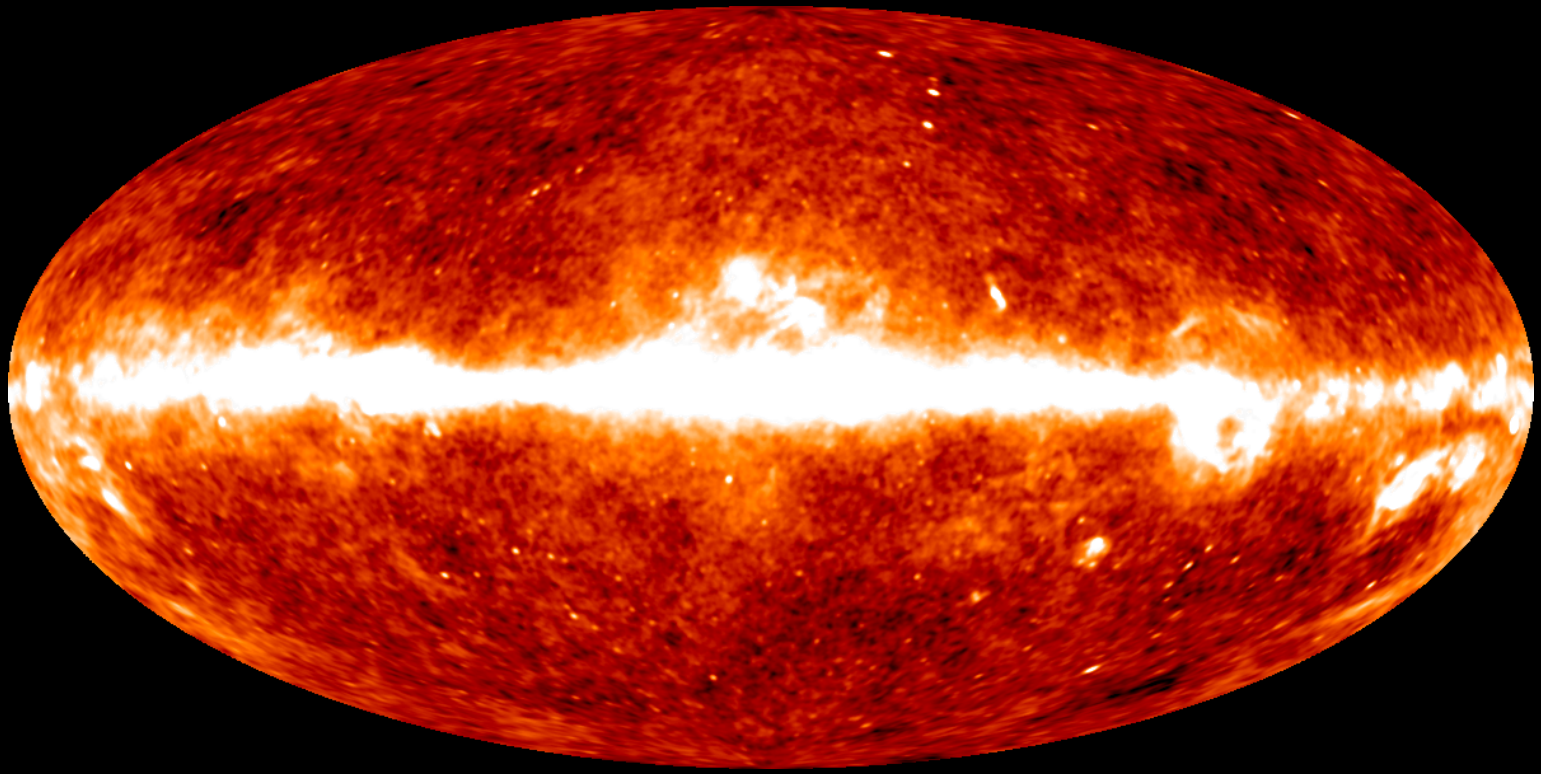
from hazes to bubbles:

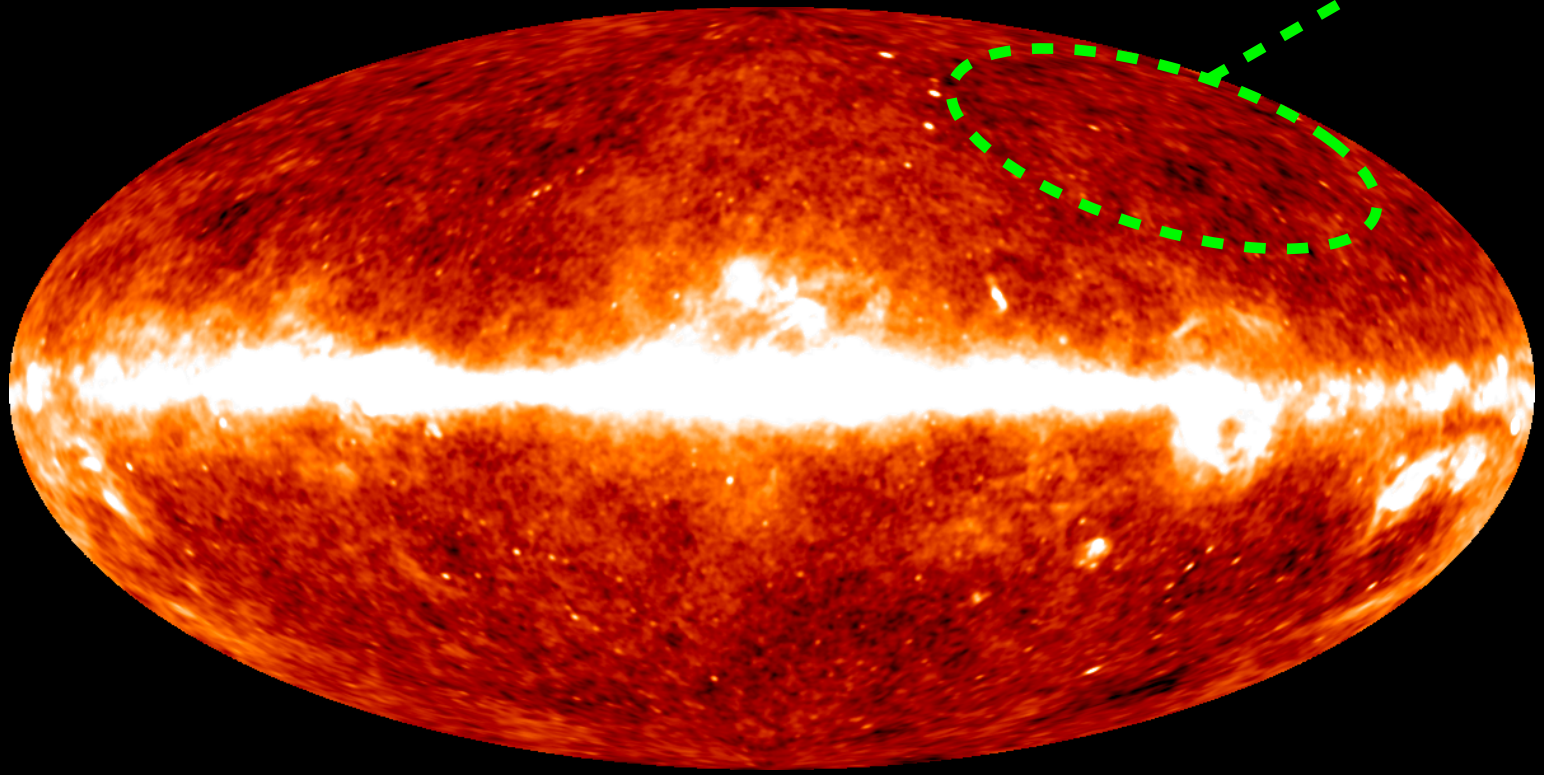
putting it all together...

microwaves...



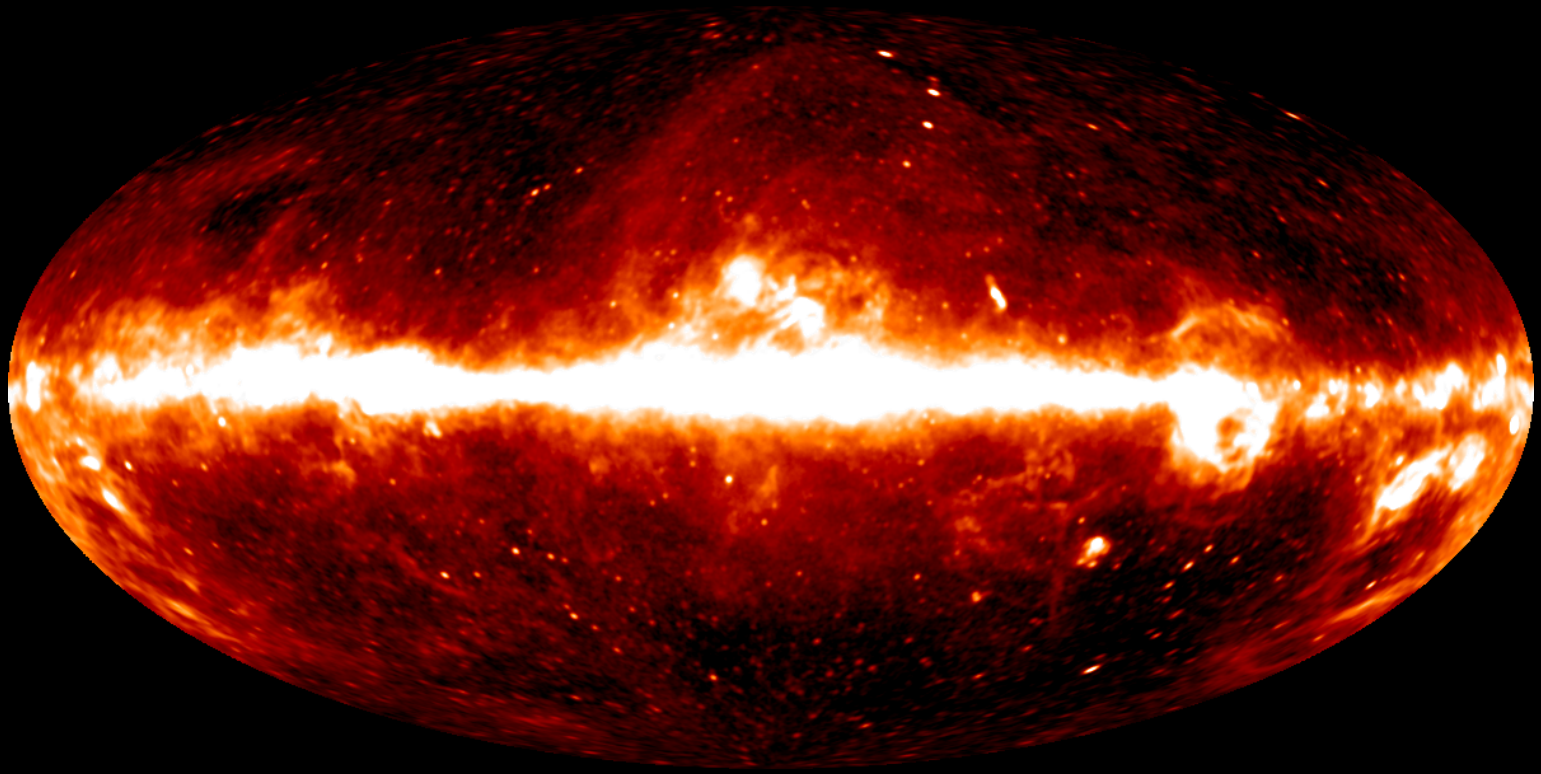
WMAP 23 GHz

microwaves...



WMAP 23 GHz

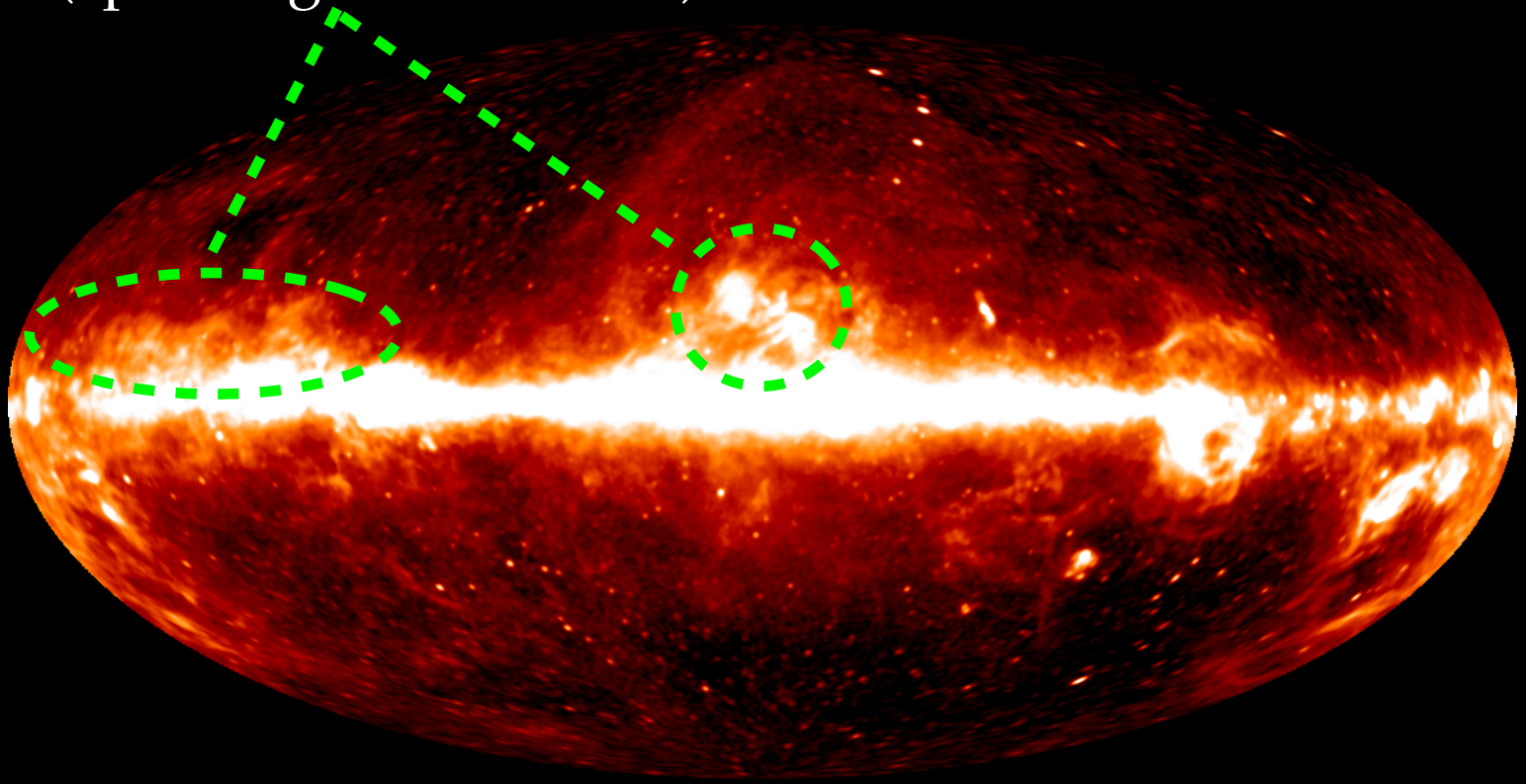
microwaves...



WMAP 23 GHz

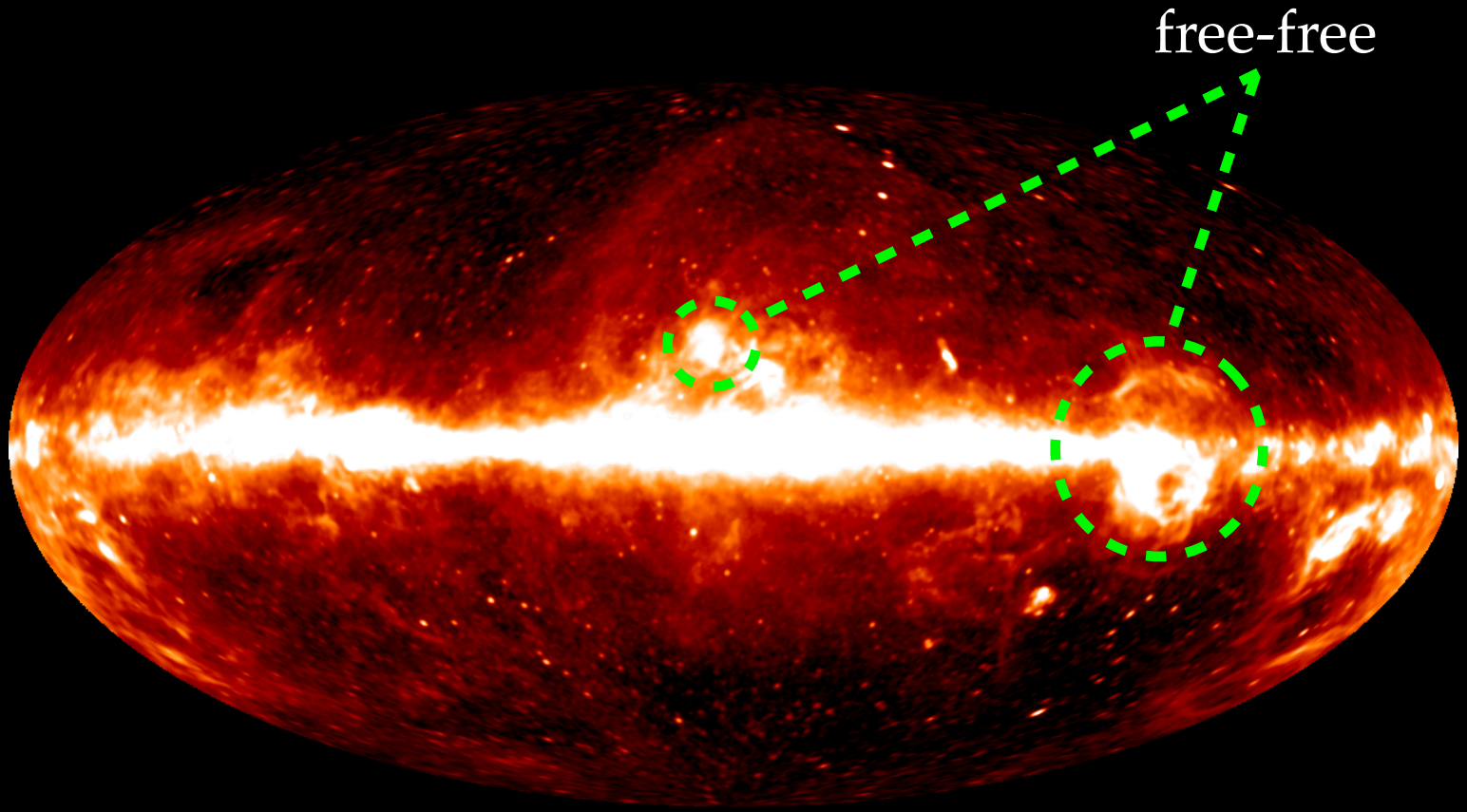
microwaves...

dust (spinning and thermal)



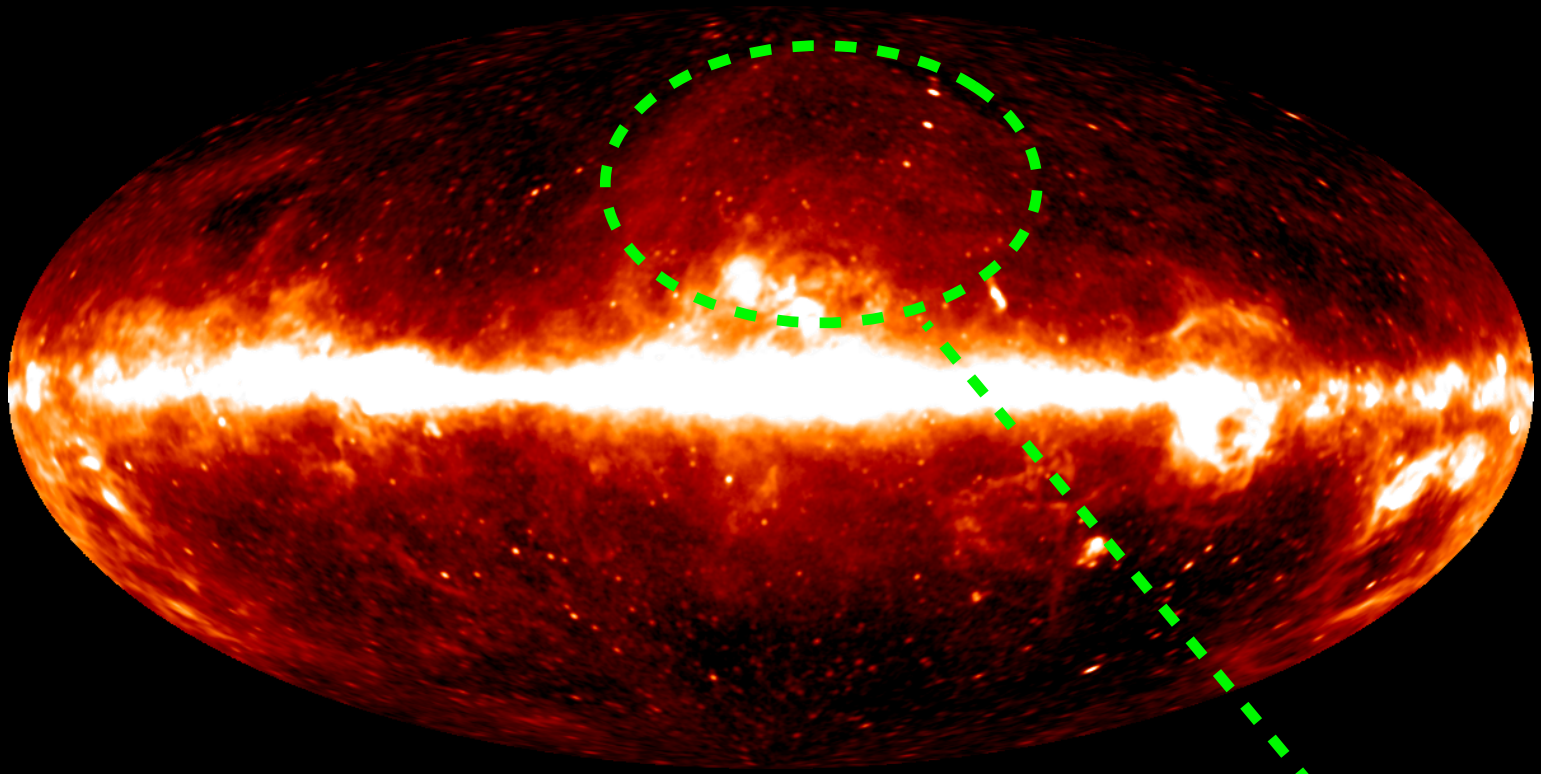
WMAP 23 GHz

microwaves...



WMAP 23 GHz

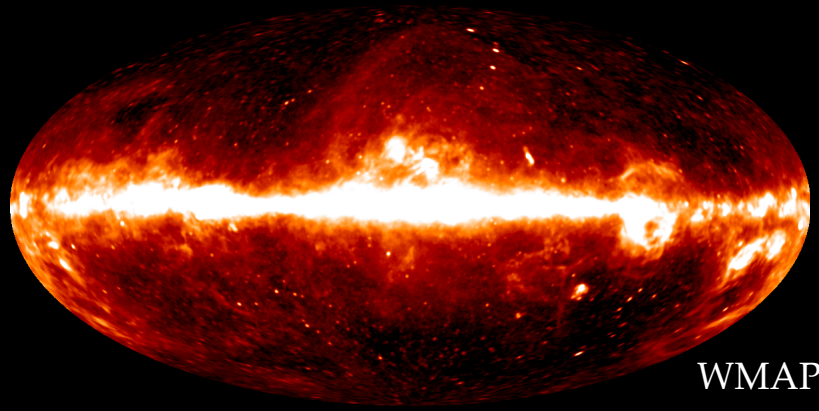
microwaves...



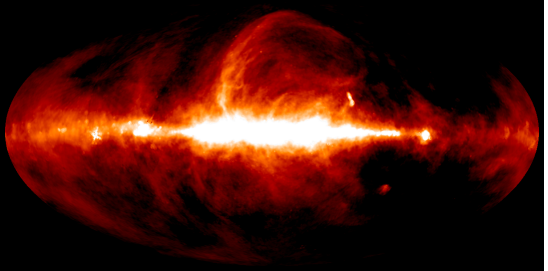
WMAP 23 GHz

synchrotron

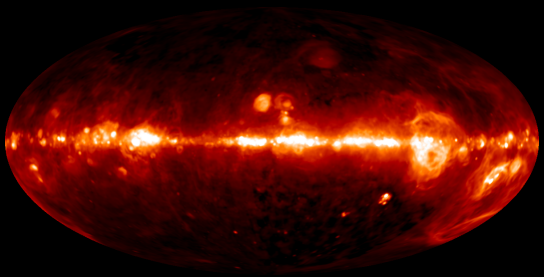
microwaves...



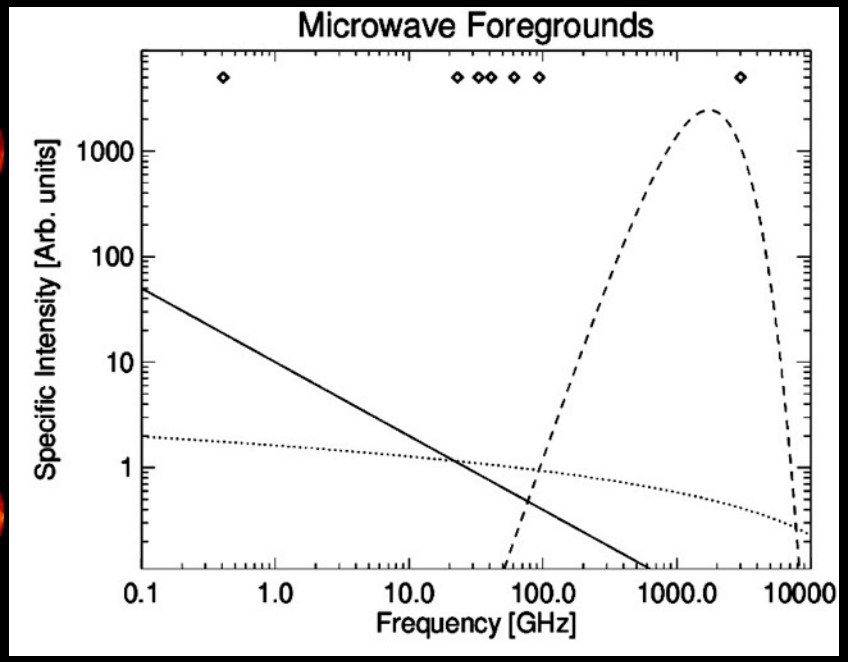
WMAP 23 GHz

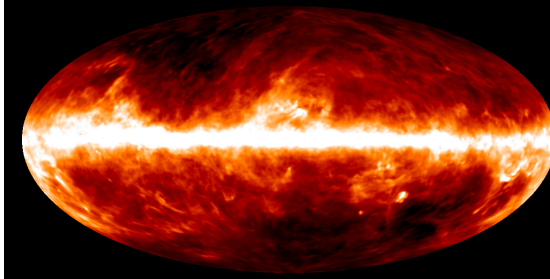


Haslam et al. (1982)



Hα *(Finkbeiner, 2003)*

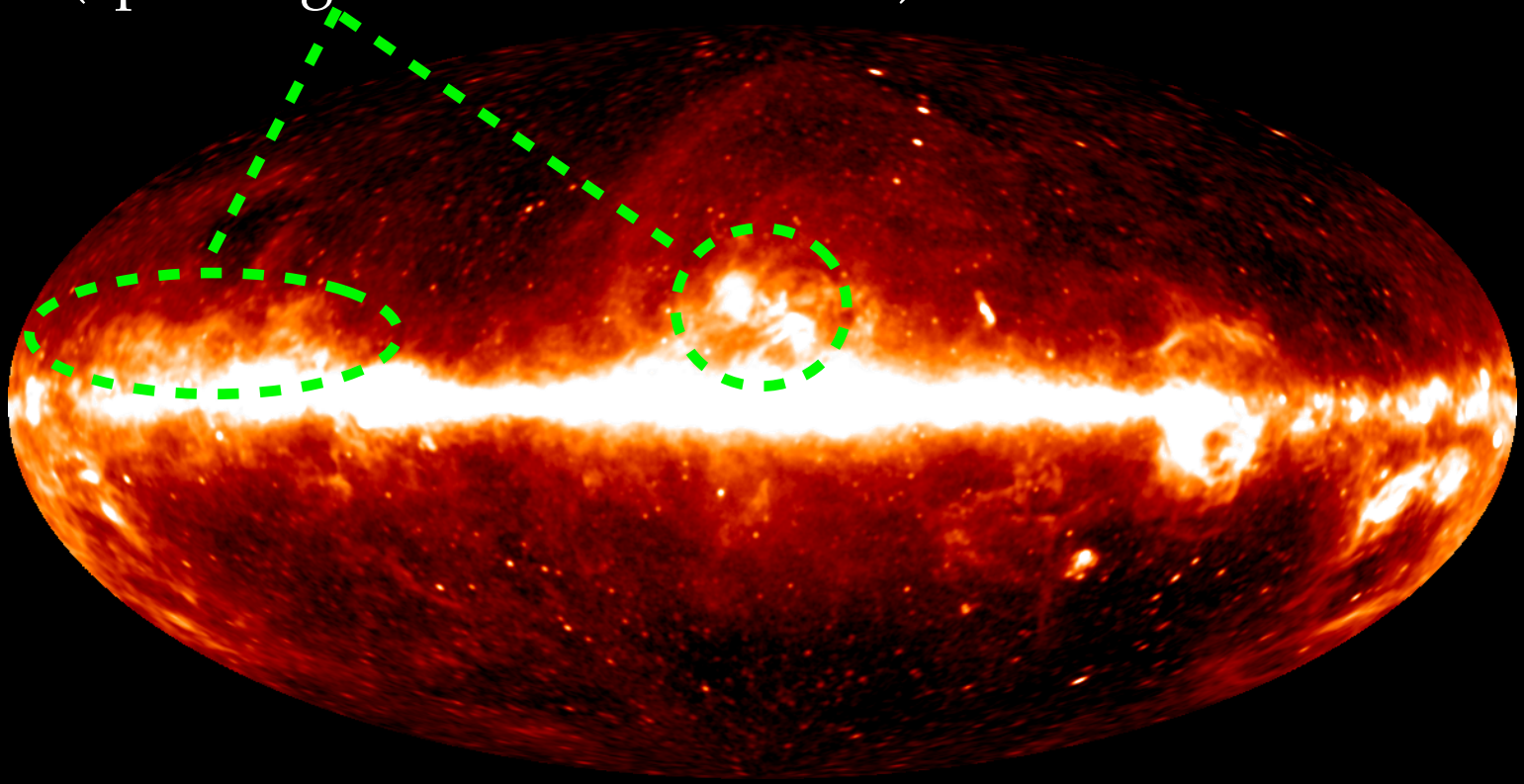




Schlegel et al. (1998)

microwaves...

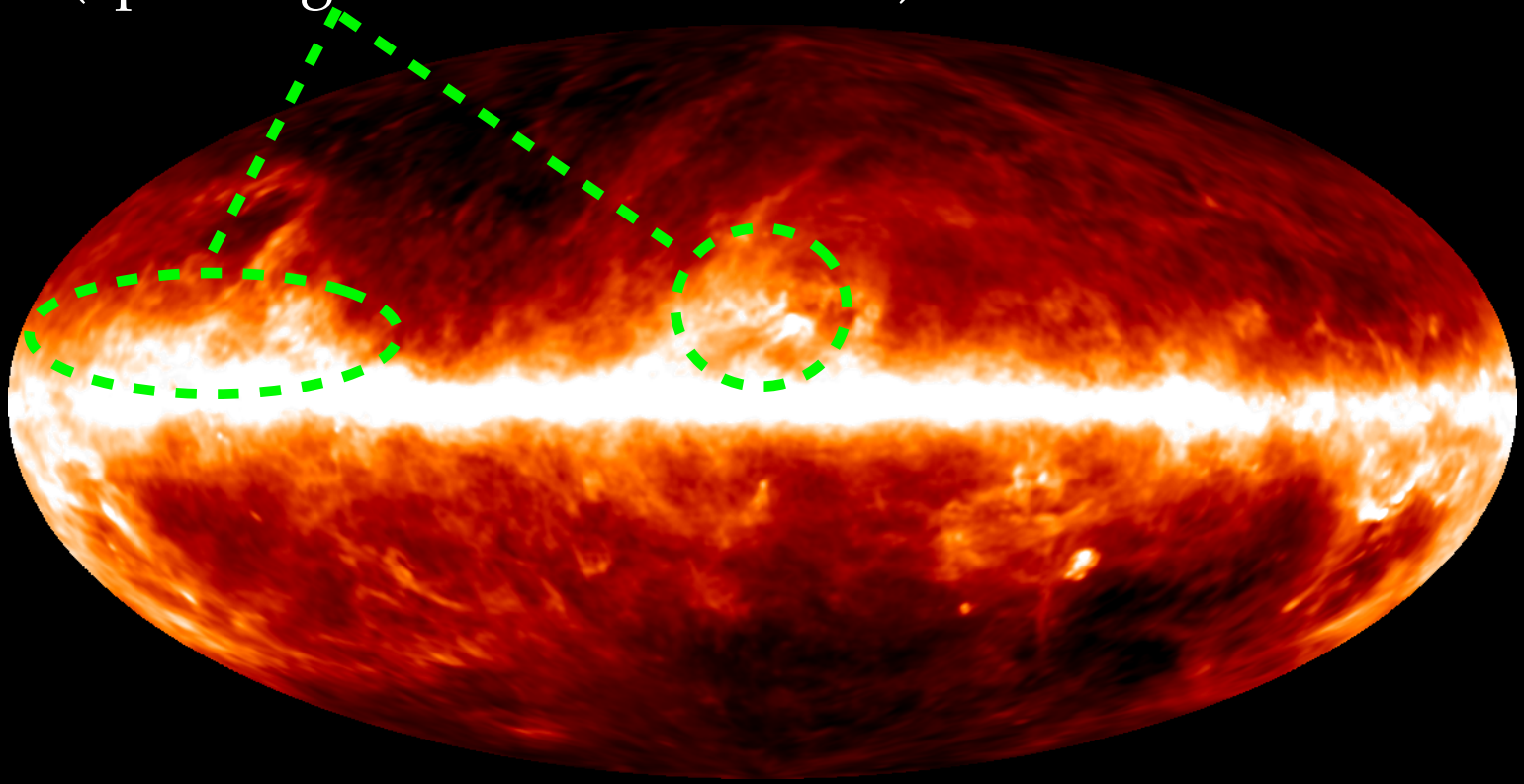
dust (spinning and thermal $T_\nu \propto \nu^{1.7}$)



WMAP 23 GHz

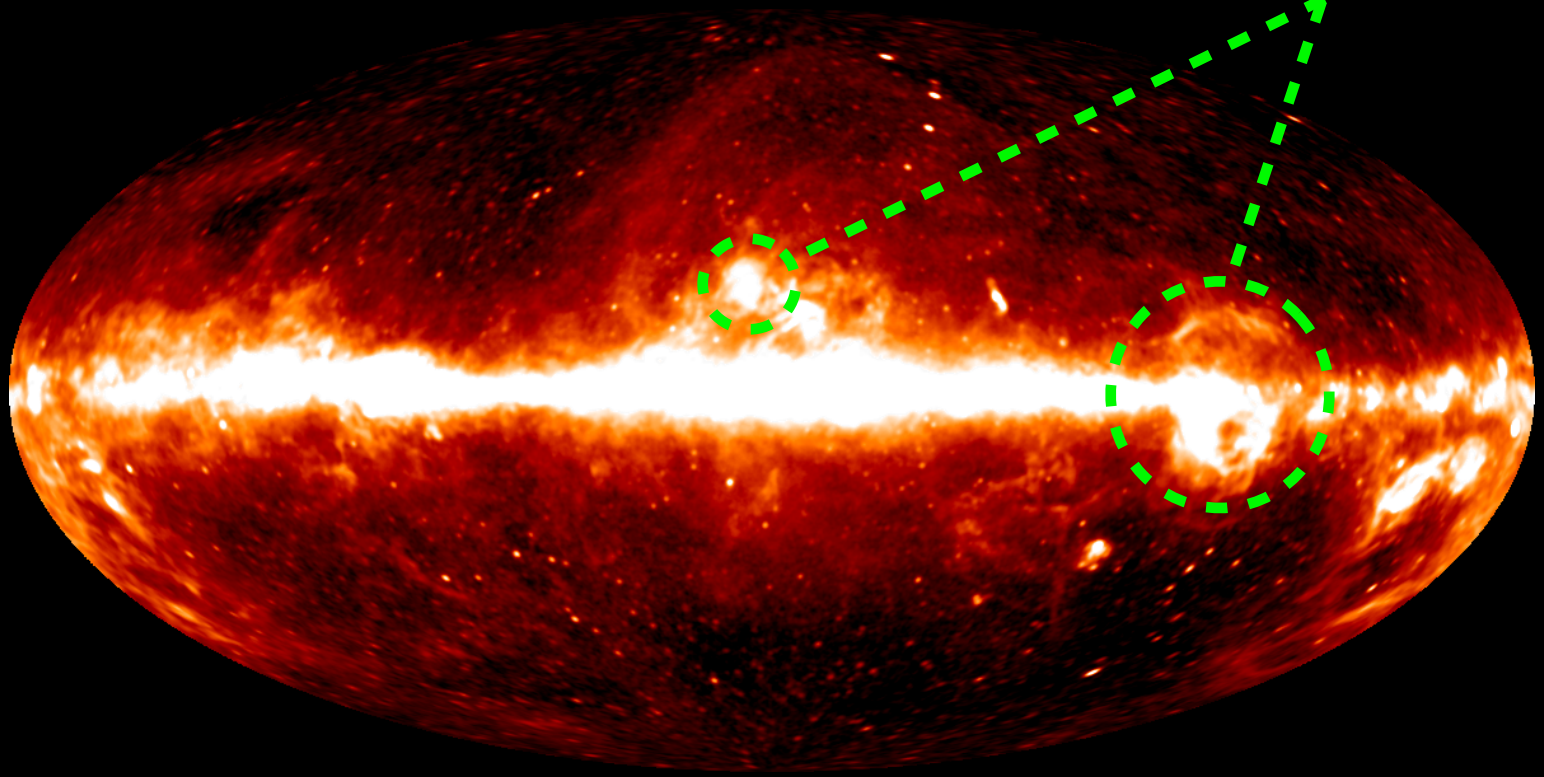
microwaves...

dust (spinning and thermal $T_\nu \propto \nu^{1.7}$)



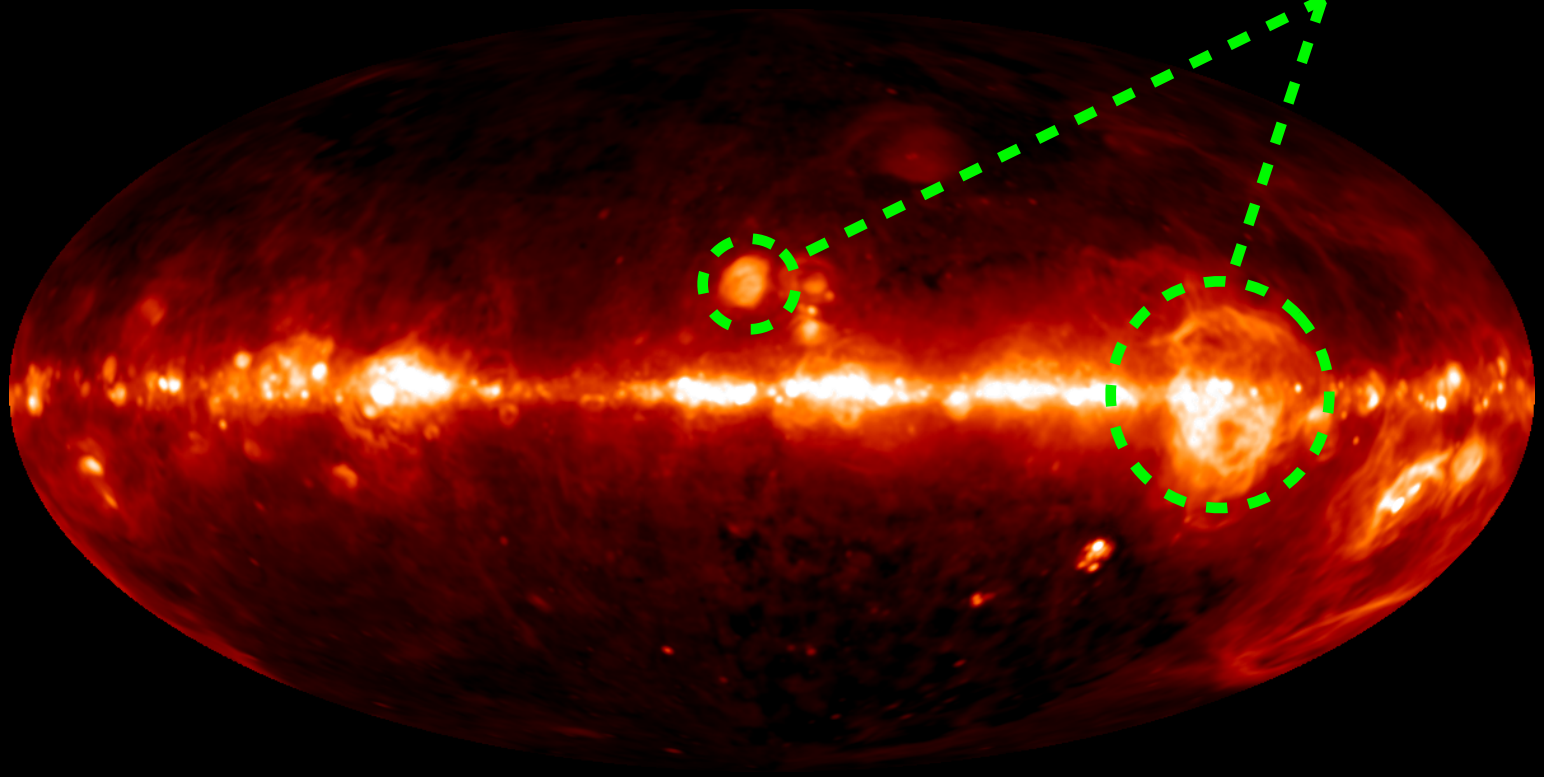
Finkbeiner, Davis, & Schlegel (1999)

microwaves...



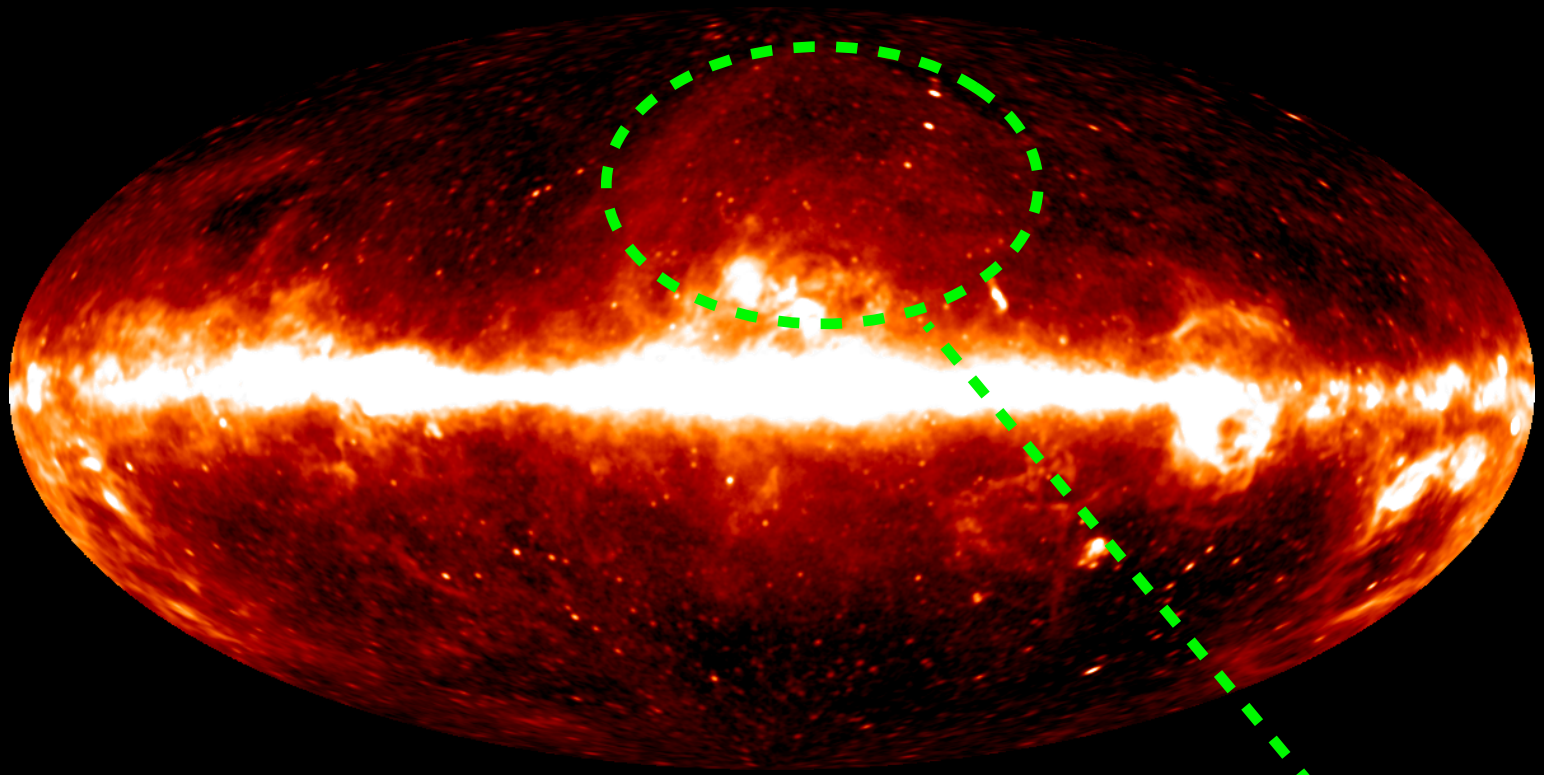
WMAP 23 GHz

microwaves...



Finkbeiner (2003)

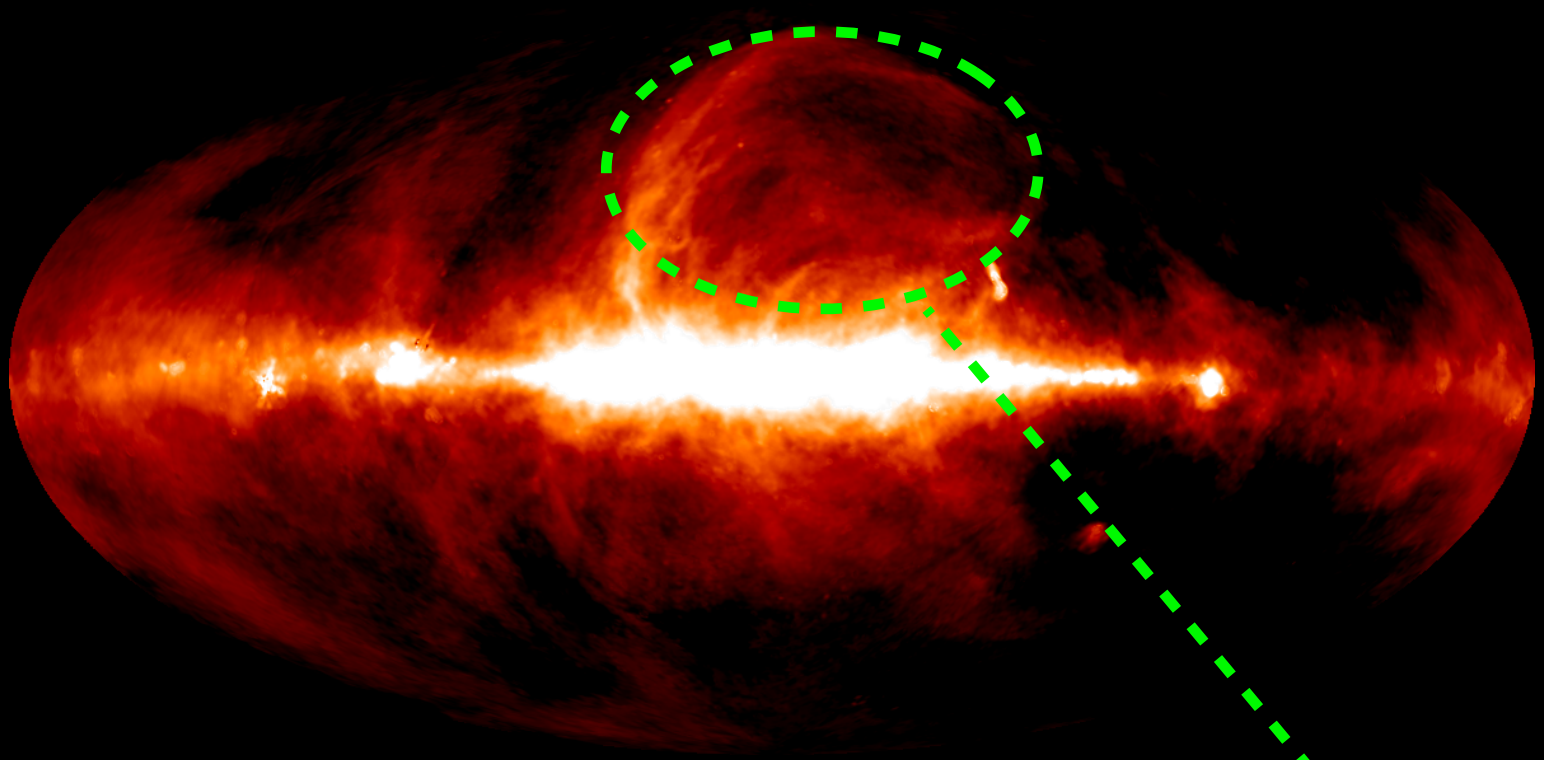
microwaves...



WMAP 23 GHz

synchrotron $T_\nu \propto \nu^{-3.0}$

microwaves...



Haslam et al. (1982)

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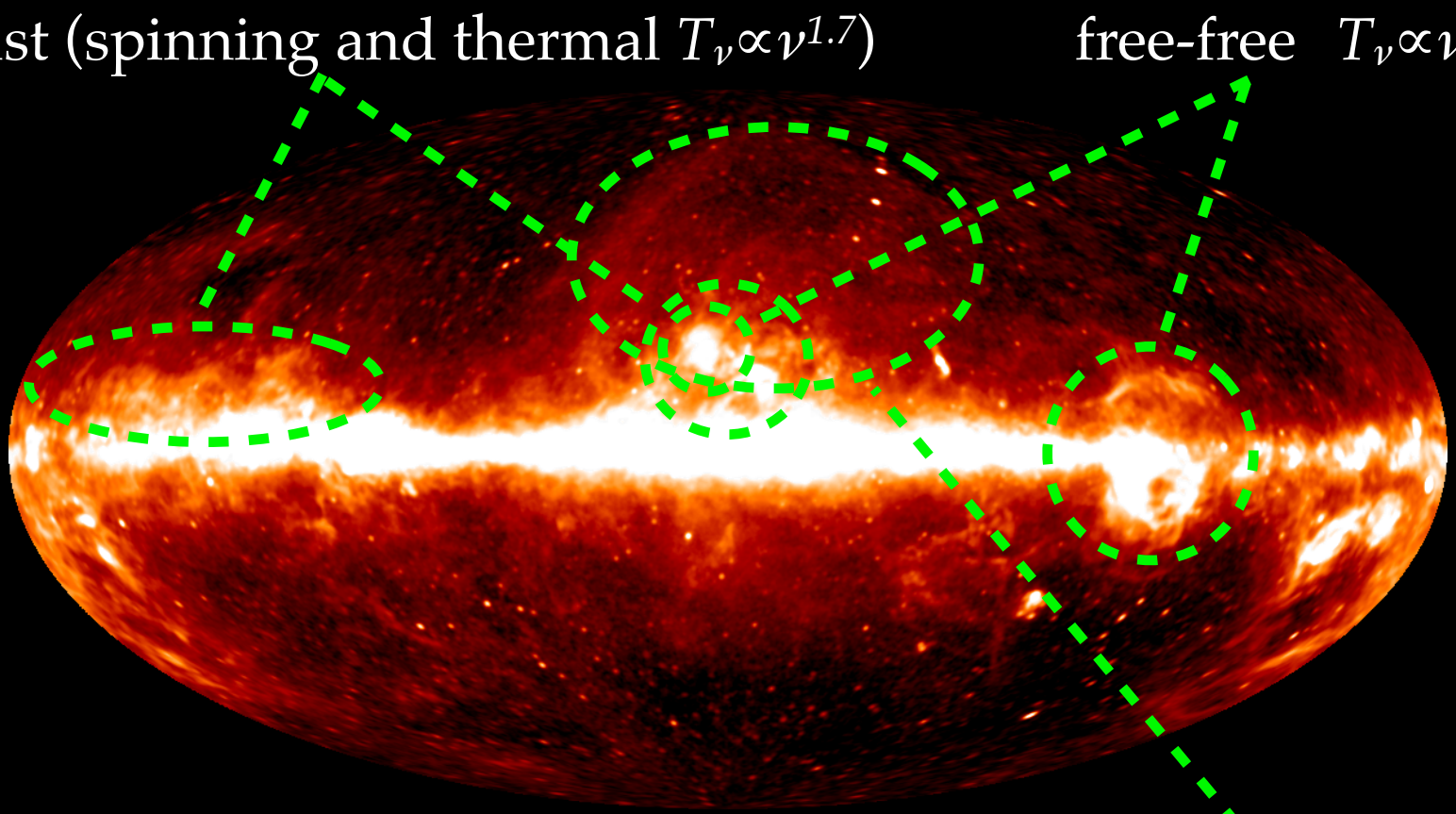
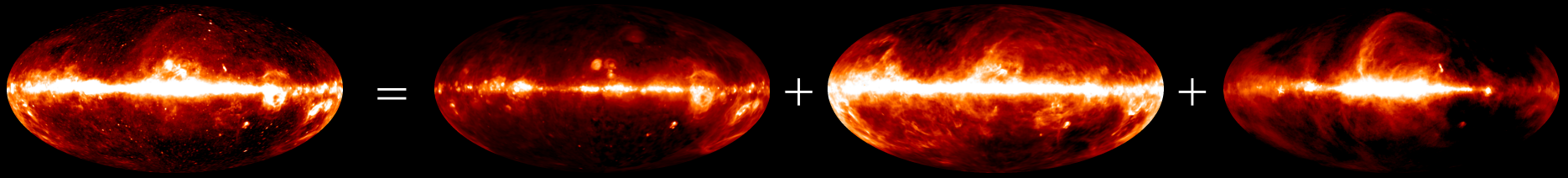
microwaves...


dust (spinning and thermal $T_\nu \propto \nu^{1.7}$)
free-free $T_\nu \propto \nu^{-2.15}$
WMAP 23 GHz
synchrotron $T_\nu \propto \nu^{-3.0}$

Greg Dobler (KITP / UCSB)

$$a_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$



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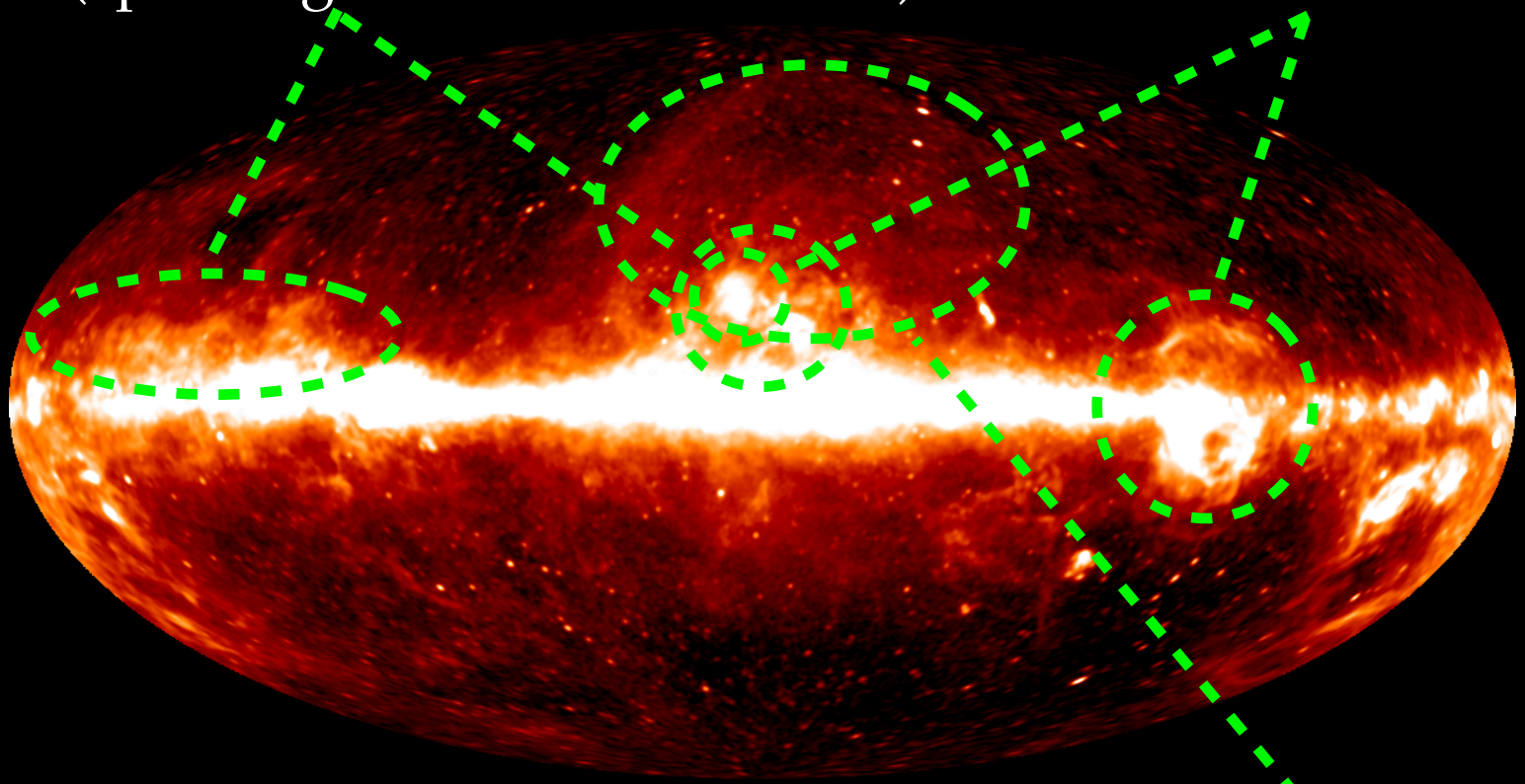
free-free $T_\nu \propto \nu^{-2.15}$



WMAP 23 GHz

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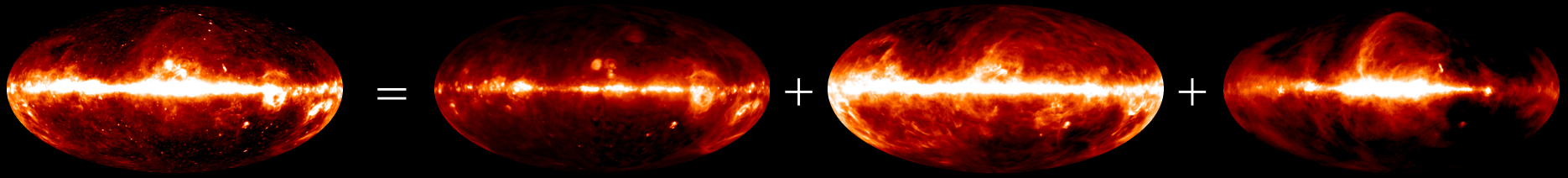

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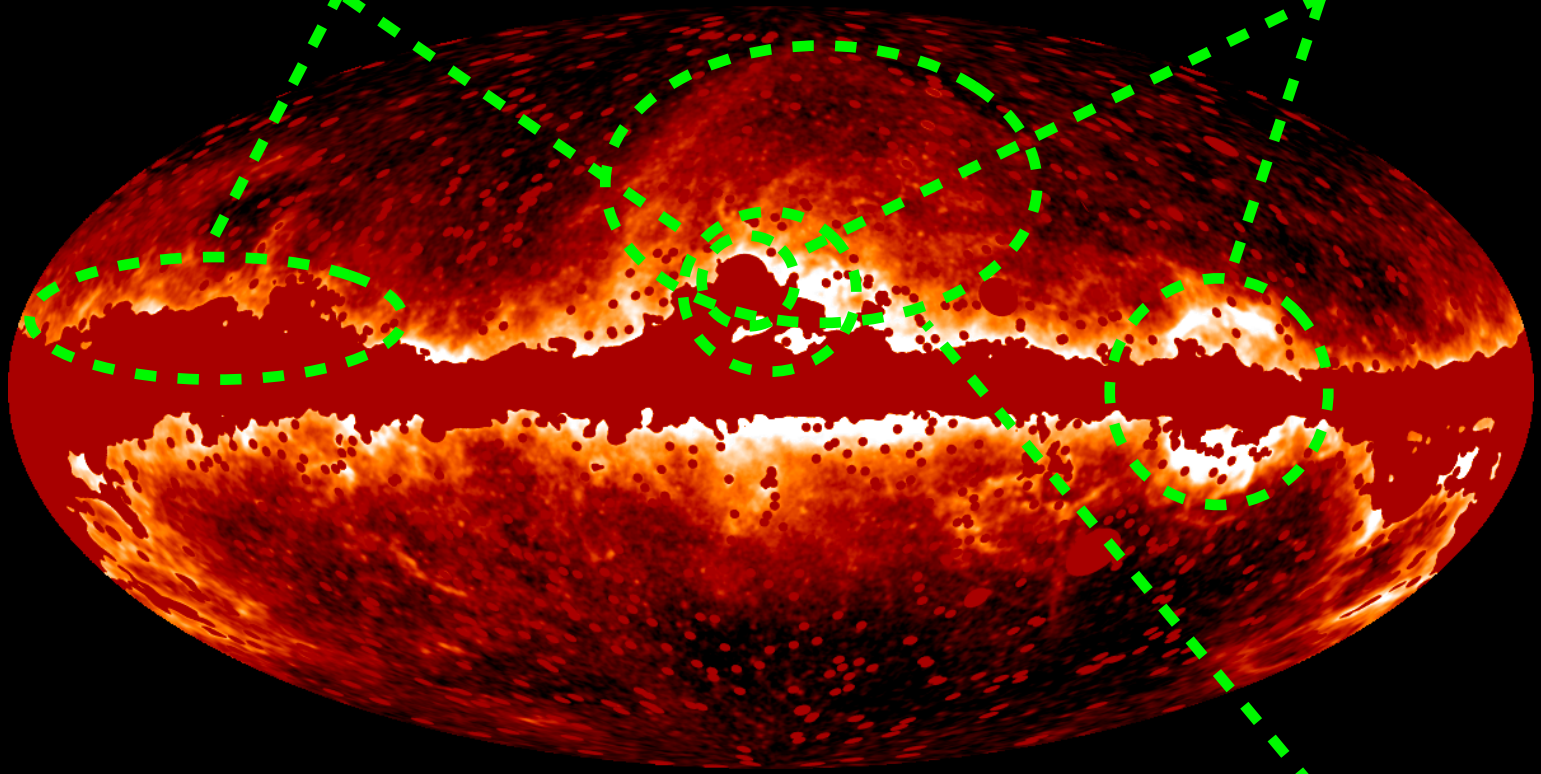

WMAP 23 GHz

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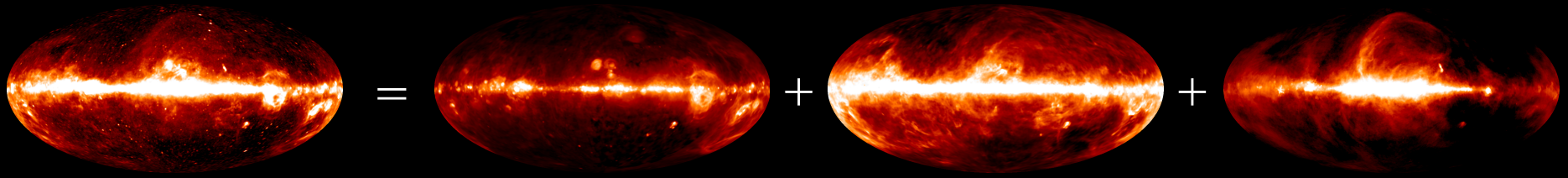

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WMAP 23 GHz

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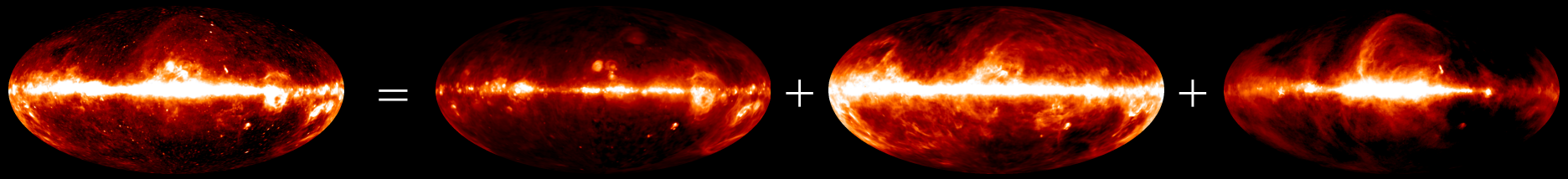

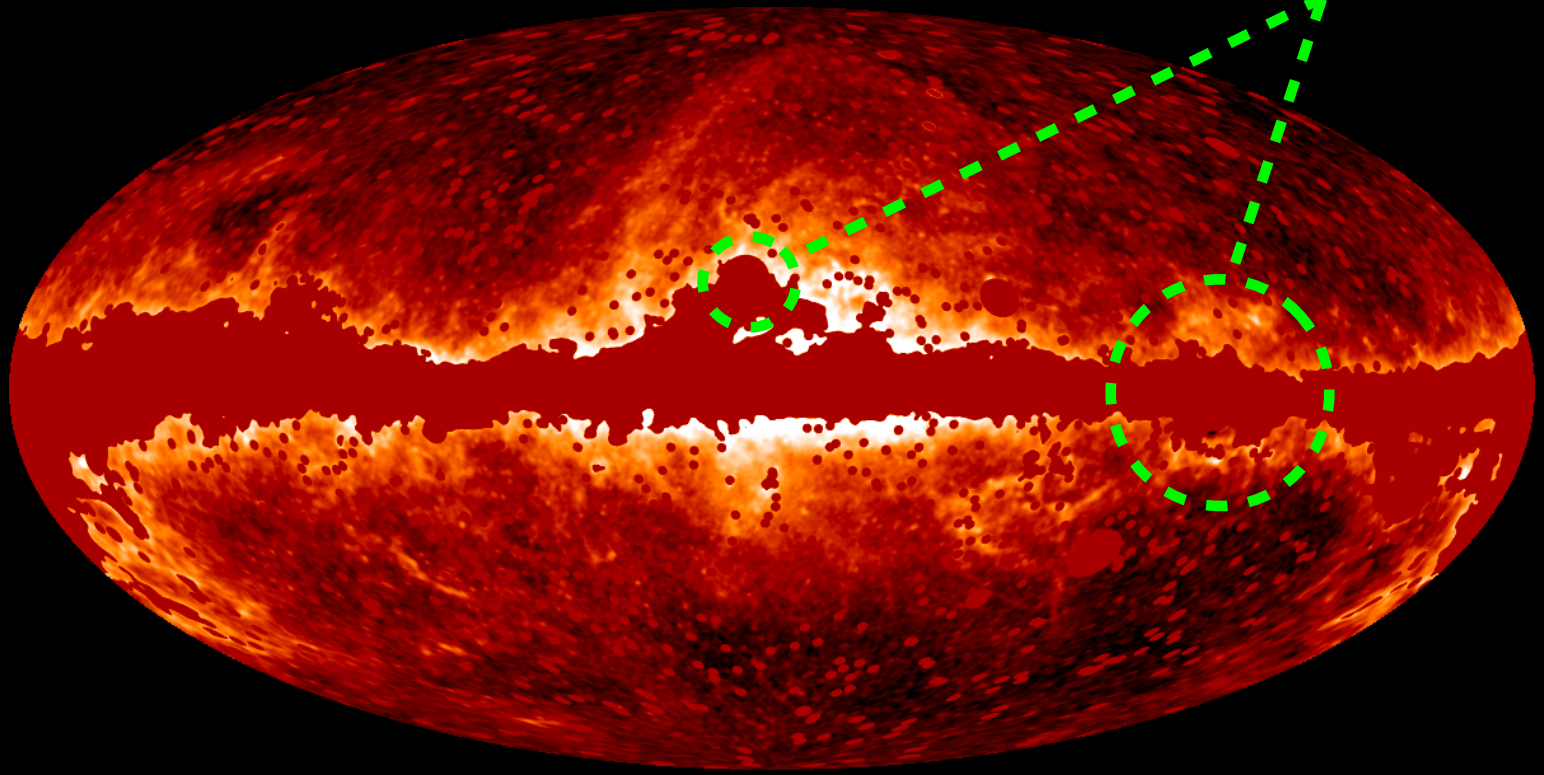

WMAP 23 GHz

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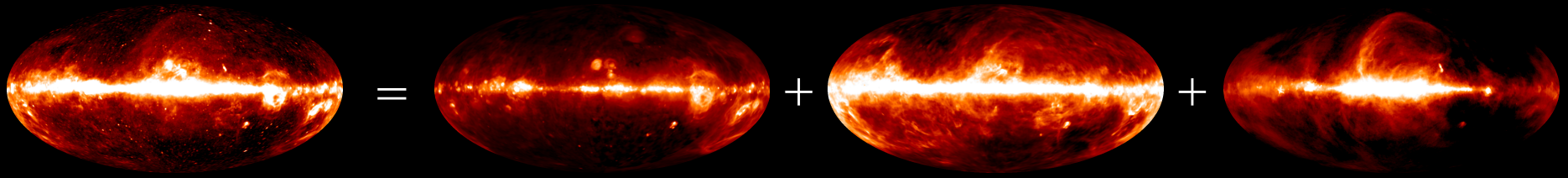

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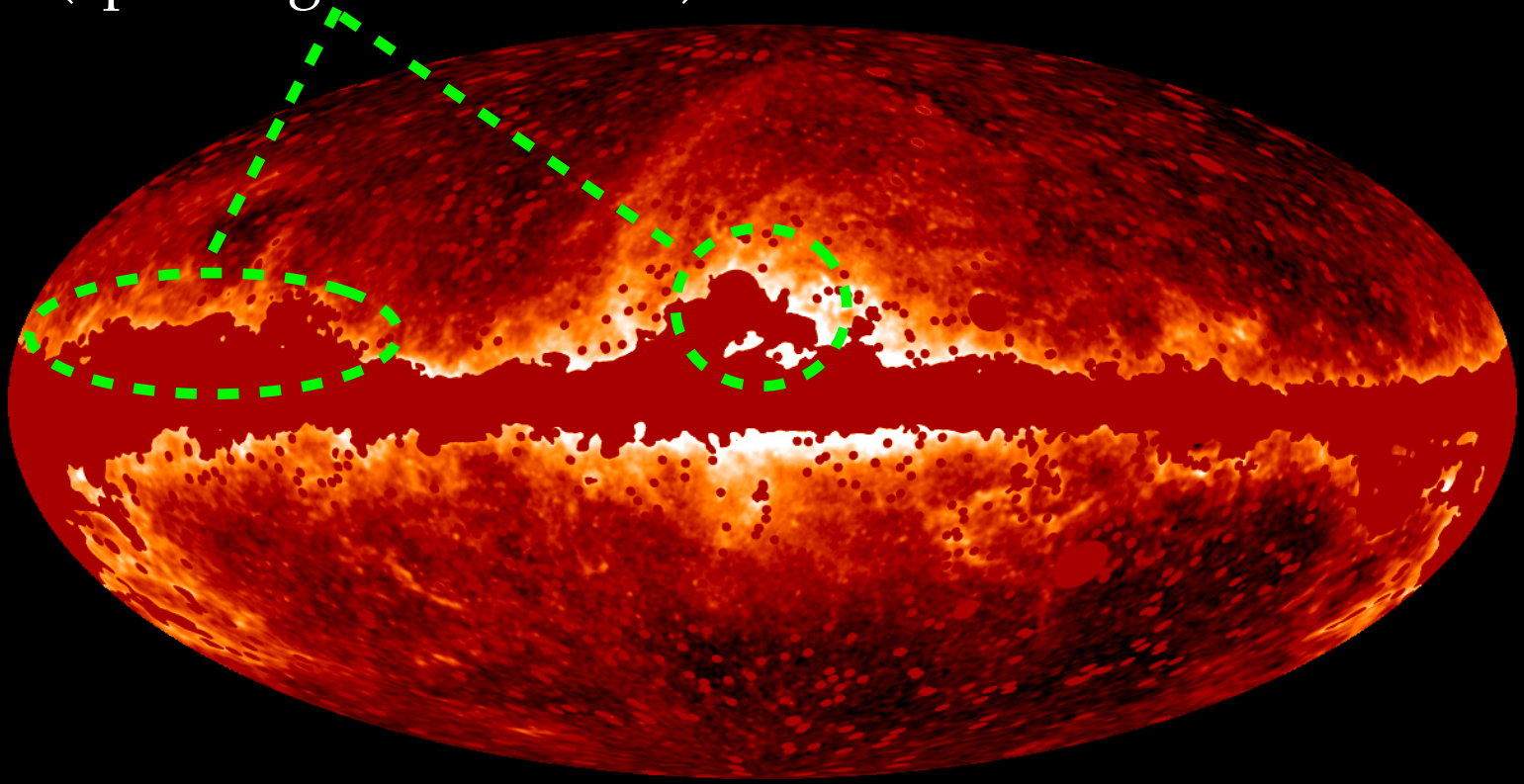

WMAP 23 GHz

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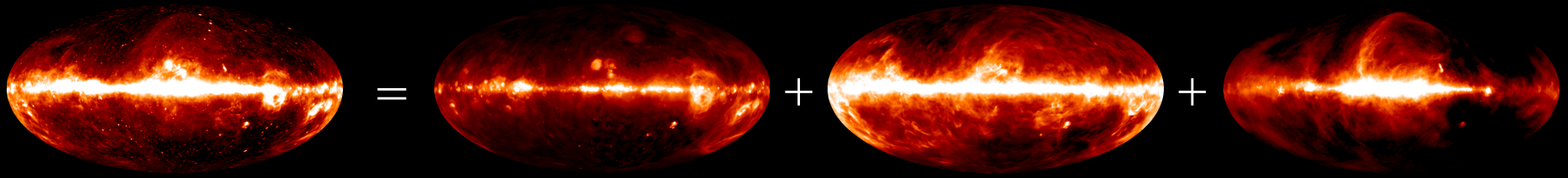

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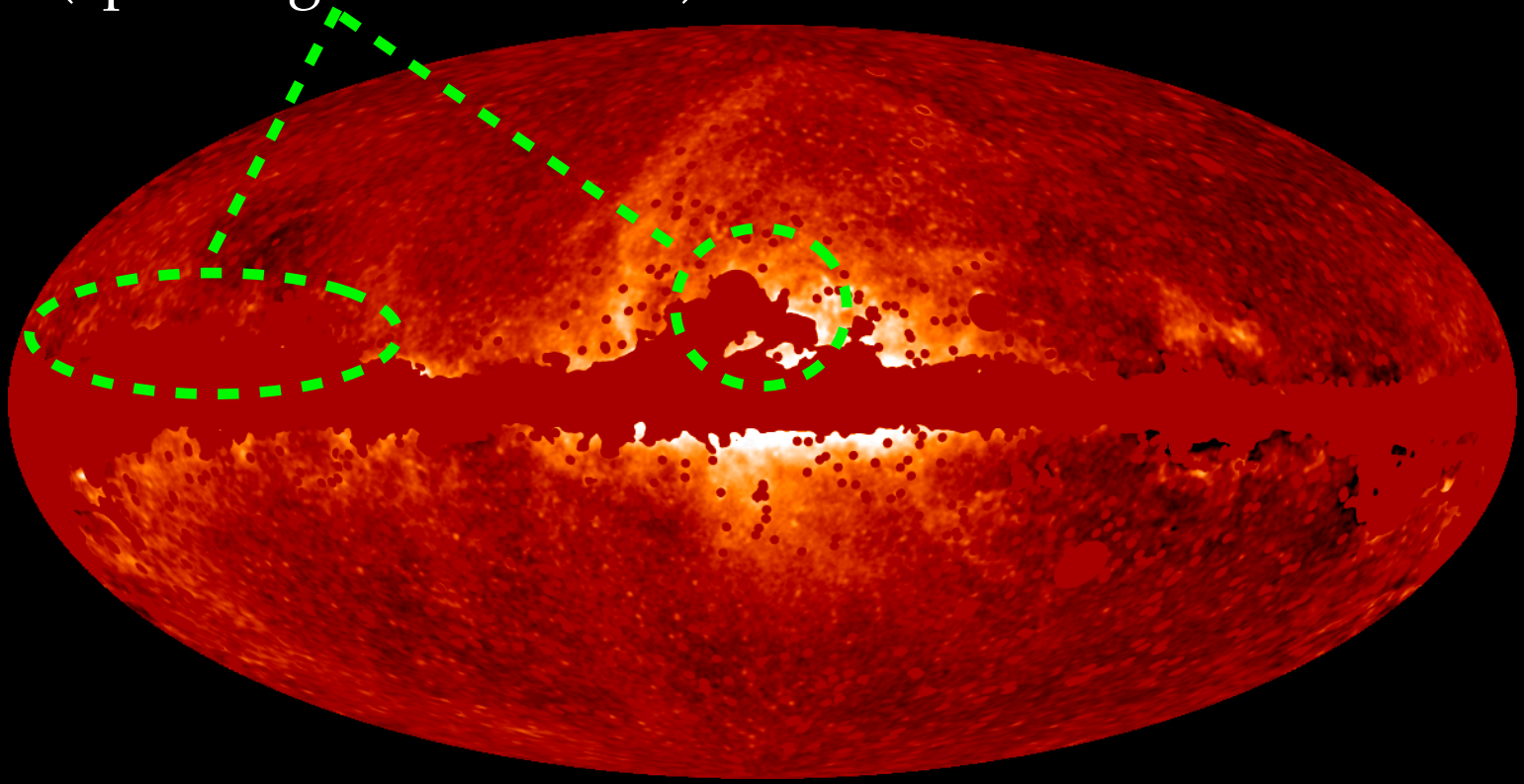

WMAP 23 GHz

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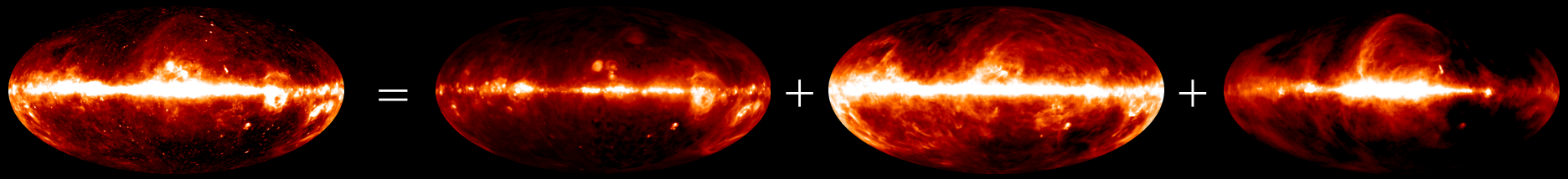

WMAP 23 GHz

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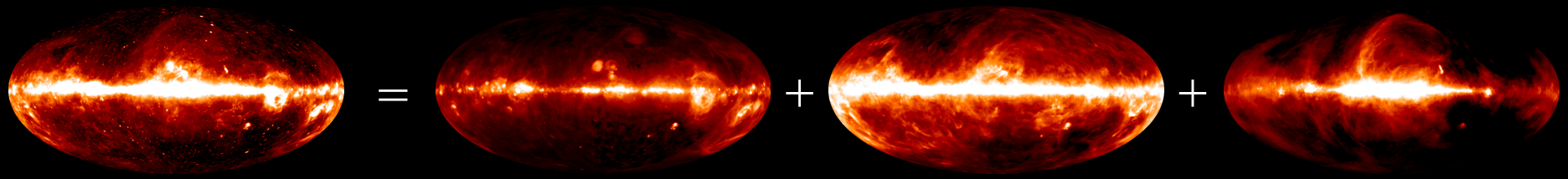

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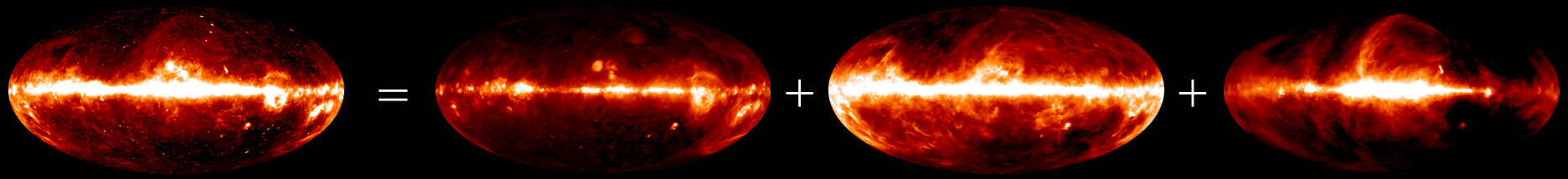

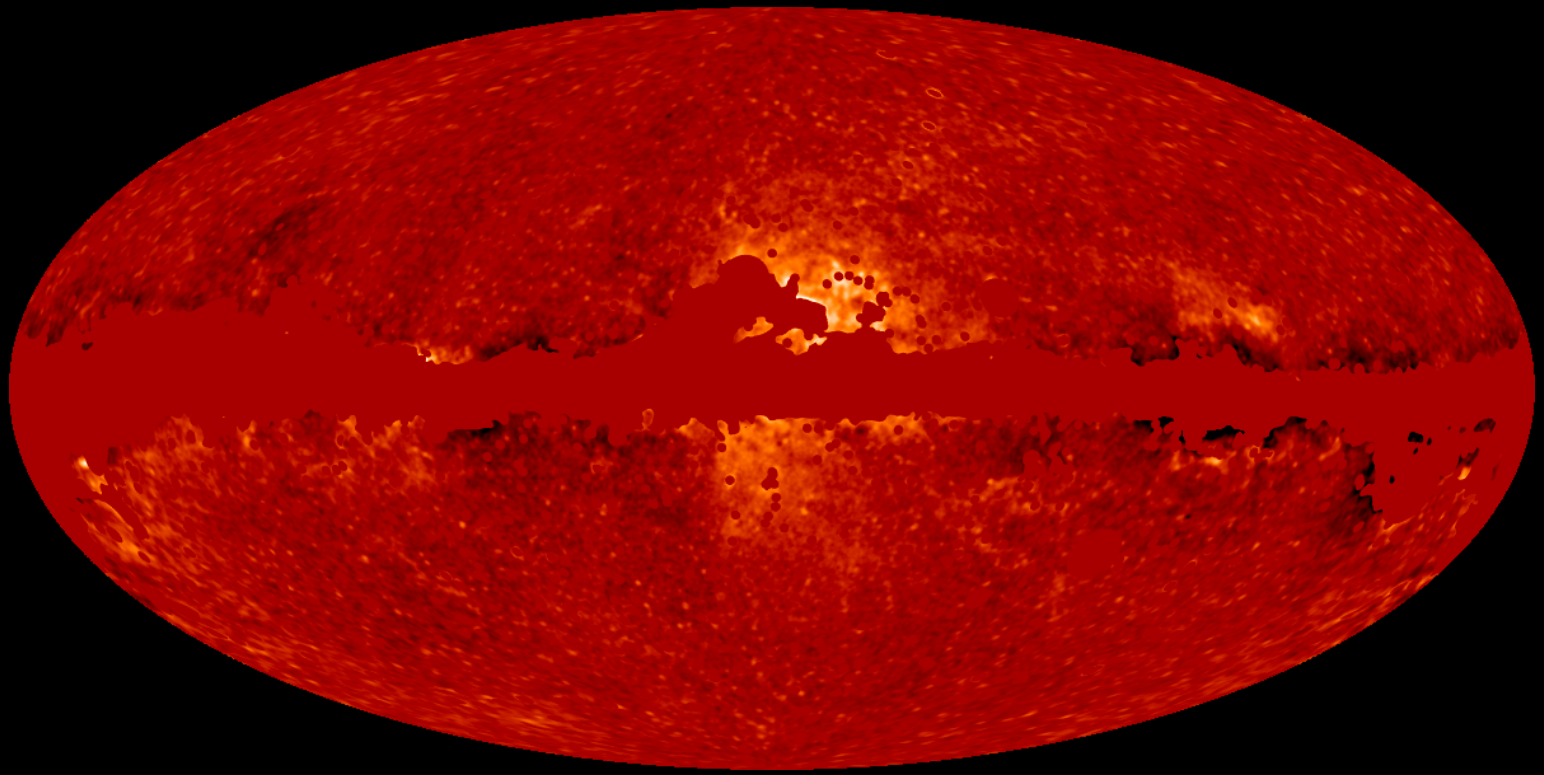

WMAP 23 GHz

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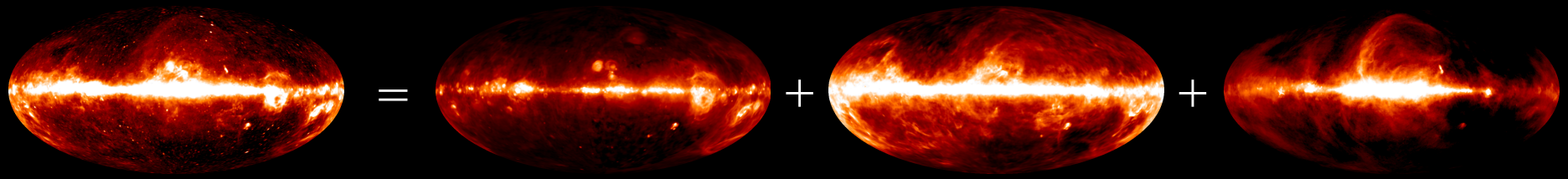
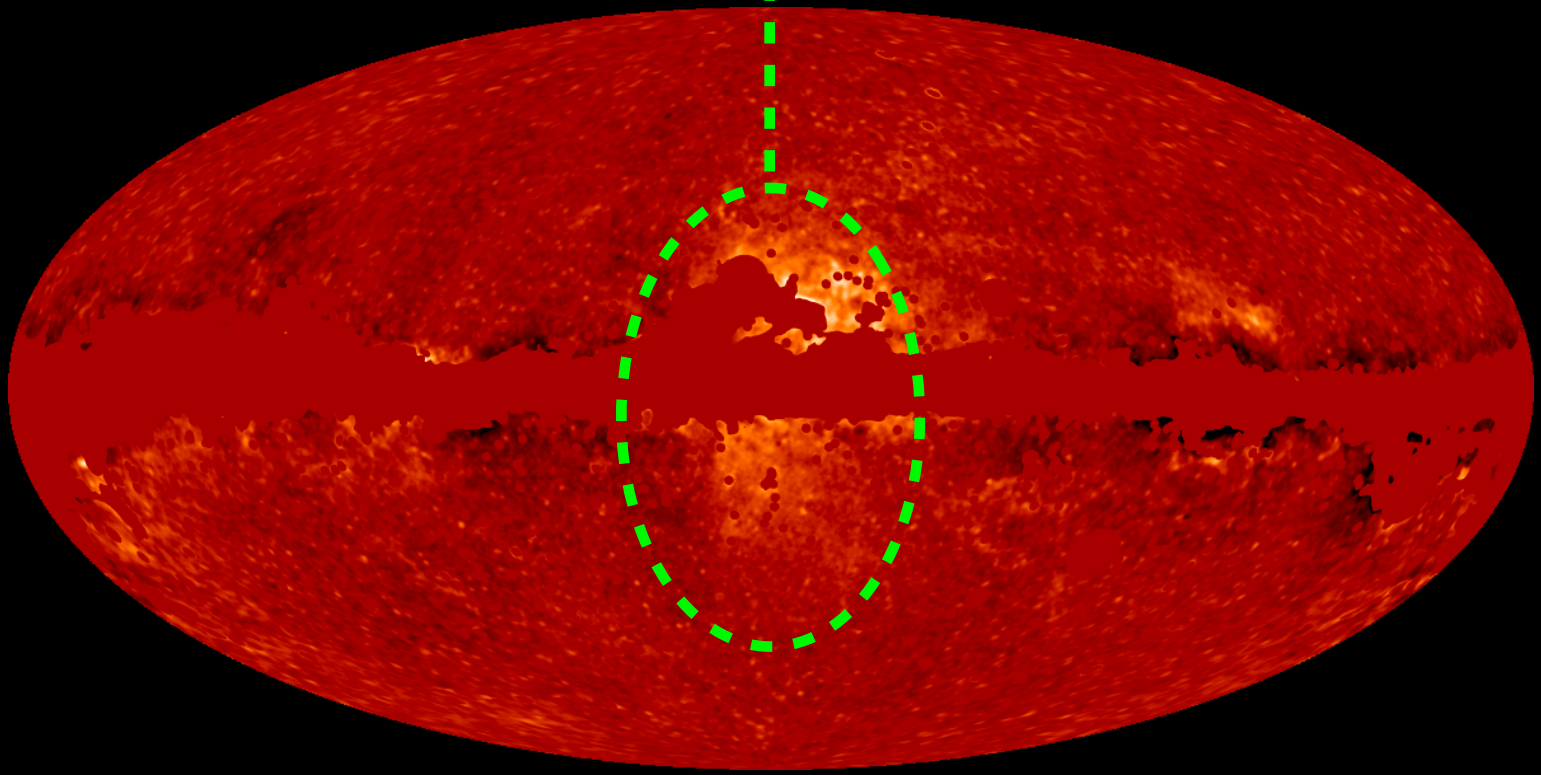


microwave “haze”



WMAP 23 GHz

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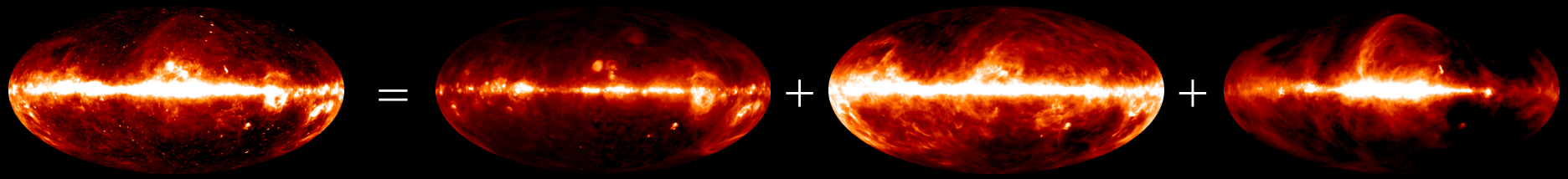
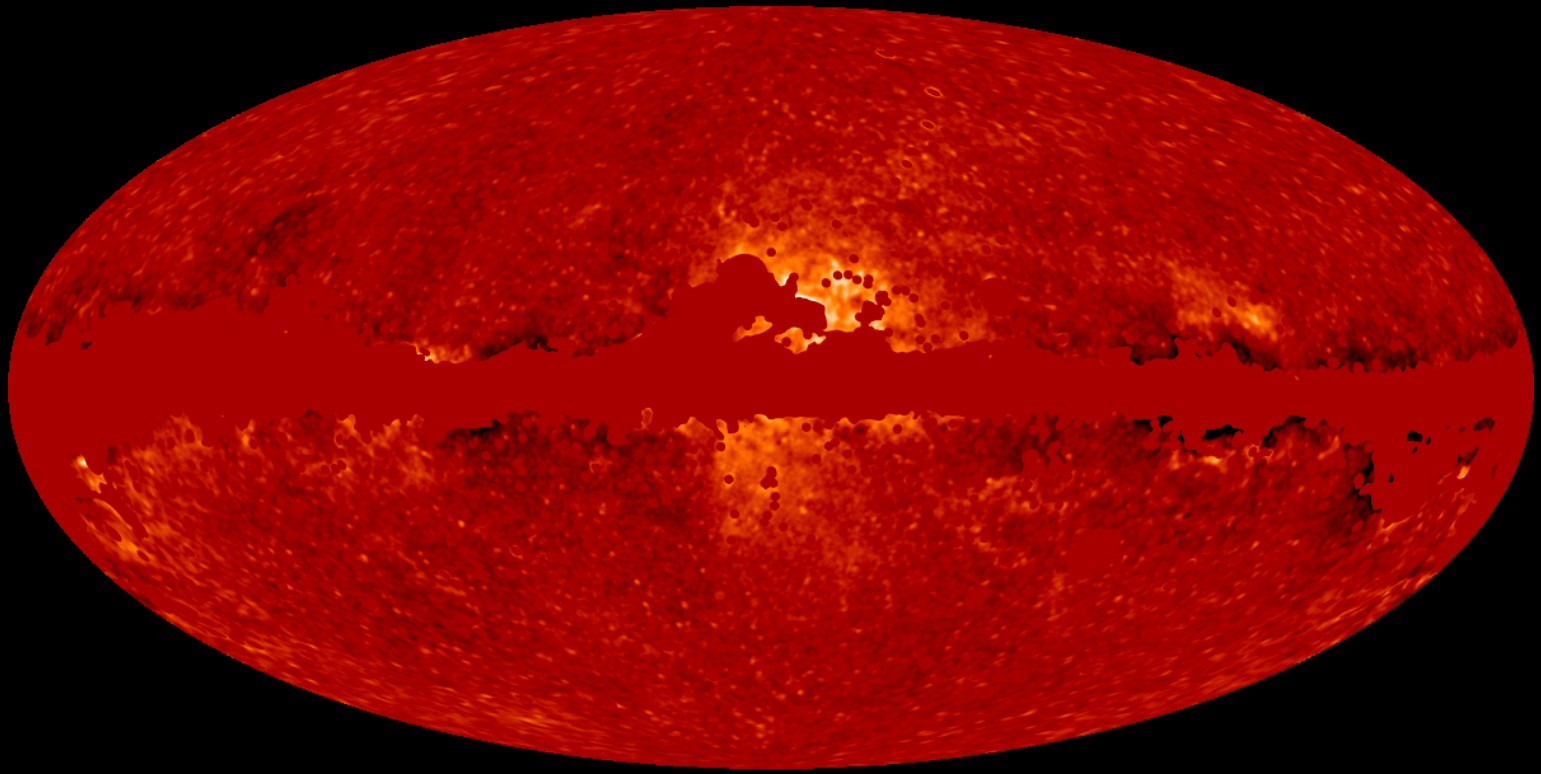


microwave haze



WMAP 23 GHz

"full sky fit"

Greg Dobler (KITP / UCSB)

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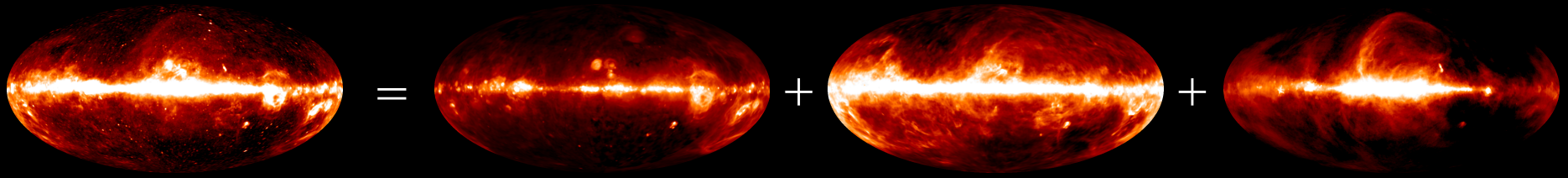
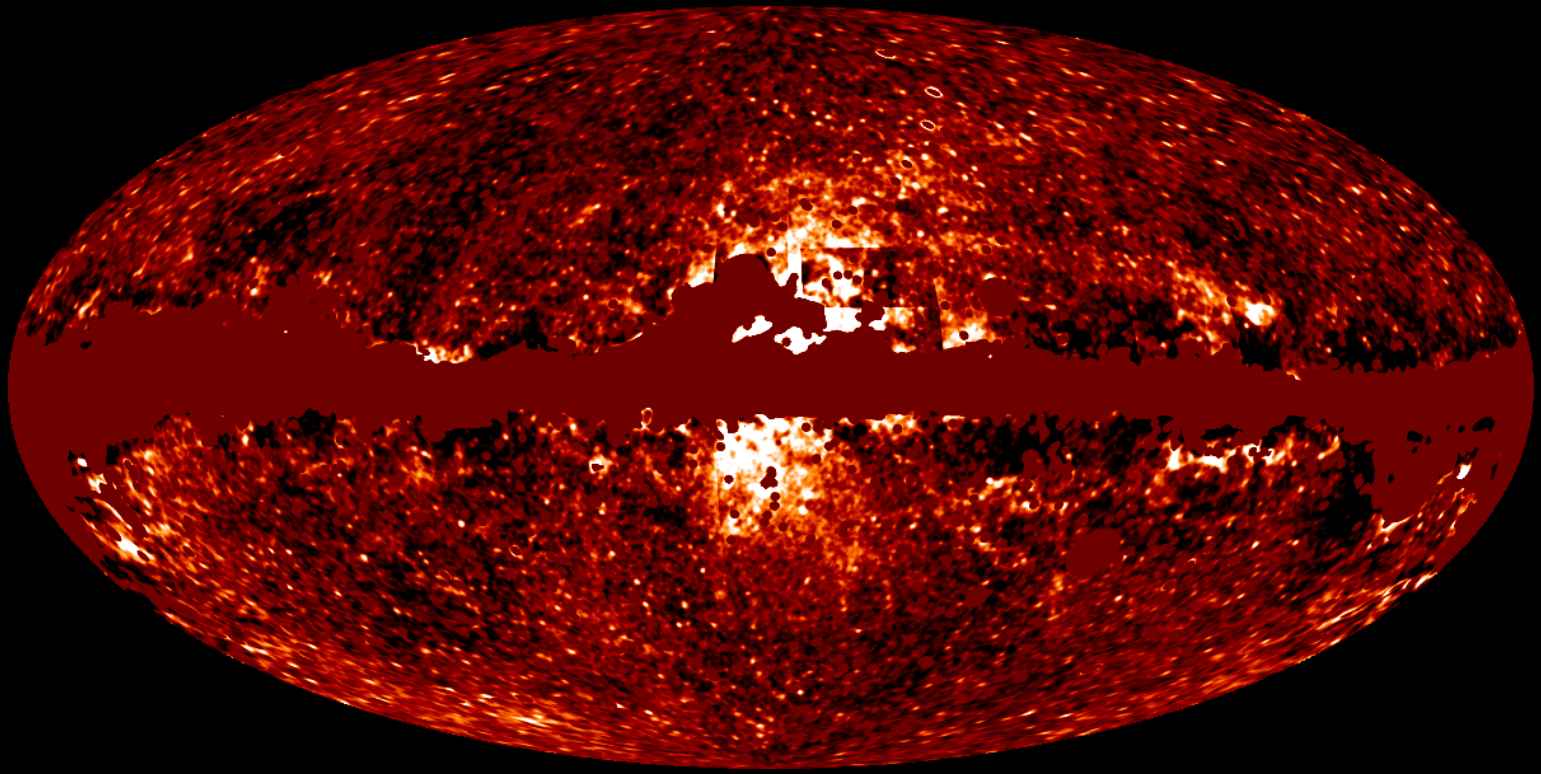


microwave haze



WMAP 23 GHz

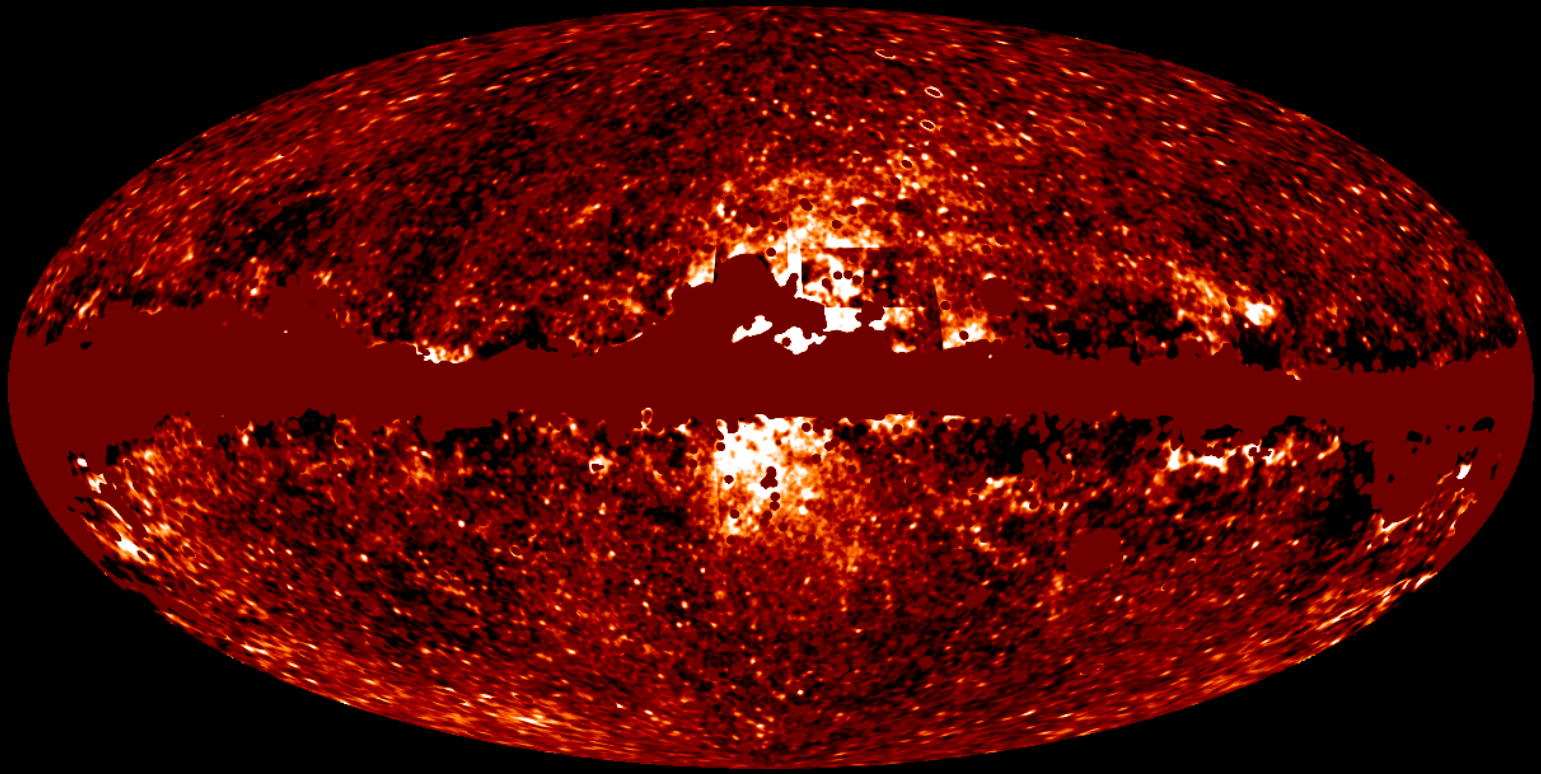
"regional fit"

what is it? (we'll get to that) but first, what makes it unique?

. diffuse and extended (~ *5* kpc x *12* kpc)

. spectrum

microwave haze



WMAP 23 GHz

Dobler (2012a)

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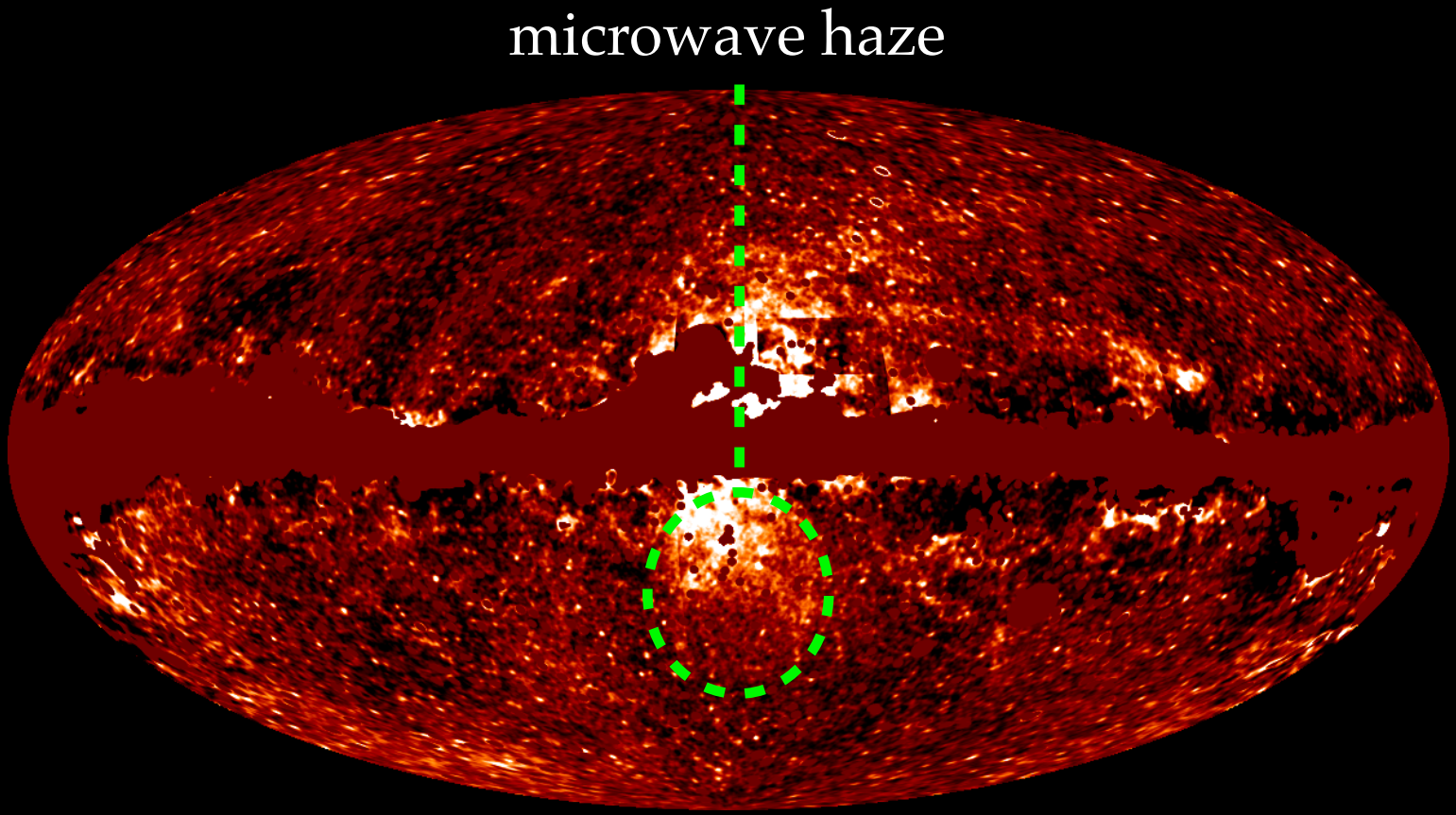

WMAP 23 GHz

Dobler (2012a)

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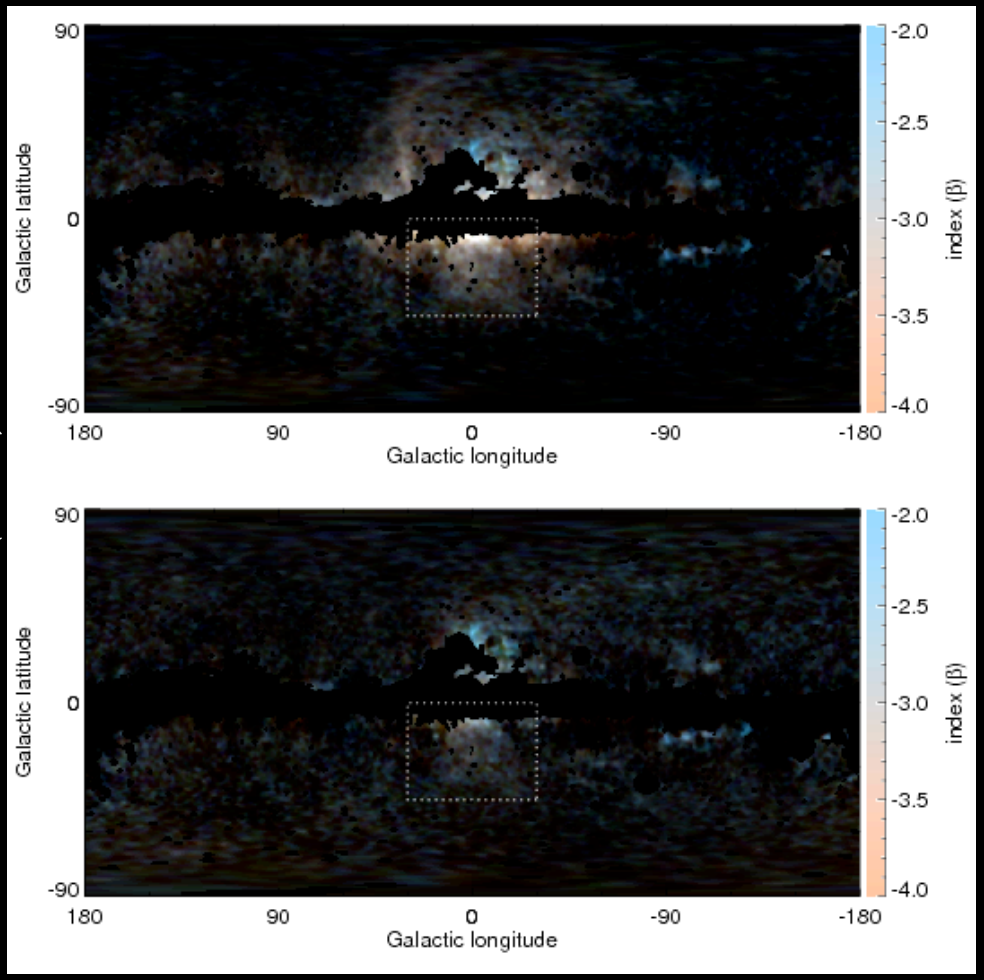
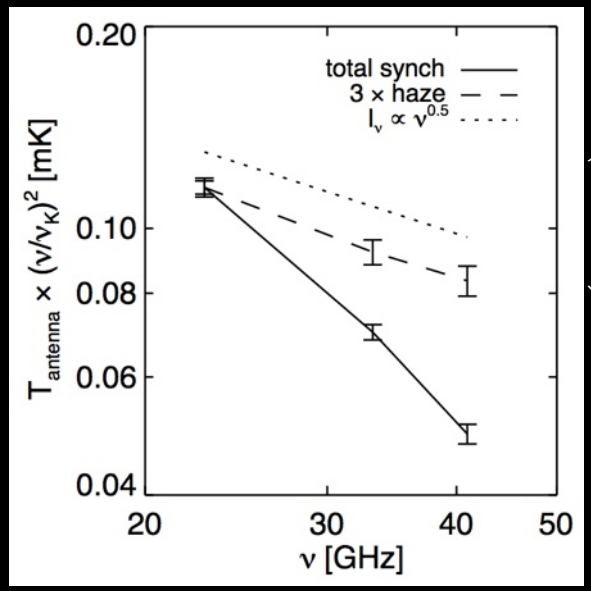


Dobler & Finkbeiner (2008)



Dobler (2012a)

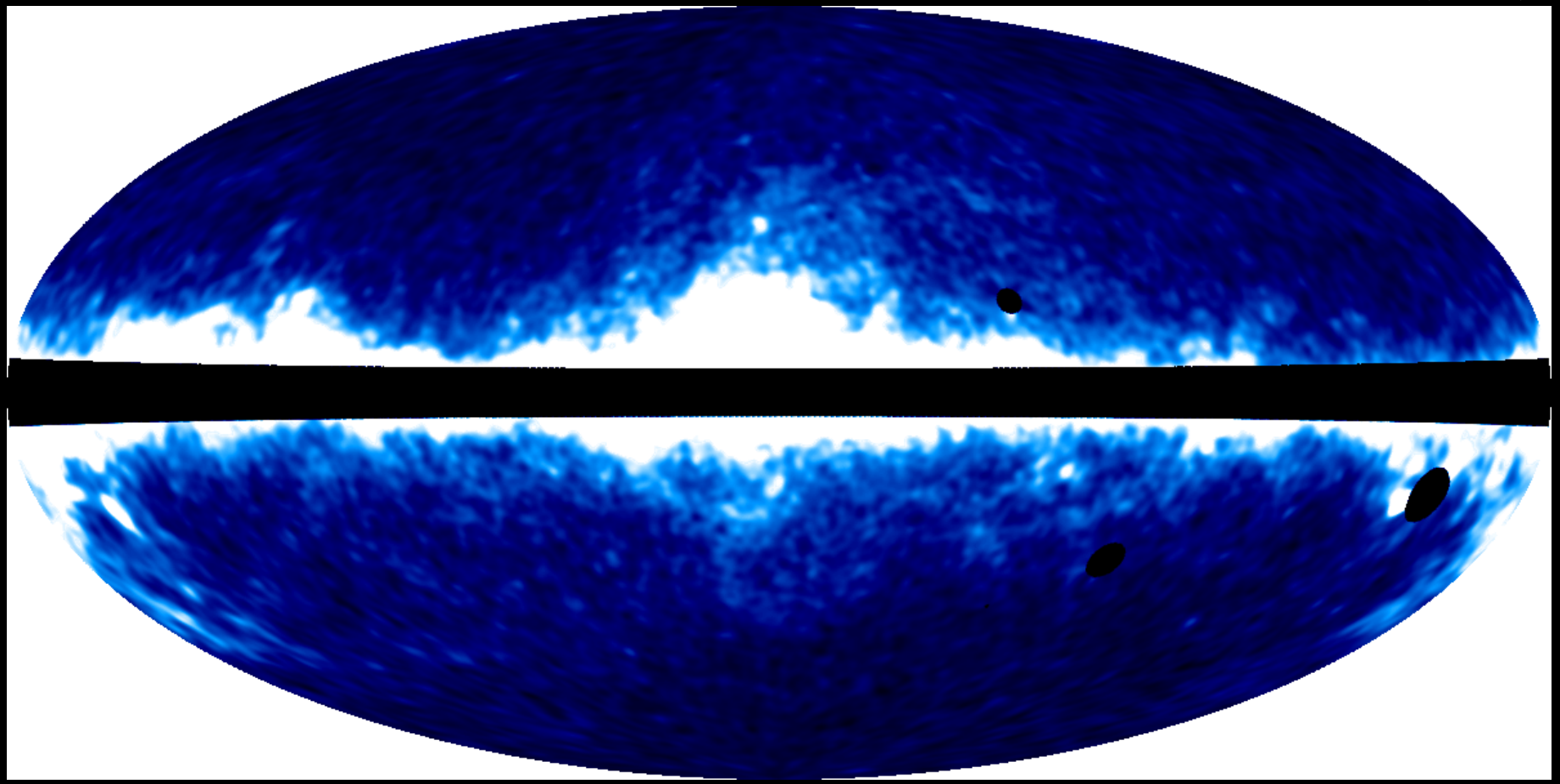
consistent with synchrotron from a ***very hard*** electron population:

$$dN/dE \propto E^{-2.0}$$

gamma-rays...

gamma-rays...

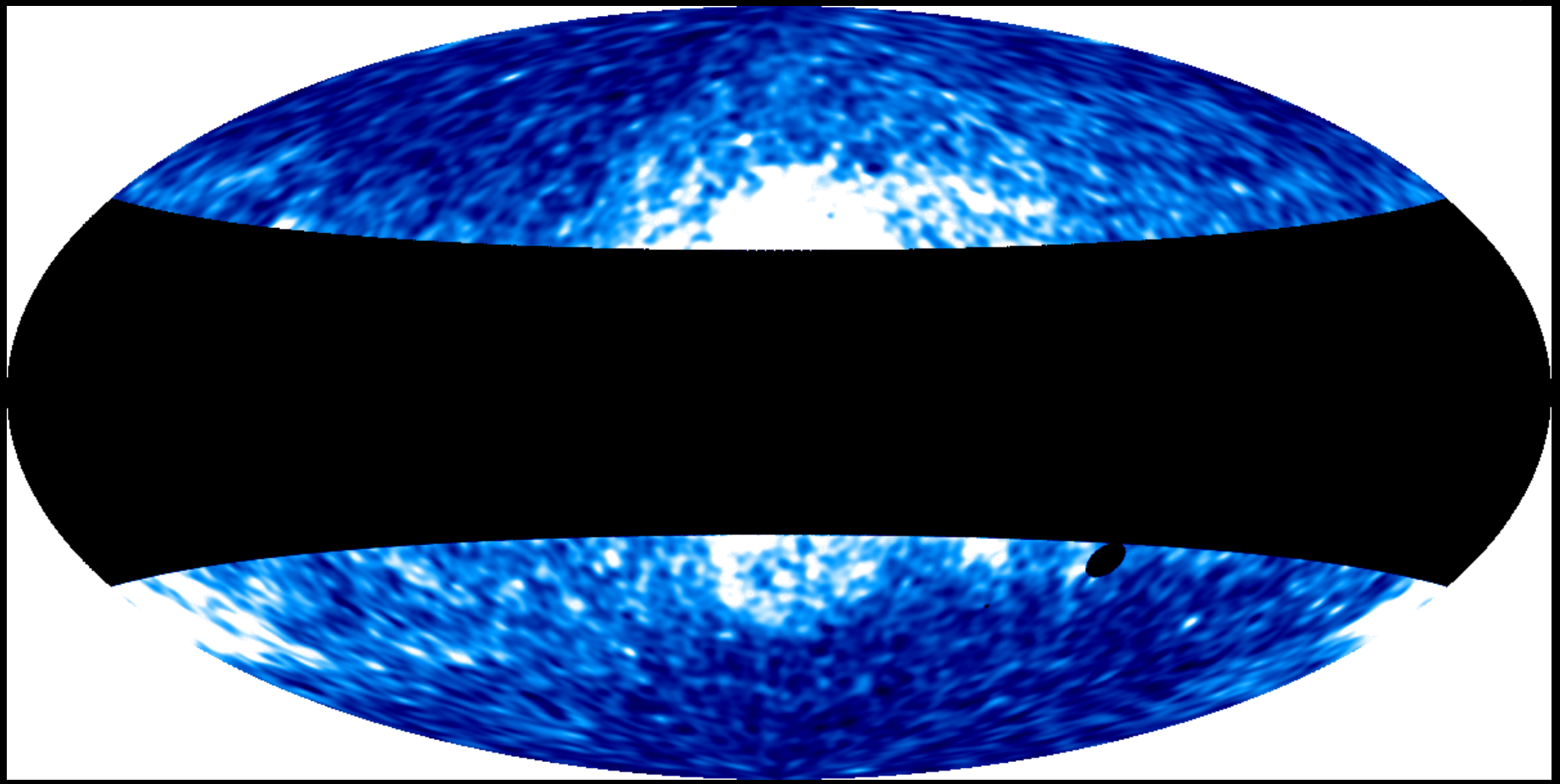
Dobler et al. (2010)



Fermi 2-5 GeV

gamma-rays...

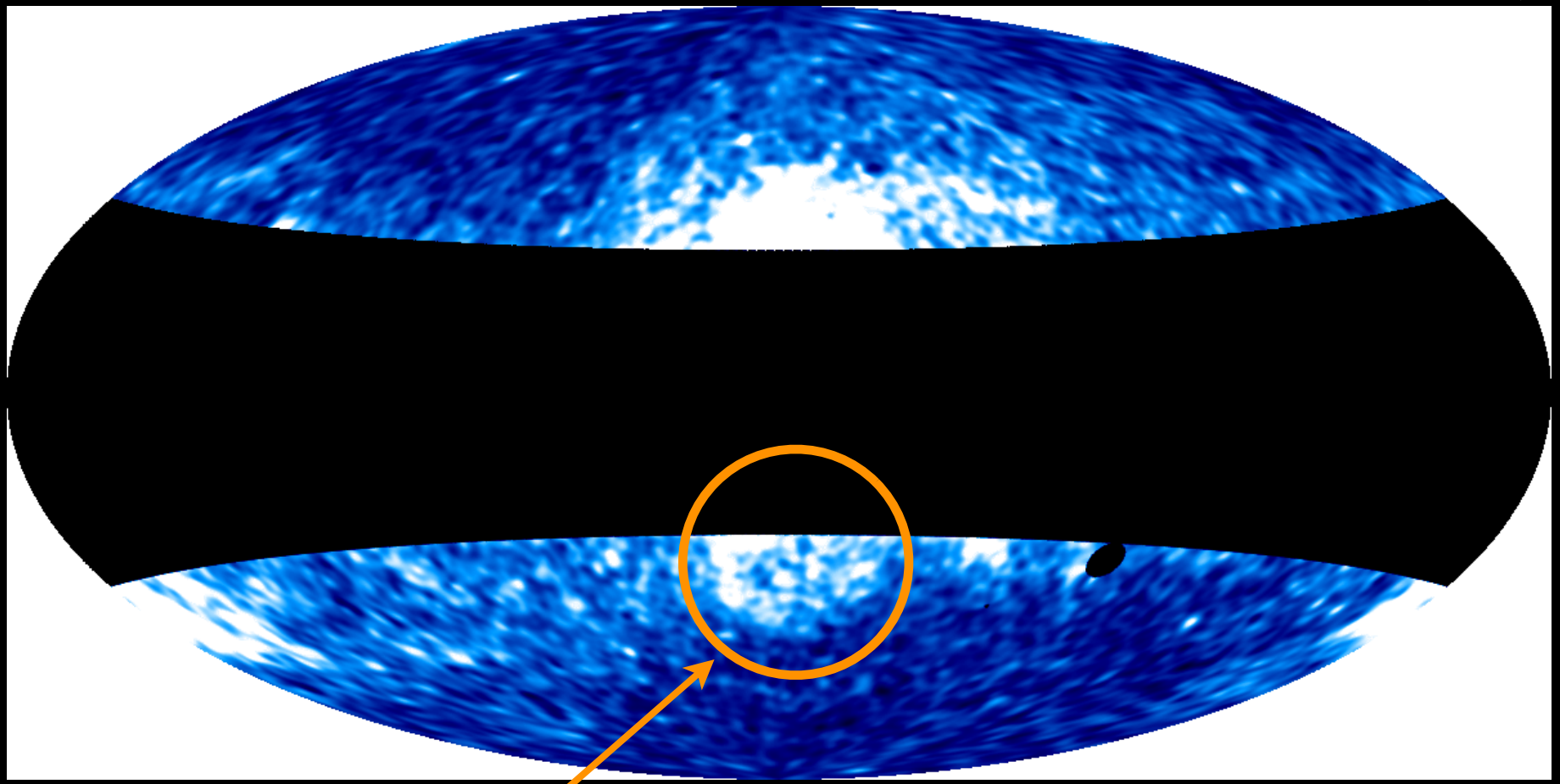
Dobler et al. (2010)



Fermi 2-5 GeV

gamma-rays...

Dobler et al. (2010)



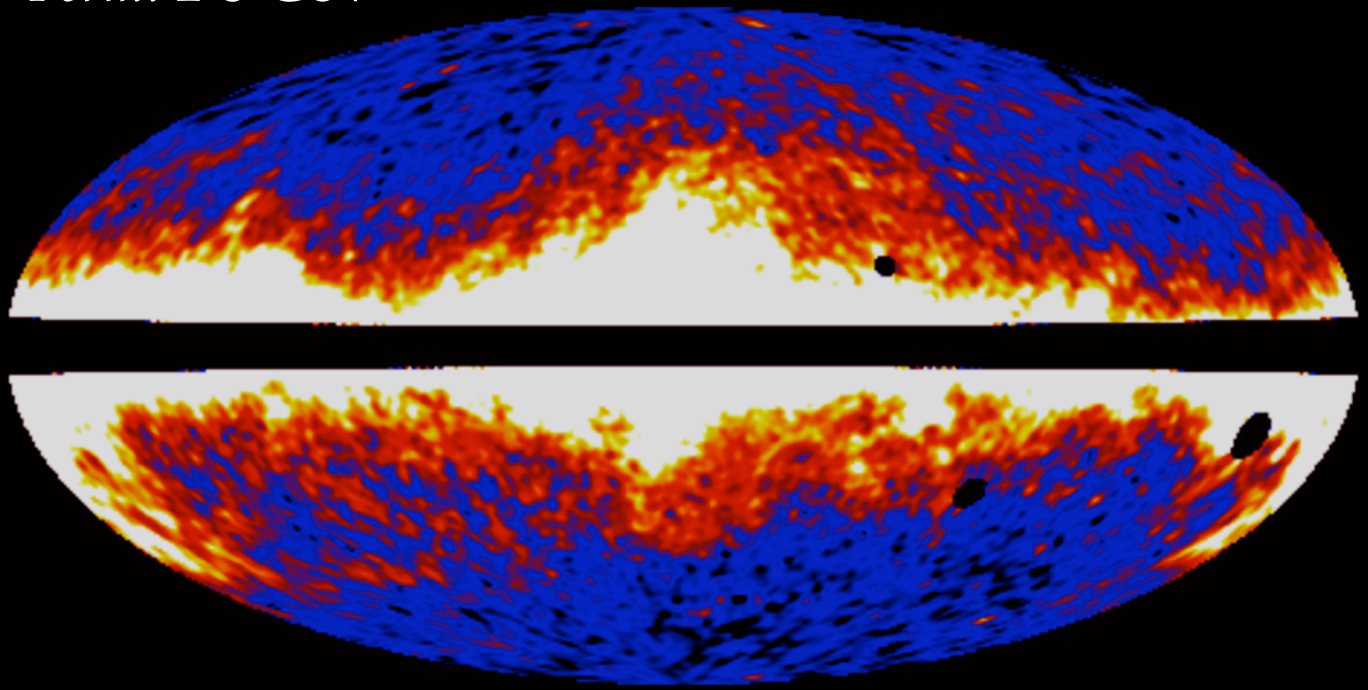
Fermi 2-5 GeV

visible ***even*** with ***no*** templates, ***no*** fitting, ***no*** subtraction, etc...

Greg Dobler (KITP/UCSB)

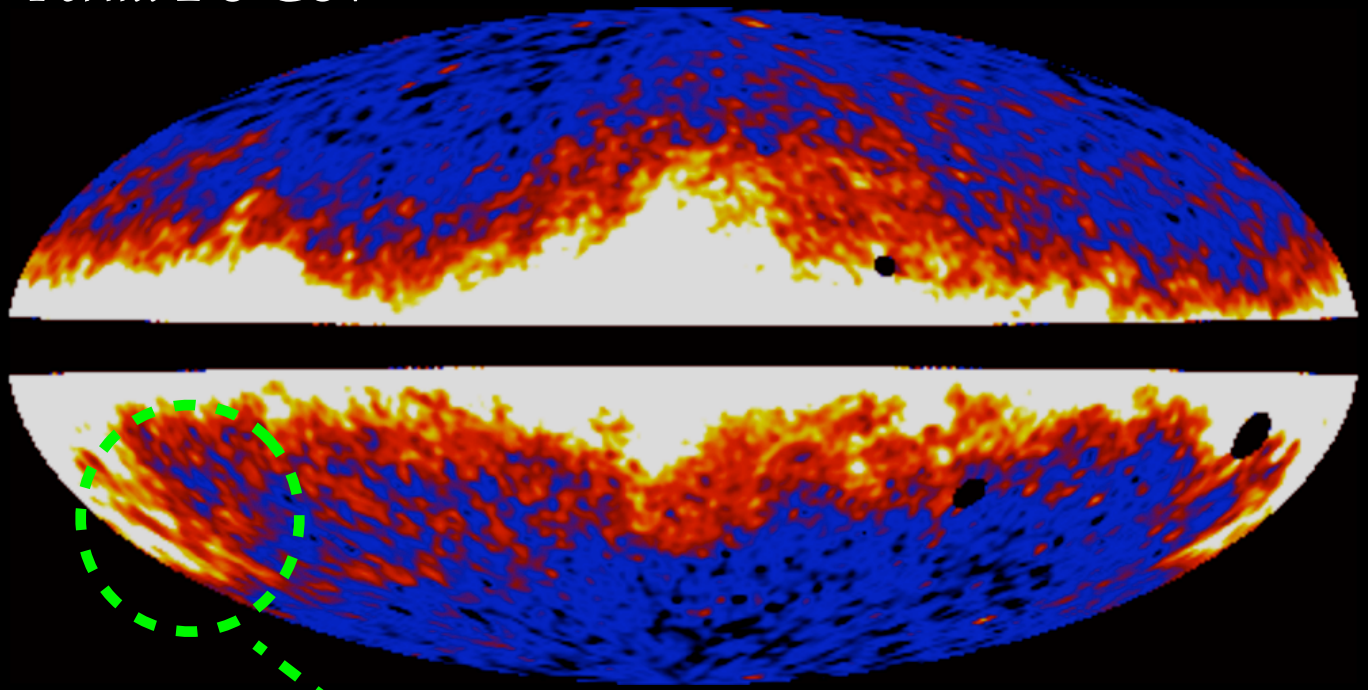
gamma-rays from the Galaxy

Fermi 2-5 GeV



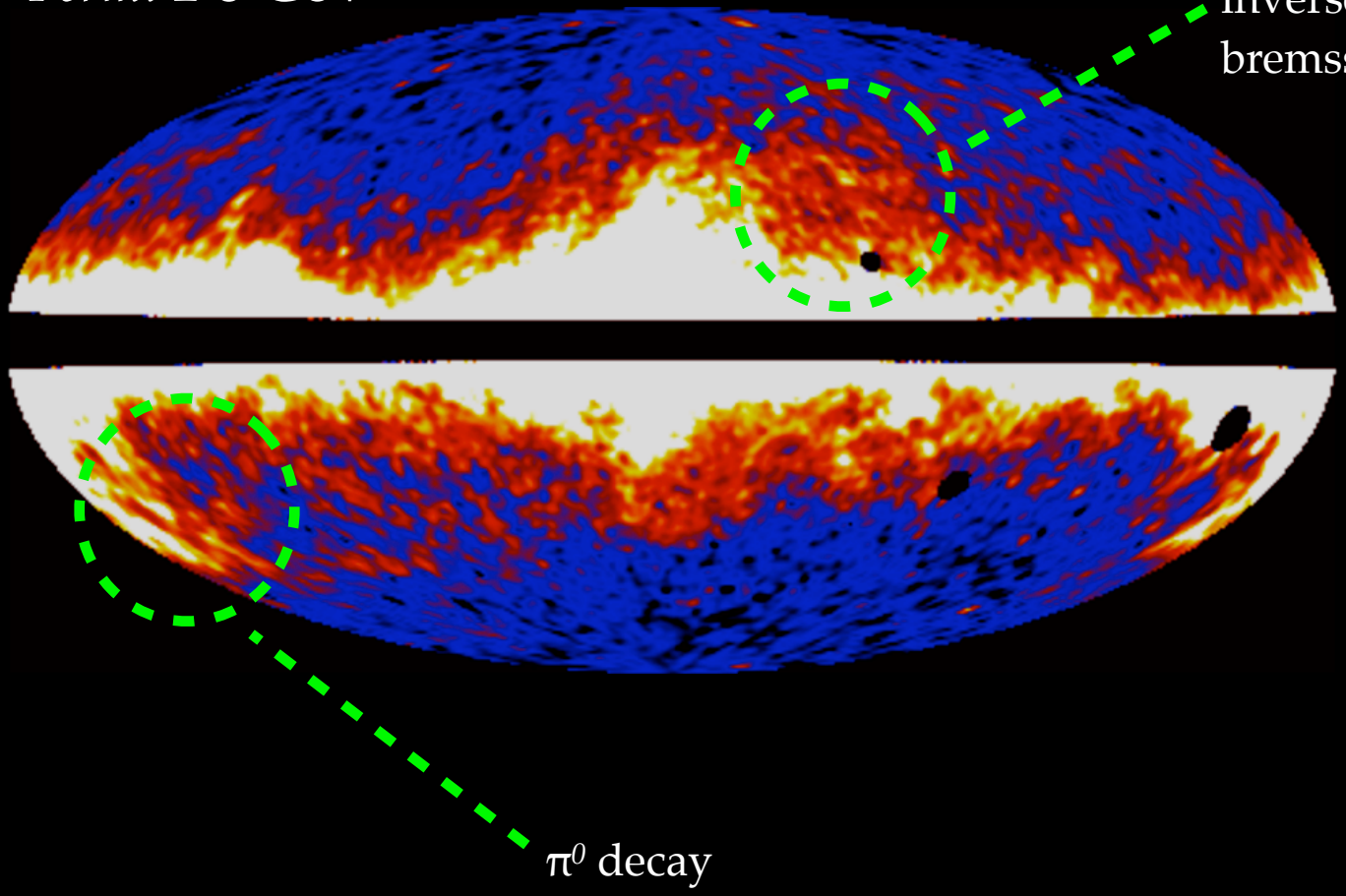
gamma-rays from the Galaxy

Fermi 2-5 GeV



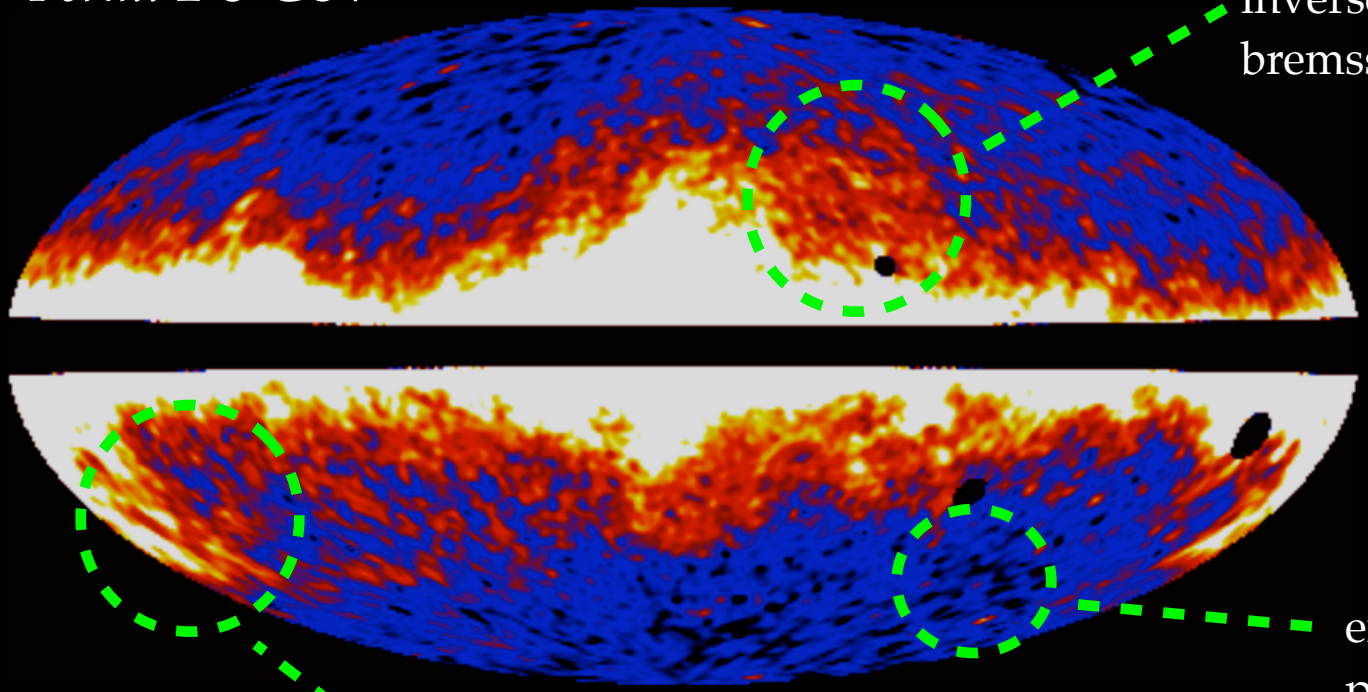
π^0 decay

gamma-rays from the Galaxy



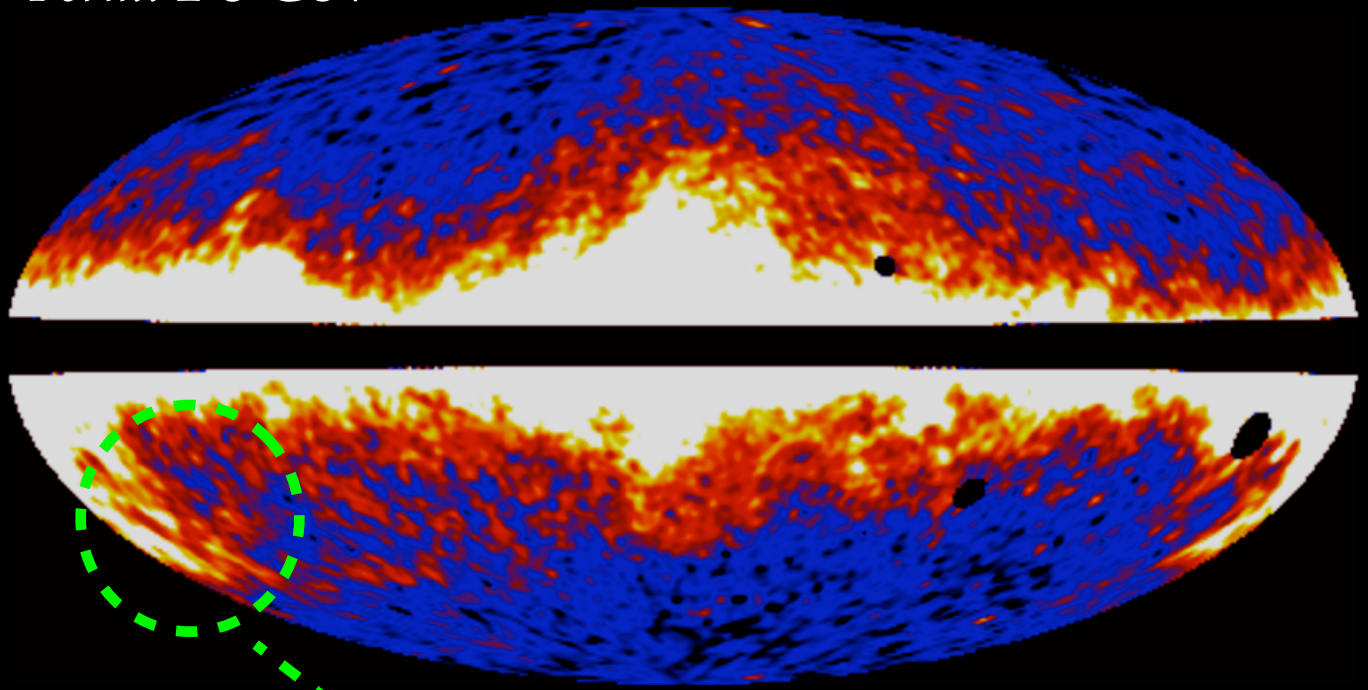
Greg Dobler (KITP/UCSB)

gamma-rays from the Galaxy



gamma-rays from the Galaxy

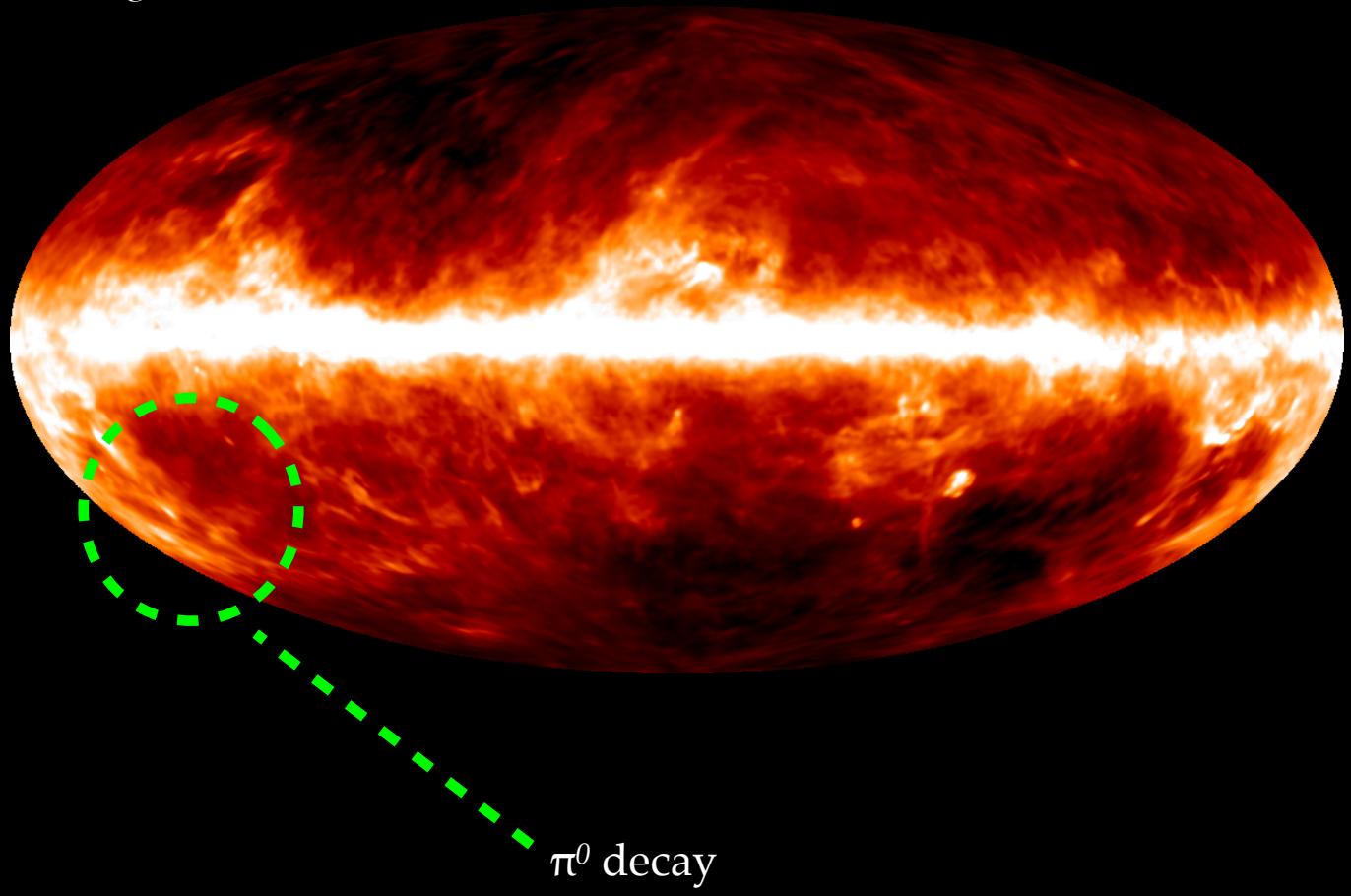
Fermi 2-5 GeV



π^0 decay

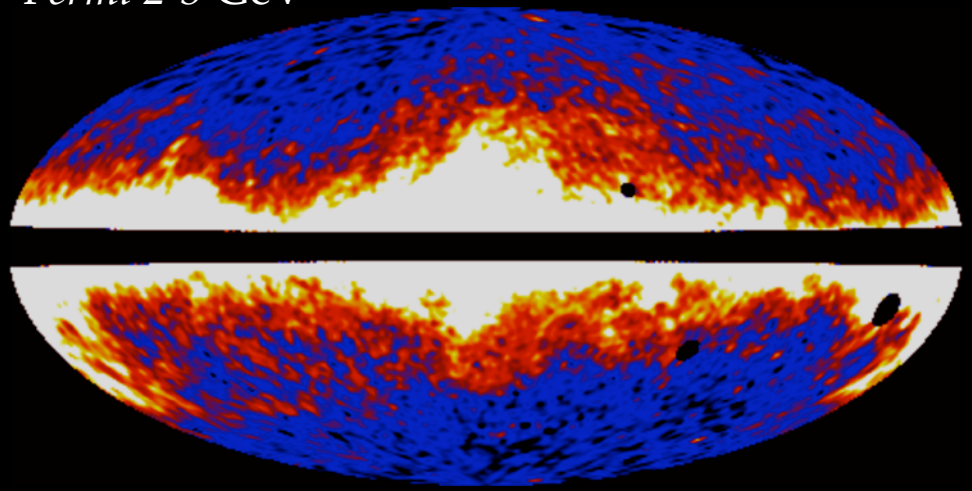
morphological tracers of emission

Schlegel, Finkbeiner, & Davis (1998)

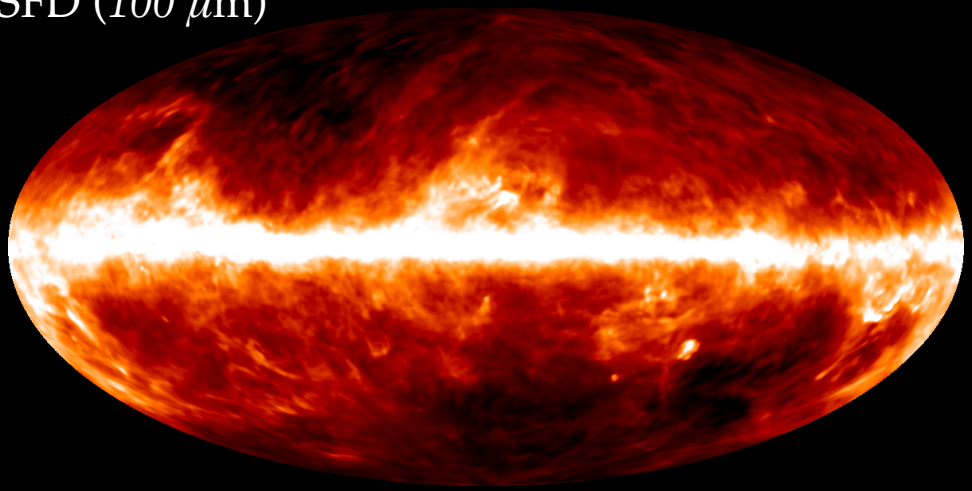


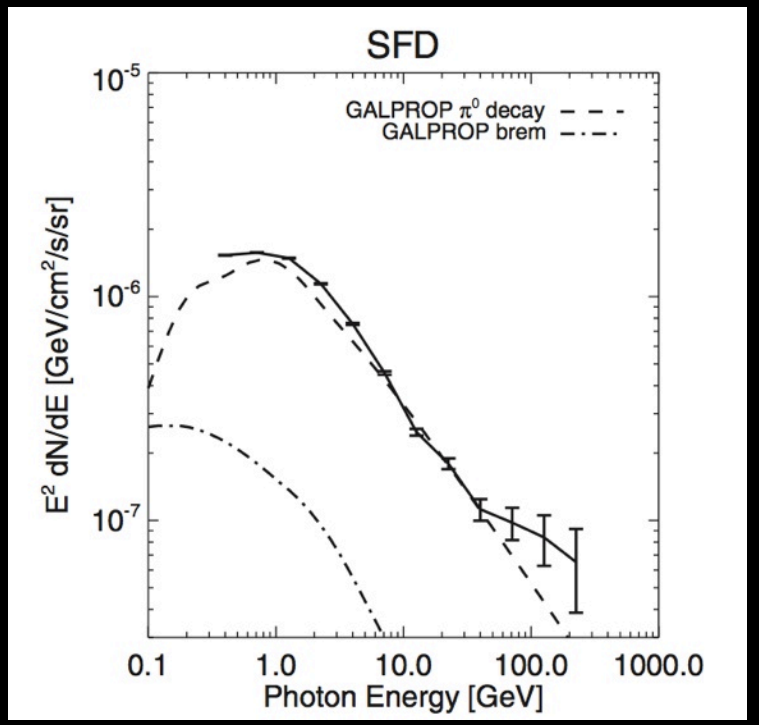
morphological tracers of emission

Fermi 2-5 GeV



SFD (*100* μm)

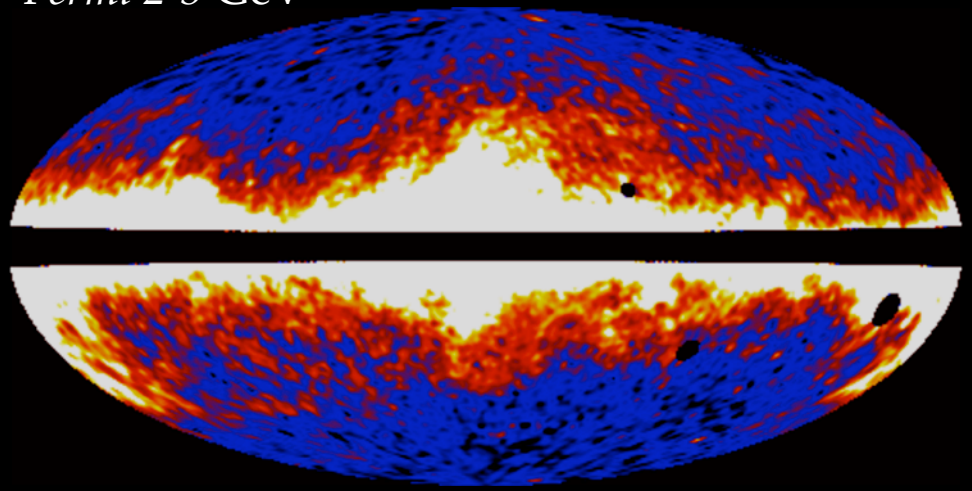




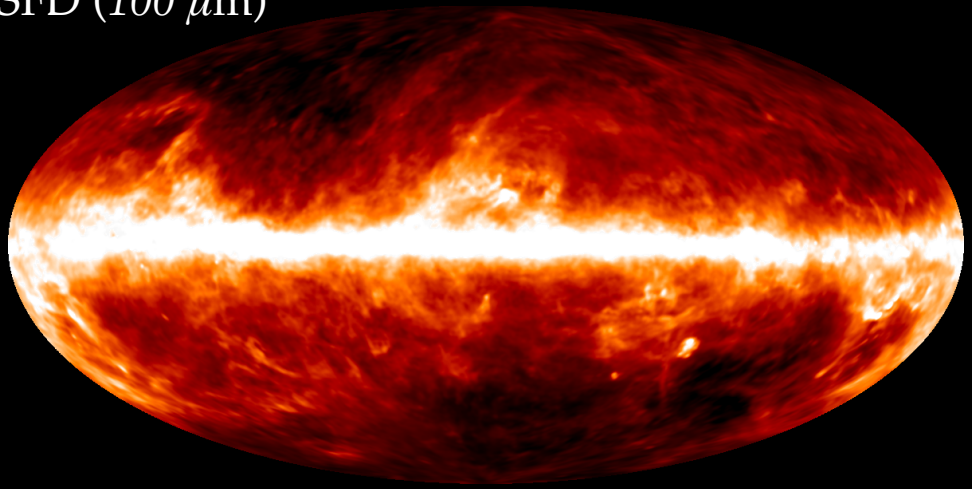
Dobler et al. (2010)

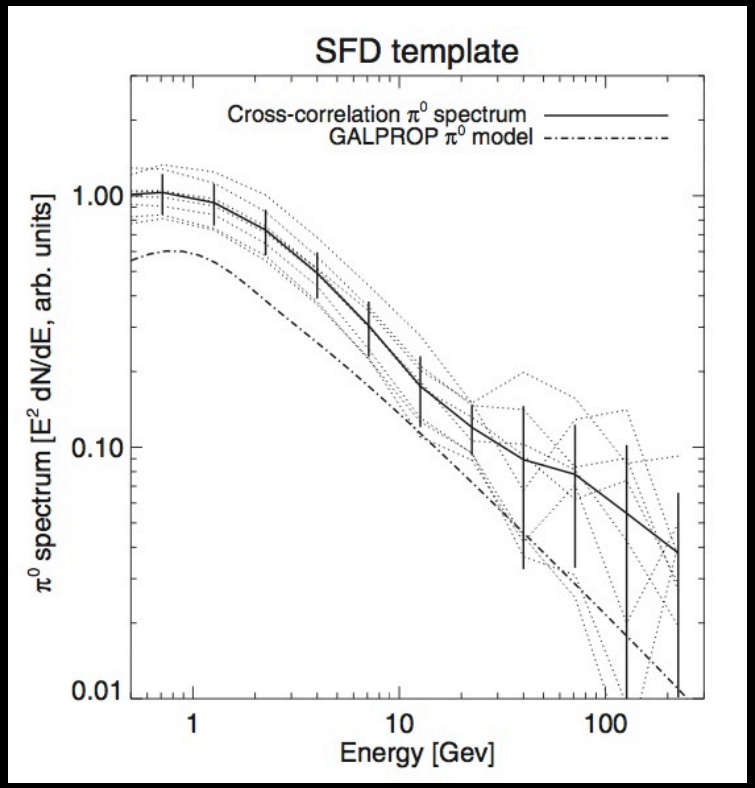
morphological tracers of emission

Fermi 2-5 GeV



SFD (*100* μm)

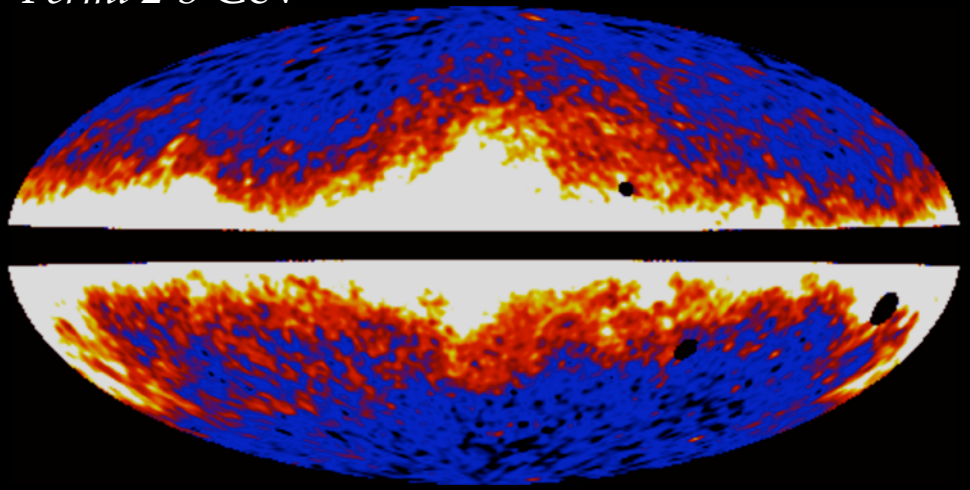


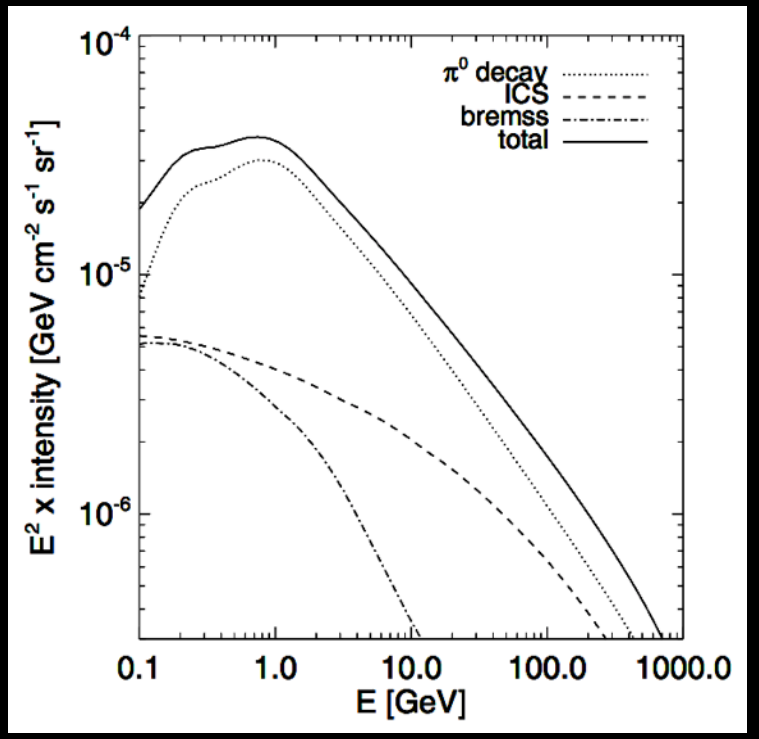


Dobler et al. (2010)

morphological tracers of emission

Fermi 2-5 GeV

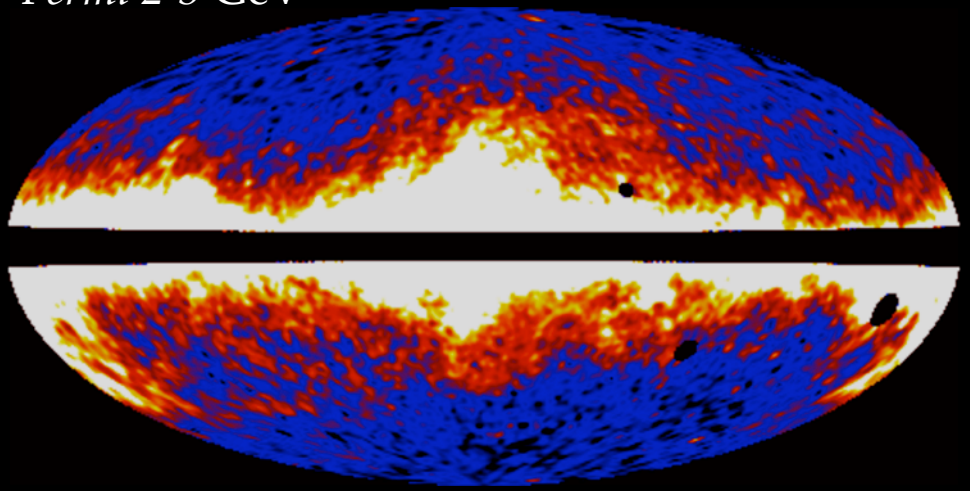


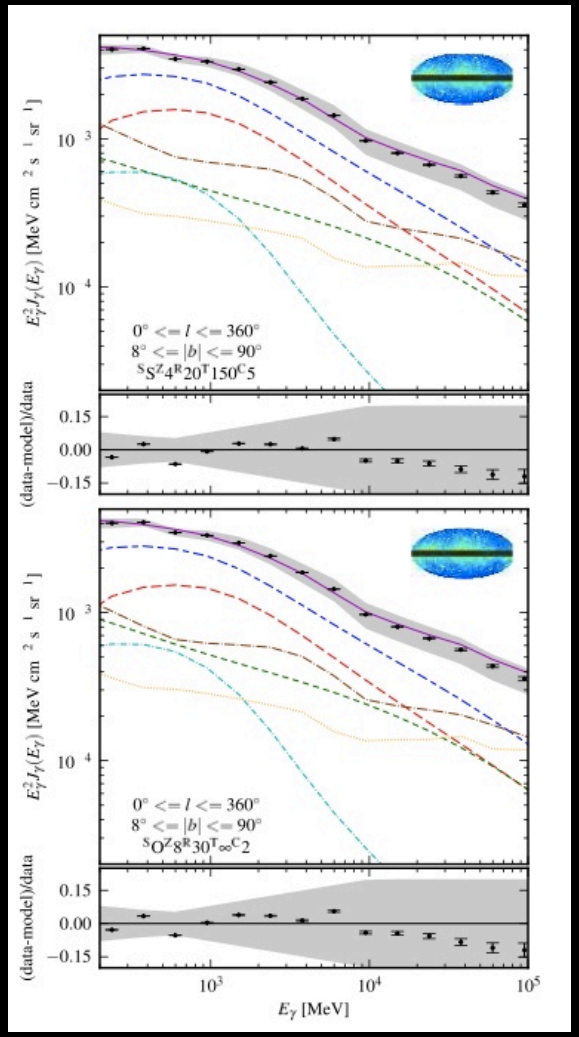


Dobler et al. (2010)

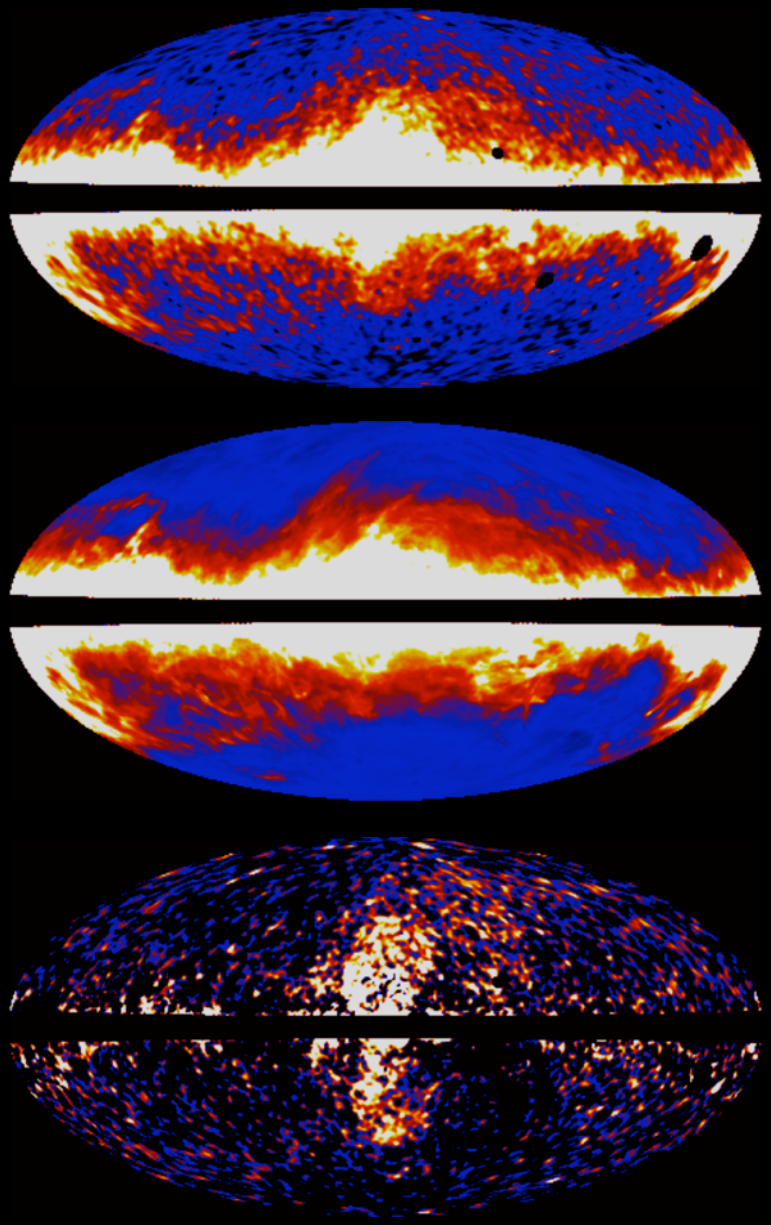
morphological tracers of emission

Fermi 2-5 GeV

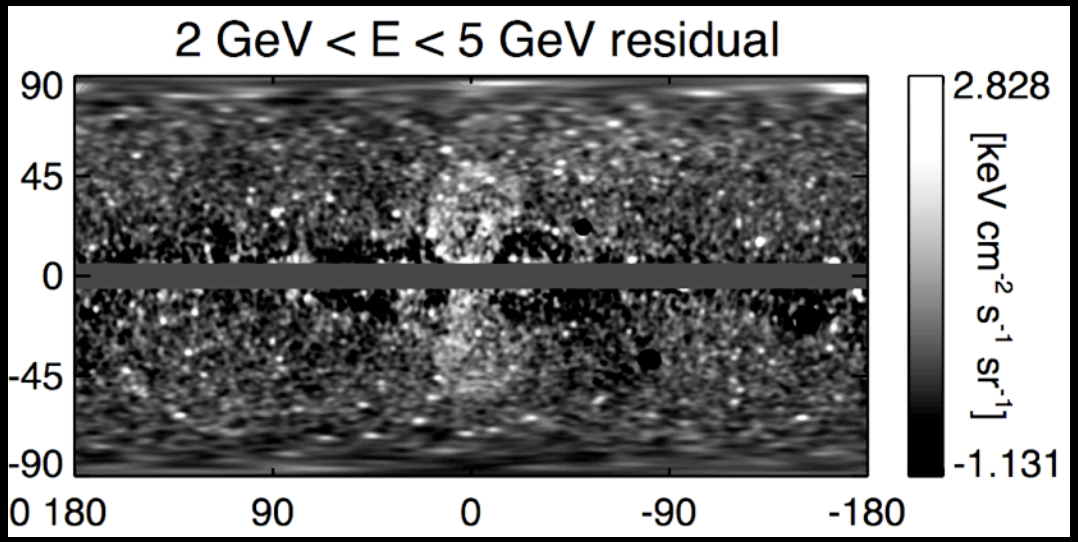




Fermi collab. (2012)



Dobler et al. (2010)



Fermi "haze"

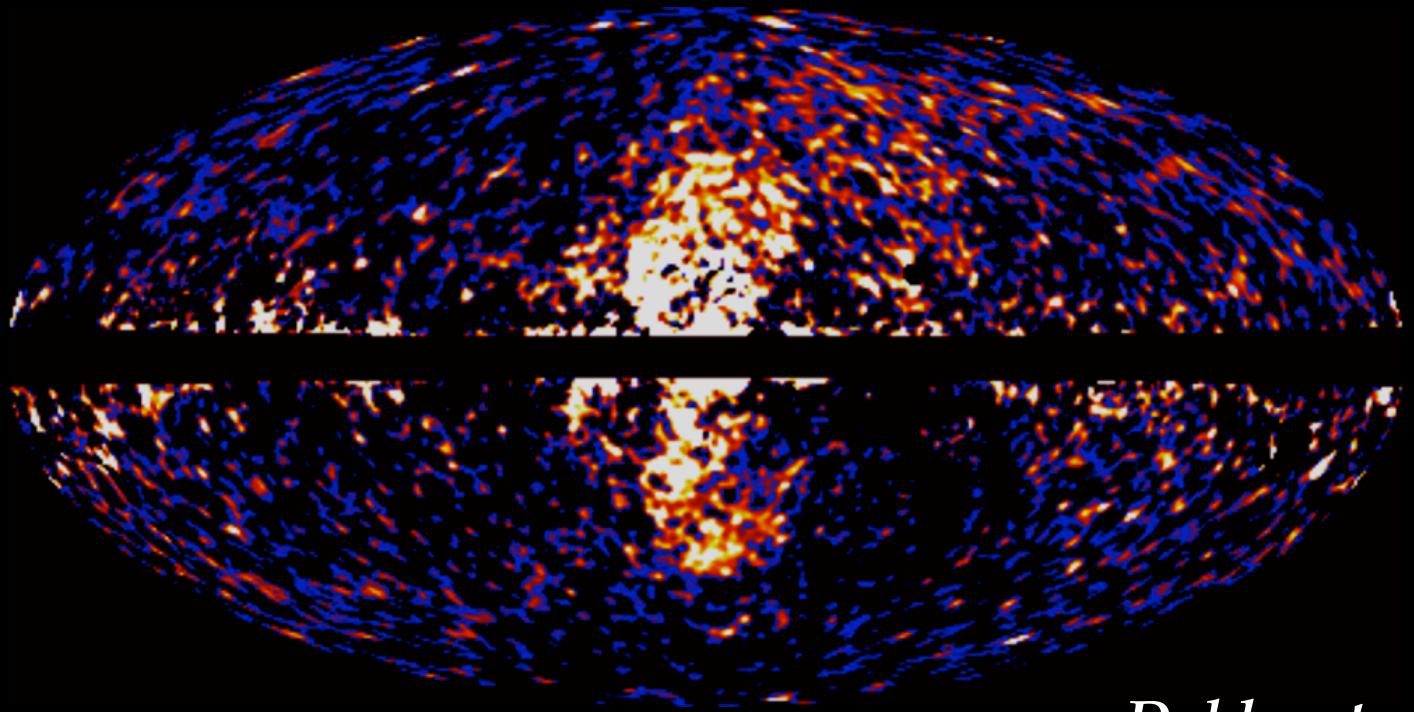
...and later the

"*Fermi* bubbles"

(Su et al., 2010)

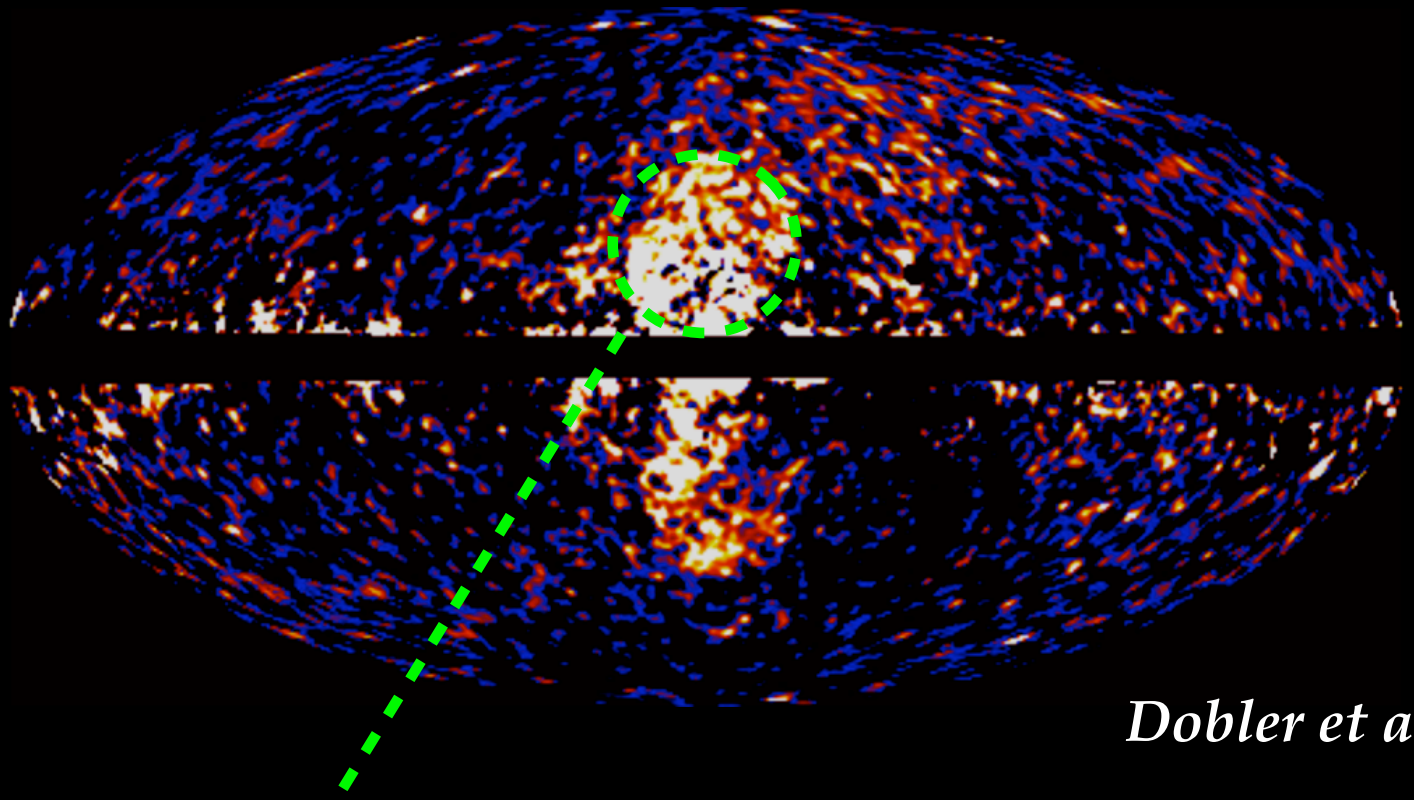
Greg Dobler (KITP/UCSB)

the Fermi *Haze a.k.a.* Fermi *Bubbles*



Dobler et al. (2010)

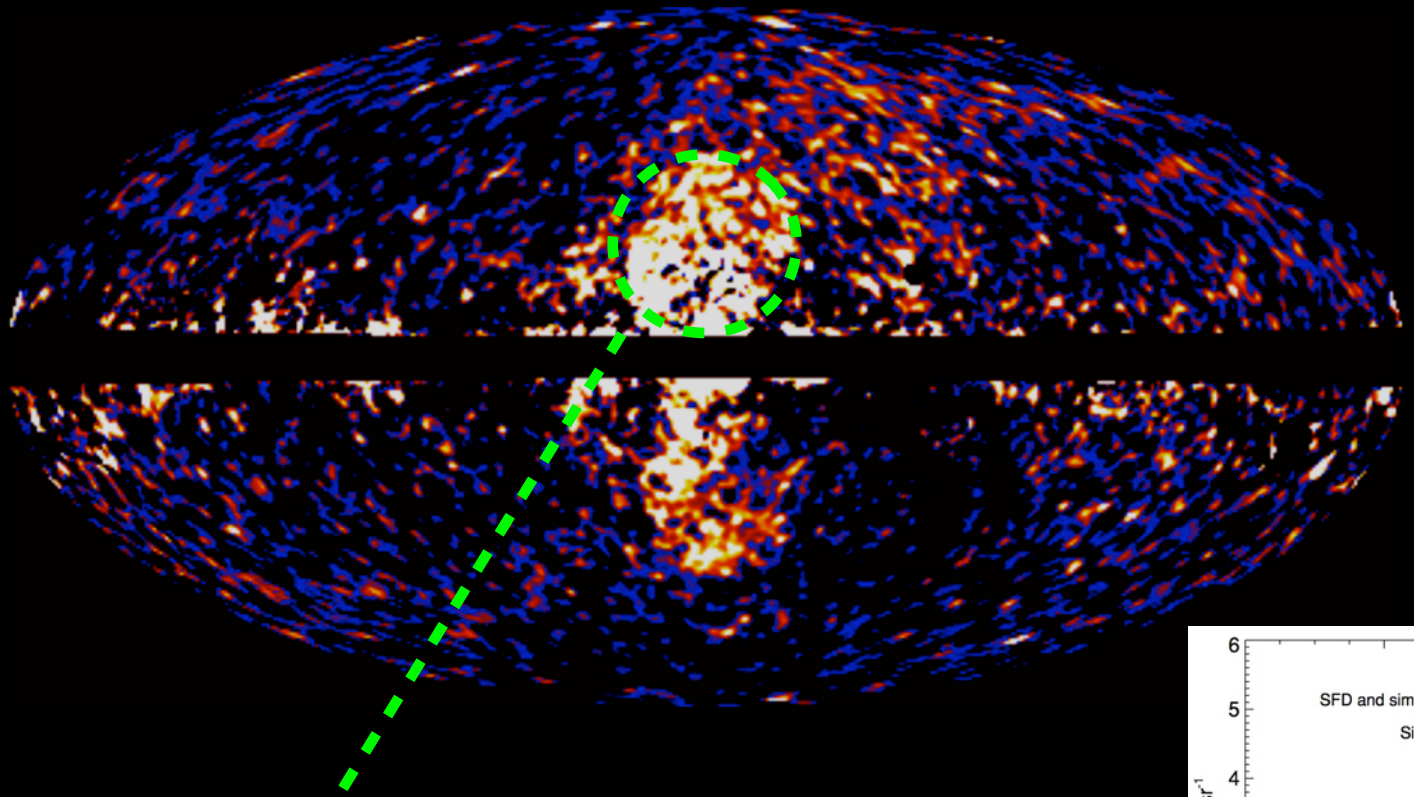
the Fermi *Haze a.k.a.* Fermi *Bubbles*



Dobler et al. (2010)

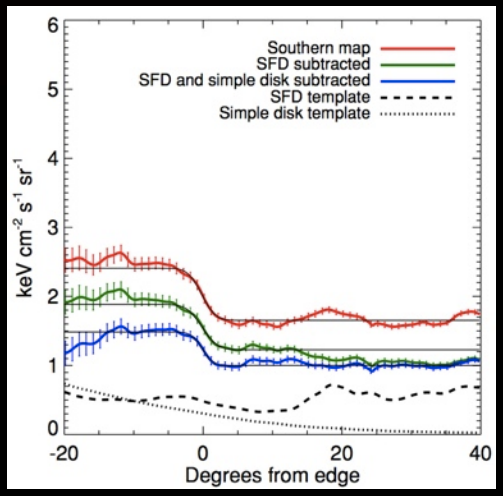
roughly “flat” brightness profile

the Fermi *Haze a.k.a.* Fermi *Bubbles*



roughly “flat” brightness profile

Su et al. (2010)

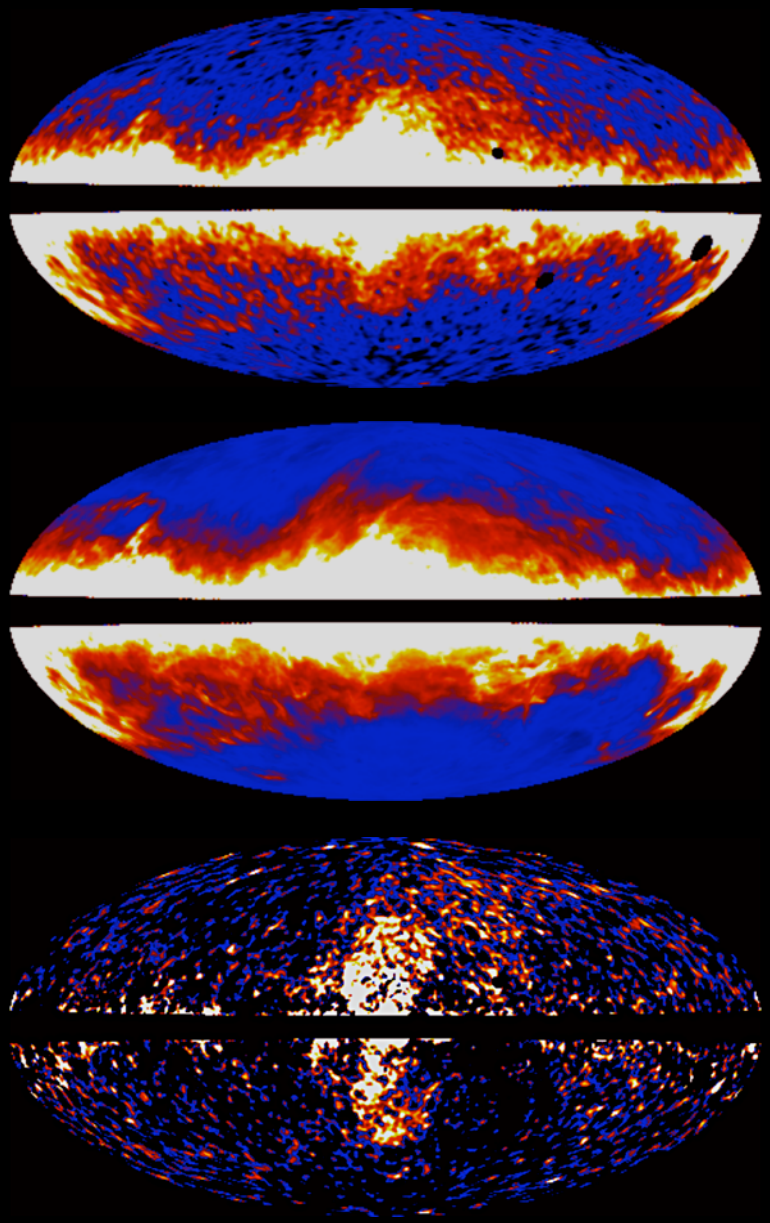


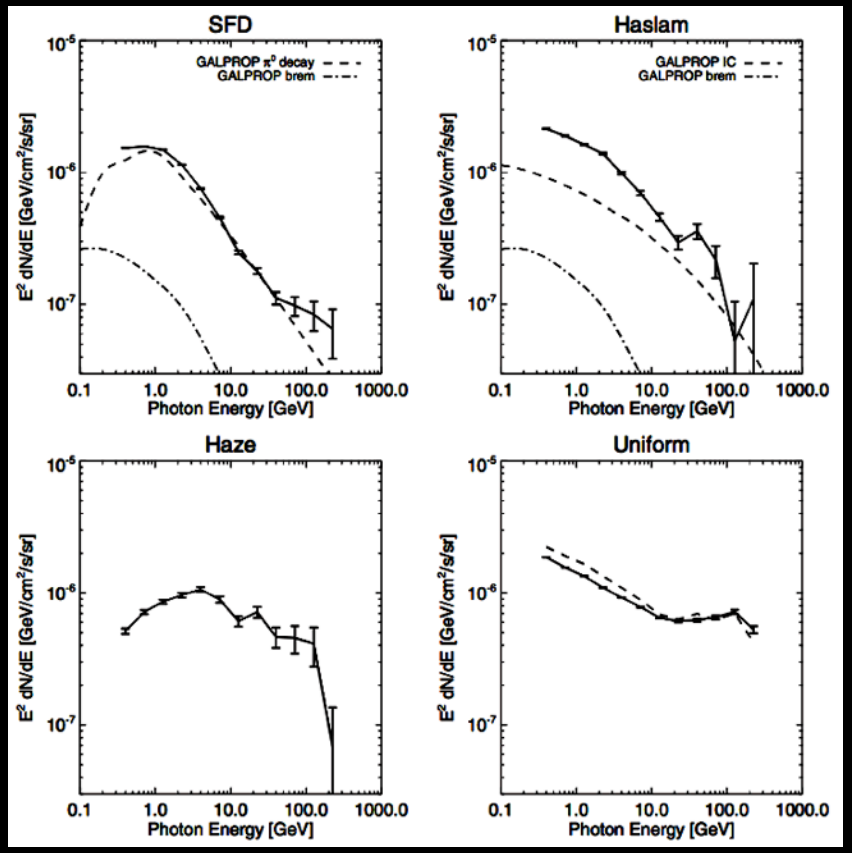
the Fermi haze/bubbles

Fermi data 2-5 GeV

diffuse model 2-5 GeV

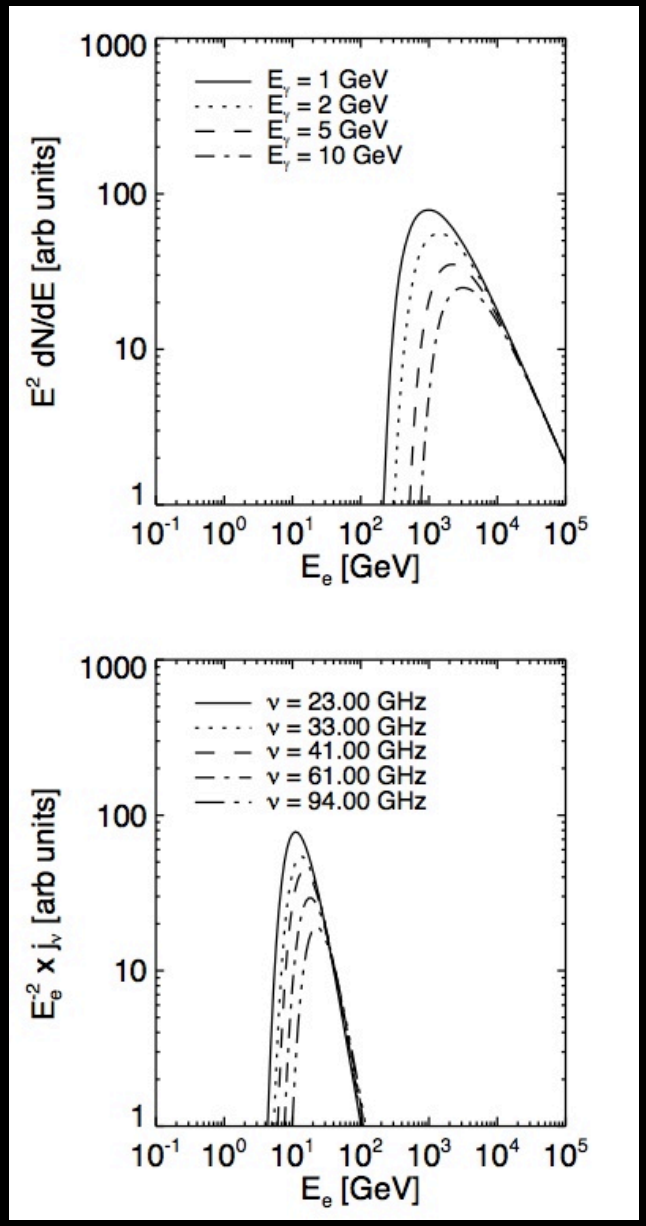
Fermi "haze/bubbles"





Dobler et al. (2010)

electron spectra



. the same spectrum (normalization and slope) reproduces the microwave and gamma-ray emission

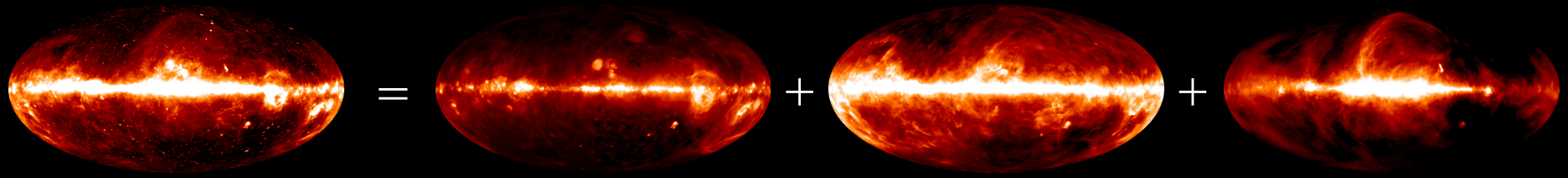
$$dN/dE \propto E^{-2.0}$$

. the characteristic energy of the emitting electrons for microwaves is $E_e \sim 10$ GeV but for gammas is $E_e \sim 1$ TeV

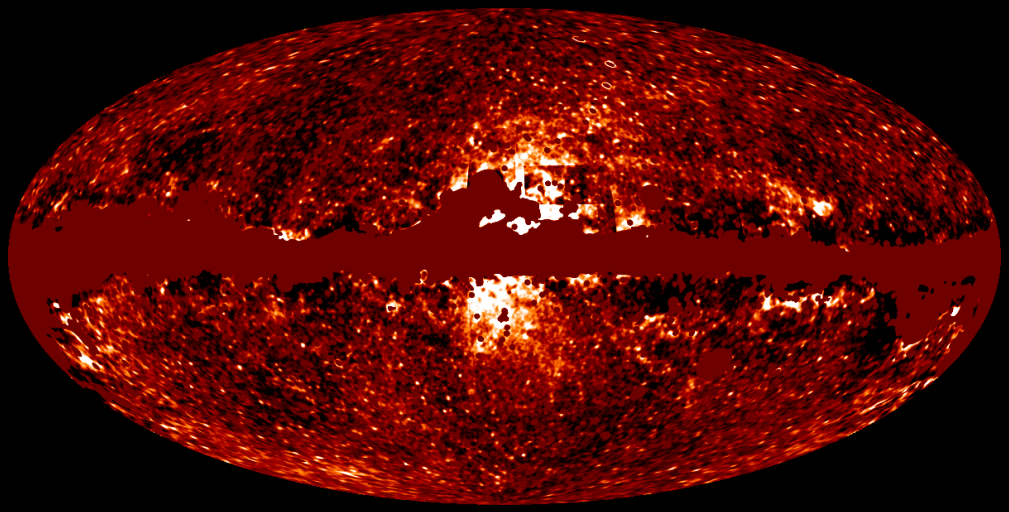
. this implies very little cooling of the cosmic-ray population

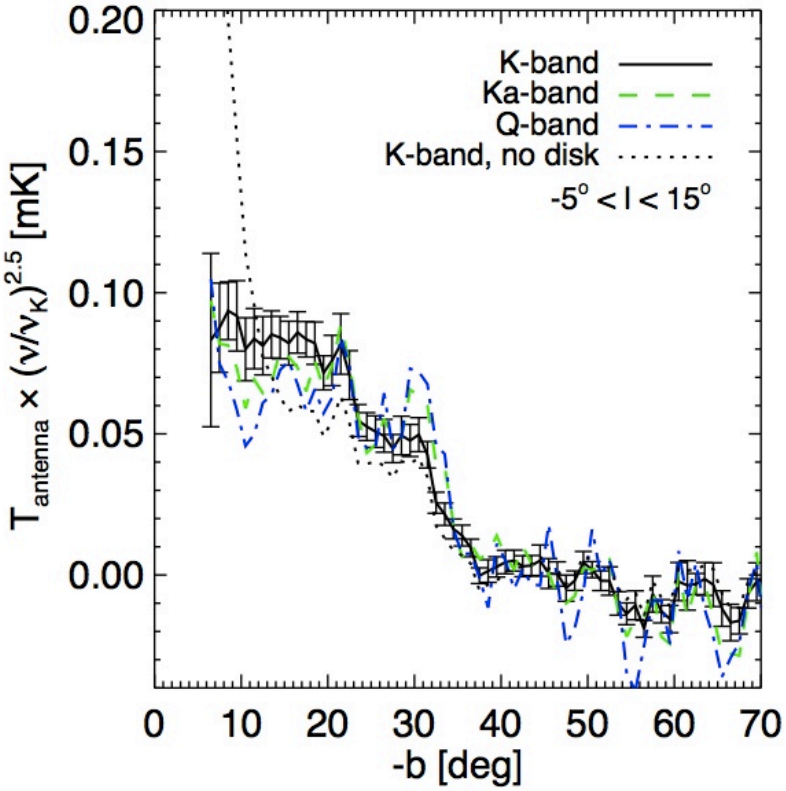
Greg Dobler (KITP/UCSB)

$$a_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$



23 GHz haze

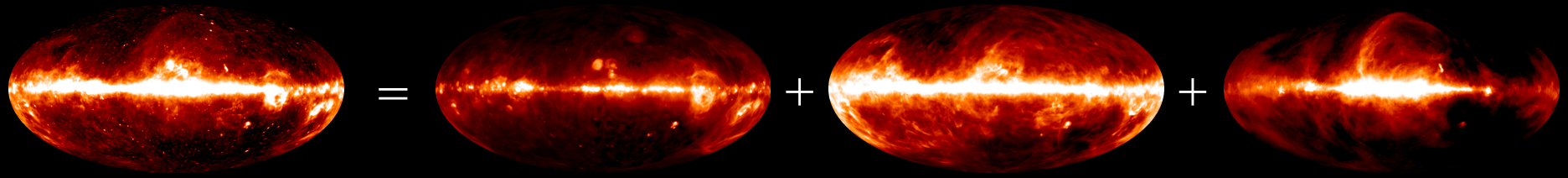




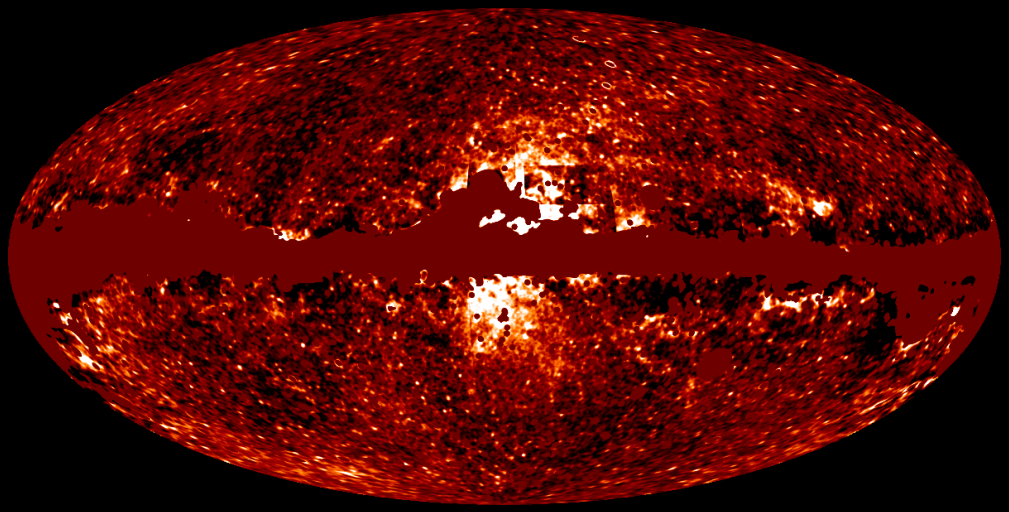
Dobler (2012)

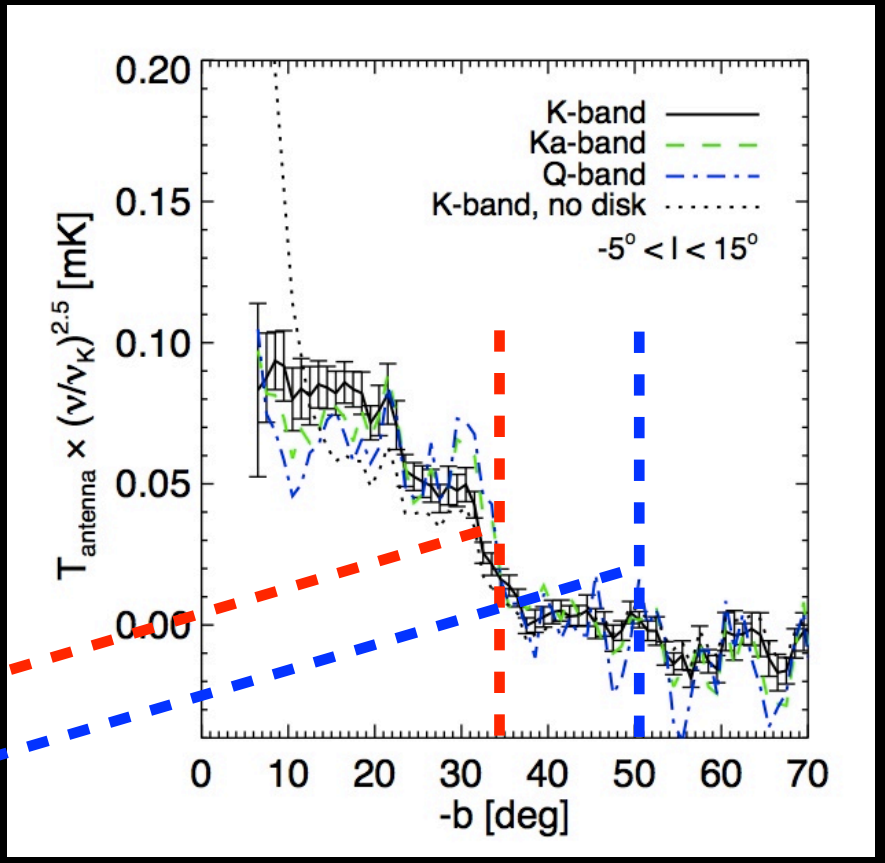
Greg Dobler (KITP/UCSB)

$$a_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$



23 GHz haze



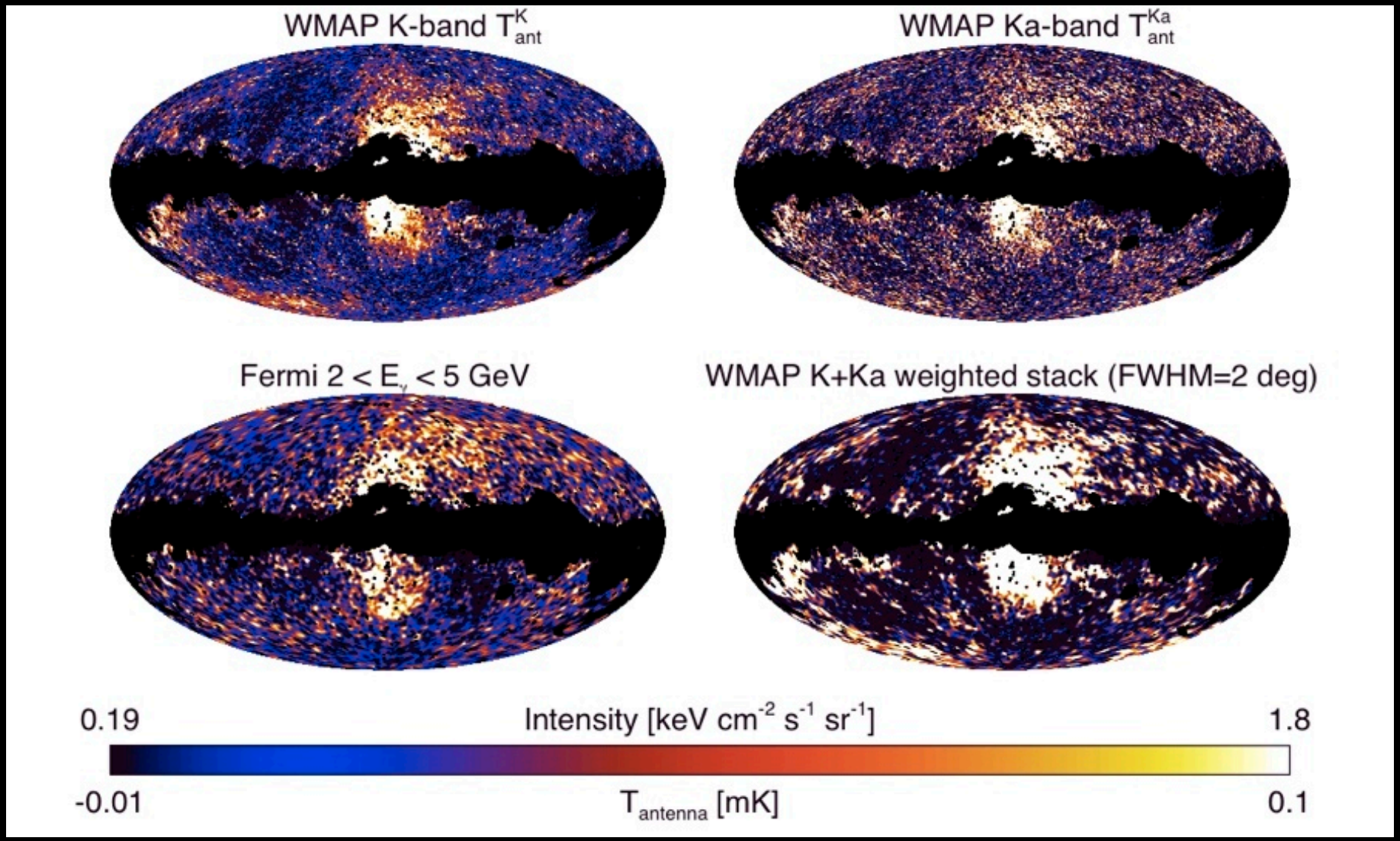


WMAP "drops" here (b~-35°)

Fermi "cuts off" here (b~-50°)

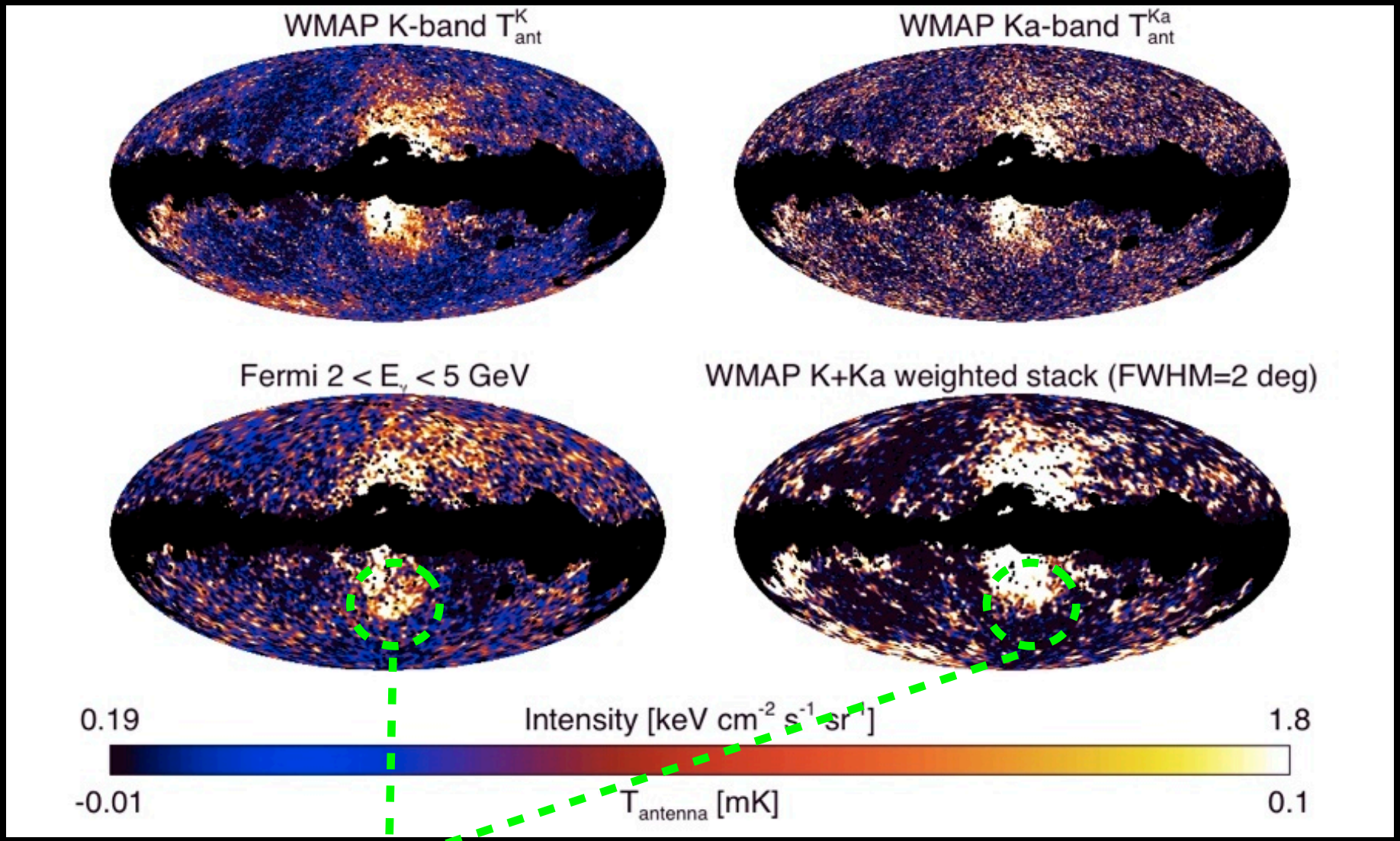
are they the same structure? are the *Fermi* edges "real"? *Dobler (2012)*

Dobler (2012b)



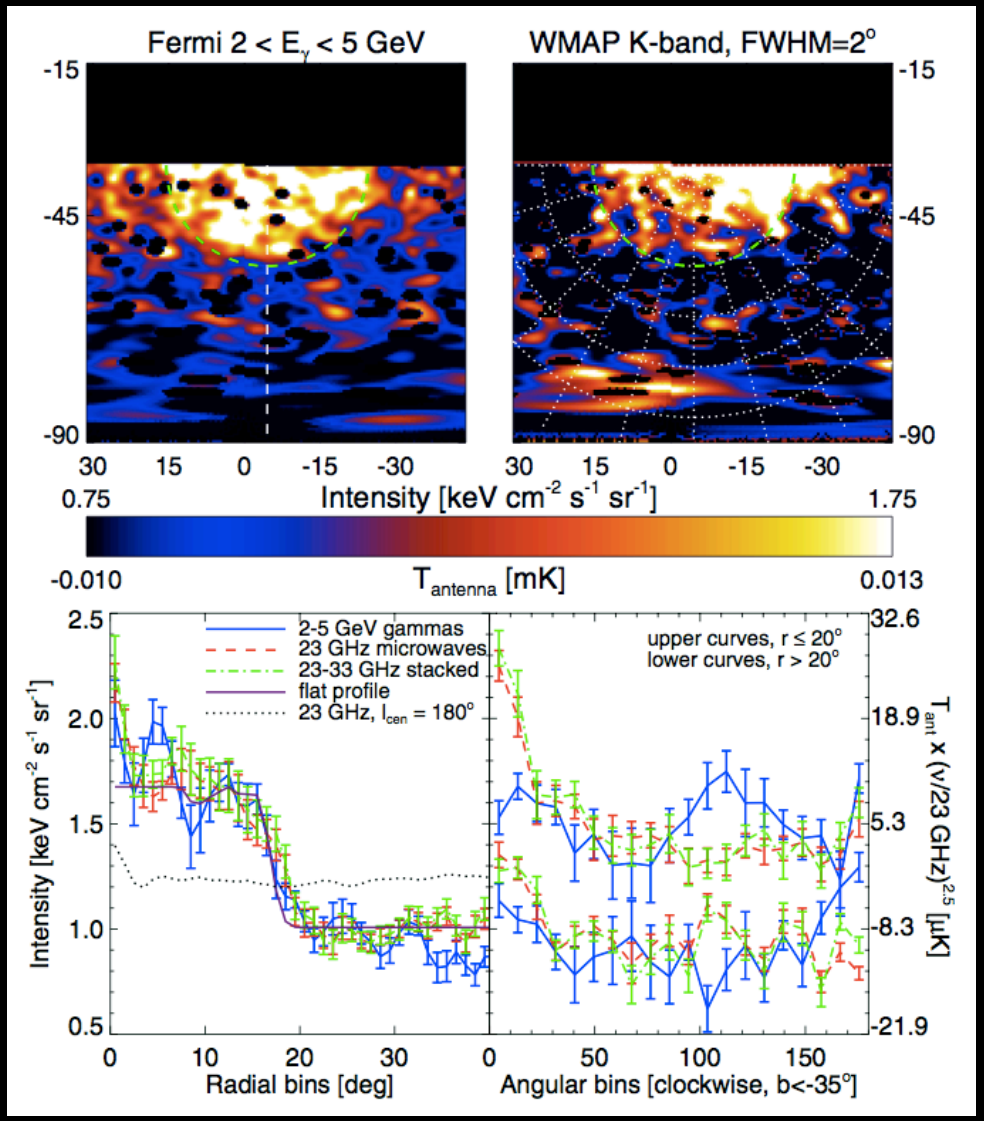
are they the same structure? are the *Fermi* edges "real"?

Dobler (2012b)



coincident "edge"?

Dobler (2012b)



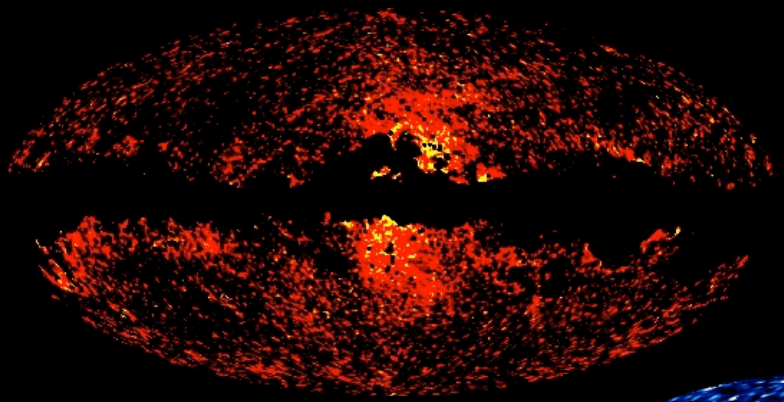
coincident "edge"? *YES!*

independent confirmation that the *Fermi* Haze/Bubbles edges are ***real***

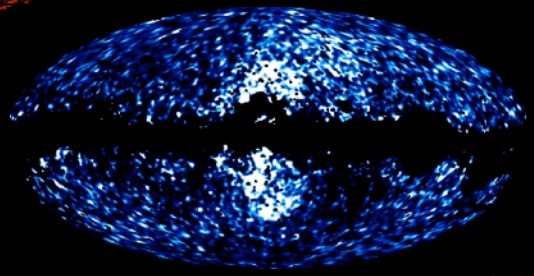
demonstrates conclusively that the microwave and gamma-ray haze/bubbles are the ***same structure*** observed at multiple wavelengths

strongly suggests an inverse Compton origin for the gamma-ray emission and that the microwave emission represents a ***separate component*** of diffuse synchrotron

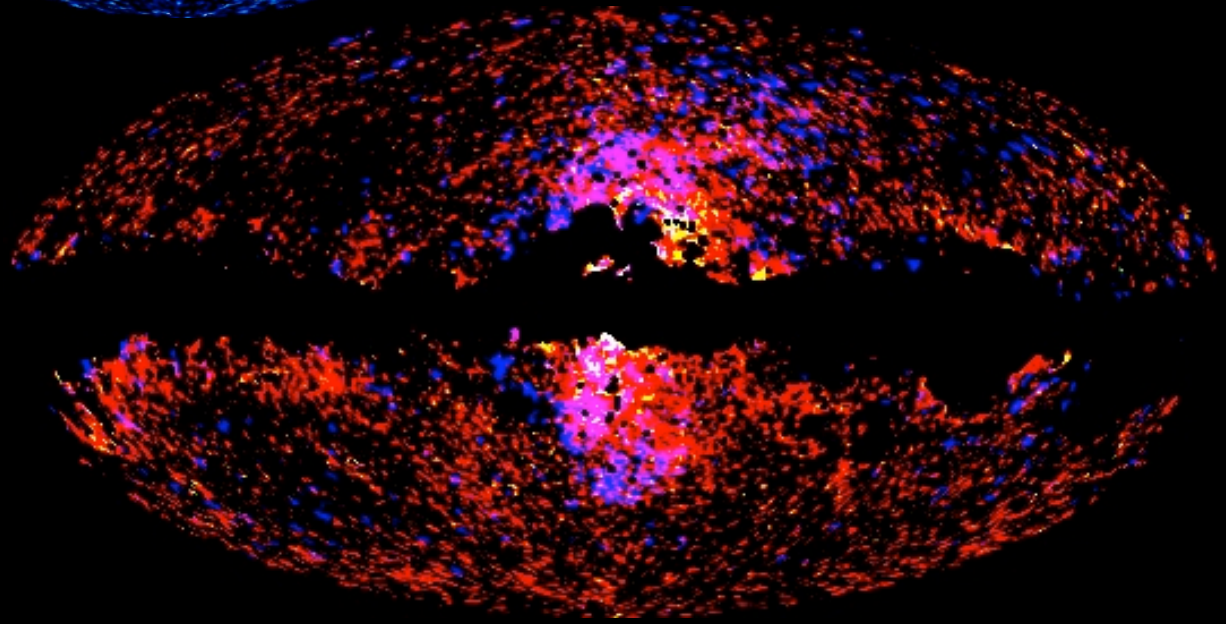
Planck



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



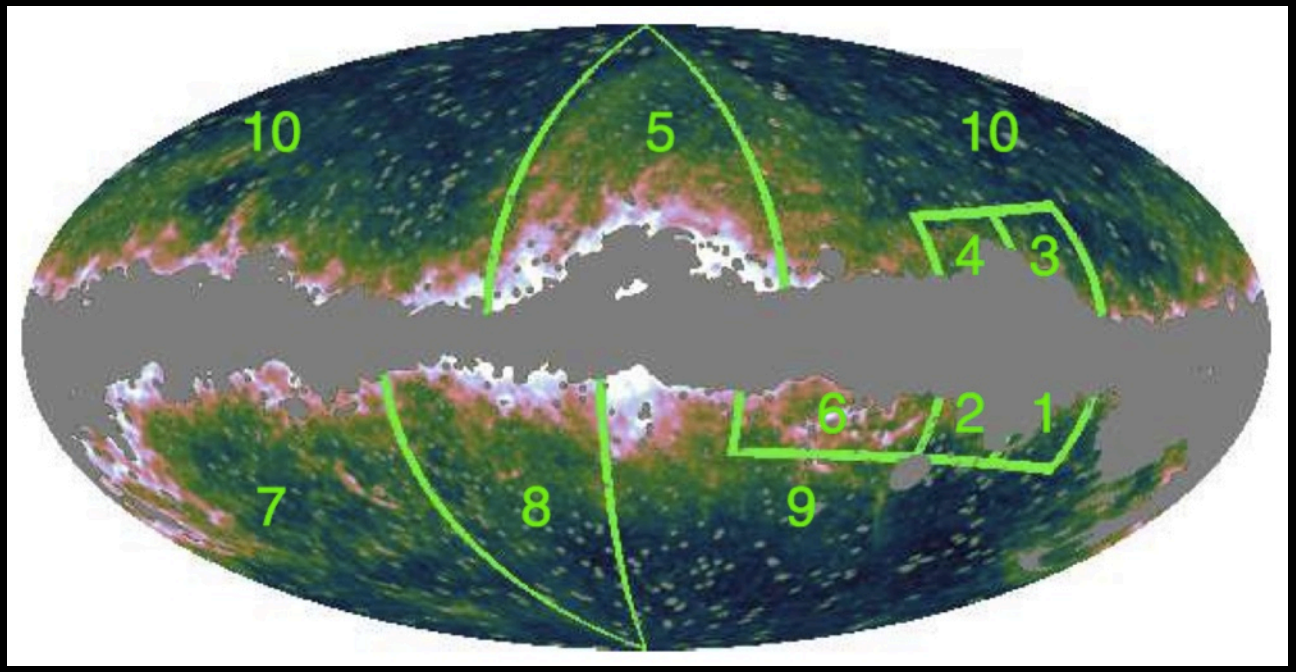
The same structure at *2-5* GeV as seen by the *Fermi Gamma-Ray Space Telescope*



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

Planck Collaboration, 2012

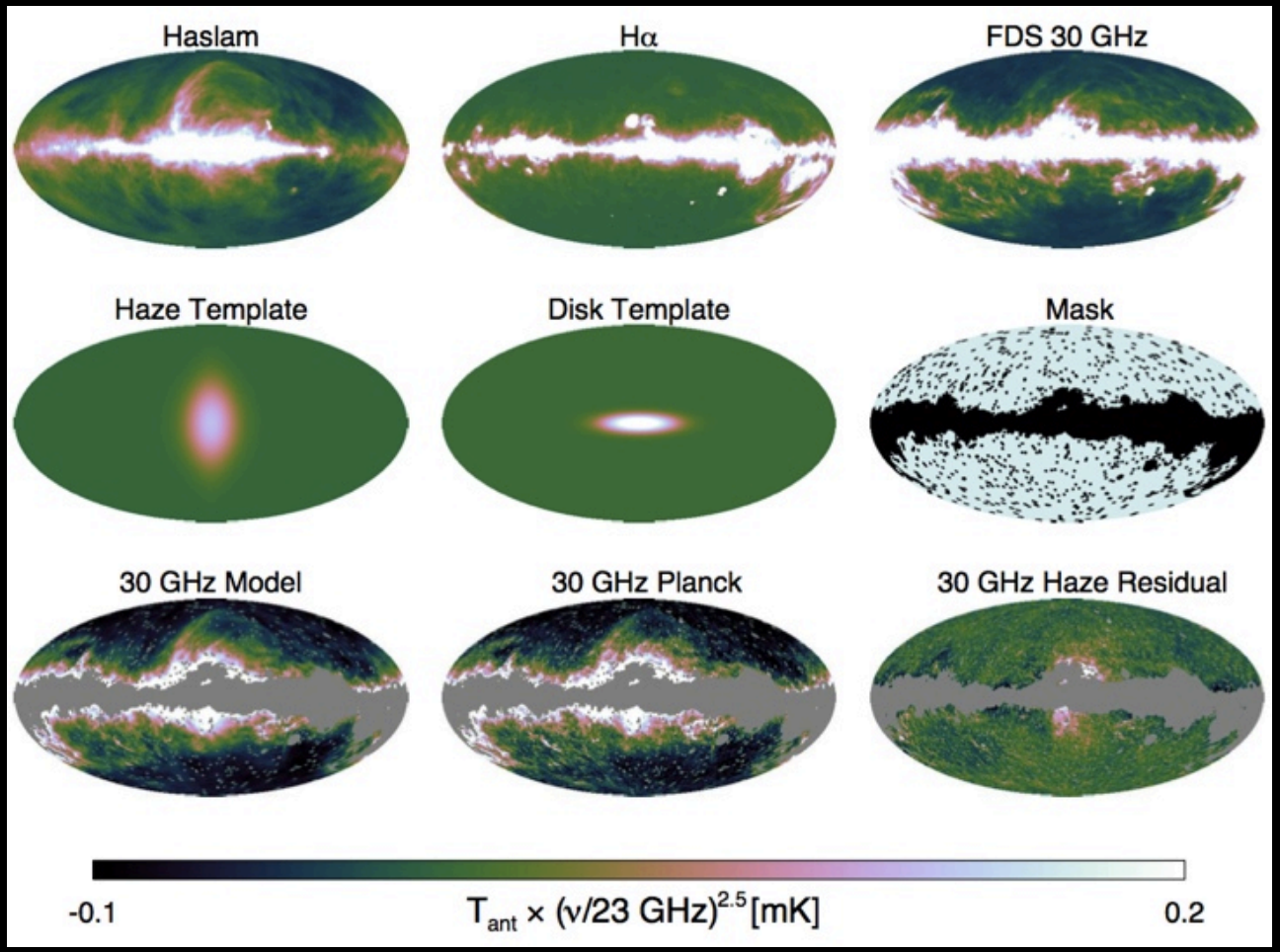
Planck



. divide sky into 10 regions

Planck Collaboration, 2012, arXiv:1208.5483

Planck



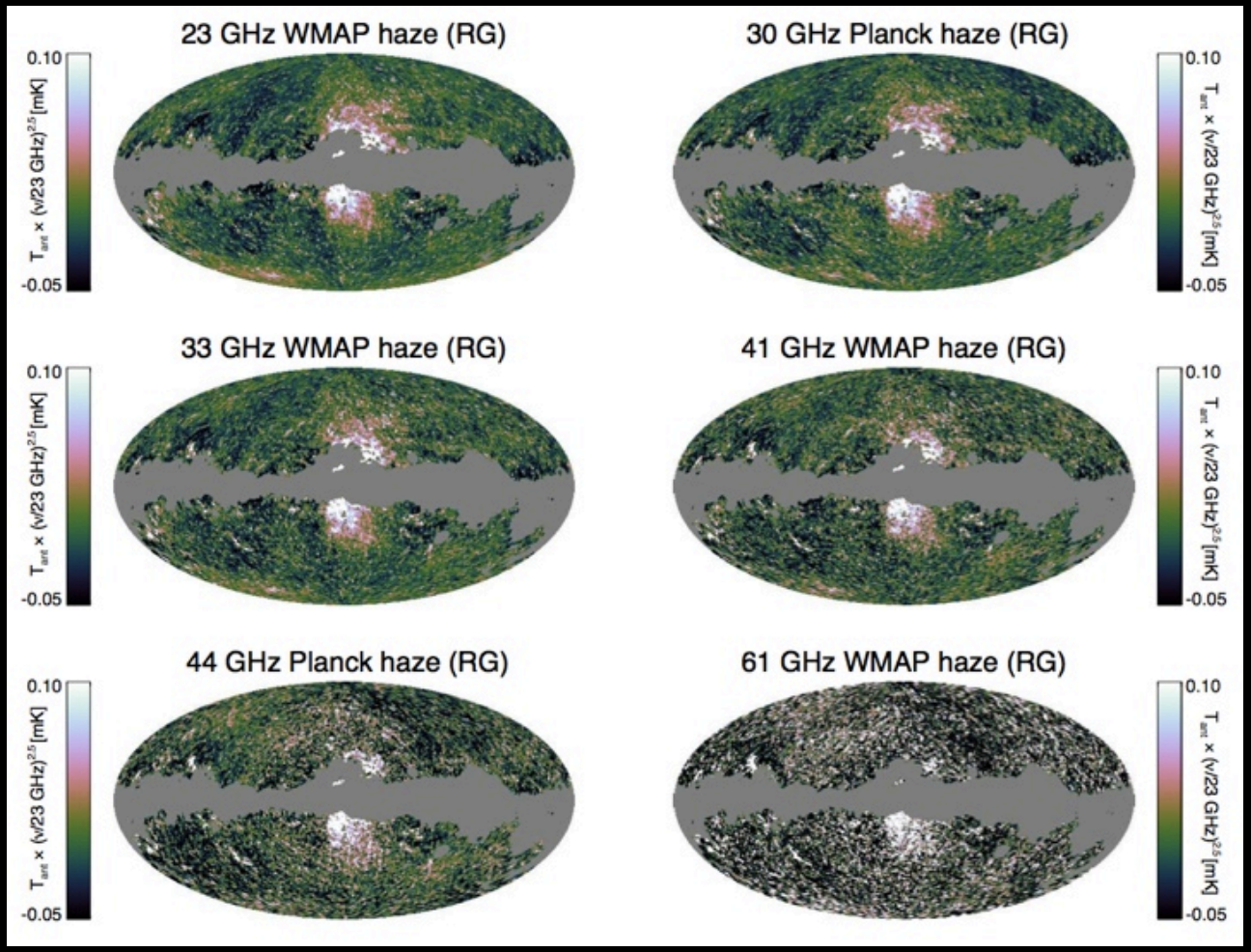
. divide sky into 10 regions

. five template fit to the data on each region independently

. "stitch" together to form a full sky model and residual map

Planck Collaboration, 2012, arXiv:1208.5483

Planck



. divide sky into 10 regions

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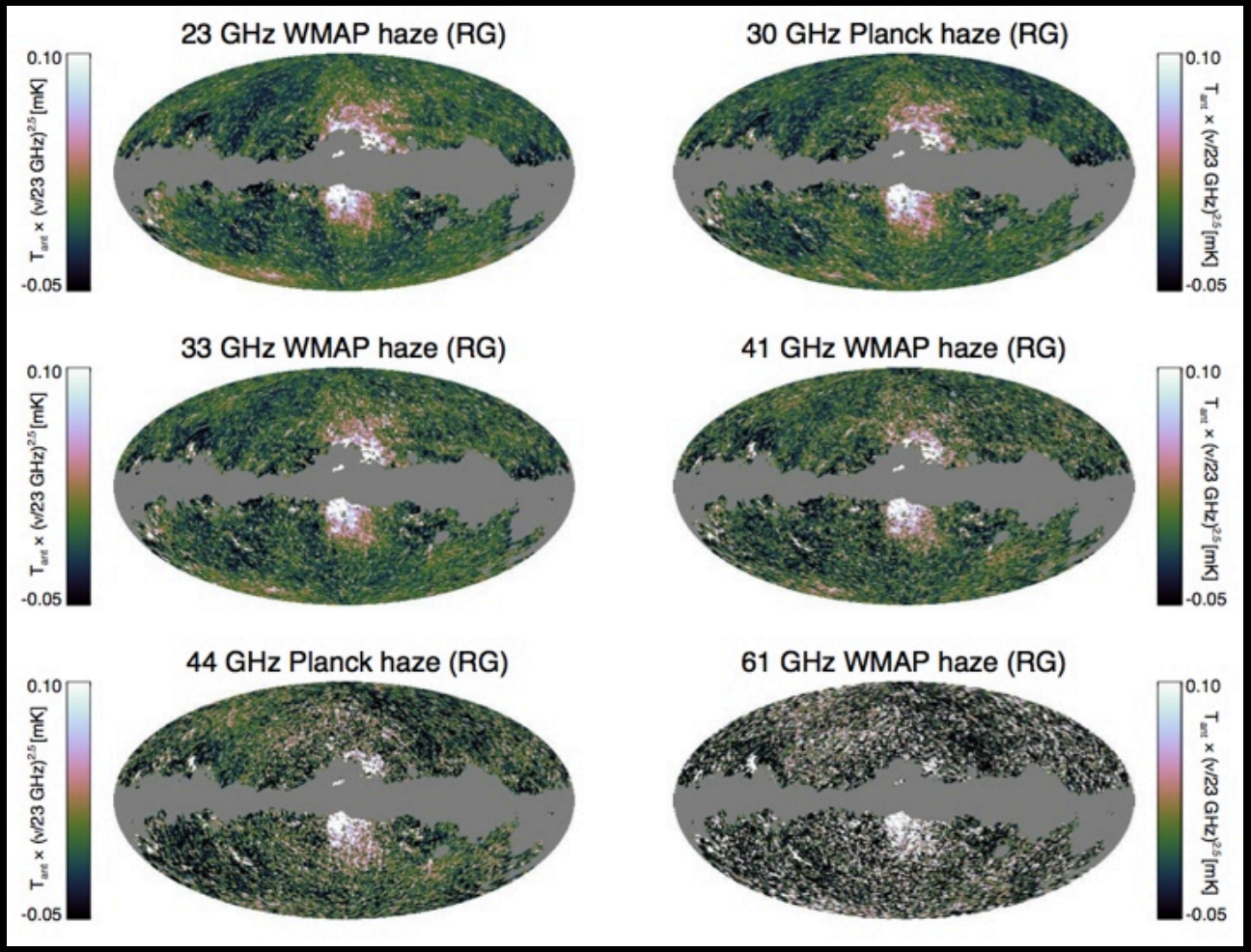
. apply multi-template, multi-region fit to each *Planck* and WMAP band

Planck Collaboration, 2012, arXiv:1208.5483

Planck



. divide sky into 10 regions

. five template fit to the data on each region independently

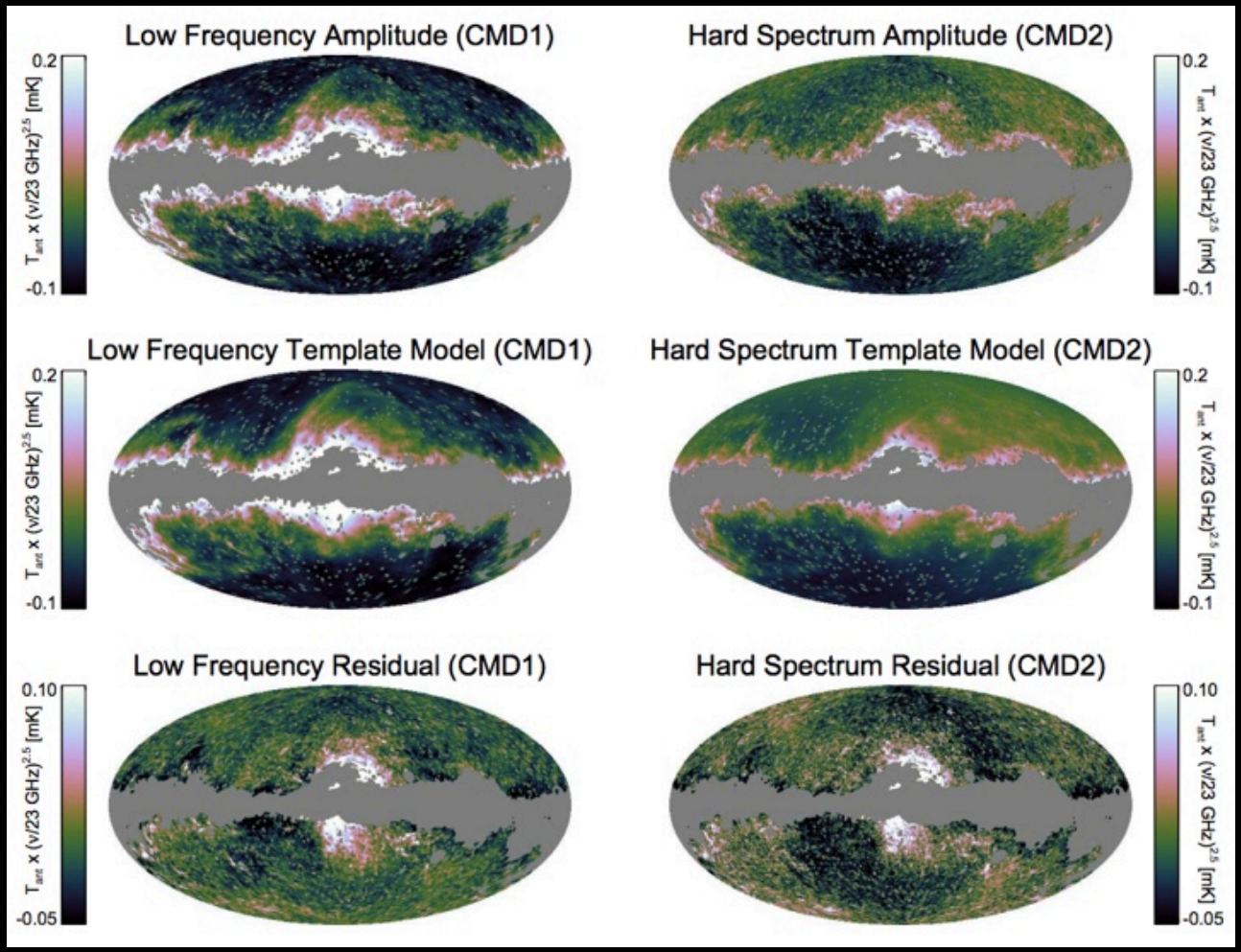
. "stitch" together to form a full sky model and residual map

. apply multi-template, multi-region fit to each *Planck* and WMAP band

$\nu^{2.5}$ scaling yields roughly constant brightness with frequency

Planck Collaboration, 2012, arXiv:1208.5483

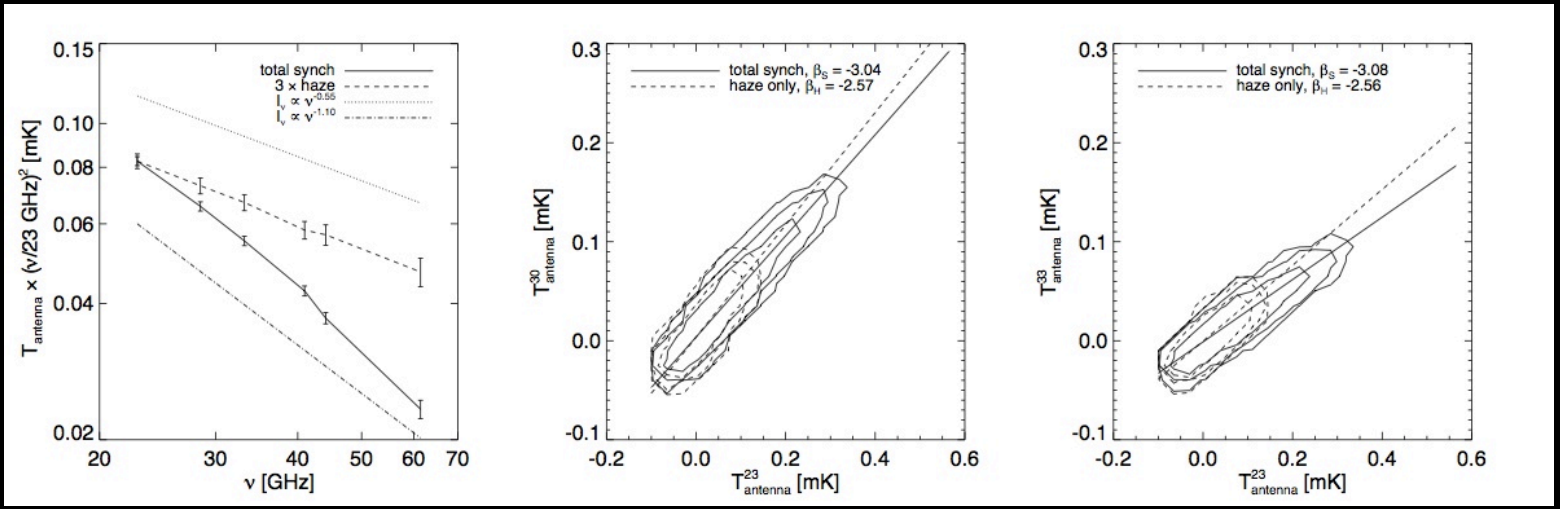
Planck



Bayesian/Gibbs haze residual

Planck Collaboration, 2012, arXiv:1208.5483

Planck

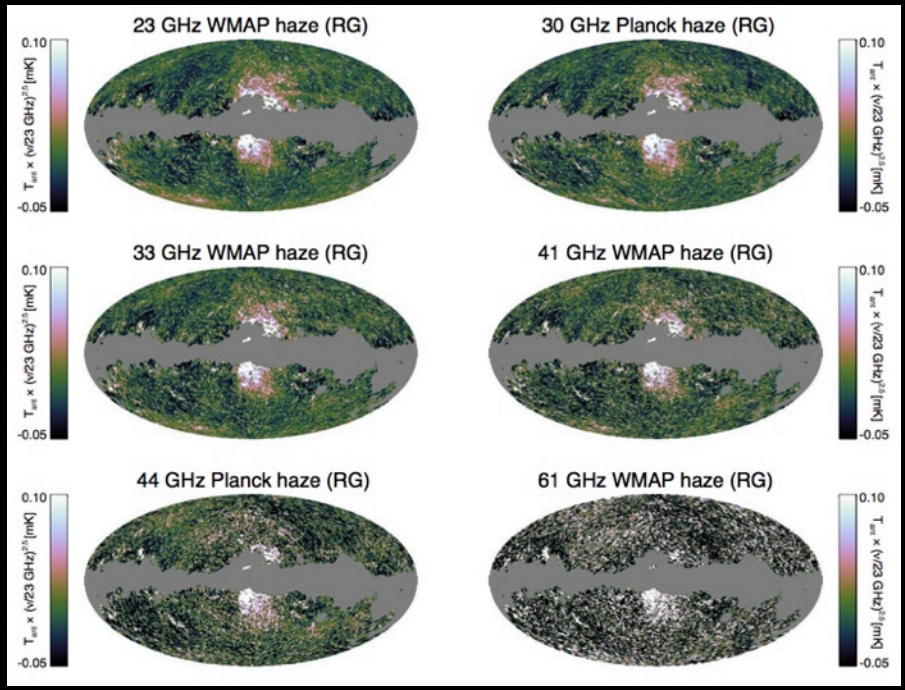


Planck wavelength coverage allows us to measure the spectrum of the haze/bubbles residual to high precision from ~*20-61* GHz and with little systematic bias:

$$T_H \propto \nu^{-2.55}$$

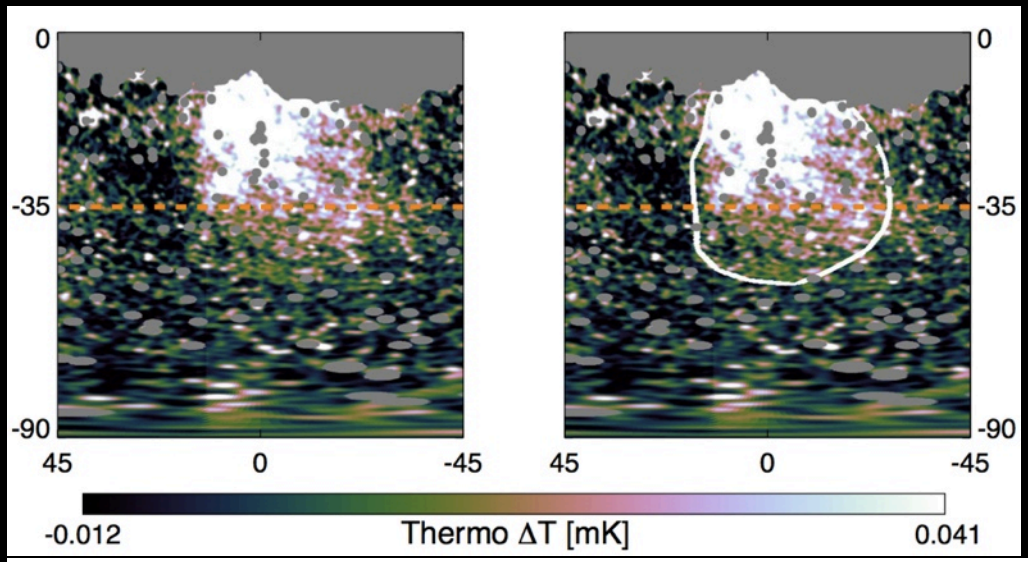
or

$$\frac{dN}{dE} \propto E^{-2.1}$$



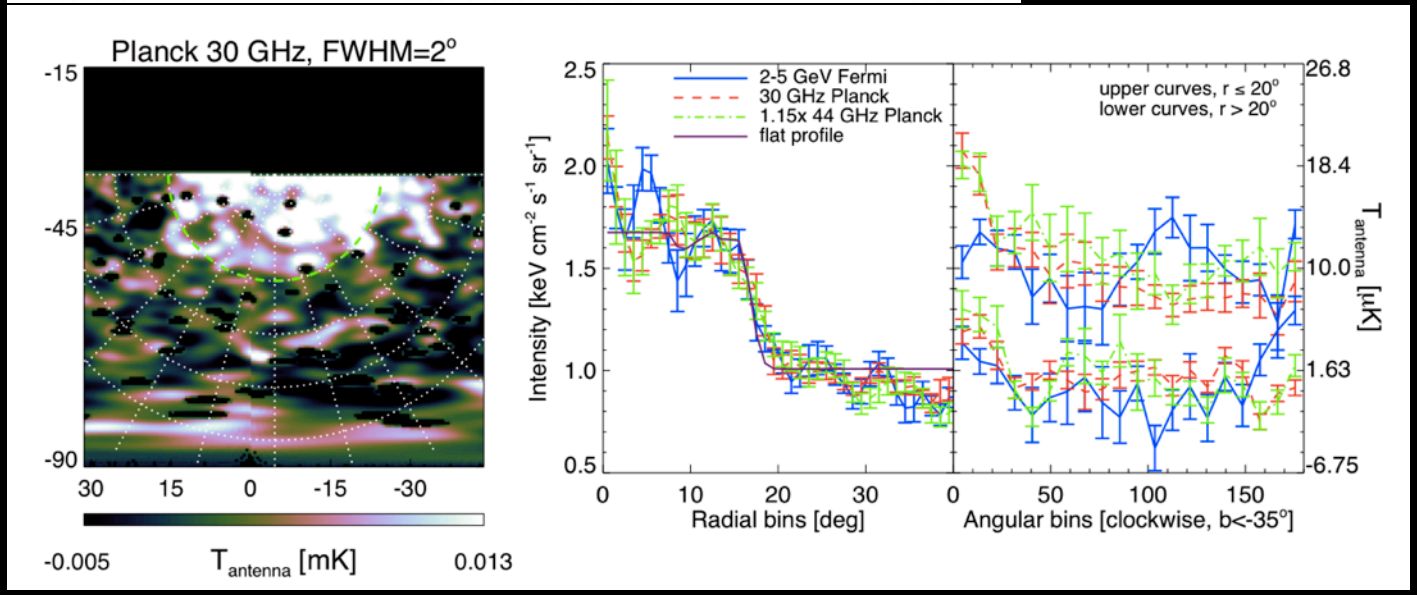
Planck Collaboration, 2012, arXiv:1208.5483

Planck



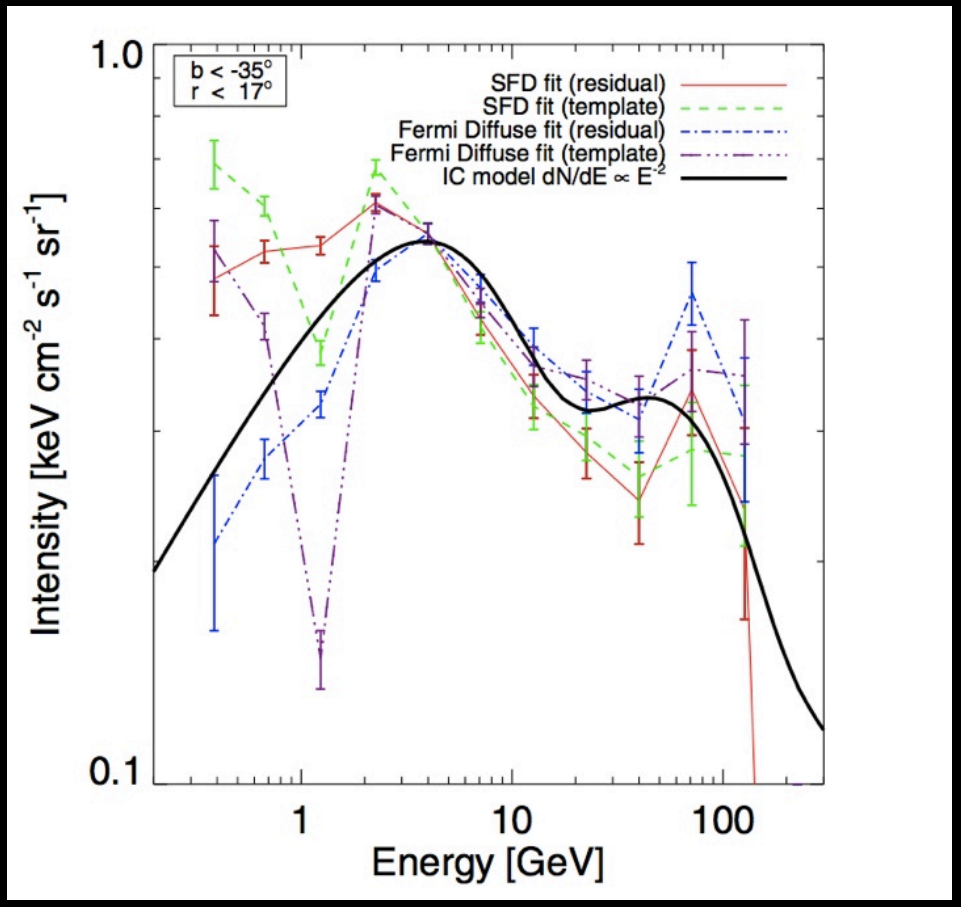
excellent spatial agreement between the low latitude "edges" in microwaves and gamma-rays

high latitude "edge" (spatially coincident with the gamma-ray edge) detected in *Planck* 30 GHz as well



Planck Collaboration, 2012, arXiv:1208.5483

measuring B-fields in radio bubbles



Dobler (2012b)

since synchrotron emissivity depends on the magnetic field strength B and the electron spectrum n_e,

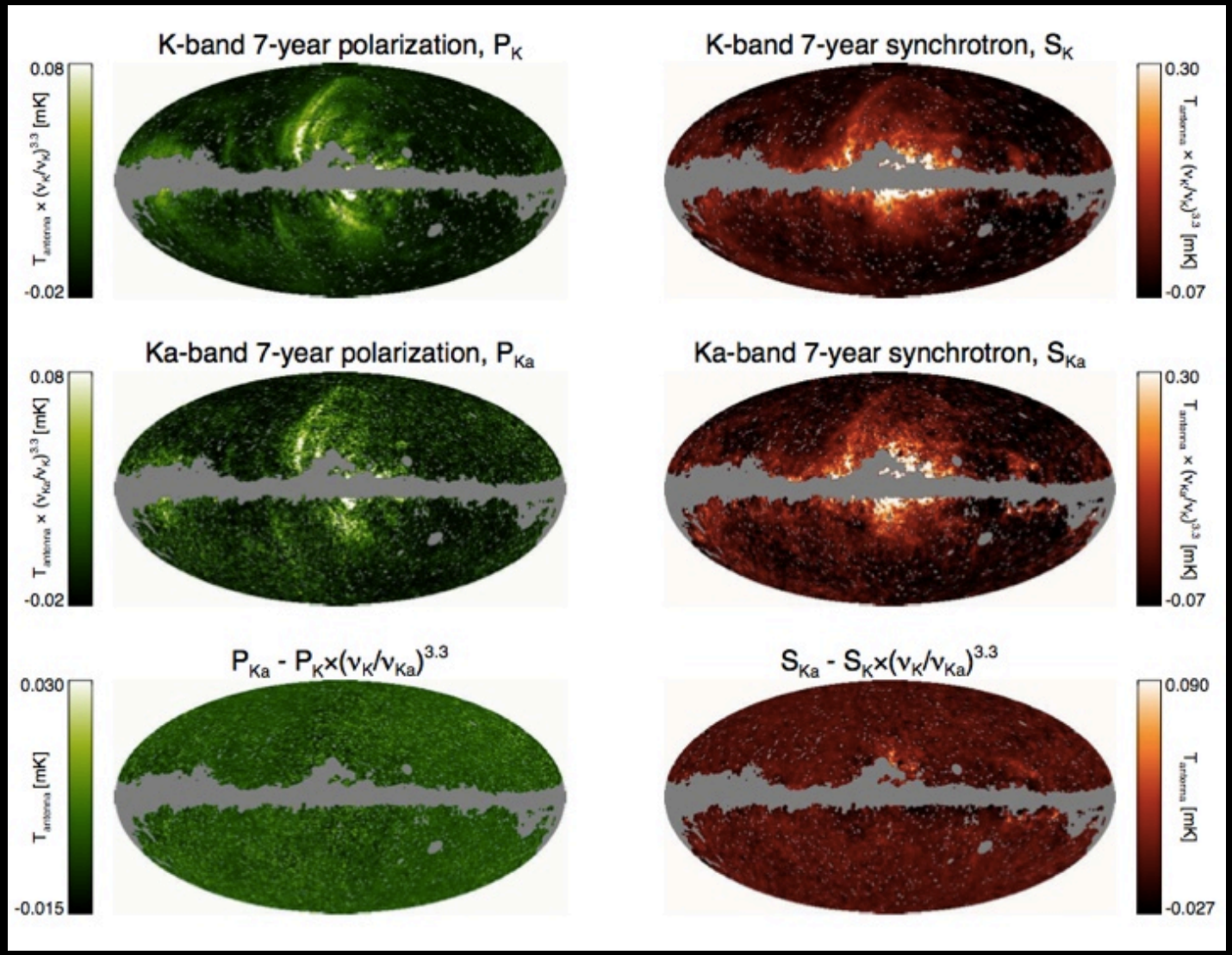
$$\text{emissivity} = j_\nu(B, n_e)$$

while the inverse Compton intensity is a function of the interstellar radiation field R and the electron spectrum n_e,

$$\text{intensity} = I_\gamma(R, n_e)$$

we can derive an estimate of $B \sim 5\ \mu$G.

polarization



Dobler (2012a)

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2.) "flat" spectrum

1.) seems to imply a very contrived electron distribution since constant volume emissivity gives limb-darkened profiles and shell emissivity gives limb brightened profiles.

2.) seems to imply injection of electrons at ~TeV with a ***very*** hard spectrum

the contenders:

- wind (e.g., *Crocker & Aharonian 2011*): time scales too long, no Hα, violates 1.)
- starburst: no Hα, likely violates 1.) and 2.)
- AGN (e.g., *Guo & Matthews 2011*): violates 1.)
- *2nd* order Fermi acc. (e.g., *Mertsch & Sarkar 2011*): violates 1.), synchrotron?
- DM annihilation (e.g., *Dobler, Cholis, & Weiner 2011*): violates 1.)

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M82: Galaxy with a Supergalactic Wind
Credit: NASA, ESA, The Hubble Heritage Team, (STScI / AURA)
Acknowledgement: M. Mountain (STScI), P. Puxley (NSF), J. Gallagher (U. Wisconsin)

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many puzzles...

but may opportunities!

- where (and how) are cosmic-rays accelerated in jets?

. jet itself? if so, then what about cooling times?

. shock front? where are the microwaves?

. what about limb brightening? *10* years of *Fermi* and / or CTA may provide answers

- why is the brightness profile so flat?

. neither constant volume nor shell emissivity fit the data

. why is the "stem" as bright or brighter than the rest of the bubble?

- what is nature of the magnetic field in jet-blown bubbles?

. no polarized signal with WMAP (but one isn't likely given the noise)

. future polarization data may constrain magnetic turbulence in jets