The Cosmological Observables When Worlds Collide

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“When Worlds Collide”
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“Watching Worlds Collide”
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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
Wealth of cosmological data from WMAP, SDSS, Supernovae
Cosmological Standard Model

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

J. Dalcanton
Discrepancies (> 2\(\sigma\) excesses)

- Some CMB/cosmology anomalies
  - Low \(l\) multipoles
    - Low and planar quadrupole
  - Alignment
- Cold Spot
- Hemispherical Asymmetries
- Dark Flows
Look for preferred axis for each multipole

Alignment for low $l \leq 5$
Cold Spot

- 10 degree spot, colder by 70 μK, centered at (l, b) ~ (200°,-56°)
- Potentially due to a large void (ISW)
Hemispherical Asymmetry

- Observed power asymmetry along axis \((l, b) \sim (225°, -27°)\)
- Amplitude is modulated by 10%
Using the kinematic SZ effect, discovered a coherent bulk flow of \( \sim 600 \text{ km/s} \).

Flow points in direction of pink ellipse.
Summary of Anomalies

- Anomalies exist, may or may not be correct
- Effects depend on a direction on the sky which are somewhat close
- Abundance of effects pushes for some new physics explanations which can explain some subset
Cosmological Collider

Early universe accesses much higher energies than colliders

Inflation a well known example of high energy physics only detectable through cosmology
String theory seems to predict a landscape of potential vacua $10^{500}$.

Predictions become cosmological.
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.
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.

\[
\begin{align*}
    ds^2_{CdL} &= -d\tau^2 + a(\tau)^2 dH_3^2 \\
    dH_3^2 &= d\xi^2 + \sinh^2 \xi d\Omega_2^2
\end{align*}
\]
Observable Initial Conditions

- Universe can only be slightly open today, need inflation after tunneling
- WMAP requires $\Omega_{\text{tot}} = 1.02 \pm 0.02$, amounting to e-fold constraint $N > 62$
- Observational limit $\Omega_{\text{tot}}^{-1} \sim 10^{-(4-5)}$, requiring $N < 66$
- CMB power spectrum affect primarily low $l$
Another Possibility

- Bubbles do not evolve in isolation
- Colliding bubbles are a generic prediction of inflating landscape
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 (following Freivogel, Horowitz, Shenker)

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

Diagram of Collision
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 $t_0 = 0$

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

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

Perturbed $t_0 \neq 0$
e.g. flat on AdS collision

Freivogel, Horowitz, Shenker

Building Blocks

Collision Diagram
Matching conditions across radiation shock and domain wall

Across shocks, determine $t_0$

Across domain wall, determines motion
All Collision Classification

For a dS bubble w/ cc of \( \Lambda \) colliding with larger \( \Lambda' \), domain wall moves away smaller \( \Lambda' \), domain wall moves away if tension\(^2 > \Lambda - \Lambda' \) stationary if tension\(^2 = \Lambda - \Lambda' \) moves toward if tension\(^2 < \Lambda - \Lambda' \)
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 $\theta$.

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
Compromise

- Treat scalar field as a simple pde with boundary condition
- Linear potential, so field changes
- Bubble Wall has scalar = 0, Domain Wall has scalar = k
- Function is continuous but not differentiable at shock

Figure 4: Sketch of the collision scenario with the null line $s$ labeled and approximate solutions for late times. The geometry and causal structure are summarized in Fig. 4. Note that region I is outside the lightcone of the collision, and the geometry can effectively be described in $\mathbb{H}_3$ coordinates up to the radiation line.

3.3 General Solutions For The Scalar Field

In this subsection we'll find the general solutions to the scalar field equation (with a linear potential) in the regions before and after the collision. Let's begin by looking at region I. Here we can make use of the $\mathbb{H}_3$ coordinates. We have

\[
\Box \phi = -\sinh^3 \tau \frac{\partial}{\partial \tau} \left( \sinh^3 \tau \frac{\partial}{\partial \tau} \phi \right) = \mu,
\]

(3.8)

where $\mu$ is the coefficient of the linear term in the potential. We require that $\phi$ and its derivative vanish along the bubble walls at $\tau = 0$. The general solution satisfying these boundary conditions is

\[
\phi(\tau) = \mu 3 \left[ \log 4 e^{\tau} (1 + e^{\tau})^2 + \frac{1}{2} \tanh \left( \frac{\tau}{2} \right) \right].
\]

(3.9)

At large and small $\tau$ this becomes

\[
\phi(\tau \gg 1) \approx -\frac{\mu}{3} \log \sinh \tau \approx -\frac{\mu}{3} \log (t \cos x),
\]

(3.10)

\[
\phi(\tau \ll 1) \approx -\frac{\mu}{4} \tau^2 \approx -\frac{\mu}{4} \left( \sqrt{1 + t^2 \cos x} - 1 \right),
\]

(3.11)

where we have used the coordinate transformations (2.4).
Figure 5: Plot of surfaces of constant $\phi$. The general solution is 
\[ \phi = f(t, x) + g(t, x) \]
where $f(t, x)$ and $g(t, x)$ are arbitrary functions and the primes denote derivatives with respect to the argument of the respective function. At large $t$, $f(t, x)$ gets the more pronounced and closer to the observer the extent the collision time $c$ is chosen to be, while the red lines project forward as if there were no collision (and the green line is the domain wall). This plot represents the actual surfaces. Black lines are the bubble walls (projection of $f(t, x)$) and reheating will not occur there, and the linear technique is used in this paper to approximate the general solution.

In Fig. 5 we draw an example with $k=0$. Increasing $f(t, x)$ gets the more pronounced and closer to the observer the extent the collision time $c$ is chosen to be, while the red lines project forward as if there were no collision (and the green line is the domain wall). This plot represents the actual surfaces. Black lines are the bubble walls (projection of $f(t, x)$) and reheating will not occur there, and the linear technique is used in this paper to approximate the general solution.

In region II we make use of two boundary conditions: the field $m$ is constant on the radiation line, and it must equal a constant at the domain wall causes the surfaces to "curl up", and $\phi$ is constant on the collision line. This plot represents the actual surfaces. Black lines are the bubble walls (projection of $f(t, x)$) and reheating will not occur there, and the linear technique is used in this paper to approximate the general solution.

Since these regions are highly perturbed away from a standard symmetric background, as well as arbitrary functions and the primes denote derivatives with respect to the argument of the respective function. At large $t$, $f(t, x)$ gets the more pronounced and closer to the observer the extent the collision time $c$ is chosen to be, while the red lines project forward as if there were no collision (and the green line is the domain wall). This plot represents the actual surfaces. Black lines are the bubble walls (projection of $f(t, x)$) and reheating will not occur there, and the linear technique is used in this paper to approximate the general solution.

Results

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In Fig. 6 we solve for $\phi$ in region II we make use of two boundary conditions: the field $m$ is constant on the radiation line, and it must equal a constant at the domain wall causes the surfaces to "curl up", and $\phi$ is constant on the collision line. This plot represents the actual surfaces. Black lines are the bubble walls (projection of $f(t, x)$) and reheating will not occur there, and the linear technique is used in this paper to approximate the general solution.

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Redshifts

- Normalized redshift back to reheating surface (not LSS), propagated through nonperturbed RD
- Makes sense: depends linearly on $\cos \theta$, transitions at radiation shock
- Of order $e^{-(N-N^*)}$
Assuming inflationary perturbations are unaffected

\[ T(\vec{n}) = T'_0 \cdot r(\vec{n}) \cdot [1 + \delta(\vec{n})] \]

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
In this section we will present our results for a few simulations using concordance cosmology values from WMAP [34, 35].

As a first approximation we can assume that terms gain more power from the collision than the modes with asymmetries. The first harmonic. The quadrapole receives only a small boost in a first peak in excess power around the cold spot, with the coldest point about 20 degrees from the center. We have chosen the angular radius of the 74 degree spot.

For our first example, we choose parameters with radius from the center. We have presented results for two specific choices of parameters.

Effects on $C_l$'s

74 degree spot

\[ \frac{C_l}{C_l^{(0)}} \]

16 degree spot

\[ \frac{C_l^{\text{left}}}{C_l^{\text{right}}} \]

In Fig. 15 we show the hemispherical power asymmetry, which is nearly identical to the two point function in the absence of a collision. We'll present results for two specific choices of parameters.
Further Possibilities

- Searching in angle space for disks with certain statistics
- Form and size of the nongaussianities, appears to be roughly equilaterial
- Polarization effects expected as well (c.f. Dvorkin et.al.), correlation can be seen w/ Planck
- Effects in large scale structure
Conclusions

- Cosmology has a tremendous potential as a probe of high energy physics
- Can search for the eternal inflation/tunneling aspects of the landscape
- Metrics & domain wall motion can be solved analytically, showing that low cc dS bubbles are “safe”
Conclusions (cont.)

- CMB effects have been estimated with a toy model.
- Hot/cold spots & hemispherical power asymmetries expected.