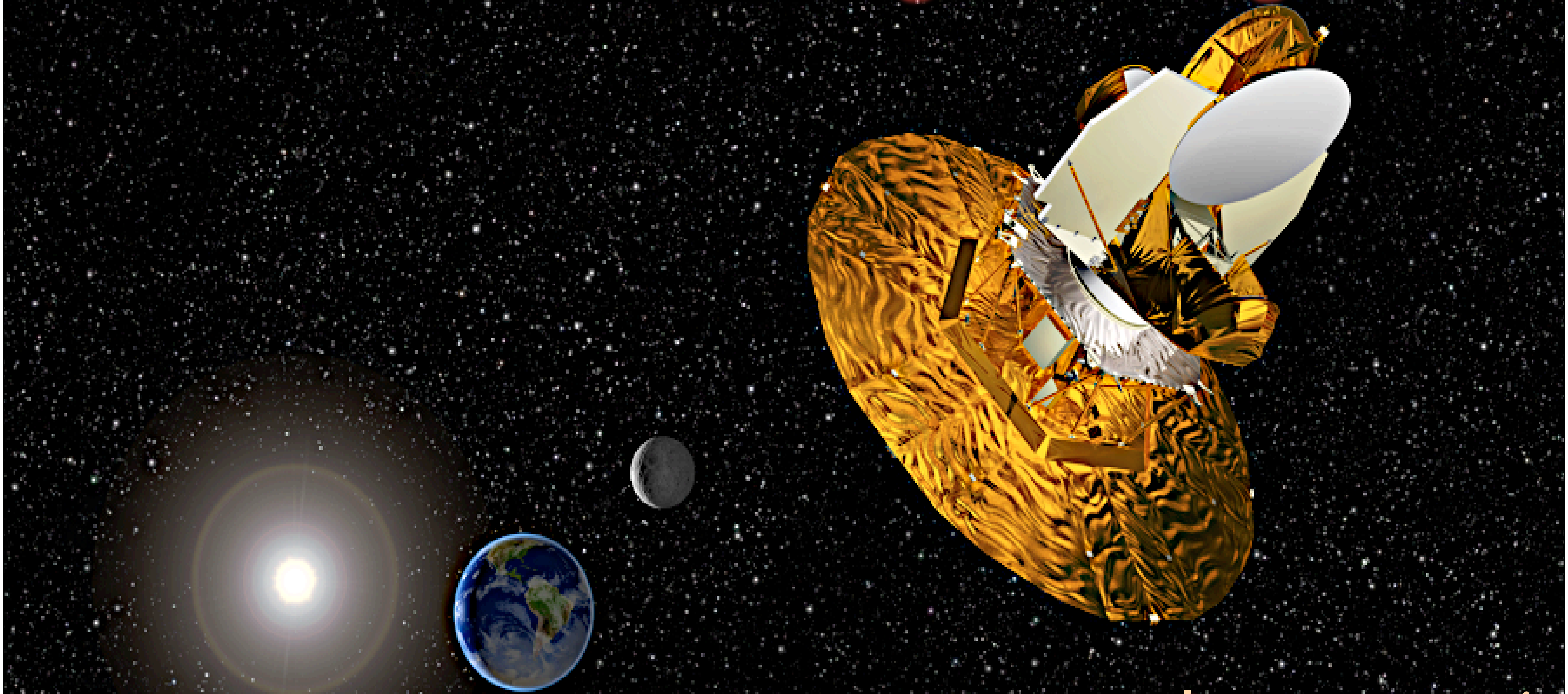
WMAP 3 years of observations: Methods and cosmological insights



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on behalf of the WMAP science team

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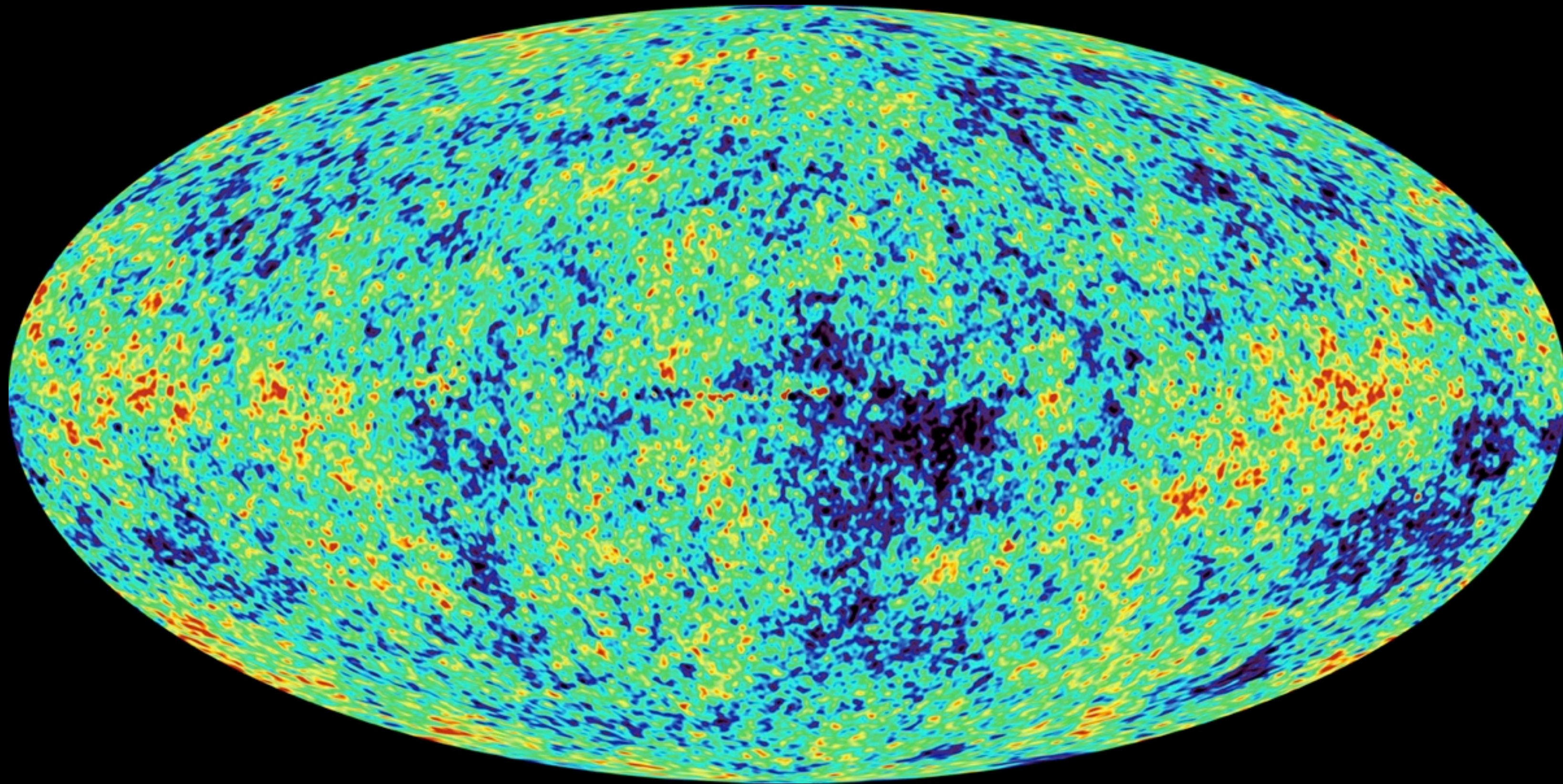
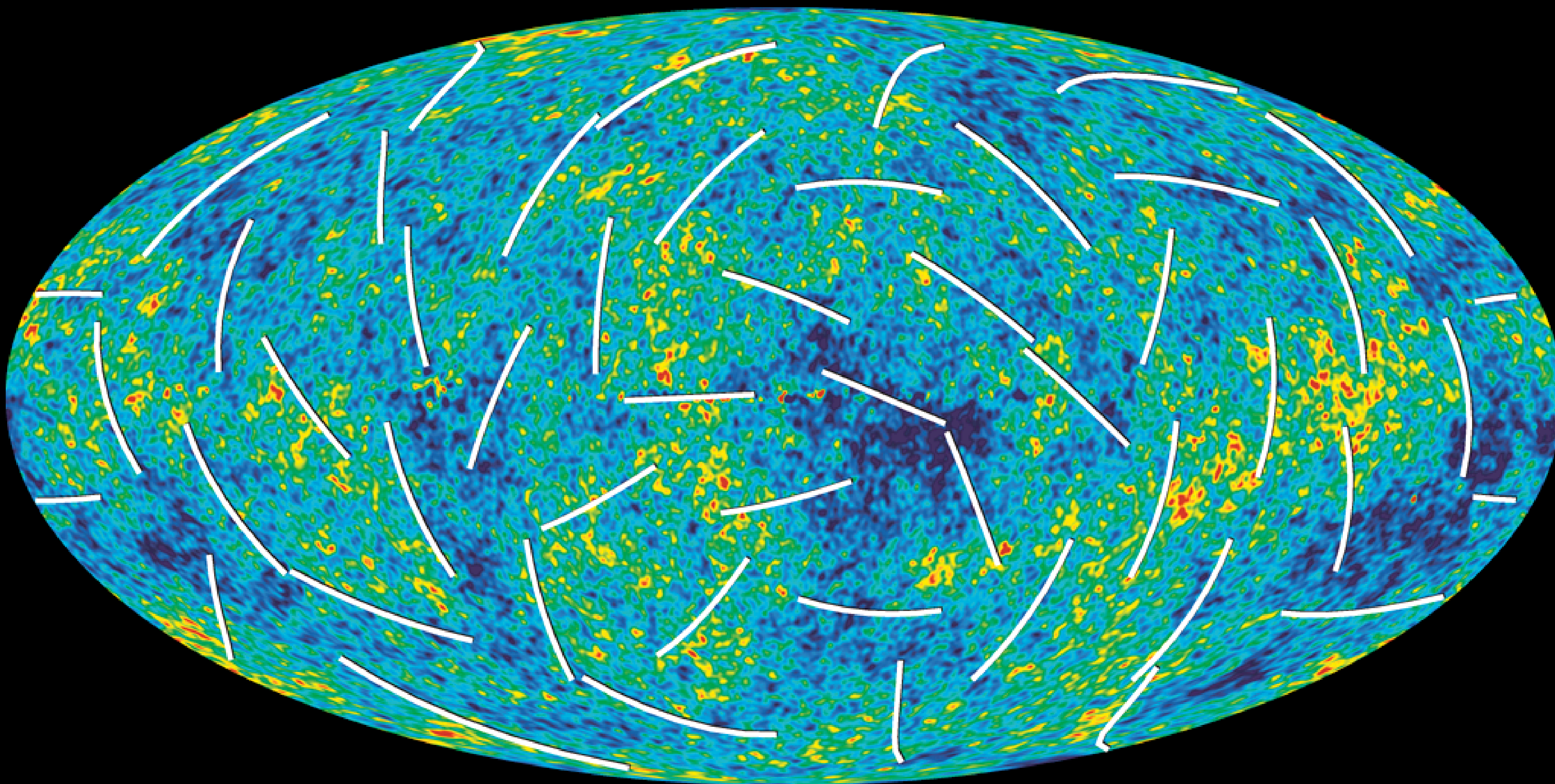
What has WMAP-1 done for us ?



- Color codes temperature (intensity), here ±100μK
- Temperature traces gravitational potential at the time of recombination, when the Universe was 372 000 ±14000 years old
- The statistical analysis of this map entails detailed cosmological information
- WMAP-1 has improved over COBE by a factor of 45 in sensitivity and 33 in angular resolution
- The mission met all its requirements after the first year... "Mission Accomplished!"... but...

What has WMAP-3 done for us?



- ... but the insights expected on Inflation theory (~10^{-18}s after BB) and the Universe reionization (364+124/-74 Myr) from large scale CMB polarization measurements were to tempting to not be pursued
- WMAP-3 has now improved over COBE by a factor of 77 in sensitivity and 33 in angular resolution
- WMAP-3 has measured the CMB polarization on very large angular scales
- To do so required us to improve control the systematics at a level 50 times higher than originally proposed!

Outline

- Quick CMB primer
- Update on WMAP and analysis improvements over the last 2 years
- A case for large scale polarized CMB detection
- Cosmological implications
  - *Phenomenological success of ΛCDM cosmology*
  - *WMAP already addresses new set of questions risen by this success*

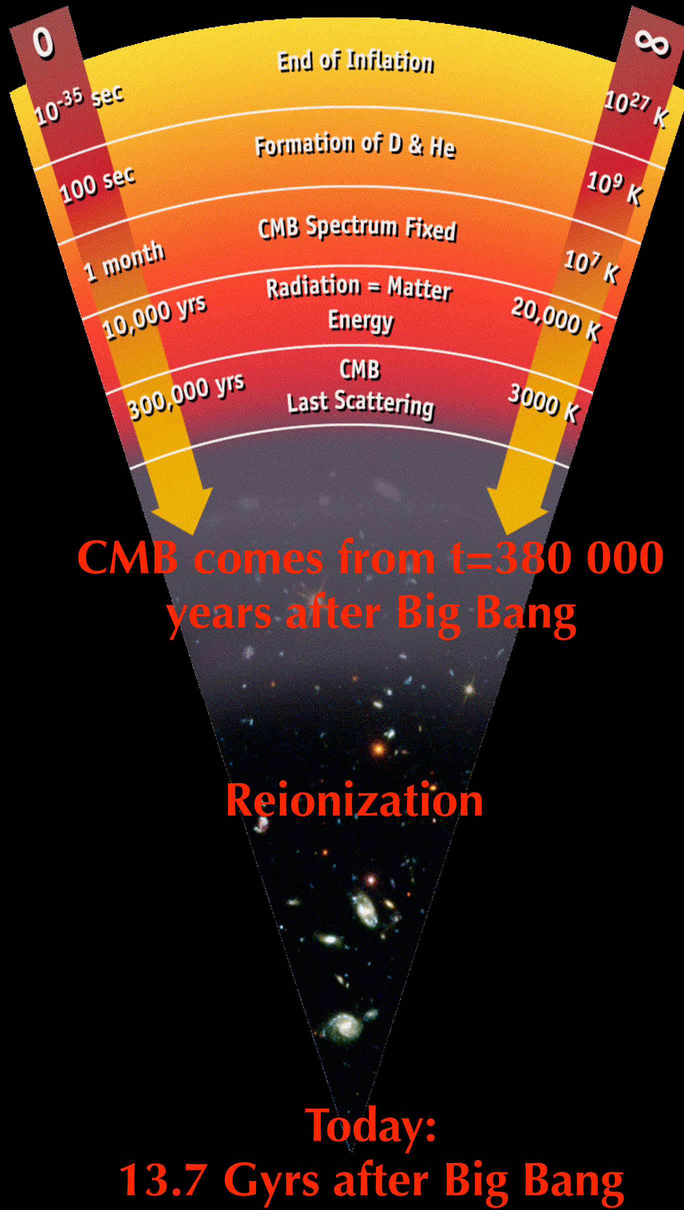
I can't cover it all now. Please ask questions.

The CMB is a leftover from when the Universe was 380 000 yrs old

- The Universe is expanding and cooling

- Once it is cool enough for Hydrogen to form, (T~3000K, t~3.8 10^5 yrs), the photons start to propagate freely *(the Thomson mean free path is greater than the horizon scale)*

- This radiation has the imprint of the small anisotropies that grew by gravitational instability into the large structures we see today



Confronting sky maps with theoretical predictions

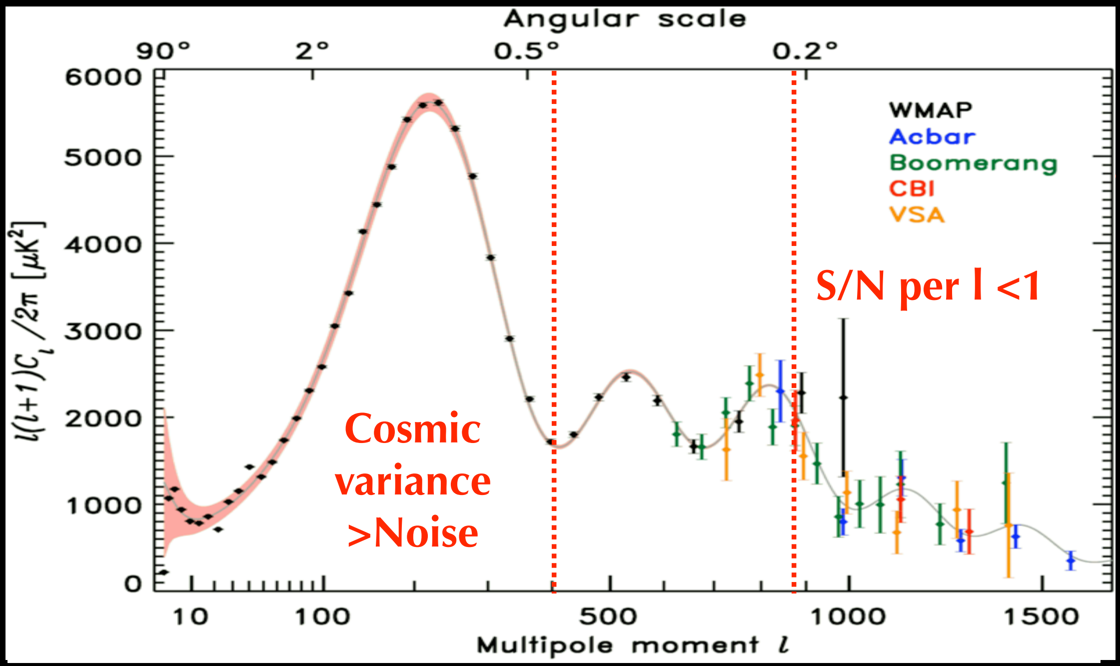
- It is both theoretically sound and observationally supported to consider the CMB temperature fluctuations as a gaussian random field so that a_{lm}'s are Gaussian random variables

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

- Thus sufficient to consider the power spectrum

$$C_\ell = \frac{1}{2\ell+1} \sum_m a_{\ell m} a^*_{\ell m}$$

- Physics in the linear regime well described by a 3000K plasma photo-baryon fluid oscillating in dark matter potential wells



Sunyaev & Zeldovich 70
Peebles & Yu 70
Bond & Efstathiou 87
Hu & White 97

The CMB is weakly polarized

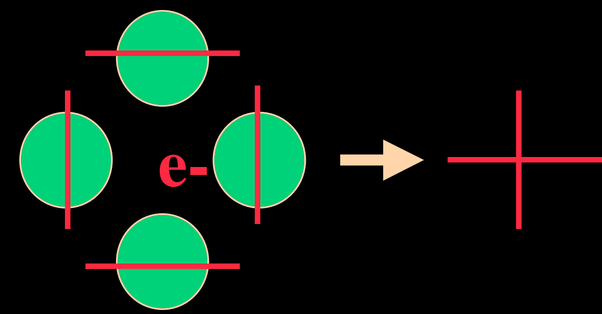
- Linear polarization of the CMB is:
  - Produced by Thomson scattering of a quadrupolar radiation pattern on free electrons
    ⇒probe recombination and reionization
  - Partially correlated with temperature
    (velocity pert. correlates with density pert.)

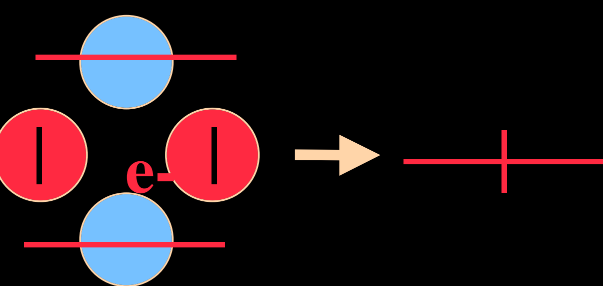
- Two types of Polarization
  - Scalar perturbation to the metric produce E-mode polarization
  - Tensor perturbations to the metric produce B-mode polarization, *i.e.* Gravity waves

- Polarization probes both perturbations themselves and ionization history

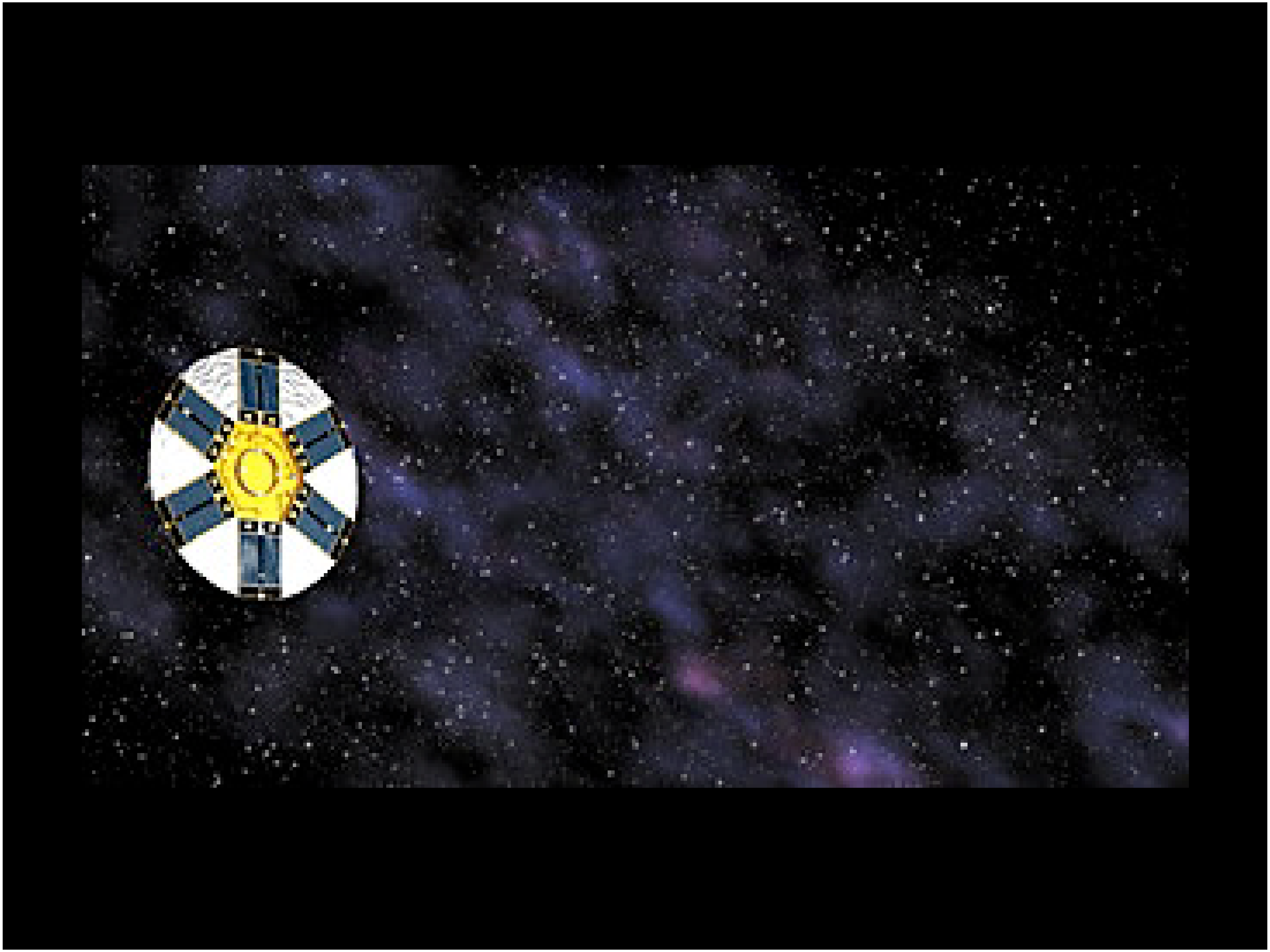
- Numerical calculation show that the polarization fraction is weak, ~1% of only

- All the statistical information is encoded in 4 angular power spectra C_l^{TT}, C_l^{EE}, C_l^{BB}, C_l^{TE}

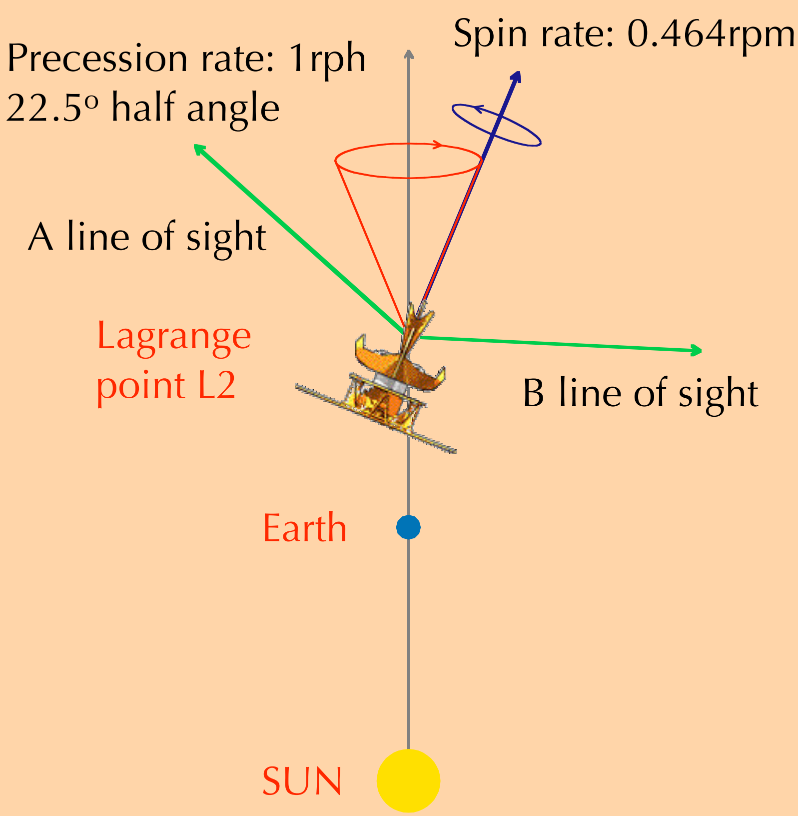




WMAP analysis over the last two years



WMAP primer



- L2 orbit
  - Constant survey mode
  - Thermal stability
  - Passive cooling
- Rapid and complex sky scan
  - Observe 30% of the sky every hour
  - Most of pixels are observed with evenly distributed orientations
- Differential measurement only
  - Most of the common modes cancel
  - Two radiometers per feed
    - $T_1+T_2 \propto$ Intensity
    - $T_1-T_2 \propto$ Polarization
  - 10 feeds, 20 DA total
- 5 microwave frequencies to monitor foregrounds
  - K, Ka, Q, V, W bands
  - 22, 33, 40, 60, 93 GHz
- Accurate calibration on the cosmological dipole and beam measurements on Jupiter

Remarks on the analysis over the last 2 years

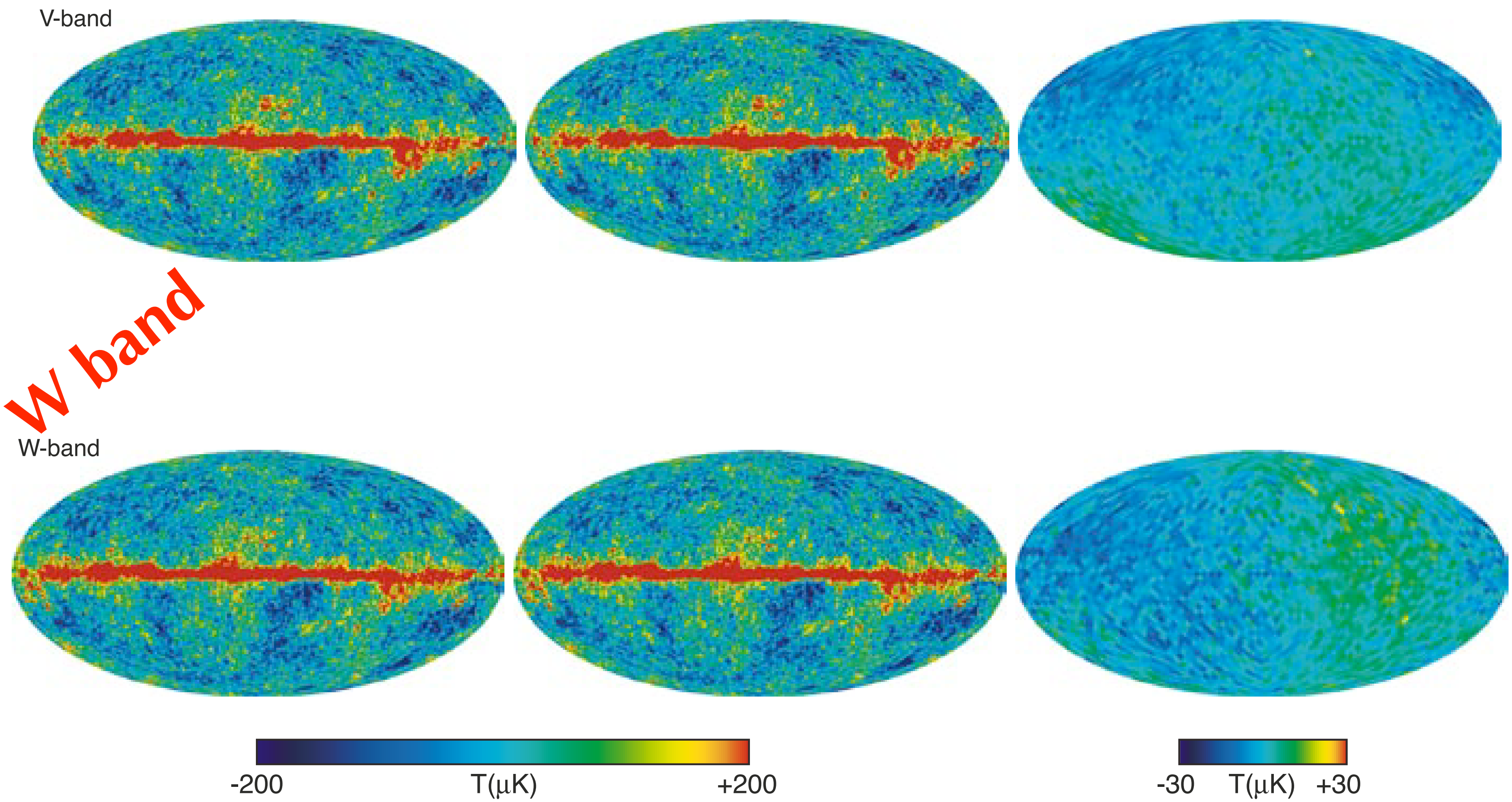
- Differential measurement and interlocked scanning strategy suppresses polarization systematics as for temperature.
- No new systematics, but the weak nature of the spinorial polarized signal requires extra-care to avoid any coupling to the much stronger T field (100 times).
- Non-trivial interactions between the slow drift gain, non-uniform weighting across the sky, time series masking, 1/f noise, galactic foregrounds, band-pass mismatch, off-set sensitivity and loss imbalance.
- The handling of these effect had to be propagated from the map-making till the power-spectrum measurement.
- To understand them required numerous end-to-end simulations (enough to have good statistics). Most of 2004-5 was spent running those and realizing that the previous short-cuts did not work anymore.
- A new pipeline was eventually required and has been designed, written and optimized.
- We rely heavily on null tests in map (various frequency) and C_l space to assess the quality of this processing

Temperature maps

V band

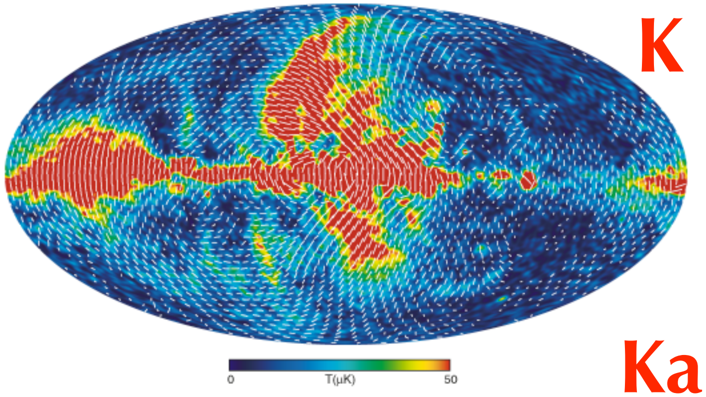
year 1 (pub) | year 3 | year 3 - year 1

W band

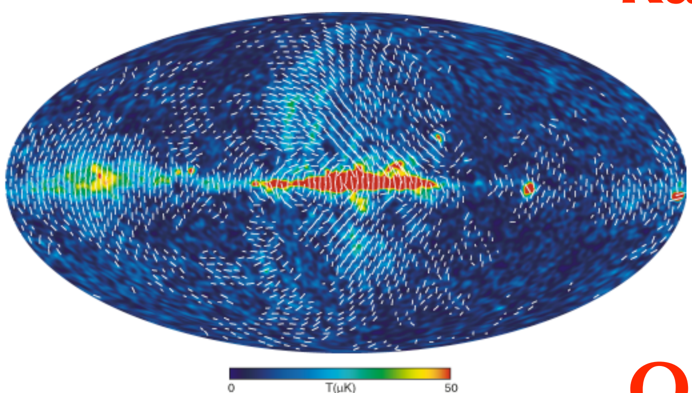


Polarization maps

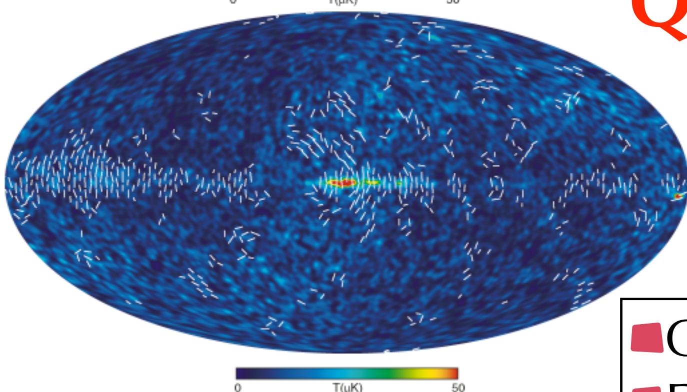
K band



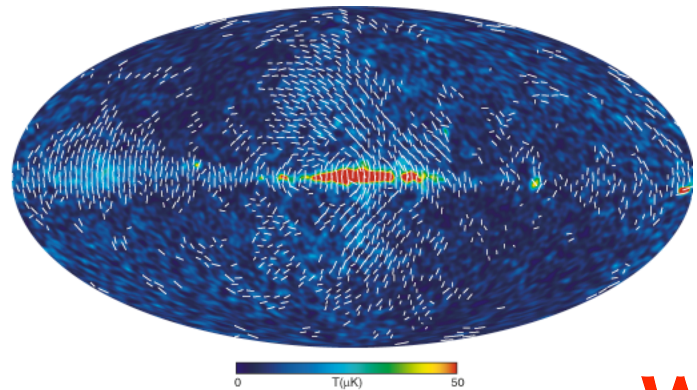
Ka band



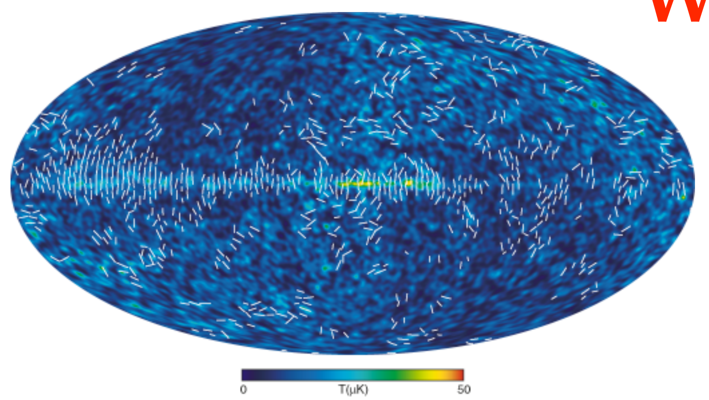
Q band



V band

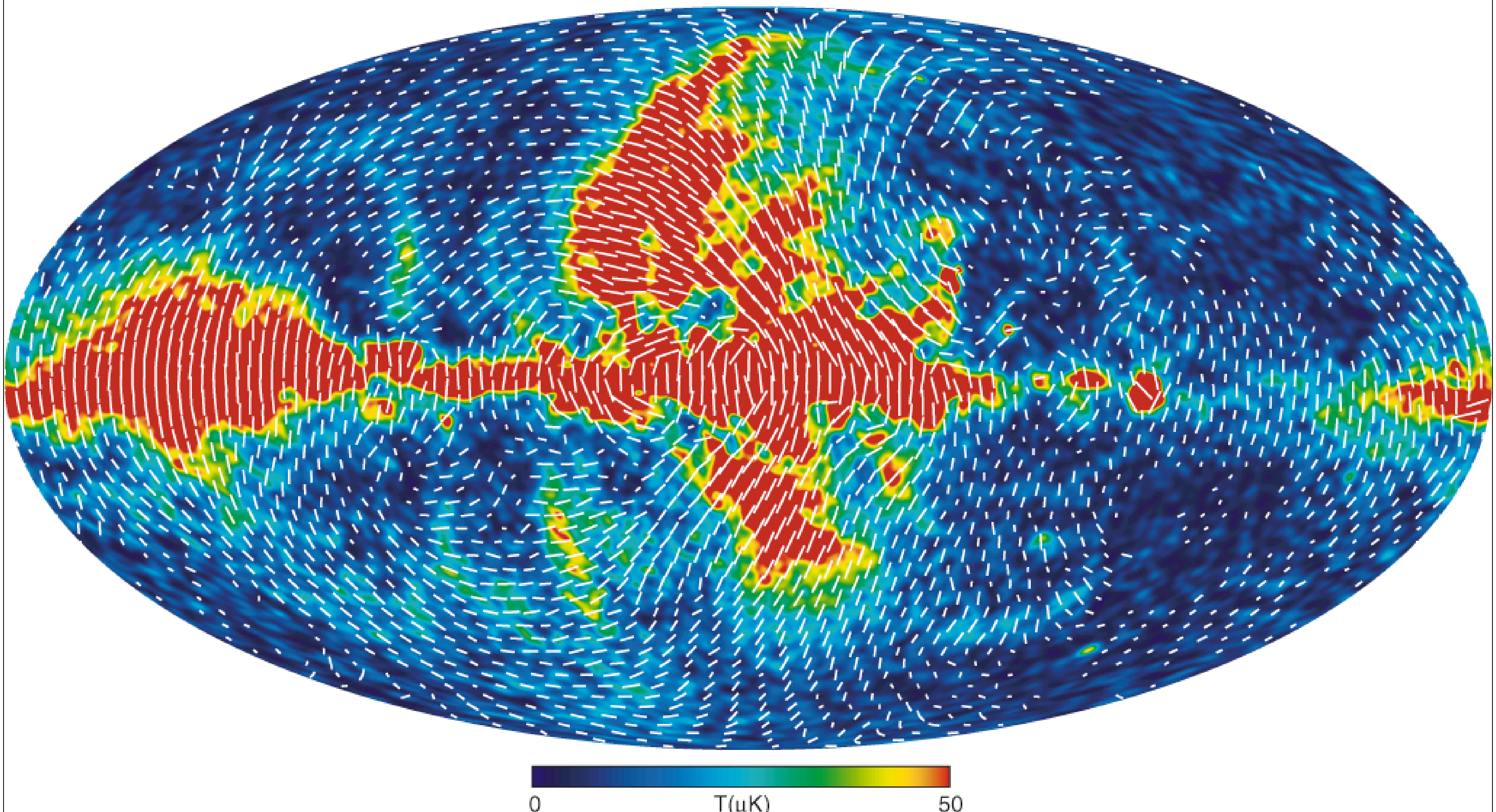


W band

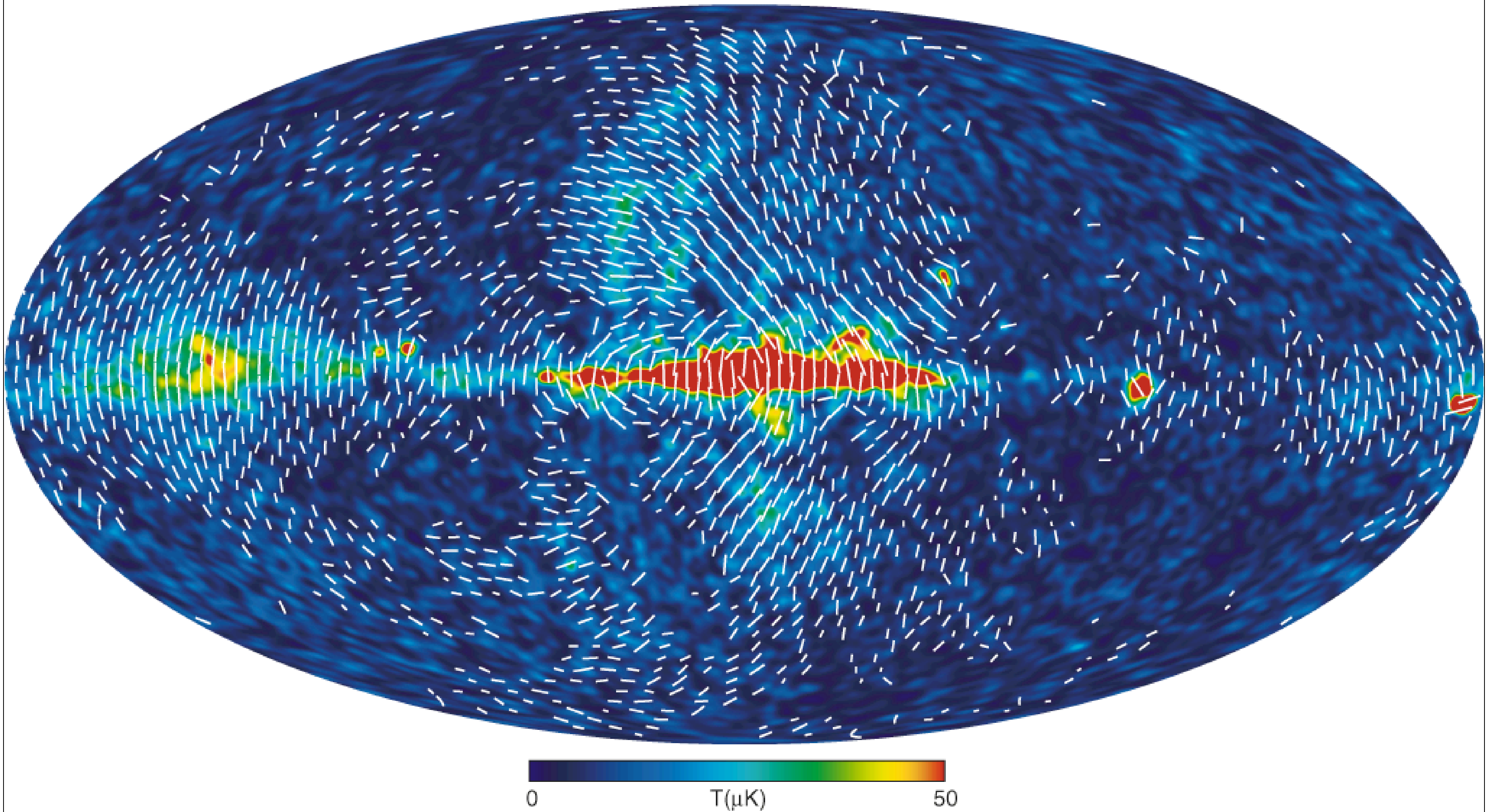


- Color code $P=(Q^2+U^2)^{1/2}$ smoothed with a 2^o fwhm
- Direction shown for S/N > 1

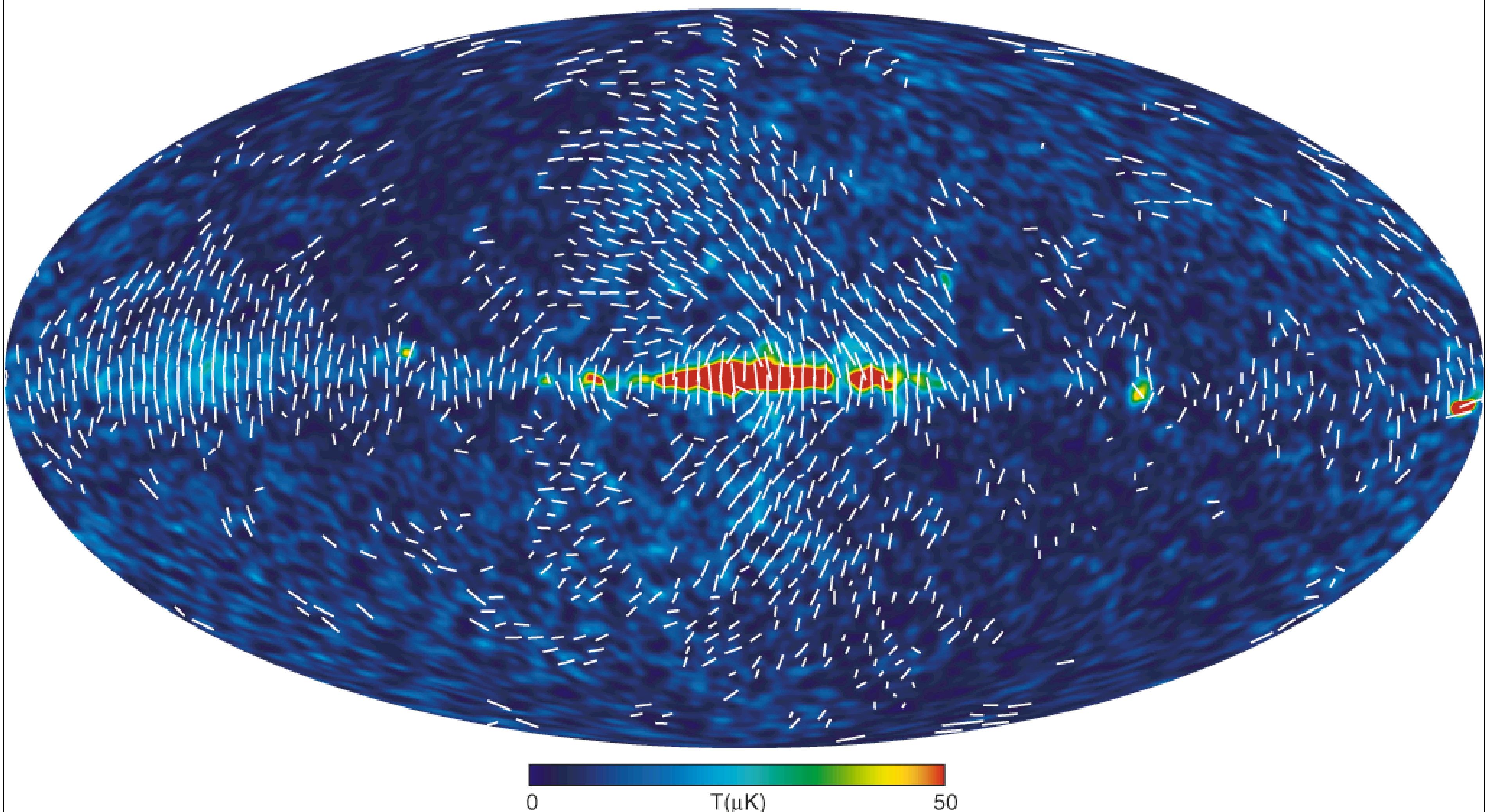
K band - 23 GHz



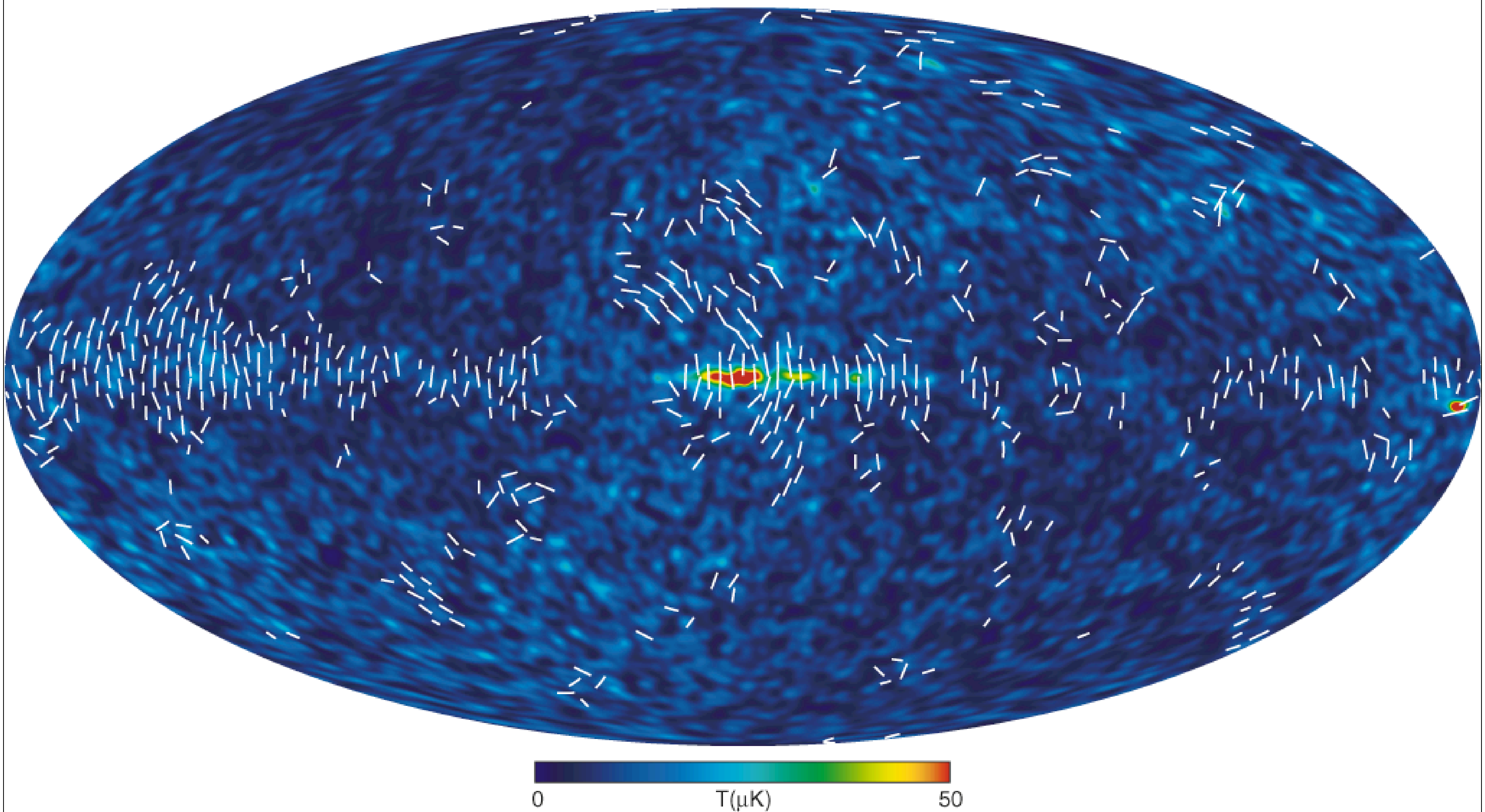
Ka band - 33 GHz



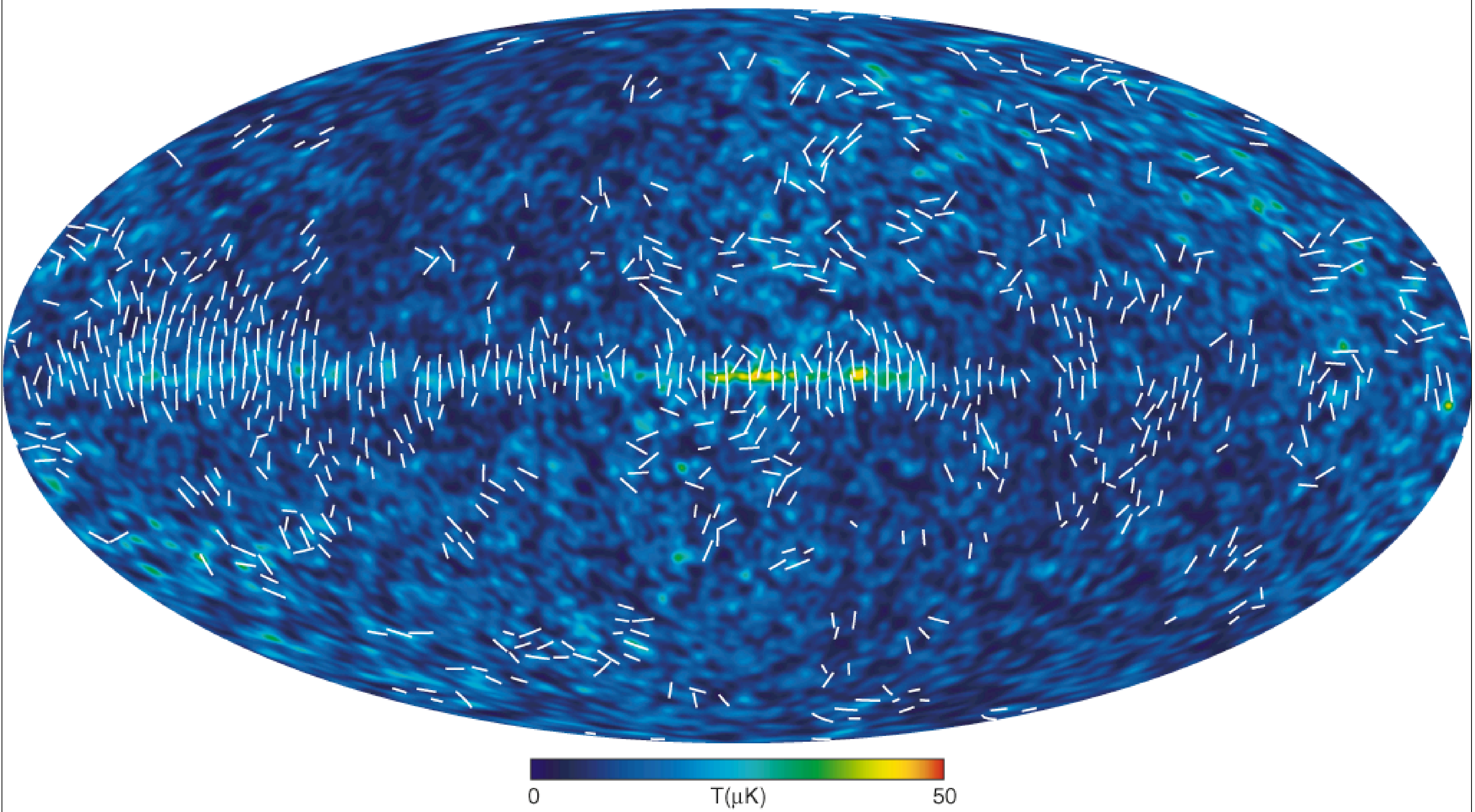
Q band - 41 GHz



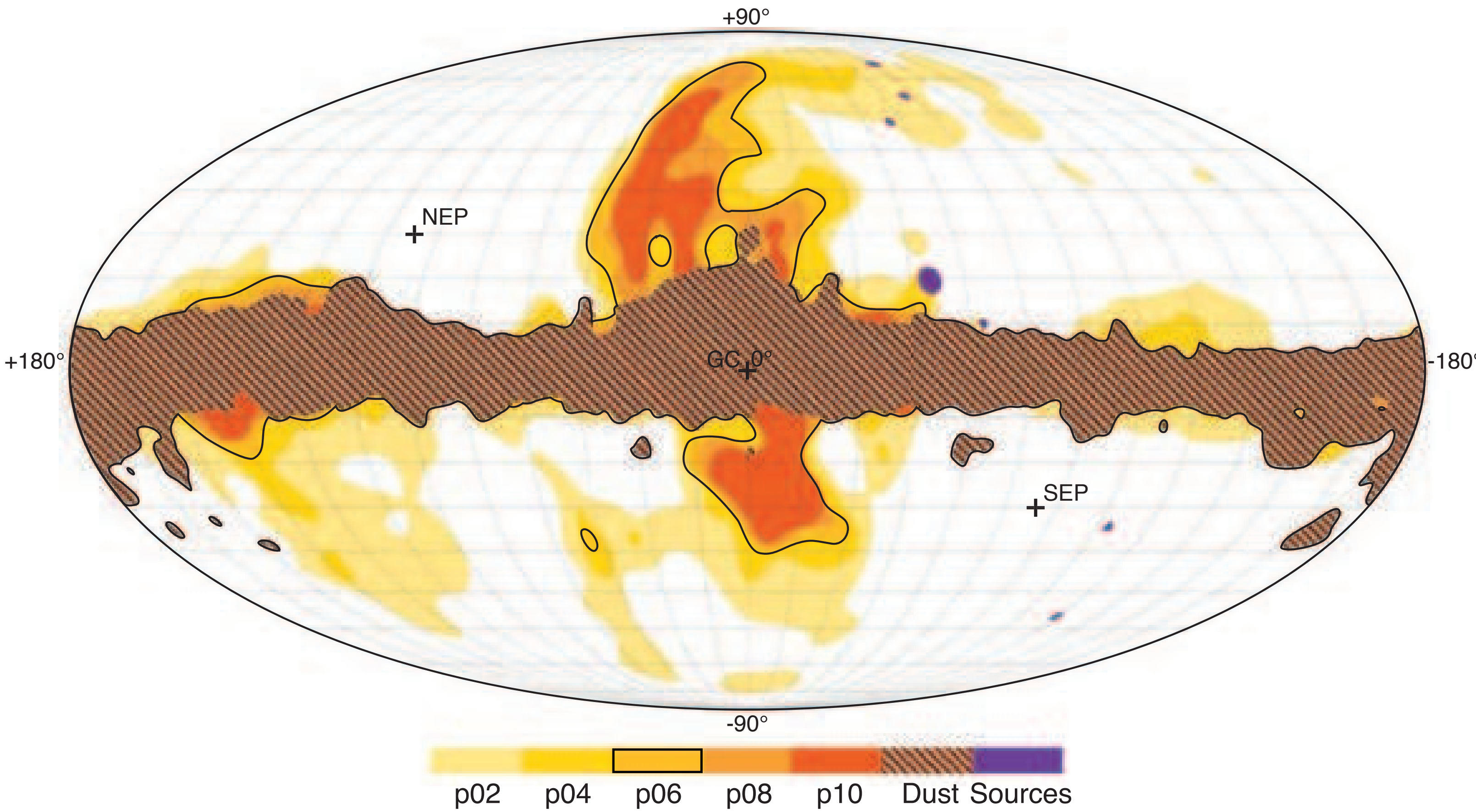
V band - 61 GHz



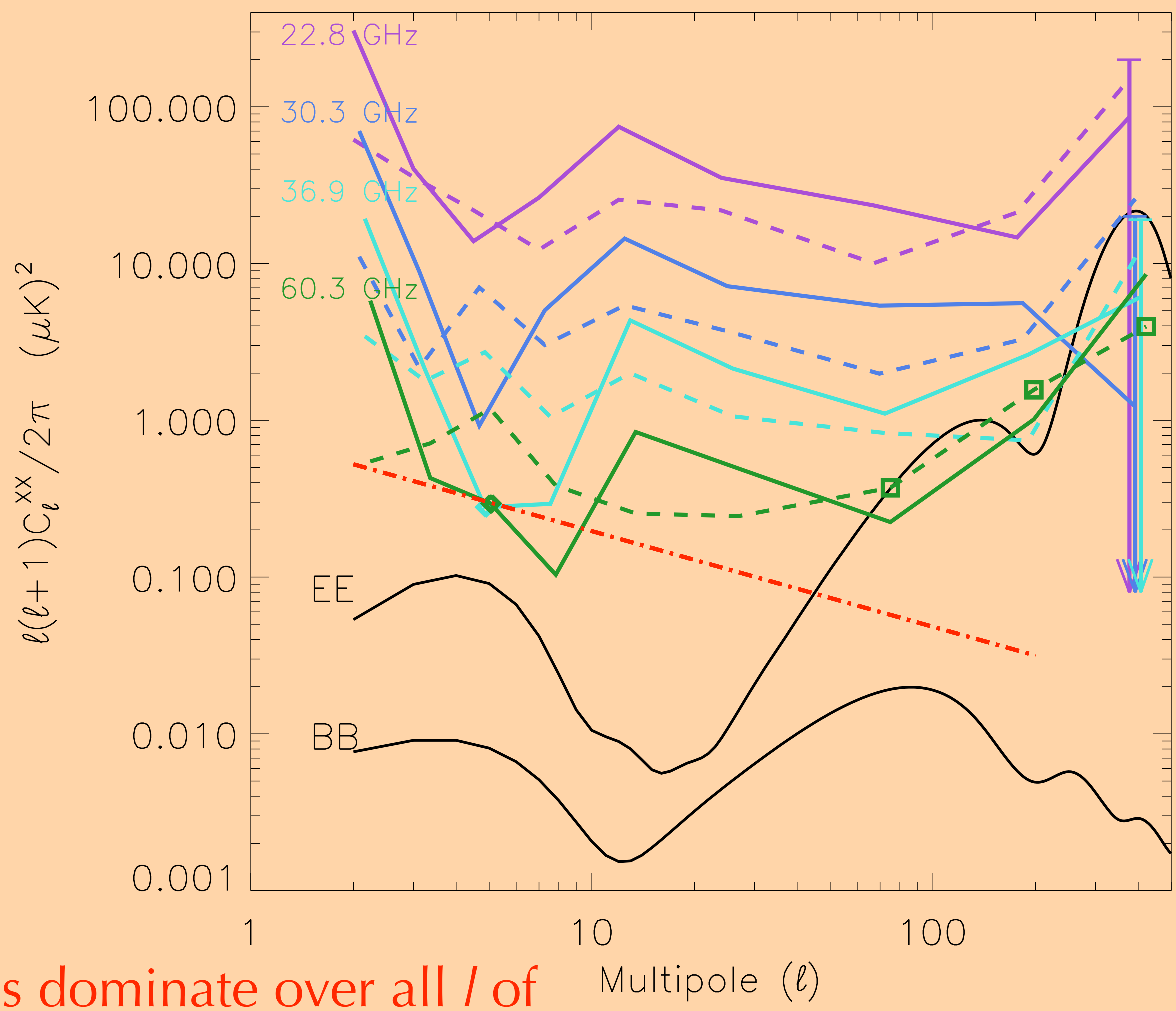
W band - 94 GHz



Polarization mask



Uncleaned power spectra



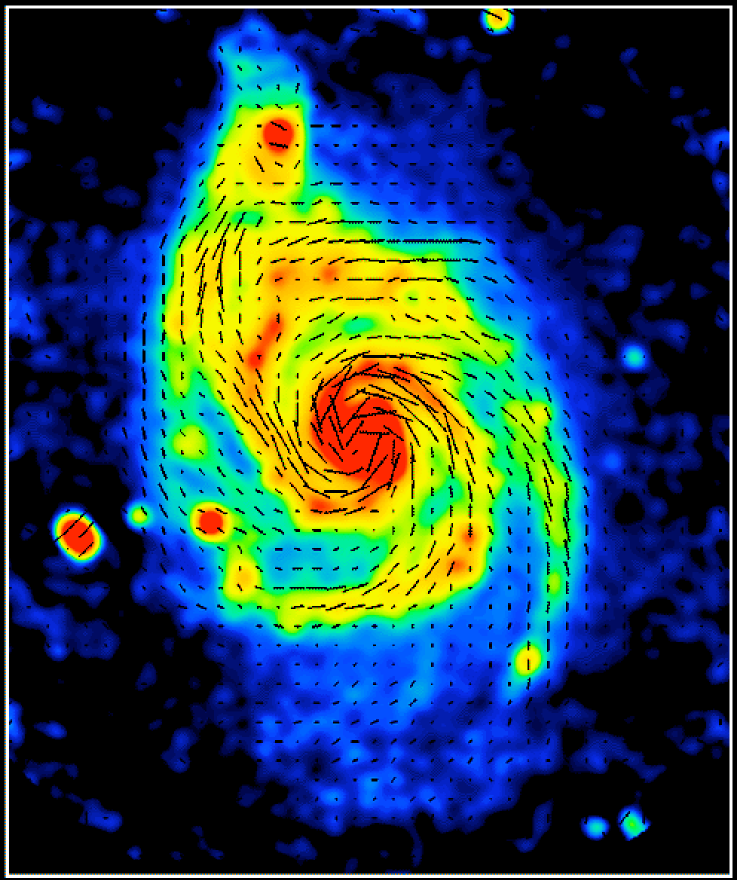
Foregrounds dominate over all *l* of interest and all frequencies unlike for temperature

Outside p06 mask

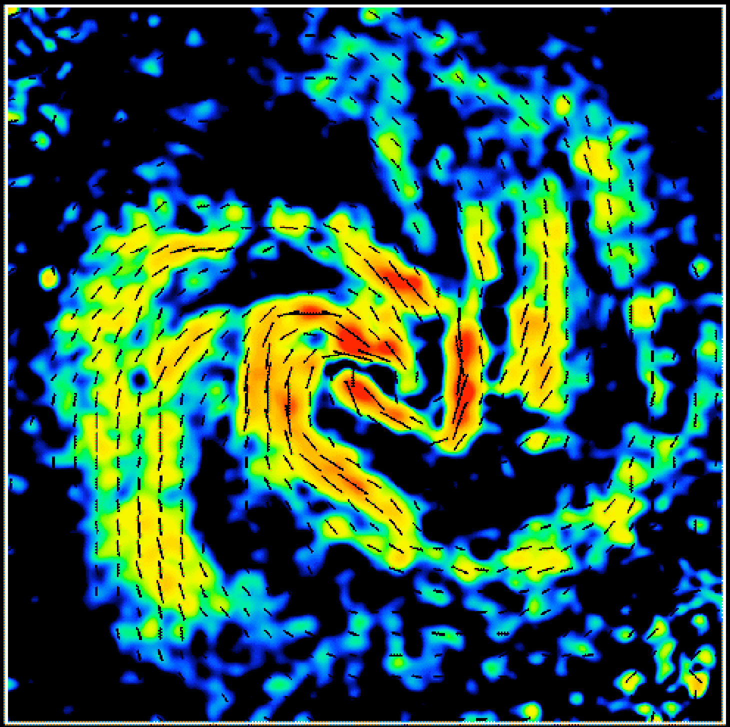
Spiral magnetic field structures seen in external galaxies

Bi-symmetric Spiral model

M51 6cm Total Int. + B-Vectors (VLA+Effelsberg)

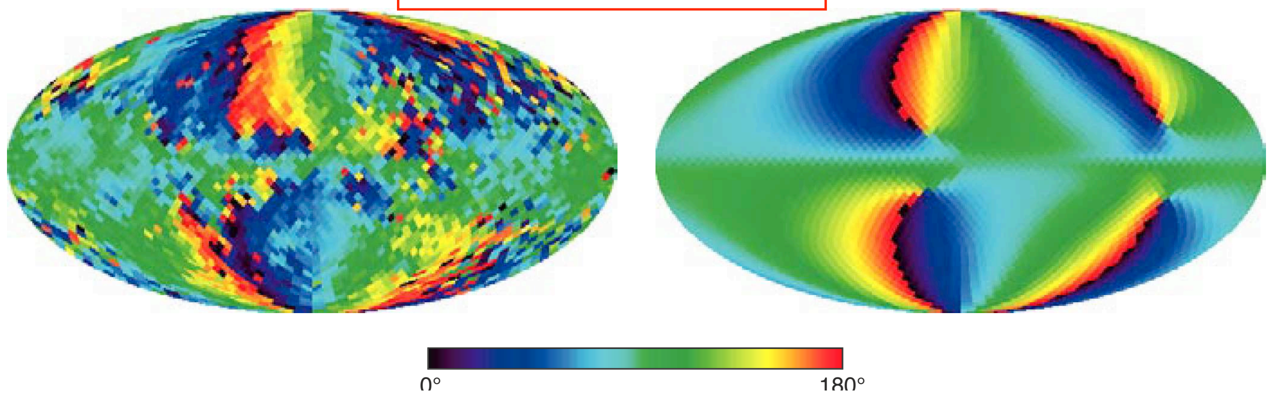


M83 6cm Polarized Int. + B-Vectors (VLA+Effelsberg)

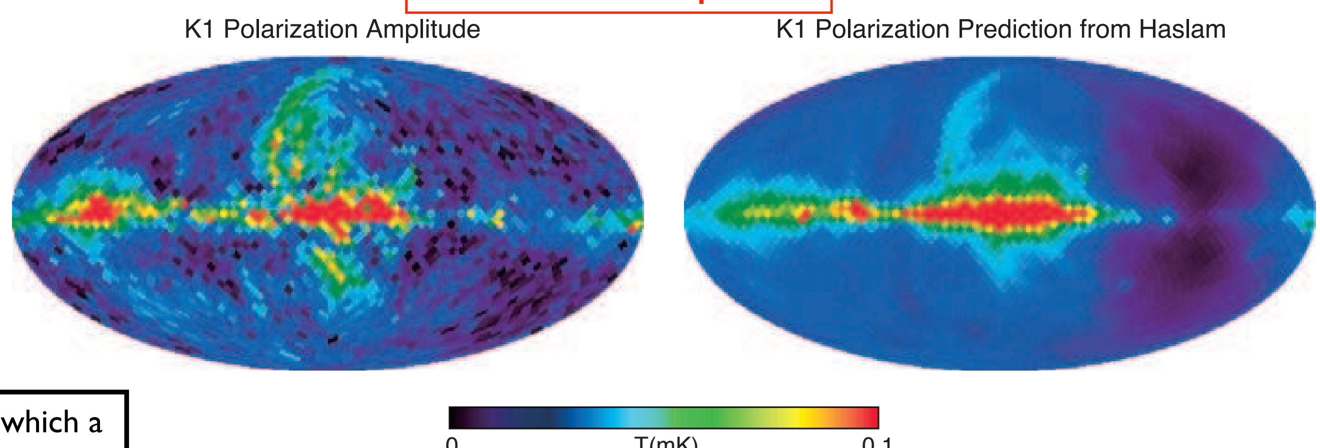


Polarized foregrounds predictions: synchrotron radiation

Polarization directions



Polarization amplitude



Based on a model in which a gas of cosmic rays electrons interact with a magnetic field following a bisymmetric spiral arm pattern

Foreground cleaned maps

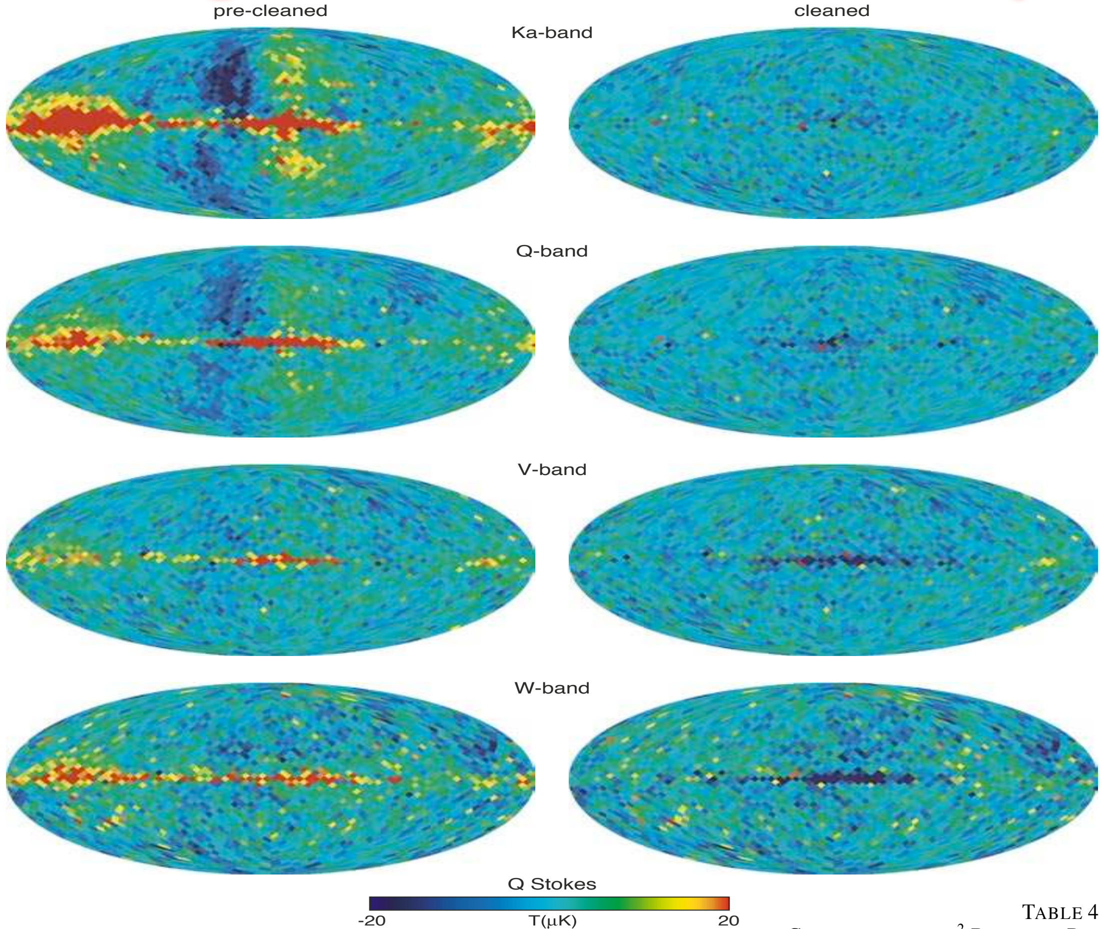
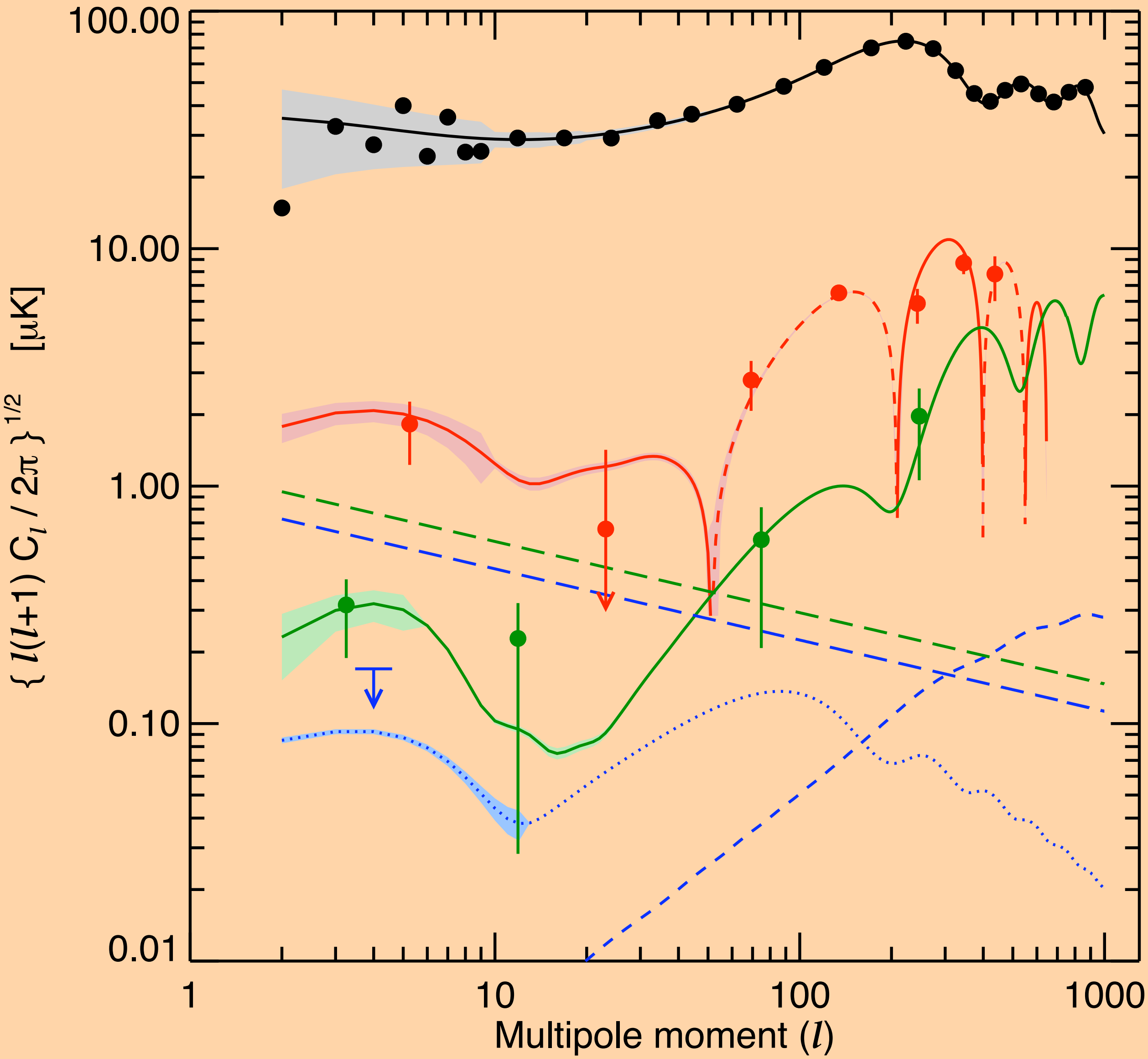


TABLE 4
COMPARISON OF χ^2 BETWEEN PRE-CLEANED AND CLEANED MAPS

Band	χ^2/ν Pre-cleaned	χ^2/ν Cleaned	ν	$\Delta\chi^2$
Ka	10.65	1.20	6144	58061
Q	3.91	1.09	6144	17326
V	1.36	1.19	6144	1045
W	1.38	1.58	6144	-1229
Ka	2.142	1.096	4534	4743
Q	1.289	1.018	4534	1229
V	1.048	1.016	4534	145
W	1.061	1.050	4534	50

- Due to correlations between foregrounds, a map based cleaning is more powerful
- 2 parameters fit only

Final CMB spectra

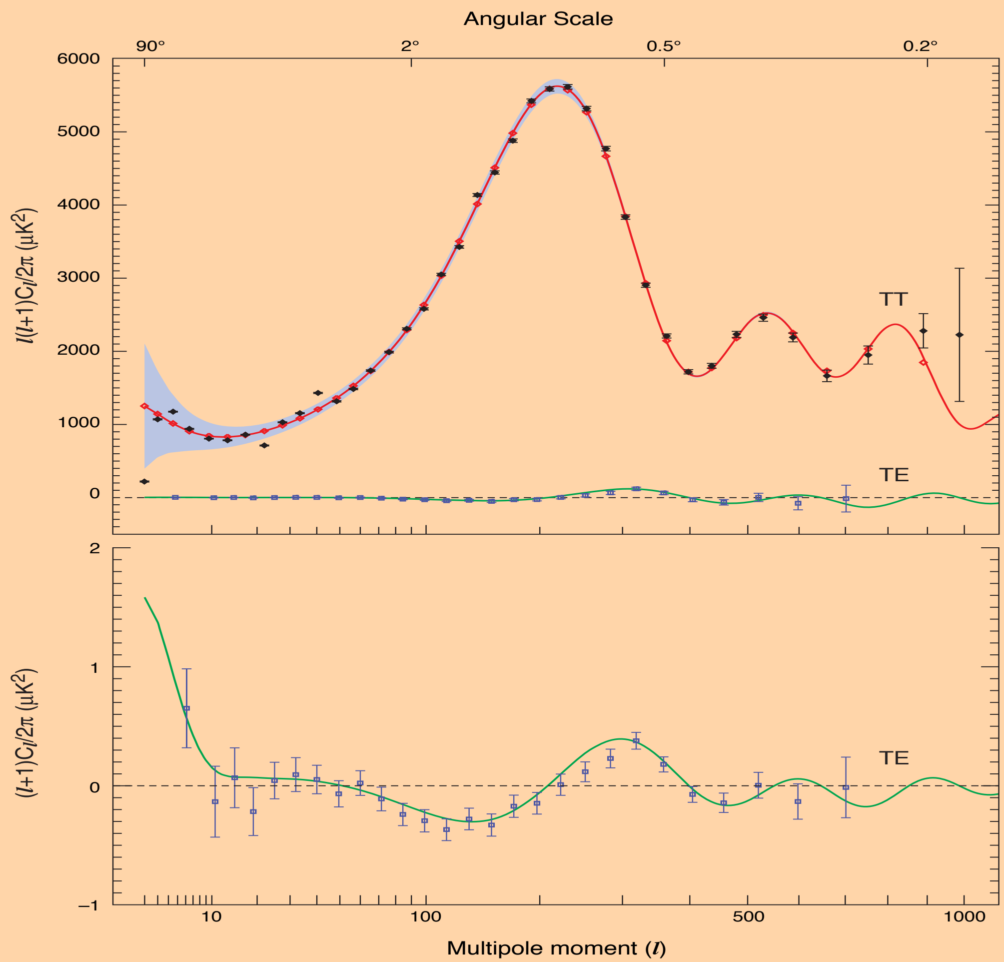


Cosmological Implications

Simple ΛCDM model fits

- Simple flat ΛCDM model with 6 parameters ($\Omega_{cdm}, \Omega_b, n_s, A_s, h, \tau$) still an excellent fit

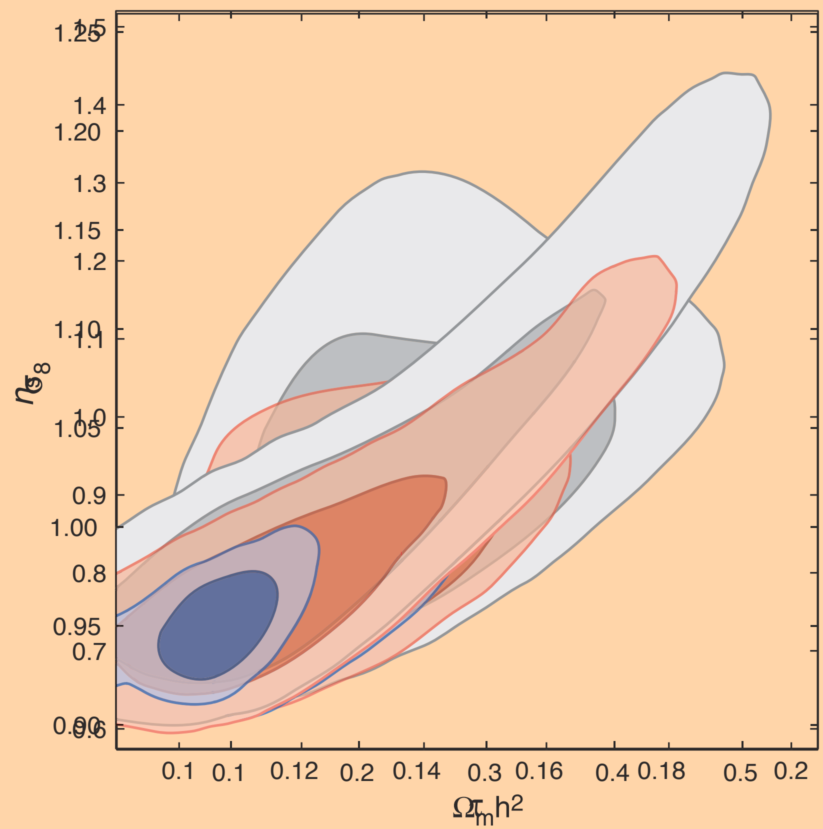
- Despite smaller error bars, the χ^2_{eff} for TT improves from 1.09 (893 dof) to 1.068 (982 dof) and from 1.066 (1342 dof) to 1.041 for TT+TE (1410 dof)
- For T, Q, U maps, we have $\chi^2_{eff}=0.981$ for 1838 pixels
- Previously discrepant points get closer



Improvement in parameter space

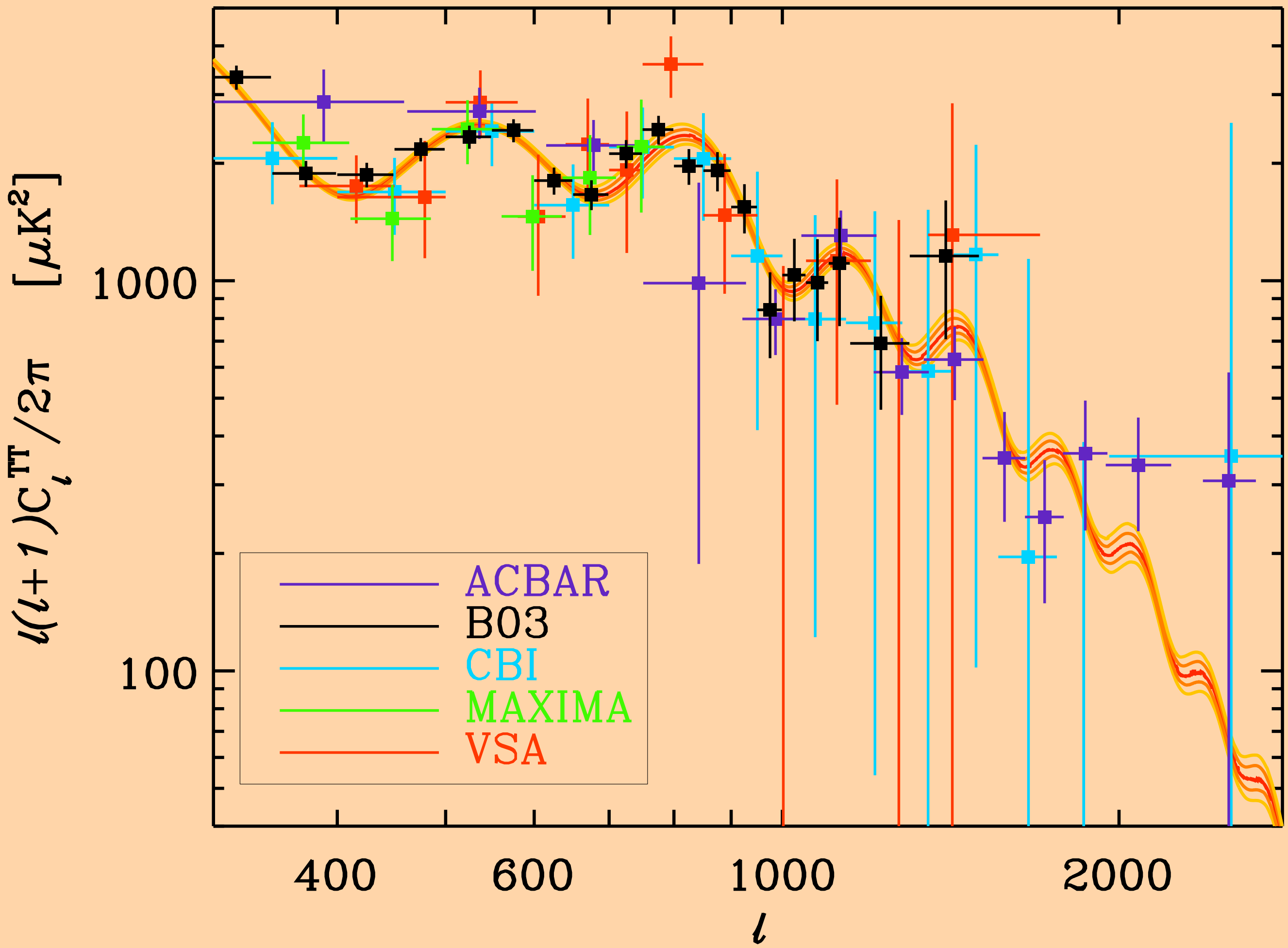
Parameter	First Year ML	WMAPext ML	Three Year ML
$100\Omega_b h^2$	2.30	2.21	2.22
$\Omega_m h^2$	0.145	0.138	0.128
H_0	68	71	73
τ	0.10	0.10	0.092
n_s	0.97	0.96	0.958
Ω_m	0.32	0.27	0.24
σ_8	0.88	0.82	0.77

First Year Mean	WMAPext Mean	Three Year Mean
$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08
$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009
72^{+5}_{-5}	73^{+3}_{-3}	74^{+3}_{-3}
$0.17^{+0.08}_{-0.07}$	$0.15^{+0.07}_{-0.07}$	0.093 ± 0.029
$0.99^{+0.04}_{-0.04}$	$0.98^{+0.03}_{-0.03}$	0.961 ± 0.017
$0.29^{+0.07}_{-0.07}$	$0.25^{+0.03}_{-0.03}$	0.234 ± 0.035
$0.92^{+0.1}_{-0.1}$	$0.84^{+0.06}_{-0.06}$	0.76 ± 0.05



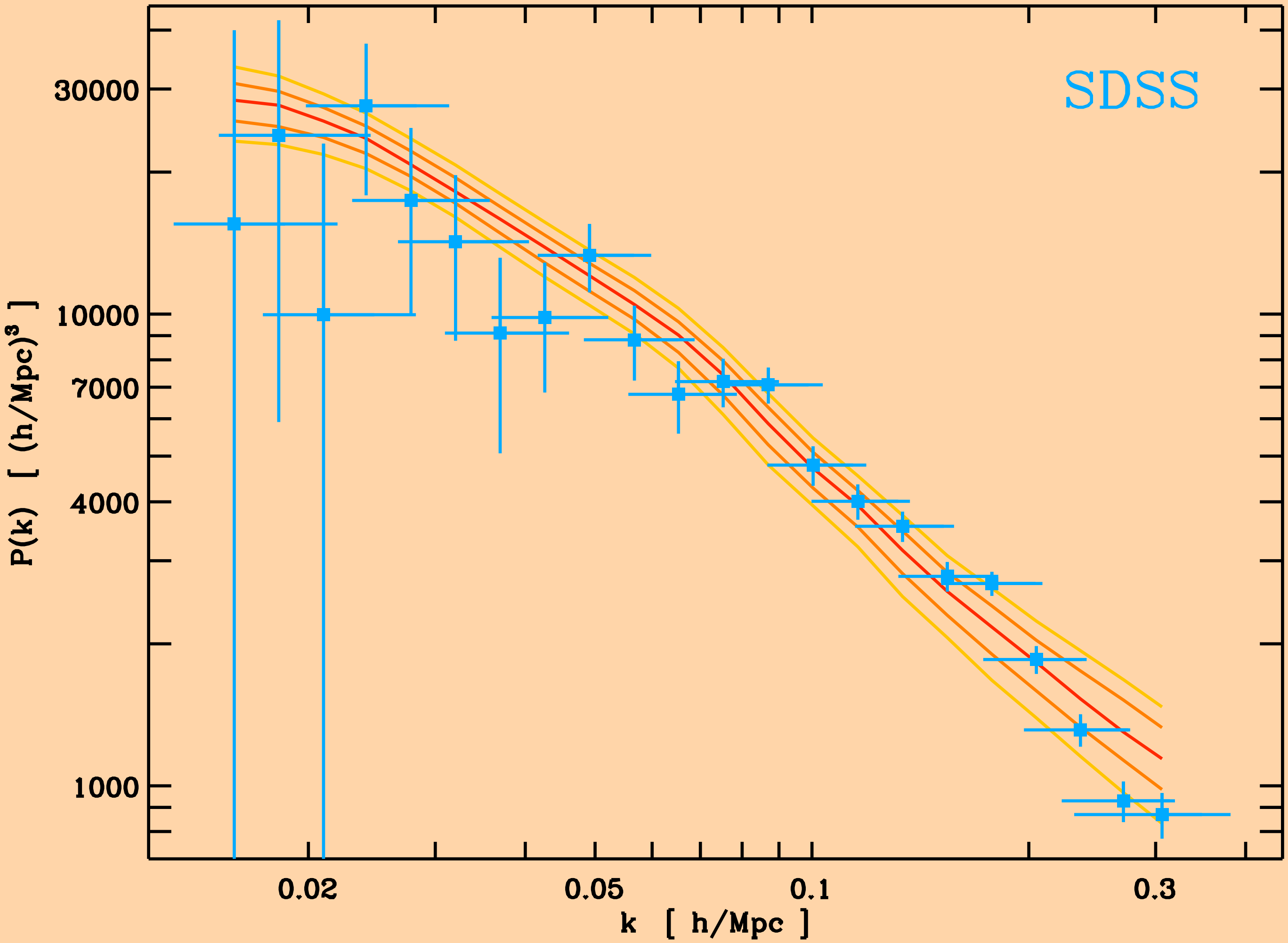
Driven by 3rd peak

Cosmological contrasts... and yet concordance



WMAP "predicts" small scale CMB experiments

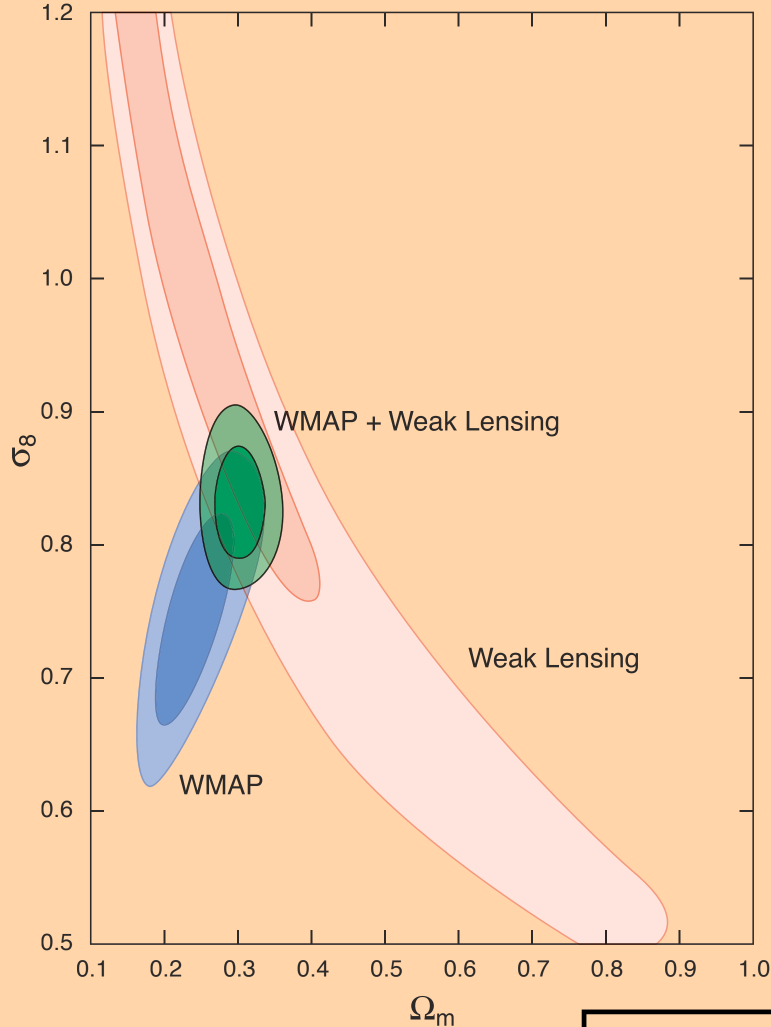
Cosmological contrasts… and yet concordance



WMAP "predicts" low *z* mass distribution

(same for 2dF)

Weak-lensing joint analysis



Weak lensing really starts to hold its promises even if slight tension here

CFHTLS current analysis
22 sq degree
Down to a magnitude i'=24.5

Hoekstra et al. 05
Sembolini et al. 05

Where are we now?

The current "phenomenological" success means:

- The primordial inhomogeneities are mostly adiabatic with a nearly scale invariant power spectrum
- We have a successful GR based theory of linear perturbations to evolve them
- We have a good description of the main components even if we do not know what they are

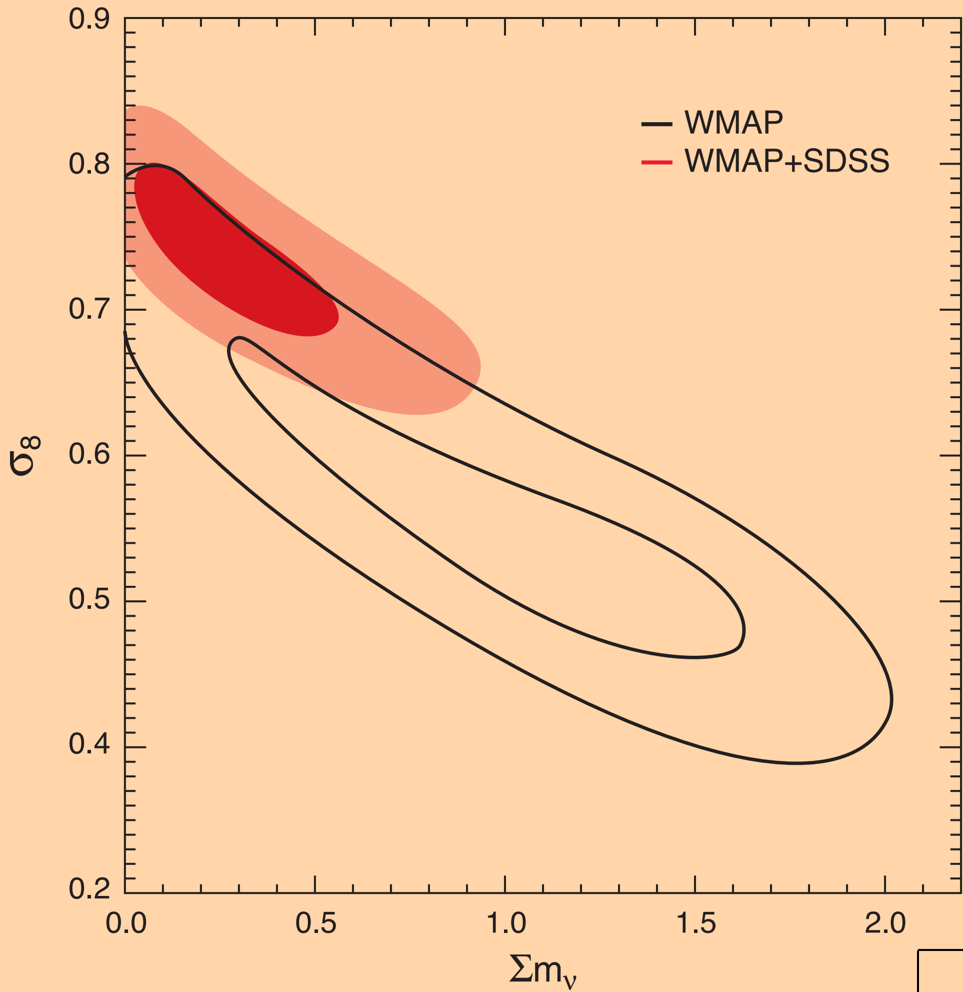
We can now ask various sets of questions:

- Ask question within the model
  - What else can we learn about the components of the model, eg neutrino?
  - What is Dark Energy?
  - What is Dark Matter?
  - Did the Universe really undergo an Inflationary phase?
  - First stars and how did the Universe get reionized?
- Explore further the data and look for "anomalies", ie deviations from this model

Fundamental Physics we don't know yet

Physics we don't know to compute

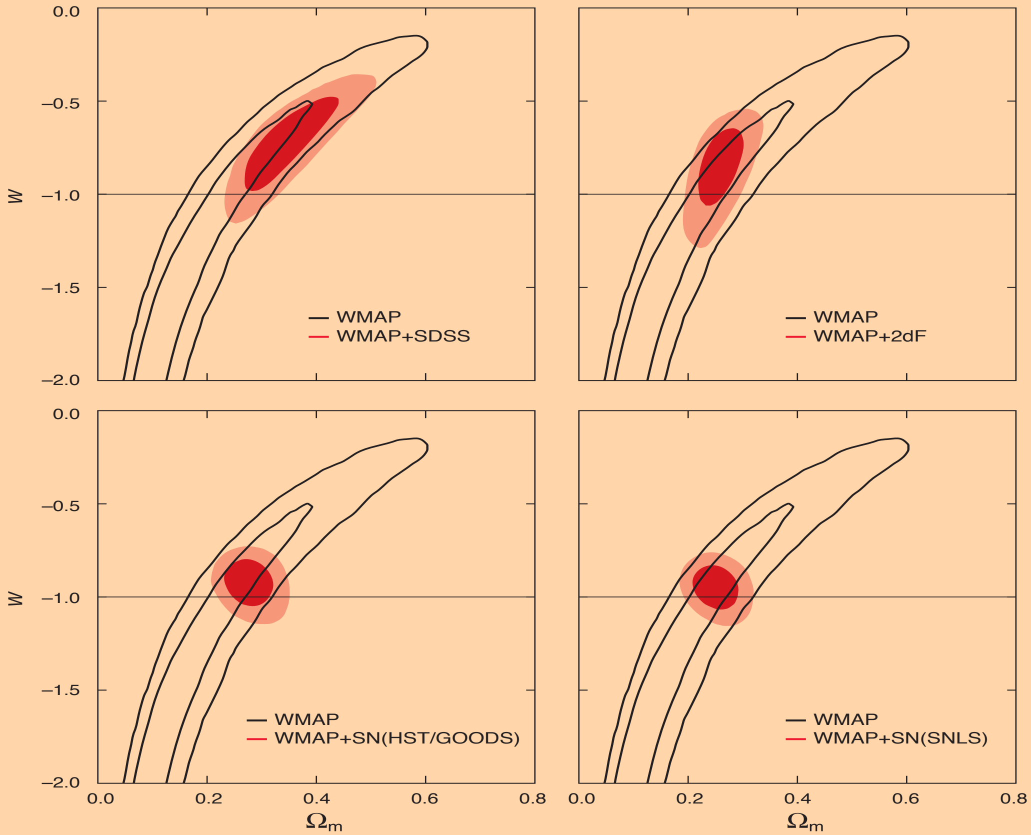
Constraining neutrino mass



Data Set	$\sum m_\nu$ (95% limit for $N_\nu = 3.02$)
WMAP	2.0 eV(95% CL)
WMAP + SDSS	0.91 eV(95% CL)
WMAP + 2dFGRS	0.87 eV(95% CL)
CMB + LSS +SN	0.68 eV(95% CL)

Dark Energy

Constraints on constant DE equation of state $w=p/\rho$

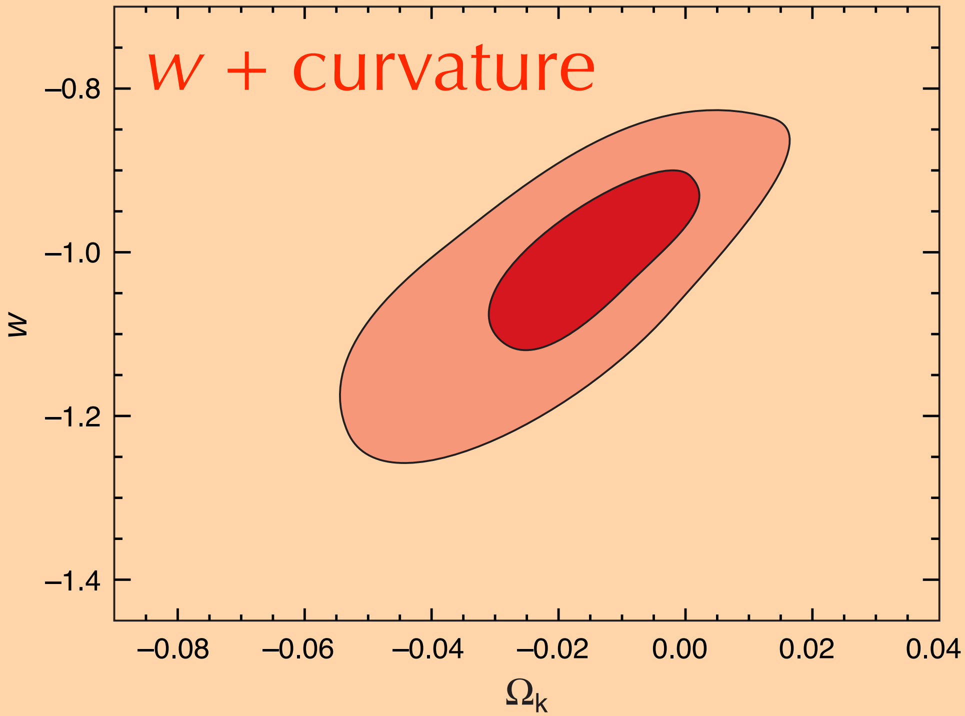


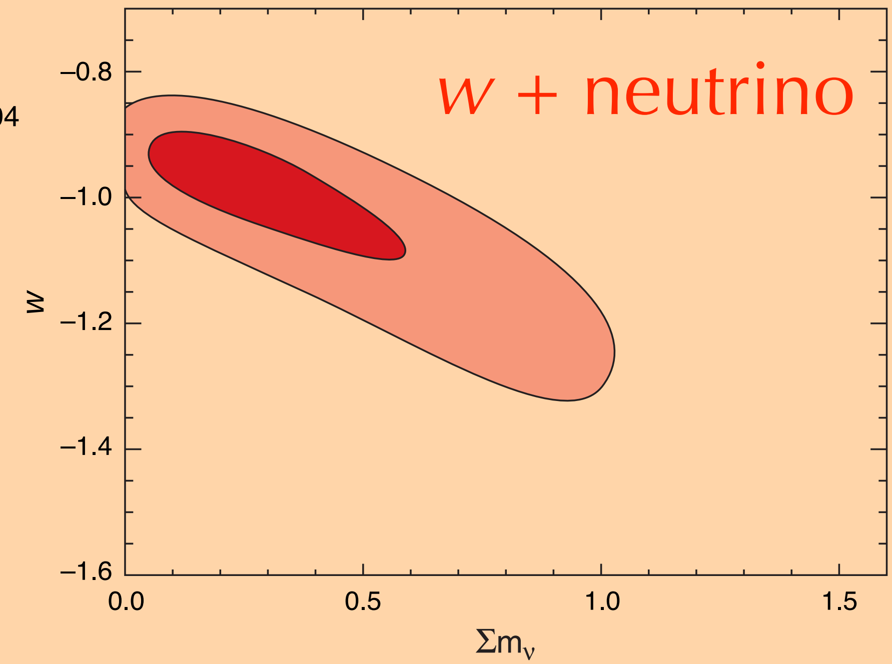
With DE perturbations

but fixed c_s^2 (cf Bean & Doré 03)

Data Set	with perturbations
WMAP + SDSS	$-0.75^{+0.18}_{-0.16}$
WMAP + 2dFGRS	$-0.914^{+0.193}_{-0.099}$
WMAP + SNGold	$-0.944^{+0.076}_{-0.094}$
WMAP + SNLS	$-0.966^{+0.070}_{-0.090}$
CMB+ LSS+ SN	$-0.926^{+0.051}_{-0.075}$

Robustness of DE constraints





What is Inflation?

- Inflation was introduced to solve the problems of the “standard Big Bang” model like *flatness* and the *horizon problem*
- Key feature: during an extended period of time, the universe is expanding exponentially. Fluctuations are generated during this phase
- This is achieved by introducing in the matter sector (a) new scalar field(s) Φ with a well chosen potential $V(\Phi)$
- For a given $V(\Phi)$ there are relations between derivatives of V and observables like n_s , r and $dn_s/d\ln k$
- Testing Inflation is mostly testing these consistency relations

Guth 81, Sato 81, Linde 82, Albrecht & Steinhardt 82
Guth & Pi 82, Starobinsky 82, Mukhanov & Chibisov 81, Hawking 82, Bardeen et al. 83
Linde 05, Lyth & Riotto 99 for reviews

What are Inflation predictions?

Most of Inflation predictions, in the 80s, when there were few evidences for any of those idea

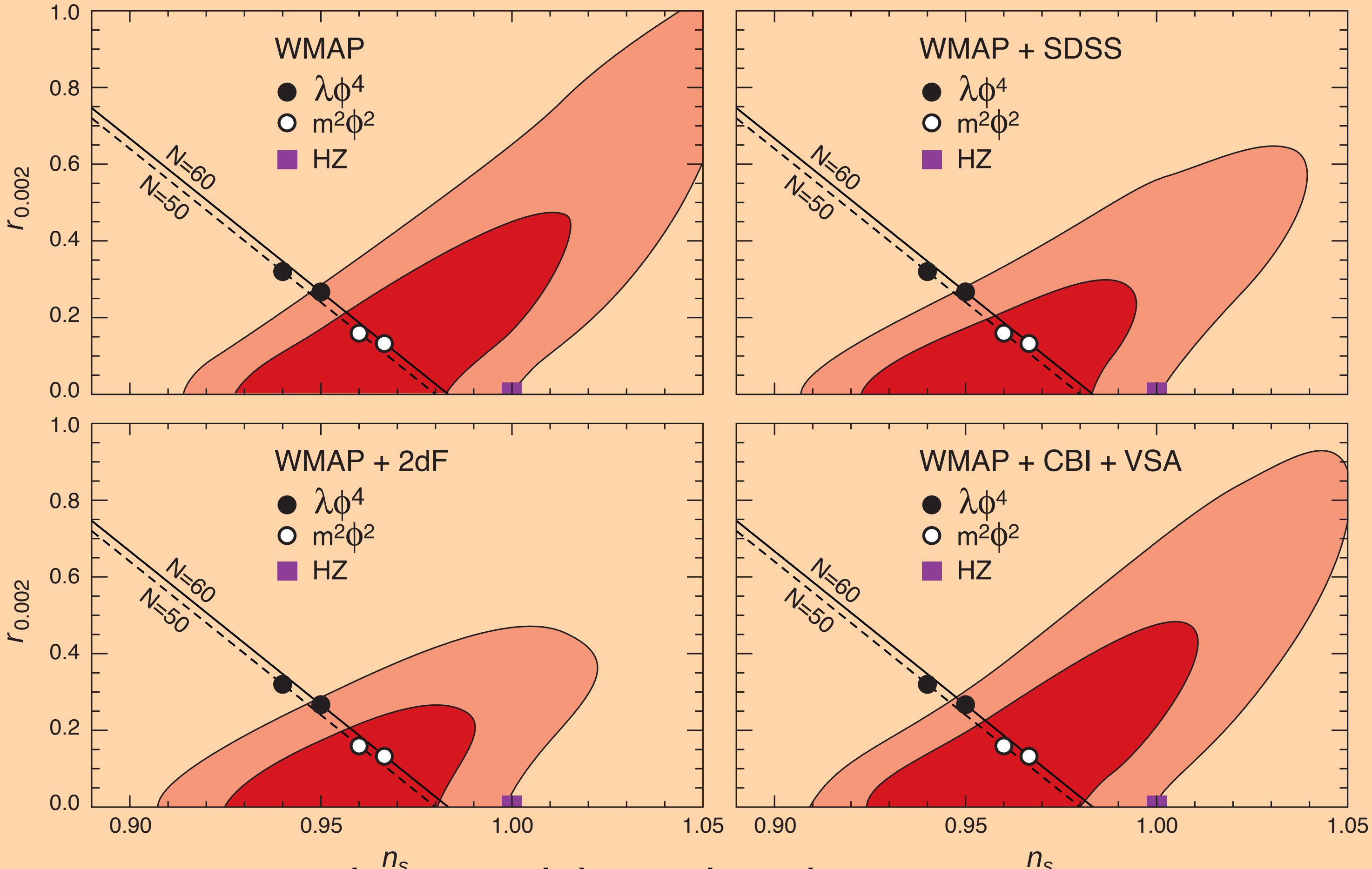
- Flatness ⇒ *TOCO, MAXIMA, BOOMERANG, WMAP...*
- Primordial perturbations nearly scale invariant ⇒ *COBE (n_s = 1.2±0.3 - Gorski et al. 96)*
- Gaussianity of fluctuations ⇒*WMAP-1*
- Adiabatic initial perturbations ⇒*WMAP-1*
- Super-Horizon perturbations ⇒ *WMAP-1 (TE at l~100)*
- Deviation from scale invariance ⇒ *WMAP-3*
- Tensor perturbations, *i.e.* Gravity Wave Background ⇒ *WMAP-8 ?, Planck?, Spider?, Biceps?*

Spectral index, tensor modes and Inflation

$V(\phi) \propto \phi^{\alpha}$ — Consistency relations ⟹

$$r \simeq \frac{4\alpha}{N}$$
$$1 - n_s = \frac{\alpha + 2}{2N}$$

where $\Delta_R^2(k) = \left(\frac{k}{k_0}\right)^{n_s - 1}$

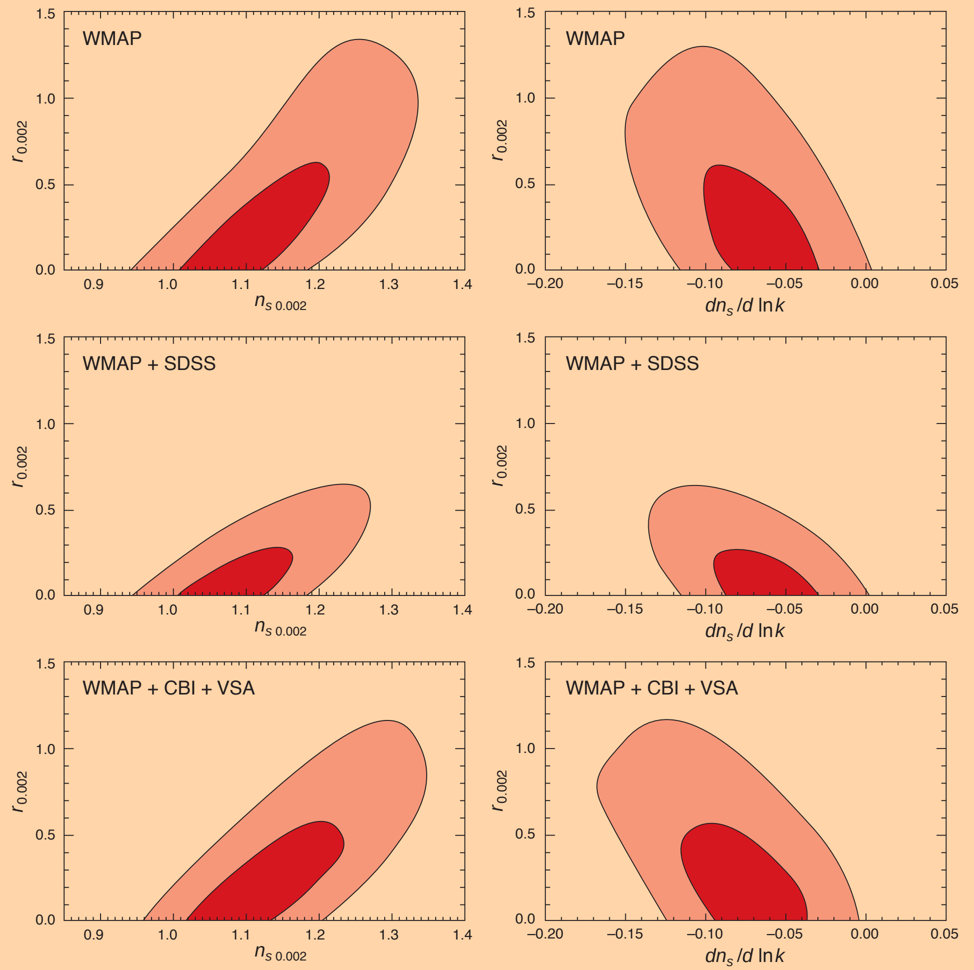


Similar constraints for B03+ACBAR

These models predict almost no running

Do we see a running spectral index?

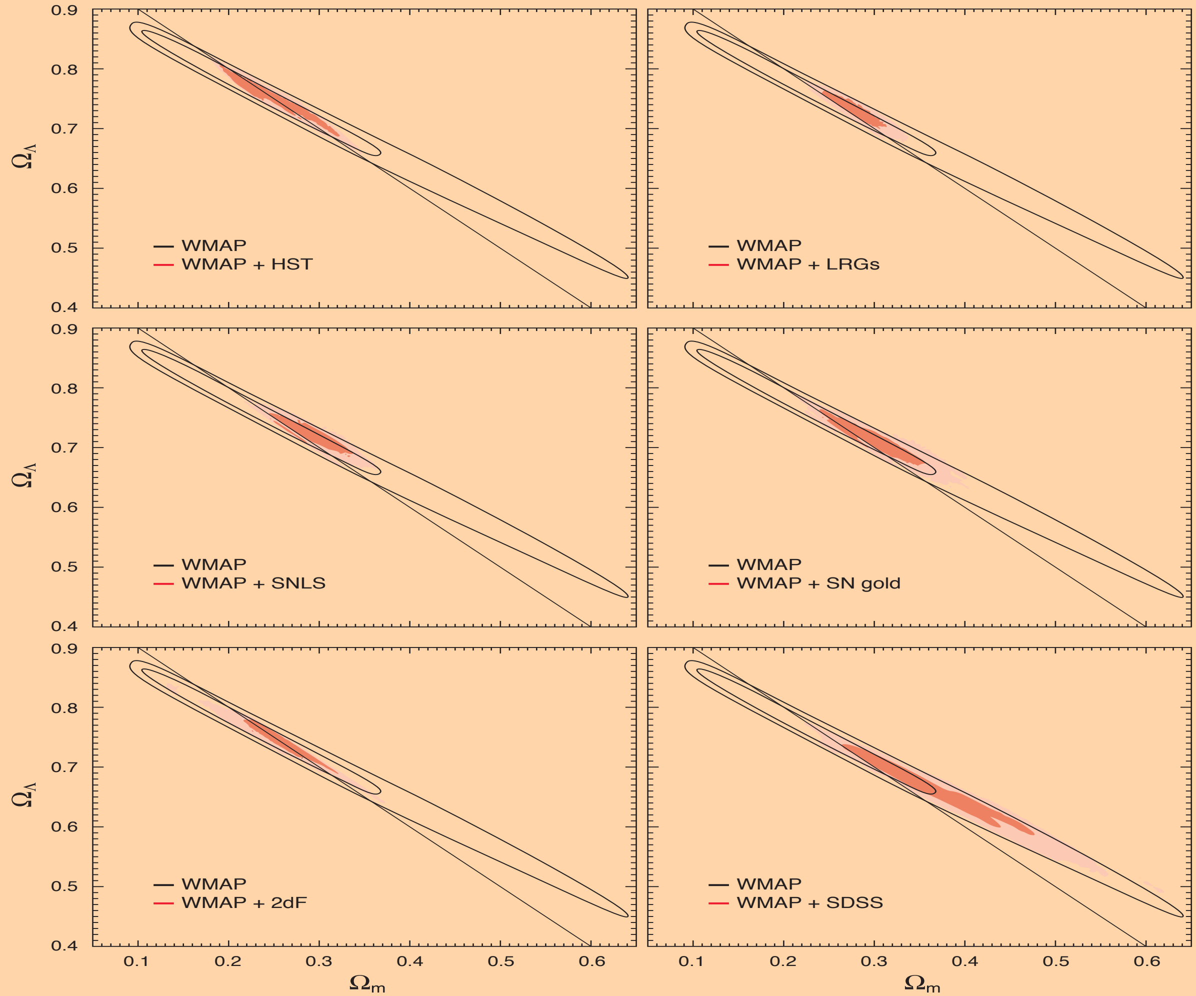
$$\frac{d\ln\Delta_R^2(k)}{d\ln k} = n_s(k_0) - 1 + \frac{dn_s}{d\ln k}\ln(k/k_0)$$



Similar constraints for B03+ACBAR

- Consistent trend but weak signal so far
- WMAP and LSS probe almost the same scales currently
- The trends come ~equally from the low *l* points and the high *l* points

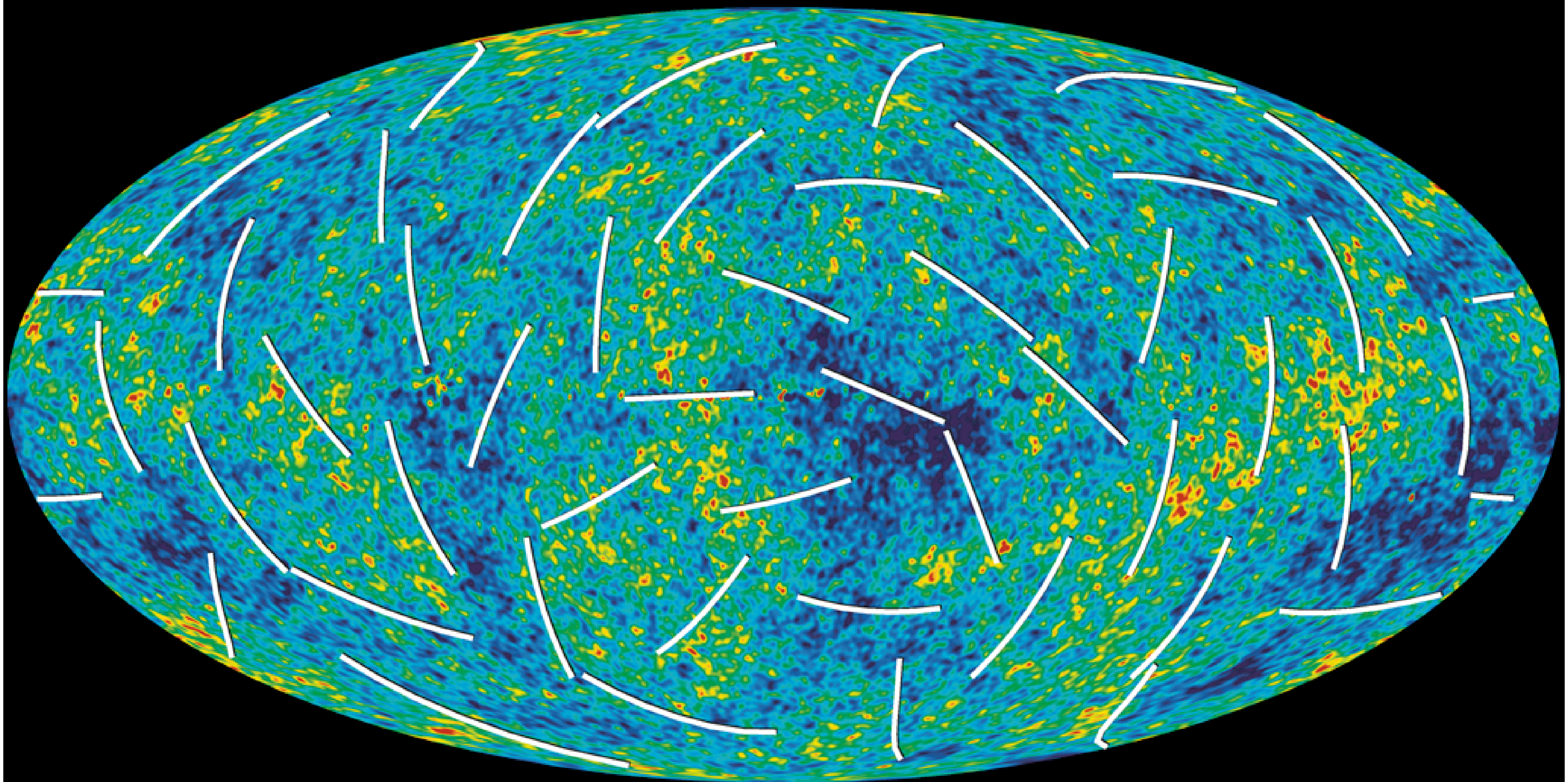
Testing flatness



Data Set	Ω_K	Ω_Λ
WMAP + $h = 0.72 \pm 0.08$	$-0.003^{+0.013}_{-0.017}$	$0.758^{+0.035}_{-0.058}$
WMAP + SDSS	$-0.037^{+0.022}_{-0.014}$	$0.650^{+0.058}_{-0.045}$
WMAP + 2dFGRS	$-0.0057^{+0.0085}_{-0.0064}$	0.739 ± 0.028
WMAP + SDSS LRG	$-0.008^{+0.011}_{-0.015}$	$0.729^{+0.021}_{-0.026}$
WMAP + SNLS	$-0.015^{+0.021}_{-0.016}$	$0.719^{+0.023}_{-0.028}$
WMAP + SNGold	$-0.017^{+0.020}_{-0.019}$	$0.703^{+0.036}_{-0.032}$

Conclusions

- WMAP has now produced well characterized temperature and polarization maps
- After removing the galactic foregrounds, WMAP has detected EE and TE signatures of reionization with optical depth of 0.09
- Simple flat ΛCDM cosmological model has survived its most rigorous test and challenges fundamental physics
- Data favors red spectral index (with values consistent with simple inflationary models) over Harrison-Zeldovich Peebles spectrum
- The combination of WMAP data and other astronomical data now places even stronger constraints on the density of dark matter and dark energy, the properties of neutrinos, the properties of dark energy and the geometry of the Universe
- All the data and the derived products (time ordered data, maps, noise covariance matrices, likelihood codes, Markov chains) are all available on Lambda http://lambda.gsfc.nasa.gov . We are looking forward your analysis!



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