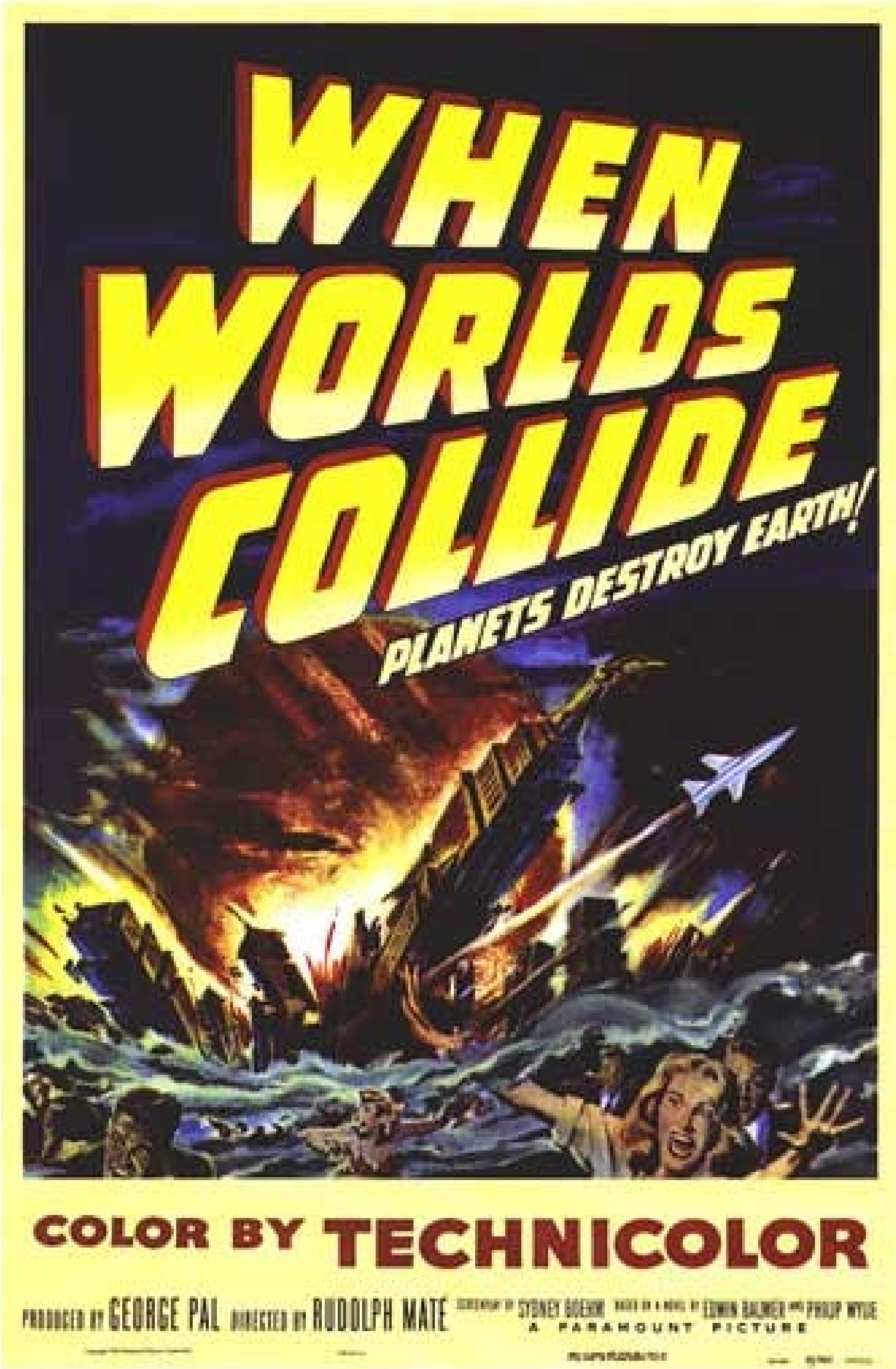

The Cosmological Observables of Pre-Inflationary Bubble Collisions

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(NYU)

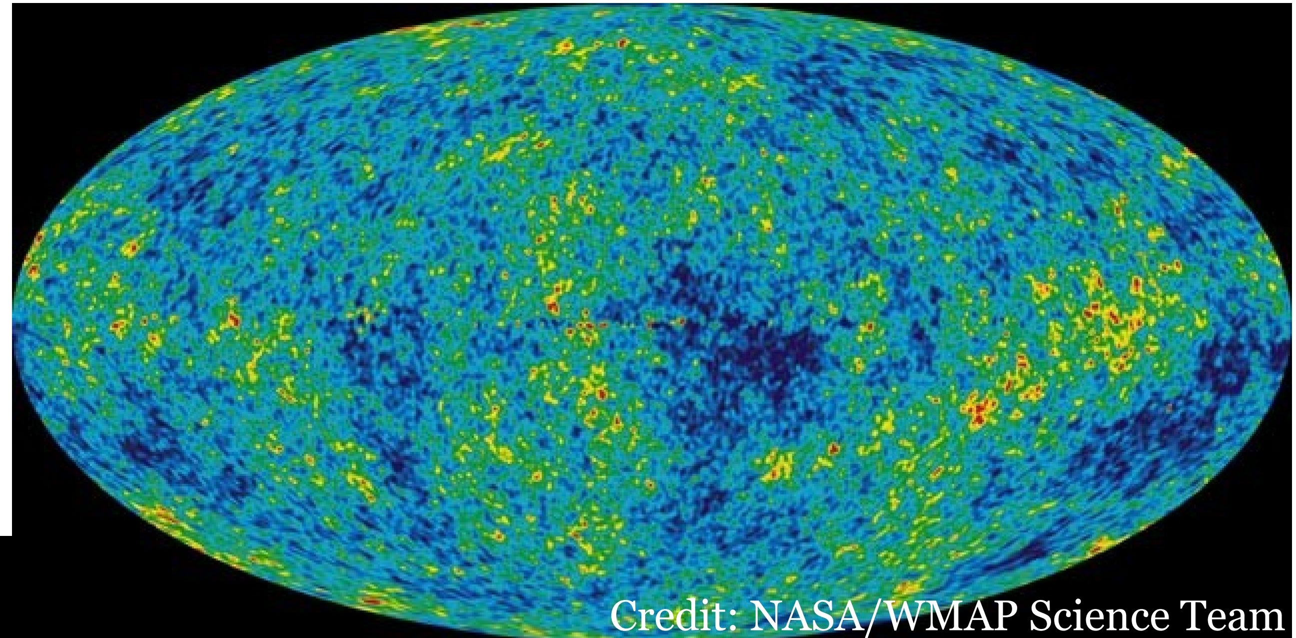
w/ M. Kleban, T. Levi

0712.2261 [hep-th]

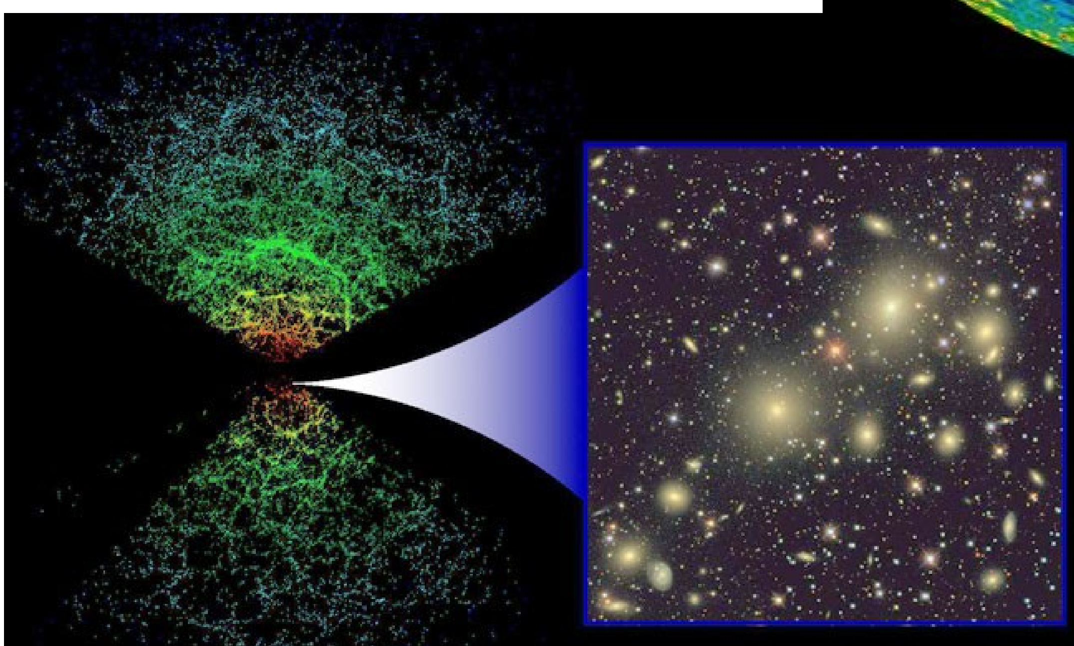
Also at Youtube, search for
"When Worlds Collide Trailer"

Cosmology

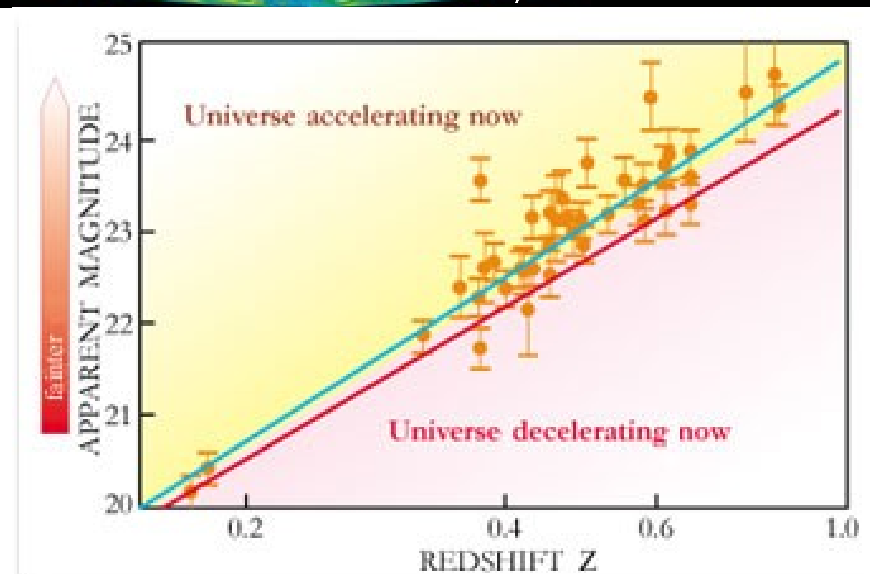
Wealth of cosmological data from WMAP, SDSS, Supernovae



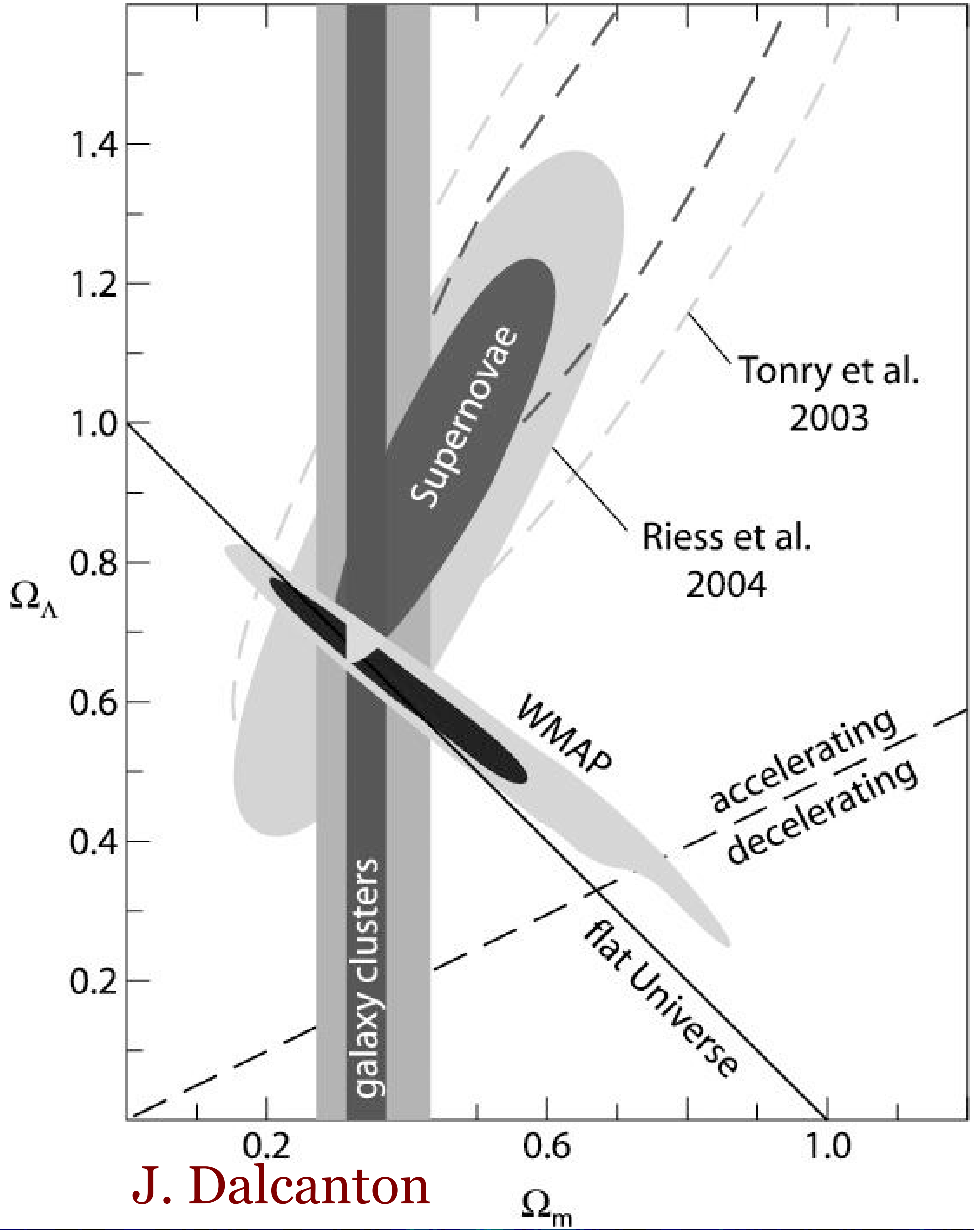
Credit: NASA/WMAP Science Team



SDSS



Concordance



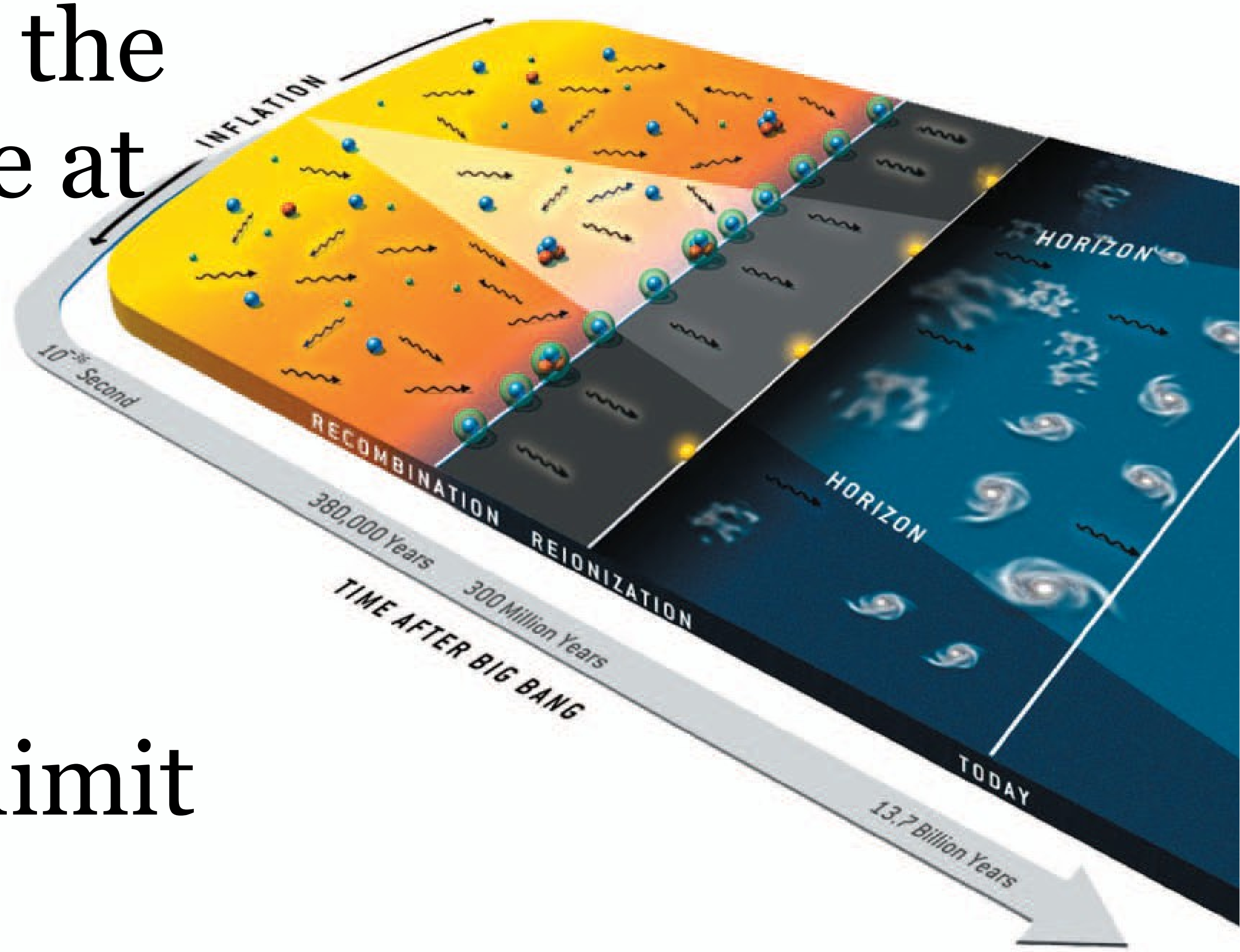
J. Dalcanton

- Universe is ~ 70% Dark Energy, ~ 25% Dark Matter, ~5% Baryons
- Experimental future is promising with Planck, SDSS-III, 21 cm experiments

Cosmological Collider

- Cosmology allows you to look into the past, to universe at higher temperatures
- In standard cosmology, Inflation is the limit

Hu and White

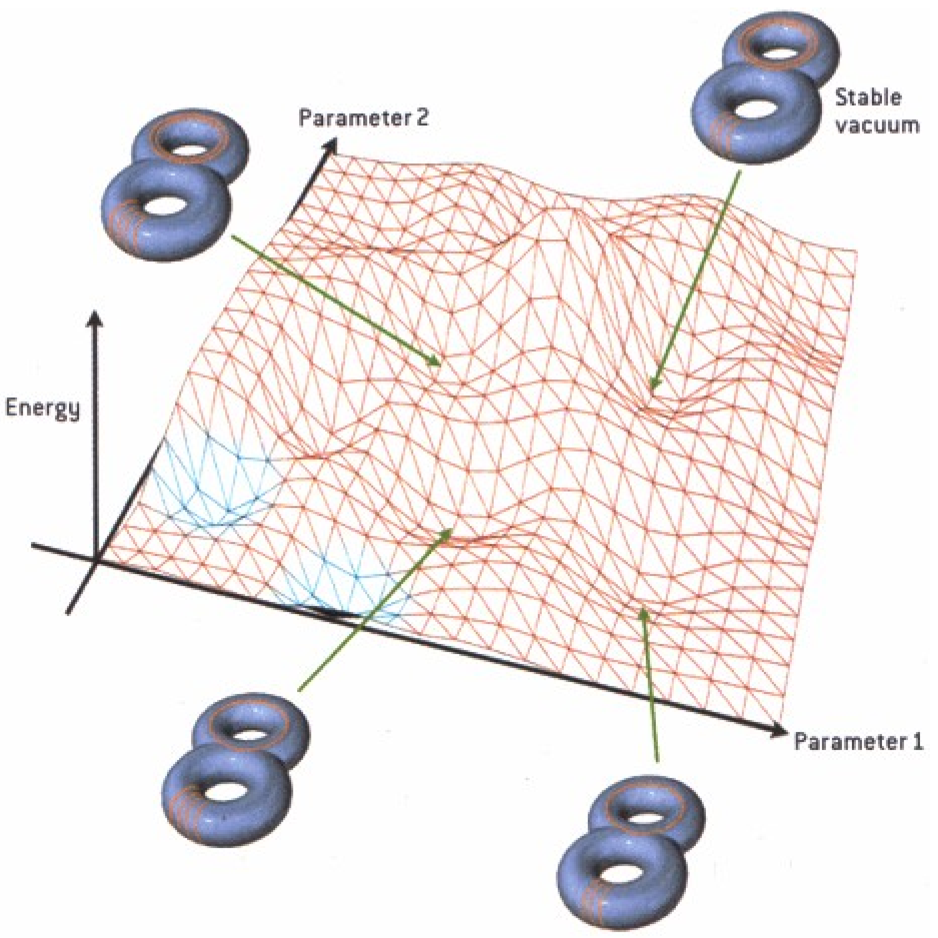


Inflation

- Designed to smooth out initial conditions to solve:
  - Horizon problem
  - Flatness problem
  - Diluting number count of heavy relics
- This wiping of the slate makes it hard to see physics before inflation

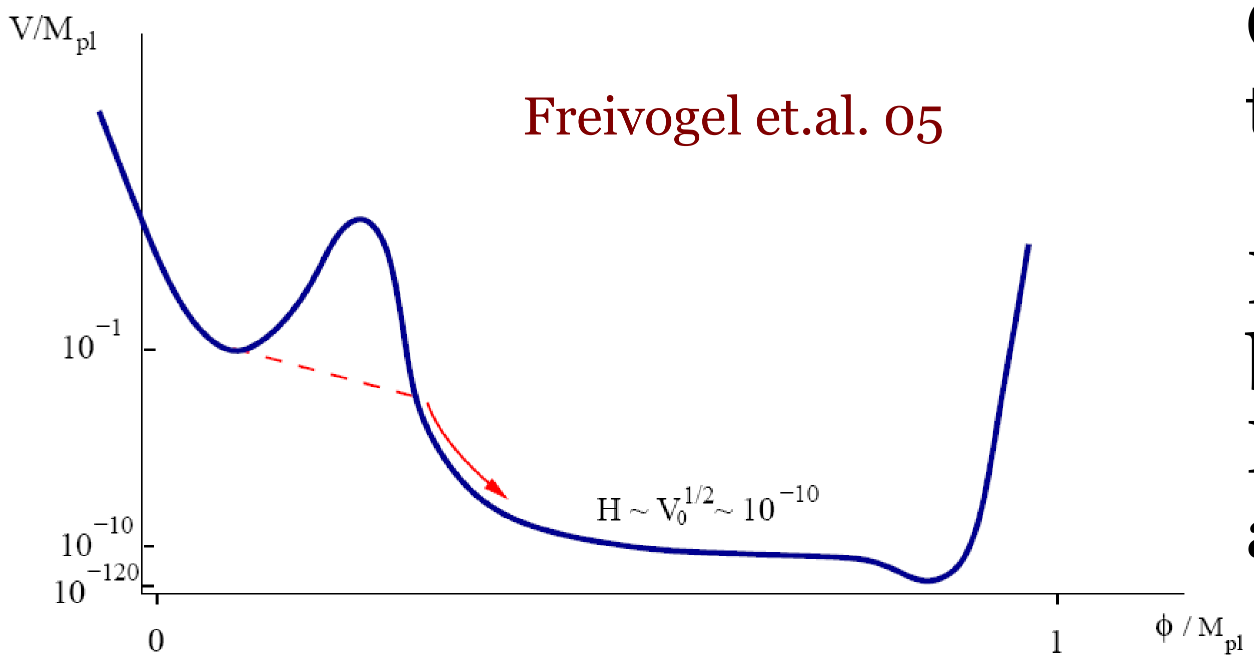
Landscape

- String Theory seems to predict a landscape of potential vacua, 10^{500}
- Our vacua no longer unique
- Have we been asking the wrong questions?



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

Landscape predictions



Cosmology might be the right approach…

Landscape vacua must be populated…
Eternal inflation serves as a mechanism

Path is unlikely to be direct… More likely to get stuck in other vacua and have to tunnel to ours.
Has to be followed by inflation to produce our observed universe.

Coleman-de Luccia Bubbles

- Bubble transitions solutions have O(4) symmetry in Euclidean space
- Expanding bubble interior is described by analytic continuation
  - Inherits O(1, 3) symmetry
  - Described by an open FRW universe

$$ds^2_{\mathrm{CdL}} = -d\tau^2 + a(\tau)^2 dH_3^2$$

$$dH_3^2 = d\xi^2 + \sinh\xi^2 \, d\Omega_2^2$$

- Scalar field homogeneous on H_3 slices

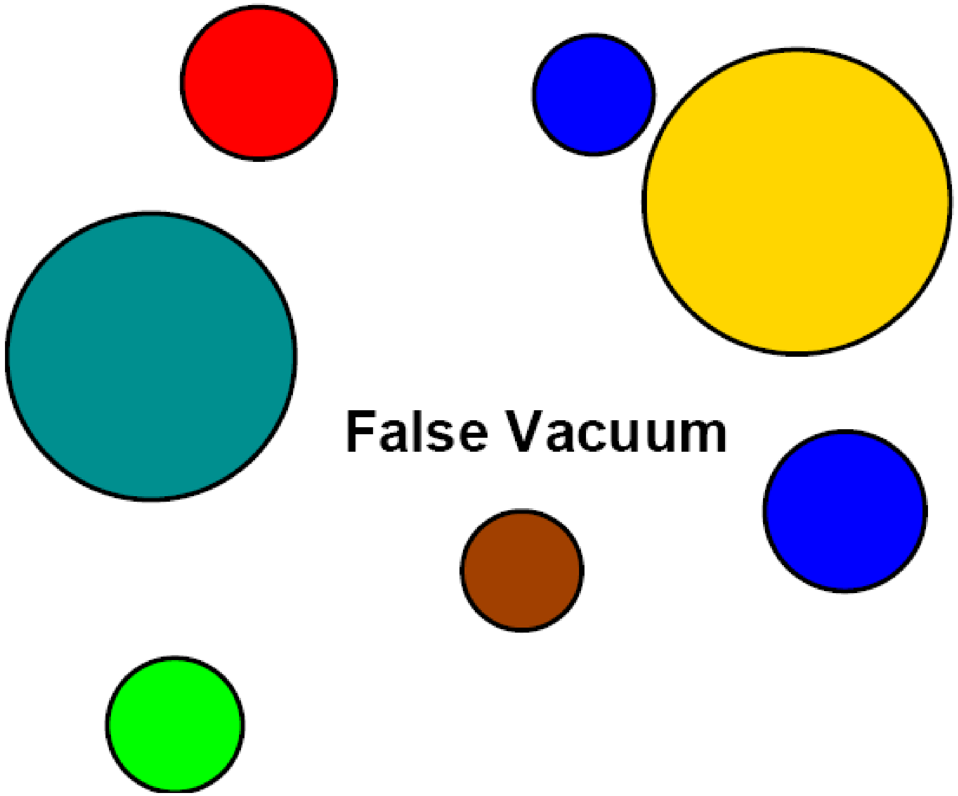
Observable Initial Conditions?

Freivogel et.al.
Garriga et.al.
...

- Universe can only be slightly open today, so need inflation after tunneling
- WMAP requires $\Omega_{tot} = 1.02 \pm .02$
- This amounts to e-fold constraint $N > 62$
- Observational limit $\Omega_{tot} - 1 \sim 10^{-(4-5)}$ requires $N < 66$
- CMB power spectrum features affect primarily low l, cosmic variance limited

A more promising direction

- A small window for bubble initial conditions to be visible
- Bubbles do not evolve in isolation
- Colliding bubbles, a generic signal of inflating landscape



Our approach

"If our calculations prove to be correct, this will be the most frightening discovery of all time." - When Worlds Collide

- Get an analytic understanding of the behavior of bubble collisions of different vacua
- We will be able to determine the metrics and behavior of the domain wall separating the two vacua
- Will discuss some potential signals qualitatively (work in progress on quantitative calculations)

Assumptions (following Freivogel, Horowitz, Shenker)

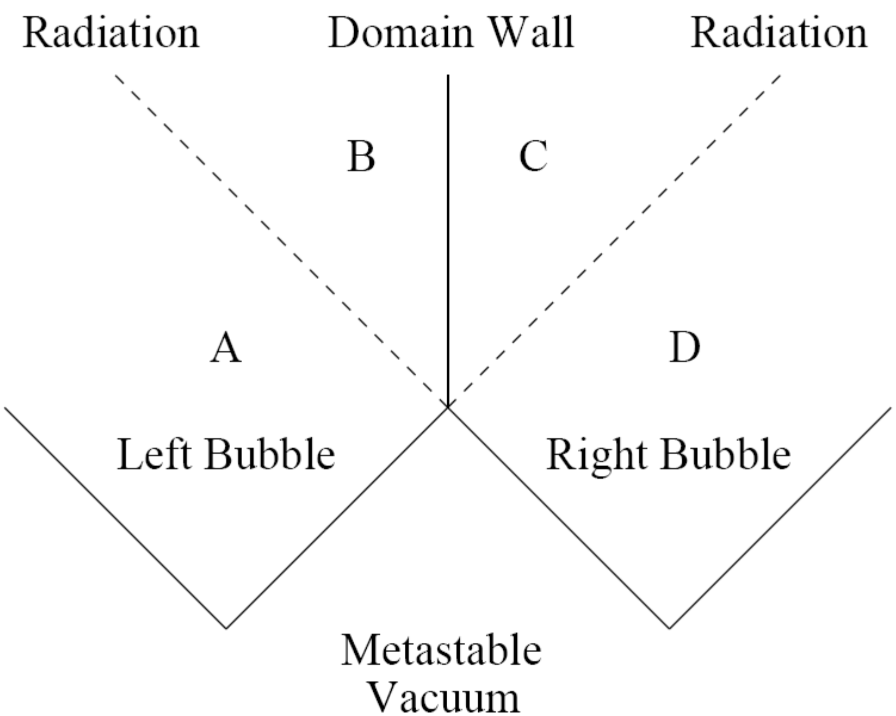


Diagram of
Assumed Collision

- Thin wall limit
- Single radiation burst into both bubbles
- Domain wall with relativistic tension
- Null Energy Condition

See also Israel et.al., Blau et.al., Bousso et.al.

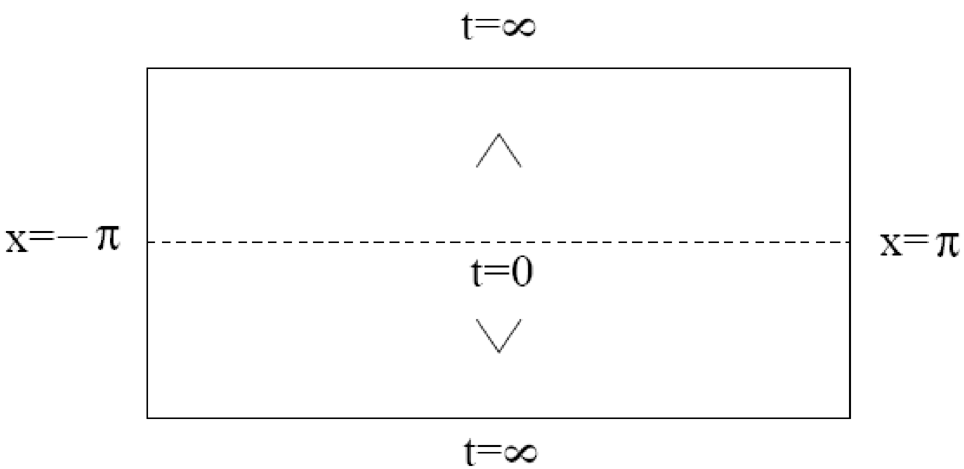
Metric Solutions

- Collisions of two bubbles have an O(2,1) symmetry (subgroup of original O(3,1)), an H_2 symmetry
- Metrics with cosmological constant and H_2 symmetry are completely known
- Act as the building block metrics for different parts of the collision

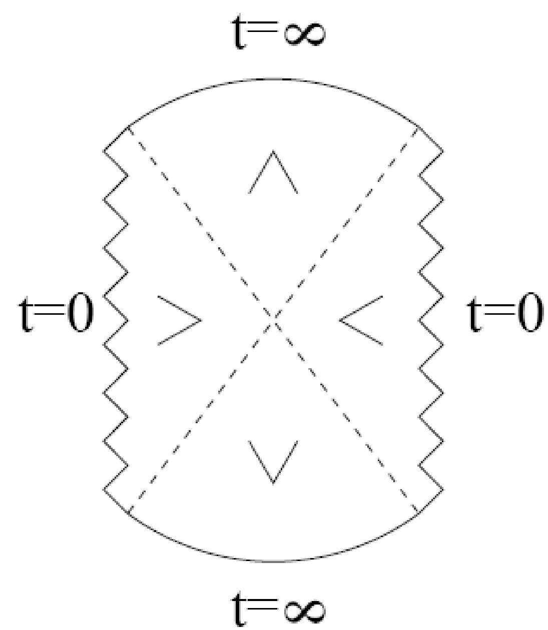
De Sitter solutions

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

$$g(t) = 1 + \frac{t^2}{\ell^2} - \frac{t_0}{t}$$ $\Lambda \equiv 3/l^2$



Unperturbed $t_0 = 0$

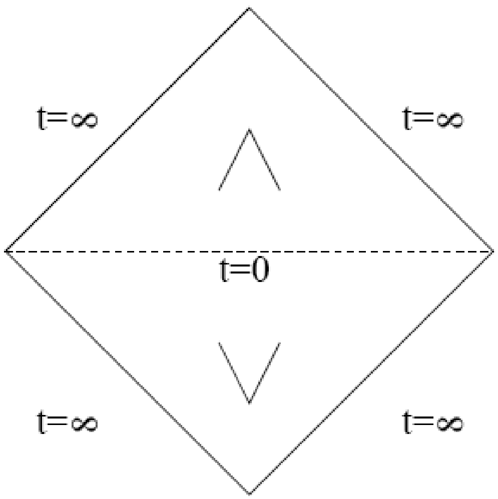


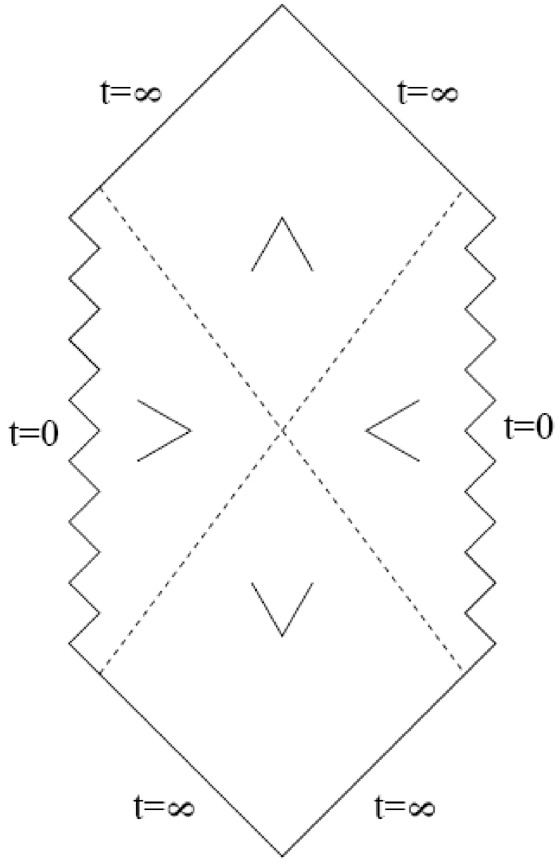
Perturbed $t_0 > 0$

Flat Space Solutions

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

$$h(t) = 1 - \frac{t_0}{t}$$





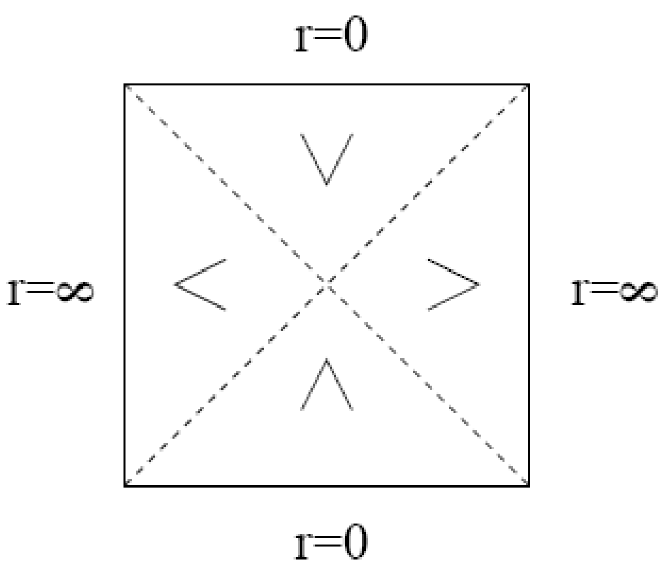
Unperturbed $t_0 = 0$ Perturbed $t_0 > 0$

Anti-de Sitter Solutions

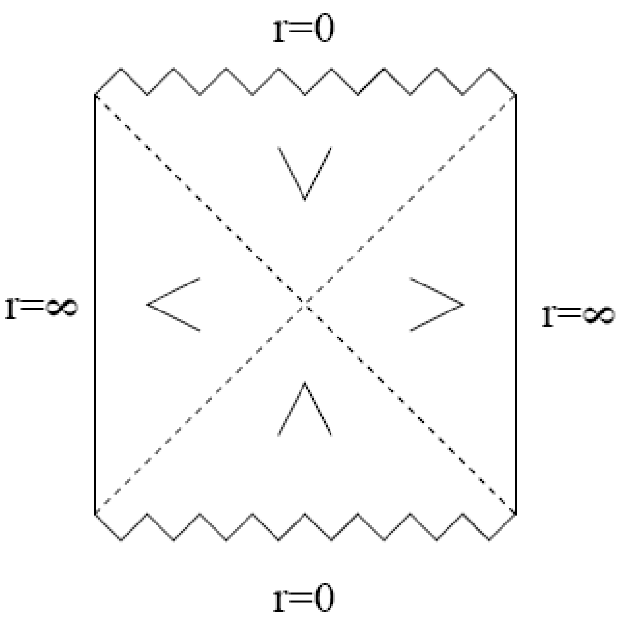
$$ds^2 = -f(r)\,dt^2 + \frac{dr^2}{f(r)} + r^2\,dH_2^2$$

$$f(r) = \frac{r^2}{\ell^2} - 1 - \frac{2GM}{r}$$

$\Lambda \equiv -3/l^2$

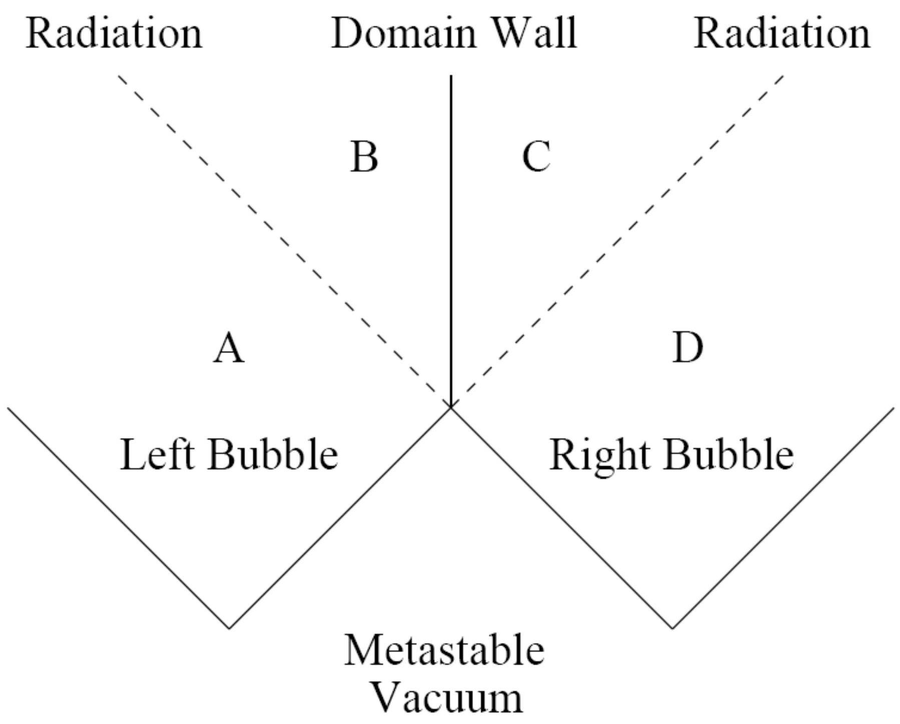


Unperturbed M = 0



Perturbed M > 0

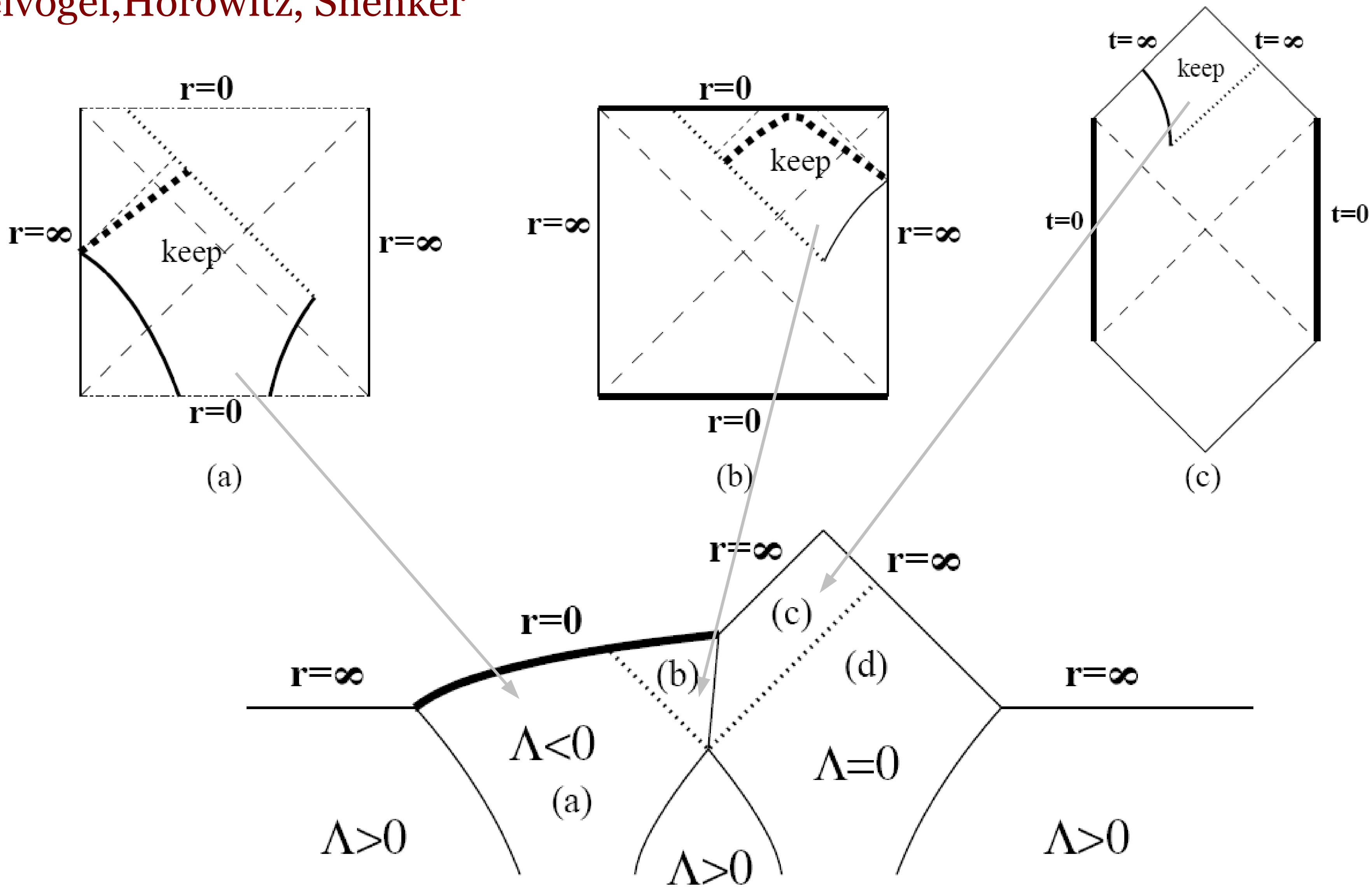
Gluing and Sewing



- Regions A and D are unperturbed solutions
- Region B (C) is perturbed solution of region A (D), determined by energy in radiation

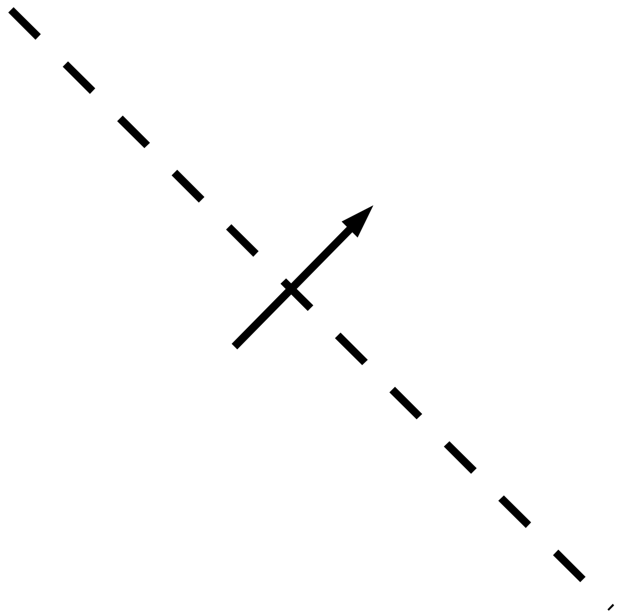
Example (flat on AdS)

Freivogel,Horowitz, Shenker



Matching across radiation shell

$$T^{\mu\nu} = \sigma\, l^\mu l^\nu\, \delta(\text{shell})$$



Israel matching condition across radiation shell determines M or t_o and t or r is continuous

$$\Delta k \equiv \left(h^{ab} k_{ab}\right)_{below} - \left(h^{ab} k_{ab}\right)_{above} = 8\pi G \sigma$$

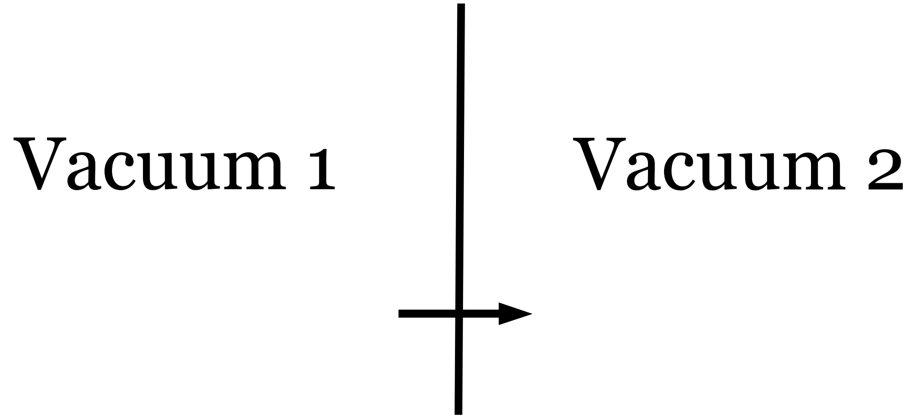
For flat or dS space $\qquad t_0 = 8\pi G\, a\, t^2 \sigma(t)$

Domain Wall Junction

- Domain Wall dominated by a relativistic tension (c.c.)
- Using proper time coordinates

$$ds^2_{\text{domainwall}} = -d\tau^2 + R(\tau)^2 dH_2^2$$

$$R(\tau) = r(\tau),\ t(\tau)$$



$$\Delta k^i_j = \left(k^i_j\right)_{left} - \left(k^i_j\right)_{right} = -8\pi G(S^i_j - \frac{1}{2}\delta^i_j S)$$

$$\Delta k^i_j = 4\pi G\rho\,\delta^i_j \equiv \kappa\,\delta^i_j$$

Effective Potential

- Junction condition can be recast as particle in potential
- Squaring the junction condition and solving gives

Jump in extrinsic curvature

$$\eta_l\sqrt{\dot{R}^2 + j_l(\tau)} - \eta_r\sqrt{\dot{R}^2 + j_r(\tau)} = \kappa R$$

η are signs related to direction of domain wall motion
and j are the metric functions
-h, -g, f for flat, dS, AdS

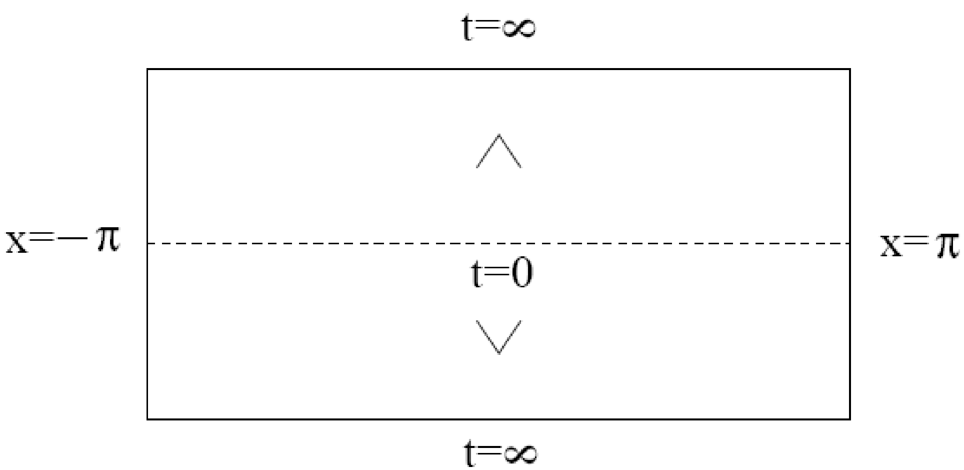
$$\dot{R}^2 = -V_{eff}(R) = -j_r(R) + \frac{[j_l(R) - j_r(R) - \kappa^2 R^2]^2}{4\kappa^2 R^2}$$

Nice way to determine consistent solutions

Bousso Wedges

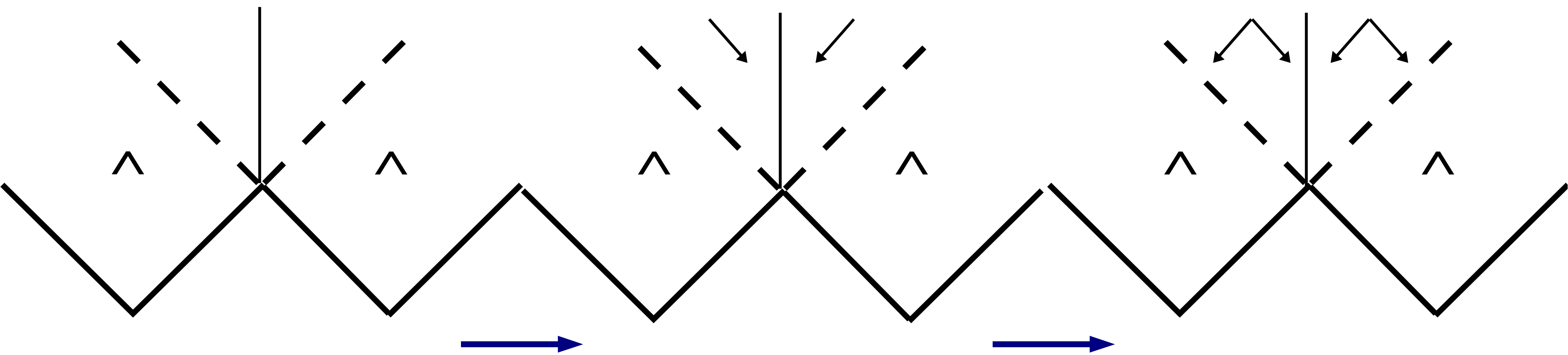
- There are interesting constraints on size of H_2 hyperboloids
- Bousso wedges describe directions where radius of curvature of H_2 hyperboloid is decreasing
- If null energy condition holds, Raychaudri's equation says that radius if decreasing, must continue to decrease to zero
- Continuity of radius across a null shell imposes that direction along null line is continuous

Possible flat/dS on flat/dS collisions



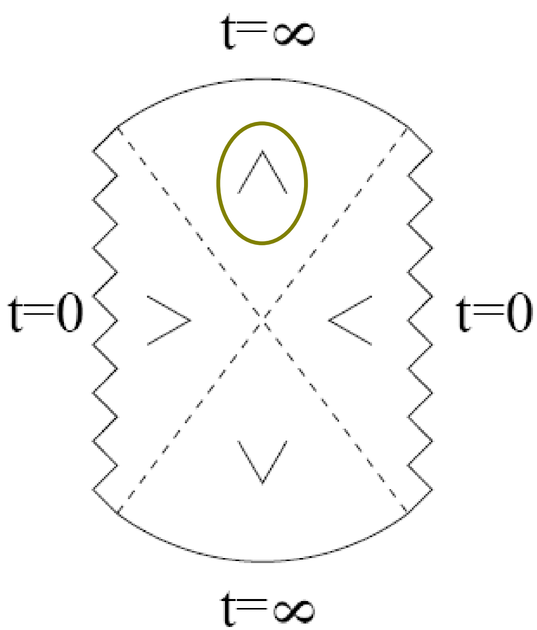
Bousso wedges for expanding bubbles must start as ^

Final wedges completely determined!



Continuity of radii   Raychaudri's Eqn.

dS/flat on dS/flat



Domain wall must be surrounded by region encircled

Timelike worldline of domain wall has t monotonically increasing, so can expand effective potential at large R

$$\dot{R}^2 \approx \lambda^2 R^2 \quad \text{where} \quad \lambda^2 \equiv \frac{1}{\ell_r^2} + \frac{1}{4\kappa^2}\left(\kappa^2 + \frac{1}{\ell_l^2} - \frac{1}{\ell_r^2}\right)^2$$

Domain wall moves away from bubble with smaller cc

Domain wall in other bubble

$$\kappa^2 \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} \frac{1}{\ell_l^2} - \frac{1}{\ell_r^2} \quad \text{Domain wall} \left\{ \begin{array}{c} \text{Moves away} \\ \text{Stays stationary} \\ \text{Moves toward} \end{array} \right\} \text{Bubble with larger c.c.}$$

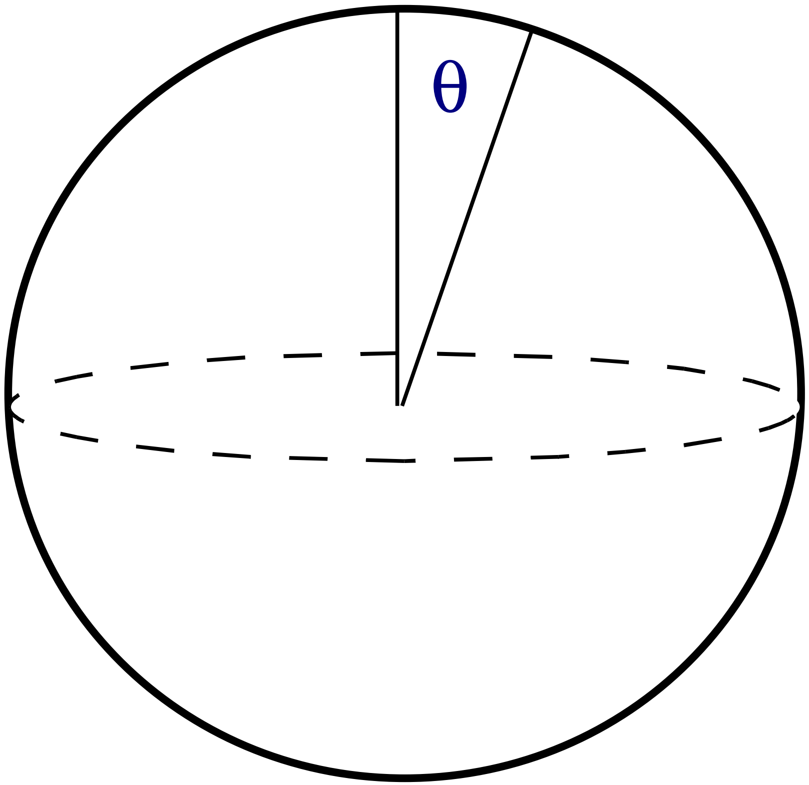
Same effect occurs for dS/flat on AdS collisions where

$$\frac{1}{\ell_l^2} - \frac{1}{\ell_r^2} \longrightarrow \frac{1}{\ell_{AdS}^2} + \frac{1}{\ell_{dS}^2}$$

Summary so far…

- Metrics and domain wall motion of bubble collisions can be solved for analytically
- Bubbles with smallest positive cosmological constant are the safest, as domain walls move away from them

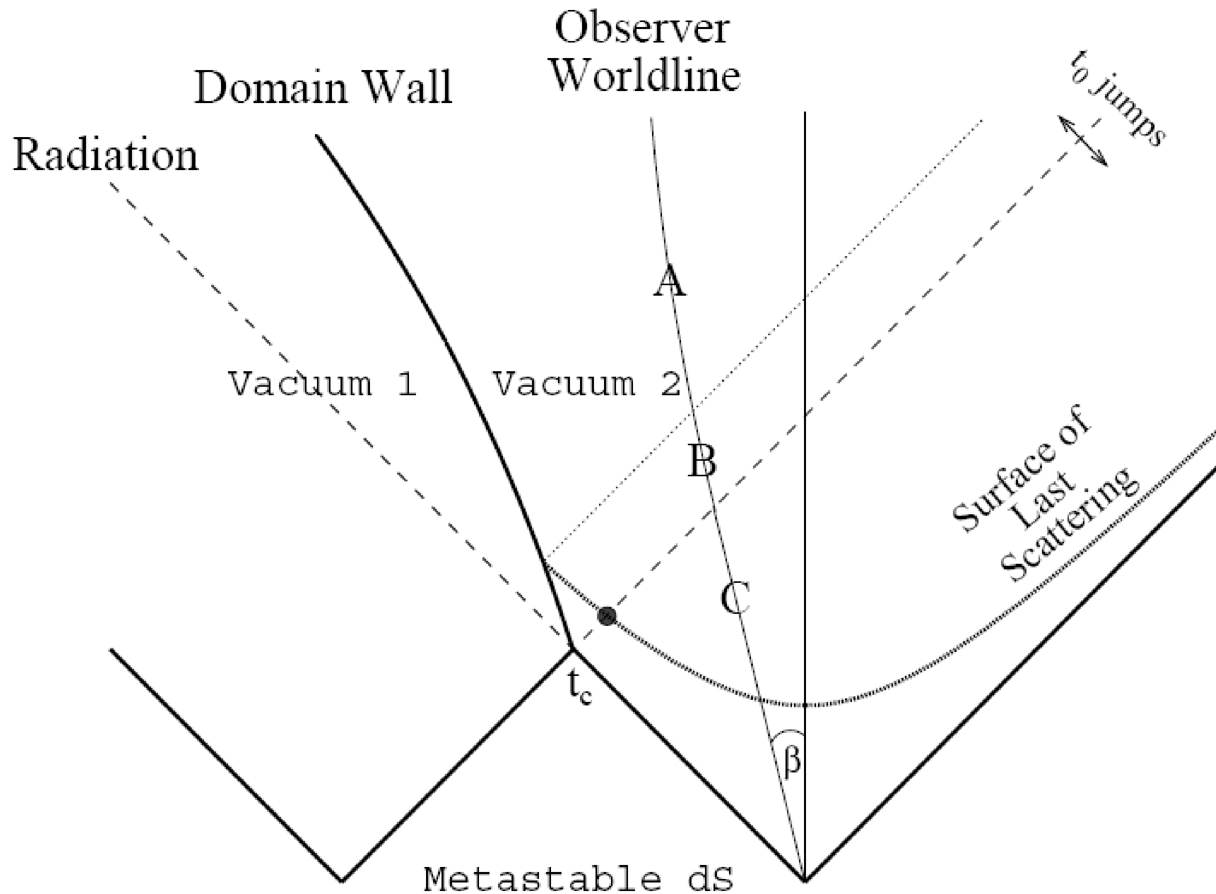
Breakdown of Rotational Symmetry



Rotational symmetry is broken by collision with other bubble, O(2,1) symmetry gives a preferred axis pointing towards other bubble with remaining symmetry in φ

Observables

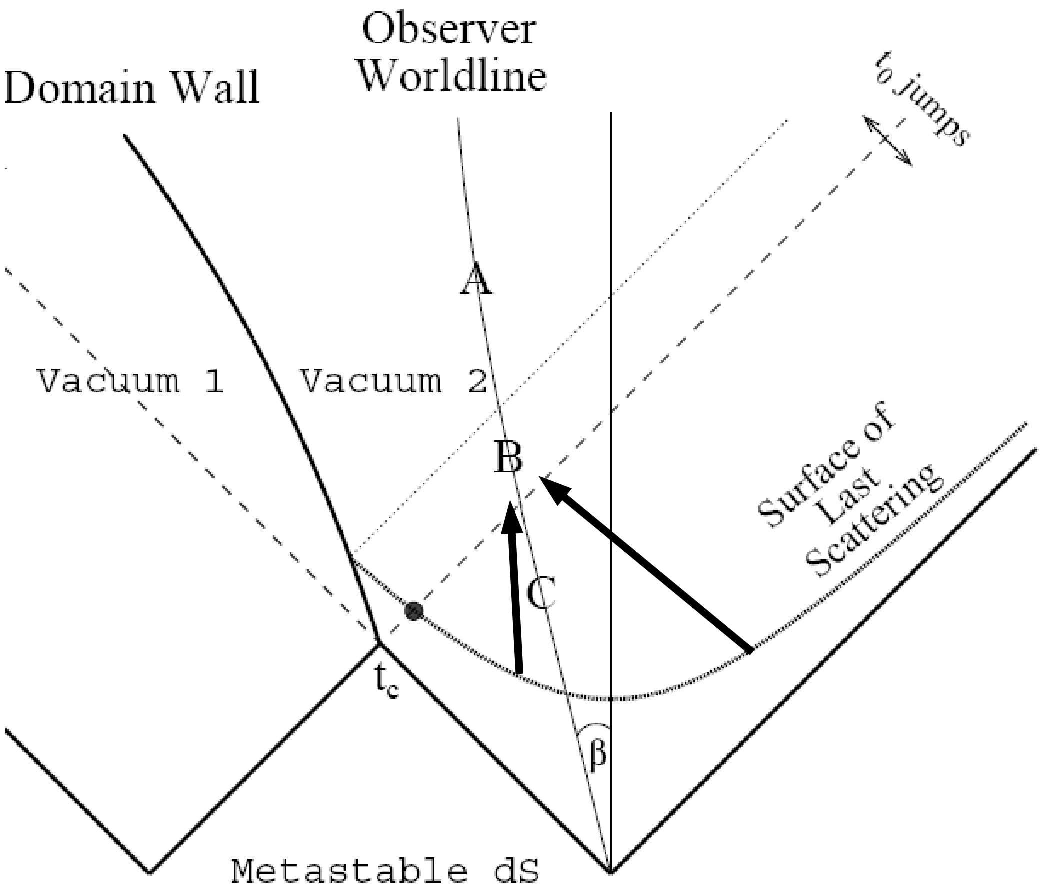
- Observer C oblivious to collision
- Observer B – can see asymmetric redshifts for CMB
- Observer A – can "see" domain wall and asymmetric redshifts



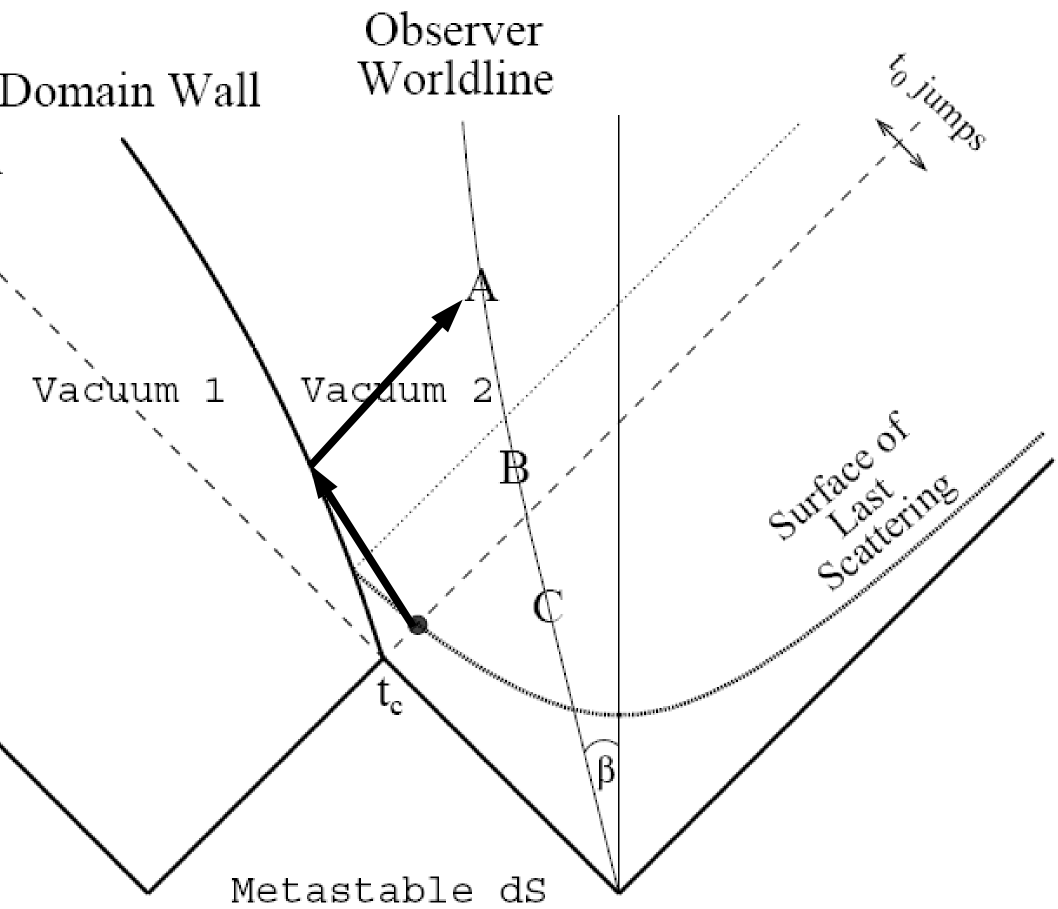
"I think all you scientists are crackpots, nothing is going to happen"
- When Worlds Collide

Asymmetric Redshifts

- Photons from different directions, travel through different metrics
- Effect is of order $t_o/t_{observer}$



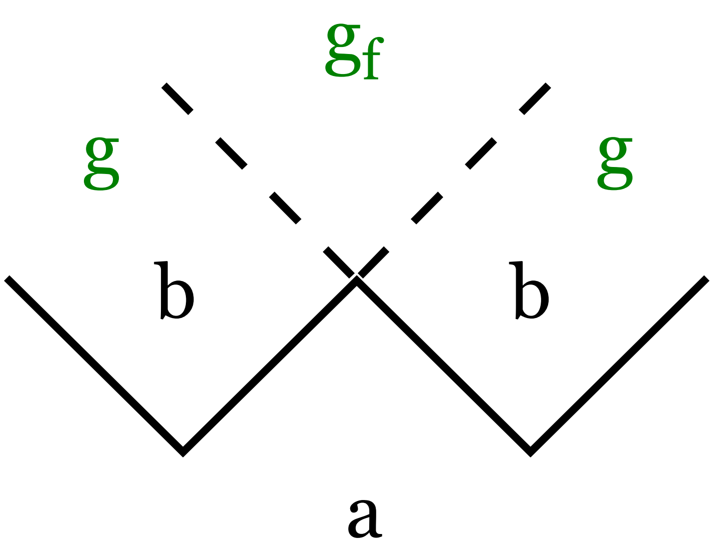
Seeing the Domain Wall



- Domain wall could be a mirror to photons
- Due to Doppler shift of moving mirror, there is a discontinuous jump between reflected and non-reflected photons

How large can these effects be?

- Can solve for t_o in simple case, two bubbles of identical dS vacua with no domain wall



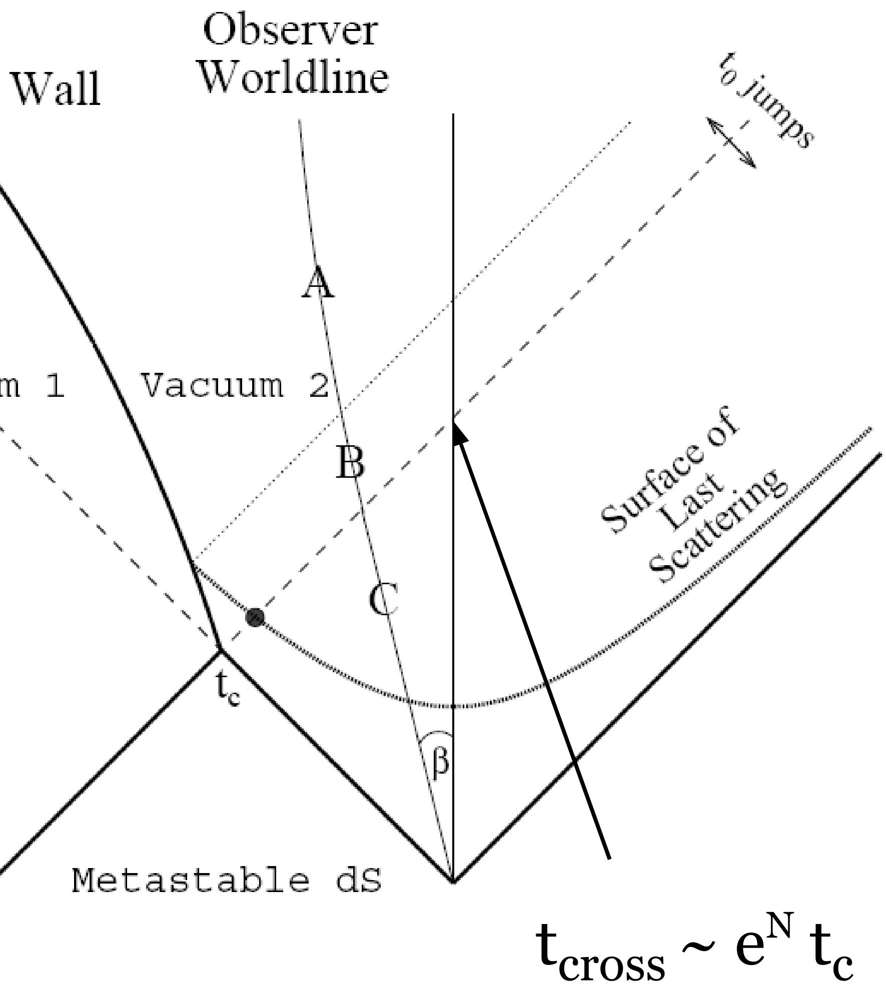
Ratio of perturbed metric to unperturbed metric

$$\frac{g_f}{g}\Big|_{t=t_c} \approx \exp\left[2\cosh^{-1}(\lambda\ell_a) - 2\cosh^{-1}(\lambda\ell_b)\right]$$

$$\sim \ell_a^2/\ell_b^2$$

When this ratio is small
$t_o/t_c \sim t_c^2/l^2$
so for large t_c this is a huge effect in the metric

Simple Model of Inflation



- Assume sharp transition from inflating to flat space, roughly at last scattering
- In this model, redshift is set between inflation and today $t_c/l \sim t_{cross}/t_{inf} = (T_{inf}/T_{now}) < e^{60}$
- But for effect to be big enough $10^{-5} < t_0/t_{cross} = e^{-N}\, t_0/t_c < e^{-N}\, t_c^2/l^2$

Inflationary limit

- There is an upper bound on t_c, so that observer is after collision
- A lower bound on t_c, so that there is an observable effect
- Together: $e^N * 10^{-5} < t_c^2/l^2 < (e^{60})^2$
- Consistency of limits, puts upper limit of $N < 130$ for effect to be observable, so strong collisions can give big effects even with substantial inflation

Known unknowns

- Our solutions do not tell us the behavior of the constant scalar field slices
  - Don't know the cosmological evolution of the universe past the radiation
- To be fully quantitative on effects on CMB, have to take into account these effects

Getting Quantitative: Toy Solutions

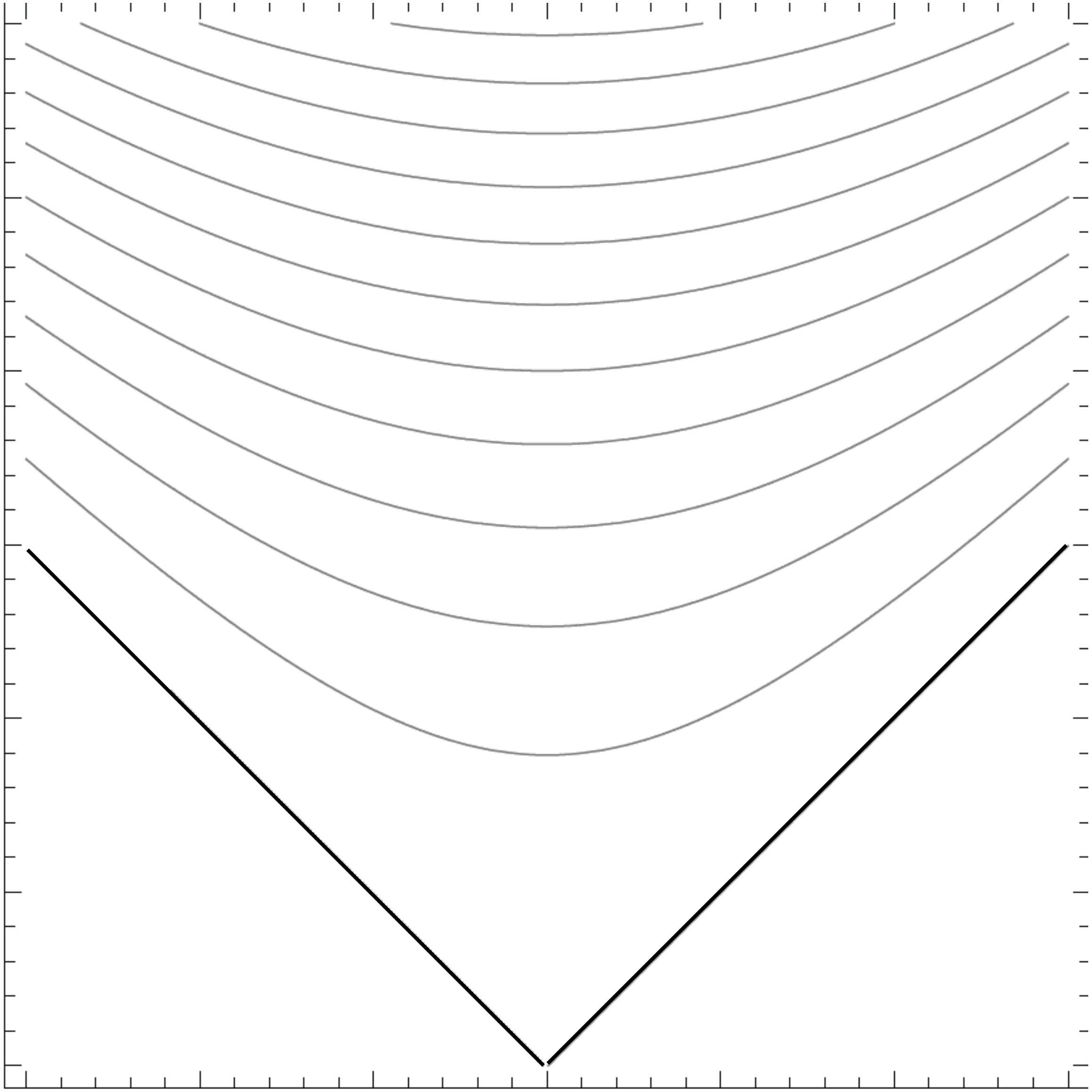
- Want some analytical understanding, so start with a toy model
- Start with flat space

$$\left[\frac{\partial^2}{\partial t^2} + \frac{2}{t}\frac{\partial}{\partial t} - \frac{\partial^2}{\partial x^2}\right]\Phi = -\frac{\partial V}{\partial \Phi} = V_1$$

$$V = V_0 - V_1\Phi + \ldots$$

$$\Phi_{\text{general}} = \frac{F(t+x) + G(t-x)}{t} + \frac{V_1}{6}t^2$$

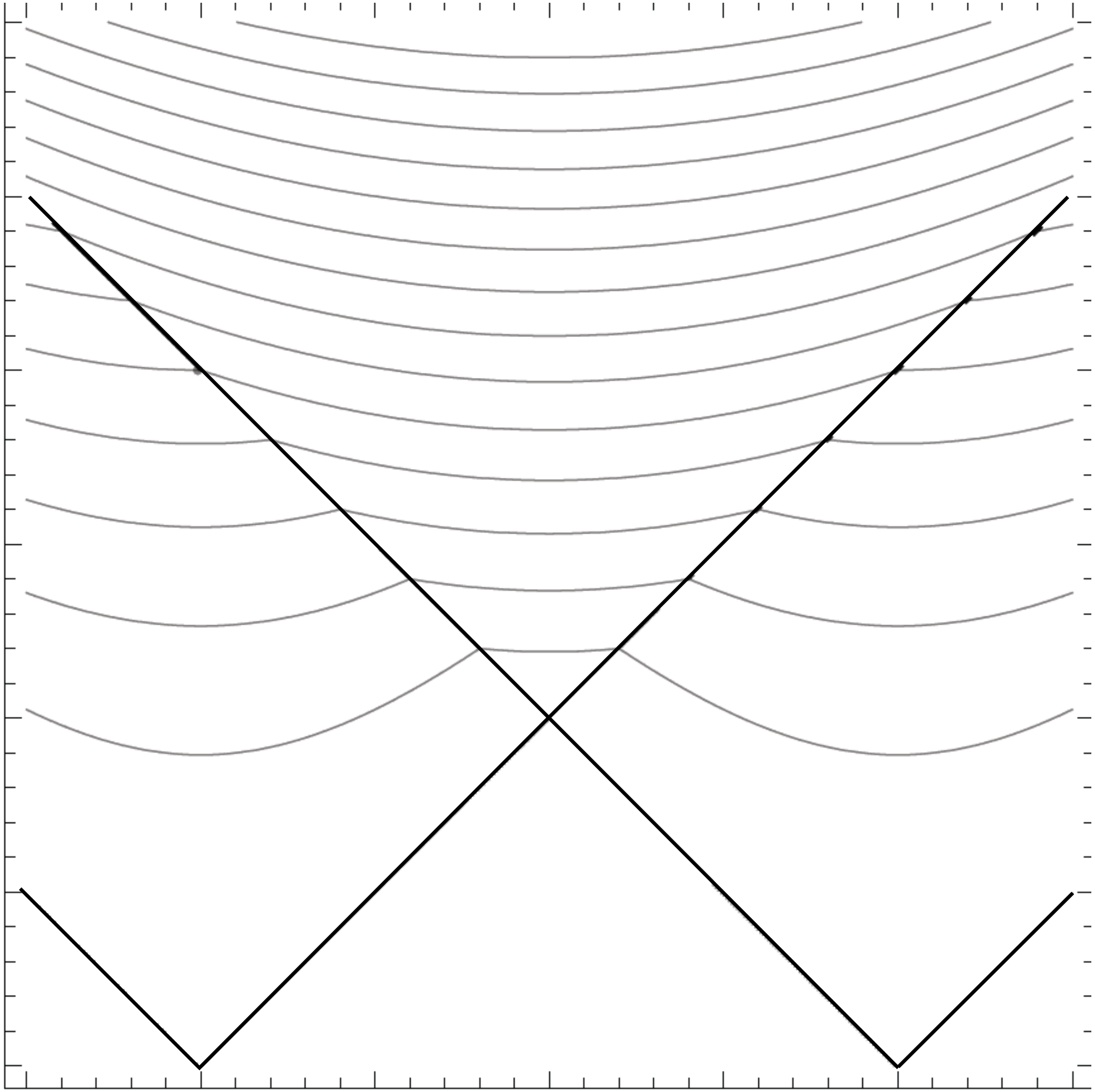
Single Bubble Solution



$$\Phi_{\text{onebubble}} = \frac{V_1}{8}\left(t^2 - x^2\right)$$

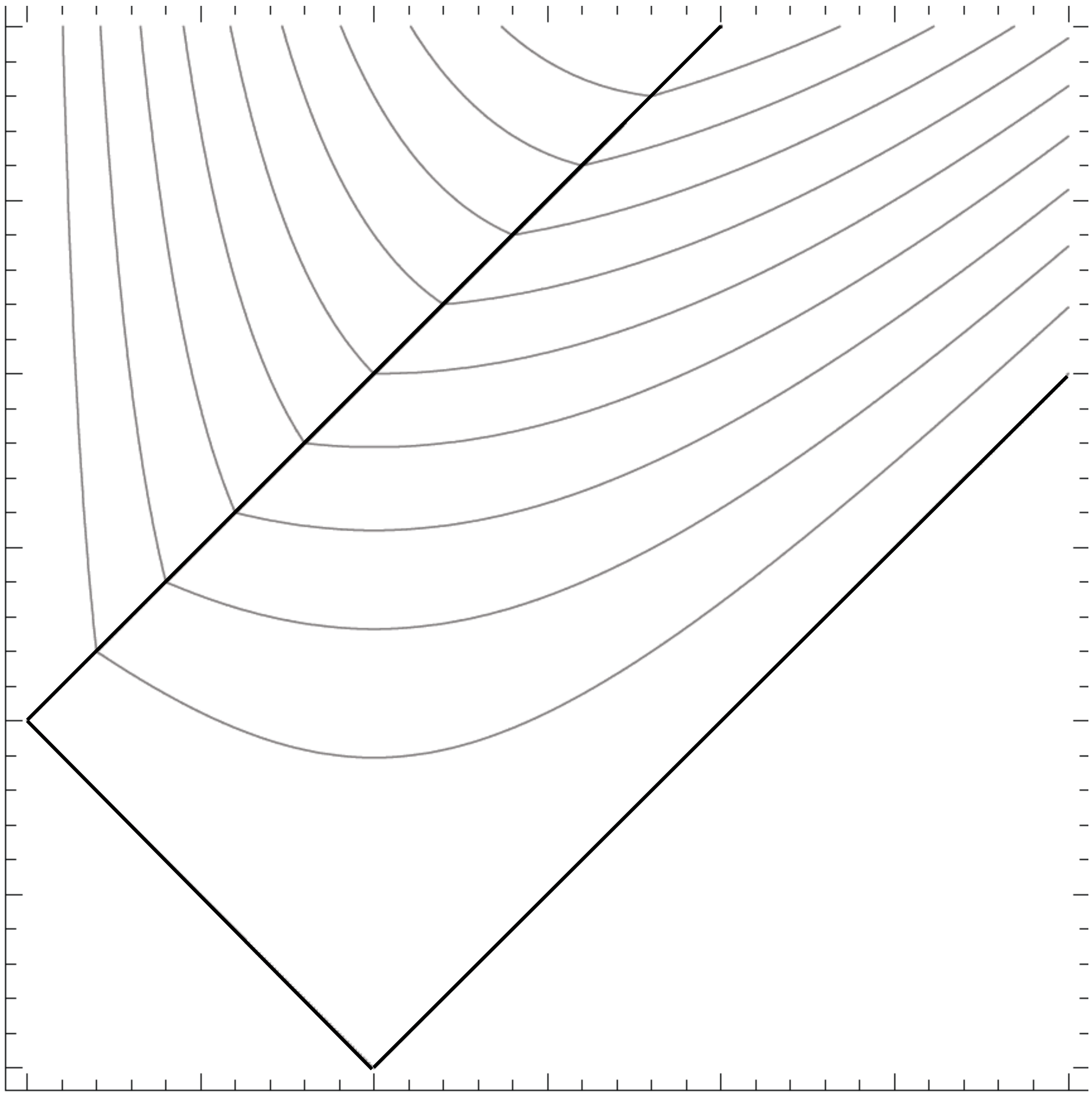
Use this as a initial condition

Symmetric Collision



Toy solution of the collision of two bubbles of the same vacuum

Asymmetric Collision



Toy solution of the collision of two bubbles of different vacua with the same cosmological constant

Measures?

"This may not happen for a million years!"
-When Worlds Collide

- Lot of work recently on measures in eternal inflation, especially false vacuum (Garriga et.al., Bousso et.al., Aguirre et.al., ...)
- Many issues and paradoxes with these measures
- Our philosophy, ignore this - a signal would be too spectacular to ignore

Conclusion

- Cosmology has tremendous potential as a probe of high energy physics
- Solved metrics and dynamics of general bubble collisions
- Early universe bubble collisions could have observable effects despite long inflation
  - CMB asymmetries due to reflection, photons propagating in asymmetric metrics
  - Quantitatively what are the effects? For e.g., WMAP cold spot?