Galactic Haze Seen by *Planck*

Planck Collaboration

presented by
Krzysztof M. Górski
(JPL Caltech and Warsaw University Observatory)

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Motto

- “The lengthy and delicate task of foreground removal provides us with excellent data sets that are being used to shed new light on several hot topics in Galactic and extragalactic astronomy,” comments Jan Tauber.
  - From ESA PR materials, Feb. 13, 2012

Acknowledgements

Planck is a very complex instrument.

It is incredibly demanding in terms of effort required for properly careful work on analysis of the precious data that it acquired.

It is also a very large, complicated, and difficult to manage collaboration.

BUT

Planck is a lot of fun, and it is a privilege to be able to participate in the mission.

SO

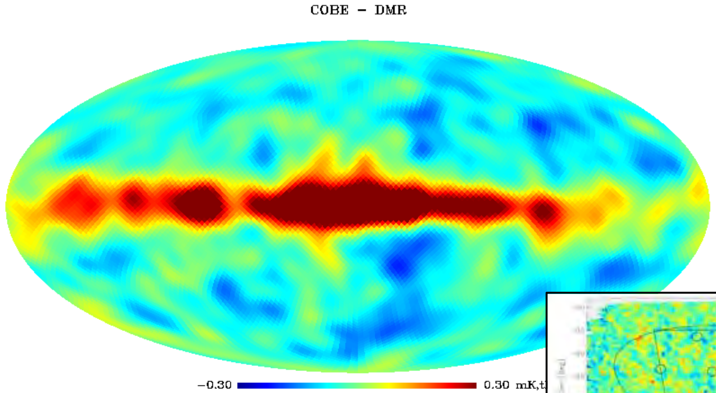
We owe enormous gratitude to those who conceived of it, made it possible, pulled through all difficulties and build it
to make it possible for the scientists to have all the fun …

Summary

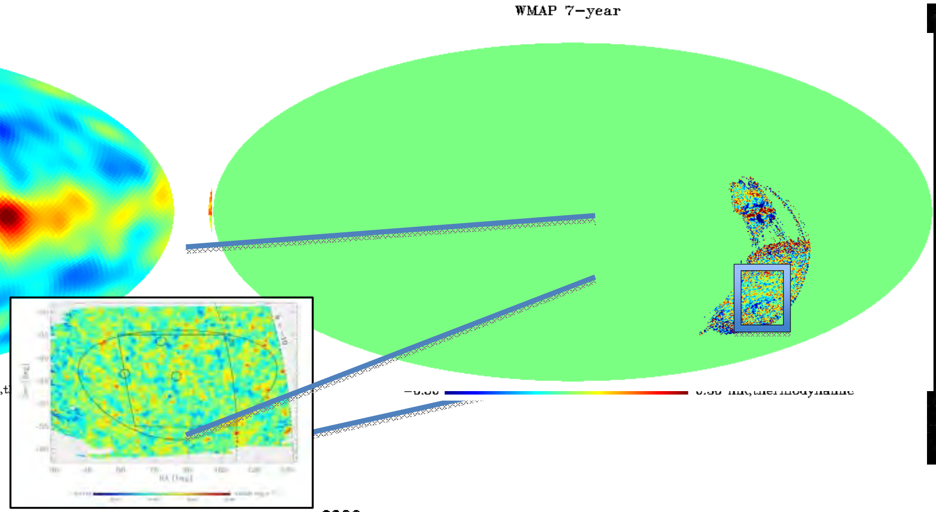
- We present the results of separation into astrophysical components of the dataset comprising:
  - Planck Nominal (15.5 months) Mission Sky Maps
  - Planck plus WMAP7
  - Auxiliary data (synchrotron, free-free, and dust emission templates)
- We use and compare two approaches:
  - Commander code/method to simultaneously estimate from the data the CMB anisotropy and foreground signals
  - The traditional approach – InternalLinearCombination-based CMB estimate
- **Results:**
  - We confirm that there exists an irreducible residual of such component separation – often referred to as the Galactic Haze
  - this Haze is concentrated around the central area of the Galaxy, <~30deg
  - Haze emission is harder than synchrotron, and softer than free-free
  - While this microwave haze appears spatially coincident with the Fermi gamma-ray bubbles in the Galaxy, its interpretation as new physical component of galactic emission remains unexplained, if heavily speculated upon …

The Cosmic Microwave Background

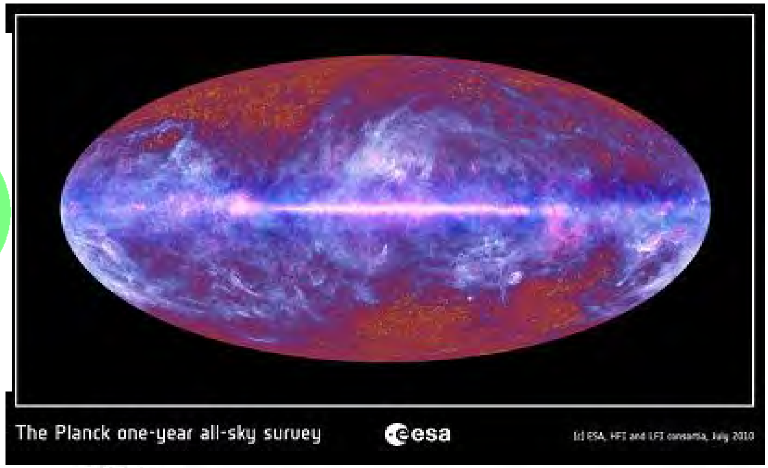
1992 - COBE

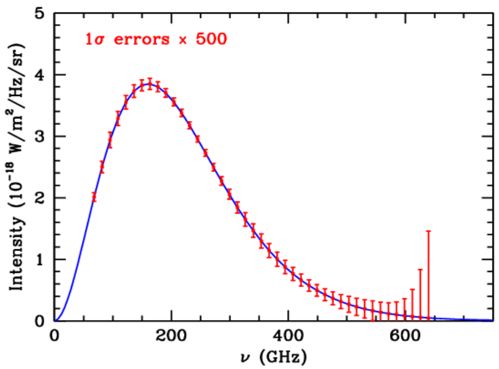


2003 - WMAP



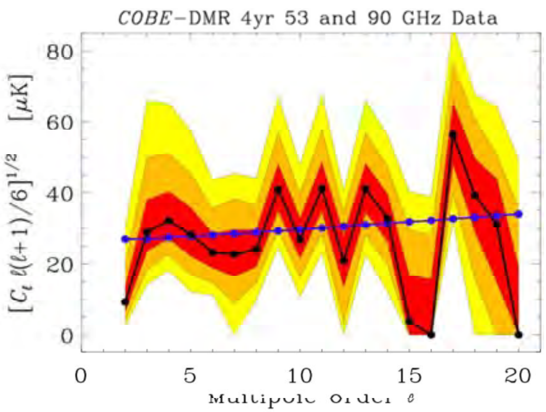
2011 - Planck

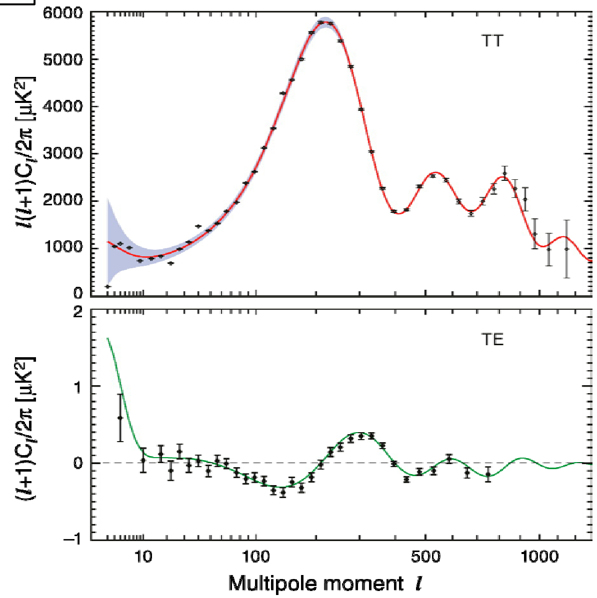




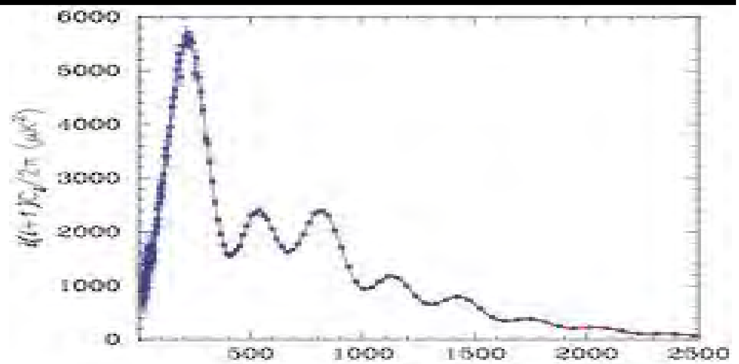
Black body spectrum
T=3K

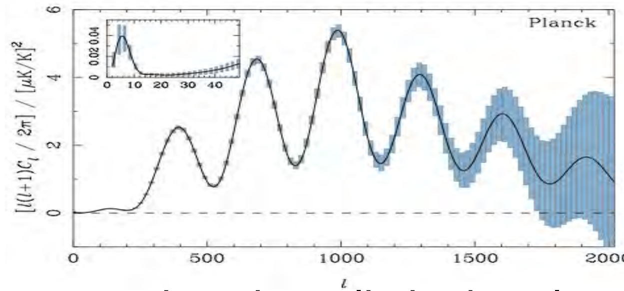
Sachs-Wolfe plateau amplitude
$\Delta T/T \approx 10^{-5}$





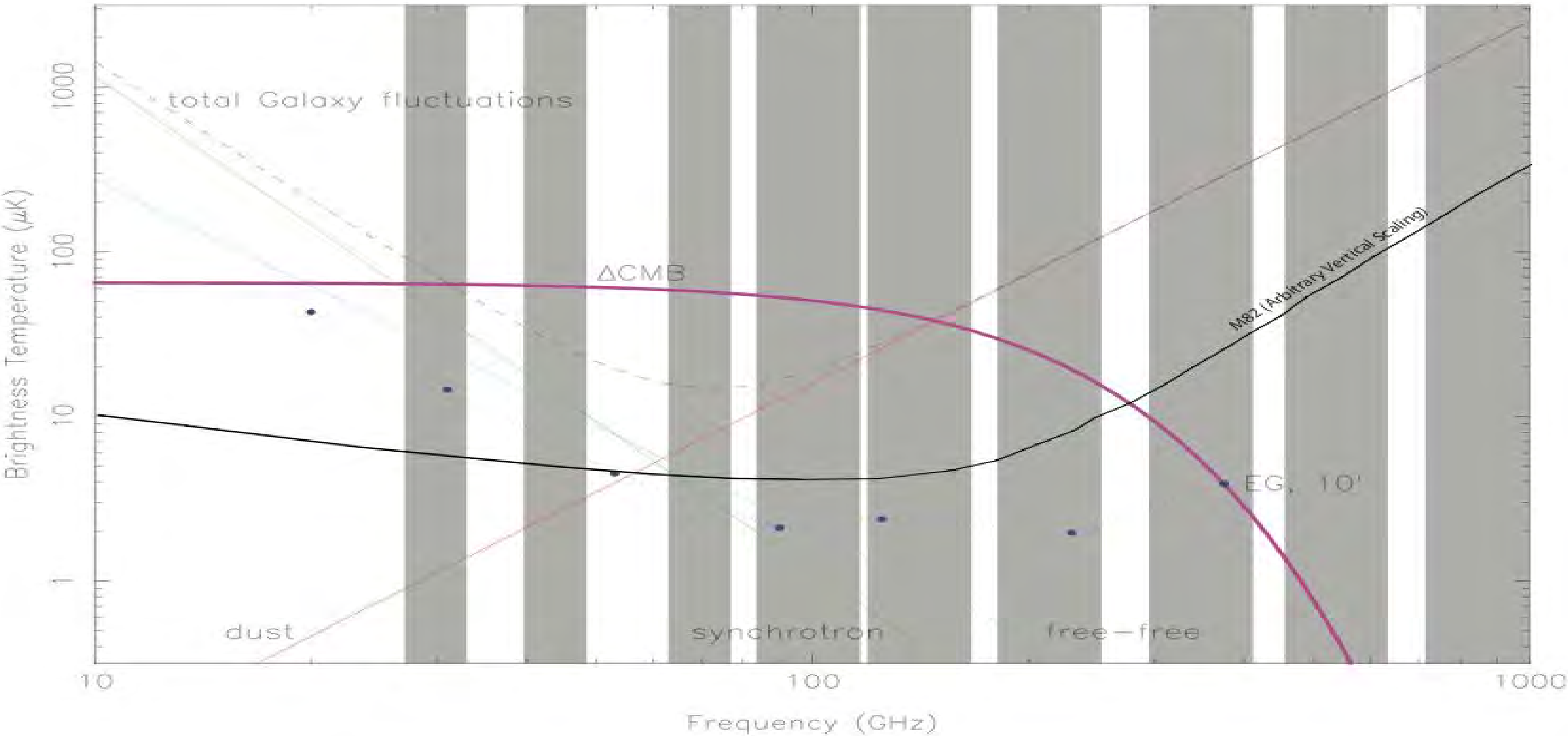
Flatness; matter content;
hint of coherent polarized signal





Cosmic variance limited; Early Universe physics; Polarization detection; reference for future surveys

Foregrounds



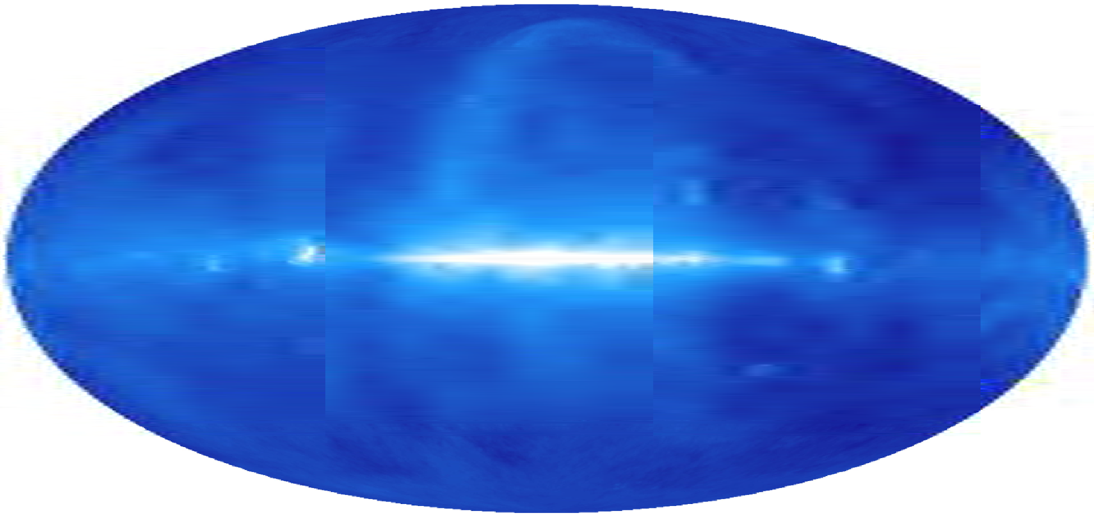
$$D(\nu) = A_d \left(\frac{\nu}{\nu_d}\right)^{\beta} \frac{B(\nu,T)}{B(\nu_d,T)}, \qquad \beta \simeq 1.6, T \simeq 18$$

$$S(\nu) = A_s \left(\frac{\nu}{\nu_s}\right)^{\alpha}, \qquad \alpha \simeq -3$$

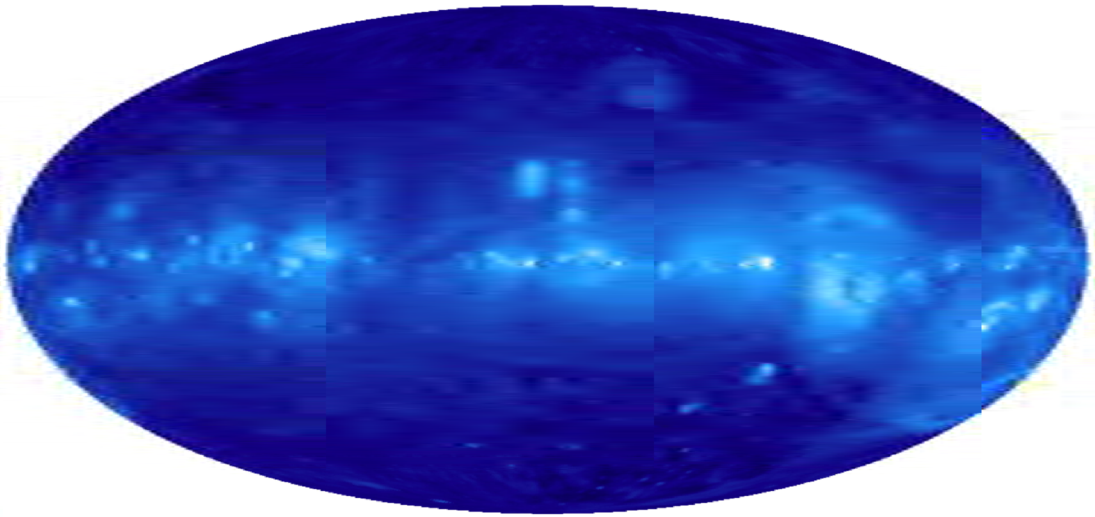
$$f(\nu) = A_f \left(\frac{\nu}{\nu_f}\right)^{\epsilon}, \qquad \epsilon \simeq -2.15$$

Classic Templates of CMB Foreground Emission

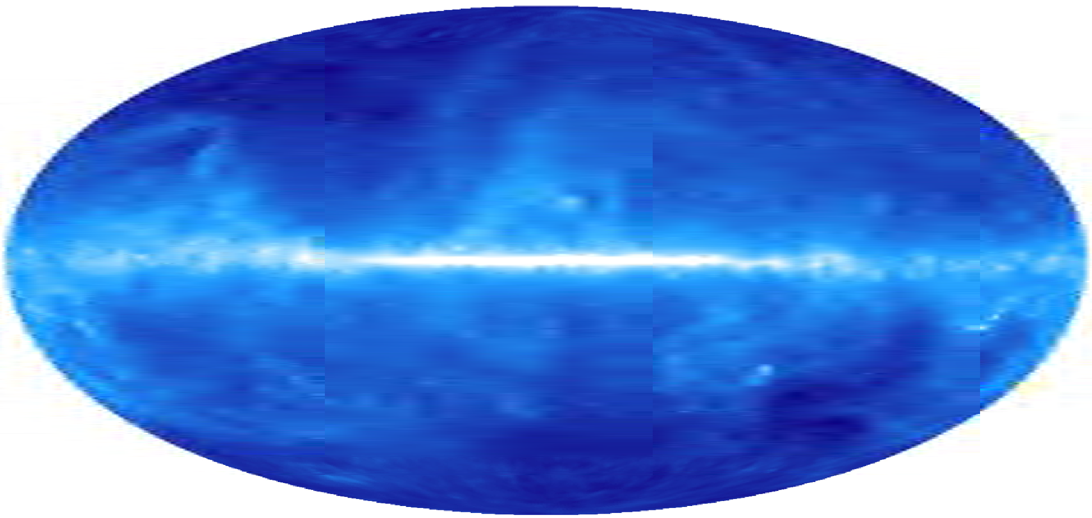
Haslam 408 ➔ Synchrotron



Hα ➔ Free-Free



IRAS/DIRBE SFD ➔ Dust Emission



History

- Bennett et al., 2003, Ap.J.Suppl., 148:97–117; “WMAP1: Foreground Emission”
- Foreground residuals
- **No Haze**

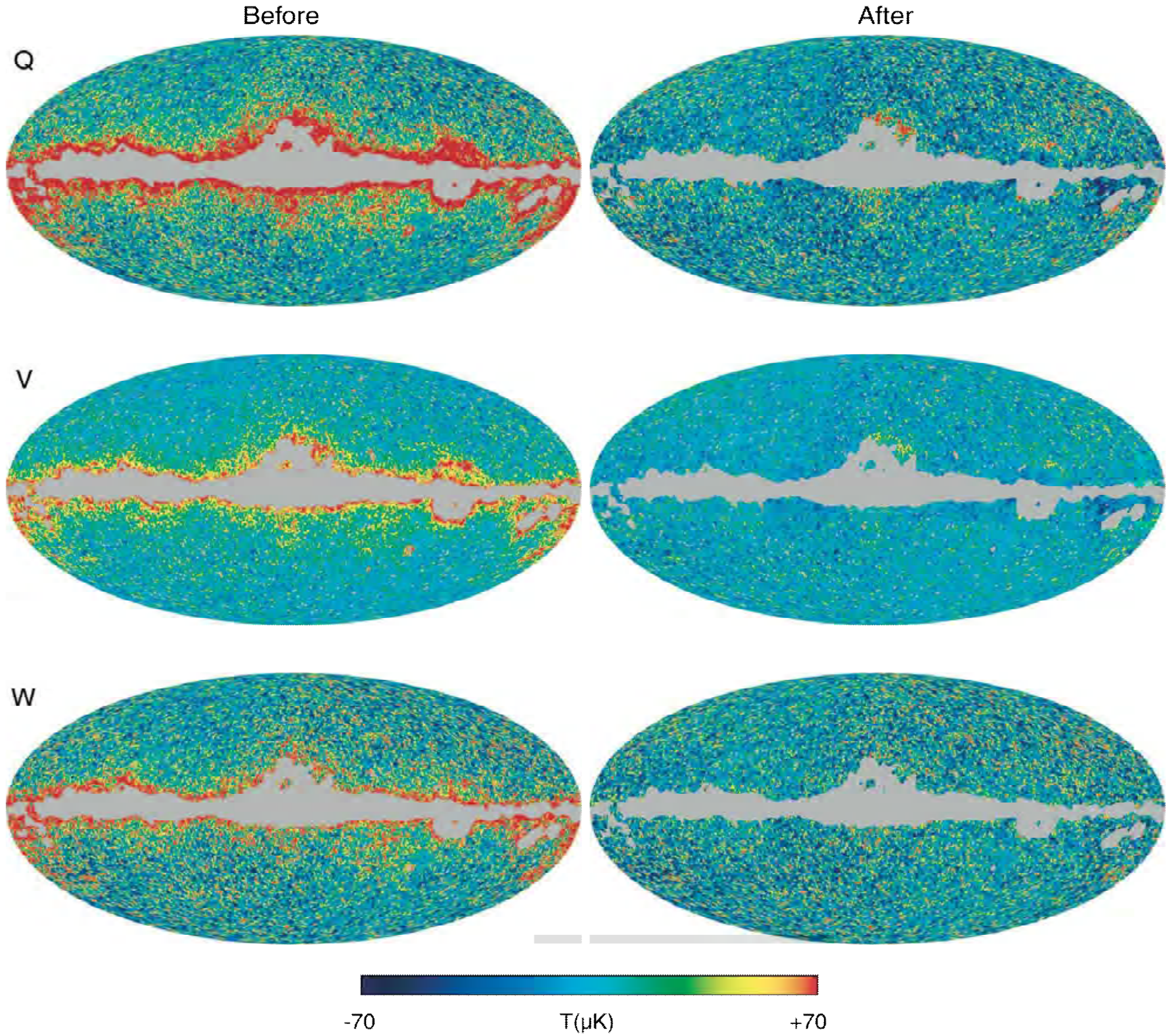


Fig. 11.—Q-, V-, and W-band maps, in CMB thermodynamic temperature, shown with the Kp2 mask applied and a CMB estimate, from Fig. 6*a*, removed. These maps are individually fitted to template maps of synchrotron, dust, and free-free emission to remove residual foreground contamination. Reduction of foreground emission after template fitting is also shown. The foreground reduction works well, despite the fact that the Haslam map is a poor tracer of synchrotron emission at microwave frequencies, because of the similarity of the thermal dust and synchrotron morphologies. The “after” template removal maps shown here represent the residual contamination present in the *WMAP* CMB cosmological analyses. Higher noise in the ecliptic plane is evident.

History

- Finkbeiner, 2004, Ap.J. 614, pp.186–193, “Microwave ISM Emission Observed by the WMAP” (astro-ph Dec. 2003)
- Foreground residuals
- **Haze !!!**

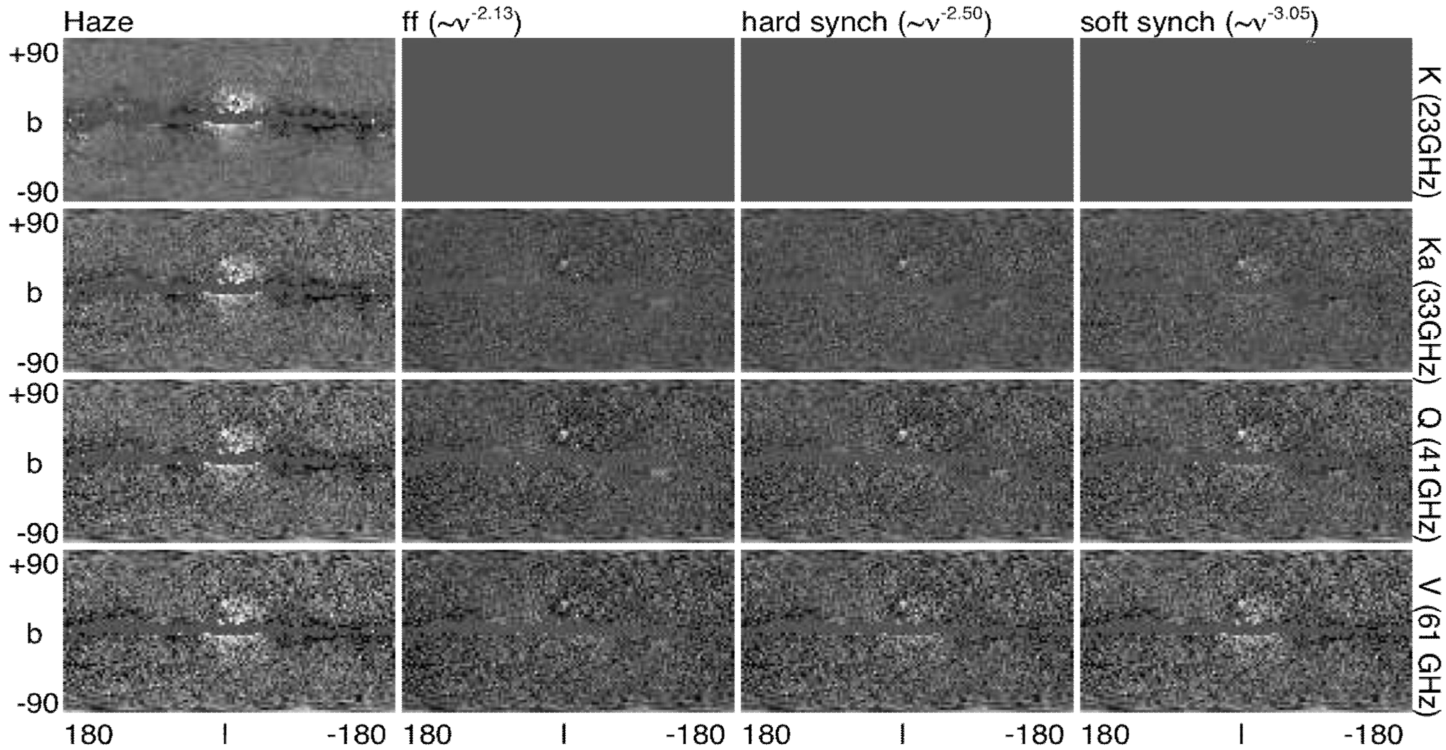


Fig. 5.— The Haze is determined in 4 WMAP bands by subtracting CMB, soft synchrotron (Haslam template), free-free (Hα template) and spinning dust. Using the K-band haze as a template, it is then subtracted from Ka, Q, and V bands assuming various power laws. A free-free spectrum fits most of the sky well, apart from the ζ Oph cloud $(l, b) = (5°, 25°)$. §3.3.

History

- Patanchon et al., 2005, MNRAS 364, pp. 1185-1194, “CMB and Foregrounds in WMAP1” (astro-ph Oct. 2004)
- Foreground residuals
- **No Haze (???), spectral mismatch ...**

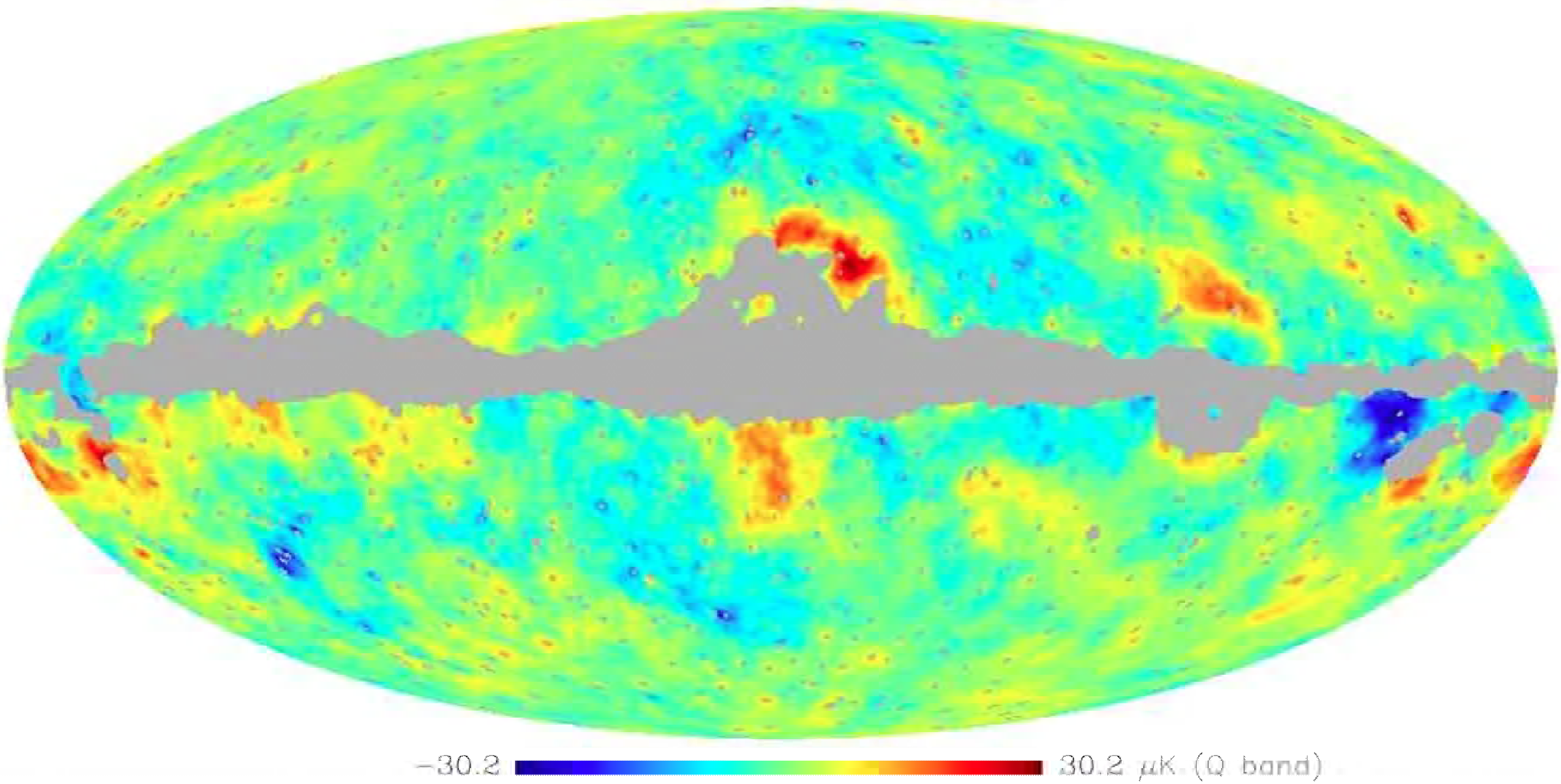


Figure 5. Map of the residual component as “seen” in the Q-band, obtained by Wiener filtering using estimated parameters.

Recent History

- Dobler, G., 2011, “A Last Look at the Microwave Haze/Bubbles with WMAP” (arXiv:1109.4418)

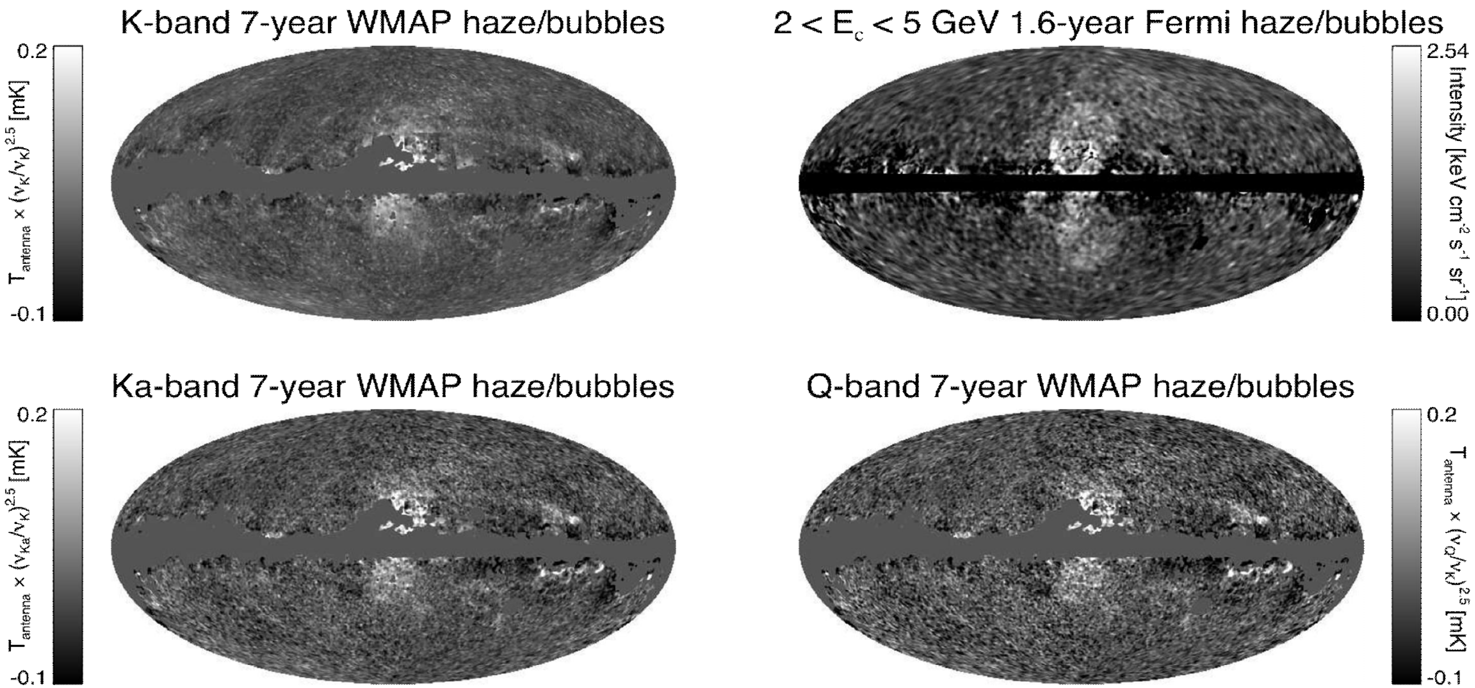


FIG. 1.— The haze/bubbles in both microwaves and gamma-rays (23 GHz, 33 GHz, 41 GHz, and 2-5 GeV, counter clockwise from top left). In the microwaves, templates have been used to regress out emission from the CMB, thermal and spinning dust, free-free, and soft synchrotron. In the gammas, the official *Fermi* diffuse model has been subtracted from the data (see Dobler et al. 2010). In all bands, the haze is seen to be elongated in latitude by a factor of roughly two reaching $\pm 50°$ in the gammas and $\sim \pm 35°$ in the microwaves. The microwaves are stretched with a $\nu^{2.5}$ scaling, which yields roughly equal brightness from K to Q band, indicating an electron spectrum of $dN/dE_e \propto E^{-2}$, broadly consistent with the gamma-ray spectrum from Dobler et al. (2010) and Su et al. (2010). The gamma-ray haze/bubbles seem to have a sharp edge near $|b| \sim 50°$ while the microwaves seem to fall off quickly for $|b| > 30°$ (particularly in the south).

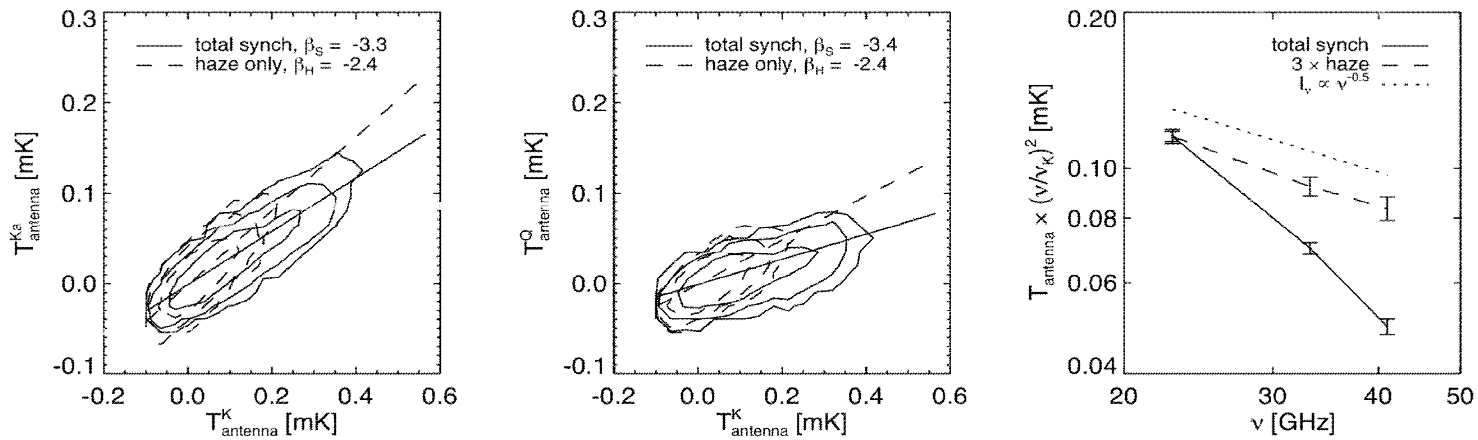


FIG. 2.— *Left* and *middle*: scatter plots (drawn with contours) for the microwave haze/bubbles residuals in Figure 1 (dashed lines) and for the total synchrotron (haze plus soft synchrotron; solid lines) in the region $|l| < 25°$, $-35° < b < -10°$. The best fit power law for this region shows that the haze emission is significantly *harder* than the soft synchrotron from 23 GHz to 41 GHz. The total emission in the region for both cases is shown in the *right* panel. The haze emission is clearly harder given the noise in the data, is consistent with a power law of roughly $\nu^{-2.5}$, and represents approximately 33% of the total synchrotron emission at K-band.

Recent History

- Pietrobon et al., 2011, arXiv:1110.5418, Haze in WMAP7

bayesian (Gibbs) WMAP+Haslam pixel based model:

. free-free component $\propto \nu^{-2.15}$

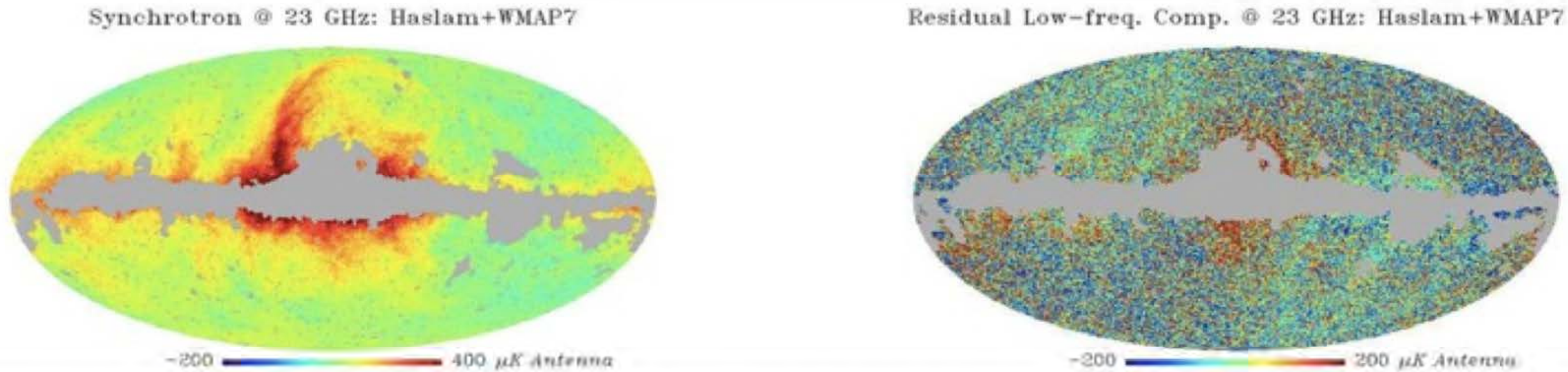
. low frequency soft synchrotron component $\propto \nu^{-3.0}$

. low frequency power law $\propto \nu^{\beta}$

. empirical thermal plus spinning dust spectrum

. C_l sampled CMB

Pietrobon et al. (2011)



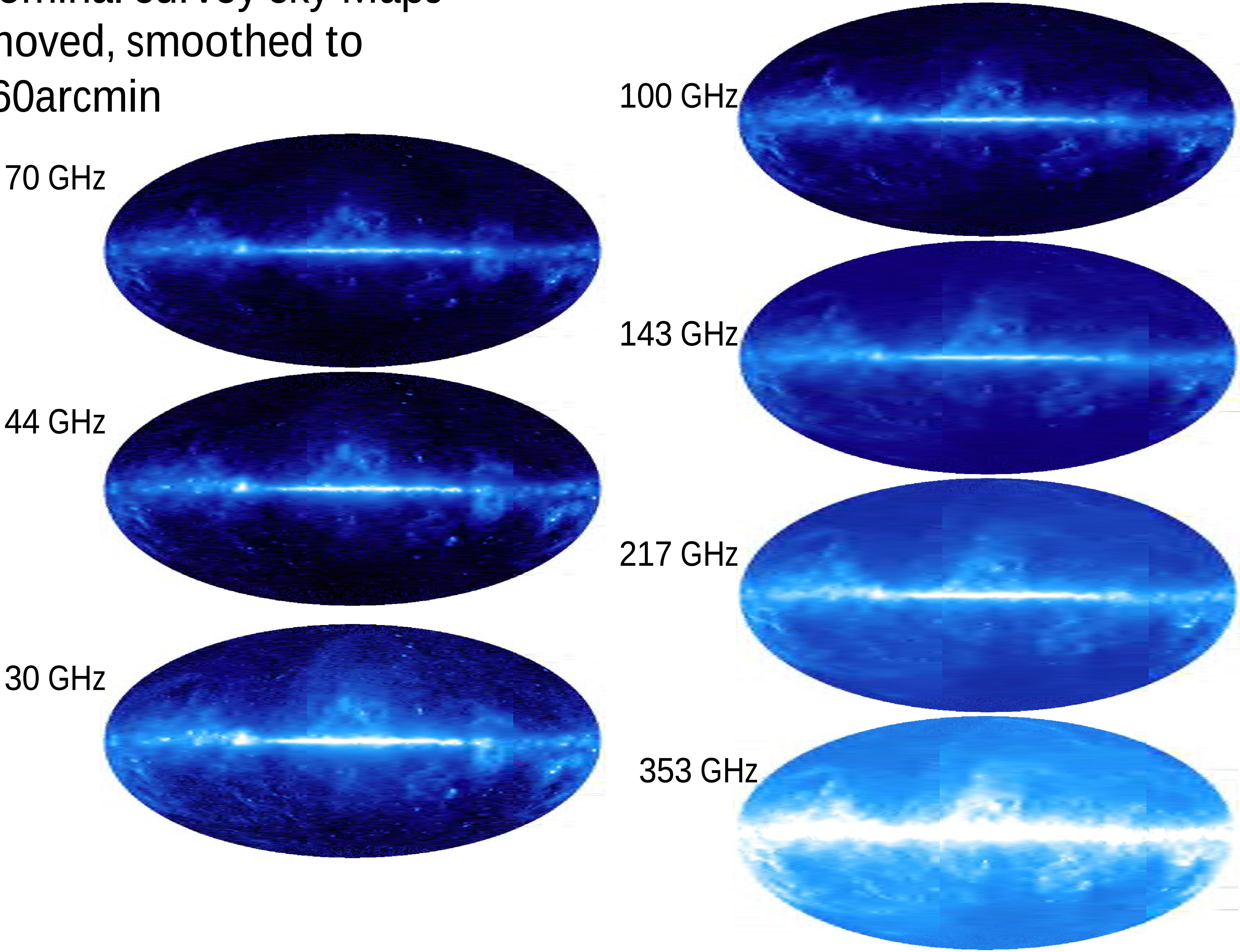
soft synchrotron component is highly correlated with Haslam: i.e., synchrotron index is ~*-3.0* everywhere except the haze region => **separate component**

Explanations? Models?

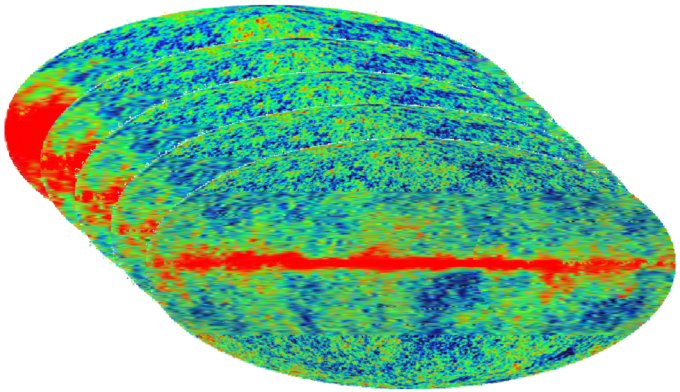
See discussion in Dobler (2011) arXiv:1109.4418
of pros and cons of all of the following proposals:

- Galactic Wind
- Starbursts/SNe
- Second Order Fermi Acceleration
- AGN
- Dark Matter Annihilation

Planck Nominal Survey Sky Maps
CMB-removed, smoothed to FWHM=60arcmin

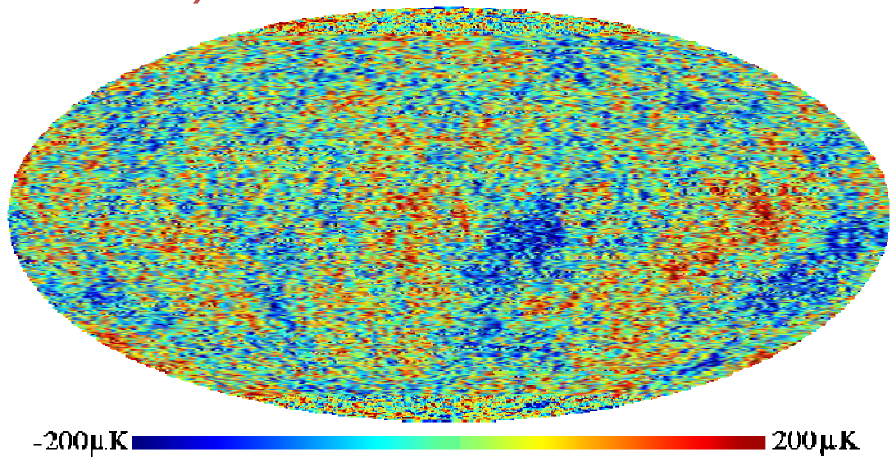


Science Extraction from the Multi-frequency CMB Sky Maps (in a Nutshell)



Frequency maps

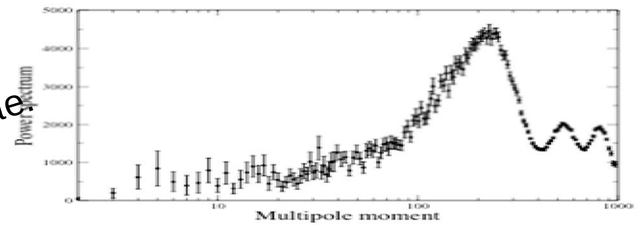
Template fitting,
Gibbs/Commander,
or else …
BYPRODUCT –
Frequency Foreground
Maps



Cleaned CMB map

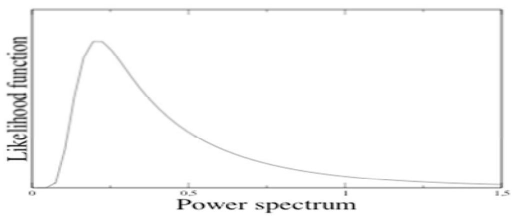
... or directly from sky maps to the likelihood by brute force or Gibbs

Pseudo-C_l estimators



Power spectrum

Fitting formulae



Likelihood

MCMC

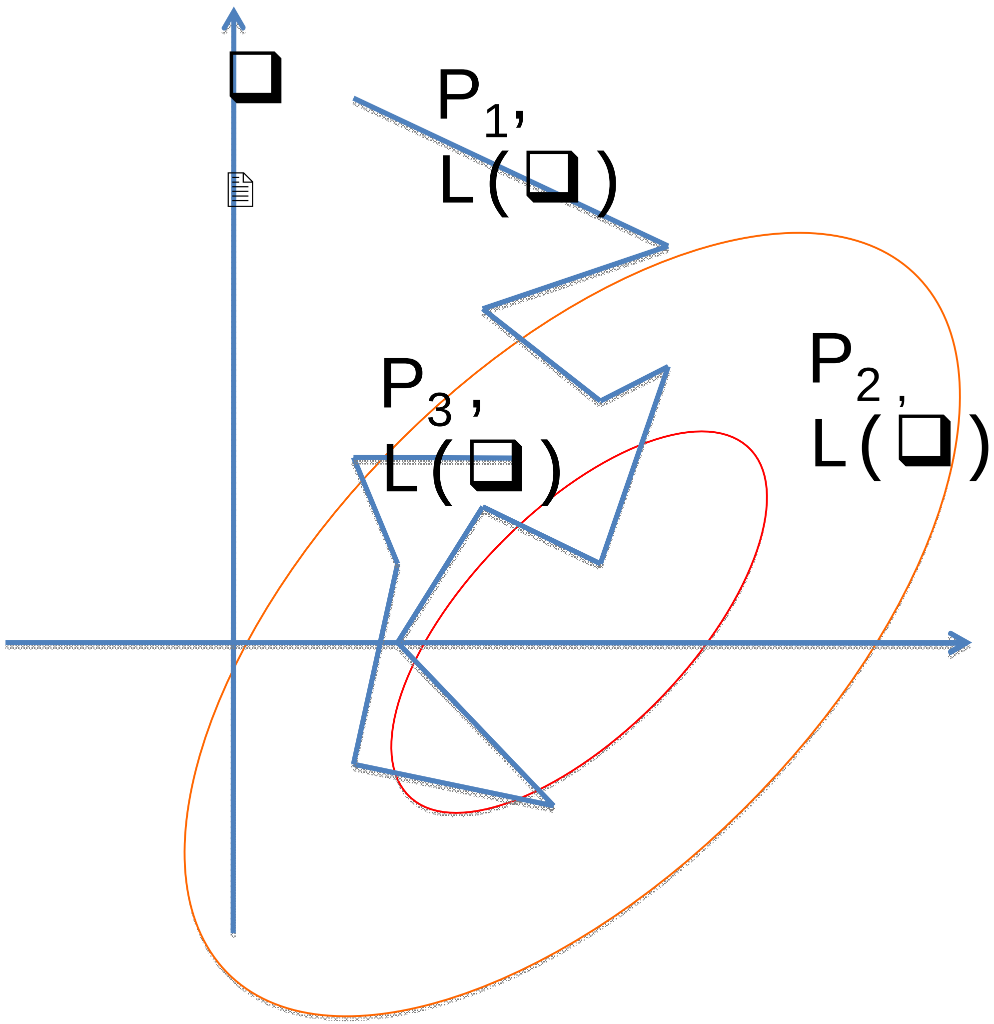
n_s Ω_b σ_8 Ω_0 h τ

Cosmological parameters

Commander

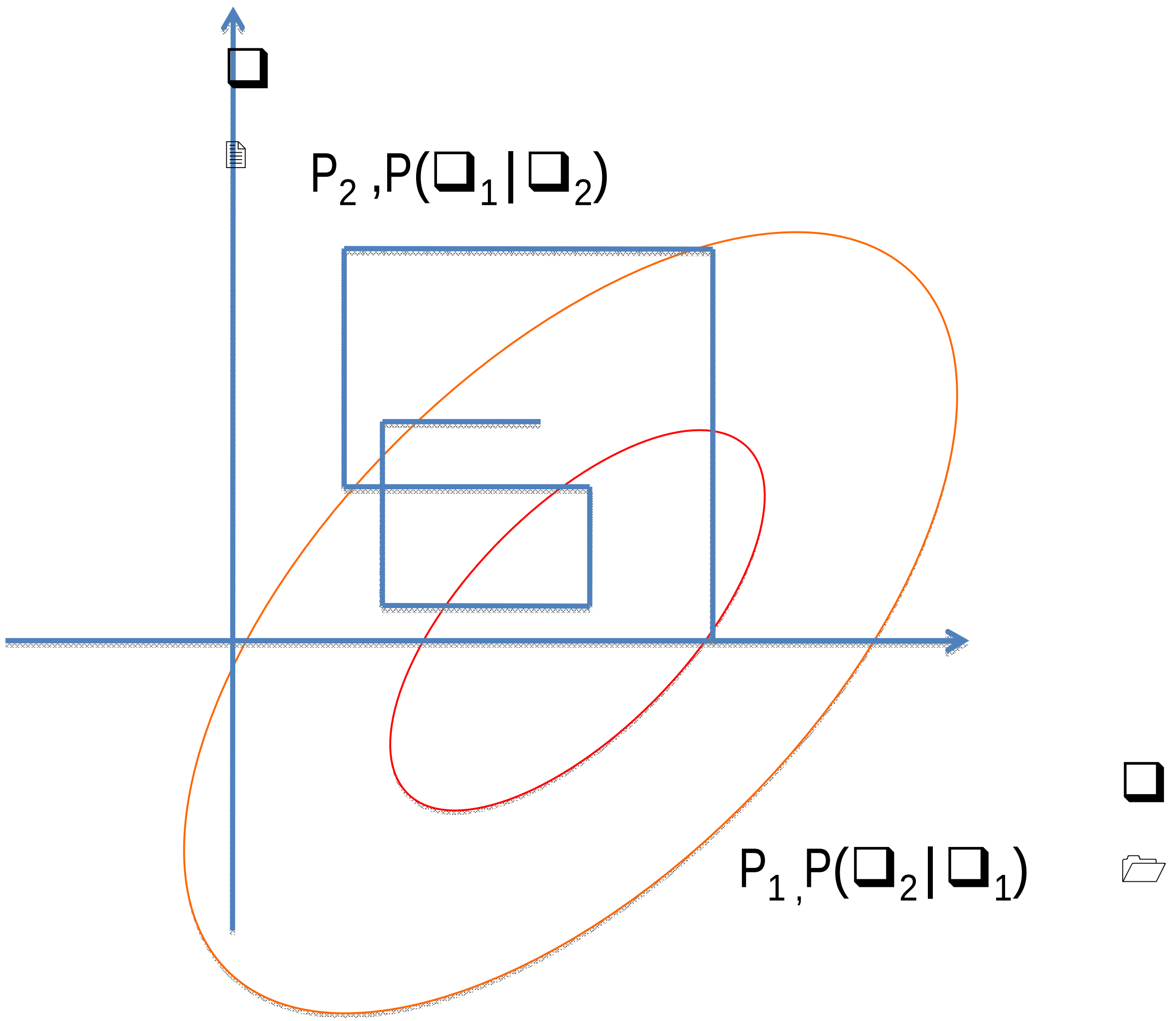
- Gibbs Sampler developed by J. Jewell, H. K. Eriksen, et al. @ JPL, and B. Wandelt, e.g.
  - Astrophys.J. 609 (2004) 1-14 - **arXiv:astro-ph/0209560;**
  - Phys.Rev. D70 (2004) 083511 - **arXiv:astro-ph/0310080;**
  - Astrophys.J.660:L81-L84,2007 - **arXiv:astro-ph/0701089;**
- CMB map, angular power spectrum;
- Foreground parameters;
- Posterior distribution: peak, mean, variance, skewness, kurtosis;
- ♍🖹 as a measure of the goodness of the model;
- Method very well suited for relatively low resolution applications (due to memory and CPU time requirements) [but, Ruler extension of Commander allows us to pursue high resolution component separation work autonomously, as in e.g. CO full sky maps extraction from Planck data]

MCMC: Metropolis-Hastings



- Huge multi-dimension parameter space to sample, grid not feasible;
- Random choice of a configuration ❑$_i$;
- Evaluation of the likelihood L(❑$_i$);
- Draw new configuration, ❑$_{i+1}$;
- Evaluation of the likelihood L(❑$_{i+1}$);
- Accept/reject the new point;

MCMC: Gibbs Sampling



- No accept/reject algorithm: every step is taken

- Sampling from the conditional distribution P(❑$_a$|❑$_b$)

$$\theta_1 \rightarrow \mathrm{CMB}$$

$$\theta_2 \rightarrow \mathcal{C}_\ell$$

Foreground model

$$
\begin{aligned}
S_\nu(\hat{\gamma}) &= M_\nu + D_\nu(\mathbf{v}_0) + C(\hat{\gamma}) + \\
&+ A^{\rm ff} H_\alpha(\hat{\gamma}) \left(\frac{\nu}{\nu_0}\right)^{-2.15} + \\
&+ A^{\rm sync}_{\mu_0}(\hat{\gamma}) \left(\frac{\nu}{\mu_0}\right)^{(\beta_{\mu_0}(\hat{\gamma}) + c_{\mu_0}(\hat{\gamma}) * \log(\nu/\mu_0))} + \\
&+ A^{\rm dust}_{\lambda_0}(\hat{\gamma}) \left(\frac{\nu}{\lambda_0}\right)^{\epsilon_{\lambda_0}(\hat{\gamma})} \left(\frac{BB(\nu, T_{\lambda_0}(\hat{\gamma}))}{BB(\lambda_0, T_{\lambda_0})}\right) + \\
&+ A^{\rm CO}_{\eta_0}(\hat{\gamma}) F(\nu)
\end{aligned}
$$

- Monopole and dipole at every frequency;
- Free-free: overall amplitude;
- Synchrotron: amplitude, spectral index and curvature per pixel;
- Dust: amplitude, emissivity and temperature per pixel;
- CO: amplitude per pixel at 100 GHz;

- Band passes included through effective frequencies (Sergi Hildebrandt).
- CO-2: ratio 217/100= 0.6, and 353/100=0.2

Input Data Processing for Commander Application

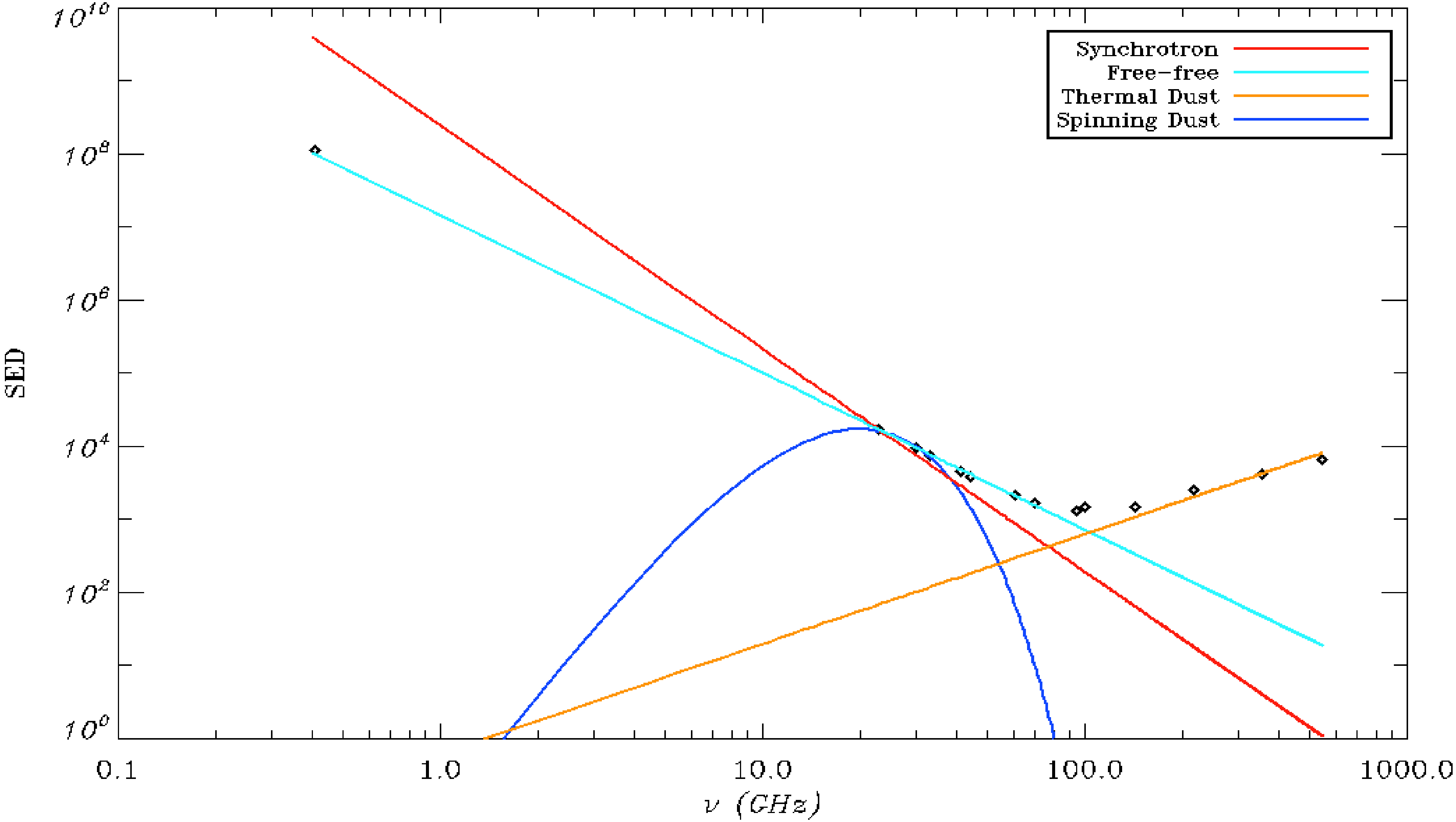
- Smoothing to FWHM=60 arcmin applied to sky maps
- HEALPix-formatted Maps Downgraded to N_{side} = 128
- White (but spatially modulated) noise derived from MC
- Commander C_l sampling on
- Residual map monopoles and dipoles fitted

- All that thrown at various versions of the parametric foreground model (per pixel), e.g.:

$$T_\nu(\hat{\gamma}) = B_\nu s(\hat{\gamma}) + N_\nu(\gamma) + M + D(\hat{\gamma}_0 \cdot \hat{\gamma}) +$$

$$A_d(\hat{\gamma}) \left(\frac{\nu}{\nu_d}\right)^{\beta(\hat{\gamma})} \frac{B(\nu, T(\hat{\gamma}))}{B(\nu_d, T(\hat{\gamma}))} + A_s(\hat{\gamma}) \left(\frac{\nu}{\nu_s}\right)^{\alpha(\hat{\gamma})} + A_f(\hat{\gamma}) \left(\frac{\nu}{\nu_f}\right)^{\epsilon}$$

Phenomenological Spinning Dust Model



$$F(\nu) \propto exp(-(\nu - \nu_0)^2/b^2)$$

Two Commander Fits for Haze

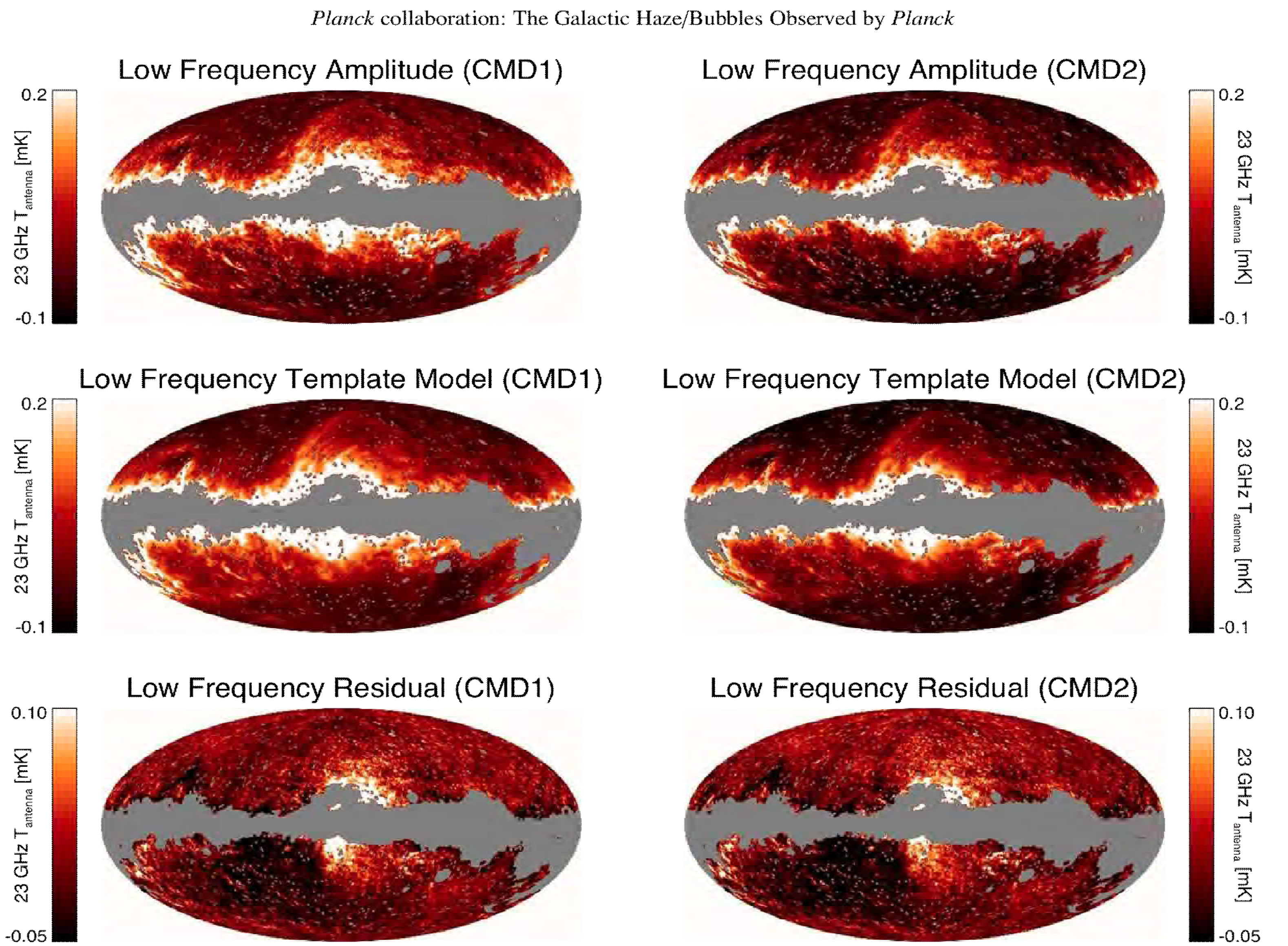


Fig. 4. *Left column:* the low frequency component shown in Figure 3 (*top*), a four component template model of this component (*middle*, see Table 1), and the haze/bubbles residual (*bottom*). The residuals are remarkably small outside the haze region indicating that the templates are a reasonable morphological representation of the different components captured by the `Commander` solution. A visual comparison of the haze bubbles in this case shows that it is strikingly similar to the template-only approach in Figure 2 *Right column:* the same but for our CMD2 model (see text) which includes the *Planck* 545 GHz channel in the fit and utilizes a slightly more sophisticated thermal dust model. Given that we are concentrating on low frequencies, the affect on the results is minimal.

Template Regressions of Three Commander Fits for Haze

Fit type	Data sets	Fit coefficient		
		H_α [mK/R]	FDS [mK/mK]	Haslam [mK/K]
CMD1	*Planck* 30-353 GHz	$9.8 \times 10^{-3} \pm 1.6 \times 10^{-5}$	$5.9 \pm 3.4 \times 10^{-3}$	$4.3 \times 10^{-6} \pm 3.5 \times 10^{-9}$
CMD2	*Planck* 30-545 GHz	$8.5 \times 10^{-3} \pm 1.7 \times 10^{-5}$	$5.1 \pm 3.7 \times 10^{-3}$	$4.1 \times 10^{-6} \pm 3.9 \times 10^{-9}$
CMD3	*Planck* 30-353 GHz, WMAP, Haslam	$3.4 \times 10^{-3} \pm 8.8 \times 10^{-6}$	$1.5 \pm 1.9 \times 10^{-3}$	$1.3 \times 10^{-8} \pm 2.0 \times 10^{-9}$

Table 1. Regression coefficients of the `Commander` foreground amplitude maps.

Full Sky Template Fits for Haze

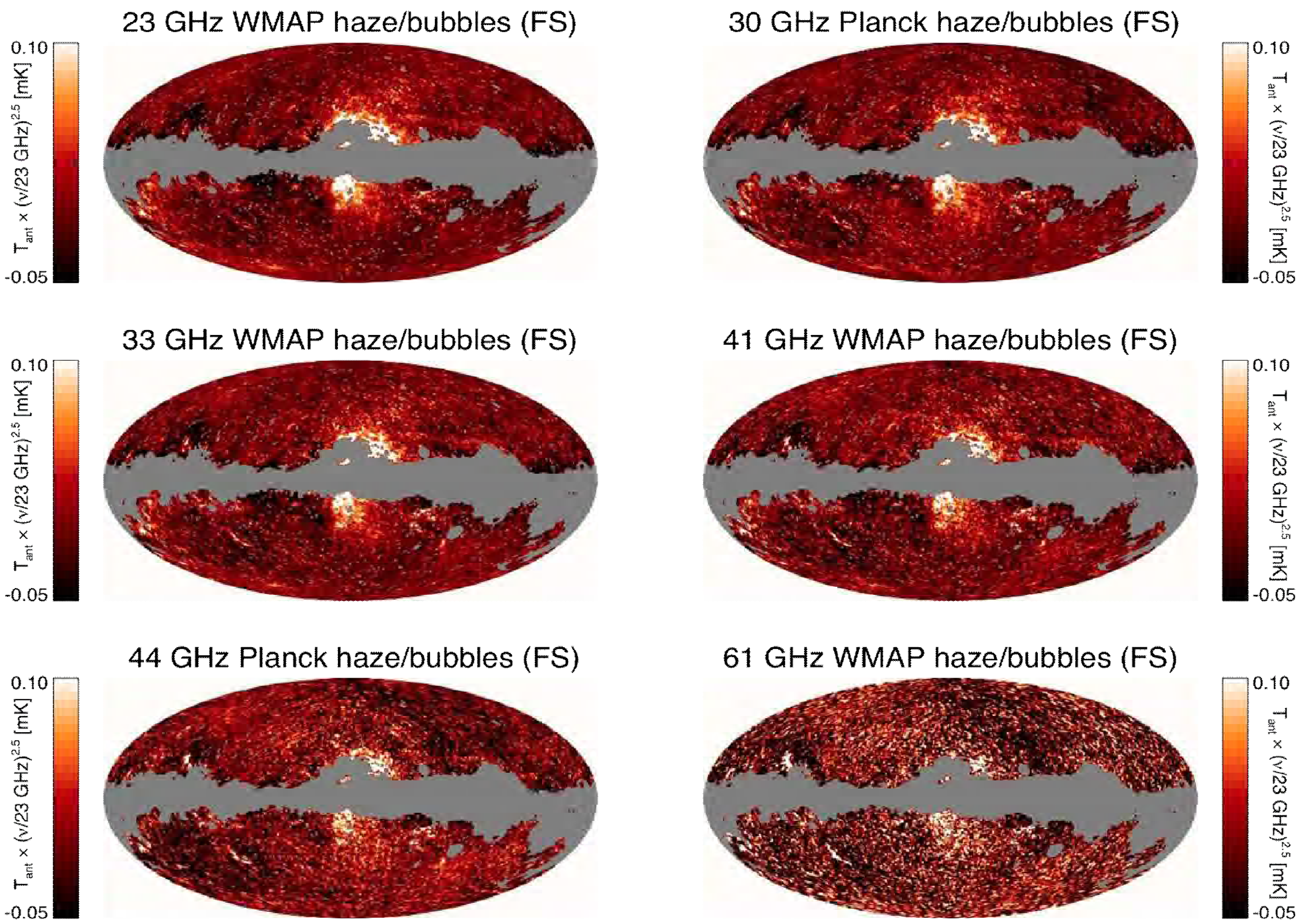
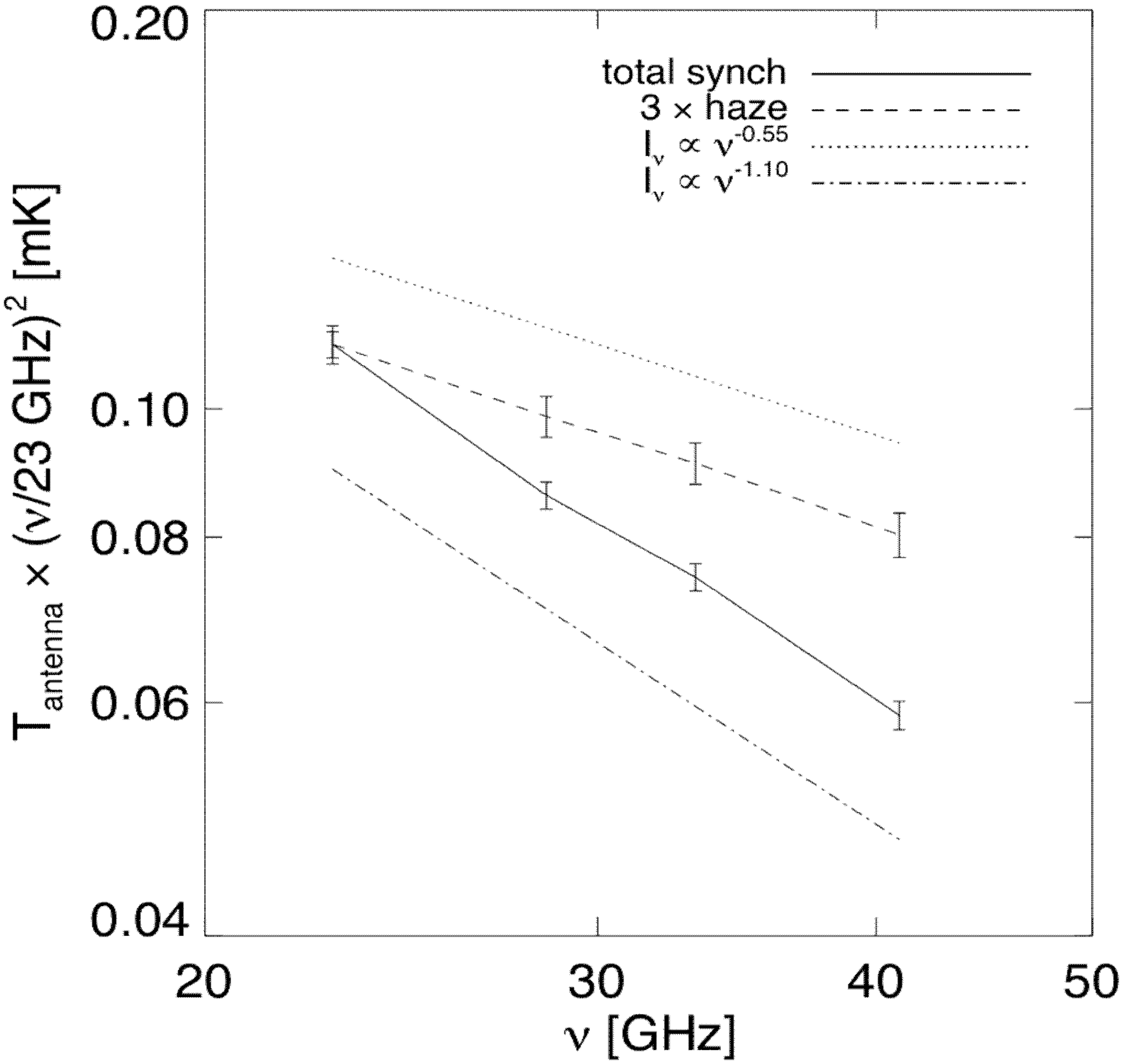
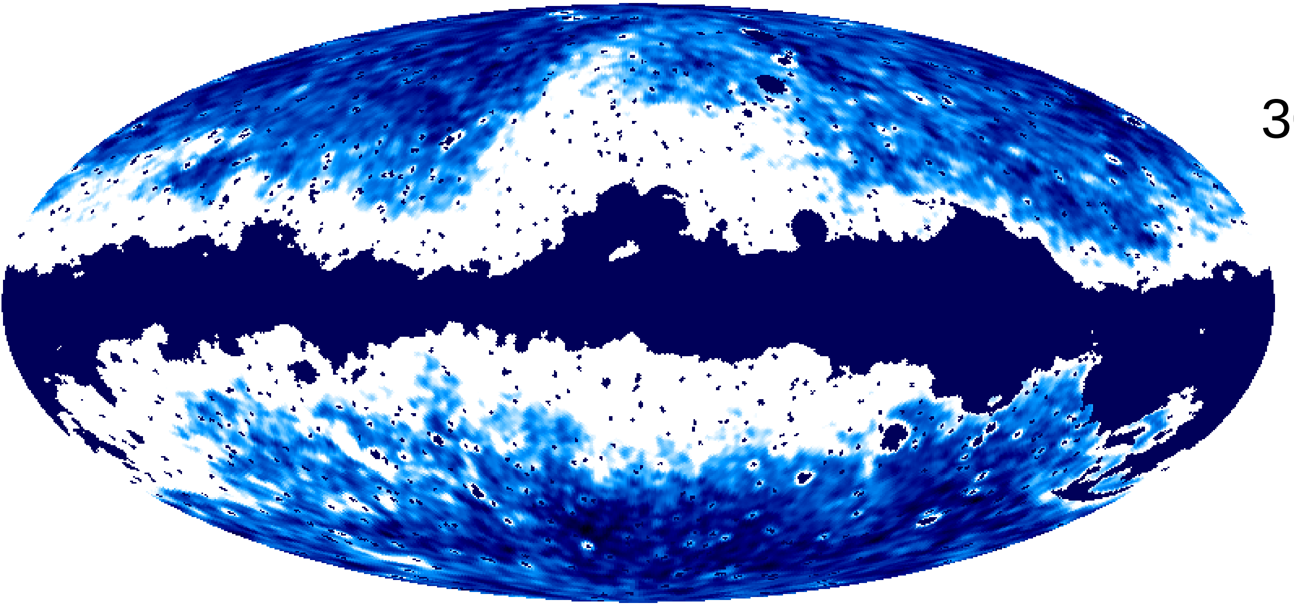


Fig. 5. The microwave haze/bubbles at both WMAP and *Planck* wavelengths using a full sky template fit to the data. The morphology of the haze is remarkably consistent from band to band and between data sets implying that the spectrum of the haze does not vary significantly with position. Furthermore, the $\nu^{2.5}$ scaling again yields roughly equal brightness residuals indicating that the haze spectrum is roughly $T_\nu \propto \nu^{-2.5}$ through both the *Planck* and WMAP channels. In addition, while striping is minimally important at low frequencies, above 41 GHz, striping dominates over the haze emission.

Spectrum Of the Haze Residual



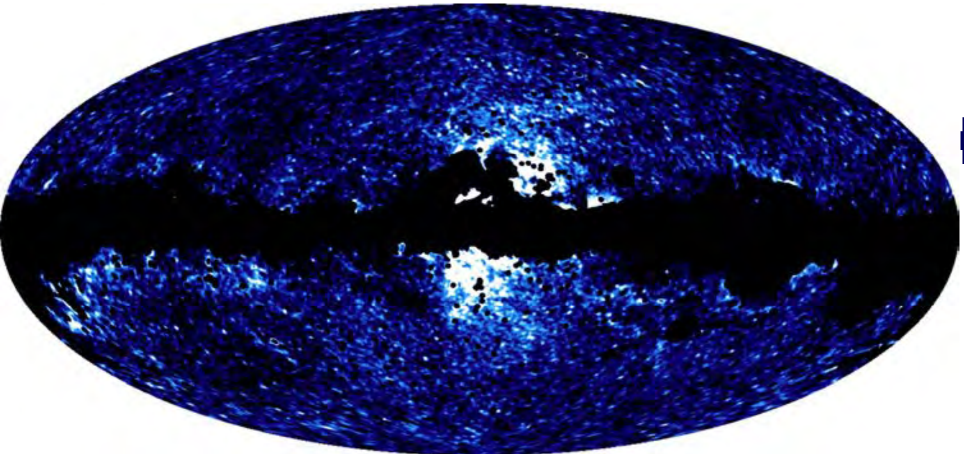
Comparison of the 30 GHz Foreground Emission with the Haze Residual Remaining after Regression of the Classical Foreground Templates

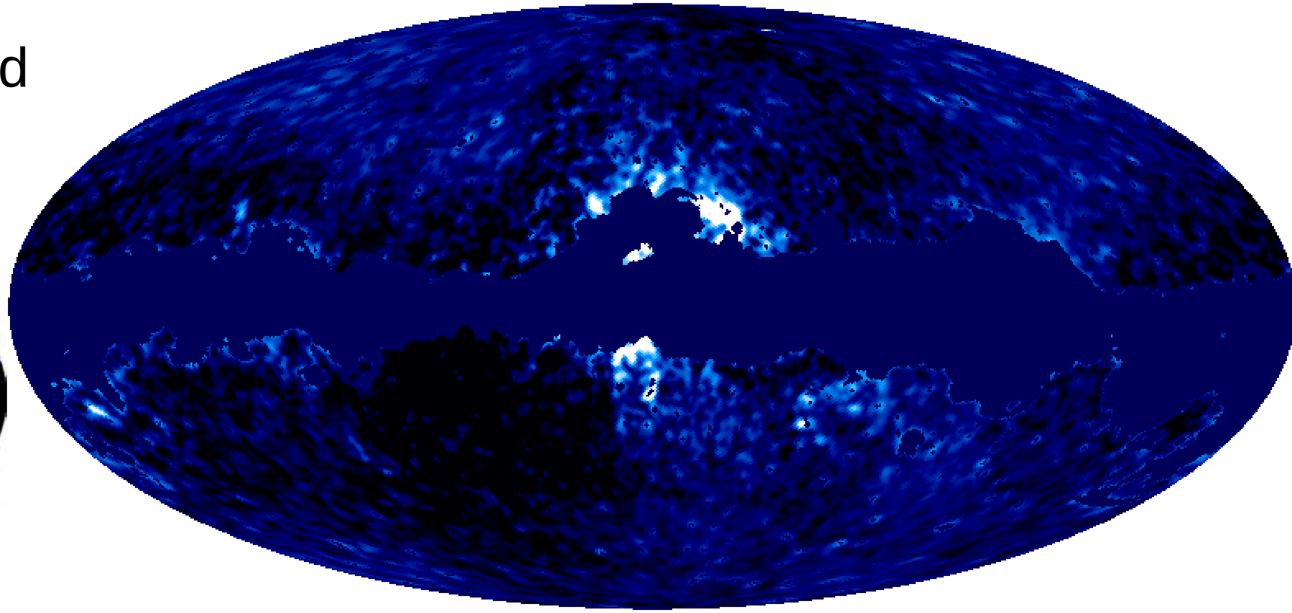


30 GHz foreground emission

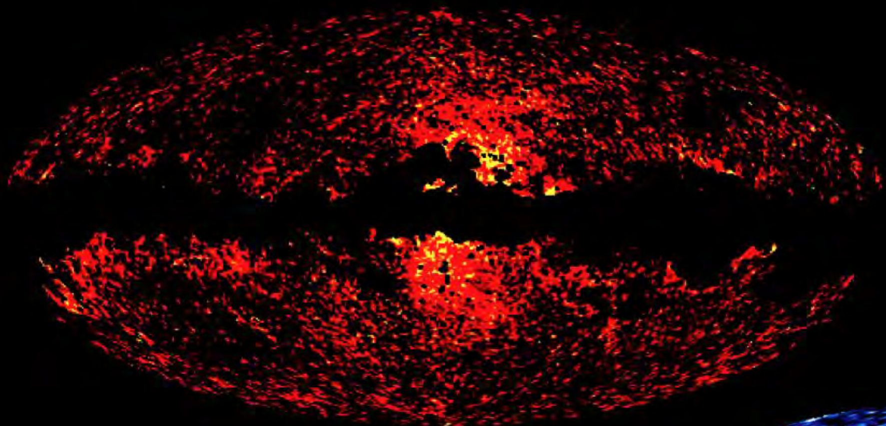
Haze residual at 30 GHz

Temperature scale capped
at 75 muK_CMB

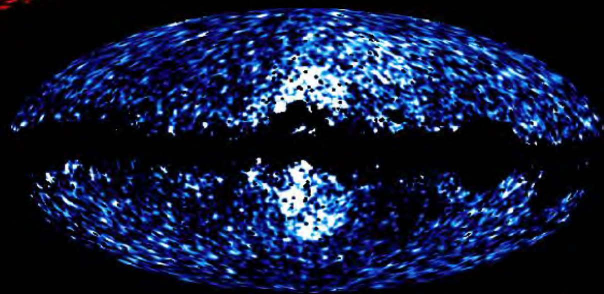




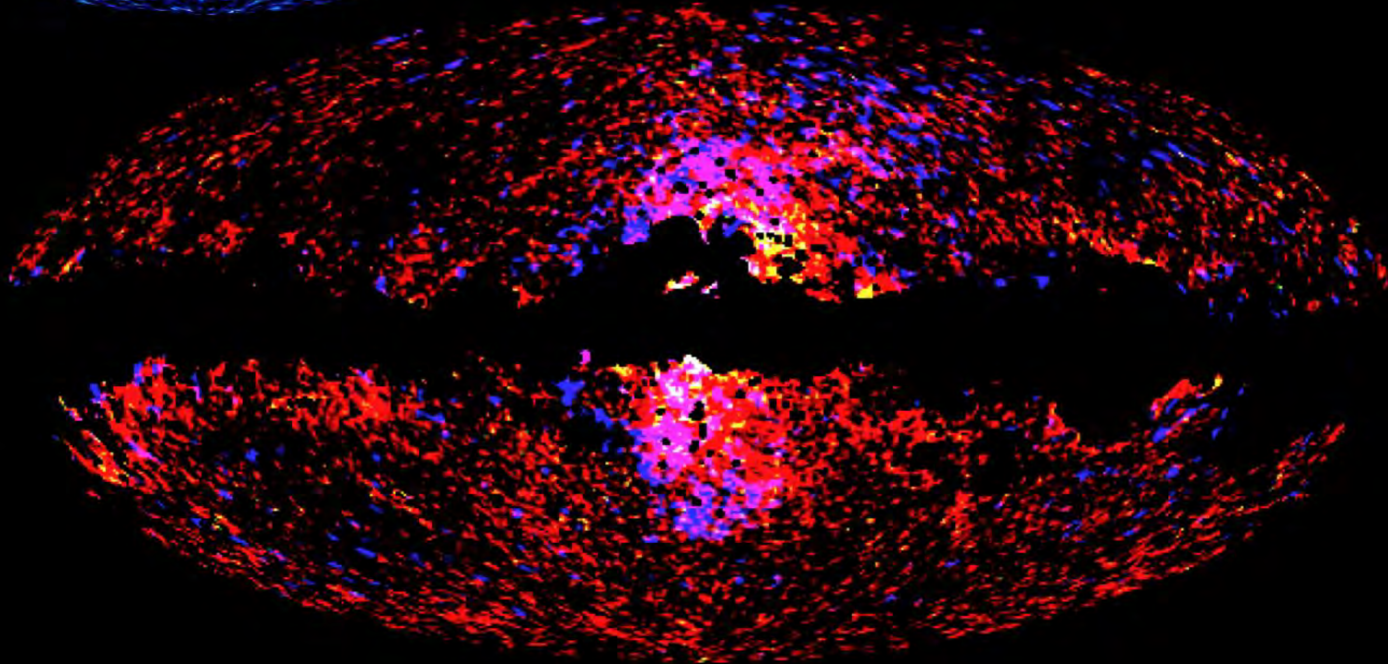
PLANCK images a giant eruption from the heart of the Milky Way



The Galactic haze/bubbles is shown here in *PLANCK* data from *30-44* GHz



The same structure at 2-*5* GeV as seen by the *Fermi Gamma-Ray Space Telescope*



A multi-wavelength composite image showing both microwaves and gamma-rays: *PLANCK 30* GHz (red), *44* GHz (green), and *Fermi 2-5* GeV (blue).

Conclusions

- “Interestingly, we detect residual diffuse emission in the surroundings of the Galactic Centre even after having removed all the 'expected' contributions due to synchrotron and free-free radiation, thermal dust, and spinning dust,”
- “To take advantage of both the excellent quality and complexity of Planck measurements, new foreground separation methods were developed by the members of Planck Collaboration,”
- “Thanks to Planck's high frequency measurements we can better characterise thermal dust emission, and this, combined with refined data-analysis tools, means that the detection of the Galactic Haze is now unambiguous,” adds Davide Pietrobon
- “Synchrotron emission associated with the Galactic Haze, however, exhibits distinctly different characteristics from the synchrotron emission seen elsewhere in the Milky Way, and we're trying to understand why,”
- The Galactic Haze has a 'harder' spectrum, meaning that its emission does not decline as rapidly with increasing frequency. Several explanations have been proposed for this unusual behaviour, including enhanced supernova rates, galactic winds and even annihilation of dark-matter particles. Thus far, none of them have been confirmed and the issue remains open.

The scientific results that we present today are the product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA) and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.