Probing the early universe from the cosmic microwave background

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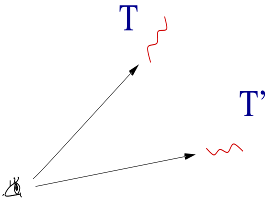
IAGRG-26

Outline of talk

- Statistical properties of the CMB.
- CMB as probe physics of early universe.
- Investigation of non-Gaussian deviations in the CMB.

Cosmic Microwave Background (CMB) Radiation



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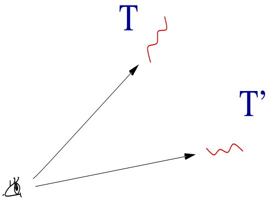
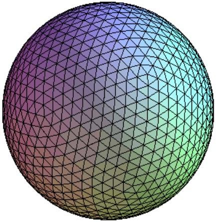


Background T_0



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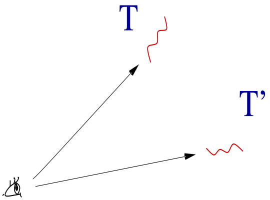

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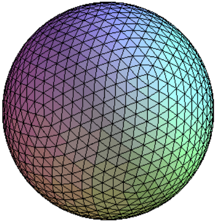
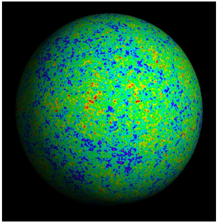


Fluctuation : $\frac{\Delta T}{T} \equiv \frac{T - T_0}{T_0}$



Properties of the CMB

Background:

- Black body spectrum with $\boxed{T_0 = 2.725 \pm 0.002\ \mu K}$

Fluctuations

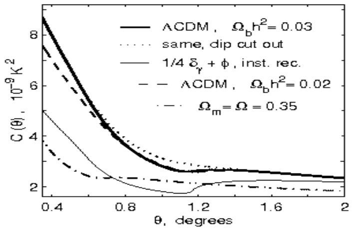
- Appear randomly distributed.
- Analyze by measuring statistical quantities.

  mean, PDF, rms, 2-point correlation, 3-point correlation, geometrical/topological quantities.

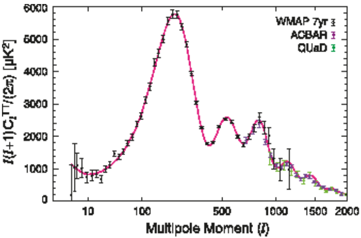
Properties of the CMB

Fluctuations : $\frac{\Delta T}{T}(\hat{n}) \longleftrightarrow a_{\ell m}$

- mean : zero by definition
- 1-point PDF : looks Gaussian
- rms $\simeq 10^{-5}$
- 2-point correlation : $C_\theta \equiv \langle \frac{\Delta T}{T} \frac{\Delta T}{T} \rangle_\theta \longleftrightarrow C_\ell \equiv \frac{1}{2\ell+1} \sum_m |a_{\ell m}|^2$



Bashinsky & Bertschinger (2001)



Larson et al (2010)

What physical process in the Universe produced the CMB ?

- Set up physical scenario how CMB photons would have evolved from past till today.
- Solve evolution equation for ΔT and obtain C_ℓ.
- Big bang picture : Universe was smaller, denser, hotter in the past due to expansion. Must have been a time when CMB photons were tightly coupled with matter.

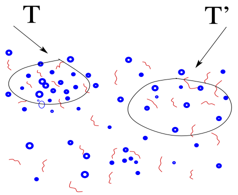
Physics of CMB

- At decoupling epoch

  $\sim$ universe filled with plasma of photons, electrons, protons, dark matter, etc.

  $\sim$ coupled by electromagnetic interaction and gravity.

  - Photons and baryons – one fluid with one equilibrium temperature, T.
  - T fluctuates from region to region : assuming some initial density fluctuation.



- Decoupling : mean free path of photons $\gg$ H^{-1}, $H \equiv \frac{\dot{a}}{a}$

Physics of CMB

[Peebles (1970)]

- Basic quantity : photon distribution function

$$f(p, T) = f_0 + \delta f$$

Then,

$$\Delta T \propto \delta f$$

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  - Boltzmann equation : $df/dt = C[f]$.
  - Perturbed Einstein's equation : $g_{\mu\nu} \to a(t) + \delta g_{\mu\nu}$.

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- The equations :
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- Schematically :

$$\Delta T(today, here, \hat{n}) \propto \int_{t_i}^{today} dt \; \{all \;\; possible \;\; sources\}$$

Physical properties of the universe encoded in the CMB

C_ℓ is primordial power spectrum $P(k)$ modulated by the physical events around decoupling epoch and later.

$$
\begin{aligned}
C_\ell &= \int dk\ k^2\ P(k)\ \Delta_\ell^2(k) \\
C_\ell &\equiv C_\ell \left\{ P(k)\ \mathrm{parameters}, \Omega_\Lambda, \Omega_c, \Omega_b, \tau, \ldots \right\}
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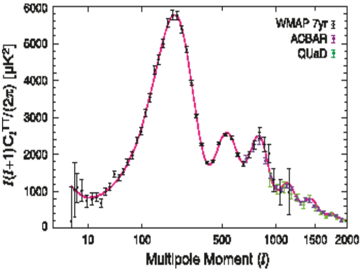
Assuming scale-invariant $P(k)$ we get theoretical C_ℓ that matches the observed one.

Physical properties of the universe encoded in the CMB : extraction of cosmological parameters

Assume $P(k) = \frac{A}{k^3}\left(\frac{k}{k_0}\right)^{n_s-1}$



Parameters best fit with WMAP 7 years data [Larsen et al (2011)]:

- $n_s = 0.963 \pm 0.014$
- $A = (2.43 \pm 0.11) \times 10^{-9}$
- $\Omega_\Lambda = 0.734 \pm 0.029$
- $\Omega_c = 0.1109 \pm 0.0056$
- $\Omega_b = (2.258^{+0.057}_{-0.056}) \times 10^{-2}$
- $\tau = 0.088 \pm 0.015$

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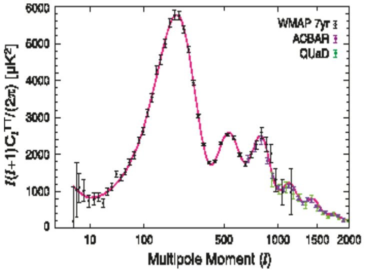

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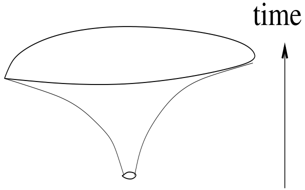
Any early universe description that attempts to explain the primordial perturbations must predict such a almost scale-invariant power spectrum.

Inflation: Origin of primordial perturbations

$\ddot{a} > 0$



Regions of space which were in causal contact and local equilibrium get stretched beyond causal contact.

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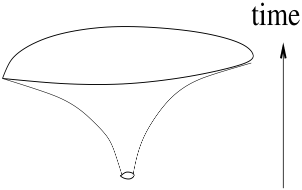

Regions of space which were in causal contact and local equilibrium get stretched beyond causal contact.

- Typically realised as the slow rolling of a scalar field called inflaton down its potential $V(\phi)$. Quantum fluctuations of inflaton produce density and metric perturbations.

$$\delta\phi \Longleftrightarrow \delta g_{\mu\nu} \longrightarrow \Phi$$

- Accelerated expansion of space dilutes the perturbations.

CMB as probe of inflationary physics: generic predictions of inflation

- Scalar perturbations with almost scale-invariant power spectrum.

$$P_\Phi(k) \sim \langle \Phi_k \Phi_k \rangle \simeq \frac{A}{k^3} \left(\frac{k}{k_0} \right)^{n_s - 1}$$

$$A \propto \frac{V}{\dot{\phi}}, \quad (n_s - 1) \propto \left(\frac{dV}{d\phi}, \frac{d^2 V}{d\phi^2} \right)$$

- Tensor perturbations (or gravity waves) with almost scale invariant power spectrum.

$$P_T \propto V$$

- Almost Gaussian distribution of perturbations.

These predictions are manifestations of the shape of the inflaton potential.

CMB as probe of inflationary physics: Hints of deviations of scalar power spectrum from scale invariance

- Running of n_s : $\frac{dn_s}{d\ln k} = -0.034 \pm 0.026$
- Outliers in C_ℓ : Few ℓ's at which the measured C_ℓ values are outside the theoretical curve.

$$\ell = 2, 22, 40$$

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- Could indication of scalar power spectrum with deviations from scale-invariance at specific scales.
  Oscillations [Hamann et al (2007), Adams & Sarkar (2001)]
  Cut-off at some scale followed by a bump [Hodges et al (1990), Leach & Liddle (2001), Sinha & Souradeep (2004), Jain et al (2008)]
- Non-trivial features in the inflaton potential ? Discontinuities, or transition of different power law regimes,. . . .

CMB as probe of inflationary physics: Tensor perturbations

- Detection of gravity waves generated during inflation would be a direct probe of the energy scale at which inflation occurred.
- However not directly detectable by present day experiments.
- Parametrized in terms of tensor-to-scalar ratio r.

$$r \equiv \frac{P_T}{P_\Phi}$$

CMB as probe of inflationary physics: Tensor perturbations

- A small fraction of the CMB photons are expected to be polarized, due to quadrupole anisotropies, as decoupling commences.

- The polarization vector is usually expressed as
  - E modes which are curl free.
  - B modes which are divergence free.

- WMAP has detected E modes.

- B modes have not been detected yet. The amplitude of its power spectrum scales with r. Hence its detection is direct measure of r.

- WMAP 7 limits : $r < 0.36 (95\% CL)$

Non-Gaussian deviations : beyond the power spectrum

• Non-Gaussian deviations provide a means to distinguish and rule out models of inflation.

Q. Are the CMB temperature fluctuations Gaussian ?

• Measure higher order statistics : 3-point function, 4-point function, etc in real or multipole space.

OR

• Geometrical/Topological quantities whose Gaussian formula are known and which encode n-point functions of all orders.

Non-Gaussian deviations

Non-Gaussian deviation of Φ

$$\Phi \sim \Phi^G + \Delta\Phi$$

Amplitude and shape of $\Delta\Phi$ is dependent on the inflation model.

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Amplitude and shape of $\Delta\Phi$ is dependent on the inflation model.

- If perturbations evolve linearly during decoupling epoch and later, ΔT must inherit its statistical properties from Φ. By studying properties of ΔT, we are 'directly' probing Φ.

Non-Gaussian deviations

Issues: non-Gaussian signals in observed ΔT can come from

1. non-Gaussian Φ : primordial
2. subsequent non-linear evolution of ΔT : secondary
3. observational contaminants in the process of detection.

Each of these needs to be understood and disentangled to be able to identify true primordial non-Gaussian signal.

How to understand non-Gaussian deviations of Φ

- Simulations of non-Gaussian maps with $\Delta\Phi$ predicted by different inflation models as input, serve as testing ground for theoretical expectations and observational systematics.
- Also useful for designing optimum statistical estimators for each type of $\Delta\Phi$.
- Measure same observables from observational data.
- Compare the theoretical predictions and measurement from observational data.

Form of non-Gaussian Φ

Some references (biased): Salopek & Bond (1990), Gangui et al (1994), Maldacena (2003), Linde & Mukhanov (1997), Lyth, Sasaki & Wands (2001), Enqvist & Takahashi (2006)

Consider expansion to cubic order as:

$$\Phi(\vec{x}) = \Phi^G(\vec{x}) + f_{NL}\left((\Phi^G(\vec{x}))^2 - \langle(\Phi^G)^2\rangle\right) + g_{NL}(\Phi^G(\vec{x}))^3 + \ldots$$

- Characterized by non-linearity parameters f_{NL} and g_{NL}.
- *Local* since the non-linear contributions depend only on same spatial point.

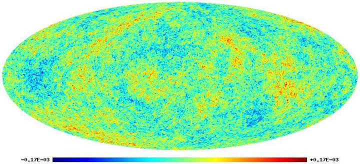
Note : simplified form, ignores the complicated scale-dependence of the 3-pt function.

Effect of f_{NL} on CMB maps

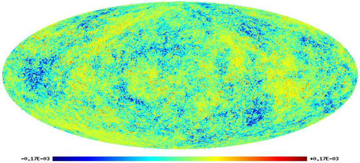
Liguori et. al. (2003)

Resolution = 13 arcmin:

Gaussian $\longrightarrow$



$f_{NL} = 3000 \longrightarrow$

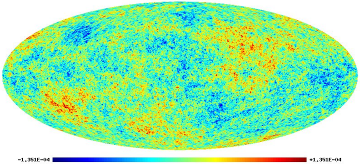


Effect of g_{NL} maps

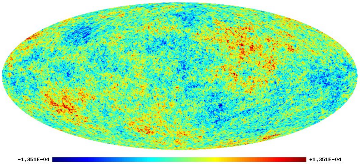
Chingangbam & Park (2009)

Resolution $= 30$ arcmin:

Gaussian $\longrightarrow$



$g_{NL} = 5 \times 10^6 \longrightarrow$



Measuring non-Gaussianity

- Define statistical tools sensitive to non-Gaussianity on harmonic space, pixel (real) space, wavelet space,. . ..
- Each statistic may be optimal for specific types of non-Gaussianity.
- Different observables/statistical tools complement each other and provide cross checks.

Constraints on $f_{\rm NL}$ and $g_{\rm NL}$ from WMAP data

- assume that measured ΔT contains either $f_{\rm NL}$ or $g_{\rm NL}$ type non-Gaussianity
- find the value of $f_{\rm NL}$ or $g_{\rm NL}$ which best fits the data.

Latest constraints:

- $f_{\rm NL}$ using bispectrum from WMAP 7 yr data, Komatsu et al (2010) :

$$-10 < f_{\rm NL} < 74 \quad (95\% CL)$$

- g_{NL} using trispectrum from WMAP 5 year data, Smidt et al (2010) :

$$-7.4 \times 10^5 < g_{\rm NL} < 8.2 \times 10^5 \quad (95\% CL)$$

Minkowski Functionals

Gott et al (1990)

- Geometrical/topological statistics defined on the temperature fluctuation field.

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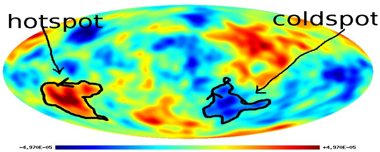
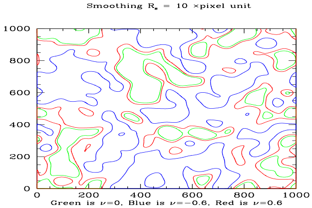
- Define threshold: $\nu \equiv \frac{\Delta T/T}{\sigma_0}, \quad \sigma_0 = \sqrt{\langle \frac{\Delta T}{T} \frac{\Delta T}{T} \rangle}$.





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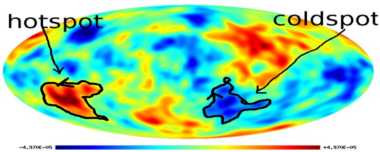
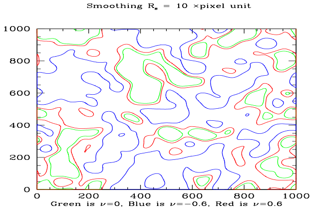




- Area fraction above threshold $\sim V_0(\nu)$
- Contour length of iso-temperature contours $\sim V_1(\nu)$
- Genus = number of hot spots - number of cold spots $\sim V_2(\nu)$

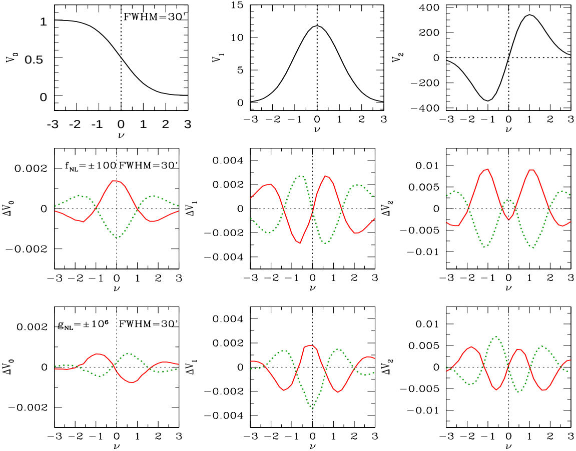
Minkowski Functionals

Hikage et al (2003), Hikage et al (2008), Chingangbam & Park (2009), Chingangbam, Rossi & Park (in preparation), Matsubara (2010)

Gaussian $\longrightarrow$

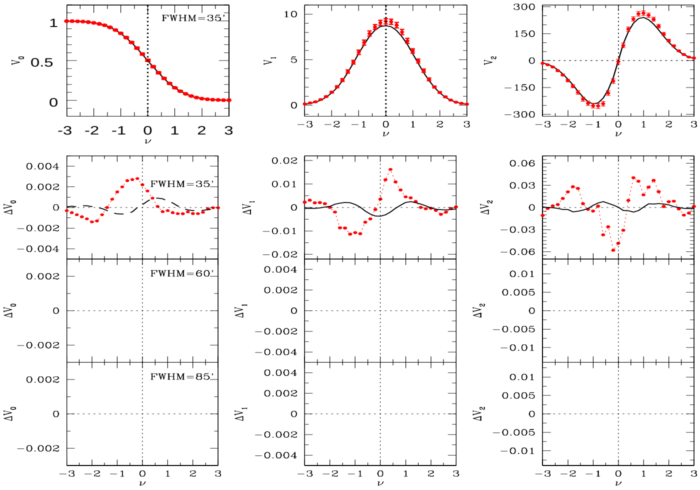
$f_{\rm NL}$ $\longrightarrow$

$g_{\rm NL}$ $\longrightarrow$



Minkowski Functionals from WMAP data

Chingangbam and Park (in preparation) from WMAP 5 years data



Minkowski Functionals from WMAP data

- Non-Gaussian deviations are present in the data.
- The area-fraction seems to prefer f_{NL} type non-Gaussianity.
- There is no clear agreement on the shape of the deviations of all 3 Minkowski Functionals for f_{NL}.
- g_{NL} deviations also do not agree with data.
- Indicates that we need to understand if these deviations are coming from residual contaminants and systematic errors.

Betti numbers

Park, Chingangbam, Weygaert, Pranav, Hellwing & Hidding (in preparation)

- At each ν the temperature field breaks up into connected components and 'circular' holes.
- Define the Betti numbers for a 2 dimensional field
  - β_0 : the number of connected components at each ν.
  - β_1 : the number of circular holes at each ν.
- The genus is a linear combination of β_1, β_0

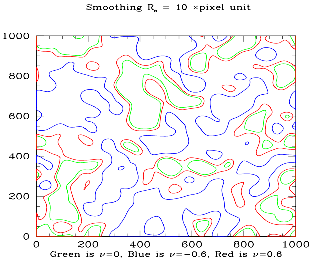
$$g = \beta_1 - \beta_0$$

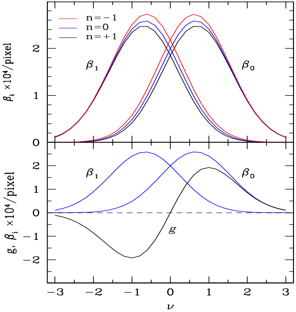
- Using β_1, β_0 can potentially give us more information about non-Gaussian deviations than the genus.

Betti numbers

Park, Chingangbam, Weygaert, Pranav, Hellwing & Hidding (in preparation)

- Analytic expressions of β_1, β_0 for a Gaussian field are not known.
- Numerically computed them for Gaussian simulations.





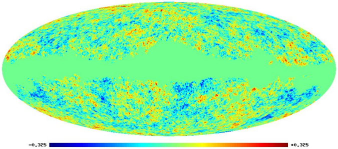
- We are currently applying them to non-Gaussian simulations.

Residual galaxy contamination in the cleaned WMAP data?

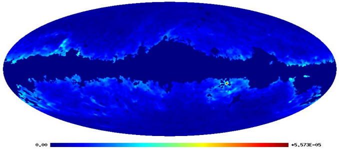
Chingangbam & Park (work in progress, requires more investigation)

- Take WMAP 7 years data

Cleaned CMB map



Foreground map: g



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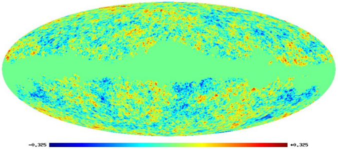

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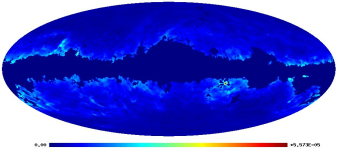
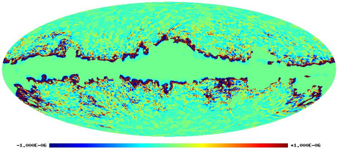


- Construct galaxy peak field: $p \equiv g^{35} - g^{105} - < g^{35} - g^{105} >$



Residual galaxy contamination in the cleaned WMAP data?

- Scale CMB and peak fields by their rms values $\rightarrow$ $\nu^{\rm CMB}$, $\nu^{\rm gal,peak}$.

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- Correlate the two : $r \equiv < \nu^{\rm CMB} \nu^{\rm gal,peak} >$.

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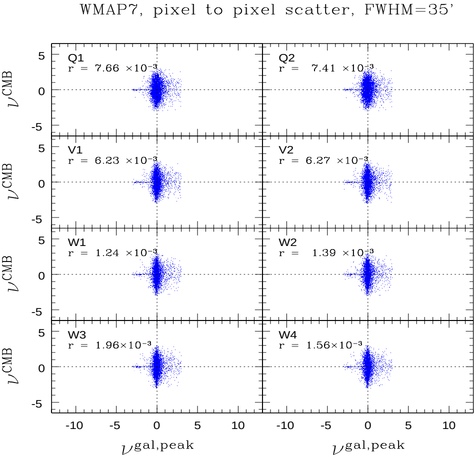

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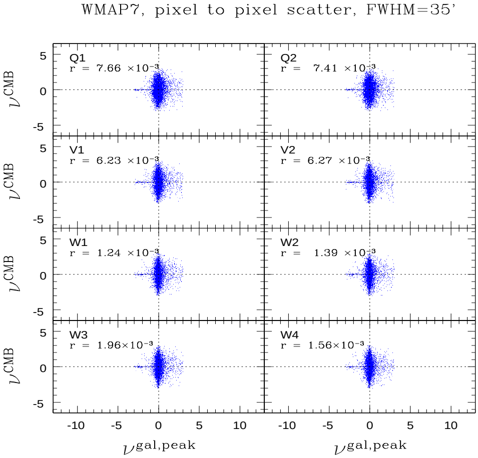
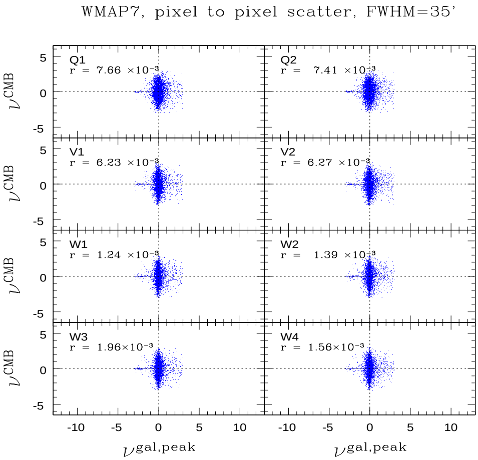


- Test significance of r : correlate $\nu^{\rm gal,peak}$ with 1000 Gaussian realizations.

Residual galaxy contamination in the cleaned WMAP data?

- Scale CMB and peak fields by their rms values $\rightarrow \ \nu^{\mathrm{CMB}},\ \nu^{\mathrm{gal,peak}}$.
- Correlate the two : $r \equiv <\nu^{\mathrm{CMB}}\nu^{\mathrm{gal,peak}}>$.



- Test significance of r : correlate $\nu^{\mathrm{gal,peak}}$ with 1000 Gaussian realizations.
- Found almost zero realizations with $r > 1.5 \times 10^{-3}$.

$\Rightarrow$ Indicates that cleaned CMB still has galaxy contamination.

Summary

- The CMB encodes the primordial fluctuation properties, composition and evolution of the universe.
- Precise measurement of the temperature fluctuations can reveal the mechanism of their generation in the early universe.
- Predictions of generic models of inflation agree well with observational data. Observables are few
- Understanding non-Gaussianity deviations in the CMB is an important frontier in probing models of inflation.
- Future consolidation of our understanding relies on higher precision data from Planck satellite and polarization experiments such as CMBPol.
- In the meantime, one can devise new optimal ways to extract physical information using available data.