# Low Frequency Interferometry

Tracy Clarke, US Naval Research Laboratory

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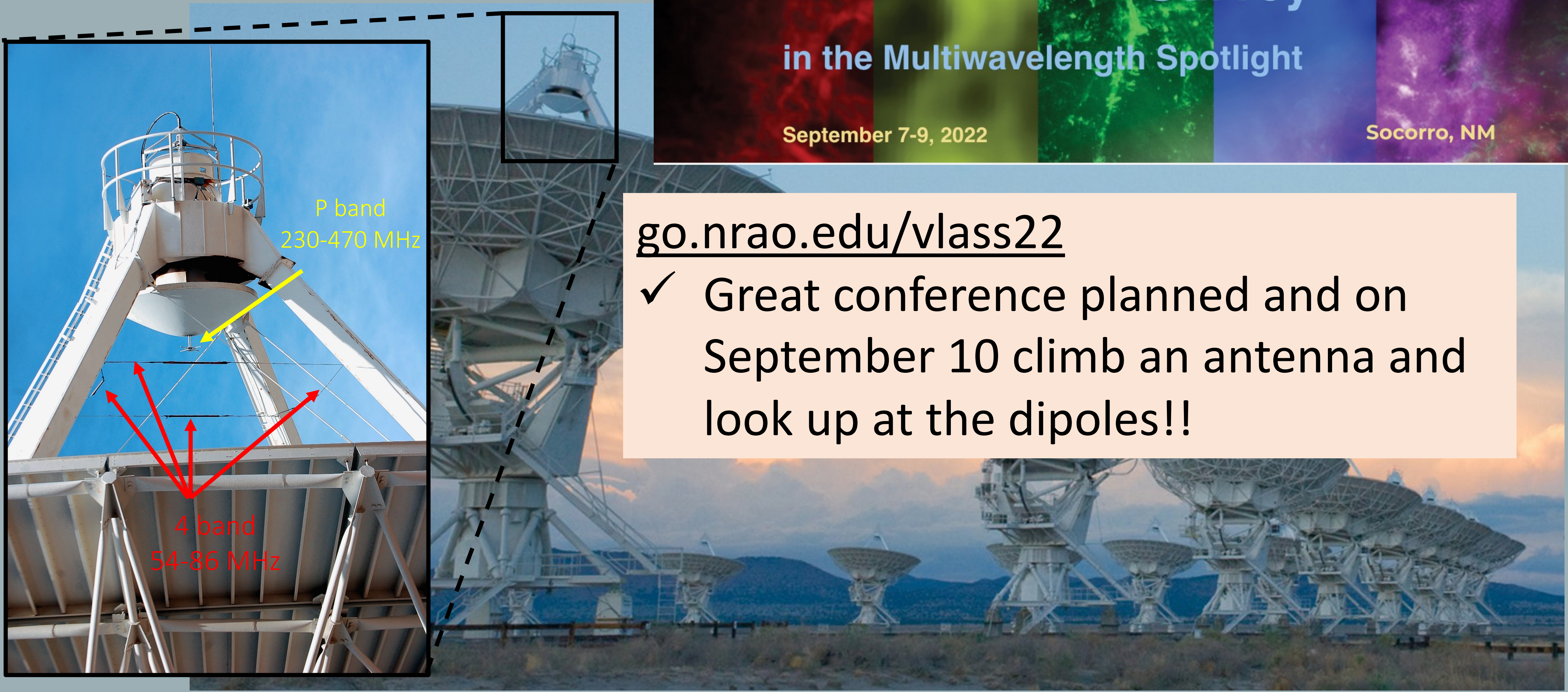
# Low Freq

Tracy Clarke,


go.nrao.edu/vlass22

- ✓ Great conference planned and on September 10 climb an antenna and look up at the dipoles!!

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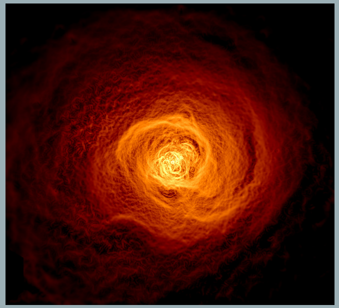
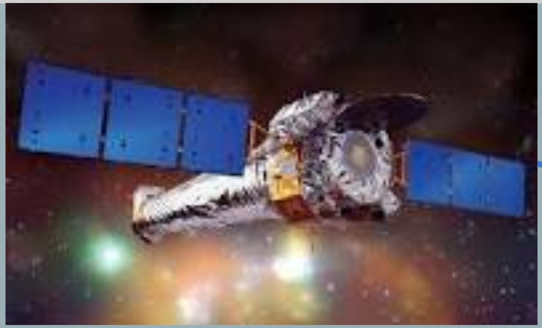
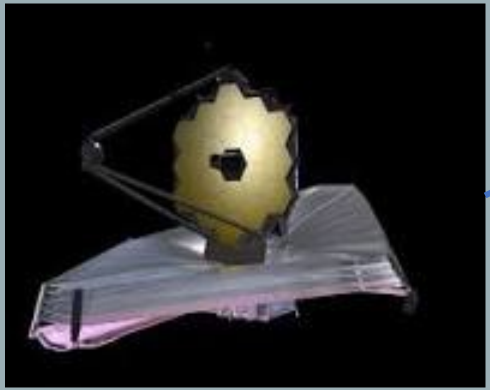
# What do we Mean by Low Frequency?

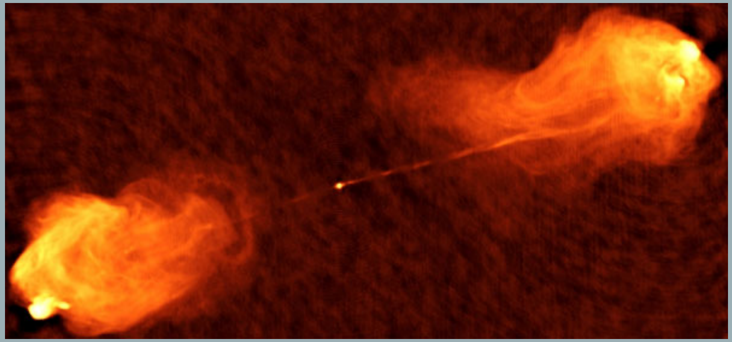




Chandra



JWST



JVLA

Low Frequency

| CLASS | FREQUENCY | WAVELENGTH | ENERGY |
|---|---|---|---|
| | 300 EHz | 1 pm | 1.24 MeV |
| Y | 30 EHz | 10 pm | 124 keV |
| HX | 3 EHz | 100 pm | 12.4 keV |
| SX | 300 PHz | 1 nm | 1.24 keV |
| | 30 PHz | 10 nm | 124 eV |
| EUV | 3 PHz | 100 nm | 12.4 eV |
| NUV | 300 THz | 1 μm | 1.24 eV |
| NIR | 30 THz | 10 μm | 124 meV |
| MIR | 3 THz | 100 μm | 12.4 meV |
| FIR | 300 GHz | 1 mm | 1.24 meV |
| EHF | 30 GHz | 1 cm | 124 μeV |
| SHF | 3 GHz | 1 dm | 12.4 μeV |
| UHF | 300 MHz | 1 m | 1.24 μeV |
| VHF | 30 MHz | 10 m | 124 neV |
| HF | 3 MHz | 100 m | 12.4 neV |
| MF | 300 kHz | 1 km | 1.24 neV |
| LF | 30 kHz | 10 km | 124 peV |
| VLF | 3 kHz | 100 km | 12.4 peV |
| VF/ULF | 300 Hz | 1 Mm | 1.24 peV |
| SLF | 30 Hz | 10 Mm | 124 feV |
| ELF | 3 Hz | 100 Mm | 12.4 feV |

# What do we Mean by Low Frequency?

- Low frequency – *eye of the beholder*:
  - HF (3 MHz – 30 MHz)
  - VHF (30 MHz – 300 MHz)
  - UHF (300 MHz – 3 GHz)
- Ground-based instruments rarely probe below 10 MHz due to the ionosphere

| CLASS | FREQUENCY | WAVELENGTH | ENERGY |
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| ELF | 30 Hz | 10 Mm | 124 feV |
| | 3 Hz | 100 Mm | 12.4 feV |

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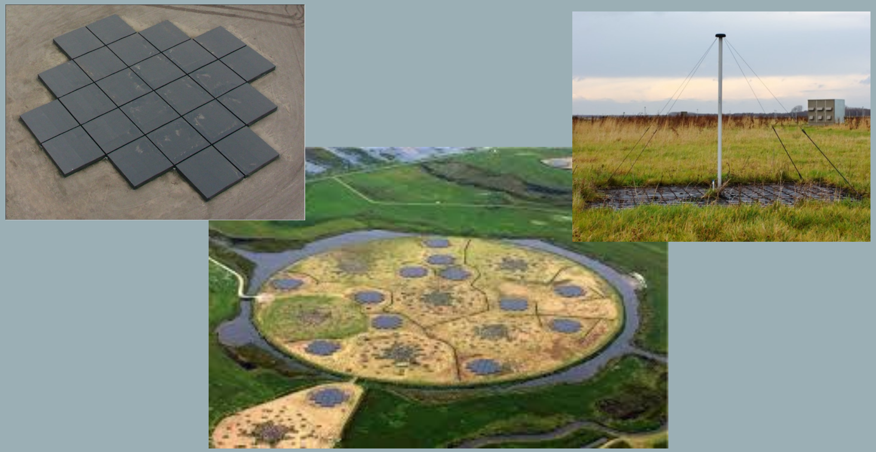
# A Few Low Frequency Telescopes

JVLA: 56-88 MHz
240-470 MHz, >1 GHz



LOFAR: 10-80 MHz,
120-240 MHz

MWA: 80-300 MHz

uGMRT: 50-1500 MHz

LWA: 10-88 MHz

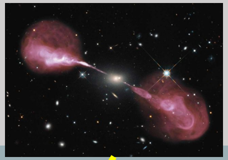
CHIME: 400-800 MHz

SKA Low: 50-350 MHz

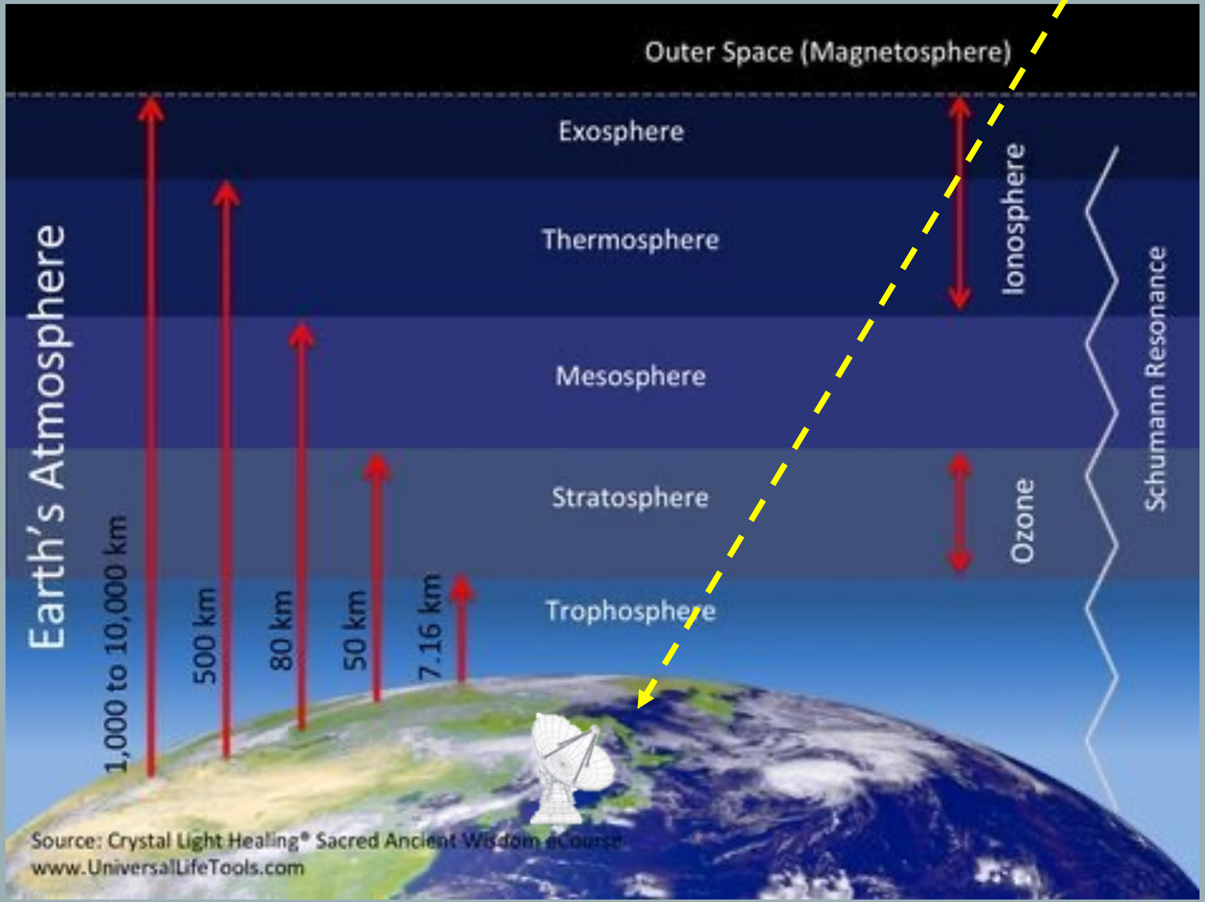
# Talk Outline:

- **Part I**
  - Meet the Ionosphere
  - LF Emission Mechanisms: Continuum & Line
- **Part II**
  - LF Instruments: Dishes and Dipoles
  - Recent LF Sky Surveys
- **Part III**
  - Brief & Biased View of LF Science
  - LF in Practice

# Getting Radio Waves to the Antennas

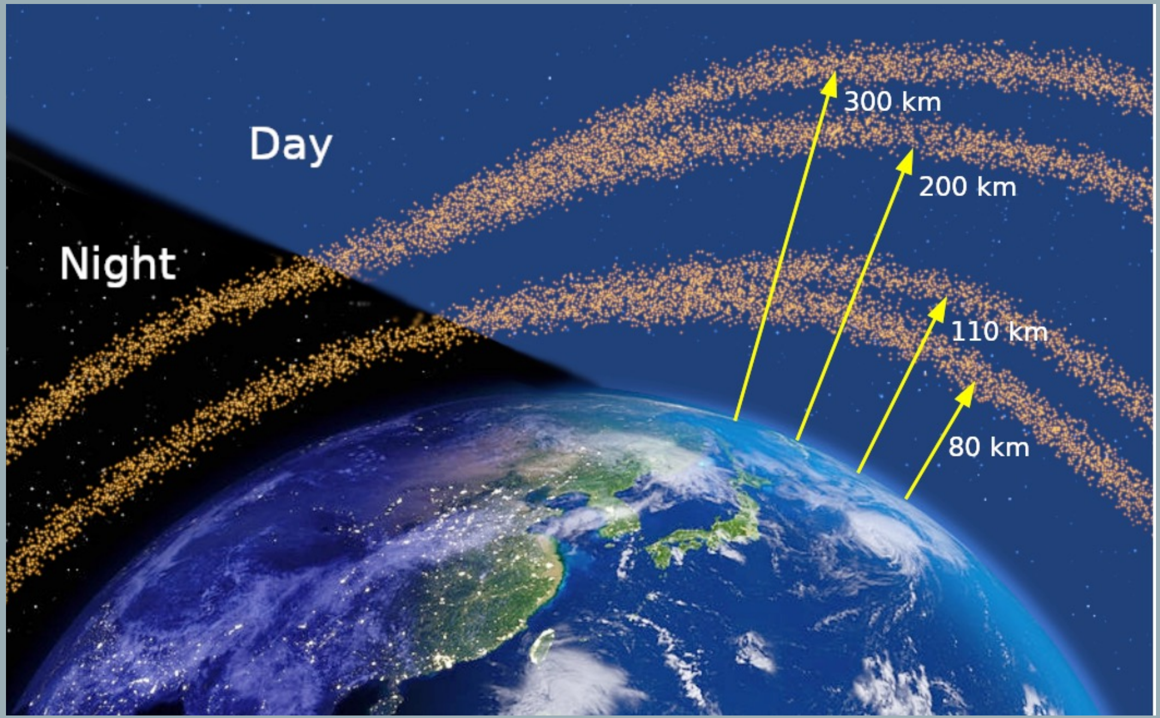


- Imaging at the diffraction limit (~$\lambda$/B) for an instrument requires good phase stability
- Radio waves from astrophysical sources pass through the ionosphere and troposphere
  - Ionosphere consists of charged plasma and responds to space weather (i.e. Sun)
  - Troposphere is a neutral component with significant (varying) water vapor density
- The effects of the Troposphere dominate above 1 GHz, the Ionospheric effects dominate below 1 GHz

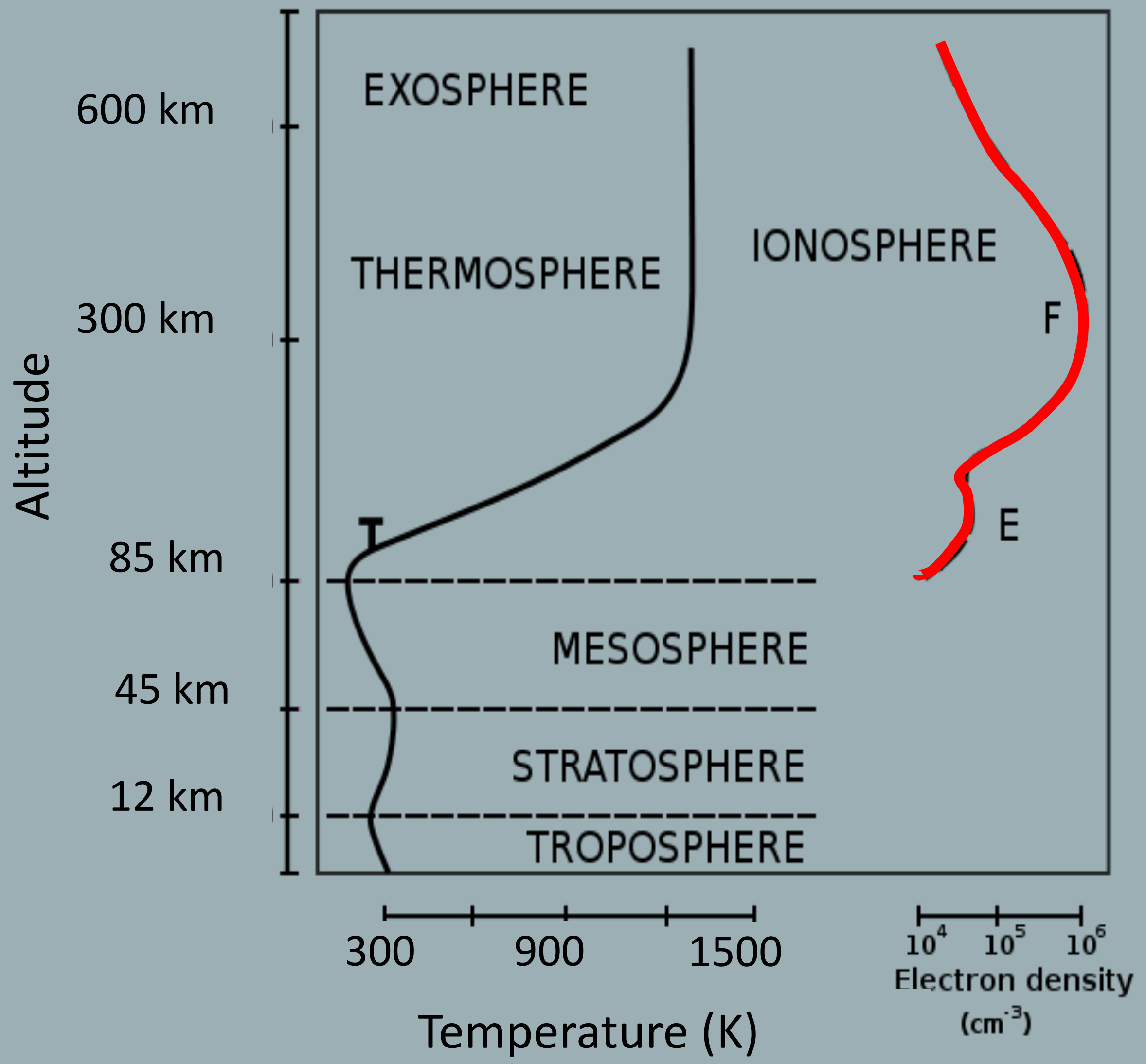


# Meet the Ionosphere

- Ionosphere extends from ~50 km to ~1000 km
- UV radiation from the Sun creates weak plasma (~1% ionized), both diurnal and seasonal effects




- Ionospheric effects on phase stability: $\phi \sim \nu^{-1}$



# Meet the Ionosphere

- Plasma interaction with electromagnetic radiation driven by two factors:
  - Plasma frequency – natural resonant frequency of plasma

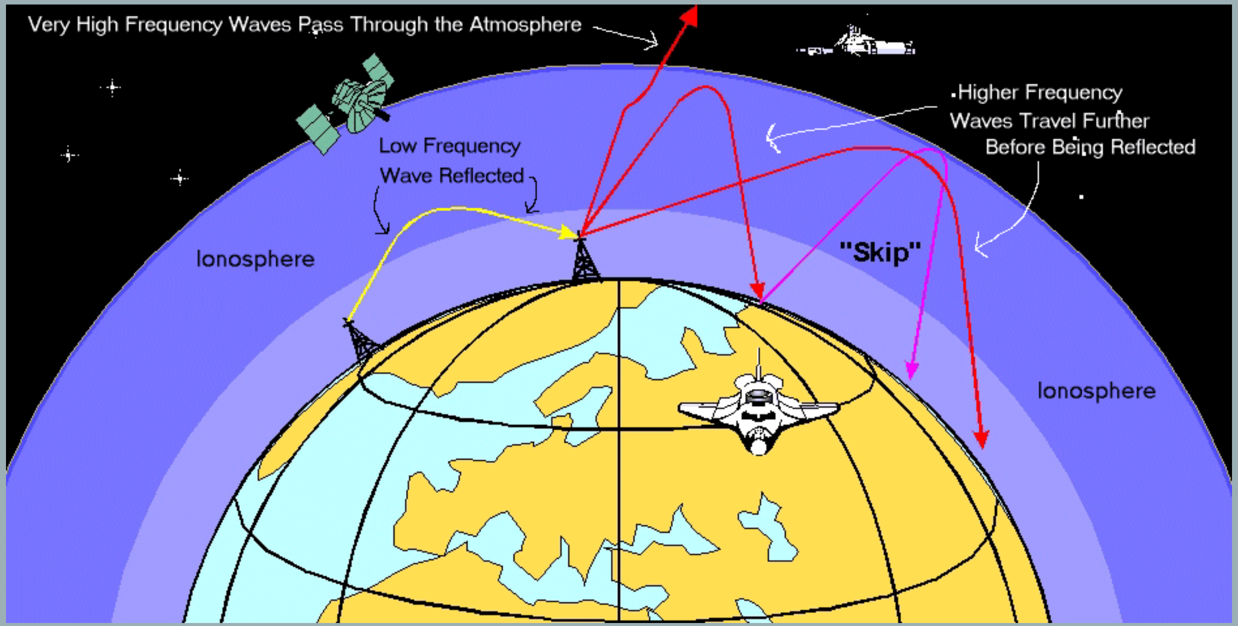
$$\nu_p = \frac{e}{2\pi}\sqrt{\frac{N_e}{m_e \epsilon_o}} \sim 9\sqrt{N_e}\ \mathrm{kHz}$$

$$N_e \simeq 10^4 - 10^6\ \mathrm{cm}^{-3}$$

  - Refractive index – describes how fast electromagnetic radiation travels

$$n_p = \sqrt{1 - (\frac{\nu_p}{\nu})^2}$$

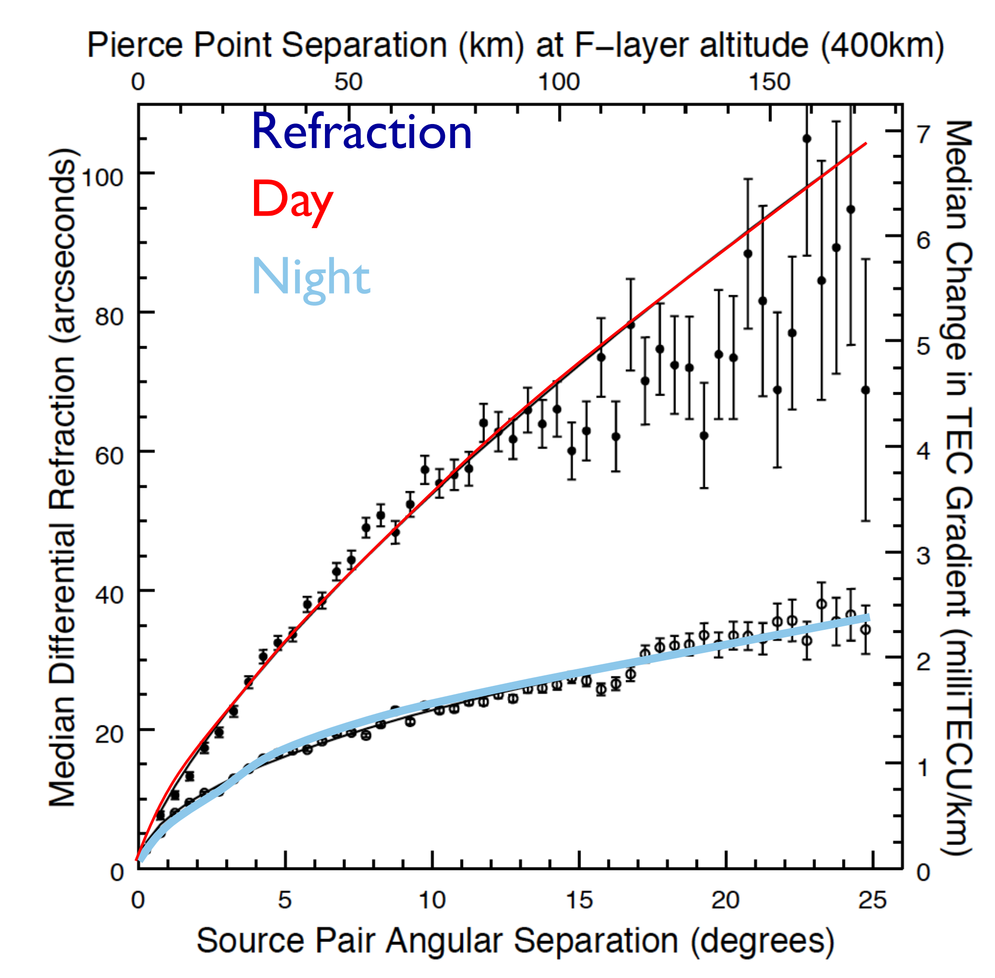
- Ionospheric impacts:
  - Reflection: $\nu < \nu_p$, cutoff 10 MHz
  - Refraction: $\nu > \nu_p$, 10 MHz to 10 GHz
  - No impact: $\nu >> \nu_p$



# Ionospheric Effects on Radio Sources

Ionosphere can have a wide range of impacts on radio emission:

- Quiescent ionosphere:
  - Refraction
  - Faraday rotation




Cohen & Röttgering (2018)

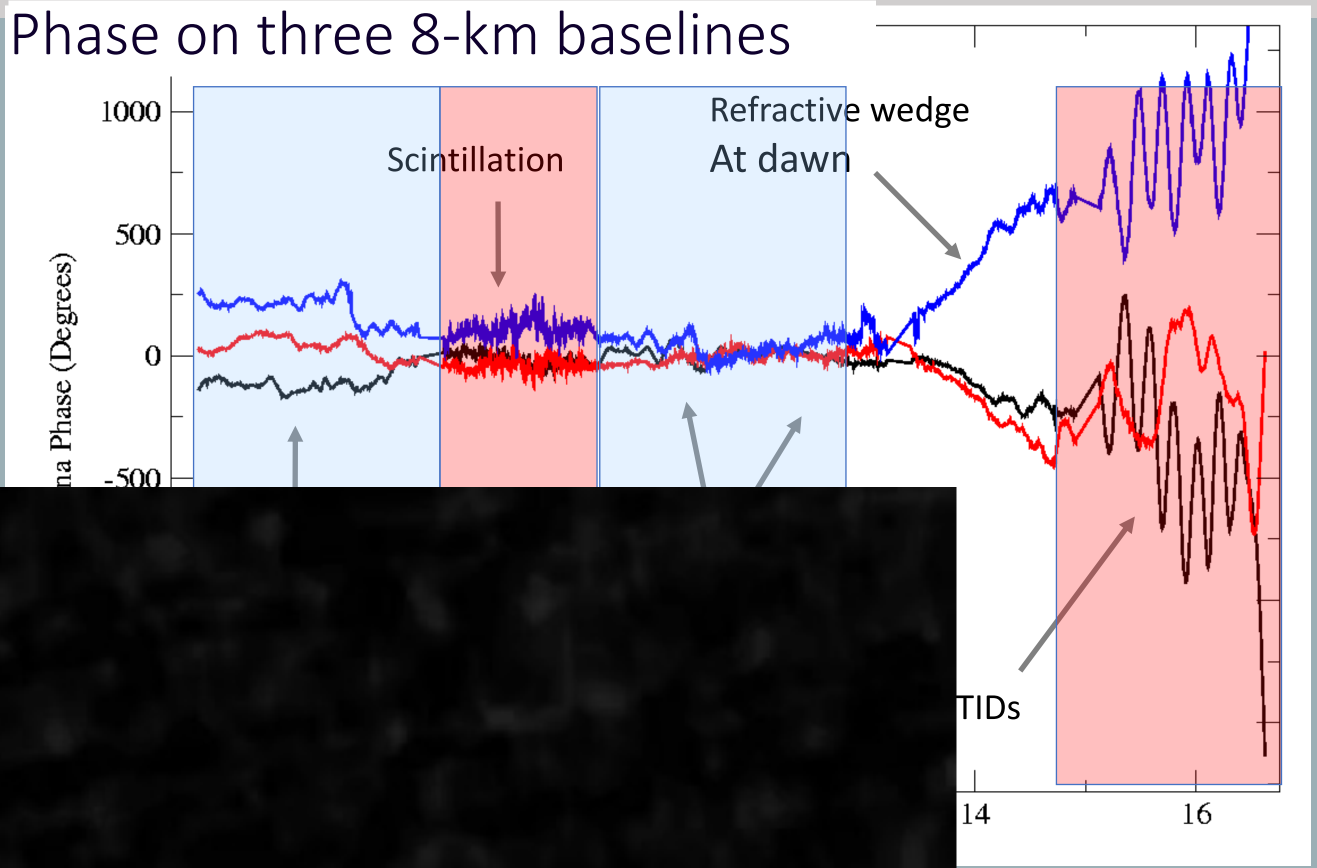
# Ionospheric Effects on Radio Sources

Quiescent Ionosphere
Disturbed Ionosphere

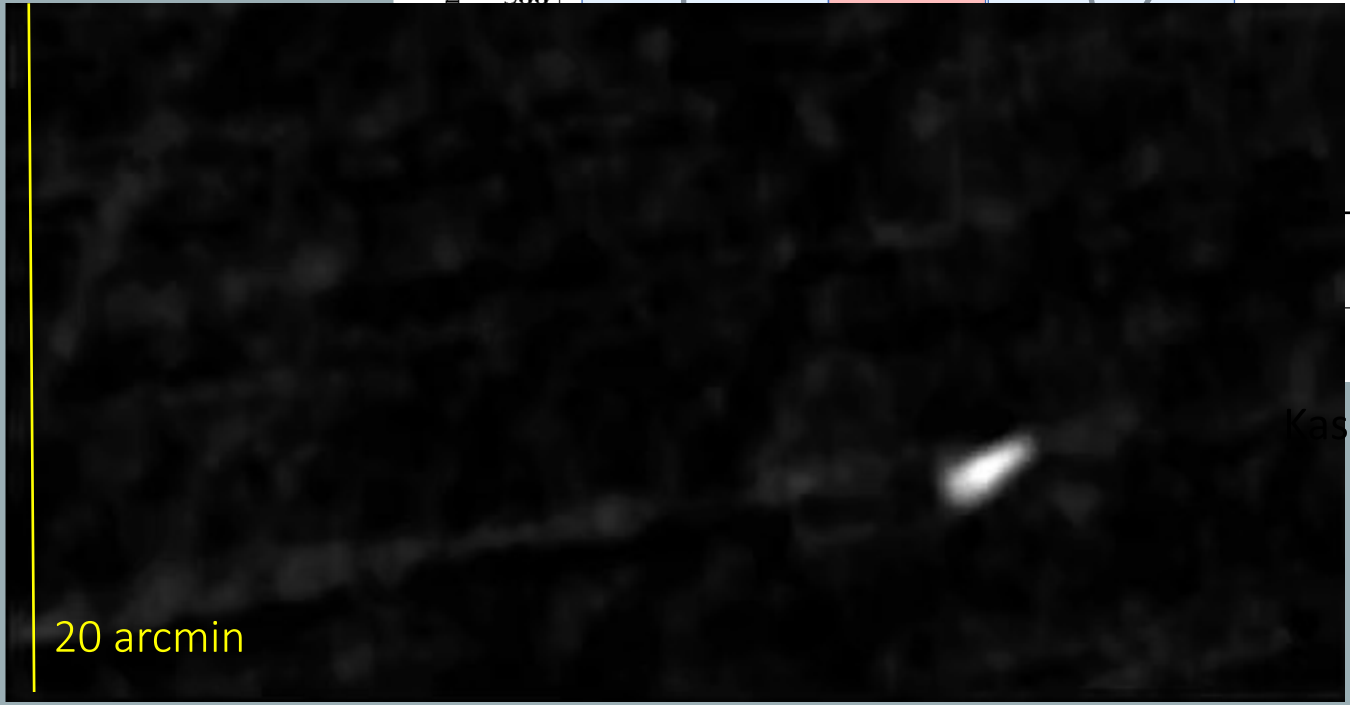
Ionosphere can have a wide range of impacts on radio emission:

- Quiescent ionosphere:
  - Refraction
  - Faraday rotation

- Disturbed ionosphere:
  - Image Distortion
  - Rapid Position Shifts
  - Scintillation



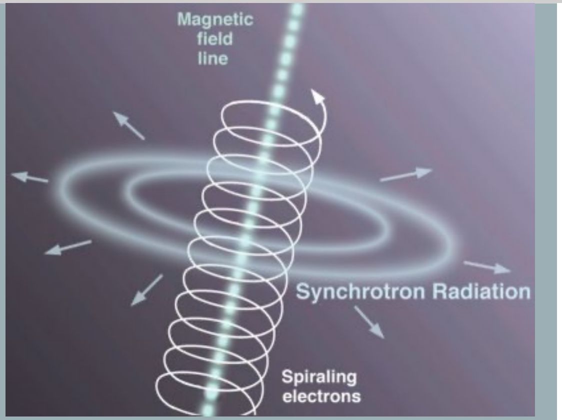

Kassim et al. (2007)

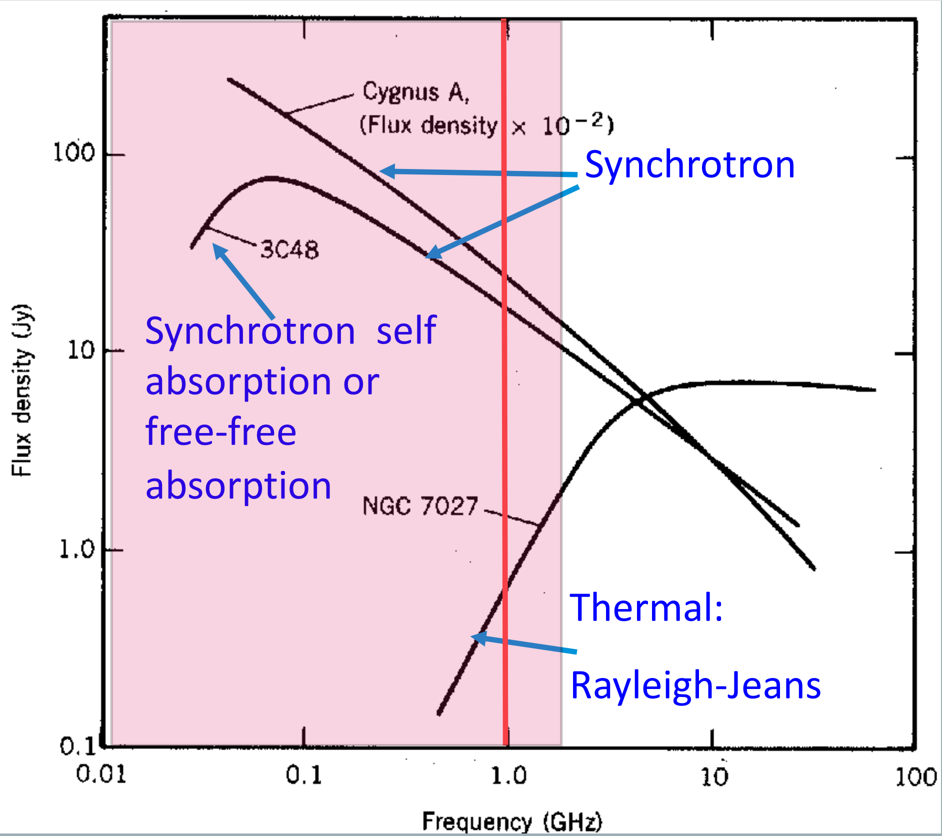



B. Cotton

# Low Frequency Emission: Continuum & Line

- Synchrotron/cyclotron emission
  - Best observed at ν < 1 GHz
  - Relativistic/non-relativistic e$^-$ in magnetic fields
  - Emission is polarized, incoherent or coherent




*Thompson, Moran, & Swenson*

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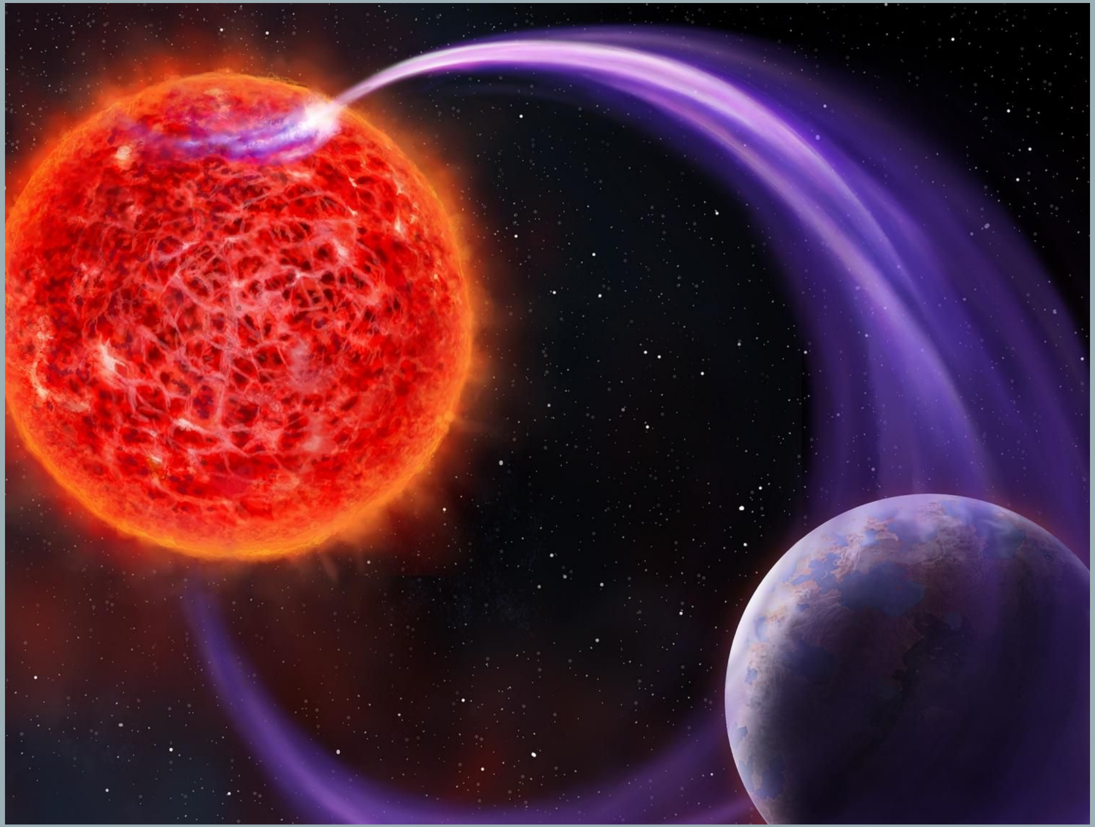
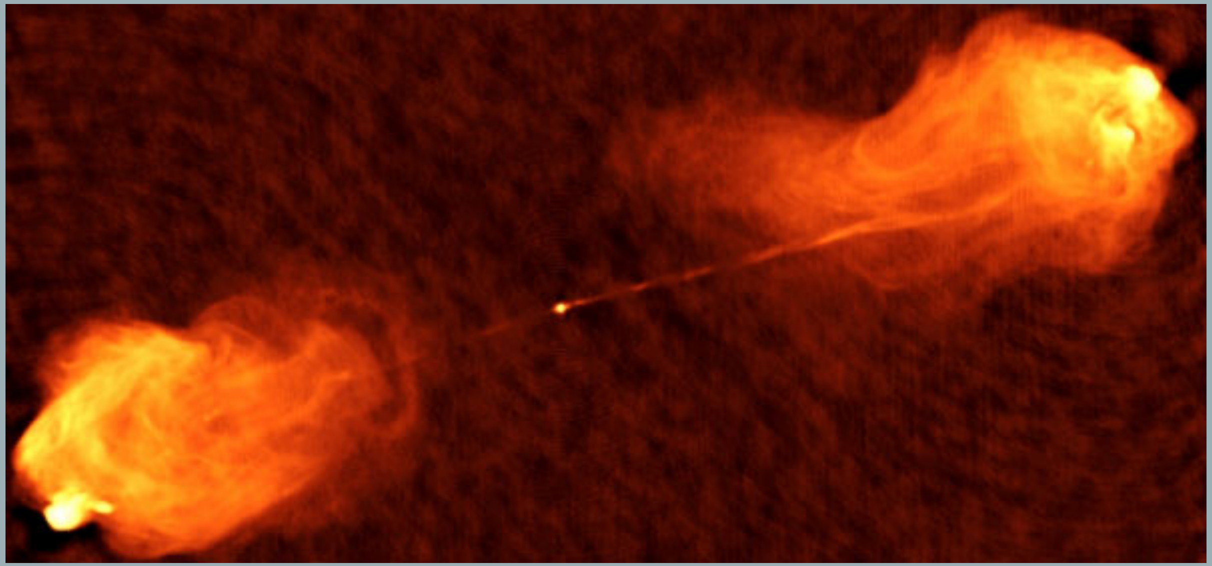


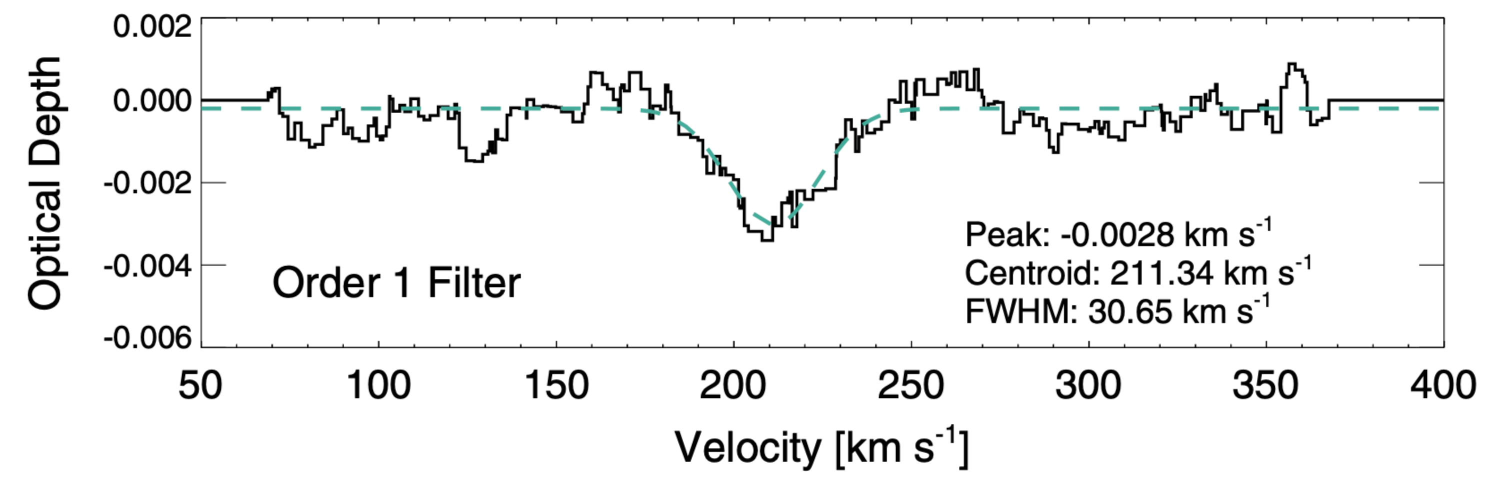
*Credit:* Danielle Futselaar (artsource.nl)



*Credit: NRAO/AUI*

# Low Frequency Emission: Continuum & Line

- Redshifted Line:
  - $\nu = 1420/(1+z)$ MHz (21 cm)
  - $\nu = 1665(7)/(1+z)$ MHz (OH Mega Maser)
- Radio Recombination Lines:
  - Probe of ISM conditions: low temp, low density




*1st extragalactic RRL (M82) LOFAR, Morabito et al. (2014)*

*M82 Credit: NASA/Chandra*

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# Low Frequency Instruments

- Advances in ionospheric calibration, wide-field imaging, and radio frequency interference (RFI) excision have led to a new focus on low frequency arrays

A Few Examples of Low Frequency Instruments

| | Instrument | Location | ν range (MHz) | Resolution (arcsec) | FoV (arcmin) | Sensitivity (mJy) |
|---|---|---|---|---|---|---|
| Dishes | JVLA (4) | NM | 54-86 | 850-24 | 700 | 50 |
| Dishes | JVLA (P) | NM | 240-470 | 200-5 | 150 | 0.1 |
| Dishes | GMRT | IN | 120-1500 | 17-2 | 152-27 | .19-0.04 |
| Dishes | MeerKAT | SA | 900-1650 | 10-4 | 105-40 | .009-.005 |
| Dishes | ASKAP | AU | 800-1800 | 15-8 | 185 | .037 |
| Dipoles (Aperture Array) | LOFAR-Low | NL | 10-80 | 40-8 | 1089-220 | 110-12 |
| Dipoles (Aperture Array) | LOFAR-Hi | NL | 120-240 | 5-3 | 272-136 | 0.41-0.46 |
| Dipoles (Aperture Array) | LWA1 | NM | 10-88 | | 600-180 | 1000 |
| Dipoles (Aperture Array) | MWA | WAu | 80-300 | 180-60 | 1482-1162 | 10 |

Note: Table numbers are not apples-apples comparison!

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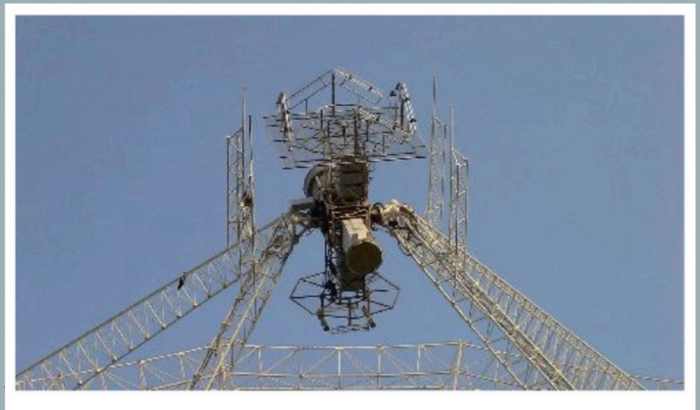
# Low Frequency Instruments: Jansky Very Large Array

- VLA low band (dish + dipole) system transitioned to wide-bandwidth (2013)
- Replaces narrow band receivers + uses legacy P band feeds:
  - P band: 240 – 470 MHz
- New 4 band feed (MJP) design 56-86 MHz
- eLWA
- VLA Low-band Ionosphere and Transient Experiment (VLITE) operating 24/7 at P band on 18 VLA antennas (Clarke et al. SPIE, 2016)

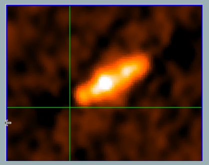

# Low Frequency Instruments: upgraded GMRT

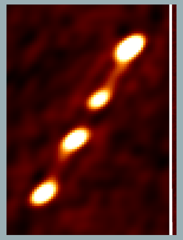
- Giant Metrewave Radio Telescope (India) feeds located at prime focus on a rotating turret
- uGMRT wide-band upgrade: 120-1500 MHz with up to 400 MHz instantaneous BW
  - 120-250 MHz (Band 2), $\sigma$=190 $\mu$Jy/bm , $\Phi$=17”
  - 250-500 MHz (Band 3), $\sigma$=50 $\mu$Jy/bm , $\Phi$=8”
  - 550-850 MHz (Band 4), $\sigma$=40 $\mu$Jy/bm , $\Phi$=4”
  - 1050-1450 MHz (Band 5), $\sigma$=45 $\mu$Jy/bm, $\Phi$=2”

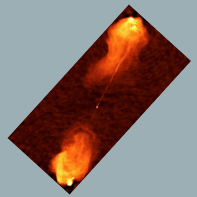


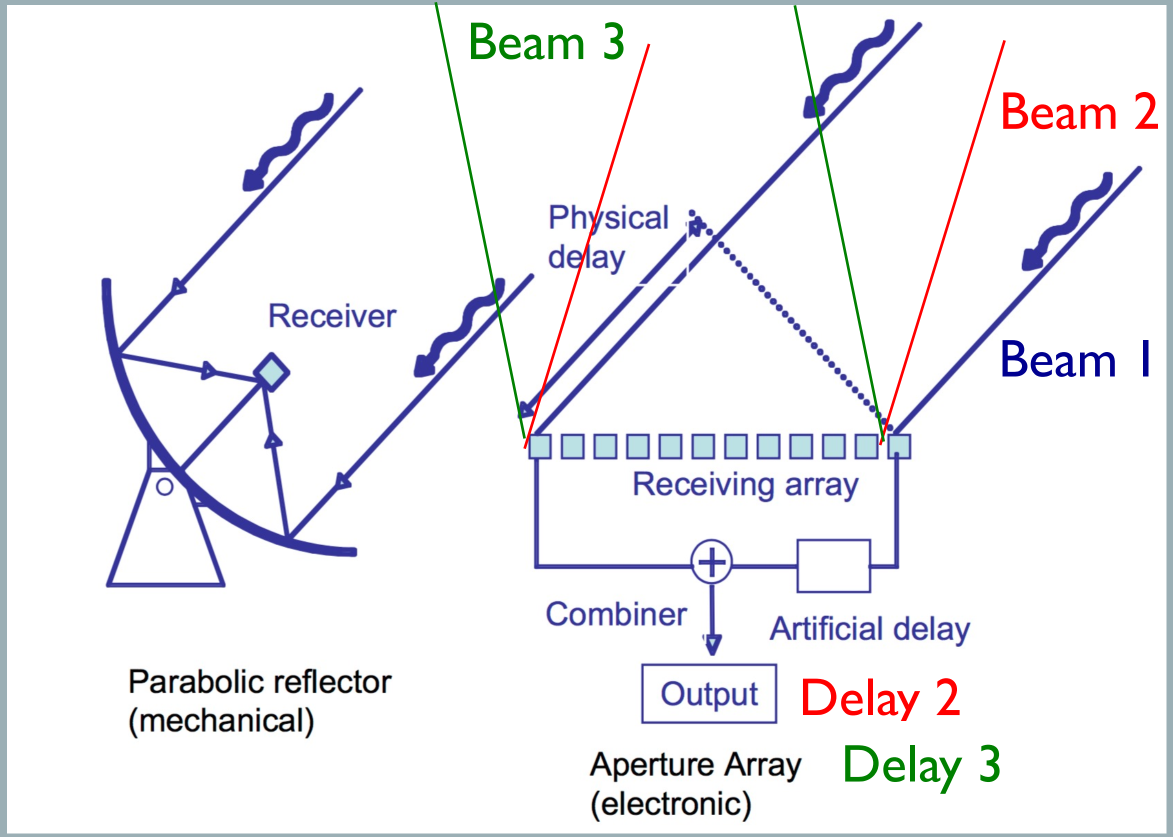
# Low Frequency Instruments: Dipole Arrays

- Low frequencies are very forgiving, no need for an accurate dish surface
- Bare dipoles + ground screens are much cheaper to build and maintain compared to dishes
- Electronic beamforming of dipole arrays allows flexibility to image anywhere on the sky and have multiple, independent and simultaneous beams!



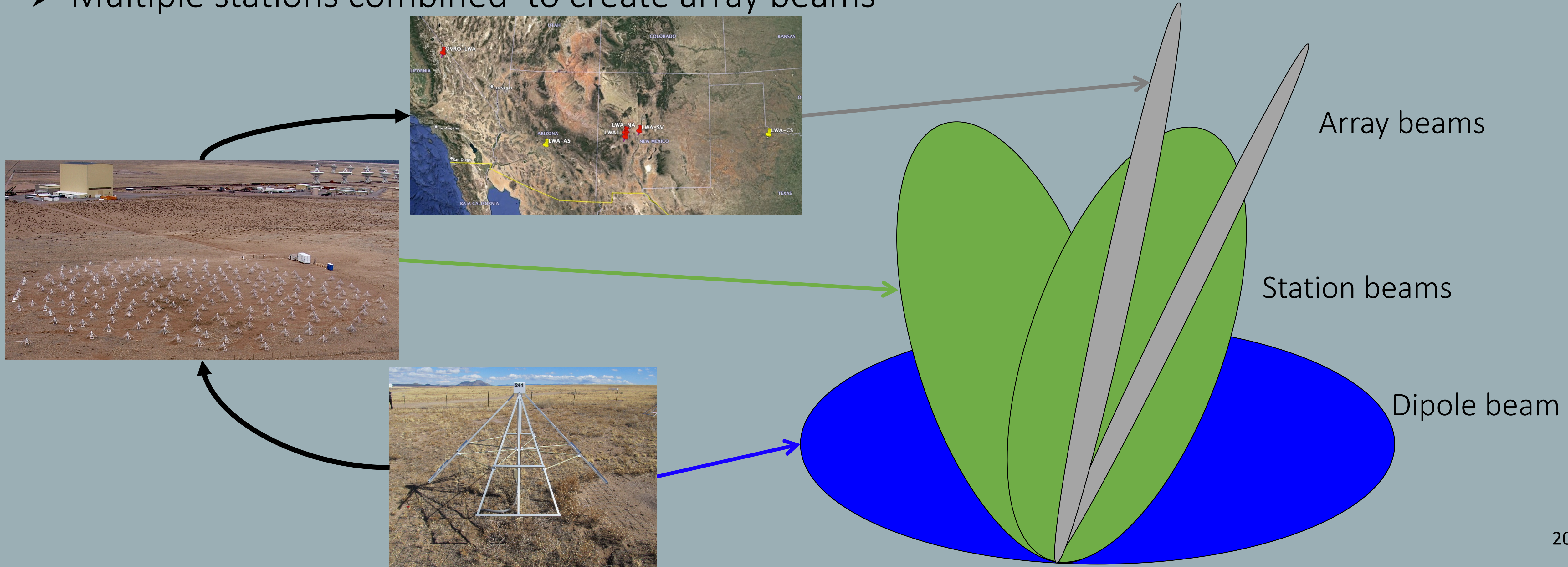






# LF Instruments: Dipole Array Beams

- A single dipole sees the entire sky (element pattern or dipole beam)
- Station of dipoles (e.g. LWA1) can be combined to create station beams
- Multiple stations combined  to create array beams

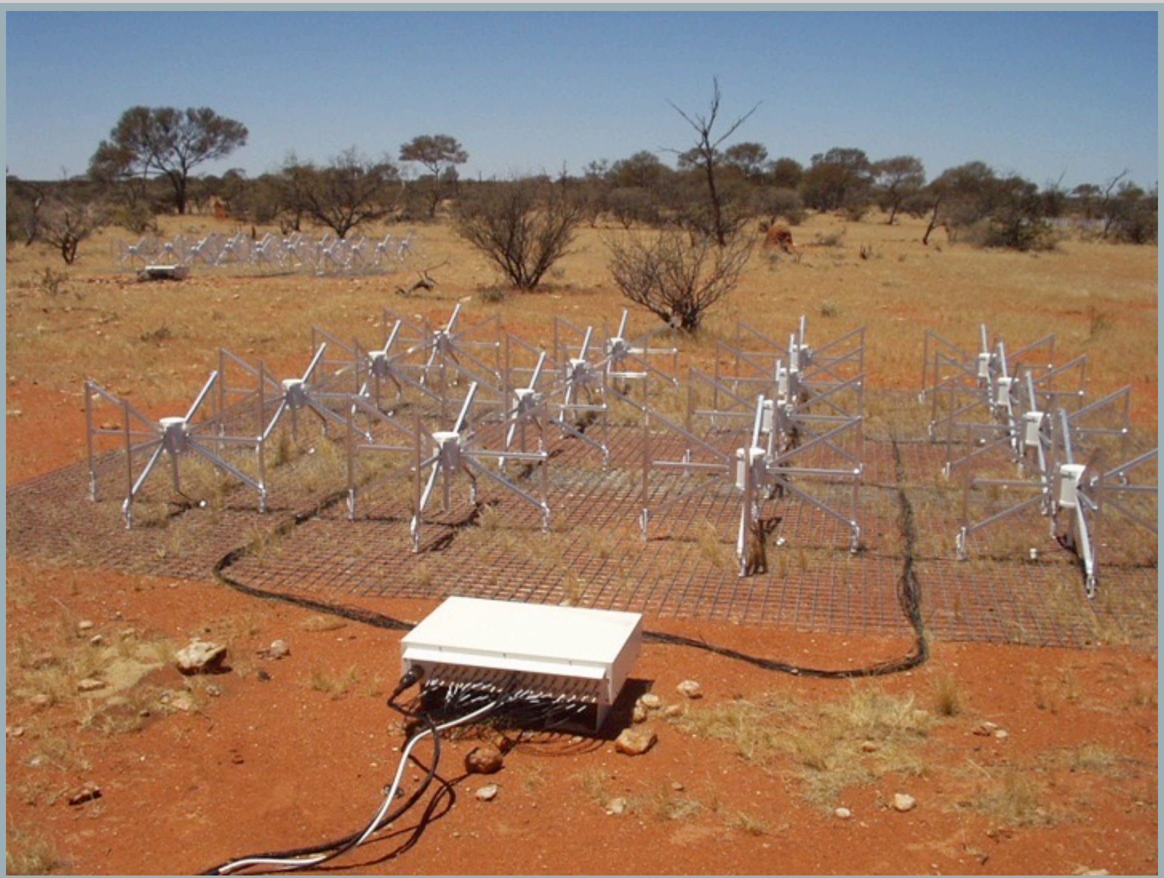


# Low Frequency Instruments: LWA1, LWA SV, OVLWA

- Long Wavelength Array Station 1 (LWA1), LWA Sevilleta (LWA SV), Owens Valley Radio Observatory LWA (OVRO LWA)
    - Operate 10(4)-88 MHz
    - LWA1-LWASV baseline 70 km (10”)
    - LWA1,LWASV: 256 dipoles in 100x110m stations
    - LWA1: 4 simultaneous beams with two tunings + dual orthogonal polz.
    - LWA SV: 1 beam simult. WB real-time correlation
    - All-sky buffers
    - Range of science
    - Open access facilities
    - Upgrade: eLWA (LWA + VLA MJPs)

# Low Frequency Instruments: MWA

- MWA
  - Murchison Wide-field Array, Australia
  - 80-300 MHz, BW=31 MHz
  - Bowtie geometry
  - Tiling increases $A_e$ (~20 $m^2$)
  - EOR, galaxy clusters, SNR, transients, Solar and space weather, ionosphere
  - Complicated beam pattern
  - Upgrade: extended configuration using 128 tiles
  - Upgrade: correlator upgrade 2022 to enable correlation of all 256 tiles of 16 dipoles



Tingay et al. (2013) PASA, 30, 7

# Low Frequency Instruments: LOFAR

- LOFAR
  - Low Frequency Array
  - Low band: 10-80 MHz
  - High band: 120-240 MHz
  - 8 beams per station
  - Core, remote and international stations
  - EOR, surveys, transients, CRs, Solar and Space Weather, magnetism, …
  - LOFAR 2.0 Upgrade: correlator, station electronics


Van Haarlem et al. (2013)

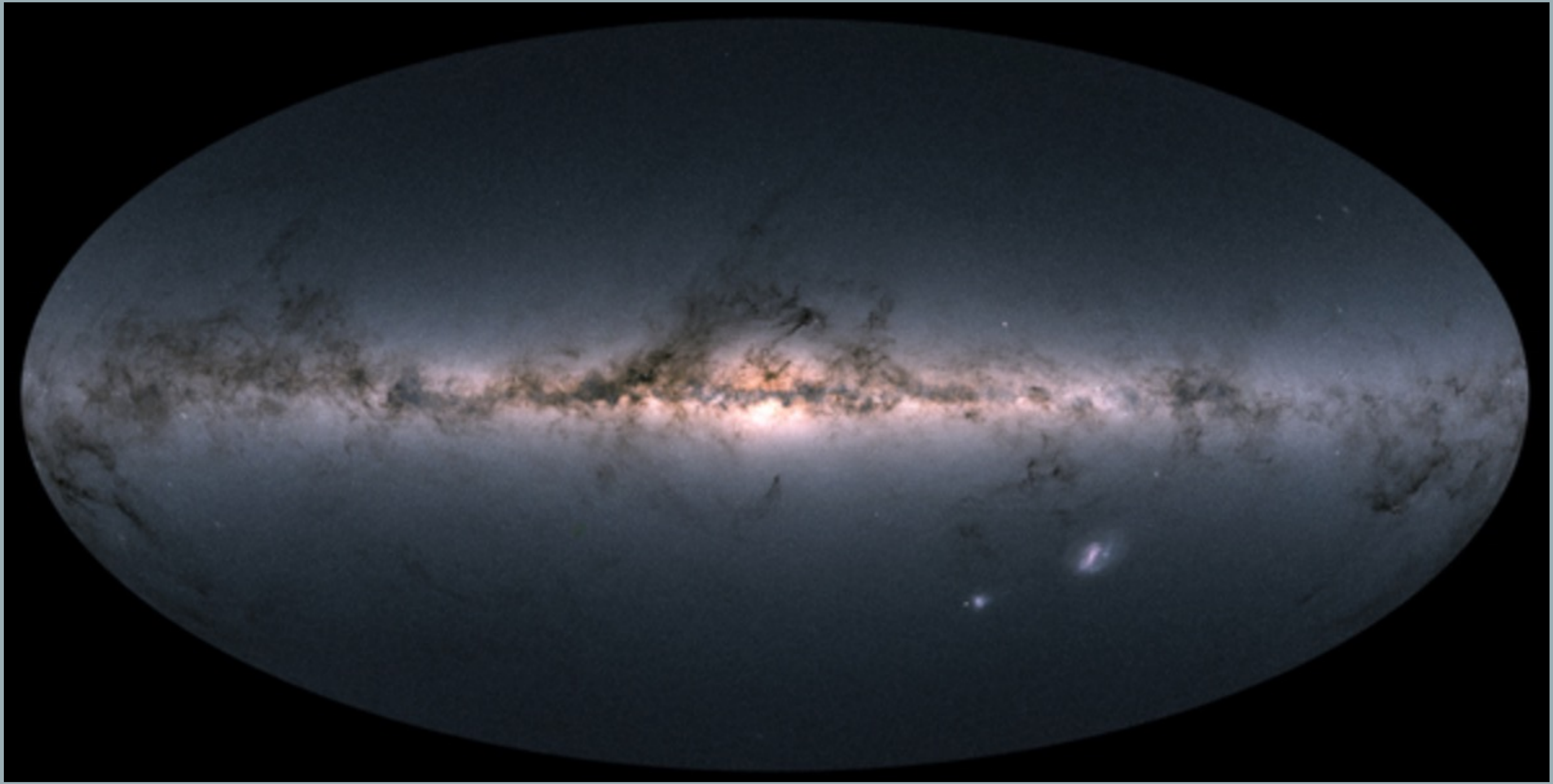
# Low Frequency Instruments: CHIME

- CHIME
  - Canadian Hydrogen Intensity Mapping Experiment
  - 400-800 MHz
  - Four 20mx100m cylindrical reflectors each with 256 dual polz. feeds
  - Transit interferometer with no moving parts or cryogenics
  - Form 1024 ‘beams’ across the sky simultaneously with 20’ resolution
  - Observes northern sky every day (Dec range -21 to +65), FRBs
  - Upgrade: Three new outriggers (Princeton, BC; Greenbank, WV; Hat Creek, CA)

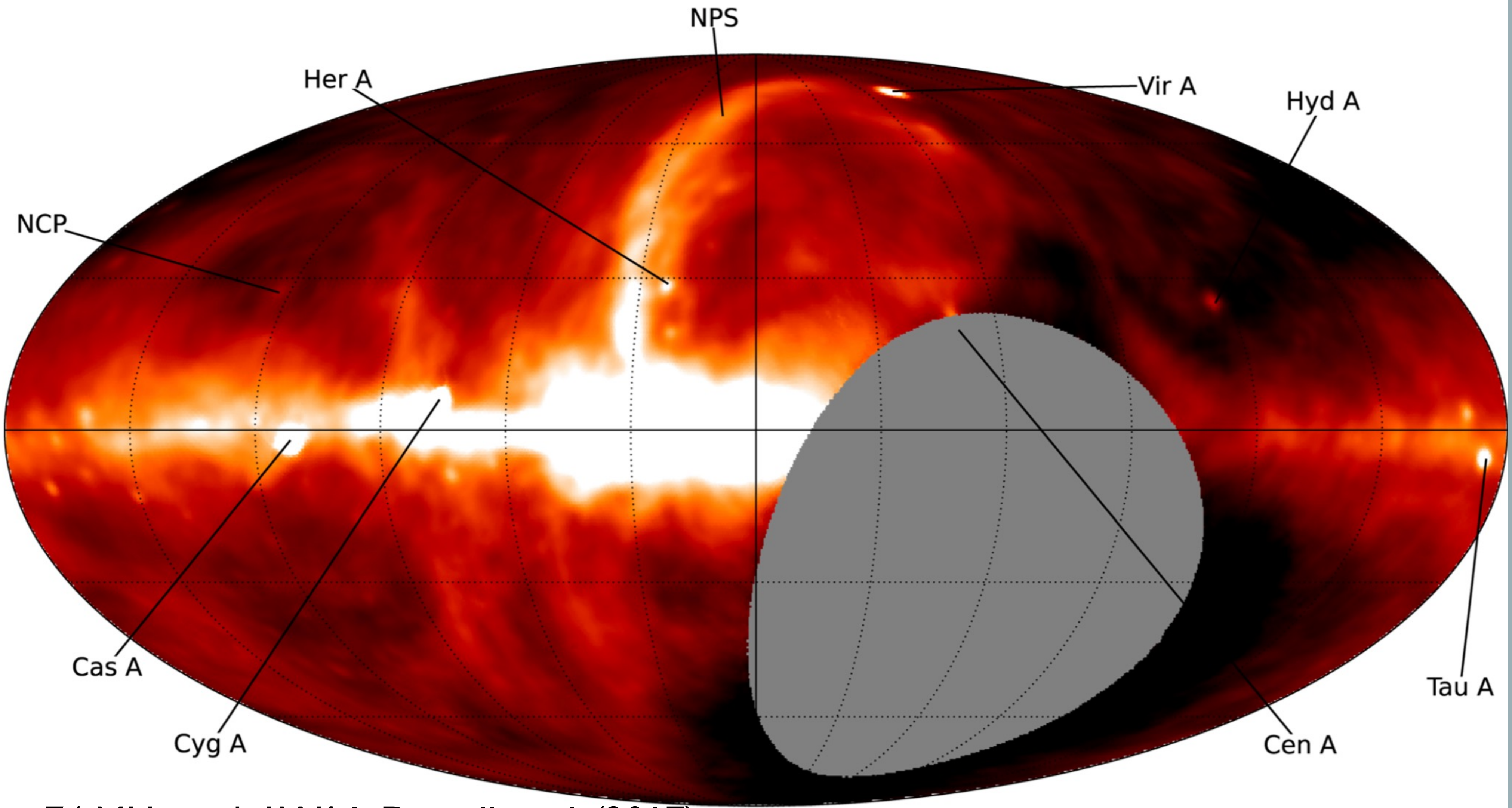
# Low Frequency Instruments: SKA-Low

- SKA-Low
  - Square Kilometre Array :Low Frequency Aperture Array
  - 50 MHz to 350 MHz
  - Goal: 131,072 antennas spread over 512 stations
  - Maximum station baseline 65 km
  - Current status: complete single station of 256 antennas being tested

# Surveys: Optical Sky

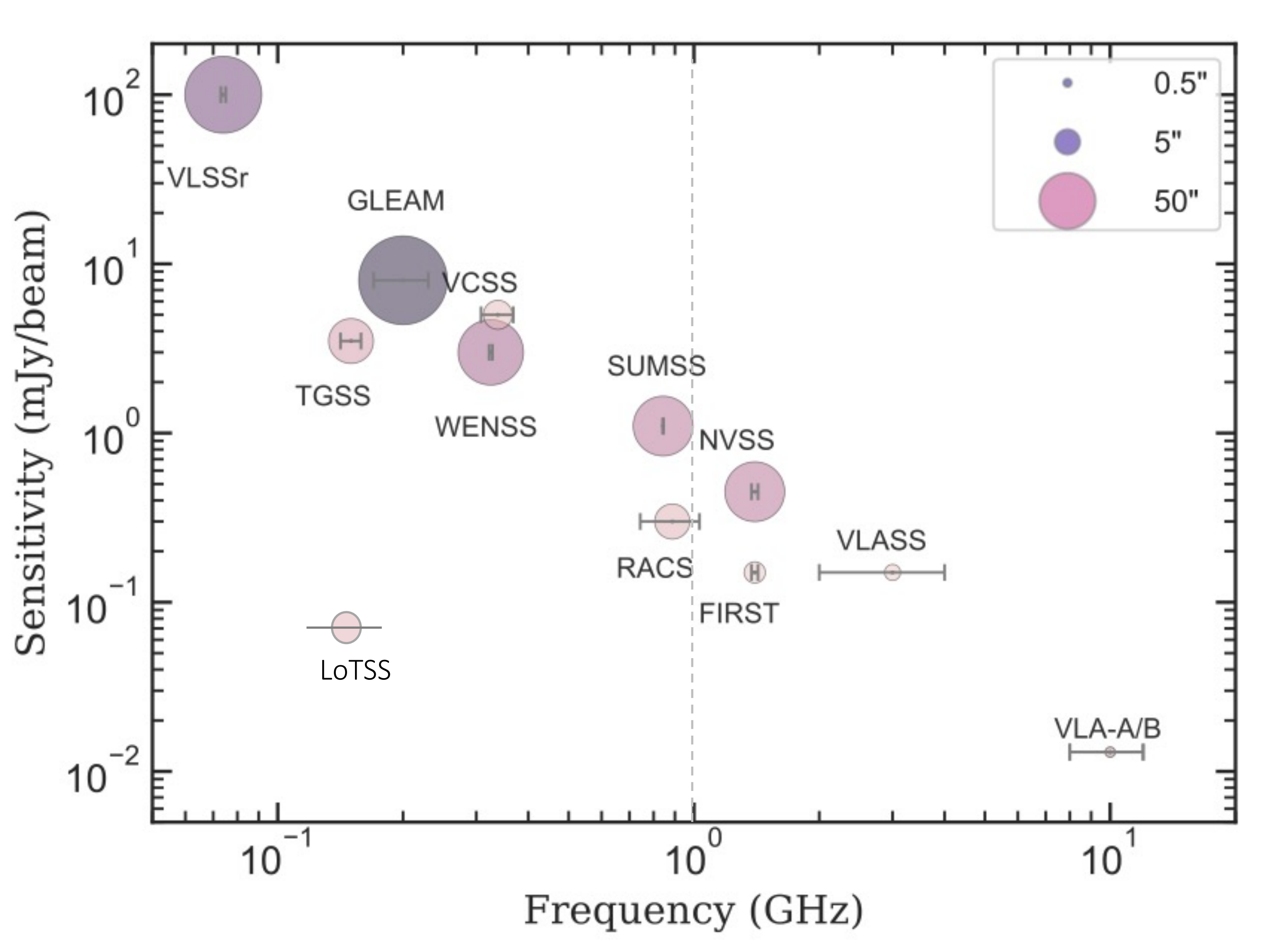


# Surveys: Radio Sky



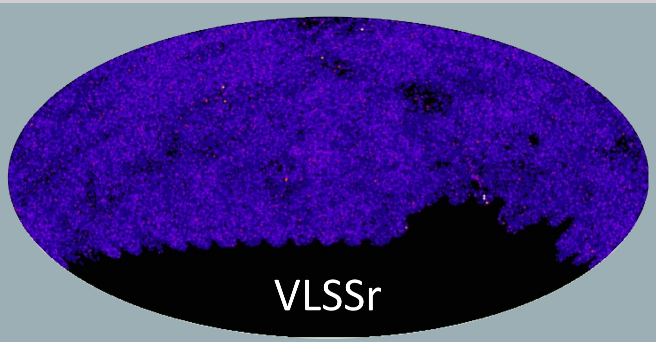

74 MHz with LWA1: Dowell et al. (2017)

# Low Frequency Surveys

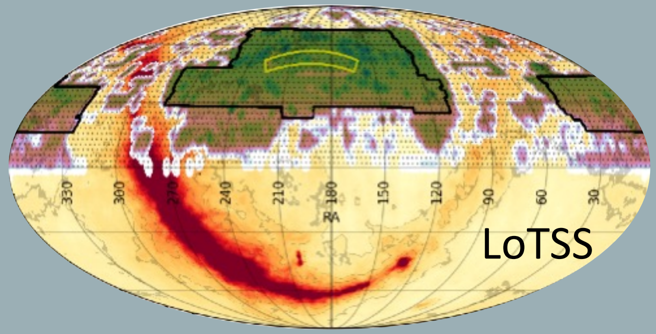



Modified from Patil et al. (2022)

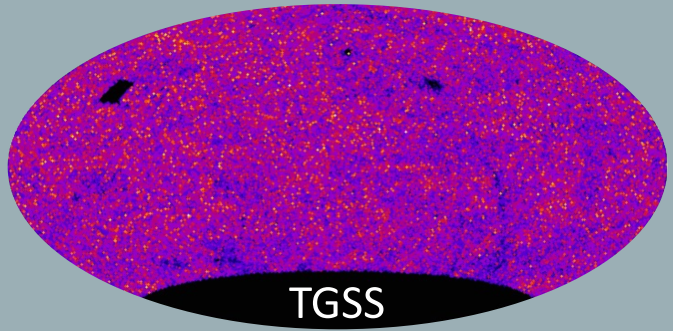
# (A Few) Low Frequency Surveys



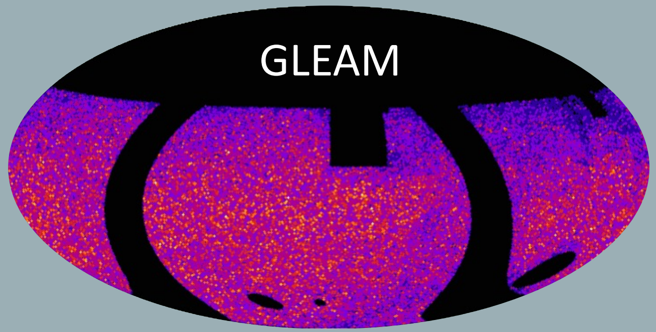

VLA Low Frequency Sky Survey redux (VLSSr)




LOFAR Two Metre Sky Survey (LoTSS)

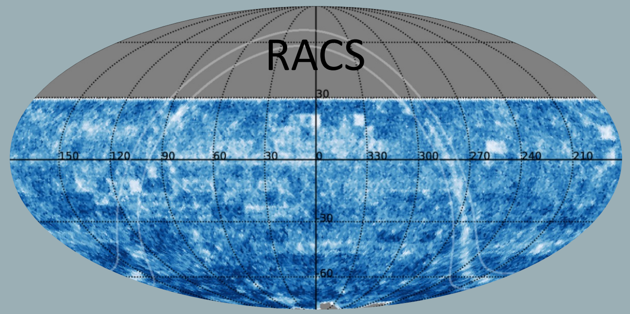



TIRF GMRT Sky Survey Alternative Data Release 1 (TGSS ADR1)




Galactic and Extragalactic All-Sky MWA Survey (GLEAM)

| Survey Name | Freq. MHz | Res. | Sensitivity mJy/bm |
|---|---|---|---|
| VLSSr | 73.8 | 75” | 100 |
| GLEAM | 87-215 | 120” | 6-10 |
| LoTSS | 120-168 | 6” | .083 |
| TGSS | 150 | 25” | 3-5 |
| RACS | 887.5 | 15” | .025-.040 |




Rapid ASKAP Continuum Sky Survey (RACS)

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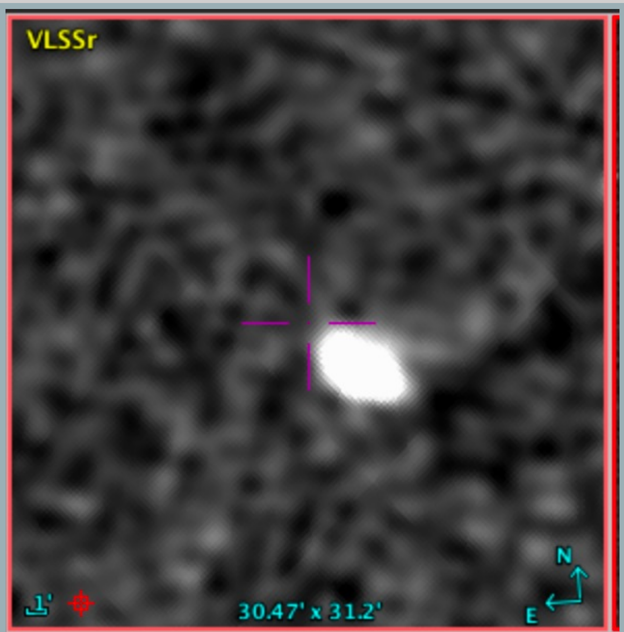
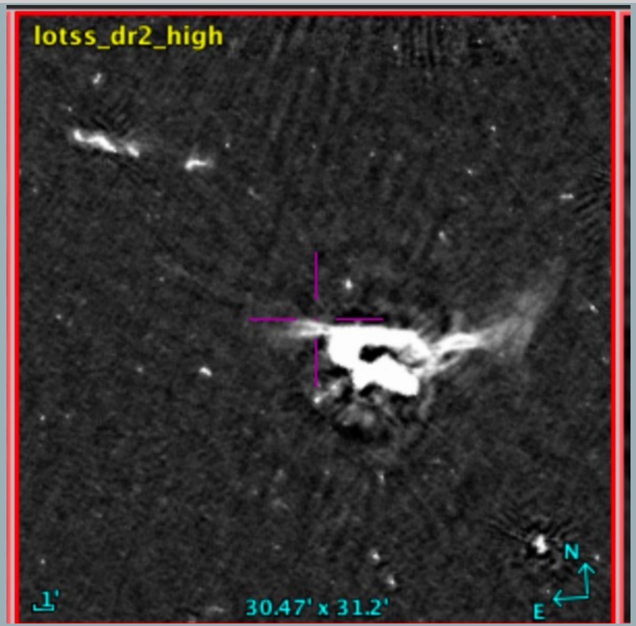
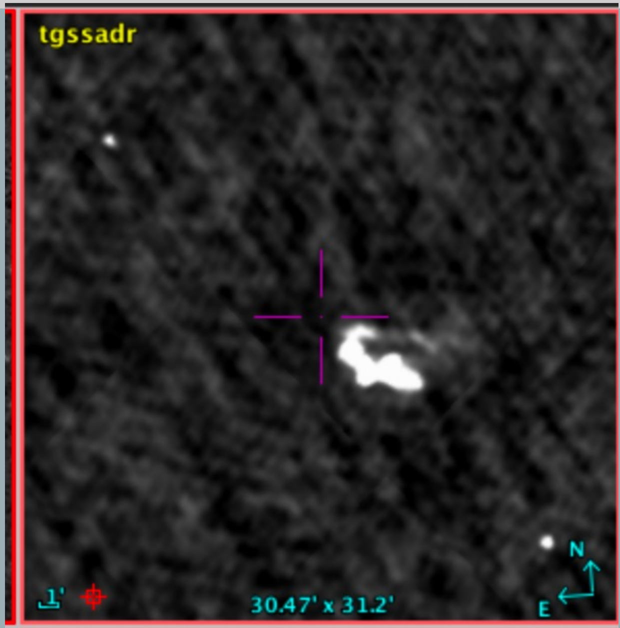
# Low Frequency Surveys




NGC 326





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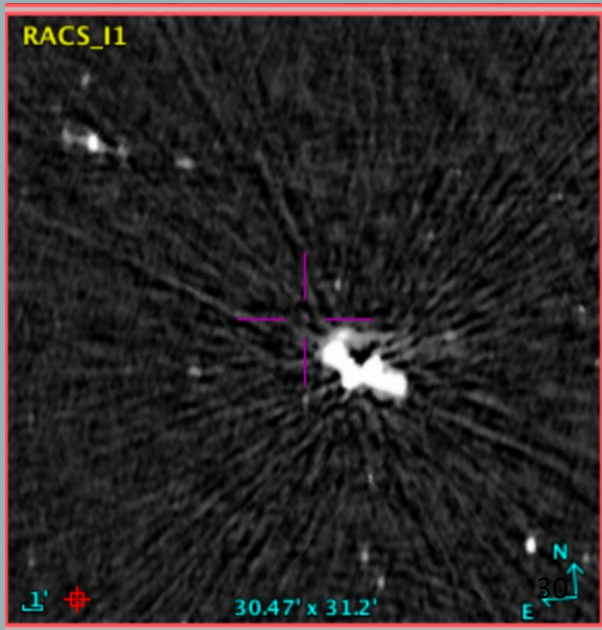

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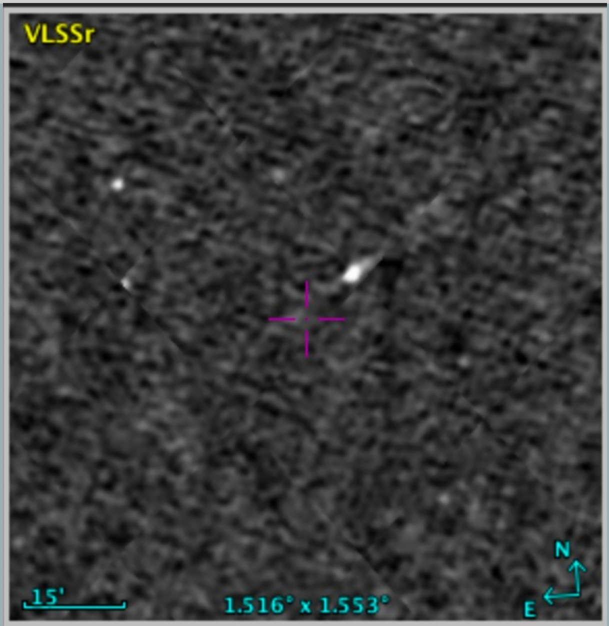
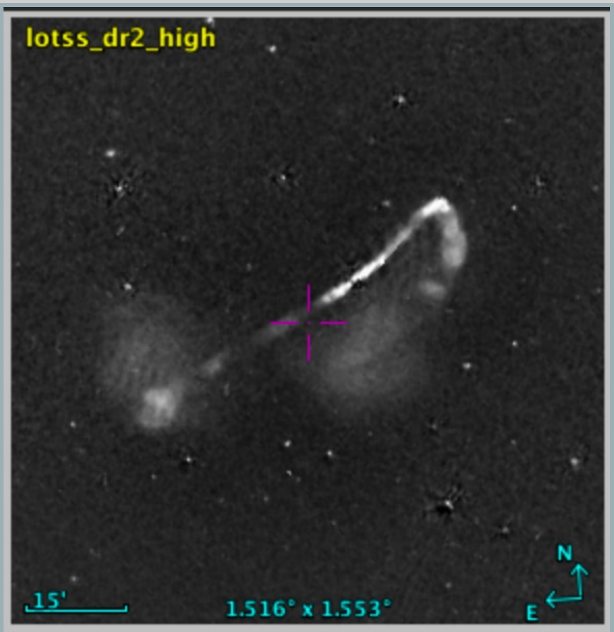
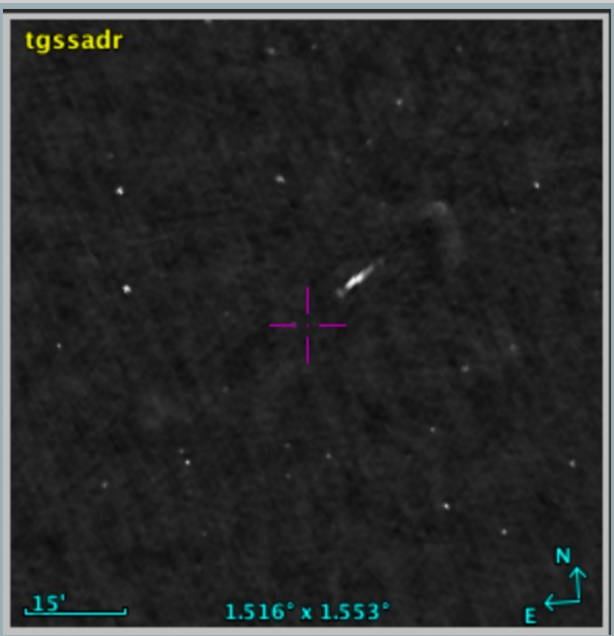
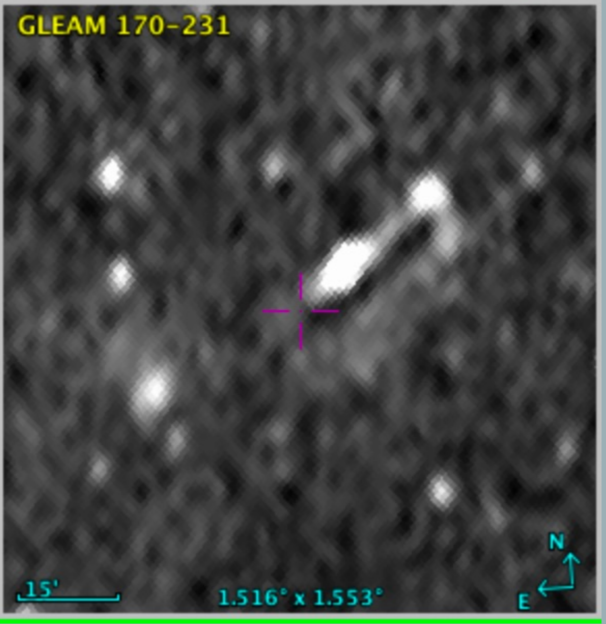


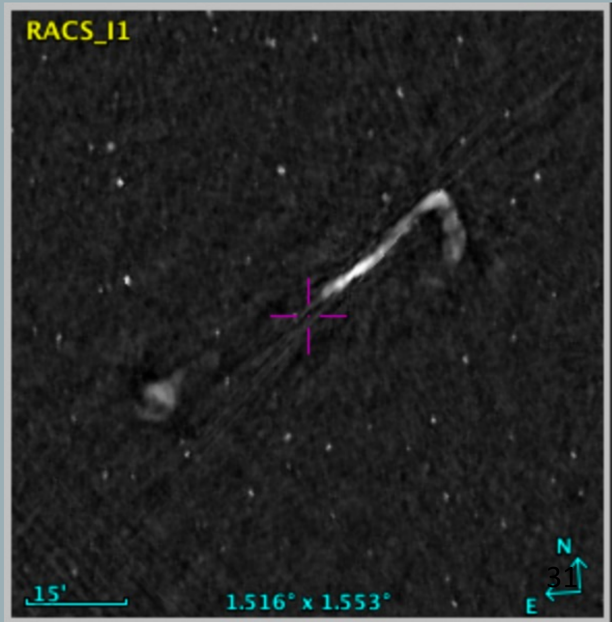

NGC 315



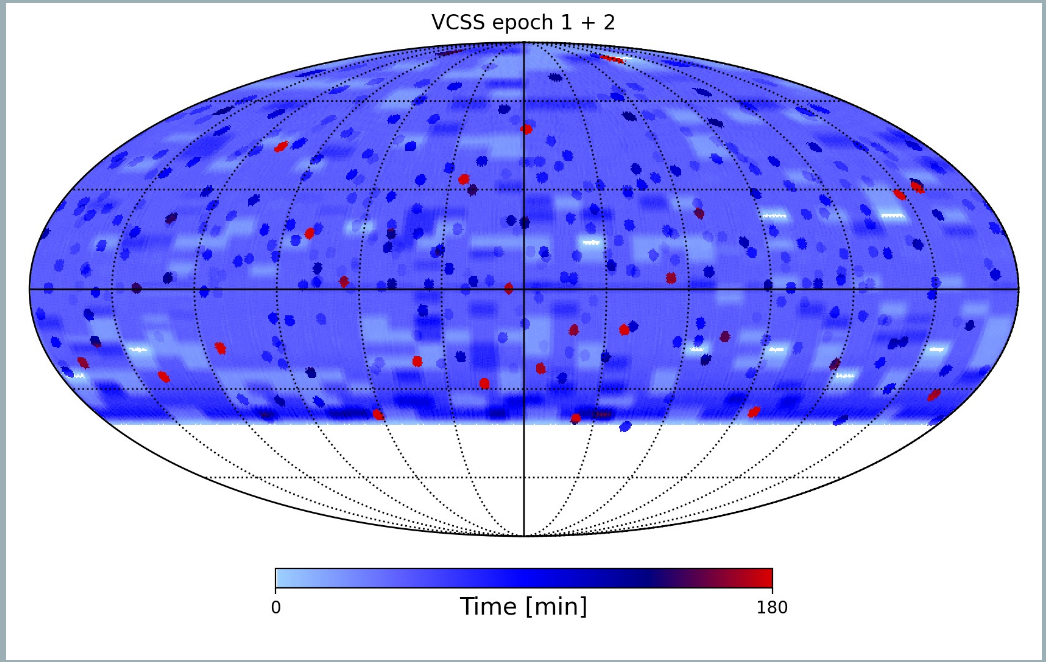



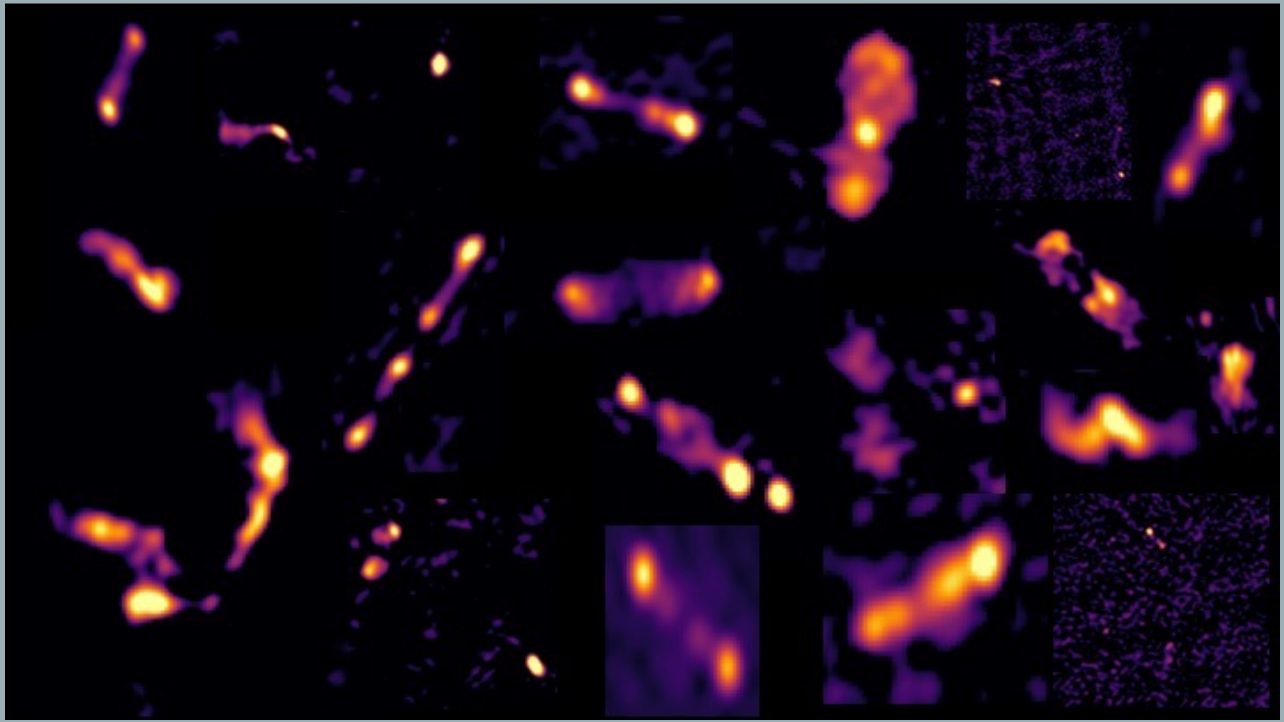

| Survey Name | Freq. MHz | Res. | Sensitivity mJy/bm |
|---|---|---|---|
| VLSSr | 73.8 | 75” | 100 |
| GLEAM | 87-215 | 120” | 6-10 |
| LoTSS | 120-168 | 6” | .083 |
| TGSS | 150 | 25” | 3-5 |
| RACS | 887.5 | 15” | .025-.040 |



# VLITE Commensal Sky Survey (VCSS)

- Commensal with VLA (δ> -45°), 320< ν < 384 MHz
- VLITE began 2014, currently ~7.5 years
- VLITE Records Data ~72% wall time (~45,000 hr)
- VCSS started in 2017 with 3 GHz VLA Sky Survey (VLASS)
- VCSS resolution 20” (VLITE resolution from 5” to 3’)
- Pipelines calibrate, image and catalog data



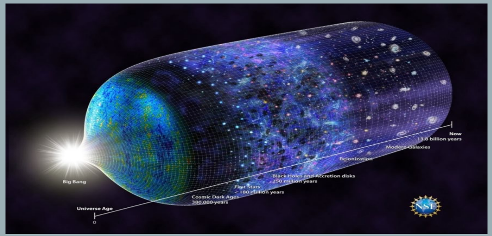
Currently data are made available on request:

- working on catalog and cutout public release

# Talk Outline:

- Part I
  - Meet the Ionosphere
  - LF Emission Mechanisms: Continuum & Line
- Part II
  - LF Instruments: Dishes and Dipoles
  - Recent LF Sky Surveys
- Part III
  - Brief & Biased View of LF Science
  - LF in Practice

# Low Frequency Science

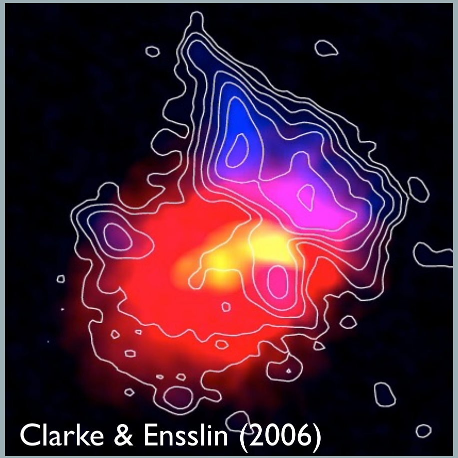


## Early Universe

Dark Ages, EoR, &
BAO 0.5<z< 100,
1400>ν>15 MHz

## Solar System and Extrasolar Planets

CME's, cyclotron maser instability, ionosphere.

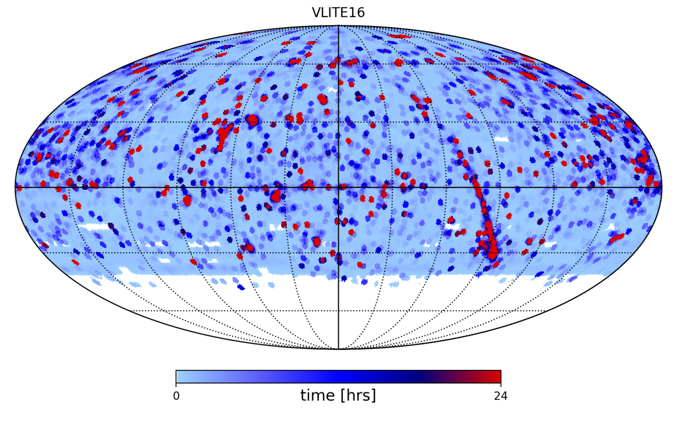


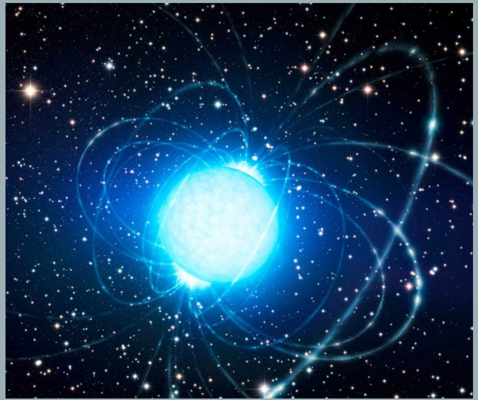

## Shocks/Turbulence

Identifying particle acceleration and magnetic field amplification in extreme environments

## Population Surveys

Large FoV - rapidly build catalogs of source flux and morphology.



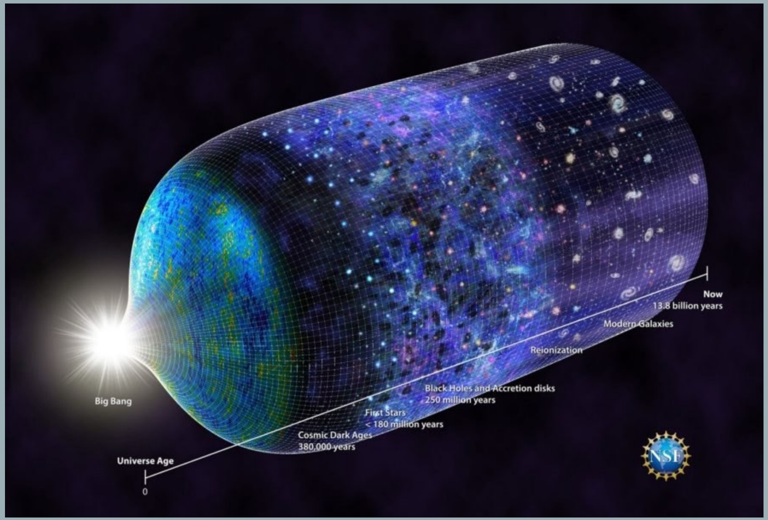
## Transients

Search for fast (e.g. FRBs, Pulsars) and slow transients (e.g. supernova)

## Serendipity

New phase space leads to discovery.

# Low Frequency Science

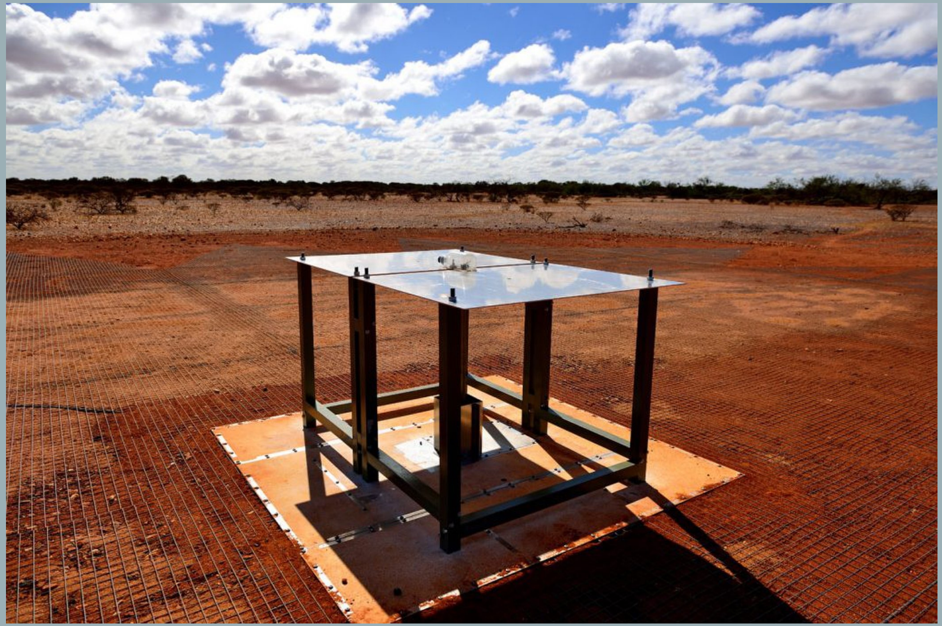



Fingerprint of First Stars

- Early Universe was filled with neutral hydrogen
- First stars collapsed from density fluctuations
- UV excited 21-cm hyperfine line allowing it to absorb CMB photons
- Absorption trough width related to early star impact on neutral hydrogen

EDGES (Experiment to Detect Global EoR Signal)

- Search for Cosmic Dawn signal requires exquisite calibration to see faint absorption signal (foreground ~1000 K, signal 0.5 K)
- Antenna is ~2 m x 1 m, band is $50 < \nu < 100$ MHz
- Located in radio-quiet MRAO in W. Australia



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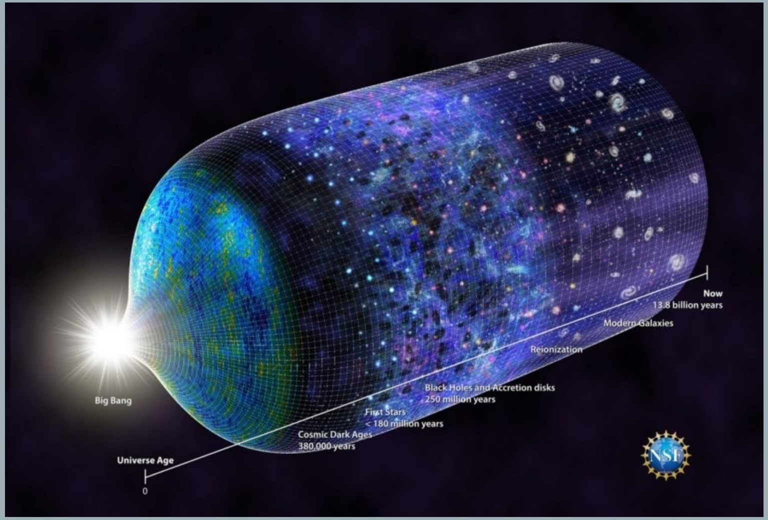
# Low Frequency Science




Fingerprint of First Stars

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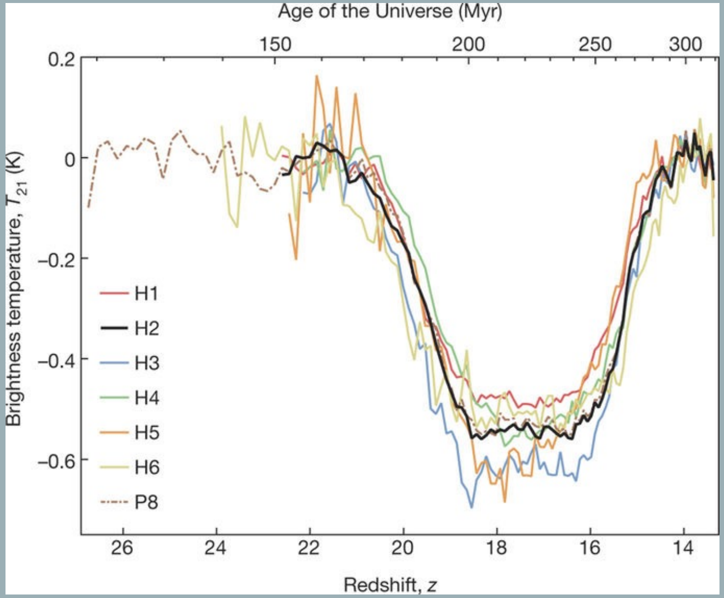
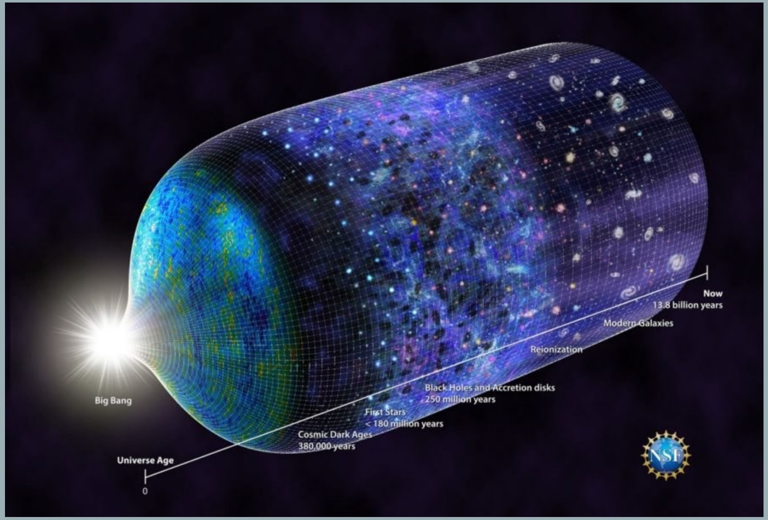


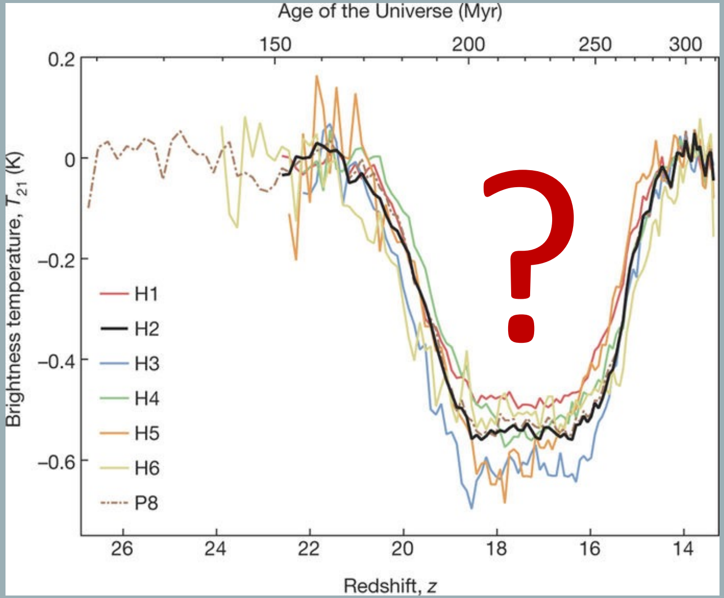

First Detection *(with caution)* at z~17

- Bowman et al. Nature (2018)
- Signal centered at 78 MHz, width 19 MHz
- Amplitude 2-3x predictions and flatter
- May imply DM has non-gravitational interactions with normal matter (Barkana et al. Nature 2018) or possibly the foreground is more complex (Hills et al. 2018)

Needs confirmation!

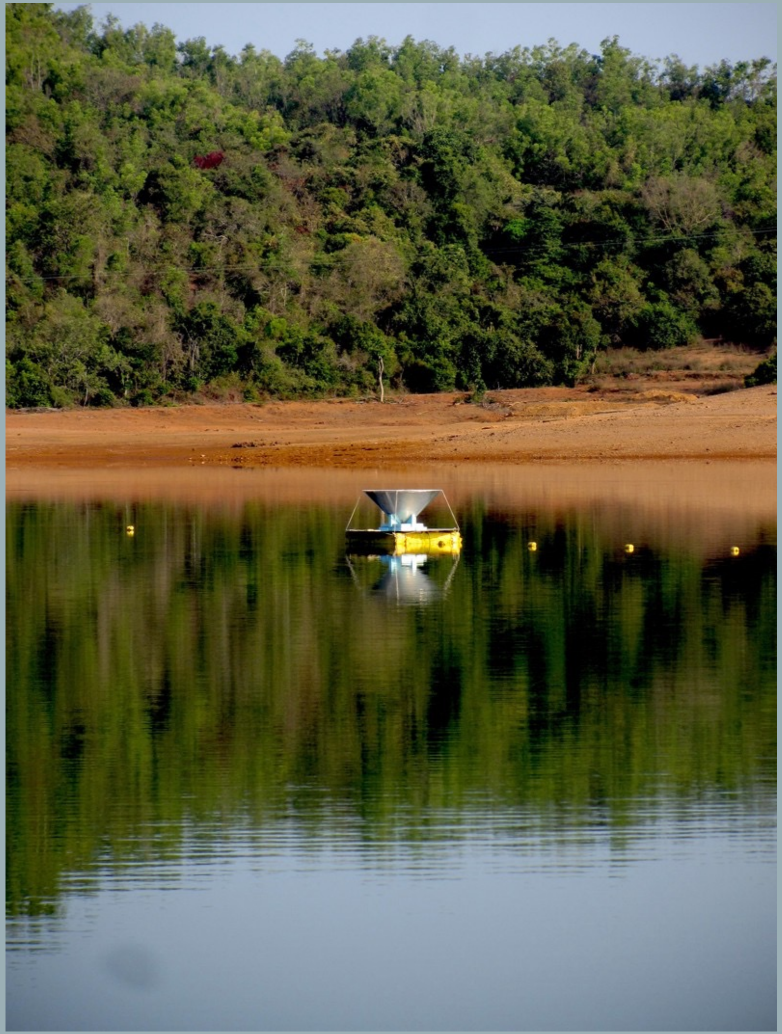
# Low Frequency Science




## New Data Raises Uncertainty

- SARAS antenna designed by Raman Research Institute for targeted program to search for Cosmic Dawn signal
- Antenna deployed on low salinity lake to reduce contaminating radio signals
- SARAS finds no trace of Edges signal (Nature Astronomy 02/2022)
- Very difficult measurement so multiple programs approaching signal search
- Stay tuned for more approaches.



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# Low Frequency Science

Magnetic Fields and Extrasolar Planet Habitability

Earth, Mercury, Ganymede and gas giants all have internal dynamos generating planetary-scale magnetic fields.

Magnetic fields maintain atmosphere and shield life from harsh radiation environment.

Mars Atmosphere and Volatile Emission (MAVEN)

Mars atmosphere pressure < 1% of Earth but surface magnetizations shows there was a magnetic field.

MAVEN showed Solar wind and radiation stripped the Martian atmosphere and the planet lost the ability to host liquid water on the surface.

# Low Frequency Science

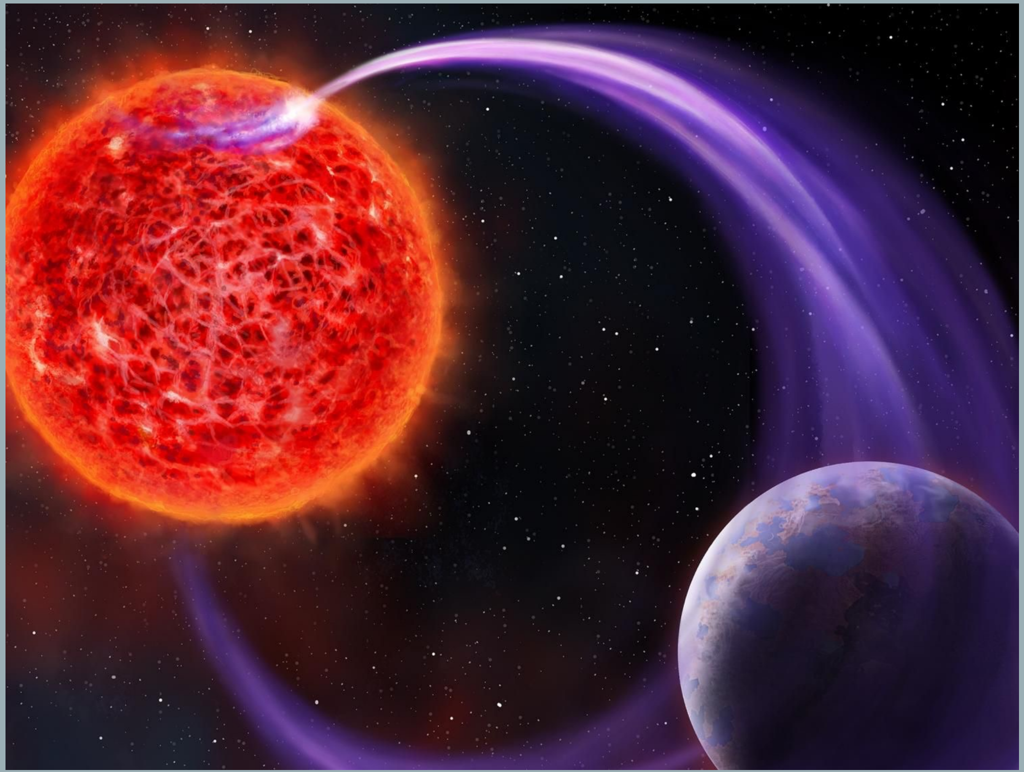
## GJ 1151

- Unremarkable red dwarf star showed evidence of planetary auroral emission
- Results suggest emission is driven by interaction with short-period planet similar to Io-Jupiter emission
- Search for potential planet is on-going

Radio Search for Exoplanets

Detection of radio emission from an extrasolar planet would open a new window on these systems:

- provides planetary field strength
- information about planetary interior
- details on ubiquity of planetary fields
- evidence of shielding of atmosphere and surface from radiation (habitability)



*Vedantham et al. (2020) Credit:* Danielle Futselaar (artsource.nl)

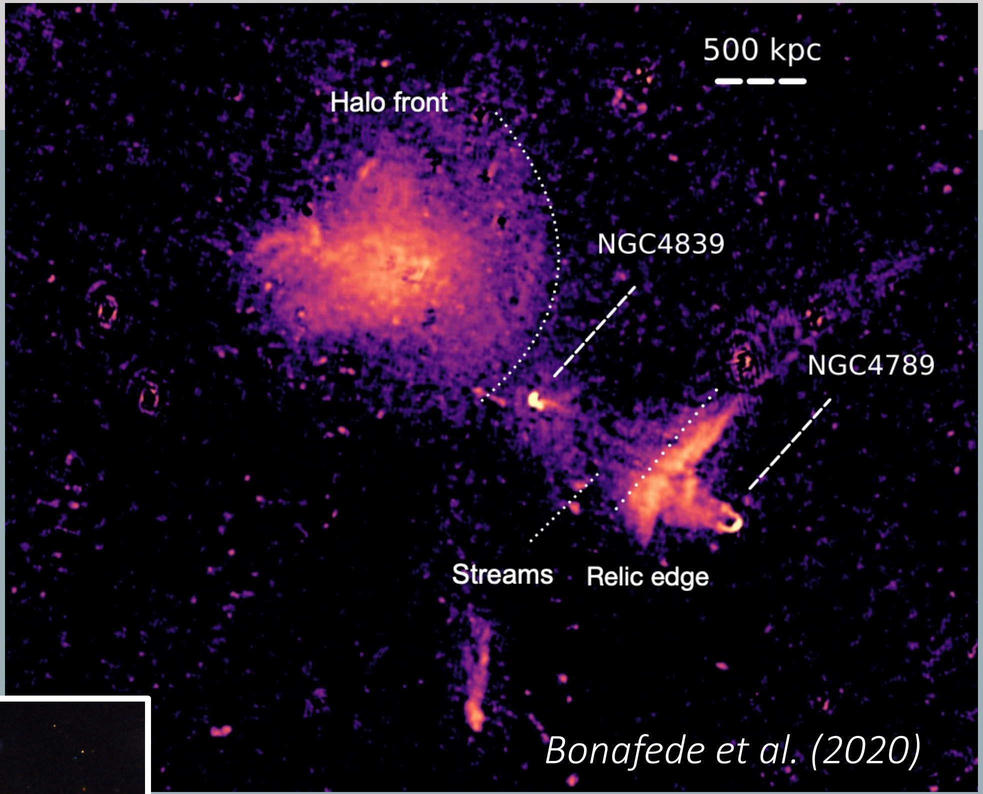
# Low Frequency Science

Active galactic nuclei:

- lifecycles traced using low radio frequencies which are sensitive to past outburst episodes

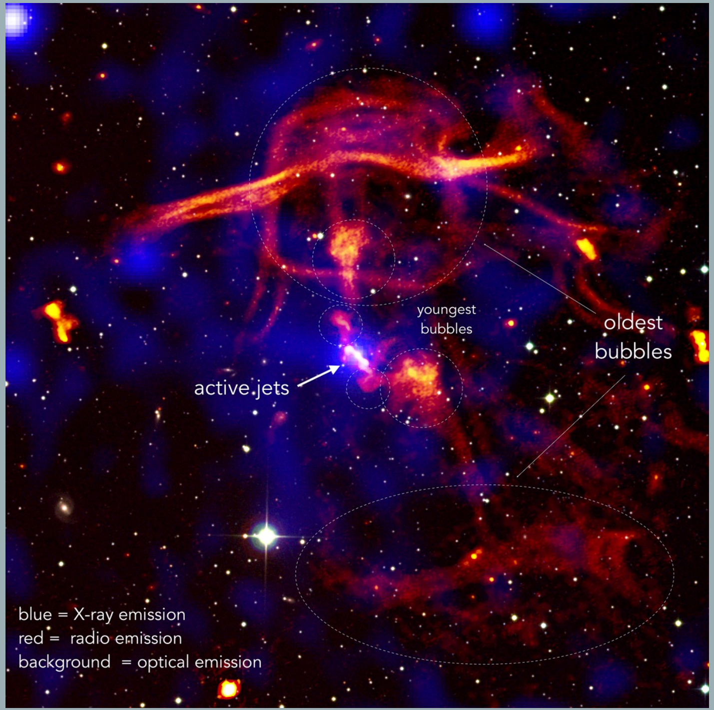
Clusters of galaxies:

- low frequencies reveal particle acceleration from shocks and turbulence

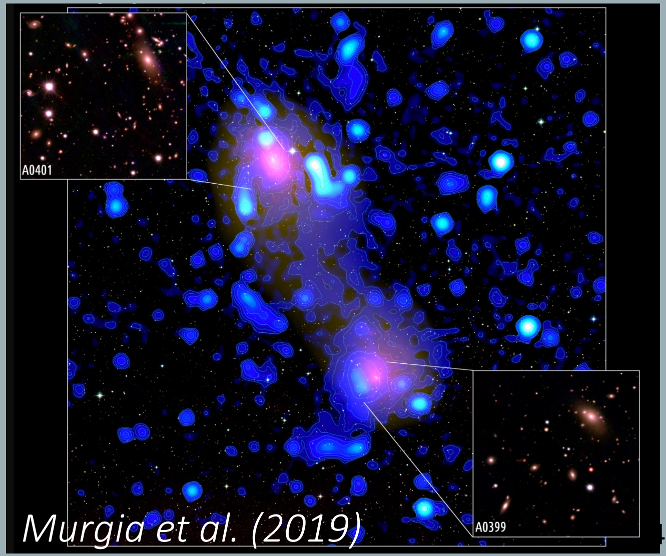


*Bonafede et al. (2020)*

*Brienza et al. (2021)*




*Randall et al. (2015)*



*Murgia et al. (2019)*

# Low Frequency in Practice

- Confusion: source blending at lower resolutions – need long baselines to overcome confusion

- Radio Frequency Interference: Severe at low frequencies

Direction Dependent Effects (DDE)

- Ionosphere: single phase correction per FoV often fails at LF

  *Quiescent*: Refraction, Faraday Rotation

  *Disturbed: Scintillation, Image Distortion, Position Shifts*

- ✓ Wide bandwidths and Large Fields of View: (Rao & Jagannathan Talks)

  Non-coplanar array (*u,v, & w*)

  -- CASA *tclean*, *wsclean*, Obit *MFImage*

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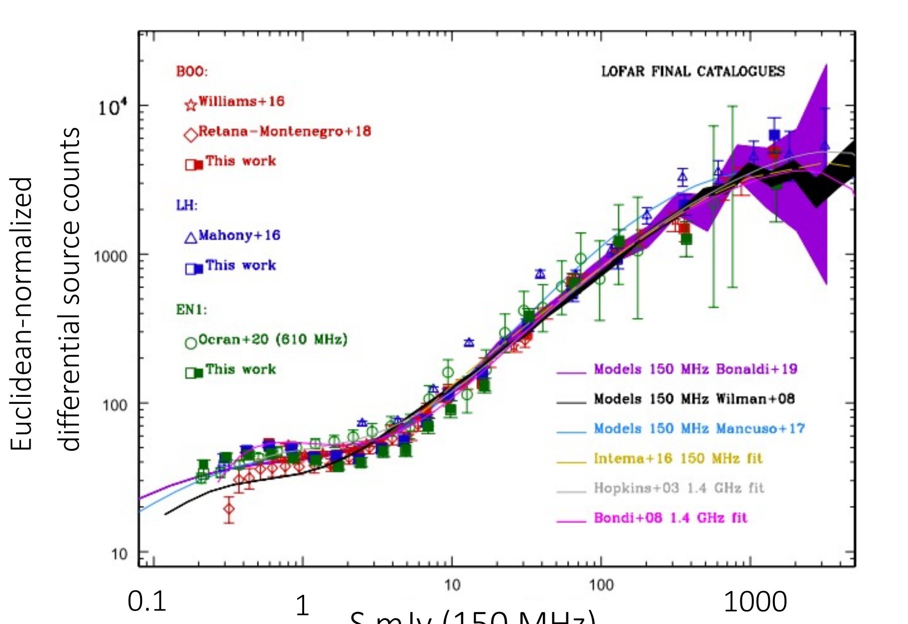
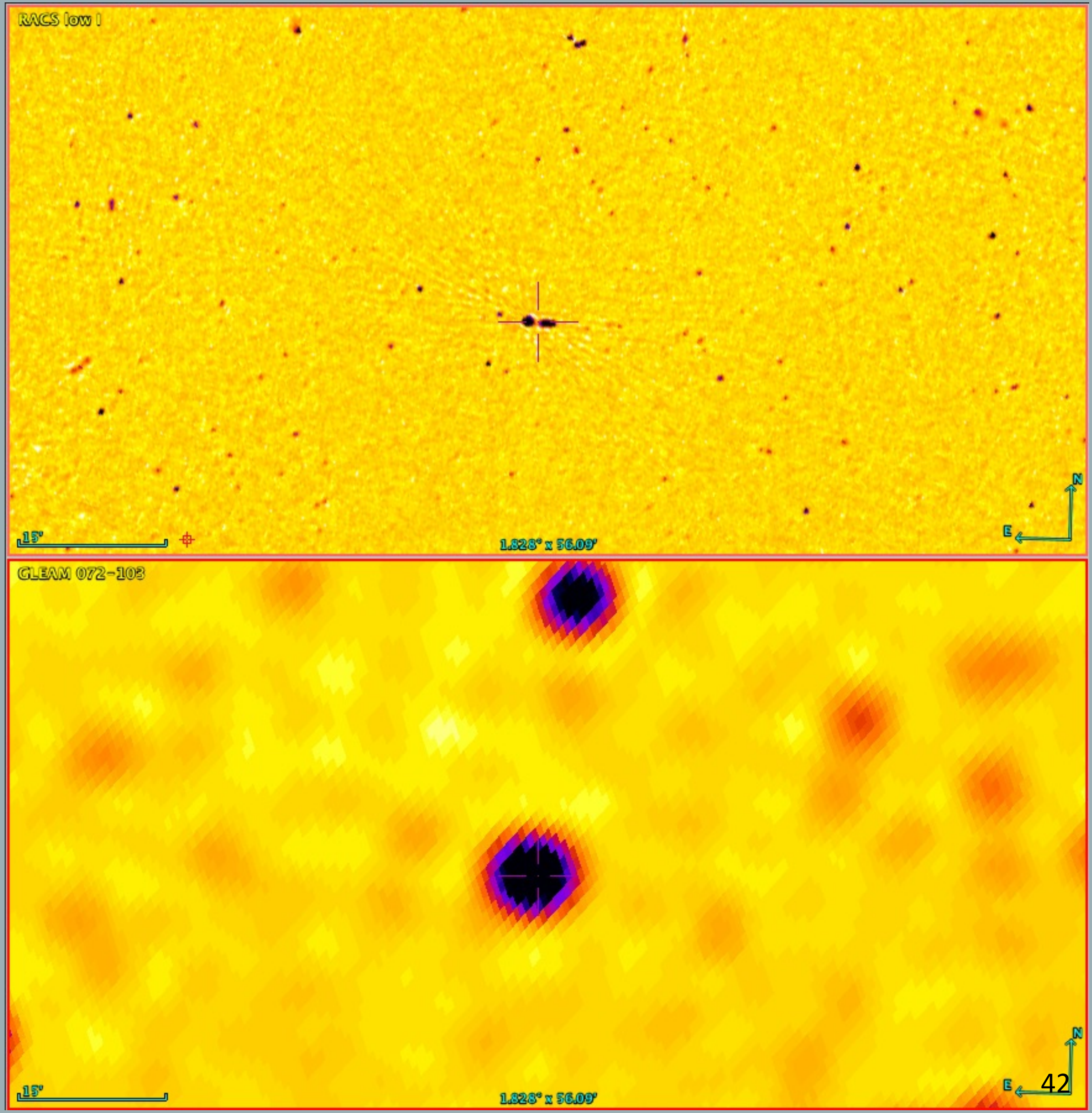
# LF in Practice: Confusion



Mandal et al. (2021)

- For any angular resolution θ:
    - there is a confusion limit
    - individual weak sources blend, resulting sky noise may exceed thermal noise
    - such cases are "confusion limited"
- See e.g. Condon et al. (2012)



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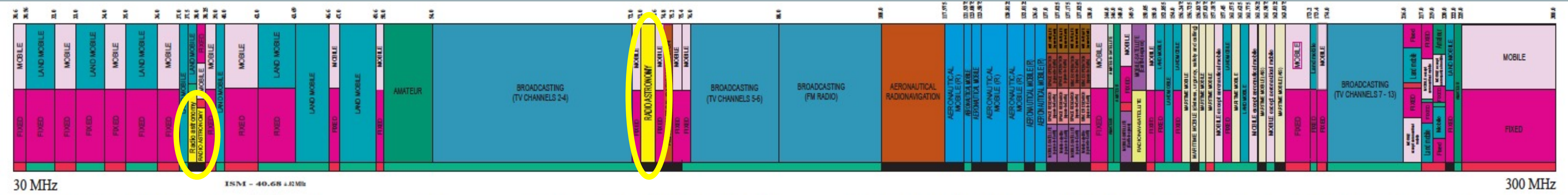
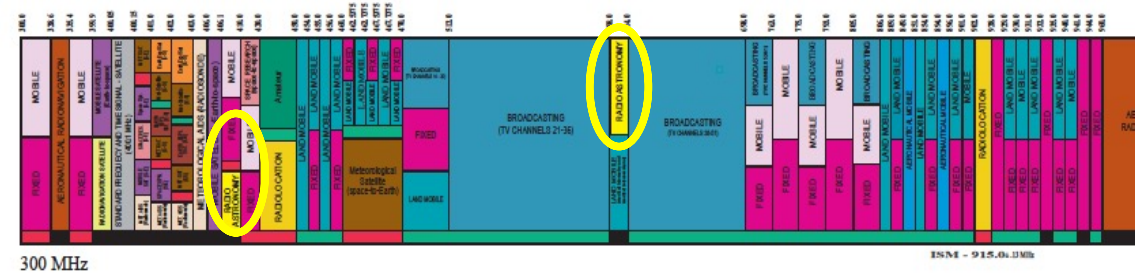
# Low Frequency Spectrum: Radio Frequency Interference




Economist (02/16/17):
84 MHz sold for $10 B and
was re-allocated at $19.6 B

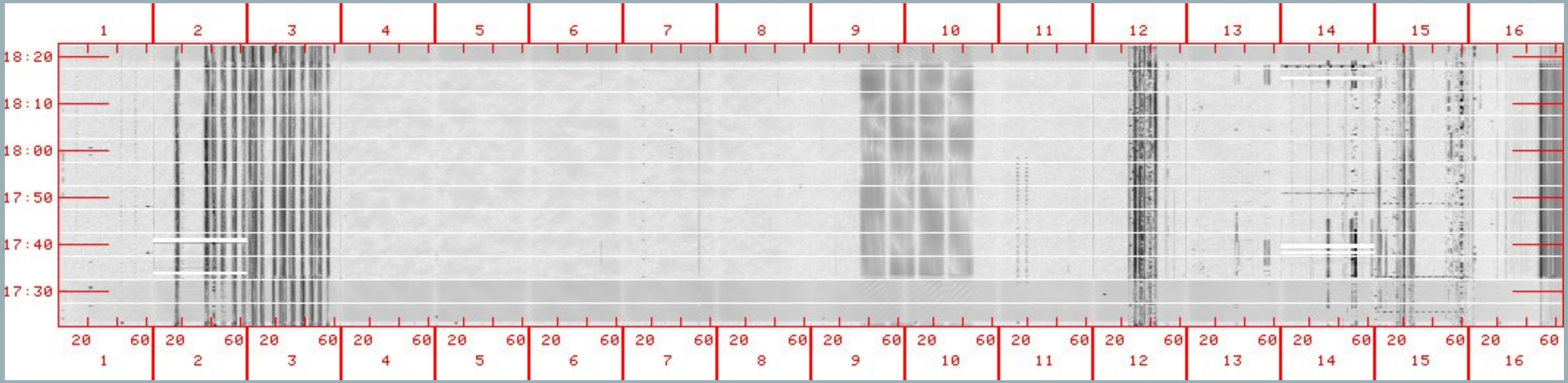
- US Spectrum allocation to Radio Astronomy between 30 MHz and 1 GHz (2011):
  - 37.5 - 38.25 MHz (0.75 MHz)
  - 73.0 – 74.6 MHz (1.6 MHz)
  - 406.1 – 410.0 MHz (3.9 MHz)
  - 608.0 – 614.0 MHz (6.0 MHz)

  Total of 12.25 MHz over 990 MHz (1.2% of spectrum)

For reference NSF entire budget ~ $6.6 B

# Radio Frequency Interference

- Natural & human-generated RFI are at best a nuisance

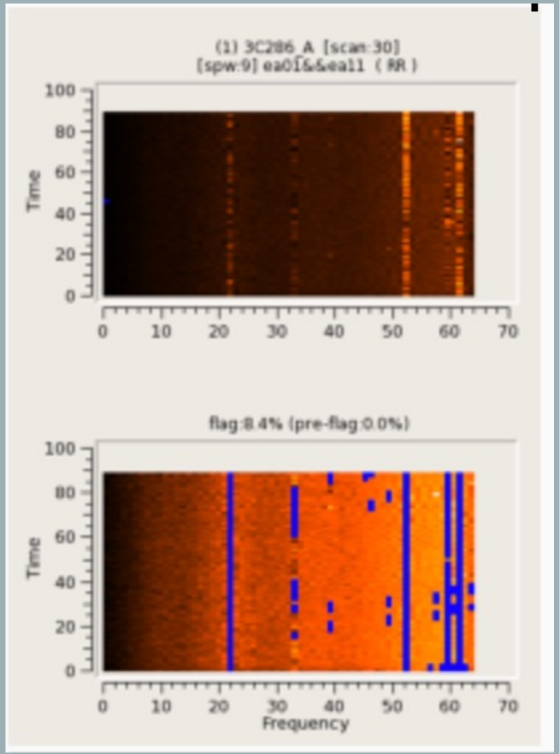


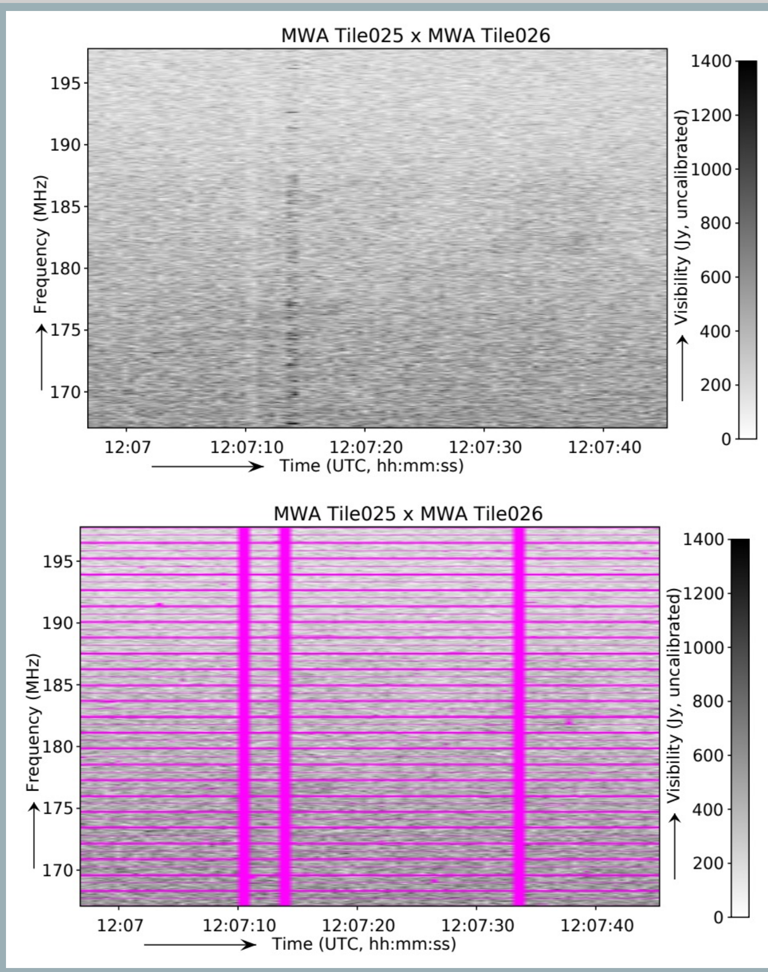

- Many different signatures seen at low frequencies:
  narrowband, wideband, time varying, ‘wandering’
- Best to deal with RFI at highest spectral resolution before averaging for imaging

- Sources: TV, FM radio, digital broadcasting, satellite, receiver/computer electronics, mobile services, …

# Radio Frequency Interference

- RFI excision tools:
  - AOFLAGGER
    - Generalized stand alone tool applicable to many instruments
    - https://gitlab.com/aroffringa/aoflagger
  - CASA flagdata (tfcrop, rflag)
    - Flagging before, during and after calibration of ms
    - [https://casa.nrao.edu/](https://casa.nrao.edu/)



# Ionosphere in Practice: What Regime?

- Lonsdale (2005) identified different calibration regimes for ionosphere

- Regimes 1 & 2 (Isoplanatic) ionospheric phase error has no FoV variation – self calibration OK

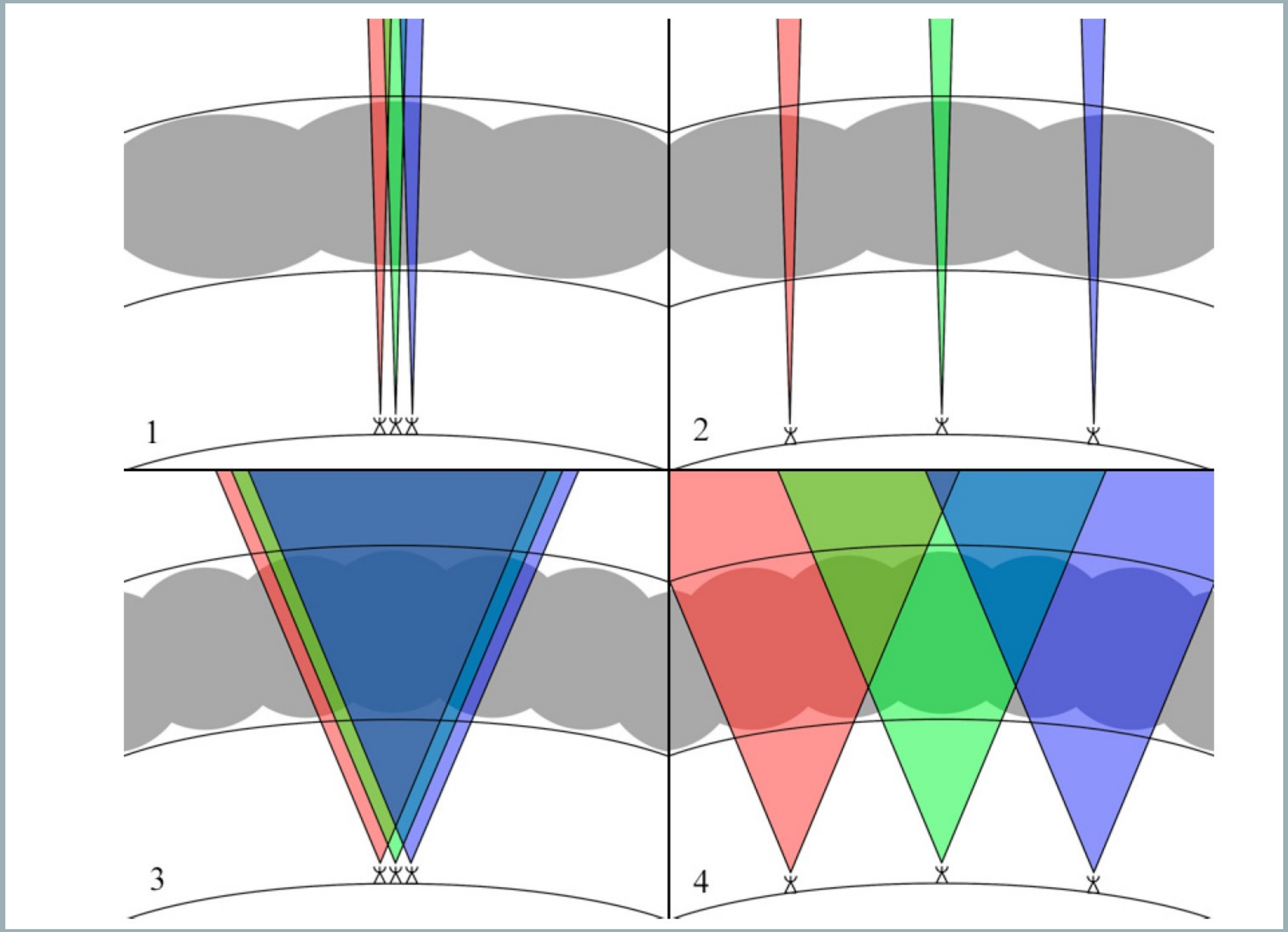
- Regimes 3 & 4: have varying phase over FoV – need <u>direction dependent</u> algorithms

Significant effort underway: field-based, source peeling, global model, multiple scale height models, …

<u>Examples</u>: *DDFacet/killMS*

https://github.com/saopicc/killMS

*CubiCal*: https://github.com/ratt-ru/CubiCal




Intema et al. (2009)

# Summary

- Next generation of low frequency instruments are being built while current instruments (such as the VLA) are being upgraded

- Low frequency interferometers are powerful, lots of complexities and a growing toolkit of approaches but still room for improvements:
  - Fully automated RFI mitigation
  - Time, direction, and frequency dependent ionospheric corrections
  - Time, direction, frequency, polz and element dependent gain corrections

- Advances will lead improved scientific capabilities for studies from Dark Ages through Cosmic Dawn to our Solar system/Space Weather
- ✓ Great time to incorporate low frequencies into your research

- NRC Postdoc opportunities at NRL in DC to work on LF astrophysics, interferometry, and ionospheric studies, contact me: tracy.clarke@nrl.navy.mil


go.nrao.edu/vlass22

Abstract deadline June 1:

- ✓ Great conference planned and on September 10 climb an antenna and look up at the dipoles!!