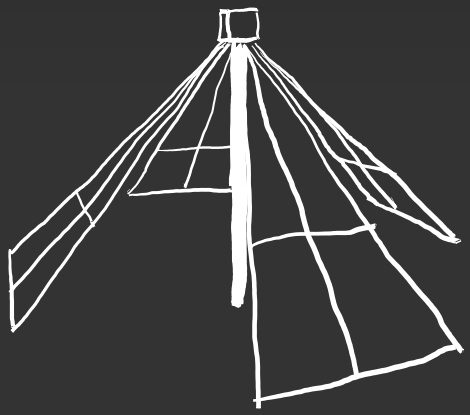

Full-Sky Maps of the VHF Radio Sky with the Owens Valley Long Wavelength Array

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California Institute of Technology

IAUS 333 – October 3, 2017

Caltech

- Gregg Hallinan
- Sandy Weinreb
- Stephen Bourke → Chalmers
- Jake Hartman → Google
- Harish Vedantham
- Jonathon Kocz
- Kate Clark
- Marin Anderson
- Ryan Monroe
- Devin Cody
- David Wang

Harvard/SAO

- Lincoln Greenhill
- Ben Barsdell → NVIDIA
- Danny Price → Swinburne
- Hugh Garsden
- Gianni Bernardi → SKA SA

OVRO

- David Woody
- James Lamb
- OVRO staff

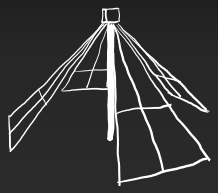
JPL

- Larry D'Addario
- Joe Lazio

and the rest of the LWA team

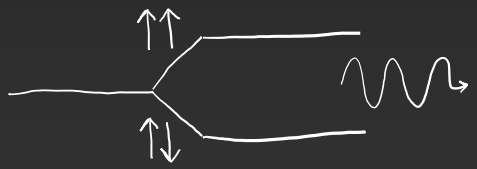
The Owens Valley LWA

Number of Antennas	288 (256 correlated)
Core Diameter	200 m
Maximum Baseline	1.5 km
Resolution	10 – 20 arcminutes
Frequency Range	27 – 85 MHz
Frequency Resolution	24 kHz
Field of View	Entire hemisphere
Integration Time (this work)	28 hours



Foregrounds in 21 cm Cosmology

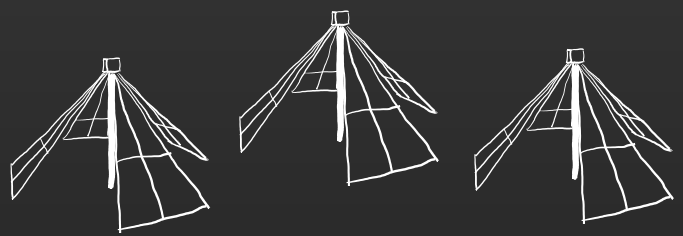
Cosmological signal



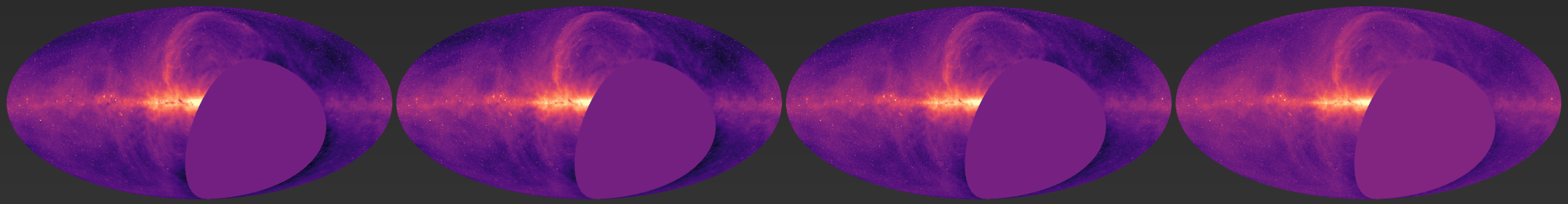
Extragalactic point sources

Galactic synchrotron emission

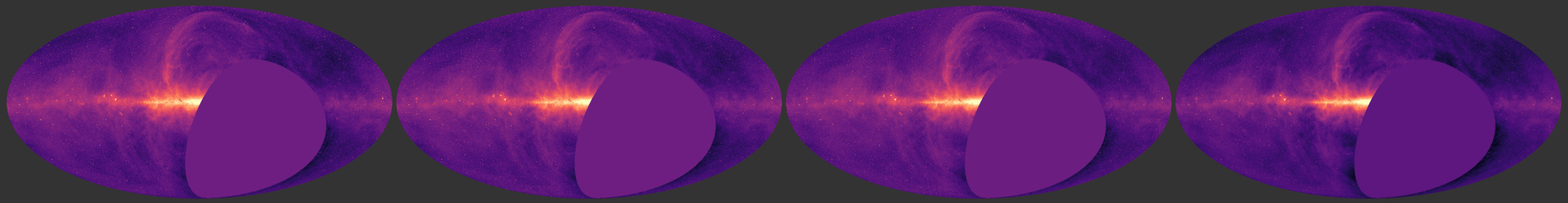
Ionosphere



Eight New Low-Frequency Sky Maps



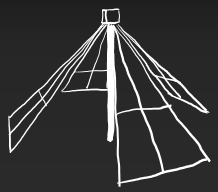
36.528 MHz | 41.760 MHz | 46.992 MHz | 52.224 MHz



57.456 MHz | 62.688 MHz | 67.920 MHz | 73.152 MHz

Eastwood et al. (in prep.)

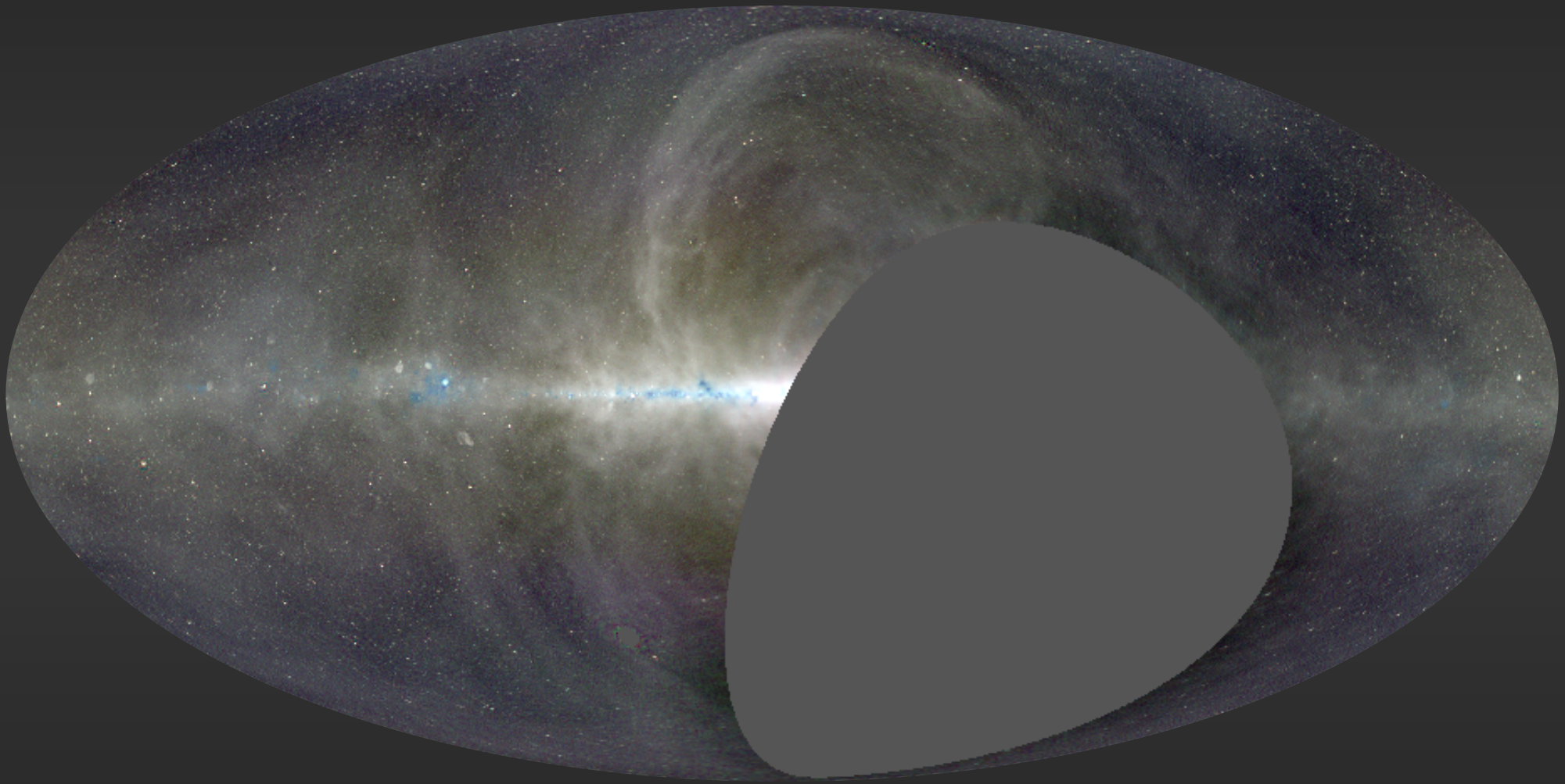
All eight sky maps will be publicly posted on LAMBDA
(already uploaded, waiting to be made public)



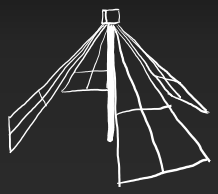
Map Properties

#	Frequency MHz	Bandwidth kHz	FWHM arcmin	Noise K	Noise mJy/beam
1	36.528	24.	18.5	595.	799.
2	41.760	24.	17.2	541.	824.
3	46.992	24.	16.3	417.	717.
4	52.224	24.	15.6	418.	814.
5	57.456	24.	15.4	354.	819.
6	62.688	24.	15.3	309.	843.
7	67.920	24.	15.3	281.	894.
8	73.152	24.	15.7	154.	598.

Three-Color Map



Eastwood et al. (in prep.)

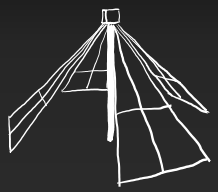


The Challenge of Widefield Imaging

$$\text{visibility} = \int (\text{sky brightness}) \times (\text{beam}) \times (\text{fringe pattern})\, \mathrm{d}\Omega$$

We want to solve this equation **quickly** and **accurately**.

Transit telescopes can exploit a symmetry that greatly simplifies the necessary computation for exact all-sky synthesis imaging.



m-Mode Analysis Fundamentals

$$\text{visibility} = \int (\text{sky brightness}) \times (\text{beam}) \times (\text{fringe pattern})\, \mathrm{d}\Omega$$

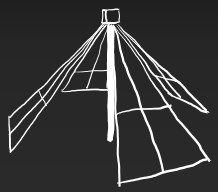
$$\text{visibility} \rightarrow \text{ sidereal time Fourier transform}$$

$$\text{sky brightness} \rightarrow \text{ spherical harmonic transform}$$

$$(\text{beam}) \times (\text{fringe pattern}) \rightarrow \text{ spherical harmonic transform}$$

$$\begin{pmatrix} \vdots \\ \text{m-modes} \\ \vdots \end{pmatrix} = \begin{pmatrix} \ddots & & \\ & \text{transfer matrix} & \\ & & \ddots \end{pmatrix} \begin{pmatrix} \vdots \\ a_{lm} \\ \vdots \end{pmatrix}$$

Shaw et al. (2014, 2015)

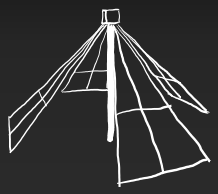


m-Mode Analysis Fundamentals

$$\boldsymbol{v} = \boldsymbol{B}\boldsymbol{a} + \text{noise}$$

- $\boldsymbol{v}$ is the vector of m-modes. This is what is measured by the interferometer.
- $\boldsymbol{B}$ is the transfer matrix. It describes the response of the interferometer to the sky. This matrix is **block diagonal**.
- $\boldsymbol{a}$ is the vector of spherical harmonic coefficients (for the sky brightness).

Shaw et al. (2014, 2015)



m-Mode Analysis Imaging

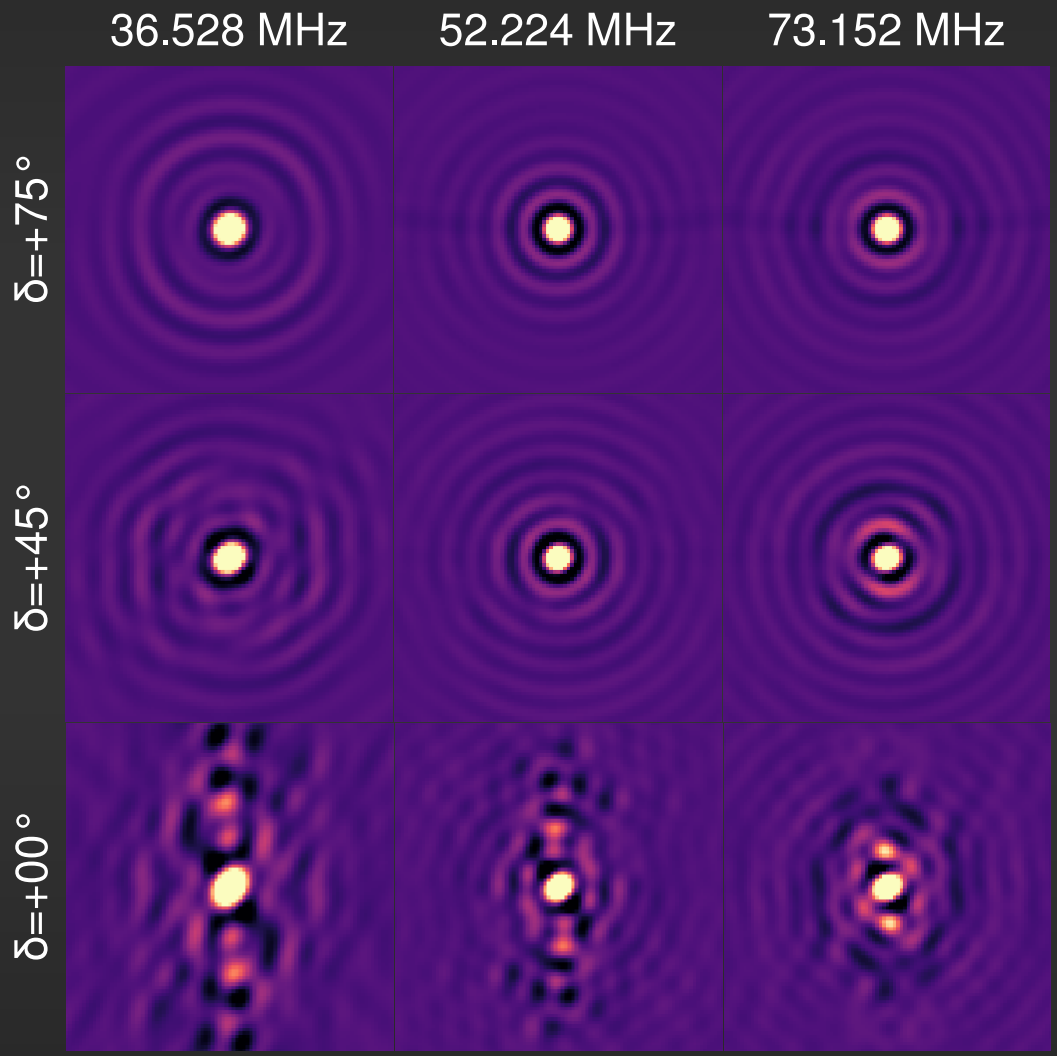
$$\boldsymbol{v} = \boldsymbol{B}\boldsymbol{a} + \text{noise}$$

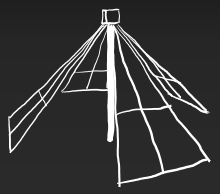
Goal: Estimate $\boldsymbol{a}$ given the observations $\boldsymbol{v}$.
Challenge: B is singular.

Tikhonov Regularized m-Mode Analysis Imaging

$$\hat{\boldsymbol{a}} = \operatorname{argmin}\left\{\|\boldsymbol{v} - \boldsymbol{B}\boldsymbol{a}\|^2 + \varepsilon\|\boldsymbol{a}\|^2\right\} = (\boldsymbol{B}^*\boldsymbol{B} + \varepsilon\boldsymbol{I})^{-1}\boldsymbol{B}^*\boldsymbol{v}$$

The Point Spread Function

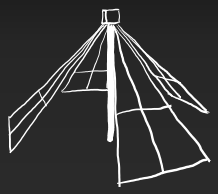




m-Mode Analysis Cleaning

function CLEAN($\boldsymbol{a}$)
  $\boldsymbol{M} \leftarrow \boldsymbol{B}^* \boldsymbol{B}$
  $\boldsymbol{U} \leftarrow \mathrm{chol}(\boldsymbol{M} + \varepsilon \boldsymbol{I})$ ▷ Cholesky decomposition
  while noise in map $>$ threshold **do**
    find N pixels with the largest residual flux
    $\boldsymbol{x} \leftarrow \sum_{i=1}^{N} (\text{pixel flux}) \times \boldsymbol{a}_{\text{PS}}(\theta_i, \phi_i)$
    $\boldsymbol{y} \leftarrow \boldsymbol{U}^{-1} (\boldsymbol{U}^*)^{-1} \boldsymbol{M} \boldsymbol{x}$
    $\boldsymbol{a} \leftarrow \boldsymbol{a} - (\text{loop gain}) \times \boldsymbol{y}$
    record subtracted components
  $\boldsymbol{a} \leftarrow \boldsymbol{a} + (\text{restored components})$
  return $\boldsymbol{a}$

Eastwood et al. (in prep.)



Advantages and Disadvantages

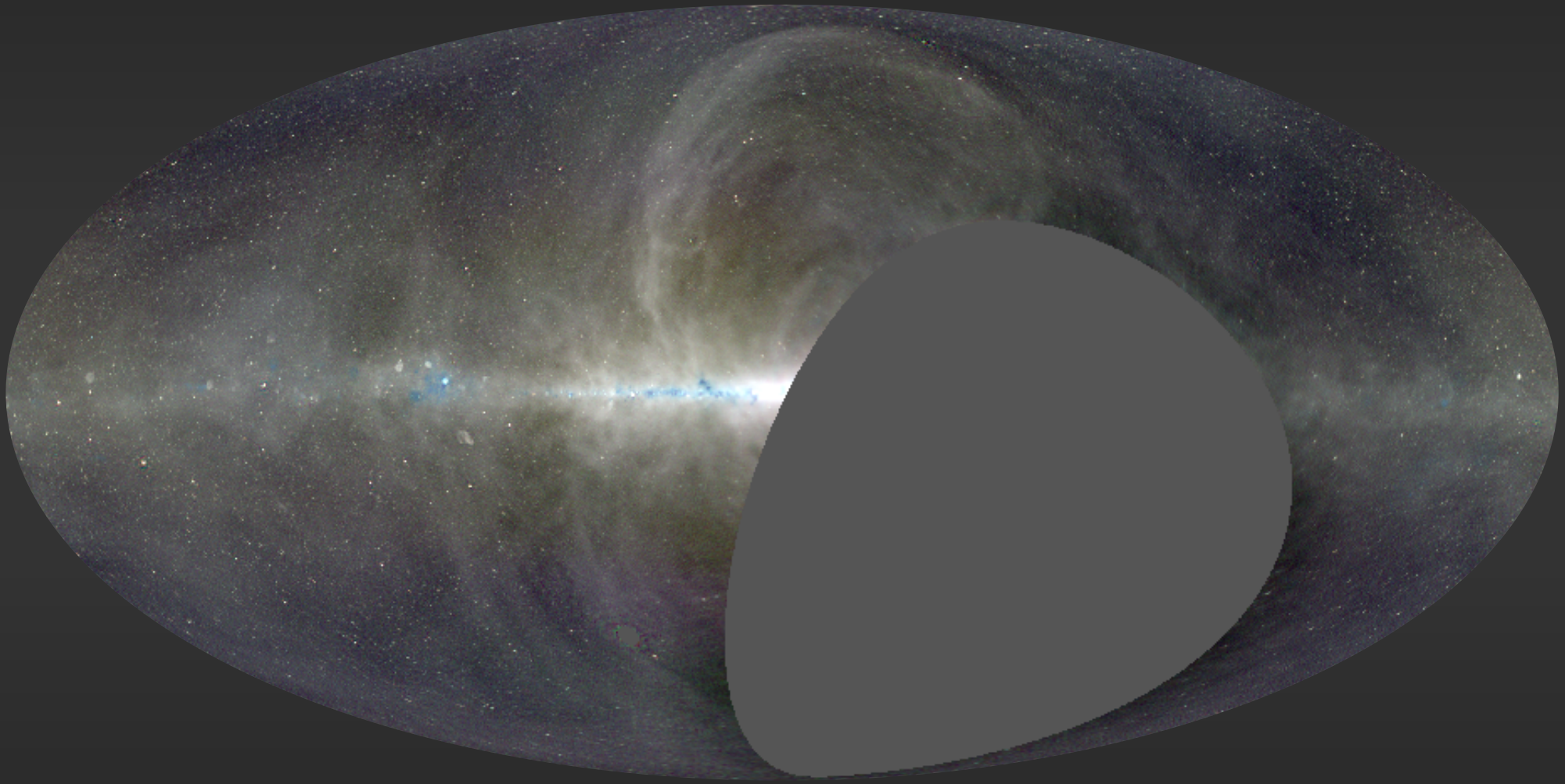
Advantages

- No gridding step
- No mosaicing step
- Exact treatment of widefield effects
- Optimal foreground filters (see Shaw et al. 2014, 2015)

Disadvantages

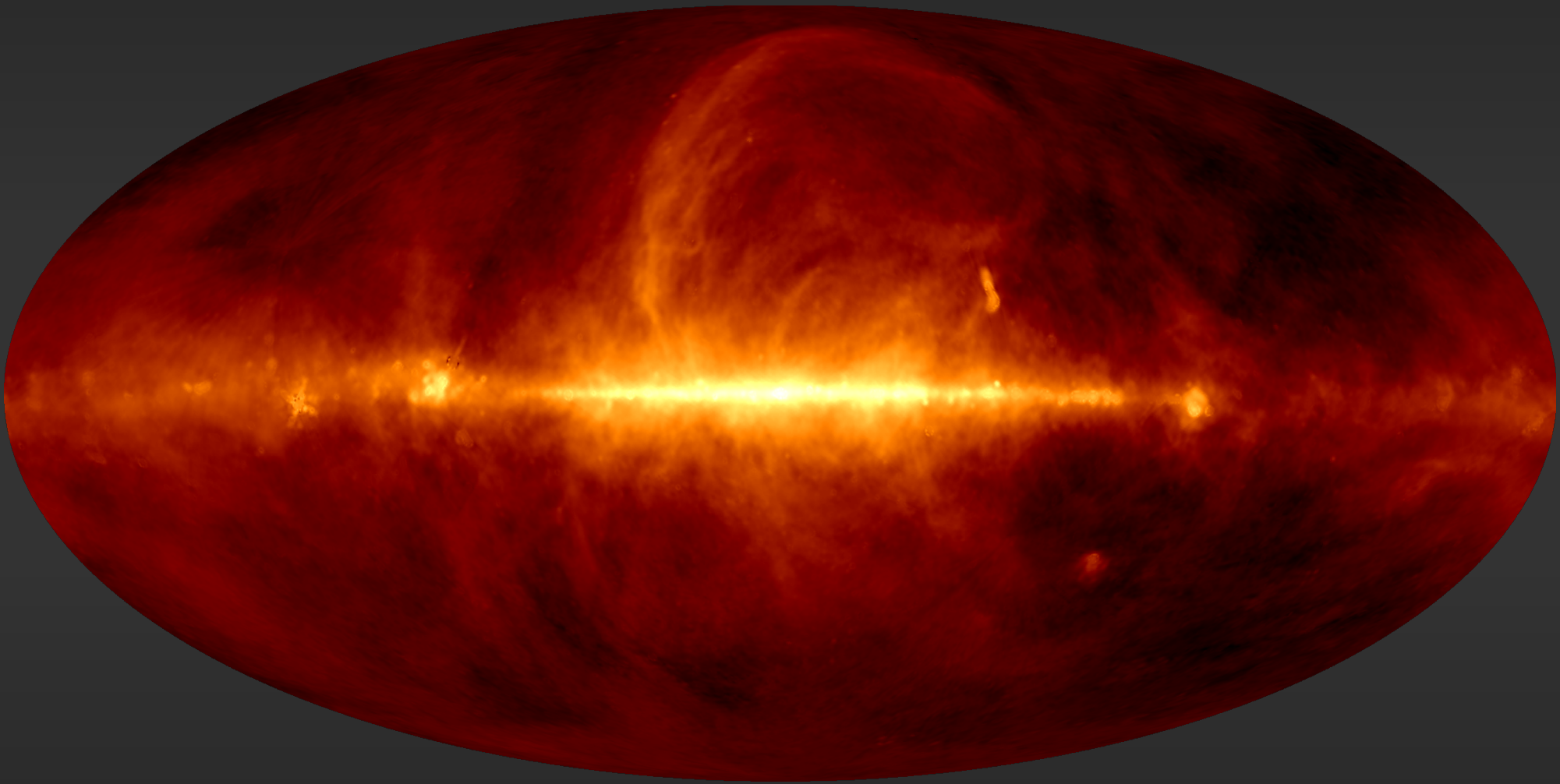
- Matrix equation is block diagonal, but still large!
- 500 GB/frequency channel (!)
- Rapid ionospheric changes break assumptions

Comparison with Haslam 408 MHz



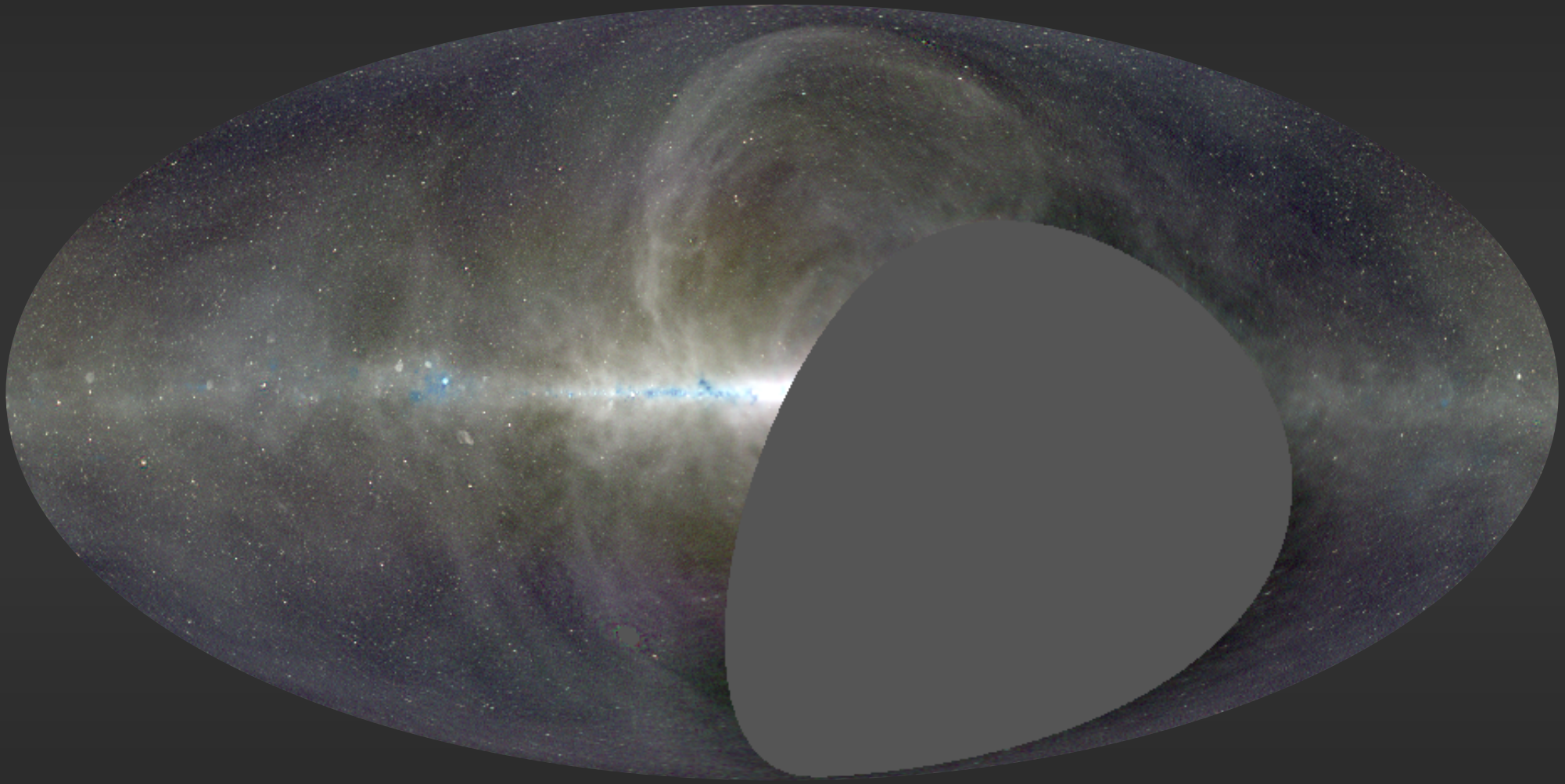
Eastwood et al. (in prep.)

Comparison with Haslam 408 MHz



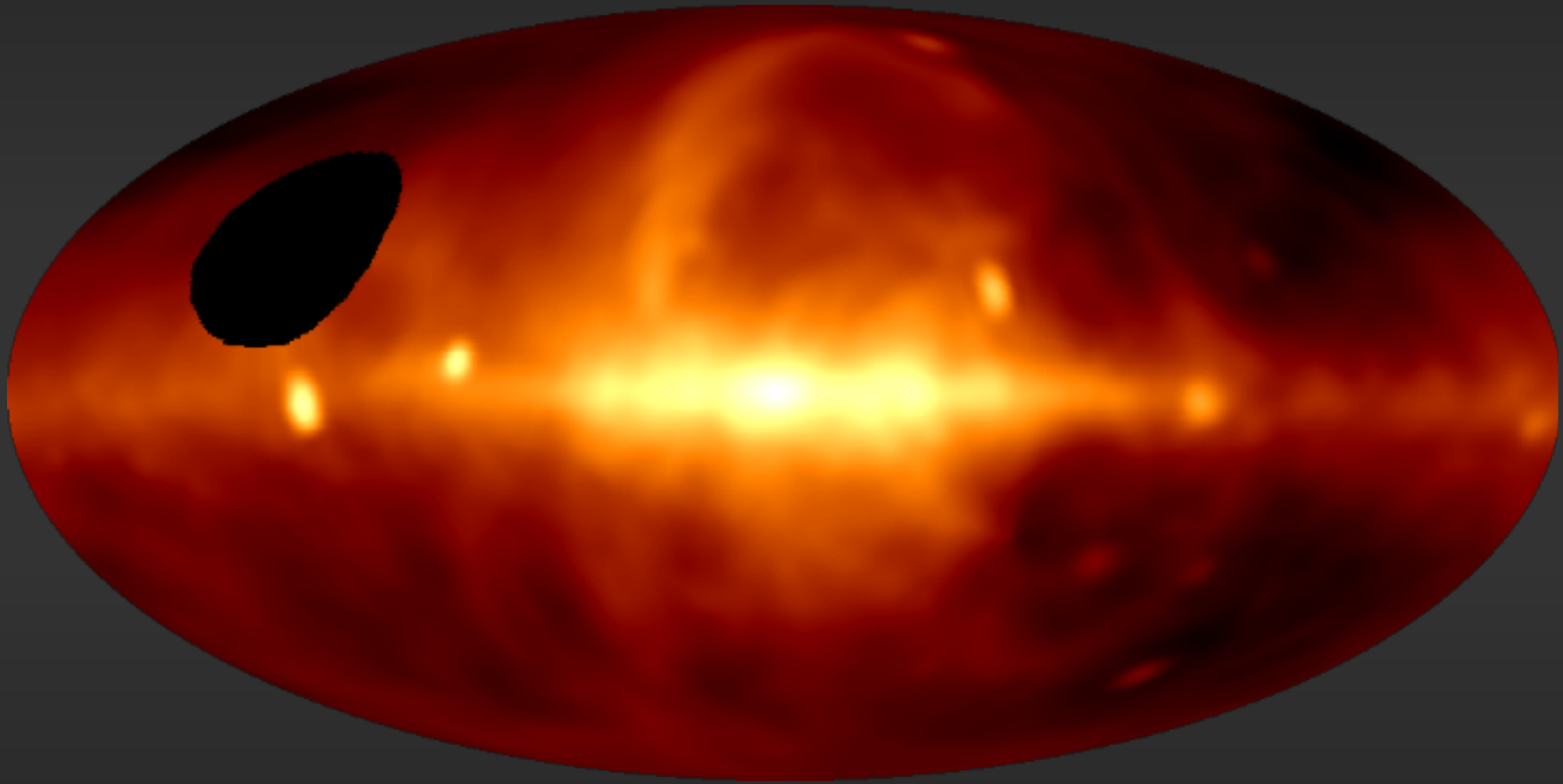
Haslam et al. (1981, 1982)

Comparison with Guzmán 45 MHz



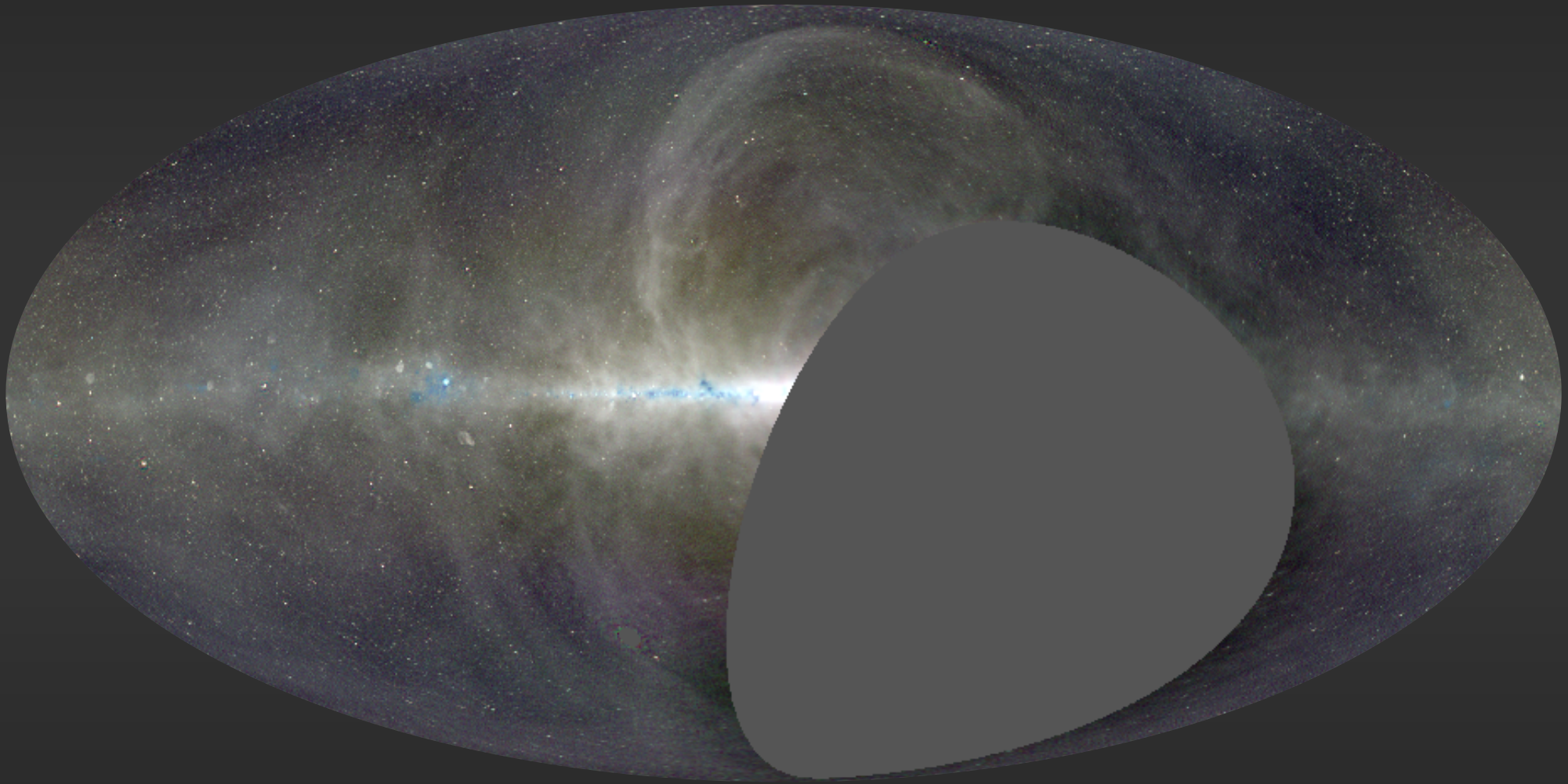
Eastwood et al. (in prep.)

Comparison with Guzmán 45 MHz



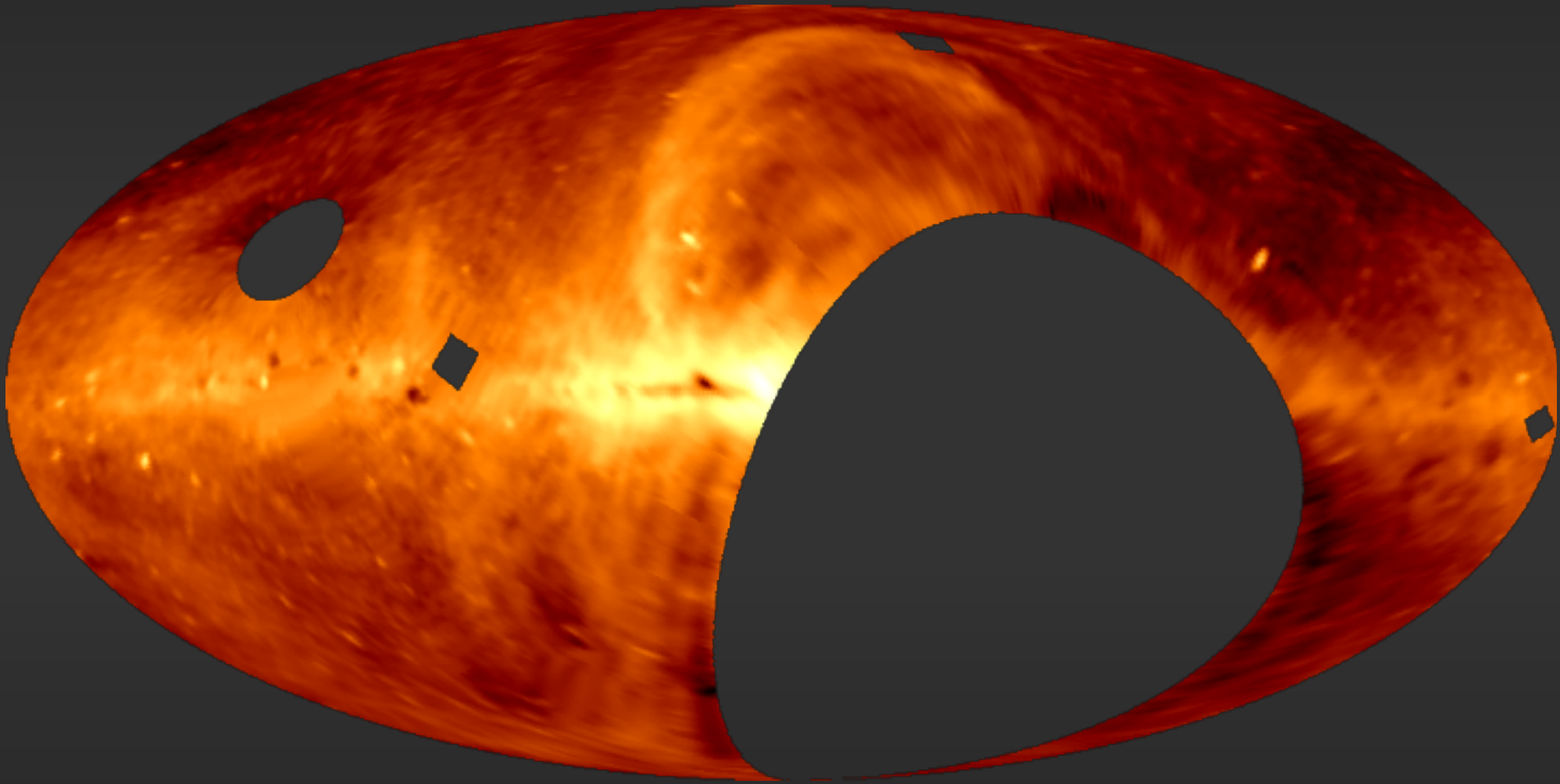
Guzmán et al. (2011)

Comparison with DRAO 22 MHz



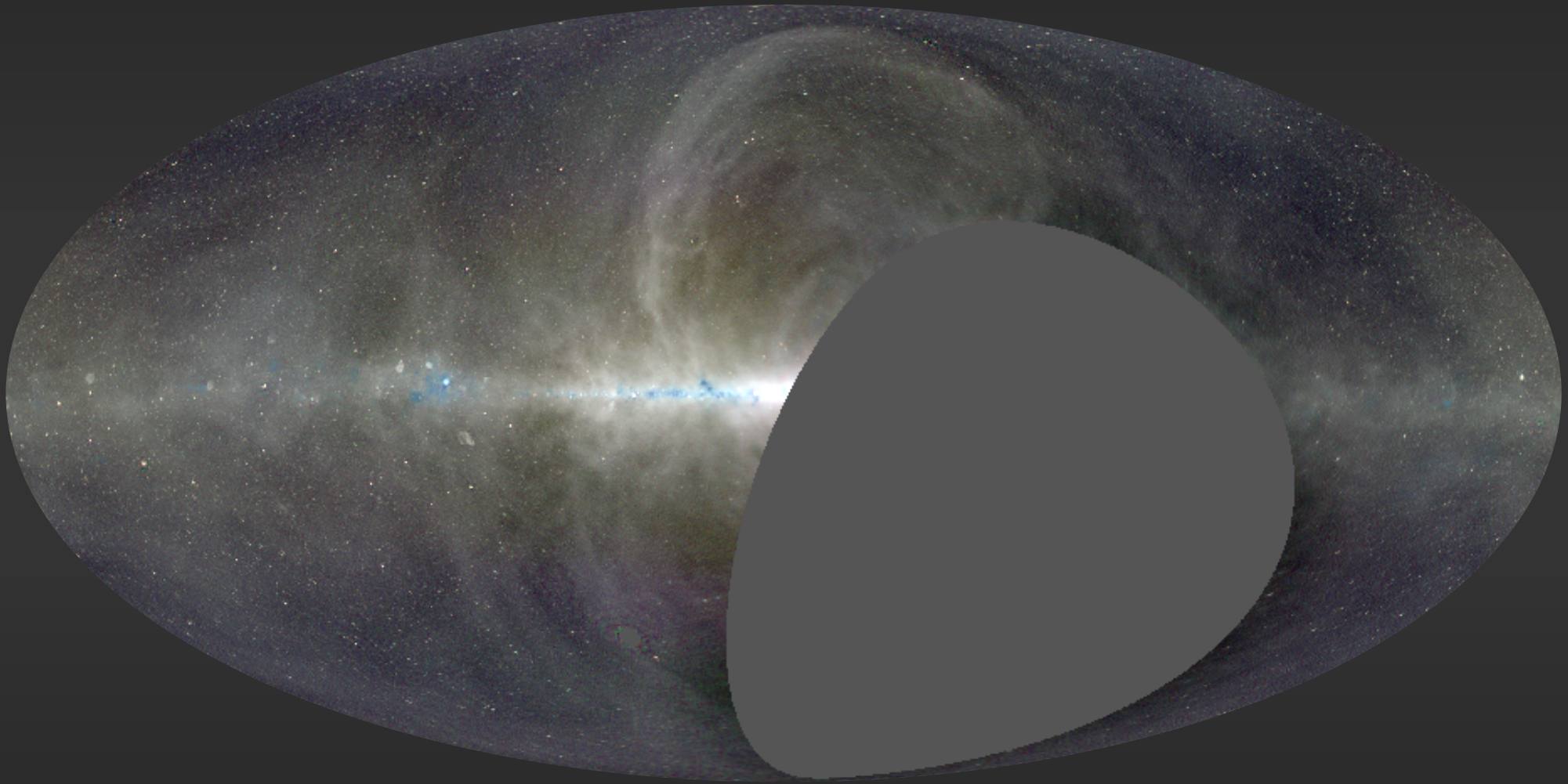
Eastwood et al. (in prep.)

Comparison with DRAO 22 MHz



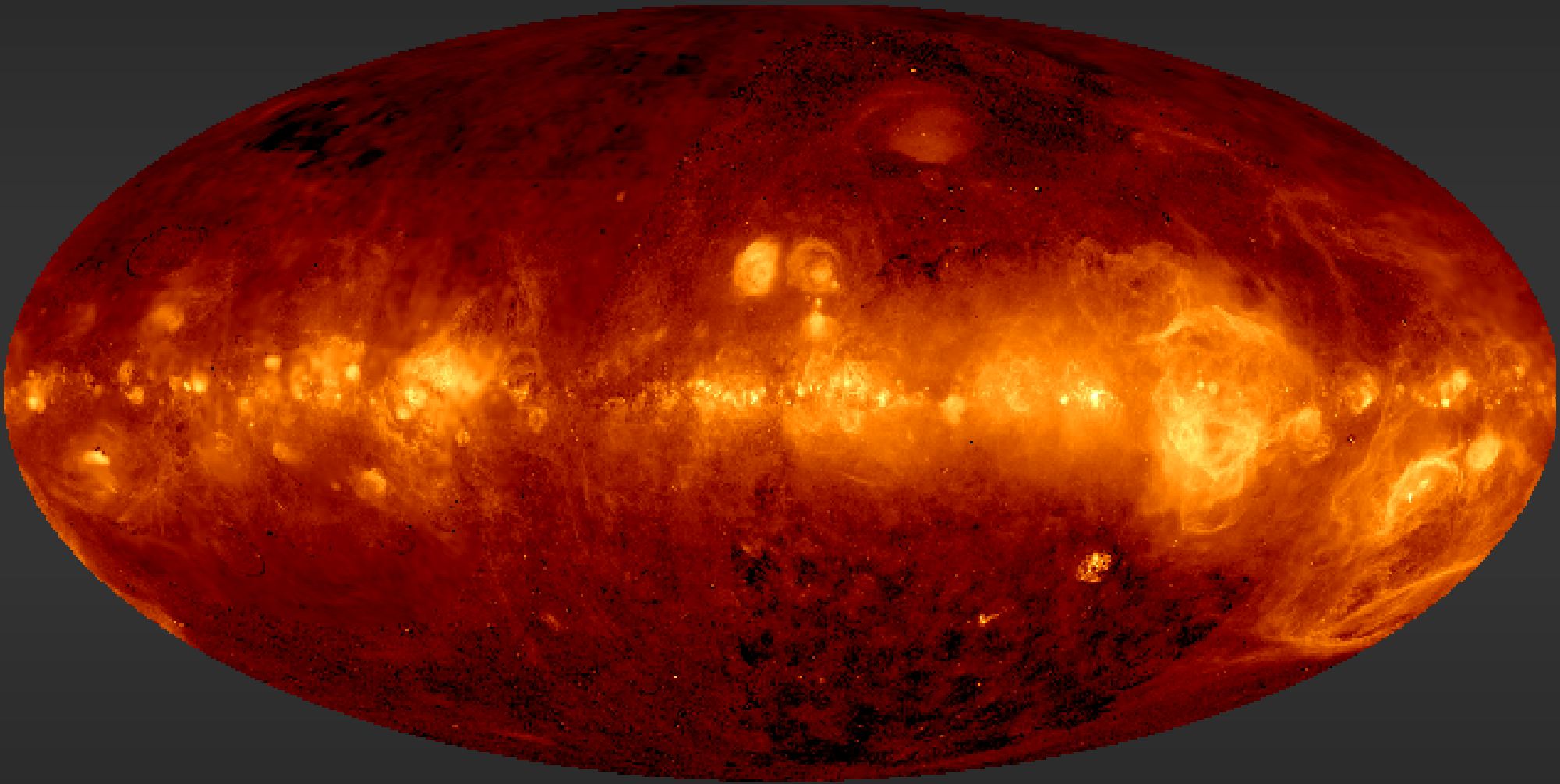
Roger et al. (1999)

Comparison with Finkbeiner Hα

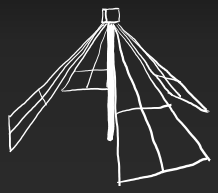


Eastwood et al. (in prep.)

Comparison with Finkbeiner Hα



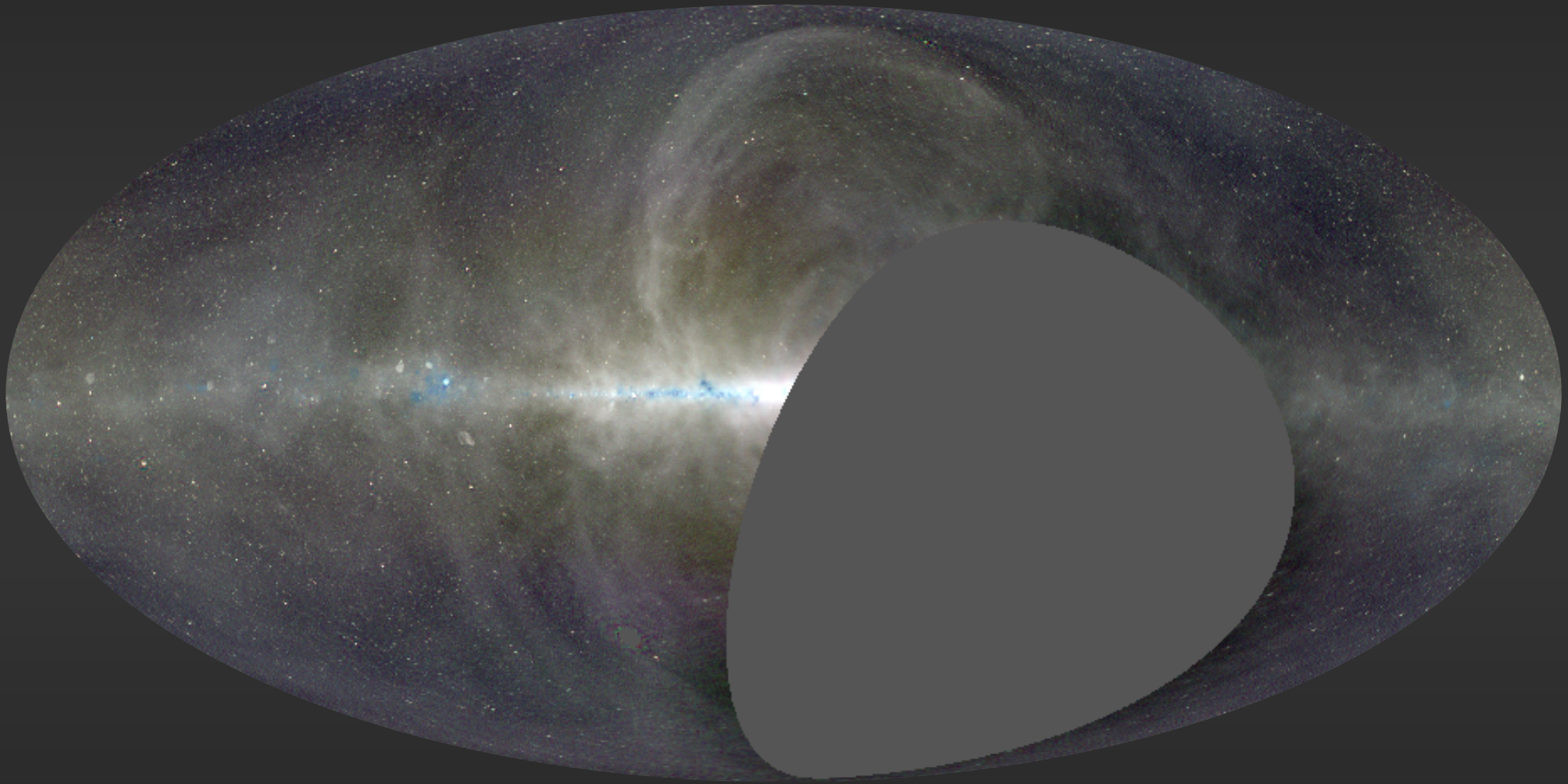
Finkbeiner et al. (2003)



Summary

- Foregrounds are bright.
- Creating high-fidelity foreground maps is challenging.
- **New imaging technique:** Tikhonov-regularized m-mode analysis imaging and cleaning.
- Eight new sky maps produced with the OVRO-LWA.
- These maps will be made publicly available on LAMBDA.

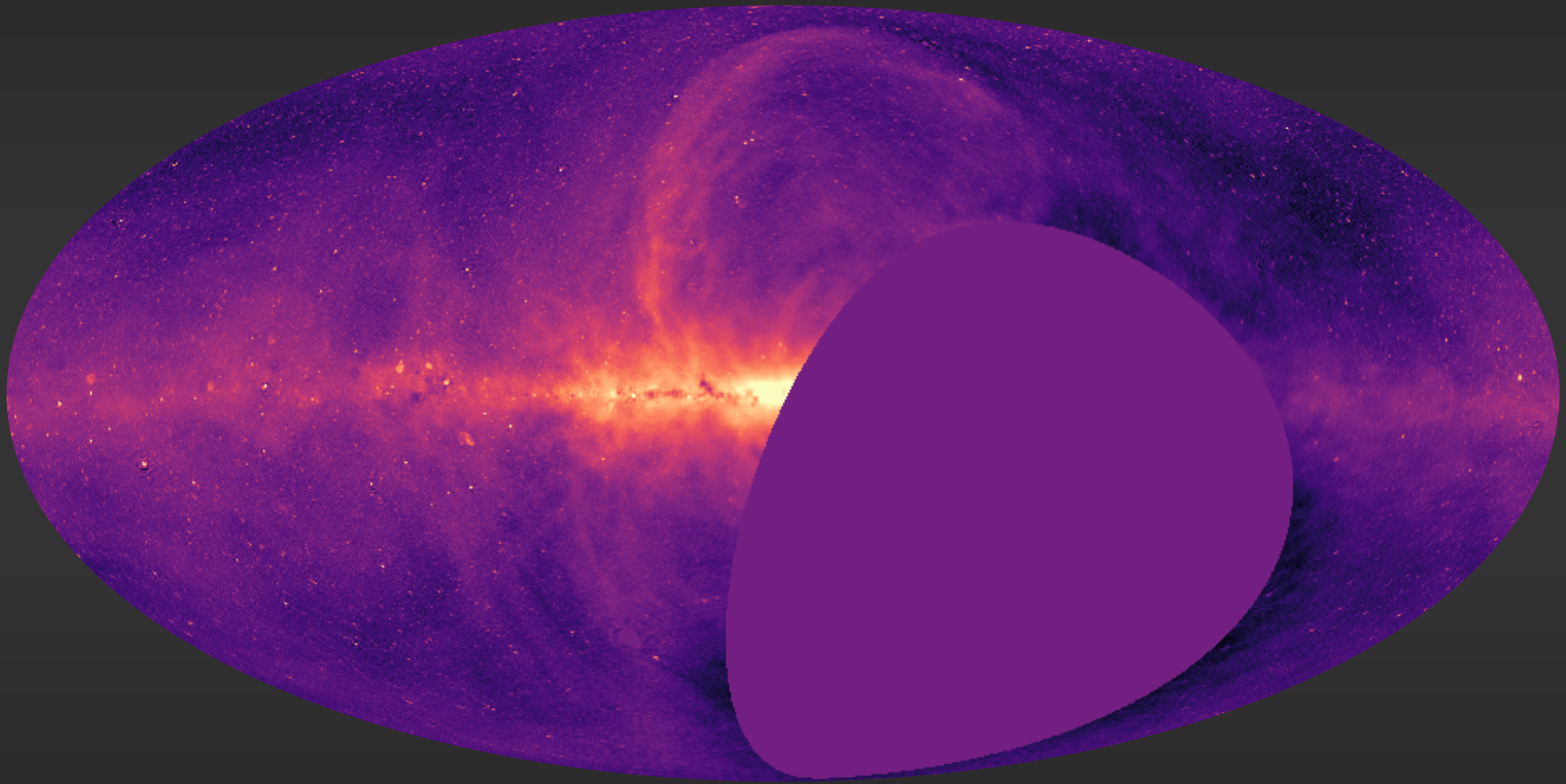
Three-Color Map



Eastwood et al. (in prep.)

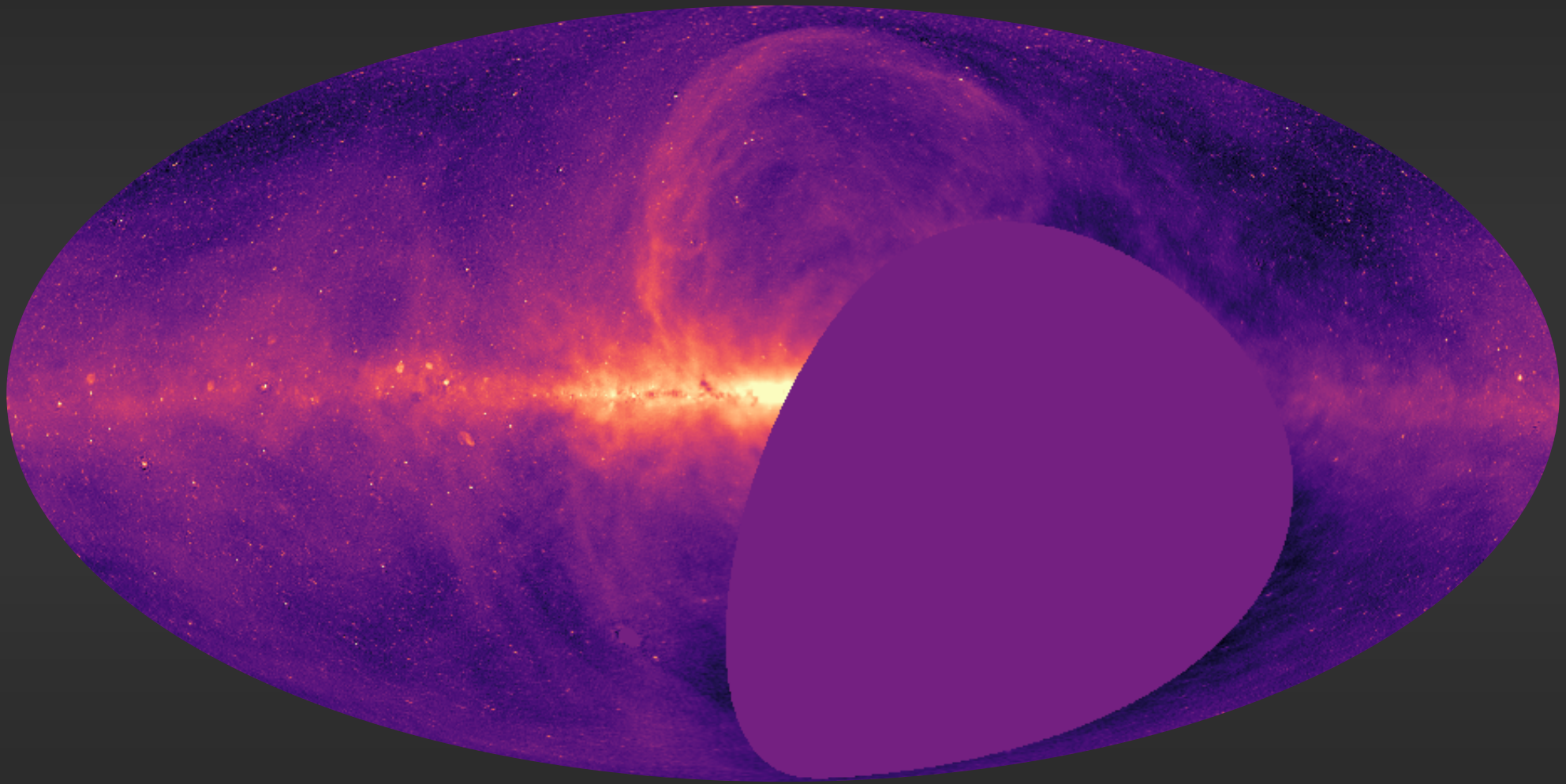
Backup Slides

36.528 MHz



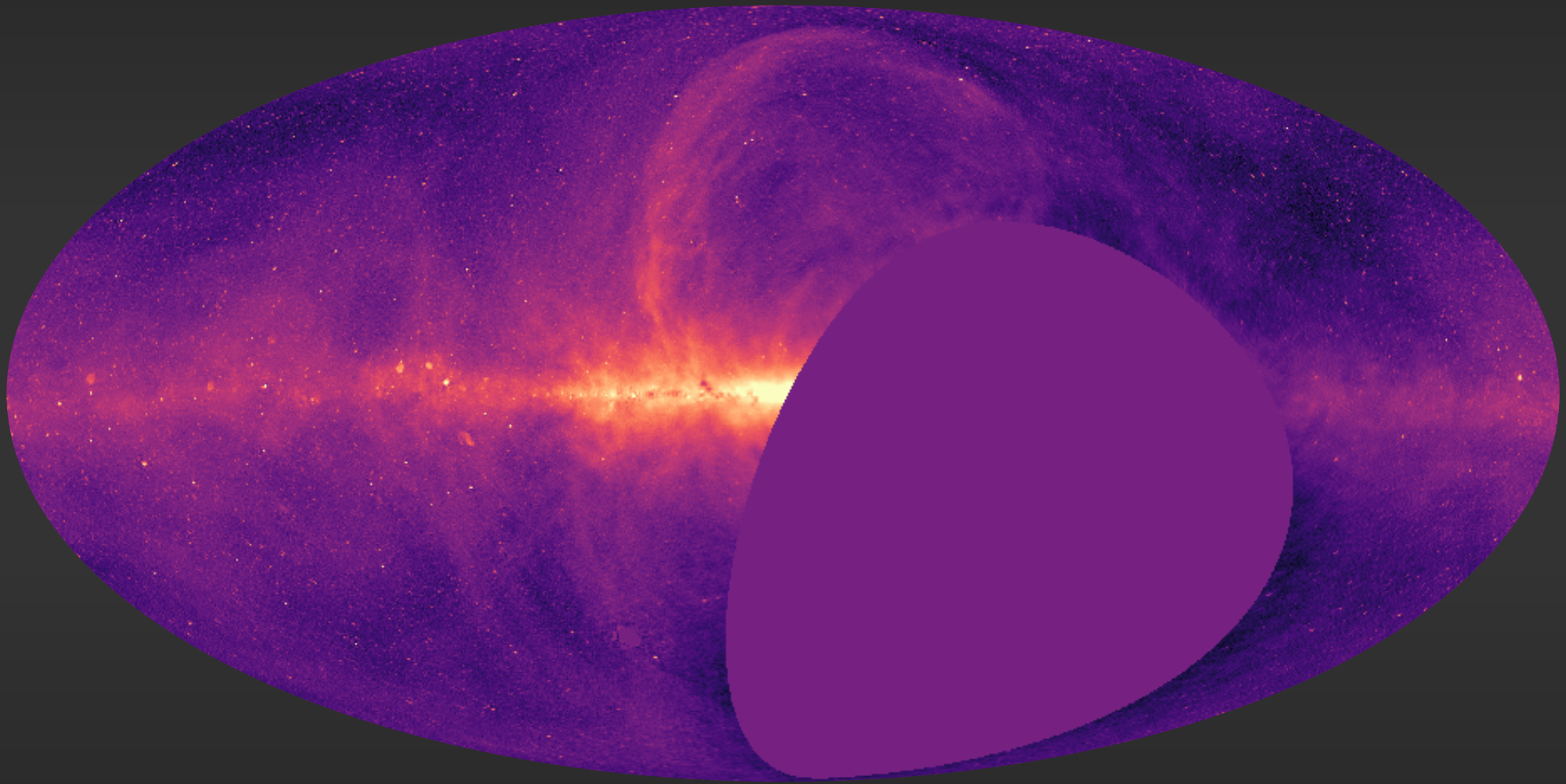
Eastwood et al. (in prep.)

41.760 MHz



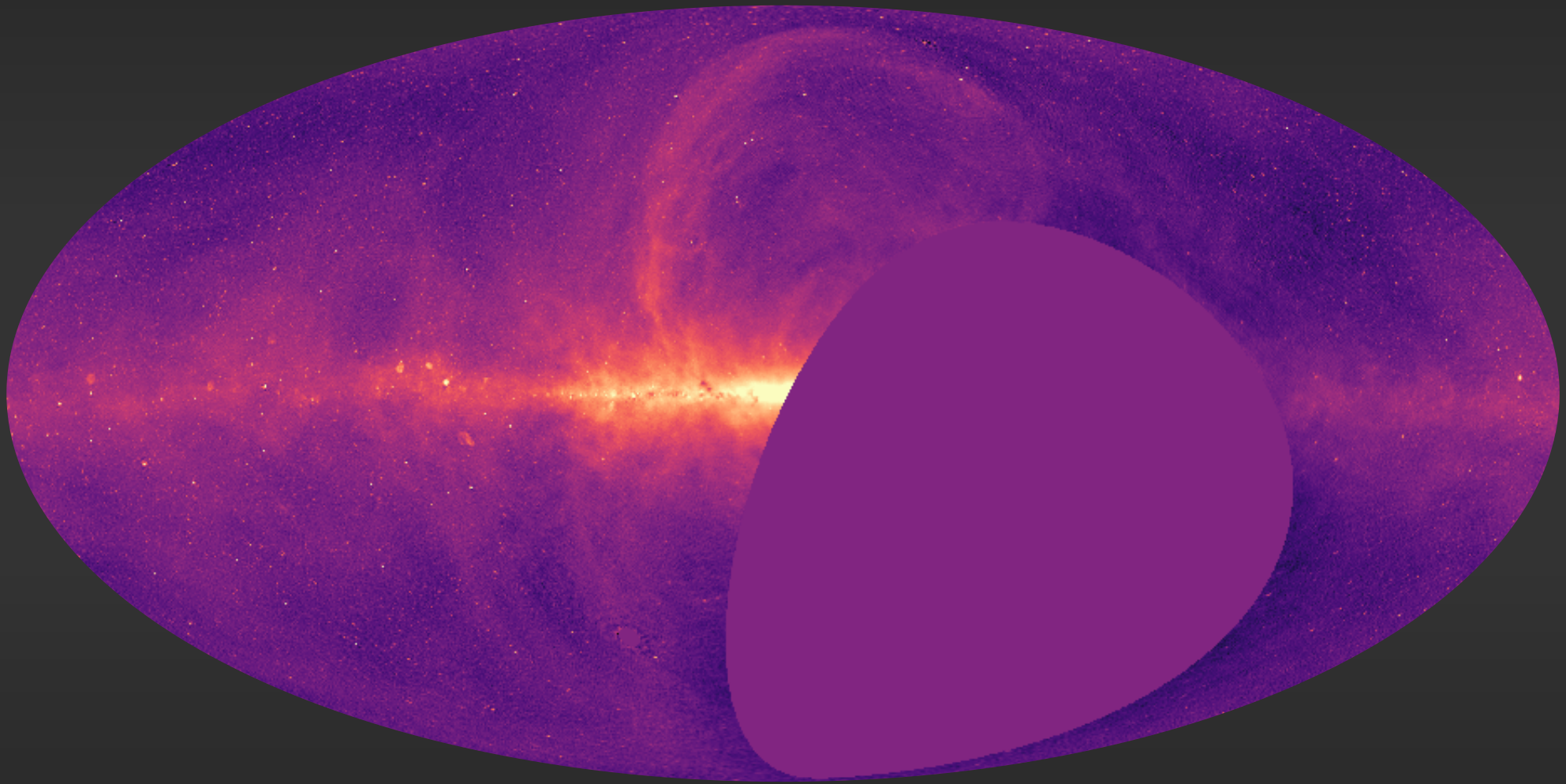
Eastwood et al. (in prep.)

46.992 MHz



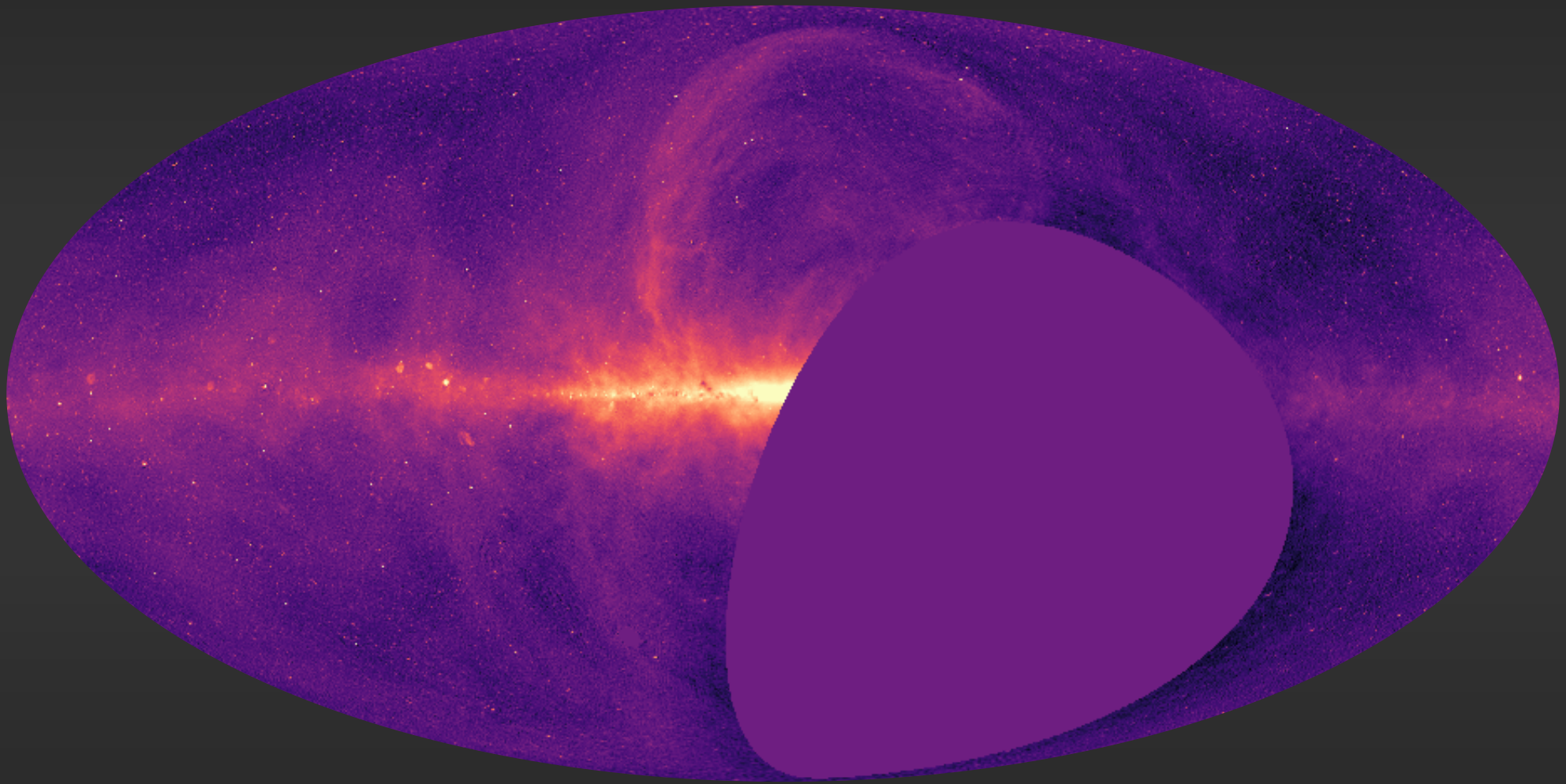
Eastwood et al. (in prep.)

52.224 MHz



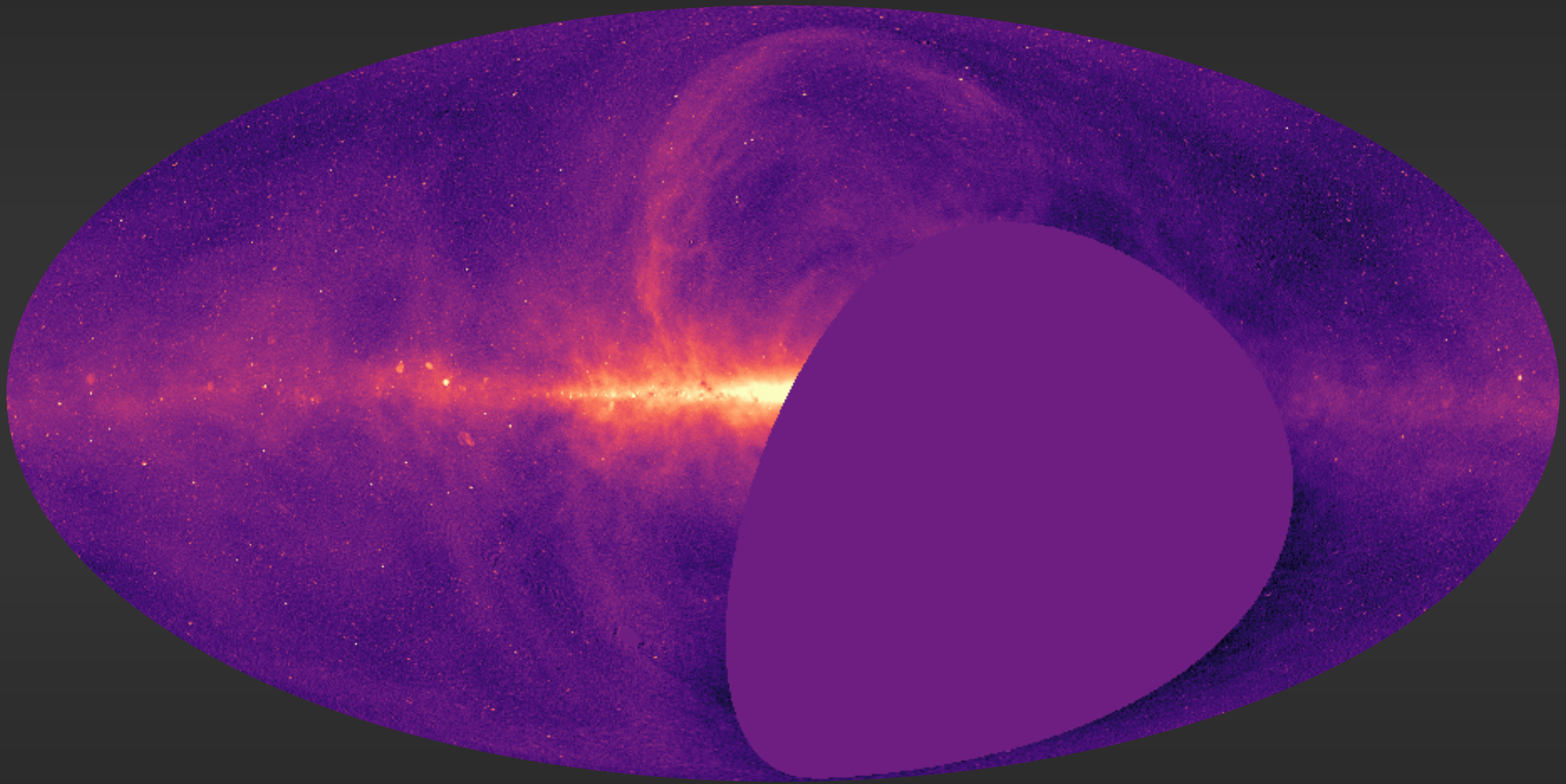
Eastwood et al. (in prep.)

57.456 MHz



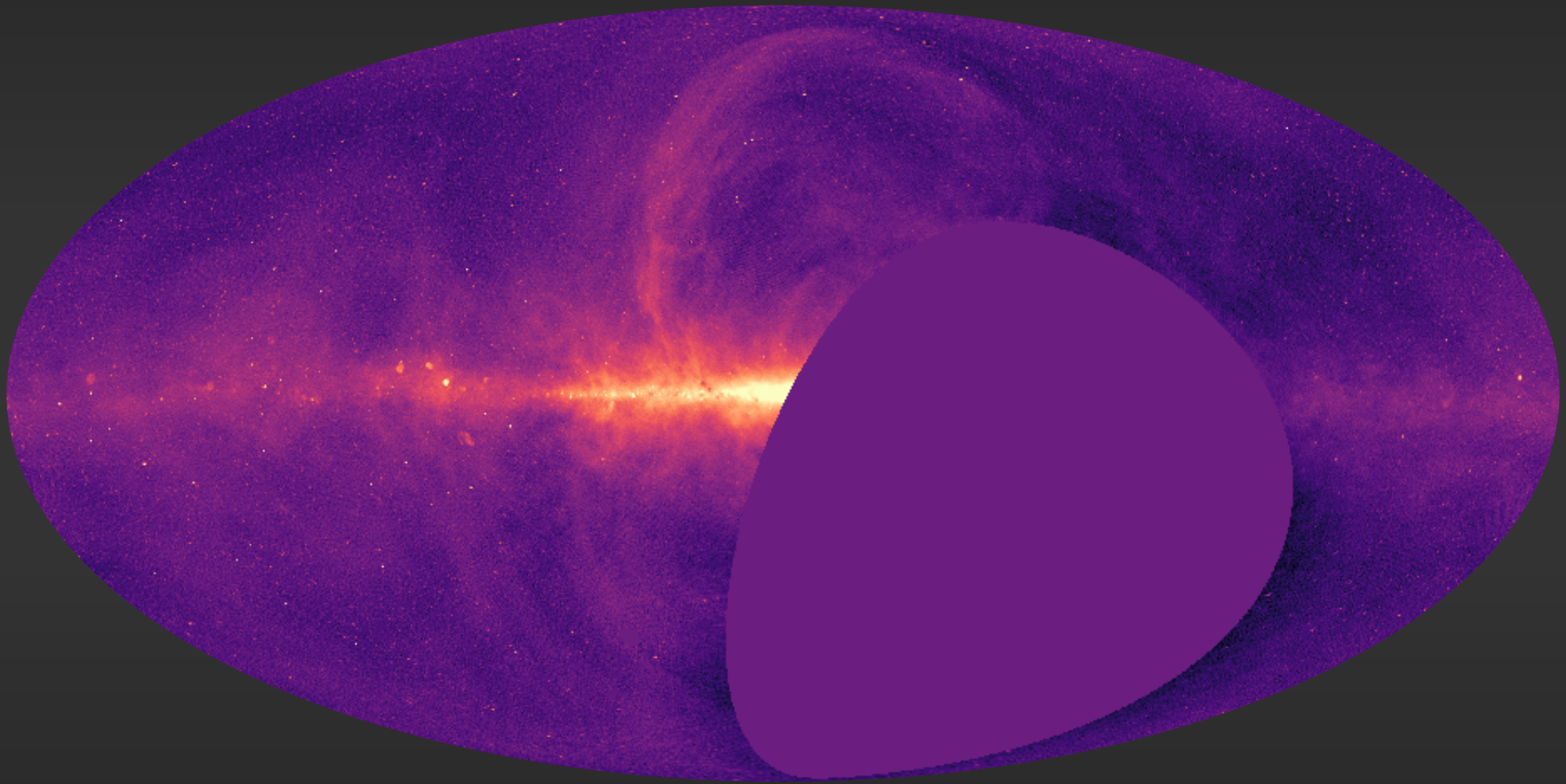
Eastwood et al. (in prep.)

62.688 MHz



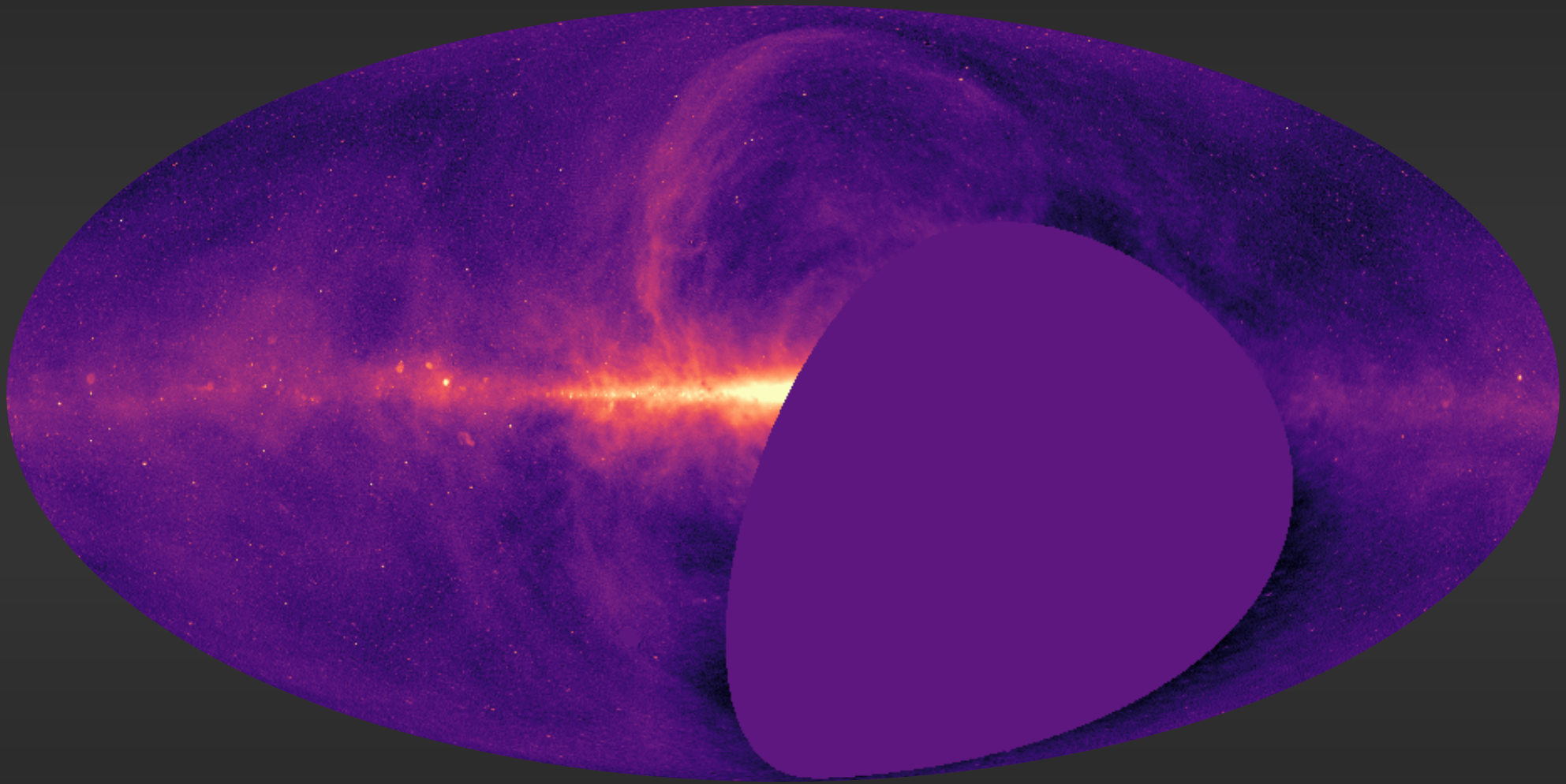
Eastwood et al. (in prep.)

67.920 MHz



Eastwood et al. (in prep.)

73.152 MHz



Eastwood et al. (in prep.)