Inflection Point Inflation:
Before and After

Ely D. Kovetz
University of Texas at Austin
HEP Seminar, Texas A&M, April 23rd, 2012

Based on:

Before

N. Itzhaki and EDK, “Inflection Point Inflation and Time Dependent Potentials in String Theory”, JHEP 2007

N. Itzhaki and EDK, “A Phase Transition between Small and Large Field Models of Inflation” Cl.Qu.Gr. 2009

After

A. Fialkov, N. Itzhaki and EDK, “Cosmological Imprints of Pre-Inflationary Particles”, JCAP 2010

EDK, A. Ben-David and N. Itzhaki, “Giant Rings in the CMB Sky”, ApJ 724, 2010

A. Ben-David, EDK and N. Itzhaki, “Parity in the CMB: Space Oddity”, ApJ 748, 2012

Outline

Before

After

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- Small/Large Field Phase Transition

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- Understanding the Critical Behavior

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- Time-Dependent D.O.F. (PIP)

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- Pre-Inflationary Particle - Signatures

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- Current work and Summary

Before

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(Itzhaki, EDK, Cl.Qu.Gr. 2009)

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Let's see some ways out of this...

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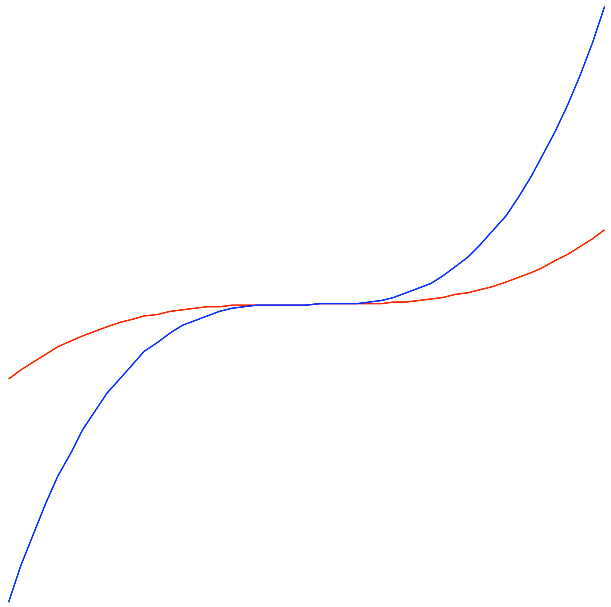

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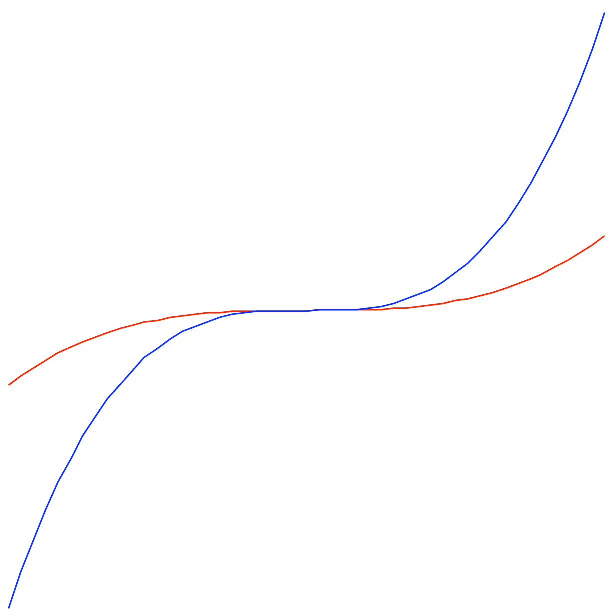

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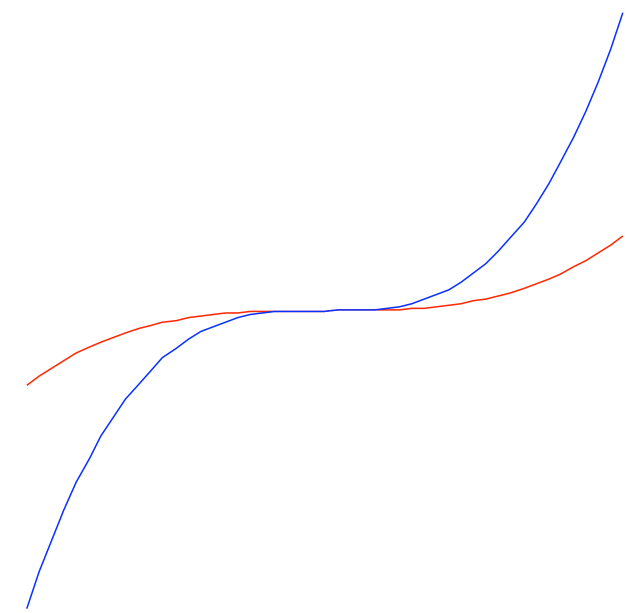

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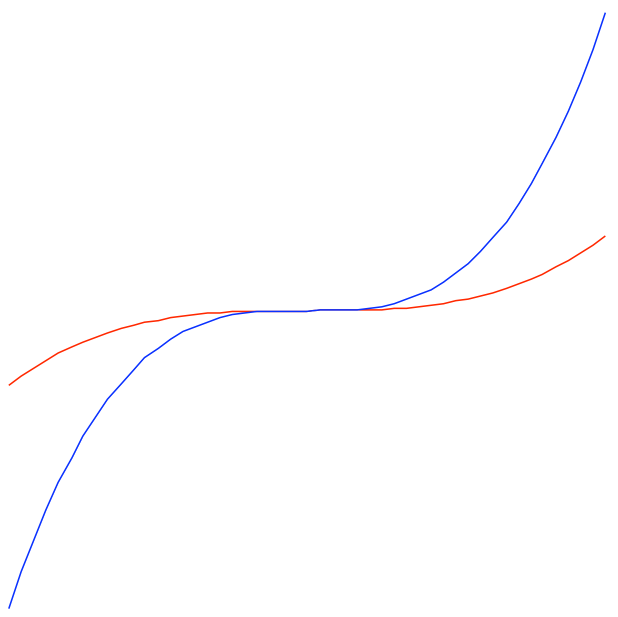

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Therefore, N is our candidate for the order parameter.

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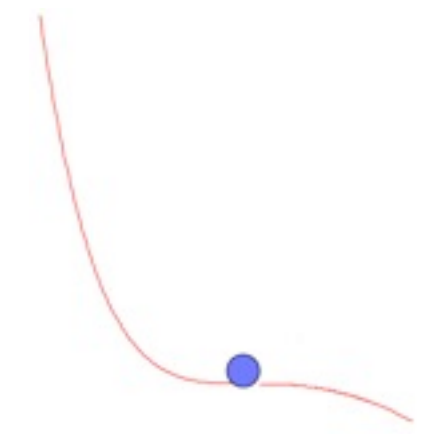

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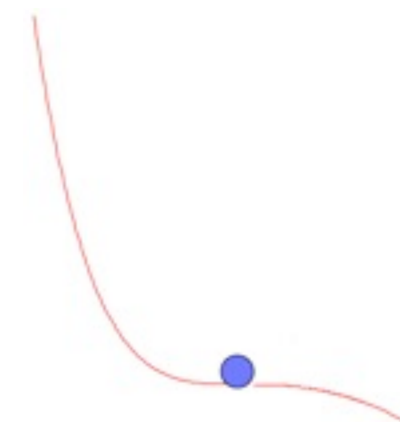

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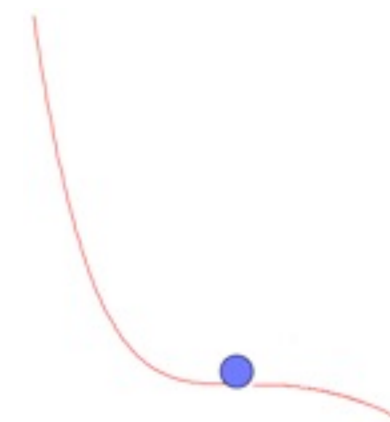

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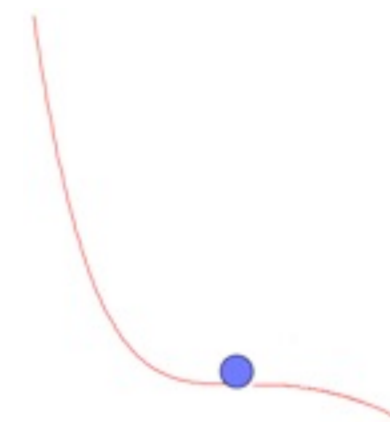

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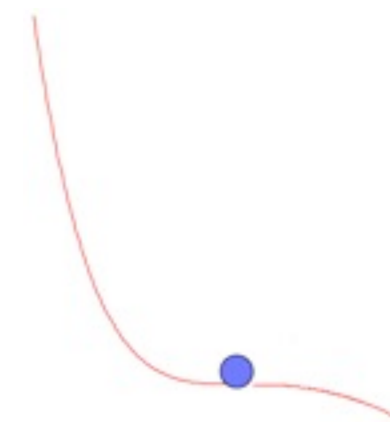

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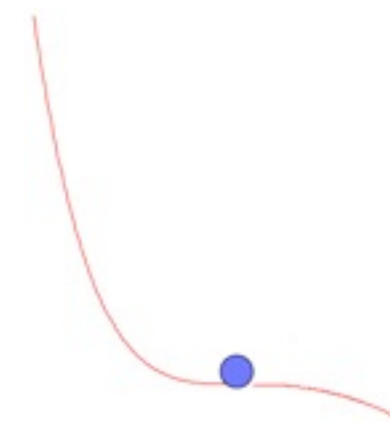

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- To demonstrate the PT property numerically, we notice that taking $\phi \to \lambda\phi$ and keeping the kinetic term fixed is equivalent to keeping ϕ fixed and transforming: $\beta \longrightarrow \lambda^3\beta$. Therefore, we can search for a critical β_c where a PT occurs between large and small field domains.

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$\beta \backslash \phi_{init}$	0.5	1	5	10	100
0.1	∞	∞	∞	∞	∞
0.7	∞	∞	∞	∞	∞
0.7744	∞	∞	∞	∞	∞
0.7745	∞	∞	38404.9097	38218.5366	38218.5365
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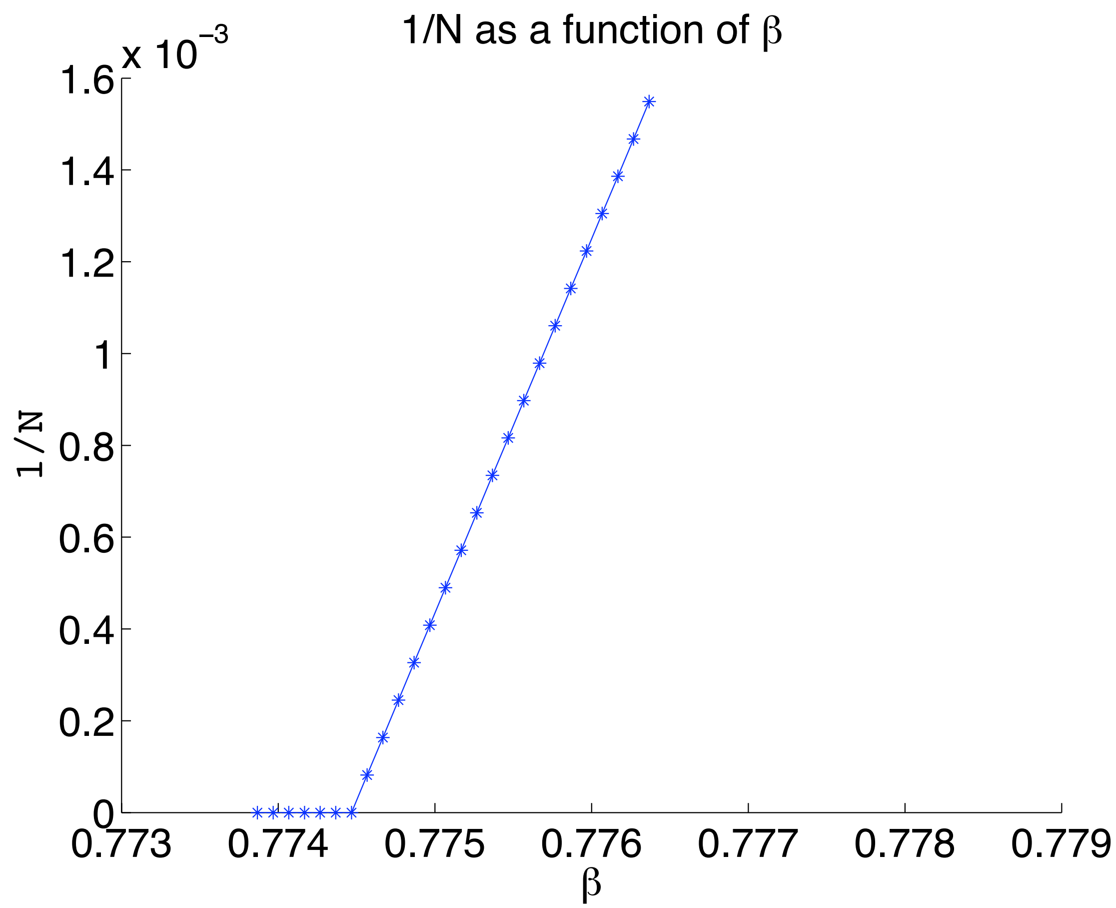

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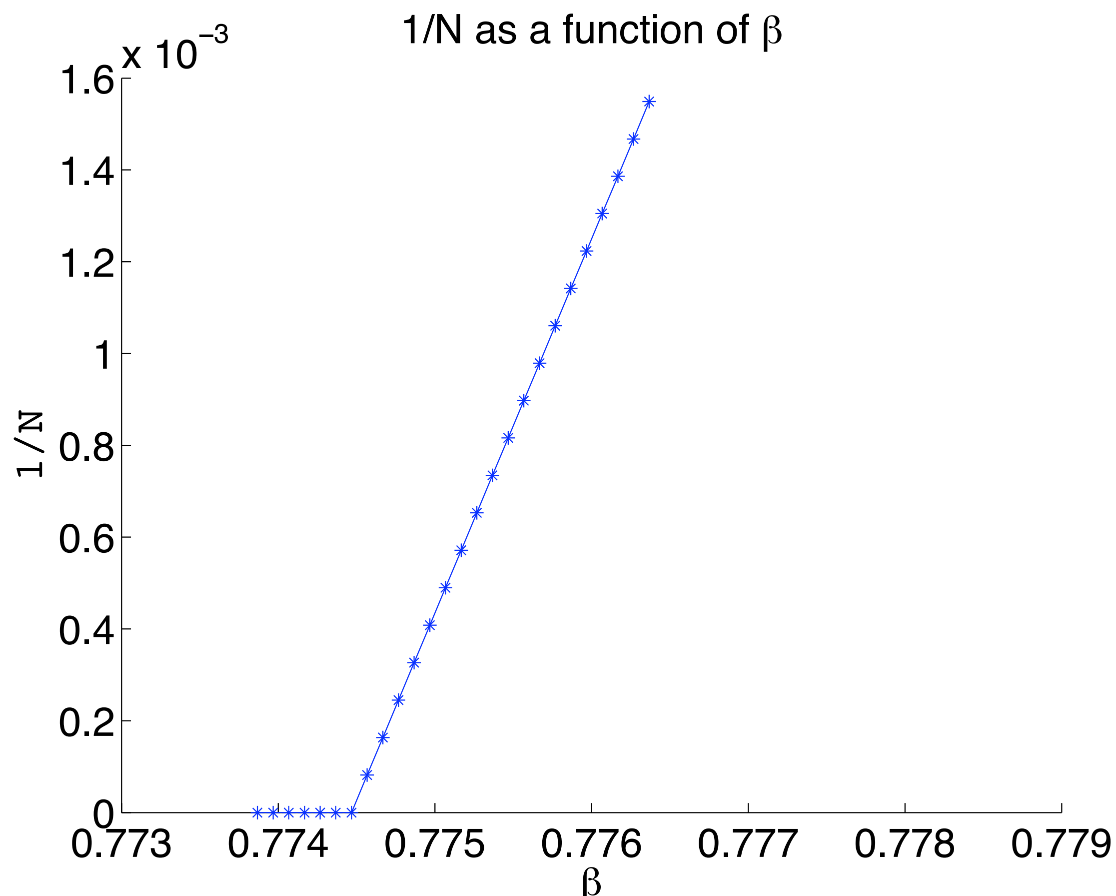

- $N_{e-folds}$ is time dependent. An alternative is to use: $\frac{1}{N} \sim \dot{\phi}(\phi = 0) \equiv \dot{\phi}_0$ and identify $\dot{\phi}_0$ as the order parameter.

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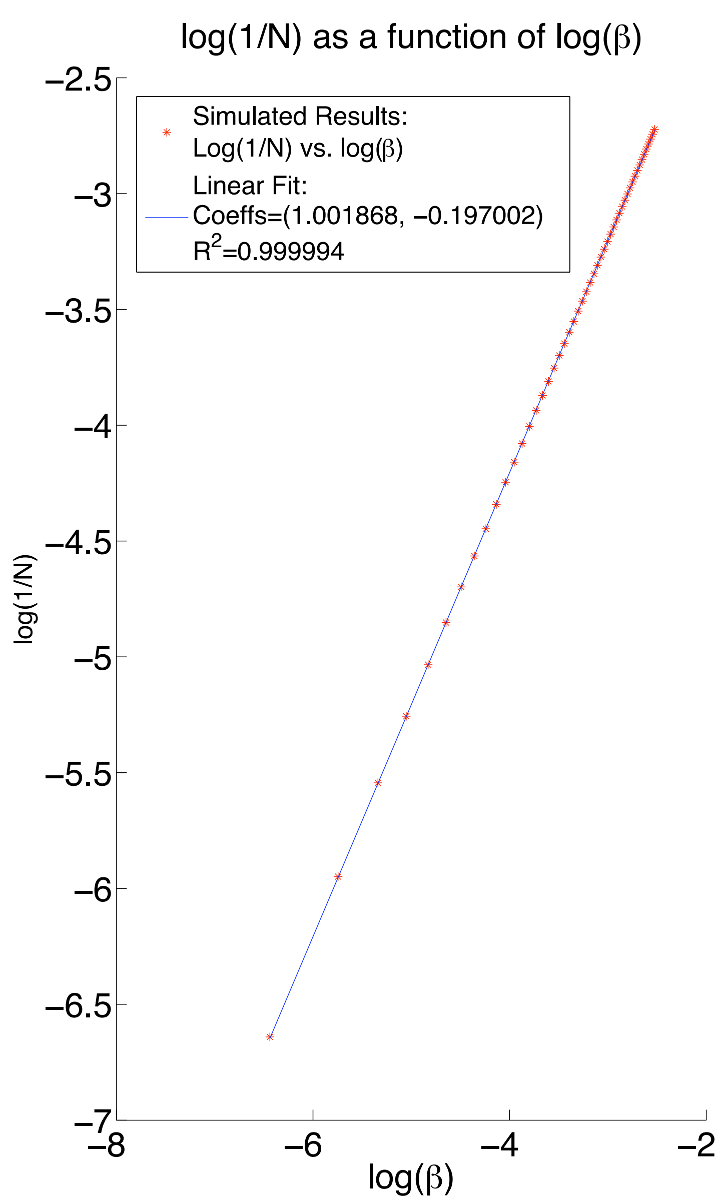

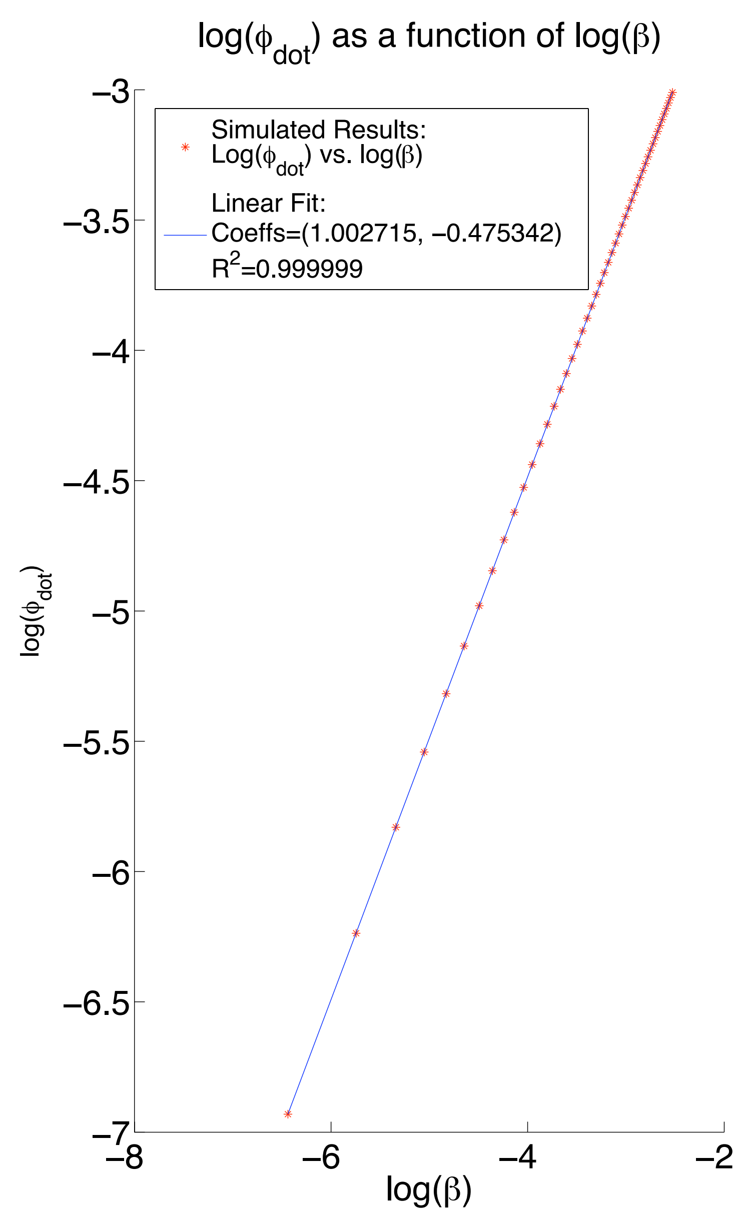

Higher Order Terms

(Itzhaki, EDK, Cl.Qu.Gr. 2009)

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- Potentials in which the lowest non-zero derivative is even exhibit no critical behavior at all.

Different Critical Exponents

(Itzhaki, EDK, Cl.Qu.Gr. 2009)

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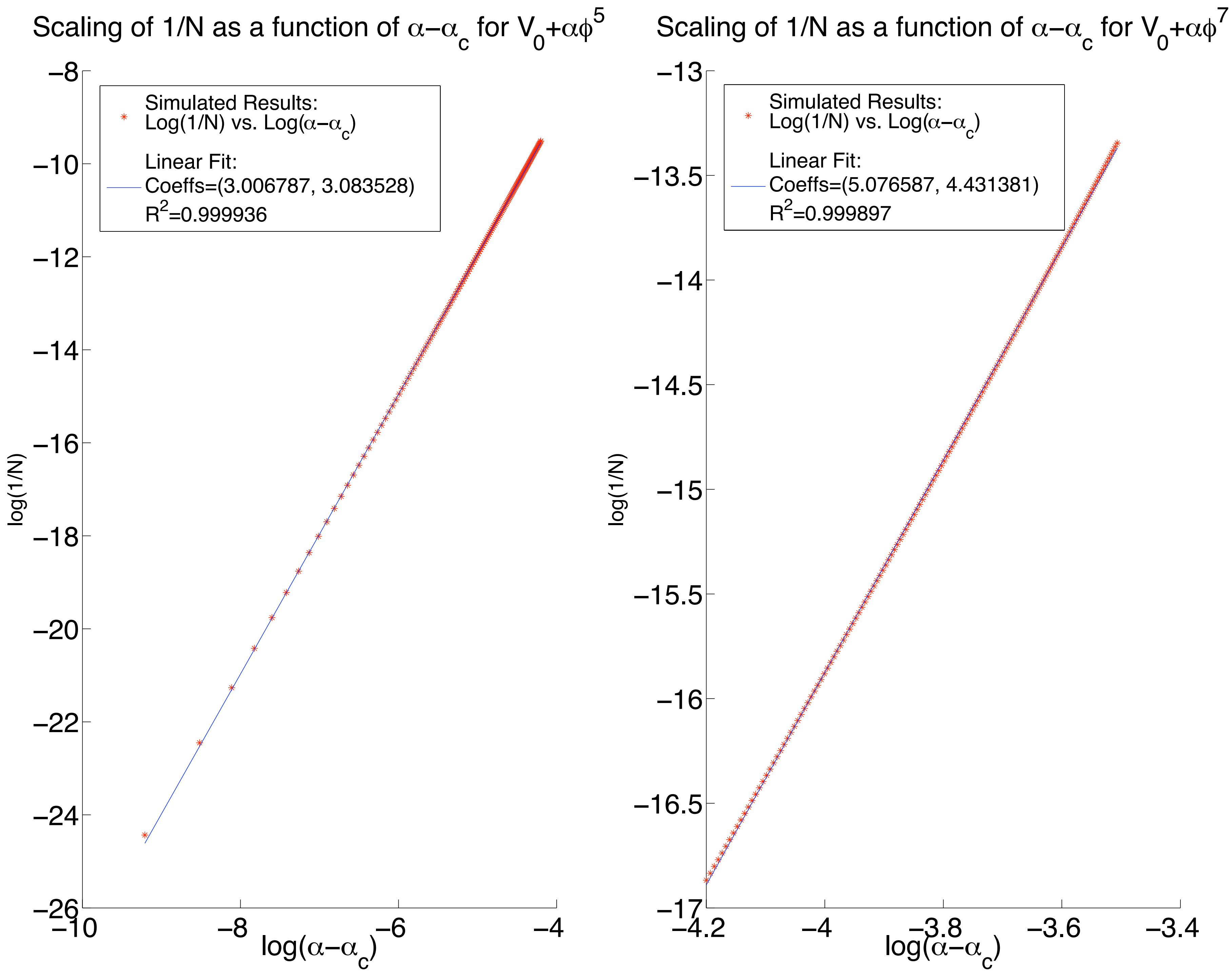

Approximated Inflection Point

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What if the inflection point in the potential is not exact?

- For a potential of the form: $V = V_0(1 + \delta\phi + \beta\phi^3)$ there will obviously be no finite λ_c in the transformation $\beta \to \lambda^3\beta, \quad \delta \to \lambda\delta$ such that $N(\lambda_c) = \infty$.

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- We find that for $\delta \neq 0$ there is a λ_c such that:

  - For $\lambda > \lambda_c$ the amount of inflation depends on the initial condition. Then, in order to maximize N we have to fine tune the initial condition.
  - For $\lambda < \lambda_c$, however, any non-singular initial condition gives $N = N_{max}$.

Before

Outline

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- Small/Large Field Phase Transition

Before

Outline

- Small/Large Field Phase Transition
- Understanding the Critical Behavior

Before

Simplifying the Equations

(Itzhaki, EDK, Cl.Qu.Gr. 2009)

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We make the following approximations:

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- Near the critical point the inflaton spends most of the time near the inflection point where H is constant, which leaves us with:

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- So if the solutions start with $\phi(0) = \phi_0$ and $\dot{\phi}(0) = 0$, then $\phi_0^2\beta$ can be used to parametrize them. Therefore, we can either fix β and vary the initial condition, or vary the initial condition with β fixed.

Using a Different Order Parameter

(Itzhaki, EDK, Cl.Qu.Gr. 2009)

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- We shall fix $\beta = 1$ and vary the initial condition to look for a phase transition. We remain with:

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- Since: $$N_{e-folds} = \int_{end}^{start} H dt \sim H_{inflc} \int_{end}^{start} dt = \frac{1}{3}(t_{end} - t_{start})$$

  we can measure the time spent in the vicinity of the inflection point instead of the amount of e-foldings.

Damped Harmonic Oscillator

(Itzhaki, EDK, Cl.Qu.Gr. 2009)

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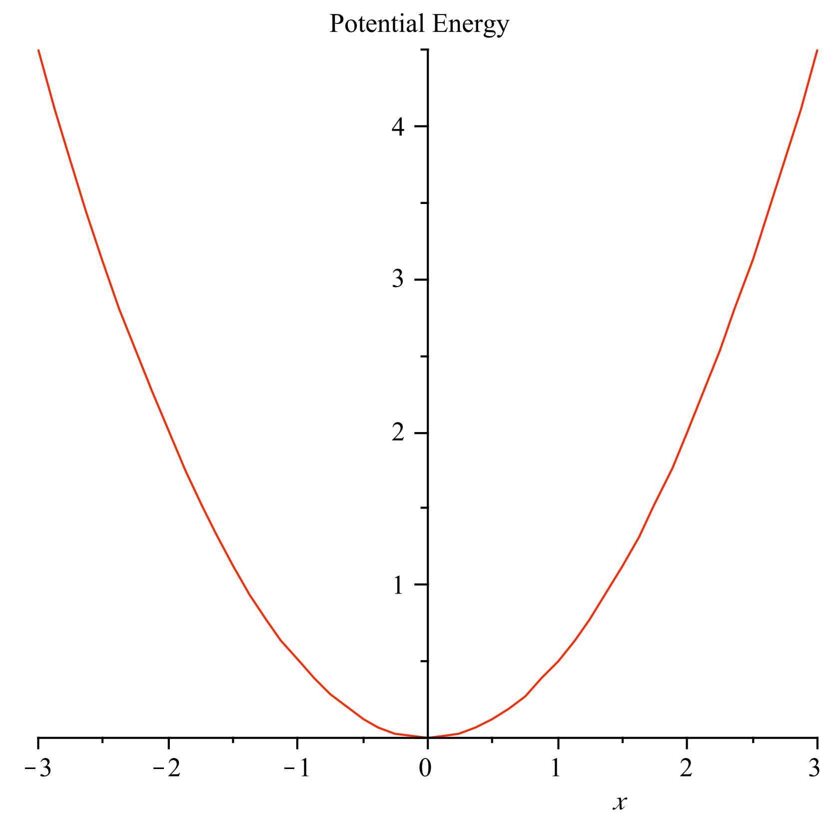
- A simpler example: a Harmonic Oscillator



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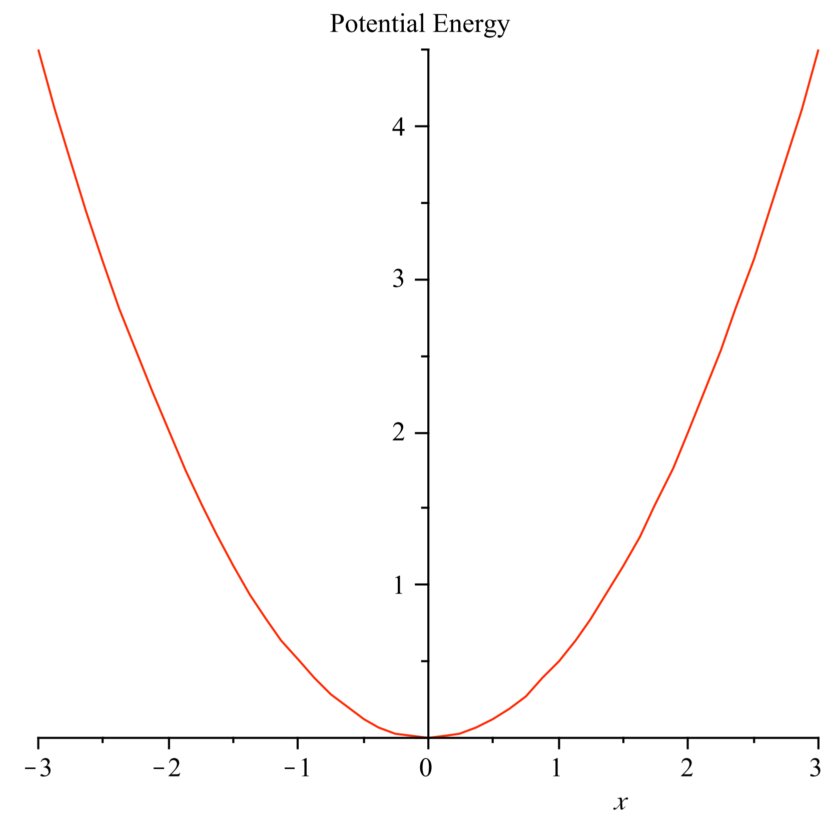
For $V = \frac{1}{2}x^2$, we get the equation:

$$\ddot{x} + \gamma\dot{x} + x = 0$$



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$$y(t) = \dot{x(t)}$$

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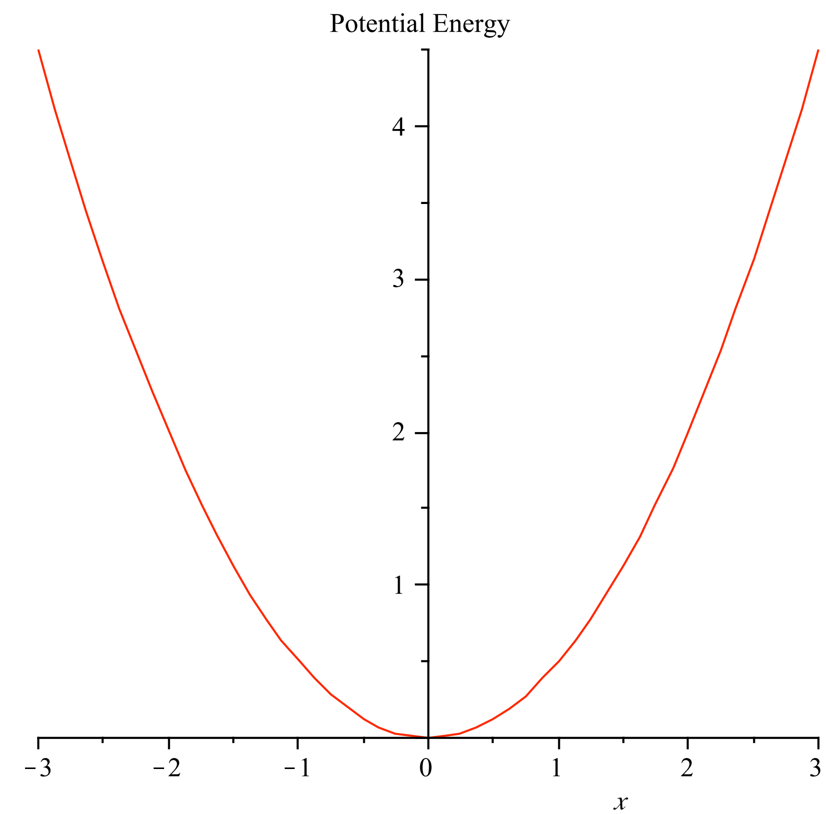

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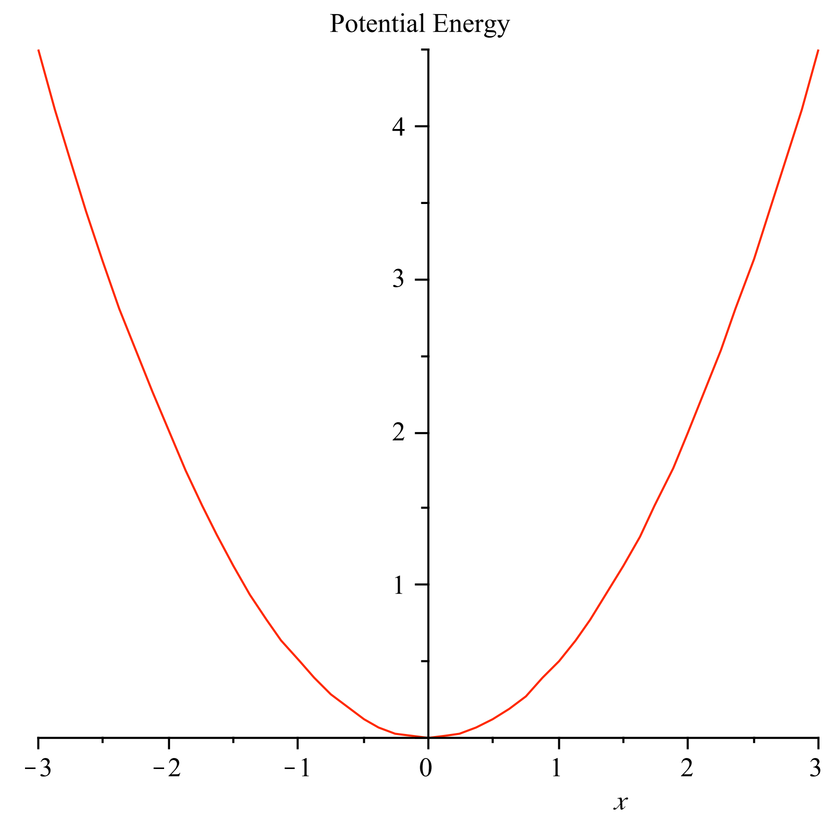

Reducing to a system of 1st order equations:

$$y(t) = x\dot{(}t)$$

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We can proceed to draw the solutions in phase space.

Harmonic Oscillator

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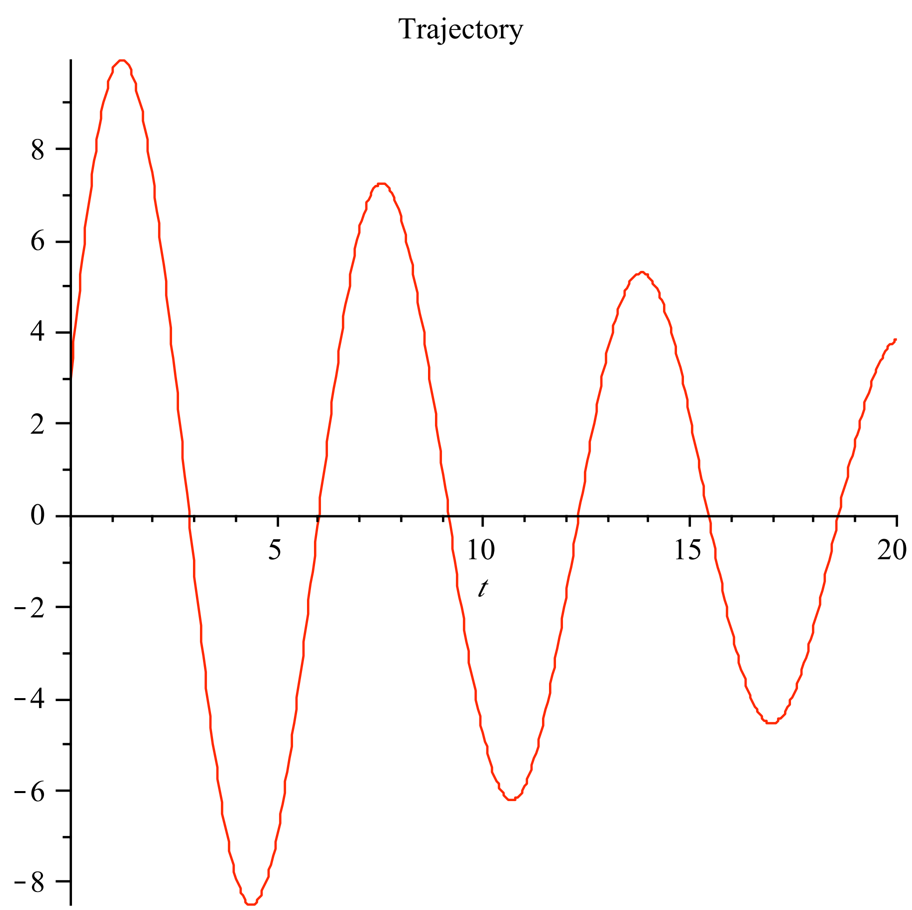
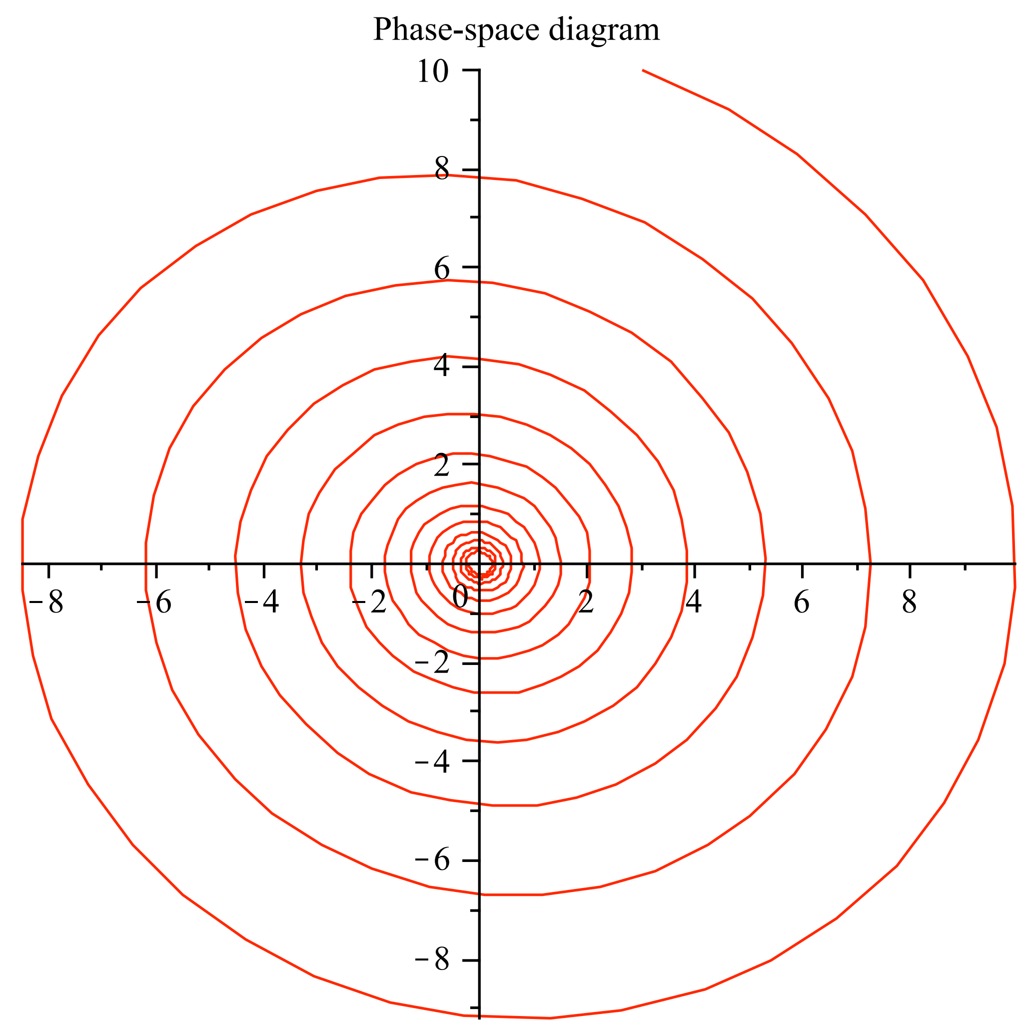
- Left: trajectory for an arbitrary initial condition and $\gamma = 0.1$.

- Right: same trajectory in phase space.





Harmonic Oscillator

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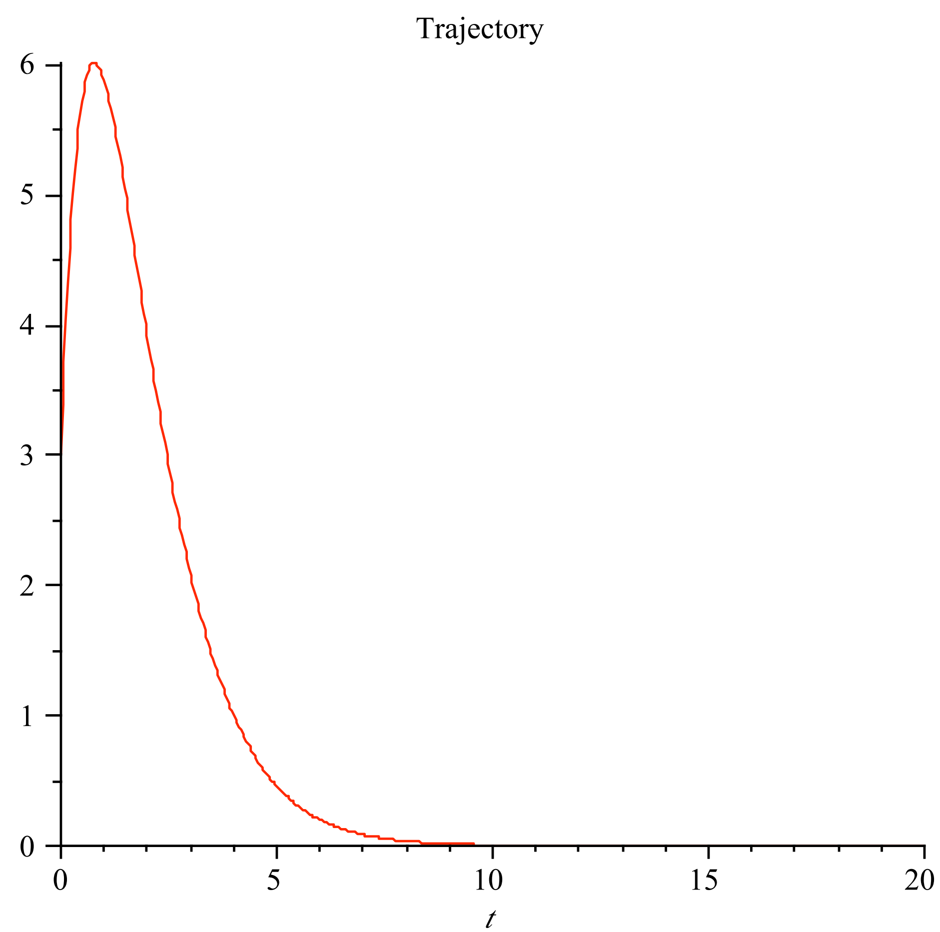
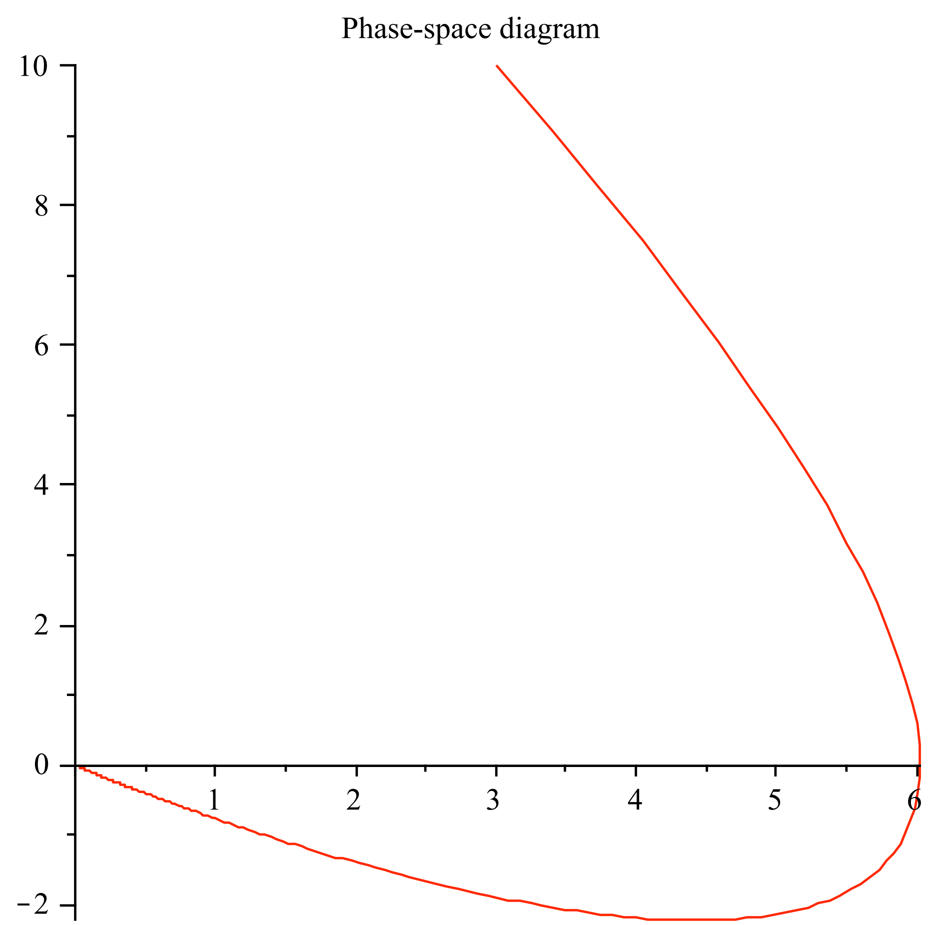
- Left: trajectory for an arbitrary initial condition and $\gamma = 2$. The motion decays before any oscillations occur. The point x=0 is asymptotically approached.

- Right: same trajectory in phase space.





Duffing Oscillator

(Itzhaki, EDK, Cl.Qu.Gr. 2009)

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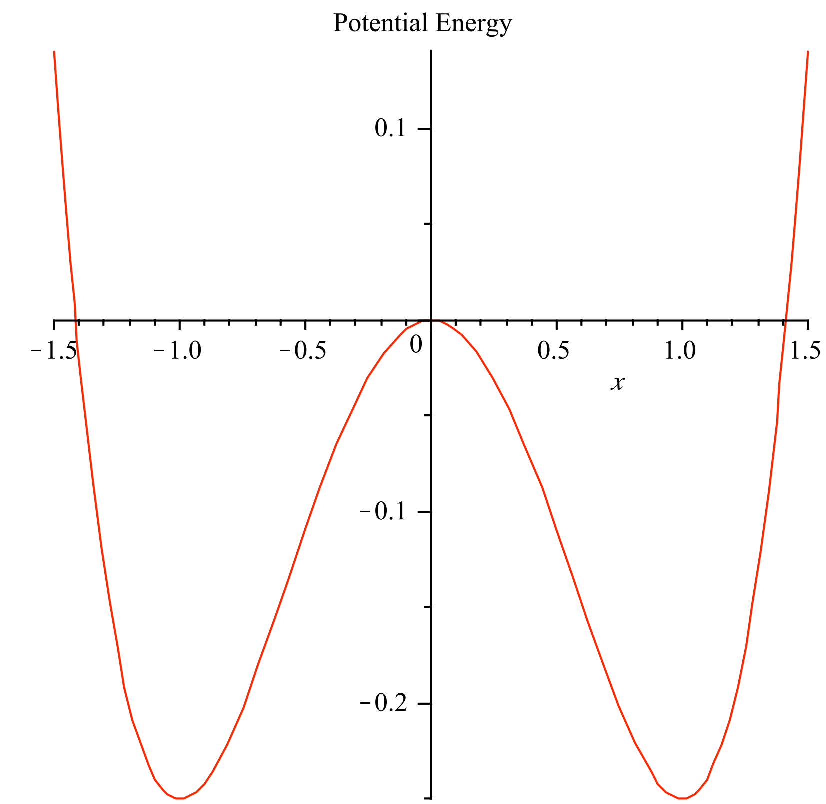

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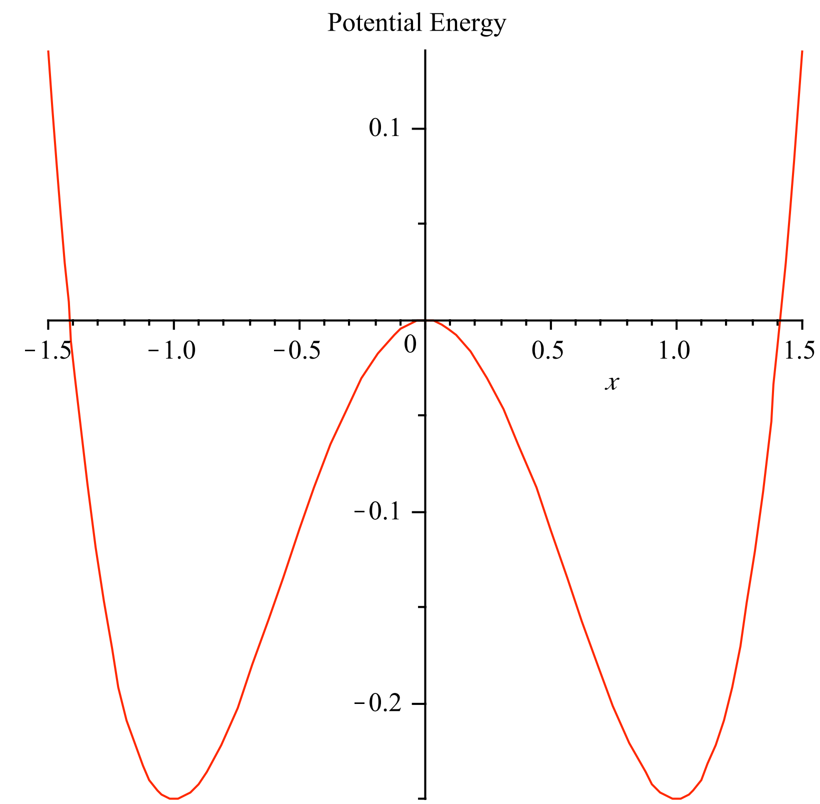
- A slightly more complicate example:

For $V = -\frac{1}{2}x^2 + \frac{1}{4}x^4$, we get the equation:

$$\ddot{x} + \gamma\dot{x} - x + x^3 = 0$$



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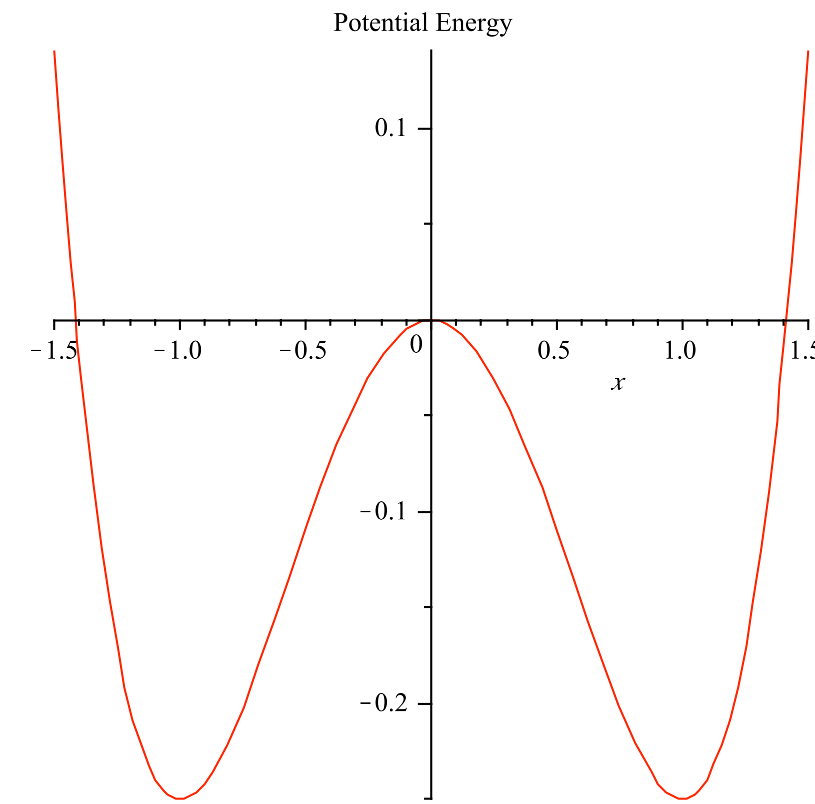

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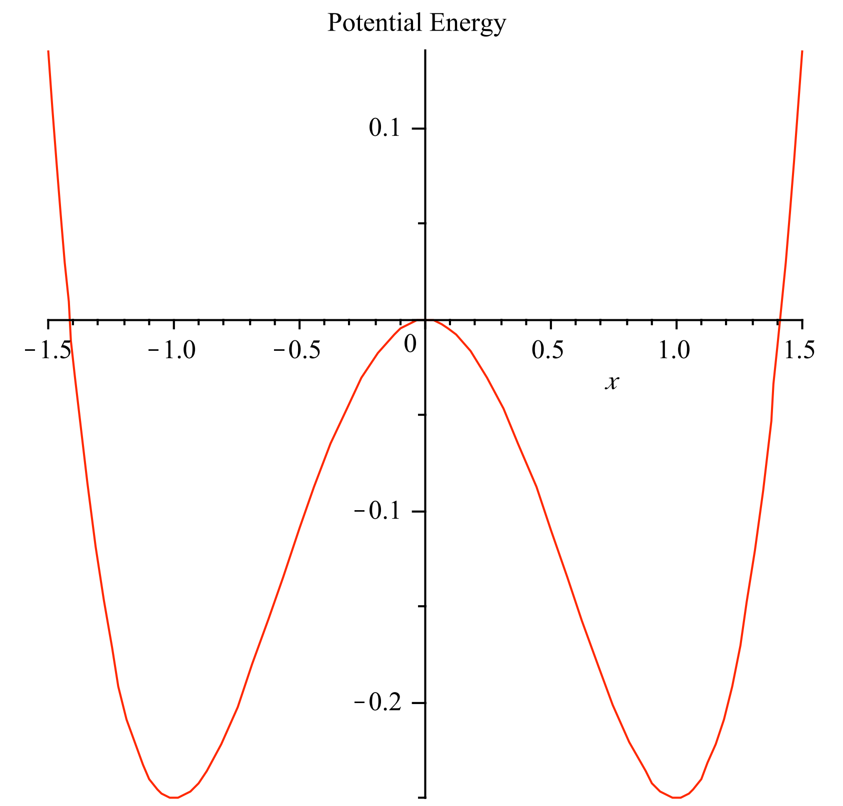

This system has the following properties:

- Potential has a double-well structure.
- x =0 is an unstable equilibrium point.
- Particle motion ends in one of the wells.
- Unique phase-space trajectory per IC.
- Chaos appears as a result of the two wells connected by the unstable equilibrium point.

Duffing Oscillator

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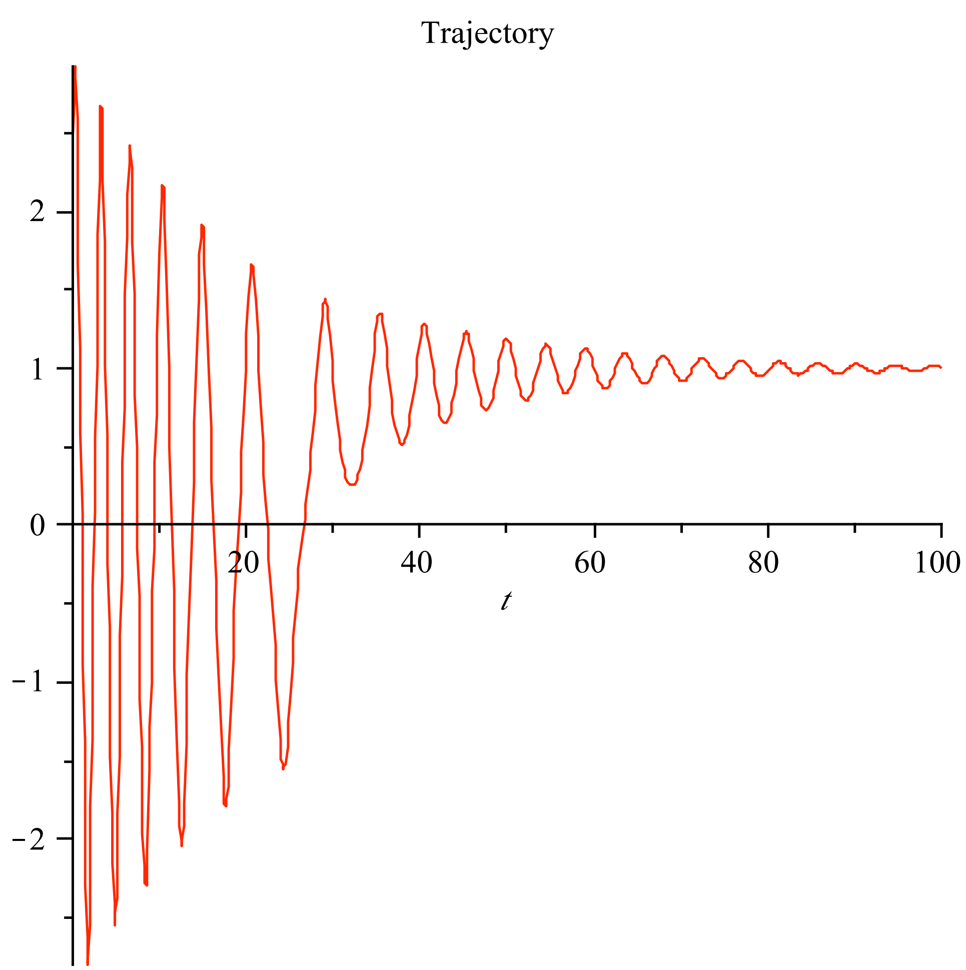
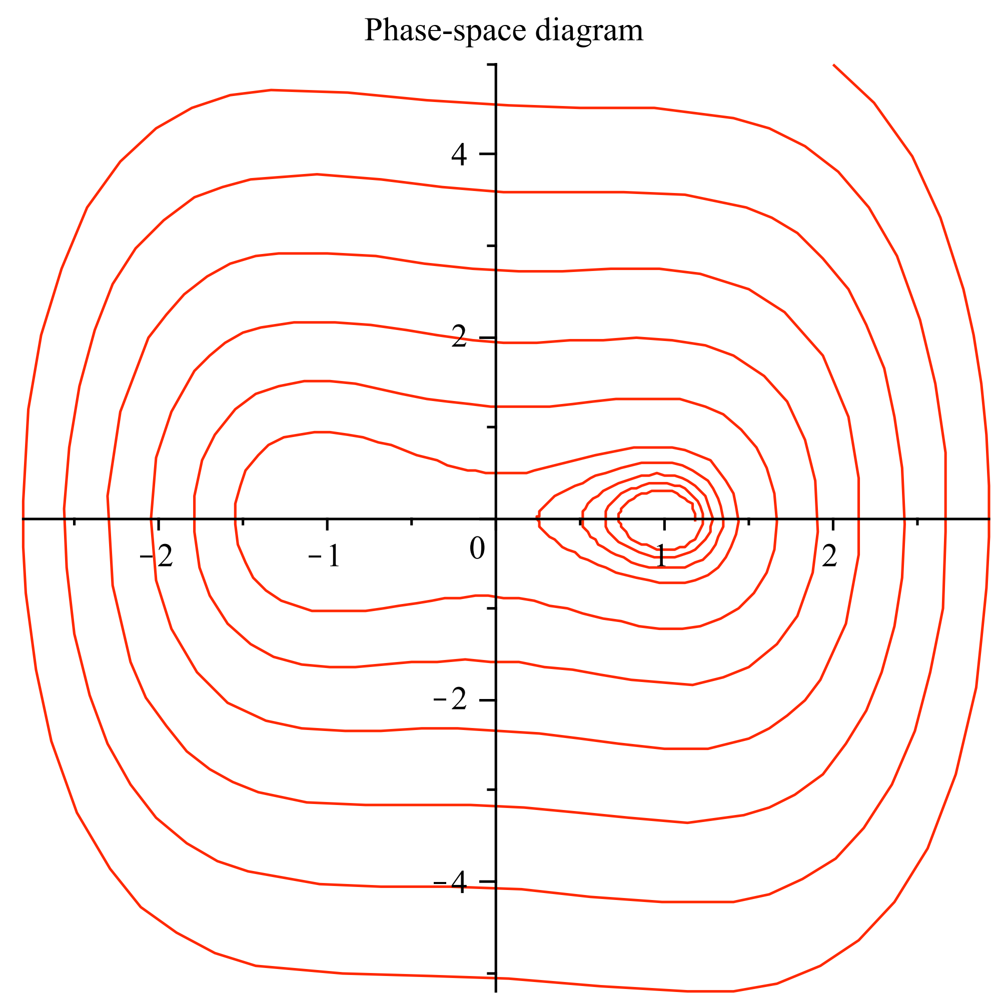
- Left: trajectory for arbitrary γ and initial condition. Particle falls into one well.

- Right: same trajectory in phase space. Trajectory converges to one side.





Phase Space Diagram

(Itzhaki, EDK, Cl.Qu.Gr. 2009)

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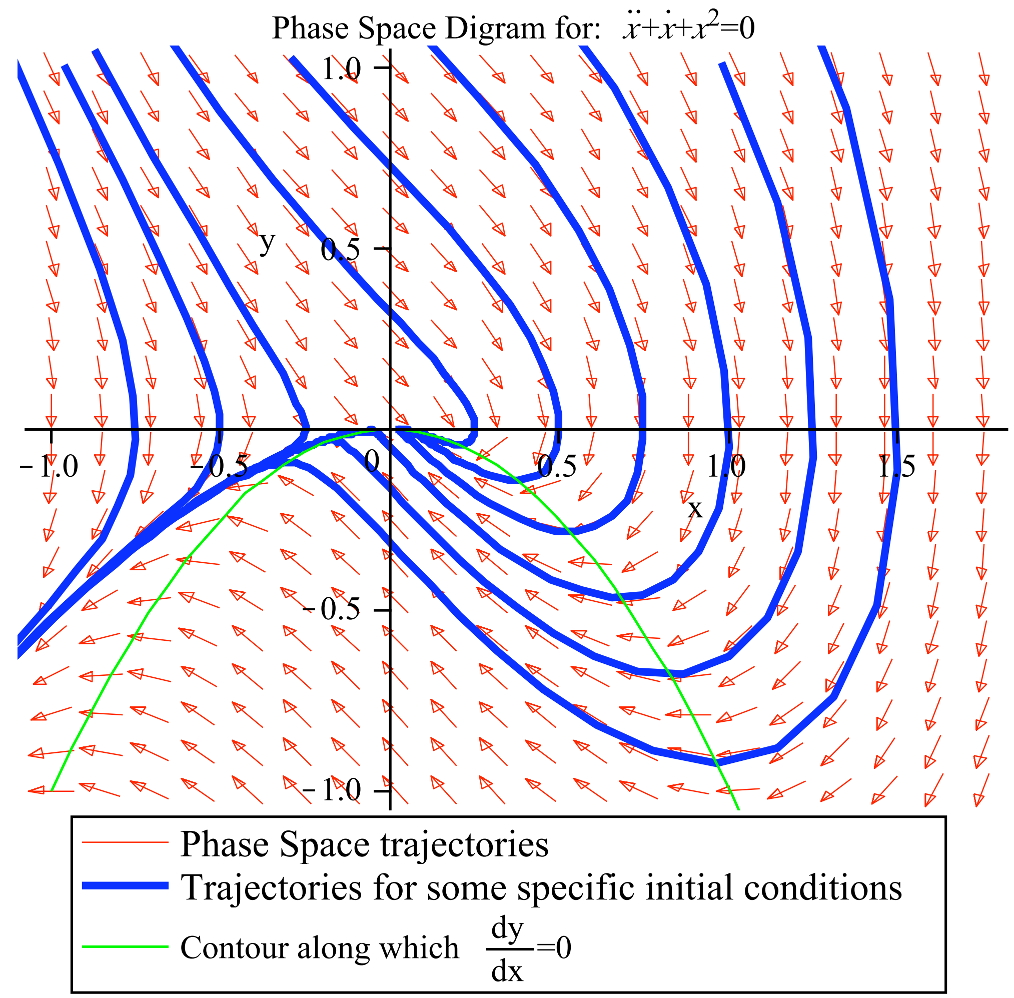
Reducing: $\ddot{x} + \dot{x} + x^2 = 0$ to:

$$\begin{aligned} \dot{x} &= y, \\ \dot{y} &= -y - x^2 \end{aligned}$$



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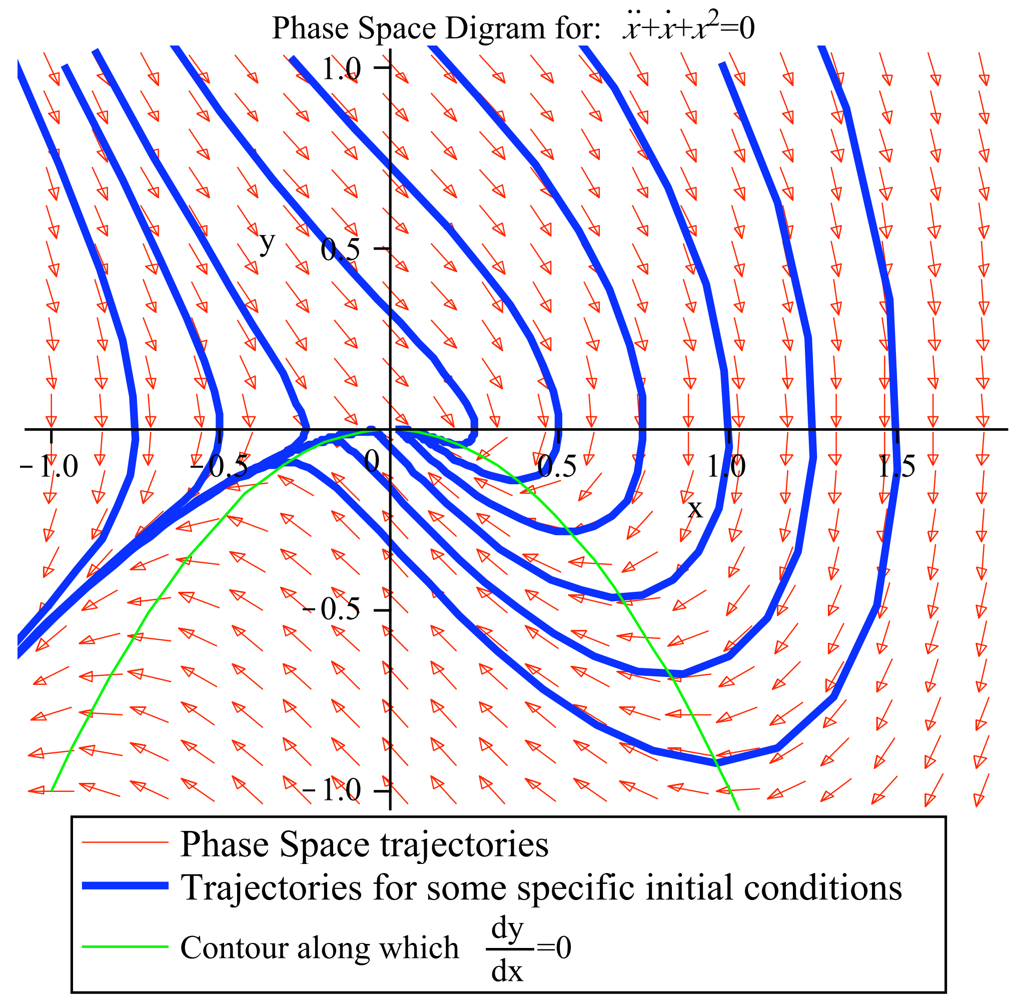

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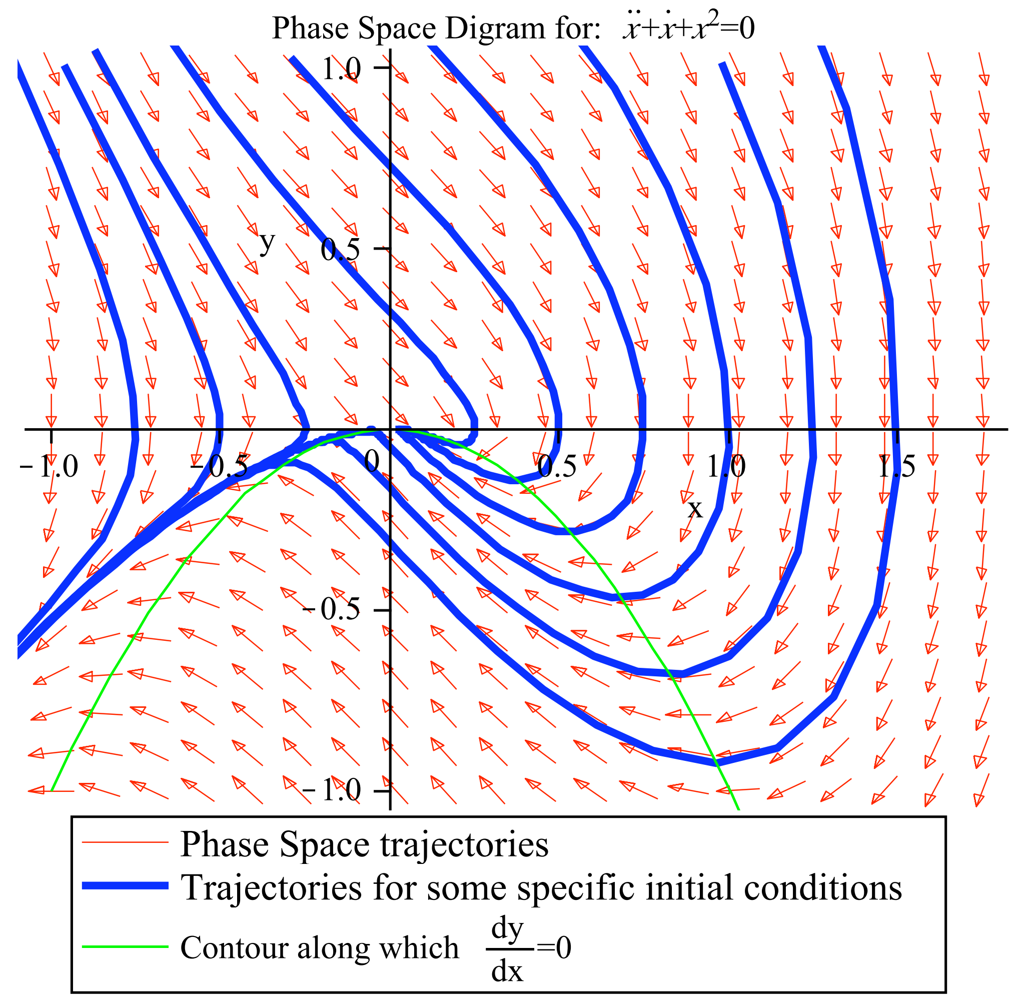

we deduce:

- Crossing the x axis (y=0) the slope is always infinite.
- Crossing the y axis (x=0) the slope is always -1.
- Crossing the contour $y = -x^2$, the slope is always zero (for $x \neq 0$).
- For y<0, outside (inside) the contour $y = -x^2$, the derivative is positive (negative) and the trajectories are monotonically increasing (decreasing).

Approximated Solutions

(Itzhaki, EDK, Cl.Qu.Gr. 2009)

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- Thus, to find the critical exponent we have to glue the two solutions.

Gluing the Solutions

(Itzhaki, EDK, Cl.Qu.Gr. 2009)

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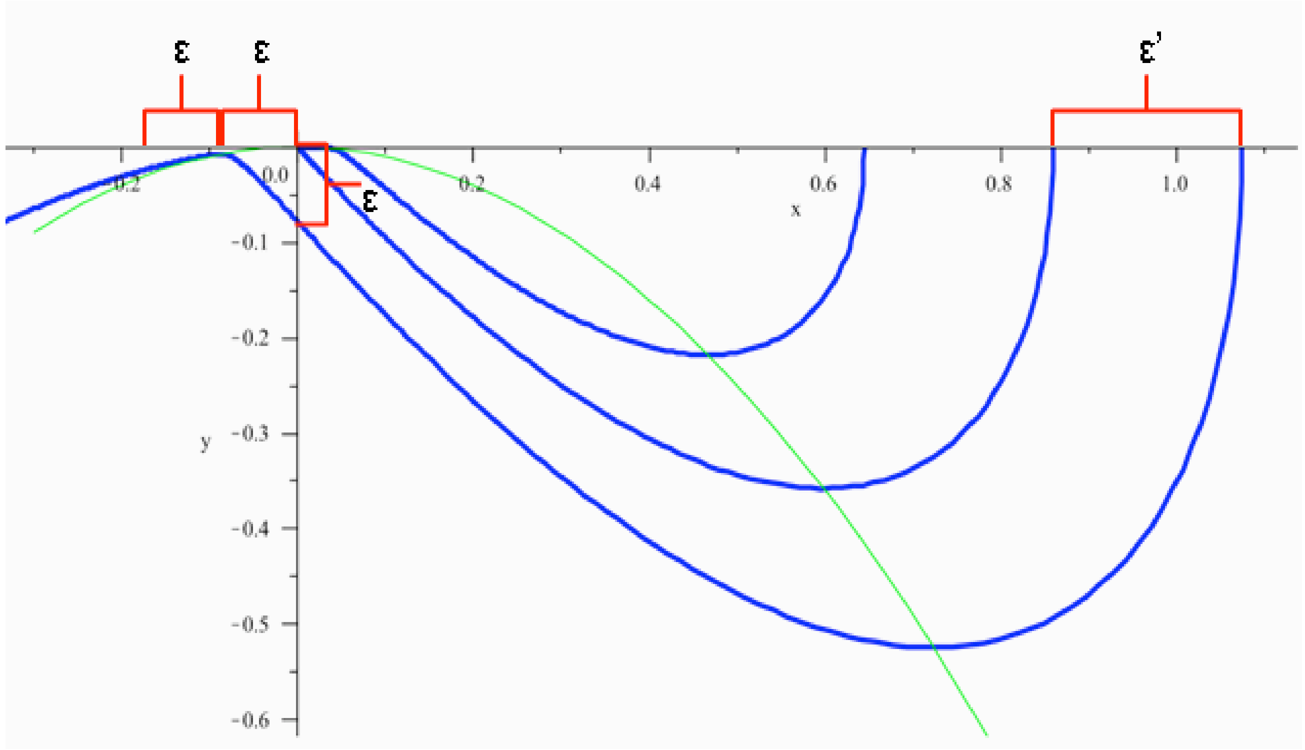

Gluing the Solutions

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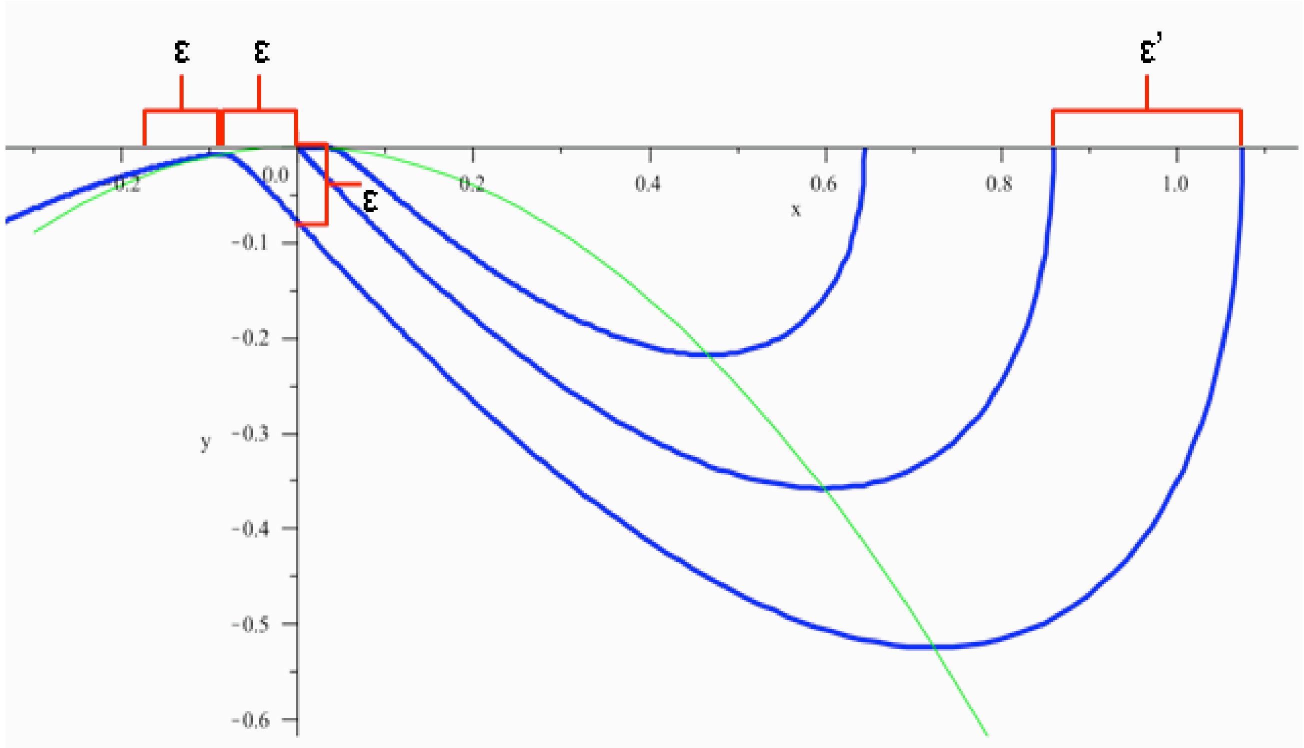
- We start with approximation (I):

$$x = ce^{-t} - \epsilon \quad , \quad y = -ce^{-t}$$



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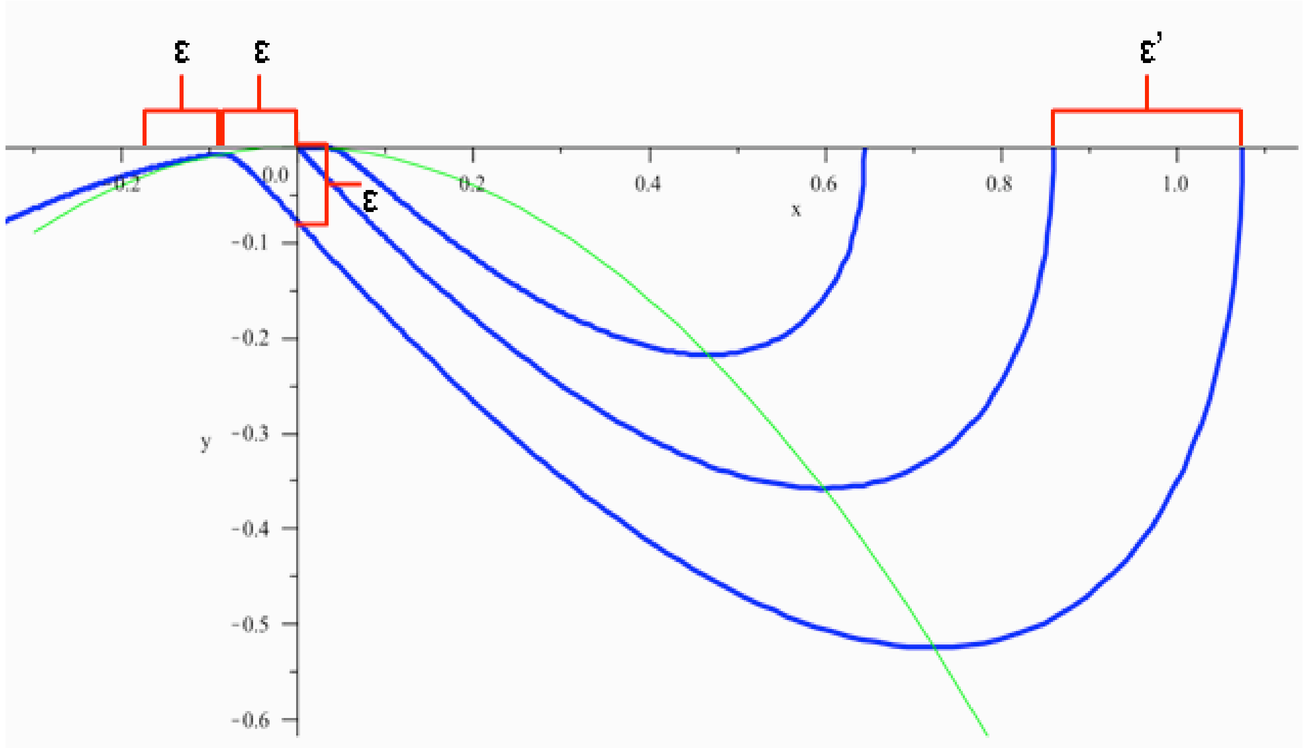
- This approximation breaks down when $\dot{x} \sim x^2 \sim \epsilon^2$, which happens at:



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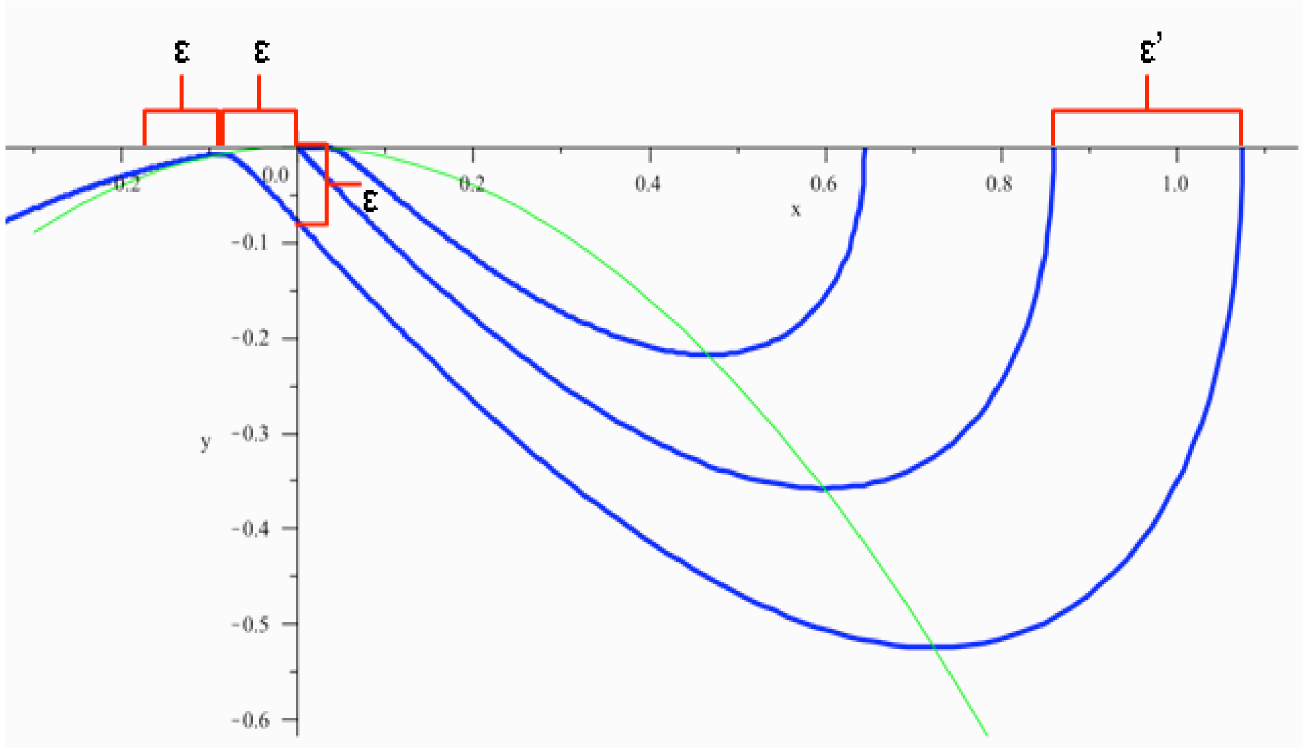

Gluing the Solutions

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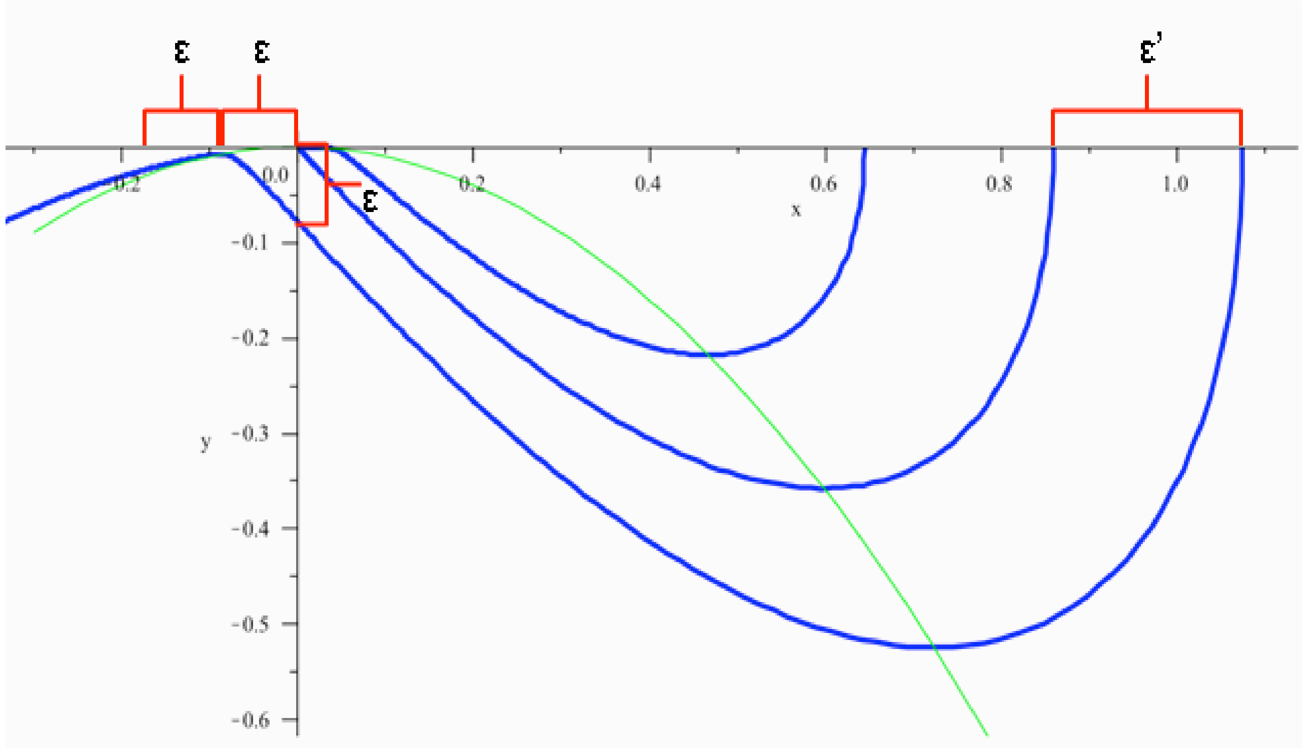
- Thus the first approximation is satisfactory up to $x \sim -\epsilon$, which, is in the vicinity of the curve along which approximation (II) is valid. However, as we saw above, the solution trajectory crosses this curve parallel to the y axis and therefore must deviate from it.



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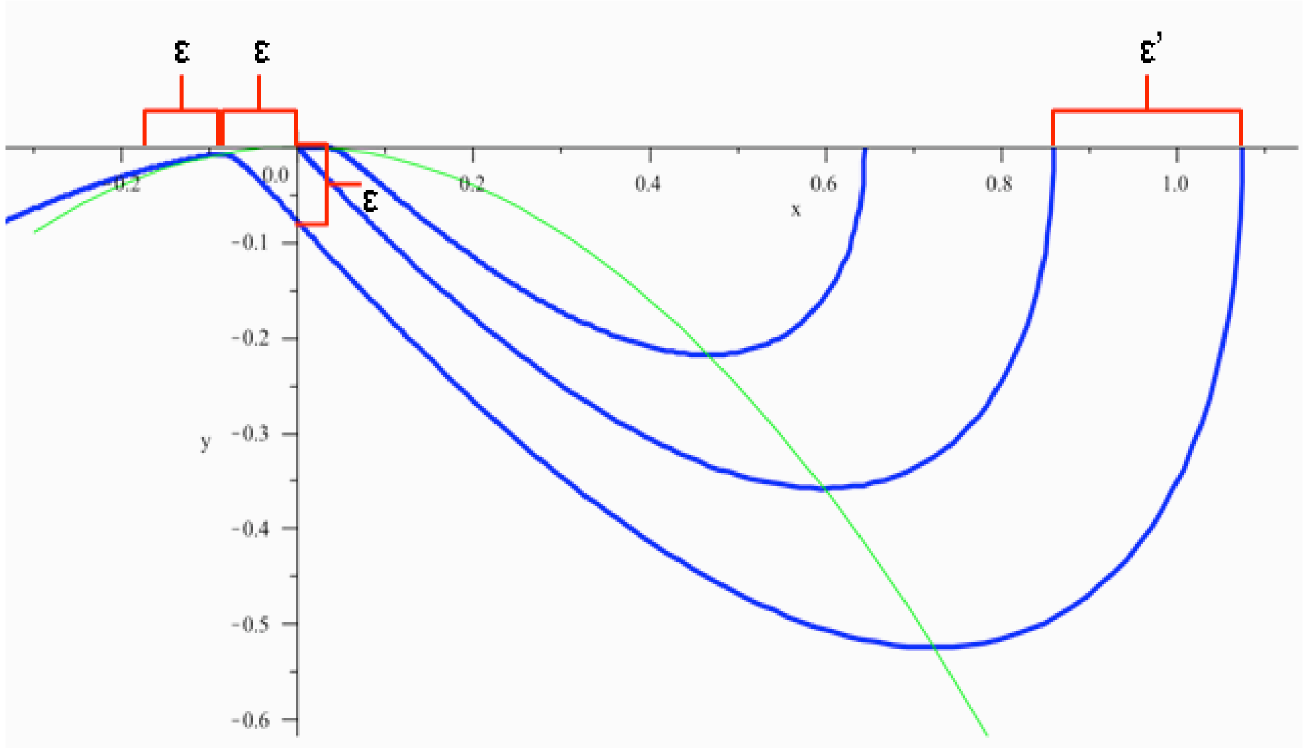

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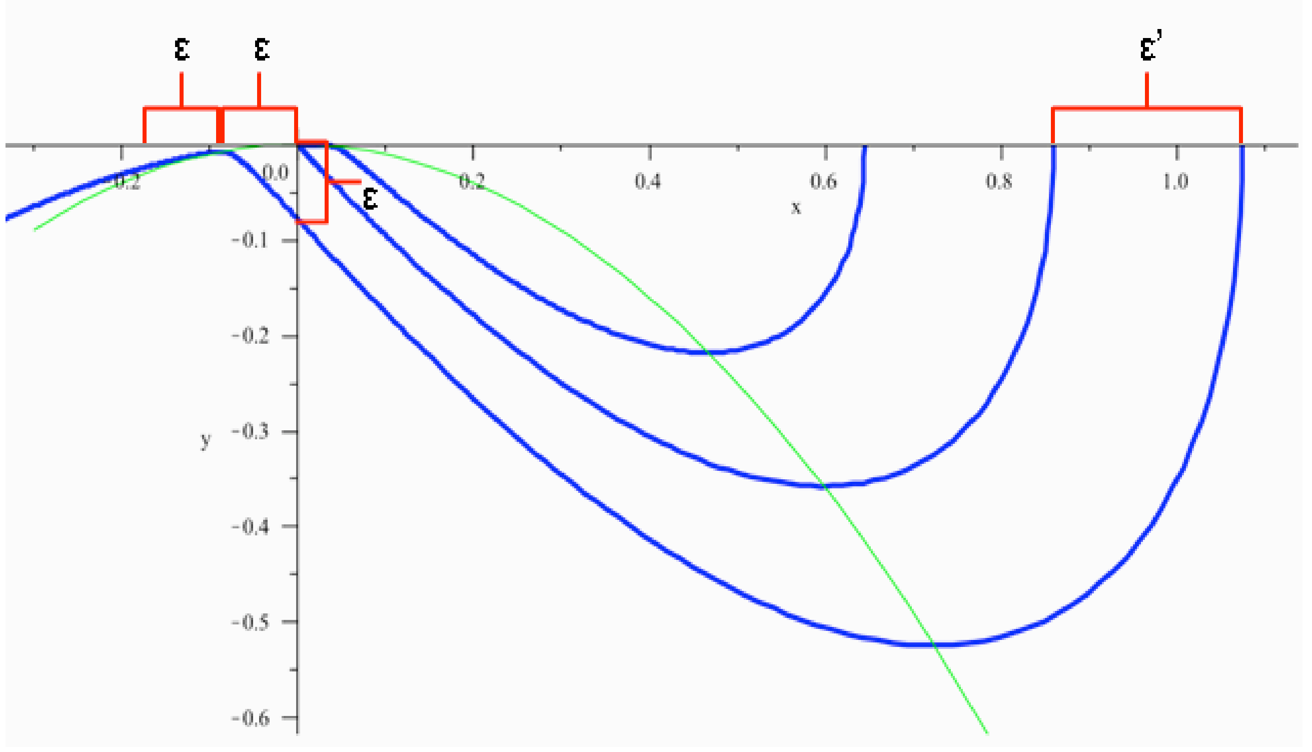

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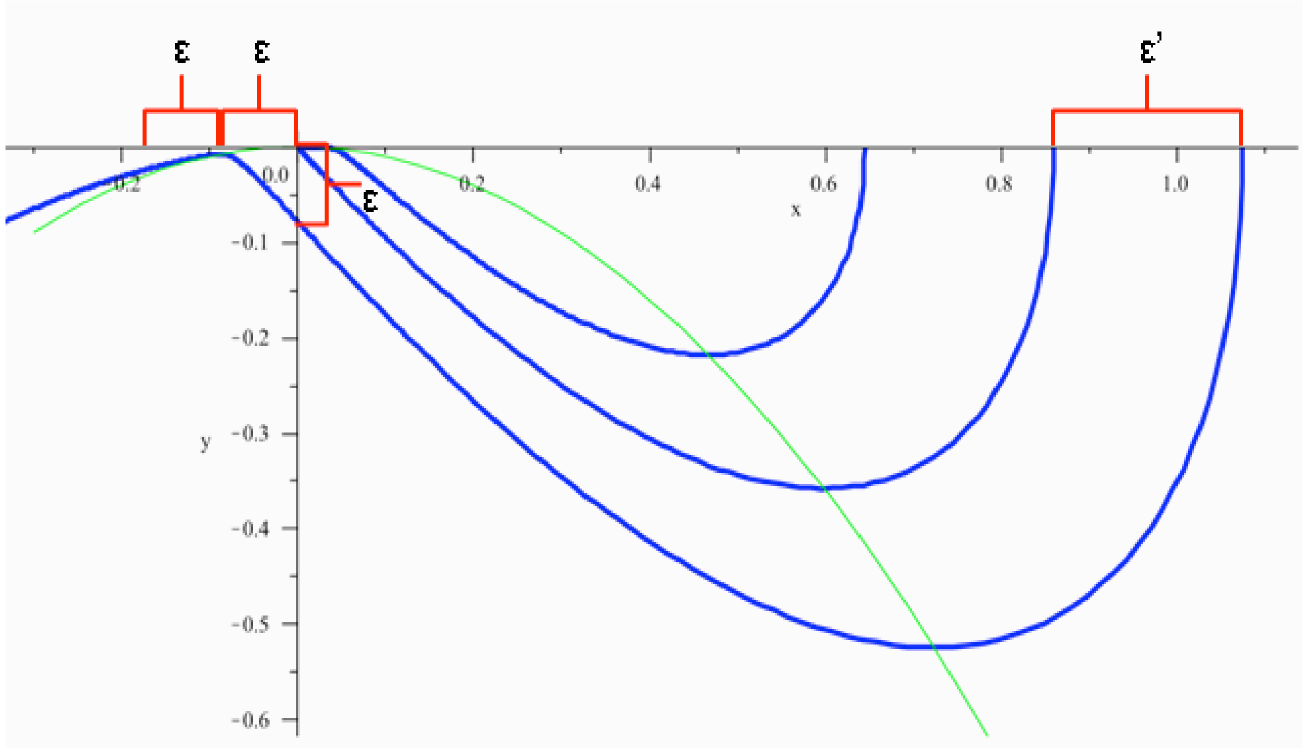

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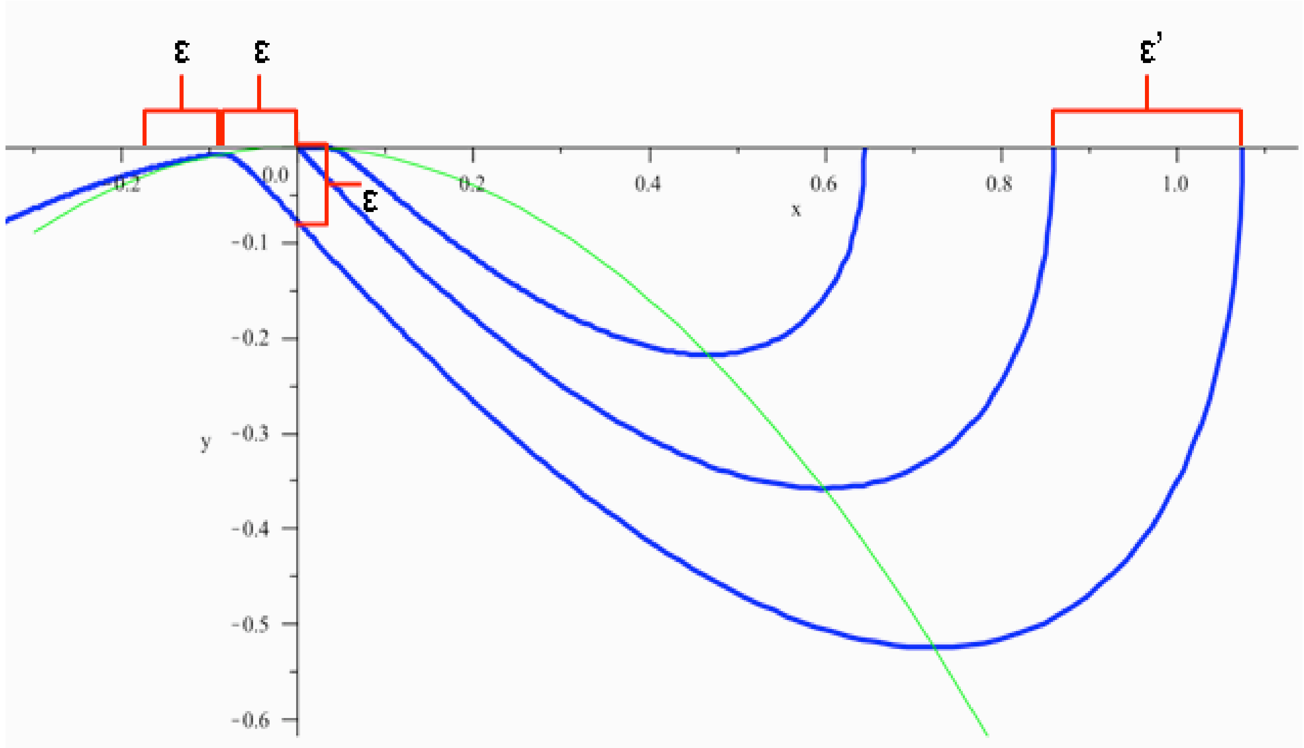

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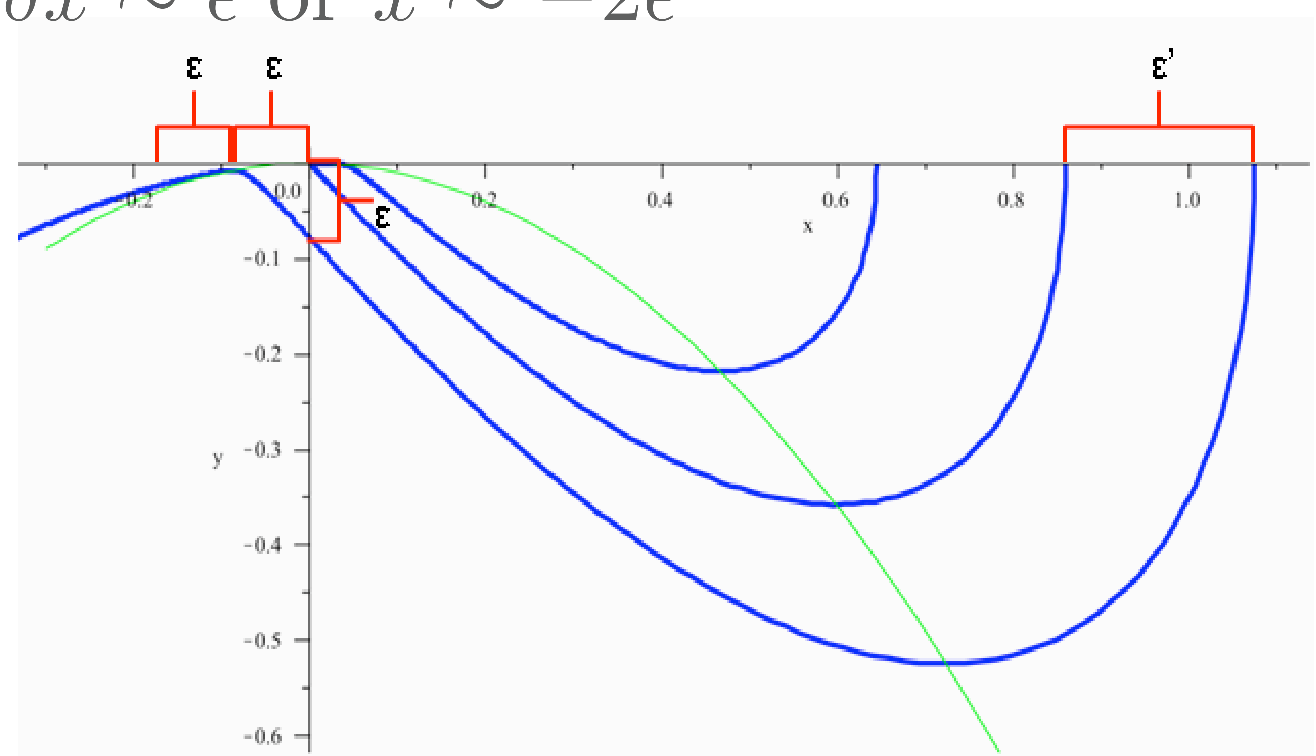

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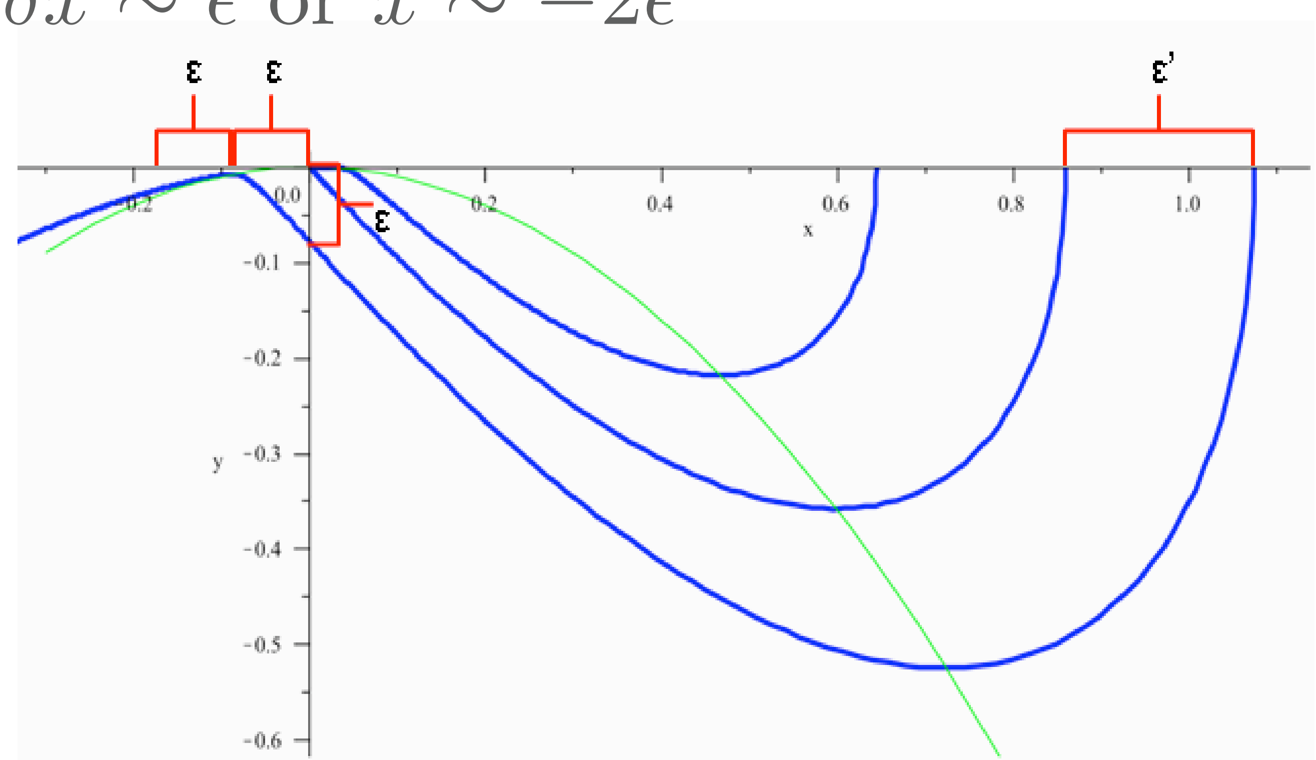

- The remaining missing link is the relation between ϵ' and ϵ. Since the equations are regular in this region the relation between them is linear:

$$\epsilon' \propto \epsilon$$

Proof for Critical Exponents

(Itzhaki, EDK, Cl.Qu.Gr. 2009)

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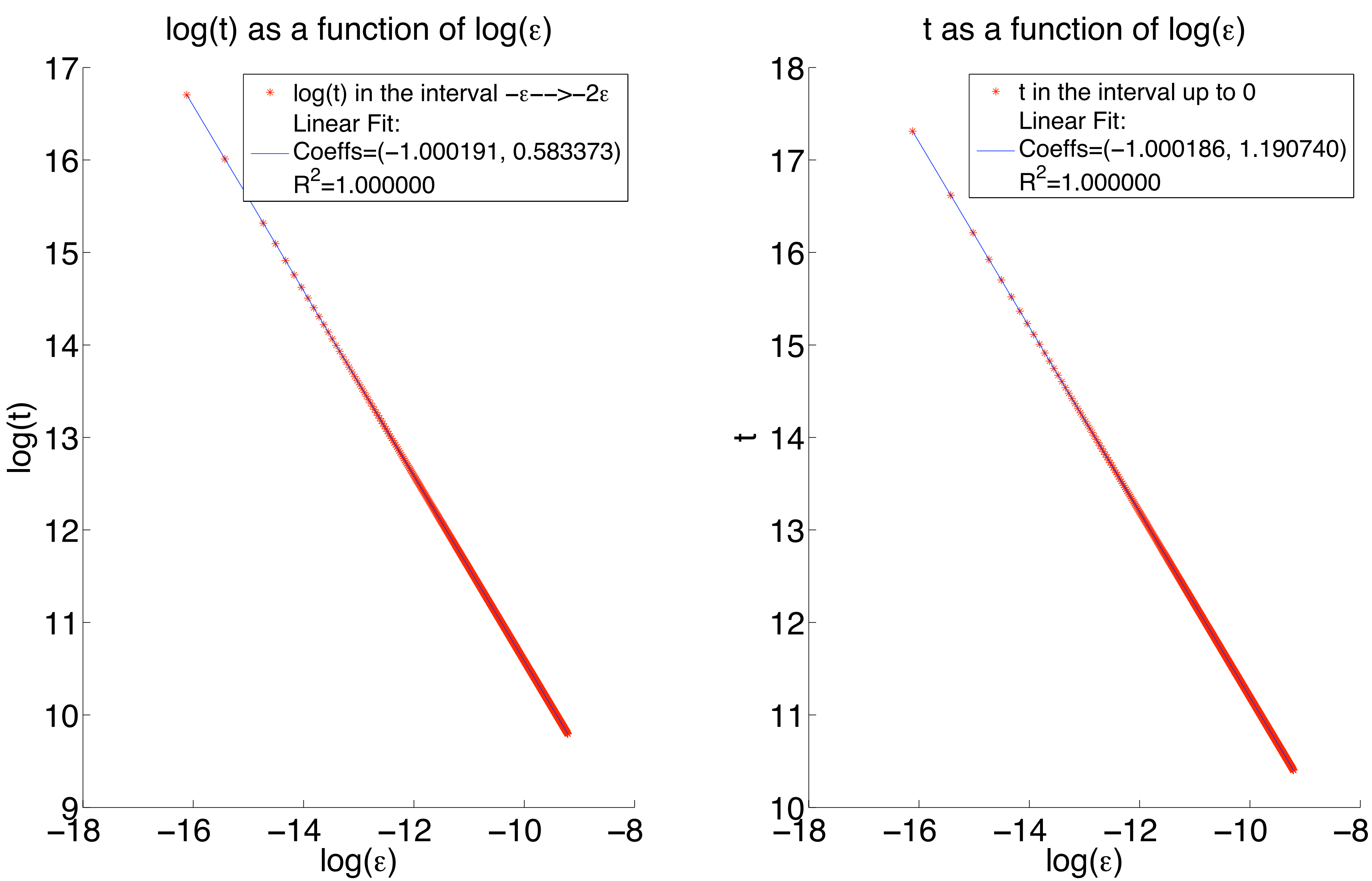

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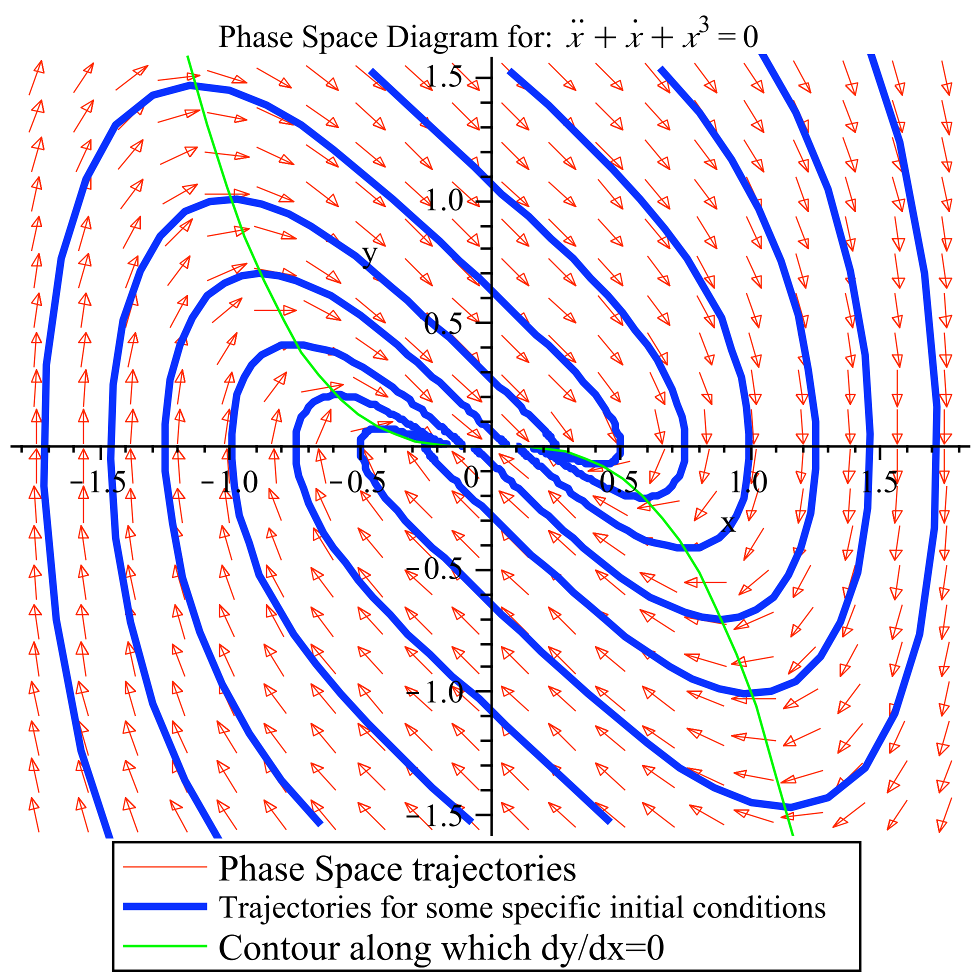

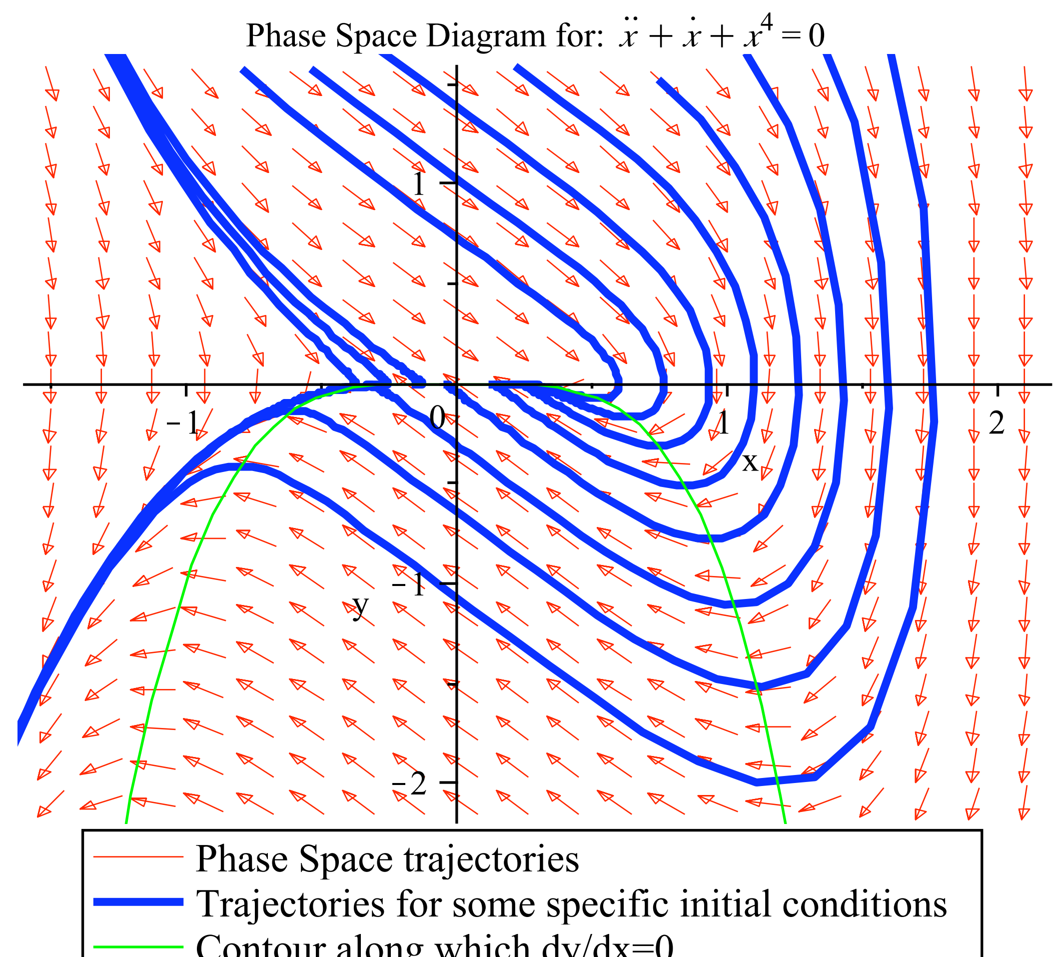

Phase Transition - Conclusions

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- Extension of this work (by Downes, Dutta & Sinha 2012) was used to demonstrate the likelihood in inflection point inflation is: $P(N_e|U) \sim 1/N_e^3$

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Before

Outline

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- Small/Large Field Phase Transition
- Understanding the Critical Behavior

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- Small/Large Field Phase Transition
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Before

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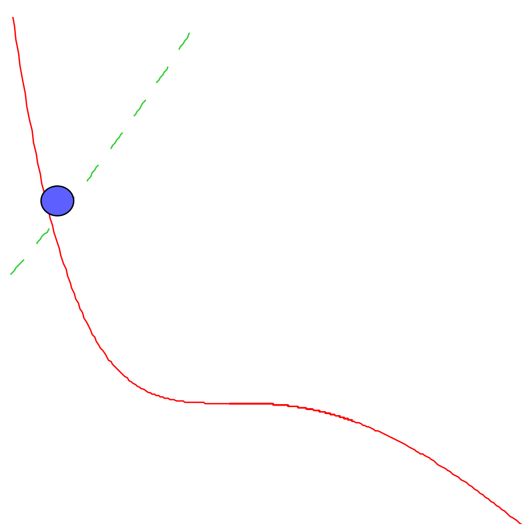

(a)

- Inflaton rolling

Solving the Overshoot Problem

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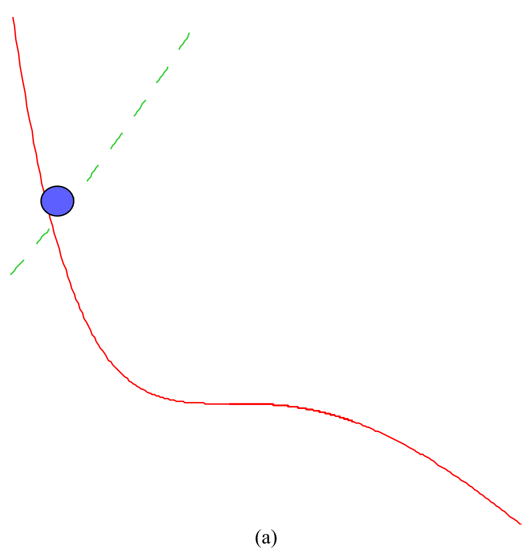

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Solving the Overshoot Problem

(Itzhaki, EDK, JHEP 2007)

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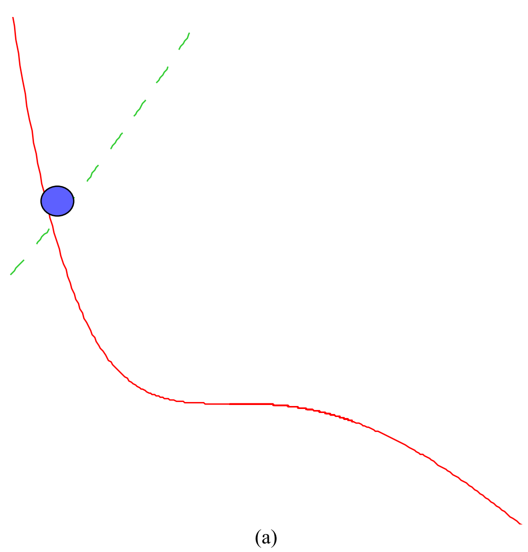

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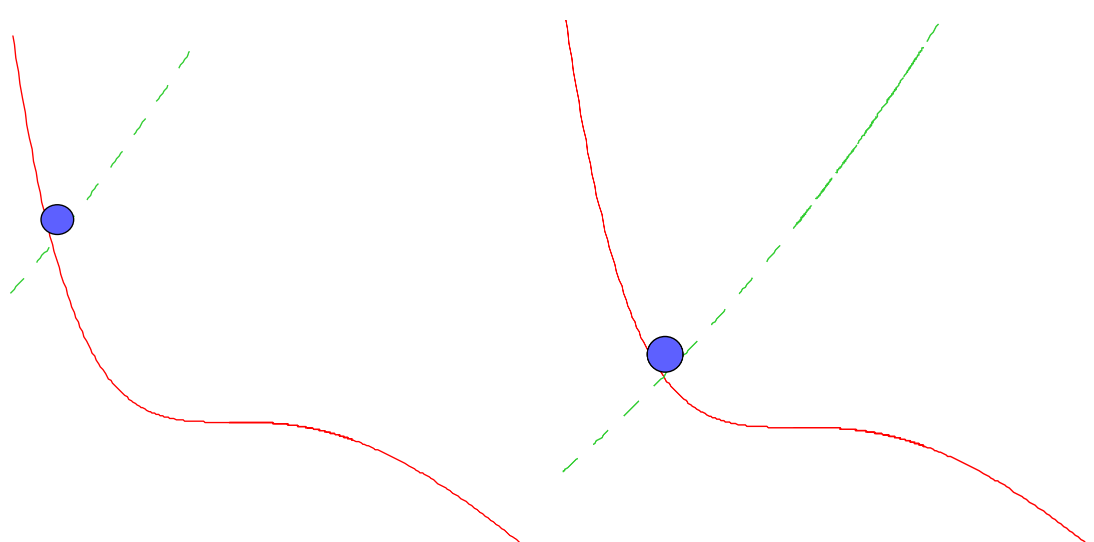

(a) (b)

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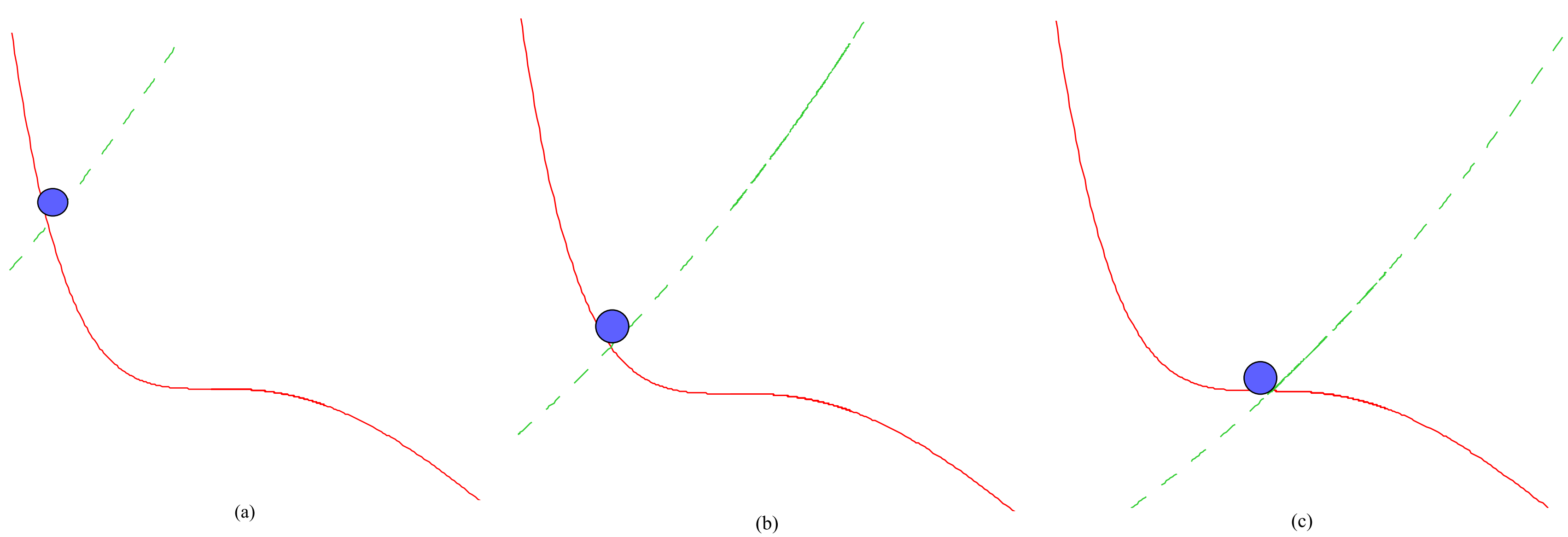

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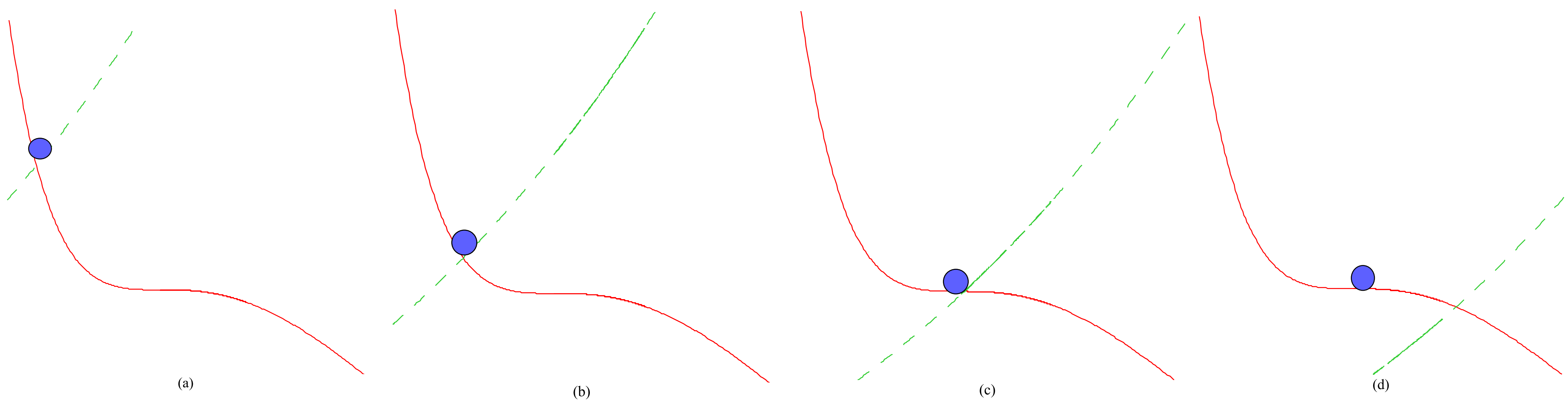

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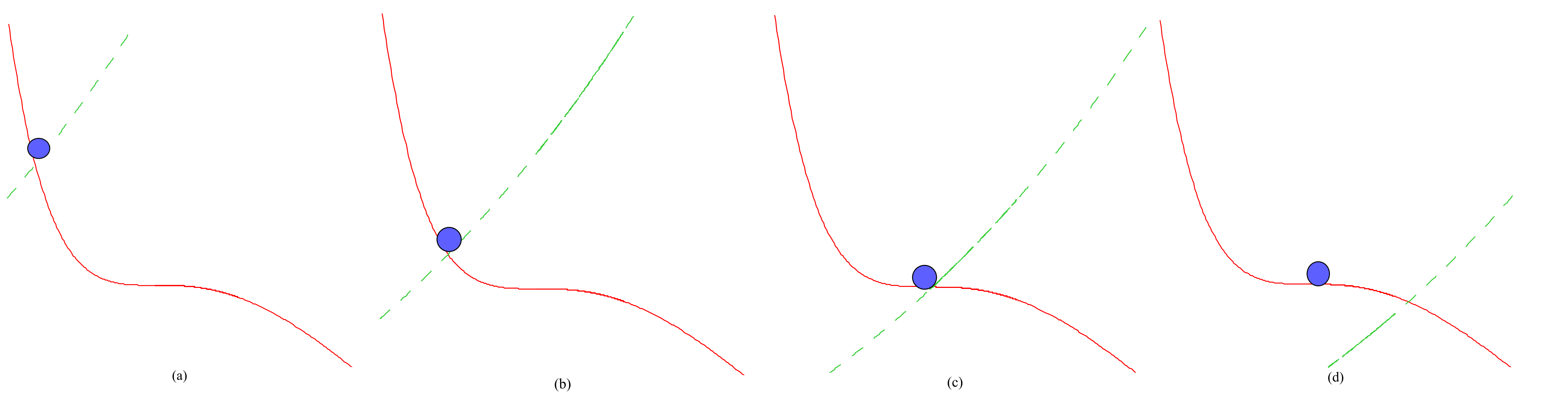

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- Sounds good! Inflation occurs in the first place thanks to the PIP(s), a small field model suffices, inflation is hence short (and the CMB quadrupole (oct?) is low!)

Phase Transition in Initial Density

(Itzhaki, EDK, Cl.Qu.Gr. 2009)

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- Indeed, for different values of the inflection point, we find an initial density that is big enough to slow down the inflaton so that inflation occurs.

$L_{inflection} \backslash n_0$	$1.5e-05$	0.000315	0.00081	0.00541	0.099035
2	0.46215	0.46474	0.46909	0.51401	51130.0048
5	0.42172	0.45187	0.51436	41.6388	∞
8	0.42516	0.89218	44.8478	∞	∞
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- In addition, we also see scaling behavior as the critical n_c is approached, again with an integer critical exponent of -1.

Outline

After

Outline

- Pre-Inflationary Particle - Signatures

After

Pre-Inflationary Particle (PIP) - Model

(Fialkov, Itzhaki, EDK, JCAP 2010)

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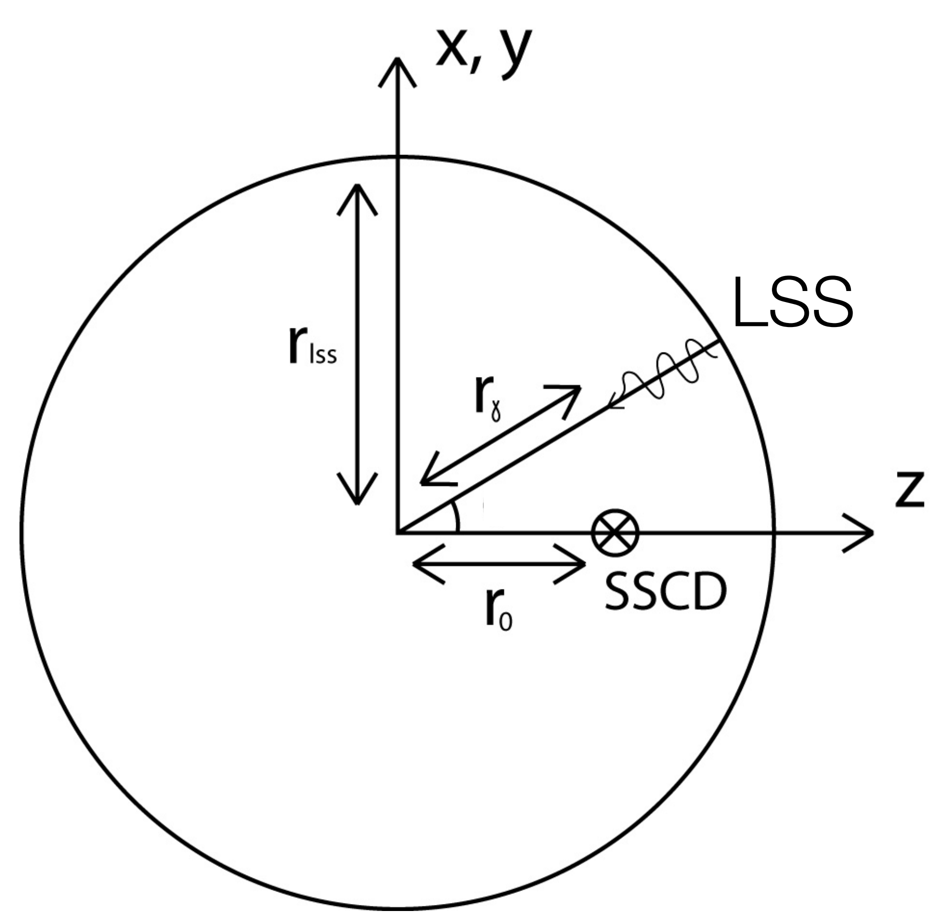

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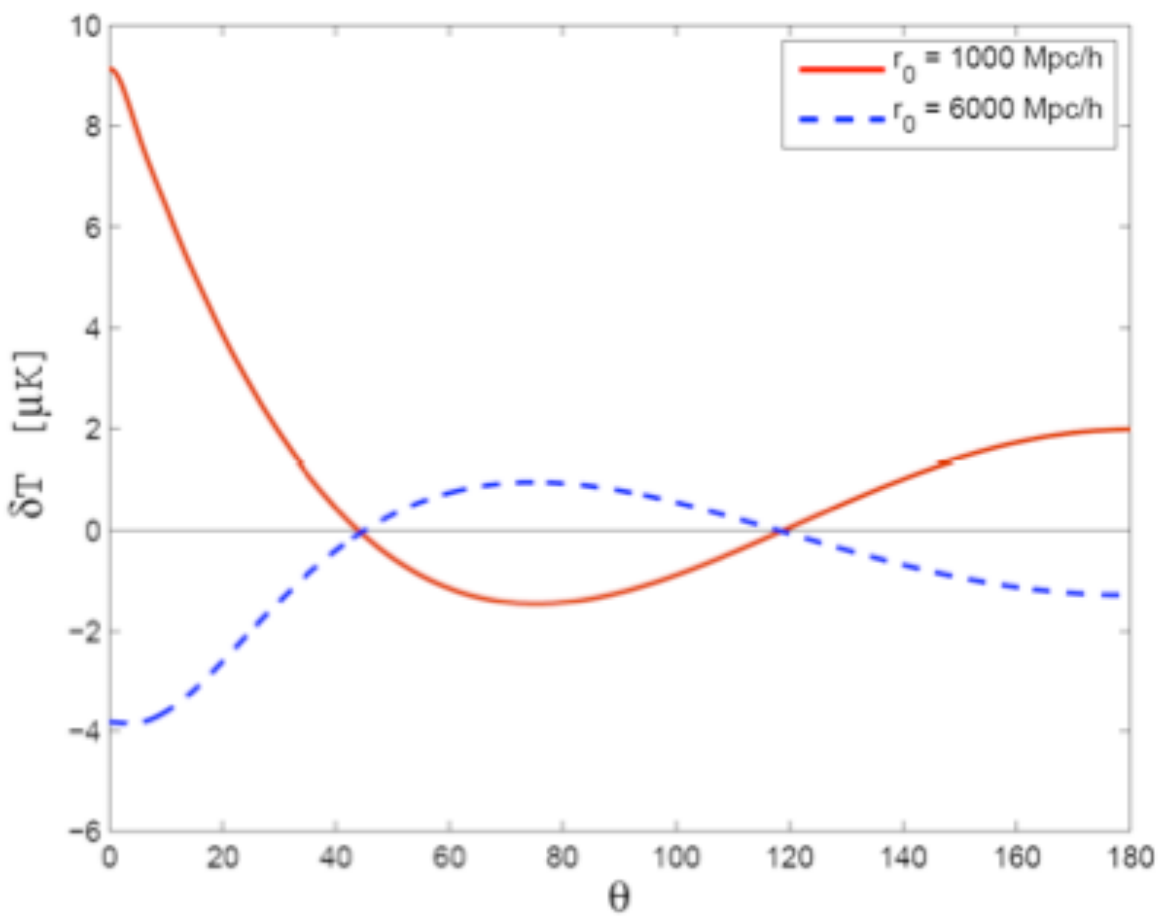

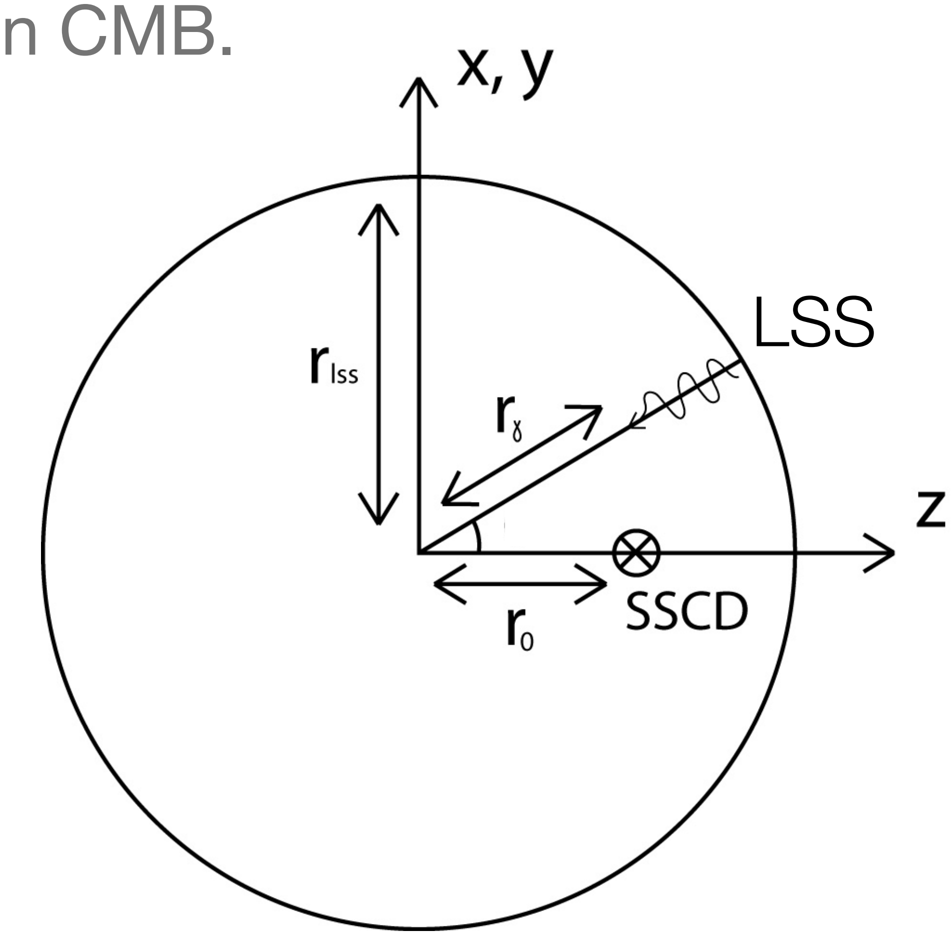

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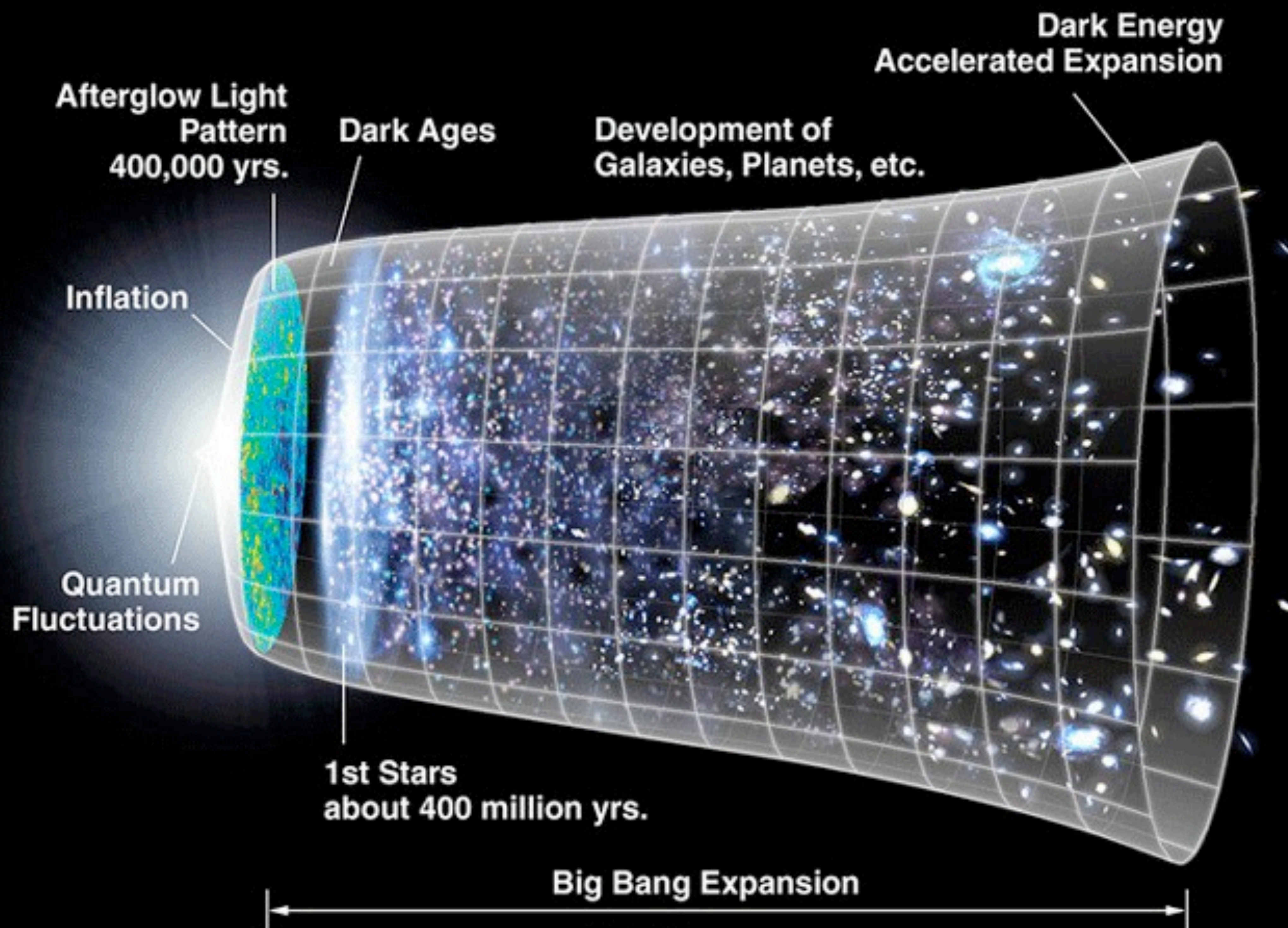
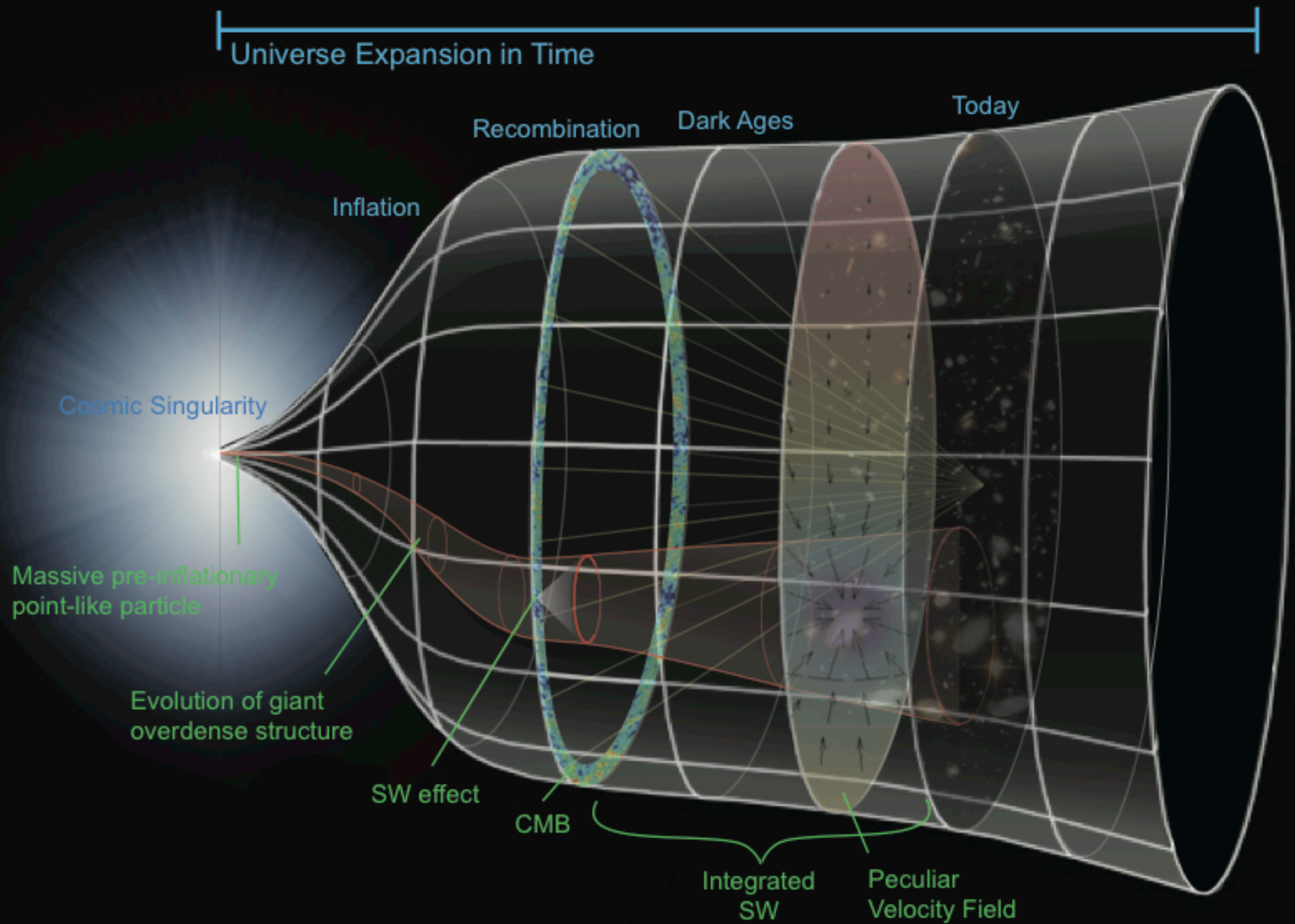


Image: NASA WMAP

ΛCDM + Pre-Inflationary Particle (PIP)



Outline

After

Outline

- Pre-Inflationary Particle - Signatures
- Where to look, what to look for?

After

Where to look? Large Scales

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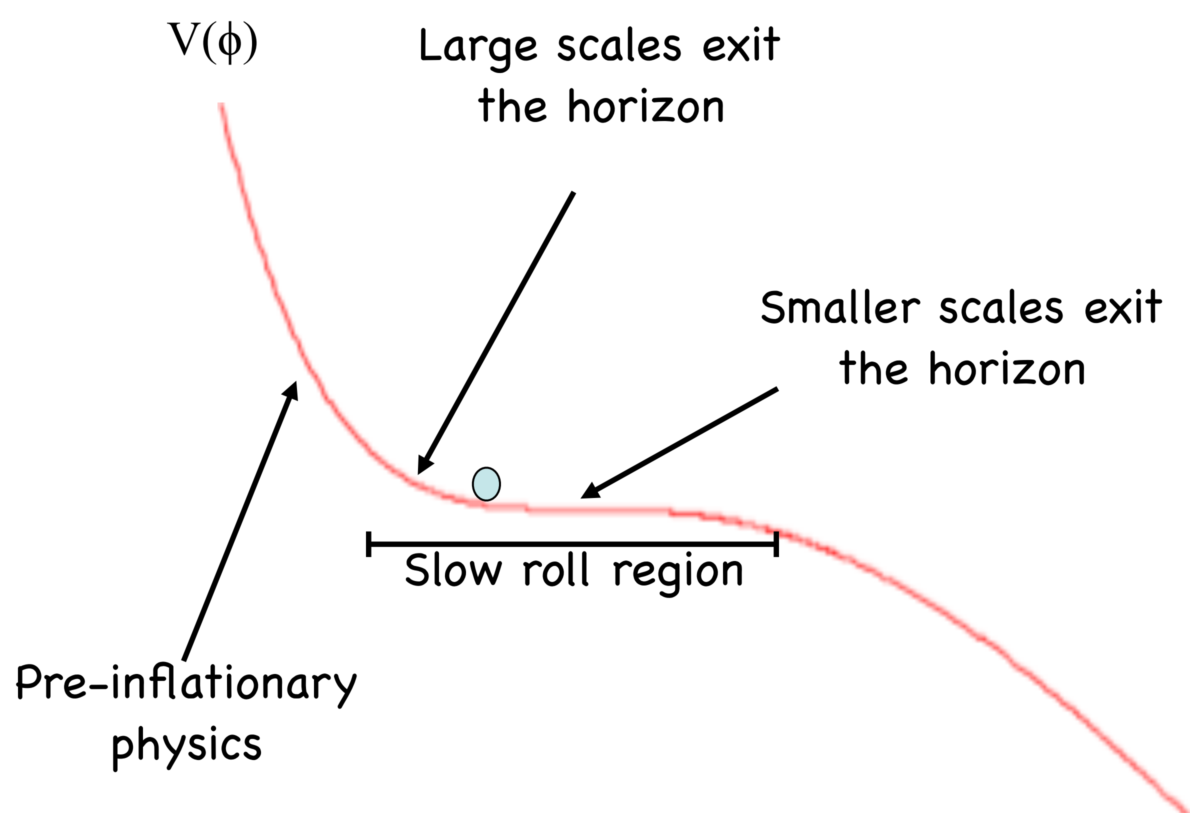

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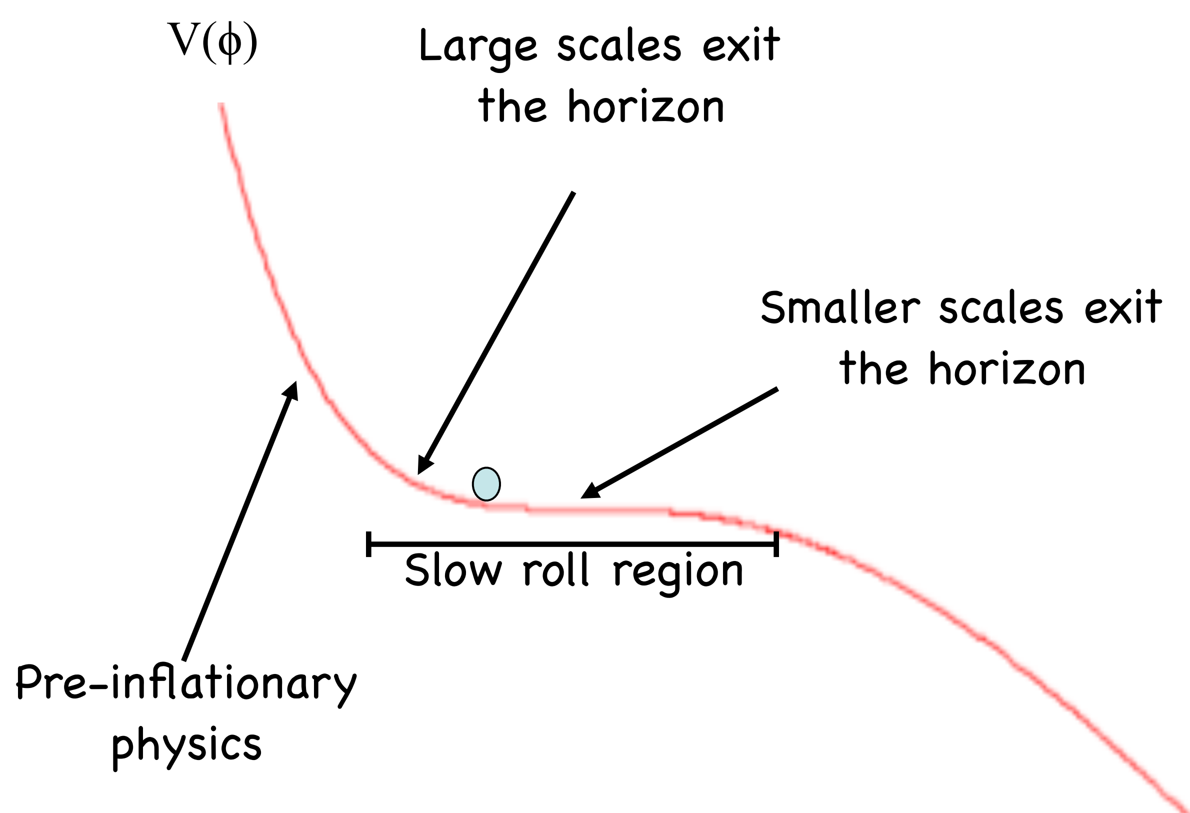

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- Logarithmic gravitational potential $\longrightarrow$ long-range effect.

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  - Test: Bulk flow (towards this “great attractor”)!

Outline

After

- Observational Tests: CMB Rings

Outline

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- Pre-Inflationary Particle - Signatures
- Where to look, what to look for?
- Observational Tests: CMB Rings

After

Rings Score - Definition

(EDK, Ben-David and Itzhaki, ApJ 2010)

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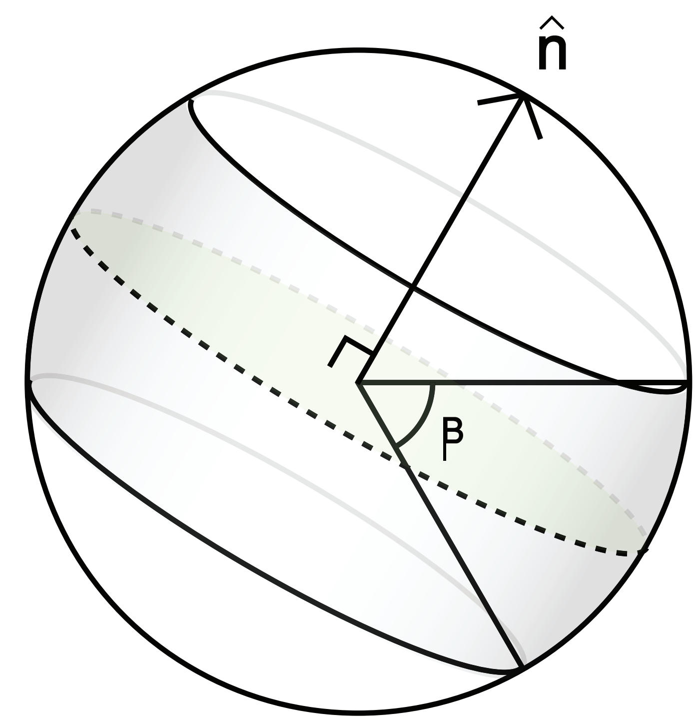

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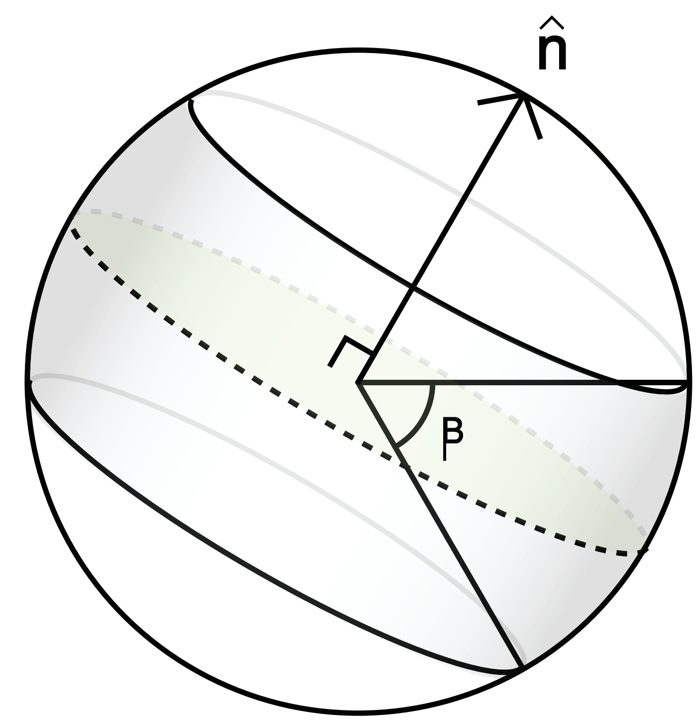

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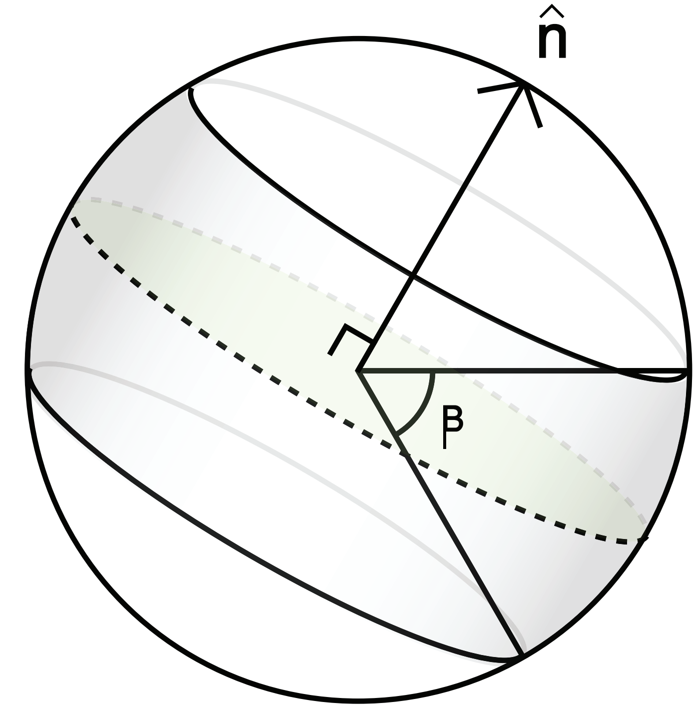

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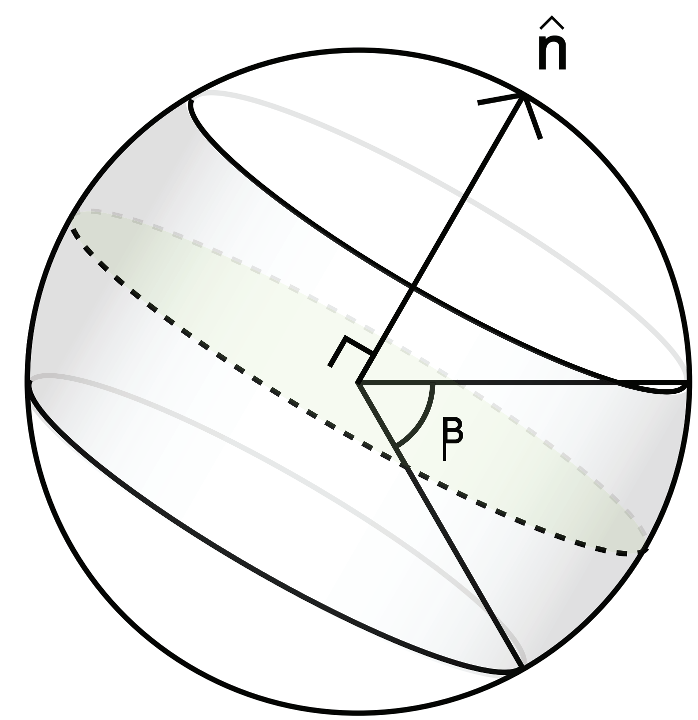

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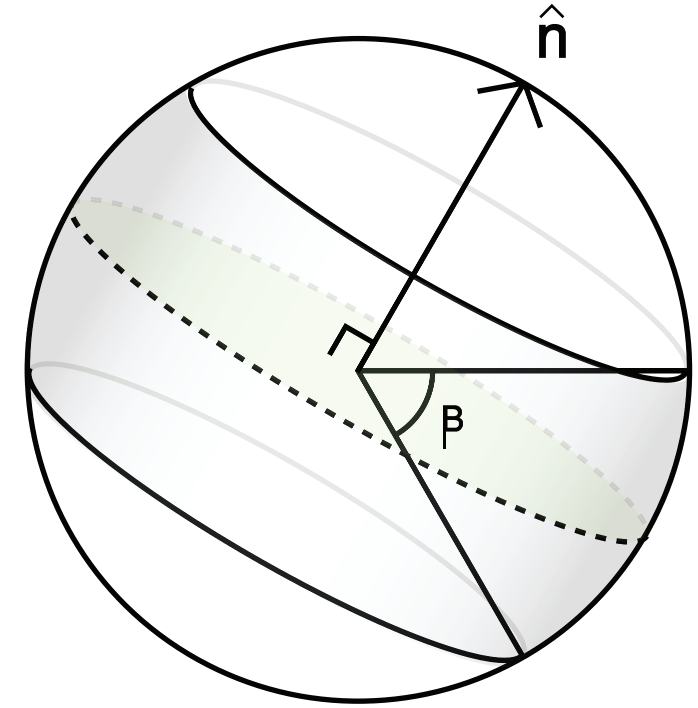

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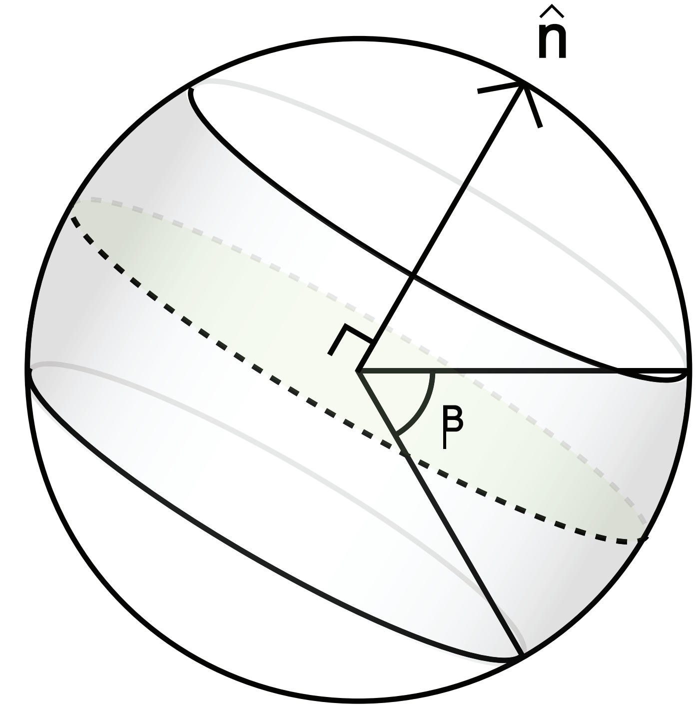
- T_0 = mean of the total map
- Calculate the following:

$$R(\beta, \hat{n}) = \int_{\frac{\pi-\beta}{2}}^{\frac{\pi+\beta}{2}} d(\cos\theta)\ \tilde{T}^2(\theta, \hat{n}),$$

$$\tilde{T}(\theta, \hat{n}) = T(\theta, \hat{n}) - T_0$$



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(EDK, Ben-David and Itzhaki, ApJ 2010)

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Our findings for WMAP7 ILC masked with KQ75:

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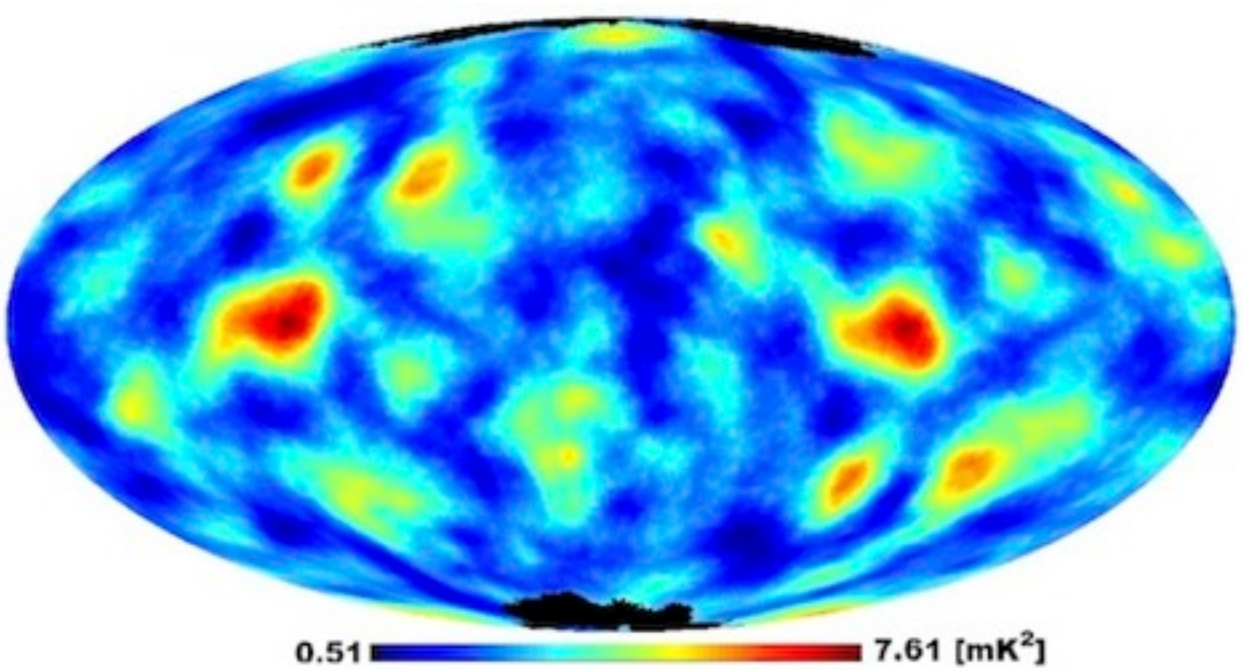

$$\beta = 90^\circ$$

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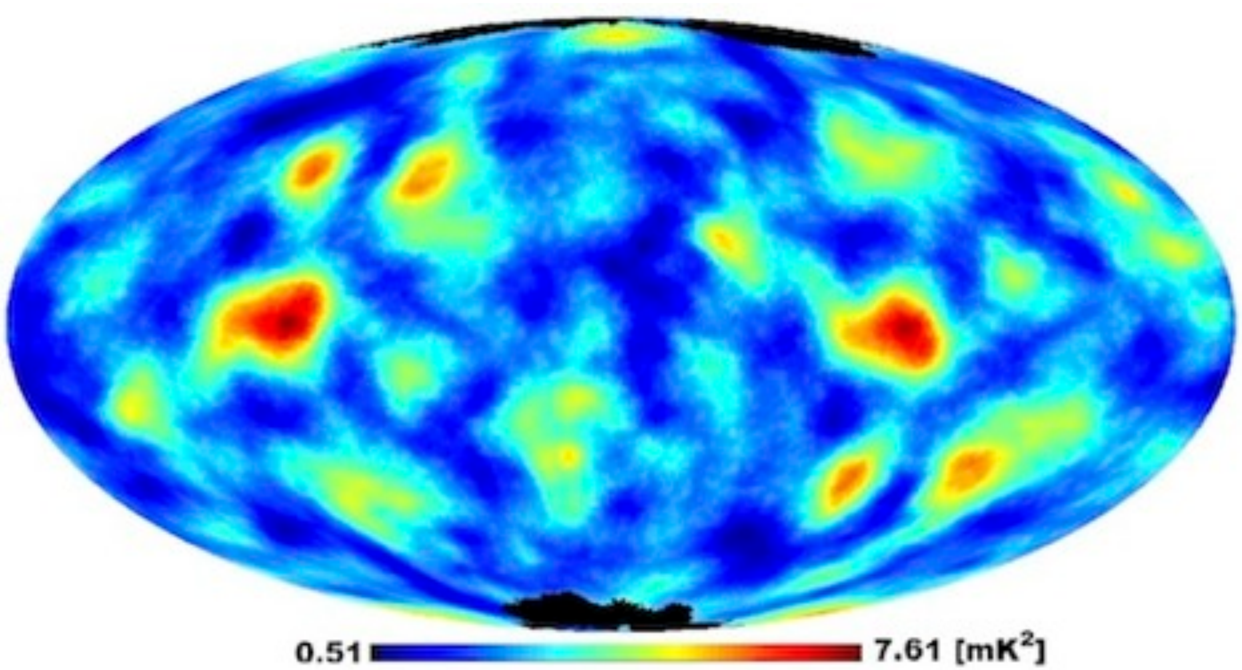

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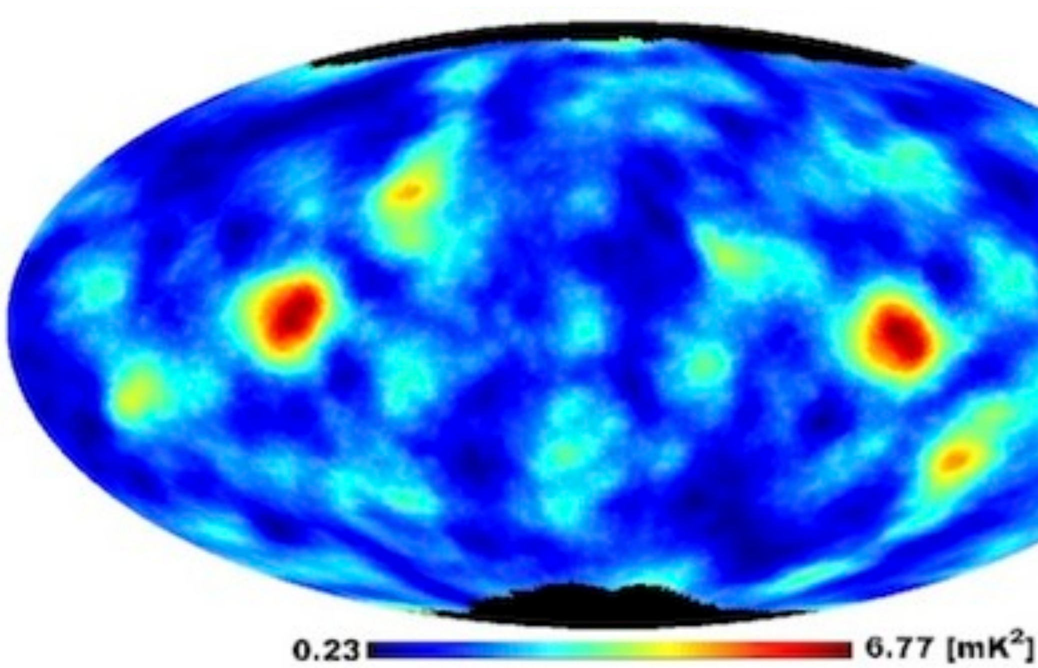

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Rings Score - Results

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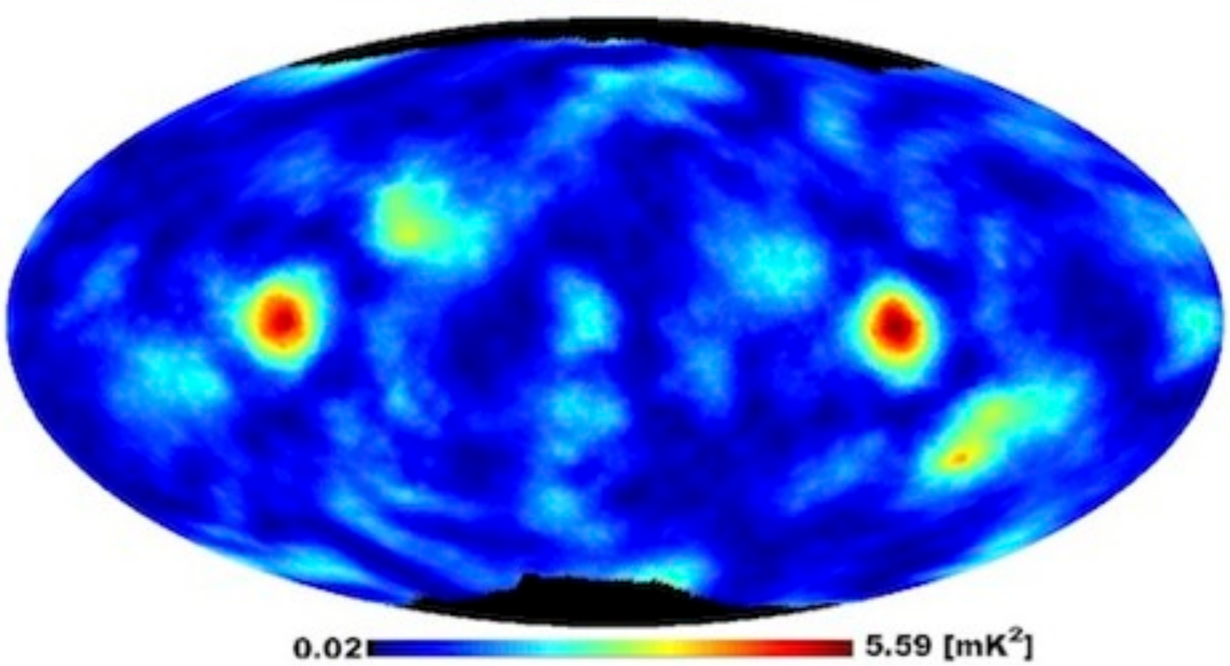

$$\beta = 30^\circ$$

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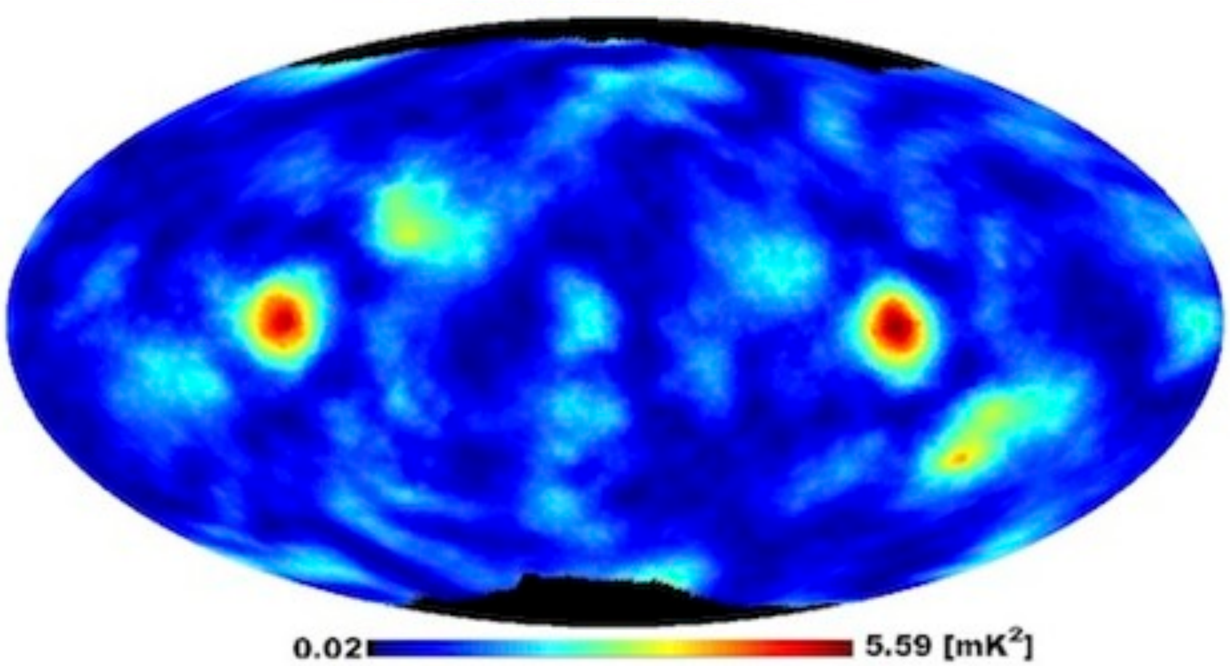

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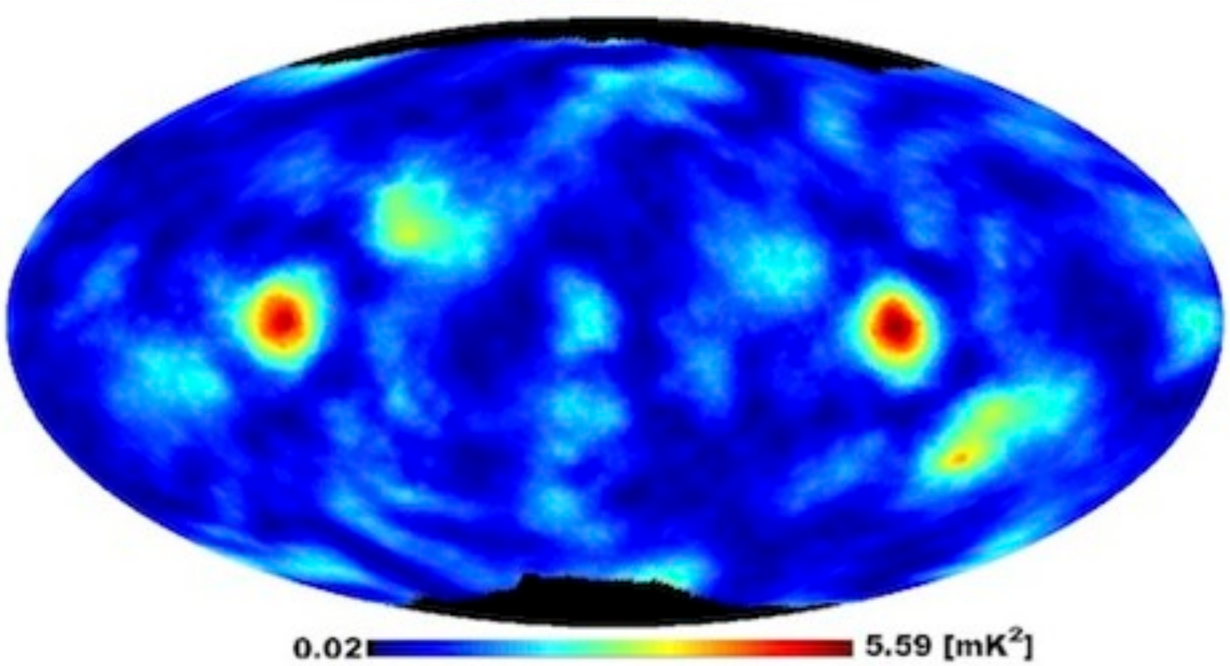

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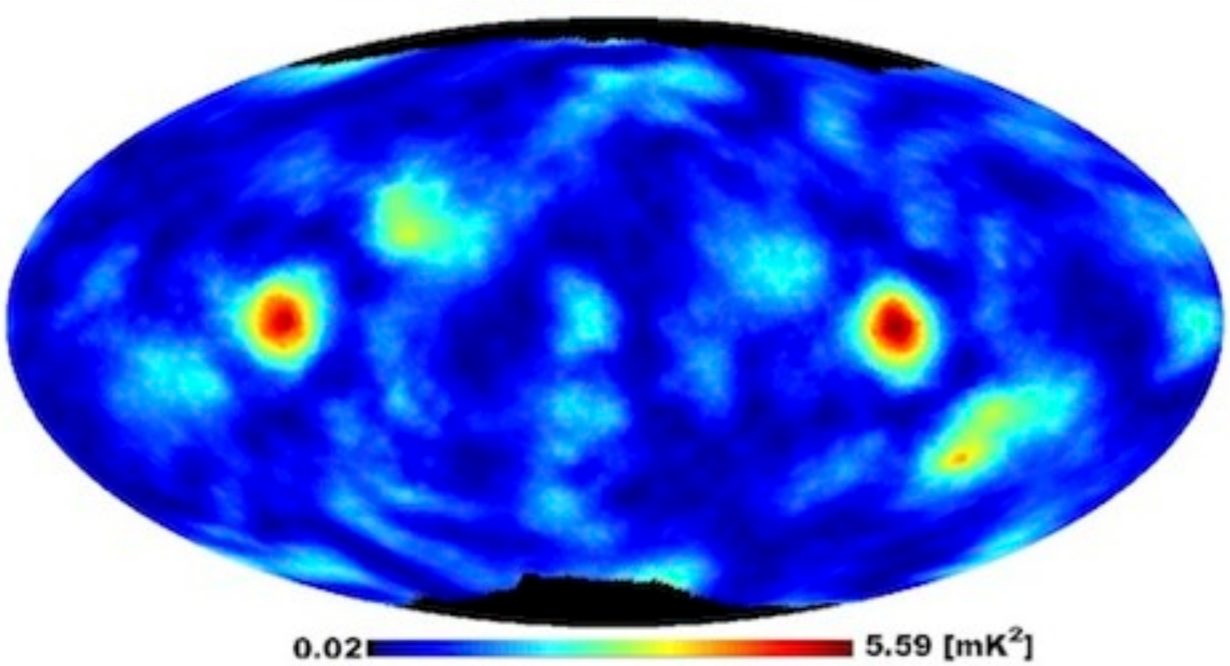

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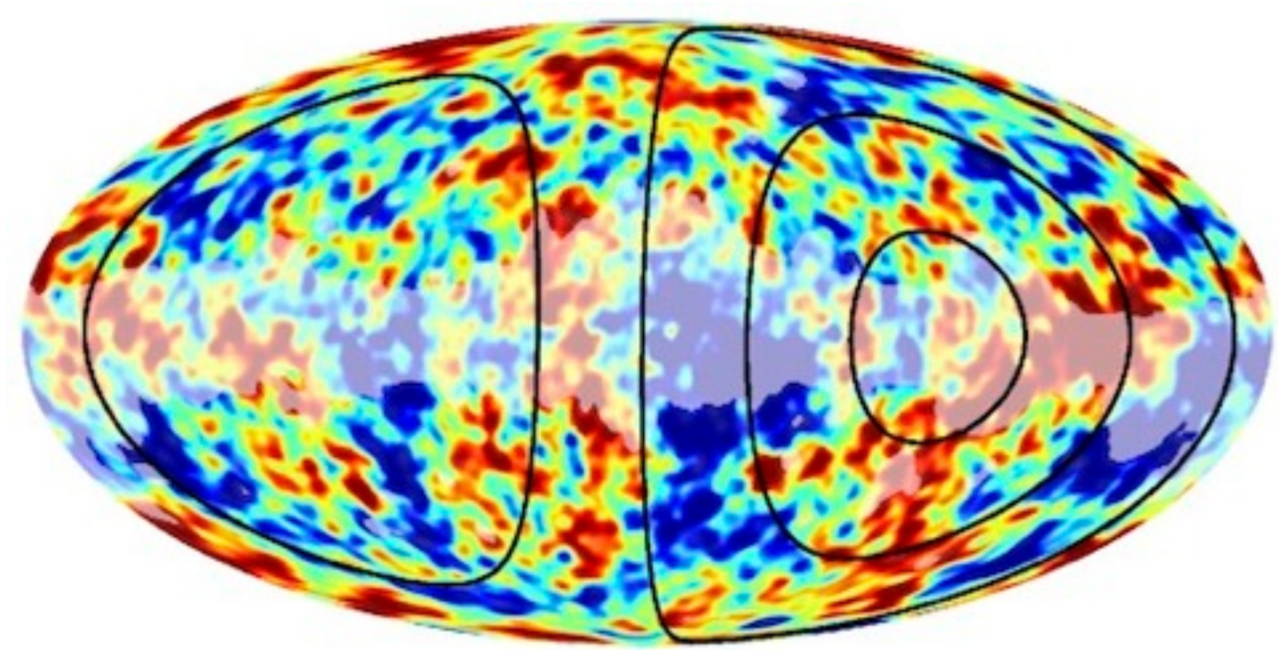
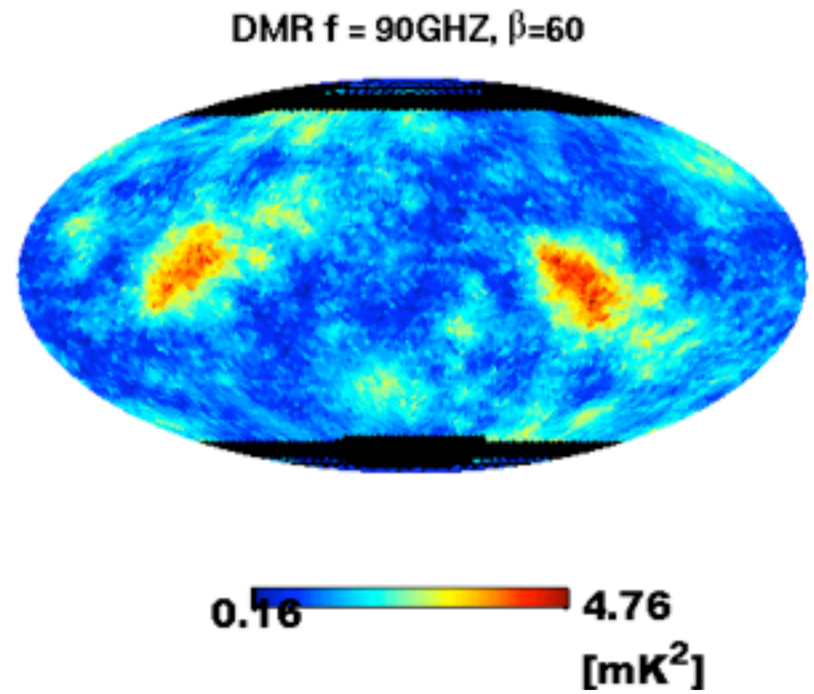
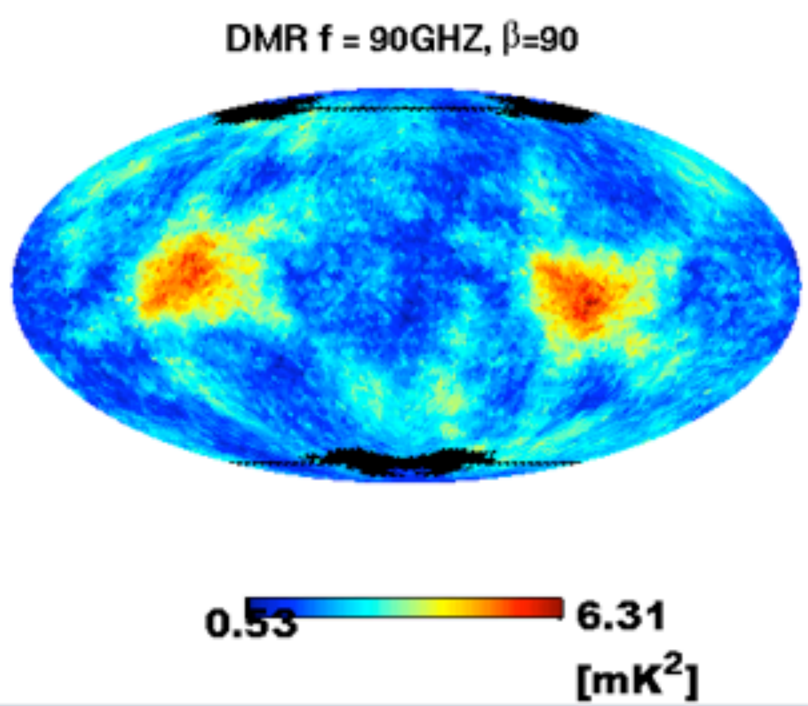


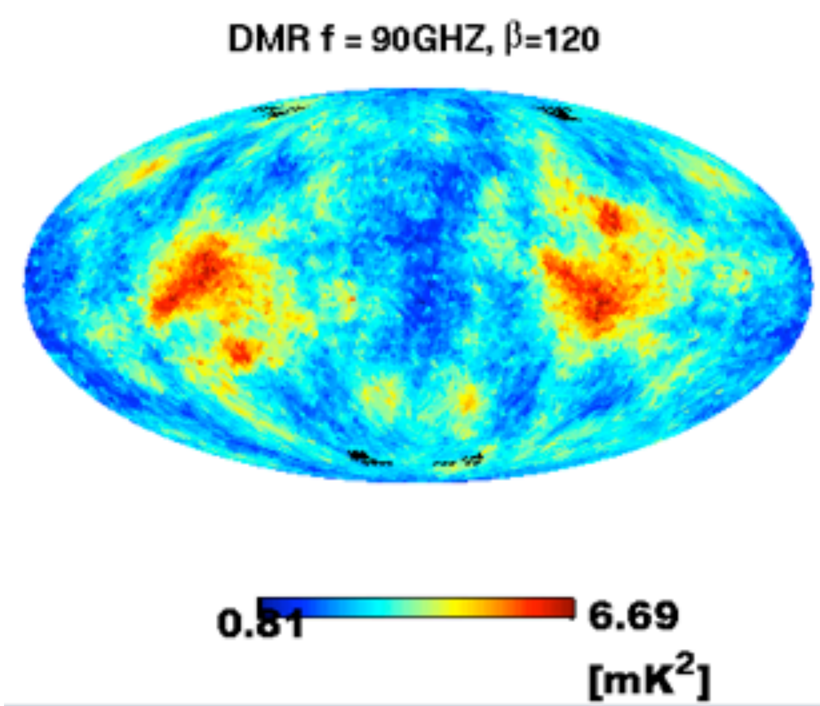
Rings in 7-year ILC map

Rings Score - COBE-DMR

Low Resolution...







Outline

After

- Observational Tests: CMB Rings,

Outline

- Pre-Inflationary Particle - Signatures
- Where to look, what to look for?
- Observational Tests: CMB Rings, Bulk Flow

After

Bulk Flow - Direction

(EDK, Ben-David and Itzhaki, ApJ 2010)

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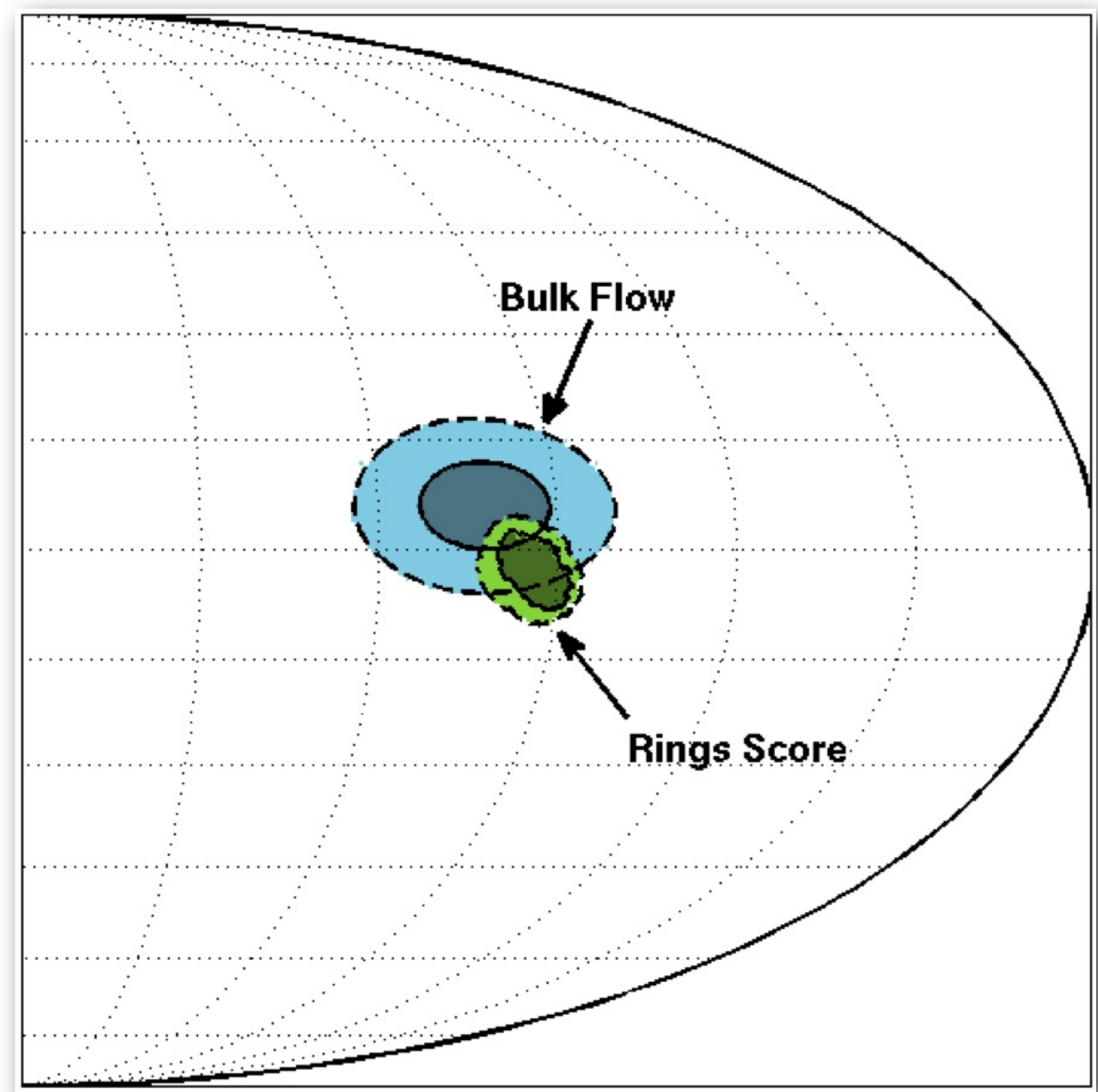

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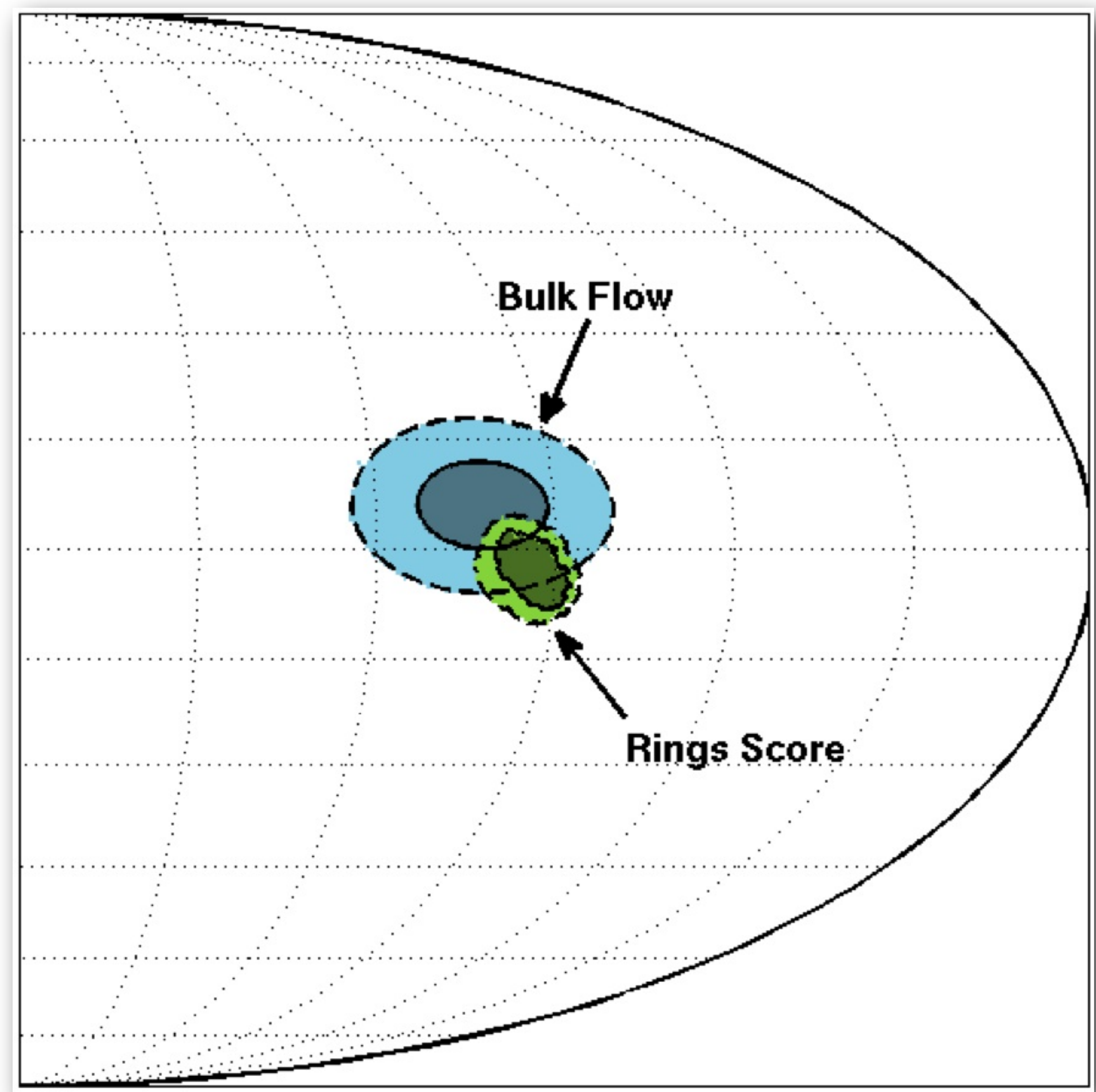
~1% chance alignment

with the center of the rings!



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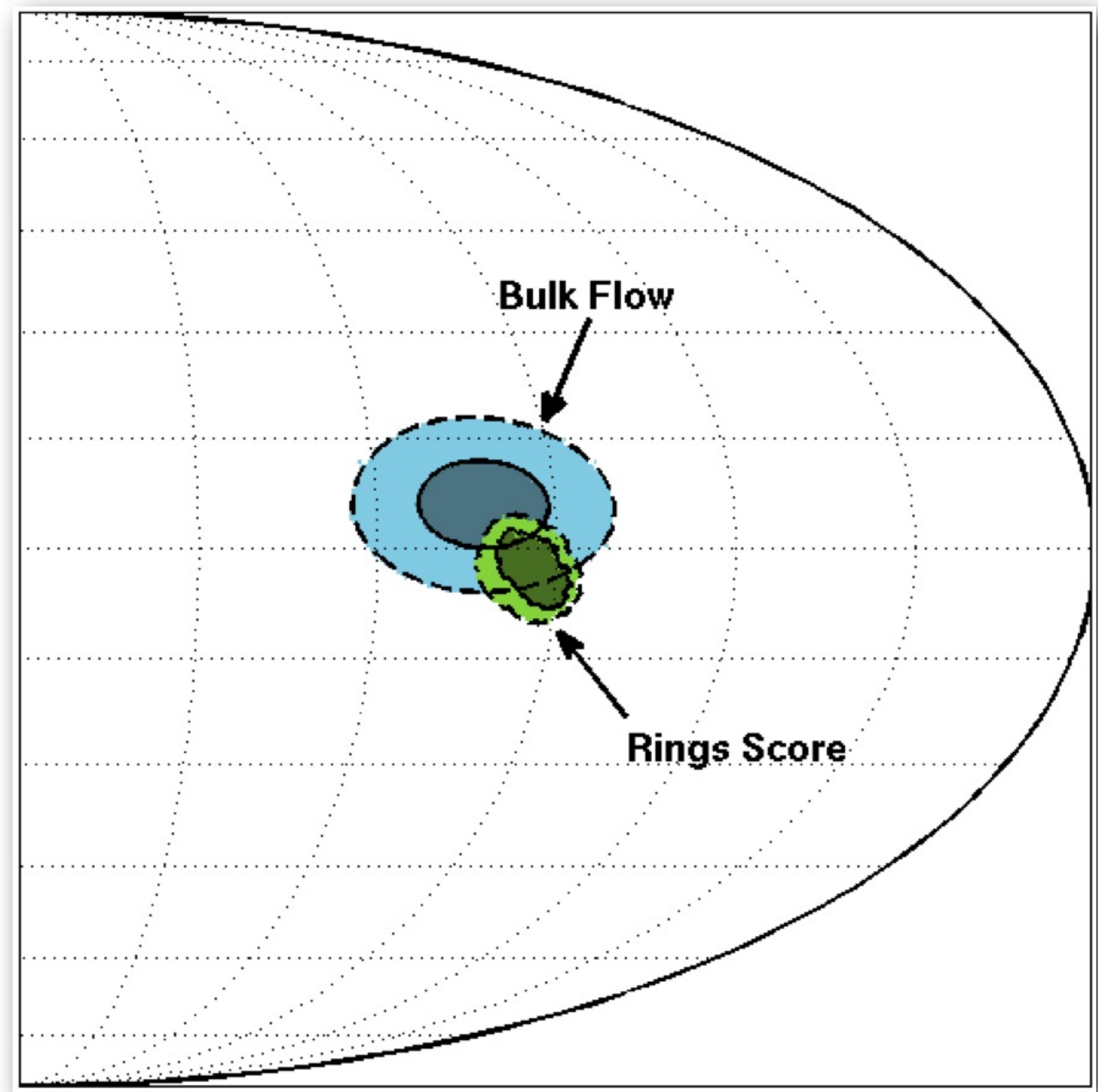

- What is the extent in z?

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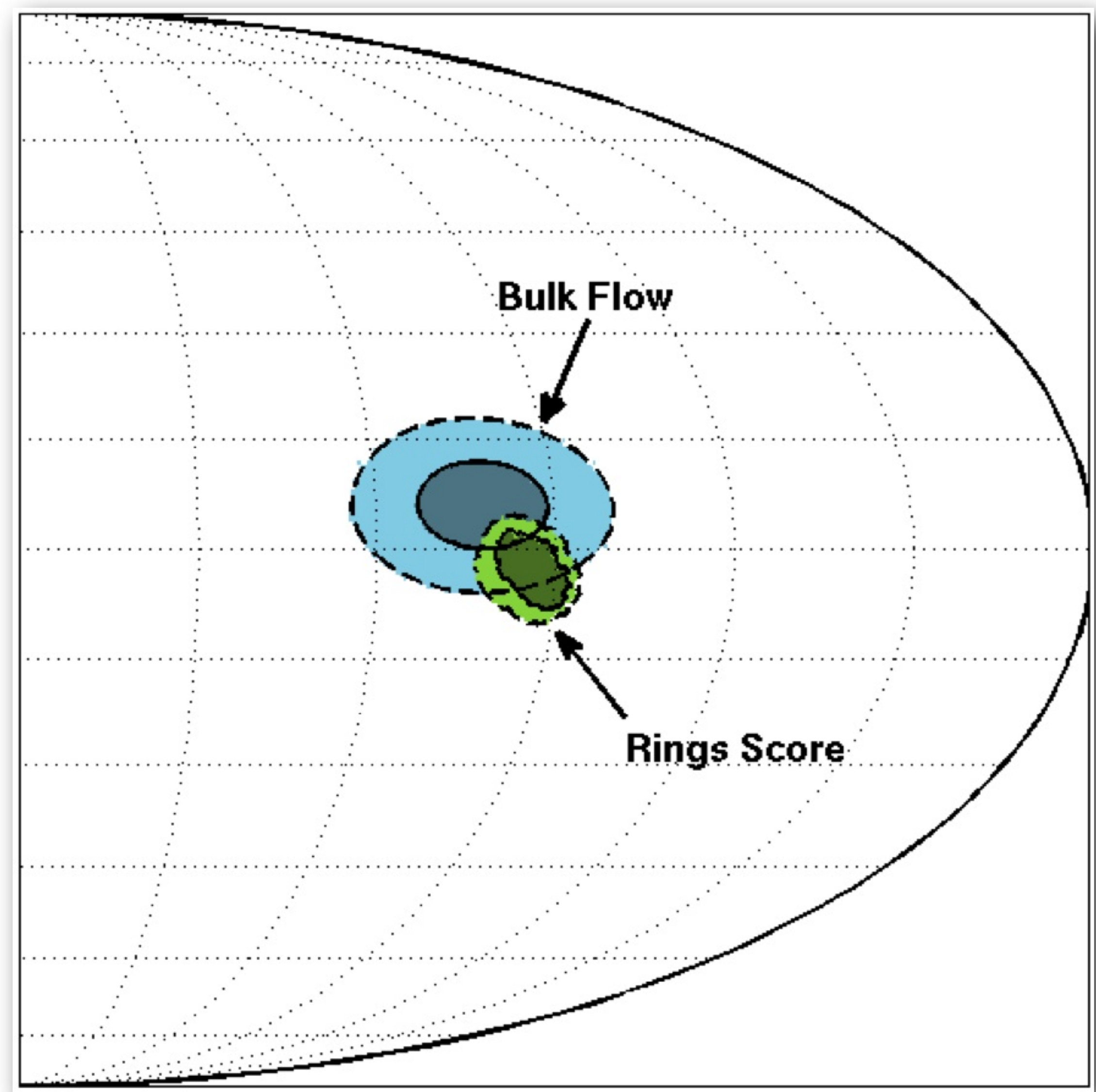

- What is the extent in z? *stay tuned*

Outline

After

- Observational Tests: CMB Rings, Bulk Flow, Mirror Parity.

Outline

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- Pre-Inflationary Particle - Signatures
- Where to look, what to look for?
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After

Parity - “S-Statistic”

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Parity - "S-Statistic"

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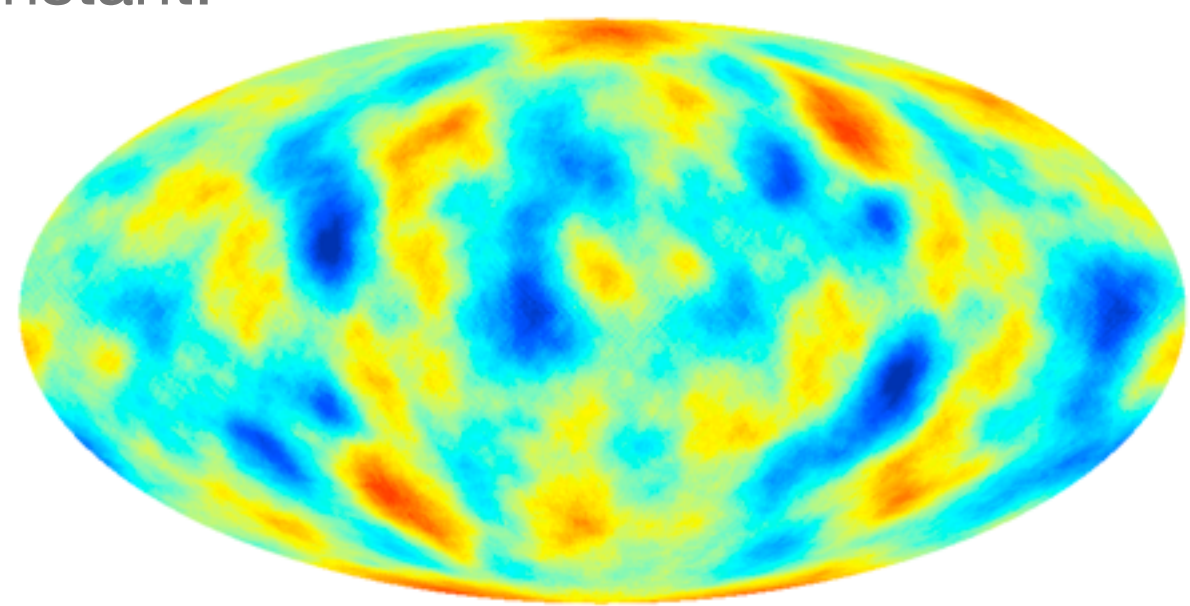

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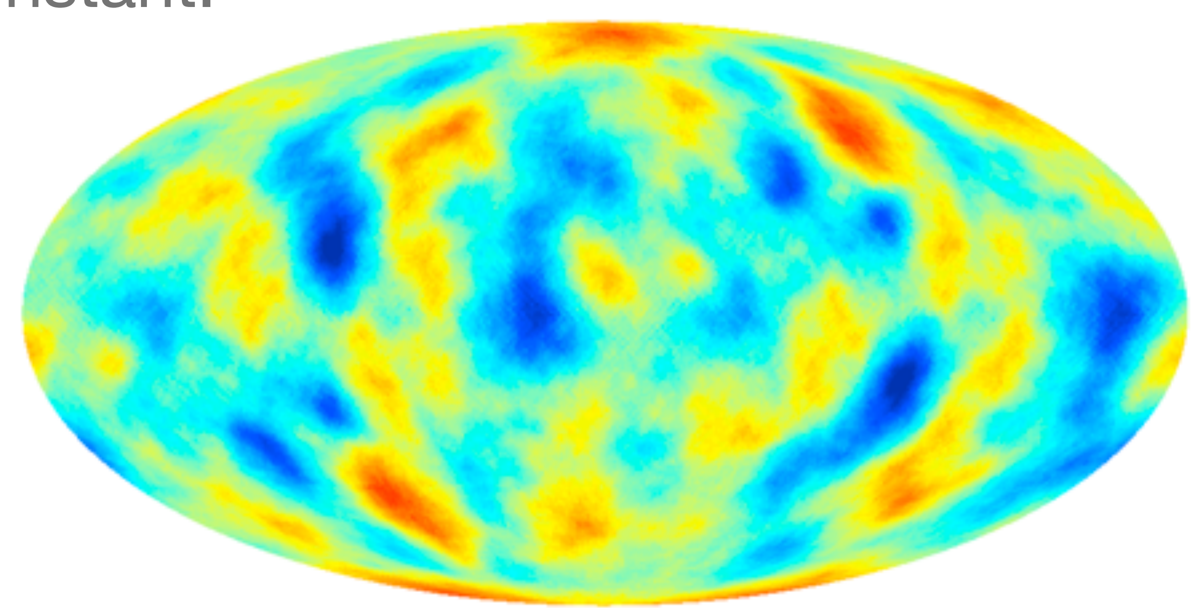

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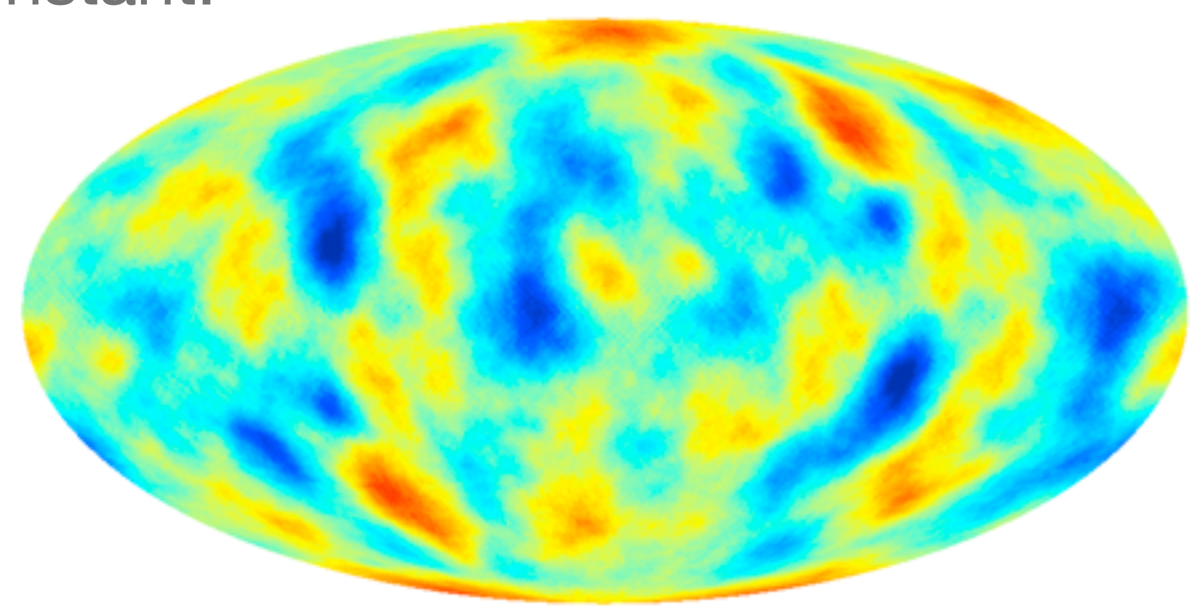

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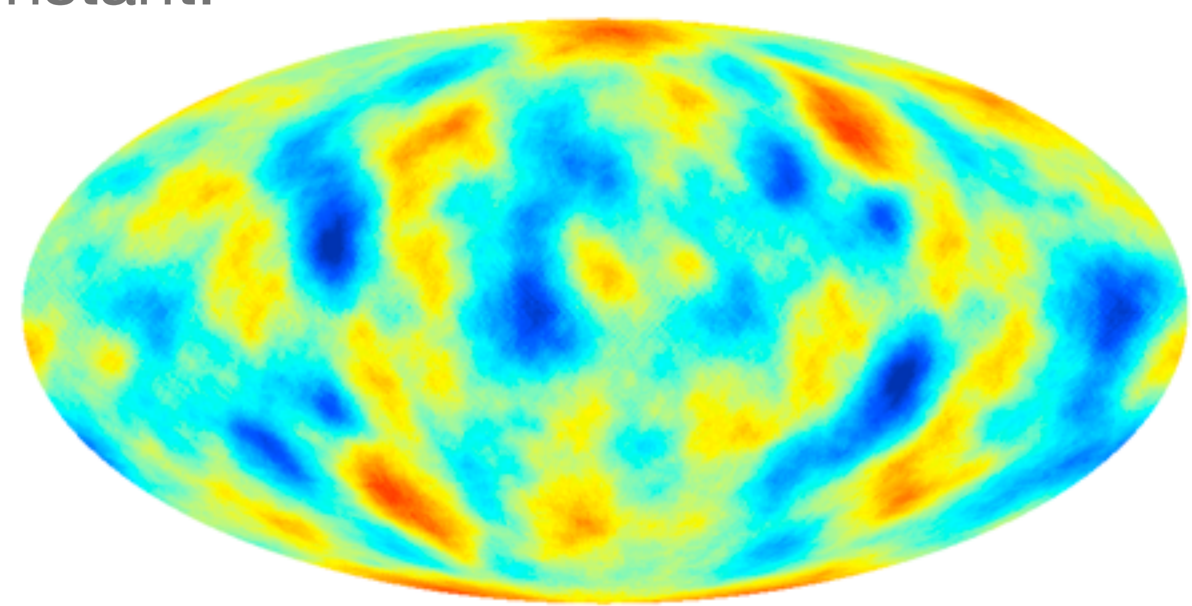

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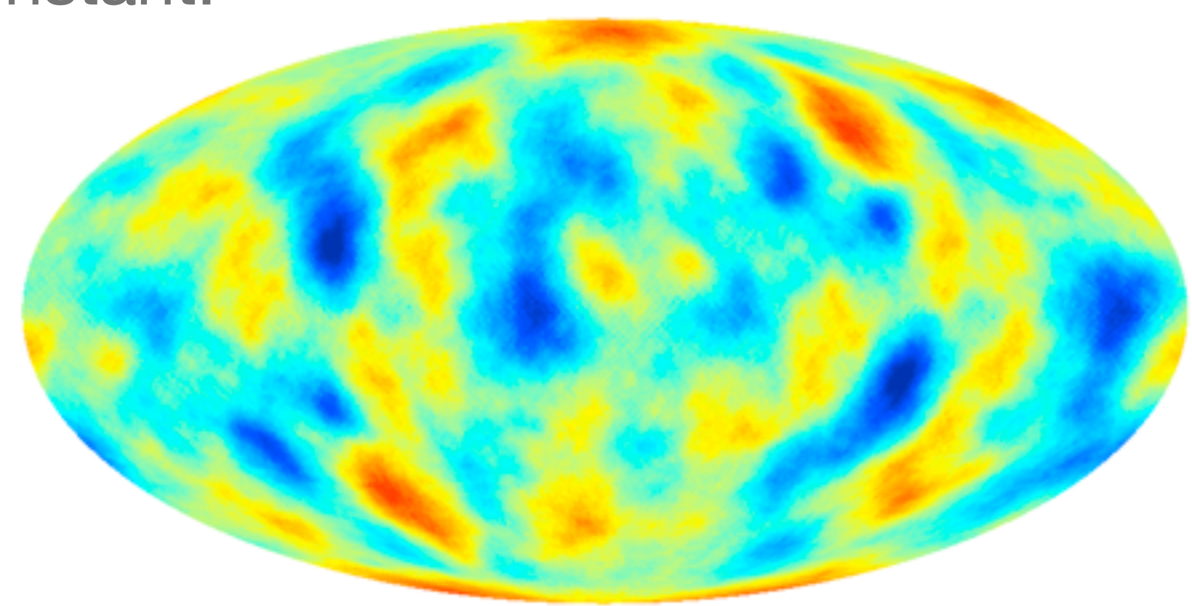

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Parity - Even/Odd Multipoles

(Ben-David, EDK and Itzhaki, ApJ 2012)

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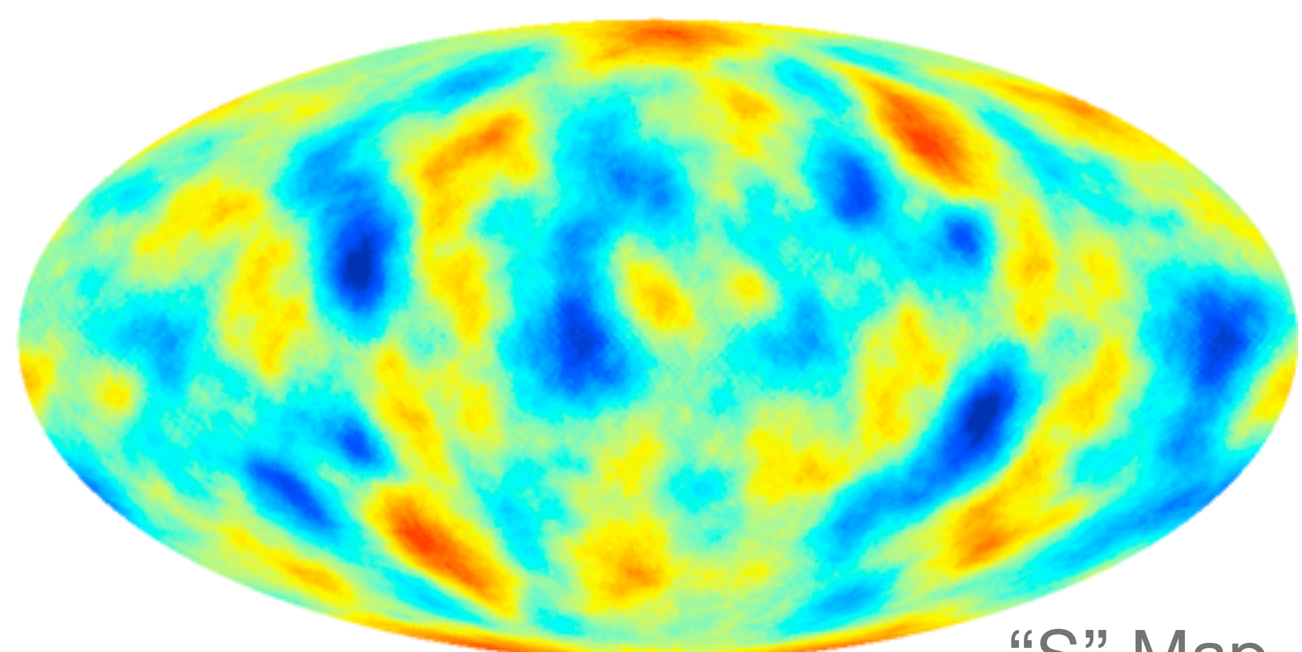

“S” Map

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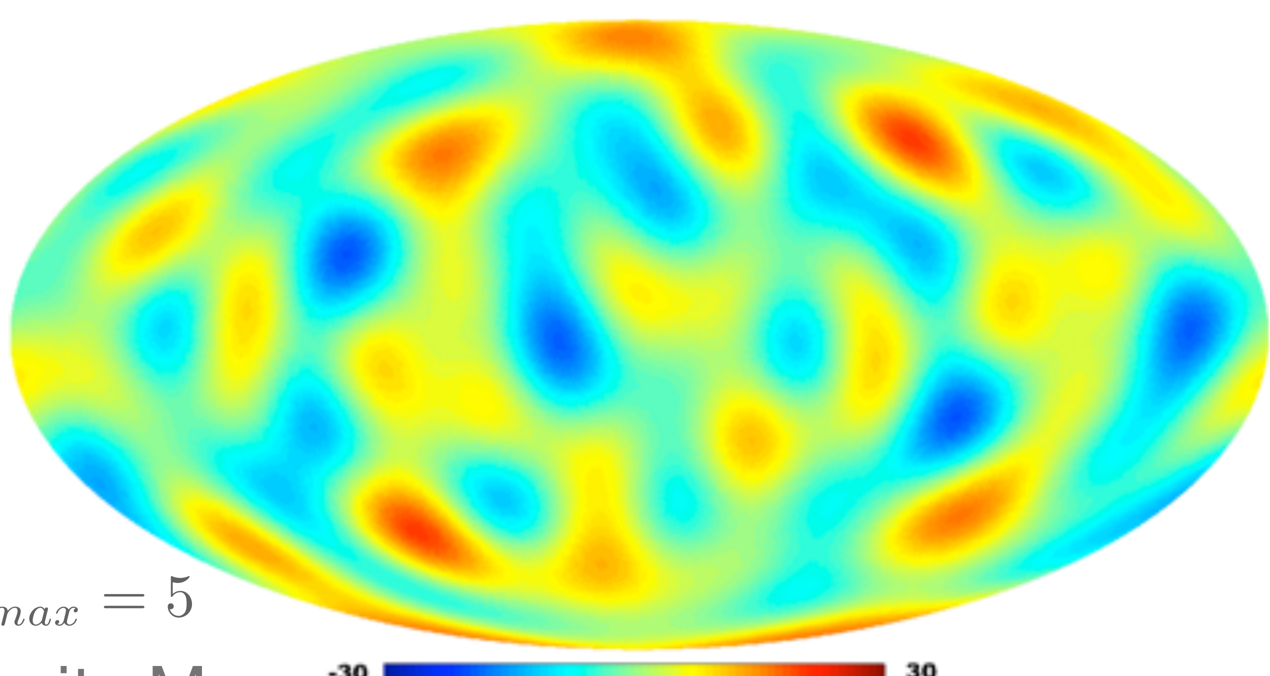
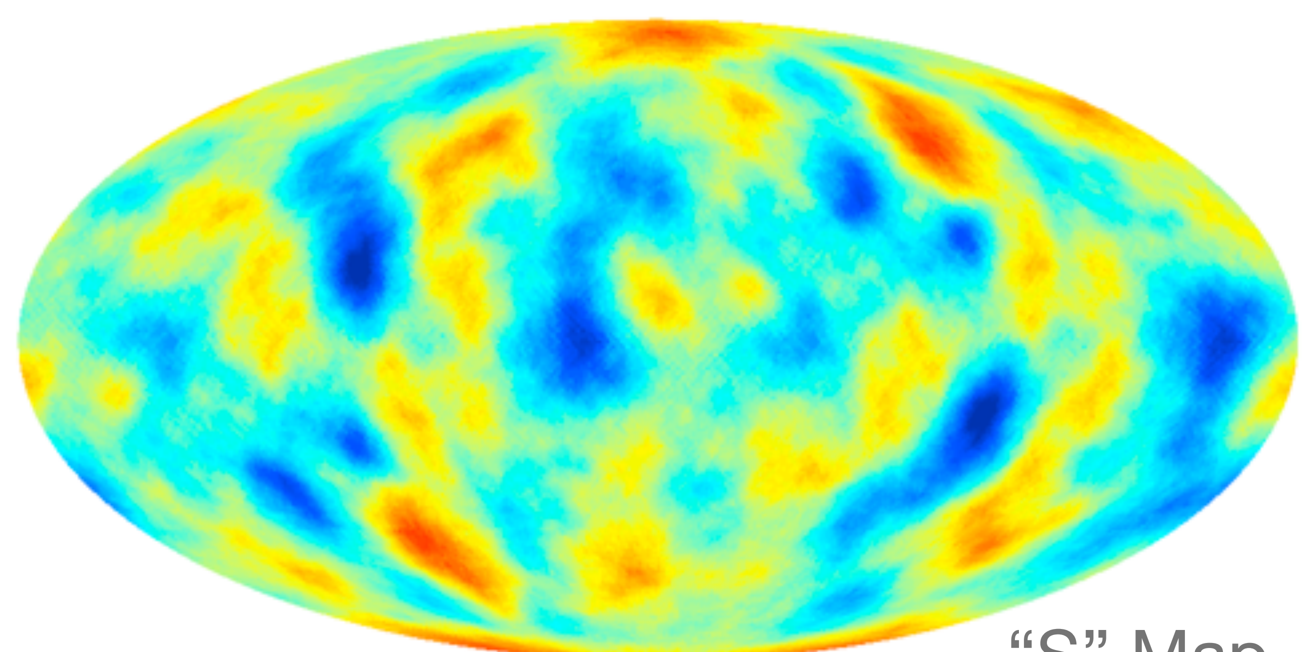


$\ell_{max} = 5$

Parity Map



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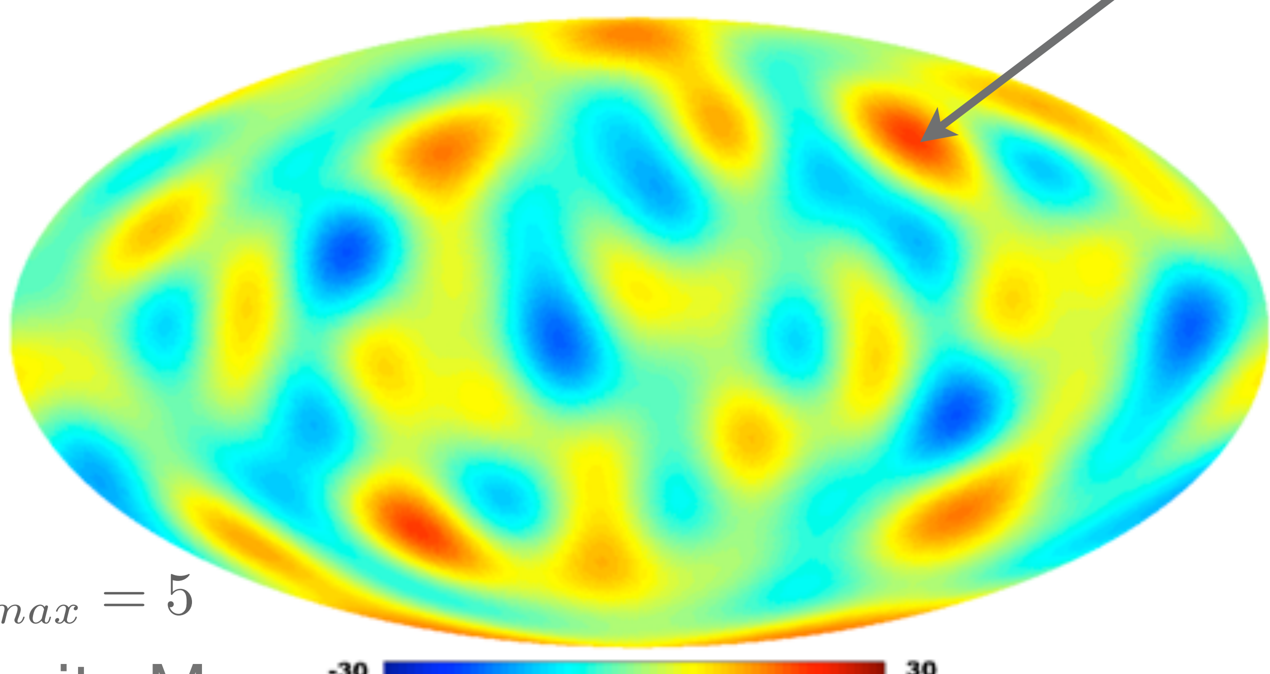
- Maximum: $(l,b) \simeq (260^\circ, 60^\circ)$, near "axis of evil" direction. (de Oliveira-Costa et al. 0307282)



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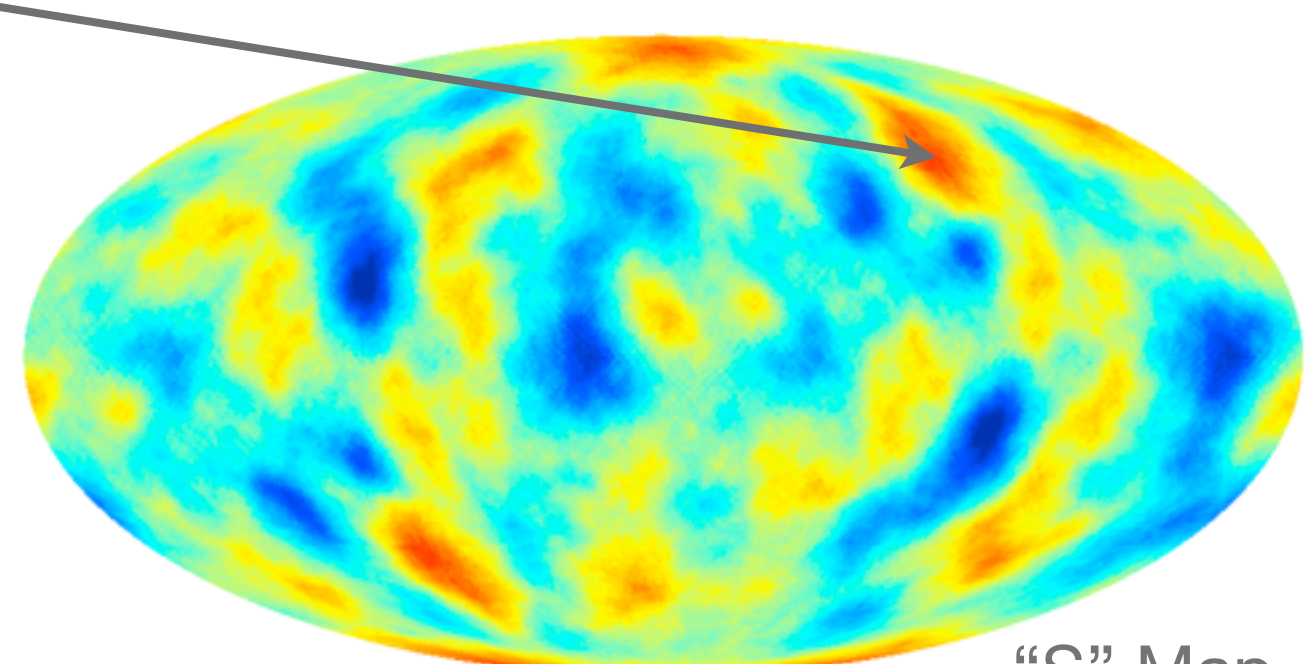

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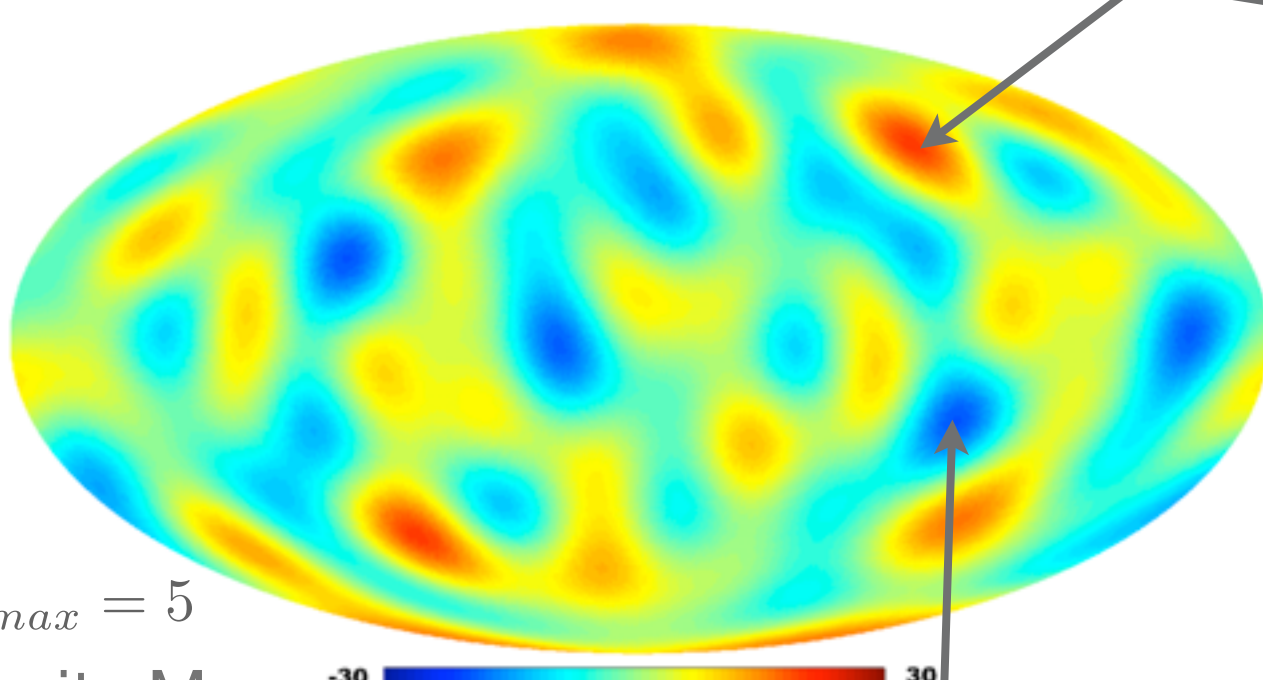

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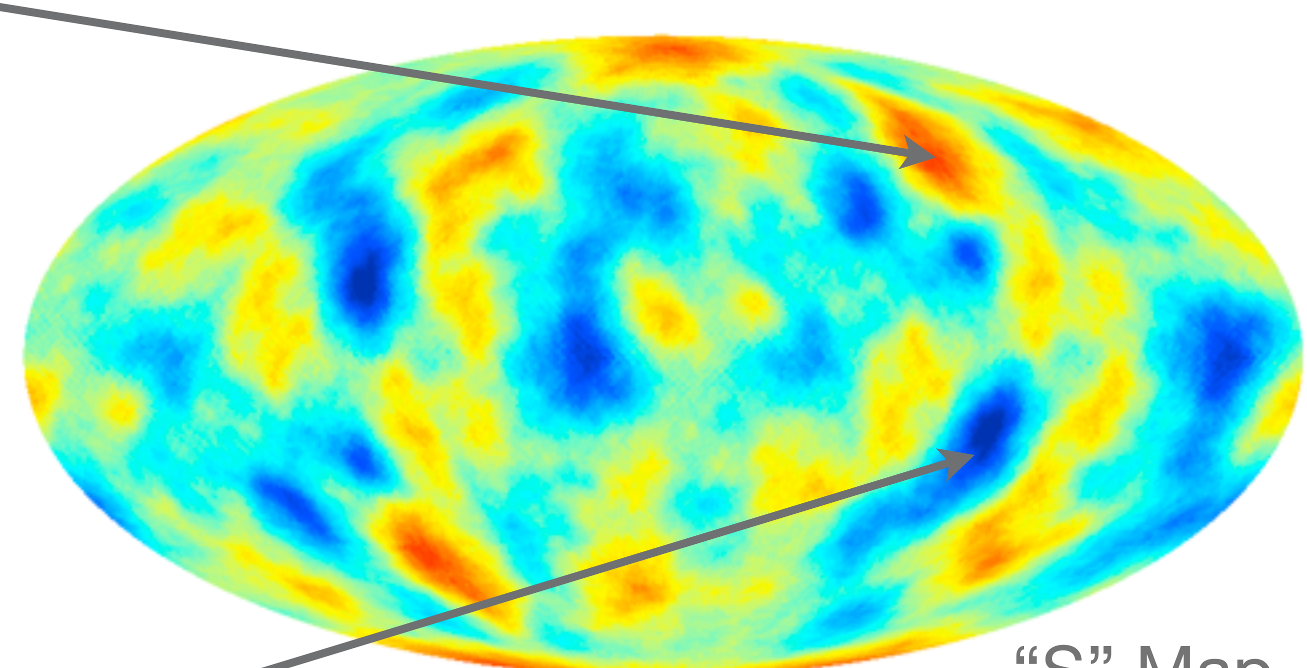

"S" Map

- Minimum: $(l, b) \simeq (266^\circ, -19^\circ)$.

Parity - Masking and Reconstruction

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- Masking is crucial!

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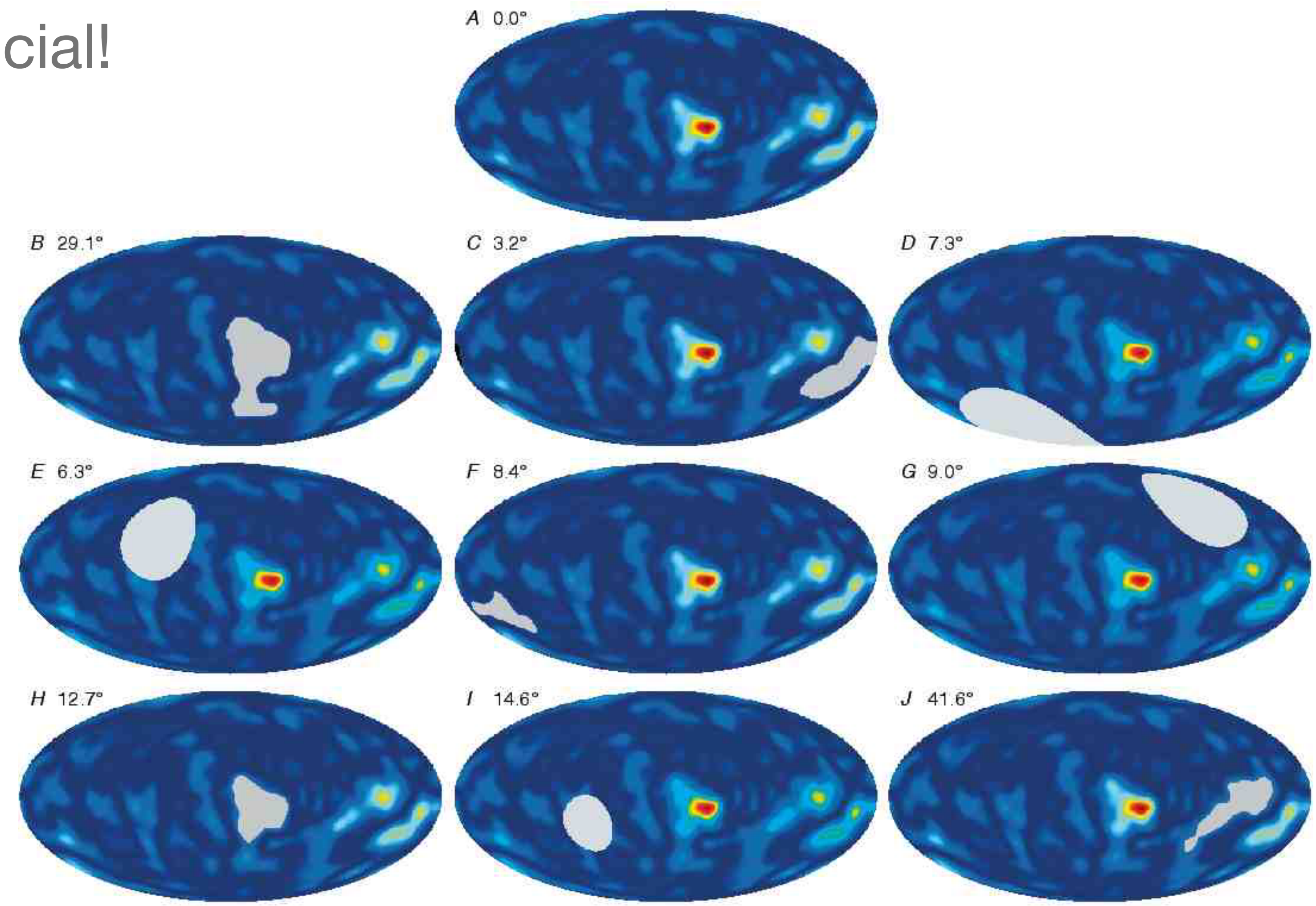

Bennet et al. 2010

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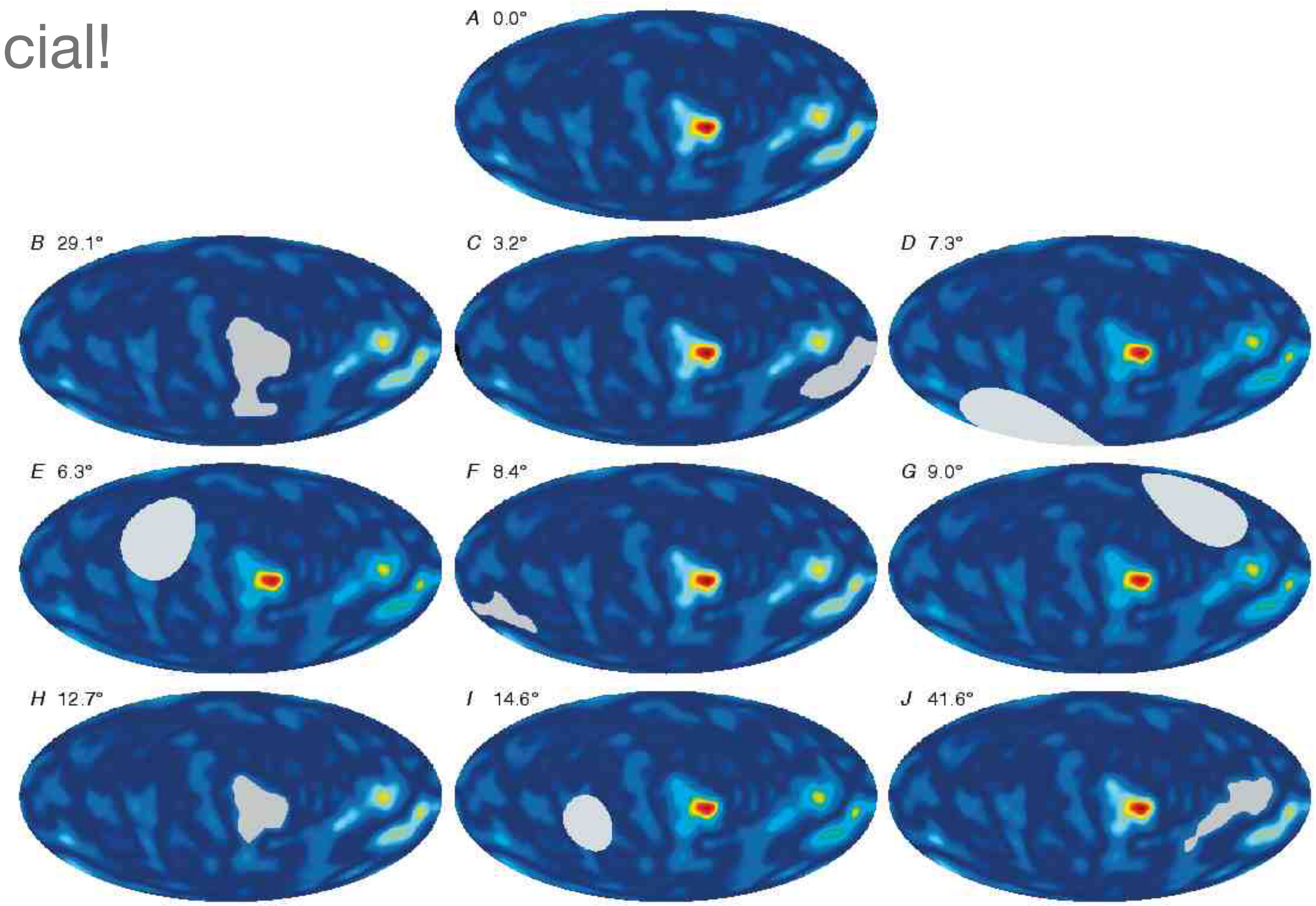

Bennet et al. 2010

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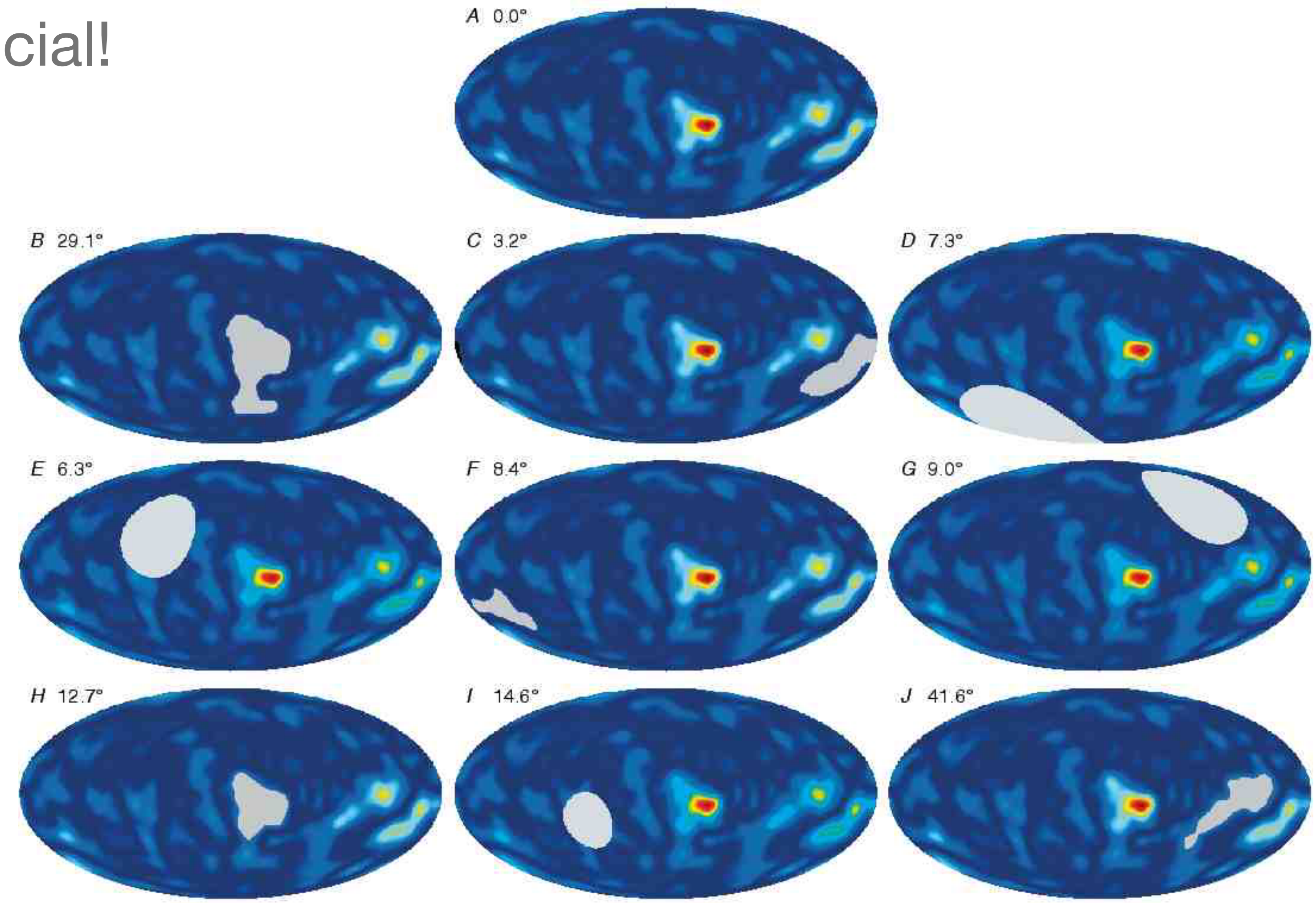

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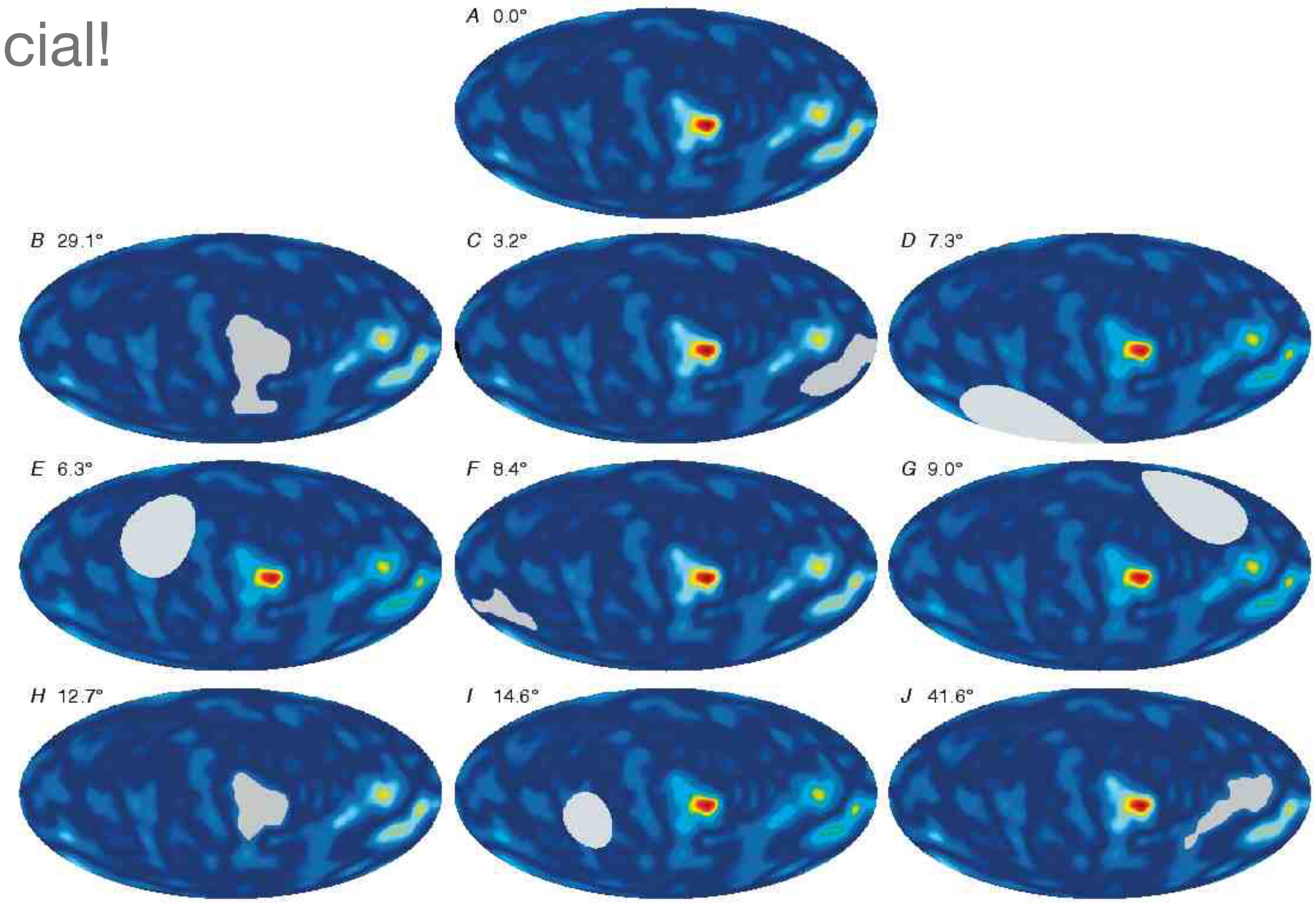

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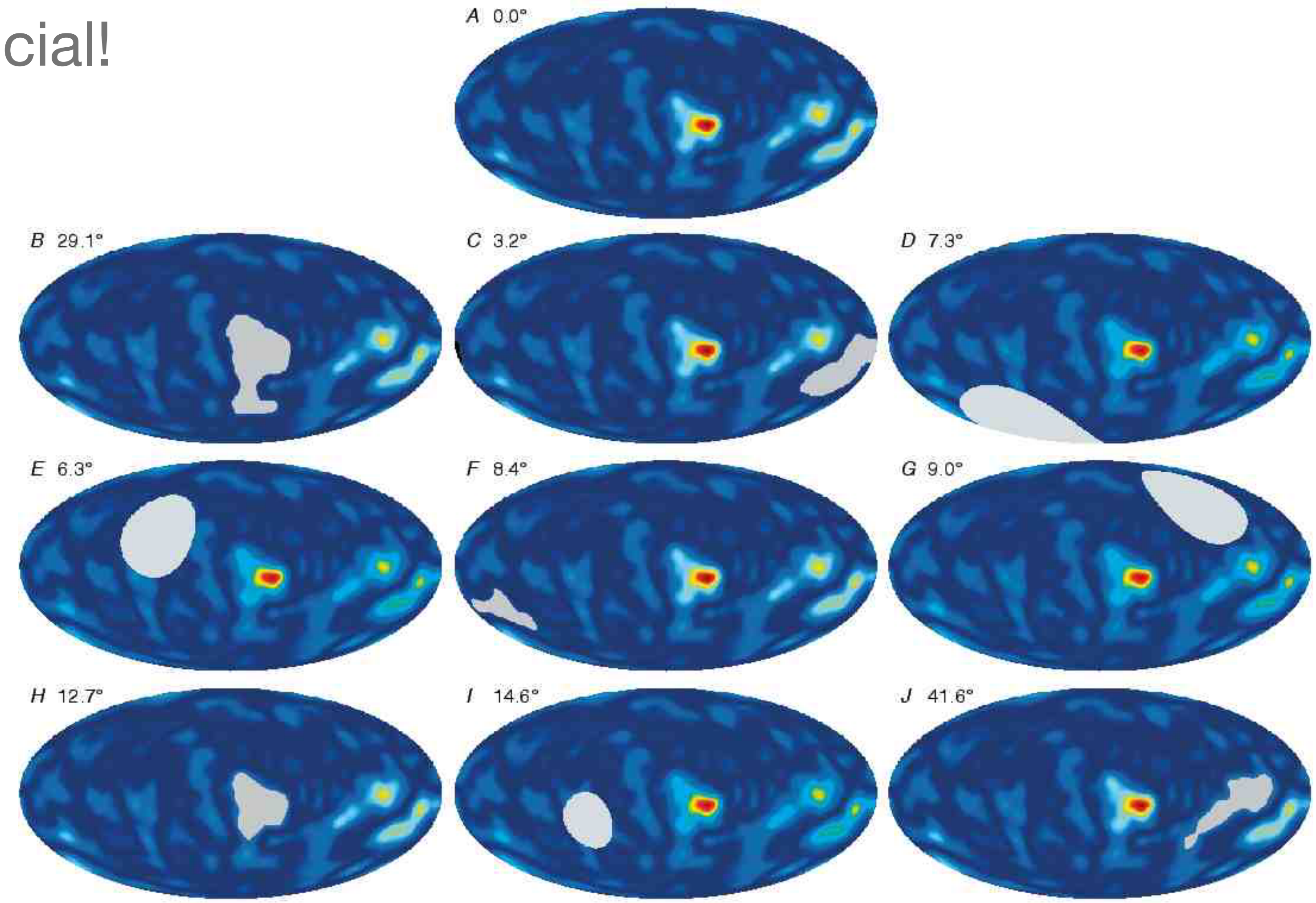

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Covariance matrix $\mathbf{C}_{ij} = \sum_{\ell=\ell_{\max}+1}^{L} \frac{2\ell+1}{4\pi} P_\ell\left(\hat{\mathbf{r}}_i \cdot \hat{\mathbf{r}}_j\right) C_\ell$

Parity - Cut-Sky Results

(Ben-David, EDK and Itzhaki, ApJ 2012)

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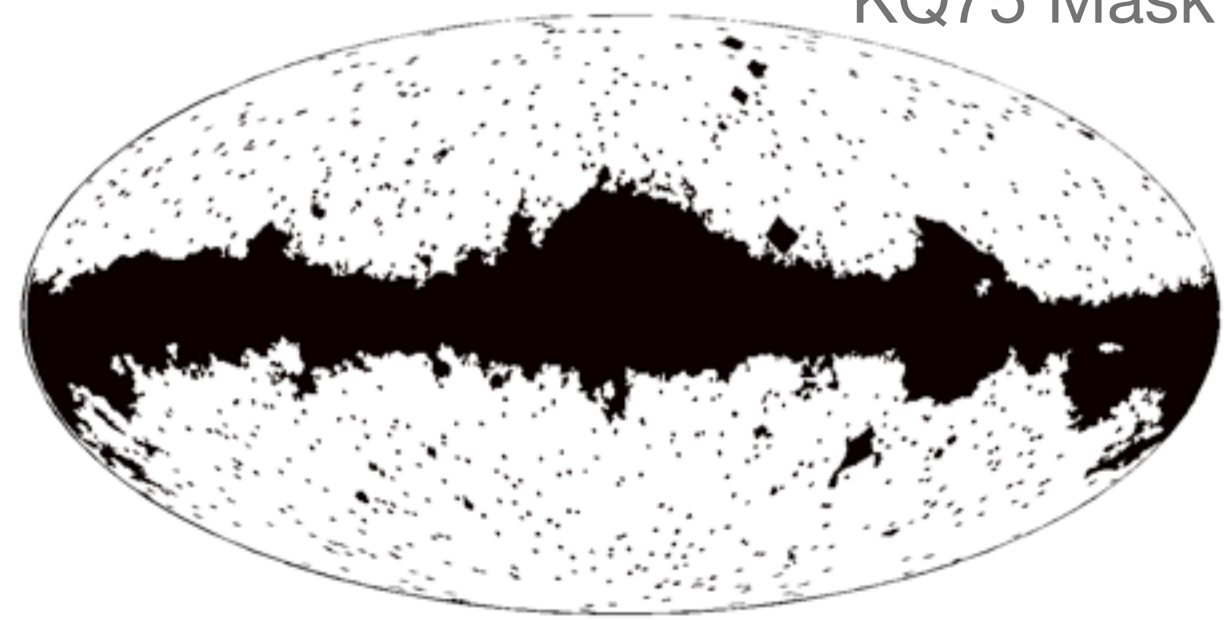
KQ75 Mask



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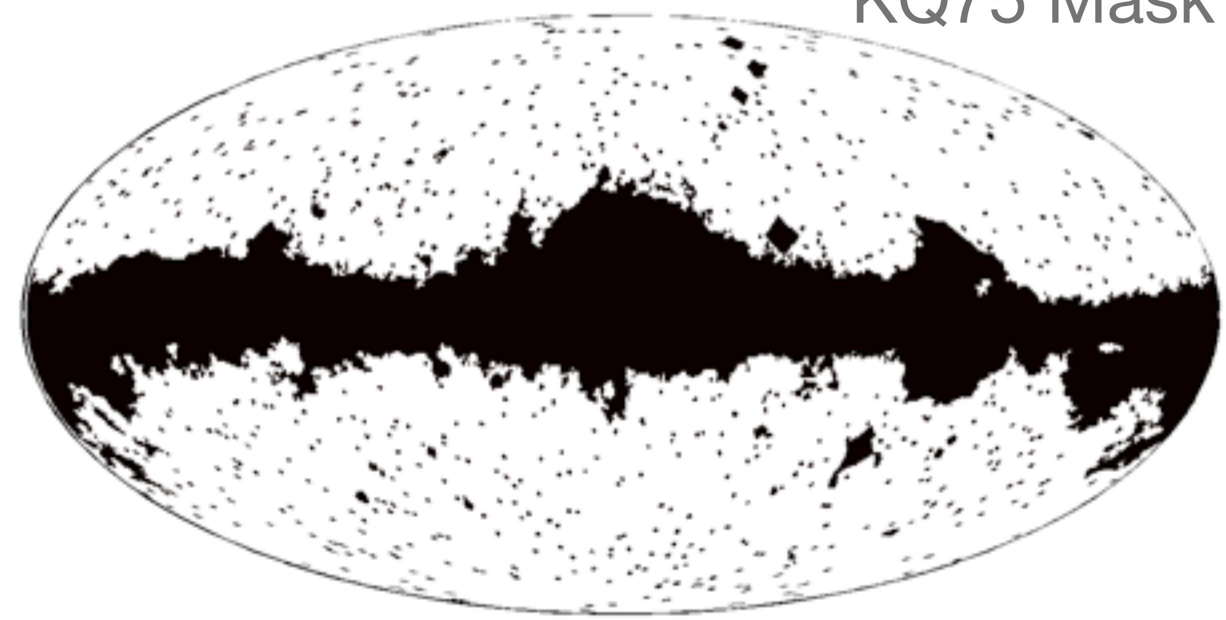

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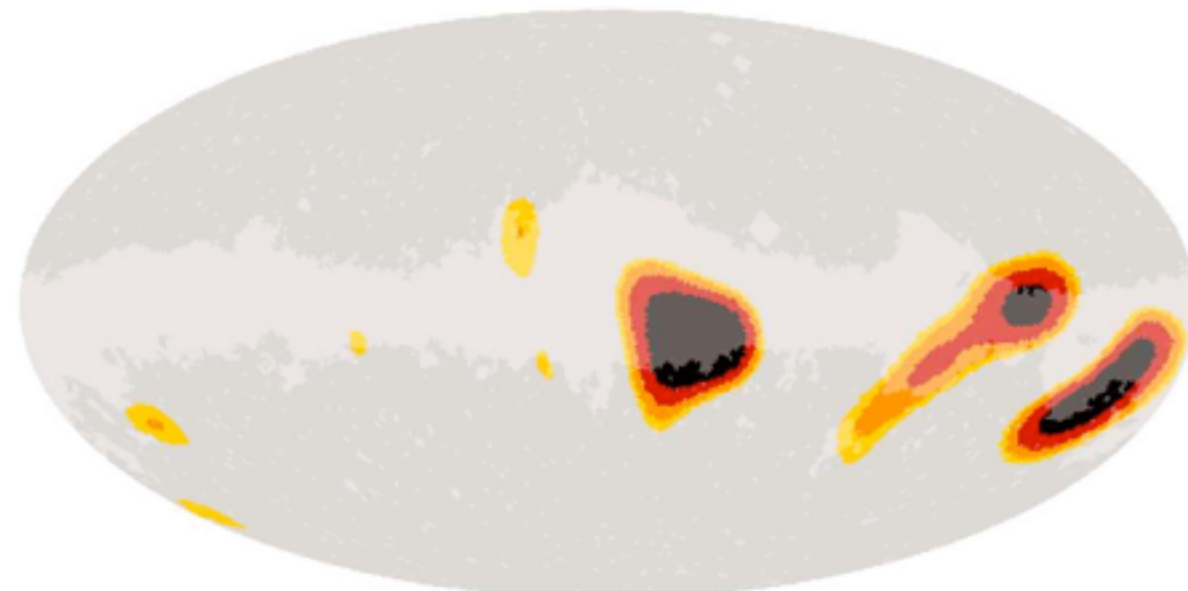

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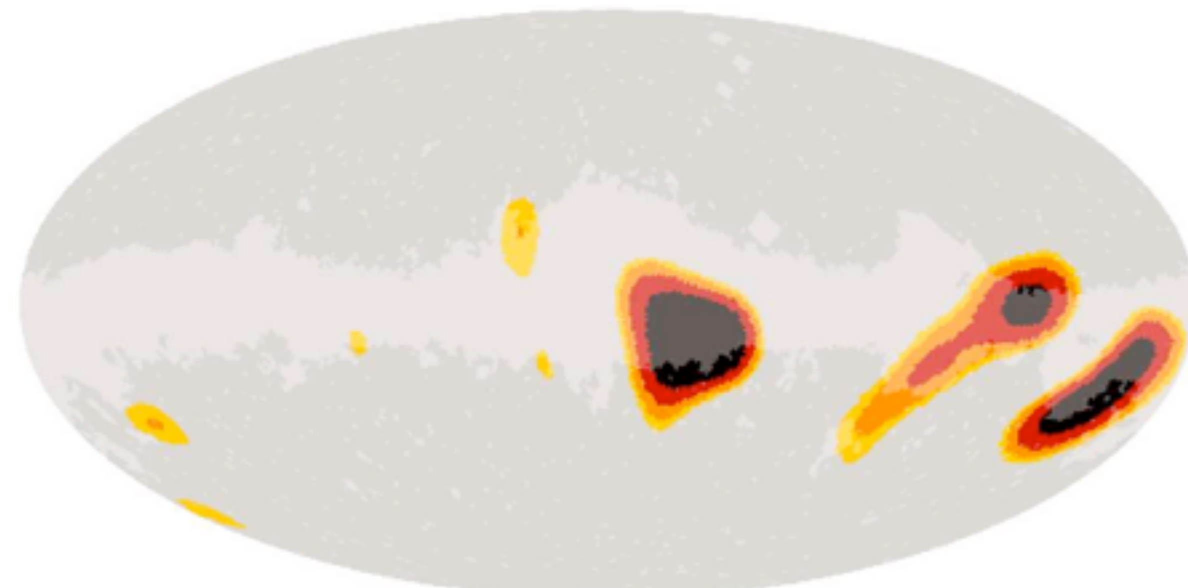

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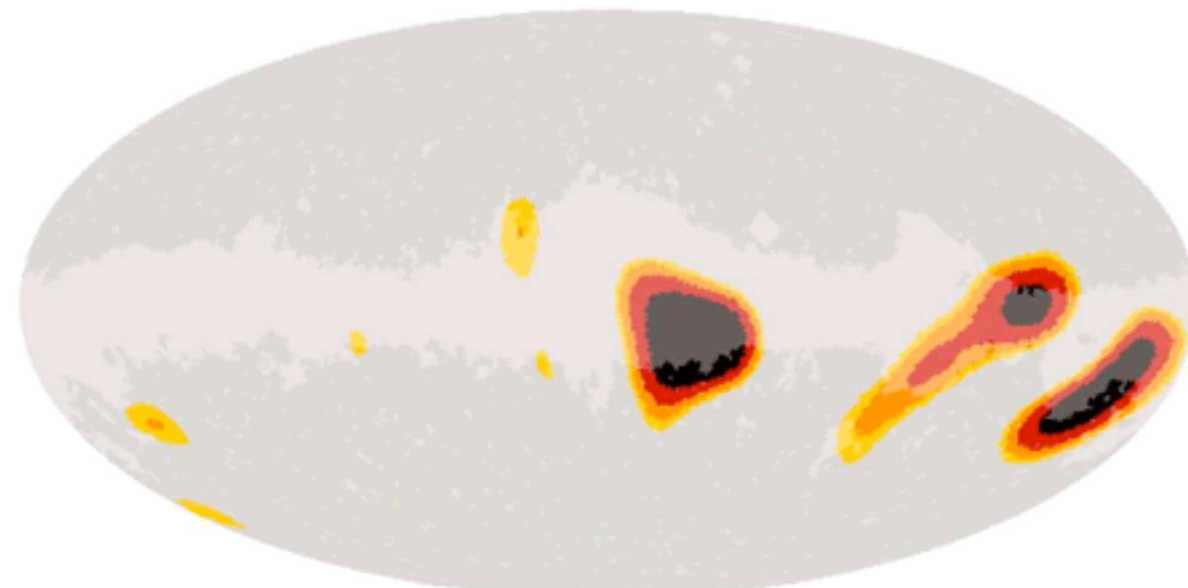

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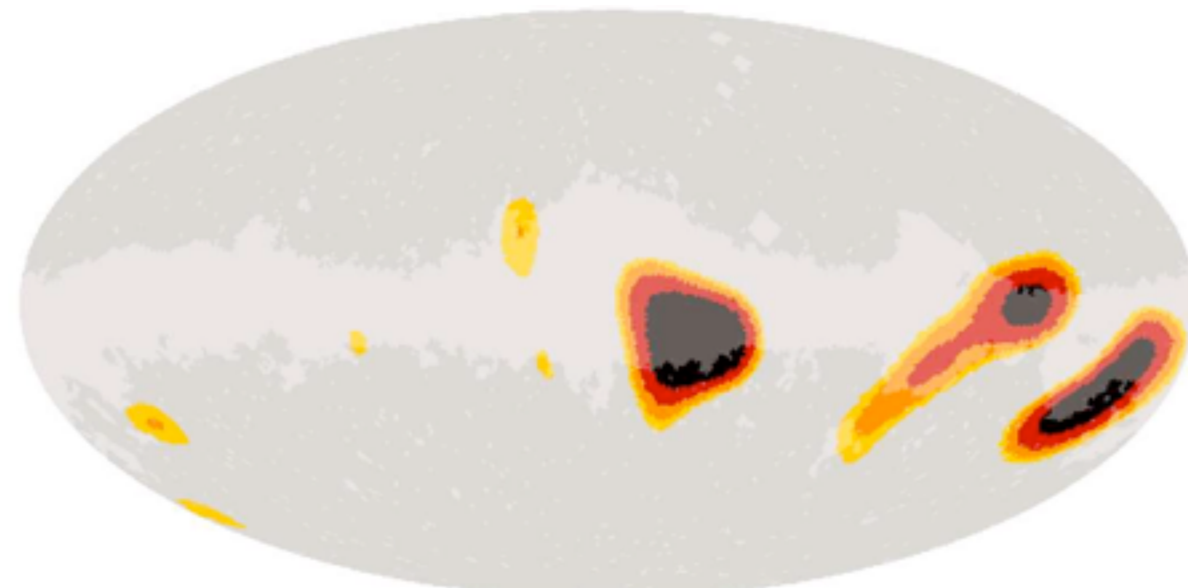

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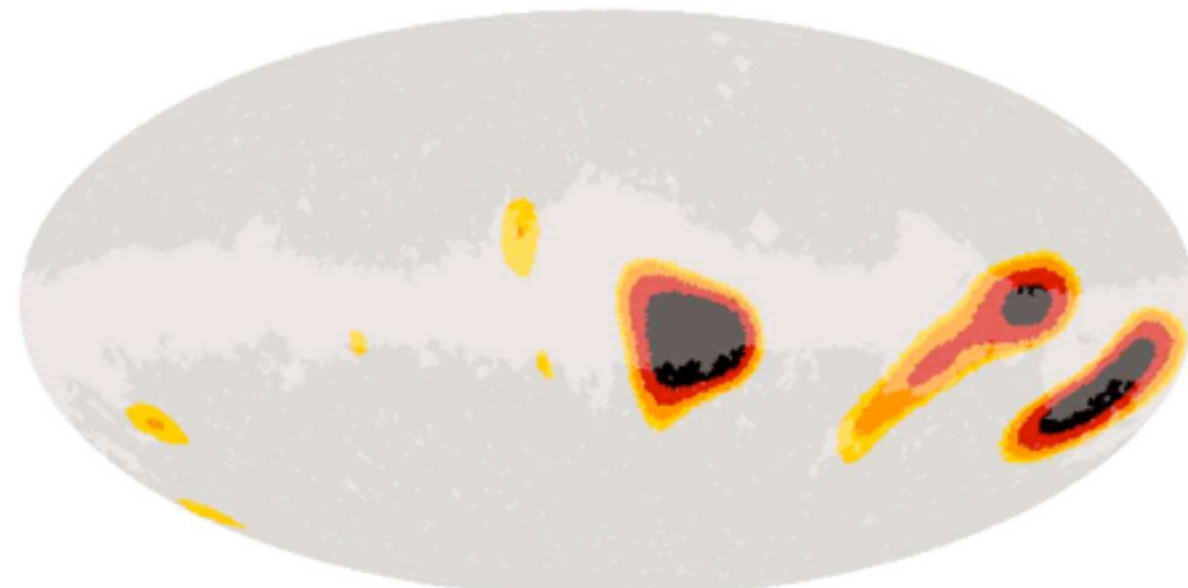

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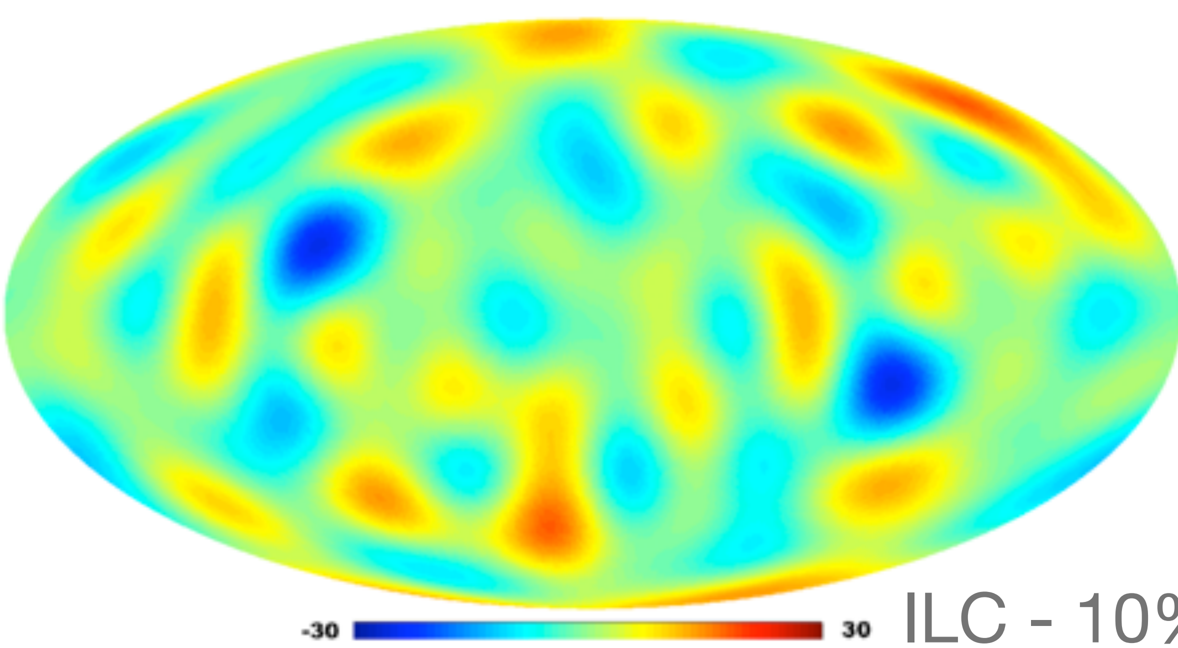

ILC - 10%

Parity - Cut-Sky Results

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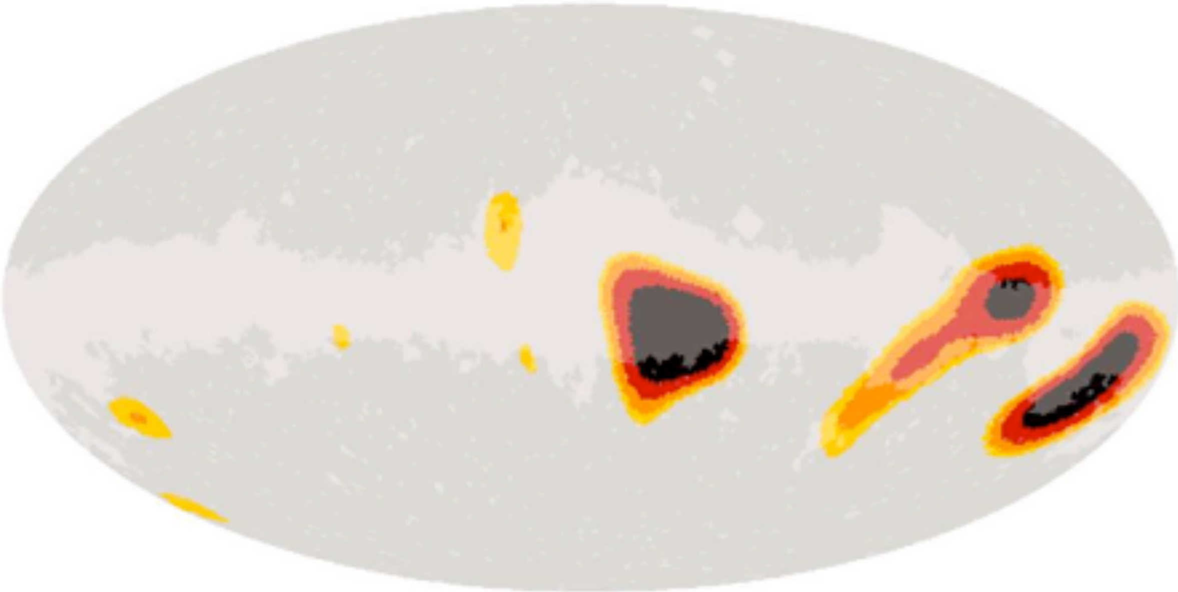

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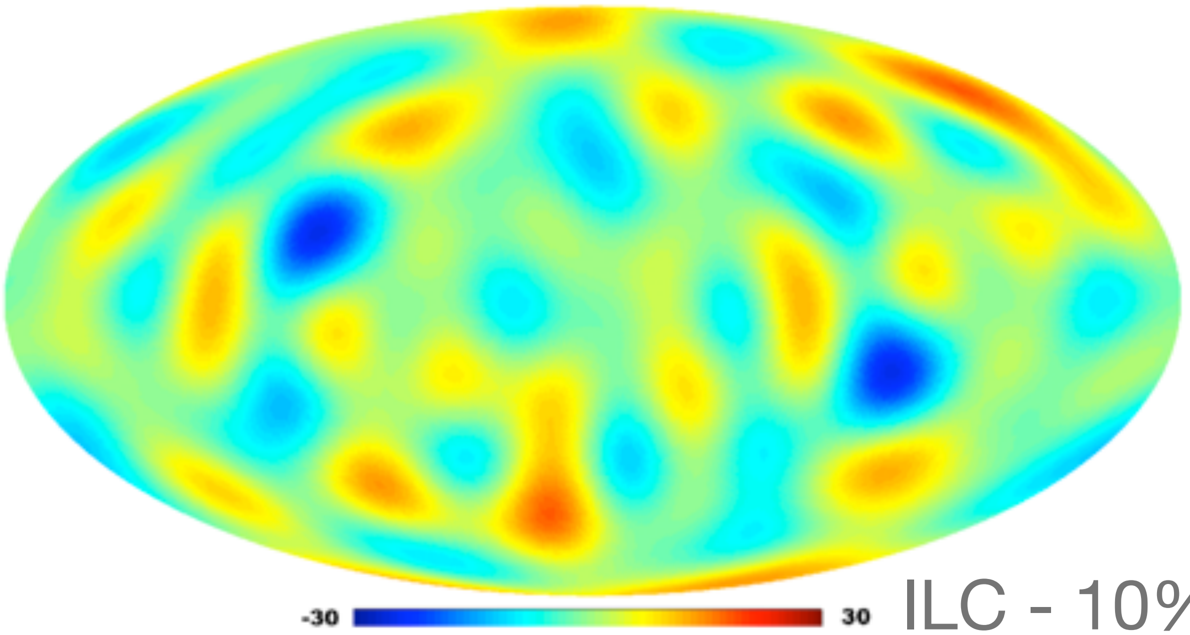

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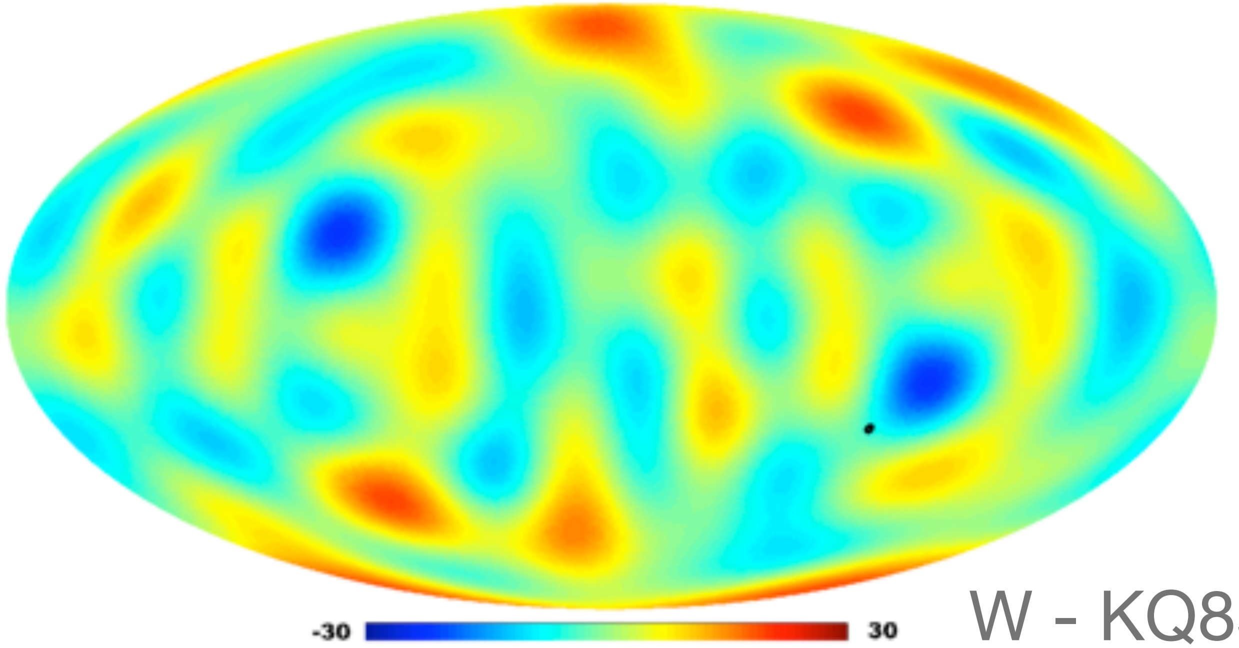

W - KQ85

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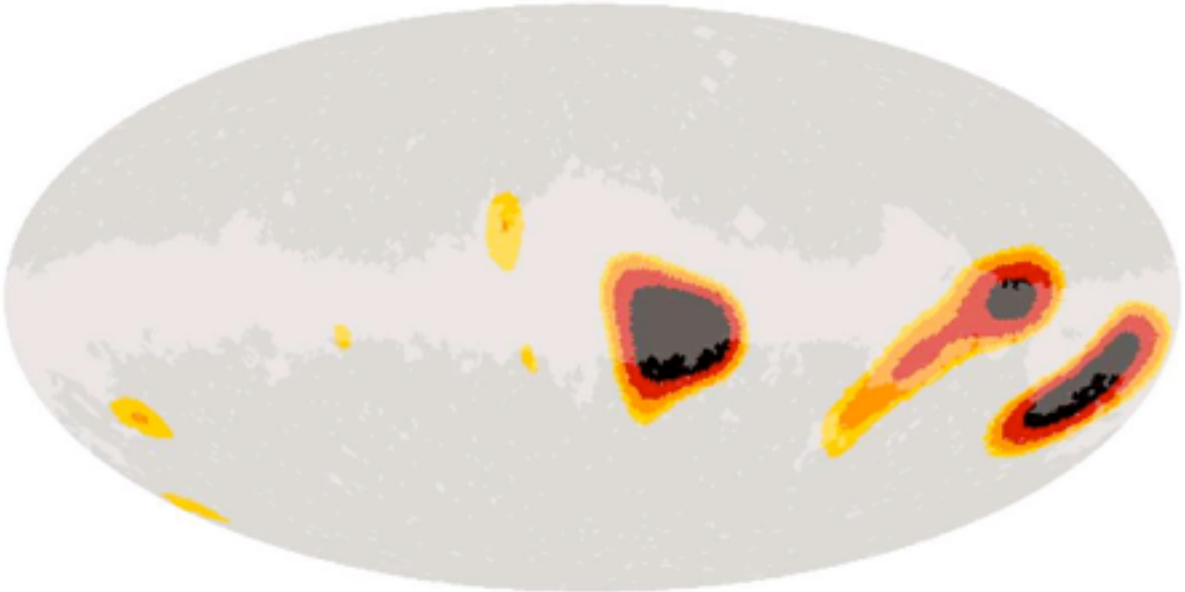

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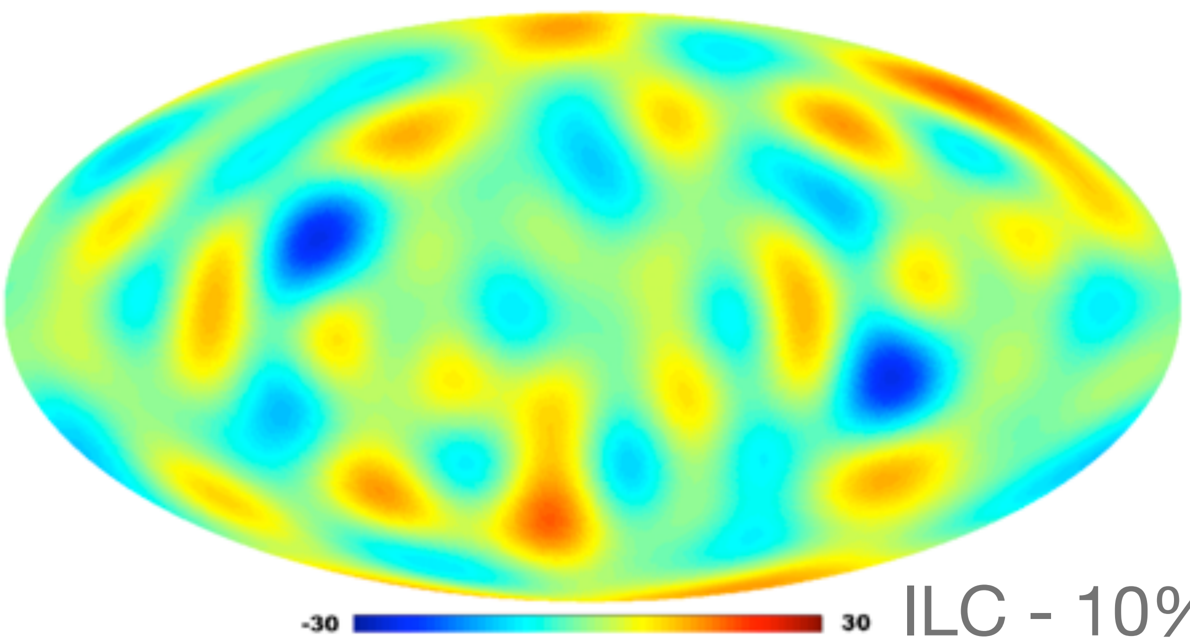

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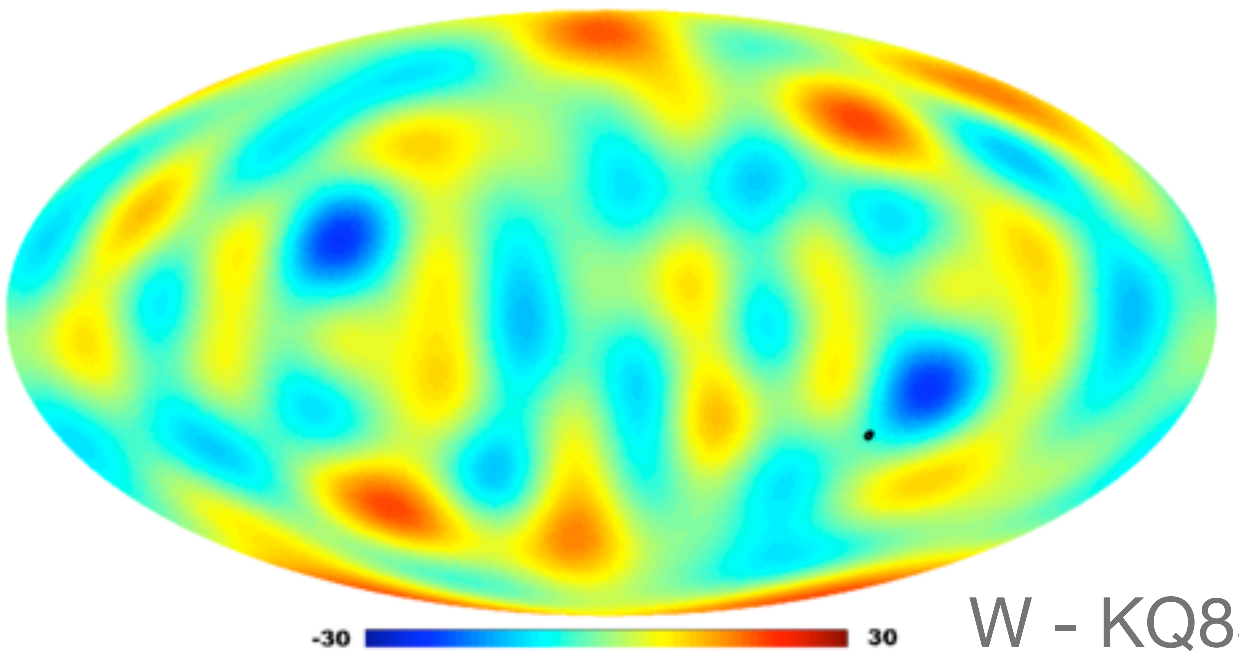

W - KQ85

  - Even parity insignificant.

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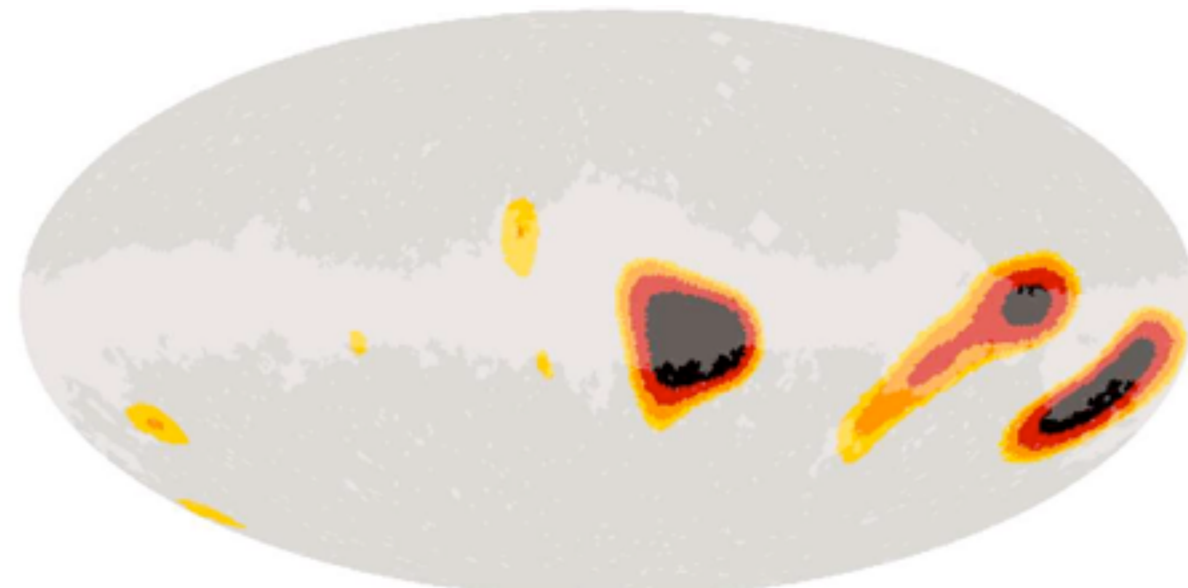

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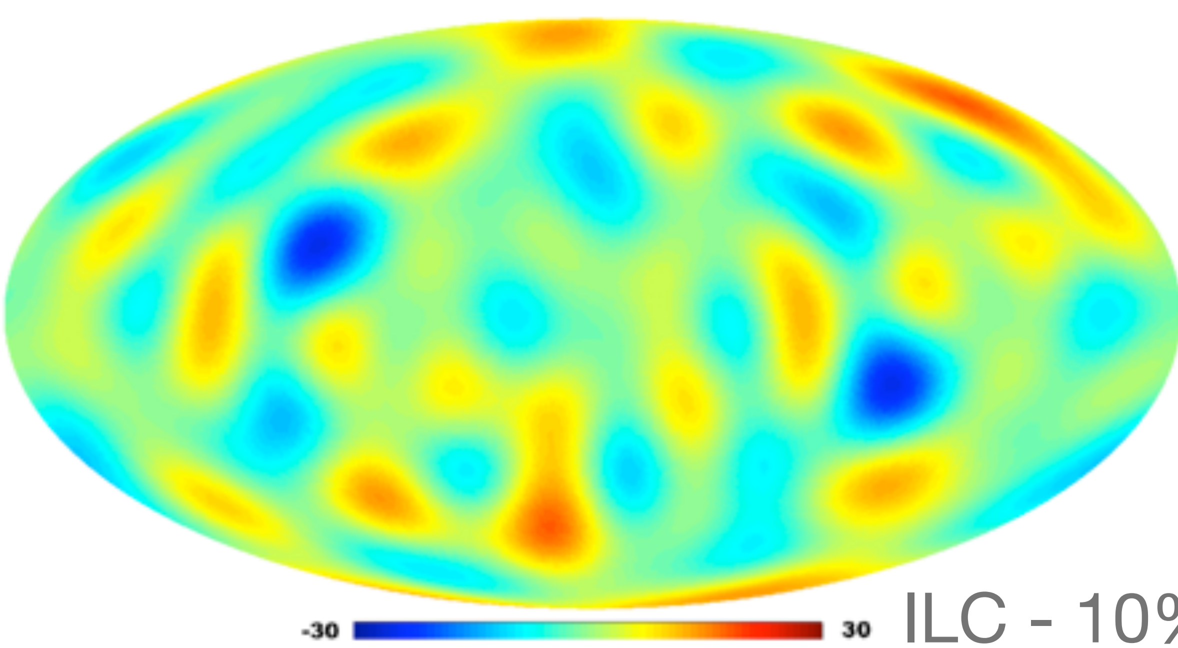

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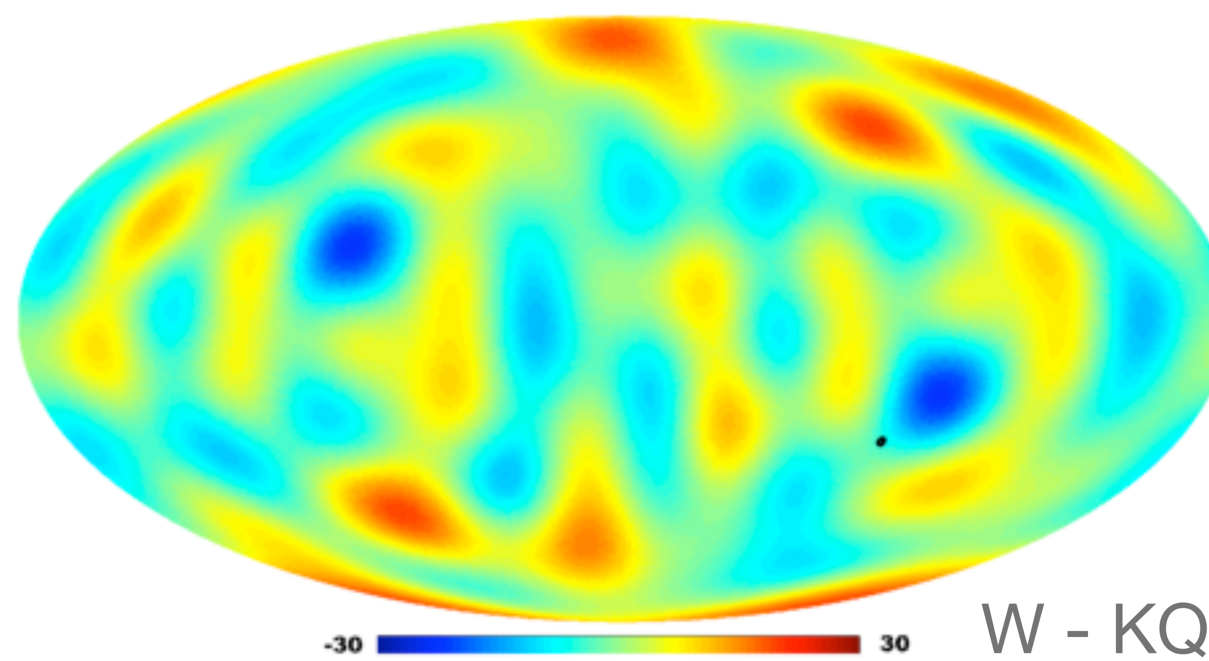

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- Odd parity at $(l, b) \simeq (264^\circ, -18^\circ)$ is significant: ~0.01% for $\ell_{max} = 5 - 7$.

Parity - COBE-DMR

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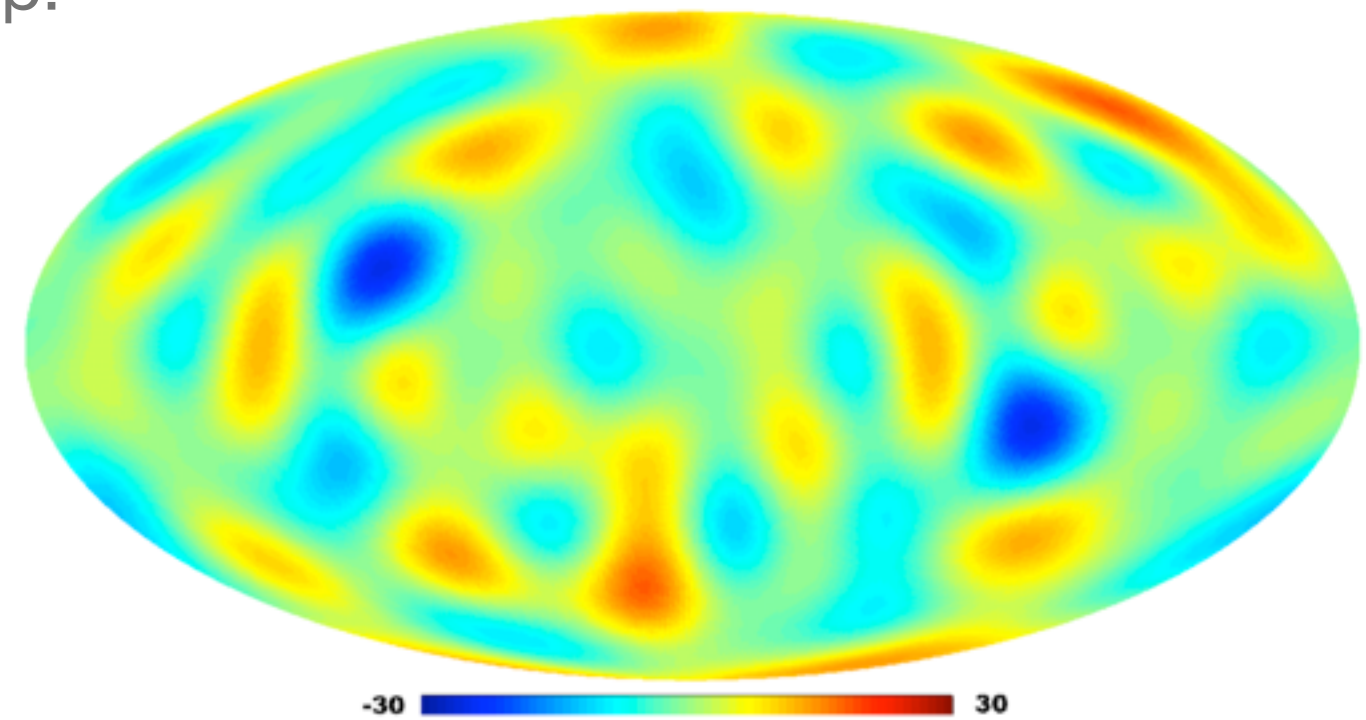
- WMAP parity map:



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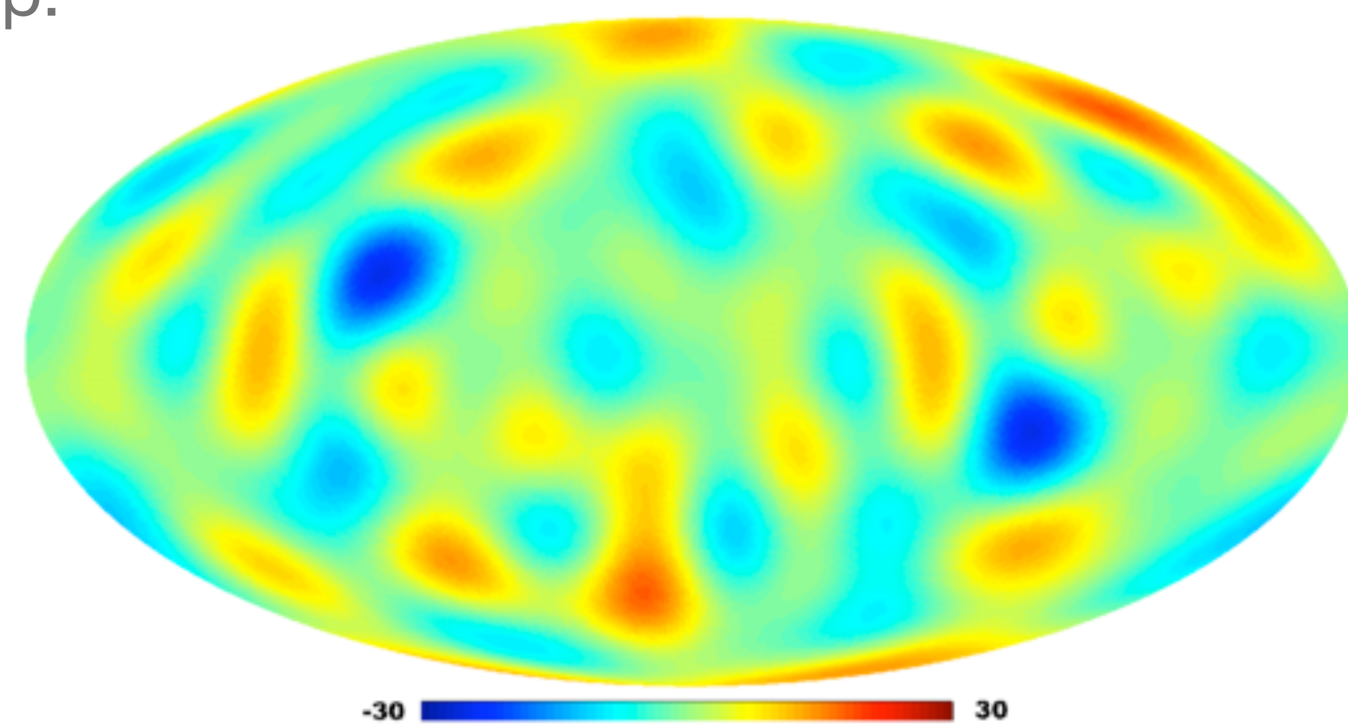

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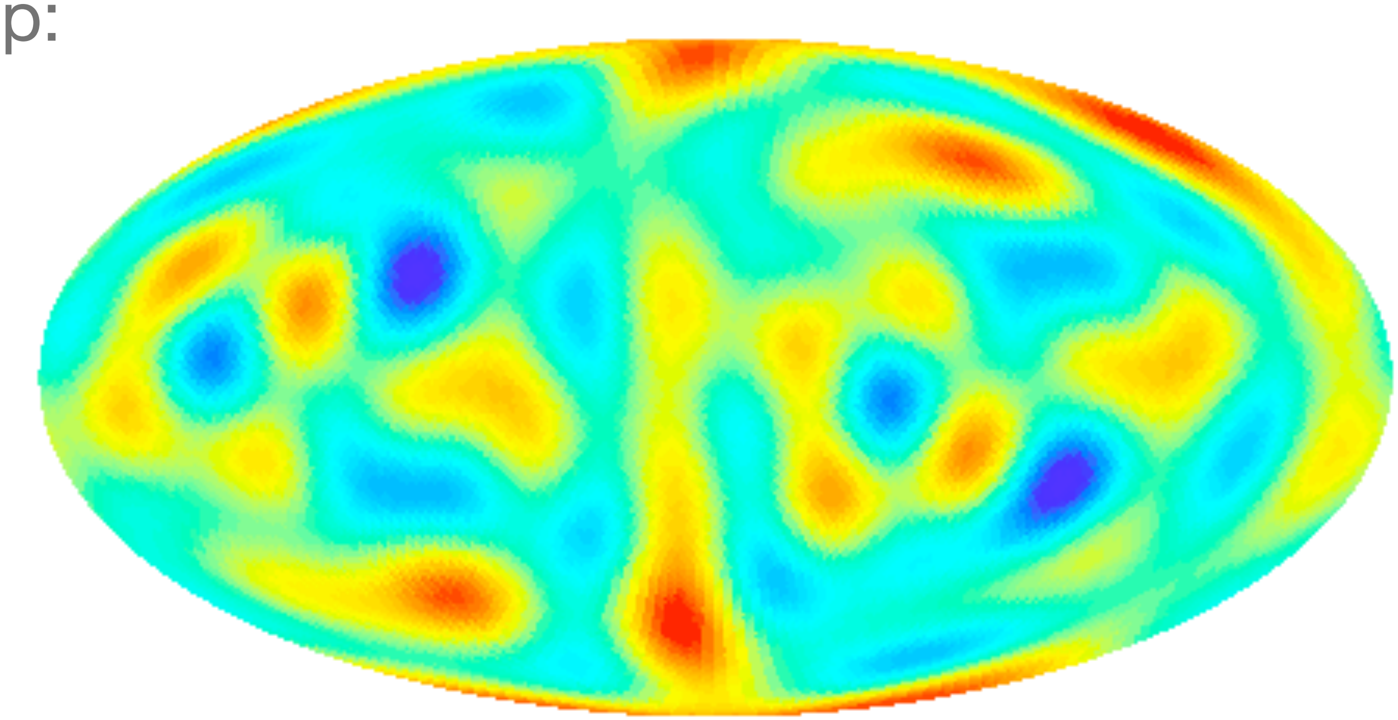

Outline

Before

After

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- Small/Large Field Phase Transition
- Understanding the Critical Behavior
- Time-Dependent D.O.F. (PIP)
- Pre-Inflationary Particle - Signatures
- Where to look, what to look for?
- Observational Tests: CMB Rings, Bulk Flow, Mirror Parity.
- Current work and Summary

Before

After

Moving PIP Model

(Ben-David, EDK and Itzhaki, *in progress*)

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- (Dipole structure could create both even and odd parity, 90° apart.)

Simulation vs. data: Moving PIP

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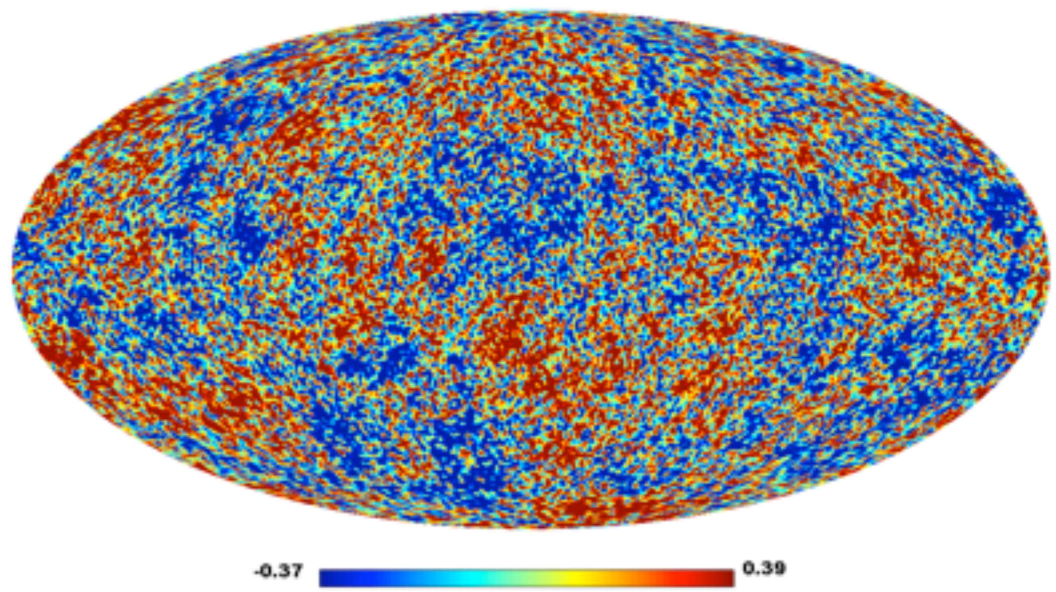

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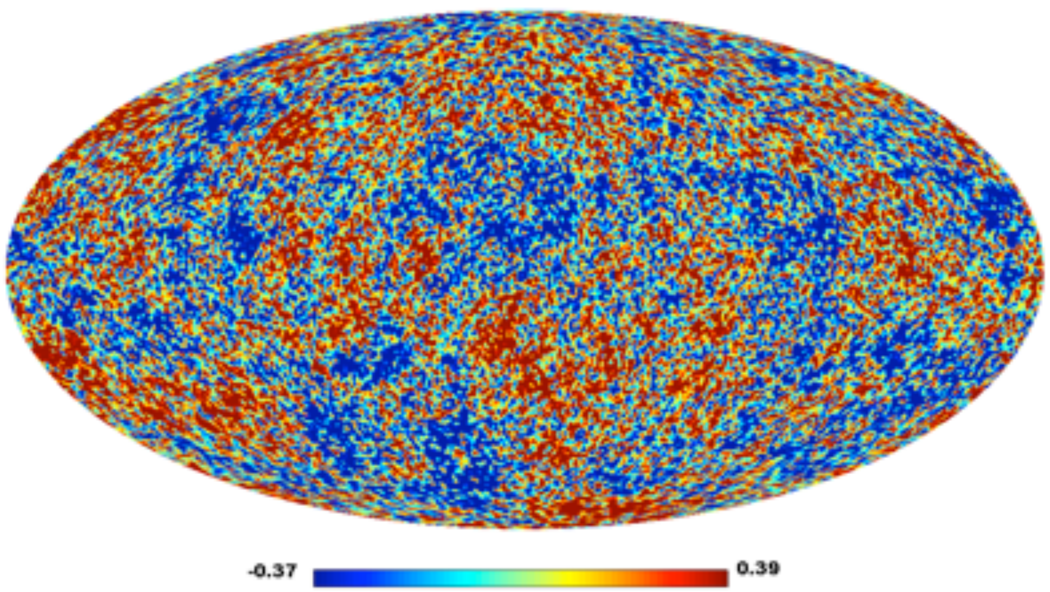

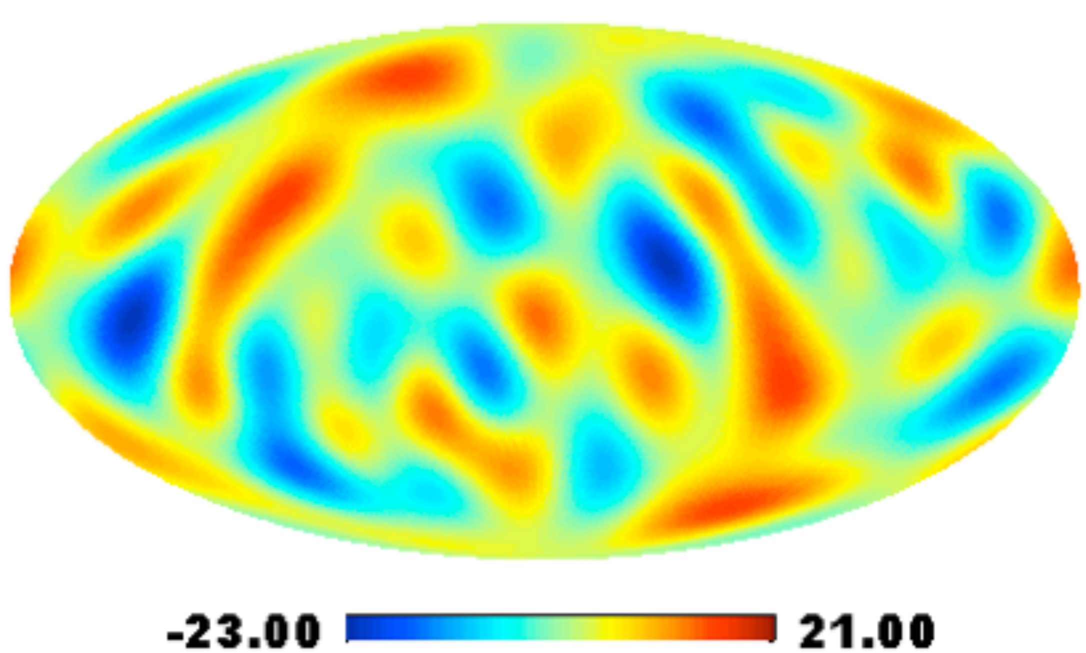

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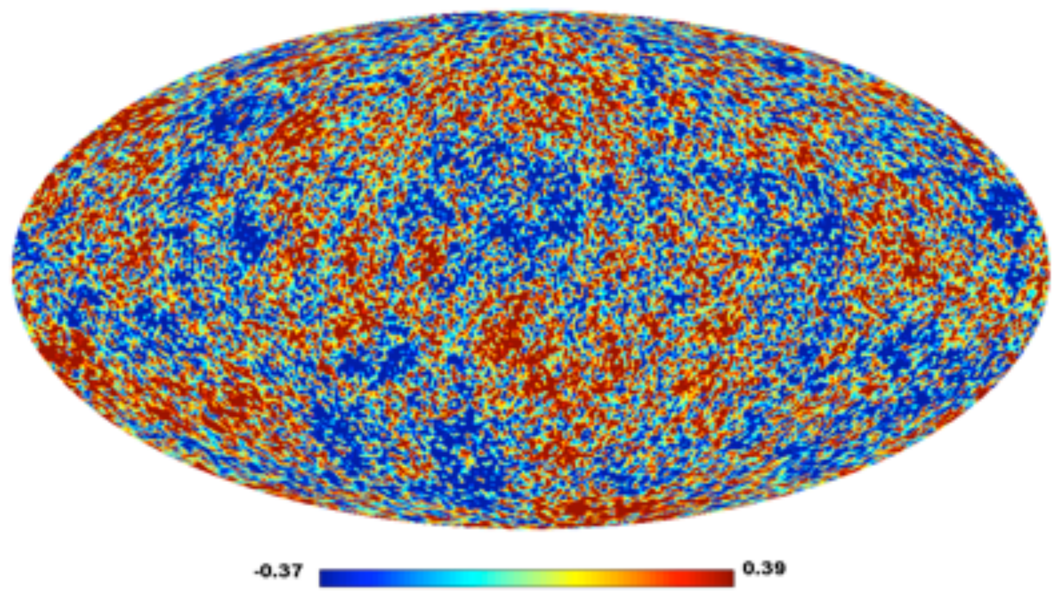

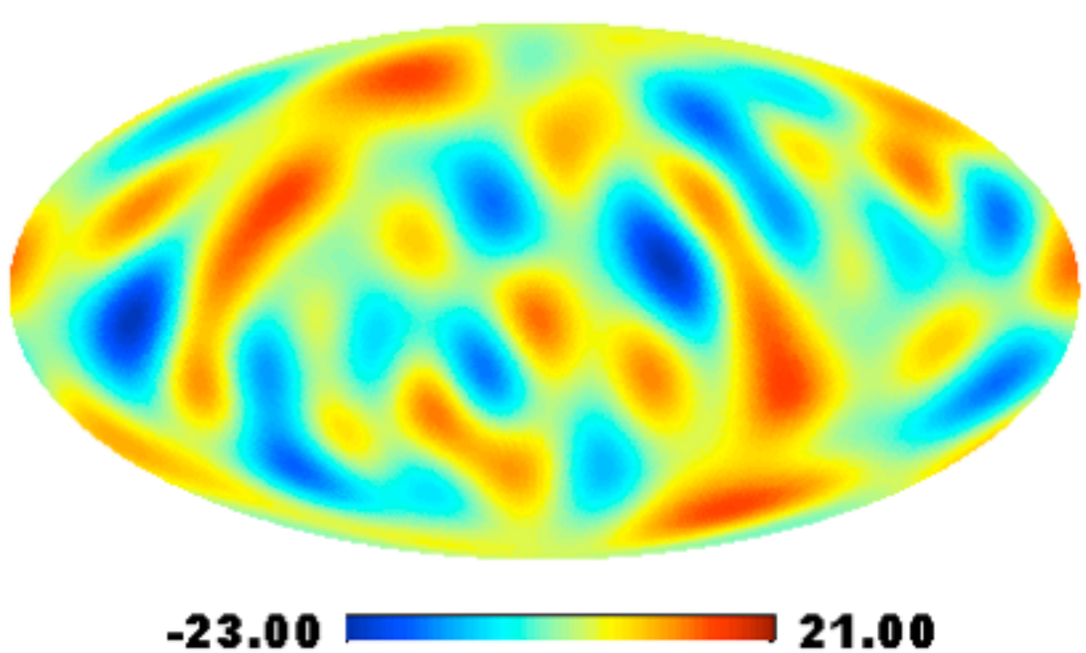

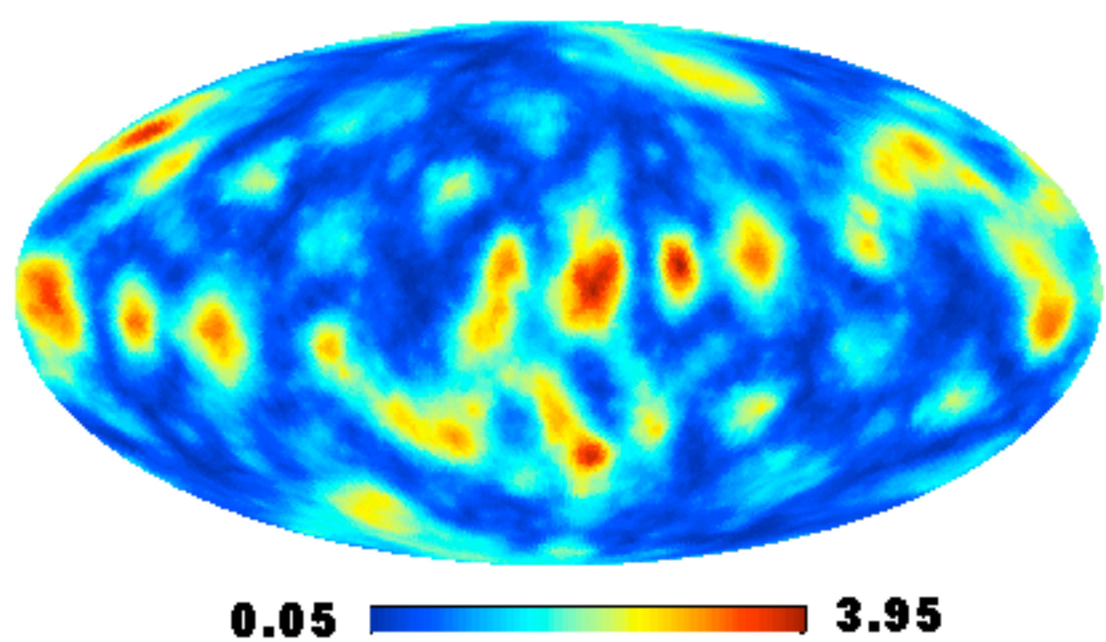

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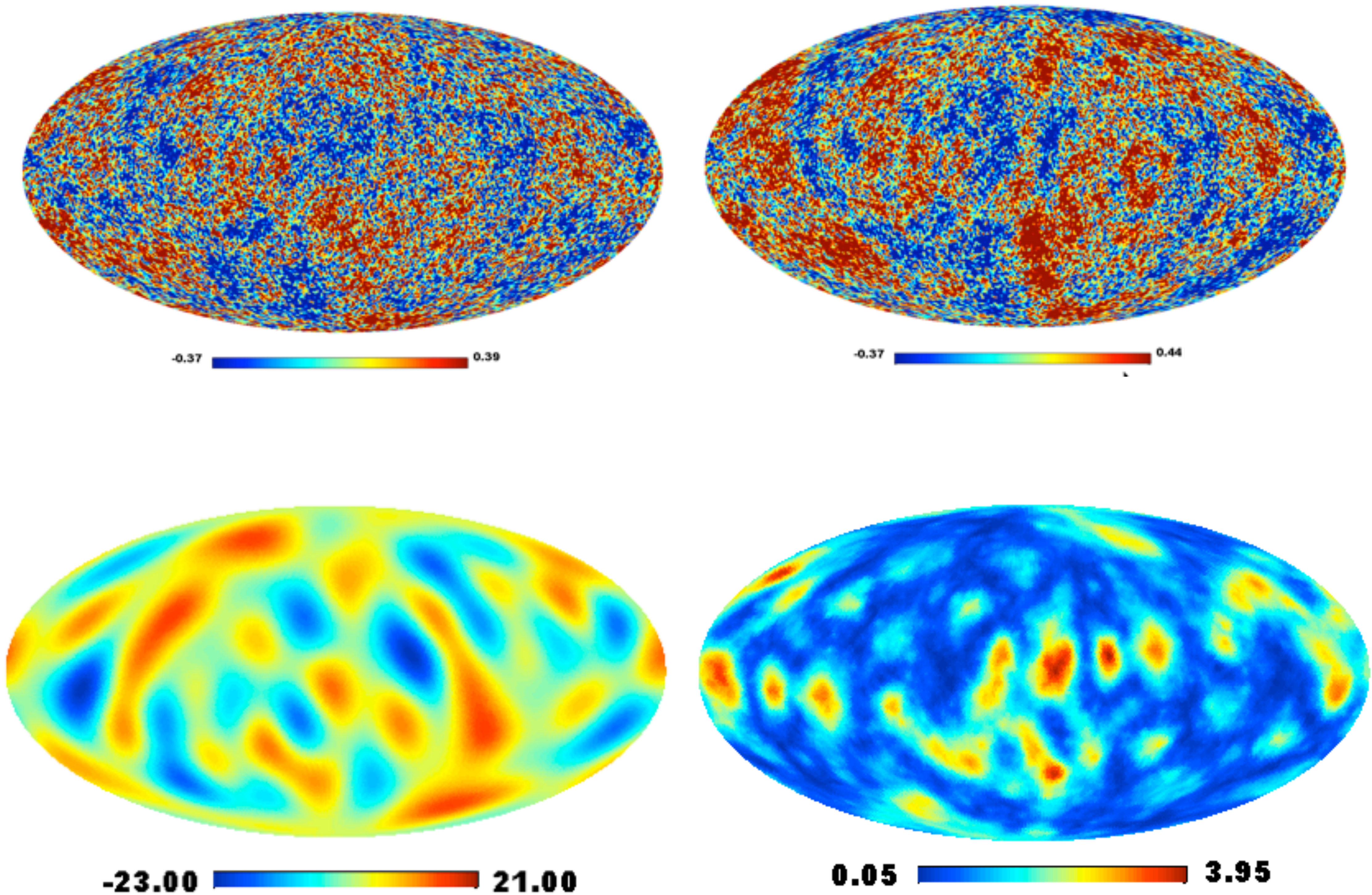

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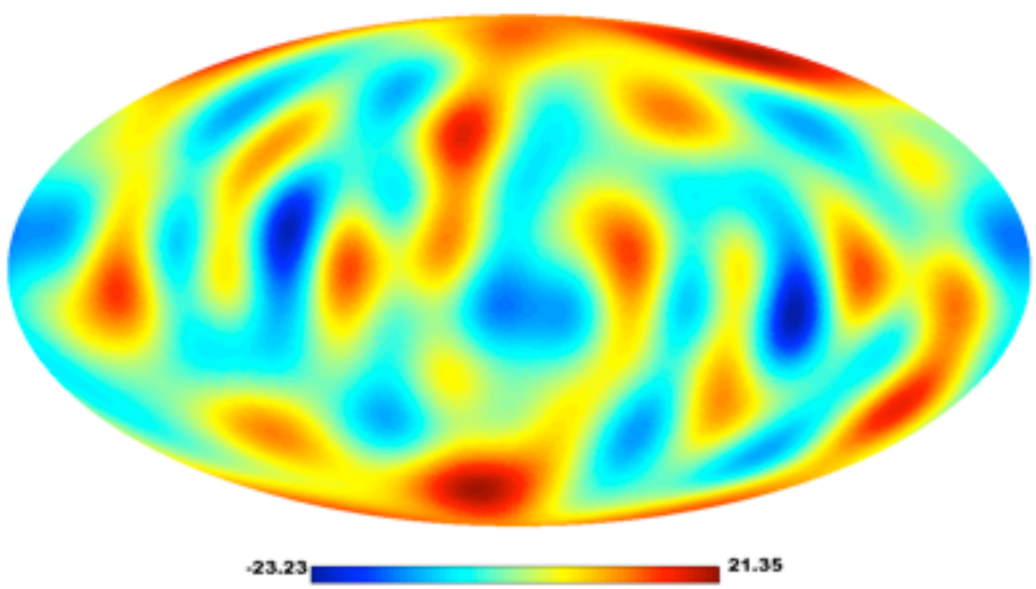

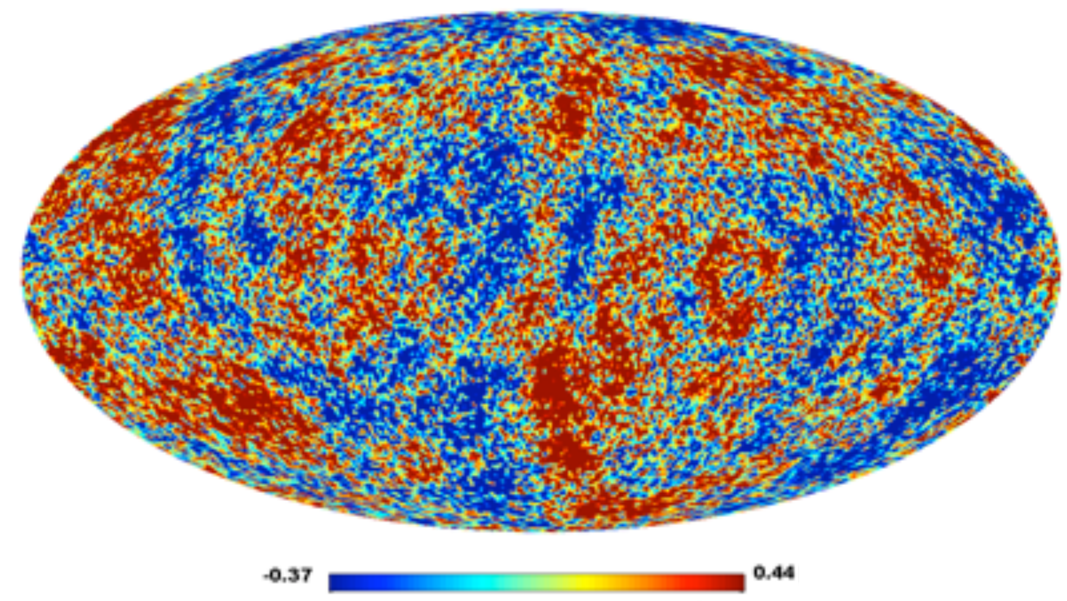

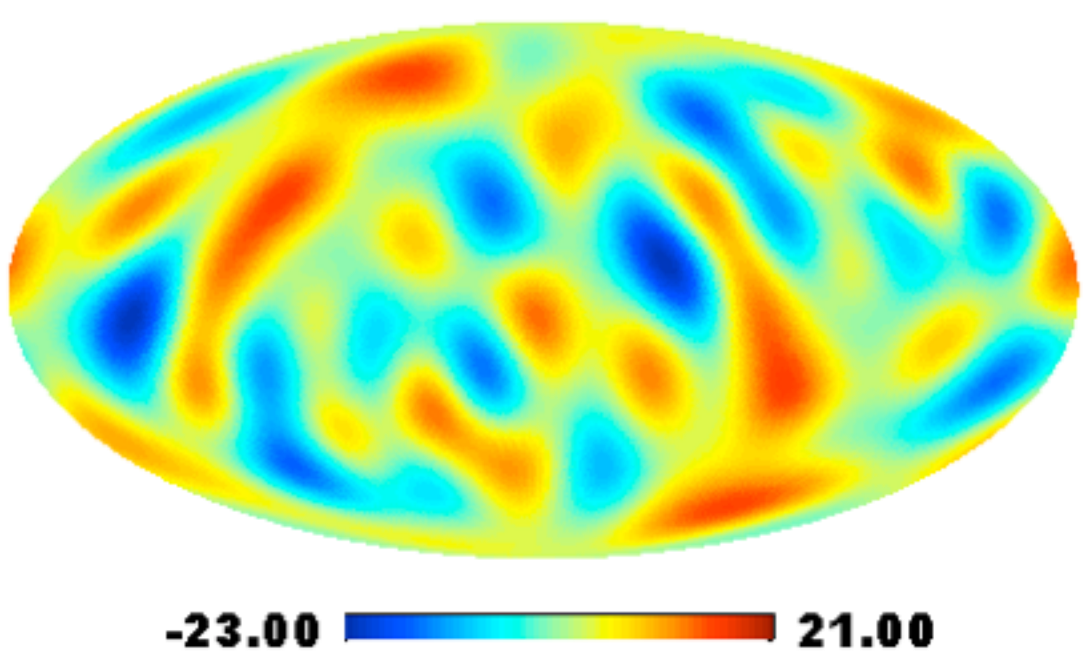

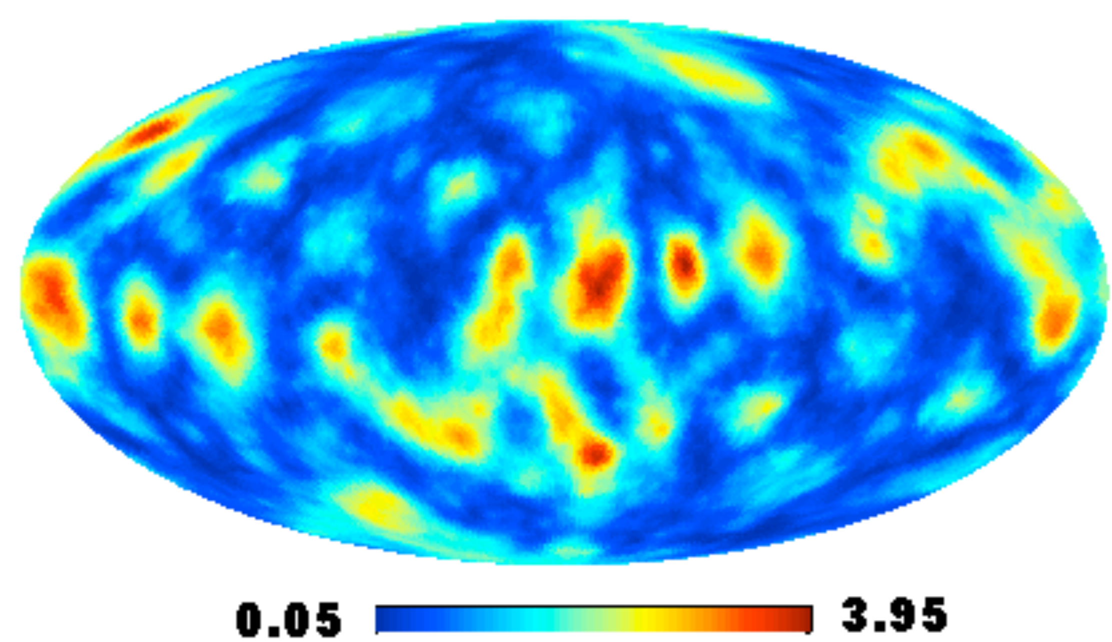

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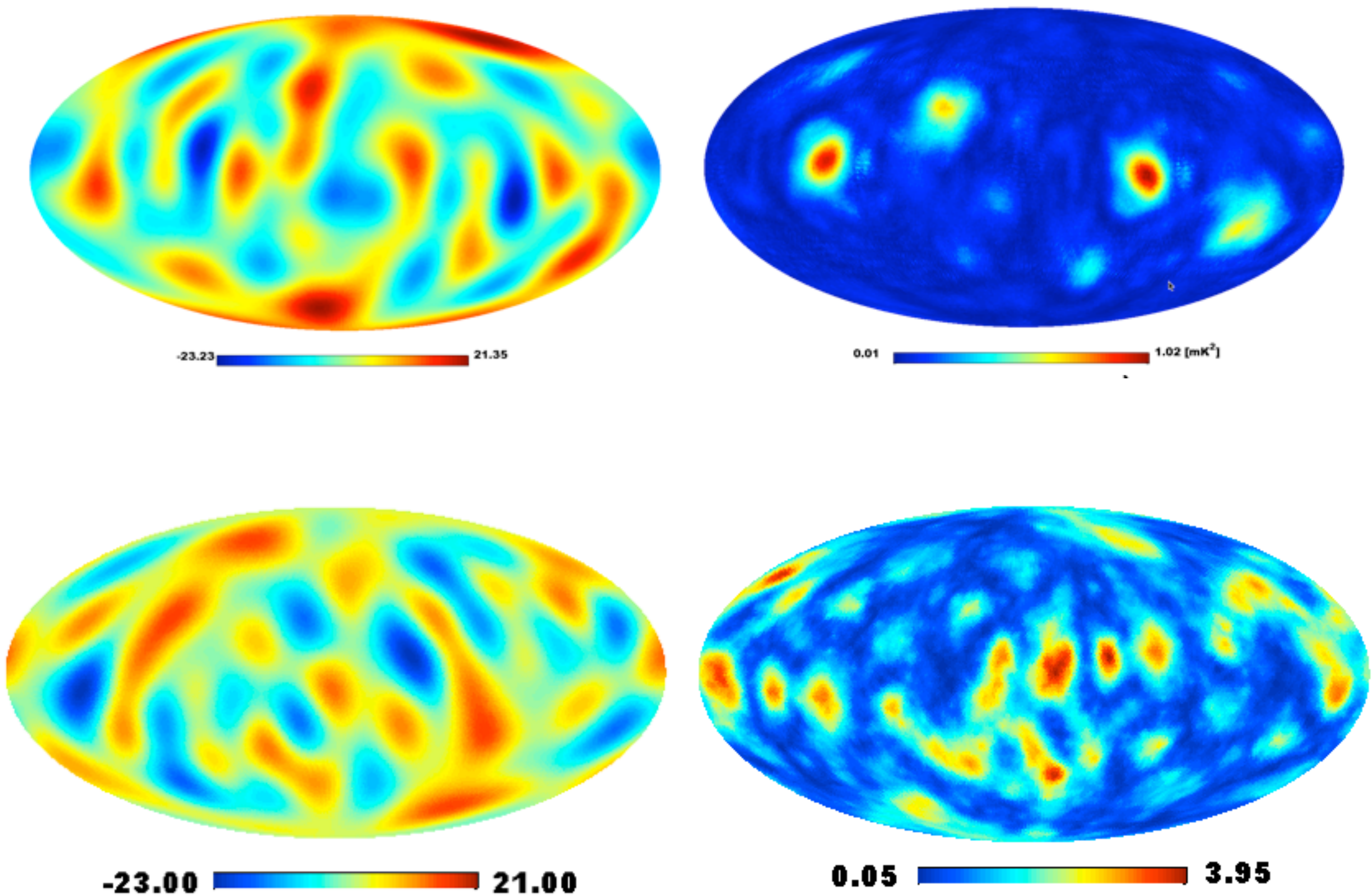

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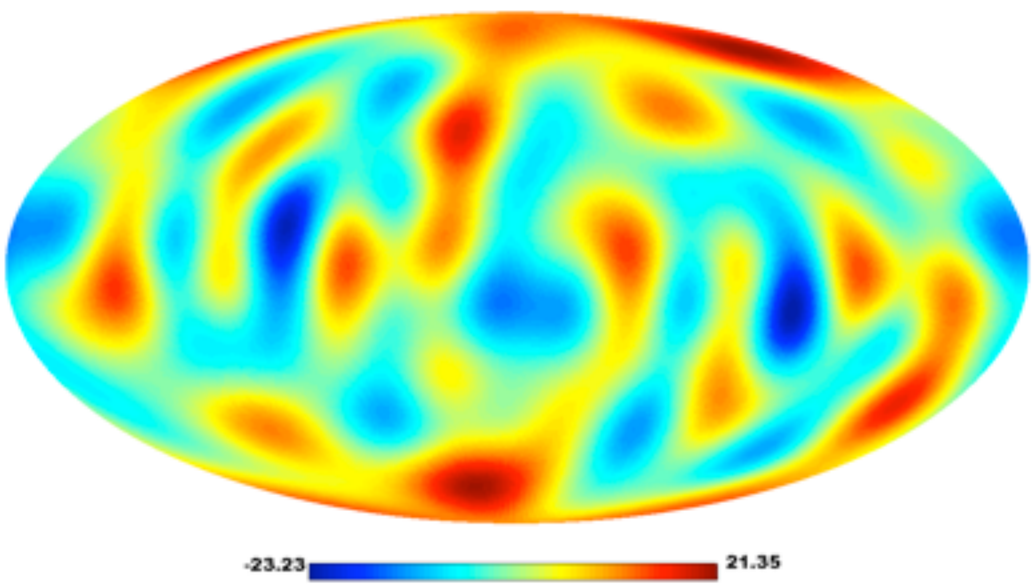

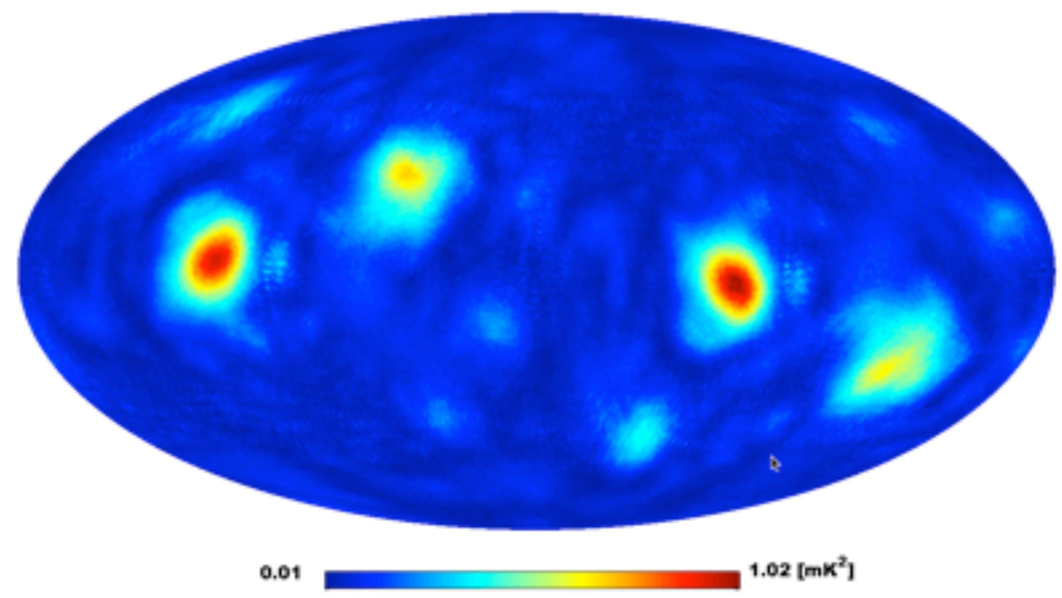

Real data:

Simulation vs. data: Moving PIP

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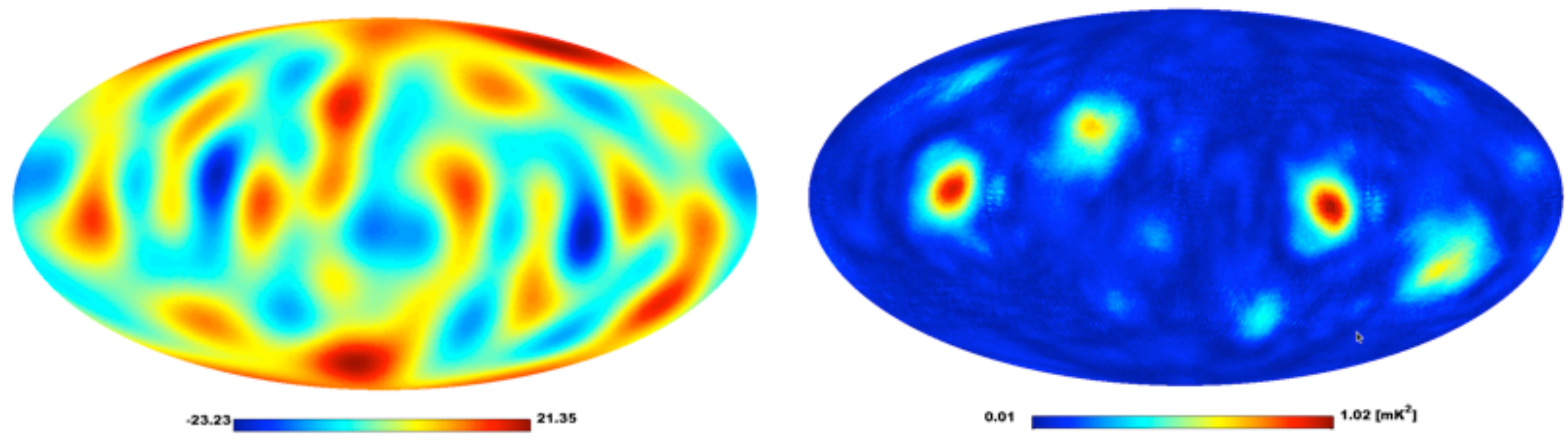

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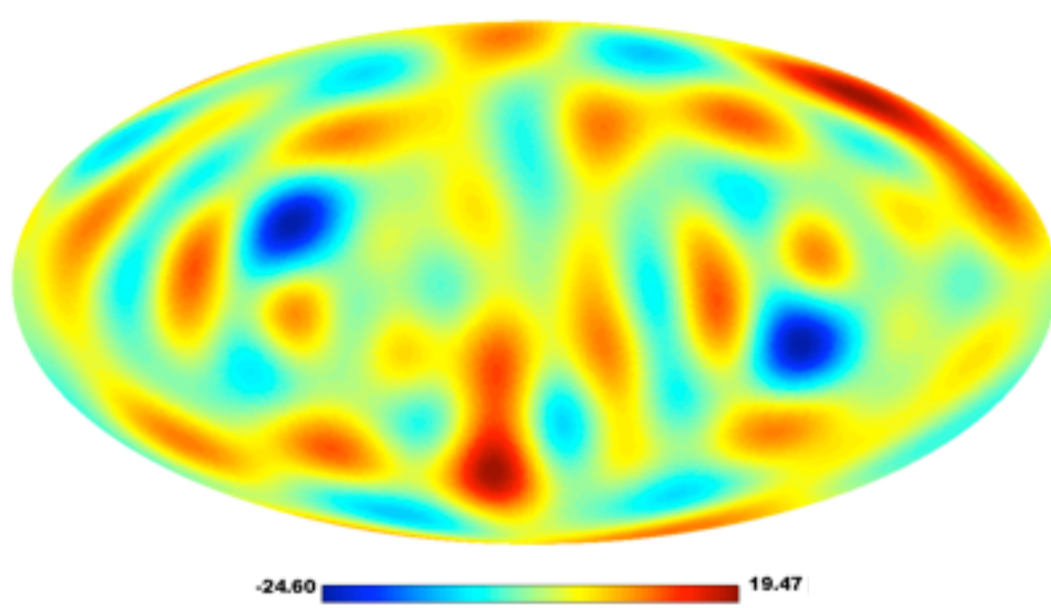

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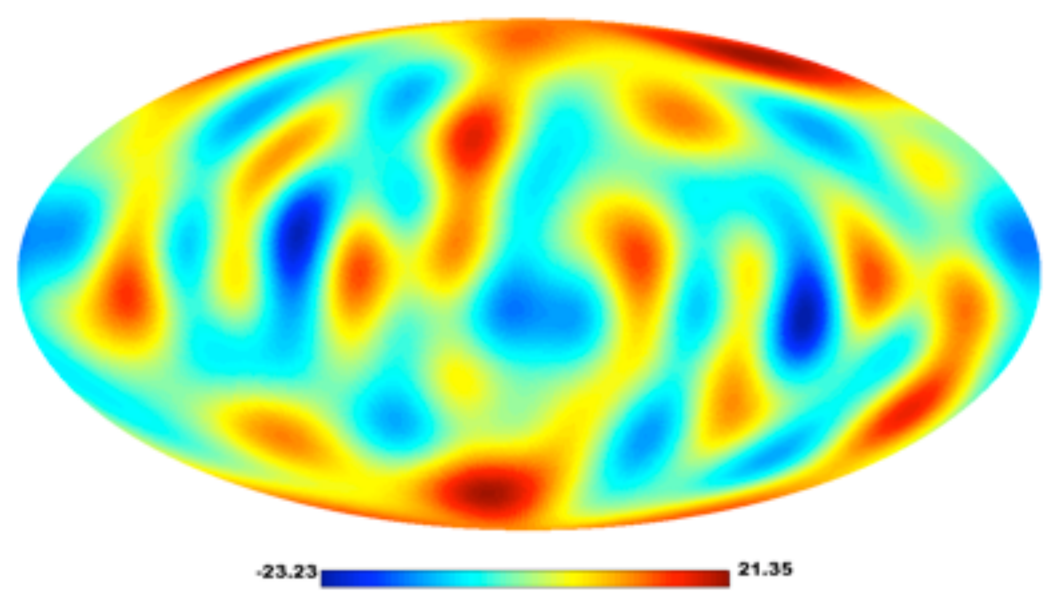

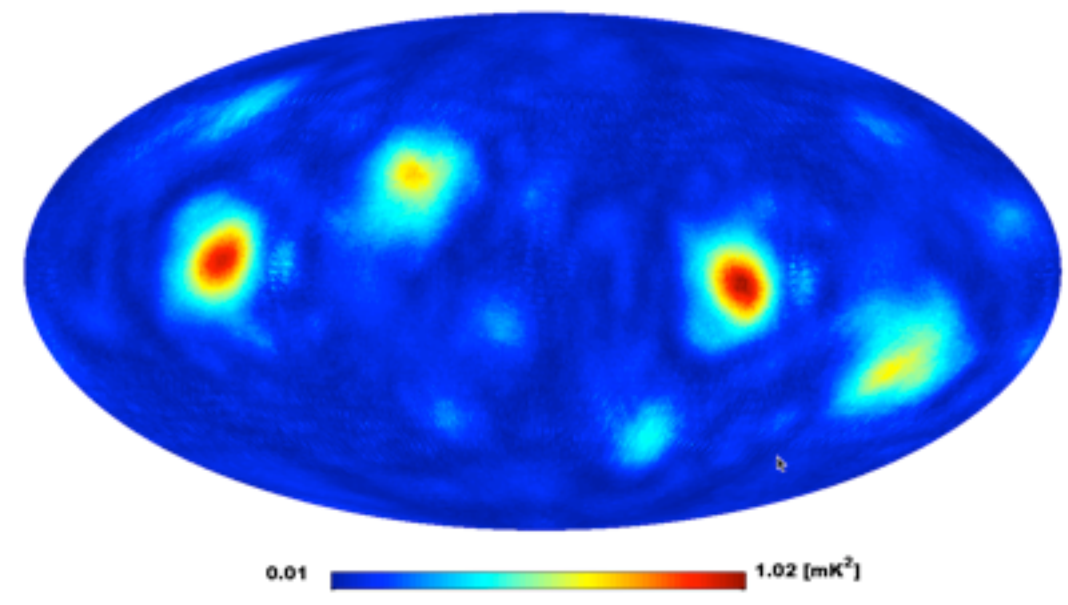

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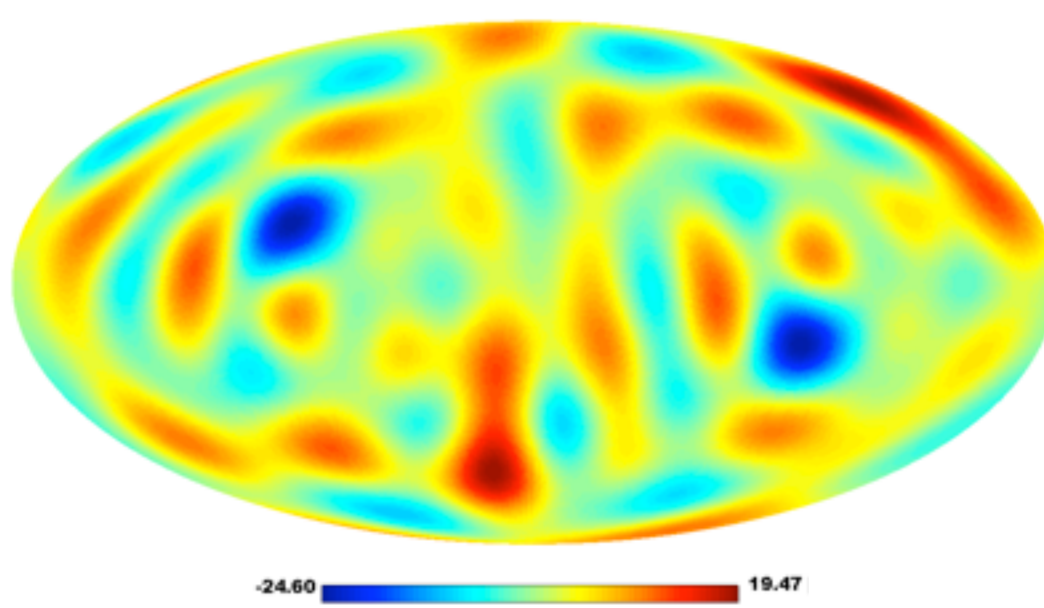

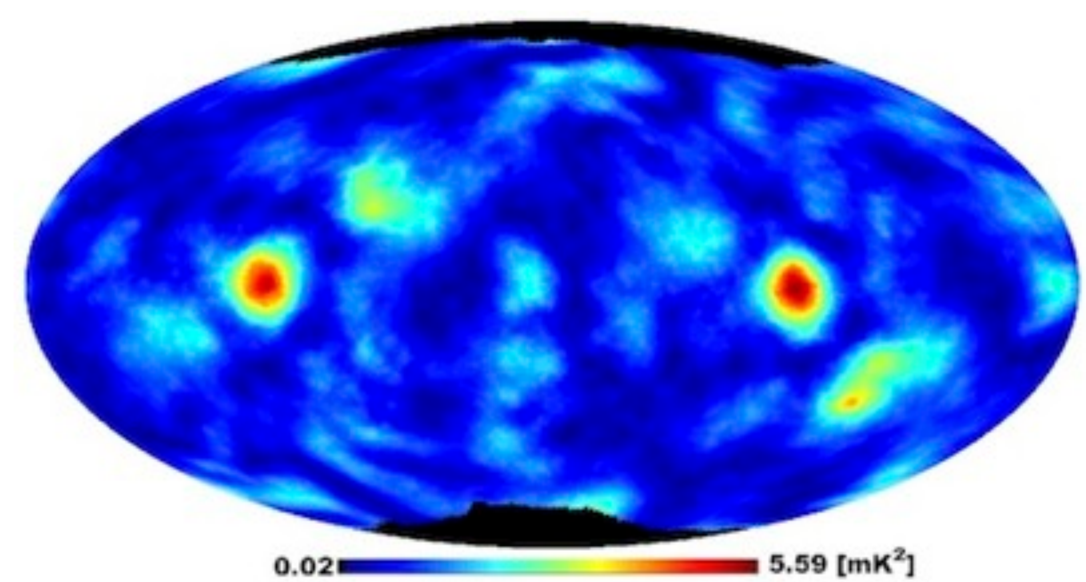

Constraining Parameter Space

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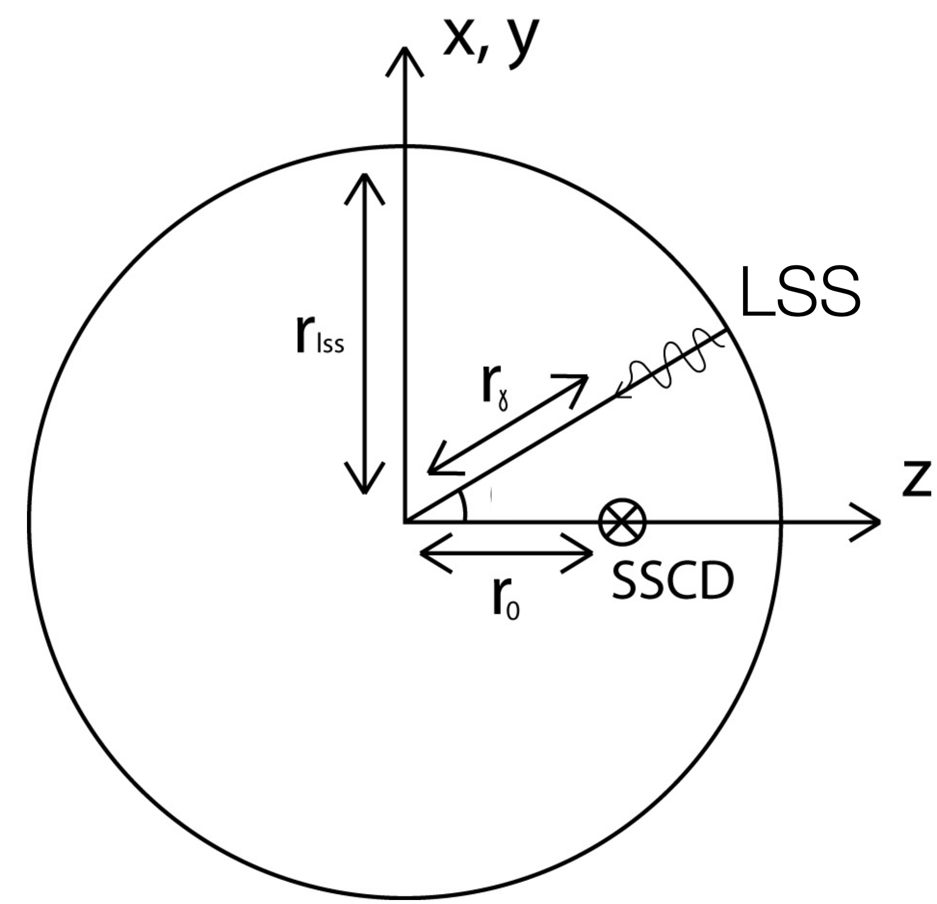

Constraining Parameter Space

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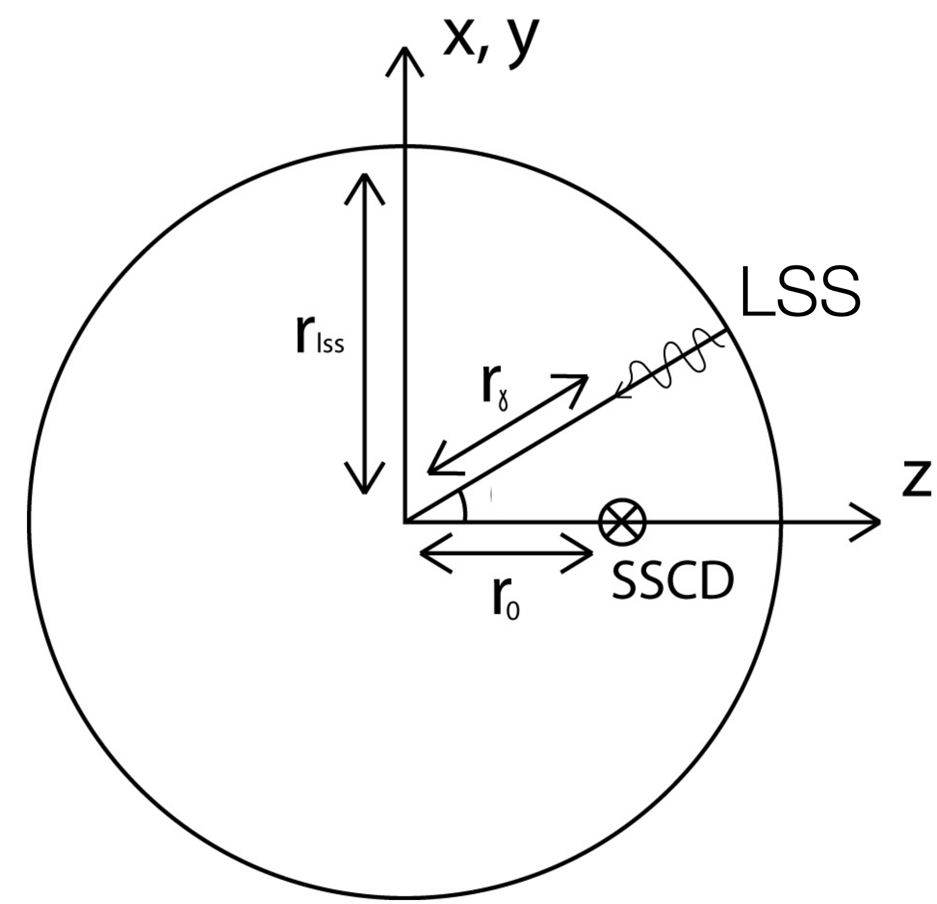

Constraining Parameter Space

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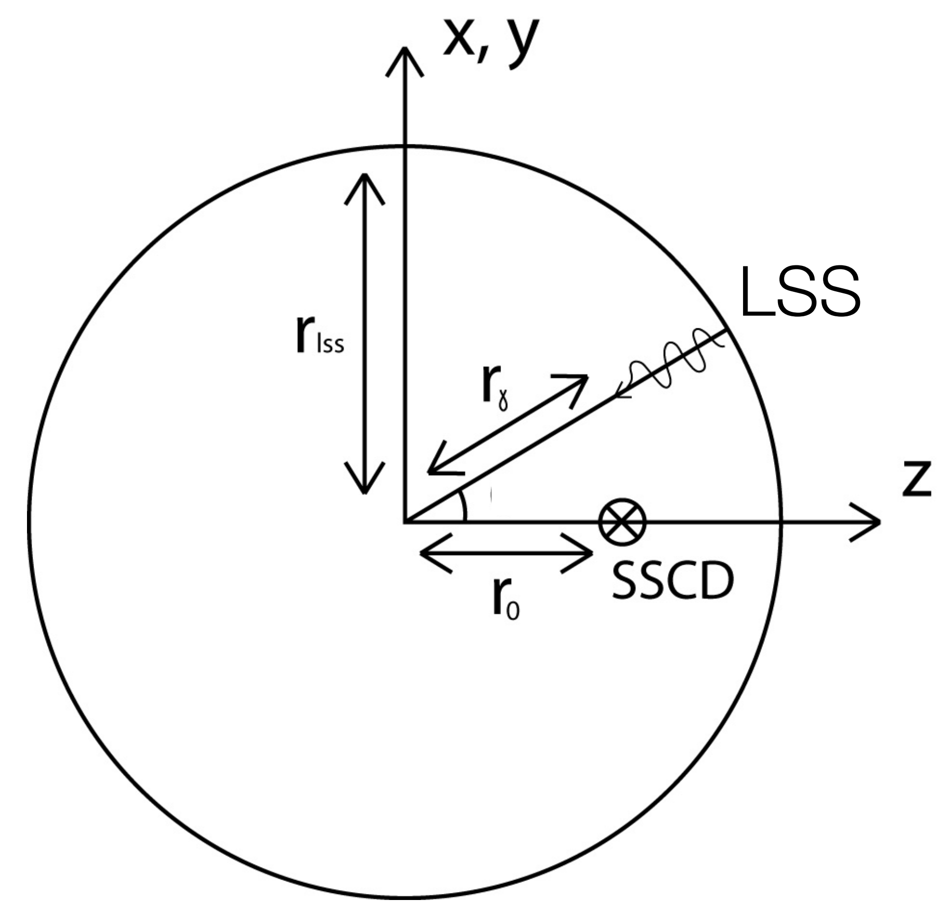

Constraining Parameter Space

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- Constrain the model with magnitude and location of:
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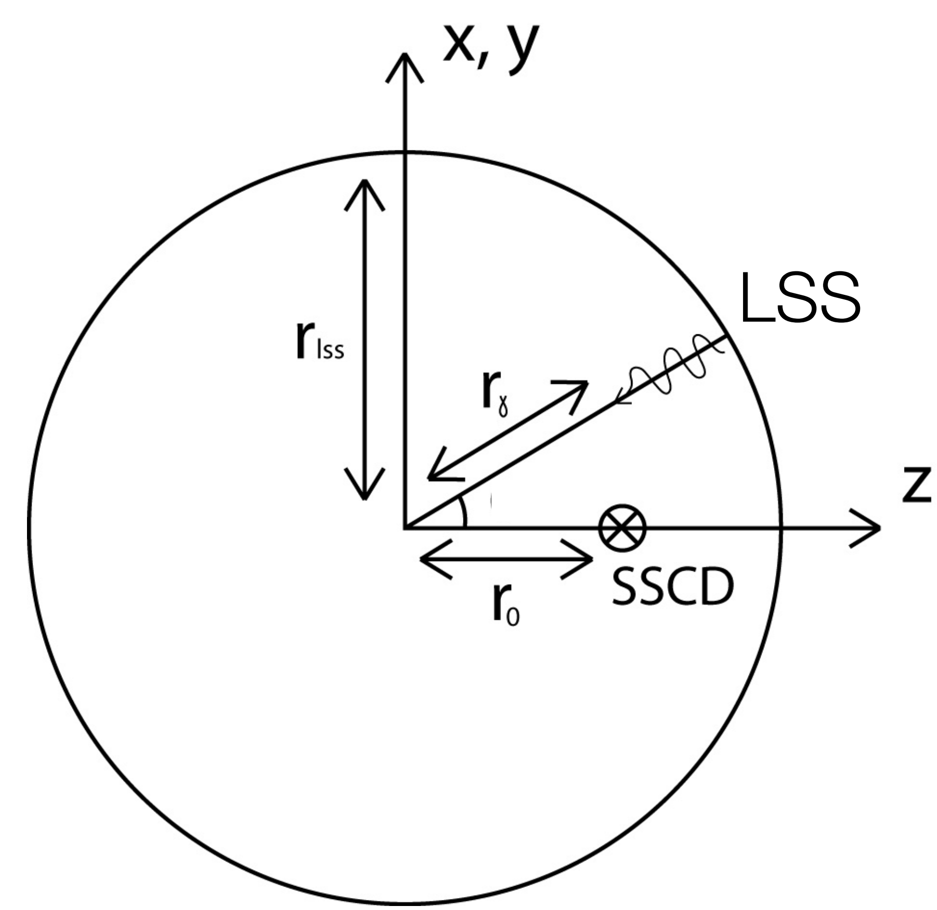

Constraining Parameter Space

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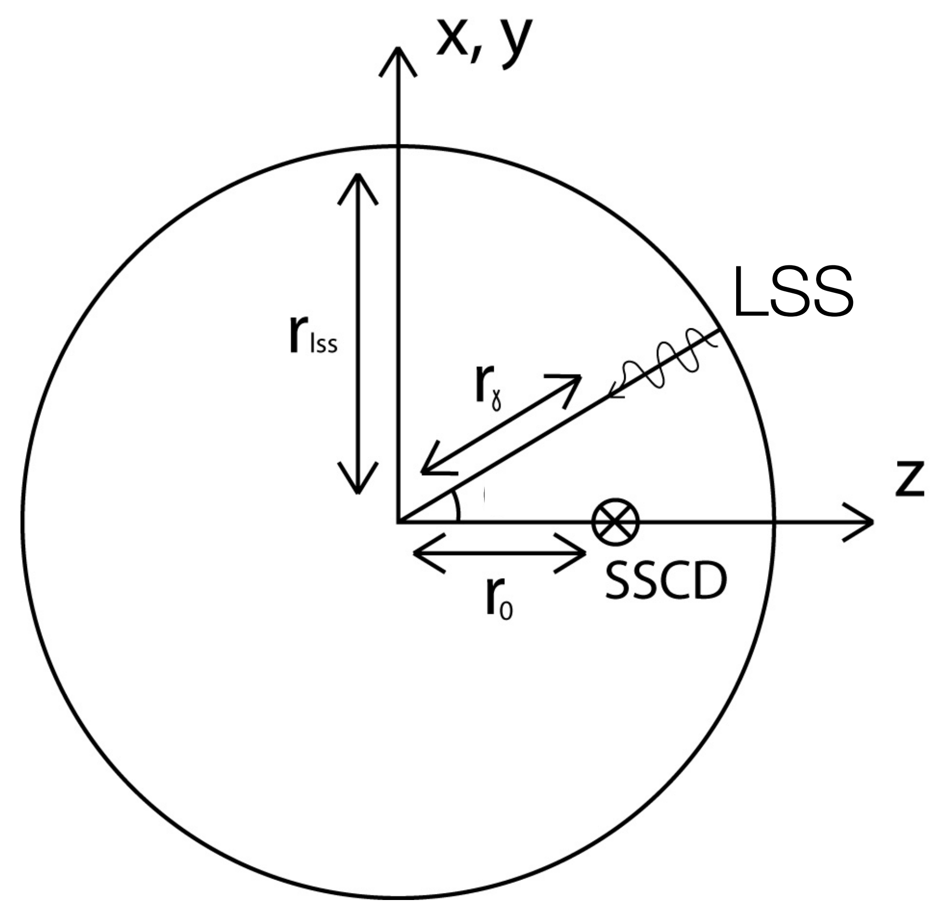

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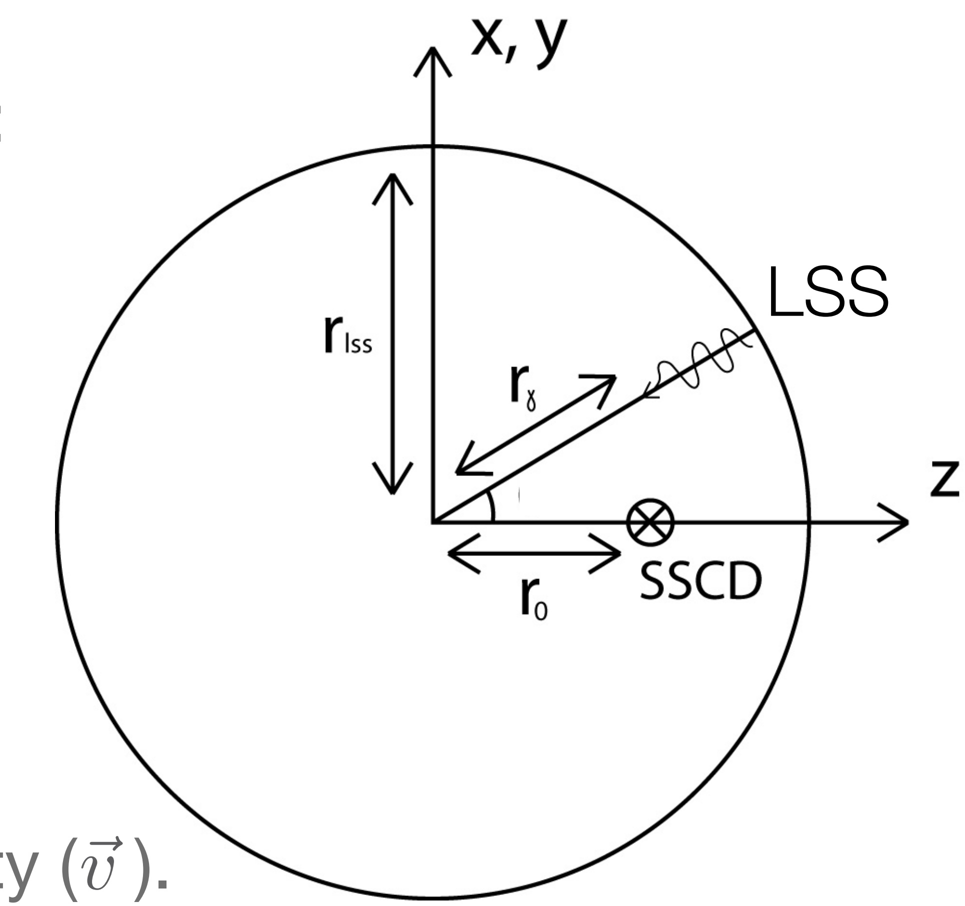

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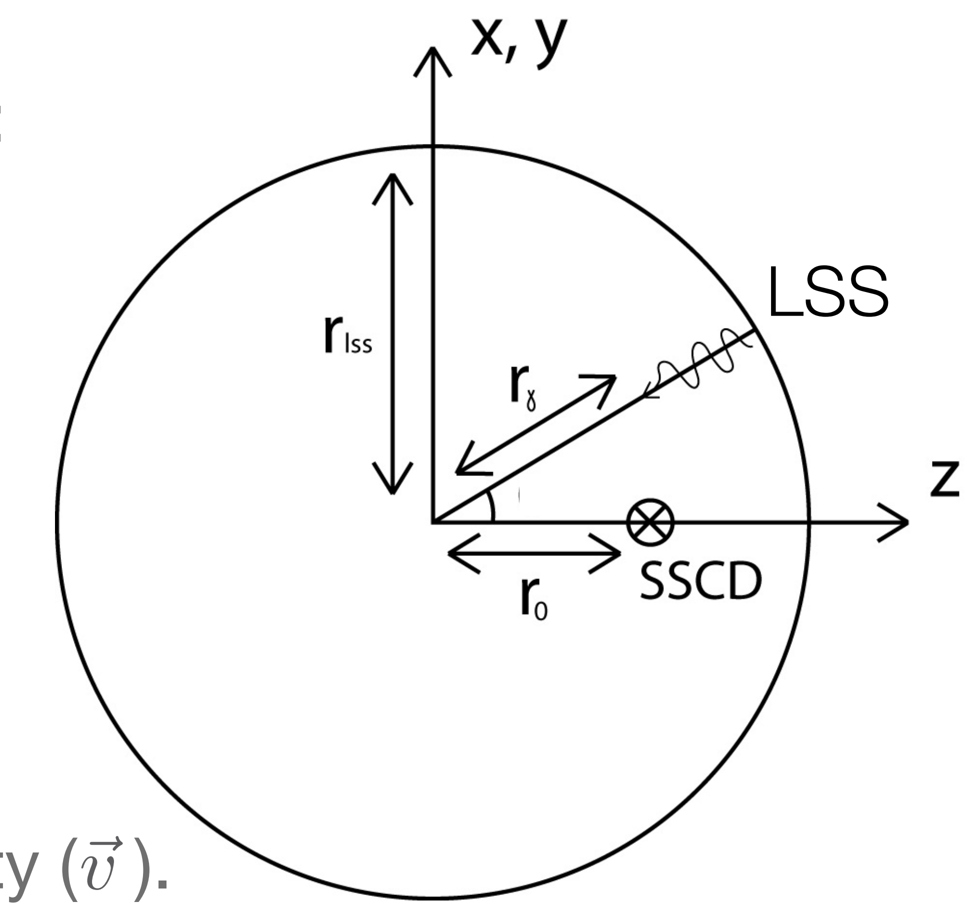

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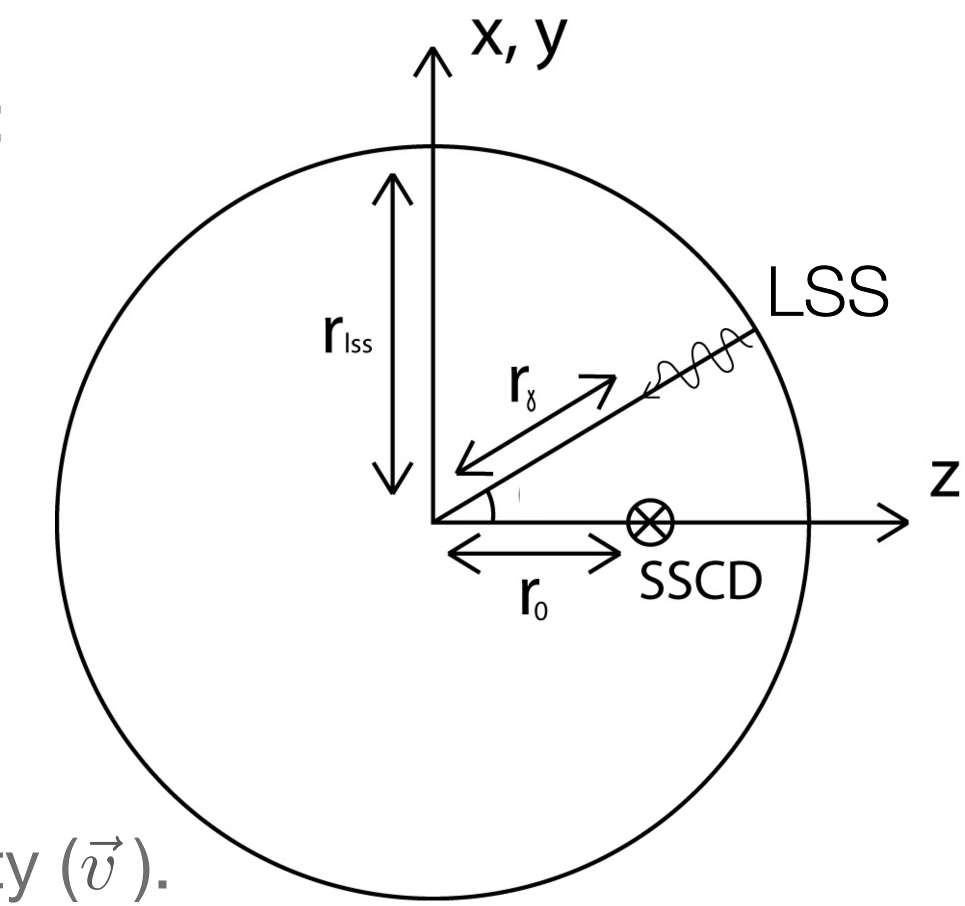

Future

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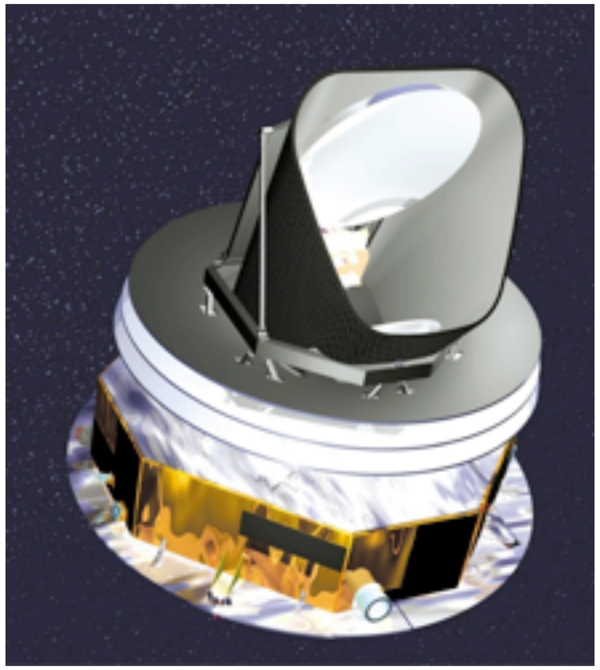
Using new observational data:



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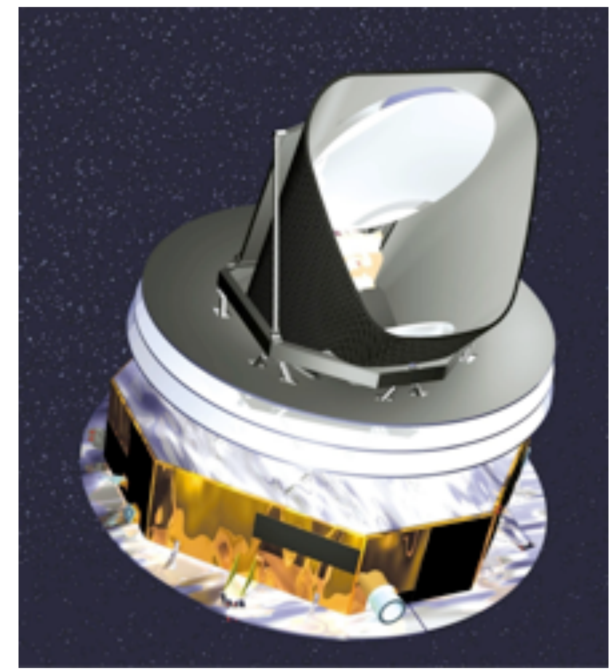

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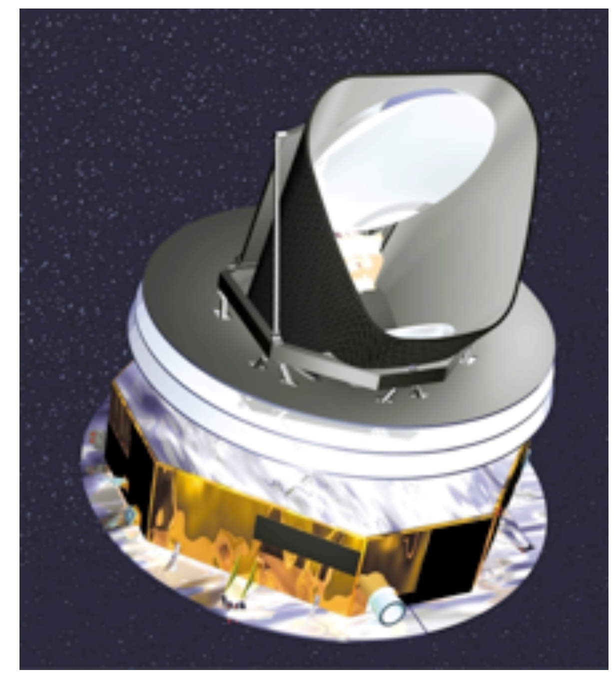

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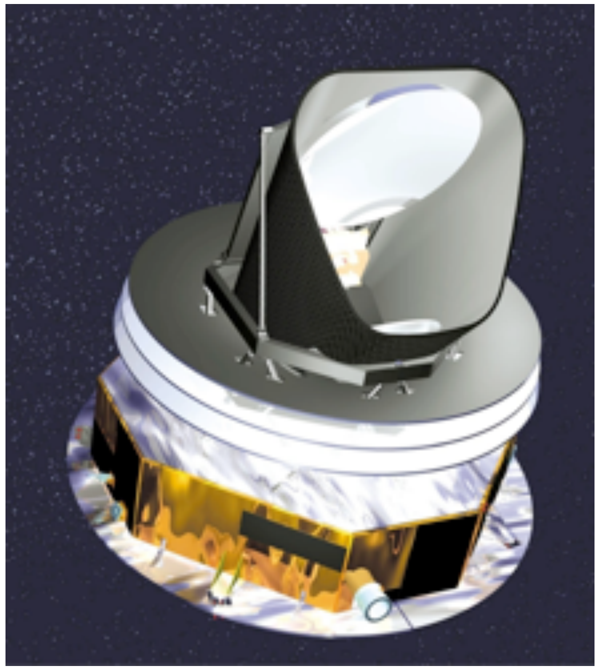

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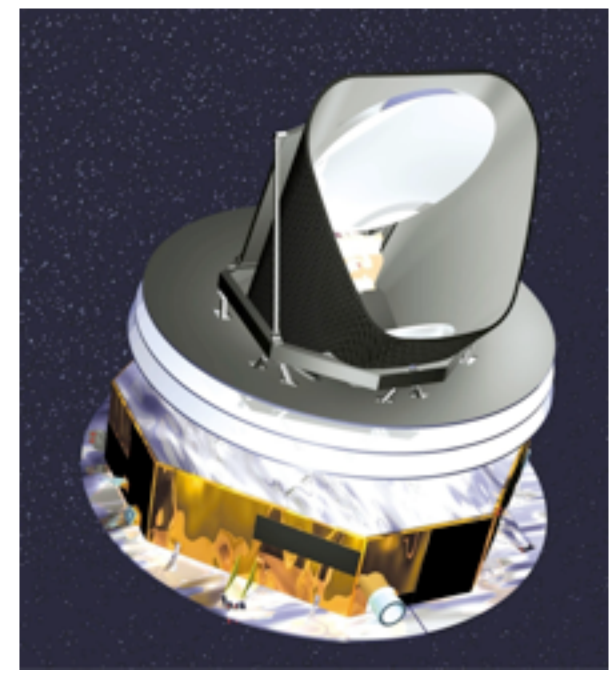

- SNIa: BF converges at high-z?

SCP Supernova Cosmology Project

Summary

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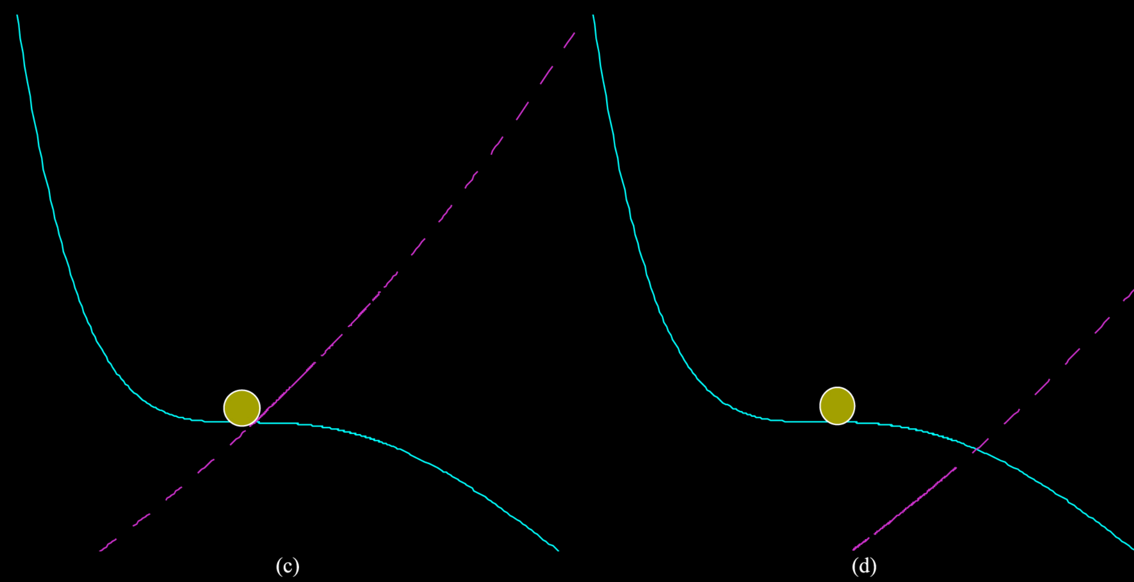

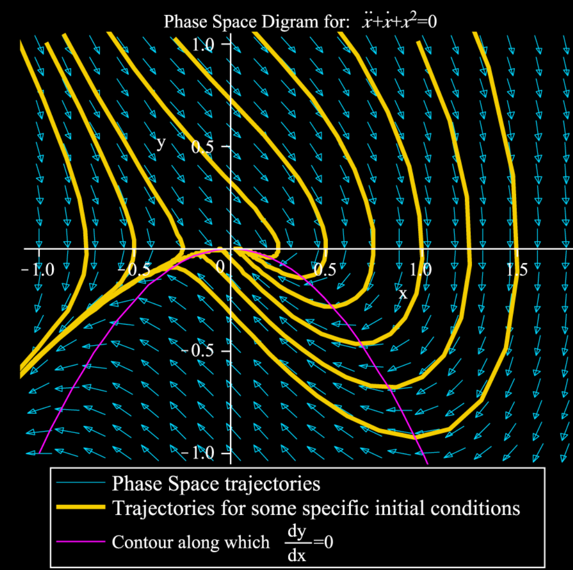

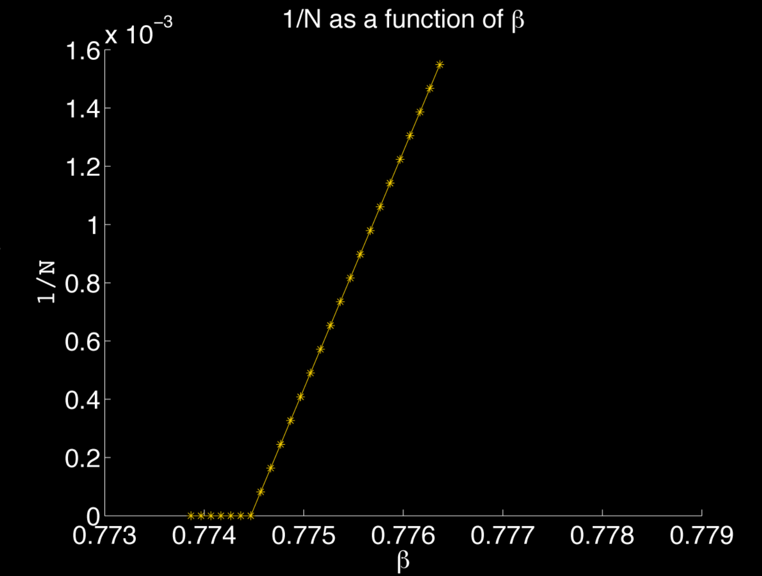

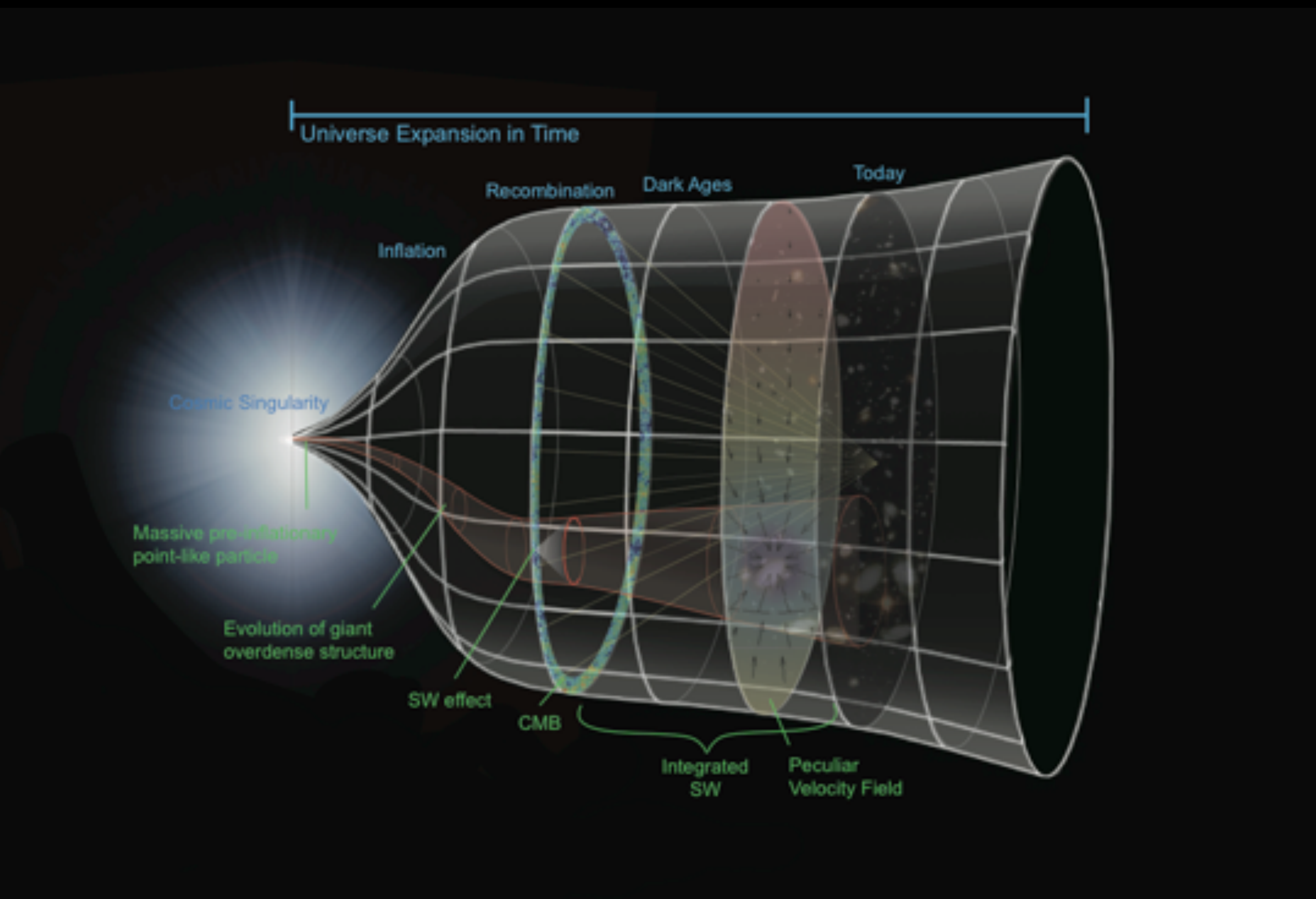

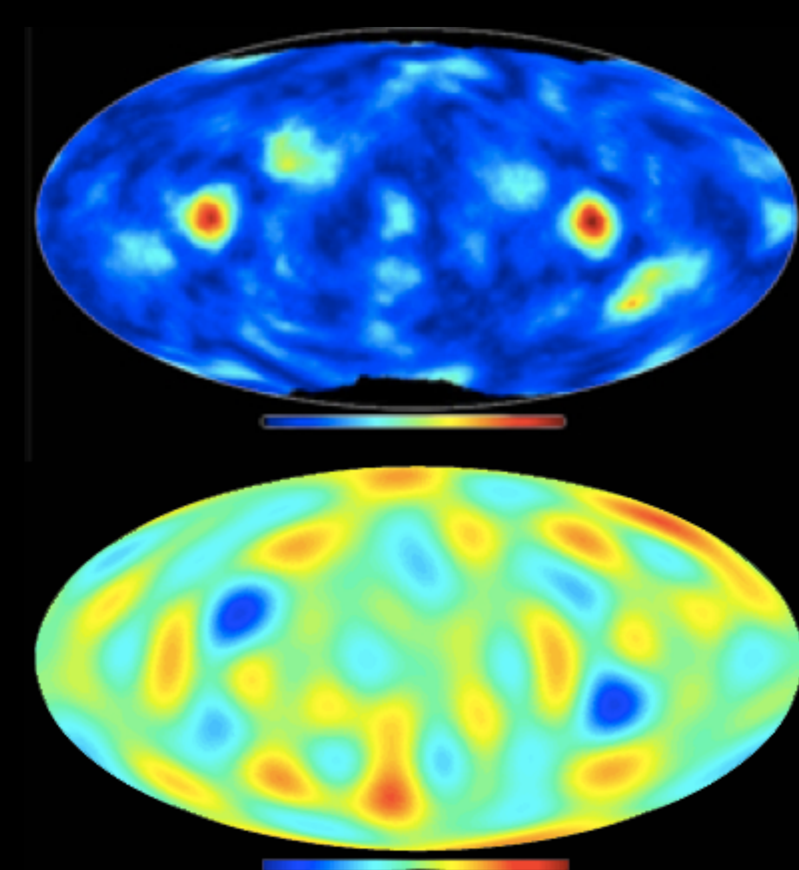

Thank You!

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