Cosmological Observables When Worlds Collide

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w/ M. Kleban, T. Levi

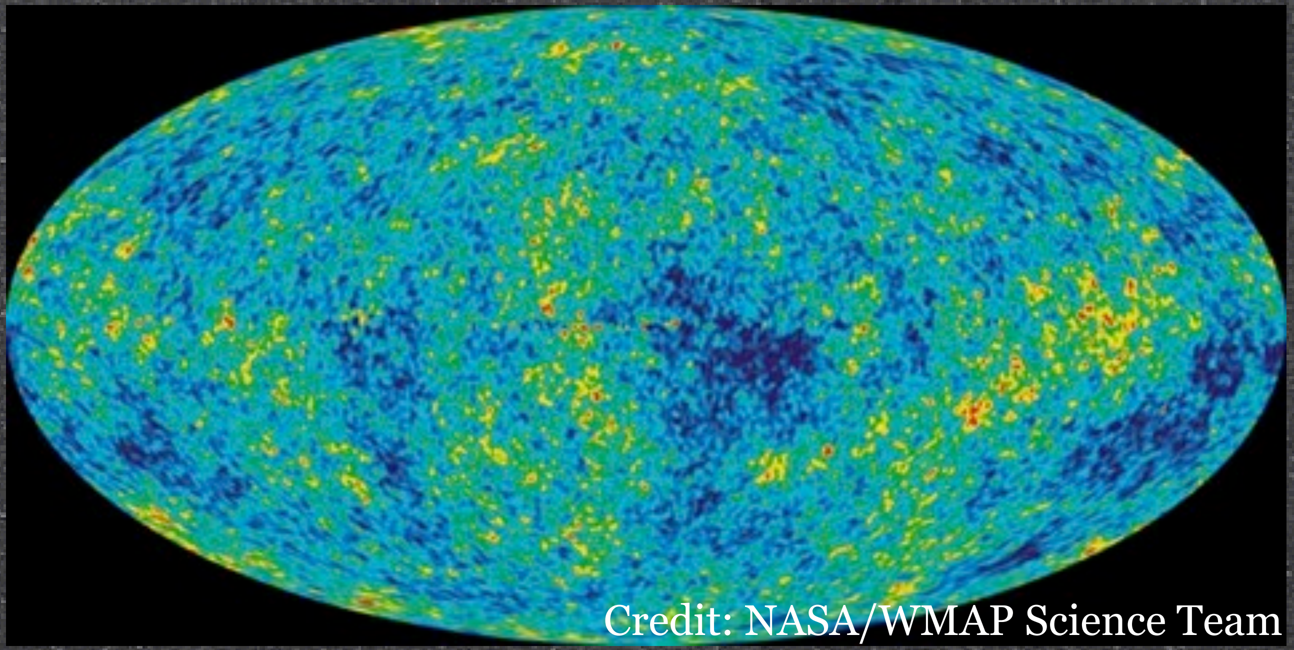
"When Worlds Collide"
JCAP 0804:034,2008
&
"Watching Worlds Collide"
arXiv:0810.5128

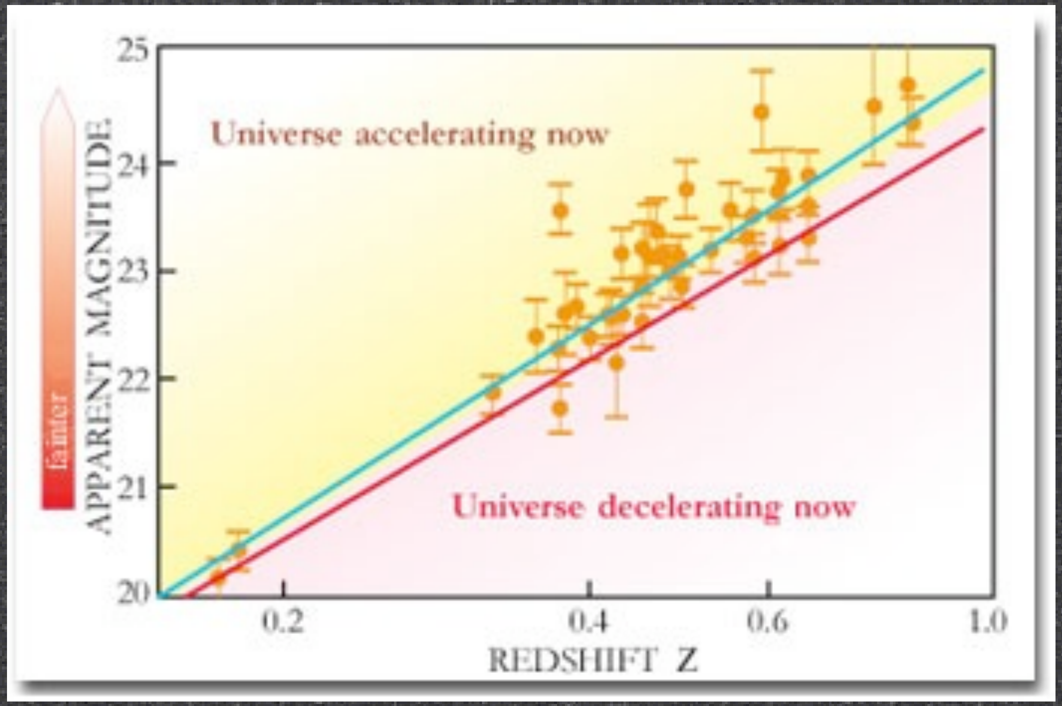
Cosmology as a probe of high energy physics

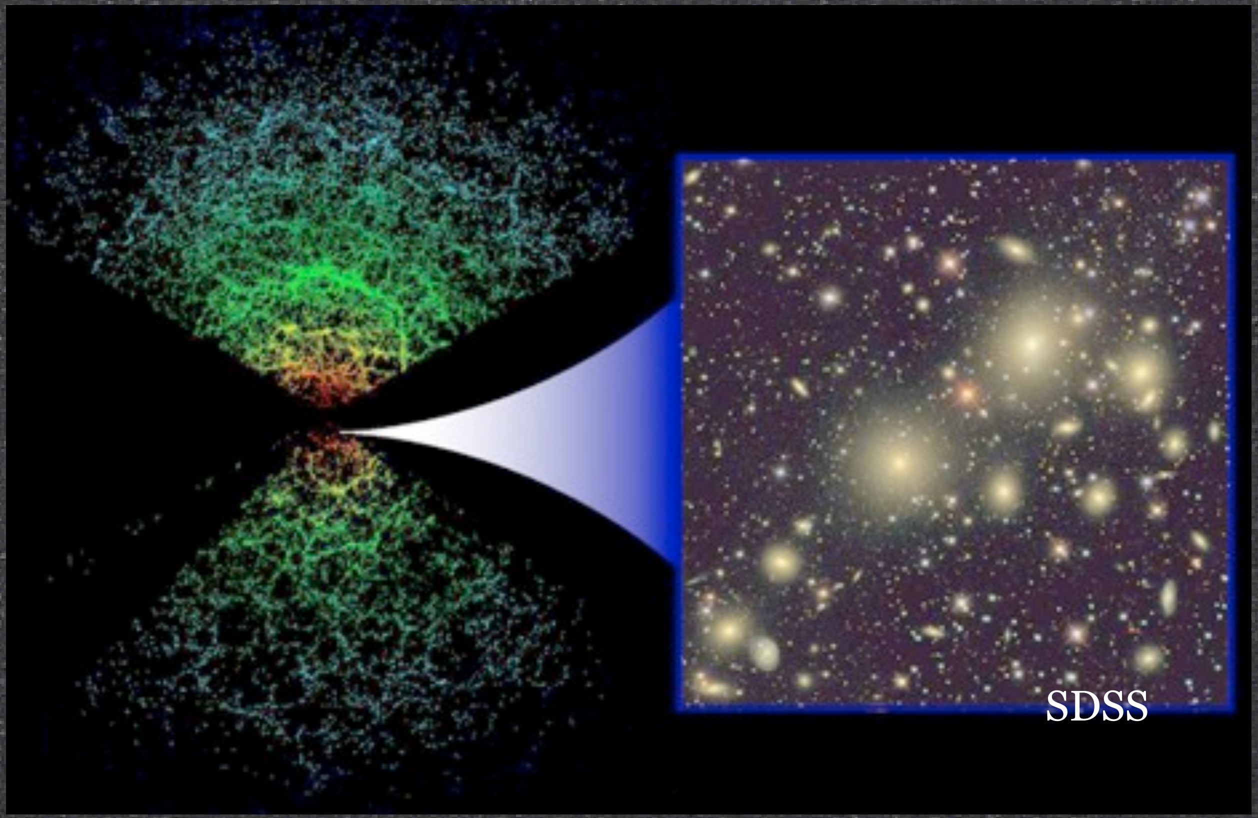
- Particle Physics Parallels
  - Established (cosmological) standard model
  - Anomalous results potentially signaling new fundamental physics
  - New experiments are coming online
- Probes different physics, answers complementary questions

Cosmology

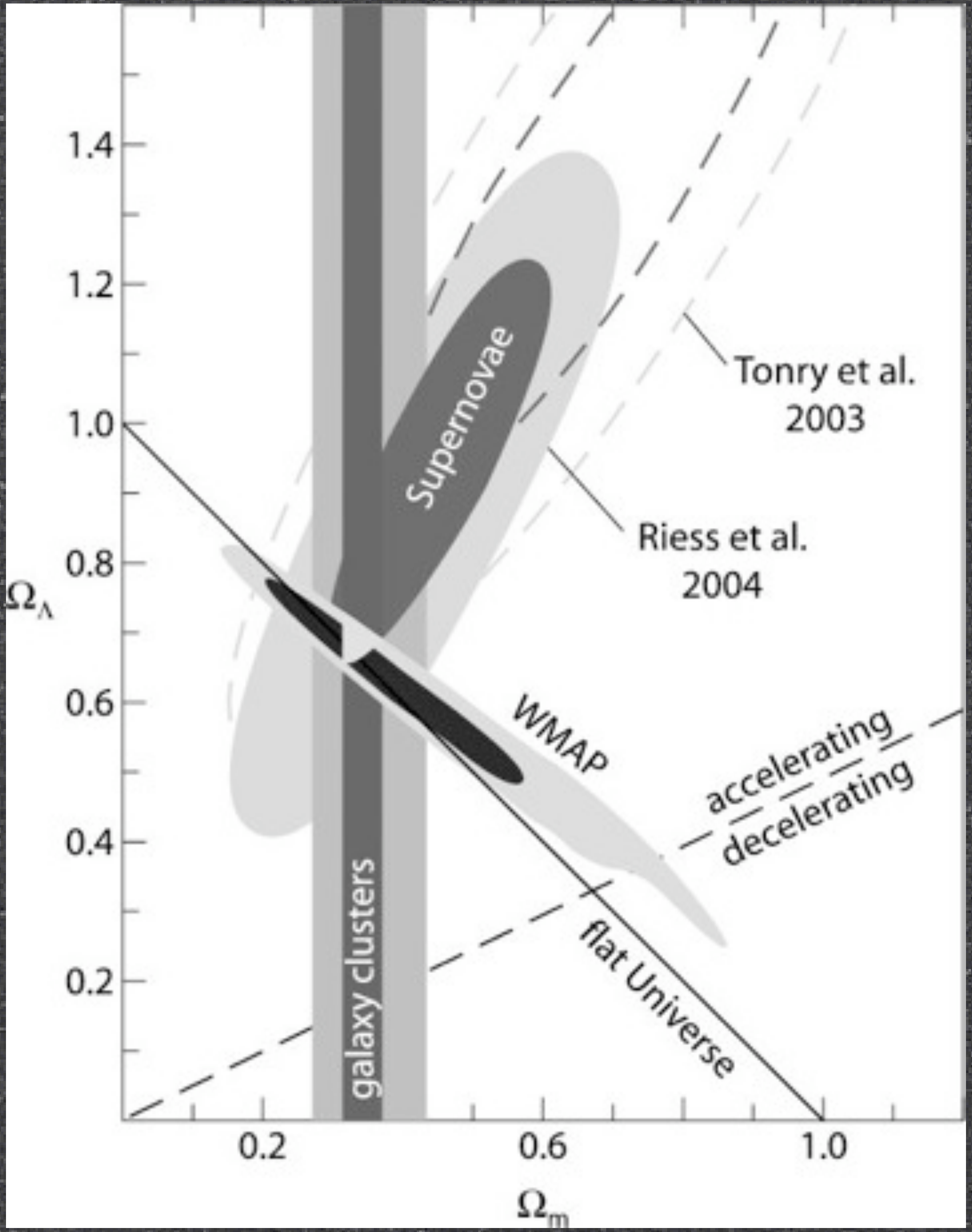
Wealth of cosmological data from WMAP, SDSS, Supernovae







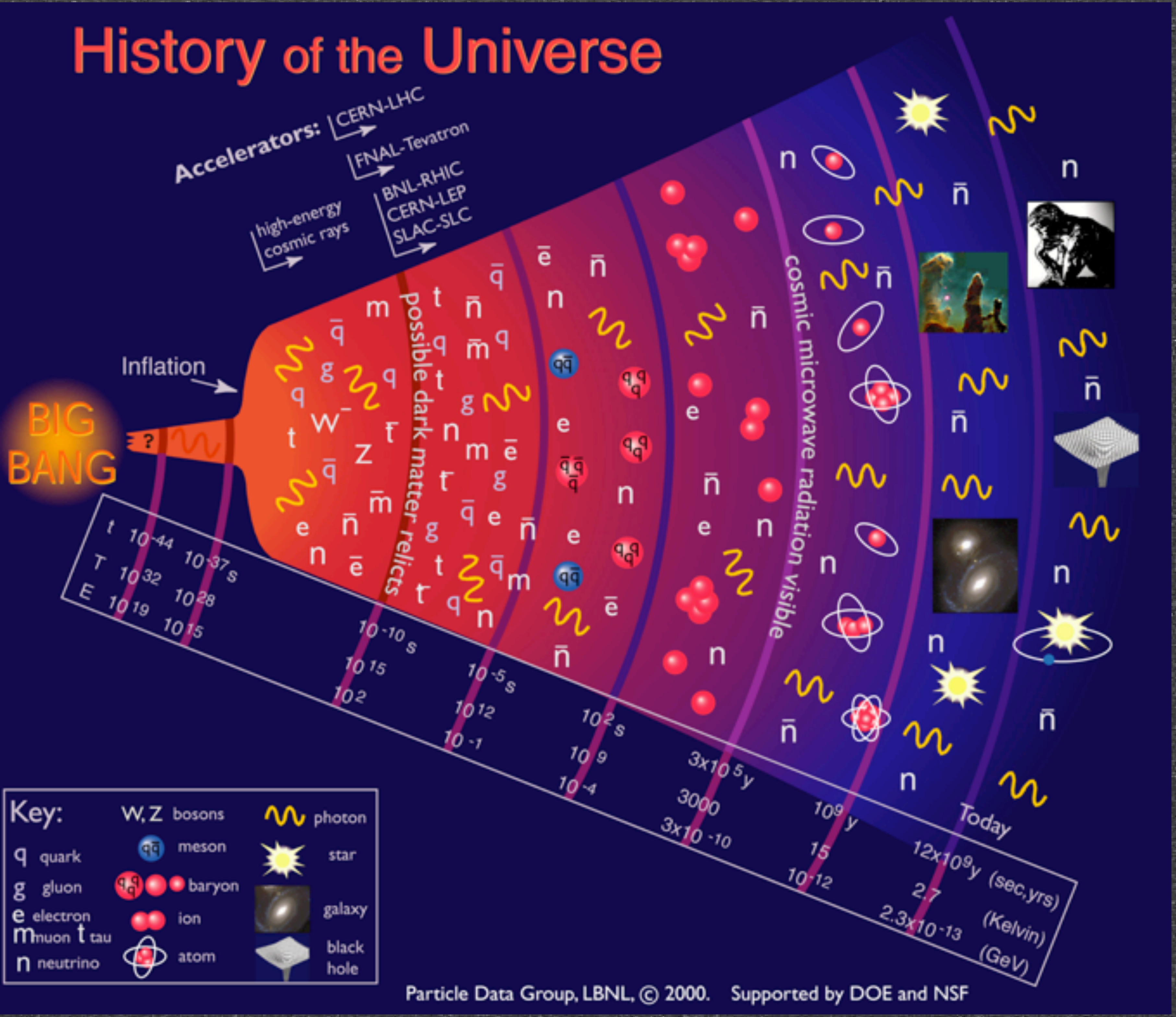
Cosmological Standard Model



J. Dalcanton

- Universe composition is now known
- Next-gen experiments to go further: Planck, SDSS-III, 21cm experiments

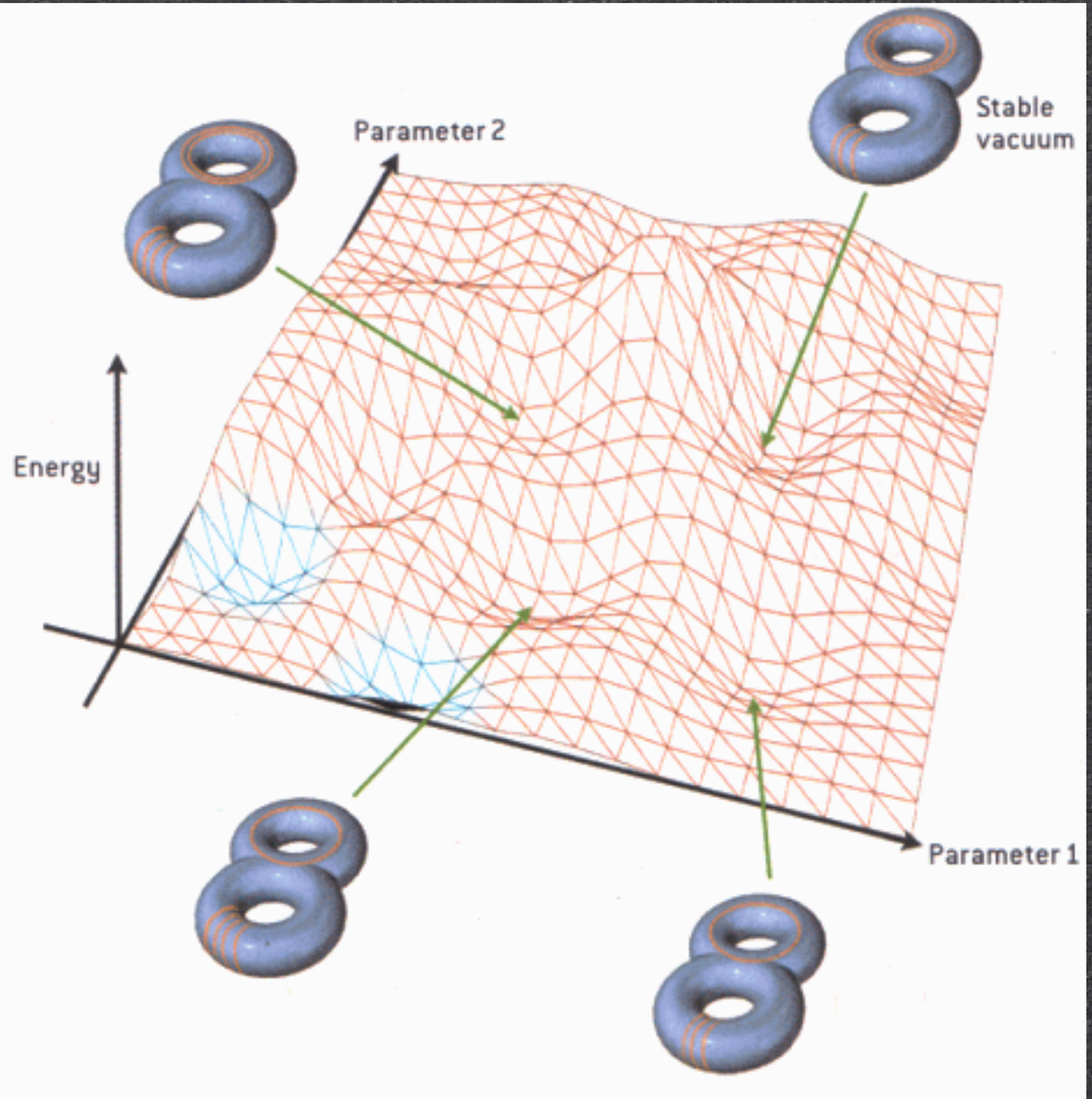
Cosmological Collider



- Early universe accesses much higher energies than colliders
- Inflation a well known example of high energy physics only detectable through cosmology

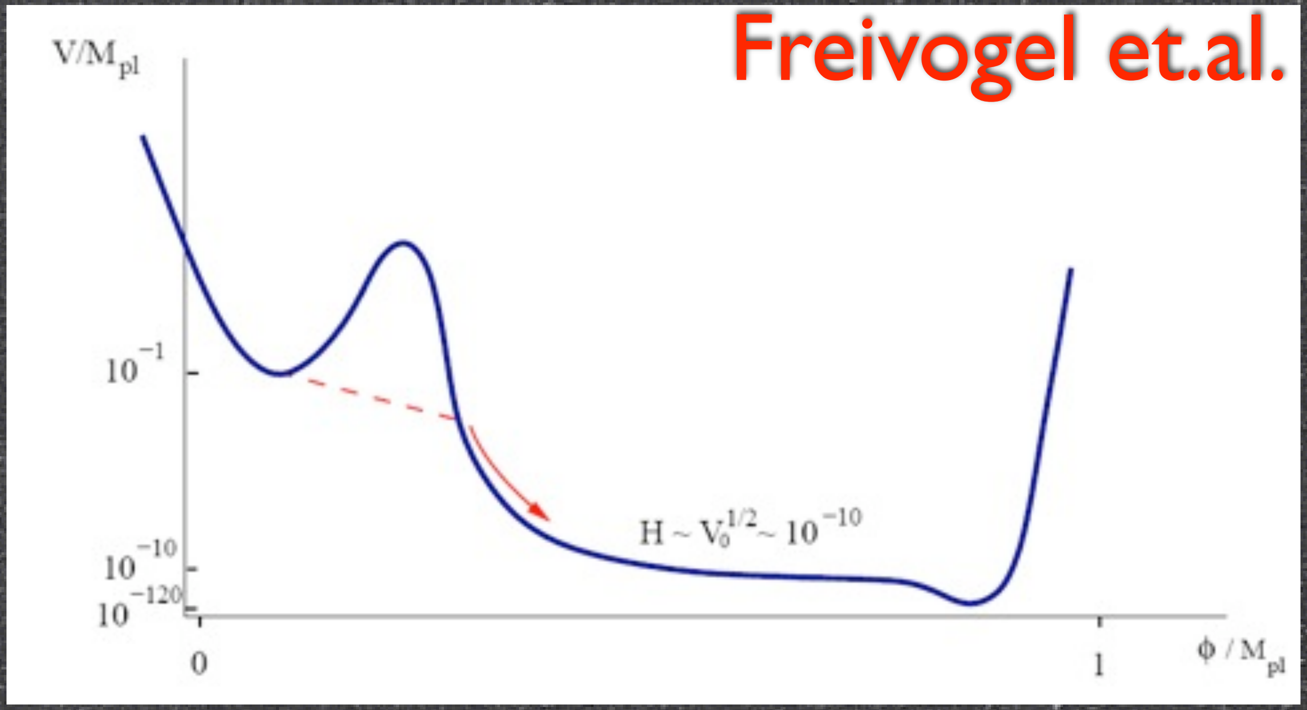
Landscape

- String theory seems to predict a landscape of potential vacua 10^{500}
- Predictions become cosmological



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

Landscape Predictions

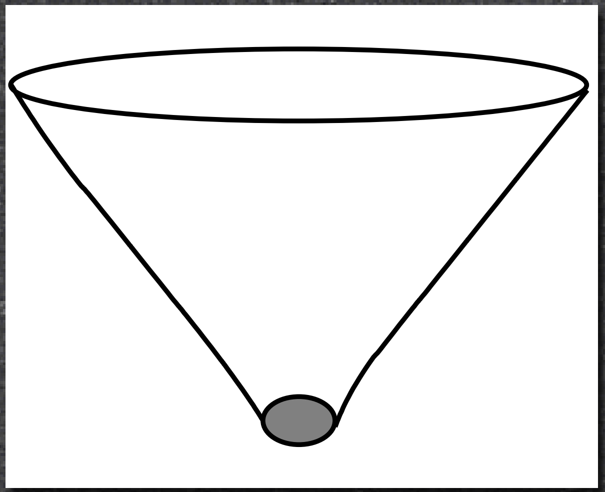


Landscape vacua are populated by eternal inflation

High energy vacua dominate the world volume

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

Coleman-de Luccia Bubbles



- Bubble transition solutions have O(4) symmetry in Euclidean space
- Expanding bubble interior is described by analytic continuation
  - Inherits O(3,1) symmetry
  - Described by an open FRW universe
  - Scalar field homogenous on H_3 slices

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

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

Freivogel et.al. ...

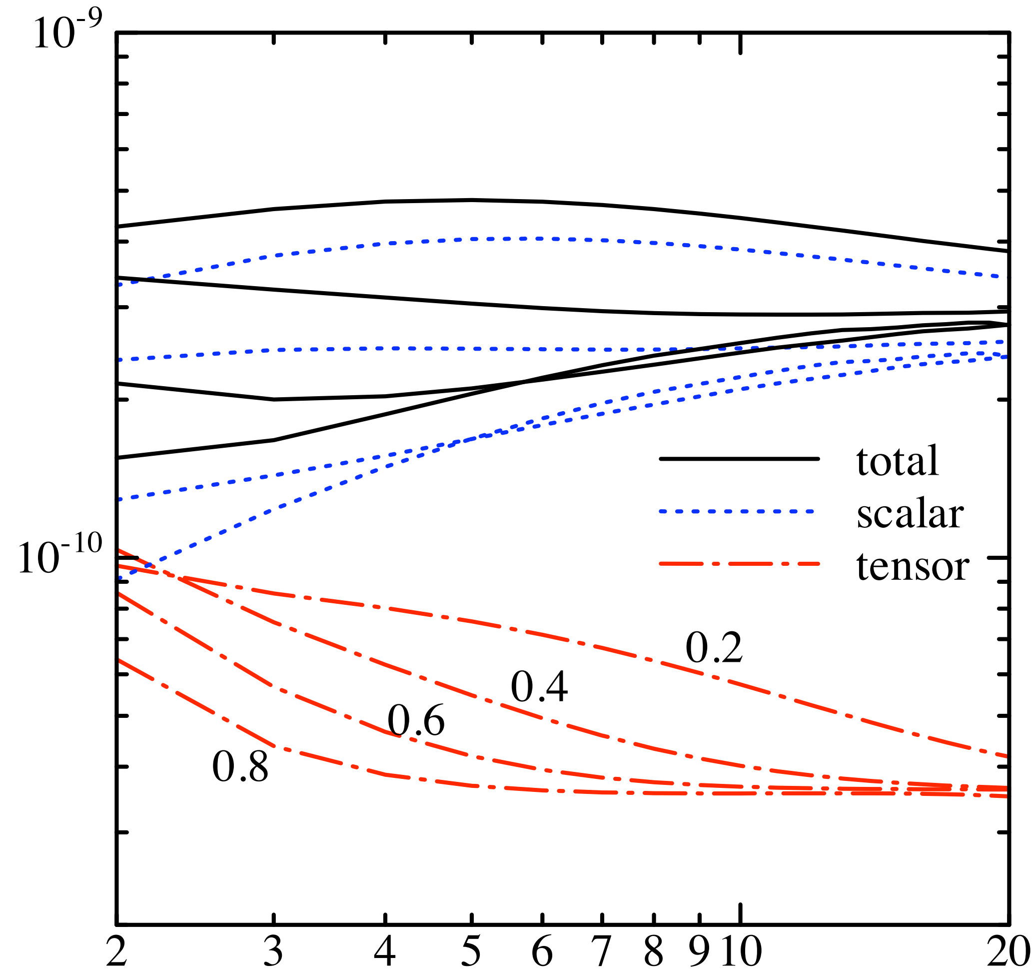
Observable Initial Conditions

- Universe is open, but subject to constraints, need inflation after tunneling
- WMAP requires $\Omega_{tot} = 1.02 \pm .02$, amounting to e-fold constraint $N > 62$
- Future sensitivity $\Omega_{tot} - 1 \sim 10^{-(4\text{-}5)}$, discovery requires $N < 66$

Observable Initial Conditions (cont.)

Linde et.al.

$\ell(\ell+1)C_\ell$

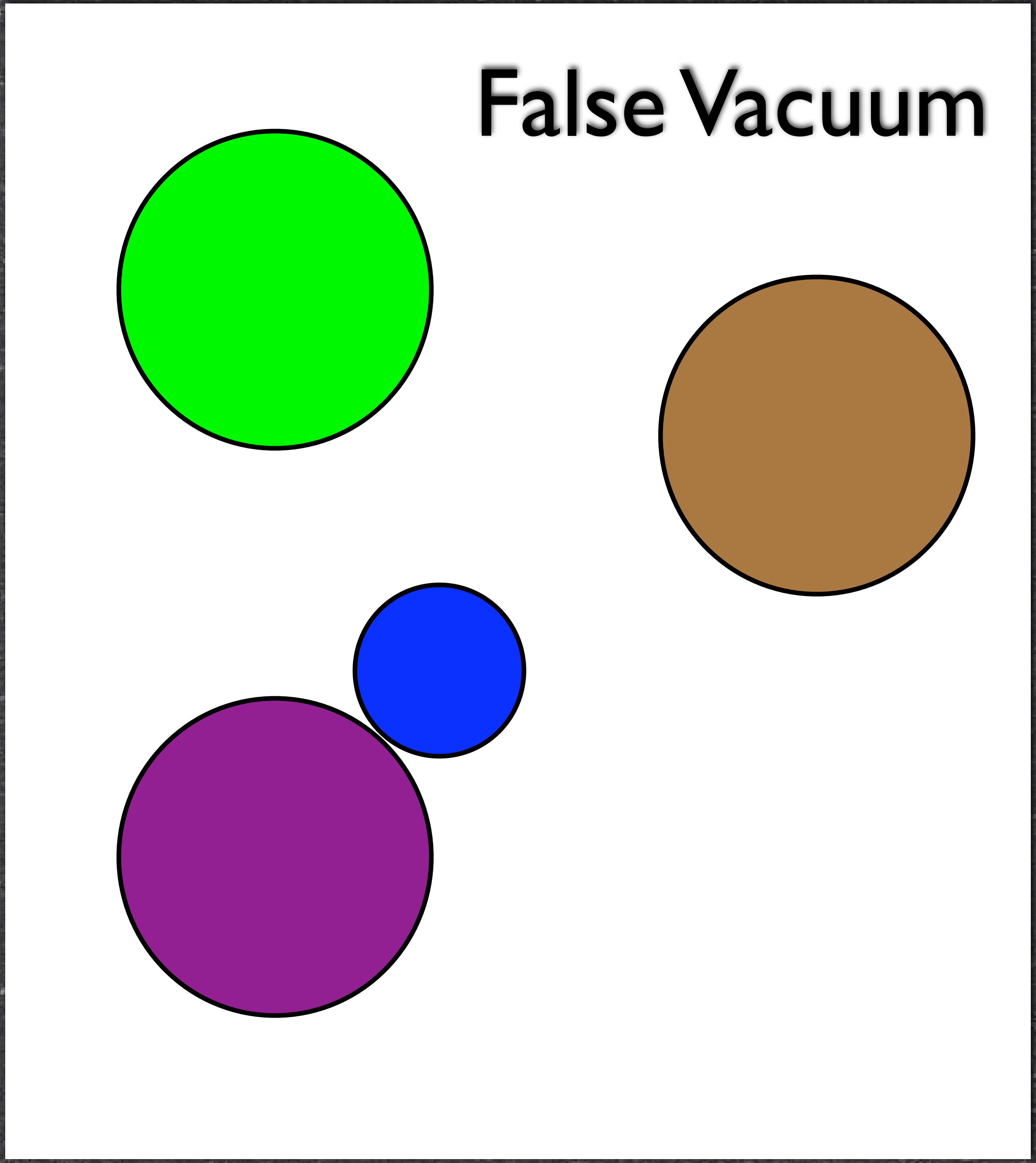


$\Omega_{tot} = .2, .4, .6, .8$

After flatness constraint, CMB power spectrum effects at very low l

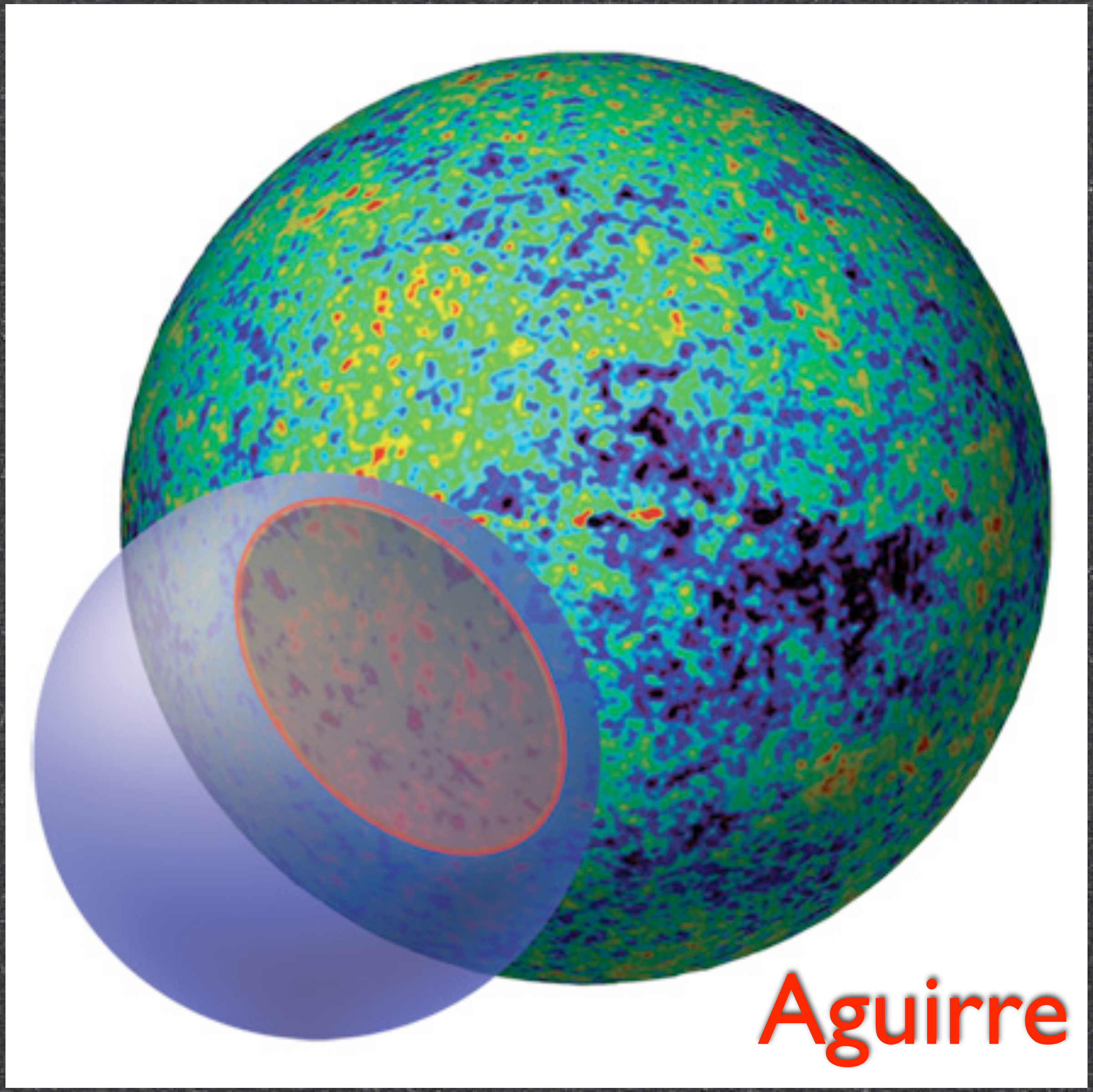
A More Promising Possibility

- Bubbles do not evolve in isolation, colliding bubbles are a generic prediction of inflating landscape
- Visible effects even after applying constraints



Our Scenario

- Study simplest case of two bubbles colliding
- Do as much analytically as possible
  - Solve for domain wall motion, metrics
- Simplify problem to solve for scalar field
  - Extract predicted deviations for CMB



Assumptions (we follow Freivogel, Horowitz, Shenker)

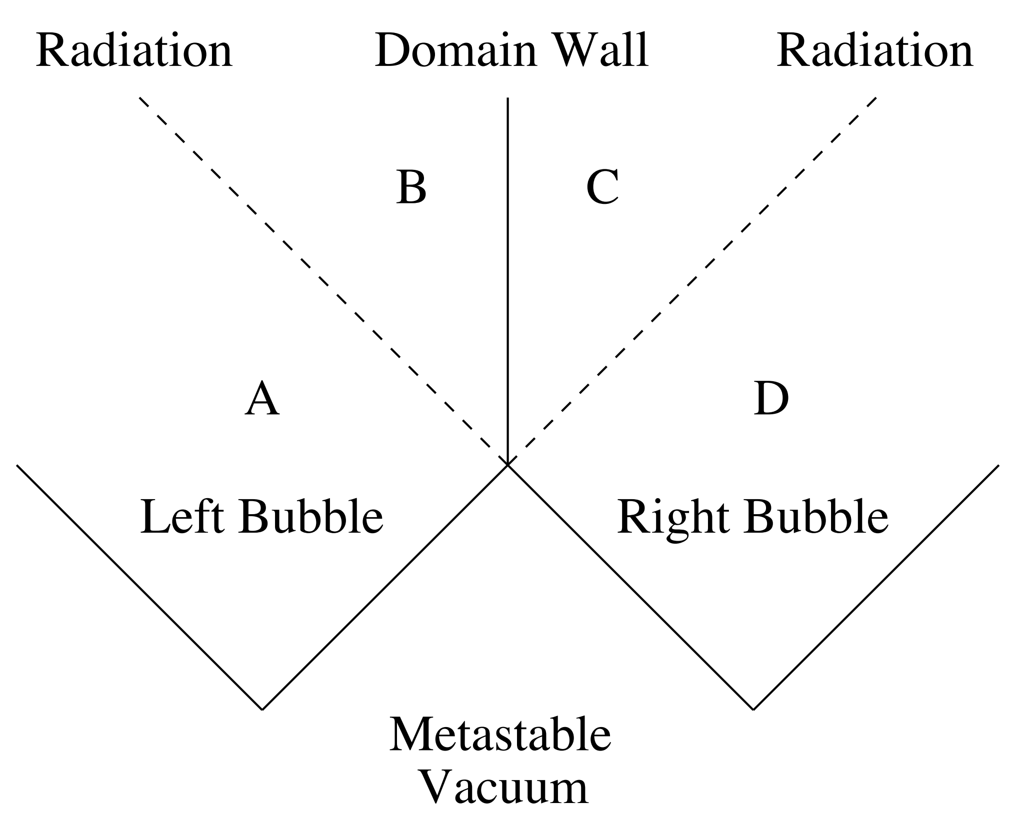


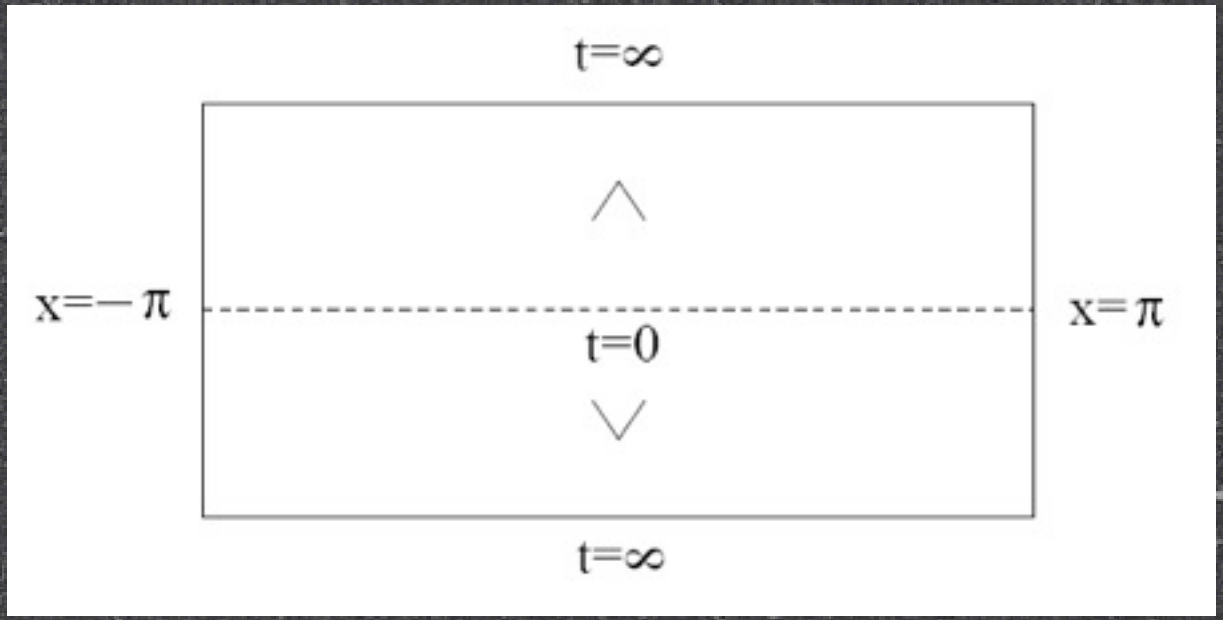
Diagram of Collision

- Thin Wall Limit
- Single radiation shock into both bulks
- Domain wall dominated by tension
- Null Energy Condition

Metric Solutions

- Collisions of two bubbles have an H_2 symmetry (since only $O(2,1) \subset O(3,1)$ is preserved)
- Metrics with cosmological constant and H_2 symmetry are completely known
- Act as building block metrics for collision

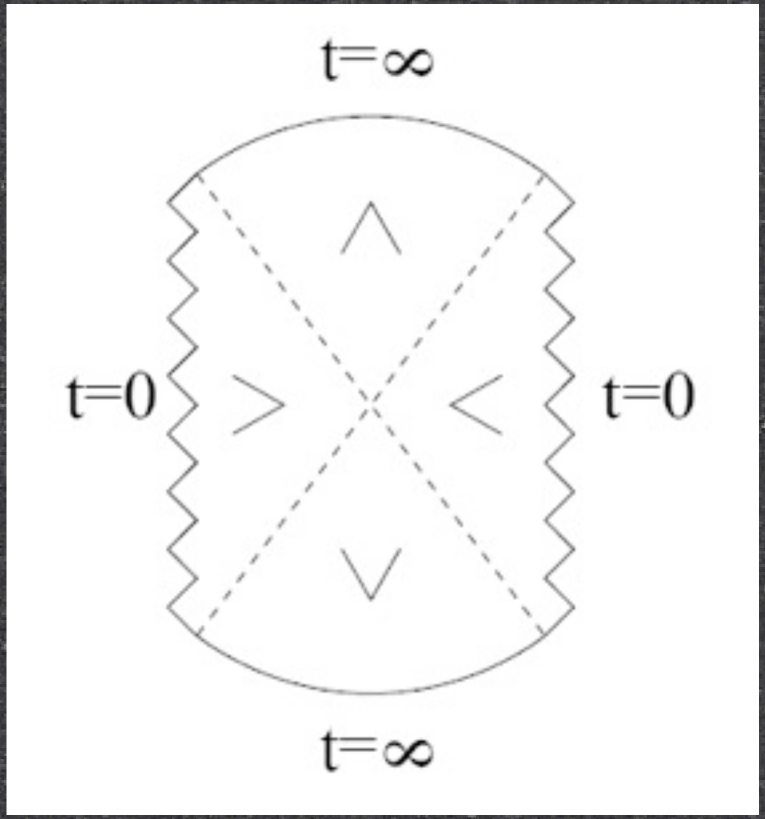
e.g. de Sitter Solutions



Unperturbed $t_0 = 0$

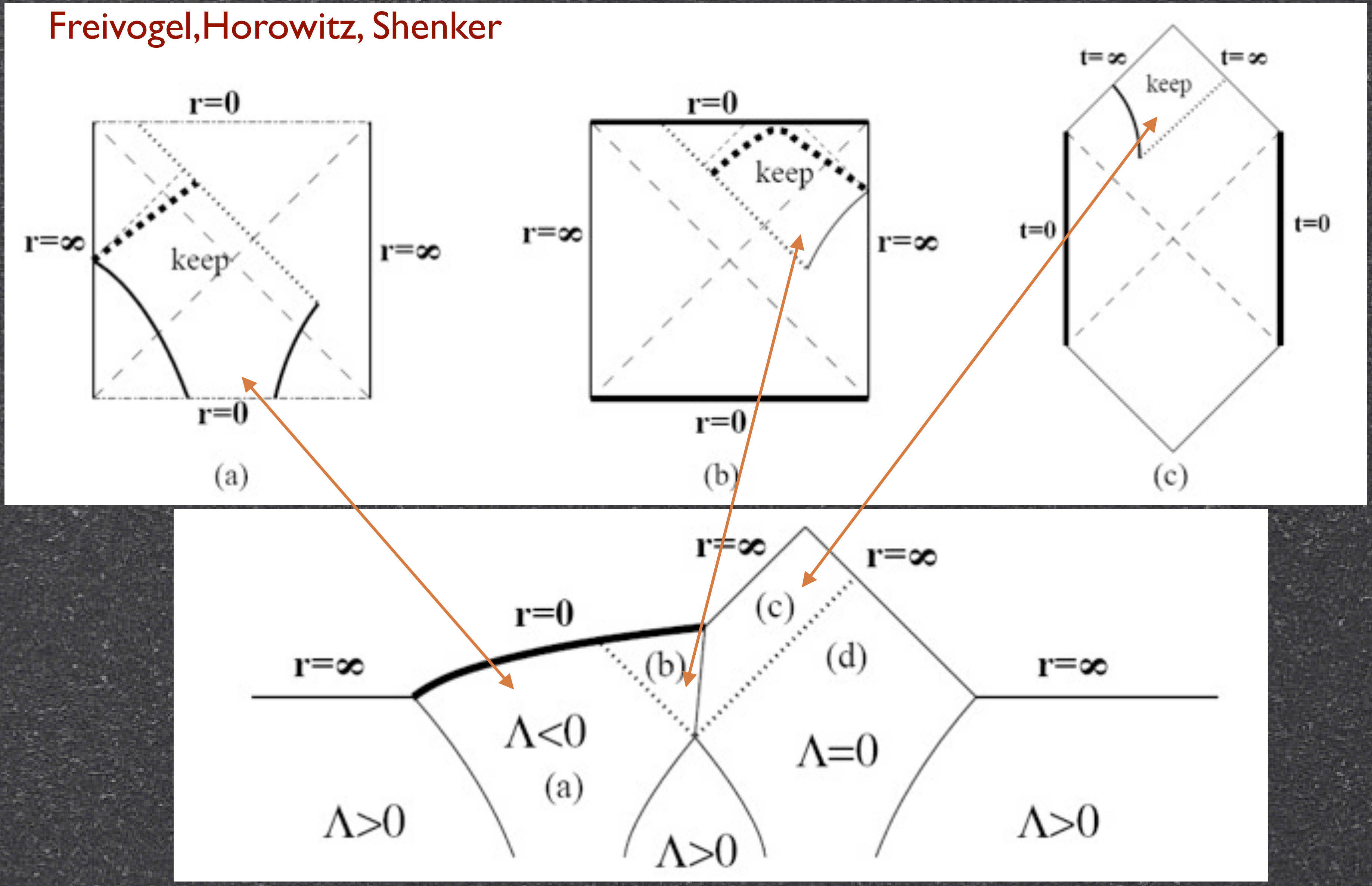
$$ds^2 = -\frac{dt^2}{g(t)} + g(t)dx^2 + t^2\, dH_2^2$$

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



Perturbed $t_0 \neq 0$

e.g. flat on AdS collision



Building Blocks

Collision Diagram

Junction Conditions & Domain Walls

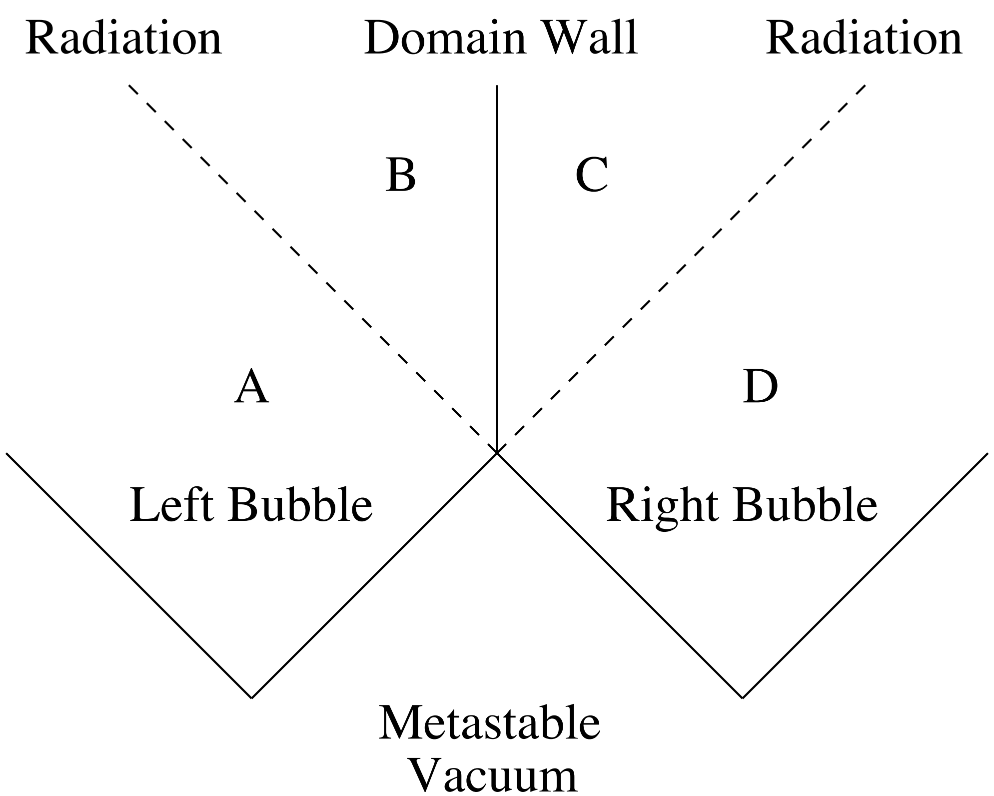


Diagram of Collision

- Matching conditions across radiation shock and domain wall
- Across shocks, determine t_0
- Across domain wall, determines motion

SC et.al.

All Collision Classification

- For a dS bubble w/ cc of Λ colliding with
  - larger Λ', domain wall moves away
  - smaller Λ', domain wall
    - moves away if $\text{tension}^2 > \Lambda - \Lambda'$
    - stationary if $\text{tension}^2 = \Lambda - \Lambda'$
    - moves toward if $\text{tension}^2 < \Lambda - \Lambda'$

Collision Summary

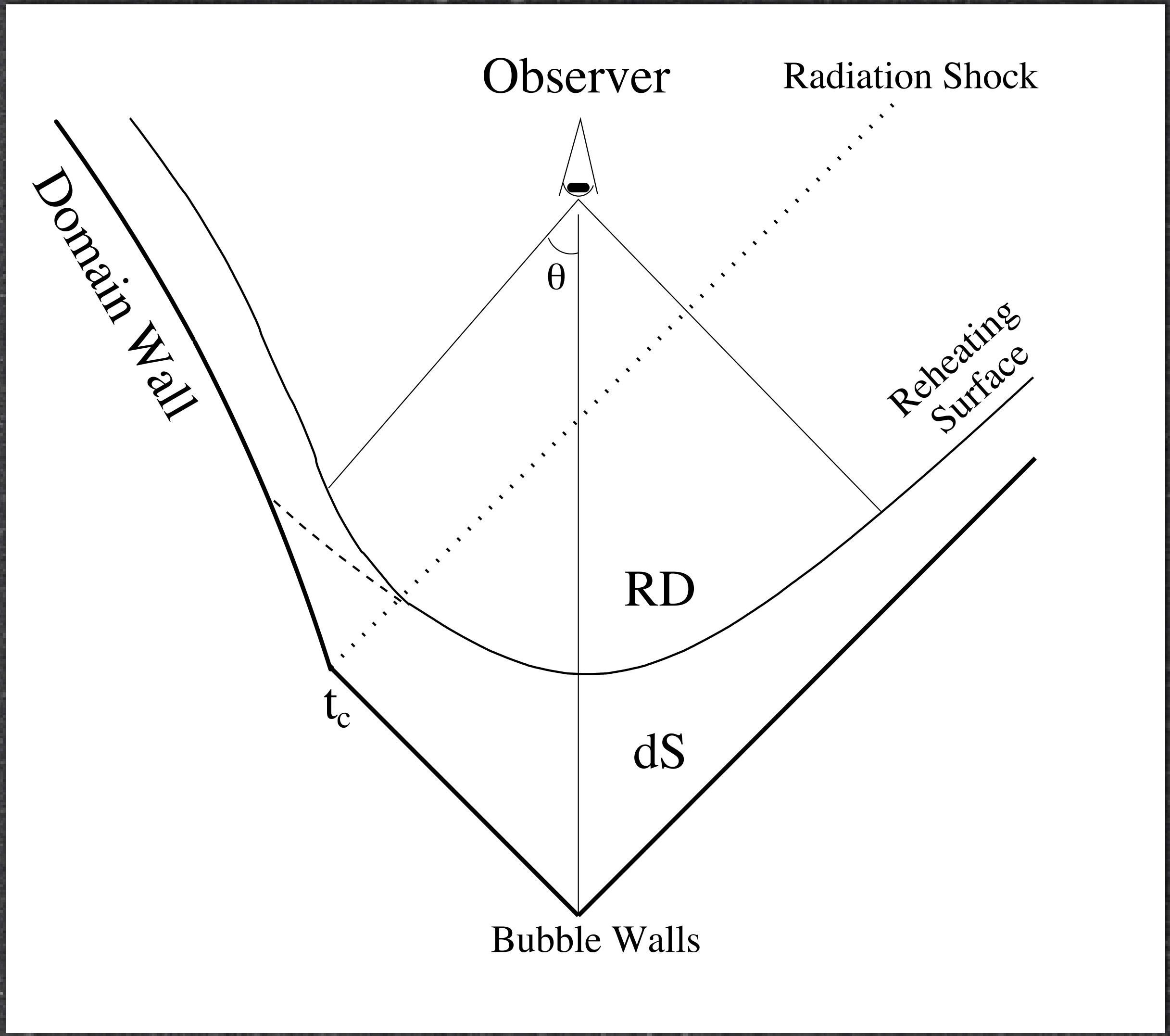
Bubble universes like ours (w/ small cc) are safe from domain walls and they don’t crunch

From higher cc bubbles, domain wall automatically moves away

From AdS bubbles, for fixed tension, lower dS cc is preferred

Signals

- Due to O(2,1) symmetry, isotropy is broken, effects depend on angle θ
- Two effects:
  - Propagation through perturbed metric
  - Deviation of last scattering surface



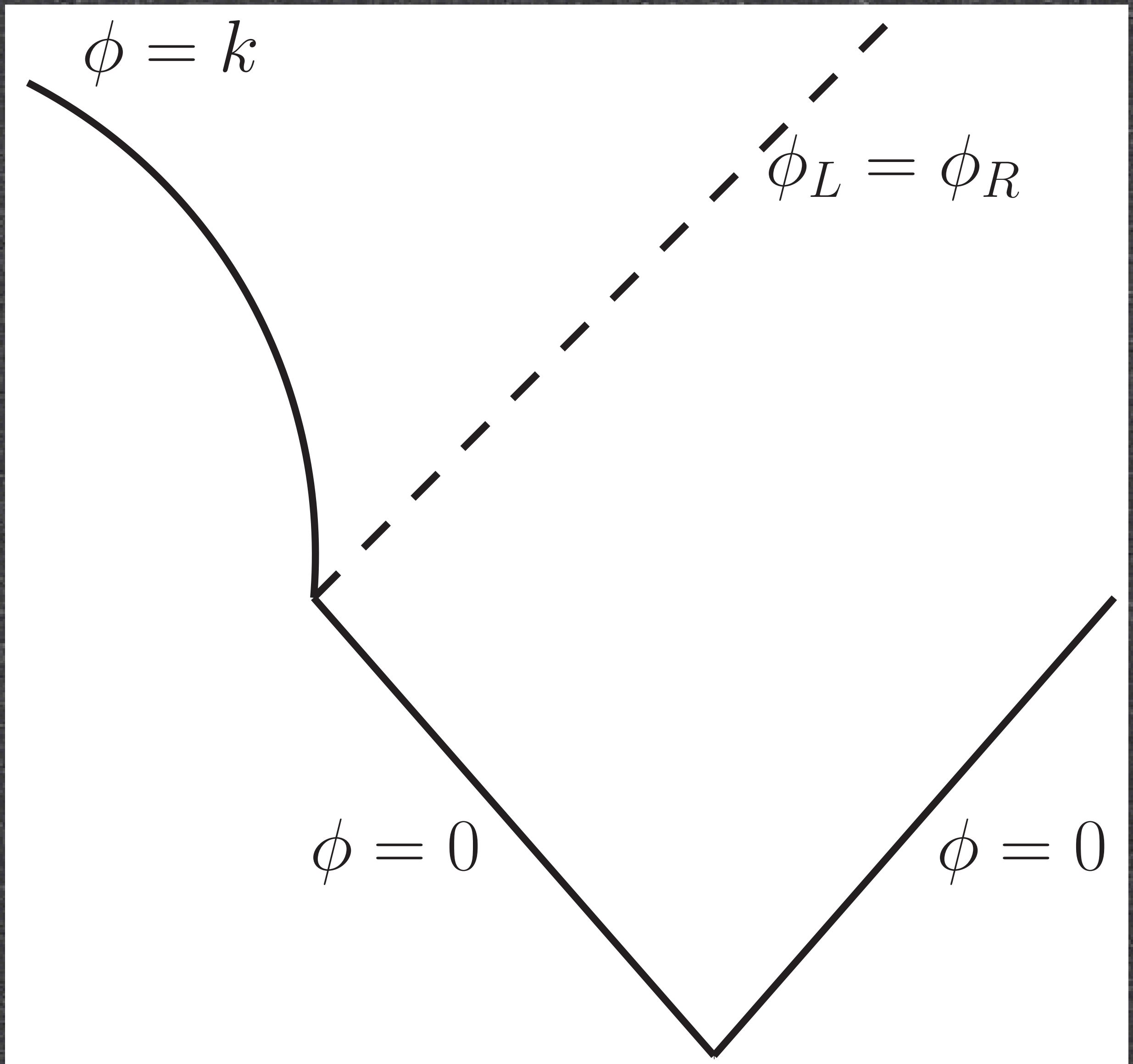
Signal Issues

- Issues with perturbed metrics
  - Unknown for radiation & matter domination
  - t_0/t is estimated to be small
- Issues with last scattering surface
  - Hard to solve scalar in perturbed metric
  - Nonanalytic

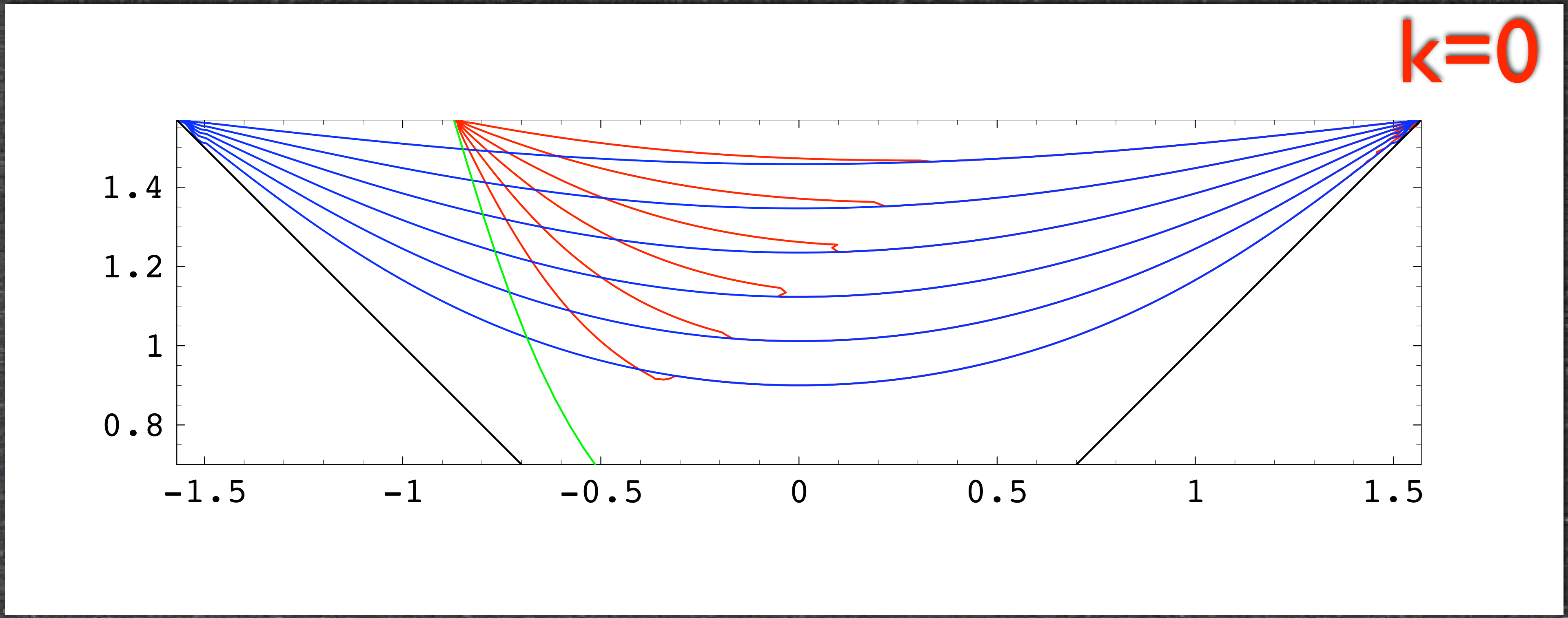
SC et.al.

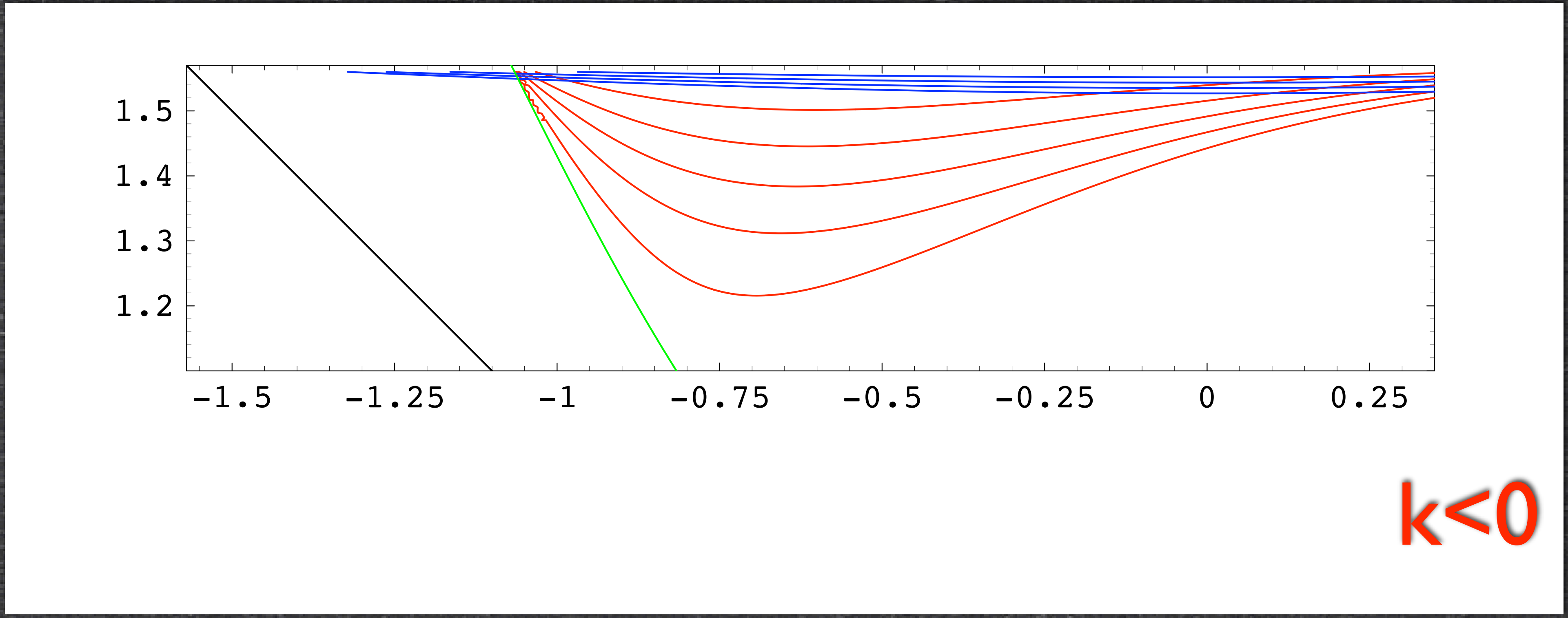
Compromise

- Treat scalar field as a simple pde with boundary condition
- Linear potential, so field changes
- Boundary conditions on bubble and domain walls
- Function is continous but not differentiable at shock

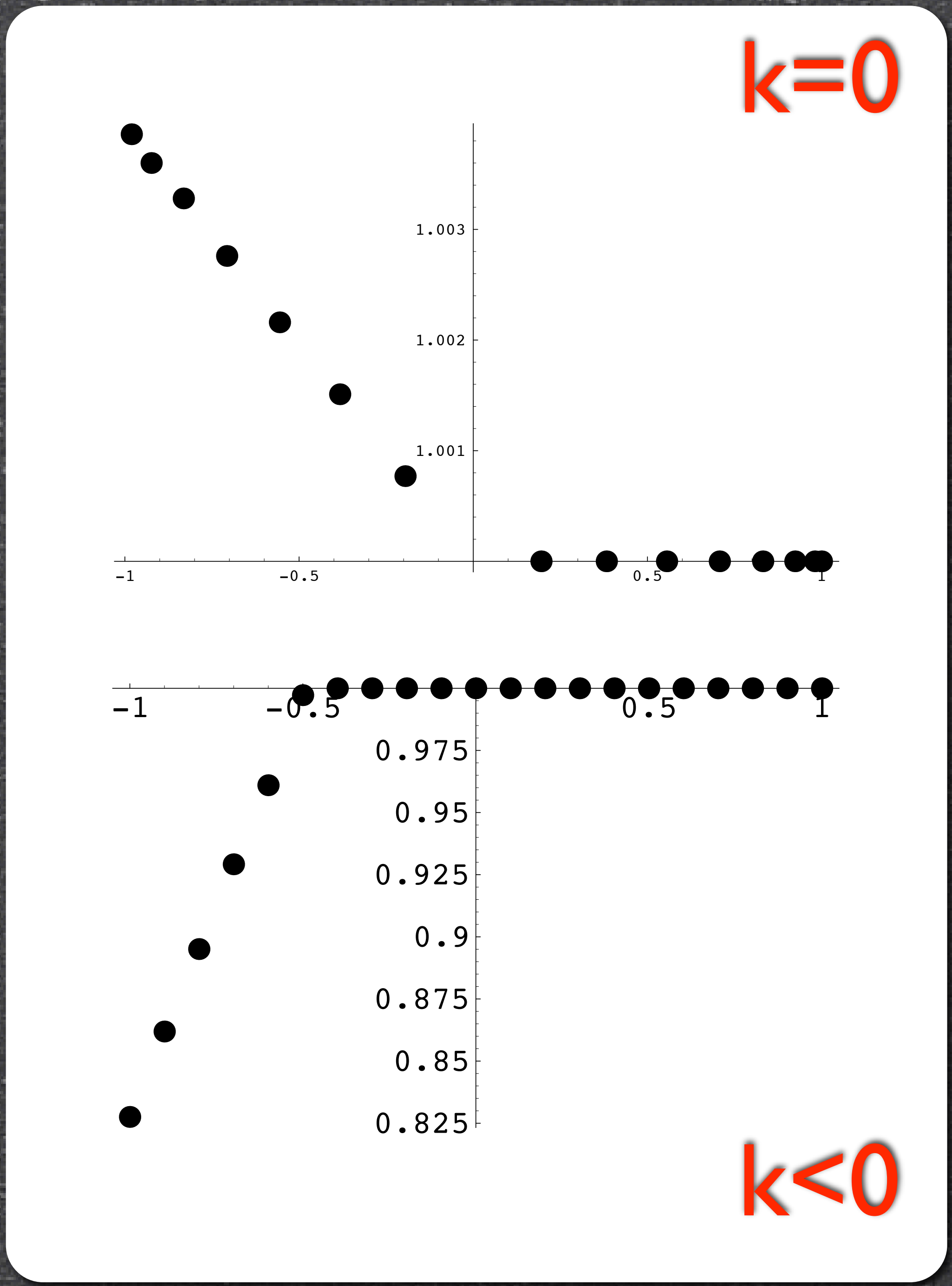


Results





Redshifts



- Normalized redshift back to reheating surface (not LSS), propagated through nonperturbed RD
- Makes sense: depends linearly on cosθ, transitions at radiation shock
- Of order $\sqrt{(1-\Omega_{tot})}$

Connecting to Observations

- Assuming inflationary perturbations are unaffected

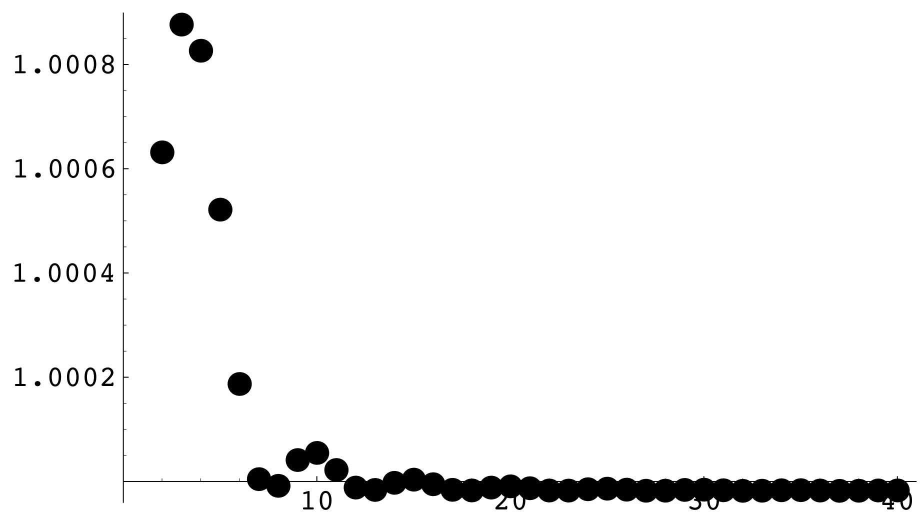
$$T(\vec{n}) = T_0' \, r(\vec{n}) \, [1 + \delta(\vec{n})]$$

- In the correct frame, redshift only affects m=0 modes, but total effect is a convolution of the a_{lm} of redshift and inflationary perturbations

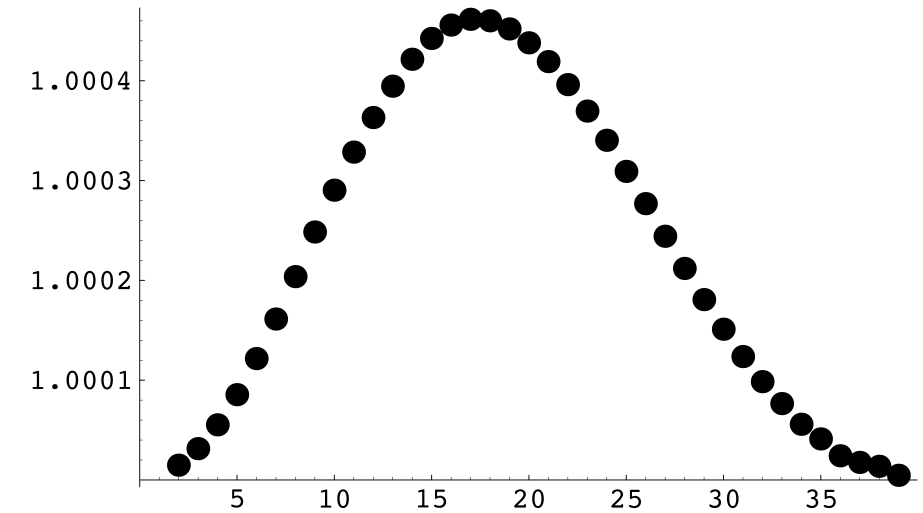
Effects on C_l's

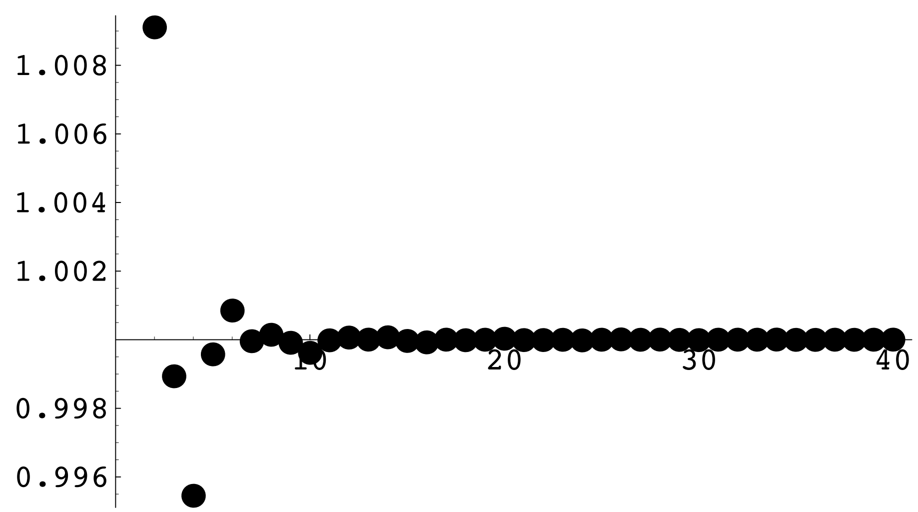
74 degree spot

16 degree spot

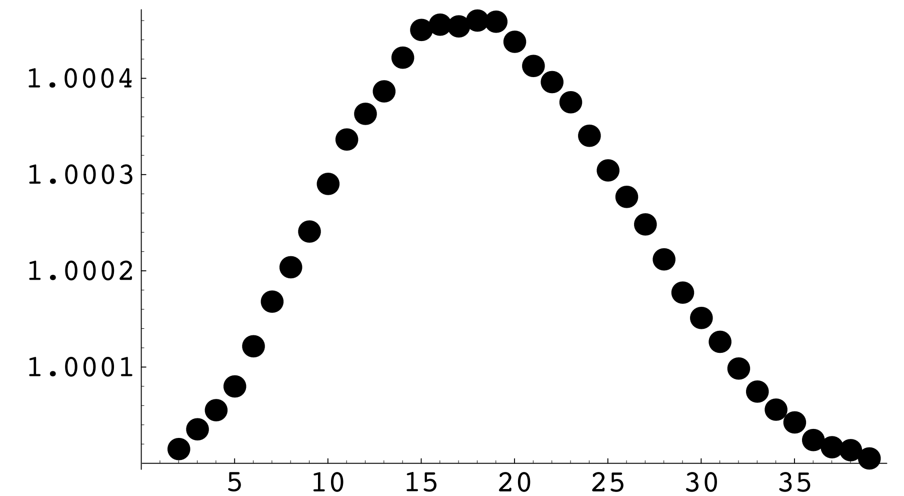


$$\frac{C_l}{C_l^{(0)}}$$





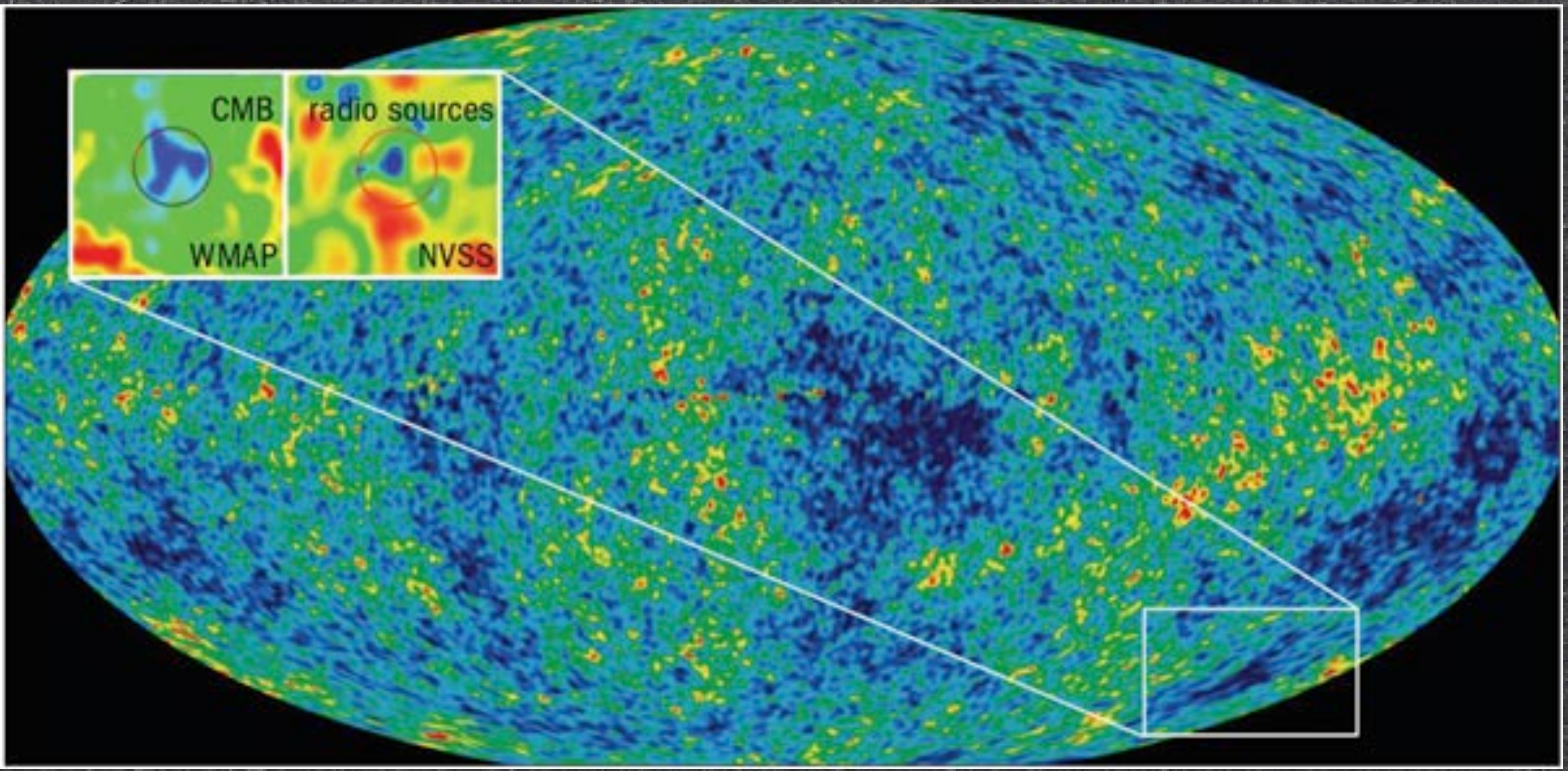
$$\frac{C_l^{left}}{C_l^{right}}$$



Cosmology anomalies (> 2σ excesses)

- Cold Spot
- Hemispherical Asymmetries
- Dark Flows

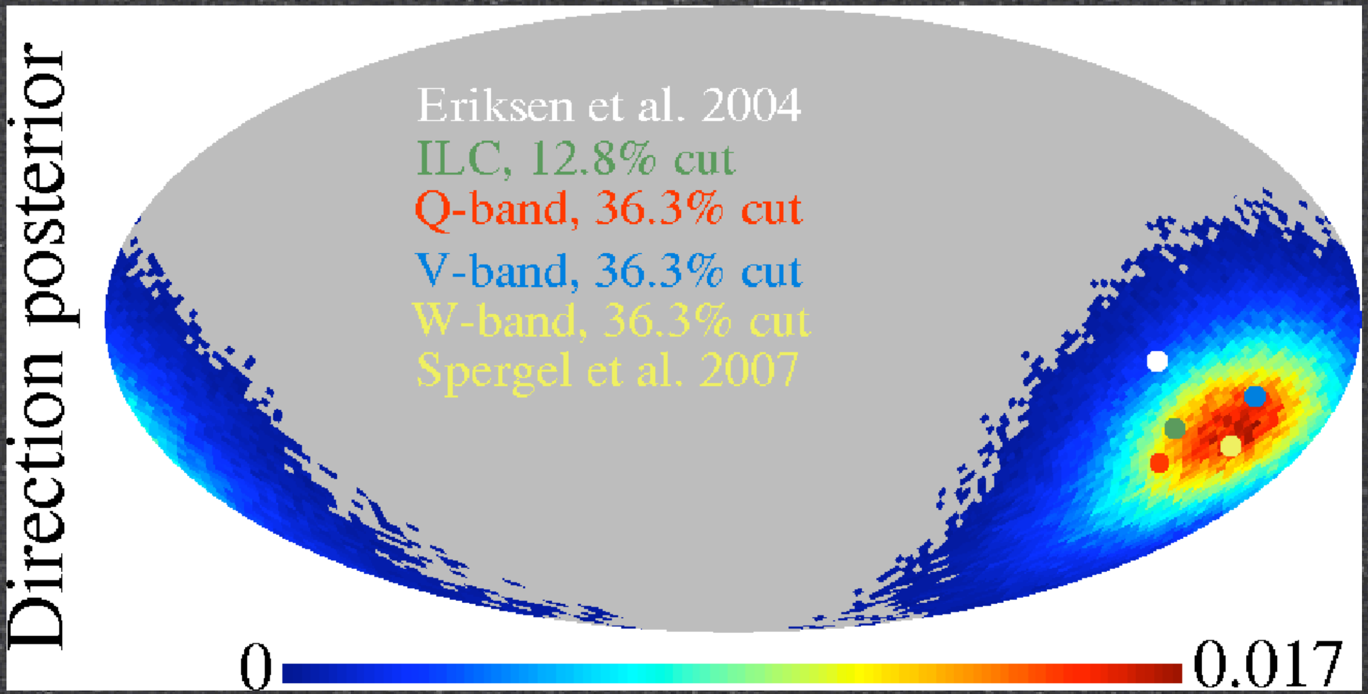
Cold Spot



- 10 degree spot, colder by 70 μK
- Potentially due to a large void (ISW)

Hemispherical Asymmetry

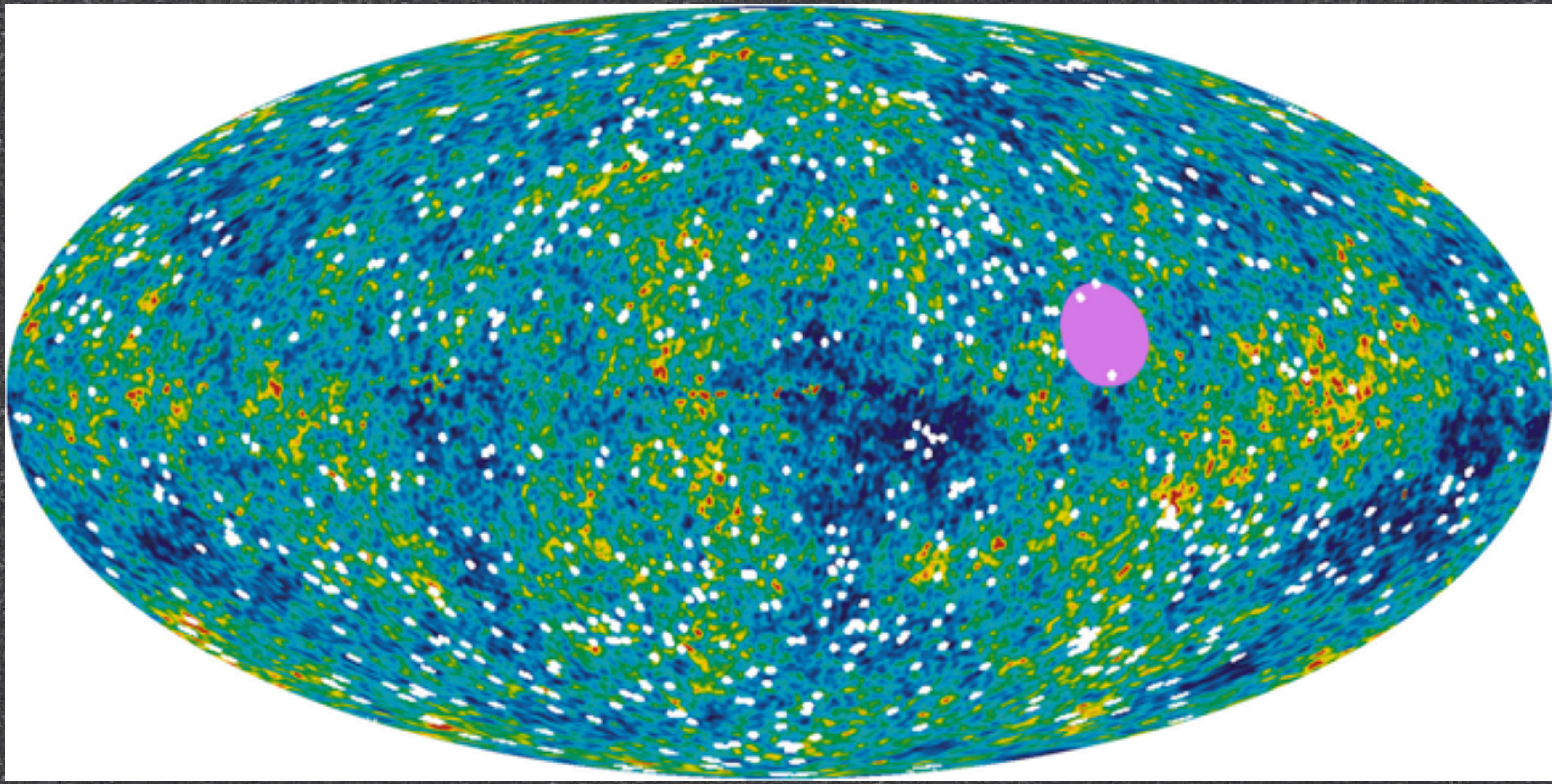
- Observed power asymmetry along axis
- Amplitude is modulated by 10%



Kashlinsky et.al.

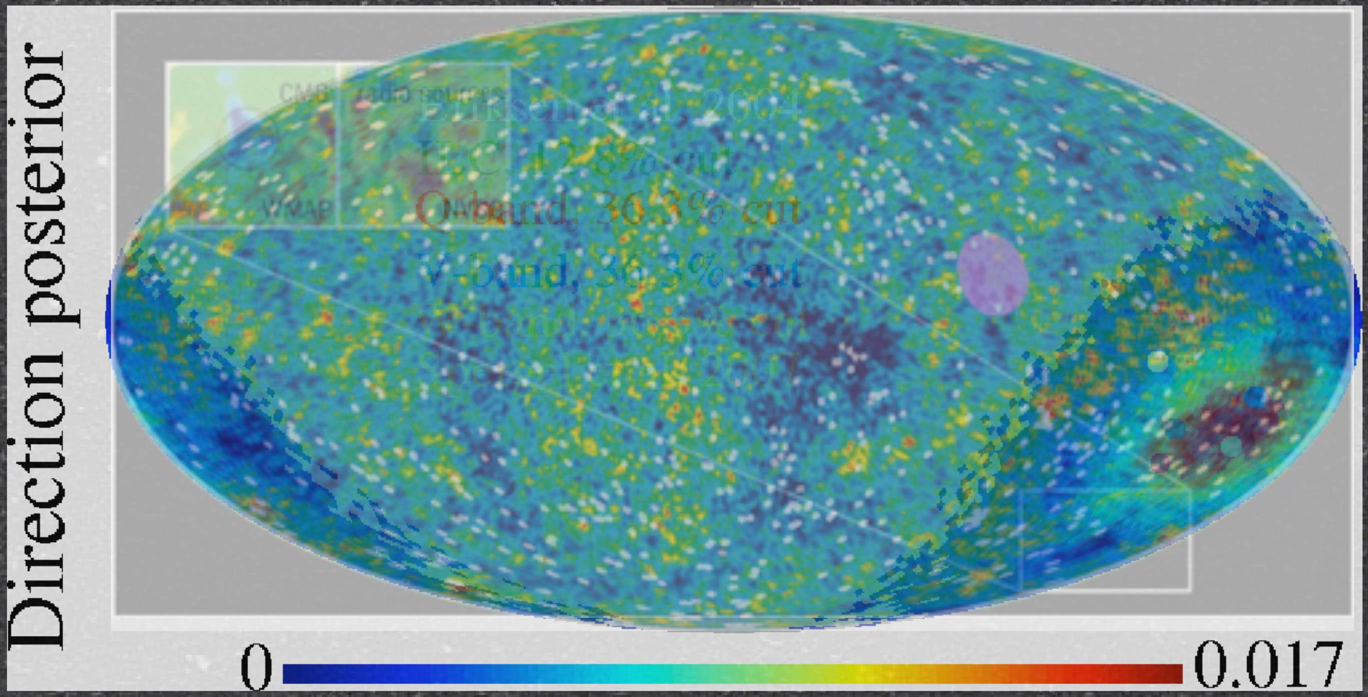
Dark Flow

- Using the kinematic SZ effect, discovered a coherent bulk flow of ~ 600 km/s
- Flow points in direction of pink ellipse



Summary of Anomalies

- Effects depend on a direction on the sky which are somewhat close
- Abundance of effects pushes for some new physics



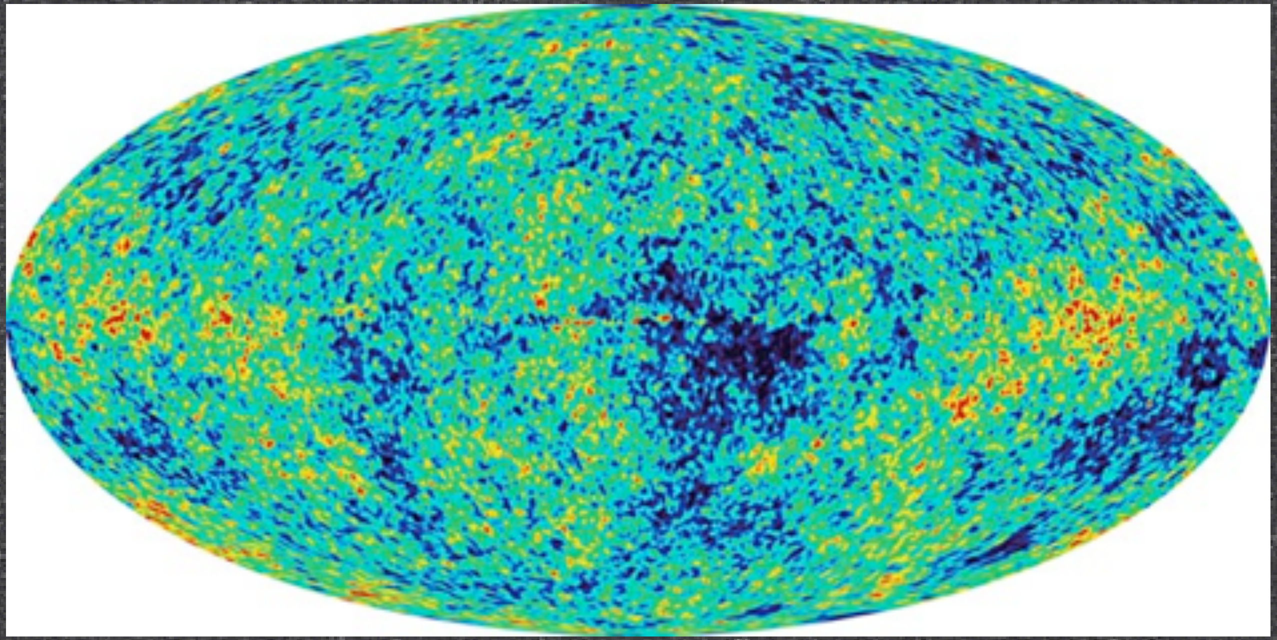
Further Possibilities

- Searching in angle space for disks with certain statistics, correlated to anomalies?
- Study nongaussianities, appears to be roughly equilateral and within limits
- Polarization effects expected as well (c.f. Dvorkin et.al.), correlation can be seen w/ Planck
- Effects in large scale structure (voids, flows?)

Conclusions

- Cosmology has a tremendous potential as a probe of high energy physics
- Can search for the eternal inflation/tunneling aspects of a landscape of vacua
- We've solved analytically metrics & domain wall motion for general collision, find that low cc dS bubbles are "safe"

Conclusions (cont.)



- We estimated CMB effects with a toy model
- Hot/cold spots & hemispherical power asymmetries expected
- Extending calculation to take in more effects