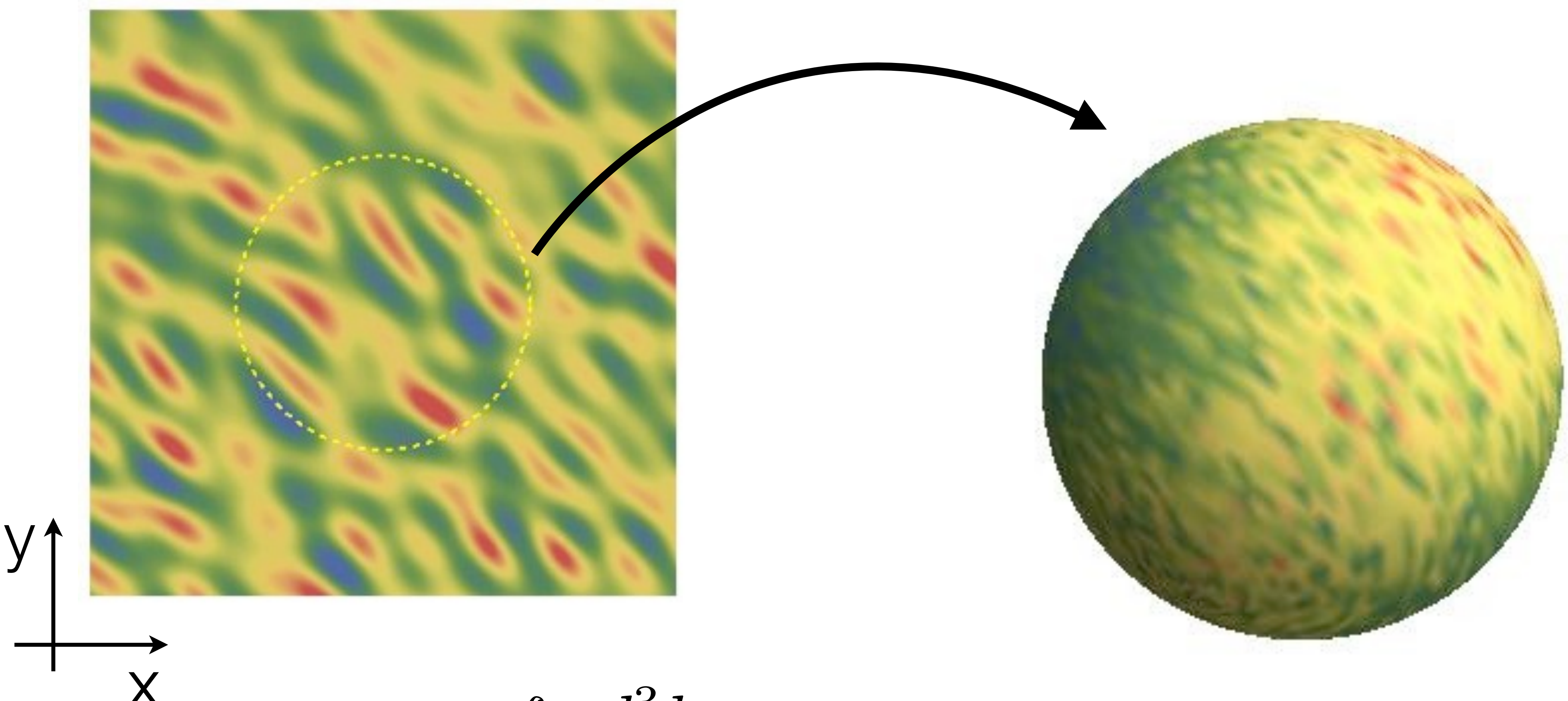
Observing the Universe(s)

Matt Johnson
Perimeter Institute/York University

The CMB

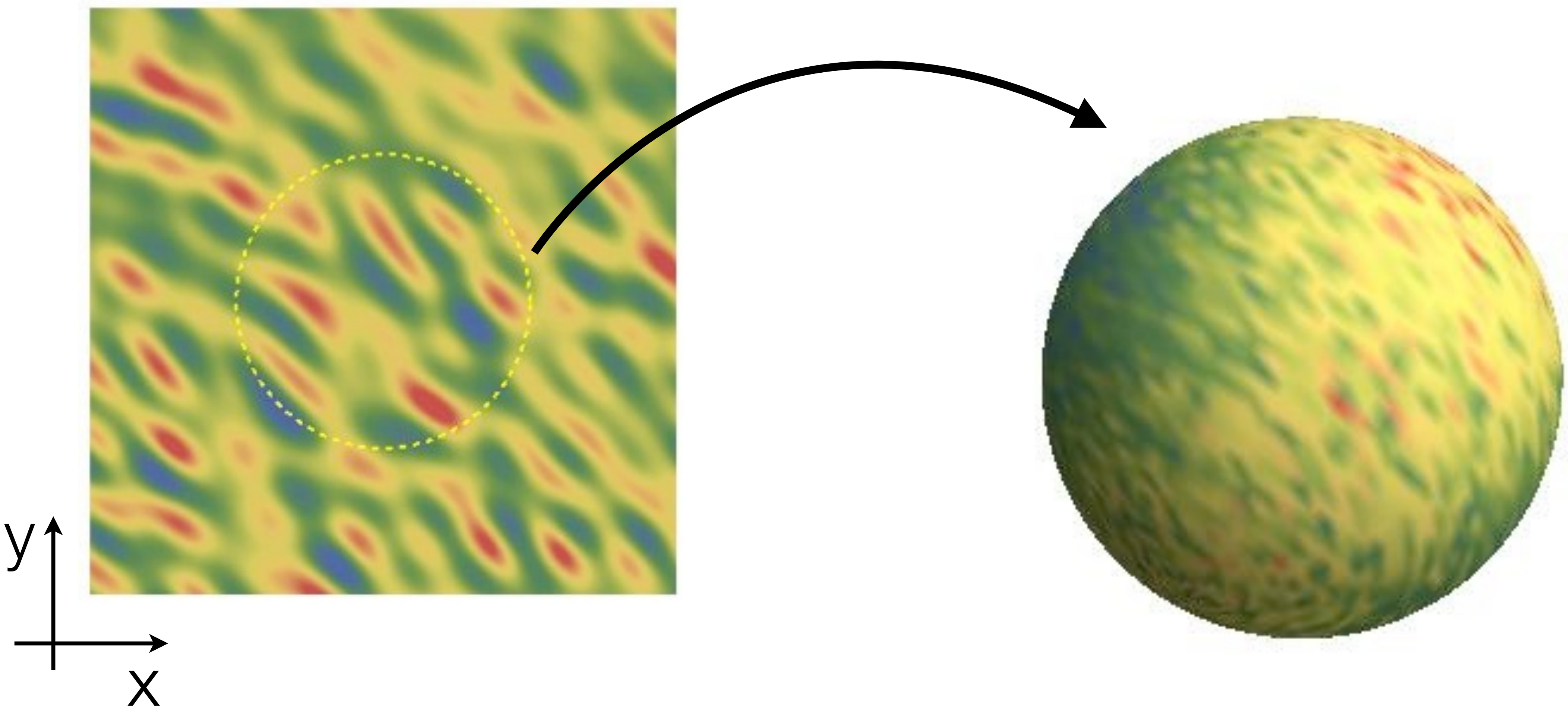
- The CMB is a 2D projection of a 3D field.



$$a_{\ell m} = \int \frac{d^3k}{(2\pi)^3} \Delta_\ell(k) \Phi_{\rm init}(k) Y_{\ell m}(\hat{k})$$

The CMB

- Different realizations of the random field can give the same CMB.



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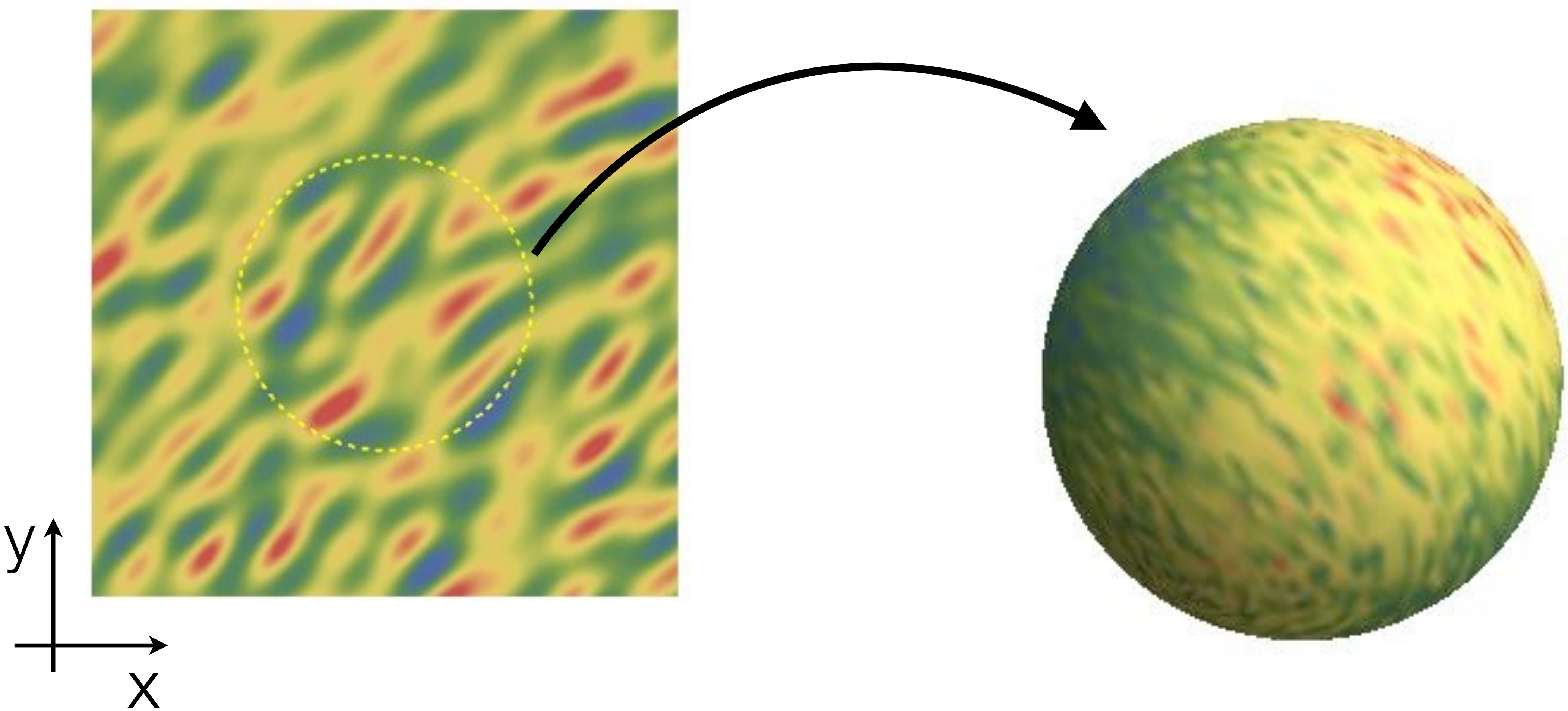

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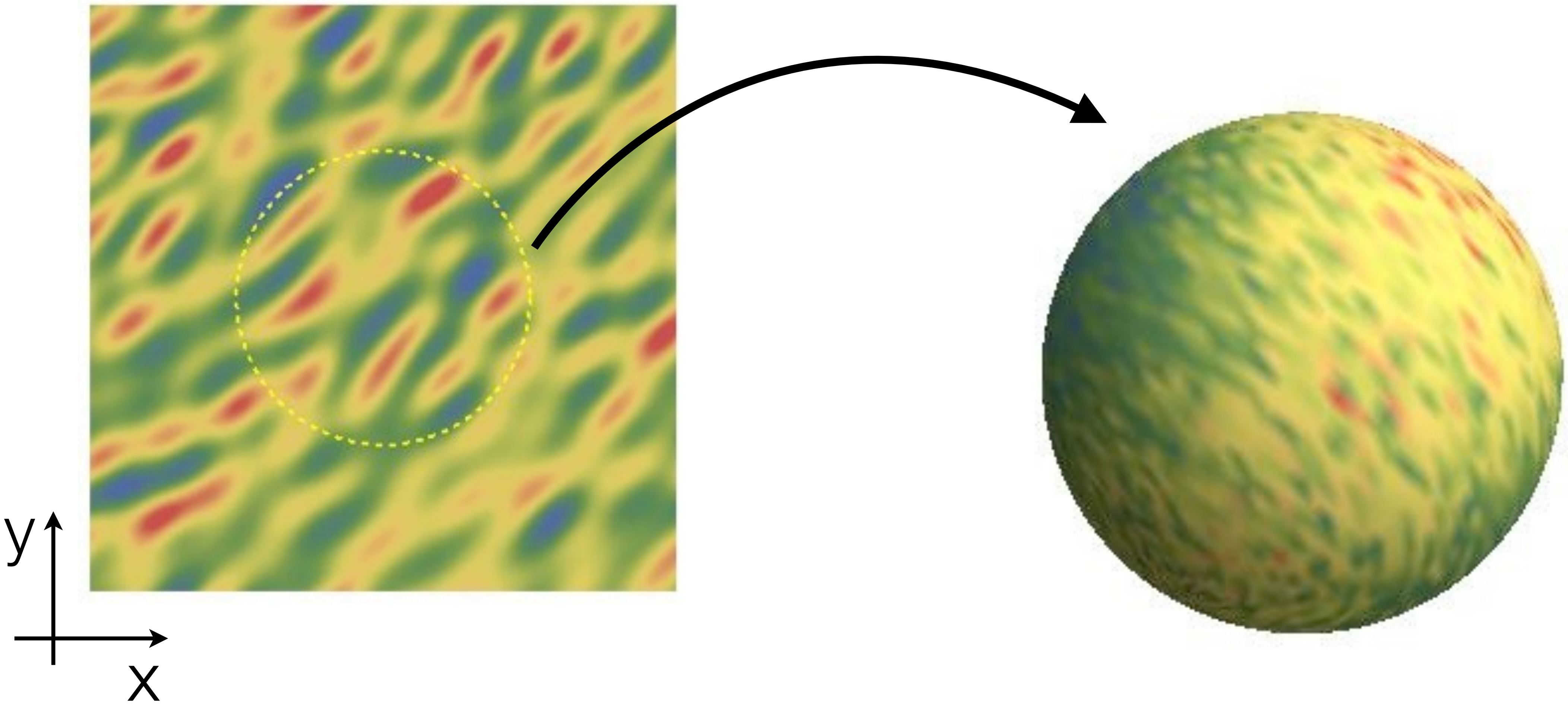

Cosmic Variance

- Measuring the power spectrum in a perfect world:

$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} a_{\ell m} a^*_{\ell m}$$

$$\frac{\Delta C_\ell}{C_\ell} = \sqrt{\frac{1}{2\ell+1}}$$

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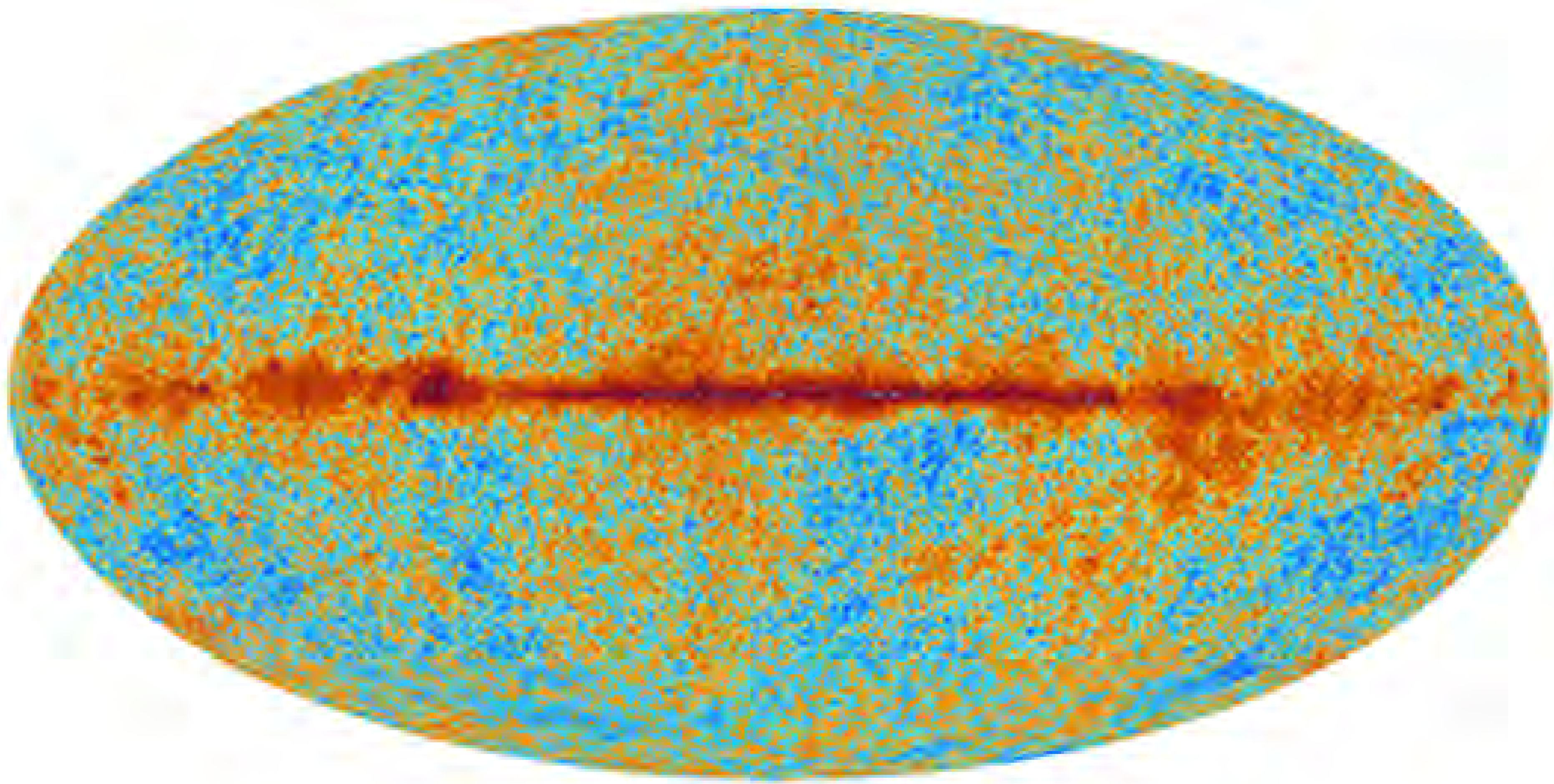
- There are a finite number of data points *in principle*.

Cosmic Variance

Cosmic Variance

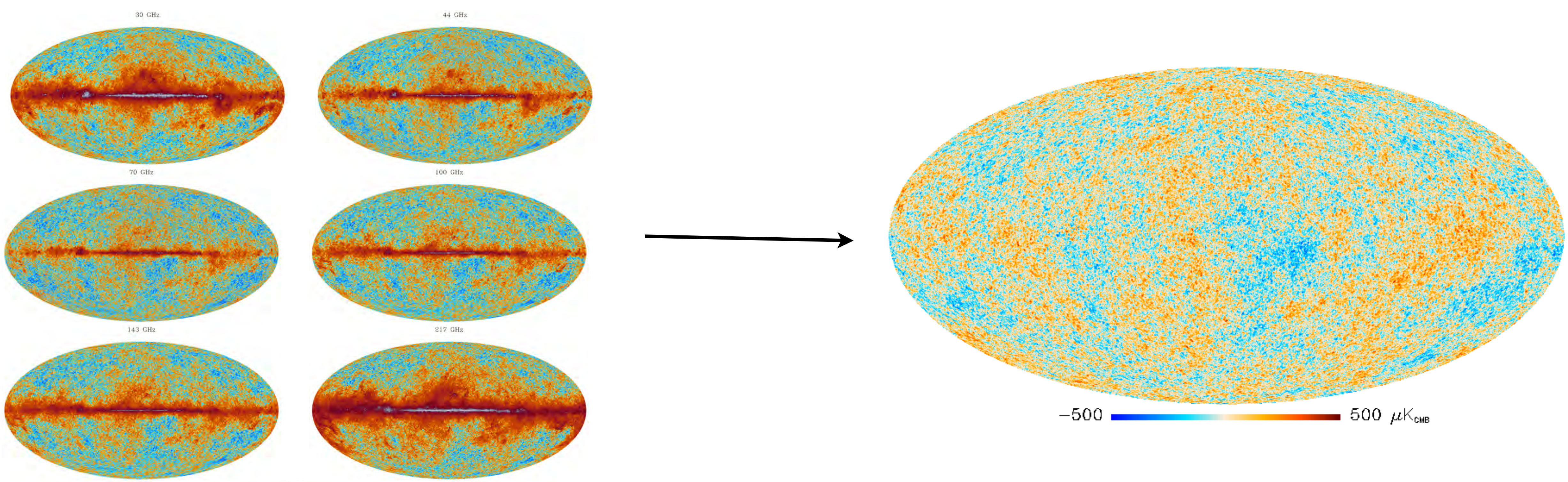
- Measuring the power spectrum in our world: foregrounds.



143 GHz

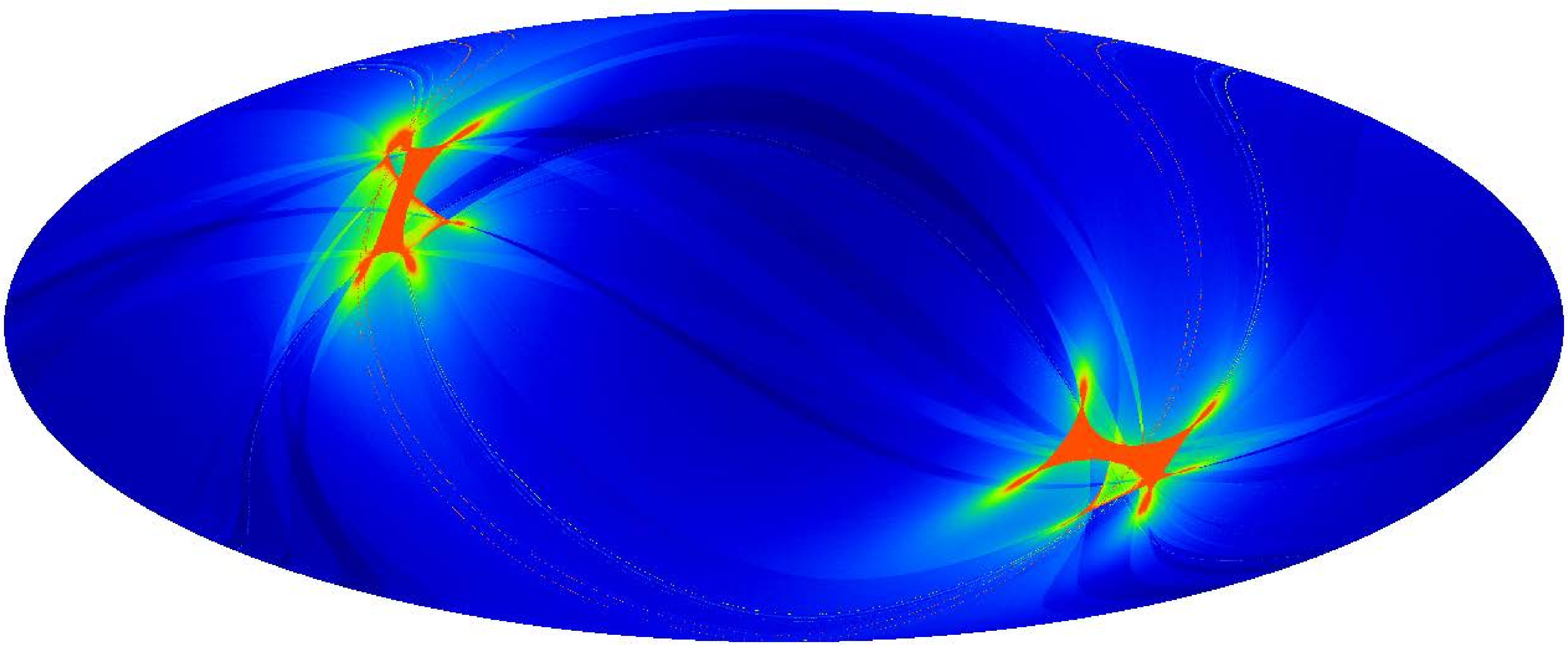
Cosmic Variance

- Measuring the power spectrum in our world: foregrounds.
- Astrophysical sources vary significantly with frequency, the CMB does not -- can use maps from different frequencies.



Cosmic Variance

- Measuring the power spectrum in our world: spatially varying noise.
- The measured signal is not completely statistically isotropic--need to understand precisely.



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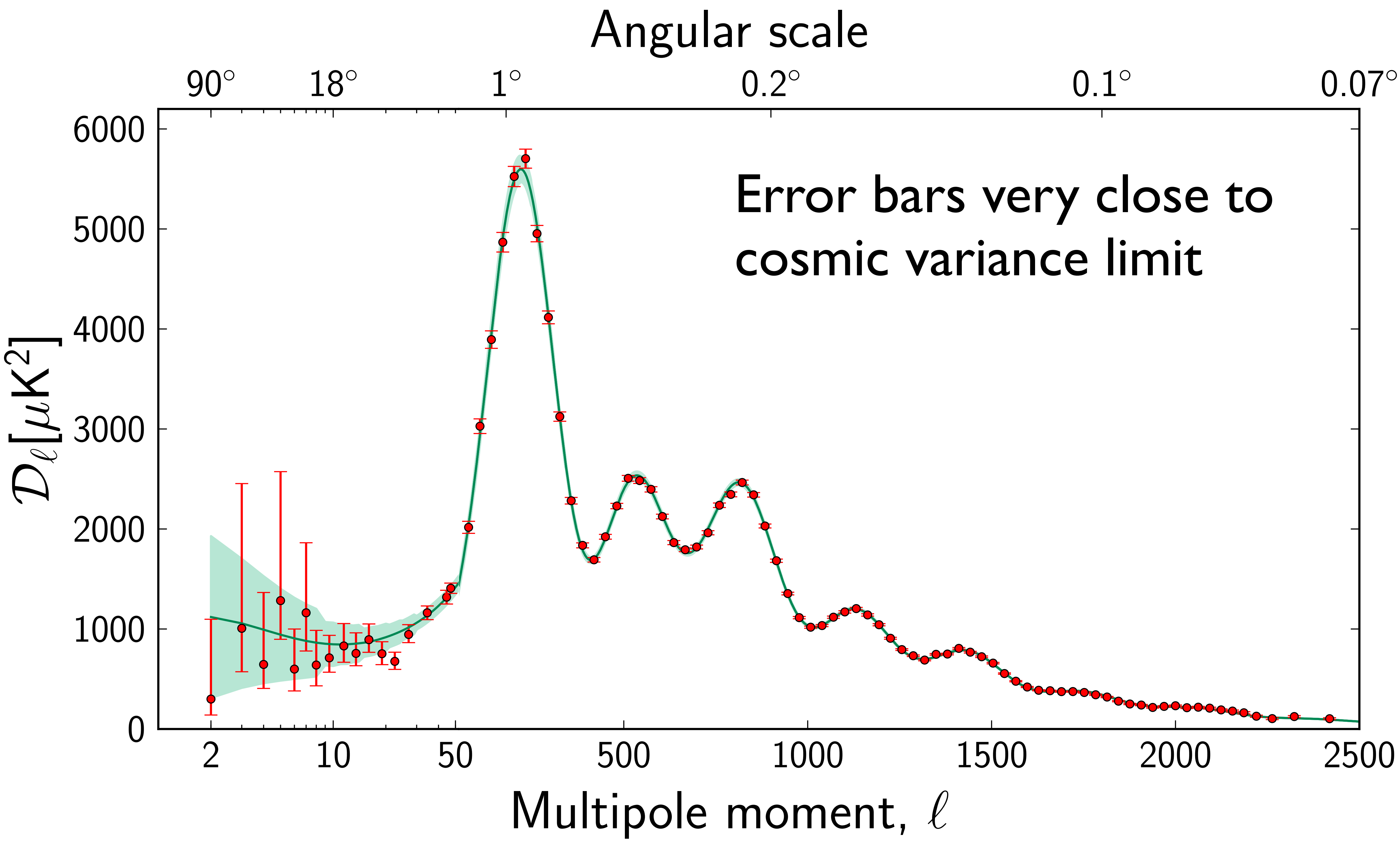

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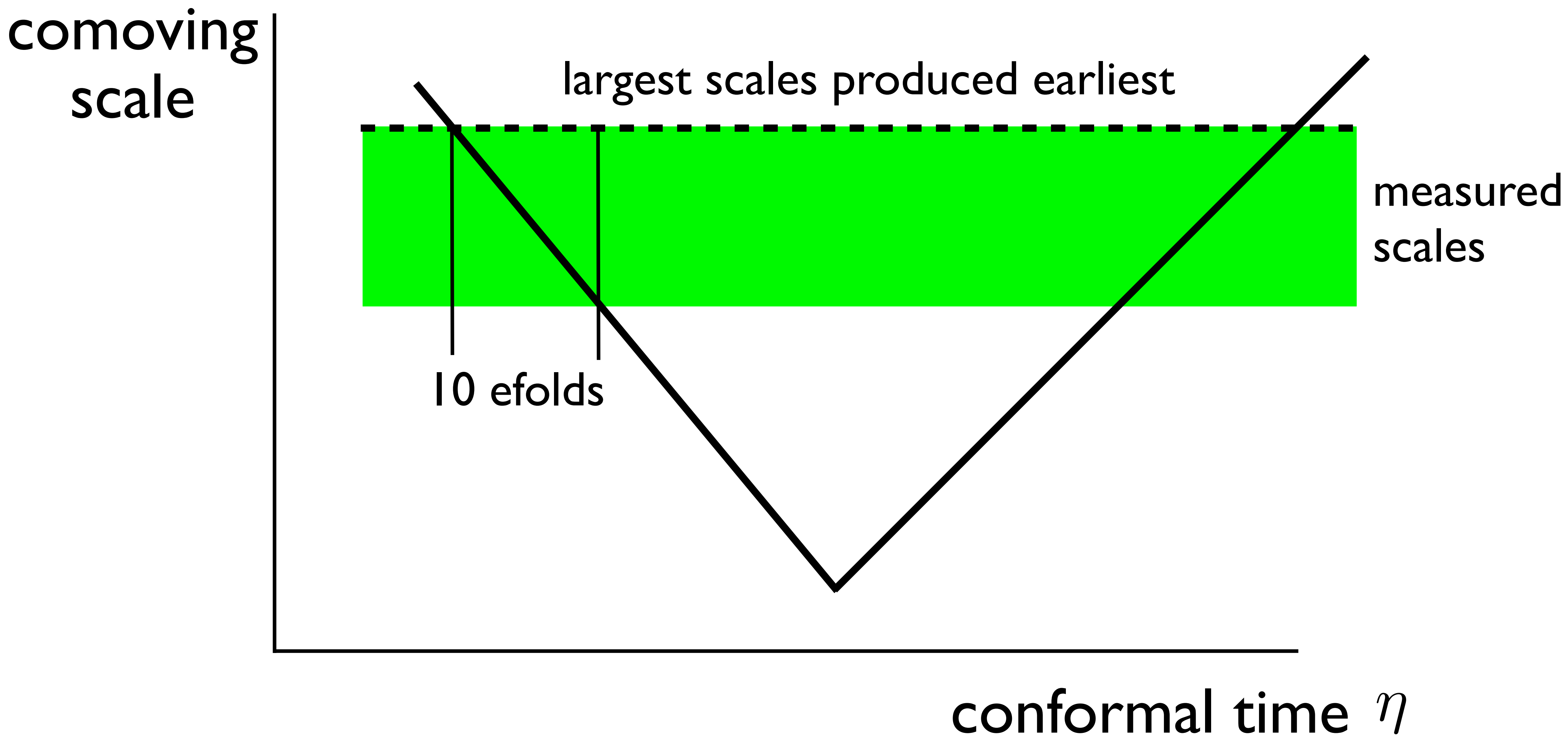
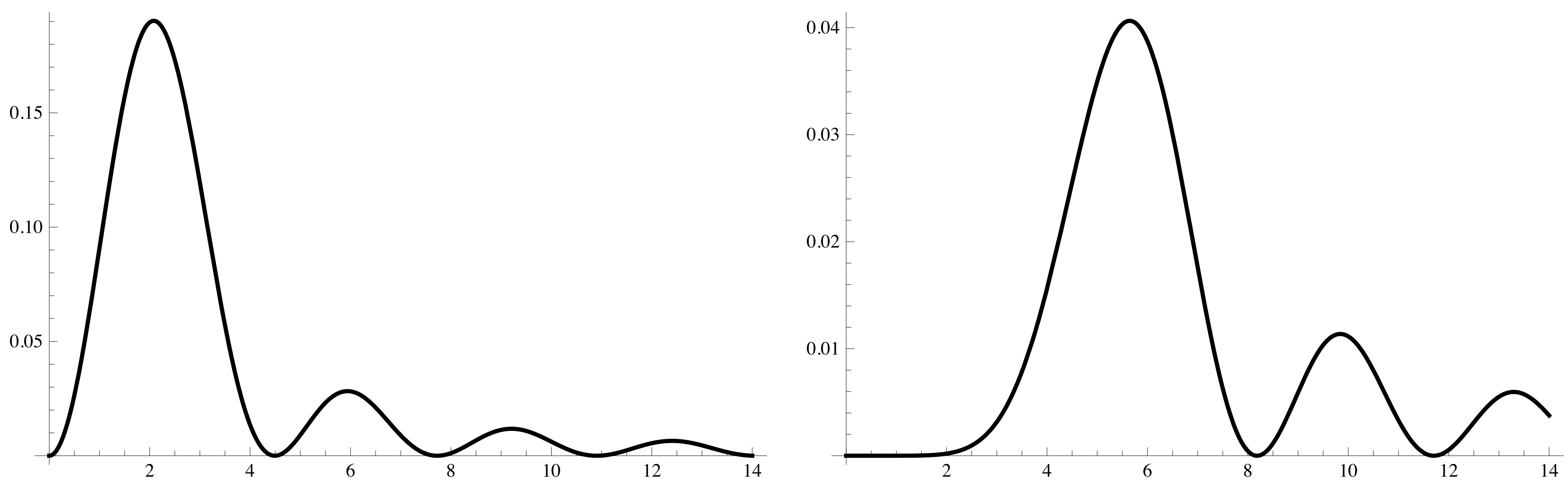


- We observe fluctuations from 10 e-folds in the CMB.

Cosmic Variance

- Each multipole gets contributions from a variety of k.
- Low multipoles get dominant contribution from largest scales.



$\Delta_{\ell=2}(k)$ $\Delta_{\ell=5}(k)$

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Can we do better?

A Finite Amount of information

- We see only what is on our light cone.
- e.g. we don't see the actual galaxies that the fluctuations in the CMB grow into.

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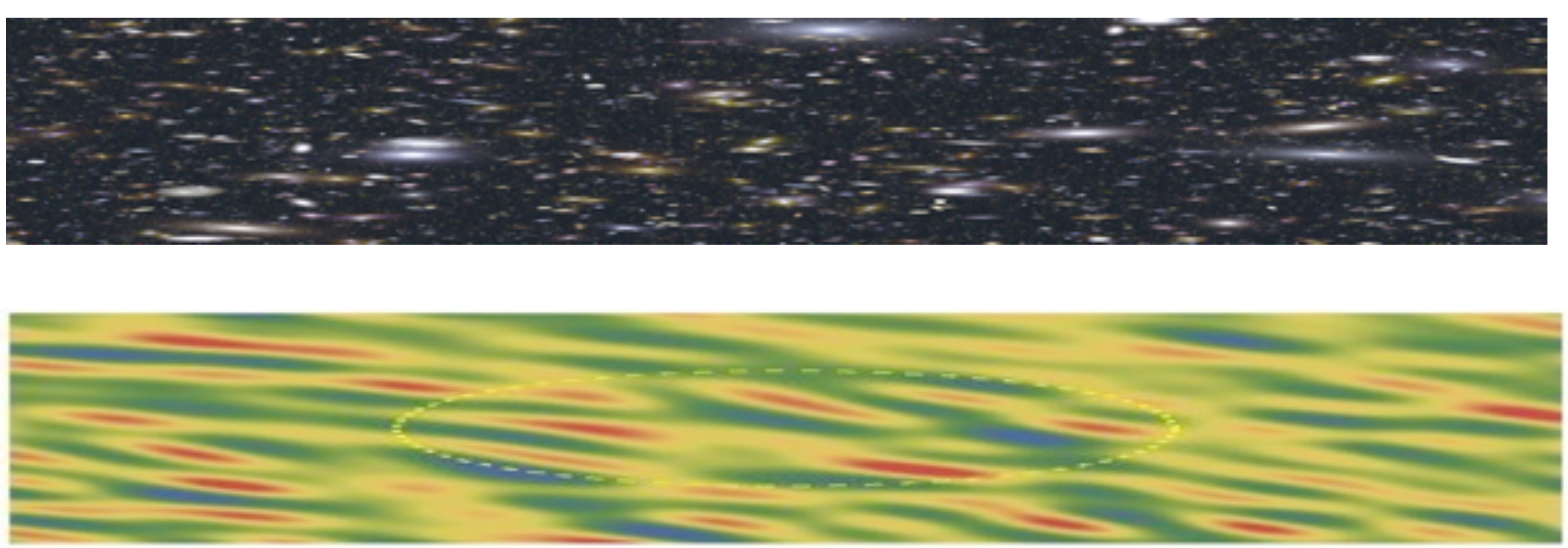
today

time 2



time 1

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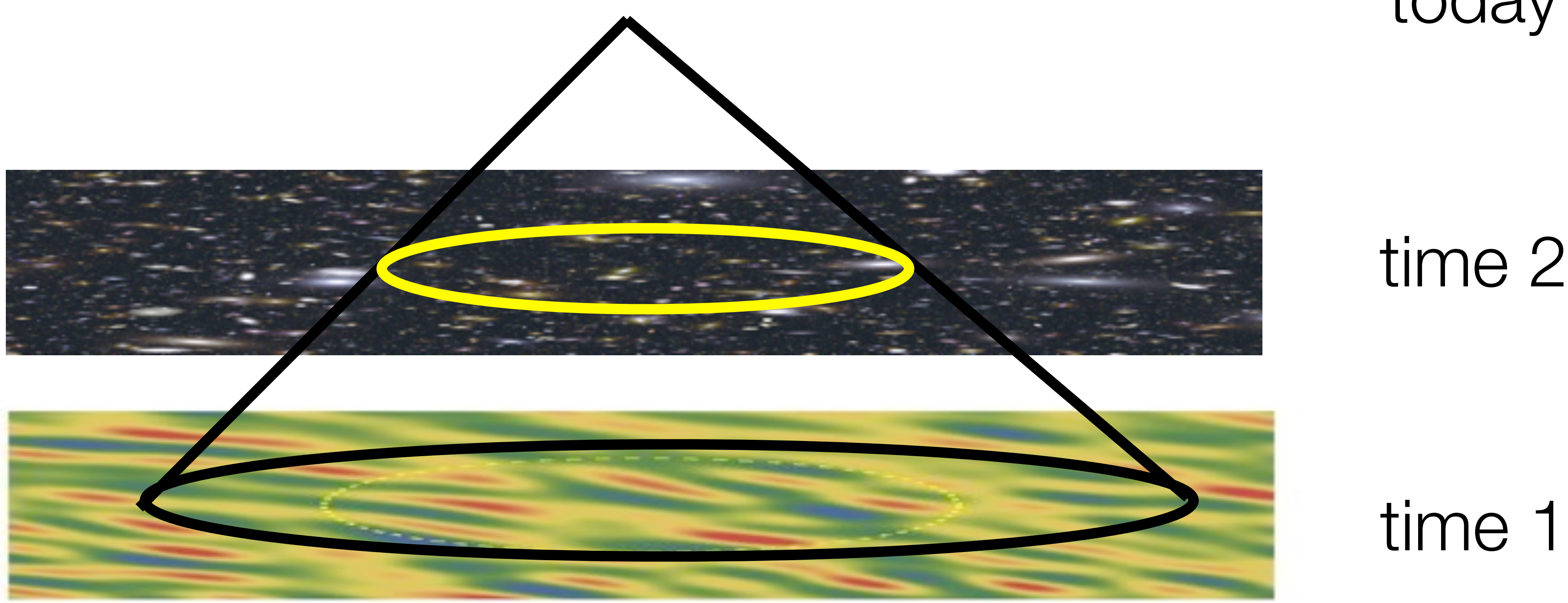

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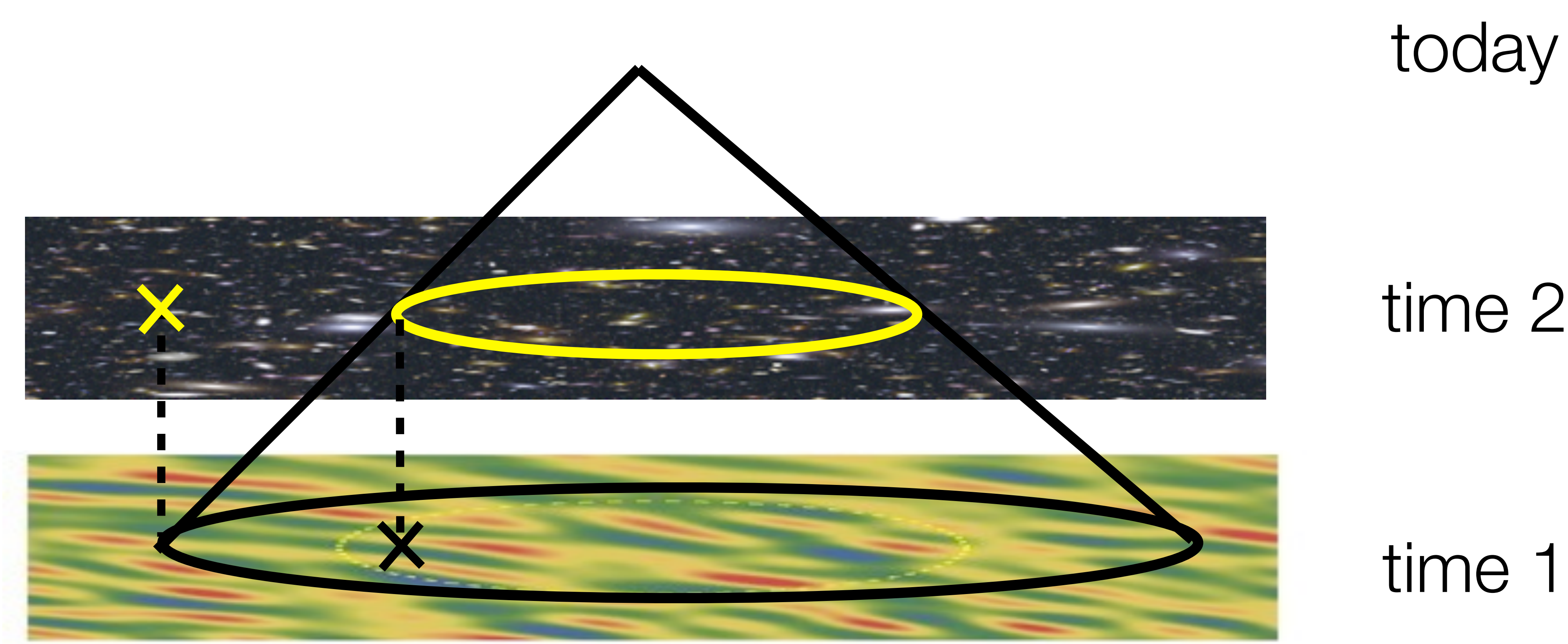

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- The best we get is a set of projections:

time 1 time 2 time 3

$\mathcal{P}(t=0)$ $\mathcal{P}(t_1)$ $\mathcal{P}(t_2)$ $\mathcal{P}(t_3)$

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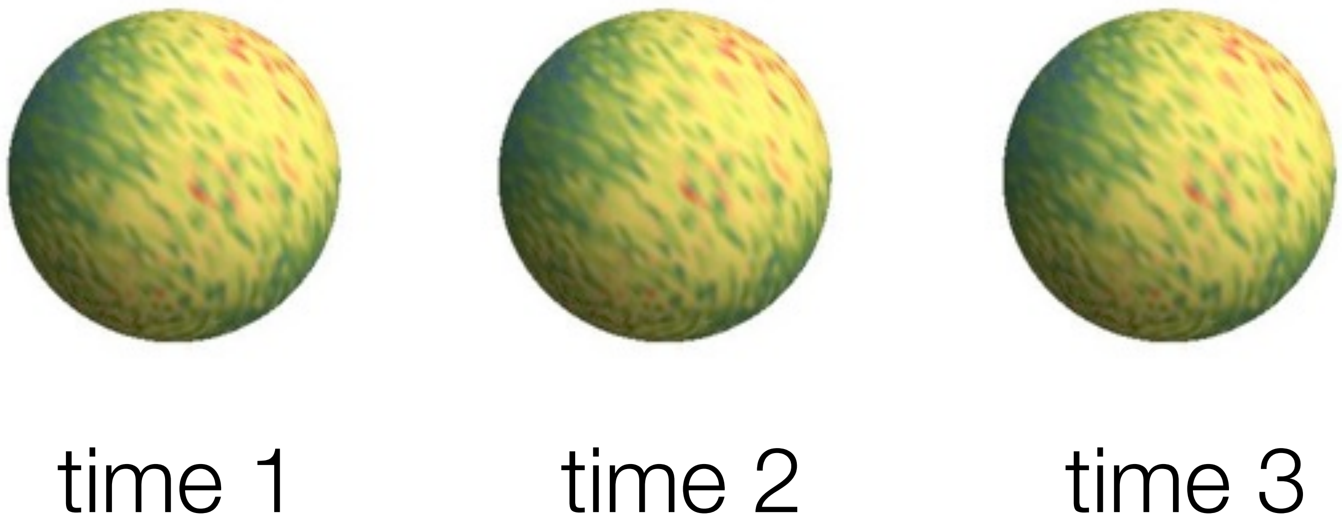

$\mathcal{P}(t=0)$ $\mathcal{P}(t_1)$ $\mathcal{P}(t_2)$ $\mathcal{P}(t_3)$

- With more projections, we can better test our theory of initial conditions and evolution for *probability distributions*.
- Hopefully realized in measurements of the 21cm hydrogen line.

A Finite Amount of information

- Finite number of linear modes to measure.

$c_s^2 = 0$

radiation	matter	dark energy
$\frac{\delta\rho}{\bar{\rho}} \propto \log(a)$	$\frac{\delta\rho}{\bar{\rho}} \propto a$	$\frac{\delta\rho}{\bar{\rho}} \propto \mathrm{const.}$

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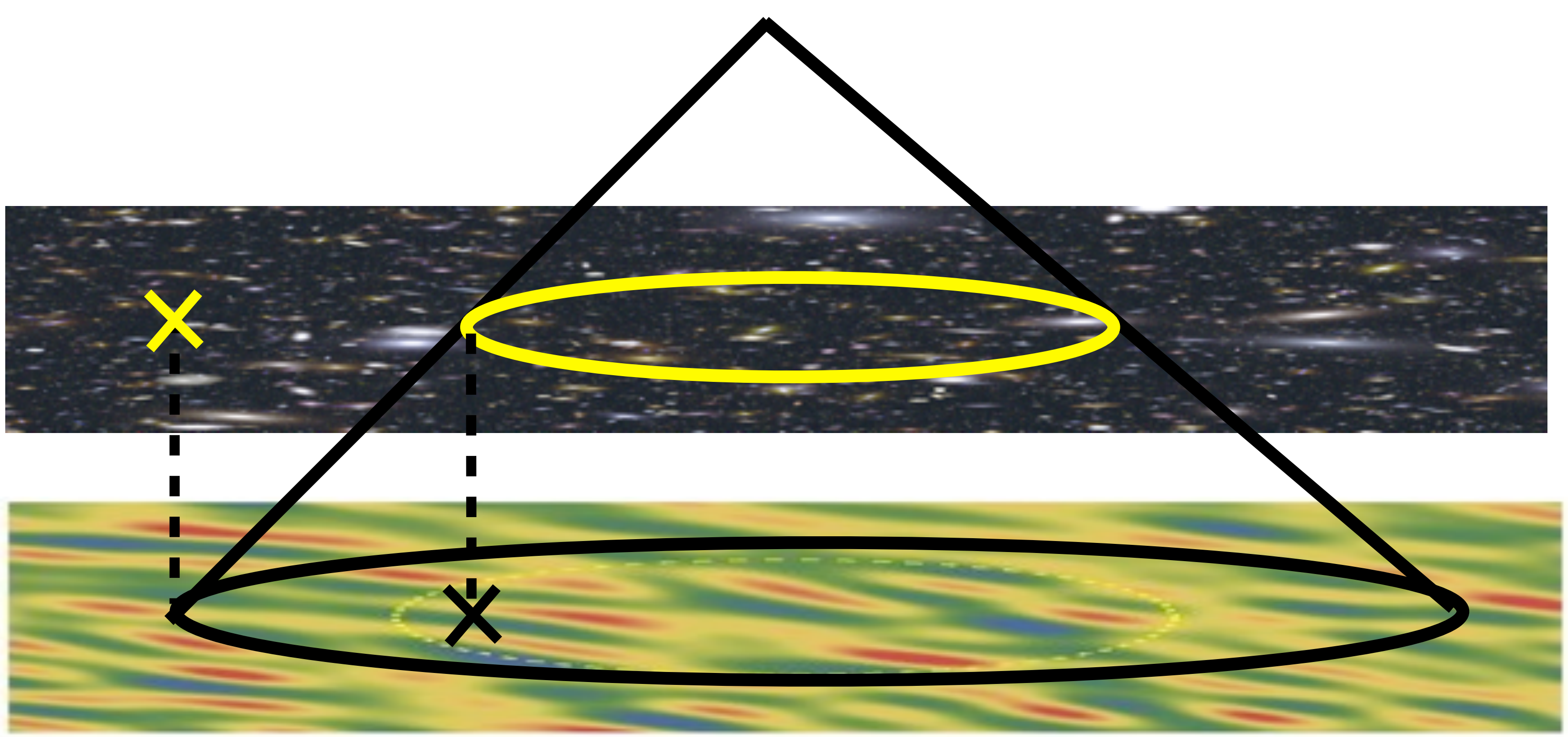

narrowing window

$$k_{\rm obs} \leq k < k_{\rm lin}$$

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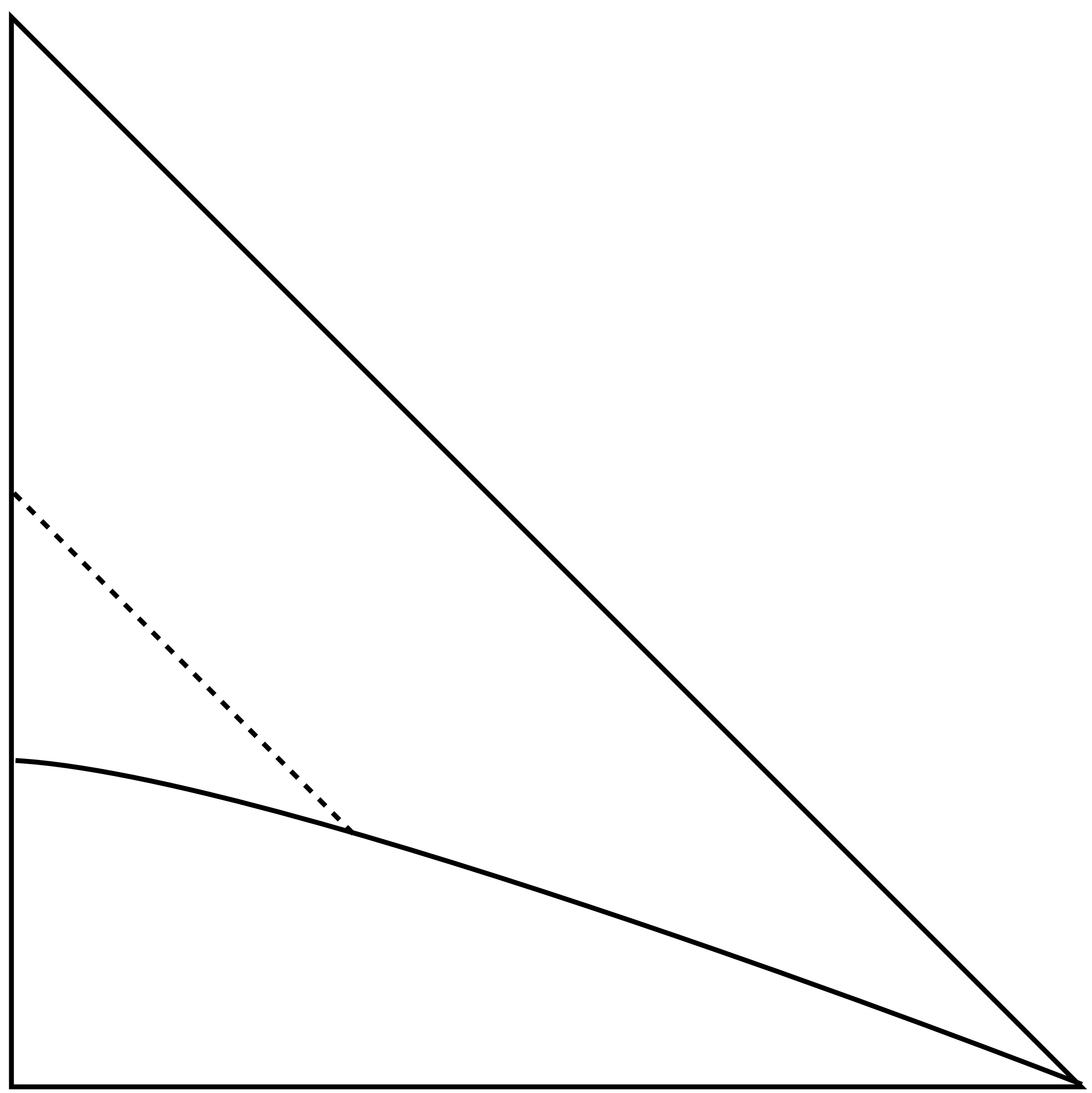
- Without a fundamental CC, we can see everything and travel to any galaxy we currently observe



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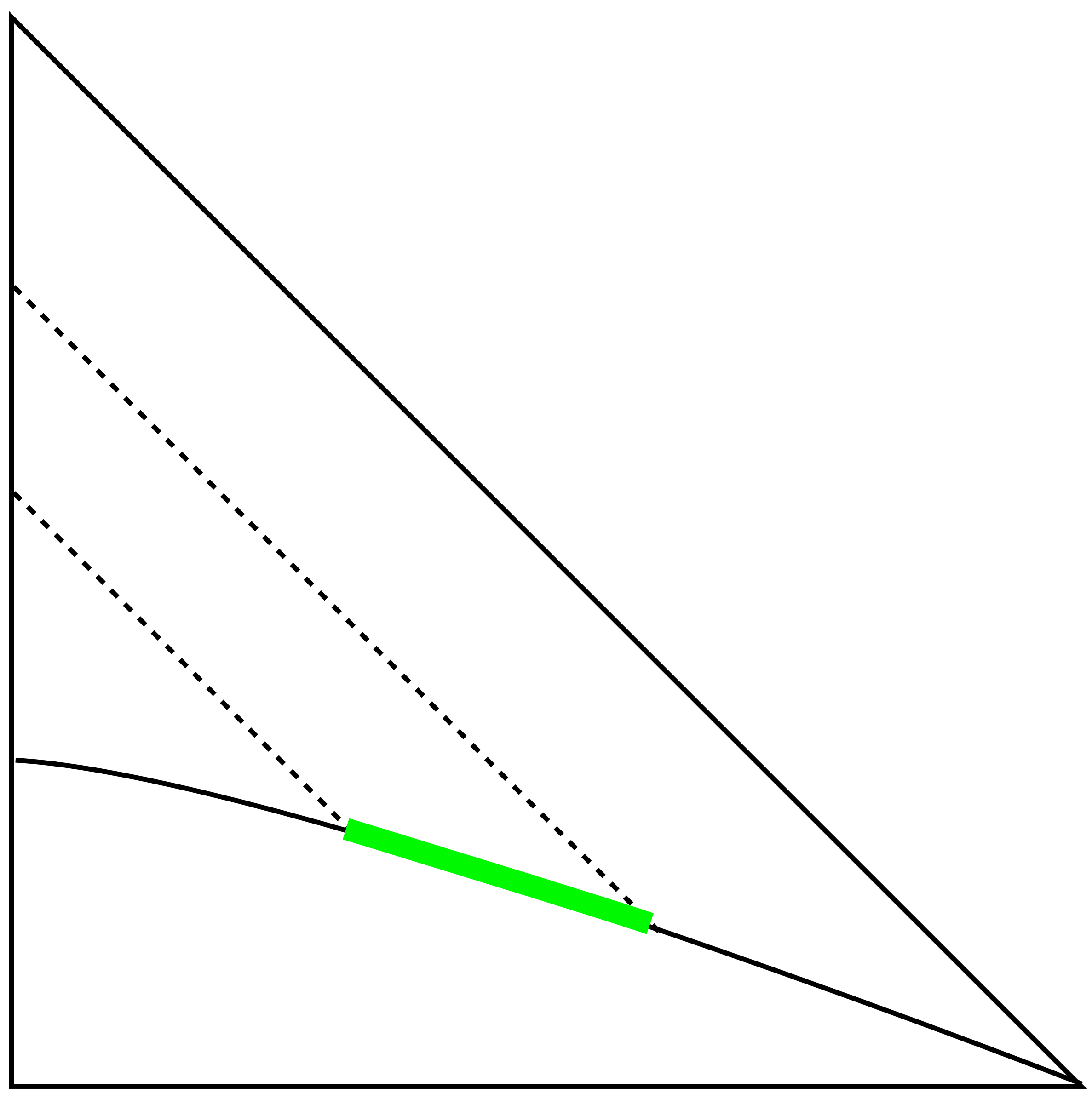

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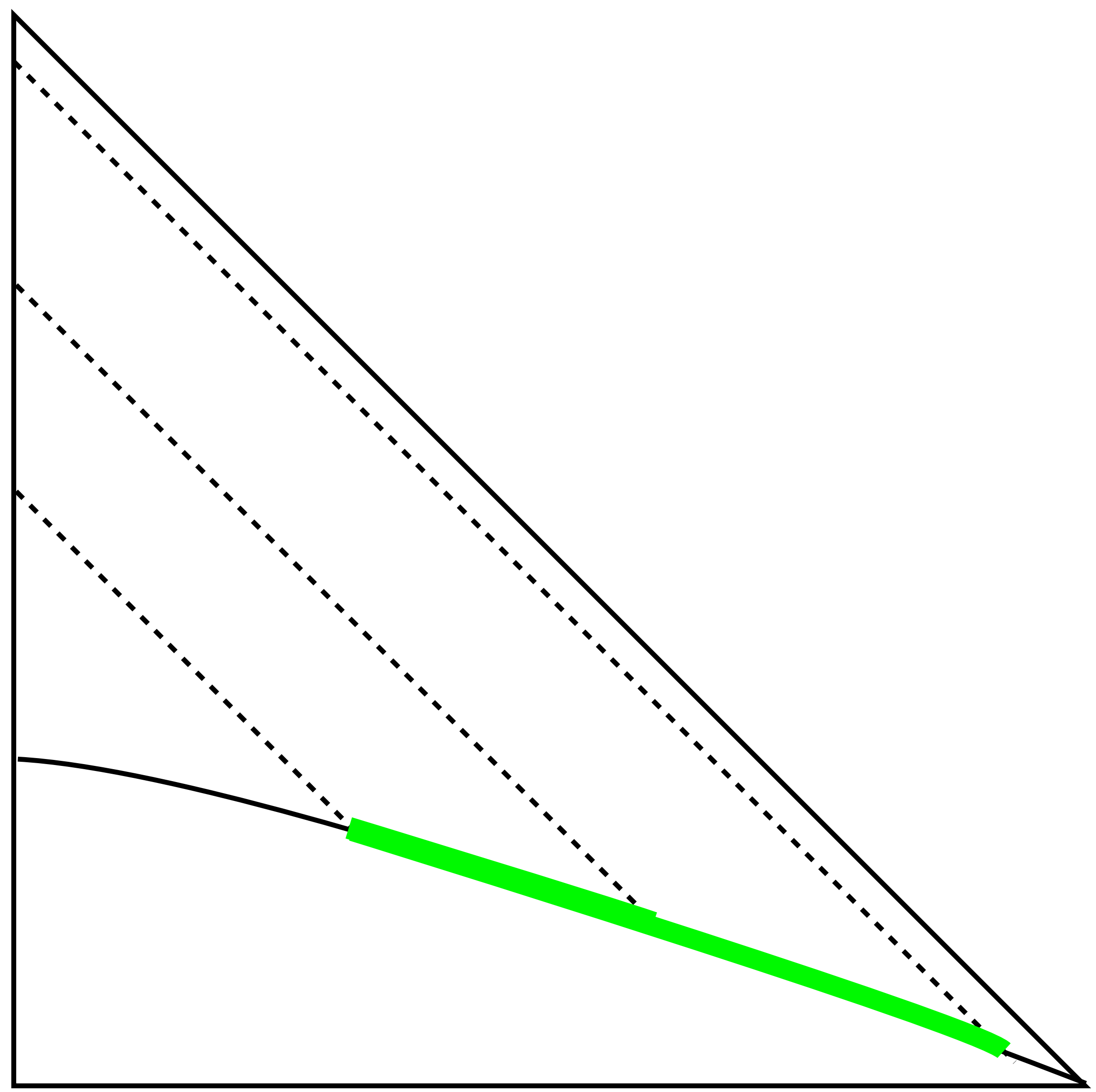

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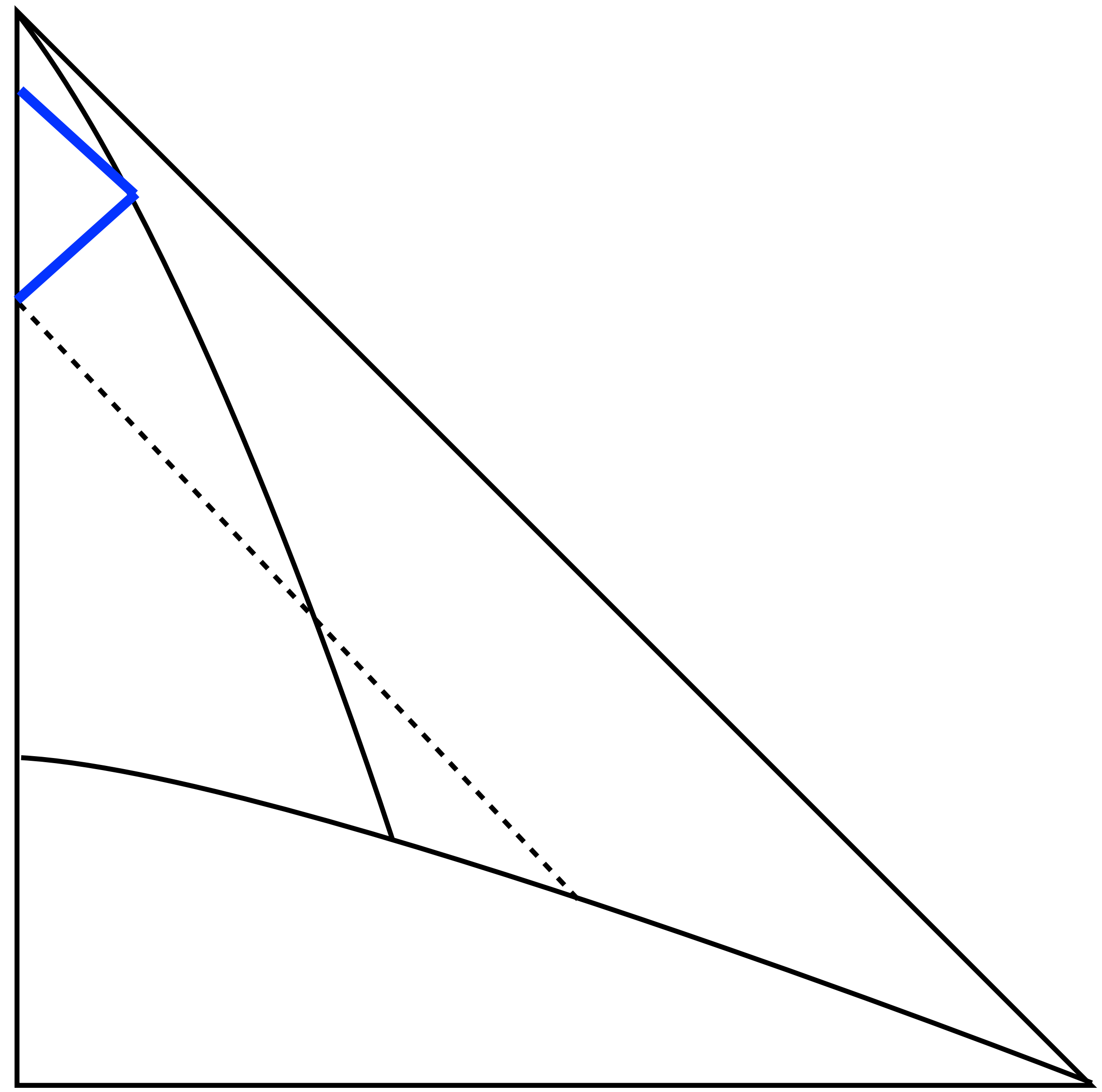

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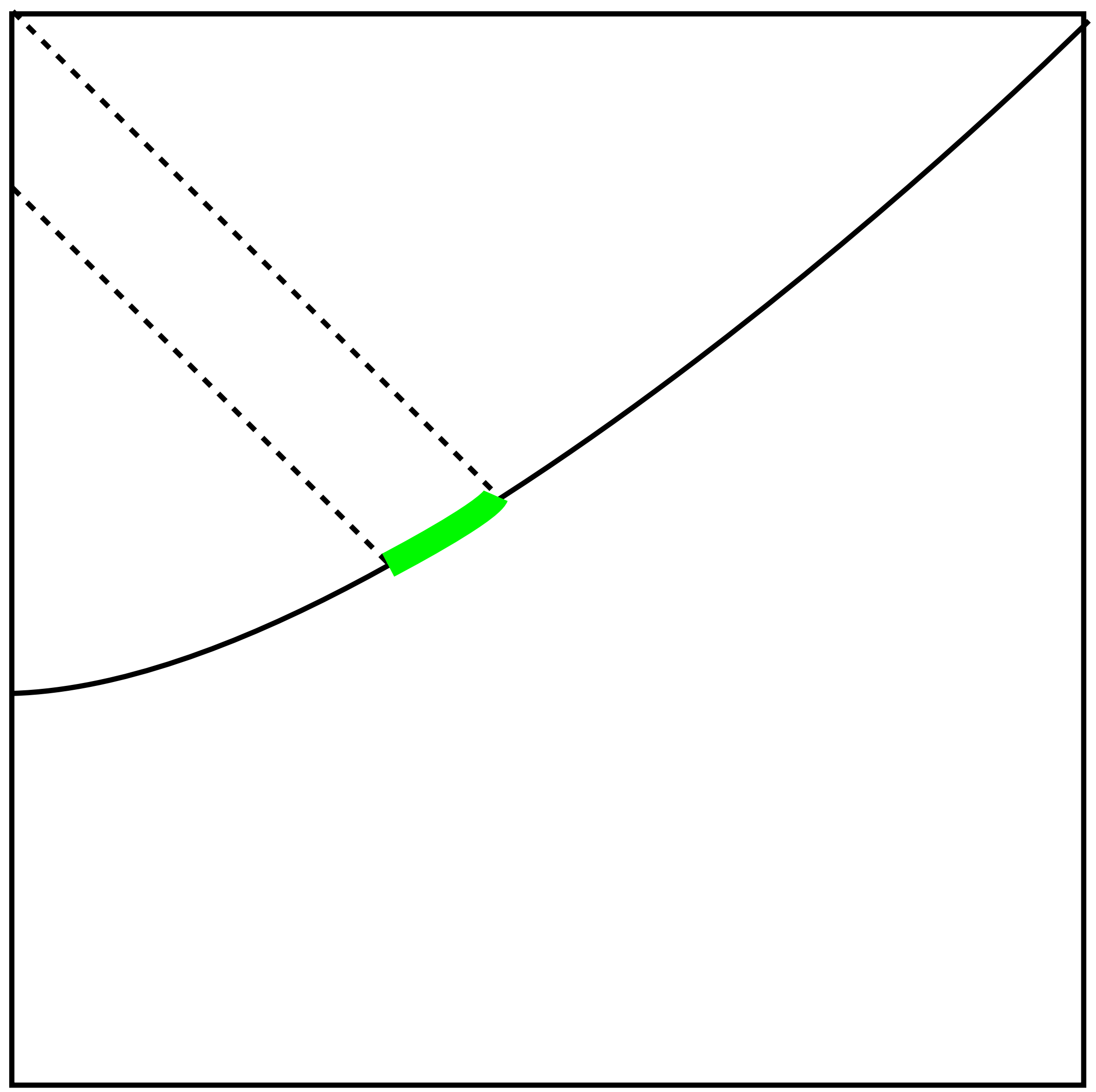

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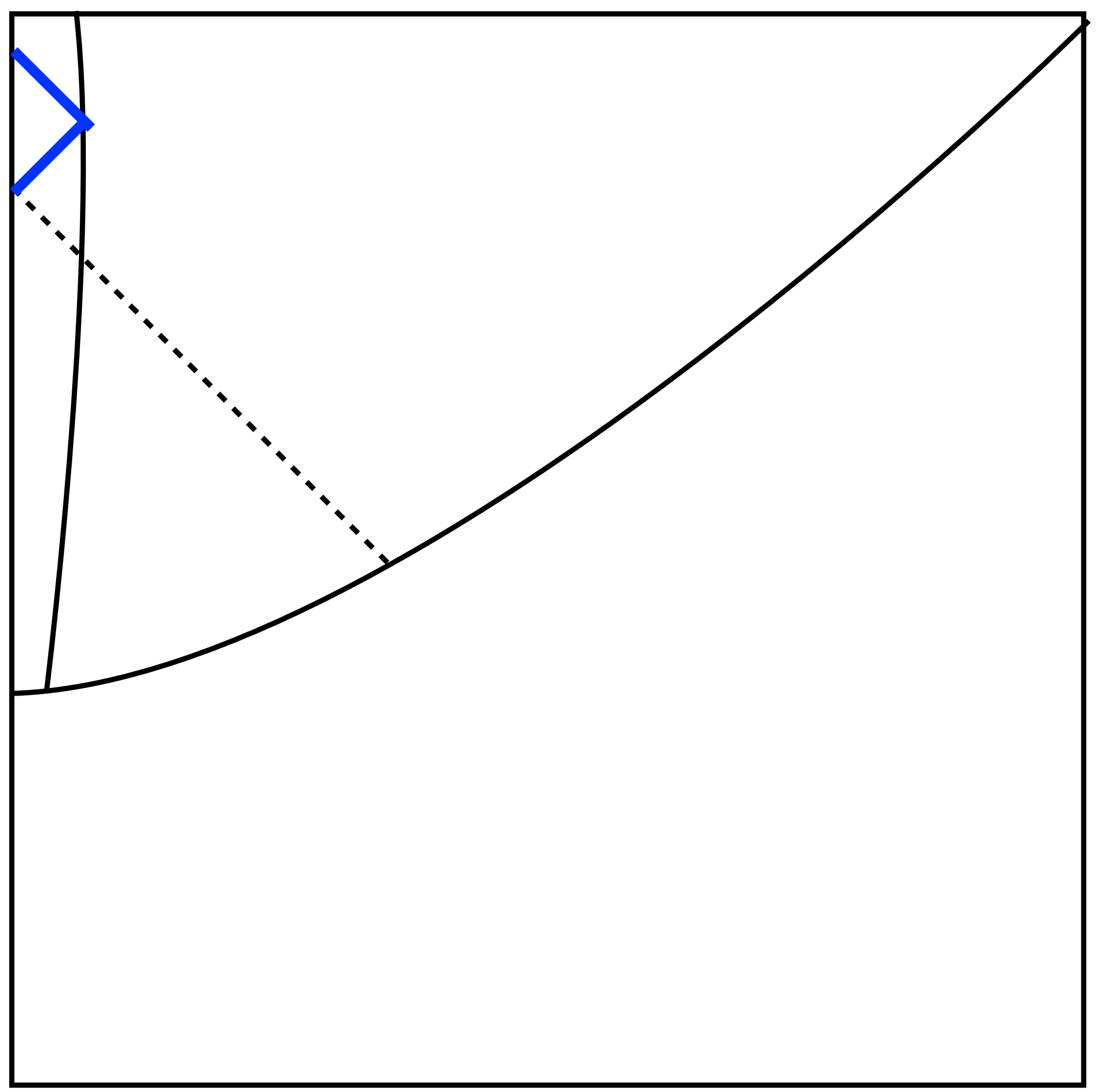

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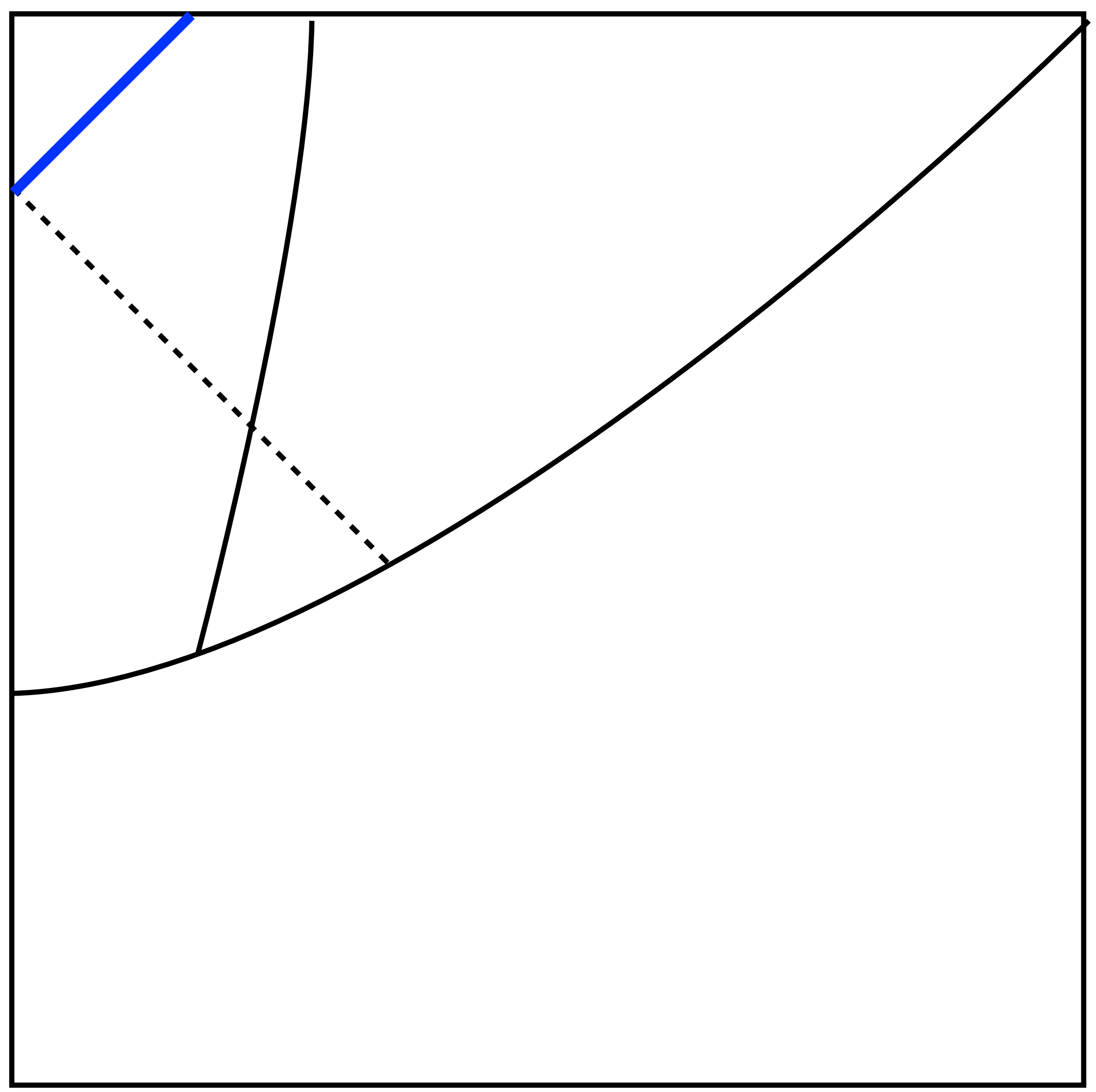
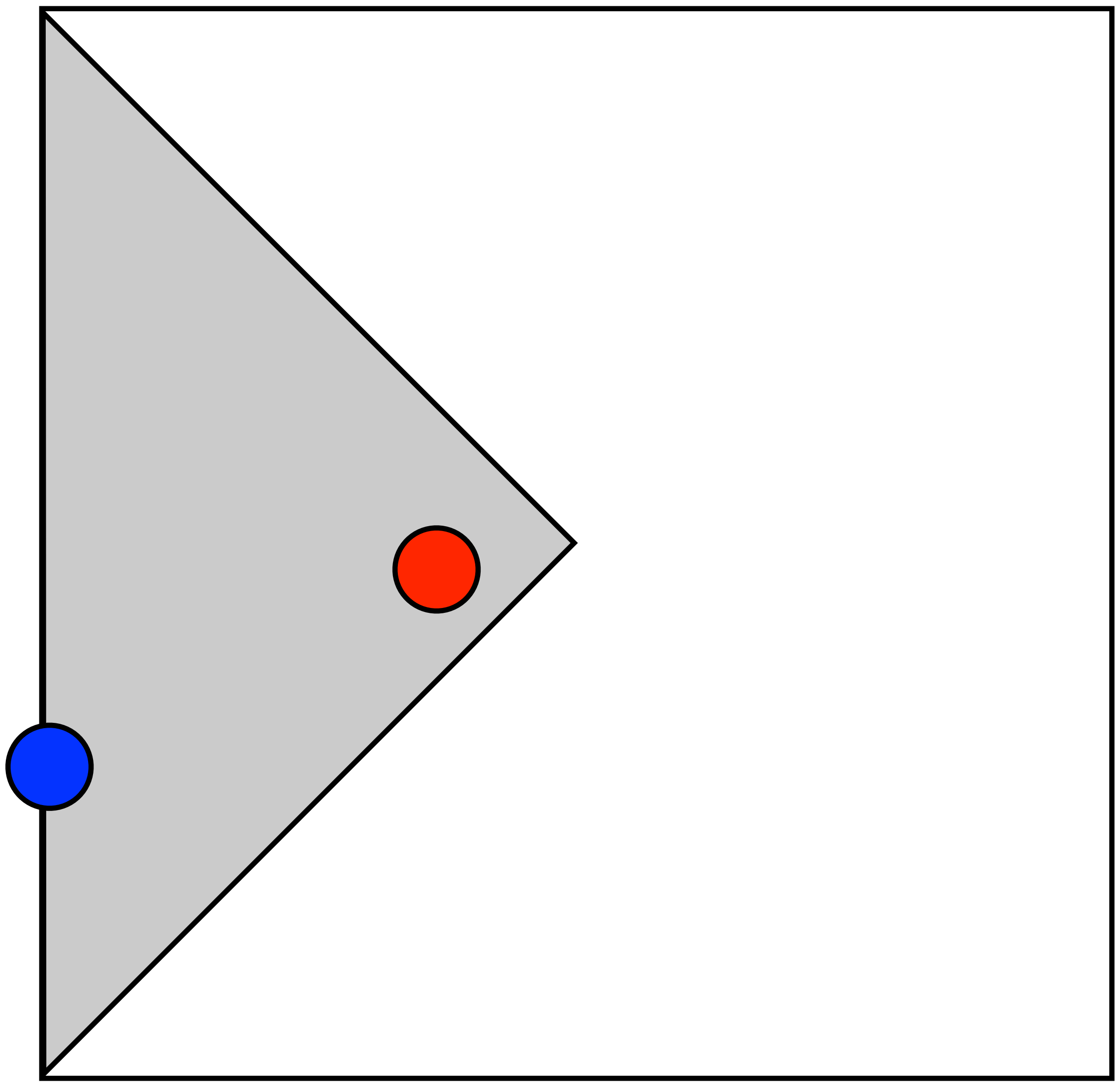


A Finite Amount of information

- Another consequence of a cosmological constant: maximum precision for any conceivable experiment.



can't separate things to arbitrarily large distances

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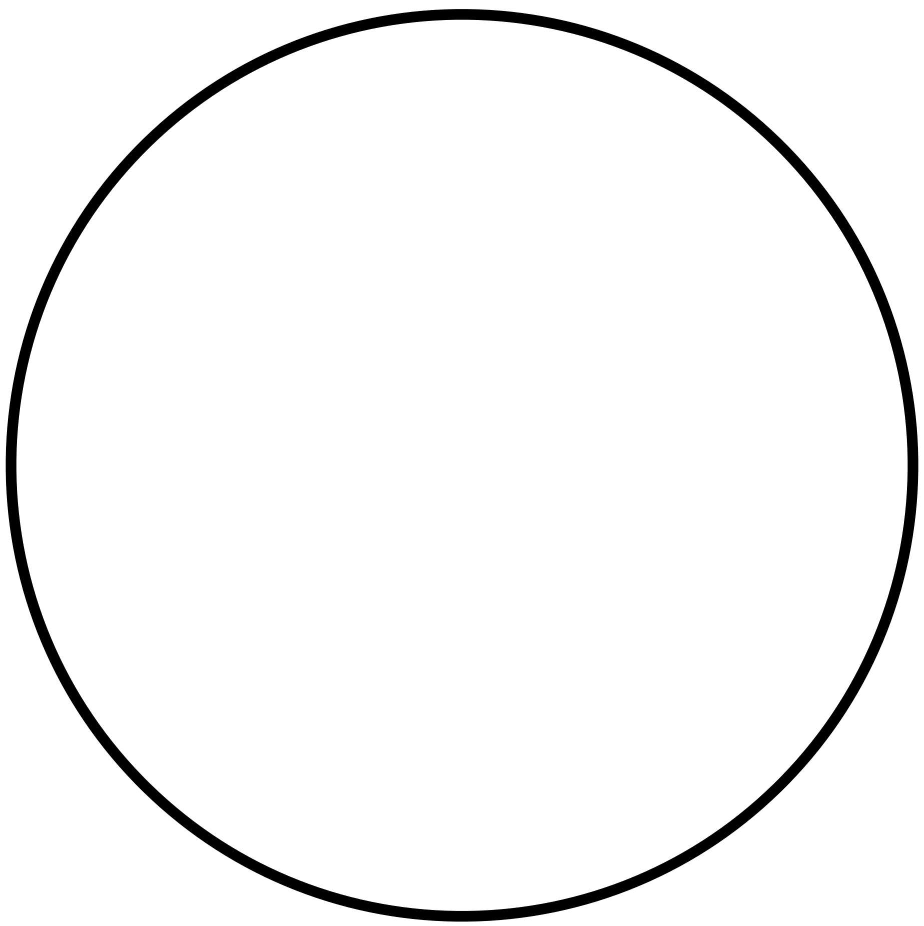

can’t make an arbitrarily large or complicated apparatus

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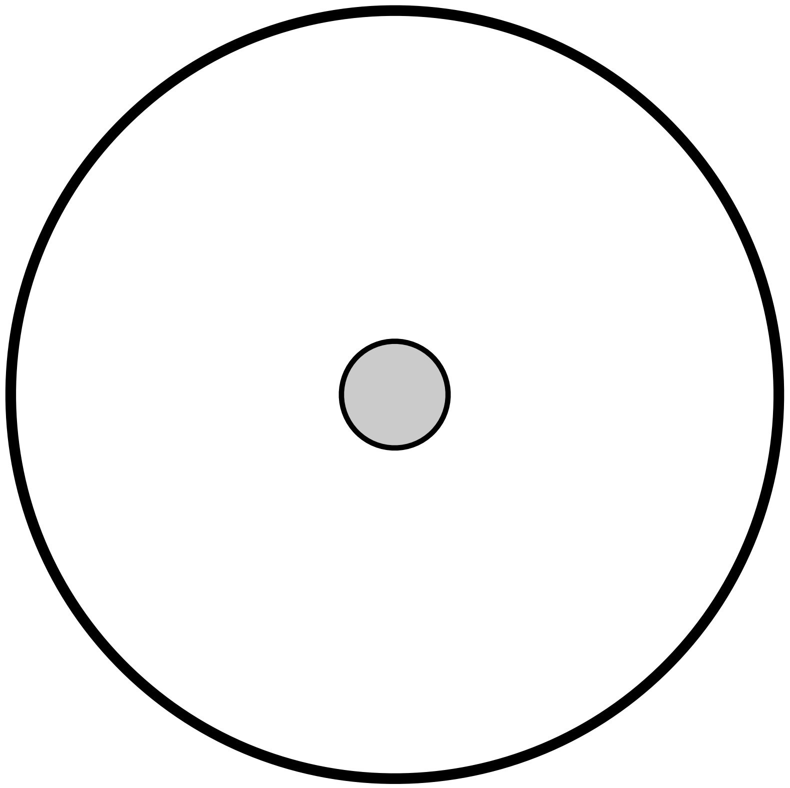

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cosmological horizon shrinks in presence of a mass

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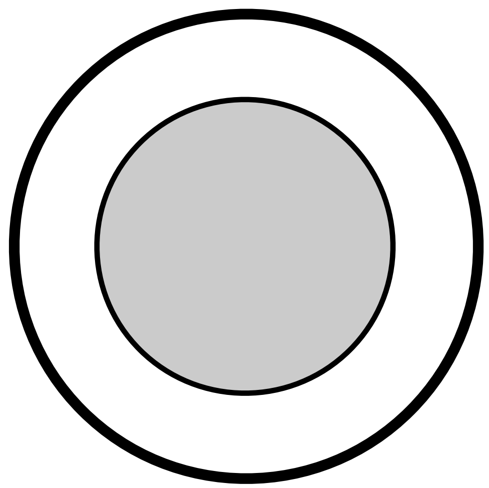

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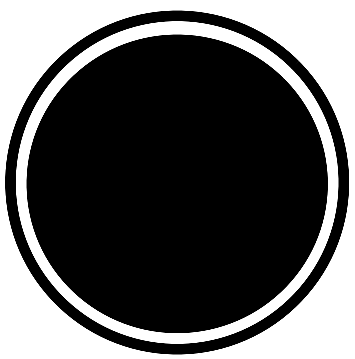

can't make an arbitrarily large or complicated apparatus

There is a biggest black hole, and therefore a biggest apparatus and a finite number of states.

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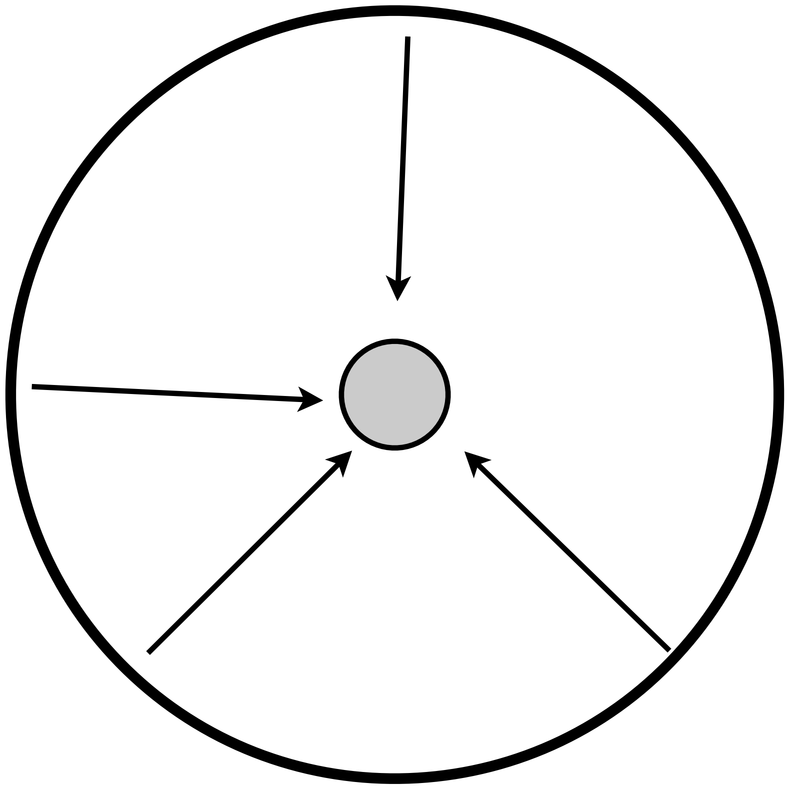

Any detector is being bombarded by Hawking radiation

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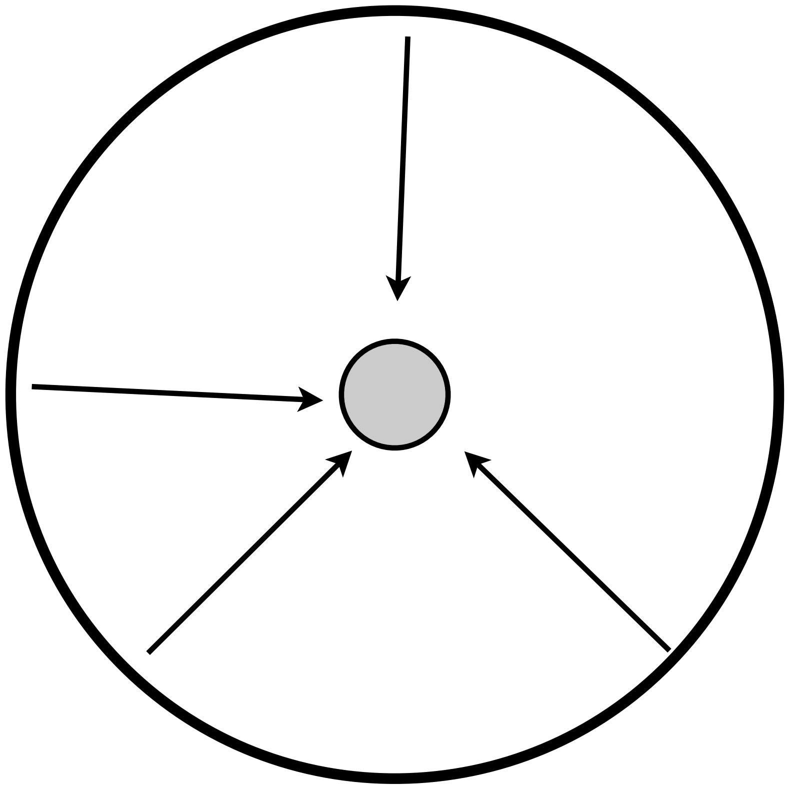


Any detector has a finite lifetime

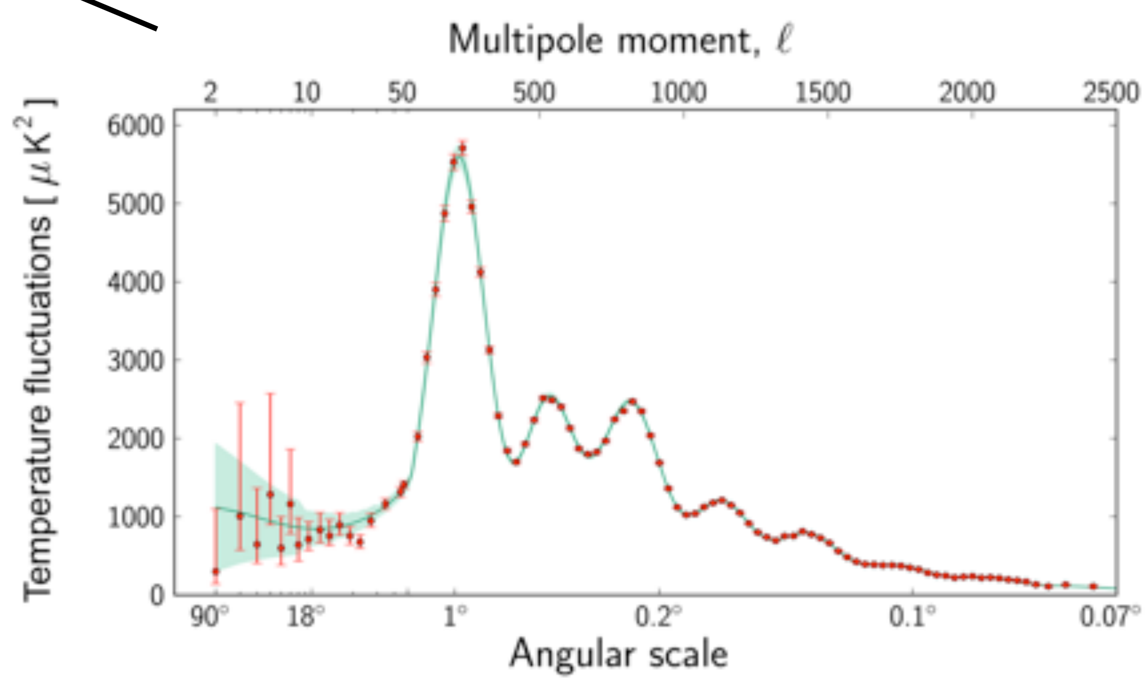
In Practice

- How do we compare data with theory?

$$\Omega_c,\ \Omega_b,\ \Omega_\Lambda,\ A,\ n_s,\ \tau$$

evolve

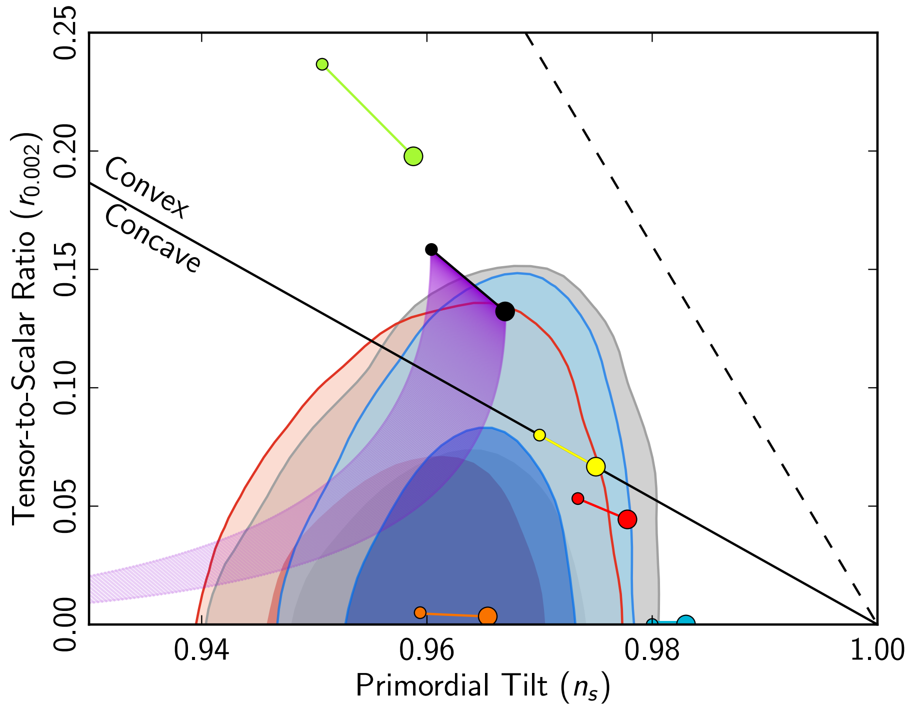
experimental details

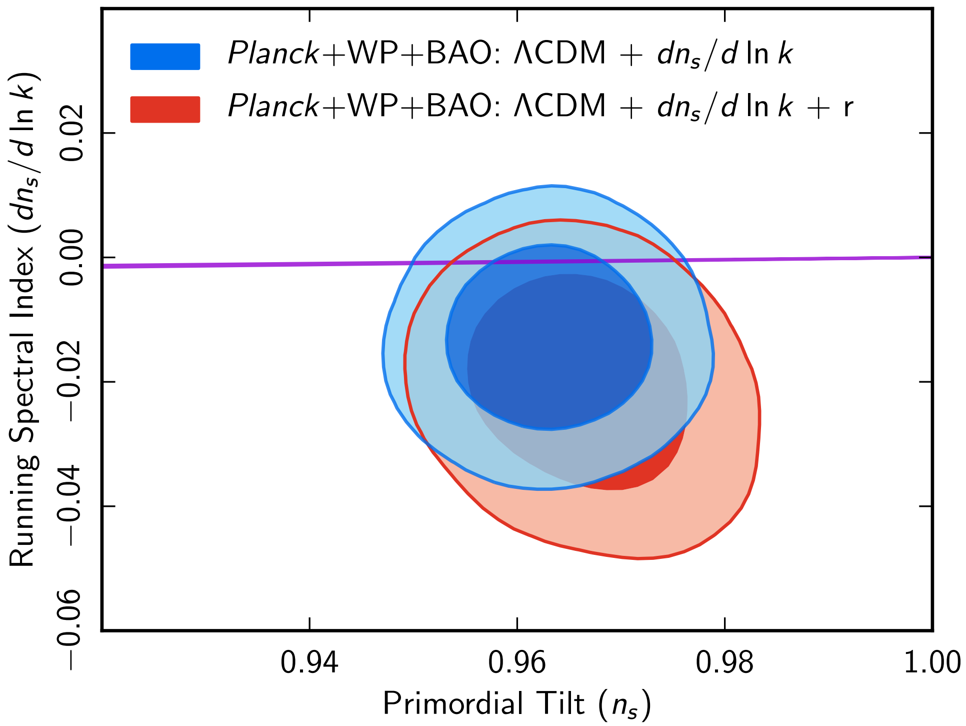


- Test the fit to data, repeat. $\mathrm{Pr(data|model)}$
- Important part: include other datasets!

In Practice

- Include more variables, and test the fit.





6 parameter model still works best!!!

Eternal Inflation: is this our universe?

Really?

- An infinite number of individually infinite universes in an infinite expanding background?

Surely I can’t be serious!

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non-unique vacuum
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(possible in standard model)

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(possible in standard model)

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non-unique vacuum state	Quantum field theory	accelerated expansion
(possible in standard model)	(works fantastically)	(observed: dark energy)
(common in BSM physics)		(inferred: inflation)
(inevitable in string theory)		

Observational Tests of Eternal Inflation

- Strong theoretical motivation, but is eternal inflation experimentally verifiable?

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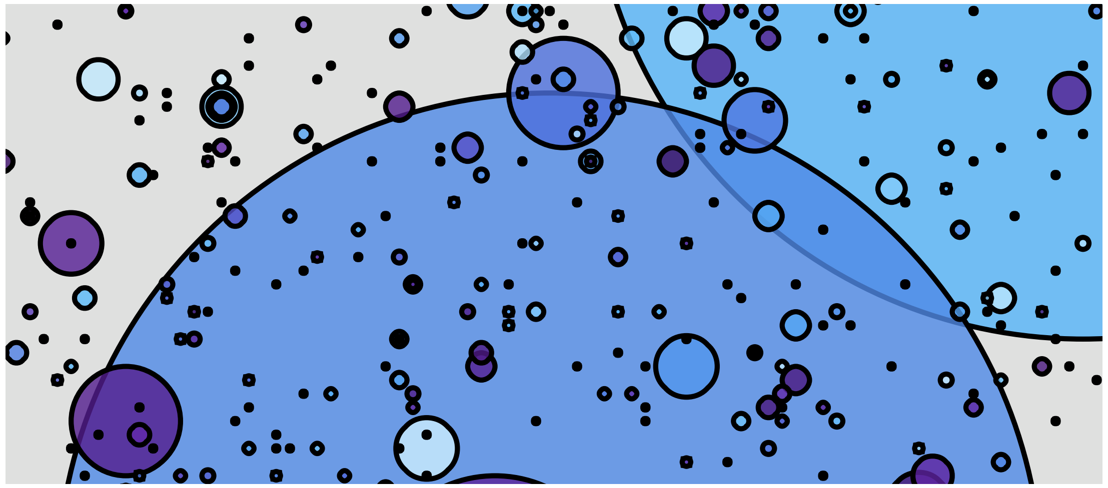
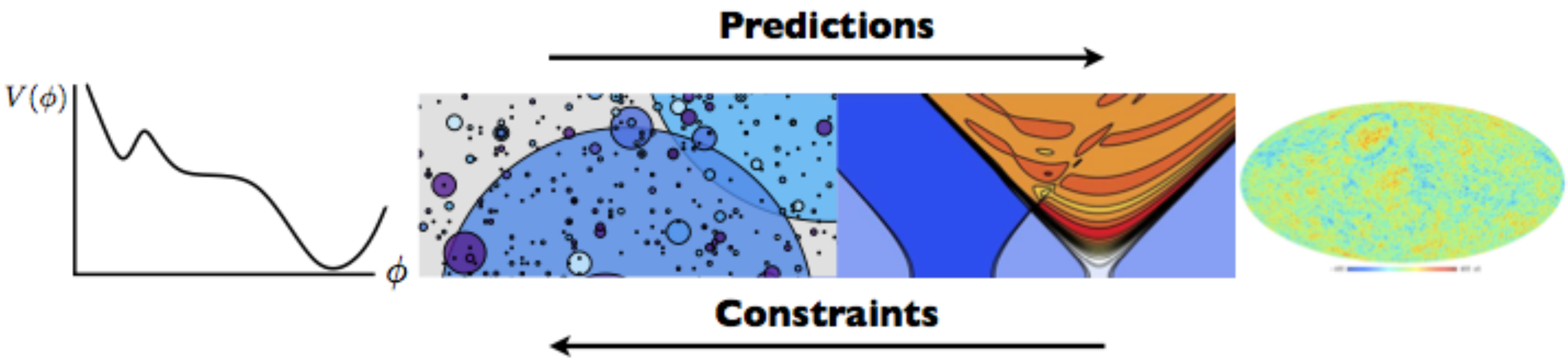
Our bubble does not evolve in isolation....



The collision of our bubble with others provides an observational test of eternal inflation.

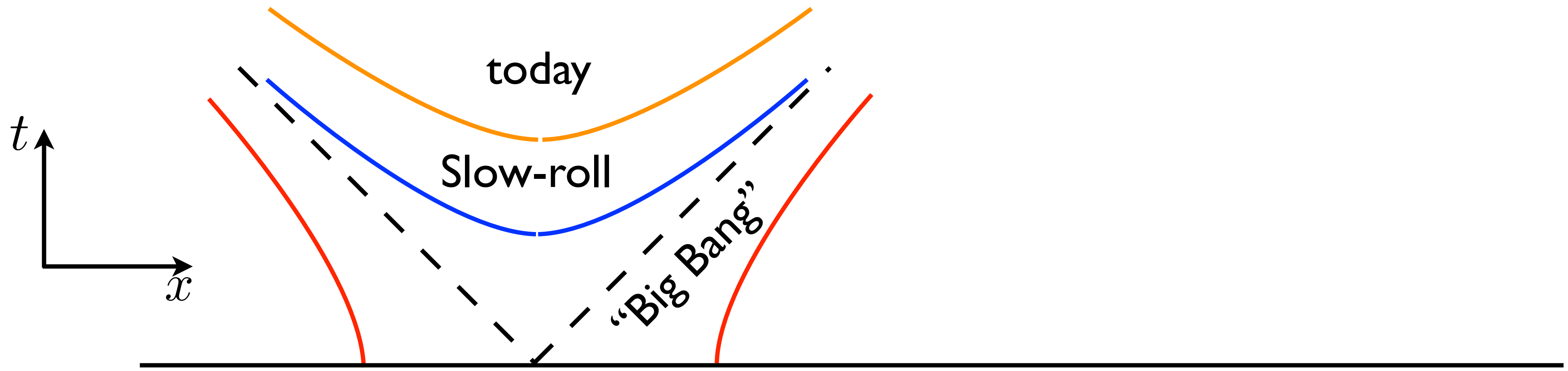
Aguirre, MCJ, Shomer

Making predictions and testing models



Scalar field Lagrangian	Eternal inflation	Bubble collisions	Observational signatures
Possible models? Motivation from theory? Constraints from observation?	Probabilities and inferences? Relation to other versions of the multiverse? How are model parameters manifest?	Predictions from specific models? Phenomenology? Perturbations inside the bubble?	Detailed signature for temperature and polarization? Best data analysis strategies?

Bubble collisions



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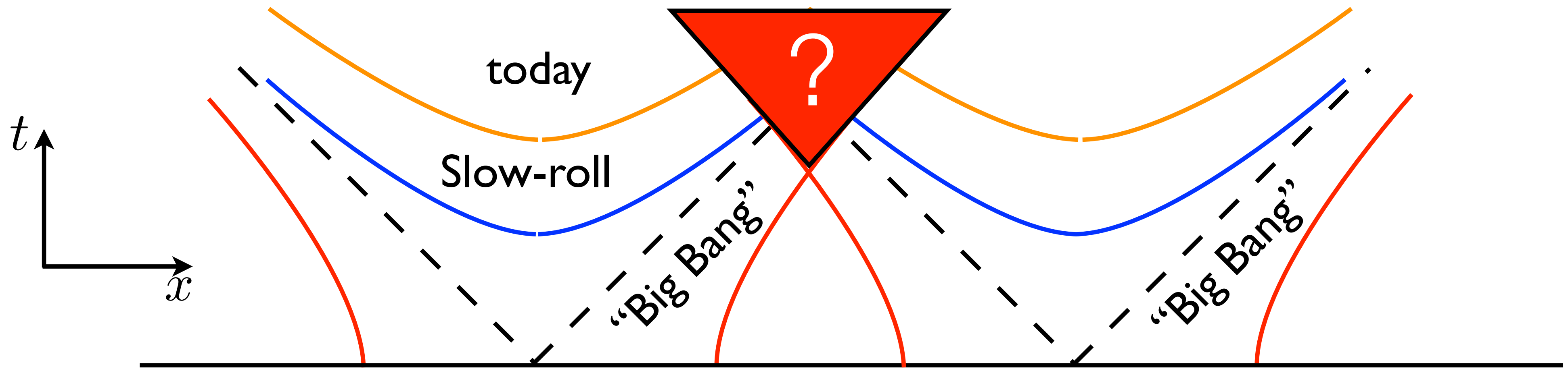

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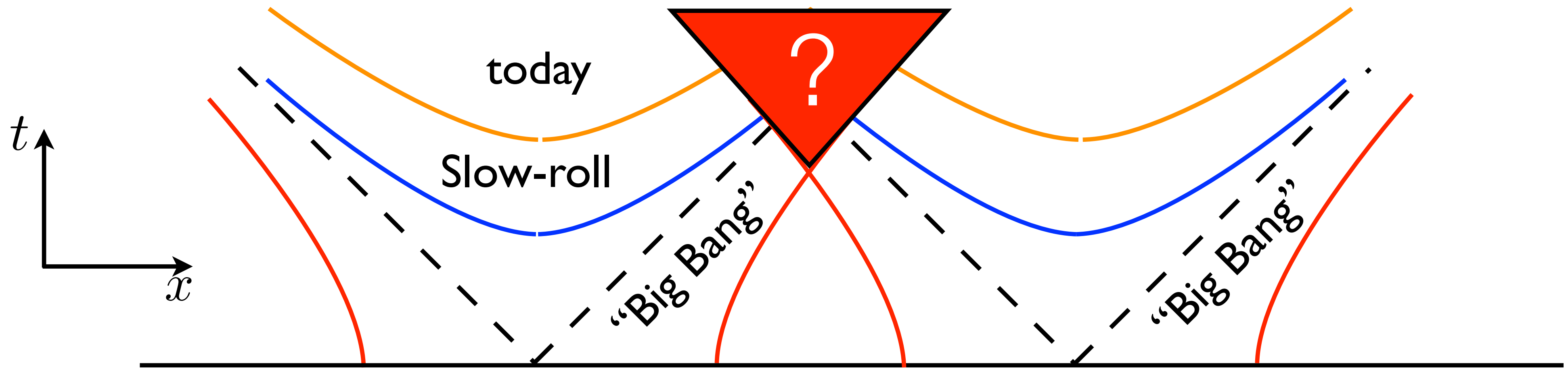

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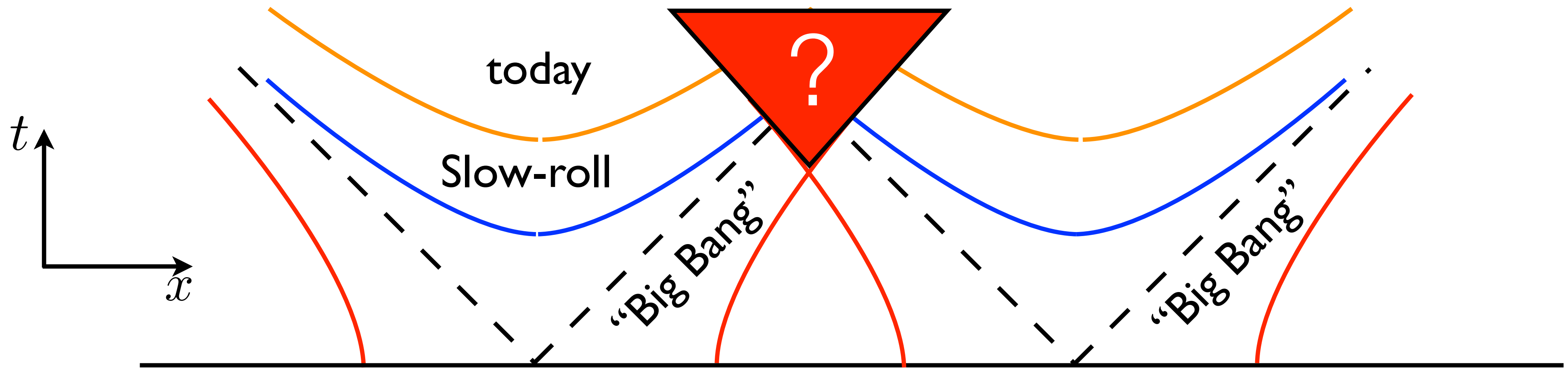
- The outcome is fixed by the potential and kinematics.

Bubble collisions



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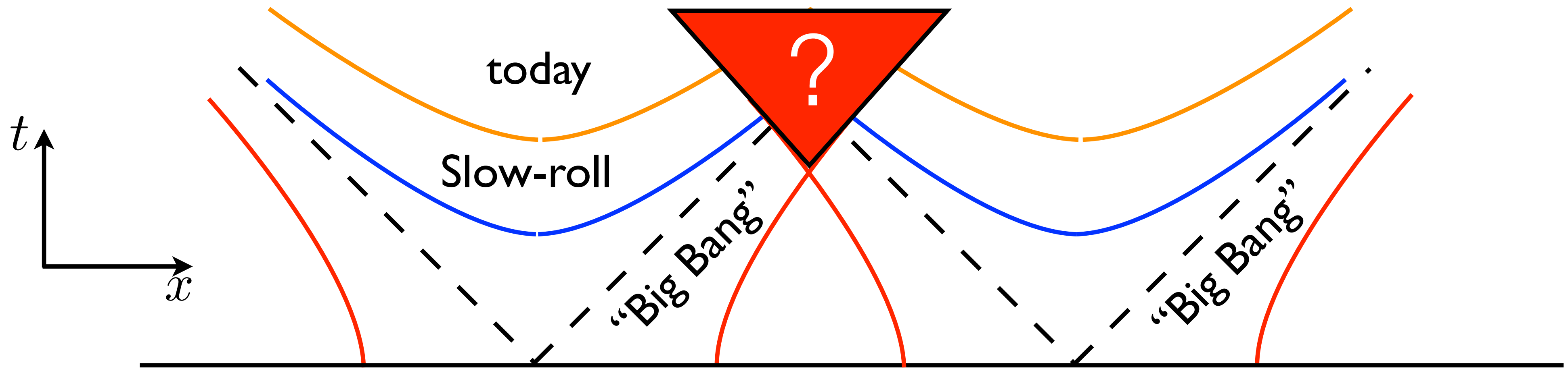


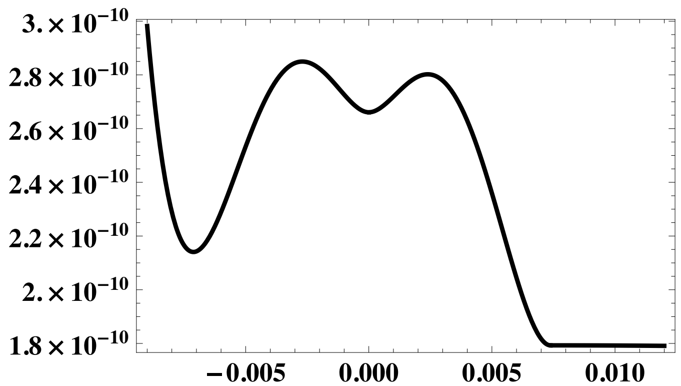
- Collisions are always in our past.
- The outcome is fixed by the potential and kinematics.
- To study what happens, need full GR.
  - We want to find the post-collision cosmology: GR.
  - Huge center of mass energy in the collision.
  - Non-linear potential, non-linear field equations.

Numerical solutions

- Numerical simulations with full GR: full dynamics.

$$ds^2 = -\alpha(x,z)dz^2 + a(x,z)dx^2 + z^2 dH_2^2 \qquad \phi(x,z)$$

$V(\phi)$



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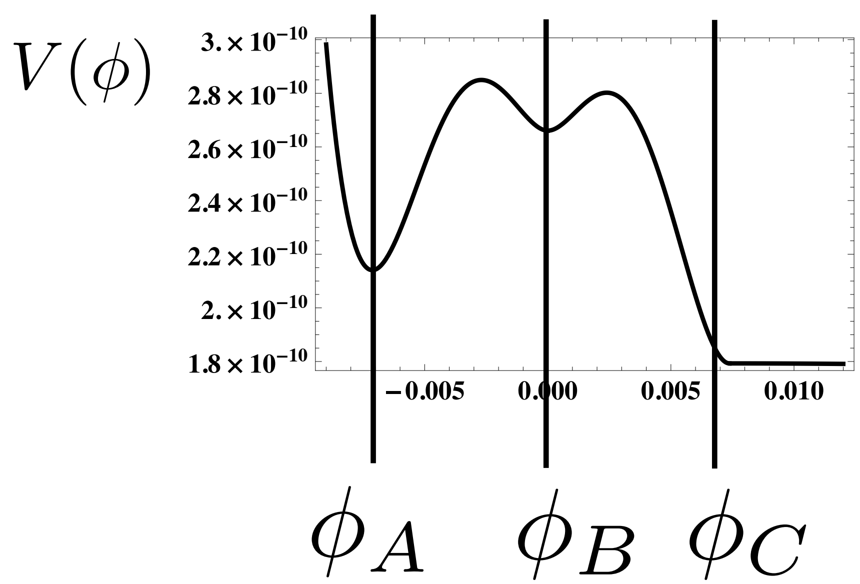

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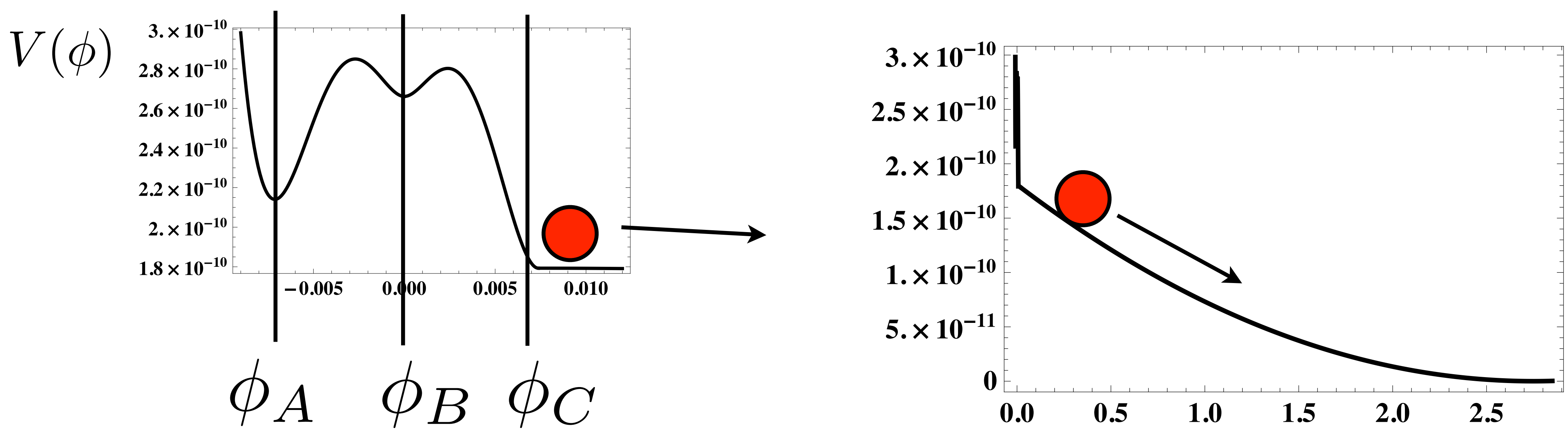


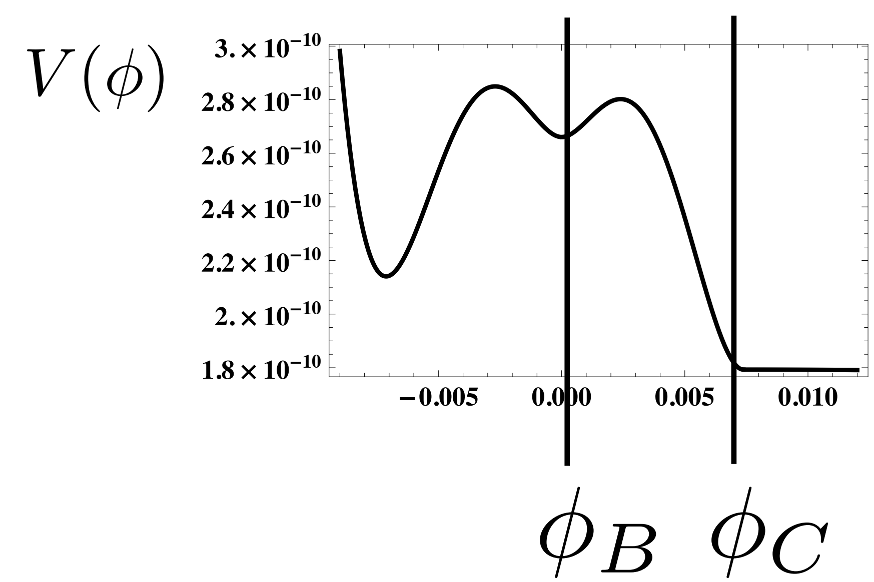
- 2 types of bubbles from false vacuum.
- Slow roll inflation inside one, starting near ϕ_C .

Numerical solutions

- Colliding identical bubbles.

$$2(\phi_C - \phi_B)$$

ϕ_C



ϕ_B

- After the collision, fields linearly superpose: potential key.

- Dynamics necessary!

Numerical solutions

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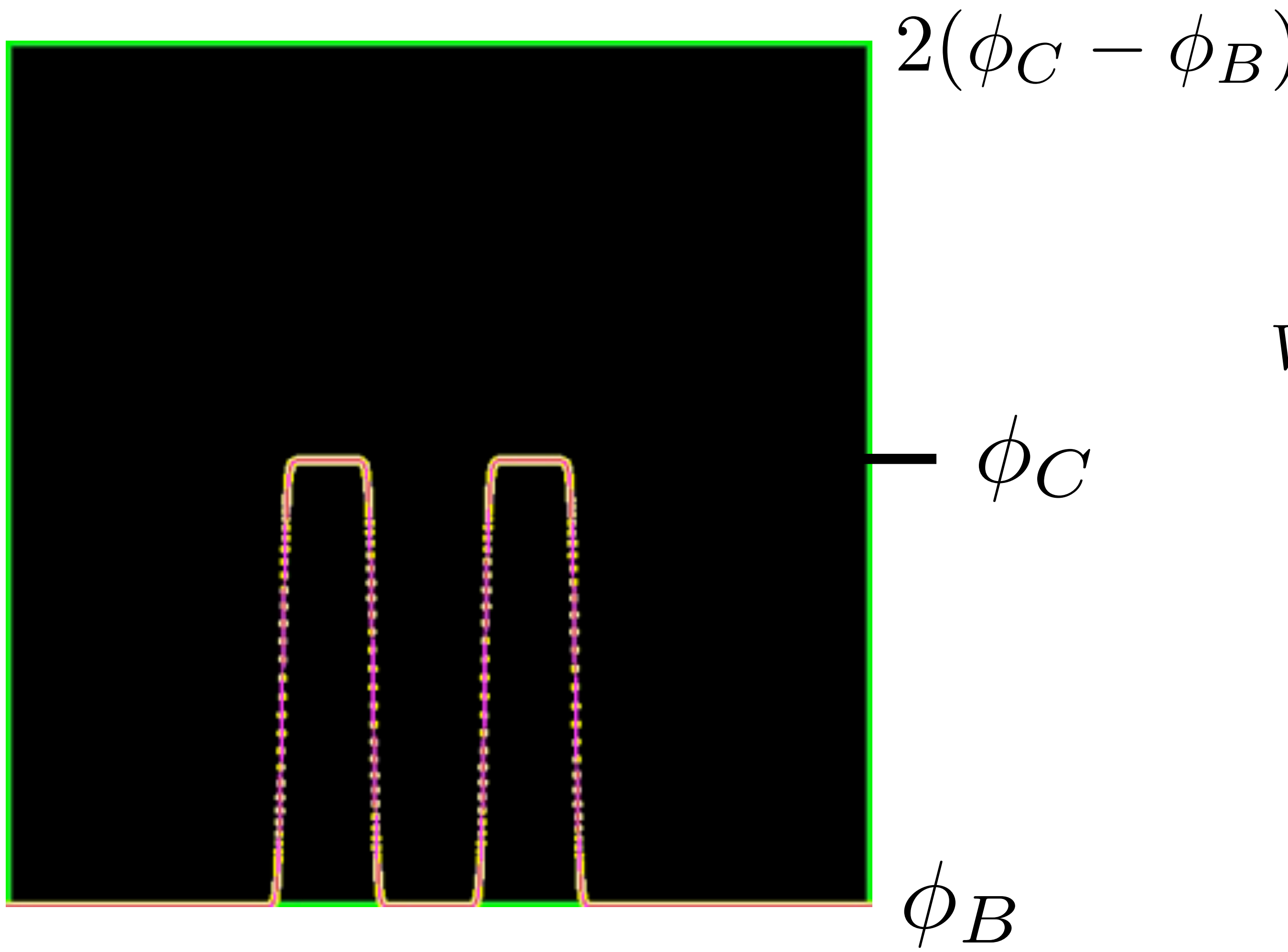

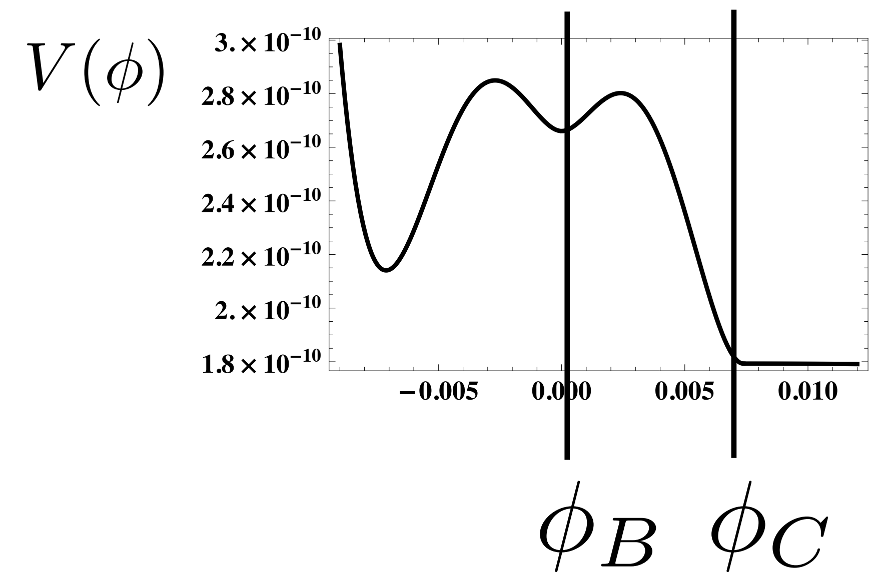

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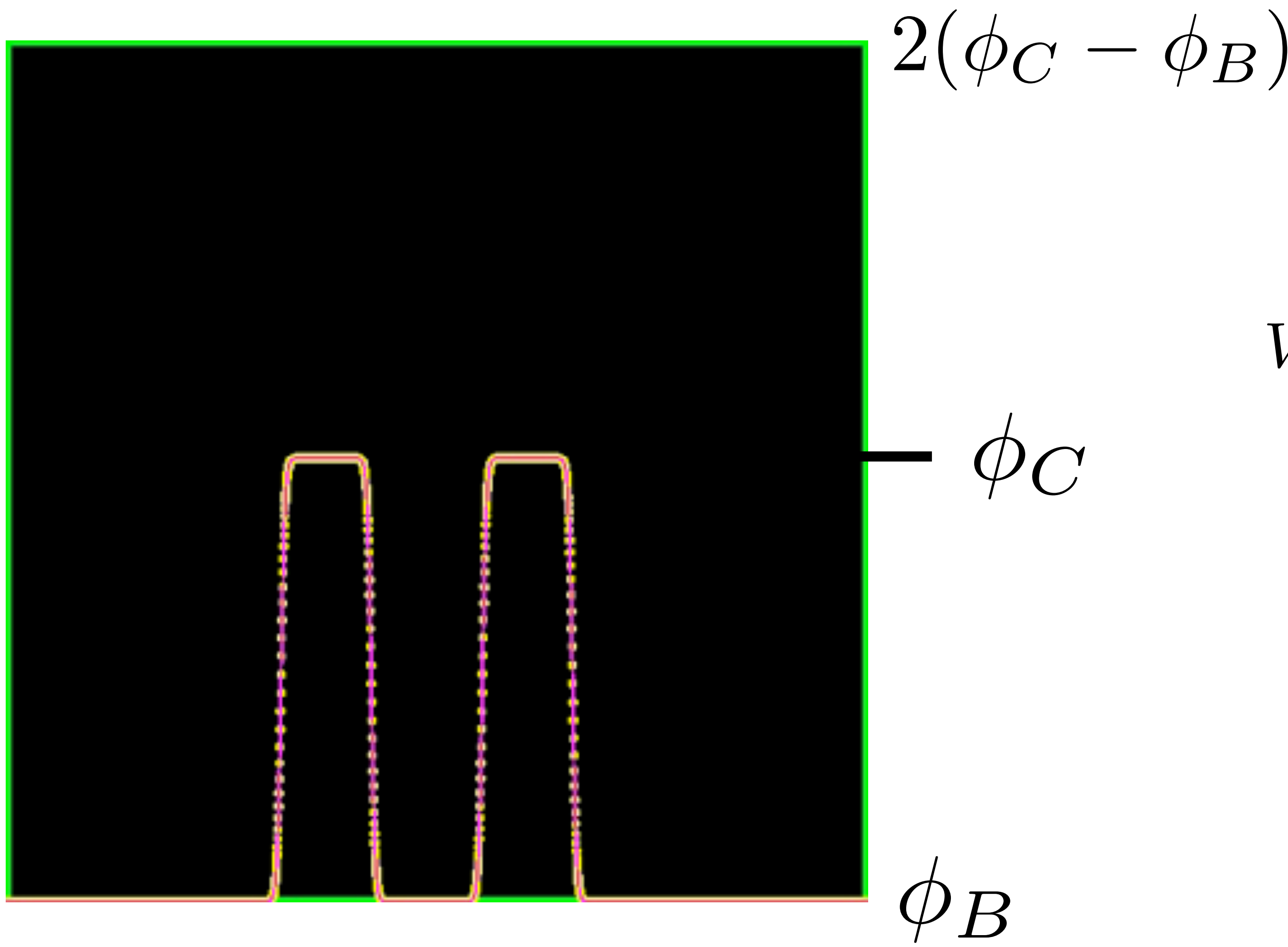

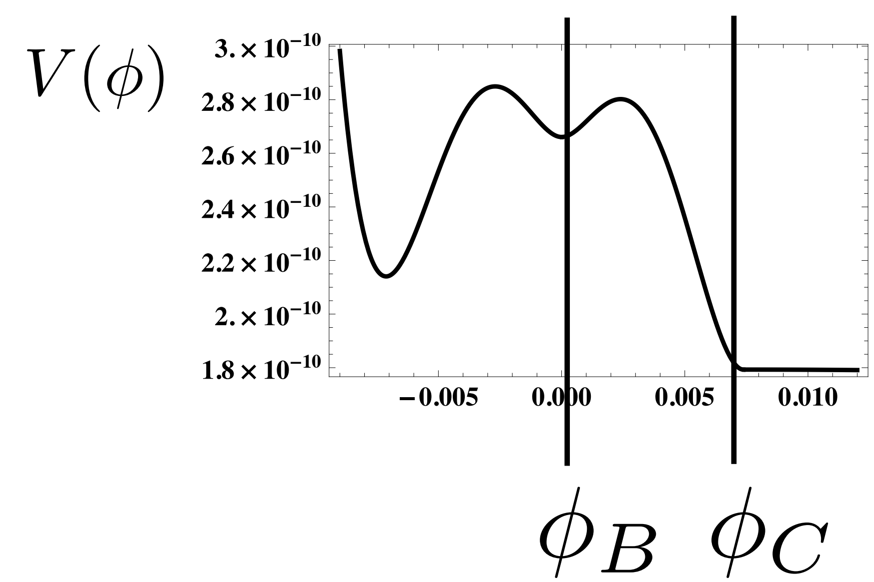

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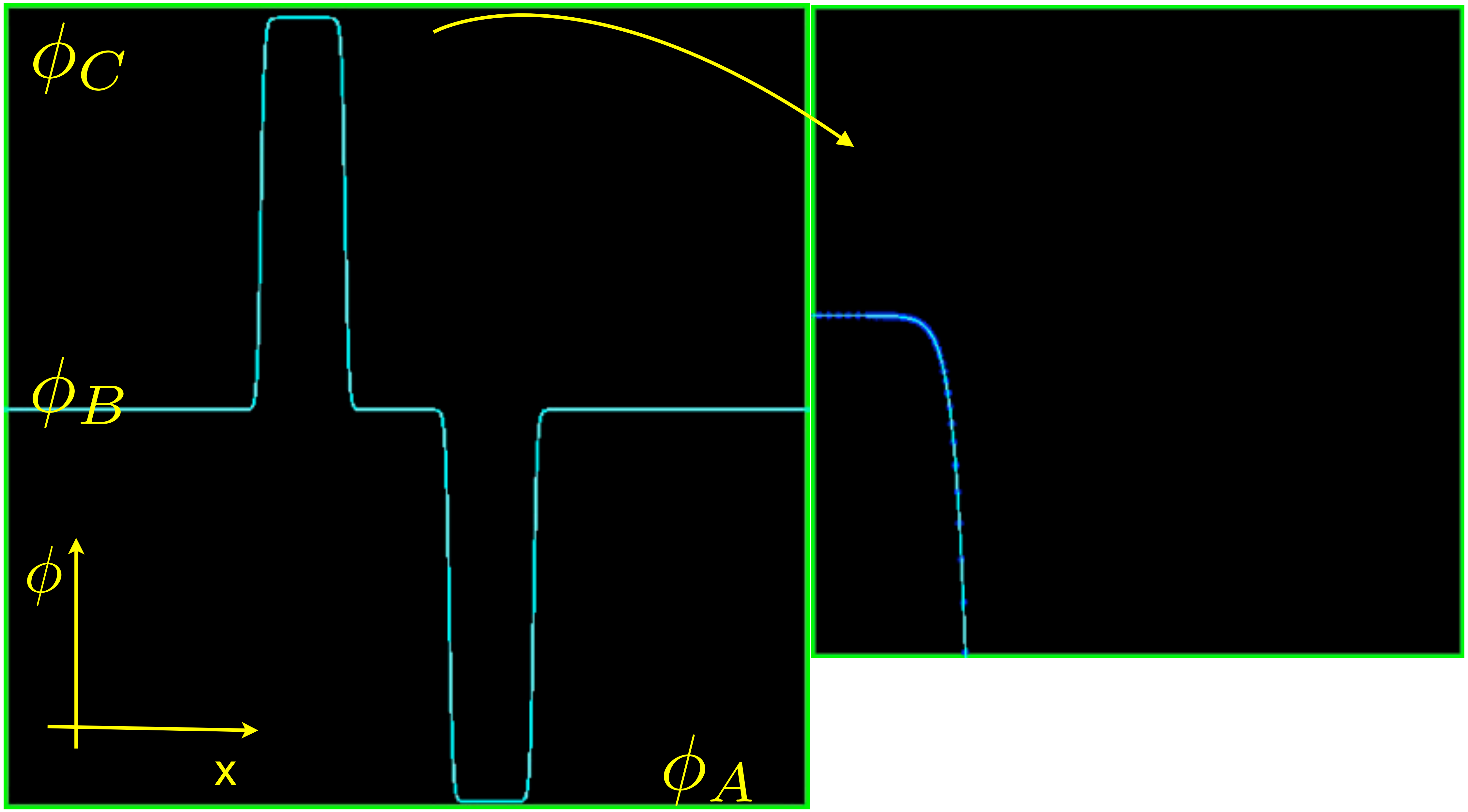

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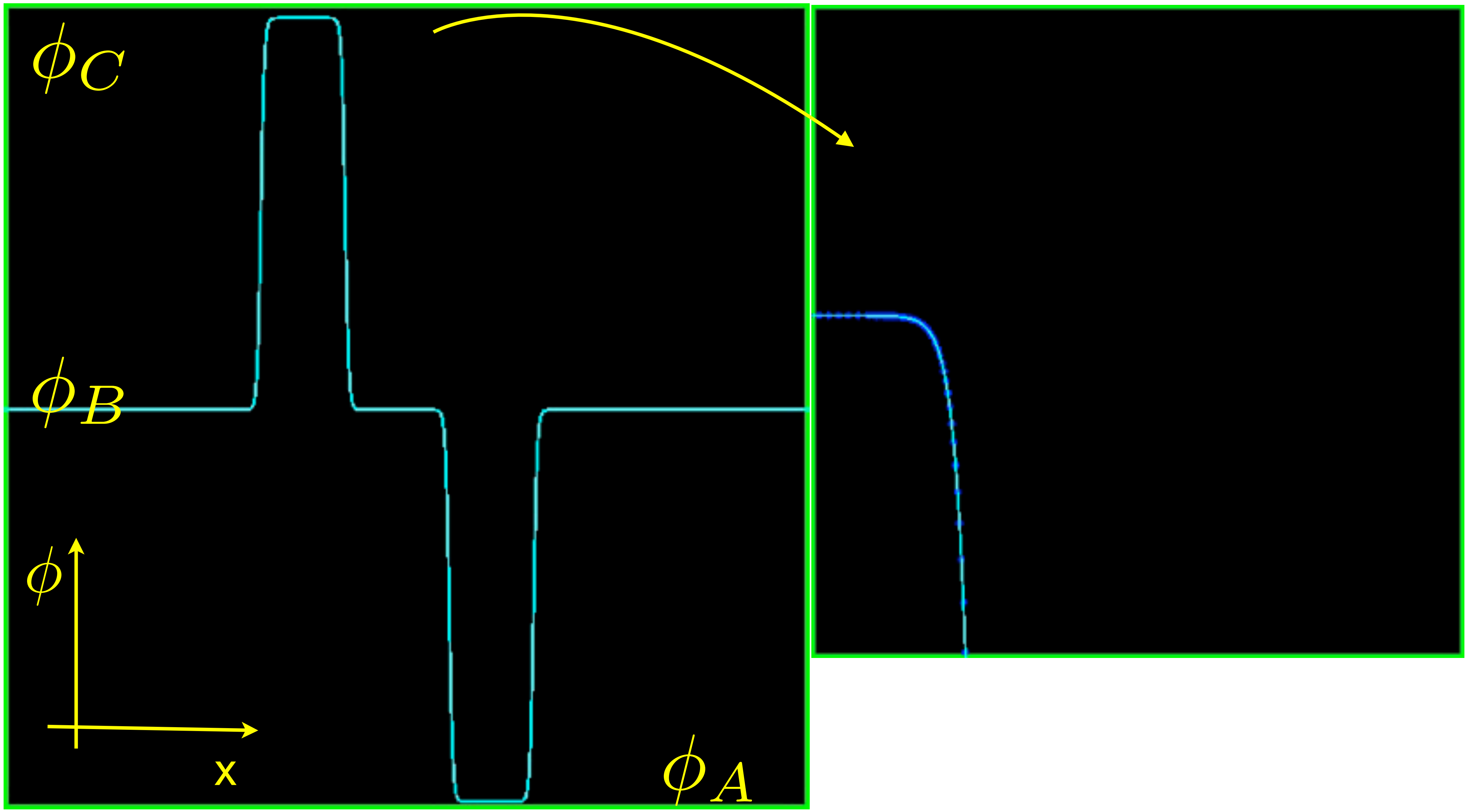

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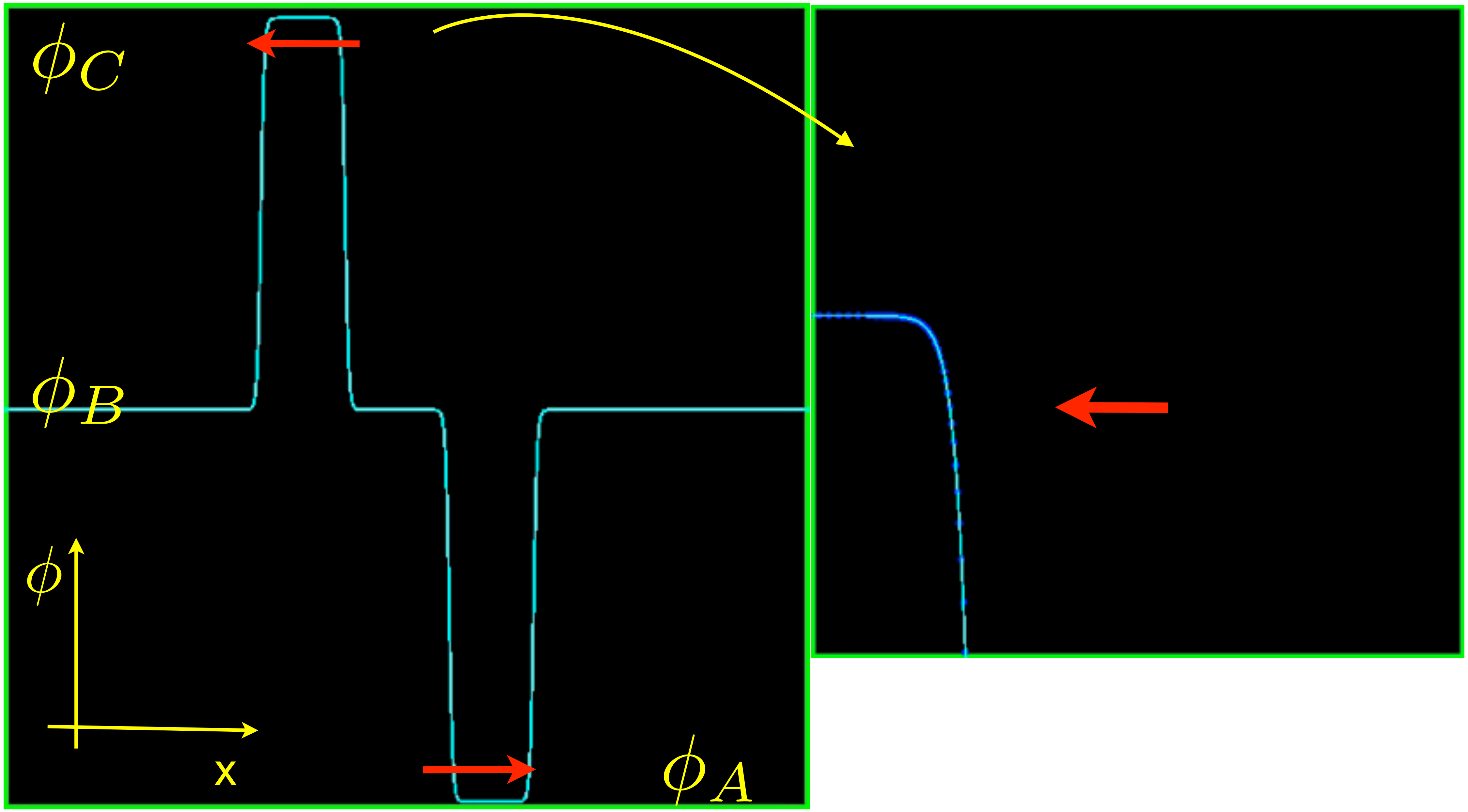
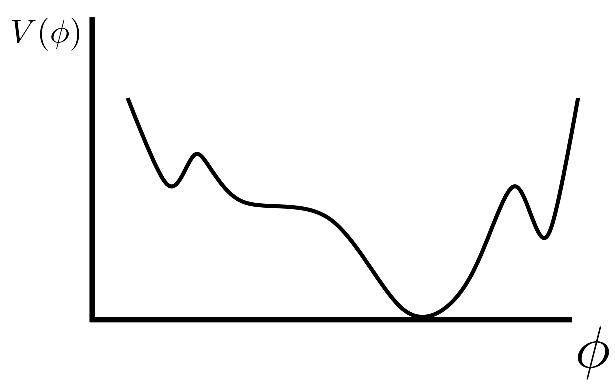


- Inflation does not end, there are new perturbations!

Observational Signatures

- Bubble collisions perturb the epoch of inflation inside our bubble.



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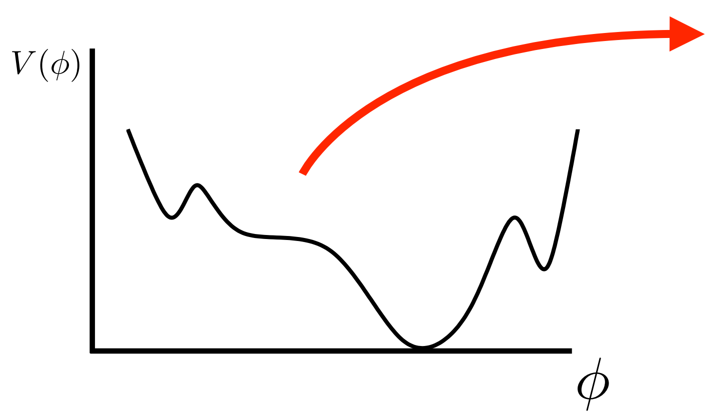

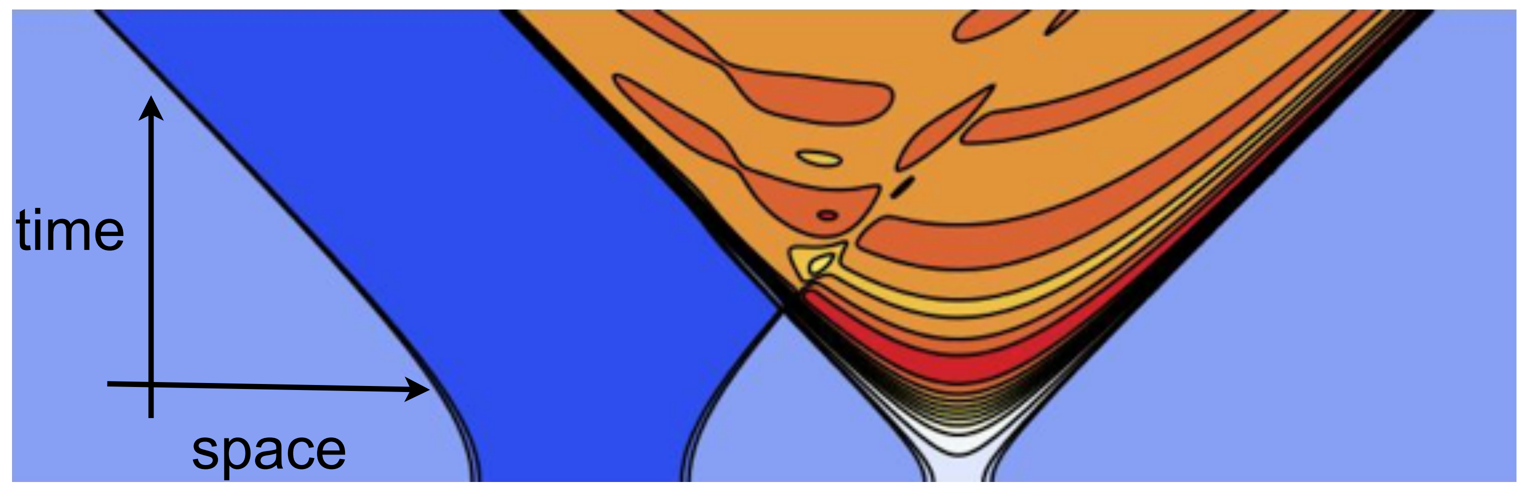

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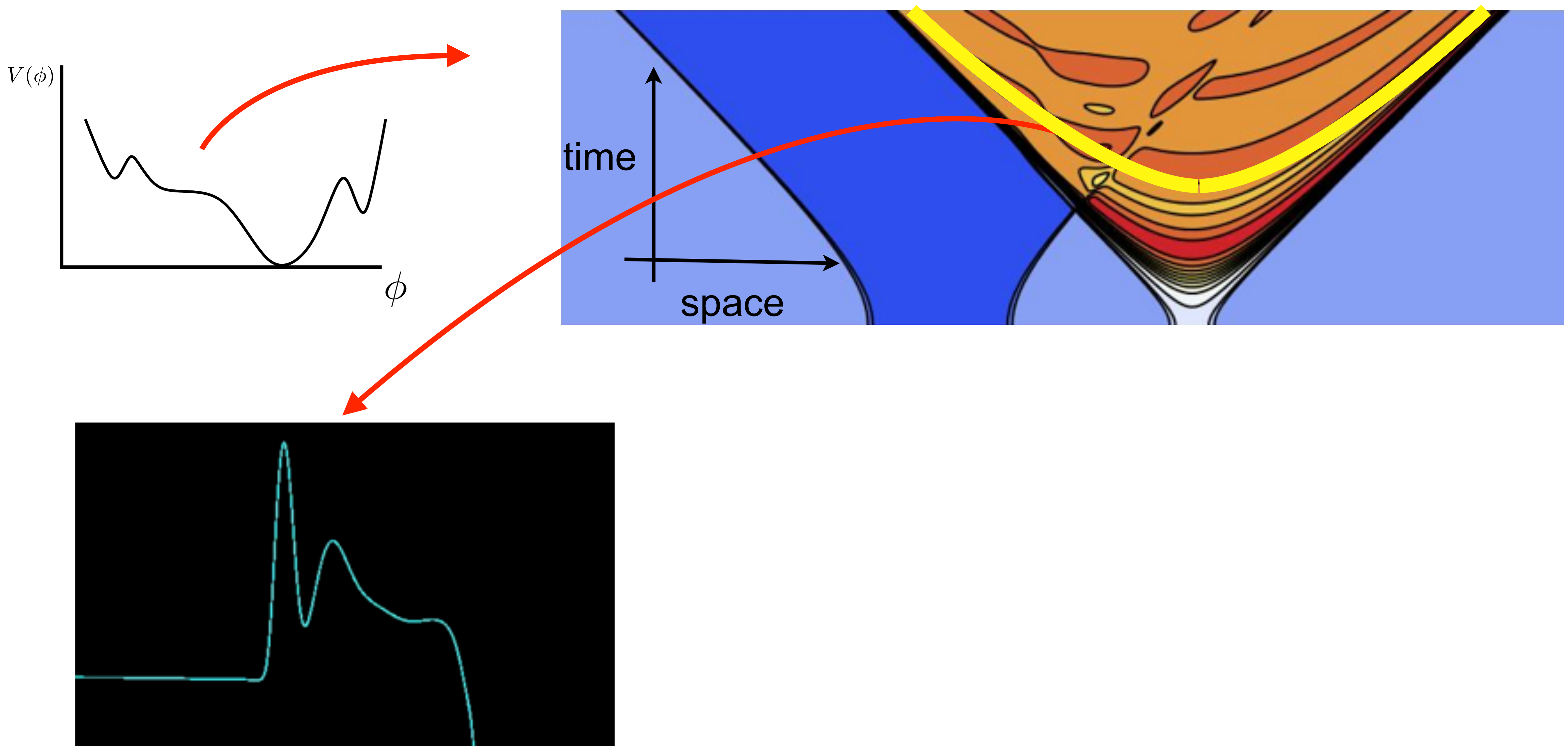

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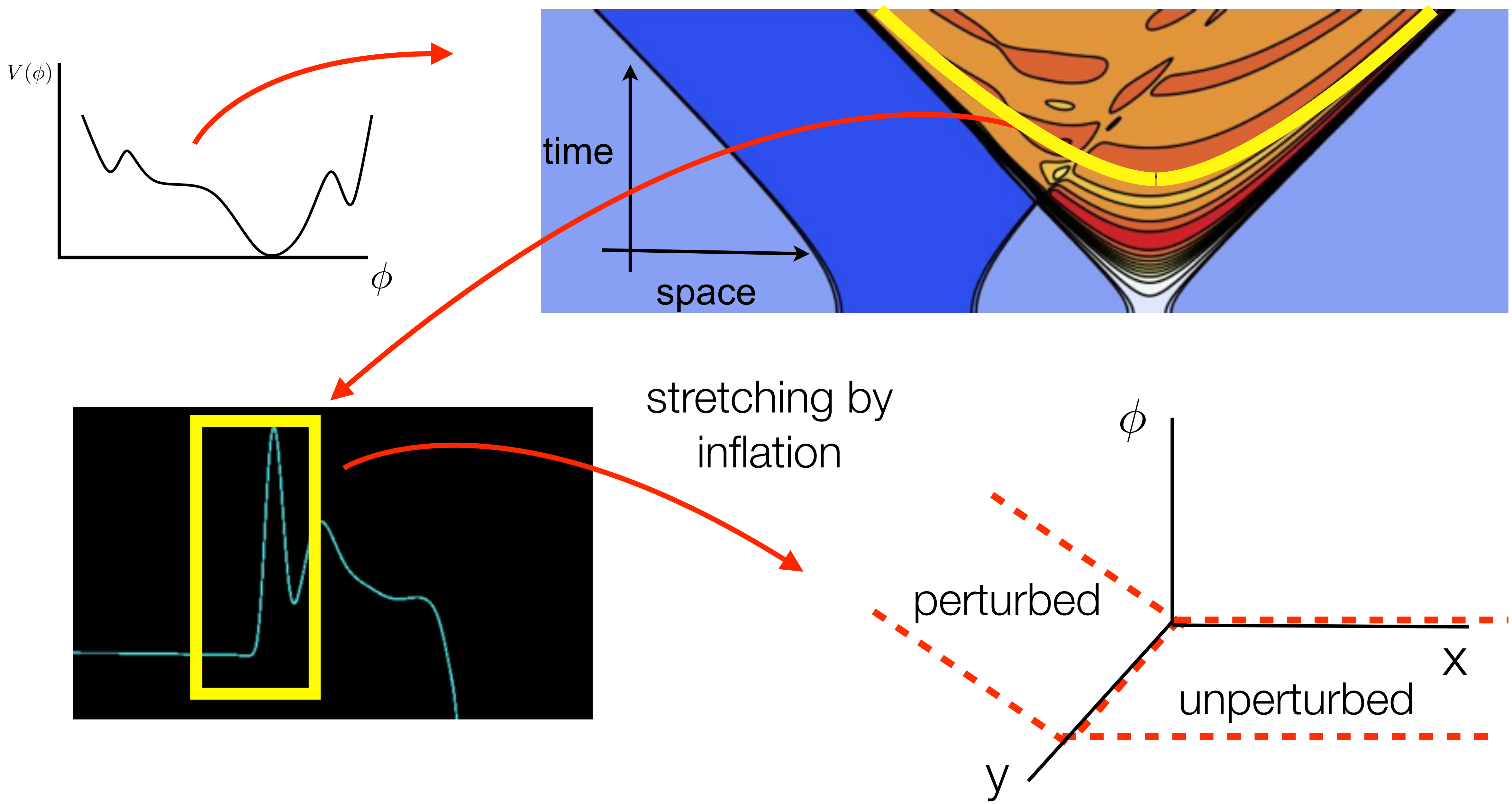

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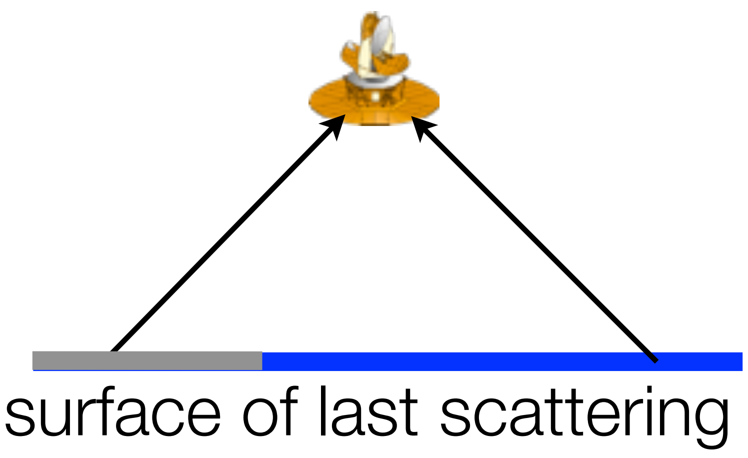

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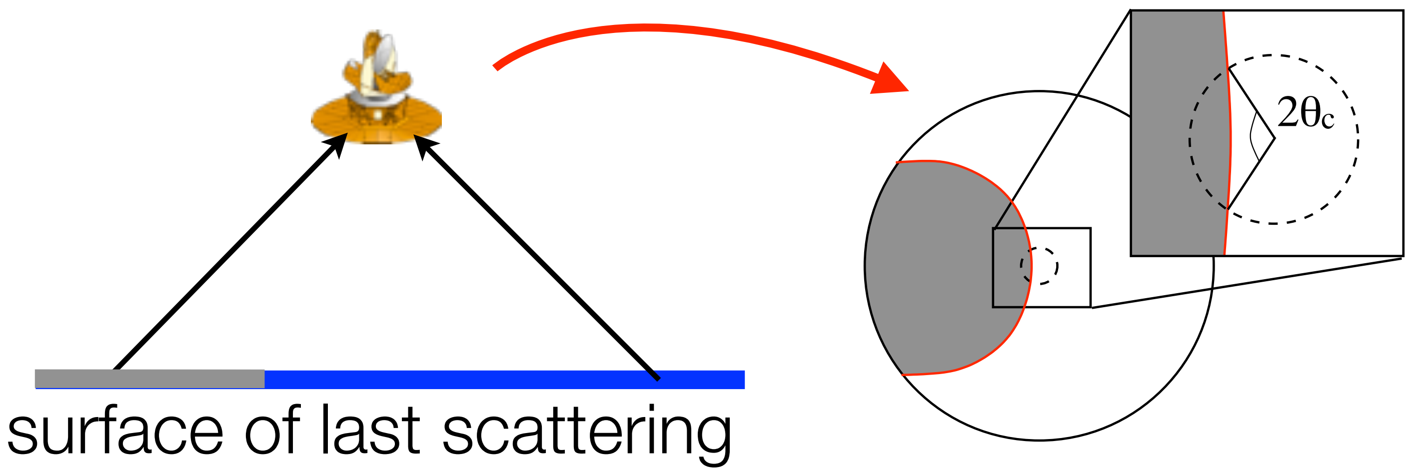

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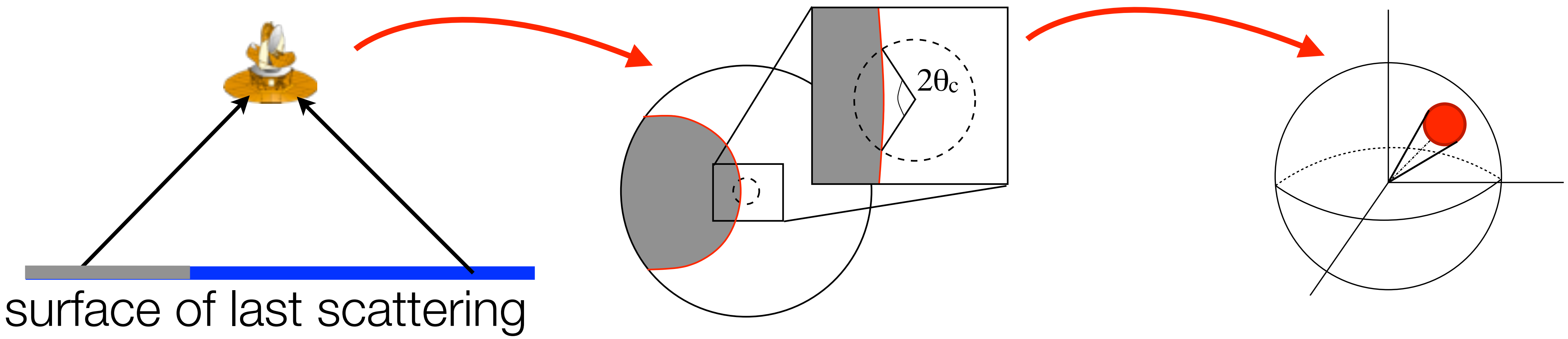
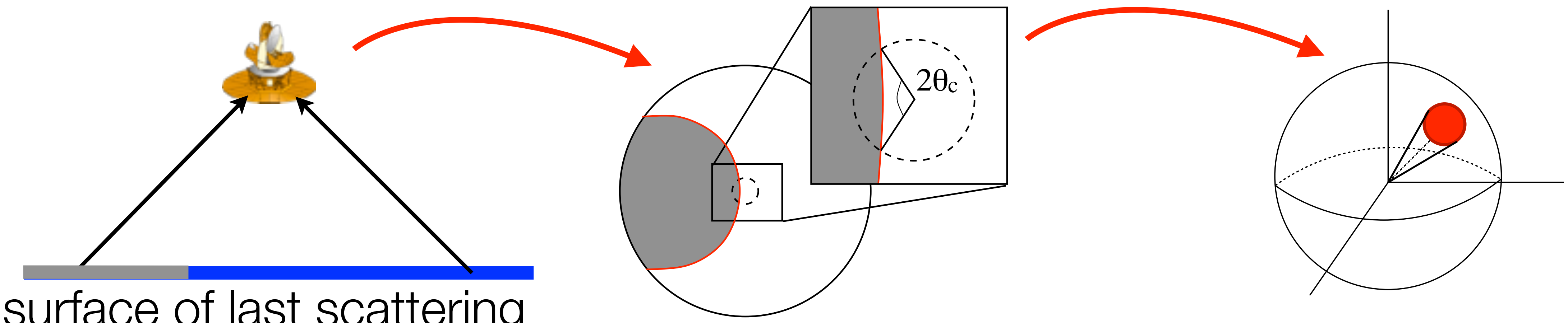


Symmetry+causality: effects confined to a disc.

Observational Signatures



surface of last scattering

Symmetry+causality: effects confined to a disc.

- Generic signature (thanks inflation!):

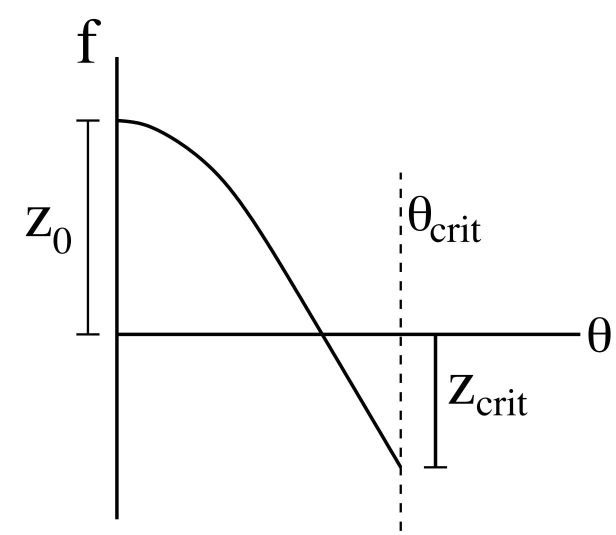
$$\frac{\Delta T(\hat{\mathbf{n}})}{T} \simeq f(\hat{\mathbf{n}}) + \delta_{\Lambda CDM}(\hat{\mathbf{n}})$$

f : analytic arguments and numerics

Feeney, MCJ, Mortlock, Peiris

Chang, Kleban, Levi

Gobetti & Kleban



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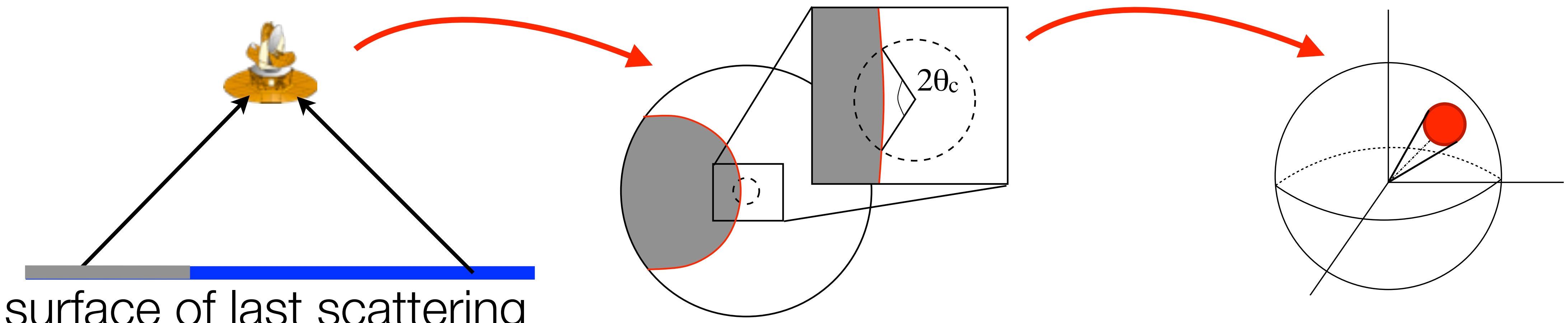

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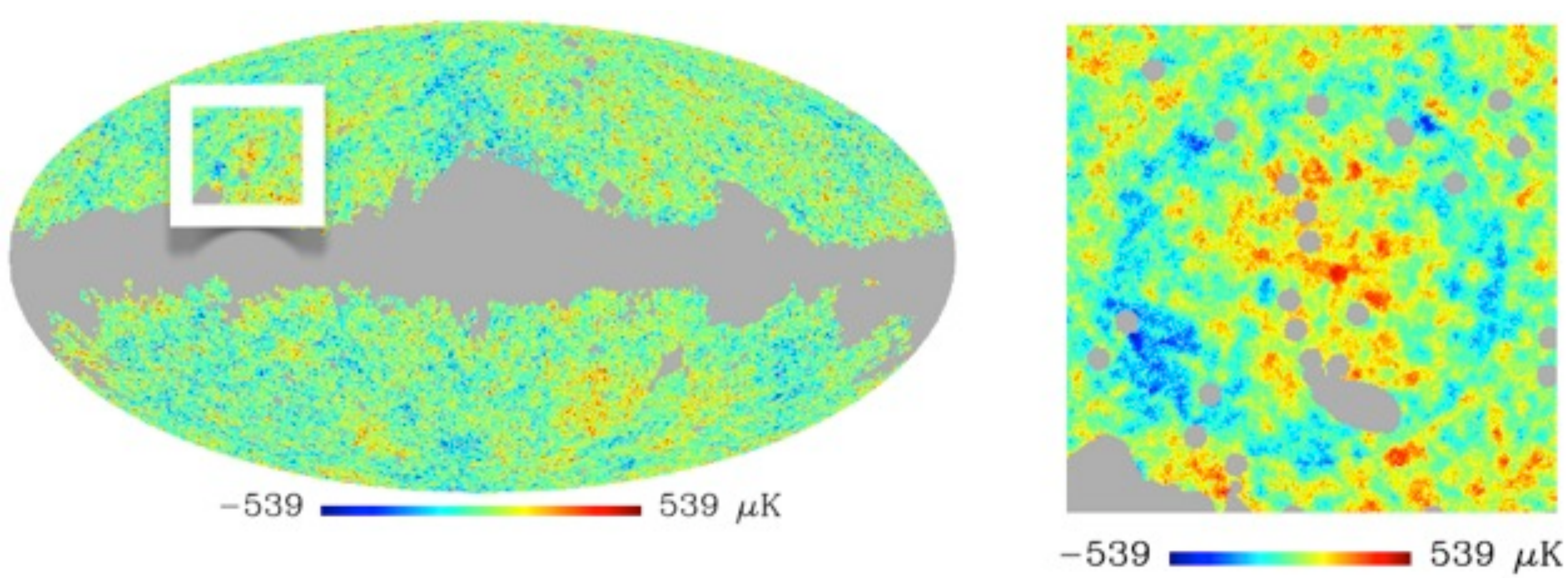
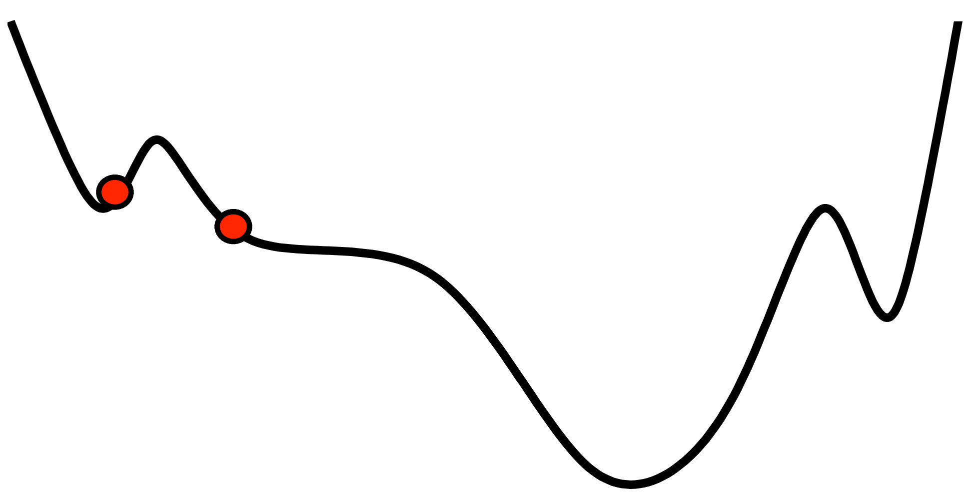
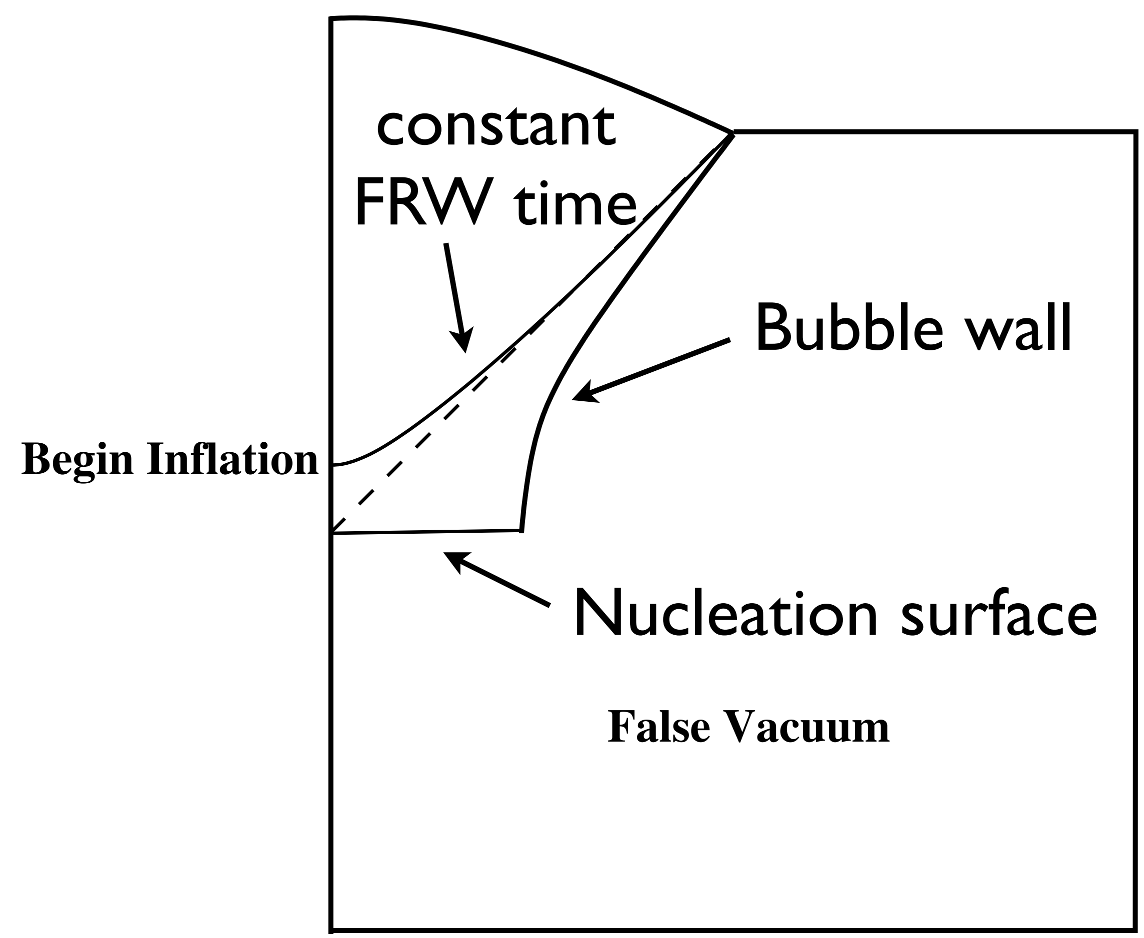


Counting collisions

- How many collisions are there?





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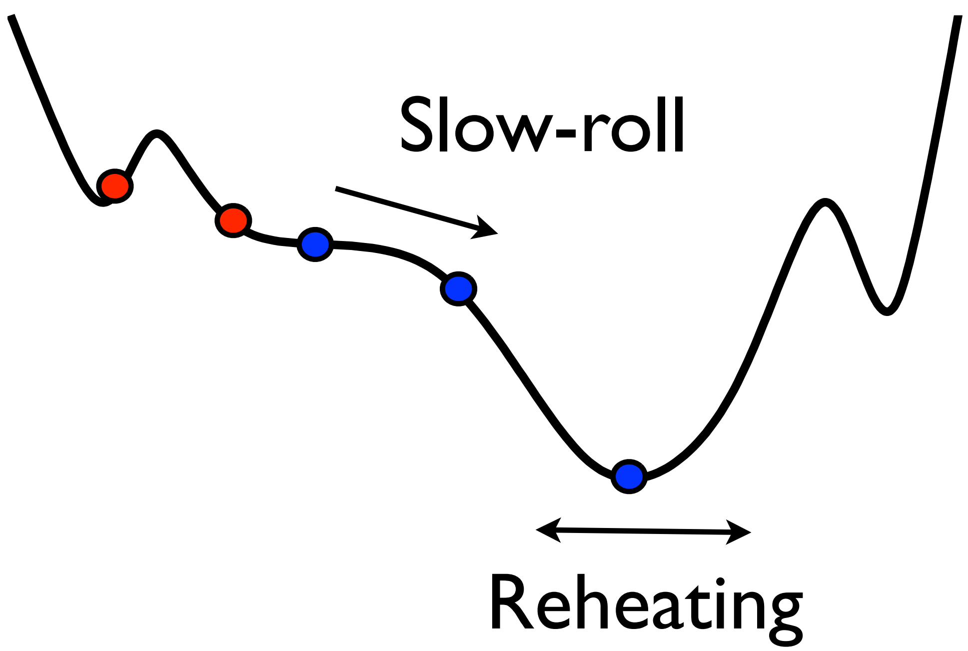

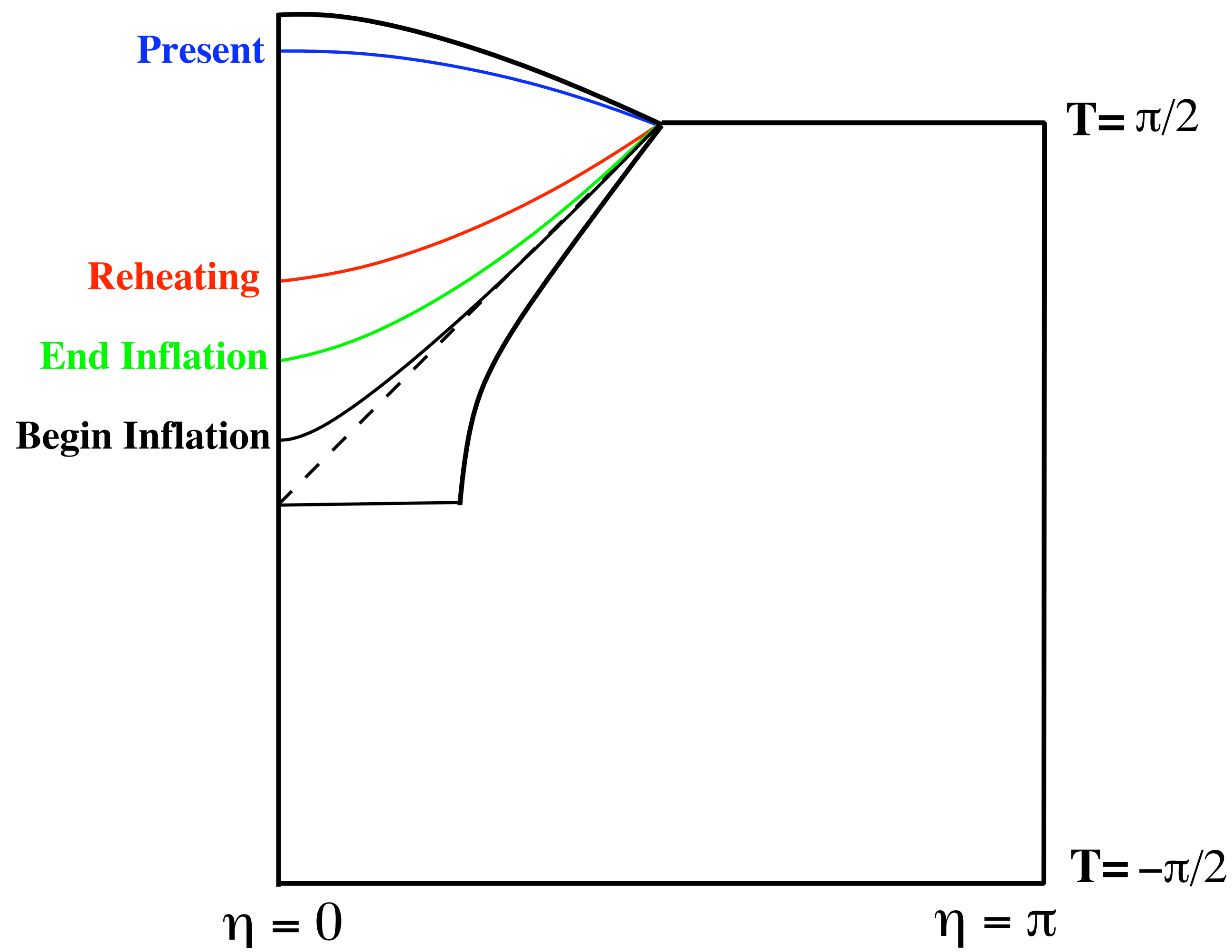

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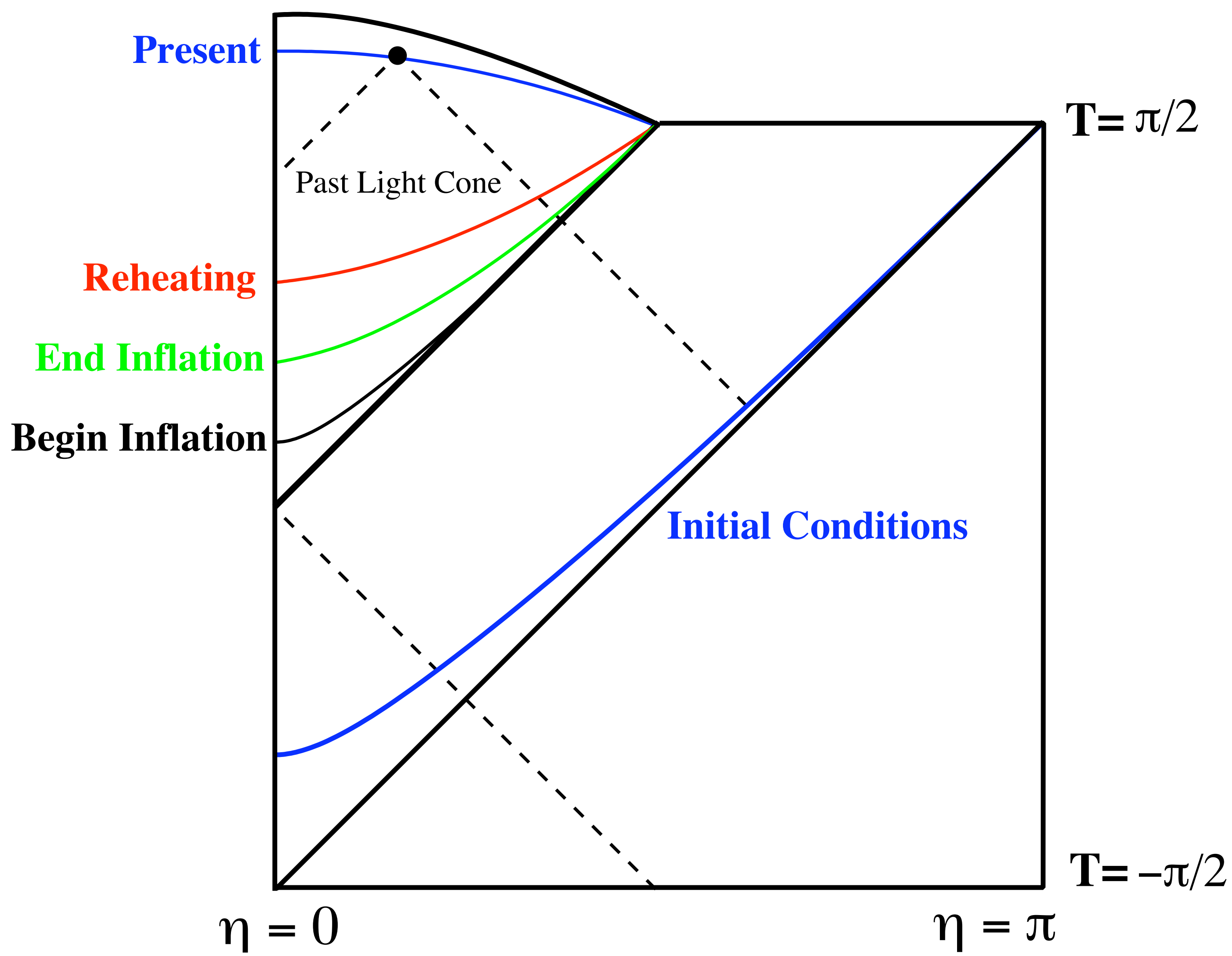

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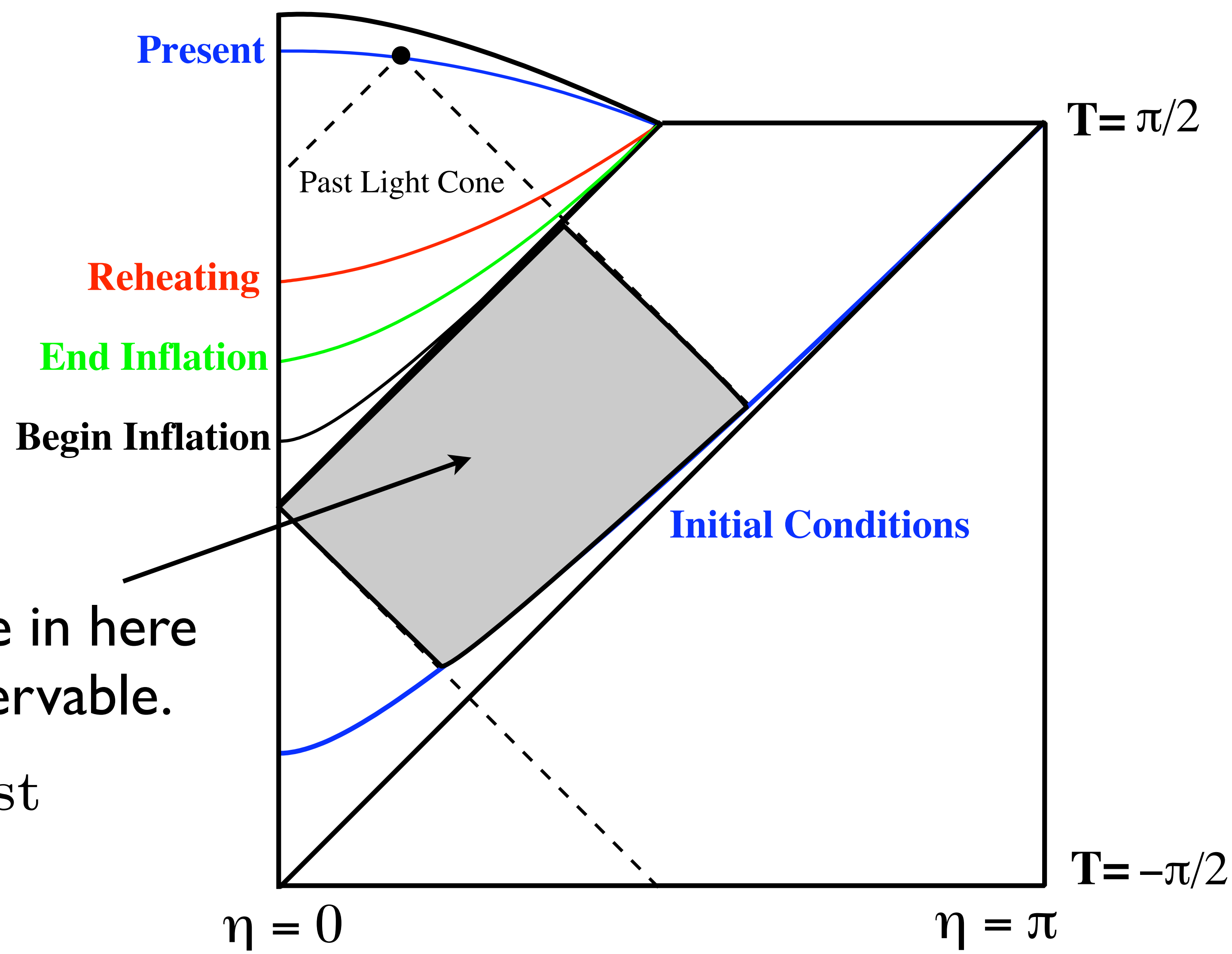
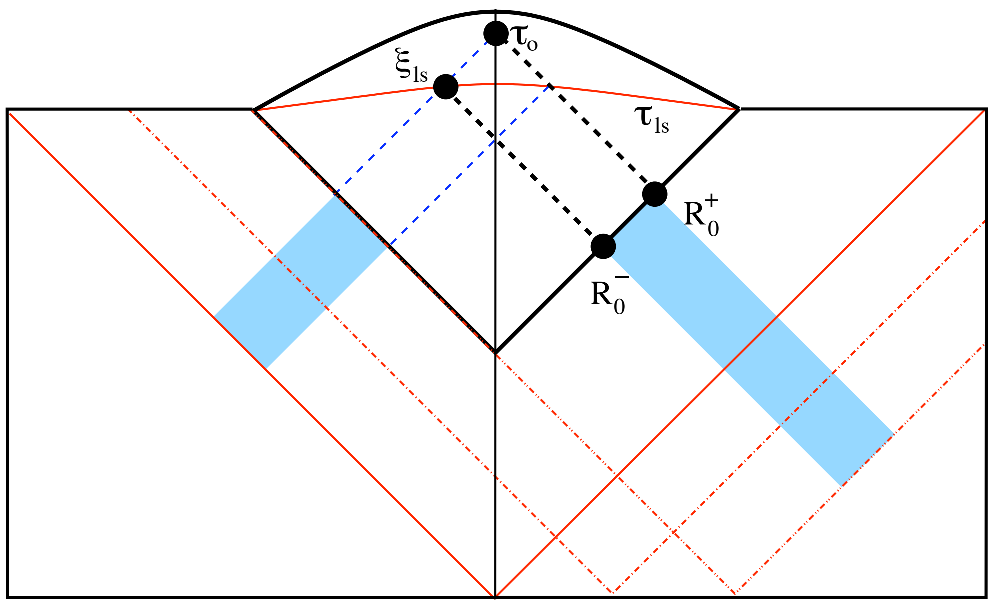


Bubbles that nucleate in here
are in principle observable.

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

Counting collisions

- Counting only collisions whose disc of influence is smaller than the whole sky:



$$N \simeq \frac{16\pi\lambda}{3H_F^4}\left(\frac{H_F^2}{H_I^2}\right)\sqrt{\Omega_c}$$

also Kleban et. al.

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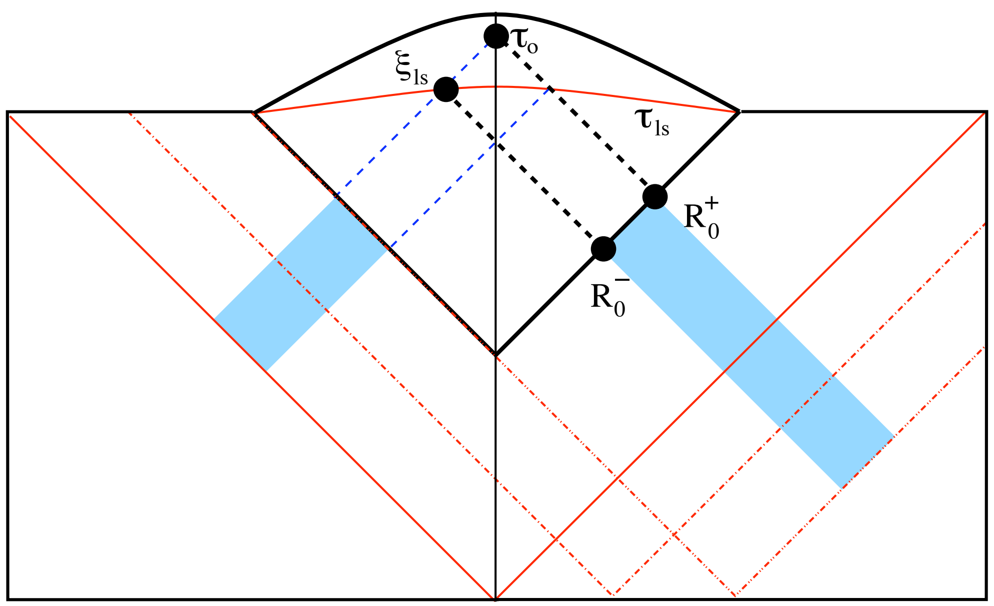

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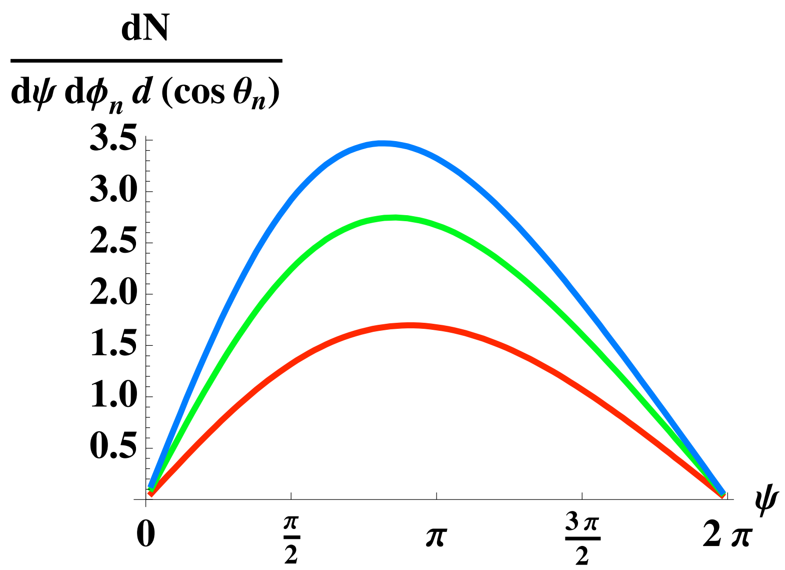
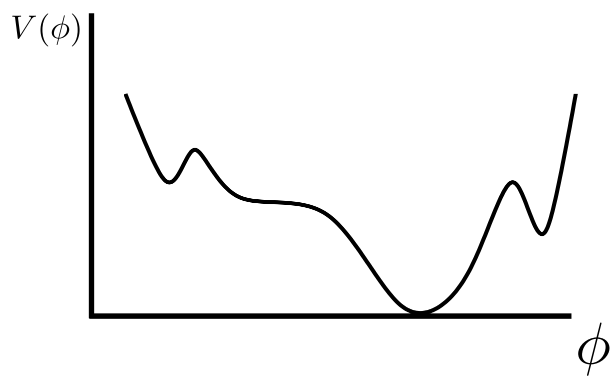
- The collisions are very nearly isotropic, and the distribution of disc sizes on the CMB sky relatively flat:



Bubble collisions model

- The model:



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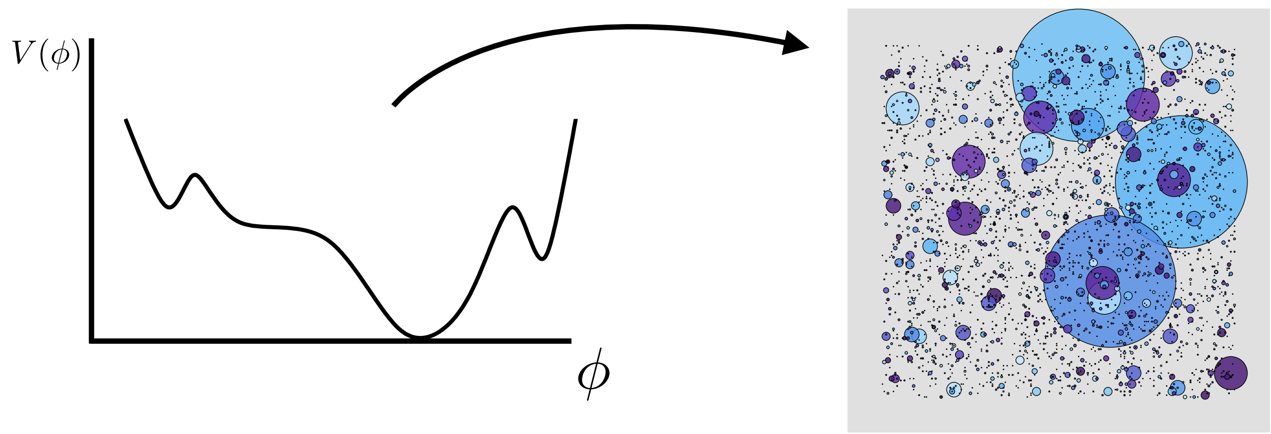

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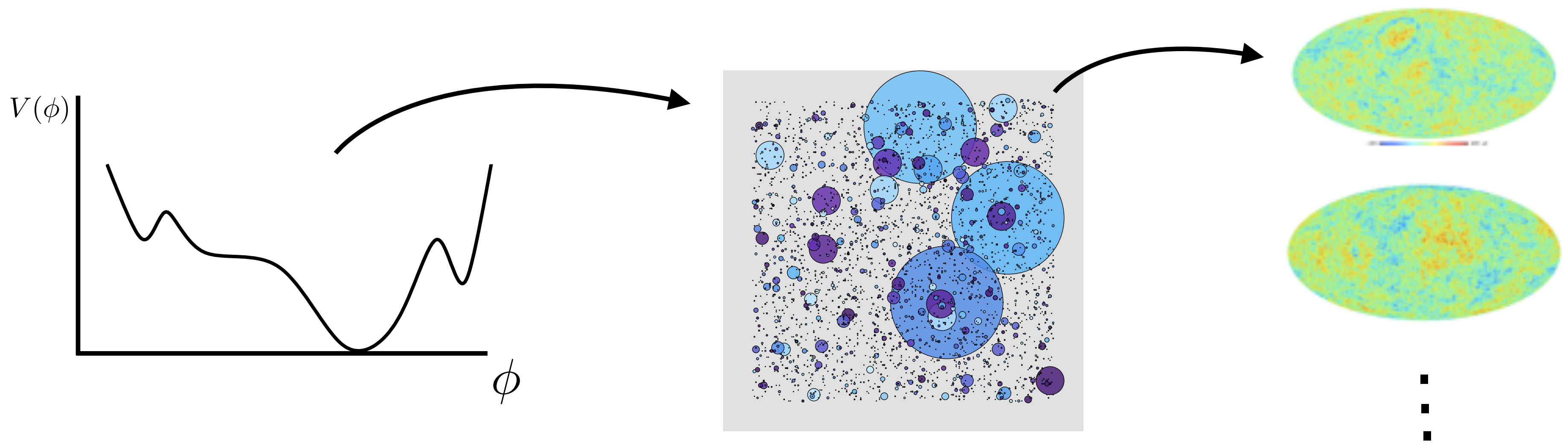

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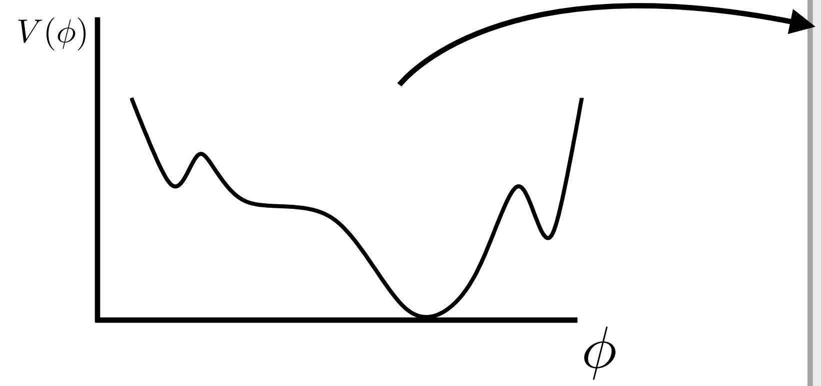
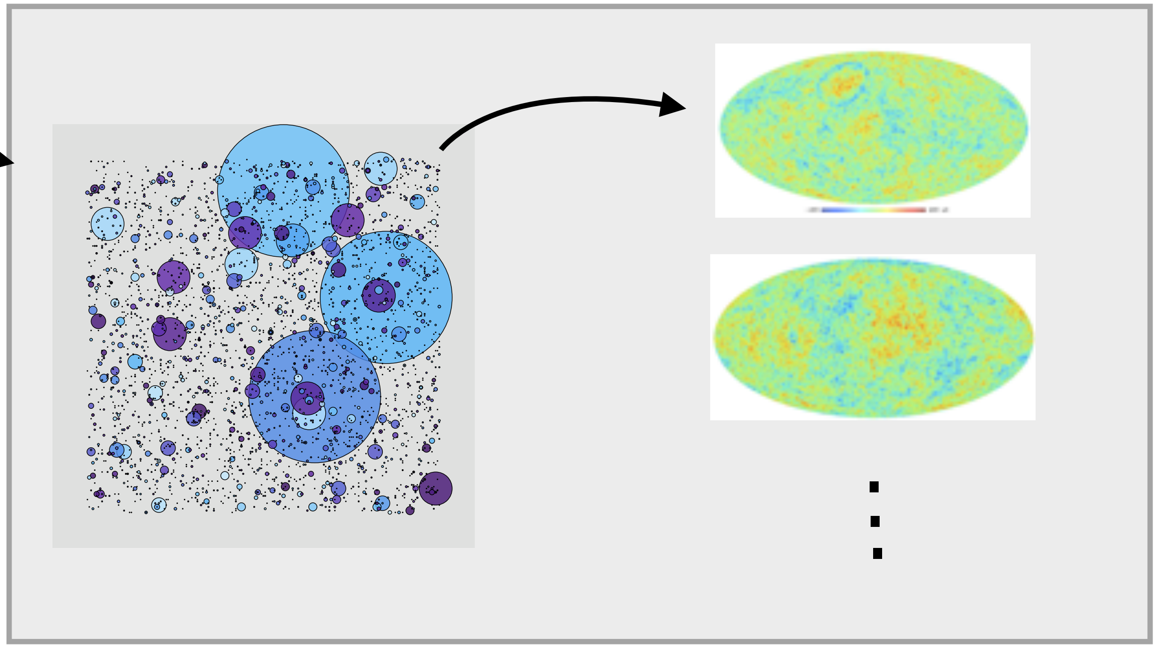


generic signature



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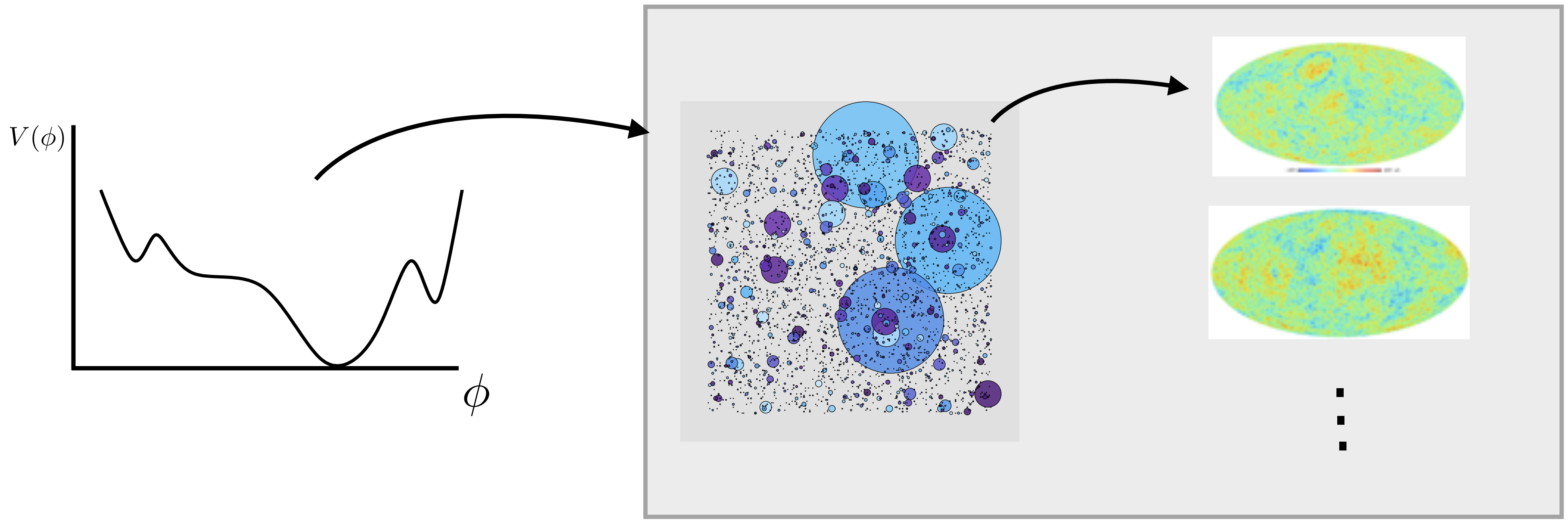
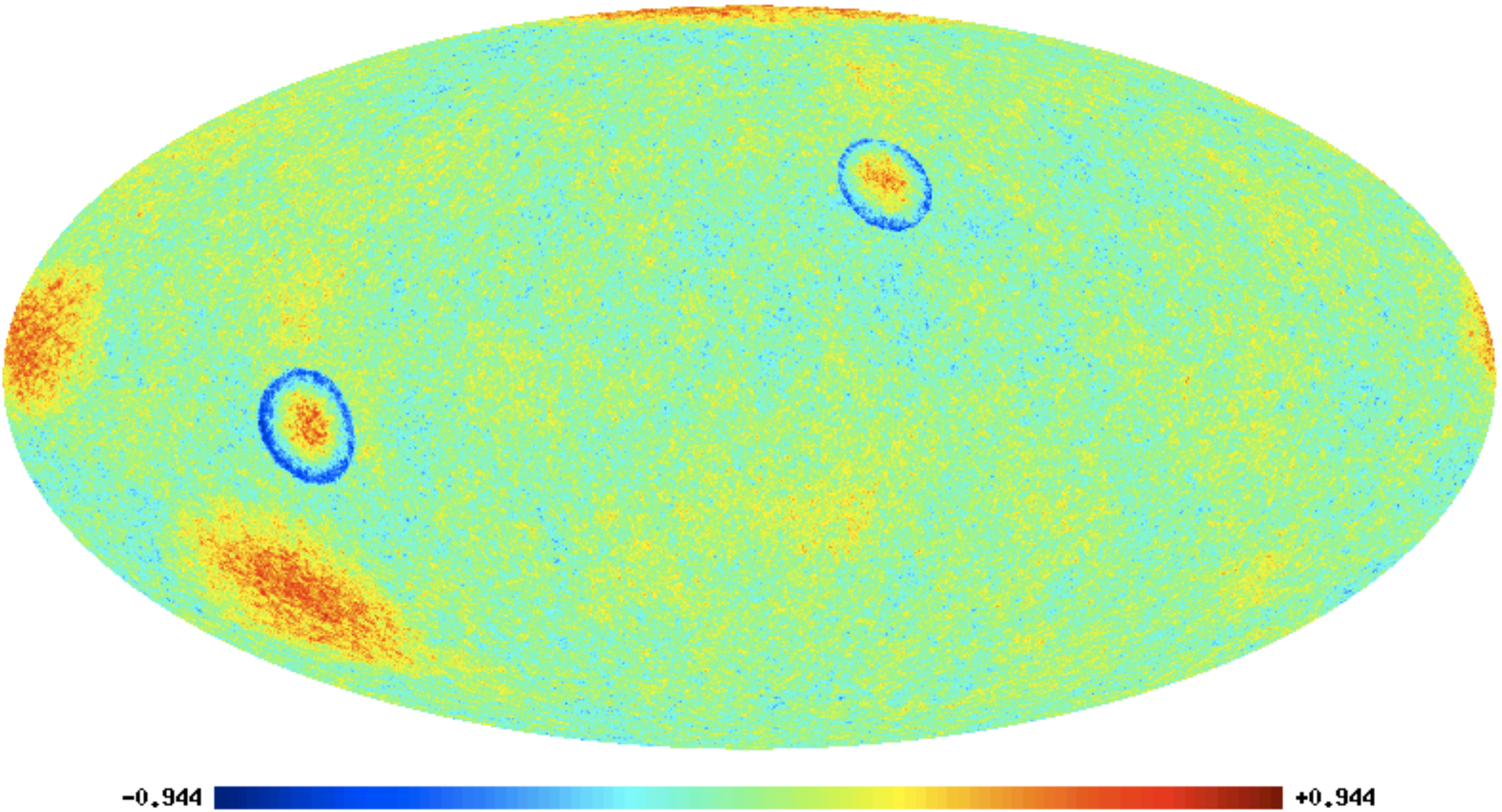


$\bar{N}_s$ expected number of collisions

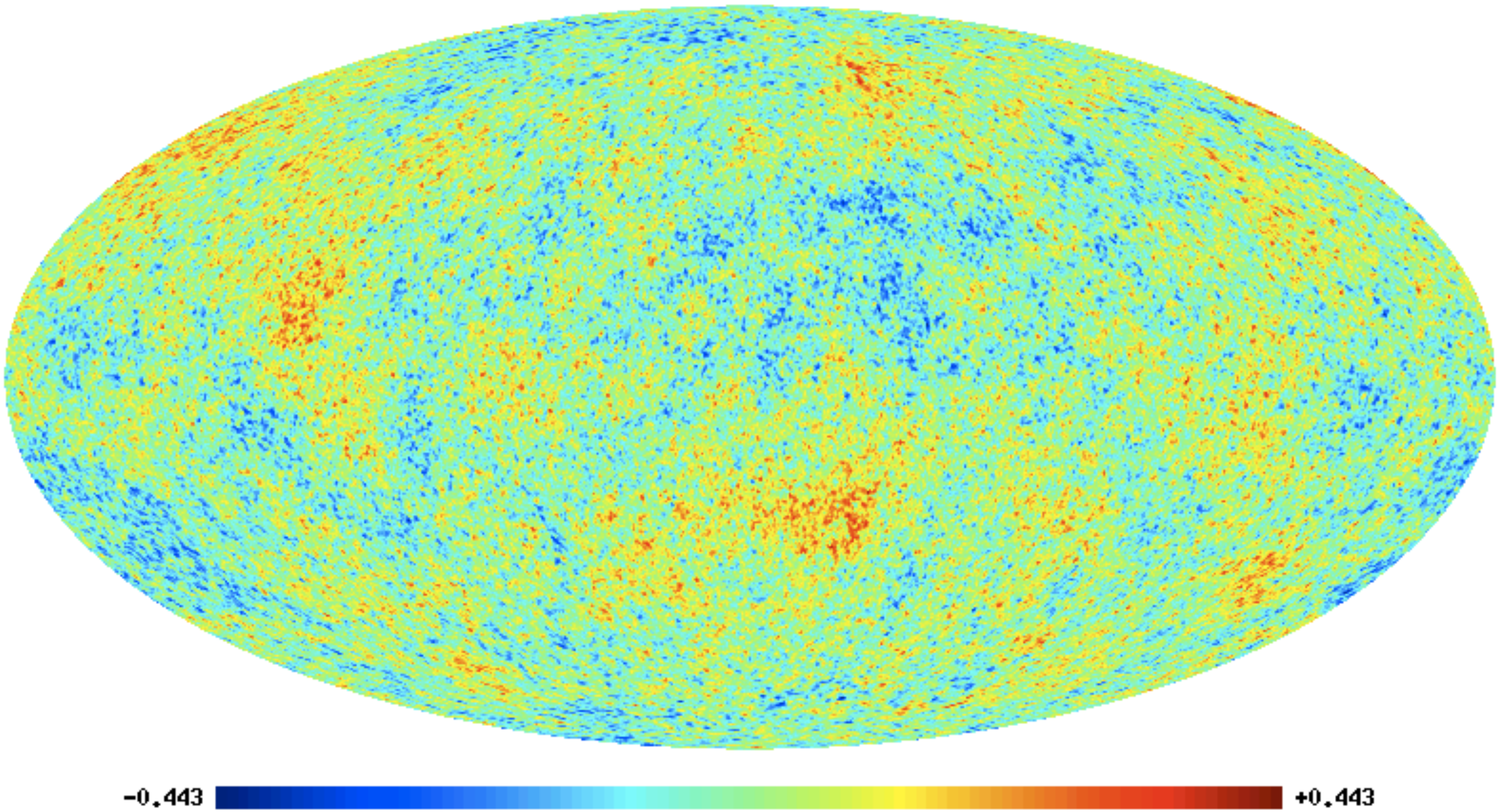
$\mathbf{m}$ parameters characterizing each collision

$\Pr(N_s, \mathbf{m})$ How many of each type do I expect to find?

Collisions (exaggerated) + CMB + instrumental noise



Collisions (realistic) + CMB + instrumental noise



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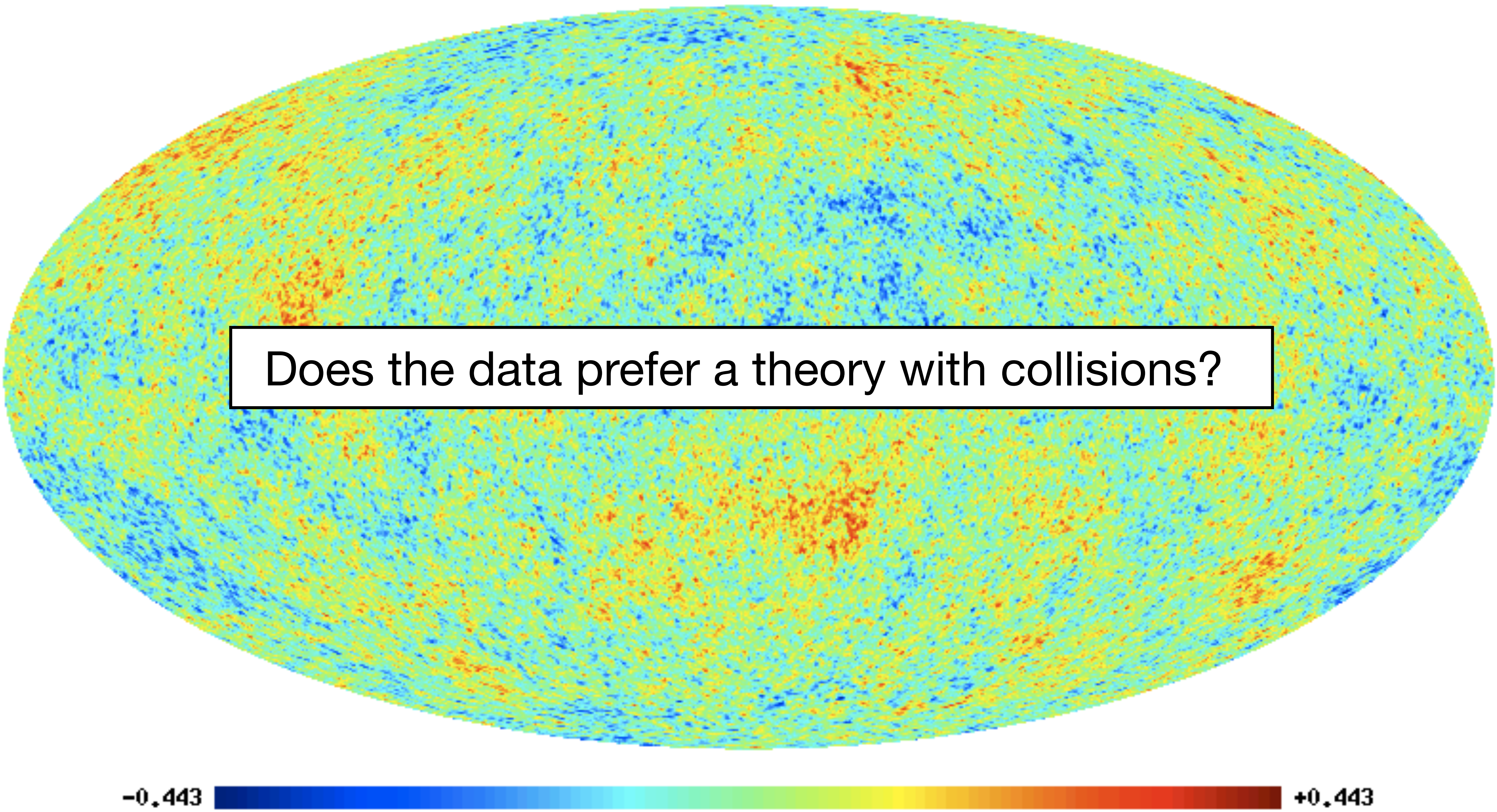
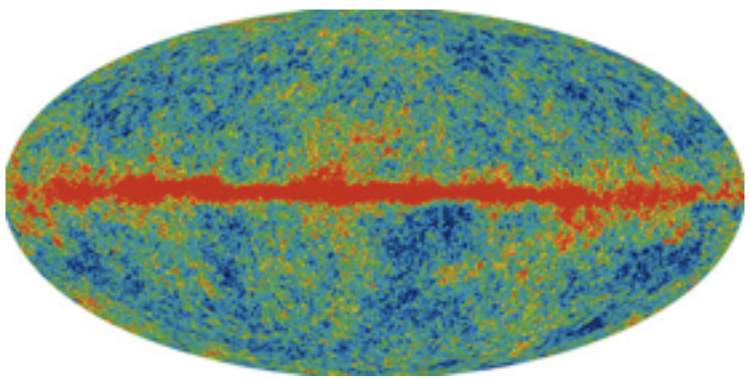
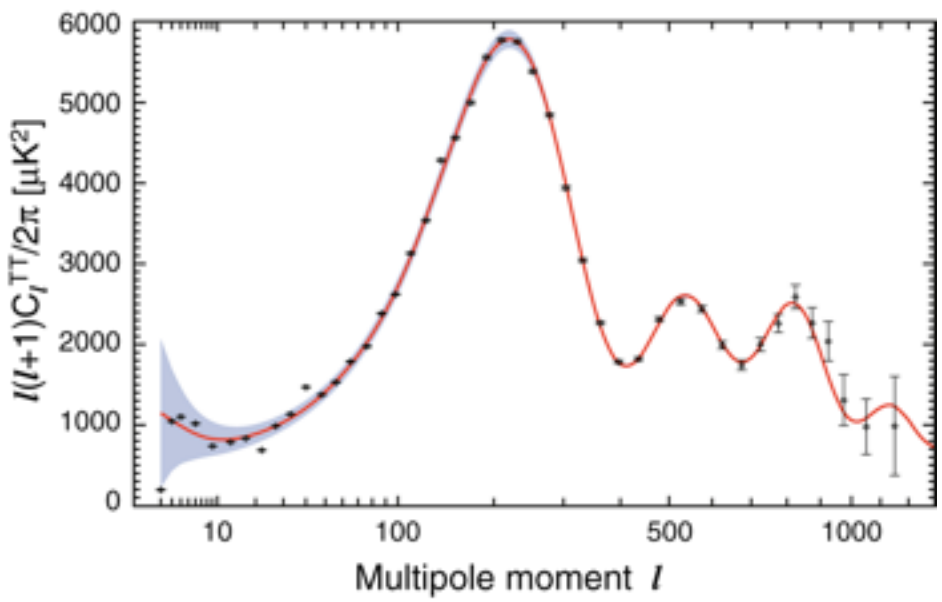


Searching for collisions

Feeney, MCJ, Mortlock, Peiris

- Lambda-CDM: very successful at describing the CMB power spectrum.





WMAP 7-year data

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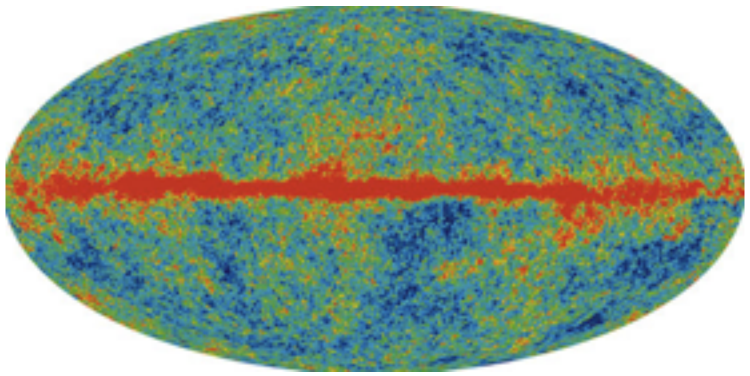

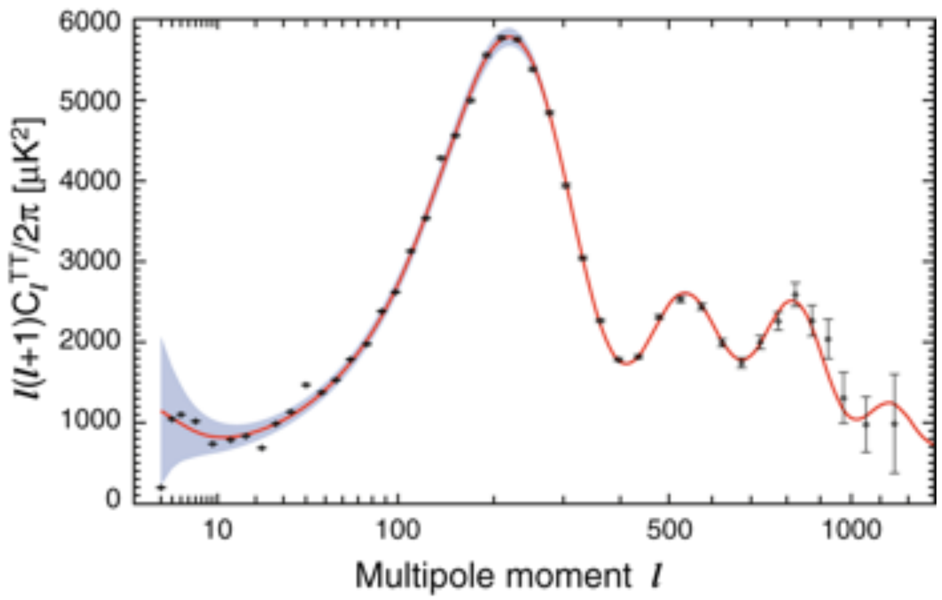

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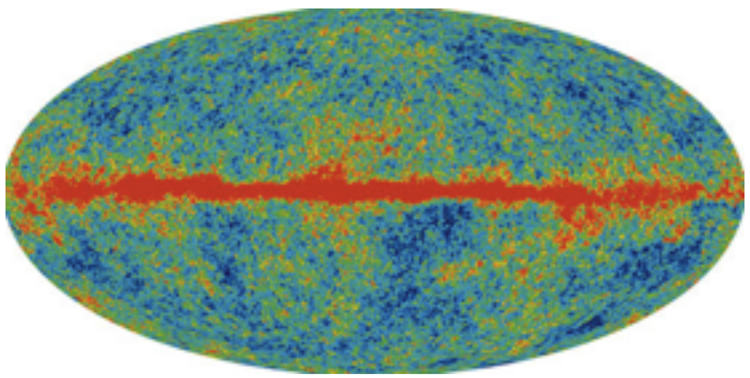

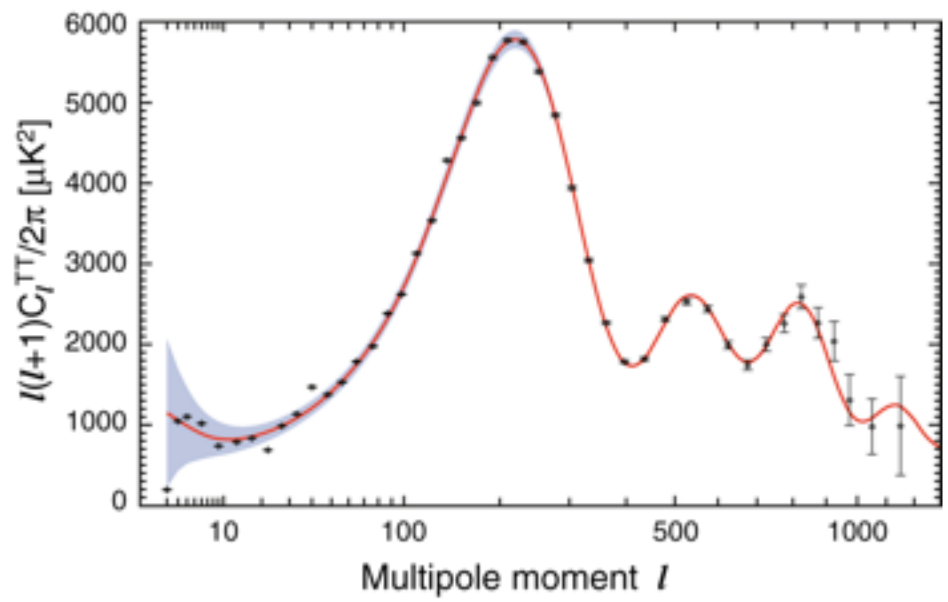

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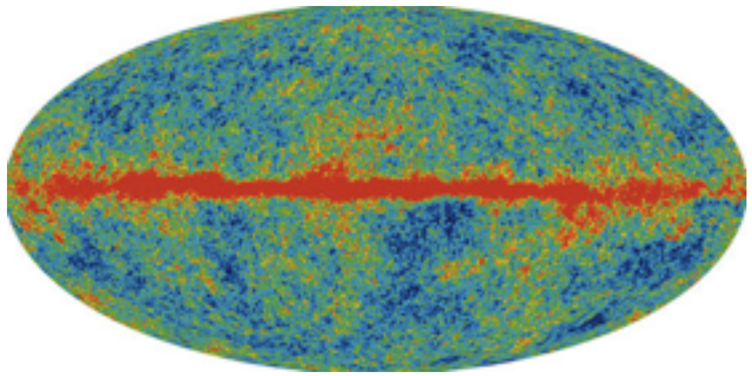

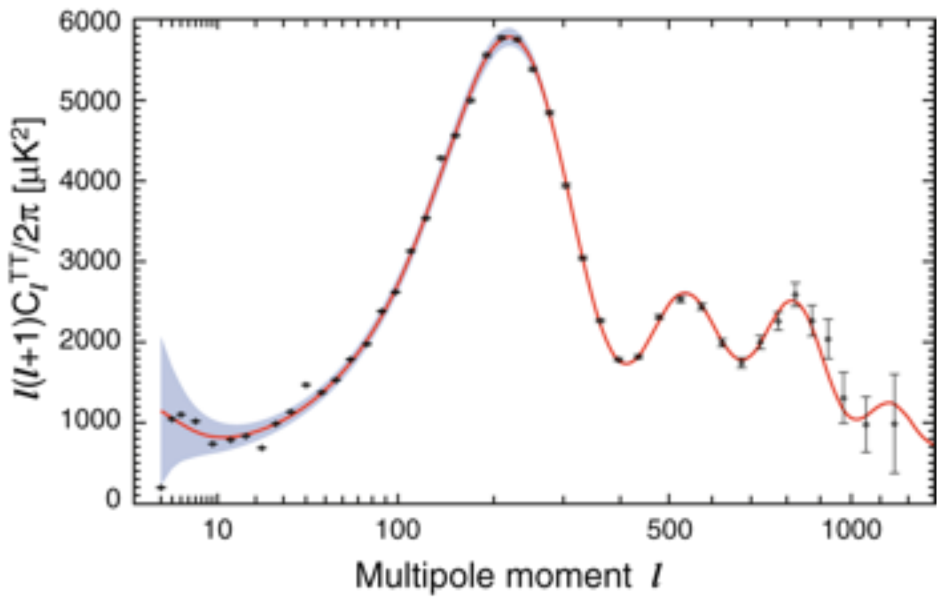

WMAP 7-year data

- Are there anomalies?

- Frequentist statistics: how discrepant is the data assuming the null hypothesis?

- Bayesian model selection: does one model fit the data better than another?

Bayesian statistics

- The goal: $P(\mathrm{Model}, \Theta \mid \mathrm{data})$

How should I bet?

Bayesian statistics

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- Bayes' Theorem:

$$P(\text{Model}, \Theta \mid \text{data}) = \frac{P(\Theta)P(\text{data } |\text{Model}, \Theta)}{P(\text{data } |\text{Model})}$$

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- Theory prior: $P(\Theta)$ $\int P(\Theta) d\Theta = 1$
- Likelihood: $P(\mathrm{data} \mid \mathrm{Model}, \Theta)$
- Evidence (model averaged likelihood): $P(\mathrm{data} \mid \mathrm{Model})$

$$P(\mathrm{data} \mid \mathrm{Model}) = \int d\Theta P(\Theta) P(\mathrm{data} \mid \mathrm{Model}, \Theta)$$

Bayesian statistics

- The likelihood is used to quantify how consistent data is with a set of model parameters.

$$P(\mathrm{data}\ |\mathrm{Model}, \Theta)$$

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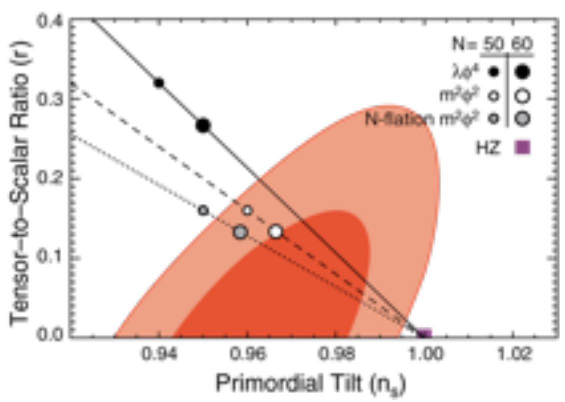
exclusion plots



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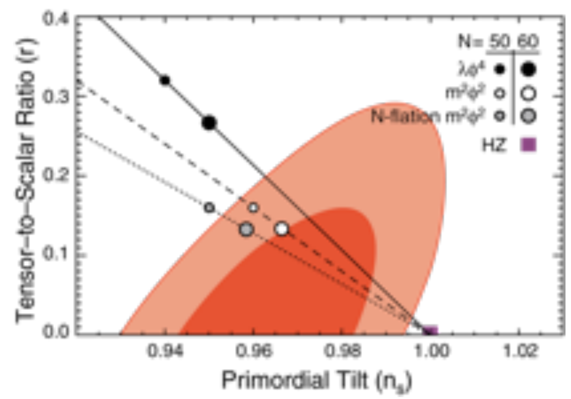

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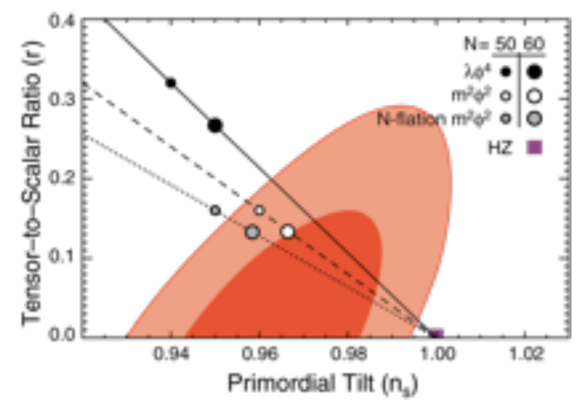

- This does NOT tell us how we should rank competing theories trying to describe the same data.

- To do so, we can apply Bayes' theorem at the level of Models:

$$P(\text{Model} \mid \text{data}) = \frac{P(\text{Model}) P(\text{data}\ |\text{Model})}{P(\text{data})}$$

Bayesian model selection

- Let’s say I have a model that fits the data fairly well, should I introduce a more complicated model that might fit it even better?

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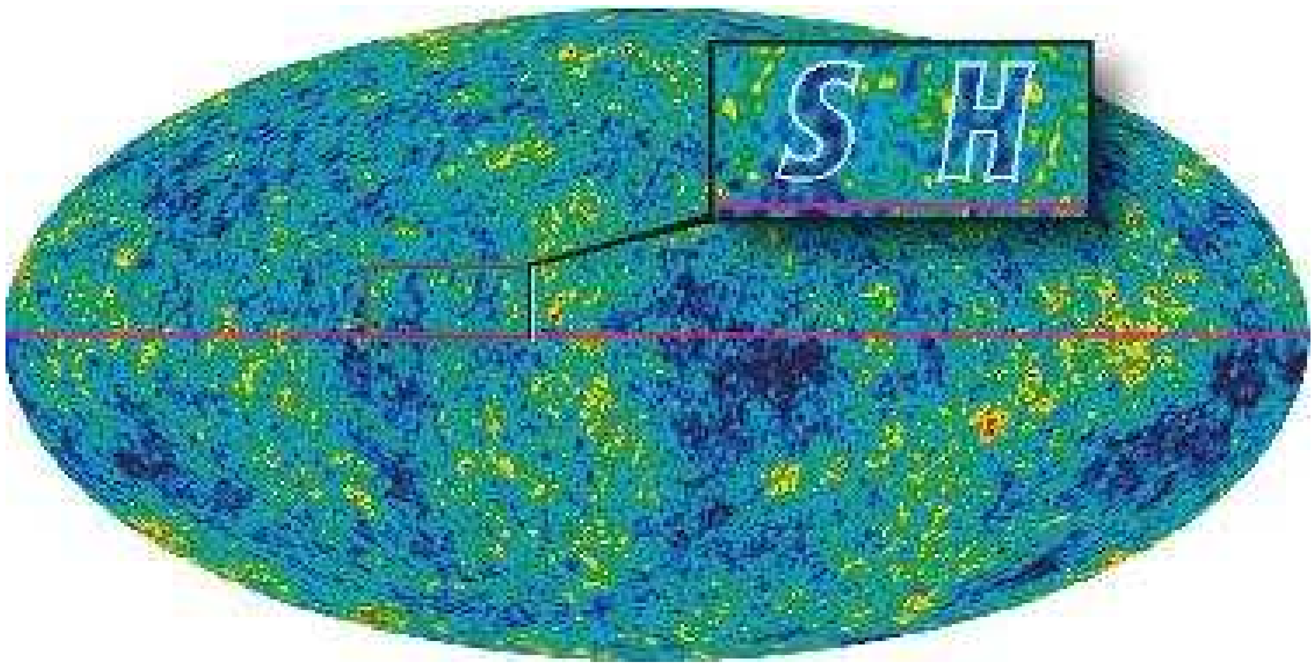
- The evidence naturally implements Occam's razor: the simpler model should be favored. Tension between volume of parameter space and goodness of fit.

$$P(\text{data } | \text{Model}) = \int d\Theta P(\Theta) P(\text{data } | \text{Model}, \Theta)$$

Is This Significant?



- Model 1: Lambda CDM.
- Model 2: Stephen Hawking's creation, signed copy.

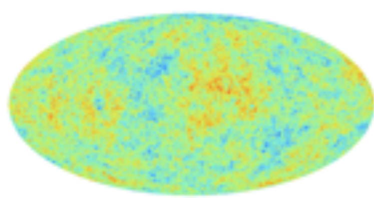
$$\frac{\Pr(\text{Model } 1|\text{data})}{\Pr(\text{Model } 2|\text{data})} = \frac{\Pr(\text{Model } 1)}{\Pr(\text{Model } 2)} \frac{\Pr(\text{data}|\text{Model } 1)}{\Pr(\text{data}|\text{Model } 2)}$$

Searching for collisions

- What any good Bayesian wants:

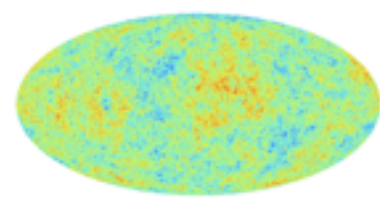
$$\frac{\Pr(\text{Model 1}|\text{Data})}{\Pr(\text{Model 2}|\text{Data})}$$

How should I bet?



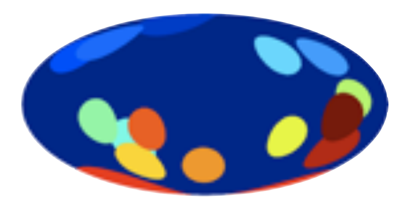
ΛCDM

VS



ΛCDM

+



$\Pr(N_s, \mathbf{m})$

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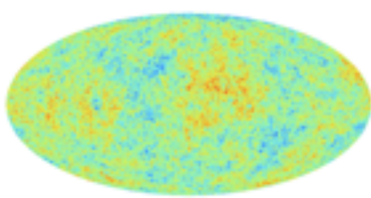

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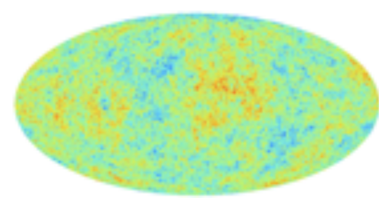

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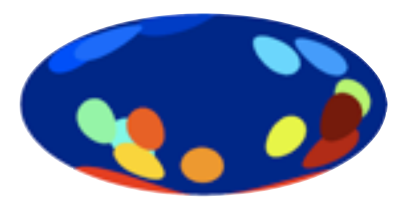
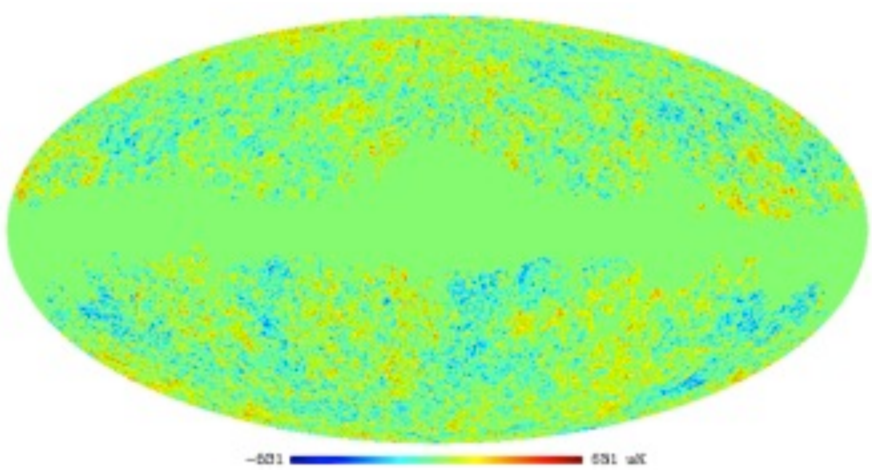


$\Pr(N_s, \mathbf{m})$

- A convenient theory label: $\bar{N}_s$. ΛCDM is specified by $\bar{N}_s = 0$.

The expected number of detectable features.

Searching for collisions



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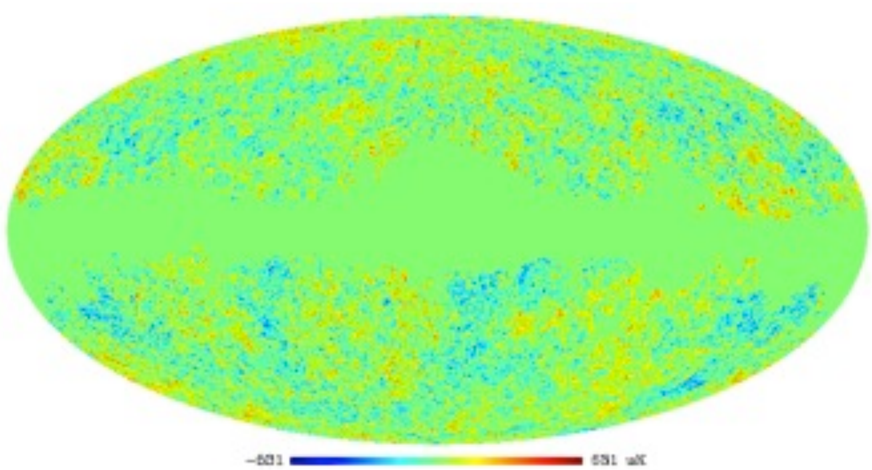
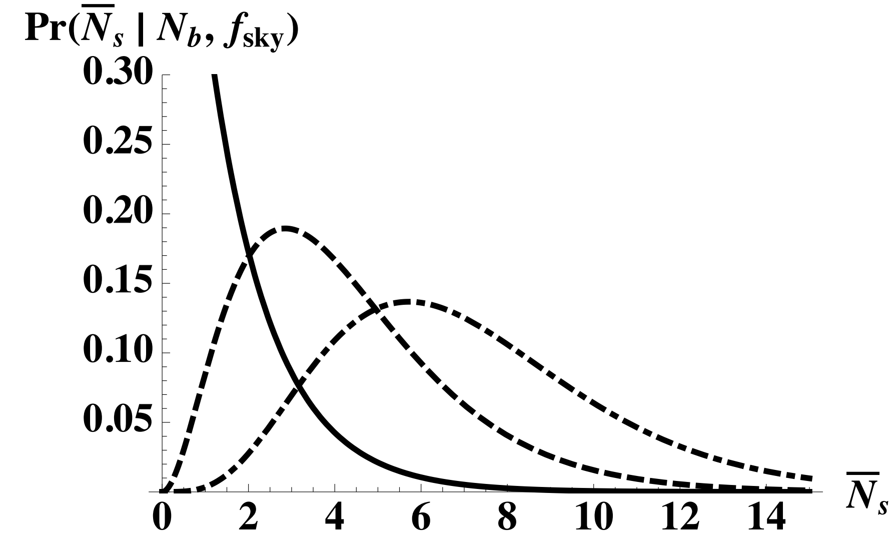


$$Pr(\bar{N}_s|\mathbf{d})$$



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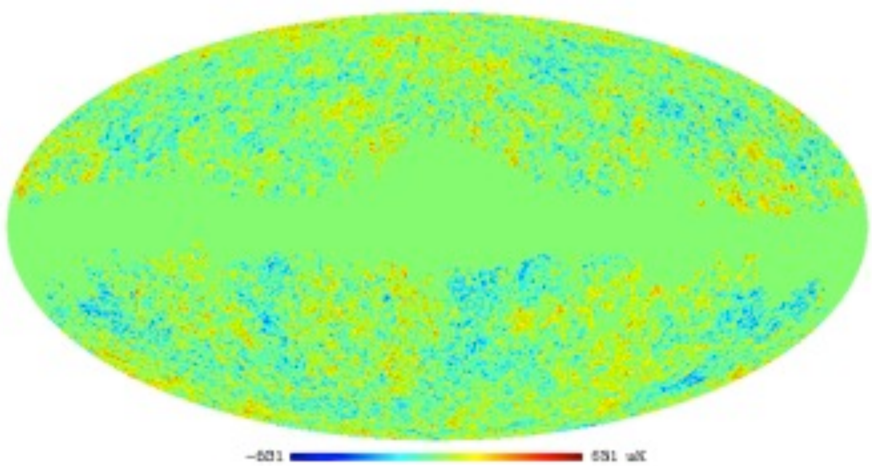

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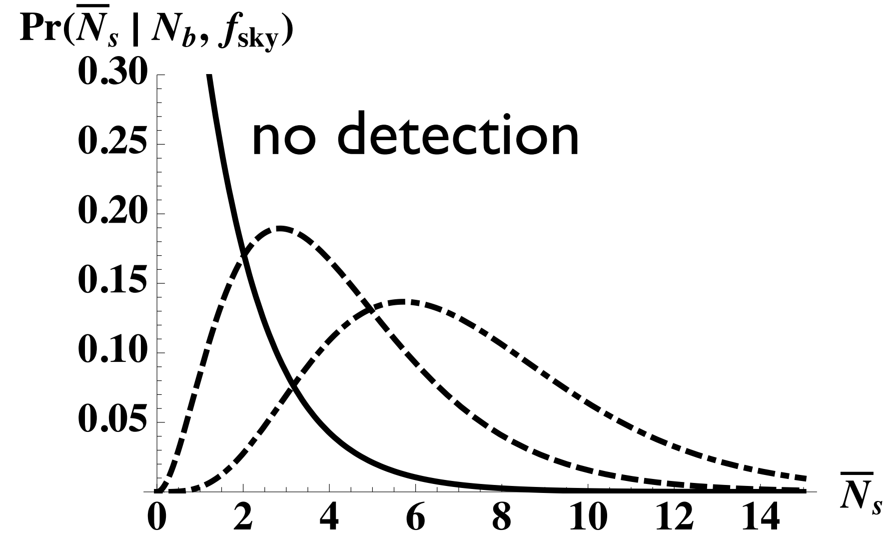

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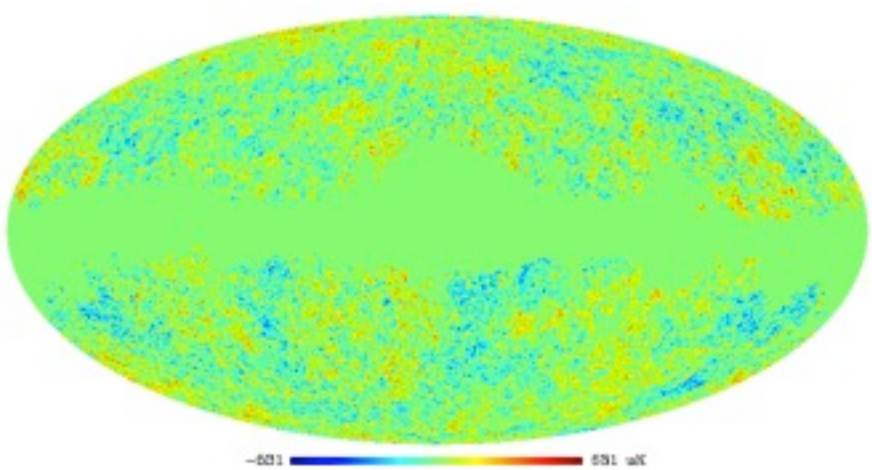

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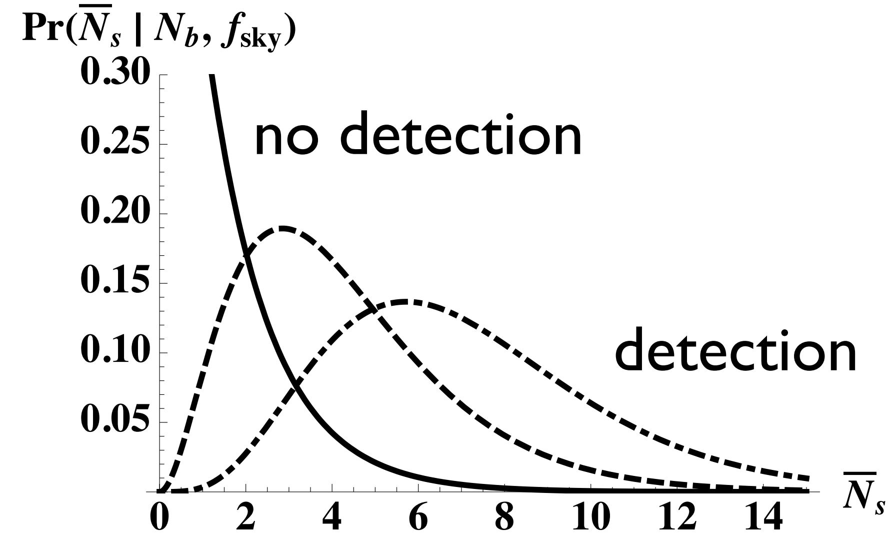
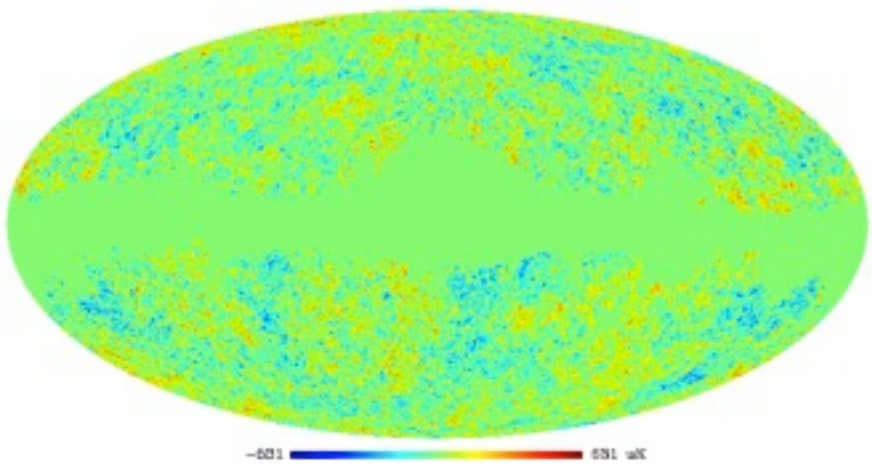


Searching for collisions



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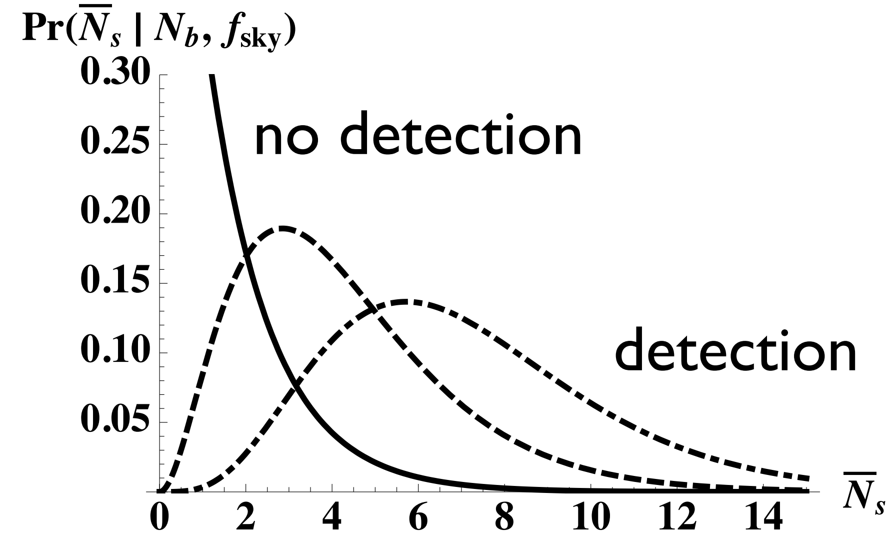

- To calculate this, need to test for:
    - Arbitrary number of templates
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    - Arbitrary amplitude, shape, and size (lying within prior $\mathrm{Pr}(N_s, \mathbf{m})$)

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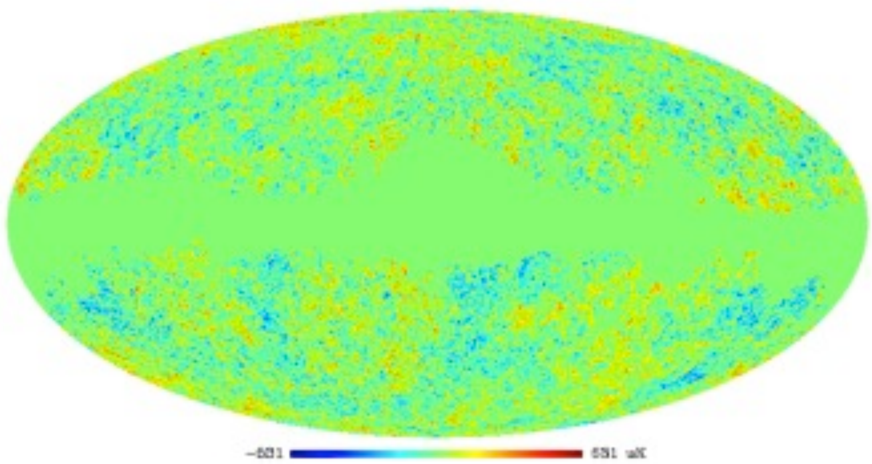

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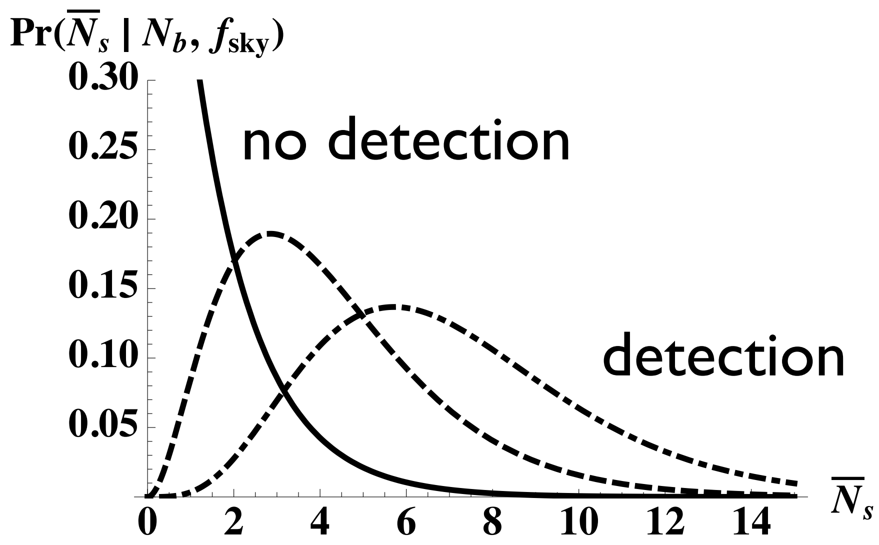

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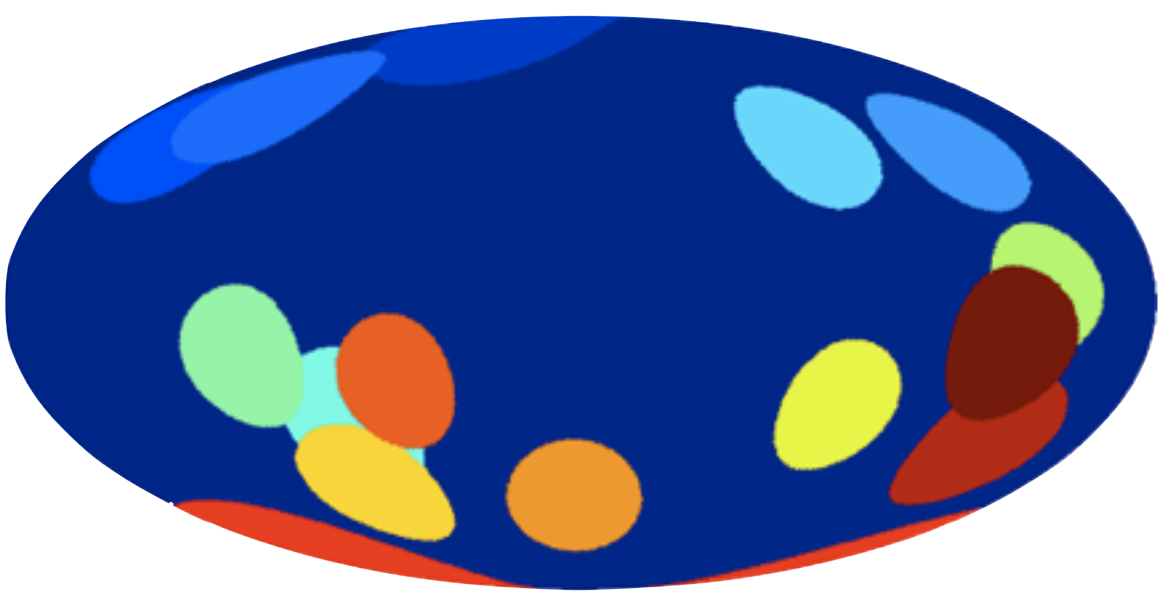
Implementing the exact calculation is impossible.

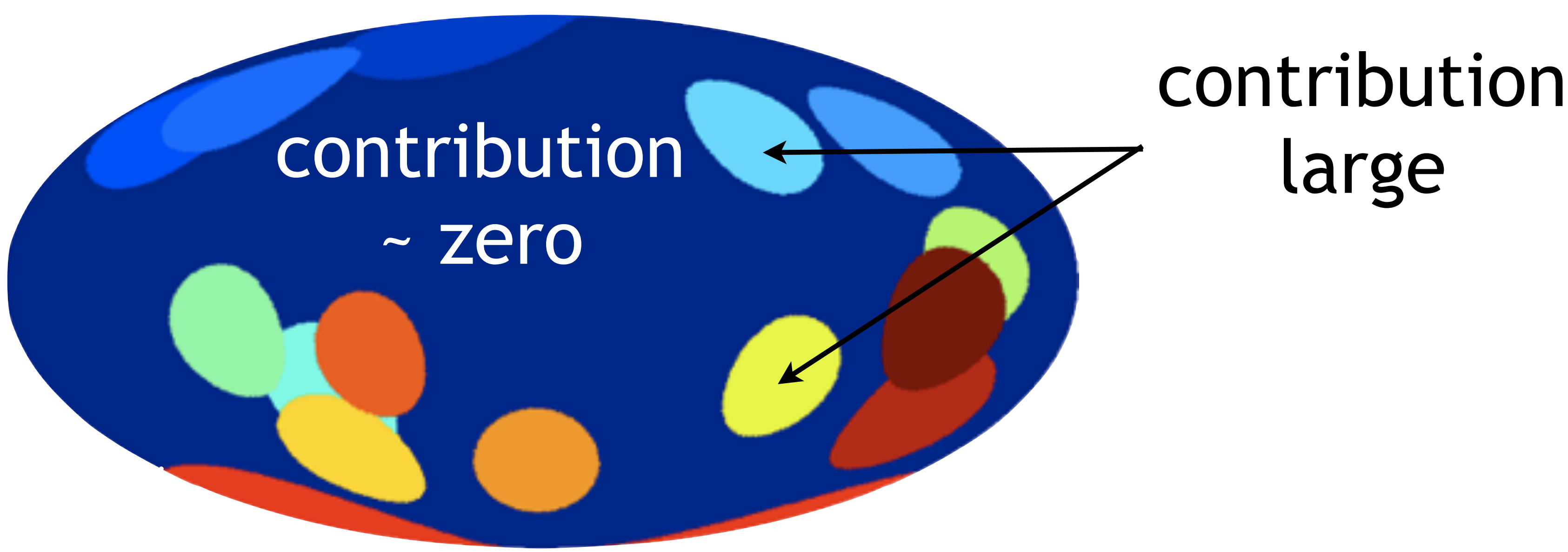
Searching for collisions

- Solution:
  - Locate candidate features with a blind analysis.



Searching for collisions

- Solution:
  - Locate candidate features with a blind analysis.
  - Find an approximation to the probability by integrating only over the regions of parameter space where the contribution is large.



Searching for collisions

Feeney, MCJ, Mortlock, Peiris

- Blind search for candidates:
  - Filter the CMB (wavelet decomposition, optimal filtering)
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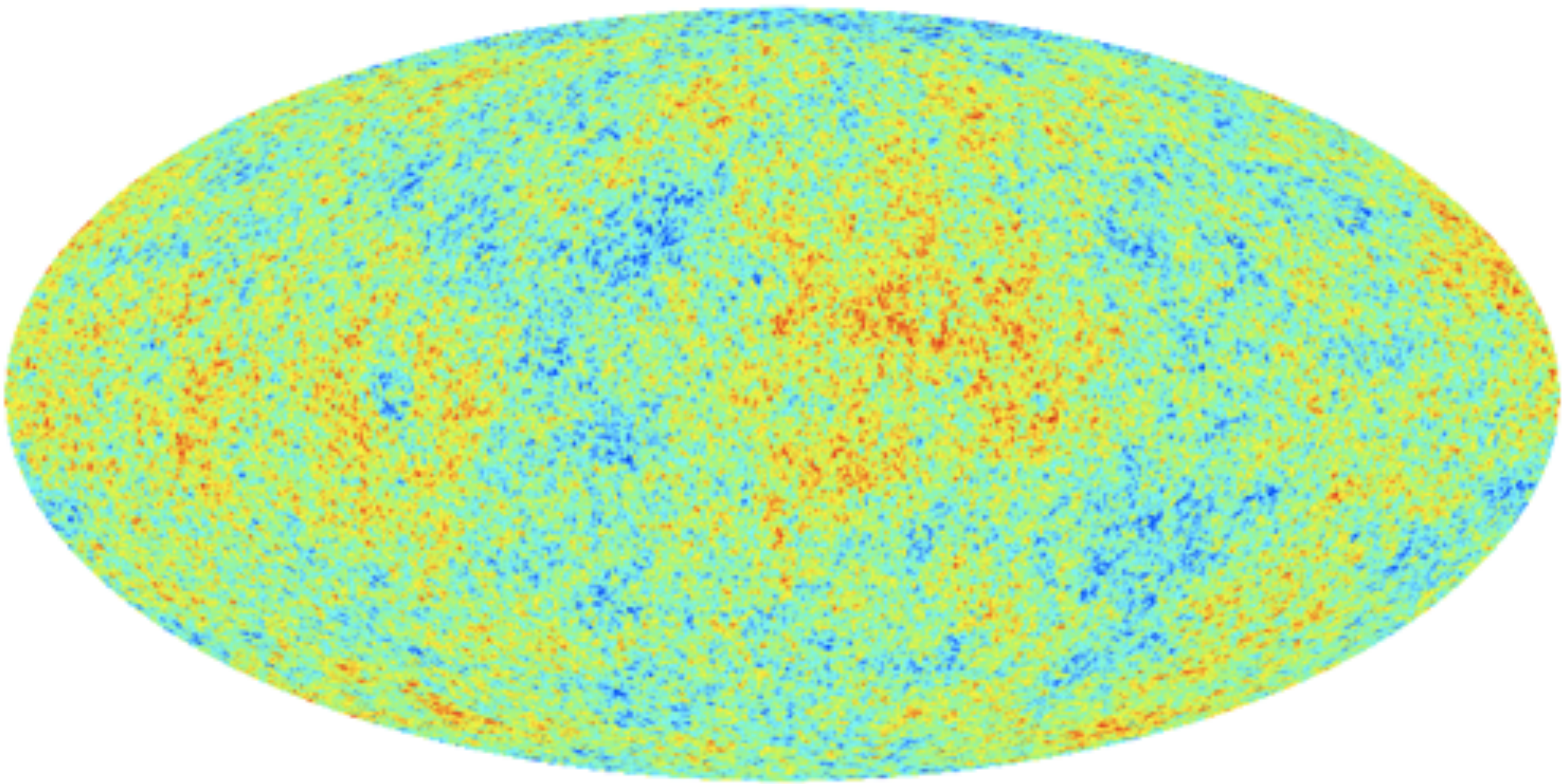

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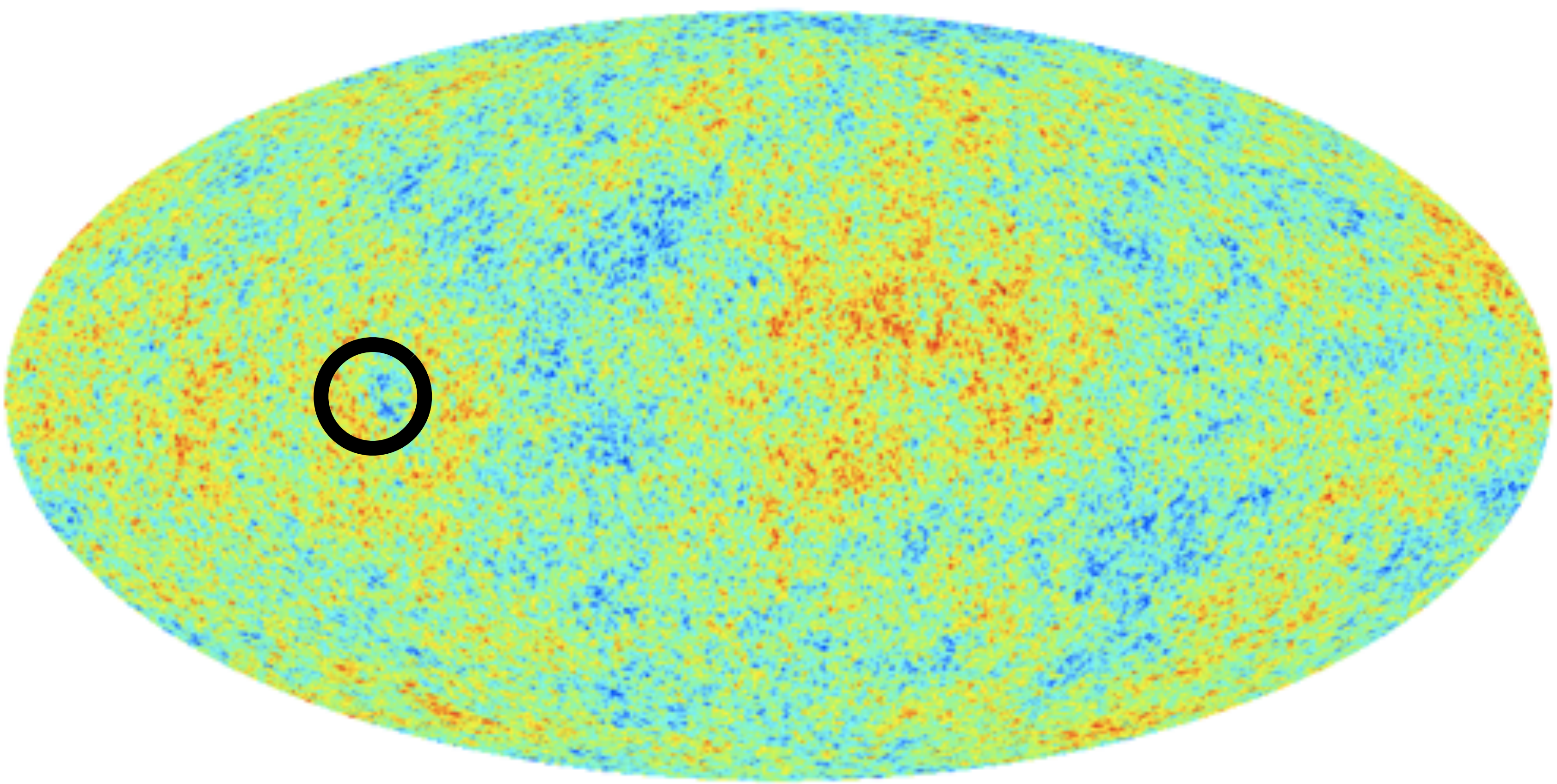

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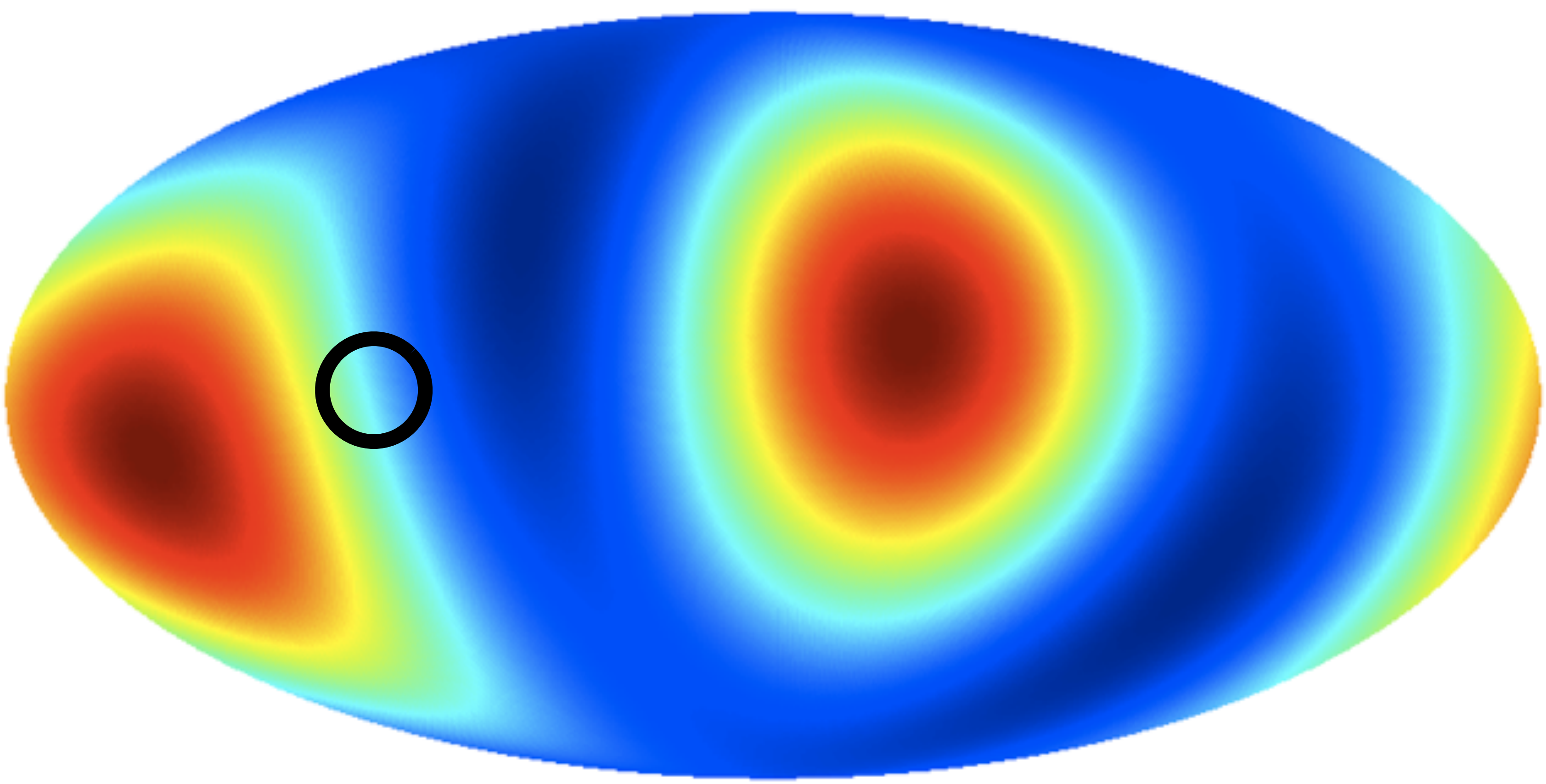

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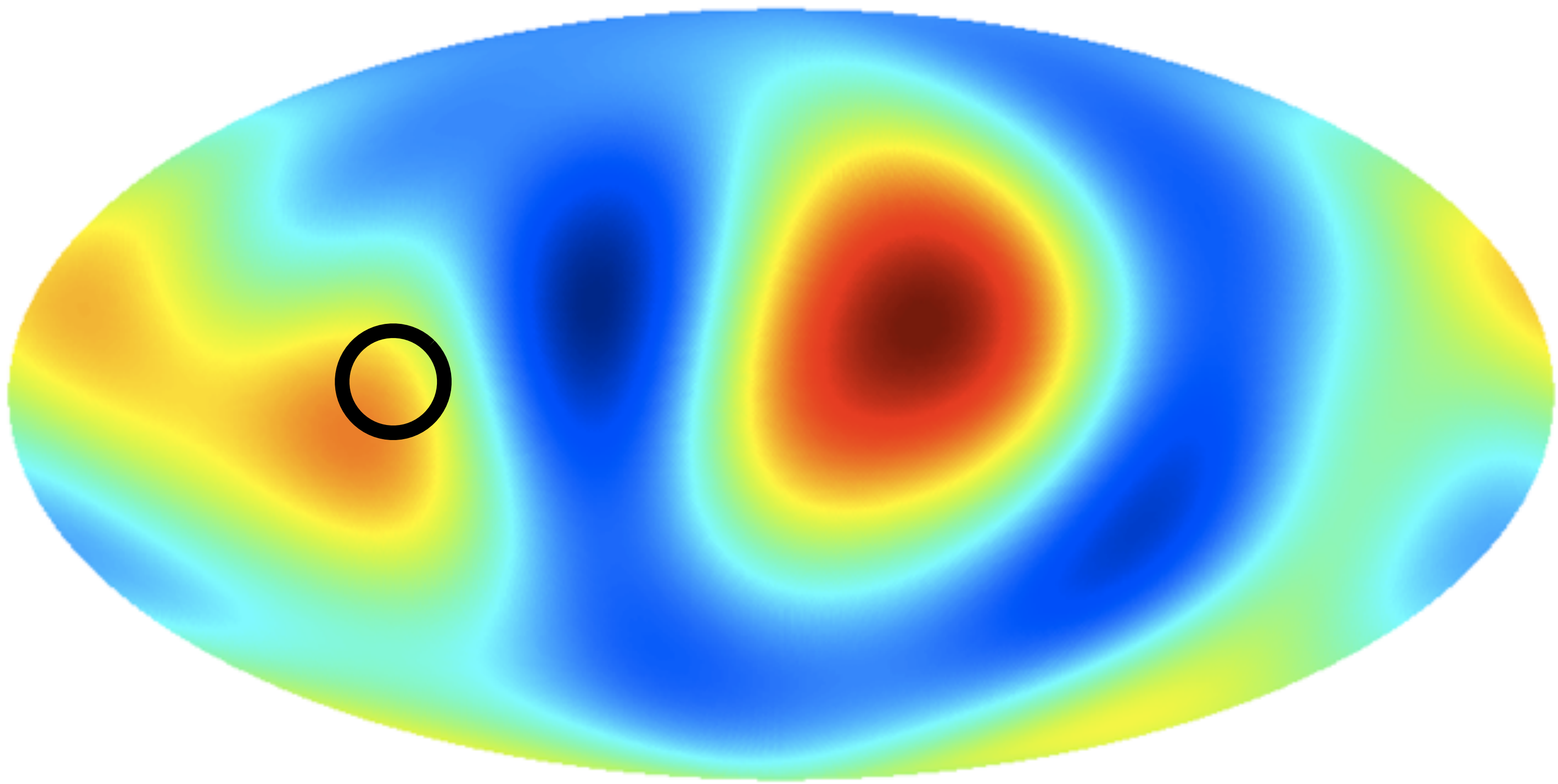

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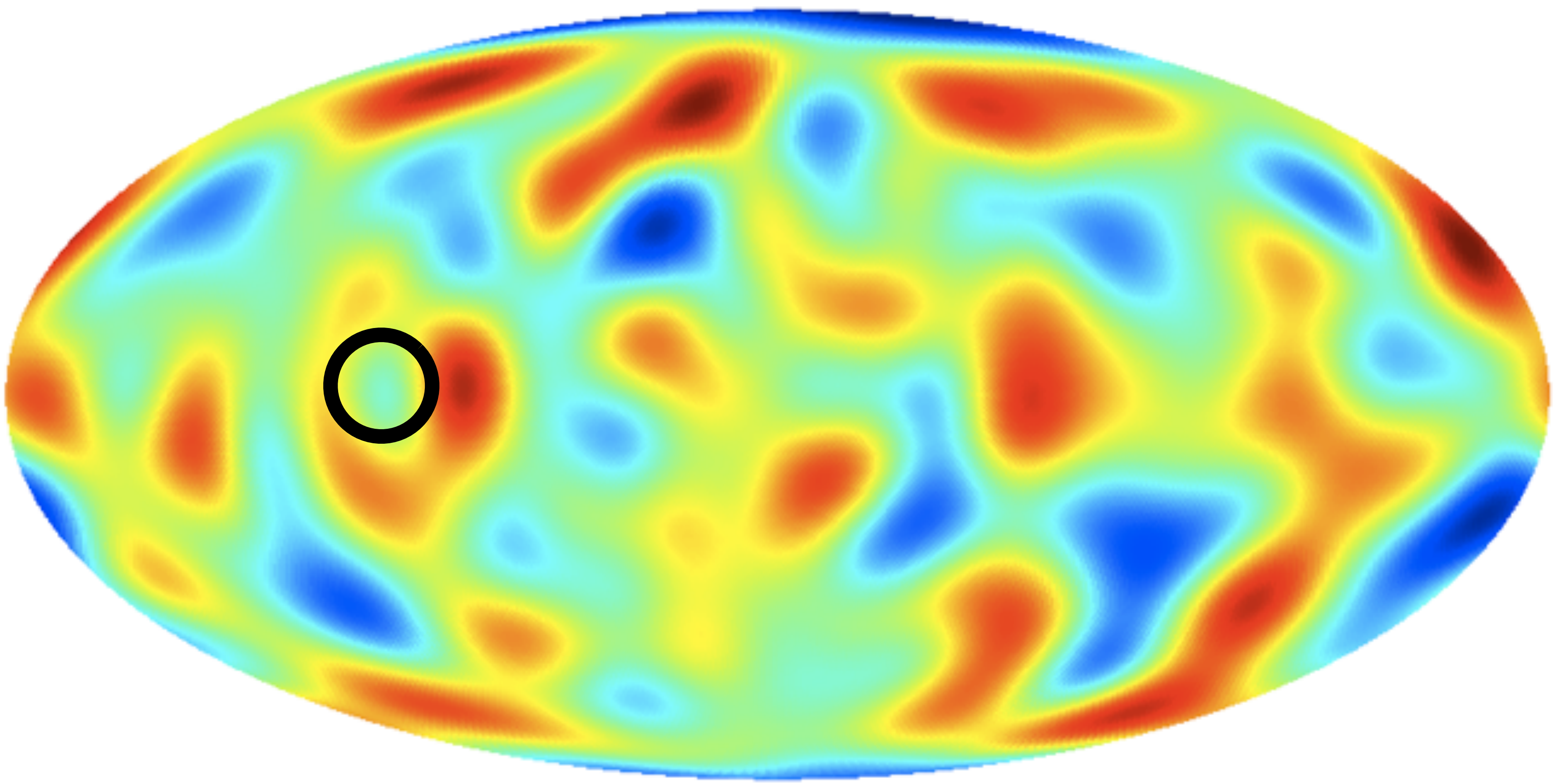

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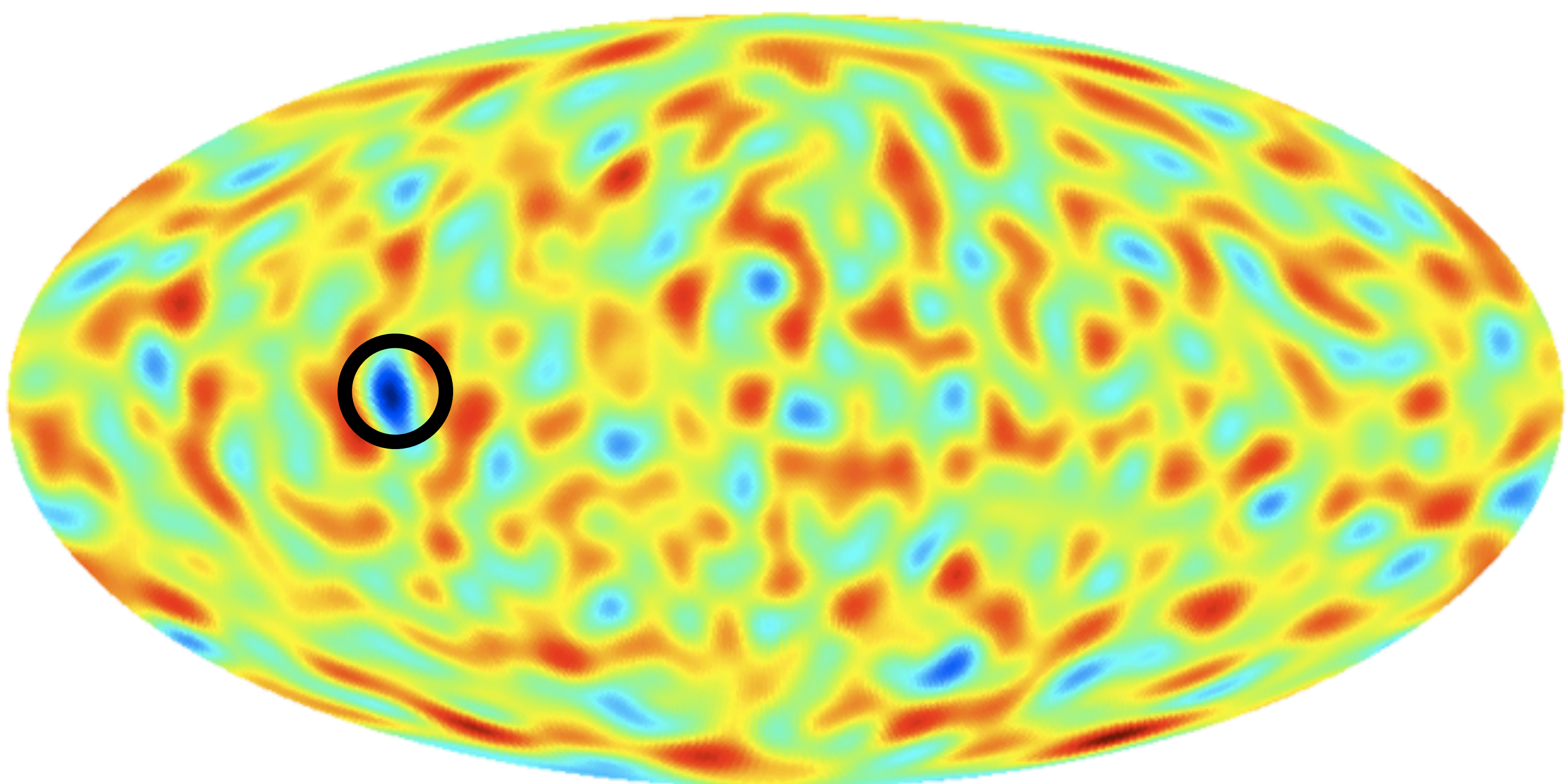
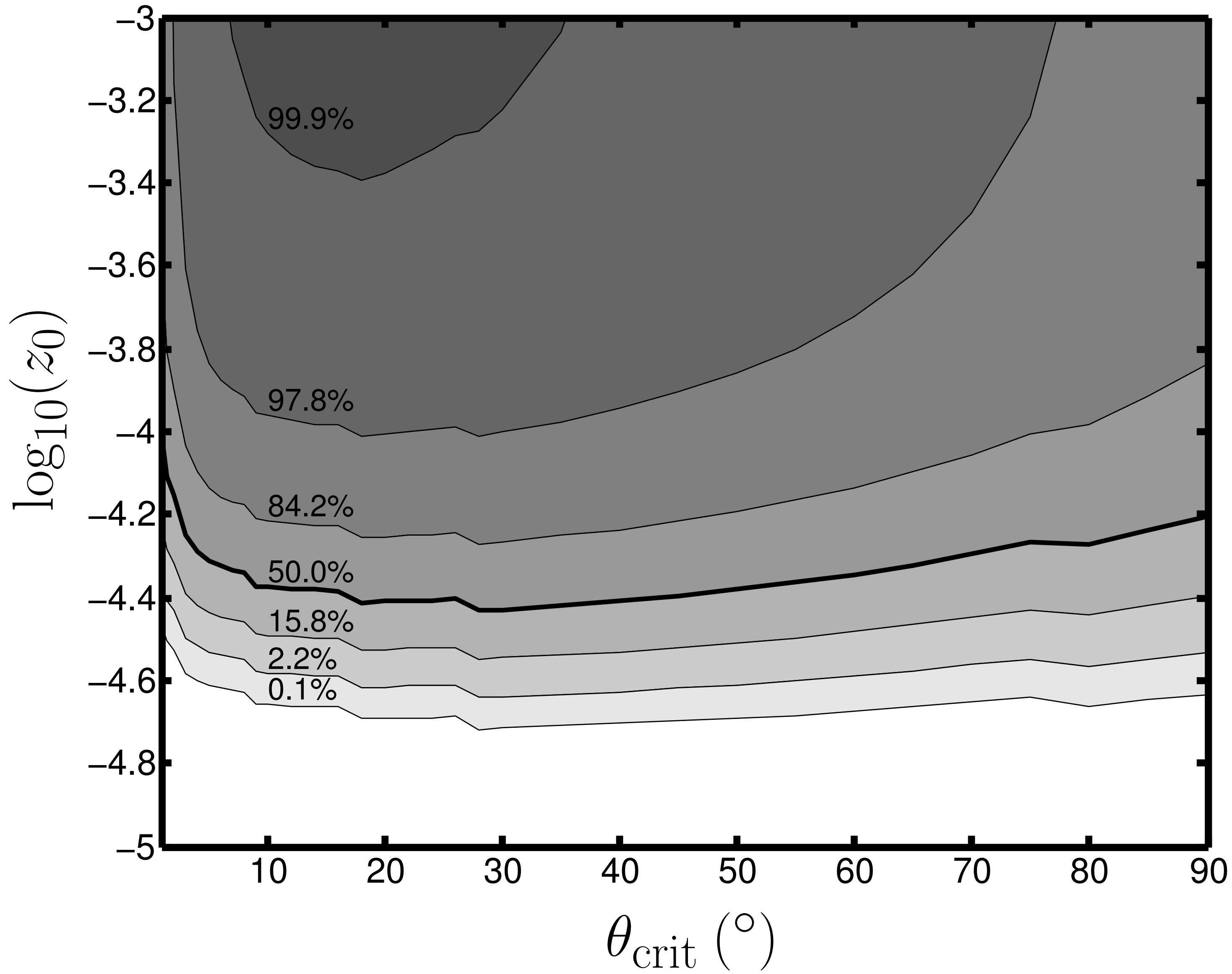
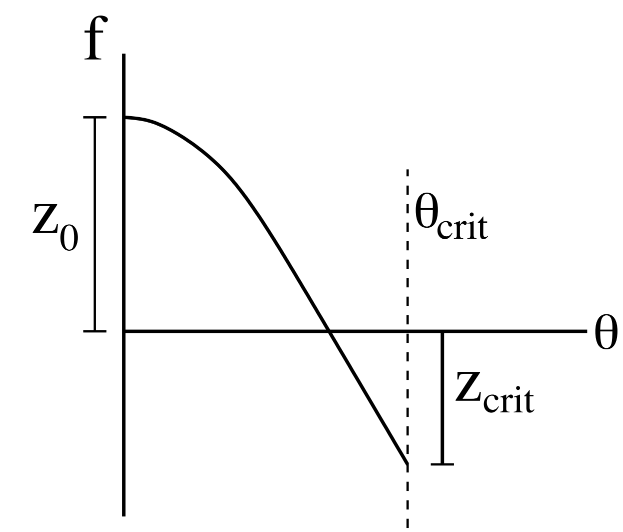


Searching for collisions

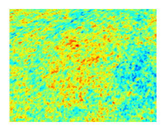
- Blind search for candidates:
    - Keep candidates that lie above threshold:

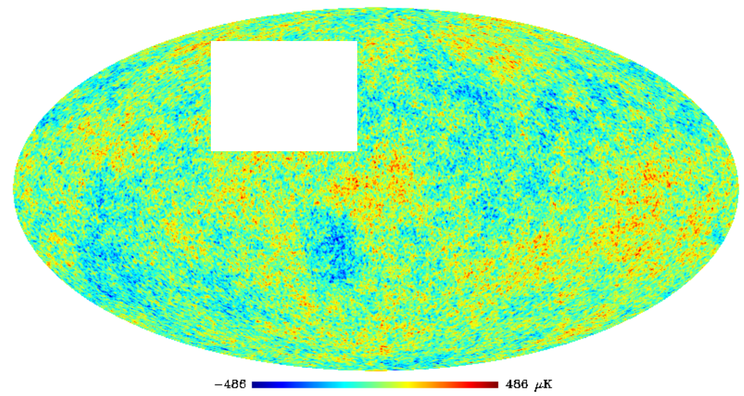




Searching for collisions

- For one candidate:





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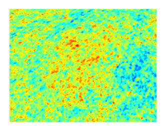

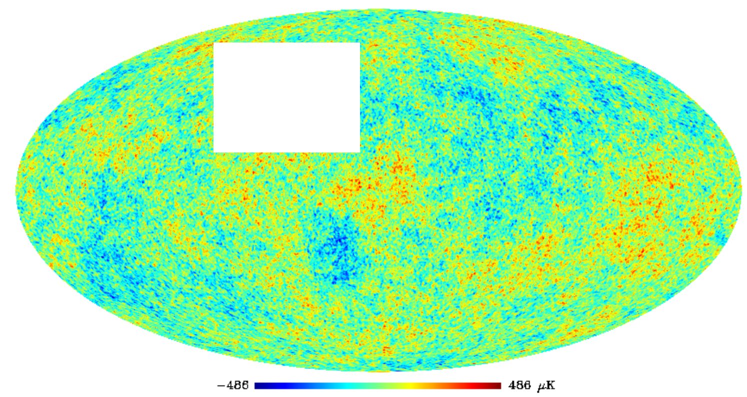

$$\rho_b = \frac{\int d\mathbf{m} \mathrm{Pr}(\mathbf{m}) L_b(\mathbf{d}|\mathbf{m})}{L_b(\mathbf{d}|\mathbf{0})}$$

Evidence ratio in the blob: how much better does one describe the data by adding a template?

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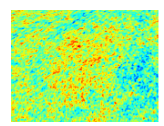

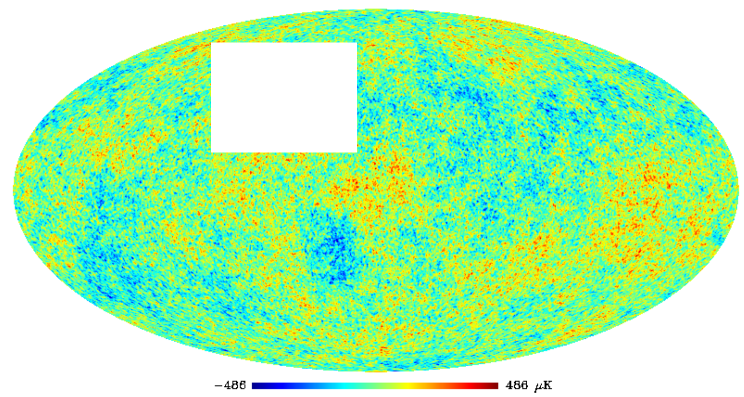

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Evidence ratio in the blob: how much better does one describe the data by adding a template?

- Pixel-based likelihood $L_b(\mathbf{d}|\mathbf{m})$ contains: CMB cosmic variance, beam, and spatially varying noise.

- Flat prior on amplitude and shape, prior on size and position from theory.

Searching for collisions

- The general expression for N_b candidates:

Theory prior

Cosmic variance

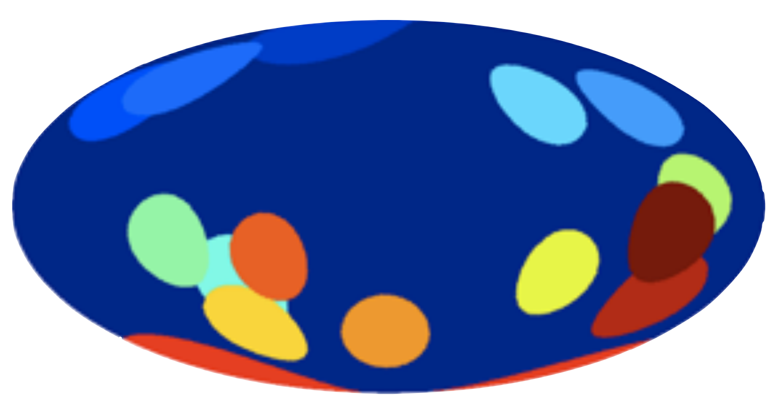
All combos of templates and blobs

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

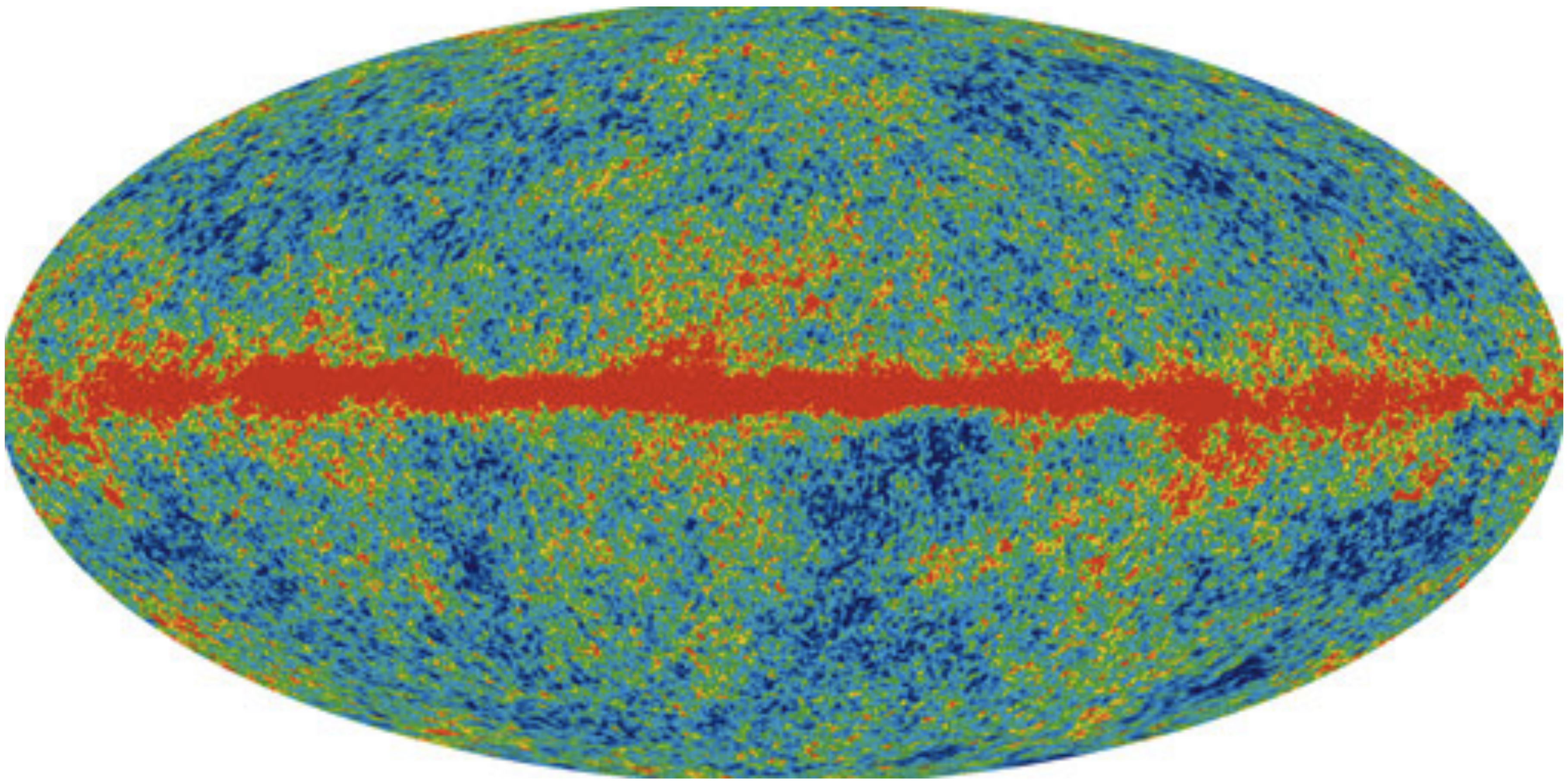
Expected number of features

Poisson process

Evidence ratio in each blob

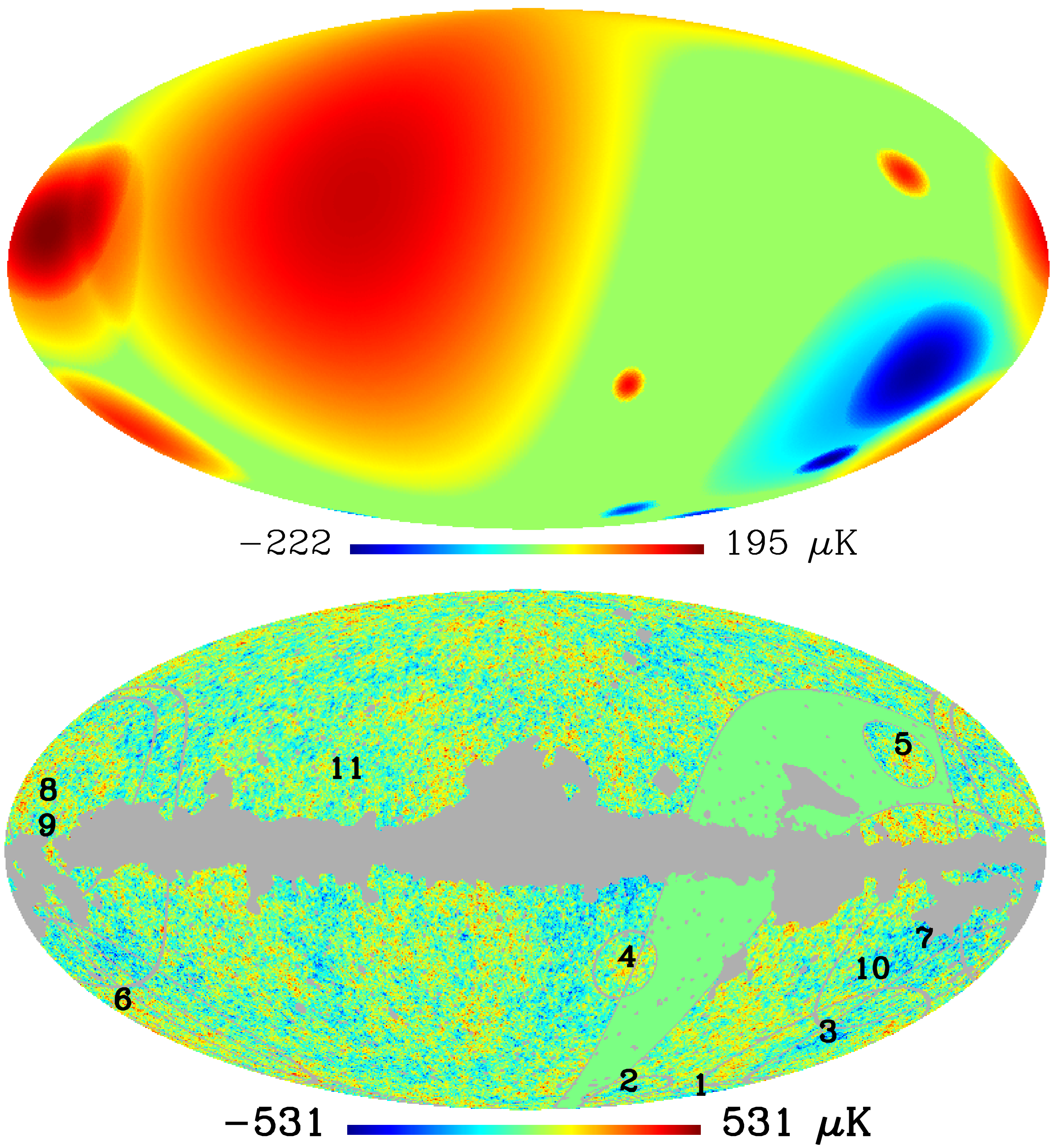


WMAP7 W-Band (94 GHz)

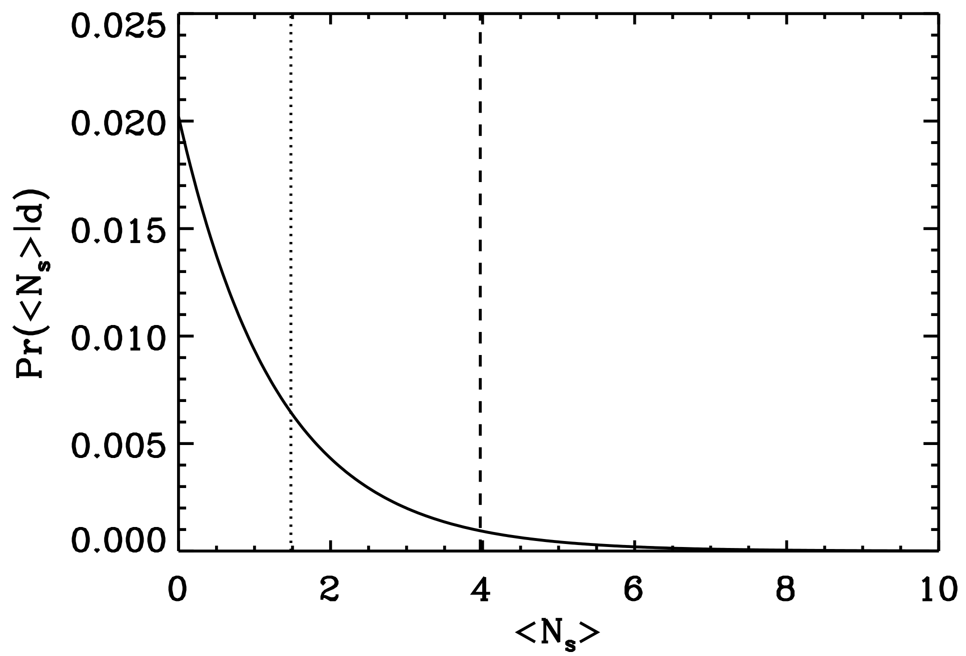


The WMAP7 W-Band data.......

WMAP7 W-Band (94 GHz) : Candidates



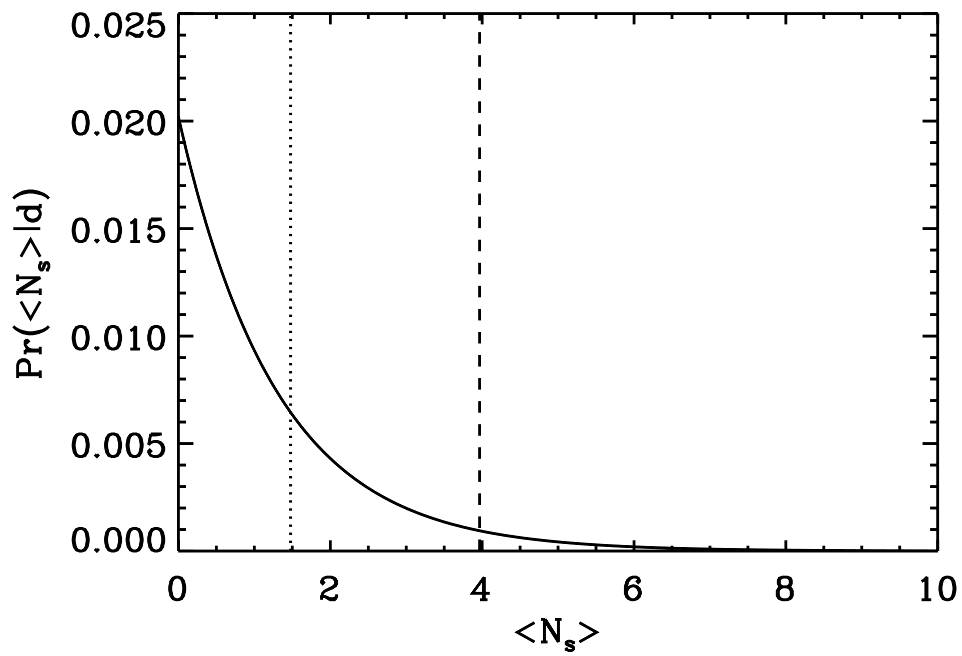
WMAP7 W-Band (94 GHz) : Posterior



- The posterior is peaked around $\bar{N}_s = 0$

The data does not support the bubble collision hypothesis.

WMAP7 W-Band (94 GHz) : Posterior



- The posterior is peaked around $\bar{N}_s = 0$

  The data does not support the bubble collision hypothesis.

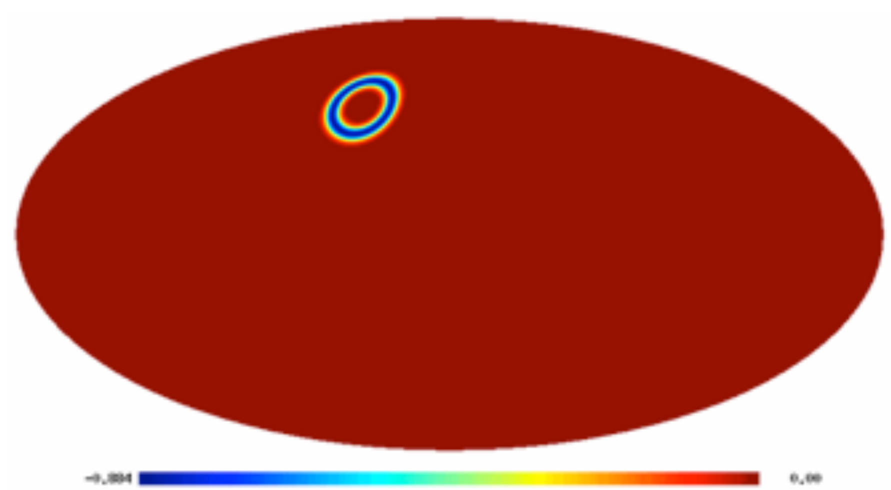
- From the shape of the posterior, we can rule out

$$\bar{N}_s < 1.6 \text{ at } 68\% \text{ CL}$$

What next?

- Check for signals in other datasets.

Polarization signal



Czech et. al.
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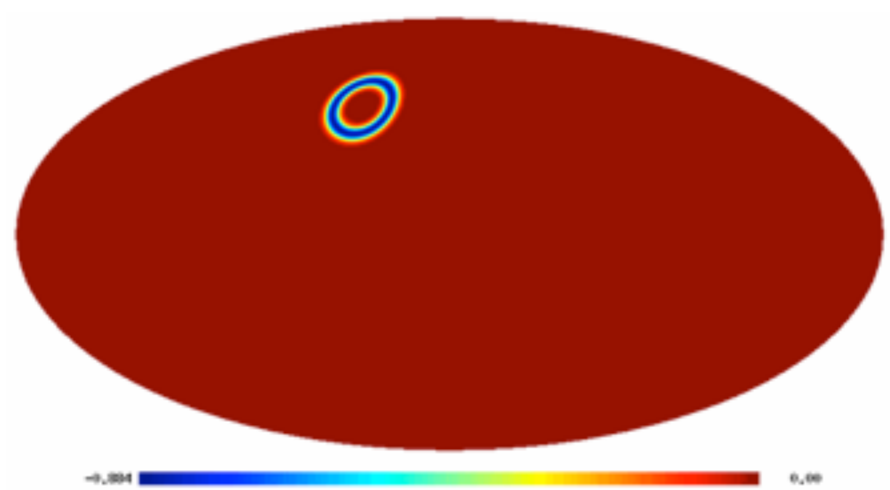

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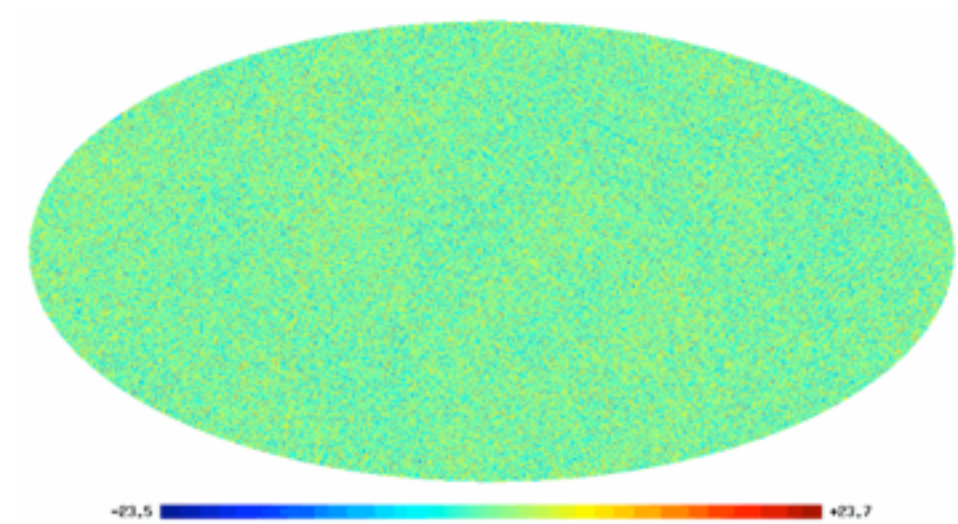
Planck res. with noise



corroborating evidence?

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$$\bar{N}_s < 1.6 \text{ at } 68\% \text{ CL}$$

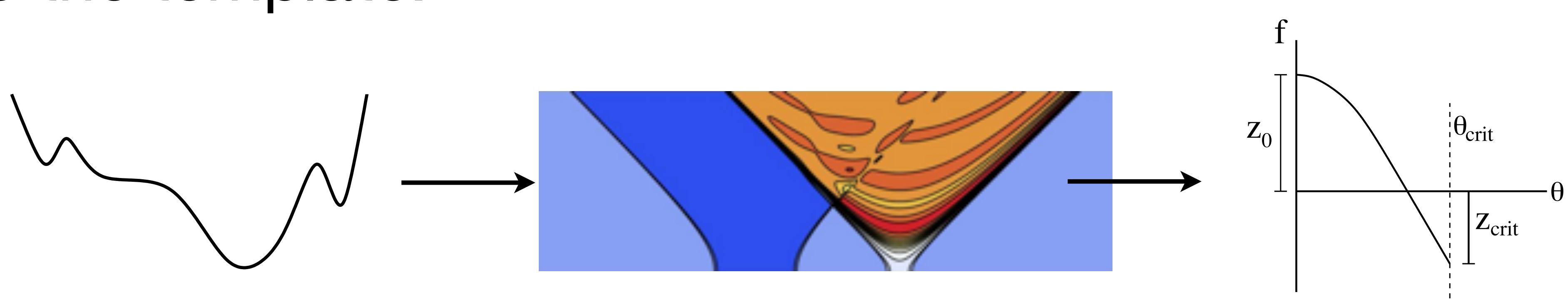
- What region of theory space have we constrained?

Novel connection between numerical relativity and observational cosmology!

What next?

$$\bar{N}_s < 1.6 \text{ at } 68\% \text{ CL}$$

- What region of theory space have we constrained?
- Numerical simulations are needed to connect the potential to the template!



(Like in inflation: general template for fluctuations needs to be connected to the potential)

Novel connection between numerical relativity and observational cosmology!