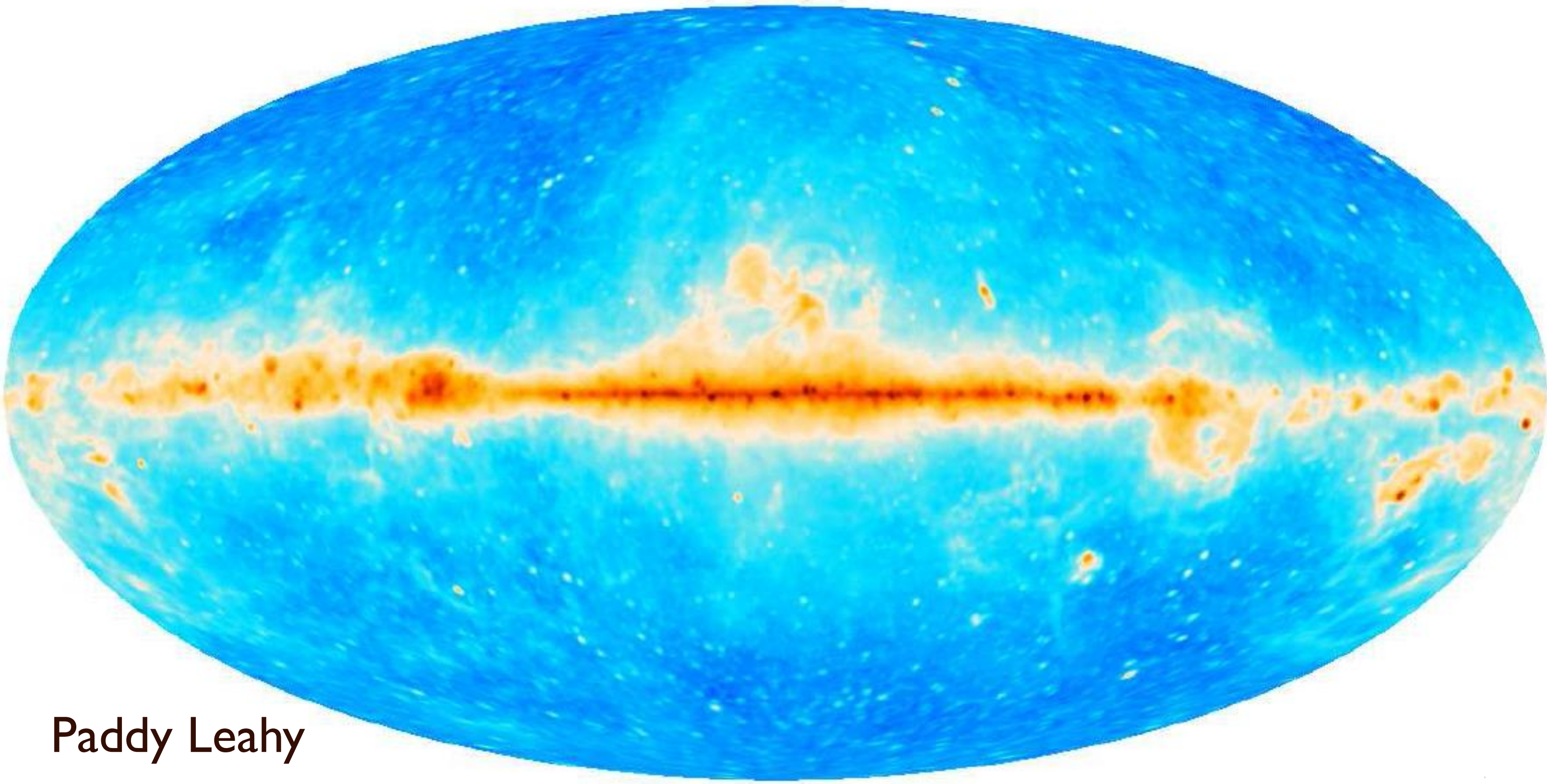
Untangling the cm-wavelength Sky



Paddy Leahy

Jodrell Bank Centre for Astrophysics, University of Manchester

on behalf of the Planck Collaboration

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

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

12th August 2015

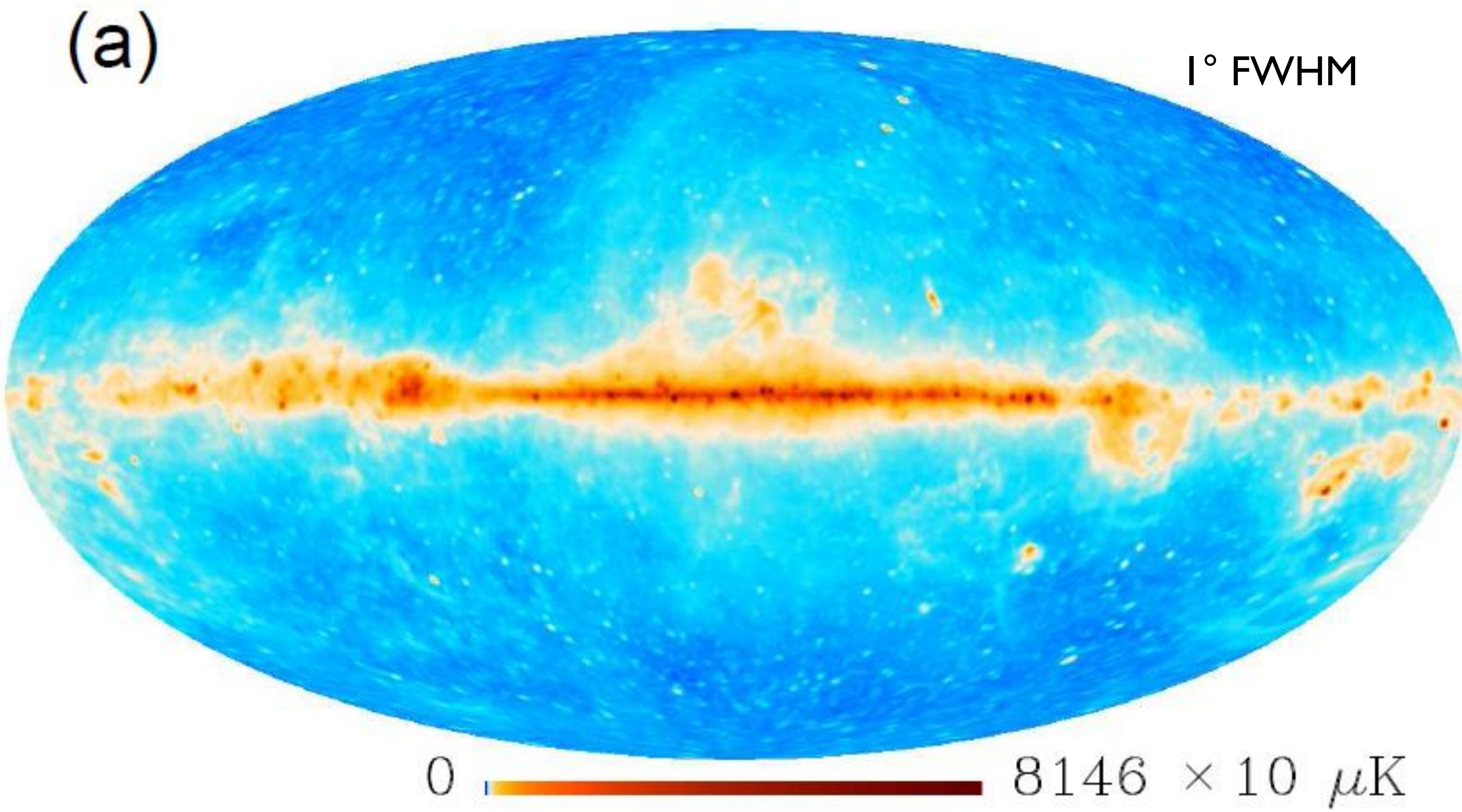
Overview

- Total Intensity Foregrounds below 70 GHz
  - Comparison of Commander model with external datasets
  - Model degeneracies and how to resolve them
- Polarization Foregrounds below 70 GHz: Synchrotron
  - Loop I: How far away is it? What is it?
  - The *Fermi* Bubbles and the microwave haze
  - New features in the polarization maps
- Future prospects including C-BASS

Based on:

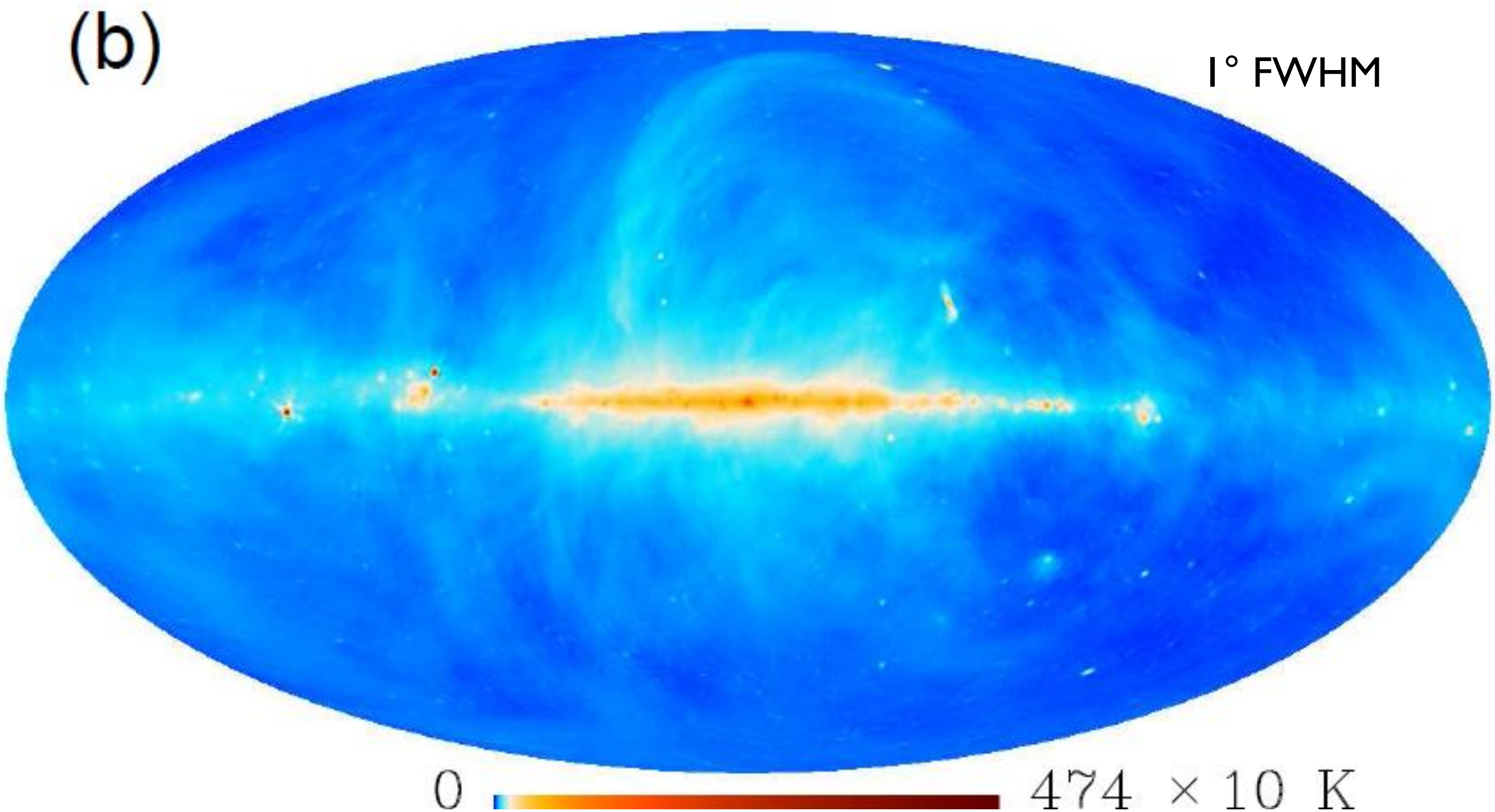
- Planck 2015 Results XXV: Diffuse Low-Frequency Foregrounds: Planck+WMAP 30 GHz polarization
- Vidal et al 2015 (arxiv:1410.4438): Unsharp masked WMAP & geometry of magnetic field in the loops
- Remazeilles et al 2015: Destriped, desourced 408 MHz

Planck 30 GHz Foregrounds



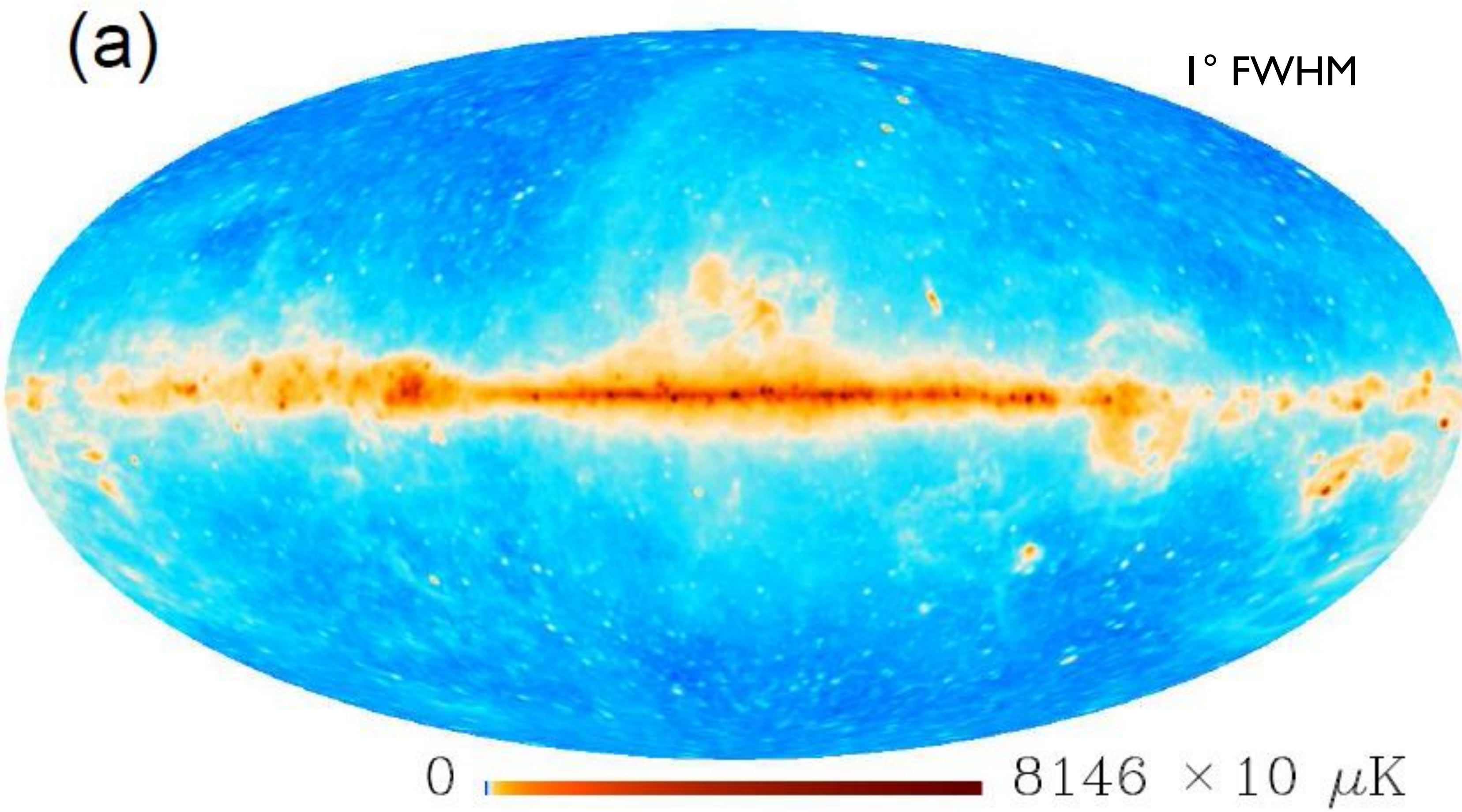
CMB killed by linear combination

Synchrotron template: 408 MHz



Haslam et al 1981 / Remazeilles et al 2015

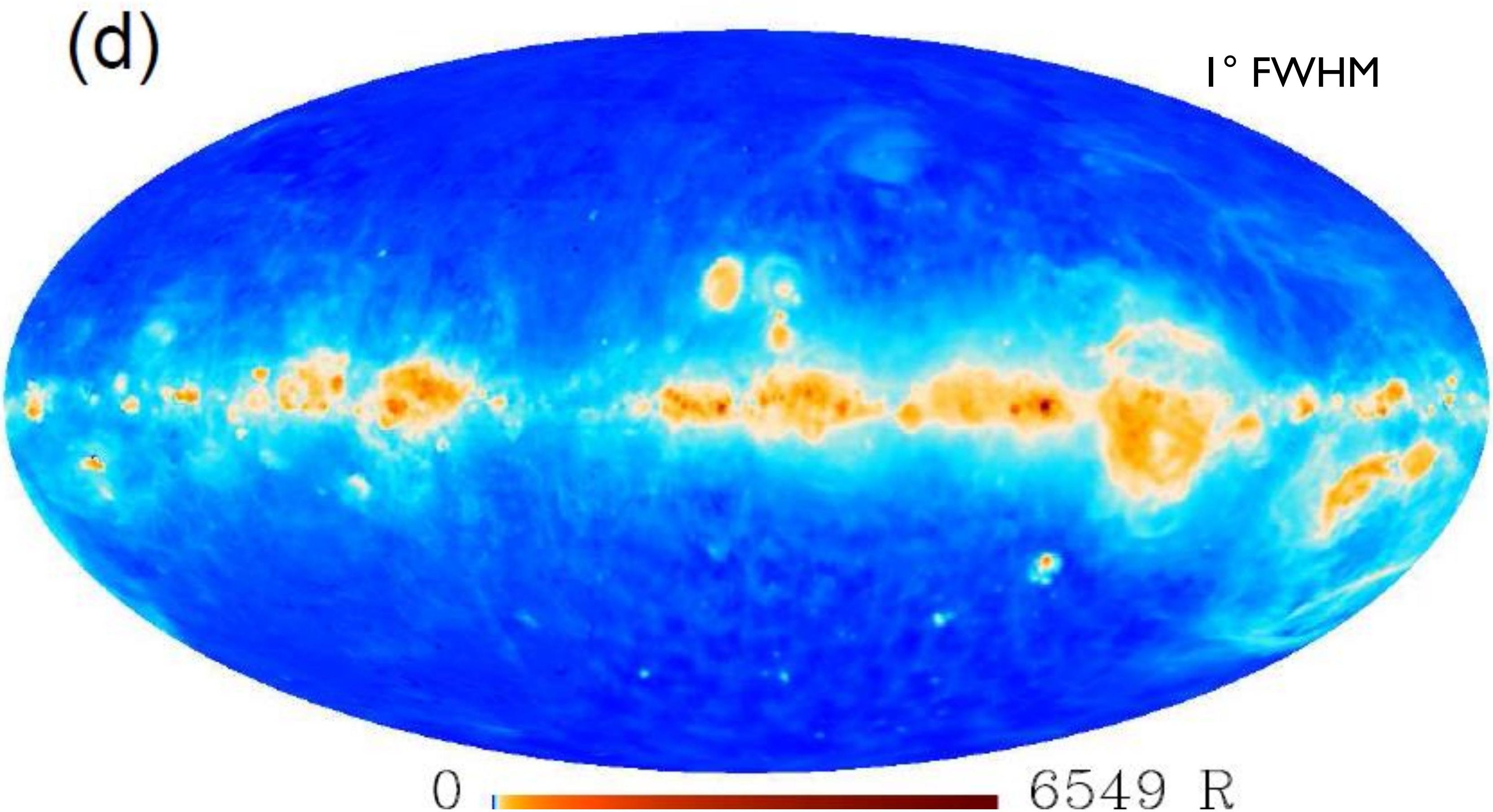
Planck 30 GHz Foregrounds



1° FWHM

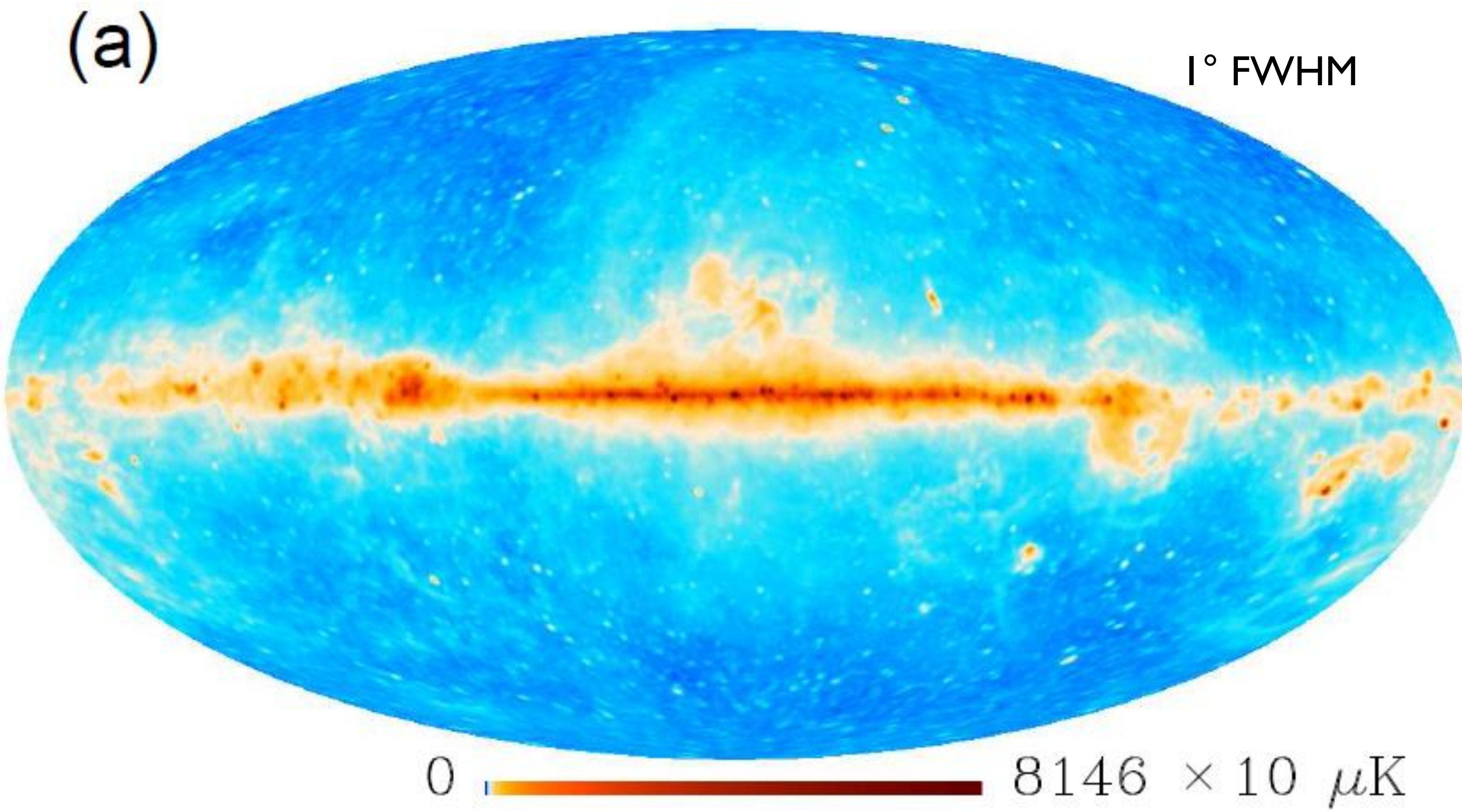
CMB killed by linear combination

Free-free Template: 457 THz



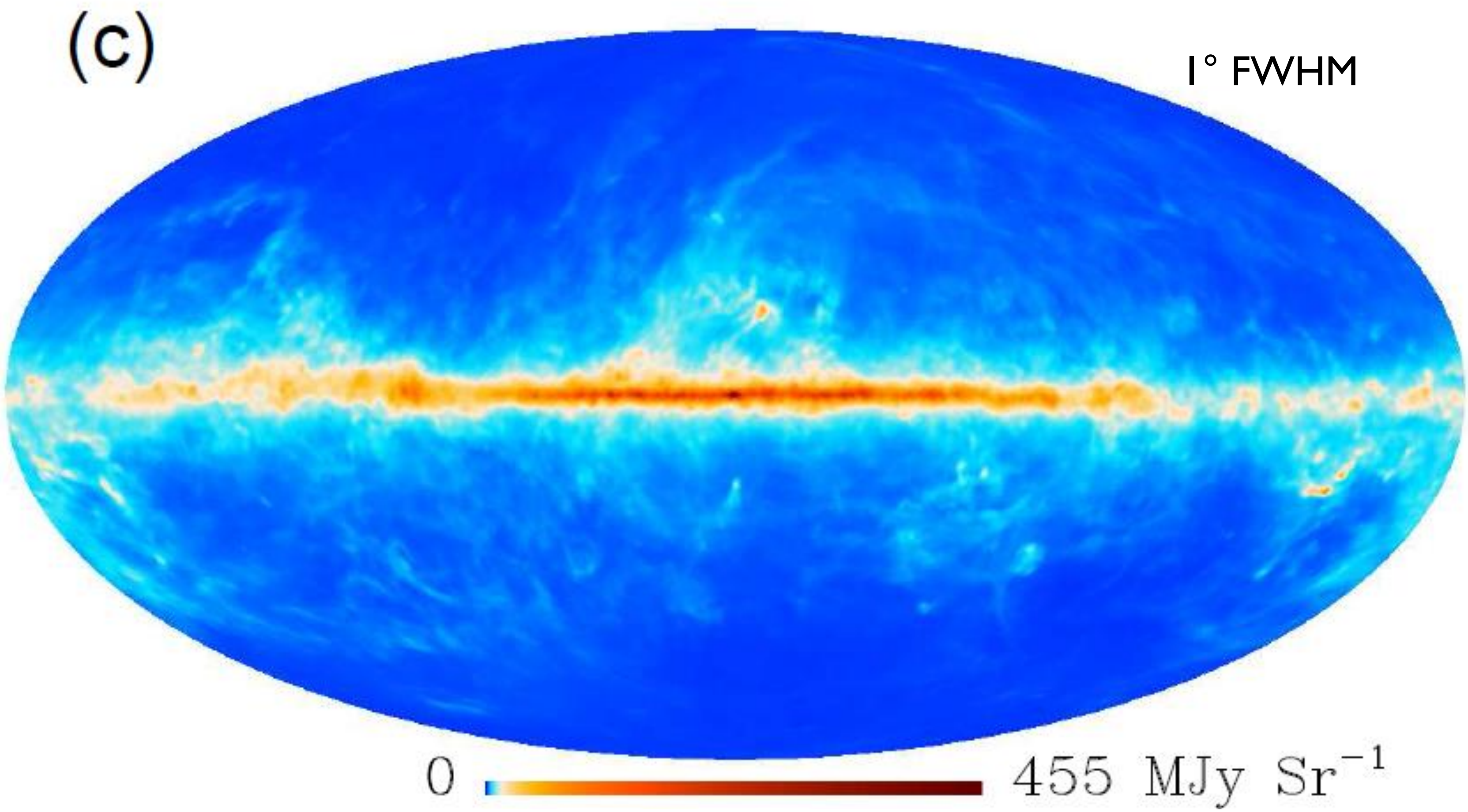
Hα WHAM+SHASSA Dickinson et al. 2003

Planck 30 GHz Foregrounds



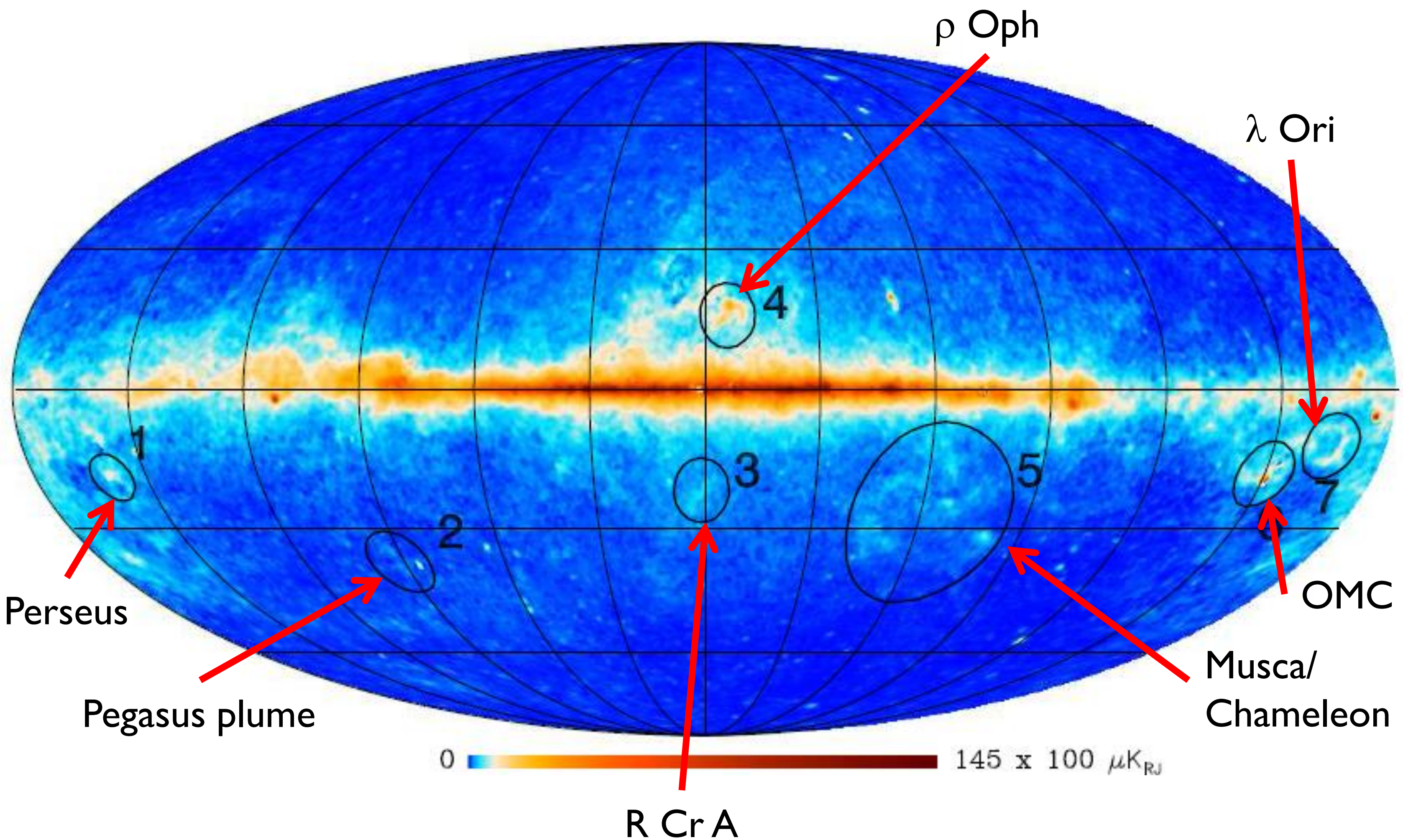
CMB killed by linear combination

Dust template: 545 GHz

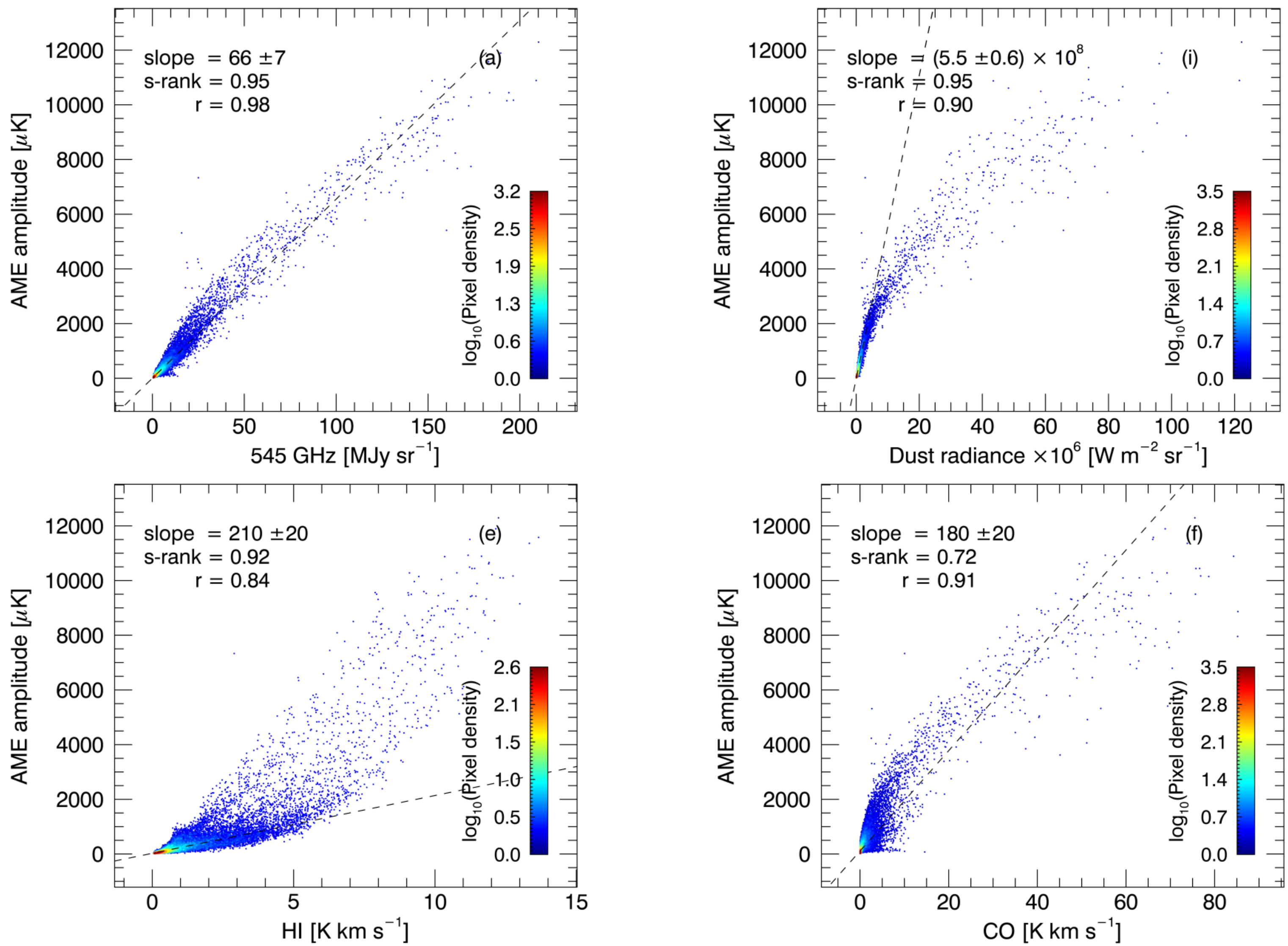


Planck HFI map

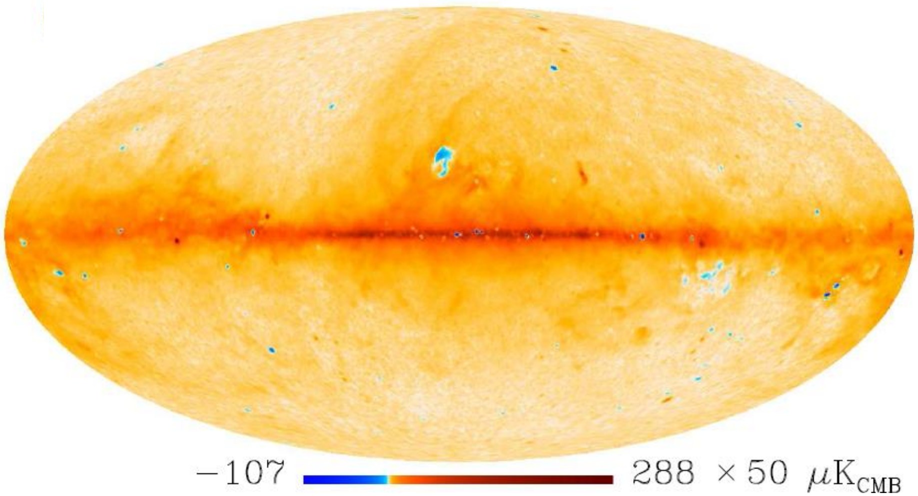
Anomalous Microwave Emission



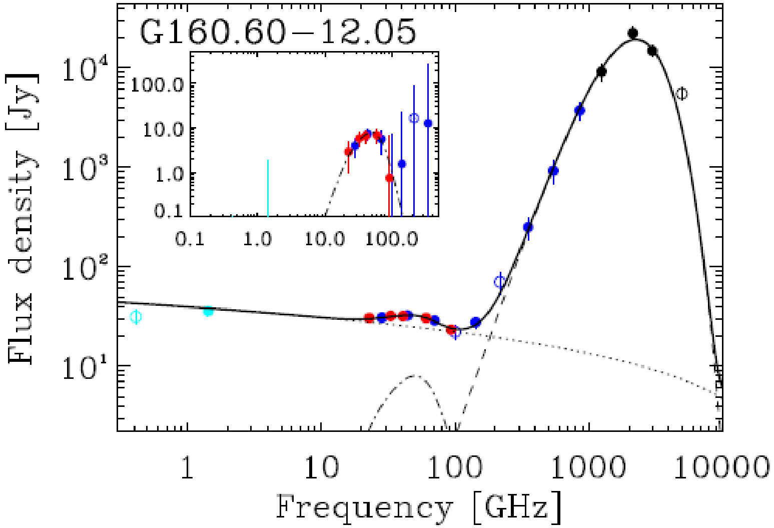
AME correlations

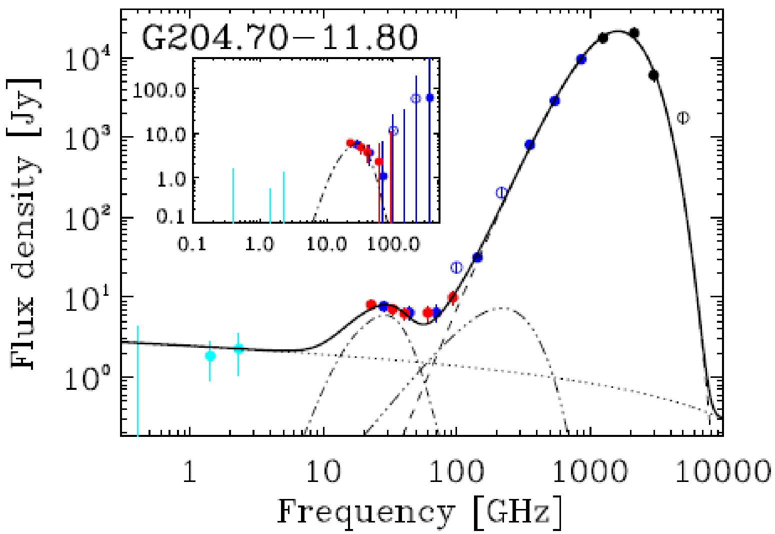


The AME Problem



Planck Int. XV (2014):



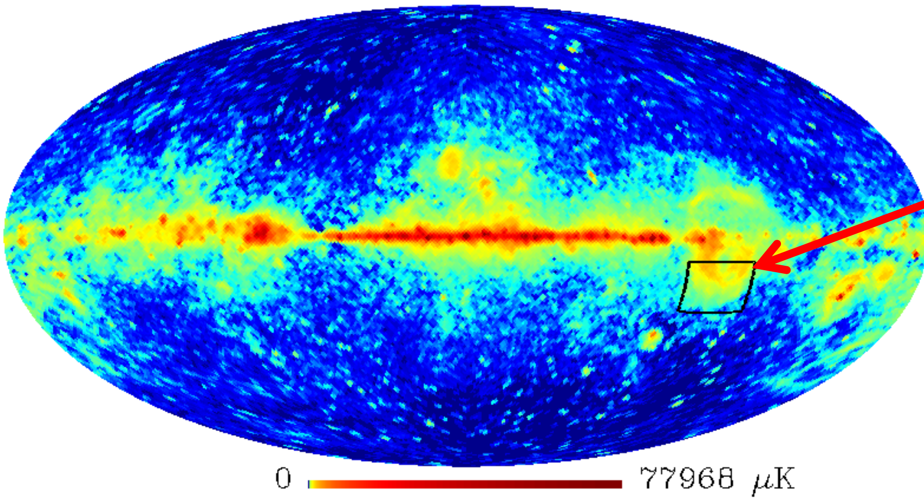


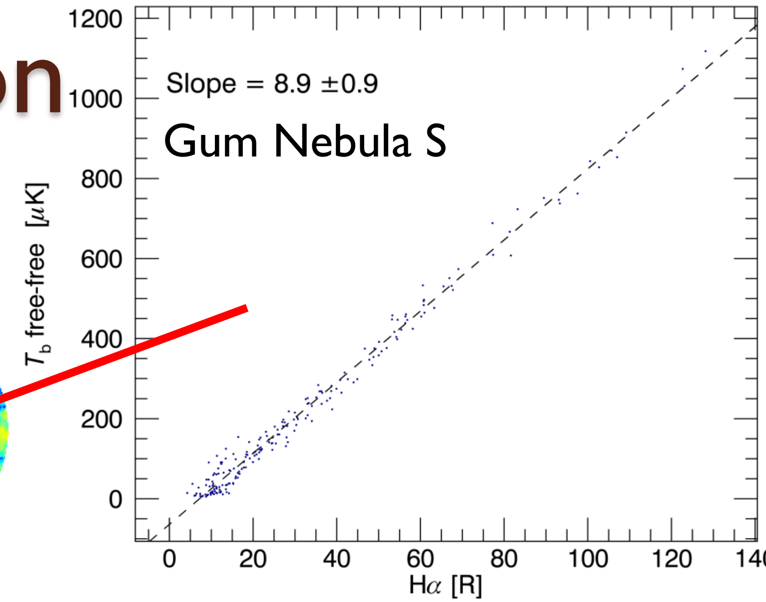
- CMB, dust and free-free killed ILC combination.
- Negative = rising spectrum between 30 & 44 GHz:
  - AME with high-frequency peak.

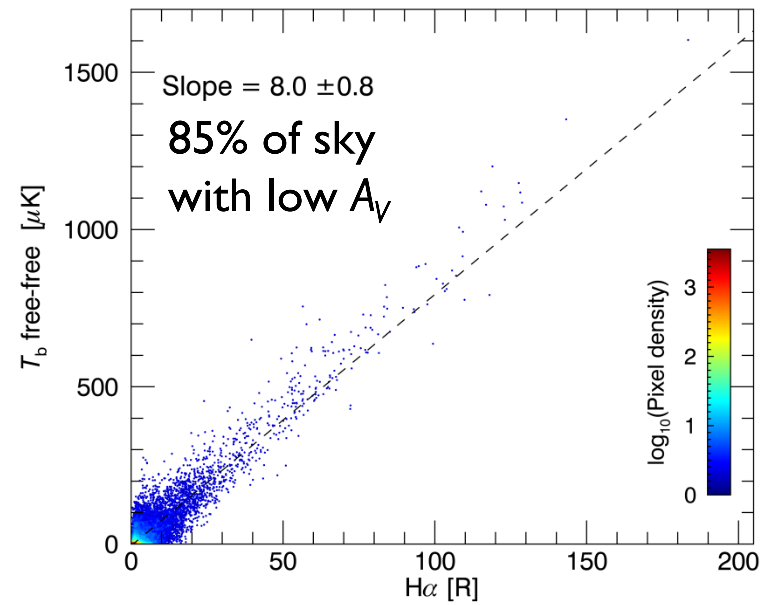
The AME Problem

- No guarantee that AME with different peaks is not superposed on line of sight
- Peaked spectrum + variable peak frequency allows AME to fit almost any spectral form in the 20-60 GHz region.
- Planck Commander model has 2 AME components:
  - Main component has variable peak with prior centred on 19 GHz
  - "High frequency" component with peak 30 GHz
    - Still too low for some regions (ζ Oph, California Nebula)
- AME flexibility forces us to use fixed template for synchrotron spectrum, despite plausible evidence for spectral variability.

Free-Free emission



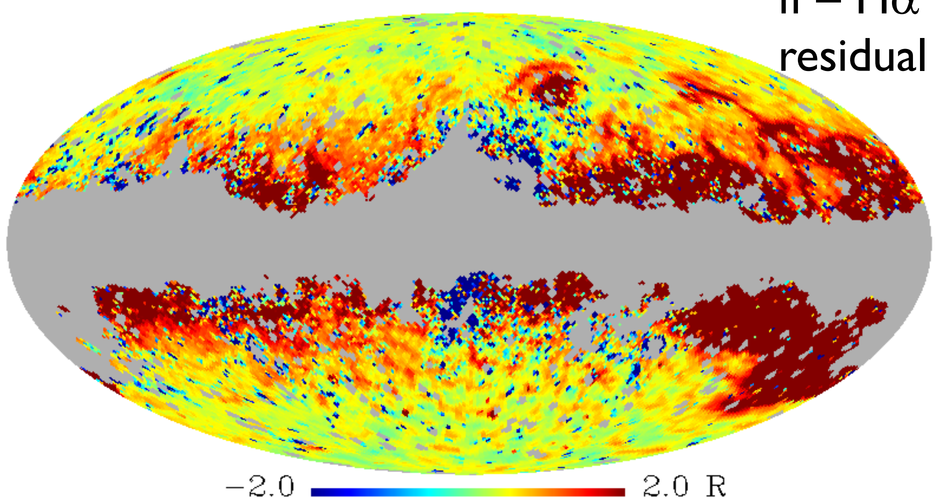


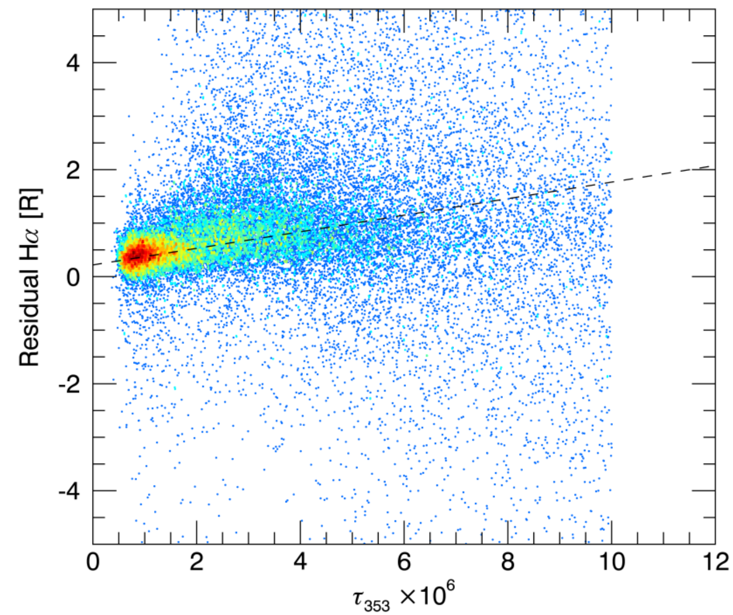


- Good correlation between Hα & free-free.
- Ratio agrees with previous analyses
- → T_e in Gum nebula 5200 ± 900 K

Scattered Hα?

ff – Hα
residual

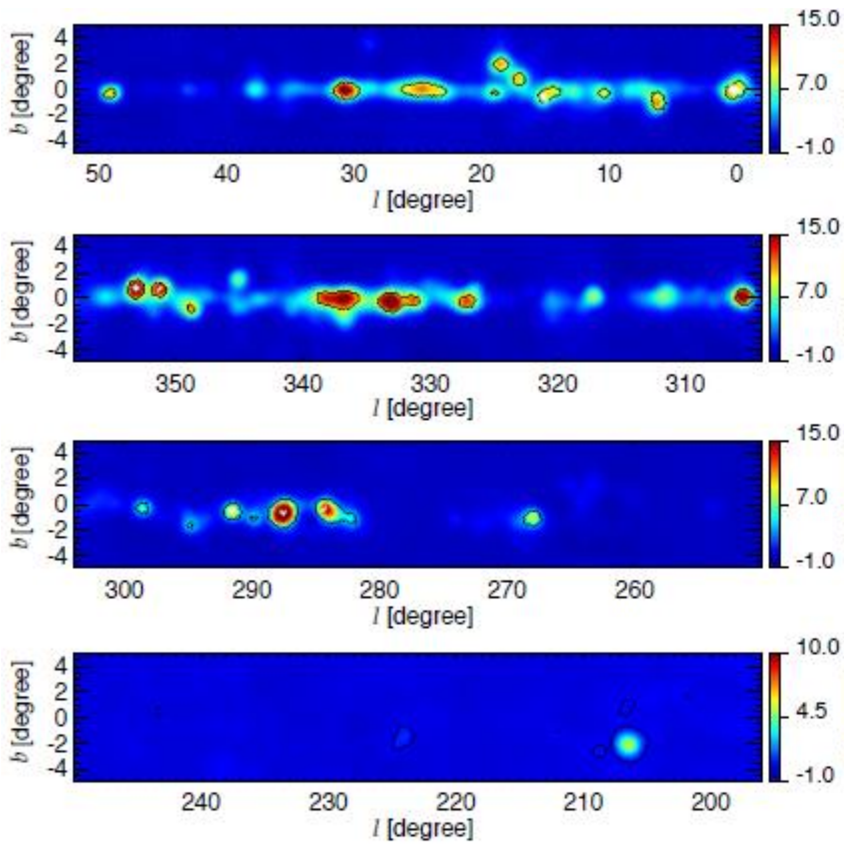




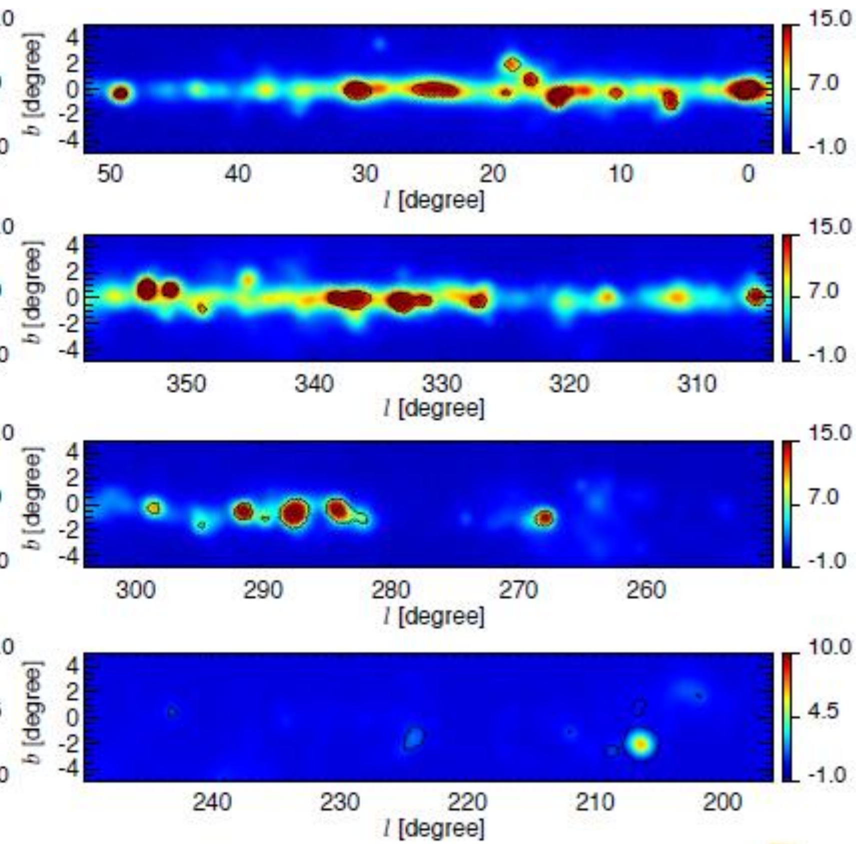
- Slope of free-free vs. Hα flatter than expected: 8.0 ± 0.8 vs 11.1 ± 0.9 μK/R
  - for LTE with T_e = 7500 ± 1000 K as found in local WIM
- T_e much lower than expected for WIM?
- Excess Hα due to dust scattering (Wood & Reynolds 1999)?
- Residual Hα correlates with dust: implies 36 ± 12% of high-latitude Hα is scattered.

Radio Recombination Lines

RRLs (Alves et al 2015)



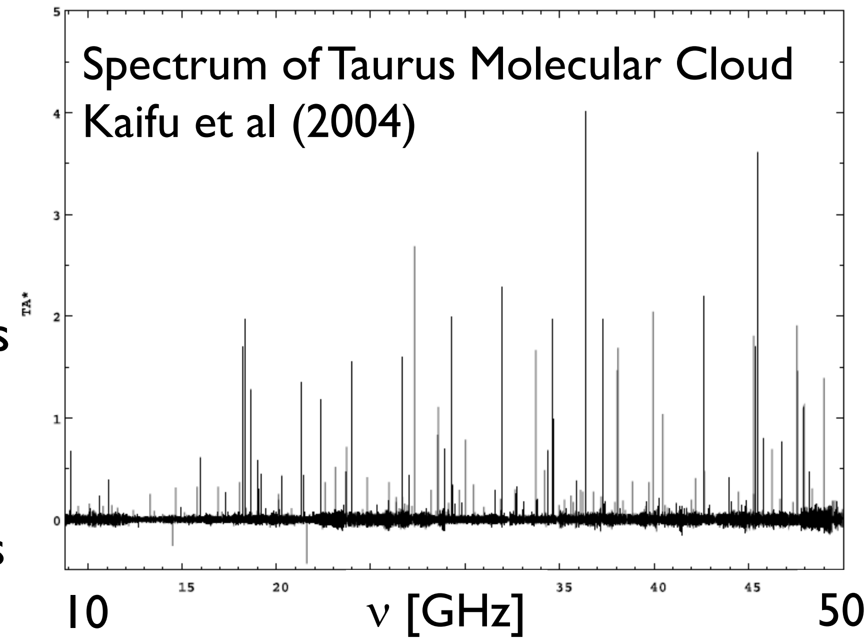
Commander Free-free model

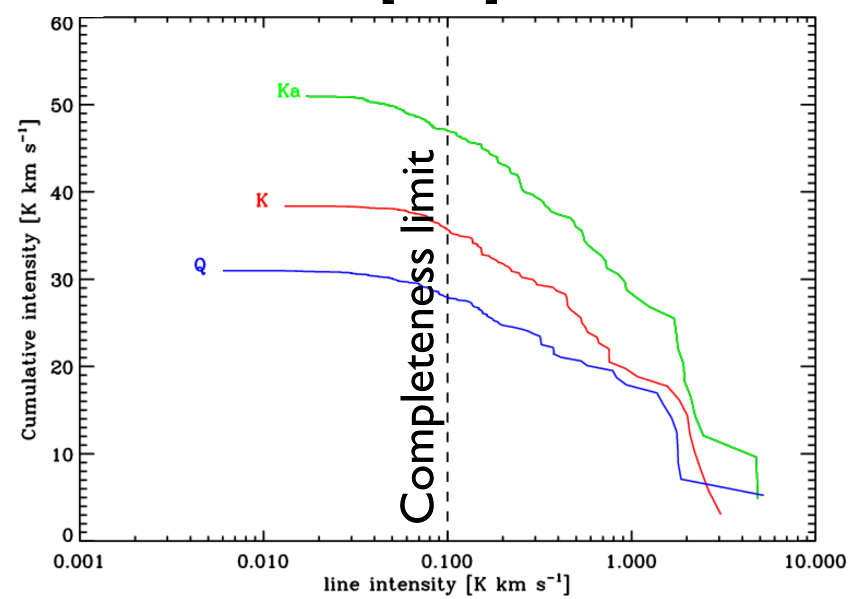


- Good correlation but model is ~50% brighter than expected and has diffuse plateau (but large-scale structure poorly recovered in RRL)

Spectral Lines

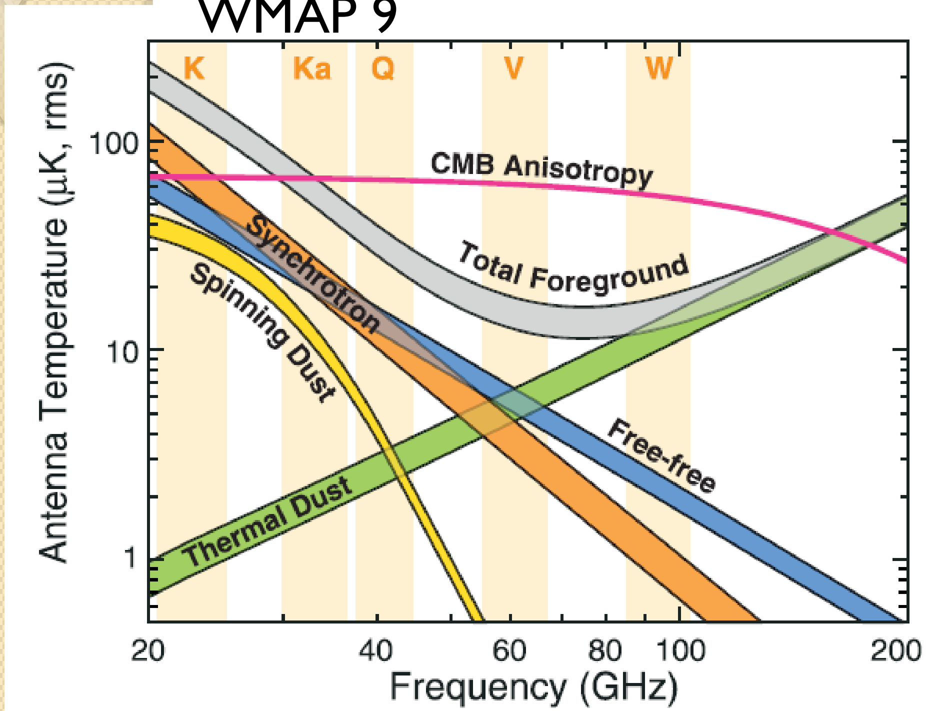
- Of 15 frequency bands fit by Commander, 4 are contaminated by spectral lines
  - CO (J=1-0) at 115 GHz gives 1/3 of "100 GHz" brightness on Galactic plane.
- Molecular lines are ubiquitous in the radio-mm spectrum
- Integrated line flux in any 20–30% bandwidth may easily exceed flux of CO line.
- Produce spurious polarization in differencing radiometers like *WMAP* & *Planck*
  - Driven by high-frequency structure in bandpass which differs between orthogonal polarizations.



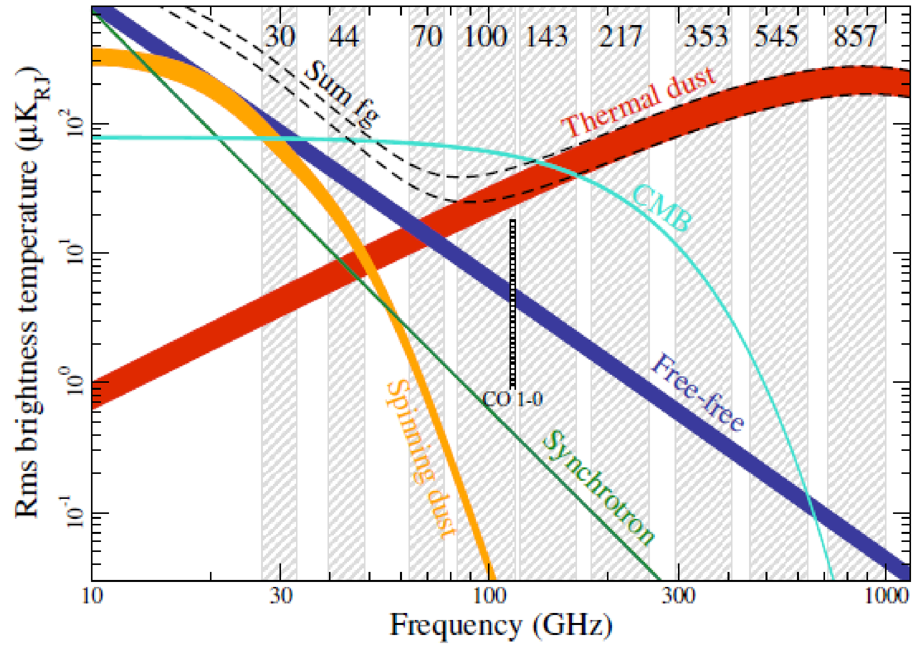


Foreground components

WMAP 9



Planck 2015



75-85% sky coverage

NB: RMS fluctuations, not absolute brightness.

81-93% sky coverage

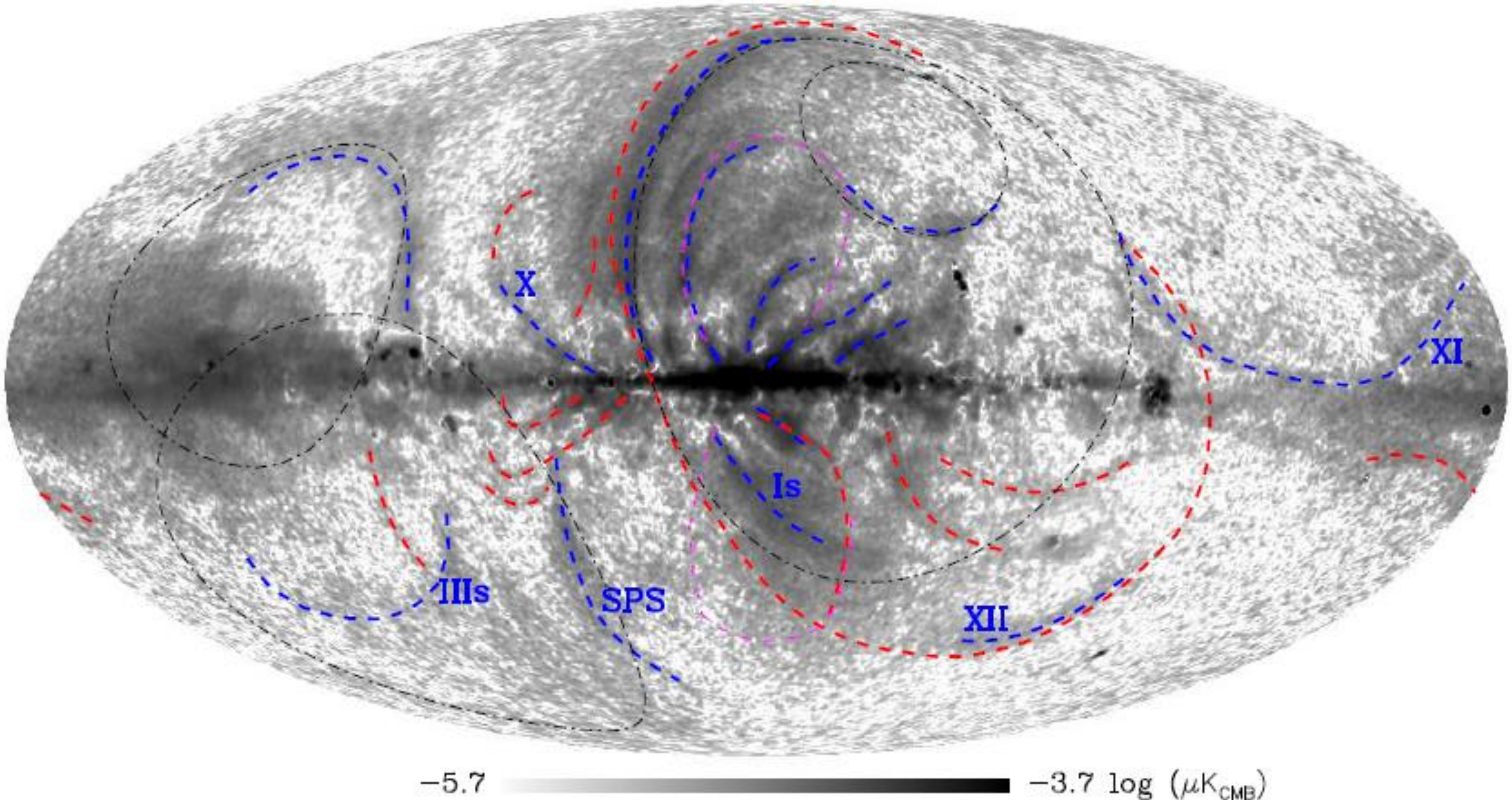
1°FWHM

c.f. common mask 78%

Conclusions I: T analysis

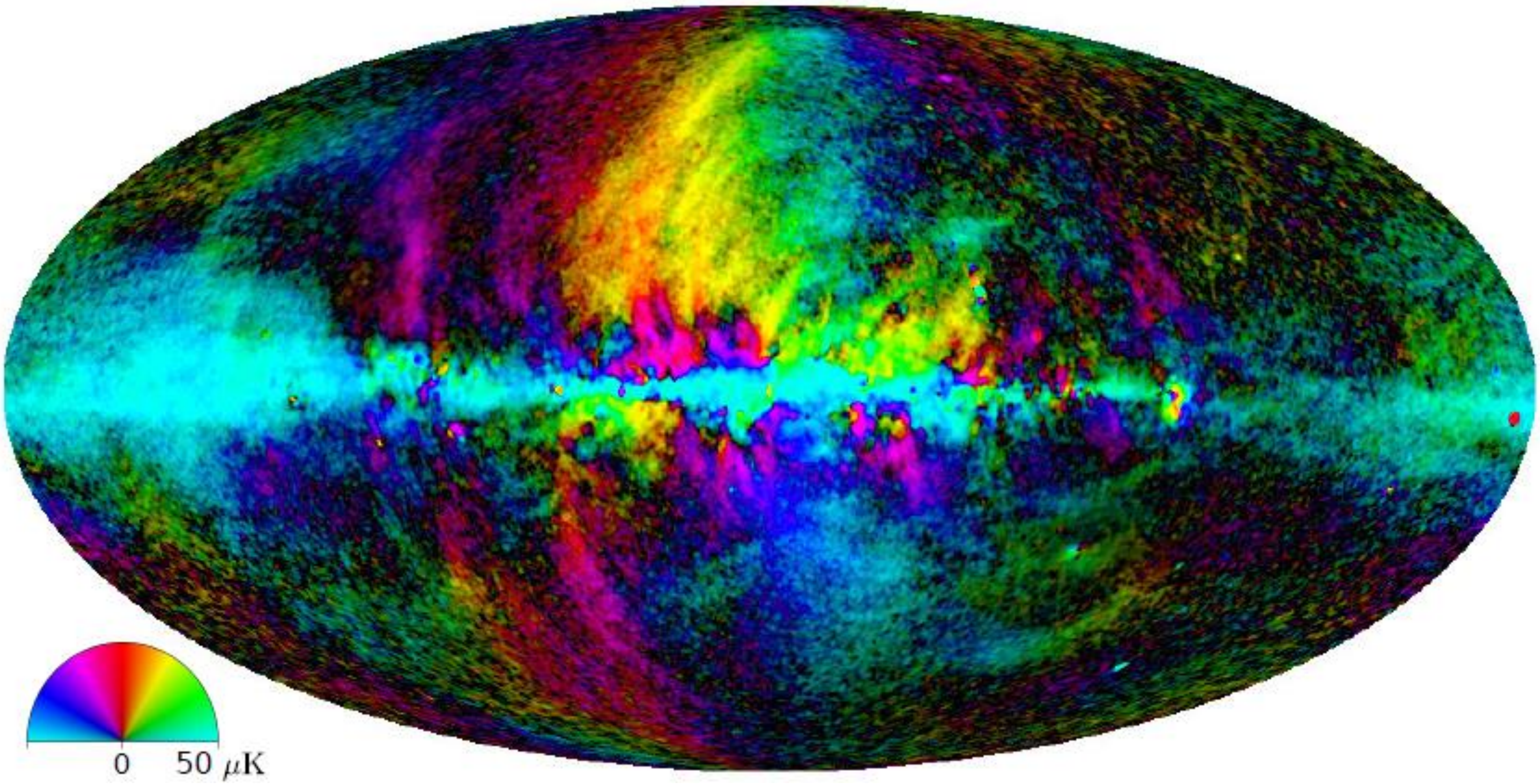
- Commander foreground model gives excellent fit to the spectrum in most sky pixels, including fitting to 1% accuracy along the Galactic plane
- Excellent qualitative agreement with external templates for free-free, AME and CO components even though spatial information is not used in the fit.
- Free-free amplitude is fainter than expected from Hα at high latitudes (definitely a real effect)…
- …but brighter than predicted from RRL along the plane
  - may be "soaking up" synchrotron emission with flatter spectrum than assumed.
- Penalty for AME flexibility is inability to fit spatial variation in synchrotron spectrum
- Data at < 20 GHz will help resolve AME/synchrotron
- Ultimate limit to component separation may be line emission

The Polarized sky at 1 cm



Planck+WMAP polarized intensity at 28.4 GHz
(log transfer)

The Polarized sky at 1 cm

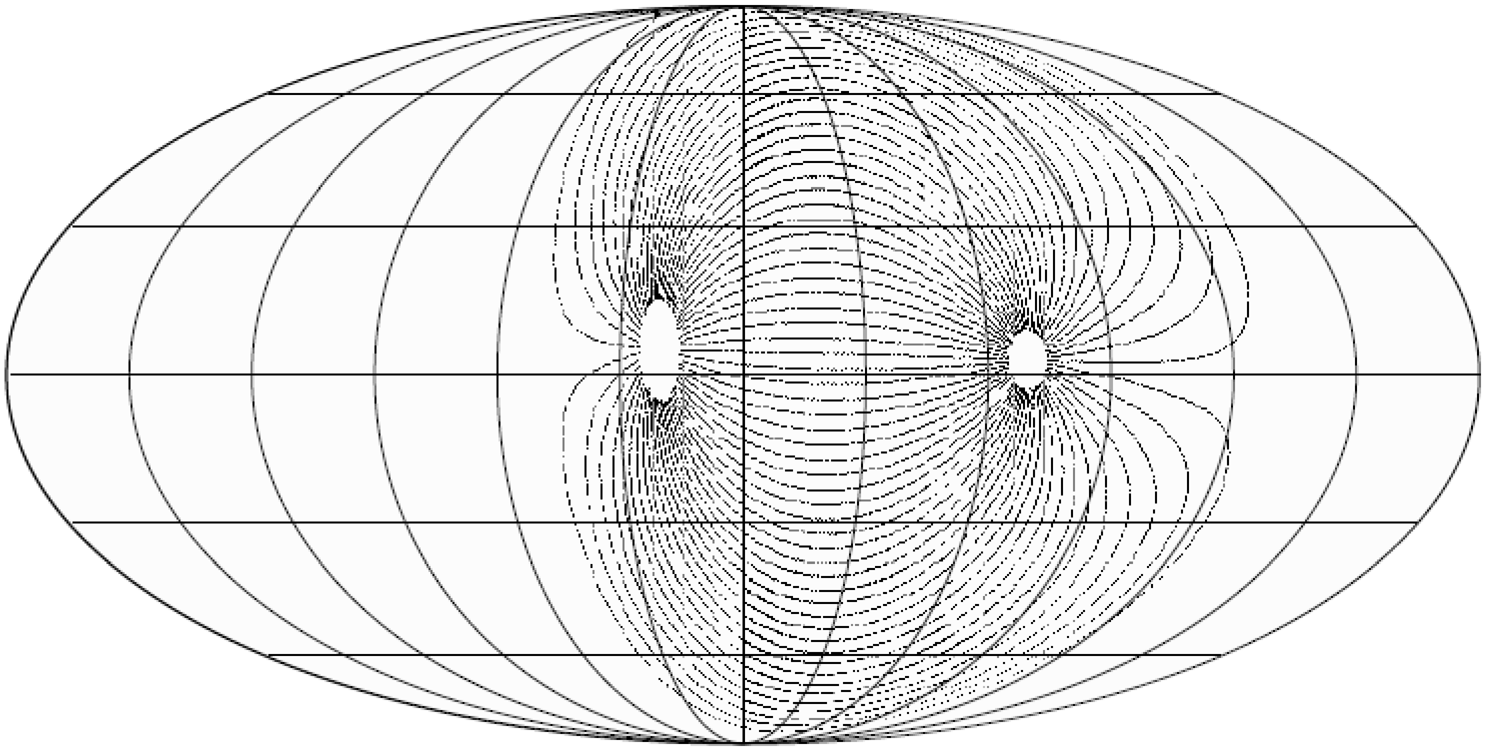


Planck+WMAP polarized intensity at 28.4 GHz (asinh transfer)
colour-coded by polarization angle

What are the loops?

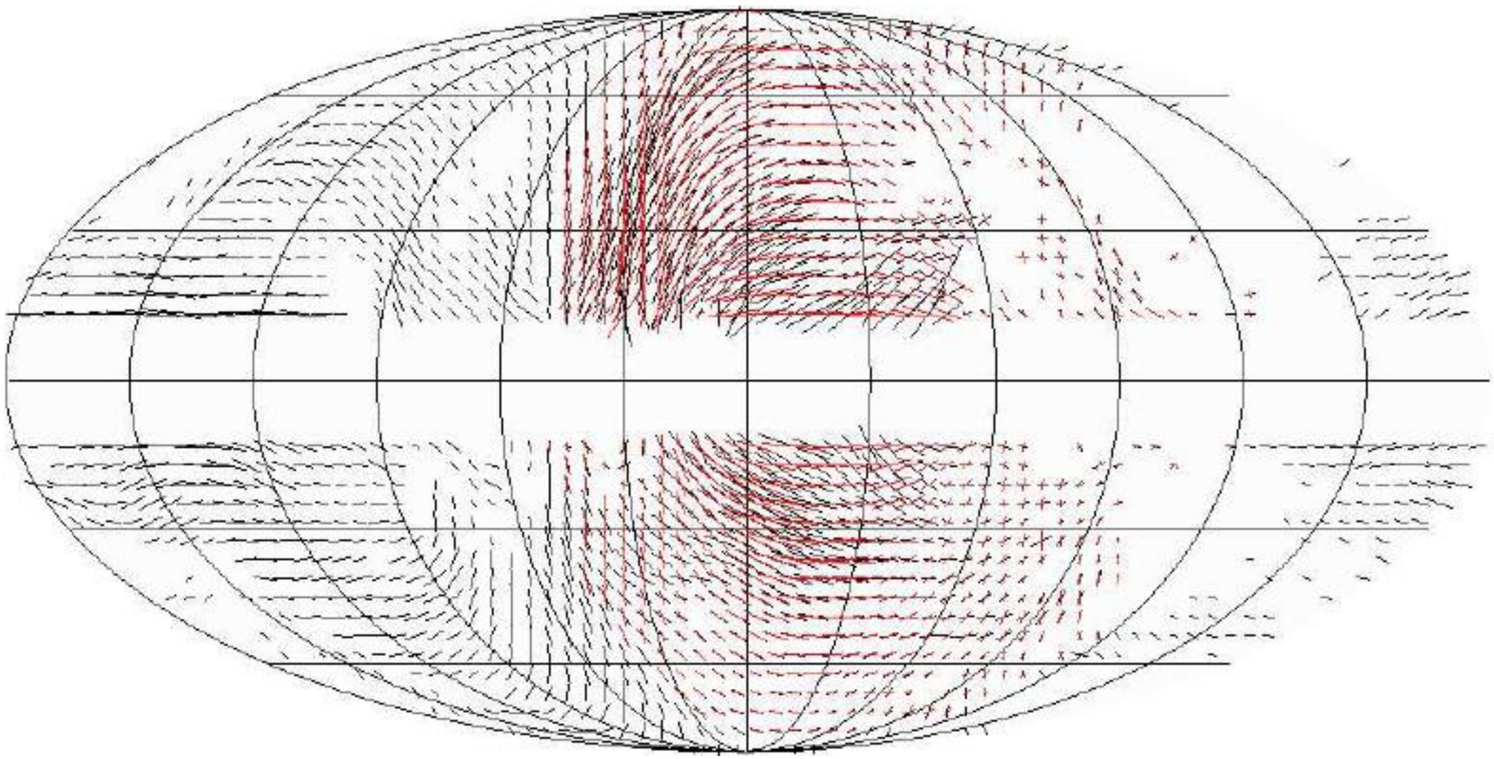
- Shock front around explosion in Galactic centre? (Loop I only)
  - Yoshiaki Sofue 1977 etc
- Supernova remants?
- Shock front around superbubbles?
  - E.g. Loop I Sco-Cen OB association, @ D = 116-140 pc
  - Multiple SNR in old cavity
  - Weaver 1977-1979
- Analogues to "solar prominence" in the Galactic corona?
- Ambient field lines stretched by superbubble expansion,
  - Heiles 1998; Vidal et al 2015
- Also, where are the more distant loops?
  - Mertsch & Sarkar 2013

Loop I Magnetic field model



Model:
Vidal et al 2015

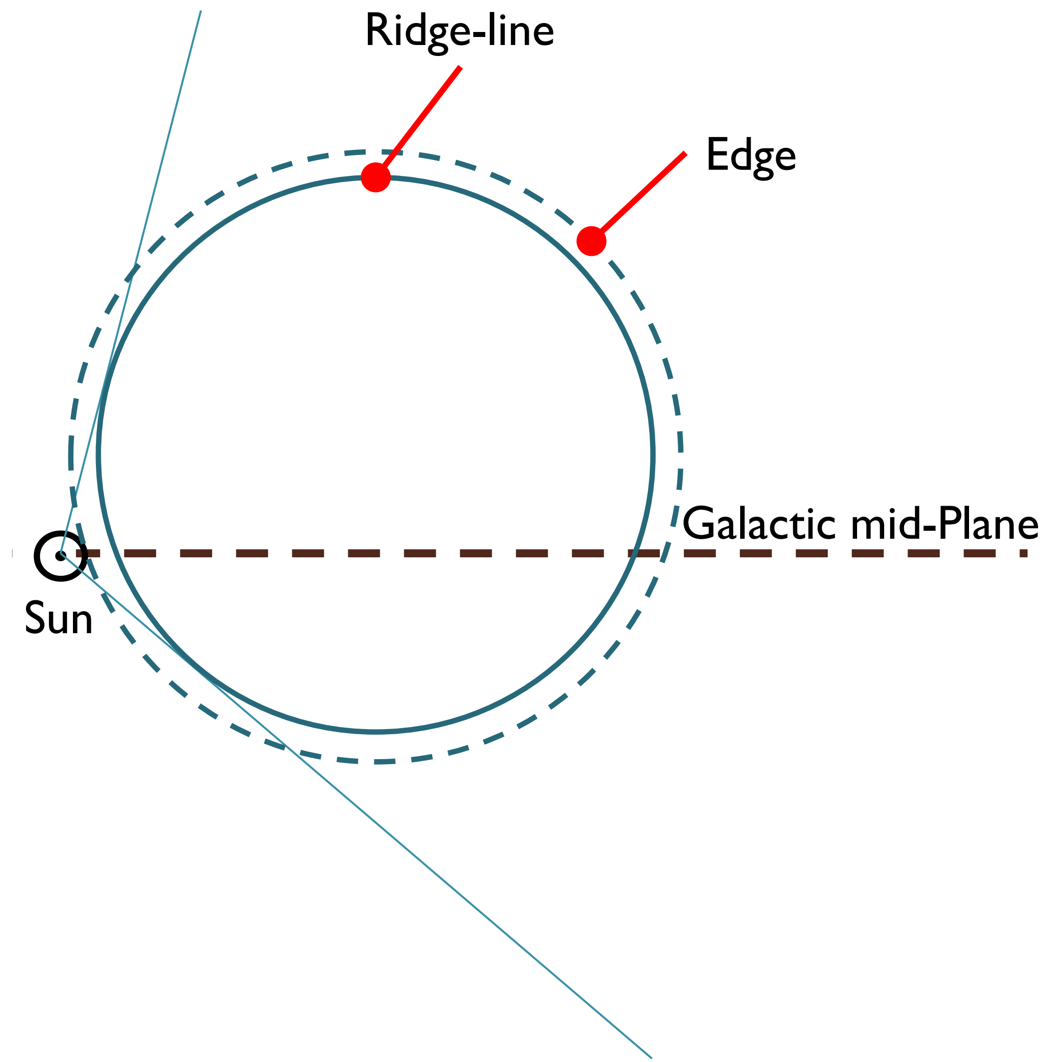
Loop I Magnetic field



Model (red) vs. WMAP polarization
Vidal et al 2015

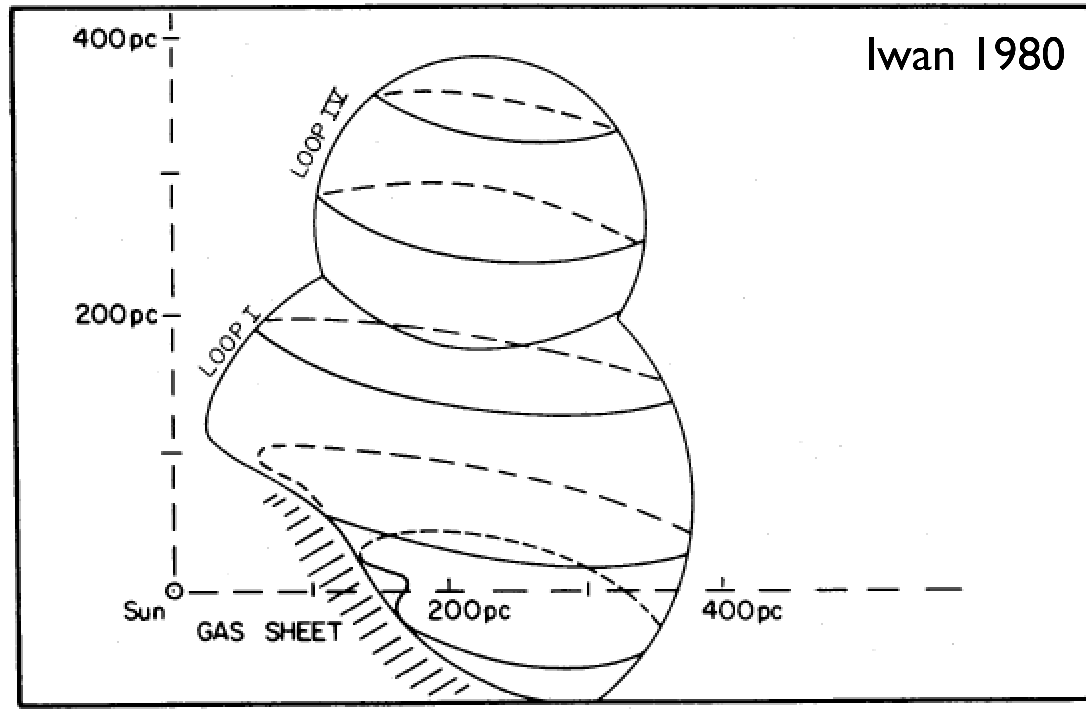
Loop I in perspective

- Perspective is very important for such large angular sizes
- Top of observed loop is nowhere near "top" of structure
- No evidence that Loop I is actually a full sphere
  - c.f. the Local Cavity is 'open' at the poles.
- Projected outline south of Galactic plane is not circular

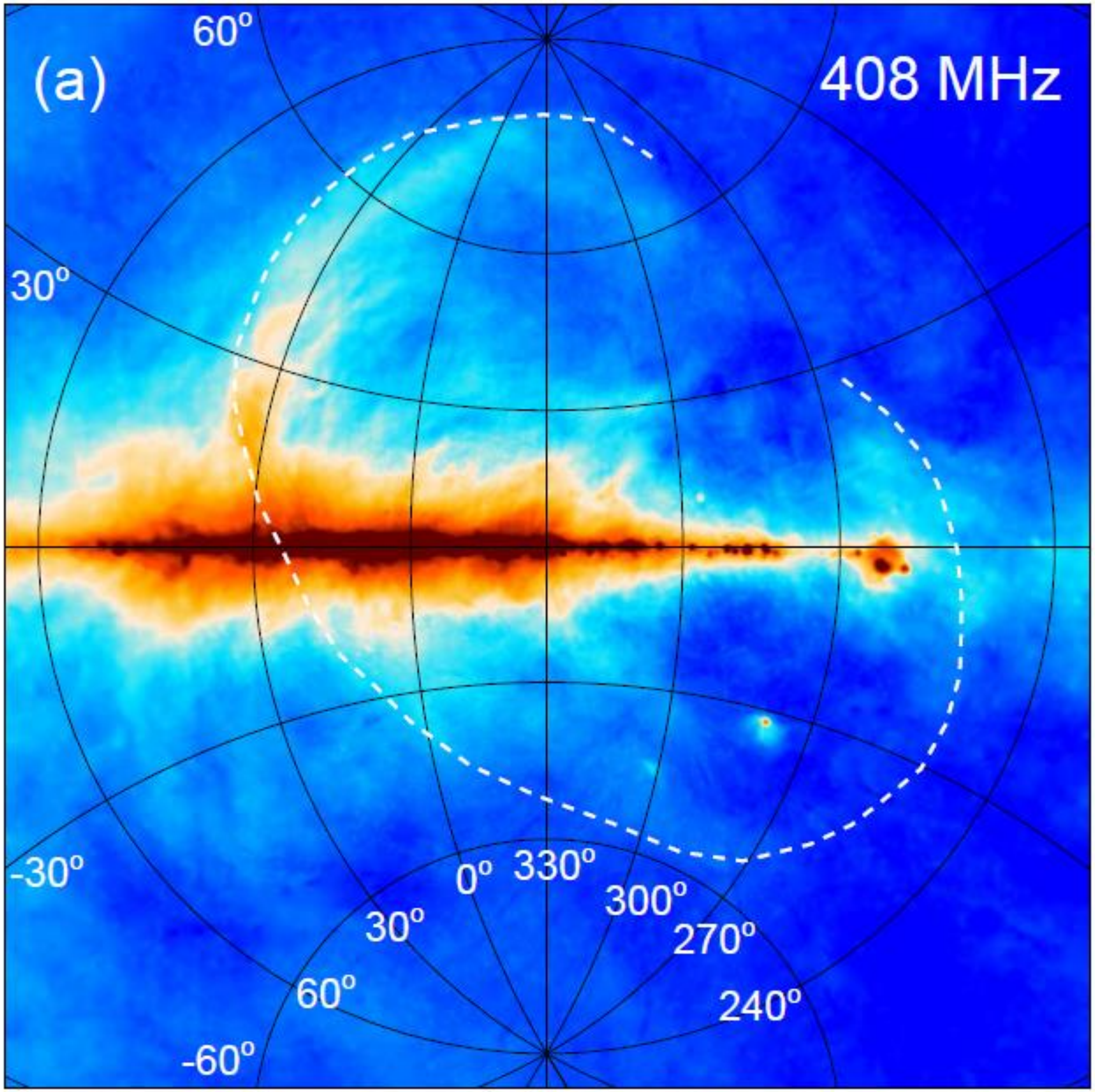


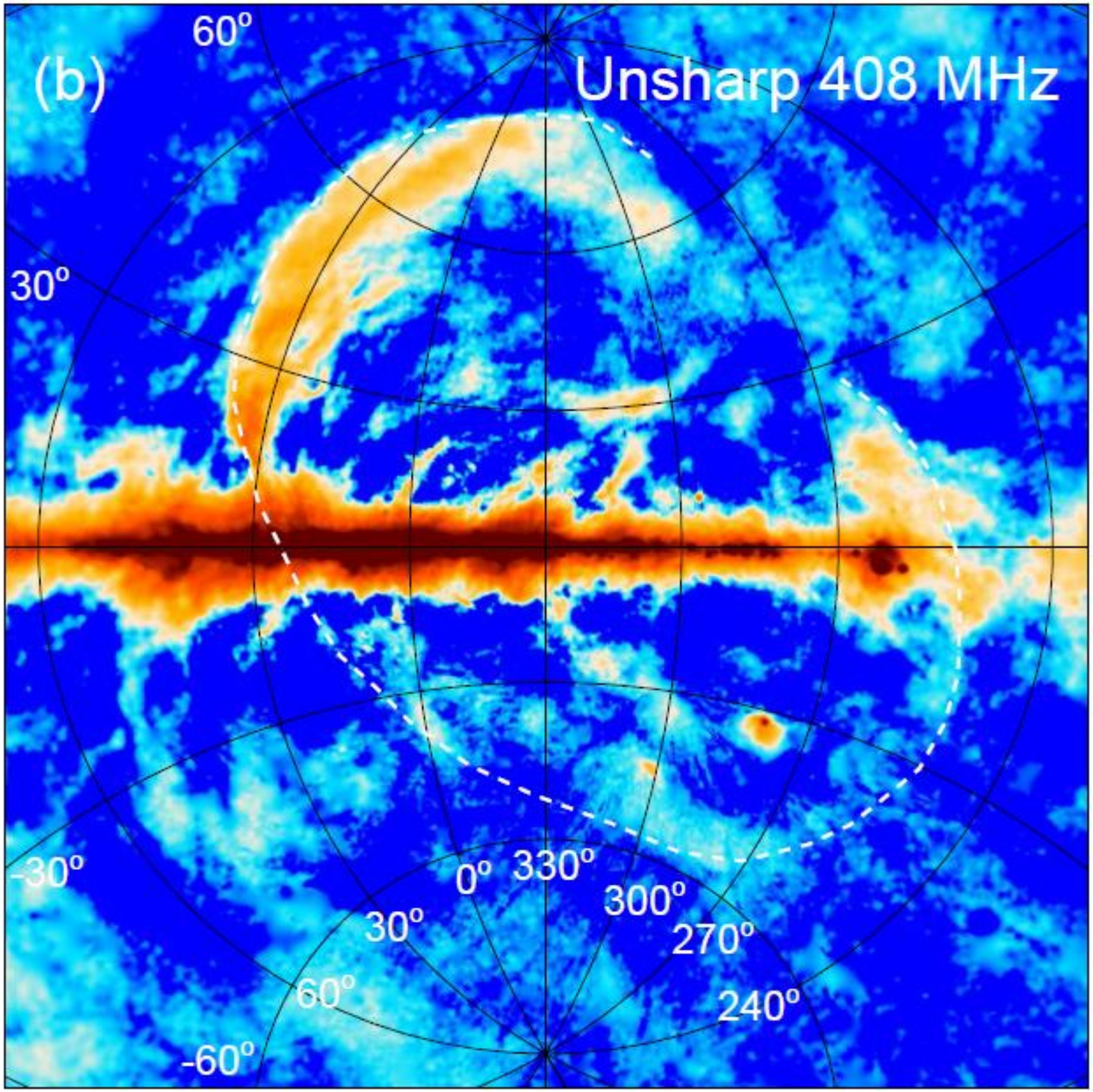
Loop I in perspective

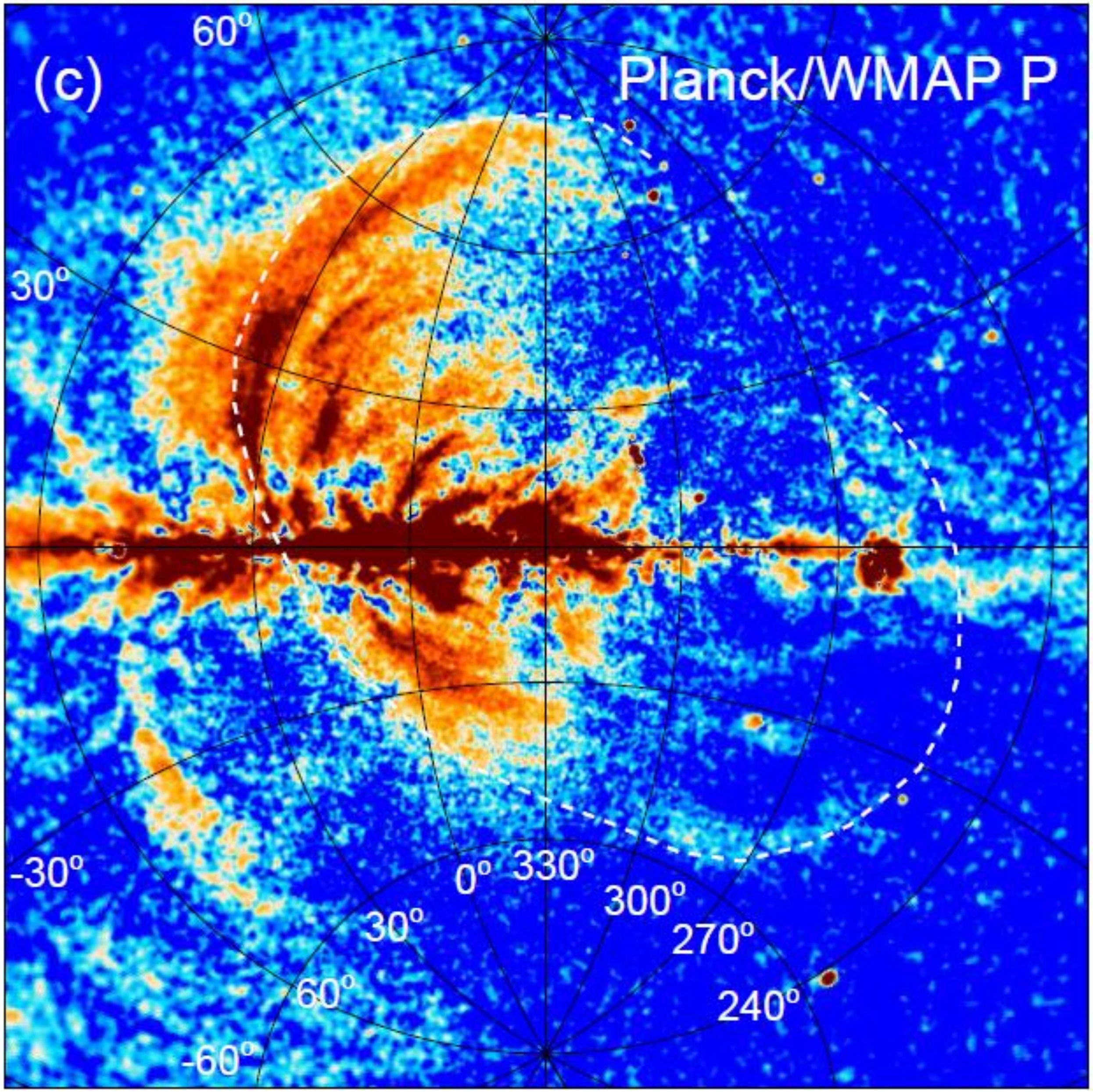
- Sun is near centre of irregular ~80 pc radius Local Cavity with very low density
- Dense gas in Local Cavity wall is seen in absorption, emission, starlight polarization in front of Loop I



- Huge "bite" out of the loop if D<300 pc !
- But does not affect projected outline?

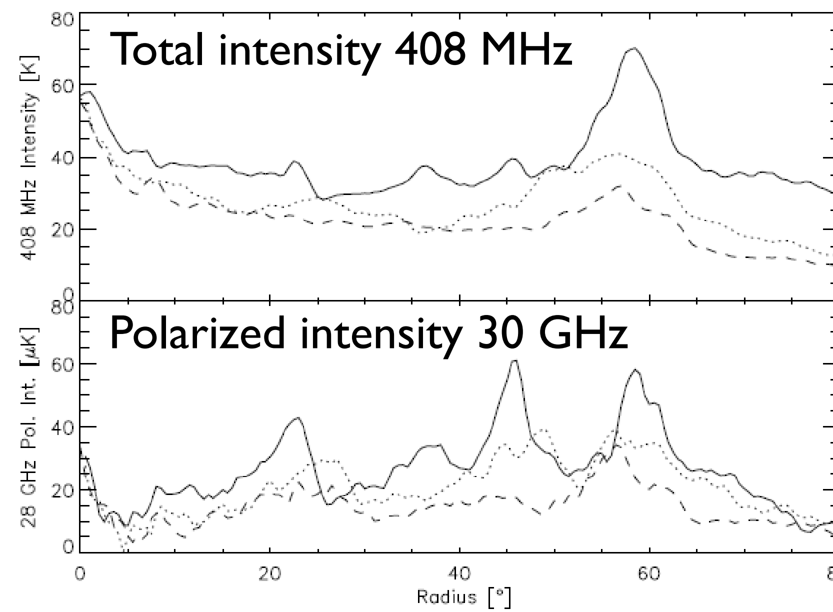

(a)
408 MHz
60°
30°
-30°
-60°
0°
330°
300°
270°
240°
30°
60°


(b)
Unsharp 408 MHz
60°
30°
-30°
-60°
0°
330°
300°
270°
240°
30°
60°


(c)
Planck/WMAP P
60°
30°
-30°
-60°
0°
330°
300°
270°
240°
30°
60°

Highly polarized internal filaments

- The internal filaments in Loop I are much more prominent in polarization than in total intensity.
- Fractional polarization seems to be much higher than outer ridge (NPS)
- Precise values uncertain as total synchrotron intensity is not accurately measured at 30 GHz.
- "Illuminated" field lines?
- Internal/reflected shocks?

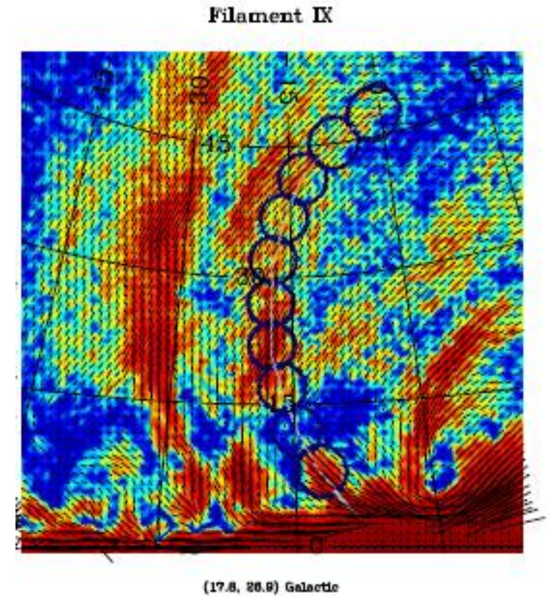


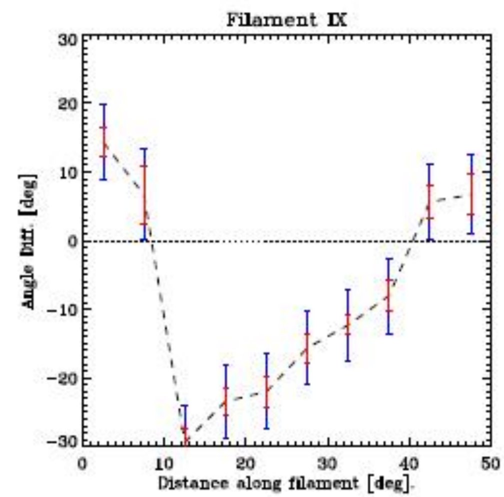
Profiles over 10°-wide sector

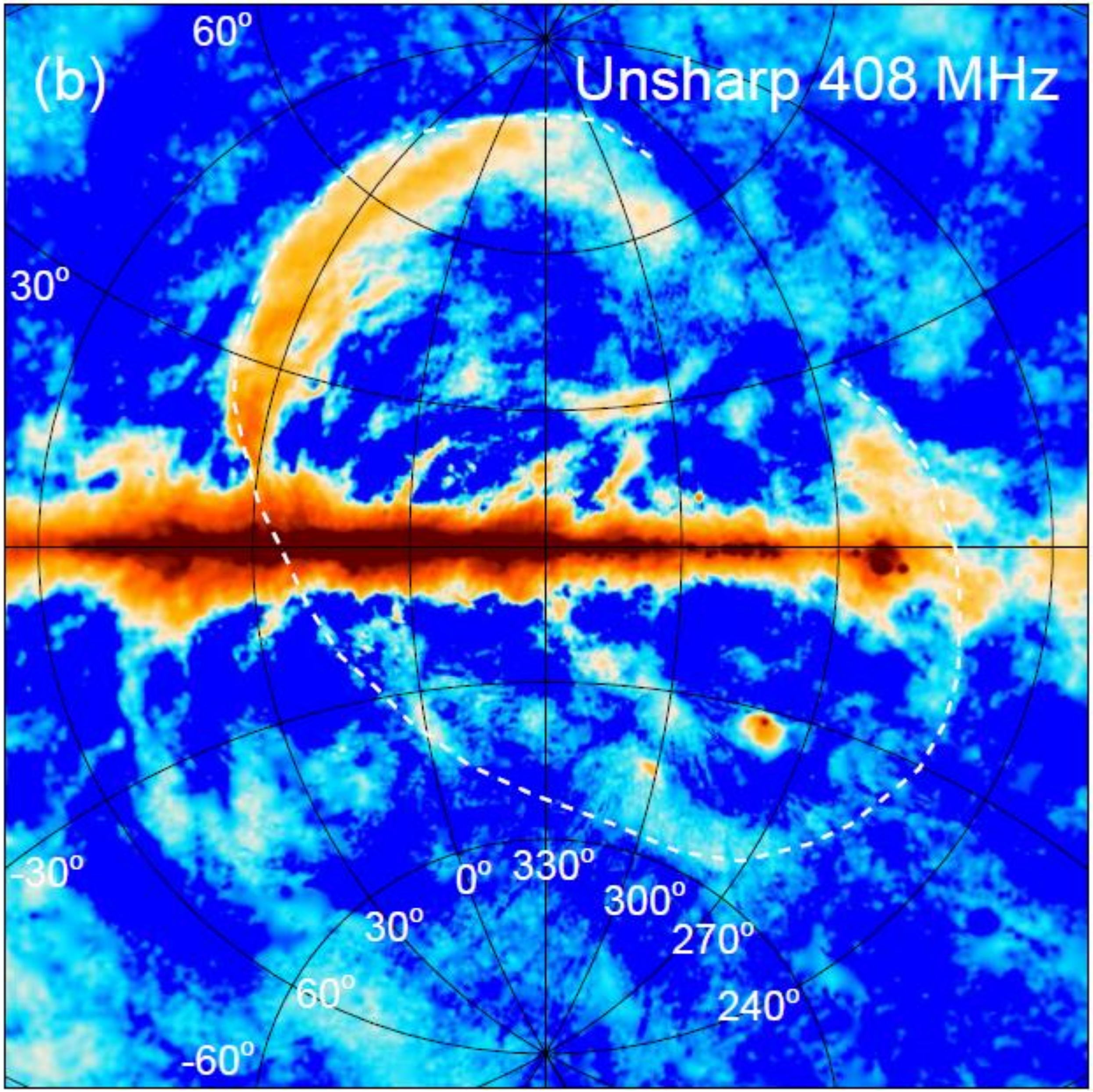
Solid: PA = 75°
Dashed: PA = 50°
Dotted: PA = 25°

Magnetic fields in the spurs

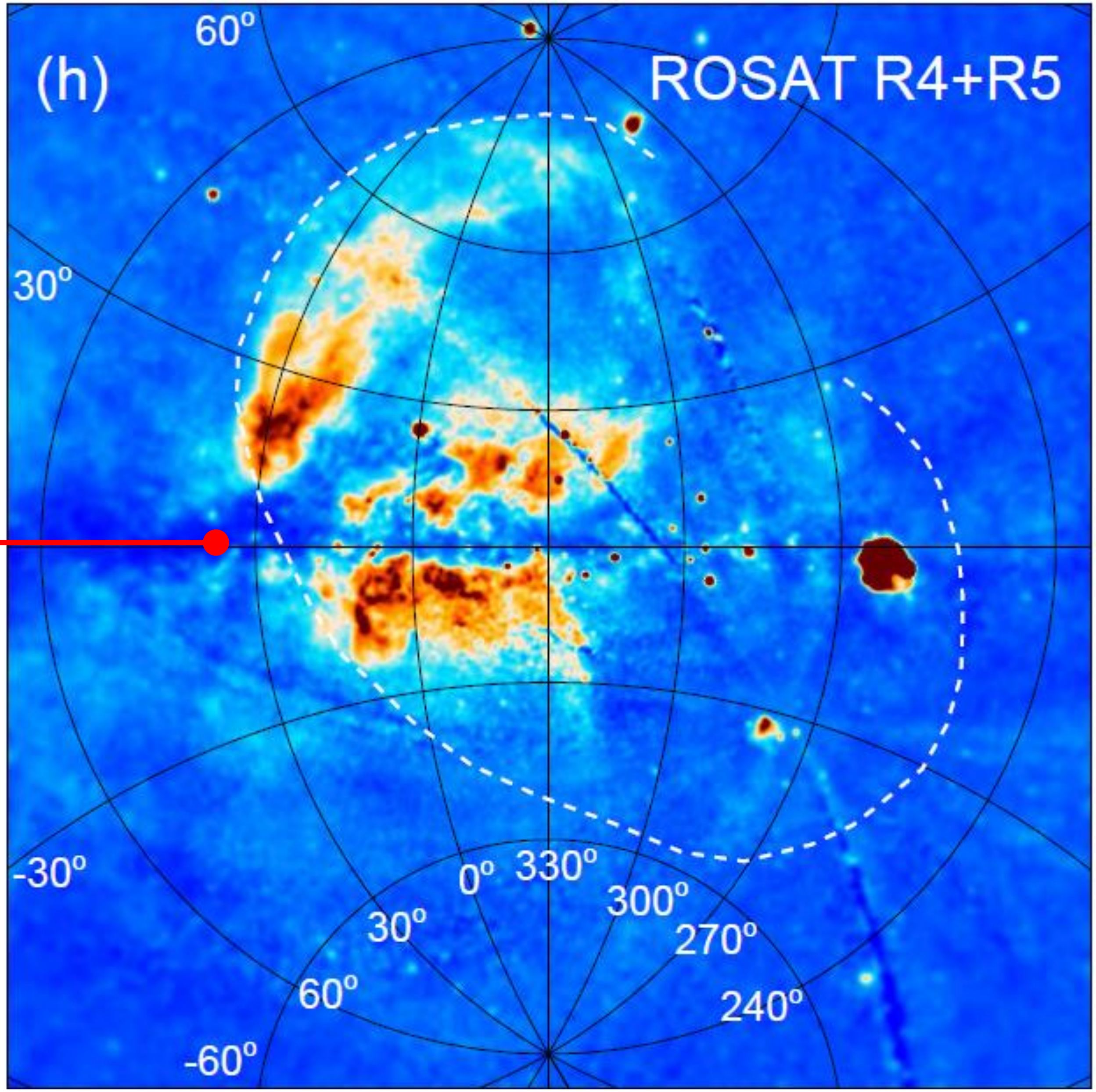
- Projected magnetic field mostly follows the ridge-line of the spurs.
- Not always, especially in centre of loop I
  - Vidal et al 2015 WMAP data.

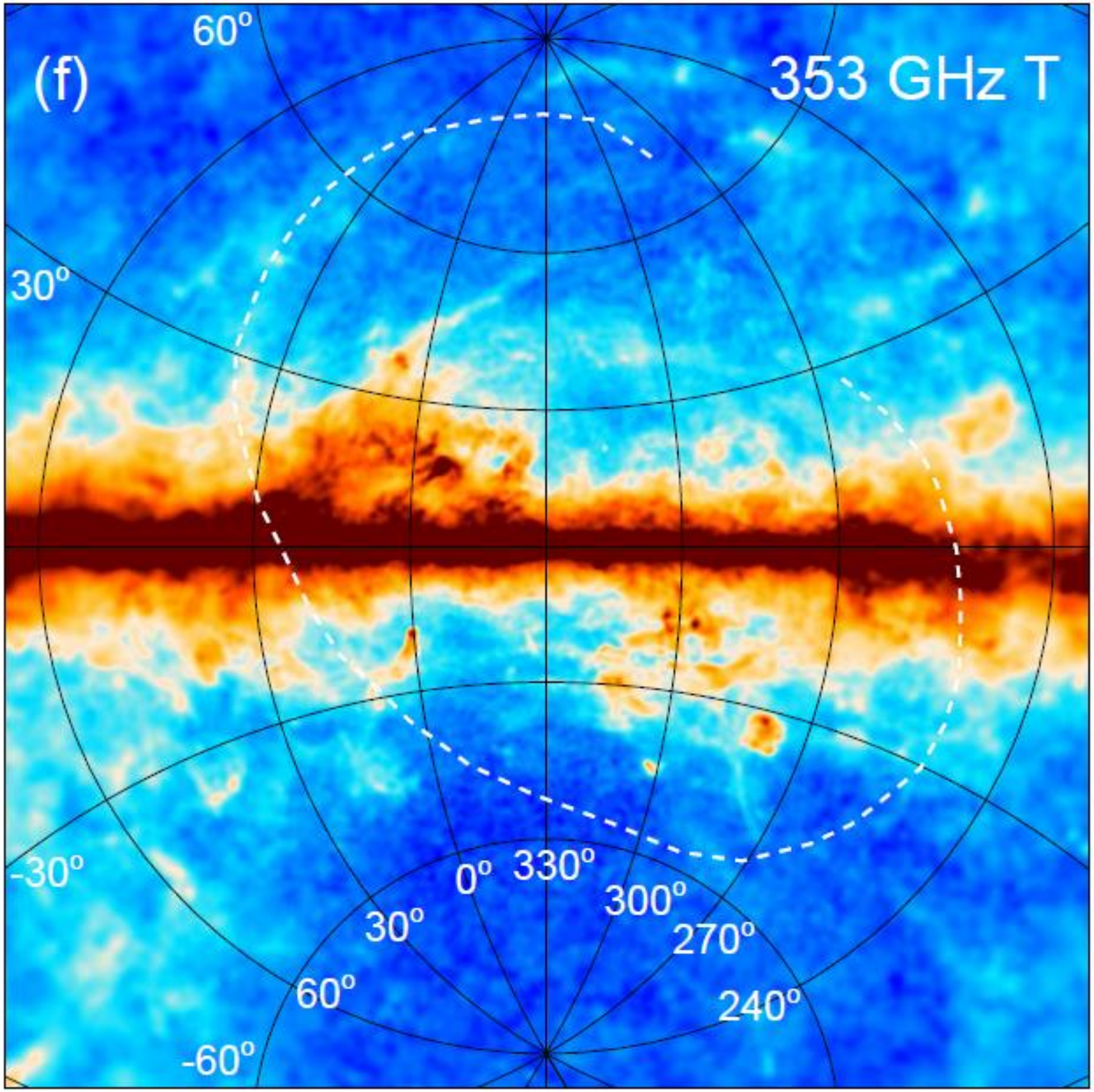





(b)
Unsharp 408 MHz
60°
30°
-30°
-60°
0°
330°
300°
270°
240°
30°
60°

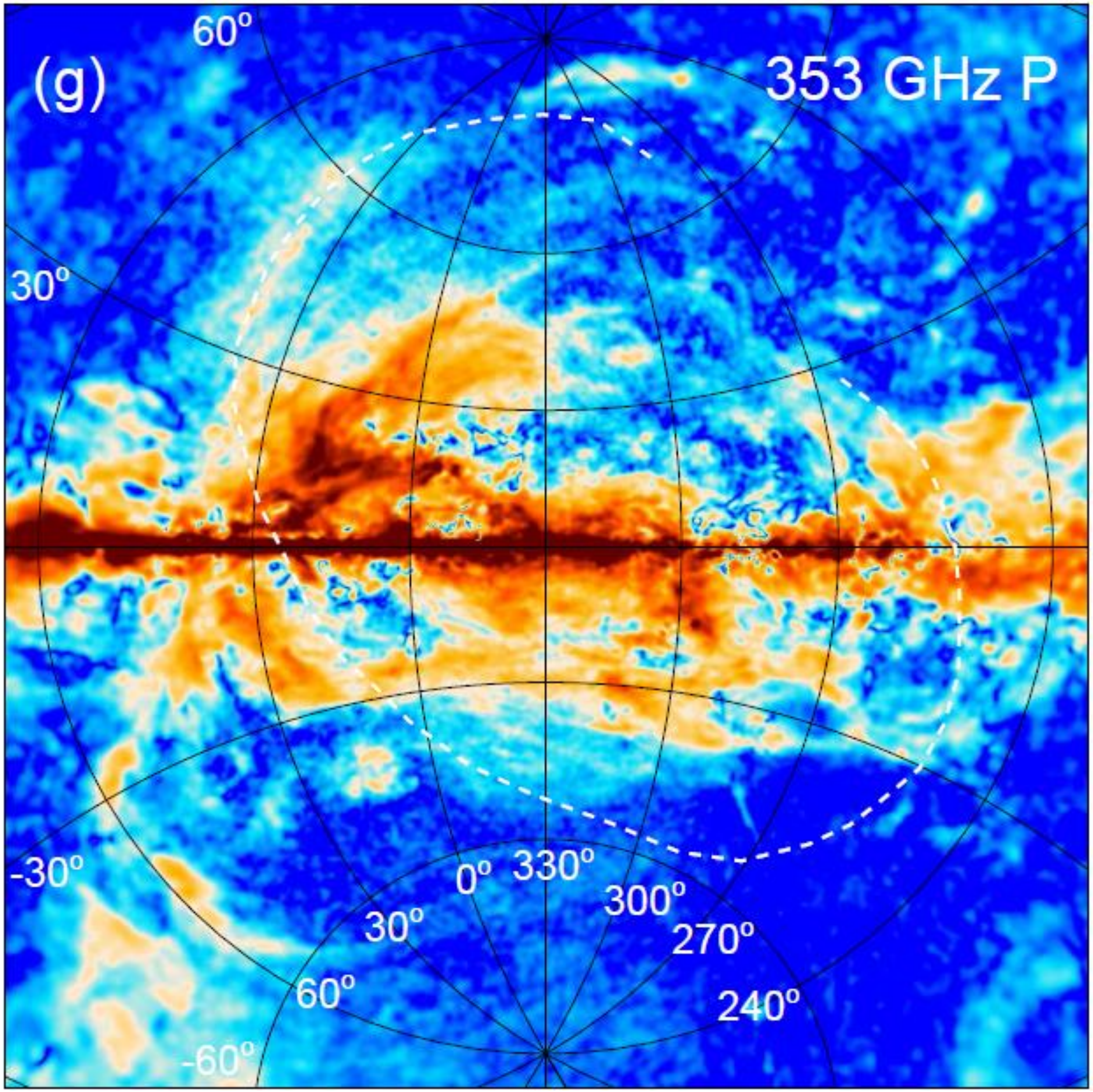
Aquila Rift




(f)
353 GHz T
60°
30°
-30°
-60°
0°
330°
300°
270°
240°
30°
60°

Radio-X-ray alignment

- Close match between border of radio and X-ray versions of the North Polar Spur
- X-rays are thermal, $T = 3\ 10^6$ K
- X-rays show absorption by intervening material
- Distribution of denser gas in local neighbourhood is mapped using extinction and absorption lines to nearby stars.
- To get enough absorption, distance D > 200 pc
  - Puspitarini et al 2014, Sofue 2015


(g)
353 GHz P
60°
30°
-30°
-60°
0°
330°
300°
270°
240°
30°
60°

Dust and starlight polarization

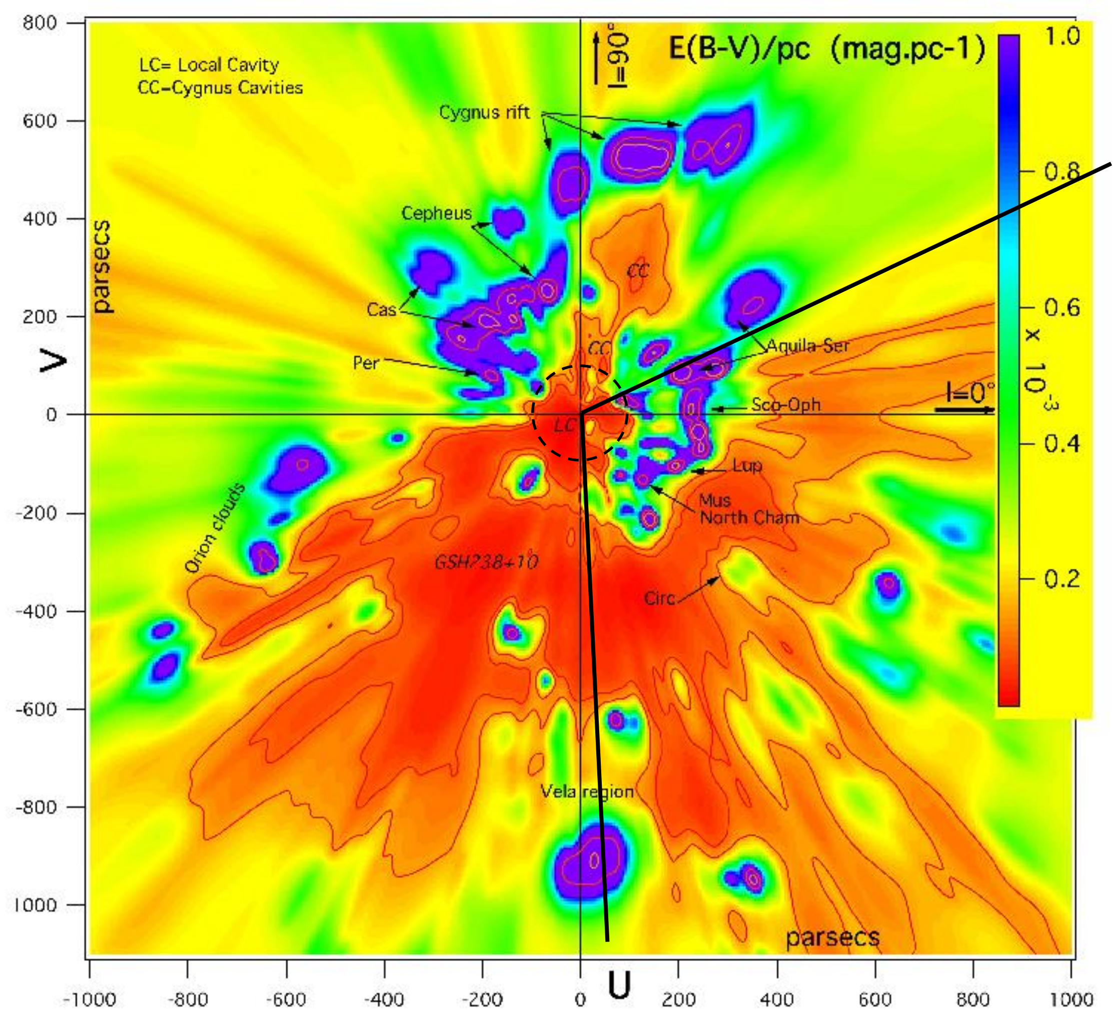
- Dust polarization seen in emission by *Planck* matches starlight polarization (e.g. Santos et al 2011) caused by dichroic extinction
- *HIPPARCOS* distances shows absorption starts at about 80 pc
  - Lower limit to distance to Loop
  - Consistent with edge of local bubble
  - Matches HI at v_{LSR}= 0–10 km/s
- Cold gas in border expanding at < 25 km/s

The local neighbourhood

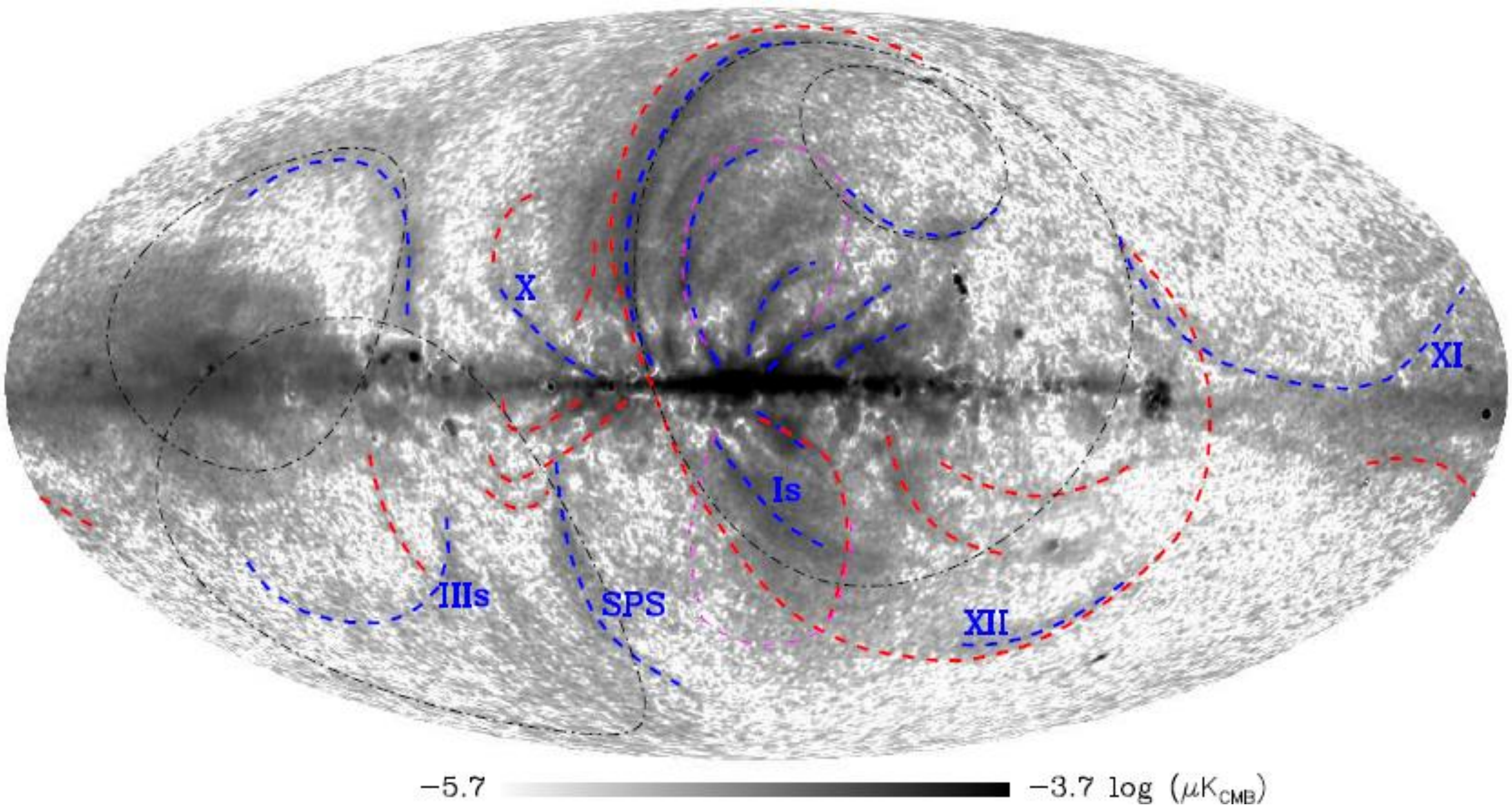
Density of ISM as measured using extinction towards stars within 1 kpc

Distance: *HIPPARCOS* (2007) or photometric

- Lallement et al 2014

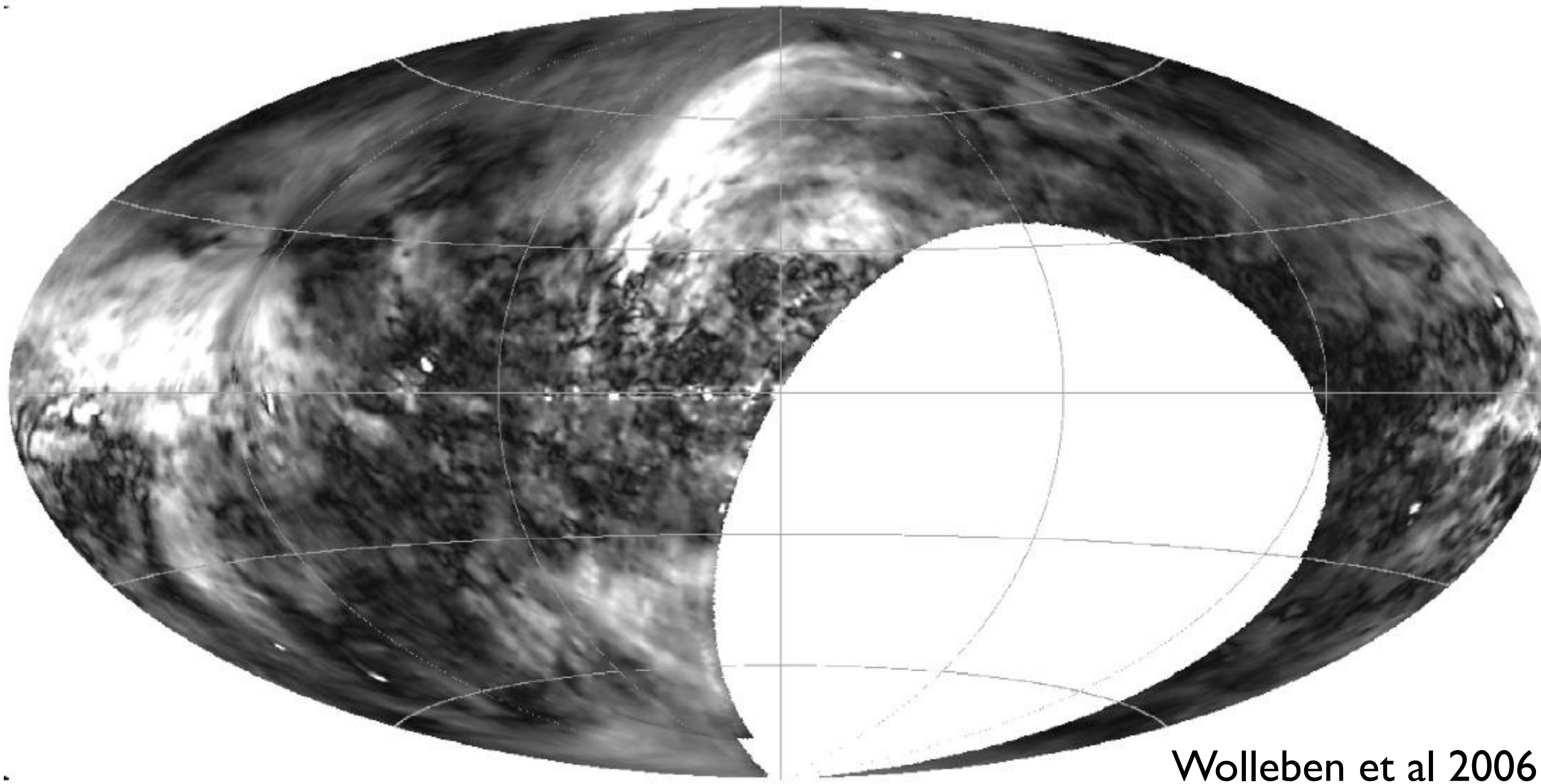


The Polarized sky at 1 cm



Planck+WMAP polarized intensity at 28.4 GHz
(log transfer)

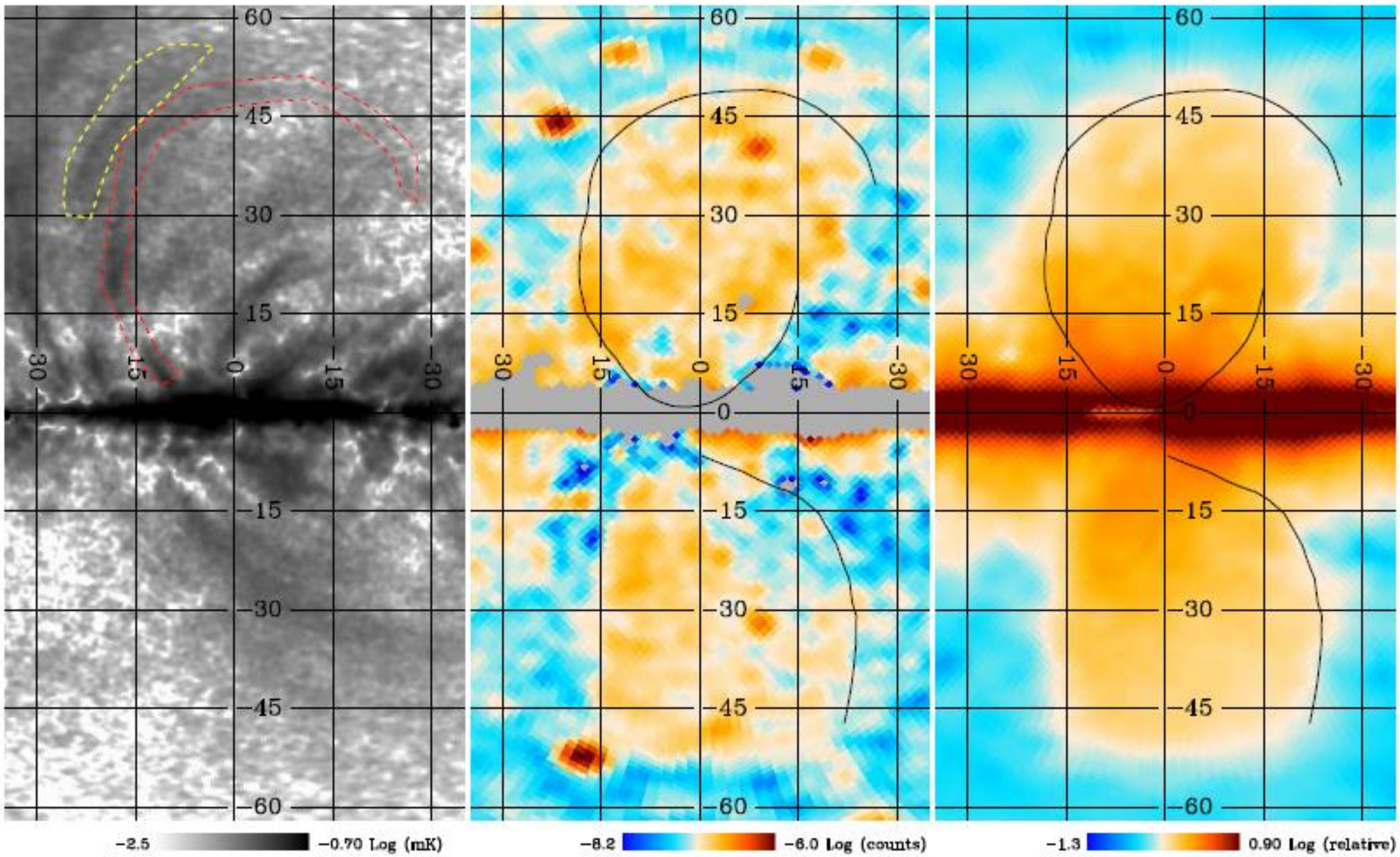
1.4 GHz DRAO Polarization Survey



Wolleben et al 2006

- Low latitudes towards Loop I depolarized
- For 1–2 kpc scale height of WIM implies D >> 150 pc

The Fermi Bubbles

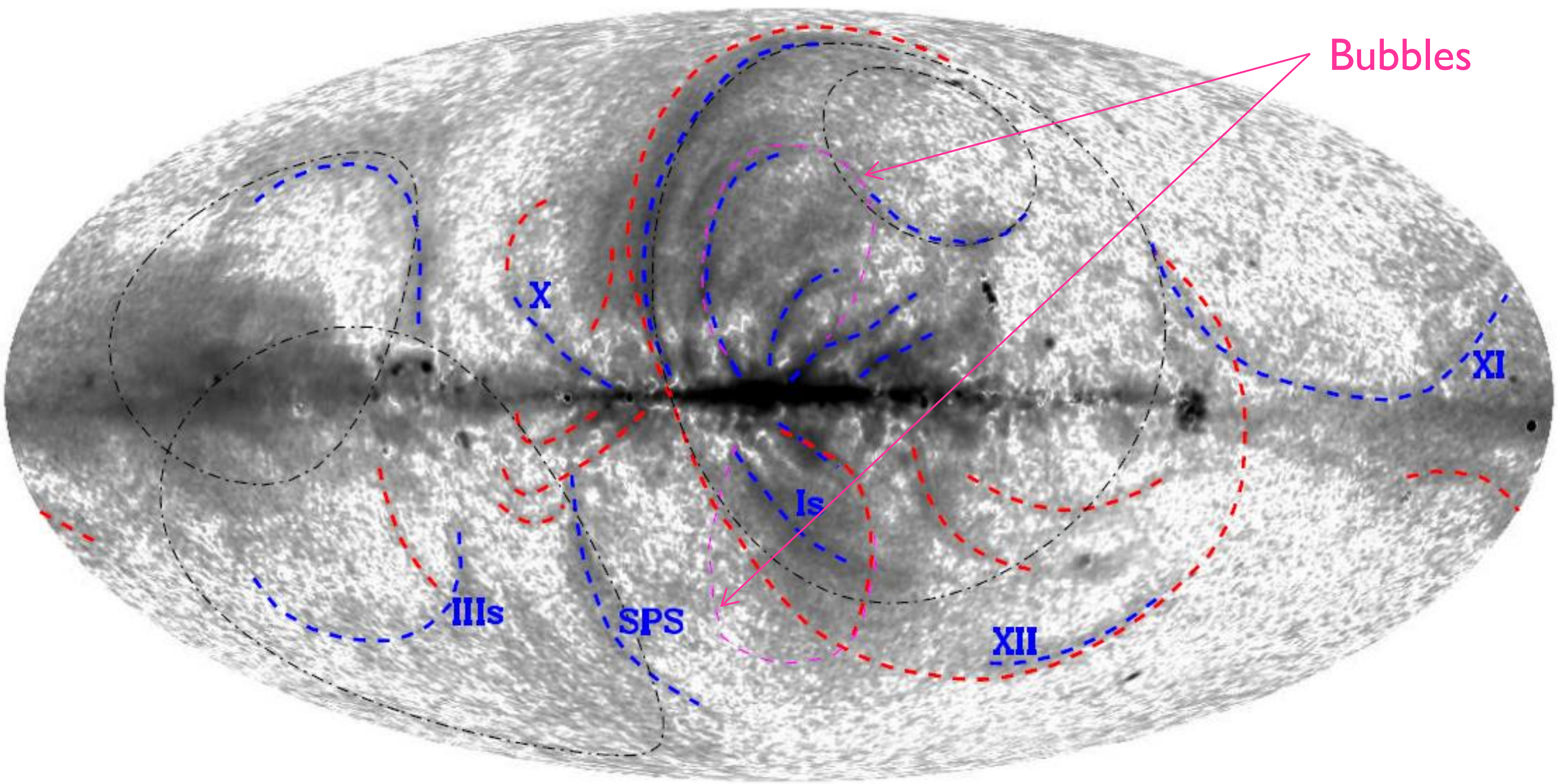


Planck+WMAP Pol

10-500 GeV Fermi data Corrected for π^0 decay

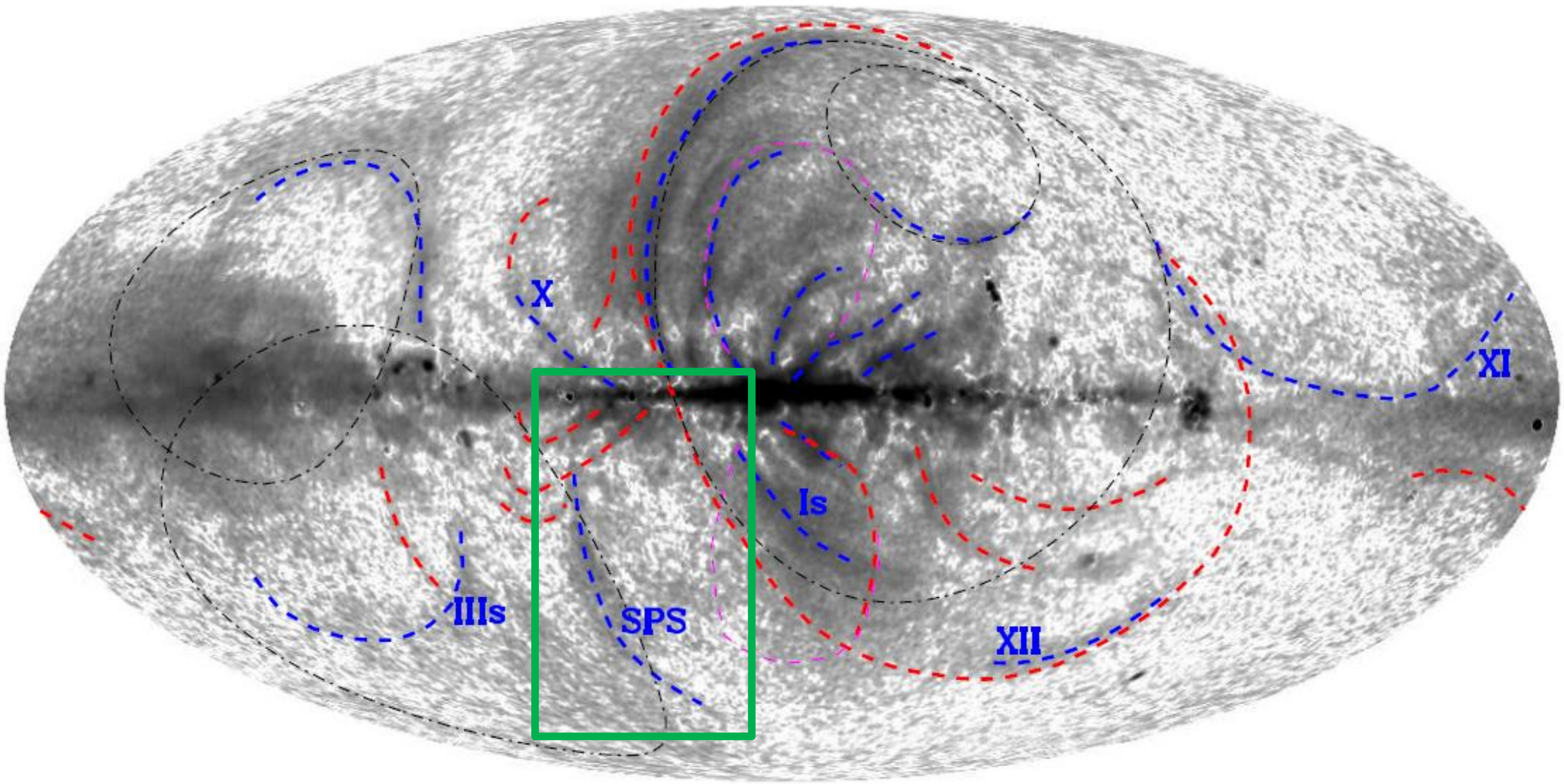
Fermi data processed by Selig et al 2014

Fermi Bubbles vs Loop I



- Southern bubble extends outside Loop I
- Bubbles centred on SgrA, loop centre is far offset
- Therefore no connection: Loop I is superposed in foreground

South Polar Spur



South Polar Spur

Alias:

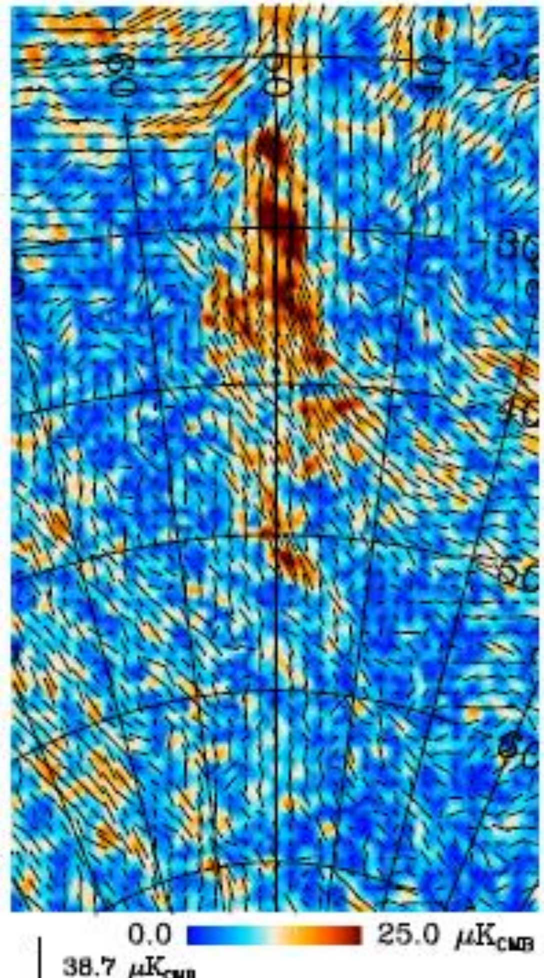
~~Part of Loop II~~

~~Part of Wolleben's S1~~

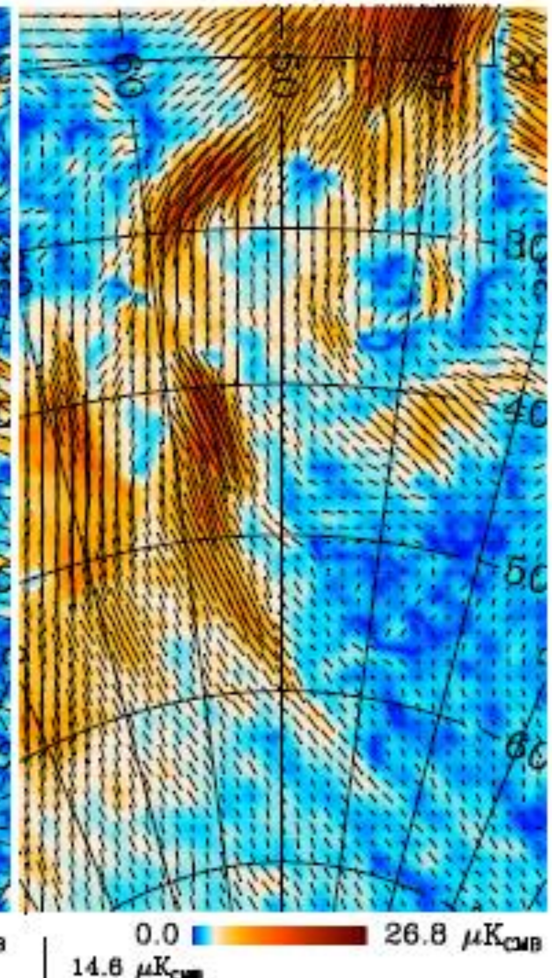
Filament VIIb

Discovered:

Large, Quigley & Haslam 1962 (?)



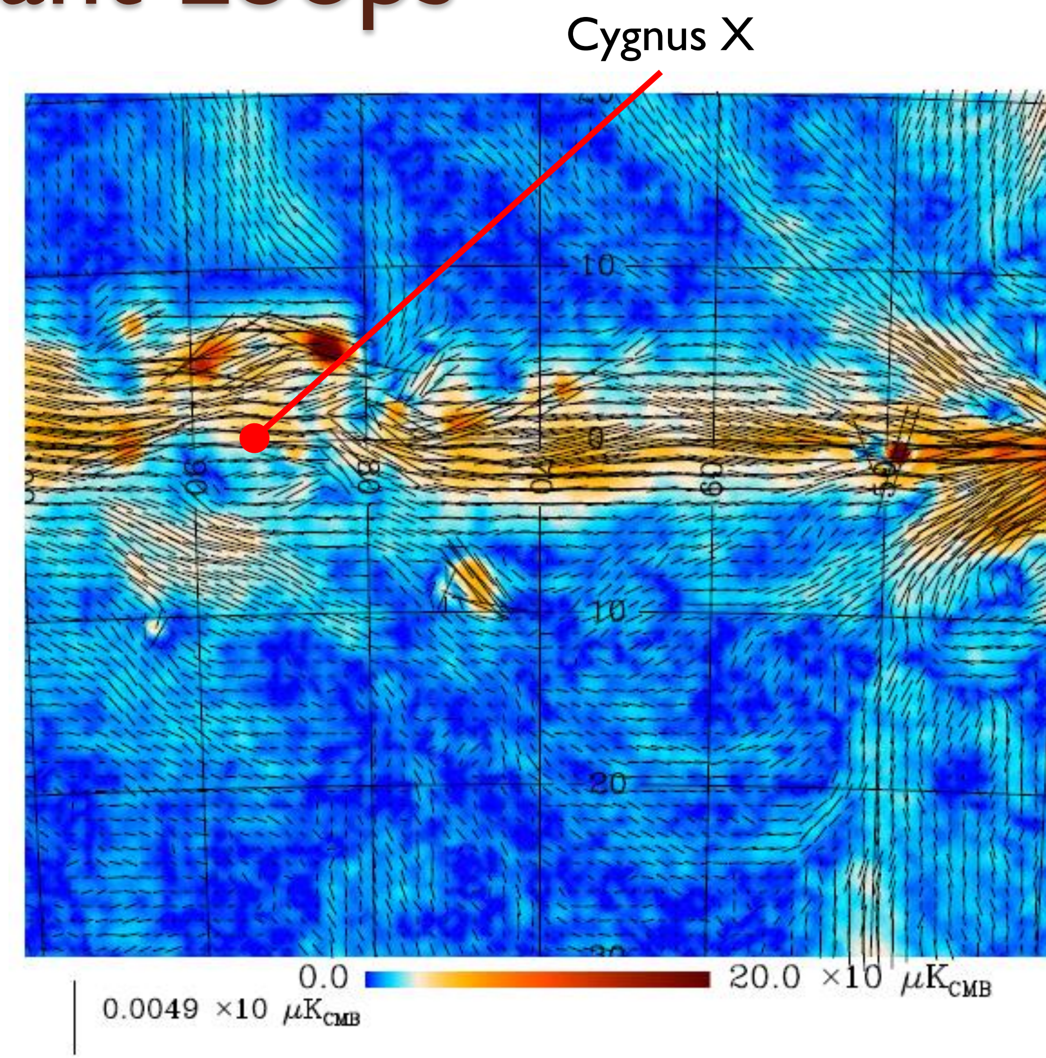
Planck-WMAP Pol



Planck 545 GHz Dust

More Distant Loops

- Should be smaller & closer to the plane (Mertsch & Sarkar 2013)
- Two examples in this field, one around Cyg X star-forming region



Conclusions 2: Loops

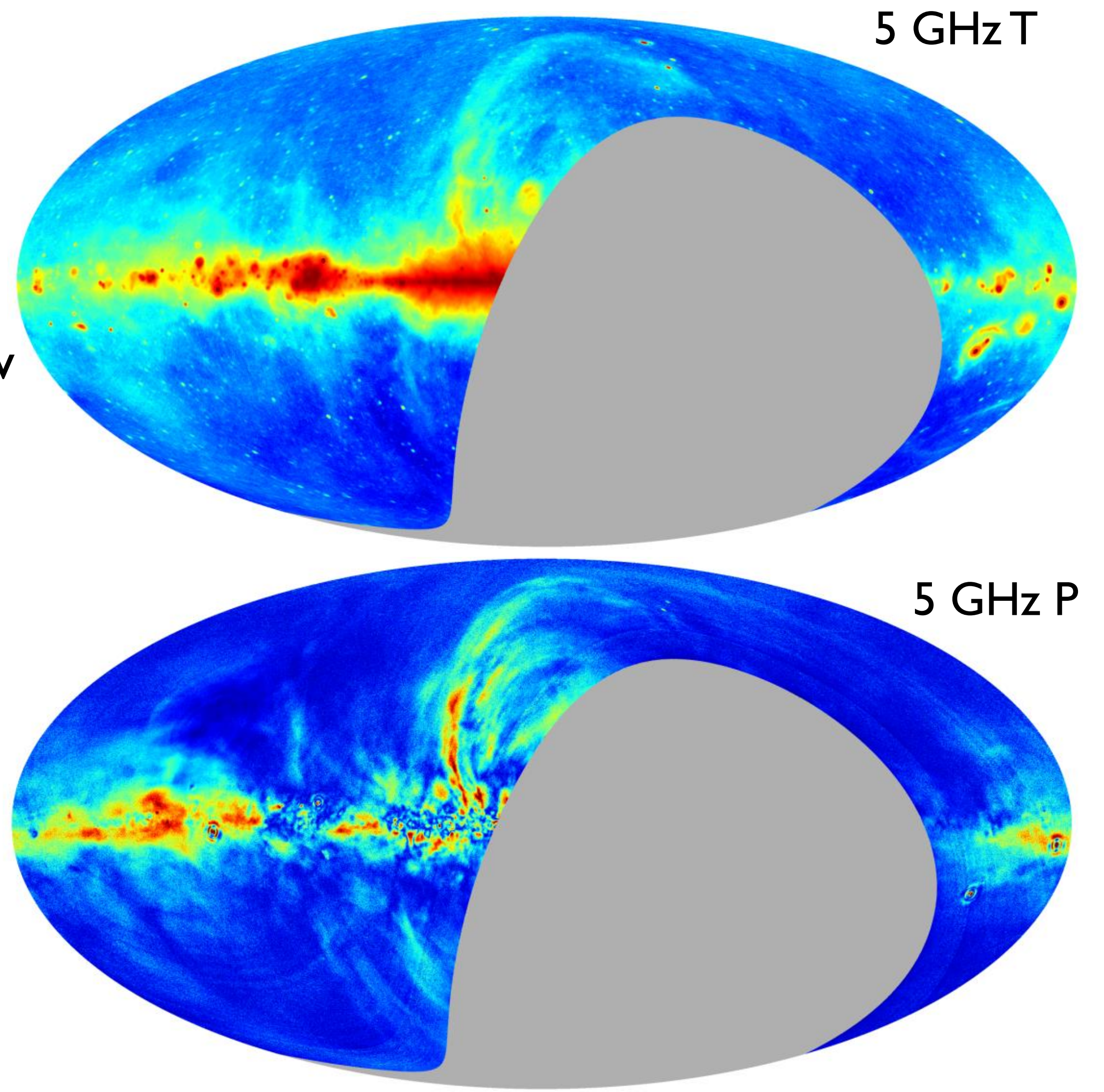
- Non-circular outlines
- Loop I is not at the Galactic centre, but is too distant to be due to the Sco-Cen OB association
- Field lines run approximately parallel to ridges.
- Multiple internal filaments suggest reflected shock waves, supporting re-energised cavity model.
- Alternatively, filaments may be illuminated flux ropes stretched out by expansion of the cavity (Vidal et al)
- Narrow polarized synchrotron border around *Fermi* bubbles
- New examples of spurs with associated dust borders
- New, distant loops including one around Cyg X

Future prospects

- Measurements of the low-frequency turnover of AME will allow much better separation from free-free and synchrotron
- Since turnover mostly around 20 GHz, need data at lower frequencies:
  - QUIJOTE (10-18 GHz) covers much of northern sky
  - C-BASS (5 GHz) covers full sky at frequency where AME should mostly be negligible $\rightarrow$ pure synchrotron + free-free
  - S-PASS (2.3 GHz) covers southern hemisphere with higher sensitivity & resolution than C-BASS
  - GMIMS (300–1800 MHz) will help pin down synchrotron spectral index & curvature.
- All these surveys include linear polarization. S-PASS & GMIMS affected by Faraday rotation at intermediate latitudes – bonus tracer!
- We need a blind Galactic plane survey across the CMB band to quantify line contamination.

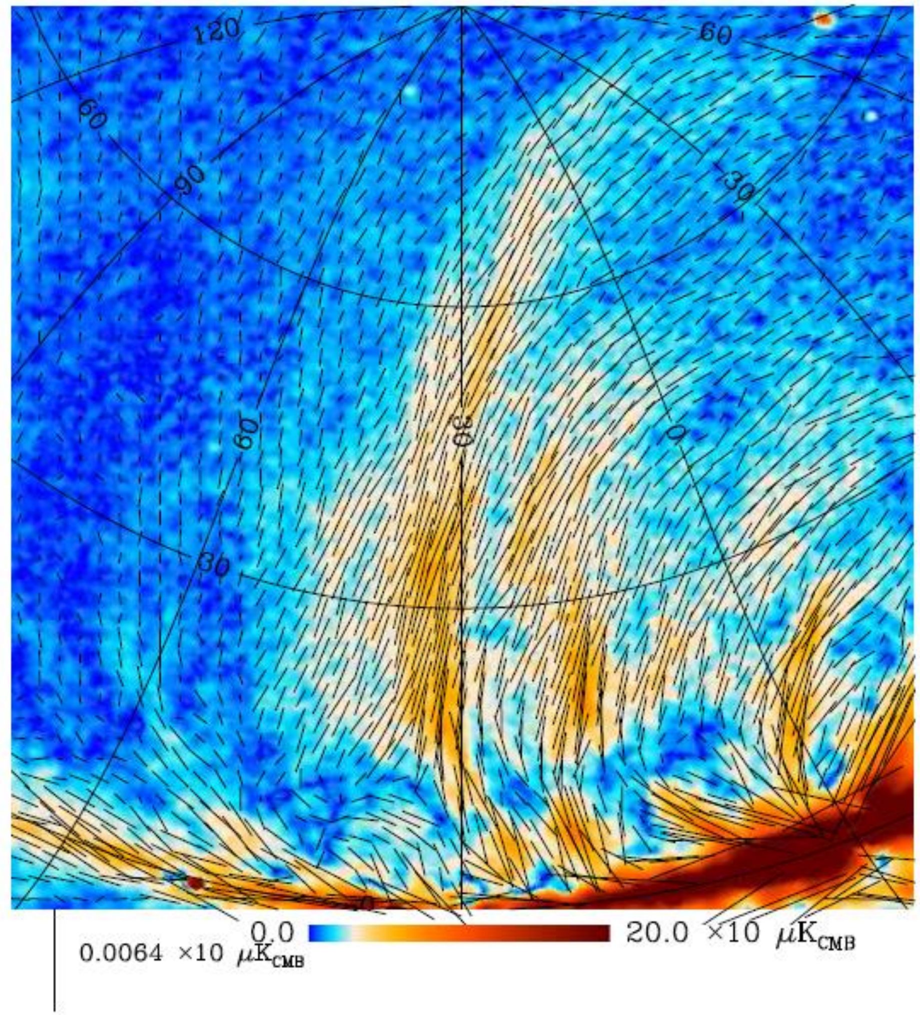
Coming attractions…

- Preliminary maps from C-BASS North
- Northern observations now complete, observations in South (SKA site) about to start.
- See poster FM5p.31for QUIJOTE!



Field outside the North Polar Spur

- Field pattern follows the arc of the spur, even beyond region occupied by cold border
- Consistent with model of Spoelstra 1972 that ambient field helps shape the structure & explains why the NPS is much brighter than rest of loop.



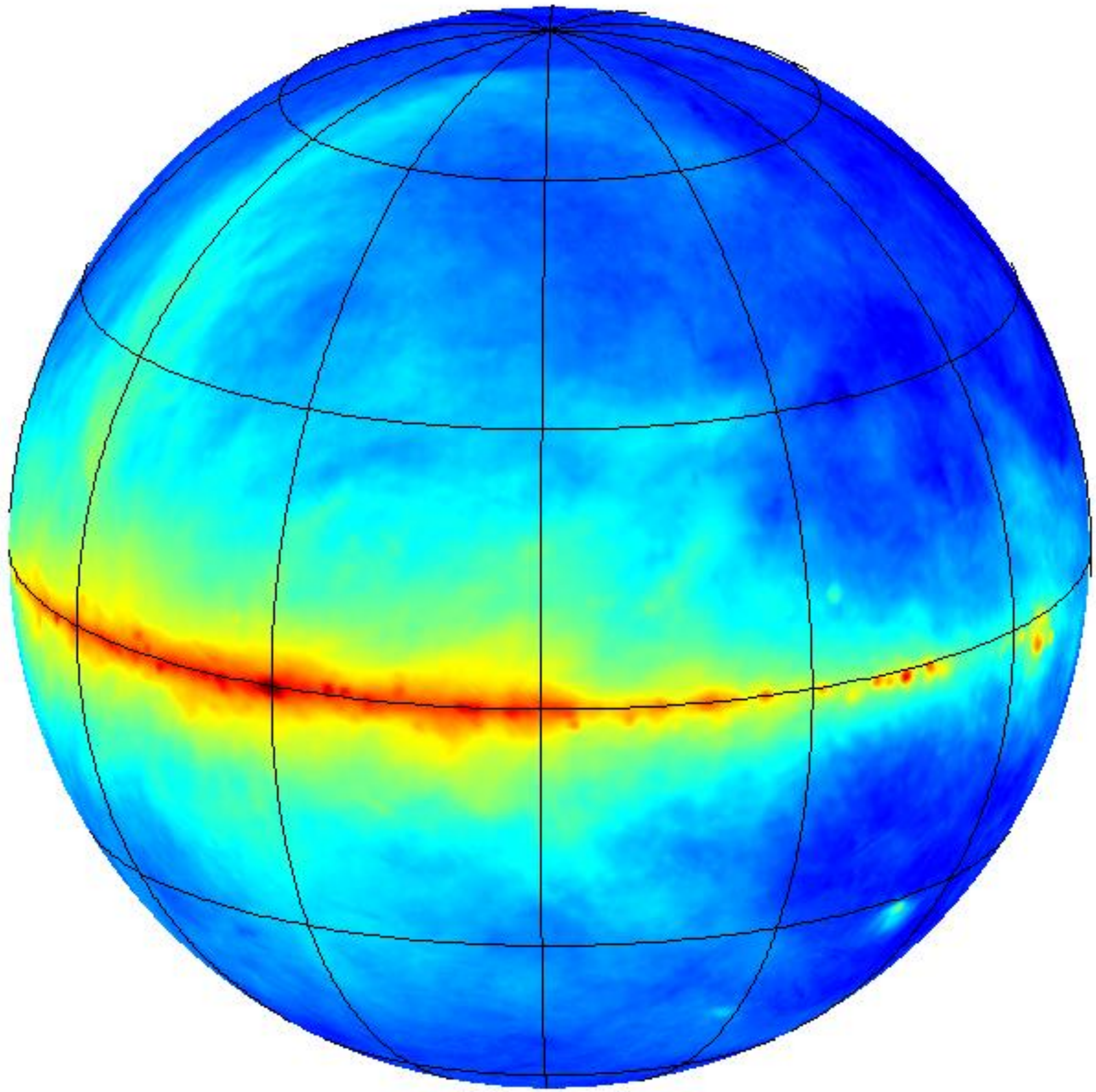
Loop I

408 MHz all-sky survey of Halsam et al 1981

reprocessed by Remazeilles et al 2015 to remove instrumental striping and destriping and extragalactic sources.

56′ FWHM

Asinh transfer function.



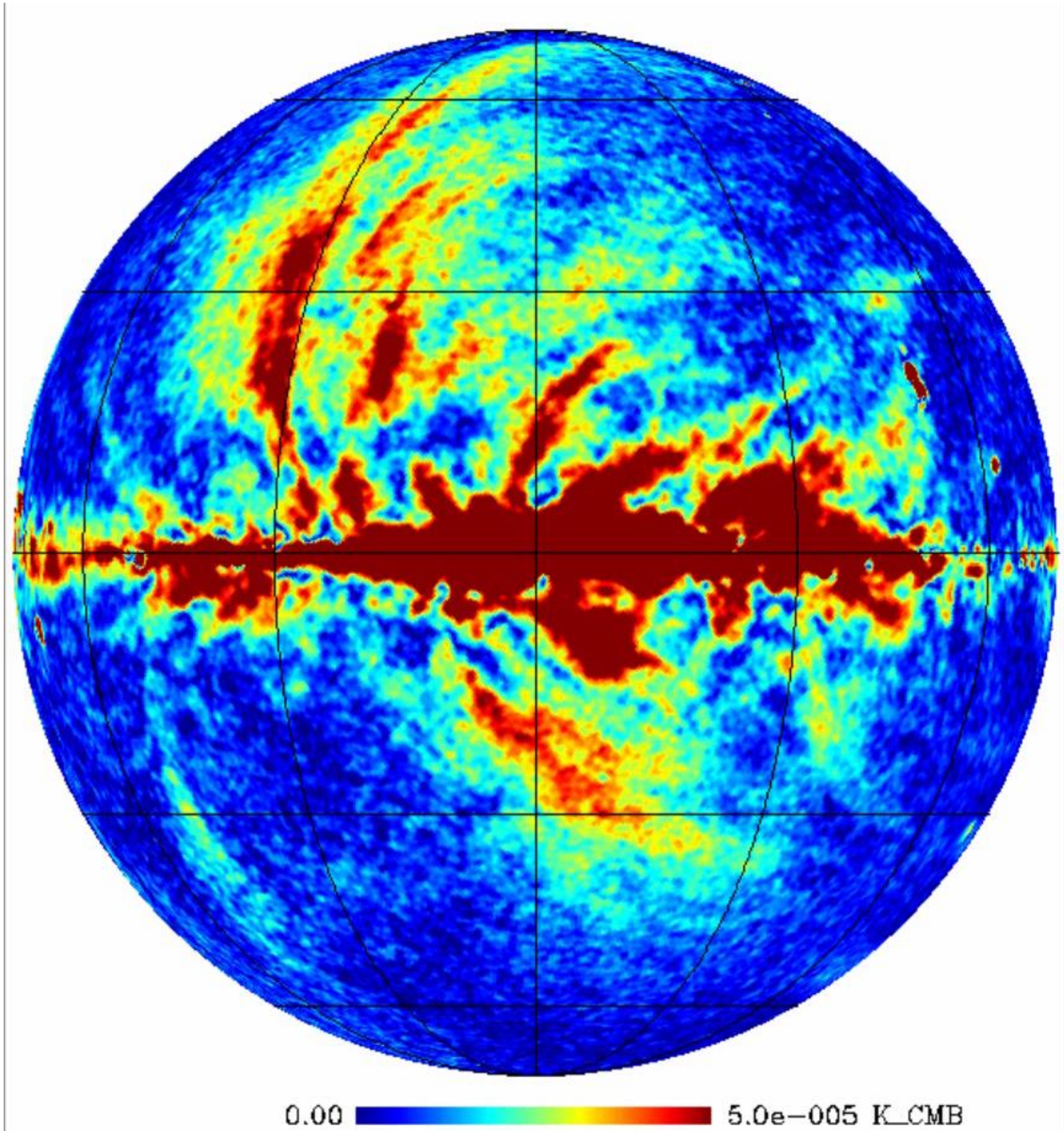
Loop I

408 MHz all-sky survey of Halsam et al 1981

reprocessed by Remazeilles et al 2015 to remove instrumental striping and destriping and extragalactic sources.

56′ FWHM

Asinh transfer function.



Loop I

Alias:

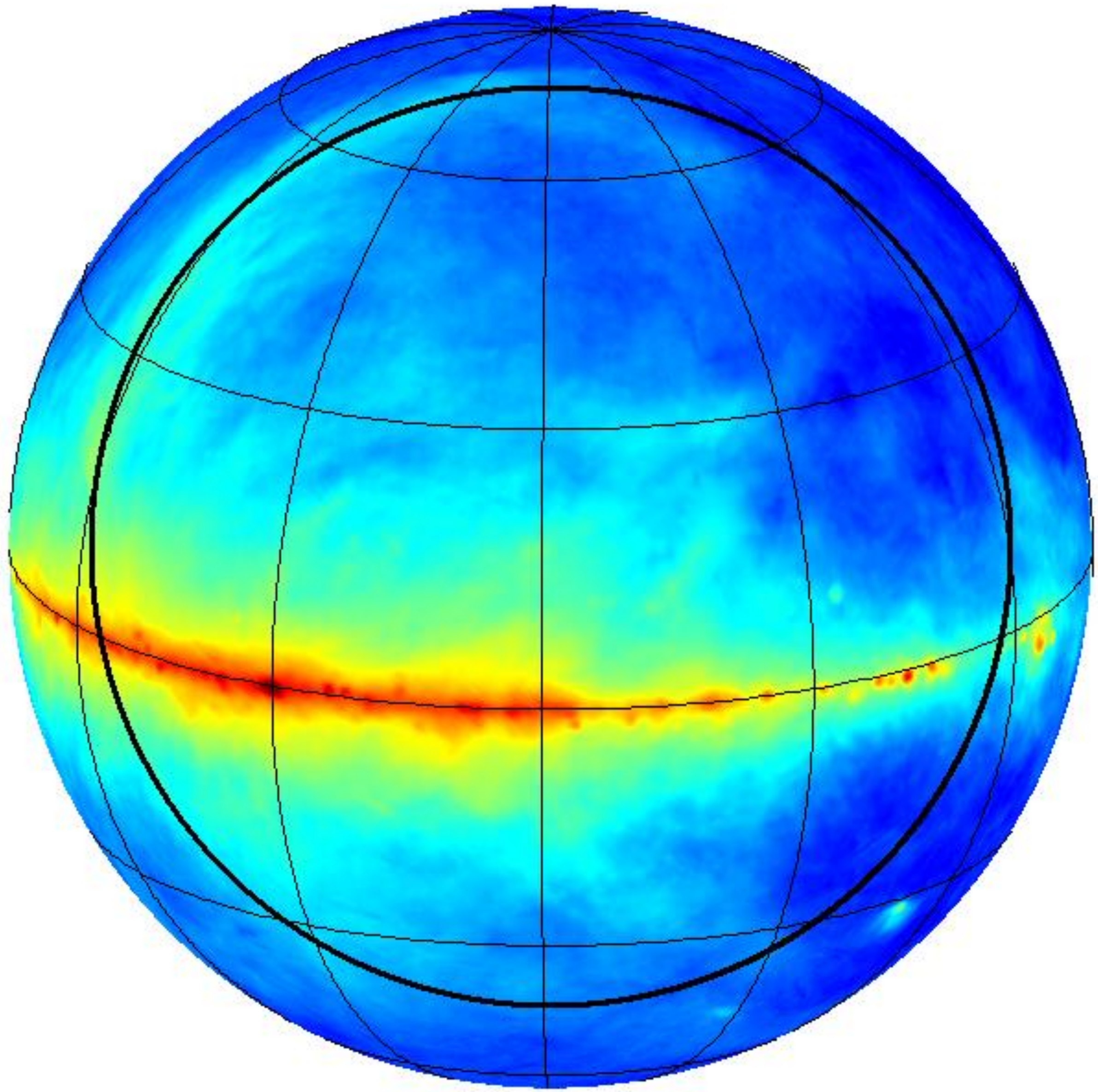
North Polar Spur

Discovered: Bolton & Westfold1950

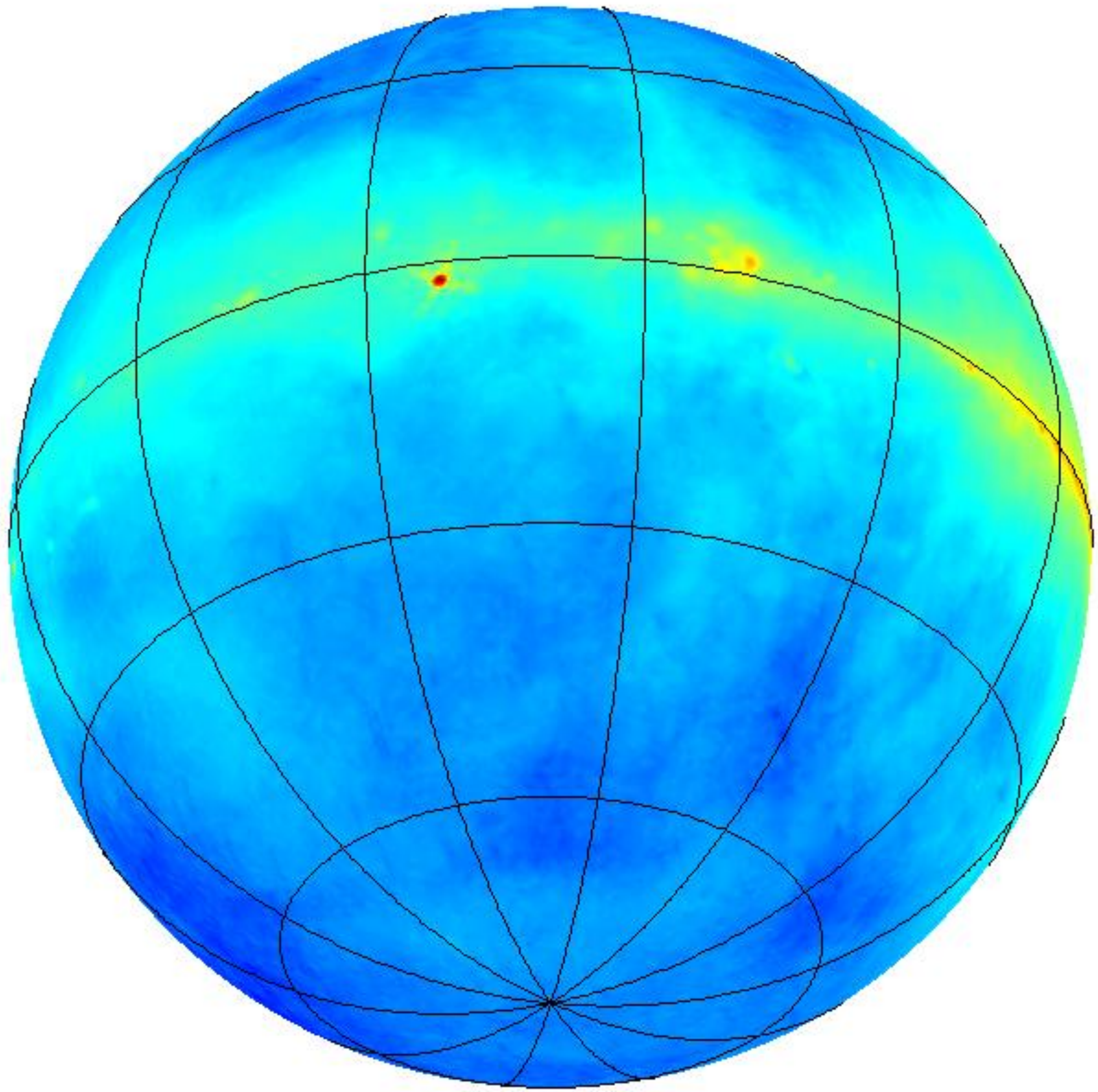
Visible in Jansky's 1935 data – Sullivan 1978

Diameter: 116°

Centre (*l*,*b*): (329, 17.5)



Loop II



Loop II

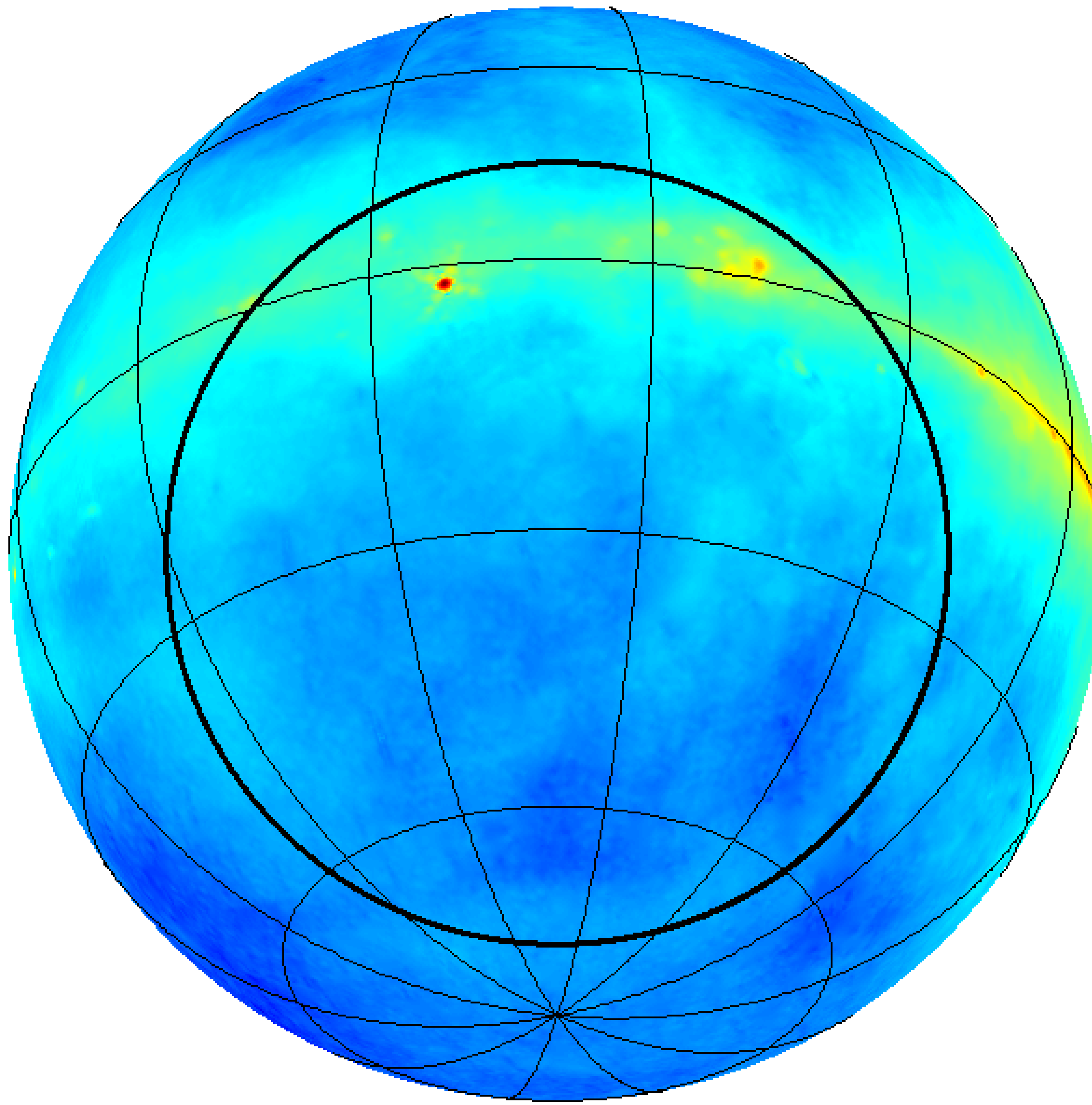
Alias:

Cetus Arc

Discovered: Large, Haslam & Quigley 1962

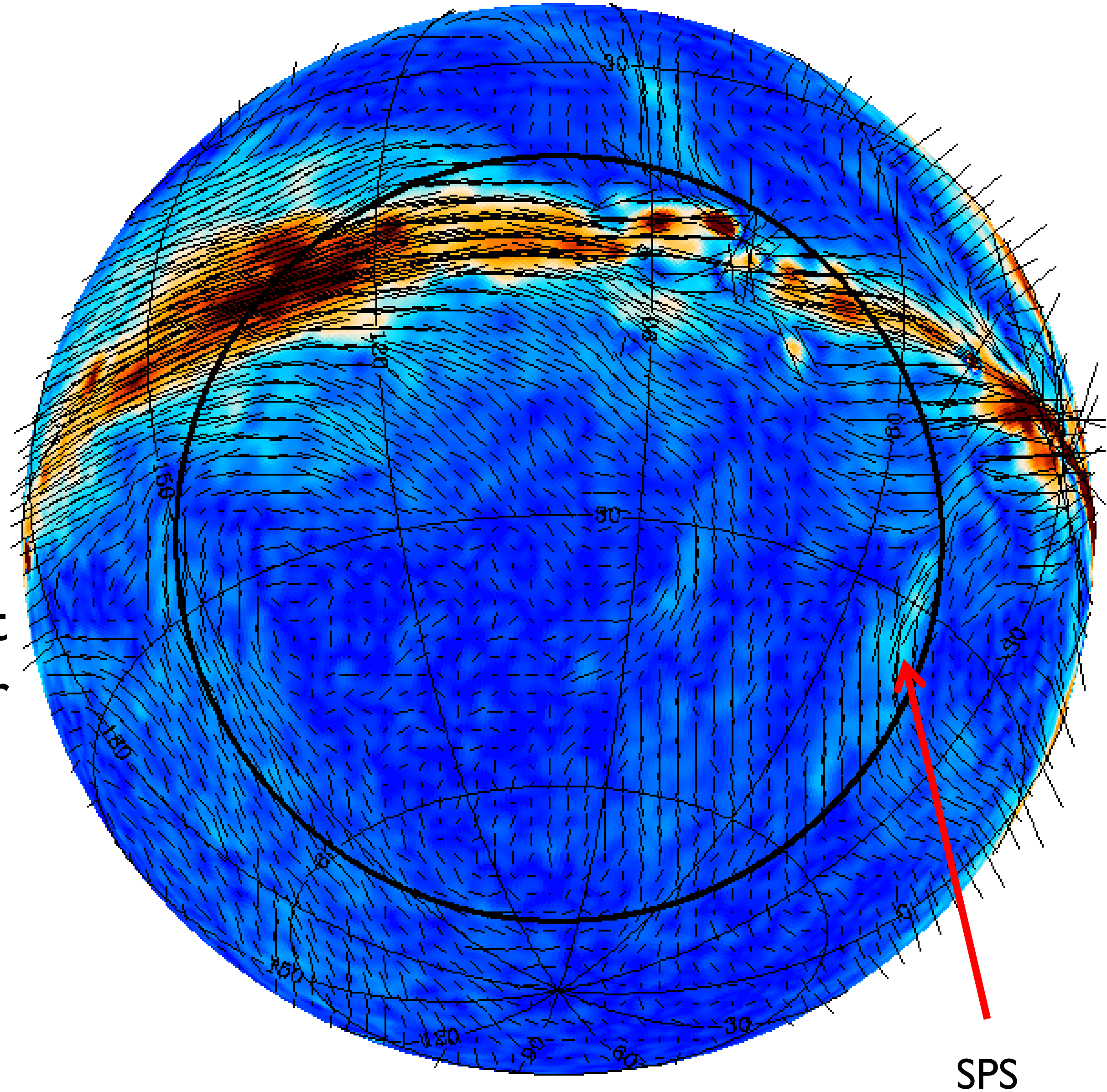
Diameter: 91°

Centre (*l*,*b*): (100, -32.5)

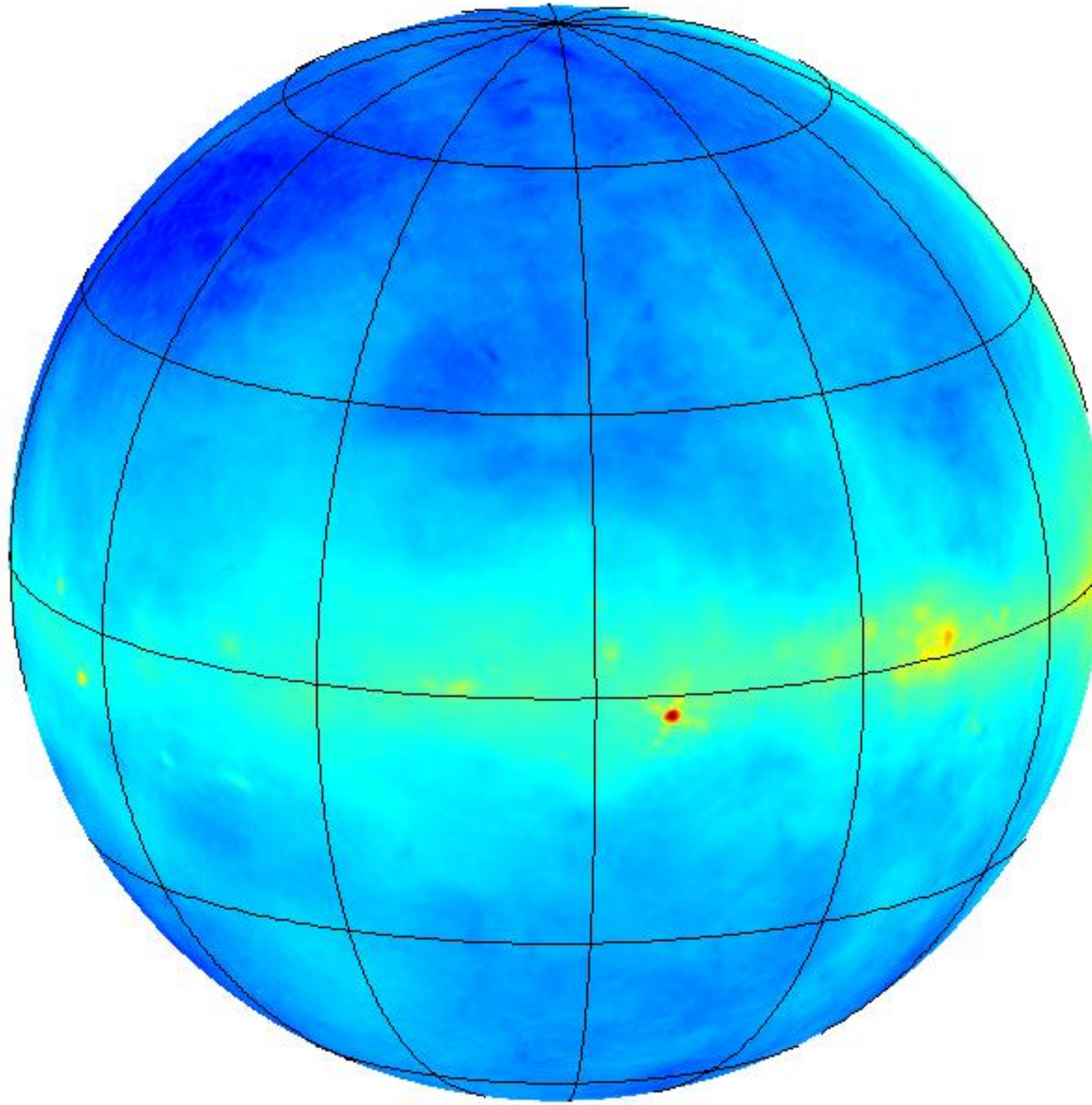


Loop II

- Planck 30 GHz polarized brightness & direction
- 2° FWHM
- South Polar Spur is not part of it… see later



Loop III



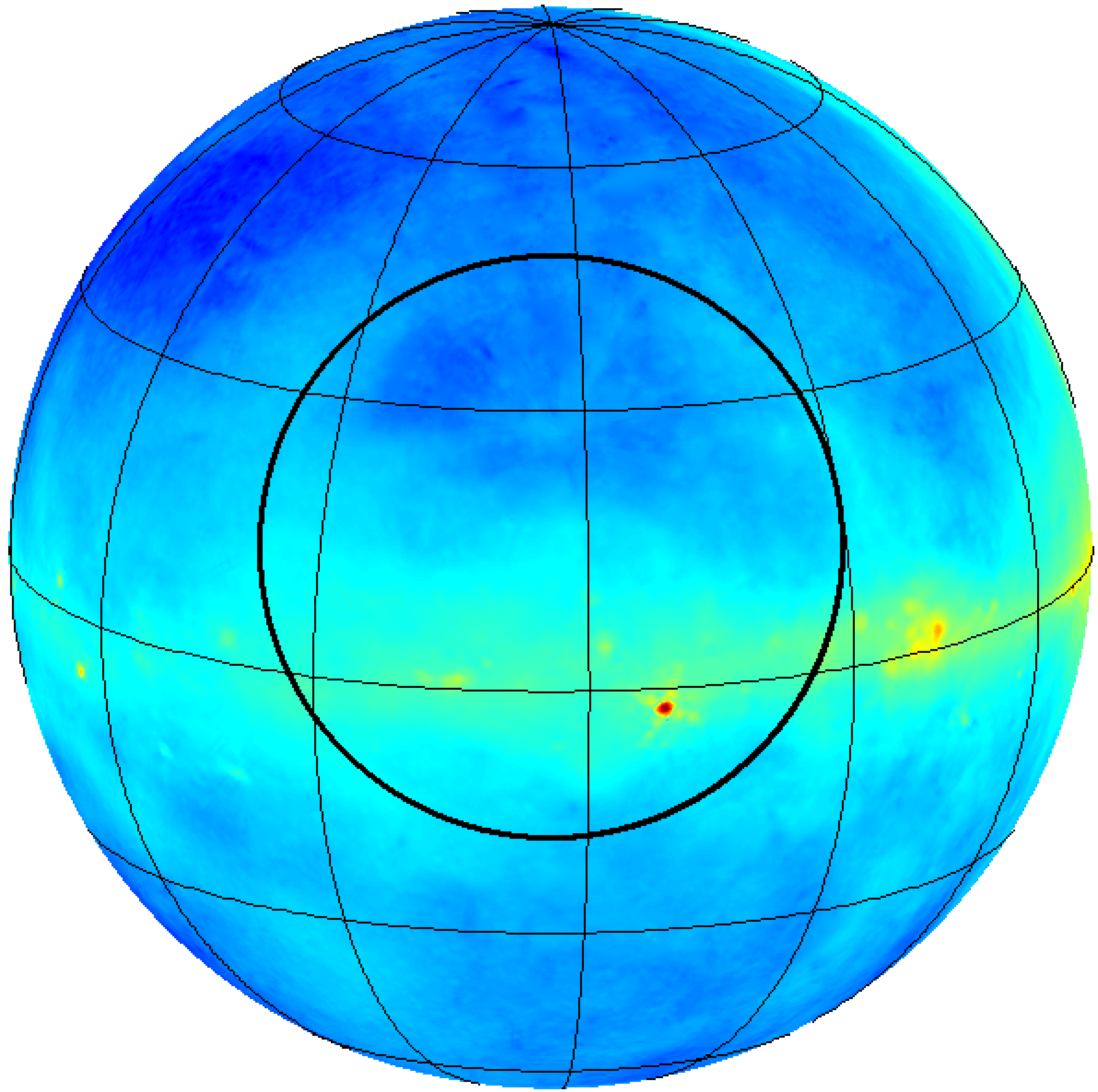
Loop III

Alias:
None

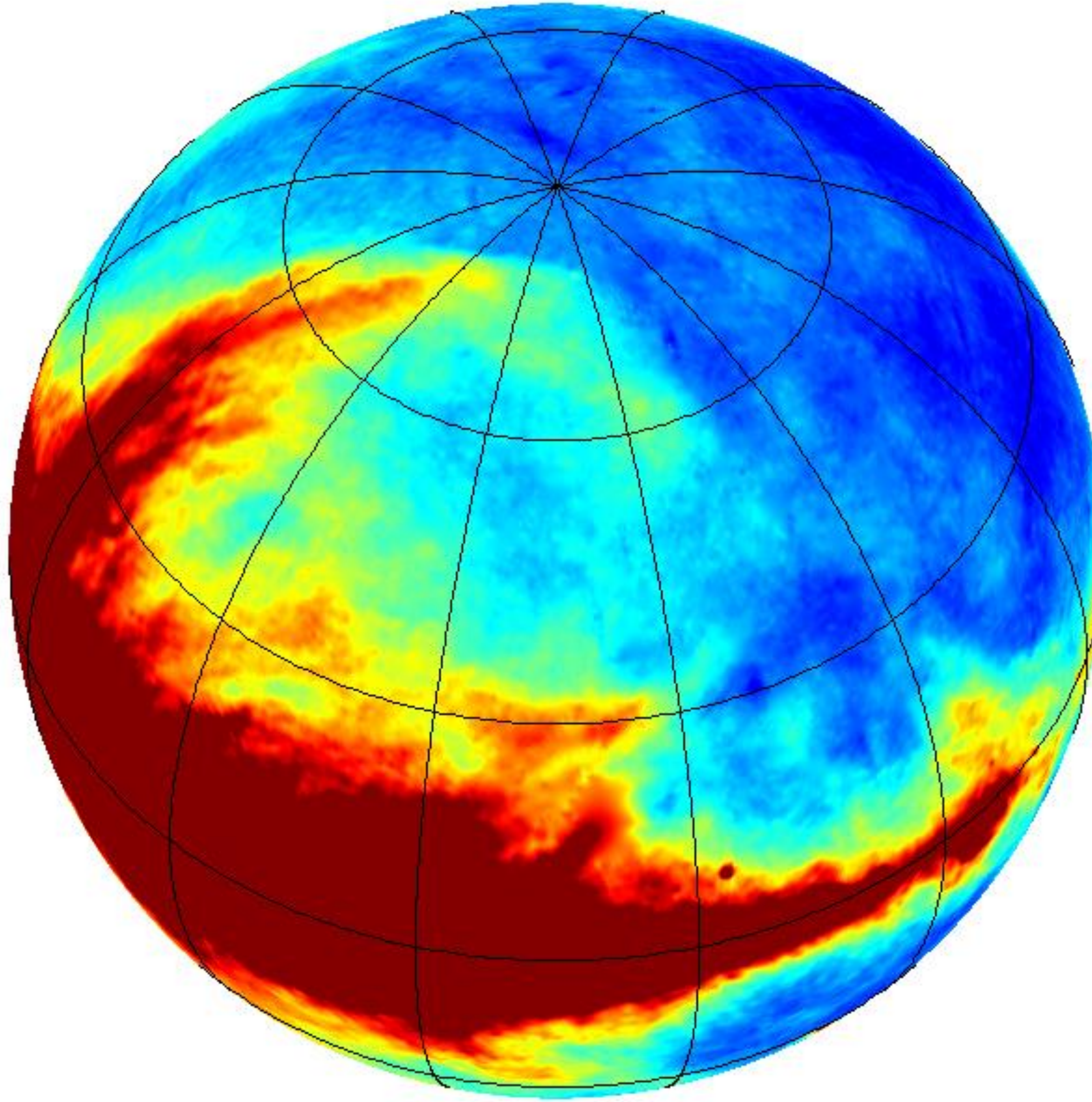
Discovered:
Quigley &
Haslam 1965

Diameter: 65°

Centre (*l*,*b*):
(124, 15.5)
…near north
celestial pole

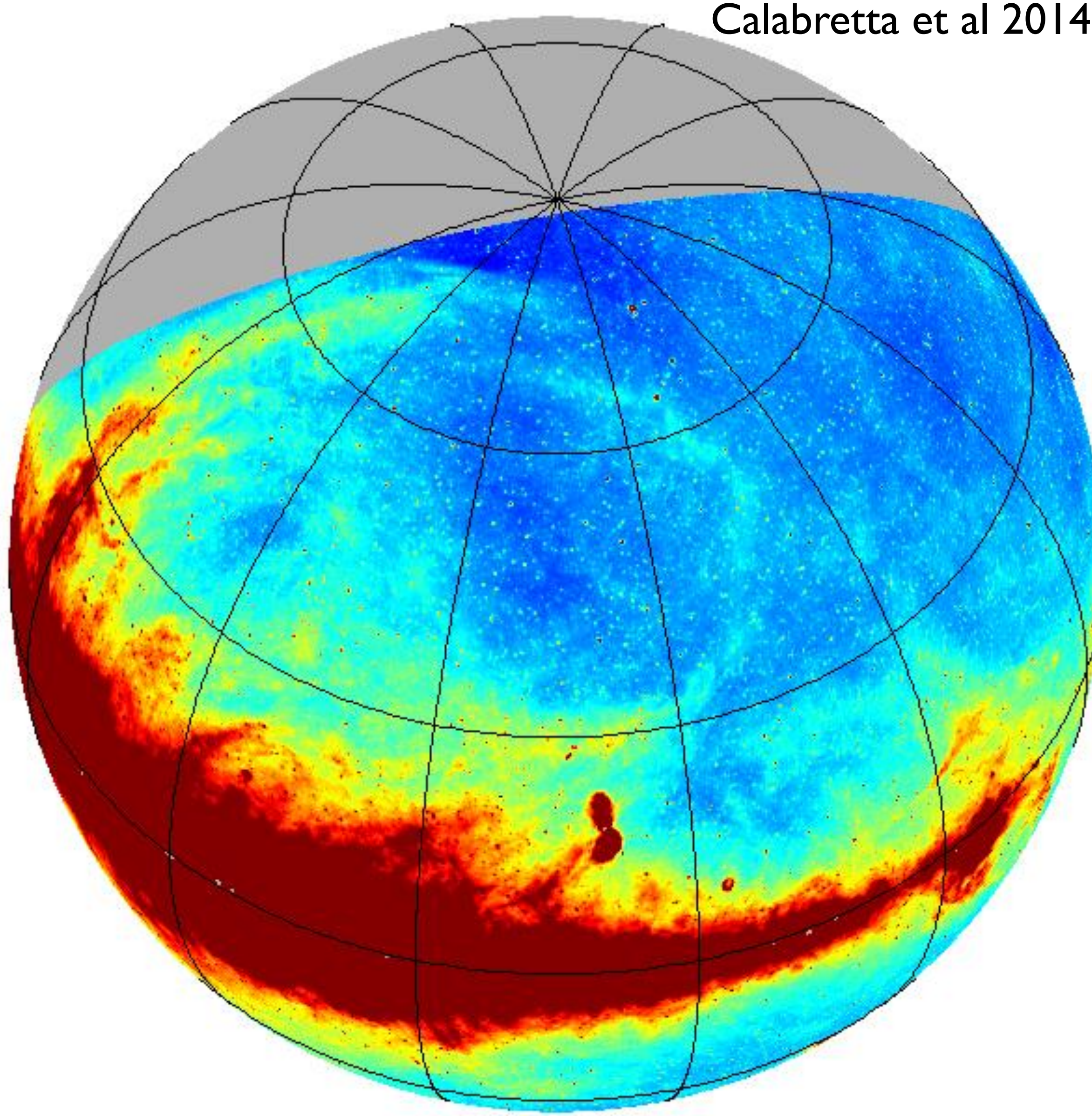


Loop IV



Loop IV

1.4 GHz CHIPASS
Calabretta et al 2014



Alias:

Ridges D, E

Discovered:

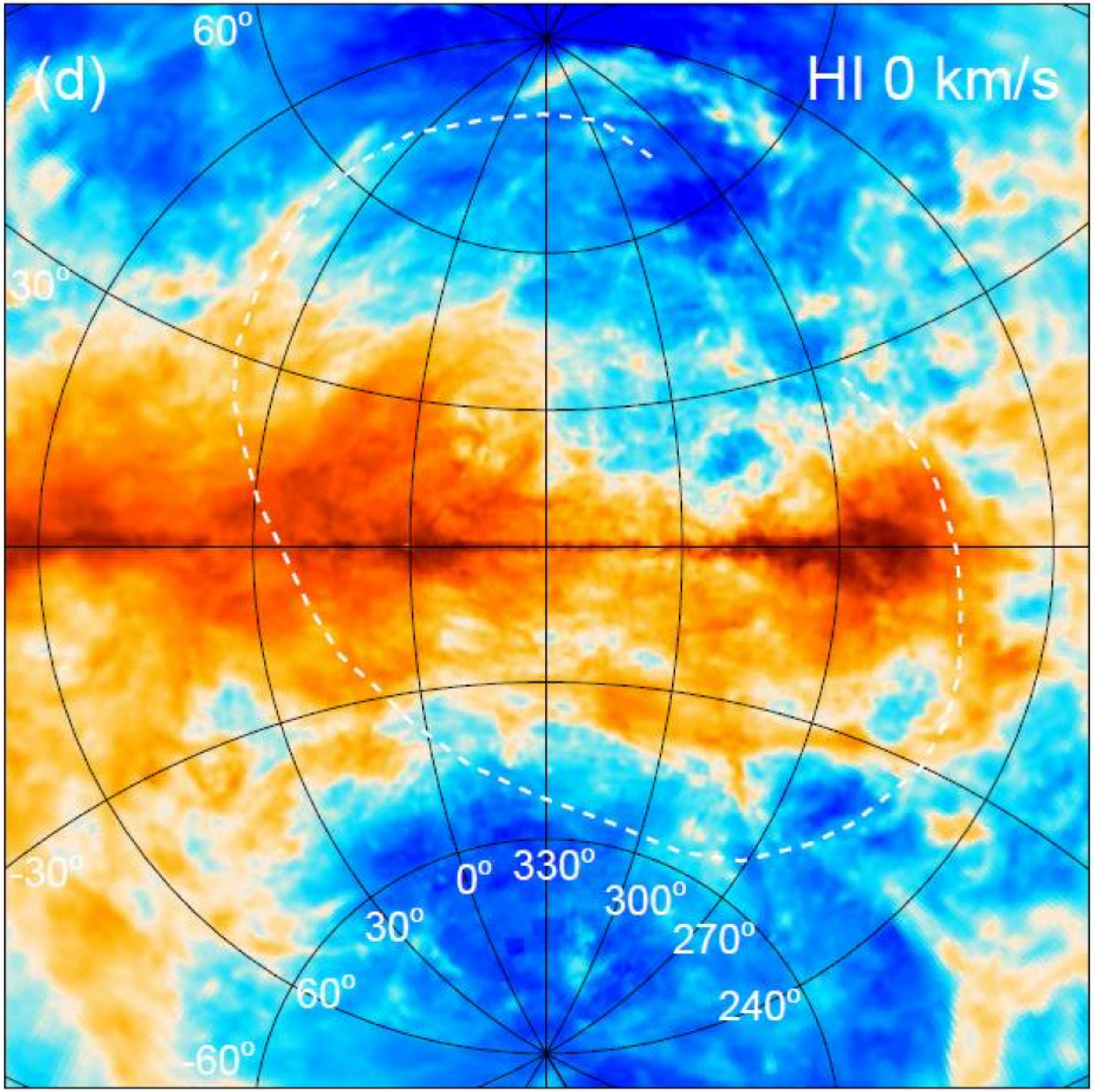
Large, Quigley & Haslam 1966; Berkhuijsen, Haslam & Salter 1971

Diameter:

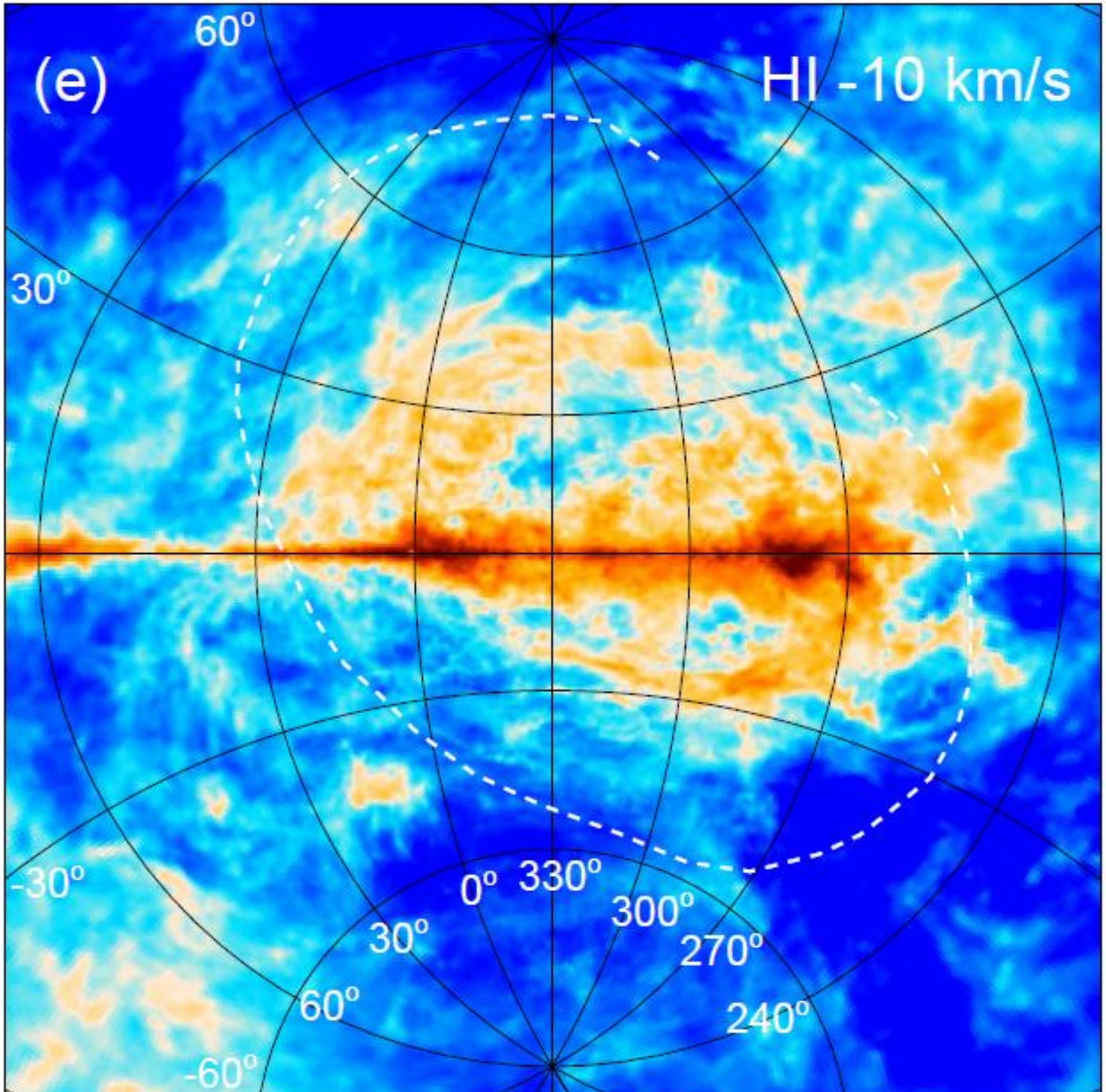
39.5°

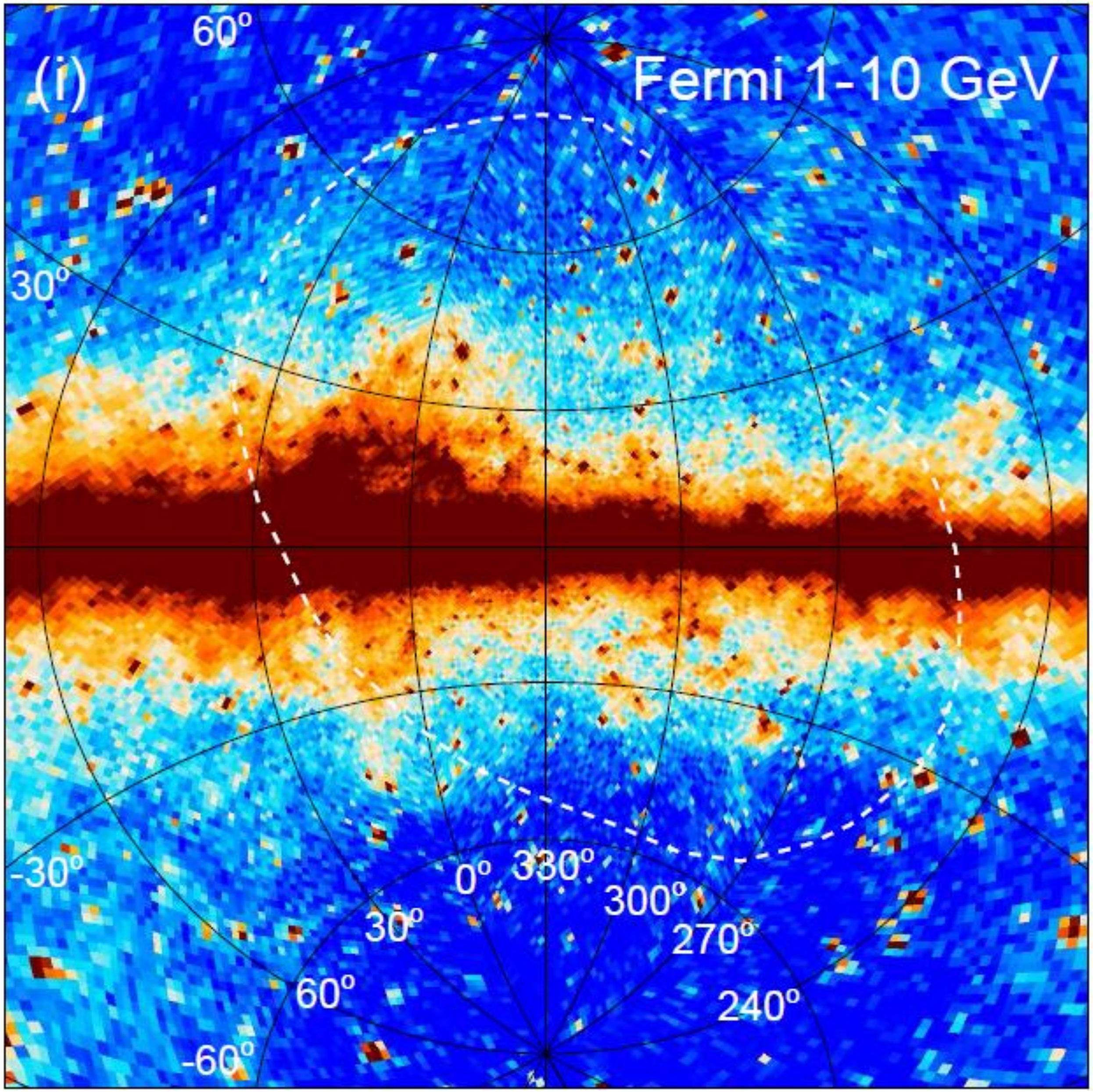
Centre (*l*,*b*):

(315, 48.5)



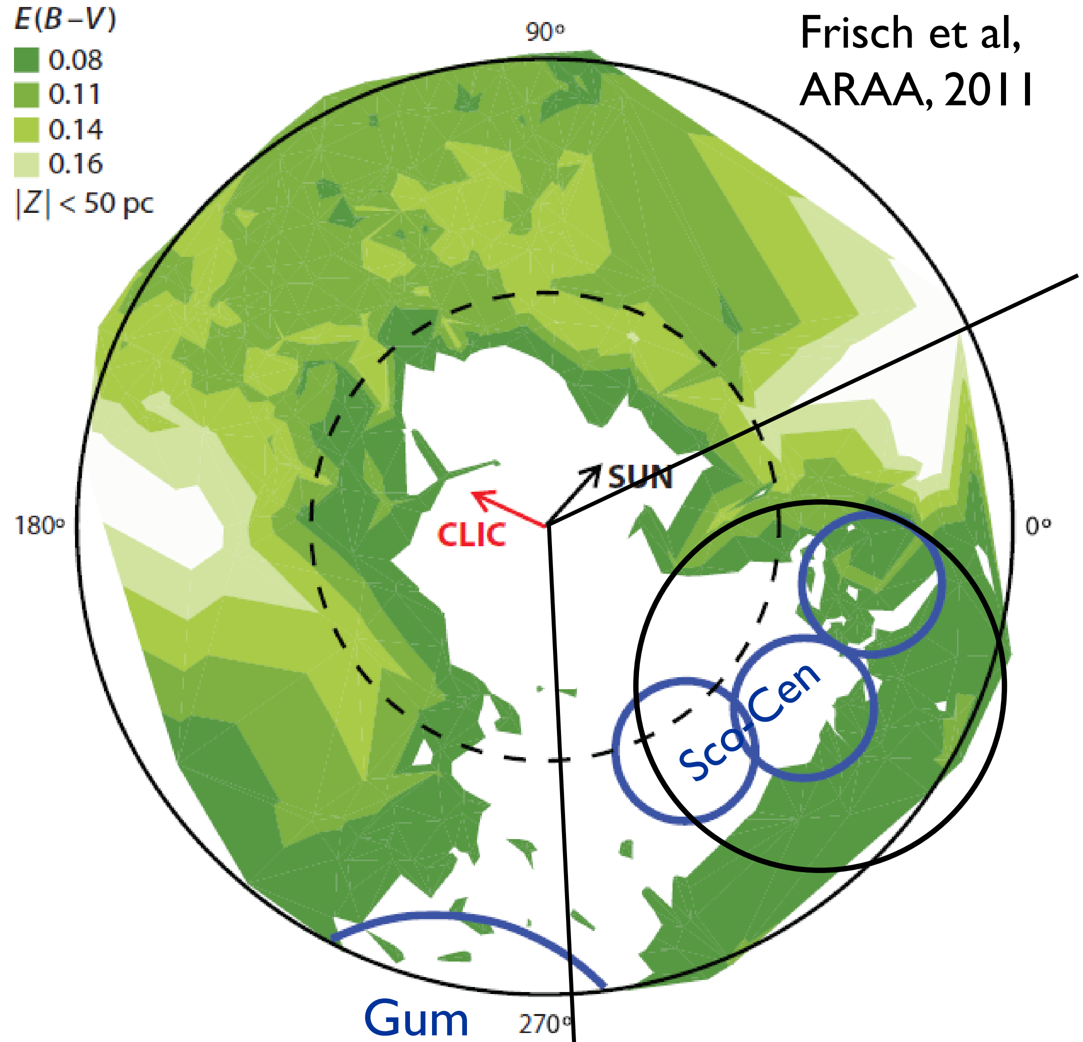
(d)
HI 0 km/s
60°
30°
-30°
-60°
0°
330°
300°
270°
240°
30°
60°


(e)
HI -10 km/s
60°
30°
-30°
-60°
0°
330°
300°
270°
240°
30°
60°


(i)
Fermi 1-10 GeV
60°
30°
-30°
-60°
0°
330°
300°
270°
240°
30°
60°

The local Neighbourhood

- Density of ISM, from extinction of *HIPPARCOS* stars
- Dashed circle 100 pc radius
- Candidate source for Loop I is the Sco-Cen OB association: 116–140 pc
- Is Loop I just an indent in Local Cavity wall?



Frisch et al, ARAA, 2011

The University of Manchester
Jodrell Bank Observatory

Oxford Physics

HartRAO

C-BASS

The C-Band All-Sky Survey

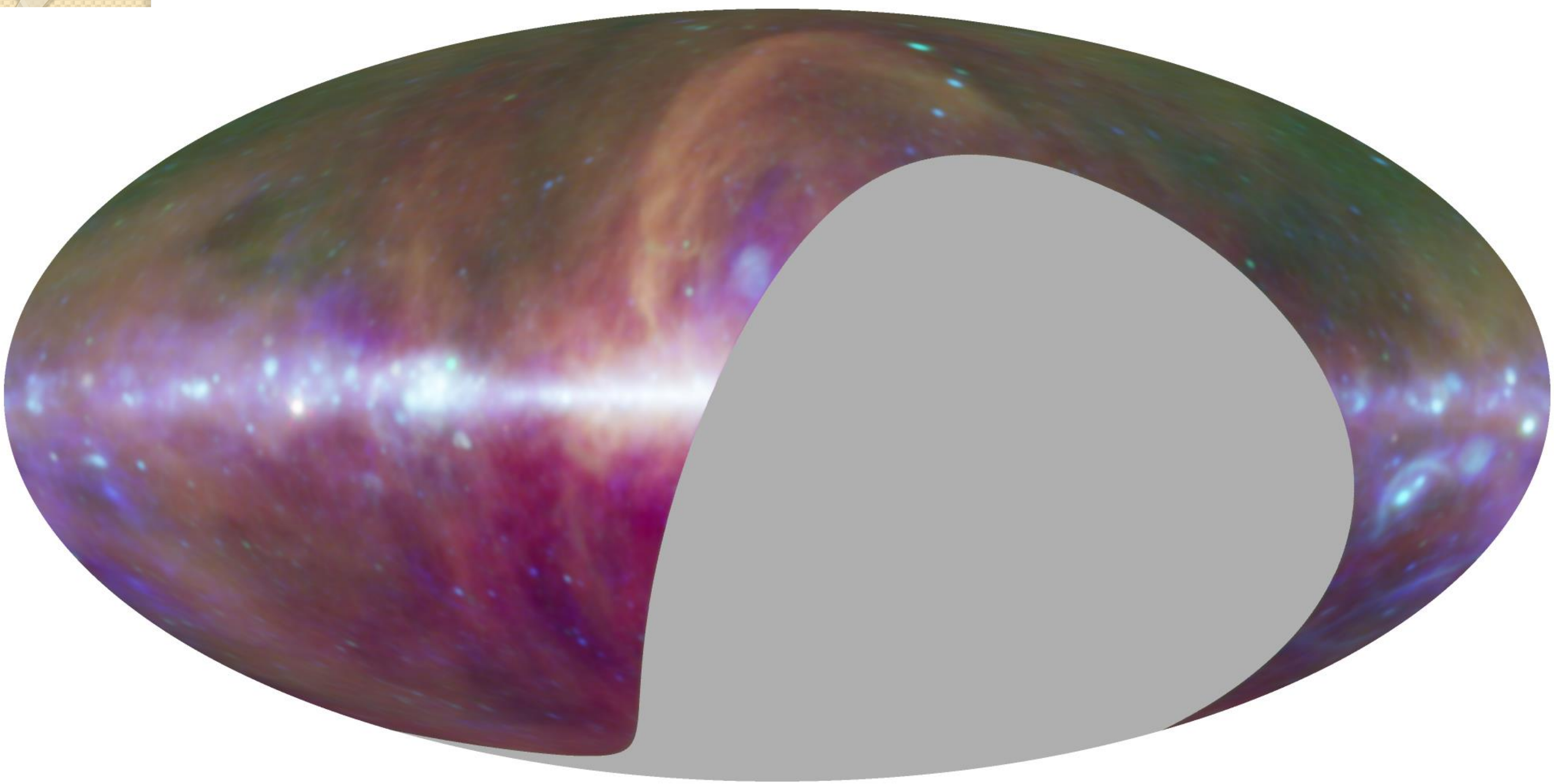
Paddy Leahy
University of Manchester
For the C-BASS collaboration

Observational status

- C-BASS North (OVRO)
- 20 months observations completed
- Observations continue until pipeline fully debugged (RSN)

- C-BASS South (Klerefontein)
- Routine observations expected to start in January 2015.

Haslam/C-BASS/WMAP



Status

- Current maps are still contaminated by a small fraction of bad data (wrong pointings, RFI, bad weather…)
- Daytime data is contaminated by solar sidelobes. We are working on correcting this for at least some day-time data to improve SNR still further
- Ground spillover is a major problem
  - subtle declination-dependent artefacts.
  - We are working on improved ground modelling
- Some deconvolution required
  - We can capitalize on circular symmetry of telescopes
- “first-draft” northern total intensity survey to be submitted spring 2015.
- Southern observations should be completed by end 2015
- Final survey papers (IQU) in 2016.