WMAP seven-year results

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HRI, 14 Dec 2010

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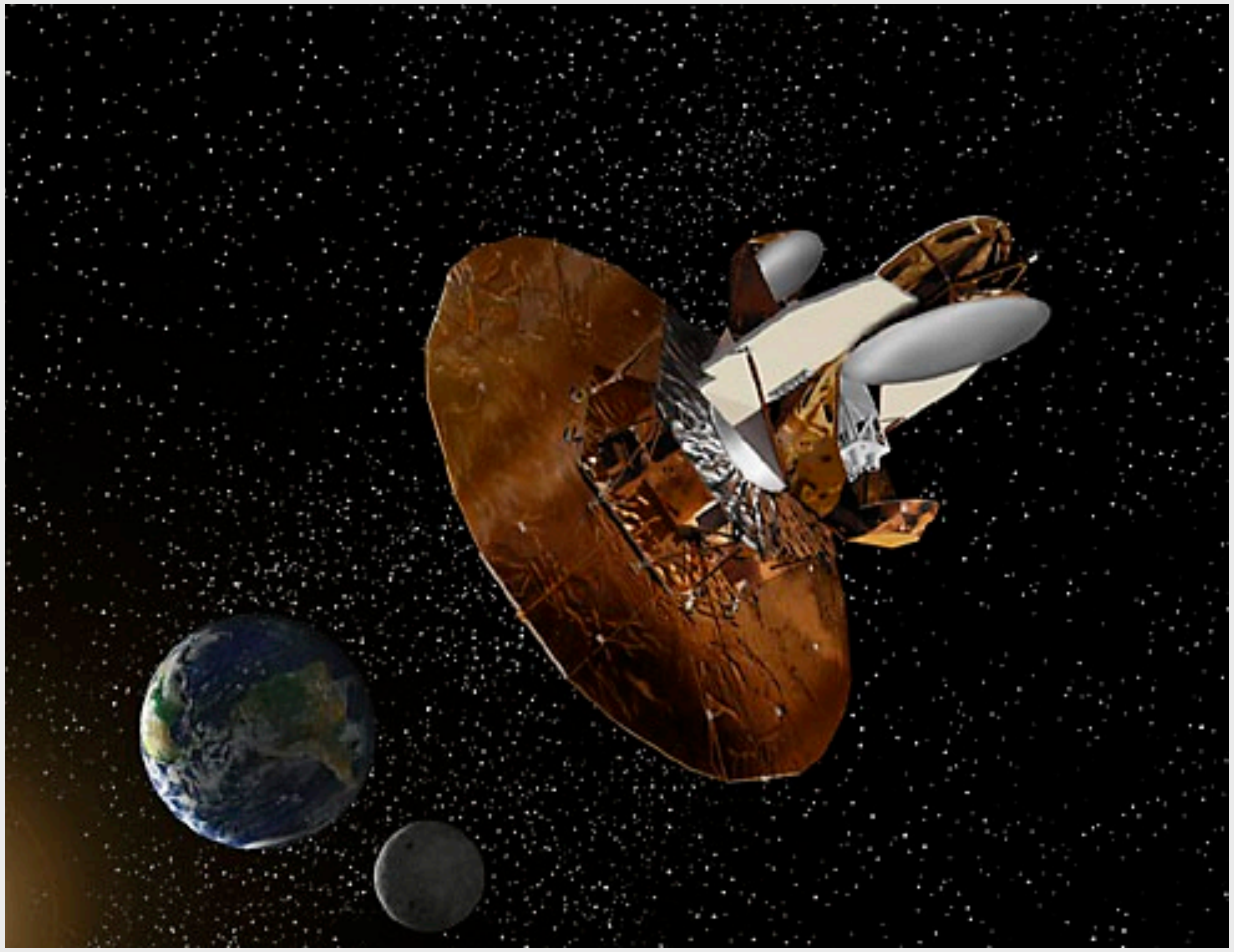
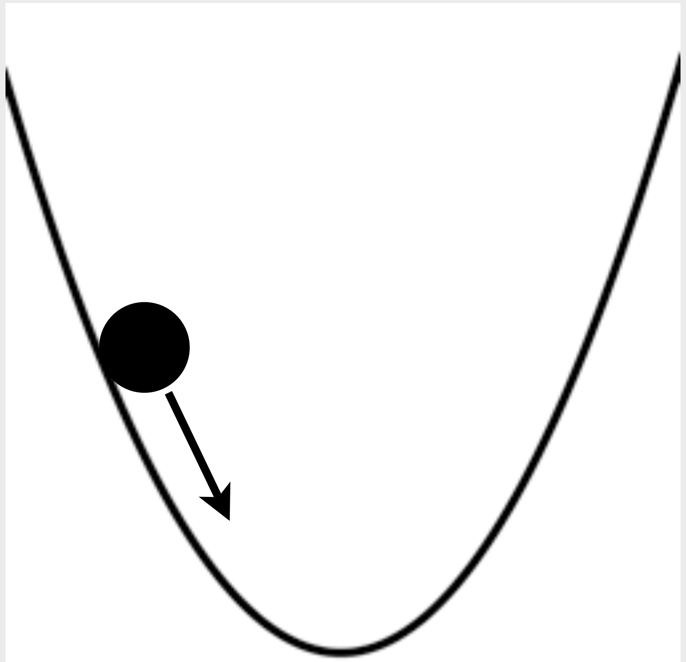


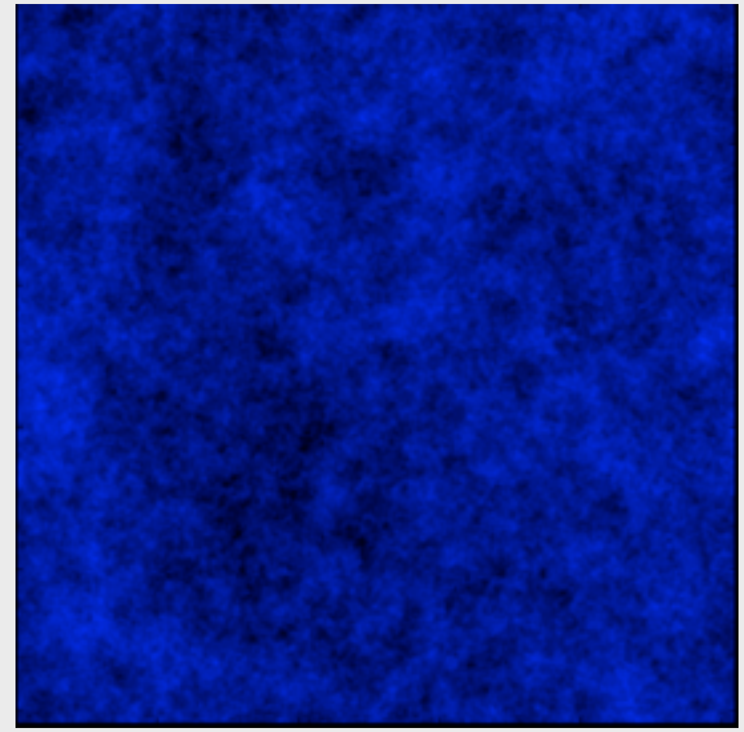
Cosmic microwave background

$$\mathcal{L} = \frac{M_{\rm pl}^2}{2} R - \frac{1}{2}(\partial\phi)^2 - V(\phi)$$



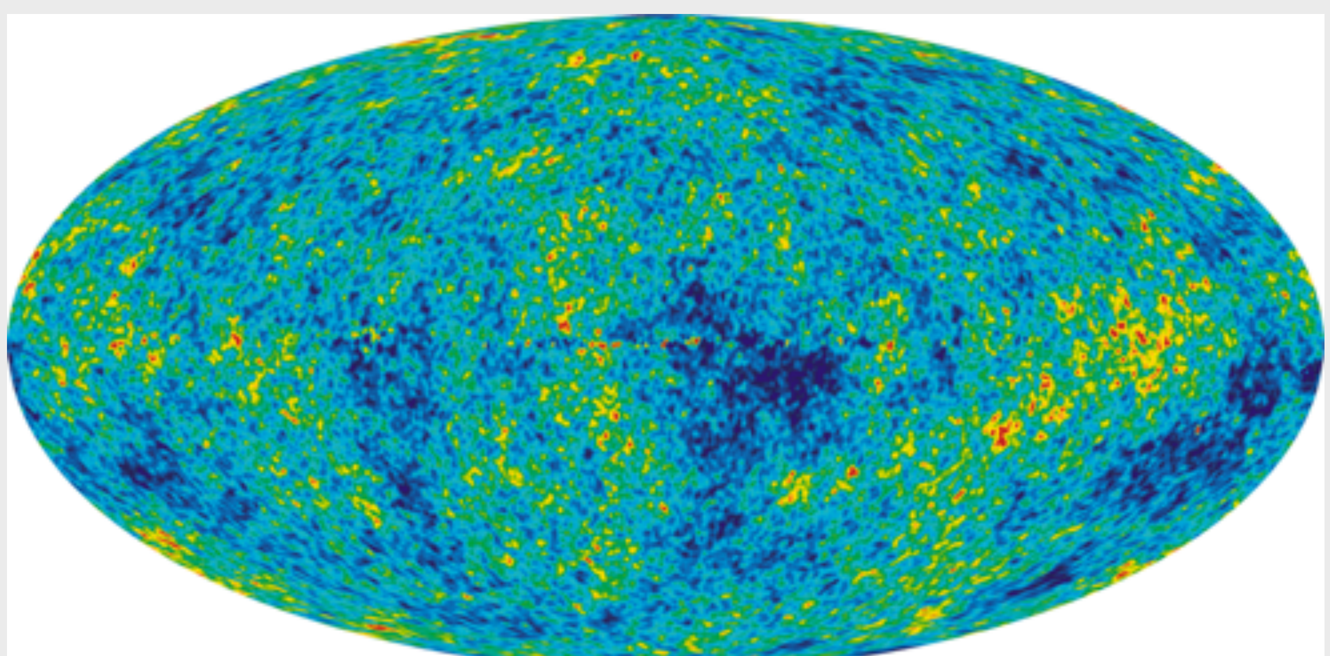
Inflation

$$\langle |\zeta(k)|^2 \rangle \propto (k_0/k)^{4-n_s}$$



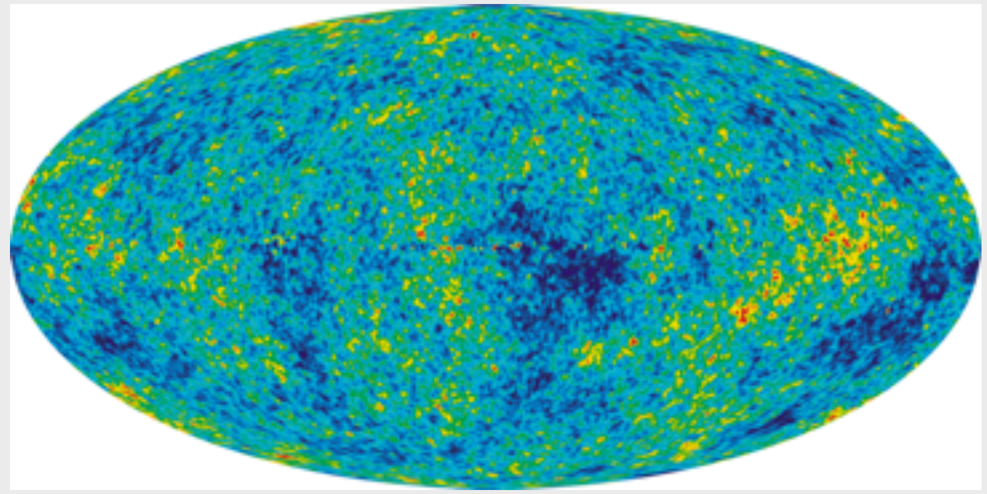
Initial curvature fluctuation

$\Omega_b h^2,\ \Omega_m h^2,$
$\Omega_\Lambda,\ \tau, \cdots$

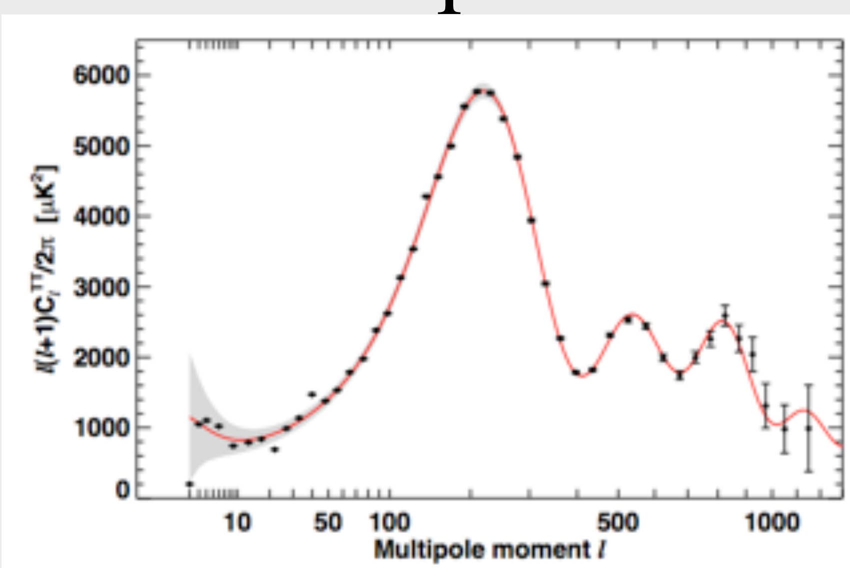


CMB temperature anisotropies

Data analysis

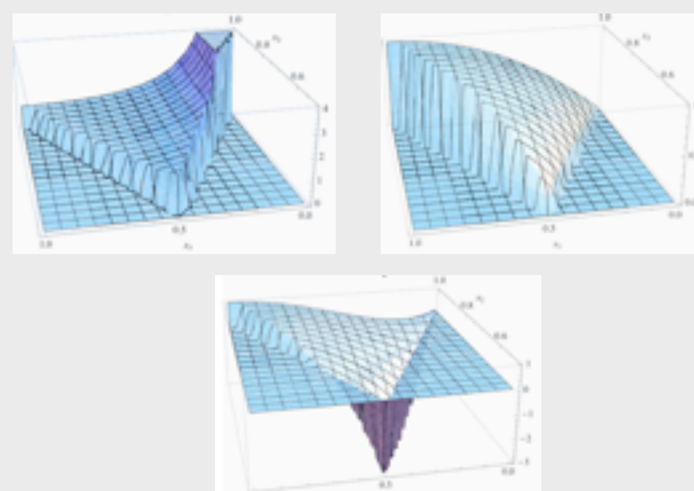


Power spectrum



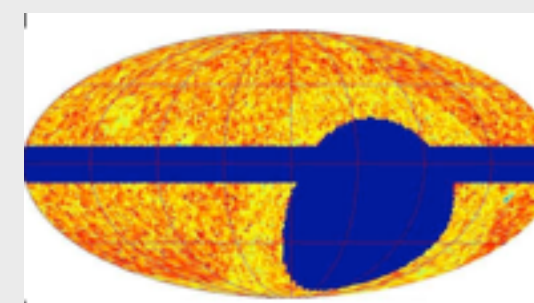
Cosmological parameters: $\{n_s, \Omega_\Lambda, \Omega_m h^2, \cdots\}$

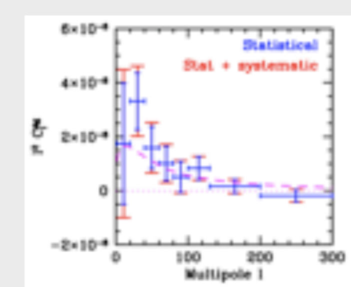
Higher-point statistics



Primordial non-gaussianity, gravitational lensing, ...

External datasets





Cluster SZ, gravitational lensing, ISW effect, ...

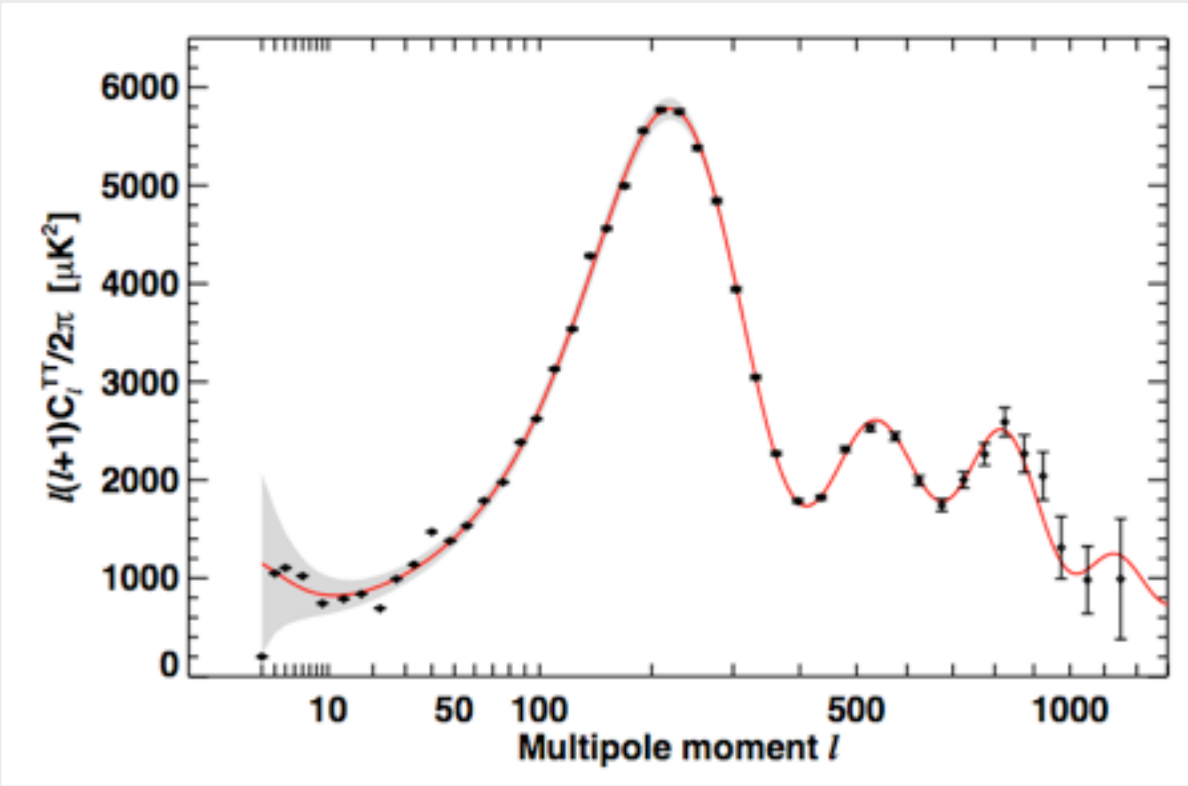
Differences between 7-year and 5-year analysis

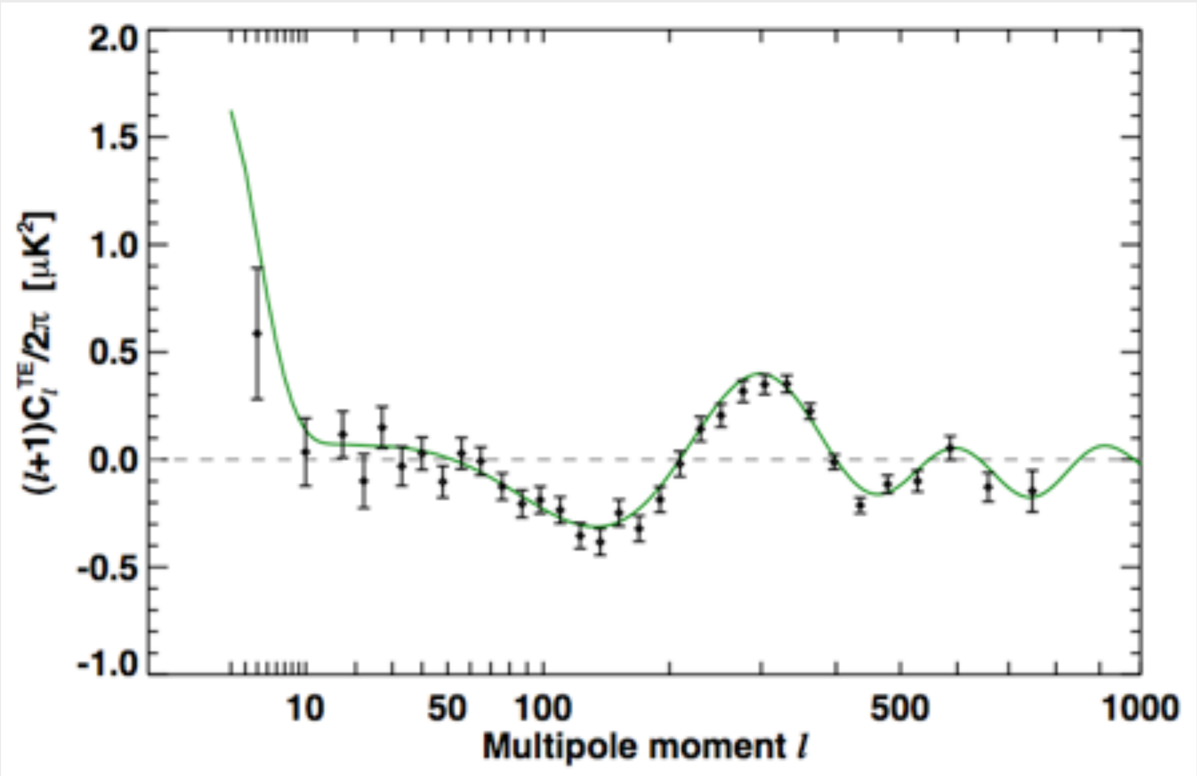
- More conservative timestream selection (planet cuts)
- More conservative galactic mask (Gum/Oph free-free emission)
- Updated beam analysis (only ~0.1% change in C_ℓ^{TT})
- W-band polarization data now included (exception: DA W4)
- Fully optimal estimators implemented in many parts of pipeline
- SZ cluster stacking analysis
- Analysis of 5 planets + 5 celestial sources
- Analysis of CMB “anomalies”

Standard cosmological model still fits the data

- Flat LCDM $(\Omega_k = -0.0023^{+0.0054}_{-0.0056},\ w = -1.10 \pm 0.14)$
- Adiabatic scalar initial conditions
  $(r < 0.24,\ \alpha_0 < 0.077,\ \alpha_{-1} < 0.0047,\ 95\%\ \mathrm{CL})$
- Gaussian initial conditions
  $(f_{NL}^{\rm local} = 32 \pm 21,\ f_{NL}^{\rm equil} = 26 \pm 140,\ f_{NL}^{\rm orthog} = -202 \pm 104)$
- Power law initial spectrum, $n_s < 1$ at $> 3\sigma$

(all results WMAP7+BAO+H_0)





$\chi^2_{1170} = 1225$ (PTE: 17.4%)

Dark energy / curvature

What can we say about dark energy from WMAP alone?

Consider the six-parameter space $\{\Omega_b h^2, \Omega_m h^2, A_s, \tau, n_s, \Omega_\Lambda\}$
First 5 parameters are well-constrained through power spectrum shape
Constraint on Ω_Λ comes entirely through angular peak scale:

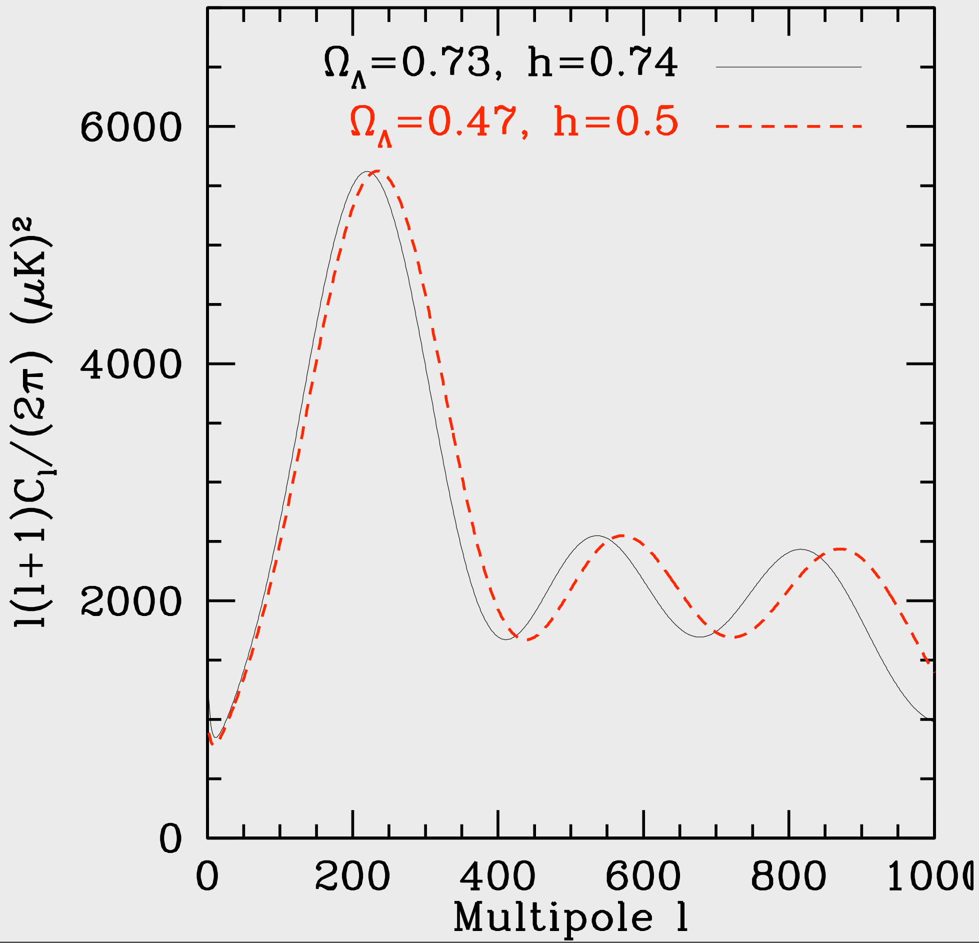
$$\ell_a = \pi \frac{D_*}{s_*}$$

$D_* \longleftarrow$ Angular diameter distance to last scattering
$s_* \longleftarrow$ Distance sound travels before last scattering

Get good constraint on Ω_Λ from WMAP alone: $\Omega_\Lambda = 0.734 \pm 0.029$

Note that we assumed flat ΛCDM:

$$\Omega_k = 0,\ \ w(z) = -1$$



Dark energy / curvature

Now suppose we add a parameter to the 6-parameter space, e.g. curvature Ω_k .

Angular diameter distance degeneracy: Only one combination (corresponding to D_*) of $\Omega_\Lambda,\ \Omega_k$ is constrained by the CMB.

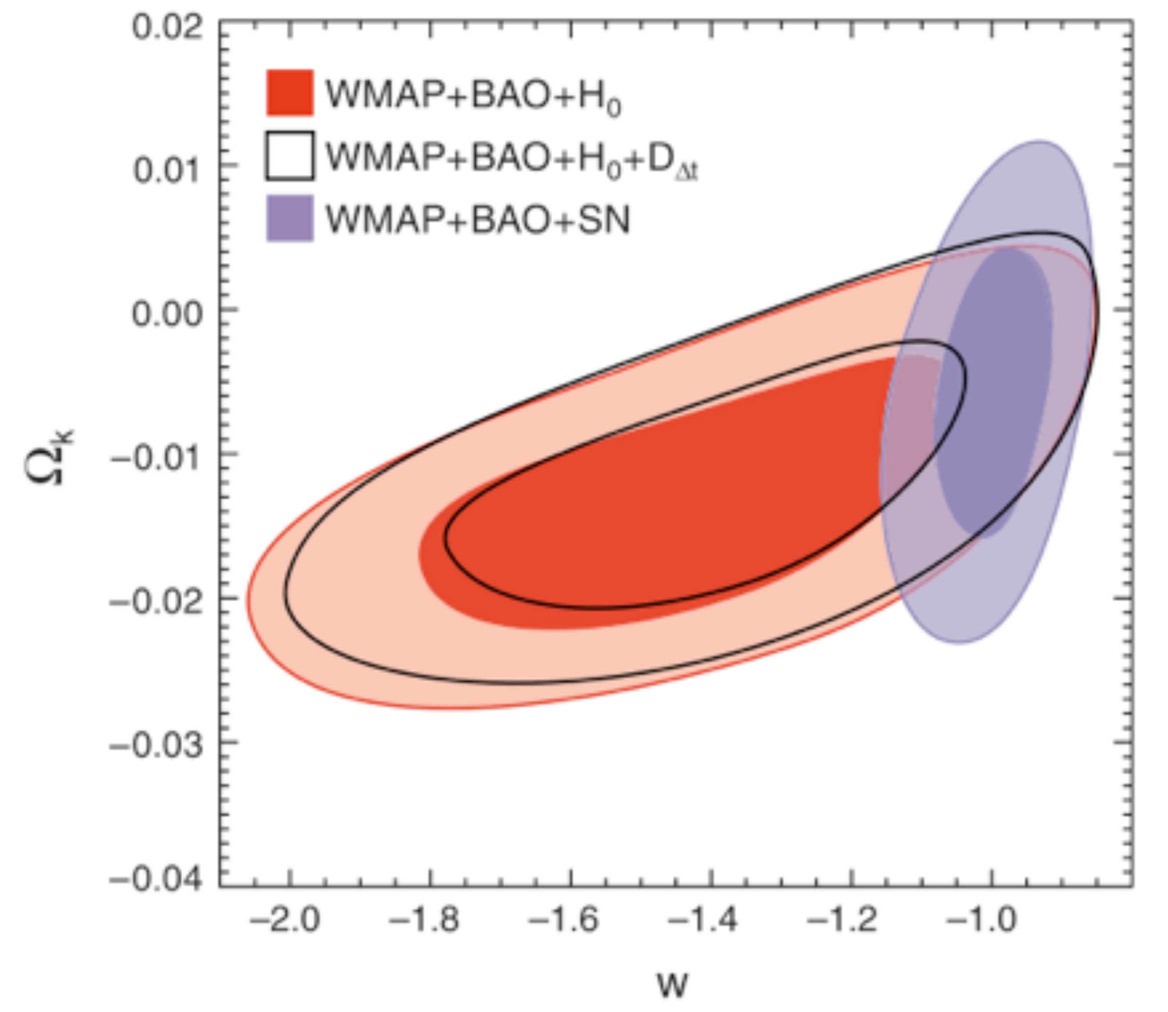
Need external datasets to break degeneracy: e.g. WMAP+BAO+H_0

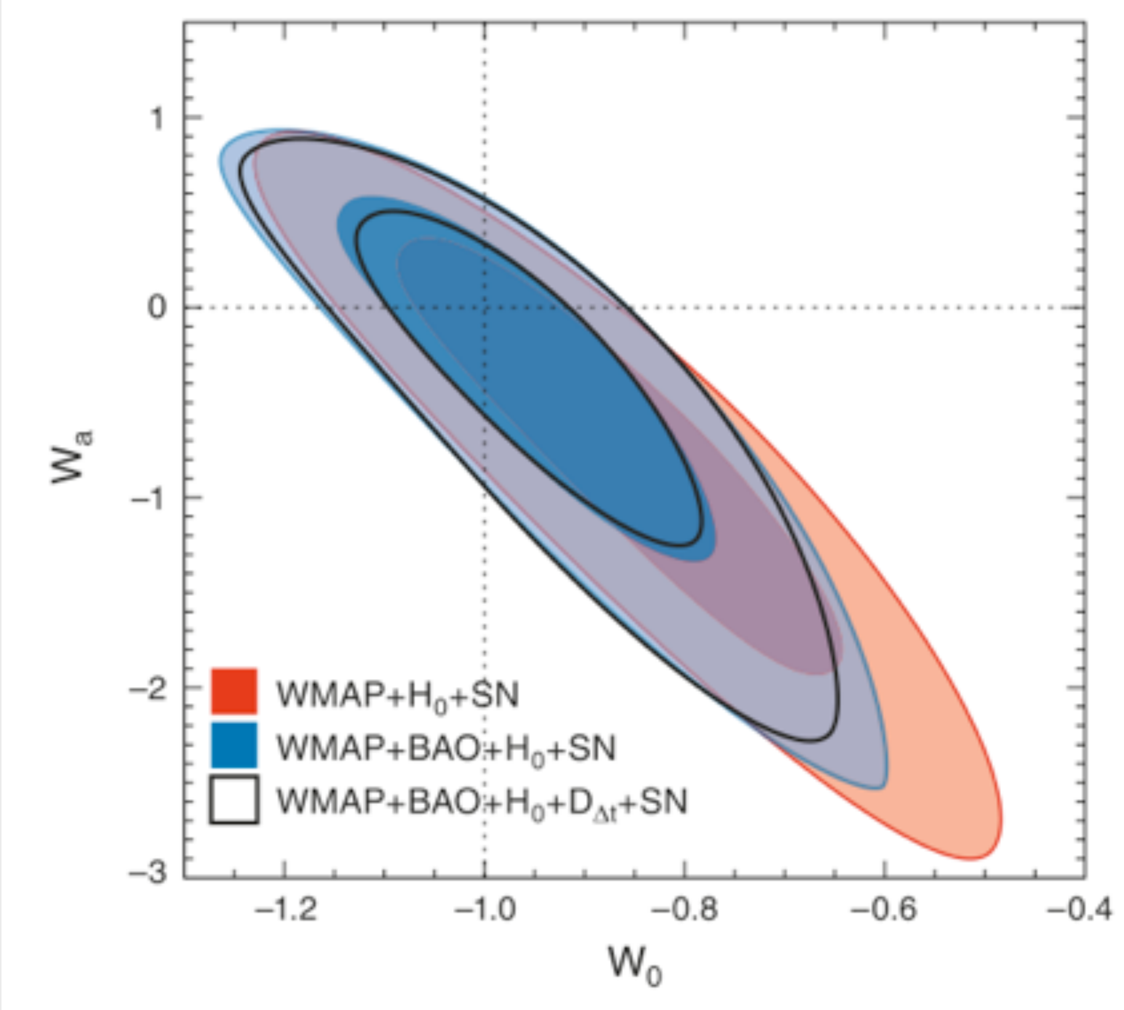
$$w = -1.10 \pm 0.14 \quad (\Omega_k = 0)$$

$$\Omega_k = -0.0023^{+0.0054}_{-0.0056} \quad (w = -1)$$

Dark energy / curvature

If we add two parameters to the 6-parameter space (e.g. if we jointly constrain $\Omega_\Lambda, \ \Omega_k, \ w$) then supernovae seem to be necessary.

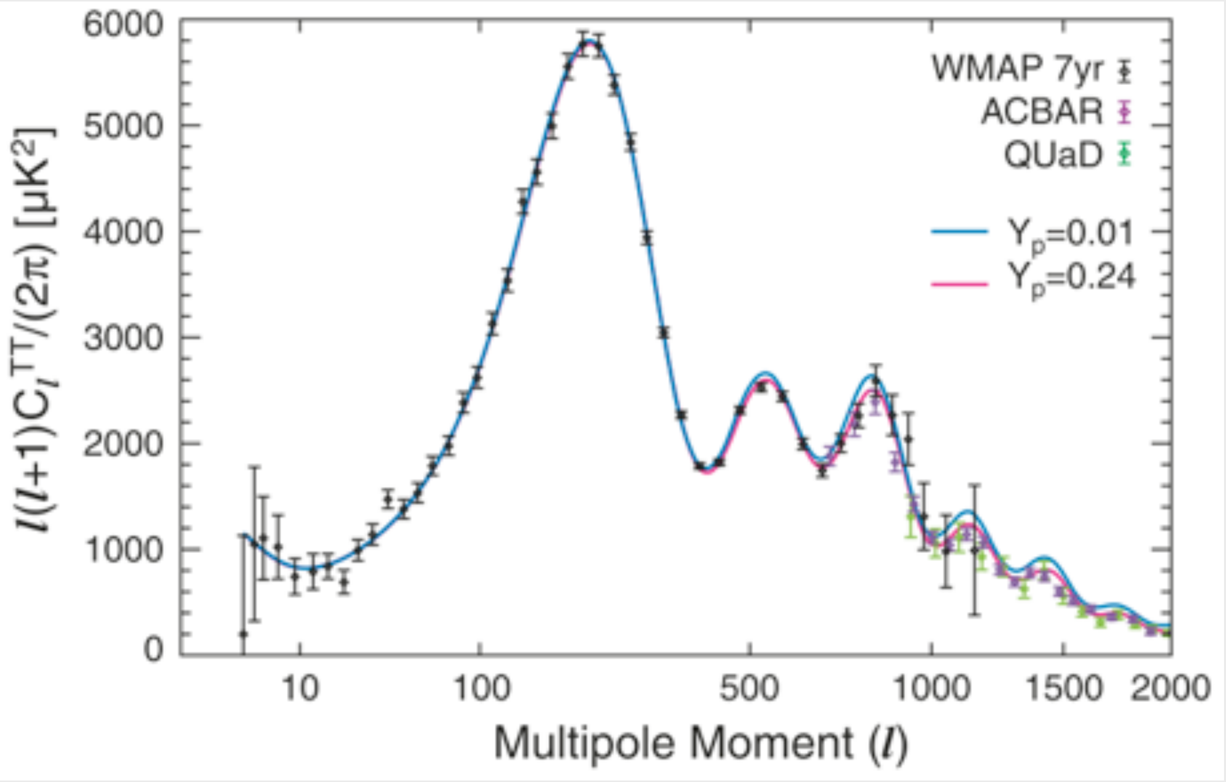




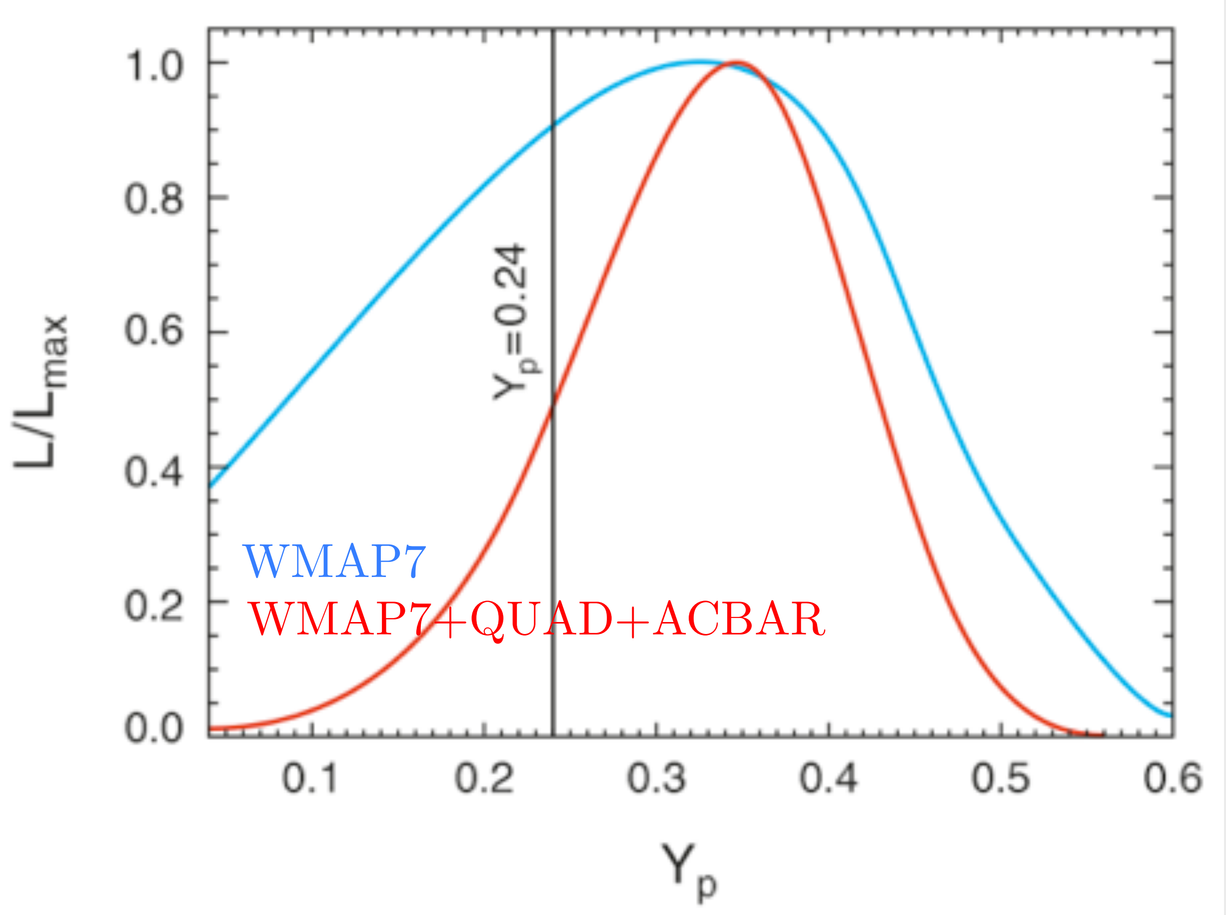
Caveat: scatter between different SN samples can be large, e.g. “w” estimates from WMAP+BAO+(SDSS SN) differ by ~2.5 sigma if analyzed with different light curve fitters (SALT, MLCS).

Primordial helium abundance

Primordial helium decreases density of free electrons at last scattering => more Silk damping



WMAP7+QUAD+ACBAR gives first 3σ detection of $Y_p > 0$



Number of neutrino species

$N_{\rm eff}$ = number of relativistic species before recombination

Redshift z_{eq} of matter-radiation equality = function of $N_{\rm eff}$, $\Omega_m h^2$

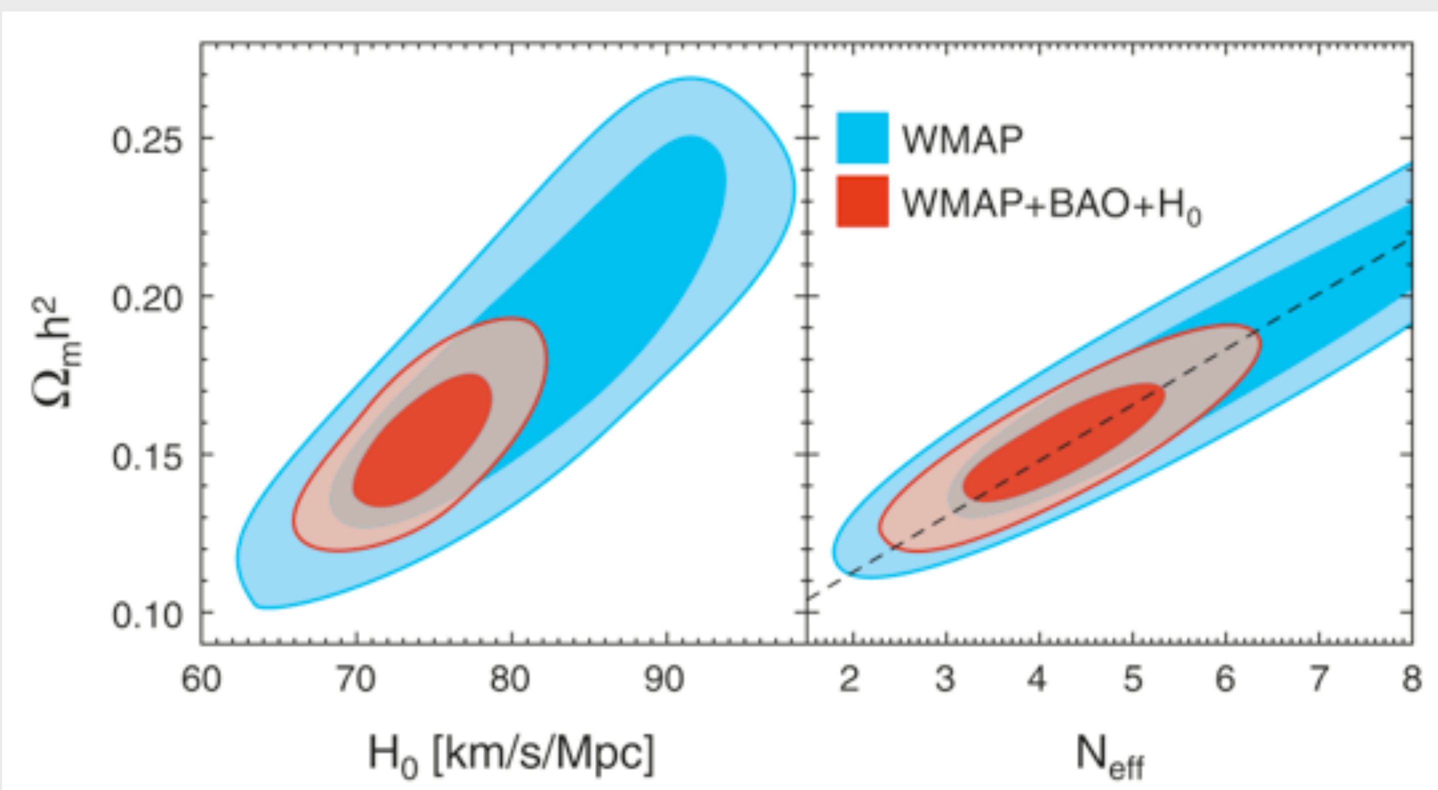
Angular diameter distance D_* = function of $\Omega_m h^2$, Ω_Λ

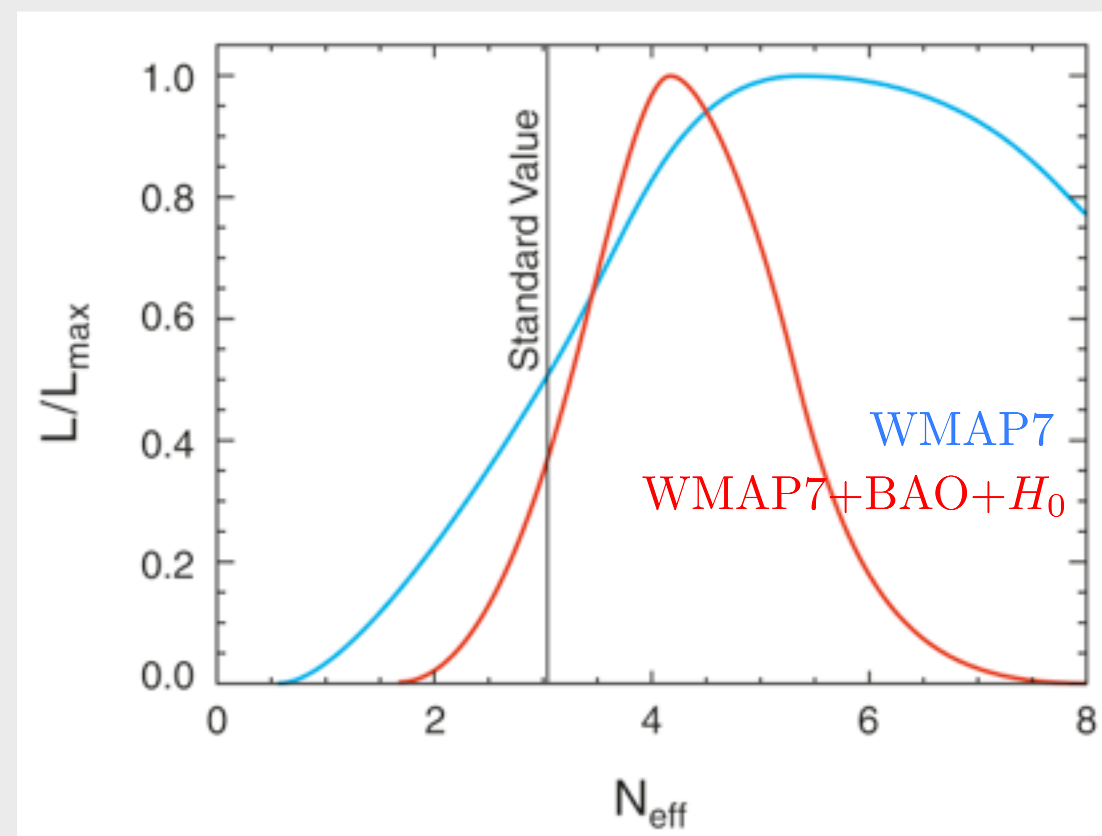
WMAP7 alone: $N_{\rm eff} > 2.7$ eV (95% CL)

(Degenerate: 3 parameters and 2 observables)

WMAP7+BAO+H_0: $N_{\rm eff} = 4.34^{+0.86}_{-0.88}$ eV (nondegenerate)

WMAP7+ACT+BAO+H_0: $N_{\rm eff} = 4.6 \pm 0.8$ (nondegenerate)





Neutrino mass

Neutrino oscillation experiments measure Δm_ν^2 between species

Current analysis of world neutrino oscillation data:

$$\begin{aligned} \Delta m_{31}^2 &= (0.049 \pm 0.0012 \text{ eV})^2 \\ \Delta m_{21}^2 &= (0.0087 \pm 0.00013 \text{ eV})^2 \end{aligned}$$

Cosmology is complementary: mainly sensitive to $\sum_\nu m_\nu$

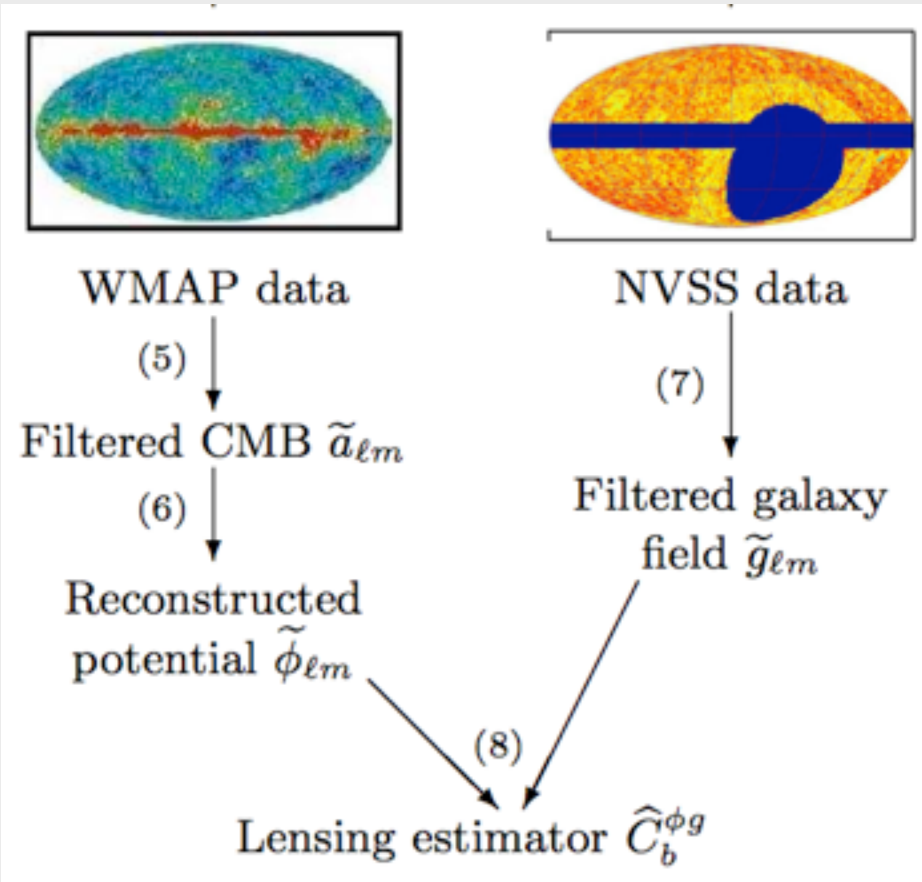
WMAP7 alone: $\sum m_\nu < 1.3 \text{ eV} \ (95\% \text{ CL})$

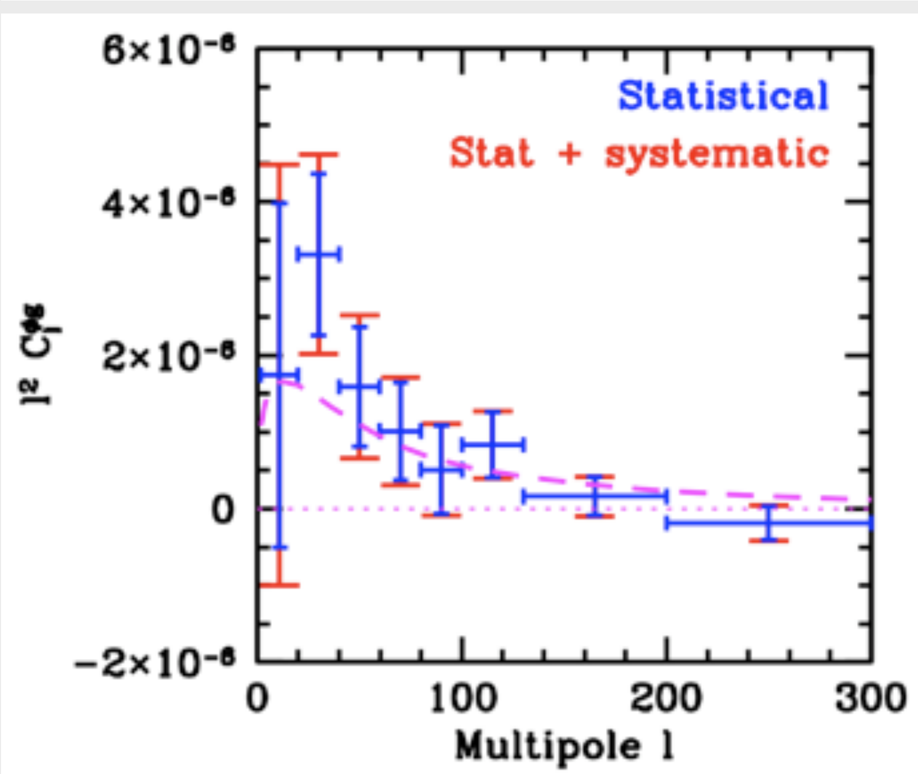
(Limited by angular diameter distance degeneracy until mass becomes large enough to alter energy density at recombination.)

WMAP7+BAO+H_0: $\sum m_\nu < 0.58 \text{ eV} \ (95\% \text{ CL})$

(Angular diameter distance degeneracy is broken.)

Future constraints on m_ν from CMB lensing





KMS, Zahn, Dore & Nolta 05

WMAP: 3.4σ detection of lensing, by cross-correlating quadratic estimator with radio galaxy counts (KMS et al 07)

Planck: "internal" lensing measurement;

$$\sigma\left(\sum_\nu m_\nu\right) \approx 0.2 \text{ eV}$$

(KMS, Hu & Kaplinghat 06)

CMBpol: approaching guaranteed signal

$$\sigma\left(\sum_\nu m_\nu\right) \approx 0.05 \text{ eV}$$

(KMS et al 09)

Inflation

Parameterize initial power spectrum by spectral index n_s, running α

$$P_\zeta(k) = P_0 \left(\frac{k}{k_0}\right)^{-4+n_s+(\alpha/2)\log(k/k_0)}$$

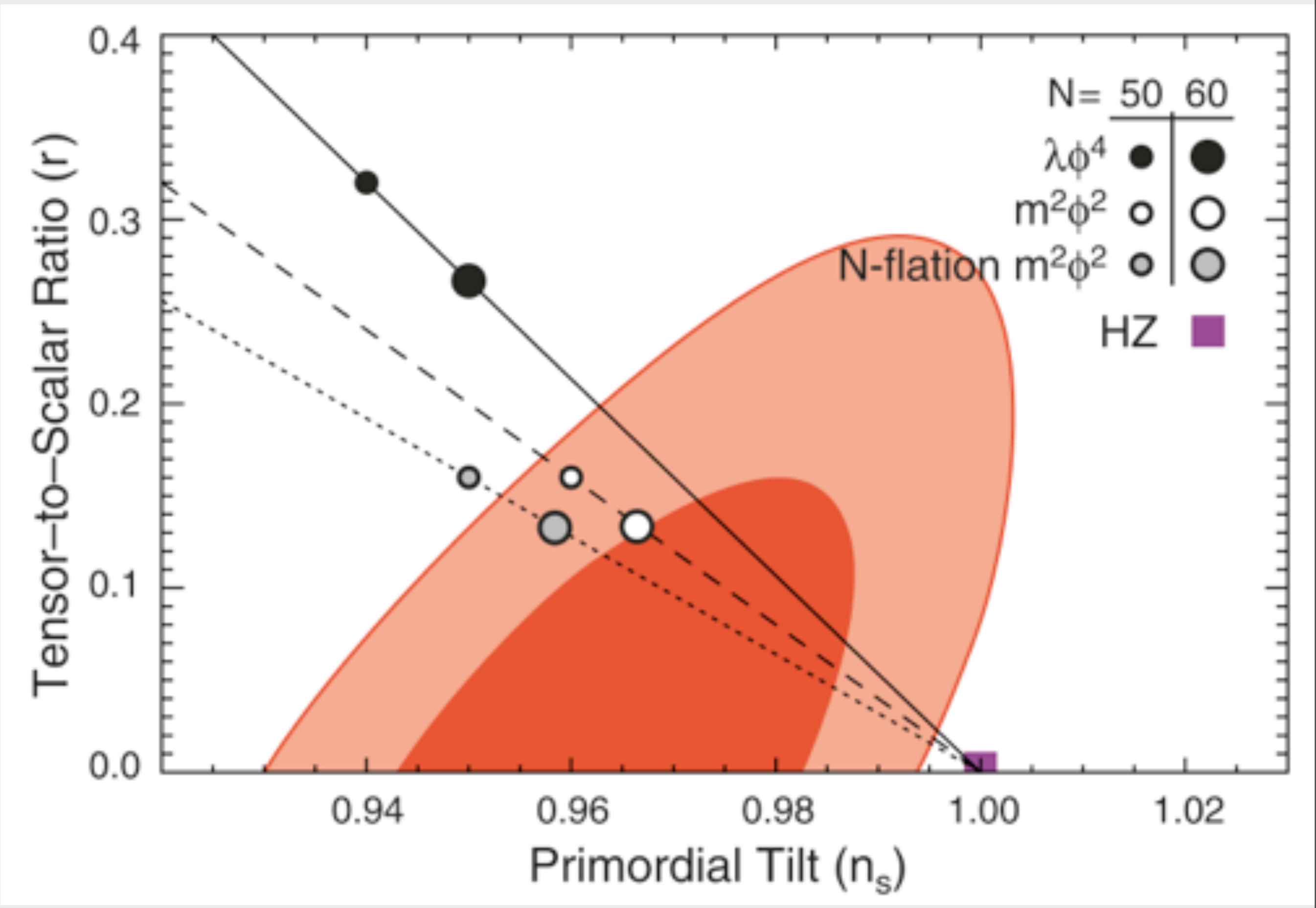
WMAP is consistent with power law spectrum ($\alpha = -0.022 \pm 0.020$) where $n_s = 0.963 \pm 0.012$ is less than 1 at 3σ

Tensor modes: WMAP+BAO+H0

$$r < 0.24 \ (95\% \ \mathrm{CL})$$

comes mostly from temperature; the WMAP limit from B-modes is

$$r < 2.1 \ (95\% \ \mathrm{CL})$$



Three-point signals from inflation

In the simplest models of inflation, initial adiabatic curvature ζ is nearly Gaussian; in particular the 3-point function vanishes

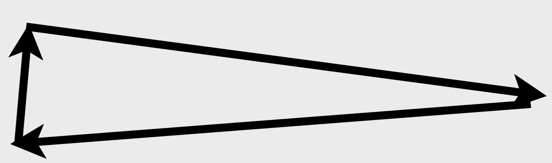
$$\langle \zeta(\mathbf{k_1})\zeta(\mathbf{k_2})\zeta(\mathbf{k_3})\rangle \approx 0$$

There are also models which generate a detectable 3-point function; thus 3-point signals can discriminate qualitative classes of models.

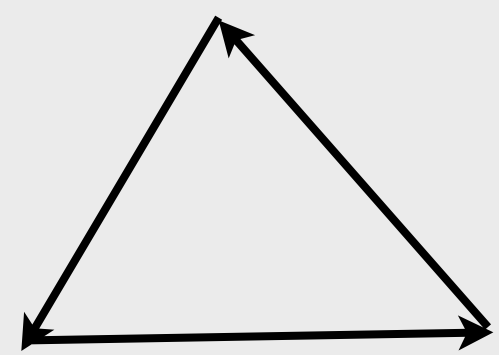
Translation + rotation invariance imply:

$$\langle \zeta(\mathbf{k_1})\zeta(\mathbf{k_2})\zeta(\mathbf{k_3})\rangle = F(k_1, k_2, k_3)(2\pi)^3\delta^3(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3)$$

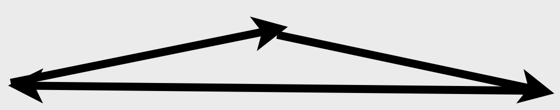
where the bispectrum $F(k_1, k_2, k_3)$ depends on shape of the triangle



"Squeezed" triangle
$k_1 \ll k_2, k_3$



Equilateral triangle
$k_1 \approx k_2 \approx k_3$



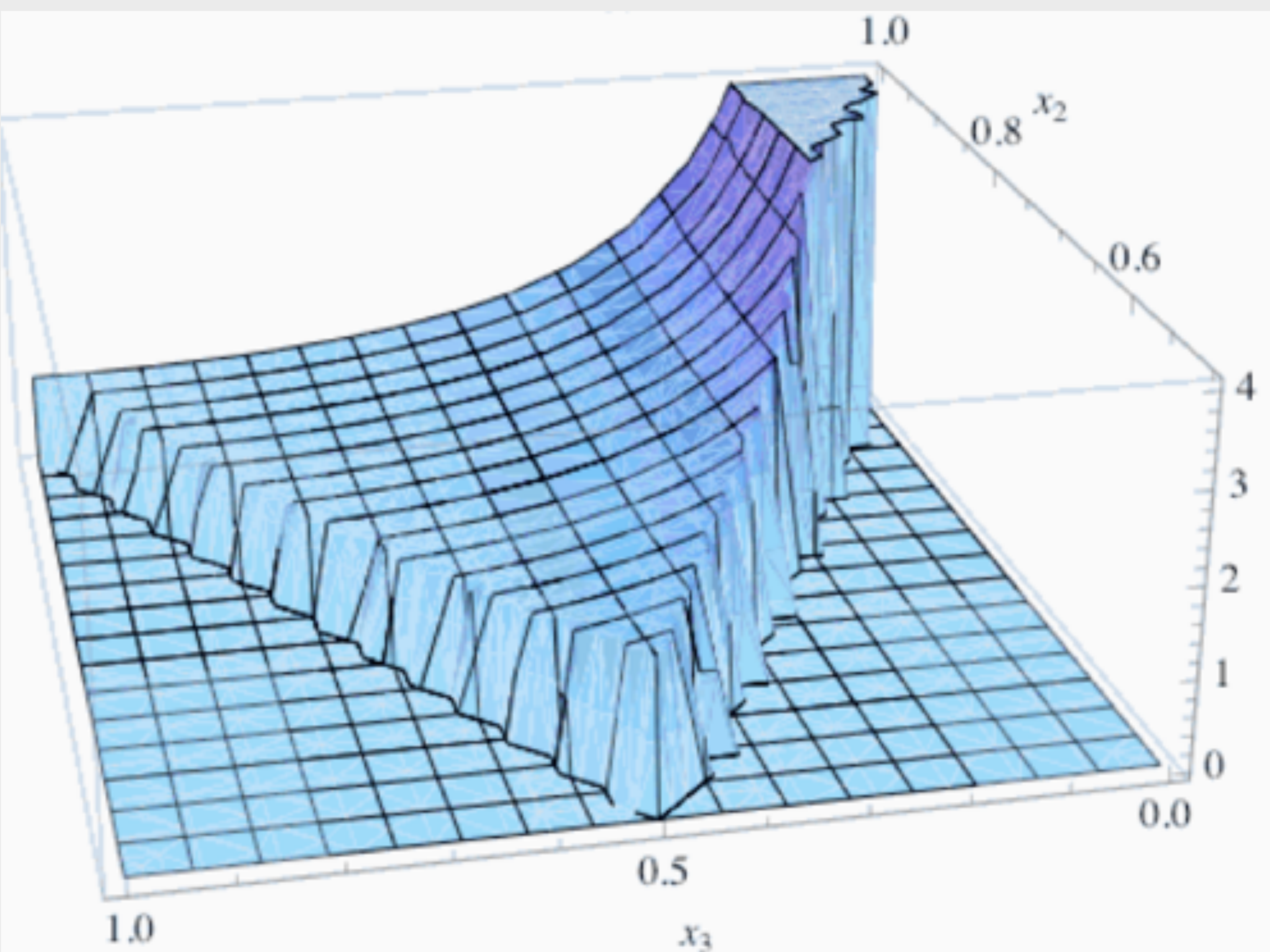
"Flattened" triangle
$k_1 \ll k_2, k_3$

Three-point signals: local shape

Multifield models can generate a 3-point function with "local" shape

$$F(k_1, k_2, k_3) = -\frac{6}{5} f_{NL}^{\mathrm{local}} P_\zeta(k_1) P_\zeta(k_2) + (2 \text{ perm.})$$

Signal is largest in squeezed triangles



Conversely, there is a theorem (single-field consistency relation) which shows that any single-field model always generates a 3-point function which is small in squeezed triangles ($f_{NL}^{\mathrm{local}} \approx 0$)

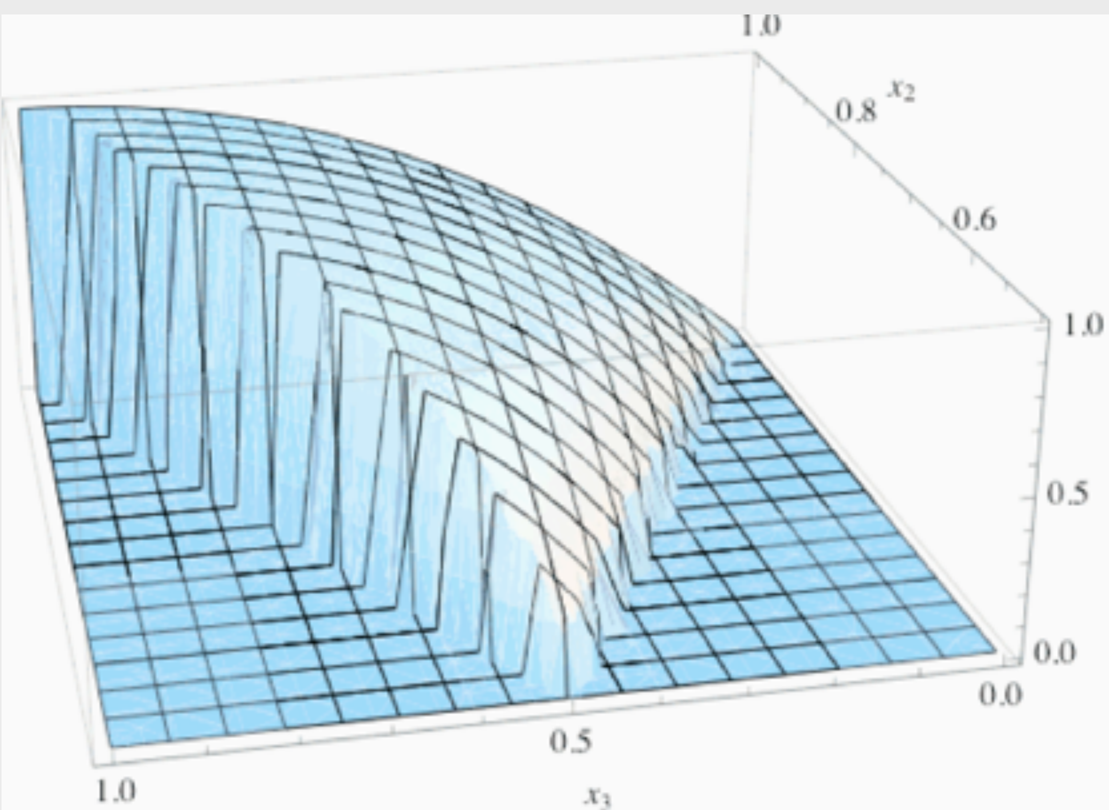
Senatore, KMS & Zaldarriaga (2005)

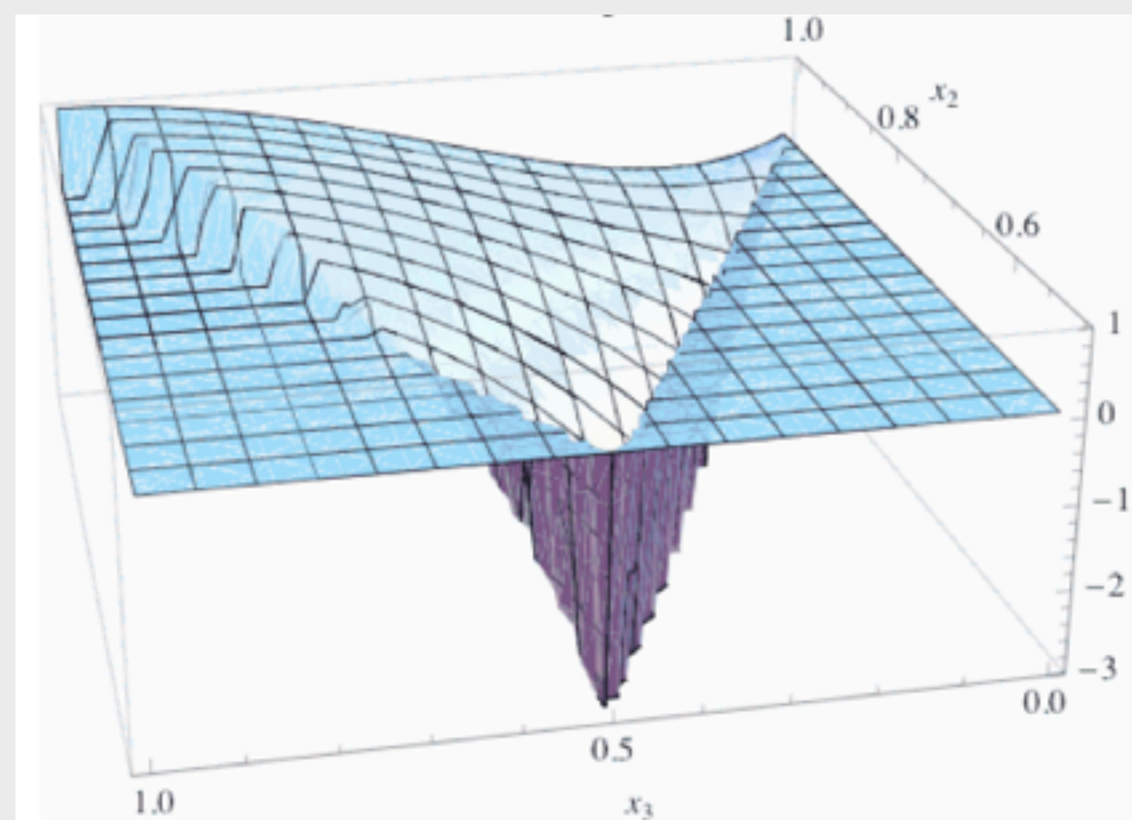
Three-point signals: single-field shapes

Classification theorem (Senatore, KMS & Zaldarriaga 2009): Any single-field model must generate a 3-point function which is a linear combination of the following two shapes:

$$F_{\text{equil}}(k_1,k_2,k_3) = 6\Delta_\Phi^2 \frac{(k_1+k_2-k_3)(k_2+k_3-k_1)(k_3+k_1-k_2)}{k_1^3 k_2^3 k_3^3}$$

$$F_{\text{orthog}}(k_1,k_2,k_3) = 6\Delta_\Phi^2 \frac{3(k_1+k_2-k_3)(k_2+k_3-k_1)(k_3+k_1-k_2) - 2k_1k_2k_3}{k_1^3 k_2^3 k_3^3}$$





Three-point signals: analysis

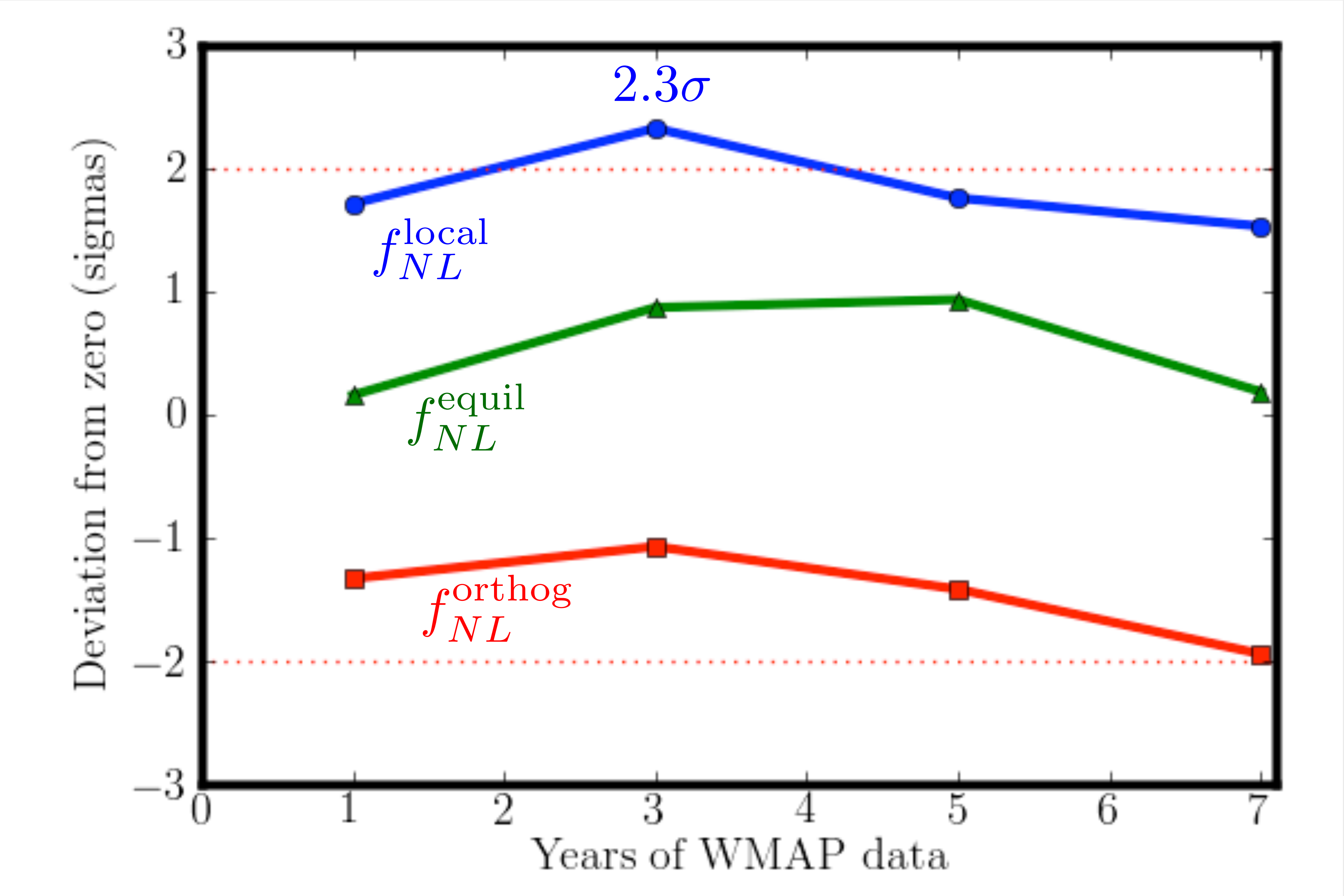
$$F(k_1, k_2, k_3) = f_{NL}^{\rm loc} F_{\rm loc}(k_1, k_2, k_3) + f_{NL}^{\rm equil} F_{\rm equil}(k_1, k_2, k_3) + f_{NL}^{\rm orthog} F_{\rm orthog}(k_1, k_2, k_3)$$

Optimal estimators for $f_{NL}^{\rm loc}$, $f_{NL}^{\rm equil}$, $f_{NL}^{\rm orthog}$ have been constructed and implemented for the WMAP dataset (Komatsu, Spergel & Wandelt 03; Creminelli et al 05; KMS & Zaldarriaga 06; KMS, Zahn & Dore 07; KMS, Senatore & Zaldarriaga 09)

Seven-year results:

Band	Foreground[b]	$f_{NL}^{\rm local}$	$f_{NL}^{\rm equil}$	$f_{NL}^{\rm orthog}$	b_{src}
V+W	Raw	59 ± 21	33 ± 140	-199 ± 104	N/A
V+W	Clean	42 ± 21	29 ± 140	-198 ± 104	N/A
V+W	Marg.[c]	32 ± 21	26 ± 140	-202 ± 104	-0.08 ± 0.12
V	Marg.	43 ± 24	64 ± 150	-98 ± 115	0.32 ± 0.23
W	Marg.	39 ± 24	36 ± 154	-257 ± 117	-0.13 ± 0.19

Non-gaussianity per WMAP release

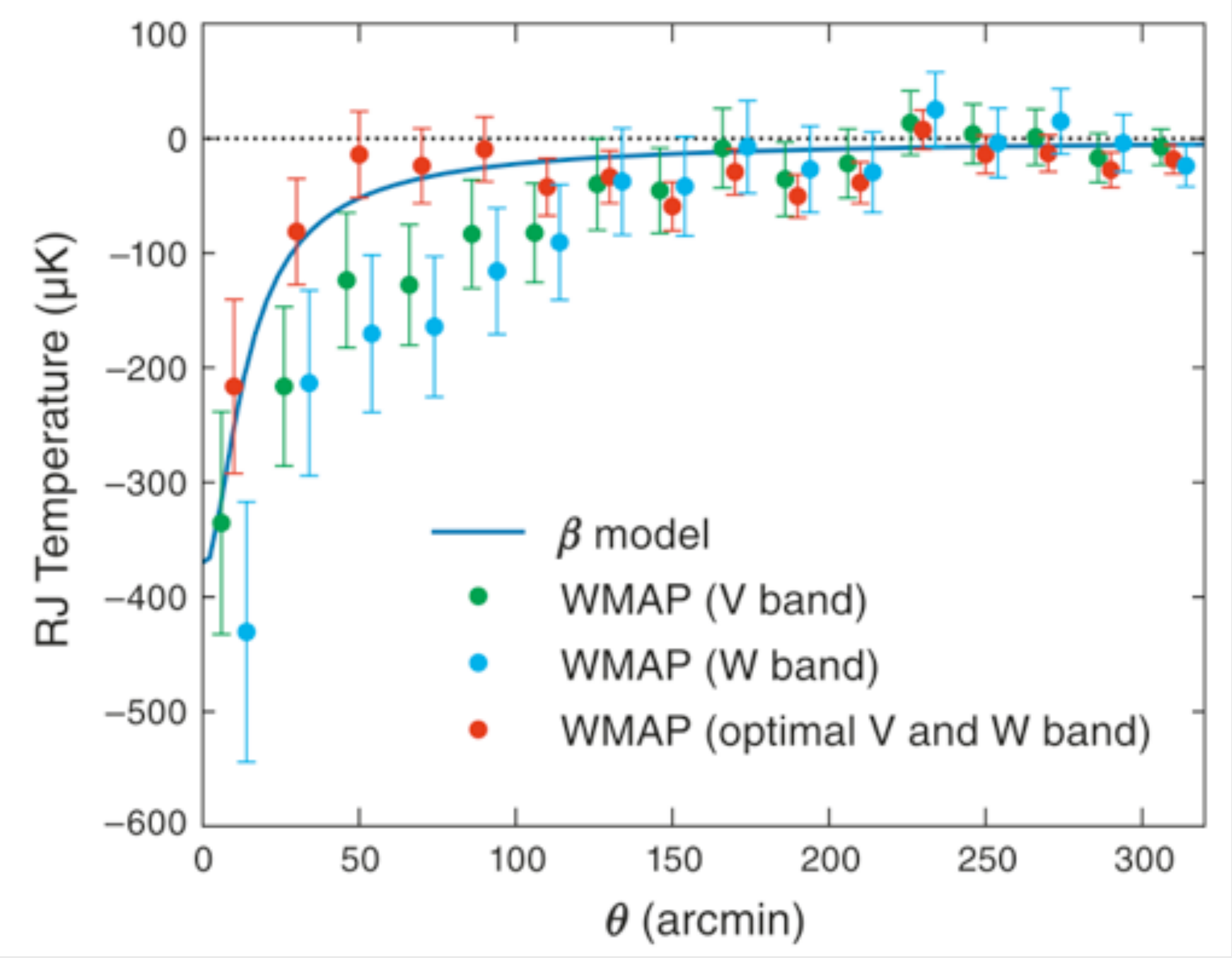


SZ cluster profiles

WMAP cannot measure SZ internally: $A_{SZ} = 0.95^{+0.69}_{-0.94}$

However, given external knowledge of cluster locations, a statistically significant detection can be obtained

Example: for Coma cluster, WMAP sees SZ at 3.6σ



Optimal estimator:

SZ profile obtained by combining high-pass filtered (V+W) map, and unfiltered (V-W) map

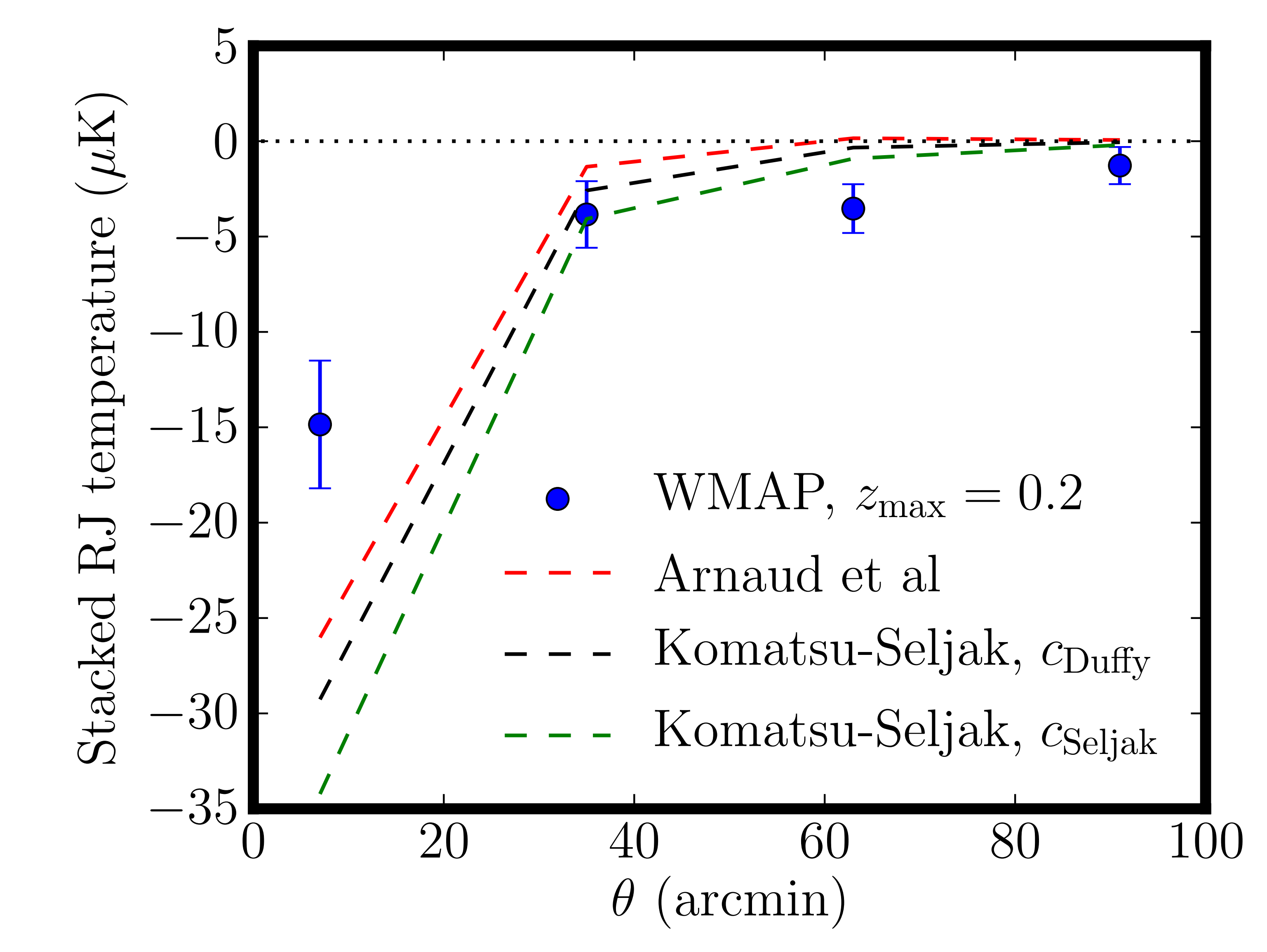
SZ profiles: stacked ROSAT clusters

Can "stack" many clusters to recover mean profile

X-ray catalog from ROSAT: 742 clusters, $z_{\text{median}} \approx 0.1$

$$L_X \longrightarrow \{M_{500}, r_{500}\} \longrightarrow T_{\text{SZ}}(\theta)$$

"scaling relation" "universal profile"



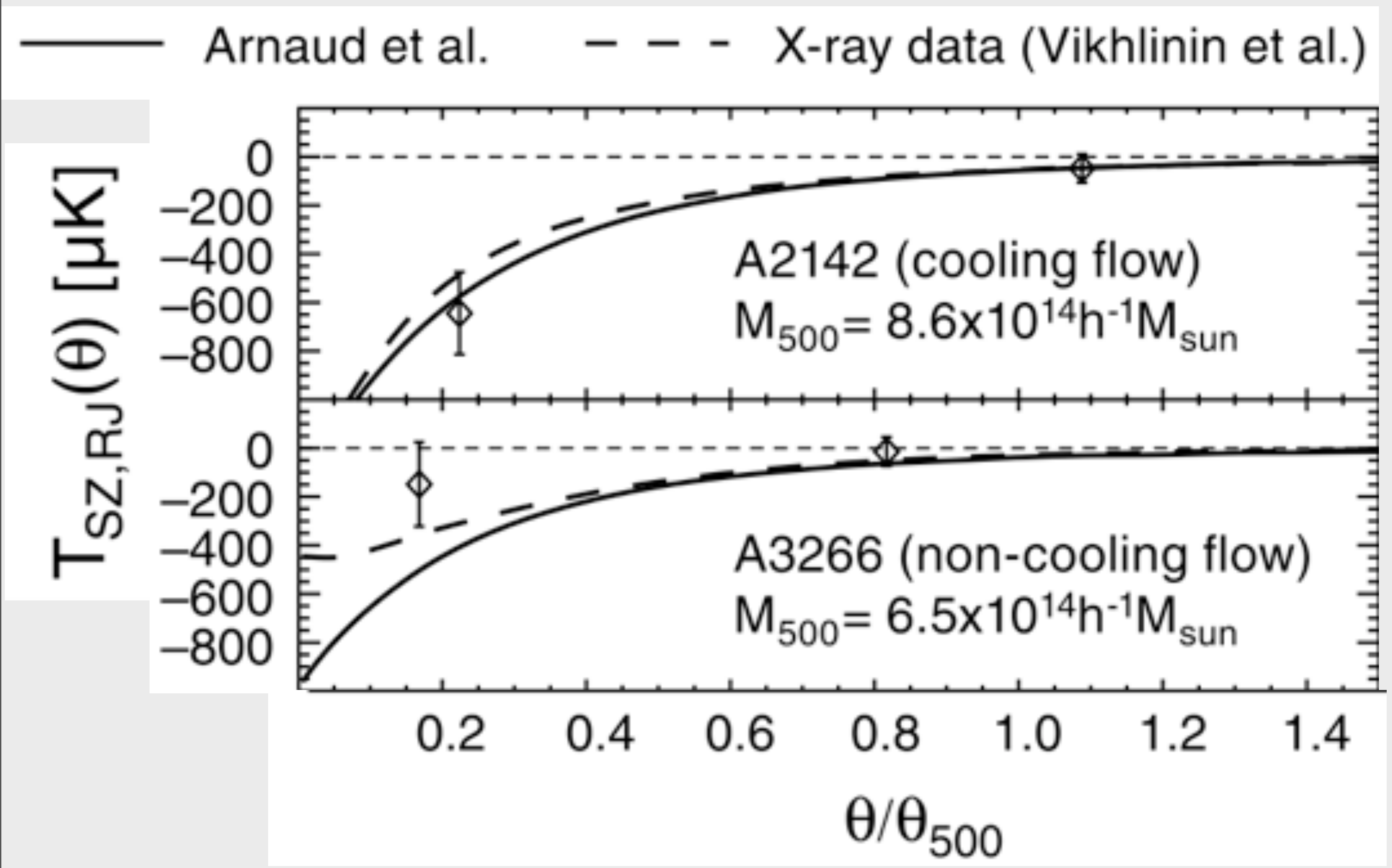
Puzzling result: observed pressure profile is smaller than prediction:

$$A_{\text{SZ}} = 0.59 \pm 0.07 \text{ (stat.)}$$

SPT power spectrum analysis also finds low SZ:

$$C_\ell^{\text{SZ}} = 0.37 \pm 0.17$$

SZ profiles: per-cluster CHANDRA analysis



(top relaxed; bottom non-relaxed)

Per-cluster analysis of 11 nearby CHANDRA X-ray clusters (Vikhlinin et al 2009):

- WMAP SZ measurements are consistent with fiducial for relaxed clusters with measured X-ray temperatures

Observed low amplitude ($A_{\rm SZ} = 0.59 \pm 0.07$) in ROSAT sample can be explained by

- implicit assumption that all clusters are relaxed
- observed difference between universal profile and X-ray temperature
- possible systematic bias in $\{L_X, M_{500}, r_{500}\}$ scaling relation

Spinning dust

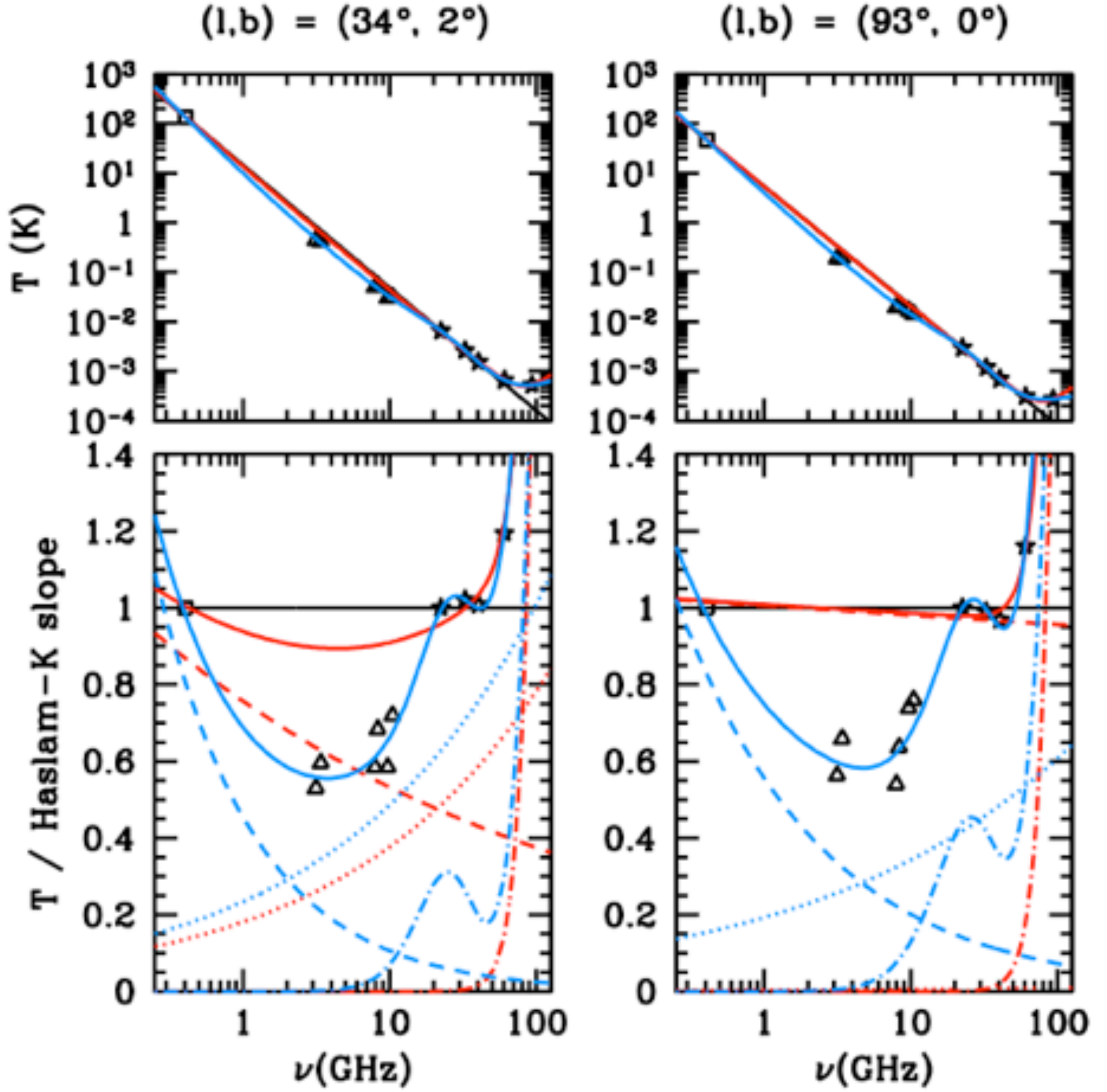


Fig. 4.— Galactic emission from two regions in the Galactic plane. ARCADE (triangles), *WMAP* (stars), and 408 MHz data (square) are all shown, smoothed to a common resolution. Upper panels show antenna temperature (absent a monopole component). The black line is a power-law connecting 408 MHz to 22 GHz ($\beta = -2.48$ for the left panel, $\beta = -2.41$ for the right panel), which is divided out in the bottom panels to better show deviations from power-law behavior. Red lines show the result of a fit to the data using three power law components for foregrounds (representing synchrotron, free-free, and dust). Blue lines show the fit resulting when an extra component representing spinning dust is added. Solid lines show the total flux, with individual components shown by dashed lines (synchrotron), dotted lines (free-free), and dot-dashed lines (dust plus spinning dust). Errors in the data are dominated by systematics and highly correlated between data points, but are estimated to be 5 – 15%, depending on experiment.

Old controversy: do rotational modes of dust grains contribute significant foreground emission at low frequency, or is the low frequency emission mainly synchrotron?

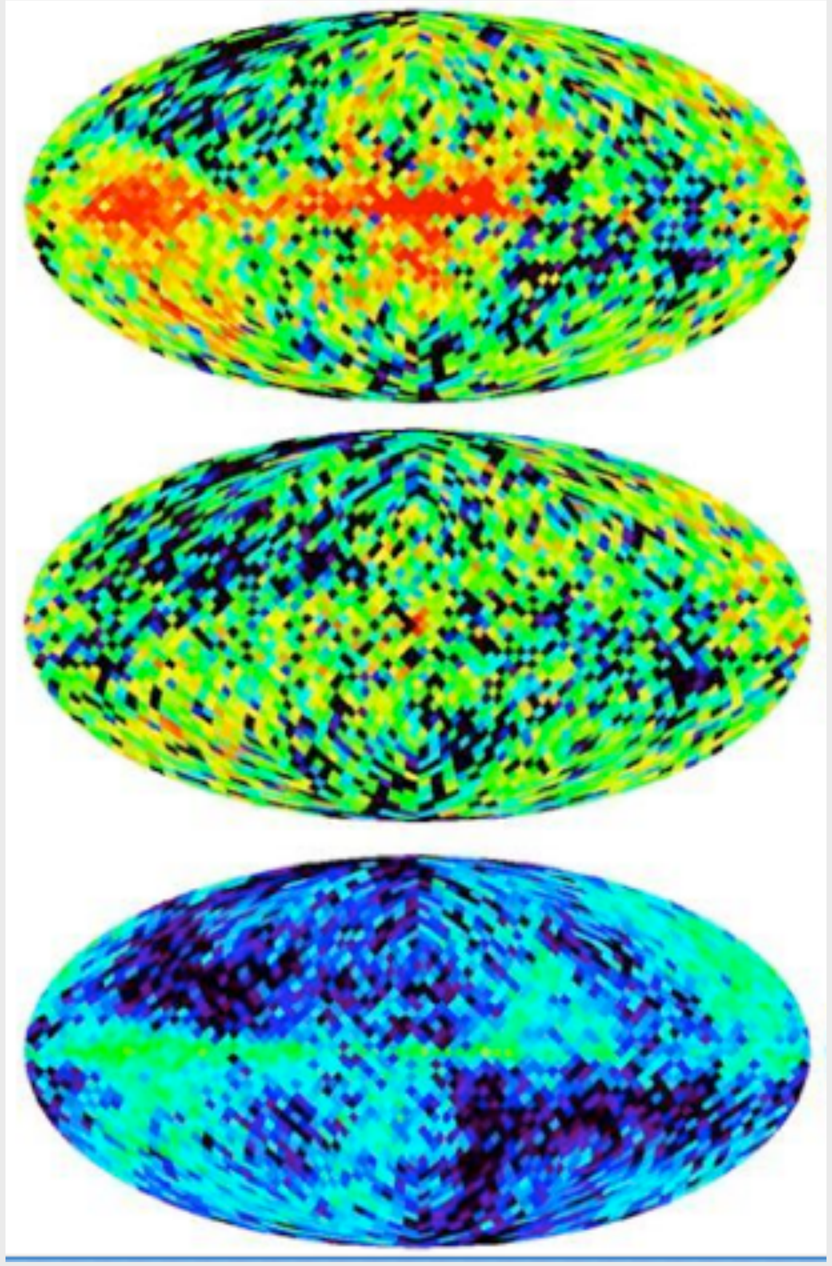
ARCADE data in conjunction with WMAP and Haslam supports the spinning dust model

(red lines = power law foregrounds, blue lines = spinning dust model)

Galactic "Haze" and Polarization

Several authors have reported a region of flattened synchrotron spectrum (or "haze") near the galactic center

We find no such region in polarization



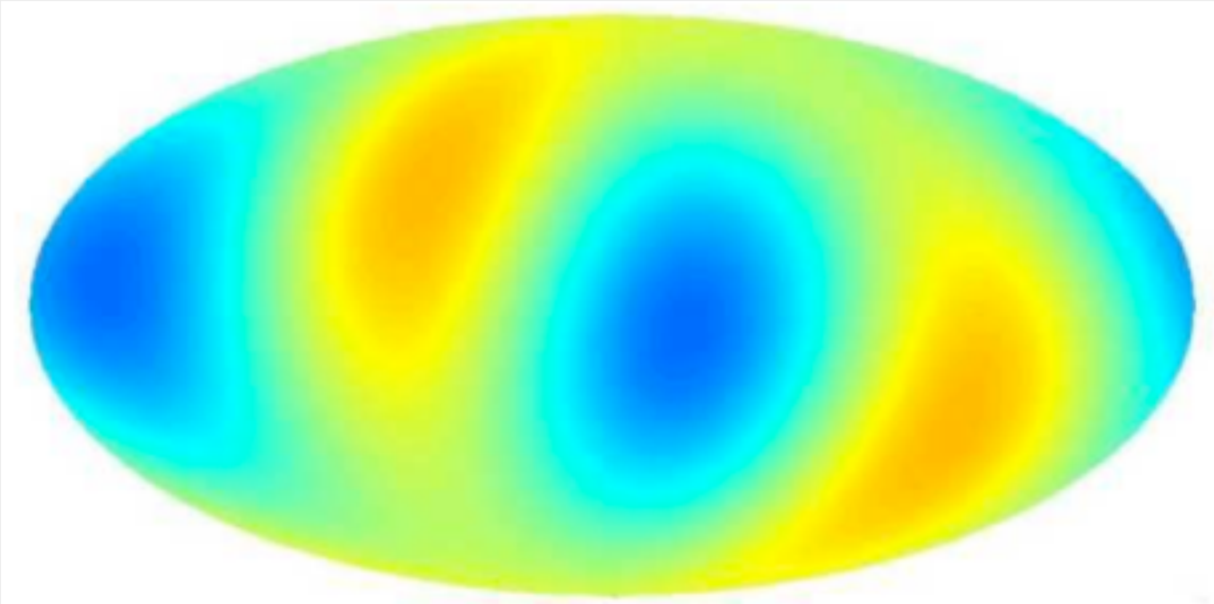
"Soft" synchrotron $(\beta = -3.1)$

"Hard" synchrotron $(\beta = -2.4)$

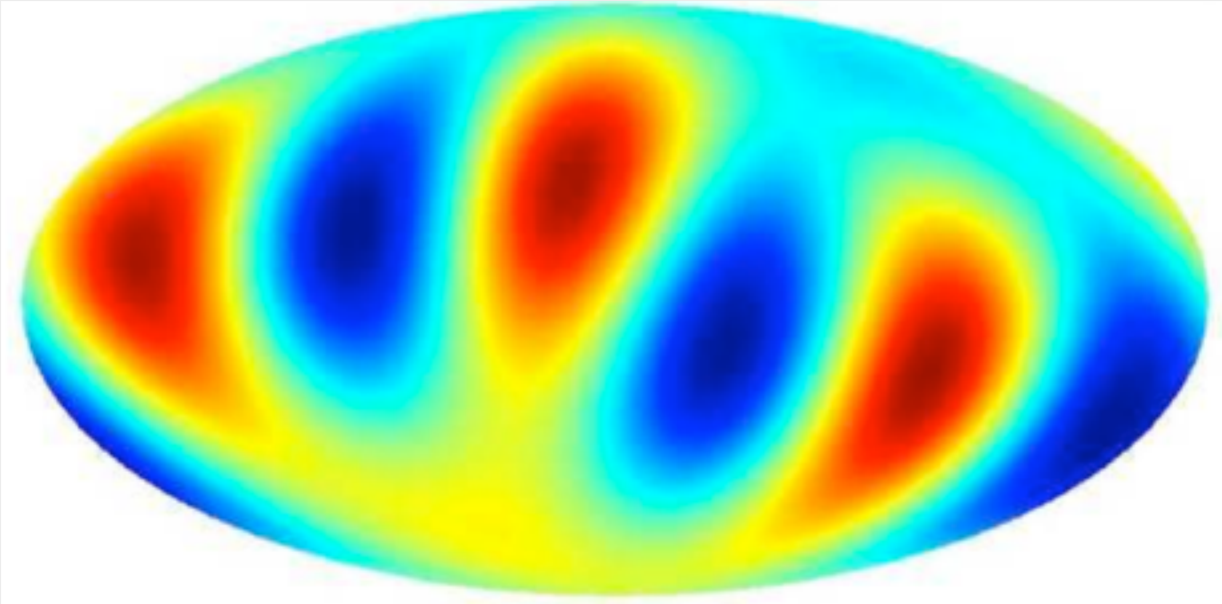
Dust $(\beta = 2.0)$

Are there "anomalies" in WMAP?

Quintessential example: quadrupole-octopole alignment (Tegmark, de Oliveira-Costa & Hamilton 2003; de Oliveira-Costa et al 2003)



$\ell = 2$

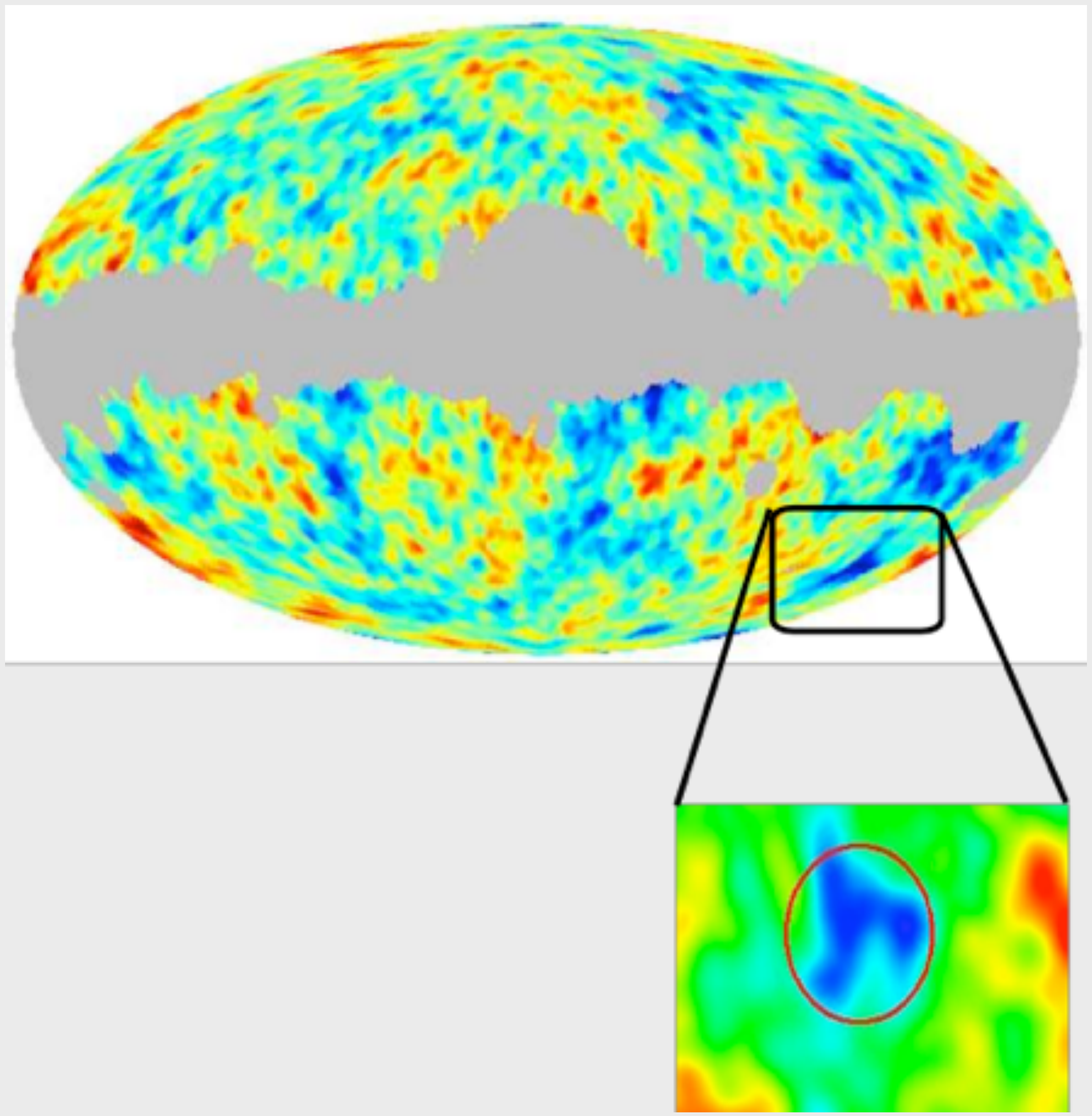


$\ell = 3$

Unlikely (~1%) to occur by chance, but no reason (such as an early universe model) to expect it. What conclusion do we draw.... ?

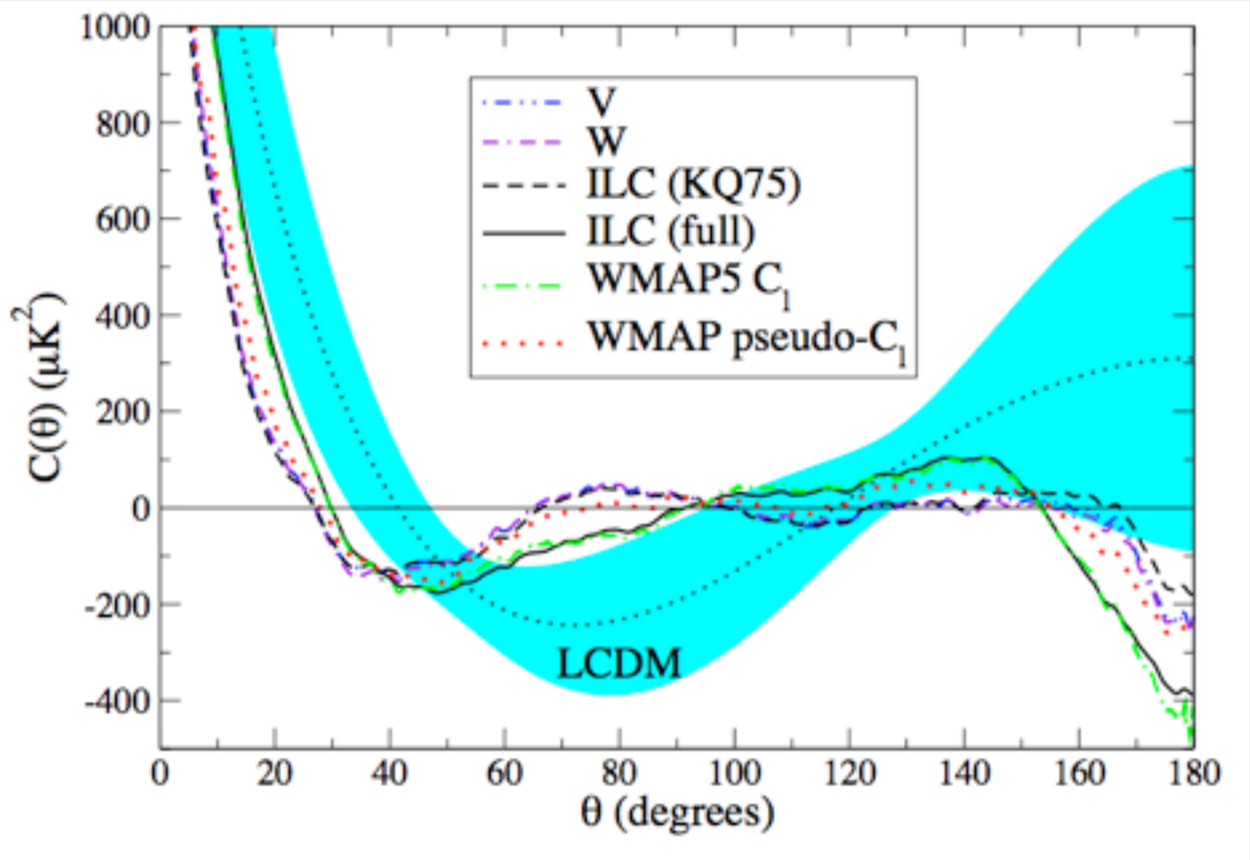
Are there "anomalies" in WMAP?

Cold spot



5° region of low temperature and high kurtosis (Cruz et al 05)

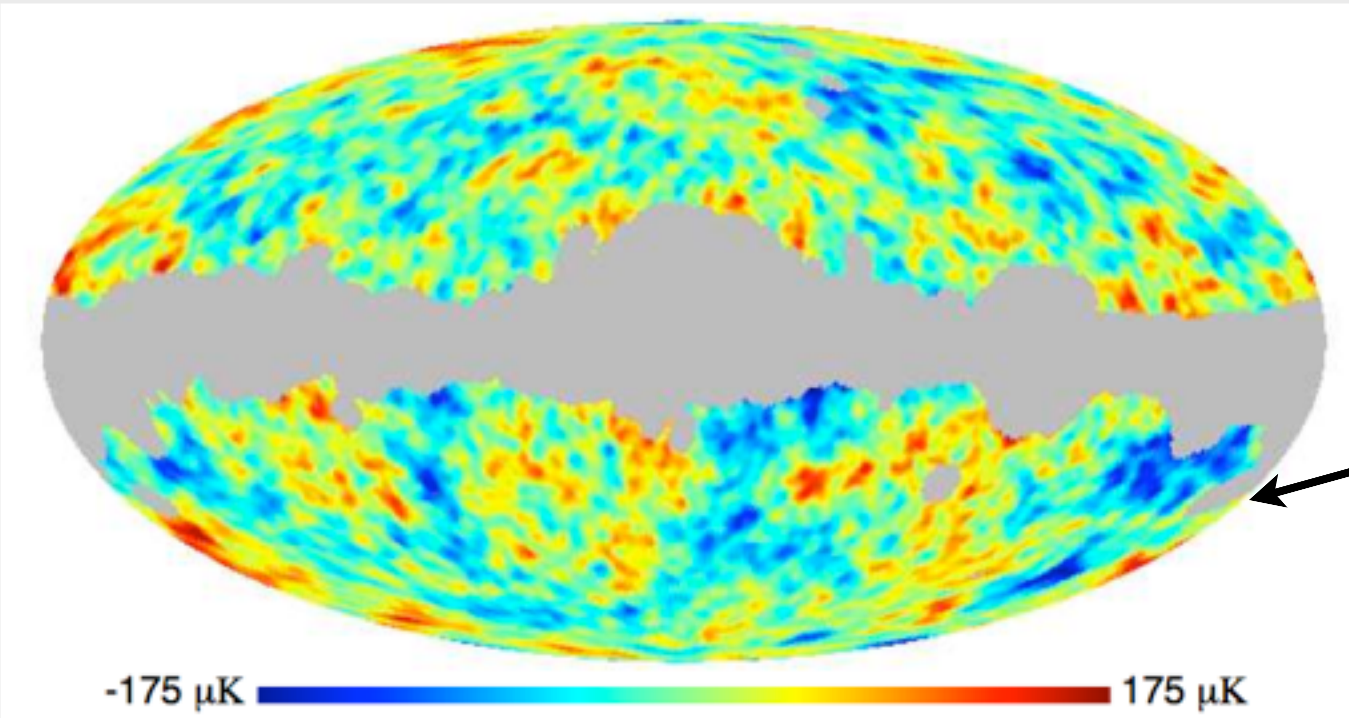
Large-angle correlation function



Two-point function $\langle T(\mathbf{n}_1)T(\mathbf{n}_2)\rangle$ is nearly zero at separations $> 60^\circ$

Are there “anomalies” in WMAP?

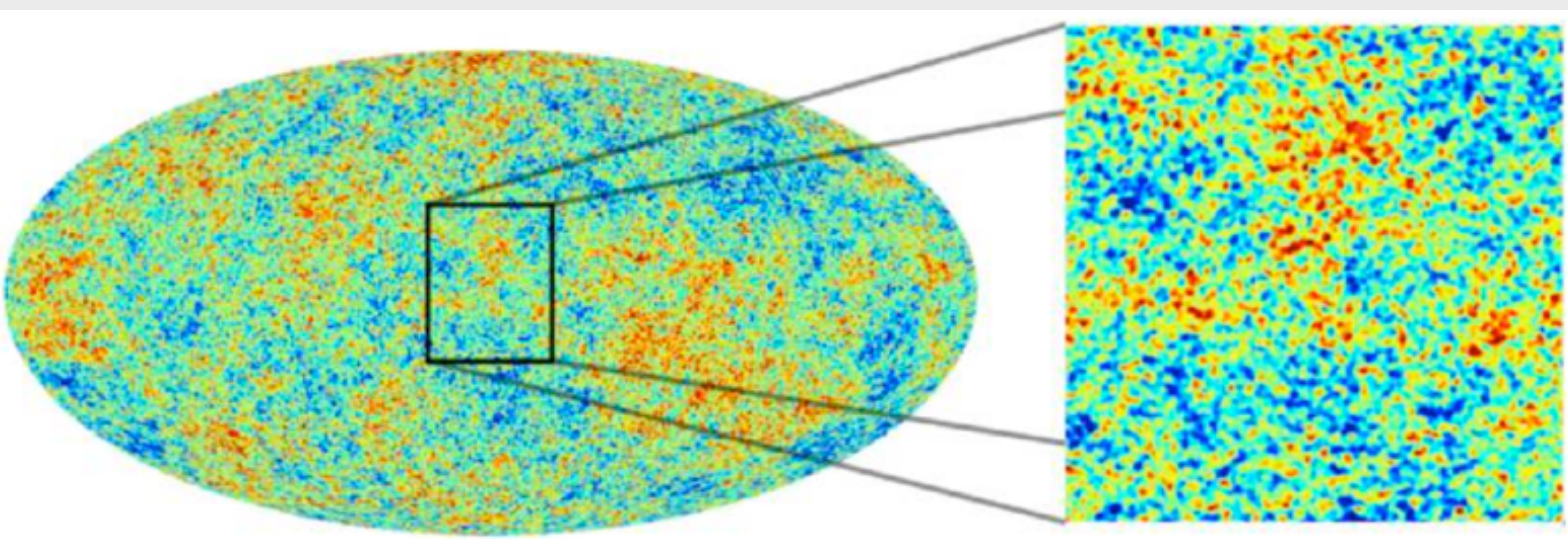
Dipole power asymmetry



More power in southern hemisphere?

Eriksen et al 2003

Quadrupolar two-point anomaly



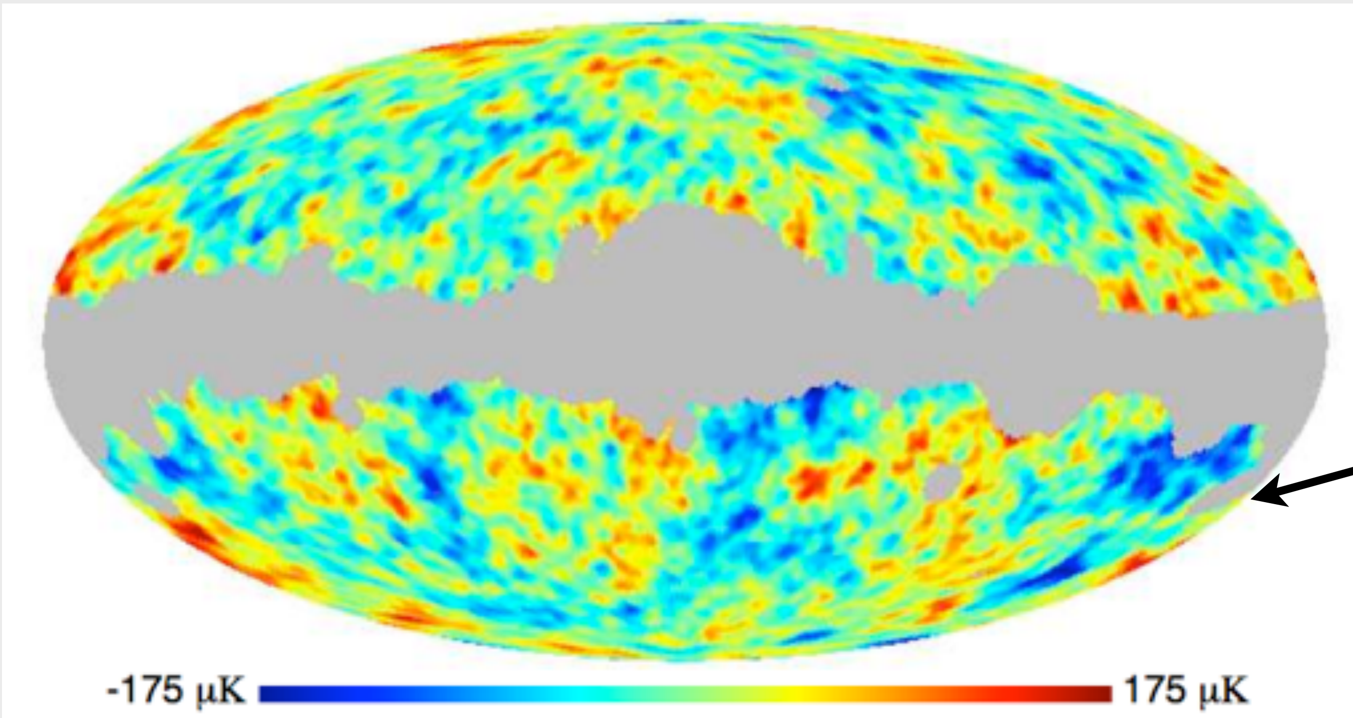
horizontal striping in equatorial region

Groeneboom & Eriksen 2008 (simulation; effect also found in WMAP 5-year data)

A non-exhaustive list of WMAP anomalies

Cold spot	$1\text{–}2.4\sigma$	Cruz et al 05 Cruz et al 07 Zhang & Huterer 09
Large-angle correlation function	$2\text{–}3.5\sigma$	Hinshaw et al 96 Spergel et al 03 Bunn & Bourdon 08 Copi et al 09
Quadrupole-octopole alignment	$2.1\text{–}2.8\sigma$	Tegmark, de Oliveira-Costa & Hamilton 03 de Oliveira-Costa et al 03 Gordon et al 05
Dipole power asymmetry	up to 3.8σ	Eriksen et al 03 Gordon et al 05 Dvorkin, Peiris & Hu 08 Hoftuft et al 09 Erickcek, Hirata & Kamionkowski 09 Hanson & Lewis 09
Quadrupolar two-point anomaly	$\approx 9\sigma$	Ackerman, Carroll & Wise 07 Groeneboom & Eriksen 08 Hanson & Lewis 09

Dipole power asymmetry



More power in southern hemisphere?

Eriksen et al 2003

Literature contains varying estimates of statistical significance, ranging as high as 3.8σ

Inflationary models have been constructed which produce dipolar power asymmetry (Erickcek, Kamionkowski & Carroll 08; Erickcek, Hirata & Kamionkowski 09)

Dipole power asymmetry: model

Replace isotropic CMB

$$T(\mathbf{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\mathbf{n})$$

by anisotropic CMB given by

$$T(\mathbf{n}) = \underbrace{(1 + \mathbf{v}\cdot\mathbf{n}) \left[\sum_{\ell \le \ell_{\rm mod}} a_{\ell m} Y_{\ell m}(\mathbf{n}) \right]}_{\text{Modulated}} + \underbrace{\sum_{\ell > \ell_{\rm mod}} a_{\ell m} Y_{\ell m}(\mathbf{n})}_{\text{Unmodulated}}$$

Four-parameter model:

$\ell_{\rm mod}$ (CMB is isotropic on scales $\ell \le \ell_{\rm mod}$, modulated for $\ell > \ell_{\rm mod}$)

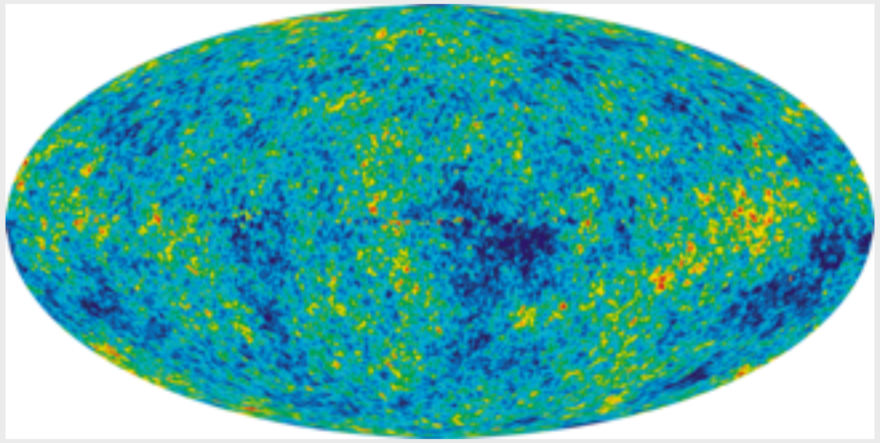
v_i (Orientation and magnitude of vector parameterize axis and amplitude of modulation)

Dipole power asymmetry: analysis

First consider case where $\ell_{\rm mod}$ is assumed fixed and v_i are parameters to be estimated from data.

There is a minimum variance unbiased estimator $\hat{v}_i$ (Hanson and Lewis 09; Dvorkin, Peiris & Hu 08) such that
- no arbitrary choices are required, such as degrading resolution
- allows statistical significance to be assessed by straightforward MC

As far as I know, $\hat{v}_i$ is the only estimator with these properties!



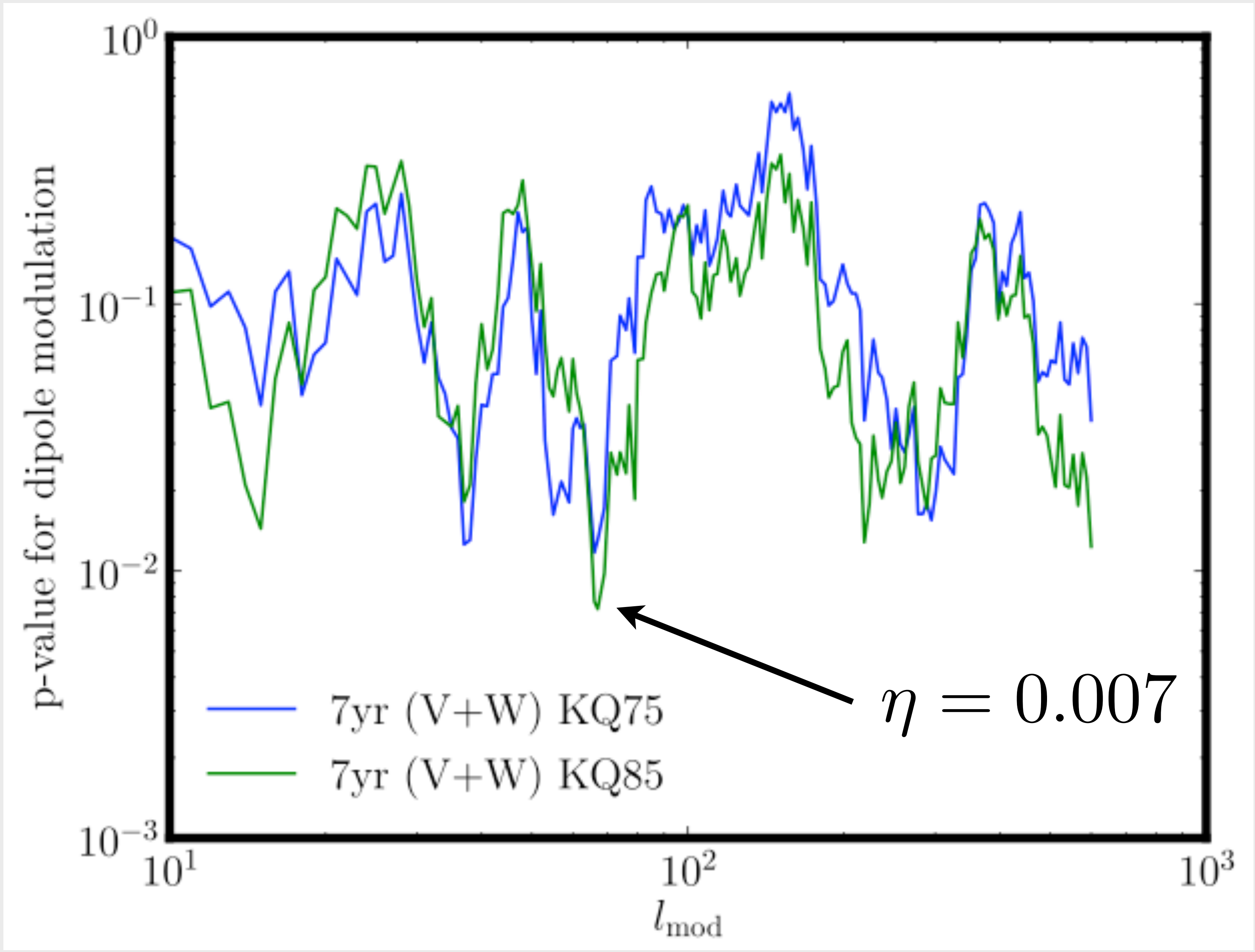
$\longrightarrow \hat{v}_i \longrightarrow \hat{\kappa}_1 = \sum_{i=1}^{3} \hat{v}_i^2$

Maps + choice of $\ell_{\rm mod}$

Estimator for components of modulation

Estimator for total amplitude of modulation

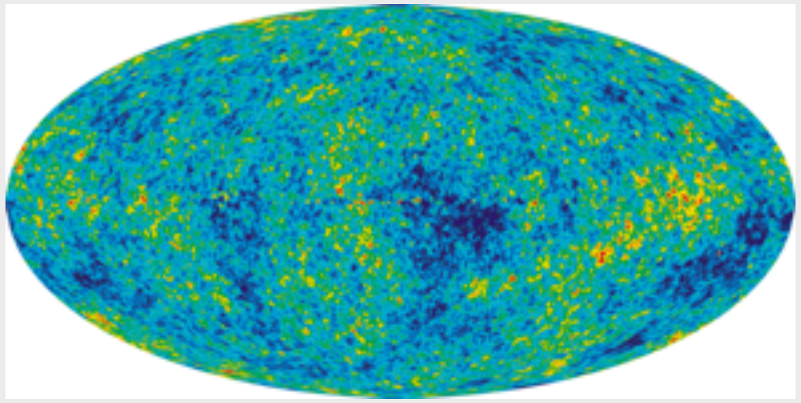
Dipole power asymmetry: results 1

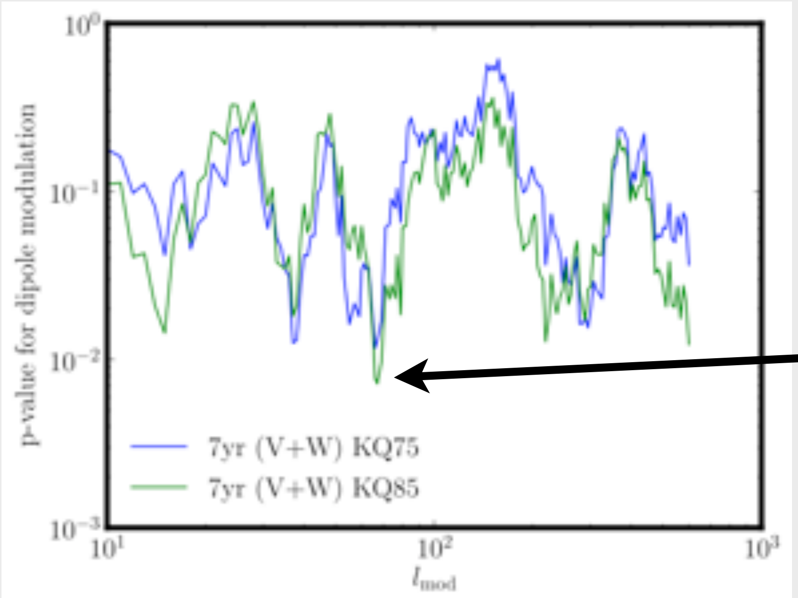


Probability for a simulation to have larger power asymmetry than the data is 0.7%, if we look specifically at $\ell_{\rm mod} = 67$

Dipole power asymmetry: results 2

In fact the choice of $\ell_{\rm mod} = 67$ is a posteriori; what we have really done is evaluate the following statistic on the WMAP data:





$\eta = 0.007$

$$\text{Maps} \longrightarrow \text{p-value}(\ell_{\rm mod}) \longrightarrow \eta = \min_{\ell_{\rm mod}}(\text{p-value})$$

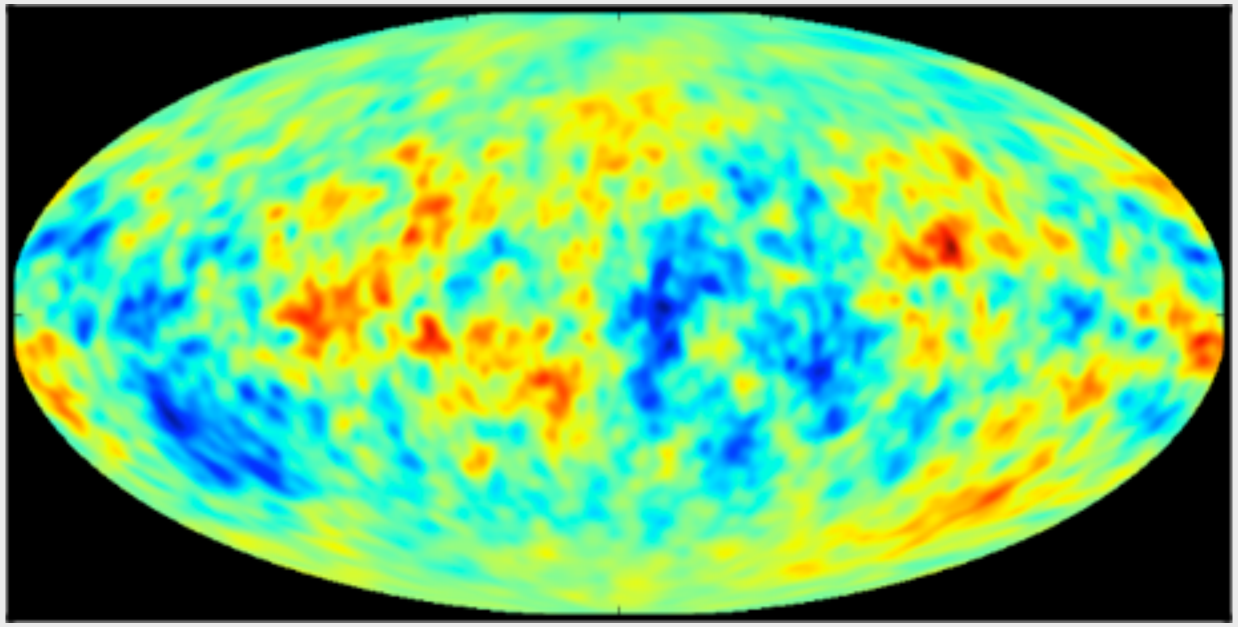
Now ask: if we compute η for a simulation in the same way, what is the probability of getting a smaller value than the WMAP data?

We find: 10%, i.e. power asymmetry is not statistically significant if the a posterori choice of scale is fairly incorporated

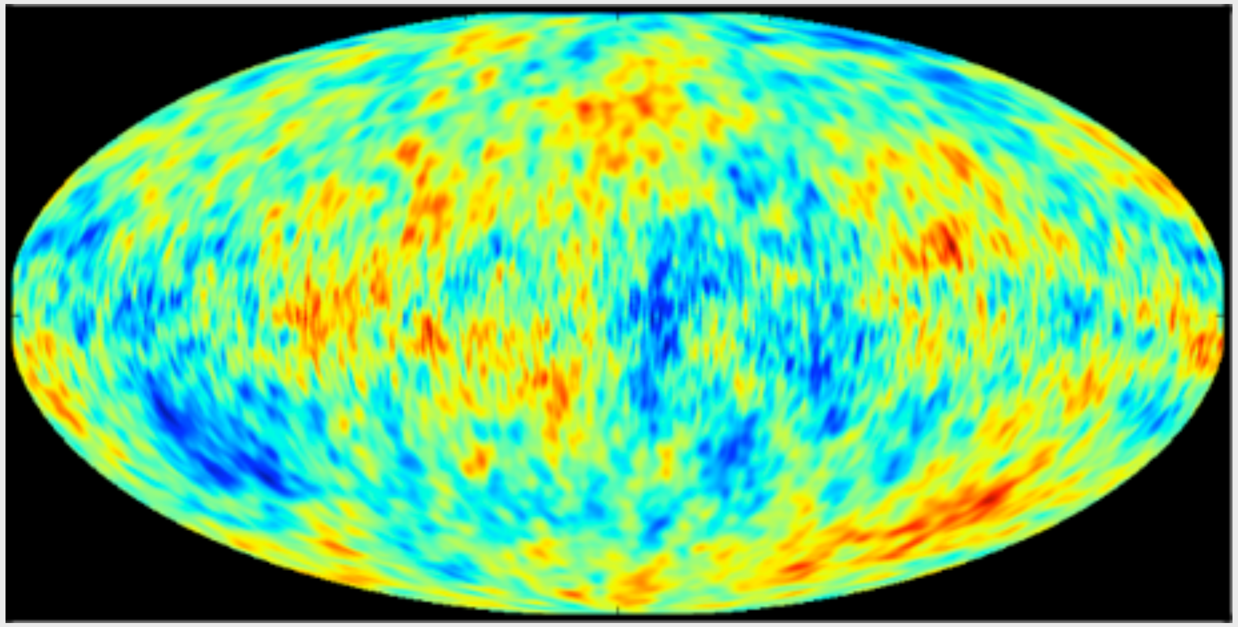
Quadrupolar two-point anomaly: history

- Inflationary model (Ackermann, Carroll & Wise 07) proposed in which CMB two-point function has quadrupolar variation
- Claimed detection in WMAP (Groeneboom & Eriksen 08; Hanson & Lewis 09) at $\sim 9\sigma$(!), but axis of effect is close to ecliptic, suggesting systematic origin
- Amplitude of quadrupole not consistent between frequency channels (in particular, sign is reversed in Q-band), suggesting systematic or foreground origin

Two "flavors" of quadrupole two-point anomaly



Power modulation: Different CMB power spectra in poles/plane, but hot and cold spots are statistically isotropic



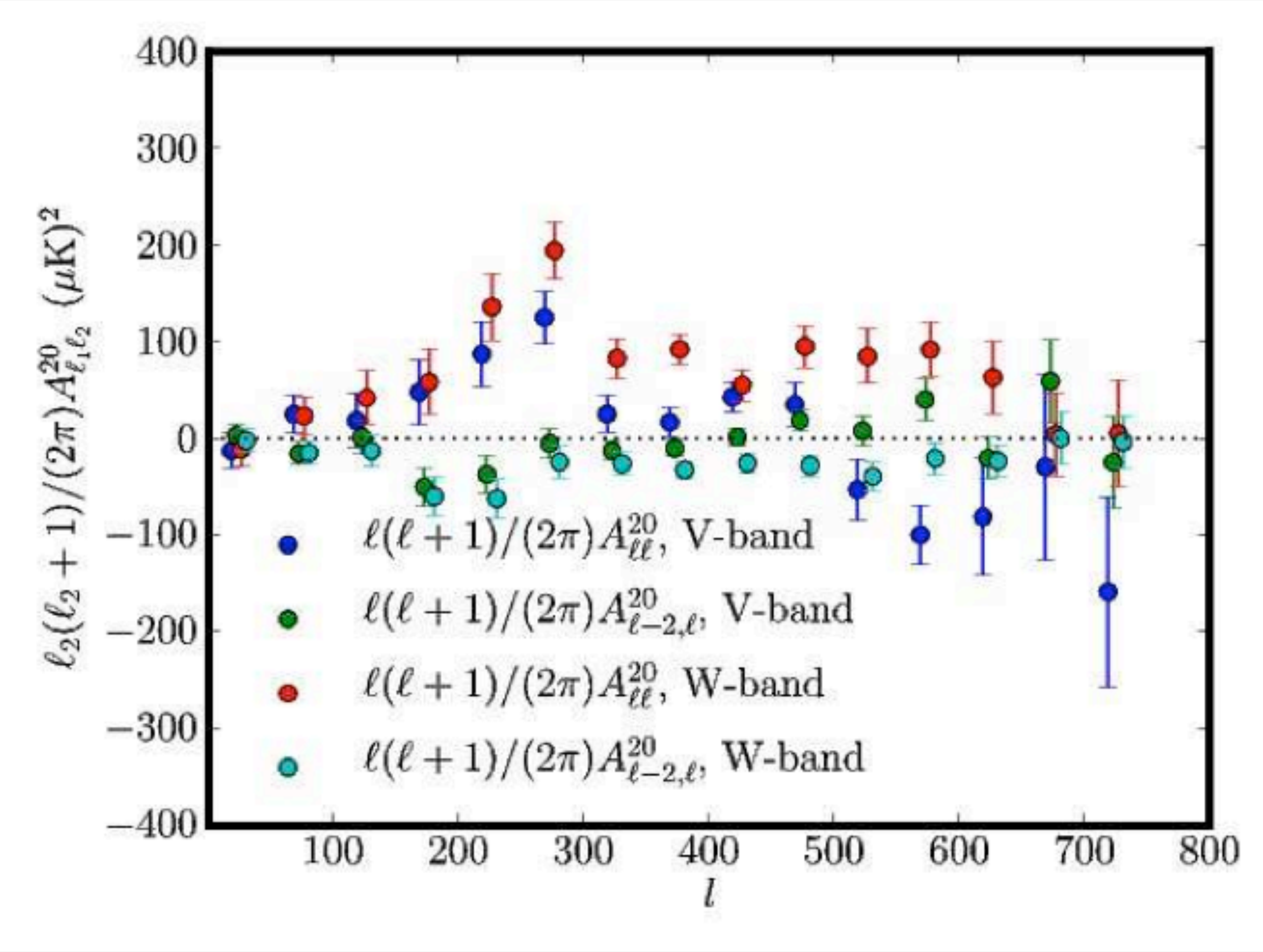
Shape modulation: Same CMB power spectrum in poles/plane, but hot and cold spots have preferred ellipticity in the plane

Bipolar power spectrum (Hajian & Souradeep 05) is a statistic which discriminates these two flavors and also gives the ℓ dependence

(Power modulation: $A^{2M}_{\ell\ell} \approx A^{2M}_{\ell-2,\ell}$;
shape modulation: $A^{2M}_{\ell\ell} \approx -2A^{2M}_{\ell-2,\ell}$)

Quadrupolar two-point anomaly: results

Huge effect (roughly 10σ), statistically significant even in narrow range of ℓ

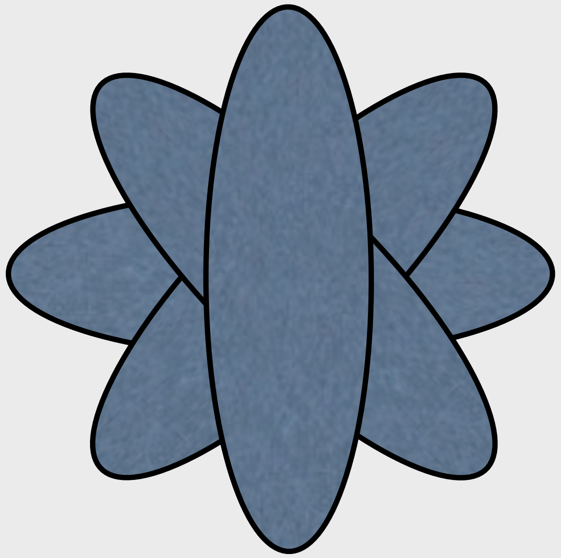


Quadrupolar two-point anomaly: diagnostics

- Only ecliptic component of signal is nonzero
- Non-blackbody: effect larger in W-band than V-band, has opposite sign in Q-band
- Angular dependence shows the first acoustic peak, disfavoring an origin from foregrounds or noise
- Consistent signal in auto vs cross correlations, disfavoring an instrumental origin
- Satisfies $A^{20}_{\ell\ell} \approx -2A^{20}_{\ell-2,\ell}$: looks like shape modulation, not power modulation

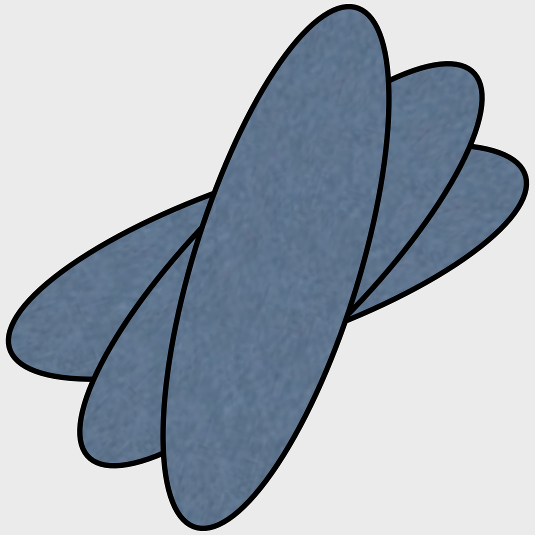
Quadrupolar two-point anomaly explained!

Hanson, Lewis & Challinor 2010: anomaly is completely explained by combining beam ellipticities and WMAP scan strategy



Near ecliptic poles:

- scan strategy is fully cross-linked
- scan-averaged beam is azimuthally symmetric
- hot/cold spots are "round"



Near ecliptic plane:

- scan strategy is not fully cross-linked
- scan-averaged beam is elliptical
- hot/cold spots have preferred ellipticity

Conclusions

- Cosmological model: WMAP7 is still consistent with flat LCDM expansion history, Gaussian adiabatic scalar power-law initial conditions.

- Milestones: W-band polarization data now included; spectral index $n_s < 1$ at 3σ; primordial helium fraction $Y_p > 0$ at 3σ

- Puzzles: quadrupolar two-point anomaly; low amplitude when fitting predicted SZ profiles