Title: WMAP 5-year Results: Measurement of f_NL

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Abstract:

WMAP 5-Year Results: Measurement of f_{NL}

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"Origins and Observations of Primordial Non-Gaussianity"
Perimeter Institute, March 8, 2008

WMAP 5-Year Papers

- **Hinshaw et al.**, "*Data Processing, Sky Maps, and Basic Results*" 0803.0732
- **Hill et al.**, "*Beam Maps and Window Functions*" 0803.0570
- **Gold et al.**, "*Galactic Foreground Emission*" 0803.0715
- **Wright et al.**, "*Source Catalogue*" 0803.0577
- **Nolta et al.**, "*Angular Power Spectra*" 0803.0593
- **Dunkley et al.**, "*Likelihoods and Parameters from the WMAP data*" 0803.0586
- **Komatsu et al.**, "*Cosmological Interpretation*" 0803.0547

WMAP 5-Year Science Team

- C.L. Bennett
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- N. Odegard
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- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta

Special Thanks to **WMAP Graduates**!

- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

What is f_{NL}?

- For a pedagogical introduction to f_{NL}, see **Komatsu, astro-ph/0206039**
- In one sentence: "f_{NL} is a **quantitative measure** of the magnitude of primordial non-Gaussianity in curvature perturbations.*"

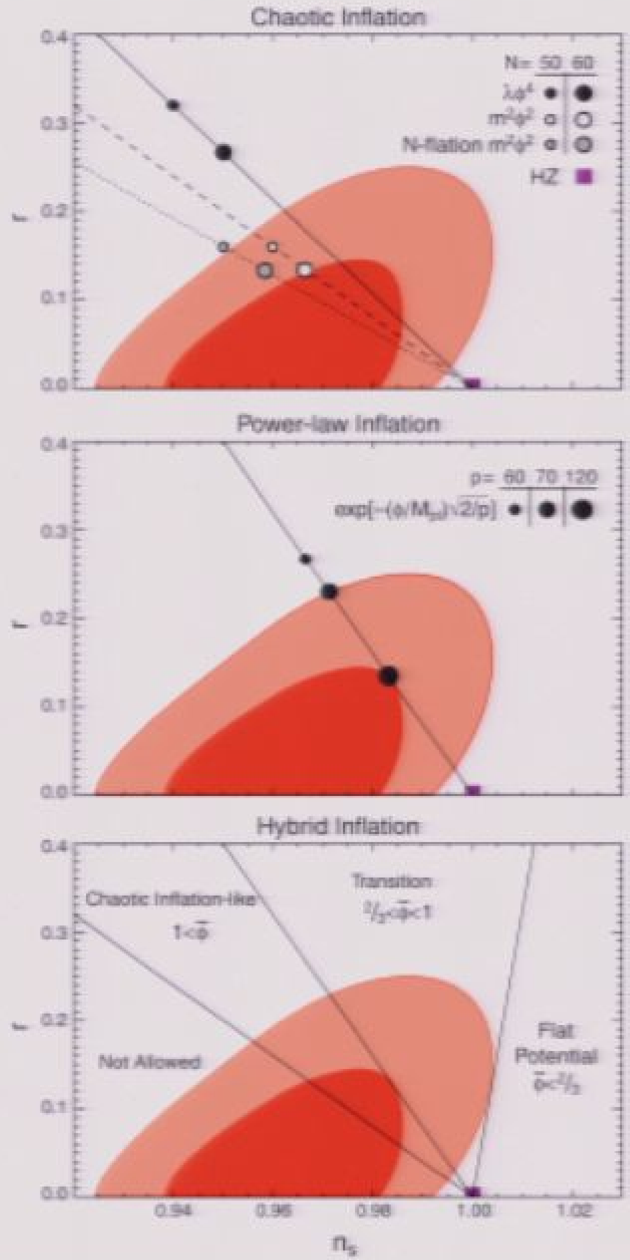
* where a positive curvature perturbation gives a negative CMB anisotropy in the Sachs-Wolfe limit

Why is Non-Gaussianity Important?

- Because a detection of f_{NL} has a best chance of ruling out the **largest** class of early universe models.
- Namely, it will rule out inflation models based upon
  - a single scalar field with
  - the canonical kinetic term that
  - rolled down a smooth scalar potential slowly, and
  - was initially in the Banch-Davies vacuum.
- ***Detection of non-Gaussianity would be a major breakthrough in cosmology.***

We have *r* and n_s. Why Bother?

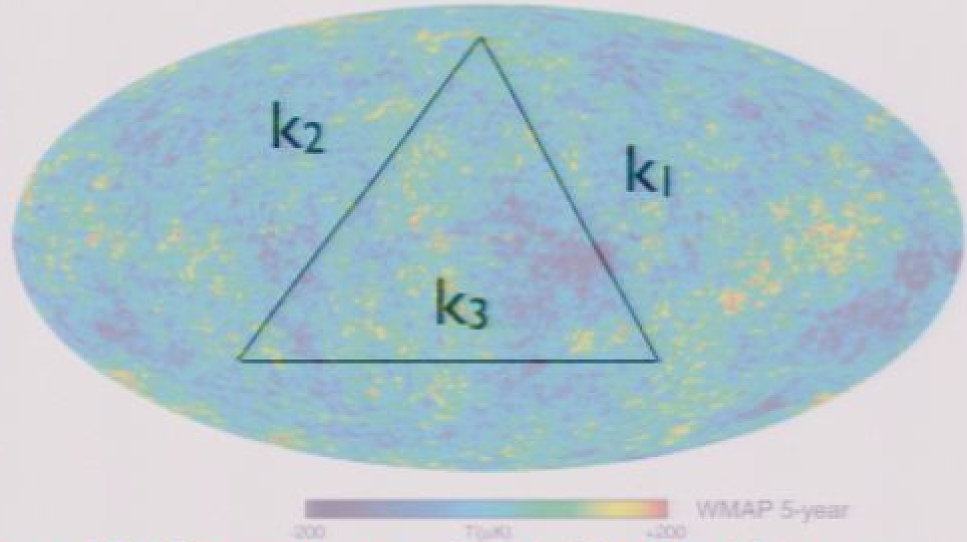
- While the current limit on the power-law index of the primordial power spectrum, $\mathbf{n_s}$, and the amplitude of gravitational waves, **r**, have ruled out many inflation models already, many still survive (which is a good thing!)
- A convincing detection of f_{NL} would rule out most of them regardless of n_s or r.
- f_{NL} offers more ways to test various early universe models!



What if f_{NL} /= 0?

- A single field, canonical kinetic term, slow-roll, and/or Banch-Davies vacuum, must be modified.
  - Multi-field (curvaton)
  - Non-canonical kinetic term (k-inflation, DBI)
  - Temporary fast roll (features in potential; Ekpyrotic fast roll)
  - Departures from the Banch-Davies vacuum
- It will give us a lot of clues as to what the correct early universe models should look like.

So, what is f_{NL}?



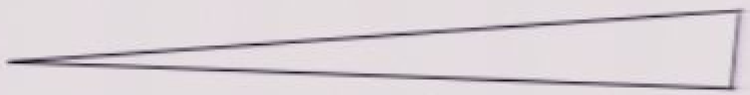
- **f_{NL} = the amplitude of three-point function**, or also known as the "bispectrum," $B(k_1,k_2,k_3)$, which is
  - $=\langle\Phi(k_1)\Phi(k_2)\Phi(k_3)\rangle=f_{NL}(2\pi)^2\delta^3(k_1+k_2+k_3)b(k_1,k_2,k_3)$
  - where $\Phi(k)$ is the Fourier transform of the curvature perturbation, and $b(k_1,k_2,k_3)$ is a model-dependent function that defines the shape of triangles predicted by various models.

Why Bispectrum?

- The bispectrum vanishes for Gaussian random fluctuations.
- Any non-zero detection of the bispectrum indicates the presence of (some kind of) non-Gaussianity.
- A very sensitive tool for finding non-Gaussianity.

Komatsu & Spergel (2001); Babich, Creminelli & Zaldarriaga (2004)

Two f_{NL}'s

- Depending upon the shape of triangles, one can define various f_{NL}'s:
- "Local" form 
  - which generates non-Gaussianity locally (i.e., at the same location) via $\Phi(x)=\Phi_{gaus}(x)+f_{NL}^{local}[\Phi_{gaus}(x)]^2$

Earlier work on the local form: Salopek&Bond (1990); Gangui et al. (1994); Verde et al. (2000); Wang&Kamionkowski (2000)

- "Equilateral" form 
  - which generates non-Gaussianity in a different way (e.g., k-inflation, DBI inflation)

Journal on f_{NL}

- Local
  - $-3500 < f_{NL}^{local} < 2000$ [COBE 4yr, $l_{max}=20$] Komatsu et al. (2002)
  - $-58 < f_{NL}^{local} < 134$ [WMAP 1yr, $l_{max}=265$] Komatsu et al. (2003)
  - $-54 < f_{NL}^{local} < 114$ [WMAP 3yr, $l_{max}=350$] Spergel et al. (2007)
  - **$-9 < f_{NL}^{local} < 111$ [WMAP 5yr, $l_{max}=500$]** Komatsu et al. (2008)
- Equilateral
  - $-366 < f_{NL}^{equil} < 238$ [WMAP 1yr, $l_{max}=405$] Creminelli et al. (2006)
  - $-256 < f_{NL}^{equil} < 332$ [WMAP 3yr, $l_{max}=475$] Creminelli et al. (2007)
  - **$-151 < f_{NL}^{equil} < 253$ [WMAP 5yr, $l_{max}=700$]** Komatsu et al. (2008)

Methodology

- I am not going to bother you too much with methodology...
  - Please read Appendix A of Komatsu et al., if you are interested in details.
- We use a well-established method developed over the years by: Komatsu, Spergel & Wandelt (2005); Creminelli et al. (2006); Yadav, Komatsu & Wandelt (2007)
  - There is still a room for improvement (Smith & Zaldarriaga 2006)

Data Combination

- We mainly use V band (61 GHz) and W band (94 GHz) data.
  - The results from Q band (41 GHz) are discrepant, probably due to a stronger foreground contamination
- These are *foreground-reduced maps*, delivered on the LAMBDA archive.
  - We also give the results from the raw maps.

Gold et al. (2008)

Mask

- We have upgraded the Galaxy masks.
  - 1yr and 3yr release
    - "Kp0" mask for Gaussianity tests (76.5%)
    - "Kp2" mask for the C_l analysis (84.6%)
  - 5yr release
    - "KQ75" mask for Gaussianity tests (71.8%)
    - "KQ85" mask for the C_l analysis (81.7%)

Gold et al. (2008)

- What are the KQx masks?
  - The previous KpN masks identified the bright region in the K band data, which are contaminated mostly by the synchrotron emission, and masked them.
    - "p" stands for "plus," and N represents the brightness level above which the pixels are masked.
  - The new KQx masks identify the bright region in the K band minus the CMB map from Internal Linear Combination (the CMB picture that you always see), as well as the bright region in the Q band minus ILC.
  - Q band traces the free-free emission better than K.
  - x represents a fraction of the sky retained in K or Q.

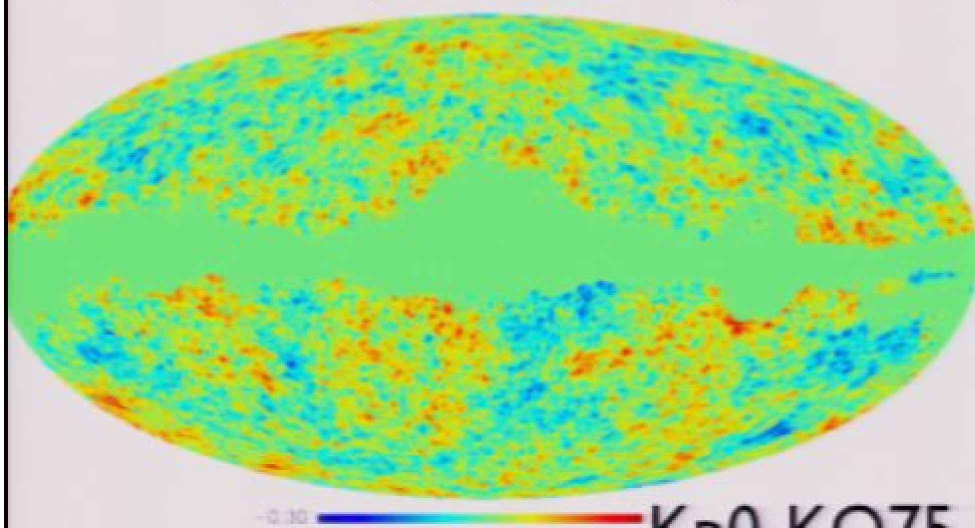
Gold et al. (2008)

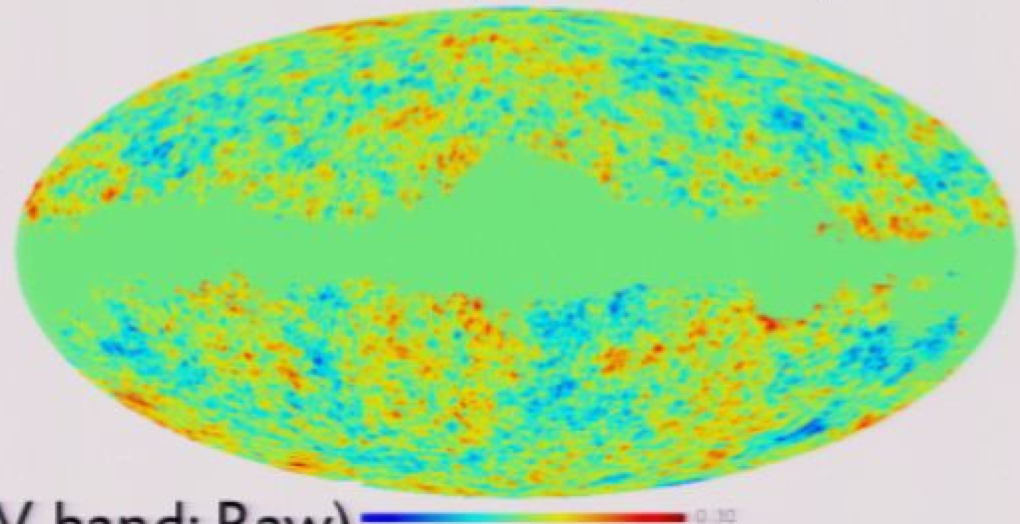
Why KQ75?

- The KQ75 mask removes the pixels that are contaminated by the free-free region better than the Kp0 mask.
- CMB was absent when the mask was defined, as the masked was defined by the K (or Q) band map minus the CMB map from ILC.
- The final mask is a combination of the K mask (which retains 75% of the sky) and the Q mask (which also retains 75%). Since Q masks the region that is not masked by K, the final KQ75 mask retains less than 75% of the sky. (It retains 71.8% of the sky for cosmology.)

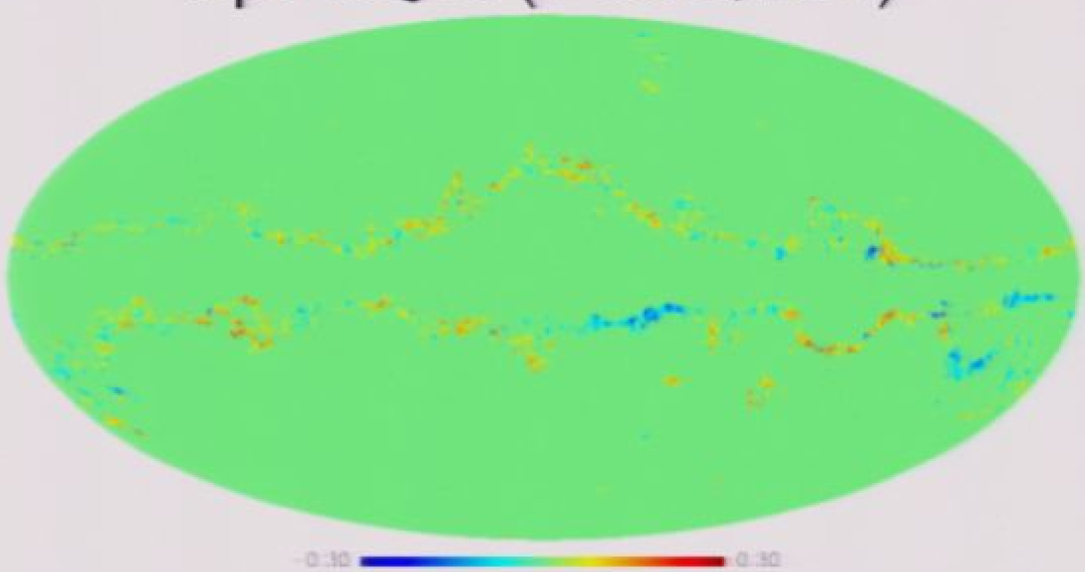
Kp0 (V band; Raw)

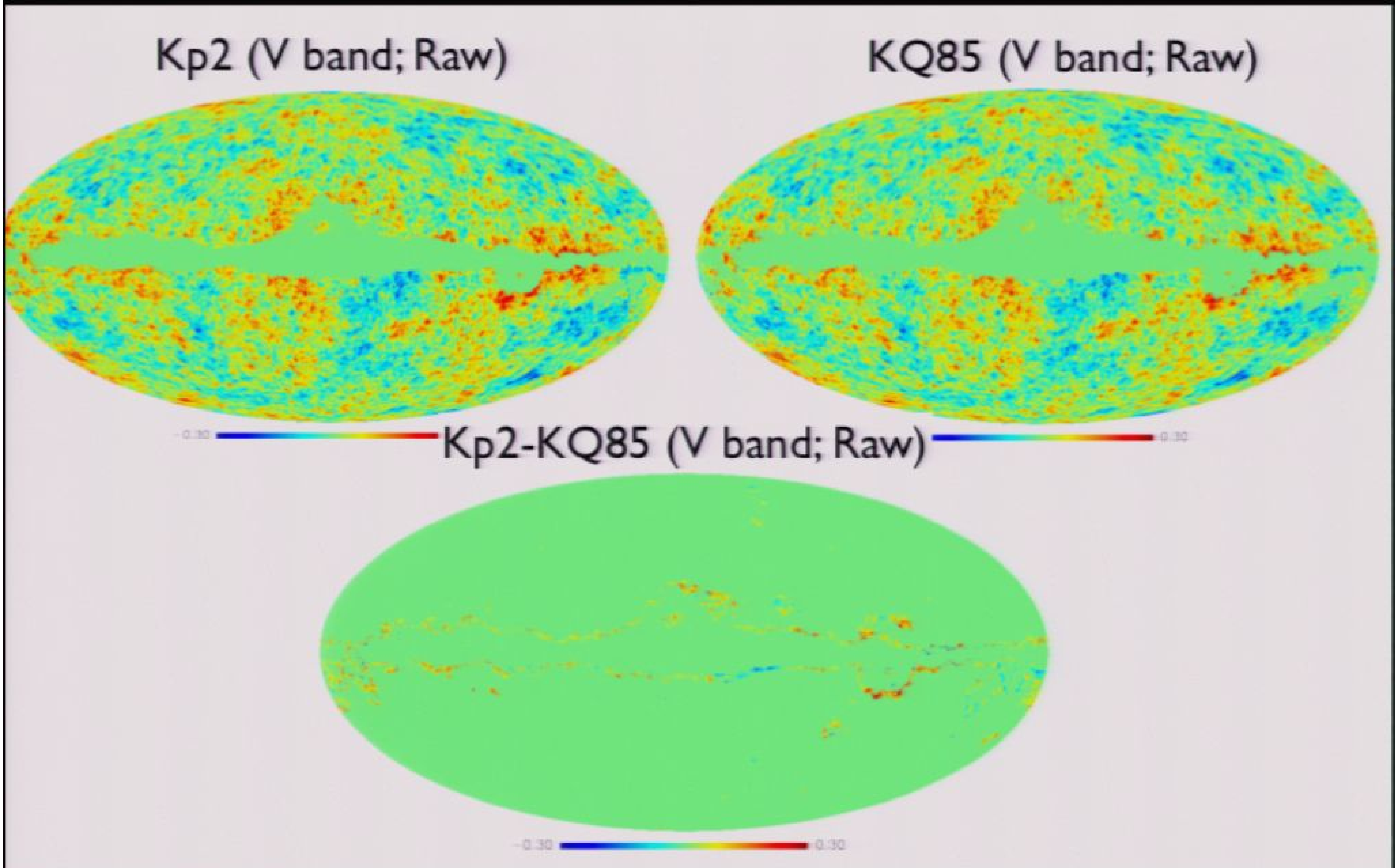
KQ75 (V band; Raw)



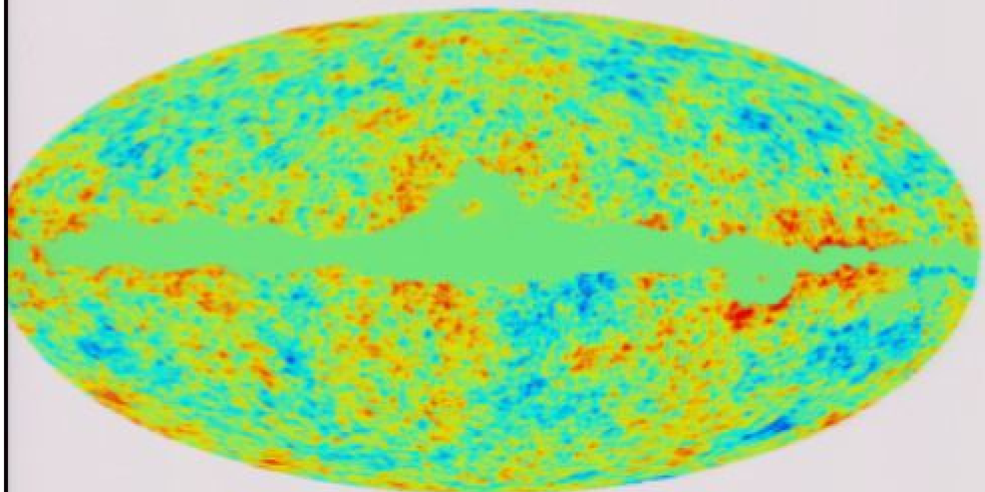


Kp0-KQ75 (V band; Raw)

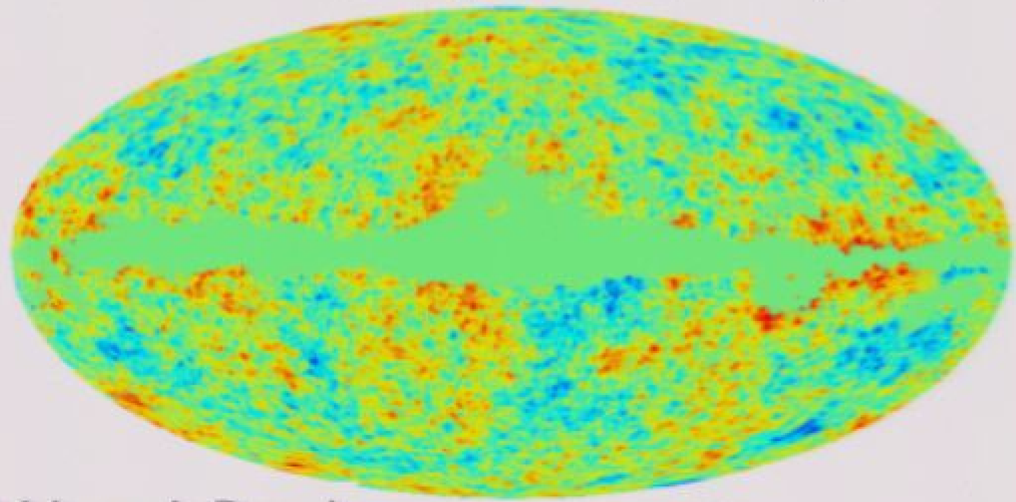



Kp2 (V band; Raw)
KQ85 (V band; Raw)
-0.30
0.30
Kp2-KQ85 (V band; Raw)
-0.30
0.30

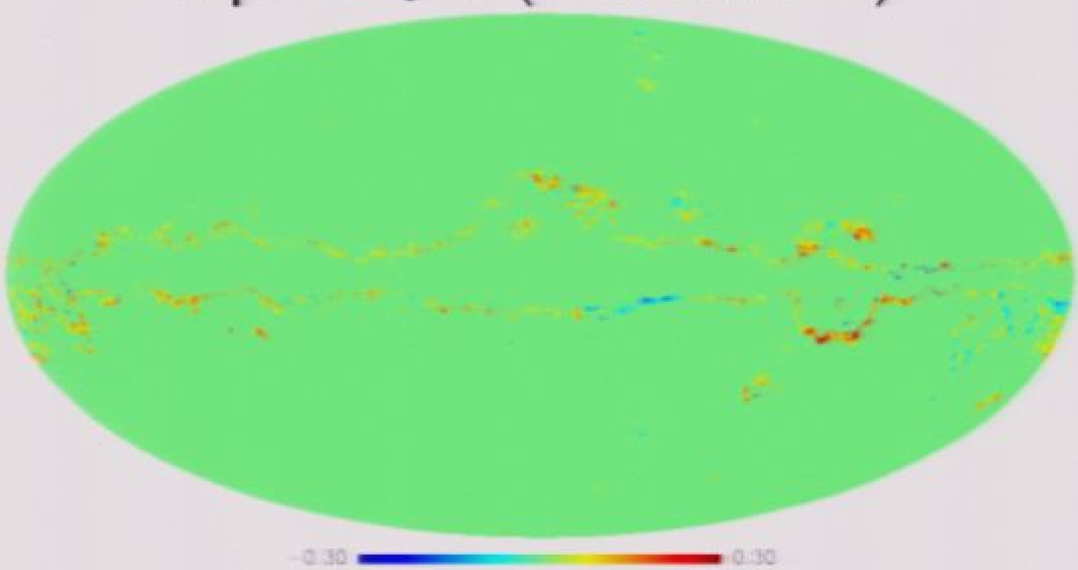
Kp2 (V band; Raw)

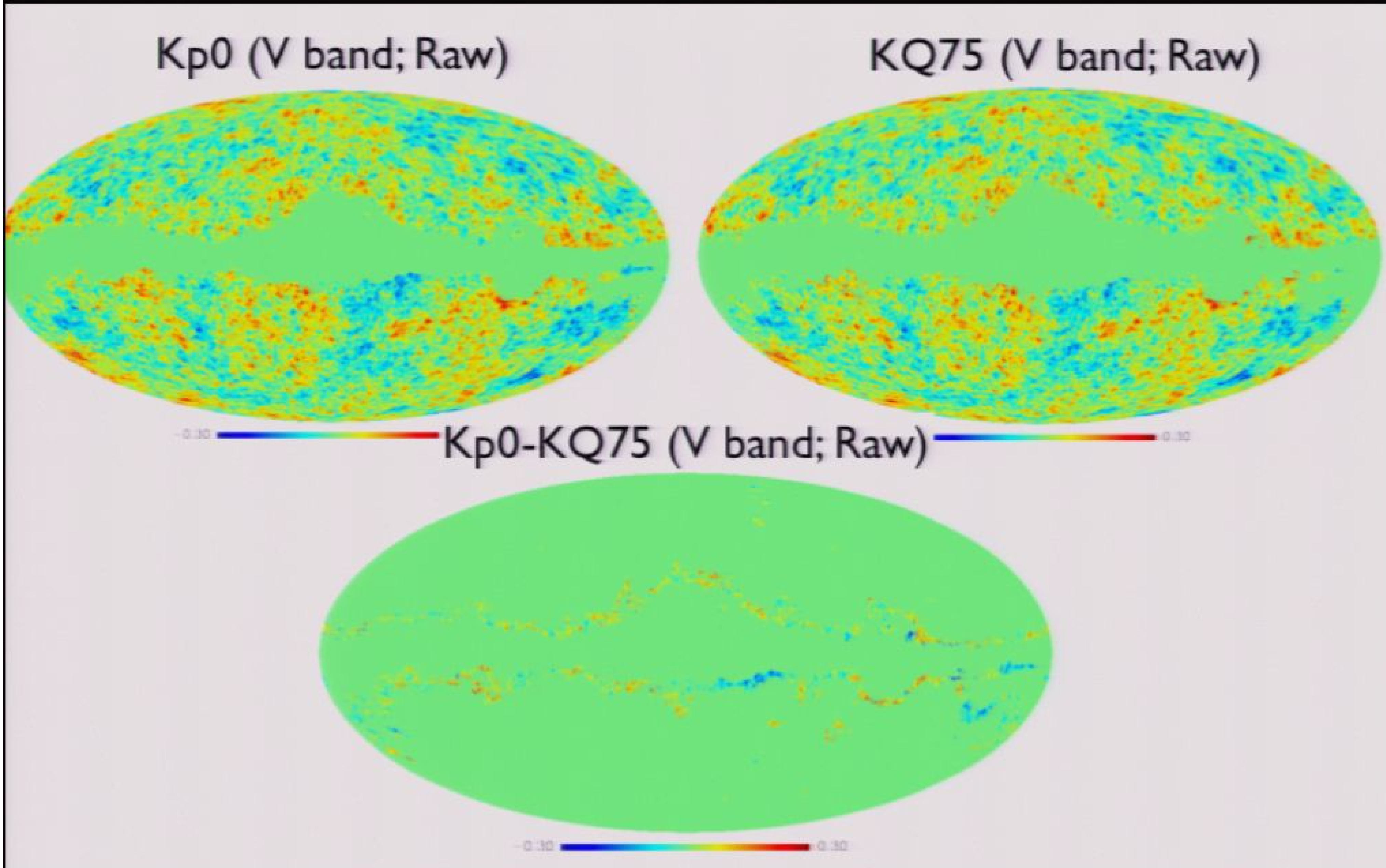


KQ85 (V band; Raw)



Kp2-KQ85 (V band; Raw)

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KQ75 (V band; Raw)
-0.30
0.30
Kp0-KQ75 (V band; Raw)
-0.30
0.30
-0.30
0.30

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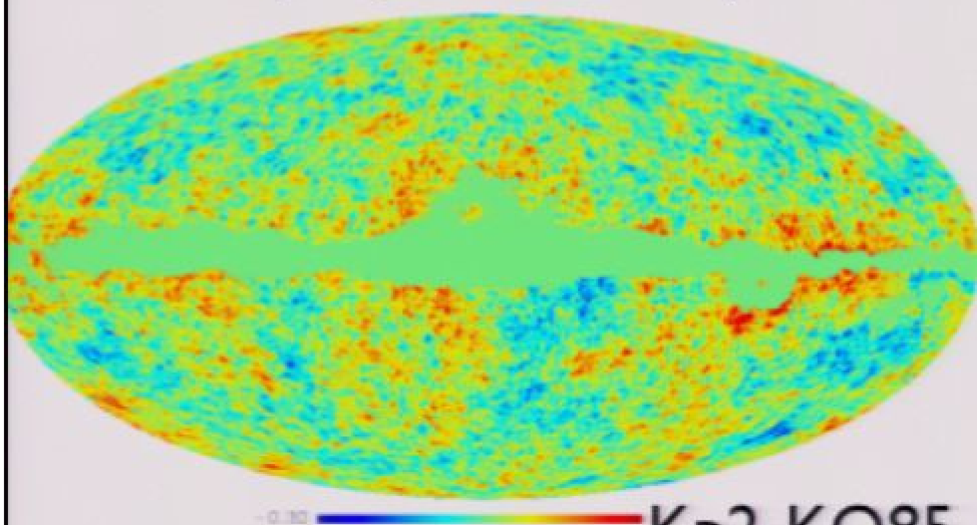
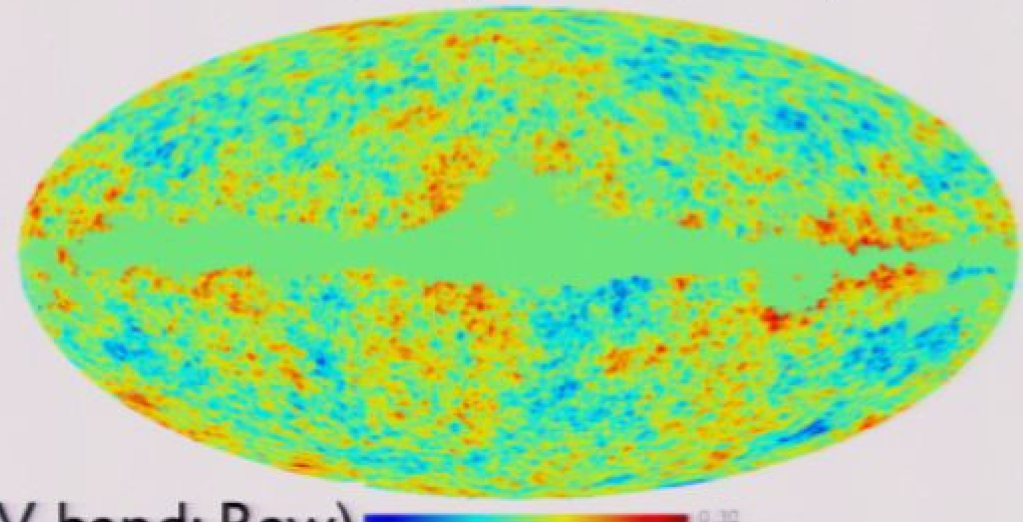
KQ85 (V band; Raw)





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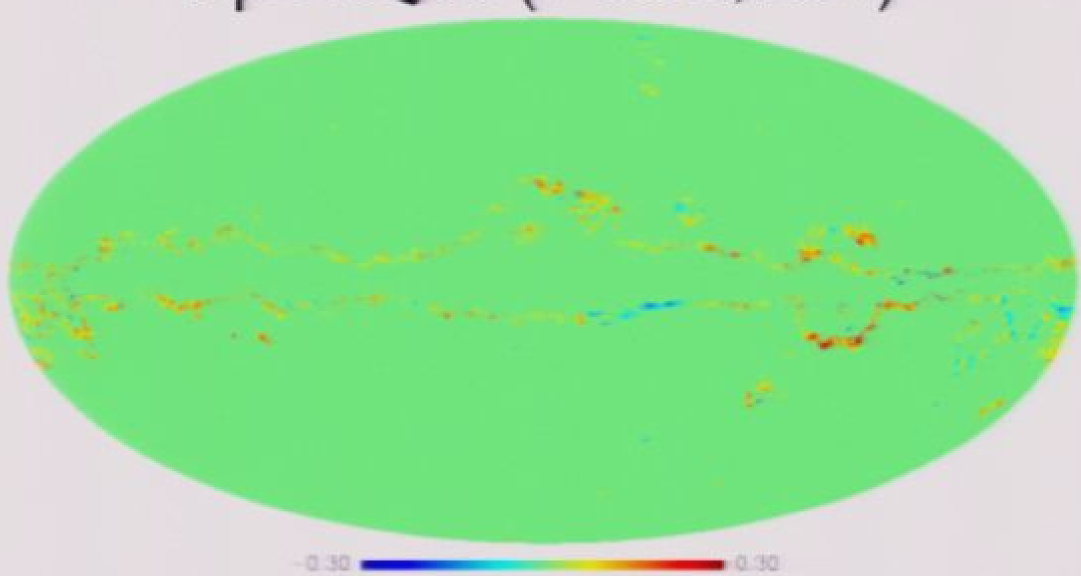

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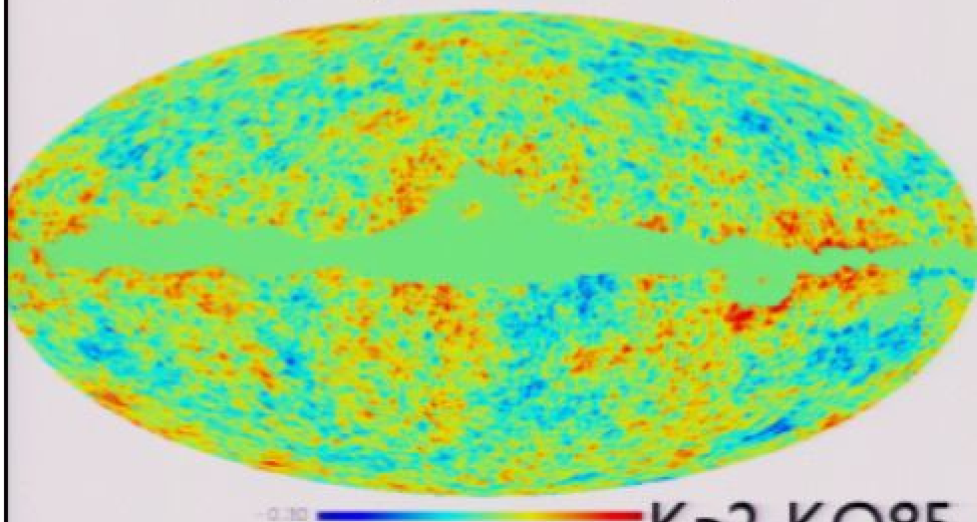
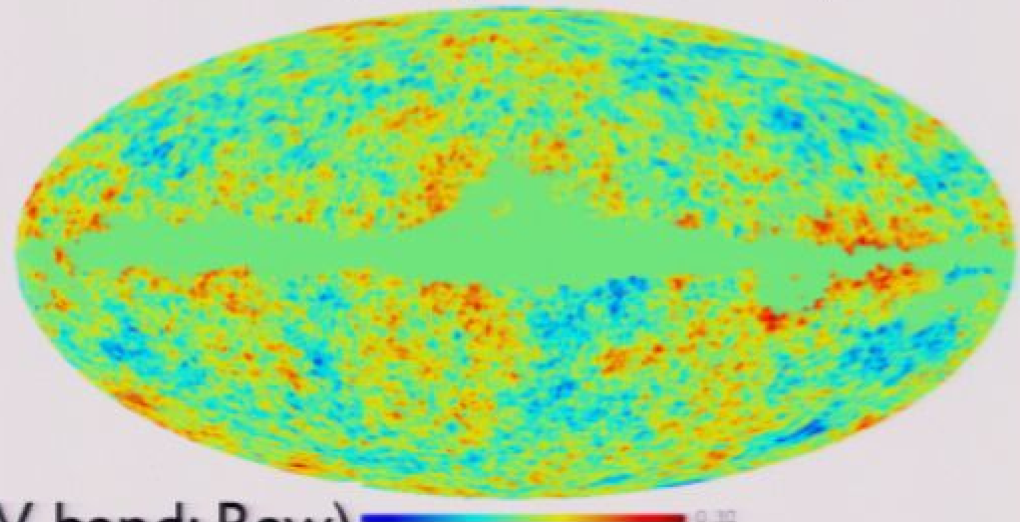
KQ85 (V band; Raw)





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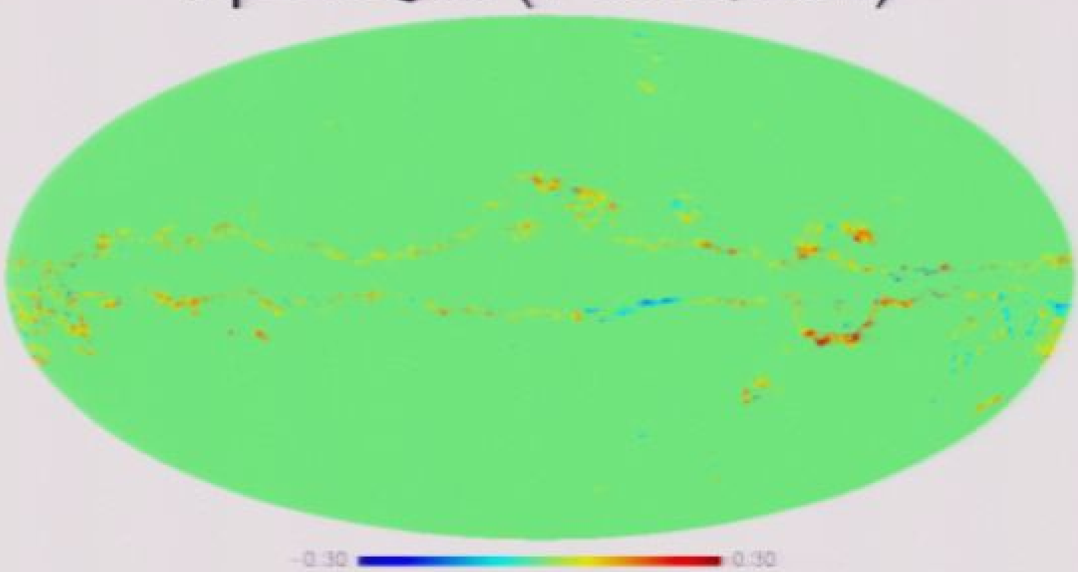

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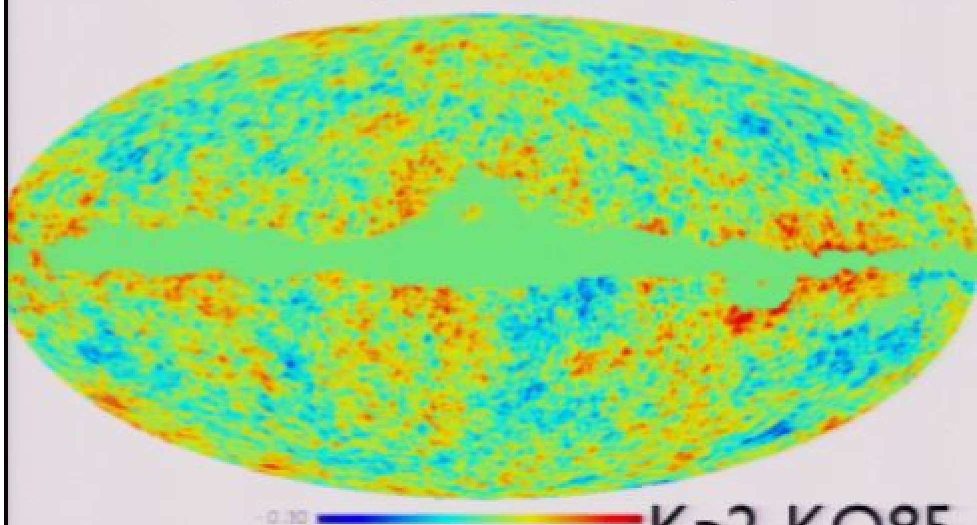

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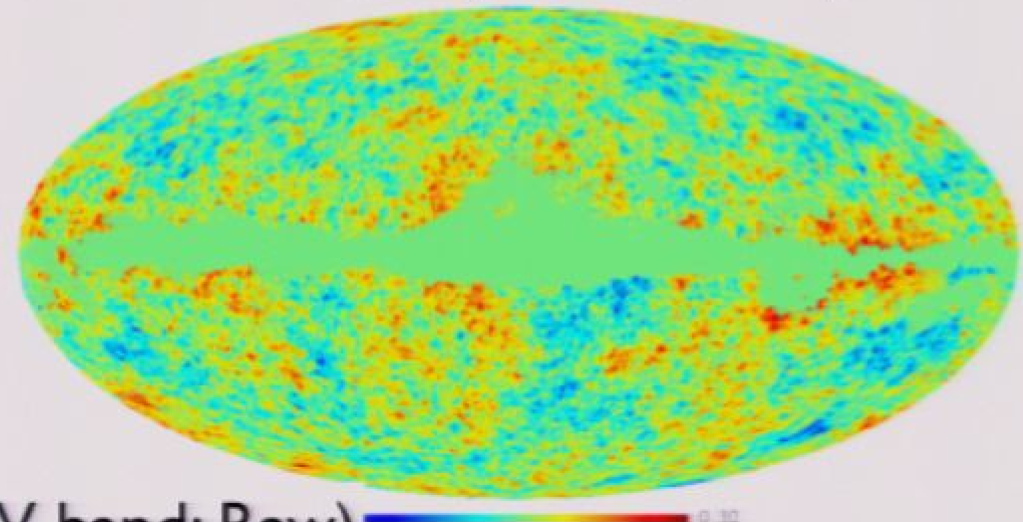
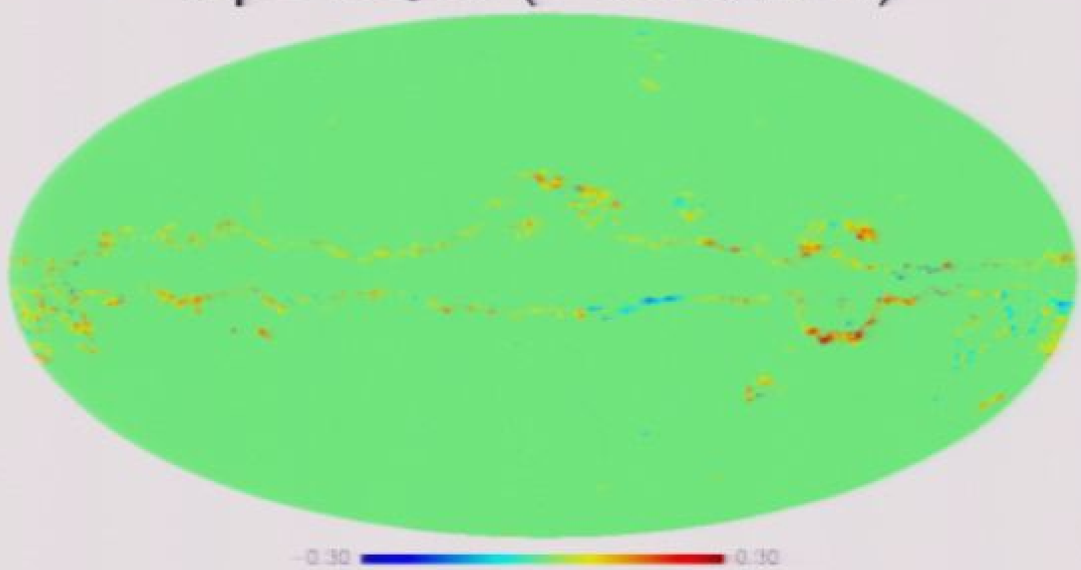
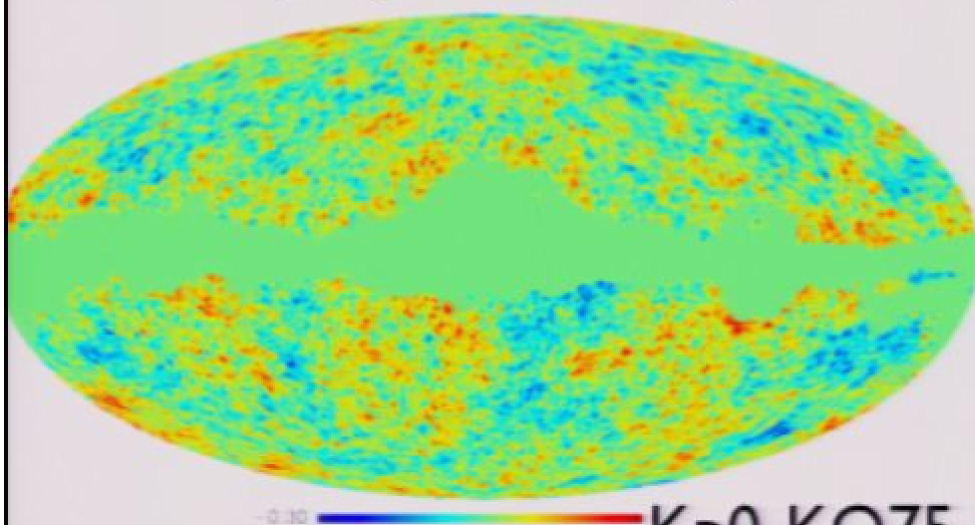


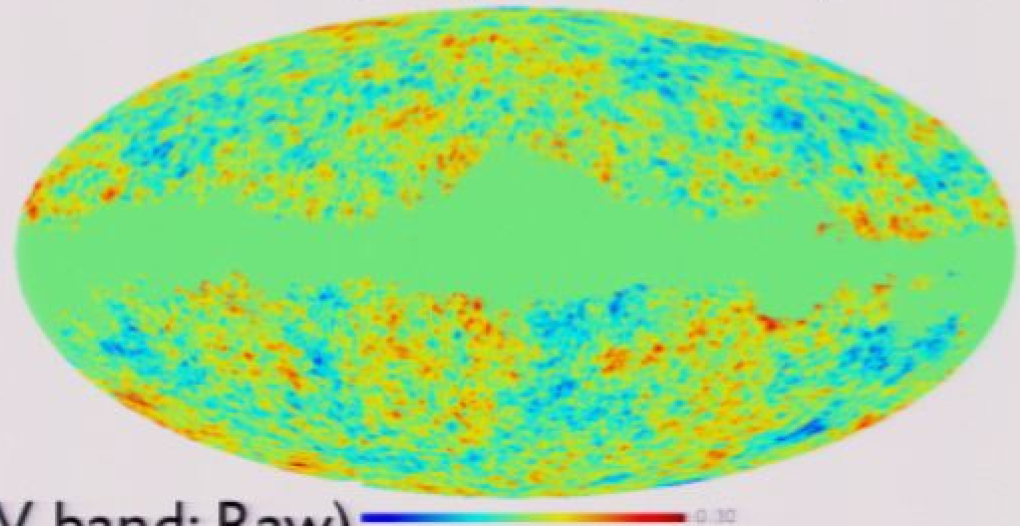
Kp2-KQ85 (V band; Raw)



Kp0 (V band; Raw)

KQ75 (V band; Raw)





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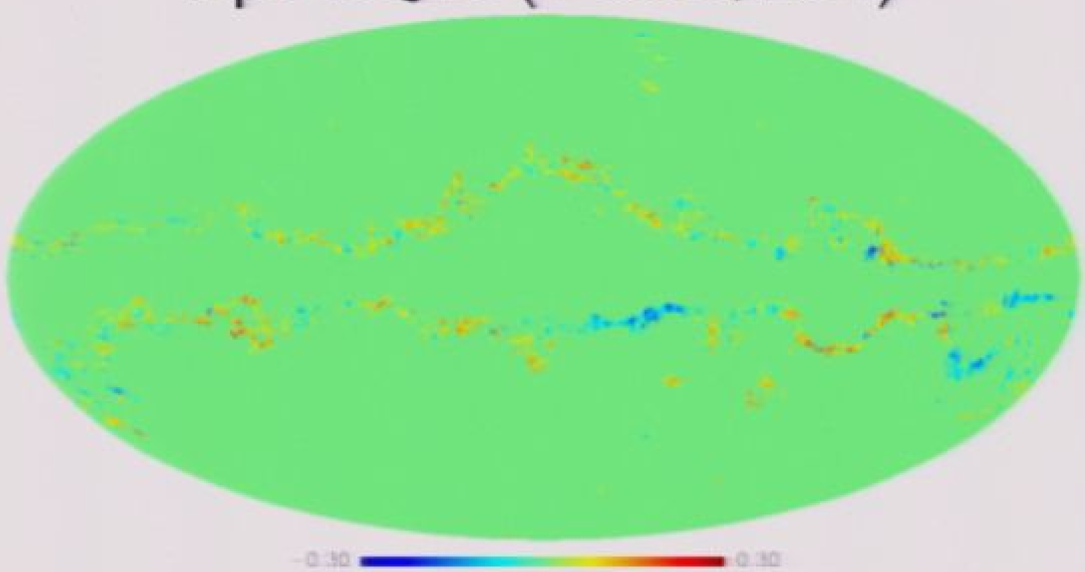

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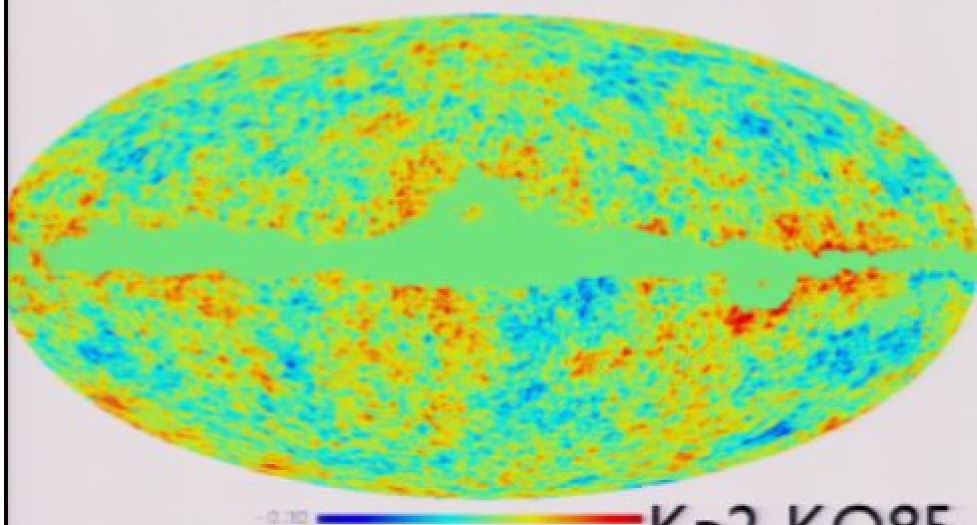

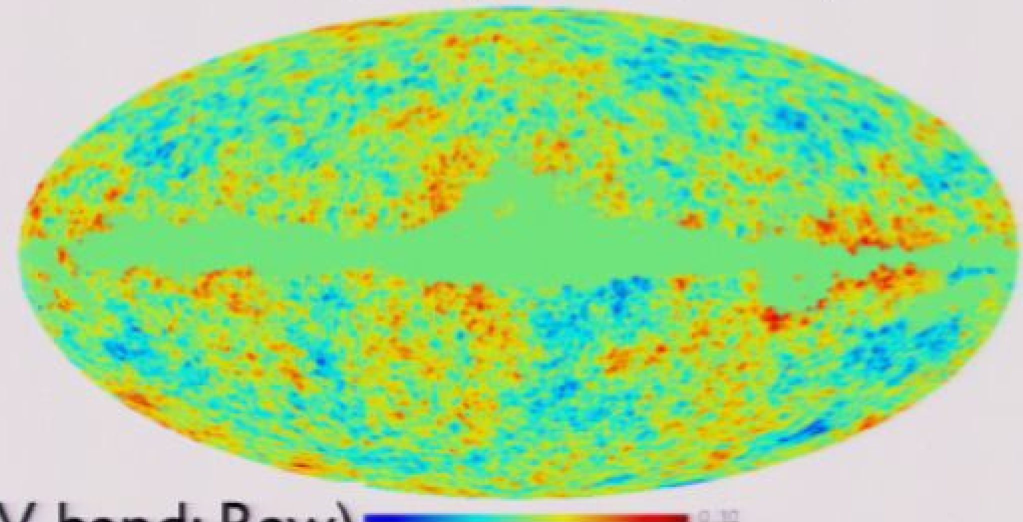

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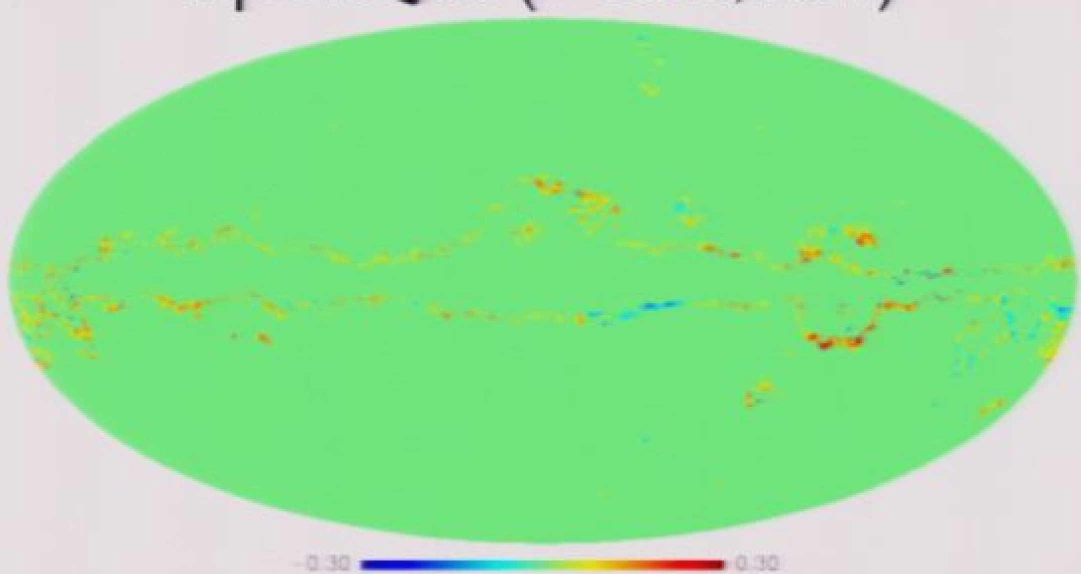

Komatsu et al. (2008)

Main Result (Local)

Band	Mask	$l_{\max}$	f_{NL}^{local}	$\Delta f_{NL}^{\text{local}}$	b_{src}
V+W	*KQ85*	400	50 ± 29	1 ± 2	0.26 ± 1.5
V+W	*KQ85*	500	61 ± 26	2.5 ± 1.5	0.05 ± 0.50
V+W	*KQ85*	600	68 ± 31	3 ± 2	0.53 ± 0.28
V+W	*KQ85*	700	67 ± 31	3.5 ± 2	0.34 ± 0.20
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V+W	*KQ75*	500	55 ± 30	4 ± 2	0.15 ± 0.51
V+W	*KQ75*	600	61 ± 36	4 ± 2	0.53 ± 0.30
V+W	*KQ75*	700	58 ± 36	5 ± 2	0.38 ± 0.21

- ~ 2 sigma "hint": **f_{NL}^{local} ~ 60 +/- 30 (68% CL)**
- 1.8 sigma for KQ75; 2.3 sigma for KQ85 & Kp0

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Komatsu et al. (2008)

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Null Tests

Band	Foreground	Mask	f_{NL}^{local}
Q$-$W	Raw	$KQ75$	-0.53 ± 0.22
V$-$W	Raw	$KQ75$	-0.31 ± 0.23
Q$-$W	Clean	$KQ75$	0.10 ± 0.22
V$-$W	Clean	$KQ75$	0.06 ± 0.23

- **No signal in the difference of cleaned maps.**

Komatsu et al. (2008)

Frequency Dependence

Band	Foreground	Mask	$f_{NL}^{\rm local}$
Q	Raw	$KQ75$	-42 ± 48
V	Raw	$KQ75$	41 ± 35
W	Raw	$KQ75$	46 ± 35
Q	Clean	$KQ75$	10 ± 48
V	Clean	$KQ75$	50 ± 35
W	Clean	$KQ75$	62 ± 35

- **Q is very sensitive to the foreground cleaning.**

Komatsu et al. (2008)

V+W: Raw vs Clean (l_{max}=500)

Band	Foreground	Mask	f_{NL}^{local}
V+W	Raw	*KQ85*	9 ± 26
V+W	Raw	*Kp0*	48 ± 26
V+W	Raw	*KQ75p1*	41 ± 28
V+W	Raw	*KQ75*	43 ± 30

- Clean-map results:
  - KQ85; 61 +/- 26
  - Kp0; 61 +/- 26
  - KQ75p1; 53 +/- 28
  - KQ75; 55 +/- 30

Foreground contamination is not too severe.

The Kp0 and KQ85 results may be as clean as the KQ75 results.

Komatsu et al. (2008)

Our Best Estimate

- Why not using Kp0 or KQ85 results, which have a higher statistical significance?
- Given the profound implications and impact of non-zero f_{NL}^{local}, we have chosen a conservative limit from the KQ75 with the point source correction (Δf_{NL}^{local}=4, which is also conservative) as our best estimate.
  - The 68% limit: f_{NL}^{local} = 51 +/- 30 [1.7 sigma]
  - **The 95% limit: $-9 < f_{NL}^{local} < 111$**

Yadav & Wandelt (2008)

Comparison with Y&W

- Yadav and Wandelt used the raw V+W map from the 3-year data.
  - 3yr: $f_{NL}^{local} = 68 \pm 30$ for $l_{max}=450$ & Kp0 mask
  - 3yr: $f_{NL}^{local} = 80 \pm 30$ for $l_{max}=550$ & Kp0 mask
- Our corresponding 5-year raw map estimate is
  - 5yr: $f_{NL}^{local} = 48 \pm 26$ for $l_{max}=500$ & Kp0 mask
  - C.f. clean-map estimate: $f_{NL}^{local} = 61 \pm 26$
- With more years of observations, the values have come down to a lower significance.

Komatsu et al. (2008)

Main Result (Equilateral)

Band	Mask	$l_{\max}$	$f_{NL}^{\rm equil}$	$\Delta f_{NL}^{\rm equil}$
V+W	*KQ75*	400	77 ± 146	9 ± 7
V+W	*KQ75*	500	78 ± 125	14 ± 6
V+W	*KQ75*	600	71 ± 108	27 ± 5
V+W	*KQ75*	700	73 ± 101	22 ± 4

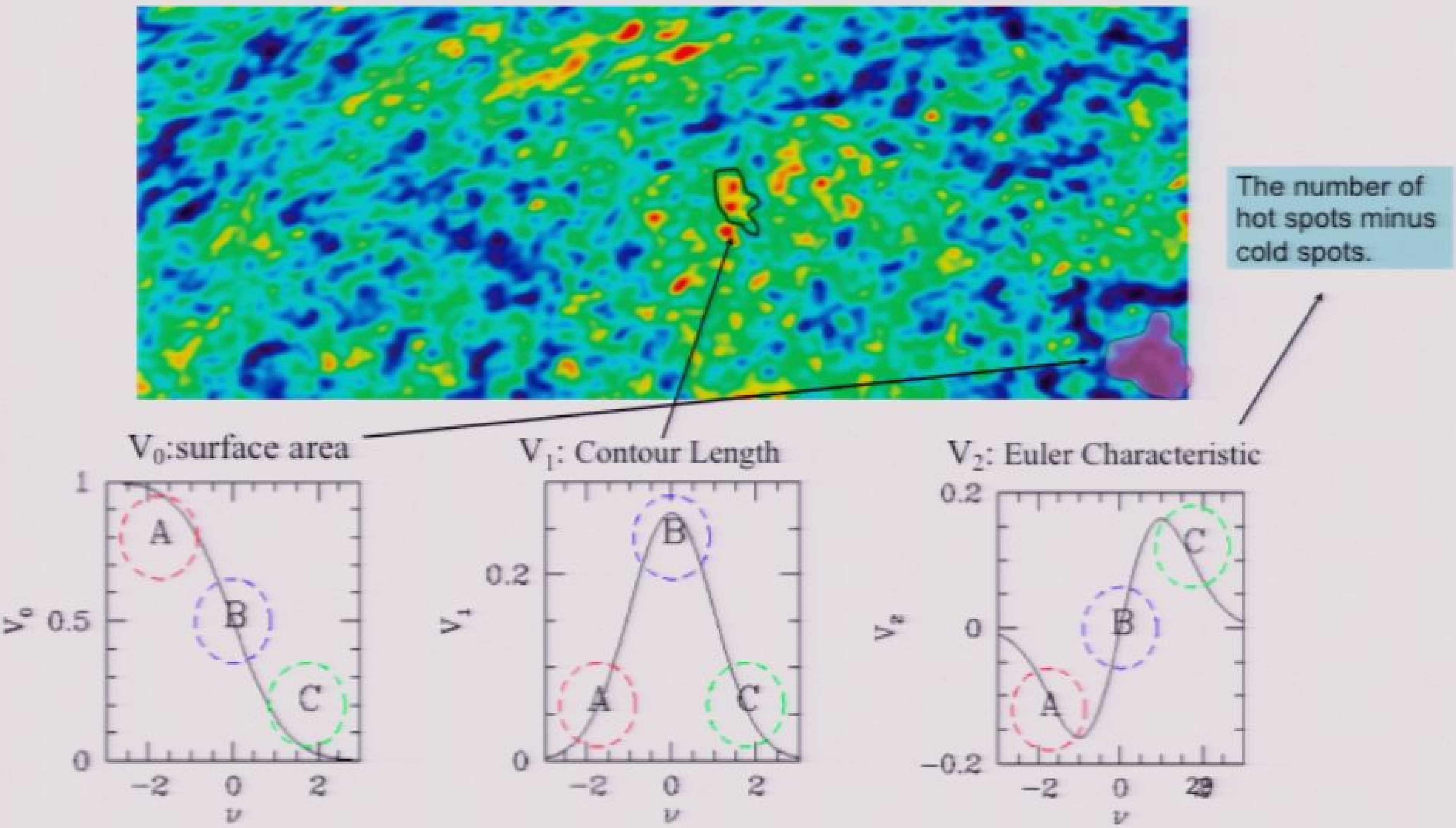
- The point-source correction is much larger for the equilateral configurations.
- Our best estimate from l_{max}=700:
  - The 68% limit: f_{NL}^{equil} = 51 +/- 101
  - **The 95% limit: $-151 < f_{NL}^{equil} < 253$**

Forecasting 9-year Data

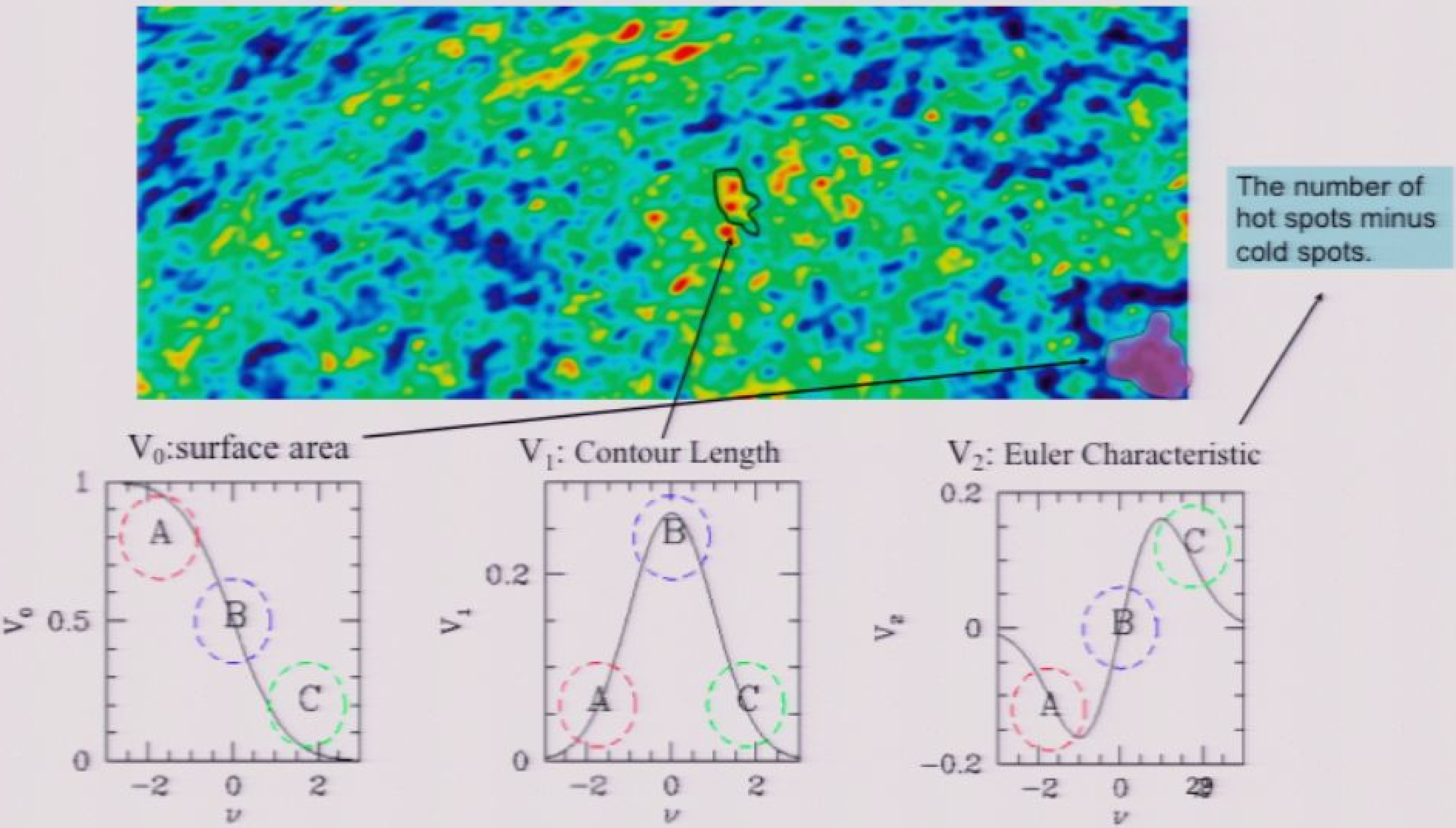
- The WMAP 5-year data do not show any evidence for the presence of f_{NL}^{equil}, but *do* show a (~2-sigma) hint for f_{NL}^{local}.
- Our best estimate is probably on the conservative side, but our analysis clearly indicates that more data are required to claim a firm evidence for $f_{NL}^{local}>0$.
- The 9-year error on f_{NL}^{local} should reach $\Delta f_{NL}^{local}=20$
  - If $f_{NL}^{local}=50\text{-}60$, **we would see it at 2.5 to 3 sigma by 2011.**

(The WMAP 9-year survey will be complete in August 2010.)

Minkowski Functionals (MFs)



Minkowski Functionals (MFs)



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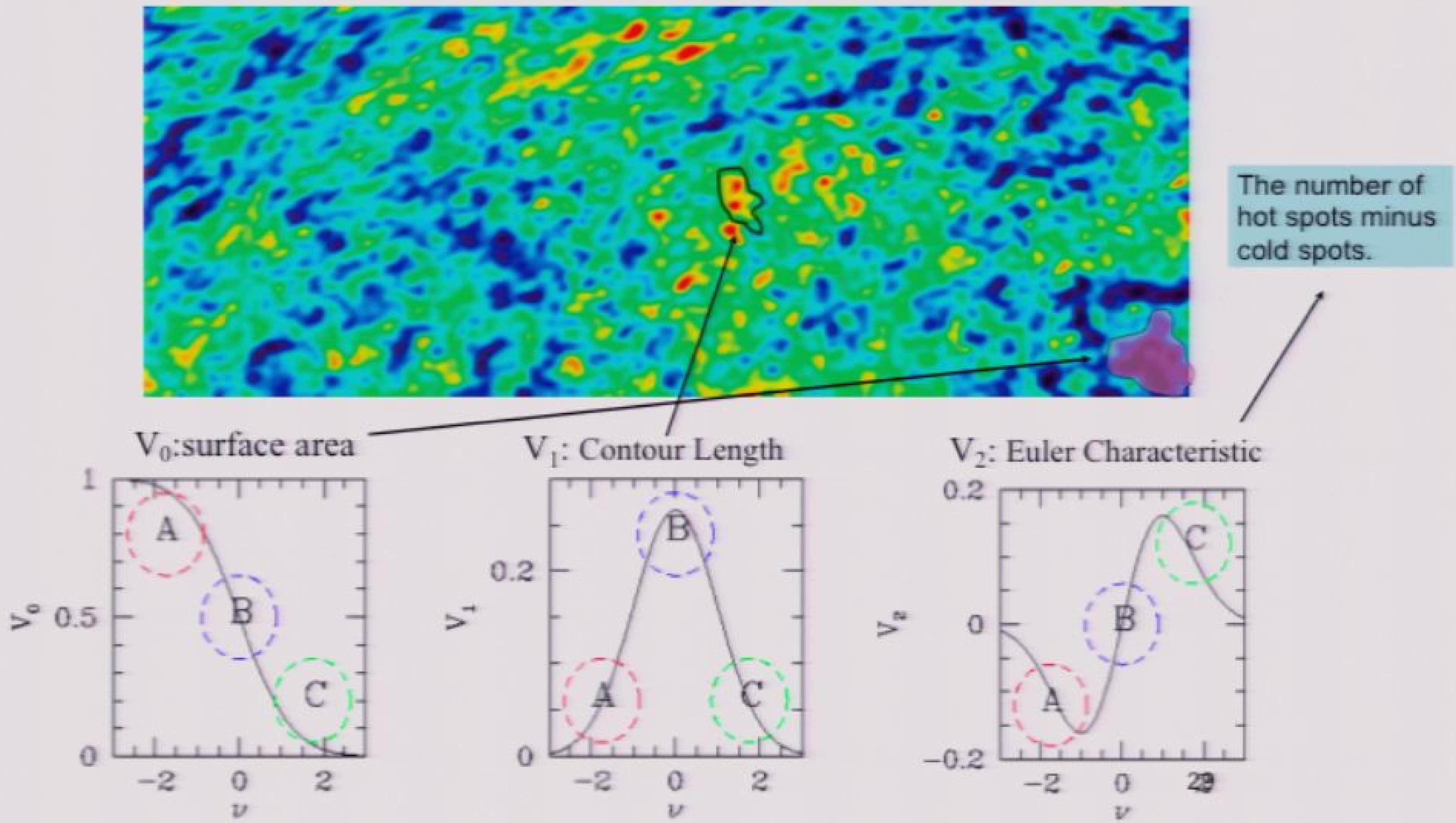
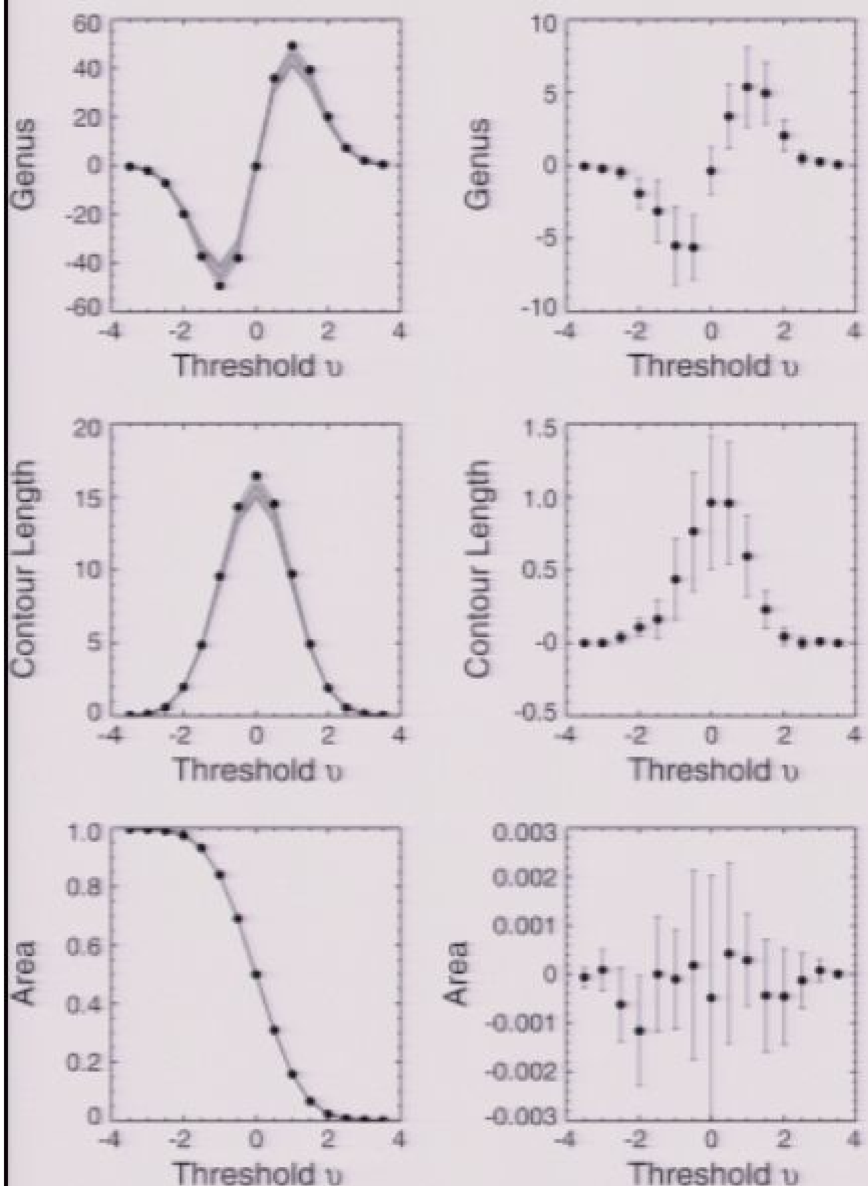


Komatsu et al. (2008)

MFs from *WMAP* *5-Year Data (V+W)*



Result from a single resolution
(N_{side}=128; 28 arcmin pixel)
[*analysis done by Al Kogut*]

f_{NL}^{local} = -57 +/- 60 (68% CL)

-178 < f_{NL}^{local} < 64 (95% CL)

Cf. Hikage et al. (2008) 3-year analysis using all the resolution:
f_{NL}^{local} = -22 +/- 43 (68% CL)
-108 < f_{NL}^{local} < 64 (95% CL)

“Tension?”

- **It is premature to worry about this**, but it is a little bit bothering to see that the bispectrum prefers a *positive* value, f_{NL}~60, whereas the Minkowski functionals prefer a *negative* value, f_{NL}~-60.
- These values are derived from the same data!
- What do the Minkowski functionals actually measure?

Hikage, Komatsu & Matsubara (2006)

Analytical formulae of MFs

Perturbative formulae of MFs (Matsubara 2003)

$$V_k(\nu) = \frac{1}{(2\pi)^{(k+1)/2}} \frac{\omega_2}{\omega_{2-k}\omega_k} \left(\frac{\sigma_1}{\sqrt{2}\sigma_0} \right)^k e^{-\nu^2/2} \{ H_{k-1}(\nu)$$

$(k = 0,1,2)$

$$+ \left[\frac{1}{6} S^{(0)} H_{k+2}(\nu) + \frac{k}{3} S^{(1)} H_k(\nu) + \frac{k(k-1)}{6} S^{(2)} H_{k-2}(\nu) \right] \sigma_0 + O(\sigma_0^2) \}$$

Gaussian term

leading order of Non-Gaussian term

$$\sigma_j^2 = \frac{1}{4} \sum_l (2l+1)[l(l+1)]^j C_l W_l^2$$

W_l: smoothing kernel

$\omega_0 = 1, \omega_1 = 1, \omega_2 = \pi, \omega_3 = 4\pi/3$ H_k : k- th Hermite polynomial

$S^{(a)}$: skewness parameters (a = 0,1,2)

In weakly non-Gaussian fields (σ_0<<1) , the non-Gaussianity in MFs is characterized by three skewness parameters $S^{(a)}$.

Matsubara (2003)

3 "Skewness Parameters"

- Ordinary skewness

$$S^{(0)} \equiv \frac{\langle f^3 \rangle}{\sigma_0^4},$$

- Second derivative

$$S^{(1)} \equiv -\frac{3}{4} \frac{\langle f^2 (\nabla^2 f) \rangle}{\sigma_0^2 \sigma_1^2},$$

- (First derivative)^2 x Second derivative

$$S^{(2)} \equiv -\frac{3d}{2(d-1)} \frac{\langle (\nabla f) \cdot (\nabla f) (\nabla^2 f) \rangle}{\sigma_1^4},$$

$$S^{(0)} = \frac{3}{2\pi\sigma_0^4} \sum_{2\le l_1 \le l_2 \le l_3} I^2_{l_1 l_2 l_3} b_{l_1 l_2 l_3} W_{l_1} W_{l_2} W_{l_3},$$

$$S^{(1)} = \frac{3}{8\pi\sigma_0^2\sigma_1^2} \sum_{2\le l_1 \le l_2 \le l_3} [l_1(l_1+1) + l_2(l_2+1) + l_3(l_3+1)] \times I^2_{l_1 l_2 l_3} b_{l_1 l_2 l_3} W_{l_1} W_{l_2} W_{l_3},$$

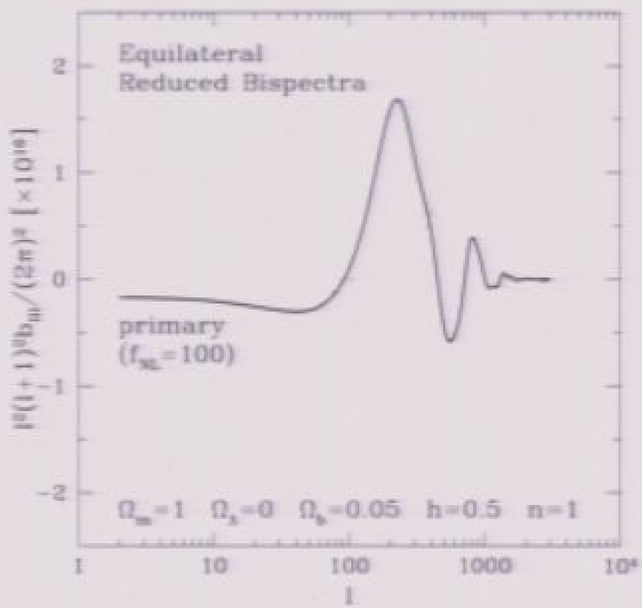
$$S^{(2)} = \frac{3}{4\pi\sigma_1^4} \sum_{2\le l_1 \le l_2 \le l_3} \{[l_1(l_1+1) + l_2(l_2+1) - l_3(l_3+1)] \times l_3(l_3+1) + (\text{cyc.})\} I^2_{l_1 l_2 l_3} b_{l_1 l_2 l_3} W_{l_1} W_{l_2} W_{l_3},$$

$S^{(0)}$: Simple average of b_{l1l2l3}

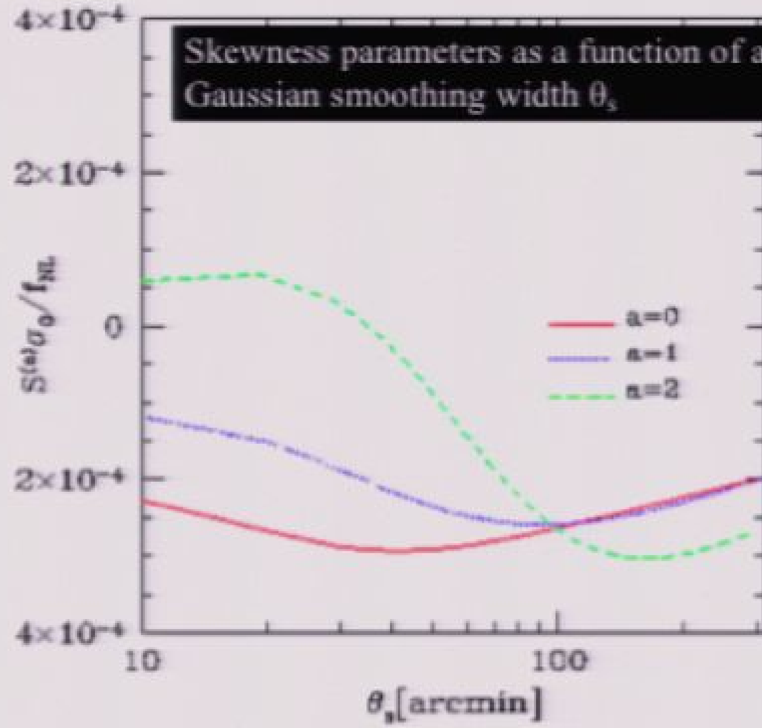
$S^{(1)}$: l^2 weighted average

$S^{(2)}$: l^4 weighted average

Analytical predictions of bispectrum at $f_{NL}=100$ (Komatsu & Spergel 2001)

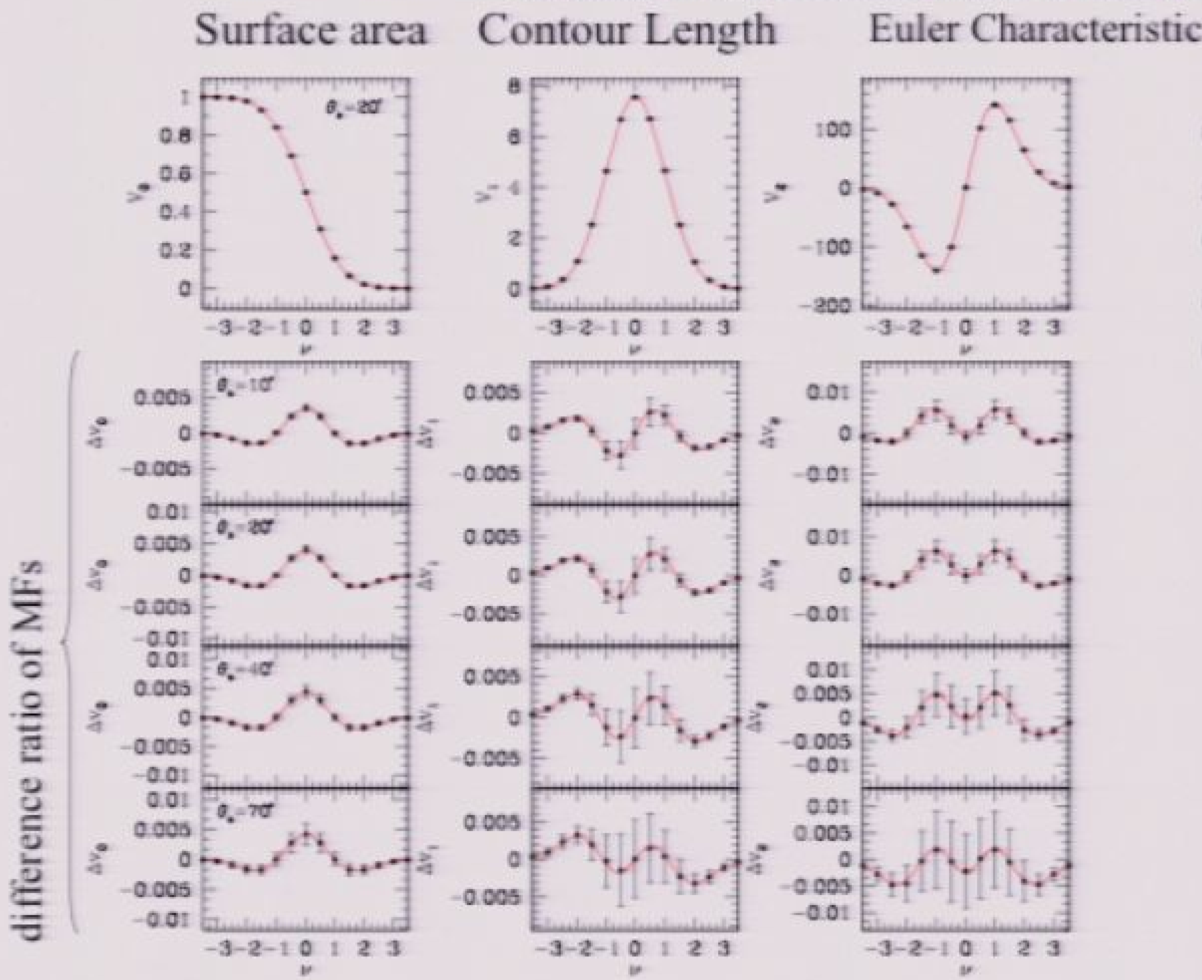


Skewness parameters as a function of a Gaussian smoothing width θ_s



Hikage et al. (2008)

Comparison of analytical formulae with Non-Gaussian simulations



Comparison of MFs between analytical predictions and non-Gaussian simulations with $f_{NL}=100$ at different Gaussian smoothing scales, θ_s

Simulations are done for WMAP.

Analytical formulae agree with non-Gaussian simulations very well.

Application of the Minkowski Functionals

- The skewness parameters are the direct observables from the Minkowski functionals.
- The skewness parameters can be calculated directly from the bispectrum.
- It can be applied to *any* form of the bispectrum!
  - Statistical power is weaker than the full bispectrum, but the application can be broader than the bispectrum estimator that is tailored for a very specific form of non-Gaussianity.

$$S^{(0)} = \frac{3}{2\pi\sigma_0^4} \sum_{2 \le l_1 \le l_2 \le l_3} I^2_{l_1 l_2 l_3} b_{l_1 l_2 l_3} W_{l_1} W_{l_2} W_{l_3},$$

$$S^{(1)} = \frac{3}{8\pi\sigma_0^2\sigma_1^2} \sum_{2 \le l_1 \le l_2 \le l_3} [l_1(l_1+1) + l_2(l_2+1) + l_3(l_3+1)] \times I^2_{l_1 l_2 l_3} b_{l_1 l_2 l_3} W_{l_1} W_{l_2} W_{l_3},$$

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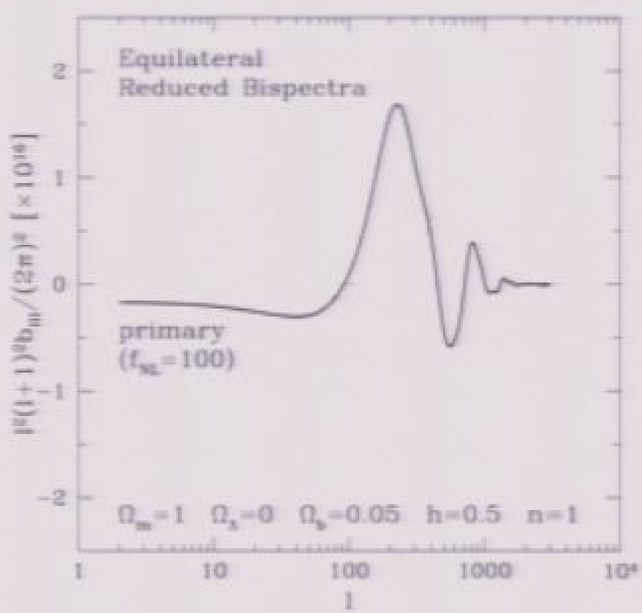

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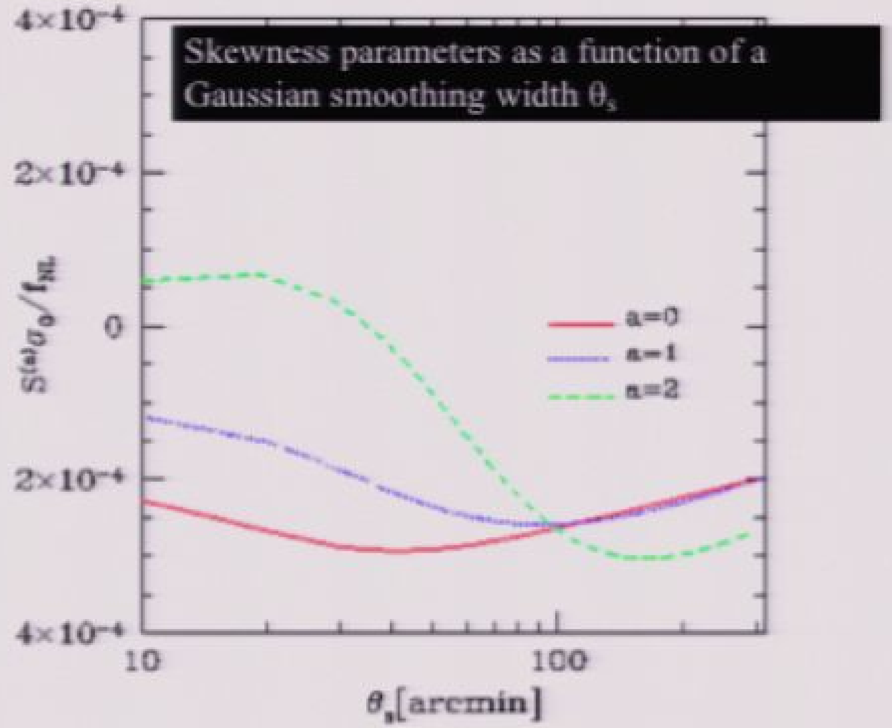

Hikage et al. (2008)

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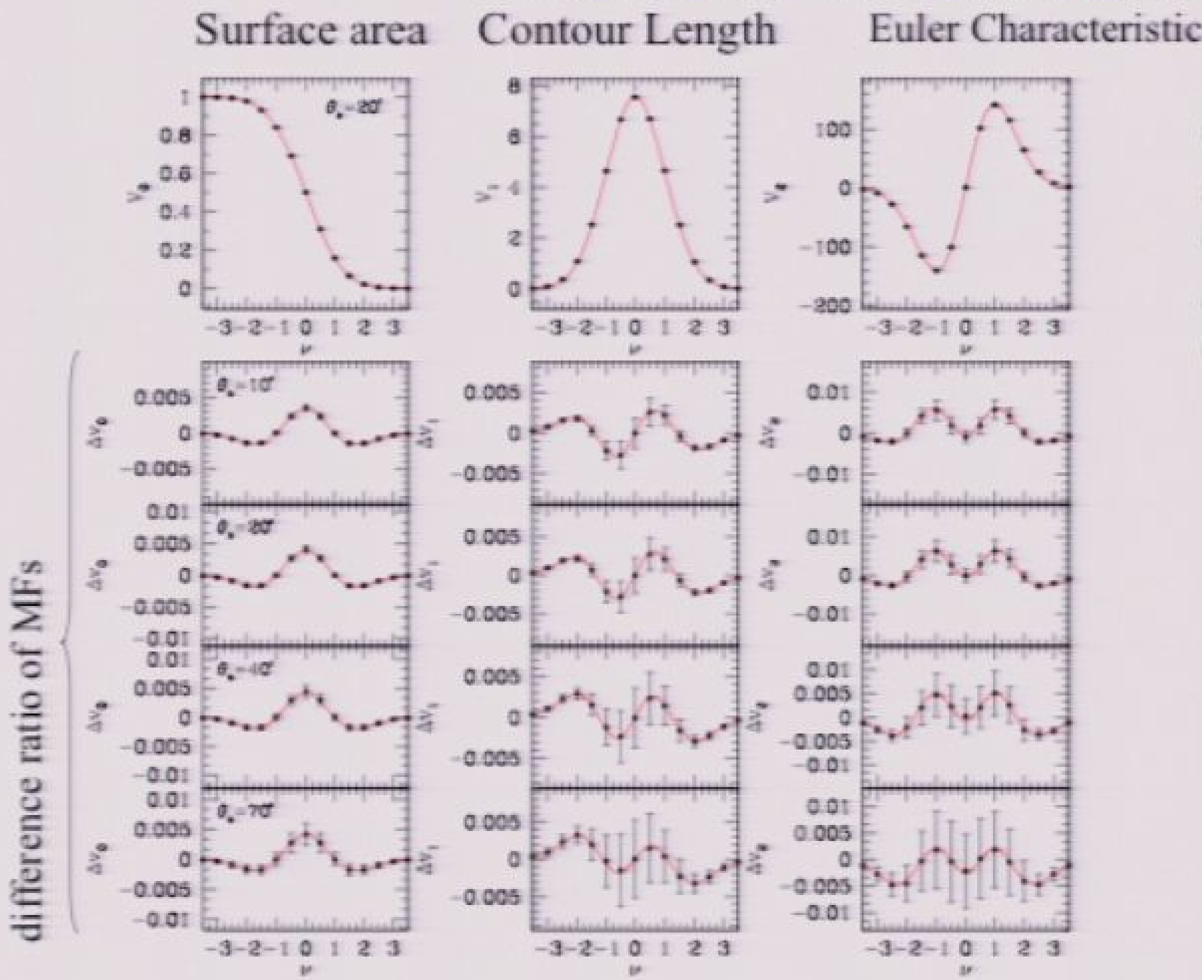

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An Opportunity?

- This apparent "tension" should be taken as an opportunity to investigate the other statistical tools, such the Minkowski functionals, wavelets, etc., in the context of primordial non-Gaussianity.
- It is plausible that various statistical tools can be written in terms of the sum of the bispectrum with various weights, in the limit of weak non-Gaussianity.
- Different tools are sensitive to different forms of non-Gaussianity - this is an advantage.

Systematics!

- Why use different statistical tools, when we know that the bispectrum gives us the maximum sensitivity?
- Systematics! Systematics!! Systematics!!!
- **<u>I don't believe any detections, until different statistical tools give the same answer.</u>**
    - That's why it bothers me to see that the bispectrum and the Minkowski functionals give different answers at the moment.

Summary

- The best estimates of primordial non-Gaussian parameters from the bispectrum analysis of the WMAP 5-year data are
  - $-9 < f_{NL}^{local} < 111$ (95% CL)
  - $-151 < f_{NL}^{equil} < 253$ (95% CL)
- **9-year data are required to test $f_{NL}^{local} \sim 60$!**
- The other statistical tools should be explored more.
  - E.g., estimate the skewness parameters directly from the Minkowski functionals to find the source of "tension"

Summary

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Komatsu et al. (2008)

Our Best Estimate

- Why not using Kp0 or KQ85 results, which have a higher statistical significance?
- Given the profound implications and impact of non-zero f_{NL}^{local}, we have chosen a conservative limit from the KQ75 with the point source correction (Δf_{NL}^{local}=4, which is also conservative) as our best estimate.
  - The 68% limit: f_{NL}^{local} = 51 +/- 30 [1.7 sigma]
  - **The 95% limit: $-9 < f_{NL}^{local} < 111$**

Komatsu et al. (2008)

Main Result (Local)

Band	Mask	l_{max}	f_{NL}^{local}	Δf_{NL}^{local}	b_{src}
V+W	*KQ85*	400	50 ± 29	1 ± 2	0.26 ± 1.5
V+W	*KQ85*	500	61 ± 26	2.5 ± 1.5	0.05 ± 0.50
V+W	*KQ85*	600	68 ± 31	3 ± 2	0.53 ± 0.28
V+W	*KQ85*	700	67 ± 31	3.5 ± 2	0.34 ± 0.20
V+W	*Kp0*	500	61 ± 26	2.5 ± 1.5	
V+W	*KQ75p1*[a]	500	53 ± 28	4 ± 2	
V+W	*KQ75*	400	47 ± 32	3 ± 2	-0.50 ± 1.7
V+W	*KQ75*	500	55 ± 30	4 ± 2	0.15 ± 0.51
V+W	*KQ75*	600	61 ± 36	4 ± 2	0.53 ± 0.30
V+W	*KQ75*	700	58 ± 36	5 ± 2	0.38 ± 0.21

- ~ 2 sigma "hint": **f_{NL}^{local} ~ 60 +/- 30 (68% CL)**
- 1.8 sigma for KQ75; 2.3 sigma for KQ85 & Kp0

Komatsu & Spergel (2001); Babich, Creminelli & Zaldarriaga (2004)

Two f_{NL}'s

- Depending upon the shape of triangles, one can define
  - $-58 < f_{NL}^{local} < 134$ [WMAP 1yr, $l_{max}=265$] Komatsu et al. (2003)
  - $-54 < f_{NL}^{local} < 114$ [WMAP 3yr, $l_{max}=350$] Spergel et al. (2007)
  - **$-9 < f_{NL}^{local} < 111$ [WMAP 5yr, $l_{max}=500$]** Komatsu et al. (2008)
- Equilateral
  - $-366 < f_{NL}^{equil} < 238$ [WMAP 1yr, $l_{max}=405$] Creminelli et al. (2006)
  - $-256 < f_{NL}^{equil} < 332$ [WMAP 3yr, $l_{max}=475$] Creminelli et al. (2007)
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Journal on f_{NL}

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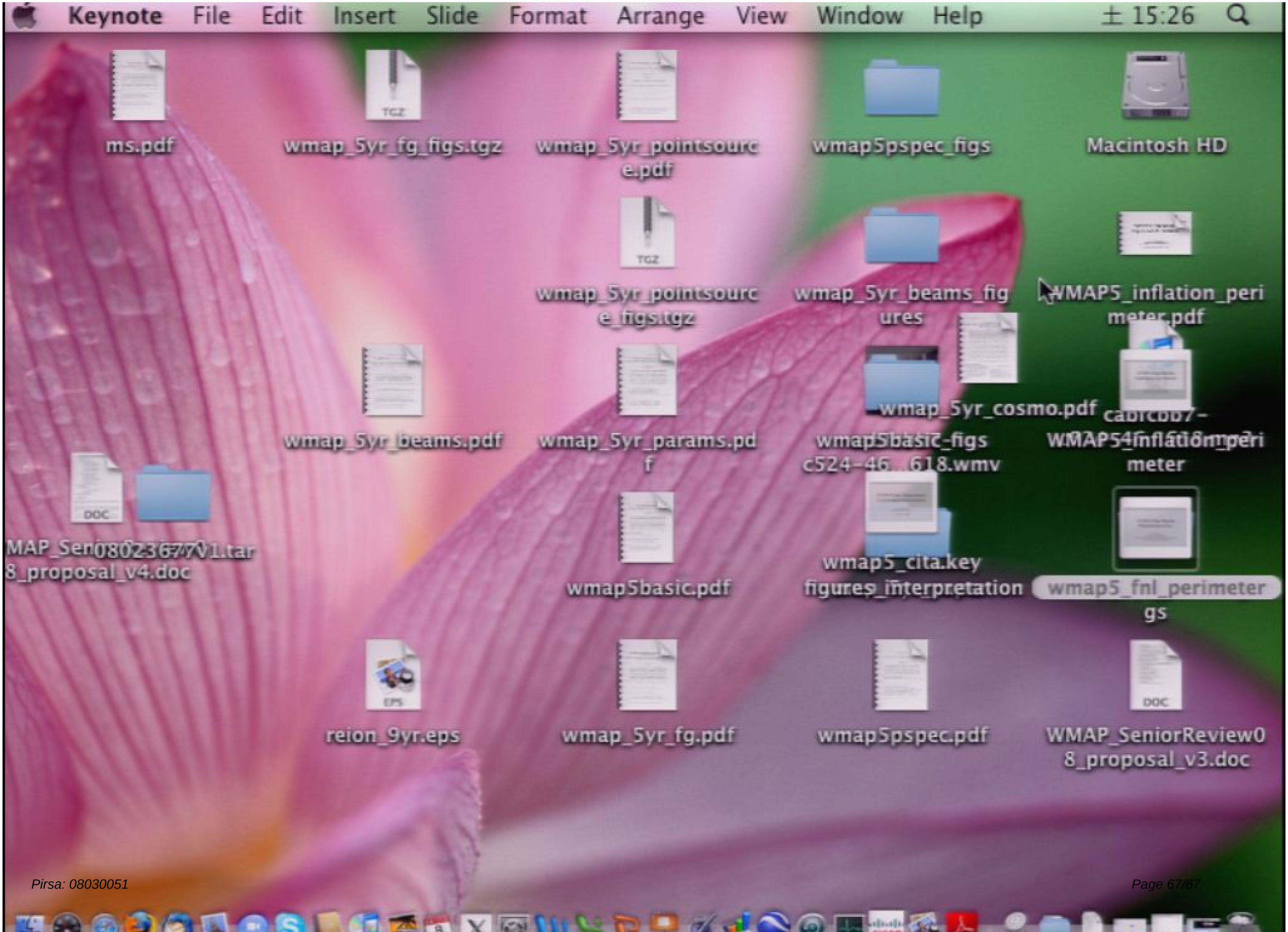
Keynote File Edit Insert Slide Format Arrange View Window Help
15:26
ms.pdf
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wmap_5yr_pointsource.pdf
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