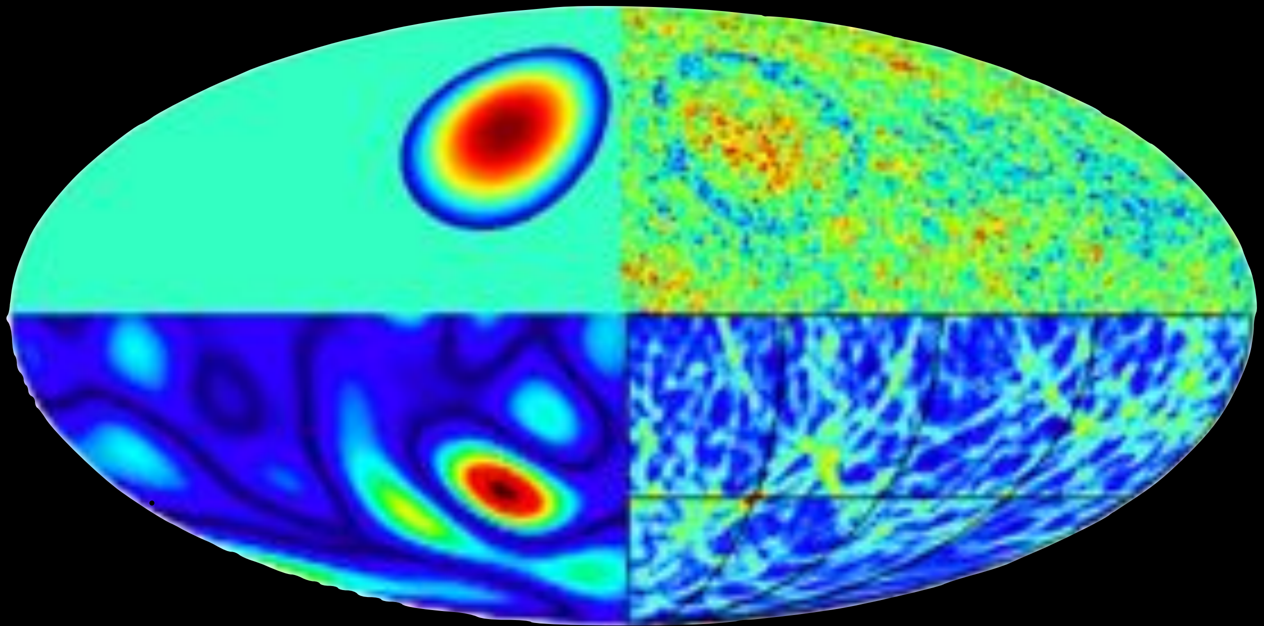
First observational tests of eternal inflation



Hiranya Peiris

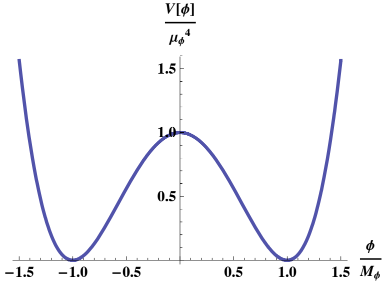
University College London

arxiv:1012.1995

With: Stephen Feeney (UCL), Matt Johnson (Perimeter Institute), Daniel Mortlock (Imperial College London)

The Vacuum Crisis

- Theories of particle physics with a unique vacuum are hard to come by.
- Spontaneous symmetry breaking gives rise to multiple vacua:



Happens in the Standard Model, Grand Unified Theories, Supersymmetry...

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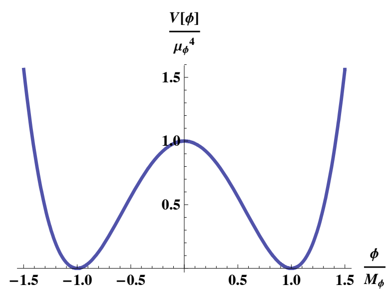

Happens in the Standard Model, Grand Unified Theories, Supersymmetry...

- A more extreme example arises in String Theory:

The extra dimensions can assume different sizes, topologies, shapes = many 4D vacua!

The Vacuum Crisis

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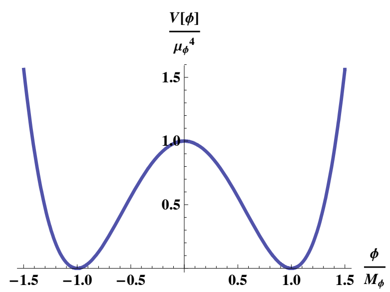
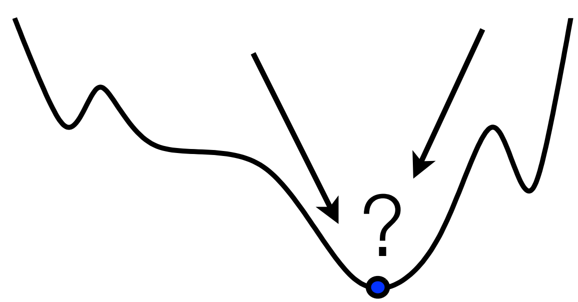


Happens in the Standard Model, Grand Unified Theories, Supersymmetry...

- A more extreme example arises in String Theory:

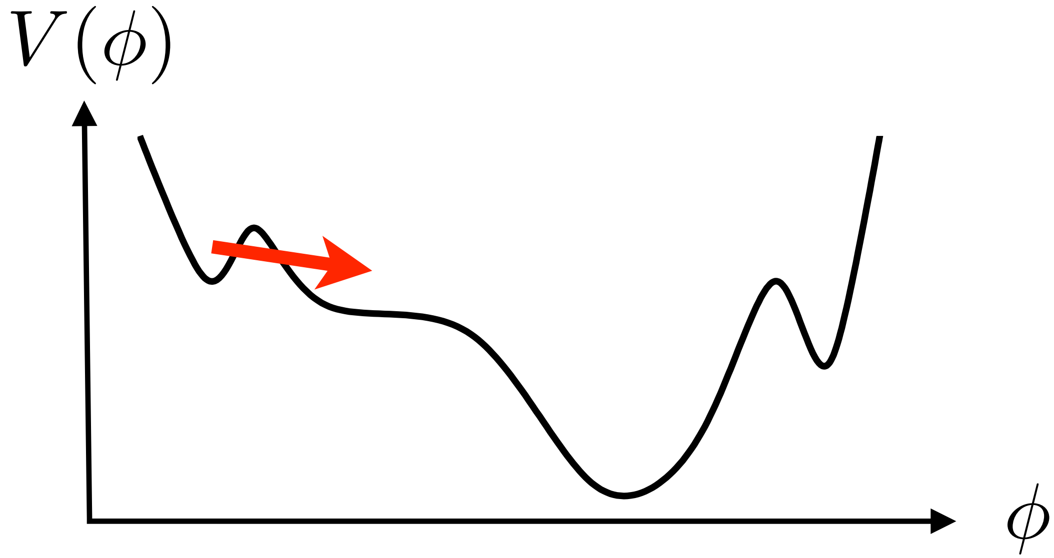
The extra dimensions can assume different sizes, topologies, shapes = many 4D vacua!

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



Eternal Inflation

- One proposal: all vacua are realized somewhere.



Tunnelling = bubble nucleation

Eternal Inflation

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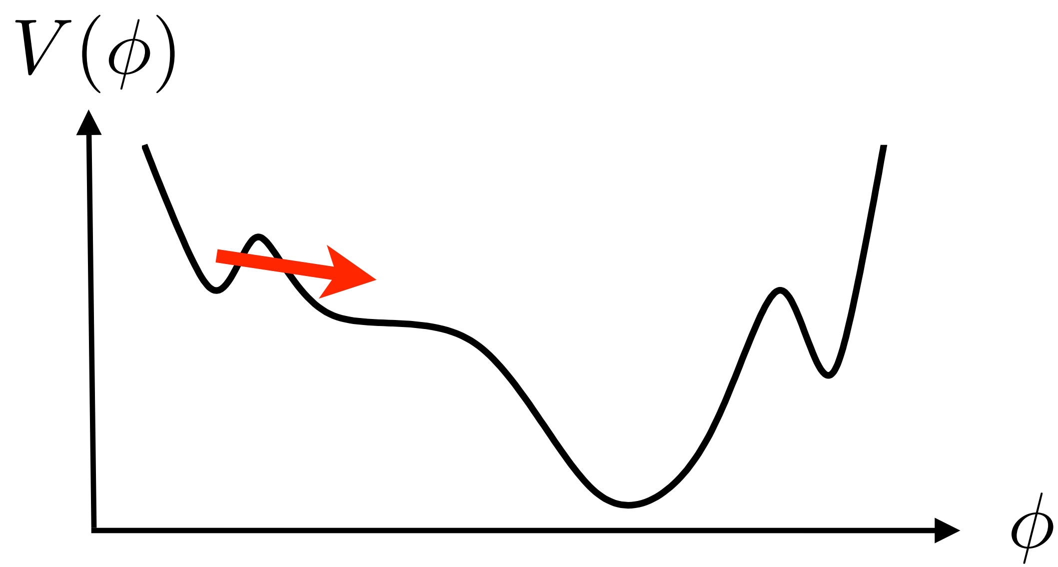
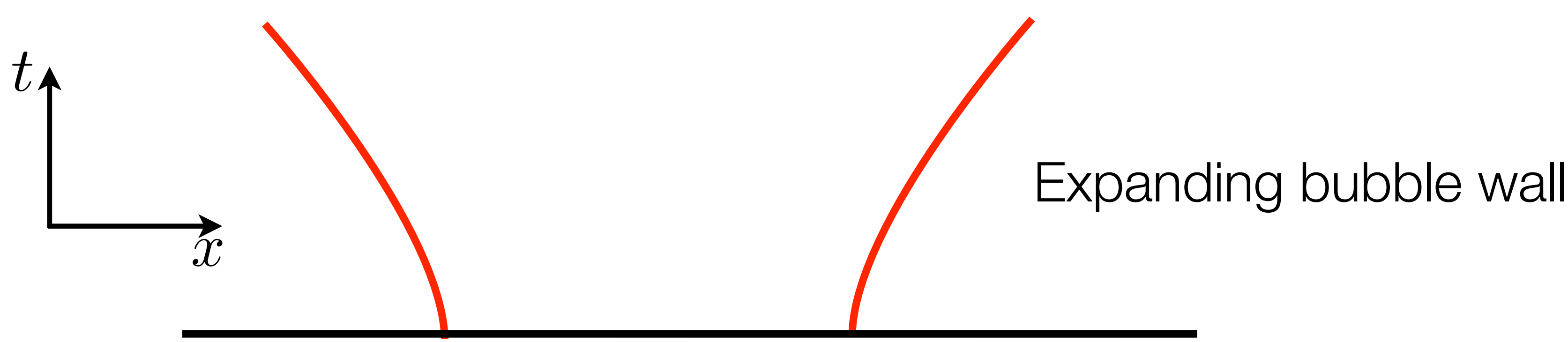


- Our cosmology can be embedded inside the bubble.



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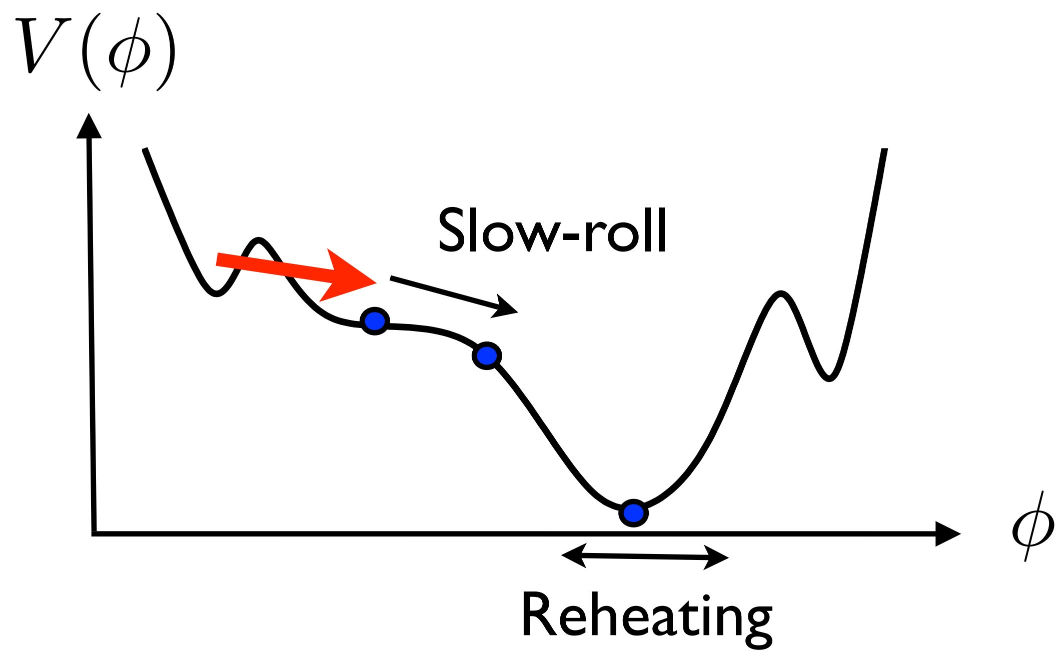

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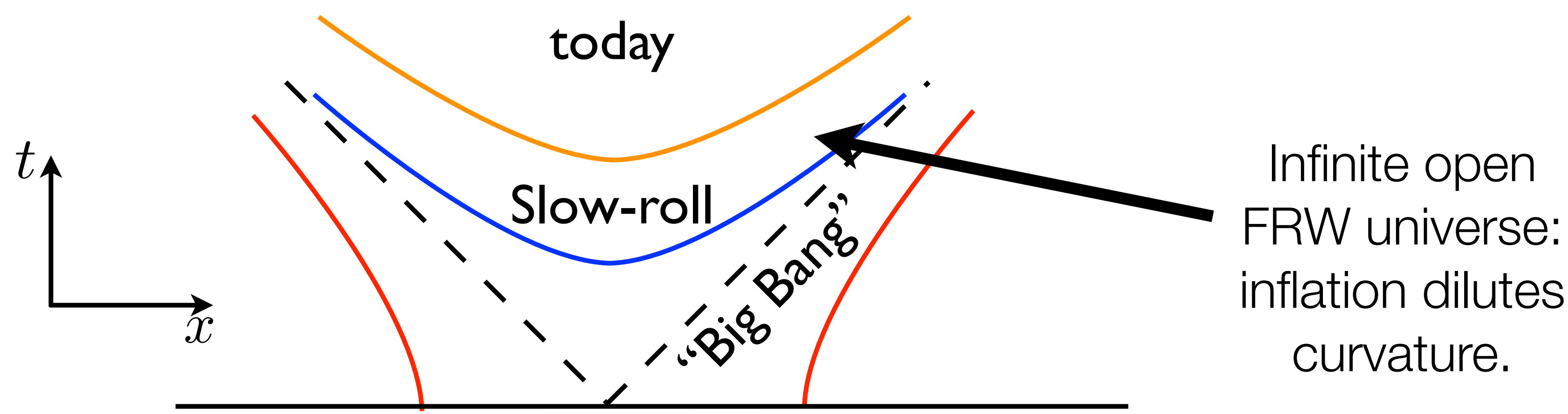
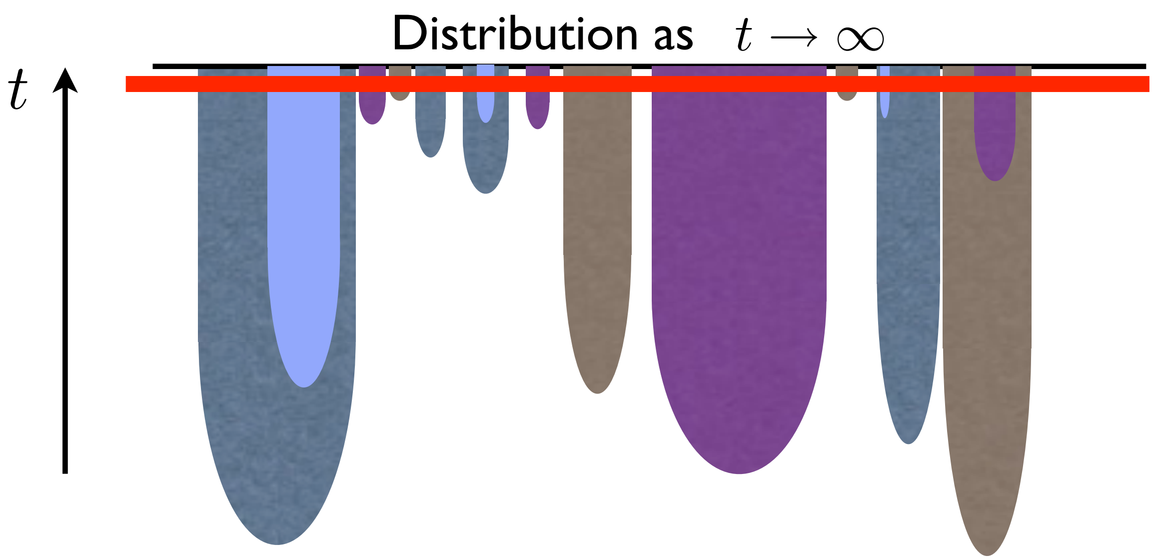
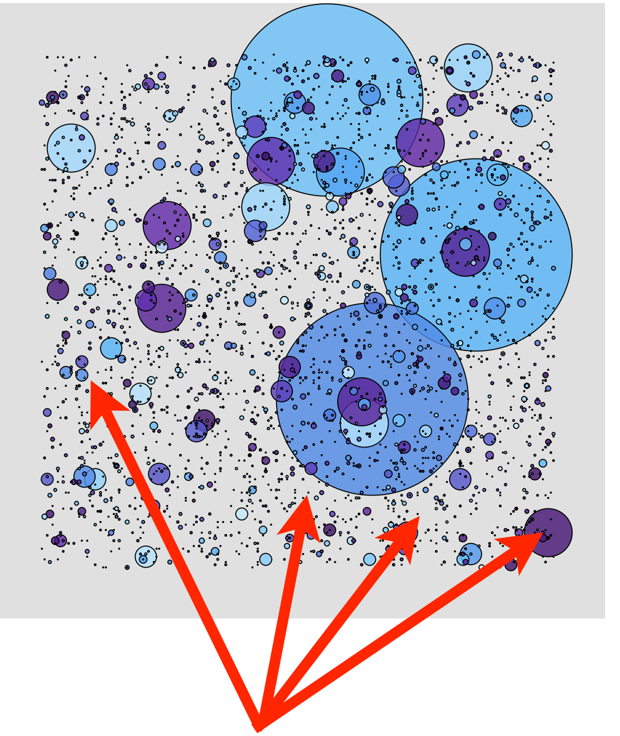


Eternal Inflation

- 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.

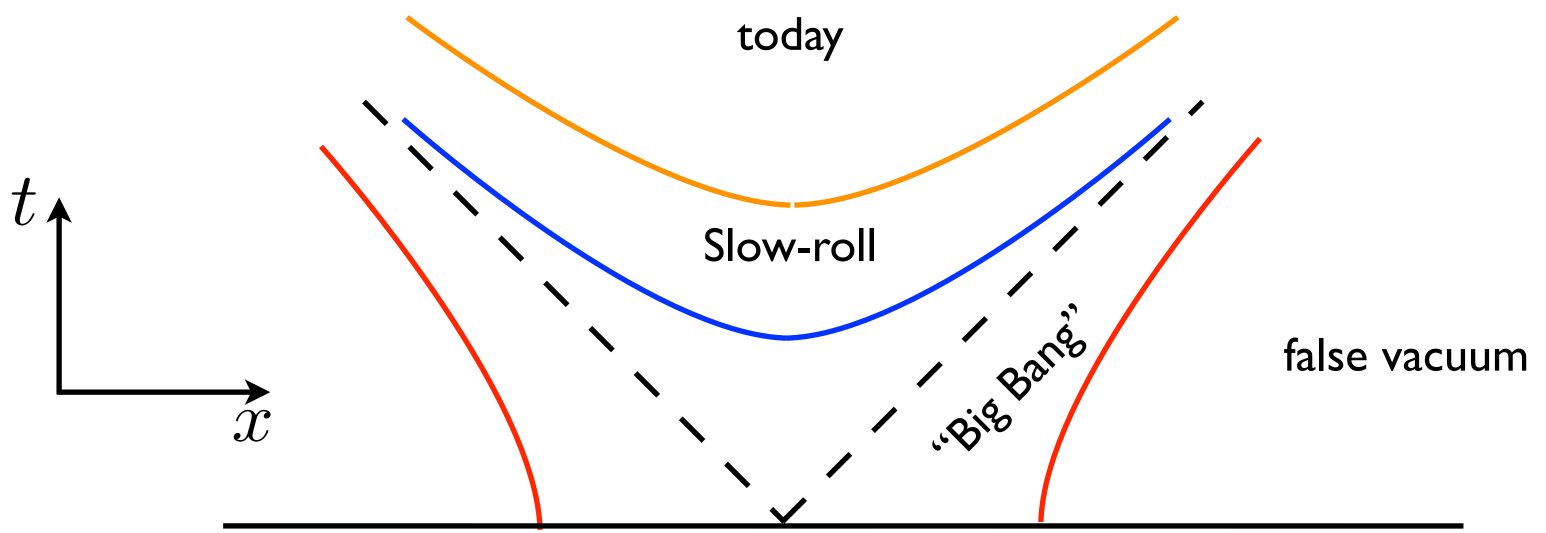
Many more possibilities...

- Landscapes are primarily motivated by extra dimensions: should include their effects!

- In flux compactifications, the dynamics can be very rich:
  - flux-changing transitions
  - decompactification transitions
  - dynamical compactification
  - topology changing transitions: bubble of nothing

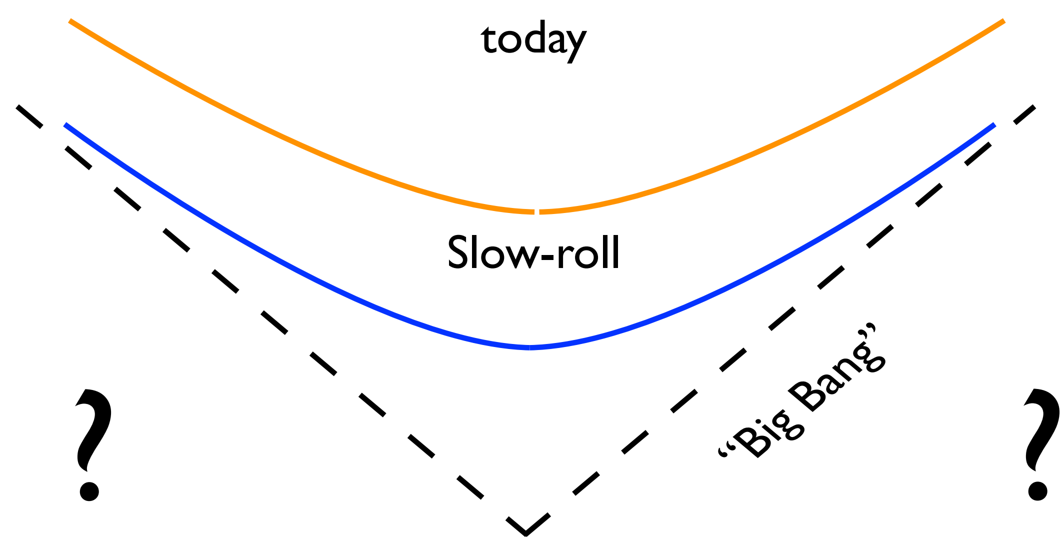
Relevance to our cosmology

- All these dynamical processes can produce a homogenous (but possibly anisotropic) universe inside a "bubble."

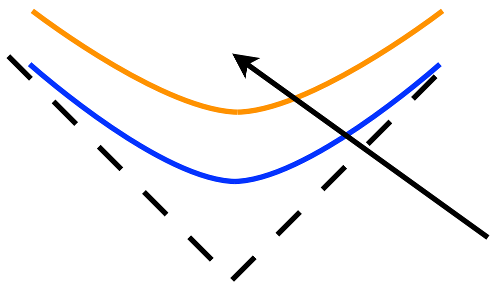


Relevance to our cosmology

- Distinguished by how they turn the "Big Bang" into a coordinate singularity, and what lies on the other side.



Is it observationally verifiable?

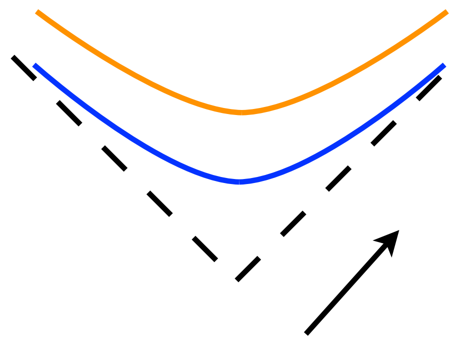


Could look in here, at the properties
of the homogenous cosmology.

- ◉Isotropic or anisotropic curvature.
- ◉Non-trivial topology.
- ◉Modified power spectrum.
- ◉Statistical anisotropy

Not necessarily direct evidence: many ways to make
a homogenous universe....

Is it observationally verifiable?



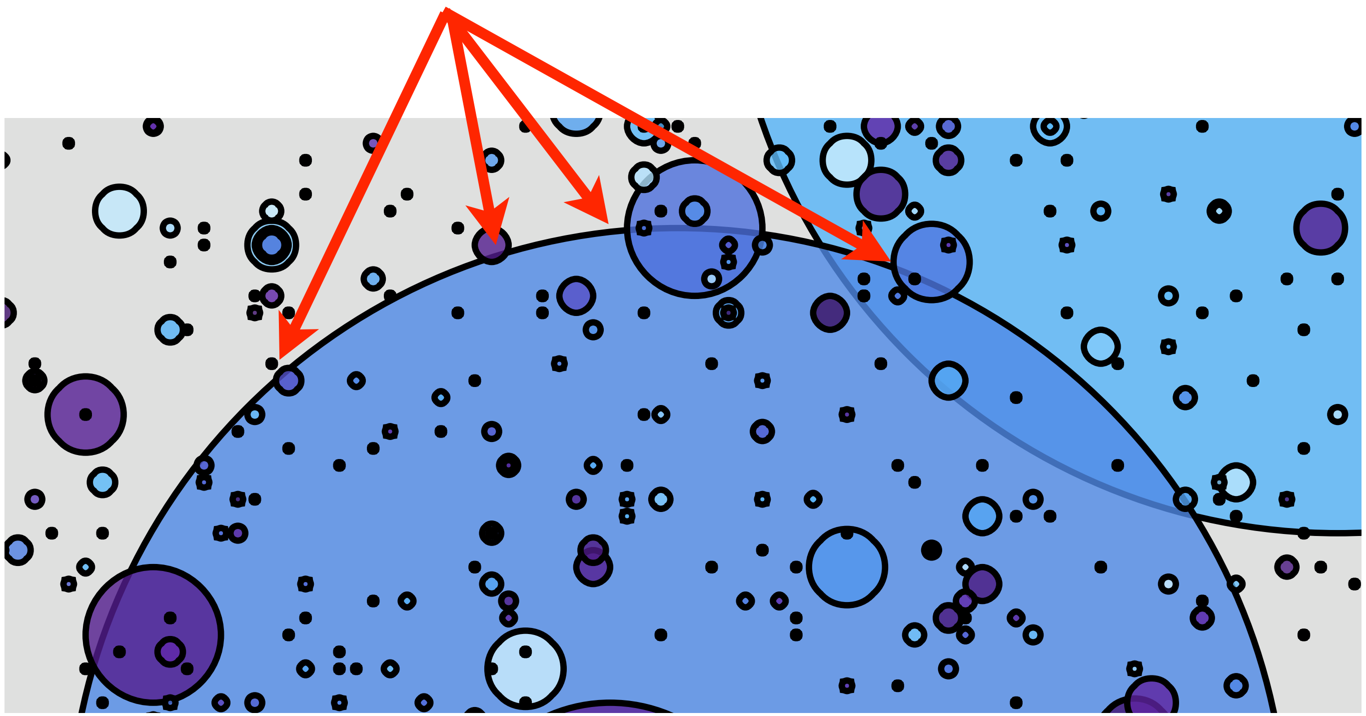
More direct evidence can be found here, by looking for things from the “other side” that can affect the homogeneity of our universe.

Science, or science fiction?

- This picture seems to be a generic consequence of multiple positive energy vacua (could be eternally inflating now!).

- Strong theoretical motivation, but is it experimentally verifiable?

Fractal distribution, so each Bubble collides an infinite number of times!



- Who gets to observe these collisions? What would they see?

To see a collision...

- **Compatibility:** collision must allow for our observed cosmology in its future.
- **Probability:** observing collision should in some sense be likely.
- **Observability:** effects of collision should not be too diluted by inflation.

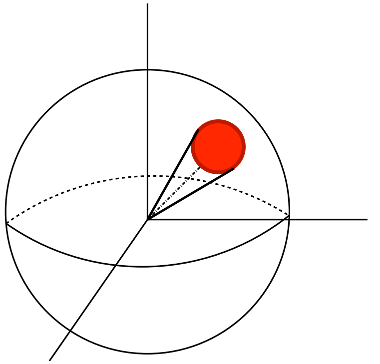
For the rest of the talk, we focus on collisions in purely 4D eternal inflation. Can be extended to the other scenarios.

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

Observability

- Collisions must pass through the cosmology inside the bubble: early universe effect, ideal cosmological probe is the CMB.

- Azimuthal symmetry is preserved in a collision:
    - they show up as discs on our sky.



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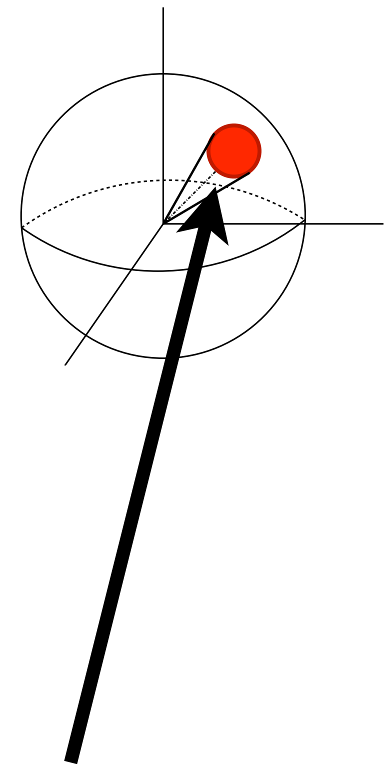
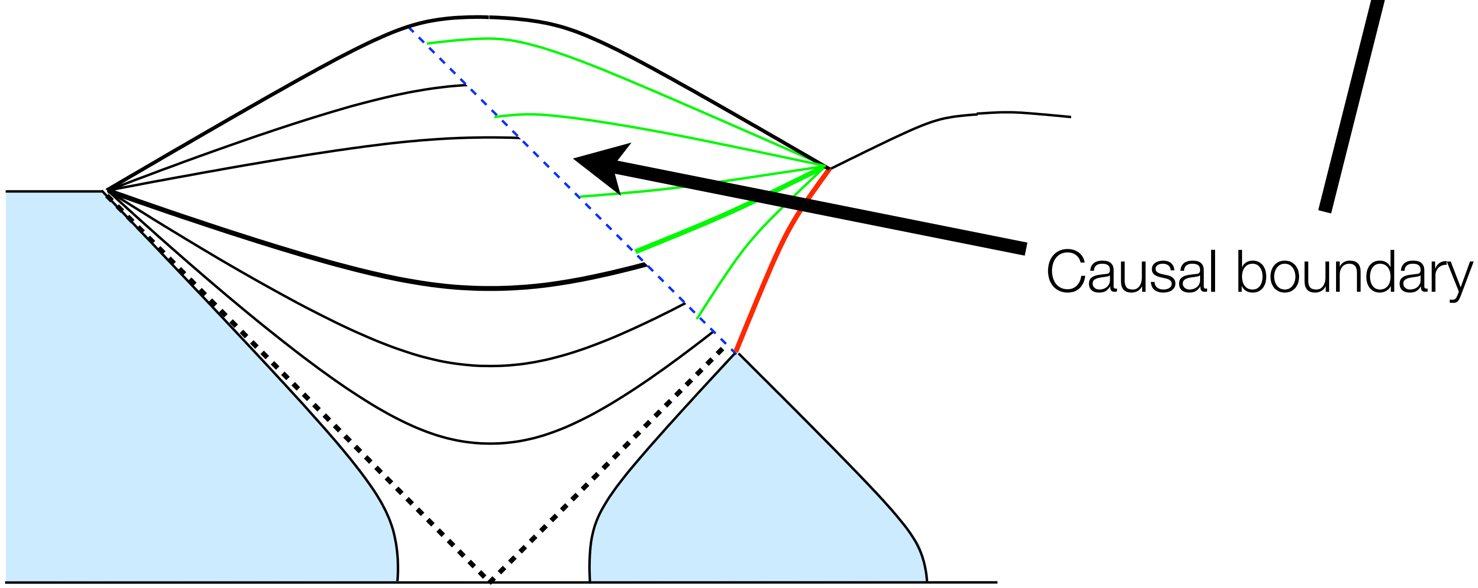
  - we might expect edges.





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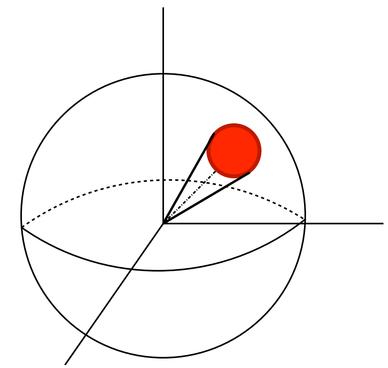

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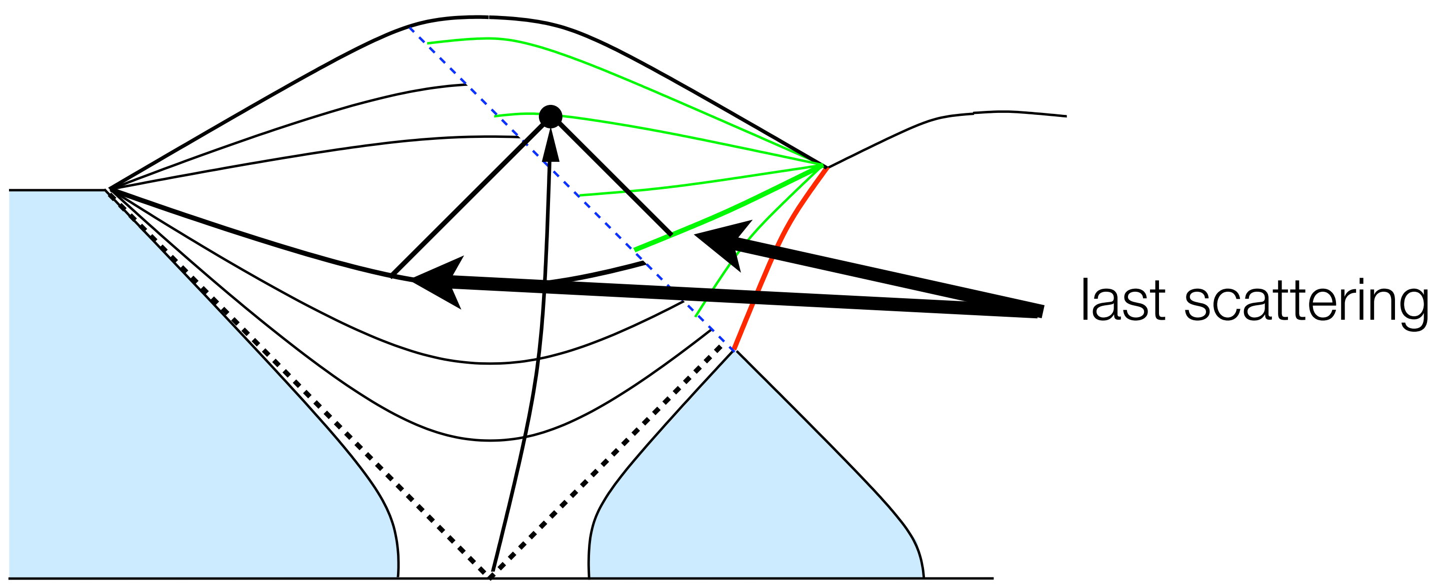
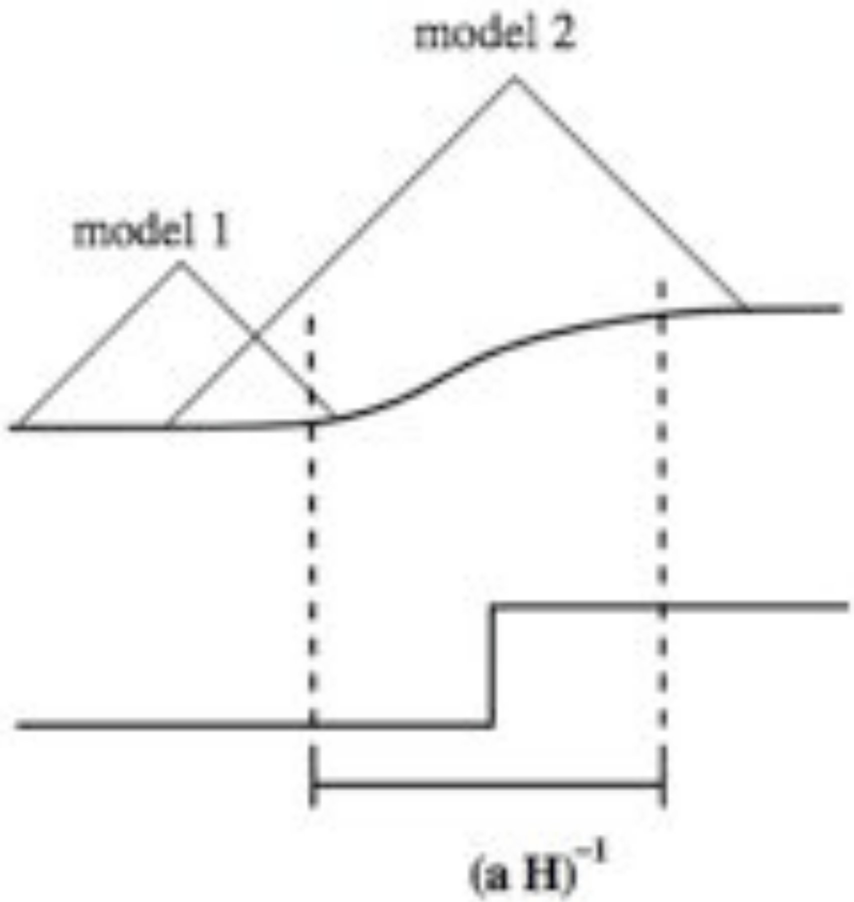
- Observers will see modulation of fluctuations on the last scattering surface.



Bubble morphologies

- Analysis will target following generic features expected in a collision (from analytic arguments backed up by simulations of Chang, Kleban & Levi.)
    - Azimuthal symmetry
    - Causal boundary
    - Long wavelength modulation inside the disk



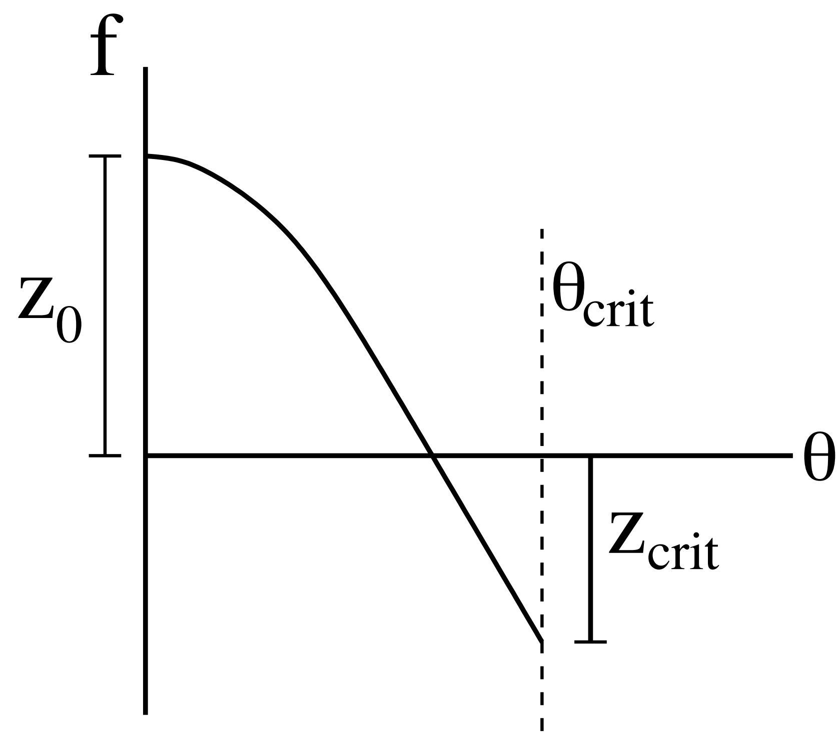
How a violent disturbance of the field at the collision is stretched and smoothed by inflation.

Bubble template

- Assume that the inflationary fluctuations are modulated by the collision (Chang et al 2009):

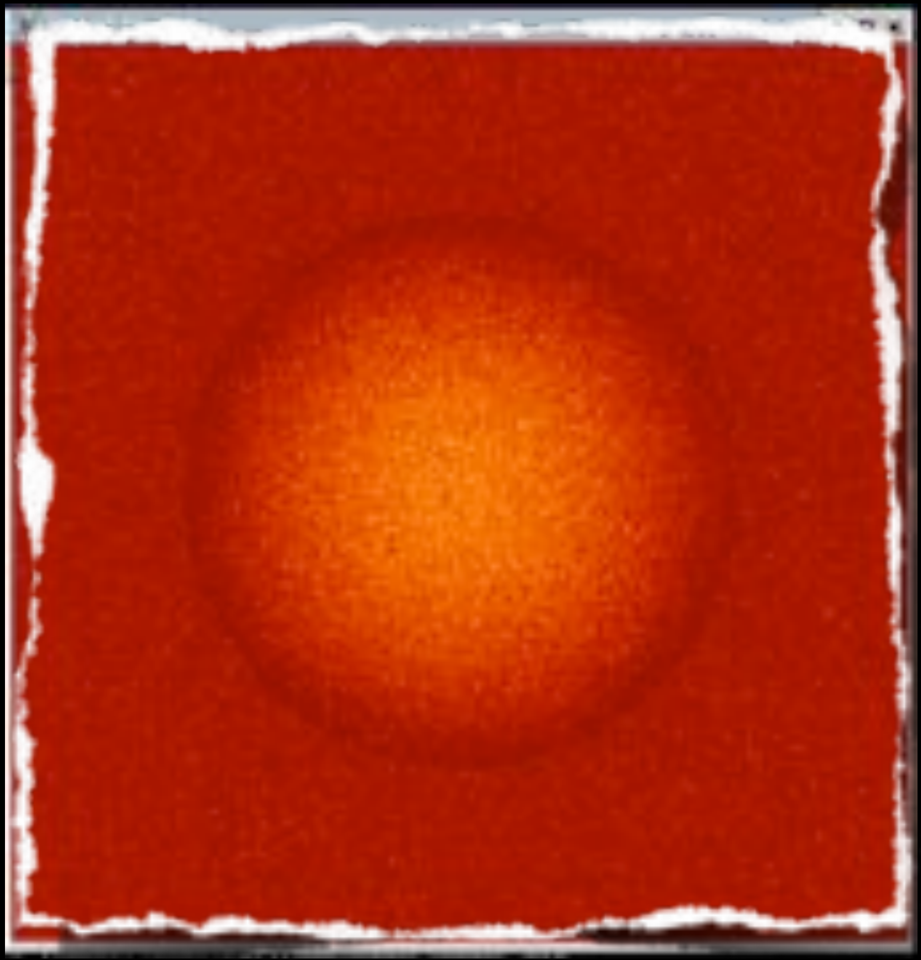
$$\frac{\delta T(\hat{\mathbf{n}})}{T_0} = (1 + f(\hat{\mathbf{n}}))(1 + \delta(\hat{\mathbf{n}})) - 1,$$

- Since the collision is a pre-inflationary relic, a reasonable template is: $f(\hat{n}) = (c_0 + c_1 \cos\theta + \mathcal{O}(\cos^2\theta))\Theta(\theta_{\rm crit} - \theta)$



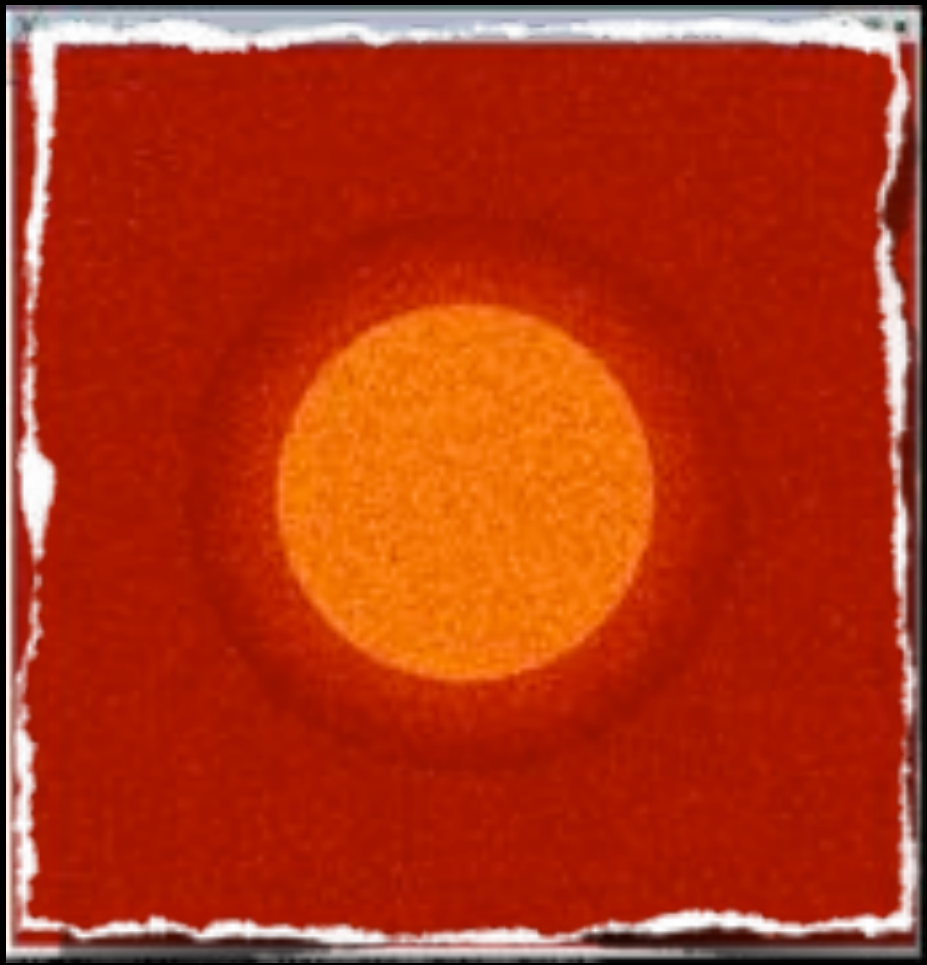
Bubble template

Model 1



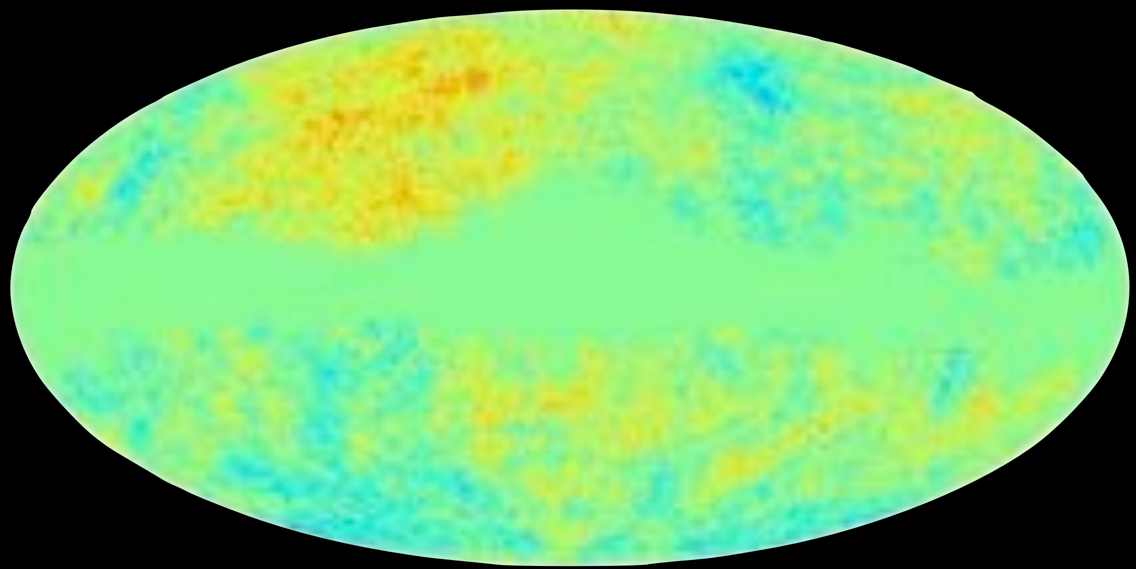
See small portion of smoothed collision

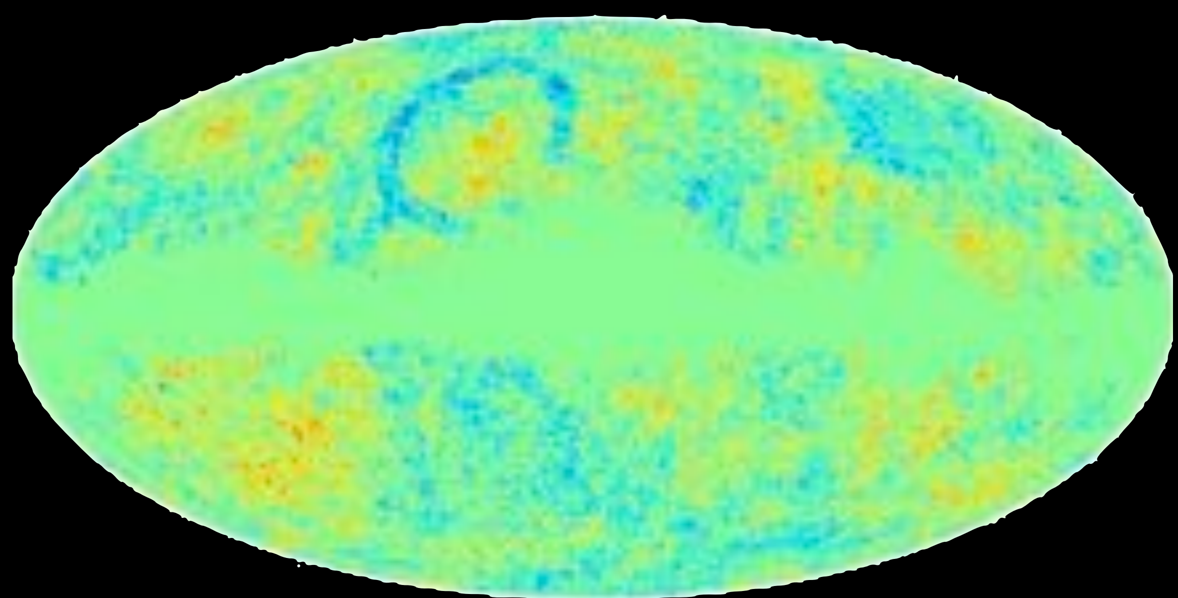
Model 2



See large portion of smoothed collision

Exaggerated CMB examples





data analysis pipeline

- collision localized on the sky: don’t want to go to harmonic space.

- Observables:
  - -azimuthal symmetry
  - -causal boundary
  - -long-wavelength modulation inside a disk

- Pipeline:
  - wavelet analysis: good for picking out localized features
  - edge detection: sensitive to causal boundary
  - Bayesian model selection/parameter estimation: sensitive to the whole model

needlet transform (a.k.a. blob detector)

- spherical needlets have nice localization properties in both real and harmonic space

- Use three types:

  -standard spherical needlets B=2.5
  -standard spherical needlets B=1.8
  -Mexican needlets with B=1.4

- "Bandwidth parameter" B chosen for physics reasons (sensitivity to bubble sizes of interest)

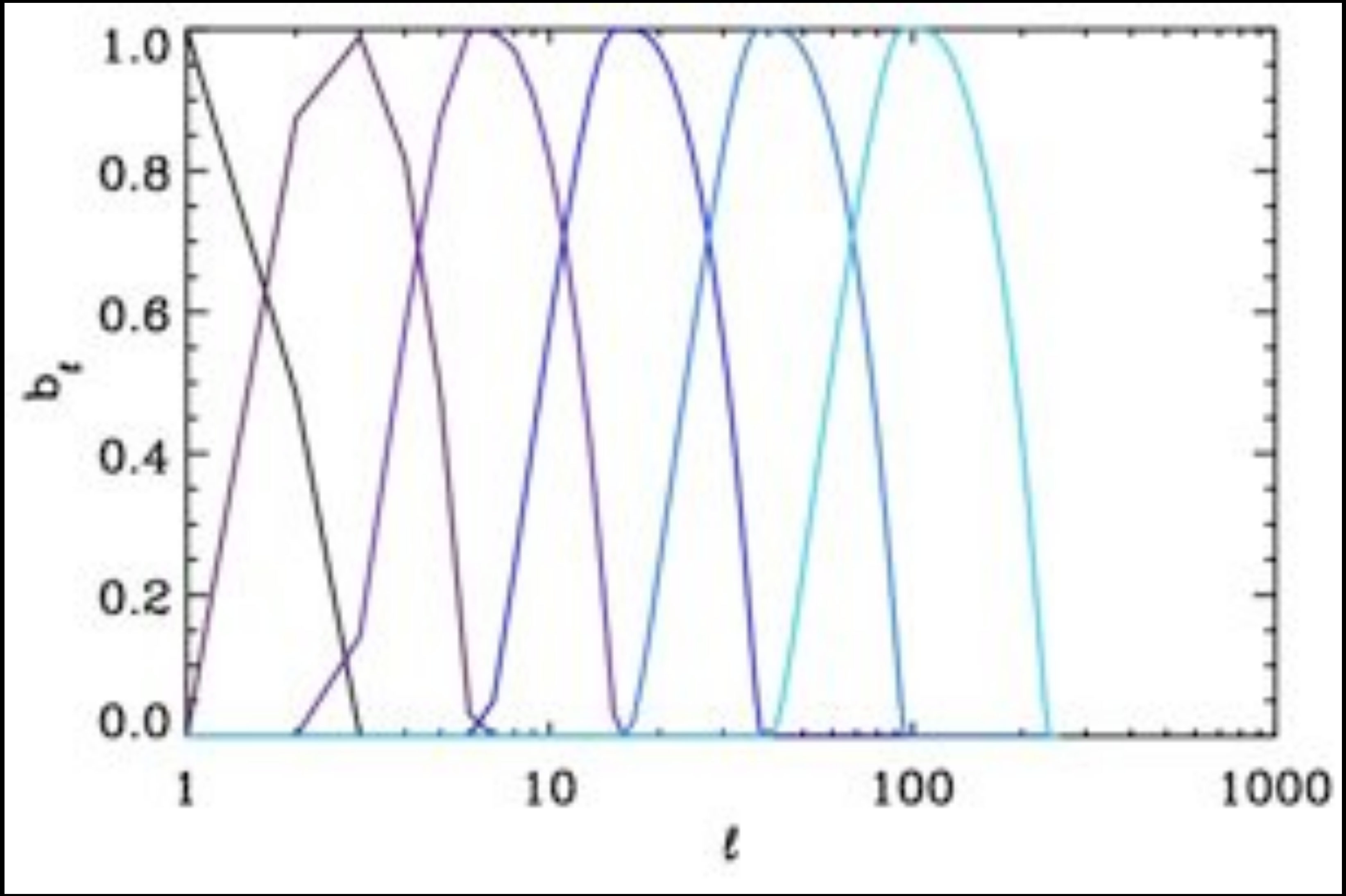
- Calibrate variance at each pixel for a given mask with 3000 cosmic variance sims (interested in features at large scales where WMAP is CV-limited)

needlet coefficient map

$$\beta_{jk} = \sqrt{\lambda_{jk}} \sum_{\ell} b\left(\frac{\ell}{B^j}\right) \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{\gamma}_k)$$

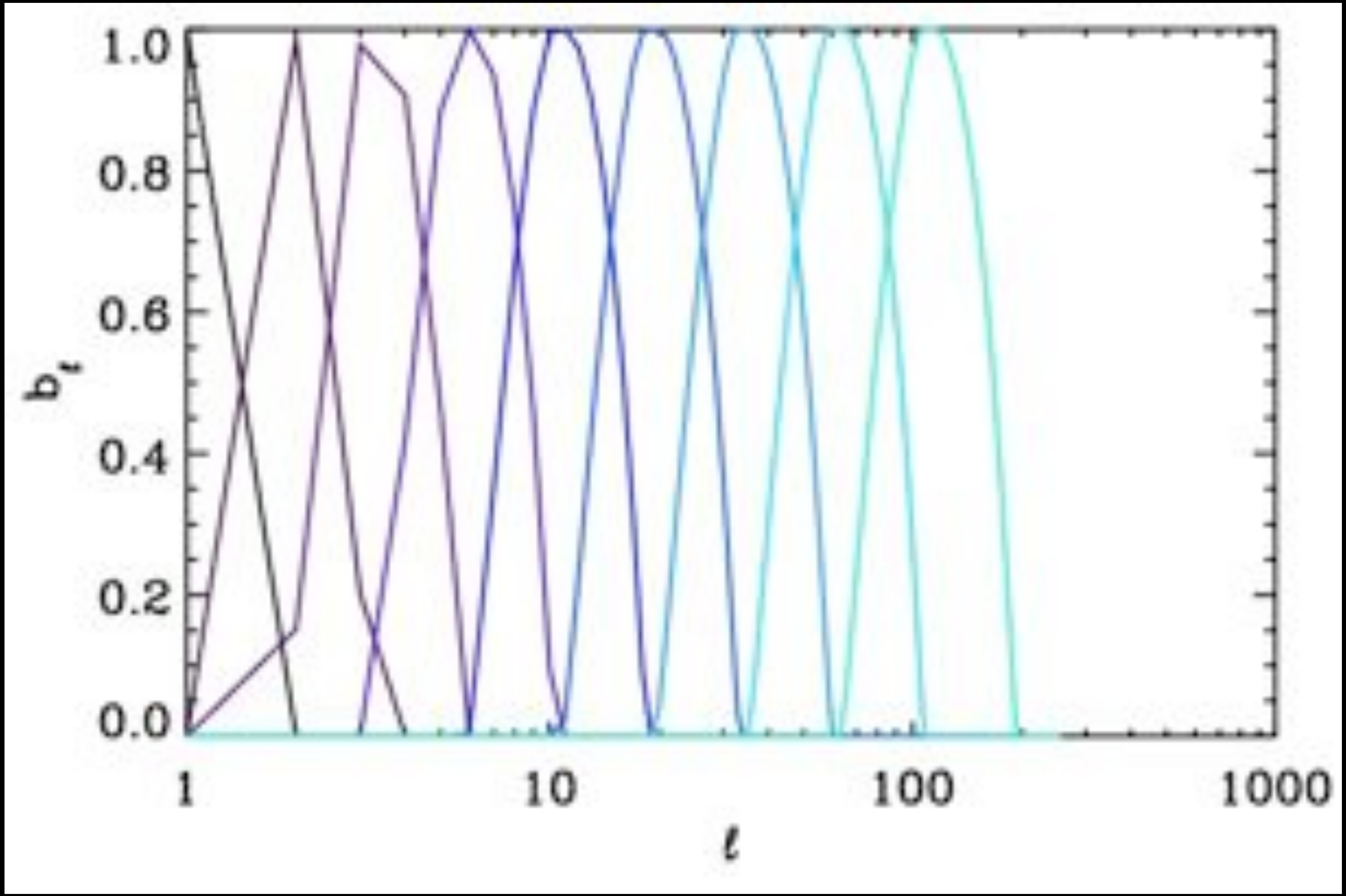
B = “bandwidth”
j = frequency
k = pixel

Standard needlets B=2.5



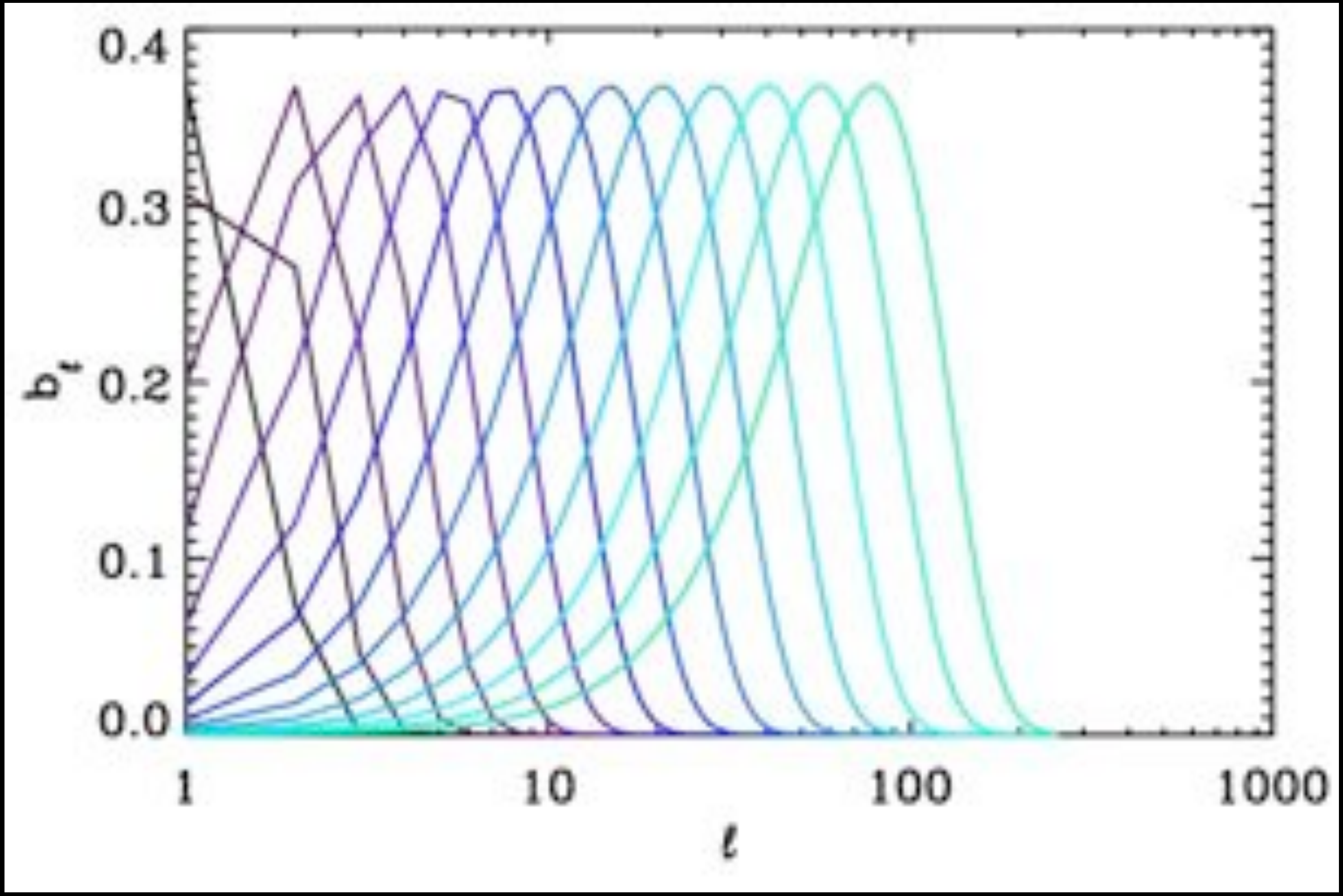
Marinucci et al. (arxiv: 0707.0844)

Standard needlets B=1.8



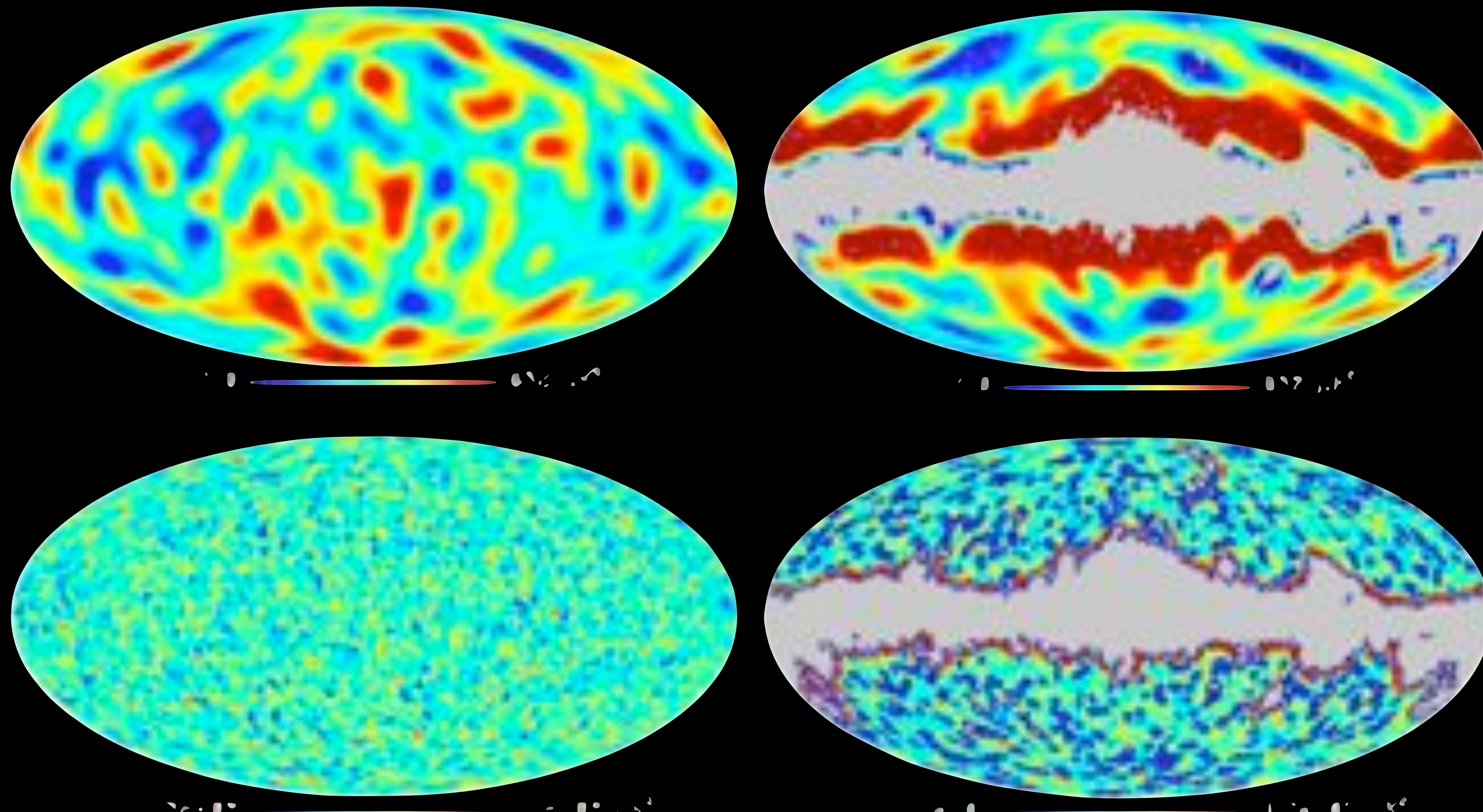
Marinucci et al. (arxiv: 0707.0844)

Mexican needlets B=1.4



Scodeller et al. (arxiv: 1004.5576)

needlet variances



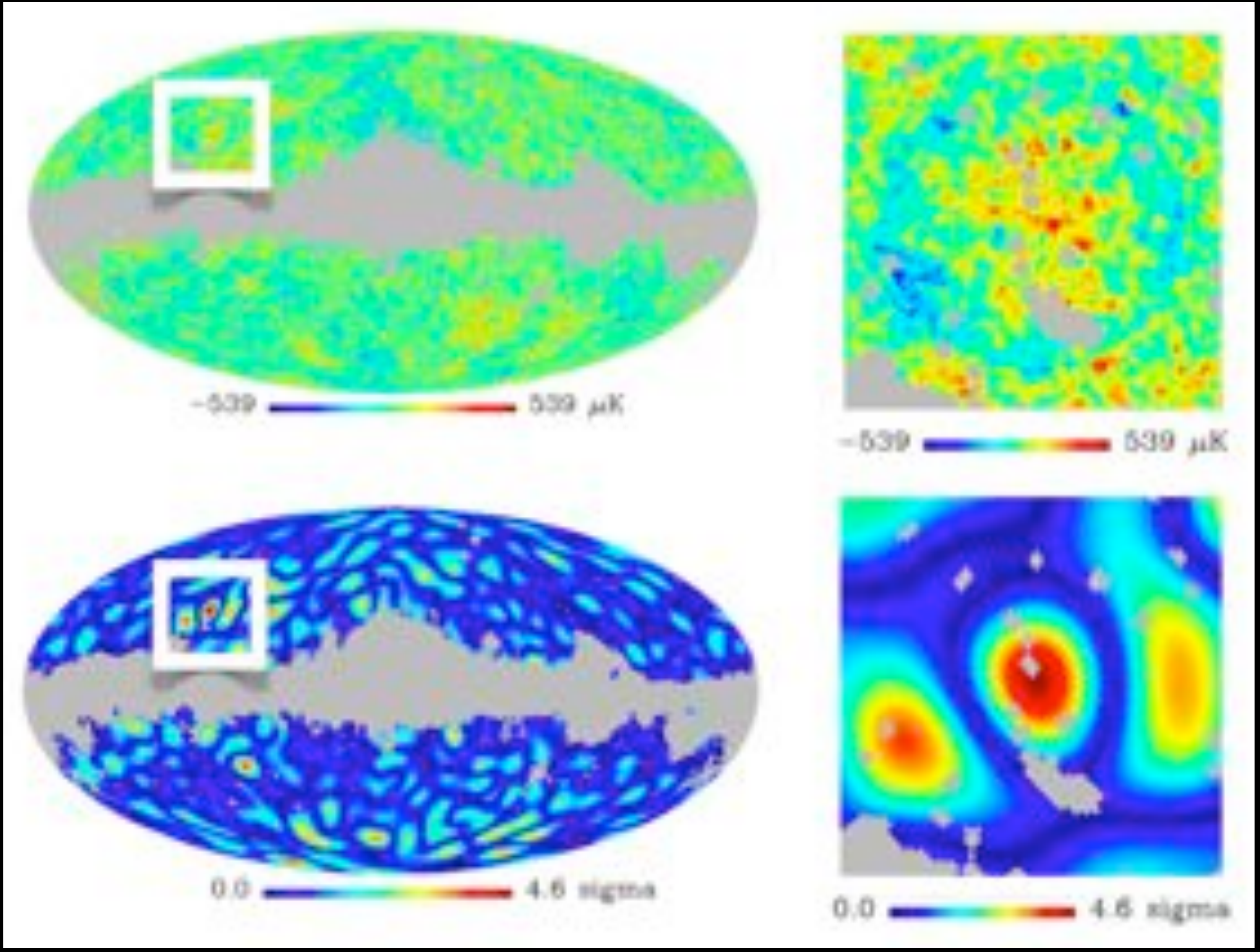
Top row: standard needlets B=2.5, j=2
Bottow row: Mexican needlets B=1.4, j=11

needlet significance statistic

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

j = frequency
k = pixel

simulated needlet detection example

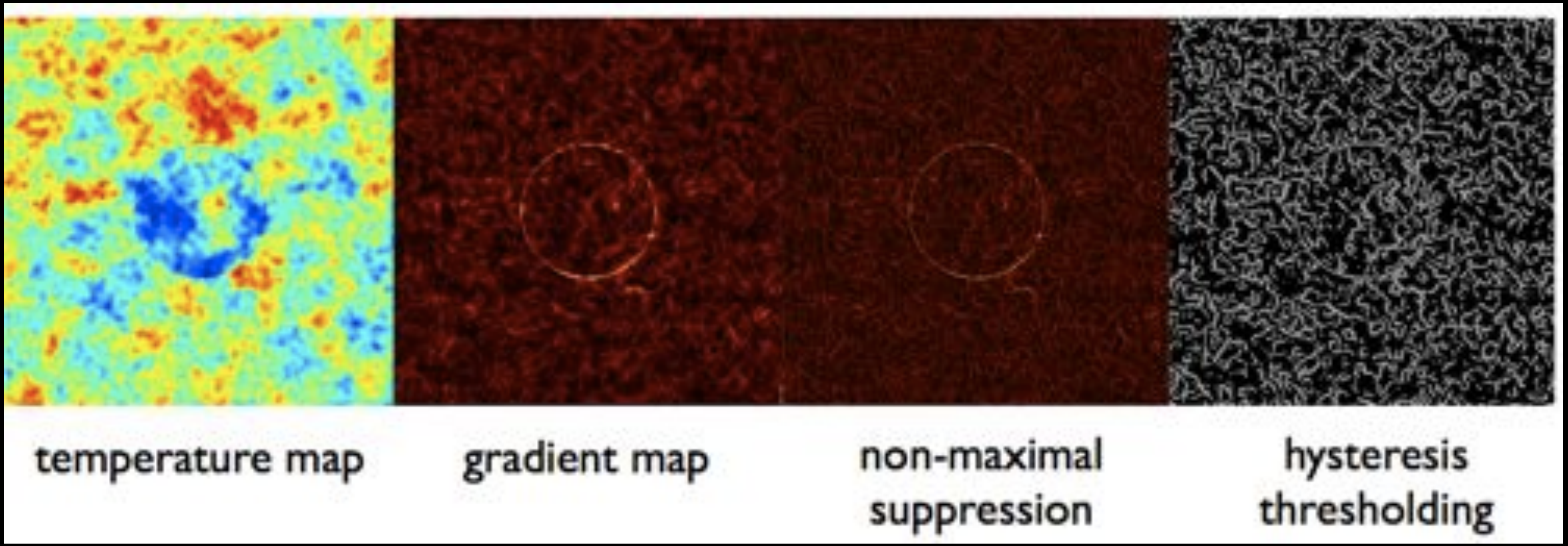


Edge detection algorithm

- Current models suggest boundary between regions of the CMB affected and unaffected by a bubble collision will form circular edge.

- Edge detection method used is Canny algorithm:

  - Generate image gradients
  - Thin into single-pixel proto-edges
  - Stitch together into “true” edges

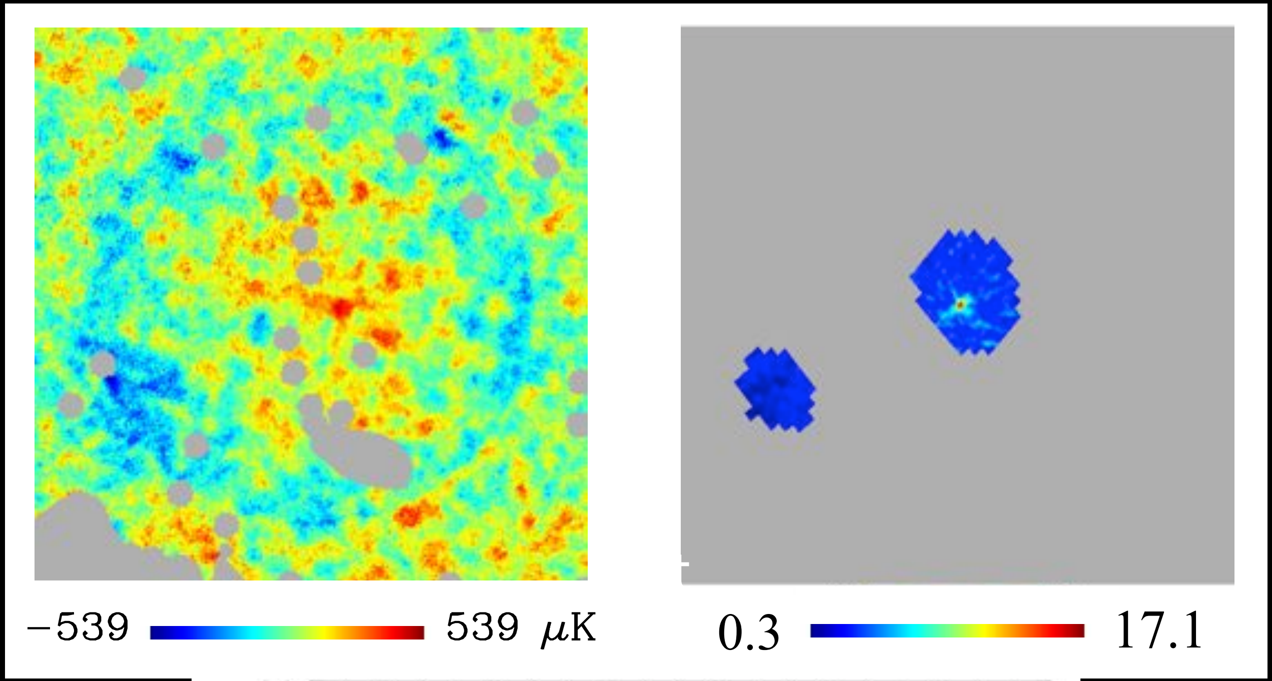


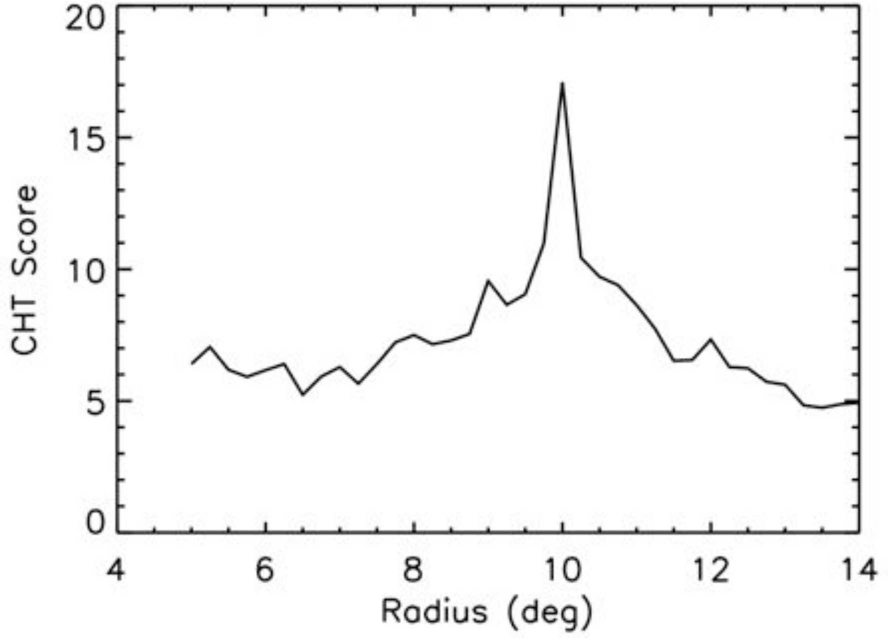
Circular Hough Transform

- Algorithm assumes each true edge pixel lies on the edge of a circle.
  - Scan true edge map accumulating most likely circle centres at a given radius.

Causal edge is a smoking gun of bubble collisions!

simulated CHT detection example





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

Bayesian parameter estimation/model selection

$$\rho = \boxed{\frac{p(M_b | D)}{p(M_0 | D)}} = \boxed{\frac{p(M_b)}{p(M_0)}} \boxed{\frac{Z_b}{Z_0}}$$

evidence ratio

D = data highlighted by needlets
M_0 = CMB + instrument effects
M_b = bubble collision model

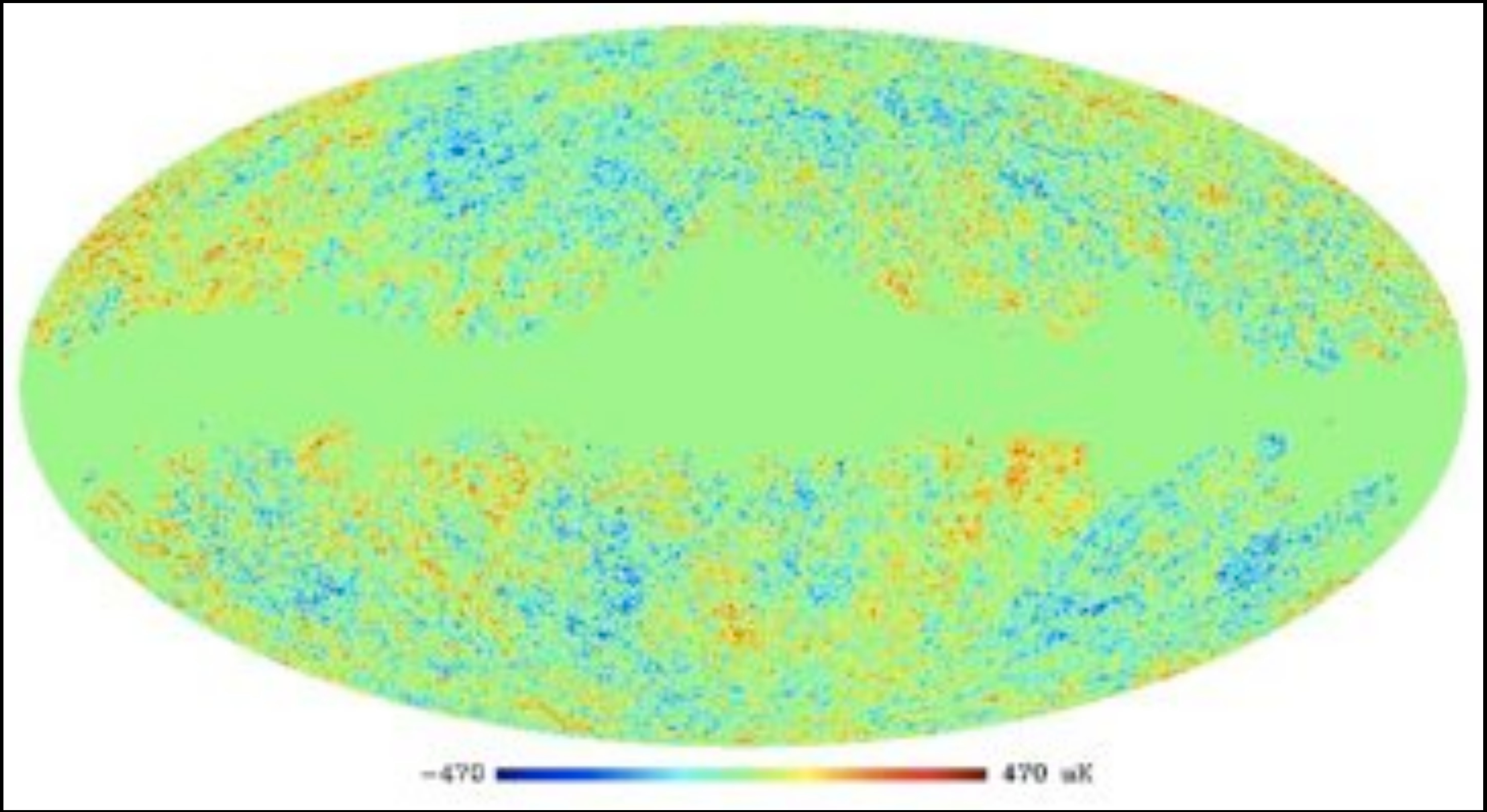
prior model probability ratio (assumed to be 1)

- Calculated using Multinest
- Computationally limited to < 11 deg patches (covmat inversion)
- model priors automatically set

Bayesian step examples

simulated model	ln ρ
large central amplitude, strong edge	130
small central amplitude, strong edge	150
large central amplitude, weak edge	36
weak central amplitude, medium edge	5
small central amplitude, weak edge	3

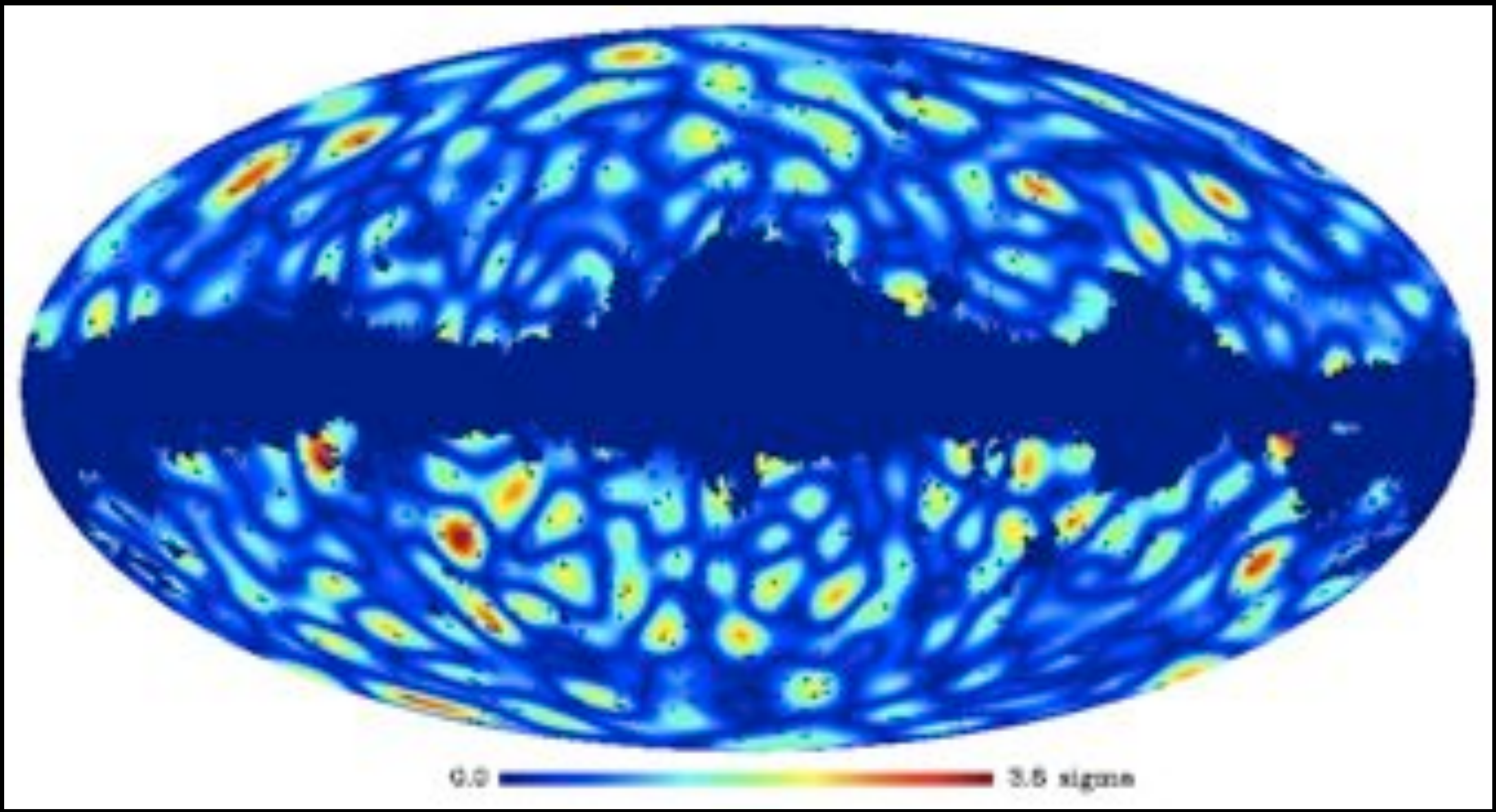
Systematics calibration simulation



WMAP7 W band end-to-end sim: starting from time stream, diffuse and point source foregrounds, realistic instrumental effects

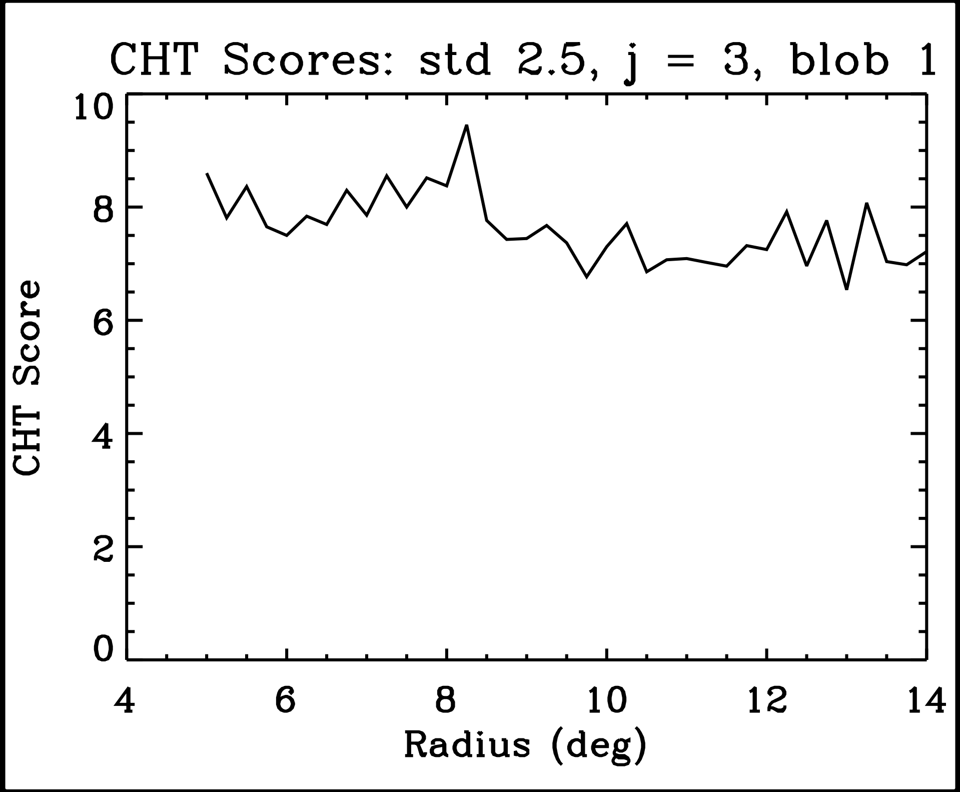
e2e simulation: needlet responses

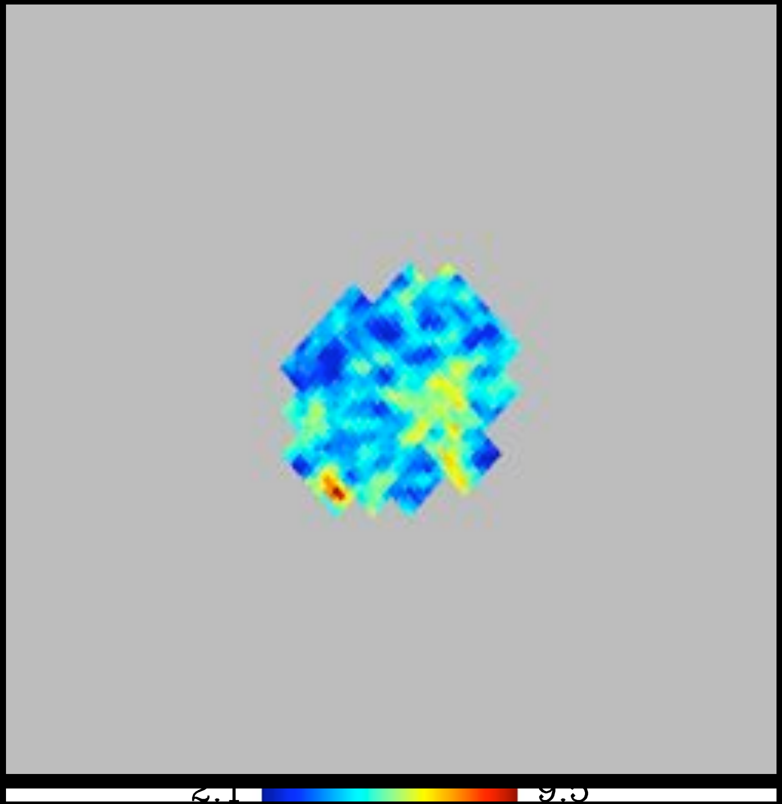
WMAP7 W band sim example: std needlet 2.5 j=3



significances (sensitive to 5 - 14 degrees)

e2e simulation: CHT responses



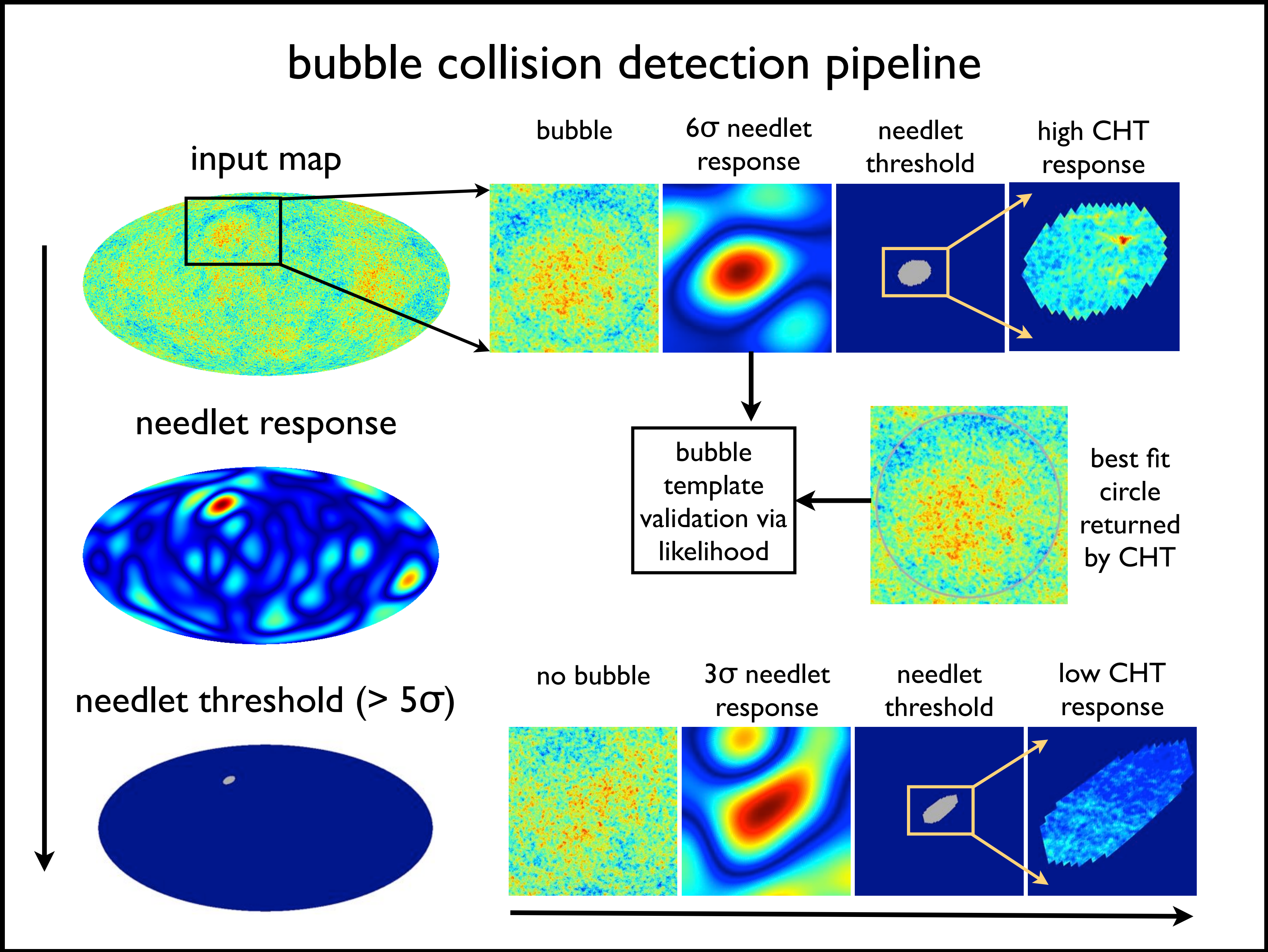


- "peakiest" CHT response found in e2e sim is small: no false detections
- confirms strong CHT peak is a "smoking gun"

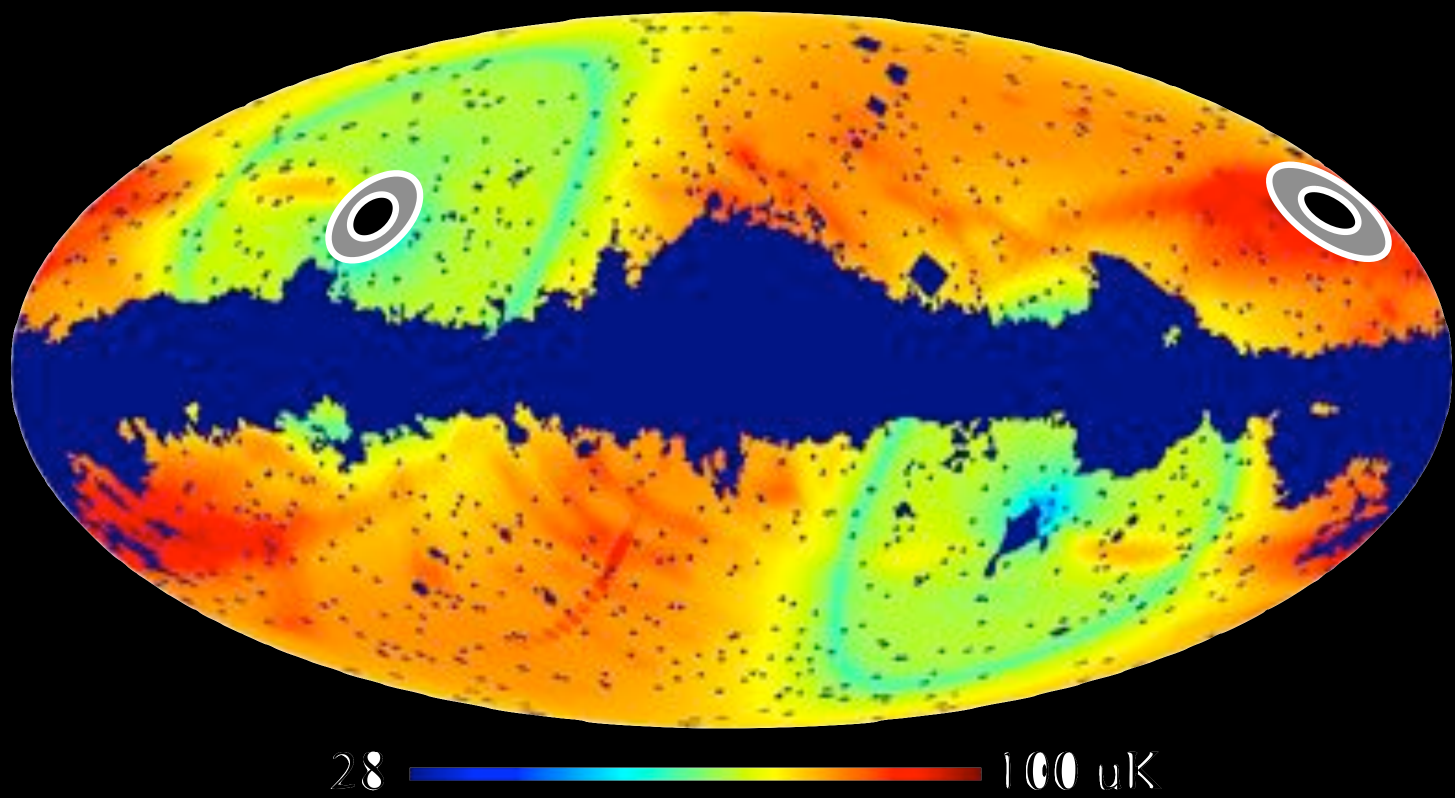
e2e simulation: Bayesian analysis

- Most “false detections” with size > 3 degrees passing the needlet threshold have $\ln \rho \leq 1$.
- The largest evidence for a “false detection” at these angular scales is $\ln \rho = 2.6$.
- For a conclusive detection we require significantly exceeding this threshold.

pipeline summary

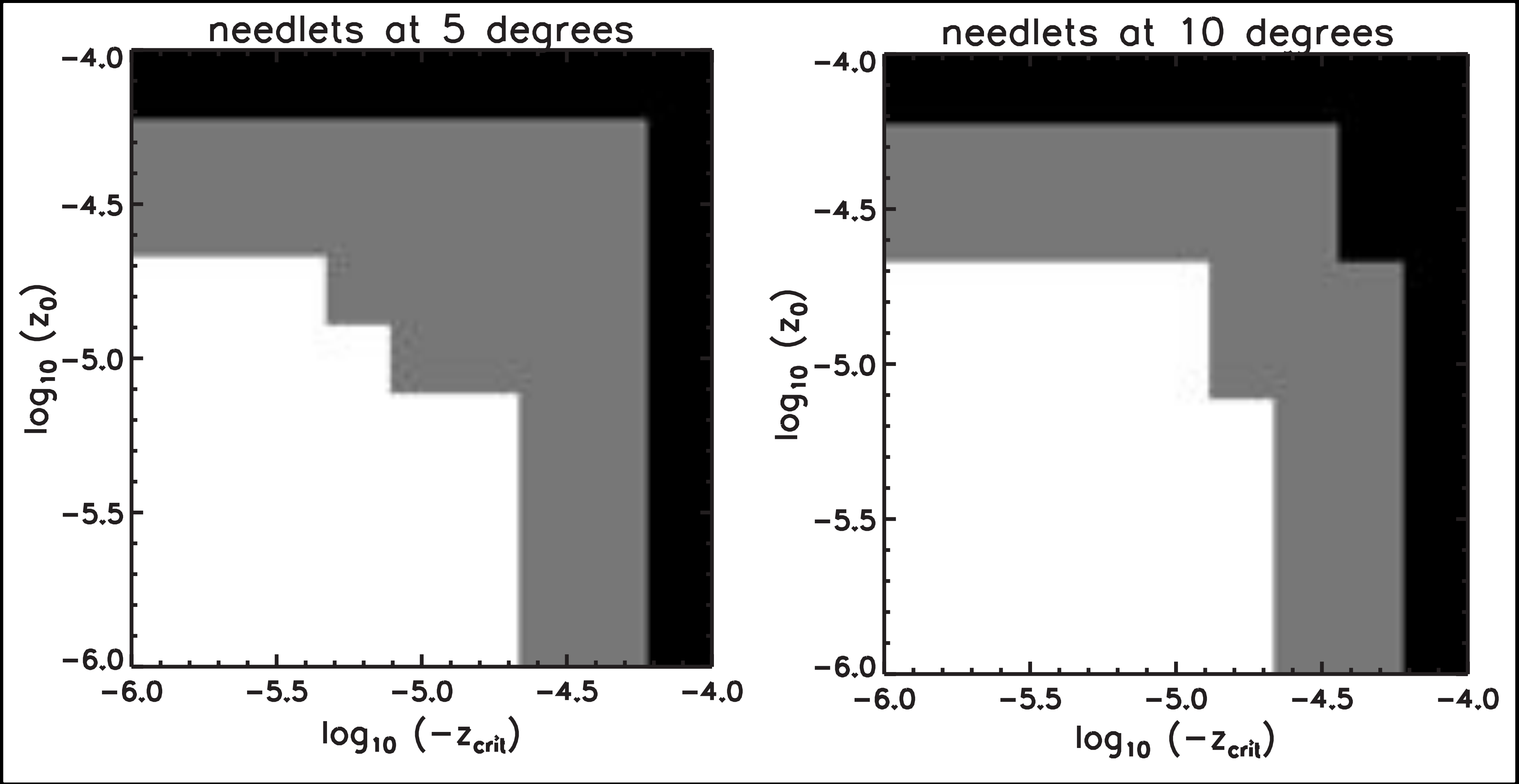


Sensitivity simulations



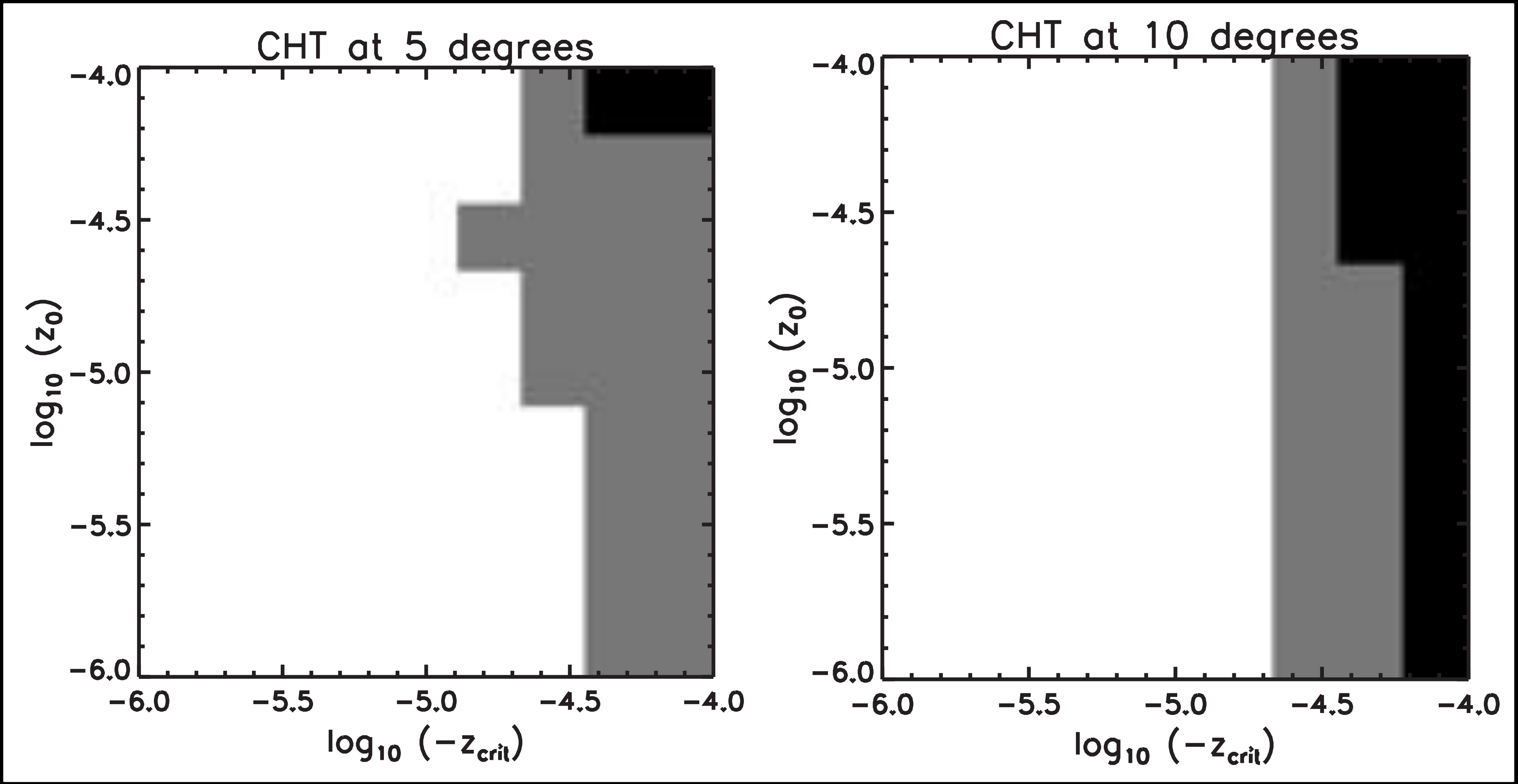
210 CMB+spatially varying noise+beam simulations of 5, 10, 25 degree collisions, sampling 35 representative parameter combinations with 3 CMB realizations each, placed at high/low noise locations

needlet sensitivity/exclusion region



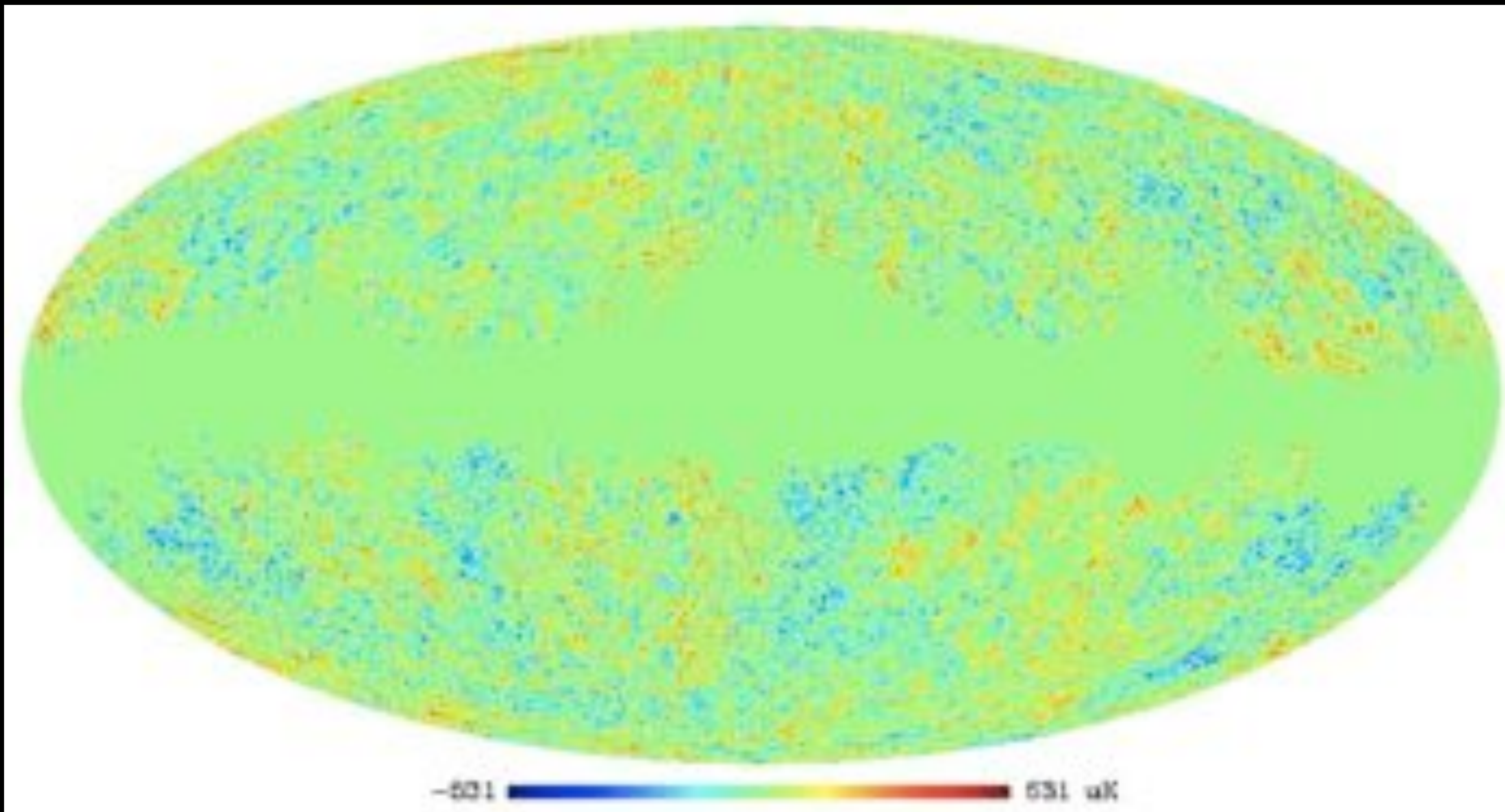
- Bayesian step is also sensitive to anything in the needlet sensitivity/exclusion regions.

CHT sensitivity/exclusion region



- Limited by 1 degree CMB “realization noise” as well as experimental sensitivity/resolution.

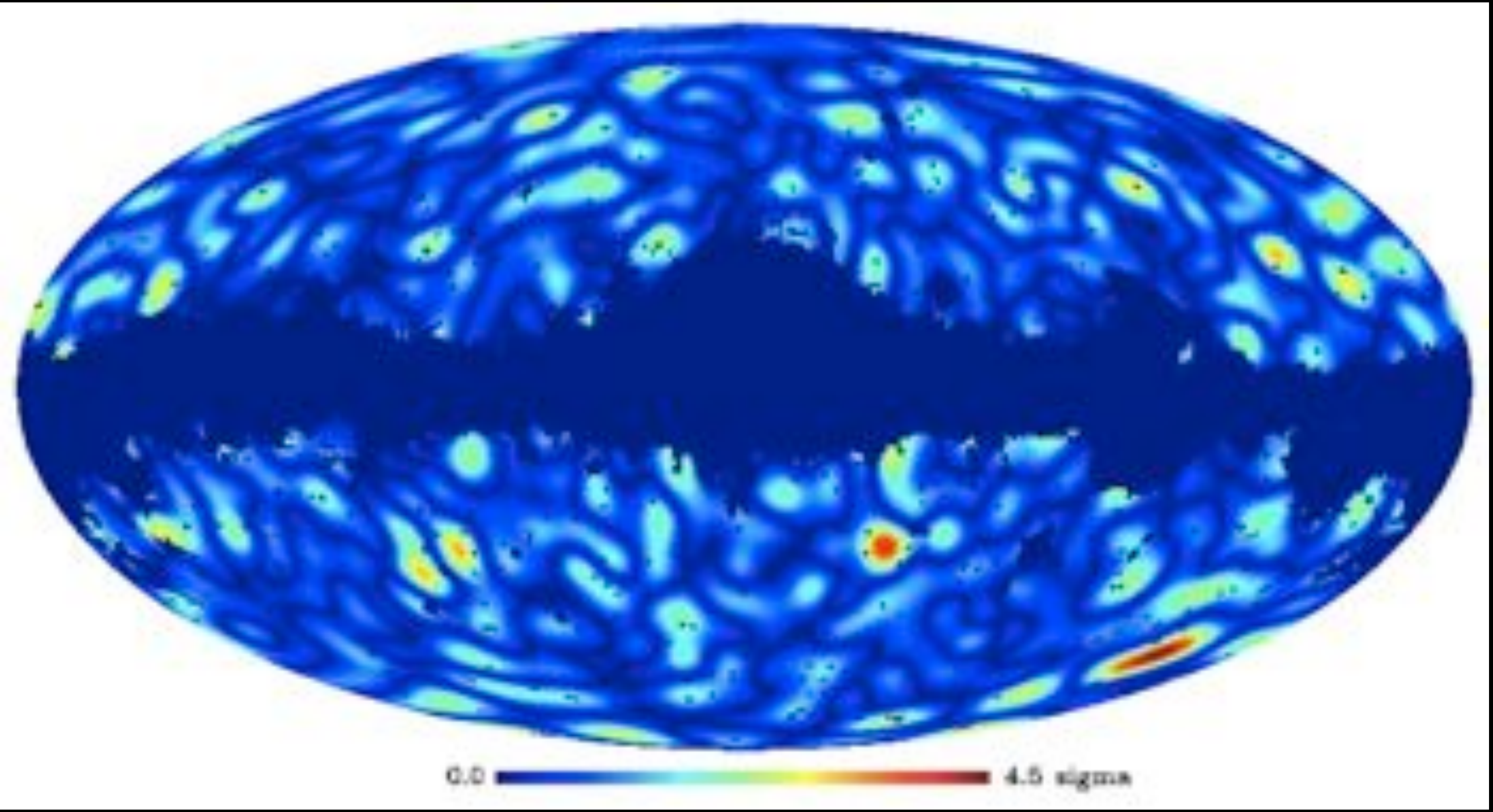
WMAP7 W band (94 GHz)



Highest resolution WMAP channel (beam 0.22 deg)

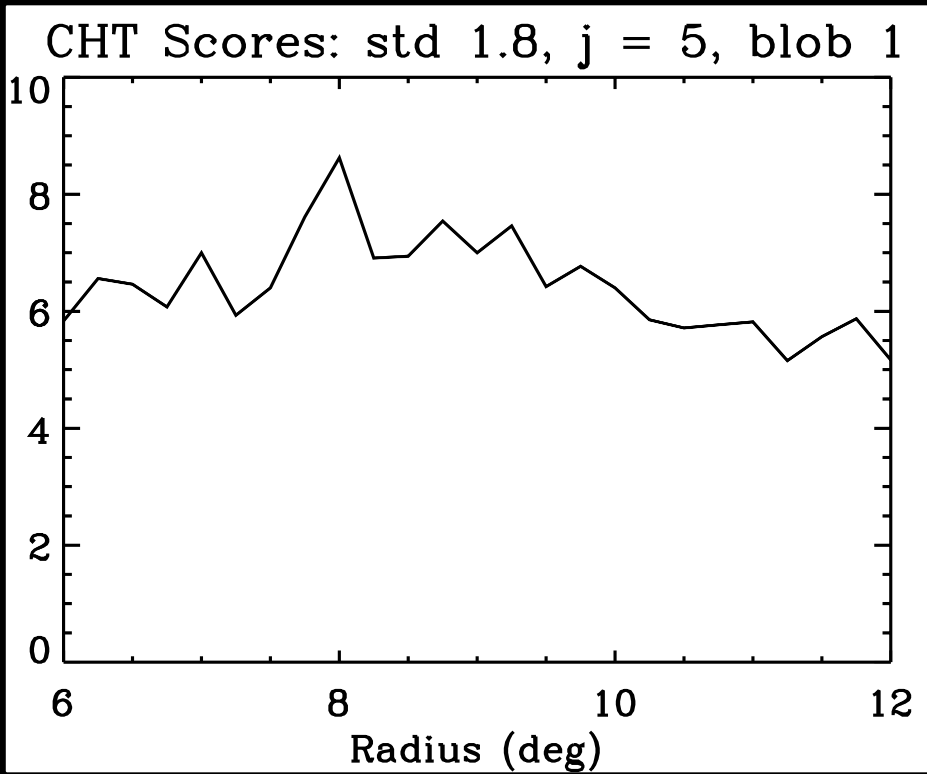
WMAP7 W band example: std needlet 2.5 j=3

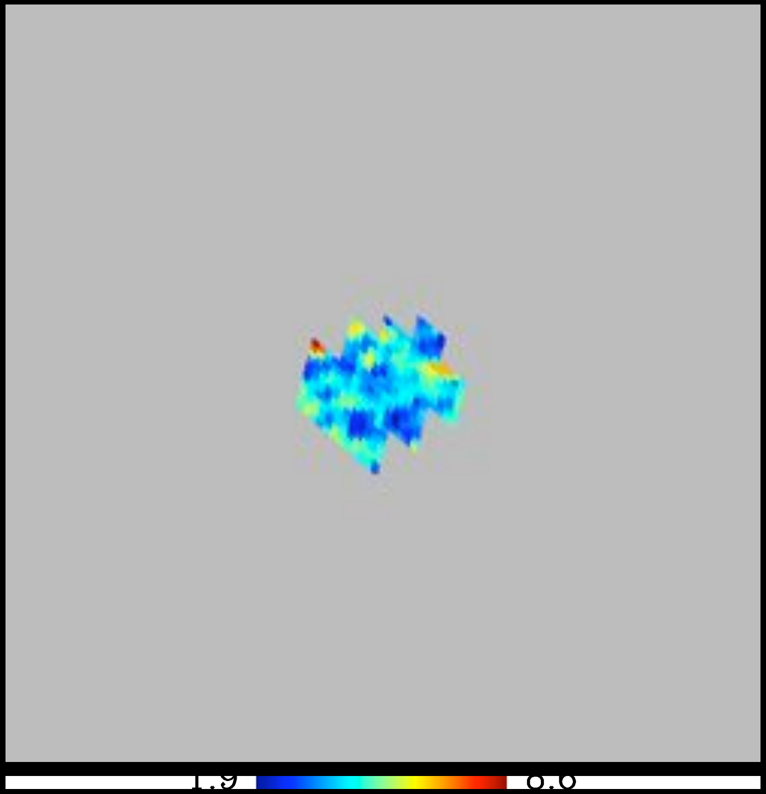
significances (sensitive to 5 - 14 degrees)



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

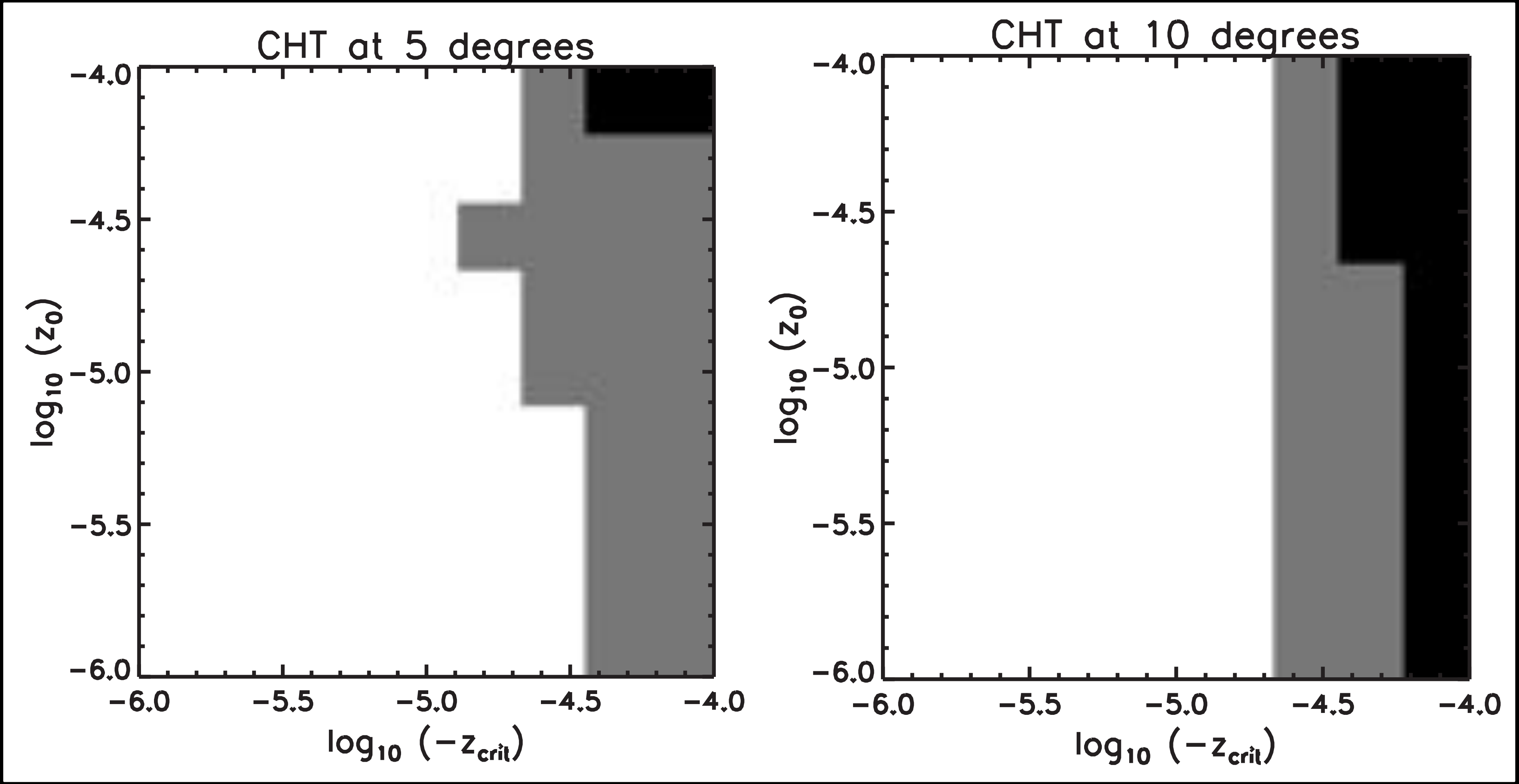
WMAP7 W band: CHT response





- "peakiest" CHT response found in W band data
- no circular temperature discontinuities detected
- no conclusive detection can be claimed

CHT sensitivity/exclusion region



- Limited by 1 degree CMB “realization noise” as well as experimental sensitivity/resolution.

Bayesian model selection

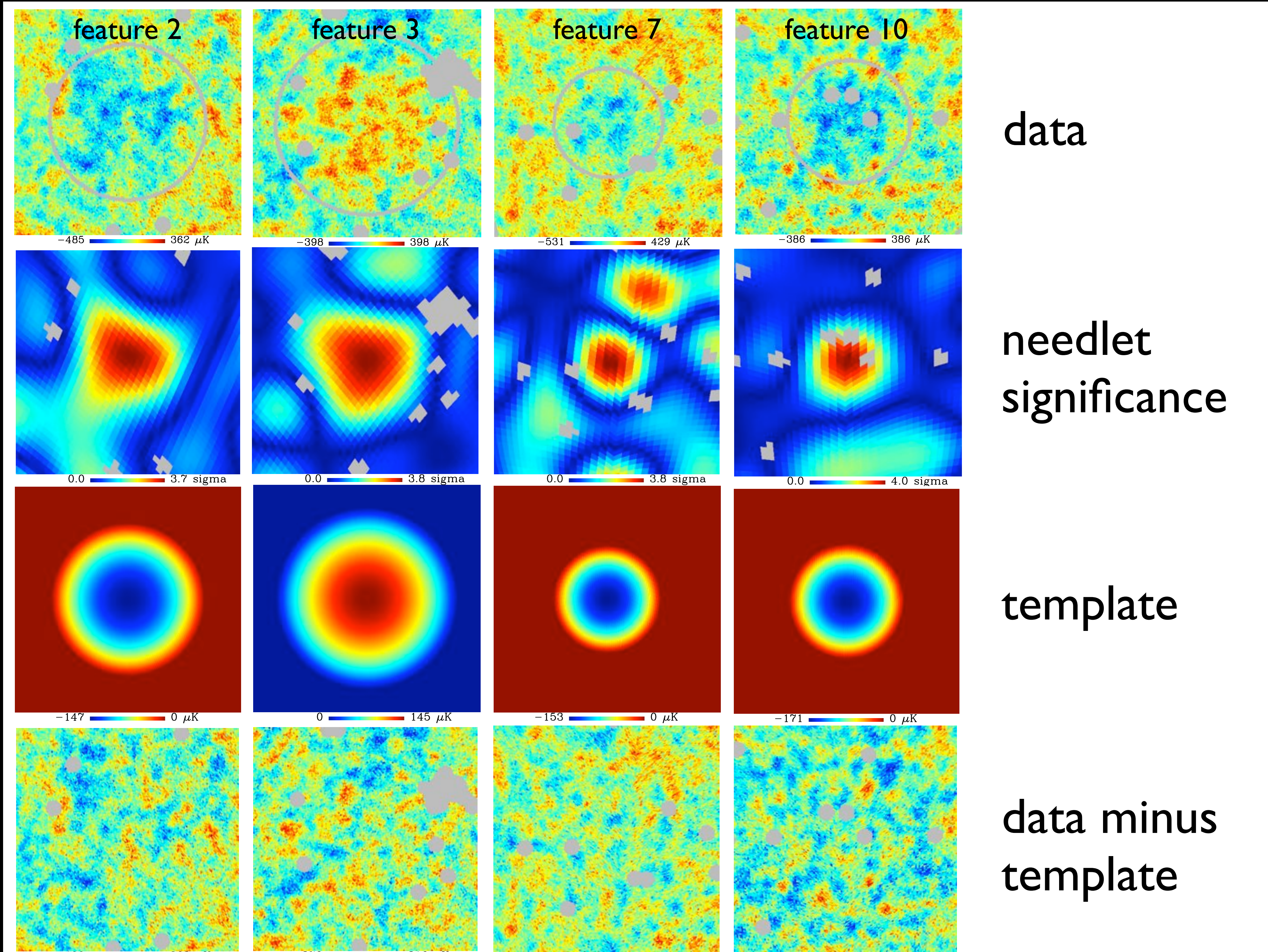
- We find four features with no detectable temperature discontinuity (at WMAP quality data) but with evidence ratios

$$4 < \ln \rho < 7$$

- Evidence ratios significantly higher than the false detection threshold evidence ratio $\ln \rho \sim 2.6$.

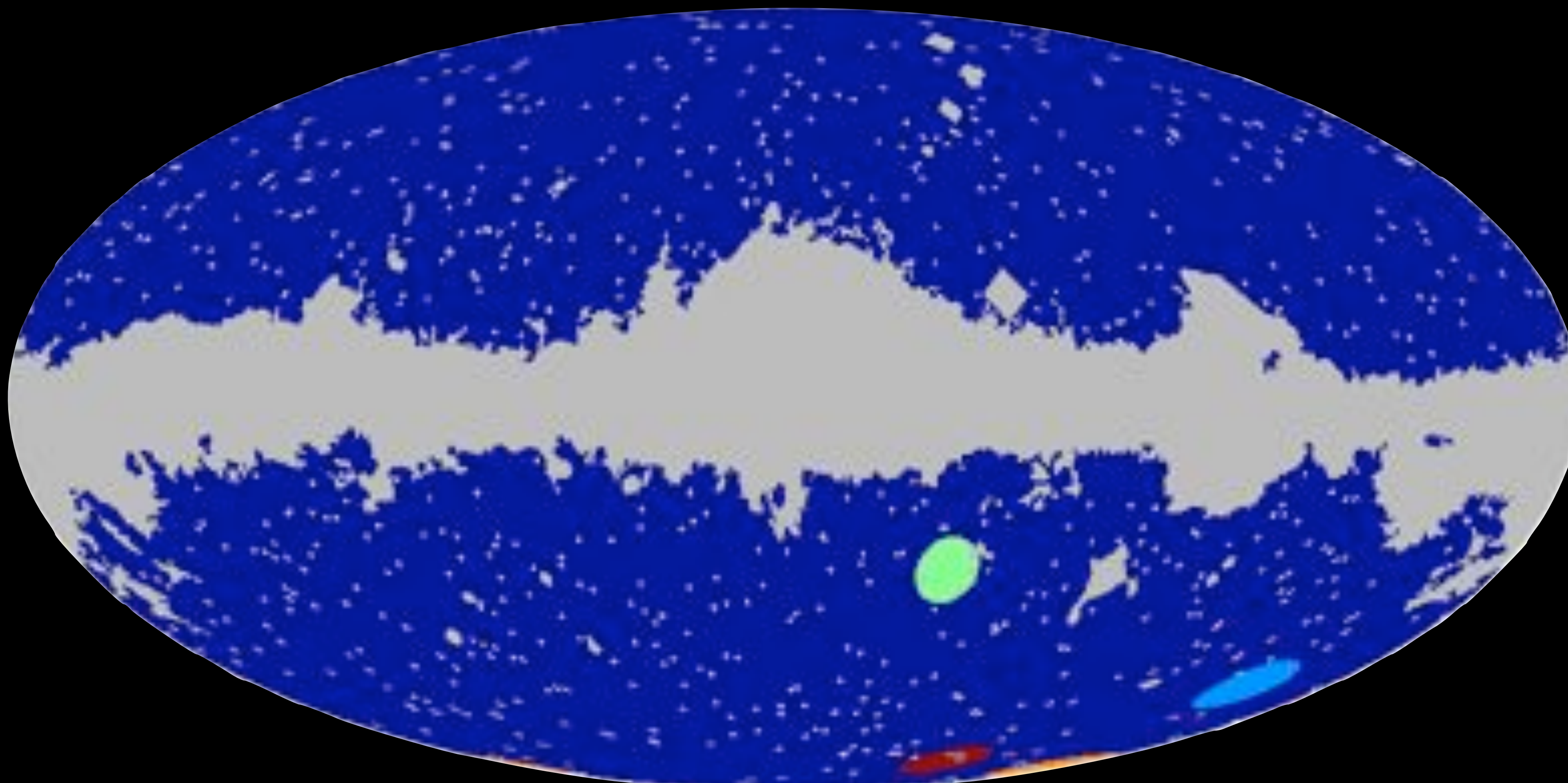
- Evidence ratios consistent with simulated collisions using marginalized parameters.

- All four features are at about our angular size CHT detection threshold of 5 deg, and within the needlet sensitivity region.

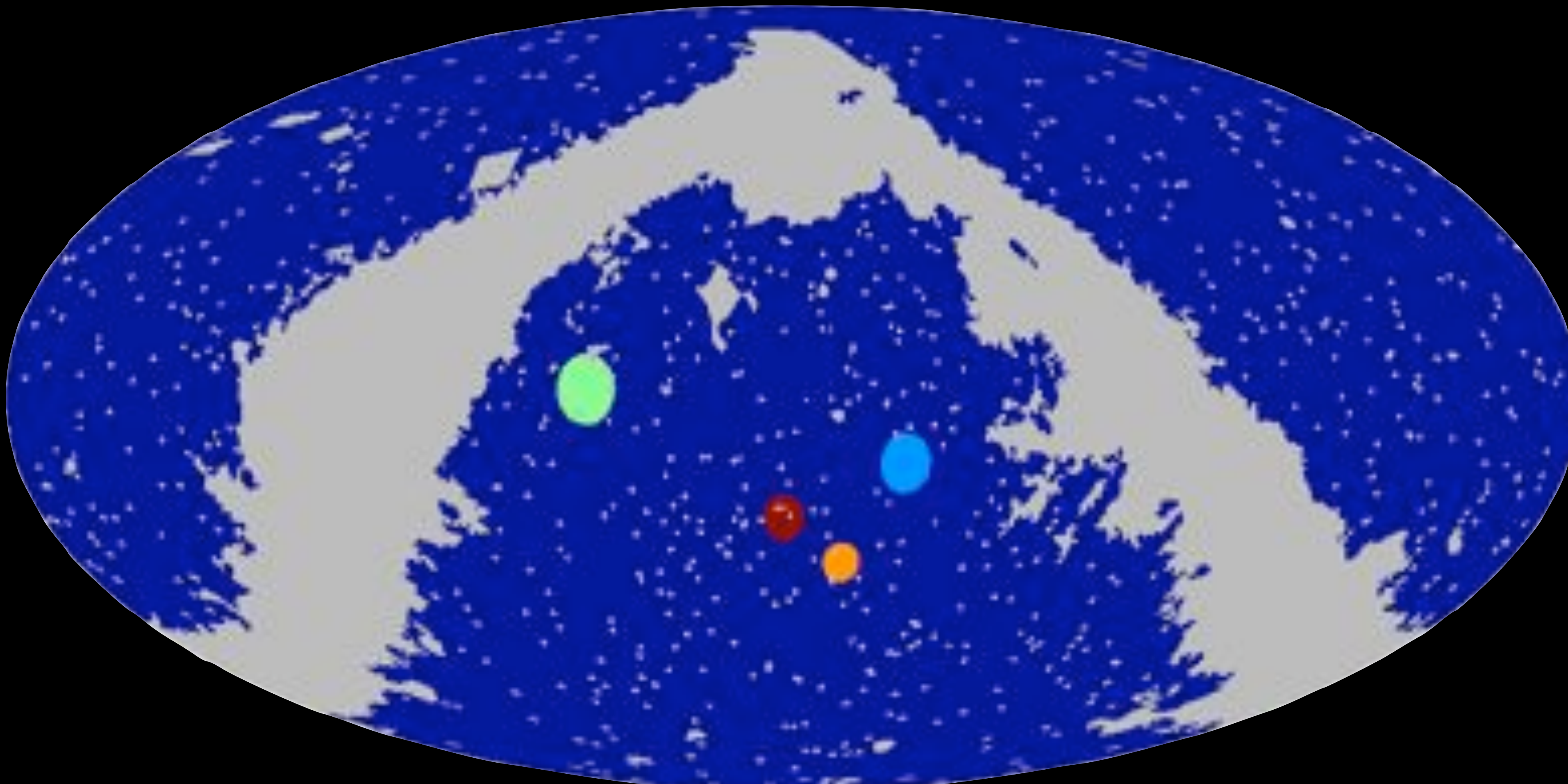


feature 2
feature 3
feature 7
feature 10
−485 362 μK
−398 398 μK
−531 429 μK
−386 386 μK
data
0.0 3.7 sigma
0.0 3.8 sigma
0.0 3.8 sigma
0.0 4.0 sigma
needlet significance
−147 0 μK
0 145 μK
−153 0 μK
−171 0 μK
template
−400 362 μK
−376 316 μK
−429 429 μK
−293 392 μK
data minus template

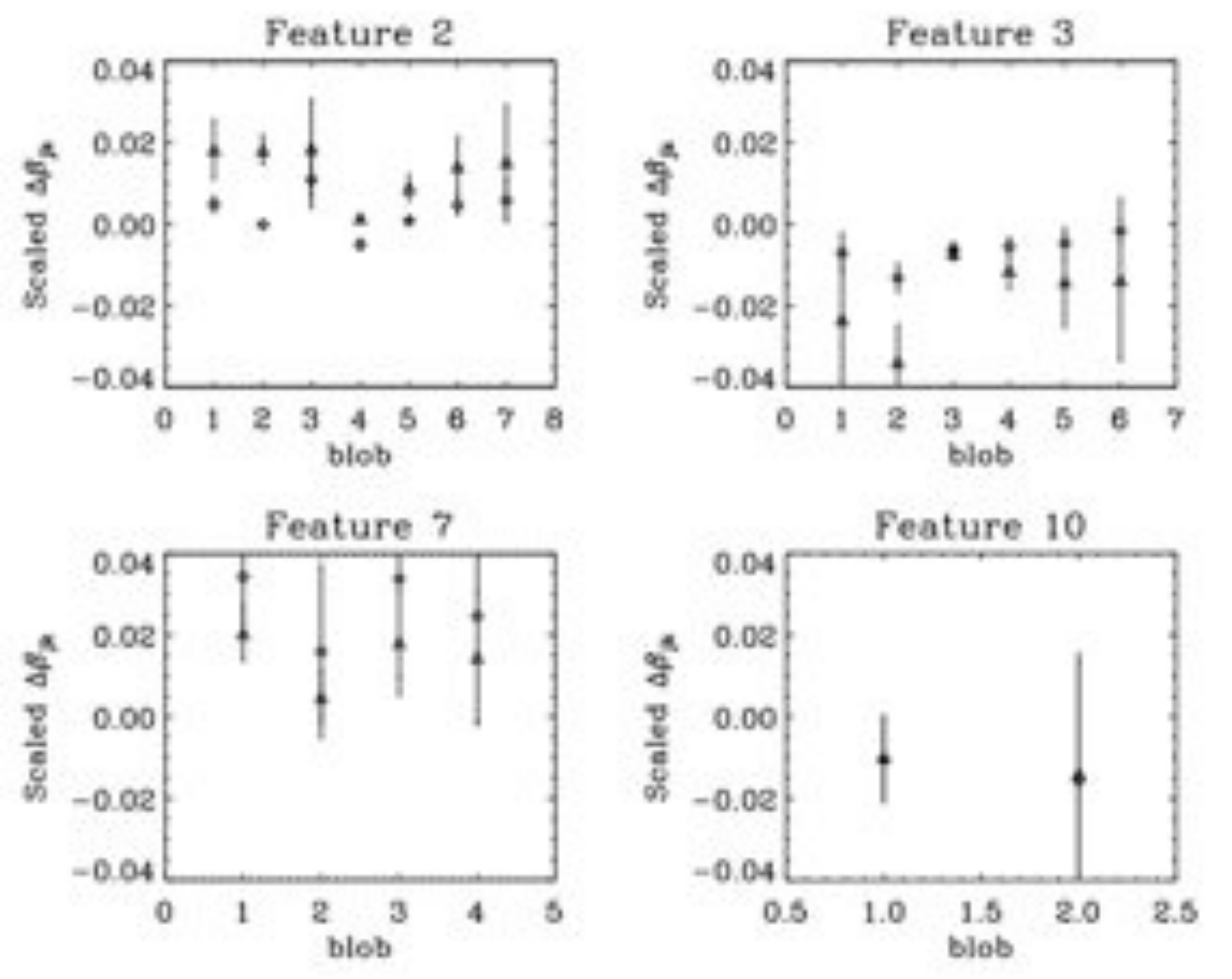
feature locations - Galactic coords



feature locations - rotated



Checking for foreground residuals



Summary

- Detecting bubble collisions in CMB: dramatic signature of pre-inflationary physics and the Multiverse.

- An automated pipeline to look for bubble collisions in the CMB without being biased by *a posteriori* selection effects.

- Applied to WMAP7 data, no “smoking gun” causal edge signature found: leads to bounds on parameter space.

- Four features consistent with bubble collisions identified.

- Planck will be able to corroborate through increased resolution (3X) and sensitivity (order of magnitude) and counterpart polarization signal (Czech et al 2010).

What would we learn about eternal inflation?

- Theory predicts number of expected collisions and strength of each collision given:
  - properties of underlying potential (energy scales of minima and potential barriers)
  - number of e-folds of inflation inside our bubble.

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