Non-Gaussianity from residual foreground contamination in the WMAP data

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CMB data from WMAP

- Observed signal = true CMB + foreground signal.
- Foreground signal is estimated and then subtracted.
- Galactic region is masked. KQ75 Galactic mask provided by WMAP.
- Locations of extra-Galactic point sources that are identified are also masked.
  - PS1 : **Gold et al. (2011)**, 471 sources.
  - PS2 : **Scodeller, Hansen and Marinucci (2012)**, 1116 sources.
  - PS3 : **Scodeller, Hansen and Marinucci (2012)**, 2102 sources.

$$f^{\text{cleaned}} = f^{\text{obs}} - f^{\text{appfg}}$$

- Accurate estimation and subtraction of the foreground is crucial for extracting cosmological information. **Komatsu et al. (2011)**

Minkowski Functionals and non-Gaussian deviations

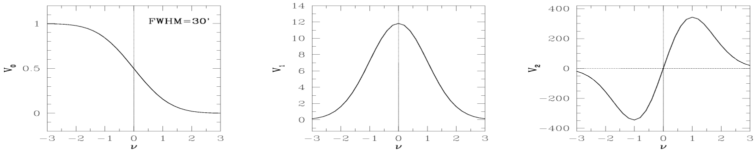
Minkowski Functionals for Gaussian random fields **Tomita (1986)**

$$\nu \equiv f/\sigma_0, \qquad \sigma_0 \equiv \sqrt{\langle f^2 \rangle}$$

$$V_0 = \frac{1}{2}\,\mathrm{erfc}\,(\nu/\sqrt{2})$$

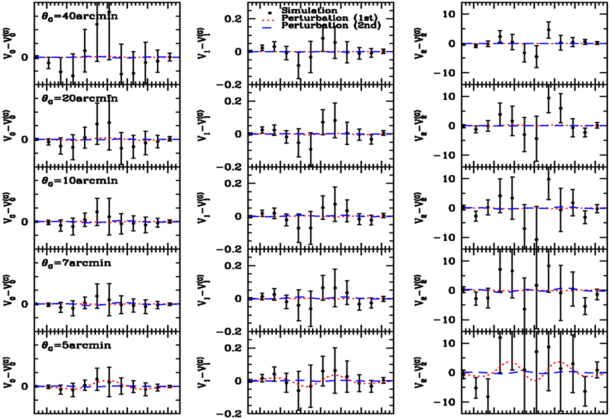
$$V_1 = A_1\, e^{-\nu^2/2}, \qquad A_1 \sim \frac{\sigma_1}{\sigma_0}, \quad \sigma_1 \equiv \sqrt{\langle |\nabla f|^2 \rangle}$$

$$V_2 = A_2\, \nu\, e^{-\nu^2/2}, \qquad A_2 \sim \left(\frac{\sigma_1}{\sigma_0}\right)^2.$$



Quantify non-Gaussian deviations as $\Delta V_i \equiv V_i^{\mathrm{NG}} - V_i^{\mathrm{G}}$.

Minkowski Functionals from WMAP 7 years data



Hikage and Matsubara (2012)

Constraint on $f_{\rm NL}$: $-22 < f_{\rm NL} < 62 \quad (95\%{\rm CL})$

Residual foreground contamination

1. Is there small but statistically significant residual foreground contamination present in $f^{\rm cleaned}$?
2. If it is present, how will it show up in the Minkowski Functionals? Can a part of the non-Gaussian deviation of the MFs of the WMAP data come from such contamination?

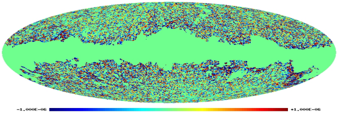
WMAP data provides both $f^{\rm obs}$ and $f^{\rm cleaned}$. By subtracting them we can obtain $f^{\rm appfg}$.

Basic premise: If there is insignificant residual foreground in the cleaned CMB signal, we should find negligibly small correlation between the cleaned CMB and foreground fields.

Residual foreground contamination

- Define peak field:

$$f^{\text{peak}} \equiv \left(f^{\text{appfg},\theta_s} - f^{\text{appfg},3\theta_s}\right) - \left(< f^{\text{appfg},\theta_s}\rangle - \langle f^{\text{appfg},3\theta_s} >\right),$$



The peak field captures the smaller scale fluctuations of the foreground field.

- Rescale: $\nu^{\text{cleaned}}(i) \equiv \frac{f^{\text{cleaned}}(i)}{\sigma^{\text{cleaned}}}, \quad \nu^{\text{peak}}(i) \equiv \frac{f^{\text{peak}}(i)}{\sigma^{\text{peak}}},$

- Calculate the correlation:

$$r_c \equiv < \nu^{\text{cleaned}}\, \nu^{\text{peak}} >_{\theta_s}$$

Correlation between cleaned CMB and foreground fields

- We calculate r_c after applying PS1, PS2 and PS3.
- Chose $\theta_s = 35$ arcmin.
- Results for PS1:

All unmasked pixels

DA	r_c
Q1	2.55×10^{-2}
Q2	2.49×10^{-2}
V1	2.00×10^{-2}
V2	1.93×10^{-2}
W1	9.47×10^{-3}
W2	7.98×10^{-3}
W3	8.85×10^{-3}
W4	6.34×10^{-3}

Excluding pixels with $\nu^{\rm peak} > 3$

DA	r_c
Q1	1.80×10^{-2}
Q2	1.75×10^{-2}
V1	1.65×10^{-2}
V2	1.60×10^{-2}
W1	8.54×10^{-3}
W2	8.29×10^{-3}
W3	6.74×10^{-3}
W4	6.93×10^{-3}

- Boundary effects checked by staying further away from the boundaries. Results are more or less unchanged.

Statistical significance of the observed correlation

1. Simulate 1000 Gaussian CMB maps with WMAP 7 years parameter values.
2. Add instrumental effects: pixel window function, beam profiles and noise characteristics for each differential assembly.
3. Calculate their correlation with the peak field. We should expect negligibly small correlation.
4. Count the number of maps having $r > r_c$ simultaneously for all channels, $N_{\rm all}$.

ALL unmasked pixels included: $N_{\rm all} = 0$.

Excluding pixels with $\nu^{\rm peak} > 3$: $N_{\rm all} = 5$.

Significance significance of the observed correlation

- Count the number of maps having $r > r_c$ for individual DAs: N.

All unmasked pixels

Channel	N
Q1	0
Q2	0
V1	4
V2	6
W1	108
W2	158
W3	131
W4	208

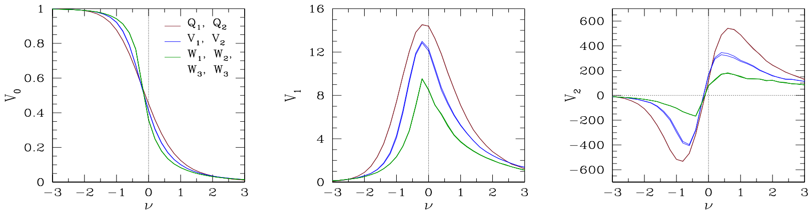
Excluding pixels with $\nu^{\text{peak}} > 3$

Channel	N
Q1	5
Q2	6
V1	98
V2	105
W1	262
W2	269
W3	305
W4	297

Summary

- The correlations between the cleaned CMB and peak fields are ALL positive for all the DAs.
- These correlations are statistically significant.
- Both the correlation and statistical significance values drop when we repeat the calculations for PS2 and PS3.

Minkowski Functionals for the peak fields



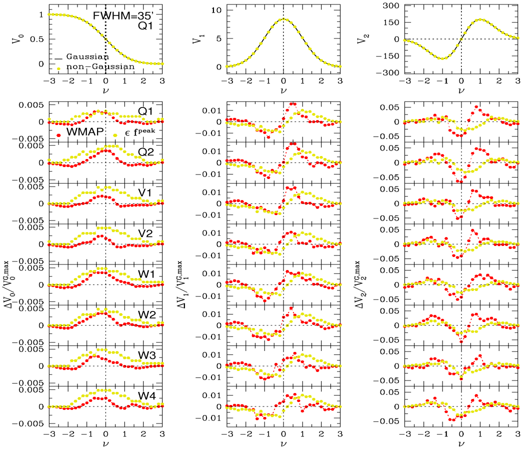
- Clearly not Gaussian shape. If a small fraction of $f^{\rm peak}$ contaminates Gaussian map, it will lead to deviation from Gaussian behaviour.
- Add contaminant fraction to the simulated Gaussian maps as

$$f^{\rm contaminated} = f^G + \epsilon f^{\rm peak}$$

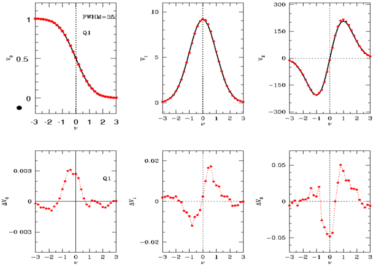
- Measure Minkowski Functionals from the contaminated maps.

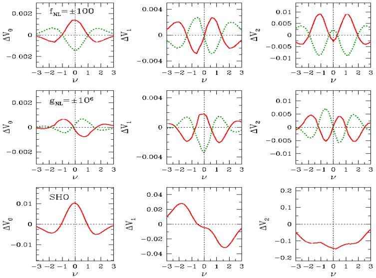
Effect of residual foreground contamination

Contaminated Gaussian with $\epsilon \simeq 4$. Average over 1000 maps.

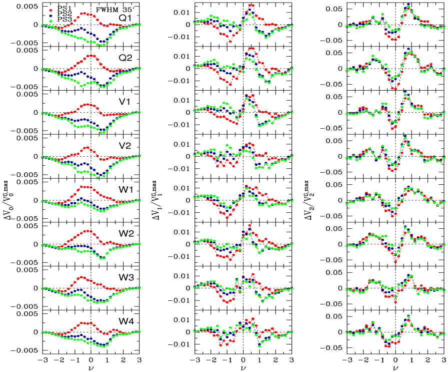


Visually, there is agreement of the non-Gaussian deviation shapes!


FWHM=35
Q1
Q1
V_0
V_1
V_2
ΔV_0
ΔV_1
ΔV_2
ν


$f_{NL}=\pm100$
$g_{NL}=\pm10^6$
SHO
ΔV_0
ΔV_1
ΔV_2
ν

Effect of PS1, PS2 and PS3 MFs for WMAP data



- V_0 is strongly affected by the removal of the larger set of point sources. Hence, not reliable for constraining non-Gaussianity parameters when point sources are not well known.
- V_1 and V_2 are less sensitive to point sources.

Findings

- Small but statistically significant residual foreground contamination present in WMAP data. Q channel has the largest and W has the least.
- For Q and V channels, a big fraction of the contamination comes from pixels where $\nu^{\mathrm{peak}} > 3$.
- 'Good' visual agreement between non-Gaussian deviations of Minkowski Functionals of WMAP data and simulated Gaussian maps to which contaminant fraction is added.
- This suggests that a big component of the observed non-Gaussianity comes from residual foreground contamination.