The WMAP Haze:

Particle Physics versus Astrophysics

Greg Dobler

Harvard/CfA

July 14th, 2009 - TeV09

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Particle Physics versus Astrophysics

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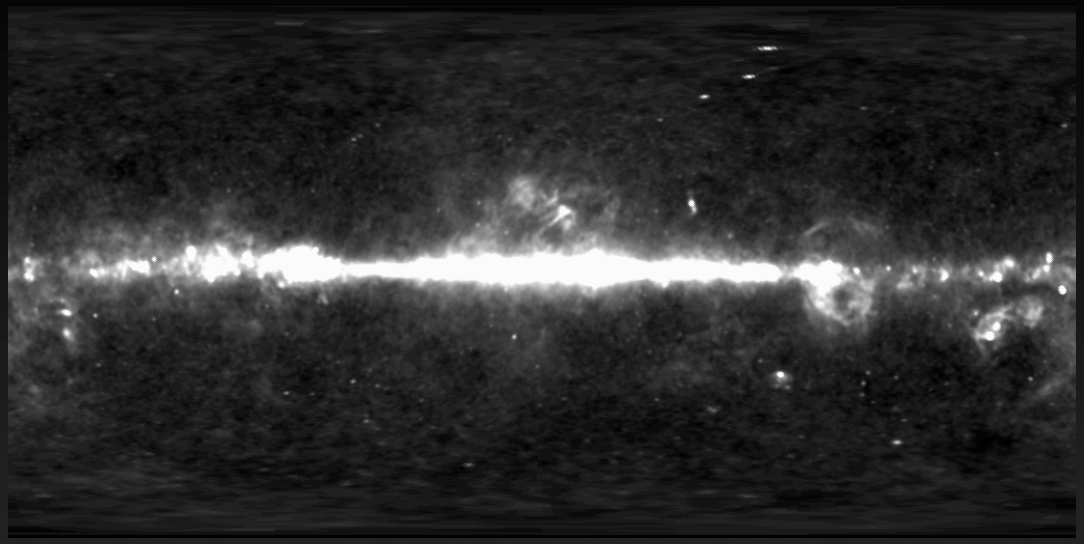
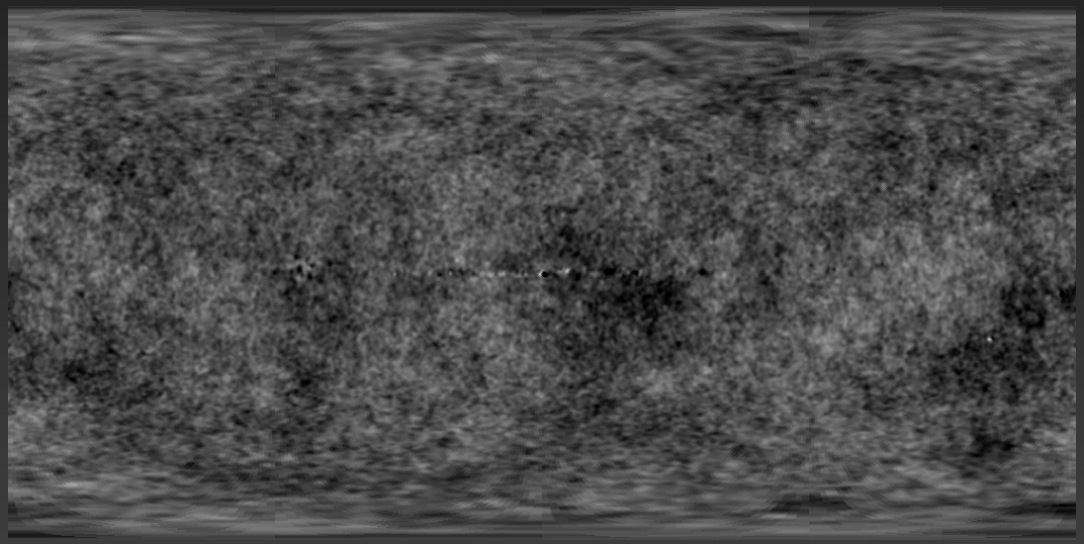
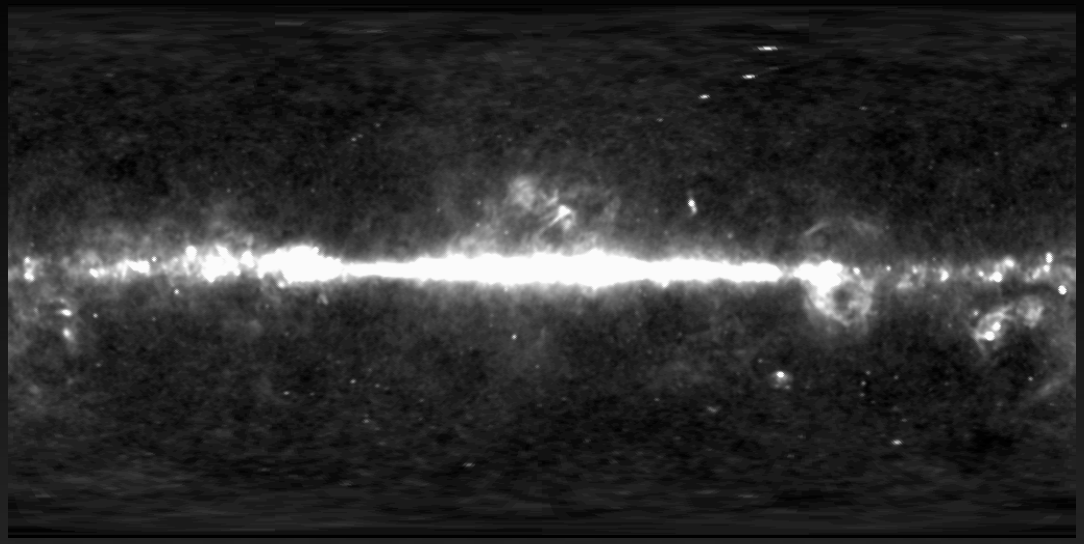
WMAP

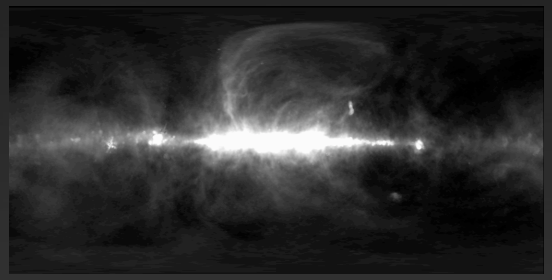




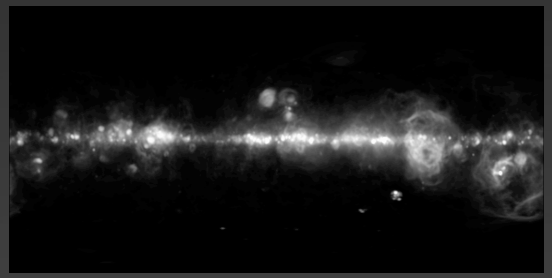
WMAP

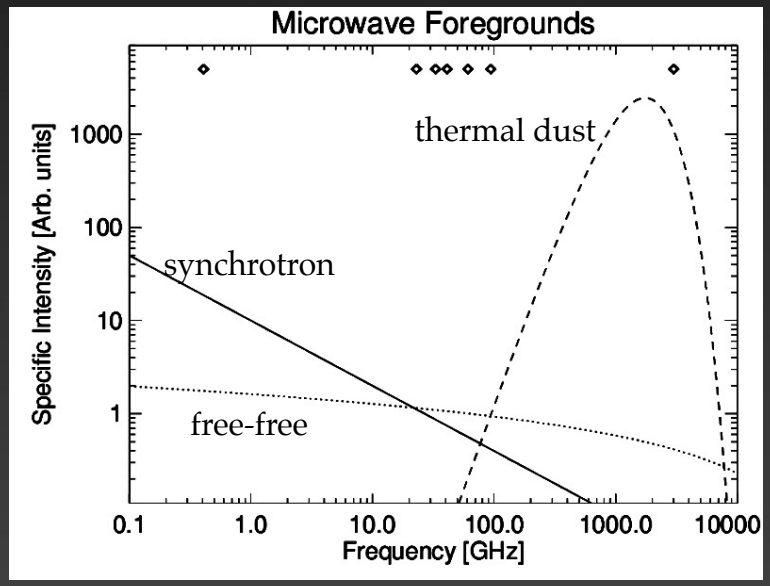


Haslam et al. (1982)

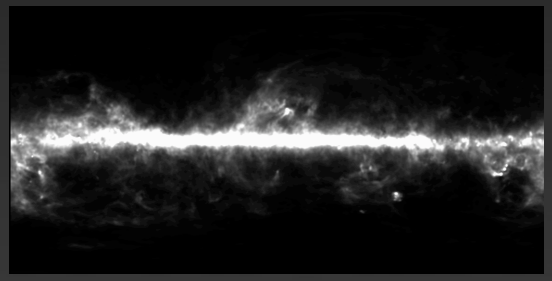


Hα *(Finkbeiner, 2003)*

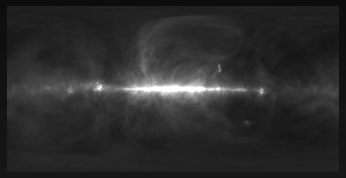
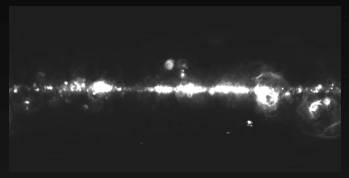
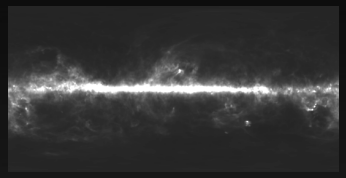




Finkbeiner et al. (1999)



template fitting

s_{23} x  + f_{23} x  + d_{23} x 

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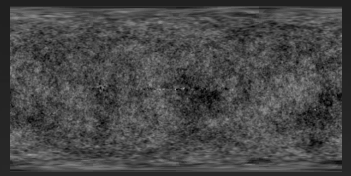
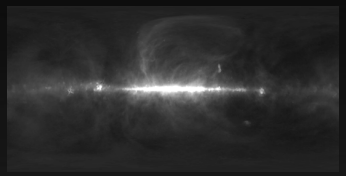
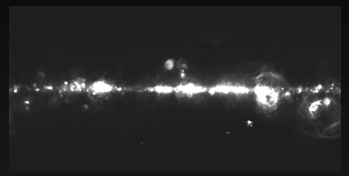
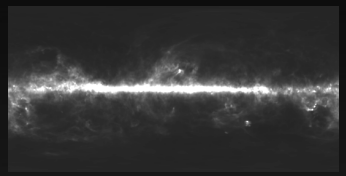
- c_{23} x 

template fitting

s_{23} x  + f_{23} x  + d_{23} x 

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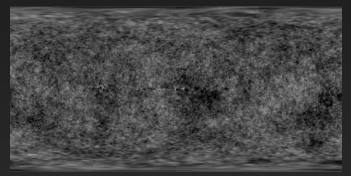
- c_{23} x 

$s(\nu_i)$, $f(\nu_i)$, $d(\nu_i)$ 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

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

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

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

Dobler & Finkbeiner, 2008

TEMPLATES

- Synchrotron: Haslam et al (*1982*)
- Dust: FDS99 (*Finkbeiner et al 1999*)
- Free-free: Hα 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

determining foreground spectra

Multi-Linear Regression
Template Fit

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

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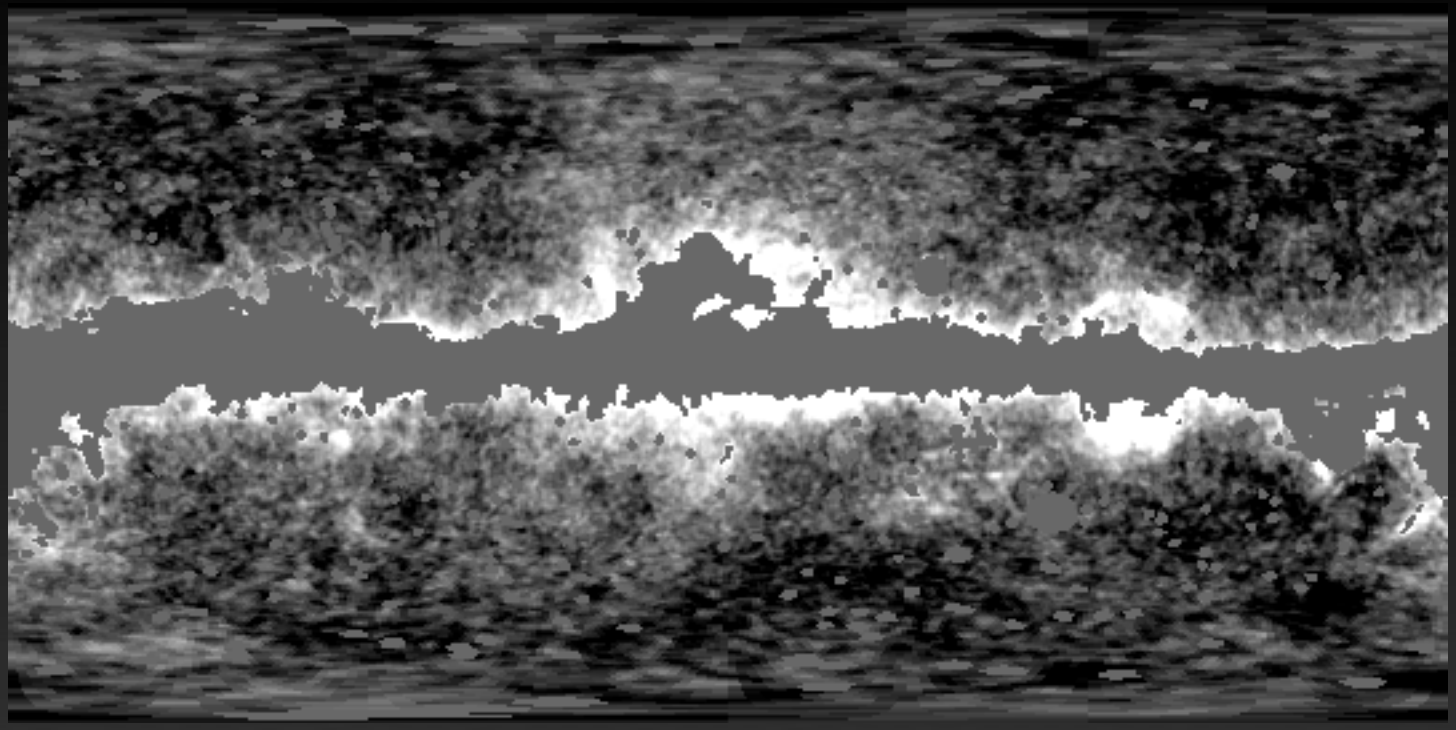
Dobler & Finkbeiner, 2008

publicly available IDL library ***coming soon***!

peeling away foregrounds

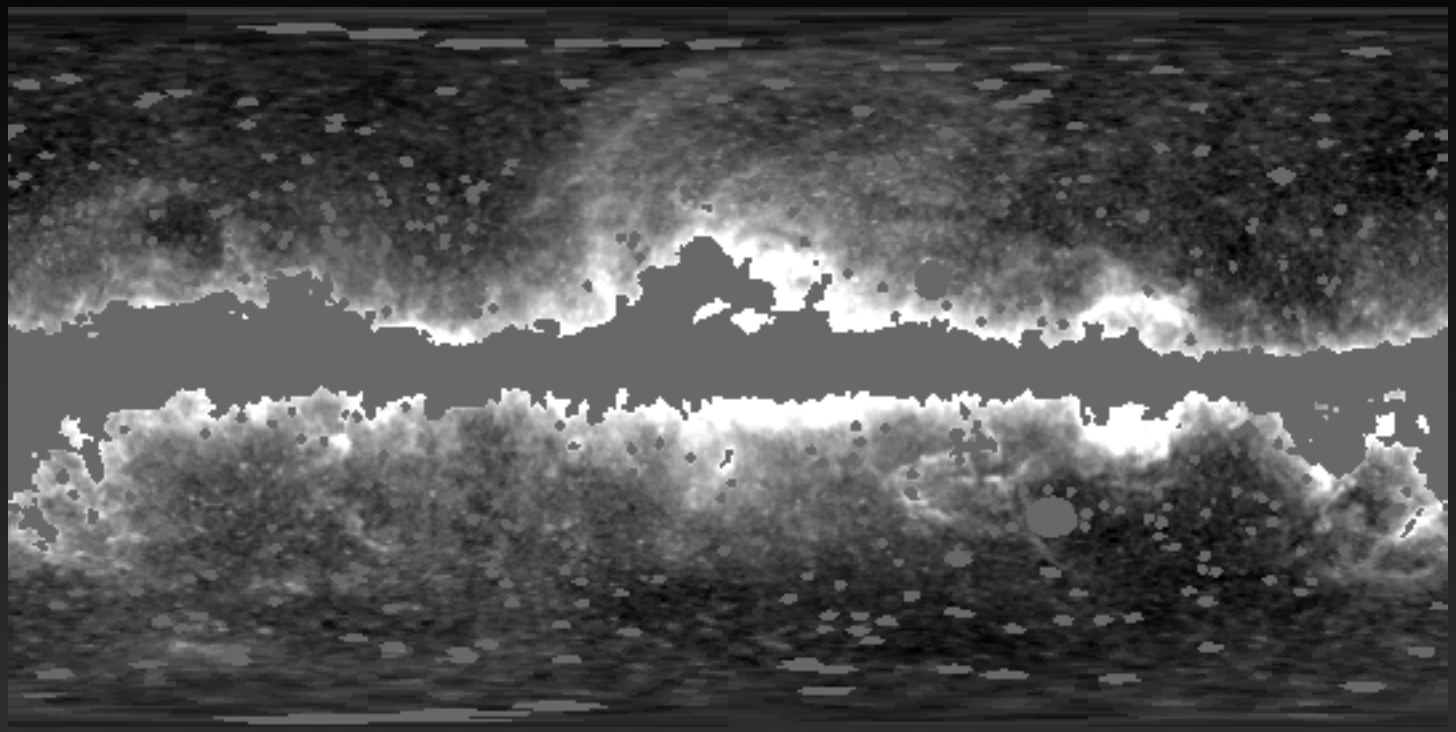
K-band: 23 GHz



WMAP

peeling away foregrounds

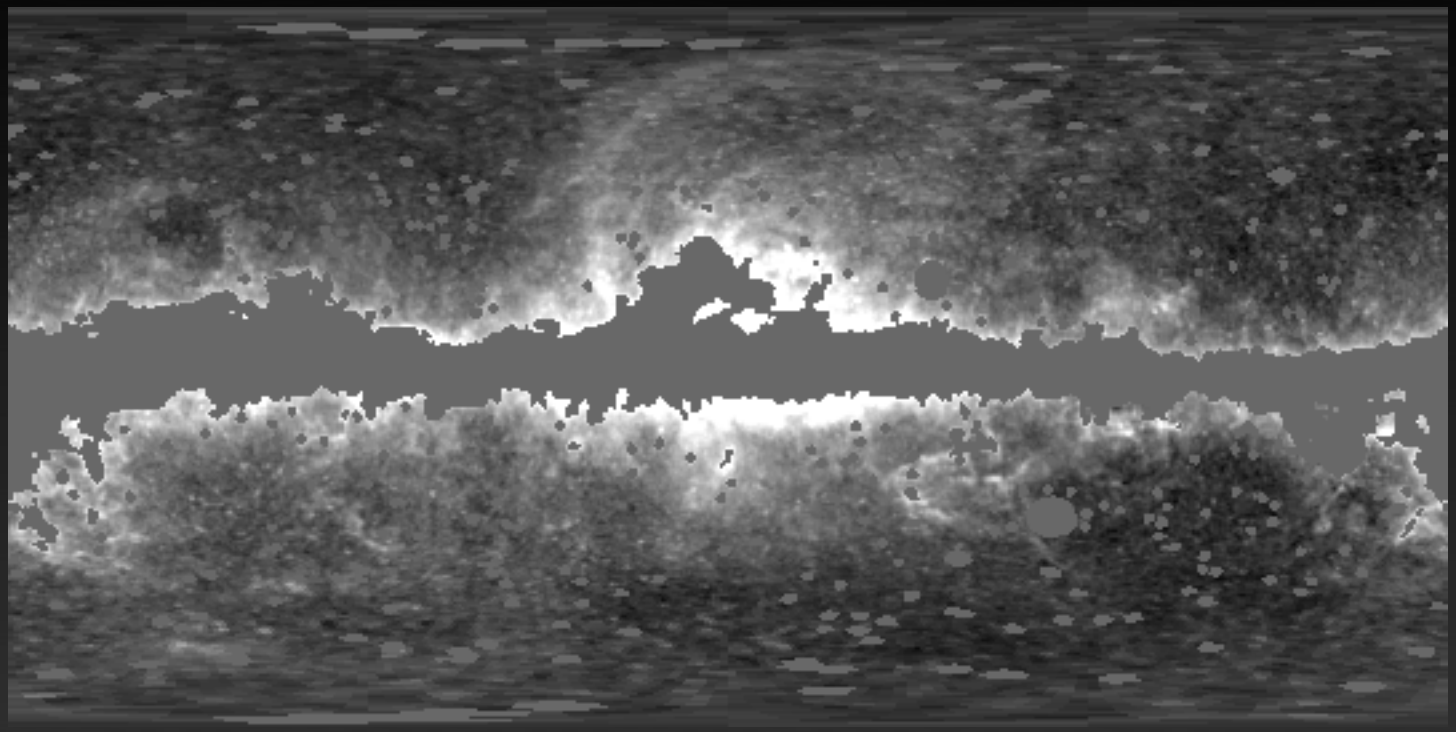
K-band: 23 GHz



WMAP - CMB

peeling away foregrounds

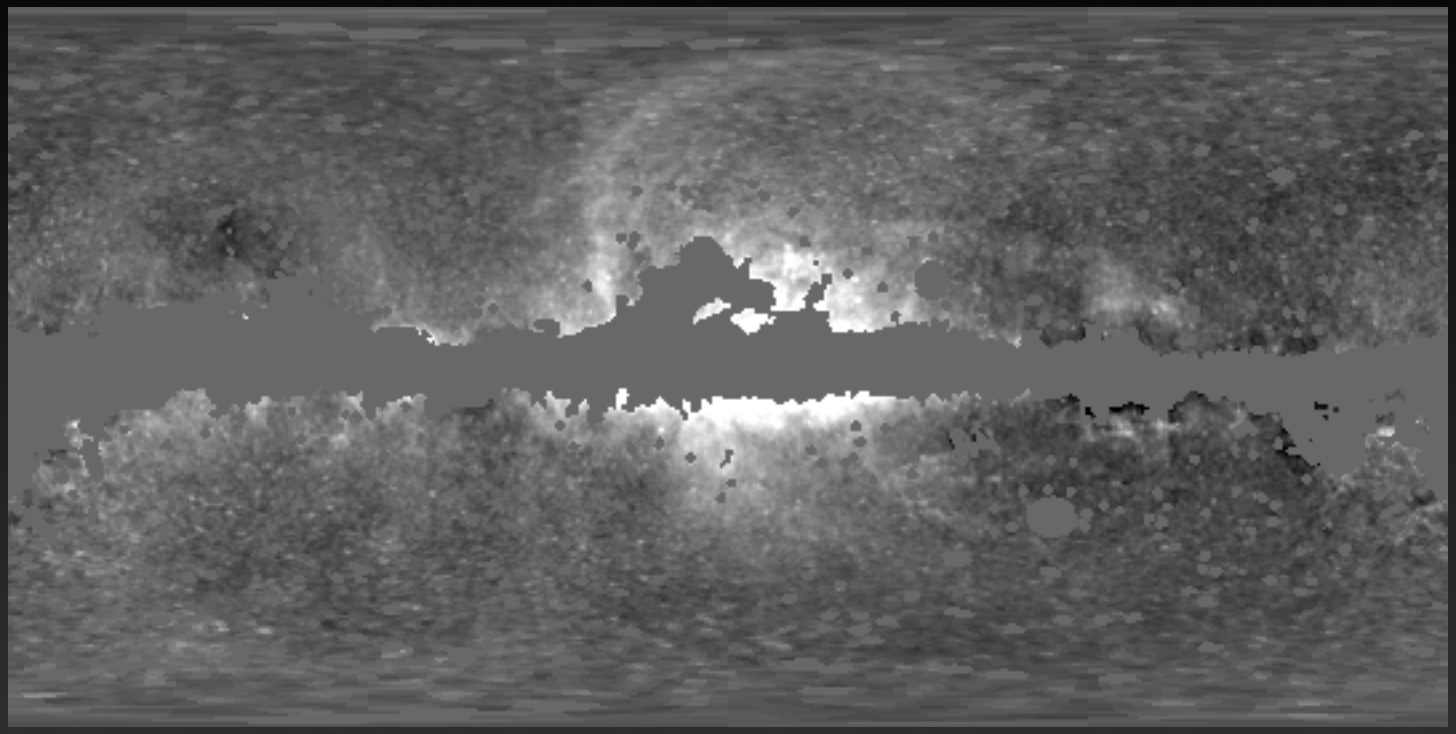
K-band: 23 GHz



WMAP - CMB - free-free

peeling away foregrounds

K-band: 23 GHz

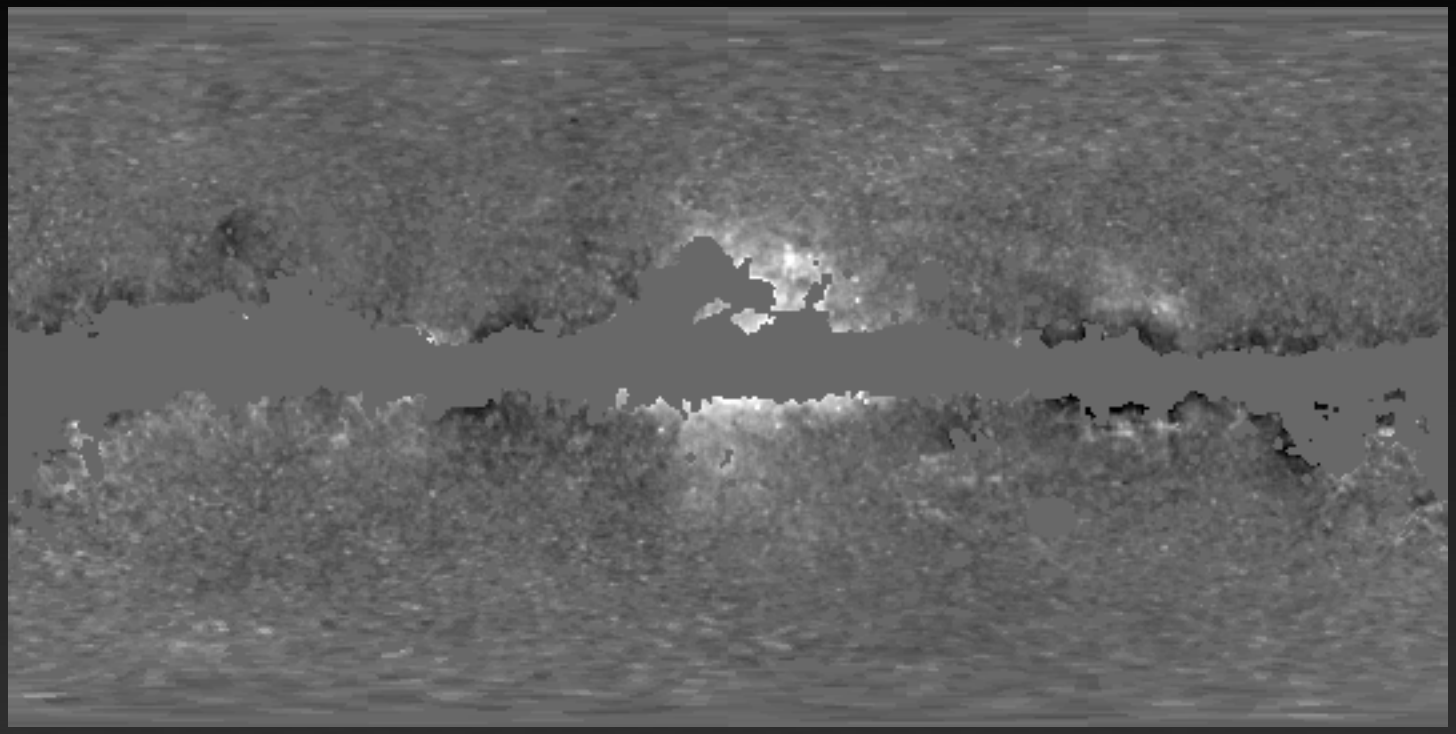


WMAP - CMB - free-free

- (thermal and spinning) dust

peeling away foregrounds

K-band: 23 GHz

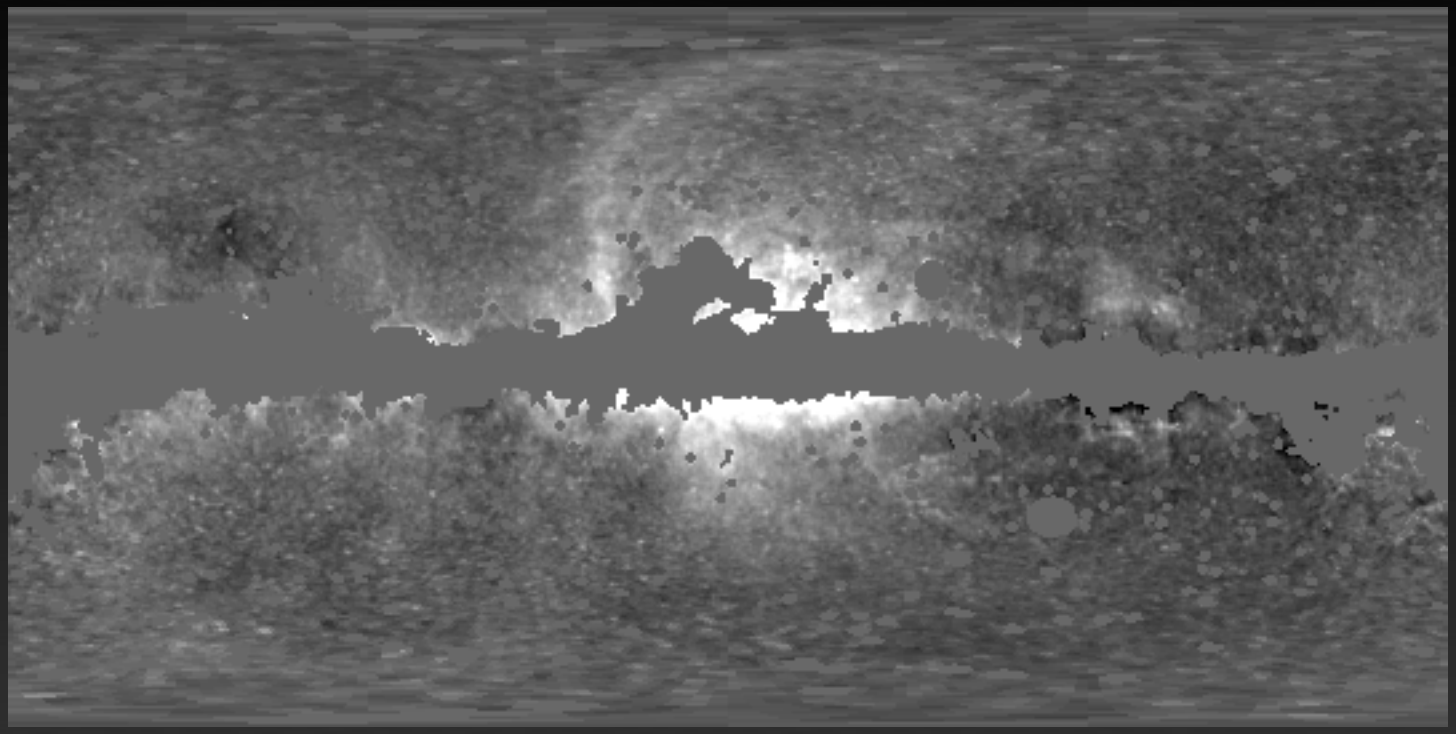


WMAP - CMB - free-free

- (thermal and spinning) dust
- (soft) synchrotron

the haze spectrum

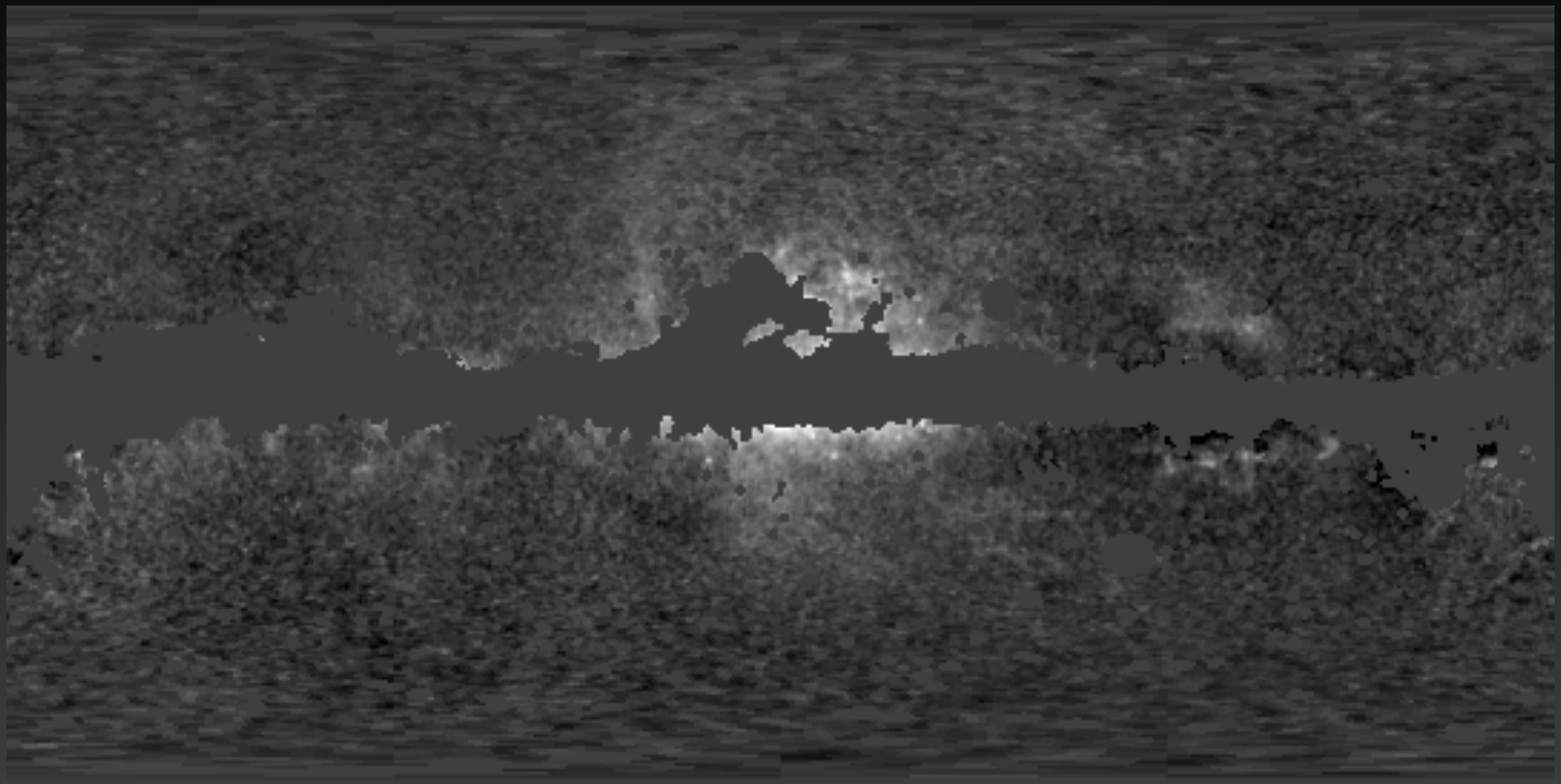
K-band: 23 GHz



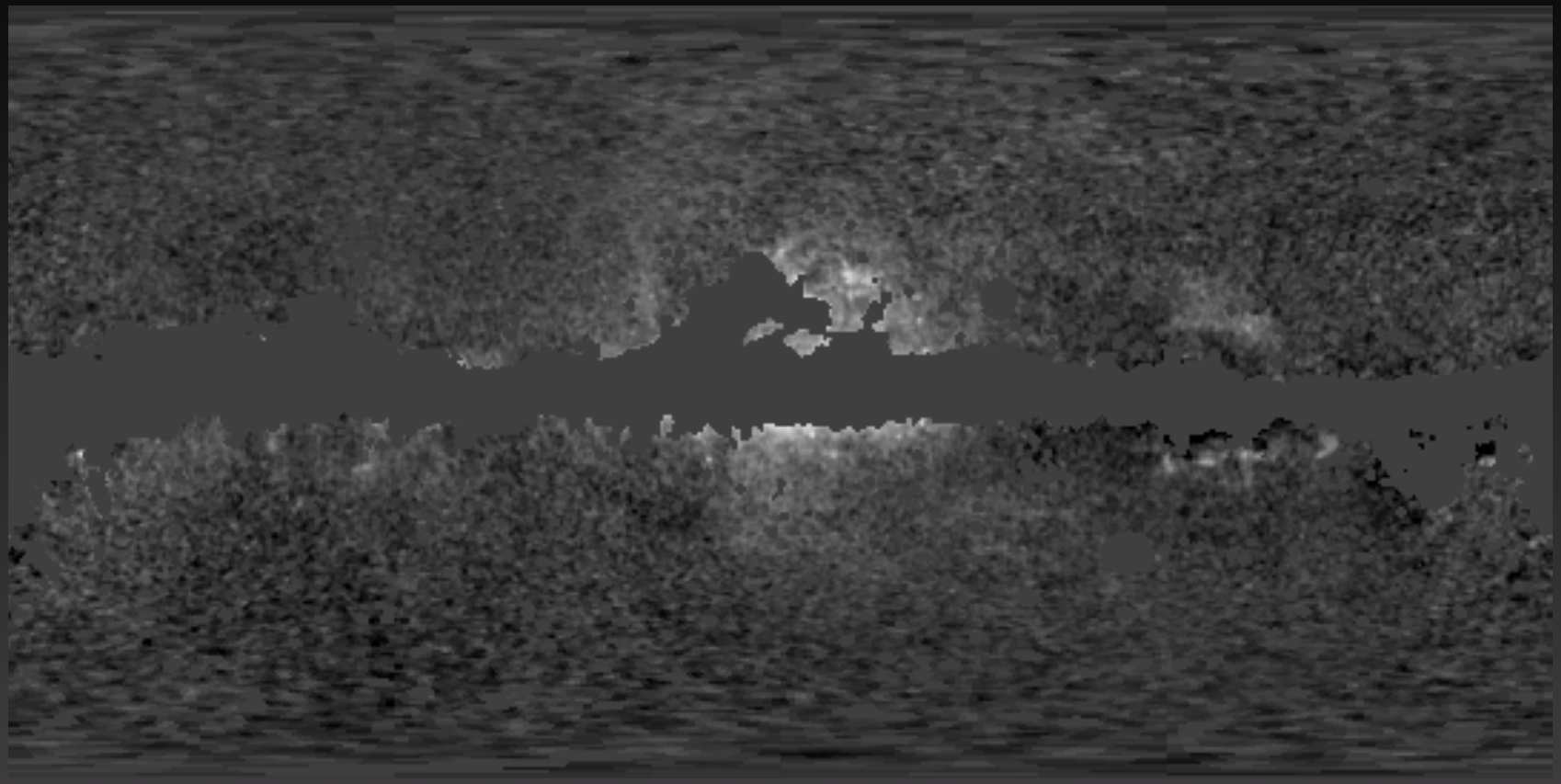
WMAP - CMB - free-free

- (thermal and spinning) dust

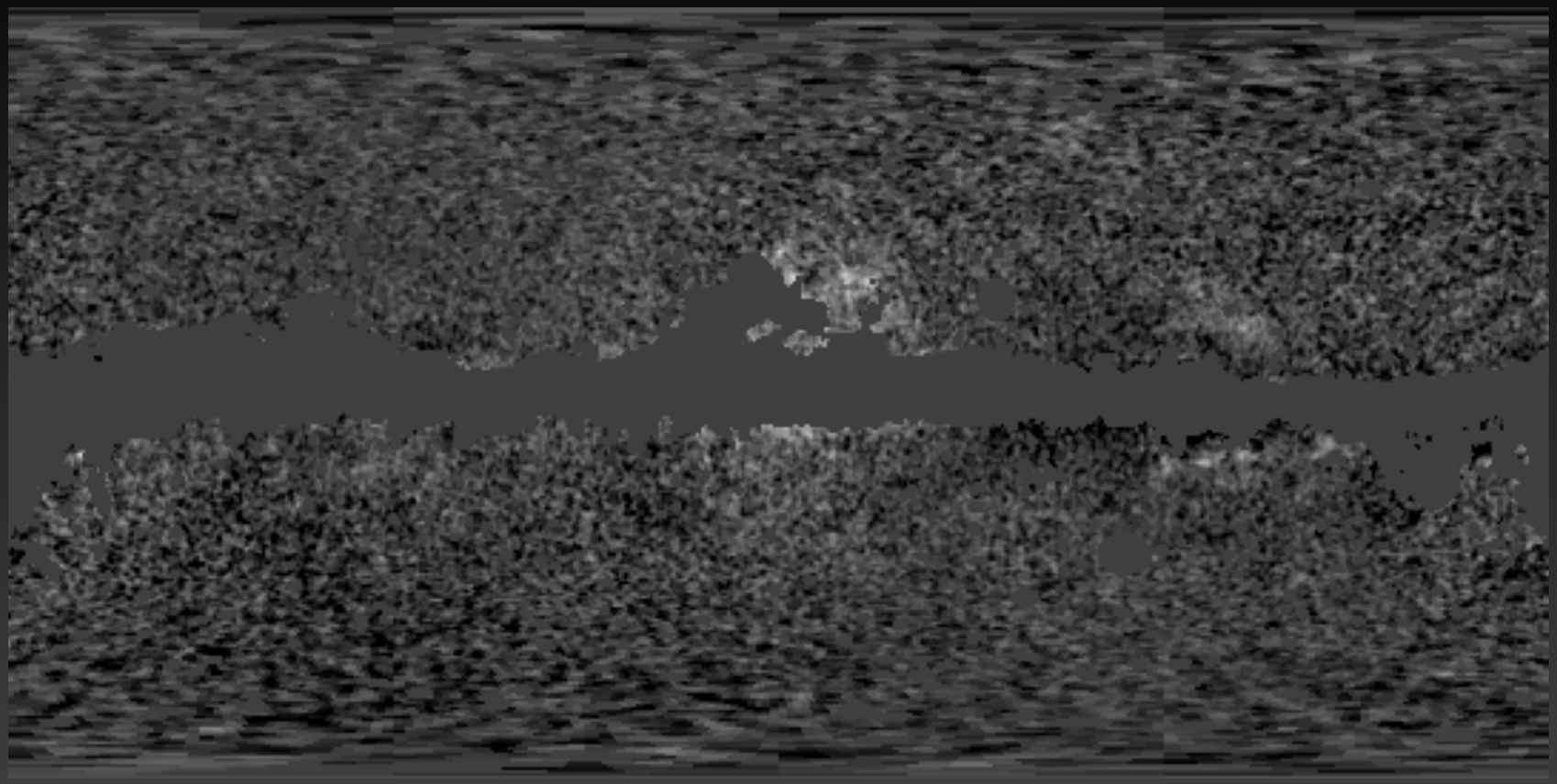
23 GHz Synchrotron



33 GHz Synchrotron

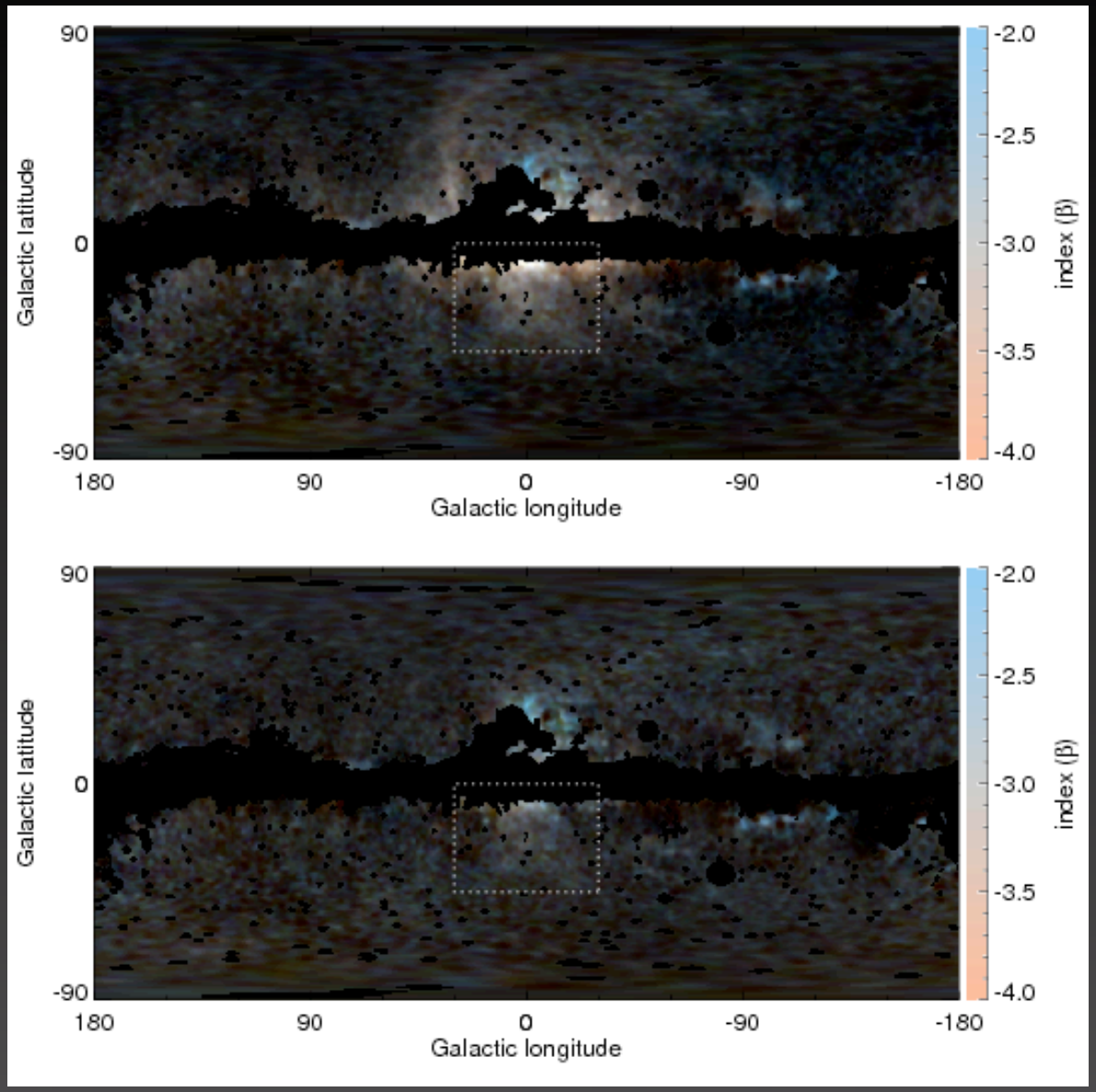


41 GHz Synchrotron



61 GHz Synchrotron

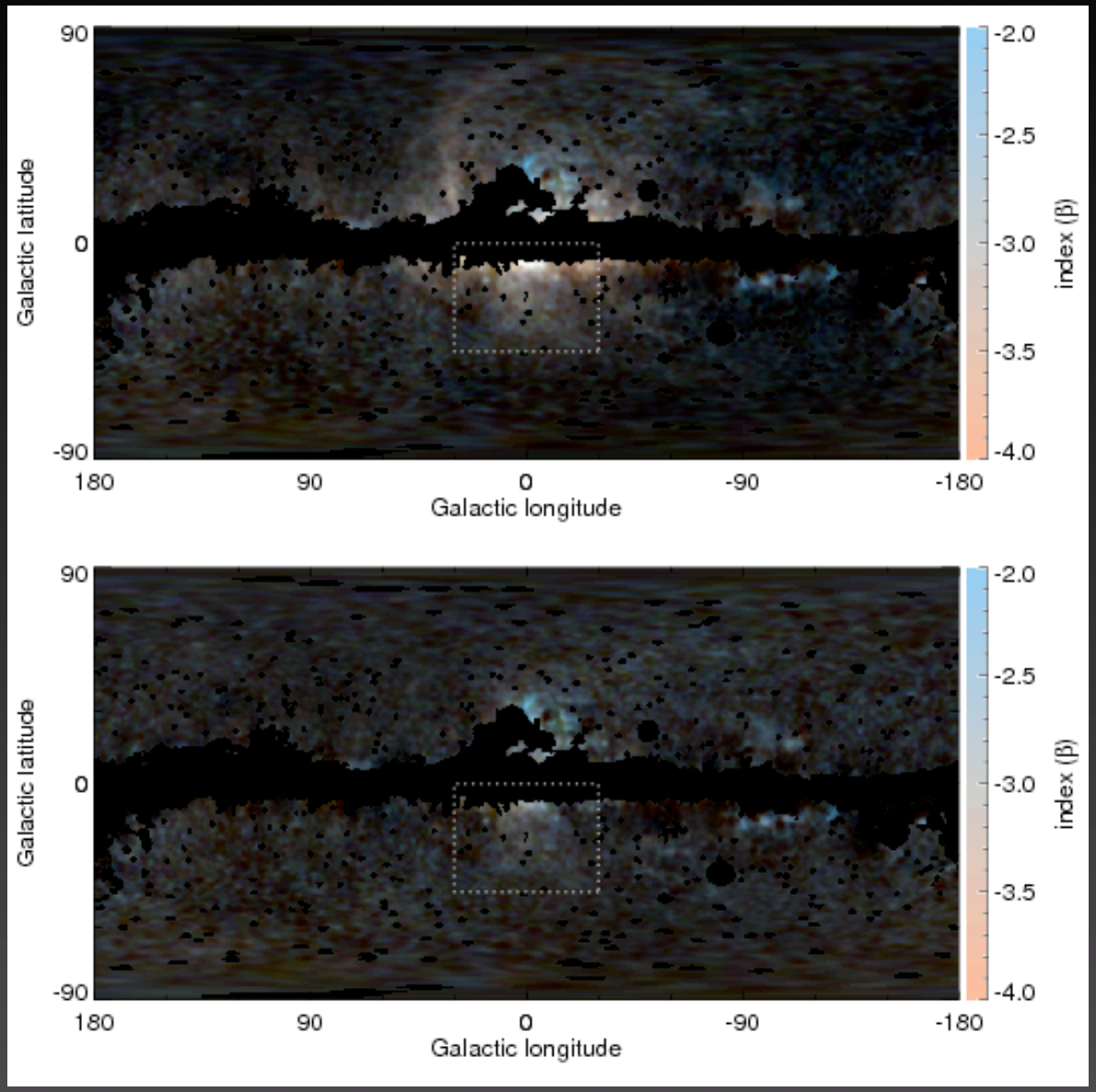
the haze spectrum



- 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

Dobler & Finkbeiner (2008)

the haze spectrum

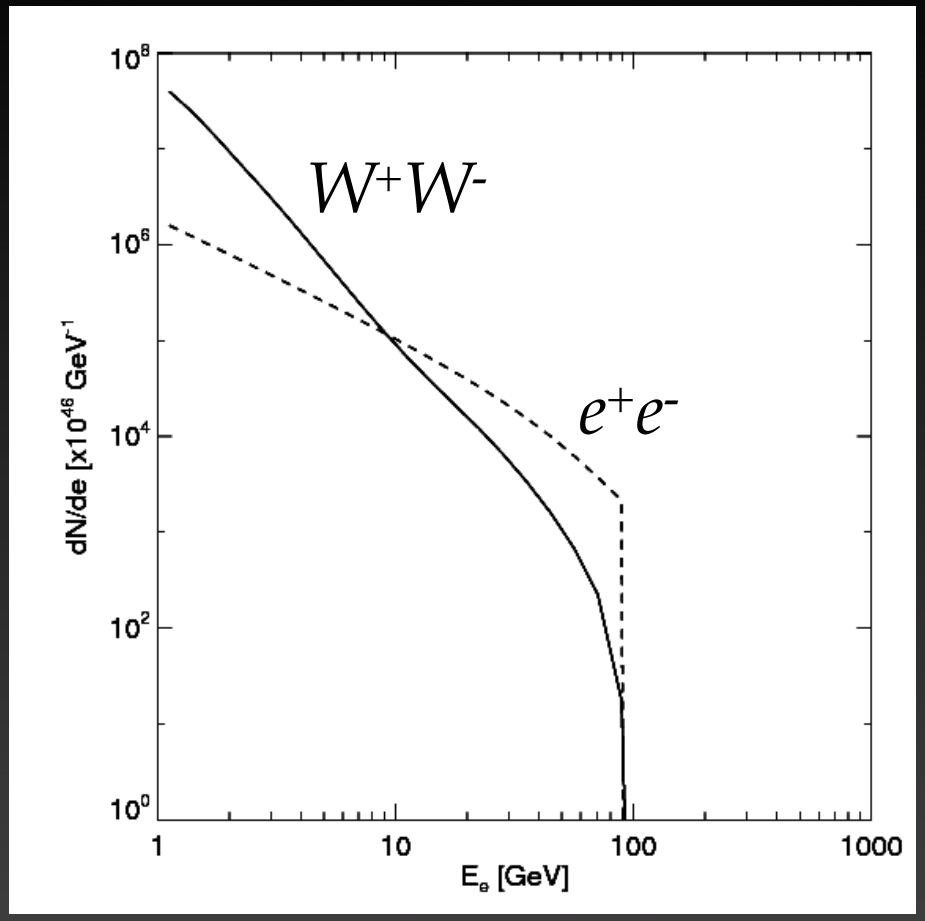


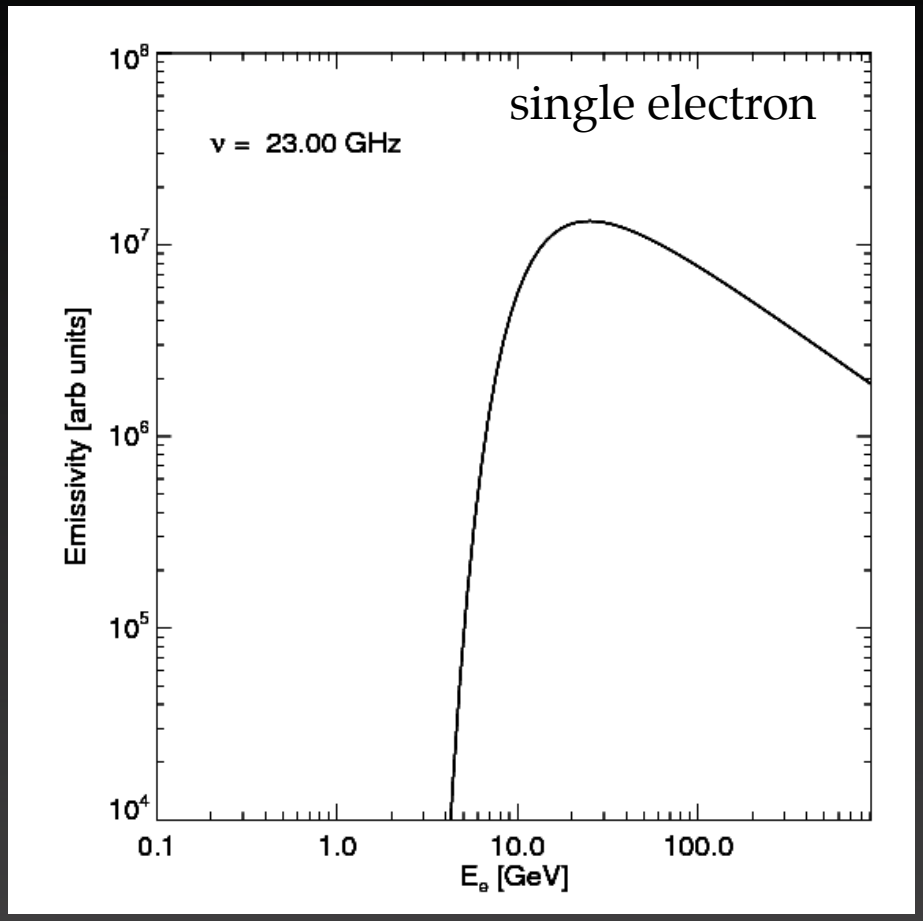
implication:

the (diffuse) cosmic-ray e^+e^- spectrum is **harder** at ***~10-100* GeV** towards the GC than elsewhere in the Galaxy

Dobler & Finkbeiner (2008)

dark matter and the haze

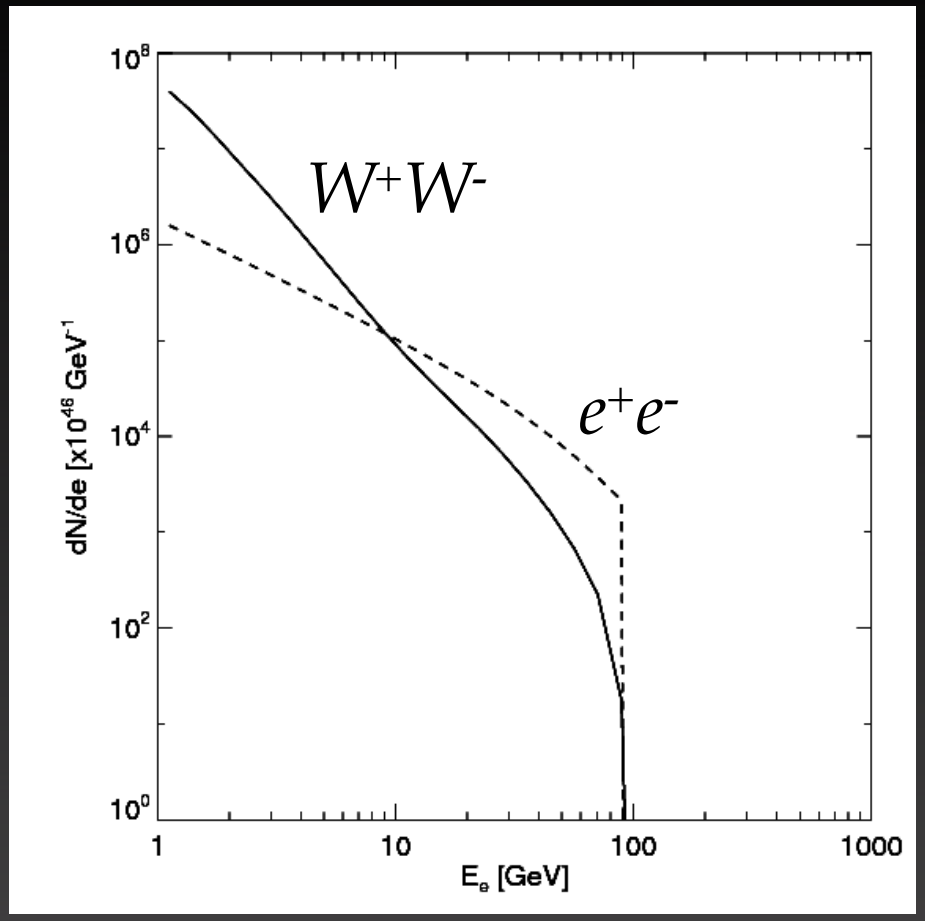


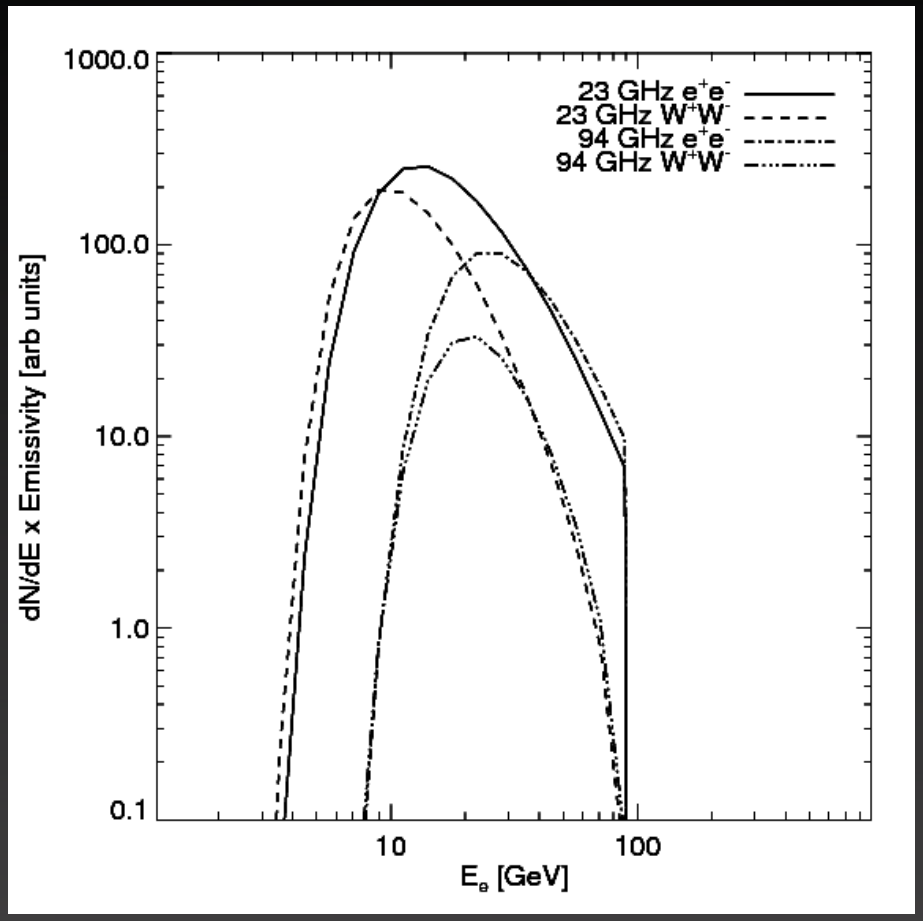


spherical shell:
r = *8.4* kpc, *dr* = *0.1* kpc

~*10-100* GeV electrons are dominant contribution to *23* GHz synchrotron emission

dark matter and the haze





e^+e^- channel yields ~10x more emission at 23 GHz compared to W^+W^-

spherical shell:
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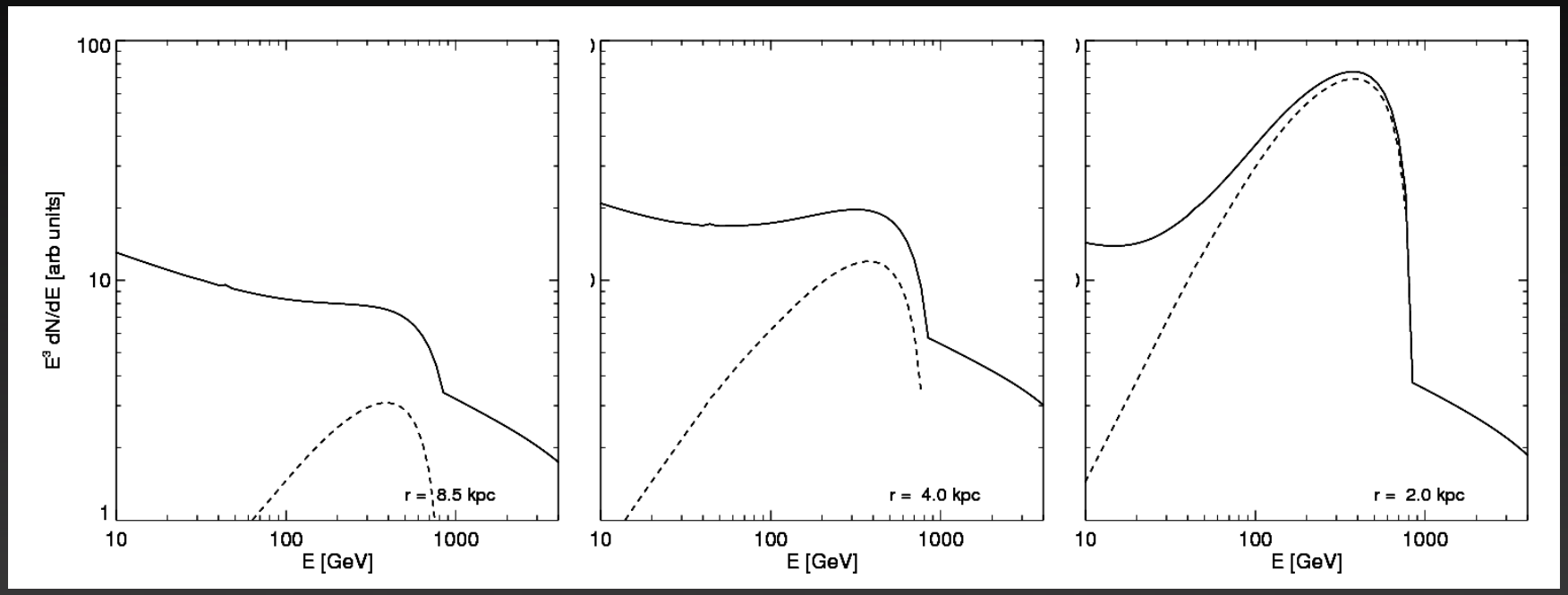
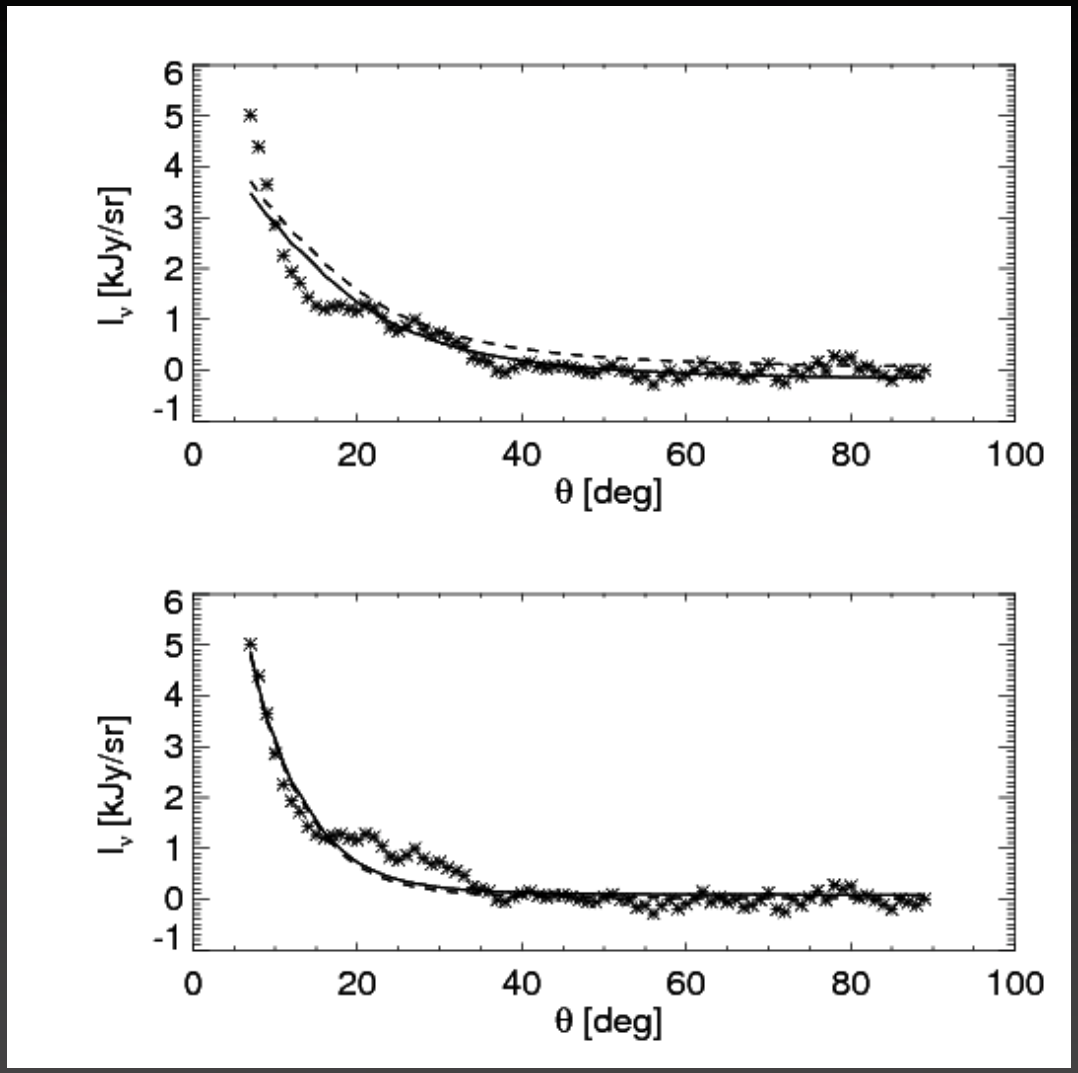
dark matter and the haze



$r = 8.5$ kpc $r = 4.0$ kpc $r = 2.0$ kpc

dark matter and the haze



Galactic/baryon params:

$B \sim 10\ \mu G$

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

Dark matter params:

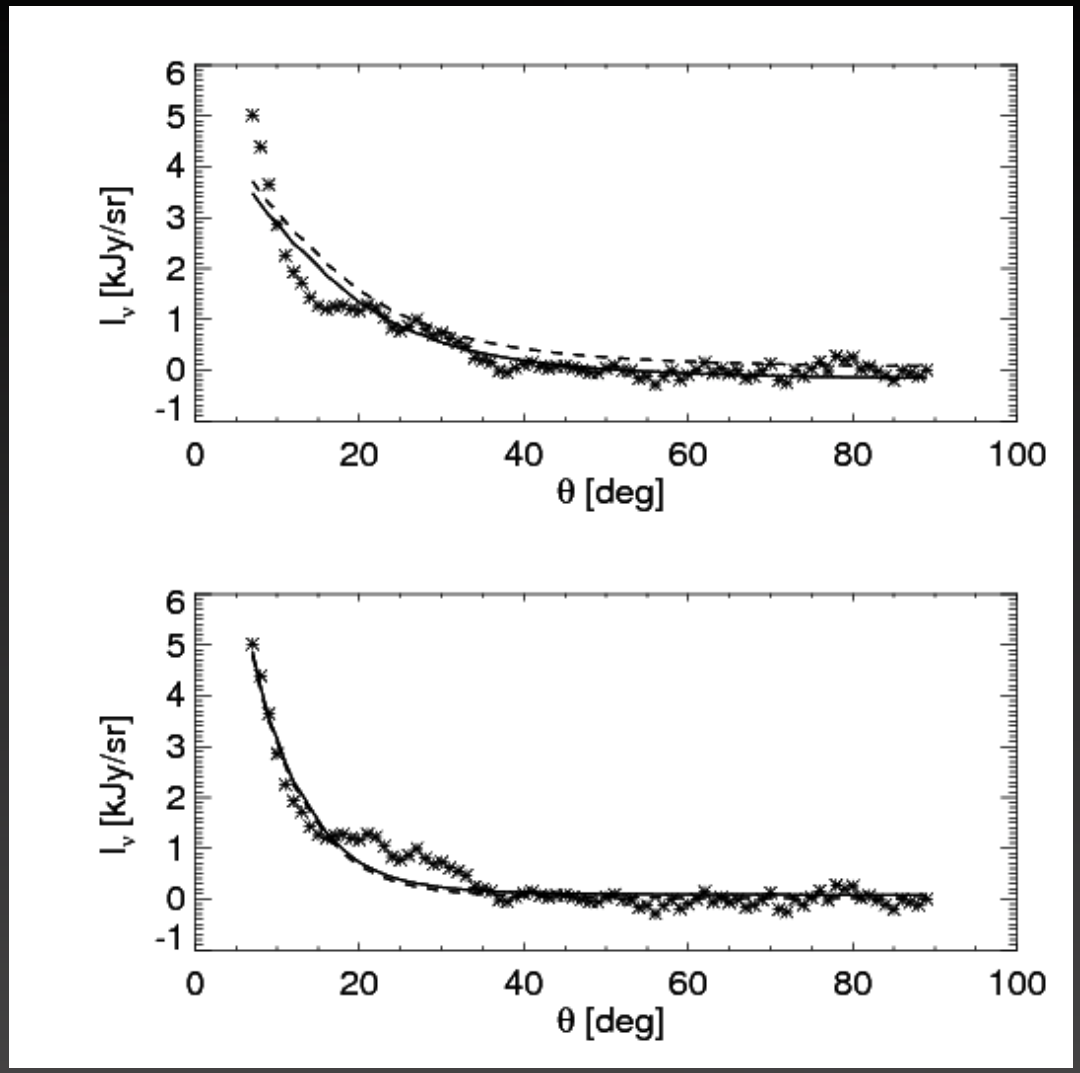
$\rho = \rho(r)$

$M \sim 100$ GeV

$\langle \sigma v \rangle_{e+e-} \sim 10^{-26}\ cm^3/s$

$\langle \sigma v \rangle_{W+W-} \sim 10^{-25}\ cm^3/s$

dark matter and the haze



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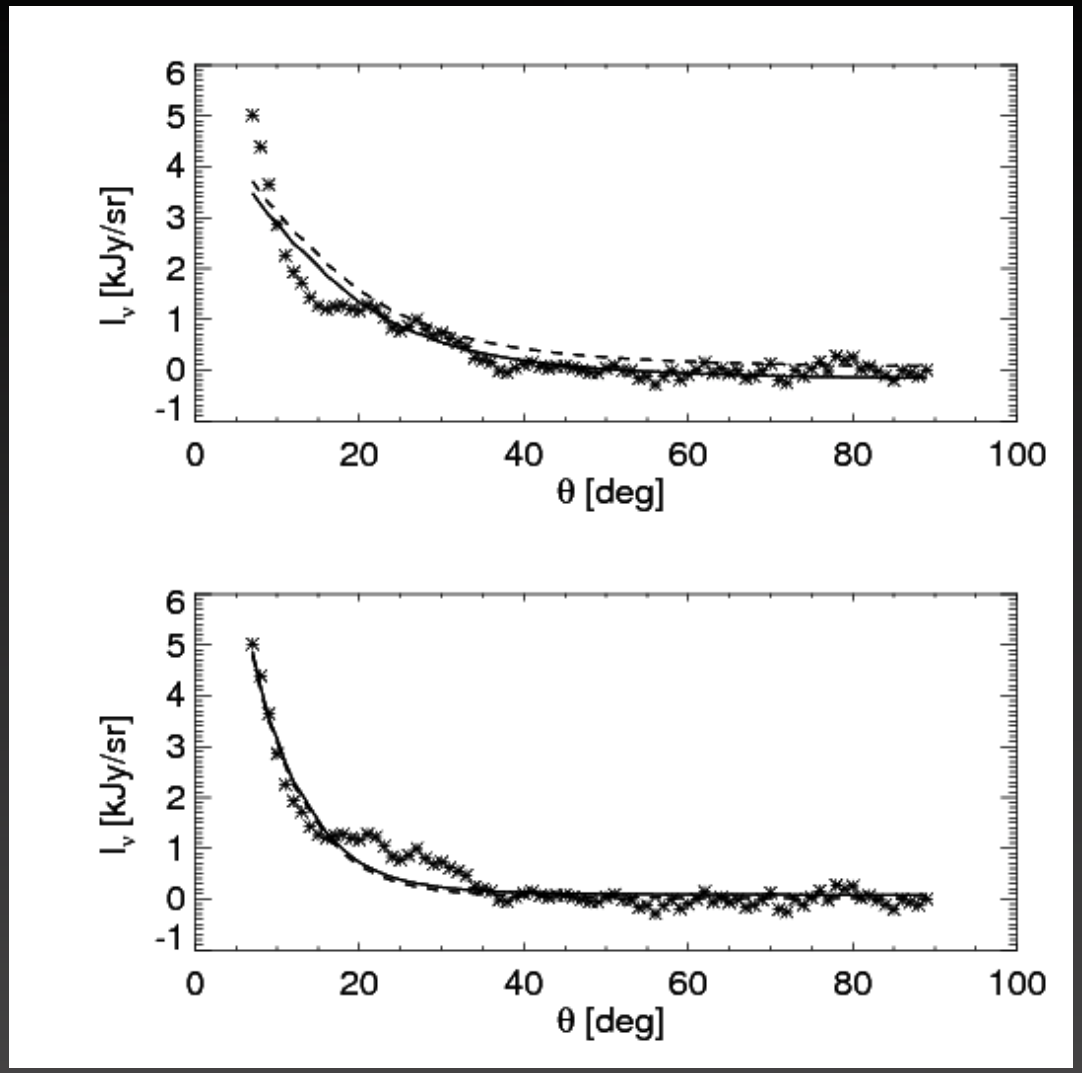
the haze is **consistent** with a WIMP annihilation scenario

dark matter and the haze



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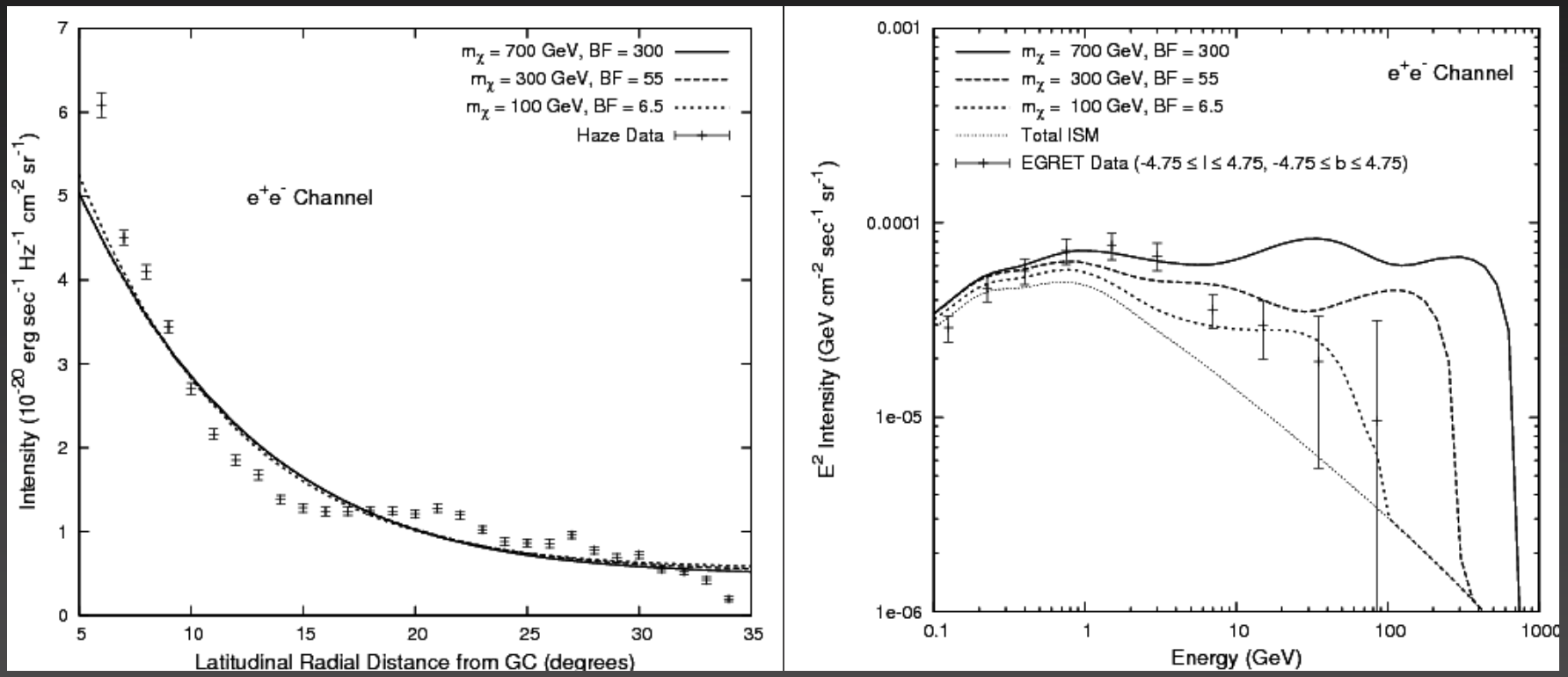
the haze is **consistent** with a WIMP annihilation scenario

*there are **large** astrophysical uncertainties!*

dark matter and the haze

the existence of the haze (regardless of its origin) ***implies*** an inverse Compton signal within a few degrees of the GC



dark matter and the haze

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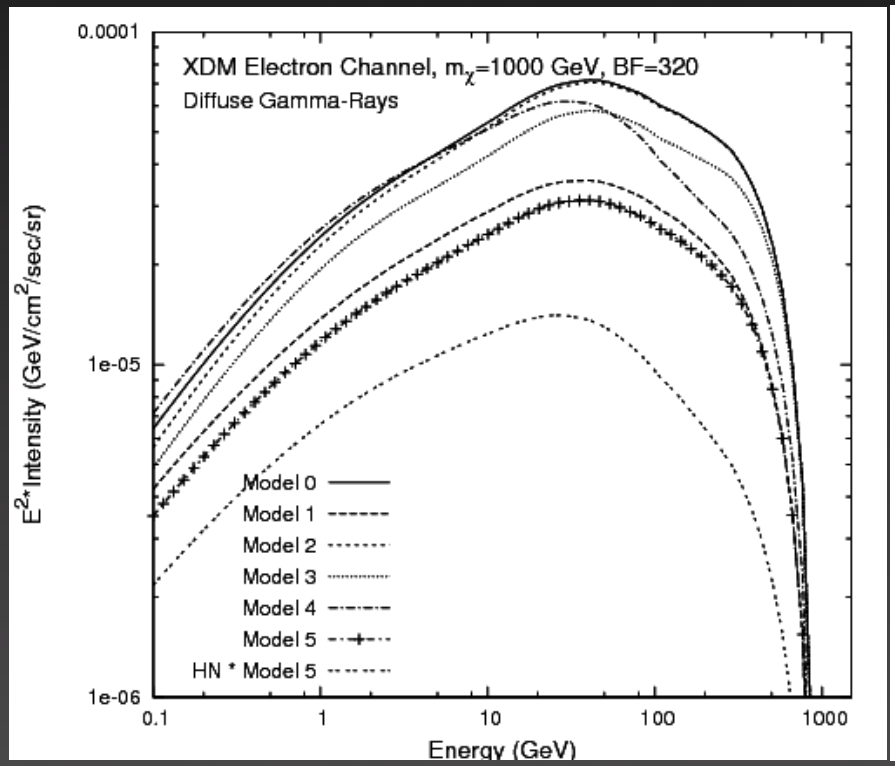
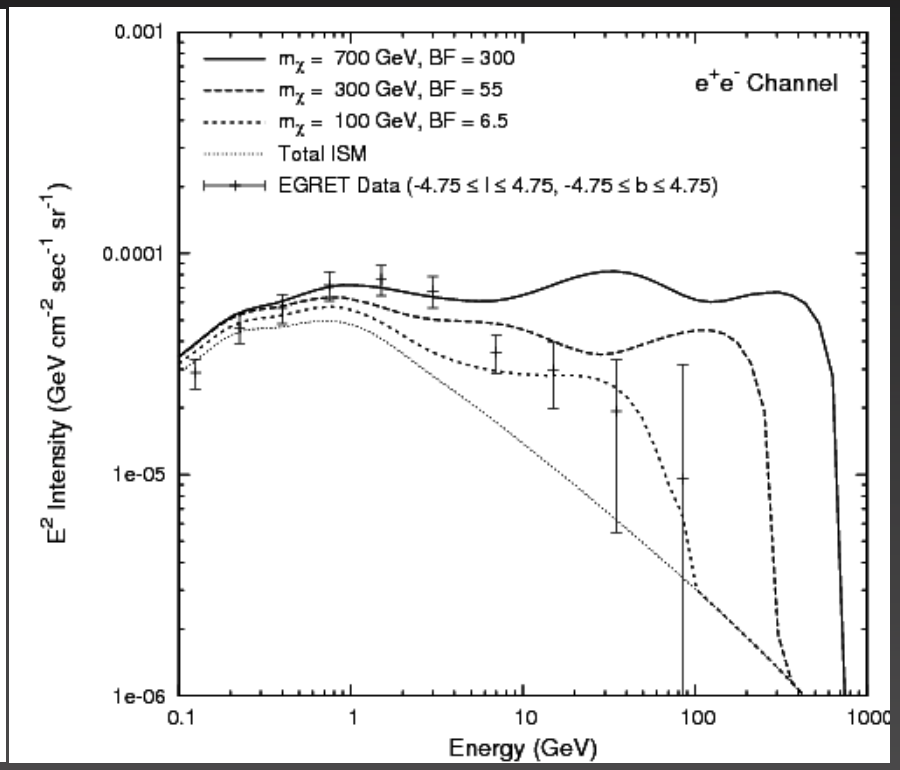




the haze...

facts and myths

the haze...

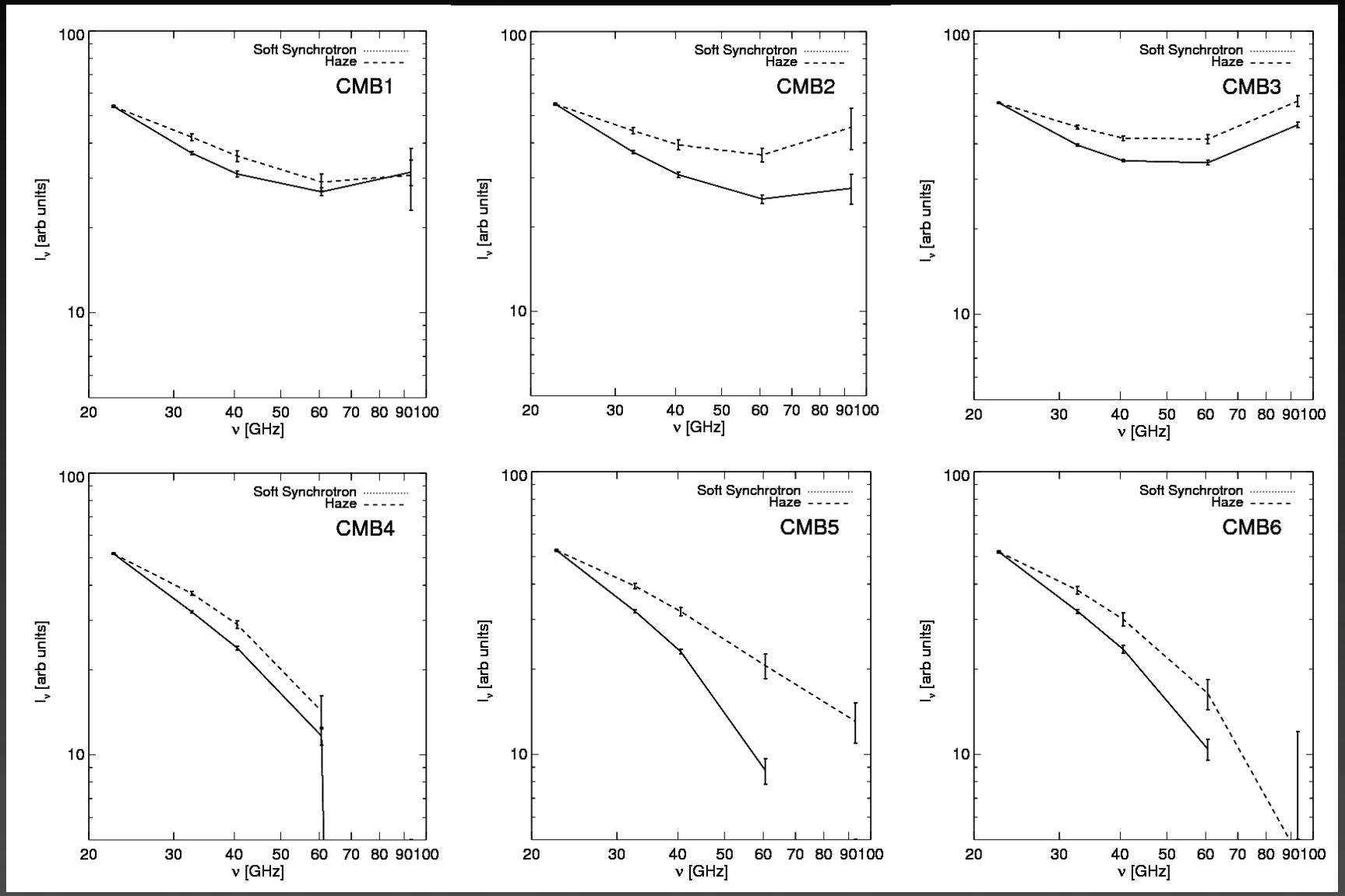
facts and ~~myths~~

misconceptions

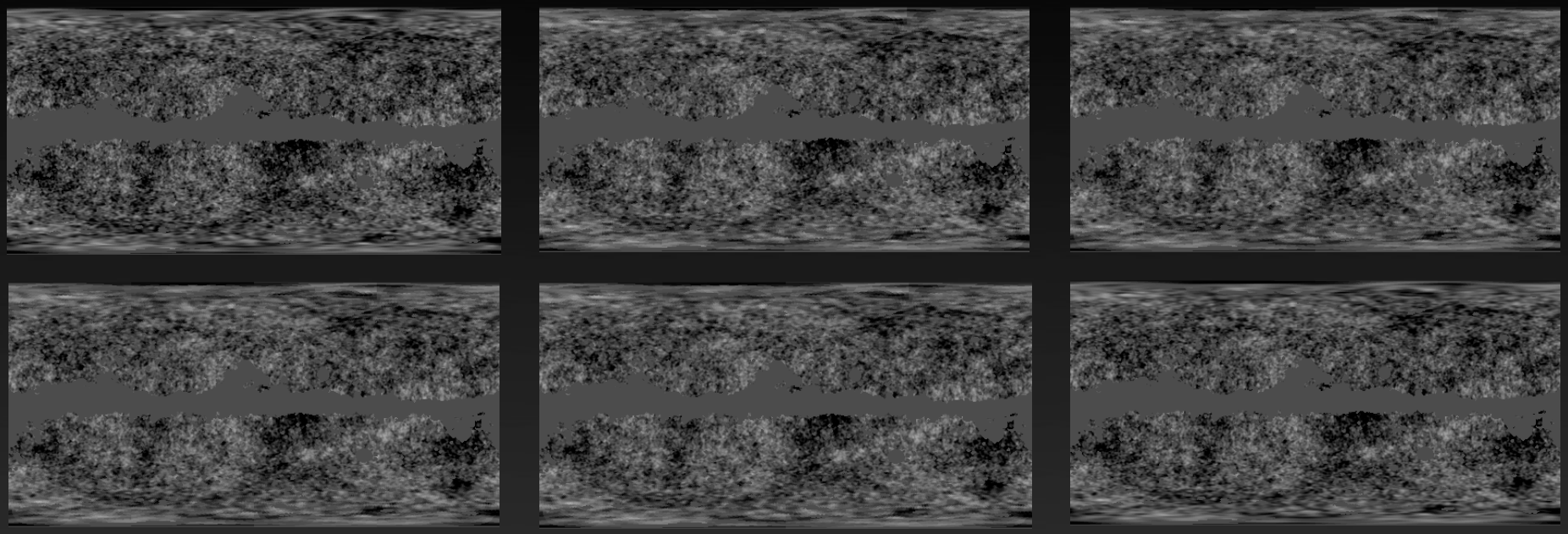
the haze: facts

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

the haze: facts



CMB "cross-correlation" bias



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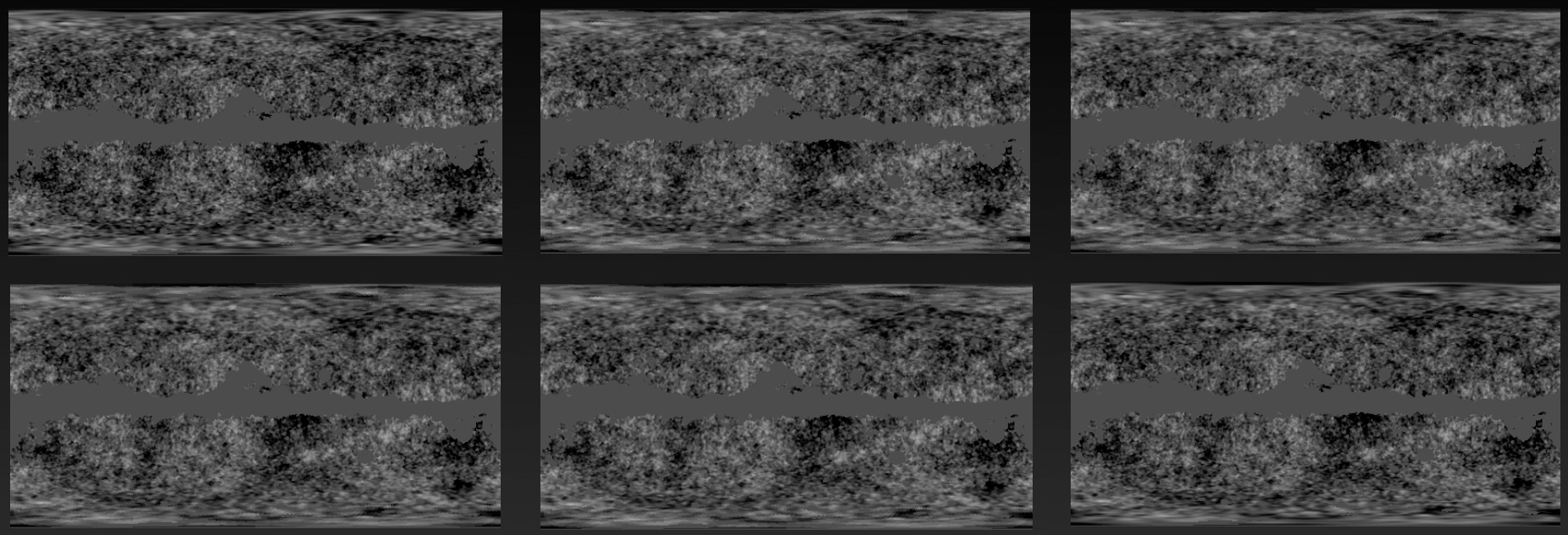
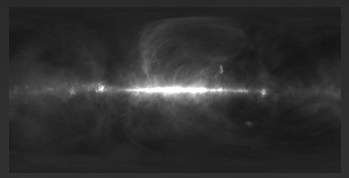
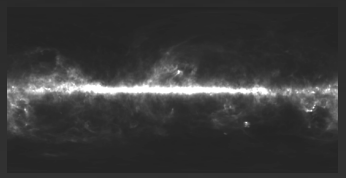
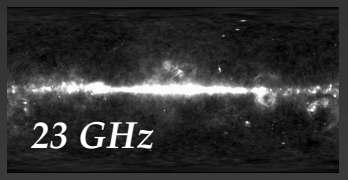
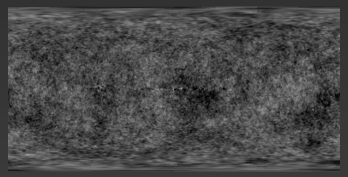


s_{23} x  + f_{23} x  + d_{23} x 

= 

- c_{23} x 

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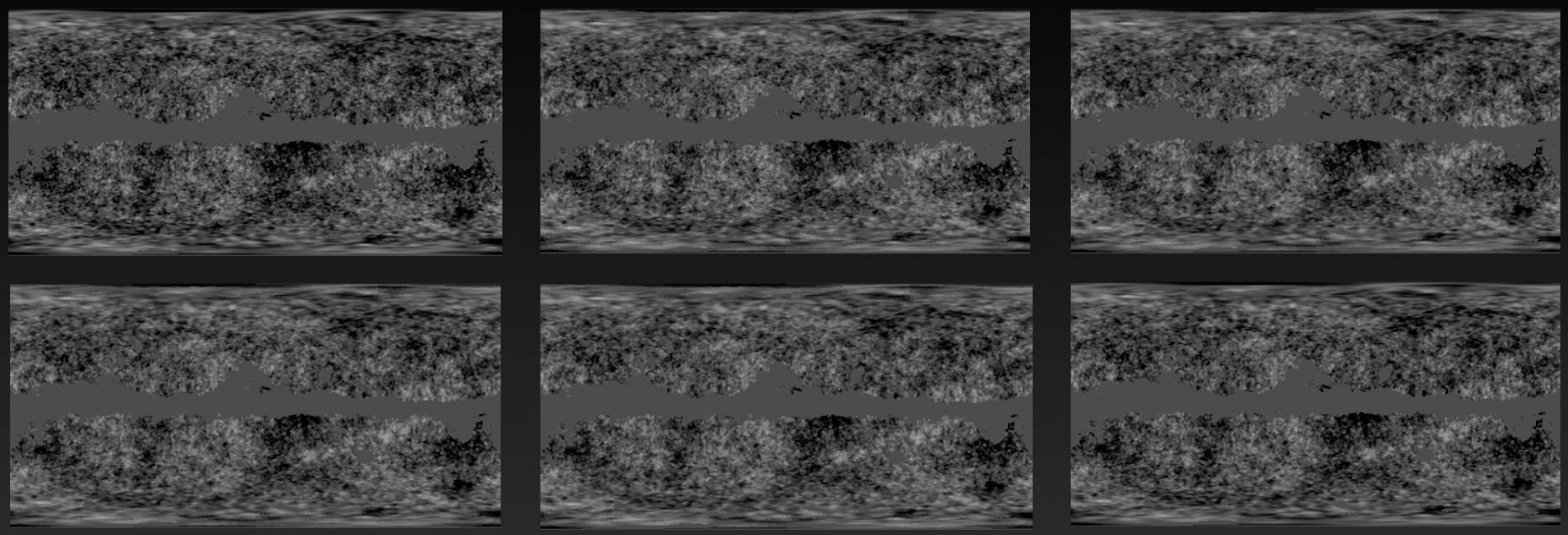

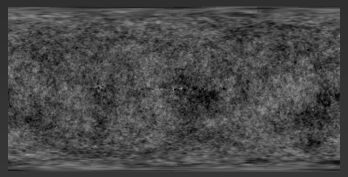

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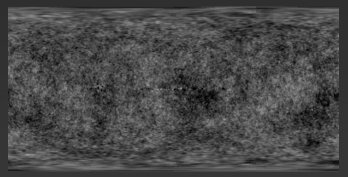
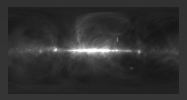
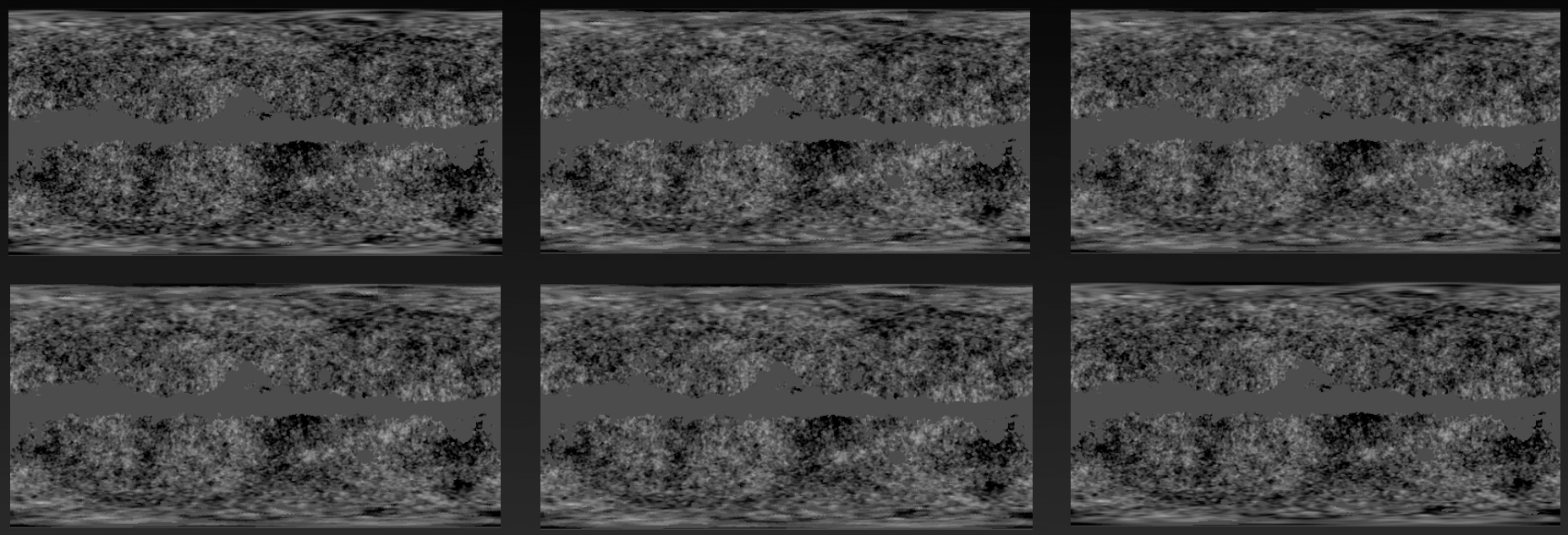
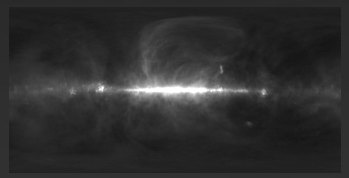
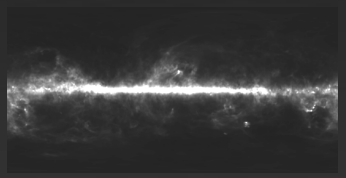


$+\ b_s\ \mathbf{x}$

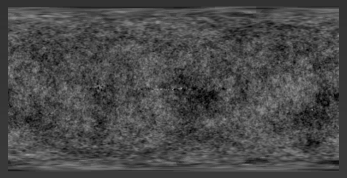
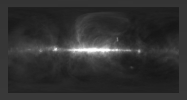


CMB "cross-correlation" bias



s_{23} x  + f_{23} x  + d_{23} x 

= 

- c_{23} x ( + b_s x )

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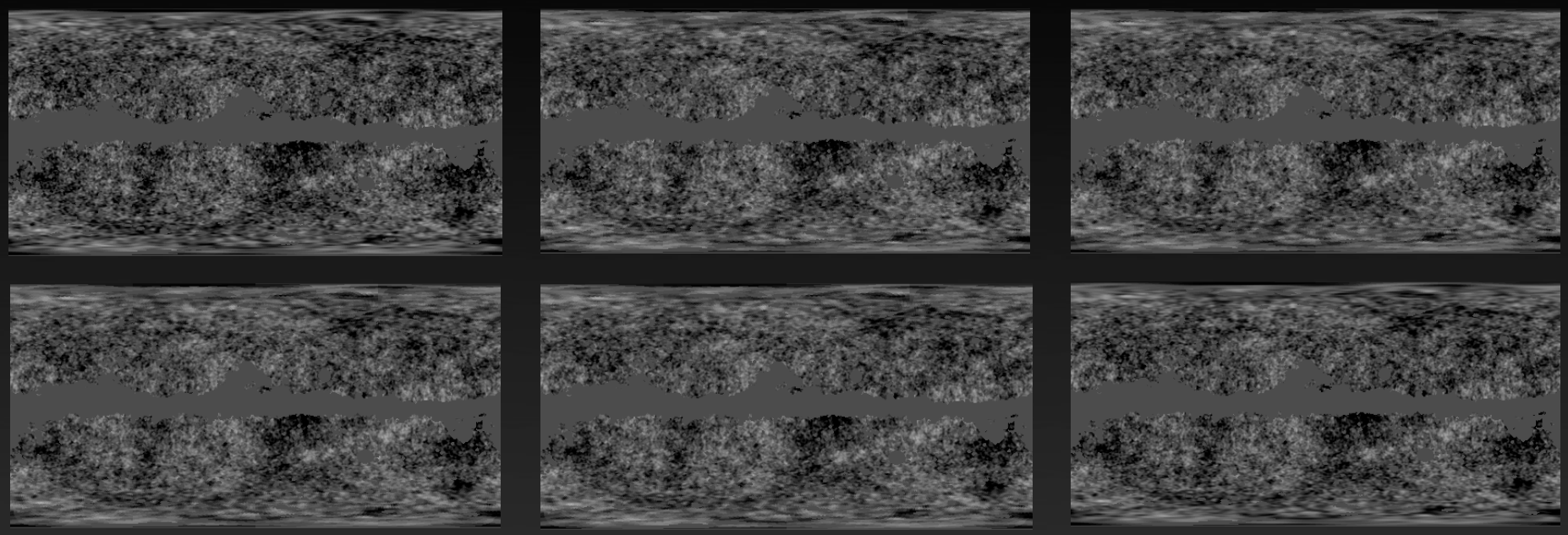
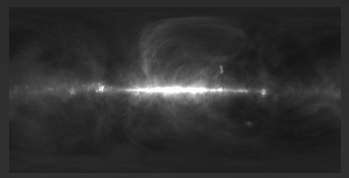
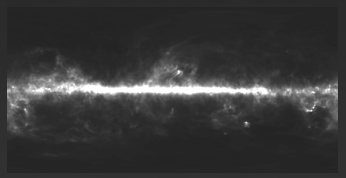
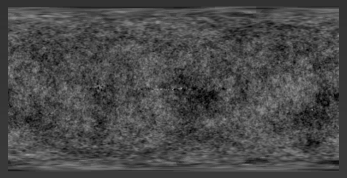
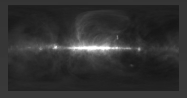


s_{23} x  + f_{23} x  + d_{23} x 

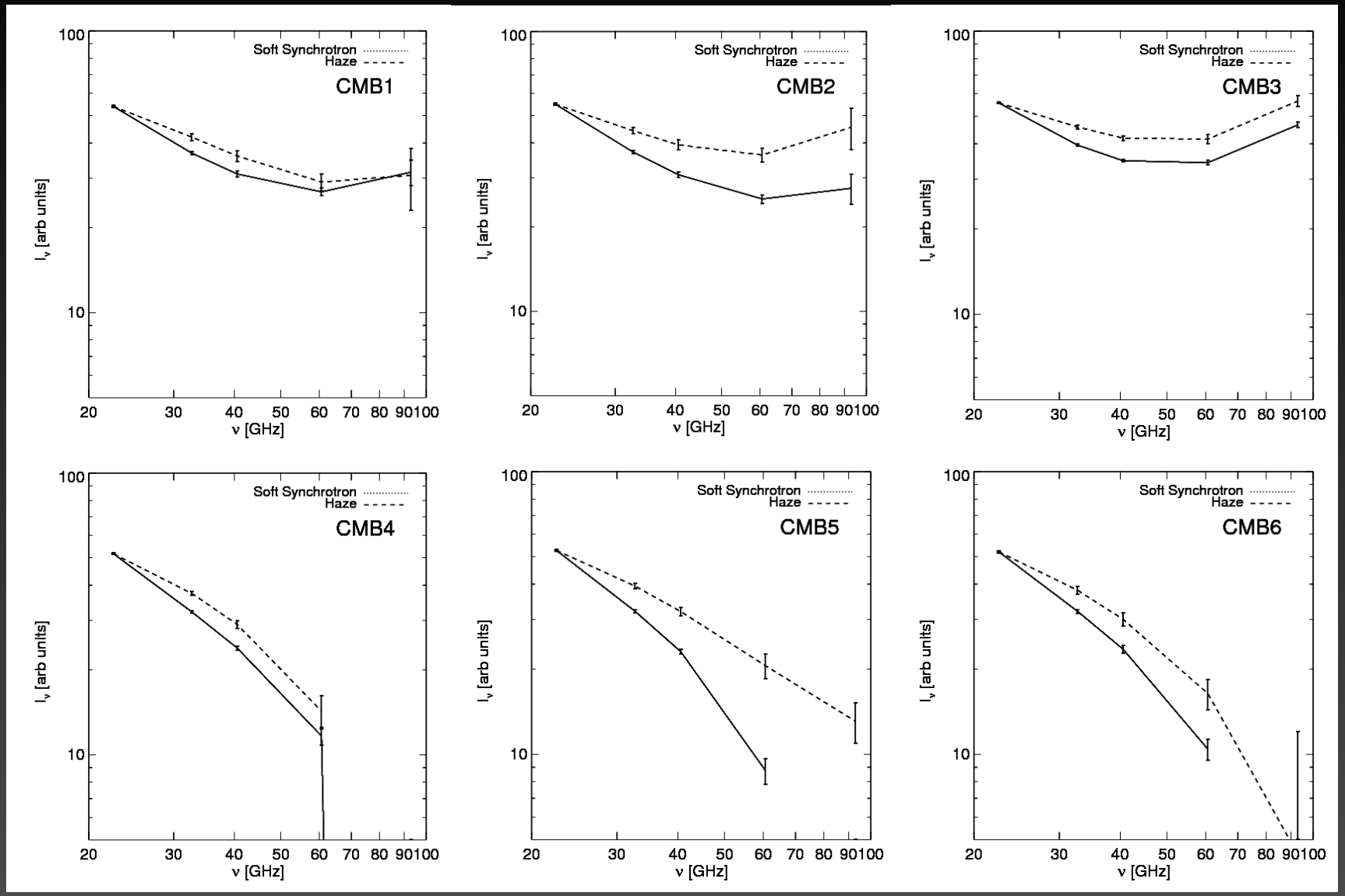
= 

- c_{23} x ( + b_s x )

$s_\nu \rightarrow s_\nu - c_\nu \times b_s$ $\quad f_\nu \rightarrow f_\nu - c_\nu \times b_f$ $\quad d_{23} \rightarrow d_\nu - c_\nu \times b_d$

the haze: facts

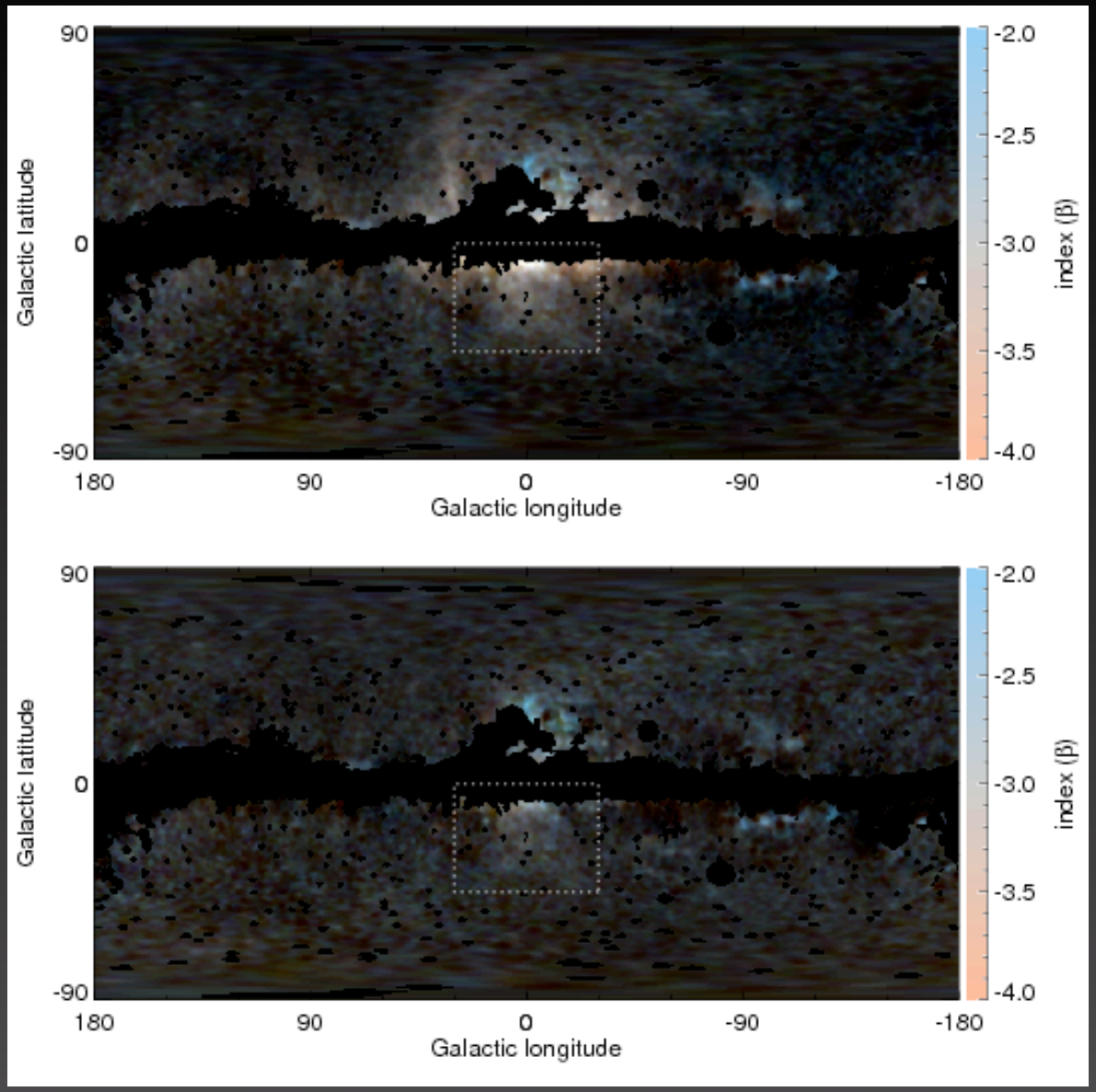
This ambiguity will be **eliminated** with *Planck*



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



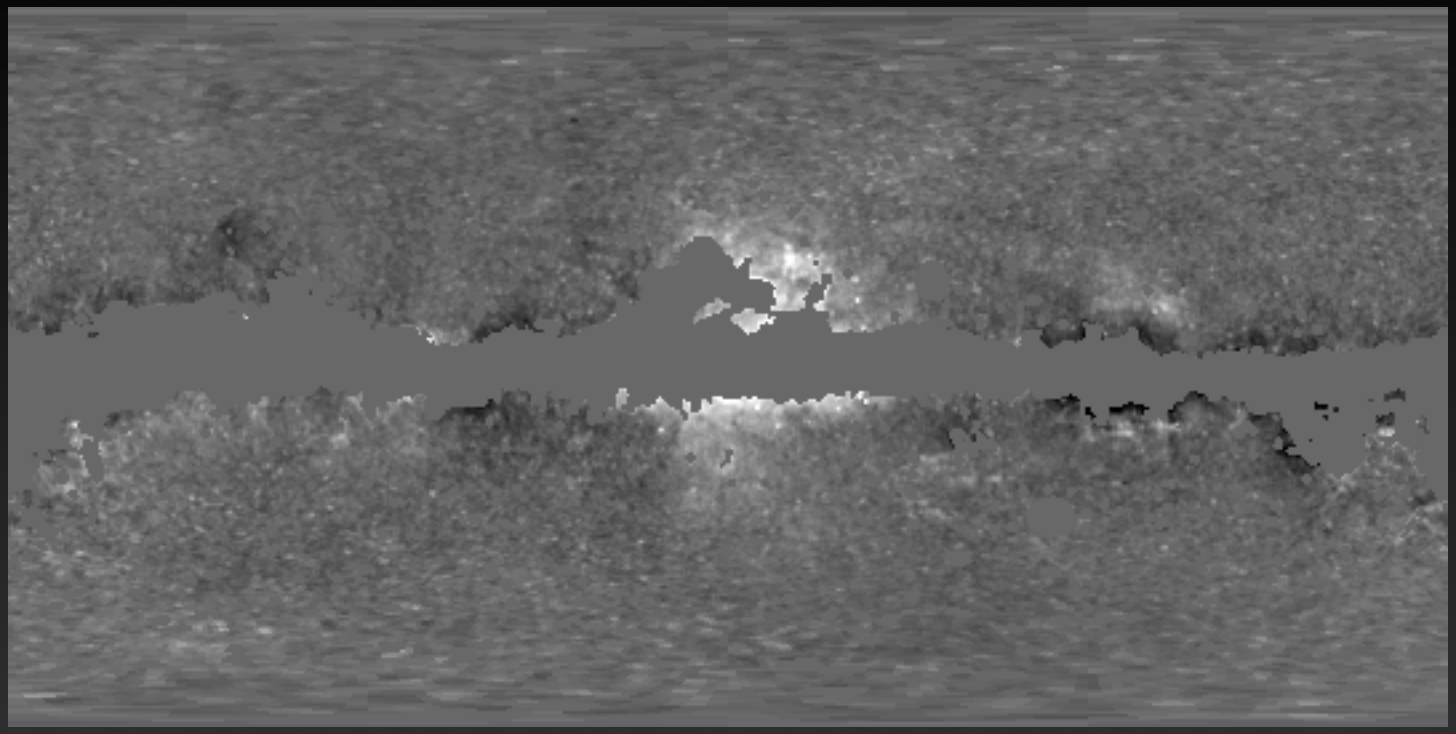
Dobler & Finkbeiner (2008)

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

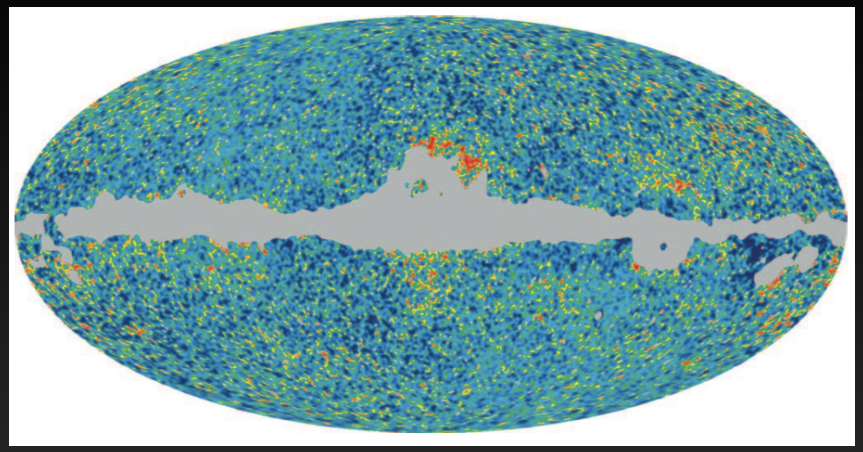
- (thermal and spinning) dust
- (soft) synchrotron

the haze: myths

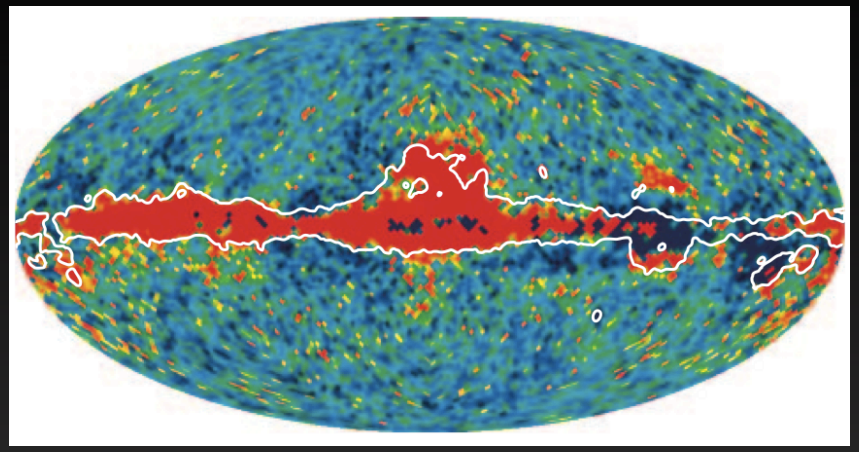
the haze...

. does not exist... nobody else sees it

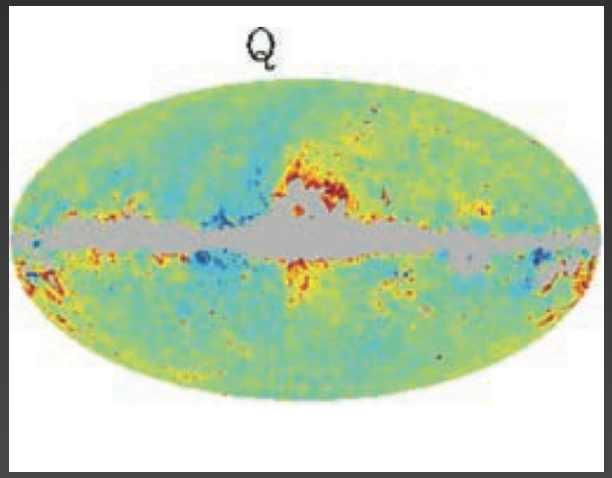
the haze: myths



Bennett et al, 2003



Hinshaw et al, 2007

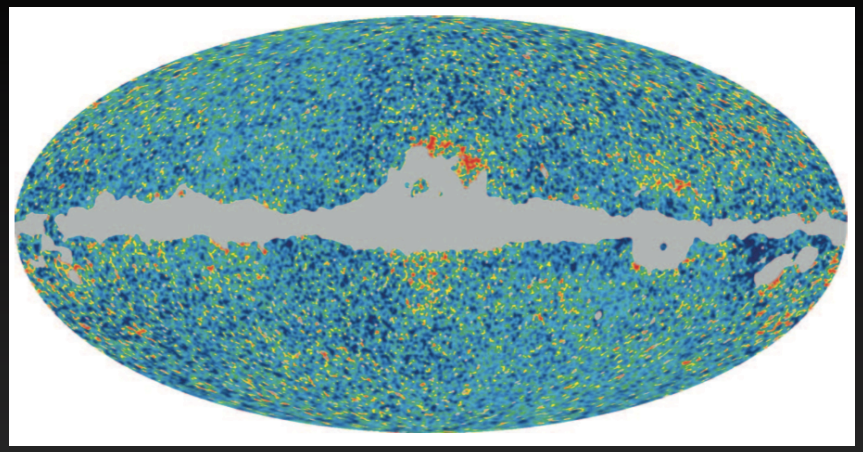


Bottino et al, 2008

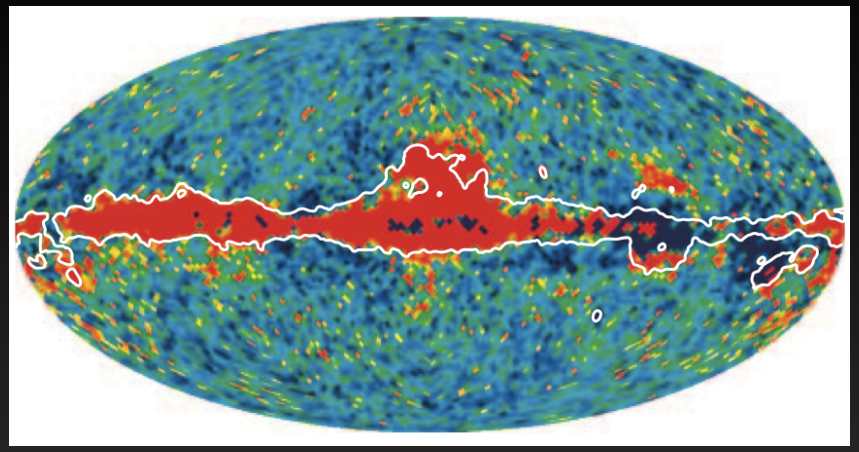
Template	Band	Mask			
		KQ85	KQ75	Kp0	Kp2
408 MHz	K	4.34 ± 0.08	4.24 ± 0.11	4.43 ± 0.13	4.57 ± 0.08
	Ka	1.67 ± 0.08	1.80 ± 0.11	1.88 ± 0.13	1.81 ± 0.08
	Q	1.02 ± 0.08	1.20 ± 0.11	1.26 ± 0.13	1.15 ± 0.08
	V	0.42 ± 0.08	0.64 ± 0.11	0.69 ± 0.13	0.55 ± 0.08
	W	0.25 ± 0.08	0.48 ± 0.11	0.52 ± 0.13	0.37 ± 0.08
Hα	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

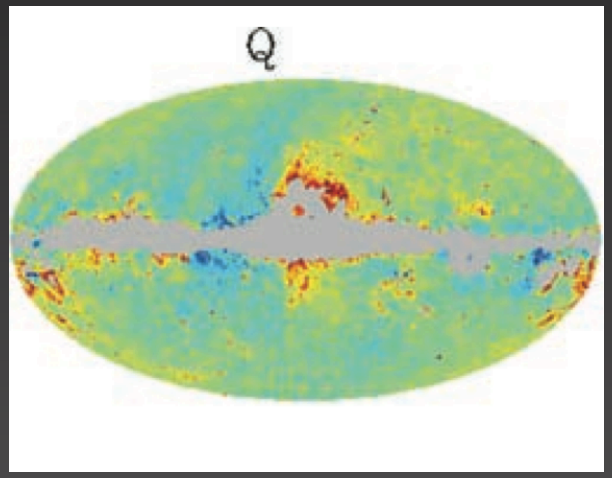
the haze: myths



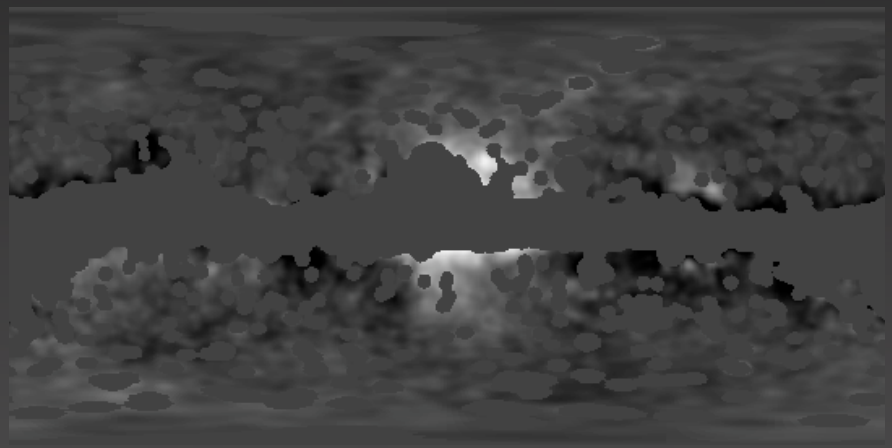
Bennett et al, 2003



Hinshaw et al, 2007



Bottino et al, 2008



Dickinson et al, 2009 (implied 23 GHz)

the haze: myths

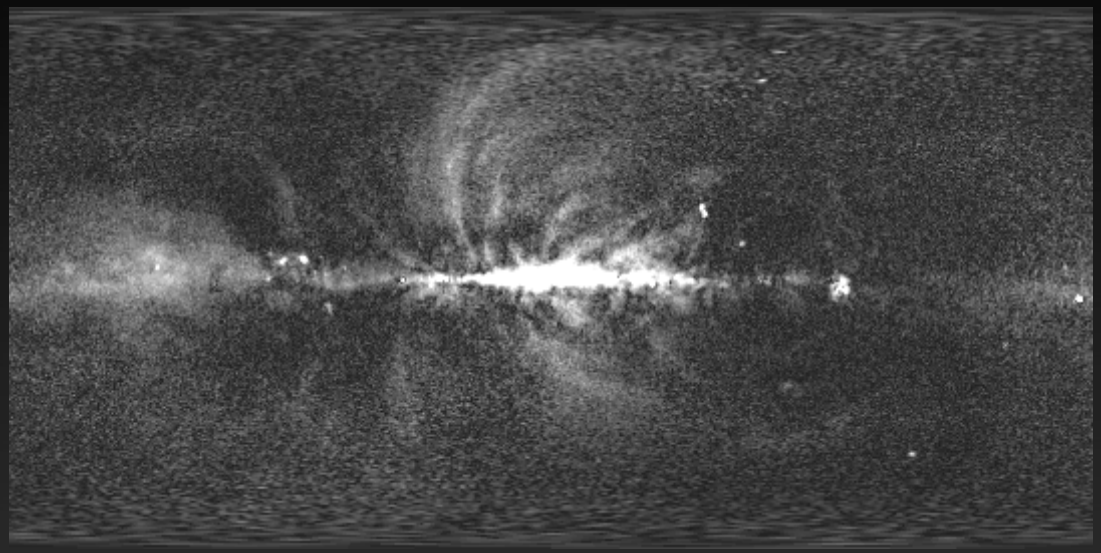
the haze...

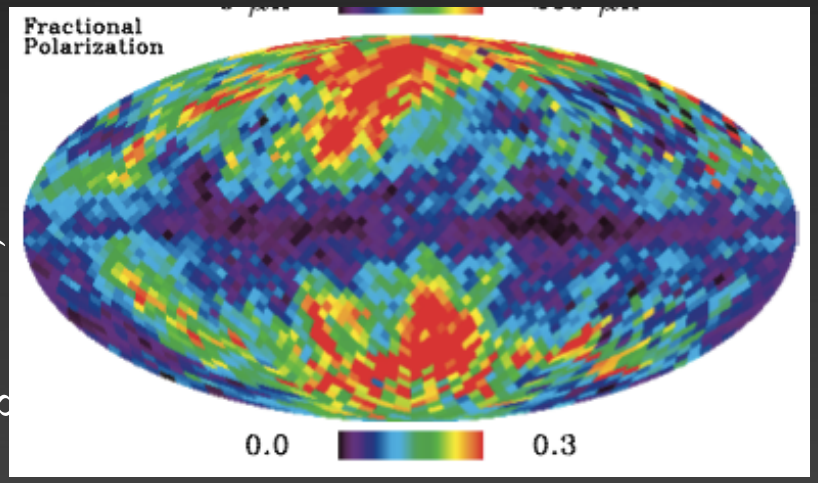
. does not exist... nobody else sees it

. should be strongly polarized

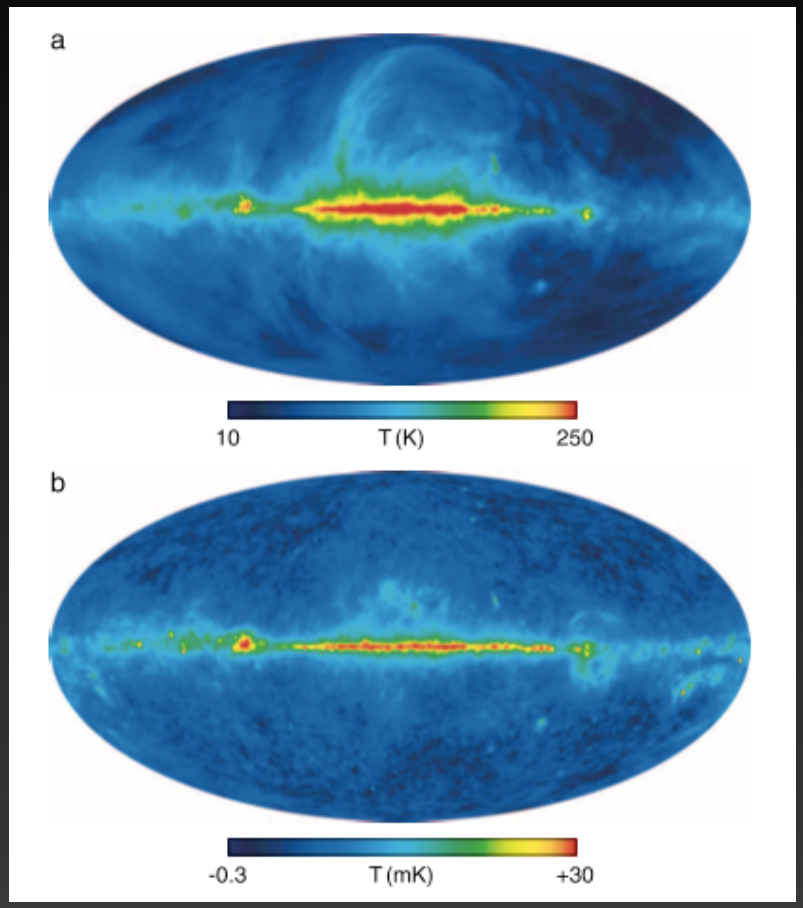
the haze: myths

WMAP 23 GHz polarized emission





Kogut et al, 2007



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

the haze: myths

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. is easily explained by SNe

the haze: myths

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. is easily explained by SNe

- **diffused** haze spectrum is (roughly) as hard as fermi spectrum extending over ~ (*4* kpc)^3 volume

the haze: myths

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. is easily explained by pulsars

the haze: myths

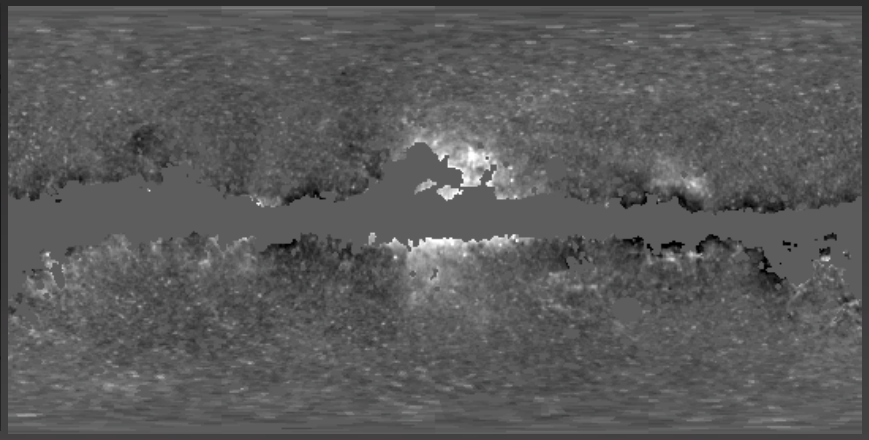
Injection spectrum :

$dN/dE = N_0 \times f(E)$ with $N_0 = ???$ and $f(E) = ???$

$\Rightarrow$ can (likely) fit the haze spectrum

Spatial distribution :

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



$\Rightarrow$ cannot fit the morphology

the haze: myths

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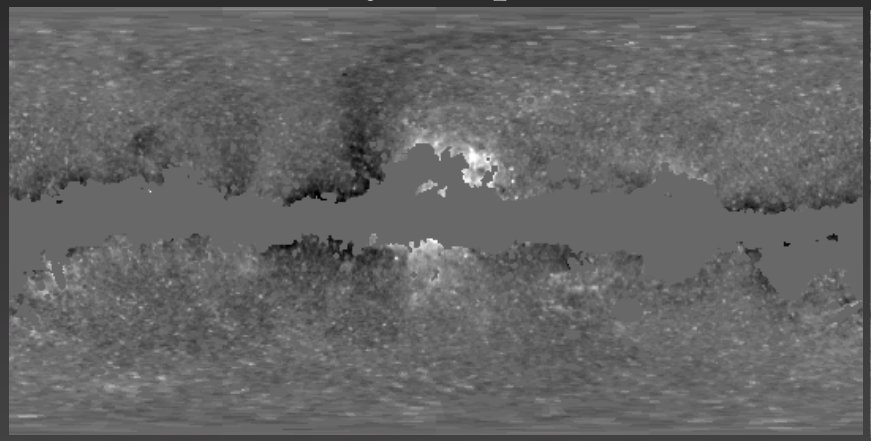
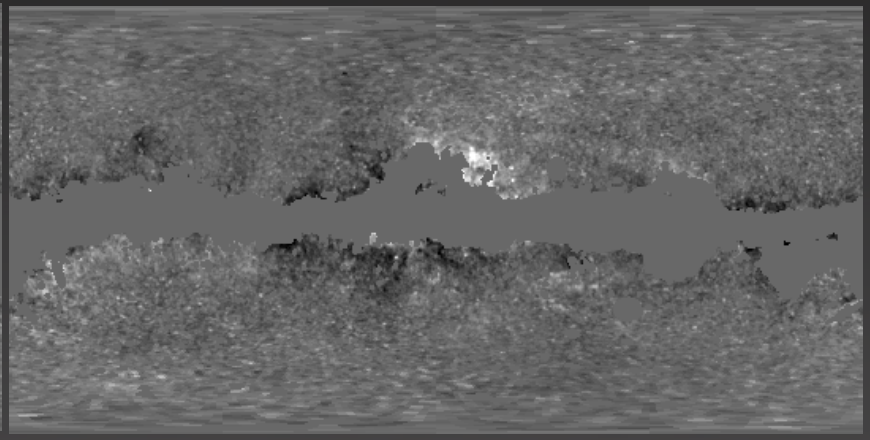
disky template



$1/r$ template



$\Rightarrow$ cannot fit the morphology

the haze: myths

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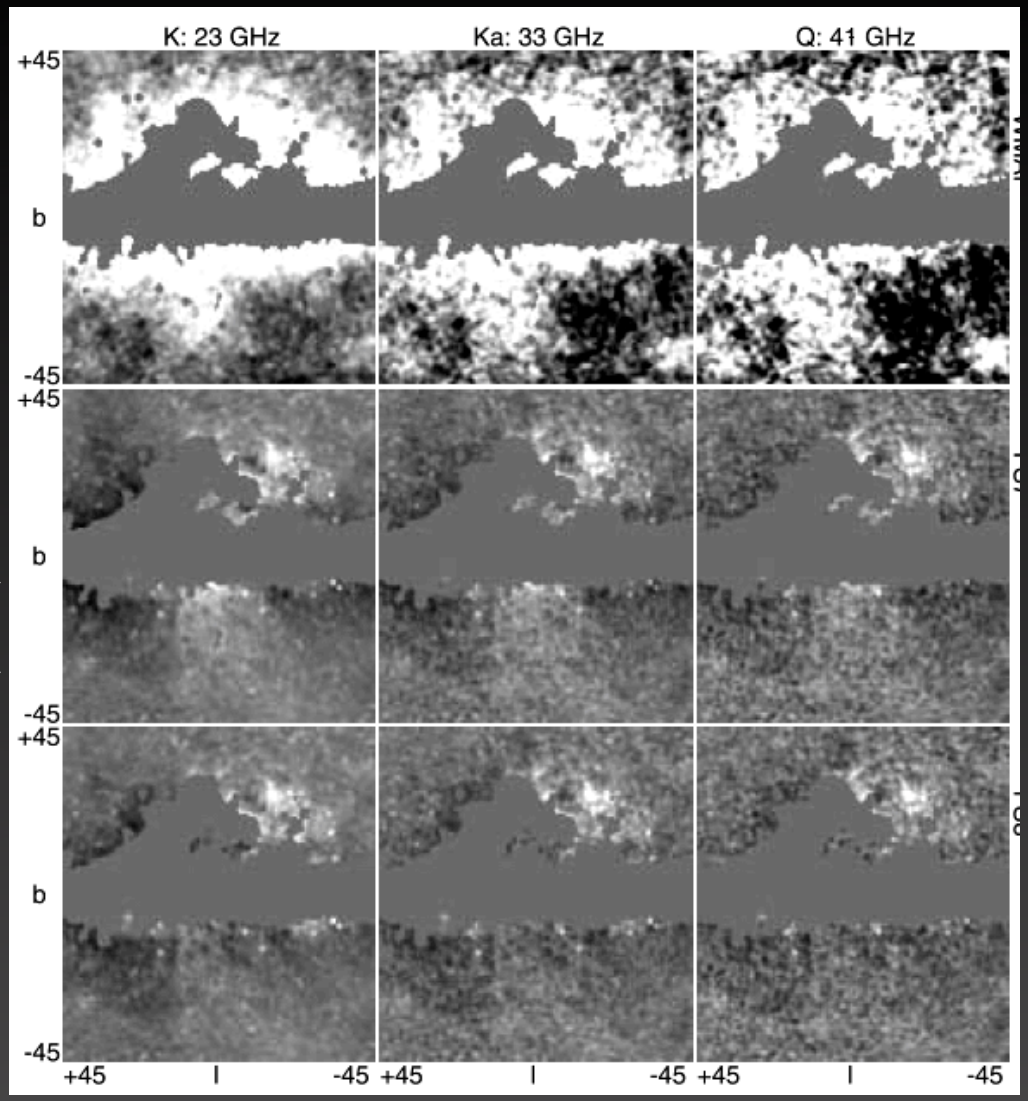
. is easily explained by pulsars

. is easily explained by small spectral index variation of Haslam

the haze: myths



Dobler & Finkbeiner (2008)

WMAP data

w/o haze template

w/ haze template

the haze is morphologically distinct from Haslam

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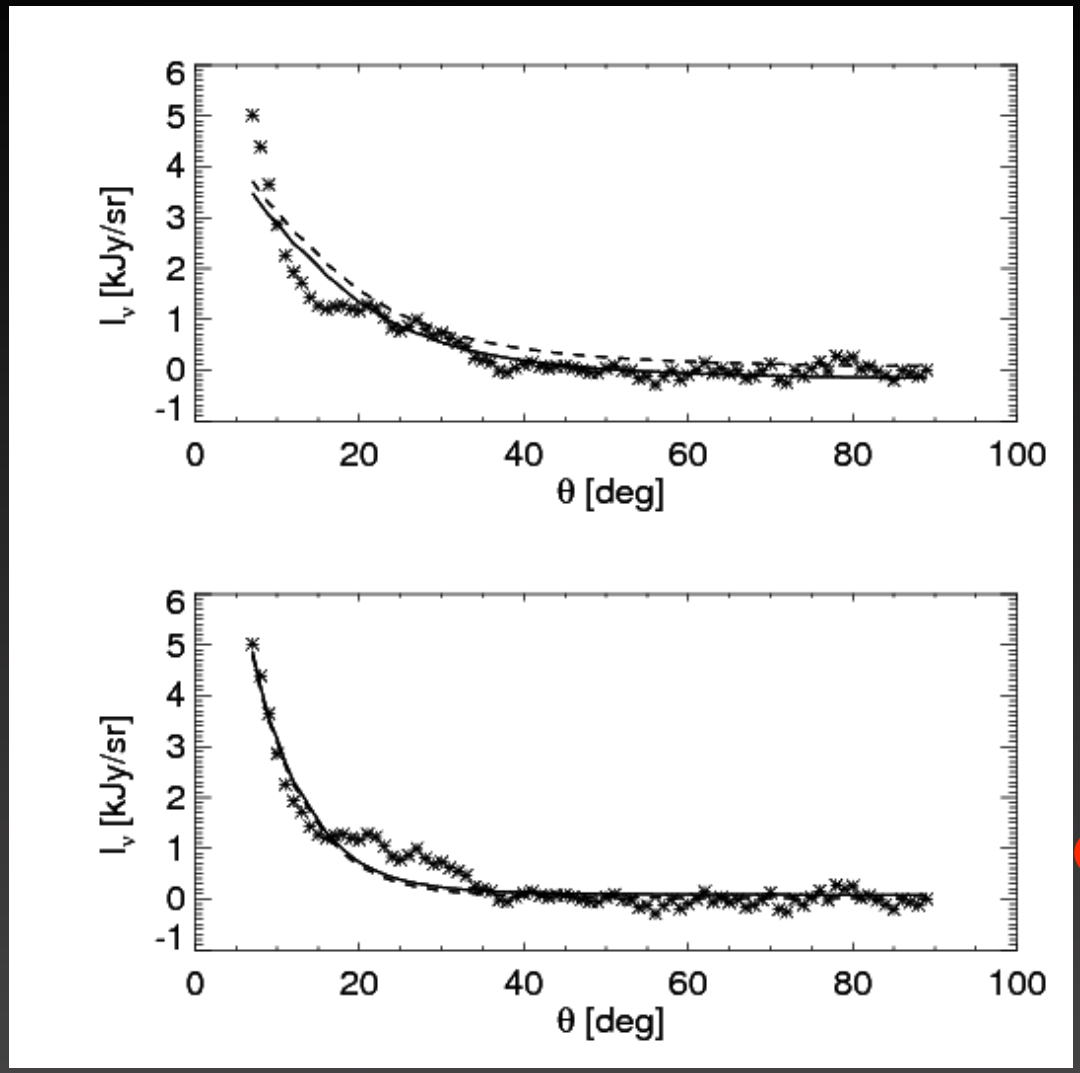
the haze: myths



Galactic/baryon params:

$B \sim 10\ \mu G$

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

Dark matter params:

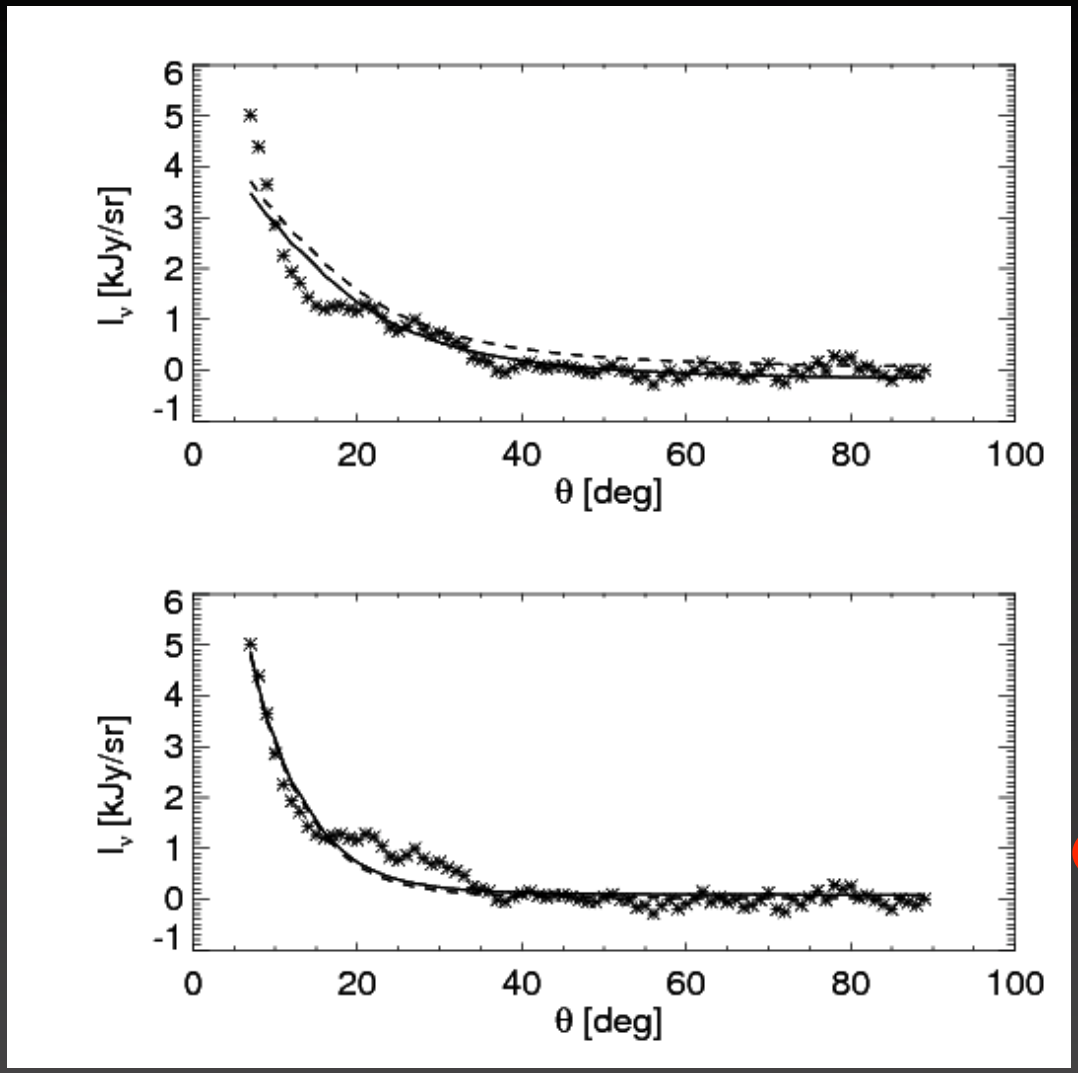
$\rho = \rho(r)$

$M \sim 100$ GeV

$\langle\sigma v\rangle \sim$ few $x10^{-26}\ cm^3/s$

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

the haze: myths



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*but again... there are **large** astrophysical uncertainties!*

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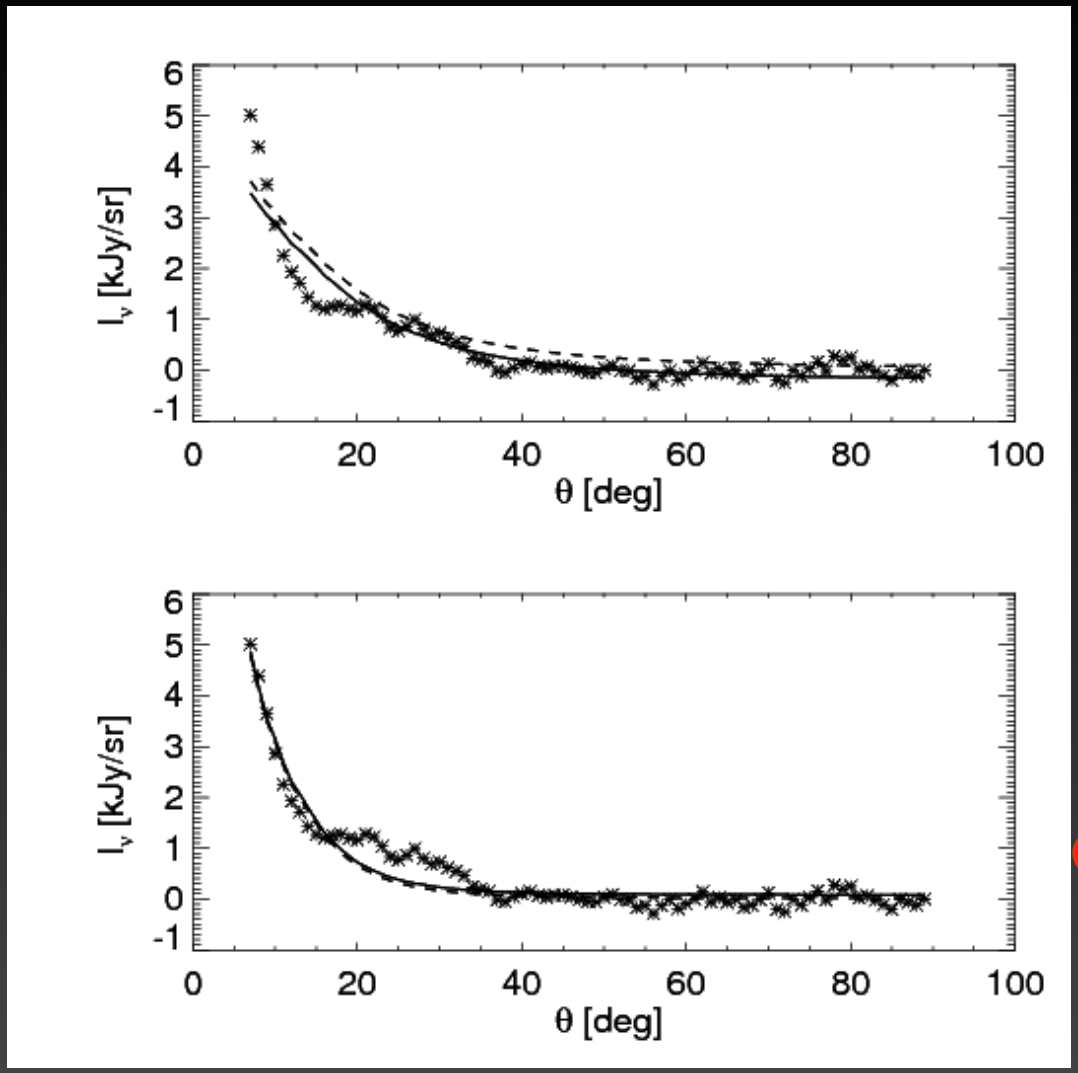
. DM model over-produces synchrotron at high latitudes

the haze: myths



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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: *~1.2-1.5* (see *Porter et al, 2008*)

- DM halo shape: ??? (local density *~2*, radial profile, sub-[sub-]structures *~5-10*)

- uncertainties in haze analysis, etc...

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

. *Planck* spectral index measurements