

COSMIC RAYS NEAR
AND FAR
...LINKS WITH
THE WMAP HAZE

Greg Dobler

Harvard / CfA

May 6th, 2009 - IAP

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Doug Finkbeiner (CfA)

Dan Hooper (FNAL)

Gabrijela Zaharijas (ANL)

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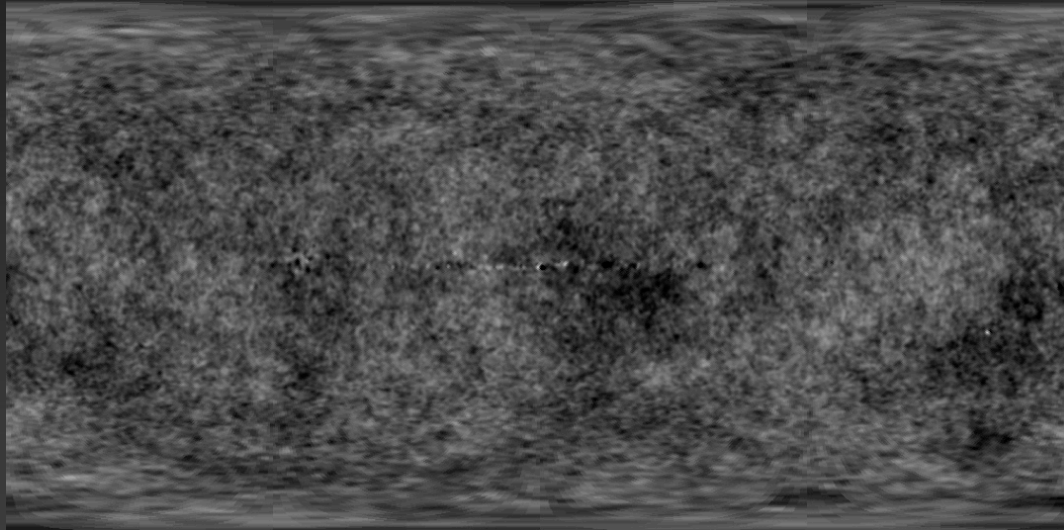
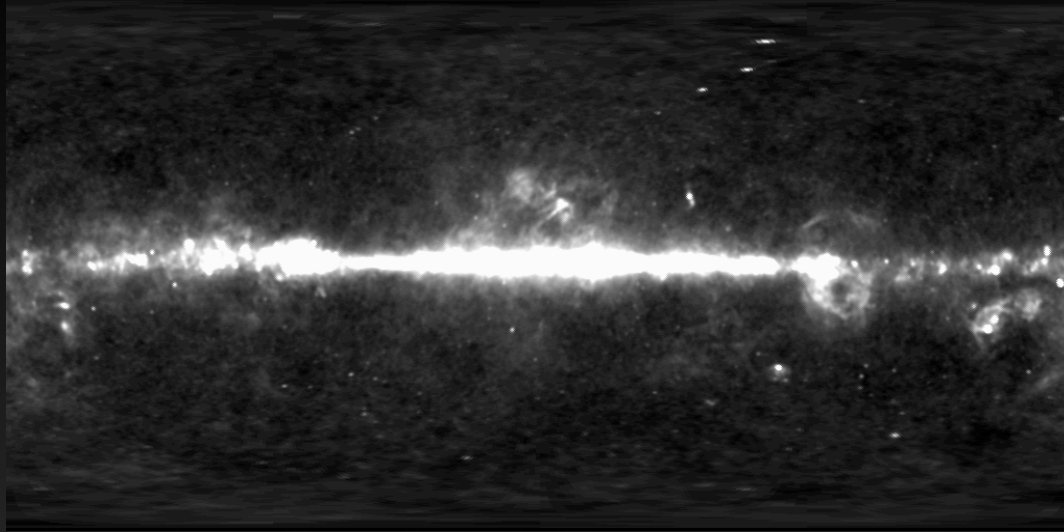
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Neal Weiner (NYU)

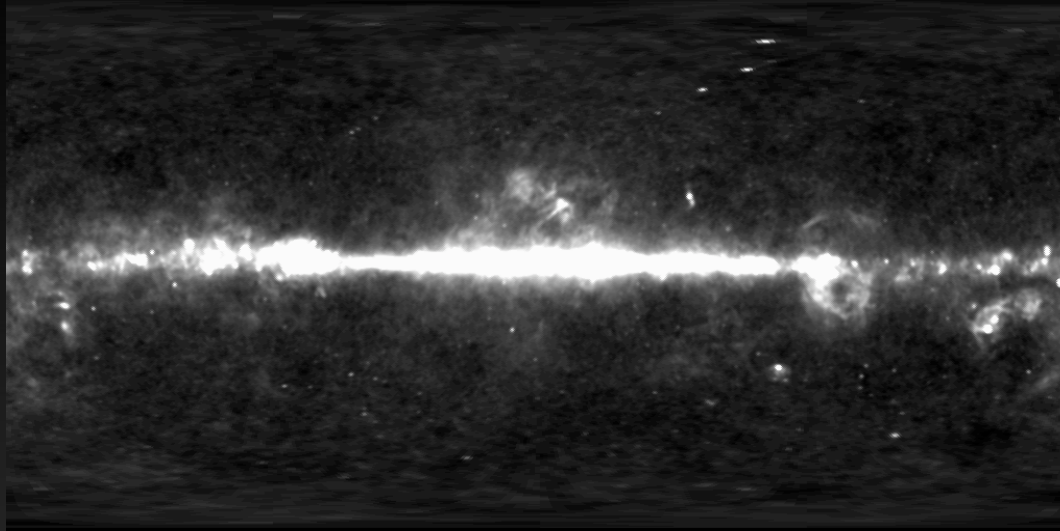
Ilias Cholis (NYU)

Lisa Goodenough (NYU)

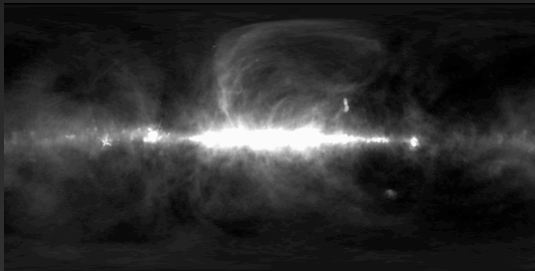
WMAP



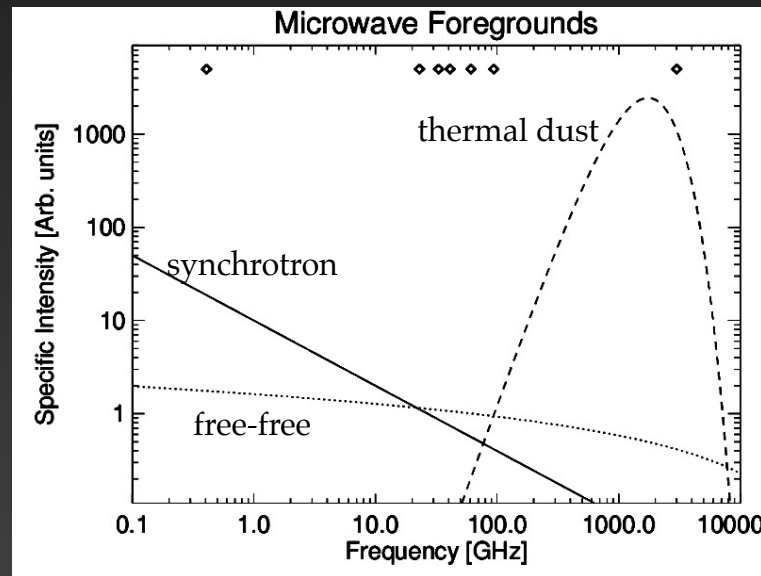
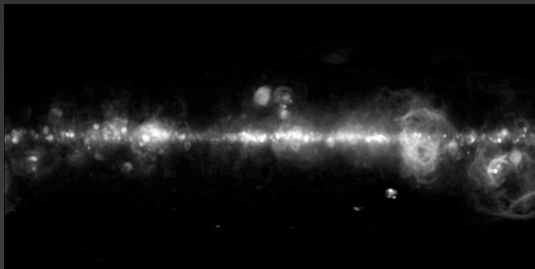
WMAP



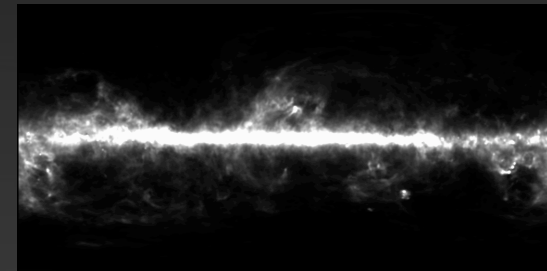
Haslam et al. (1982)



$H\alpha$ (*Finkbeiner, 2003*)



Finkbeiner et al. (1999)



template fitting

$$S_{23} \times \text{[Image 1]} + f_{23} \times \text{[Image 2]} + d_{23} \times \text{[Image 3]} = \text{[Image 4]} - c_{23} \times \text{[Image 5]}$$

The diagram illustrates the template fitting process for a 23 GHz observation. It shows the decomposition of the observed signal into a model fit and a residual component.

The first row shows the model fit components:

- $S_{23} \times$ [Image 1]: A template image showing a diffuse, irregular structure.
- $+ f_{23} \times$ [Image 2]: A template image showing a more structured, elongated feature.
- $+ d_{23} \times$ [Image 3]: A template image showing a bright, horizontal band of emission.

The second row shows the result of the fit:

- $=$ [Image 4]: The observed data at 23 GHz, labeled "23 GHz".
- $- c_{23} \times$ [Image 5]: A residual image showing the difference between the observed data and the model fit, appearing as a noisy, textured pattern.

template fitting

$$s_{23} \times \text{[Galaxy Image]} + f_{23} \times \text{[Galaxy Image]} + d_{23} \times \text{[Galaxy Image]} = \text{[23 GHz Image]} - c_{23} \times \text{[Noise Image]}$$

The equation illustrates the template fitting process for a 23 GHz radio galaxy image. The left side shows the sum of three template spectra: s_{23} (synchrotron), f_{23} (free-free), and d_{23} (dust), each multiplied by its respective coefficient and applied to a galaxy image. The right side shows the resulting 23 GHz image, which is equal to the sum of the templates minus a noise component c_{23} multiplied by a noise image.

$s(\nu_i)$, $f(\nu_i)$, $d(\nu_i)$ represent estimates of the synchrotron, free-free, and dust spectra

determining foreground spectra

Multi-Linear Regression

Template Fit

- Bands are completely decoupled
- Spectral shapes are unconstrained
- Constant across the sky

$$P\vec{a} = w$$

$$\vec{a} = (P / \sigma)^+ (w / \sigma)$$

$$\left\| \frac{P}{\sigma} \vec{a} - \frac{w}{\sigma} \right\|^2 = \frac{\|P\vec{a} - w\|^2}{\sigma^2} \equiv \chi^2$$

Dobler & Finkbeiner, 2008

TEMPLATES

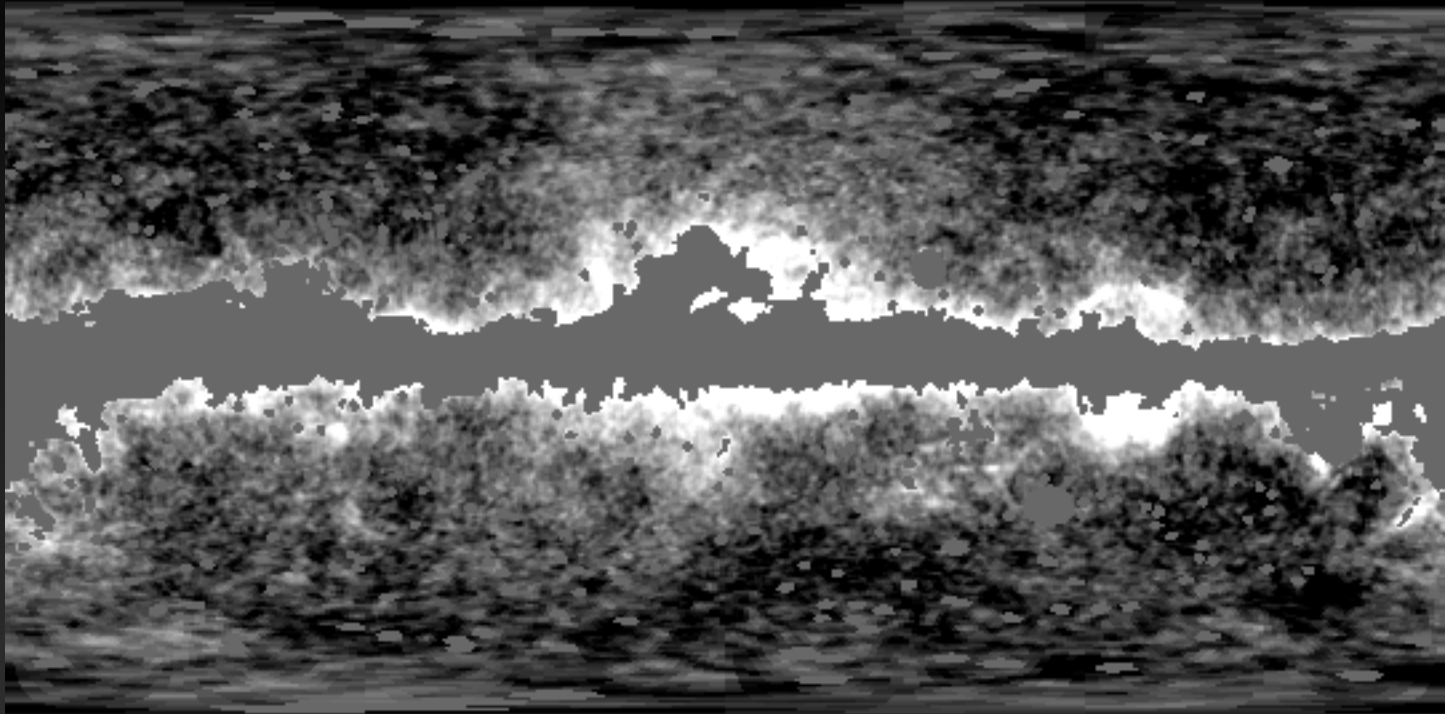
- Synchrotron: Haslam et al (1982)
- Dust: FDS99 (*Finkbeiner et al 1999*)
- Free-free: H α Map (WHAM, SHASSA, VTSS; assembled and corrected for dust by Finkbeiner 2003)

CMB ESTIMATORS

- 6 different types
- introduces a cross-correlation bias
- mean zero
- largest source of uncertainty

peeling away foregrounds

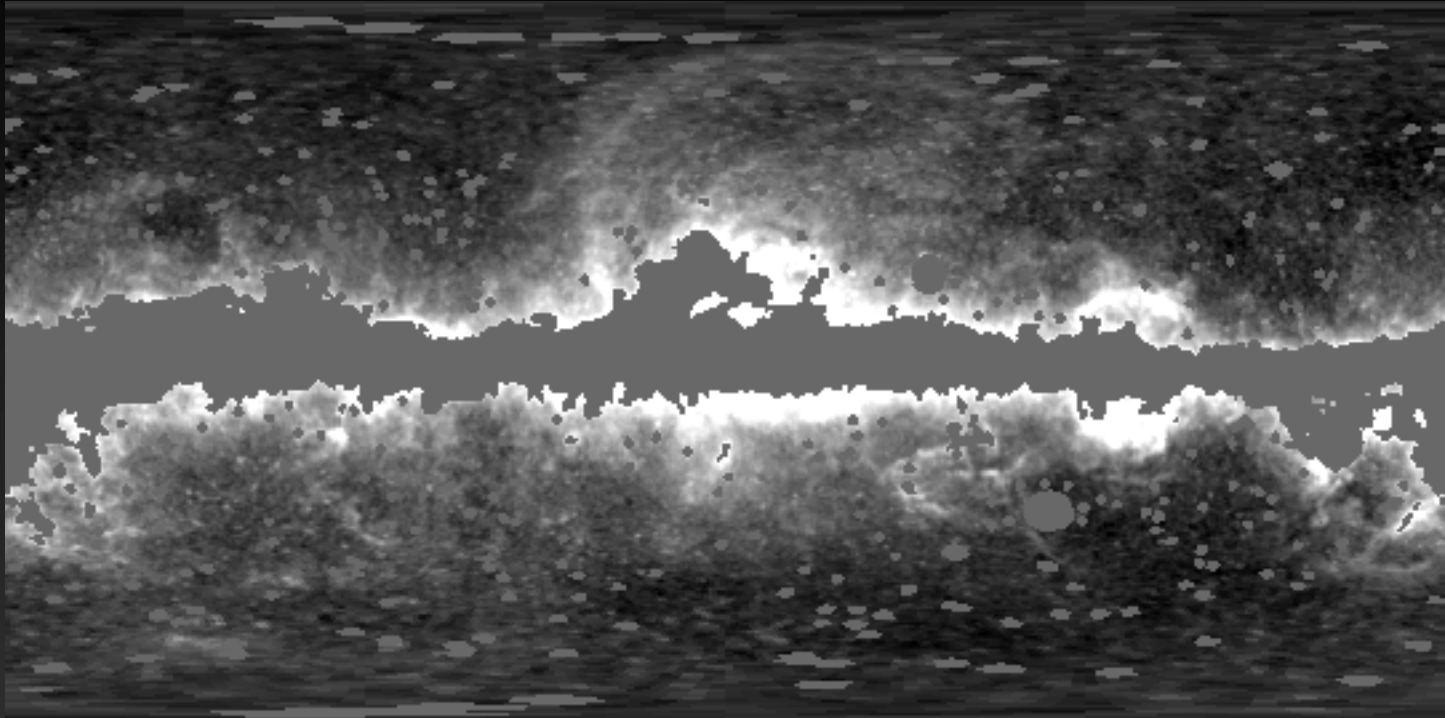
K-band: 23 GHz



WMAP

peeling away foregrounds

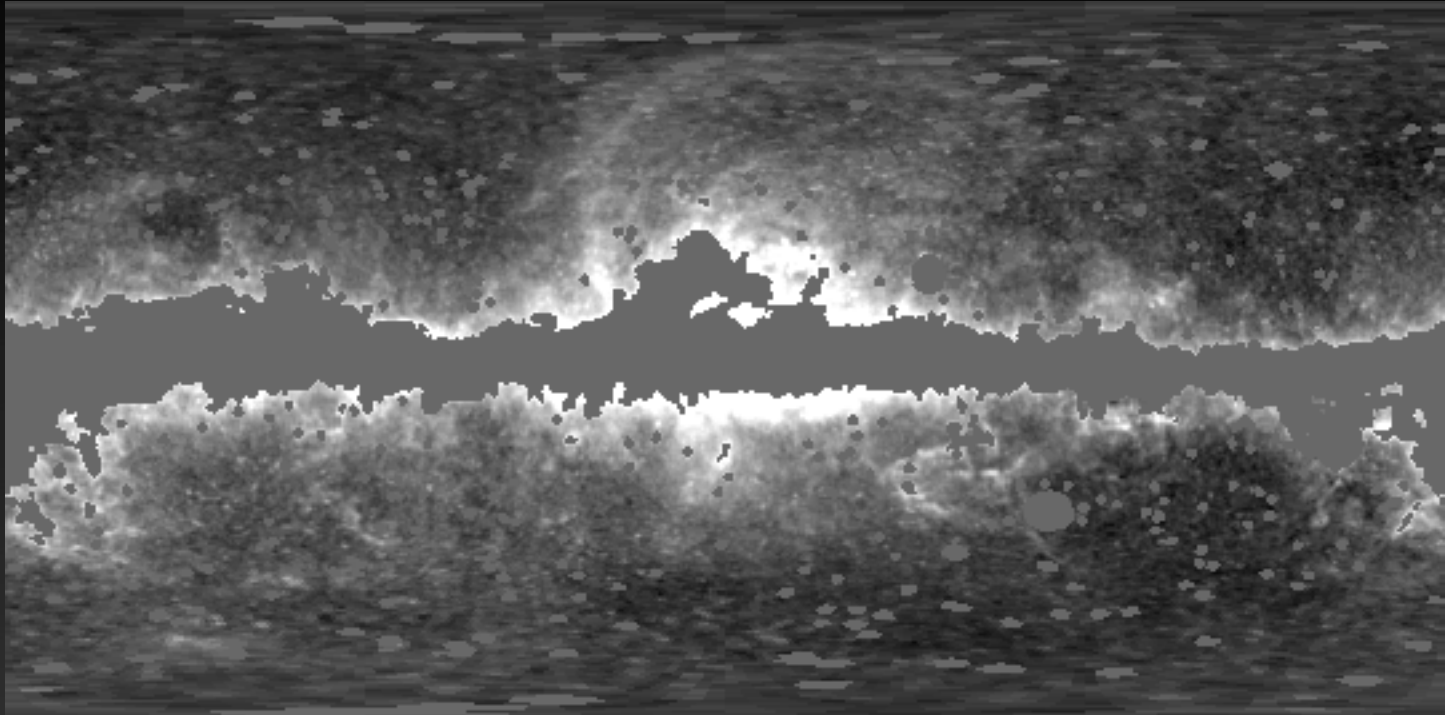
K-band: 23 GHz



WMAP - CMB

peeling away foregrounds

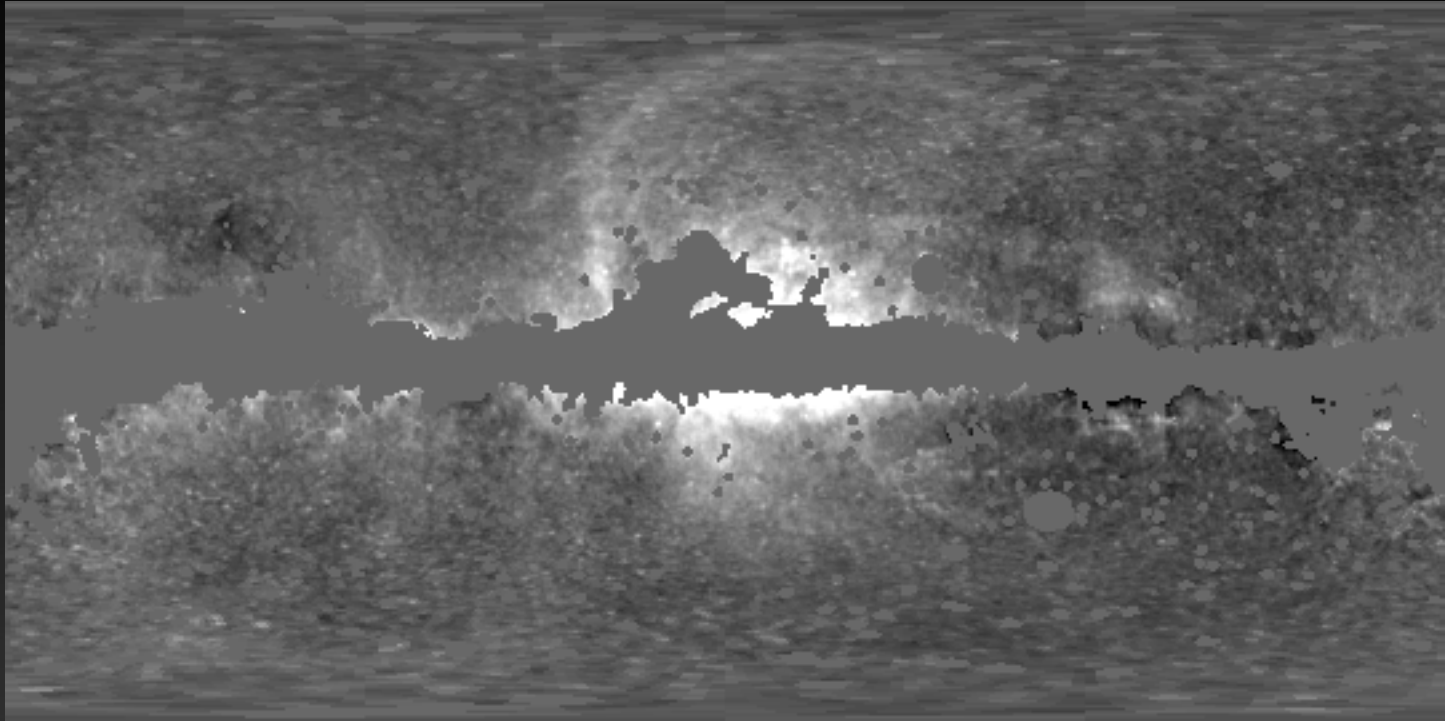
K-band: 23 GHz



WMAP - CMB - free-free

peeling away foregrounds

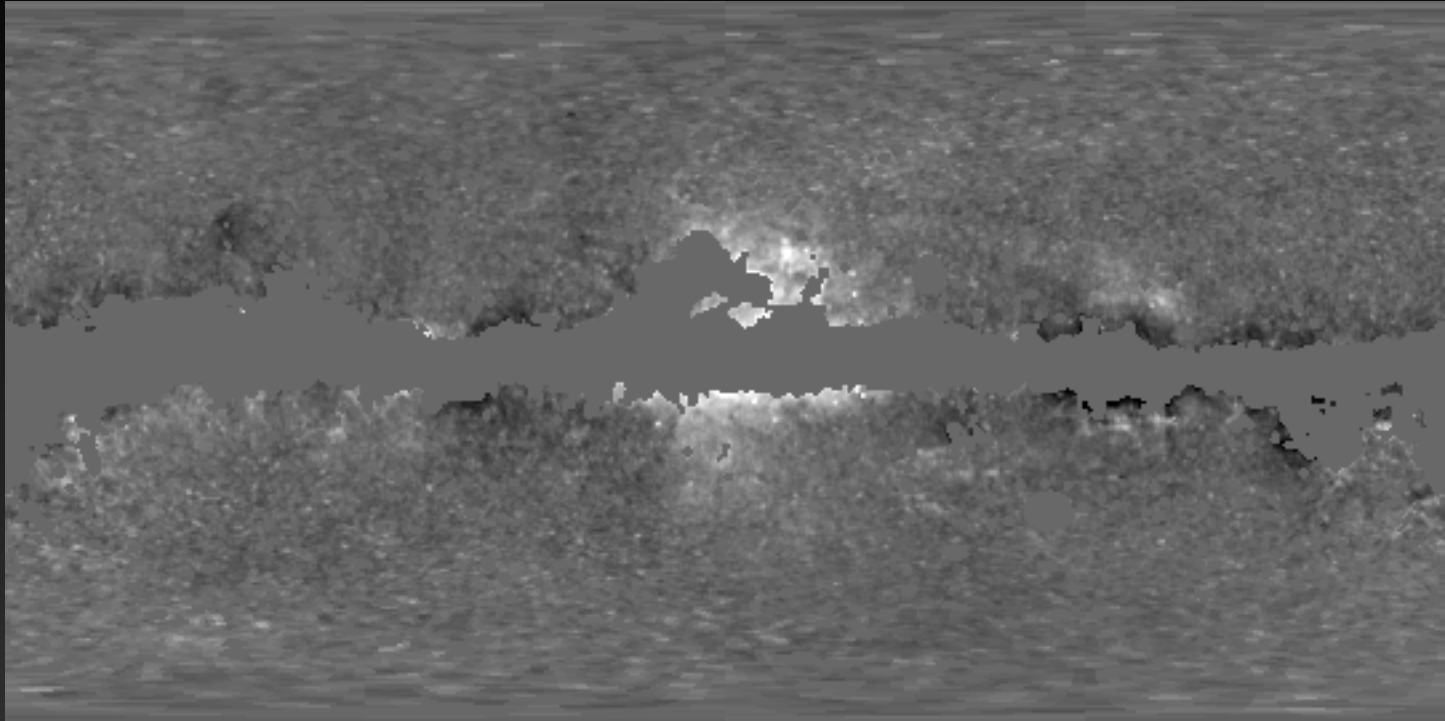
K-band: 23 GHz



WMAP - CMB - free-free
- (thermal and spinning) dust

peeling away foregrounds

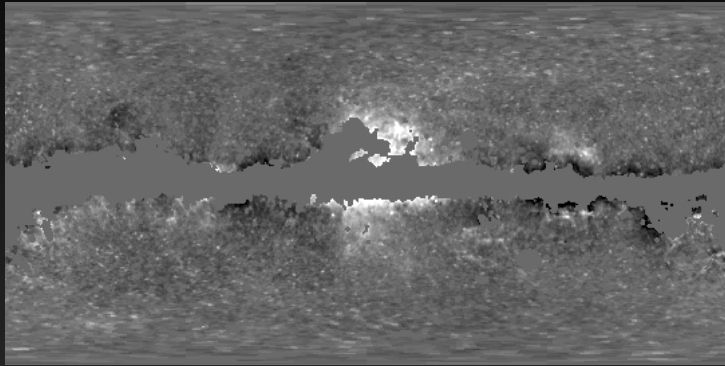
K-band: 23 GHz



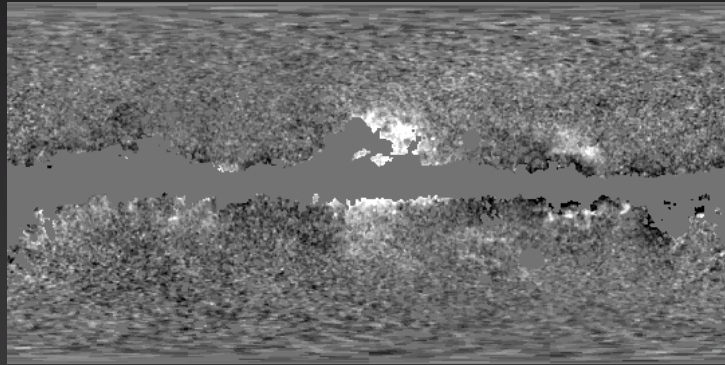
WMAP - CMB - free-free
- (thermal and spinning) dust
- (soft) synchrotron

the haze

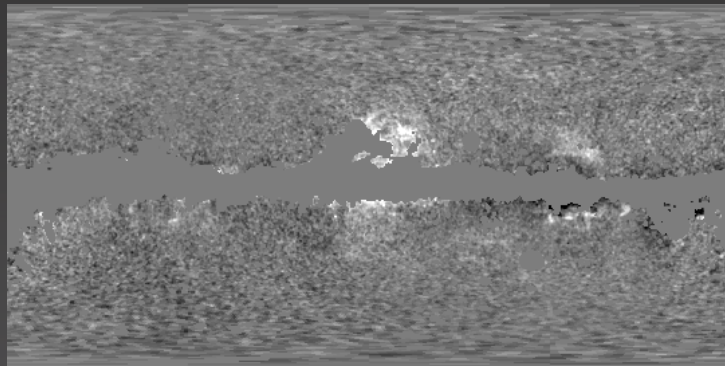
K: 23 GHz



Ka: 33 GHz



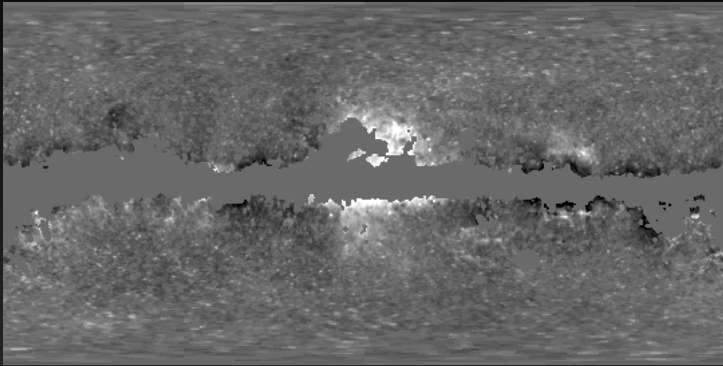
Q: 41 GHz



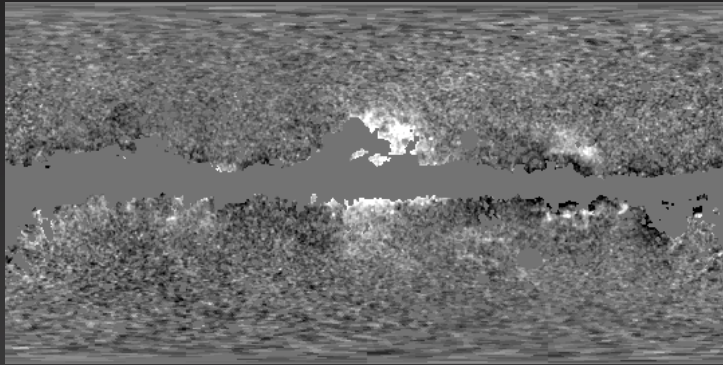
- Multi-linear regression fit
- Excess towards the GC

the haze

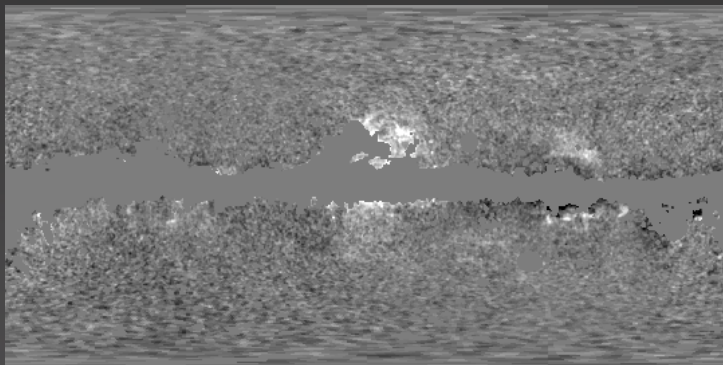
K: 23 GHz



Ka: 33 GHz



Q: 41 GHz



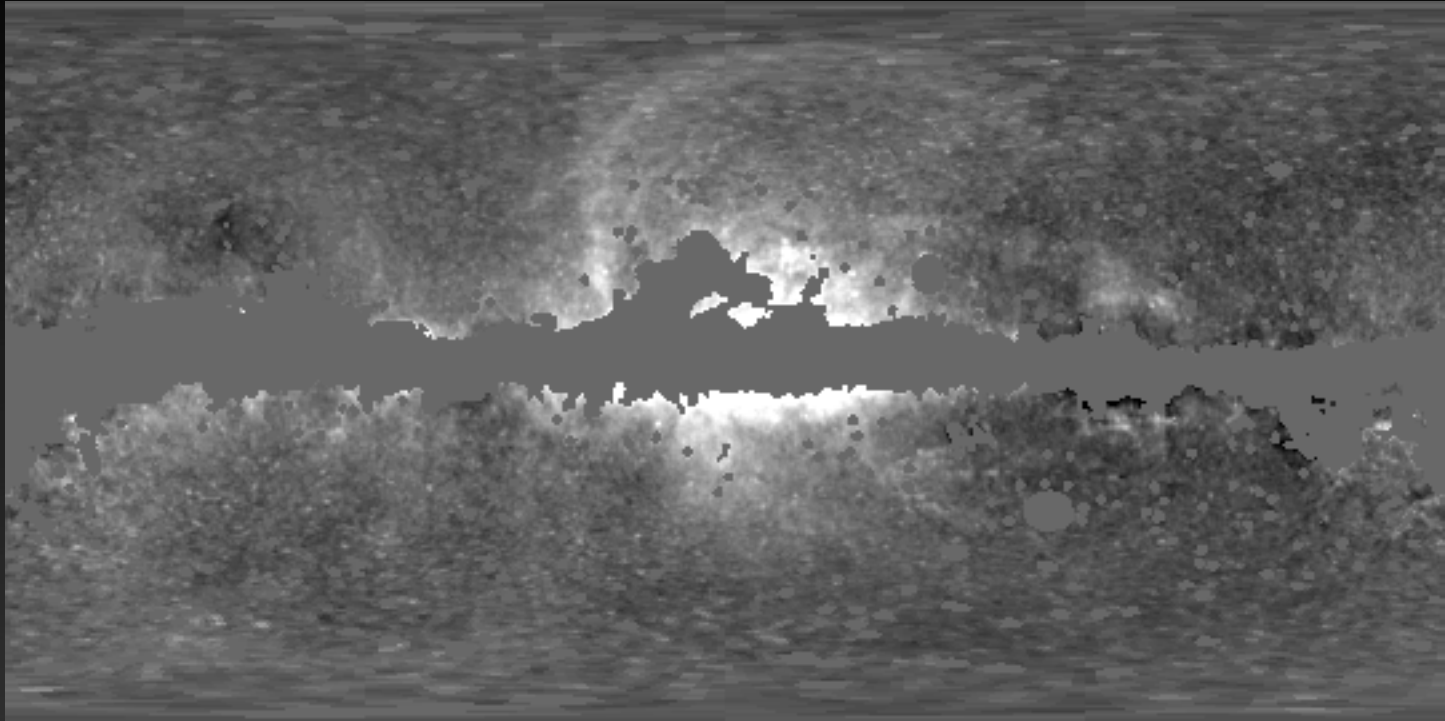
- Multi-linear regression fit
- Excess towards the GC

Separate, *hard* synchrotron component

Upcoming surveys at 5 GHz (CBASS), 15 GHz, and especially *Planck* will provide A LOT more information!

the haze spectrum

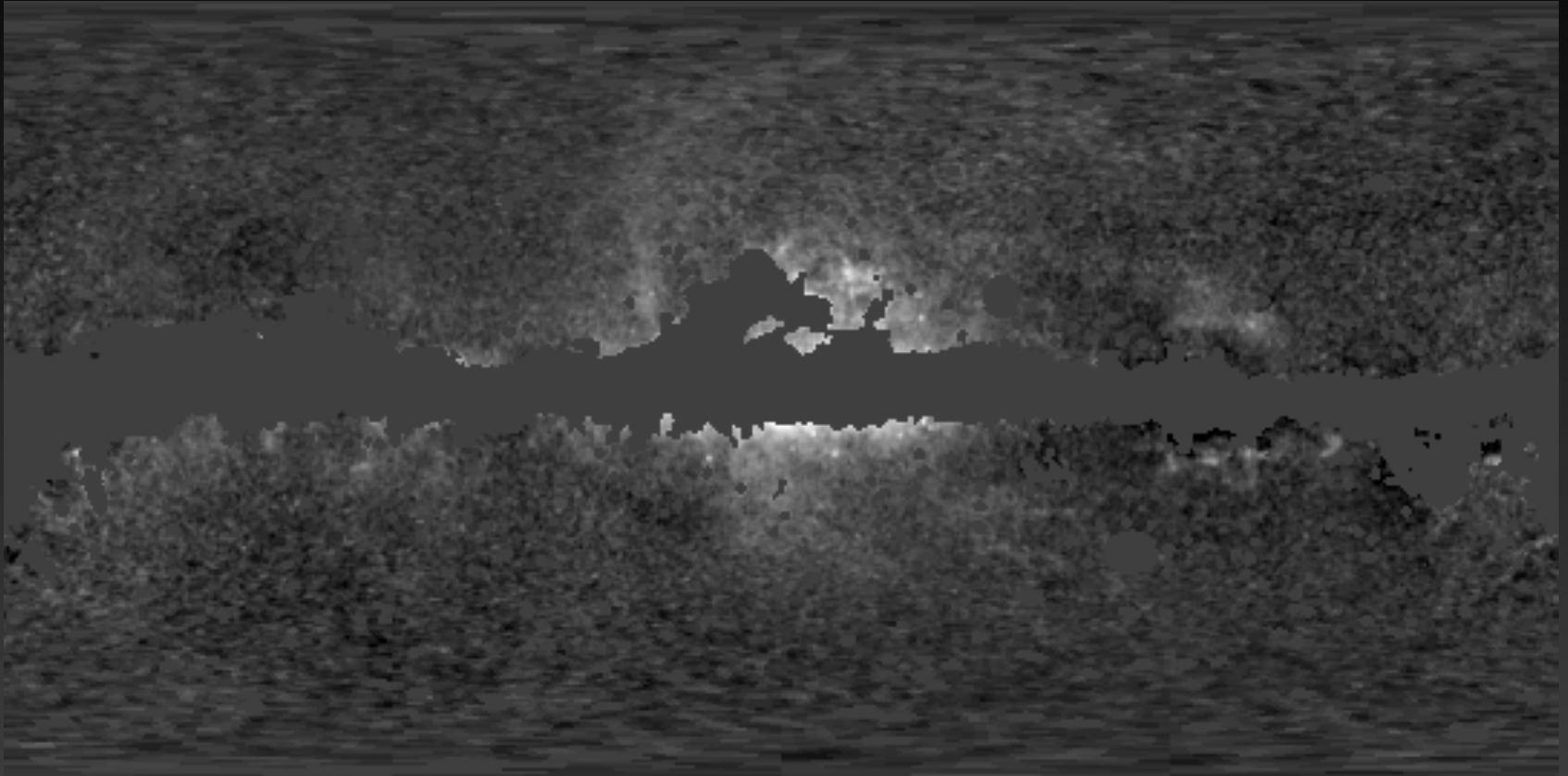
K-band: 23 GHz



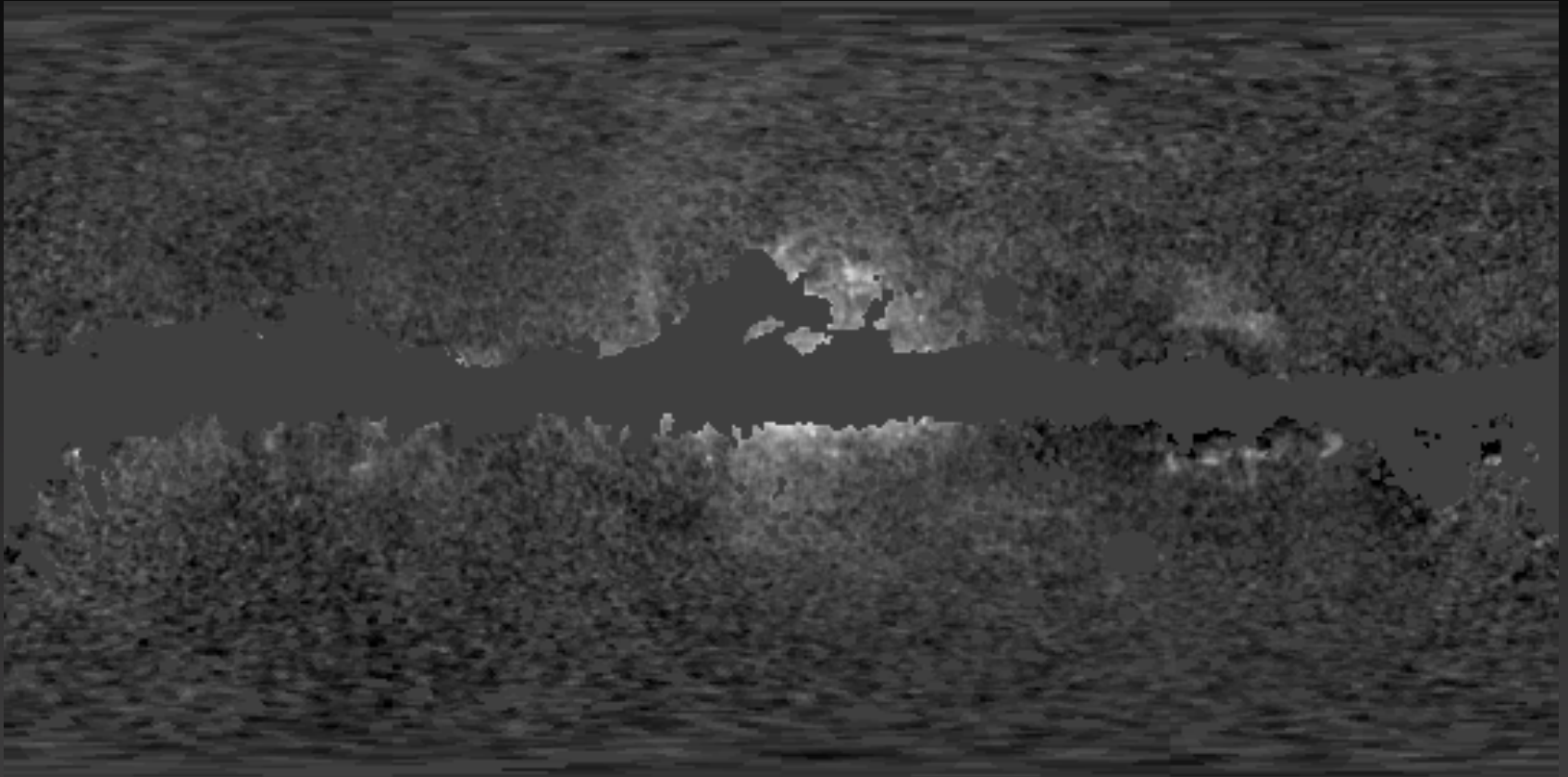
WMAP - CMB - free-free
- (thermal and spinning) dust



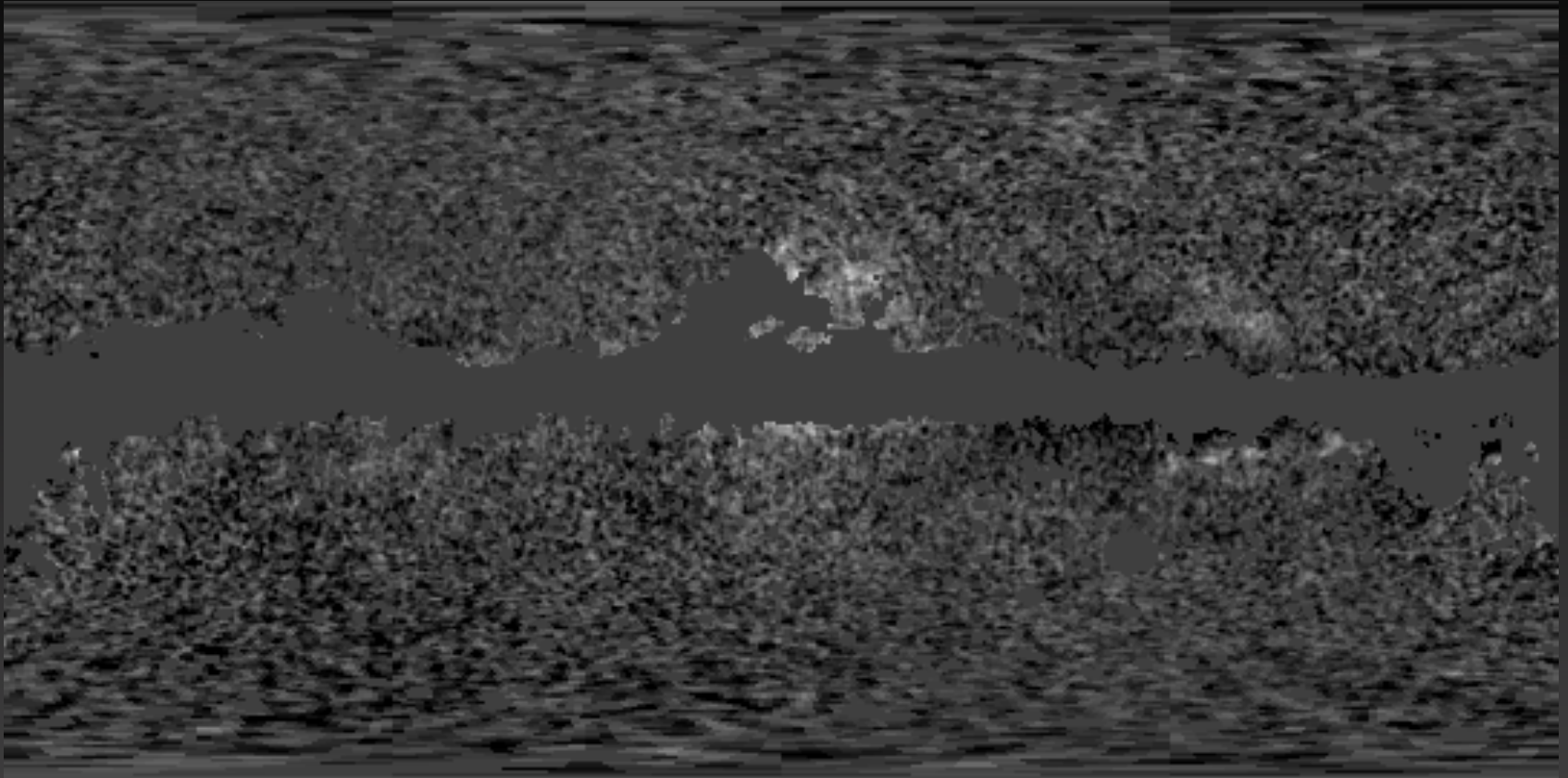
23 GHz Synchrotron



33 GHz Synchrotron

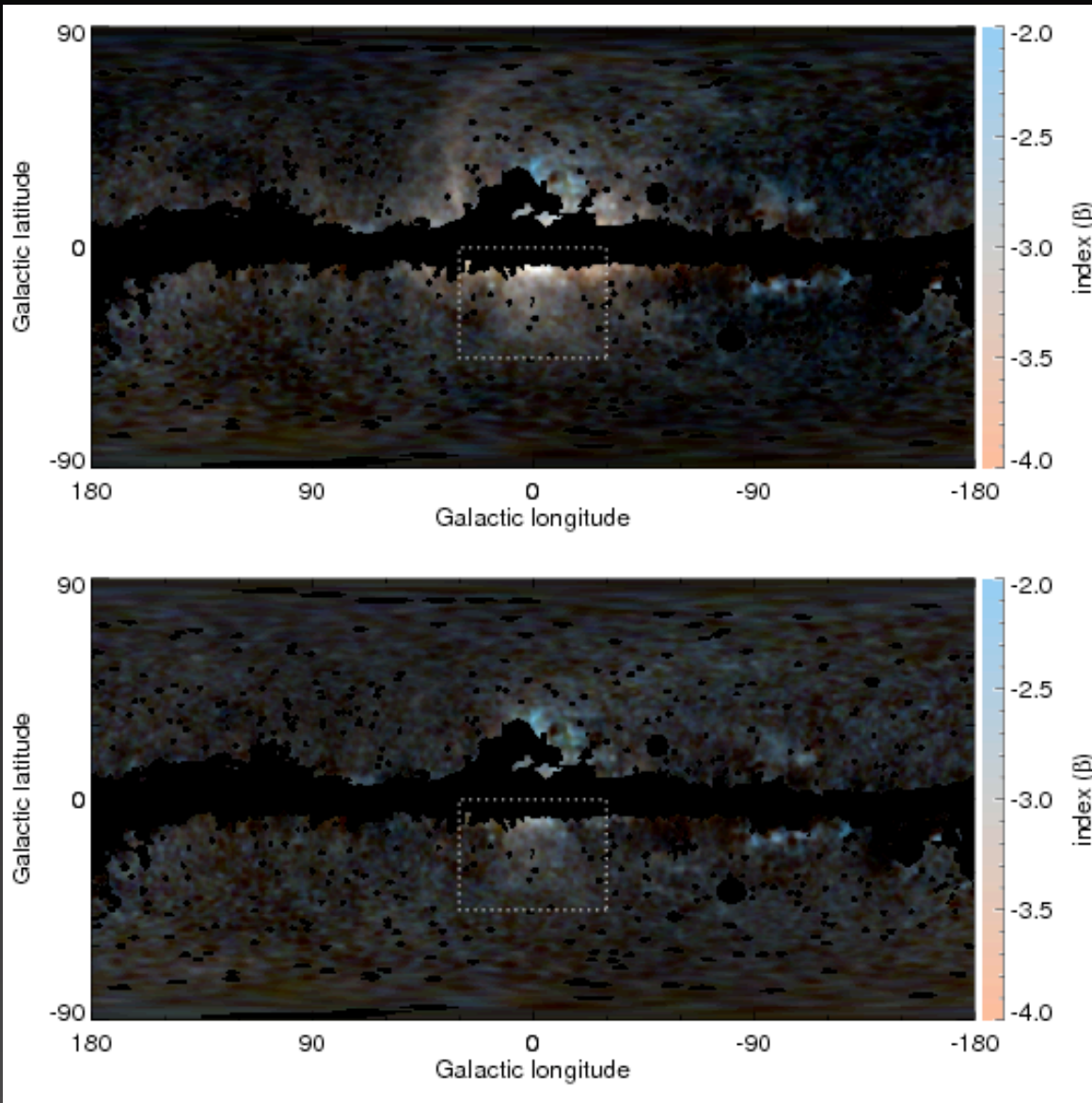


41 GHz Synchrotron



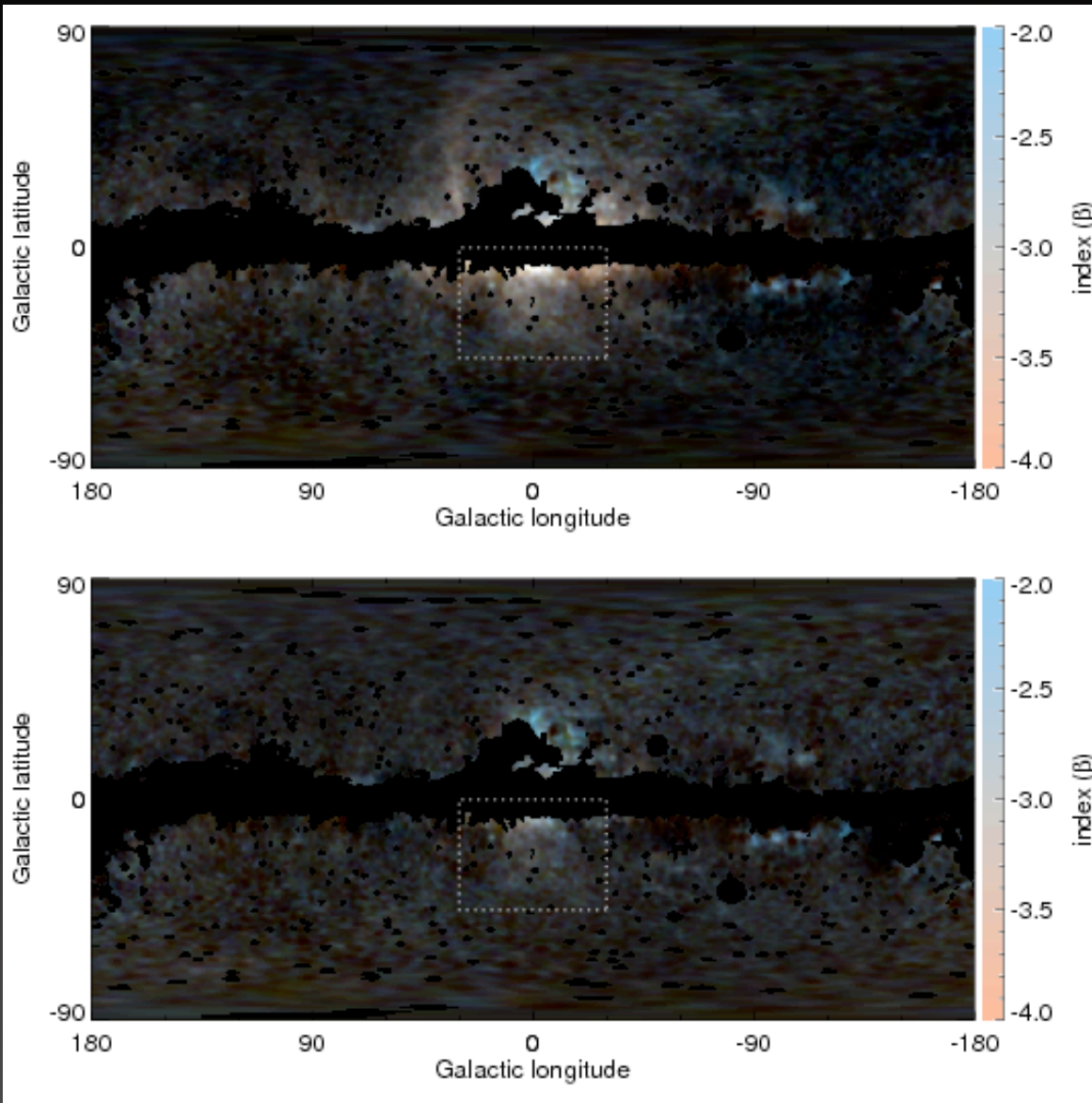
61 GHz Synchrotron

the haze spectrum



- Looks like synchrotron with,
 $E^2 dN/dE \propto E^\alpha$ $-0.1 \leq \alpha \leq 0.2$
- If it is synchrotron, it requires
 - hard e^+e^- spectrum
 - extended emission
- Very difficult to produce astrophysically

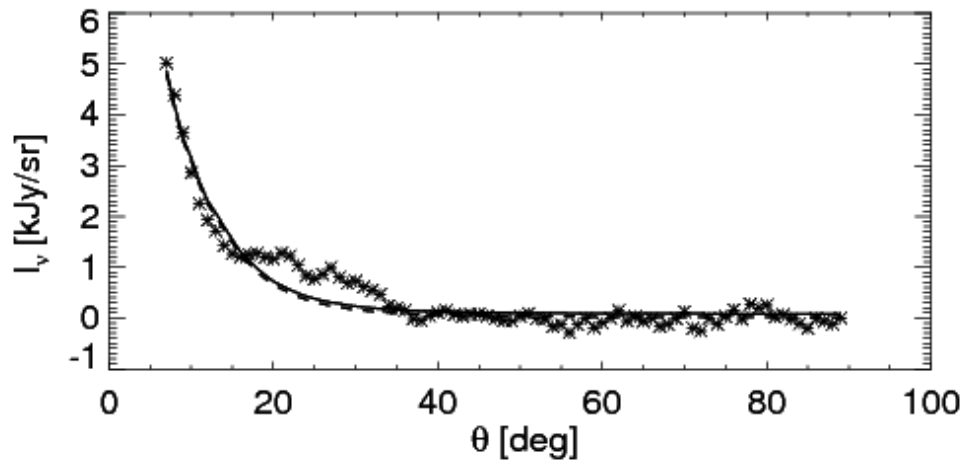
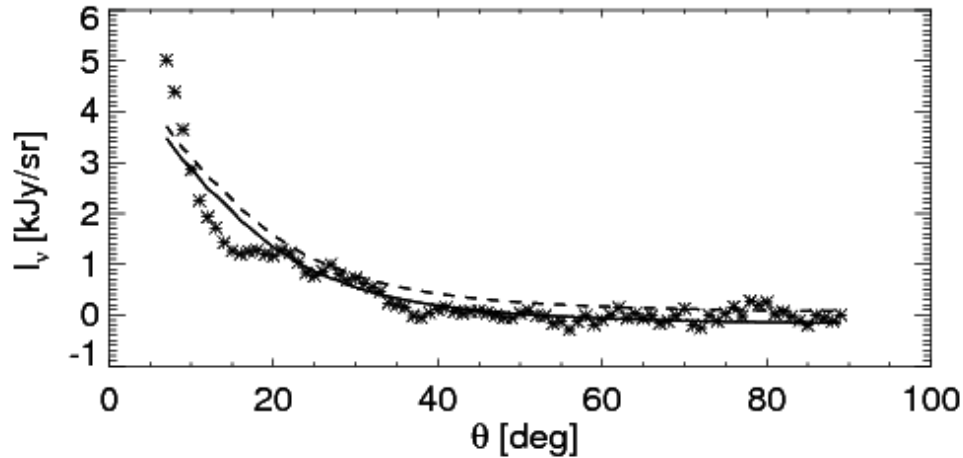
the haze spectrum



- Looks like synchrotron with,
 $E^2 dN/dE \propto E^\alpha$ $-0.1 \leq \alpha \leq 0.2$

Can be confirmed
by ICS signal in
Fermi!

dark matter and the haze



Galactic/baryon params:

$$B \sim 10 \mu\text{G}$$

$$K(E) \sim 10^{28} \text{ cm}^2/\text{s}$$

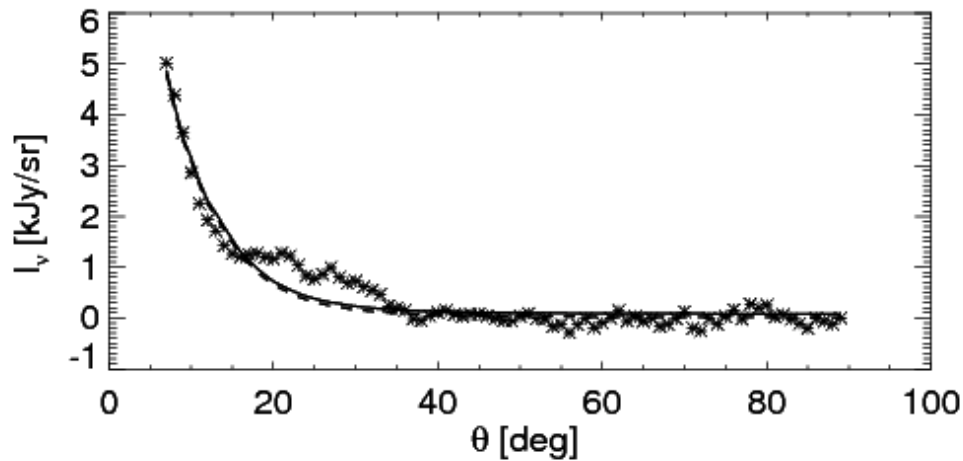
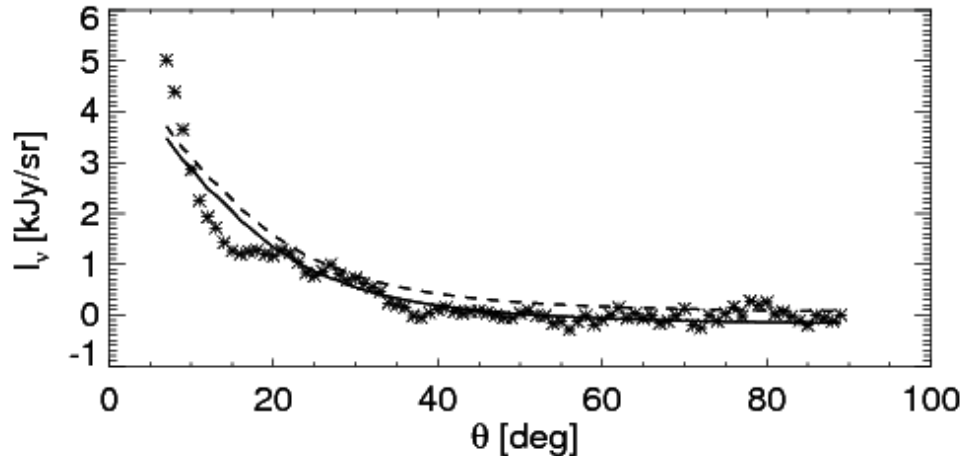
Dark matter params:

$$\rho = \rho(r)$$

$$M \sim 100 \text{ GeV}$$

$$\langle \sigma v \rangle \sim \text{few } \times 10^{-26} \text{ cm}^3/\text{s}$$

dark matter and the haze



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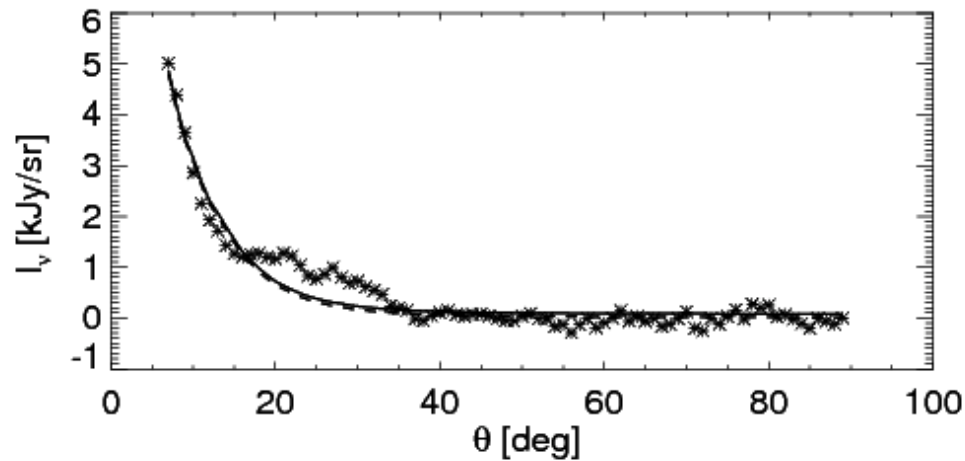
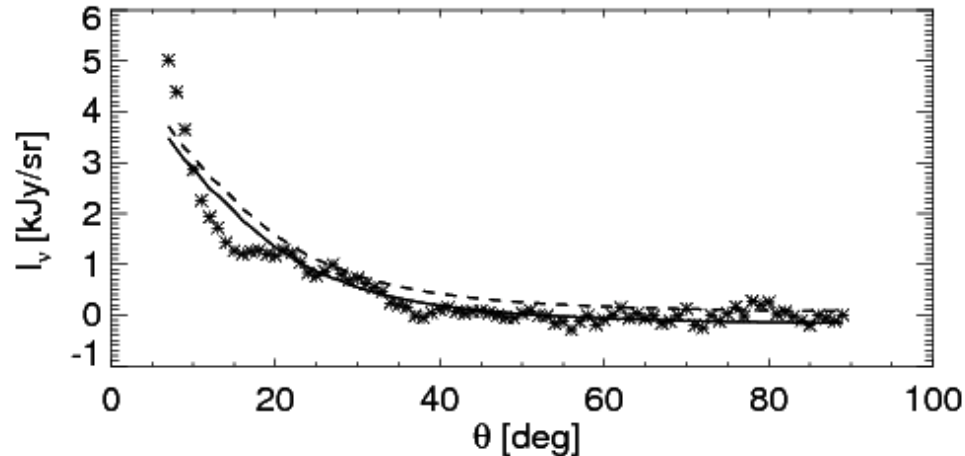
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the haze is
consistent with a
WIMP annihilation
scenario

dark matter and the haze



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Dark matter params:

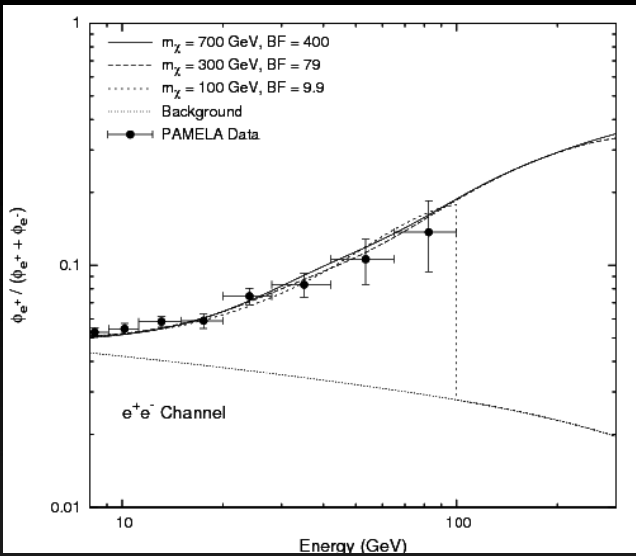
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the haze is
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WIMP annihilation
scenario

there are large astrophysical uncertainties!

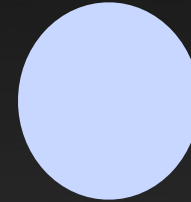


PAMELA

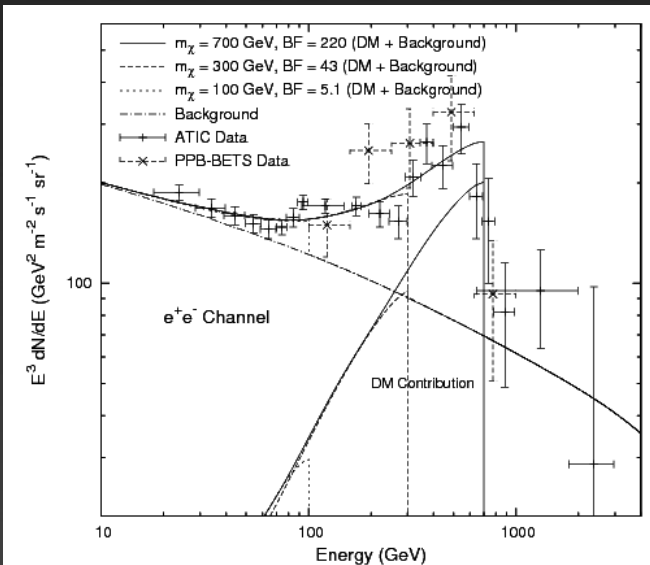


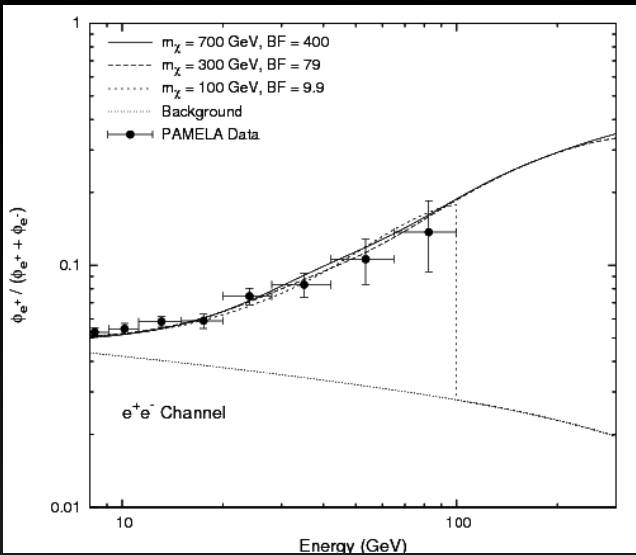
ATIC

8.5 kpc



Haze





PAMELA

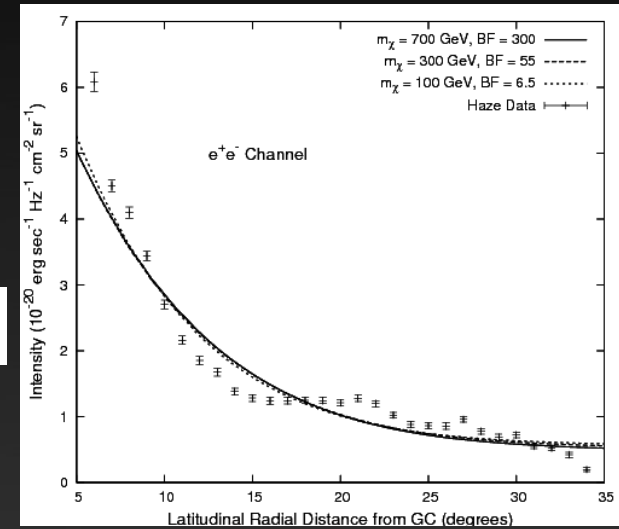
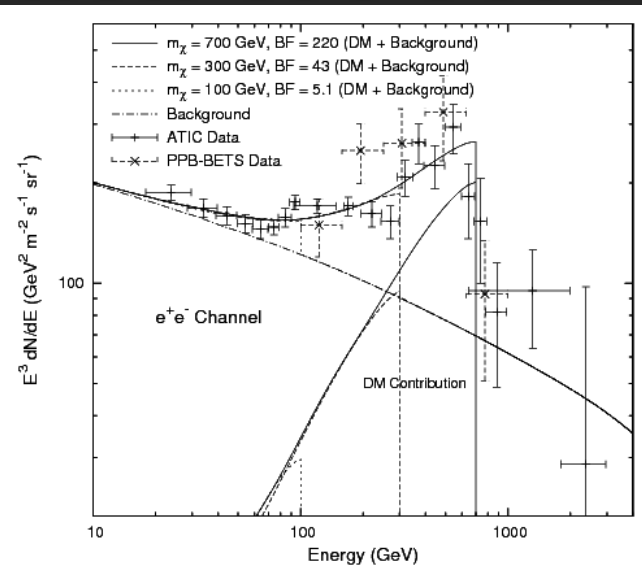


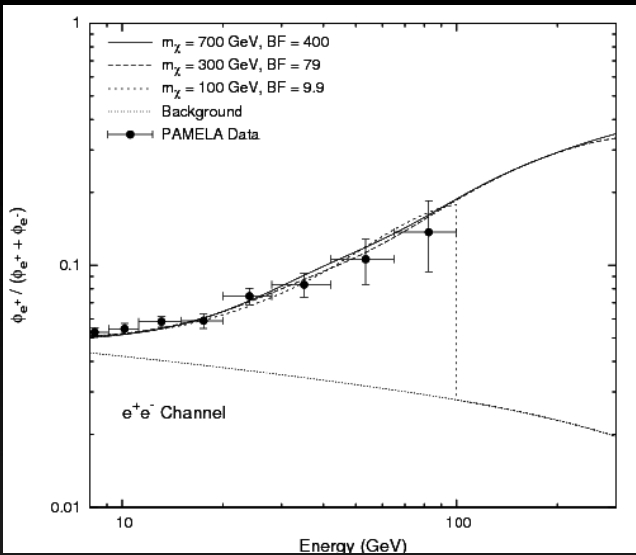
ATIC

8.5 kpc

$$\ln(\rho/\rho_{-2}) = -(2/\alpha)(x^\alpha - 1)$$

$$d \ln \rho / d \ln r = -2(r/r_{-2})^\alpha$$





PAMELA



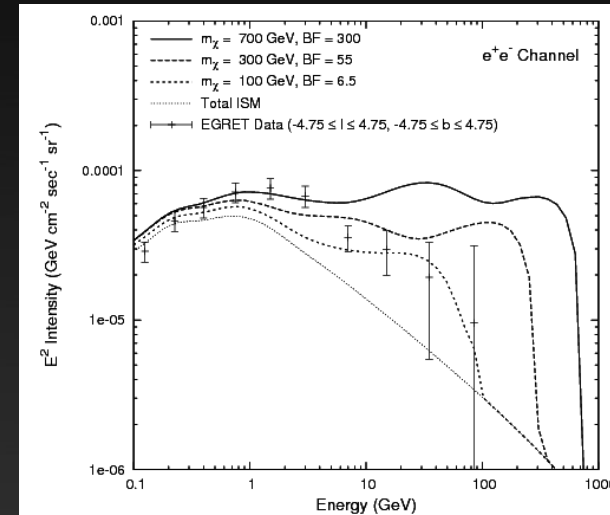
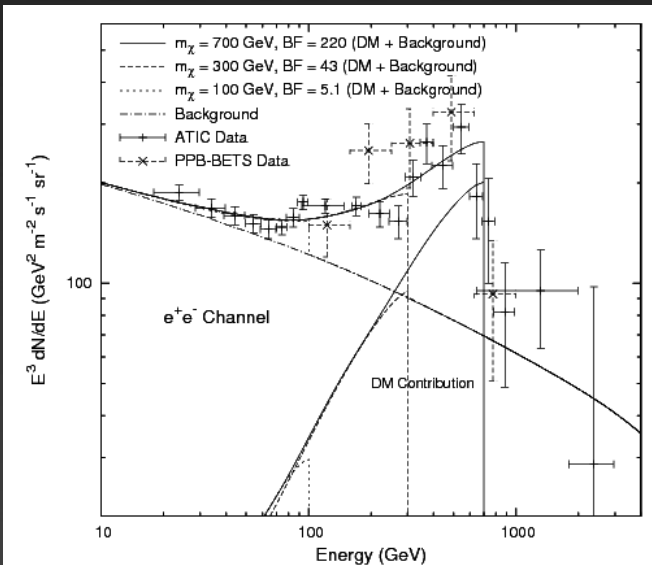
ATIC

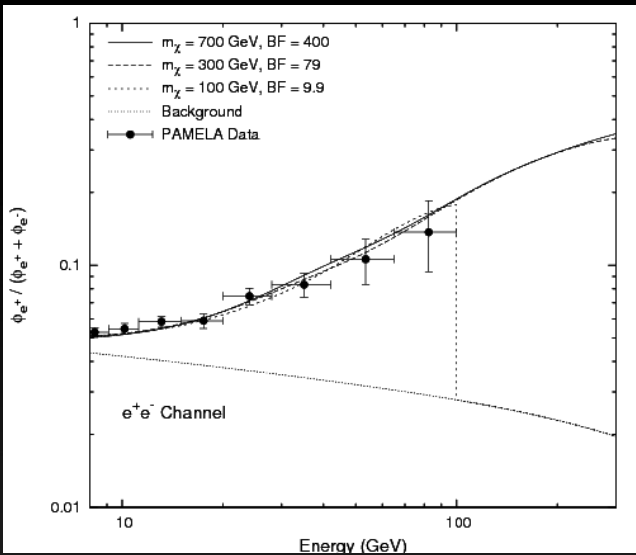
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PAMELA



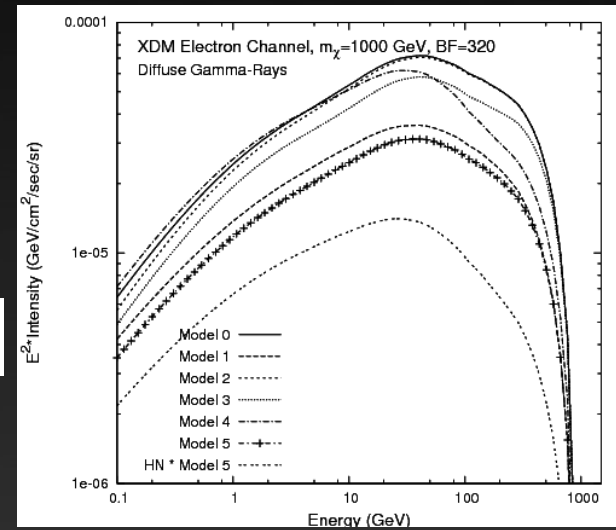
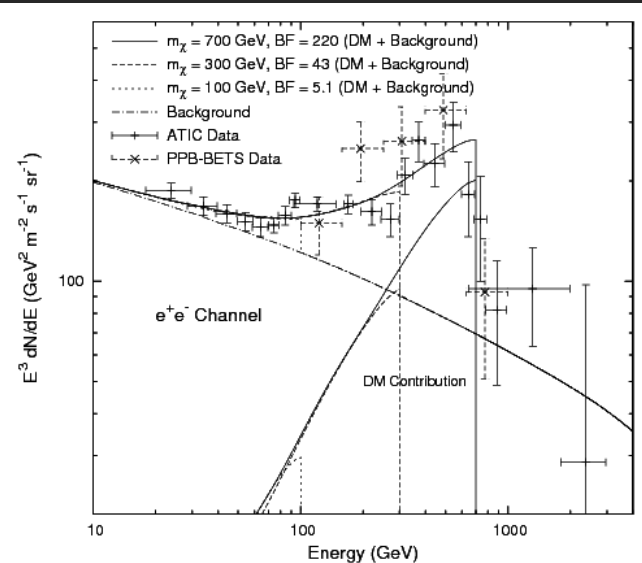
ATIC

8.5 kpc



$$\ln(\rho/\rho_{-2}) = -(2/\alpha)(x^\alpha - 1)$$

$$d \ln \rho / d \ln r = -2(r/r_{-2})^\alpha$$



the haze...

facts and myths

the haze...

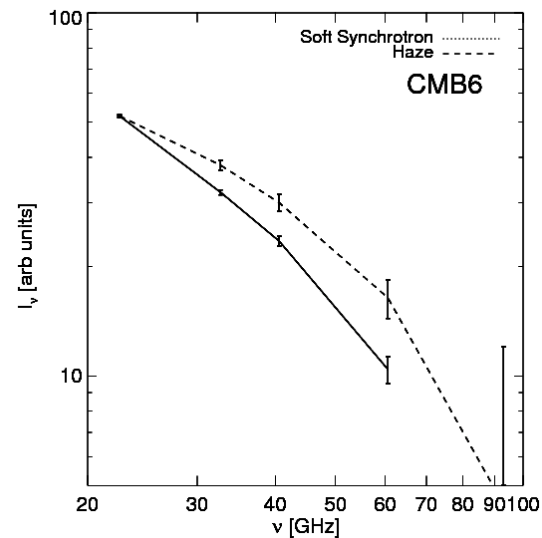
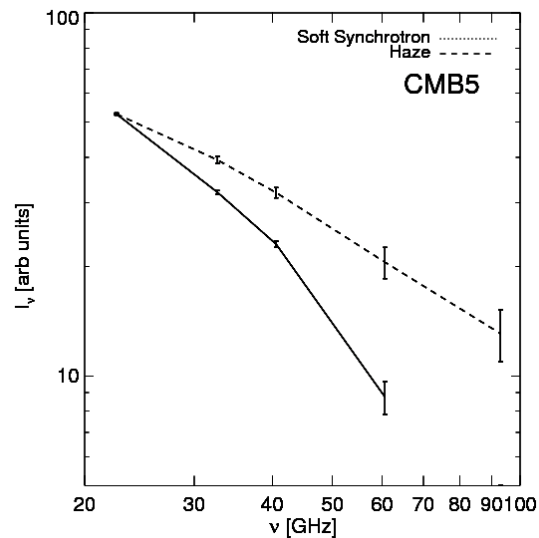
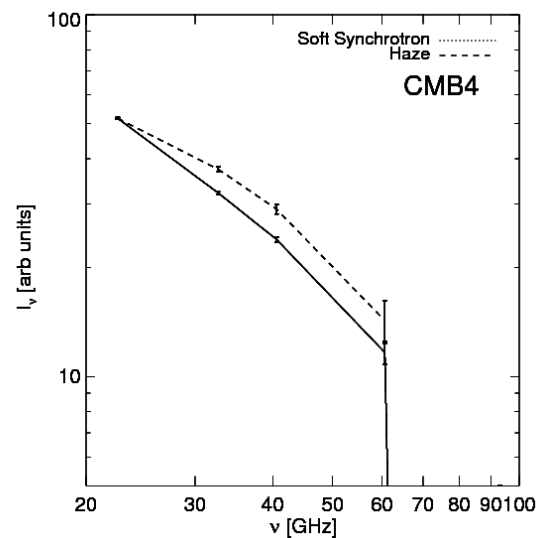
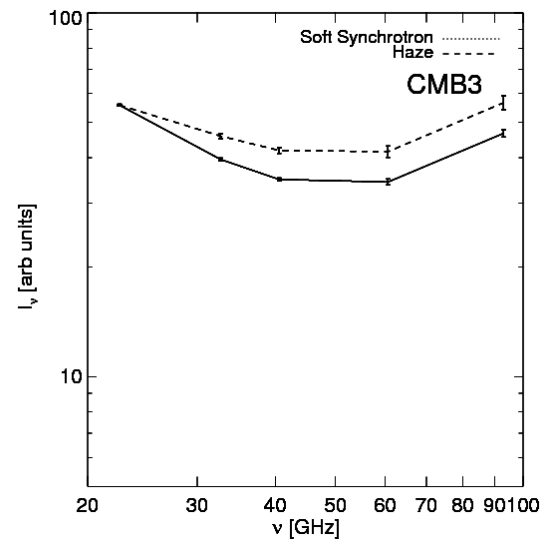
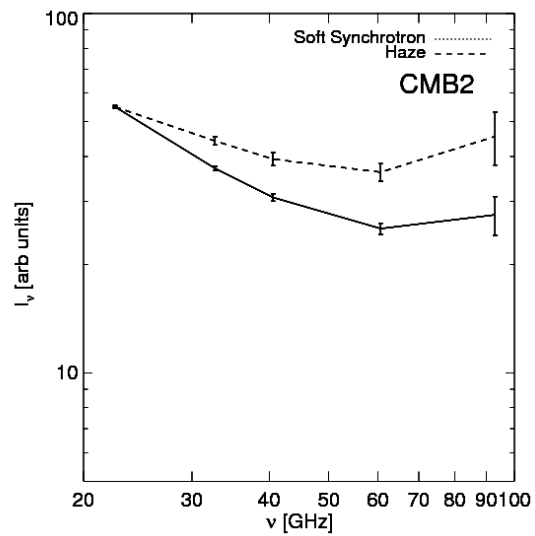
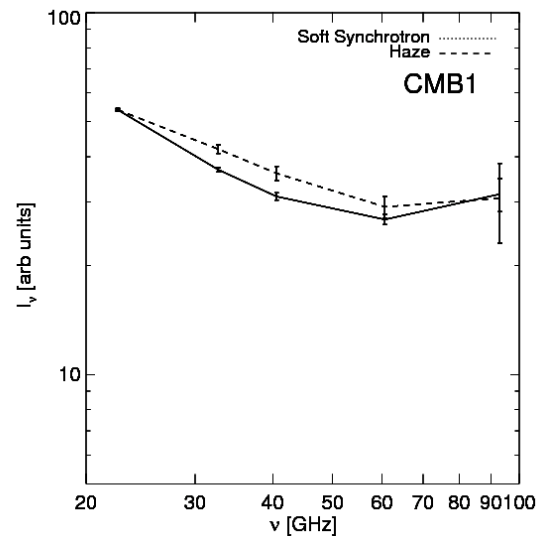
facts and ~~myths~~

misconceptions

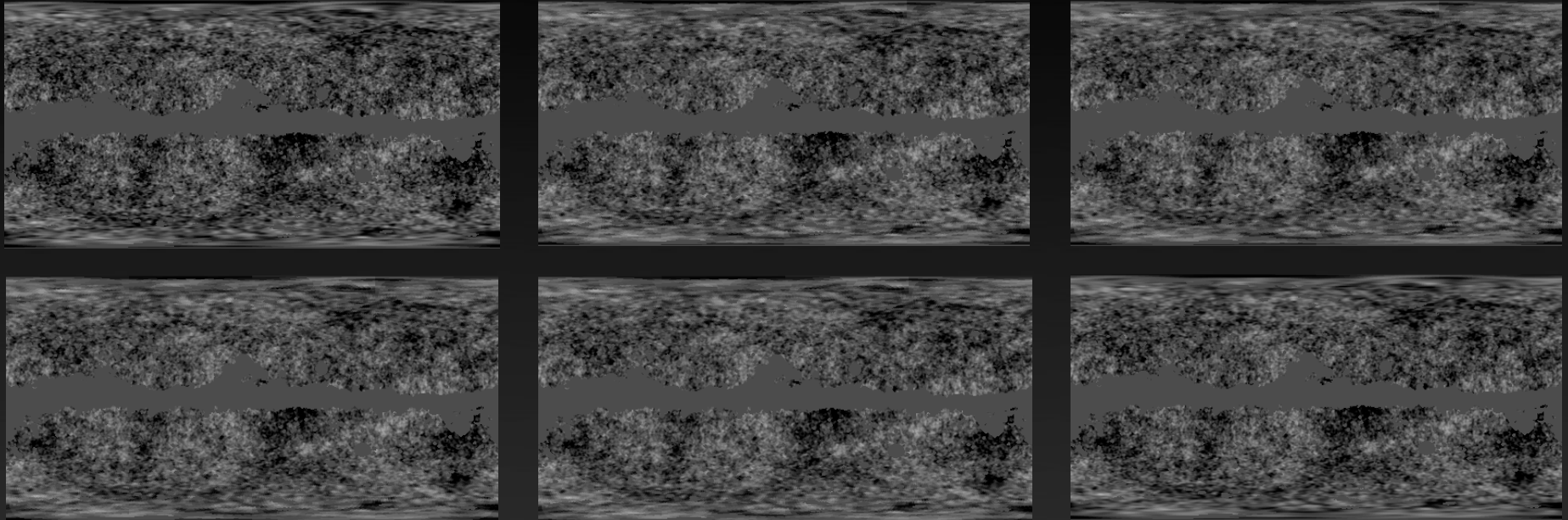
the haze: facts

- foreground spectra have significant uncertainties
 - CMB cross-correlations (systematic)
 - template approximations

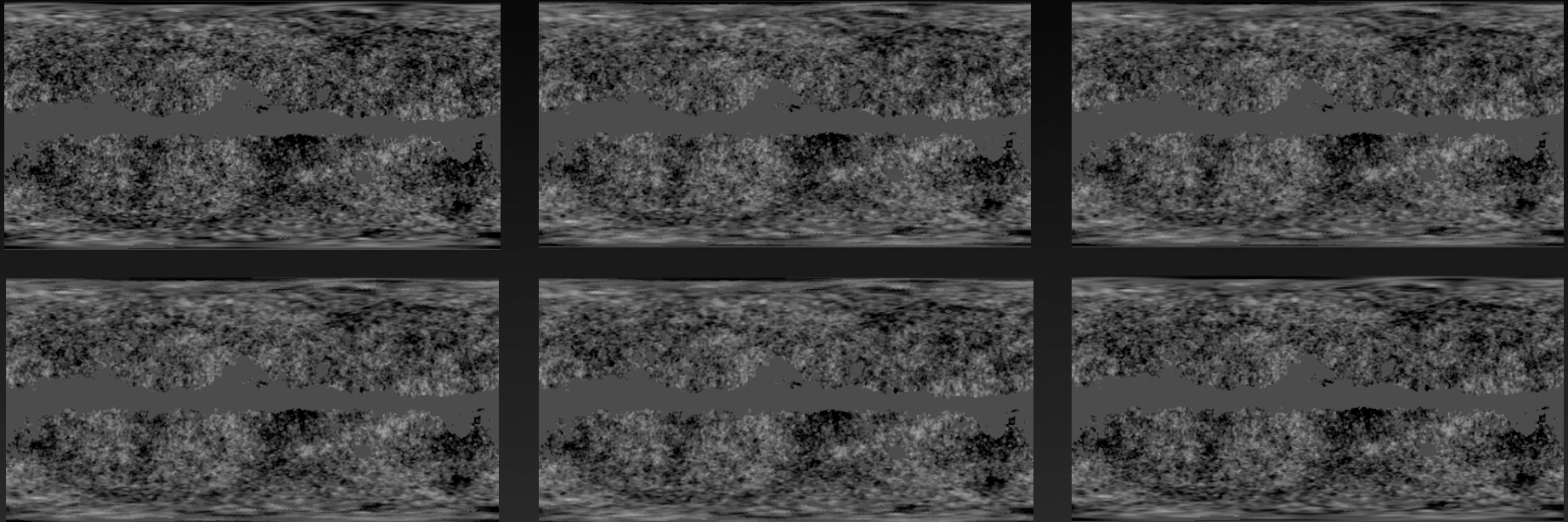
the haze: facts



CMB “cross-correlation” bias



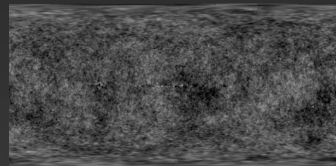
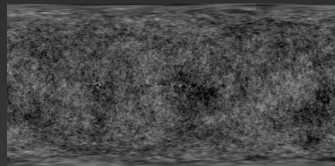
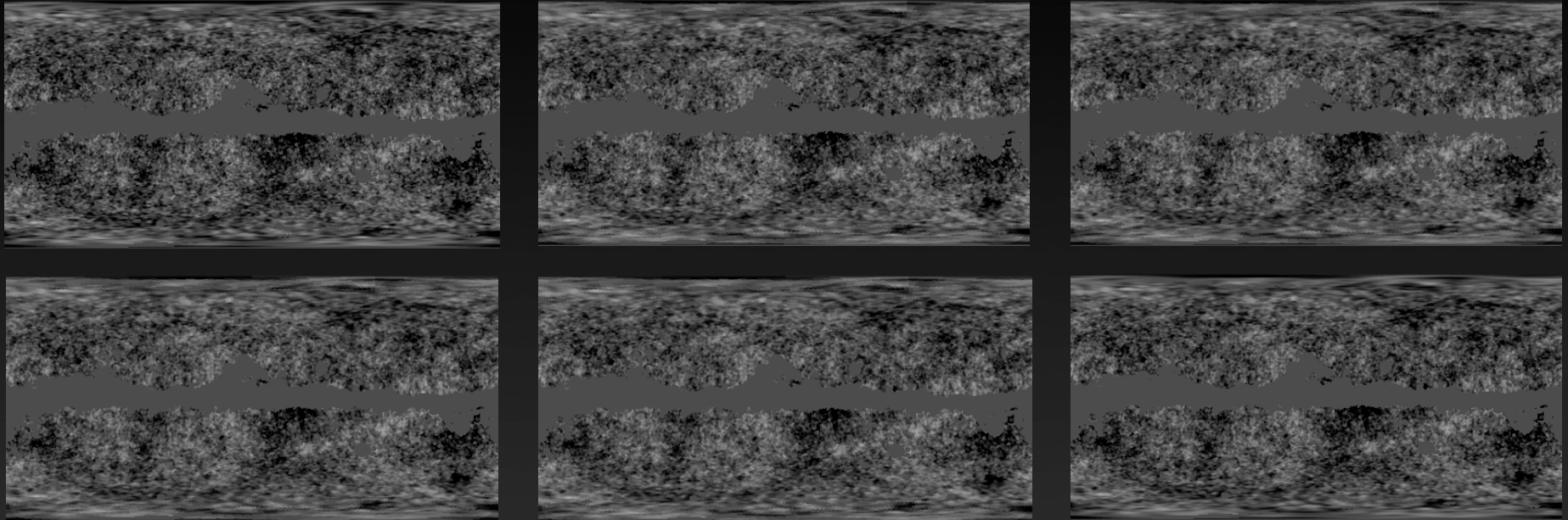
CMB “cross-correlation” bias



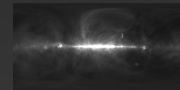
$$S_{23} \times \text{[CMB Map]} + f_{23} \times \text{[Galaxy Map]} + d_{23} \times \text{[Galaxy Map]} = \text{[23 GHz Map]} - C_{23} \times \text{[CMB Map]}$$

The diagram illustrates the decomposition of the cross-correlation signal. On the left, the product of the cross-correlation coefficient S_{23} and a CMB map is shown. This is equal to the difference between the product of the 23 GHz map and the cross-correlation coefficient C_{23} and the sum of the products of the galaxy map and the coefficients f_{23} and d_{23} .

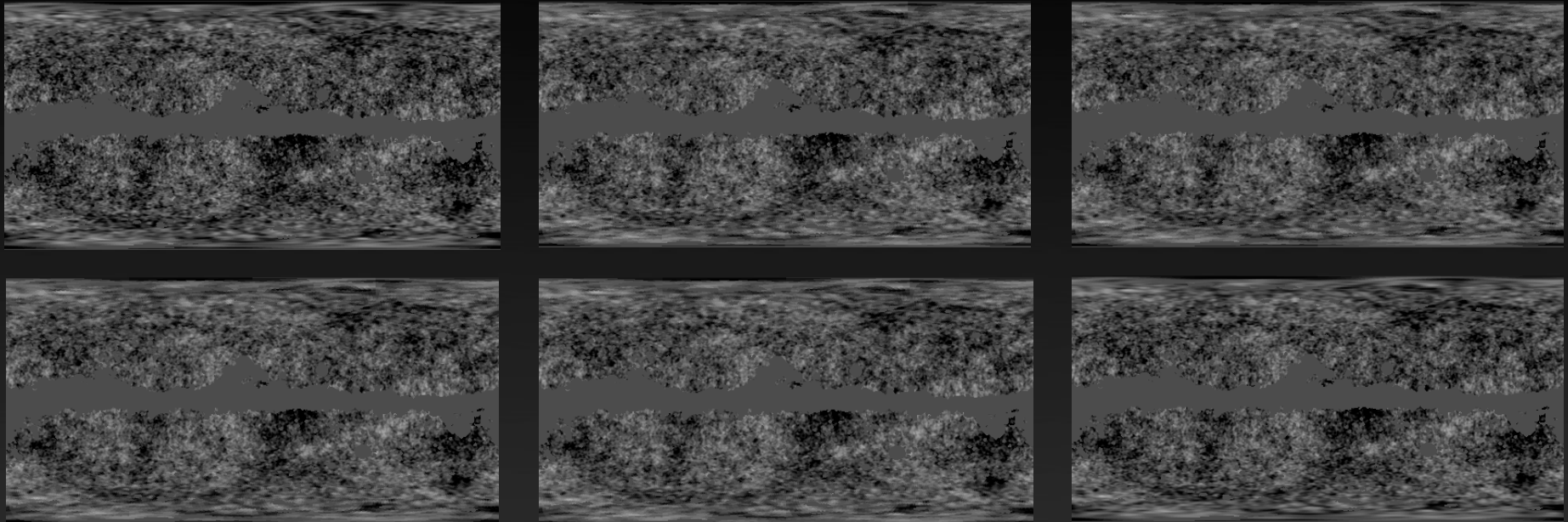
CMB “cross-correlation” bias



+ $b_s \times$

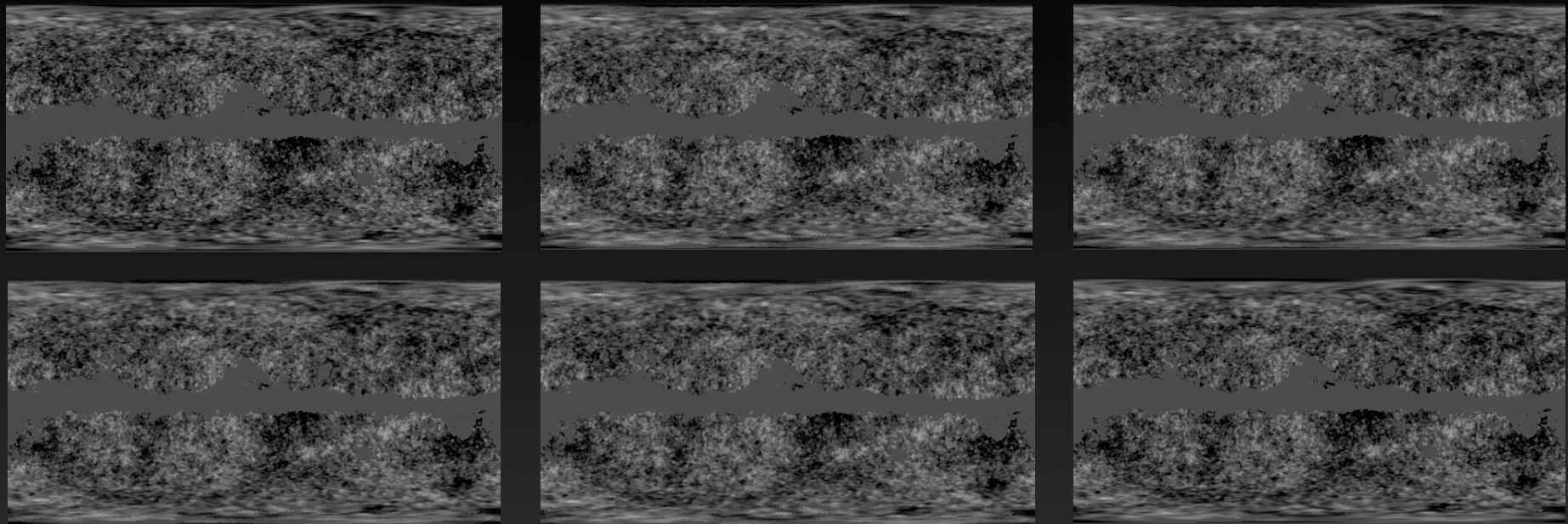


CMB “cross-correlation” bias



$$\begin{aligned}
 S_{23} \times & \text{[CMB map]} + f_{23} \times \text{[Galaxy map]} + d_{23} \times \text{[Galaxy map]} \\
 = & \text{[23 GHz map]} - c_{23} \times \left(\text{[CMB map]} + b_s \times \text{[Galaxy map]} \right)
 \end{aligned}$$

CMB "cross-correlation" bias

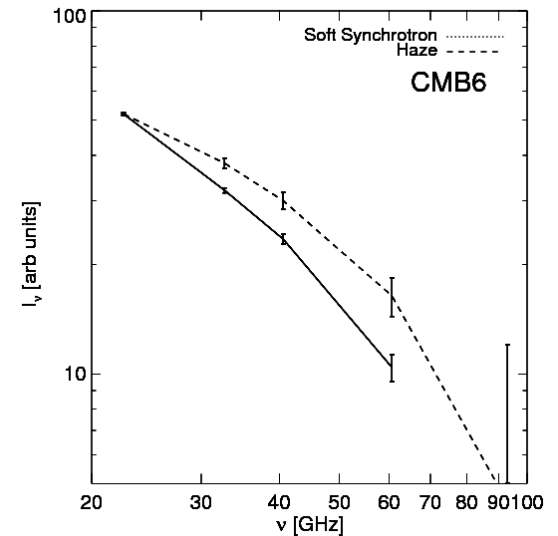
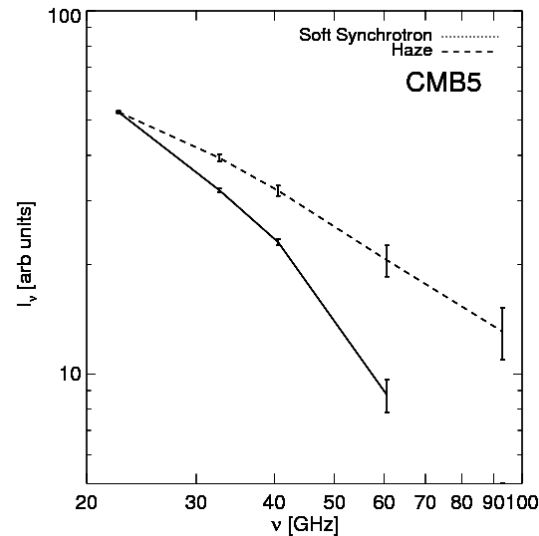
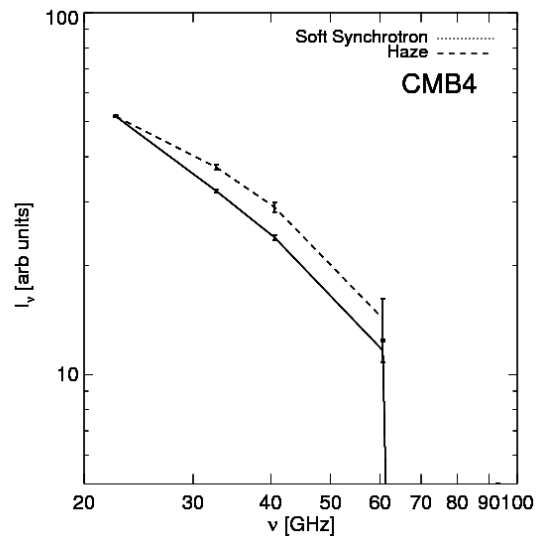
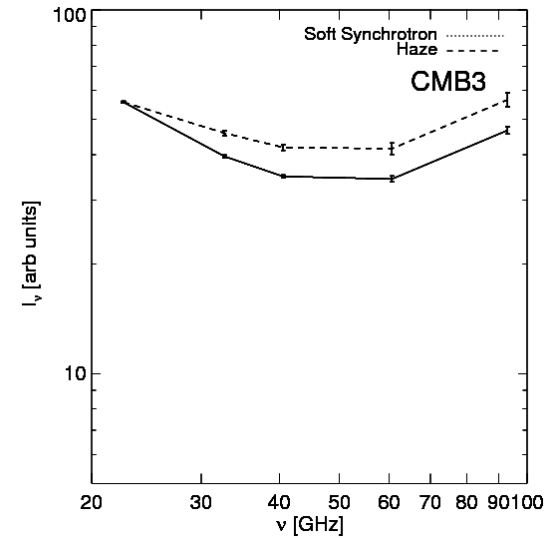
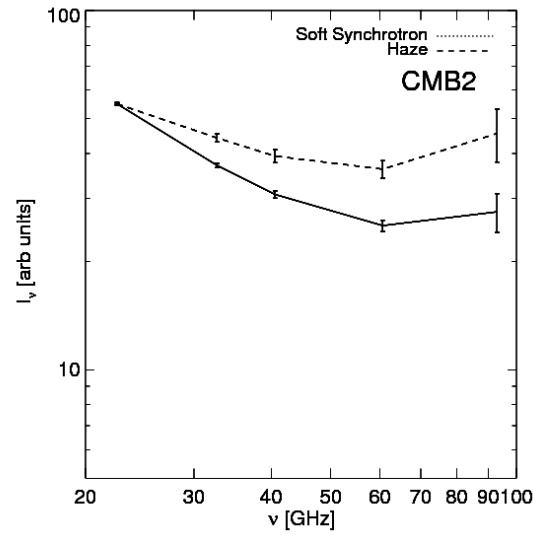
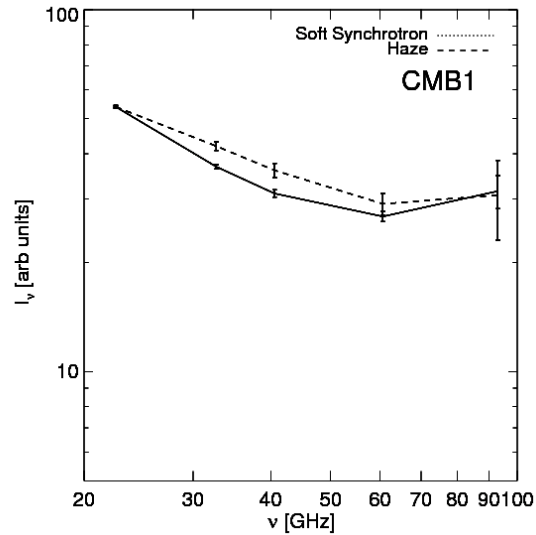


$$\begin{aligned}
 S_{23} \times \text{[Galaxy Map]} &+ f_{23} \times \text{[Galaxy Map]} + d_{23} \times \text{[Galaxy Map]} \\
 = \text{[23 GHz Map]} &- c_{23} \times \left(\text{[Noise Map]} + b_s \times \text{[Galaxy Map]} \right)
 \end{aligned}$$

$$s_v \rightarrow s_v - c_v \times b_s \quad f_v \rightarrow f_v - c_v \times b_f \quad d_{23} \rightarrow d_v - c_v \times b_d$$

the haze: facts

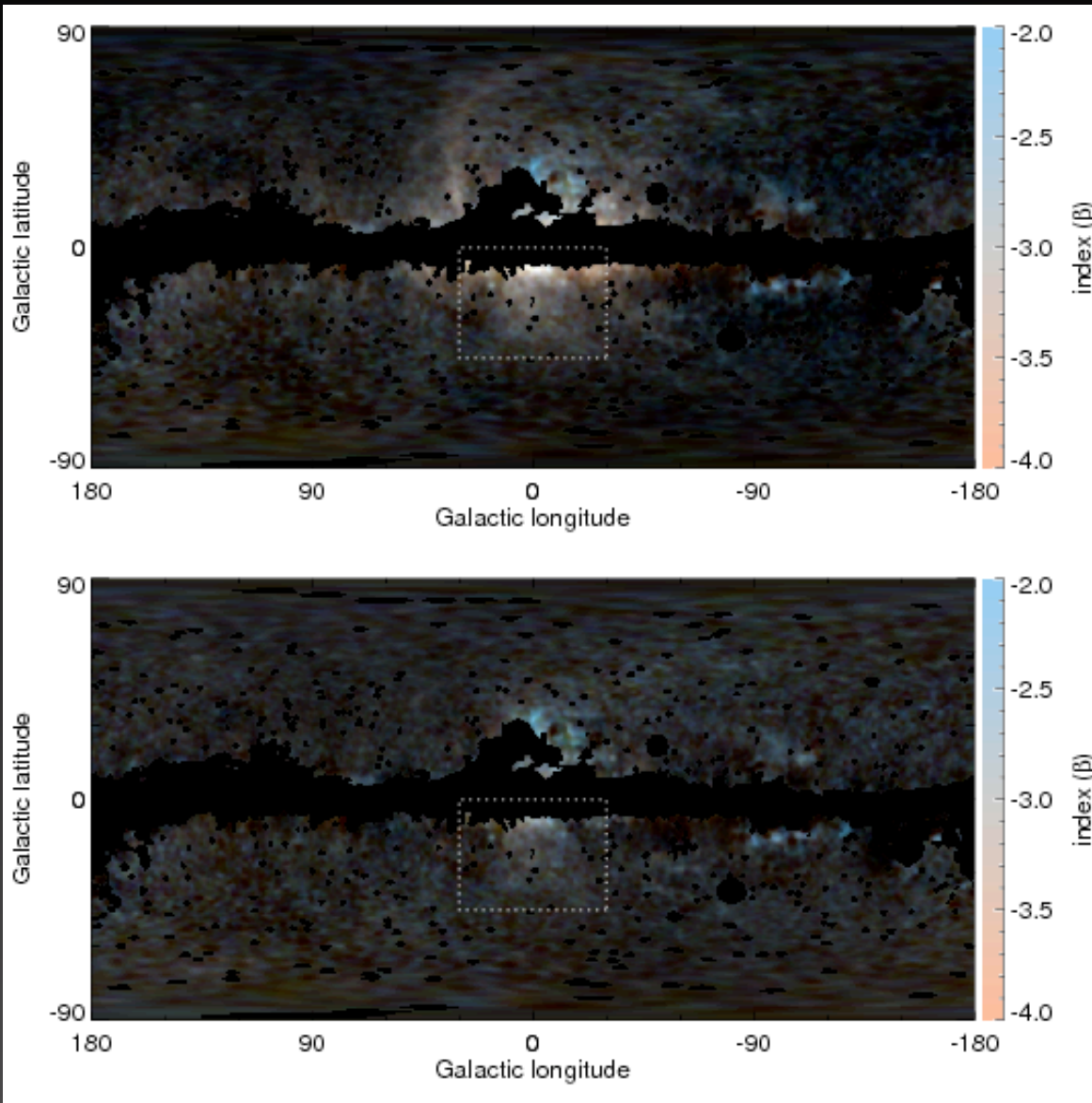
This ambiguity will be **eliminated** with *Planck*



the haze: facts

- foreground spectra have significant uncertainties
 - CMB cross-correlations (systematic)
 - template approximations
- spectrum is harder than synchrotron elsewhere in the galaxy
 - $I_{SN} \propto \nu^{-\alpha} \Rightarrow dN/dE \propto E^{-(2\alpha+1)}$
 - $I_{haze} \propto \nu^{-(\alpha-0.5)} \Rightarrow dN/dE \propto E^{-(2\alpha+1)}$

the haze: facts



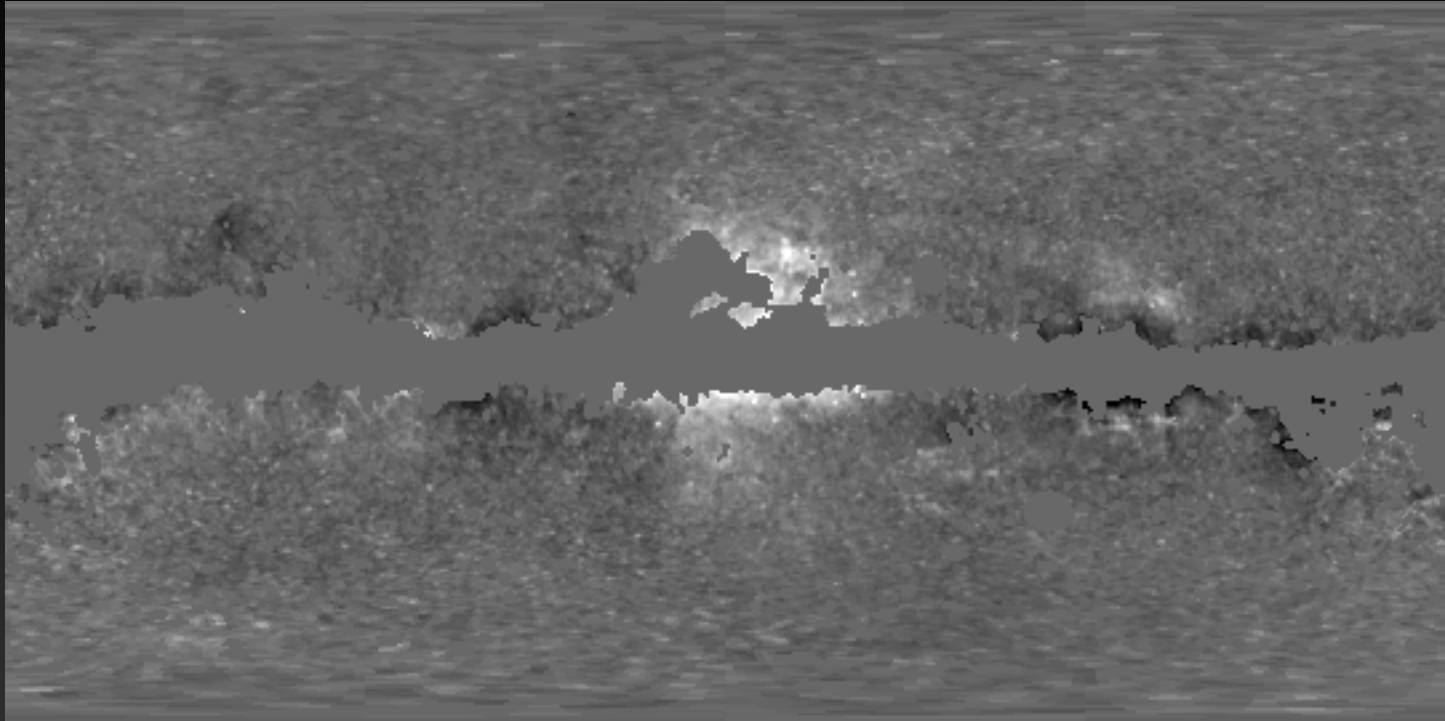
Dobler & Finkbeiner (2008)

the haze: facts

- spectra of foreground emissions have uncertainties
 - CMB cross-correlations (systematic)
 - template approximations
- spectrum is harder than synchrotron elsewhere in the galaxy
 - $I_{SN} \propto \nu^{-\alpha} \Rightarrow dN/dE \propto E^{-(2\alpha+1)}$
 - $I_{haze} \propto \nu^{-(\alpha-0.5)} \Rightarrow dN/dE \propto E^{-(2\alpha+1)}$
- morphology is **roughly** spherical, but there are inhomogeneities

the haze: facts

K-band: 23 GHz



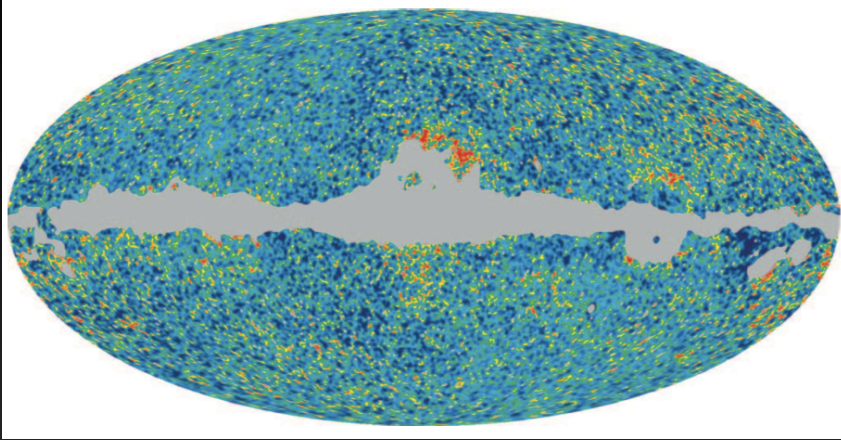
- WMAP - CMB - free-free
- (thermal and spinning) dust
- (soft) synchrotron

the haze: myths

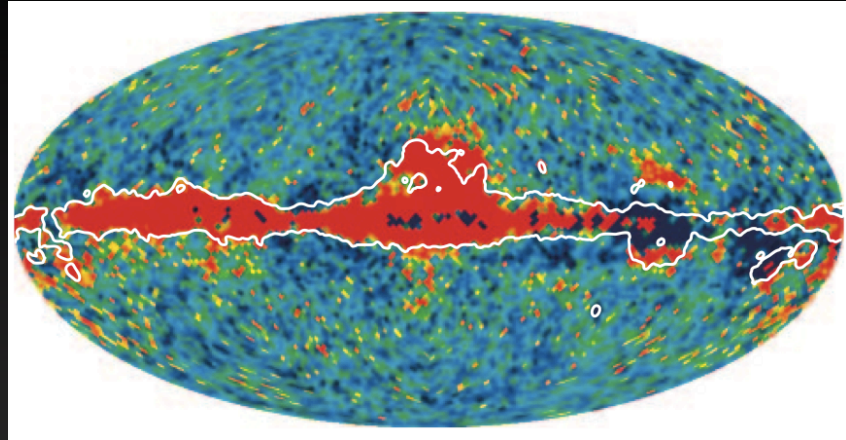
the haze...

. does not exist... nobody else sees it

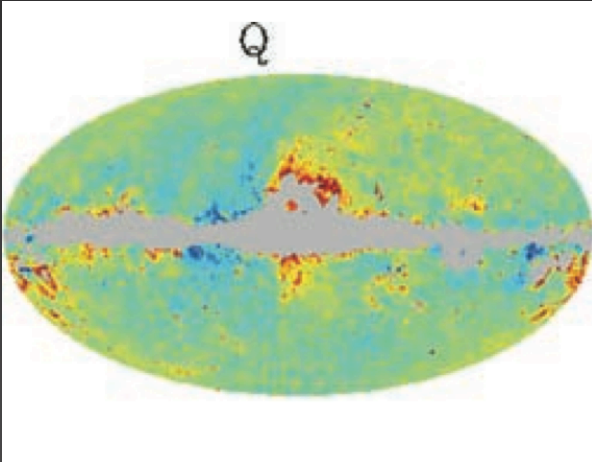
the haze: myths



Bennett et al, 2003



Hinshaw et al, 2007

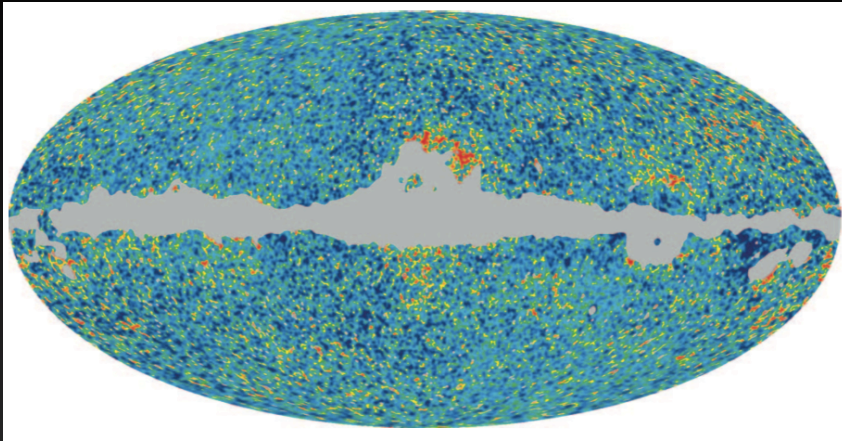


Bottino et al, 2008

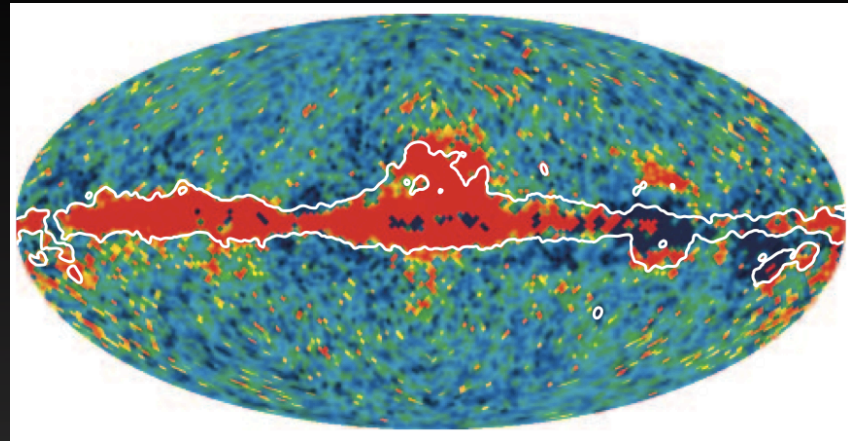
Template	Band	Mask			
		KQ85	KQ75	Kp0	Kp2
408 MHz	K	4.34 ± 0.08	4.24 ± 0.11	4.43 ± 0.13	4.57 ± 0.08
	Ka	1.67 ± 0.08	1.80 ± 0.11	1.88 ± 0.13	1.81 ± 0.08
	Q	1.02 ± 0.08	1.20 ± 0.11	1.26 ± 0.13	1.15 ± 0.08
	V	0.42 ± 0.08	0.64 ± 0.11	0.69 ± 0.13	0.55 ± 0.08
	W	0.25 ± 0.08	0.48 ± 0.11	0.52 ± 0.13	0.37 ± 0.08
H α	K	6.67 ± 0.09	6.76 ± 0.16	7.38 ± 0.14	8.52 ± 0.09
	Ka	3.87 ± 0.09	4.62 ± 0.16	4.49 ± 0.14	5.20 ± 0.09
	Q	2.82 ± 0.09	3.67 ± 0.16	3.37 ± 0.14	4.20 ± 0.09
	V	1.62 ± 0.09	2.50 ± 0.16	2.11 ± 0.14	2.74 ± 0.09
	W	1.19 ± 0.09	2.06 ± 0.16	1.64 ± 0.14	2.26 ± 0.09
FDS99 94GHz	K	6.03 ± 0.11	5.64 ± 0.11	5.58 ± 0.16	5.62 ± 0.09
	Ka	1.79 ± 0.11	1.15 ± 0.11	1.23 ± 0.16	1.33 ± 0.09
	Q	0.81 ± 0.11	0.11 ± 0.11	0.22 ± 0.16	0.30 ± 0.09
	V	0.36 ± 0.11	-0.36 ± 0.11	-0.25 ± 0.16	-0.18 ± 0.09
	W	0.89 ± 0.11	0.13 ± 0.11	0.26 ± 0.16	0.34 ± 0.09

Dickinson et al, 2009

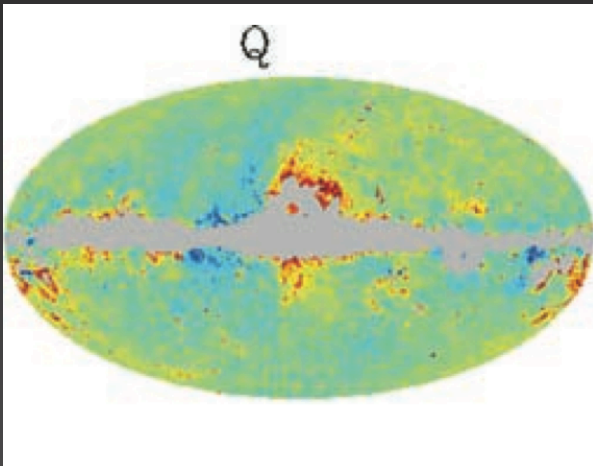
the haze: myths



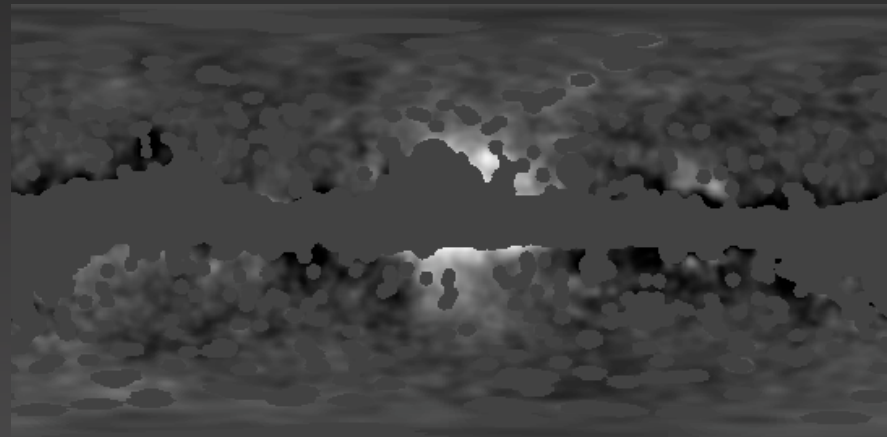
Bennett et al, 2003



Hinshaw et al, 2007



Bottino et al, 2008



Dickinson et al, 2009 (implied 23 GHz)

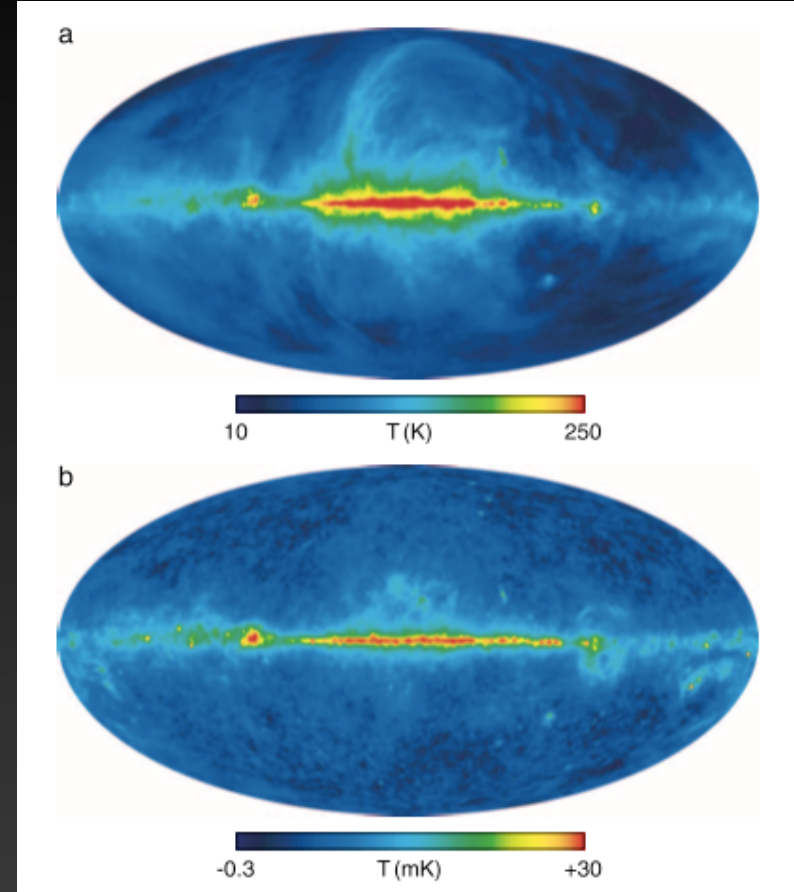
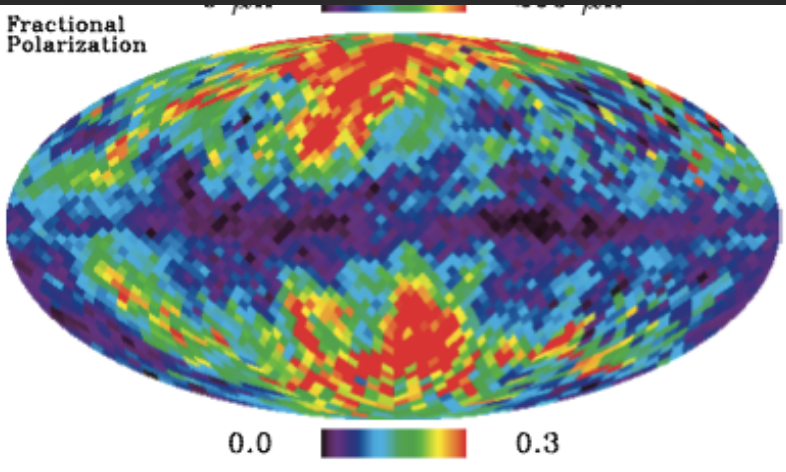
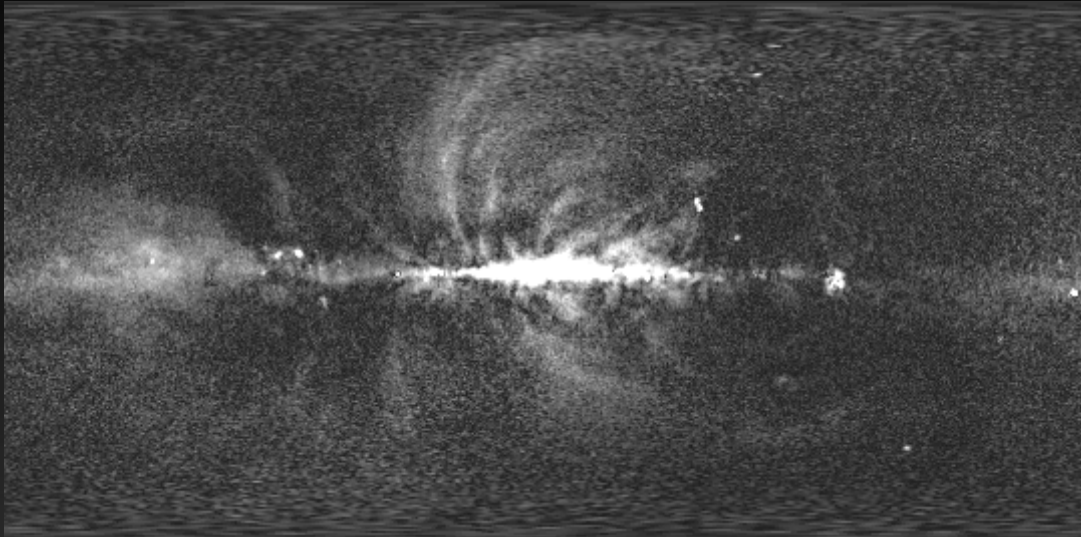
the haze: myths

the haze...

- . does not exist... nobody else sees it
- . should be strongly polarized

the haze: myths

WMAP 23 GHz polarized emission



Note: spinning dust is important when comparing to 23 GHz total intensity!

the haze: myths

the haze...

- . does not exist... nobody else sees it
- . should be strongly polarized
- . is easily explained by SNe

the haze: myths

the haze...

- . does not exist... nobody else sees it
- . should be strongly polarized
- . is easily explained by SNe
 - **diffused** haze spectrum is (roughly) as hard as fermi spectrum extending over $\sim (4 \text{ kpc})^3$ volume

the haze: myths

the haze...

- . does not exist... nobody else sees it
- . should be strongly polarized
- . is easily explained by SNe
- . is easily explained by pulsars

the haze: myths

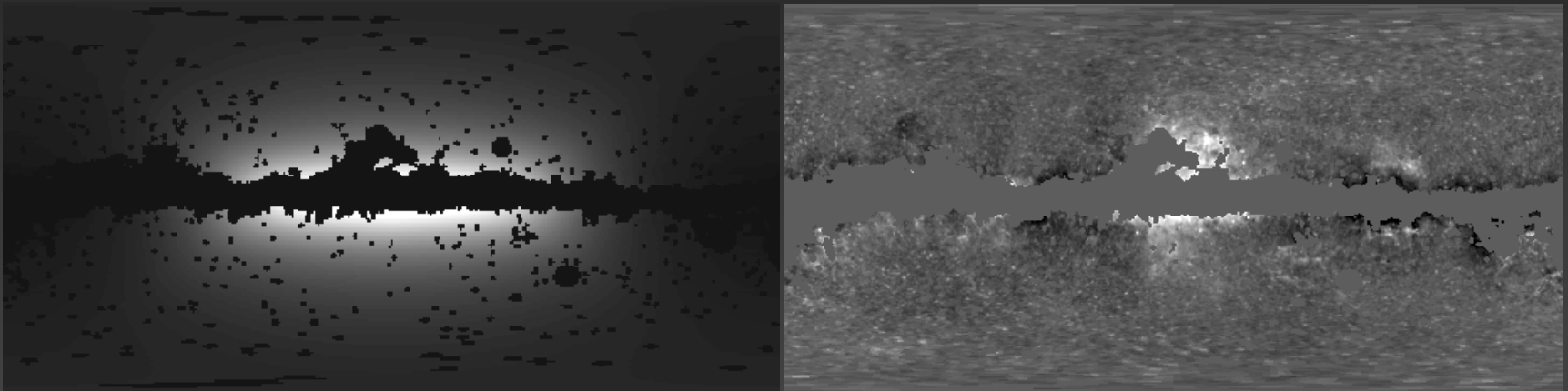
Injection spectrum :

$$dN/dE = N_0 \times f(E) \quad \text{with } N_0 = ??? \text{ and } f(E) = ???$$

⇒ can (likely) fit the haze spectrum

Spatial distribution :

$$\ln \rho(r,z) = -r/r_0 - |z|/z_0 \quad \text{with } r_0 = 4.5 \text{ kpc and } z_0 = 0.08 \text{ kpc}$$



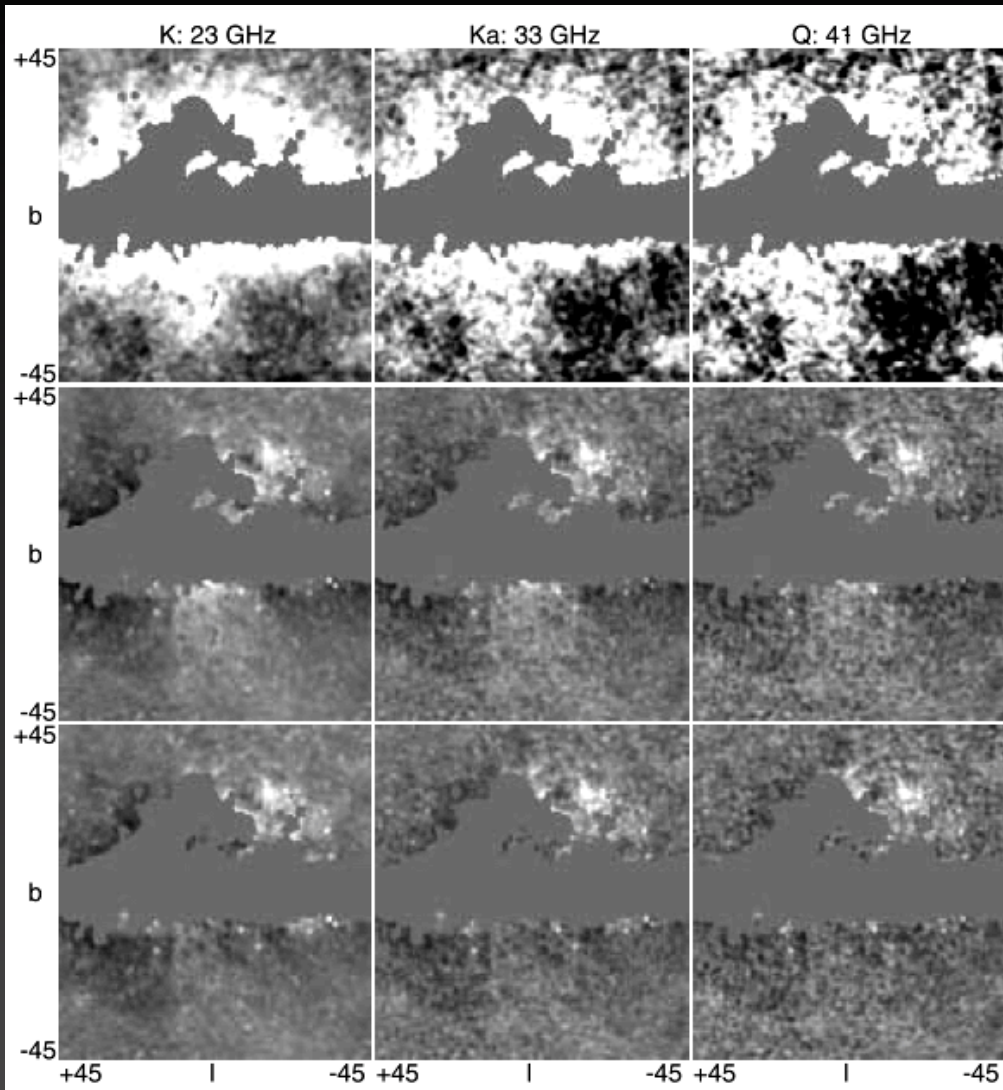
⇒ cannot fit the morphology

the haze: myths

the haze...

- . does not exist... nobody else sees it
- . should be strongly polarized
- . is easily explained by SNe
- . is easily explained by pulsars
- . is easily explained by small spectral index variation of Haslam

the haze: myths



WMAP data

w/o haze
template

w/ haze
template

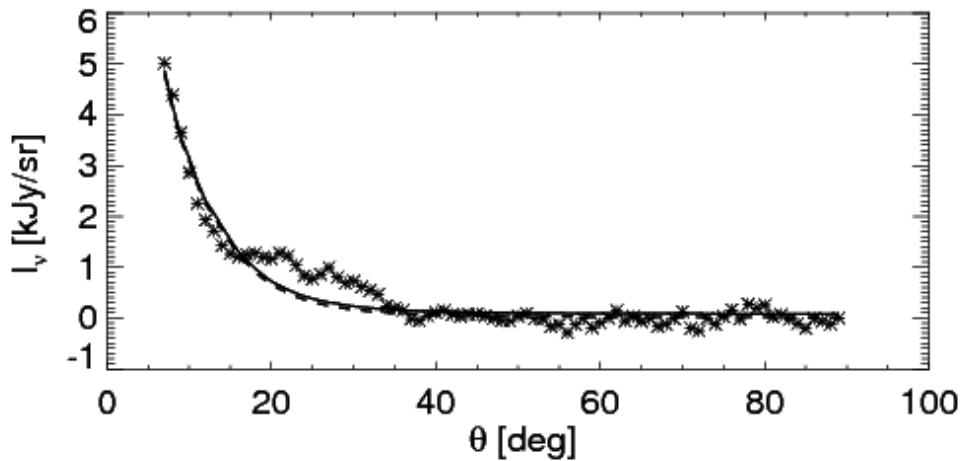
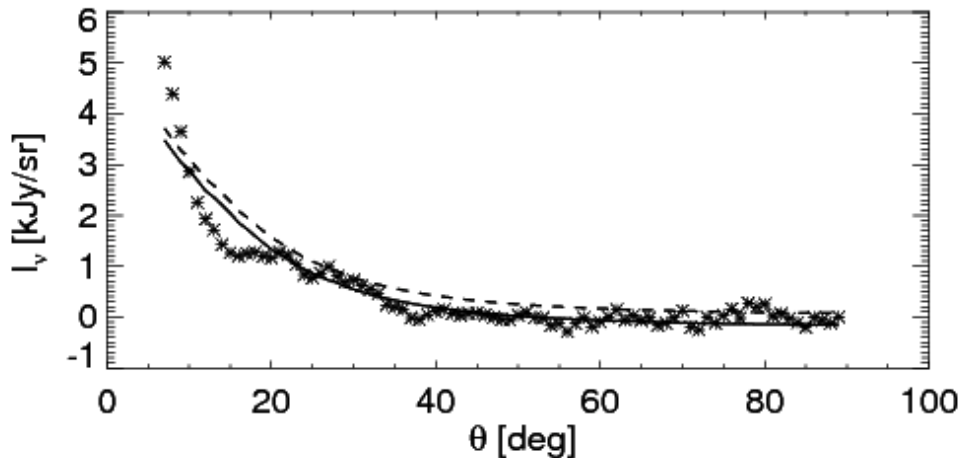
the haze is morphologically distinct from Haslam

the haze: myths

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- . is easily explained by SNe
- . is easily explained by pulsars
- . is easily explained by small spectral index variation of Haslam
- . is direct evidence of particle DM annihilation

the haze: myths



Galactic/baryon params:

$$B \sim 10 \mu\text{G}$$

$$K(E) \sim 10^{28} \text{ cm}^2/\text{s}$$

Dark matter params:

$$\rho = \rho(r)$$

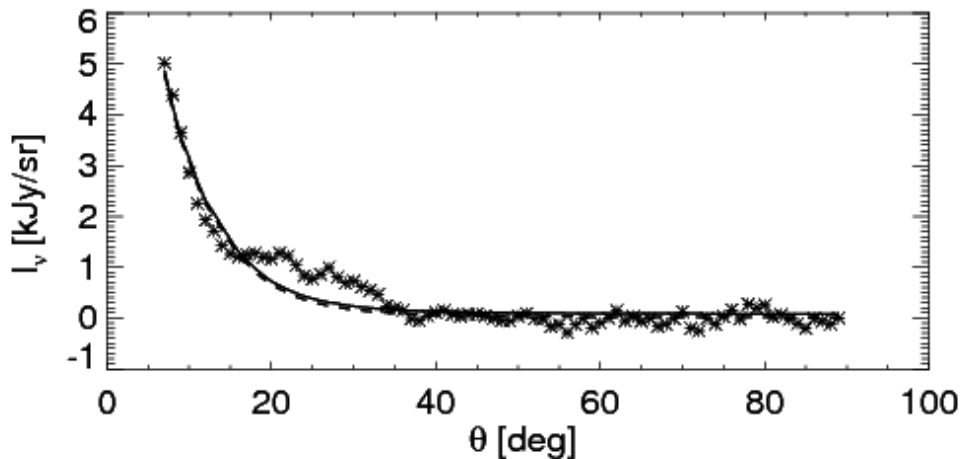
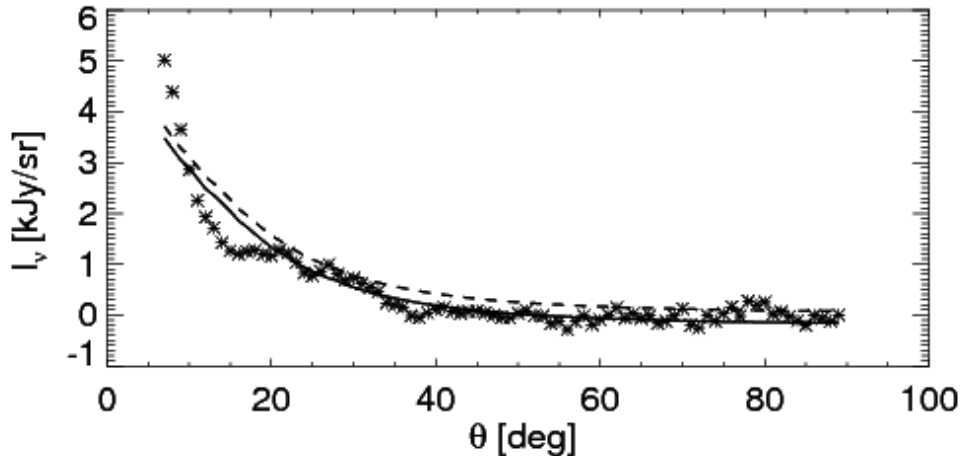
$$M \sim 100 \text{ GeV}$$

$$\langle\sigma v\rangle \sim \text{few } \times 10^{-26} \text{ cm}^3/\text{s}$$

the haze is

consistent with a
WIMP annihilation
scenario

the haze: myths



Galactic/baryon params:

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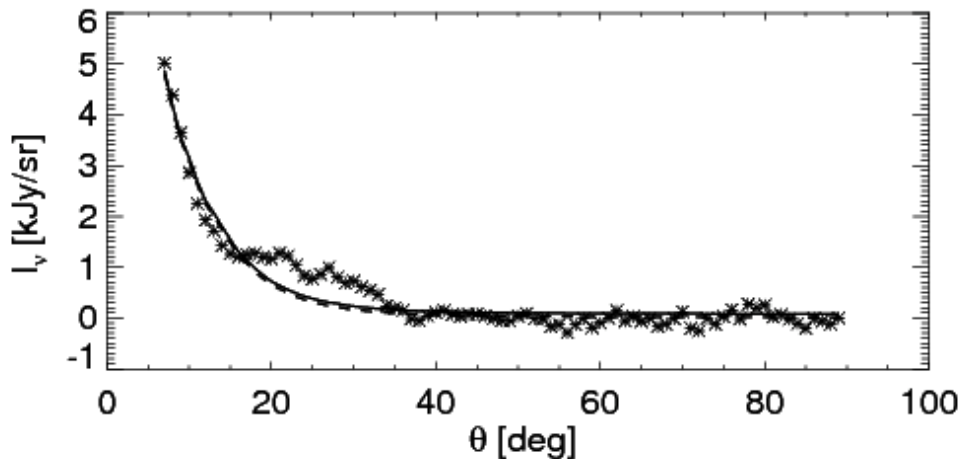
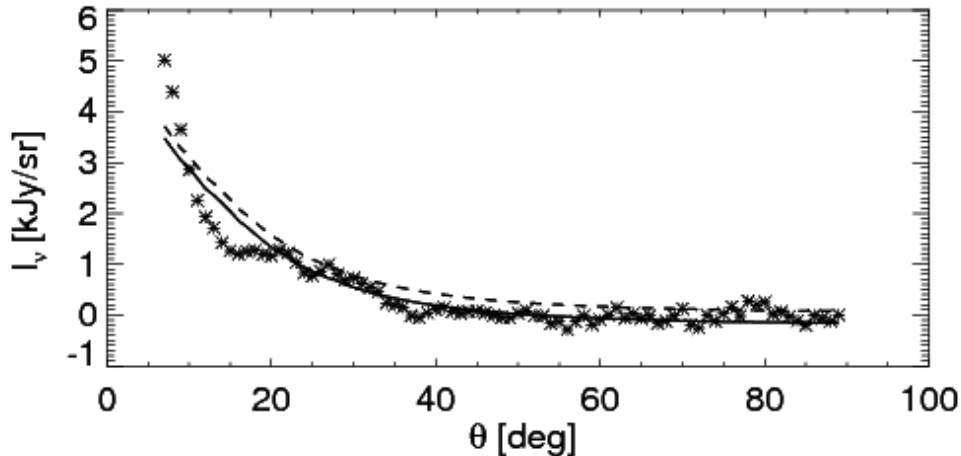
but again... there are large astrophysical uncertainties!

the haze: myths

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- . should be strongly polarized
- . is easily explained by SNe
- . is easily explained by pulsars
- . is easily explained by small spectral index variation of Haslam
- . is direct evidence of particle DM annihilation
- . DM model over-produces synchrotron at high latitudes

the haze: myths



Galactic/baryon params:

$$B \sim 10 \mu\text{G}$$

$$K(E) \sim 10^{28} \text{ cm}^2/\text{s}$$

Dark matter params:

$$\rho = \rho(r)$$

$$M \sim 100 \text{ GeV}$$

$$\langle\sigma v\rangle \sim \text{few } \times 10^{-26} \text{ cm}^3/\text{s}$$

the haze is **consistent** with a WIMP annihilation scenario

but again... there are large astrophysical uncertainties!

comments and the future of the haze

. boundary conditions

- $dN/dE \rightarrow 0$ at boundary not very realistic
- spherical halo with $K(E) \rightarrow K(E,r,z)$

. full astro-uncertainties analysis for cross section and masses

- Galactic magnetic field: ≥ 2 (amplitude, shape, turbulence, etc.)
- ISRF: $\sim 1.2-1.5$ (see *Porter et al, 2008*)
- DM halo shape: ??? (local density ~ 2 , radial profile, sub-[sub-]structures $\sim 5-10$)
- uncertainties in haze analysis, etc...

. *Fermi* ICS emission towards the GC (regardless of origin)

. *Planck* spectral index measurements

