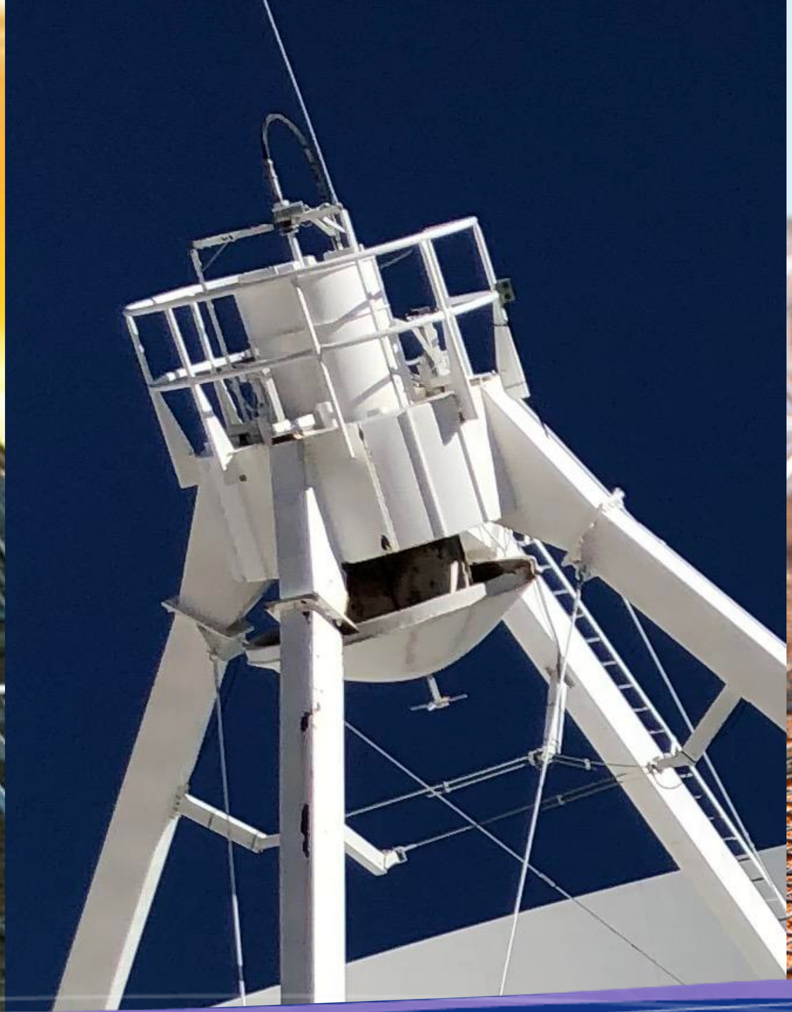
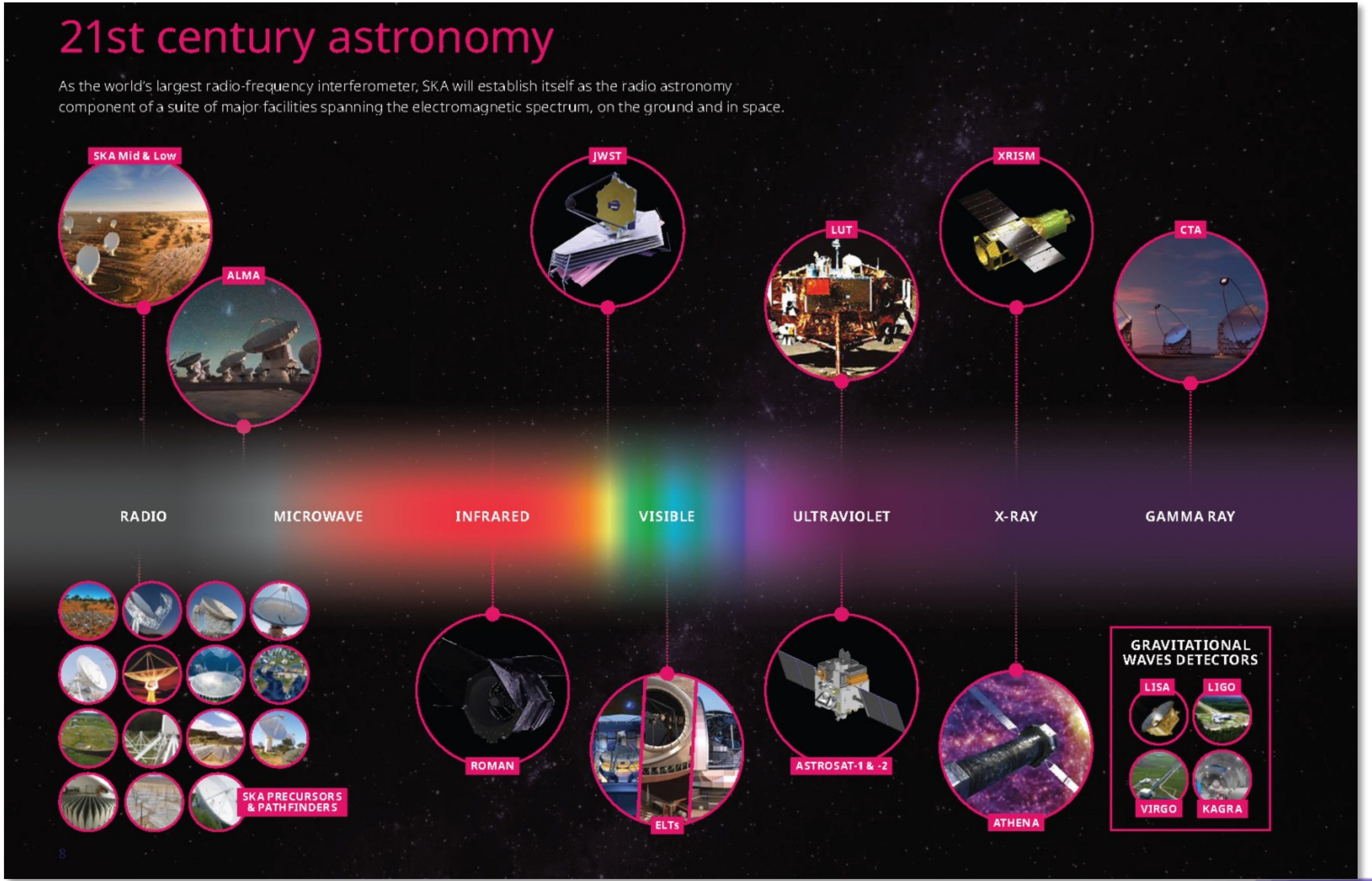




Low Frequency Radio Astronomy

Steven Tremblay (NRAO)

Low Frequency: What do we mean by 'Low'?

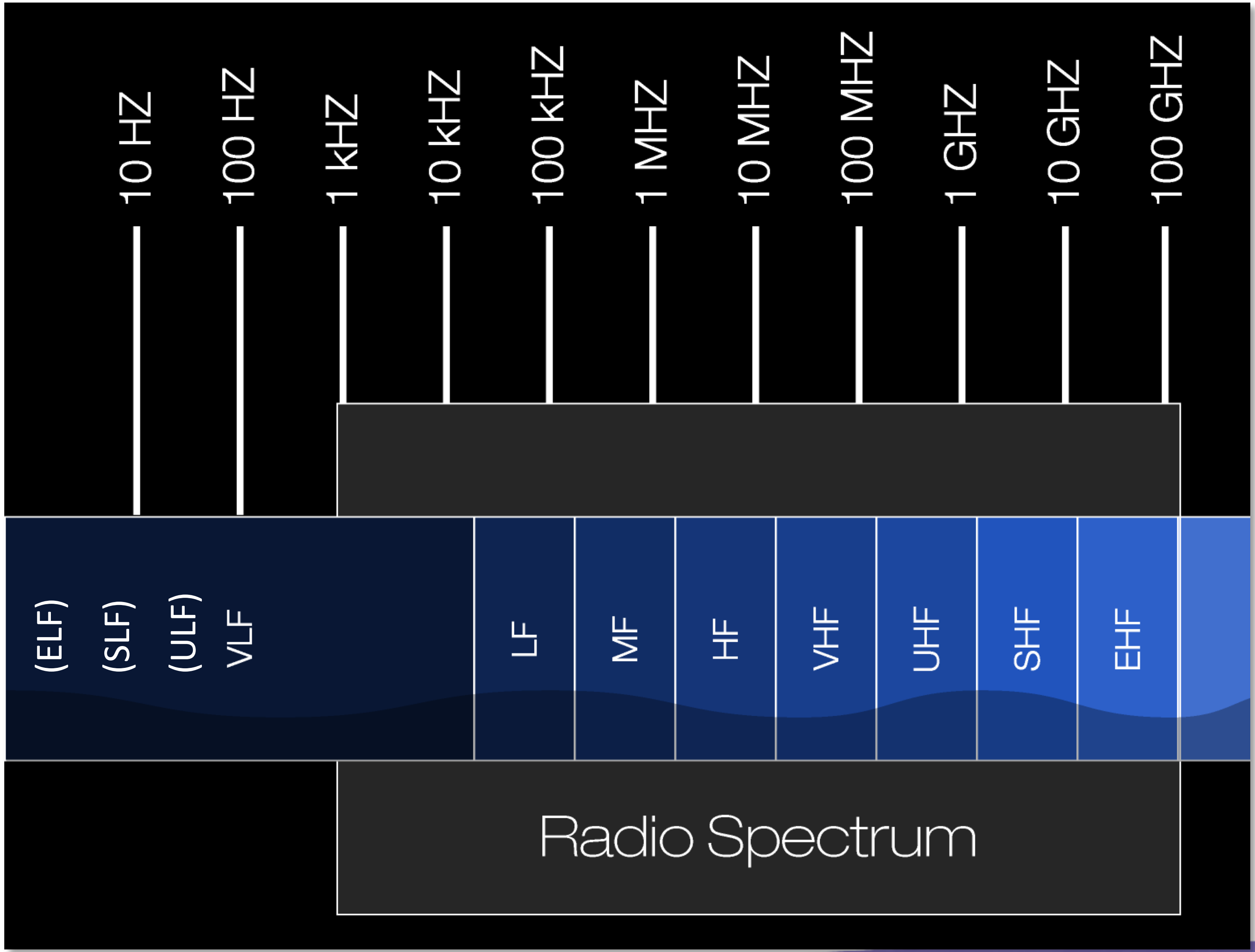


Credit: SKAO

Low Frequency: What do we mean by 'Low'?

Radio Spectrum:

- Very Low Frequency (3 kHz – 30 kHz)
- Low Frequency (30 kHz – 300 kHz)
- Medium Frequency (300 kHz – 3 MHz)
- High Frequency (3 MHz – 30 MHz)
- Very High Frequency (30 MHz – 300 MHz)
- Ultra High Frequency (300 MHz – 3 GHz)
- Super High Frequency (3 GHz – 30 GHz)
- Extremely High Frequency (30 GHz – 300 GHz)



Credit: Adapted from NASA

Low Frequency:
The Good, the Bad, and the Ugly

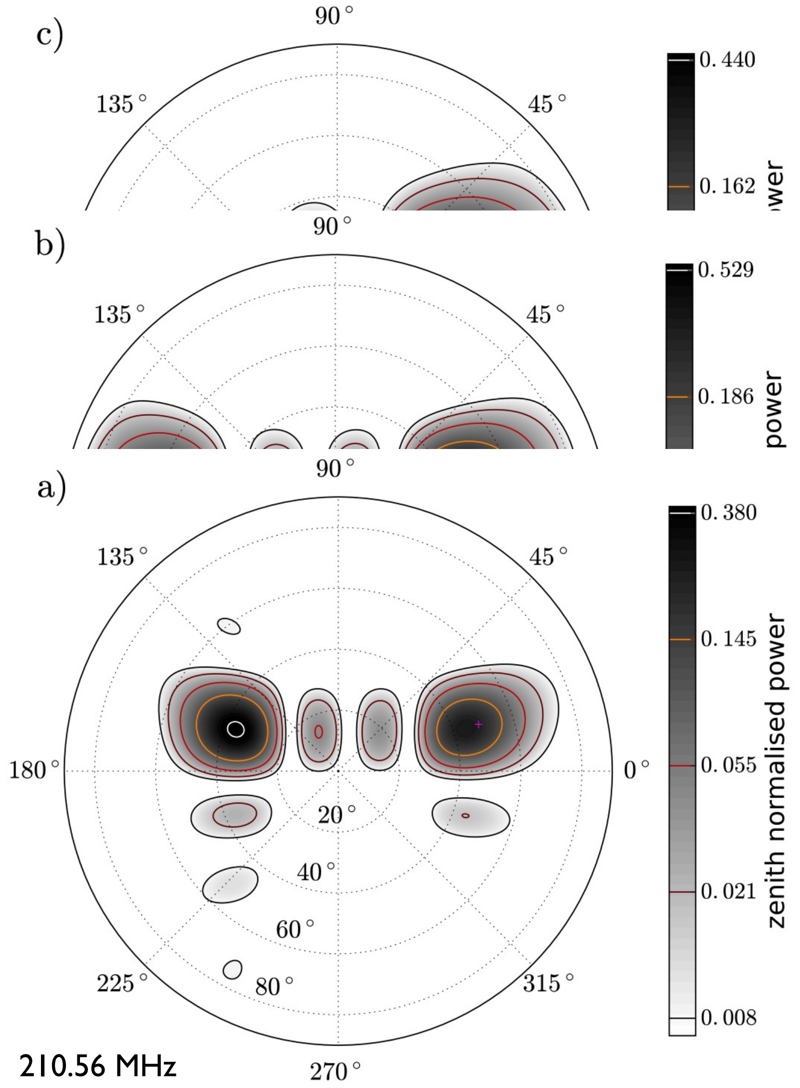
Low Frequency: The Good, the Bad, and the Ugly

- The Good:
  - Large Field of View (FoV)
    - Fantastic for Survey Science!
  - Sensitive to large-scale structure
    - Resolution: $\frac{\Lambda}{A_{\{eff\}}}$ where $\Lambda \sim$ 30cm – 30m
  - Simpler Systems
    - Not all systems need mechanical pointing
    - Often can digitize from DC up to frequency (No Local Oscillator)
    - Less expensive*
    - Reduced maintenance
    - Fantastic for hands on learning
  - Can be easier to build large collecting area

Low Frequency: The Good, the Bad, and the Ugly

- The Bad:
  - Can have highly direction dependent gains
    - MWA example on right
  - Can be computationally expensive
    - Therefore possibly actually expensive (or evens out)
  - Wide FoV means more affected by source confusion
    - Challenging to calibrate
  - Can be RFI prevalent environment
    - Satellites
    - Powerlines

Meyers et al. 2017



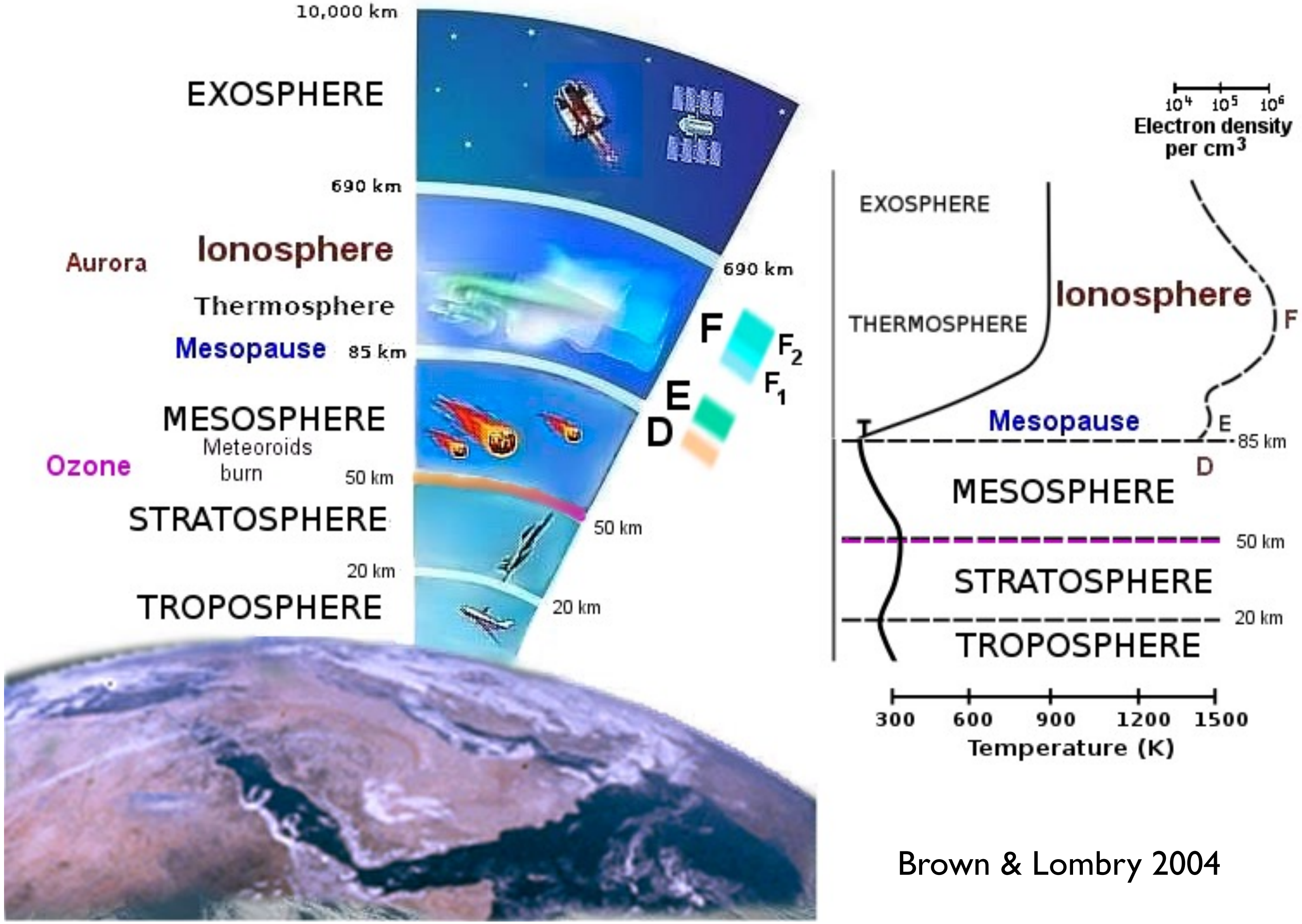
Low Frequency: The Good, the Bad, and the Ugly

- The Ugly:
  - Ionosphere

"After you find a bigger task to dread, the little chores will be a breeze. Here's another reason to have a devil on hand. It does make all the little demons more . . . bearable."
— **Chuck Palahniuk, Haunted**

Ionosphere

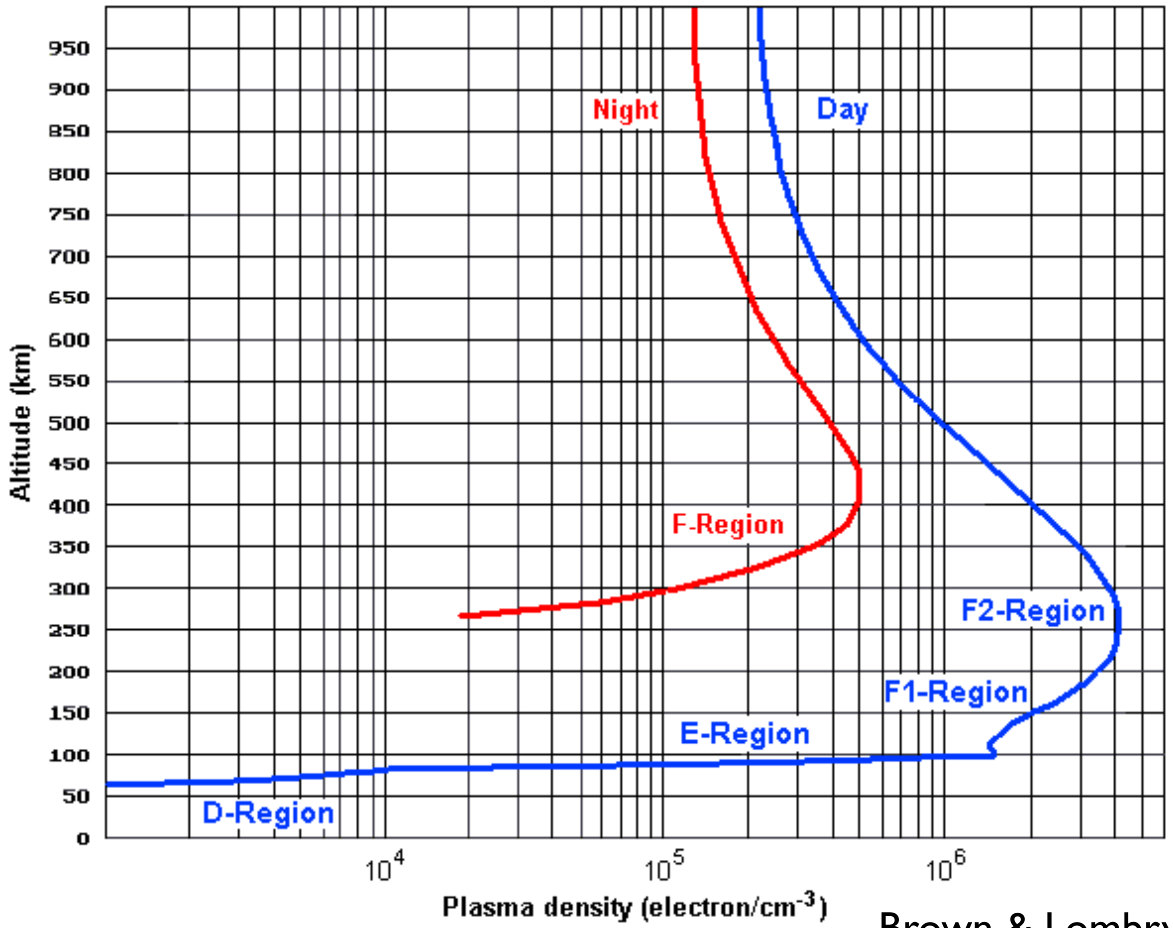
- Region of atmosphere between ~80 and ~600 km where extreme ultraviolet (EUV) and x-ray solar radiation ionizes the atoms and molecules thus creating a layer of electrons



Brown & Lombry 2004

Ionosphere

- Region of atmosphere between ~80 and ~600 km where extreme ultraviolet (EUV) and x-ray solar radiation ionizes the atoms and molecules thus creating a layer of electrons
- Time variable on multiple time-scales



Brown & Lombry 2004

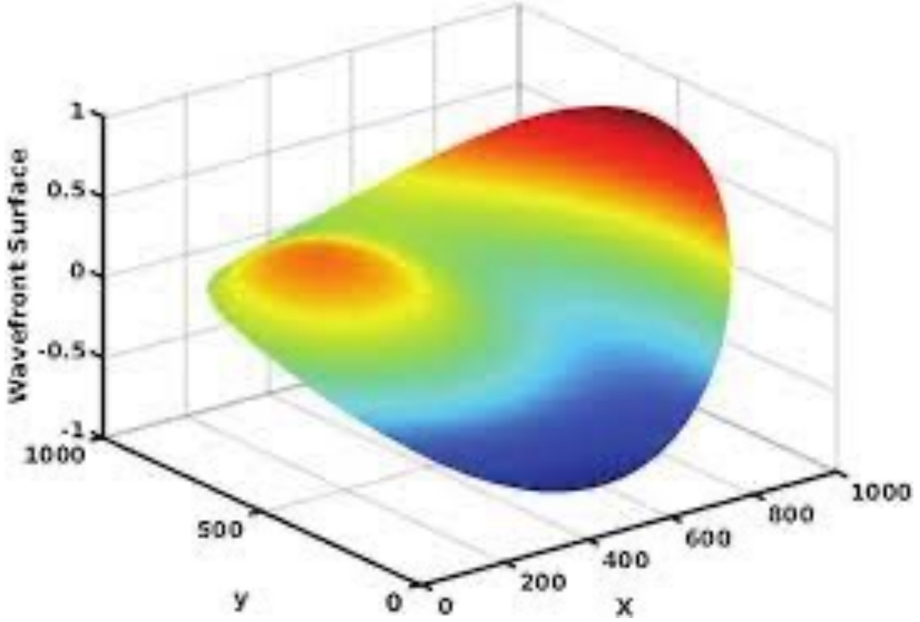
See Ian Heywood's second talk for what Dawn & Midnight wedges can look like!

Ionosphere: What does it do?

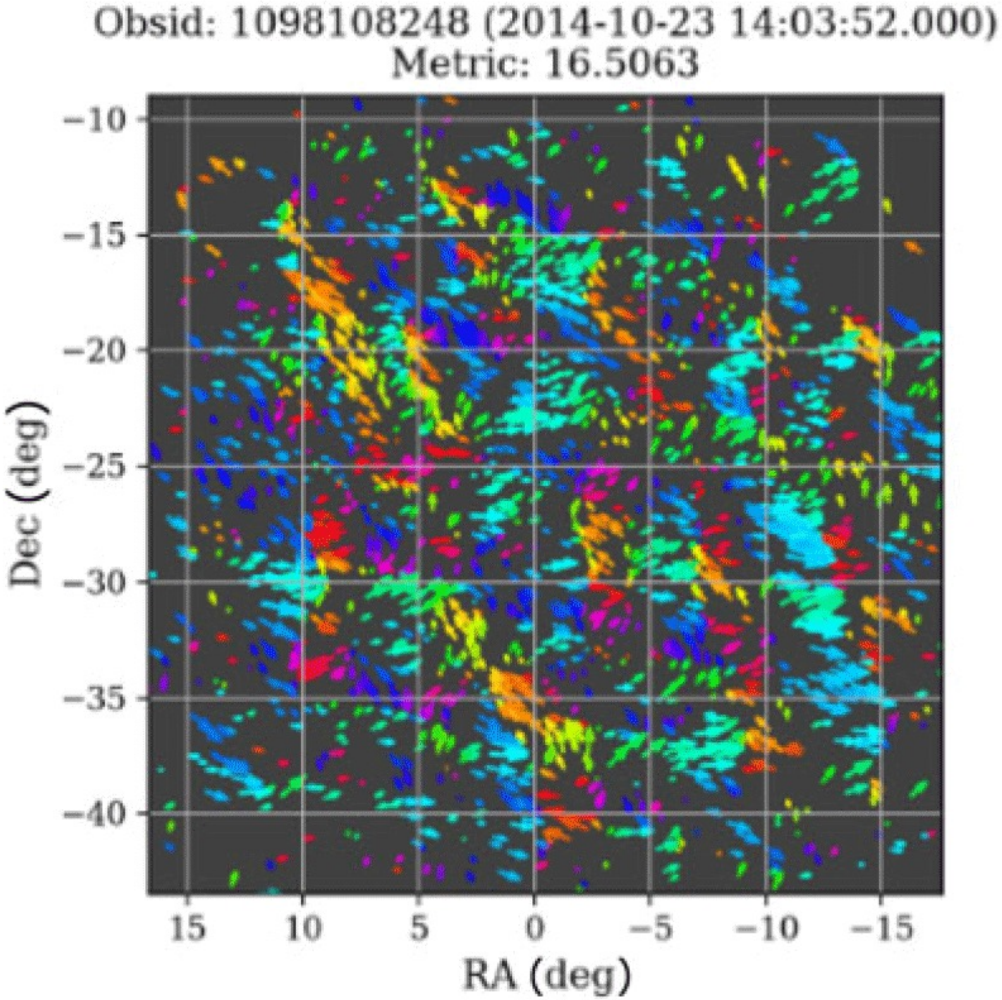
- Ionosphere is a charged plasma that your radio waves propagate through
- $\nu_p = \frac{e}{(2\pi)}\sqrt{\frac{N_e}{m_e \epsilon_0}} \approx 9\sqrt{n_e}\, kHz;\ \ n_e \approx 10^4 - 10^5 cm^{-3}$
  - $\nu_p \sim 10\ MHz$
- So? (Roughly)
  - $\nu < \nu_p$ Incoming waves are reflected (below 10MHz)
  - $\nu > \nu_p$ Incoming waves are refracted (10MHz – 10GHz)
    - Source Position Shifts / Image Distortion
    - Scintillates Flux Densities
    - Also plays havoc with the polarimetry
  - $\nu \gg \nu_p$ Incoming waves are not noticeably impacted (above 10GHz)

Ionosphere: What can we do?

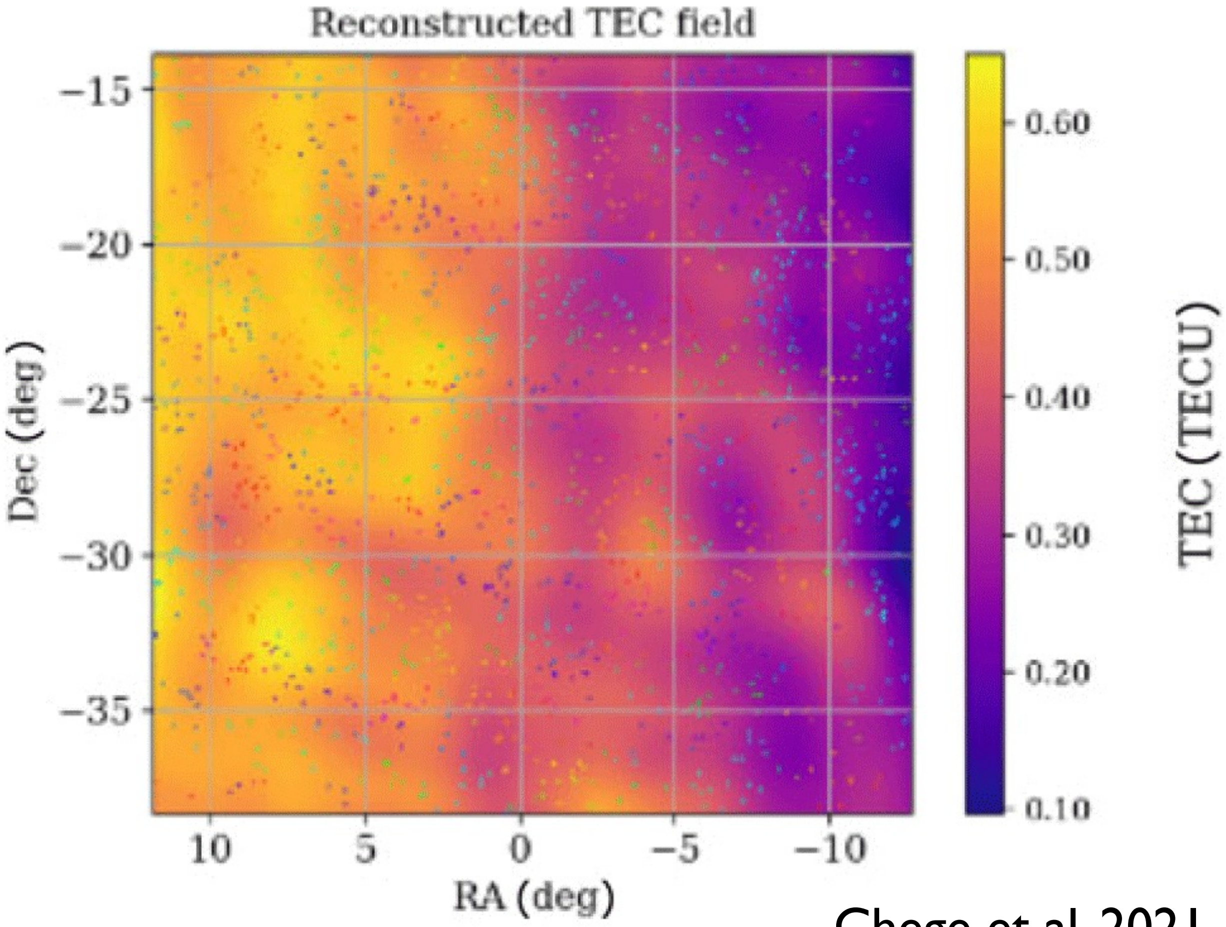
- Simple Models
  - Slab of constant thickness
  - Slab + Wedge
  - Slab + Wedge + Waves
- Time-variable Zernike Polynomial Phase Screen
  - 2D & 3D representations
  - Can be applied to
    - (l, m) grid
    - Visibilities
    - (u, v) plane + direction dependent gridding
- Use position offsets and image distortions as an input to your model



Ionosphere

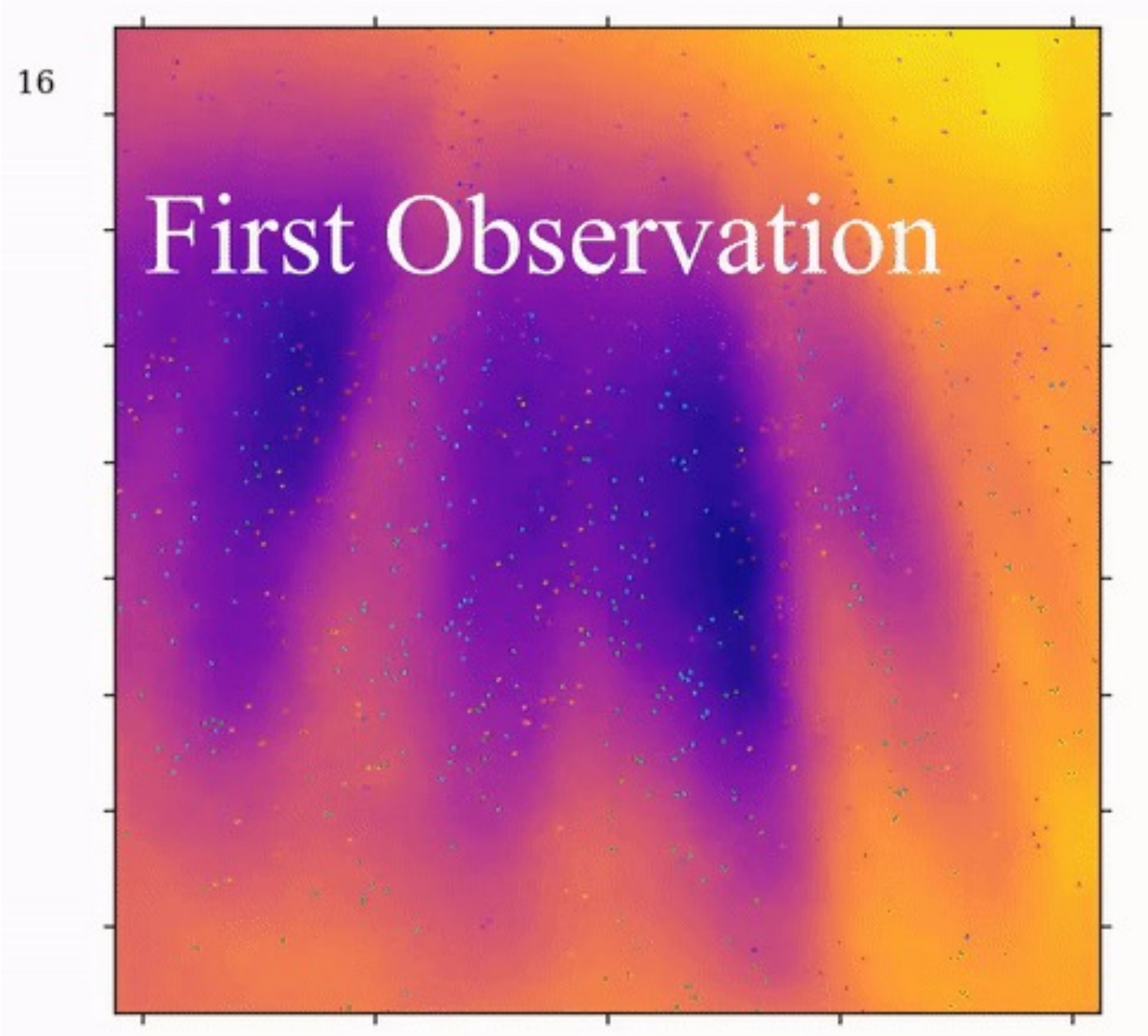


Vector source offsets
(154 MHz)



Chege et al. 2021

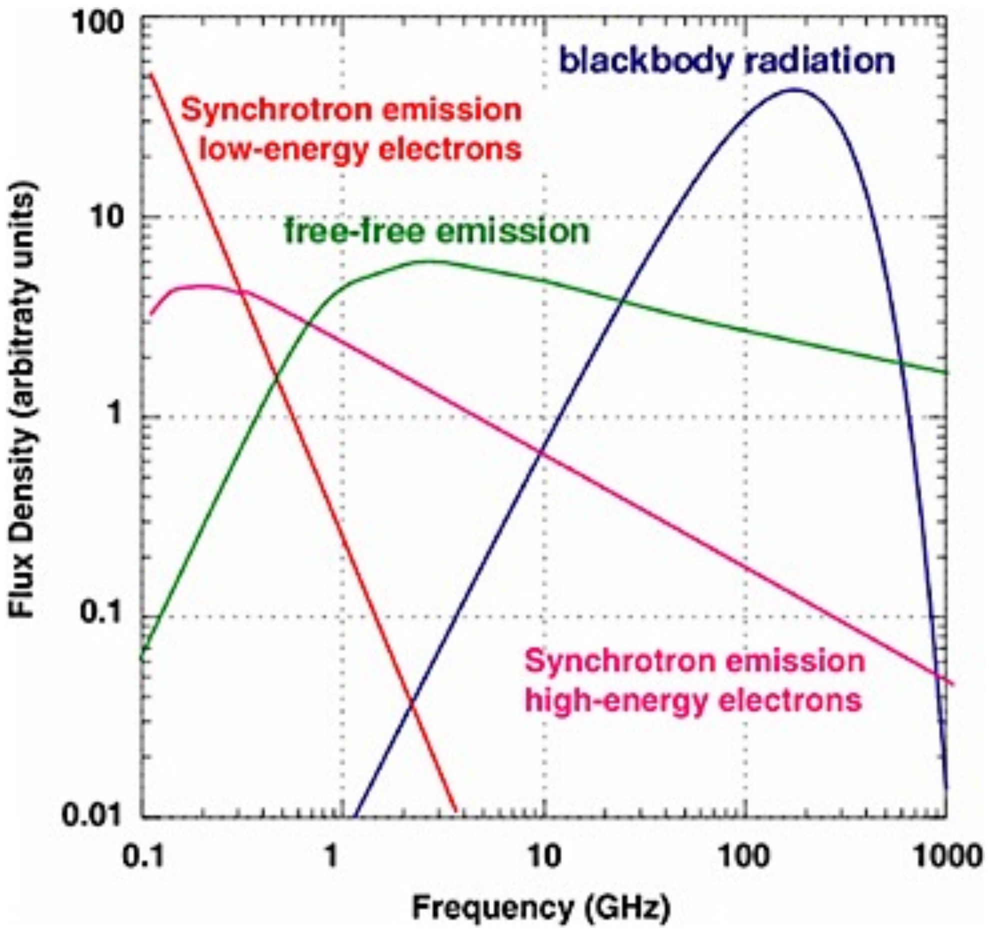
Ionosphere



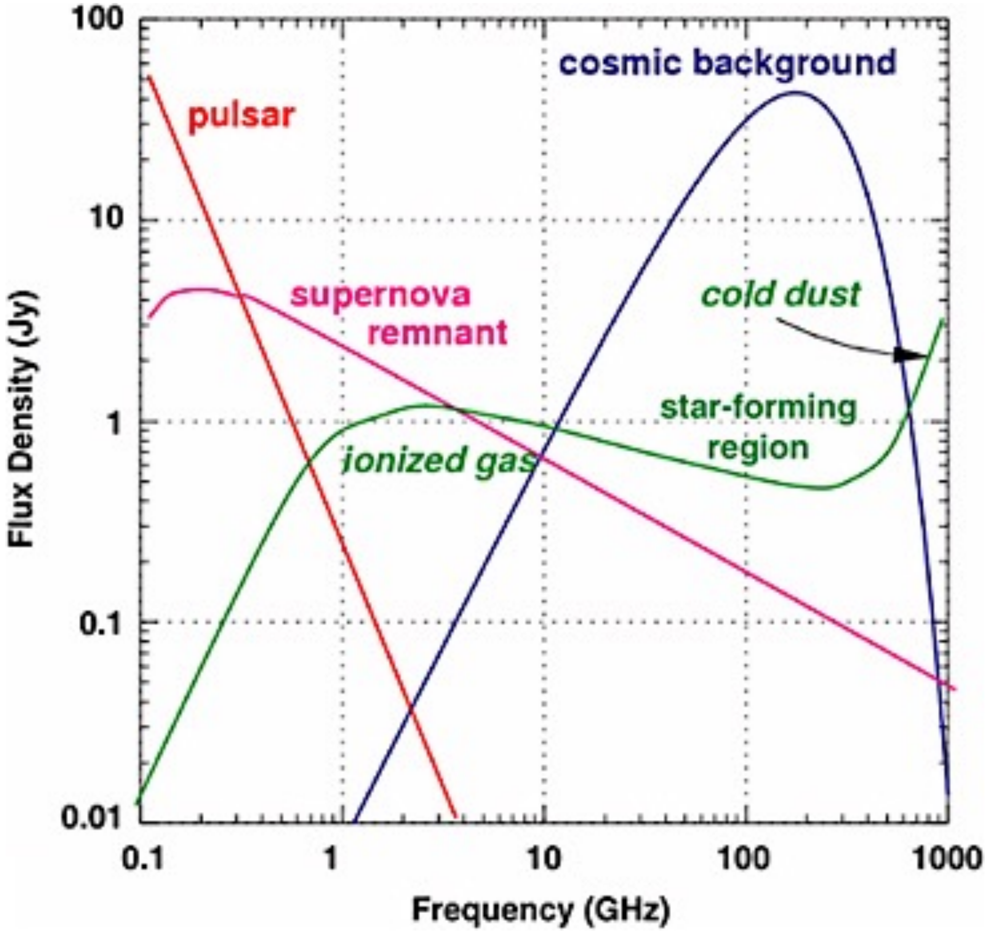
Credit: Chris Jordan

Low Frequency:
What are we looking at?

What emits at low frequency?

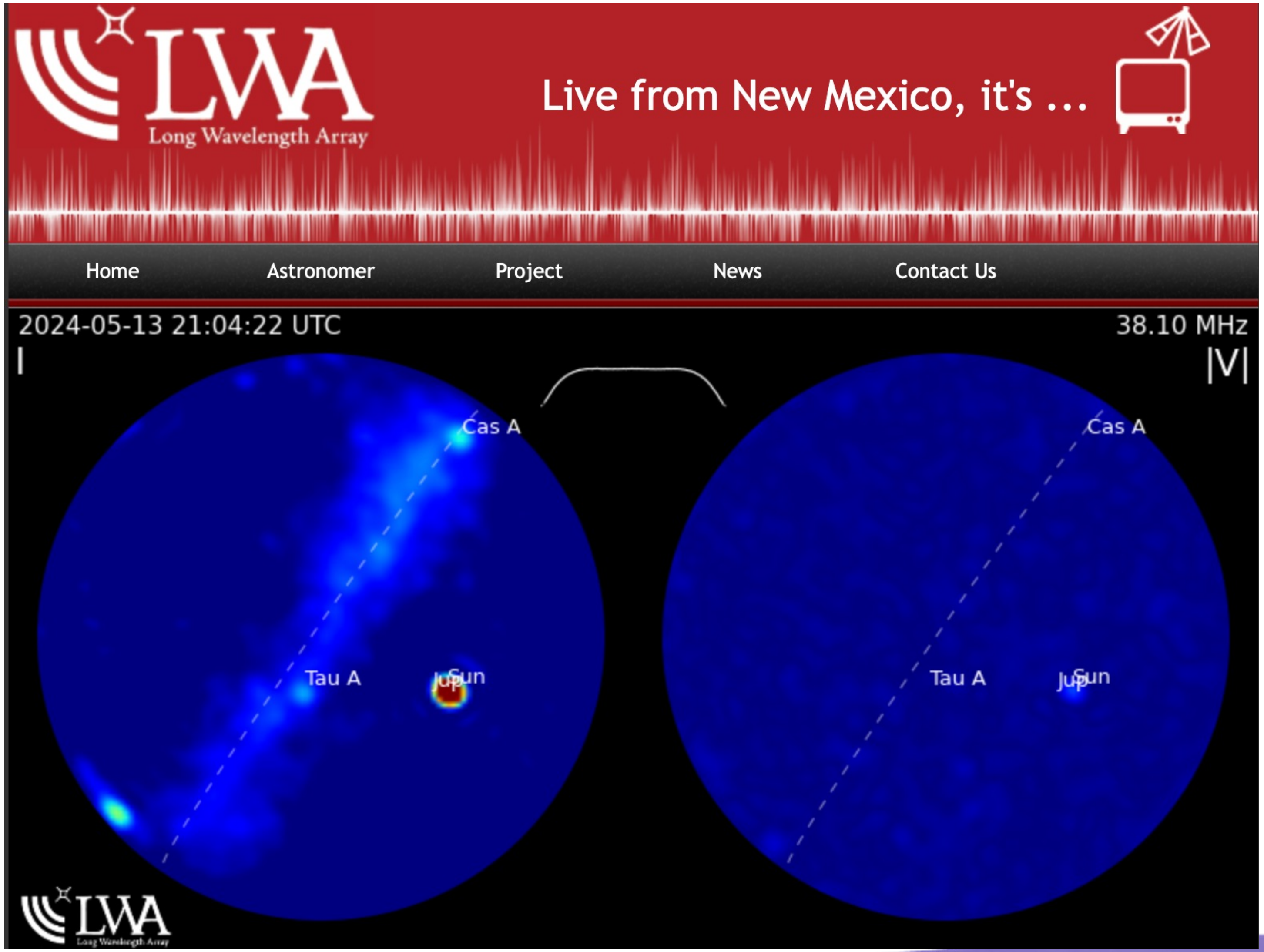


Handbook of Frequency Allocation and Spectrum Protection for Scientific Uses (2007)



What emits at low frequency?

https://leo.phys.unm.edu/~lwa/lwatv.html



Low frequency science

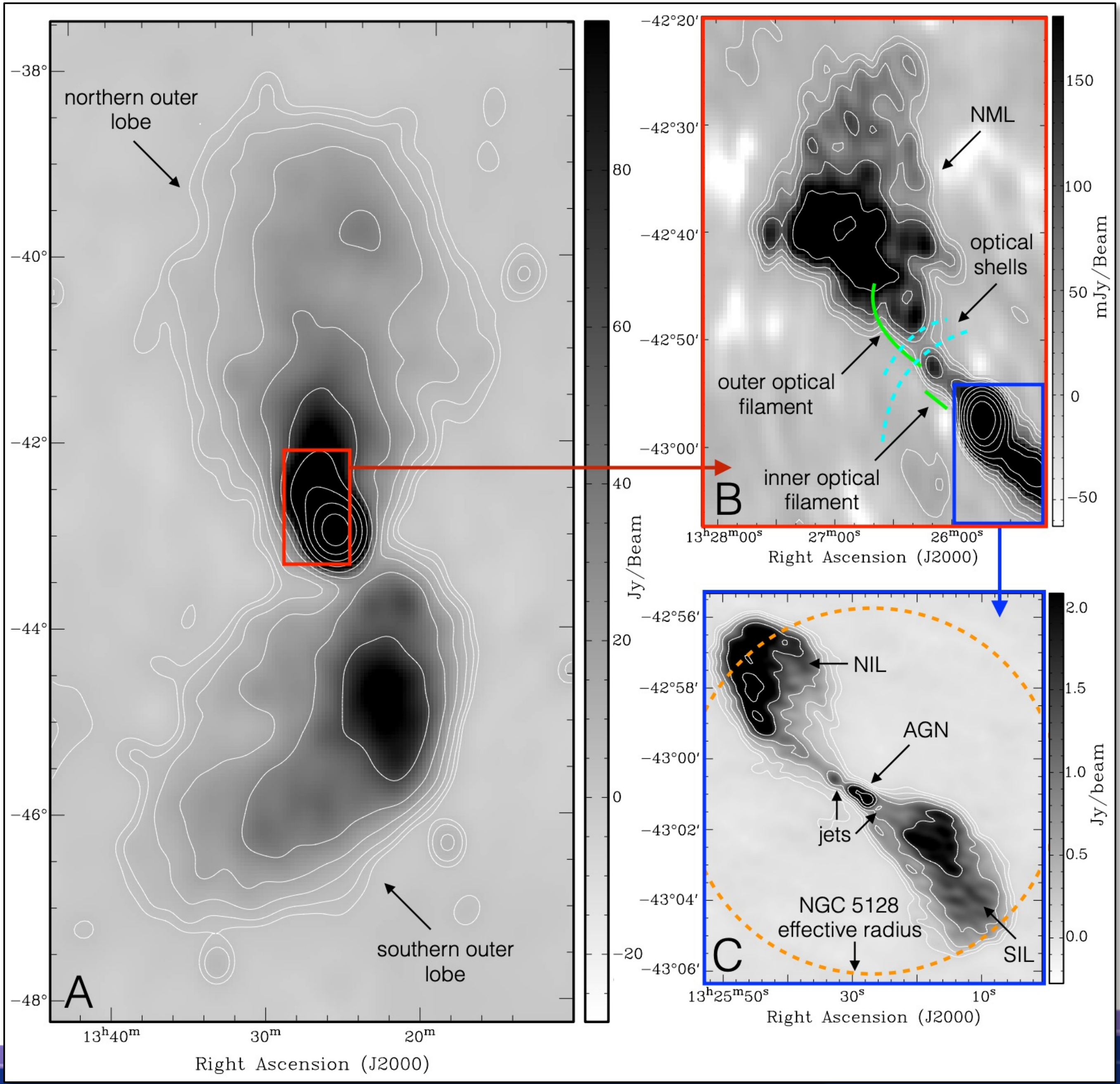
- Early Universe (EoR, Dark Ages)
- Pulsars (Surveys, MSPs, Single-pulse)
- Shocks / Turbulence / Jets (Active Galactic Nuclei, Supernova Remnants)
- Transients (Fast Radio Bursts, Tidal Disruption Events)
- Solar / Heliospheric
- Survey Science
- Ionospheric*
- Cosmic Ray
- Radio Recombination Lines / Spectral Lines
- Interstellar / Interplanetary Medium
- Serendipity
- Etc.

Imaging:

- Centaurus A imaged with the MWA 32 MHz bandwidth centered @154 MHz
- 9 deg extent
- ‘Science’ images from 112 seconds of data in a ‘drift scan’ mode

McKinley et al. 2017

McKinley & Matherne 2021

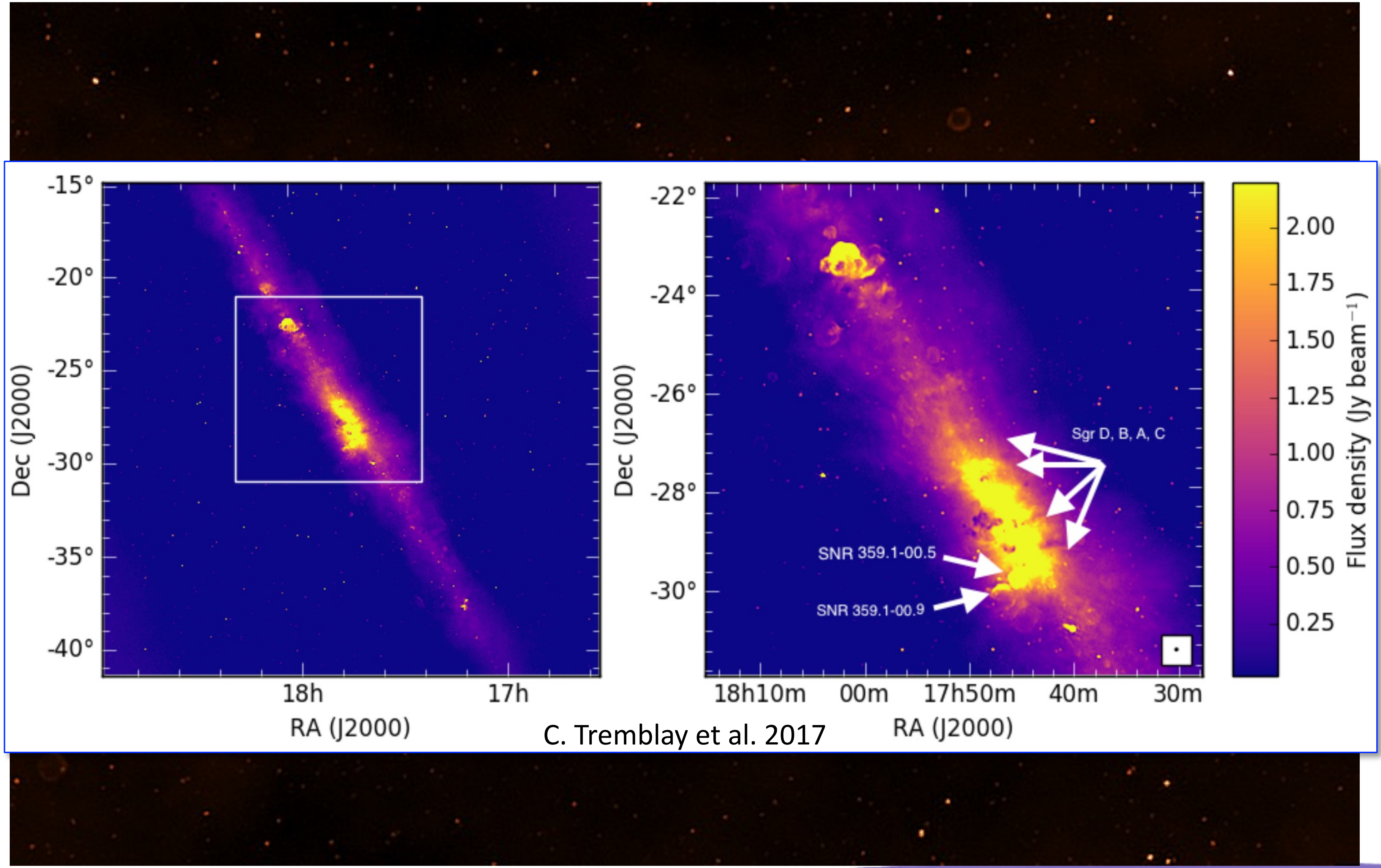


Imaging:

Galactic Center imaged with the MWA

Part of spectral line search

Nominal detections of NO

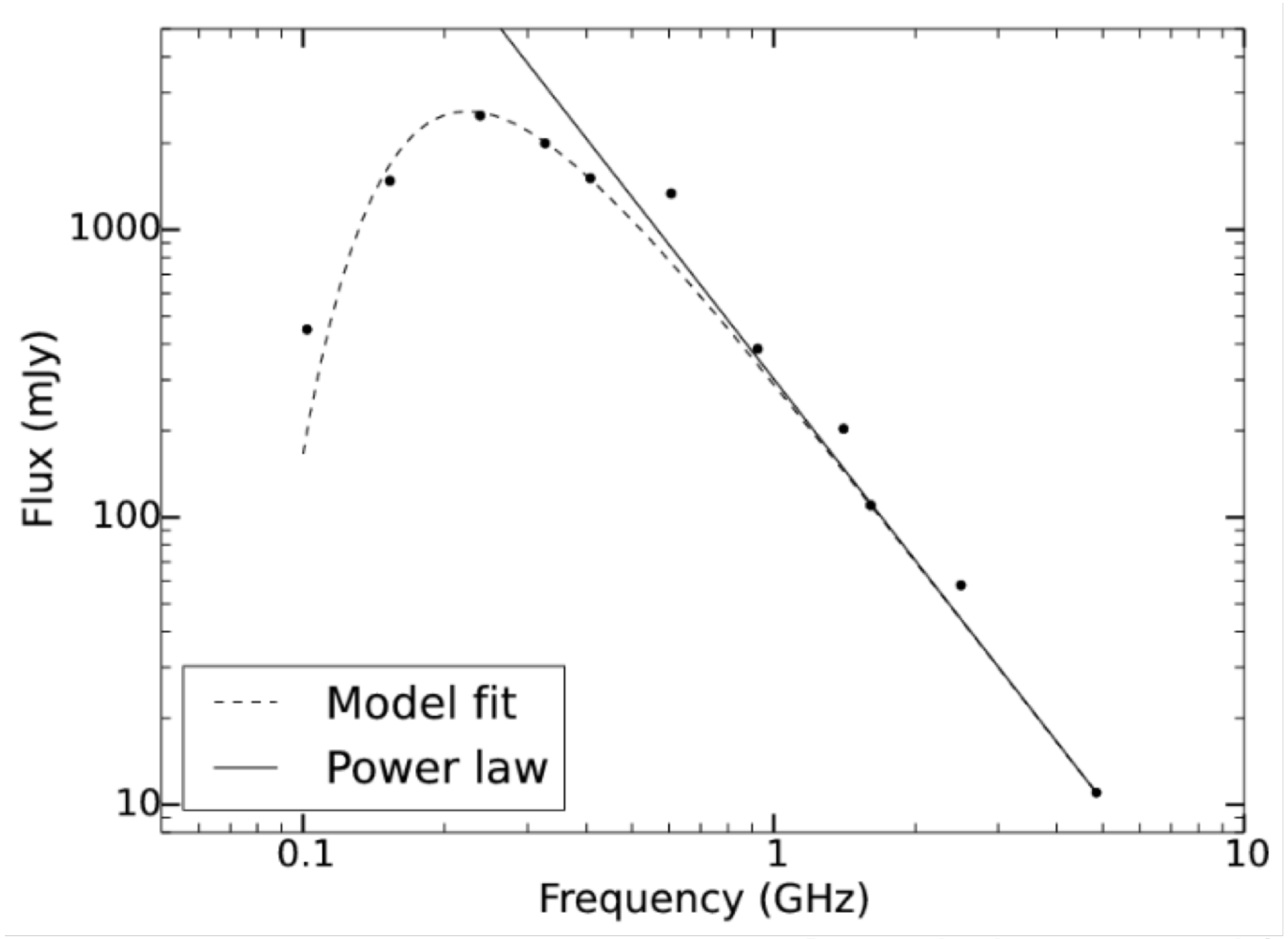


C. Tremblay et al. 2017

C. Tremblay 2018
PhD Thesis

Low frequency science

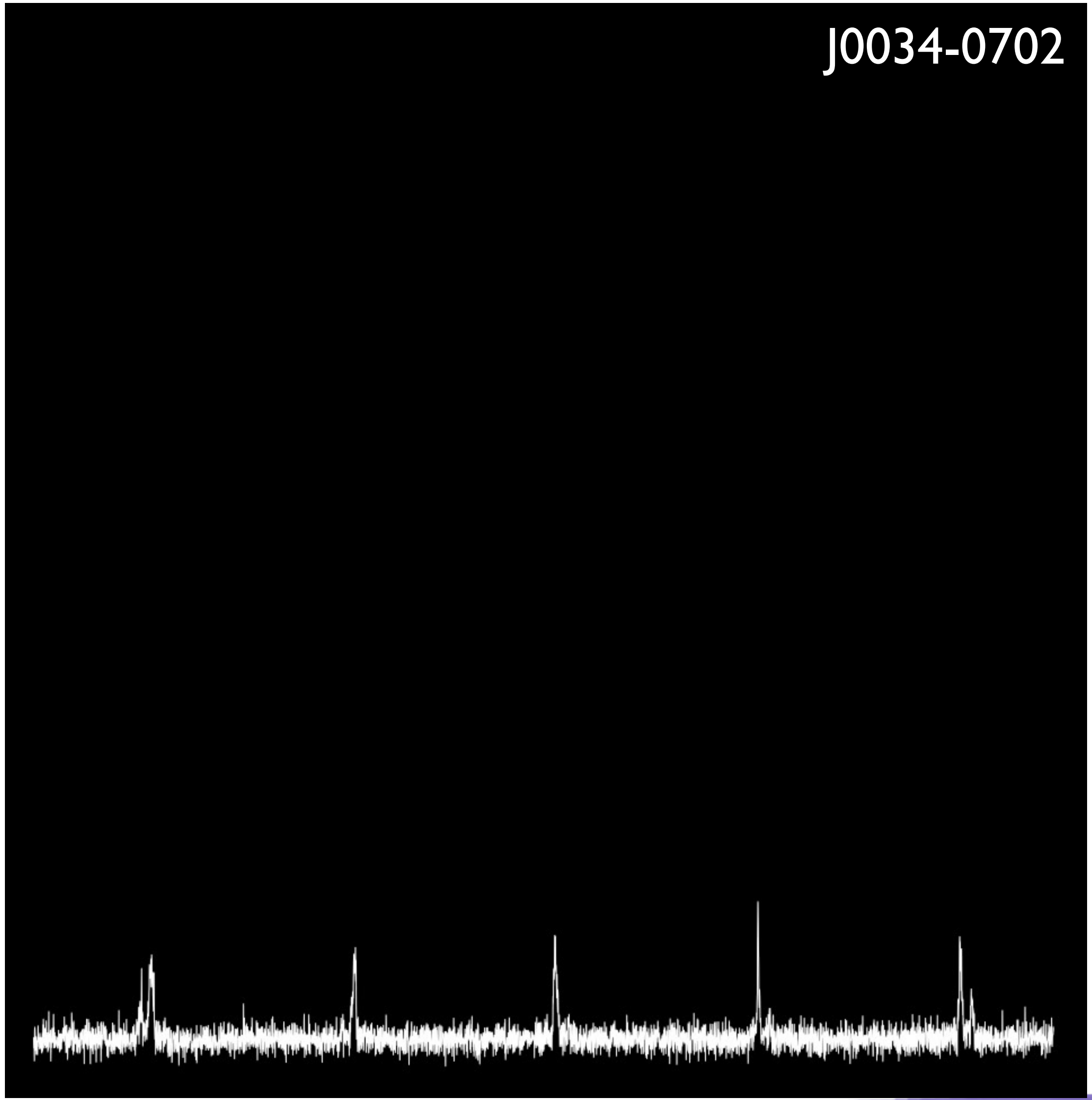
- Pulsars: Spectral Index
- Turnover currently poorly understood
- Important clues to understanding pulsar emission mechanism
- Other consequences:
  - Great frequency range to survey pulsars
  - Allows more single-pulse studies of individual pulsars



Rajwade, Lorimer, and Anderson 2016

Low frequency science

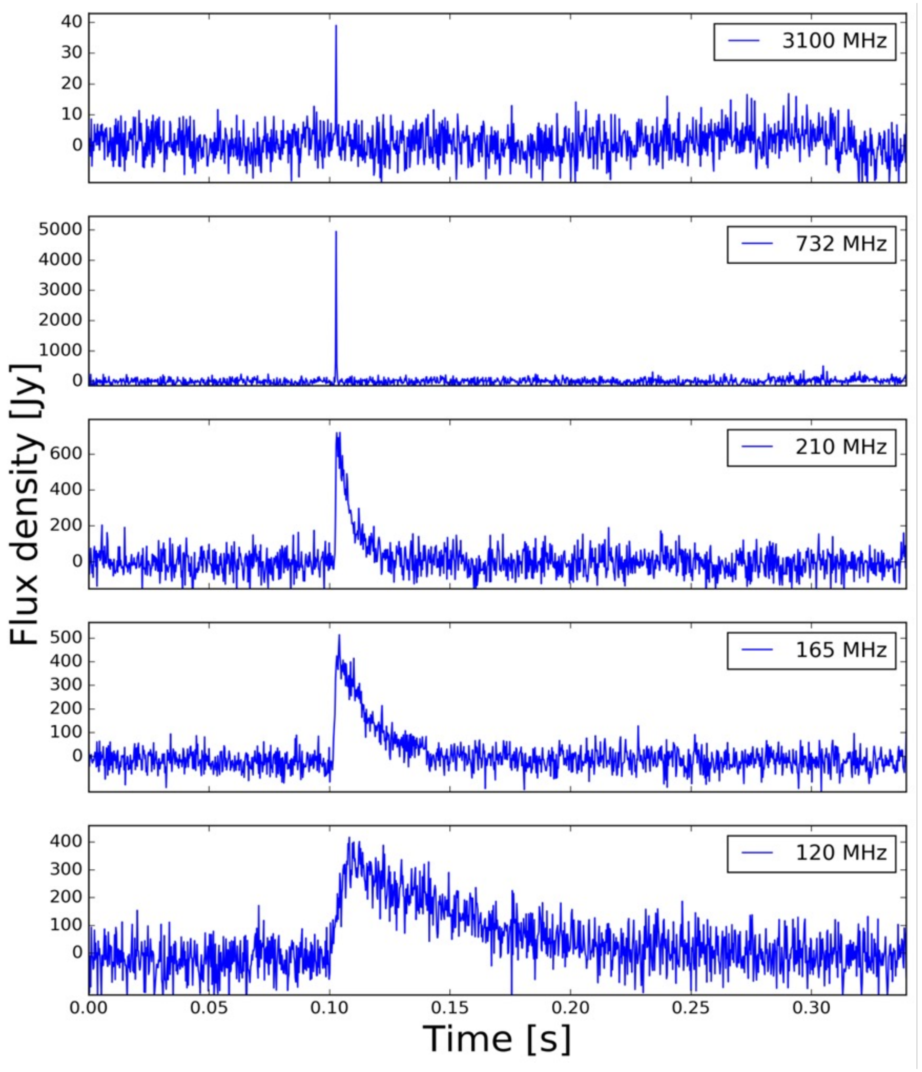
- Single-pulse analysis of a 'sub-pulse drifter' with MWA
- Not all pulsars exhibit this behavior
- Ones that do often have multiple 'modes'
- These can also exhibit 'nulling', consecutive spin rotations where no emission is detected
- McSweeney et al. 2017 and subsequent papers



Credit:
Sammy McSweeney

Low frequency science

- Pulsars: Scattering
- $\tau \propto d^2 f^{-4}$
- Low freq. best way to study scattering
- Gives critical Interstellar Medium insight
- Also an important limitation to pulsar observations along with dispersion – see Michael Lam's Talk



Meyers et al. 2017

Low frequency science

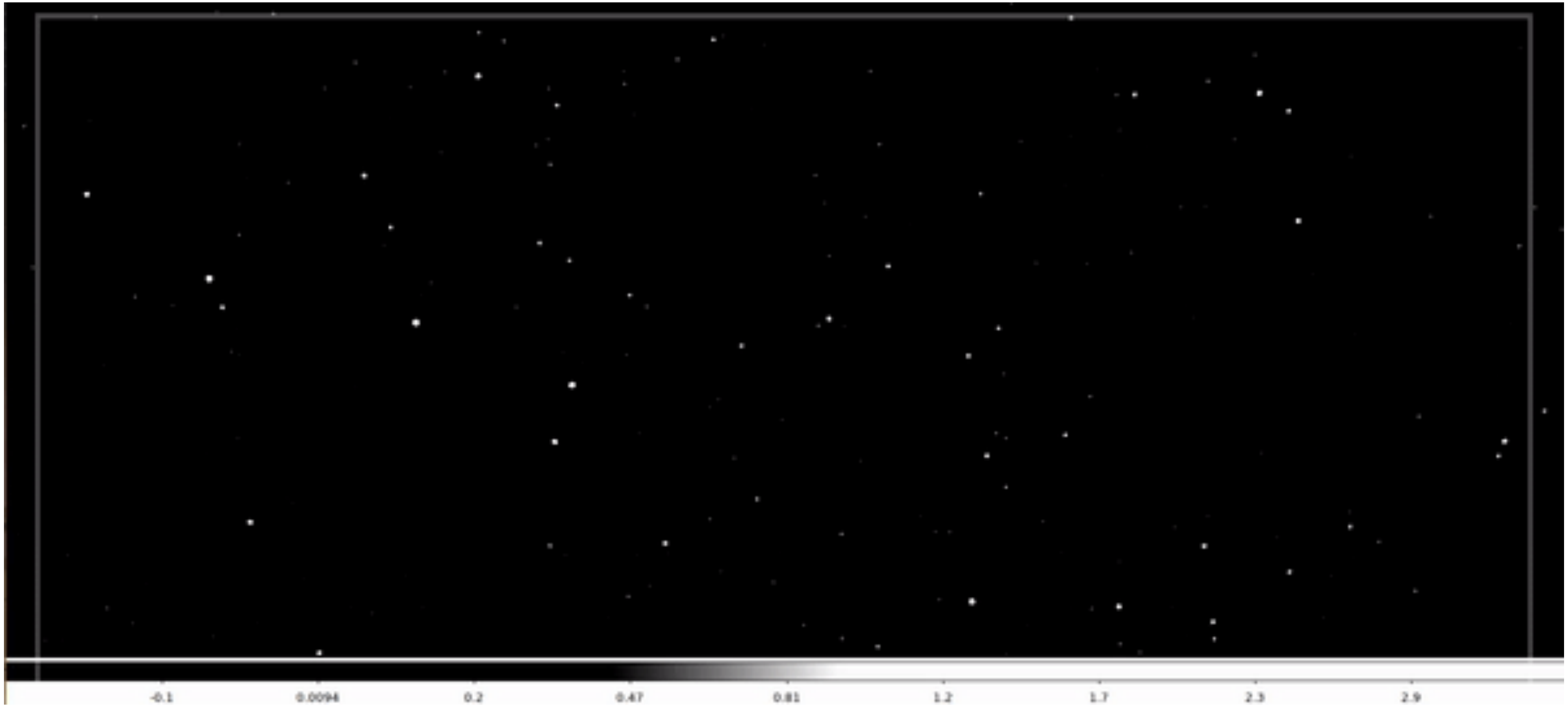
Solar/Heliospheric: Interplanetary Scintillation (IPS)

Imaged 900deg^2

79 & 158 MHz

350 scintillating sources

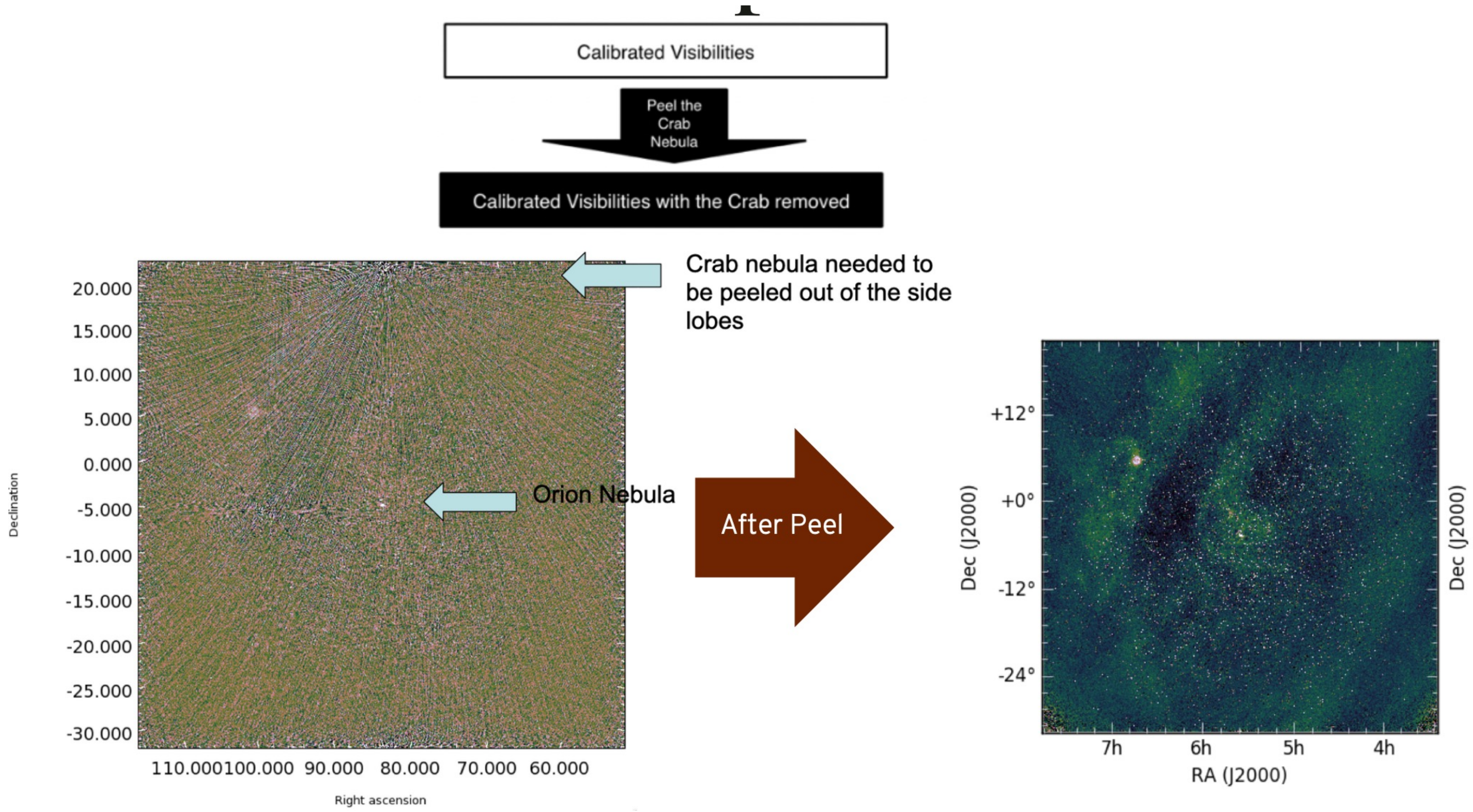
4x real-time



Morgan et al. 2008

Low frequency Calibration

- Direction dependent gains must be accounted for:
  - ‘Easy’ to model based on simulations/empirical data
- Ionosphere must be tamed
  - FoV actually helps
- Confusion needs to be dealt with:
  - Peeling and its successors
- All of these add to increased computational burden

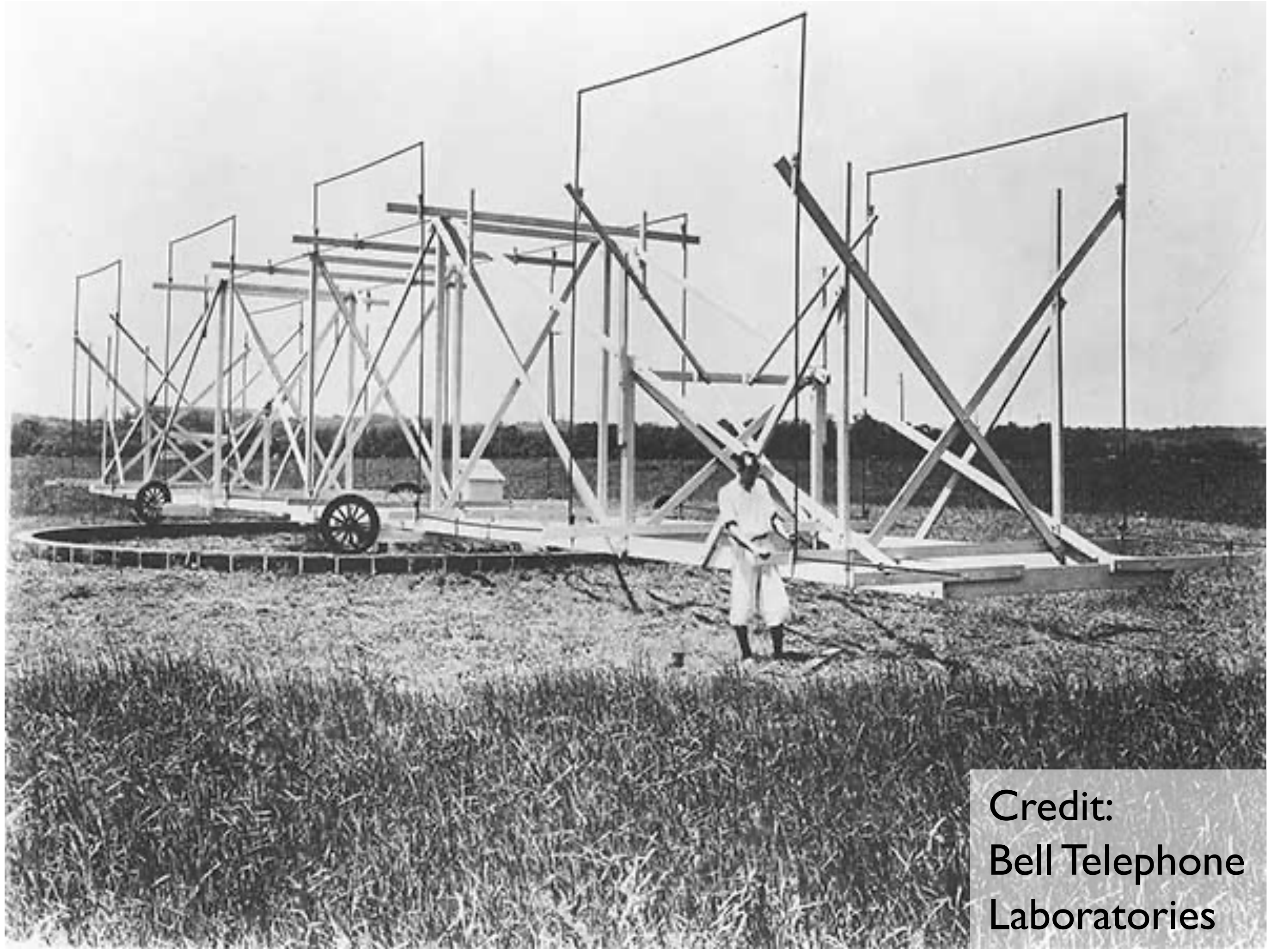


Credit: C. Tremblay

Low Frequency: Instruments

Low Frequency: In the beginning…

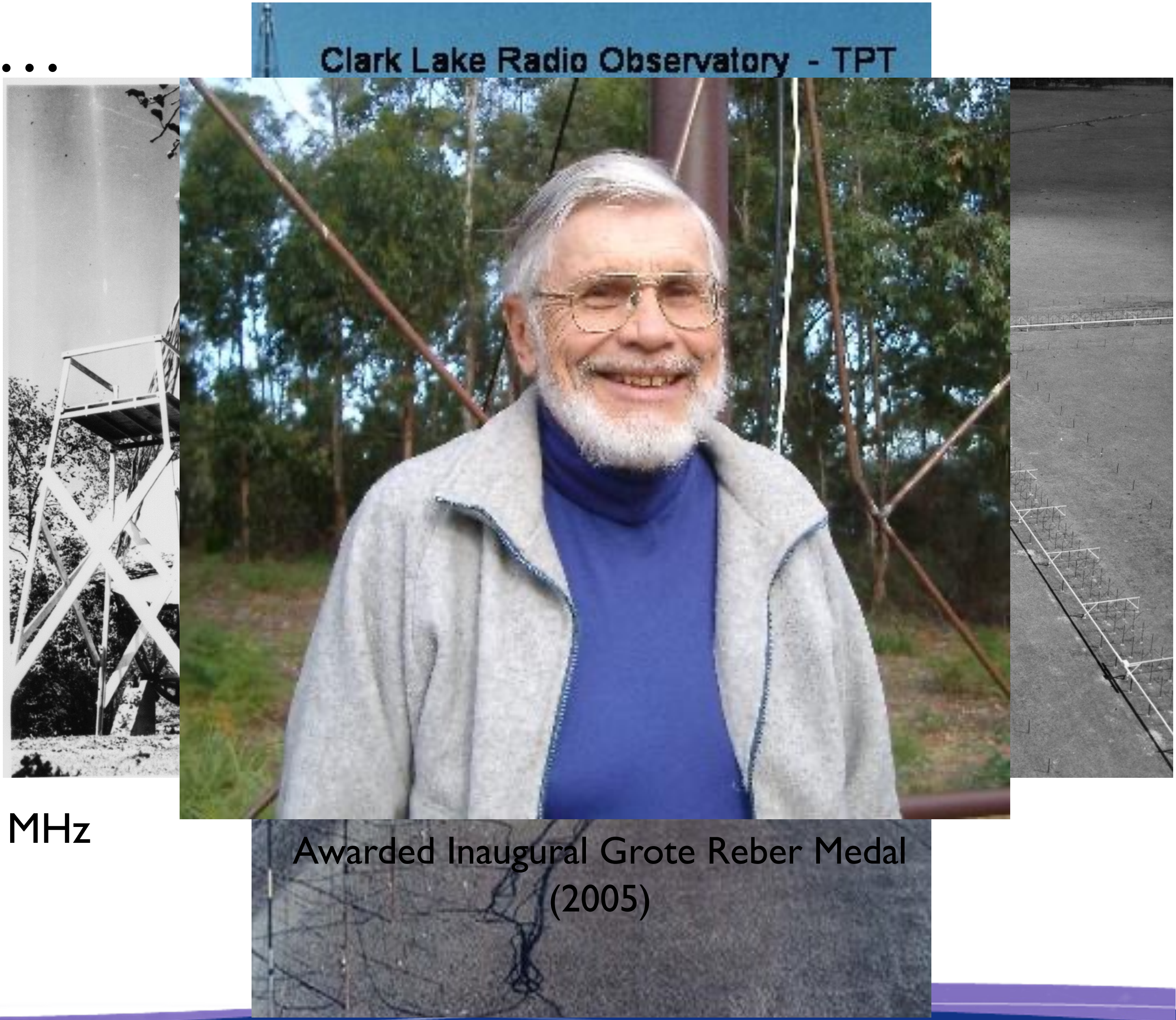
- K.G. Jansky started working for Bell Labs in 1928
- Jansky's merry-go-round
  - Model-T wheels on circular track
- Detected
  - Local T-Storms
  - Distant T-Storms
  - Repeatable 'Steady Hiss' (Sag A*)
- Published first results in 1932



Credit:
Bell Telephone
Laboratories

Low Frequency: In the middle…

- Grote Reber
  - Reber Telescope (1937)
  - 3.3 GHz, 900 MHz, 160 MHz
- Bernard Mills et al.
  - 'Mill's Cross' (1954)
  - 85.5 MHz
  - 450 m arms
- Bill Erickson
  - Clark Lake (selected)
    - 23.6 MHz Array (1961)
    - Jupiter Antennas (1968) 1.6 & 22.2 MHz
    - TeePee-Tee (1971) 20-125 MHz

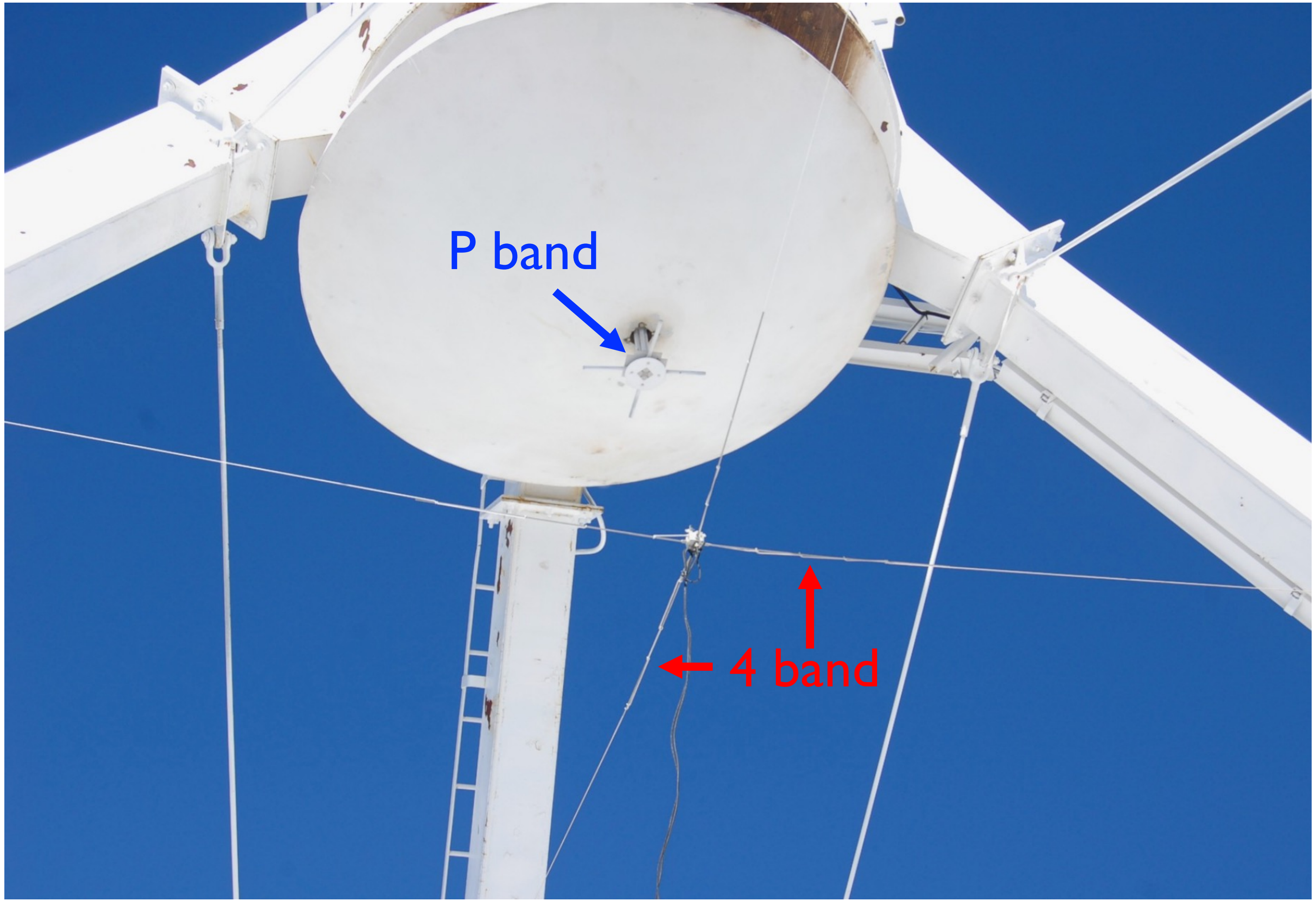


Awarded Inaugural Grote Reber Medal (2005)

Low Frequency Instruments: Dishes

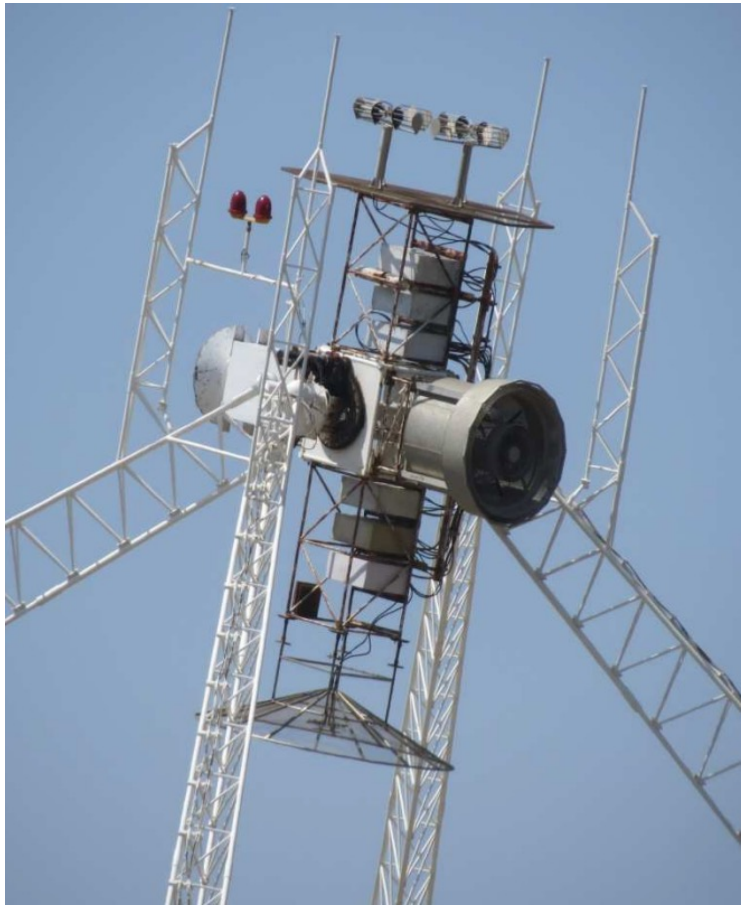
Low frequency instruments:VLA

- 4 band
  (56-88 MHz)
- P band
  (240-470 MHz)
- Naval Research Lab led effort
- VLA Low-band Ionosphere and Transient Experiment (VLITE) operating 24/7 at P band on 18VLA antennas
  – Reference:
    Clarke et al. SPIE, 2016



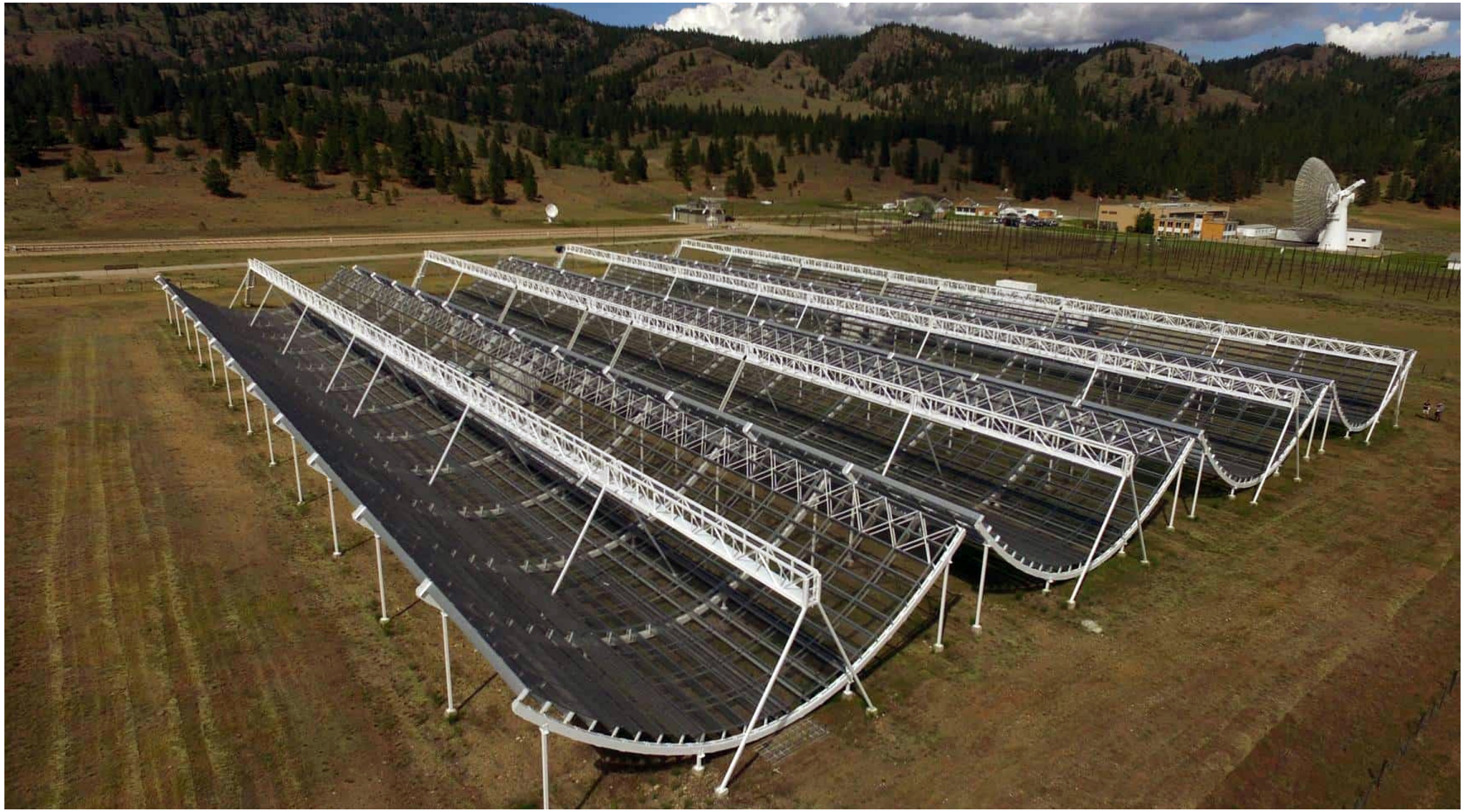
Low frequency instruments: GMRT

- 30 x 45m Dishes
- 80 km North of Pune, India
- 7% Solidity
- Up to 400 MHz instantaneous bandwidth
- Bands:
  - 120-250 MHz
  - 250-500 MHz
  - 550-850 MHz
  - (1050-1450 MHz)



Low frequency instruments: CHIME

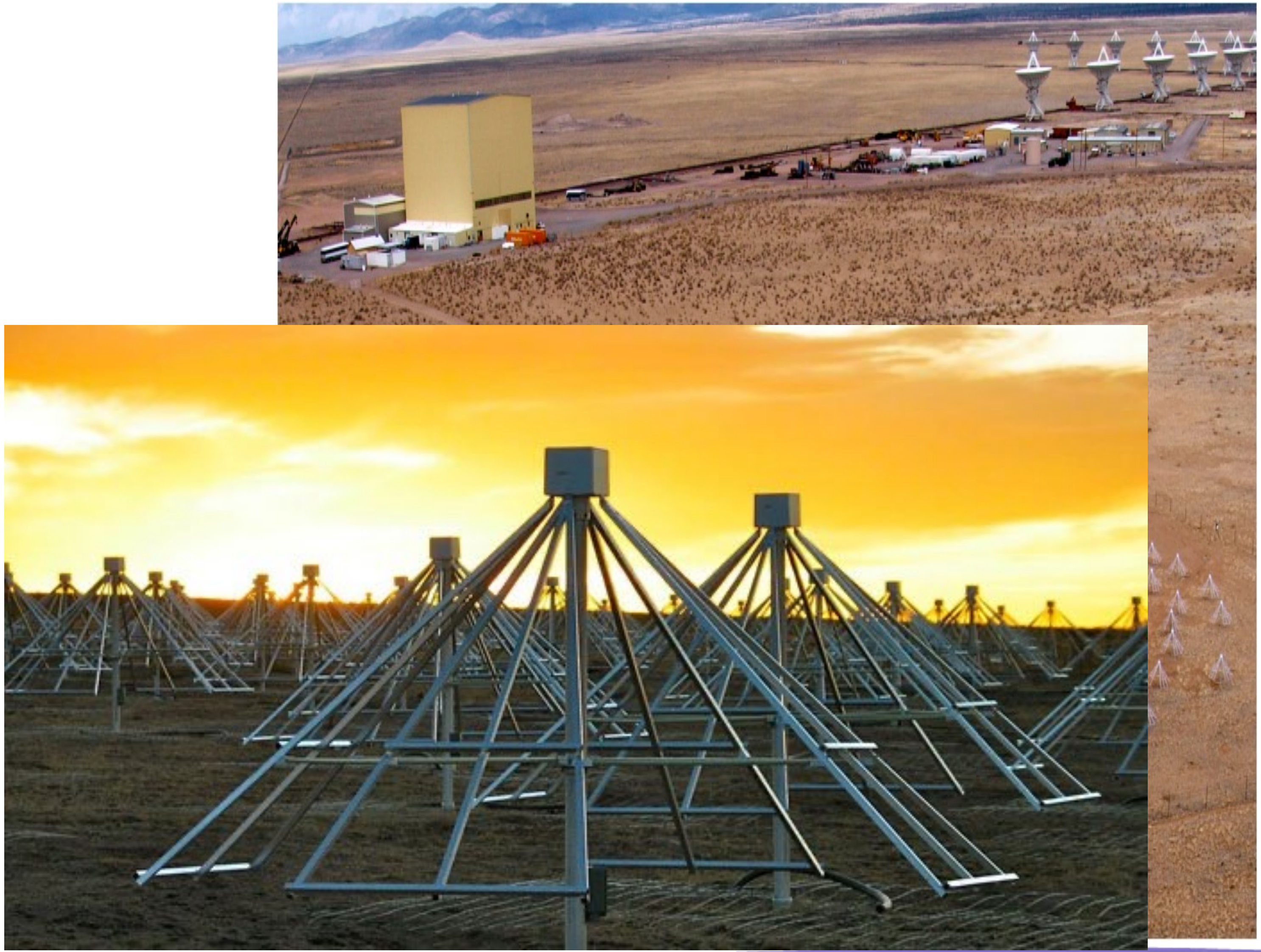
- Canadian Hydrogen Mapping Experiment
- Near Penticton, Canada
- 400-800 MHz
- $\sim 200 \, \mathrm{deg}^2$ FoV
- 4 20m x 100m cylindrical reflectors
- Outriggers
  - KKO (~66 km)
  - Hat Creek (~2200 km)
  - GB (~3300 km)



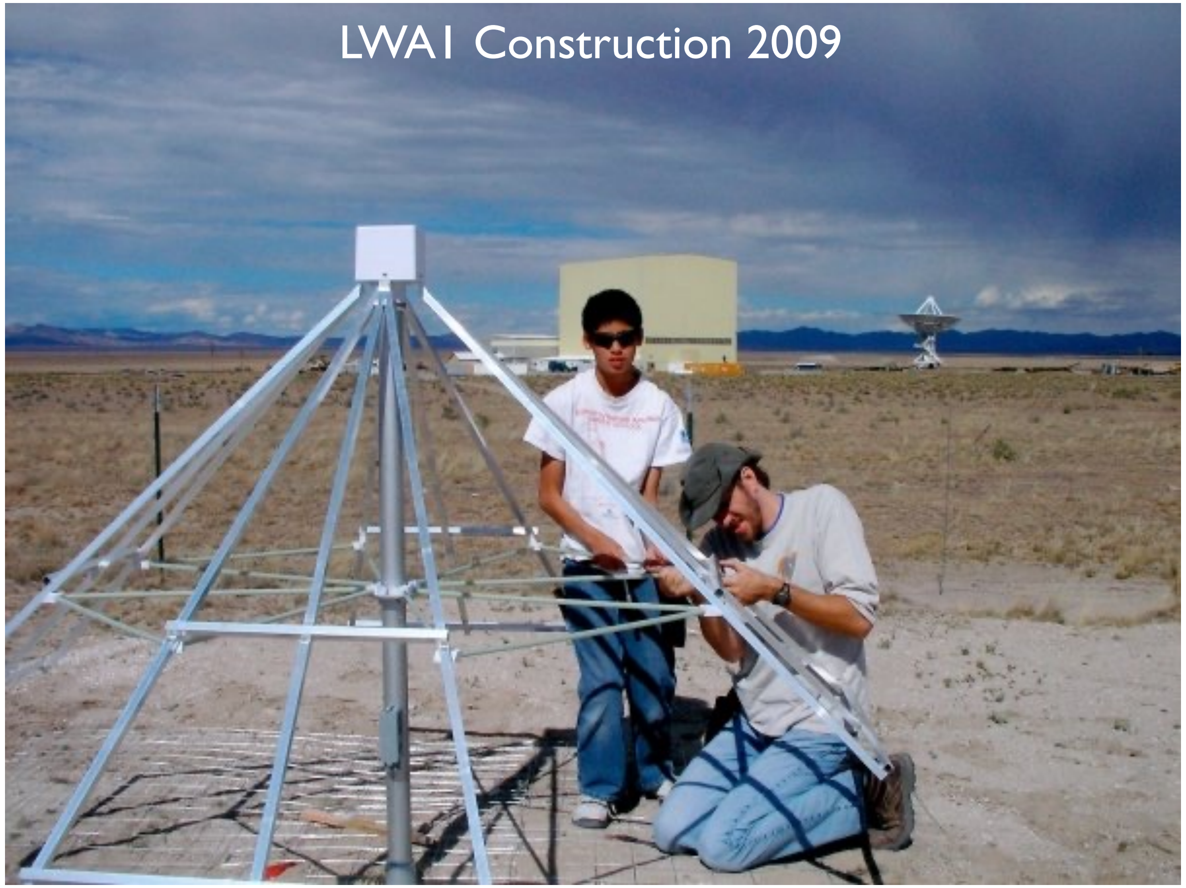
Low Frequency Instruments:
Bare Dipoles

Low frequency instruments: LWA

- 10-88 MHz
- 256 dual-pol angled dipoles
- Stations designed to be used independently or combined
- Sky-noise dominated
- 3* Full Stations
  - LWA1
  - SV
  - OVRO* (288 dipoles, 1.5 km)



Low frequency Instruments: LWA



LWA1 Construction 2009

LWA-CS Surveying 2024

Low frequency instruments: LWA

- LWA Swarm: mini-stations
- 64 antennas distributed within 80m diameter
- Key
  - Dark Blue – Existing Full Stations
  - Light Blue – Existing mini-Station
  - Red – Planned Stations

Low frequency instruments: MWA

- Murchison, Australia
- 70-300 MHz
- Consists of 'Tiles'
  - 4x4 grid of cross-dipoles
- 128 Tiles*
- 'Reconfigurable'
  - Compact: ~800 m
  - Extended: ~5 km

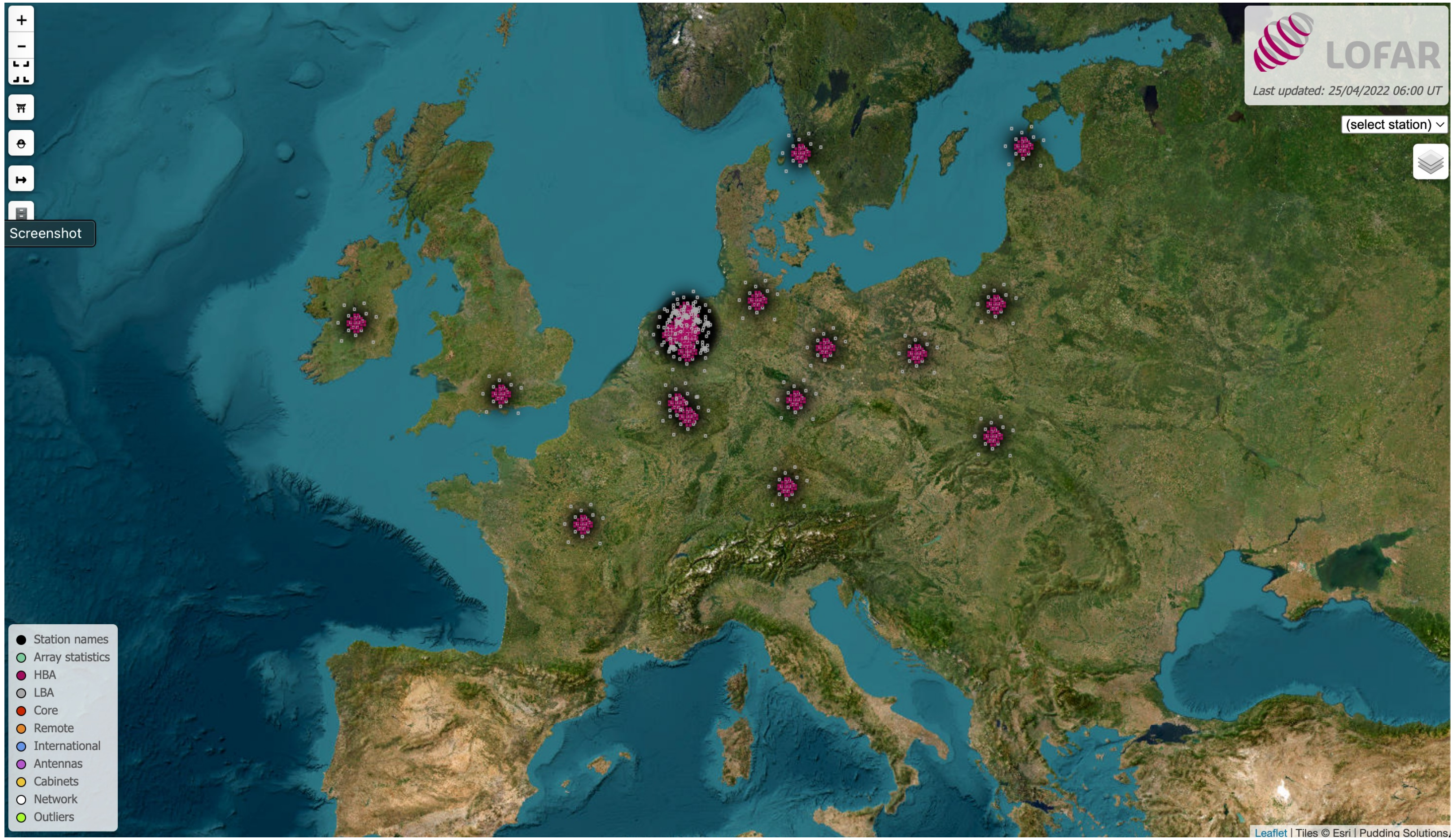
Low frequency instruments: LOFAR

- Europe
  - Netherlands centered
- 10-80 MHz (LBA)
- 120-240 MHz (HBA)
- 52 Stations
  - Core & Remote stations consist of 48 HBA's and 96 LBA’s
  - International stations consist of 96 HBA’s and 96 LBA’s

Low frequency instruments: LOFAR

LOFAR is a dedicated low frequency very long baseline interferometer

See Adam Deller's VLBI talk!



Low Frequency Instruments: The Future…

Low frequency instruments: LuSEE-Night

- 0.1-50 MHz
- 4 monopole antennas in cross formation
- Far side of the Moon
- Late 2025
- NASA & DoE collaboration
- Study ‘Dark Ages’

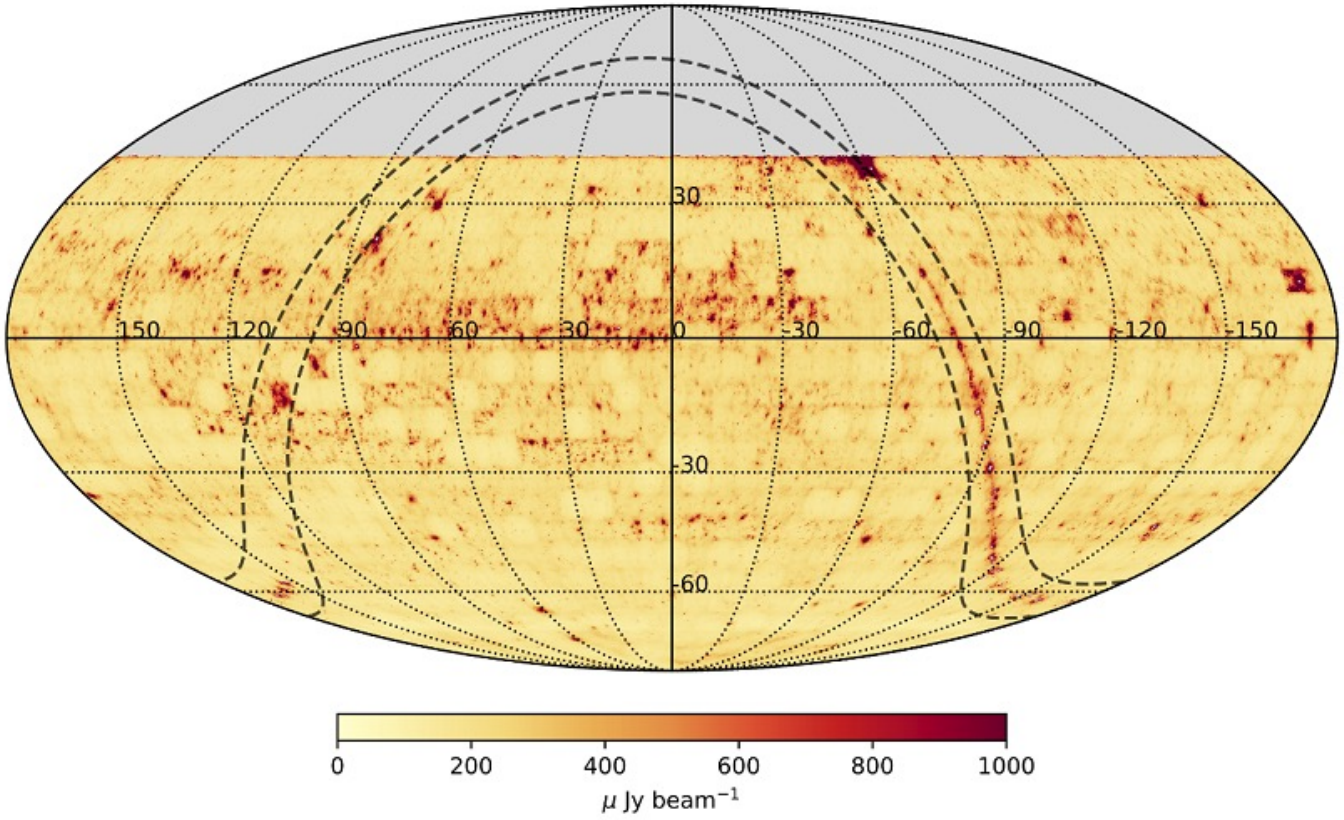
Low frequency instruments; SKA-Low

- 50 MHz - 350 MHz
- Western Australia
- 131,072 log-periodic antennas spread between 512 stations
- Collecting area: 419,000m^2
- Extent: 74km

Low Frequency:
Selected Surveys

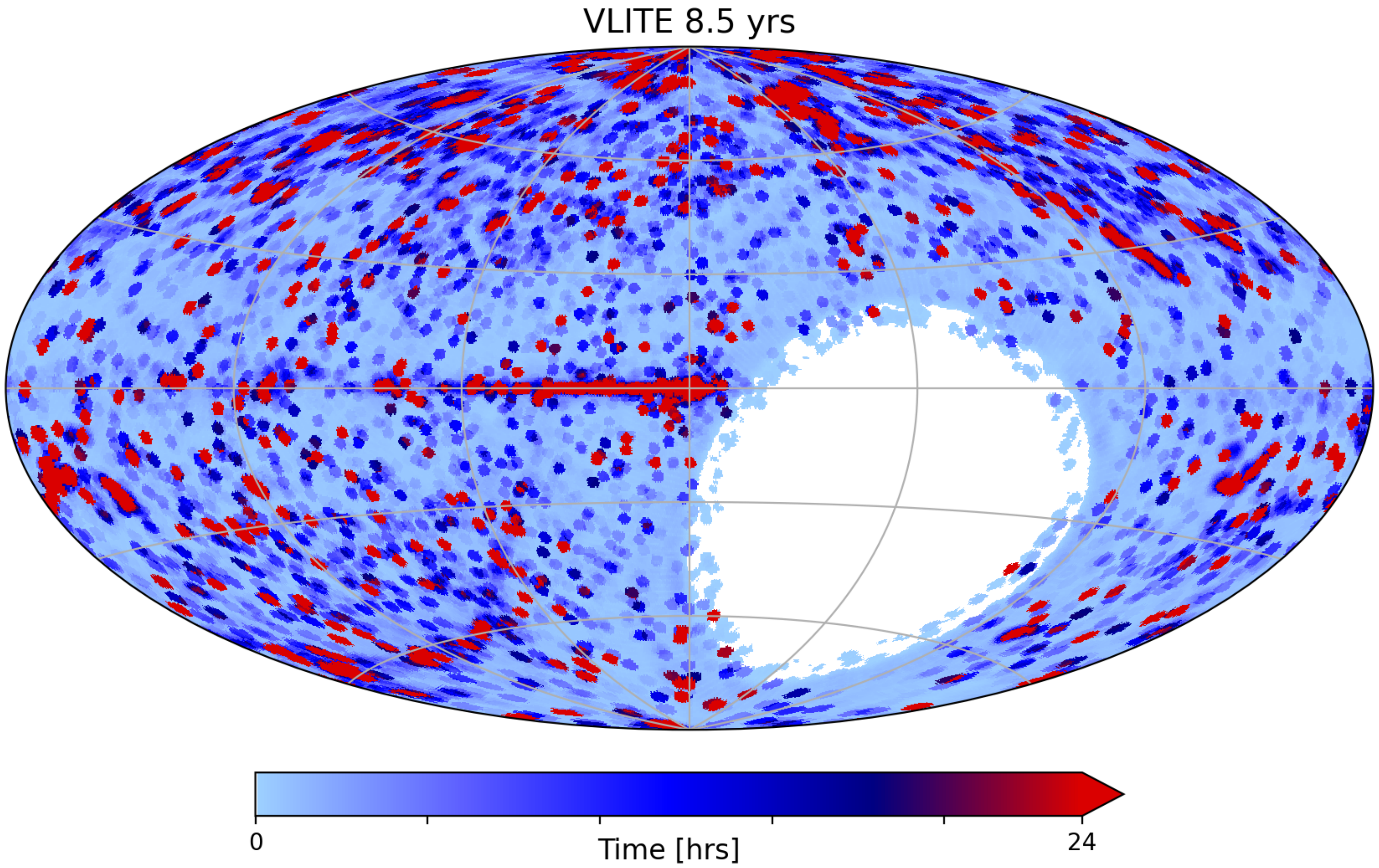
Rapid ASKAP Continuum Survey (RACS)

- Telescope
  - ASKAP
- Frequency
  - 887.5 MHz
- Resolution
  - 15”
- Sensitivity
  - 0.025 to 0.040 mJy/beam
- Reference
  - McConnel et al. 2020



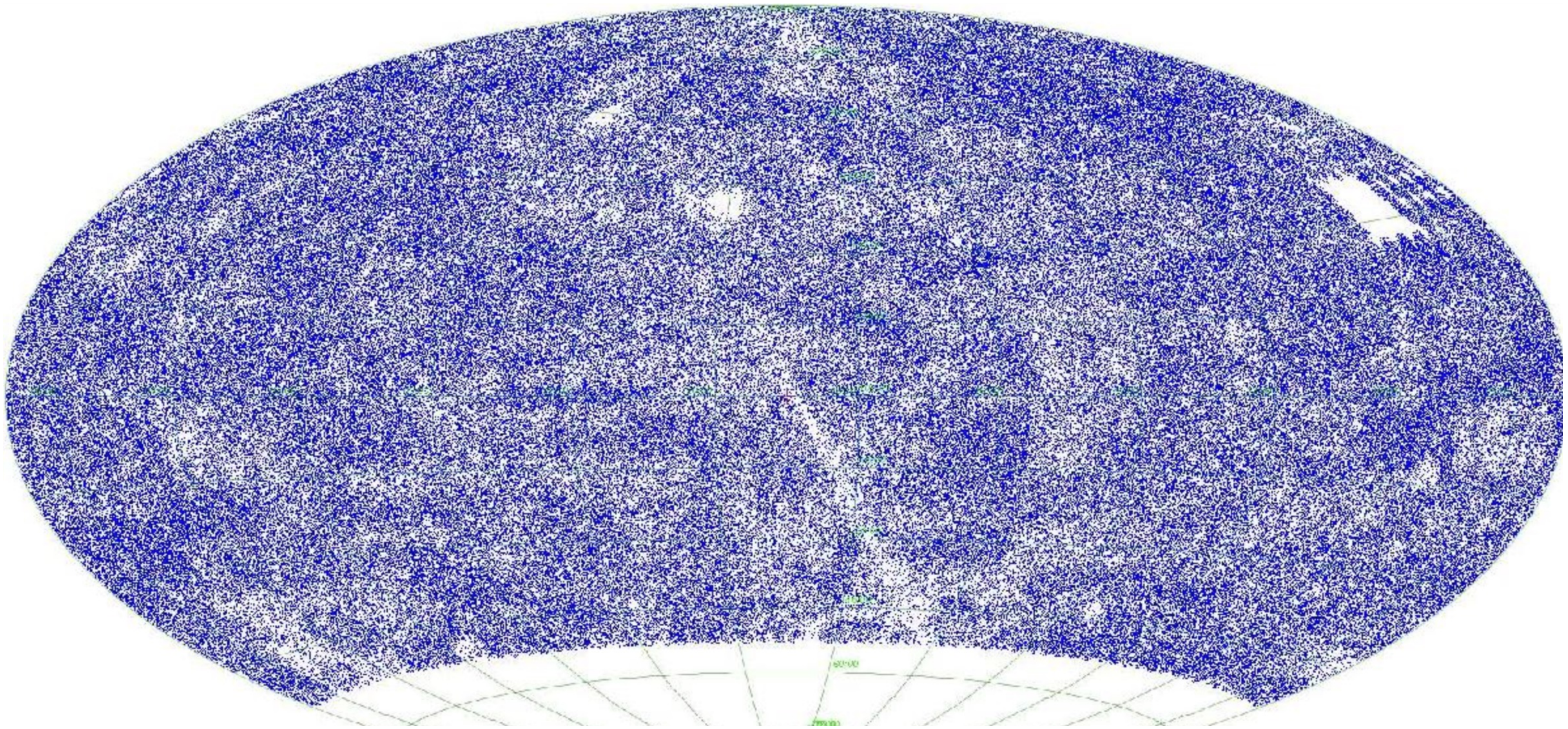
VLITE Commensal Sky Survey (VCSS)

- Telescope
  - VLA (10 Antennas)
- Frequency
  - 320 to 384 MHz
- Resolution
  - 15”
- Sensitivity
  - 7 to 10 mJy/beam



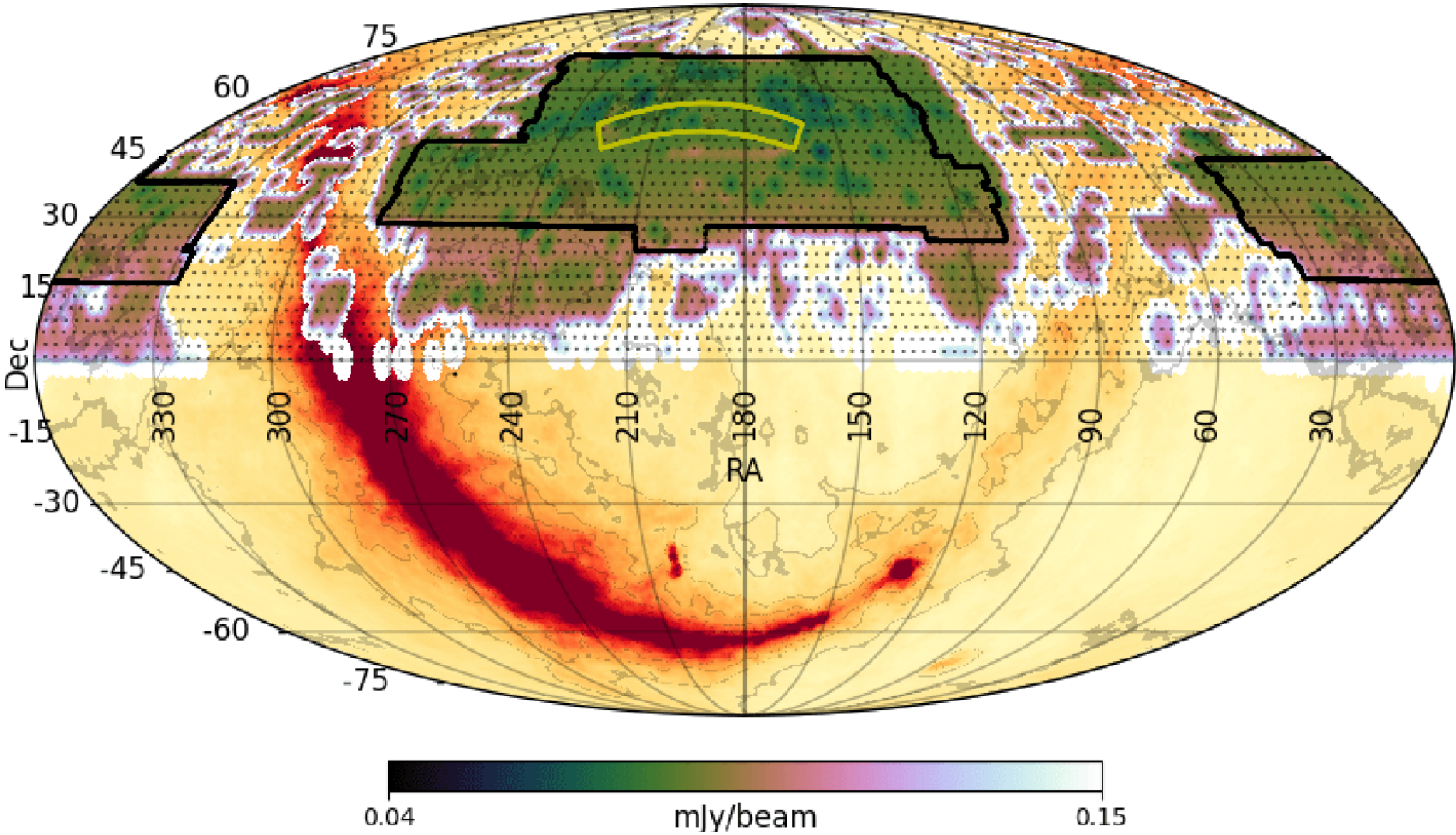
TGSS

- Telescope
  - GMRT
- Frequency
  - 150 MHz
- Resolution
  - 25”
- Sensitivity
  - 3 to 5 mJy/beam



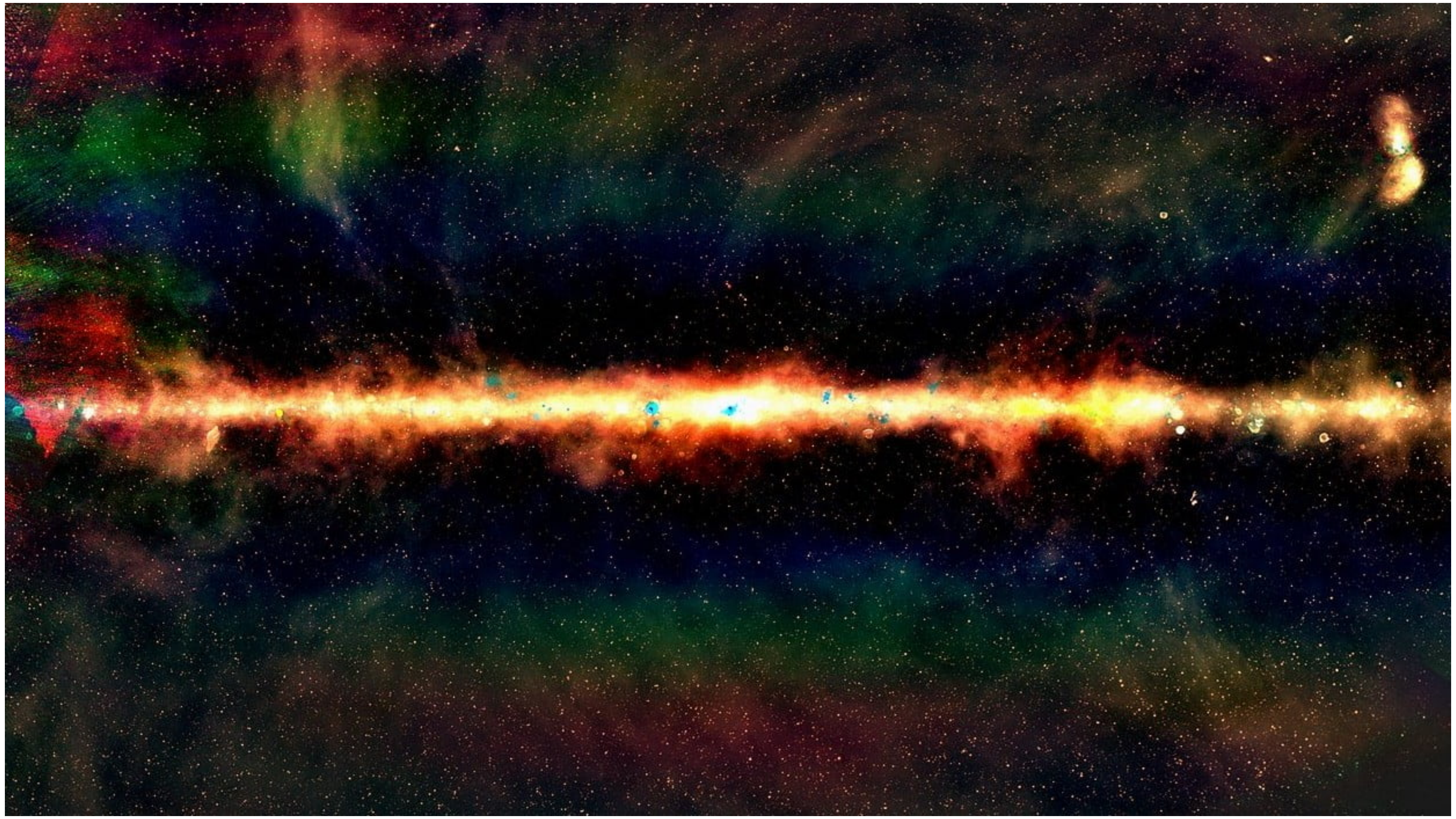
LoTSS

- Telescope
  - LOFAR
- Frequency
  - 120 to 168 MHz
- Resolution
  - 6”
- Sensitivity
  - 0.083 mJy/beam



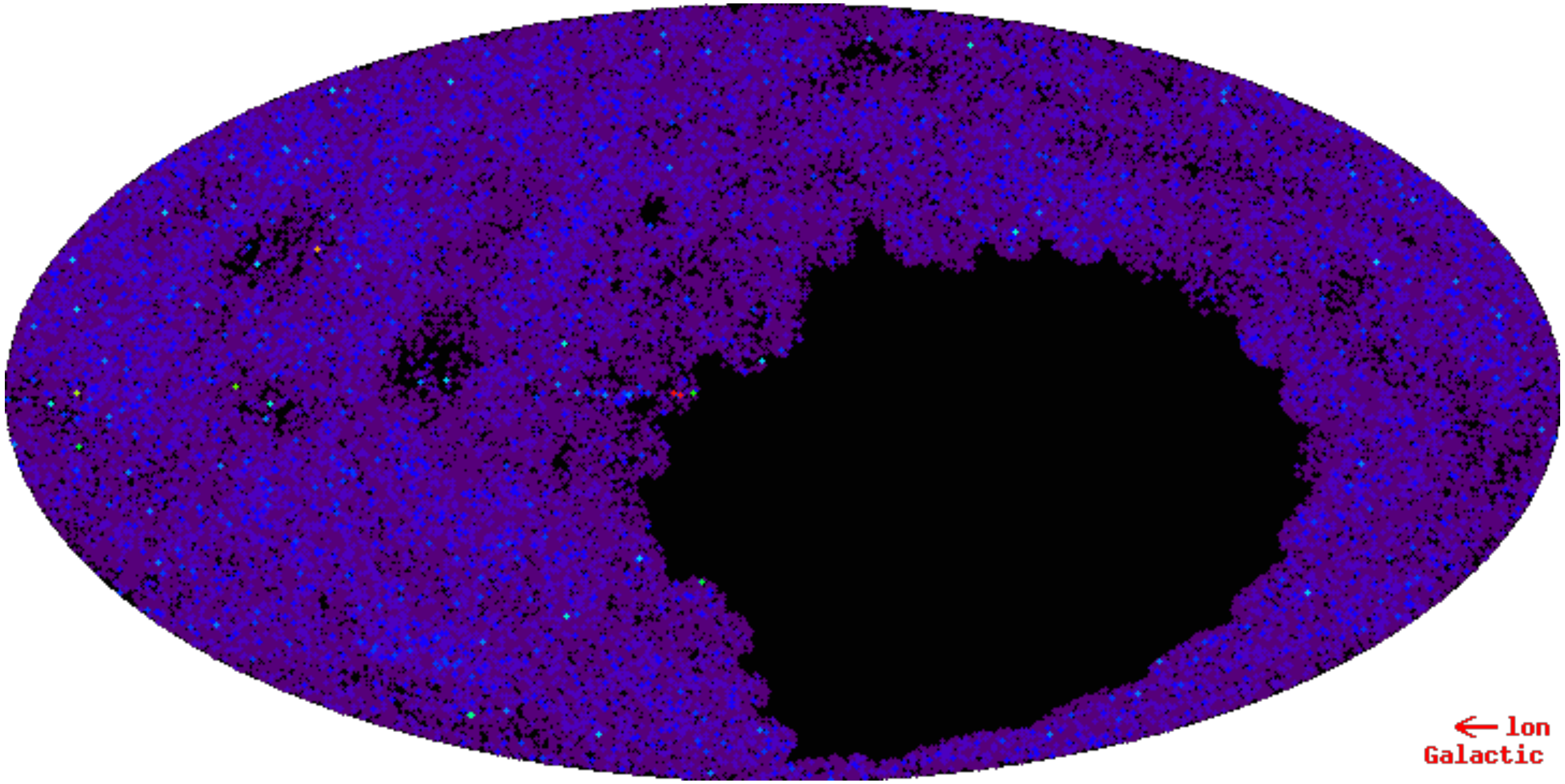
GLEAM

- Telescope
  - MWA
- Frequency
  - 87 to 215 MHz
- Resolution
  - 120"
- Sensitivity
  - 6 to 10 mJy/beam



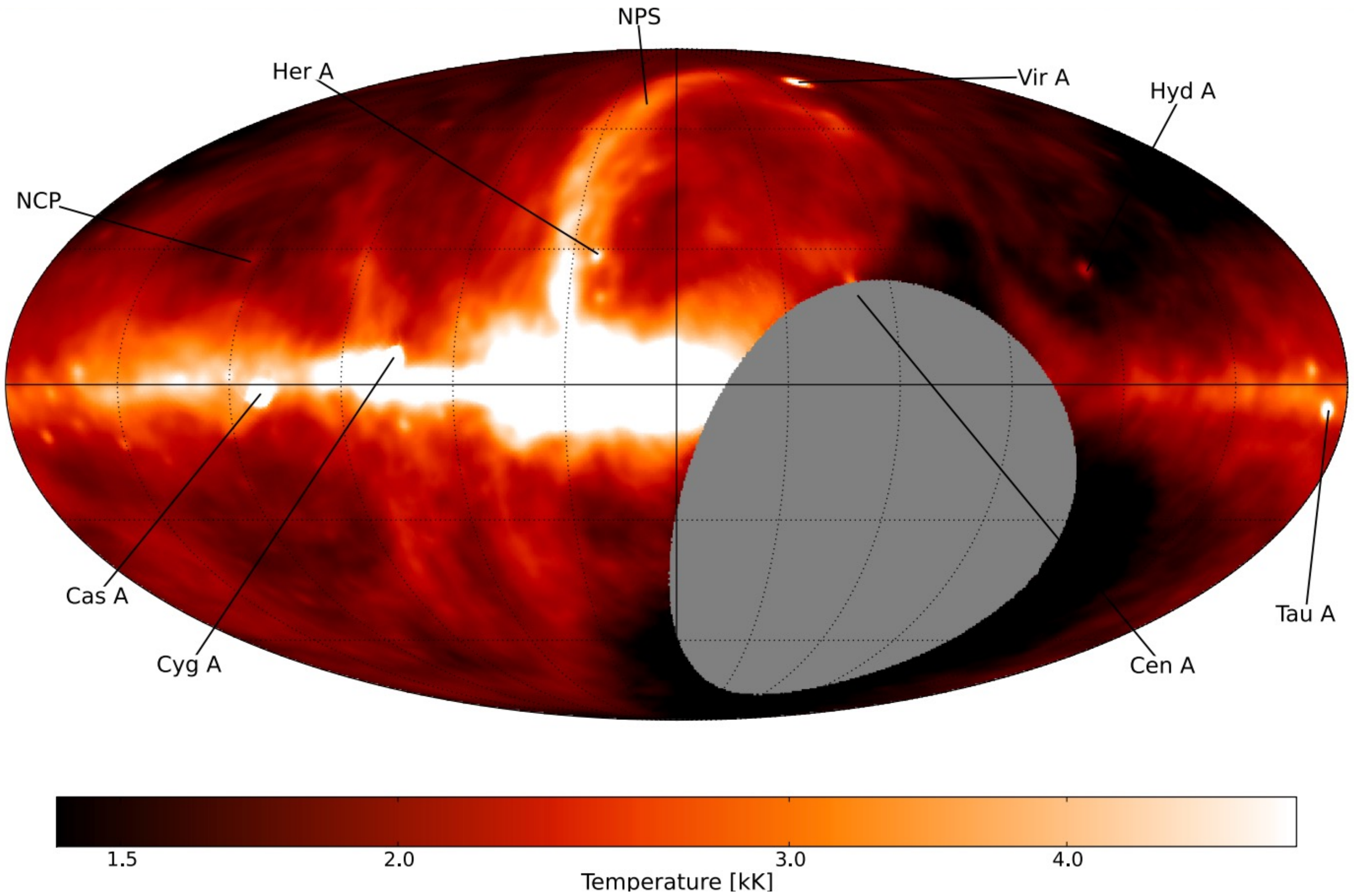
VLSSr

- Telescope
  - VLA
- Frequency
  - 73.8 MHz
- Resolution
  - 75”
- Sensitivity
  - 100 mJy/beam



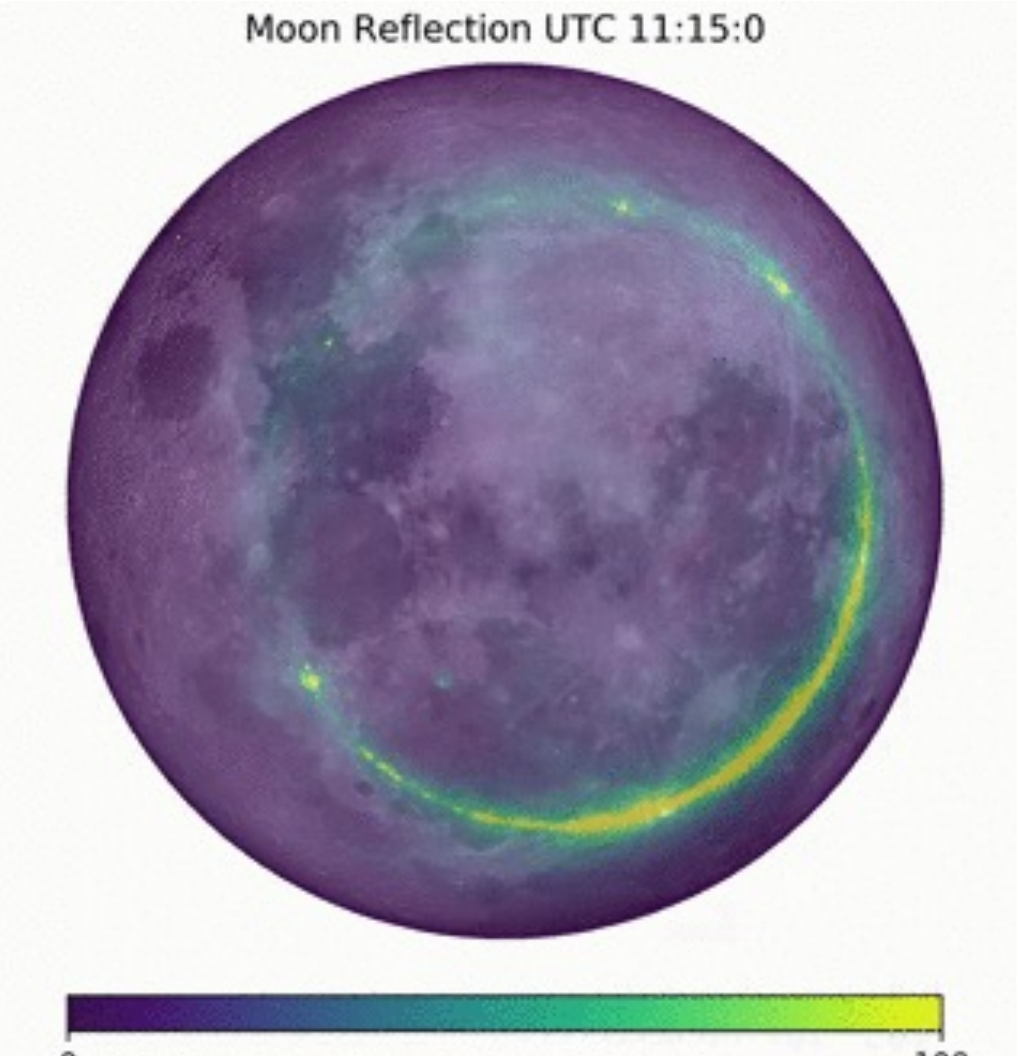
LWA1 Low Frequency Sky Survey

- Telescope
  - LWA1
- Frequency
  - 35 to 80 MHz
- Resolution
  - 75”
- Thermal noise
  - 38 to 5 Jy/beam
- Confusion noise
  - 163 to 18 Jy/beam
- Reference
  - Dowell et al. 2017



Low Frequency Radio Astronomy

- Really easy…but also kinda hard
- Fantastic regime to learn Radio Astronomy in a 'hands on' environment
- Ionosphere can dominate errors
- MHz regime opens up new areas of study for many science topics
- This is an amazing age for <1GHz Radio Astronomy with a plethora of instruments across the globe
- Use the survey data that's being gifted to you
- Have fun with it!



Credit: Ben McKinley


Low Frequency Radio Astronomy
Thank You