Title: Observational tests of eternal inflation

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Abstract: In the picture of eternal inflation, our observable universe resides inside a single bubble nucleated from an inflating false vacuum. Some of the theories giving rise to eternal inflation predict that we have causal access to collisions with other bubble universes, providing an opportunity to confront these theories with observation. In this talk, I will outline progress on the theoretical description of eternal inflation and bubble collisions, and present results from the first search for the effects of bubble collisions in the WMAP 7-year data.

Observational tests of eternal inflation

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In collaboration with:
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Daniel Mortlock
Hiranya Peiris

arXiv:1012.1995 **arXiv:1012.3667**

The vacuum crisis

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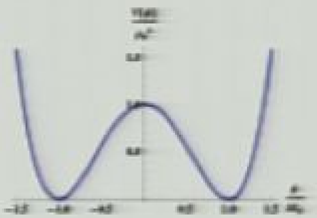
- Spontaneous symmetry breaking gives rise to multiple vacua:



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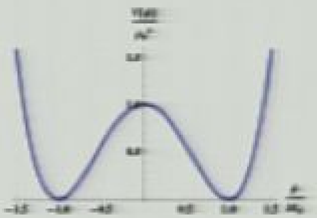

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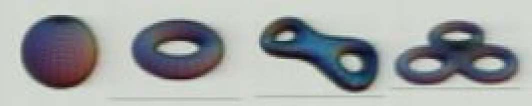

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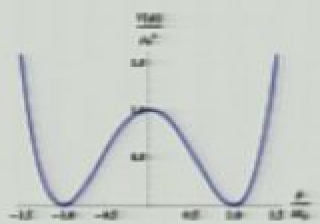

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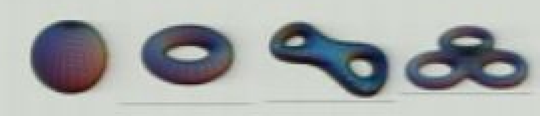

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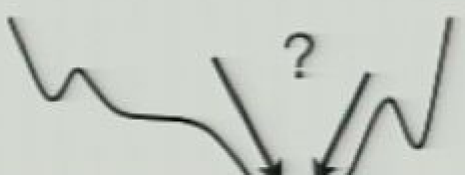
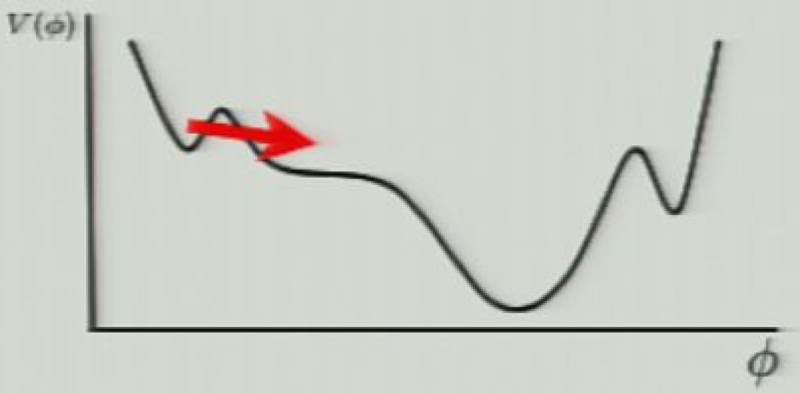
- How did we evolve into this vacuum? Are there cosmological signatures?

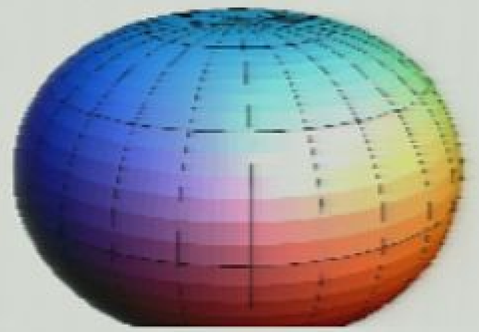


Eternal Inflation

- One proposal: all vacua are realized somewhere.



- Tunneling = Bubble nucleation.



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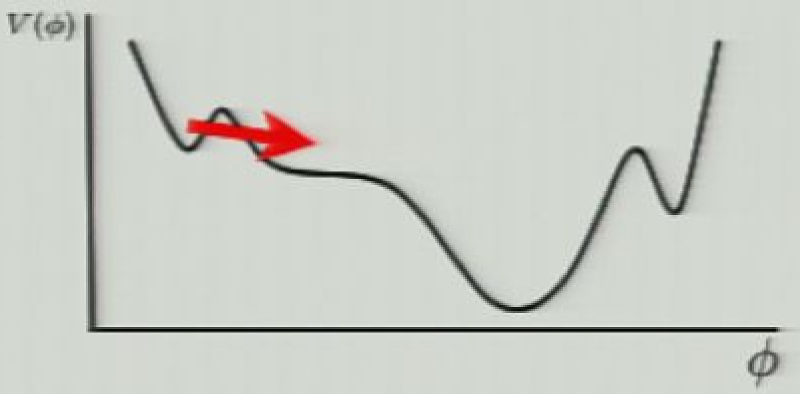

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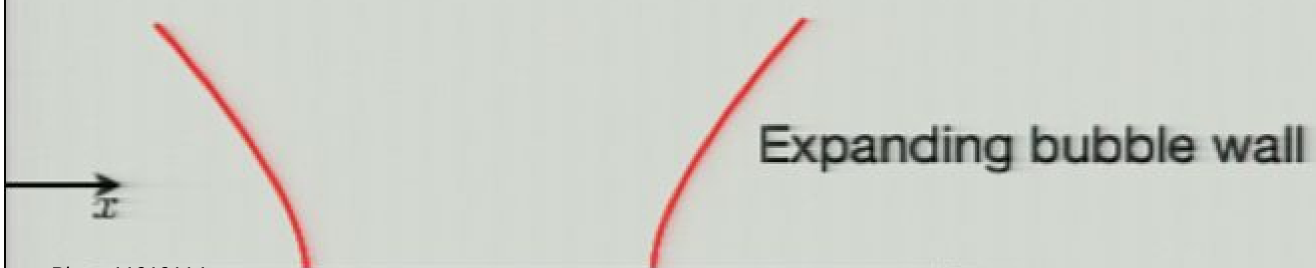

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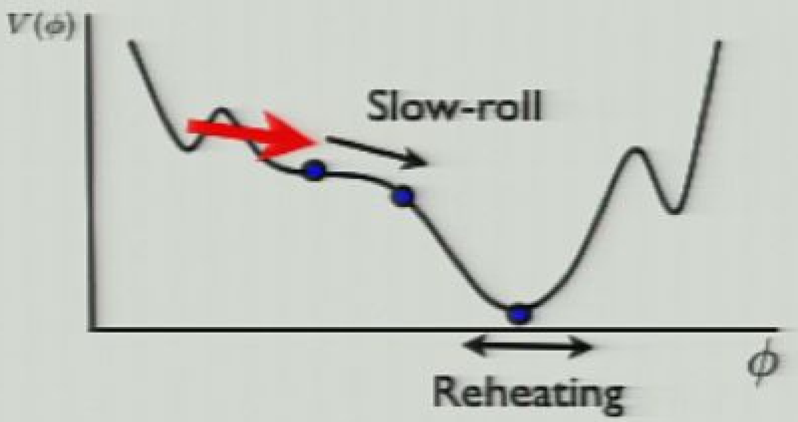

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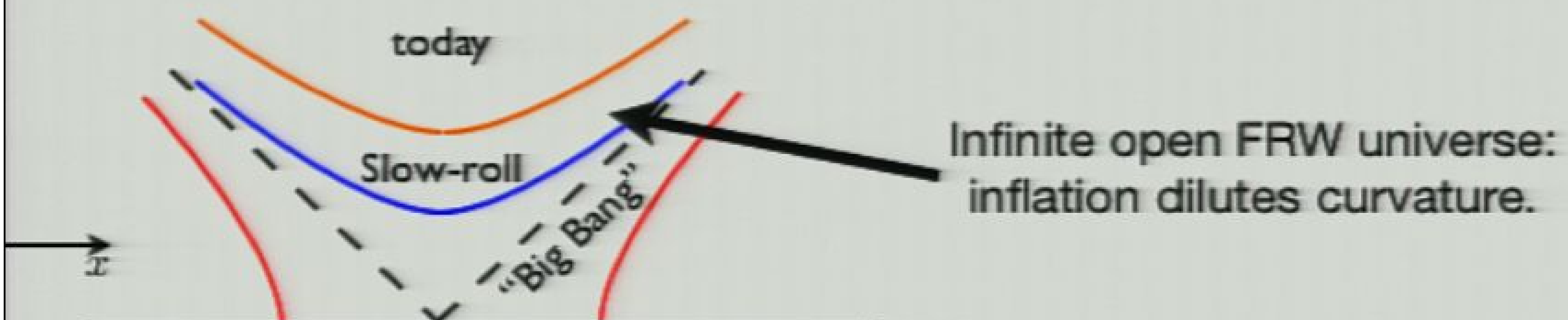
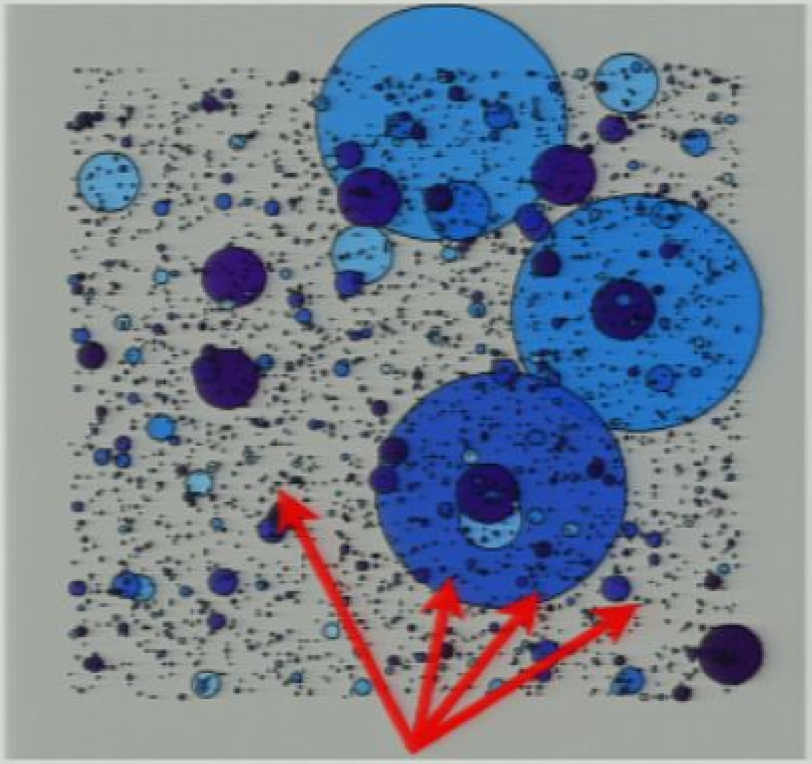


Eternal Inflation

- With positive vacuum energy, bubbles form, but space expands between them: inflation can become eternal.



Many cosmologies evolving to many vacua.
We are somewhere in here.

Science or science fiction?

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- Strong theoretical motivation, but is it experimentally verifiable?

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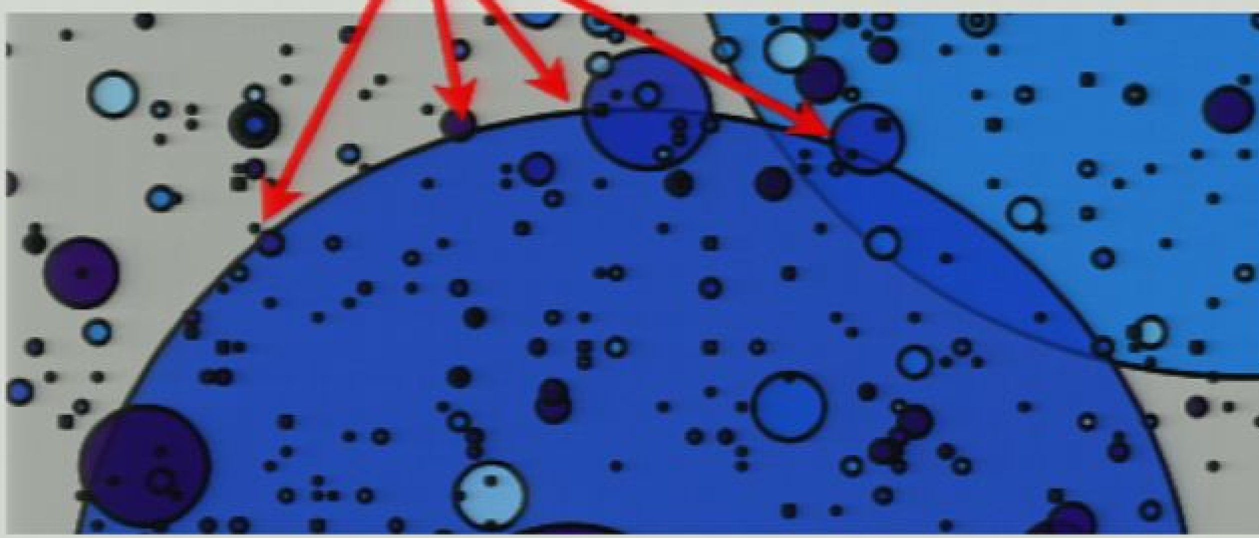
Each Bubble collides an infinite number of times!



- Who gets to observe these collisions and what would they see?

Bubble collisions

- Two necessary conditions to see a collision:

  1) Observers must exist to the future of a collision to see it.
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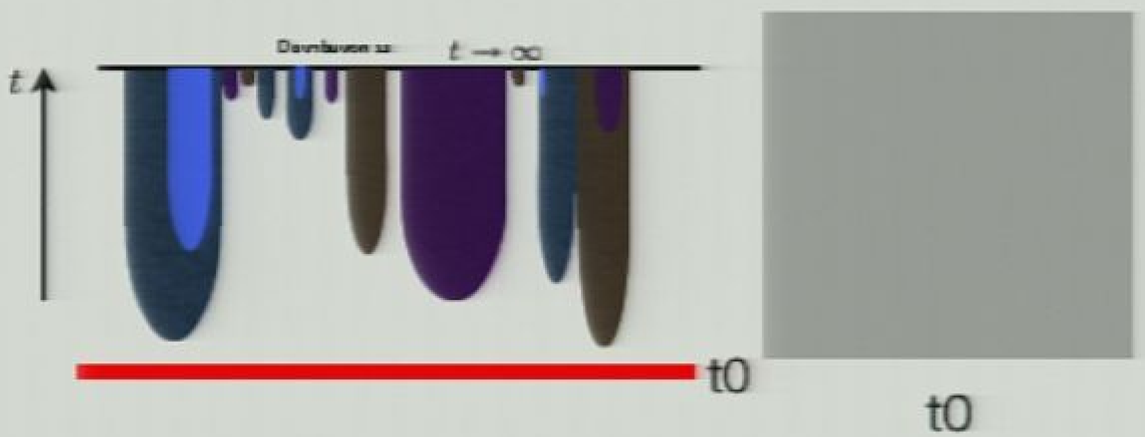
- To determine the observability of bubble collisions we need to assess:

  1) How lucky do we need to be?
  2) What is the spacetime structure in the aftermath of a collision?
  3) What could the observational effects of a collision be?

How lucky do we have to be?

- How likely is it that a collision is in our past?
- Here are the assumptions:
- At some initial time, the universe was in the false vacuum:



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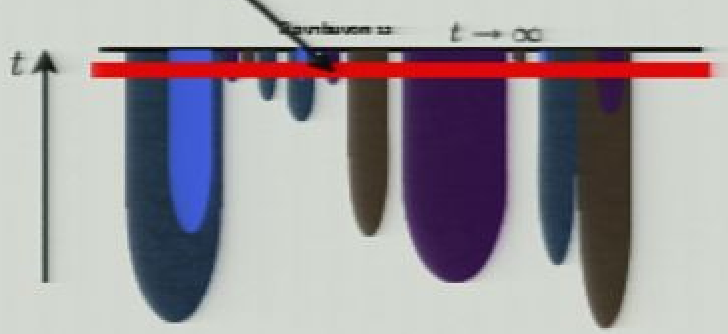

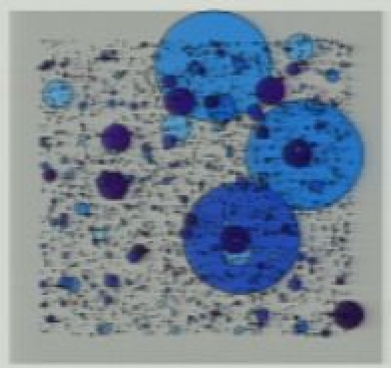

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- Bubbles are approximated as light cones.

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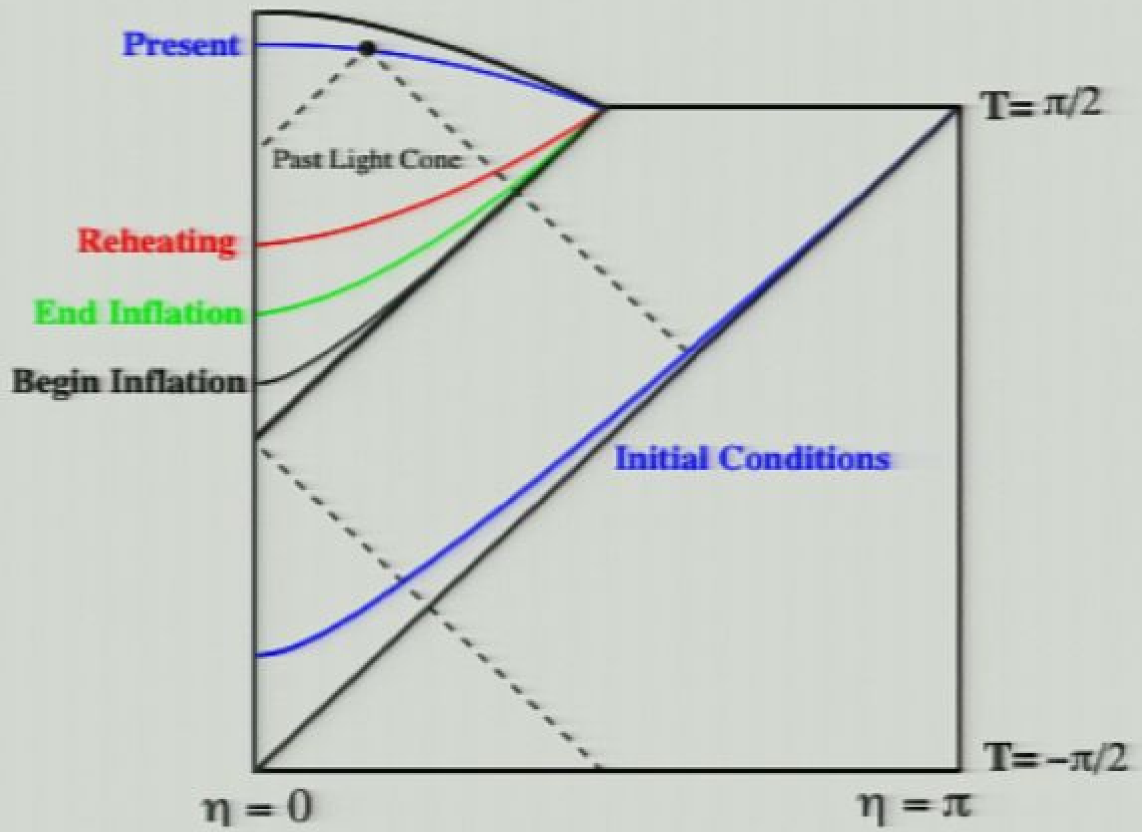

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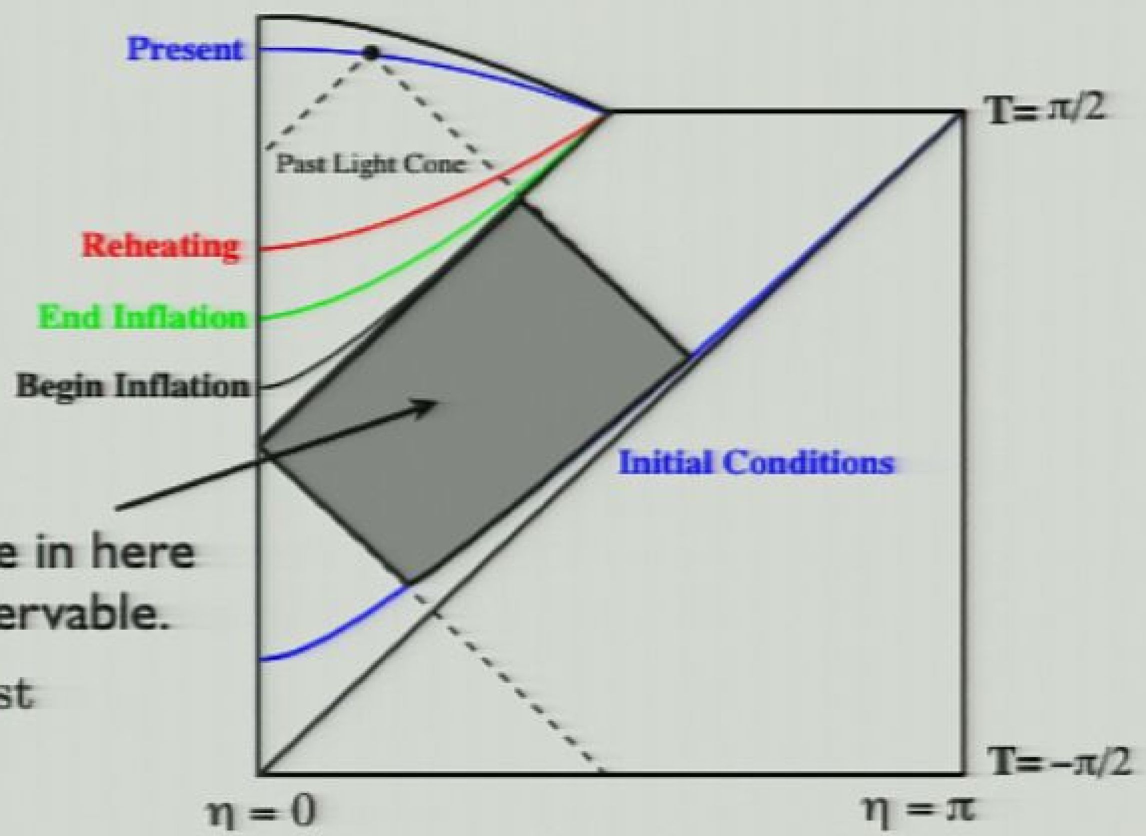
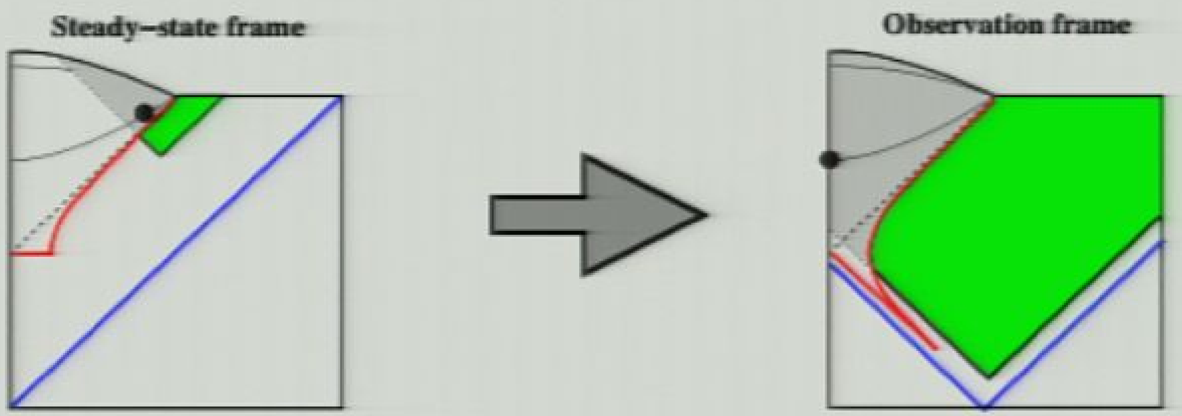


Bubbles that nucleate in here
are in principle observable.

$$N = \lambda V_4^{\mathrm{past}}$$

nitial value surface

- The initial value surface breaks the original SO(3,1) symmetry of the bubble: we can be boosted with respect to the initial value surface.



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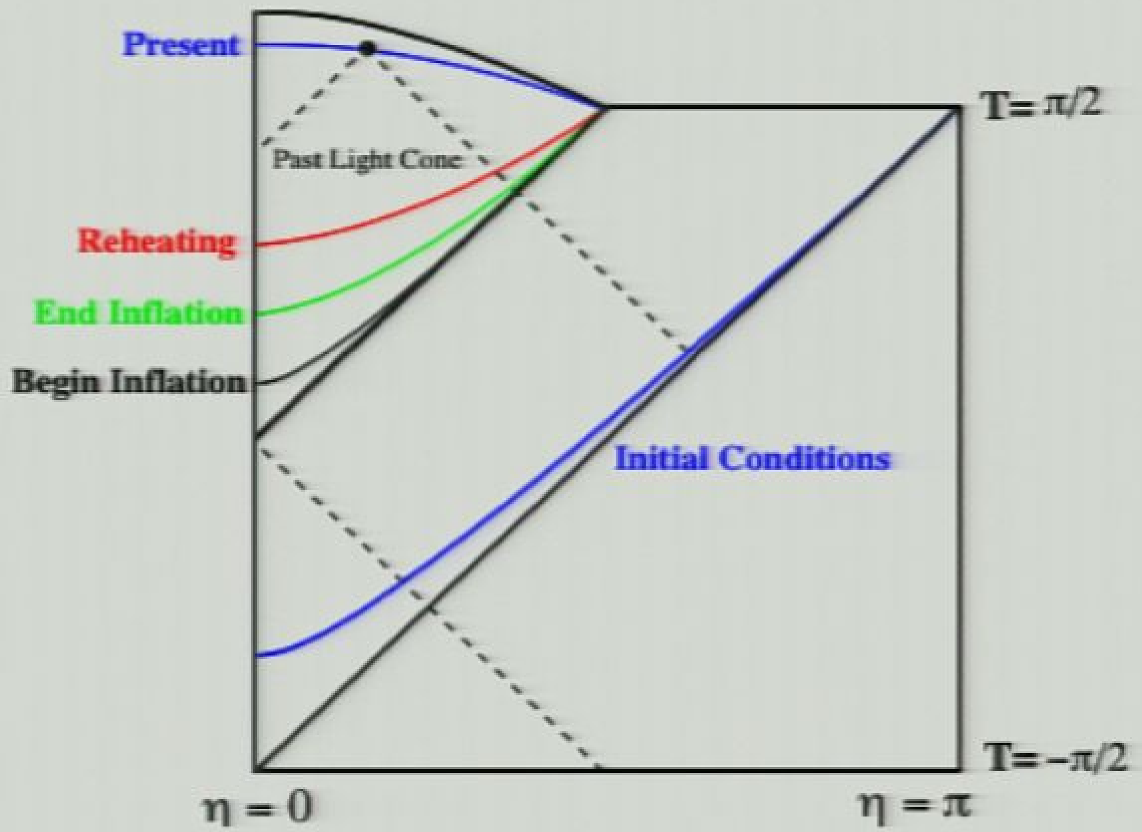

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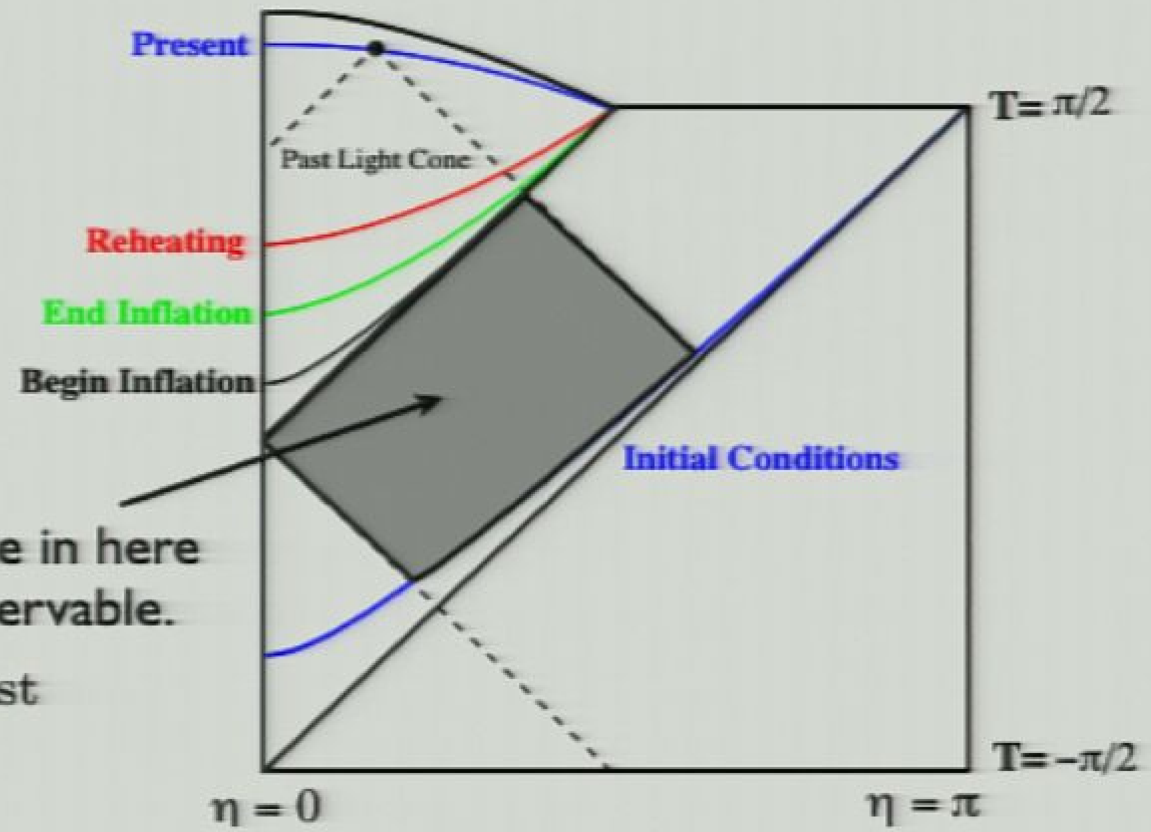

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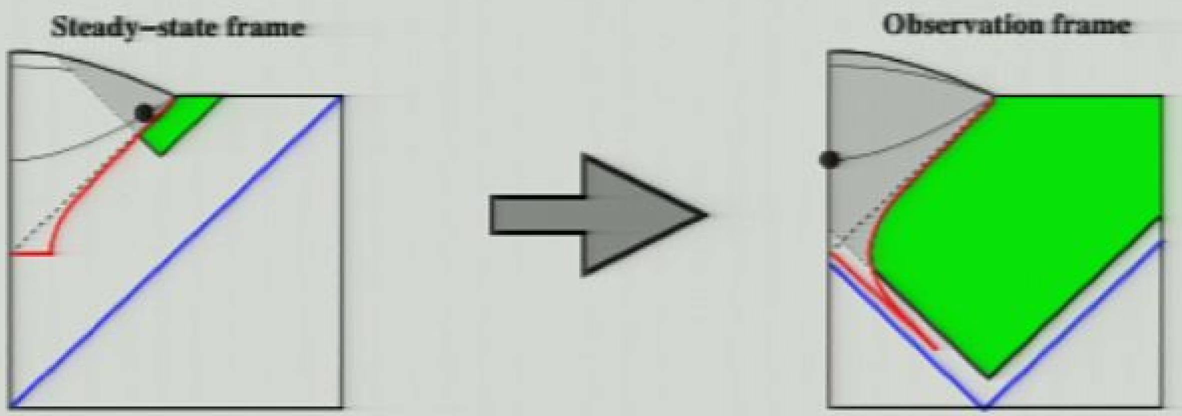

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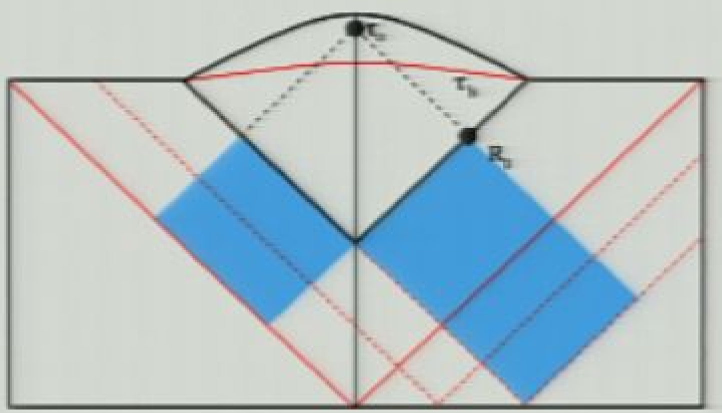
- If we are not at rest with respect to the initial value surface, the direction of arrival for collisions is anisotropic. Garriga, Guth, and Vilenkin



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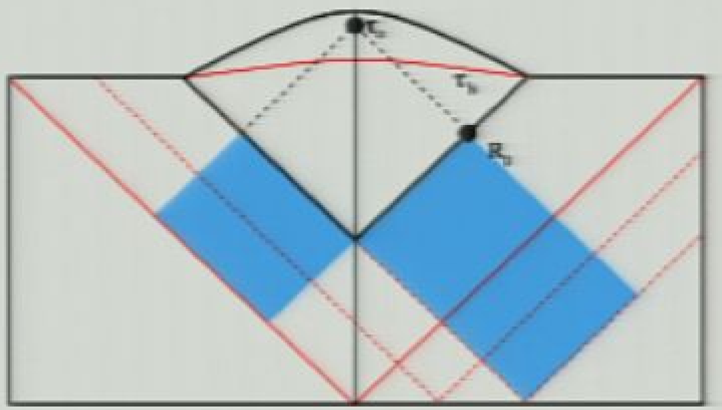

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- All of the volume is at large ξ_o, so if we are at a randomly chosen position, we should have many collisions in our past.

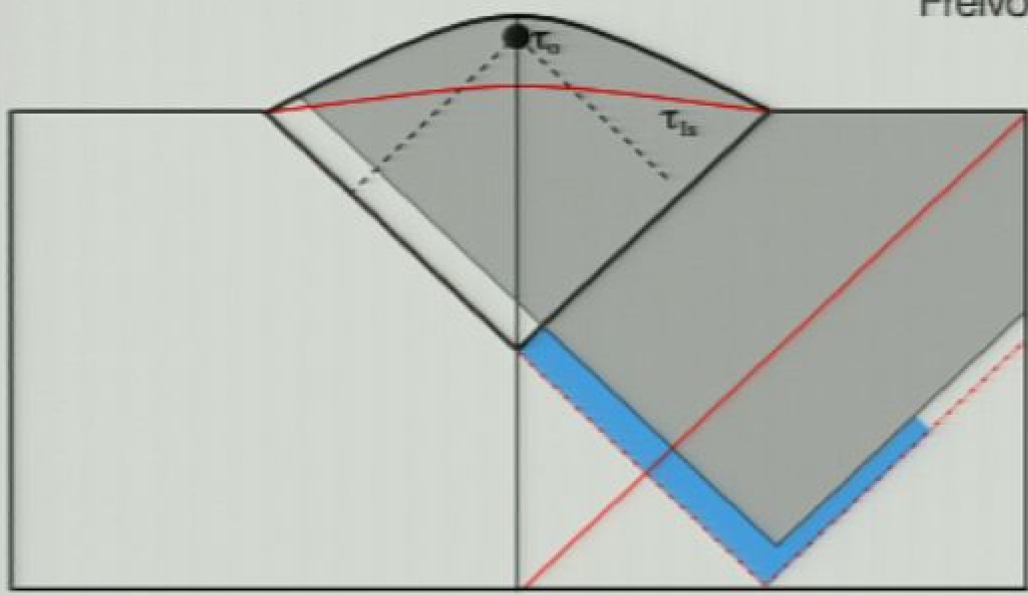
Aguirre, Johnson, and Shomer

- But.....

How lucky do we have to be?

- Most such collisions are larger than the observable portion of the SLS.

Freivogel, Kleban, Nicolis, and Sigurdson



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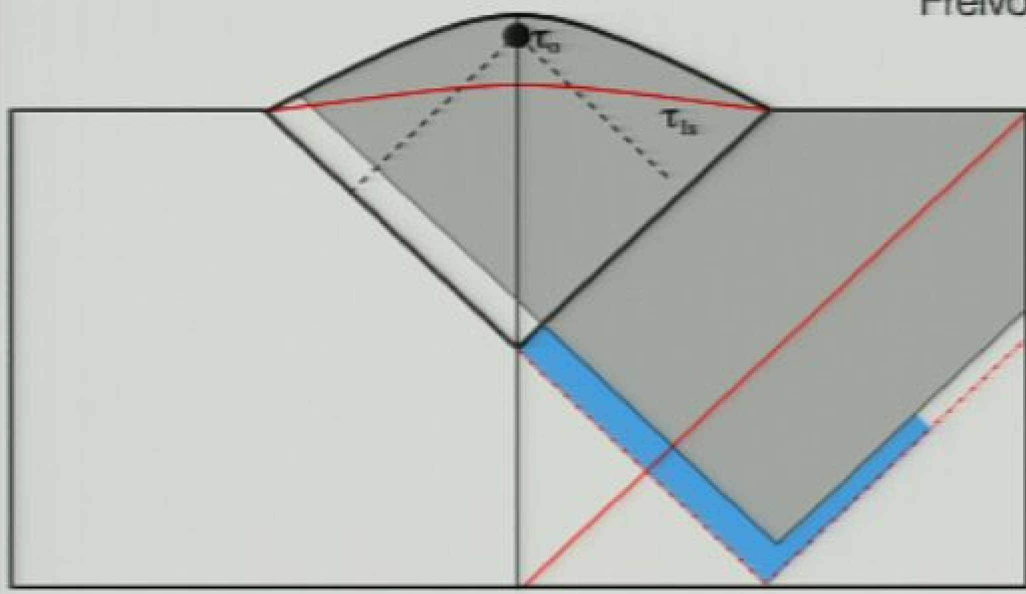
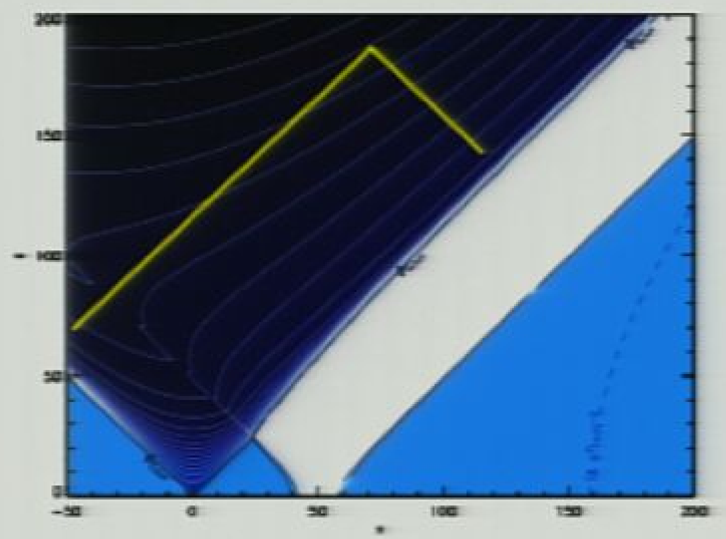
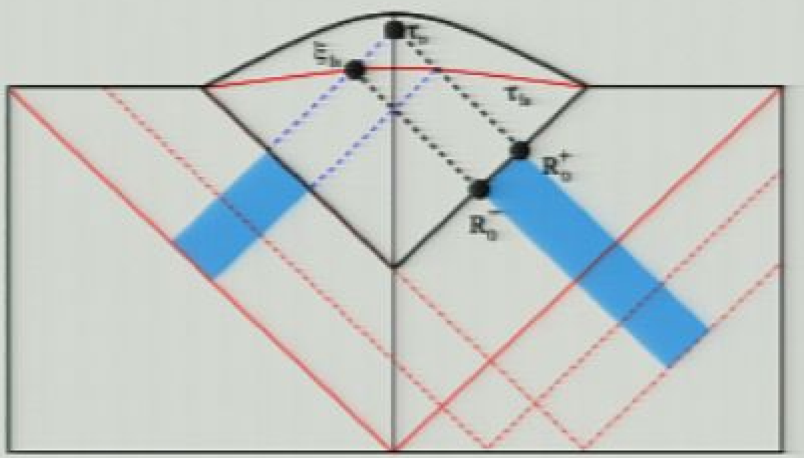




- This means that the only conceivable signatures are at large wavelengths: hard to see....

How lucky do we have to be?

- Counting only collisions which intersect the observable part of the surface of last scattering:



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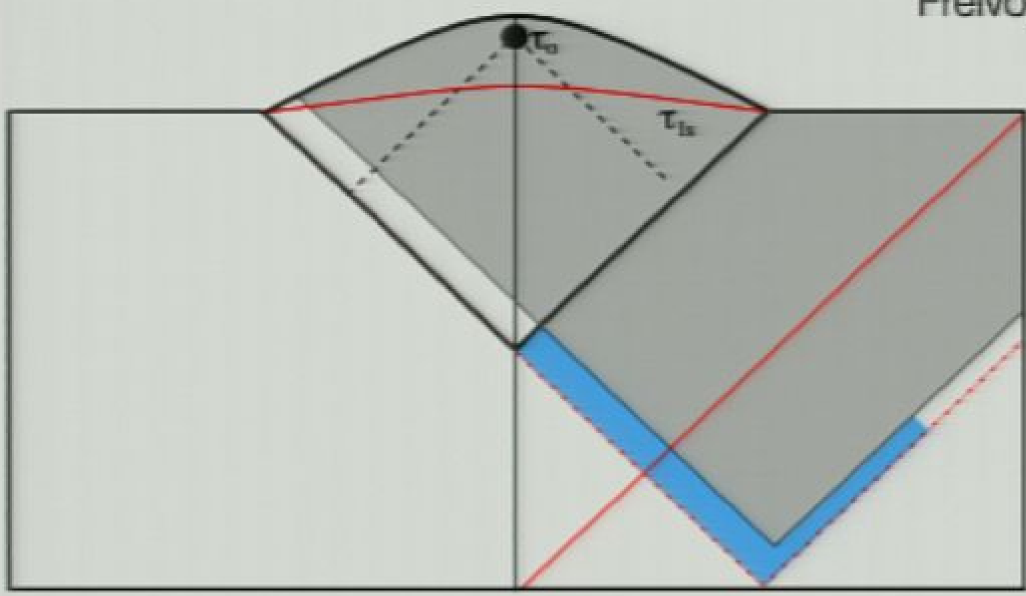

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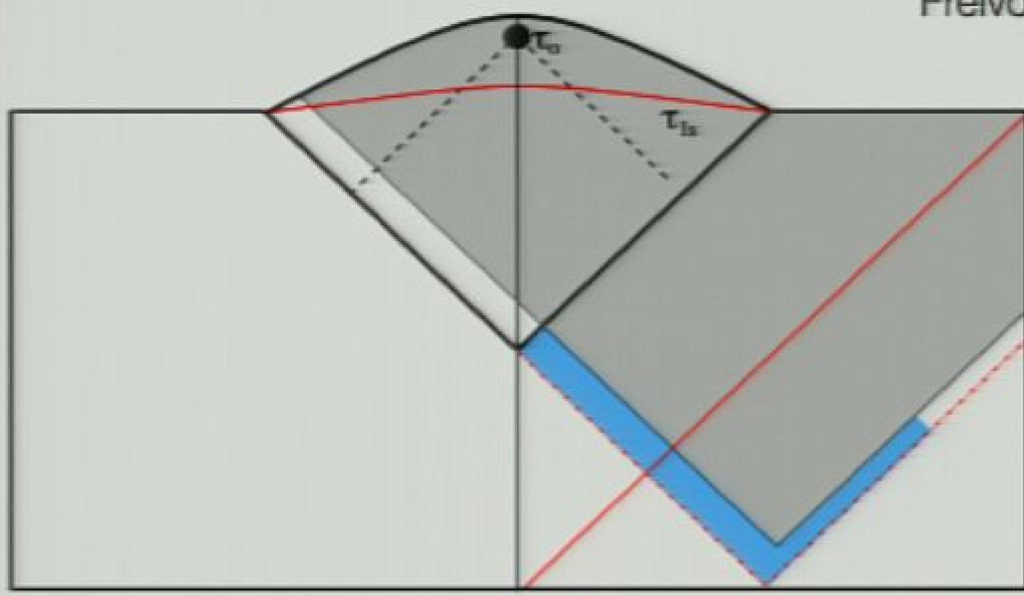

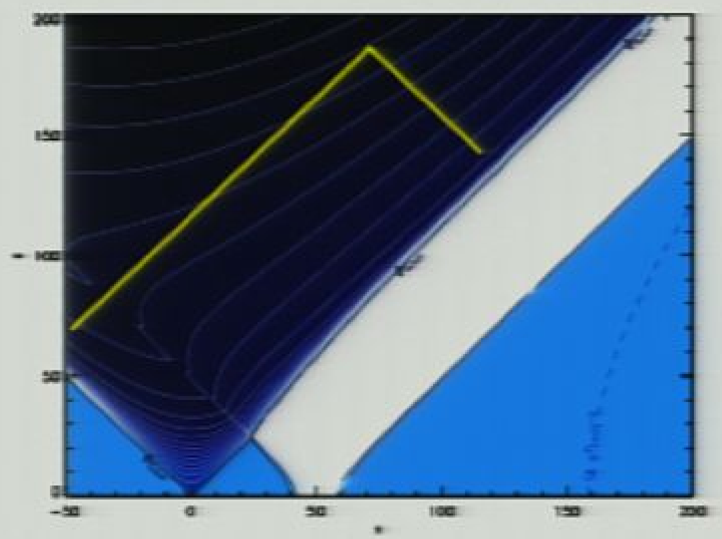

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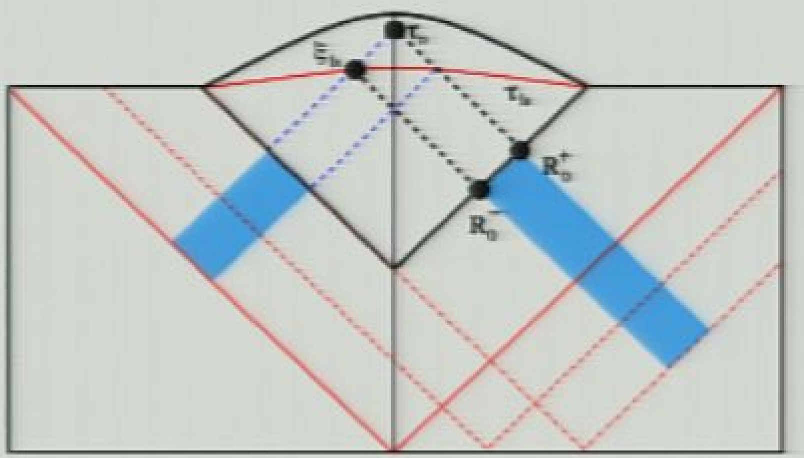

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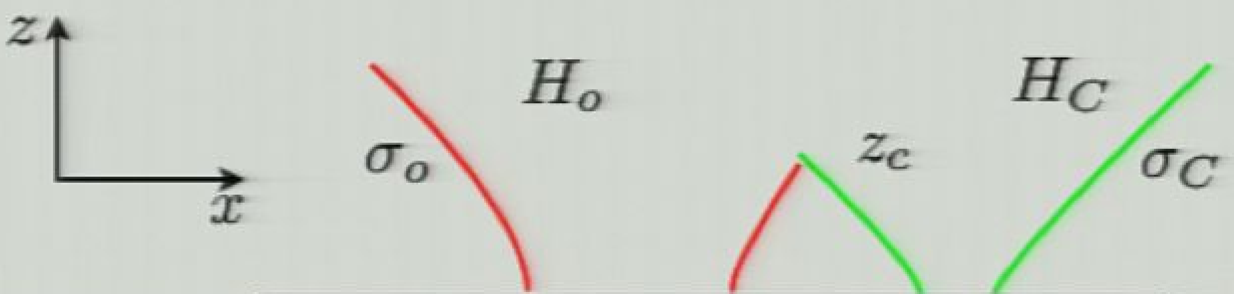
Bottom line

- If collisions are survivable, we almost certainly have one in our past.
- But, to expect more than 1 ***visible*** collision to our past,
- at least one type of transition from the false vacuum must satisfy:

$$\lambda H_F^{-4} > \left(\frac{H_I}{H_F}\right)^2$$

Bubble collision spacetime

- The collision spacetime has SO(2,1) symmetry.
- Hyperbolic Birkhoff's theorem: no gravitational wave solutions, just as for a spherical source!
- Thin wall matching:



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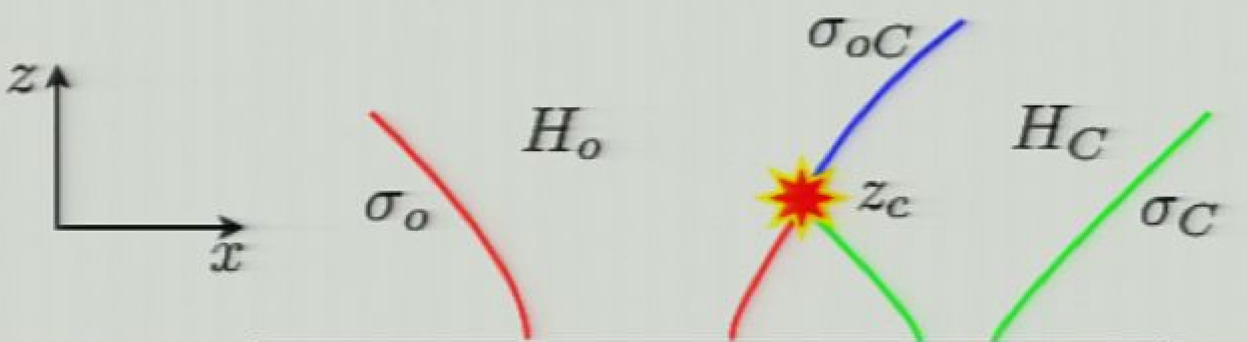
- Accelerates to the right if $H_C^2 - H_o^2 + 16\pi^2\sigma_{oC}^2 > 0$ (roughly $H_C > H_o$)

Aguirre and Johnson also Kleban, Chang, and Levi



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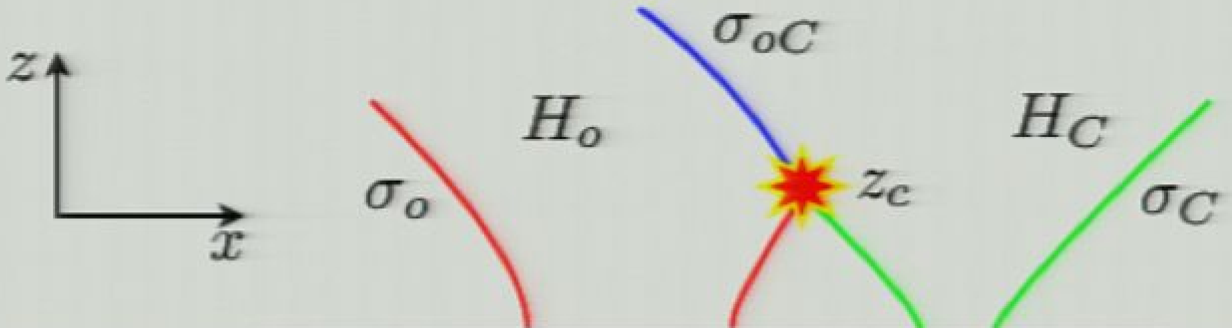

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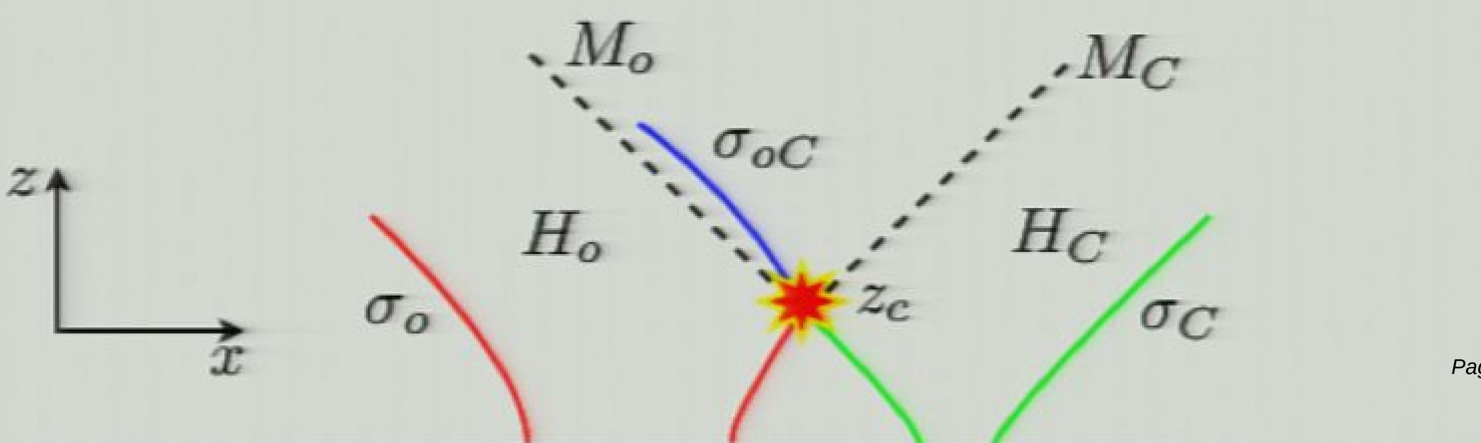
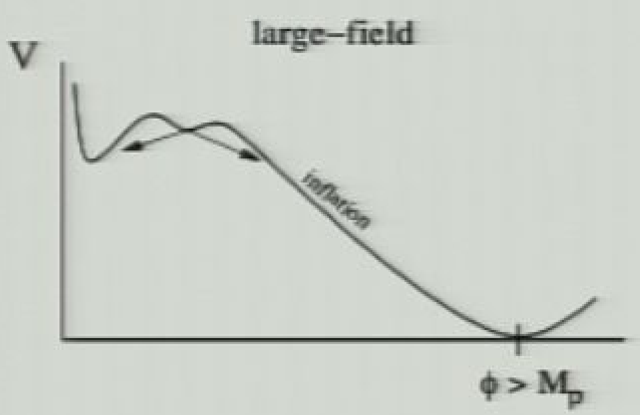
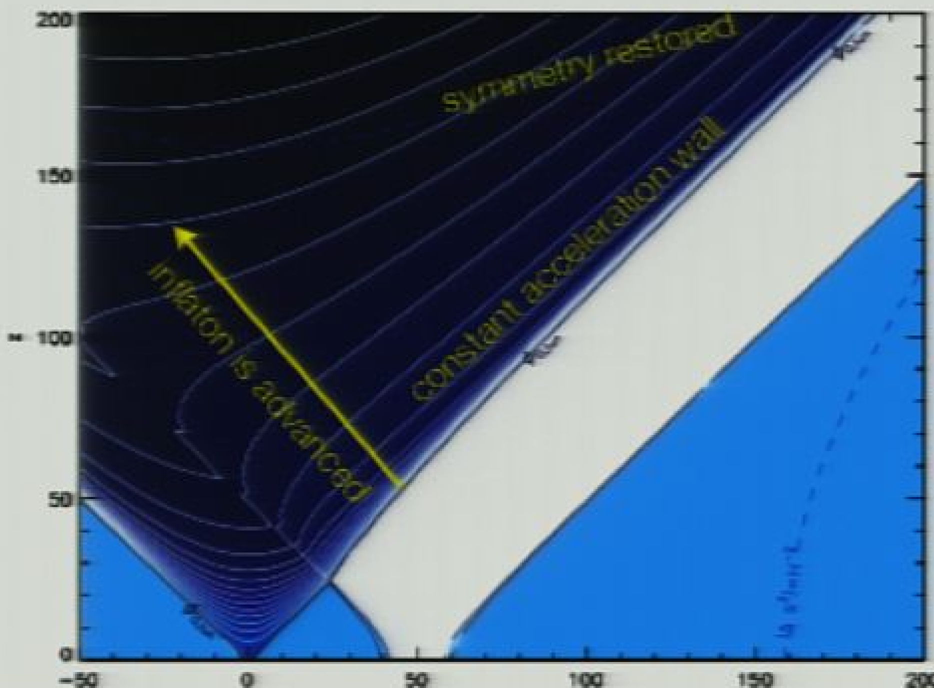
- Accelerates to the left if $H_C^2 - H_o^2 + 16\pi^2\sigma_{oC}^2 < 0$ (roughly $H_C < H_o$)
- Energy conservation indicates there are extra debris shells: M_o, M_C



Bubble collision spacetime

- Performing numerical simulations, there are examples where inflation can survive a collision.
- The original FRW symmetry is approximately restored to the future of the collision.





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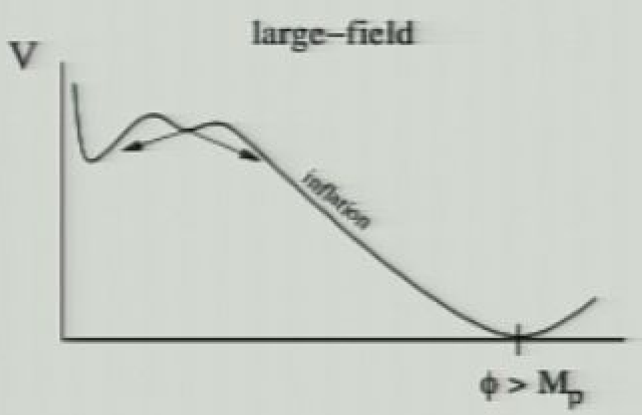

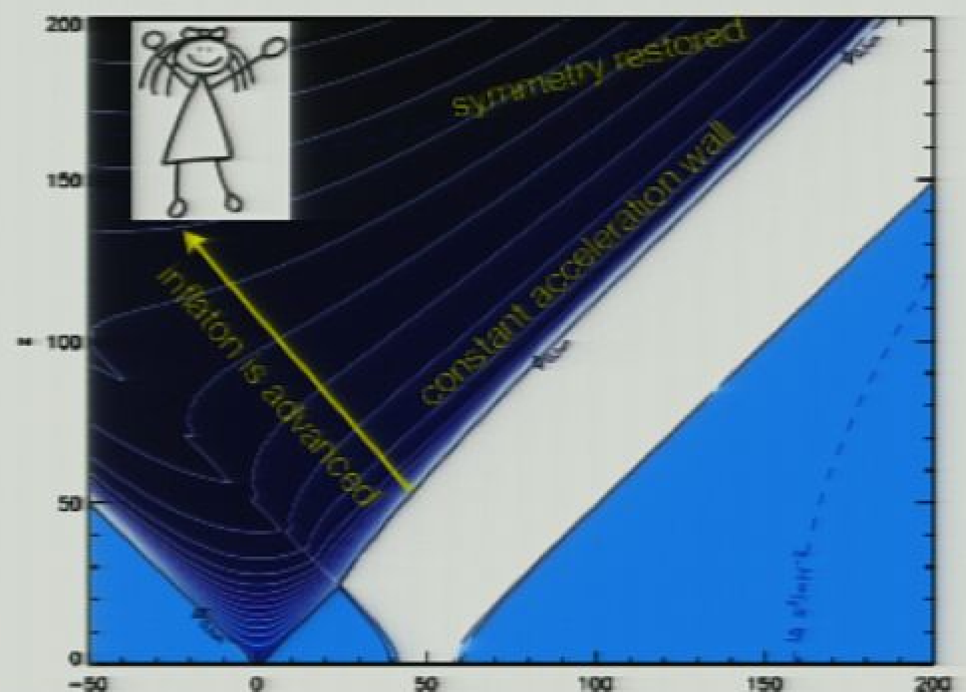

Theory

- Assessing the details of this story has been the topic of many papers:

Aguirre, Chang, Czech, Dahlen, Easther, Garriga, Giblin, Guth, Hui, Kleban, Larjo, Levi, Lim, Nicolis, Sigurdson, Shomer, Tysanner, Vilenkin......

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  - Possible outcomes of collisions.
  - Model building to see in what cases we get observable collisions.
  - Simulations of bubble collisions.
  - The exact imprint left in the CMB.

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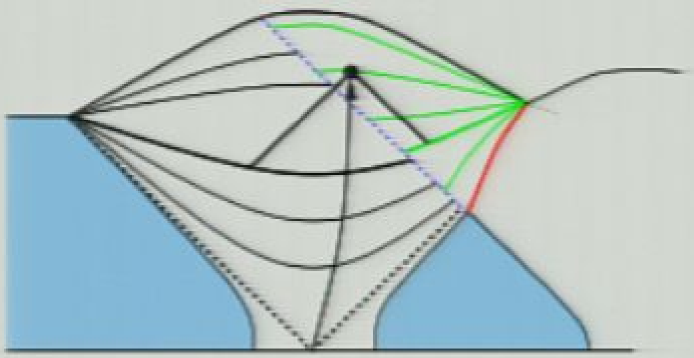
- For this talk: What is a good guess for the signature? How might we look for signatures of this type?

Observational effects



- At last scattering, there will be a causal boundary for the collision.

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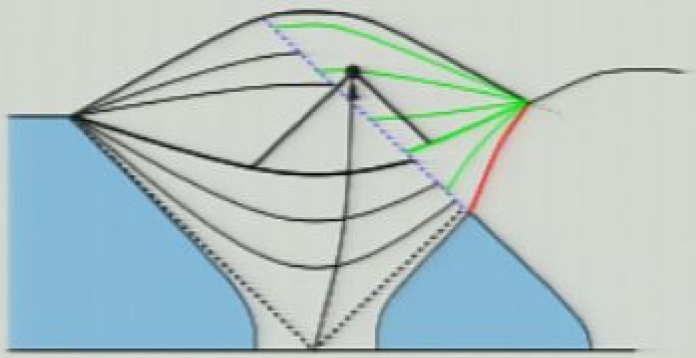

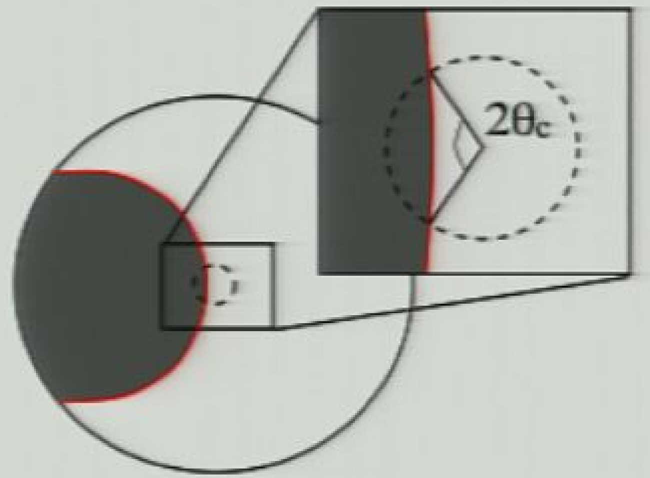

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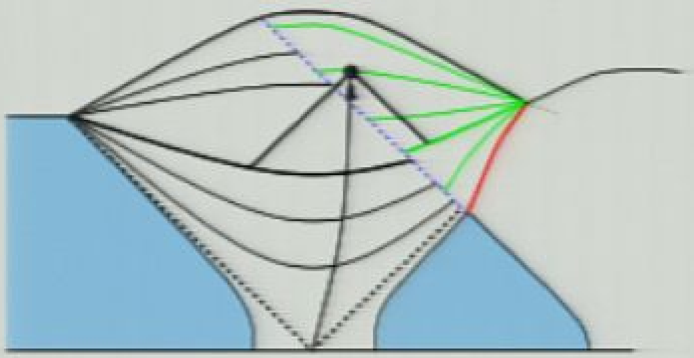

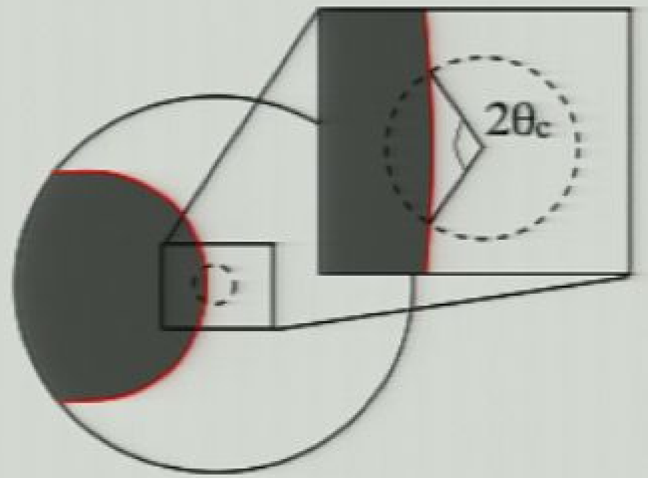

- At last scattering, there will be a causal boundary for the collision.
- A collision has approximate planar symmetry in vicinity of our PLC.
- A collision will have azimuthal symmetry on the CMB sky.

Observability

- Assume that the inflationary fluctuations are modulated by the collision:

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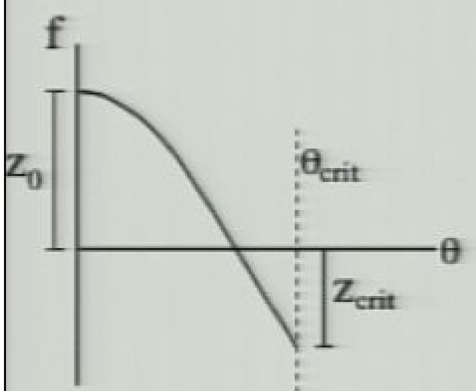

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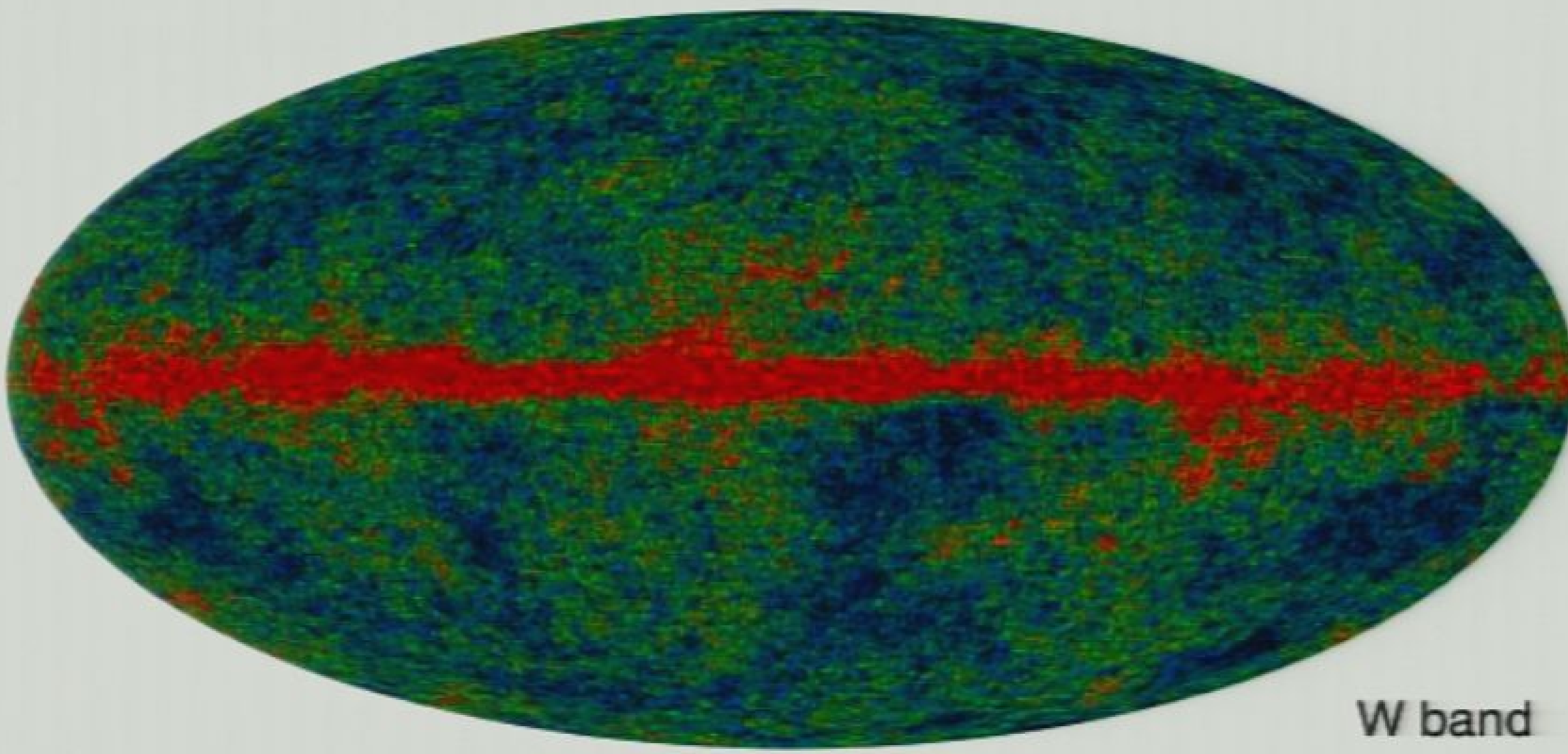

n a perfect world....

- The optimal way to test the hypothesis that there might be bubble collisions on the CMB sky: Bayesian model selection.
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$$\frac{P(M_\mathrm{b}|\mathbf{d})}{P(M_0|\mathbf{d})} = \frac{P(M_\mathrm{b})}{P(M_0)} \frac{P(\mathbf{d}|M_\mathrm{b})}{P(\mathbf{d}|M_0)} \qquad \rho \equiv \frac{P(\mathbf{d}|M_\mathrm{b})}{P(\mathbf{d}|M_0)}$$

model prior — evidence — evidence ratio

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model parameters

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data model covariance

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    - Azimuthal symmetry
    - Causal boundary
    - long-wavelength modulation inside a disc

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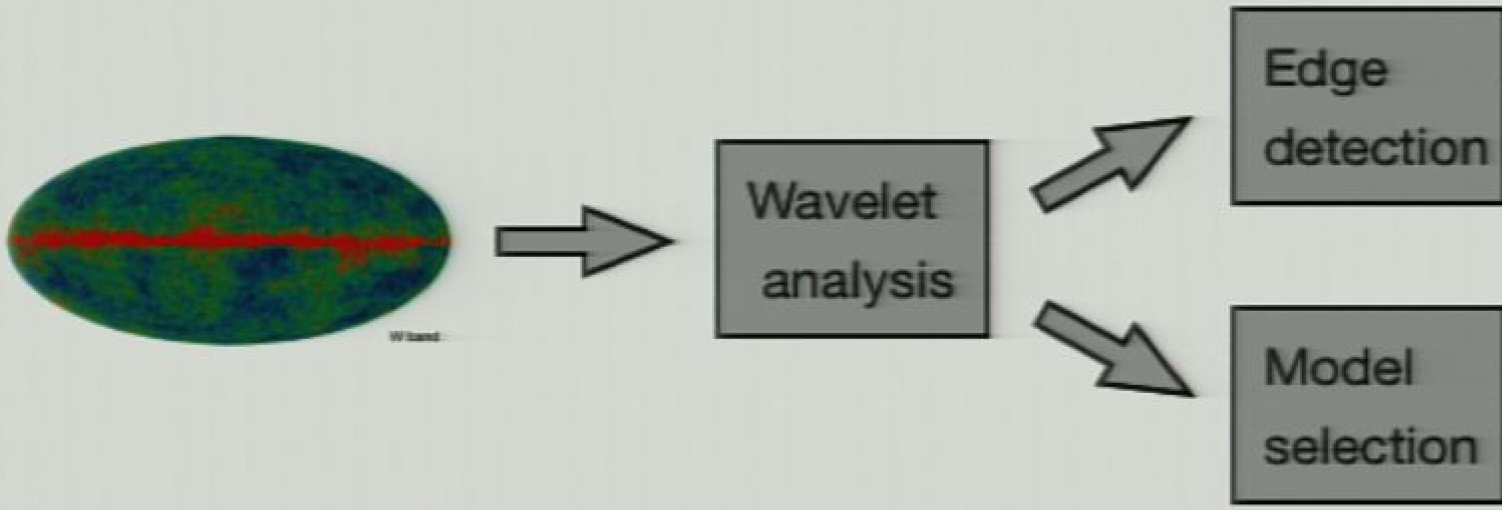
- Our targets:
  - Azimuthal symmetry
  - Causal boundary
  - long-wavelength modulation inside a disc

- We use the following tools:
  - Wavelet analysis - good for picking out localized features.
  - Edge detection - sensitive to the causal boundary.
  - Model selection - sensitive to the postulated form of the modulation.

n a not-so perfect world....

- What about isolating the most promising candidate signatures?
- Important to do a blind analysis to avoid a posteriori choices!

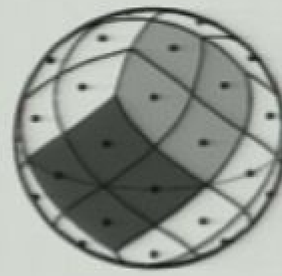


- Our pipeline is fully automated.
- We calibrate it with simulations and freeze all free parameters before looking at real data.

- Now to describe the steps......

Wavelet analysis

- Wavelets: a way to pick out localized features of varying angular scale.
- Real data is given on a pixelated sphere:



pixels labeled by integer k

- We use the "spherical needlet transform"

$$T(\hat{\gamma}) = \sum_{j,k} \beta_{jk}\psi_{jk}(\hat{\gamma}) \qquad \beta_{jk} = \int T(\hat{\gamma})\psi_{jk}(\hat{\gamma})d\Omega.$$

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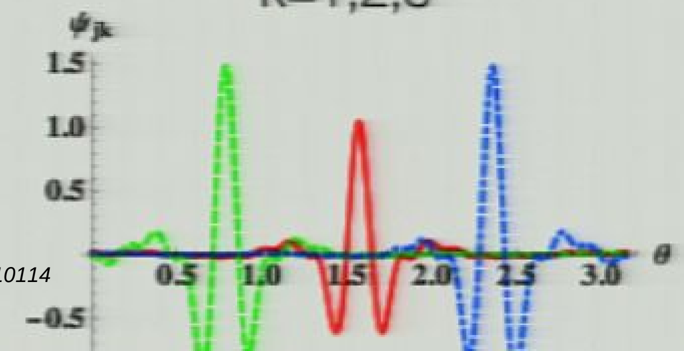
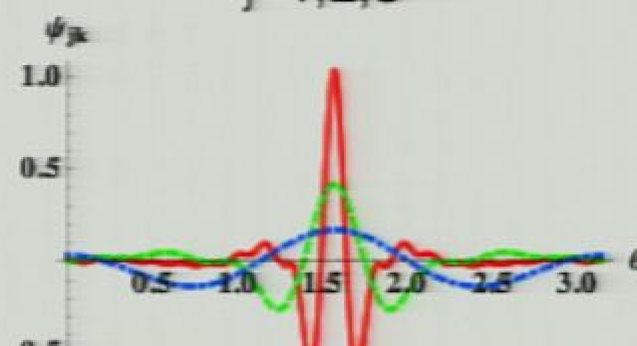
k=1,2,3



j=1,2,3



Assess the significance

- For a gaussian CMB on a full sky without noise we expect:

$$< \beta_{jk} >= 0 \qquad < \beta_{jk}^2 >= \sum_l f(l,j) C_l$$

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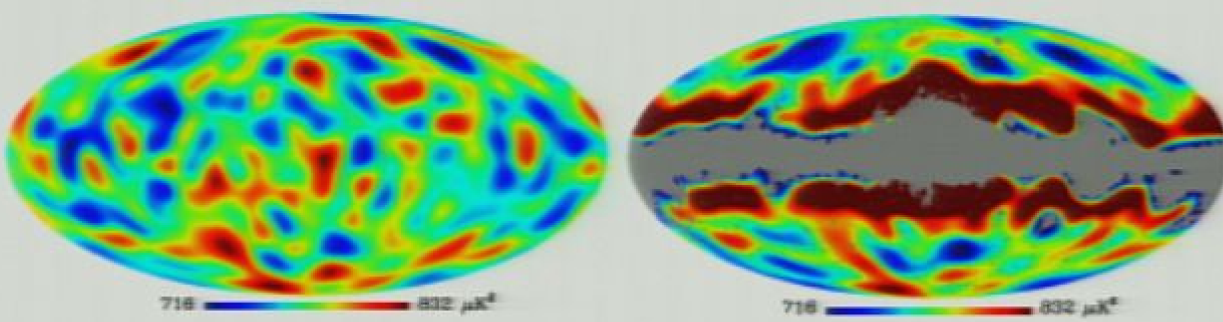
- On a cut sky with noise, there is a mildly biased variance and mean:



(variance from 1000 gaussian realizations)

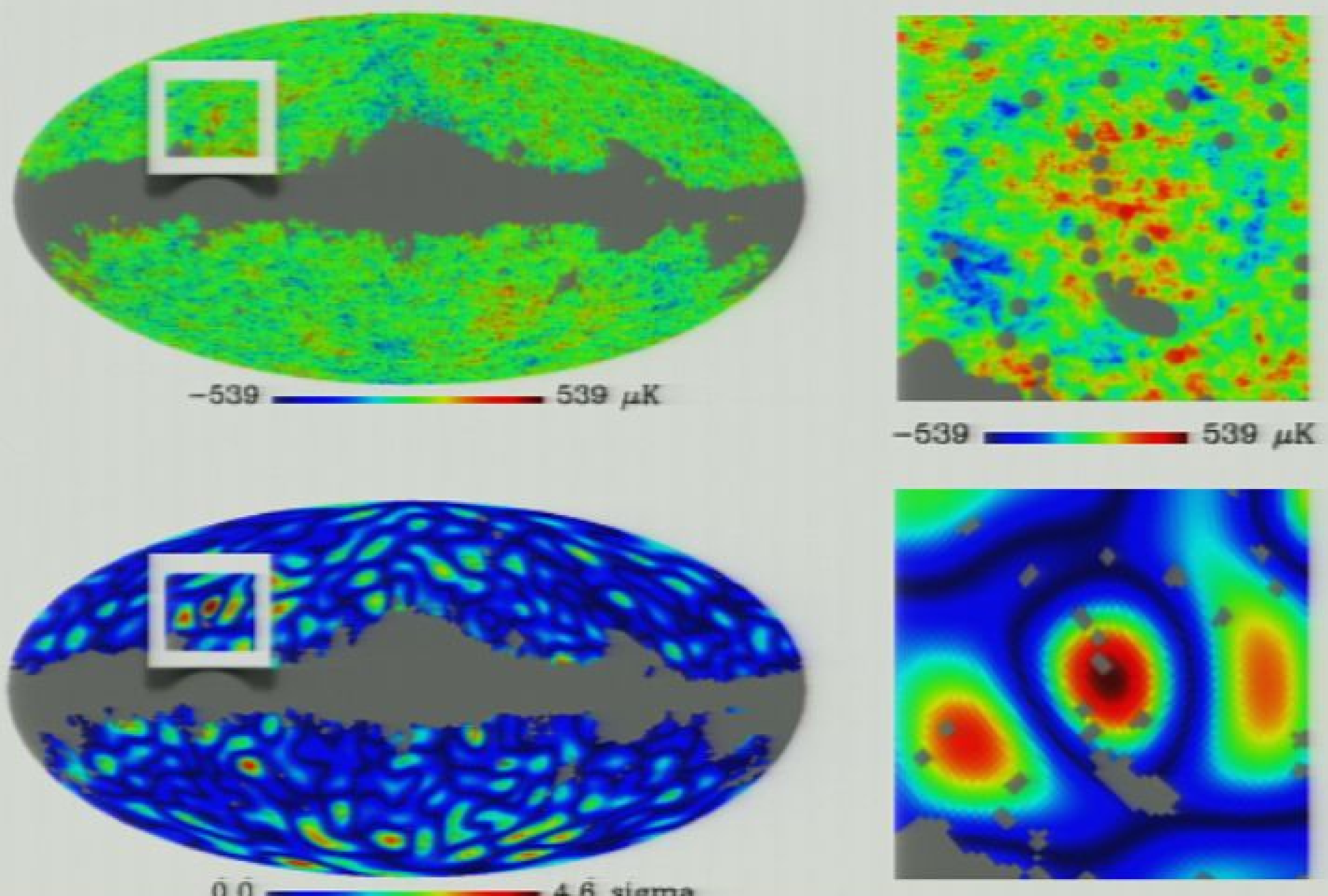
- So, define an unbiased statistic....

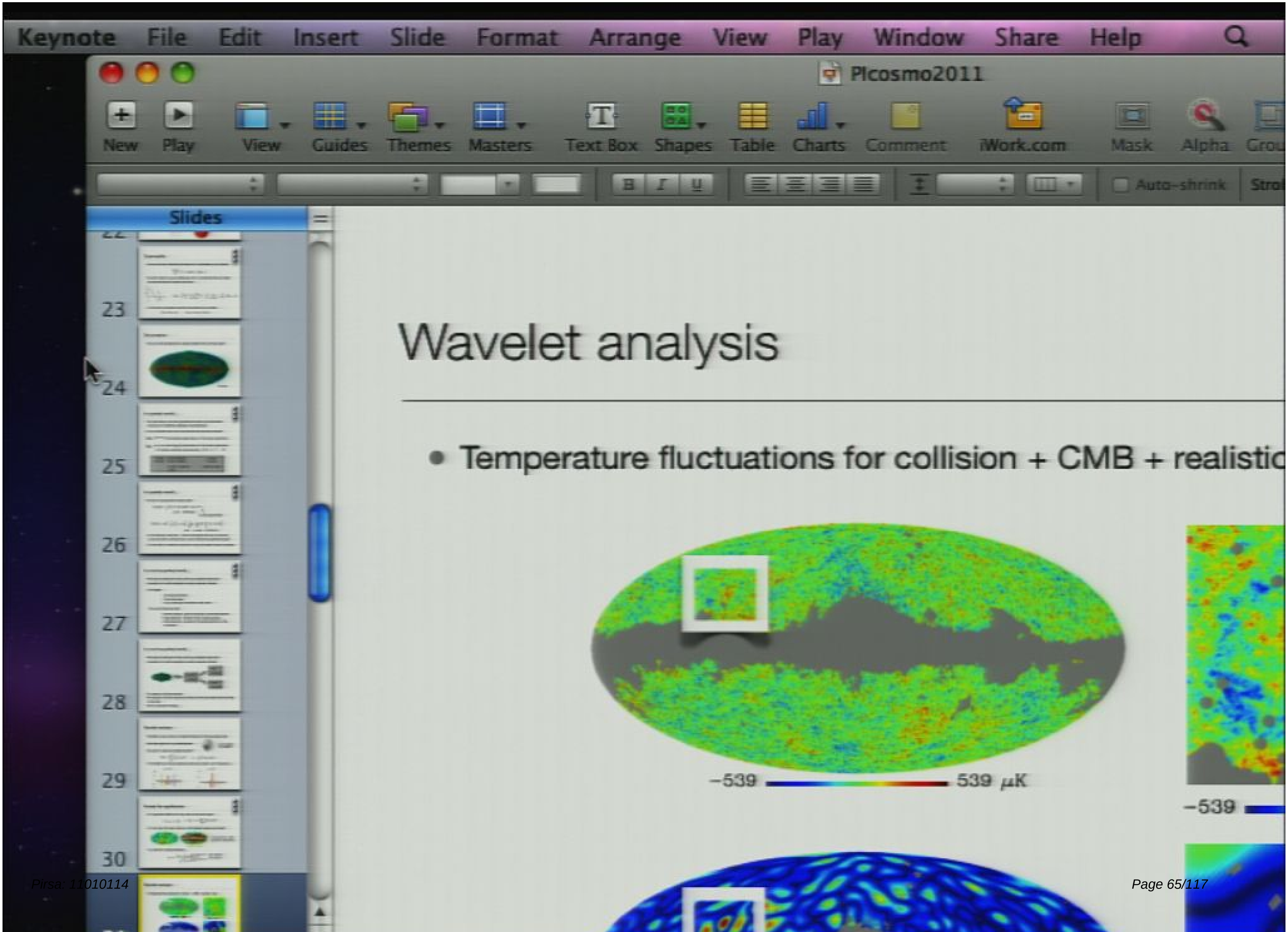
$$S_{jk} = \frac{|\beta_{jk} - \langle \beta_{jk} \rangle_{\mathbf{gauss,cut}}|}{\sqrt{\langle \beta_{jk}^2 \rangle_{\mathbf{gauss,cut}}}}$$

Calculated from sims

Wavelet analysis

- Temperature fluctuations for collision + CMB + realistic noise:

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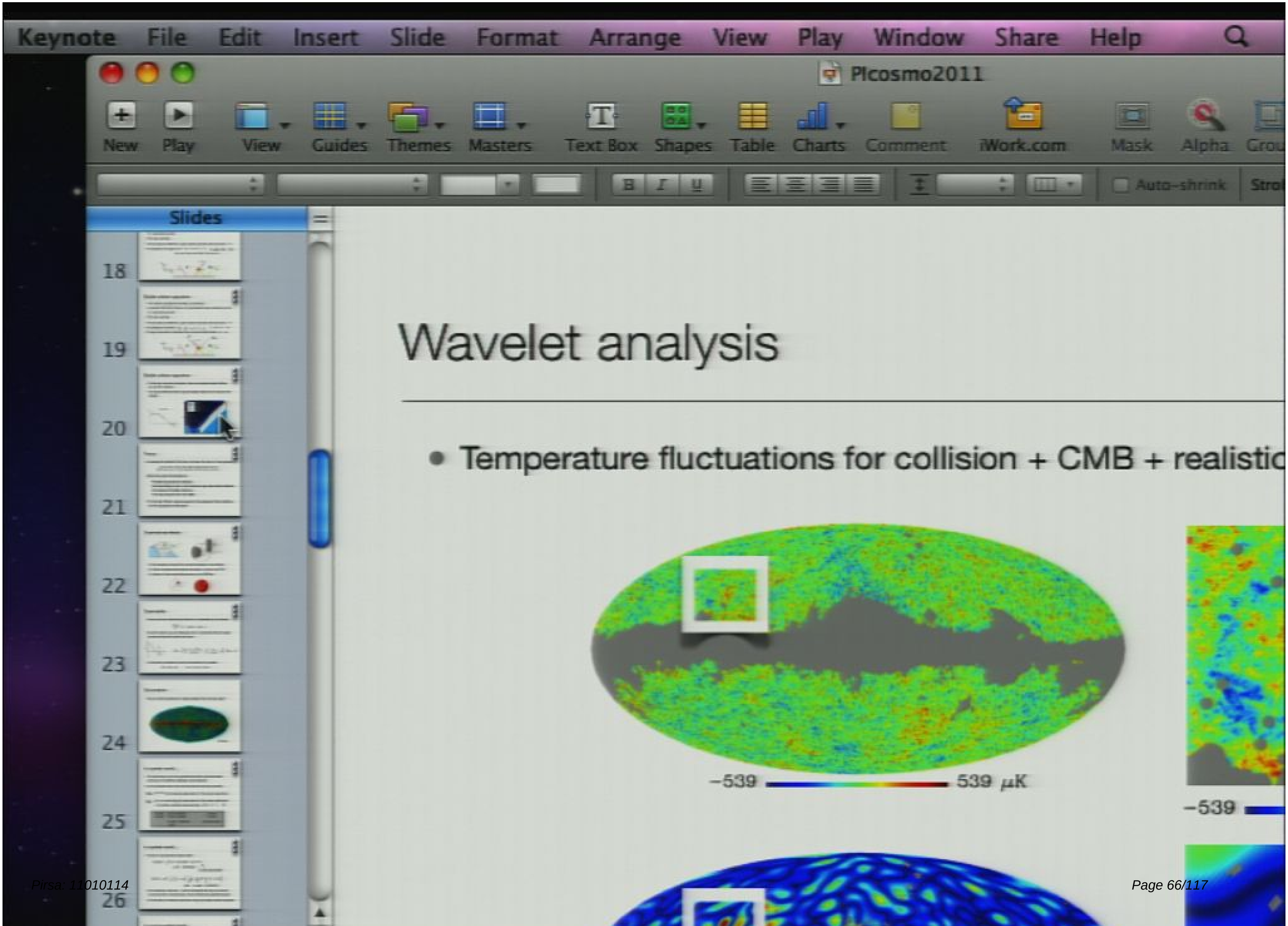
Auto-shrink
Slides
Wavelet analysis
Temperature fluctuations for collision + CMB + realistic
−539 539 μK
−539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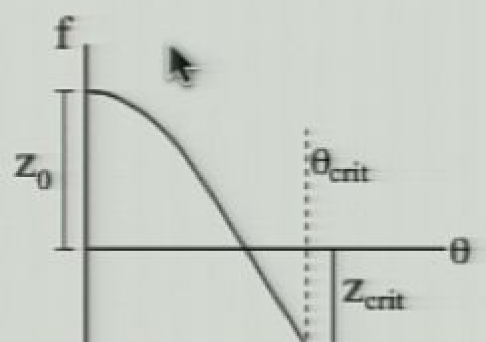

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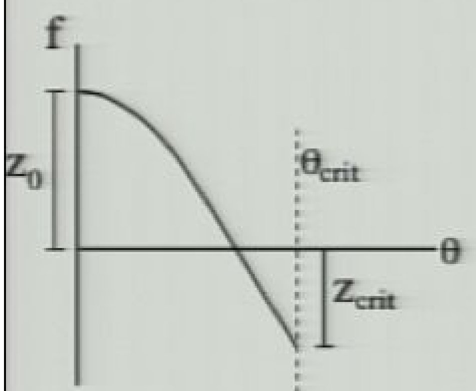

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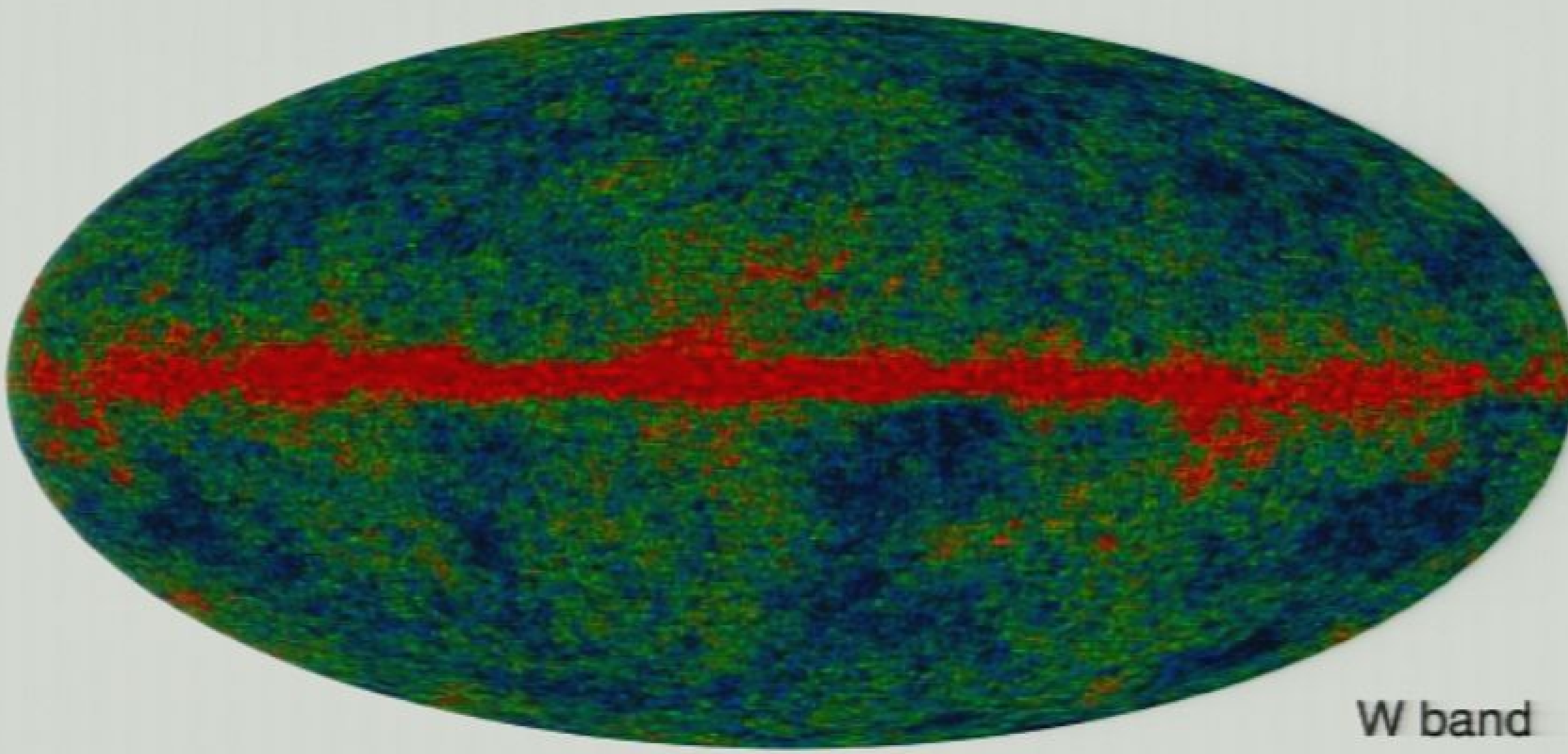

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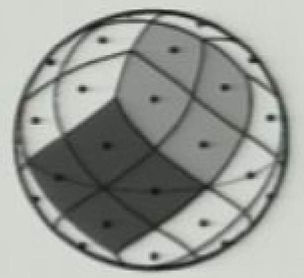

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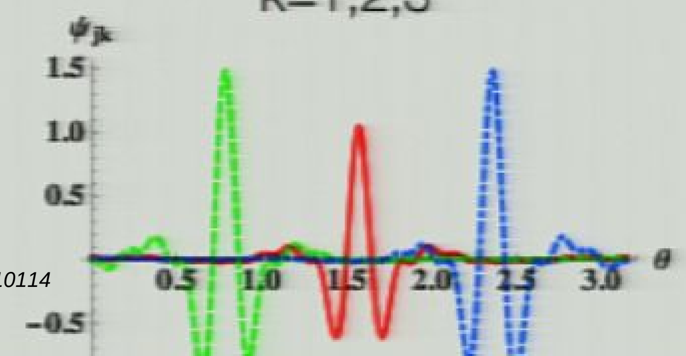

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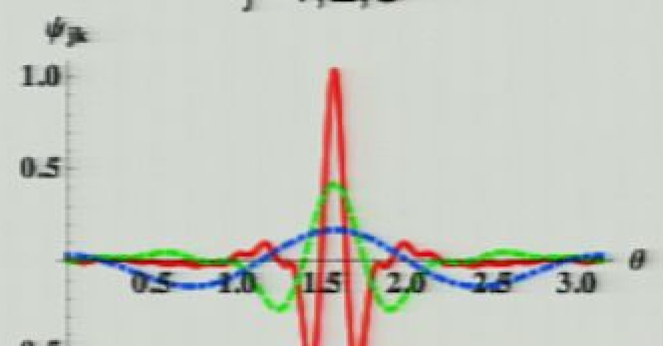

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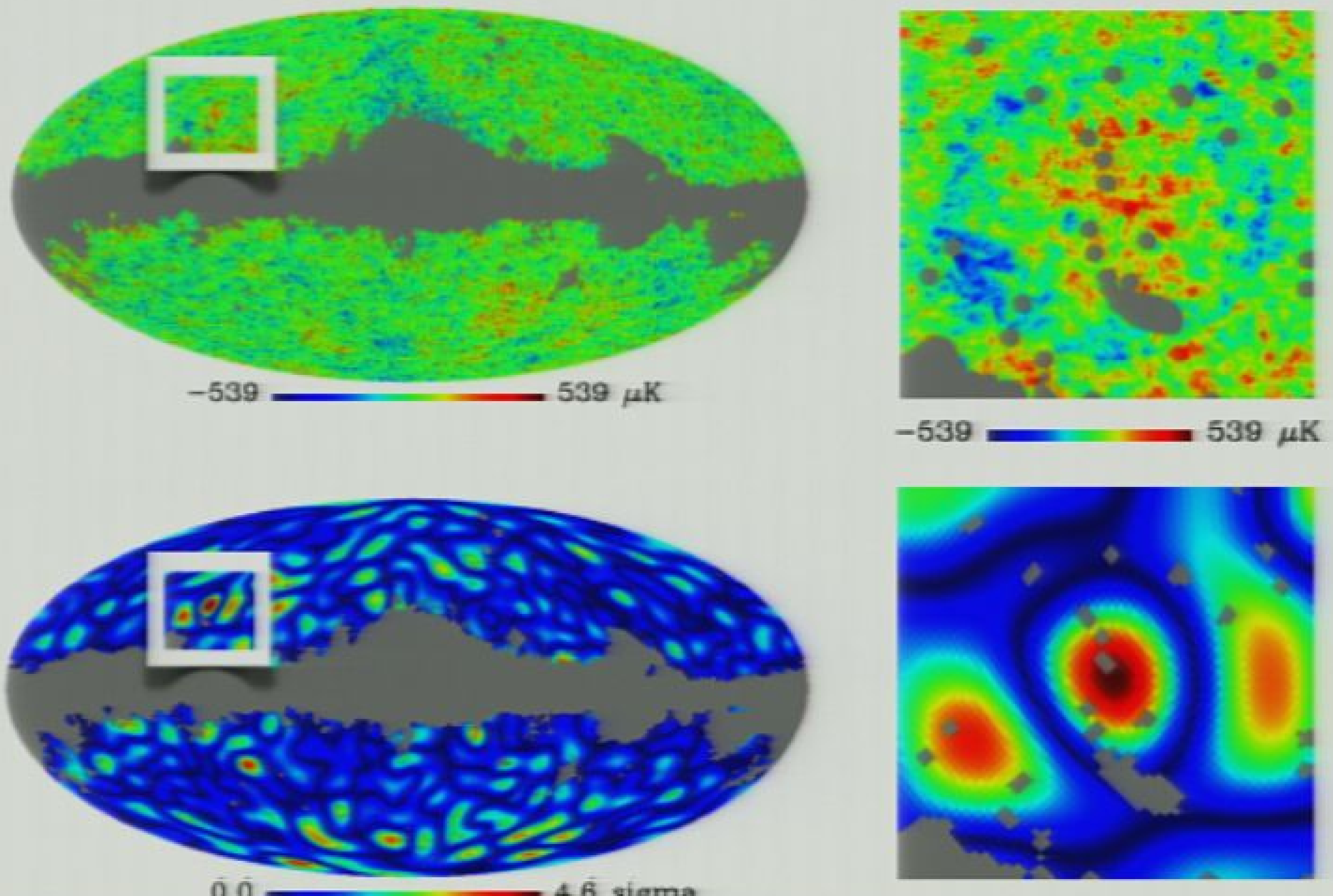
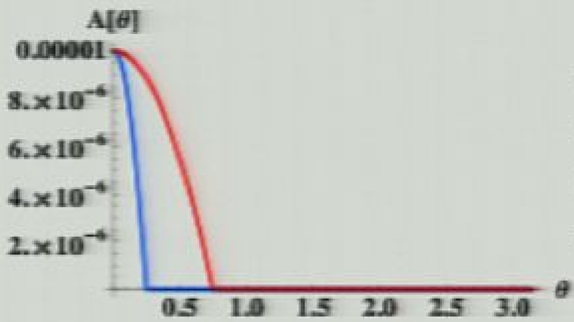
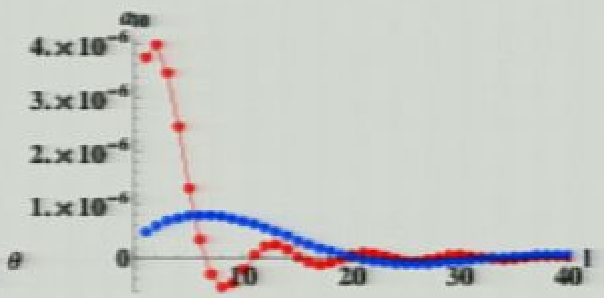


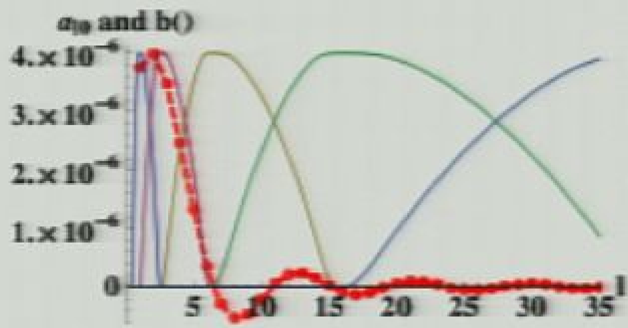
Wavelet analysis

- For our collision templates:

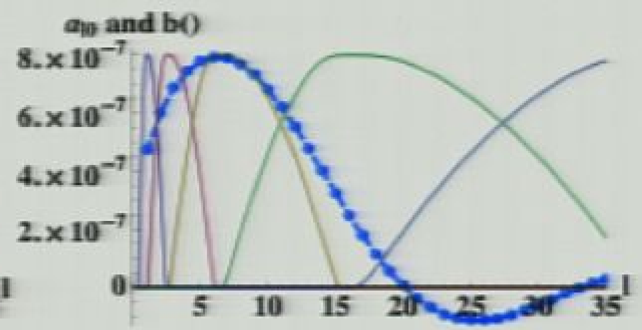




- The needlets are most sensitive to a collision of a given angular scale at some j.



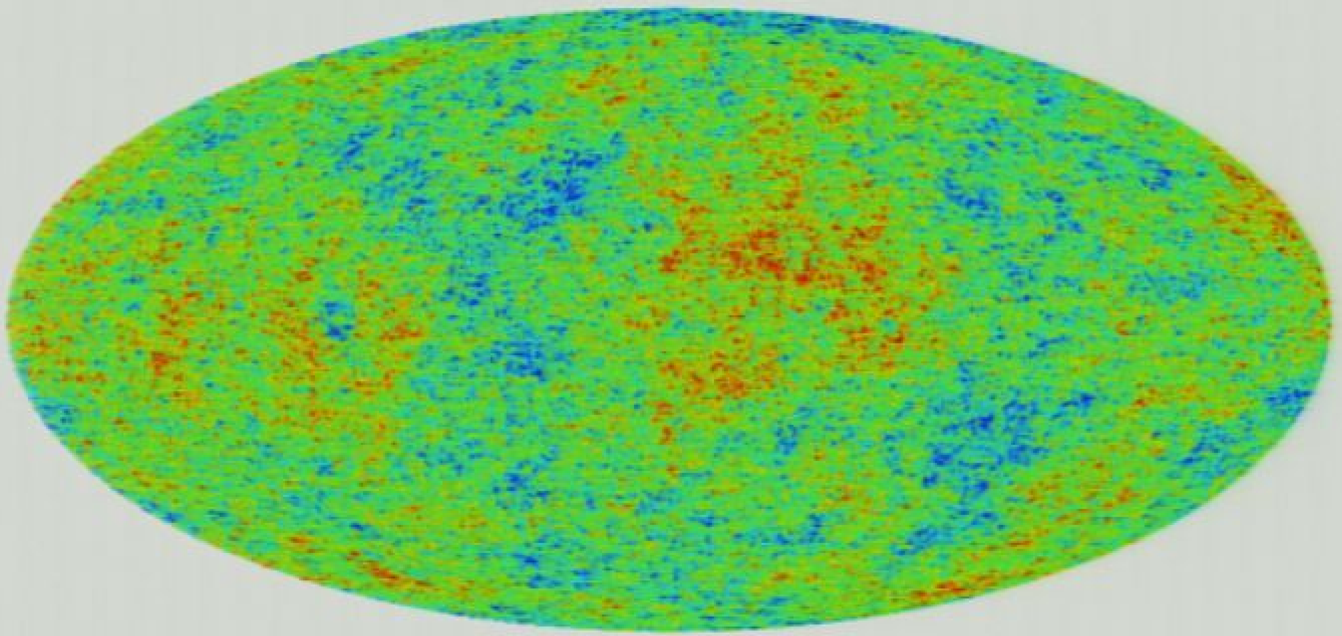
peaks at j=2



peaks at j=3

- Can learn about size of candidate feature from value of j at which you find a signal.

Wavelet analysis



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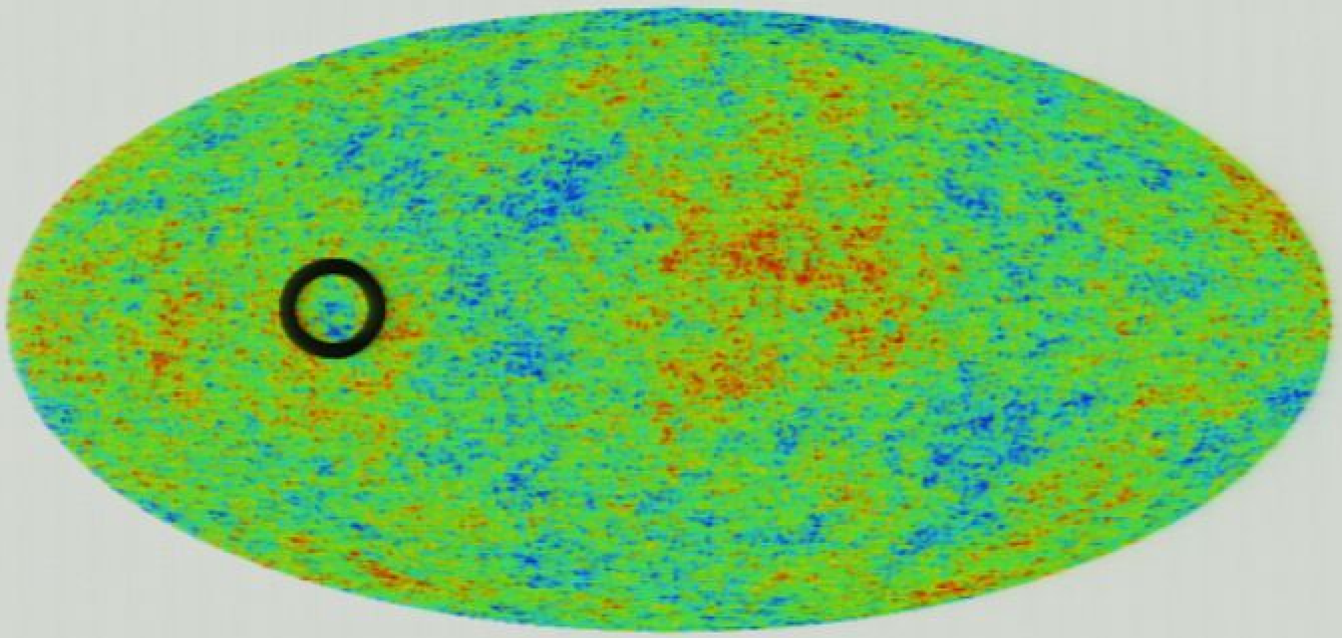

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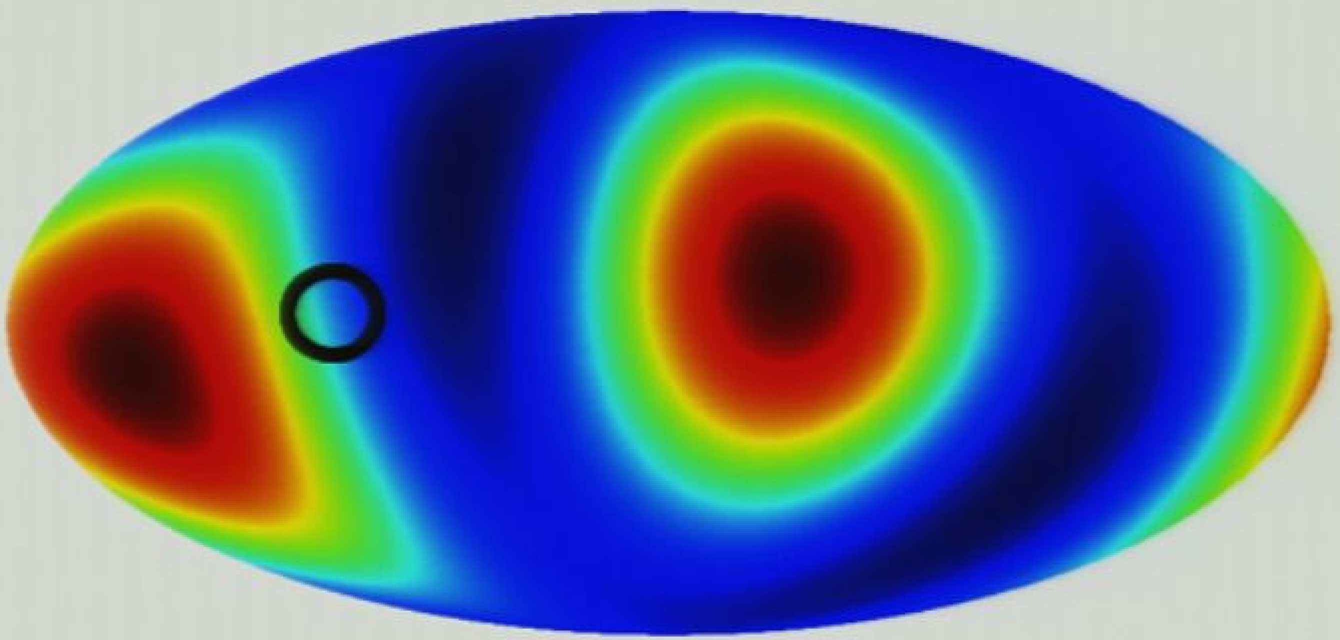
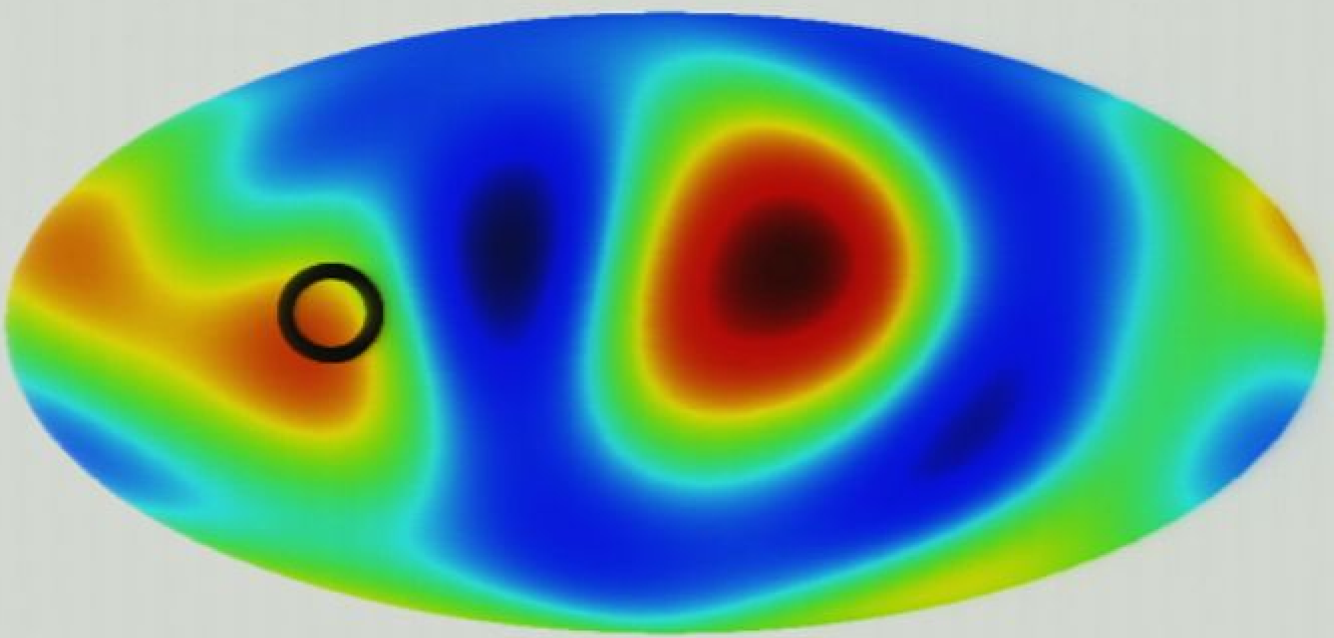


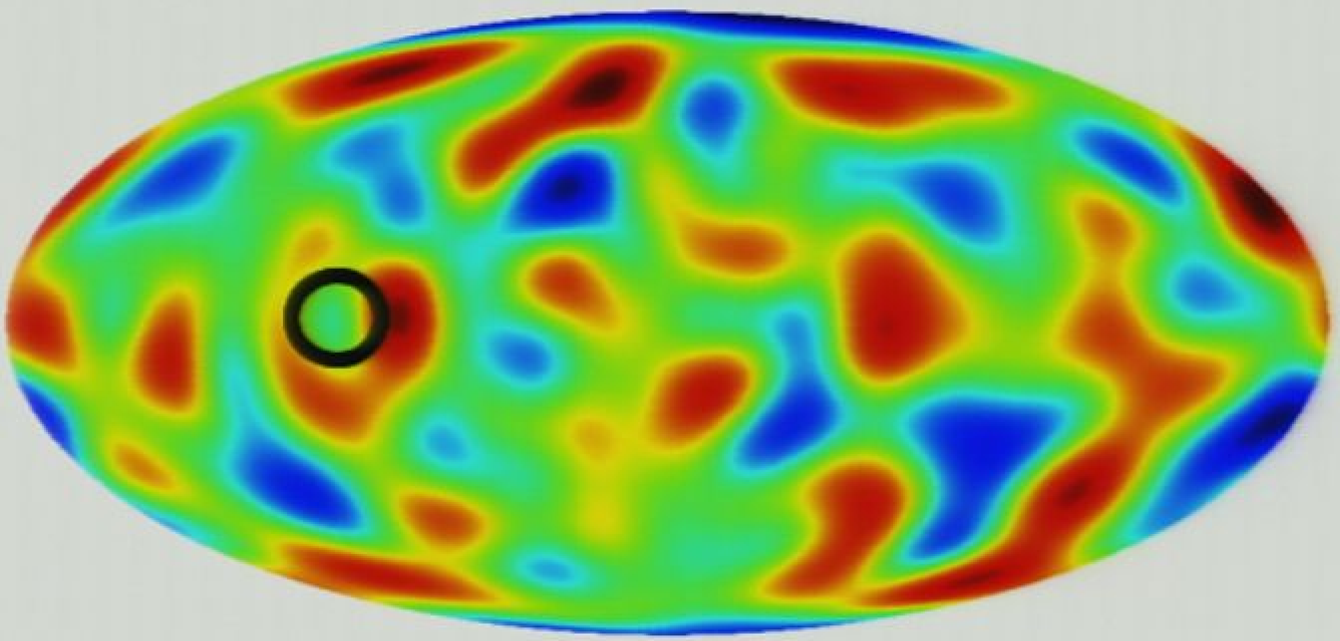
j=0

Wavelet analysis



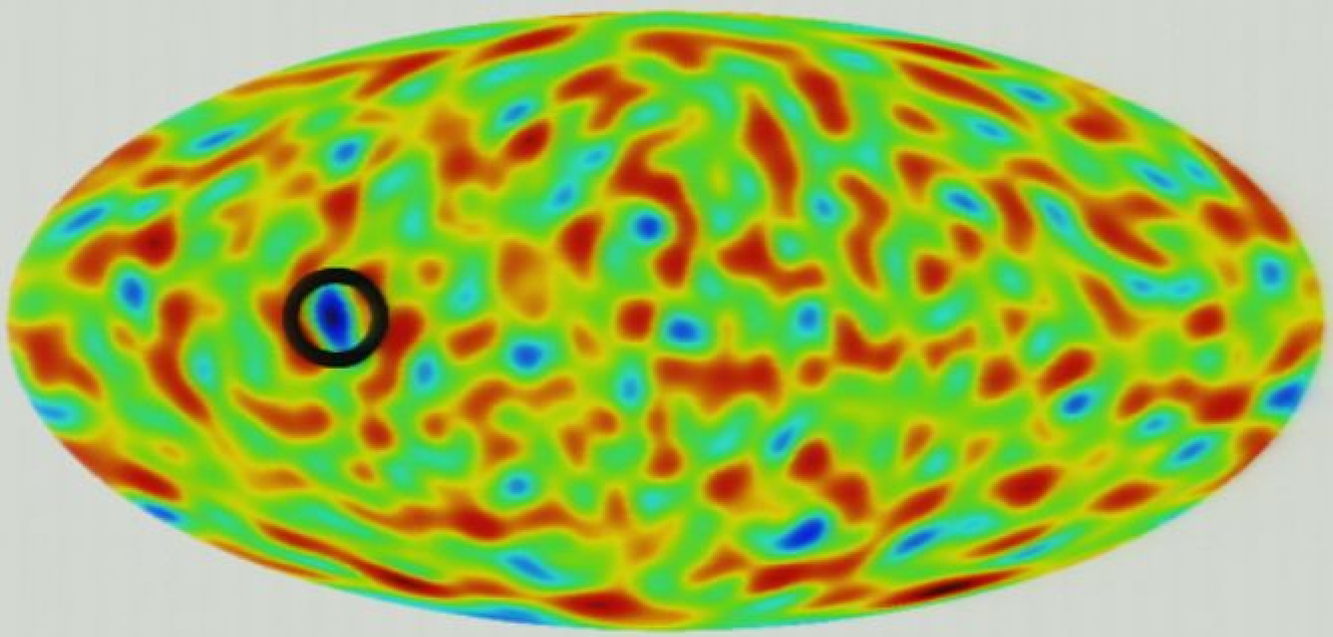
j=1

Wavelet analysis



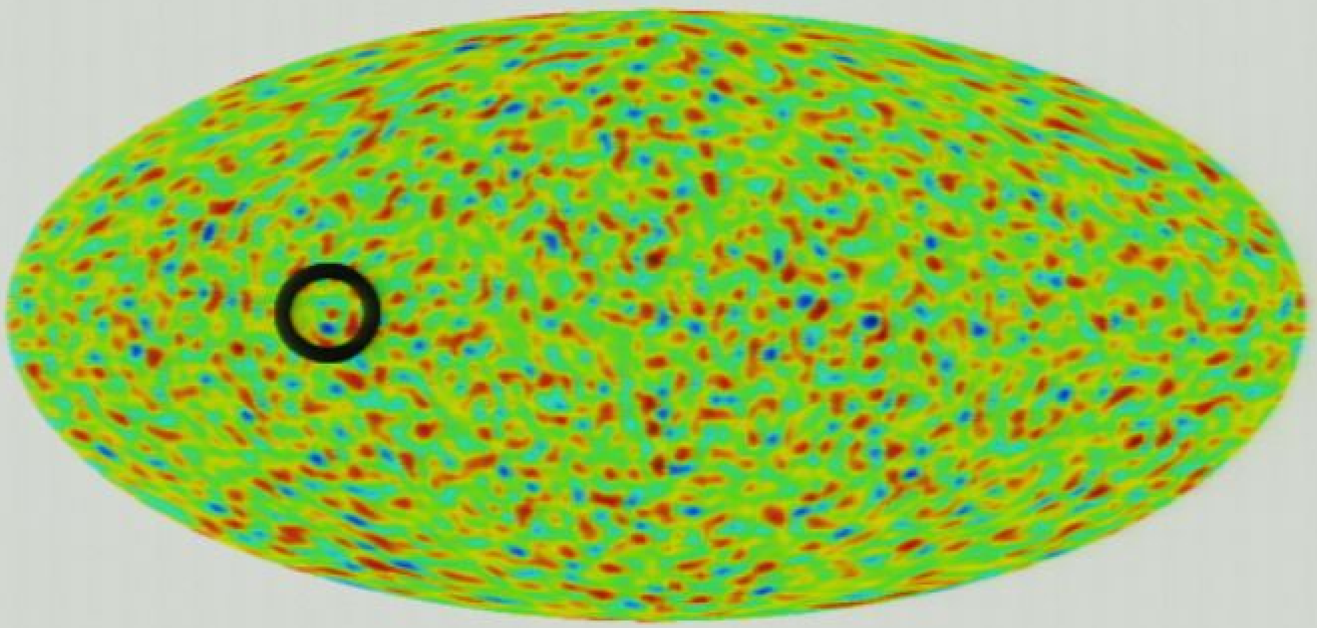
j=2

Wavelet analysis



j=3

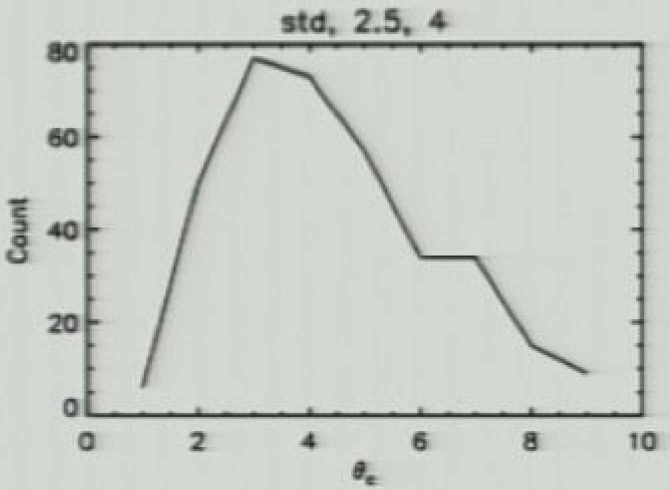
Wavelet analysis



j=5

Wavelet analysis

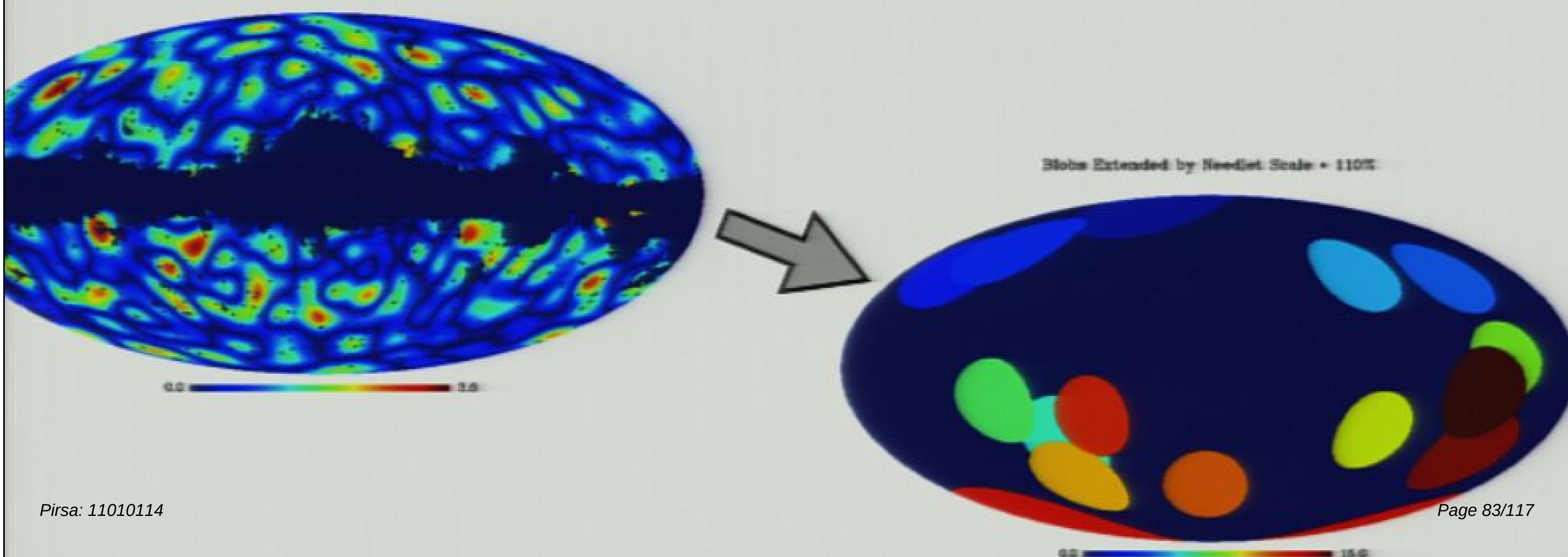
- Sampling many templates, we define a range in possible disc sizes for each needlet frequency.



j	$\theta_{\rm crit,min}$	$\theta_{\rm crit,max}$
0	60°	90°
1	33°	71°
2	12°	32°
3	5°	14°
4	2°	5°
5	1°	2°

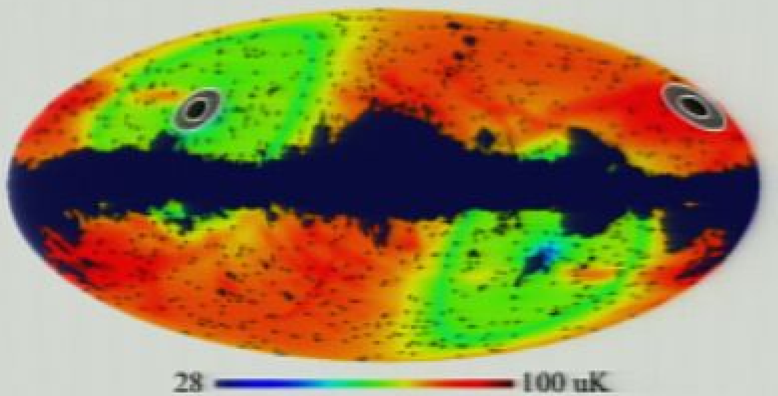
Blobs

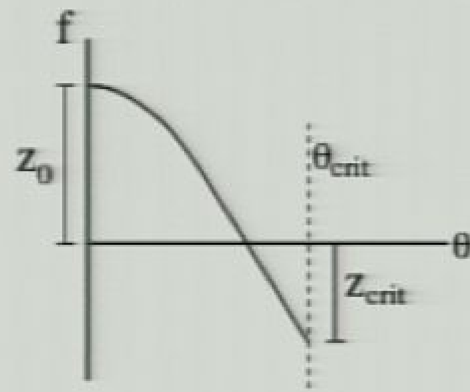
- Define a significance threshold from a bubble-free end-to-end simulation of the experiment - controls for systematics and quantifies expected signals.
- Use needlet information to segment the CMB sky into ``Blobs.”
- Repeat for a variety of needlet shapes.



Simulations

- Does this method work to find bubble collisions?





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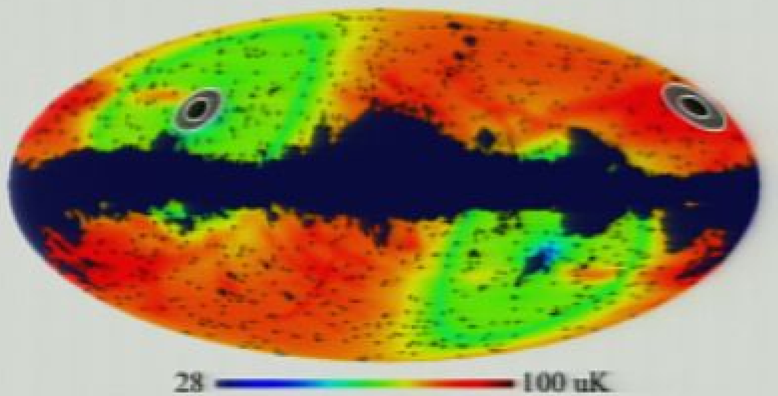
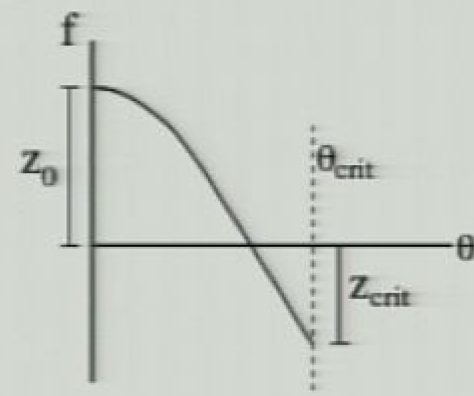
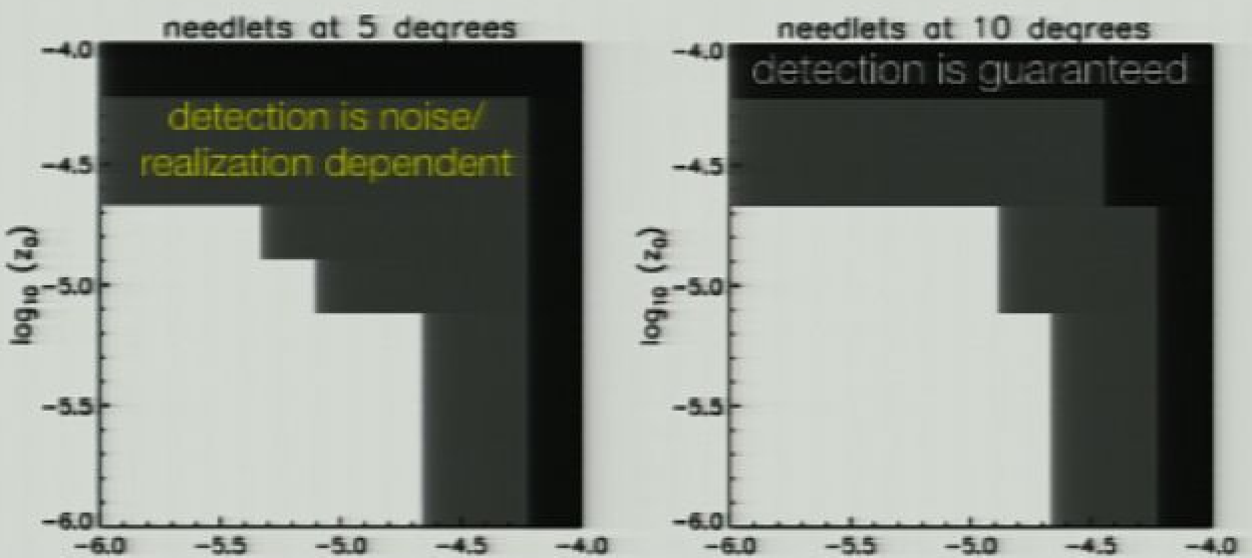
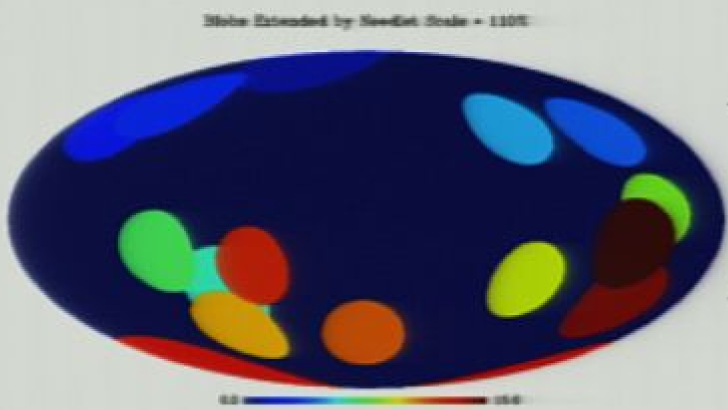






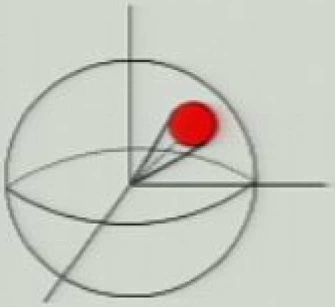
Next steps....



Edge detection

Model selection

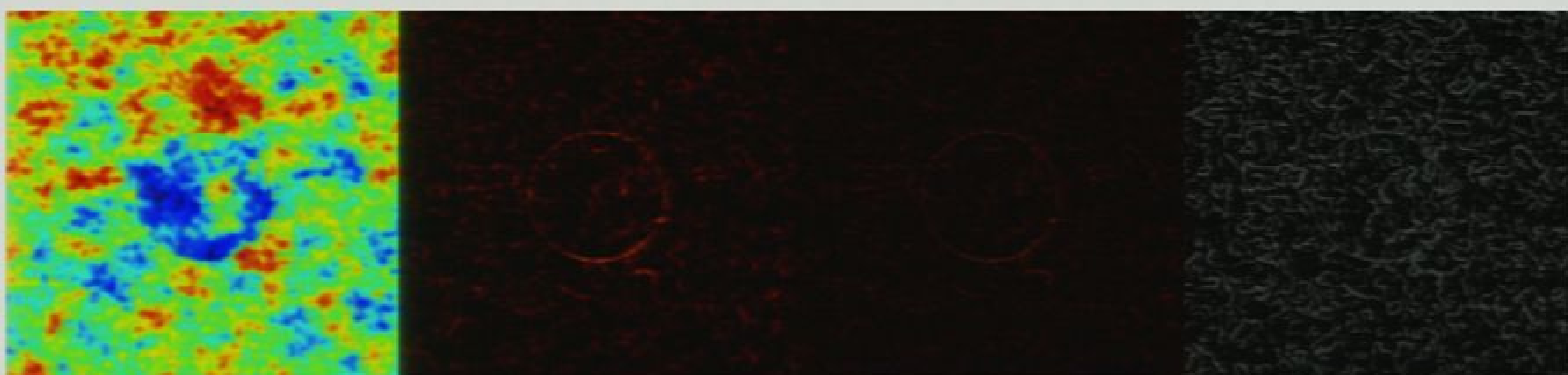
Edge detection



- The causal boundary can form a detectable edge in the temperature field and its derivatives.

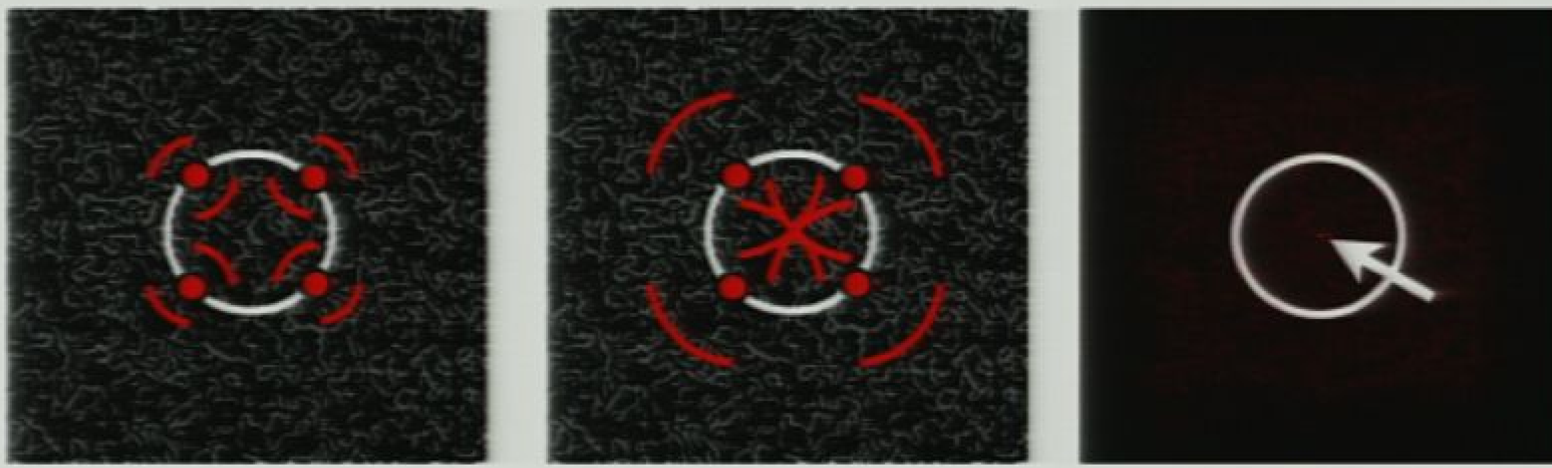
- Detection schemes similar to those used in searches for cosmic strings.
- The Canny algorithm:

Amsel, Berger, Brandenburger, Danos



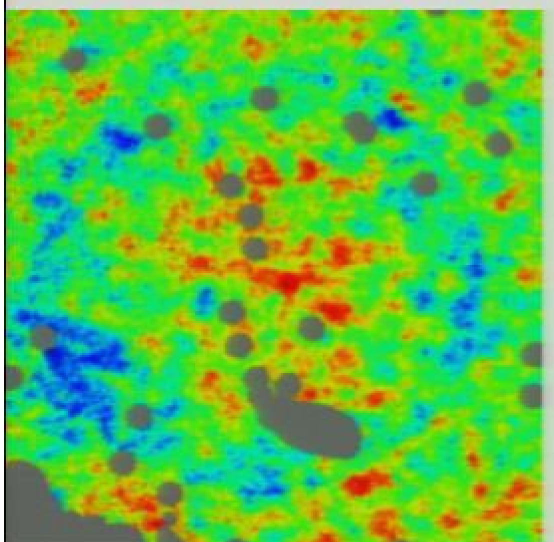
Edge detection

- To find circular edges, we apply the Circular Hough Transform (CHT):



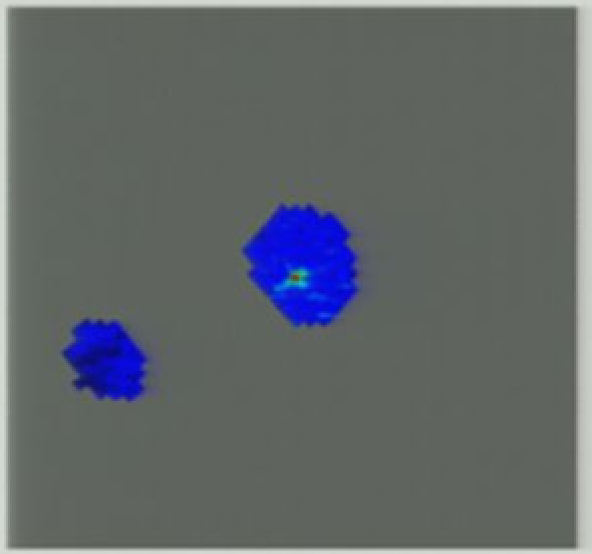
$$\text{CHT Score} = \frac{N_{\mathbf{hits}}}{\theta_{\mathbf{circ}}}$$

Edge detection



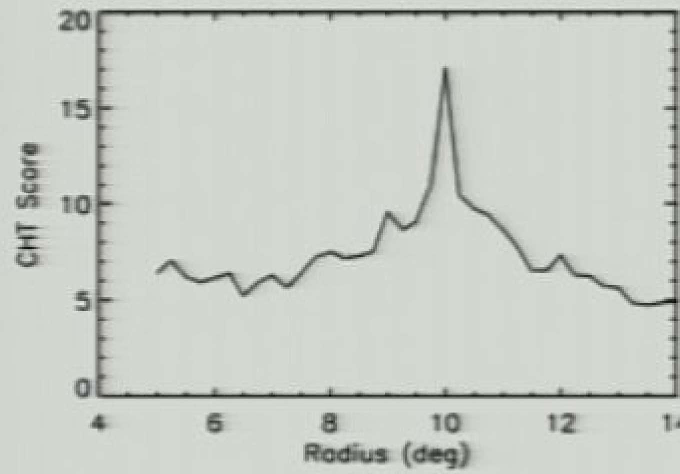
539 539 μK

10° collision



0.3 17.1

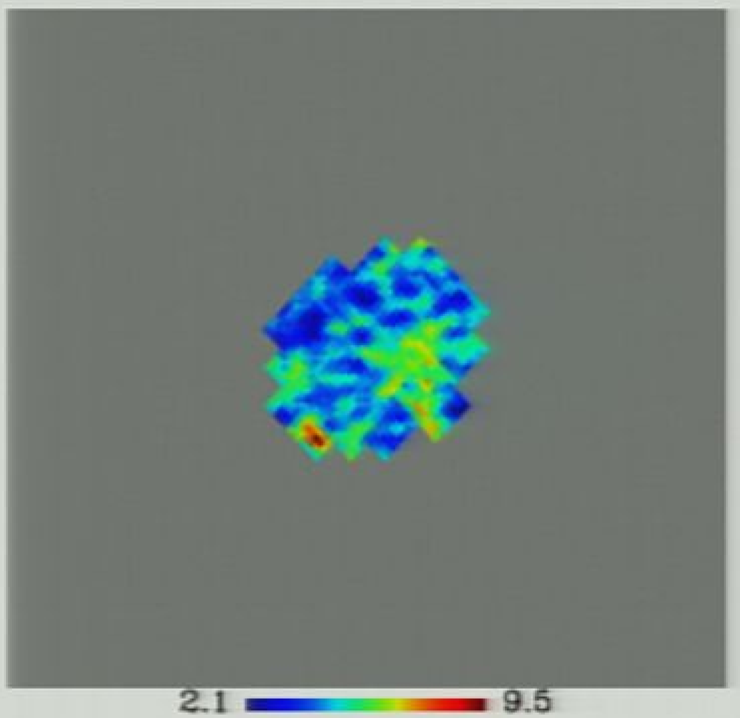
CHT Score 10°

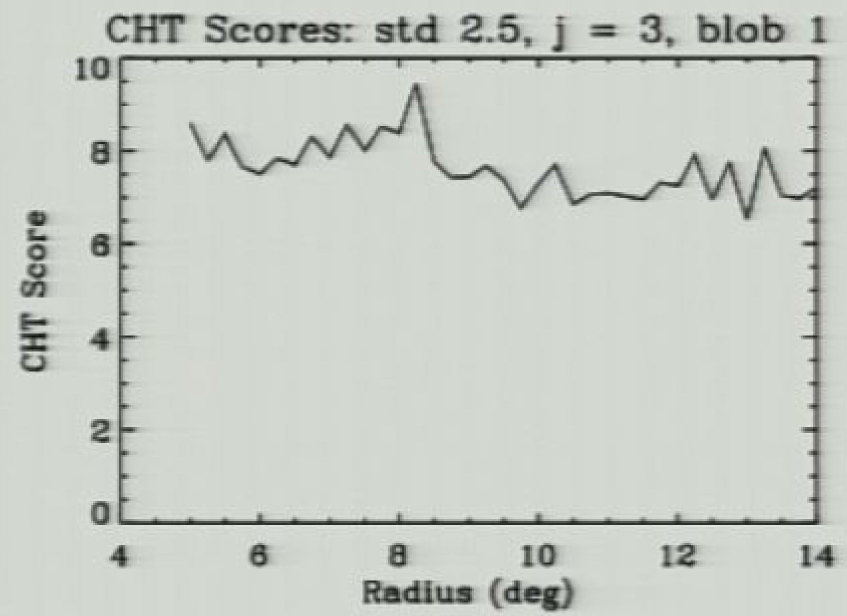


global max CHT score

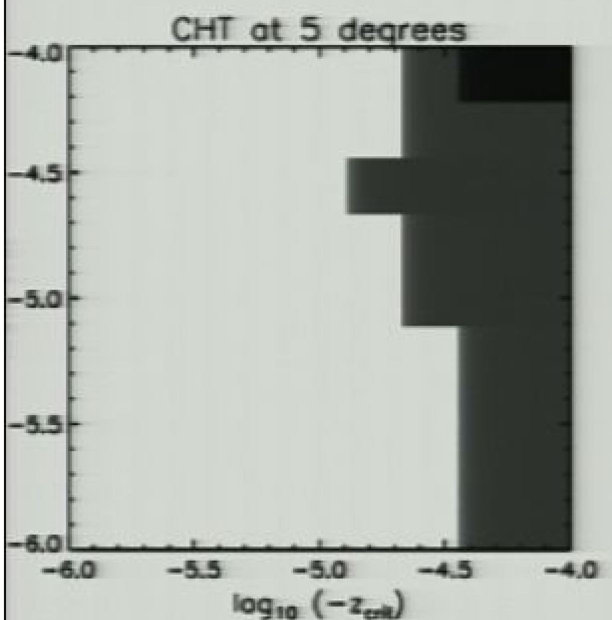
Edge detection

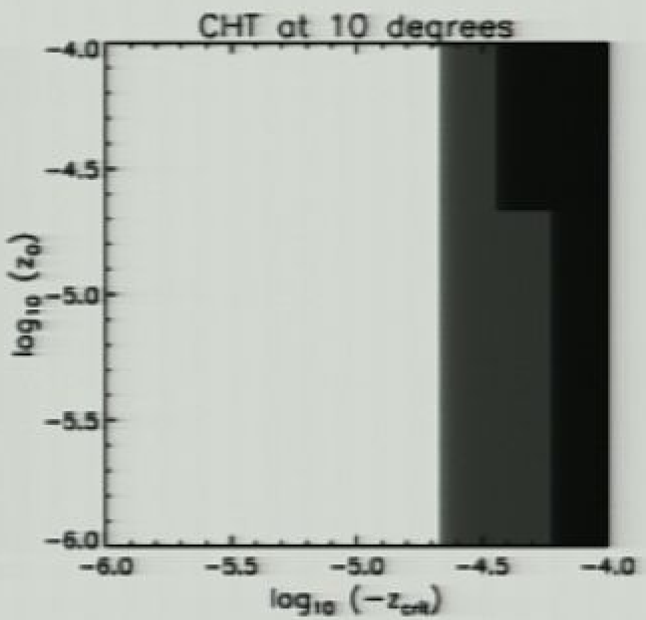
"peakiest" example from the end-to-end sim:

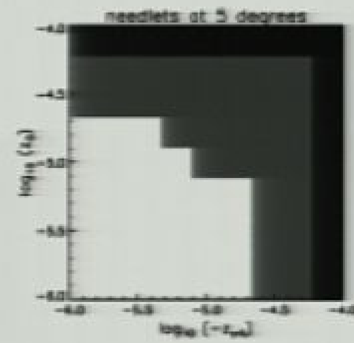


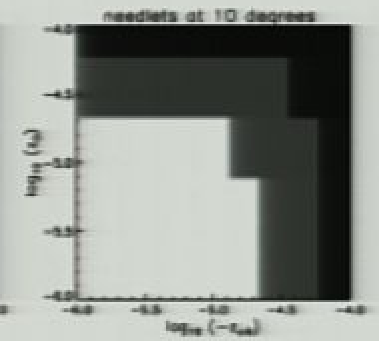


Sims









- For small collisions, the ~1 degree blobs in the CMB affect performance.

Model selection

- For each blob, compute the evidence ratio: $\rho \equiv \frac{P(\mathbf{d}|M_{\mathrm{b}})}{P(\mathbf{d}|M_0)}$

$$P(\mathbf{d}|M) = \int P(\mathbf{\Theta}, M) P(\mathbf{d}|\mathbf{\Theta}, M)\, \mathrm{d}^n\mathbf{\Theta}$$

$$P(\mathbf{d}|\mathbf{\Theta}) \propto \exp\left(-\frac{1}{2}\chi^2\right) = \exp\left\{-\frac{1}{2}[\mathbf{d} - \mathbf{t}(\mathbf{\Theta})]^{\mathrm{T}}\mathbf{C}^{-1}[\mathbf{d} - \mathbf{t}(\mathbf{\Theta})]\right\}$$

$$\Theta = \{\theta_0, \phi_0, z_{\mathrm{crit}}, z_0, \theta_{\mathrm{crit}}\}$$

noise and cosmic variance

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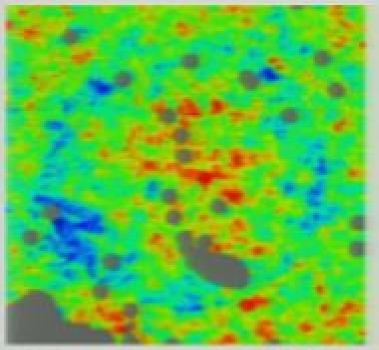
noise and cosmic variance

- Computationally limited to use data from regions of diameter $\leq 22^\circ$
- We use flat priors for all parameters.
- Priors on $\{\theta_0, \phi_0, \theta_{\mathrm{crit}}\}$ are set by the needlet step.
- Priors on $\{z_0, z_{\mathrm{crit}}\}$ are set by the amplitude of fluctuations in the CMB.

Model selection



$z_0 \times 10^5$	$z_{\rm crit} \times 10^5$	$\theta_{\rm crit}$	θ_0	ϕ_0
5.0	−5.0	10.0	57.7	99.2
$5.2^{+1.0}_{-1.0}$	$-5.0^{+0.3}_{-0.3}$	$10.0^{+.002}_{-.002}$	$57.7^{+0.00}_{-0.00}$	$99.2^{+0.00}_{-0.00}$

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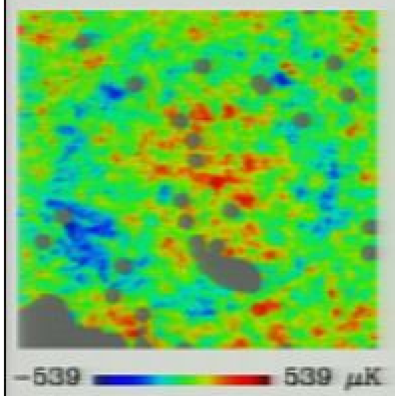

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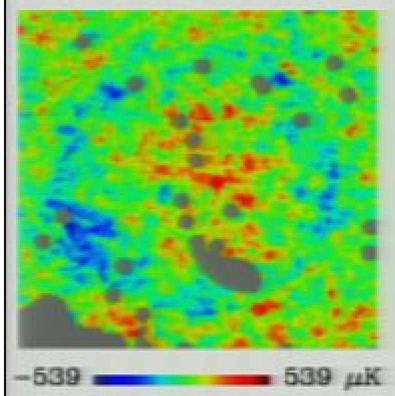
$$\ln \rho = 127.9 \pm 0.3$$

- This is an overwhelmingly strong detection!

Model selection



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- This is an overwhelmingly strong detection!
- Running the whole pipeline on simulated bubble collisions:

The presence of an edge really helps!

$$\ln \rho \simeq 130 \longrightarrow \ln \rho \simeq 30$$

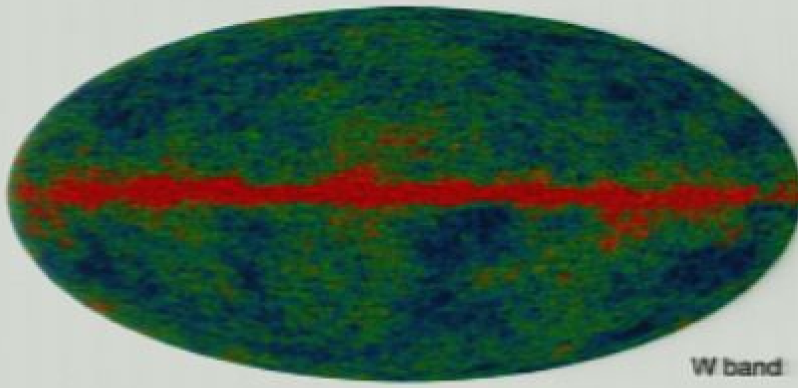
Model selection

- Running the whole pipeline on the end-to-end sim:

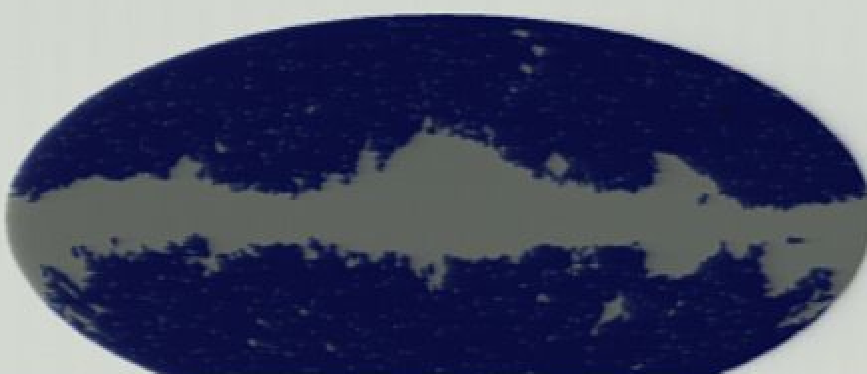
feature	blob	$\theta_{\rm crit}$ prior	$\log\rho$
1	1	$5-14$	1.5 ± 0.1
1	2	$6-12$	-0.02 ± 0.1
2	1	$10-21$	-0.04 ± 0.1
3	1	$6-12$	-0.8 ± 0.1
4	1	$6-12$	0.5 ± 0.1
4	2	$4-8$	2.6 ± 0.1
5	1	$3-7$	0.6 ± 0.1
9	1	$3-6$	1.8 ± 0.1

- For features on a scale larger than a few degrees, we shouldn't expect foregrounds or systematics to mimic a bubble collision.

WMAP 7 Year data



- We primarily use the W band (94 GHz), which has the highest resolution.
- Foregrounds are removed using the KQ75 mask (cuts ~30% of the sky).



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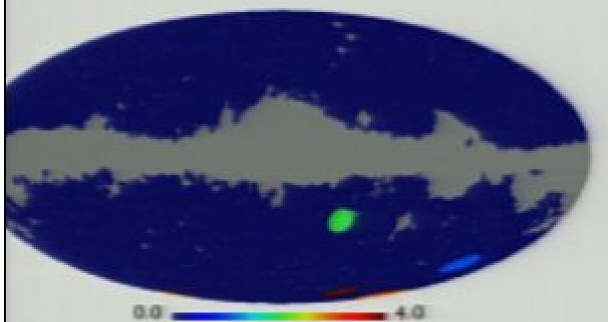
Four candidates consistent with bubble collisions



$$\log \rho = 4.8 \pm .2$$

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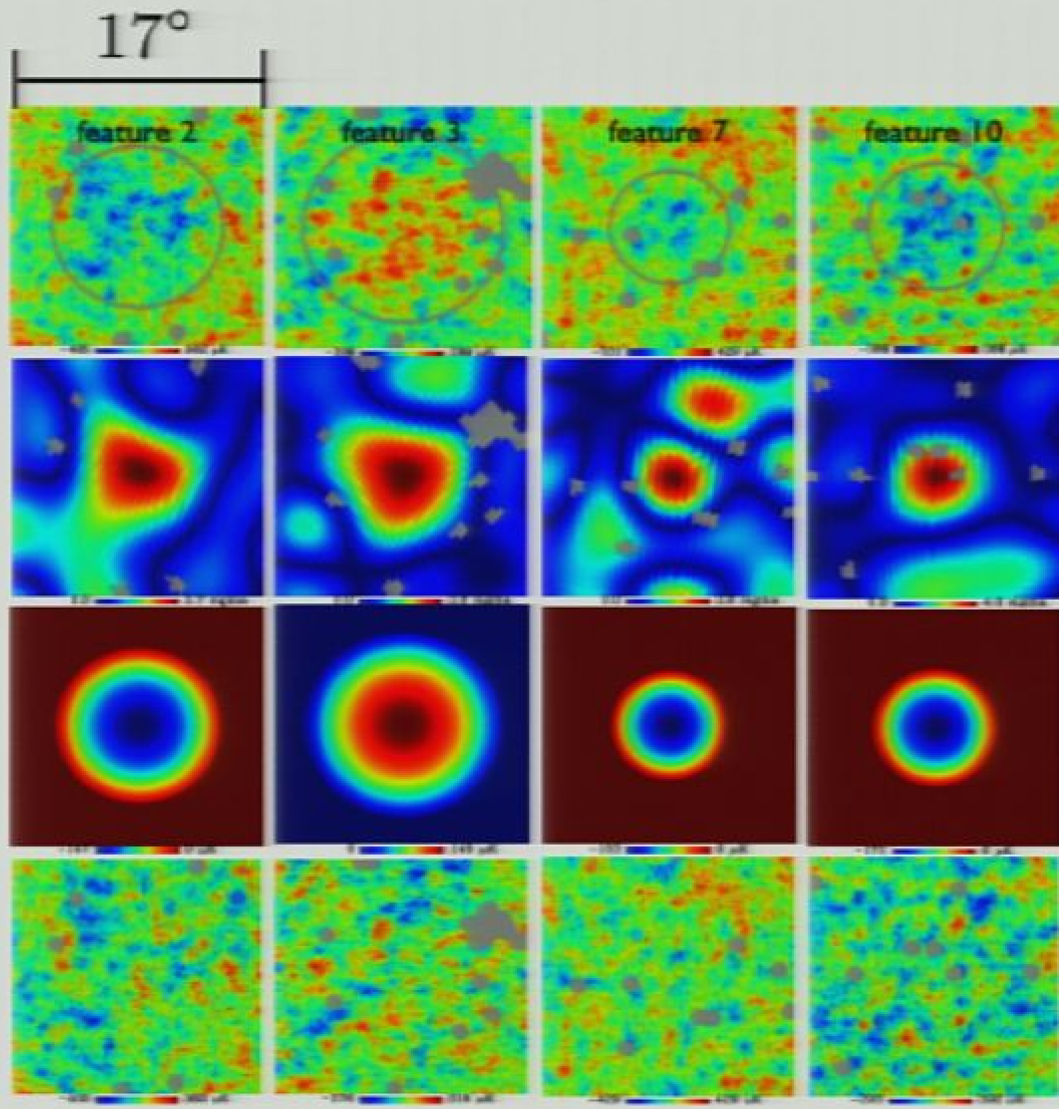
values consistent with collision sims



data

needlet significance

template

data minus template

Future work and Planck

- How well can we distinguish hypotheses in feature finding?
  ie bubbles vs textures.
- With more simulations of bubble collisions, we can update our template.
- Planck temperature data: 3 x better resolution, 10 x lower noise. This data will improve every step in the pipeline.
- Planck polarization data: provides a complementary signature of bubble collisions (Czech, Kleban, Larjo, Levi, Sigurdson).
- Cross correlation with large-scale structure (Larjo and Levi)?

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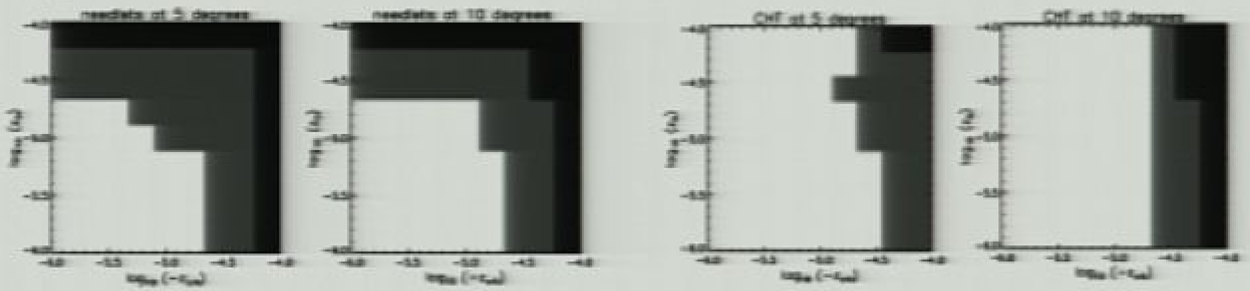

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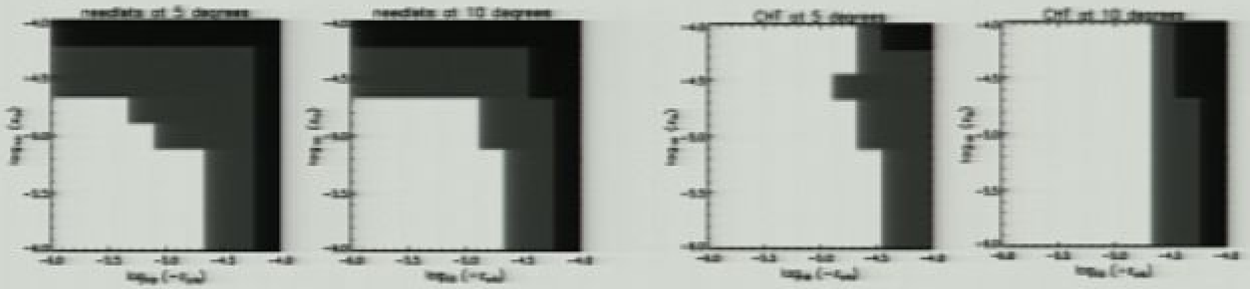

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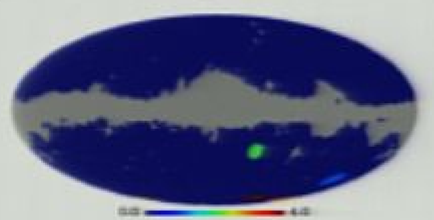

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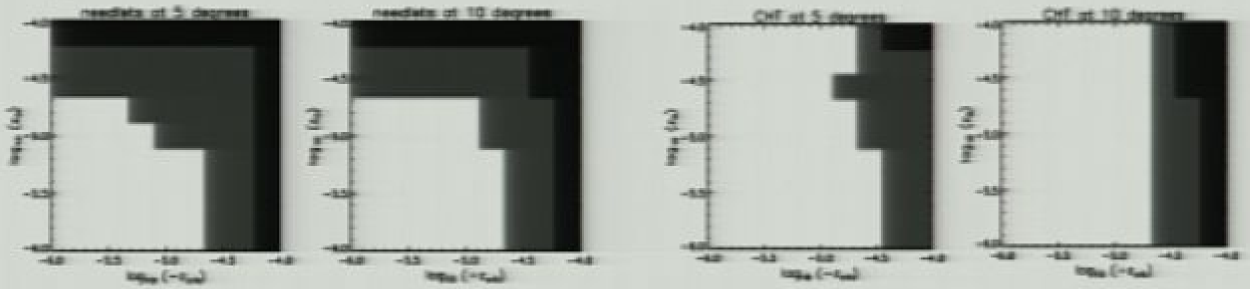

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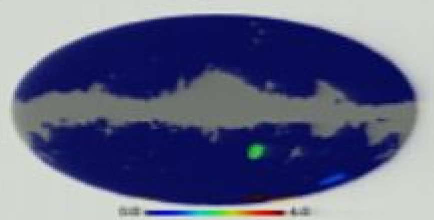

- Planck will go a long way towards determining if these are in fact signatures of other bubble universes!

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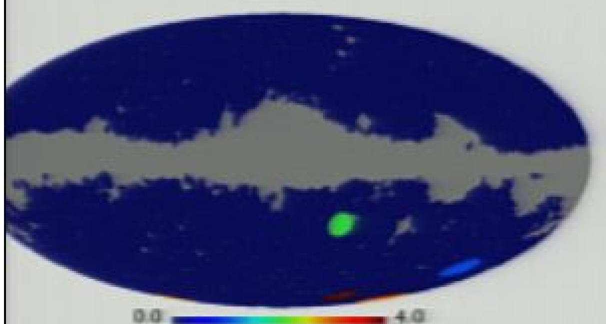

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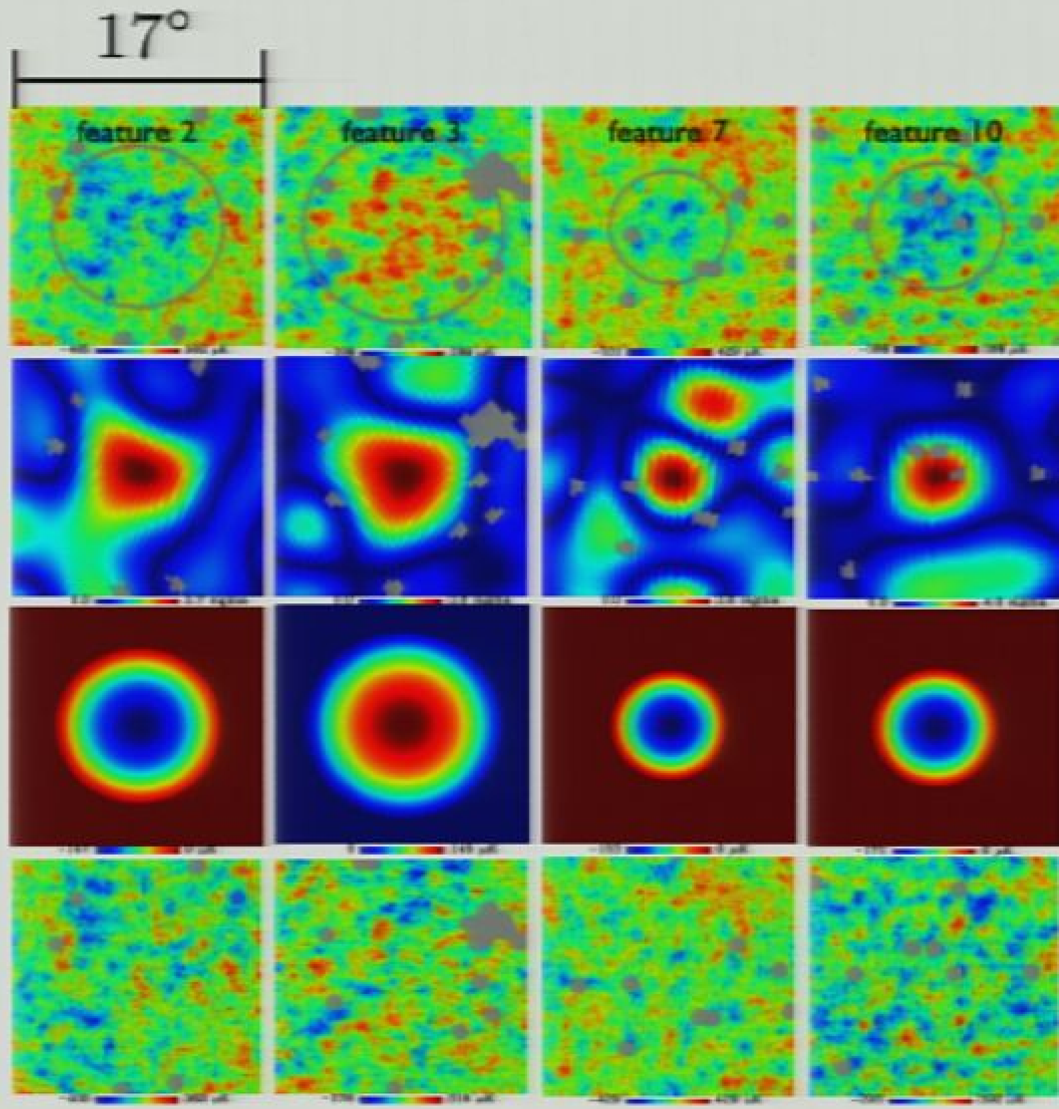

data

needlet
significance

template

data minus
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Edge detection

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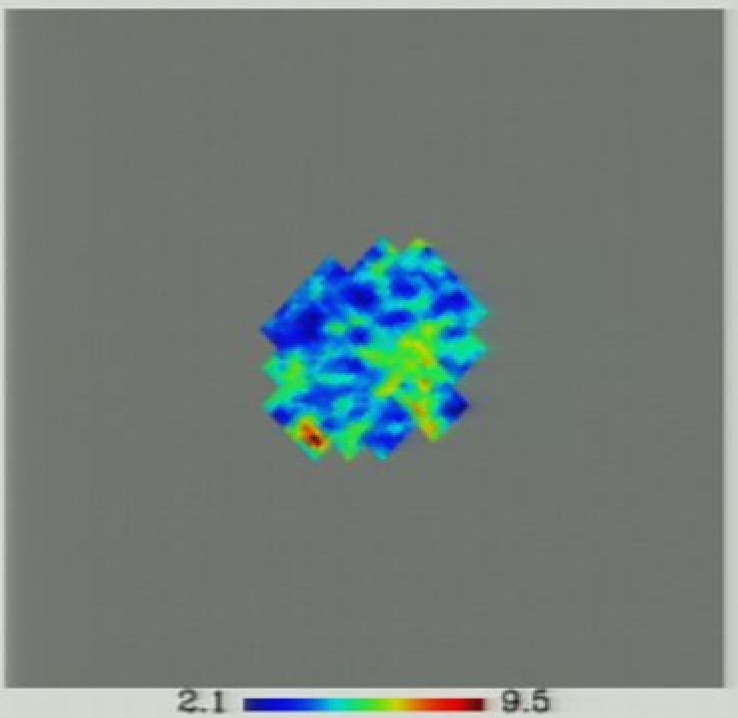
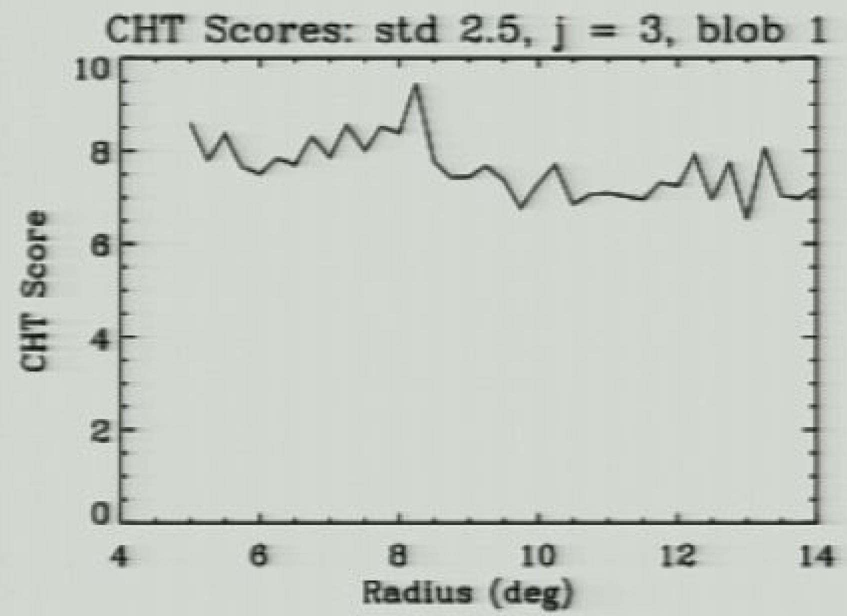
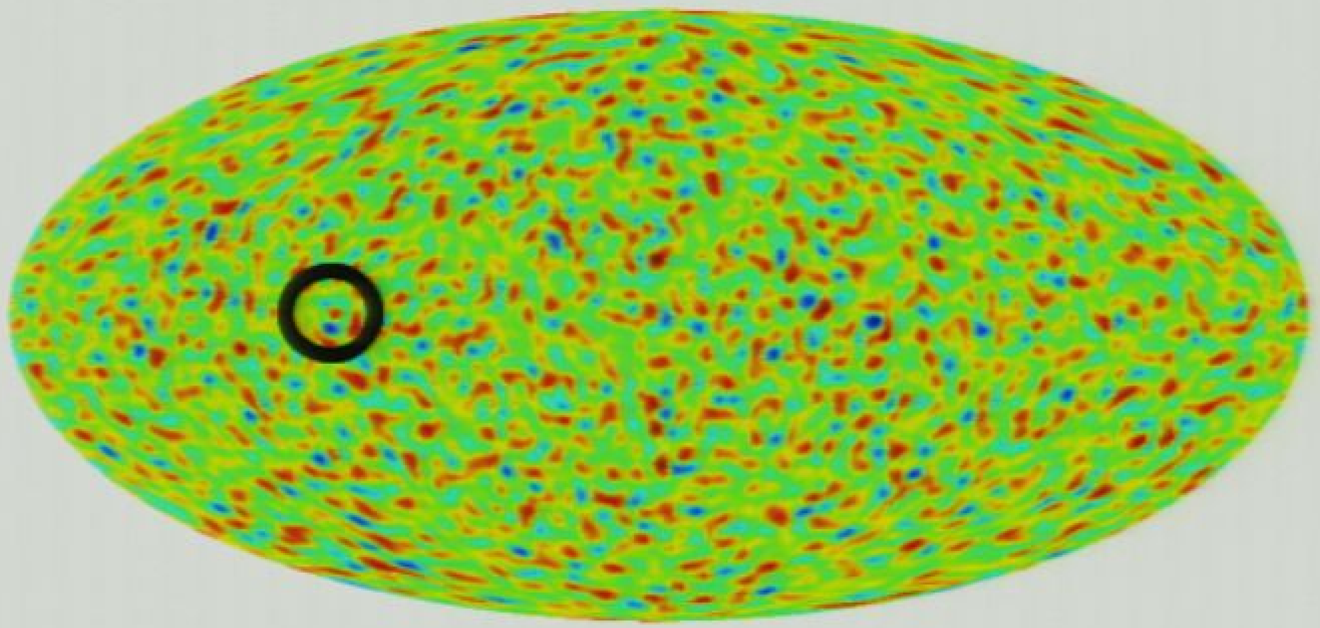




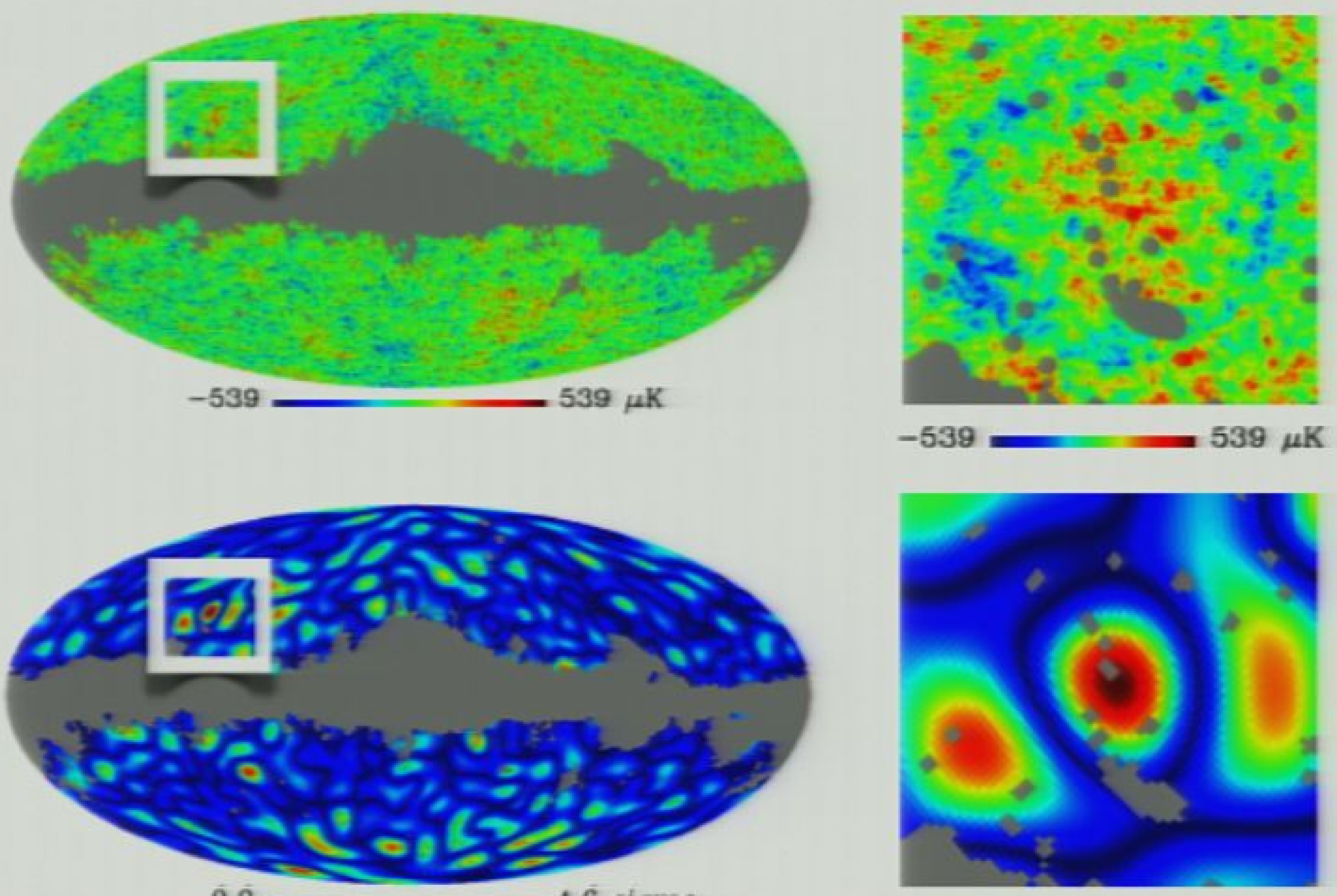
Wavelet analysis



j=5

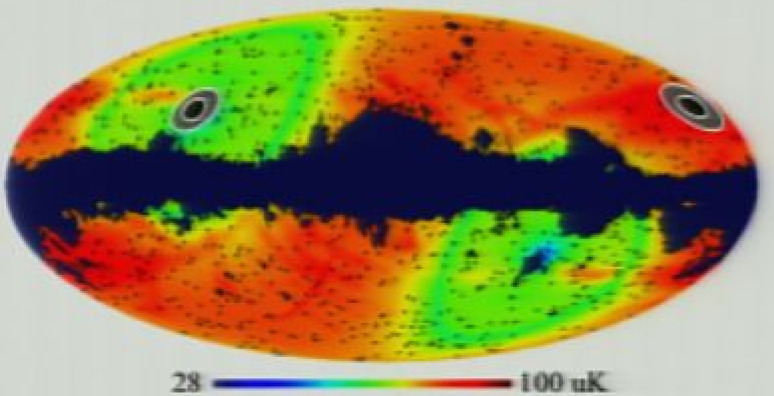
Wavelet analysis

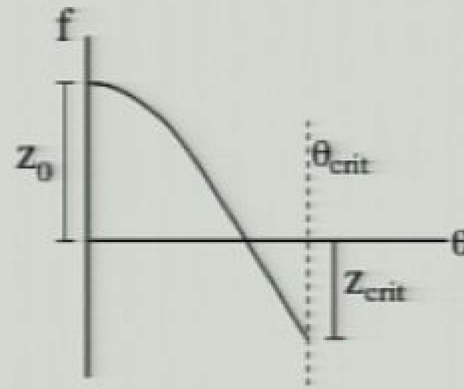
- Temperature fluctuations for collision + CMB + realistic noise:

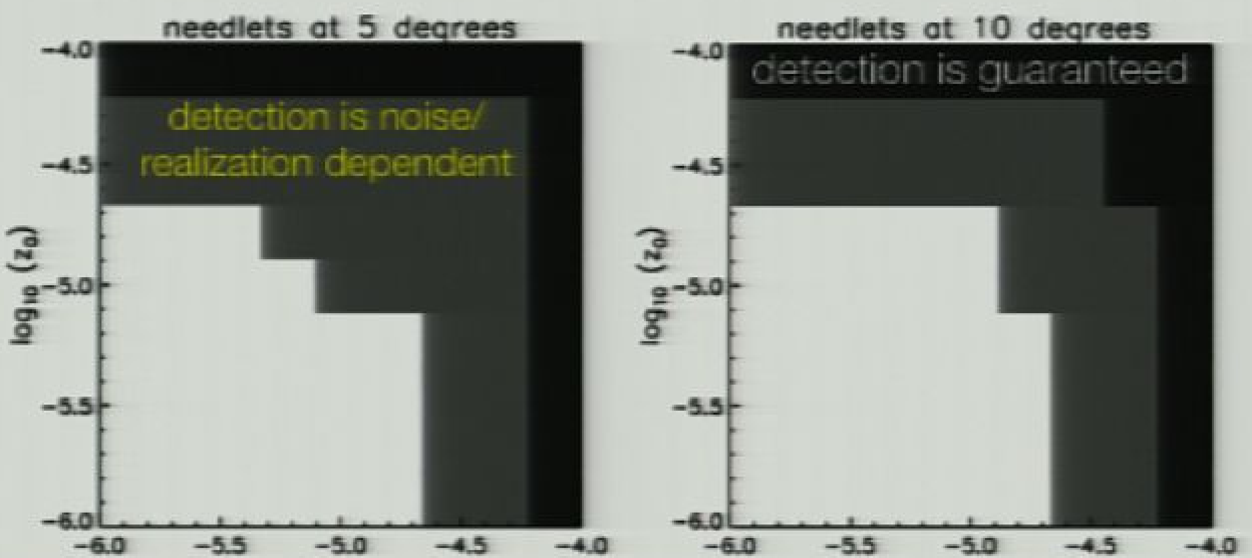


Simulations

- Does this method work to find bubble collisions?







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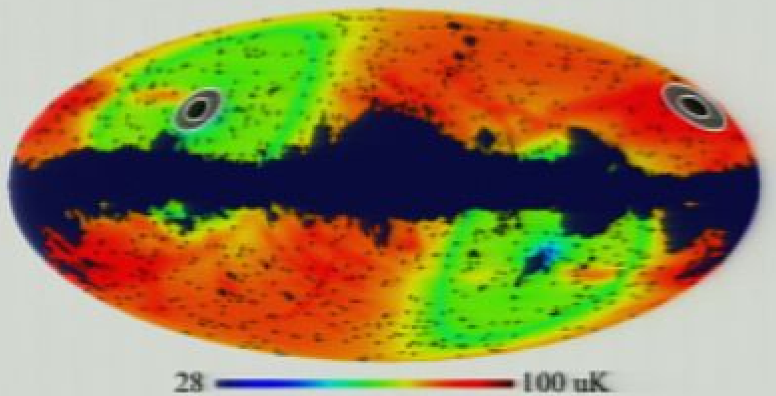

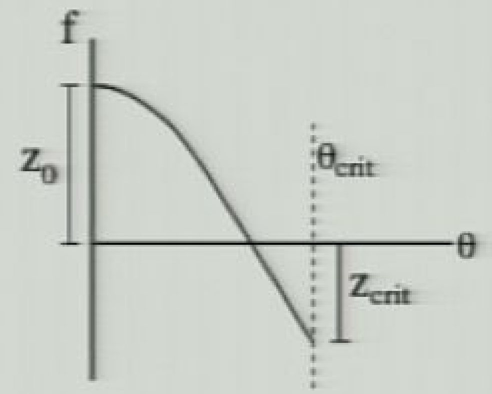

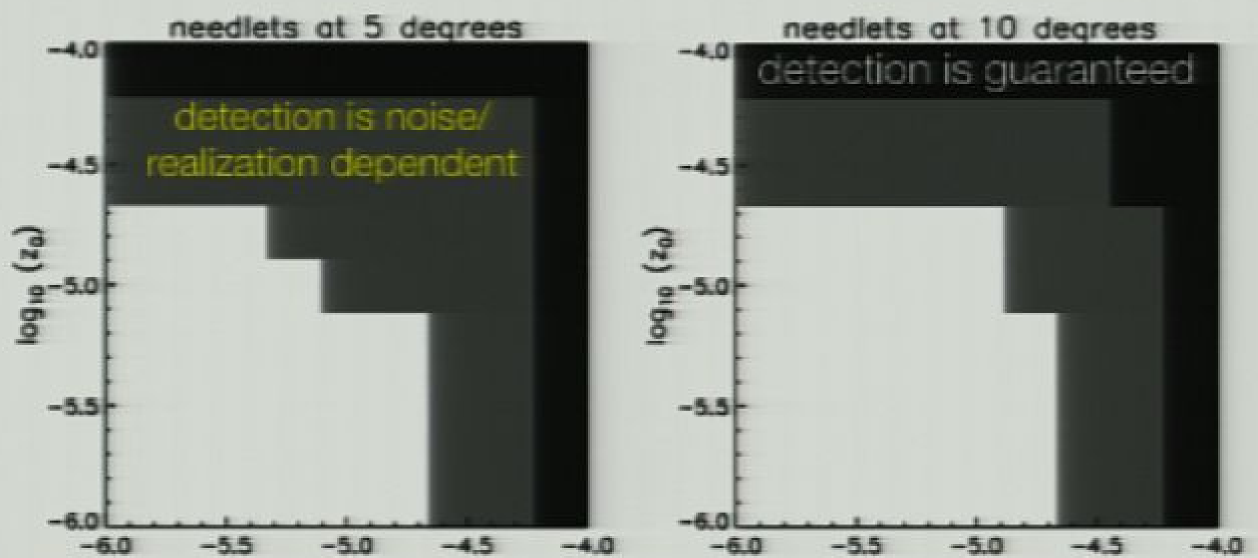

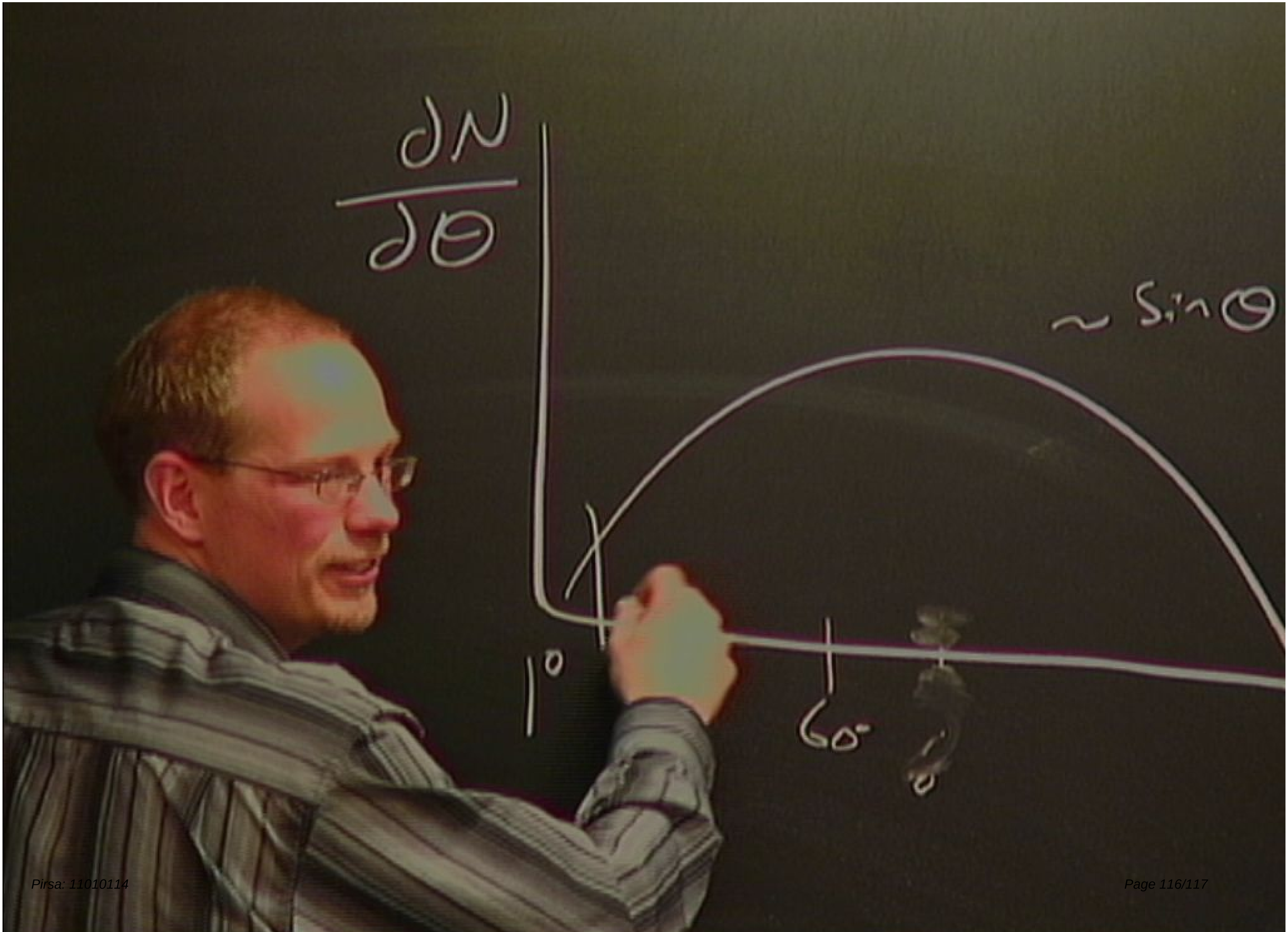

dN
dθ
~ Sin θ
1°
60°

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