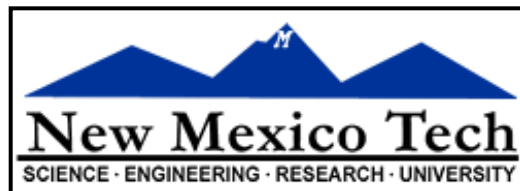
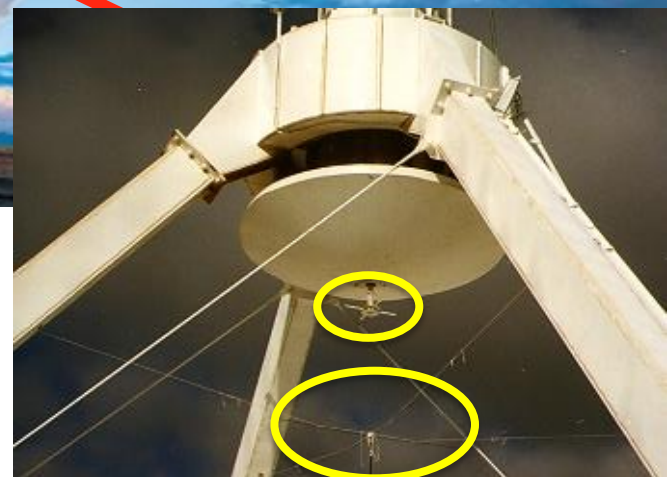


# Low Frequency Interferometry

Tracy Clarke (Naval Research Laboratory)



Fourteenth Synthesis Imaging Workshop  
2014 May 13-20

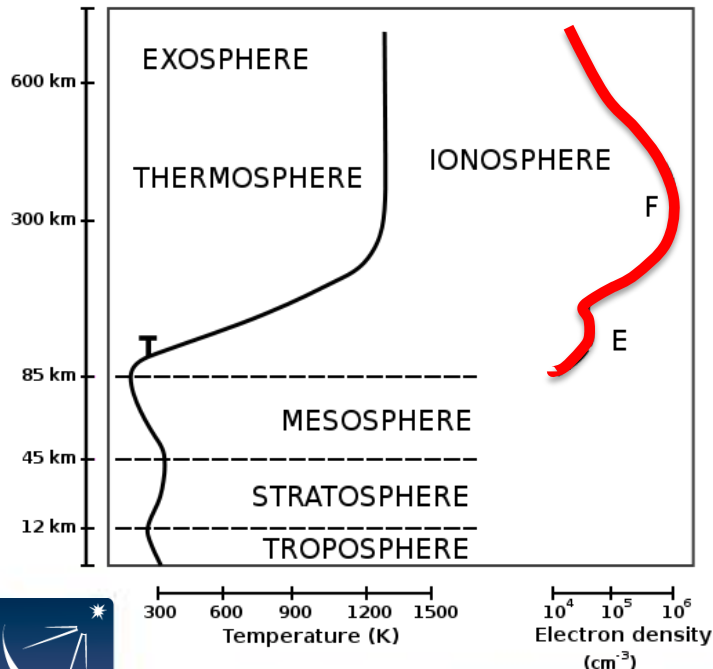


# What do we mean by Low Frequency?

## ➤ 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 ionospheric effects

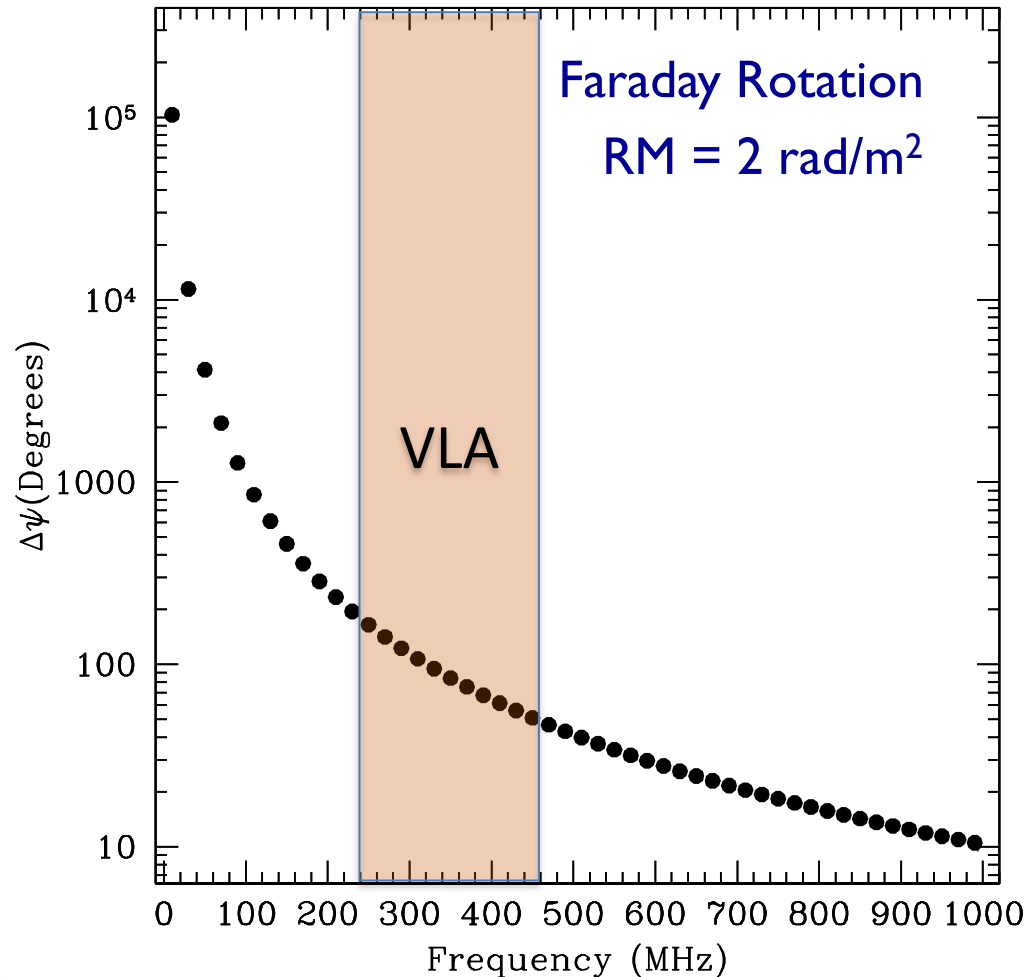


CLASS	FREQUENCY	WAVELENGTH	ENERGY
Y	300 EHz	1 pm	1.24 MeV
HX	30 EHz	10 pm	124 keV
SX	3 EHz	100 pm	12.4 keV
EUUV	300 PHz	1 nm	1.24 keV
NUV	30 PHz	10 nm	124 eV
NIR	3 PHz	100 nm	12.4 eV
MIR	300 THz	1 μm	1.24 eV
FIR	30 THz	10 μm	124 meV
EHF	3 THz	100 μm	12.4 meV
SHF	300 GHz	1 mm	1.24 meV
UHF	30 GHz	1 cm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

# Ionosphere and Radio Astronomy (Briefly)

- Ionospheric Cutoff
  - Plasma opacity
- Quiescent Ionosphere
  - Refraction
  - Faraday Rotation
- Disturbed Ionosphere
  - Scintillation
  - Image distortion
  - Rapid position shifts

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



Moellenbrock Talk

Brentjens Talk

# Outline

- LF Emission: Continuum & Line
- Brief & biased overview of LF Science
- LF Instruments: Dishes and Dipoles
- Recent LF Sky Surveys
- LF in Practice:
  - Confusion
  - Ionosphere
  - Radio Frequency Interference
  - Large Field of View (Myers Talk)
  - Wide Bandwidth (Rau Talk)
  - Polarization (Brentjens Talk)

# Low Frequency Emission

## Synchrotron Continuum:

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

## Redshifted 21cm Line:

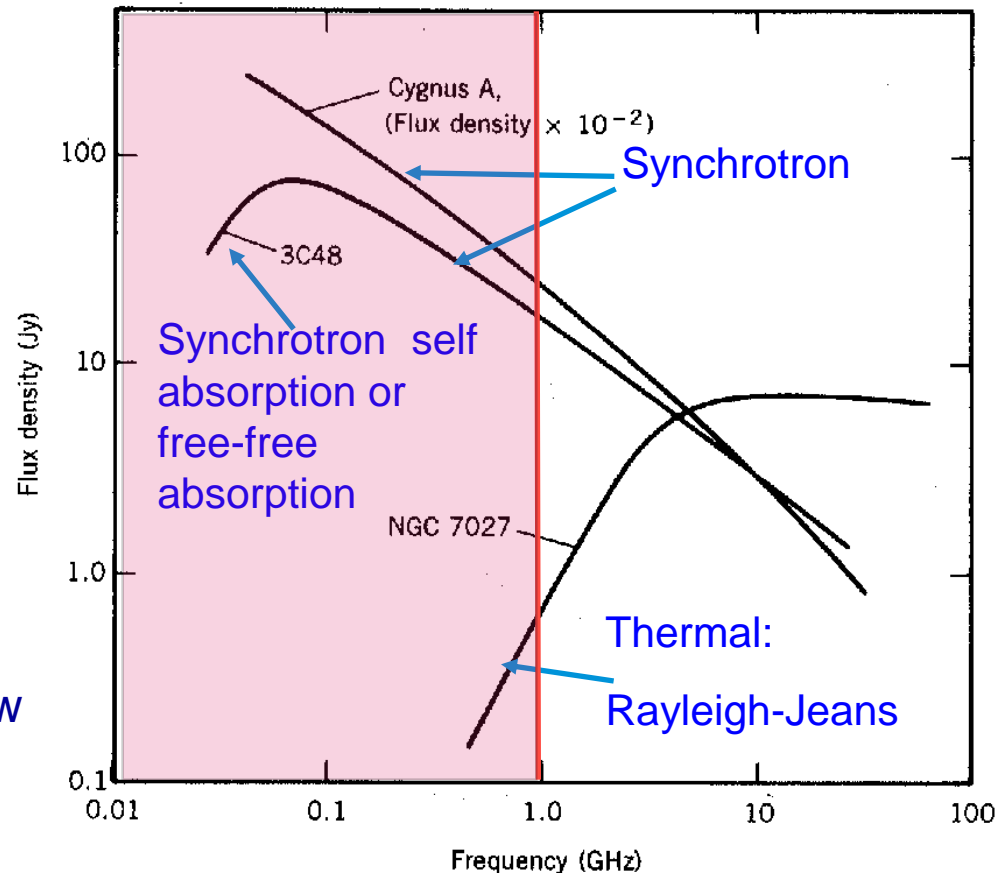
- $\nu = 1420/(1+z)$  MHz

## Radio Recombination Lines:

- Probe of ISM conditions: low temp, low density

## Bremsstrahlung: (thermal free-free):

- Best observed at  $\nu > 1$  GHz
- Acceleration of free electrons by ions



*Thompson, Moran, & Swenson*

# Low Frequency Science

## ➤ Key science drivers at low frequencies:

- Dark Ages (spin decoupling)
- Epoch of Reionization (highly redshifted 21 cm lines)
- Early Structure Formation (high  $z$  RG)
- Evolution of Dark Matter & Dark Energy (LSS & Clusters)
- Large Sky Surveys for Population Studies
- Transient Searches (including extrasolar planets)
- Galaxy Evolution (distant starburst galaxies)
- Interstellar Medium (CR, HII regions, SNR, pulsars)
- Solar System Planetary Emission
- Solar Burst Studies
- Ionospheric Studies
- Ultra High Energy Cosmic Ray Airshowers
- Serendipity (exploration of the unknown)

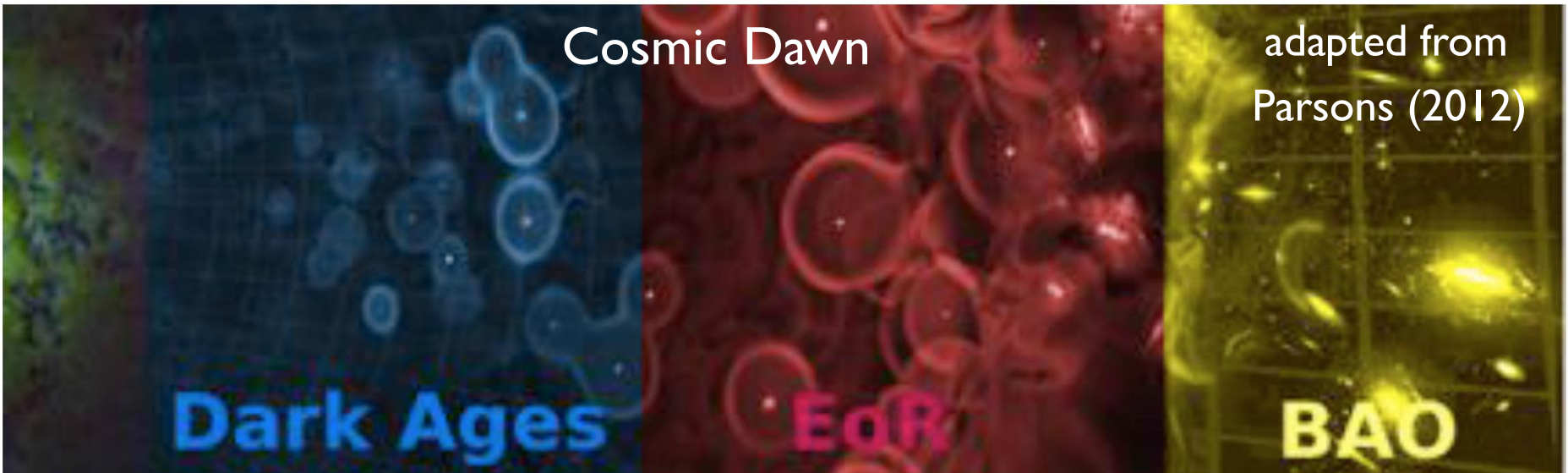


# Low Frequency Science

Neutral hydrogen  
absorbs CMB & imprints  
inhomogeneities

Hydrogen 21 cm line  
during EoR

Measure HI power  
spectrum to get  
BAO peaks vs  $z$



$z = 100$  to  $20$   
15 to 70 MHz

LEDA, HERA  
DARE

$z = 20$  to  $5$   
70 to 240 MHz

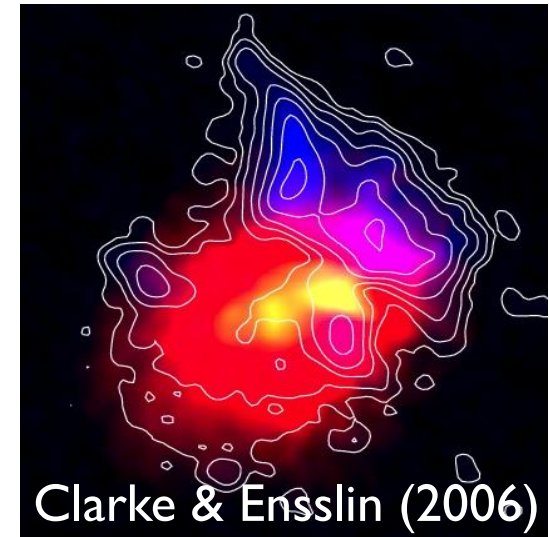
MWA, PAPER  
Edges, LOFAR,  
GMRT, 21CMA

$z = 5$  to  $0$   
240 to 1400 MHz

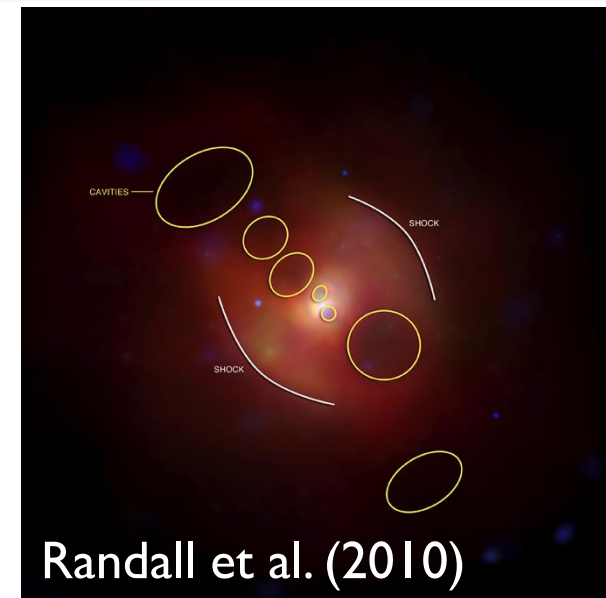
GBT, CHIME

# Low Frequency Science

- LSS forms in a cosmic web with galaxy clusters at nodes. Structure growth drives shocks and turbulence generating relics and halos
- Study of plasma microphysics, dark matter and dark energy
- Emission is steep spectrum and best traced at low frequencies



- Supermassive black-hole driven AGN feedback in clusters can offset catastrophic cooling and limit the size of the host galaxy
- Low Frequencies trace older outbursts as they are sensitive to particles which have undergone significant aging

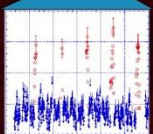
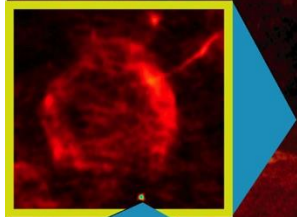




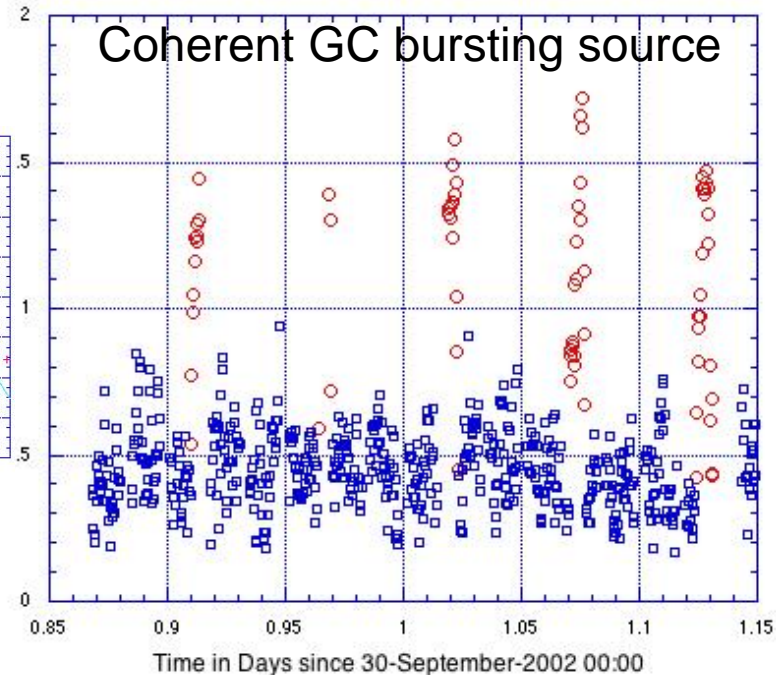
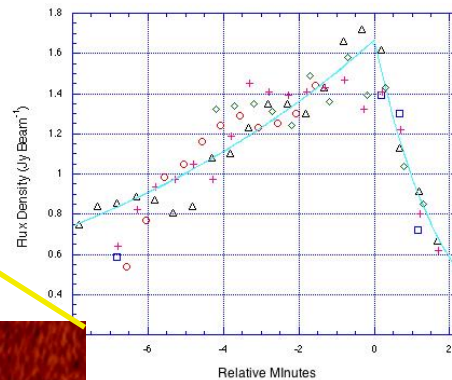
# Transients: Galactic Center

- Transients: wide fields at low frequencies provide powerful opportunity to search for new transient sources - VLITE
- Candidate coherent emission transient discovered near Galactic center

GCRT J1745-3009  
~10 minute bursts  
every 77 minutes –  
timescale implies  
**coherent** emission



Lang et al. (1999)



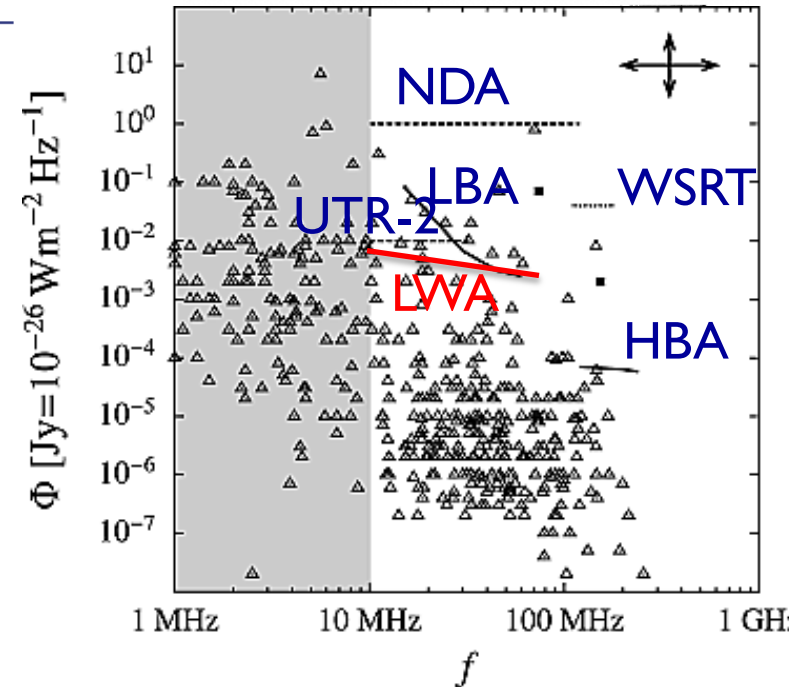
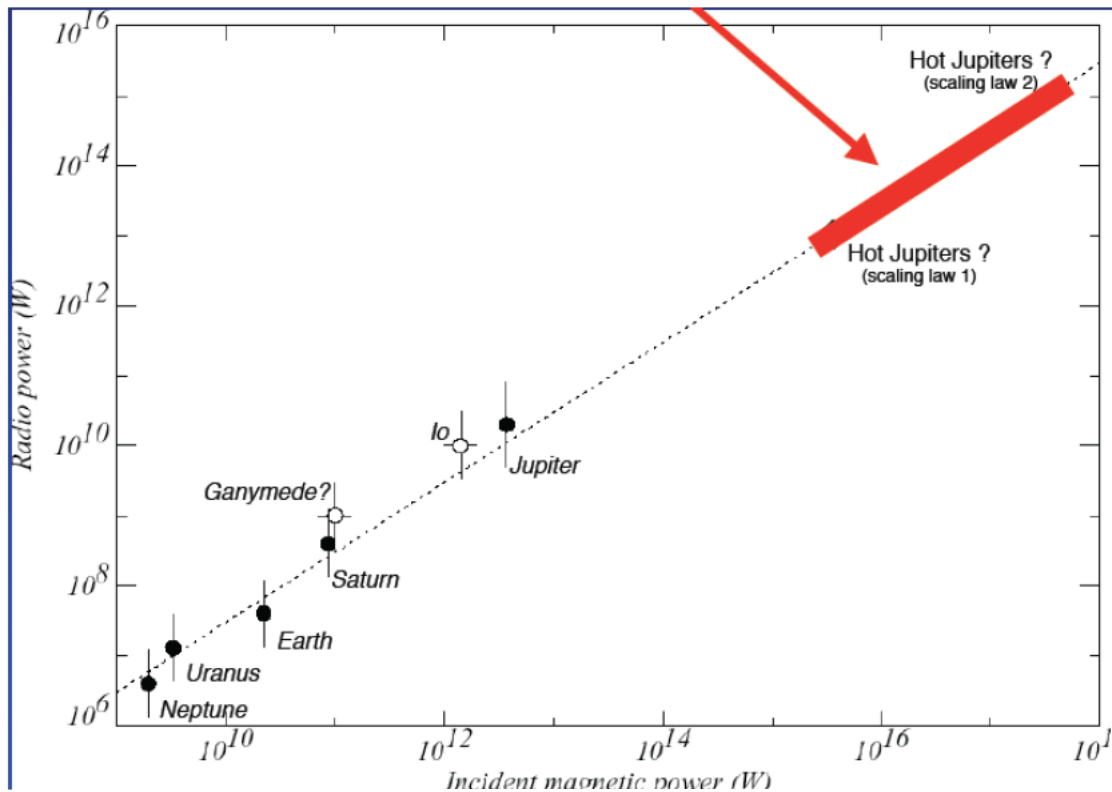
Hyman, et al., (2005) - Nature;  
Hyman et al. (2006, 2007)



# Jupiter and Extrasolar Planets

- Jupiter's coherent cyclotron emission: complex interaction of Jupiter's magnetosphere with Io torus
- Future instruments will resolve Jupiter and may detect extra-solar planets

POSSIBLE TO  
DETECT BURST  
EMISSION  
FROM DISTANT  
"JUPITERS"



Grißmeier et al. (2011)

Adapted from Zarka et al. (2001)

# 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	range (MHz)	Resolution (arcsec)	FoV (arcmin)	Sensitivity (mJy)
Dishes	VLA	NM	73.8-330	24-5	700-150	20-0.2
	GMRT	IN	151-610	20-5	186-43	1.5-0.02
	WSRT	NL	115-615	160-30	480-84	5.0-0.15
	...					
Dipoles	LOFAR-Low	NL	10-90	40-8	1089-220	110-12
	LOFAR-Hi	NL	110-250	5-3	272-136	0.41-0.46
	LWA I	NM	10-88		600-180	1000
	MWA	WAu	80-300	180-60	1482-1162	10
	.....					

Note: Table numbers are not apples-apples comparison!

# Low Frequency Receivers: VLA



- VLA low band (dish + dipole) system transitioned to wide-bandwidth (2013)
- Replaces narrow band receivers but still using legacy feeds:
  - **P band: 240 – 470 MHz**
  - 4 band: 50 – 86 MHz
- New 4 band feed design being tested by NRAO for continuous deployment





# Low Frequency Receivers: GMRT

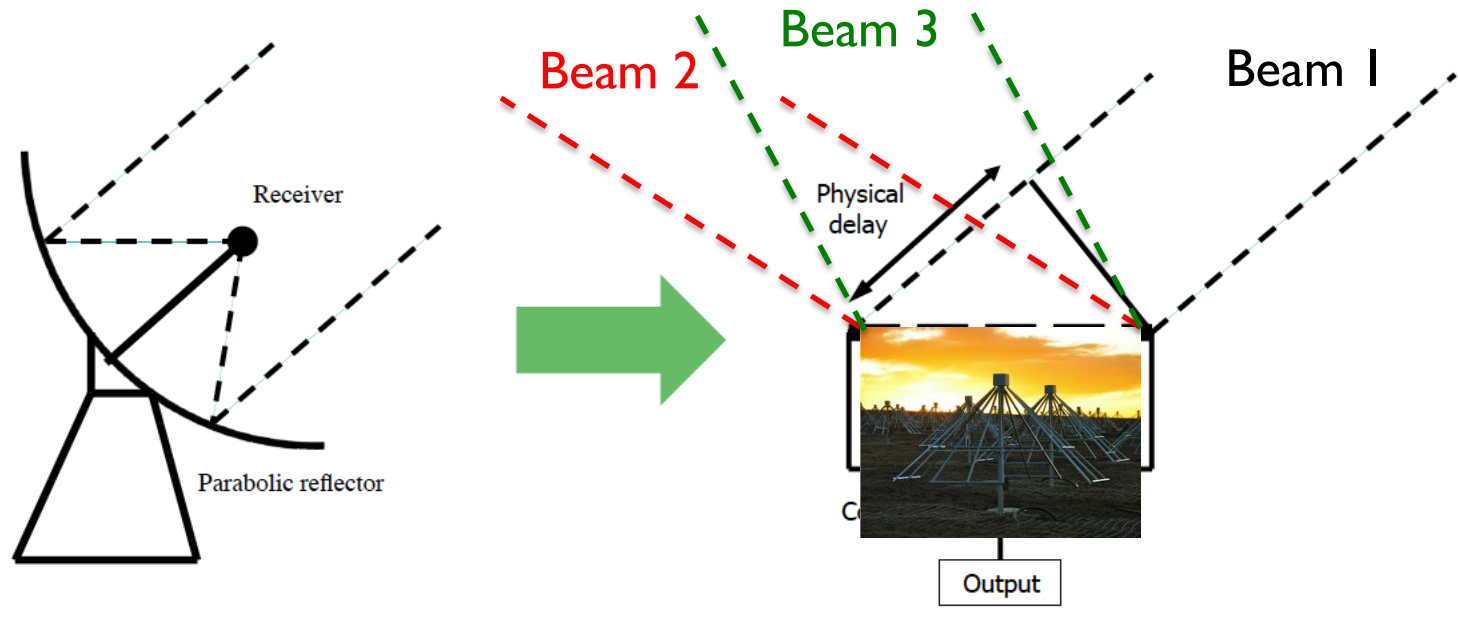
- Giant Metrewave Radio Telescope feeds located at prime focus on a rotating turret + 50 MHz feeds on support legs
  - 150 MHz
  - 235/610 MHz: dual band on same face of turret,
  - 330 MHz
  - 610 MHz
- GMRT wide-band upgrade: 50-1500 MHz with 400 MHz instantaneous BW





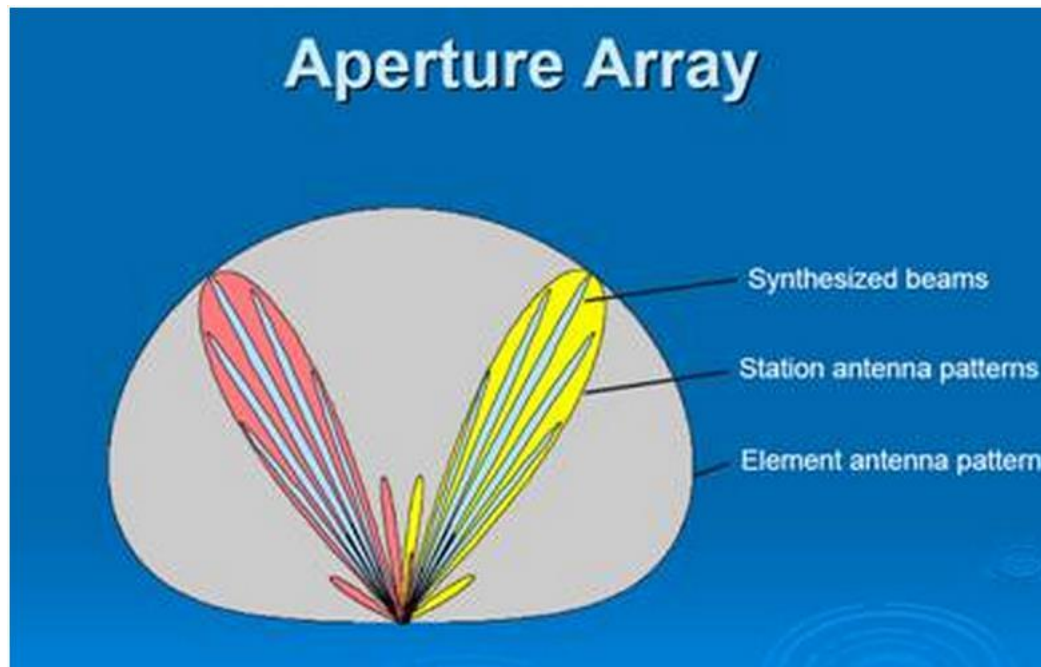
# Re-Energizing Low Frequencies: Dipole Arrays

- 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!



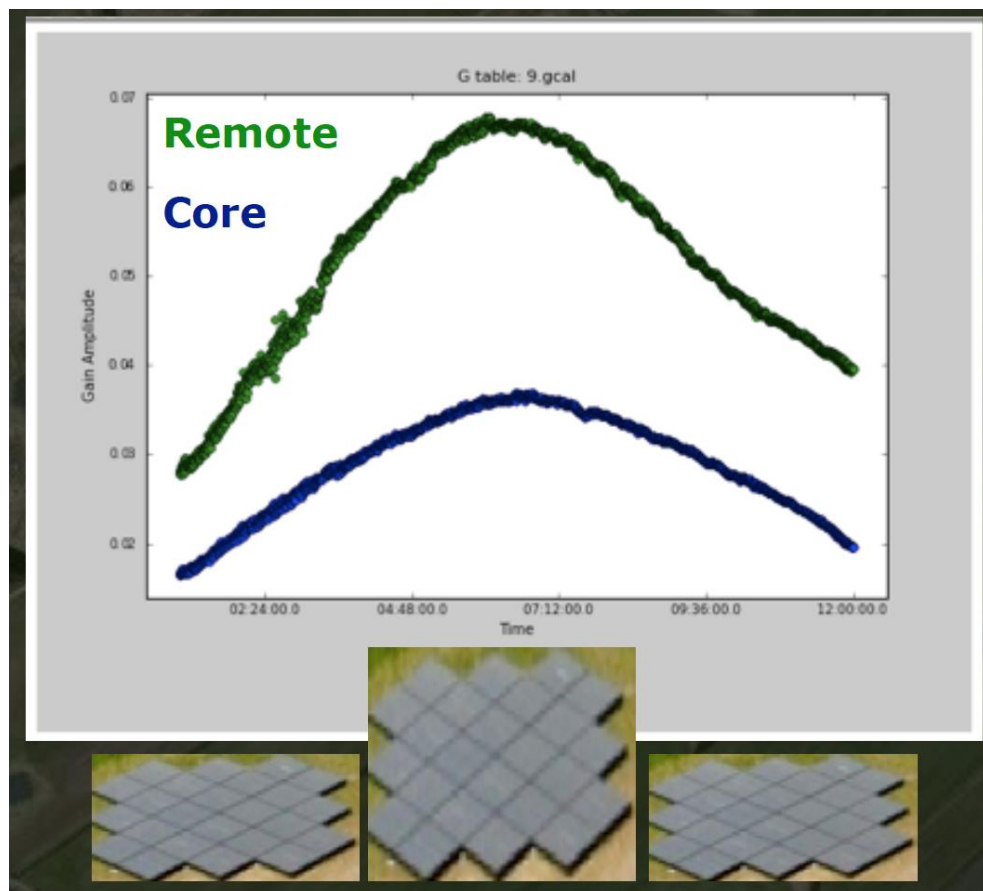
# Dipole Array Beams

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



# Dipoles: Changing Gain with Time

- dipoles see the entire sky
- projected area of dipole station changes with zenith angle, result is a gain change with time
- different parts of a large instrument can have different area so different gain change with time: e.g. LOFAR core and remote stations

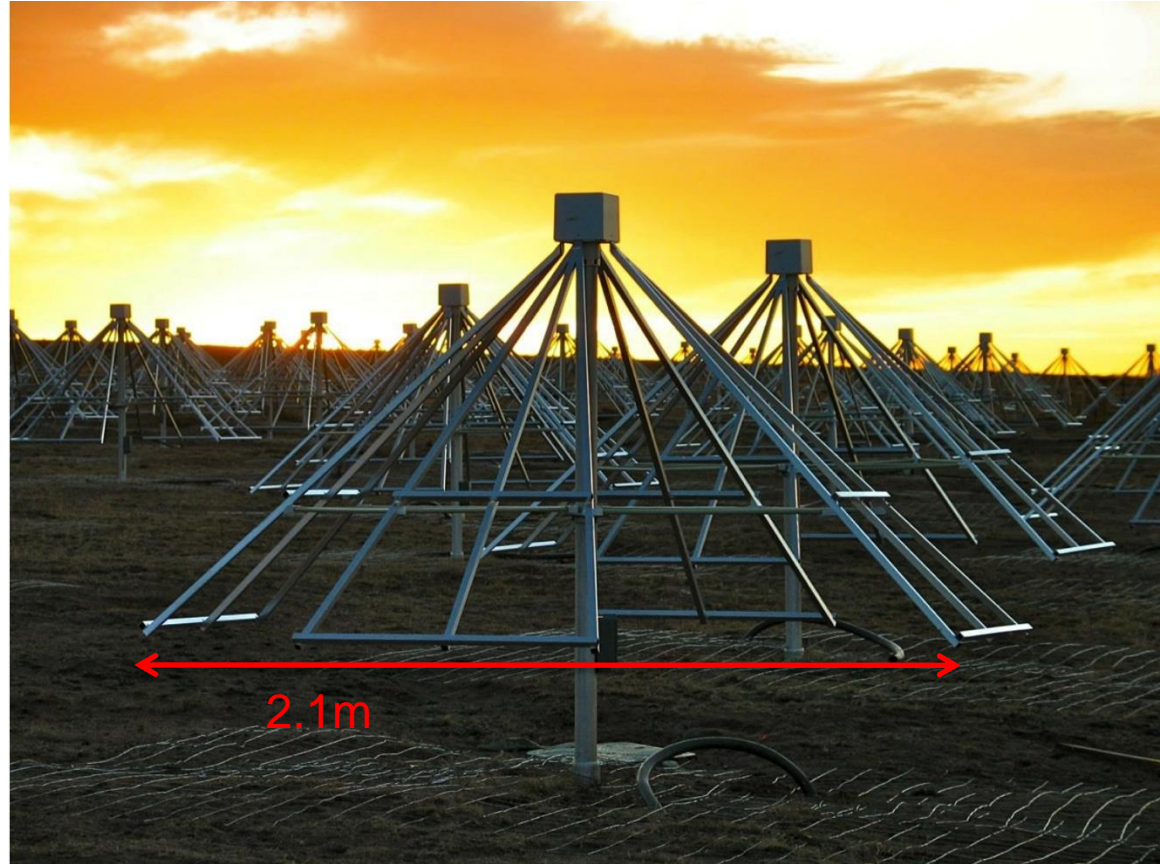


McKean (2013)

# Low Frequency Receivers: LWA I

## ➤ LWA1

- Long Wavelength Array Station 1
- 256 dipoles in 100x110m station
- Operates 10-88 MHz
- 4 simultaneous beams with two tunings + dual orthogonal polz.
- All-sky buffers
- Range of science
- open access facility (CfP5 due Aug 15, 2014)
- <http://www.phys.unm.edu/~lwa/index.html>

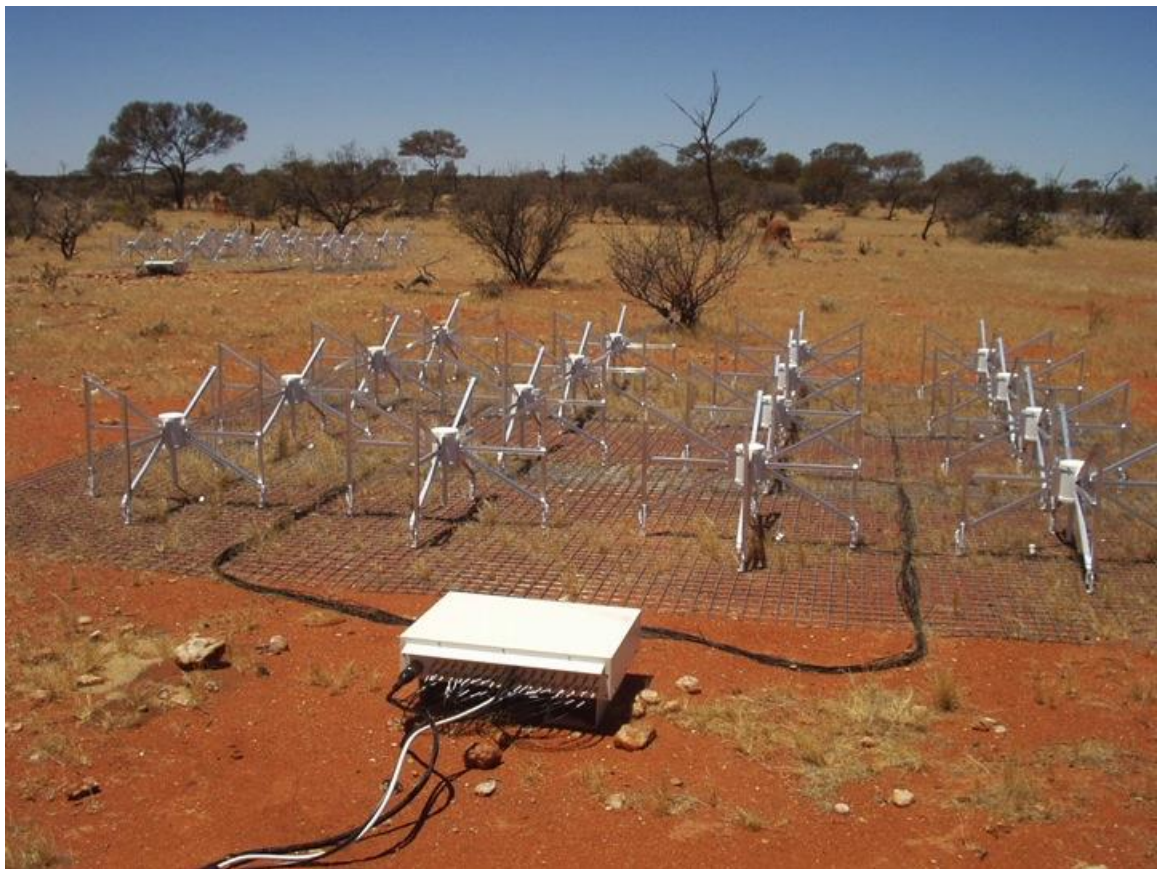




# Low Frequency Receivers: MWA

## ➤ MWA

- Murchison Wide-field Array
- 80-300 MHz, BW=31 MHz
- bowtie geometry
- 128 tiles of 16 dipoles
- tiling increases  $A_e$  ( $\sim 20 \text{ m}^2$ )
- EOR, SNR, transients, Solar and space weather
- complicated beam pattern
- [mwatelescope.org](http://mwatelescope.org)





# Low Frequency Receivers: LOFAR

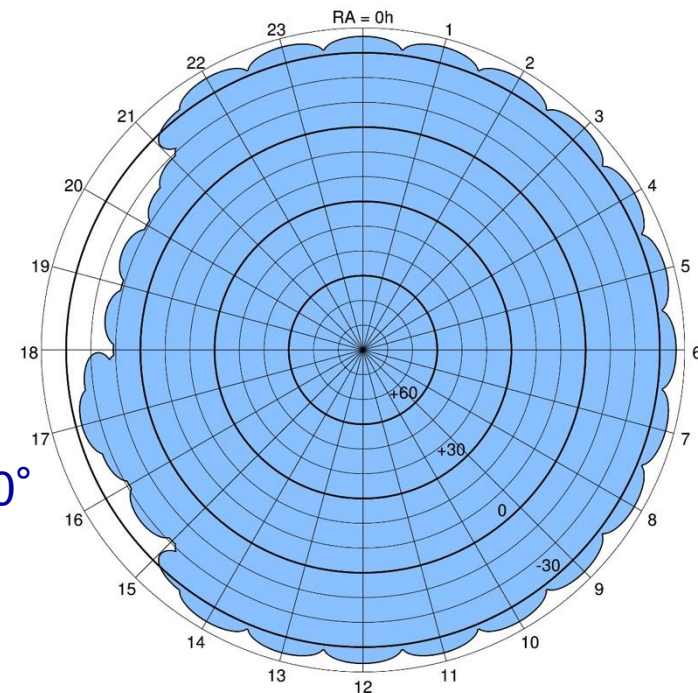
## ➤ LOFAR

- Low Frequency Array
- Low band: 30-90 MHz
- High band: 110-240 MHz
- 8 beams per station
- Core, remote and international stations
- EOR, surveys, transients, CRs, Solar and Space Weather, magnetism
- <http://www.astron.nl/lofar-telescope/lofar-telescope>
- Van Haarlem et al. (2013)



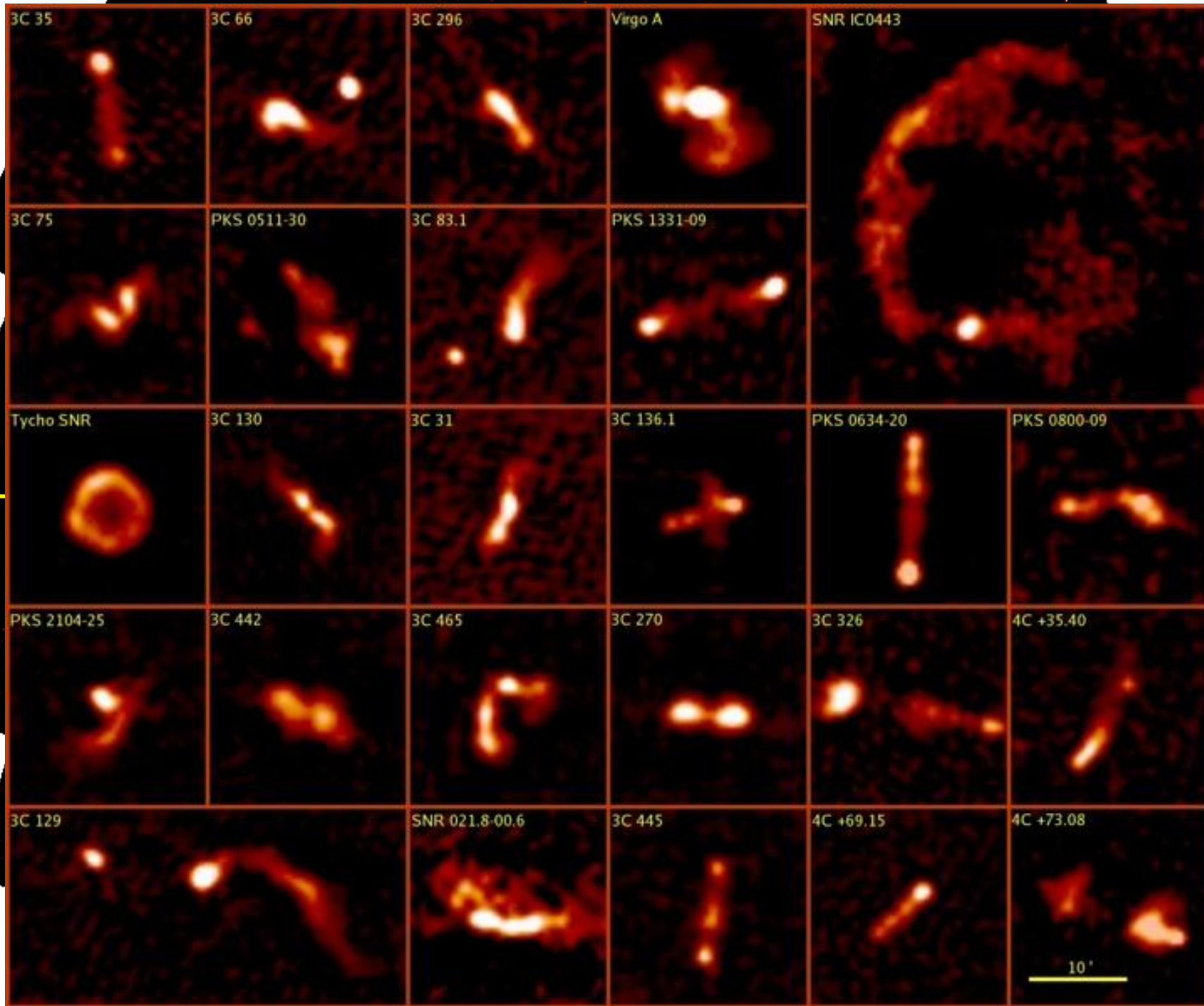
# VLA Low Frequency Sky Survey Redux: VLSSr

- Survey Parameters:  $\Delta\nu = 74$  MHz,  $\delta_{\text{min}} > -30^\circ$ ,  
 $\theta = 75''$  resolution,  $\sigma \sim 100$  mJy/beam
- Status: completed, re-released
- Reprocessed with new RFI excision software,  
original survey as ionospheric model,  
improved primary beam
- Final catalog:  $N \sim 92\,964$  sces in  $\sim 95\%$  of sky  $\delta_{\text{min}} > -30^\circ$   
Statistically useful samples of sources  
=> fast pulsars, distant radio galaxies, cluster radio  
halos and relics, unbiased view of parent  
populations for unification models
- Important calibration grid for VLA, GMRT, LOFAR, etc
- Data online at NRAO VLSSr server



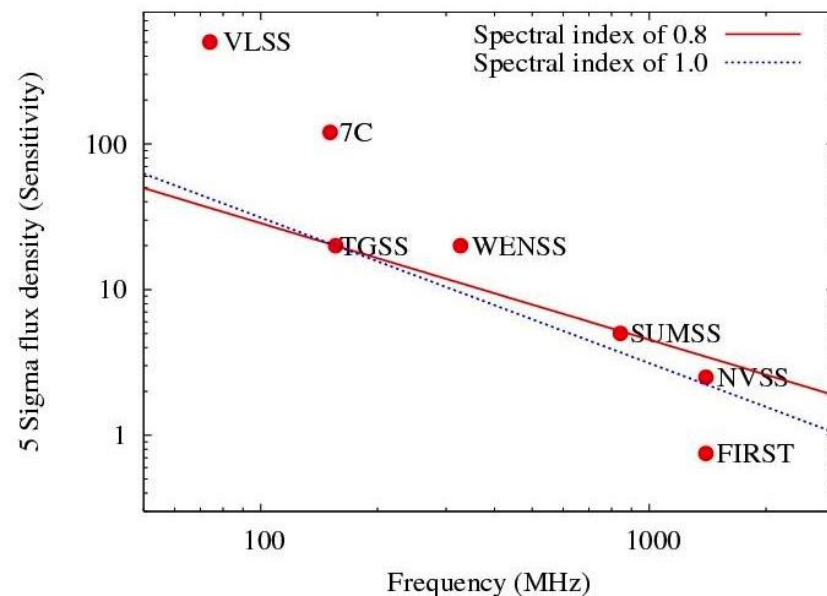
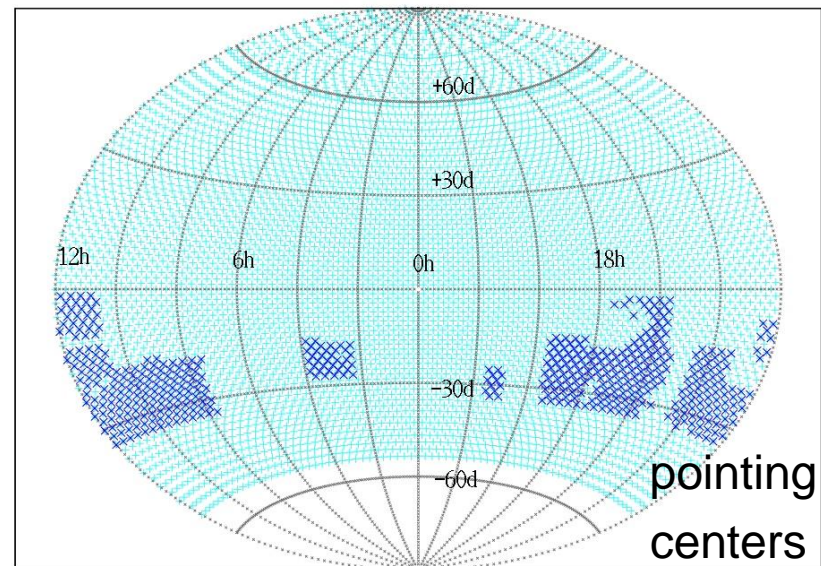
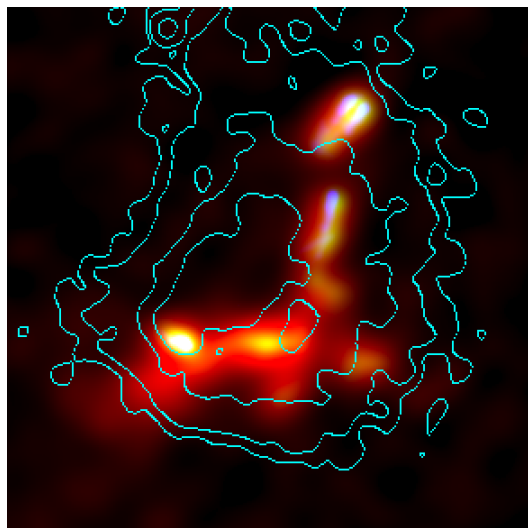
Lane et al. (2012, 2014)





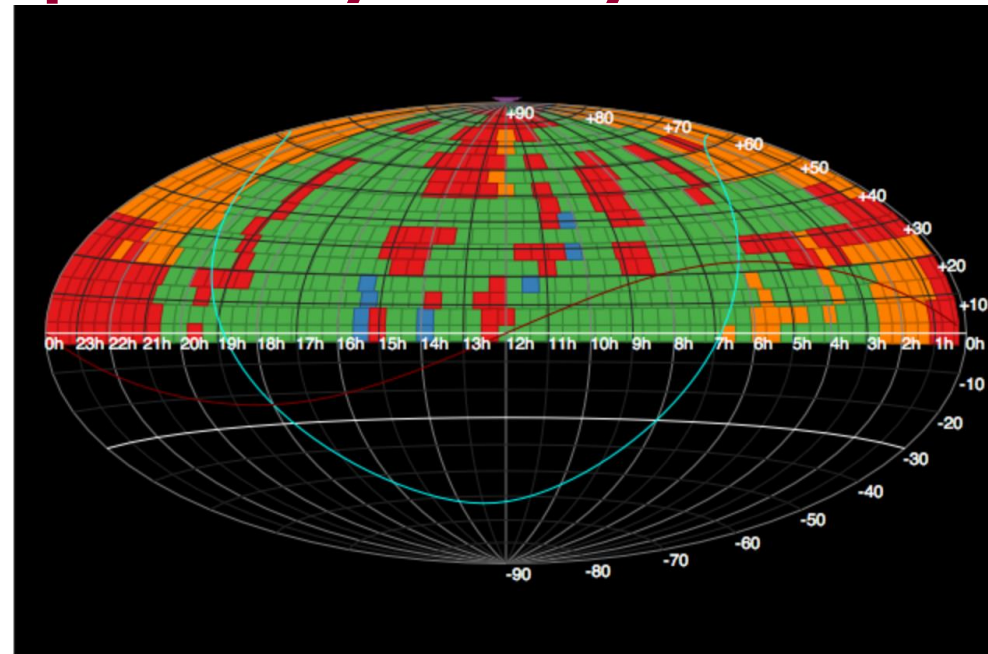
# TIFR GMRT Sky Survey: TGSS

- 150 MHz survey of  $\delta > -55^\circ$
- Status: in progress
- survey parameters:
  - $\theta = 20''$ ,  $\sigma \sim 10$  mJy/beam
- enhances low-freq. calibration grid
- data online at <http://tgss.ncra.tifr.res.in/150MHz/>



# LOFAR Multifrequency Snapshot Sky Survey: MSSS

- Covers 20,000 deg<sup>2</sup>
- LBA:  $\sigma < 15$  mJy,  $\theta \sim 100''$
- HBA:  $\sigma < 5$  mJy,  $\theta \sim 120''$
- Status: in progress
- data online at <http://msss.astron.nl>



Hammer Projection

Map based on code from [this project](#).

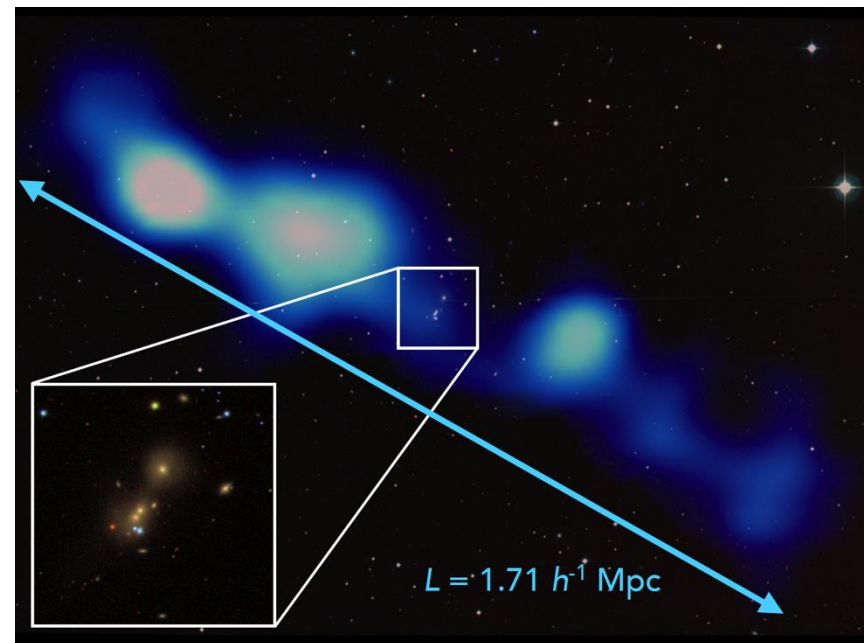
Data archived (57.0%)

Data available on CEP (0.2%)

Partial data available (1.4%)

Data missing or invalid (23.0%)

Not yet observed (18.5%)



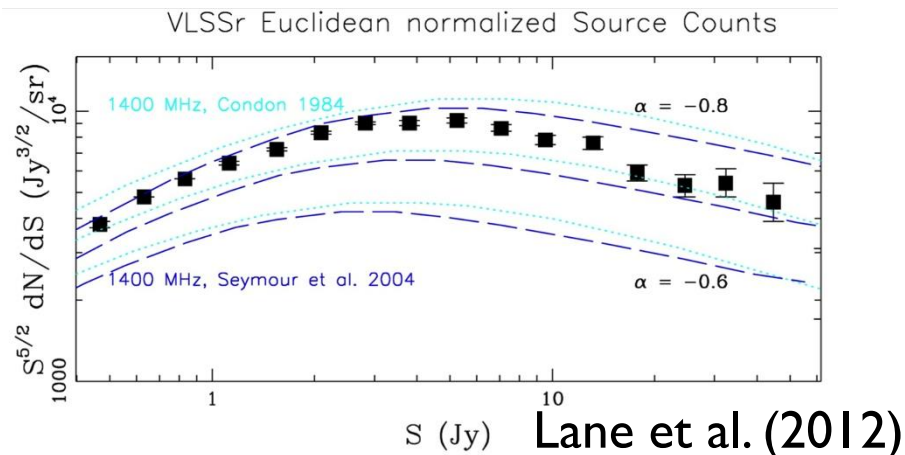


# Low Frequency Interferometry In Practice:

- Confusion: source blending at lower resolutions – need long baselines to overcome confusion
- Ionosphere: single self-cal. phase correction per FoV often fail at LF
  - Quiescent*: Refraction, Faraday Rotation
  - Disturbed*: Scintillation, Image Distortion, Position Shifts
- Radio Frequency Interference:
  - Severe at low frequencies
- Large Fields of View: (Myers Talk)
  - Non-coplanar array ( $u, v$ , &  $w$ )
  - Dipoles see entire sky: Demixing for A-team with LOFAR*
- Wide Bandwidth: (Rau Talk)
- Polarization: (Brentjens Talk, Moellenbrock Talk)

# Confusion: Need Long Baselines

➤ source counts rise to mJy level

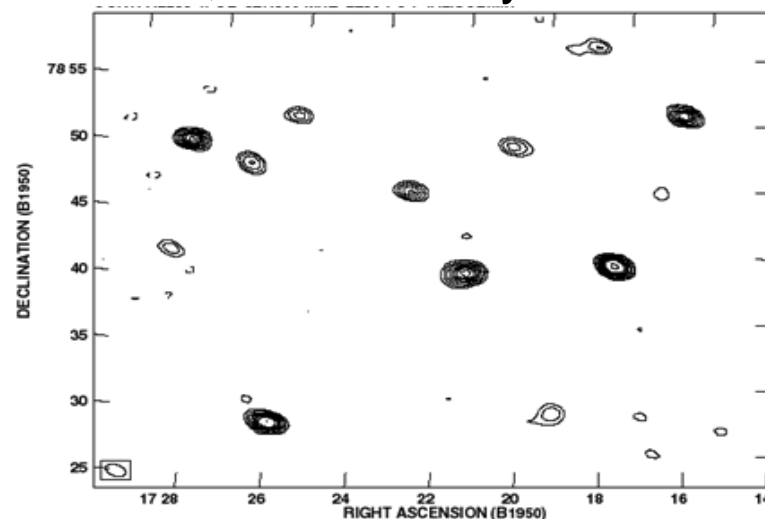


➤ for any angular resolution  $\theta$

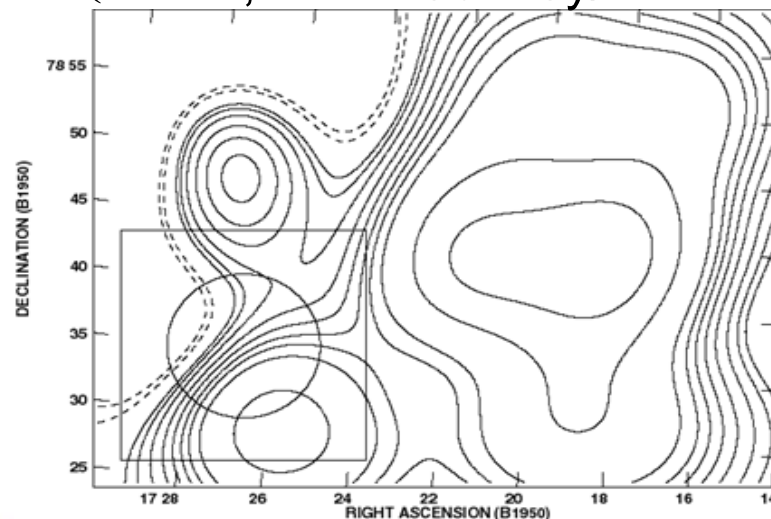
- there is a confusion limit
- individual weak sources blend
- the resulting sky noise may exceed thermal noise
- such cases are “confusion limited”



$\sim 1'$ , rms  $\sim 3$  mJy/beam

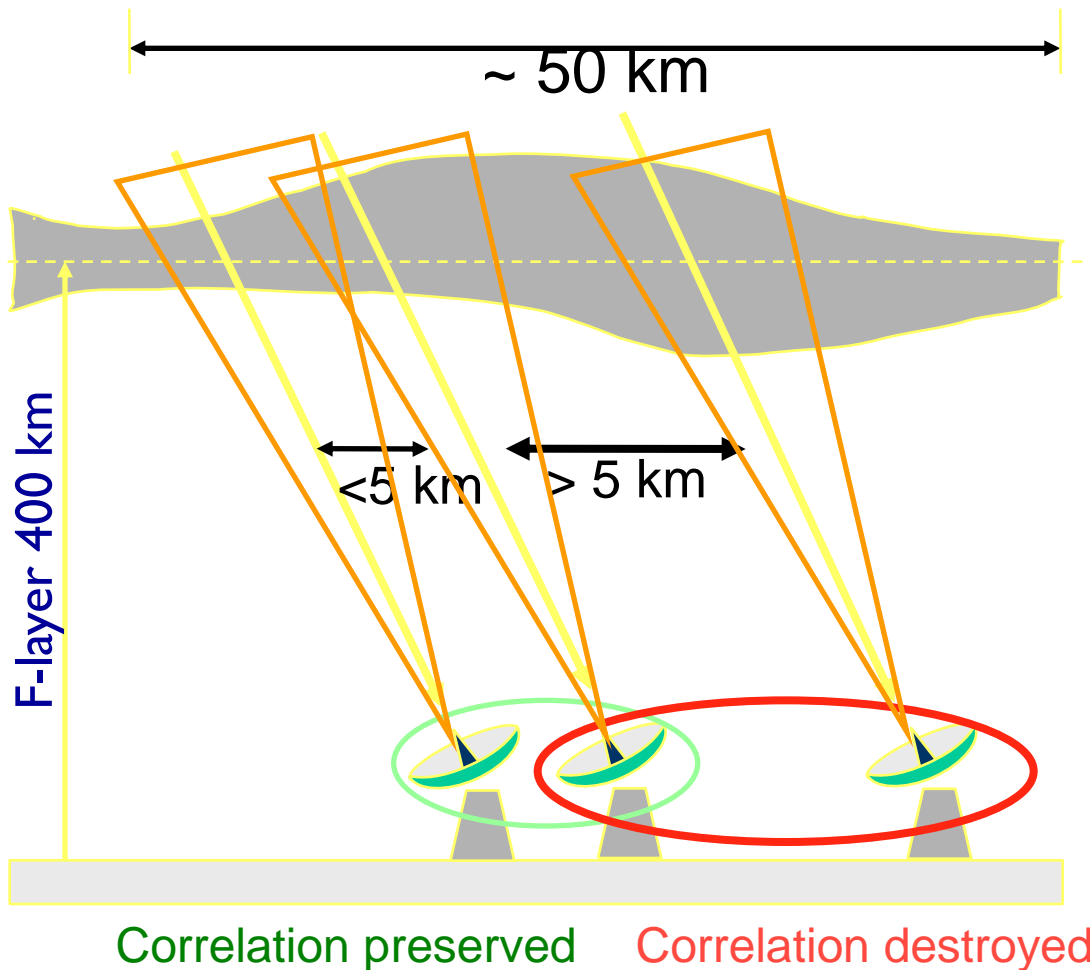


$\sim 10'$ , rms  $\sim 30$  mJy/beam



# Ionosphere

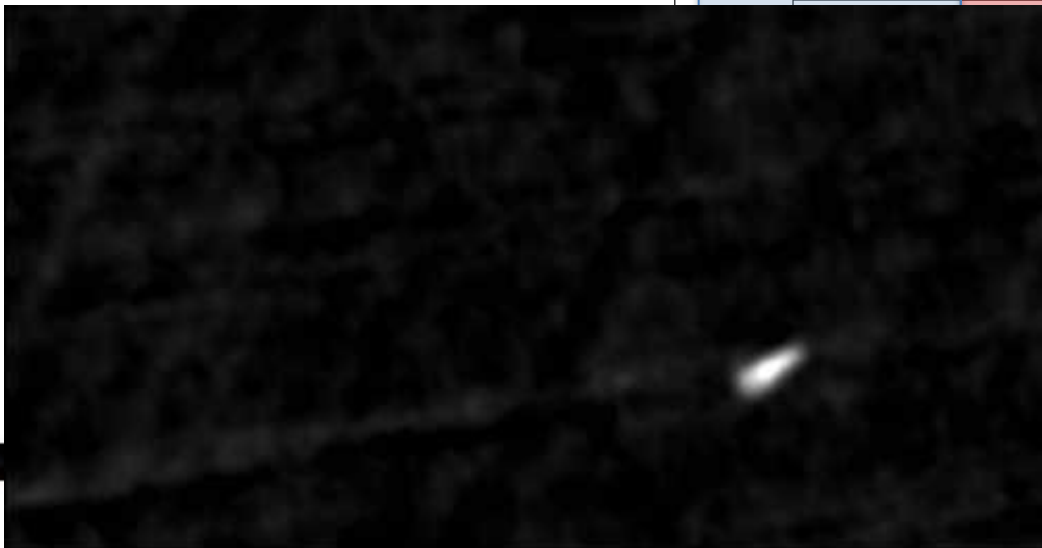
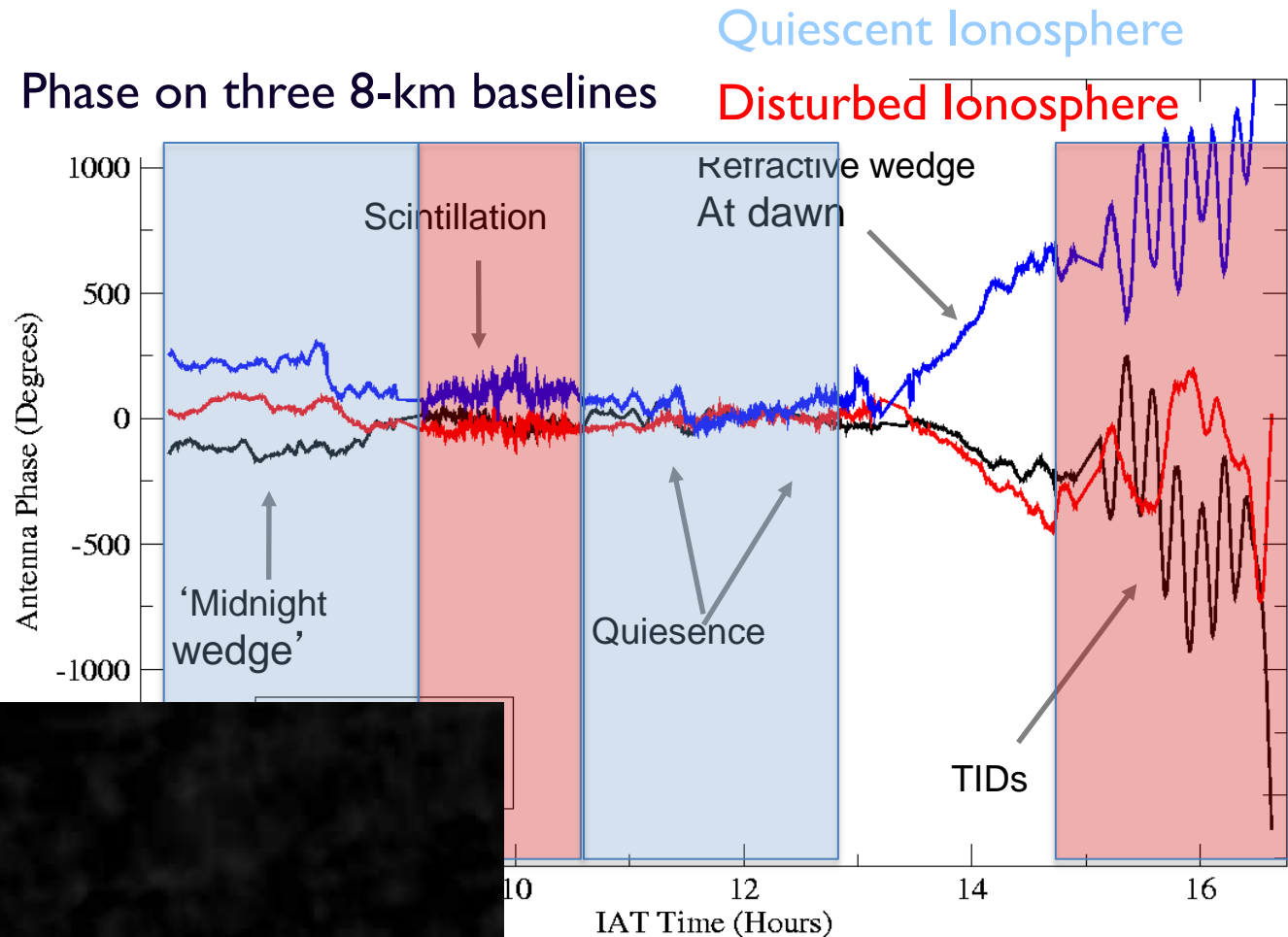
- Ionosphere introduces phase errors in radio signal



- Waves in the ionosphere introduce rapid phase variations ( $\sim 1^\circ$  /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



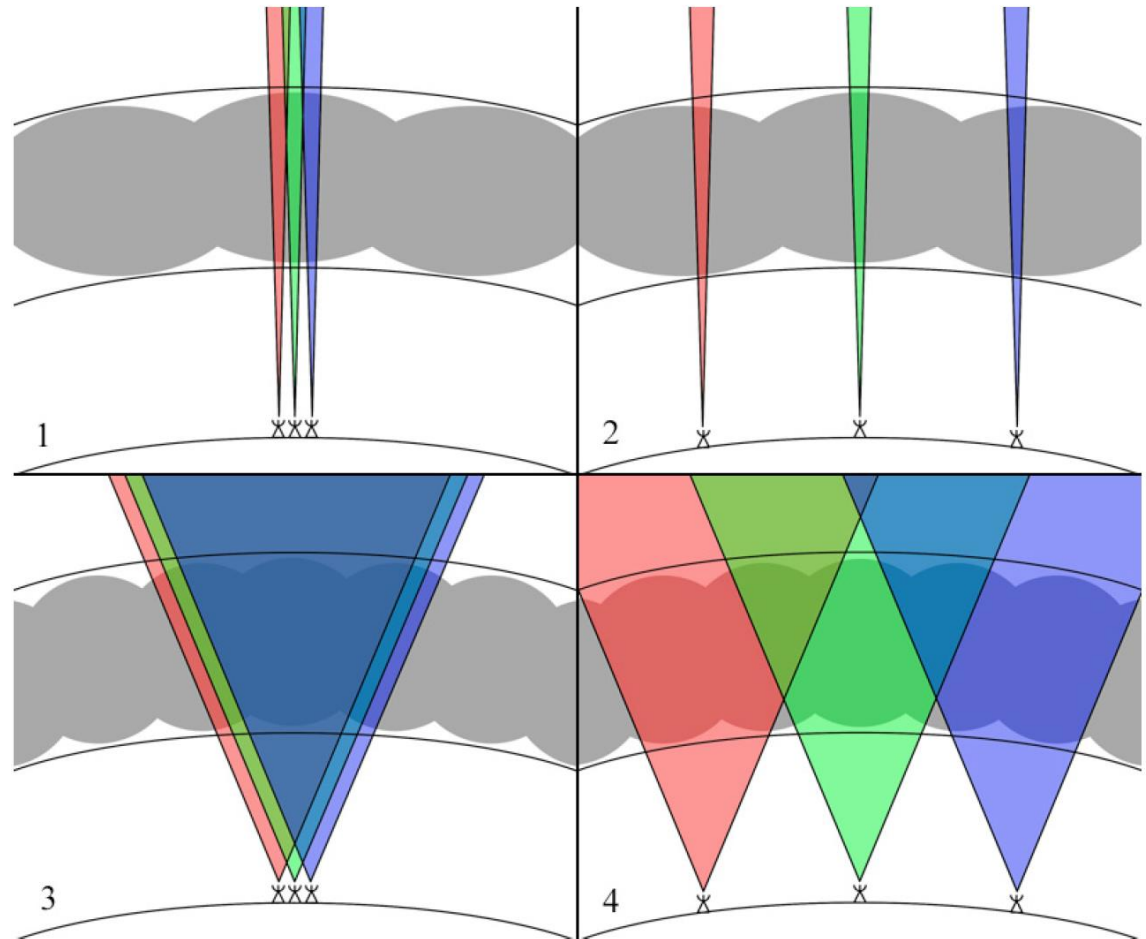
# Ionosphere in Practice: What Regime?

- Lonsdale (2005) identified different calibration regimes for ionosphere

- Regimes 1 & 2  
ionospheric phase  
error has no FoV  
variation – self cal OK

- Regimes 3 & 4 have  
varying phase over  
FoV – need direction  
dependent algorithms

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

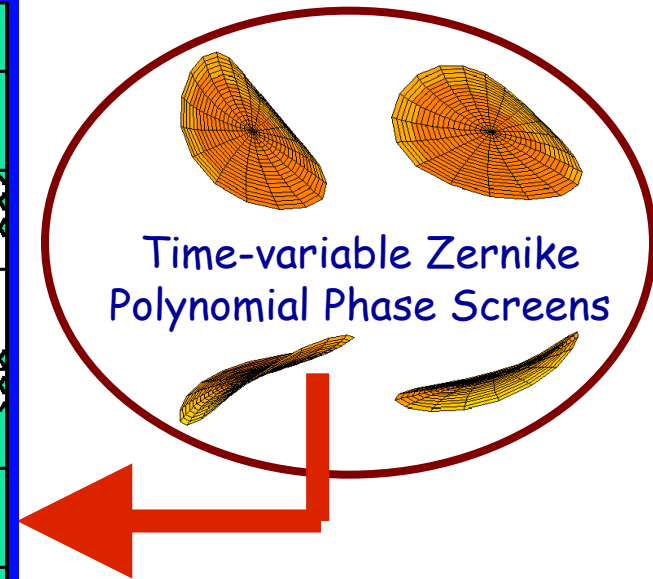
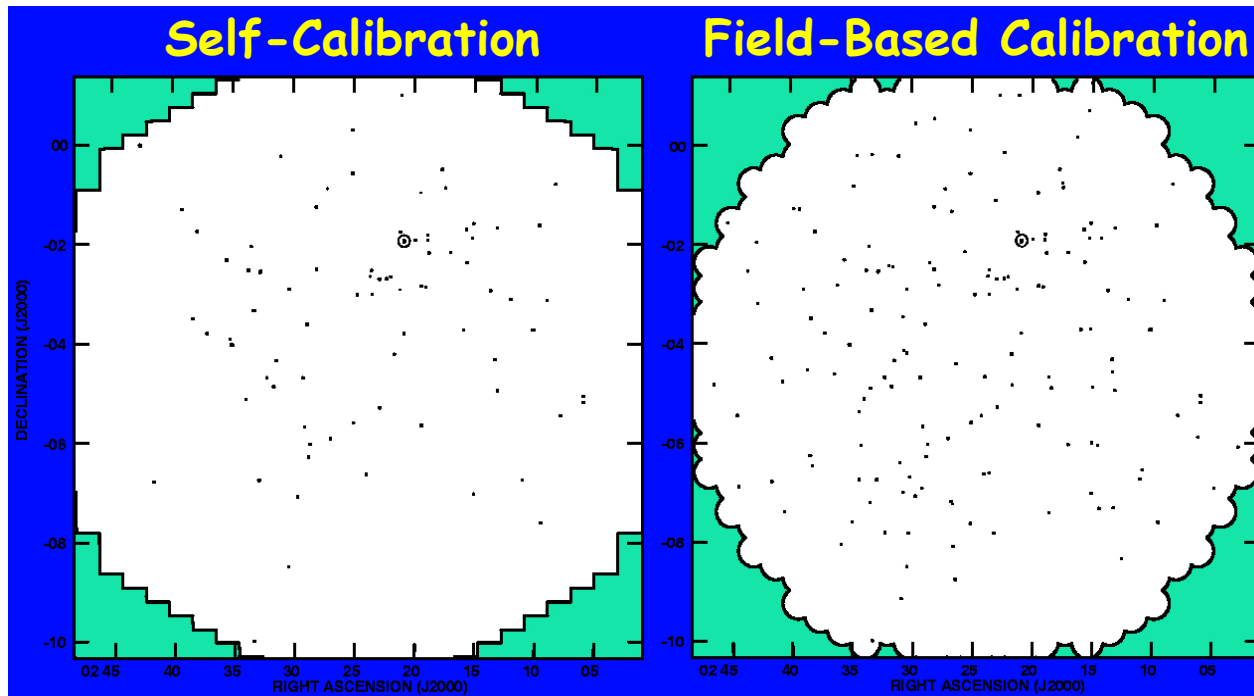


Intema et al. (2009)



# Ionosphere: Field-Based Calibration

- Compare bright sources to sky model positions (5-10 sources per FoV)
- Fit phase delay screen (Zernike polynomial) & apply to correct image



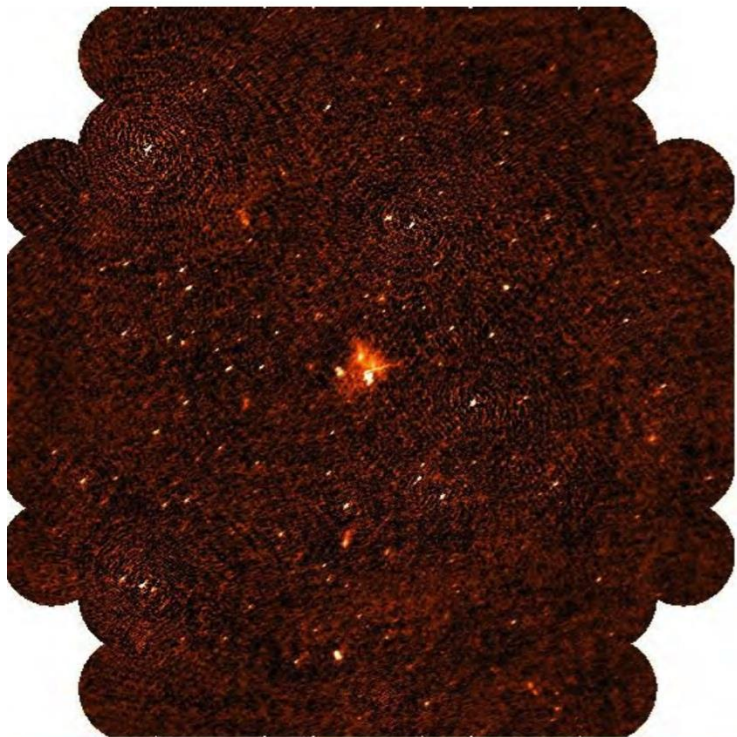
Average positional error decreased from  $\sim 45''$  to  $17''$

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

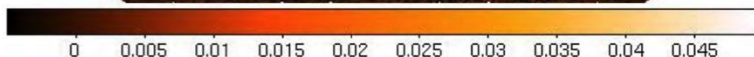
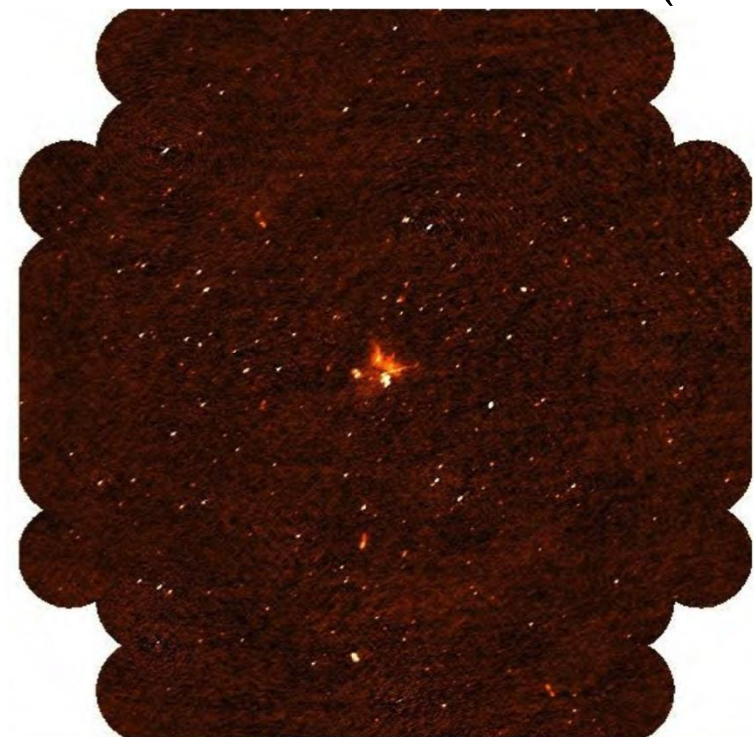
# Ionosphere: SPAM

- 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)



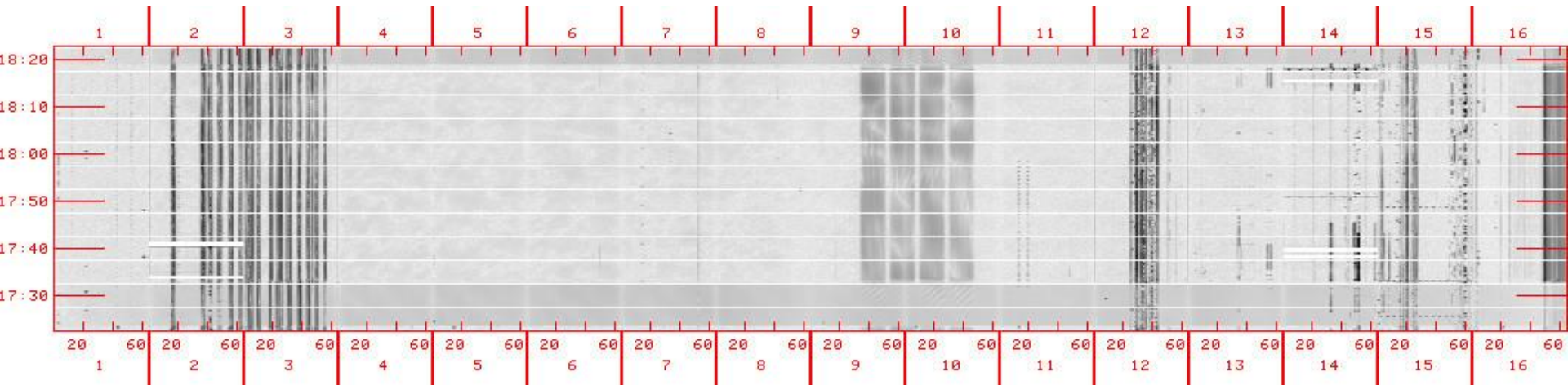
Self-calibration



SPAM calibration

# Radio Frequency Interference: RFI

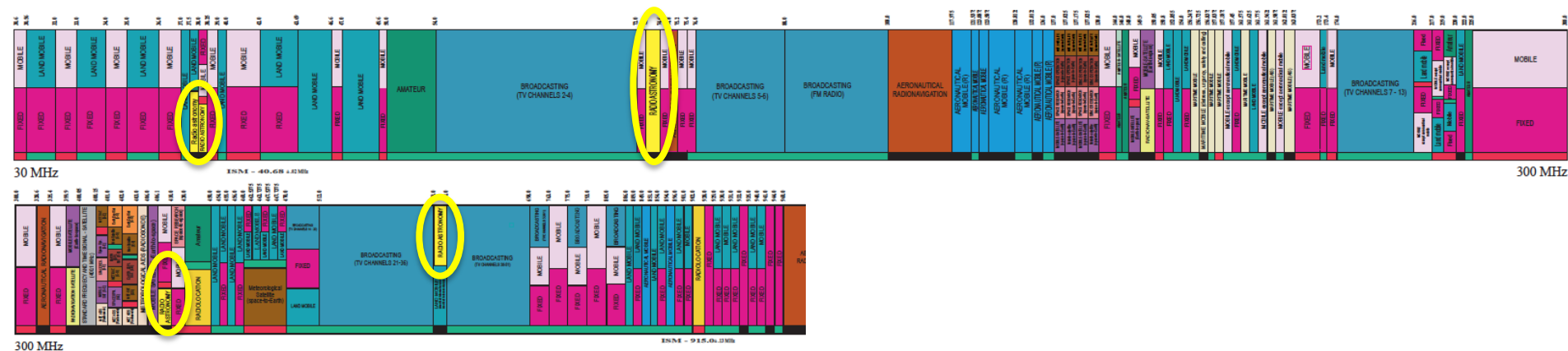
- Natural & man-generated RFI are at best a nuisance



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

# When do you deal with RFI?

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



- 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)

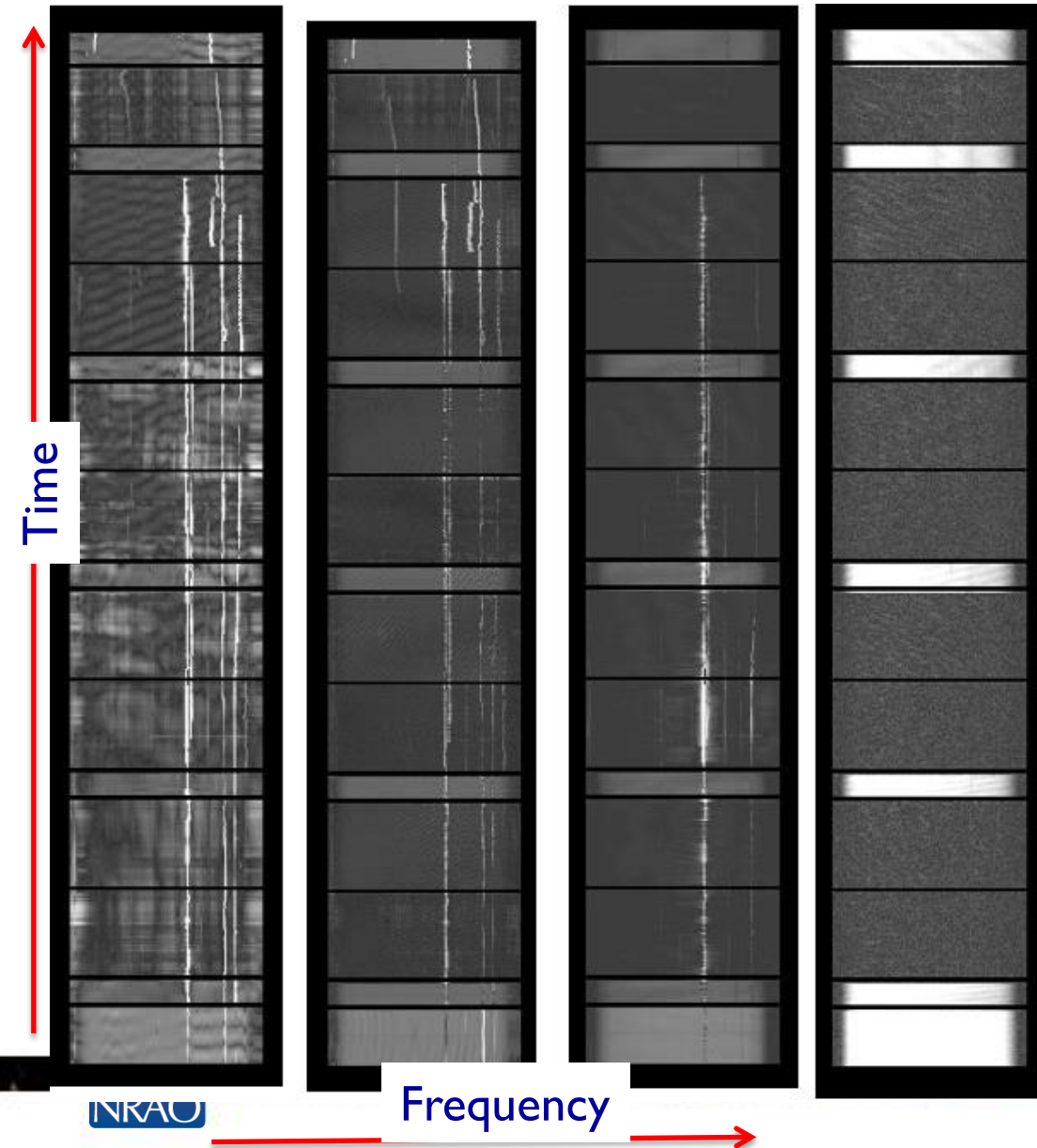


# RFI In Practice: Options! Options! Options!

- AIPS: RFLAG, FLAGR, EDITA, FLGIT, SPFLG, CLIP, WIPER, UVLIN, ...
- CASA: flagdata (manual, clip, tfcrop, rflag, ...), plotms (by hand), ...
- Obit: AutoFlag, MednFlag, SrvrEdt, RFIFilt, UVFlag, ...
- RfiX, UVRFI: Fringe stopping to separate celestial and terrestrial signals
- AOFlagger: Generalized tool using Offringa et al. (2010, 2012) techniques
- RFI Nulling: adaptively place beam nulls on RFI
- General Notes:
  - ✓ RFI is generally circularly polarized – Look at Stokes V!
  - ✓ Collapse data to a single channel so low level RFI adds up
  - ✓ Look at image residuals for lower-level RFI
  - ✓ Image analysis of errors (**talk by Taylor**)

# RFI Examples

Short baseline  Long baseline



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

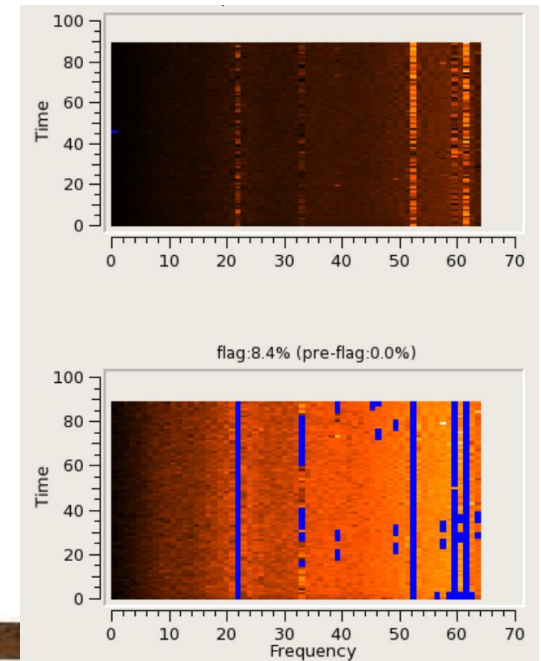
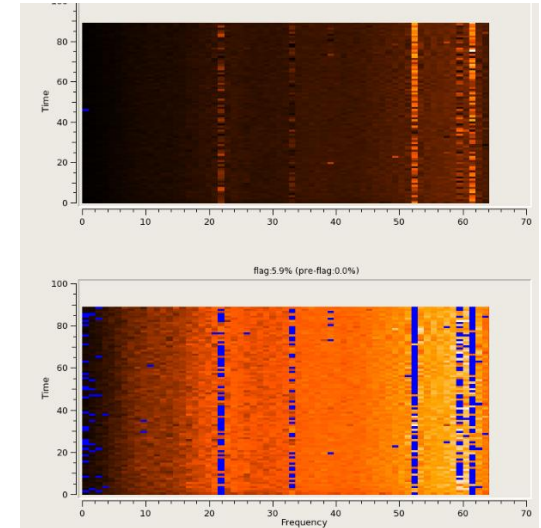
# RFI Excision: AIPS

- TVFLG: manual flagging visual of time vs baseline cycle channels
- SPFLG: manual flagging visual of time vs channels cycle baselines
- WIPER: visual diagnostic tool
- UVFLG: manual command-line flagging
- EDITA: manual flagging visual to flag on antenna gains, Tsys or SysPower
- CLIP: cut the top off (not generally a good idea)
- FLGIT: removed continuum from channels
- RFLAG: automated task to ID RFI via rms vs time
- FLAGR: automated, converts baseline-based to antenna-based
- ...
- In desperation ZAP – really not recommended but deleting ALL uv data does get rid of RFI!



# RFI Excision: CASA flagdata modes

- tfcrop: detects amp. outliers in 2D freq-time plane
  - operates on uncalibrated or calibrated data
    - average data in time
    - fit piecewise polynomial to background
    - identify and flag deviant points
    - repeat for frequency dimension
    - 'spiky' RFI is relatively easy, wider RFI need more tuning
- rflag: detects outliers in sliding windows in frequency and time
  - operates on calibrated data (2 passes)
    - for each channel calc. rms of Re and Im vis in sliding window
    - calculate median rms and deviations across time windows
    - flag on outliers



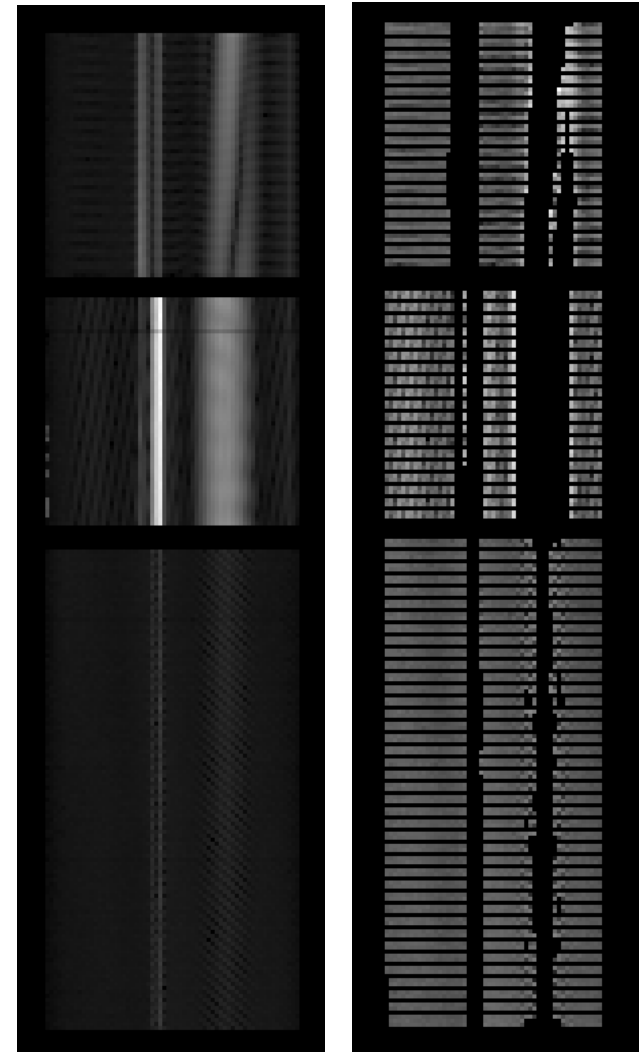


# RFI Flagging: Obit

- Pipeline processing: Developing a new low band reduction pipeline for VLA & VLITE\*
- One 16 MHz IF shown
- LF Pipeline:
  - Drops end channels and applies manually defined flags (PFlag)
  - Removes beginning and end of scans (Quack)
  - Flags shadowed antennas (UVFlag)
  - Edits on median window over time (MednFlag)
  - Edits on median window over frequency (AutoFlag)

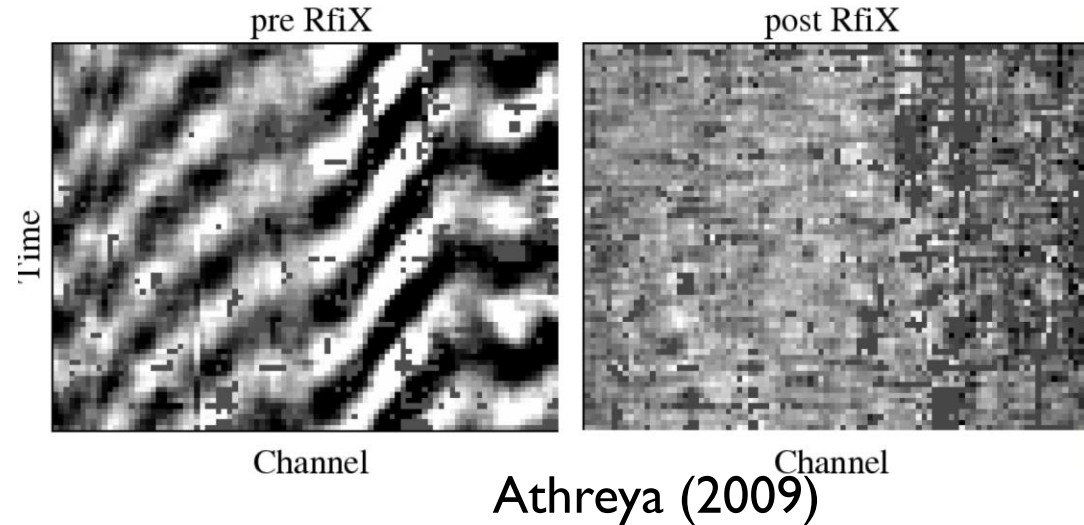
\*VLITE – VLA Ionospheric and Transient Experiment

- 3 yr, 10 antenna through software correlator



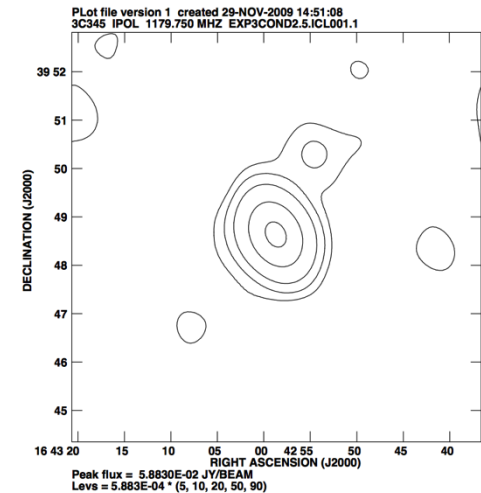
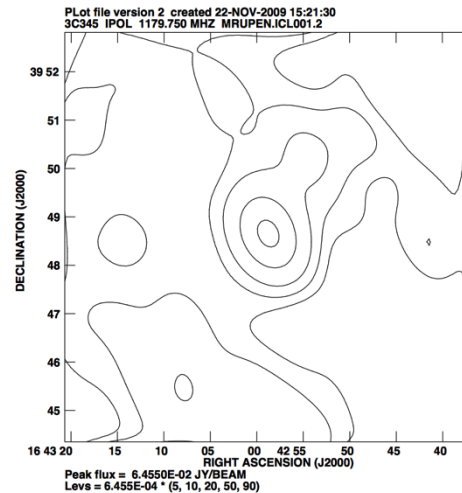
# Fringe Stopping: RFI Cancellation (RfiX)

- Exploit different fringe rates of sky and terrestrial RFI
- removes ground-based, constant amplitude RFI from visibilities



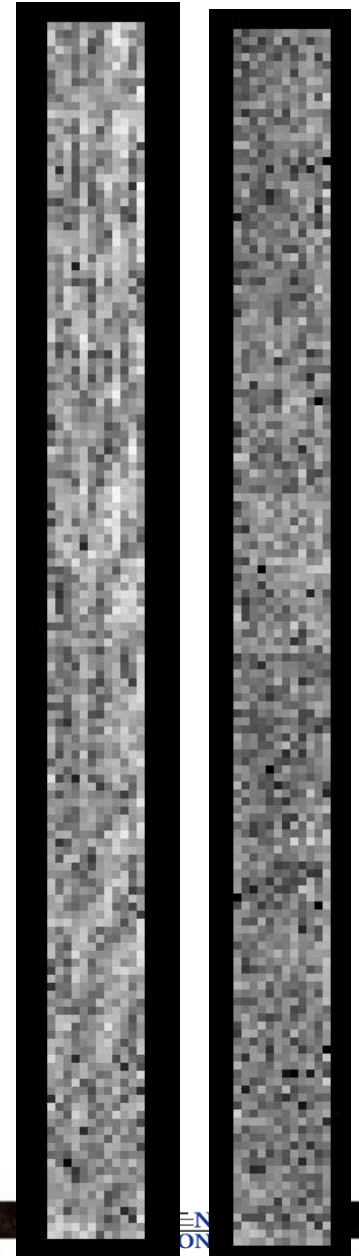
## Fringe Stopping: AIPS UVRFI

- Athreya algorithm modified to allow amplitude variations and multiple sources of RFI moving at different speeds (i.e. ground and satellite-based)



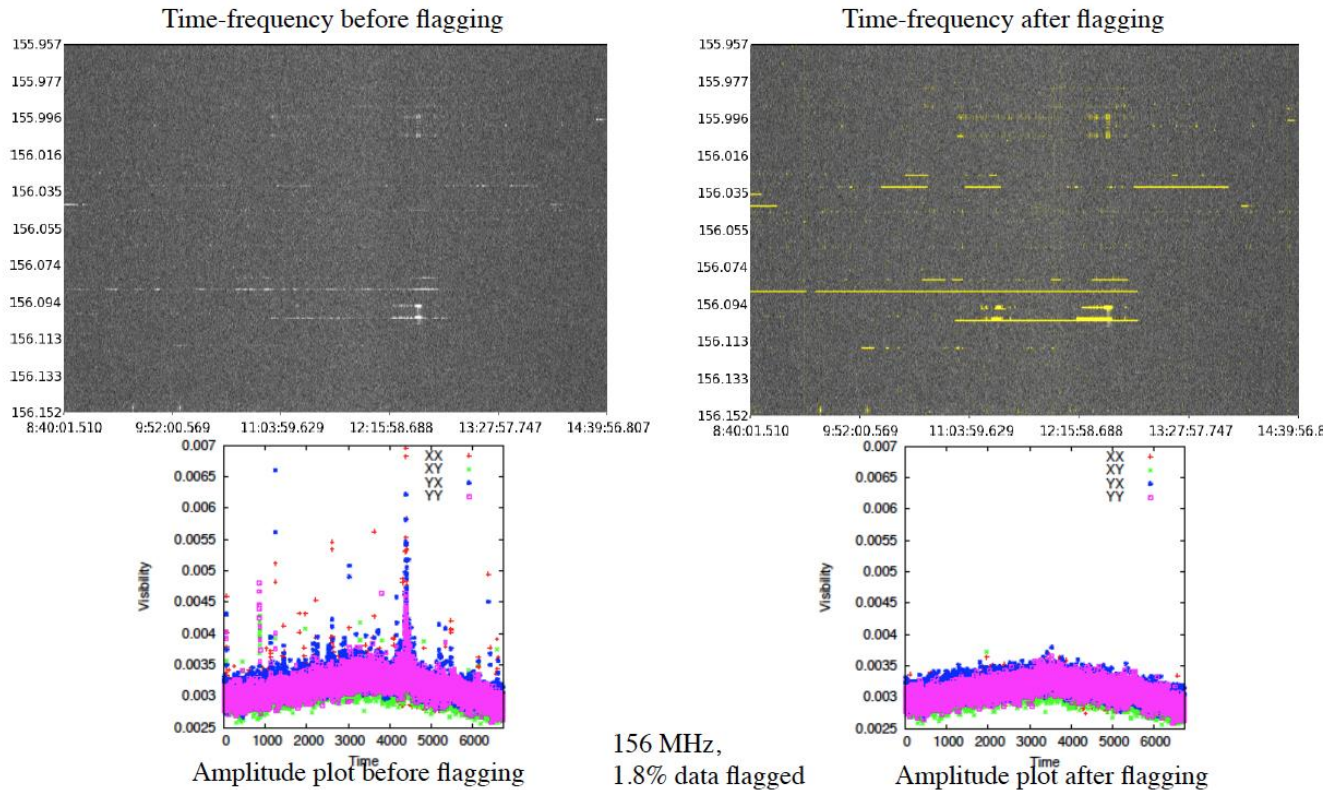
# Fringe Stopping: Orbit

- RFI subtraction 74 MHz VLSSr survey data.
- Orbit class UVRFIXize: (Orbit memo # 16)
  - Differs from Athreya's code as this works on the residuals visibilities
  - Counter-rotate residuals to make constant terrestrial RFI zero phase
  - Time average to smear celestial signal and get RFI model
  - Filter the RFI model as desired to application to visibilities (sub or flag)
  - Interpolate filtered RFI model to time of each observed visibility and subtract or flag
- ✓ Orbit Task: LowFRFI



# RFI Flagging: AOFlagger

- ‘*SumThreshold*’ method to detect series of samples with high values
- Iterative analysis for entire obs., per subband and spectral channel
- Used for LOFAR but available as stand-alone package

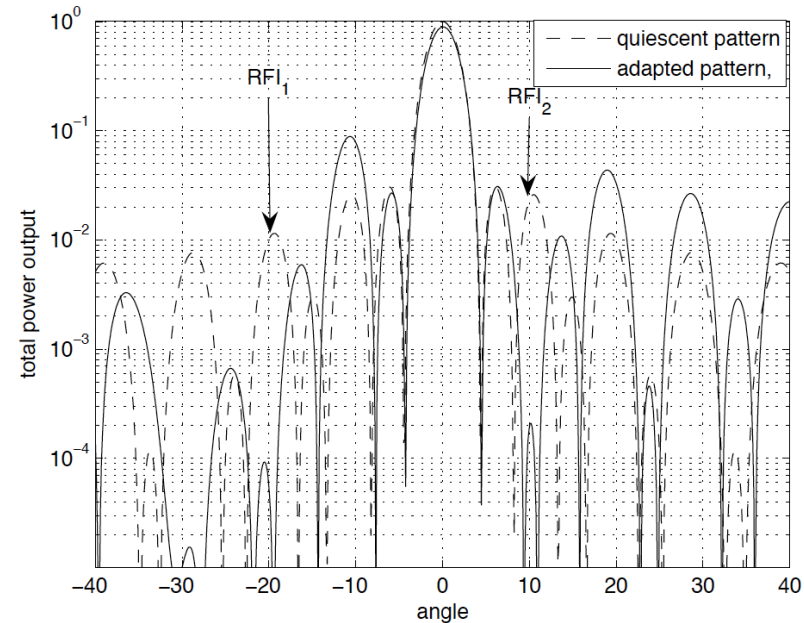
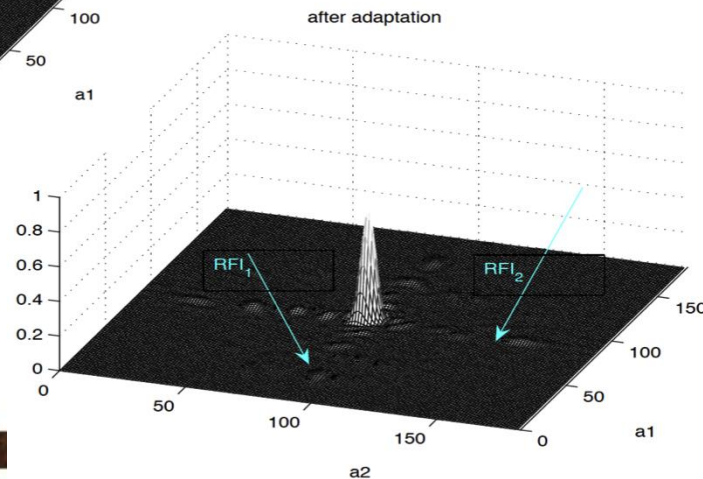
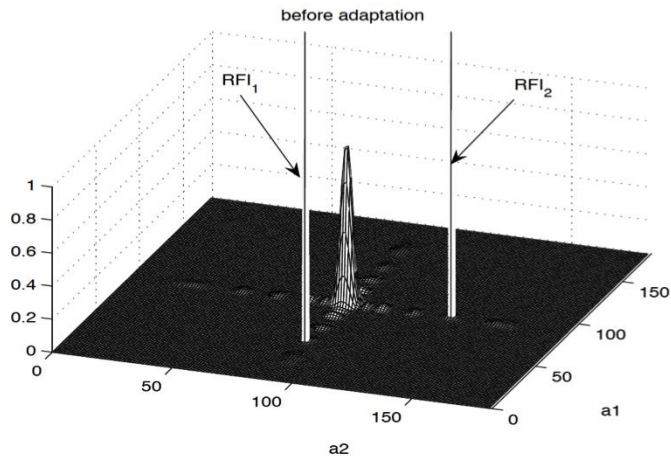


Offringa et al. (2010, 2012)



# RFI Nulling

- Low frequency dipole arrays are electronically steered to source of interest
- Beamforming coefficients can be adaptively modified to place beam null(s) at locations of RFI sources



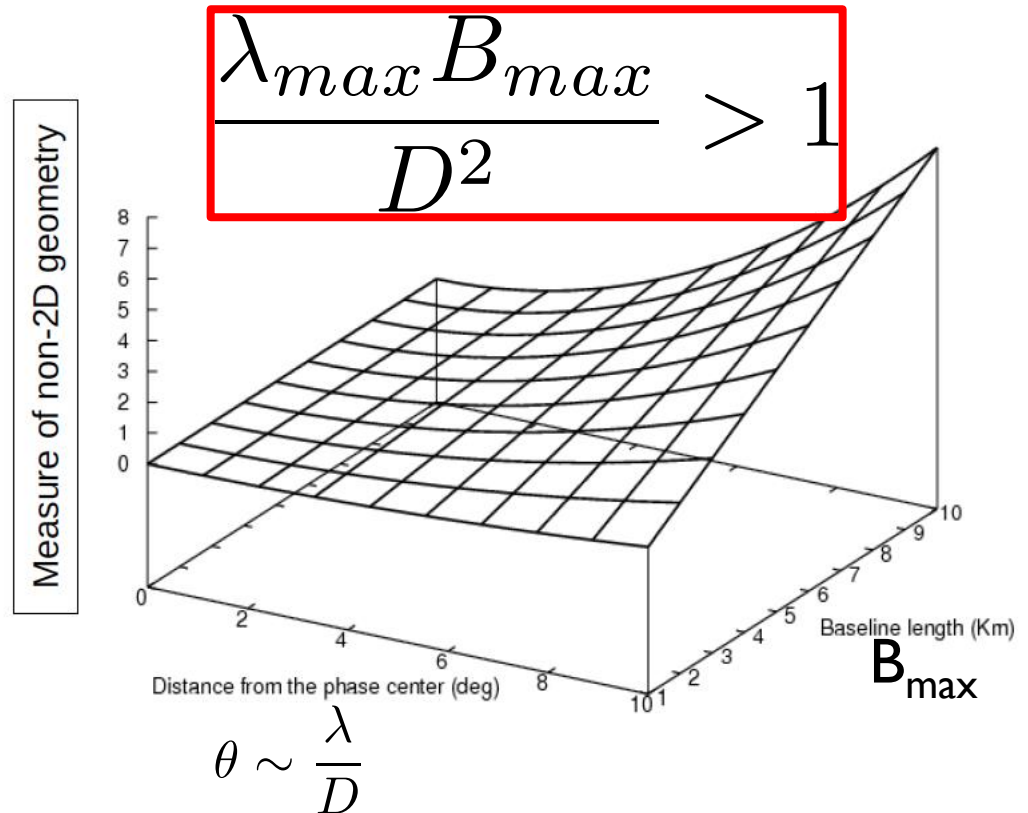
Fridman (2010)

# Wide Field of View (Myers Lecture!)

- Need to image bright sources over the entire primary beam and even into the far out sidelobes
- 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.

➤ Deviation from 2D approx. increases with distance from phase center and baseline length

➤ Limits DR in full field by deconvolution errors from distant sources



# Wide Field of View

## ➤ Approaches to Wide Field Imaging:

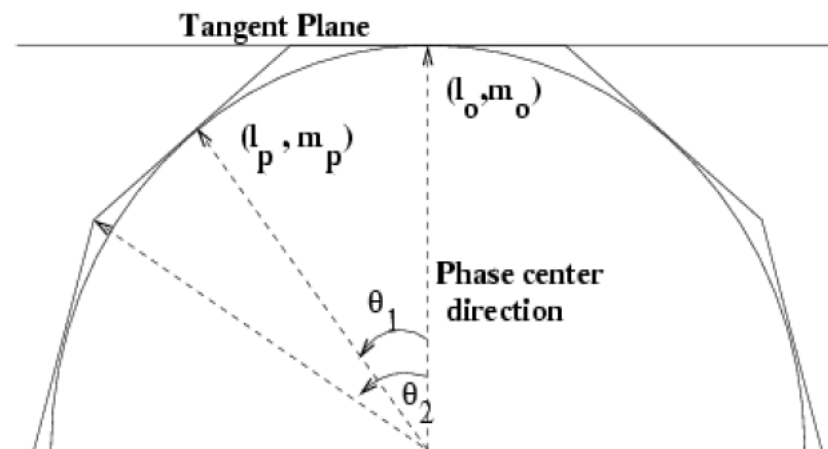
- Facets: phase rotate uv data to different positions on the celestial sphere
  - 3D: facets not co-planar
  - 2D: facets projected to common plane tangent to phase center
- W-Projection: use  $w$ -dependent convolution function in gridding to get corrected image in 2D FFT
- A-Projection: adds direction dependent gain to the W-Projection method for dipole arrays
- 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! (Myers Lecture)

# Wide Field of View: Faceting

## ➤ 3D faceting:

- FoV broken into smaller facets which satisfy 2D approx.
- Image each facet separately then project to a single image at the tangent plane
- ✓ CASA: clean
- ✓ AIPS: IMAGR
- ✓ Obit: Imager, MFIImager



## ➤ 2D faceting:

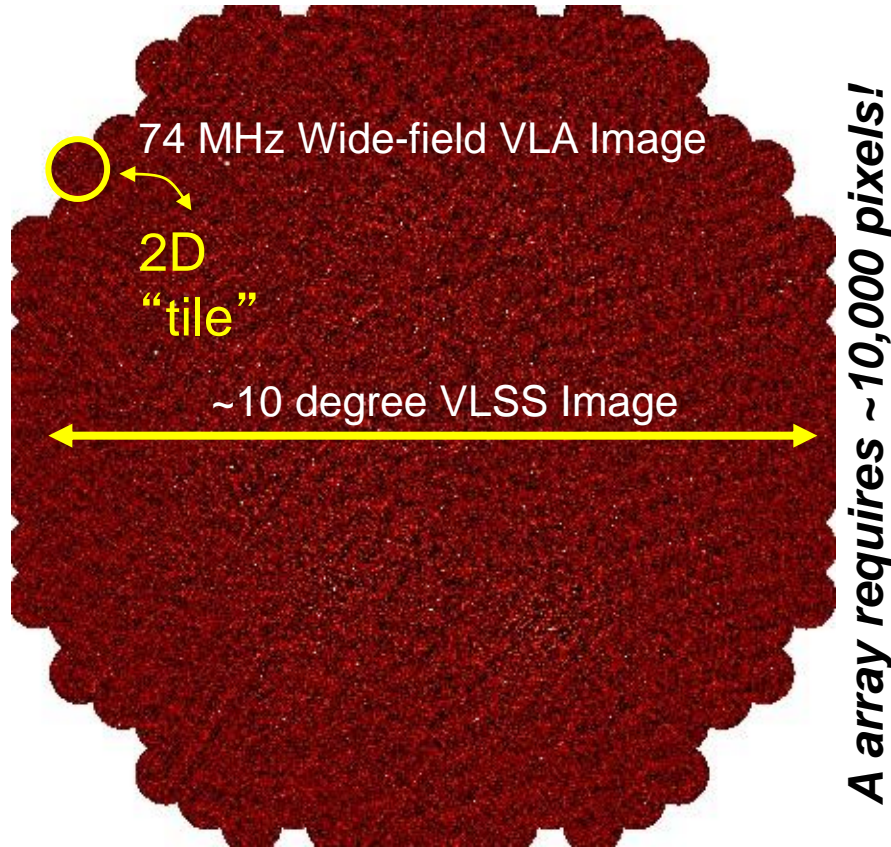
- Project facets to a common plane (1 tangent) with a common grid
- ✓ Obit: do3D = False
- ✓ AIPS: DO3DIMAG = -1

Cotton (2009) Obit memo # 15

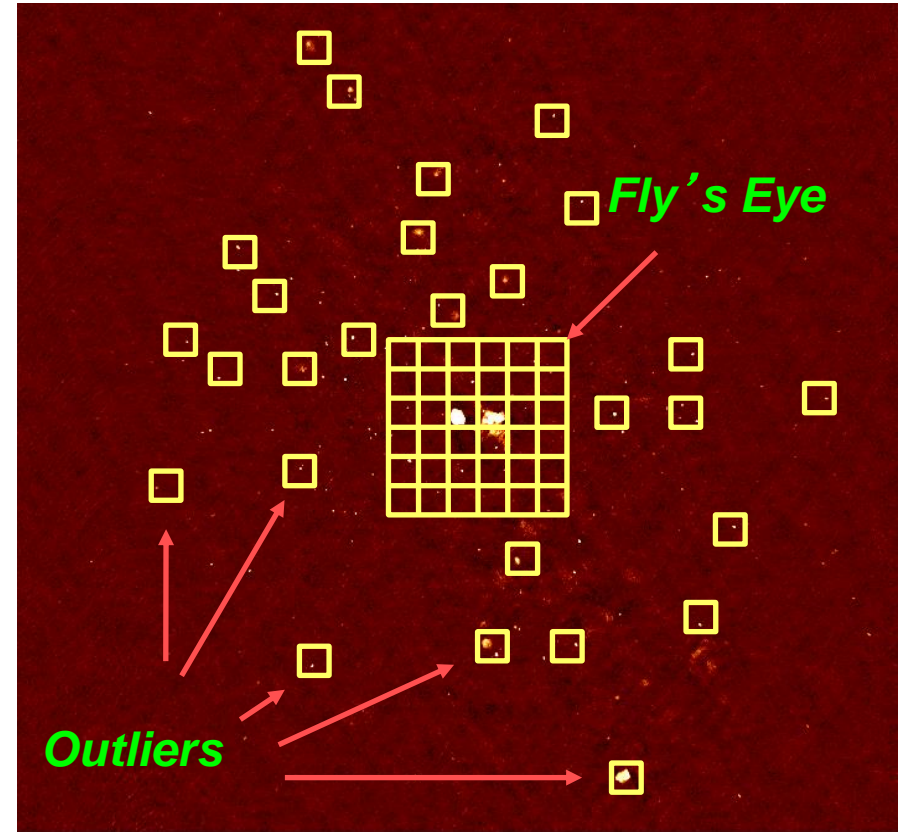
Kogan & Greisen (2009) AIPS memo #113



# Full Field vs Targeted Imaging



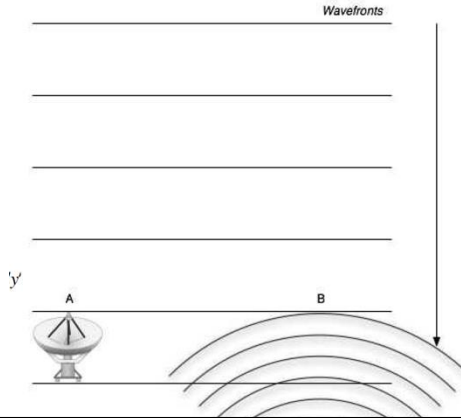
- 2D faceted imaging of entire FoV is very computationally expensive



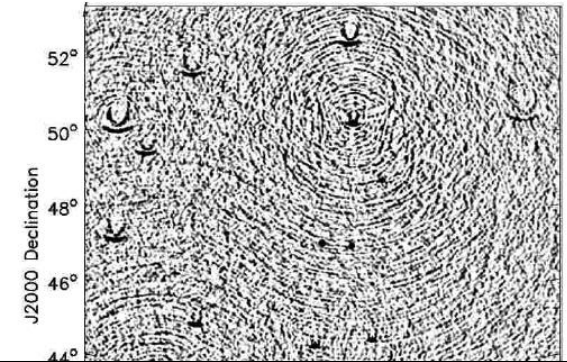
- Fly's eye of field center and then targeted facets on outlier is less demanding BUT potential loss of interesting science

# Wide Field of View: W-Projection

- Coplanar array A and B would be a 2D FT
- Propagation to B' in a non-coplanar array experiences diffraction



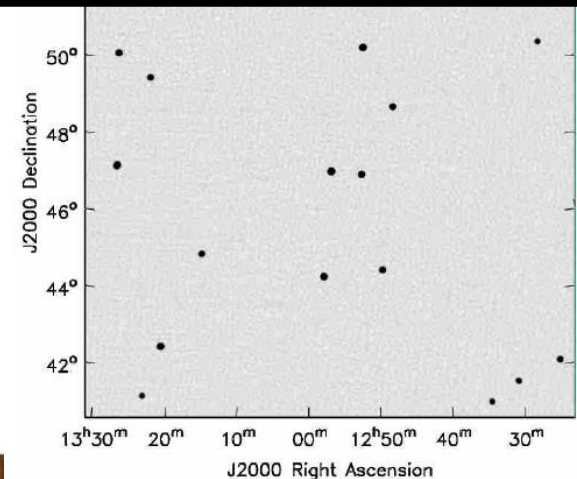
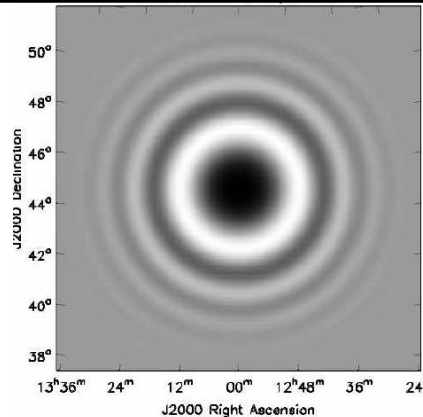
Cornwell et al. (2008)



- 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.

space before Fourier transform

✓ CASA: clean



# Wide Field of View: WB A-Projection

- w-Projection deals with wide FoV but not direction-dependent effects
- A-Projection (Bhatnagar et al. 2008) developed a narrow-band technique to deal with DD primary beam effects
  - corrects for time and polarization of PB
- WB A-Projection (Bhatnagar et al. 2013) expands algorithm to handle wideband primary beam DD effects
  - corrects for time, polarization and frequency of PB

# 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, polarization and element depended gain corections
  - Advances will lead improved scientific capabilities for studies from Dark Ages through Cosmic Dawn to our Solar system
- ✓ Great time to incorporate low frequency information into your research



# Looking Forward:

