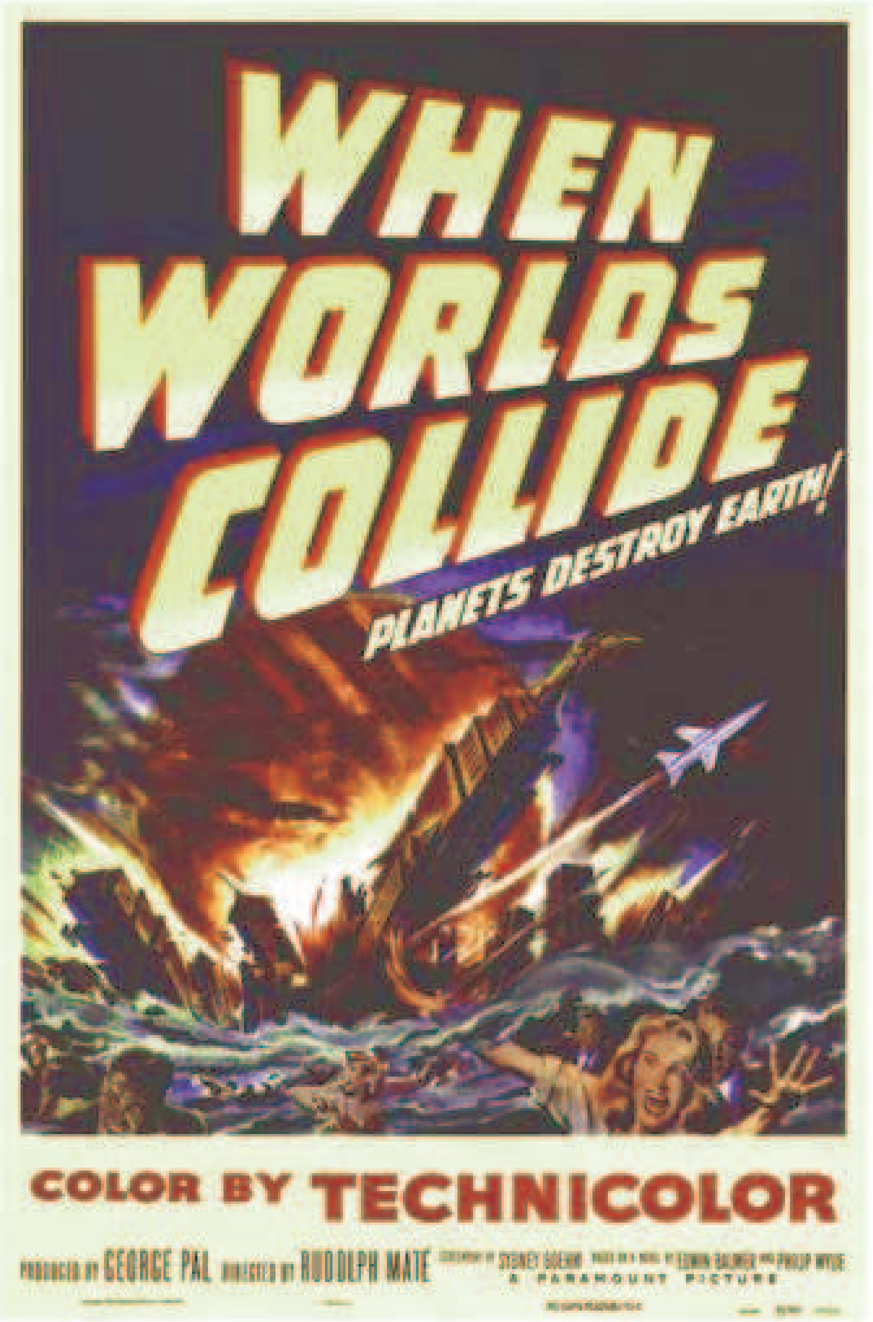


Thomas Levi
NYU

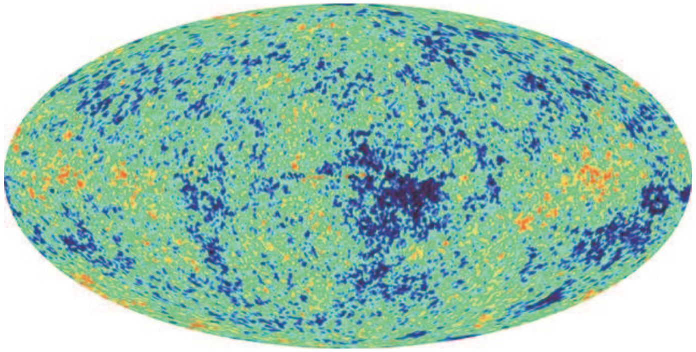
arXiv:0712.2261 [hep-th]

Spencer Chang, Matthew Kleban and TSL

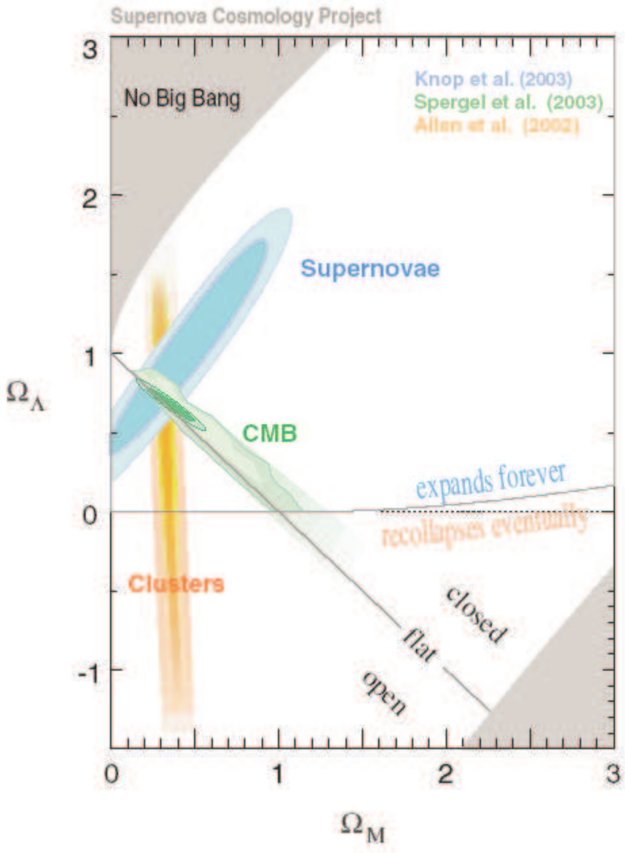
Work in progress

Cosmology

- The universe was at very high energies early on
- And there's a huge amount of cosmological data from experiments like WMAP, SDSS, Supernovae, Planck, upcoming 21cm experiments…

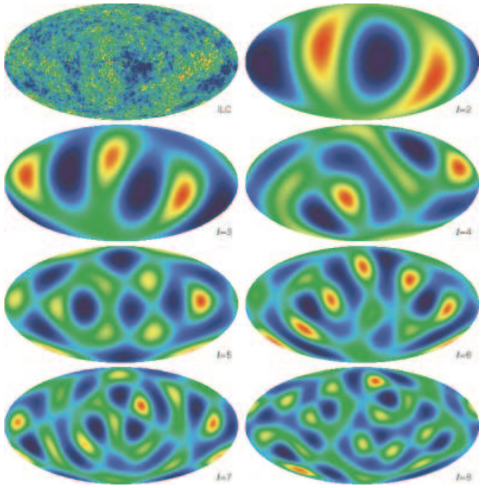


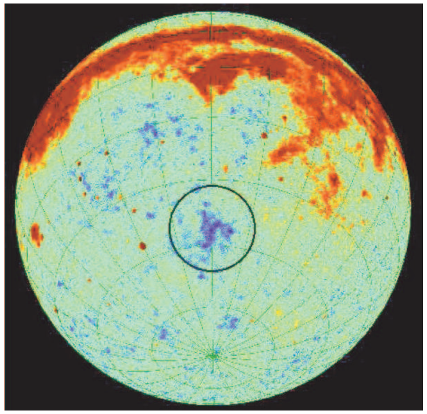
Perhaps we can use cosmology to tell us about physics at high energies



Inflation

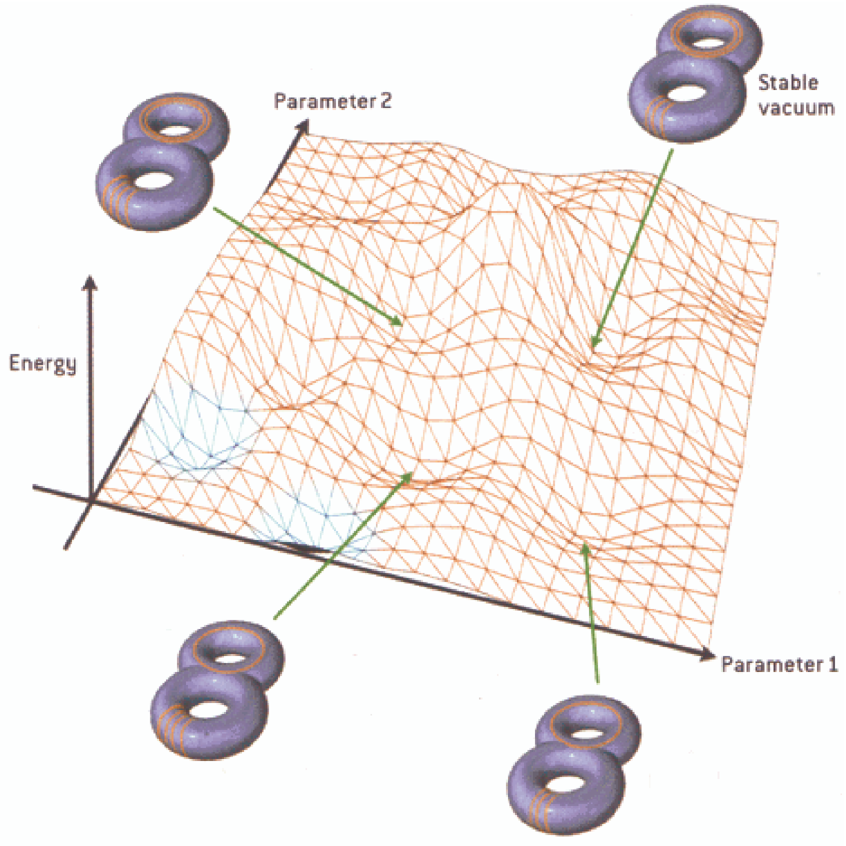
- But inflation tends to smooth out the physics in the early Universe (at high energies). That’s what it was designed to do
- Is it possible to find effects which can survive reasonable amounts of inflation?
- Have we perhaps already seen hints of this?





Motivation

- String theory has a huge number of possible stable and metastable vacua
- New ideas have led to a picture of a landscape, where different patches of the Universe correspond to different metastable vacua, inflating at different rates
- Instantons lead to bubble nucleation of open universes with different physics and cosmological constants
- These bubbles do not evolve in isolation, in fact, they can collide
- Is there any way we can detect this with present or future cosmological measurements?



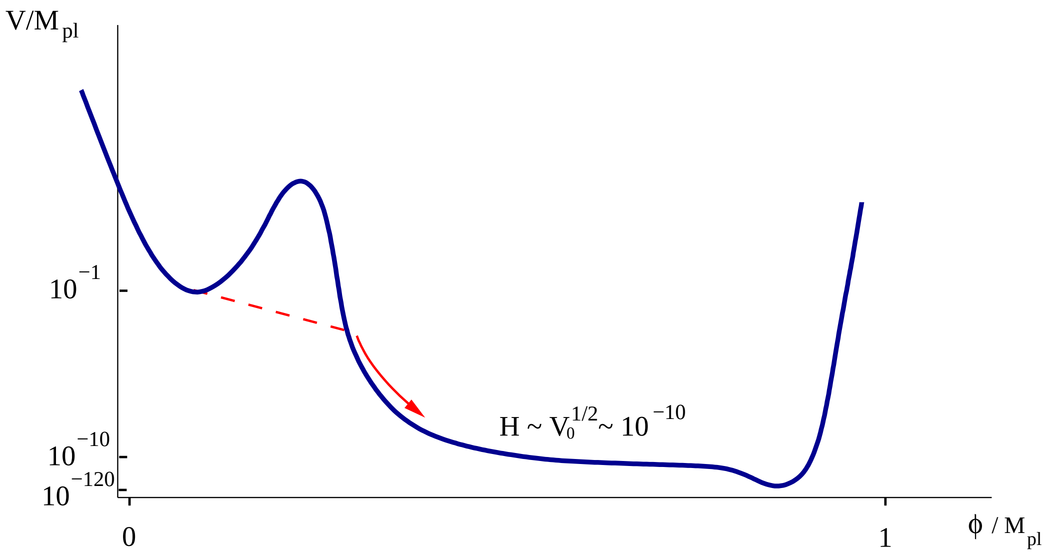
"The Landscape" (Picture from *Scientific American*)

Outline

- The landscape, bubbles and collisions
- Building blocks of collisions
- Dynamics of collisions
- Effects of collisions
  - Radiation from the collision
  - Hitting the wall
  - Doppler Shift
  - Mirror Images
  - Sachs-Wolfe
- Caveats, unknowns and prospects for the future

The Landscape and Bubbles

- The string landscape has of order 10^{500} vacua
- Most vacua are meta-stable
- Tunneling, via a Coleman-de Luccia instanton creates a bubble
- Each tunneling leads to the creation of a bubble whose walls expand out, rapidly approaching the speed of light
- The geometry inside each bubble is that of an open FRW universe



From Freivogel et al. 05

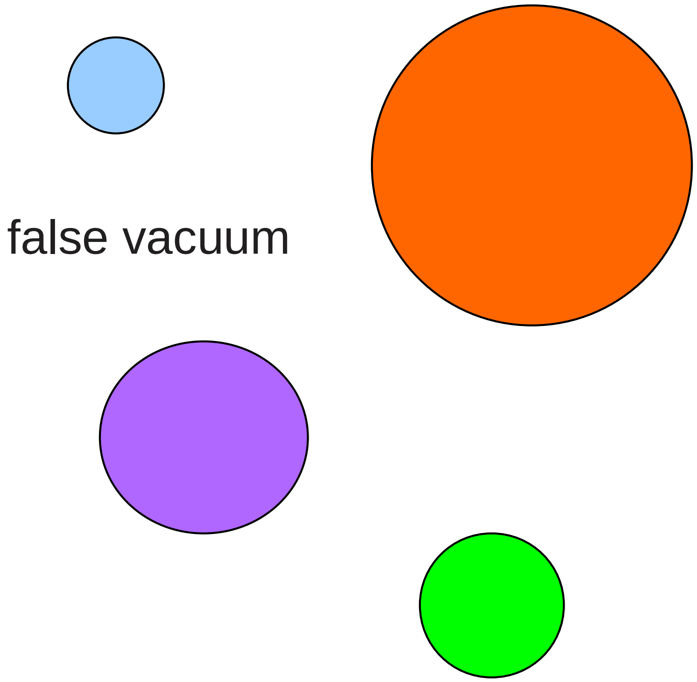
•Current WMAP data has $\Omega_{tot}=1.02 \pm .02$

•Inflation washes away most bubble initial conditions

•Current data suggests we have N>62 e-folds

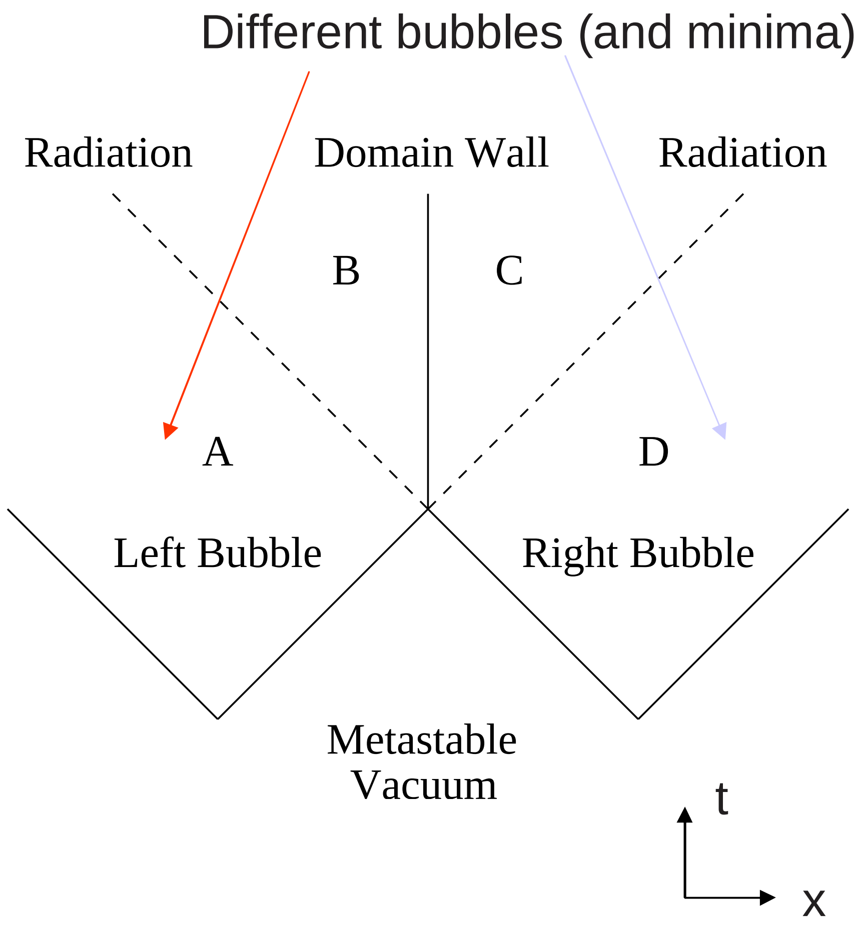
More on bubbles

- Each bubble alone has an SO(3,1) symmetry inherited from the SO(4) of the instanton
- The bubbles do not expand in isolation
- Generically, bubbles collide
- When two bubbles collide the symmetry is broken down to SO(2,1)
- Can signals of these collisions survive inflation?



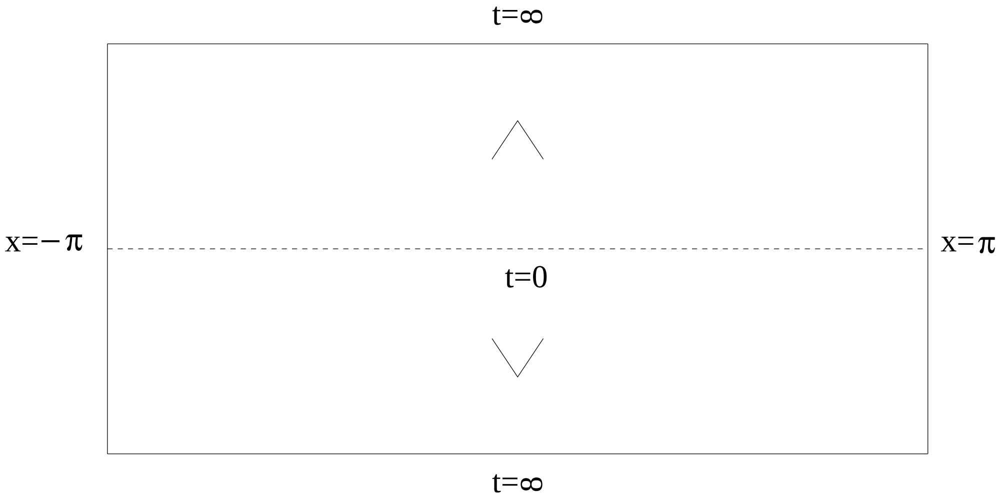
Collisions

- There are several possible collision scenarios with bubbles of dS ($\Lambda>0$), AdS ($\Lambda<0$) and flat ($\Lambda=0$) bubbles colliding
- Use junction conditions to analyze the trajectory of the *domain wall* that forms between the two bubbles
- After collision, the spacetime in each bubble is a “perturbed” version of the original spacetime

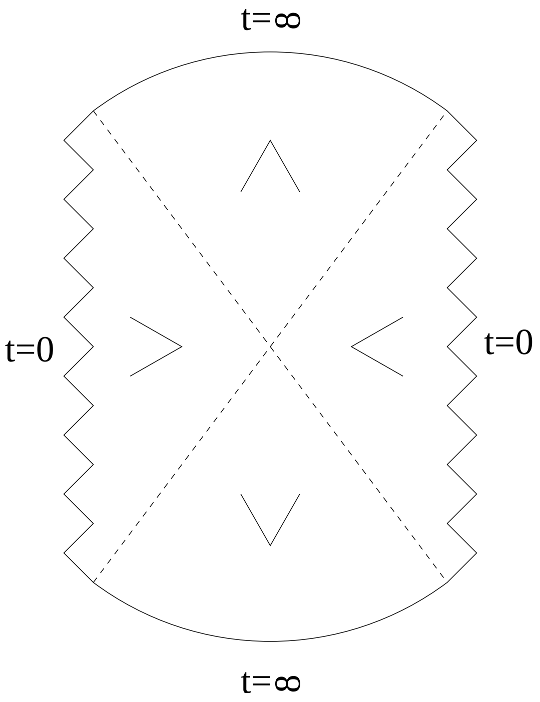


The building blocks: dS space

$$\begin{aligned} ds^2 &= -\frac{dt^2}{g(t)} + g(t)\,dx^2 + t^2\,dH_2^2 \\ g(t) &= 1 + \frac{t^2}{\ell^2} - \frac{t_0}{t} \end{aligned}$$

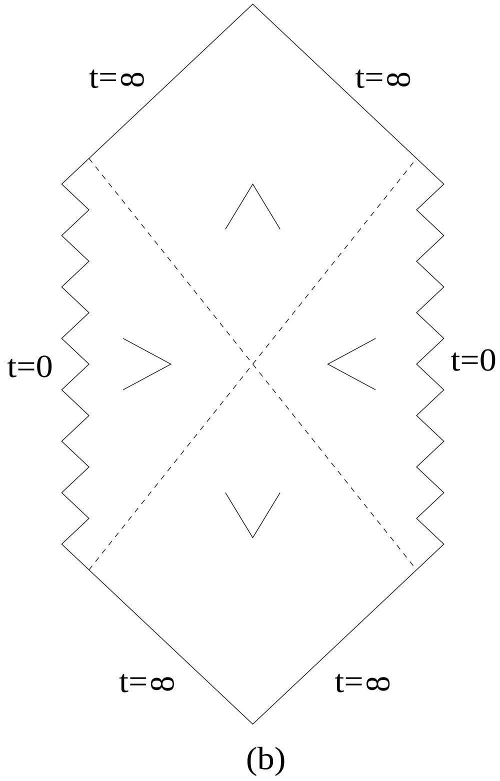


Unperturbed $t_0=0$

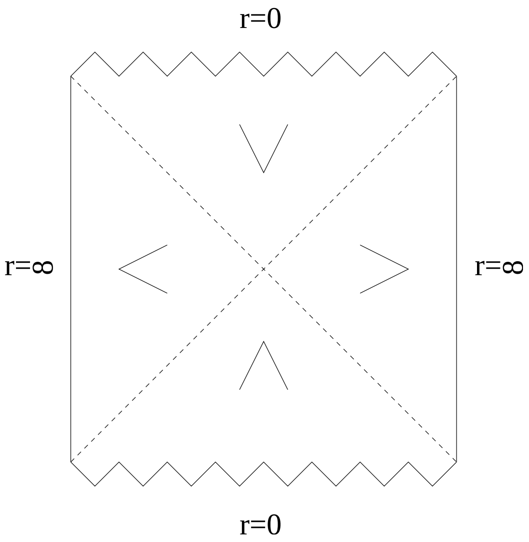


Perturbed $t_0>0$

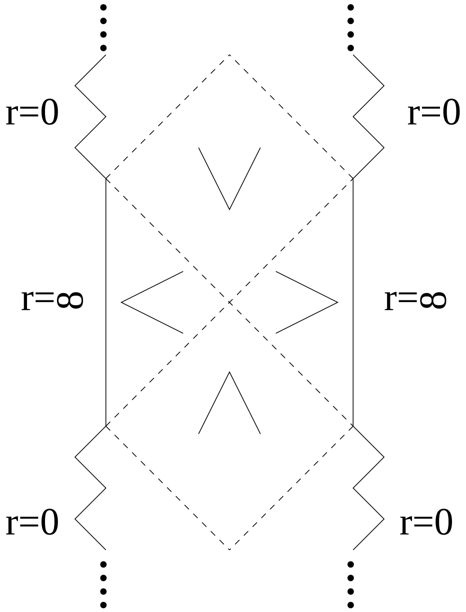
More building blocks



Hyperbolic flat space



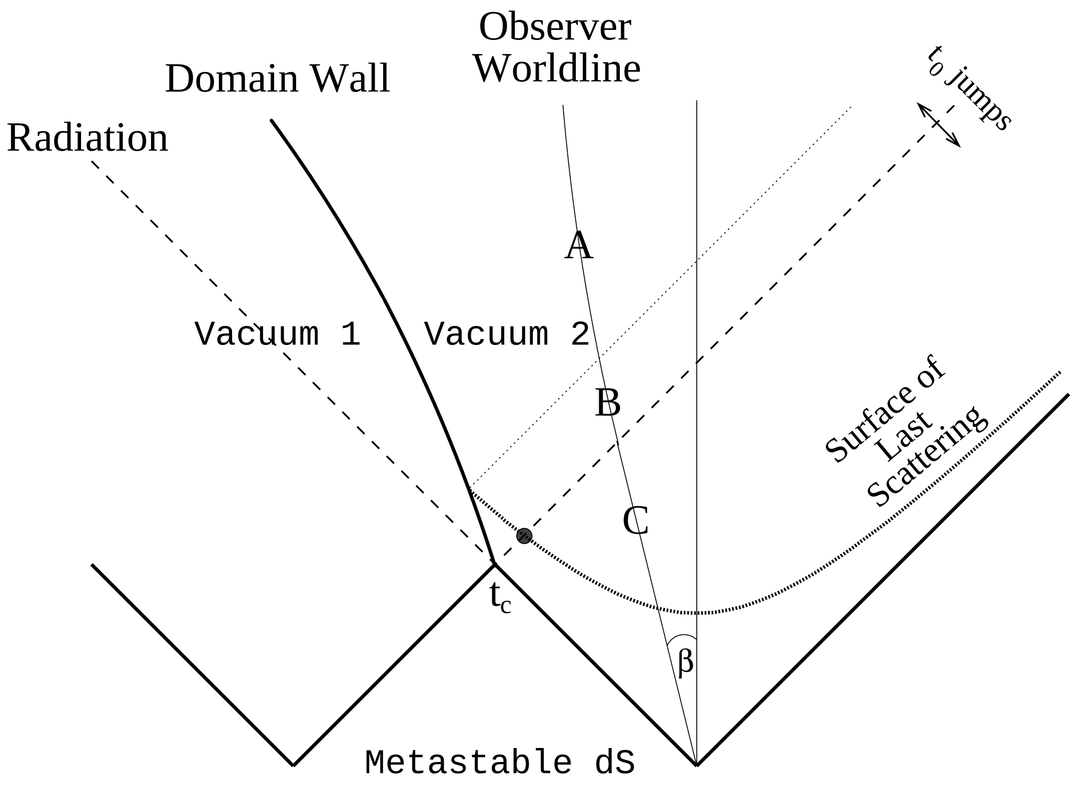
Hyperbolic AdS ($t_0 > 0$)



Hyperbolic AdS ($t_0 < 0$)

Analytic solutions

- We can find exact solutions in the approximation that the bulk is vacuum energy dominated and find the trajectory of the domain walls
- Like the walls of the bubbles, they undergo constant acceleration (though don't necessarily approach the speed of light)



Some results: dS on dS/flat

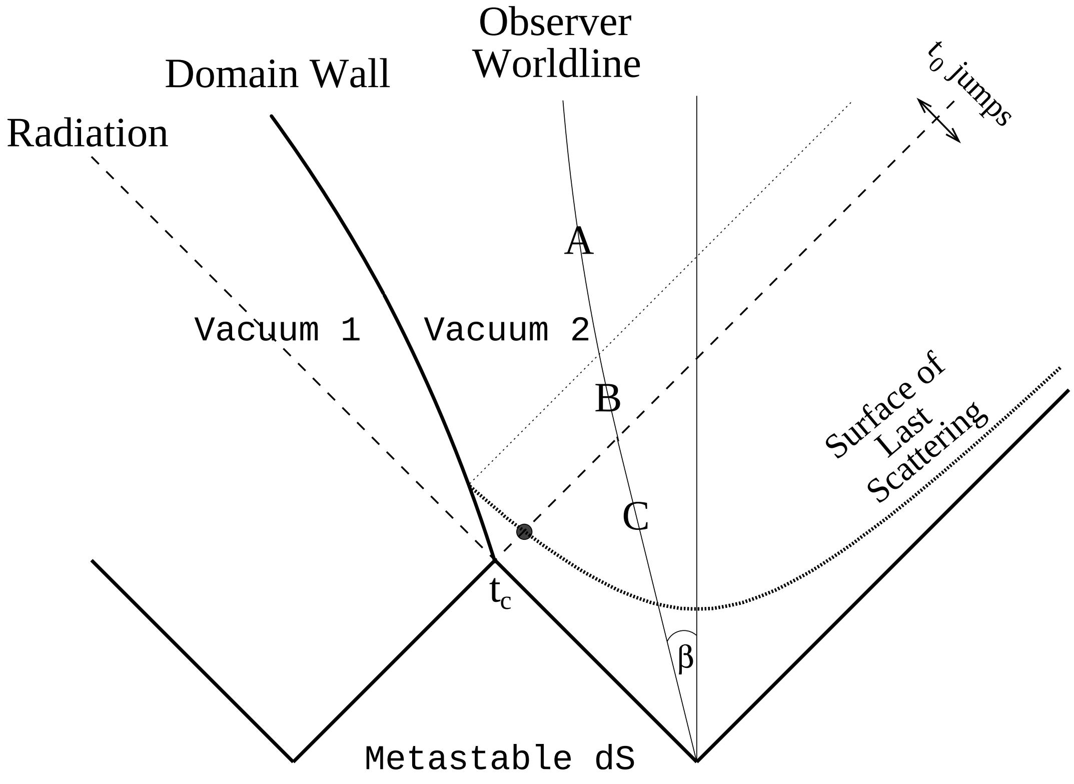
- Domain wall moves *away* from the bubbles with smaller Λ (conservation of energy)
- The wall can sometimes move both towards and away from the bubble with larger Λ (depends on the tension of the wall and the difference in Λs)
- A small positive Λ, such as the one we observe protects the bubble from catastrophic collisions with bubbles with larger, positive Λ
- We may also be safe from collisions with bubbles of negative Λ due to the tension of the wall (BPS bound) Freivogel, Horowitz and Shenker

So far…

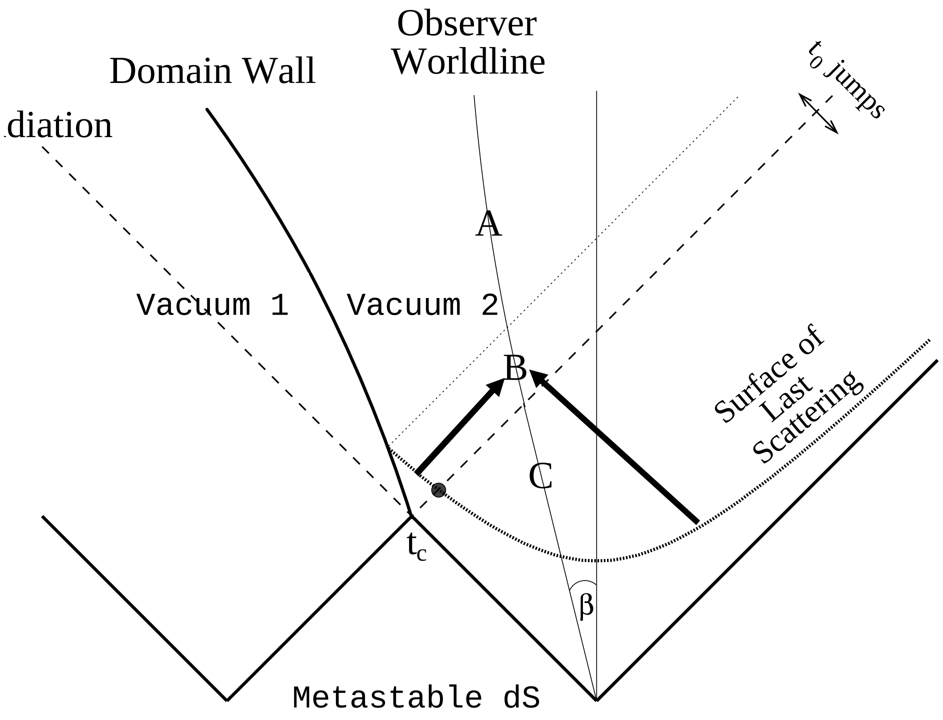
- Metrics and domain wall motion can be solved for analytically in the thin wall limit
- Bubbles with the smallest positive cosmological constant are the safest
- Now lets look at what effects we may be able to see from these collisions

Observables

- Observer C is oblivious to the collision
- Observer B can see asymmetric redshifts in the CMB
- Observer A can see the asymmetric redshifts and “see” the domain wall
- Can see radiation from collision along the line where t_0 jumps

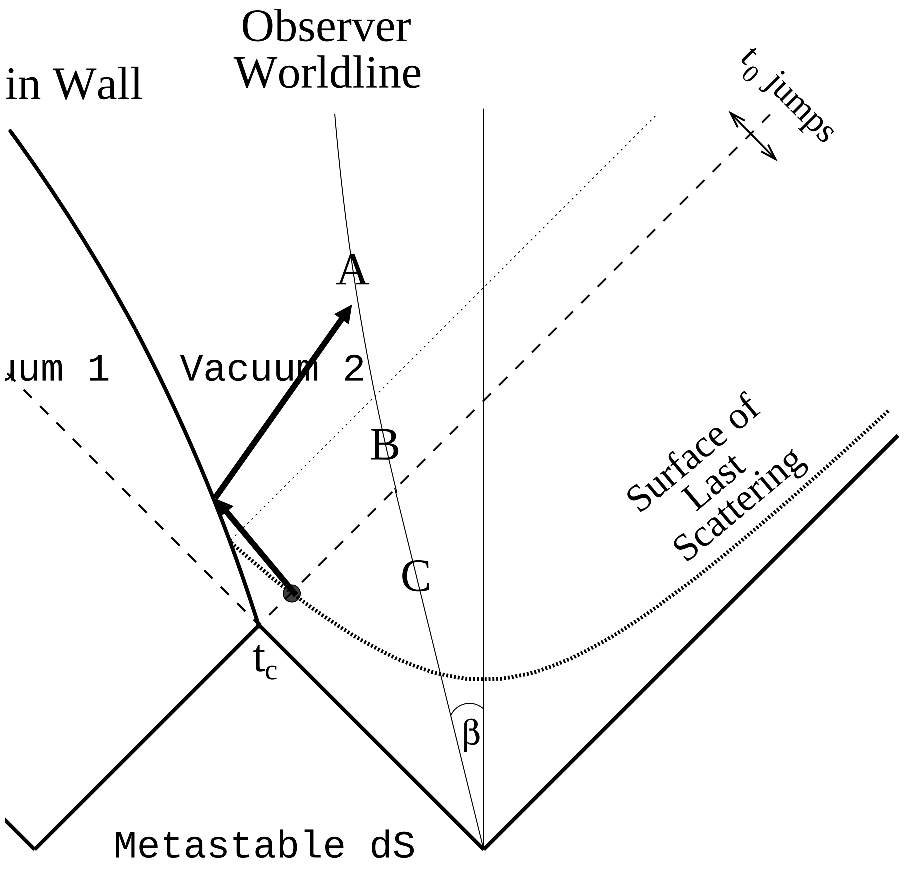


Asymmetric redshifts



- Photons from different directions travel through different metrics
- This leads to different redshift based on direction. The biggest difference will be from photons that originate inside the shell and those outside of it→divides the sky into two discs
- Effect is of order $t_0/t_{observer}$

Seeing the wall



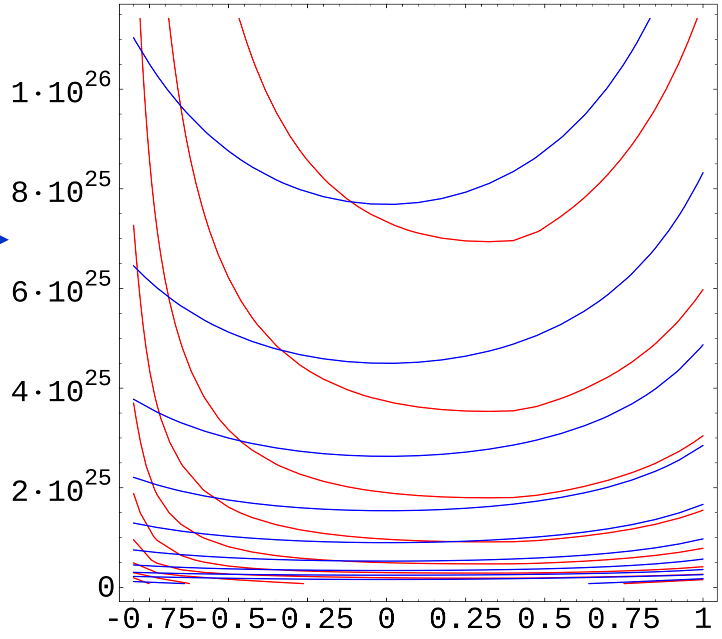
- If the two vacua are different the domain wall will likely be a near perfect reflector for photons
- Since the wall is moving, these photons will be doppler shifted
- Will show up as a circular disc with T red (or blue) shifted. The doppler shift is a function of the radial distance from the center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

Limits from inflation

- But the larger t_c is, the longer an observer will have to wait for any effects to come within his lightcone, this sets an upper bound on t_c
- There is a lower bound for the effect to be visible. Roughly we require an 10^{-5} effect
- To get some idea of this, we use a toy model, a sharp transition from inflation to flat space, roughly at last scattering
- Putting them together using standard values for the parameters like the reheating temperature requires $N<130$
- These effects can survive significant inflation!

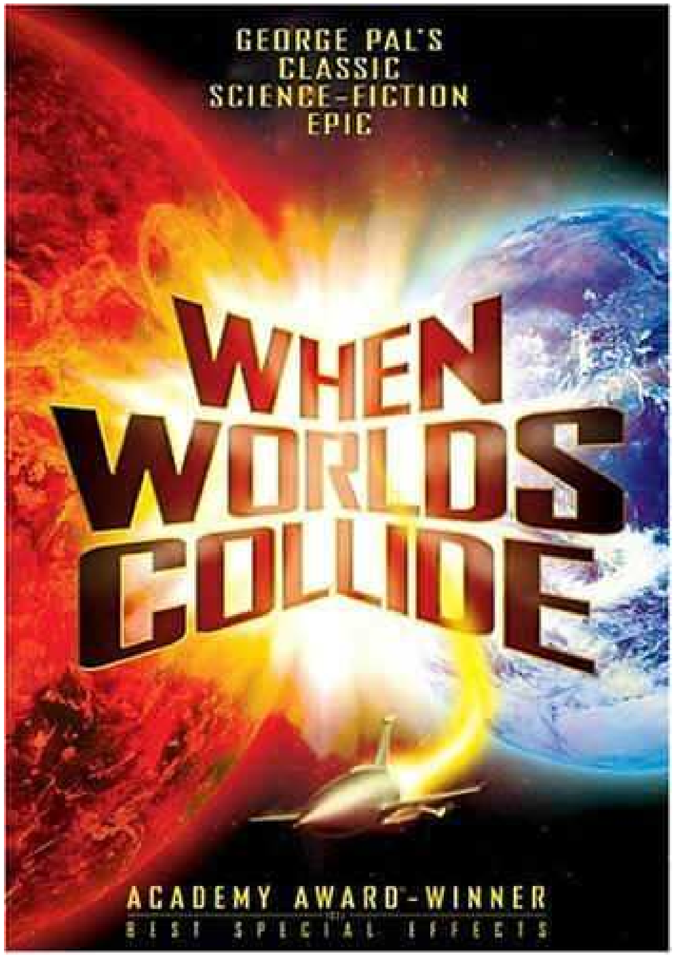
Caveats

- So far we've been mostly qualitative in our analysis of the effects of the collisions, we'd like to make this more quantitative
- Need to understand how slices of constant scalar field are changed as a result of collisions
- Need to patch on radiation or matter domination to understand full evolution
- We've ignored the measure issue. Many such measures exist (Bousso et al, Garriga et al, Aguirre et al,…) → We think a signal would be too spectacular to ignore



Lines of constant ϕ
for an *early* collision
If no collision happened

Conclusions and future directions



- Cosmology has tremendous potential as a probe of high energy physics and string theory
- We've analyzed the dynamics of bubble collisions analytically
- More work needs to be done on the effects and potential observables
- How do these things effect the CMB, 21cm radiation, structure formation, etc.?
- Can things like the "axis of evil" and the cold spot tell us anything?