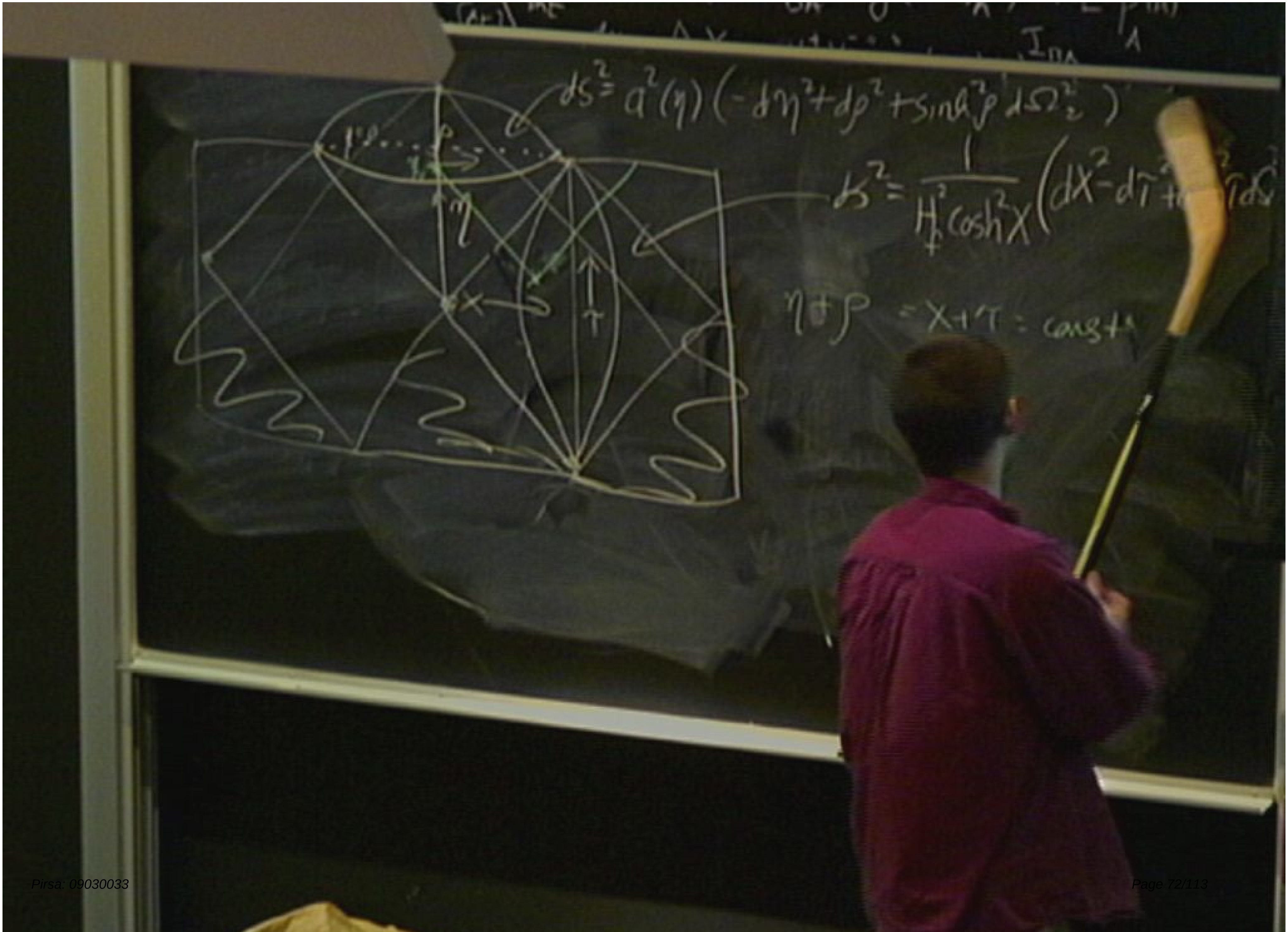
Label collision bubbles by:
$\mathcal{X}$ controls intrinsic properties of collision
(θ, ϕ) give the angular location of the nucleation event.
η_v is the conformal time at which the future lightcone of the collision crosses $\rho = 0$.

$$\eta_v = \mathcal{X} + \tau \tag{11}$$

Distribution:

$$dN = \gamma \frac{\cosh^2(\eta_v - \mathcal{X})}{\cosh^4 \mathcal{X}} d\eta_v d\mathcal{X} d^2\Omega_2 \ \ (naive) \tag{12}$$

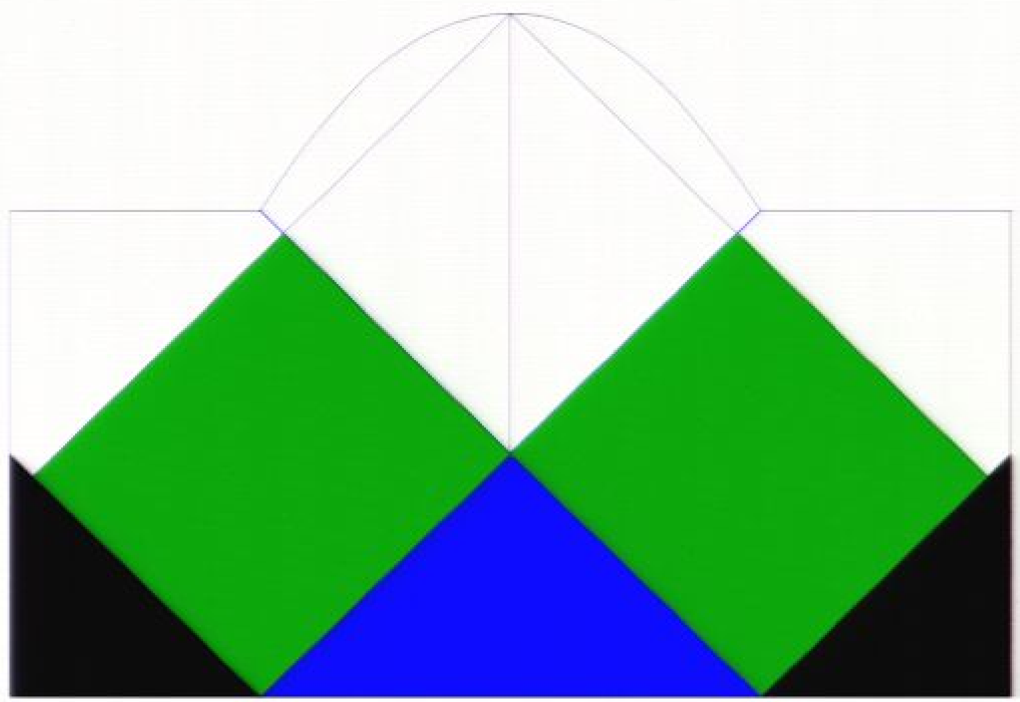

ds² = a²(η) (-dη² + dρ² + sinh²ρ dΩ₂²)
ds² = 1 / (H² cosh²χ) (dχ² - dτ² + cosh²τ dΩ²)


$ds^2 = a^2(\eta)(-d\eta^2 + d\rho^2 + \sinh^2\rho \, d\Omega_2^2)$
$\eta + \rho = X + T = const$

Integrate out $\mathcal{X}$ to count bubbles:

$$dN = \frac{2\gamma}{3}(1 + 2\cosh 2\eta_v)d\eta_v d^2\Omega_2 \tag{13}$$

Divergent at early times, as expected.
Potential divergence at large η_v cut off: $\eta_{\rm now} \sim \log \frac{H_f}{H_i}$.



Need more physics...

Integrate out $\mathcal{X}$ to count bubbles:

$$dN = \frac{2\gamma}{3}(1 + 2\cosh 2\eta_v)\, d\eta_v d^2\Omega_2 \qquad (13)$$

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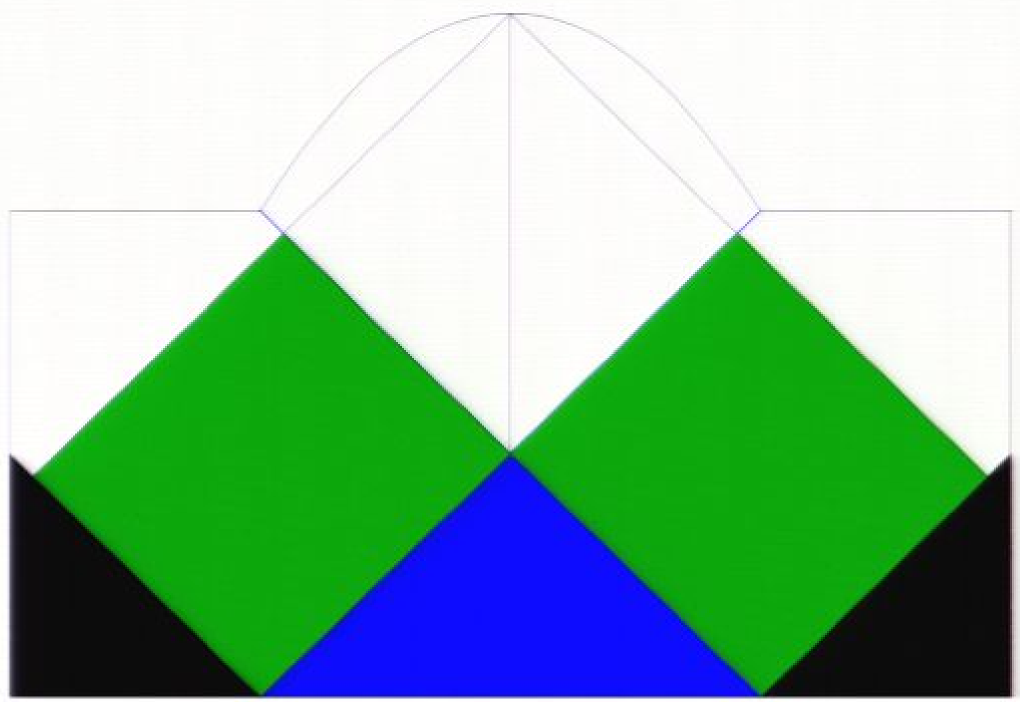
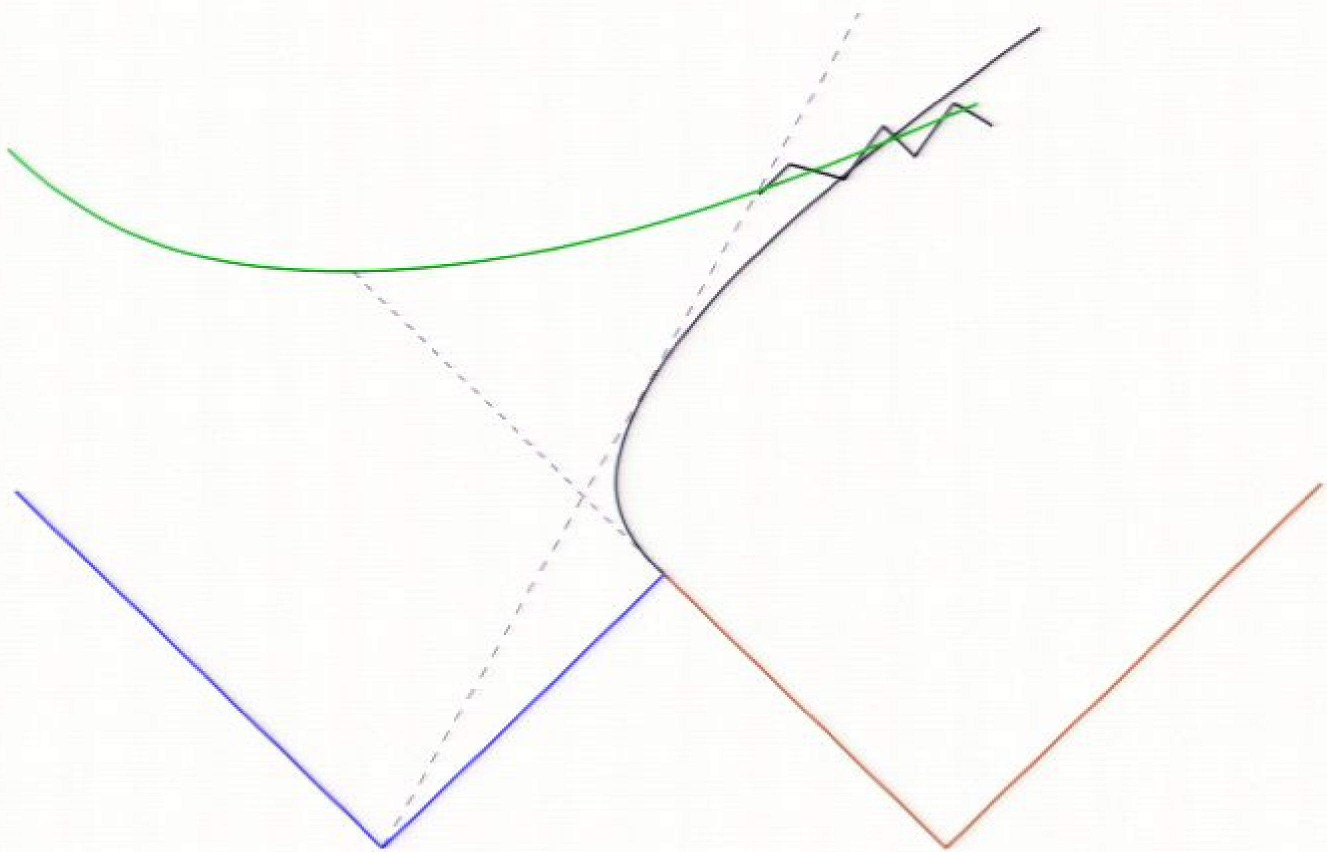


Need more physics...

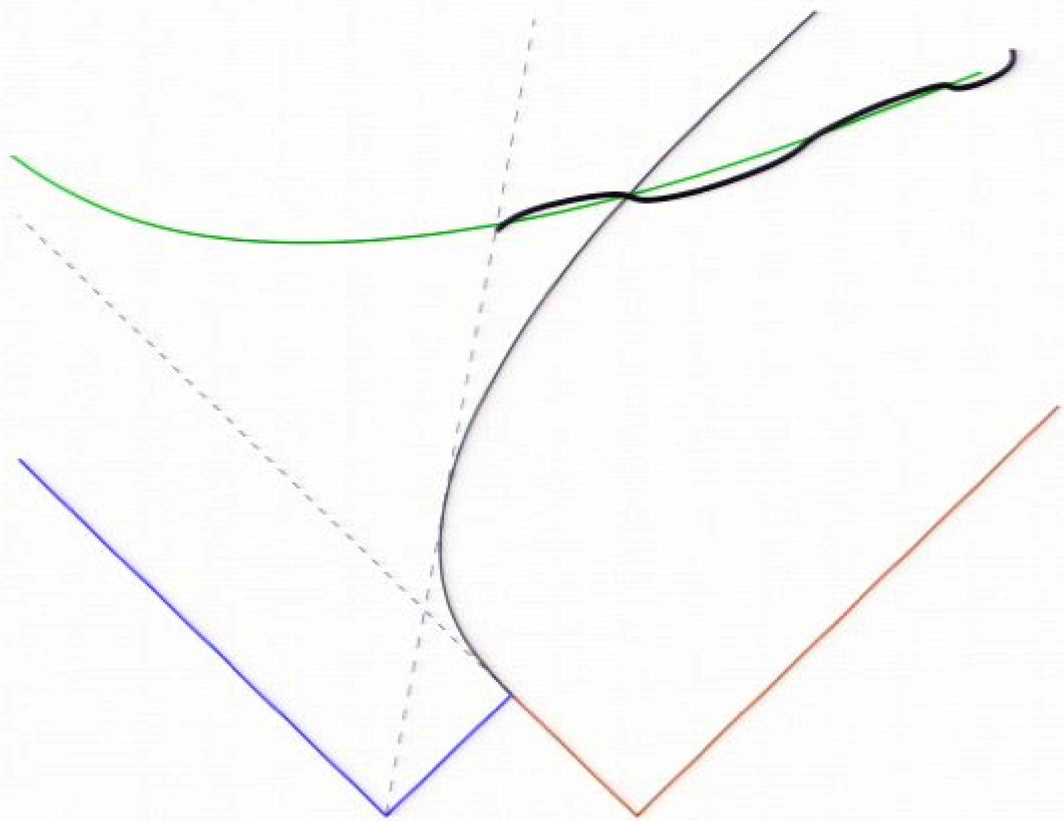
What happens in the future of a bubble collision?

Suppressing the H_2 symmetry directions,



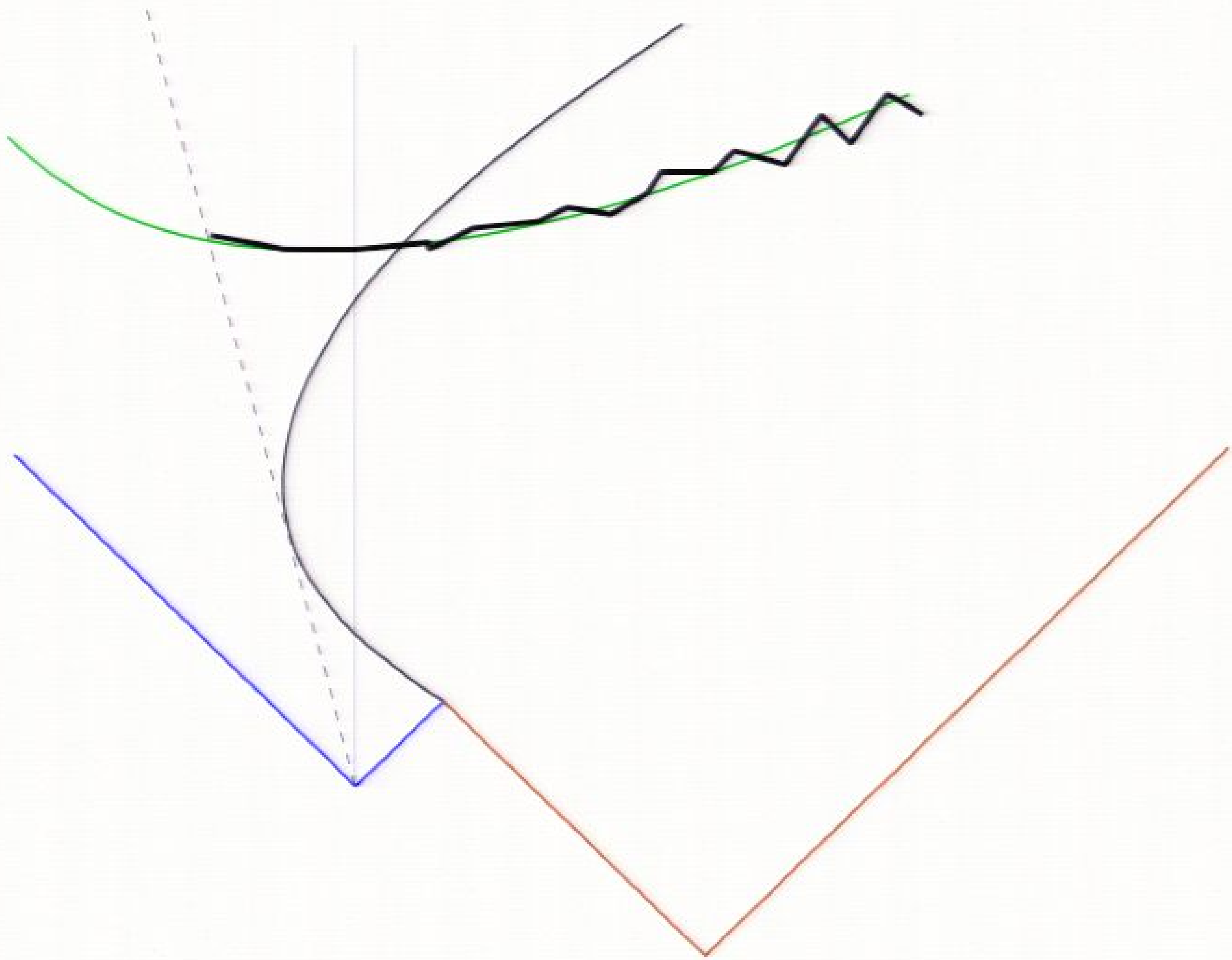
Assumptions about collisions

- The collision is with a bubble different from our own, so a domain wall separates us after the collision
- The domain wall accelerates *away* from our bubble
- Observer formation is disrupted in some part of the future lightcone, but not all of it



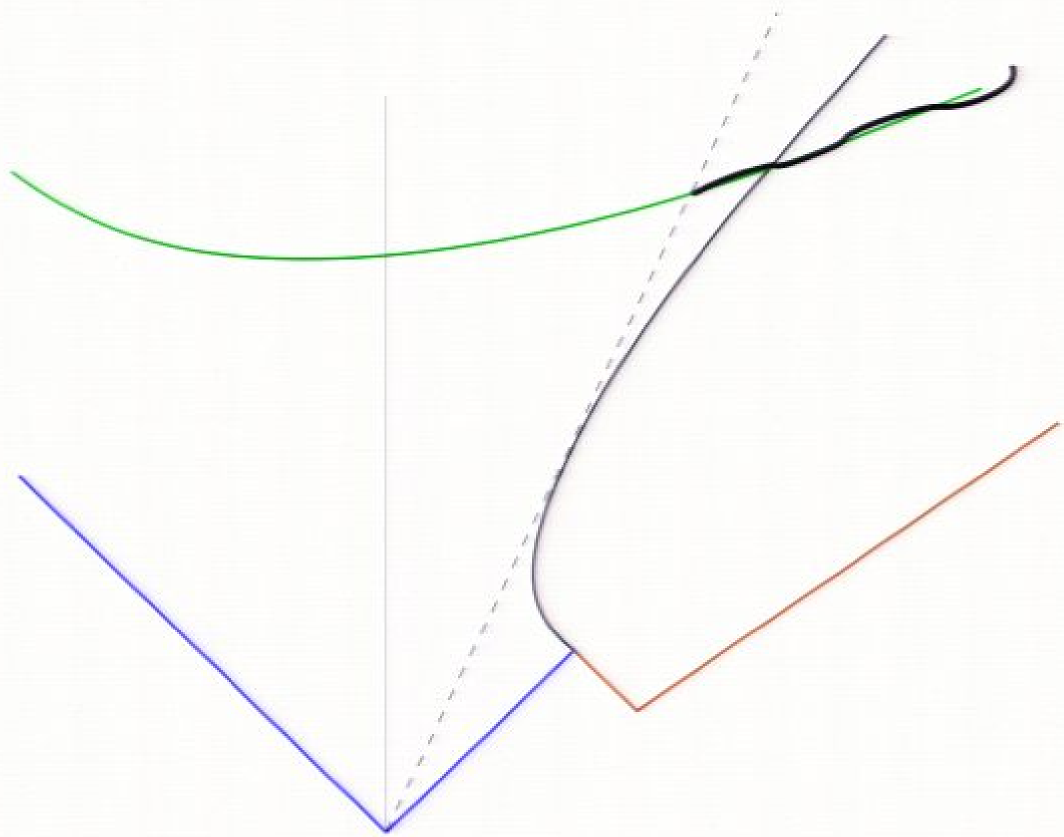
- Natural to assume that all energy scales in the problem are high (near the Planck scale) except V_i
- The characteristic time when domain wall starts moving away is set by H_f^{-1}
- Inflation is disrupted in the region near the domain wall

A Big Bad Bubble



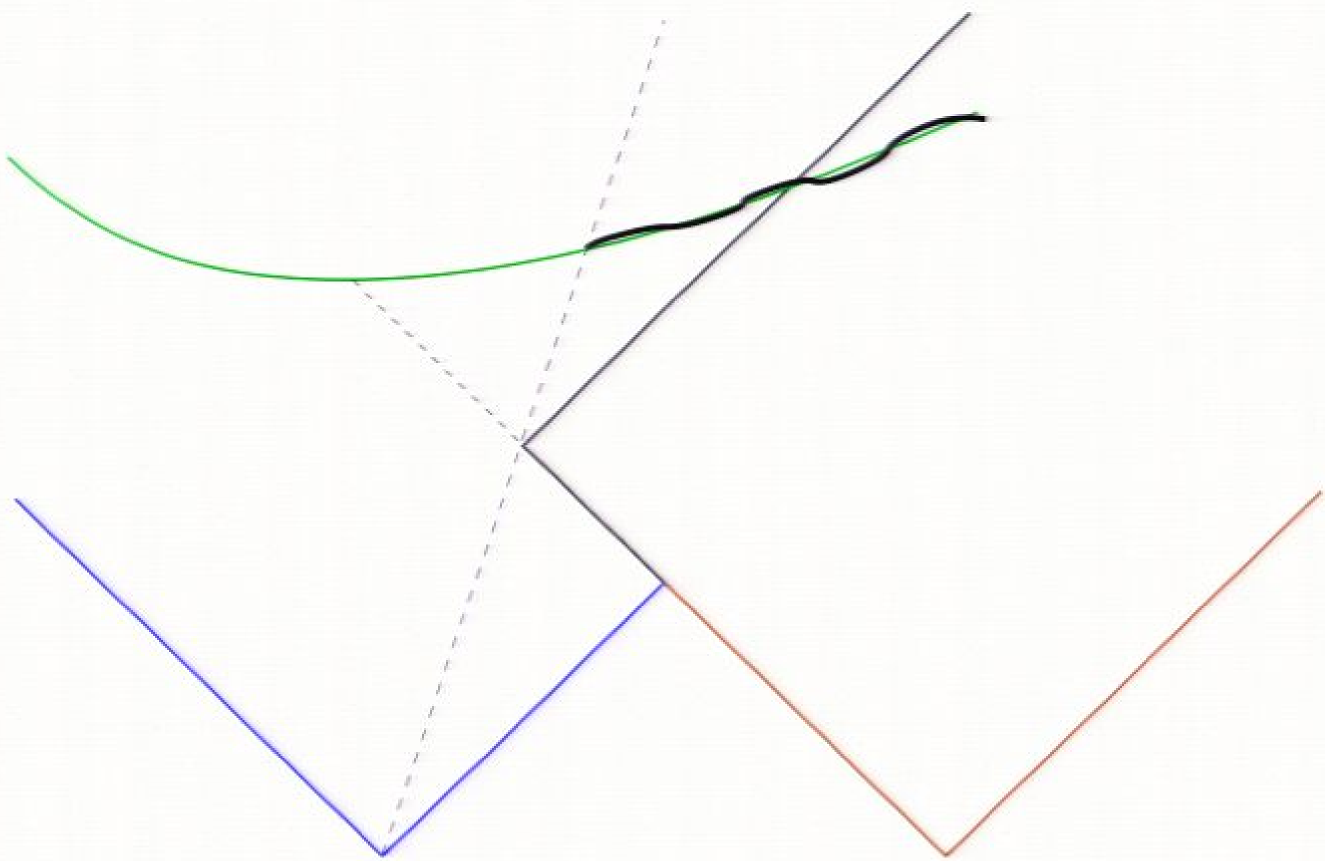
Inflation is disrupted.

Small bubbles are not disruptive



A small perturbation.

Caricature of the future of a collision



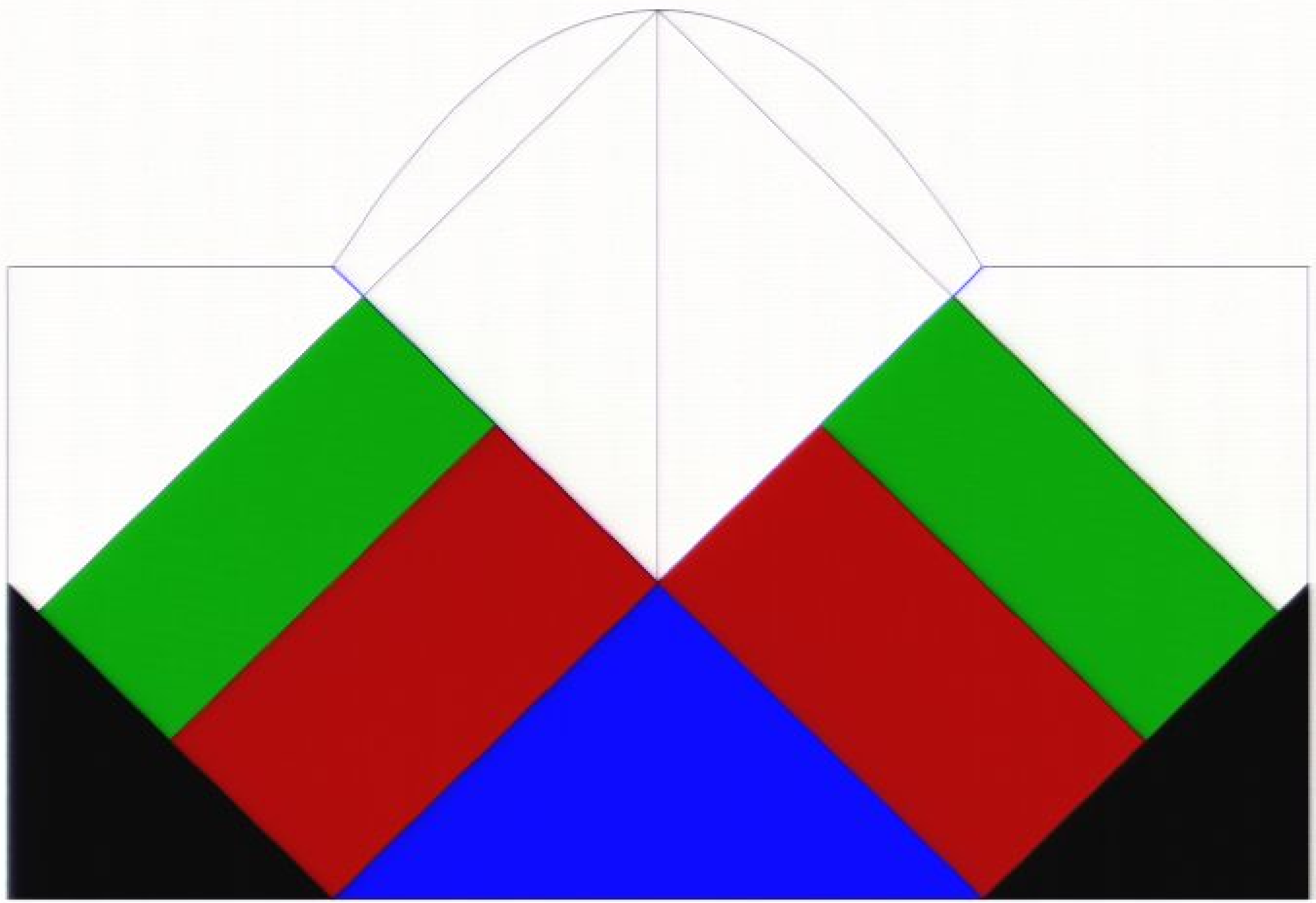
- Domain wall moves in at the speed of light until H_f^{-1}, and then moves out at the speed of light
- Observer formation does not occur along geodesics which cross the domain wall, and is undisturbed otherwise

Clearly room for further analysis here, but our conclusions are robust.

It is crucial that we assumed the domain wall accelerates away from our bubble.
If it accelerates into our bubble, no observers form in the future of collisions.

Suspect our results are not changed much for collisions with identical bubbles.
Focus here on collisions with non-identical bubbles.

Region available to nucleate collision bubbles without disrupting structure formation



Detailed shape of the red region depends on our caricature.
Very robust that it covers the bottom of the diagram.

Distribution for bubble collisions

$$dN = \gamma \frac{\cosh^2(\eta_v - \mathcal{X})}{\cosh^4 \mathcal{X}} d\mathcal{X} d\eta_v d^2\Omega_2 \tag{14}$$

$$0 < \eta_v < \eta_0 \tag{15}$$

The restriction $0 < \eta_v$ comes from requiring that observer formation is not disrupted.

Integrate out $\mathcal{X}$

$$dN = \frac{2\gamma}{3}(1 + 2\cosh 2\eta_v) d\eta_v d^2\Omega_2 \qquad \text{for } \eta_v > 0 \tag{16}$$

Requiring structure formation eliminates the divergence!

Total number before η_0 is

$$N(\eta_0) = \frac{8\pi\gamma}{3}(\sinh 2\eta_0 + \eta_0) \ . \tag{17}$$

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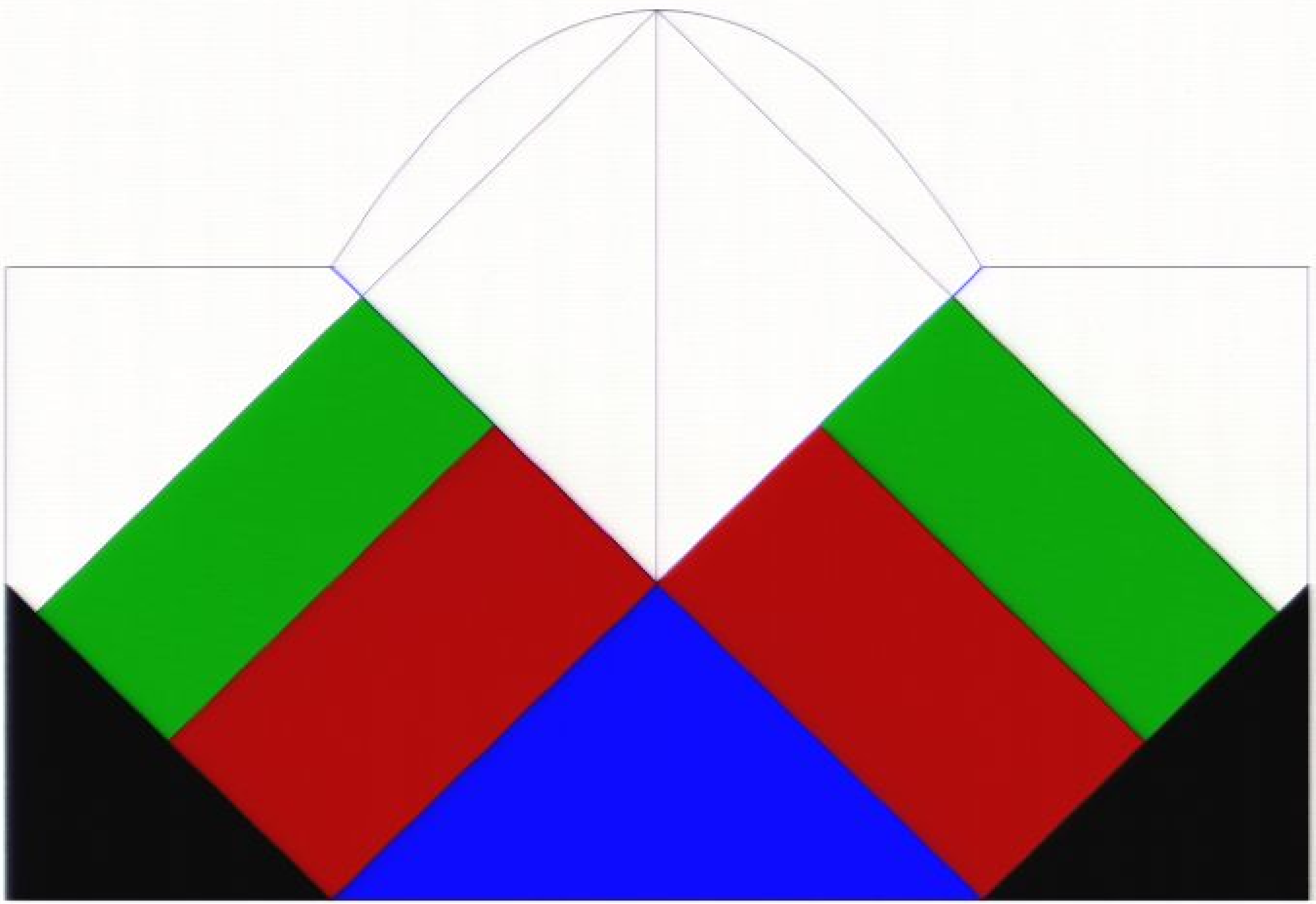

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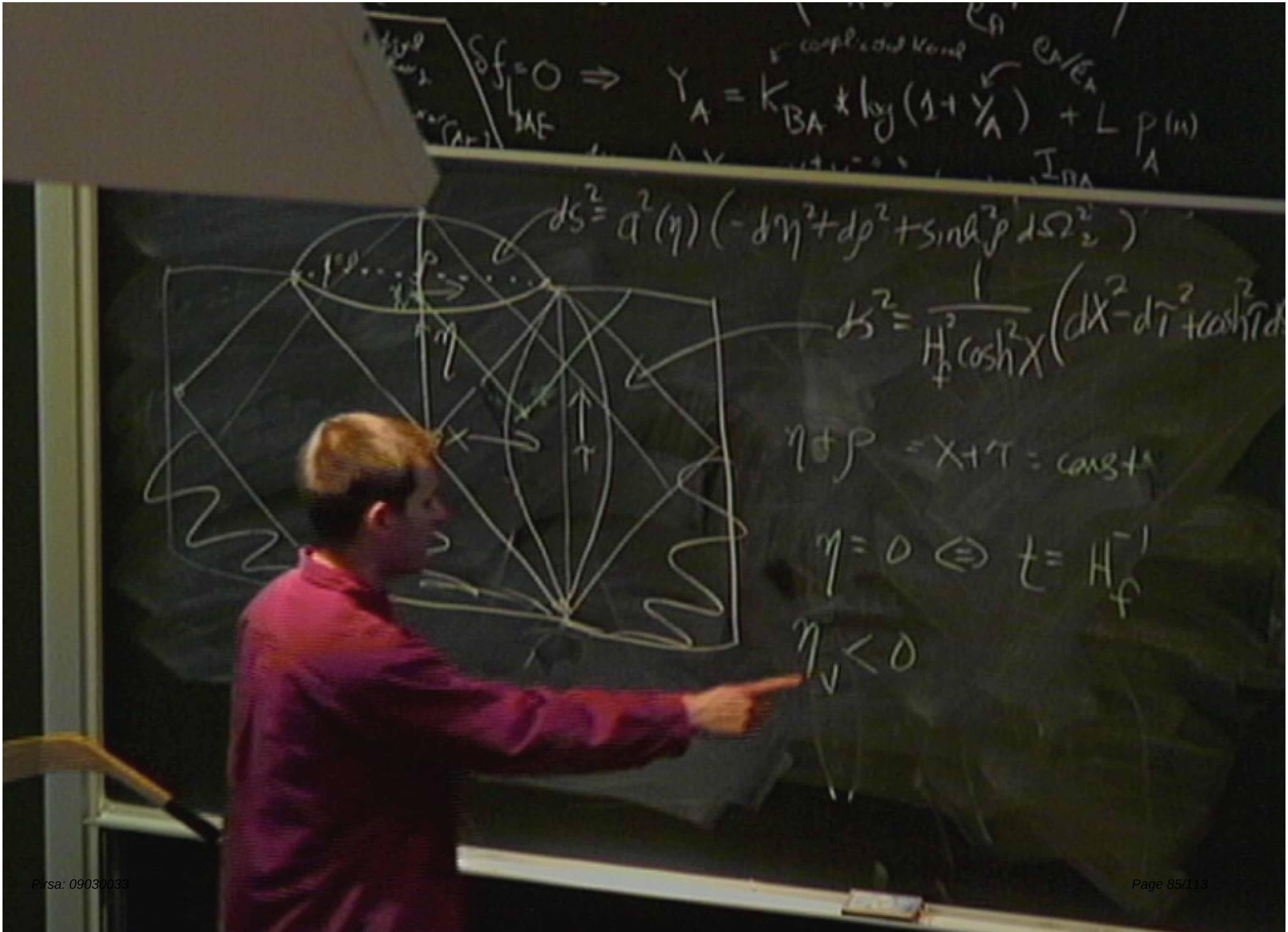
δf = 0 ⇒ Y_A = K_BA * log(1 + Y/A) + L ρ_A (in)
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η = 0 ⇔ t = H_f⁻¹
η_v < 0

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Number of collisions in our past lightcone

We have not yet taken into account the effects of the initial conditions surface.
But jumping ahead, need to compute the conformal time today.

$$\eta_0 \approx \log \frac{H_f}{H_i} + 2\sqrt{\Omega} \tag{18}$$

The amount of the domain wall in our backward lightcone is mostly set by H_i.

$$N \approx \frac{4\pi\gamma}{3} \left(\frac{H_f}{H_i} \right)^2 \tag{19}$$

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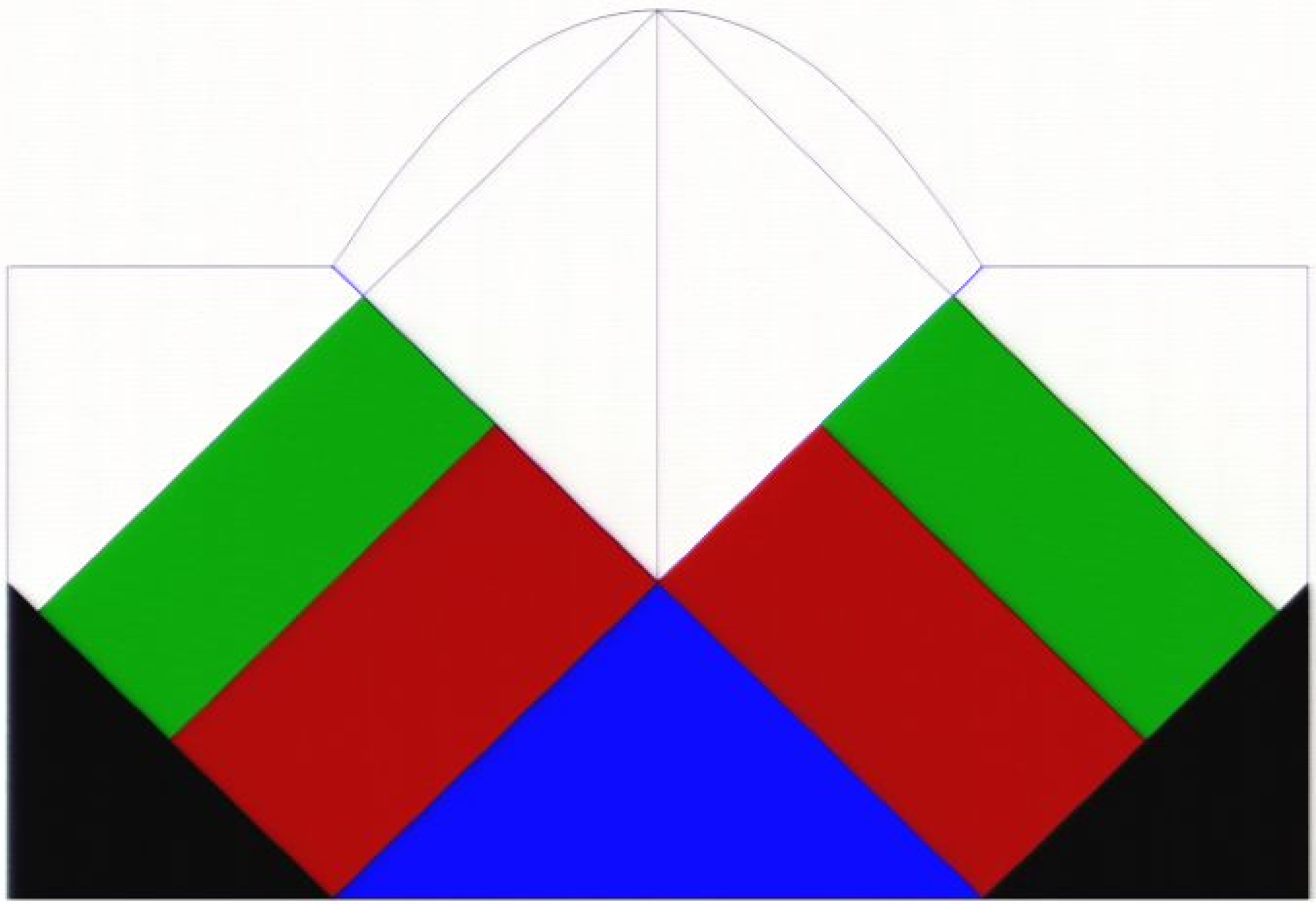
Quick and Dirty Derivation



Area of $S_2 \sim H_i^{-2}$ $\qquad V_4 \sim H_f^{-2} H_i^{-2}$

$N \sim \gamma \left(\frac{H_f}{H_i}\right)^2 = \gamma \frac{V_f}{V_i}$

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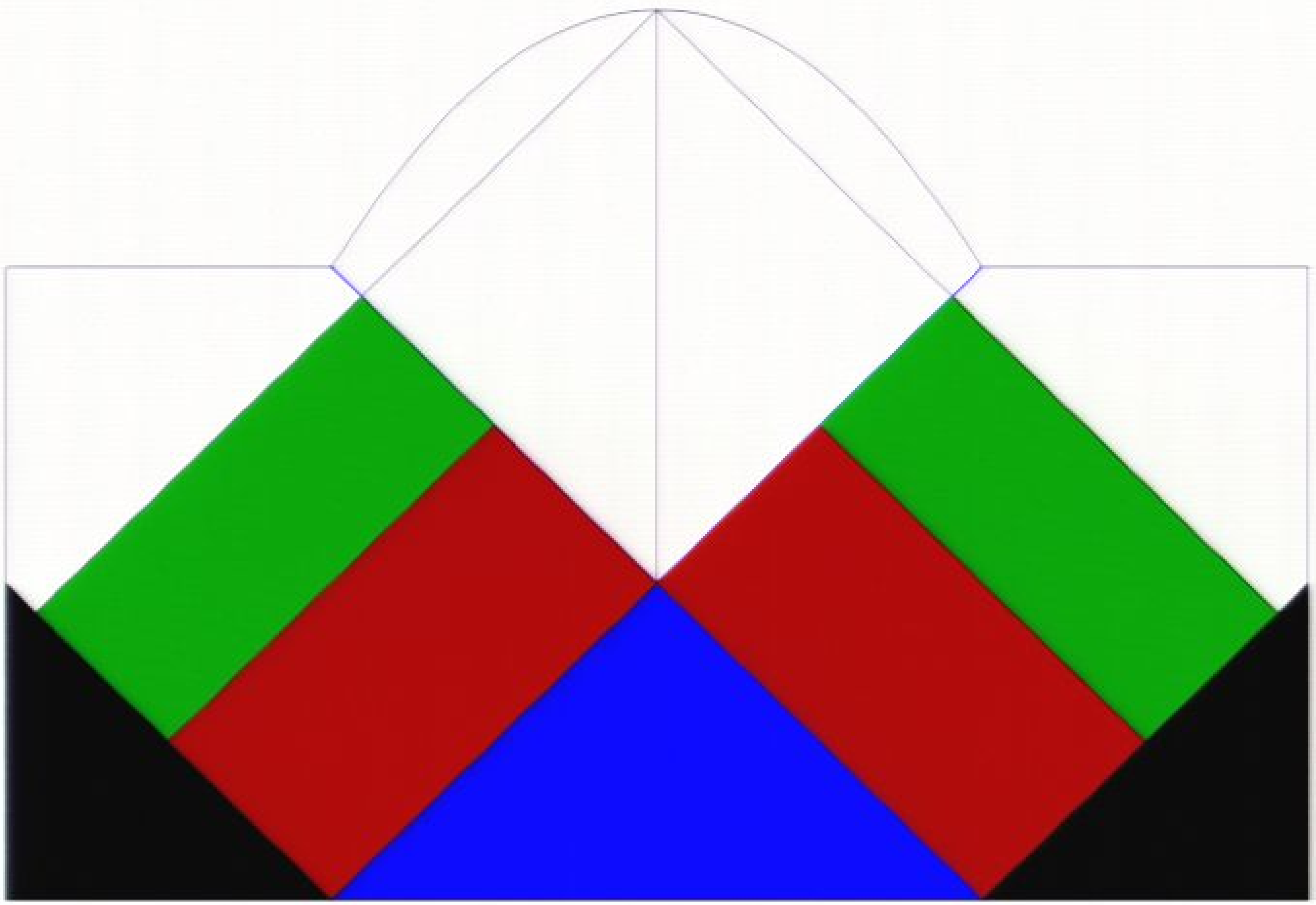

Area of $S_2 \sim H_i^{-2}$ $\qquad$ $V_4 \sim H_f^{-2} H_i^{-2}$

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Number of Collisions in our past

$$\boxed{N \approx \frac{4\pi}{3}\gamma\frac{V_f}{V_i}} \qquad (20)$$

Is it likely that $N > 1$?

Yes, *if* we believe V_f is close to the Planck scale.

$$\frac{V_f}{V_i} \gtrsim 10^{12} \tag{21}$$

No reason for tuning; many possible decay channels in string theory landscape $\rightarrow$

$$\gamma \sim e^{(-few)} \tag{22}$$

- It would be interesting to analyze this in some model.

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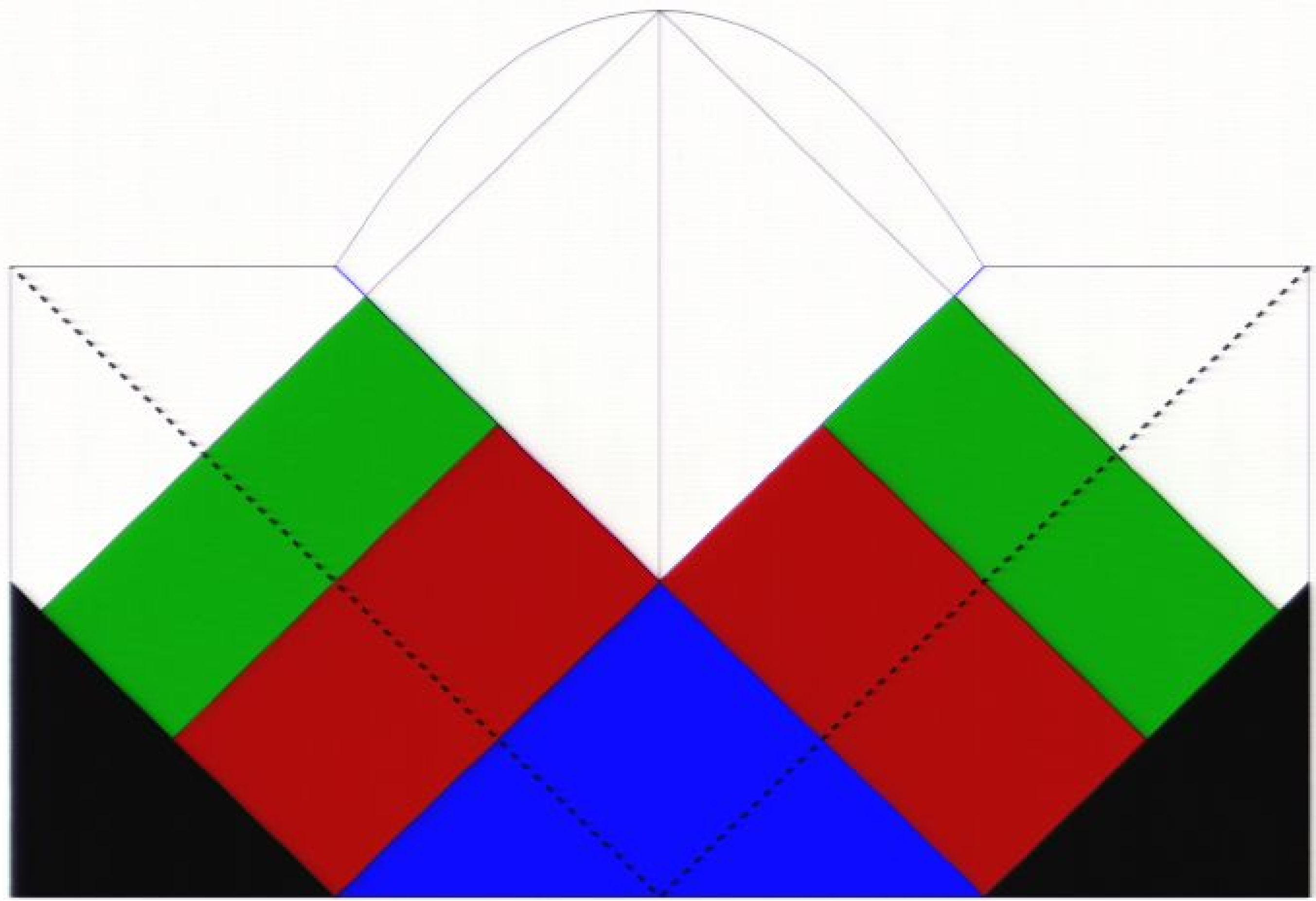
How Persistent is Memory?

Effect of the initial condition surface at zero boost



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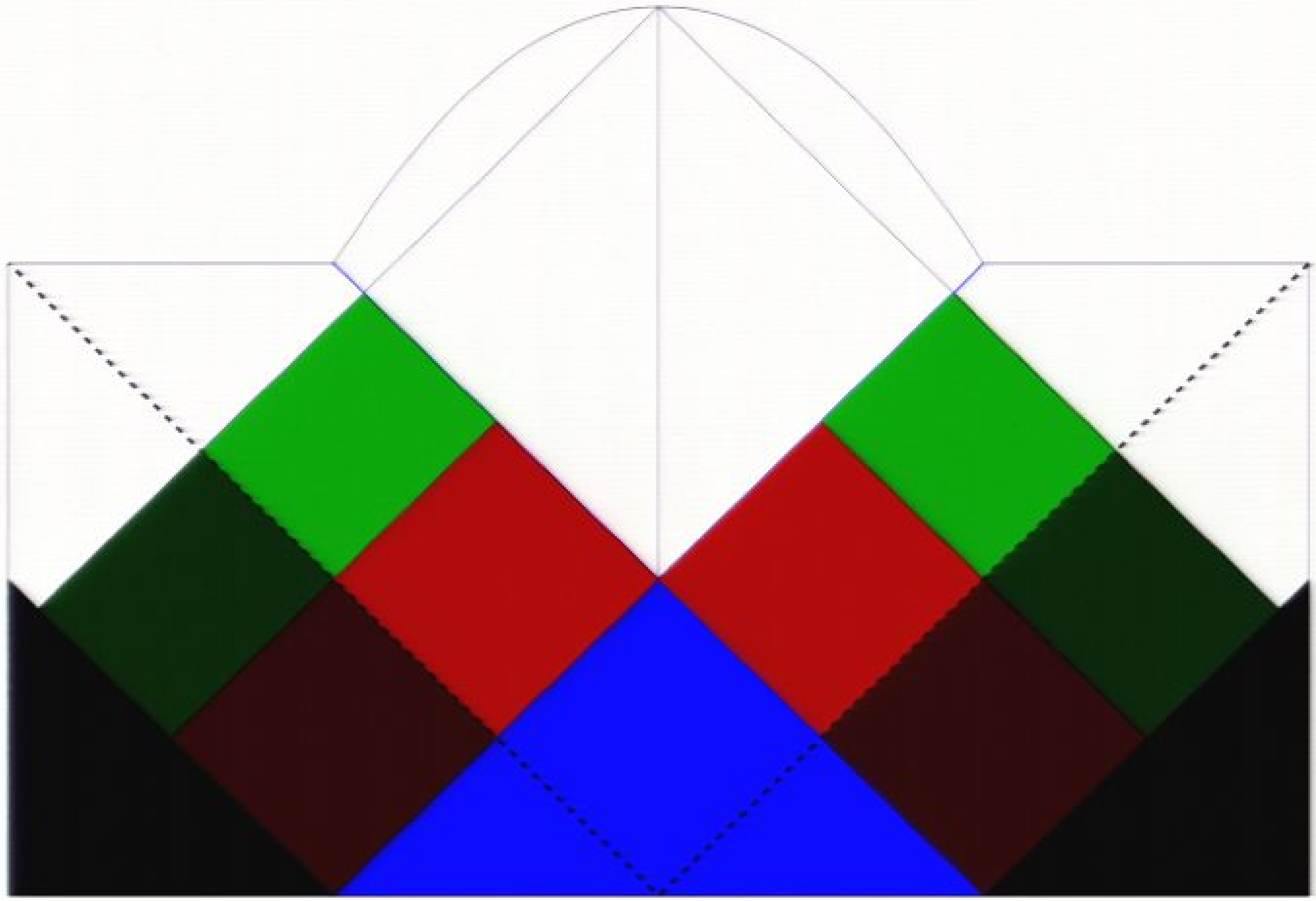

$$\Delta N \approx \frac{4\pi\gamma}{3}(1 + \ln 4) \quad (23)$$

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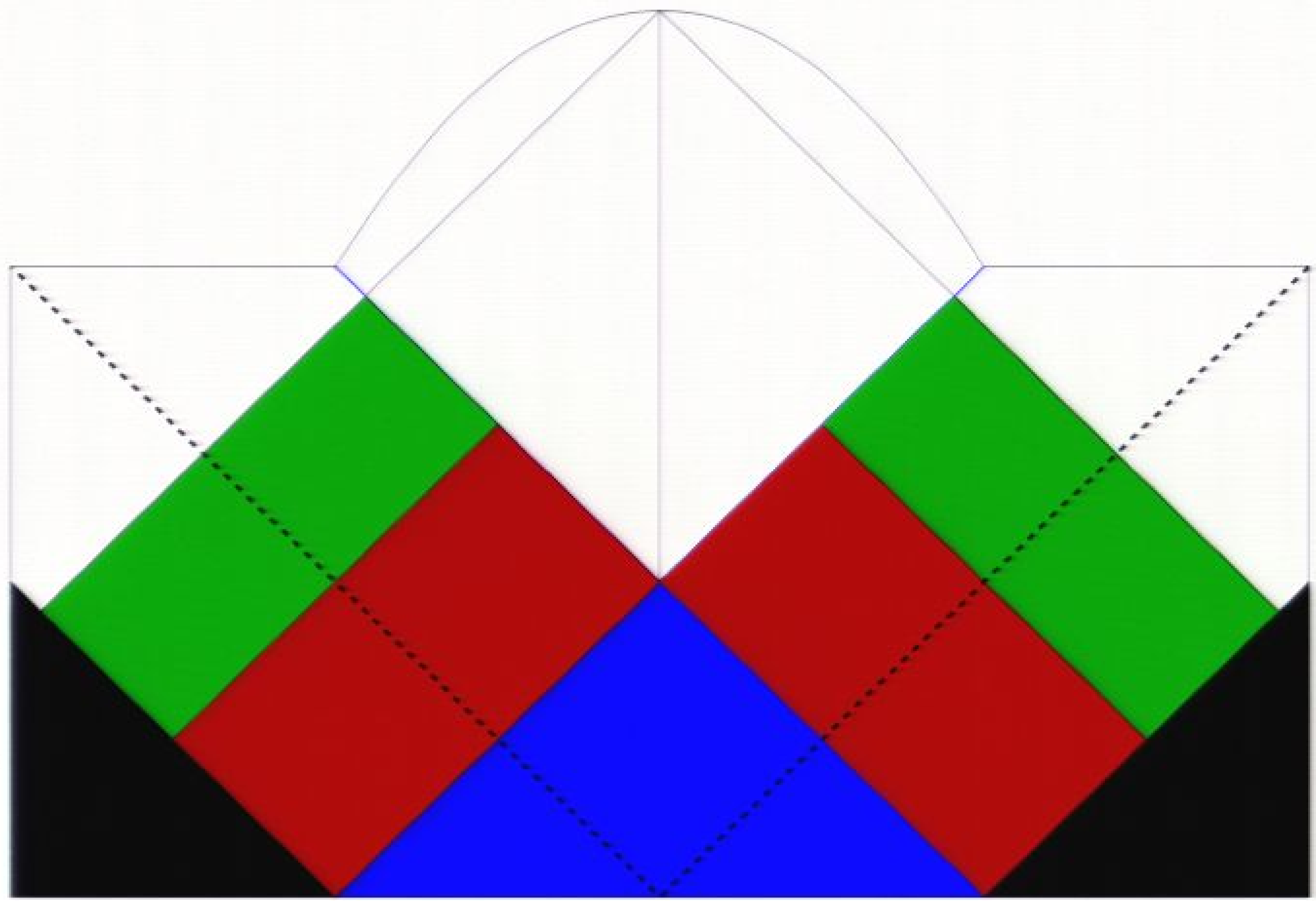

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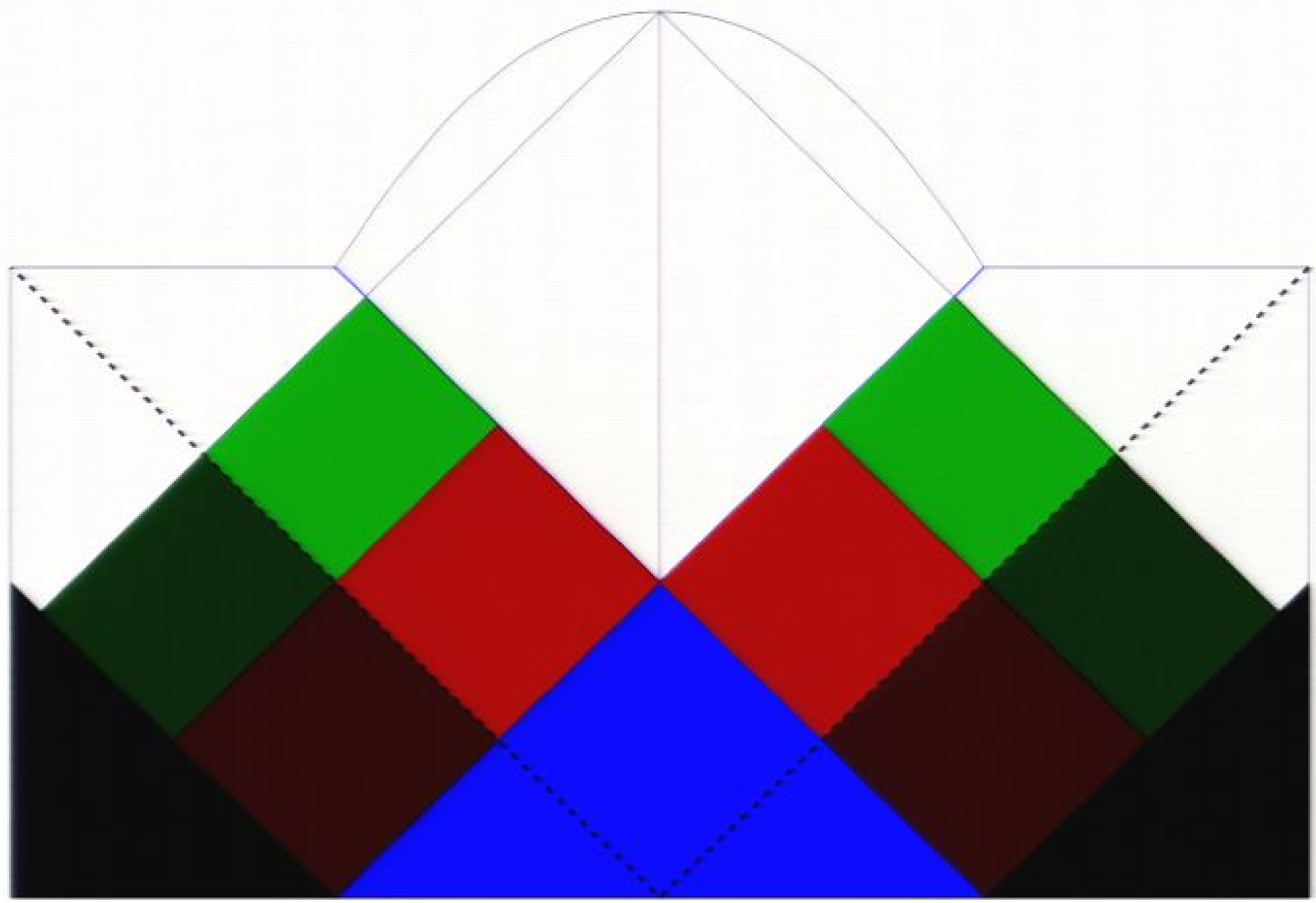

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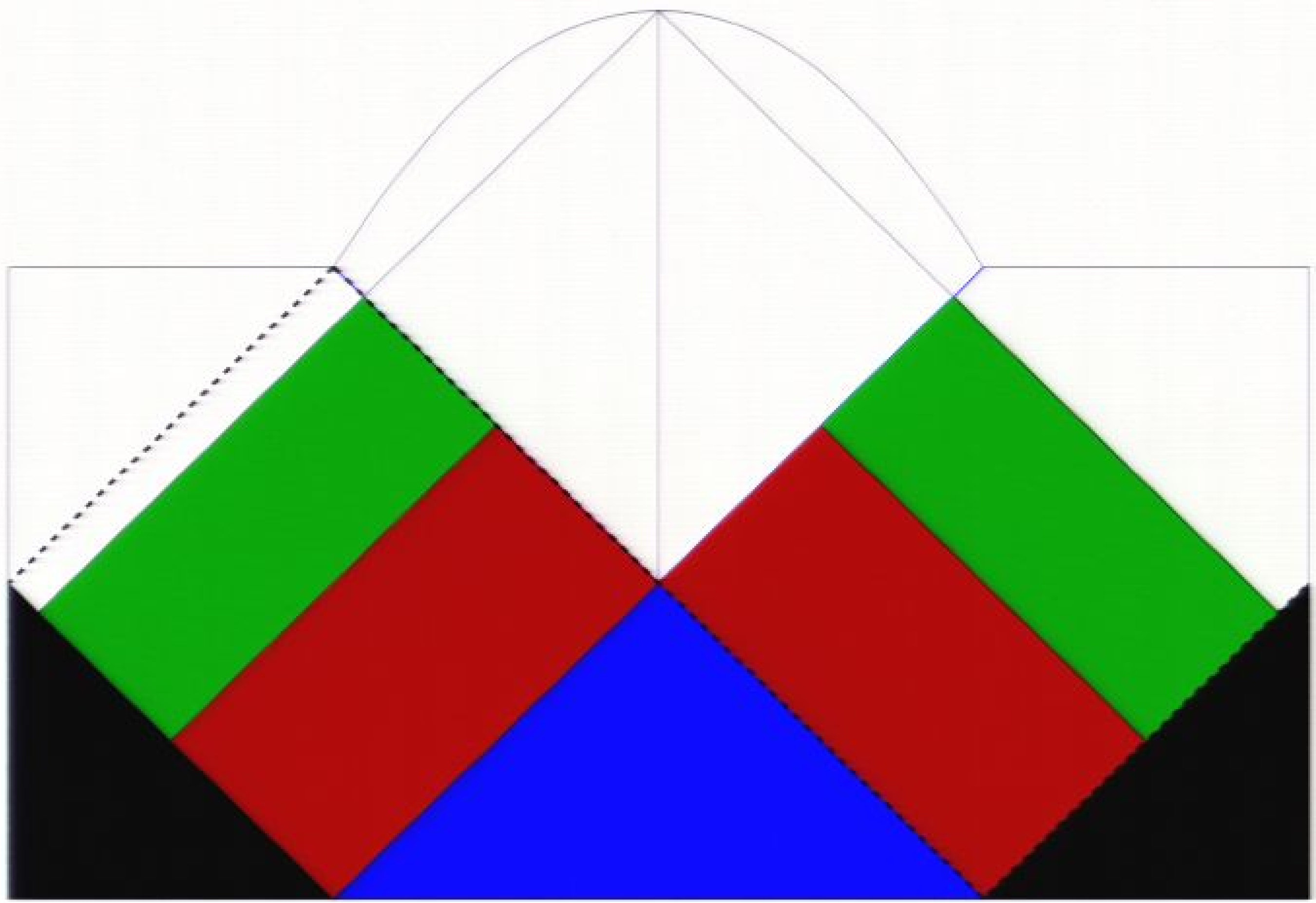

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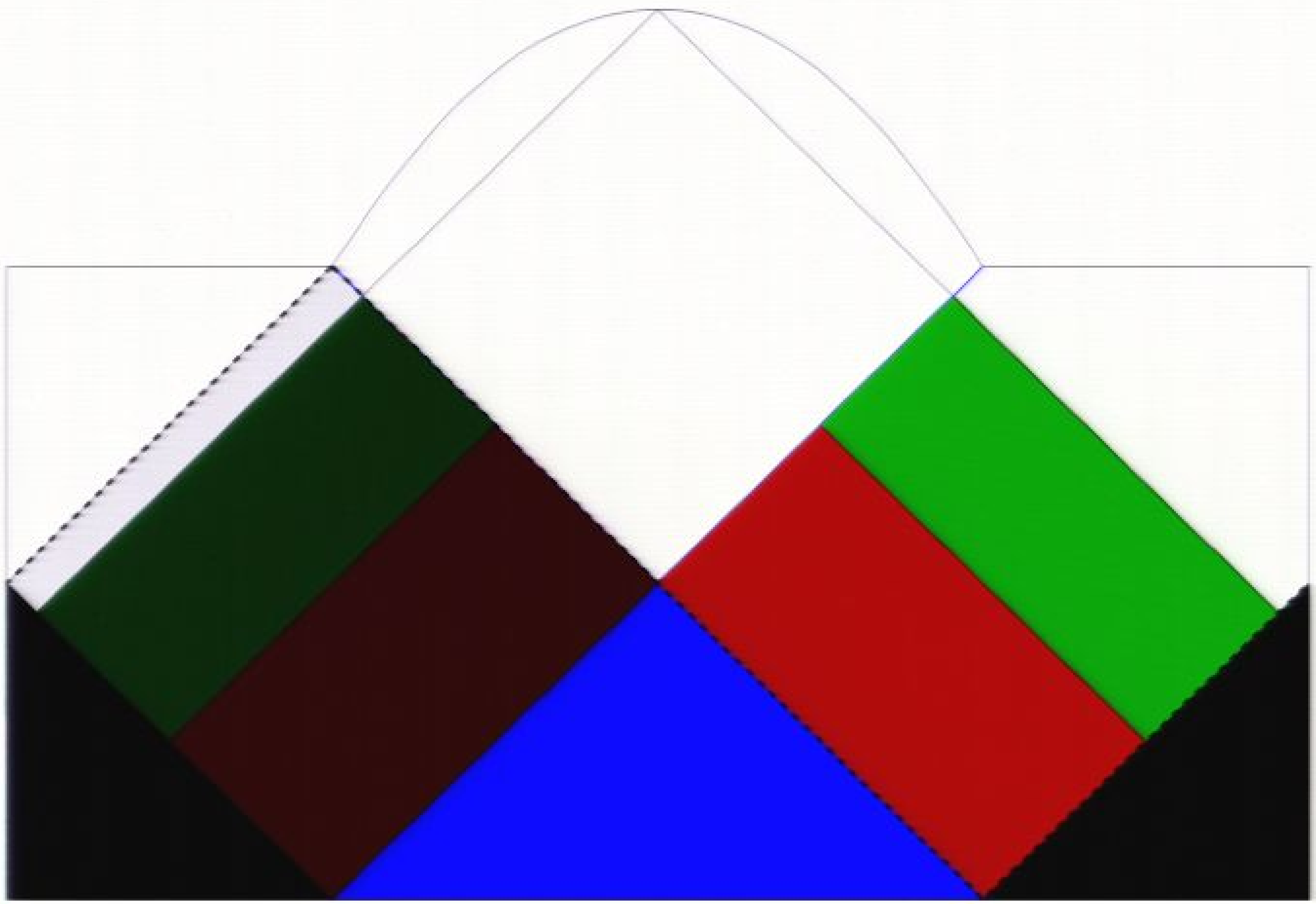


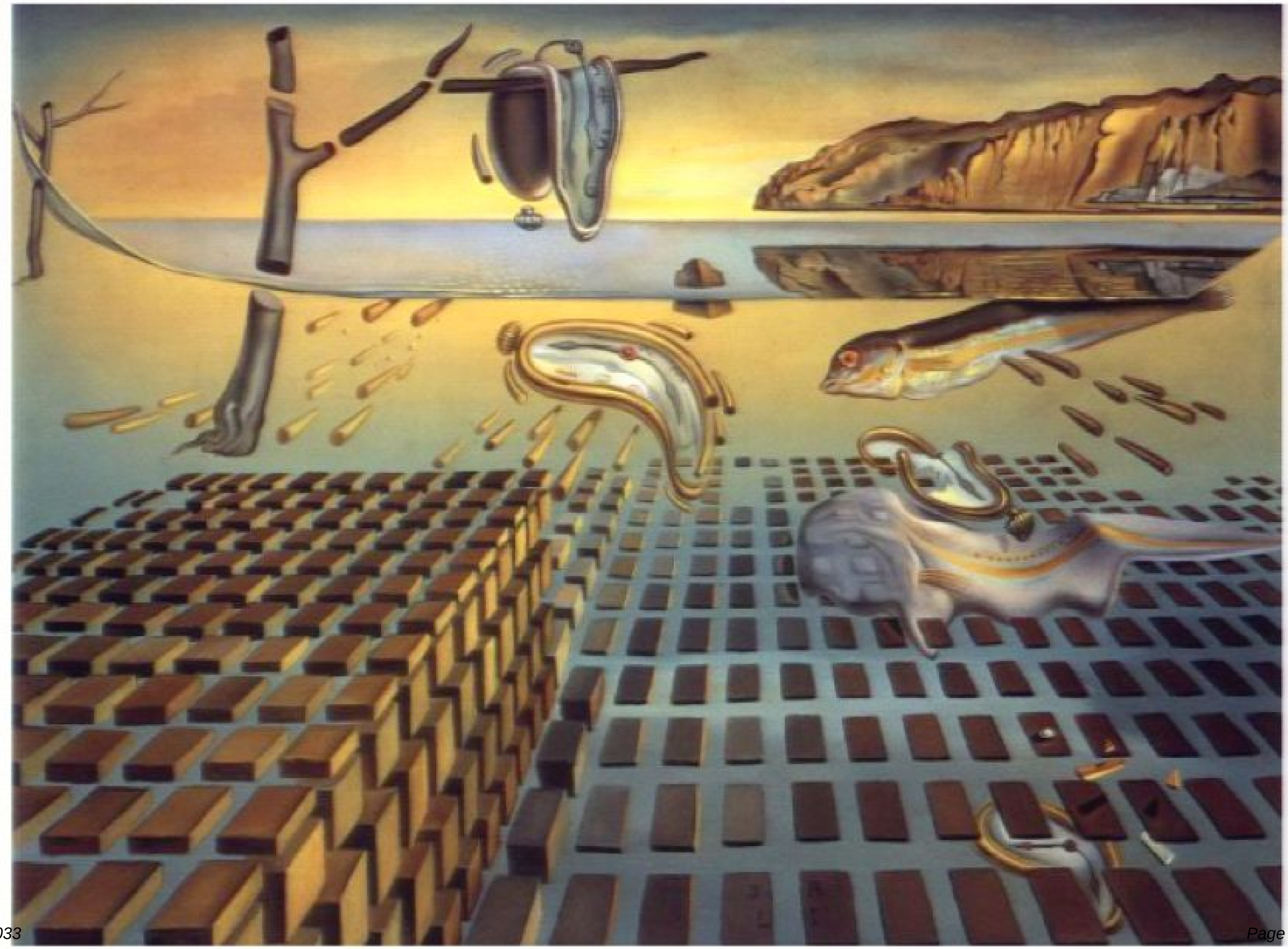
$$\Delta N \approx \frac{4\pi\gamma}{3} \log \frac{H_f}{H_i} \qquad (24)$$

So for natural parameter choices $\Delta N \ll 1$, and certainly

$$\frac{\Delta N}{N} \ll 1 \tag{25}$$

The Distribution is very nearly isotropic, and independent of boost.

The Disintegration of the Persistence of Memory!



Observability of Collisions

Direct gravitational waves coming from the collision will be stretched to huge wavelengths by inflation.
Best signal may be to look for effects on CMB.
Collisions give a distinctive signal. (Chang, Kleban, Levi)

The easiest collisions to see influence only part of the last scattering surface.
Danger: Too much slow roll inflation will stretch the signal far beyond our horizon.

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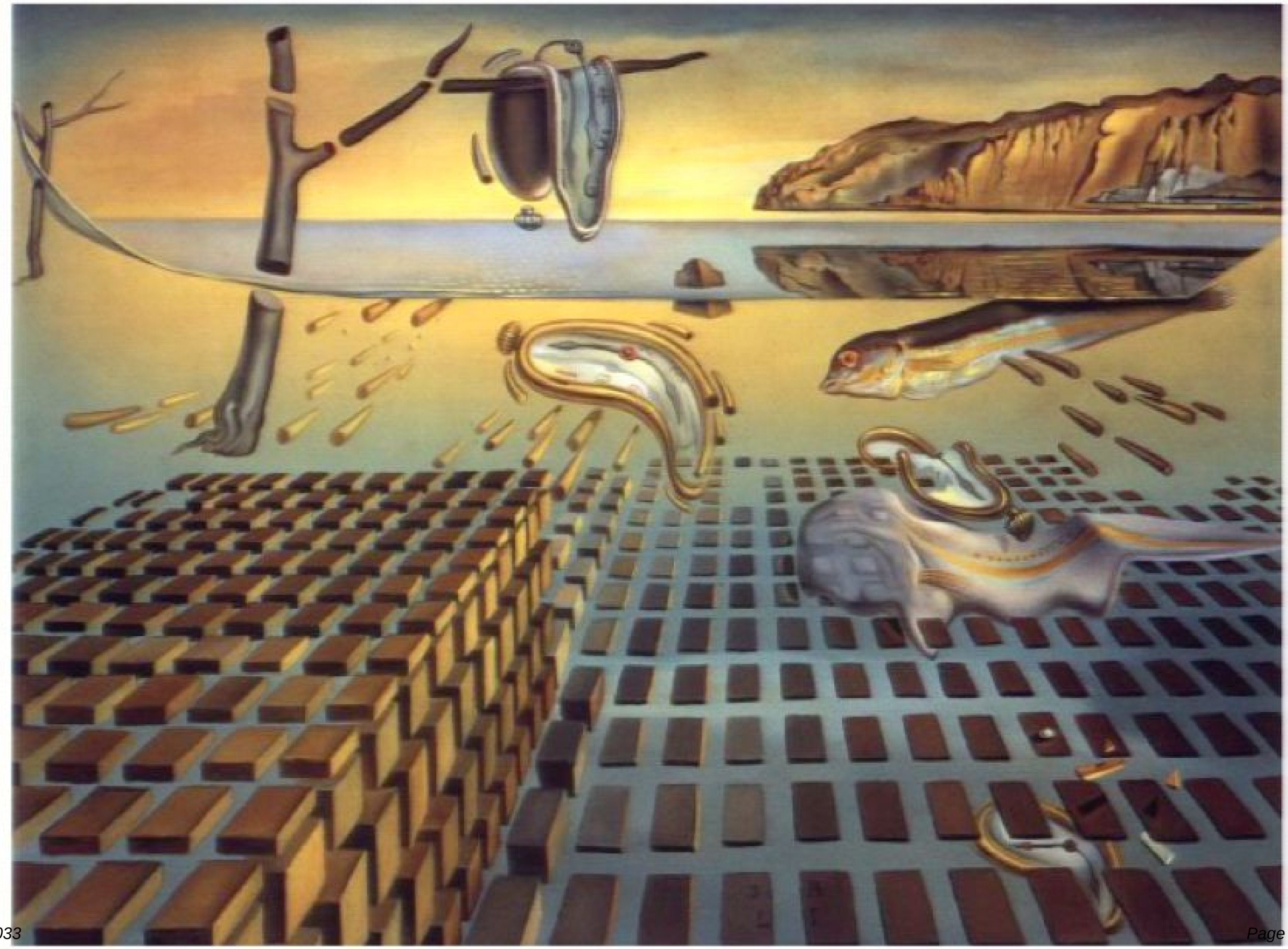

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Distribution at last scattering

Number of collisions which affect only part of the last scattering surface:

$$N_{LS} \approx 8\sqrt{\Omega_k(t_0)}\, N \tag{26}$$

Distribution of angular sizes is featureless,

$$dN \propto d(\cos\psi_{LS}) \ . \tag{27}$$

Future Directions

- Look for bubble collisions in the sky.
- More detailed analysis of the future of a collision: effects on inflation, reheating, etc.
- Analyze observational signatures in CMB
- More generally, what are the observational consequences of a tunneling event in our past?
  (power spectrum, tensor modes, ...)
- Does quantum gravity shed light on the problem of initial conditions, or on the attractor behavior of eternal inflation?
- How complete is the disintegration of the persistence of memory?