

Title: First Observational Tests of Eternal Inflation

Date: Feb 27, 2012 11:00 AM

URL: <http://pirsa.org/12020157>

Abstract: Inflation, a postulated epoch of accelerated expansion in the early universe, has become a principal component of the standard model of cosmology. From a wide variety of initial conditions, inflation produces a nearly homogeneous universe populated by density fluctuations that seed large-scale structure. However, inflation is such a good homogenizer that, once unleashed, in many cases it becomes eternal, ending only within spontaneously nucleated bubbles. In this scenario, our observable universe resides inside one such bubble. Surprisingly, it is possible to perform direct observational tests of eternal inflation. The most dramatic and detectable signatures of eternal inflation arise from the collision between bubbles in the very early universe, which leave an imprint on the cosmic microwave background (CMB) radiation. In this talk, I will motivate and describe the eternal inflation scenario and present the results of a search for the signatures of eternal inflation in CMB data from the Wilkinson Microwave Anisotropy Probe.

# First observational tests of eternal inflation

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Perimeter Institute

**Collaborators:**

**S. Feeney, J. McEwan, D. Mortlock, H. Peiris**  
**M. Larfors, A. Shomer**  
**A. Aguirre, S. Carroll, L. Randall, I-S. Yang**  
**L. Lehner, S. Liebling**

## Outline

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How big is the universe?

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Modern ideas in cosmology:  
Dark energy; Inflation

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Our observable universe might be just  
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### How big is the universe?

Modern ideas in cosmology:

Dark energy; Inflation

Issues in theoretical physics:

Vacuum non-unique

**Experimentally verifiable!**

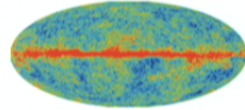
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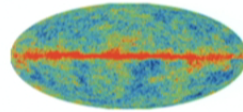
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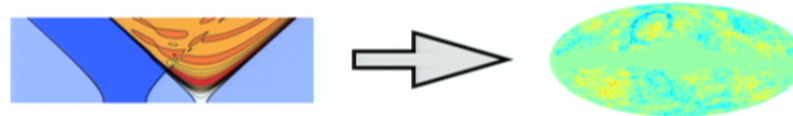
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$$\text{wavy line} + \Lambda = \text{bubble diagram}$$

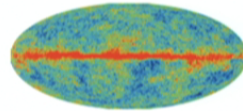
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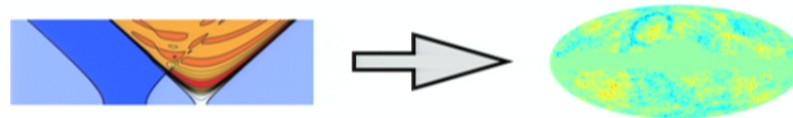
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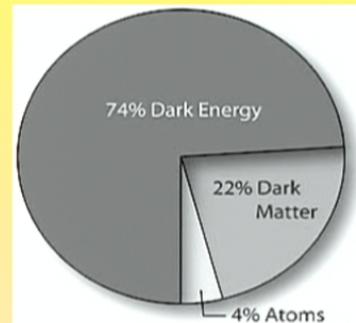
- WMAP 7-year data analysis: Is there any evidence?

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# What we know

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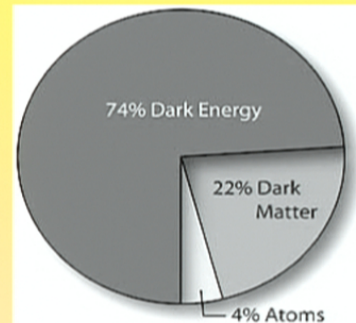
- We live in a nearly **flat, accelerating universe**, composed almost entirely of **dark energy** and dark matter, seeded by **nearly scale invariant gaussian adiabatic density perturbations**.



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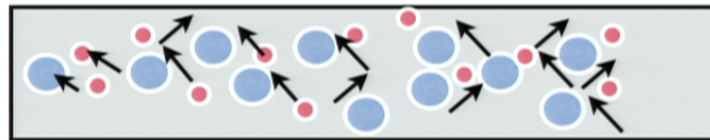
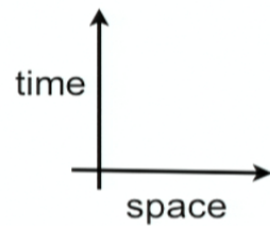
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How do we know it?

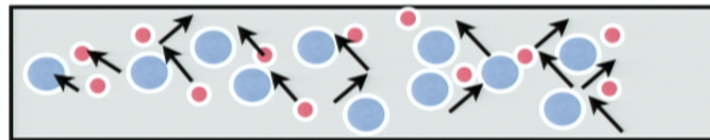
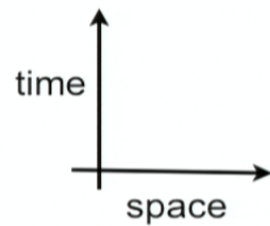
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- Temperature anisotropies encode density perturbations.



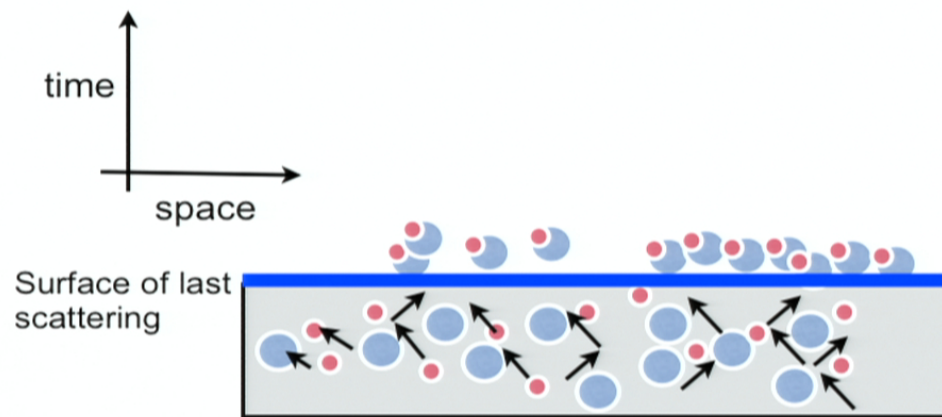
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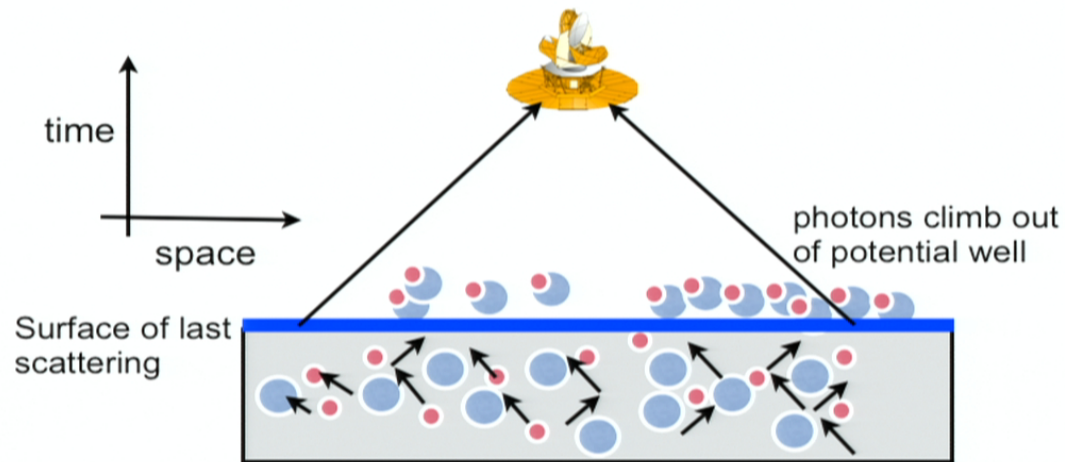
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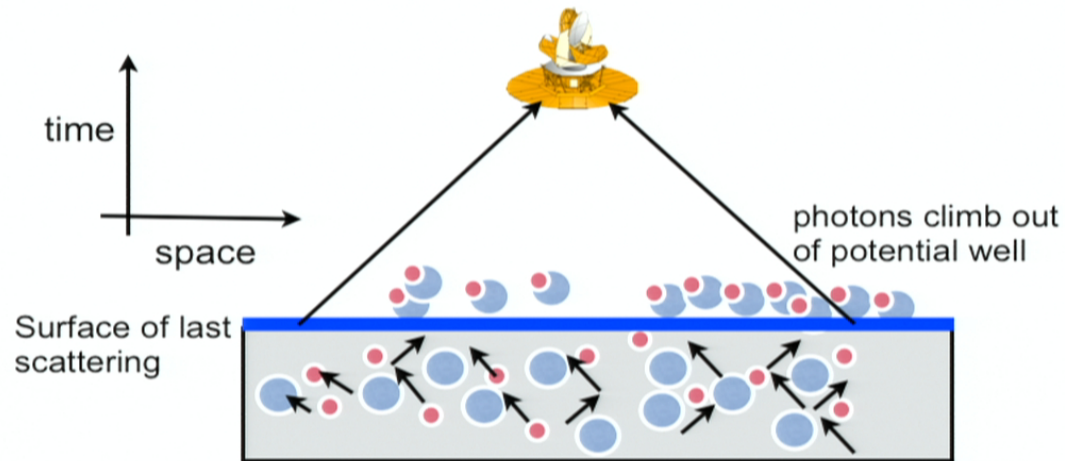
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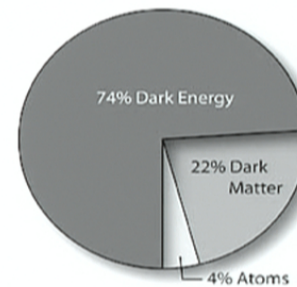
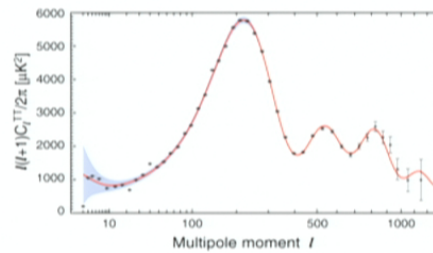
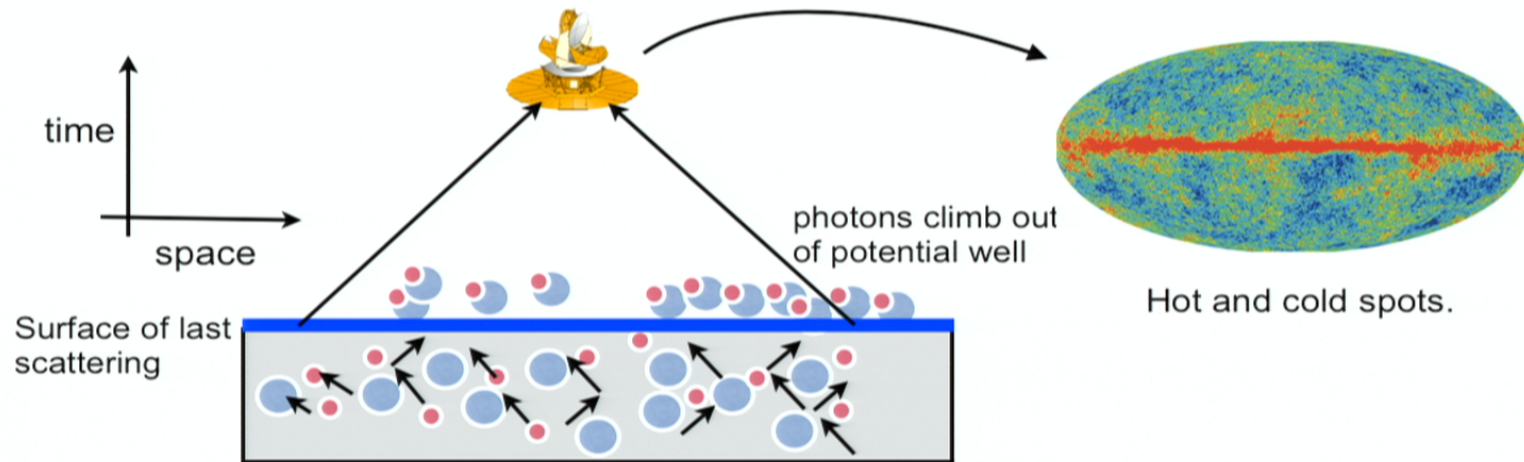
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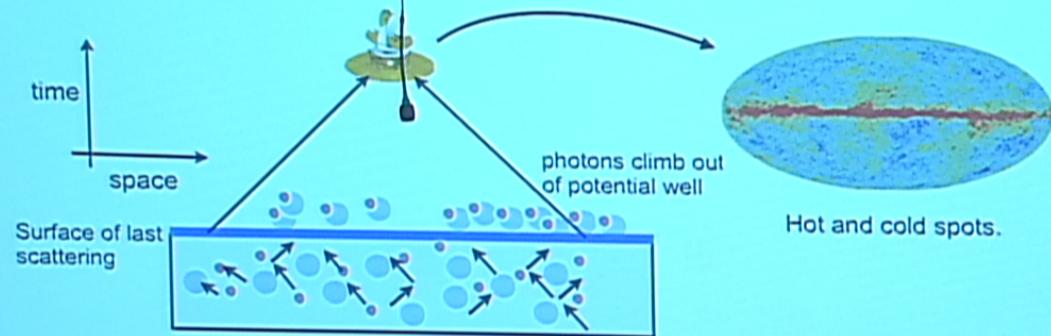
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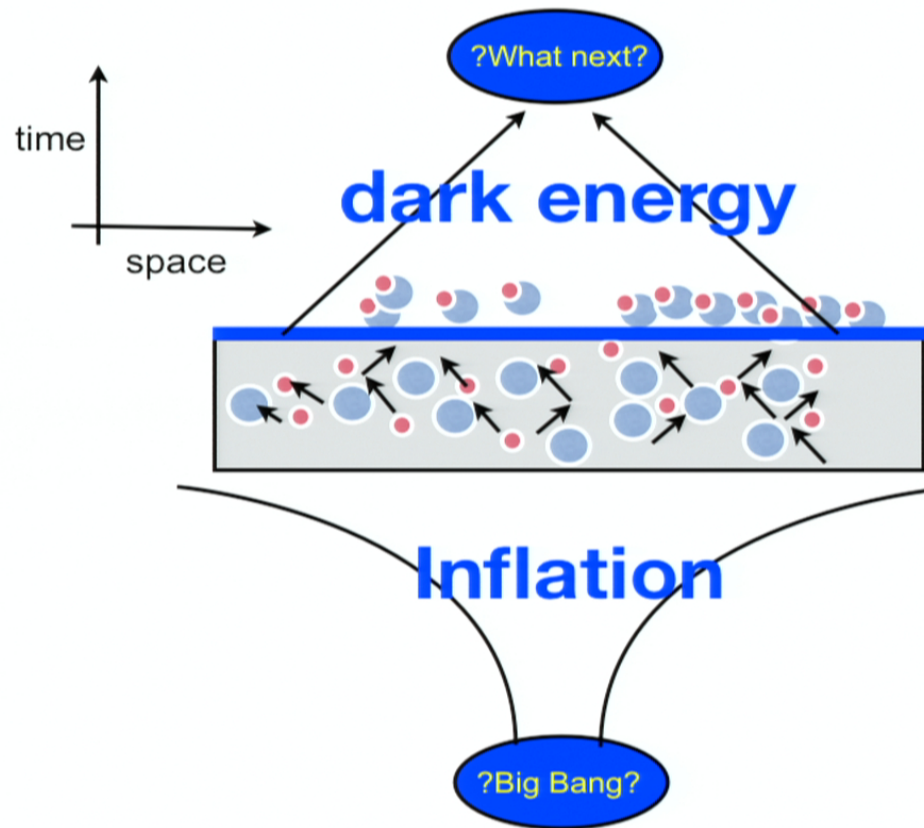
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# $\Lambda$ CDM

# Accelerated expansion



Strong evidence for at least two epochs of accelerated expansion.

# The big questions

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- Evidence for accelerated expansion has lead us ask to some truly fundamental questions!

How did the thermodynamic arrow of time arise?

Is the current accelerated expansion due to vacuum energy?  
If so, why is the density so small compared to particle physics scales?

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How big is the universe?  
Are there other universes?

Are there other forces?

What is dark energy and what is responsible for inflation?

# The big questions

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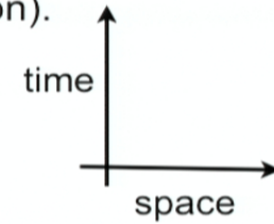
- Answering any of these questions would yield invaluable insight into the fundamental laws of nature.
- One answerable question which has surprisingly broad implications for all of these big questions:

How does accelerated expansion begin and end?

A question both for theory *and* observation!

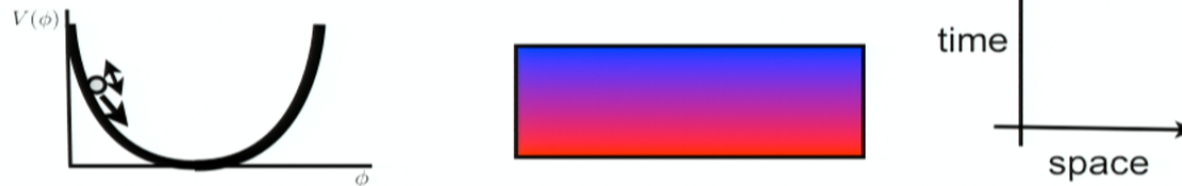
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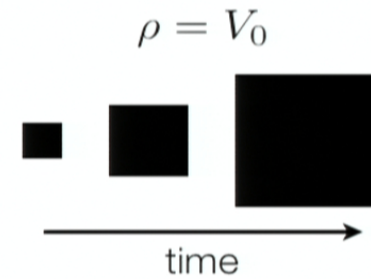
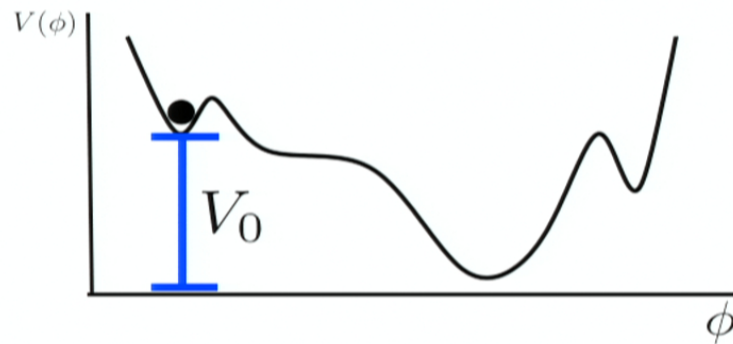


Begins but does not end anywhere (cosmological constant).

$$G_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

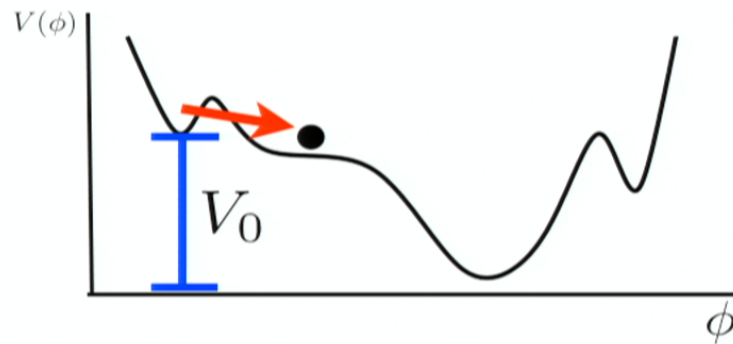


## When accelerated expansion ends locally



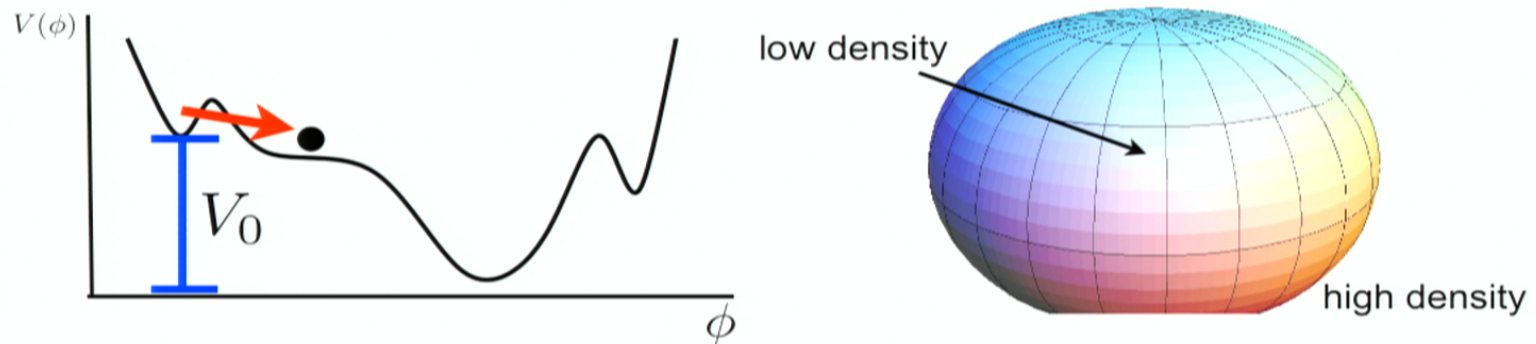
Classically, the universe undergoes accelerated expansion forever.

## When accelerated expansion ends locally



Quantum mechanically, the field tunnels through the barrier!

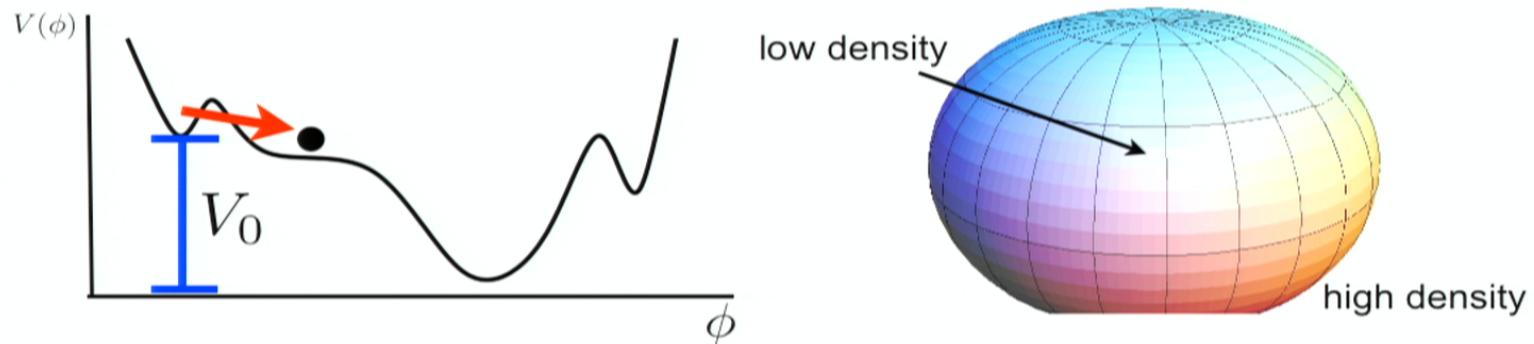
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Quantum mechanically, the field tunnels through the barrier!

- Doesn't happen everywhere, only inside bubbles.

## When accelerated expansion ends locally



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- Doesn't happen everywhere, only inside bubbles.
- The probability per unit time per unit volume to form a bubble:

$$\lambda = A e^{-S_E} \quad S_E \propto \frac{\sigma^4 \text{ (surface tension)}}{\Delta V^3 \text{ (energy difference)}}$$

Typically, the probability is quite small.

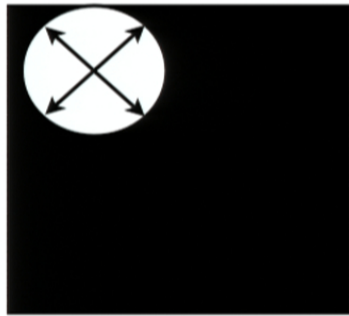
Coleman  
Coleman & de Luccia



# Does the accelerated expansion ever end?

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- In a static or decelerating universe:



time →

# Does the accelerated expansion ever end?

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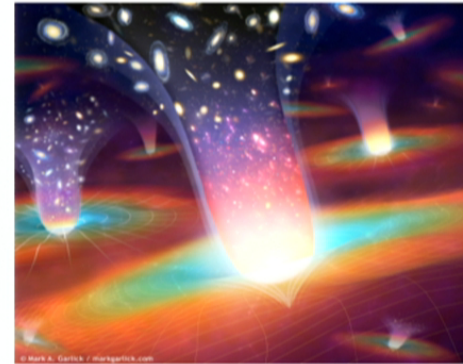
- In an accelerating universe:



# Eternal Inflation

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- Eternal inflation: the Universe is infinitely big!

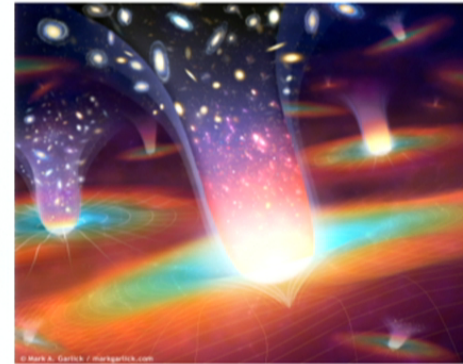
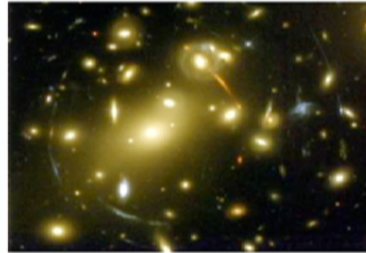


Intrinsically interesting!  
Also well-motivated!

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- How does our observable universe fit into this picture?

Vacuum decay could be in our past.



Alan Guth's original  
proposal for inflation:

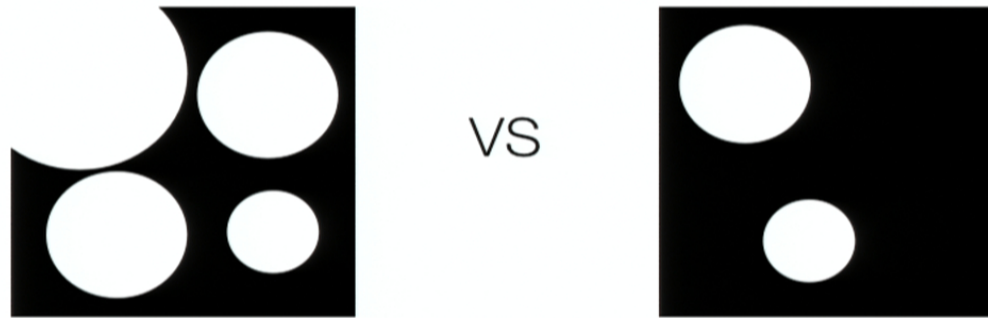


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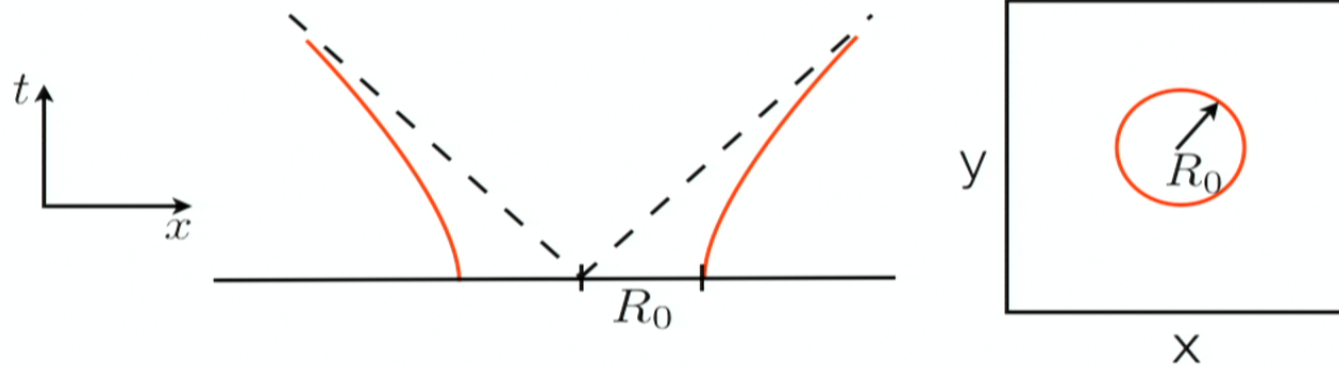
Problem: single bubbles contain a dead open universe.

open universe: symmetries of a spherically symmetric  
bubble expanding with constant acceleration

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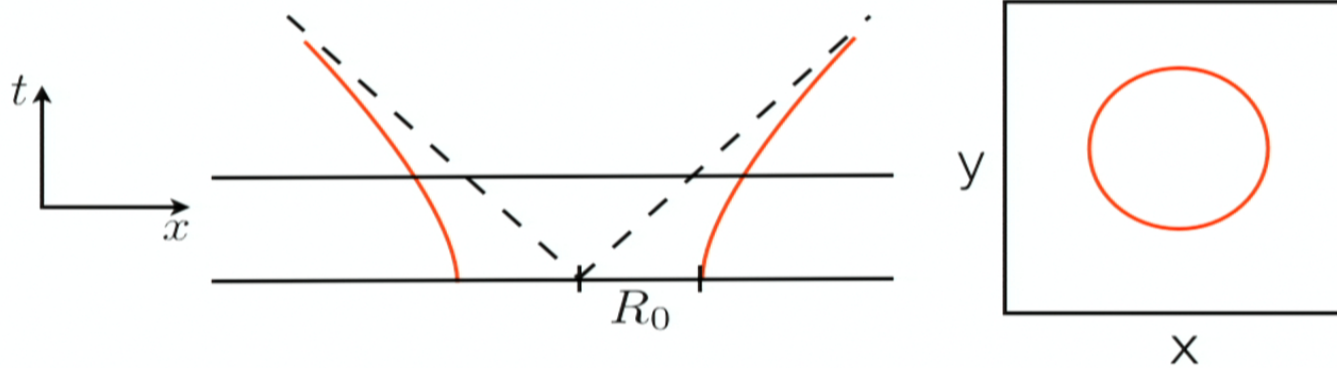
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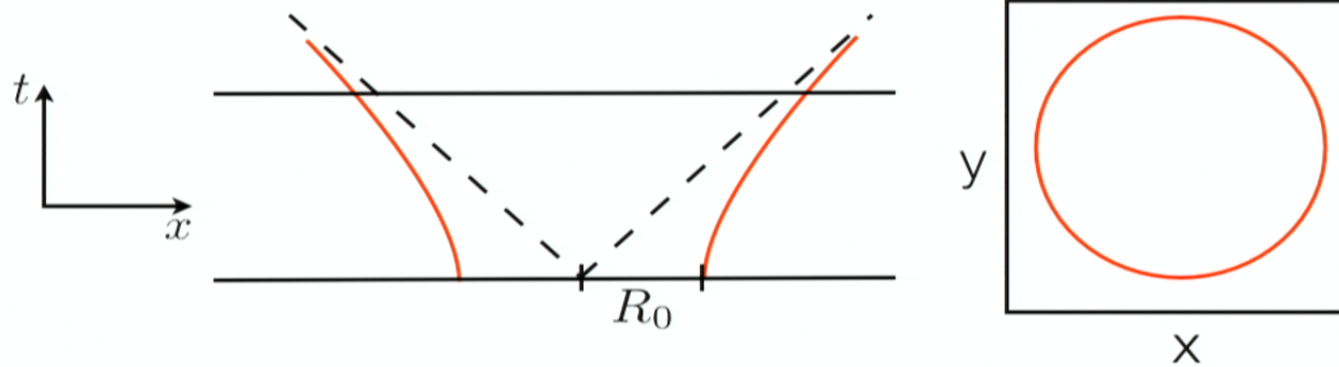




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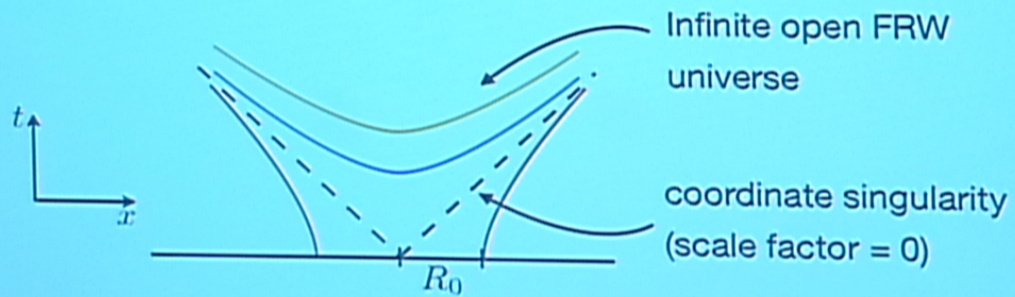
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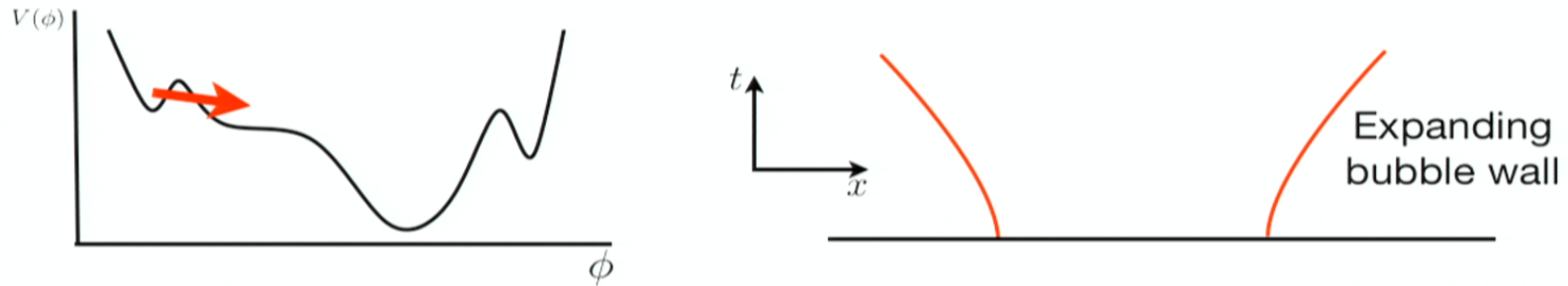
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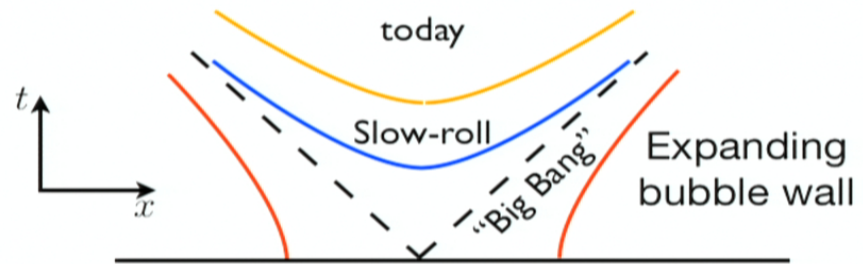
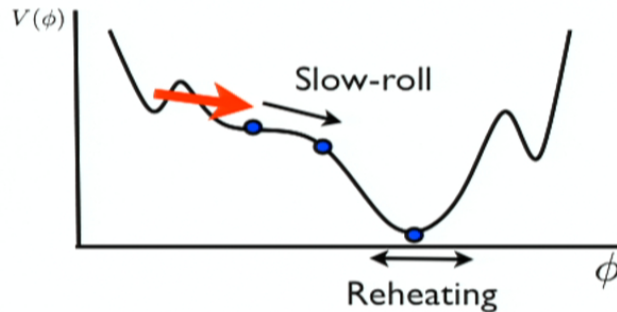
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"Open Inflation" - Bucher, Goldhaber, Turok; Gott

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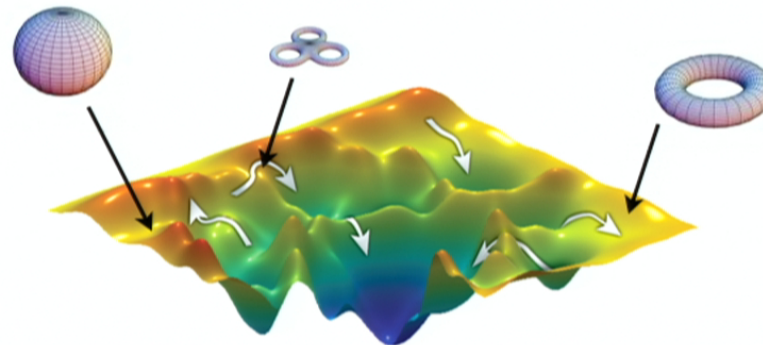


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Potential "Landscape"  
of string theory

Susskind



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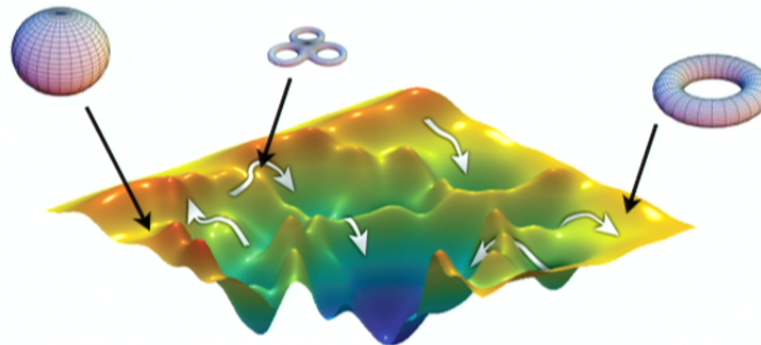


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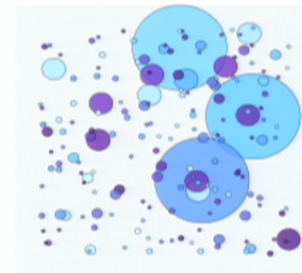
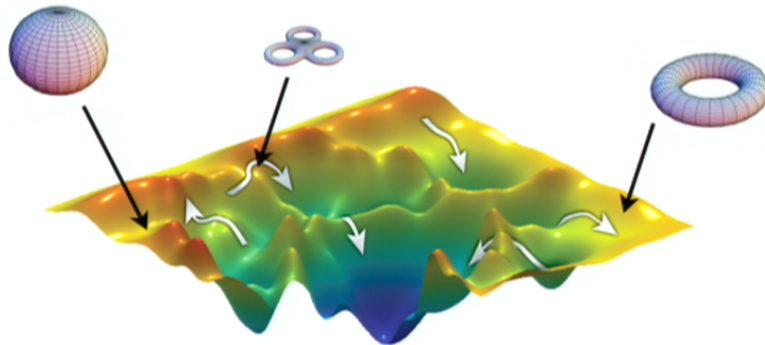
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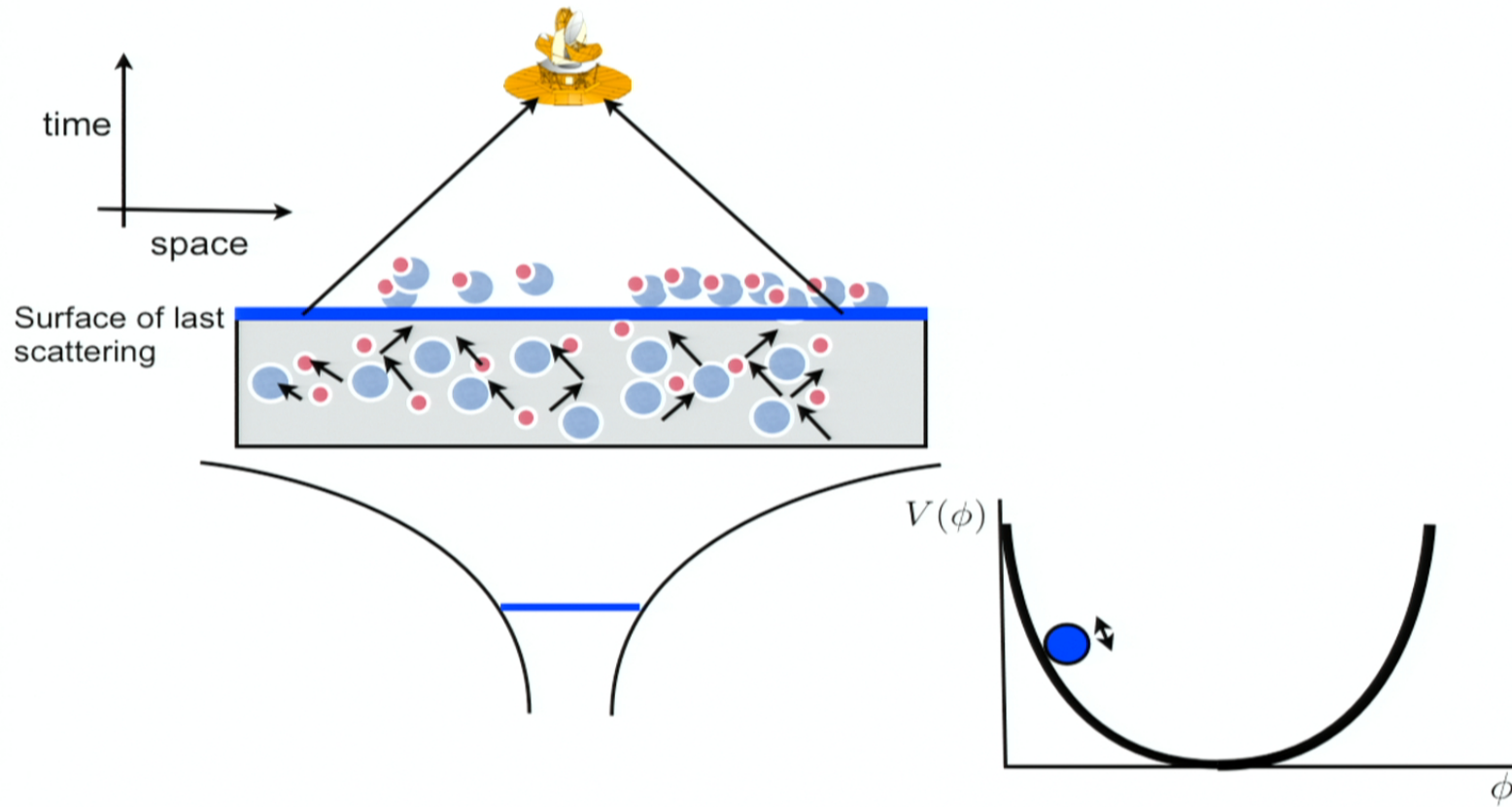
- How does our observable universe fit into this picture?

Eternal inflation is nearly inevitable in string theory.

- Positive energy vacua generically drive eternal inflation.
- Many states can be populated.



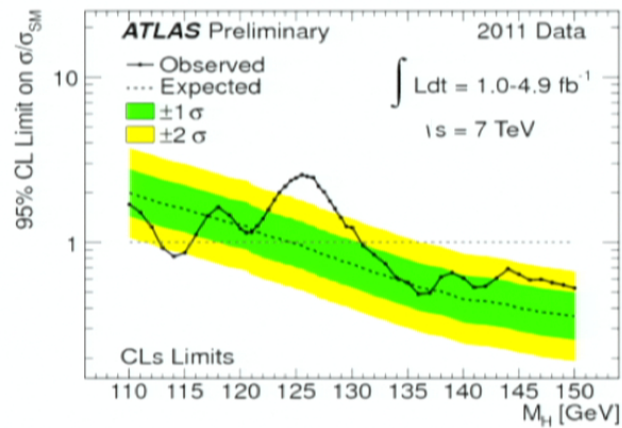
# Another variant of the eternal inflation scenario



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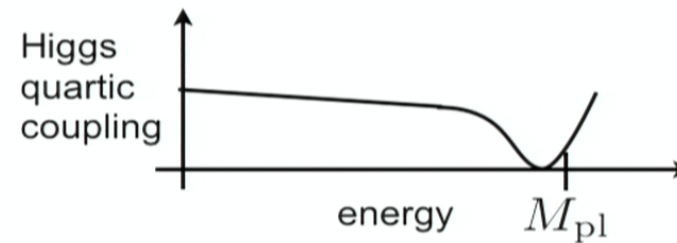
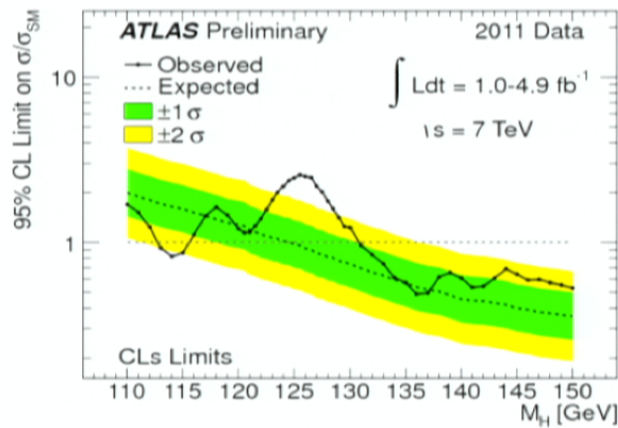
Decay could be in our future.



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In the Standard Model,  
our vacuum can be unstable,  
giving rise to eternal inflation.

(Don't panic, in this case, we have many years before our vacuum expires.)

Sher  
Lindner & Sher  
Arkani-Hamed et. al.

latest bound: Elias-Miro et. al.

# Really?

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- An infinite number of individually infinite universes in an infinite expanding background?

Surely I can't be serious!

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(possible in standard model)

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(inevitable in string theory)

Quantum field  
theory

(works fantastically)

accelerated  
expansion

(observed: dark energy)  
(inferred: inflation)



# Observational Tests of Eternal Inflation

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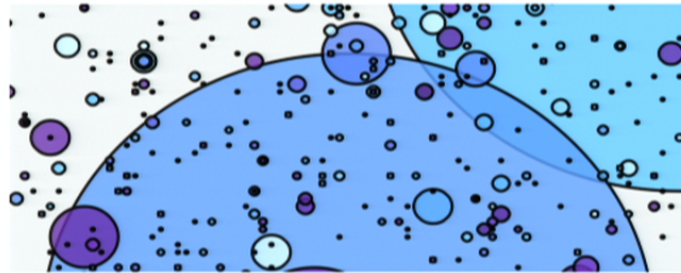
- Strong theoretical motivation, but is eternal inflation experimentally verifiable?

# Observational Tests of Eternal Inflation

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Our bubble does not evolve in isolation....



The collision of our bubble with others provides an observational test of eternal inflation.

Aguirre, [MCJ](#), Shomer

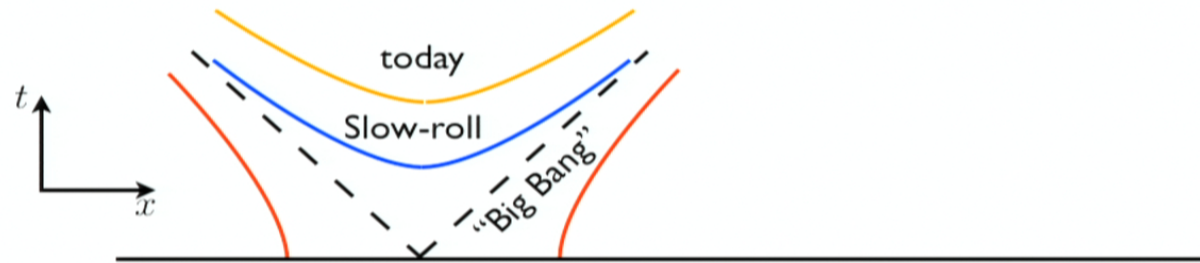
# Detecting cosmic bubble collisions

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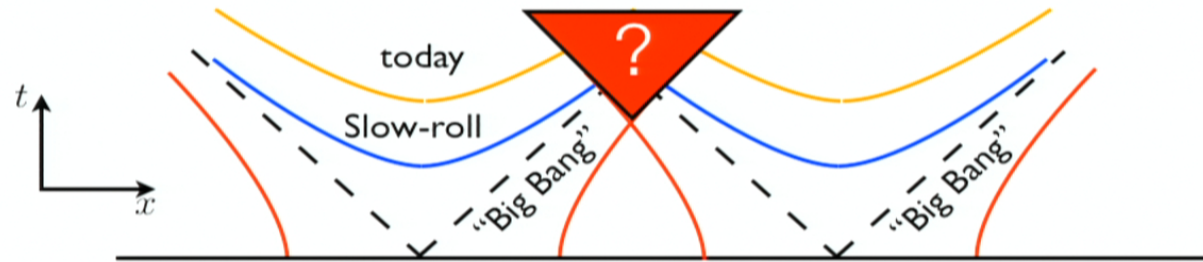
- The aftermath of bubble collisions.
- A generic signature of bubble collisions.
- Counting collisions.
- A search in WMAP data for bubble collisions.
- What next?

# Bubble collisions

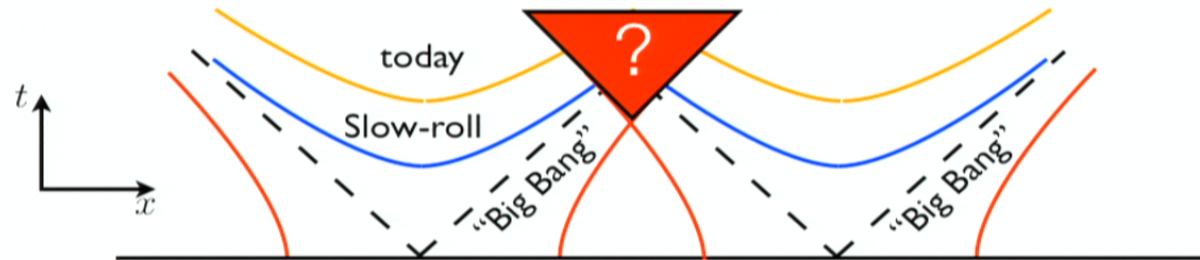
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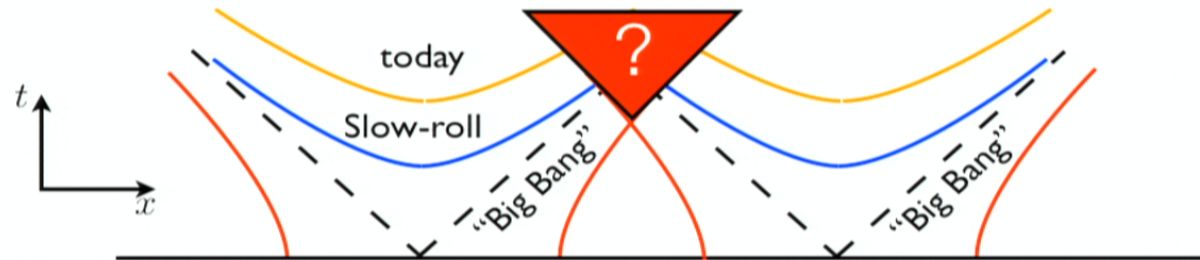


# Bubble collisions



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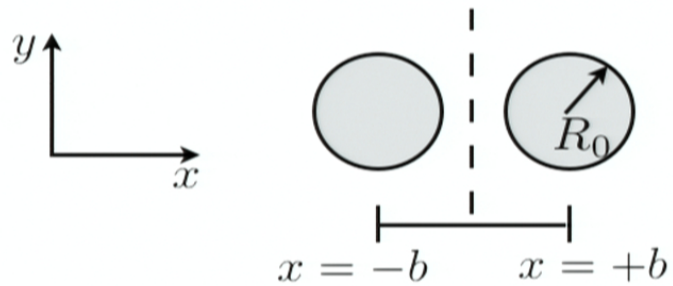


- Collisions are always in our past.
- The outcome is fixed by the potential and kinematics.
- To study what happens, need full GR.
  - We want to find the post-collision cosmology: GR.
  - Huge center of mass energy in the collision.
  - Non-linear potential, non-linear field equations.

# Symmetries

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- Symmetries of the collision spacetime:



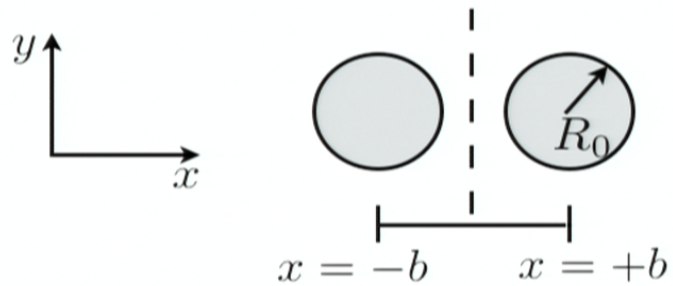
$$(x \pm b)^2 + y^2 + w^2 - t^2 = R_0^2$$



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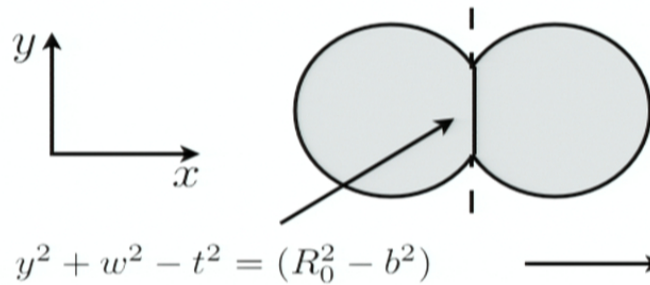
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# Symmetries

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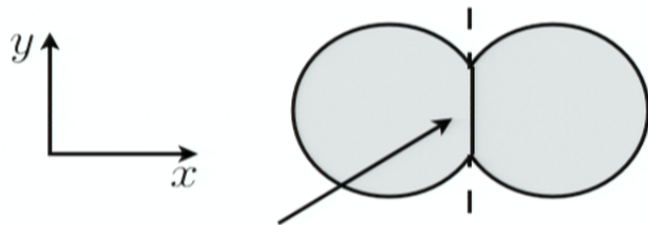
$$(x \pm b)^2 + y^2 + w^2 - t^2 = R_0^2$$

Collision spacetime has  $SO(2,1)$  symmetry

Hawking, Moss, Stewart

# Symmetries

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$$(x \pm b)^2 + y^2 + w^2 - t^2 = R_0^2$$

$$y^2 + w^2 - t^2 = (R_0^2 - b^2)$$

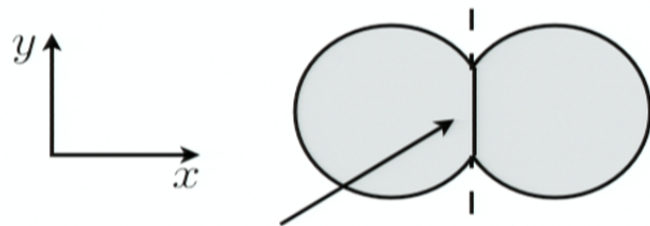
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Hawking, Moss, Stewart

- There are enough symmetries to reduce the problem to 1 space and 1 time dimension.

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- There are enough symmetries to reduce the problem to 1 space and 1 time dimension.

Analytic solutions: kinematics, causal structure.

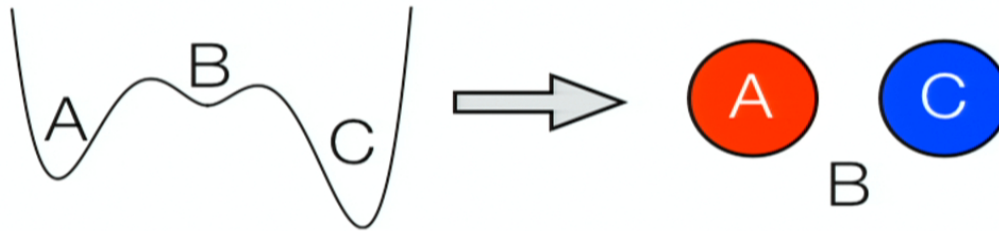
Numerical solutions: dynamics.

# Analytic solutions

Aguirre and MCJ

MCJ and Yang

- Israel Junction Conditions: causal structure, kinematics.

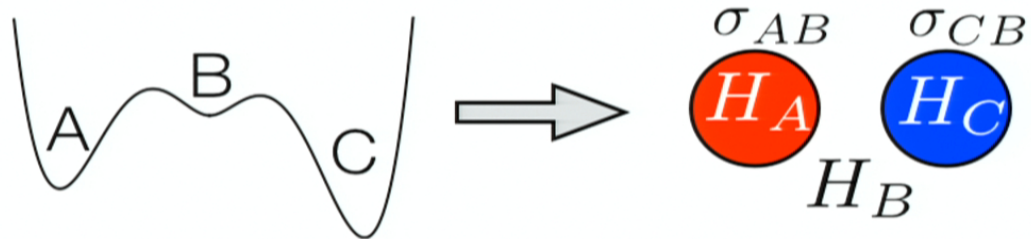


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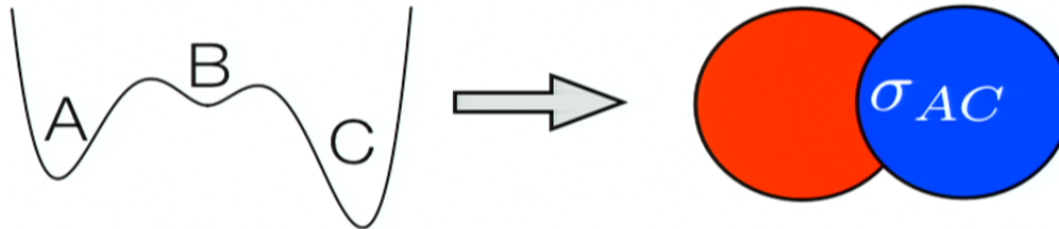


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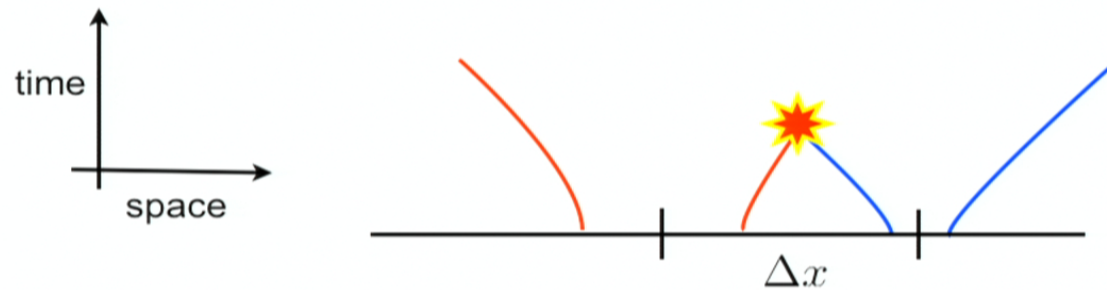


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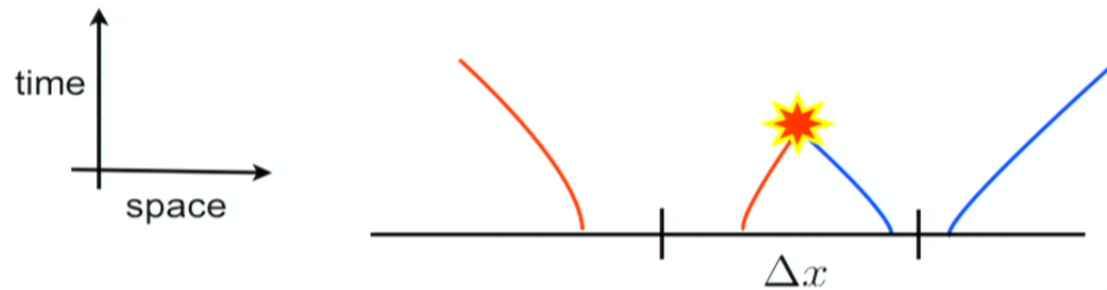


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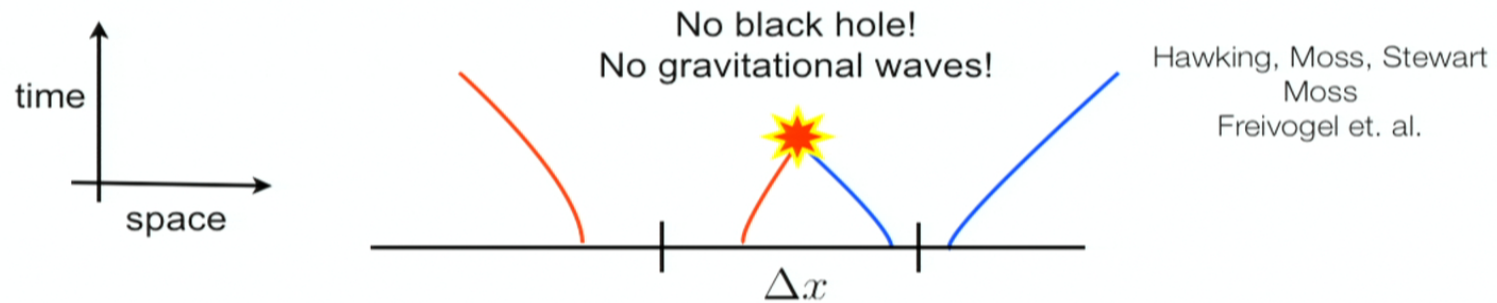


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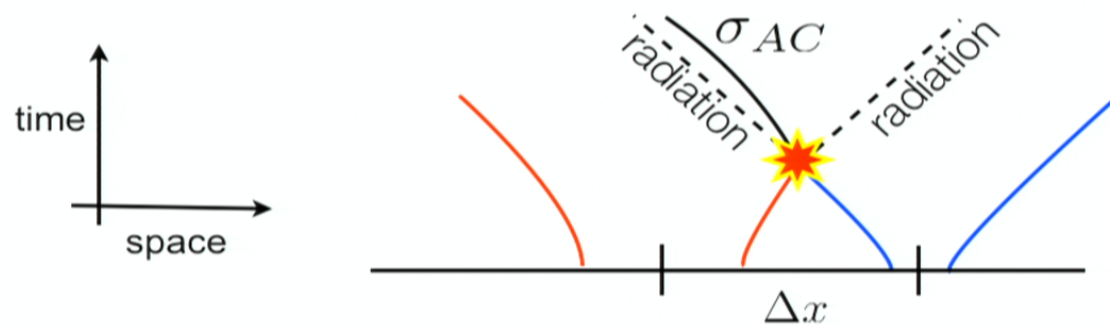


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Bubble with lower energy interior wins!

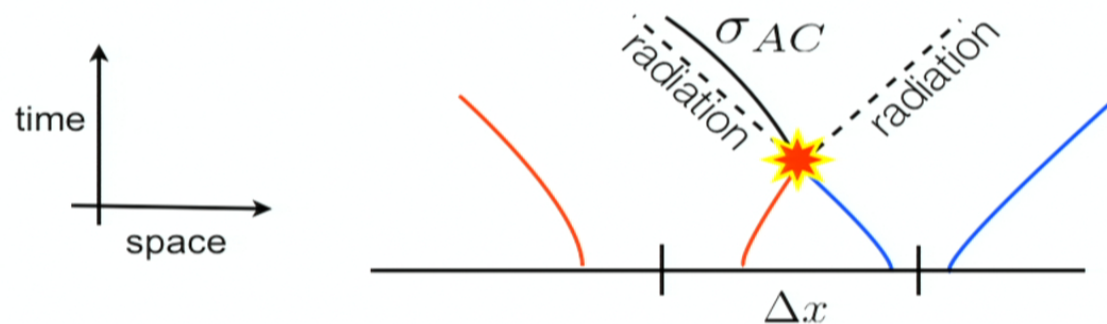
$$H_A^2 - H_B^2 + 16\pi^2 \sigma_{AC}^2$$

# Analytic solutions

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Bubble with lower energy interior wins!

$$H_A^2 - H_B^2 + 16\pi^2 \sigma_{AC}^2$$

- Complete classification of causal structure.
- First hints of the observational signatures of bubble collisions.

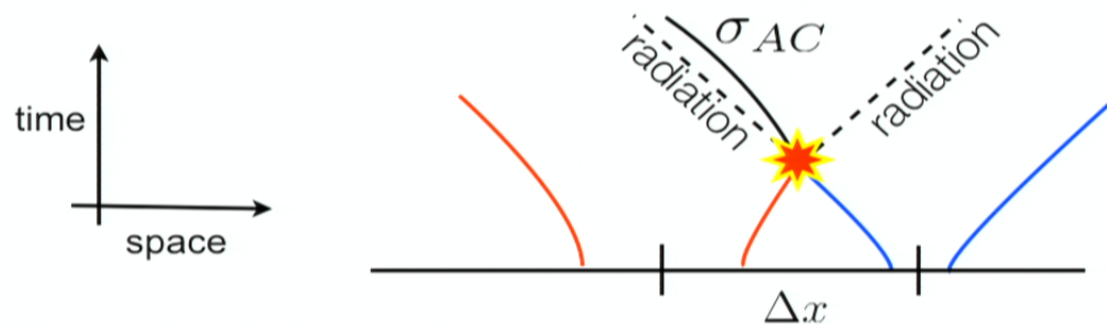
Also Chang et. al.

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# Analytic solutions

Aguirre and MCJ

MCJ and Yang

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Israel Junction conditions: can only tell us what is kinematically allowed!

Numerical simulations are necessary to determine dynamically what actually happens!

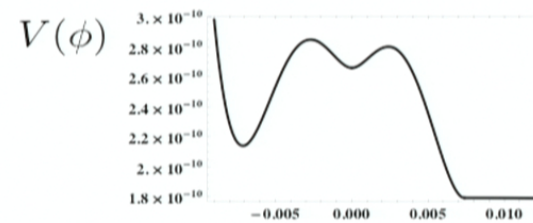
# Numerical solutions

MCJ, Lehner, Peiris

MCJ, Lehner, Liebling, Peiris

- Numerical simulations with full GR: full dynamics.

$$ds^2 = -\alpha(x, z)dz^2 + a(x, z)dx^2 + z^2 dH_2^2 \quad \phi(x, z)$$



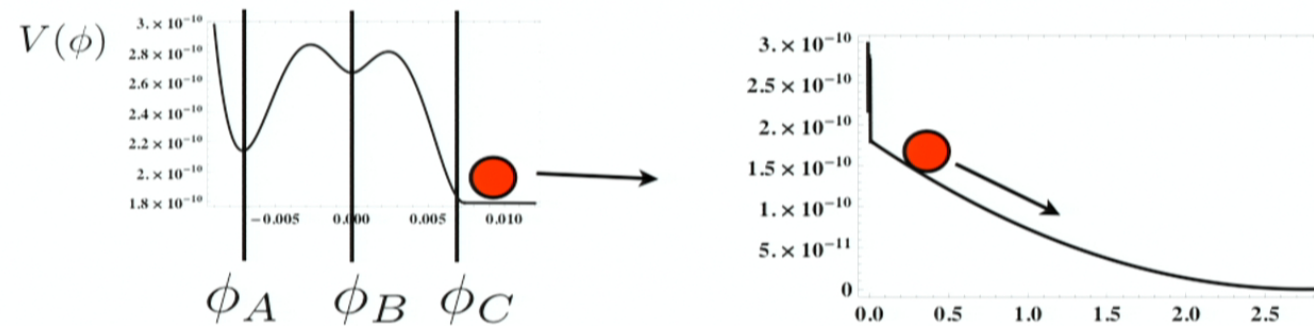
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- 2 types of bubbles from false vacuum.
- Slow roll inflation inside one, starting near  $\phi_C$  .

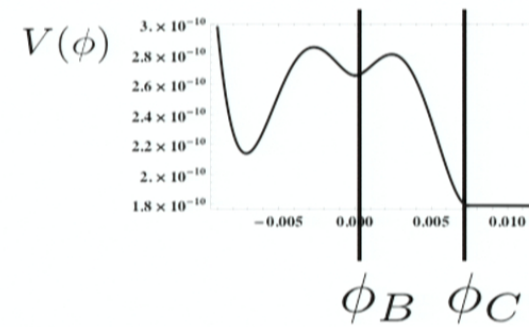
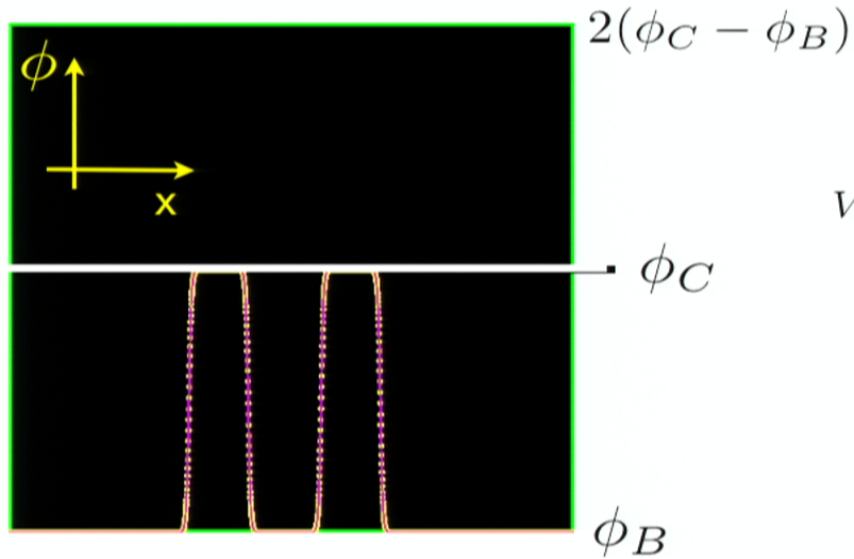


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MCJ, Lehner, Peiris

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- Colliding identical bubbles.

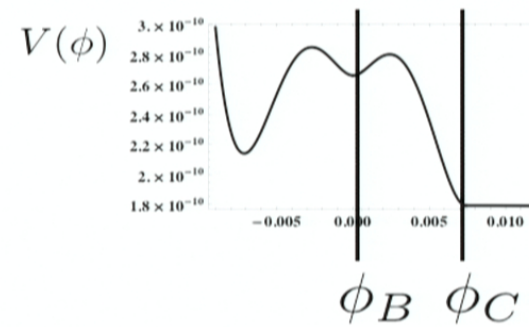
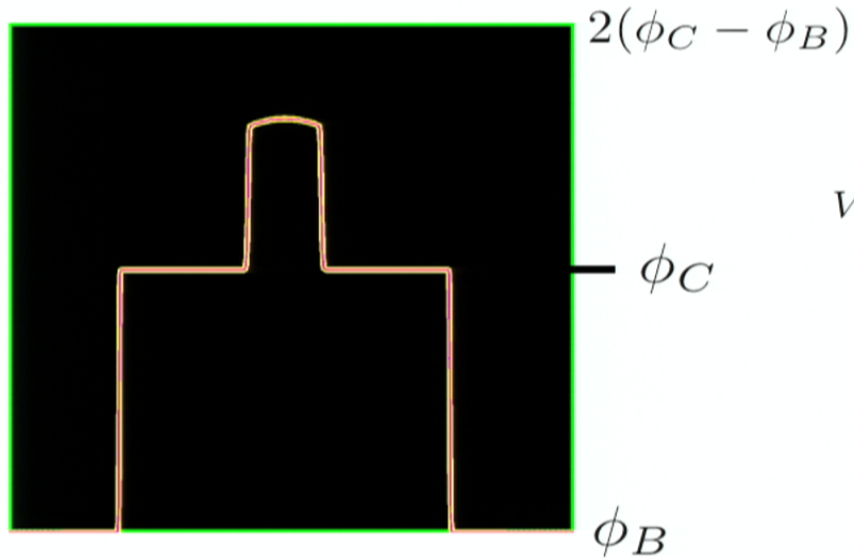


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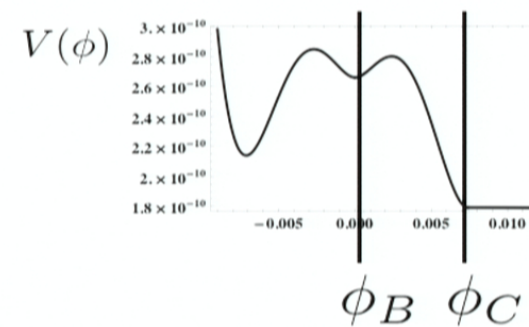
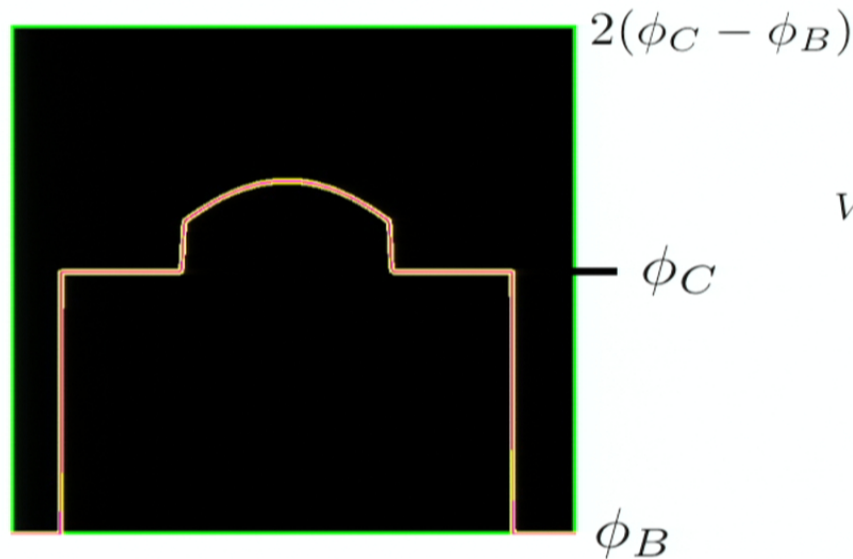


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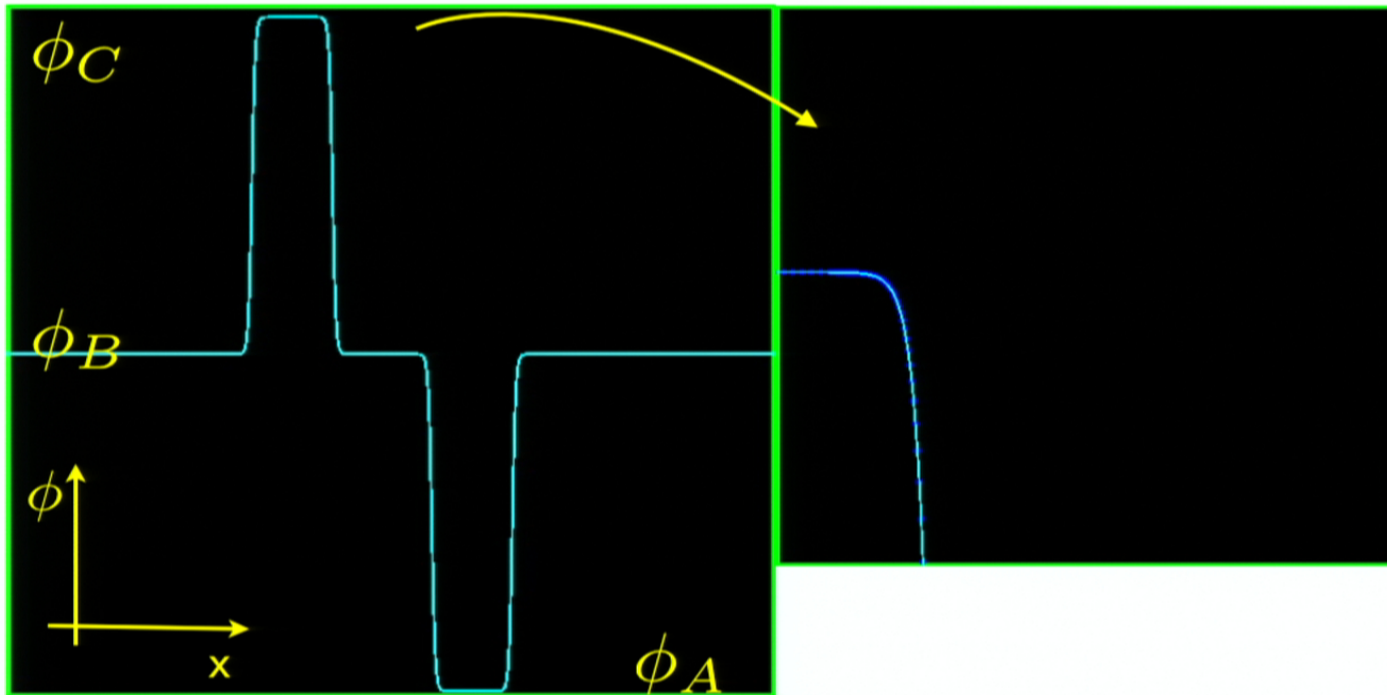
- After the collision, fields linearly superpose: potential key.  
Same effect as in classical transitions.
- Dynamics necessary!

# Numerical solutions

MCJ, Lehner, Peiris

MCJ, Lehner, Liebling, Peiris

- Colliding different bubbles.

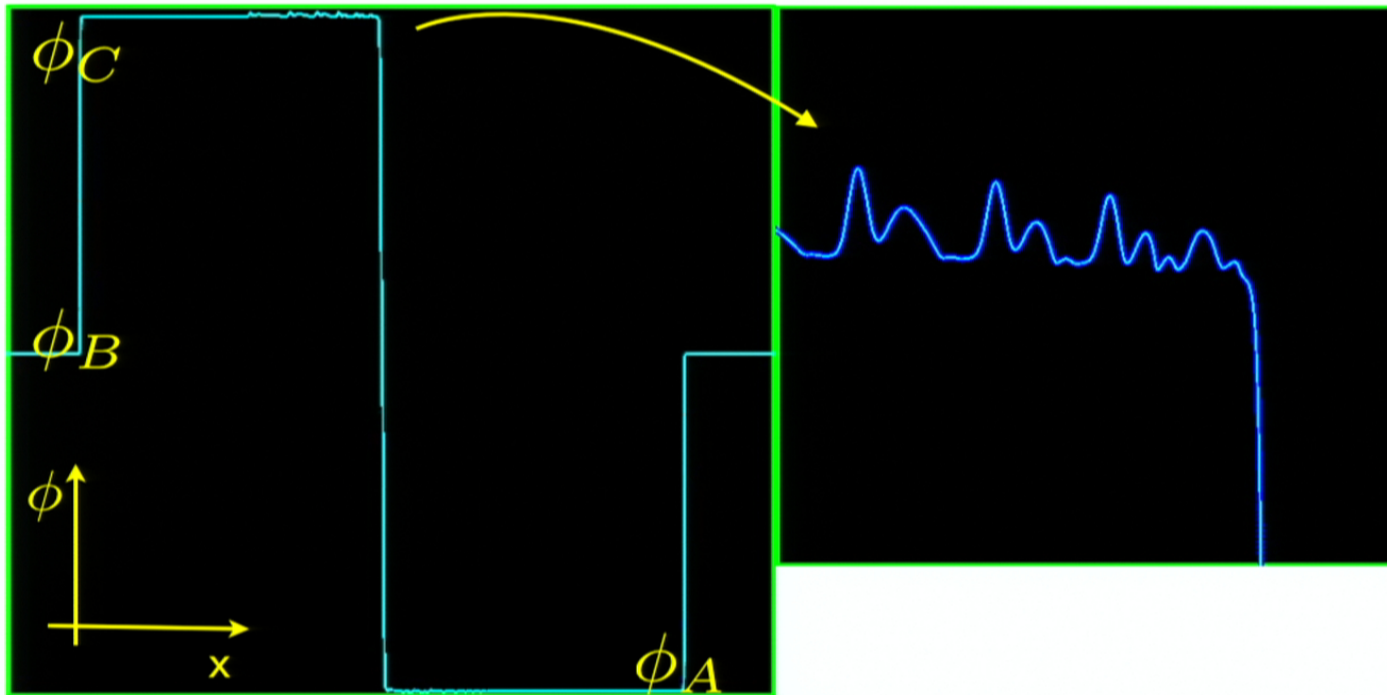


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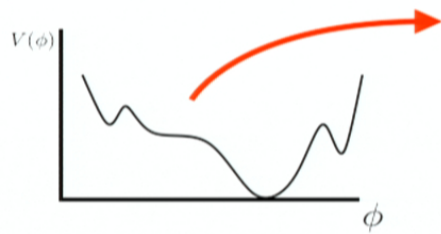




# Observational Signatures

Feeney, MCJ, Mortlock, Peiris

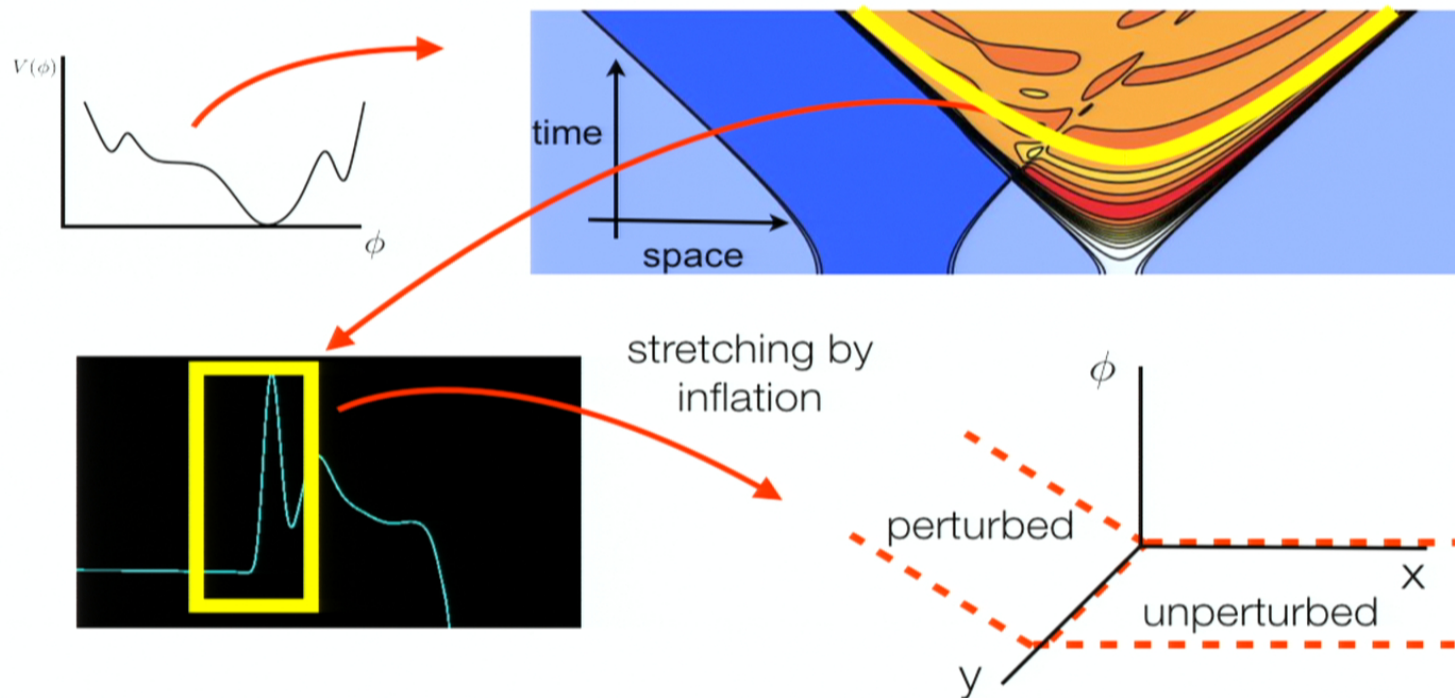
- Bubble collisions perturb the epoch of inflation inside our bubble.



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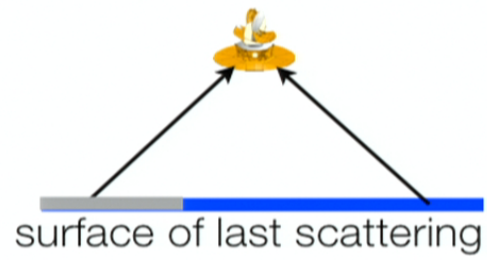
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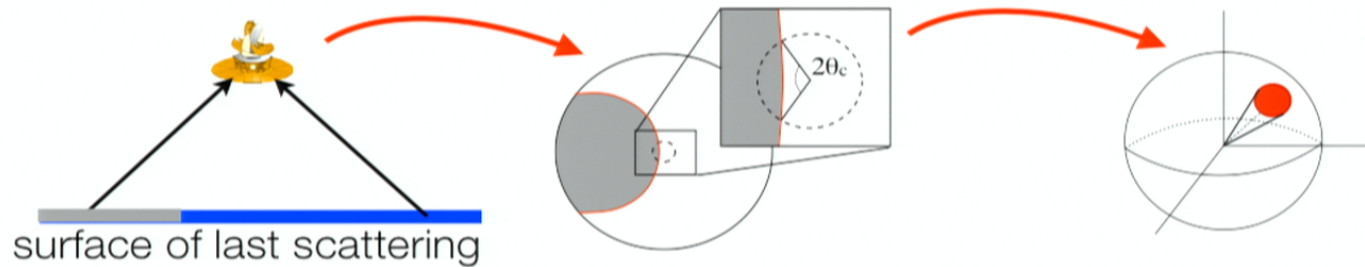
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Feeney, [MCJ](#), Mortlock, Peiris



# Observational Signatures

Feeney, MCJ, Mortlock, Peiris



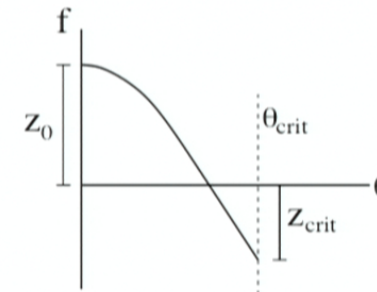
Symmetry+causality: effects confined to a disc.

- Generic signature (thanks inflation!):

$$\frac{\Delta T(\hat{\mathbf{n}})}{T} \simeq f(\hat{\mathbf{n}}) + \delta_{\Lambda\text{CDM}}(\hat{\mathbf{n}})$$

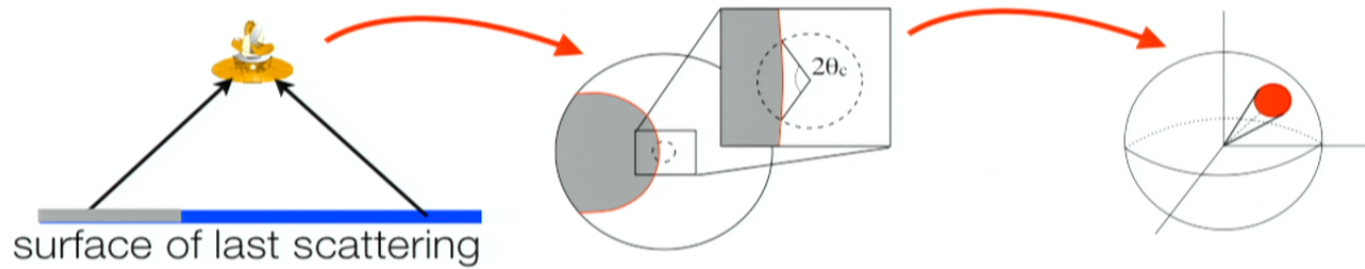
$f$  : analytic arguments and numerics

Feeney, MCJ, Mortlock, Peiris  
Chang, Kleban, Levi  
Gobetti & Kleban



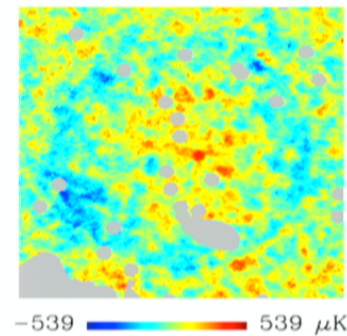
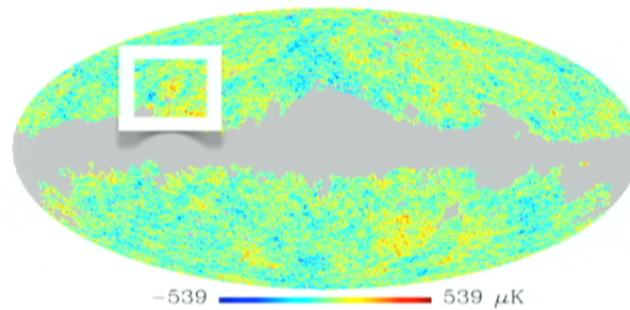
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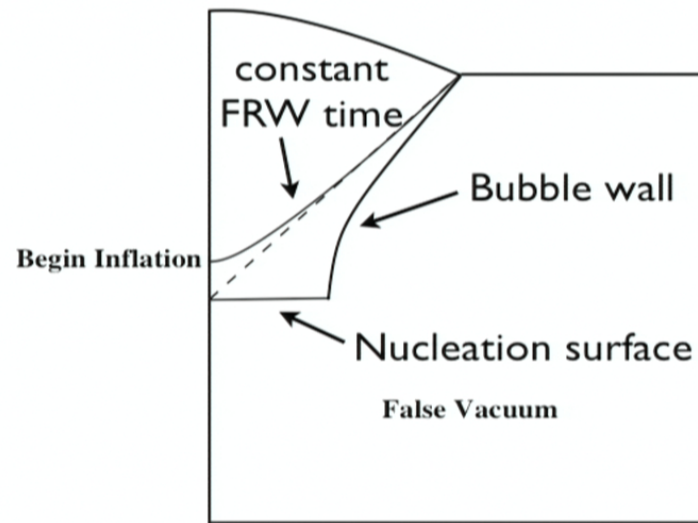


# Counting collisions

Aguirre, MCJ, Shomer

Aguirre, MCJ

- How many collisions are there?

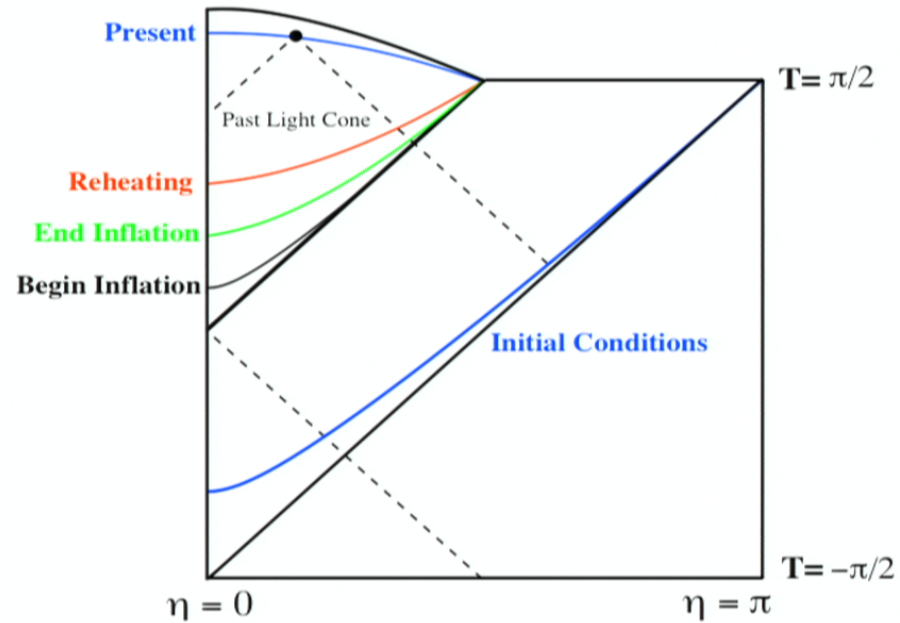


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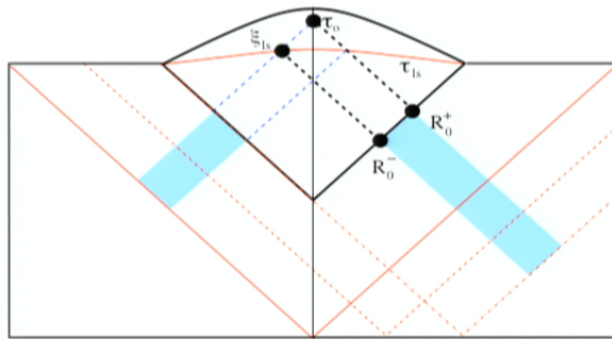


# Counting collisions

Aguirre, MCJ, Shomer

Aguirre, MCJ

- Counting only collisions whose disc of influence is smaller than the whole sky:



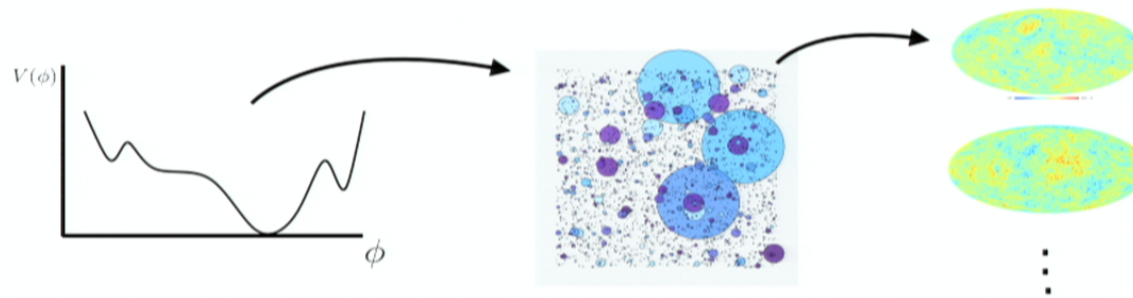
$$N \simeq \frac{16\pi\lambda}{3H_F^4} \left( \frac{H_F^2}{H_I^2} \right) \sqrt{\Omega_c}$$

also Kleban et. al.

# Bubble collisions model

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- The model:



# Searching for collisions

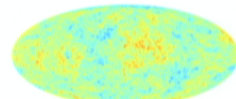
Feeney, MCJ, Mortlock, Peiris

- What any good Bayesian wants:

$$\frac{\Pr(\text{Model 1}|\text{Data})}{\Pr(\text{Model 2}|\text{Data})}$$

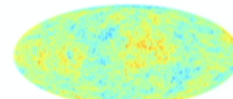


How should I bet?



$\Lambda$ CDM

VS



$\Lambda$ CDM

+



$\Pr(N_s, \mathbf{m})$



# Searching for collisions

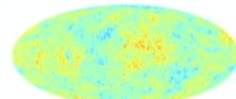
Feeney, MCJ, Mortlock, Peiris

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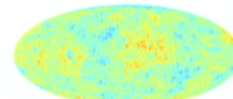


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+



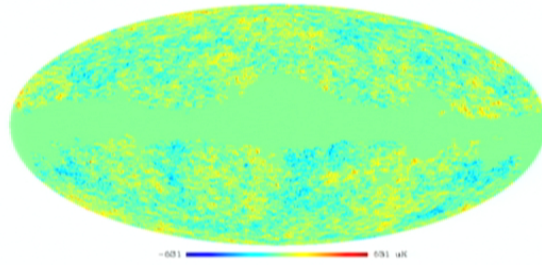
$\Pr(N_s, \mathbf{m})$

- A convenient theory label:  $\bar{N}_s$ .  $\Lambda$ CDM is specified by  $\bar{N}_s = 0$ .

The expected number of detectable features.

# Searching for collisions

Feeney, MCJ, Mortlock, Peiris



# Searching for collisions

Feeney, MCJ, Mortlock, Peiris

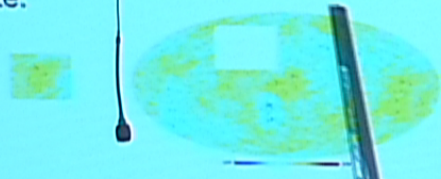
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- Blind search for candidates:
  - Filter the CMB (wavelet decomposition, optimal filtering)
  - Judge significance of features against expectations from LCDM.
  - Calibrate with simulations that don't contain collisions.

## Searching for collisions

Feeney, MCJ, Mortlock, Peiris

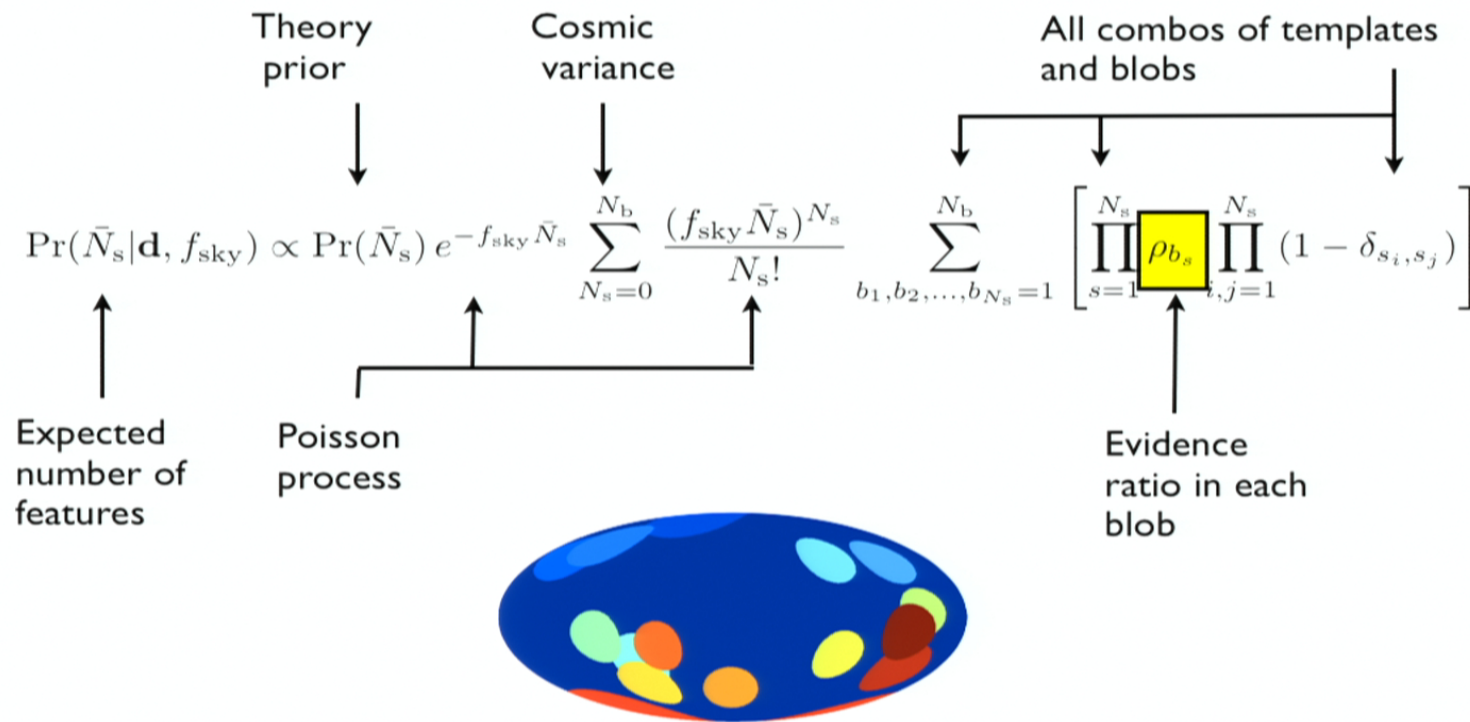
- For one candidate:



# Searching for collisions

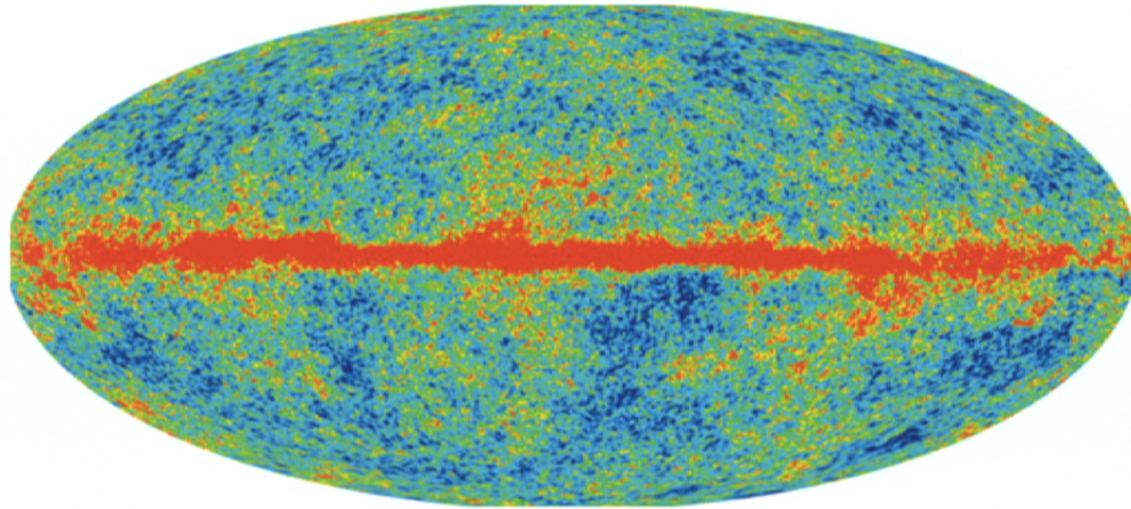
Feeney, MCJ, Mortlock, Peiris

- The general expression for  $N_b$  candidates:



## WMAP7 W-Band (94 GHz)

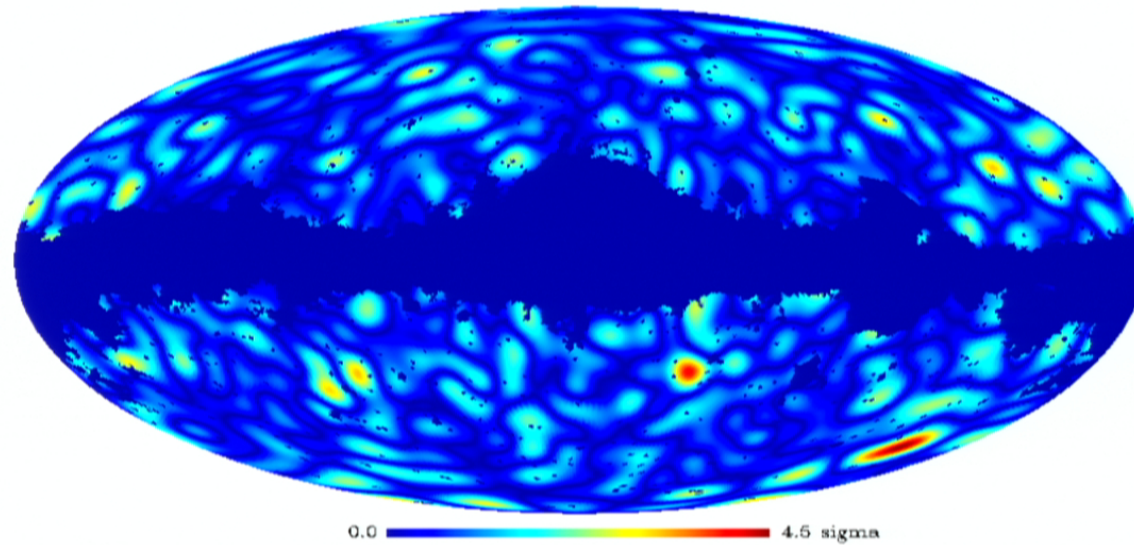
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The WMAP7 W-Band data.....

## WMAP7 W-Band (94 GHz) : Needlets

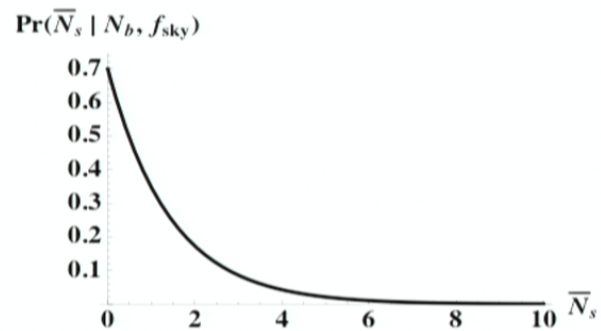
---



(sensitive to 5-14 degree templates)

11 features pass thresholds, with detections in multiple needlet types/frequencies

## WMAP7 W-Band (94 GHz) : Posterior



- The posterior is peaked around  $\bar{N}_s = 0$

The data does not support the bubble collision hypothesis.



## Conclusions

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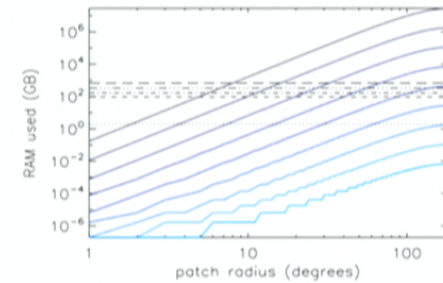


- Non-unique vacua and accelerated expansion give strong motivation for the eternal inflation scenario.

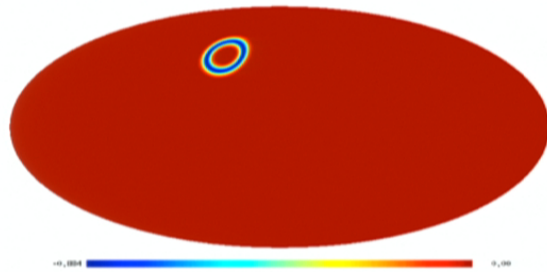
## What next?

- Other improvements to the algorithm:

Multiresolution analysis for Planck: big blobs



Polarization signal



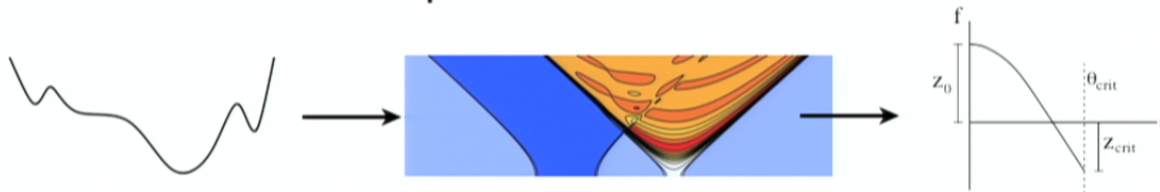
Czech et. al.  
Kleban et. al.

## What next?

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$$\bar{N}_s < 1.6 \text{ at } 68\% \text{ CL}$$

- What region of theory space have we constrained?
- Numerical simulations are needed to connect the potential to the template!

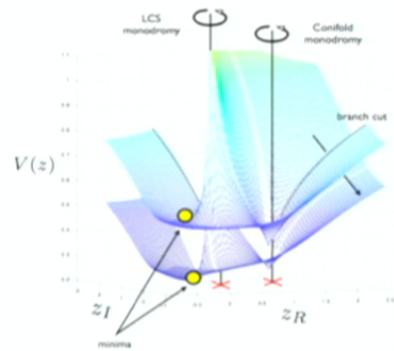


(Like in inflation: general template for fluctuations needs to be connected to the potential)

Lehner

# What next?

- What are the allowed dynamics on the string landscape?



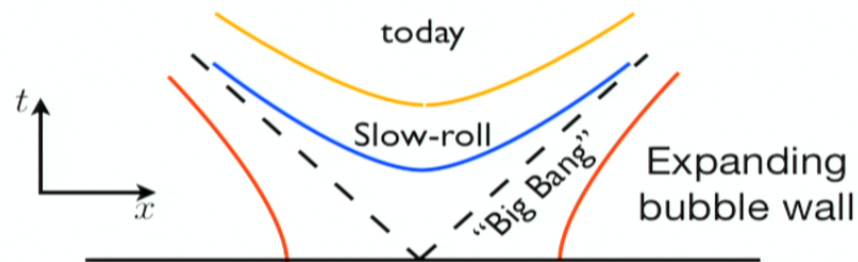
map of the potential landscape  
computed using monodromies



MCJ & Larfors

## What next?

- What are the allowed dynamics on the string landscape?



Giddings & Myers  
Carroll, MCJ, Randall

- Eternal inflation provides a mechanism to change the effective dimensionality of space!