Title: First observational tests of eternal inflation

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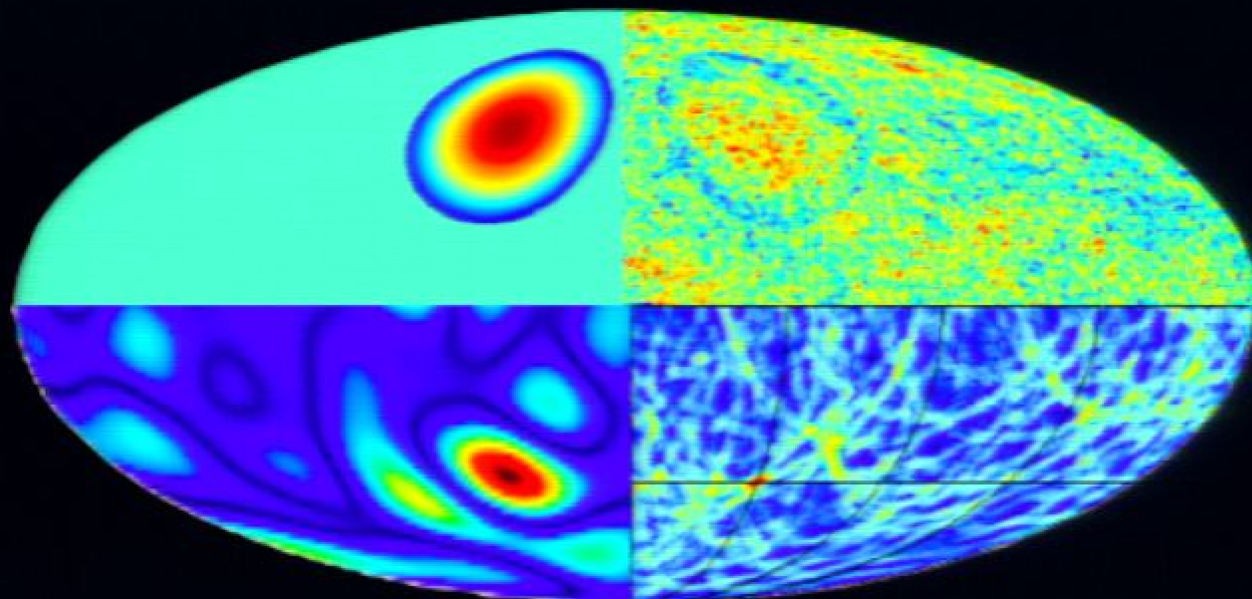
Abstract: The eternal inflation scenario predicts that our observable universe resides inside a single bubble embedded in a vast inflating multiverse. Collisions between bubble universes imprinted in the CMB sky provide a powerful observational test of this idea. I will describe a robust algorithm for non-Gaussian source detection in massive datasets, and present its application to the search for bubble collision signatures in CMB data from WMAP.

First Observational Tests of Eternal Inflation



Hiranya Peiris

University College London

arXiv:1012.1995 (PRL in press) & arXiv:1012.3667 (PRD in press)

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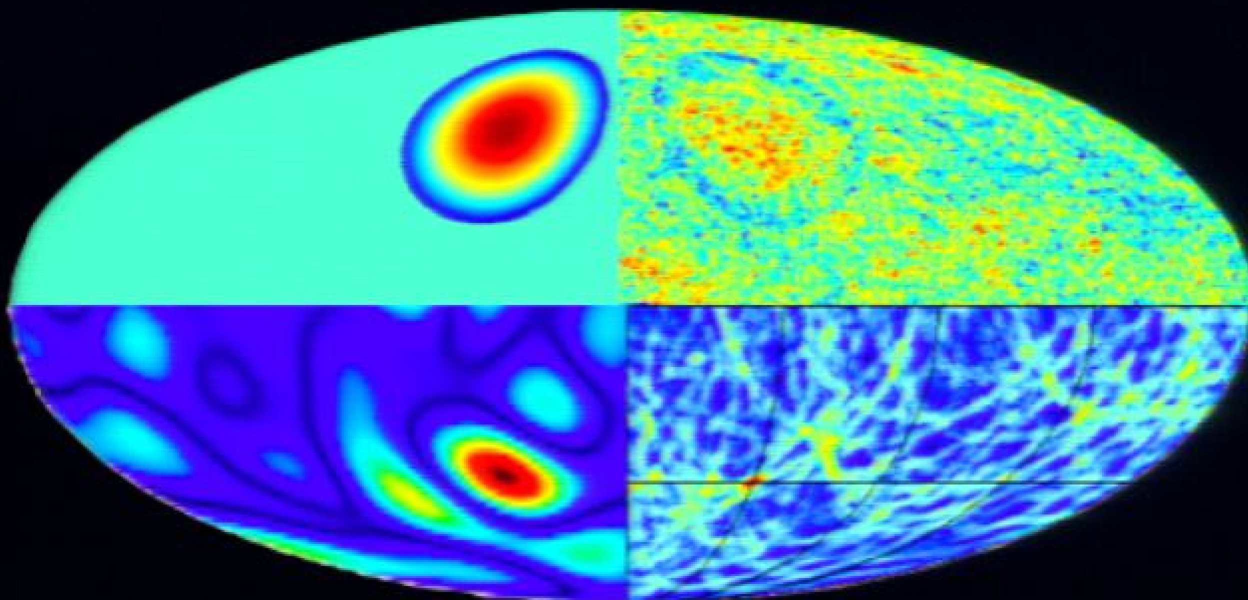

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Collaborators

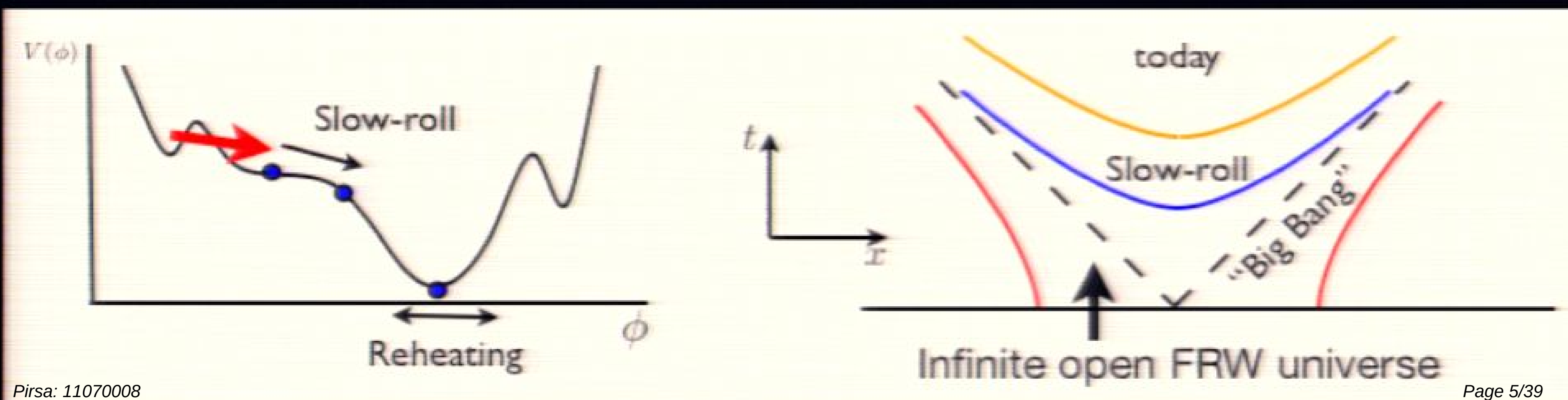
Stephen Feeney (UCL)

Matt Johnson (Perimeter Institute)

Daniel Mortlock (Imperial College London)

Eternal Inflation in the String Landscape

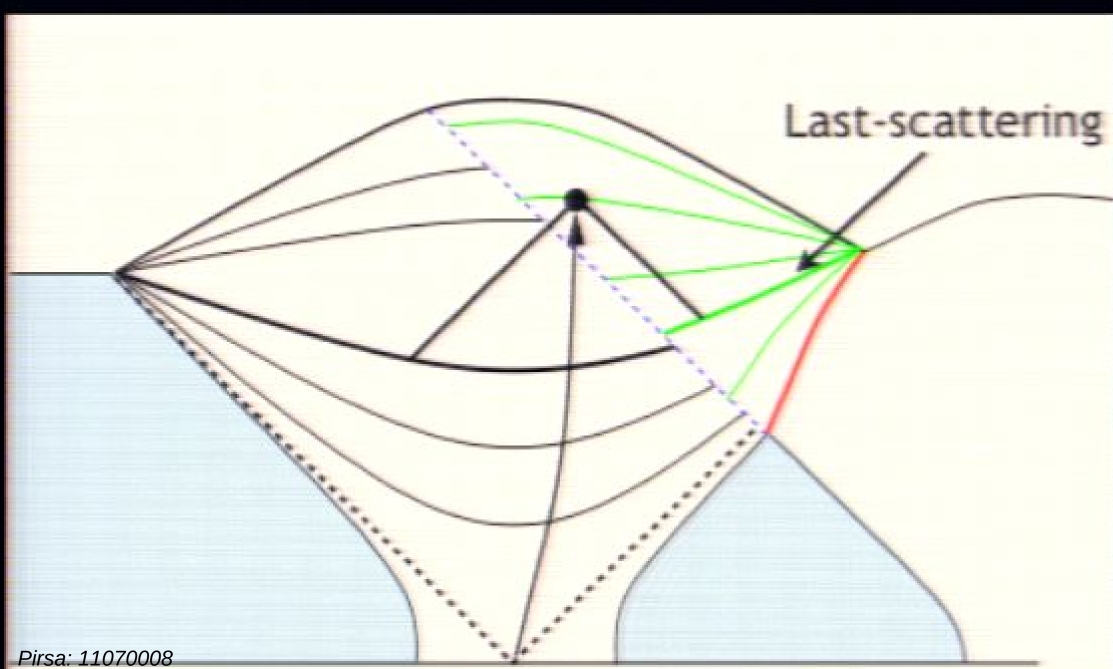
- Landscape predicts many false vacua, all occupied
- Field trapped in false vacuum inflates forever
- Tunneling creates a bubble: infinite open universe
- Further period of slow-roll inflation dilutes curvature

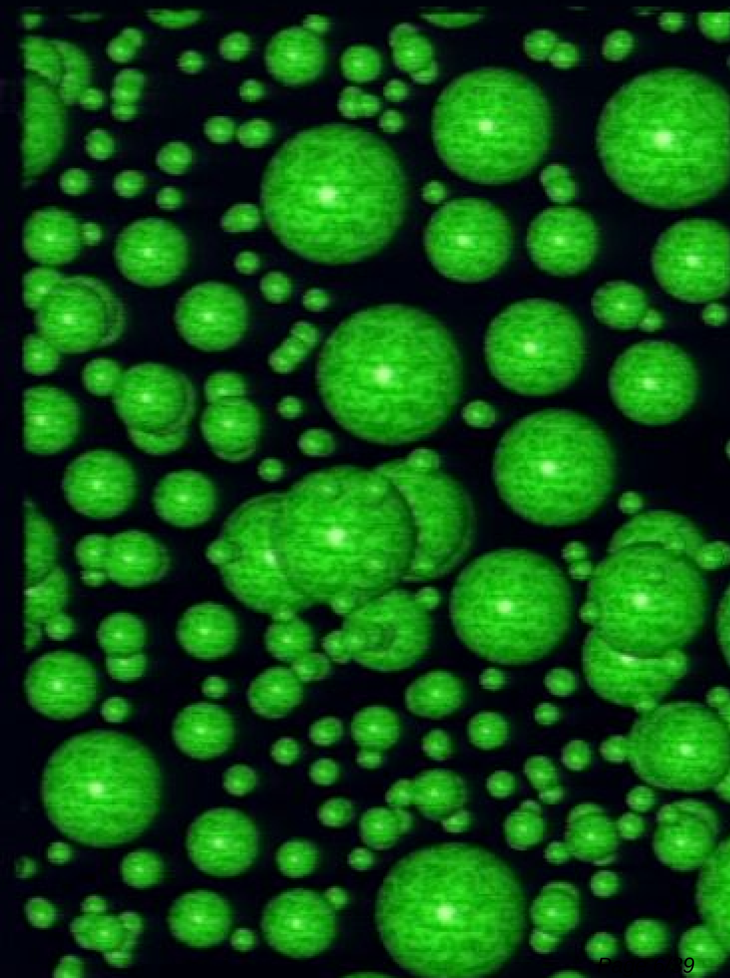


see Aguirre & Johnson (arxiv:0908.4105) for a review

Eternal Inflation: Bubble Collisions

- What if this happens more than once? Collisions!
- In fact, a formally infinite number





Could We Hope to See a Collision?

- Compatibility: collision must allow observed cosmology to exist
- Probability: observing collisions should be likely

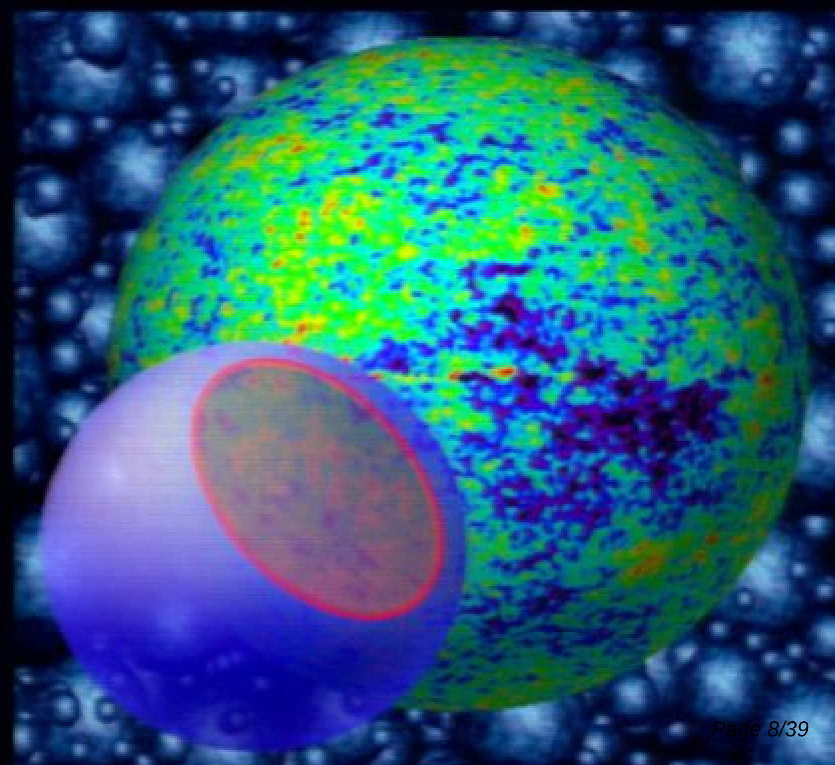
$$N \propto \frac{\lambda}{H_F^4}\left(\frac{H_F}{H_I}\right)^2 \sqrt{\Omega_\kappa}$$

Freivogel et al (arXiv:0901.0007)

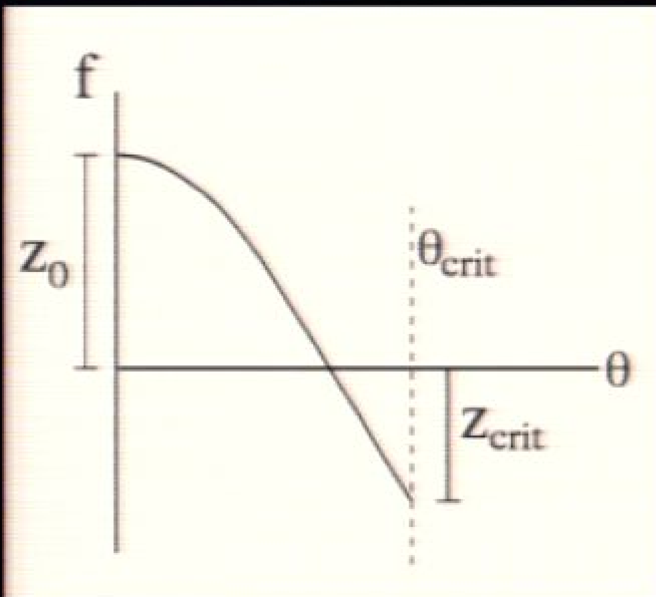
- Observability: not so much slow-roll that collision signatures diluted away

If So, What Would We See?

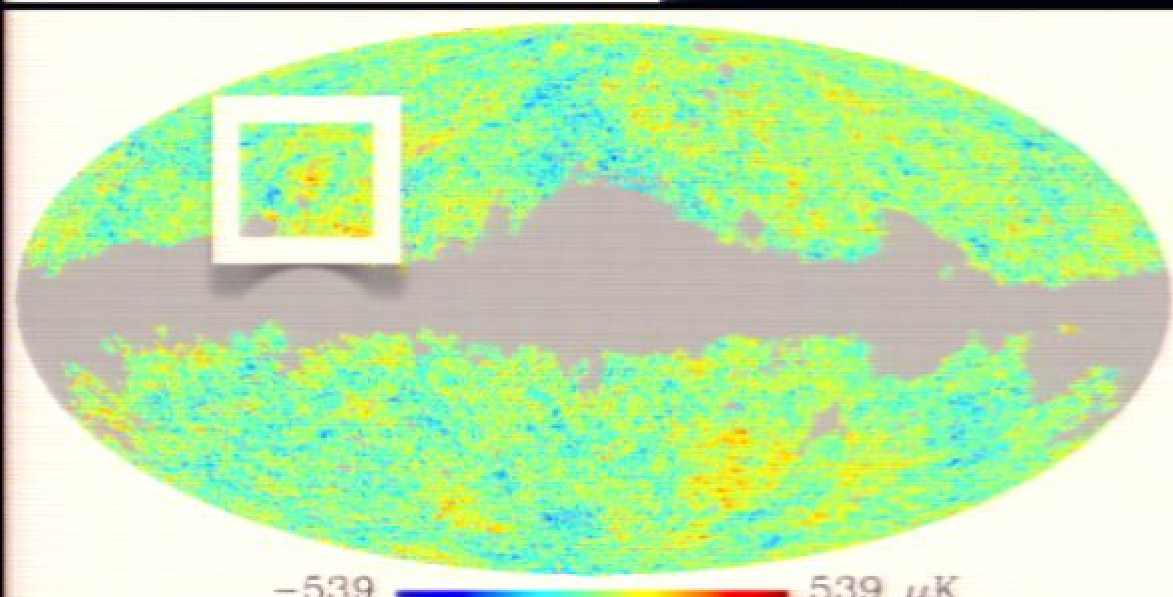
- Early-Universe effect: perturbed CMB, long-wavelength
- Azimuthal symmetry: spheres intersecting
- Localized in real-space
- Causal boundary: edge?

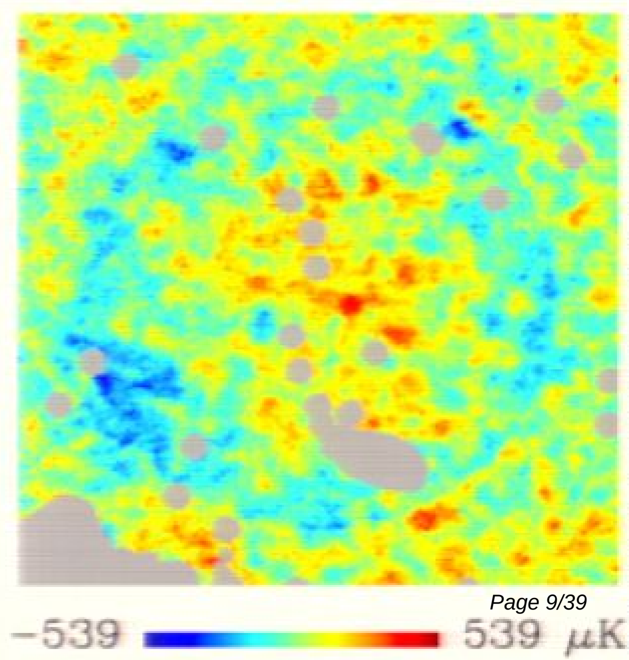


How Can We Characterize Collisions?



- Multiplicative cosine modulation
  (Chang, Kleban & Levi arxiv:0810.5128)
- Parameterized by central amplitude and location, edge amplitude and radius





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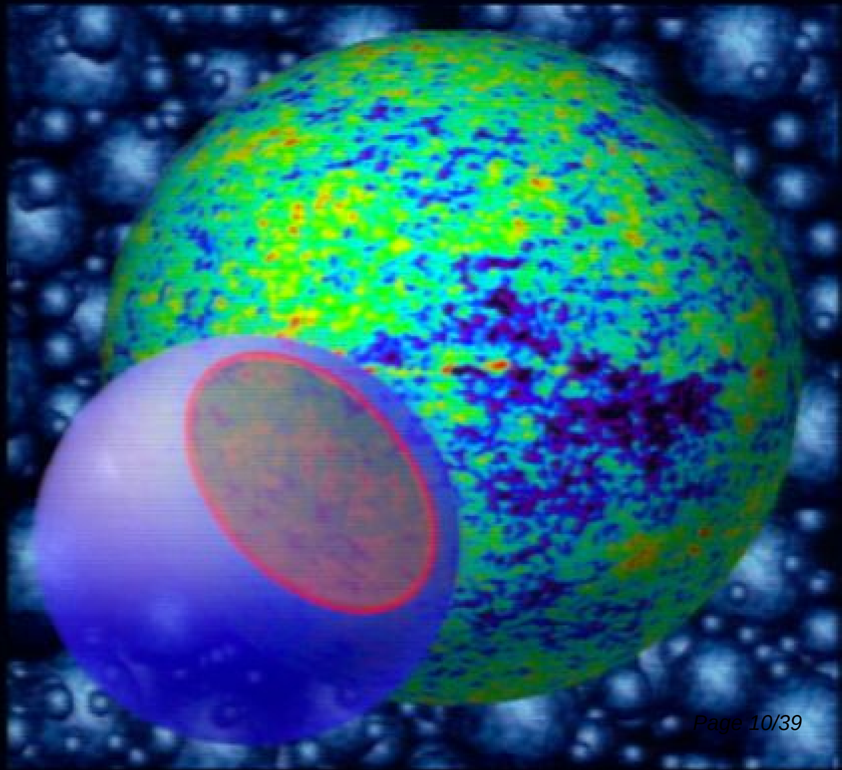

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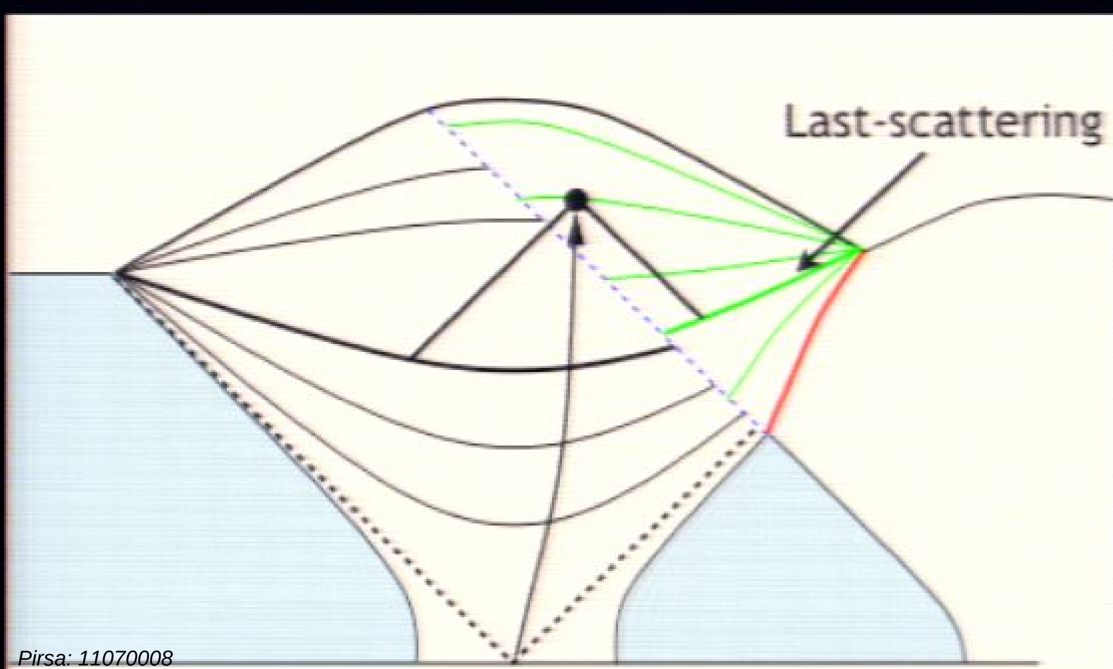

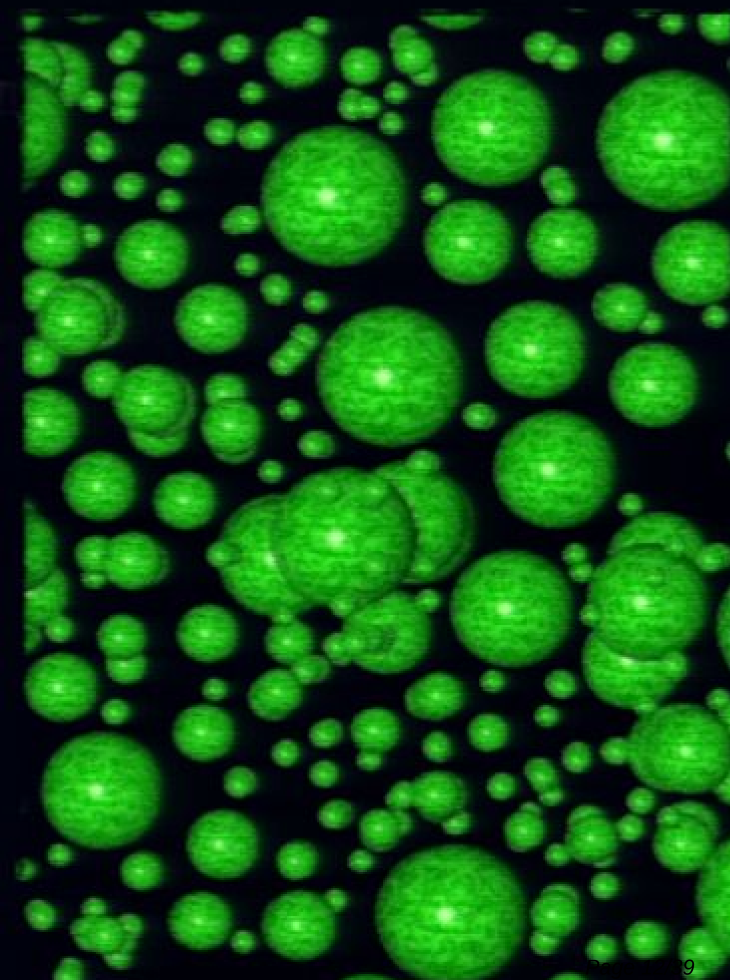

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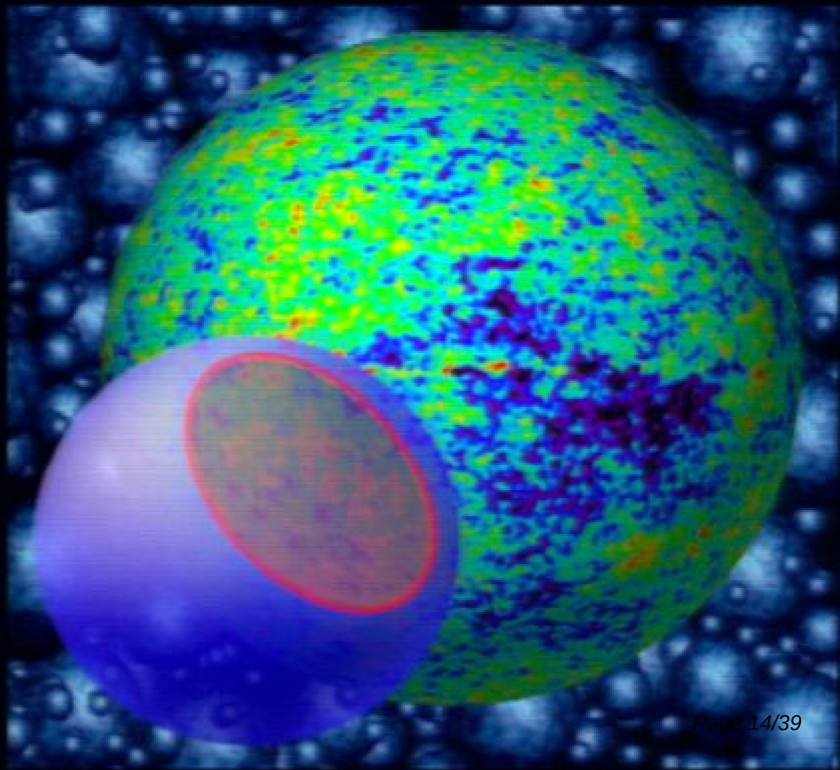

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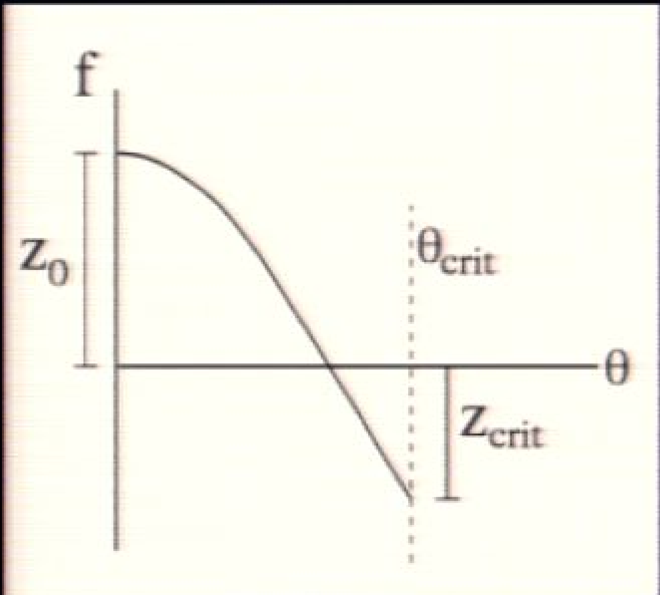

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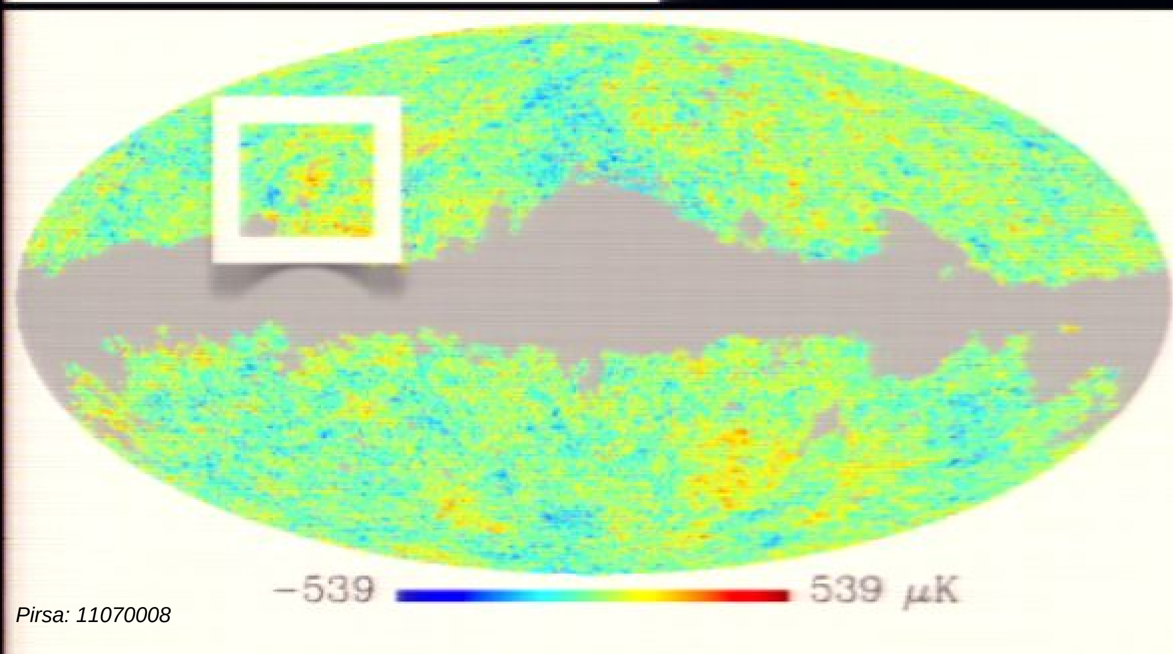
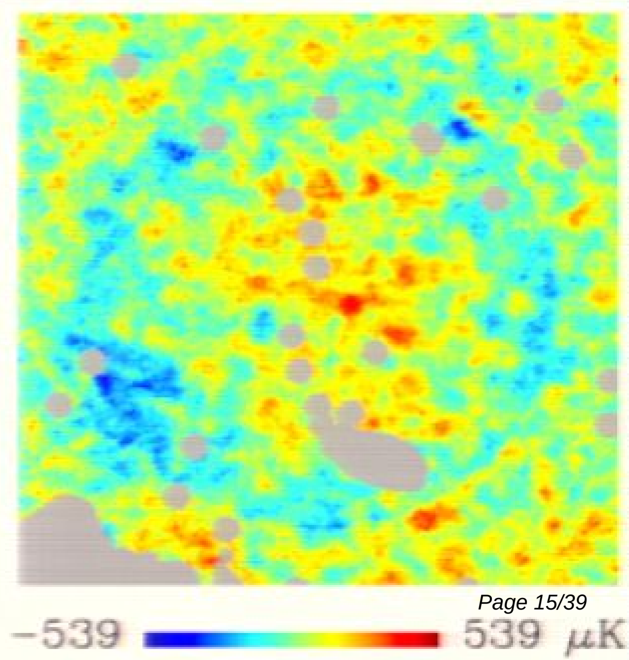
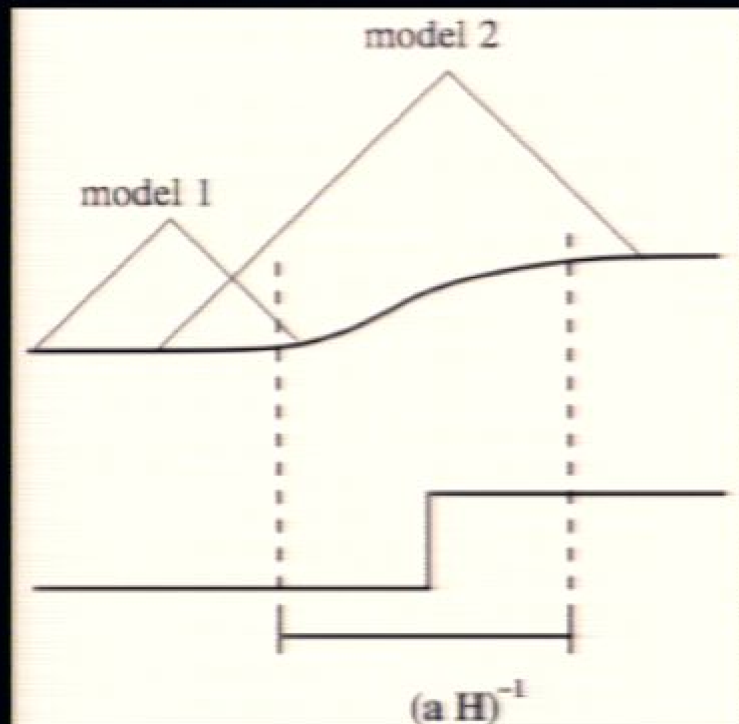
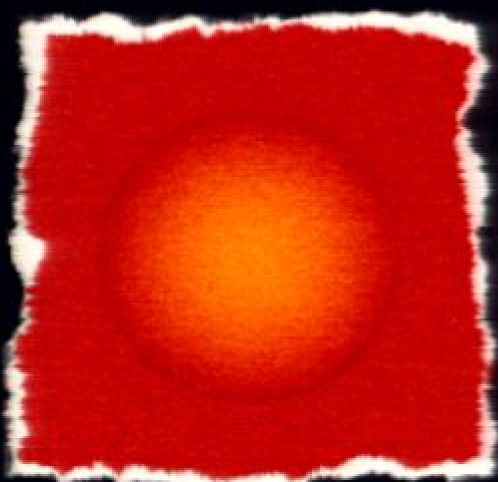




Bubble template

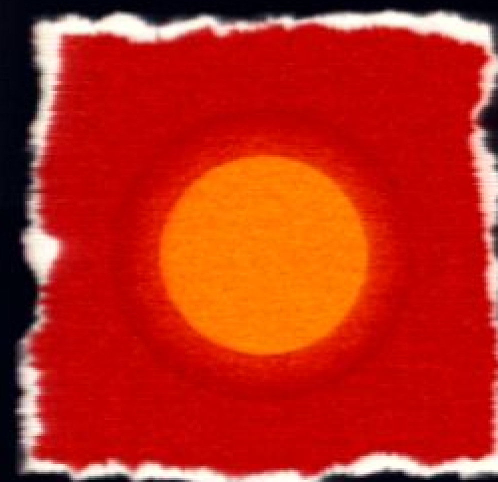


Model 1



See small portion of smoothed collision

Model 2



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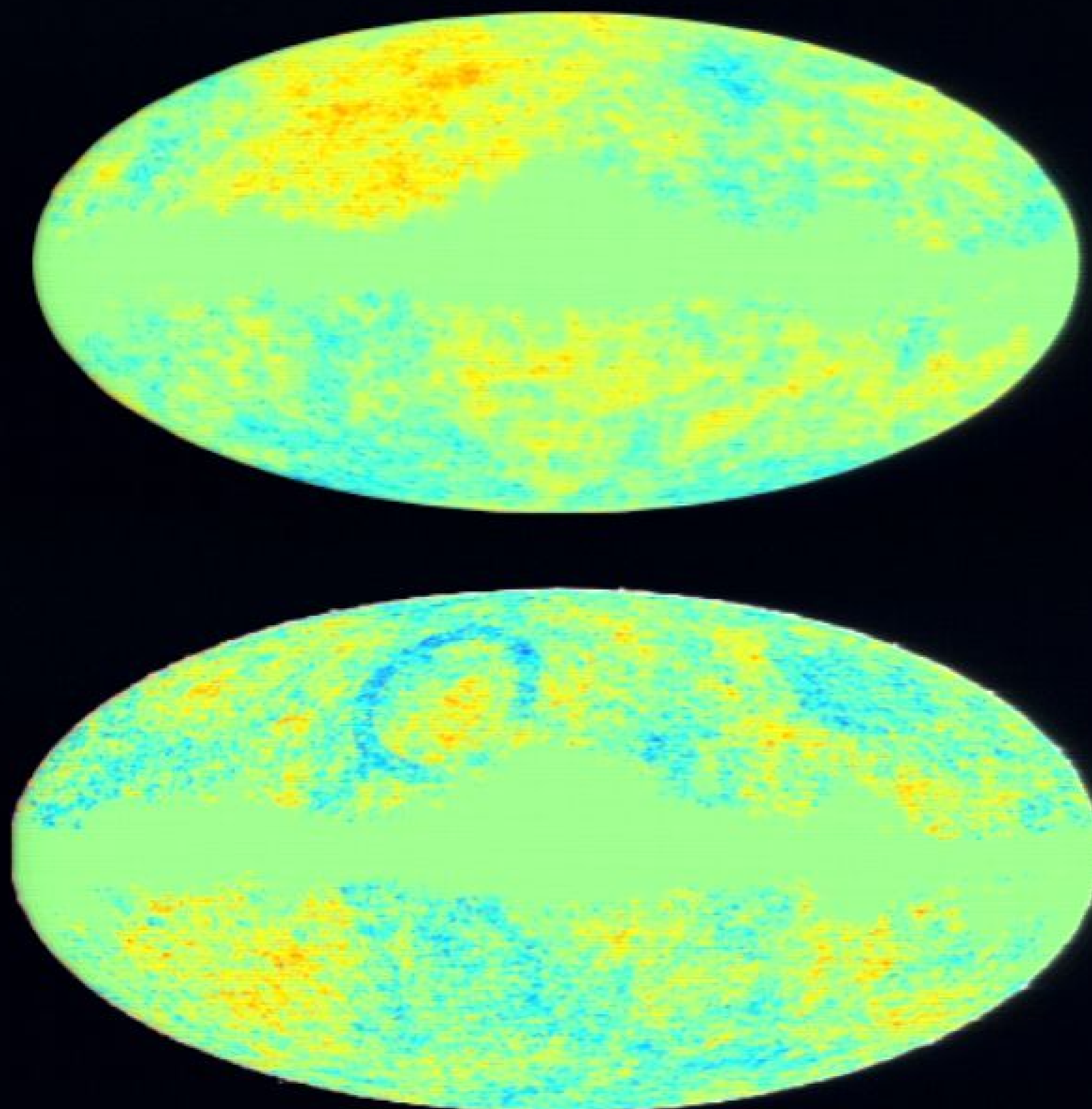
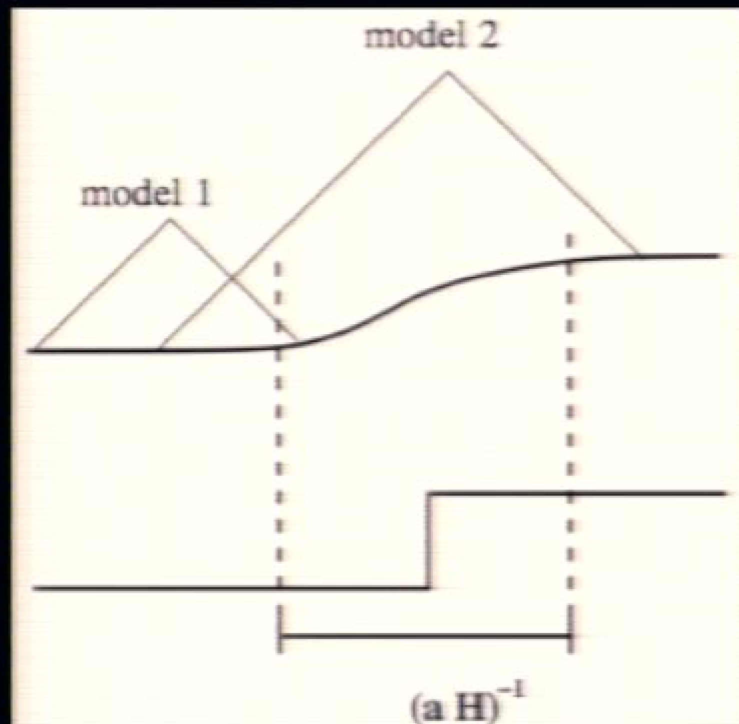
Exaggerated CMB examples



Bubble template



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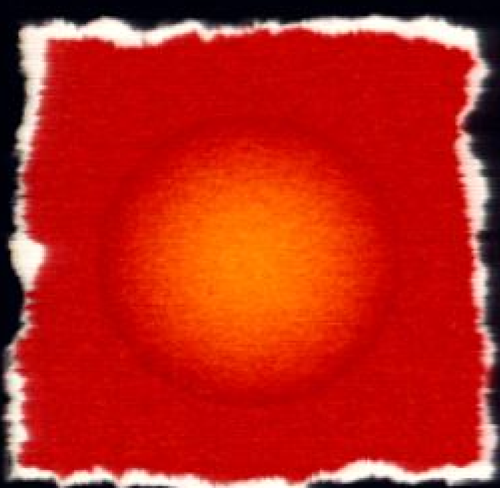

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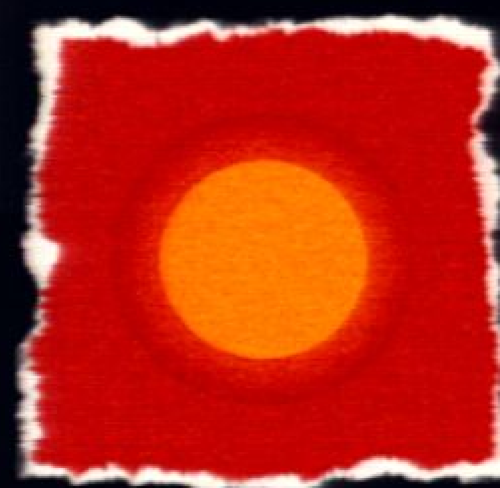
smoothed collision

Model 2



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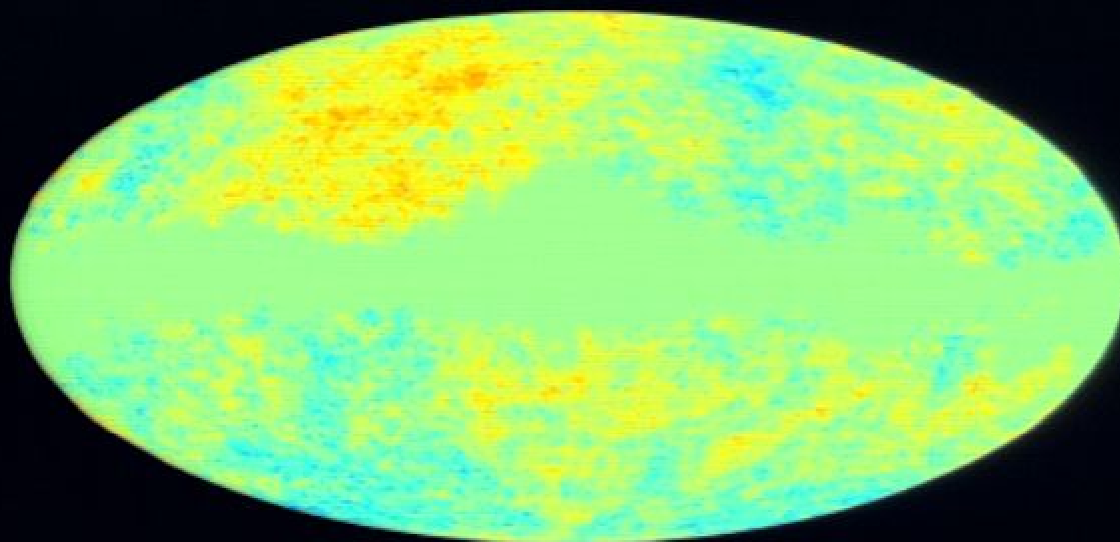
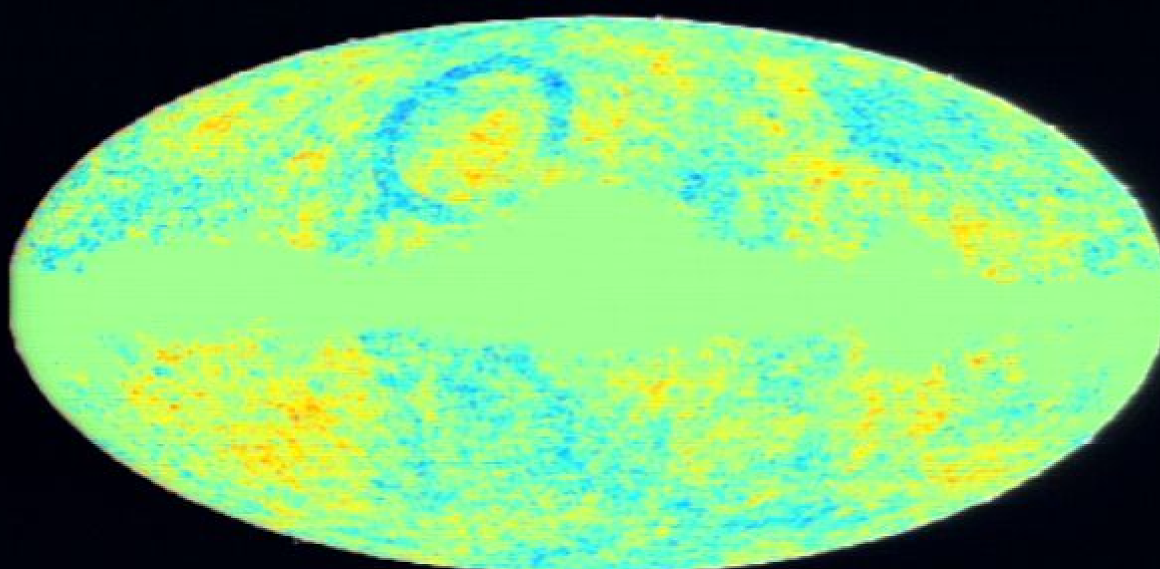




Data Analysis Pipeline

- Very important to perform blind analysis with no *a posteriori* selection effects!

  - Design pipeline with model and specific dataset in mind
  - Calibrate using instrument simulation: null test
  - Test sensitivity of pipeline to simulated dataset with signal
  - Pipeline "frozen" before looking at data

P-values vs model selection

- Frequentist *p*-values quantify how discrepant a data statistic is under the "null hypothesis"
- Cannot be used to perform model selection!

$$p(A|B) \neq p(B|A)$$

100% 0.01%

A = I am a scientist

B = I am a CMB cosmologist

$$p(A|B) \neq p(B|A)$$

?? 0.01%

A = The standard model is basically correct

B = CMB anomalies

(“some subset of the CMB data which we don’t like the look of”)

Reminder: parameter estimation vs model selection

posterior: probability of the model given the data

probability of the data given the model

prior probability

$$P(\theta|D) = \frac{P(D|\theta)P(\theta)}{\int P(D|\theta)P(\theta)\mathrm{d}\theta}$$

Evidence: normalizing factor

Evidence: model-averaged likelihood

Exact (pixel) likelihood includes CMB, spatially varying noise, Gaussian beam

How Should We Search for Collisions?

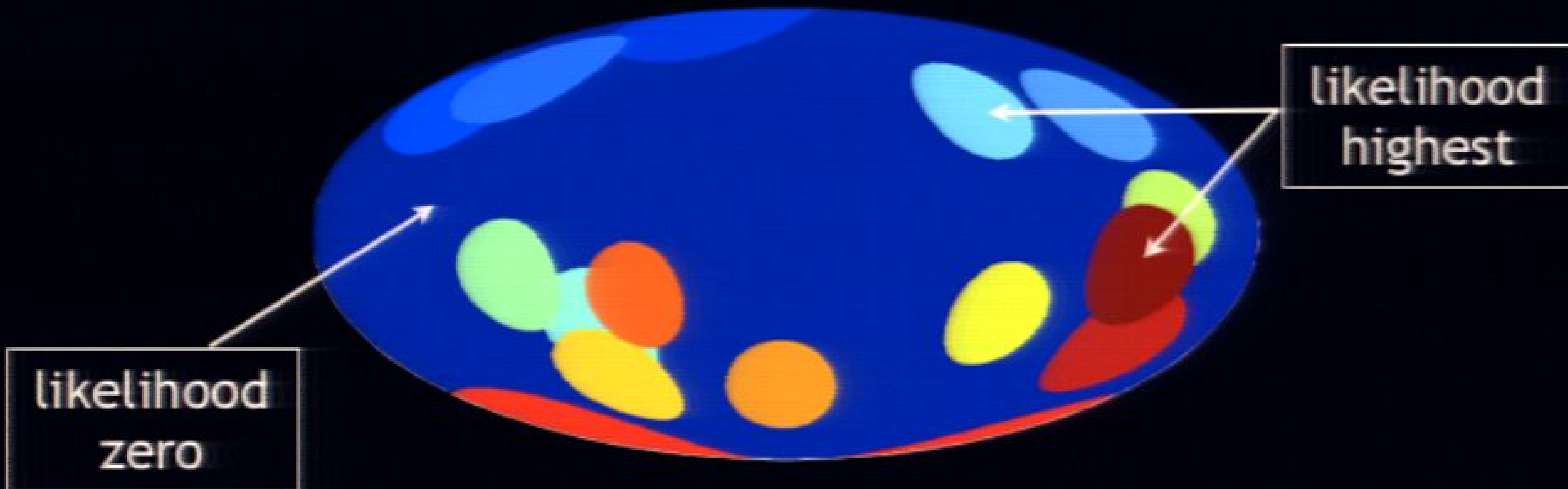
- Blind analysis: no *a posteriori* selection effects
- Bayesian algorithm to calculate posterior distribution of expected number of observable collisions

$$\Pr(\bar{N}_s|\mathbf{d}, f_{\rm sky}) \propto \Pr(\bar{N}_s)\,\Pr(\mathbf{d}|\bar{N}_s, f_{\rm sky})$$

  - assumptions clearly encoded as priors
  - considers full predictive power of model

- Full problem computationally intractable

Making the Problem Tractable 1



- Conservatively approximate the full problem, assuming:
  - likelihood is zero outside candidate collision regions ("blobs")
  - each blob uncorrelated with rest of sky

Making the Problem Tractable 2

- Then only need Bayesian evidence ratio between LCDM and LCDM + 1 collision template in each blob

$$\rho_b = \frac{\int d\mathbf{m}\, \Pr(\mathbf{m})\, L_b(\mathbf{m})}{L_b(\mathbf{0})}$$

- Pixel likelihood *L* contains (LCDM) CMB cosmic variance, WMAP beam and spatially-varying noise
- Computationally limited to <11° blobs

Priors

- Priors derived from theory, previous experimental results and limitations of pipeline (*observable* collisions)
  - assume all values of N_s - including $N_s = 0$ (LCDM) - are equally probable (theory, or lack of!)
  - collision equally likely to occur anywhere on sky (theory)
  - collision amplitudes uniform in the range -10^{-4} to 10^{-4} (larger amplitudes would already have been observed)
  - collision sizes uniformly distributed in the range 2° to 11° (pipeline limitations)

Approximating the Full Posterior Probability

theory prior

cosmic variance

all combos of templates and blobs

$$\Pr(\bar{N}_{\rm s}|\mathbf{d}, f_{\rm sky}) \propto \Theta(\bar{N}_{\rm s})\, e^{-f_{\rm sky}\bar{N}_{\rm s}} \sum_{N_{\rm s}=0}^{N_{\rm b}} \frac{(f_{\rm sky}\bar{N}_{\rm s})^{N_{\rm s}}}{N_{\rm s}!} \sum_{b_1,b_2,\ldots,b_{N_{\rm s}}=1}^{N_{\rm b}} \prod_{s=1}^{N_{\rm s}} \rho_{b_s} \prod_{i,j=1}^{N_{\rm s}} (1-\delta_{s_i\, s_j})$$

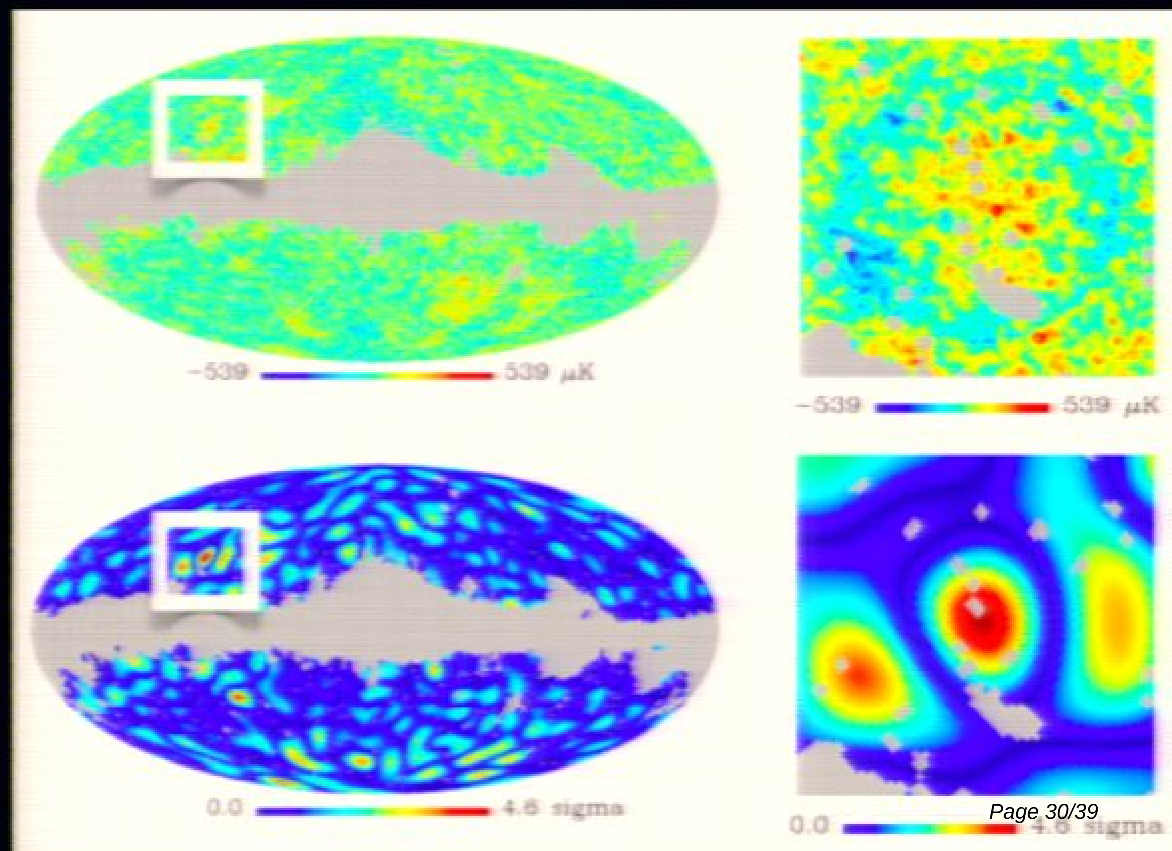
Expected number of observable collisions

Poisson process

Bayesian evidence ratio in blob

Locating Candidate Collisions With Needlets

- Convolve map with needlets: sets of functions on sphere with good localization in both pixel and harmonic space
- Yield information on location and scale of features
- Location info defines blobs
- Scale info restricts range of parameter space we must integrate



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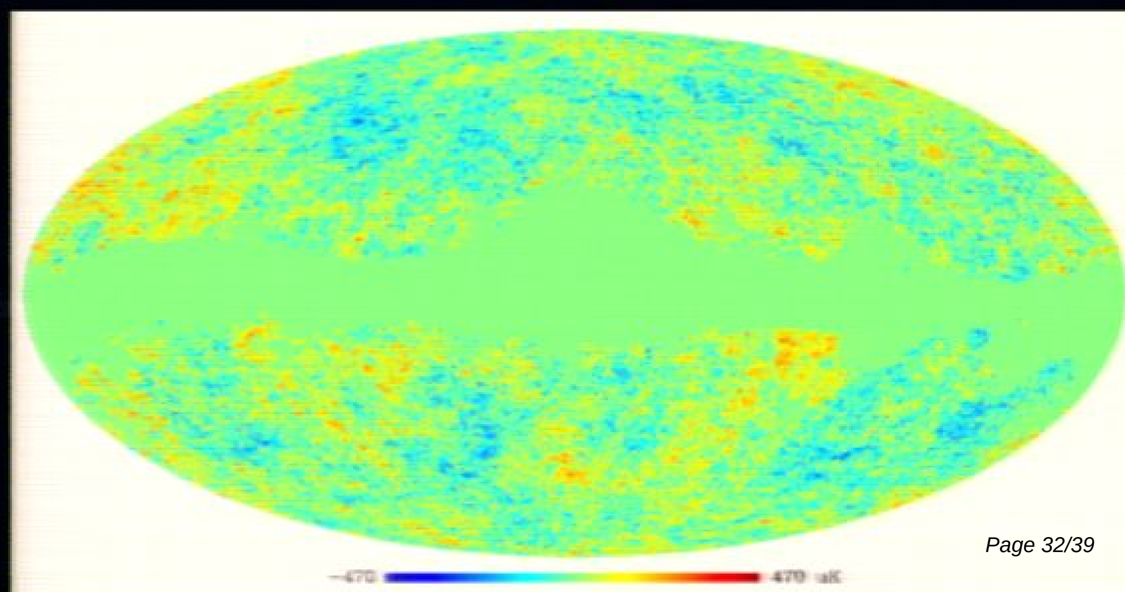
Calibrating Effects of Systematics

- Can't include all instrumental / processing systematics in likelihood: some not released
- Calibrate their effects using WMAP7 W-band end-to-end sim: simulated time-stream data, diffuse and point-source foregrounds, realistic instrumental and data-processing effects
- No false detections!
  - posterior peaked at 0
  - max blob evidence $e^{-6.6}$



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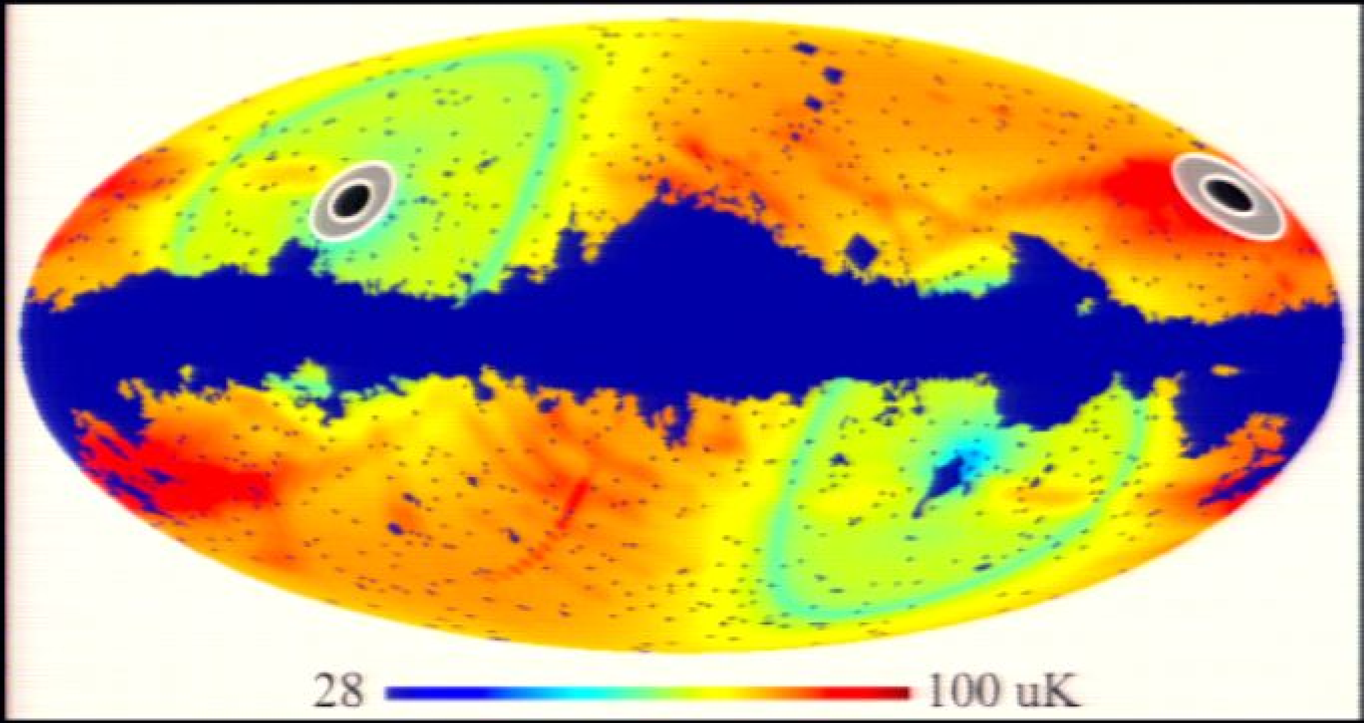
Determining Sensitivity



- Process simulations sampling template parameter space, effects of spatially-varying instrument noise and CMB
- Always detect amplitudes > 5×10^{-5}; depending on realization, can detect amplitudes > 3×10^{-5}

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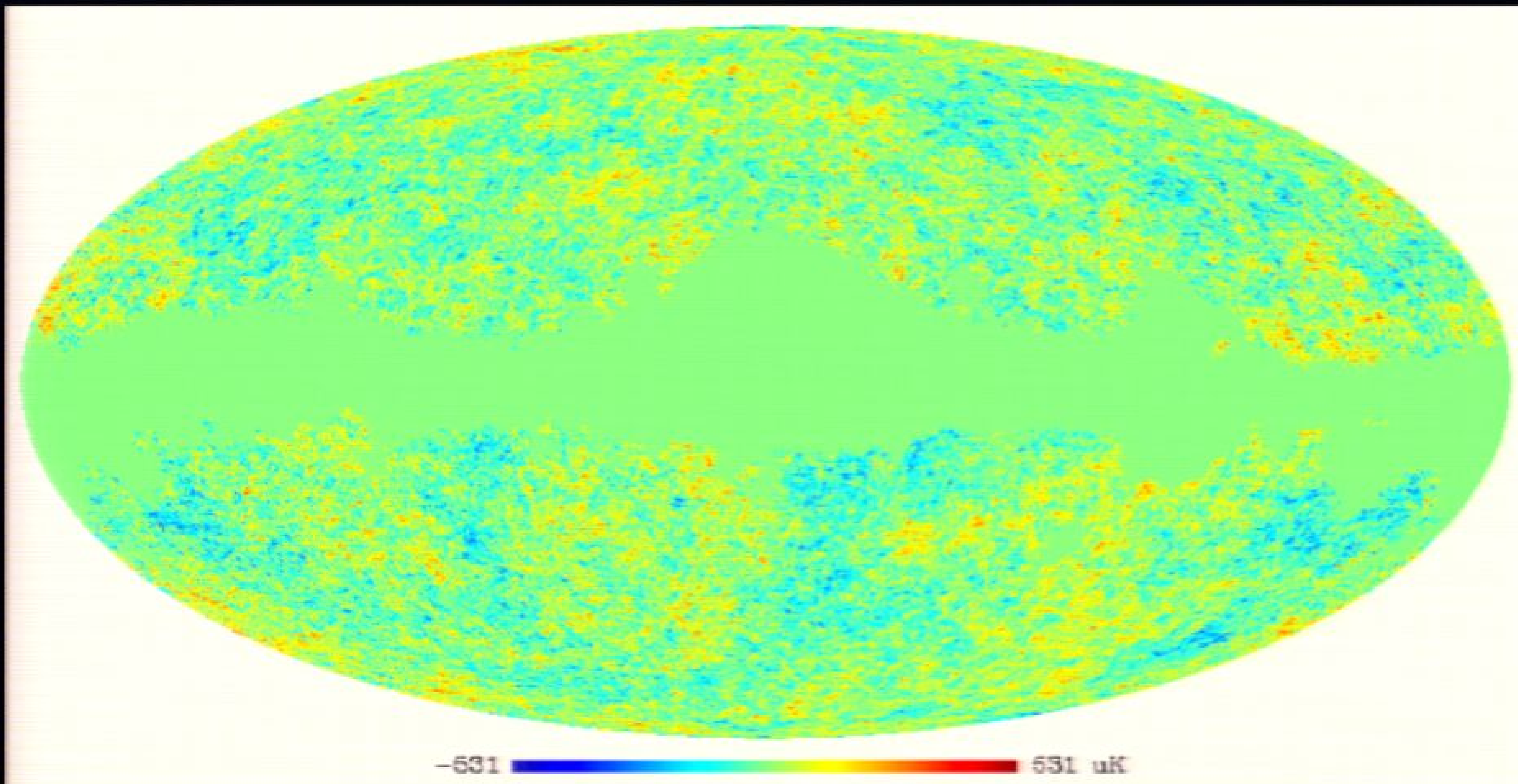
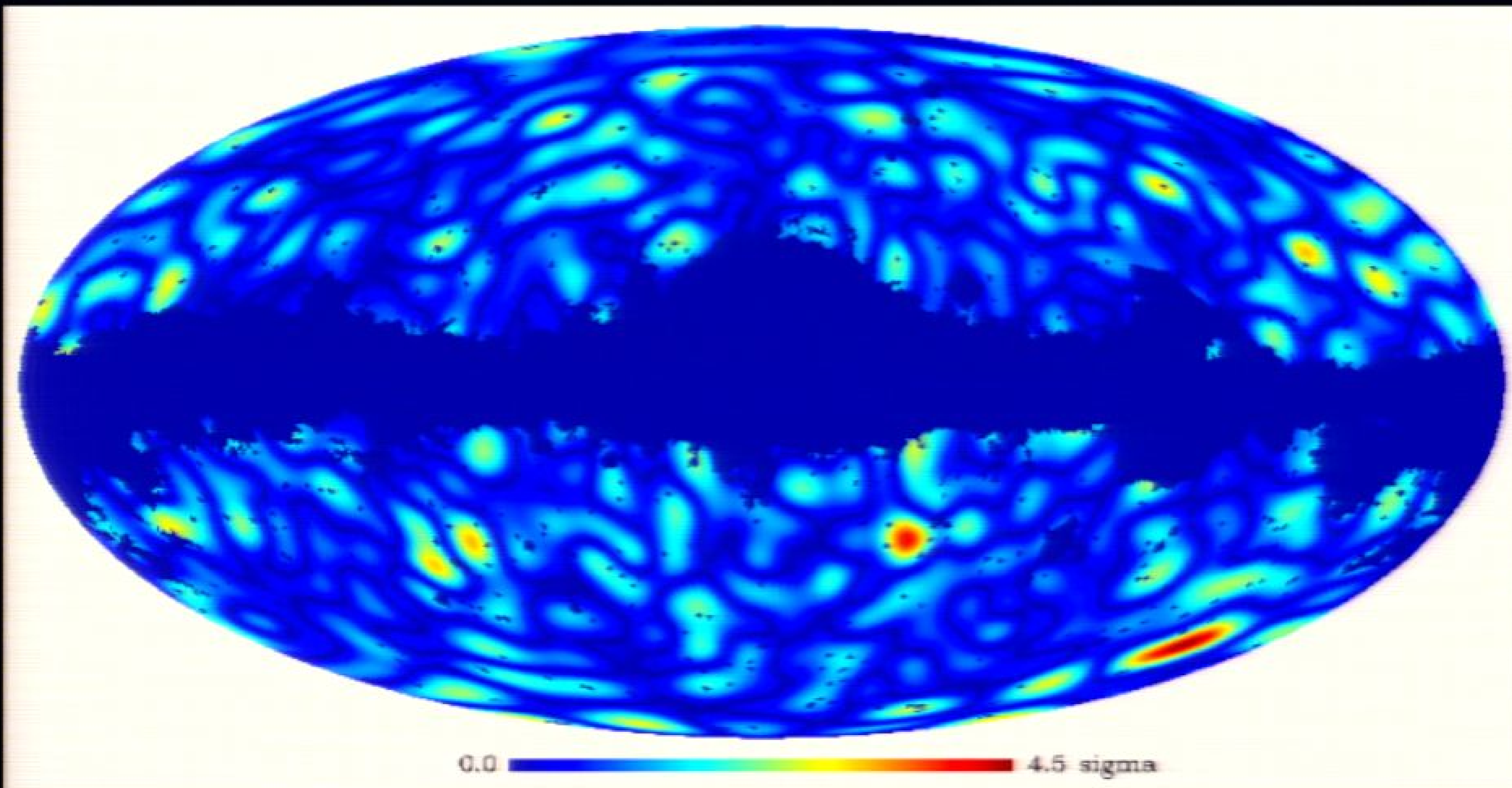
Final Data: WMAP7 W-Band (94 GHz)



Highest resolution (needed to detect edge) WMAP channel (beam 0.22°), KQ75 mask, foreground-reduced

WMAP7 W-Band: Needlet Response

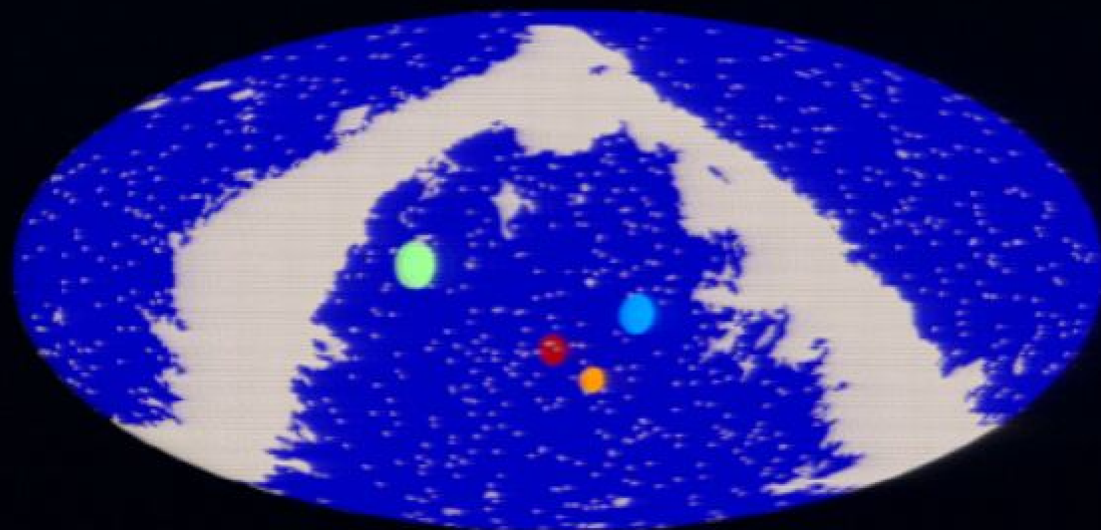
significances (sensitive to 5 - 14 degrees)



11 features pass thresholds, with detections in multiple needlet types/frequencies

WMAP7 W-Band: Bayesian Analysis

- Main contribution to posterior from 4 blobs



- Obtain $N_S < 1.6$ at 68% CL: no need to supplement LCDM with bubble collisions (yet)
- *Planck* will provide increased resolution (3x) and sensitivity (10x) to discern weaker signals