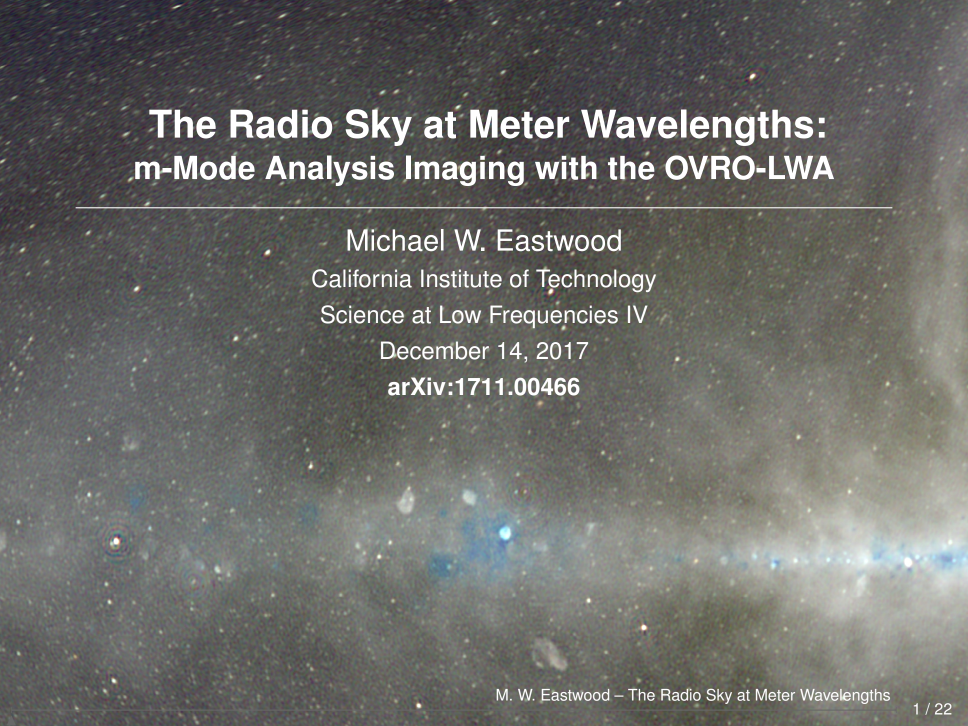

The Radio Sky at Meter Wavelengths:
m-Mode Analysis Imaging with the OVRO-LWA

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Science at Low Frequencies IV
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OVRO

- David Woody
- James Lamb
- OVRO staff

JPL

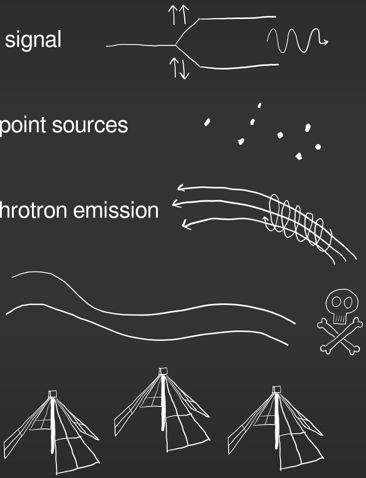
- Larry D'Addario
- Joe Lazio

and the rest of the LWA team

The OVRO-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



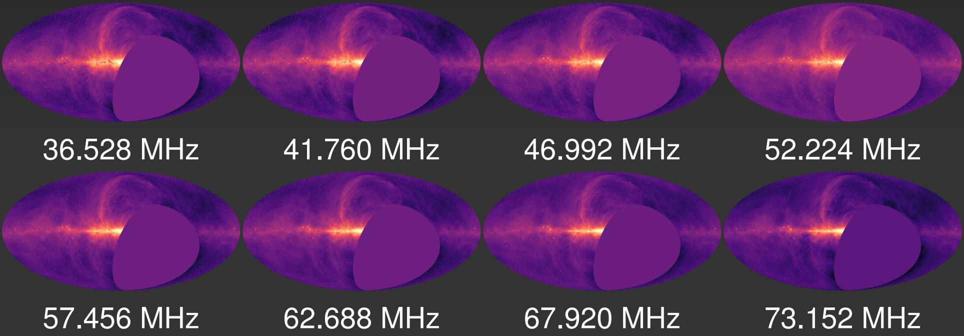
Cosmological signal

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. (2017)

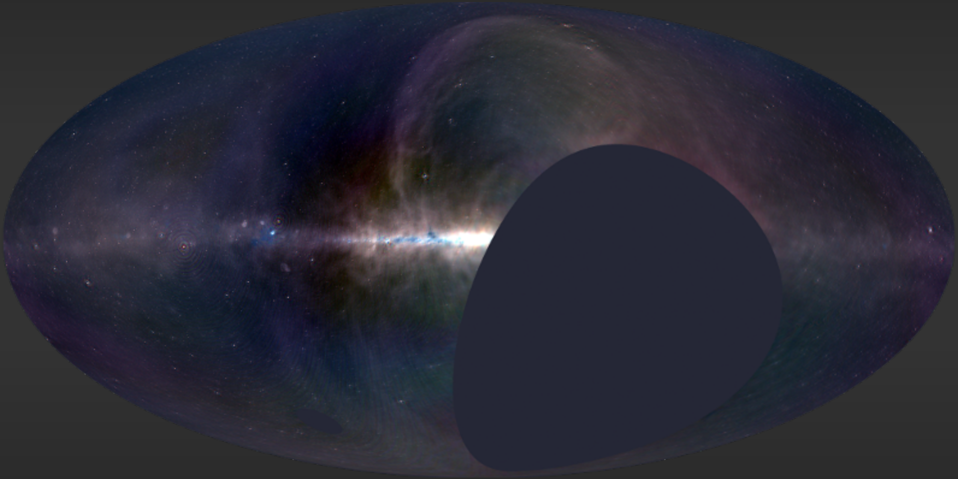
`https://lambda.gsfc.nasa.gov/product/foreground/ovrolwa_radio_maps_info.cfm`

Map Properties

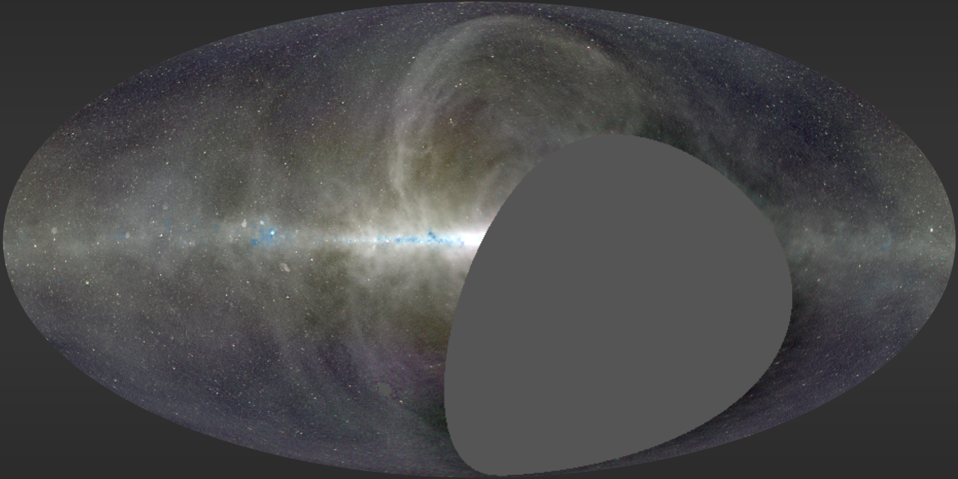
	Frequency	Bandwidth	FWHM	Noise	
#	MHz	kHz	arcmin	K	mJy/beam
1	36.528	24.	18.5	595.	799.
2	41.760	24.	17.2	541.	824.
3	46.992	24.	16.3	417.	717.
4	52.224	24.	15.6	418.	814.
5	57.456	24.	15.4	354.	819.
6	62.688	24.	15.3	309.	843.
7	67.920	24.	15.3	281.	894.
8	73.152	24.	15.7	154.	598.

Eastwood et al. (2017)

Science at Low Frequencies III



Science at Low Frequencies IV



Eastwood et al. (2017)

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

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

$$\begin{aligned}\text{visibility} &\rightarrow \textsf{ sidereal time Fourier transform}\\ \text{sky brightness} &\rightarrow \textsf{ spherical harmonic transform}\\ (\text{beam}) \times (\text{fringe pattern}) &\rightarrow \textsf{ spherical harmonic transform}\end{aligned}$$

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

Shaw et al. (2014, 2015)

m-Mode Analysis Fundamentals

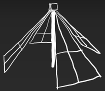
$$\boldsymbol{v} = \boldsymbol{B}\boldsymbol{a} + \text{noise}$$

$\boldsymbol{v}$ 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

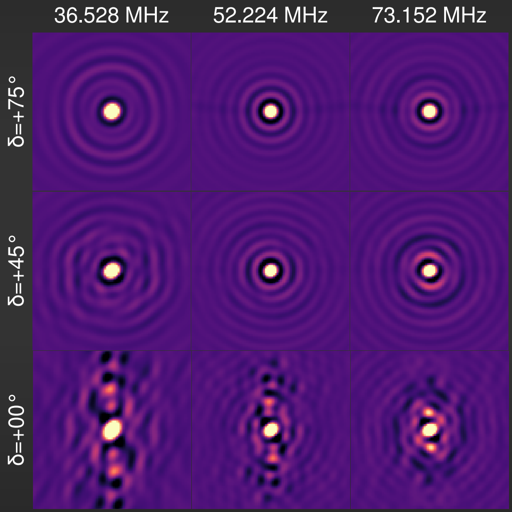
$$\boldsymbol{v} = \boldsymbol{B}\boldsymbol{a} + \text{noise}$$

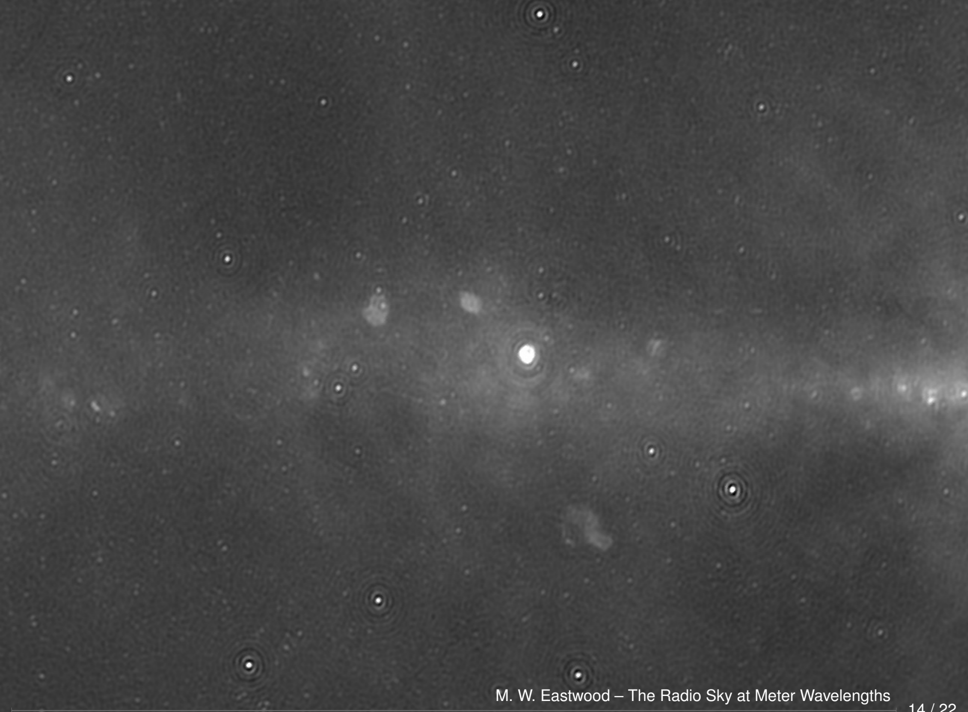
Goal: Estimate $\boldsymbol{a}$ given the observations $\boldsymbol{v}$.
Challenge: B is singular.

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





Advantages and Disadvantages

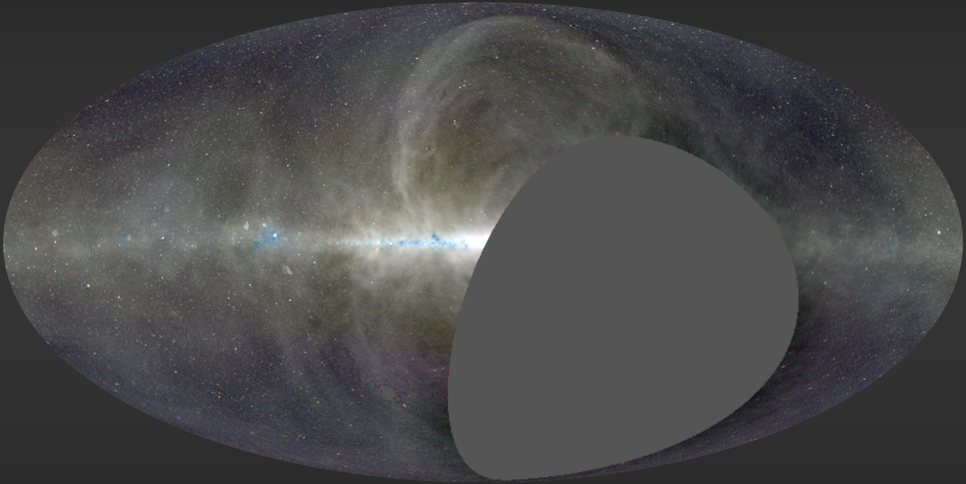
Advantages

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

Disadvantages

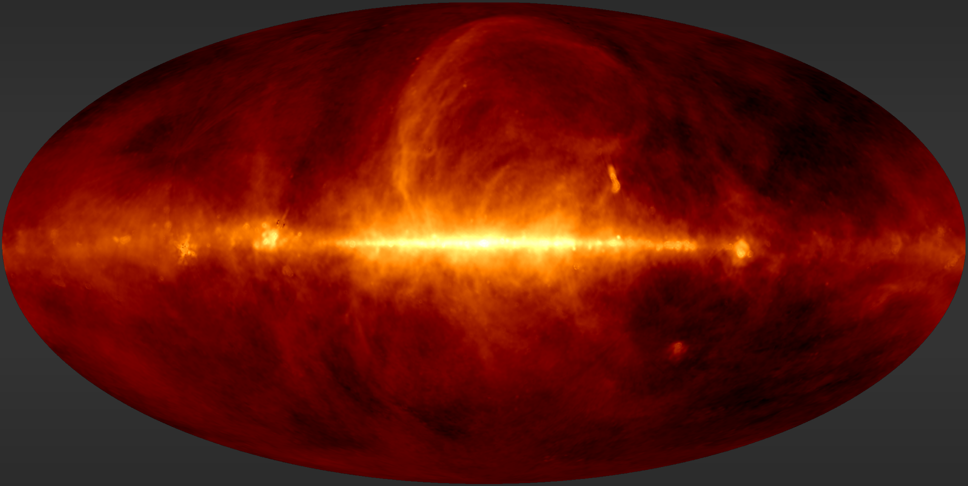
- Matrix equation is block diagonal, but still large!
- 500 GB/frequency channel (!)
- Rapid ionospheric changes break assumptions

Comparison with Haslam 408 MHz



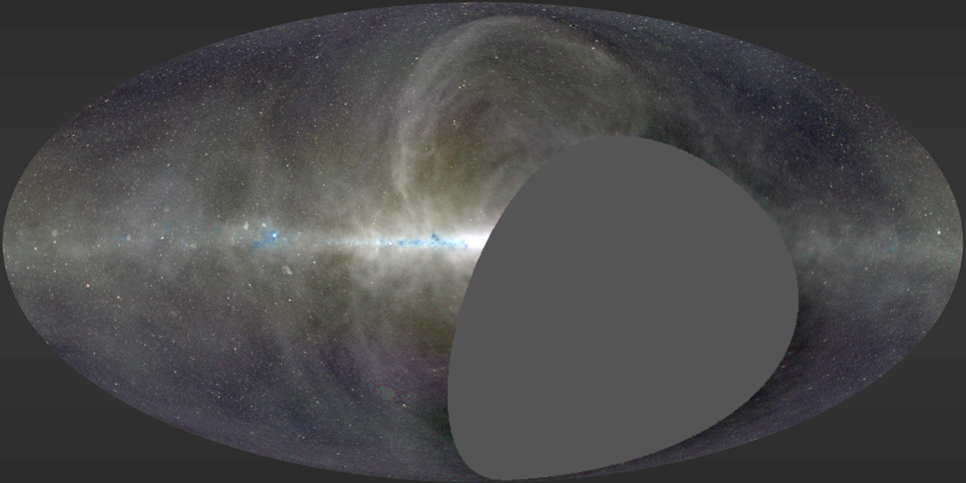
Eastwood et al. (2017)

Comparison with Haslam 408 MHz



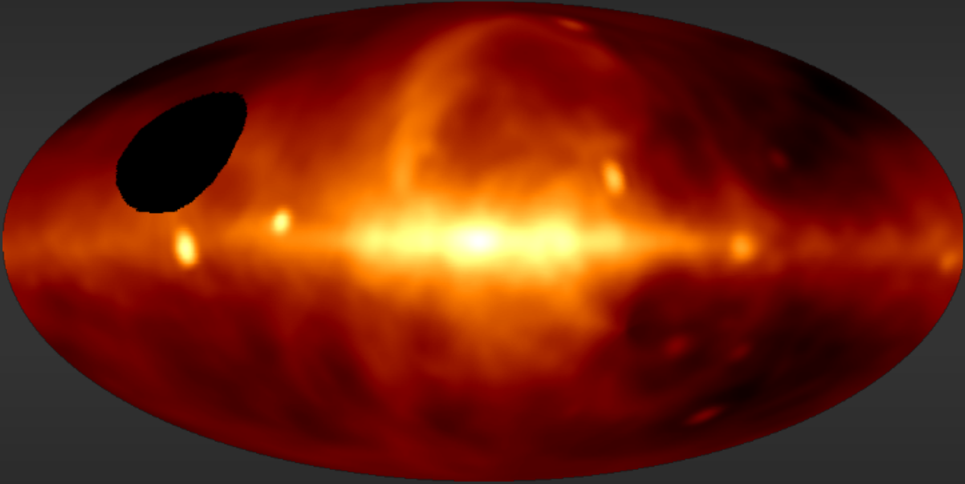
Haslam et al. (1981, 1982)

Comparison with Guzmán 45 MHz



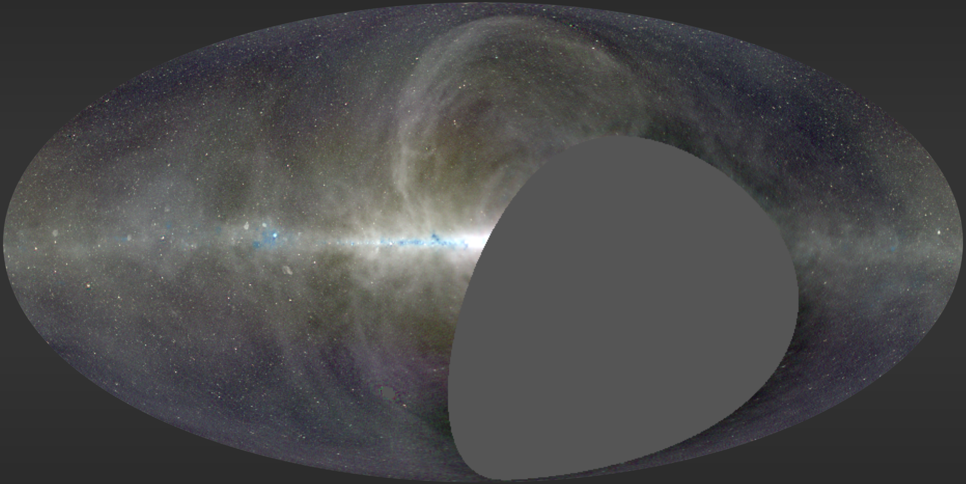
Eastwood et al. (2017)

Comparison with Guzmán 45 MHz



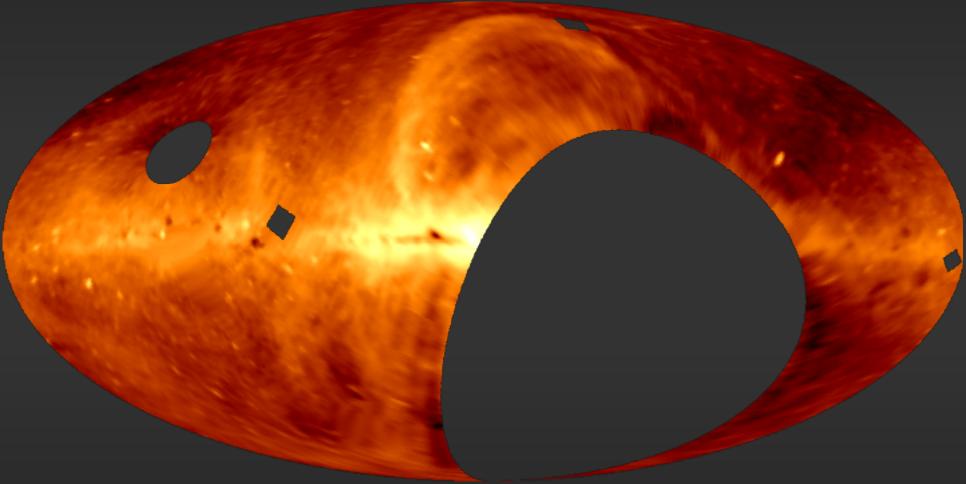
Guzmán et al. (2011)

Comparison with DRAO 22 MHz



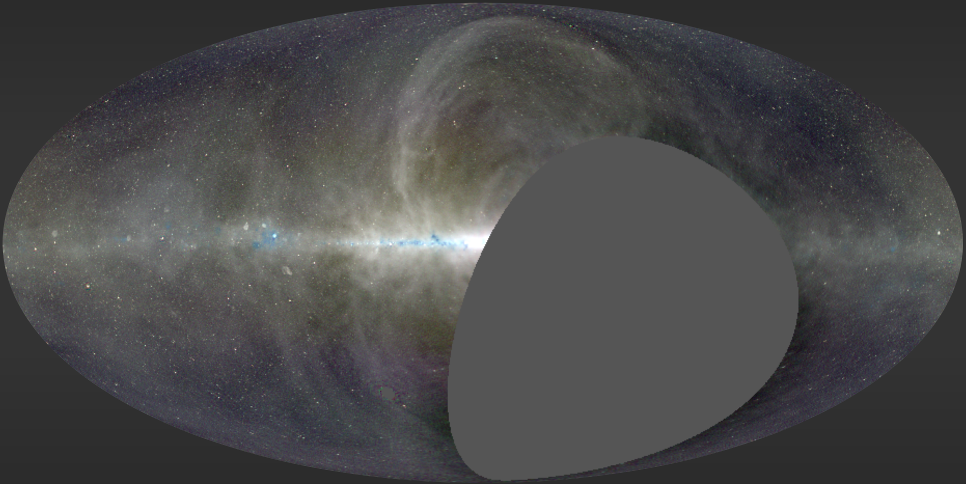
Eastwood et al. (2017)

Comparison with DRAO 22 MHz



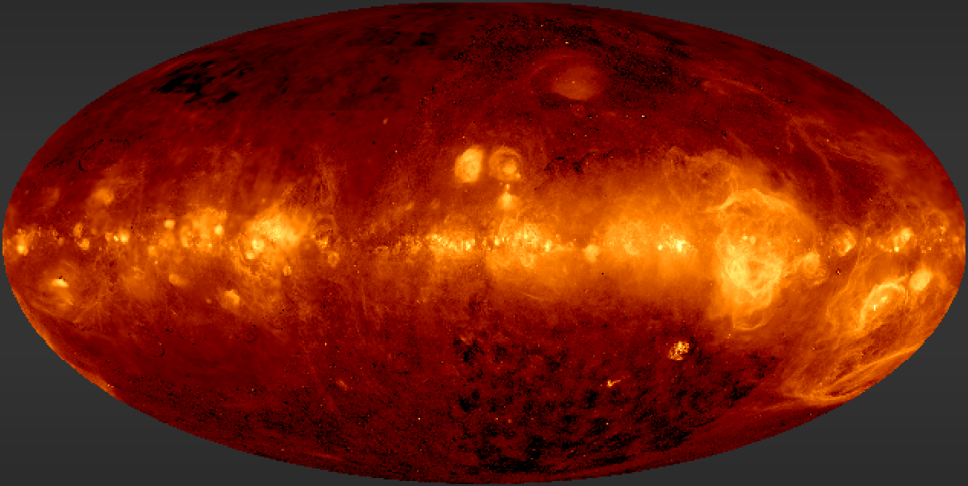
Roger et al. (1999)

Comparison with Finkbeiner Hα

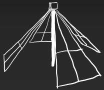


Eastwood et al. (2017)

Comparison with Finkbeiner Hα



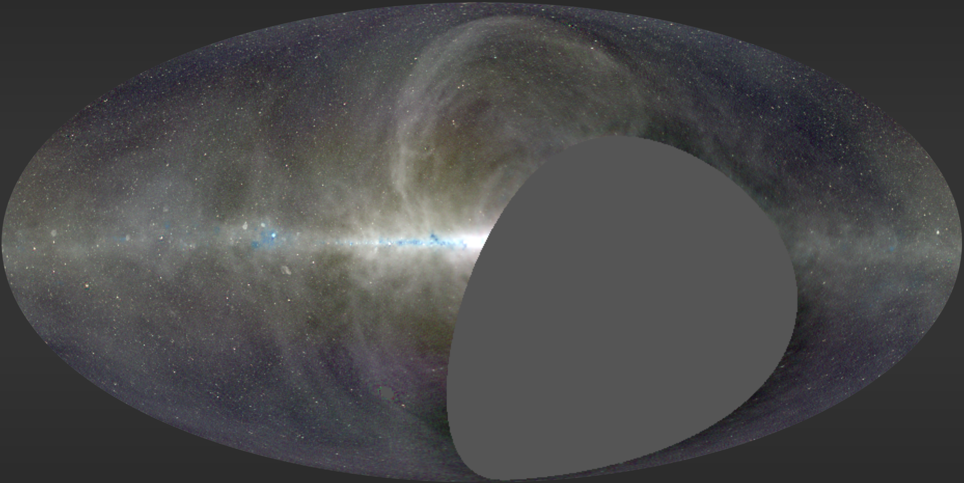
Finkbeiner et al. (2003)



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.

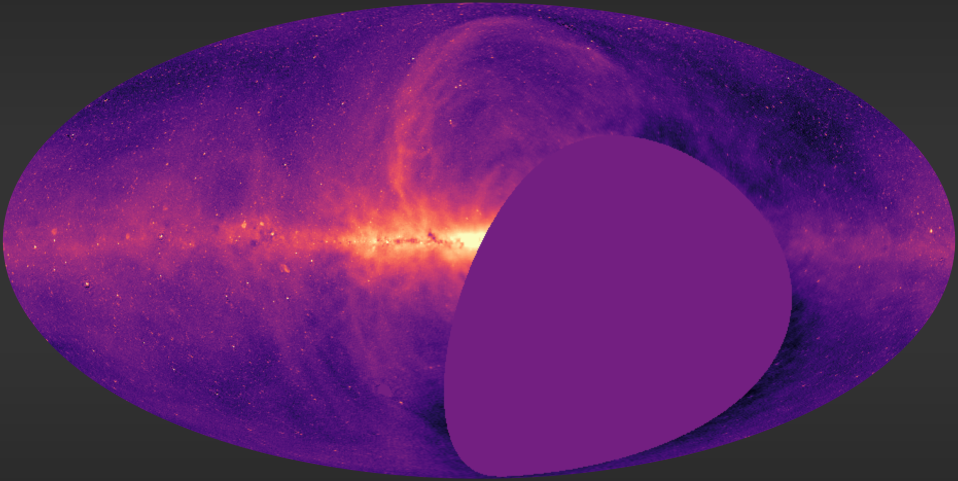
Three-Color Map



Eastwood et al. (2017)

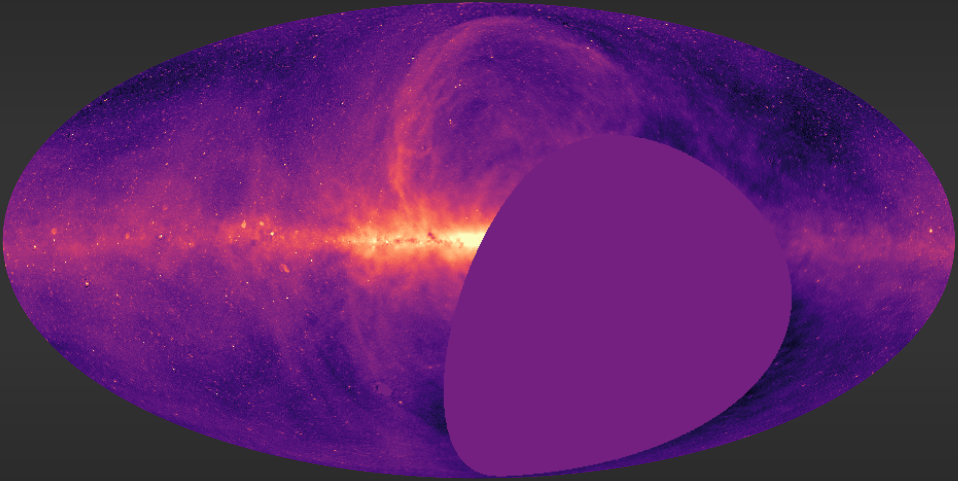
Backup Slides

36.528 MHz



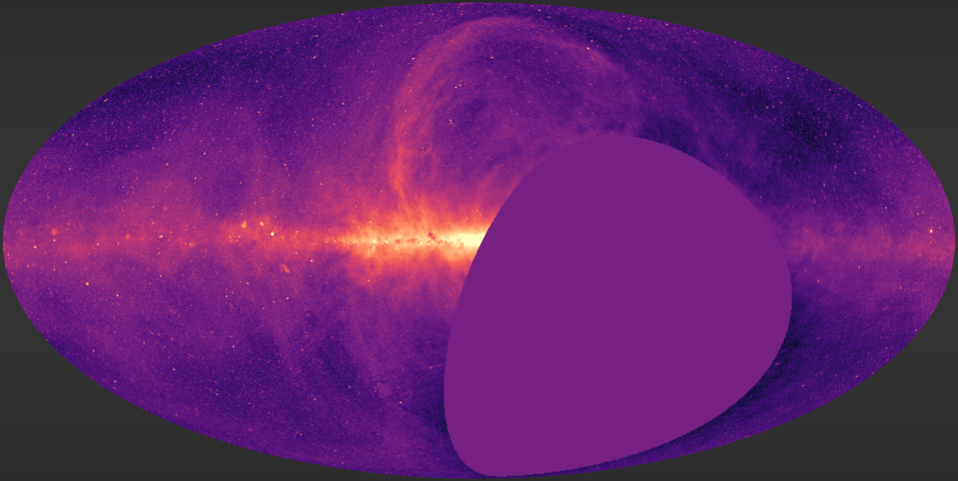
Eastwood et al. (2017)

41.760 MHz



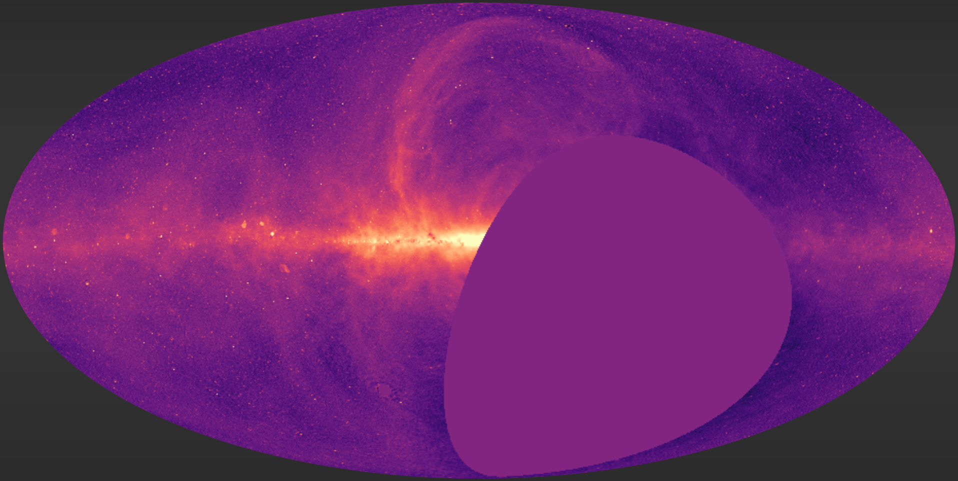
Eastwood et al. (2017)

46.992 MHz



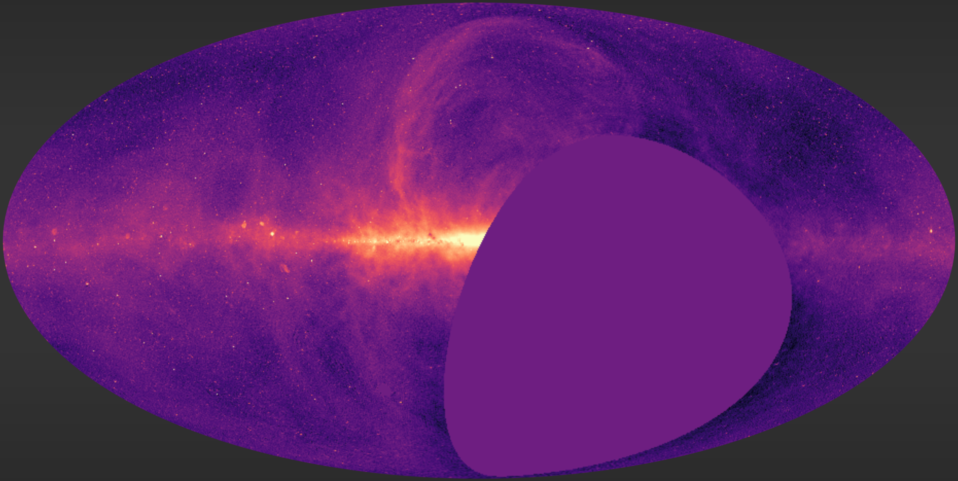
Eastwood et al. (2017)

52.224 MHz



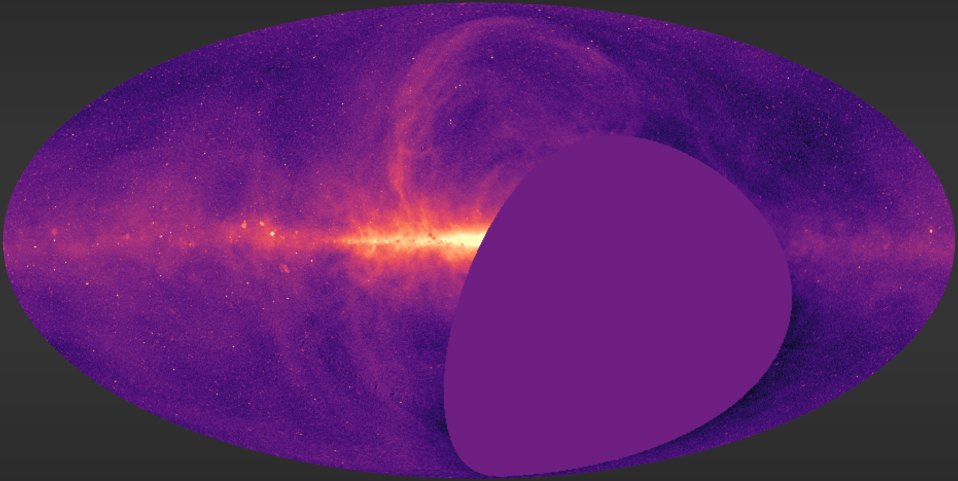
Eastwood et al. (2017)

57.456 MHz



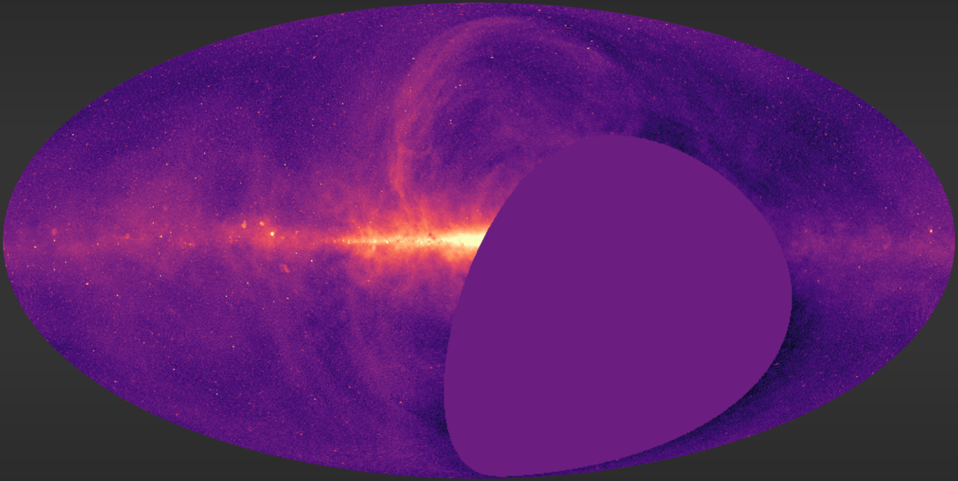
Eastwood et al. (2017)

62.688 MHz



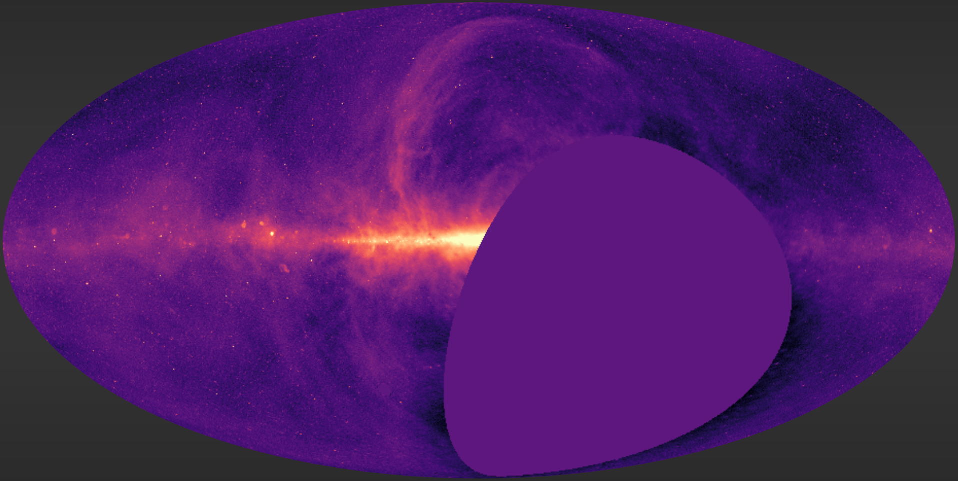
Eastwood et al. (2017)

67.920 MHz



Eastwood et al. (2017)

73.152 MHz



Eastwood et al. (2017)