Cosmic Bubble Collisions

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JCAP 1205 (2012) 025, RG, Matthew Kleban

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Outline

- Introduction and Background
  - What are bubbles/Why do we care?
- The collision perturbation
  - Goal and Assumptions
  - Late time perturbation
- What can we see?
- Did we see it already?
- Conclusions

What are bubbles?

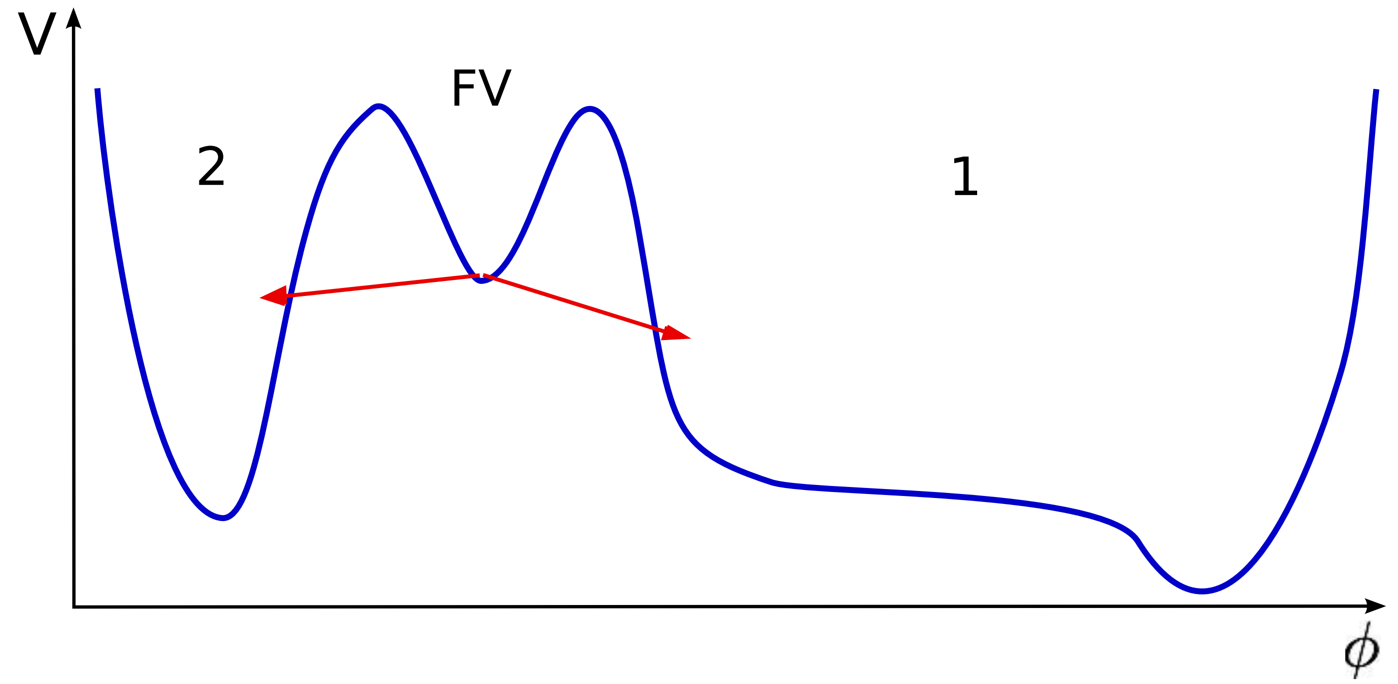
The framework is False Vacuum Eternal Inflation.

We suppose the existence of a landscape, i.e. a potential (complicated enough): every minimum is a possible (meta-)stable state for the universe.

String Theory is an example of a theory that provides such landscape (and much more).

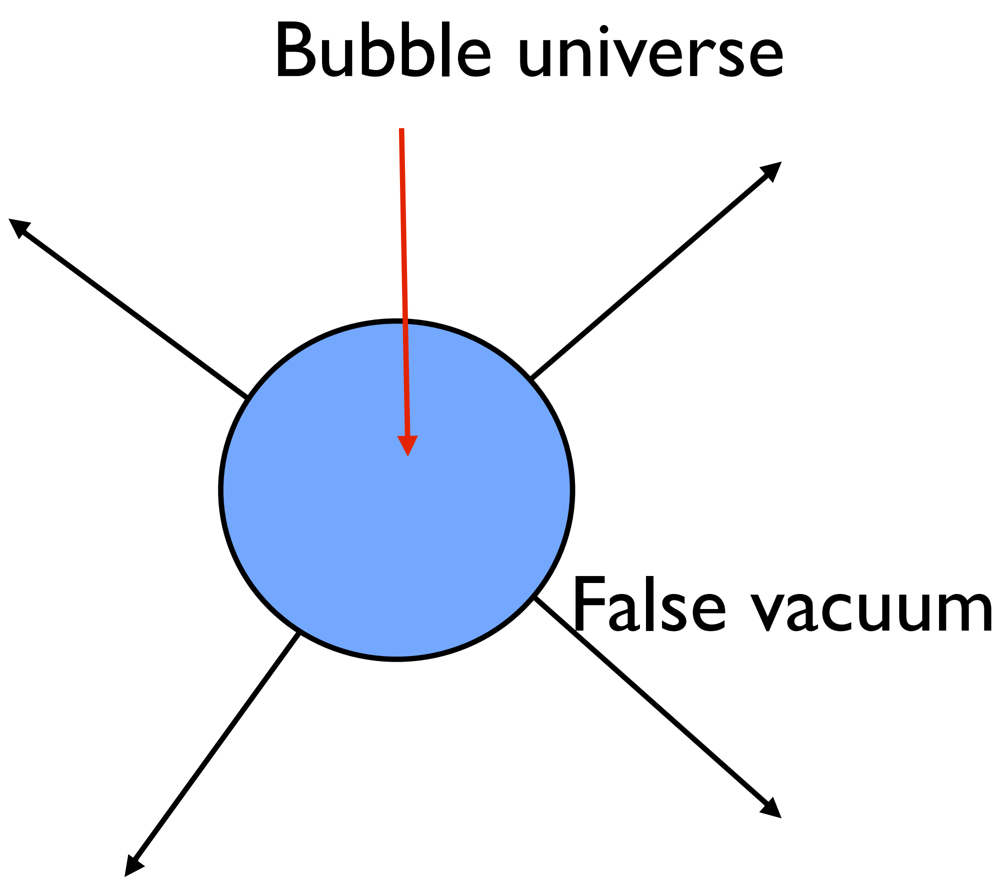
How to nucleate one

- The landscape has several minima
- The fields can (and will) tunnel from a metastable minimum to a lower one
- This process is a first order phase transition and it is instanton driven



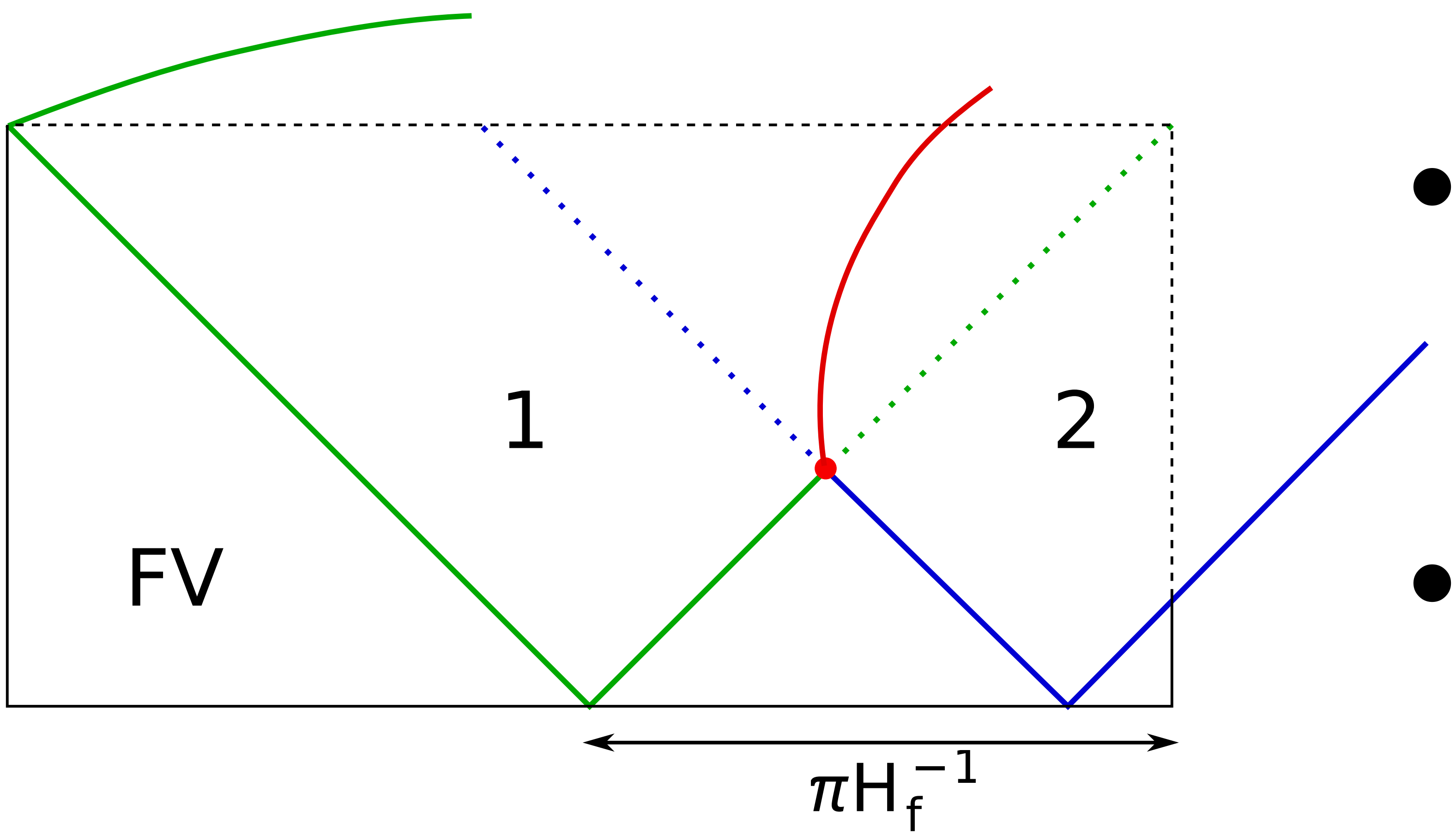
Phys.Rev. D21 (1980) 3305, Coleman, de Luccia

- A bubble nucleates inside a parent vacuum through quantum tunneling
- The pressure on the wall drives its expansion with constant proper acceleration
- The geometry on the inside is an open FRW cosmology
- The new bubble would not "eat up" the parent vacuum (if that was de Sitter)

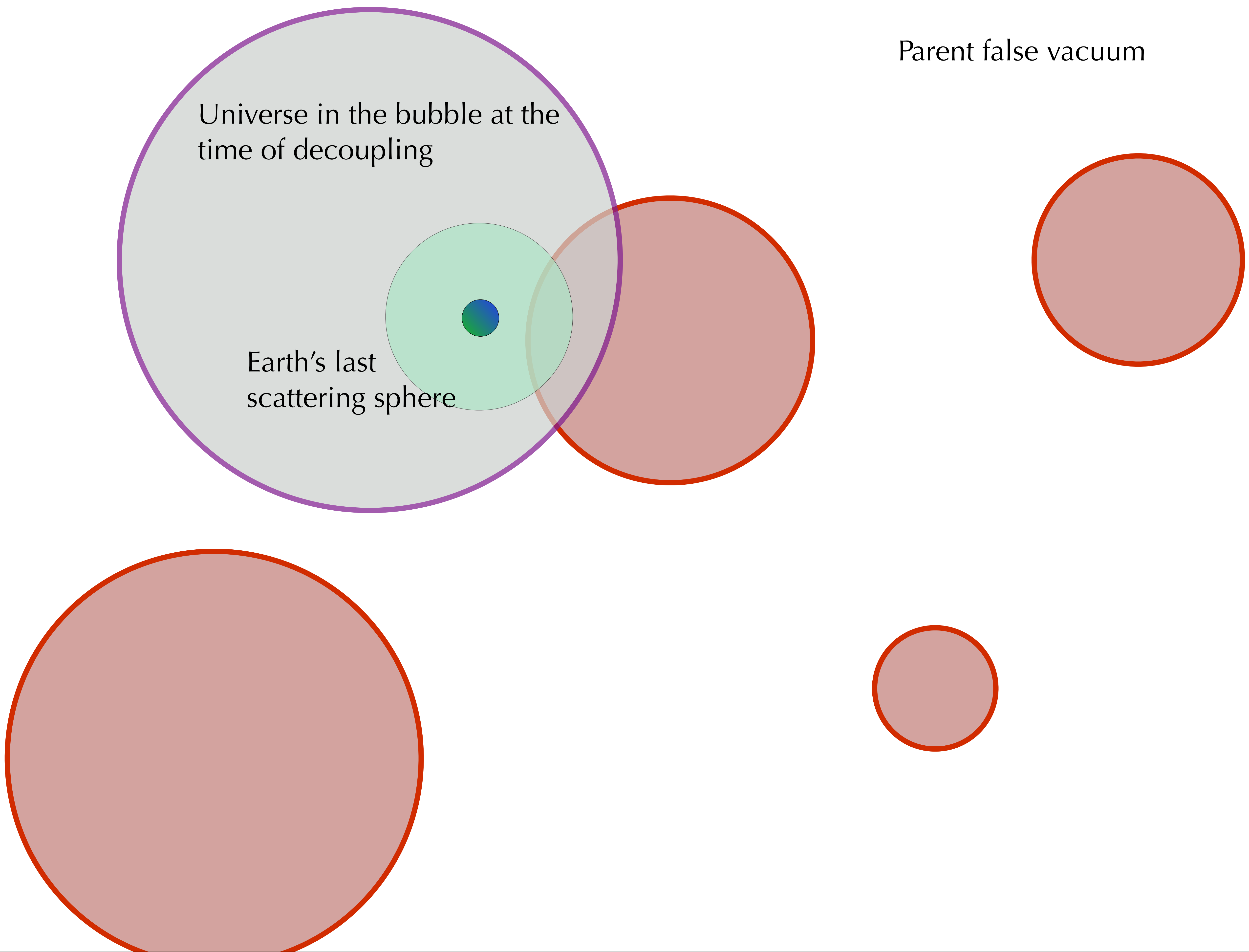


The instanton that drives the process is a solution of the Euclidean equations of motion and has a SO(4) symmetry which translates in SO(3,1) once we go back to the Lorentzian signature

If it happens once, it will happen again!



- More than only one bubble would nucleate
- If they nucleate "close enough", then they would collide during expansion
- Such a collision would cause a large scale inhomogeneities
- We have a testable phenomenon for a theory with a landscape (string theory?)!


Parent false vacuum
Universe in the bubble at the time of decoupling
Earth's last scattering sphere

Why do we care?

- We might live in such a bubble
- The collisions might be observable!
- This is an observational test for False Vacuum Eternal Inflation
- If we take String Theory as a model for landscape, we have a first test

Downside

- It might be difficult to observe such a collision, since too much inflation would hide the results

- Collisions might be rare

$$\langle N \rangle \sim \gamma \frac{V_f}{V_i} \sqrt{\Omega_k} \qquad \Omega_k \sim e^{2(N^* - N)}$$

JCAP 0908 (2009) 036, B. Freivogel et Al.

- Nevertheless, a discovery would be revolutionary!

"Phenomenology"

- The domain wall accelerates with constant proper acceleration set by the relative pressure
- It accelerates away from the bubble with lower Λ
- It can accelerates either away or towards a bubble with positive Λ which collides with one with negative Λ
- A small positive Λ protects against the catastrophe
- We seem to be safe! And I will concentrate on the wall going away from us

JCAP 0804 (2008) 034, S. Chang et Al.

Collision

- Goal: find how the collision of a bubble with our bubble affects the inflaton field
- Assumptions (main ones):
  1. Effective field theory in 3+1 dimensions
  2. Each collision is independent from the others
  3. Prior to collision each bubble has an SO(3,1) symmetry
  4. Collision breaks symmetry to SO(2,1)
  5. There is a single inflaton
  6. Thin wall of the bubble
  7. Small curvature at the end of inflation

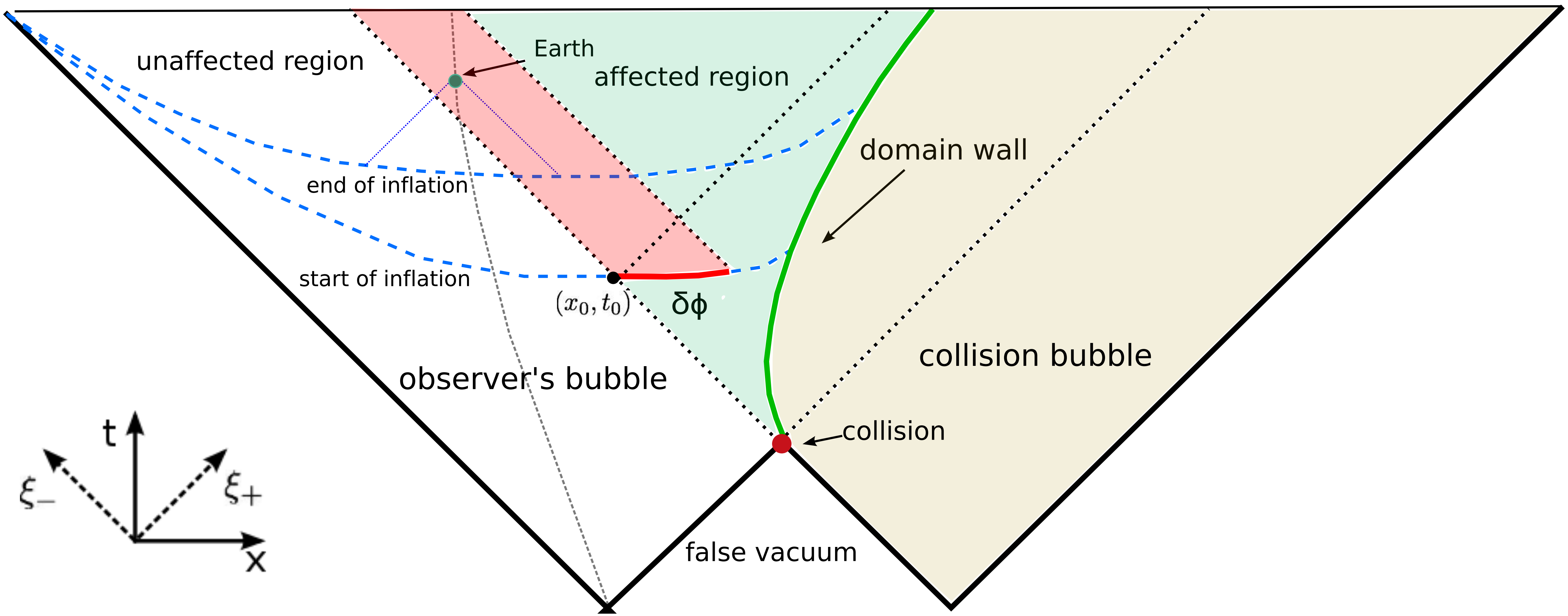
1. Can be violated in model where tunnel is allowed between vacua with different dimension
2. Valid if the effect of the collision is in a perturbative regime
3. We can describe each bubble independently with a CdL instanton
4. Rotations and boosts in the plane transverse to axis between centers are preserved. Well supperted by simulations
5. Ignoring multiple fields
6. The wall of the bubble is “thin”, this assumptions can be relaxed
7. This is valid for our universe or if there has been enough inflation

Given arbitrary initial conditions I want to find the late time perturbation of the inflaton due to a bubble collision.

An important role is played by SO(2,1) invariance. I choose a dS metric with explicit SO(2,1) symmetry

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

$$dH_2^2 = d\rho^2 + \sinh^2\rho d\phi^2$$



Bubbles colliding

The inflaton is perturbed by the collision

To lowest order in the slow roll expansion ($V \approx 0$), the perturbation $\delta\varphi$ satisfies

$$-\frac{1}{t^2}\partial_t\left[t^2(1+(H_i t)^2)\partial_t \delta\phi\right] + \frac{1}{1+(H_i t)^2}\partial_x^2 \delta\phi = 0$$

Which is a free, massless wave equation in de Sitter space-time (with the SO(2,1) invariant metric)

Assuming hyperbolic symmetry (as we did) this can be solved generally

$$\delta\phi(t,x) = f(\xi_-) - \frac{1}{H_i^2 t} f'(\xi_-) + g(\xi_+) + \frac{1}{H_i^2 t} g'(\xi_+)$$

$$\xi_\pm = x \pm \eta$$

$$\eta = \int \frac{dt}{1+(H_i t)^2} = H_i^{-1} \tan^{-1}(H_i t) - \pi/(2H_i)$$

f and g are generic functions to be specified with the boundary conditions.

I am interested in a solution at late times (after inflation ended)

$$t \sim \frac{e^N}{H_i} \longrightarrow \eta \sim -\frac{1}{H_i^2 t}$$

$$N \sim 60$$

Therefore

$$\delta\phi(t,x) \approx f(\xi_-) + \eta f'(\xi_-) + g(\xi_+) - \eta g'(\xi_+)$$

Since the perturbation can not exist outside the region inside the light sheet, only g can be non zero

We can solve expanding around the light sheet and giving generic initial conditions

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

Which gives the generic result

$$\delta\phi(x,\eta) = \sum_{n=0}^{\infty} c_n (-)^{n+1} n! \left[e^{\xi_+/\eta_0} - \sum_{m=0}^{n} \frac{1}{m!} \left(\frac{\xi_+}{\eta_0}\right)^m \right.$$

$$\left. - \frac{\eta}{\eta_0} \left(e^{\xi_+/\eta_0} - \sum_{m=0}^{n} \frac{1}{(m-1)!} \left(\frac{\xi_+}{\eta_0}\right)^{(m-1)} \right) \right] \theta(\xi_+)$$

The result simplifies a lot after few efolds!

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

- It still might look complicated, but we need to look order by order

- Each term is effectively “integrated”

- In general, the lowest order of the expansion would be the leading one, the initial condition would then be a jump in the field

- This evolves in a kink at late time, or jump in the first derivative

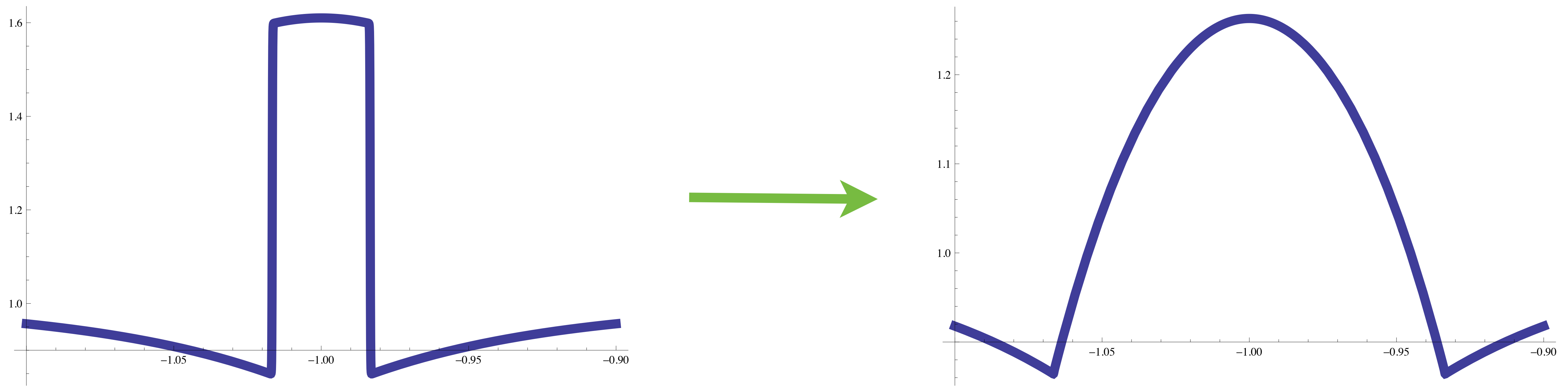
$$c_0\theta(x-x_0) \to \delta\phi(x,\eta) \sim c_0(x+\eta)\theta(x+\eta) + O(x^2)$$

- Higher order gets integrated as well

- As an example we can take two incoming solitons and have them colliding and running through each other

Phys.Rev. D82 (2010) 045019, J.T. Giblin Jr. et Al.

- This sets automatically the initial conditions (a jump) and we can let the system evolve with our method



The initial jump evolves into a kink at late time around the light sheet and freezes

Simulations

- Numerical simulations of bubble collisions have been worked out and seem to agree with our results
- Both as what to expect as generic initial condition (step function) and on the behavior at late times
- Nevertheless, simulations can only investigate few efolds, so an analytic calculation is needed to incorporate the full inflationary period

Phys.Rev. D79 (2009) 123514, A. Aguirre et Al.

Phys.Rev. D85 (2012) 083516, M. C. Johnson et Al.

Observing the collision

Without observations we would not be able to prove anything

We expect signatures in the CMB
(if we are lucky!)

- Temperature anisotropies
- Polarization anisotropies

Temperature anisotropies

- To compute the temperature we have to translate the inflaton perturbation to a perturbation of the Newtonian potential Φ
- Φ is proportional to $\delta\varphi$ at the end of inflation
- Using Sachs-Wolfe effect, the temperature today is proportional to Φ at last scattering
- We know can use the result just computed to find the effect at reheating and then evolve from there

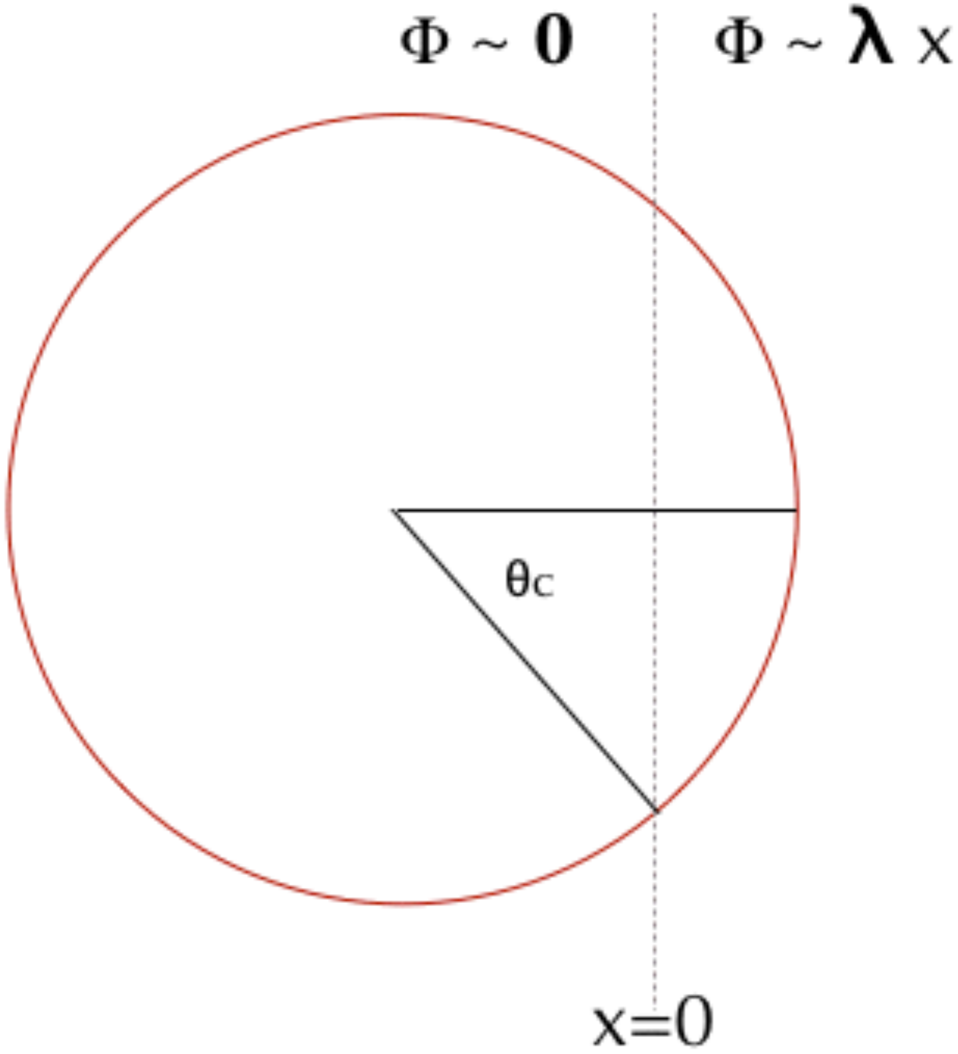
- At reheating, at lowest order $\Phi \sim \lambda x \theta(x)$, x=0 is the edge of the collision light cone

- The reheating surface is unperturbed for $x<0$ and there is a linear gradient for $x>0$

- A linear gradient corresponds to a dipole, since $x \sim \cos\theta$, that only affects the right-hand region

- We expect a disk with temperature $T \approx T_{max}(\cos\theta - \cos\theta_c)$

- Either hot or cold spots

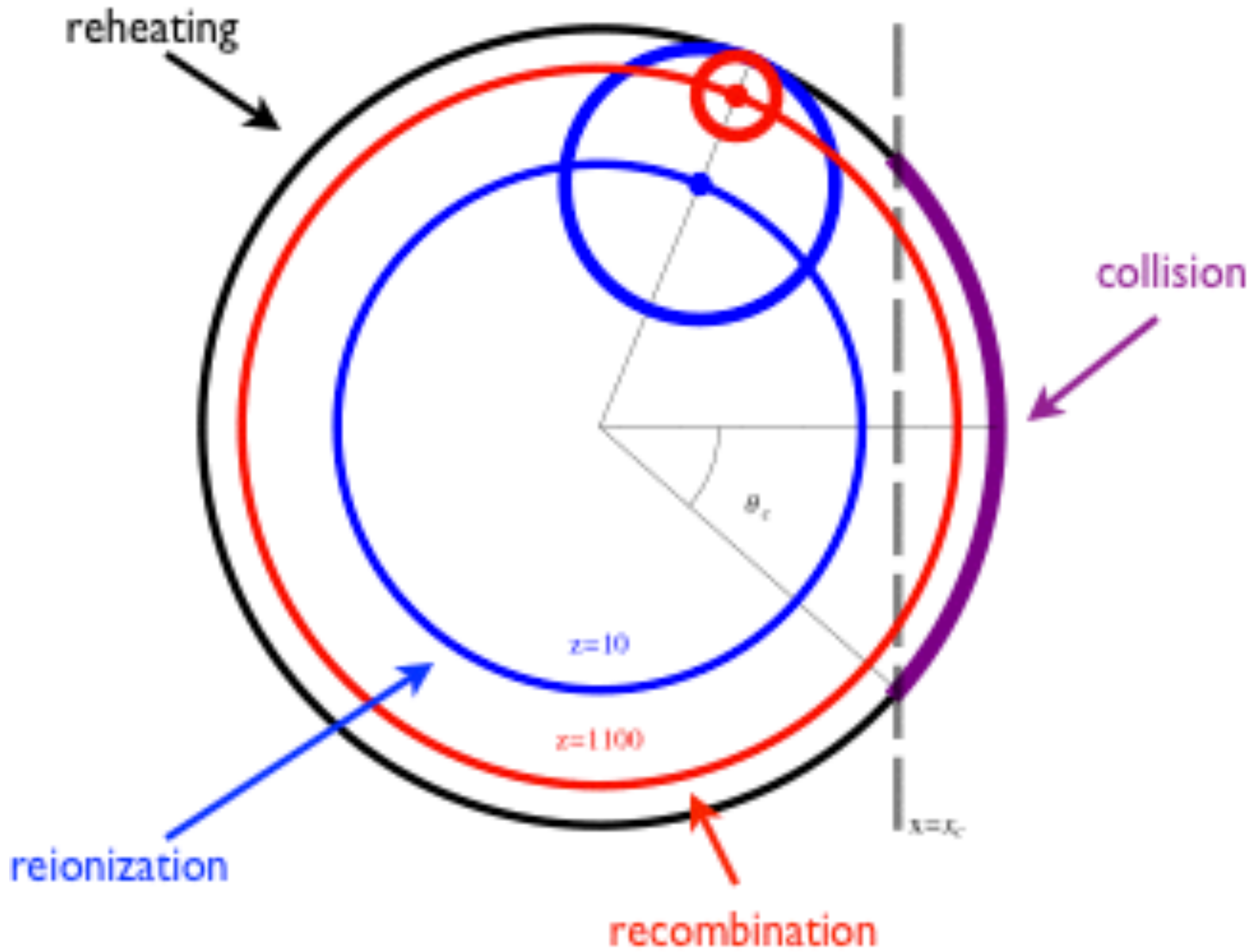


The predicted signal turns out to be smooth and therefore it would be difficult to distinguish it from a Gaussian fluctuation

JCAP 0904 (2009) 025, S. Chang et Al.

Polarization

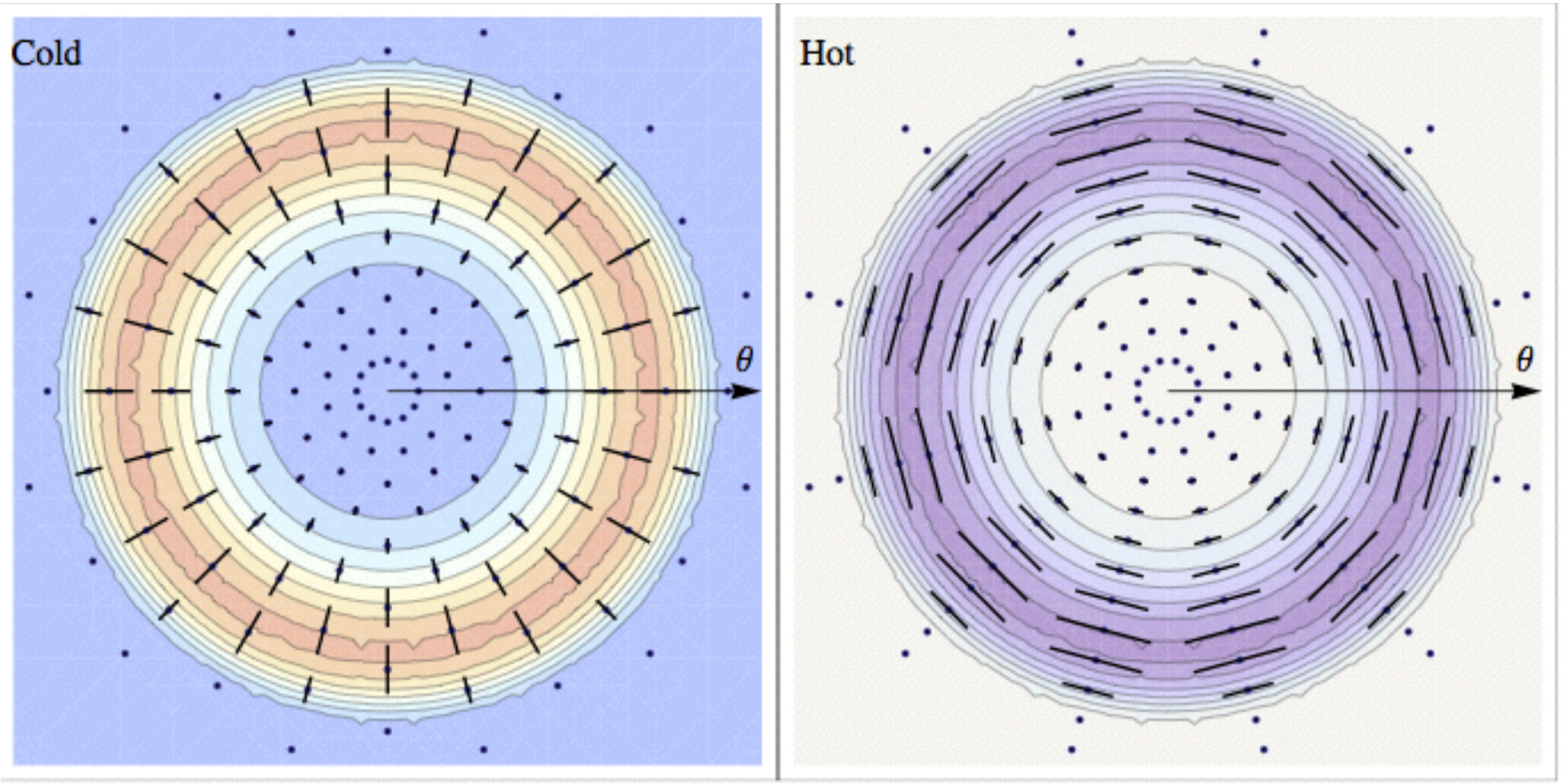
- Free photons scatter with electrons causing linear polarization if the electron sees a distribution of incident radiation with a non zero quadrupole moment
- Scattering occurs primarily at recombination (z~1100) and reionization (z~10)
- Inside the collision region, we have a pure dipole (so no polarization), but the edge contributes to a quadrupole



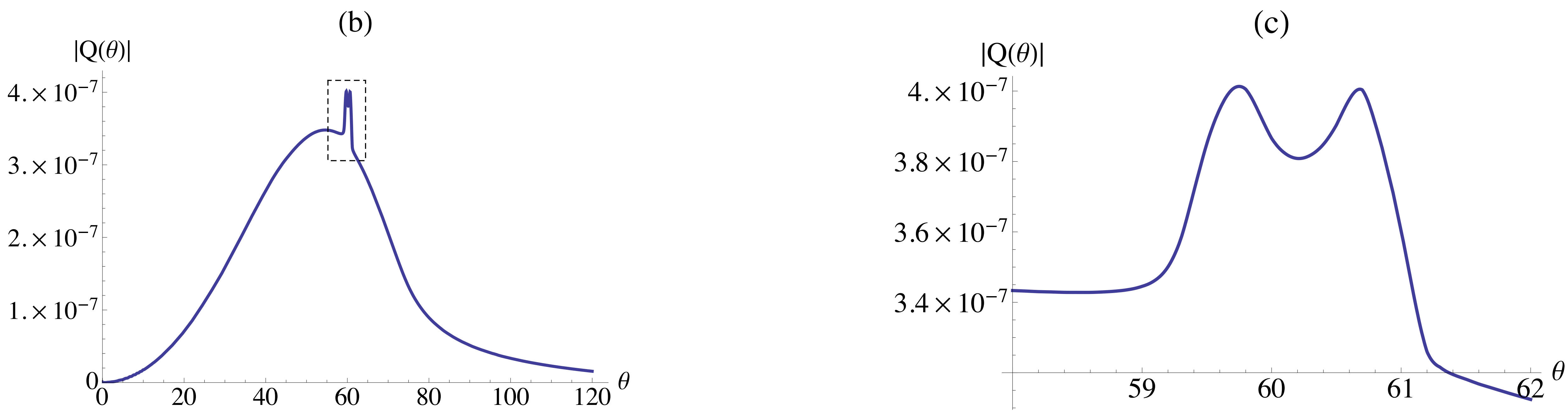
JCAP 1012 (2010) 023, B. Czech et Al.

- By symmetry, the polarization should only depend on the angular distance from the spot and its temperature
- So we have E-mode polarization, as expected from a scalar perturbation
- Q Stokes parameter can be investigated, choosing coordinates whose center is centered with the spot (hot or cold)

JCAP 1012 (2010) 023, B. Czech et Al.



Some results



A double (or single, depending on the parameters) peak on top a broader peak can be expected when the size of the edge of the collision is comparable with the size of the past light cone of an electron at recombination

The analysis of the polarization could be a smoking gun for bubble collision!

JCAP 1012 (2010) 023, B. Czech et Al.

What is observed so far?

- There is no observation of a bubble collision so far (otherwise we would all know)
- People are working on it using data from WMAP7
- Recently 8 new possible candidates have been isolated, for a total of 16
- Planck data still need to be analyzed and could provide interesting results

Phys.Rev. D84 (2011) 043507, S. M. Feeney et Al.

arXiv:1206.5035 (2012), J. D. McEwen et Al.

What's next?

- On possible new prediction: not much, probably
- Assumptions can be relaxed to find maybe more refined predictions, though
- Barnacles: bubbles that could nucleate inside the wall
- But the main difficulty now is analyzing the data
- Analyze Planck data as soon as available

Conclusions

- We could find the generic late time behavior of the inflation perturbation due to a bubble collision
- Based on that, it is possible to make prediction of signatures in the CMB
- Work is being done analyzing data
- The discovery of a collision would be a first observation of string theory