A status report on the observability of cosmic bubble collisions

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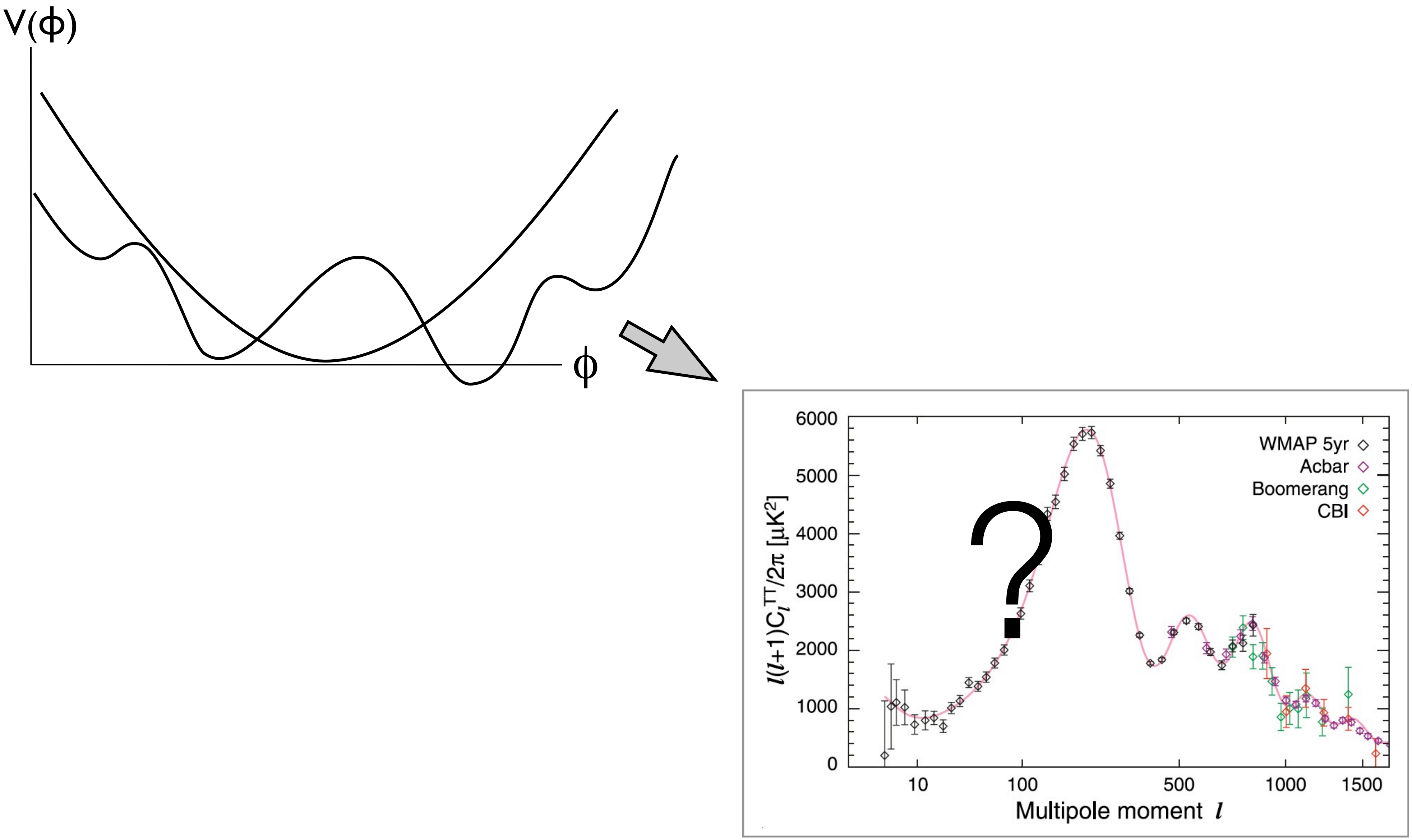
(work with M. Johnson, A. Shomer, M. Tysanner, J. Kozaczuk)

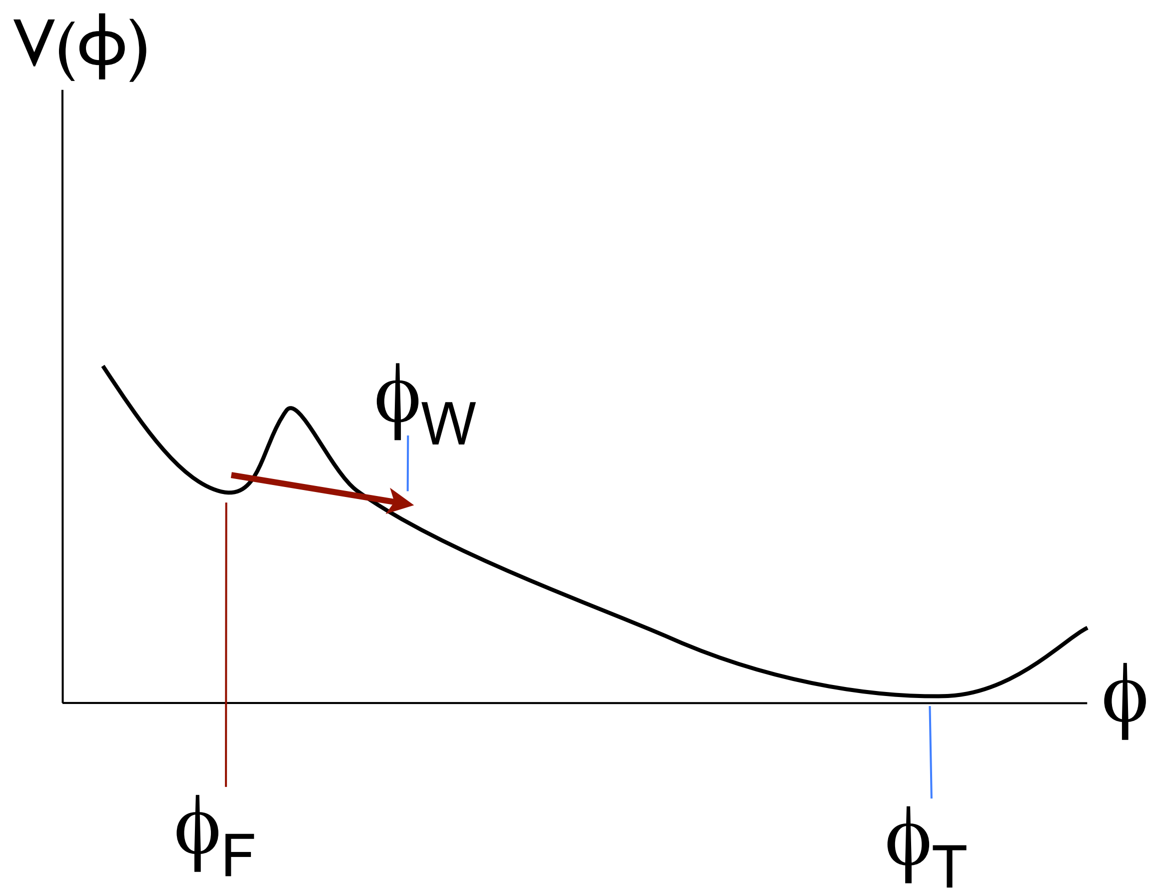
Inflation



V(φ)
φ
WMAP 5yr
Acbar
Boomerang
CBI
?
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Multipole moment l
l(l+1)C_l^TT/2π [μK²]

Everlasting open inflation

- (Multiple minima) + (slow transitions) = **eternal inflation**



Everlasting open inflation

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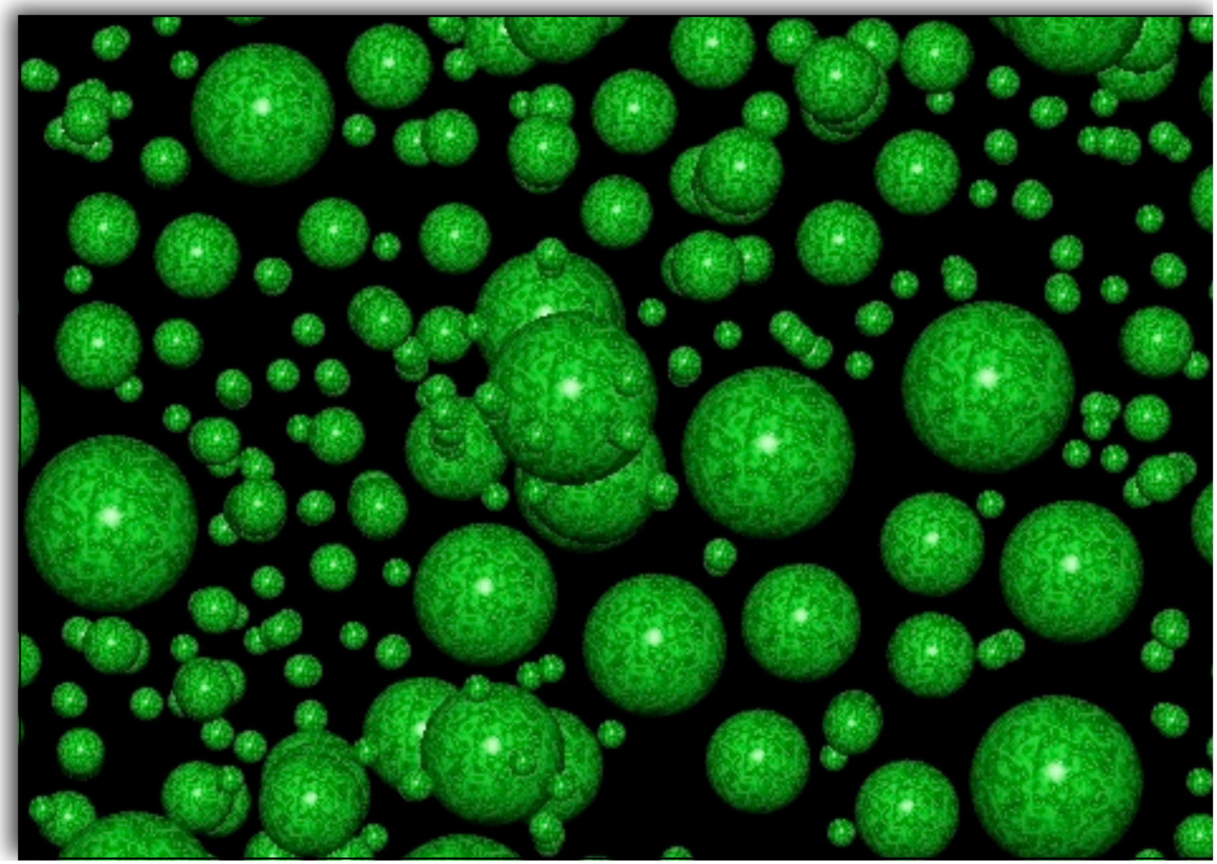
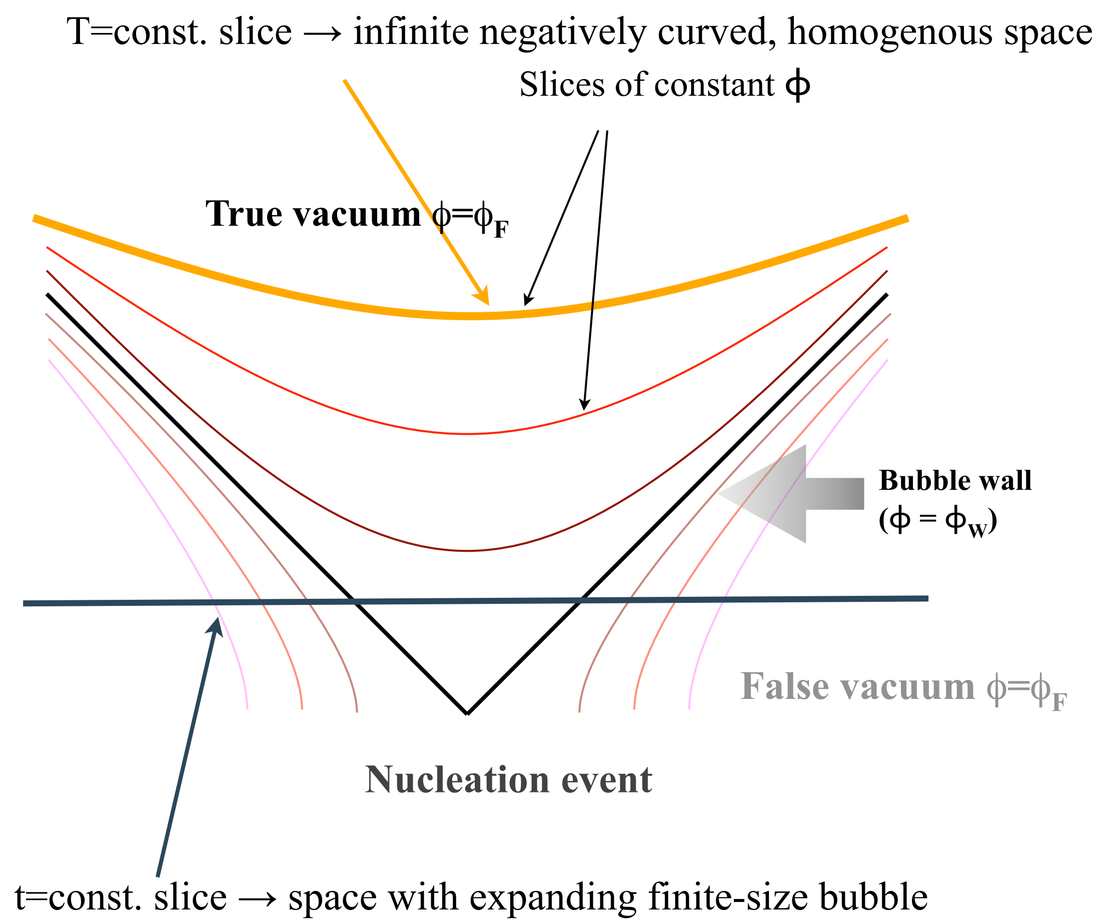


Everlasting open inflation

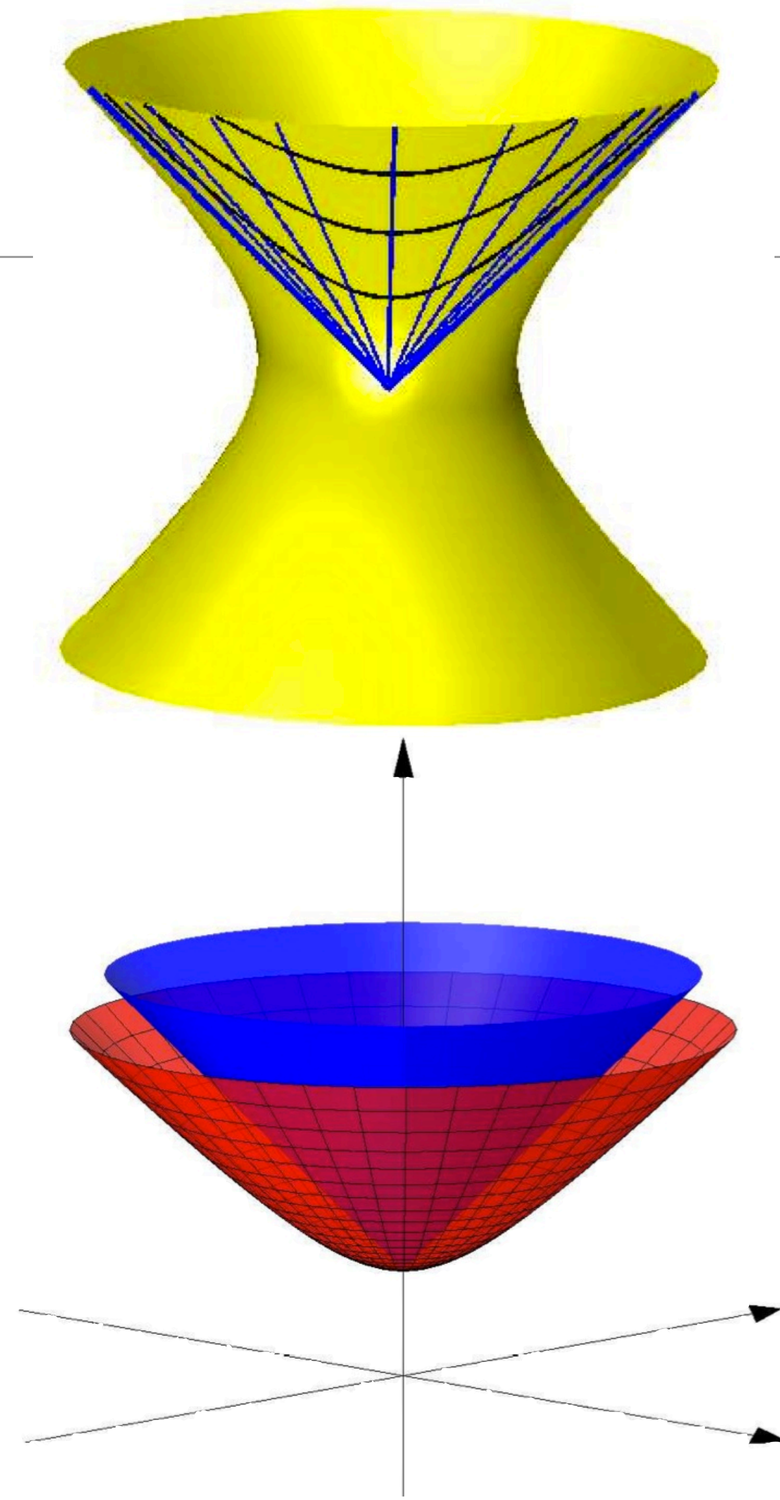
- (Multiple minima) + (slow transitions) = **eternal inflation**

- Each bubble has **open FRW cosmology** inside.

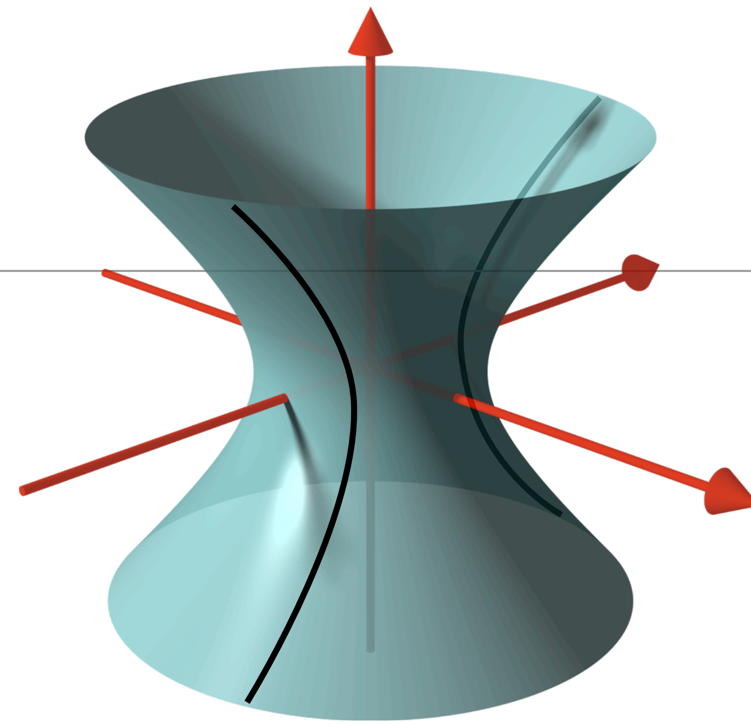


An embedded bubble

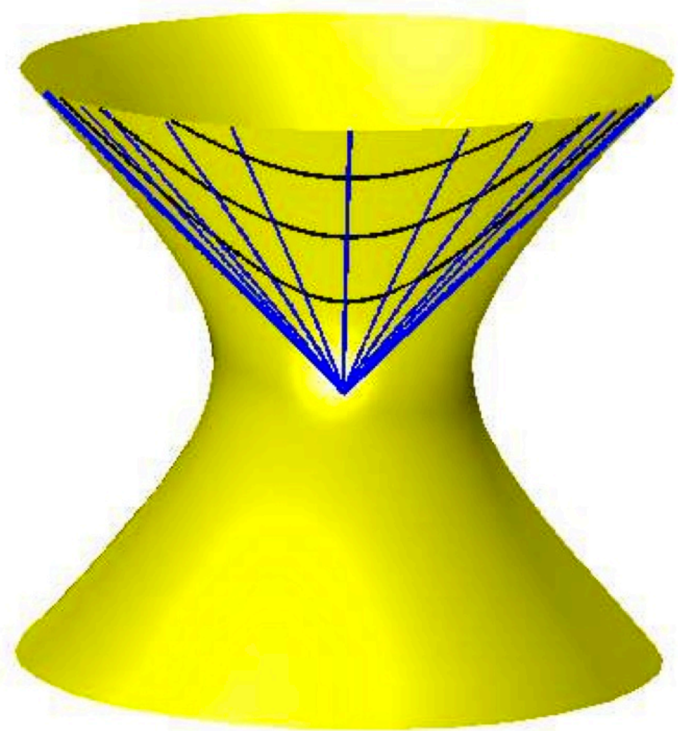
- D-dim de Sitter (dS)
  - Hyperboloid in D+1 Mink.
  - Maximally SO(D,1) symmetric
- X_i = const. > H^{-1} → spacelike D-1 hyperboloid.
  - This is 'open slicing'.



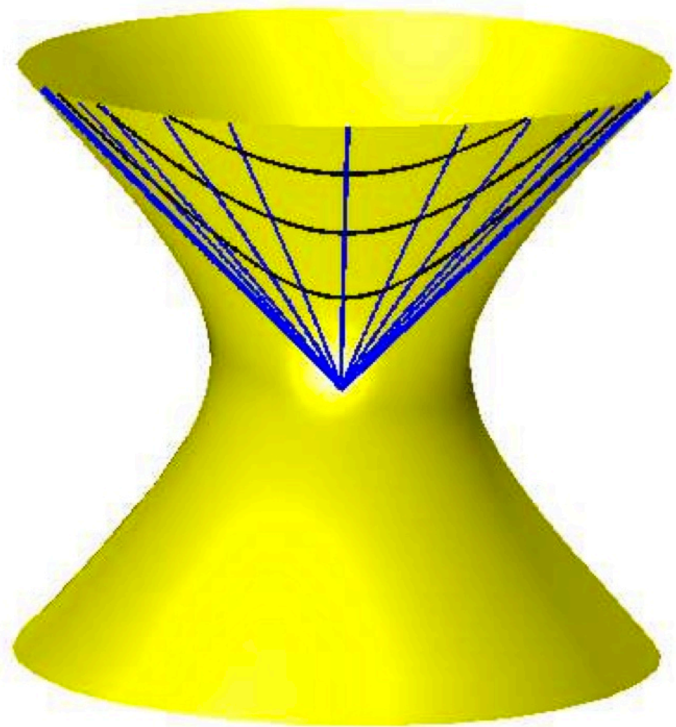
An embedded bubble



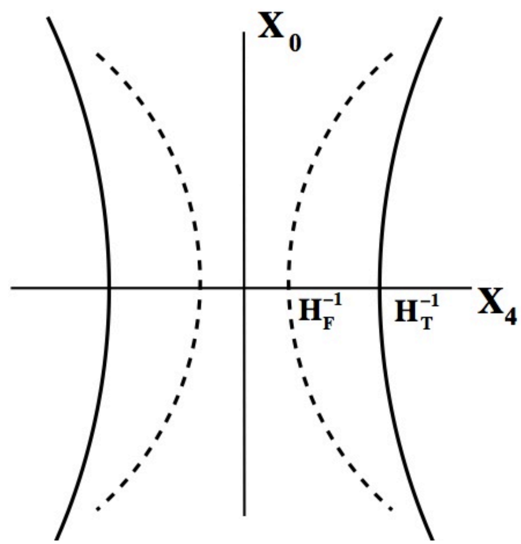
- X_i = const. > H^{-1} → timelike D-1 hyperboloid (D-2 sphere of constant outward acceleration)
- X_i = const. = H^{-1} → null cone.
- Boosts ∥ to X_i translate 'origin'.
- Boosts ⊥ to X_i do nothing overall, but translate points on D-1 hyperboloid.

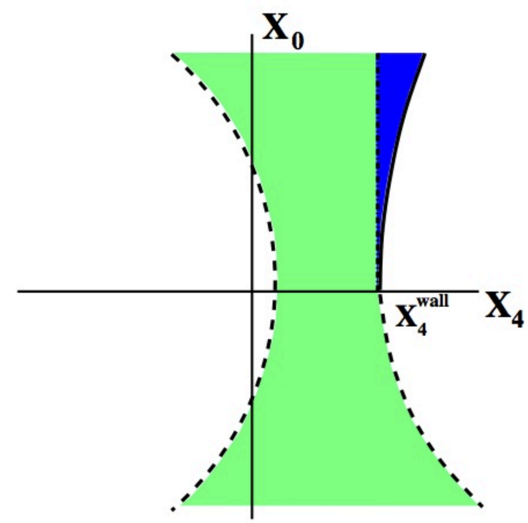


An embedded bubble

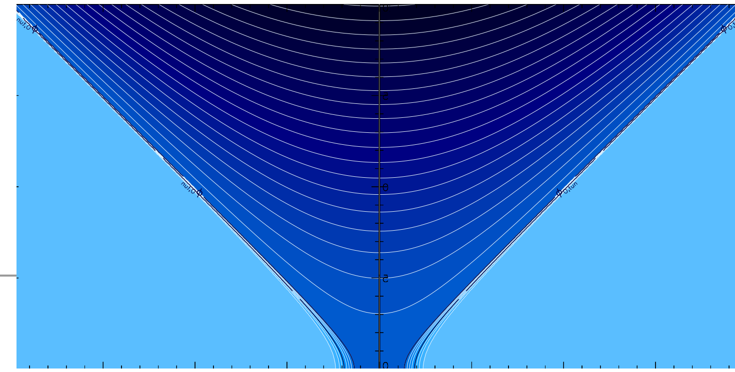


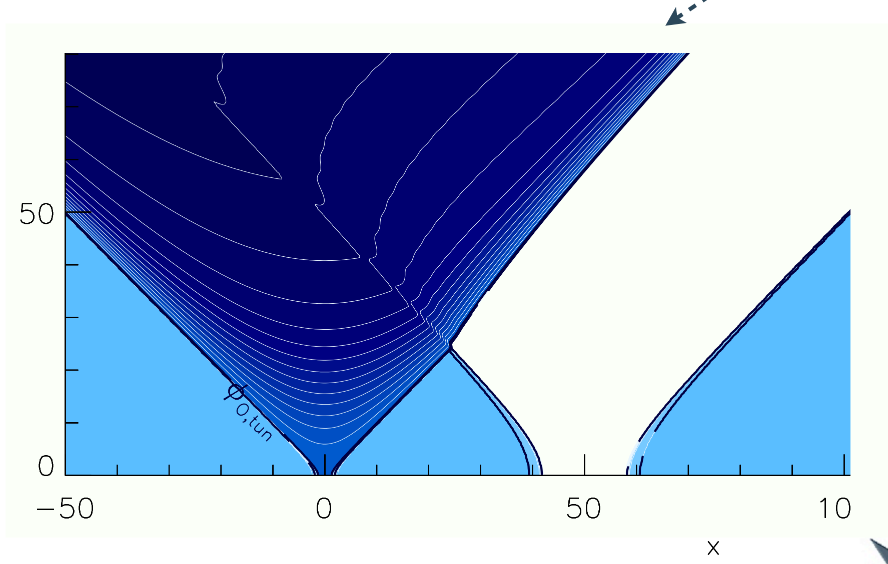
- Can embed arbitrary open FRW cosmology in similar manner; has SO(D-1,1) symmetry, described by one parameter.
- Can match across timelike hyperboloid for ‘vacuum bubble’ like thin-wall CDL



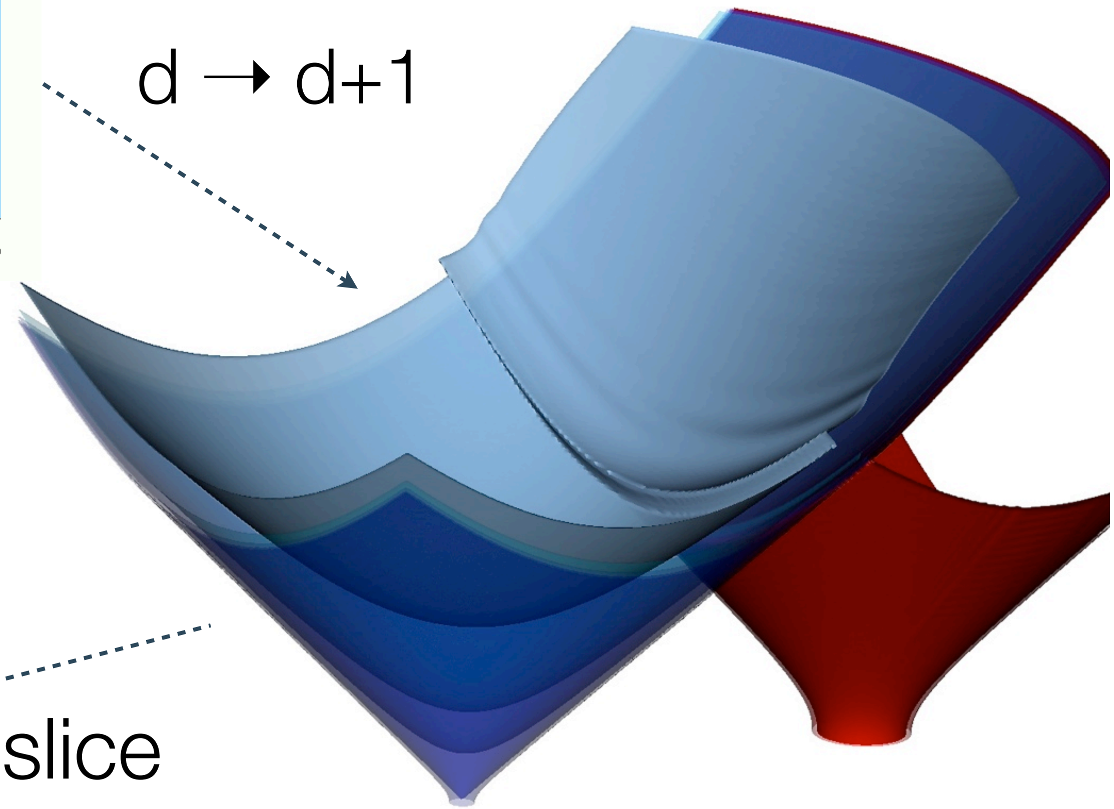


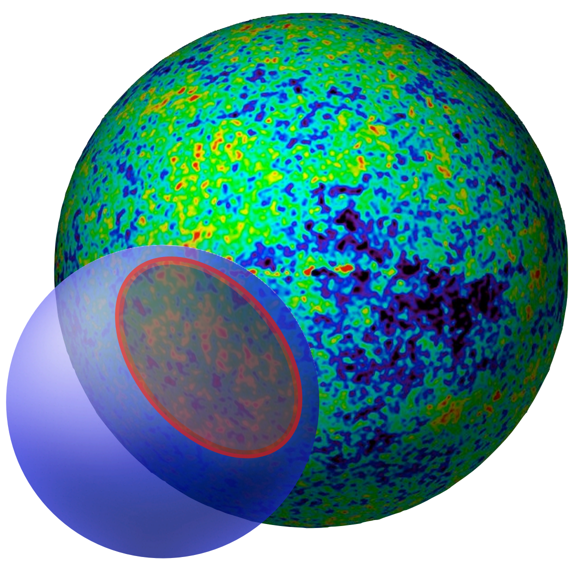
Bubble collisions





d → d+1





slice

Bubbles collide. Can we see the other ones?

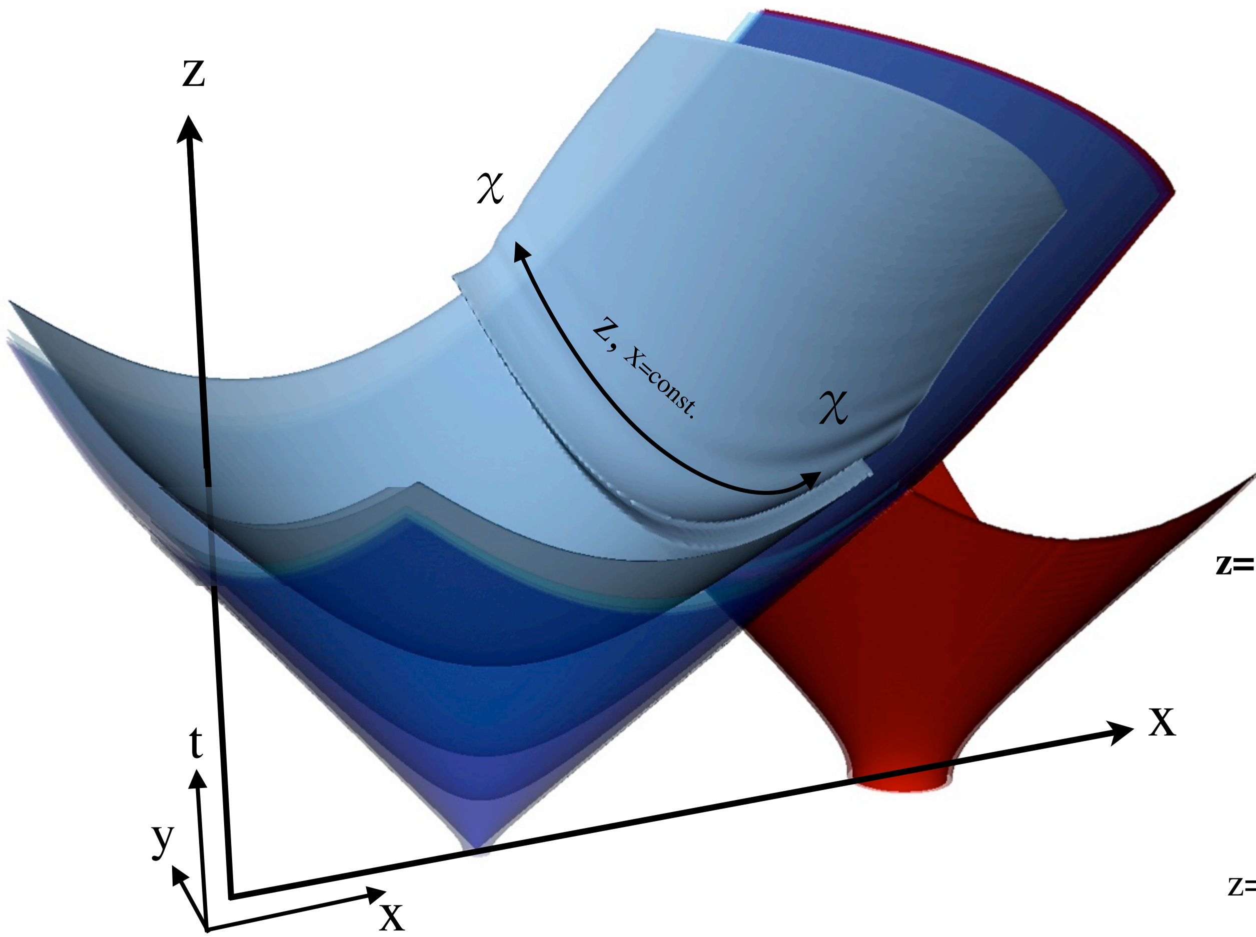
Three basic issues:

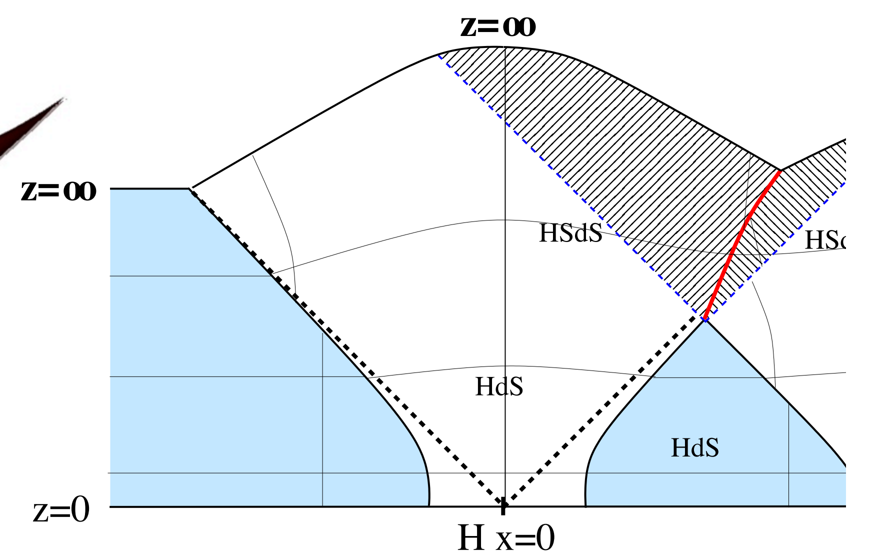
- What is the structure of a general collision spacetime?
- What is effect on post-collision observers?
    - Non-existent: No collisions exist in observer's past lightcone.
    - Invisible: unobservable effect.
    - Perturbative: small effect observable but not yet observed.
    - Falsifiable: incompatible with our observations, but not with observers.
    - Fatal: collisions prevent the formation of observers to their future.
- How could we observer perturbative or falsifiable effects?
- What are the relative probabilities for these five, especially: (falsifiable+perturbative)/(fatal+non-existent+invisible)

What is the structure of a post-collision spacetime?

Basic Structure

Each: SO(3,1)
Together: SO(2,1)

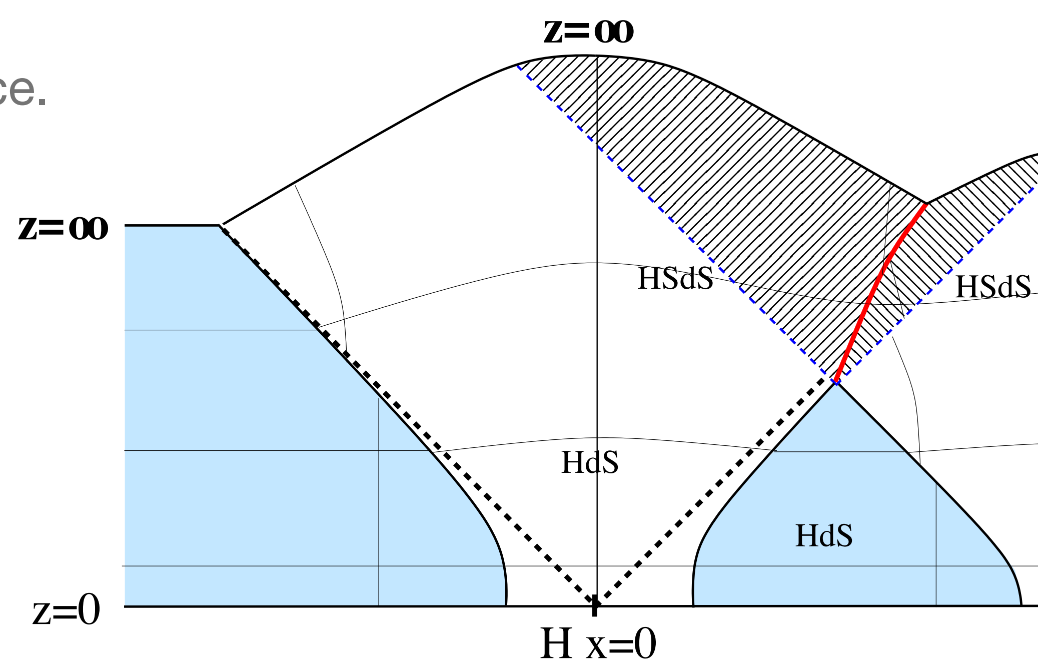




What is the structure of a post-collision spacetime?

Model I: Exact Solutions splicing vacuum bubbles

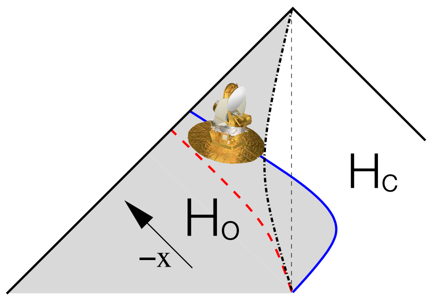
- Aguirre & Johnson 08 (or Chang, Kleban & Levi 08): generalize Freivogel, Horowitz & Shenker 07.
  - Small bubbles, Hyperbolic symmetry, thin walls connecting vacuum regions.
  - Thin domain wall between post-collision bubbles, tension κ
  - Radiation 'shell' from collision surface.
- Equations from:
  - Junction across shell
  - Junction across wall
  - Energy Conservation
- All determined by potential, initial separation, one unknown quantity (microphys.)



What is the structure of a post-collision spacetime?

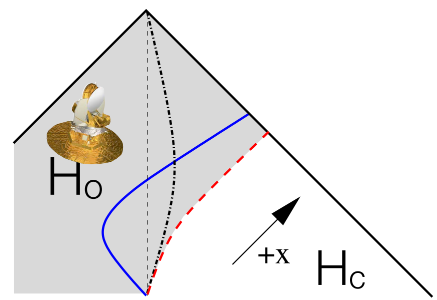
Model I: Exact Solutions splicing vacuum bubbles

- Results:
  - Asymptotic trajectory determined by vacuum energies, wall tension.
  - Roughly, accelerates towards higher vacuum energy.
  - Null shell necessary, but small overall effect possible.
  - Do constant field surfaces near domain wall go timelike or spacelike?



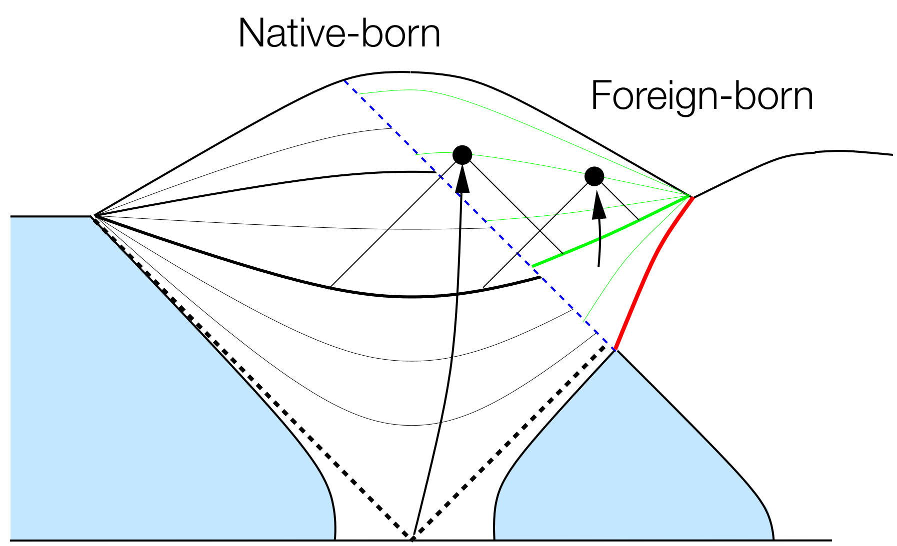
$$H_C^2 \leq H_o^2 - \kappa^2$$

(fatal)



$$H_C^2 \geq H_o^2 - \kappa^2$$

(falsifiable/perturbative/ invisible)

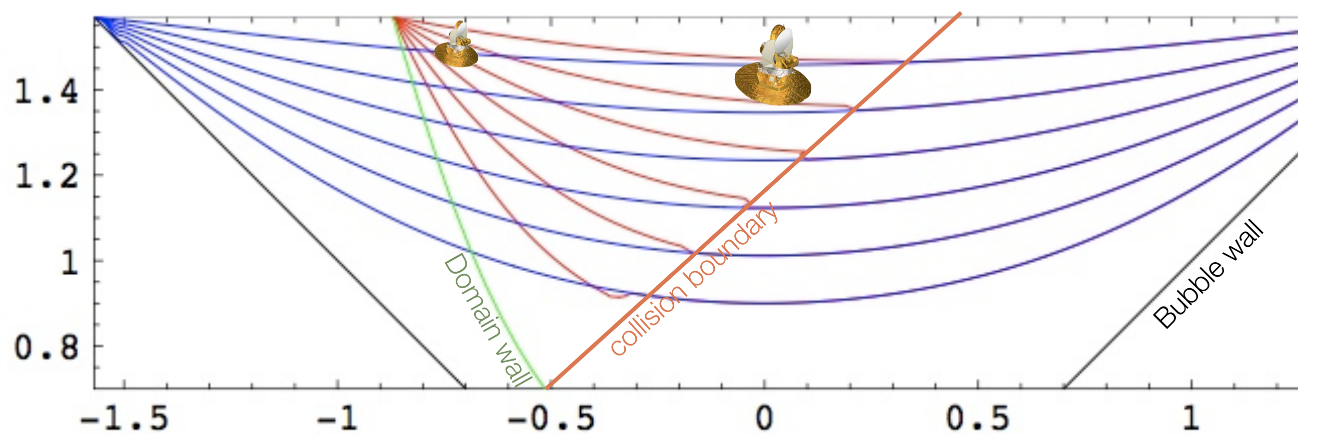


What is the structure of a post-collision spacetime?

Model II: Analytic model in fixed bubble background

- Chang, Kleban & Lev 09
  - Look at bubble interior, with fixed dS background.
  - Linear potential, boundary conditions on bubble wall and collision boundary
  - Joined by ‘null wave’ collision boundary with discontinuous field derivative.

- Asymptotically lines *look* timelike, but are spacelike (Aguirre et al. 09): very ‘foreign’ observers are possible, way up the domain wall.

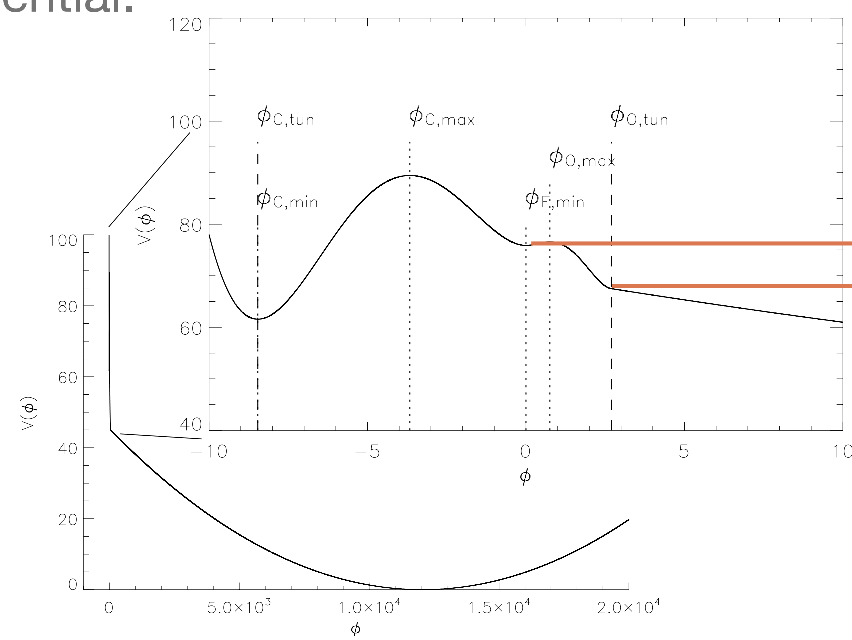


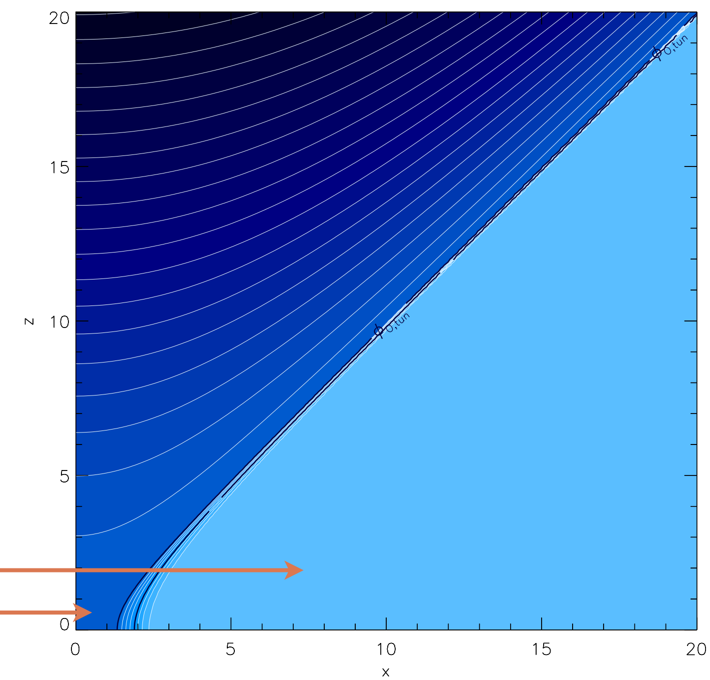
(adapted from) Chang et al. 09

What is the structure of a post-collision spacetime?

Model III: Numerical solutions in flat background

- Aguirre, Johnson & Tysanner 09
  - Single-field, flat background
  - Initial conditions from patched-together instantons for small bubbles.
  - ‘large-field’ inflation triple-well potential.

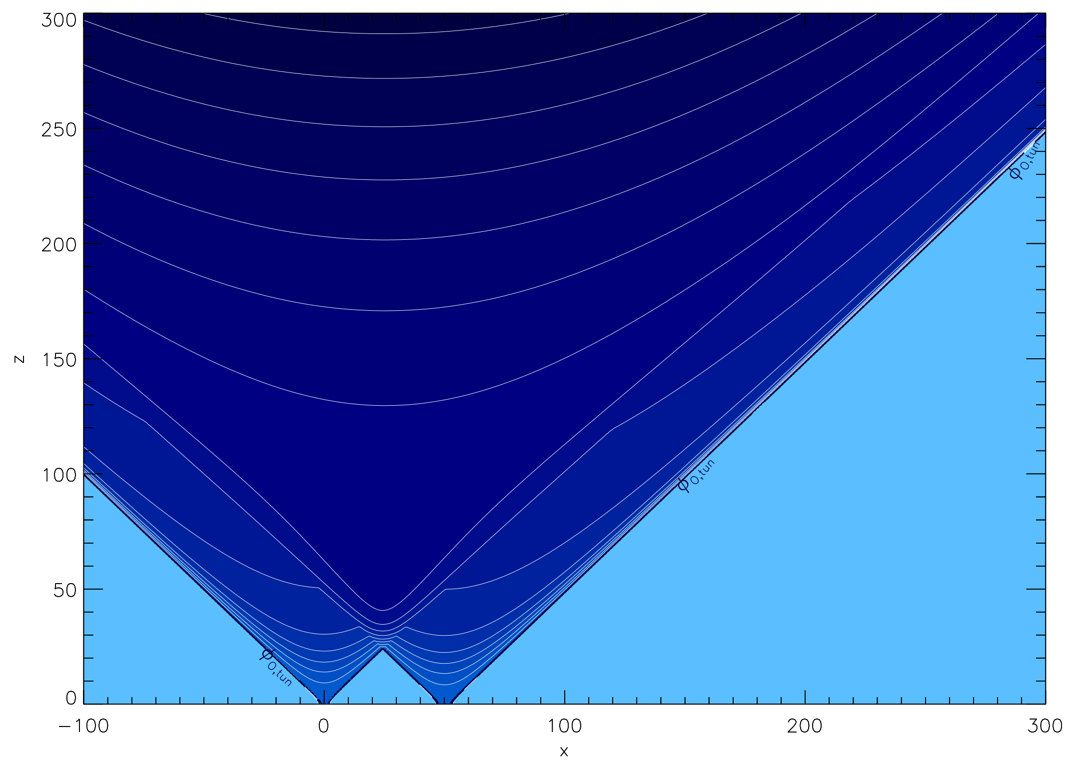




What is the structure of a post-collision spacetime?

Model III: Numerical solutions in flat background

- Aguirre, Johnson & Tysanner 09
  - Bubble self-collisions: merge into homogeneous* slices! (const. field lines are hyperbolas)



*really they are homogeneous in two directions with an axial symmetry. But at large z they regain homogeneity.

What is the structure of a post-collision spacetime?

Model III: Numerical solutions in flat background

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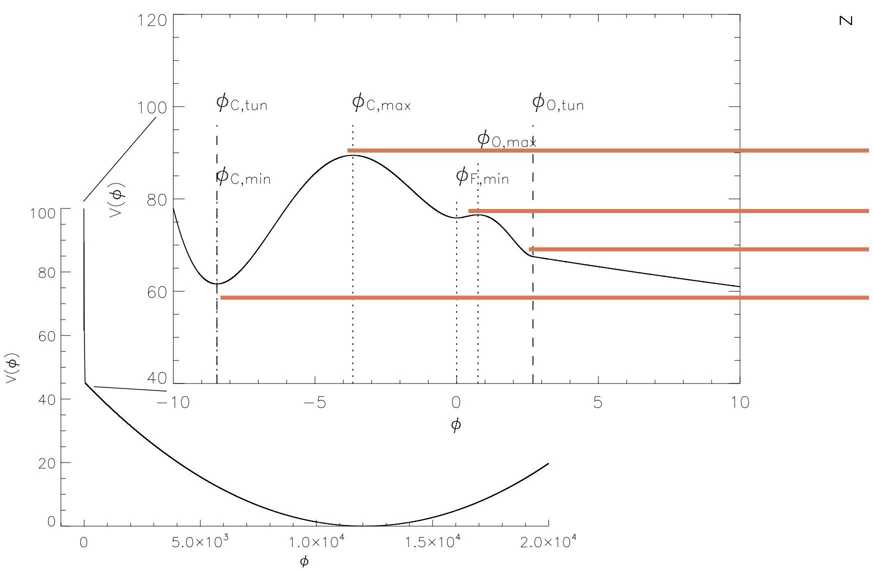
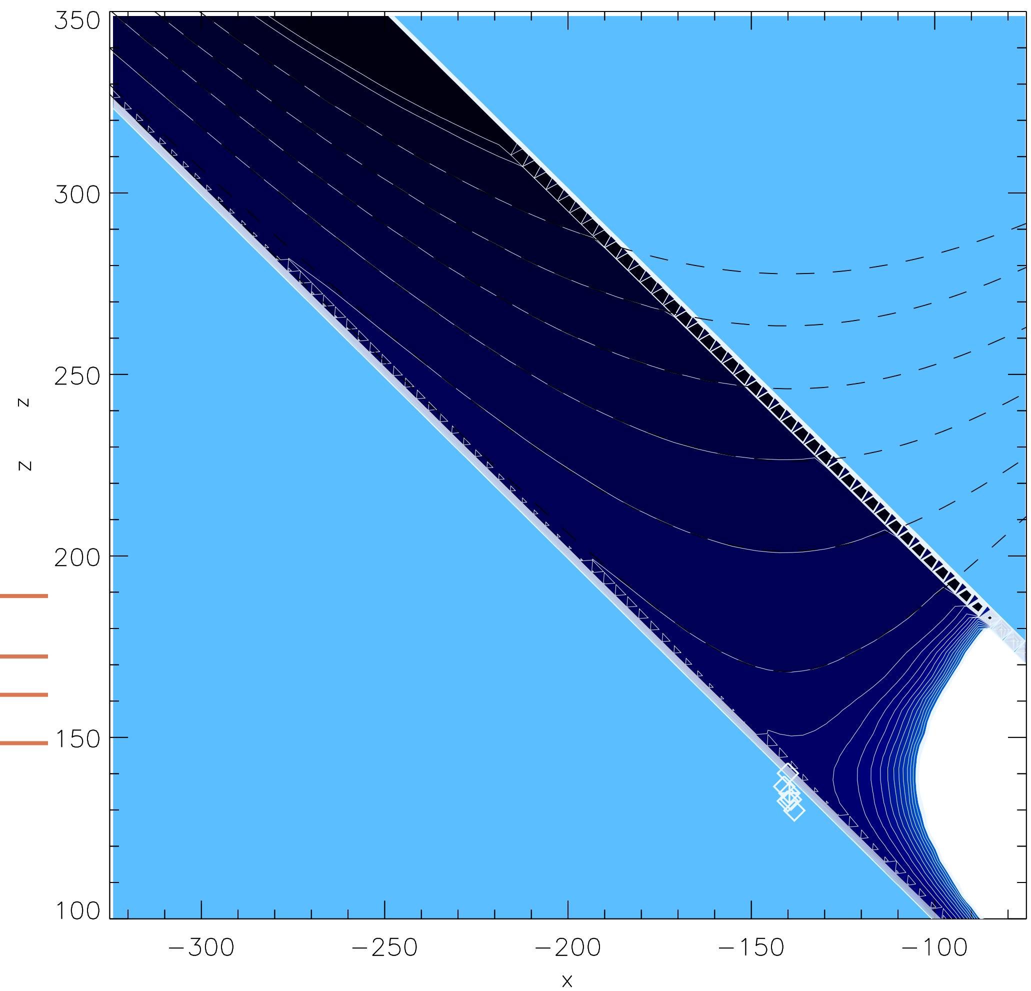
  - Bubble self-collisions: merge into homogeneous slices!
  - Two different bubbles: some perturbation, then return to homogeneity.





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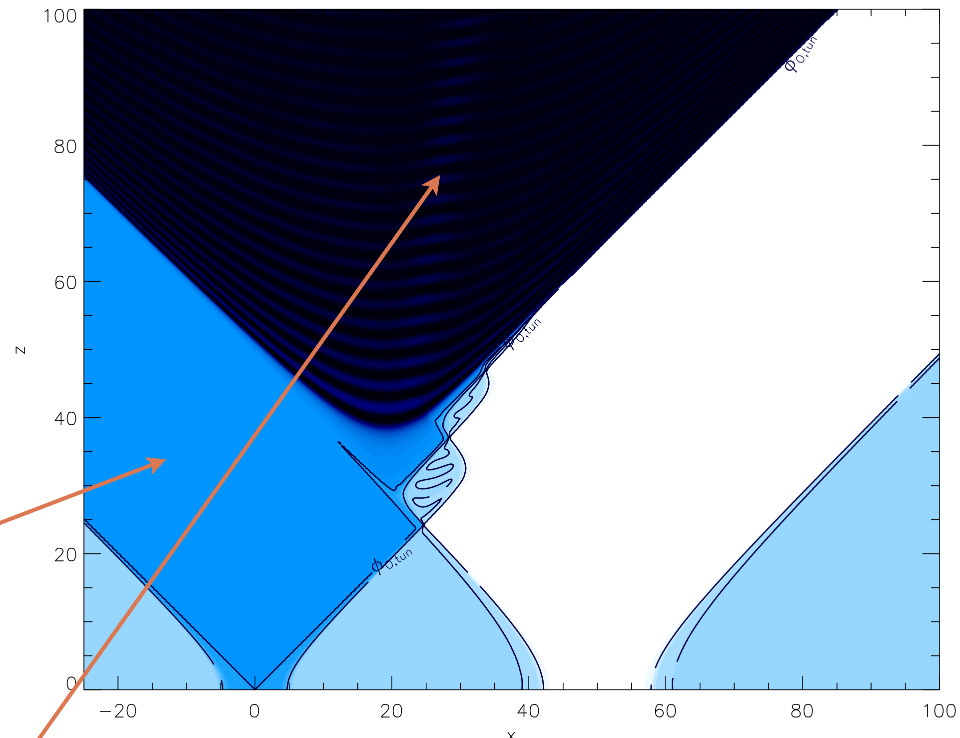

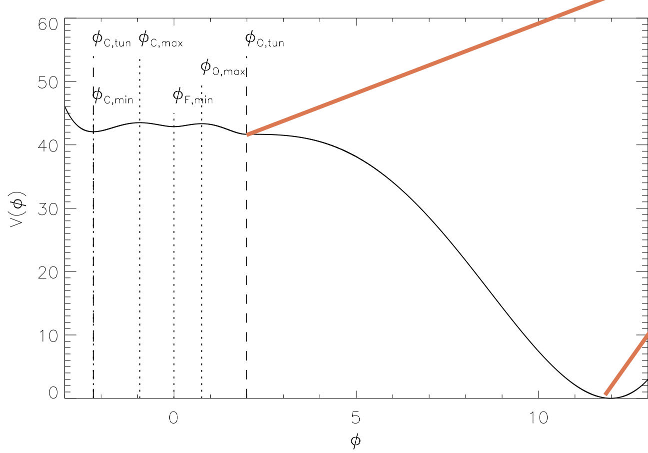

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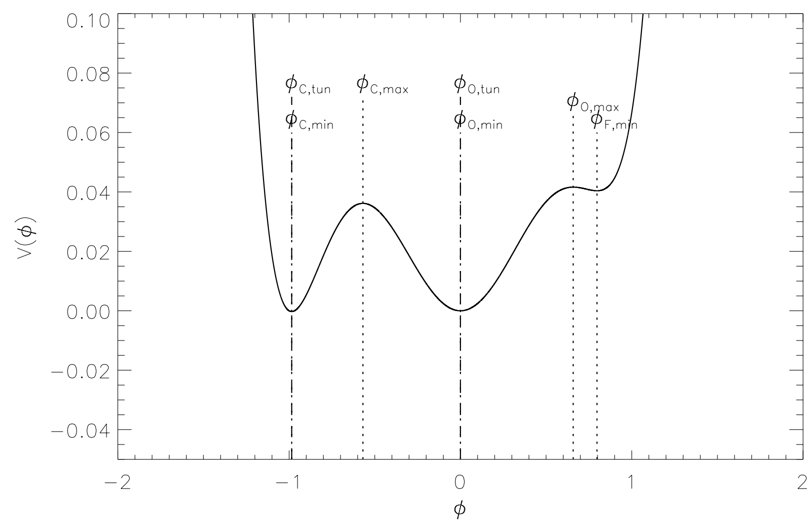
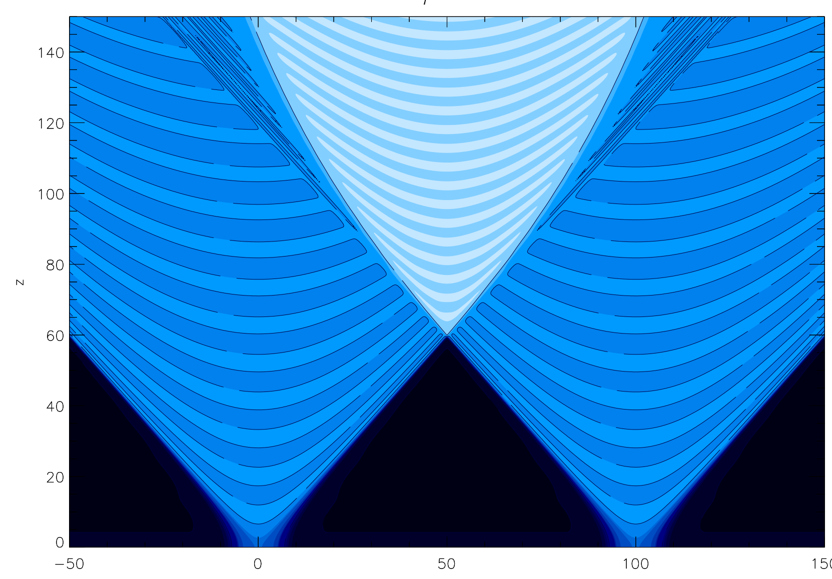
  - Many more possibilities:
    - Form yet lower vacuum bubbles (Easther et al. 09)





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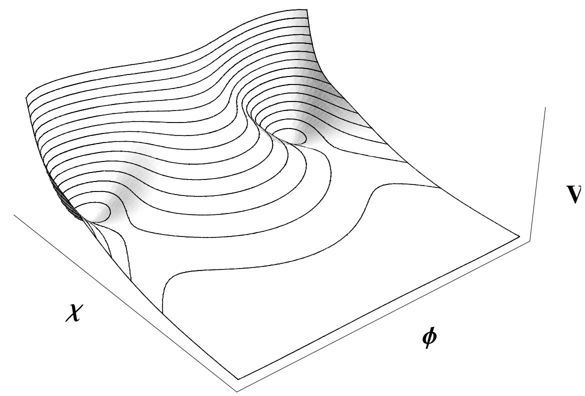
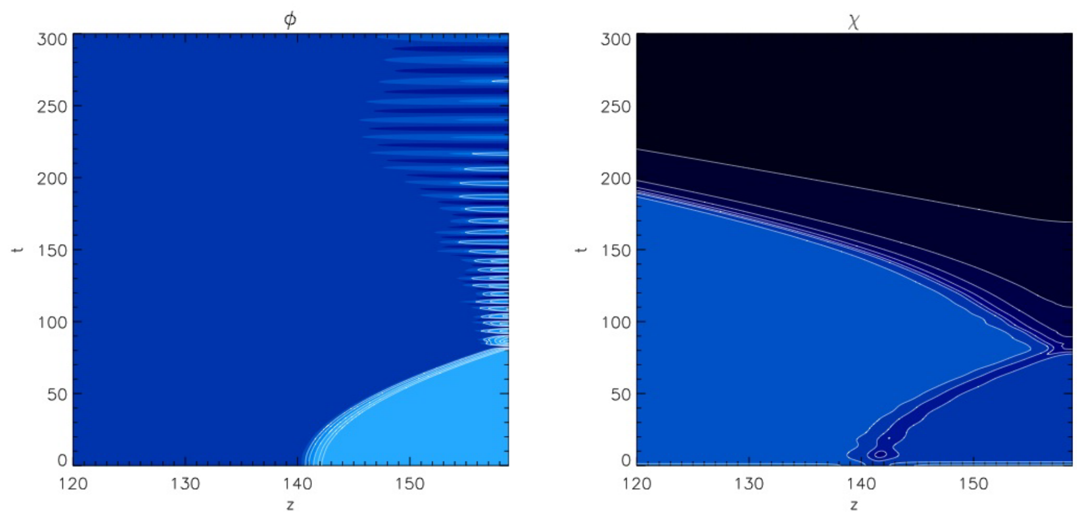
  - Many more possibilities:
    - Form yet lower vacuum bubbles (Easther et al.)
    - Multifield: lots more.





Collision-induced decompactification

(Aguirre, Johnson & Larfours 10)

What is the structure of a post-collision spacetime?

Model III: Numerical solutions in flat background

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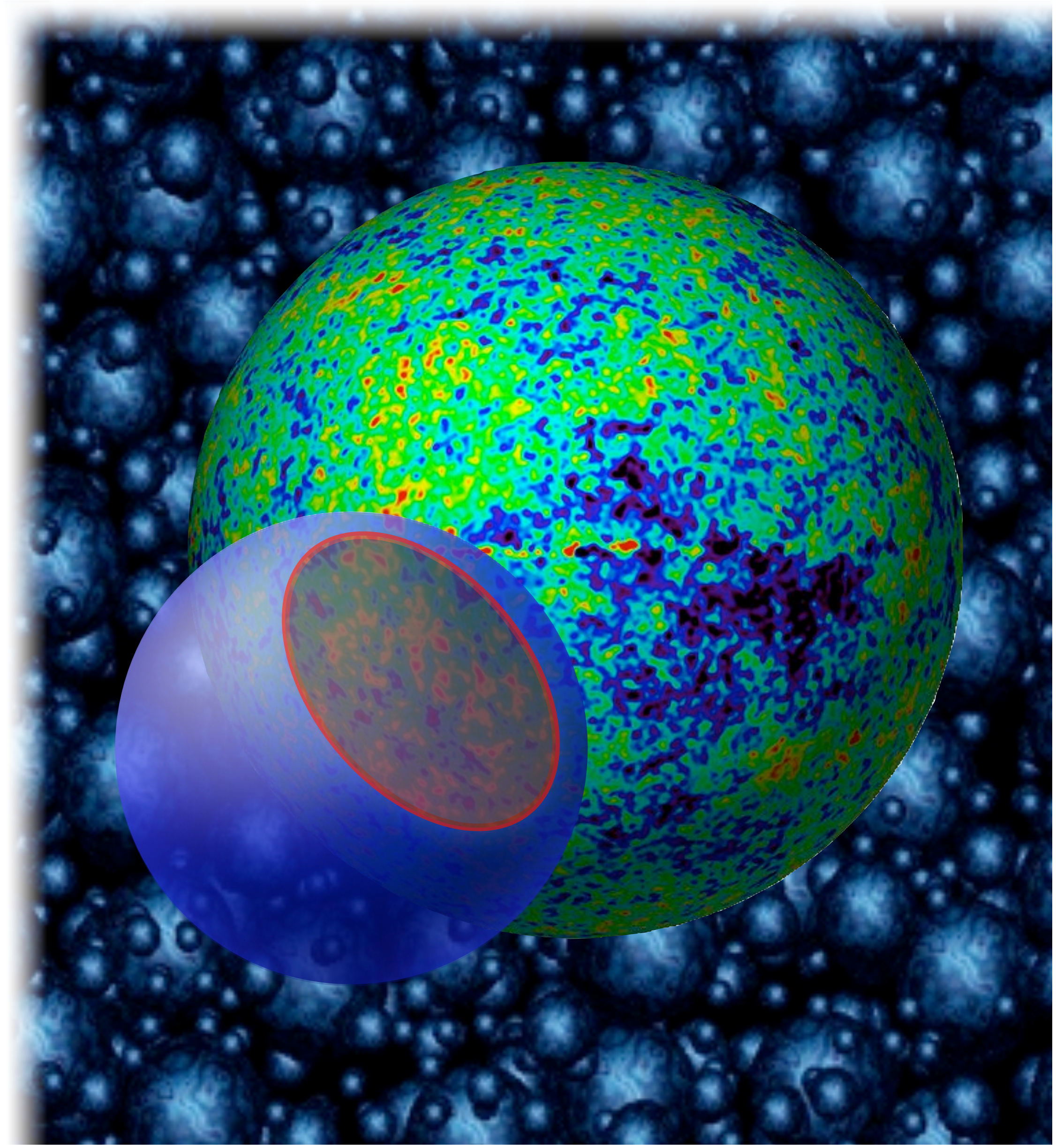
  - Many more possibilities:
    - Form yet lower vacuum bubbles (Easther et al.)
    - Multifield: lots more.

colliding decompactifying bubbles
(See Salem 10)

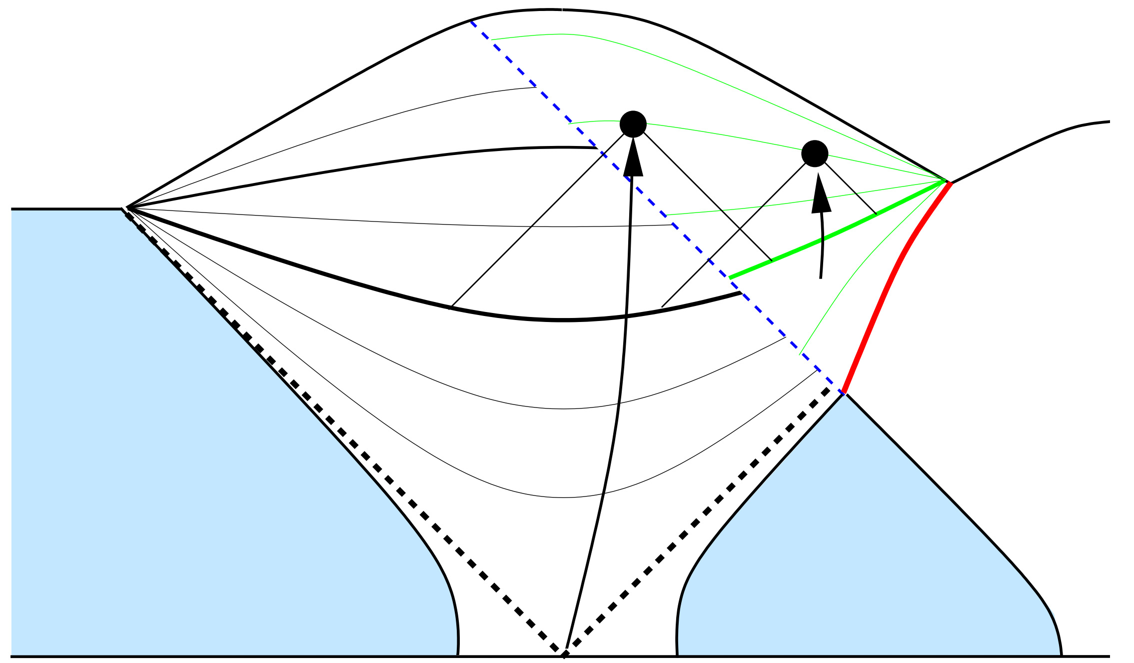
Observables (see Chang et al. 08; 09; Aguirre & Johnson 09)

- General considerations:
  - Must be no obliteration (but strong selection effect...)
  - Axisymmetric effects about collision direction.



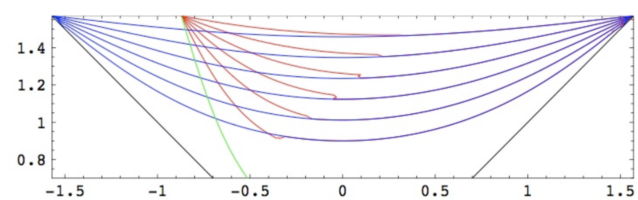
Observables (see Aguirre & Johnson 09; Chang et al. 08; 09)

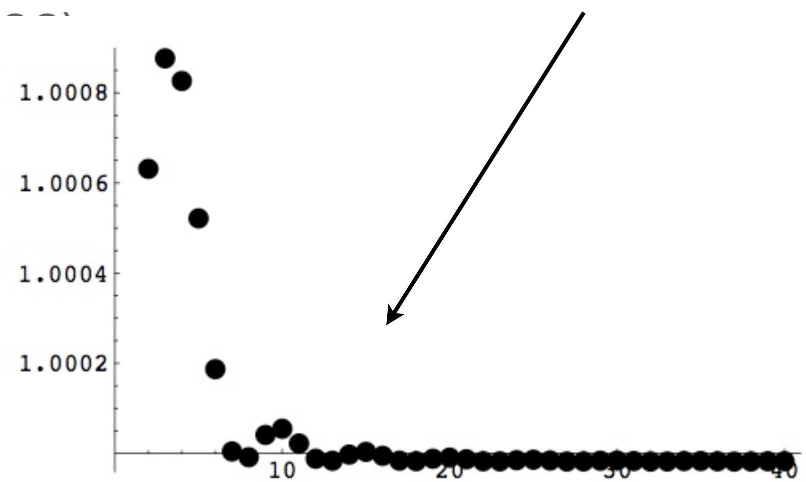
- Collision 'debris':
  - Radiation wall, but probably too diluted to see.
  - Gravity waves vanish to first order (if progenitor bubbles have full SO(3,1) symmetry).



Observables

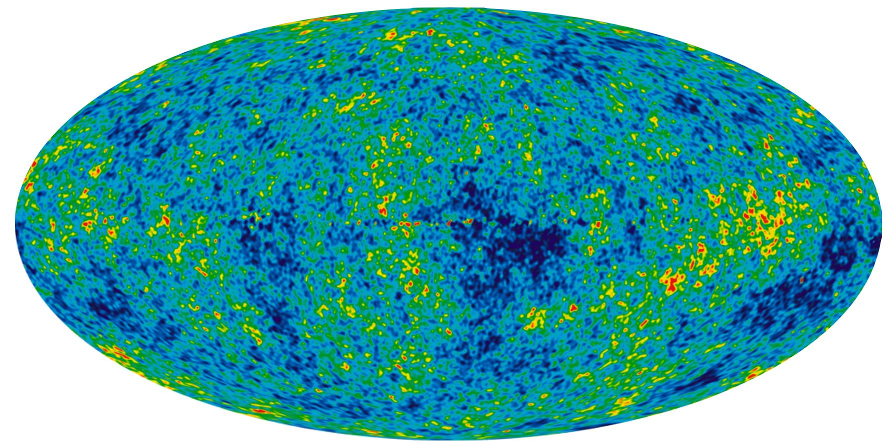
- Distortion of early equal-field surfaces
  - Density Perturbations (CMB, 21cm)
  - Polarization (see Levi talk)
  - Each collision: disk of affect.
    - Model as redshift back to perturbed reheating surface (Chang et al.
    - In simple model, find C_ls
    - Should do ‘real’ perturbative calculation.
  - Large-scale flows possible



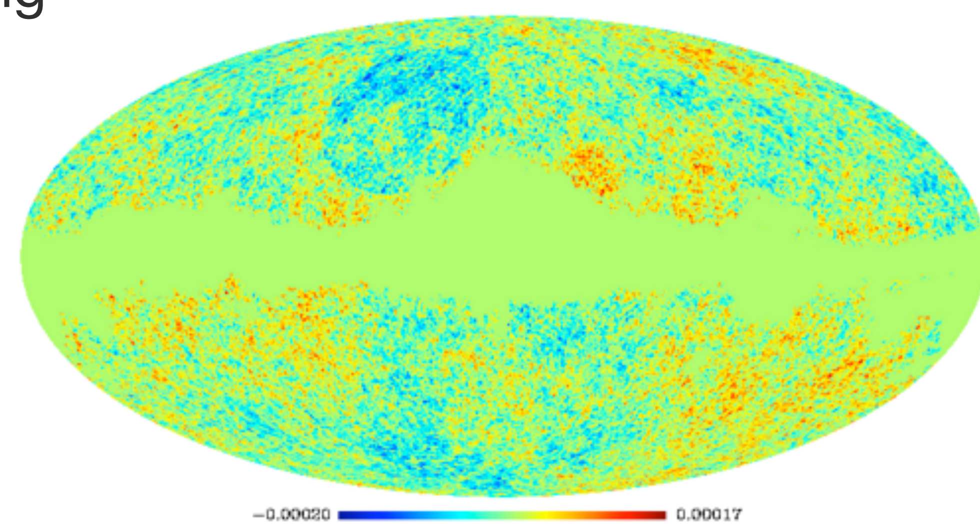


Bubble in Planck 1-year data?

- All-sky map data leak
- Processed with iterated self-similar wavelet edge-detection
- Redundant Bayesian prior analysis
- Integrated monte-carlo fold-in testing
- Likeliness Fisher ratio of $\sim 10^8$
- 1st non-vanilla inflation evidence?



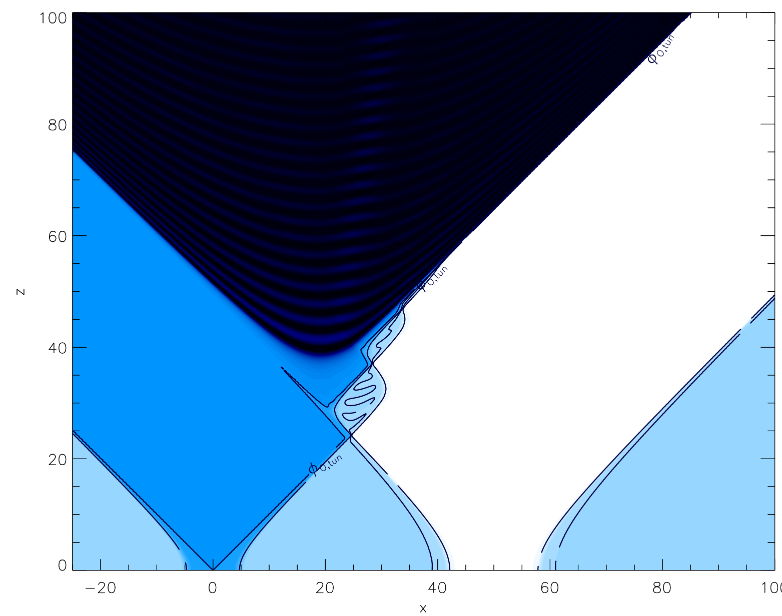
WMAP year 7 cleaned



Planck year 1, fractal wavelet edge-enhanced

Observables

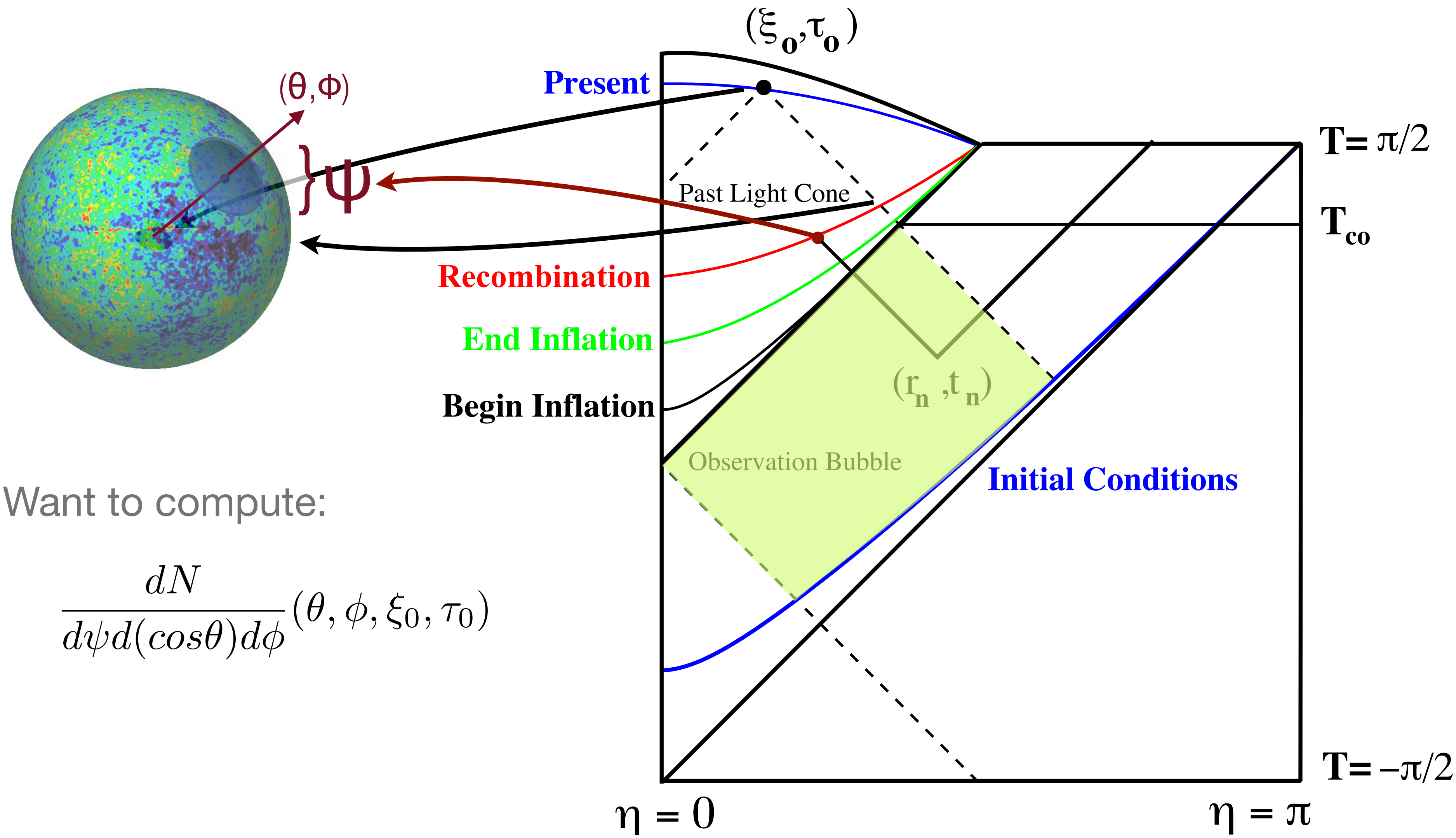
- Different inflationary history in collision region.
  - Disruption of inflation ('hole' in sky, falsifiable.)
  - Less e-folds in collision region.
  - Different field directions for multifield.
- Inflationary perturbations will be affected by this difference.



What are the probabilities for observing (various types of) collisions.

- Core Model (Garriga, Guth & Vilenkin 06):
  - Observation bubble forms at ‘late times’, so that we can model as t=0 bubble with $t \rightarrow -\infty$ initial ‘no bubble’ surface.
  - Incoming bubbles do not affect observation bubble.
  - Thin walls and small nucleation size → incoming bubbles are lightcones.
  - How many bubbles enter observer’s past lightcone?
- 3 Extensions.

The setup

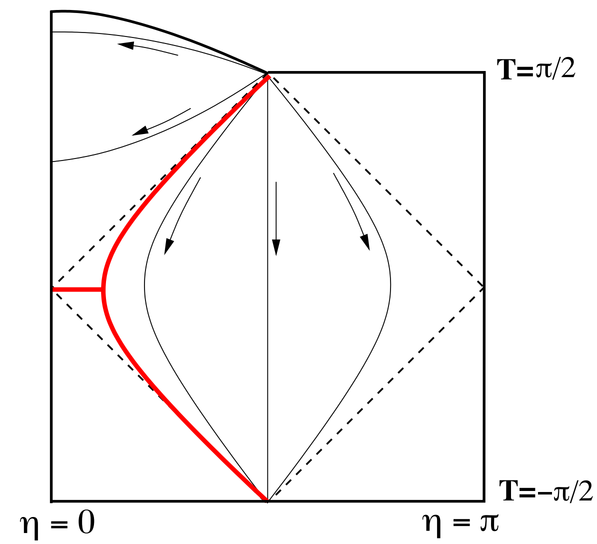


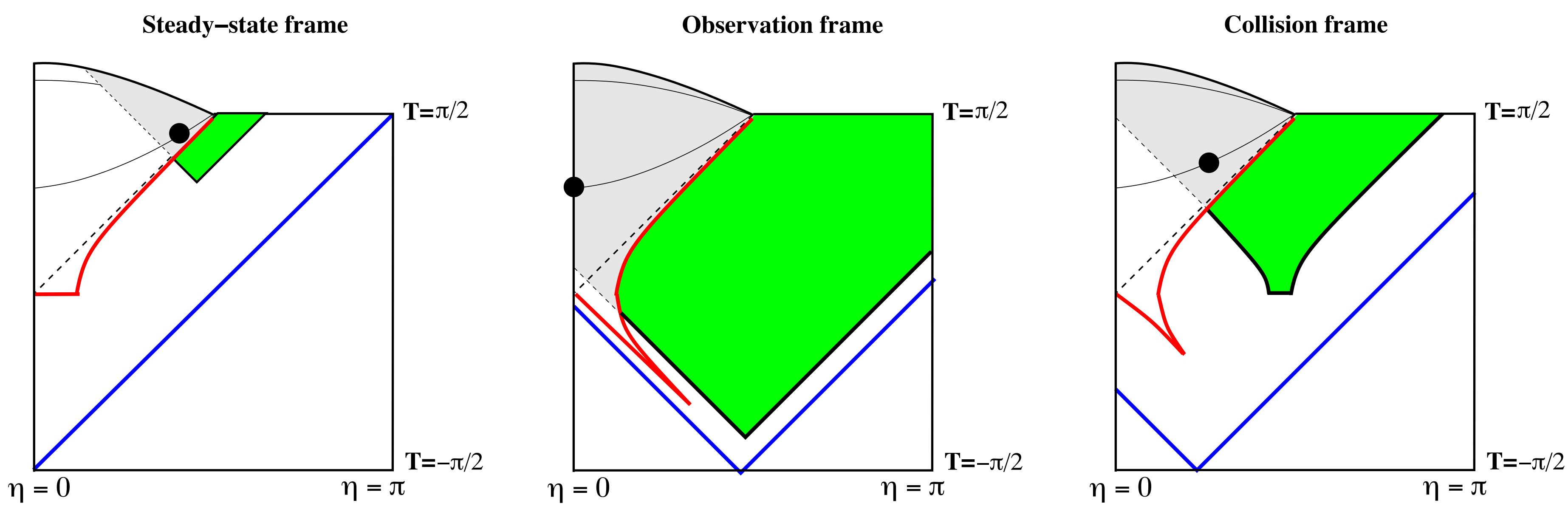
- Want to compute:

$$\frac{dN}{d\psi d(cos\theta)d\phi}(\theta,\phi,\xi_0,\tau_0)$$

Frames and classifications

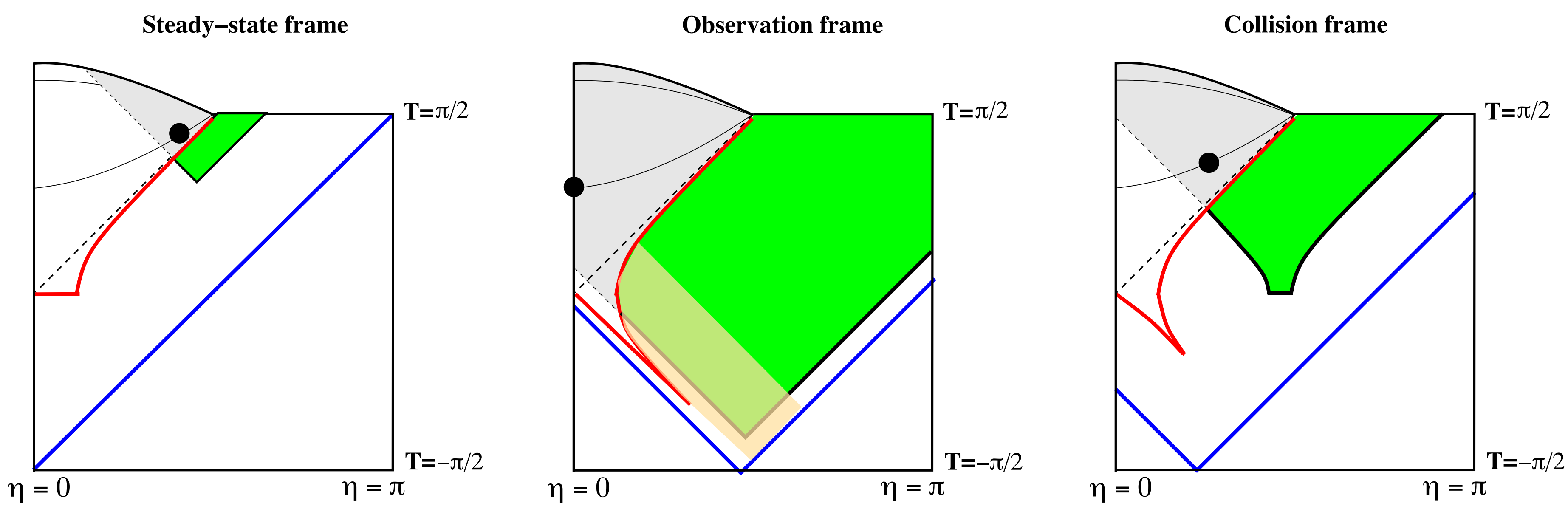
- Neglecting effect of collisions, we can ‘boost’ spacetime in well-defined way.





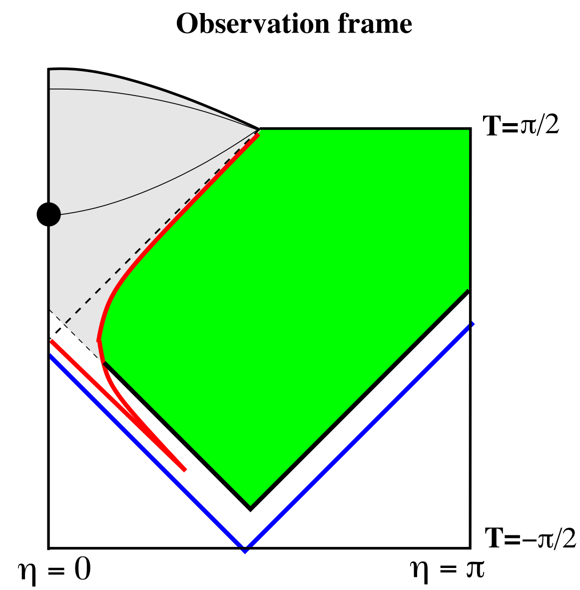
Frames and classifications

- Neglecting effect of collisions, we can 'boost' spacetime in well-defined way.
- Can put observer at origin, and can look for regions of large 4-volume inside past lightcone.



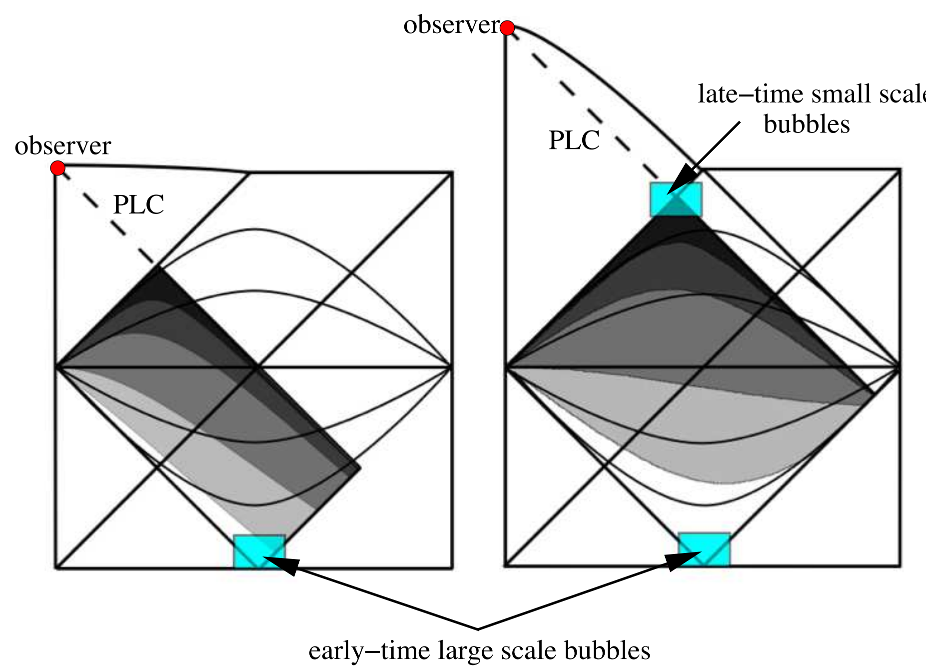
What are the probabilities: Results

- Core Model (Garriga, Guth & Vilenkin 06):
  - Go to observation frame.
  - Effect of boost is to distort initial condition surface.
  - Minimal expected number at zero boost, $N \sim \lambda(4\pi/3)H_F^{-4}$. Large-boost (up the bubble wall) gives divergent rate.
  - Preferred position pointing to preferred frame in background "persists", "remembers" initial surface.



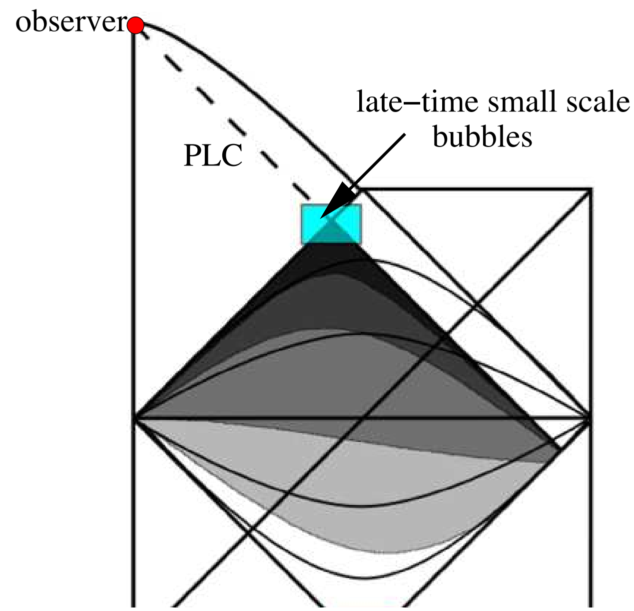
What are the probabilities: Results

- Extension I: Arbitrary FLRW cosmology inside observation bubble; what are angular sizes on $\tau \rightarrow 0$ surface? (Aguirre, Johnson & Shomer 07, 08; see also Gott 1984)
- Bimodal distribution, two classes of bubbles:
  - ‘Early’ bubbles enter p.l.c. at $\tau << H_I$, have large angular size, and have divergent number at large boost.
  - ‘Late’ bubbles enter p.l.c. at $\tau > H_I$, have range of angular sizes, boost-independent number.



What are the probabilities: Results

- Extension I: Arbitrary FLRW cosmology inside observation bubble; what are angular sizes on $\tau \to 0$ surface? (Aguirre, Johnson & Shomer 07, 08; see also Gott 1984)
- Number of 'late' depends on 'Hat size' from cosmology inside: how many false-vacuum Hubble 4-volumes H_F^{-4} can be seen.
  - With inflation inside at H_I, to 'solve horizon problem' or to get near-flatness, must see O(1) inflationary Hubble volumes.
  - If $H_I < H_F$, boost of $(H_F/H_I)^2$. (Could be large!)
  - No further late-time enhancement unless there is curvature-dominated epoch.

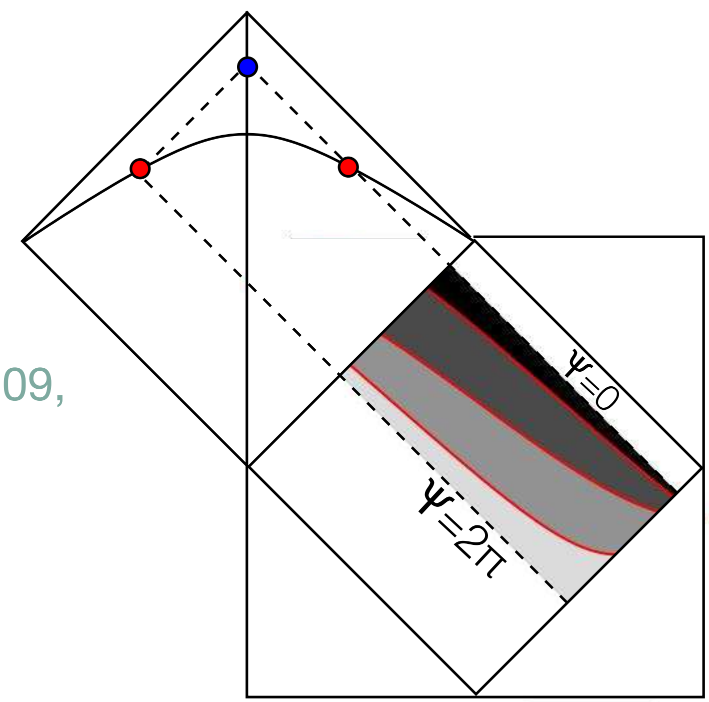


What are the probabilities: Results

- Extension II (Freivogel et al. 09: Ignore early and all-sky bubbles; assume collision effect propagates as null disturbances inside observation bubble; What are angular sizes Ψ on ***$\tau \neq 0$ surface***?)
  - For small current curvature, find disks of influence on last-scattering surface 'sky' obey

$$dN = \frac{4\lambda}{3}\left(\frac{H_F}{H_I}\right)^2 d(\cos\Psi)d\Omega_2^2$$

  - This distribution is fairly flat. (see Aguirre & Johnson 09, for slight generalization, plots and details.)



What are the probabilities:
Connecting to bubble structure.

- Extension III: What is the effect of back-reaction on the observation bubble? (See AA et al. 09; AA & Johnson 09; Freivogel et al. 09:)
  - Extend 'homogeneous volume' measure across collision regions.
    - Restricted to native-born observers, not much difference.
    - But if they are allowed, 'all' observers should be foreign born (by the arguments of GGV)
    - But same argument re-capitulated applies: 'all' should be foreign-foreign born...
  - Global, (e.g. scale factor cutoff, etc.) may well matter.
  - Collisions may come in to global measure:
    - Comparing volumes in some ways -> 'victorious' bubbles have vastly more volume.
    - Bubbles allowing foreign-born observers may likewise have vastly more observers.

Conclusions

- **Basics results:**
  - Even if the universe is not observably open, it may very well have formed in an open inflation bubble-nucleation event.
  - In this case, our bubble will collide with infinitely many others.
  - There’s been huge progress in understanding the resulting picture. Some fun results:
    - Even for exponentially suppressed nucleation rates, these collisions probably lie to the past of most observers.
    - For large enough (but still small) nucleation rates, could see ‘disks of influence’ of finite angular size on CMB etc.
    - Depending on potential, collisions ‘eat’ either fraction 1 or 0 of the observation bubble.

Conclusions

- **Basics results:**
  - Even if the universe is not observably open, it may very well have formed in an open inflation bubble-nucleation event.
  - In this case, our bubble will collide with infinitely many others.
  - There's been huge progress in understanding the resulting picture. The bottom line:
    - **If we live in open eternal inflation and if our parent vacuum can nucleate other bubbles (that do not invade ours) at a rate $\lambda H_F^{-4} > (H_F/H_I)^2$, and if there are not too many extra efolds of inflation in our bubble, then we should expect to 'see' collisions.**

Conclusions

- **Open questions:**
    - Could bubble collisions be crucial for measures over vacua? Or vice-versa?
    - What is the expected maximum nucleation rate from our parent vacuum?
    - Any good reason to hope for the ‘just right’ number of efolds?
    - How, precisely, do the effects of the collision propagate inside the observation bubble? What is effect on CMB?
    - What about more thick wall/large bubble, decompactifying, classical-transitioning, multifield, etc. models?
    - *Are* there bubble collisions in the observed sky (see Johnson, Pieris talks)?