Low Frequency Interferometry

Tracy Clarke (US Naval Research Laboratory)

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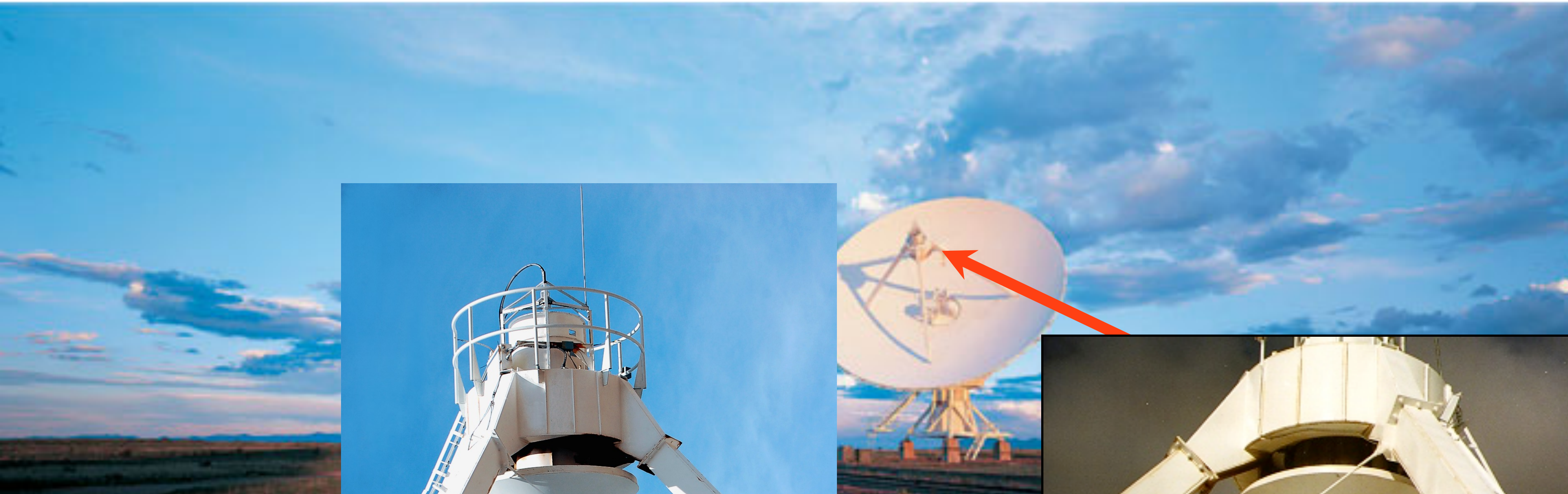

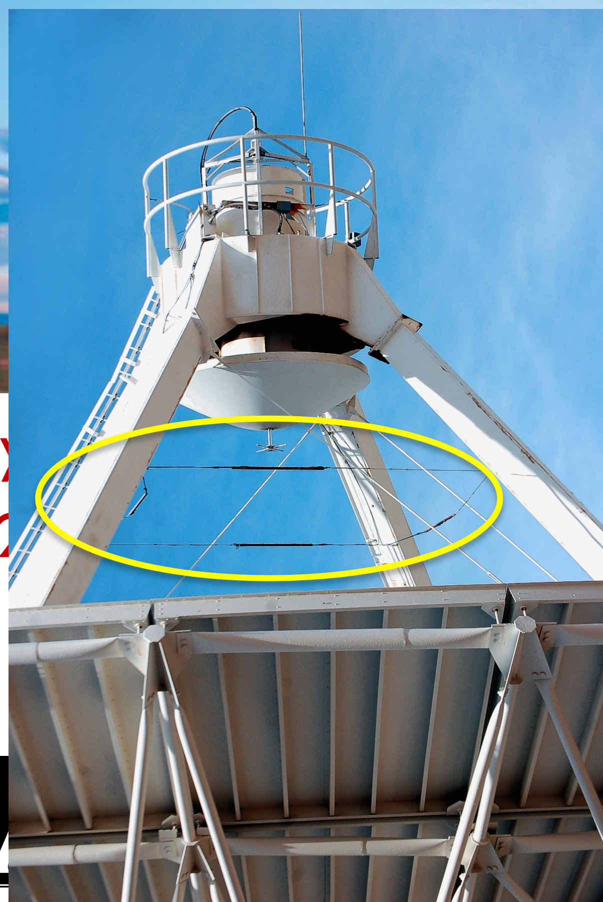

Sixteenth Sy hop

16-23 May 2

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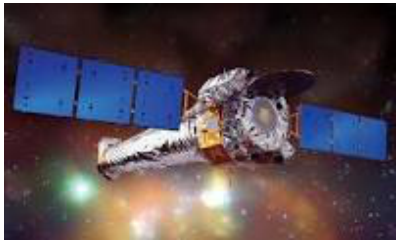
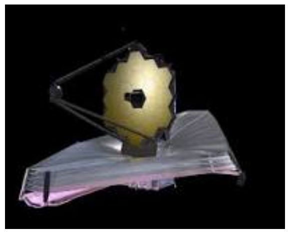
What do we mean by Low Frequency?





Chandra

JWST

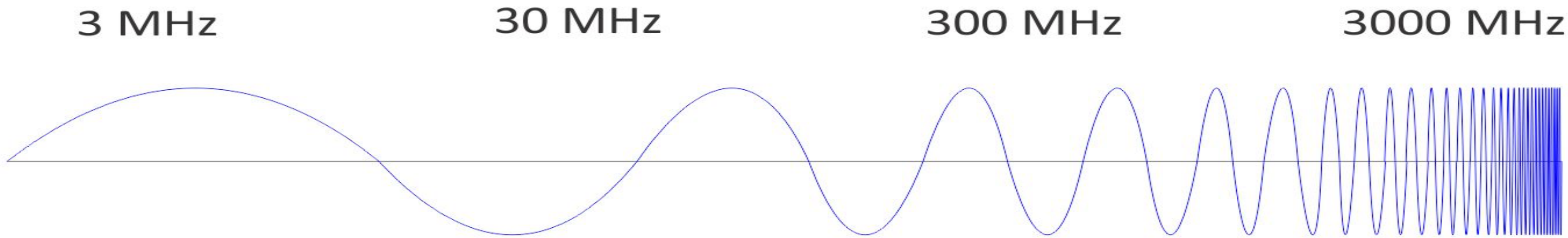
Herschel

JVLA

Low Frequency

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

Telescopes that Observe at Low Frequency …



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

LOFAR: 10-80 MHz,
120-240 MHz

MWA: 80-300 MHz

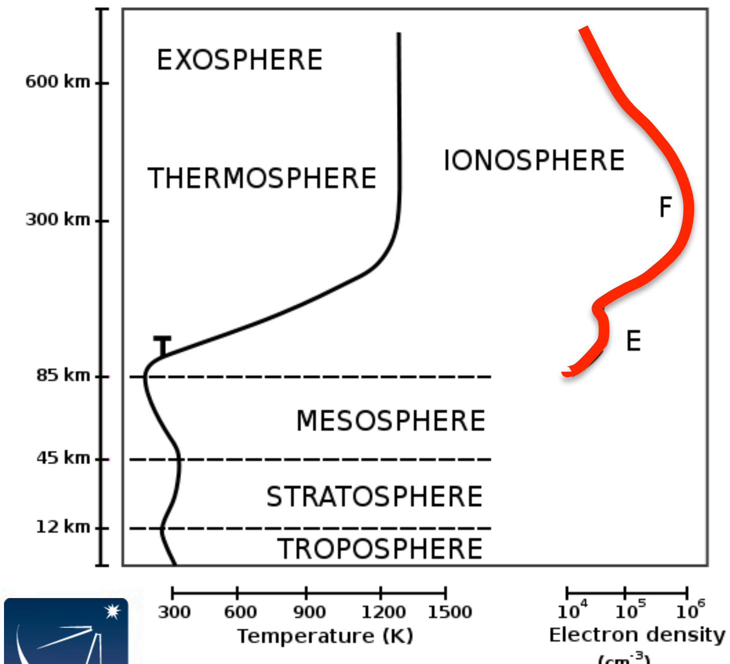
uGMRT: 50-1500 MHz

LWA: 10-88 MHz

CHIME: 400-800 MHz

What do we mean by Low Frequency?

- Low frequency:
  - 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 impact of Earth's ionosphere



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NUV			
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EHF			
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SHF			
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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			
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Outline

- Meet the Ionosphere
- LF Emission: Continuum & Line
- Brief & Biased View of LF Science
- LF Instruments: Dishes and Dipoles
- Recent LF Sky Surveys
- LF in Practice:
  - Confusion, Radio Frequency Interference
  - Direction Dependent Effects (DDEs)
    - Ionosphere
    - Wide Field of View (Rao Venkata Talk)

Diffraction Limited Imaging and the Ionosphere

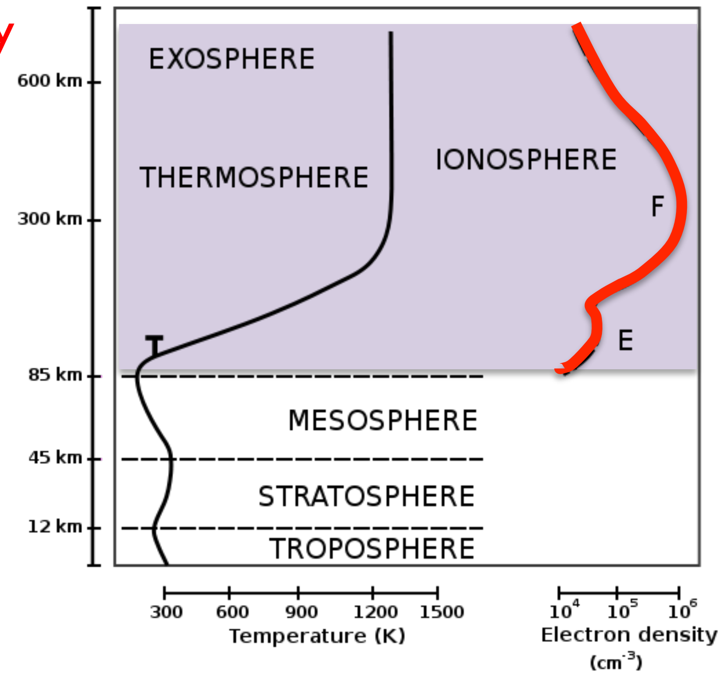
- Imaging at the diffraction limit (~λ/B) is only possible when phase stability is controlled

  - Instrumental phase (electronics)
  - Atmospheric Phase (troposphere and ionosphere)

Phase delay

- Troposphere (h~0-10 km)
  - neutral, wet component $\Phi \sim \nu$
- Ionosphere (h~100-1000 km)
  - ionised component $\Phi \sim \nu^{-1}$

- At 1 GHz contributions can be equal but at low frequencies the ν^{-1} means we cannot ignore the ionosphere!



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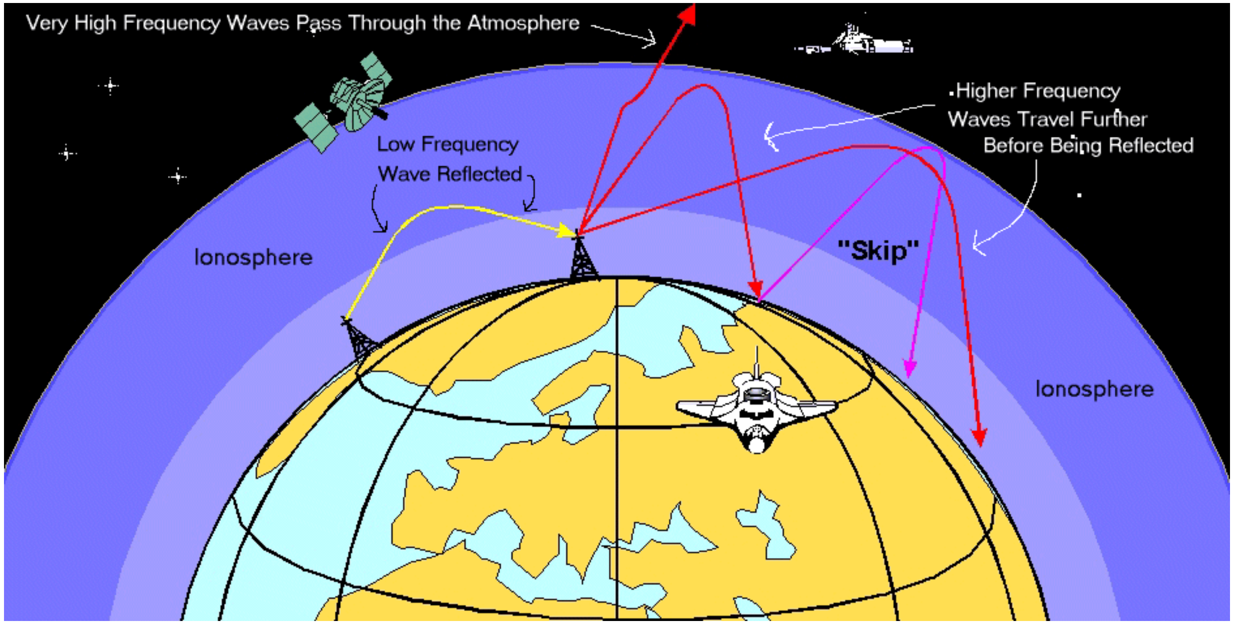
Ionosphere and Radio Astronomy (Briefly)

- Ionospheric Cutoff
  - Plasma opacity

$$\nu_p \simeq 9\sqrt{n_e}\ kHz, n_e \sim 10^4 - 10^5 cm^{-3}$$
$$\nu_p \sim 10MHz$$

- Quiescent Ionosphere
  - Refraction
  - Faraday Rotation (Schinzel talk)

- Disturbed Ionosphere
  - Scintillation
  - Image distortion
  - Rapid position shifts



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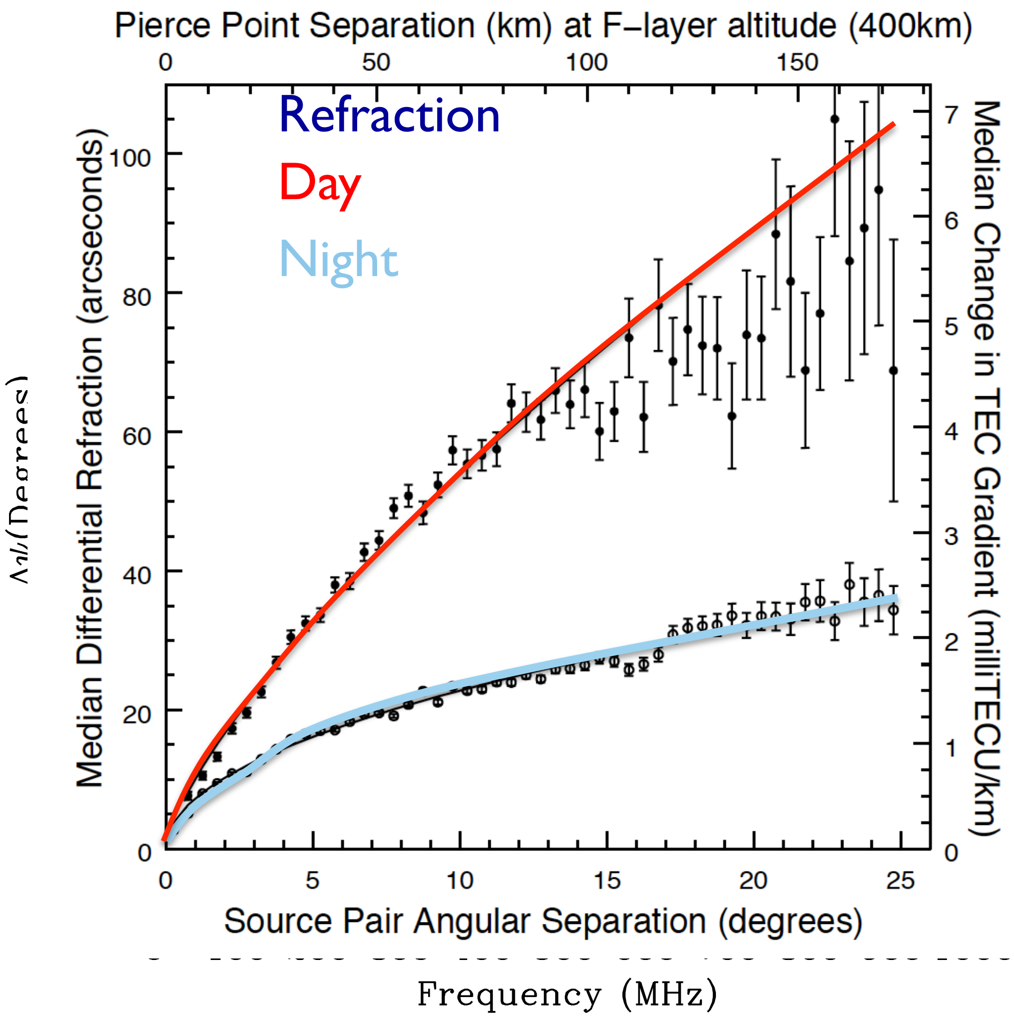

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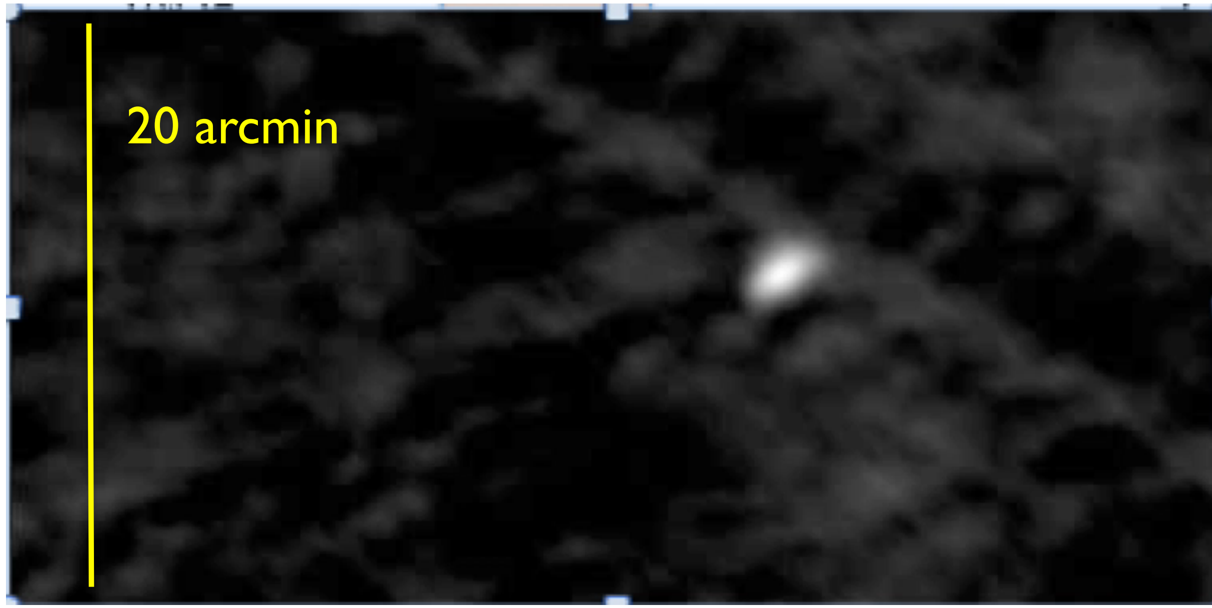


Low Frequency Emission

Synchrotron Continuum:

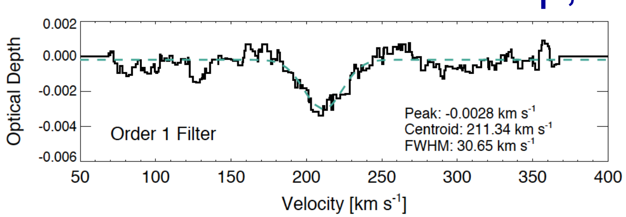
- Best observed at $\nu < 1$ GHz
- Relativistic e^- in magnetic fields
- F(energy of the e^-, density, B)
- Emission is polarized
- Coherent or incoherent

Redshifted Line:

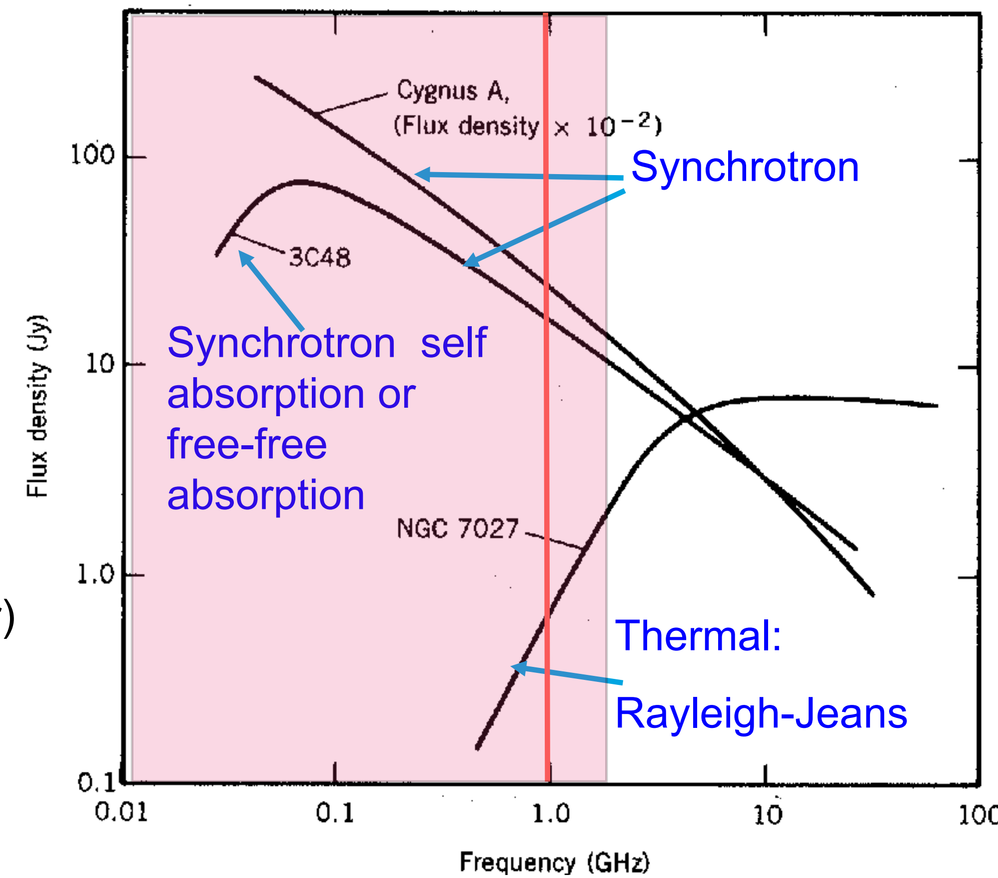
- ν = 1420/(1+z) MHz (21 cm)
- ν = 1665(7)/(1+z) MHz (OH Mega Maser)

Radio Recombination Lines:

- Probe of ISM conditions: low temp, low density

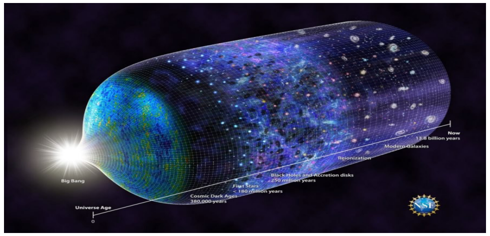


1st extragalactic RRL (M82)
LOFAR, Morabito et al. (2014)



Thompson, Moran, & Swenson

Low Frequency Science

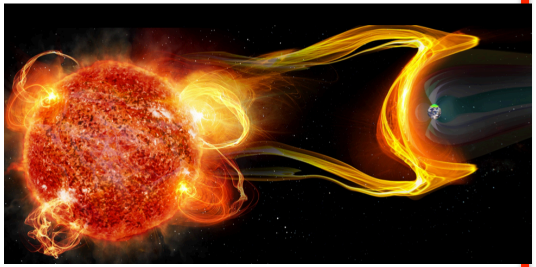


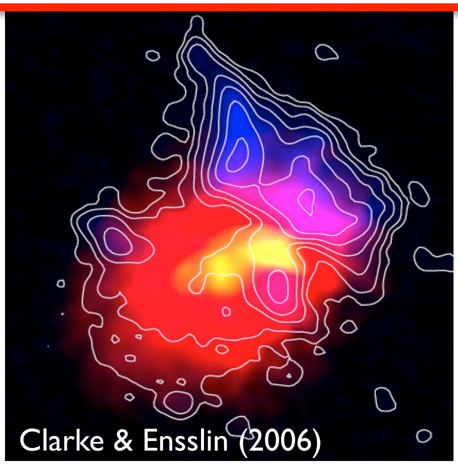
Early Universe

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

Solar System and Extrasolar Planets

CME's, cyclotron maser instability, ionosphere.





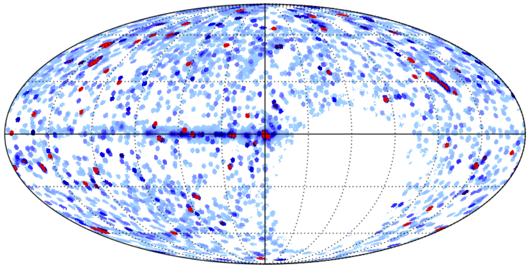
Clarke & Ensslin (2006)

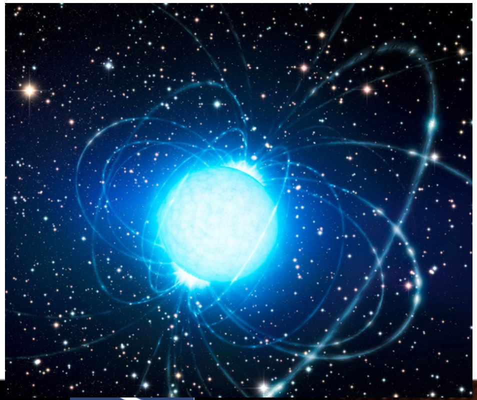
Shocks/Turbulence

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.

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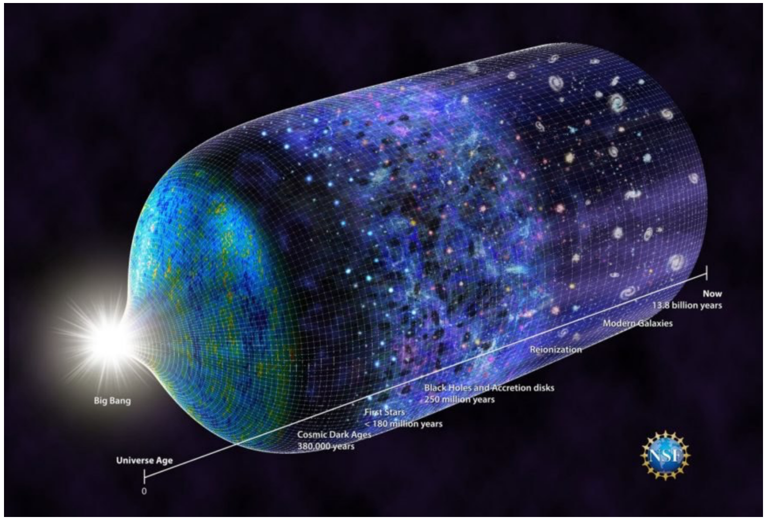
Low Frequency Science

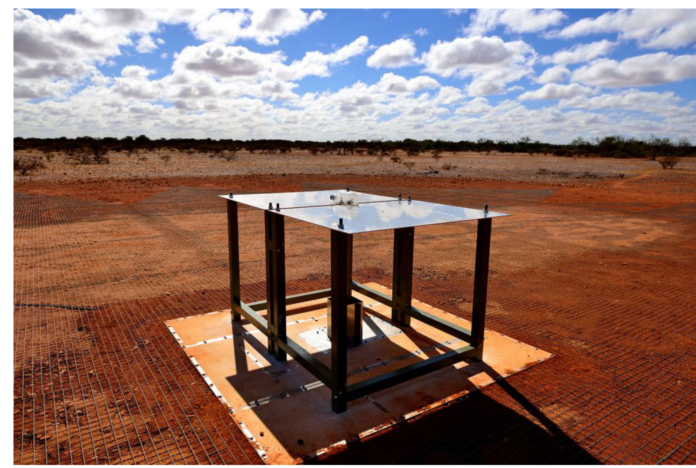


Fingerprint of First Stars

- 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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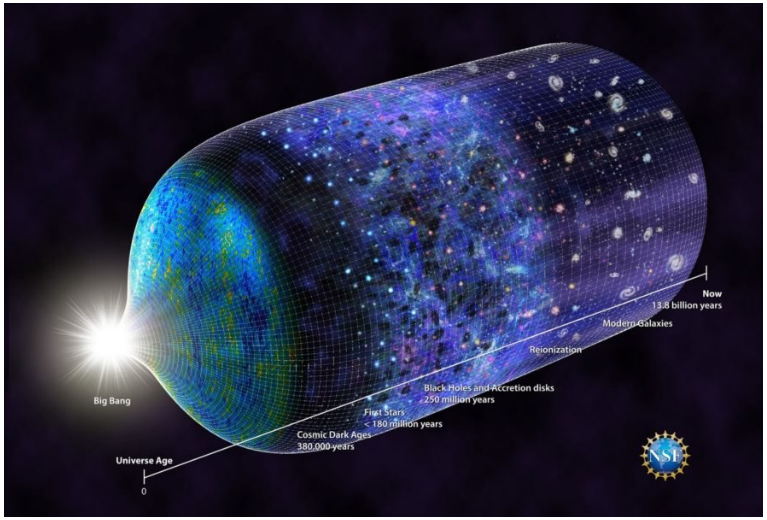

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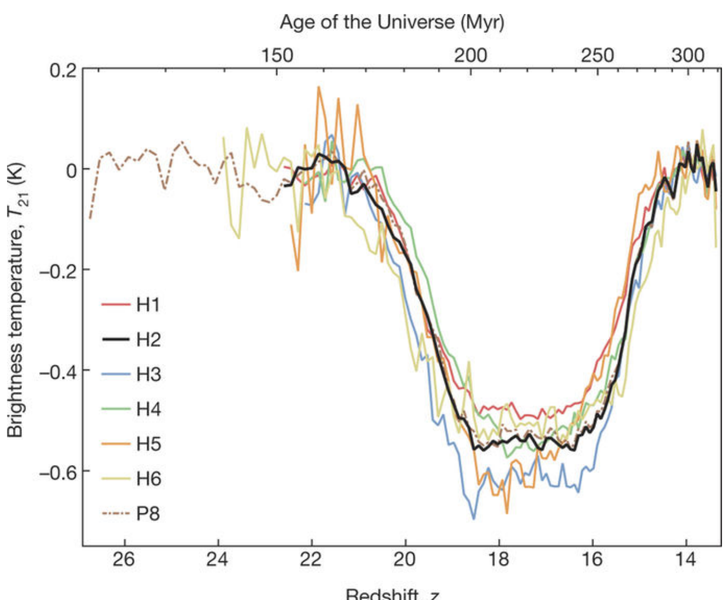

First Detection *(with caution)* at z~17

- 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

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

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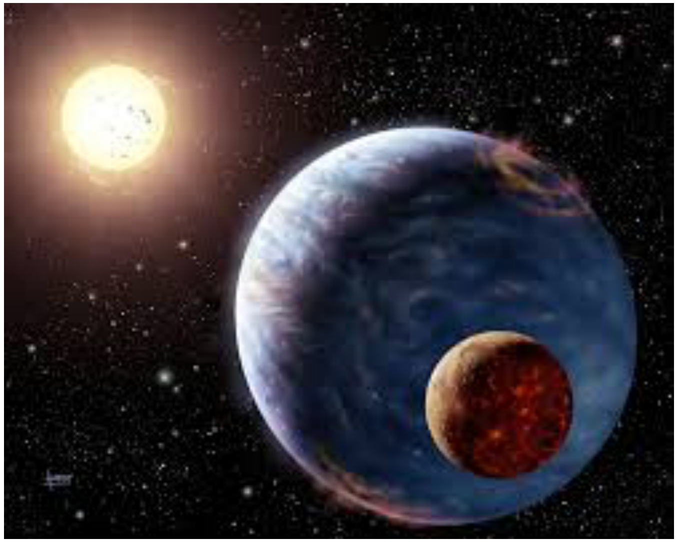

Radio Search for Exoplanets

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)

Low Frequency Arrays

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

	Instrument	Location	ν range (MHz)	Resolution (arcsec)	FoV (arcmin)	Sensitivity (mJy)	
Dishes	VLA	NM	73.8, 330	24-5	700-150	20-0.2	
Dishes	GMRT	IN	151-610	20-5	186-43	1.5-0.02	
Dishes	MeerKAT	SA	900-1650	10-4	105-40	.009-.005	
Dishes	FAST	CN	70-3000	174(Lbnd)	26		
	…						
Dipoles	LOFAR-Low	NL	10-80	40-8	1089-220	110-12	Aperture Array
Dipoles	LOFAR-Hi	NL	120-240	5-3	272-136	0.41-0.46	Aperture Array
Dipoles	LWA1	NM	10-88		600-180	1000	Aperture Array
Dipoles	MWA	WAu	80-300	180-60	1482-1162	10	Aperture Array
	…..						

Note: Table numbers are not apples-apples comparison!

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Low Frequency Receivers: JVLA

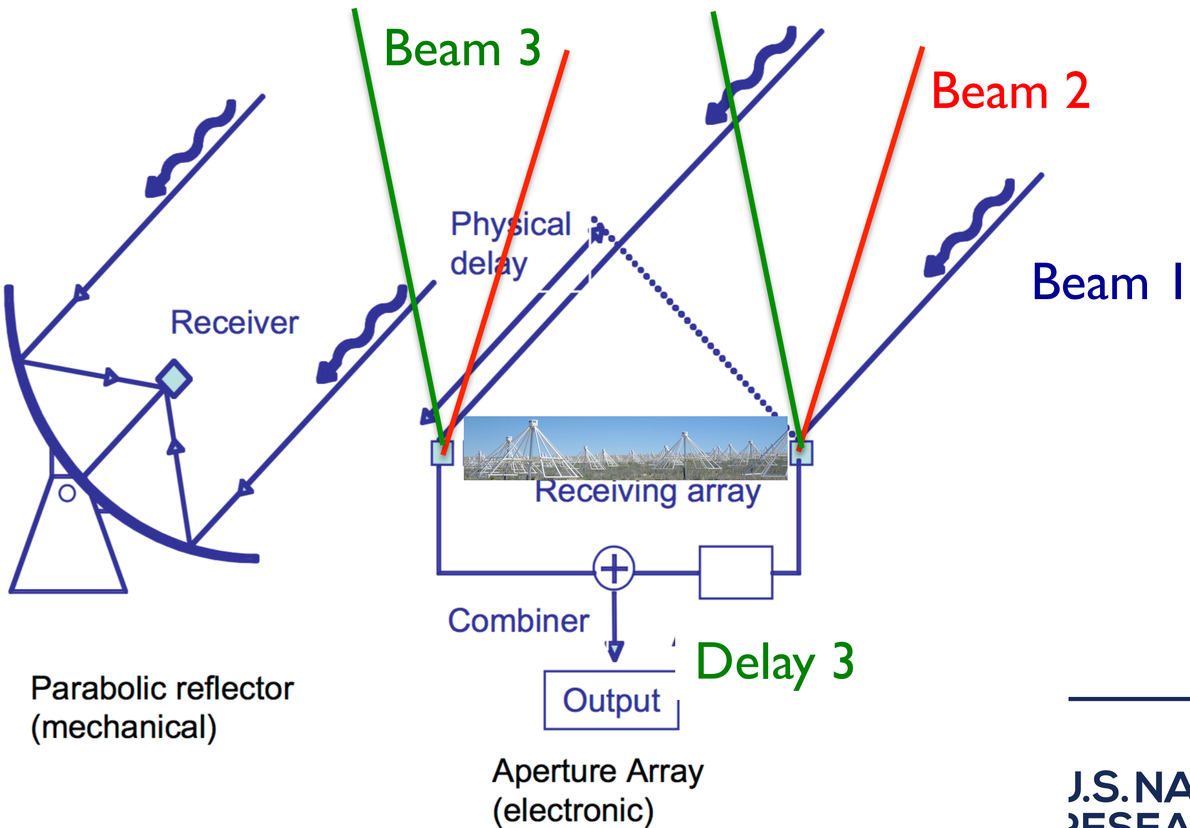
- ➢ VLA low band (dish + dipole) system transitioned to wide-bandwidth (2013)
- ➢ Replaces narrow band receivers but still using legacy P band feeds:
  - ➢ **P band: 240 – 470 MHz**
- ➢ Upgrade: new 4 band feed (MJP) design
- ➢ Commensal VLA Low-band Ionosphere and Transient Experiment (VLITE) operating 24/7 at P band on 16 VLA antennas (Clarke et al. SPIE, 2016)

Low Frequency Receivers: GMRT

- Giant Metrewave Radio Telescope feeds located at prime focus on a rotating turret + 50 MHz feeds on support legs
- uGMRT wide-band upgrade: 50-1500 MHz with 400 MHz instantaneous BW
    - 150 MHz (120-250 MHz)
    - 235/610 MHz: dual band on same face of turret (550-900 MHz)
    - 330 MHz (250-500 MHz)
    - 1400 MHz

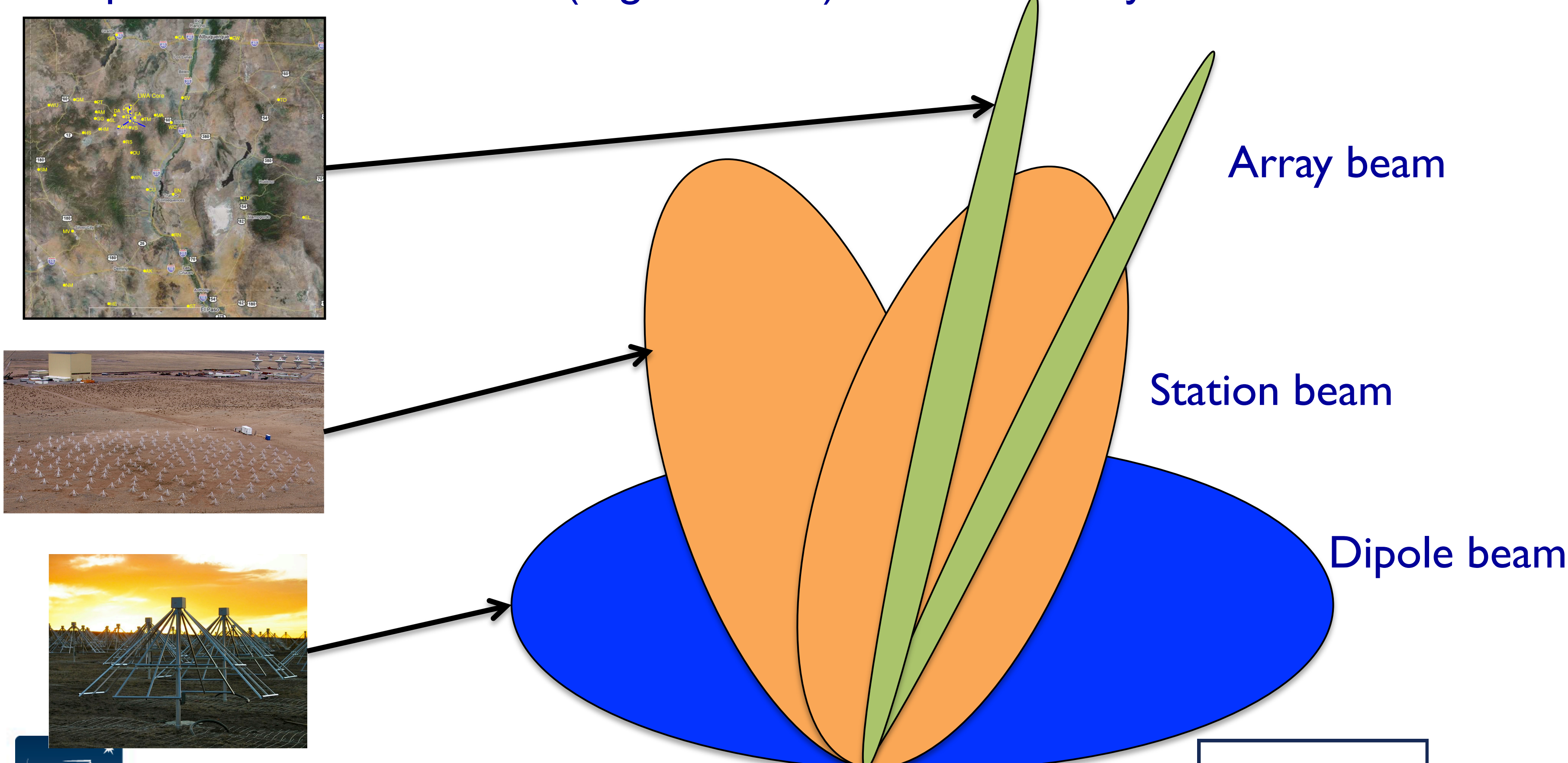
Re-Energizing Low Frequencies: Dipole Arrays

- 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!



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 (e.g. LOFAR) to create array beams

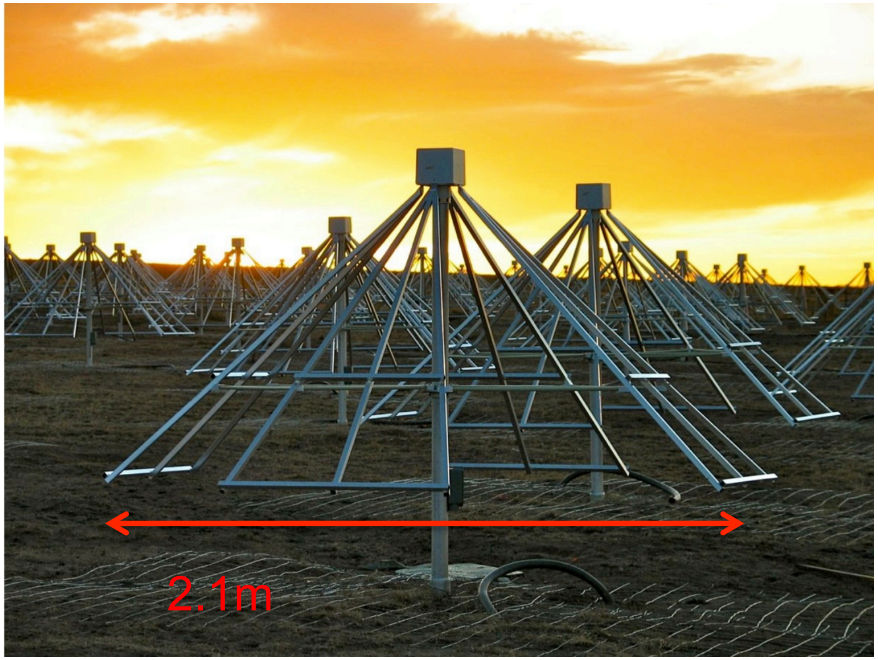


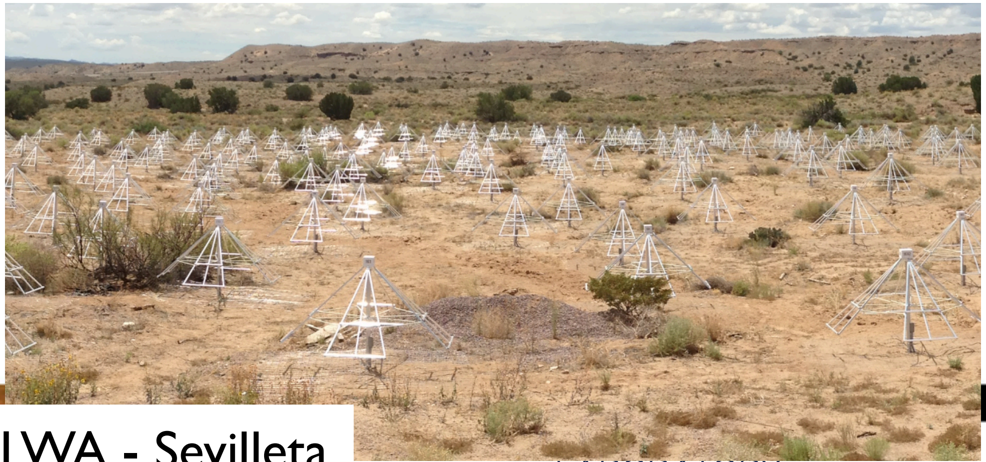
Low Frequency Instruments: LWA1 + LWA SV

- Long Wavelength Array Station 1 (LWA1) and LWA Sevilleta (LWA SV)
  - Baseline 70 km (10”)
  - 256 dipoles in 100x110m stations
  - Operate 10(4)-88 MHz
  - LWA1: 4 simultaneous beams with two tunings + dual orthogonal polz.
  - LWA SV: 1 beam simult. WB real-time correlation
  - Open access facilities
  - Upgrade: eLWA (LWA + VLA MJPs)
  - http://www.phys.unm.edu/~lwa/index.html

Data tutorial on Wednesday!

Taylor et al. (2012) JAI, 1, 50004

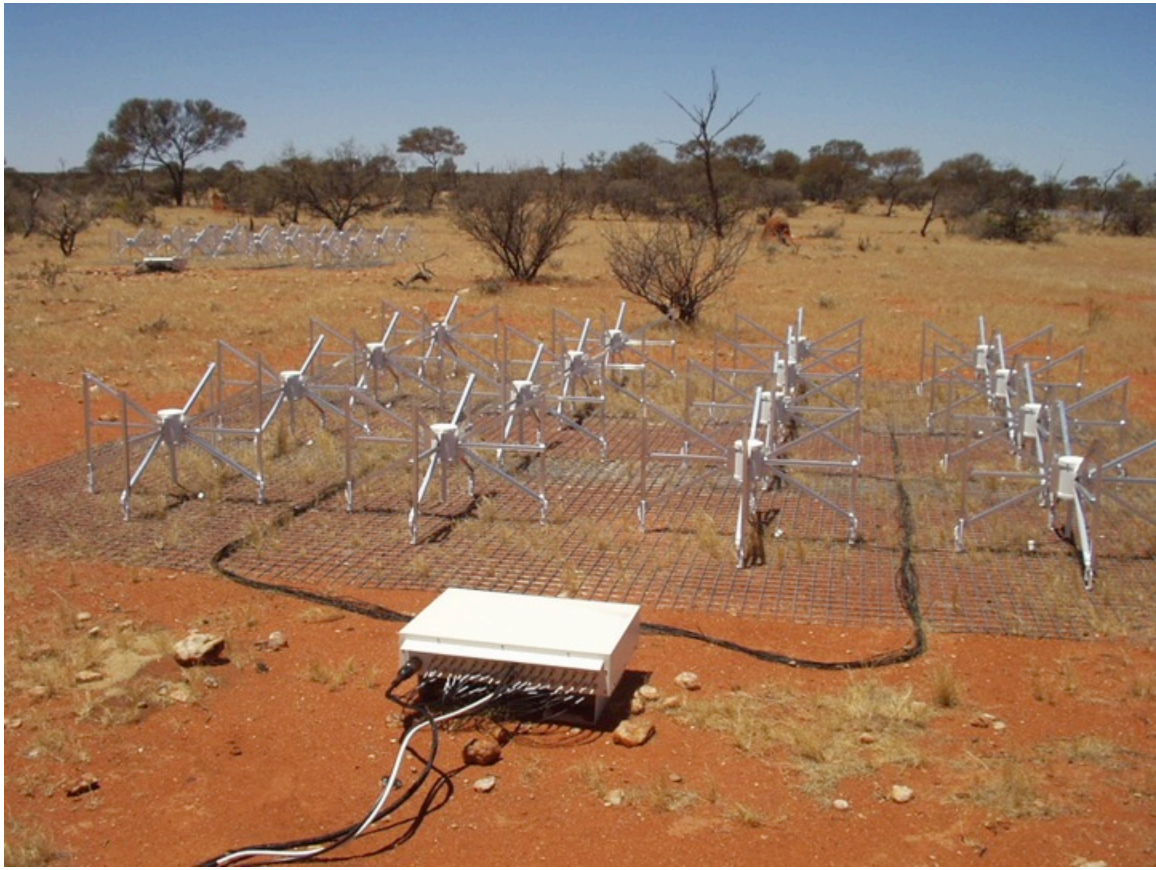




LWA - Sevilleta

Low Frequency Instruments: MWA

- MWA
  - Murchison Wide-field Array
  - 80-300 MHz, BW=31 MHz
  - Bowtie geometry
  - Upgrade: 256 tiles of 16 dipoles
  - Tiling increases A_e (~20 m^2)
  - EOR, SNR, transients, Solar and space weather
  - Complicated beam pattern
  - mwatelescope.org



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

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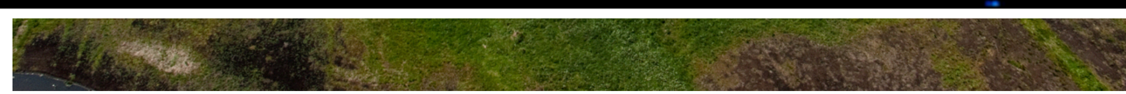
Low Frequency Instruments: LOFAR

- 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, correlator
  - http://www.astron.nl/lofar-telescope/lofar-telescope

Van Haarlem et al. (2013)

Low Frequency Instruments: LOFAR

- LOFAR
  - Low Frequency Array
  - Low band: 10-80 MHz

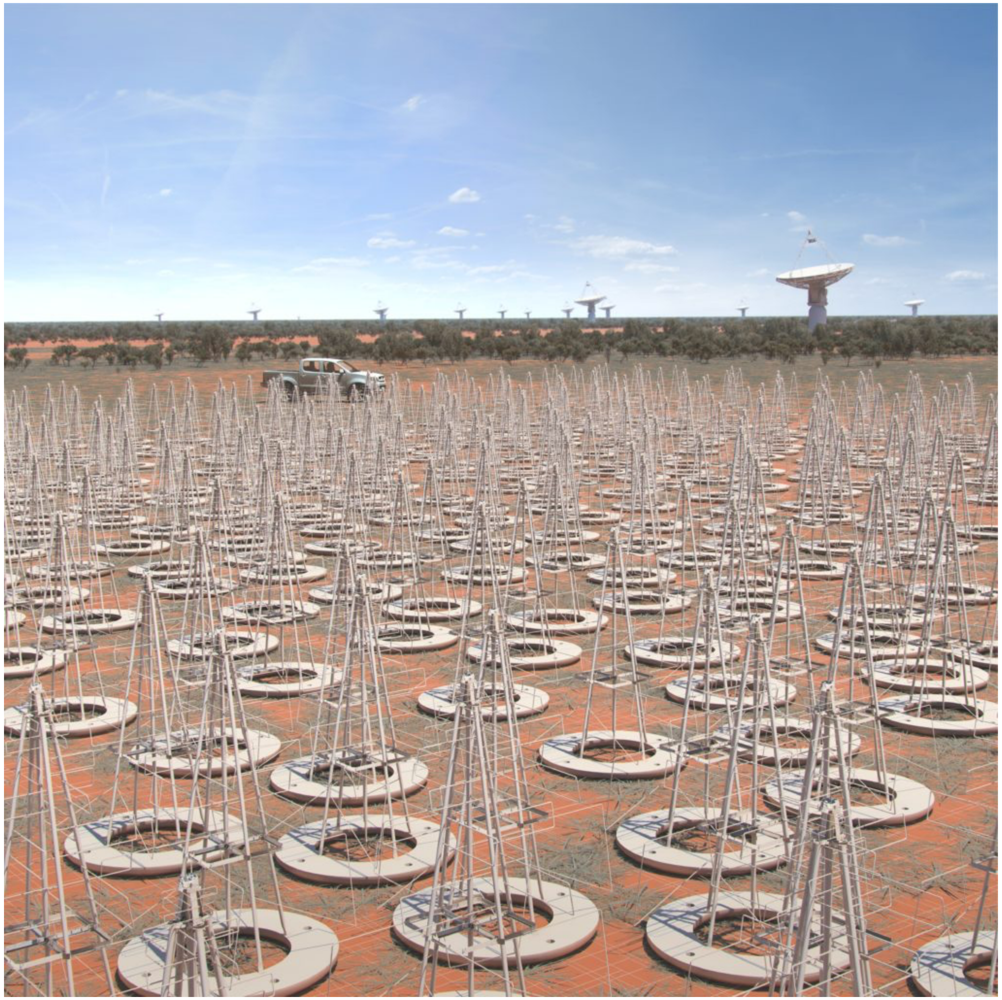


  - http://www.astron.nl/lofar-telescope/lofar-telescope

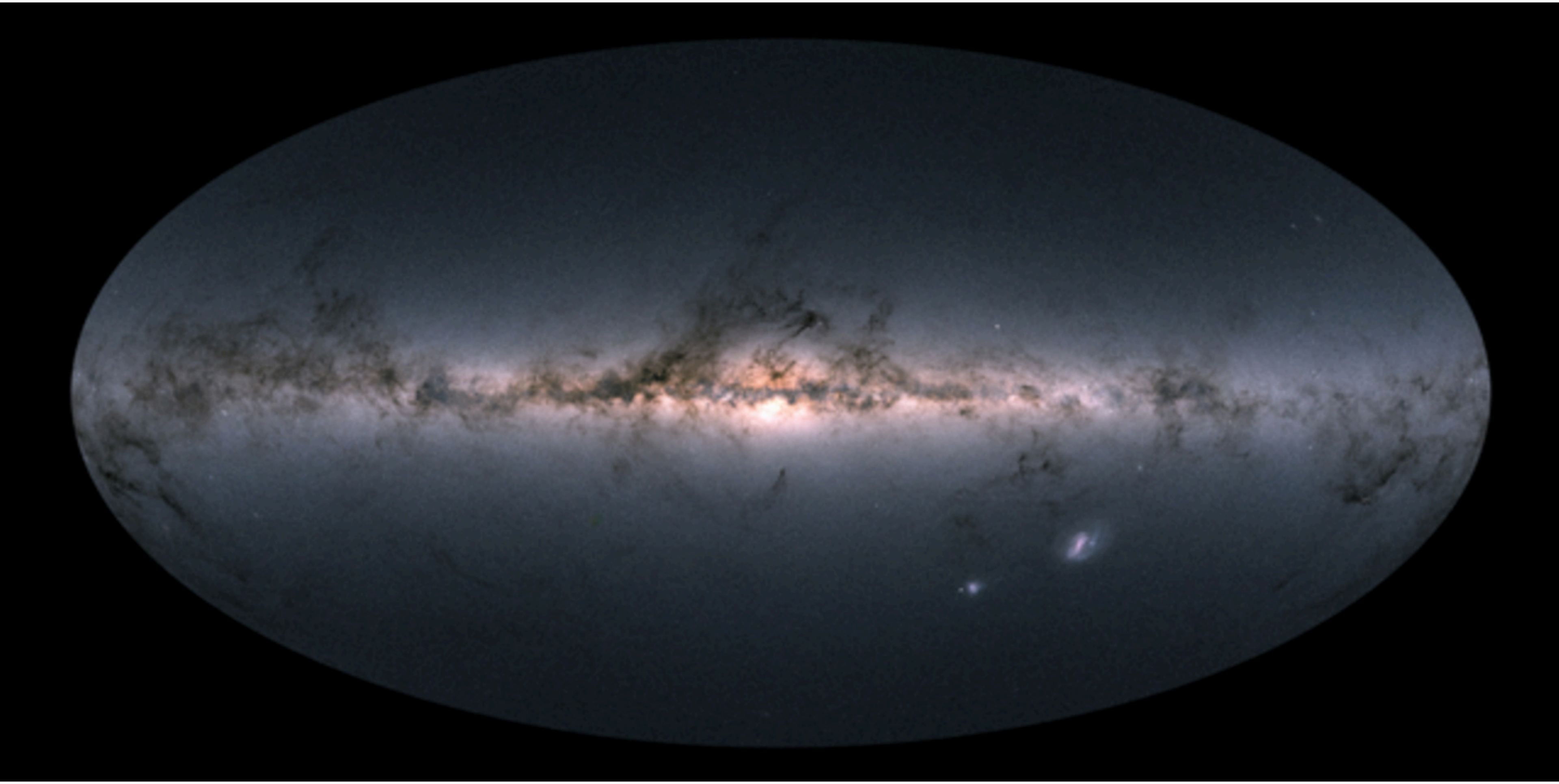
Van Haarlem et al. (2013)

SKA: Low Frequency Aperture Array (LFAA)

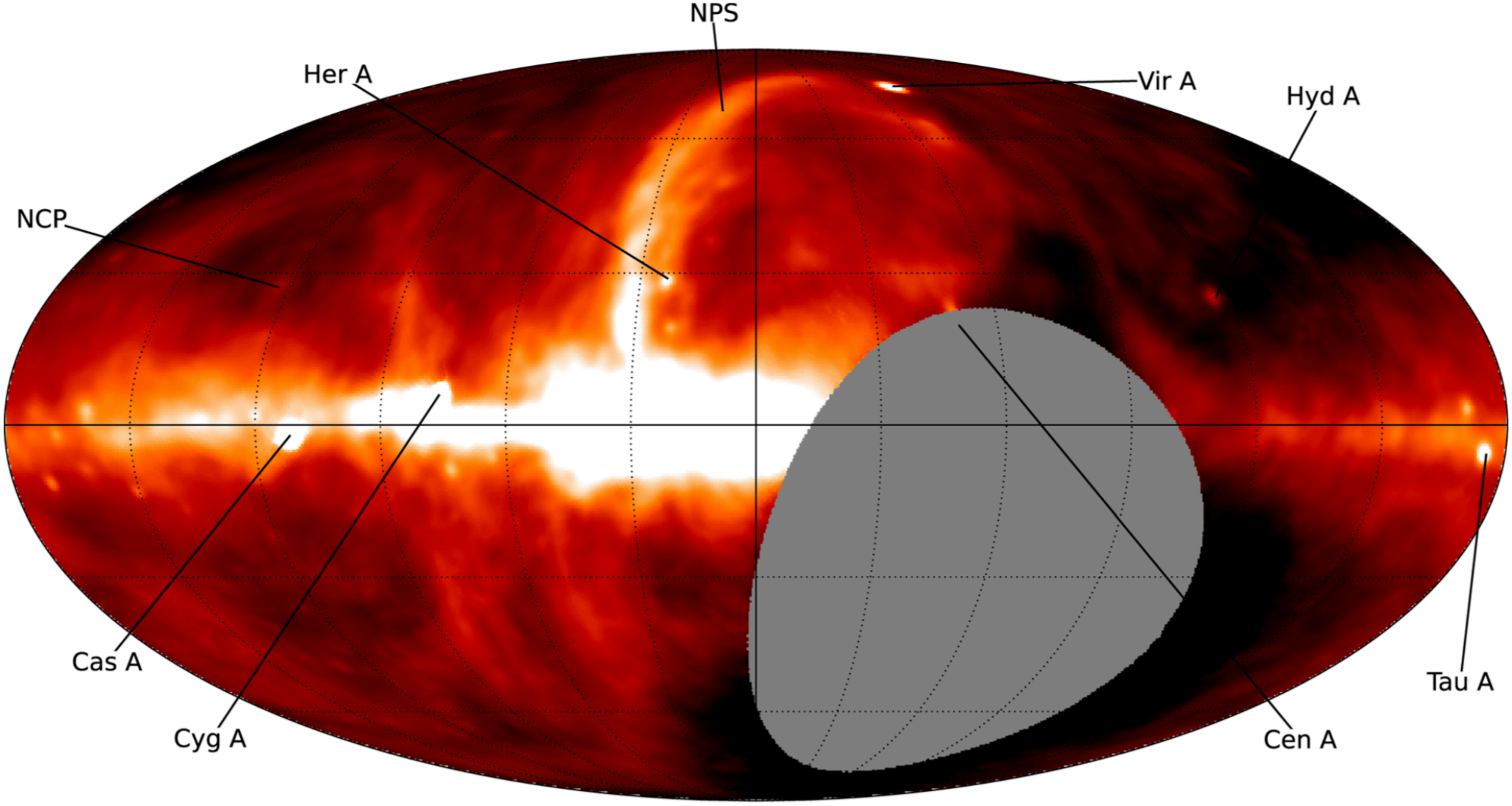
- Square Kilometre Array
  - LFAA: 50-350 MHz
  - LOFAR, MWA, ASKAP, MeerKAT, HERA are pathfinders
  - 250,000 dipoles
  - 75% antennas in 2 km core, remaining on 3 spiral arms out to 50 km
  - www.skatelescope.org/lfaa/
  - ‘Phase 1 construction 2019’
  - ‘Initial Science in 2020’s’
  - western Australia



The Optical Sky

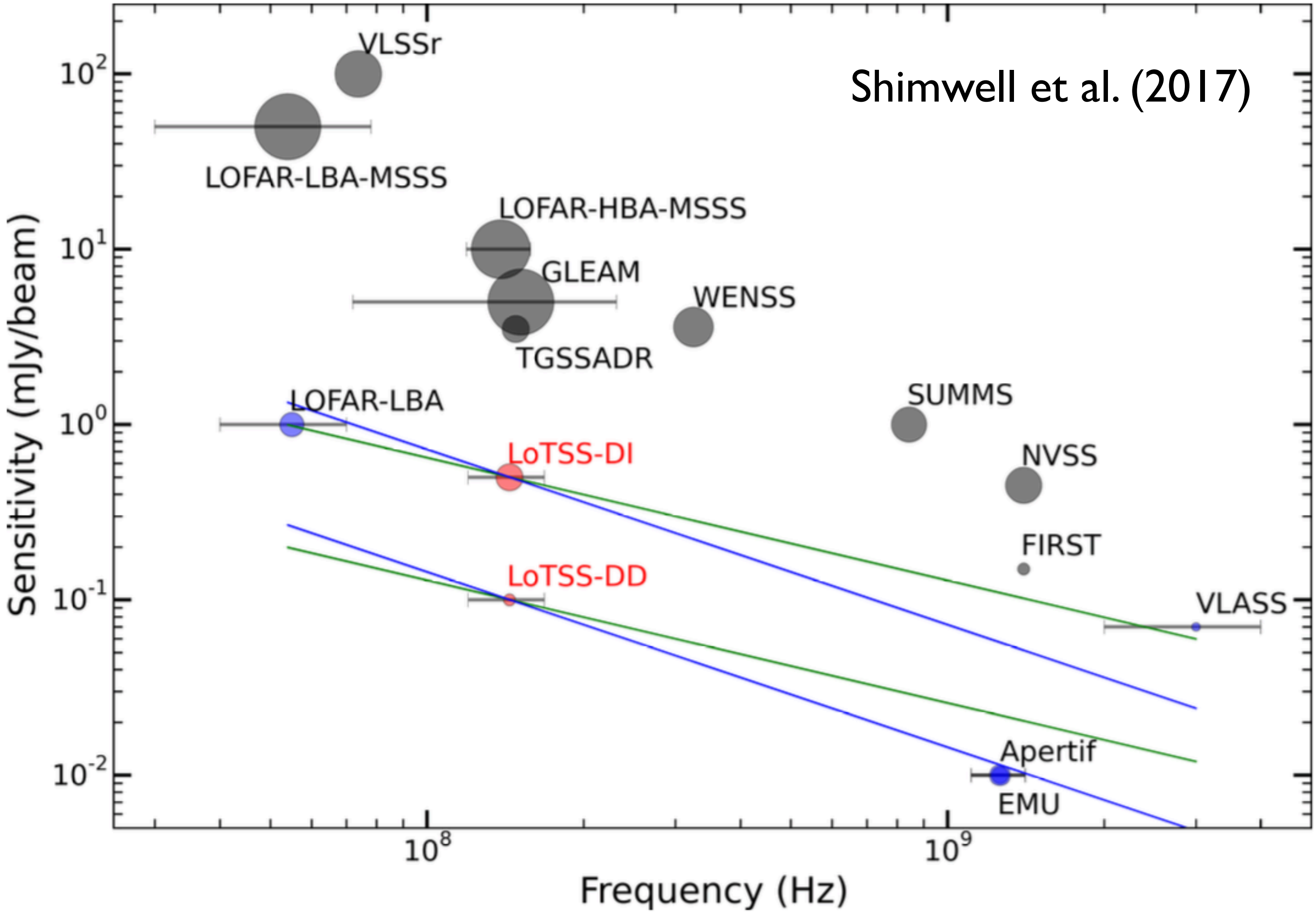


The Sky at Low Frequencies



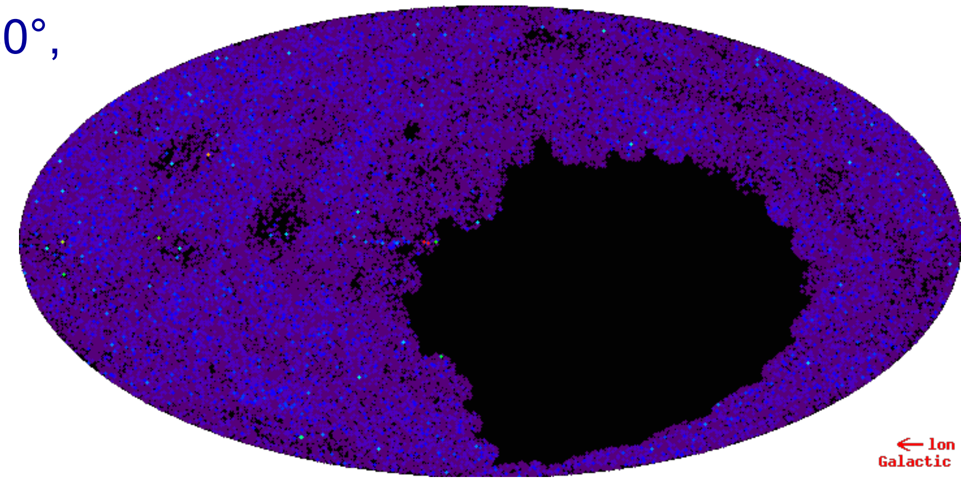
74 MHz with LWA1: Dowell et al. (2017)

A few Recent Low Frequency Sky Surveys



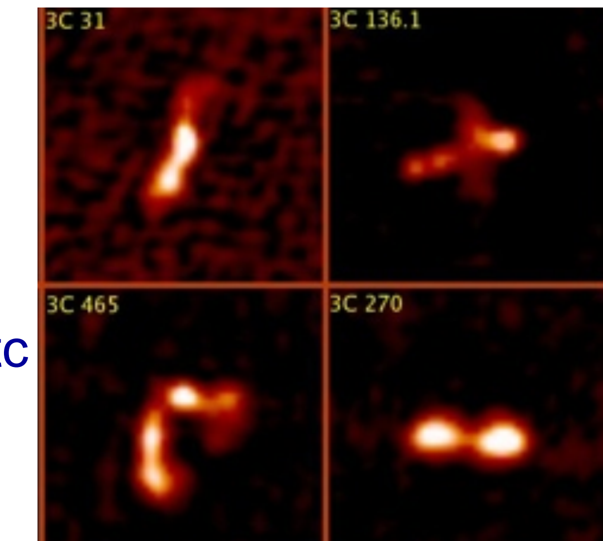
VLA Low Frequency Sky Survey Redux: VLSSr

- Survey Parameters: ν = 74 MHz, δ > -30°, Θ= 75” resolution, σ~100 mJy/beam
- Status: completed, re-released
- Reprocessed with new RFI excision software, original survey as ionospheric model, improved primary beam model



- Final catalog: N ~ 92 964 sources in ~ 95% of sky δ> -30°
  Statistically useful samples of sources
  => fast pulsars, distant radio galaxies, cluster radio halos and relics, unbiased view of parent populations for unification models

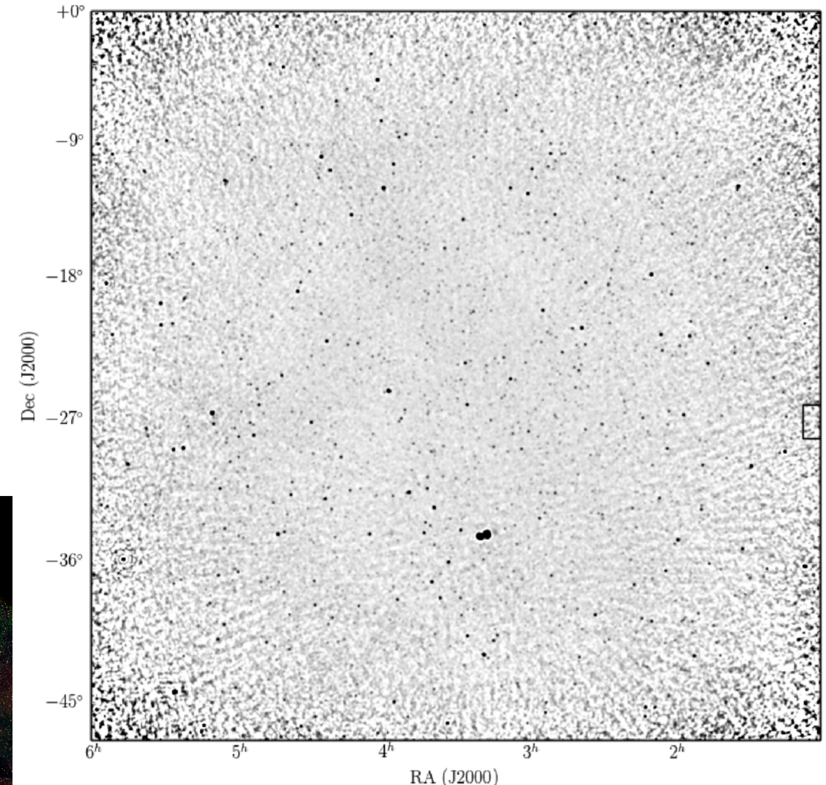
Lane et al. (2012, 2014)



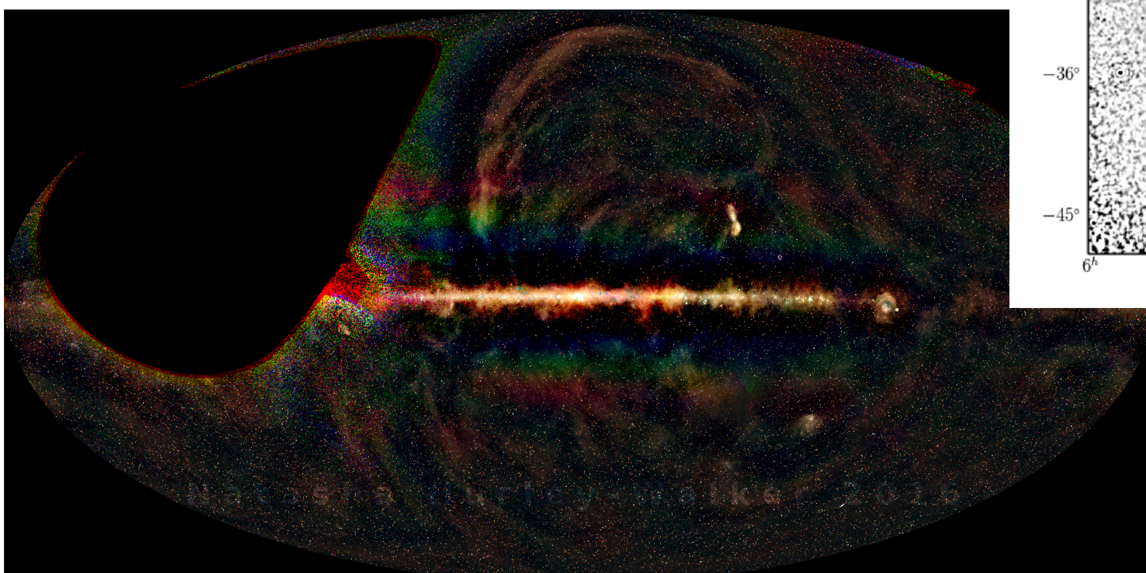
- Important calibration grid for VLA, GMRT, LOFAR, etc
- Data online at NRAO VLSSr server

GLEAM: The GaLactic and Extragalactic All-Sky MWA Survey

- Covers sky at $\delta < +30°$
- $72 < \nu < 231$ MHz
- Status: Hurley-Walker et al. (2016)
  - 307,455 sources
- θ~2 arcmin
- rms ~ 10-30 mJy/bm



45x45 degree field centered on Dec=-27 from Hurley Walker et al. (2016).

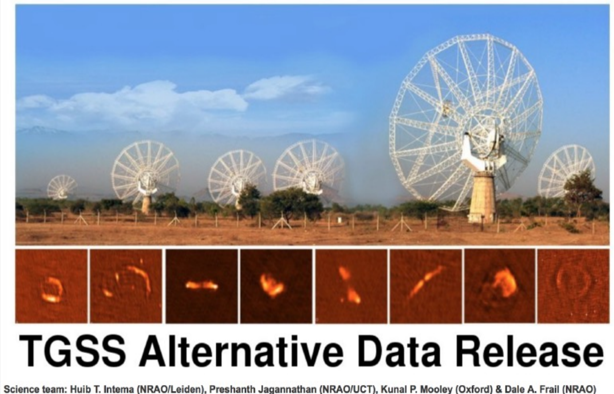


Credit: Hurley-Walker

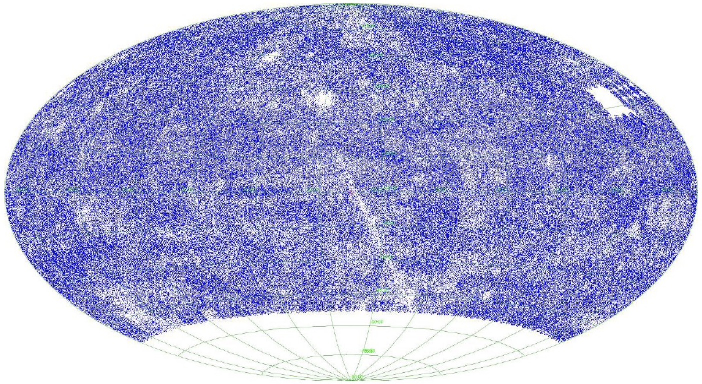
TGSS ADR1

- GMRT 150 MHz survey, dates 2010-2012, covering radio sky at $\delta > -53°$
- Catalog ~ 620,000 sources above 7σ
- Independent processing in 2015 using SPAM-based pipeline (Intema+ 2016)
- 5000+ continuum images and 7-sigma source catalog (ADR1)
- Low-frequency reference survey at 25" resolution and 2-5 mJy/beam noise. Significant sky overlap with LOFAR, LWA, MWA and SKA-LOW
- Powerful tool for finding steep-spectrum sources (HzRGs, pulsars, cluster halos & relics, etc.)

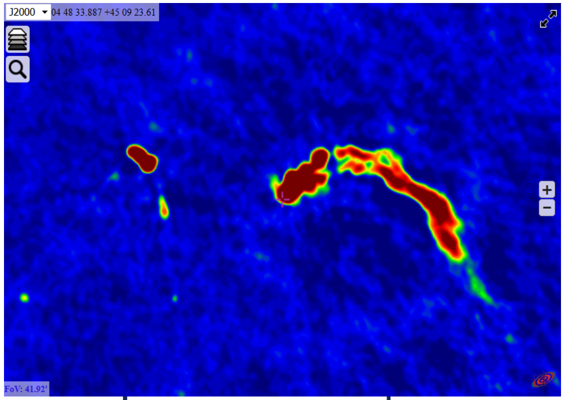
http://tgssadr.strw.leidenuniv.nl



620 thousand sources

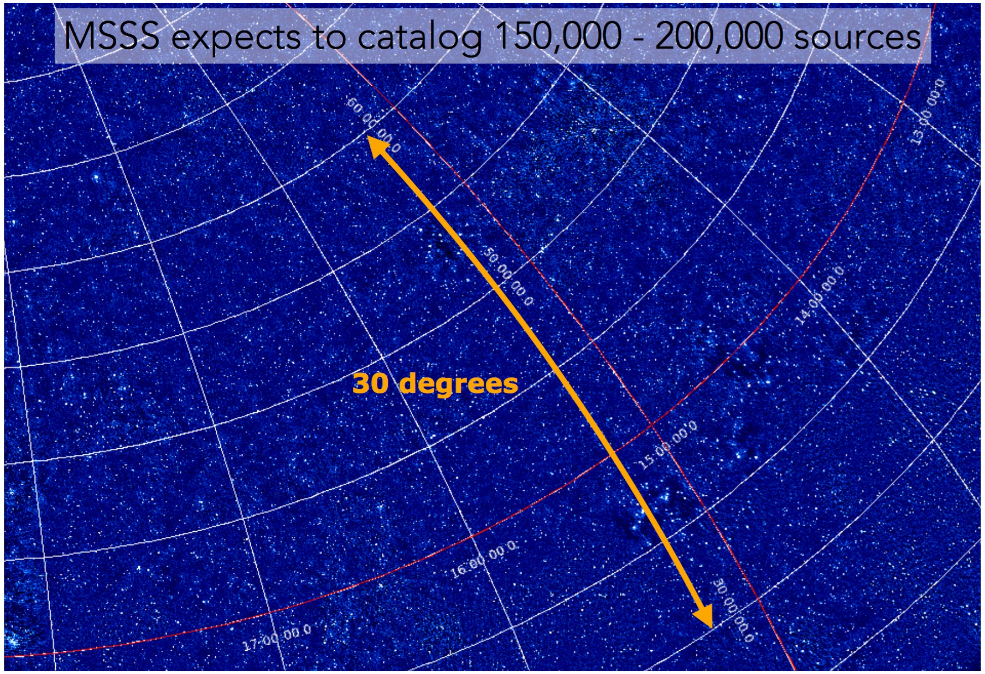


Interactive access through CDS Aladin



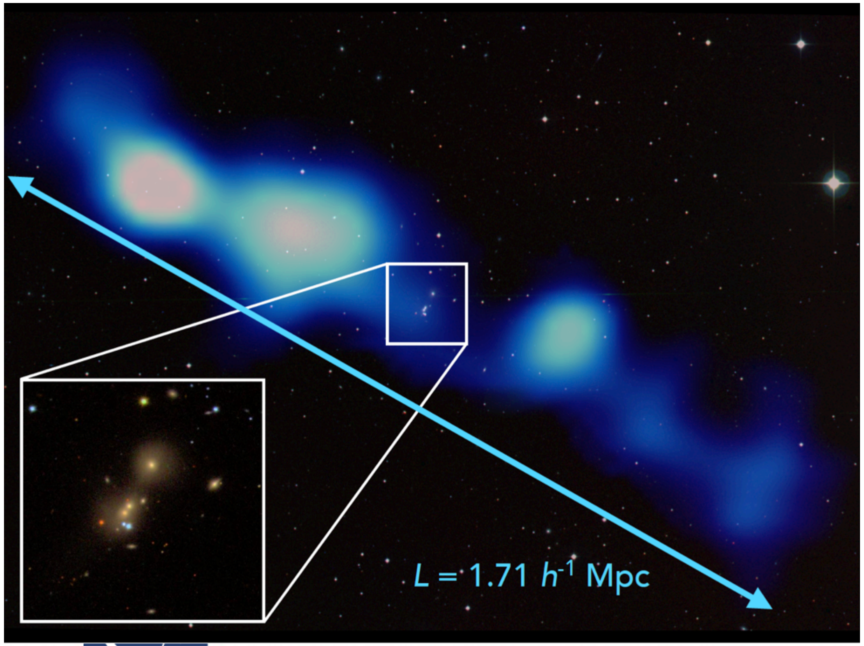
LOFAR Multi-frequency Snapshot Sky Survey: MSSS

- Covers 20,000 deg^2, $\delta > 0°$
- LBA: σ<50 mJy, θ ~120”
- HBA: σ<10 mJy, θ ~150”
- Status: initial publication (Heald et al. (2015)
- data online at http://msss.astron.nl



MSSS field.

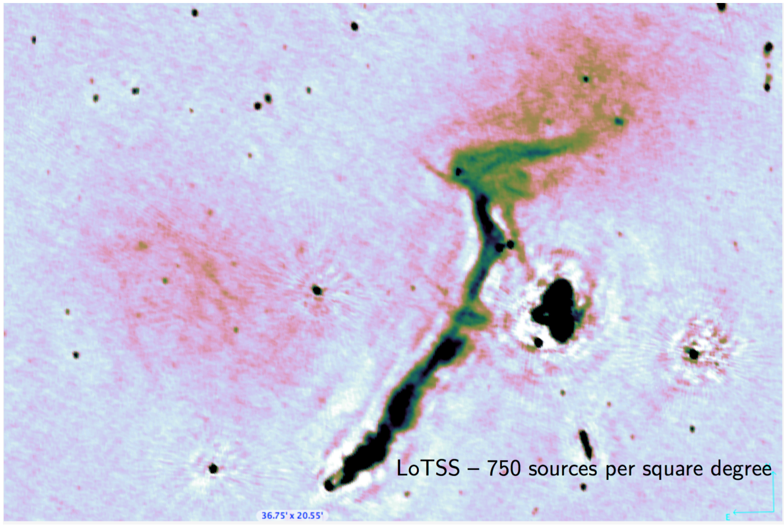
Credit: LOFAR/Heald



MSSS discovery of giant radio galaxy.
Credit: LOFAR

LOFAR Two-Meter Sky Survey: LoTSS

- Covers 20,000 deg^2, $\delta > 0°$
- HBA: σ<0.1 mJy, θ ~5”
- Status: initial publication (Shimwell et al. (2017)
- Survey will require 50 PB of archive and processing space

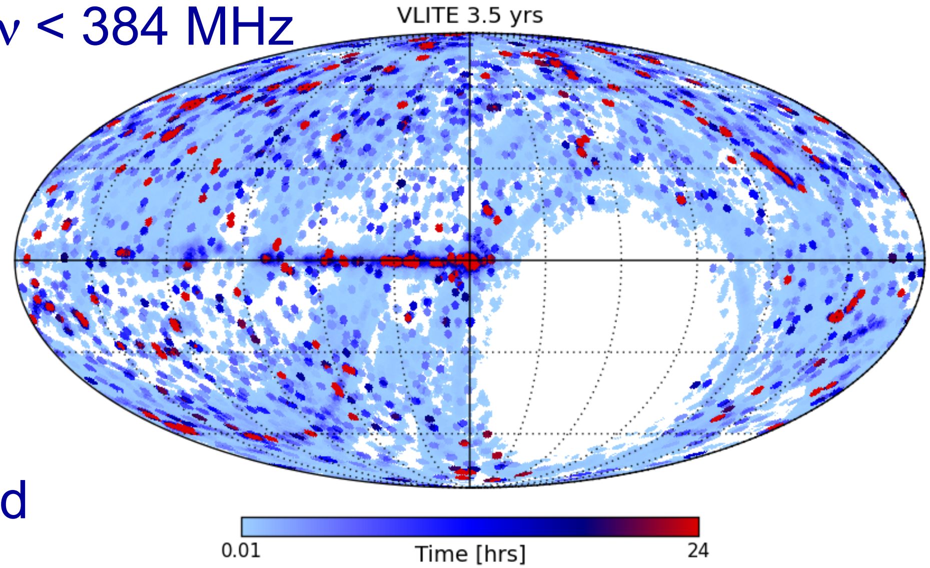


LoTSS field.

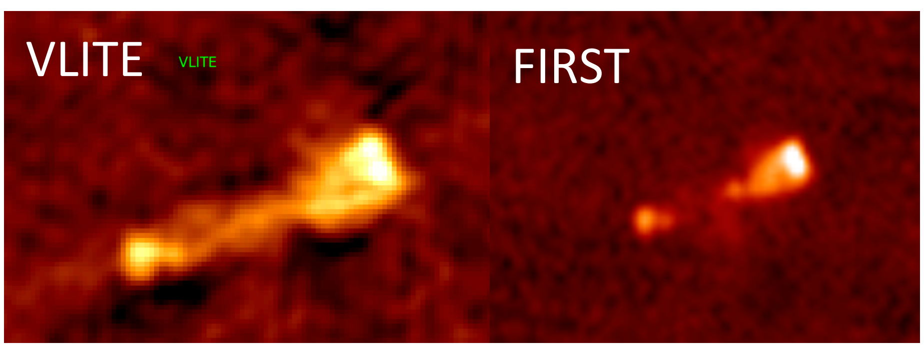
Credit: LOFAR/Shimwell

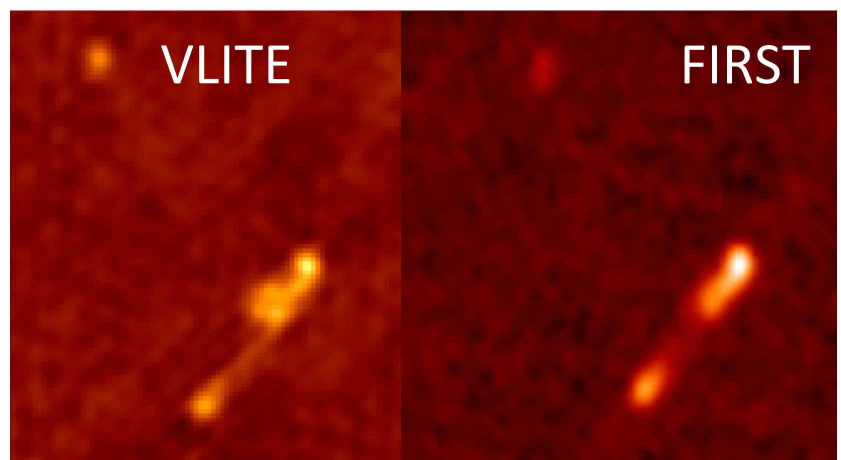
VLA Low-band Ionosphere and Transient Experiment: VLITE

- Commensal with VLA (δ> -45°), 320< ν < 384 MHz
- Began 2014, currently ~3.5 years
- Data ~72% wall time (~21,800 hr)
- Resolution: 5” to 3’
- Catalog: 1.7 million sources
- Catalog release 1 in prep., working on postage stamp release
- Goal is upgrade to full 27 antennas and wider bandwidth



VLITE 3.5 year sky coverage. Credit: VLITE/NRL





Low Frequency Interferometry In Practice:

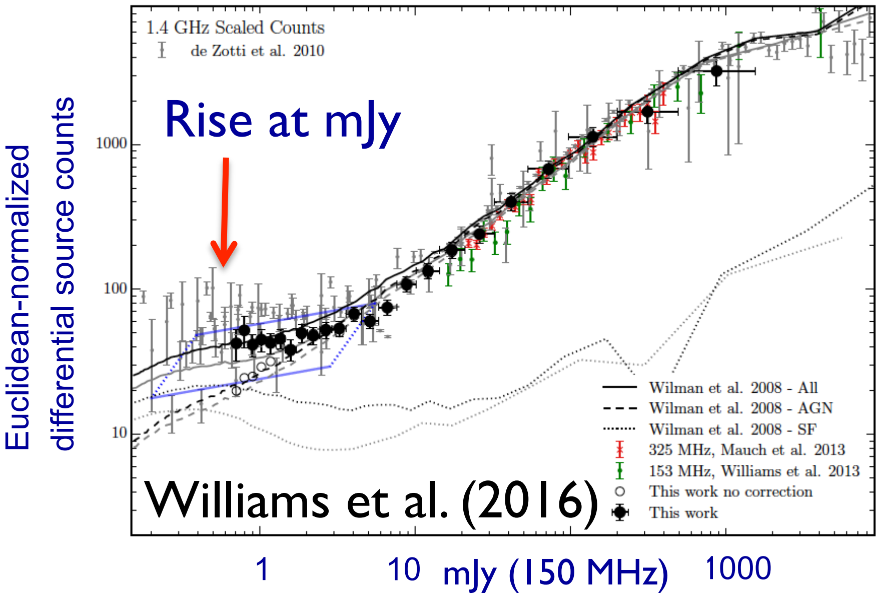
- Confusion: source blending at lower resolutions – need long baselines to overcome confusion
- Radio Frequency Interference: Severe at low frequencies

Direction Dependent Effects (DDE)

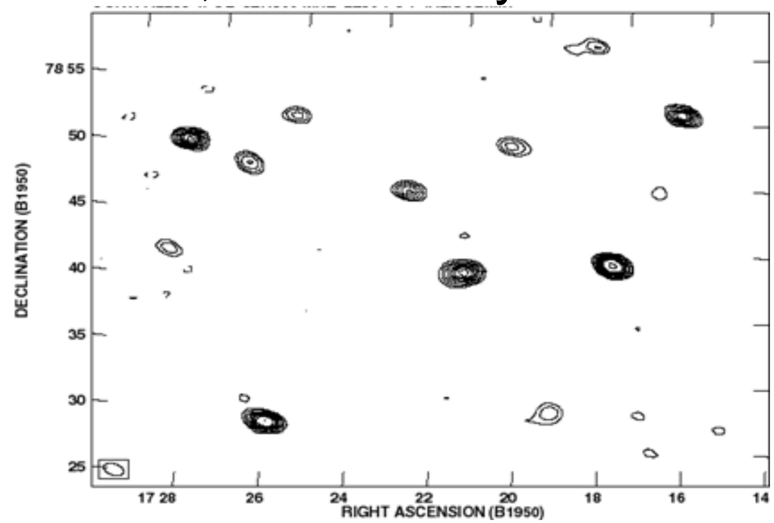
- Ionosphere: single phase correction per FoV often fails at LF
  - *Quiescent*: Refraction, Faraday Rotation
  - *Disturbed: Scintillation, Image Distortion, Position Shifts*
- Large Fields of View: (Perley Talk, Rao VenkataTalk)

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

Confusion: Need Long Baselines

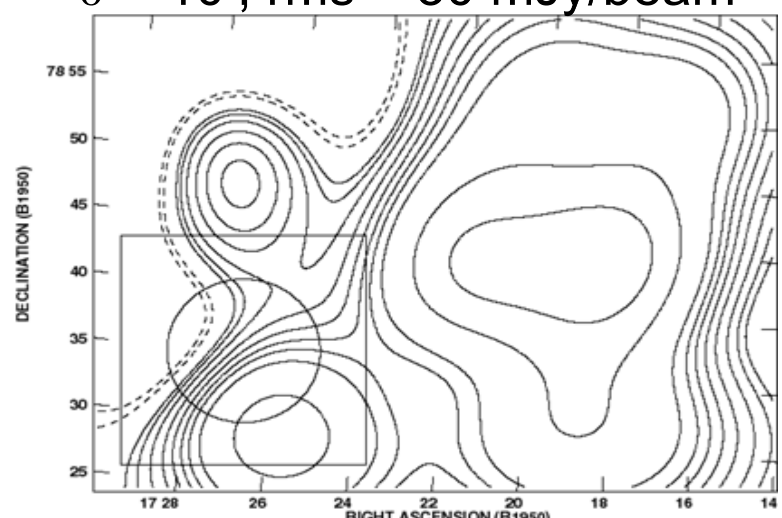


θ ~ 1', rms ~ 3 mJy/beam



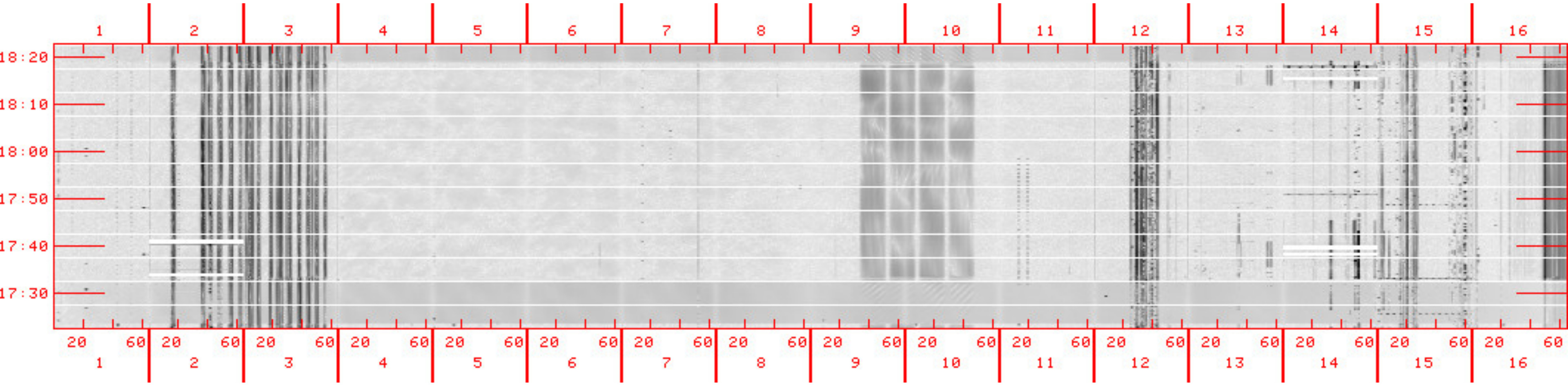
- for any angular resolution θ
  - there is a confusion limit
  - individual weak sources blend
  - the resulting sky noise may exceed thermal noise
  - such cases are "confusion limited"

θ ~ 10', rms ~ 30 mJy/beam



Radio Frequency Interference: RFI

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



➢ Many different signatures seen:

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, …

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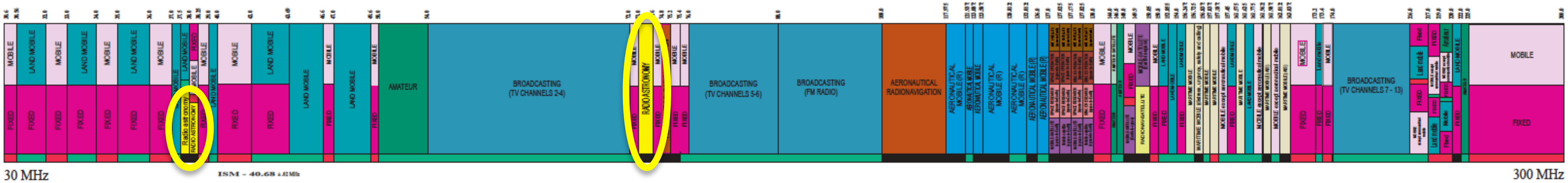
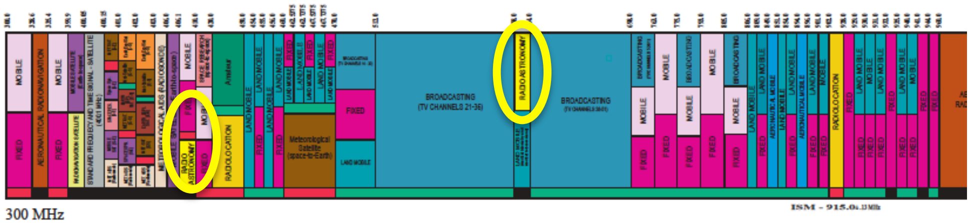
When do you deal with RFI?

➢ Pre-detection: coordination & frequency spectrum regulation, RQ zones, …





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

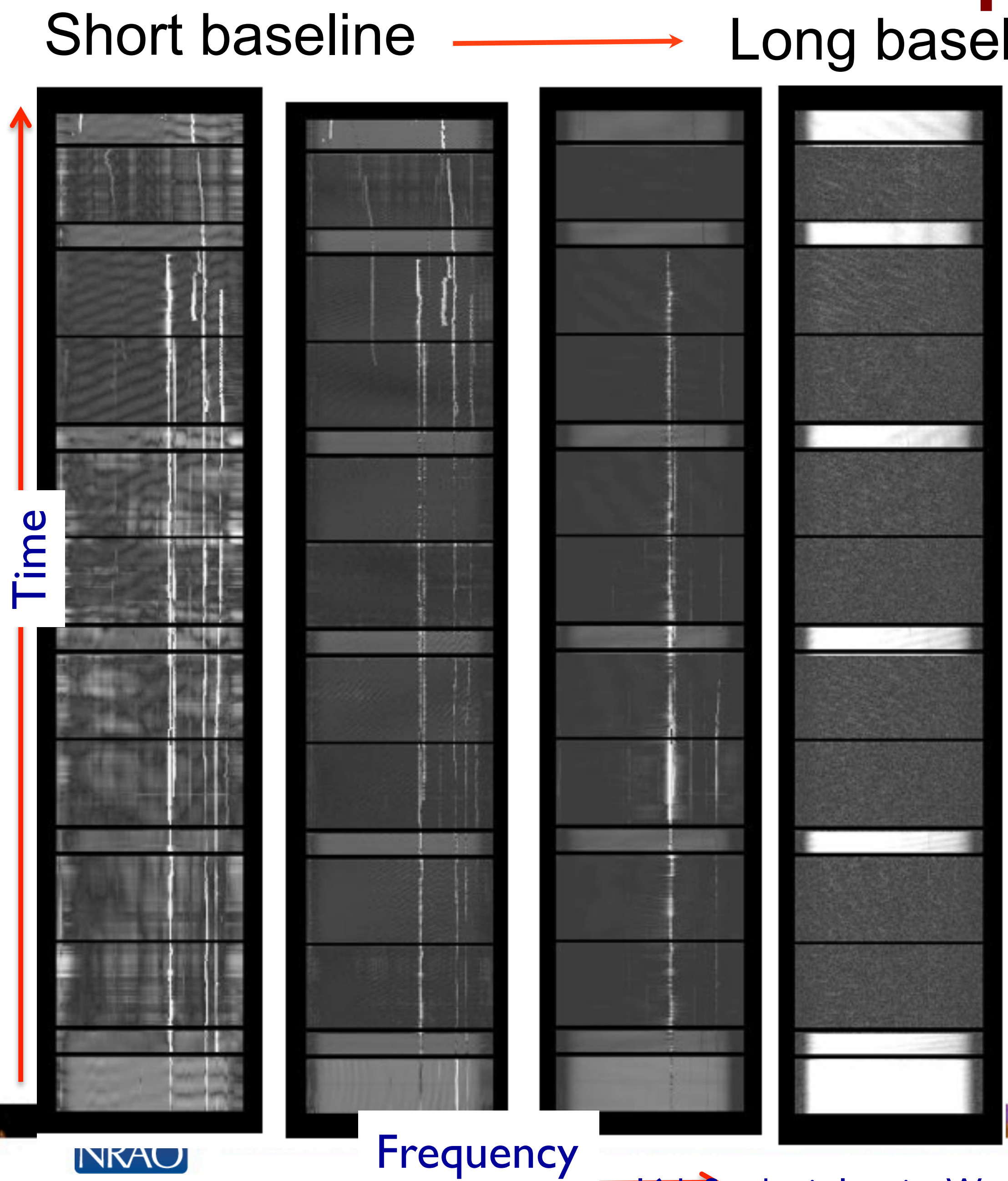
➢ US Spectrum allocation to Radio Astronomy between 30 MHz and 1 GHz (2011):

- 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

RFI Examples



- RFI environment worse on short baselines
- Several 'types': narrow band, wandering, wideband, ...
- Wideband interference hard for some automated routines

RFI In Practice: TFCrop

For each 2D time-freq plane (per antenna pair)

- Form an average along one dimension
- Calculate a robust piece-wise polynomial fit across the base of RFI spikes
- Flag un-averaged values deviating from the fit by > N-sigma
- Repeat along the other dimension

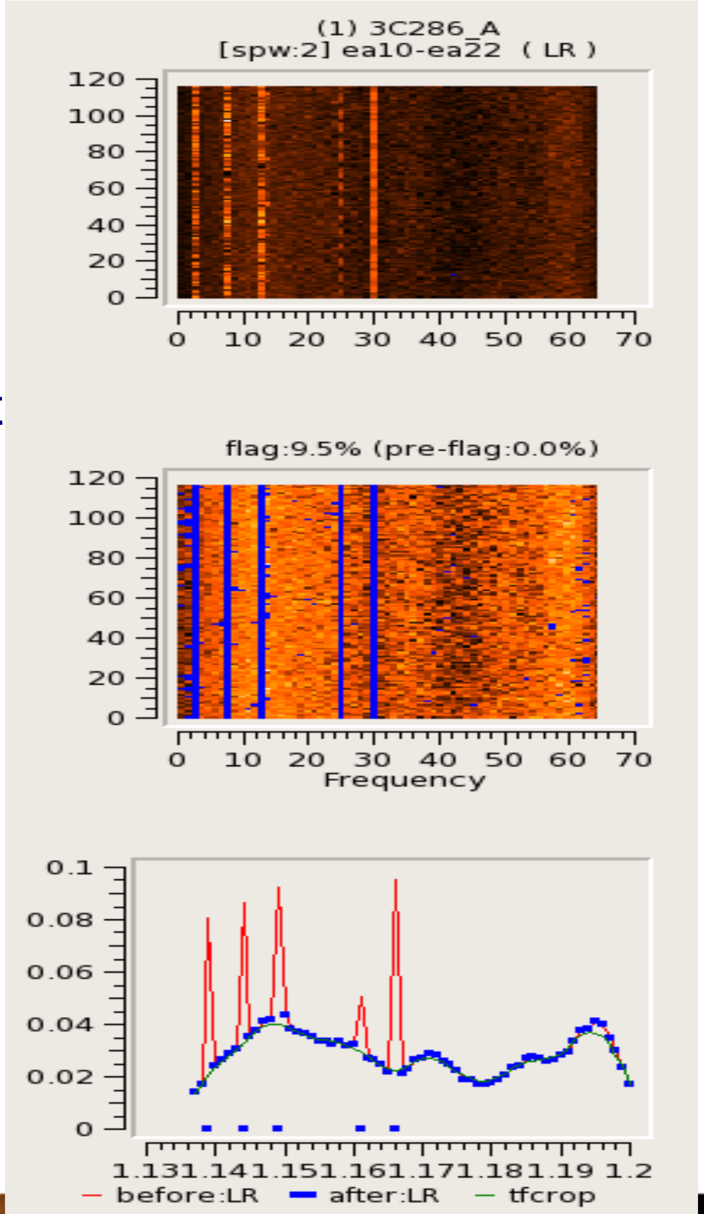
Spikey RFI easy, wider RFI needs more tuning.

Relevant Parameters :

timecutoff, freqcutoff : N-sigma thresholds

usewindowstats : Ways to detect deviation from the fit

maxnpieces : Tuning the robust polynomial fits



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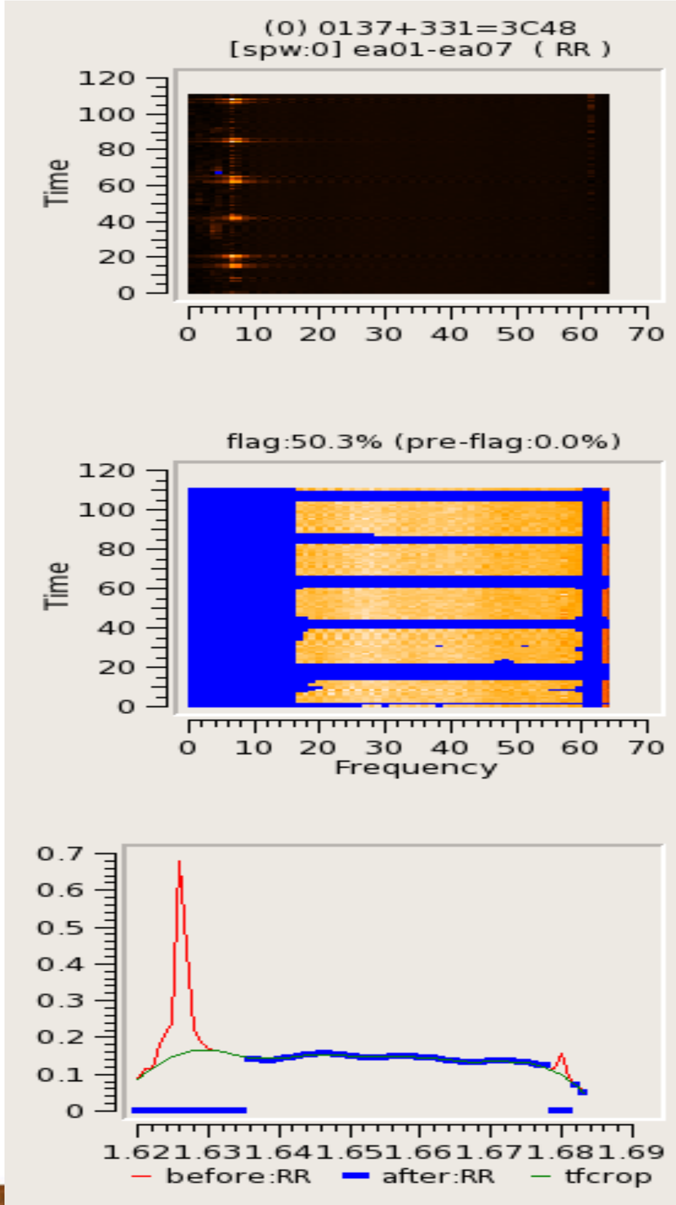


RFI In Practice: RFLAG

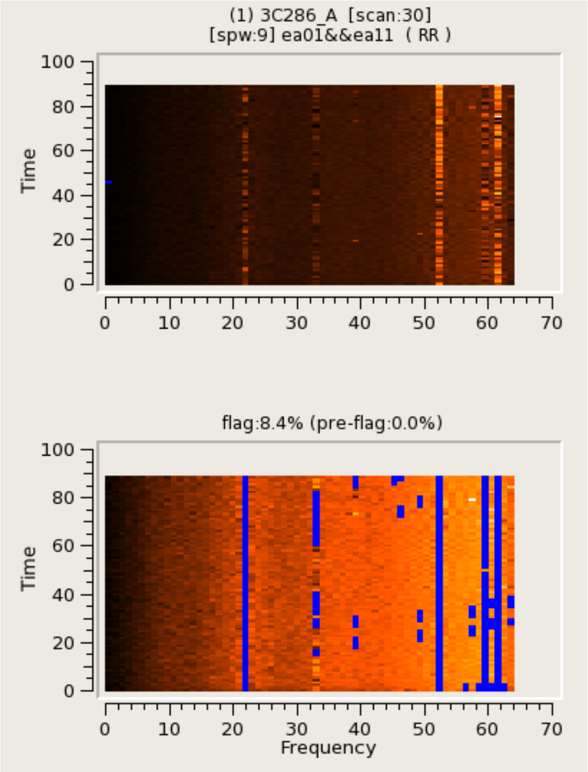
Repeat along time and frequency axes :

- Calculate local RMS of real and imag parts of visibilities within a sliding window.
- Calculate the median RMS across windows, deviations of local RMS from this median, and the median deviation
- Flag if local RMS > N x (medianRMS + medianDev)

(Most) Relevant Parameters :

timedevscale, freqdevscale : Threshold scale factors

winsize: Sliding window size

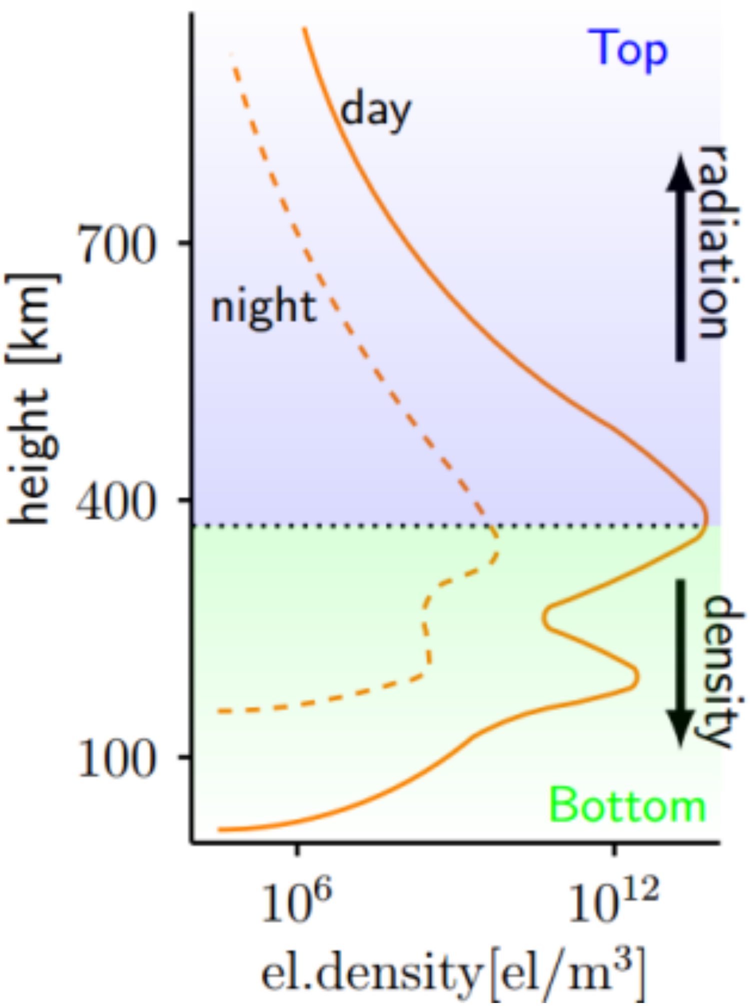


Direction Dependent Effects (DDE)

Severe at low frequencies but also impact 1-2 GHz band:

- Non-isoplanatic ionosphere
- Non-coplanar effects (*w*-term)
- Time-variable primary beam
- Frequency and polarization dependent primary beam

Ionosphere

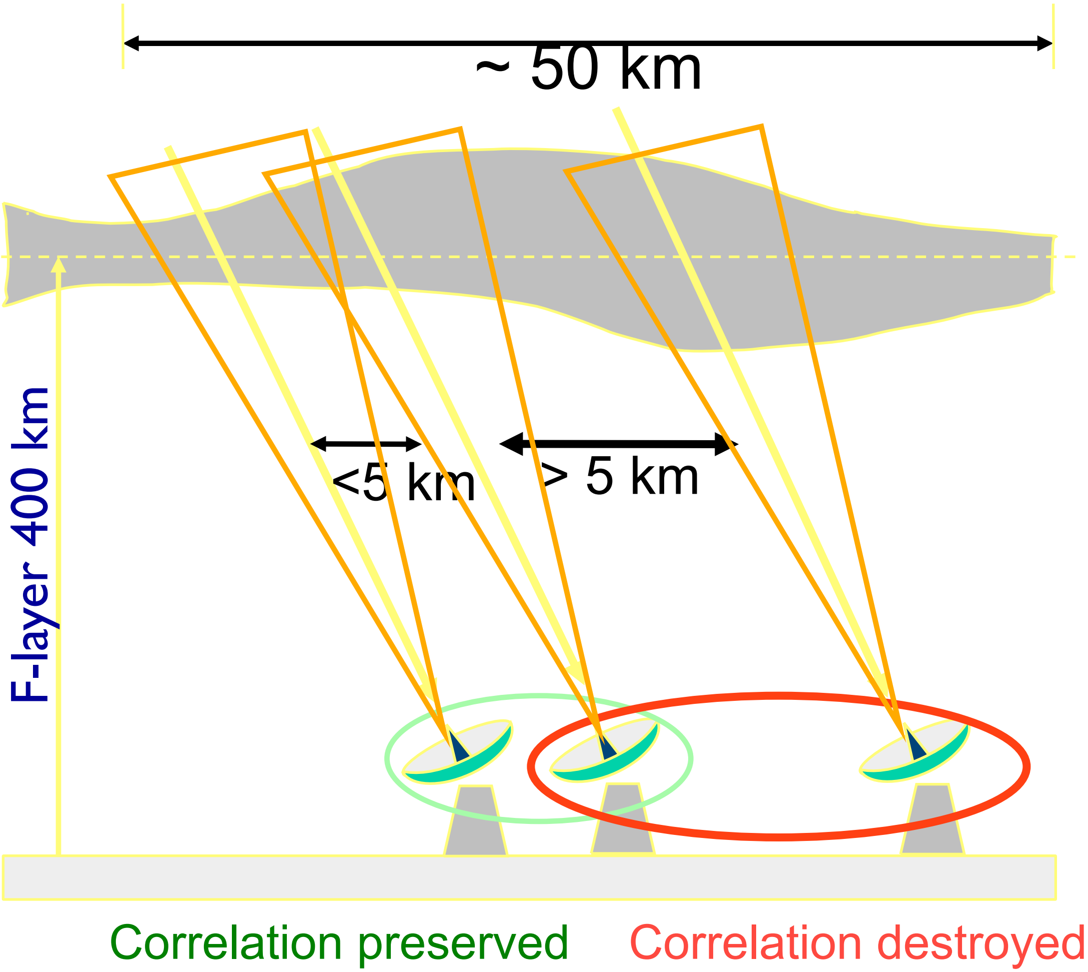


- Daytime e- density increase due to solar radiation
- Recombination at night reduces e- density
- Dusk and dawn often show a refracting wedge due to large changes in e- density

$$\nu_p \simeq 9\sqrt{n_e}\ kHz, n_e \sim 10^4 - 10^5 cm^{-3}$$
$$\nu_p \sim 10MHz$$

Ionosphere

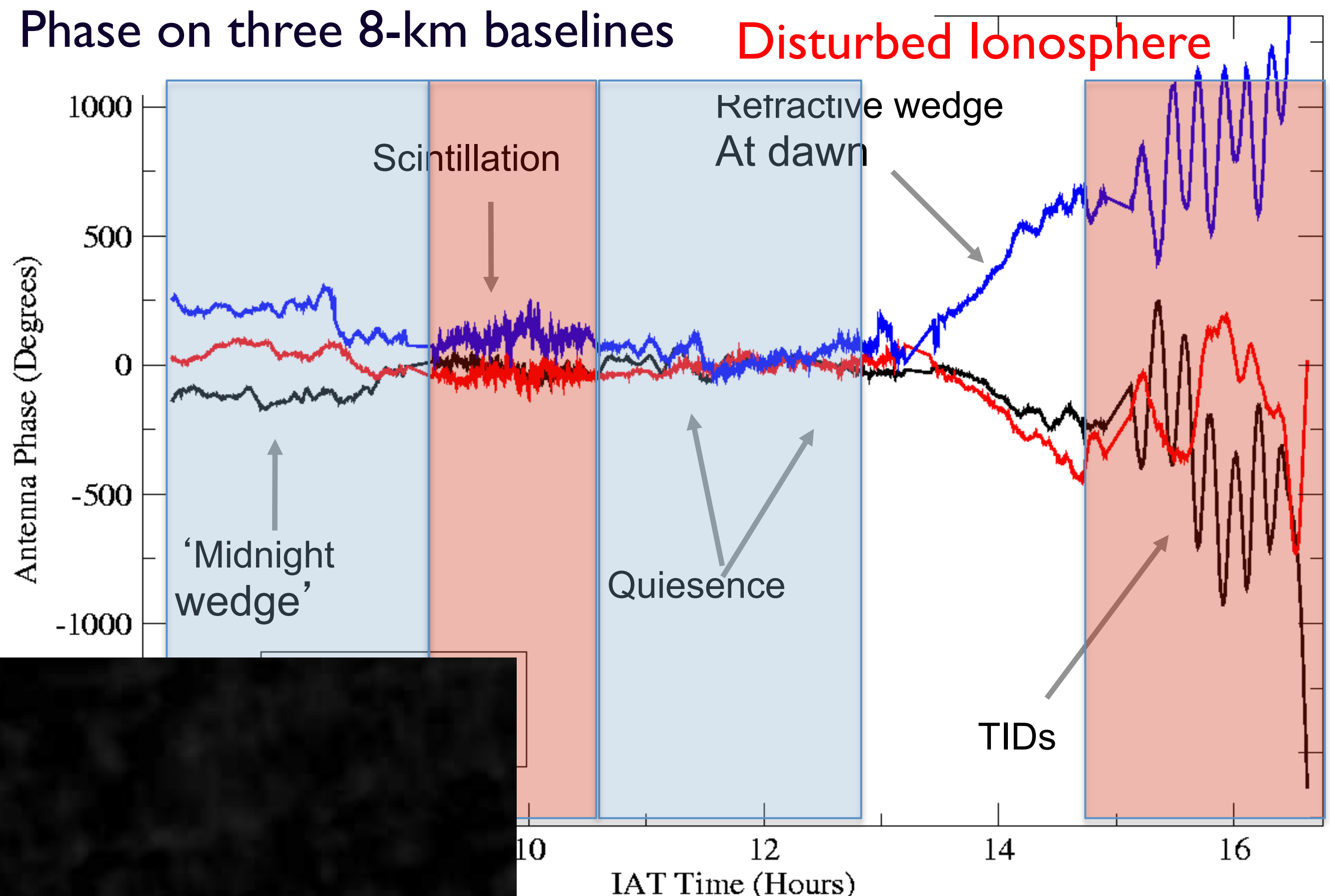
- Ionosphere introduces phase errors in radio signal

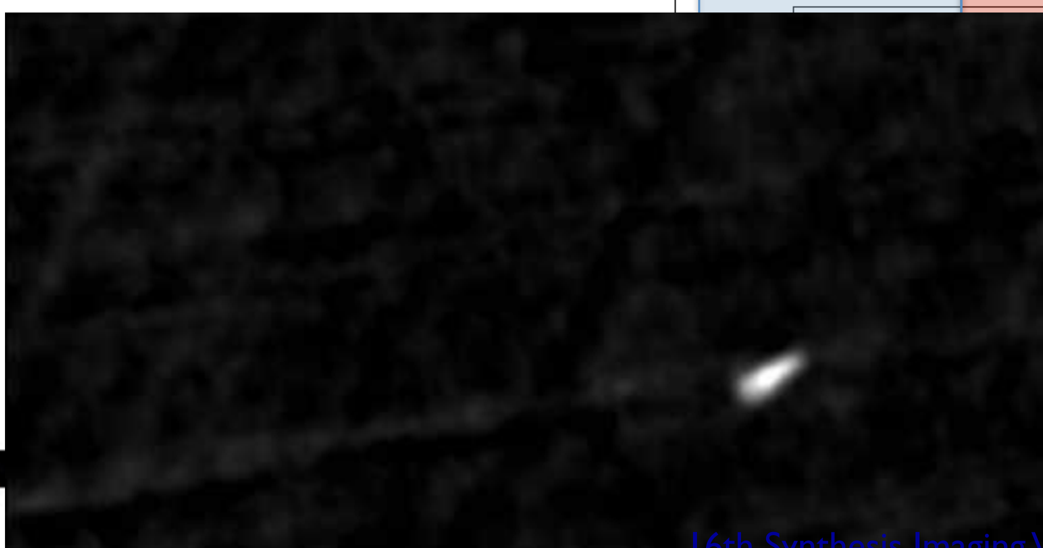


- Waves in the ionosphere introduce rapid phase variations (~1°/s on 35 km BL)
- Phase coherence is preserved on BL < 5km (gradient)
- BL > 5 km have limited coherence times
- Without proper algorithms this limits the capabilities of low frequency instruments

Disturbed Ionosphere: Antenna Phase vs Time

- A wide range of phenomena were observed over the 12-hour observation
- Often daytime (not dawn) has stable conditions but more RFI





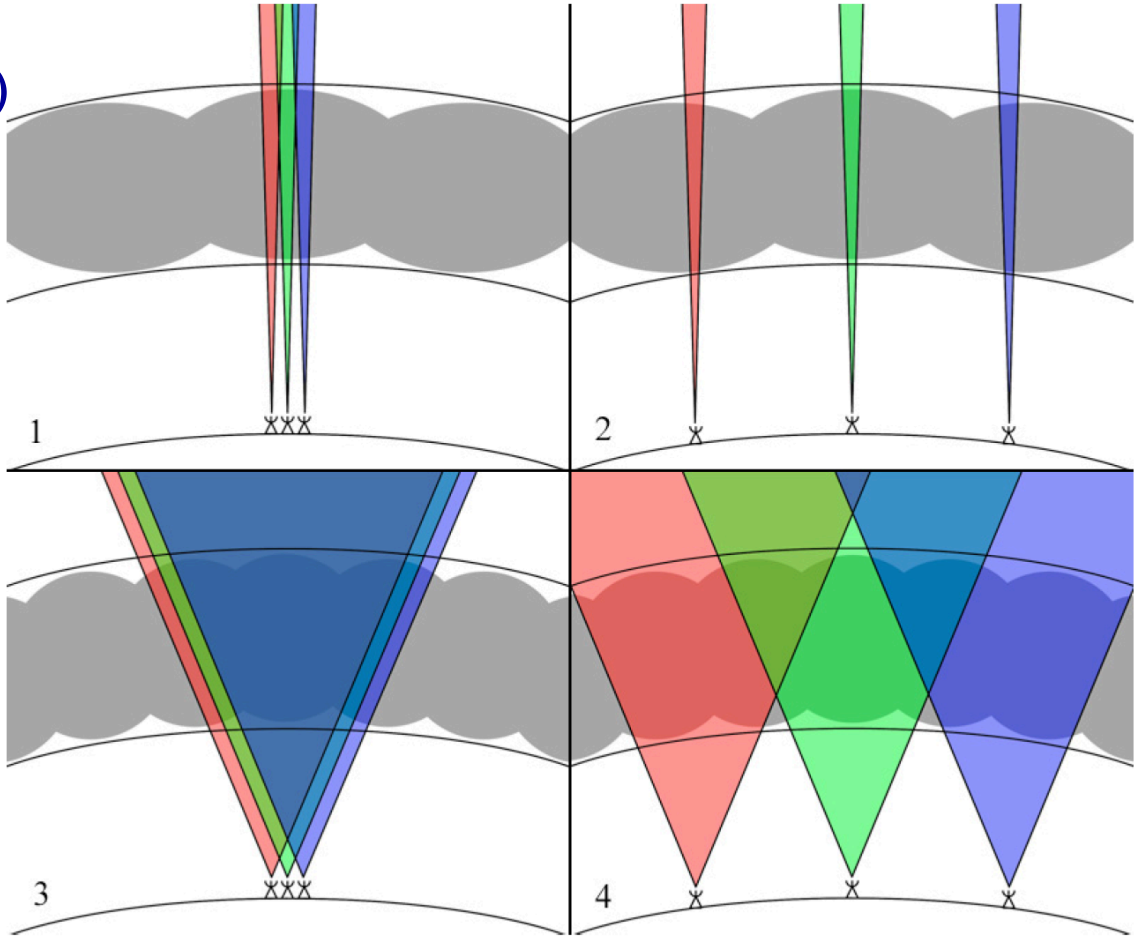
Ionosphere in Practice: What Regime?

- 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

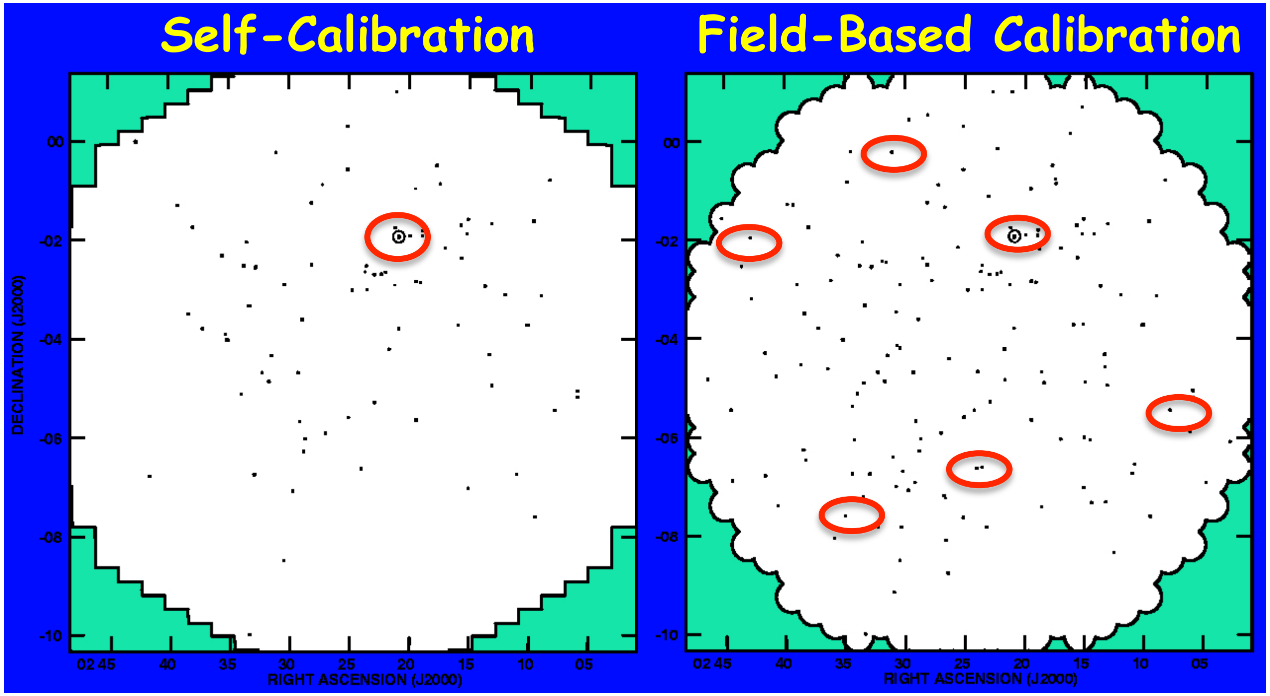
Significant effort underway: field-based, source peeling, global model, multiple scale height models, …



Intema et al. (2009)

Field-Based Calibration: Regime 3

- Compare snapshot images of bright sources to sky model positions (5-10 sources per FoV). Fit phase delay screen (Zernike polynomial) & apply to correct image. Breaks down in Regime 4 (long baselines).



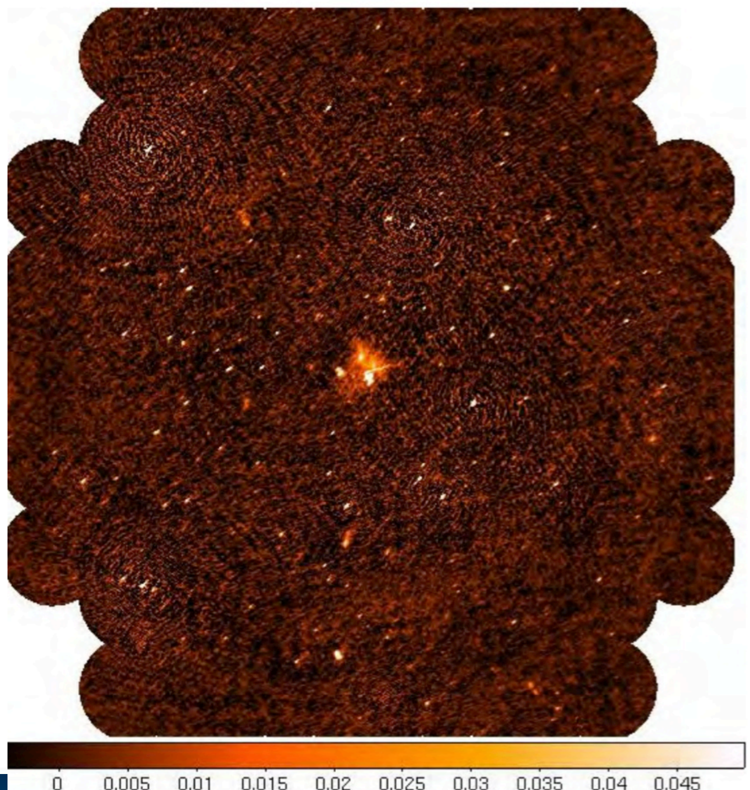
Average positional error decreased from ~45” to 17”

Obit: IonImage [for Obit see B. Cotton (NRAO) webpage]

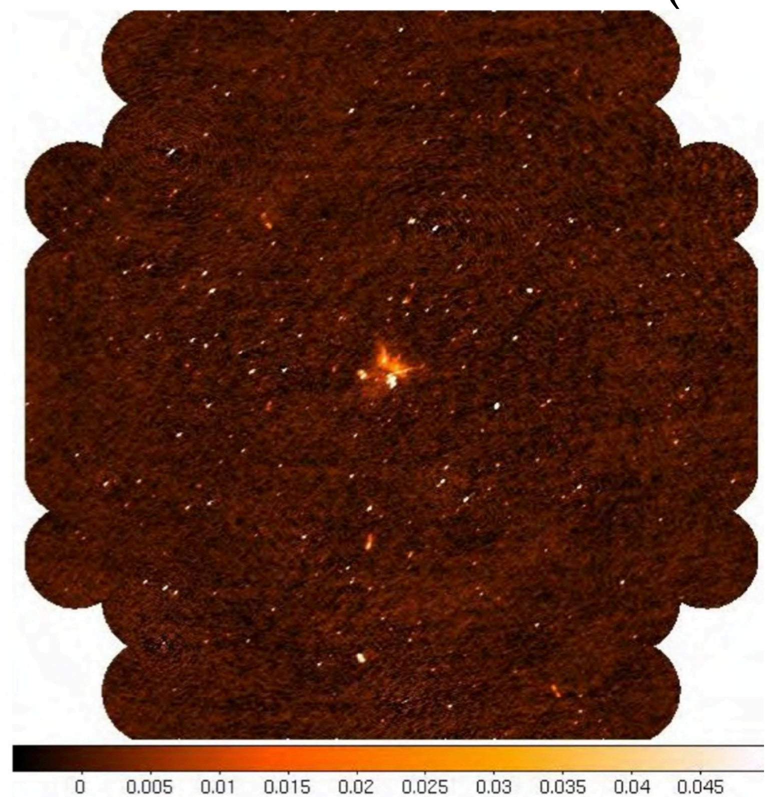
Peeling + Ionospheric Modeling: Regime 4

- Source Peeling and Ionospheric Modeling: SPAM (python + AIPS)
- Constrain ionospheric phase model based on calibration phases from 'peeling' (sequential self-calibration) of bright sources
- Fit a phase screen to pierce point solutions and apply to imaging

Intema et al. (2009)

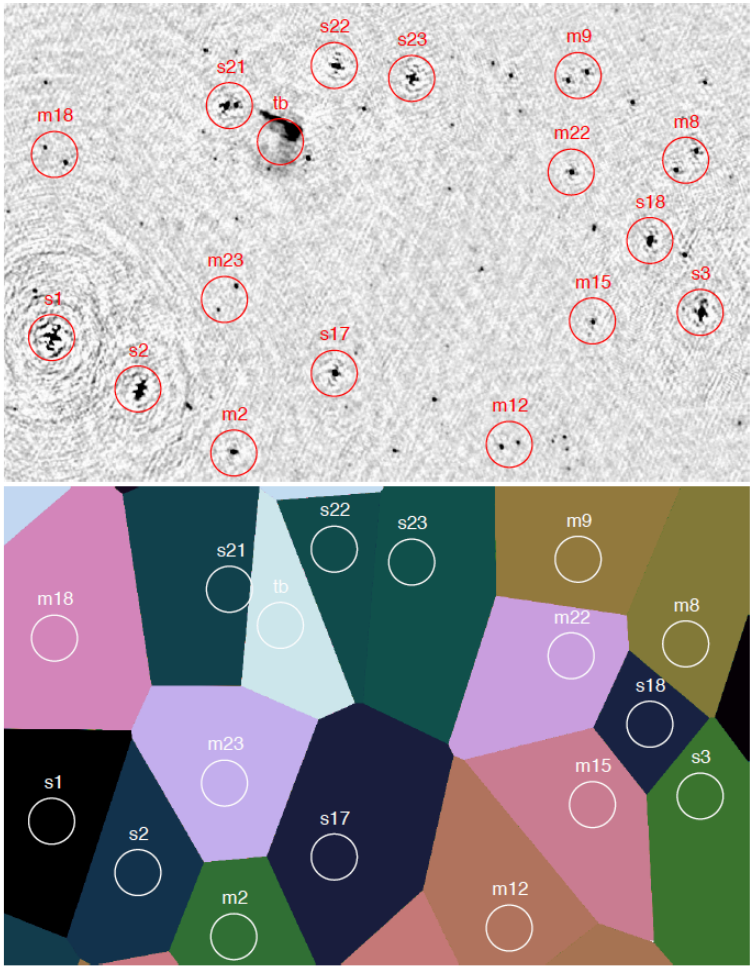


Self-calibration



SPAM calibration

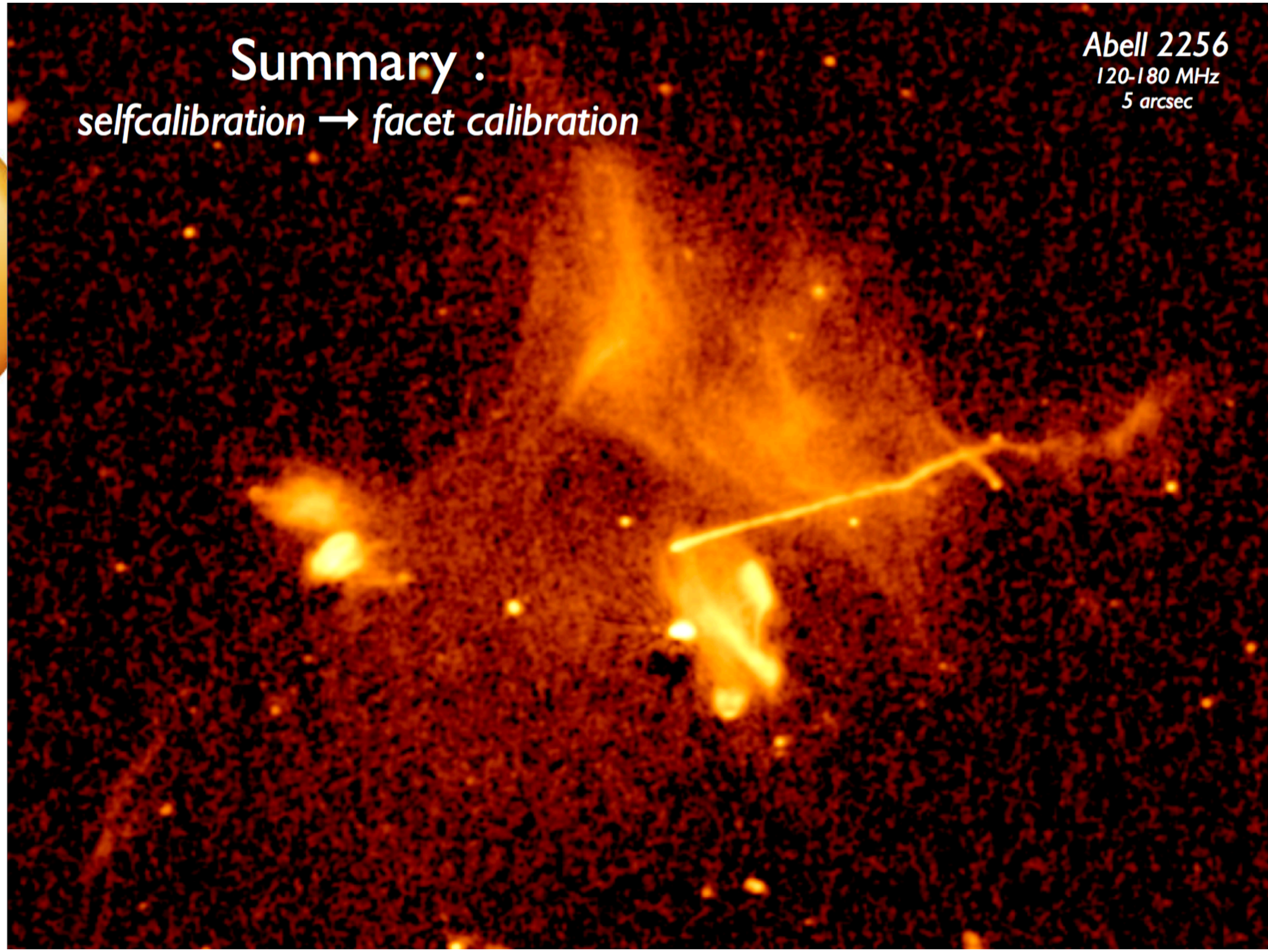
Facet-Based Calibration: Regime 4



van Weeren et al. (2016)

- Allows for correction for ionosphere and time-varying beam shapes (LOFAR)
- Divide the sky in facets (Veroni tesselation) and assume DD calibration for each source/ group applies to all sources in facet
- Subtract all sources from sky except bright source/group for facet in use, self-cal
- Add back faint sources in facet, apply solutions to them, image to make a new sky model, subtract that new model from data
- Move to next facet and start again
- Once all facets are completed, combine images or re-image all-facets with DDE applied

Facet-Based Calibration: Regime 4



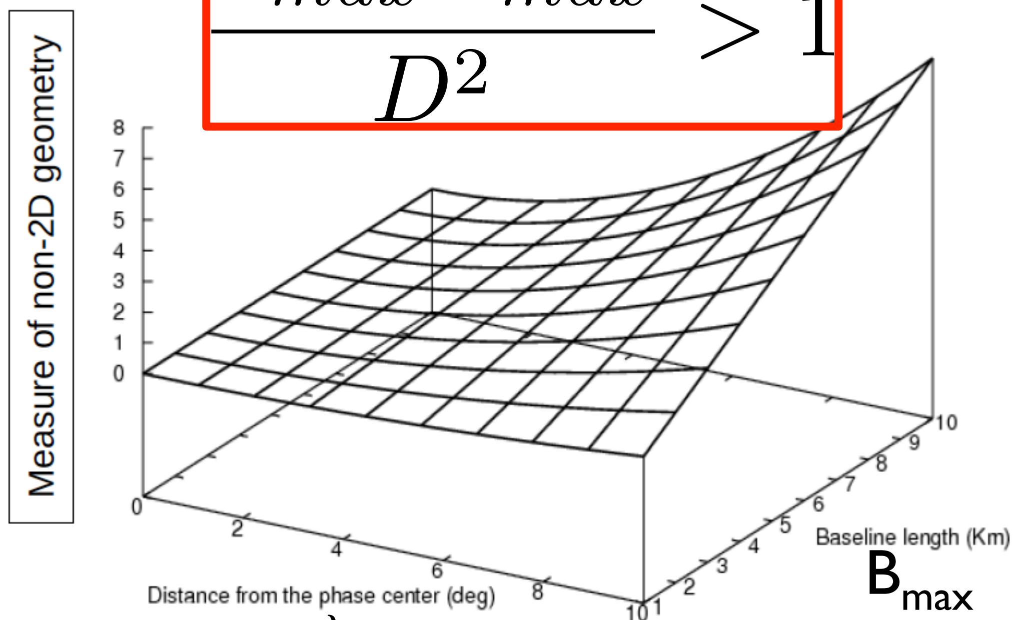
van Weeren et al. (2016)

Wide Field of View (Rao Venkata Talk)

- Need to image bright sources over the entire primary beam and even into the far out sidelobes (*~14° wide plateau at JVLA P band is -10 dB from peak*)
- 2D Fourier inversion of visibilities is only true if the visibilities lie in a plane (no *w* term) and the FOV is a small angular region (Perley talk)

$$\frac{\lambda_{max} B_{max}}{D^2} > 1$$

- Deviation from 2D approx. increases with distance from phase center and baseline length
- Limits DR in full field by deconvolution errors from distant sources



$$\theta \sim \frac{\lambda}{D}$$

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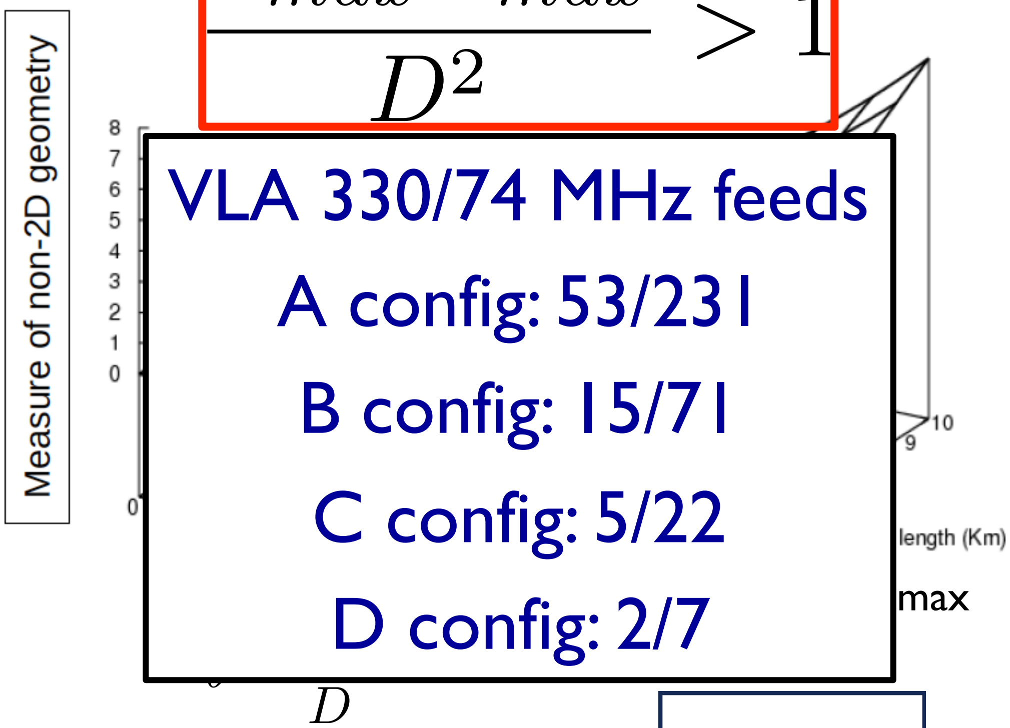


VLA 330/74 MHz feeds

A config: 53/231

B config: 15/71

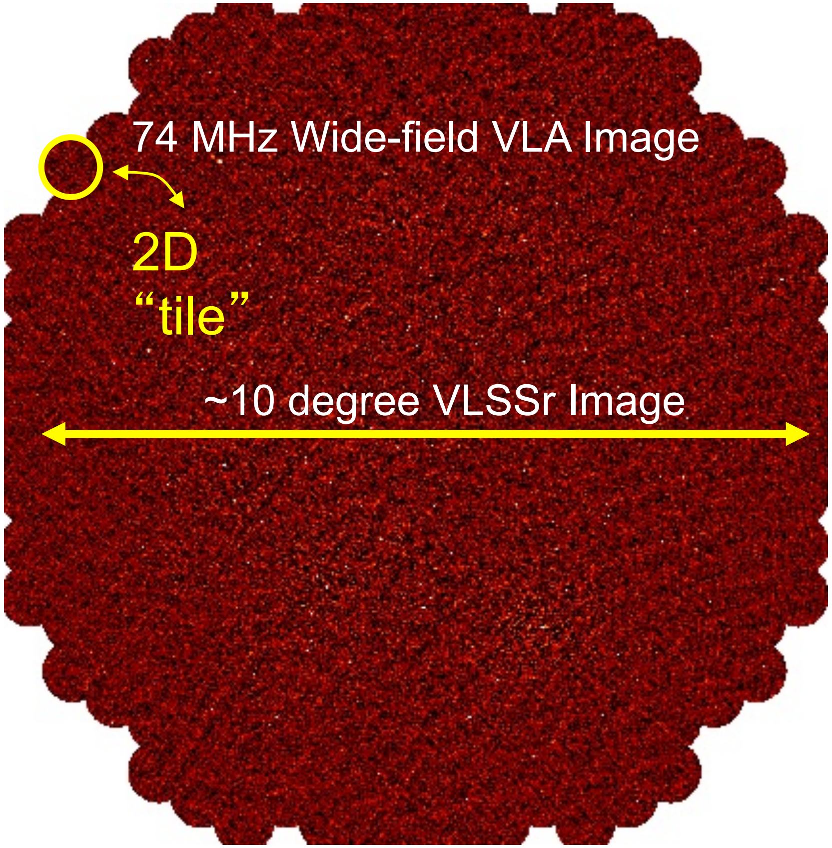
C config: 5/22

D config: 2/7

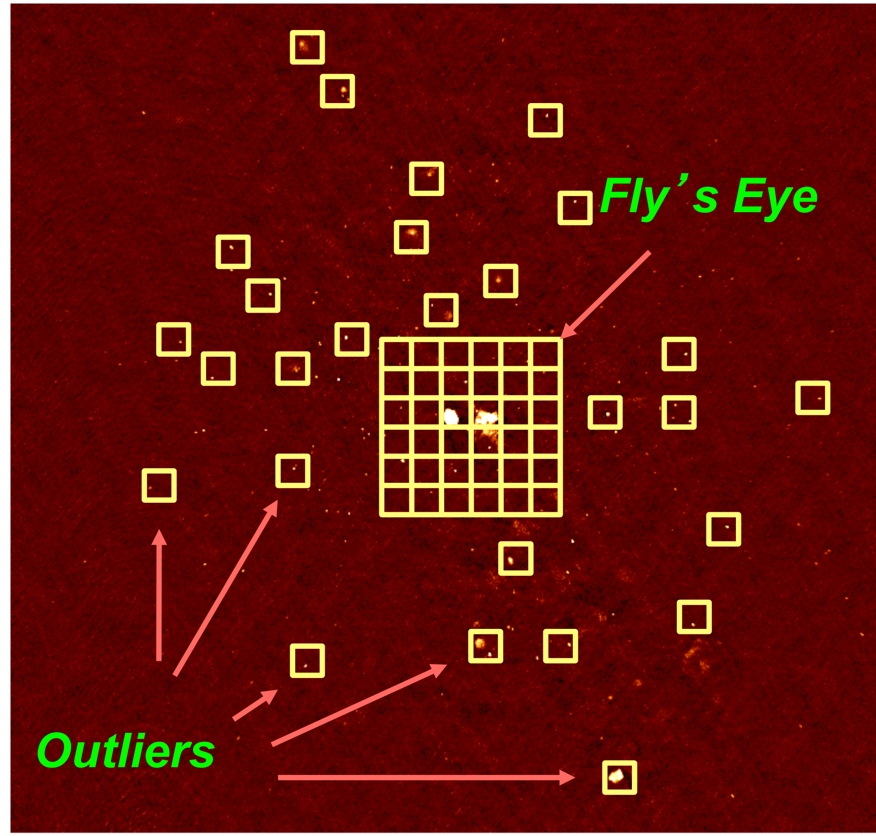
Wide Field of View

- Approaches to Wide Field Imaging:
  - Facets: divide sky into a large number of small images, each of which individually satisfy the small-angle criterion, flatten facets to make final sky image
  - *w*-projection: use *w*-dependent convolution function in gridding to get corrected image in 2D FFT
  - *w*-stacking/w-snapshot (WSCLEAN, Offringer et al. 2014) speedup over *w*-projection for very large FoV (MWA, LOFAR, SKA)
  - Full 3D Fourier Transform: Too computationally expensive, not used
- Primary beam changes with frequency, polarization, and time, must be incorporated into wide field, wide bandwidth, direction-dependent techniques! (Talk by Rao Venkata will bring these all together)

Full Field vs Targeted Imaging



A array requires ~10,000 pixels!



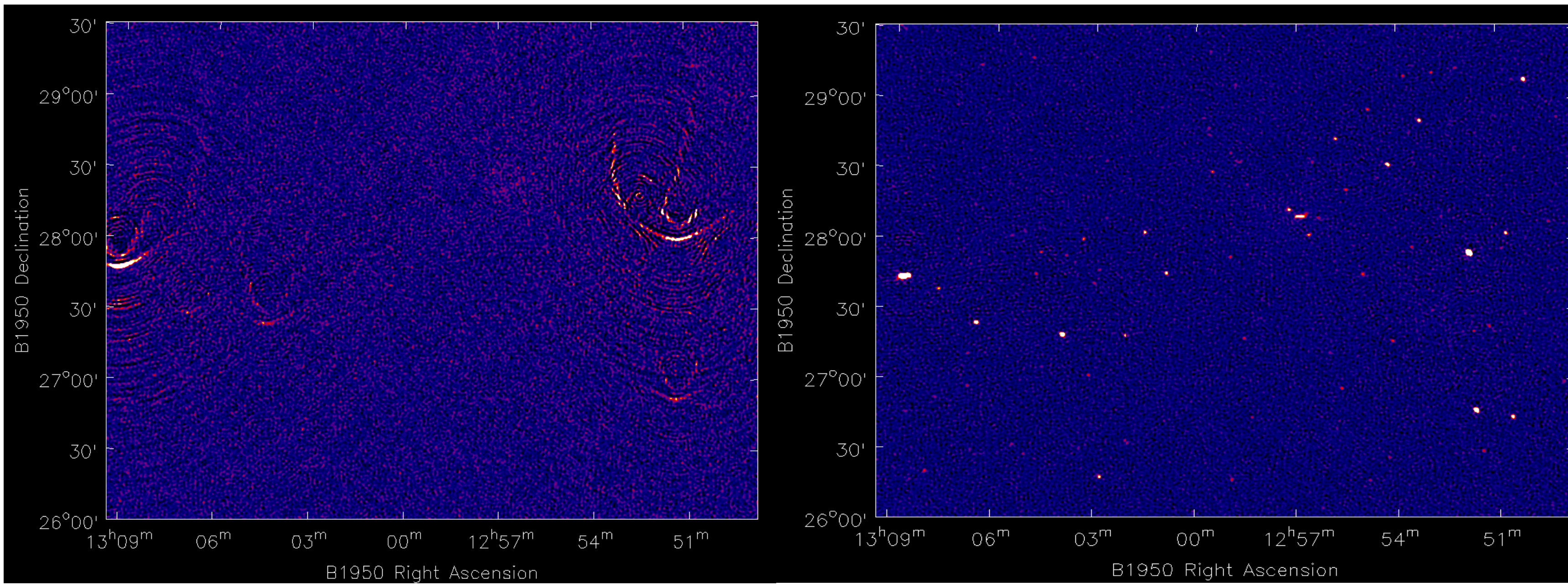
- 2D faceted imaging of entire FoV is very computationally expensive
- Fly’s eye of field center and then targeted facets on outlier is less demanding BUT potential loss of interesting science

Wide Field of View: *W*-Projection

Cornwell et al. (2008)

➢ Work with the visibilities instead of images and project the visibilities onto the *w*=0 plane

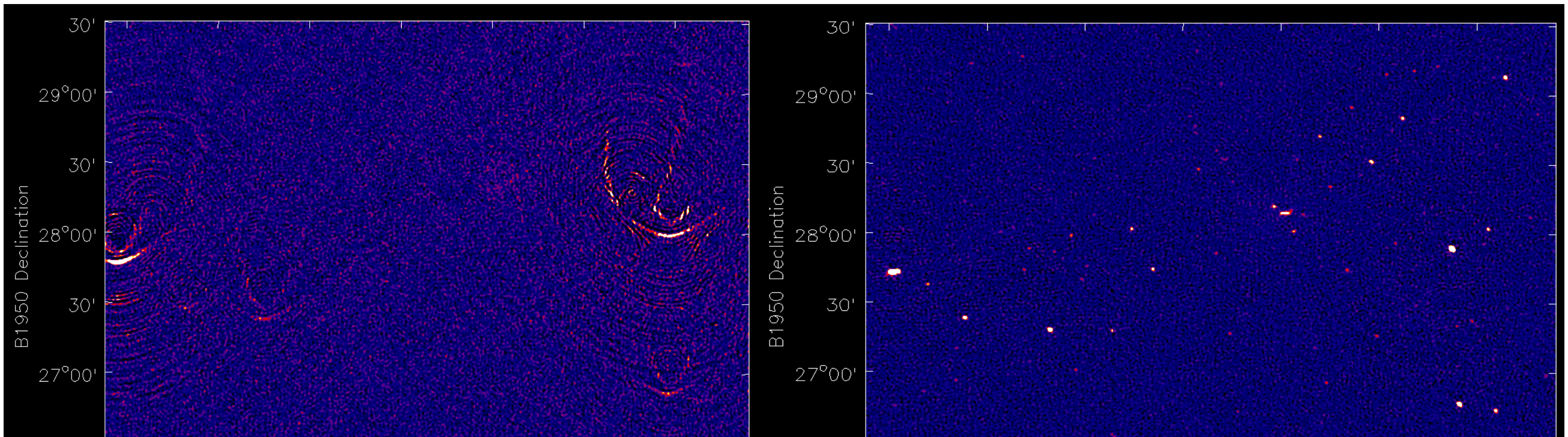
- ✓ CASA: clean – gridmode=‘widefield’, wprojplanes=#planes



Wide Field of View: *W*-Projection

Cornwell et al. (2008)

- Work with the visibilities instead of images and project the visibilities onto the w=0 plane
  - ✓ CASA: clean – gridmode=‘widefield’, wprojplanes=#planes



At low frequencies with very large field of view you would need many *w*-planes. A hybrid approach of faceting and *w*-projection is best.

Summary

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

- Low frequency interferometers are powerful and we know a lot about problems but we don't have all the tools in our calibration toolkits:
  - 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

✓ Great time to incorporate low frequencies into your research

❖ Postdoc opportunities at NRL to work on LF interferometry/ionosphere studies. Talk to me!