Phases and Generalized Phases of the Cosmic Microwave Background

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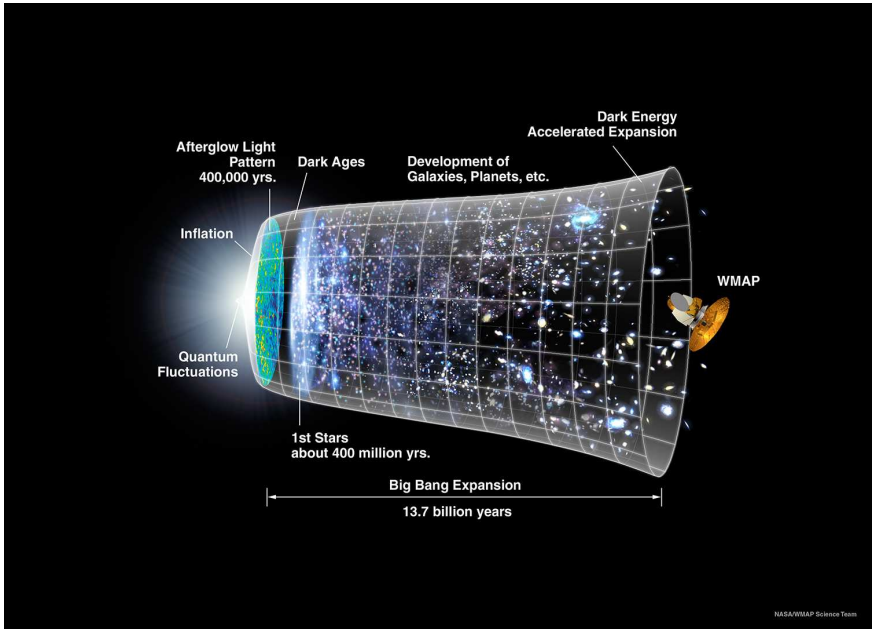
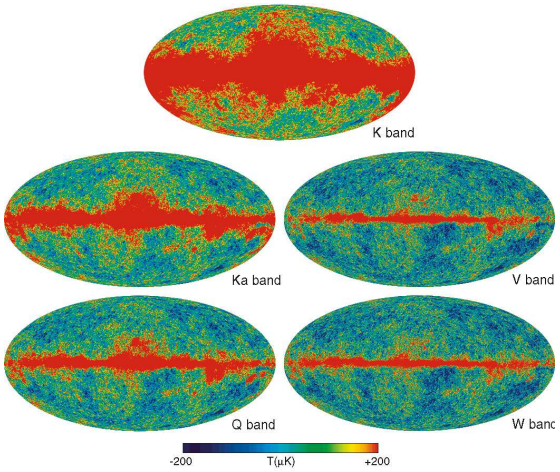
CMB physics

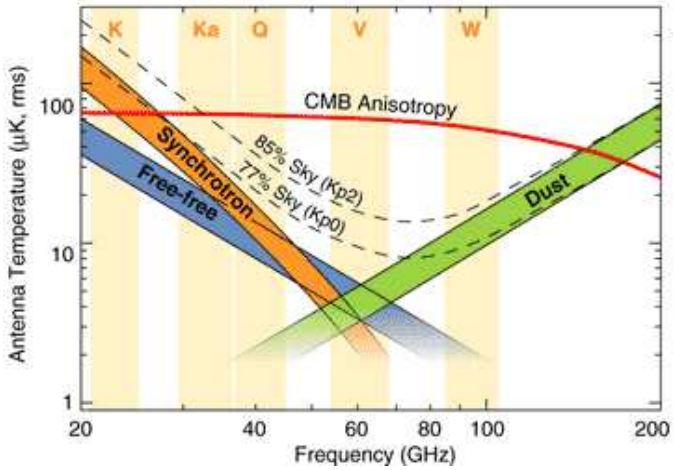


What can we learn from CMB?

- inflation - early Universe
- the Universe at the recombination epoch
- "foreground" effects

WMAP data





What are the data products?

- observations in 5 frequency bands: K, Ka, Q, V és W
- instrumental noise and additional foreground effects
- galactic contaminations

Mathematical tools

- spherical harmonics
- complex a_{lm} coefficients
- we need the ϕ_{lm} phases and $\Delta\phi_{lm}$ phase differences

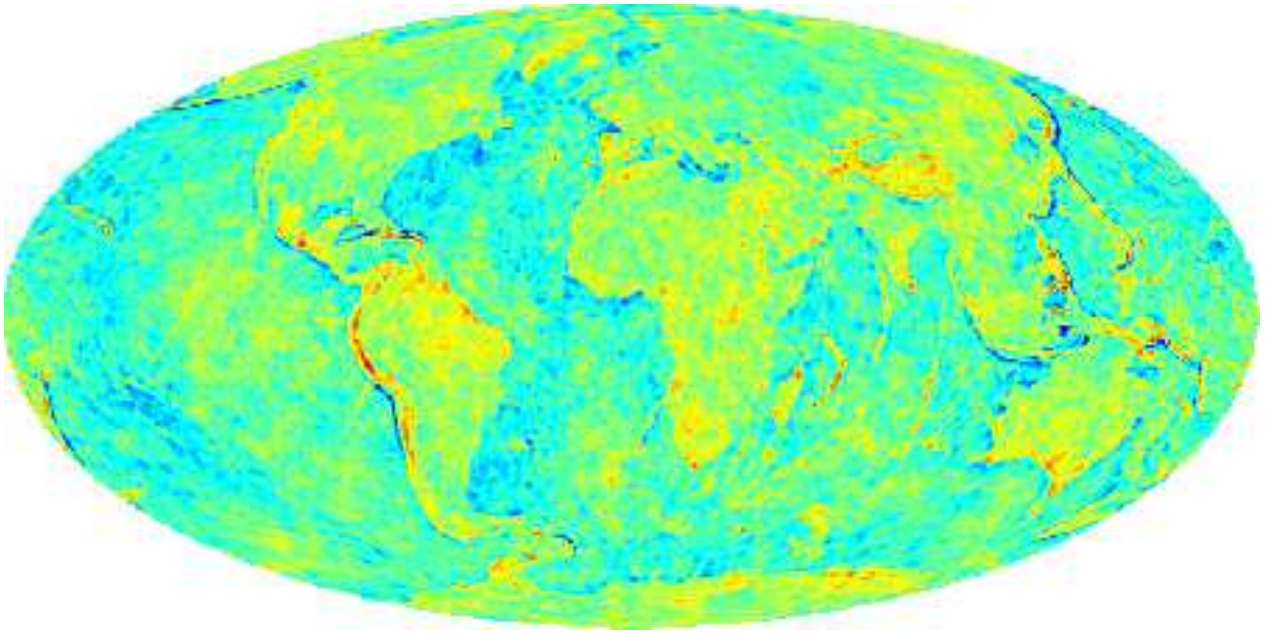
$$\Delta T(\theta,\phi) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi) \qquad a_{lm} = |a_{lm}| \cdot exp(i\phi_{lm}) \quad (1)$$

$$Y_{lm}(\theta,\phi) = (-1)^m \sqrt{\frac{(2l+1)(l-m)!}{4\pi(l+m)!}} P_{lm}(cos\theta) exp(im\phi) \quad (2)$$

$$\Delta\phi(l,m) = \phi_{l+1,m} - \phi_{l,m} \quad (3)$$

Why phases?

- uniformity and gaussianity according to inflationary models
- a_{lm} and ϕ_{lm} should be also random for physical reasons
- consequence: no information beyond the power spectrum
- but what if this is not the case...?



Problems to solve

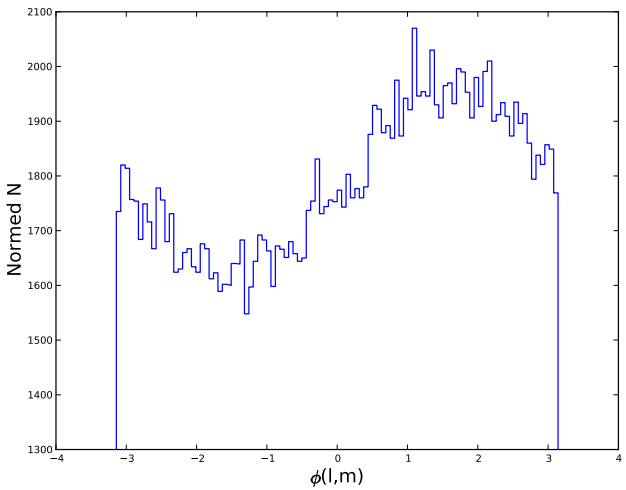
Phase distributions and "Axis of evil"

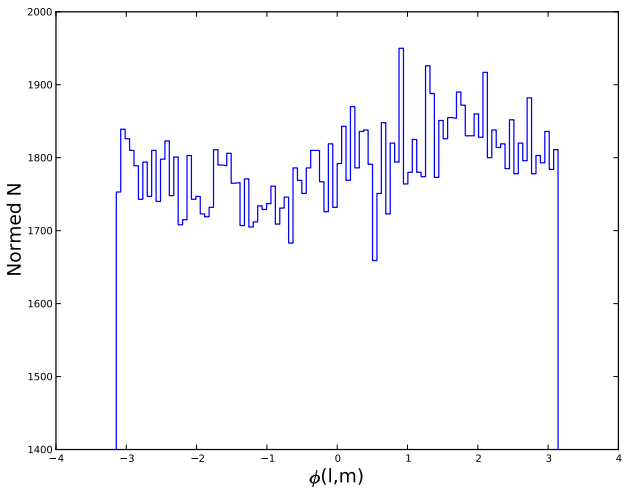
- non-gaussianities were reported using WMAP 1 year data relase
- phase correlations using all multipoles
- we review these types of non-gaussianities with latest data
- another kind of non-gaussianity: a few low-l modes have unusually correlated phases
- our solution: Generalized Phases

Phase representations and tests

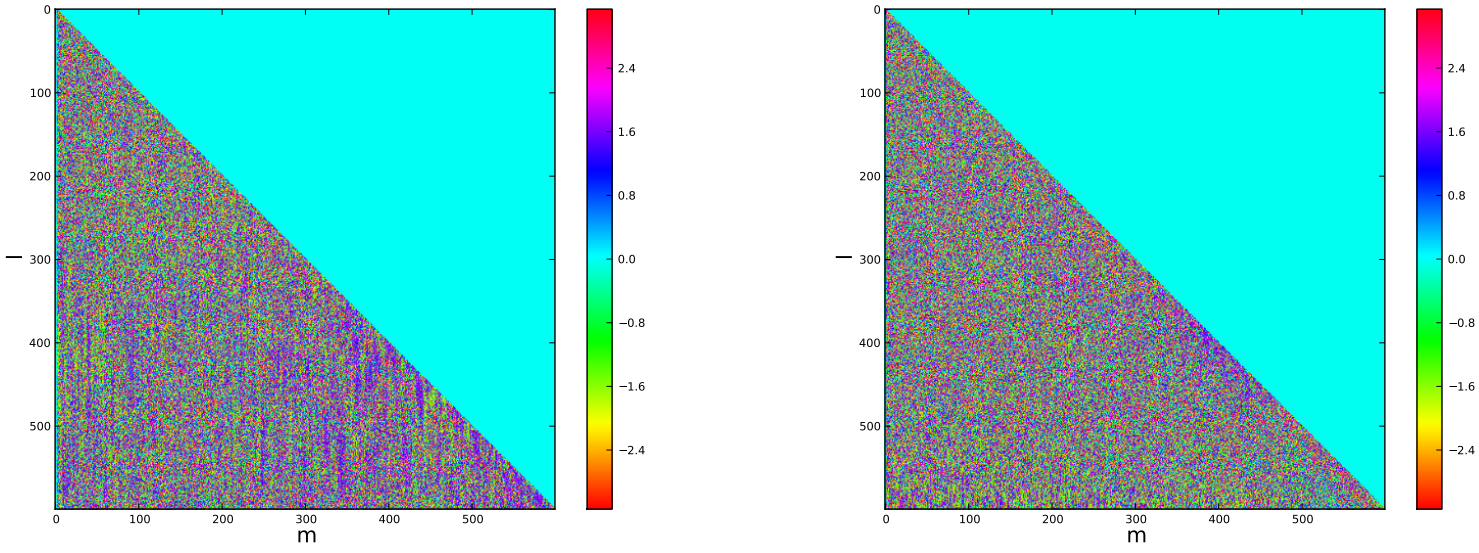
Histograms of WMAP1 and WMAP7

- statistics of ϕ_{lm}
- correlations by-eye
- significance tests (KS-test)
- $>4\sigma$ deviation from uniformity
- but does the signal come from all l-ranges?



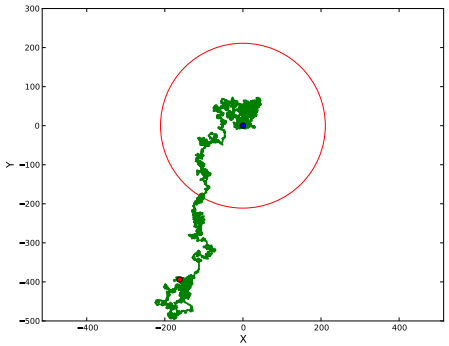


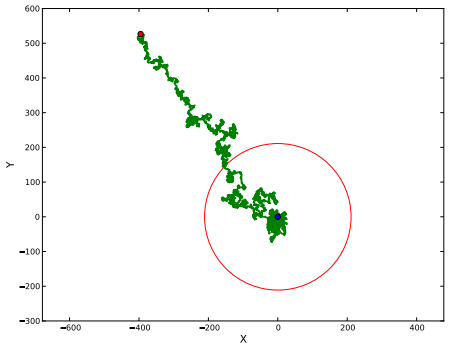
Visualization with colors

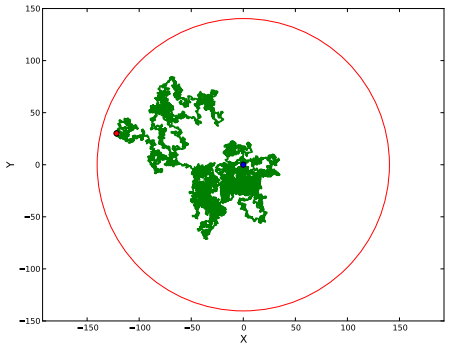


- correlations only from high l-ranges
- results using WMAP1 are more or less reproduced
- WMAP7 is cleaner but still correlated
- noise is high at $l > 200$ regions, unreliable results
- one more test...

Phases and random walks





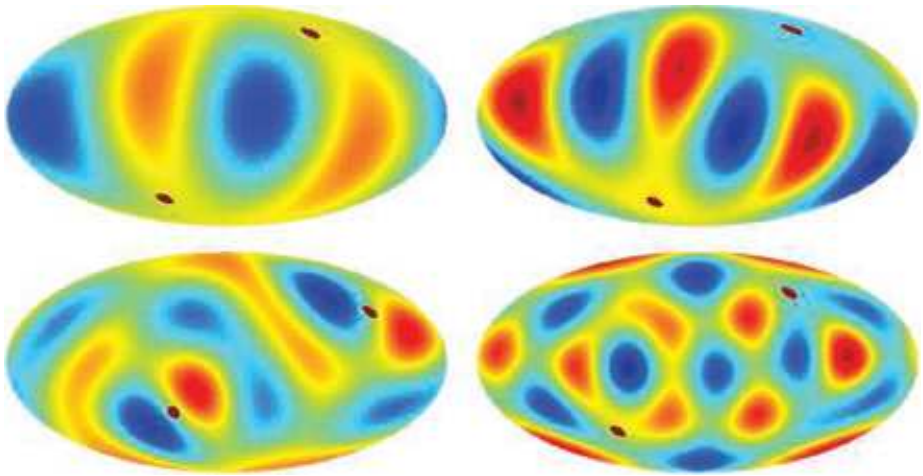


Why random walks?

- phases as steps in random directions with unit-length steps
- visual and statistical tool
- $l_{max} = 200$ - no significant deviation
- $l_{max} = 300$ -the distance travelled is $>4\sigma$ higher than from simulated RWs

The axis of evil

- a special type of non-gaussianity at low-l
- alignment of multipoles, randomness breaking
- the modes have correlated phases as well



Generalized Phases

A 3D direction needed...

- AoE statistics - one 3D vector at a given l
- Maxwell multipole vectors - l pieces of 3D at a given l (unclear definition because of several vectors)
- an l multipole has $(2l+1)$ m modes, using these we can define $(2l+1)$D vectors for all l
- normalizing these vectors we get unit vectors in a $(2l+1)$D space
- these structures are mathematically similar to the ordinary phase: rotation of a standard unit vector
- we can clearly define a $(2l+1)$D vector at each l, but we cannot easily compare or correlate them...

Summary

What are our most important results?

1. we reproduced WMAP1 results and found remnant non-gaussianities up to $l_{max} = 600$ in WMAP7
2. the origin of the non-uniformity is at high-l where noise is significant
3. based on RWs we obtained a $>4\ \sigma$ deviation from simulations
4. we started to work out the theory of the Generalized Phases

Thank you for your attention!

Any Questions?