Low Frequency Interferometry

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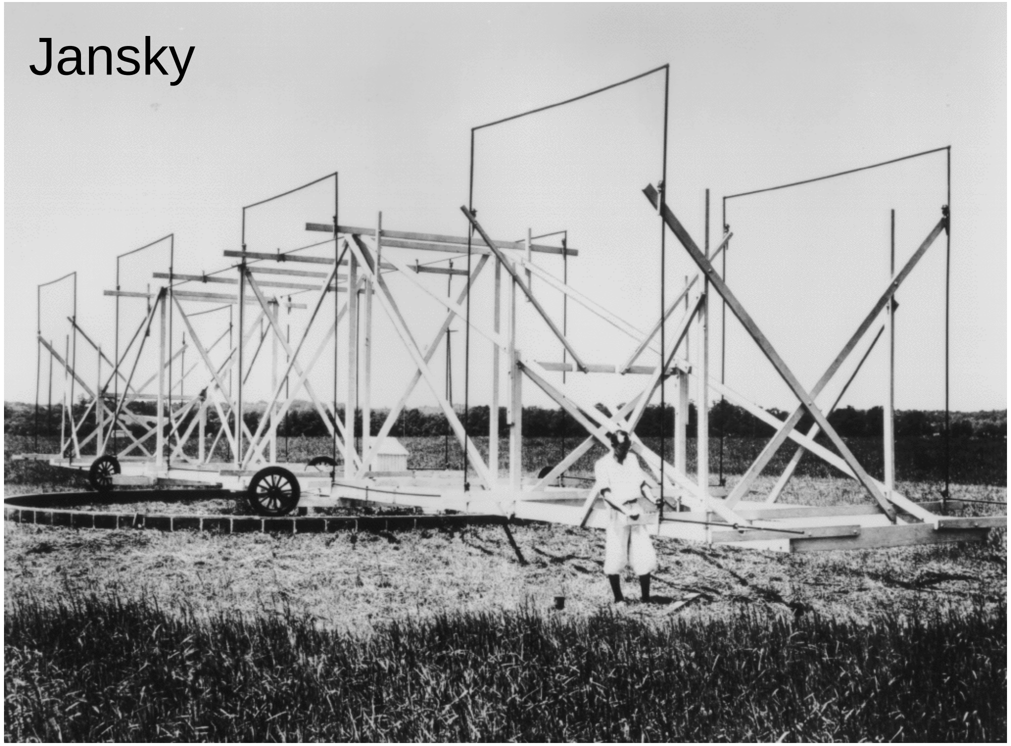
What is Low Frequency?

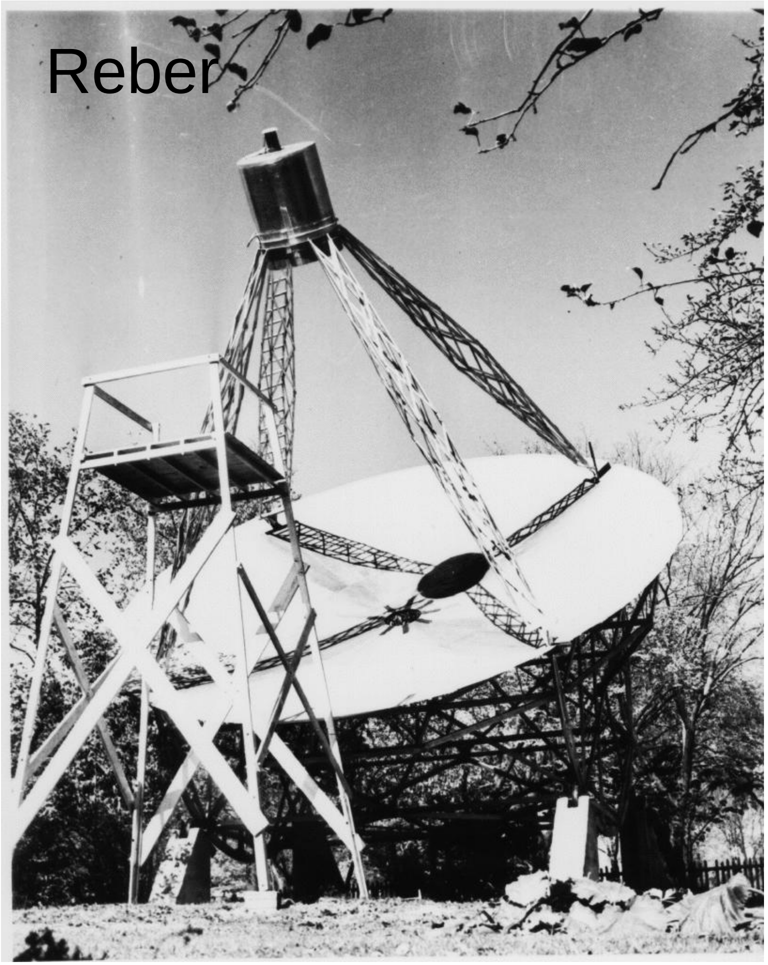
- Wikipedia: '~~Low frequency or low freq or LF refers to radio frequencies (RF) in the range of 30 kHz – 300 kHz.~~'
- Not the definition normally used by radio astronomers.
- Low freq radio astronomy = HF (3 MHz – 30 MHz), VHF (30 MHz – 300 MHz) and UHF (300 MHz – 3 GHz)
- Ground-based instruments only reach to ~10 MHz due to ionosphere

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

Low Frequencies: Origin of Radio Astronomy

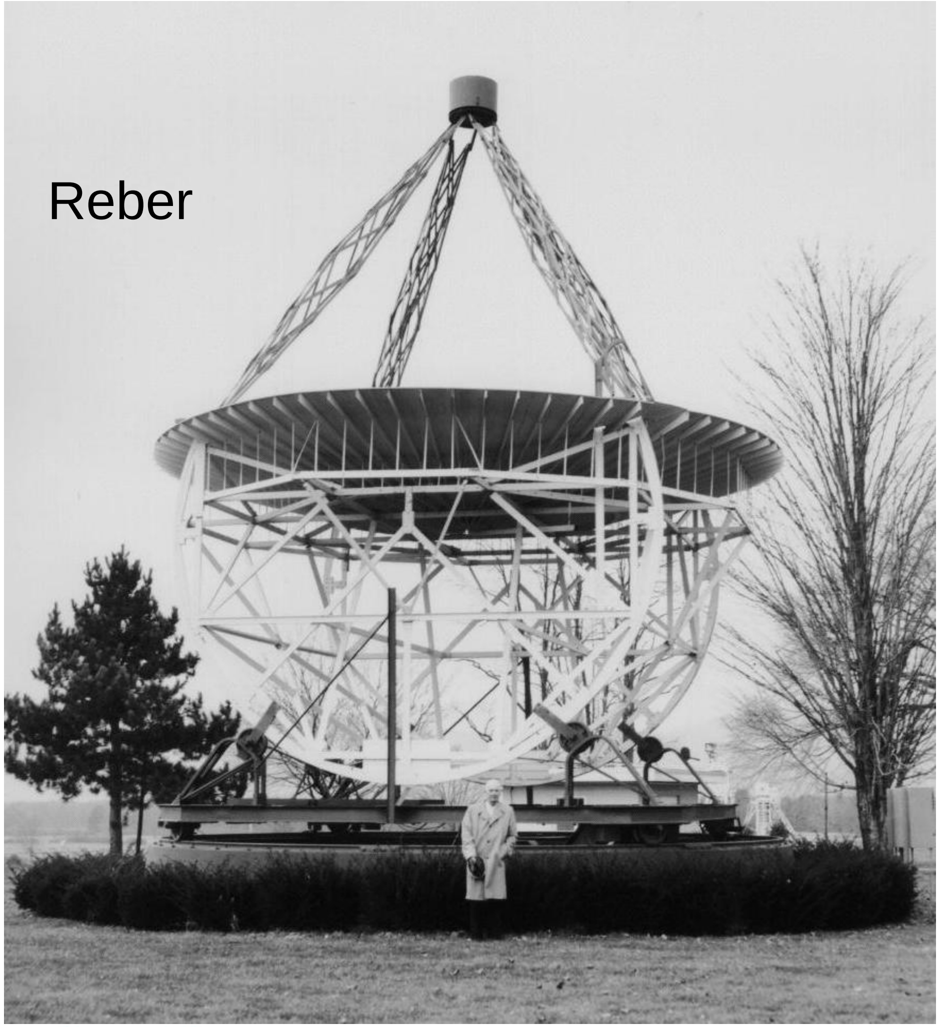


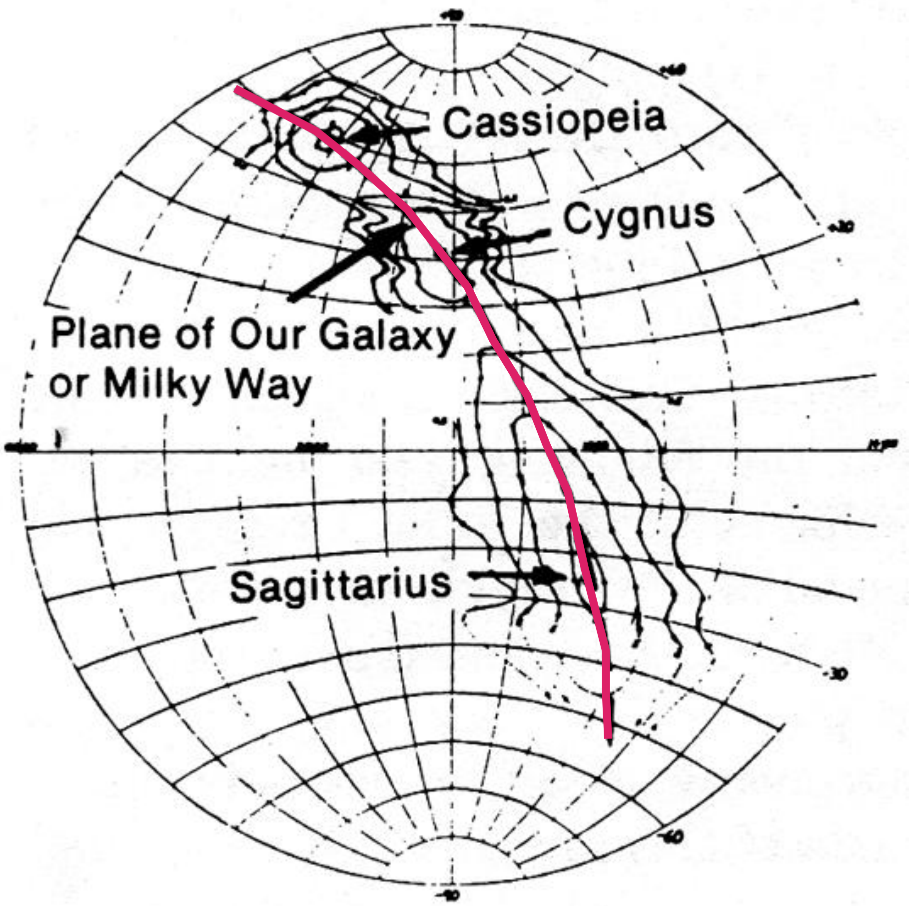
➢ Radio astronomy was born in the 1930's with Karl Jansky's work at 20.5 MHz (14.5 m) at Bell labs



➢ Reber continued work at 160 MHz (1.9 m) in his back yard

Reber's Radio Sky in 1944





- 160 MHz sky image from Reber, resolution ~12 degrees

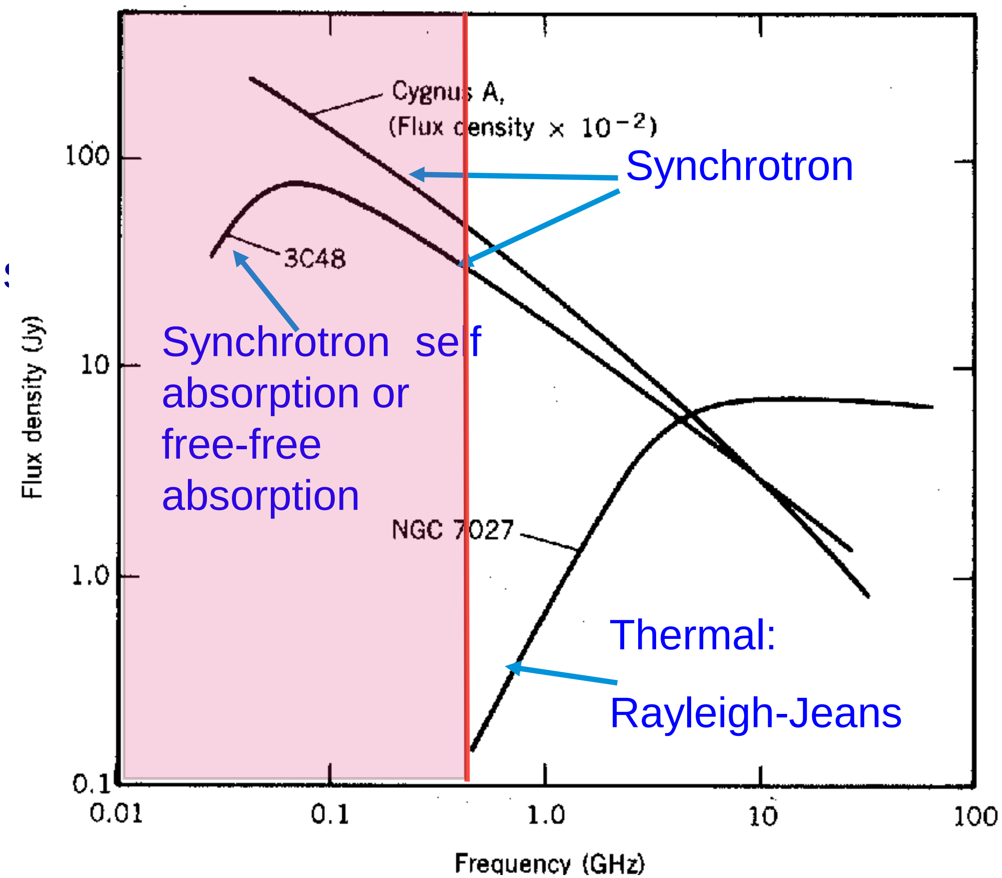
Emission Mechanisms at Low Frequency

<u>Synchrotron Emission:</u> ***(Lang Talk)***

- Best observed at m λ ($\nu < 1$ GHz)
- Relativistic electrons spiraling around magnetic field lines
- Depends on the energy of the electrons and magnetic field strength
- Emission is polarized
- Can be either coherent or incoherent

<u>Thermal Emission:</u> ***(Brogan Talk)***
(Free-Free, Bremsstrahlung):

- Best observed at cm λ ($\nu > 1$ GHz)
- Deflection of free electrons by ions
- Depends on temperature of the gas
- Can be emission or absorption at low ν

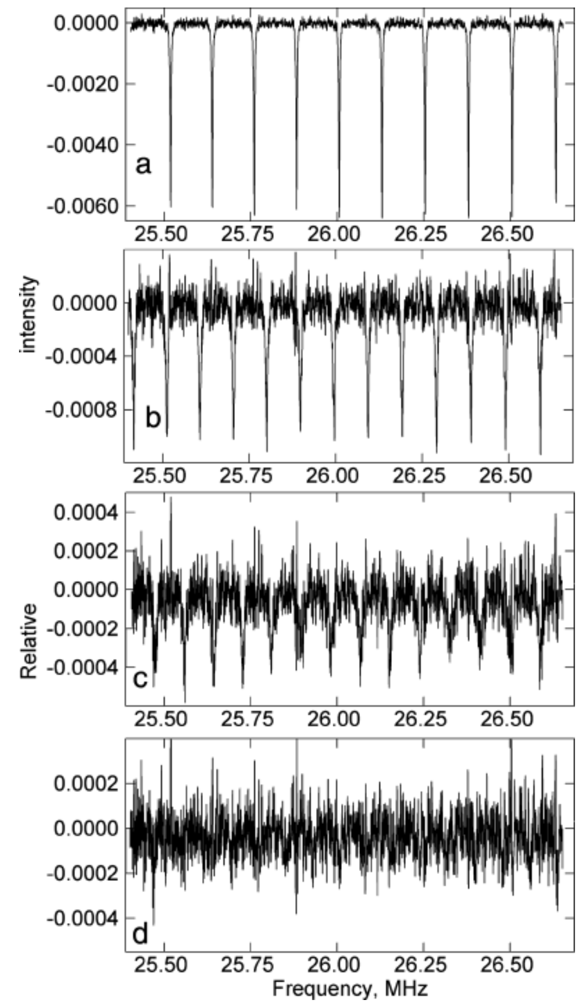


Thompson, Moran, & Swenson

Recombination Lines

Radio Recombination Lines: ***(Lang Talk)***

- High quantum number *n* state (*n*>100 for low frequencies), formed in transition region between fully ionized regions and neutral gas (PDRs)
- Nomenclature: $n+\Delta n \rightarrow n$, $\Delta n=1$ is $n\alpha$, $\Delta n=2$ is $n\beta$, ν_o□$\Delta n/n^3$ (e.g. C441α)
- Largely observed toward the Galactic Plane and discrete source. Detected in absorption below ~150 MHz.
- Diagnostics of the physical conditions of the poorly probed cold ISM, e.g. *temperature, density, level of ionization, abundance ratios*
- Frequency variable signal could adversely impact sensitive Dark Ages and Epoch of Reionization observations.



Stepkin et al. (2007)

Fundamental Limitation

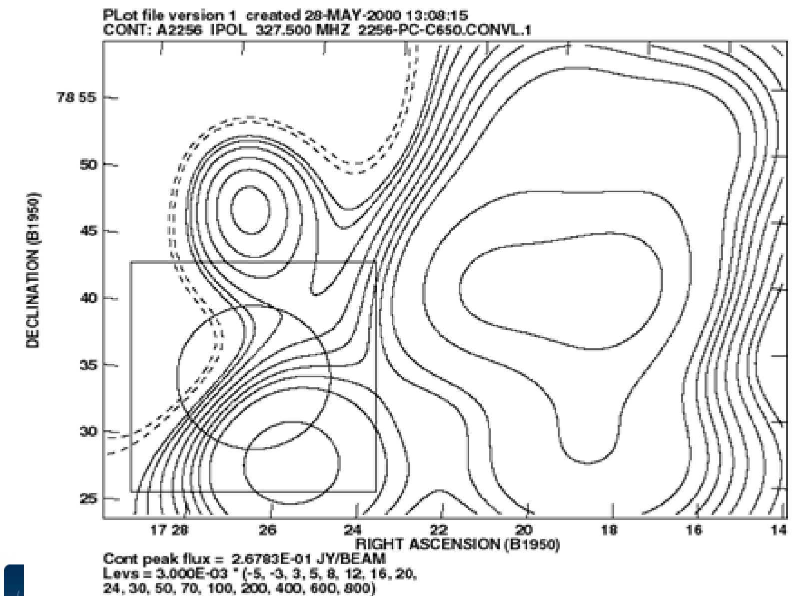
- Spatial resolution depends on wavelength and antenna diameter: $\theta \simeq \frac{\lambda}{D}$
- First long wavelength antennas had very low spatial resolution
- Astronomers pushed for higher resolution and moved to higher frequencies were the *T*T_{SYS} is also lower: $T_{sys}(K) = 131000 \left(\frac{\nu}{15\ MHz}\right)^{-2.55}$

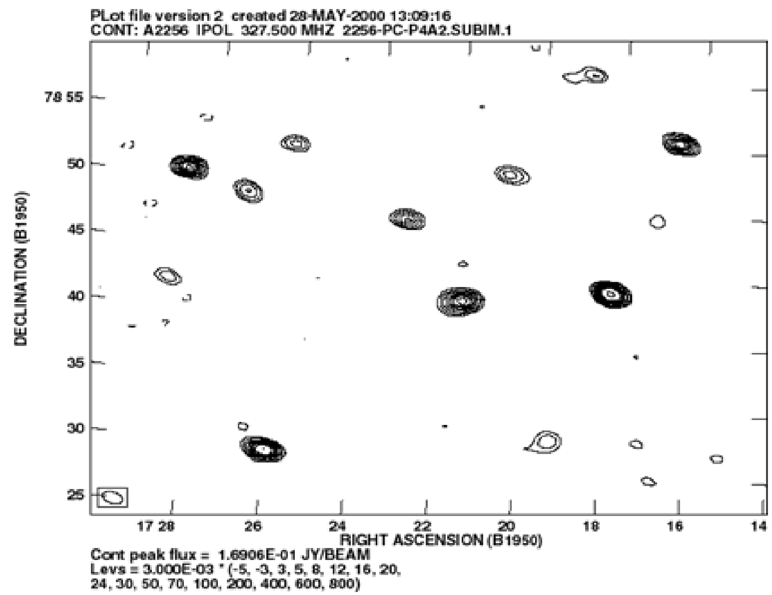
(McKinnon Talk)

Confusion:

~ 10', rms ~ 30 mJy/beam

~ 1', rms ~ 3 mJy/beam





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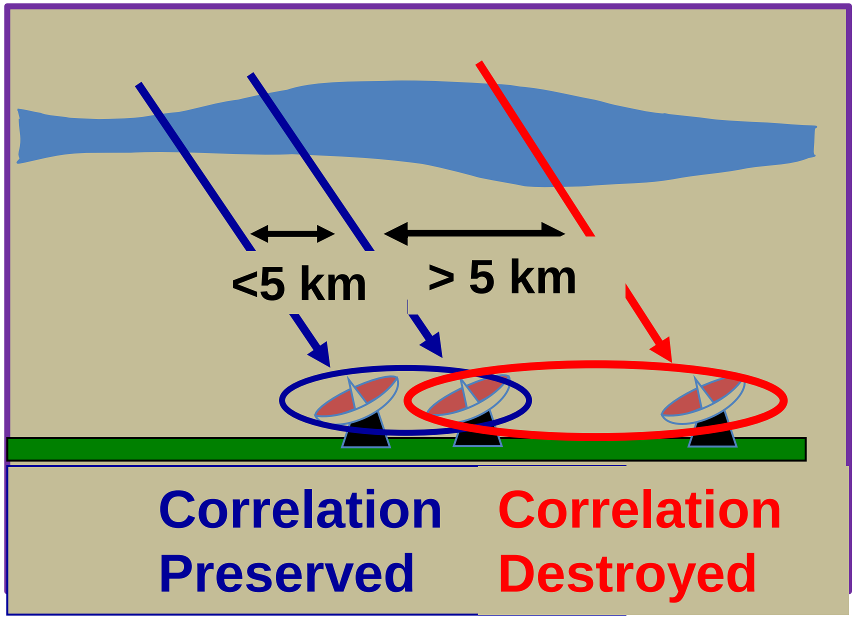
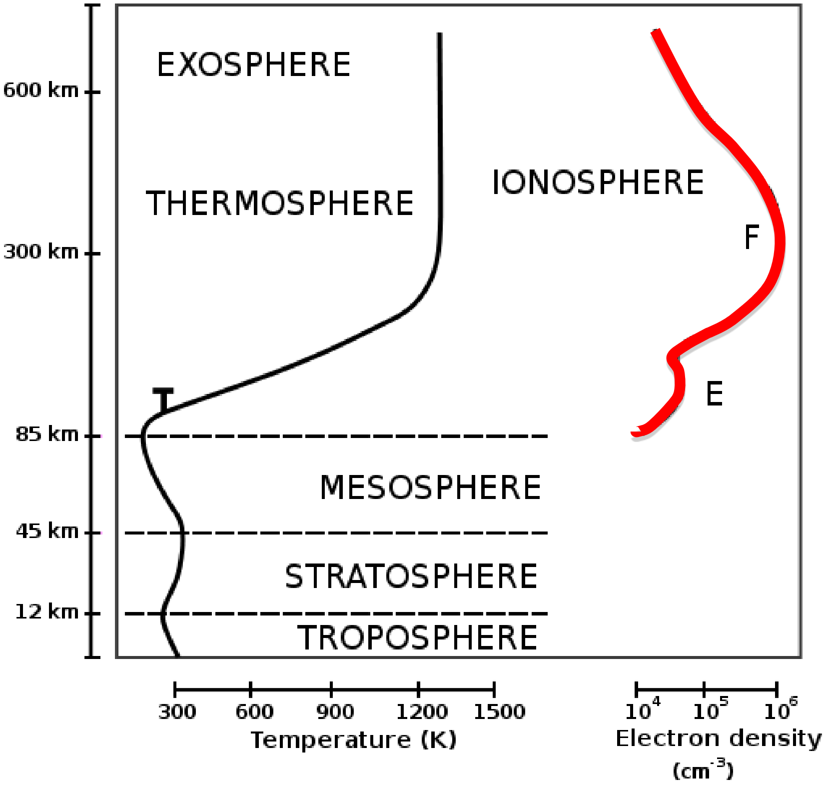
Why 'Abandon' Low Frequencies?

- Low frequency instruments had limited aperture due to ionosphere (B< 5 km)





- Confusion limit reached quickly with only short baselines
- Imaging large fields of view posed enormous computing problem
- Removal of radio frequency interference (RFI) was very difficult

Overcoming the Resolution Problem

- Currently in a transition of moving to high resolution at low frequencies

Why has this taken nearly 50 years?

- Software/Computing:

- Ionospheric decorrelation on baselines > 5 km is overcome by software advances of Self-Calibration in the 1980's

- Wide-field imaging only recently (sort of) possible

- RFI excision development

- Data transmission from long distances became feasible using fiber-optic transmission lines

Low Frequency Arrays

➢ Recent advances in ionospheric calibration, widefield imaging, and RFI 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	NM	10-88	16-1.8	16-1.6	1.0
	…..					

★ 330 MHz system not compatible with EVLA, 74 MHz system to be evaluated soon

– New receiver system under development

EVLA Low-Band Receiver
Evolution of Low-Frequency Capabilities on the VLA

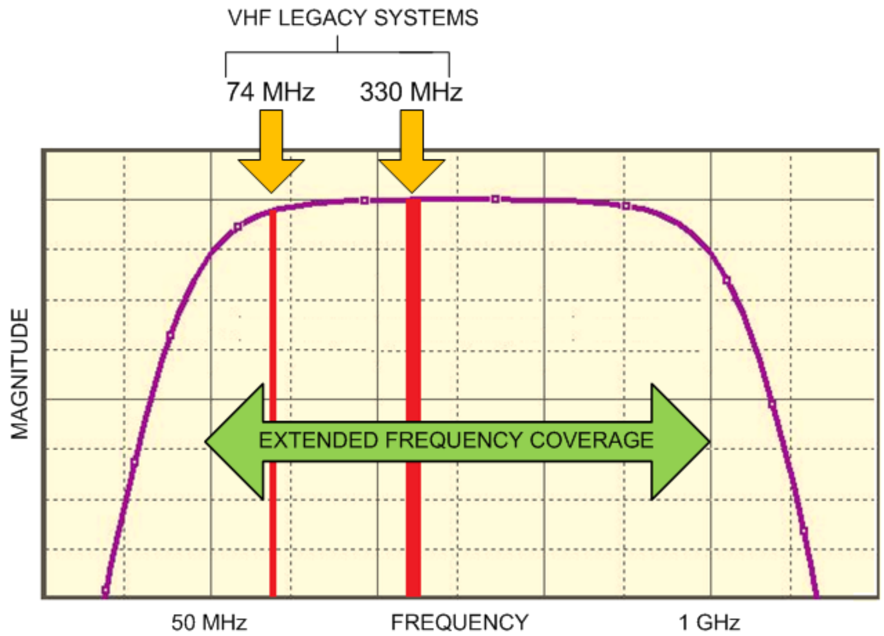
- 1983 P-Band (330 MHz) System Installed on the VLA
- 1984 Pearson and Readhead introduce the self-calibration technique
- 1991 Single 4-Band (74 MHz) Antenna Installed on the VLA
- 1994 Eight 4-Band VLA Antennas
- 1998 Full 4-Band VLA – All 27 Antennas (ϴ ~ 25”)
- 2002 Pie Town Link at 74 MHz (ϴ ~ 8”)
- **2008 P-Band system incompatible with EVLA electronics**

EVLA Low-Band Receiver
Design Goals for New Low-Frequency Receiver

- Restore legacy low-frequency (LF) capabilities to EVLA
- Improve sensitivity with lower receiver noise temperature
  - Marian Pospiezalski of NRAO CDL building P band amplifier
  - 4 band and spare channel amplifiers are commercial devices
- Increase receiver bandwidth to enable future broadband feeds
- Consolidation of LF capabilities into a single receiver subsystem
- Provide an easily extensible platform for future LF feeds
  - Two completely independent "spare" channels provide
    - ✓ LNA –Ultra-Low Noise front end with high-dynamic range
    - ✓ Noise Calibration
    - ✓ Filter position to define a future frequency band
      - Upgrades to EVLA IF structure could enable frequency coverage from 50 MHz to 1 GHz

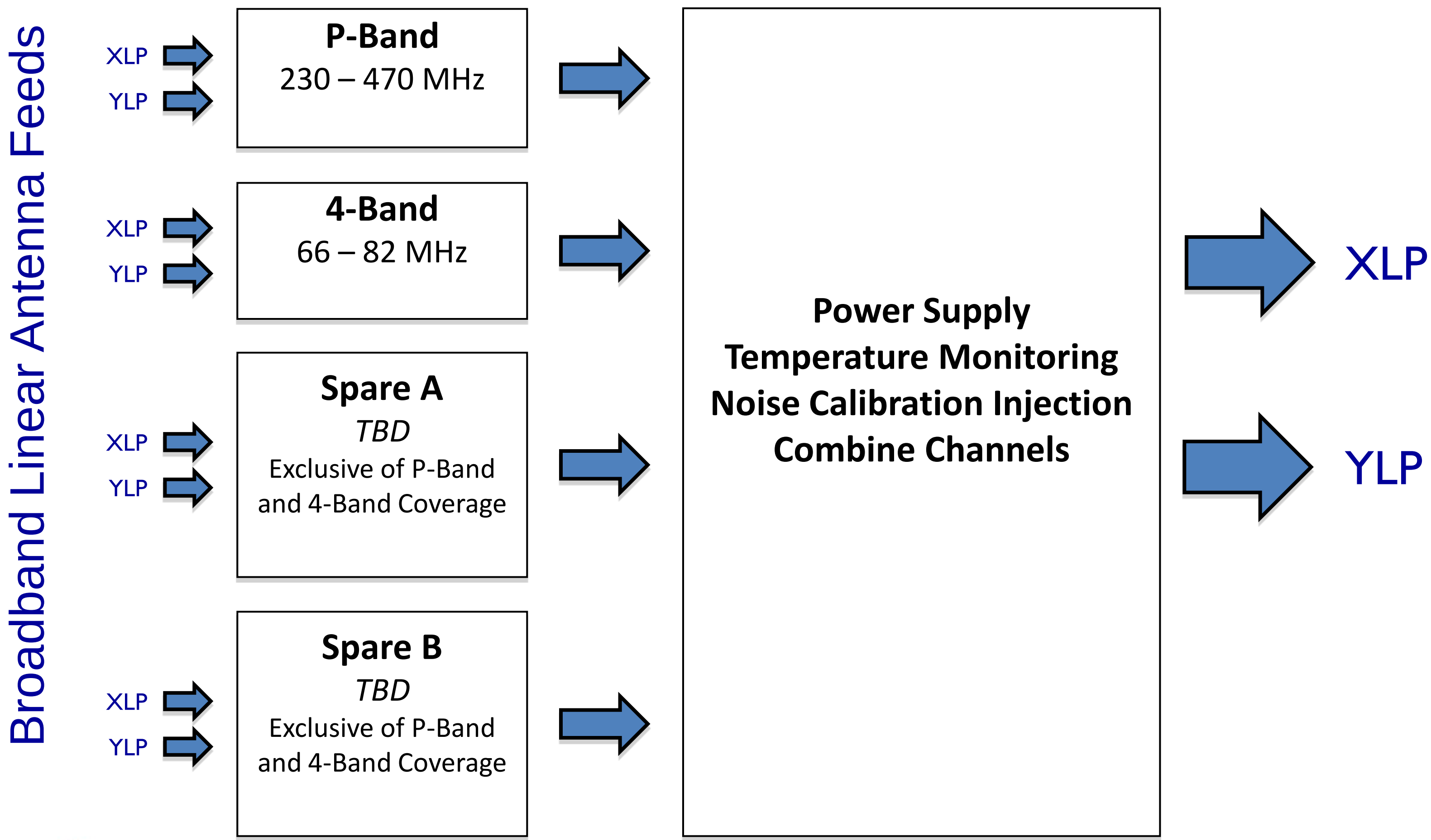
EVLA Low-Band Receiver
Increased Bandwidth

- 4-band: Increased from 1.5 MHz to ~16 MHz (66 to 82 MHz)
  - Limited on low end by present EVLA IF structure
  - Limited on high end by start of FM band (87.5 MHz)
- P-band: Bandwidth increased from 40 MHz to 240 MHz (230 to 470 MHz)



EVLA Low-Band Receiver

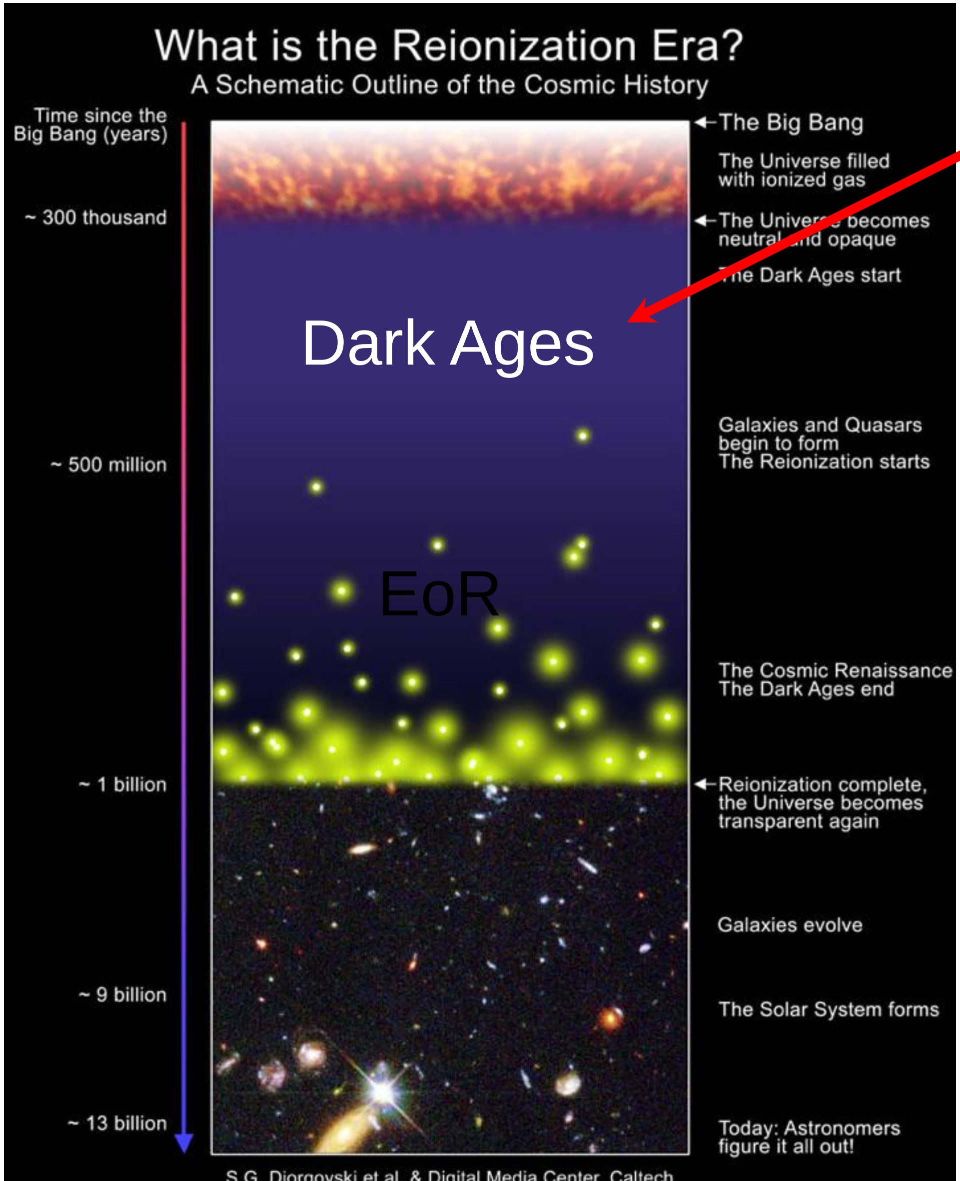
Consolidated LF Platform to Enable Feed Development

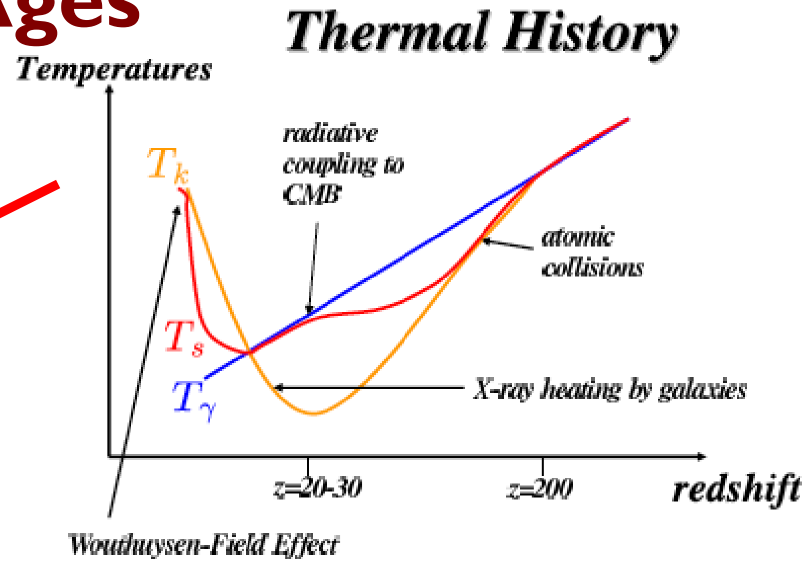


Low Frequency Science

- Key science drivers at low frequencies:
  - Dark Ages (spin decoupling)
  - Epoch of Reionization (highly redshifted 21 cm lines)
  - Early Structure Formation (high z RG)
  - Large Scale Structure evolution (diffuse emission)
  - Evolution of Dark Matter & Dark Energy (Clusters)
  - Wide Field (up to all-sky) mapping
  - Large Surveys
  - Transient Searches (including extrasolar planets)
  - Galaxy Evolution (distant starburst galaxies)
  - Interstellar Medium (CR, HII regions, SNR, pulsars)
  - Solar Burst Studies
  - Ionospheric Studies
  - Ultra High Energy Cosmic Ray Airshowers
  - Serendipity (exploration of the unknown)

Dark Ages

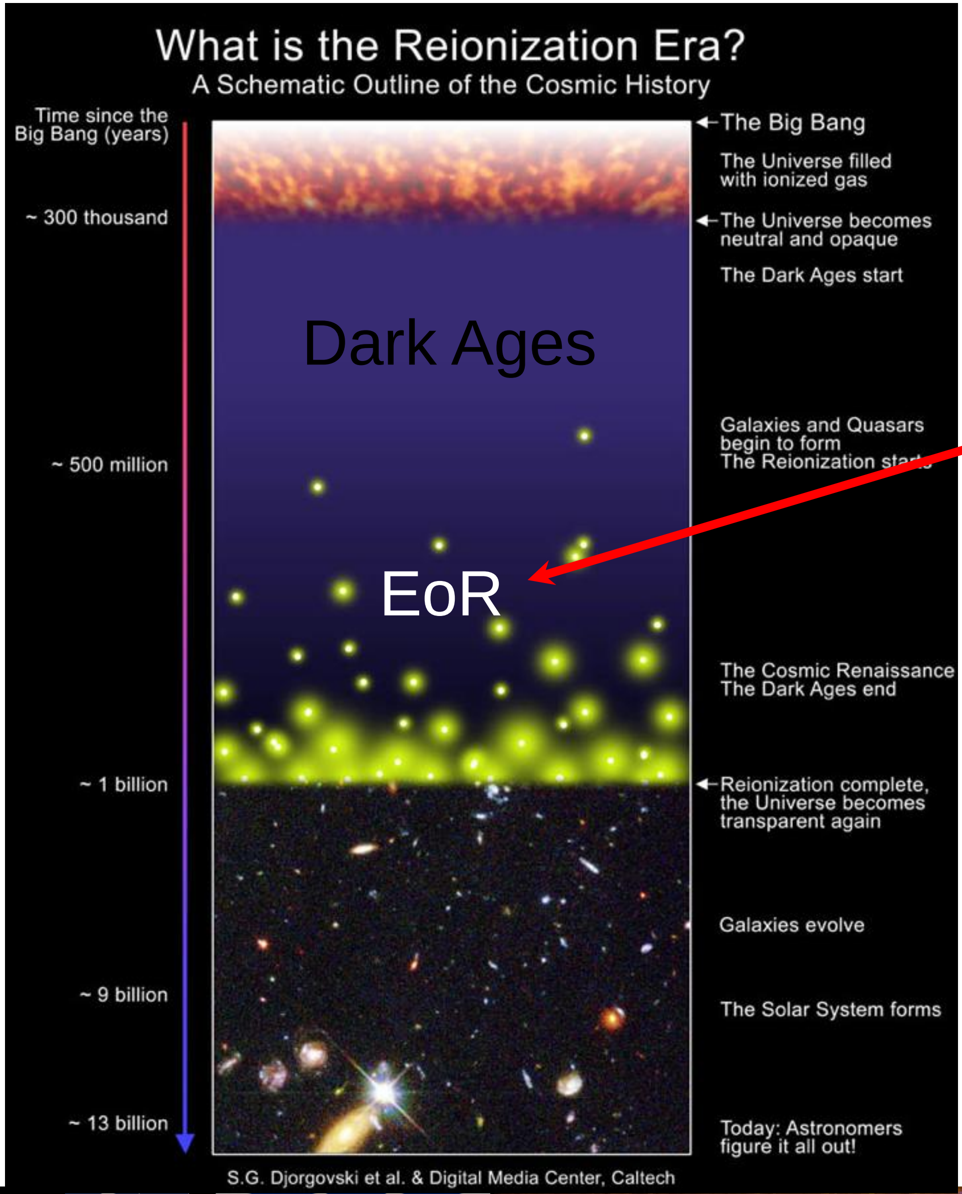


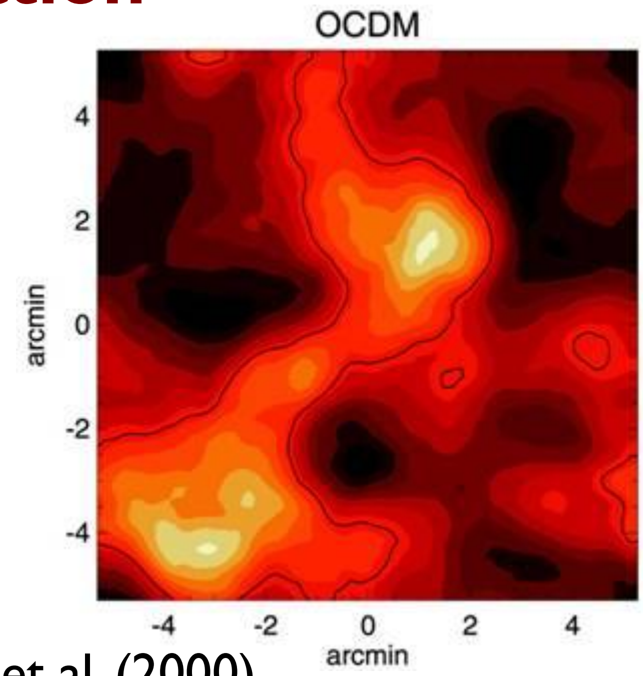


Loeb (2006)

- Spin temperature decouples from CMB at z~200 (ν =7 MHz) and remains below until z~30 (ν =45 MHz)
- Neutral hydrogen absorbs CMB and imprints inhomogeneities

Epoch of Reionization



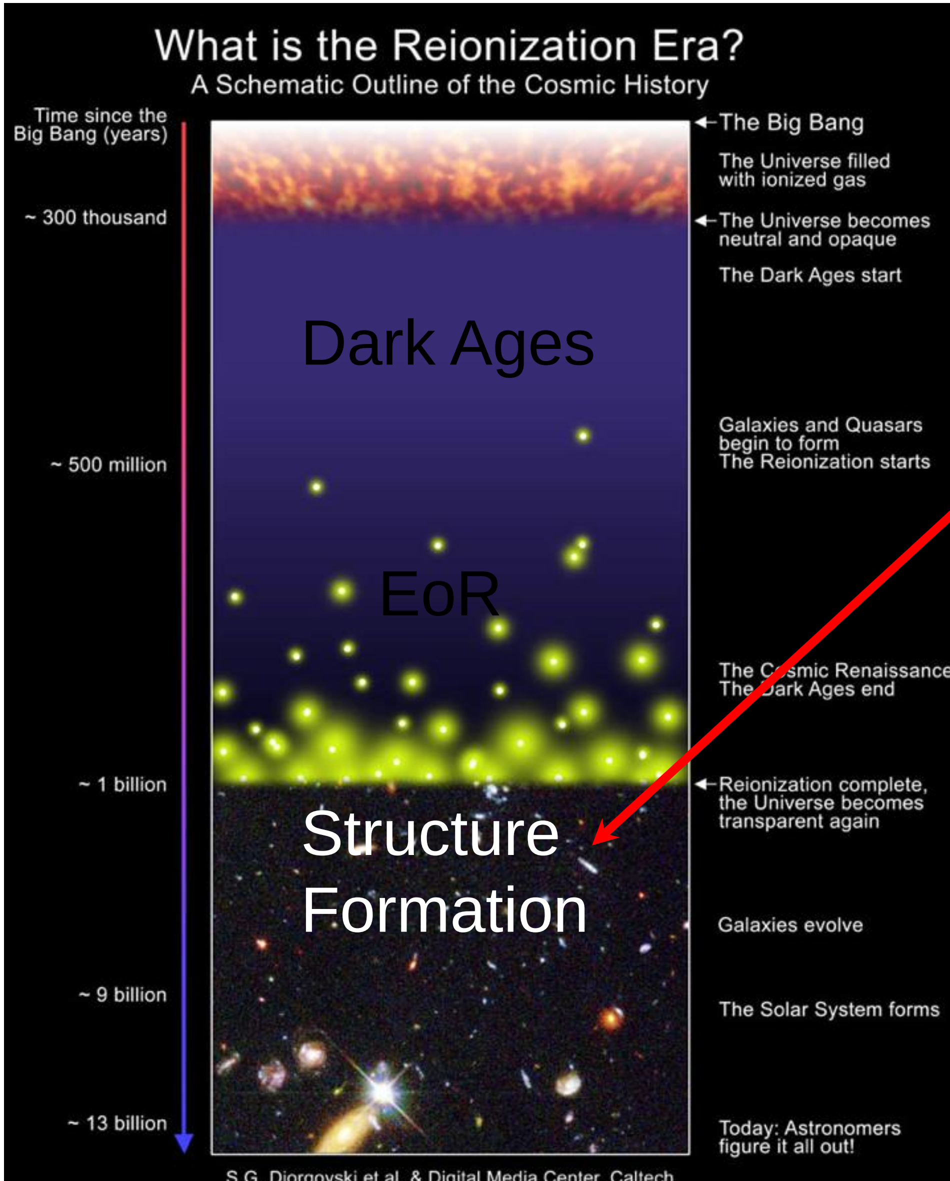


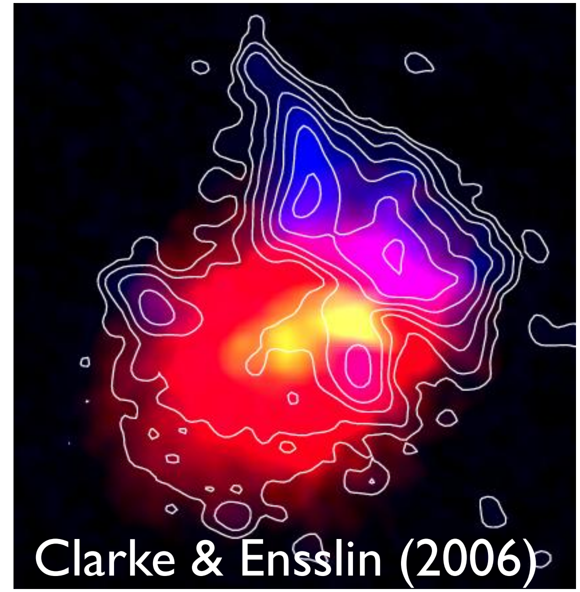
Tozzi et al. (2000)

- Hydrogen 21 cm line during EoR between z~6 (ν ~ 200 MHz) and z~11 (ν ~ 115 MHz)

EoR Intruments: MWA, LOFAR, 21CMA, PAPER, SKA

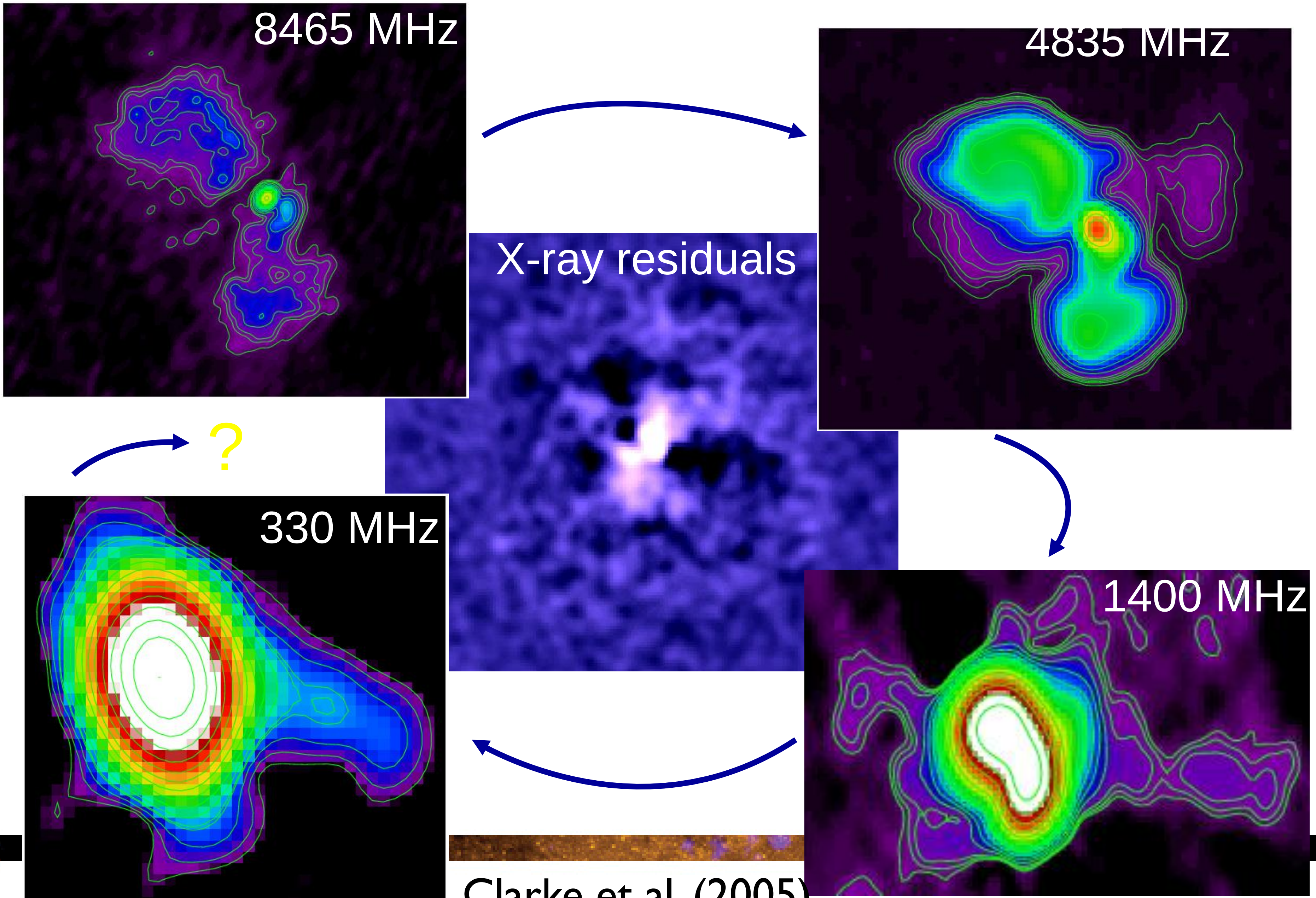
Structure Formation





- Galaxy clusters form through mergers and are identified by large regions of diffuse synchrotron emission (halos and relics)
- Important for study of plasma microphysics, dark matter and dark energy

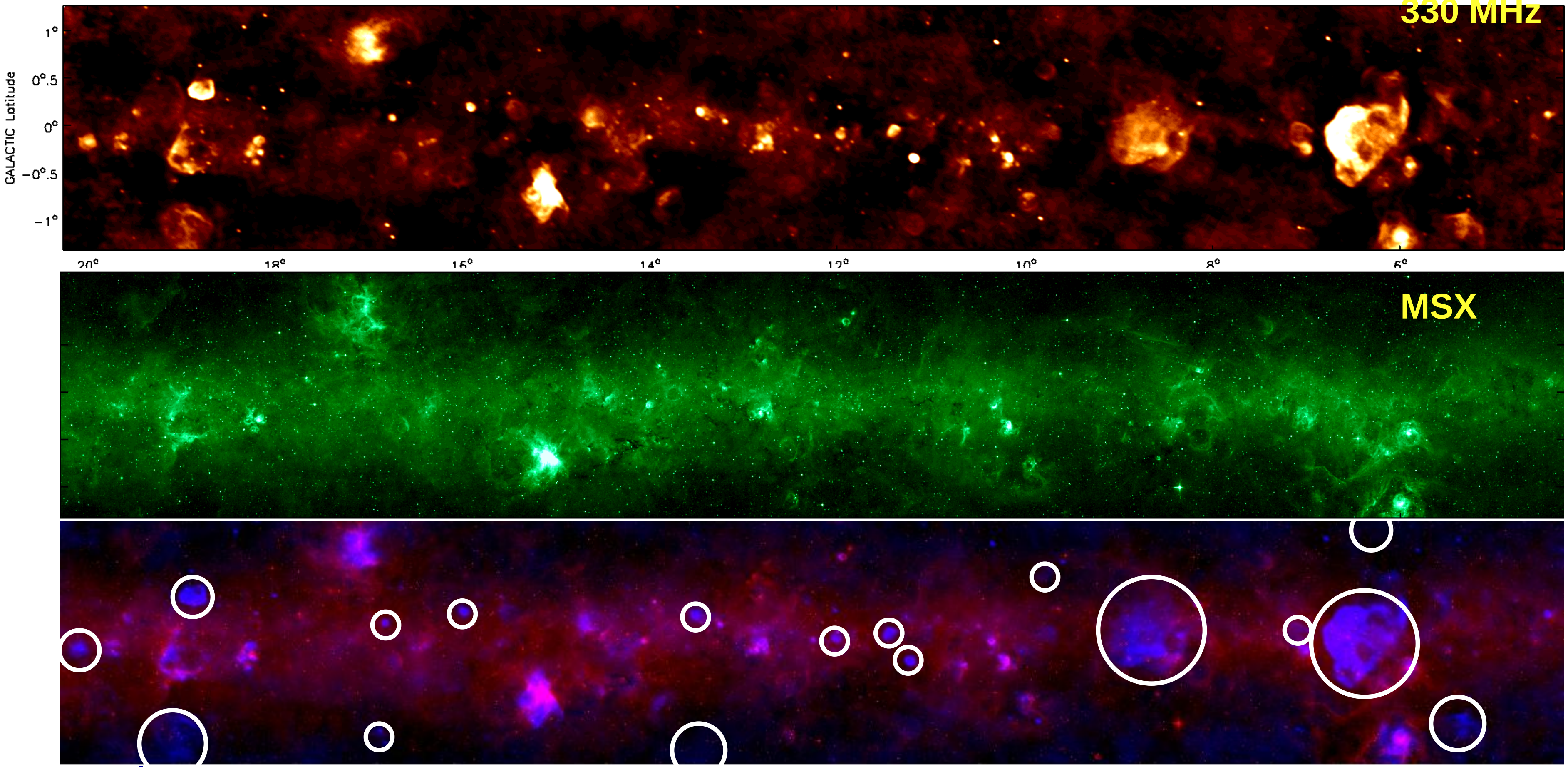
Evolution of AGN Activity/Feedback



Clarke et al. (2005)

Galactic Supernova Remnant Census

Census: expect over 1000 SNR and know of ~230



2 Color Image:
Red: MSXat 8 ⌠m
Blue: VLA 330 MHz

Tripled (previously 17, 36 new) known SNRs in survey region!

Brogan et al. (2006)

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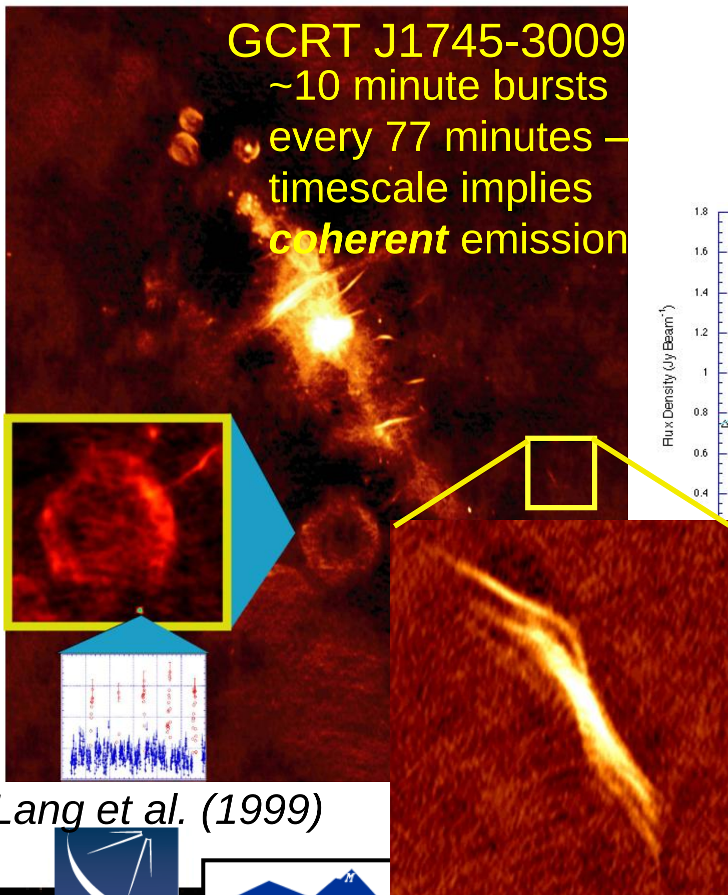
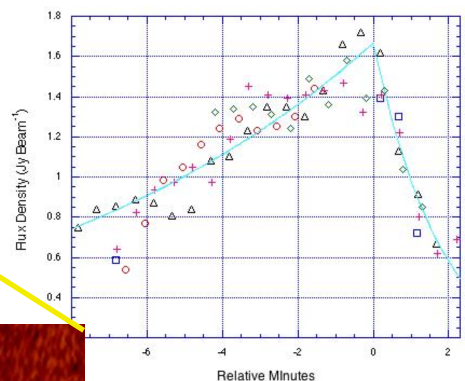
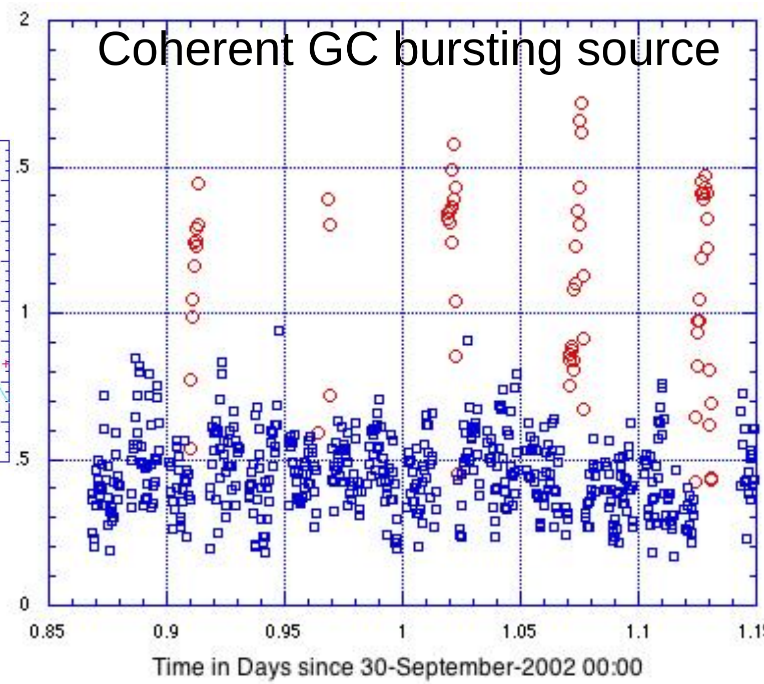
Transients: Galactic Center

- ➢ Filaments trace magnetic field lines and particle distribution
- ➢ Transients: sensitive, wide fields at low frequencies provide powerful opportunity to search for new transient sources
- ➢ Candidate coherent emission transient discovered near Galactic center



Lang et al. (1999)





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

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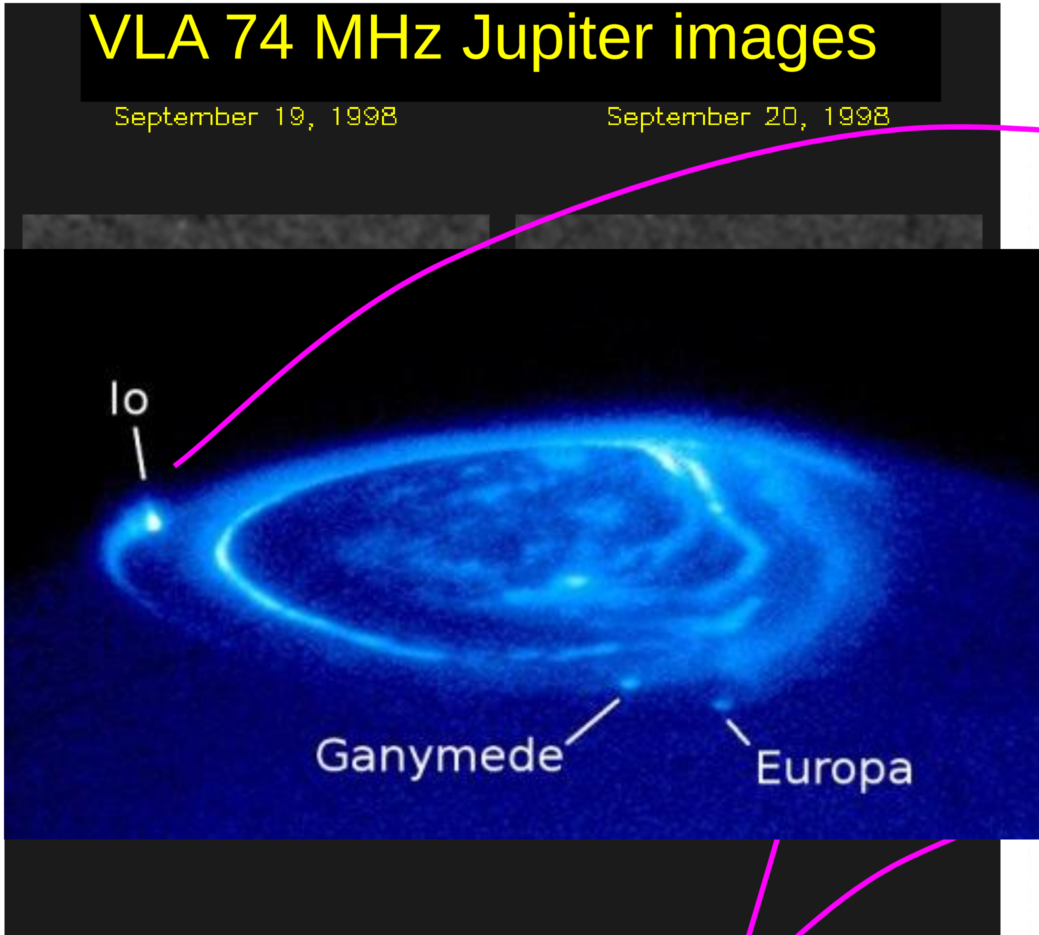
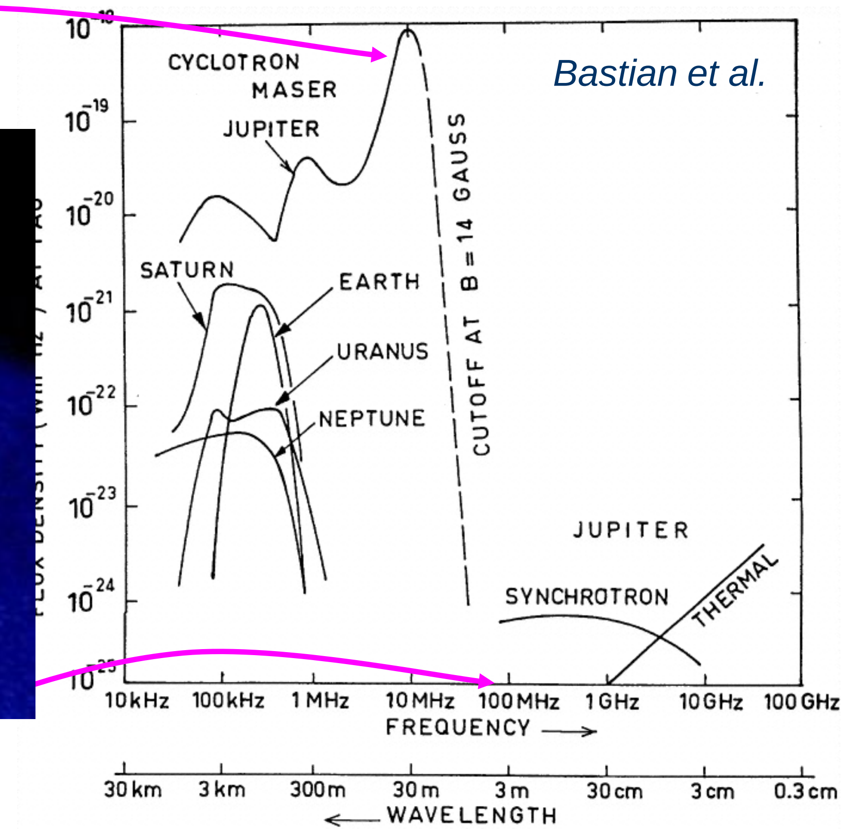
Extrasolar Planets

➢ Jupiter's coherent cyclotron emission: complex interaction of Jupiter's magnetosphere with Io torus



POSSIBLE TO DETECT BURST EMISSION FROM DISTANT "JUPITERS"

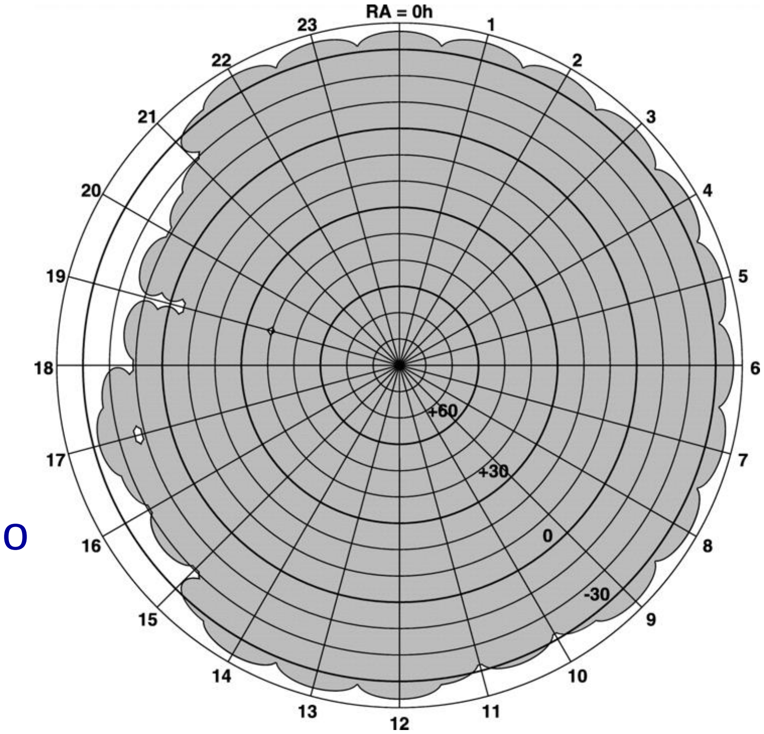


VLA SYSTEM
CAN DETECT QUIESCENT EMISSION

➢Future instruments will resolve Jupiter and may detect extra-solar planets

VLA Low Frequency Sky Survey:VLSS

- Survey Parameters: { = 74 MHz, ™ > -30°,
  ∪= 80” resolution, σ~100 mJy/beam

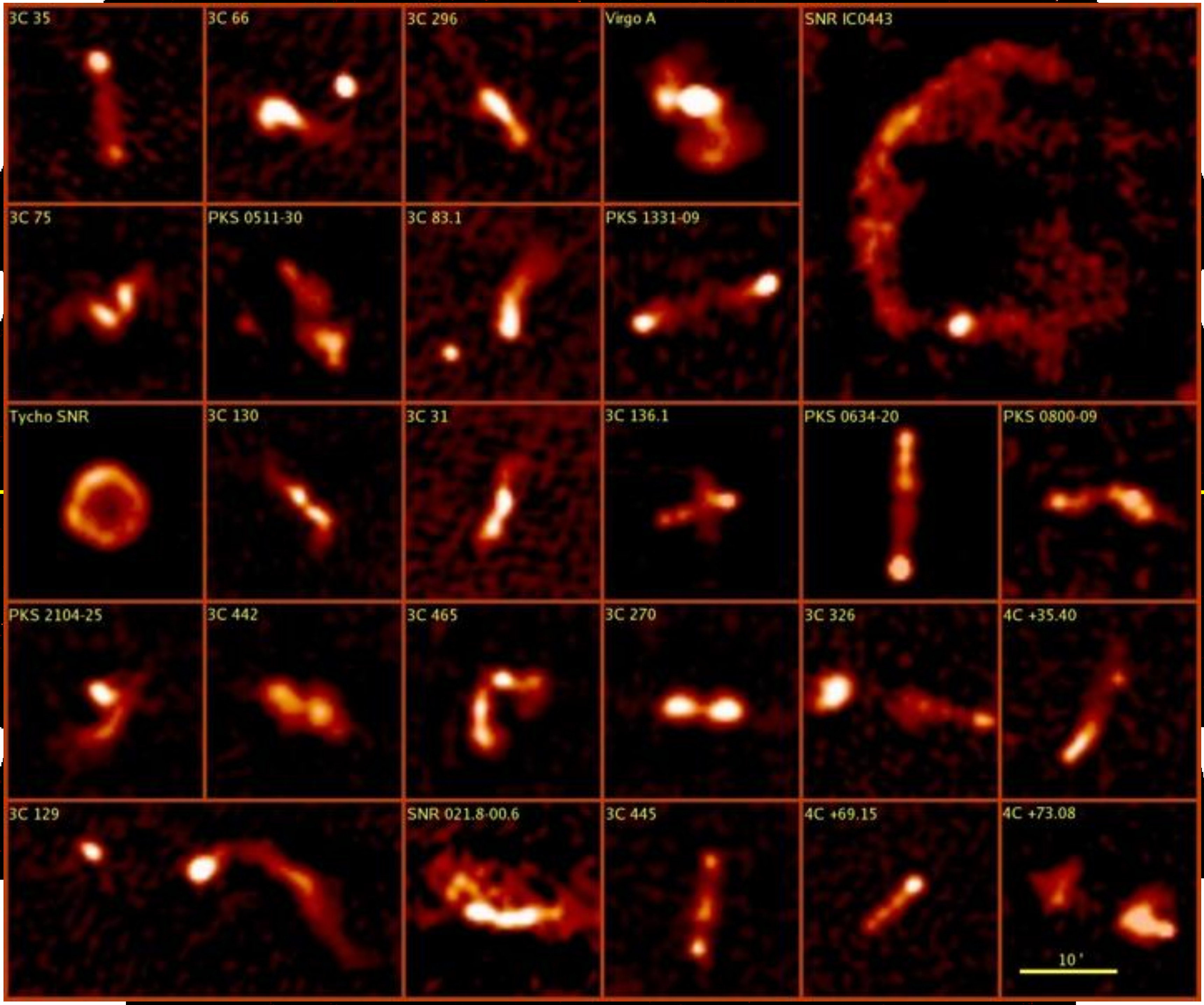


- Deepest & largest LF survey
  N ~ 70 000 sources in ~ 95% of sky > -30°
  Statistically useful samples of rare sources
  => fast pulsars, distant radio galaxies, cluster radio halos and relics, unbiased view of parent populations for unification models

- Important calibration grid for EVLA, GMRT, & future LF instruments

Cohen et al. (2007)

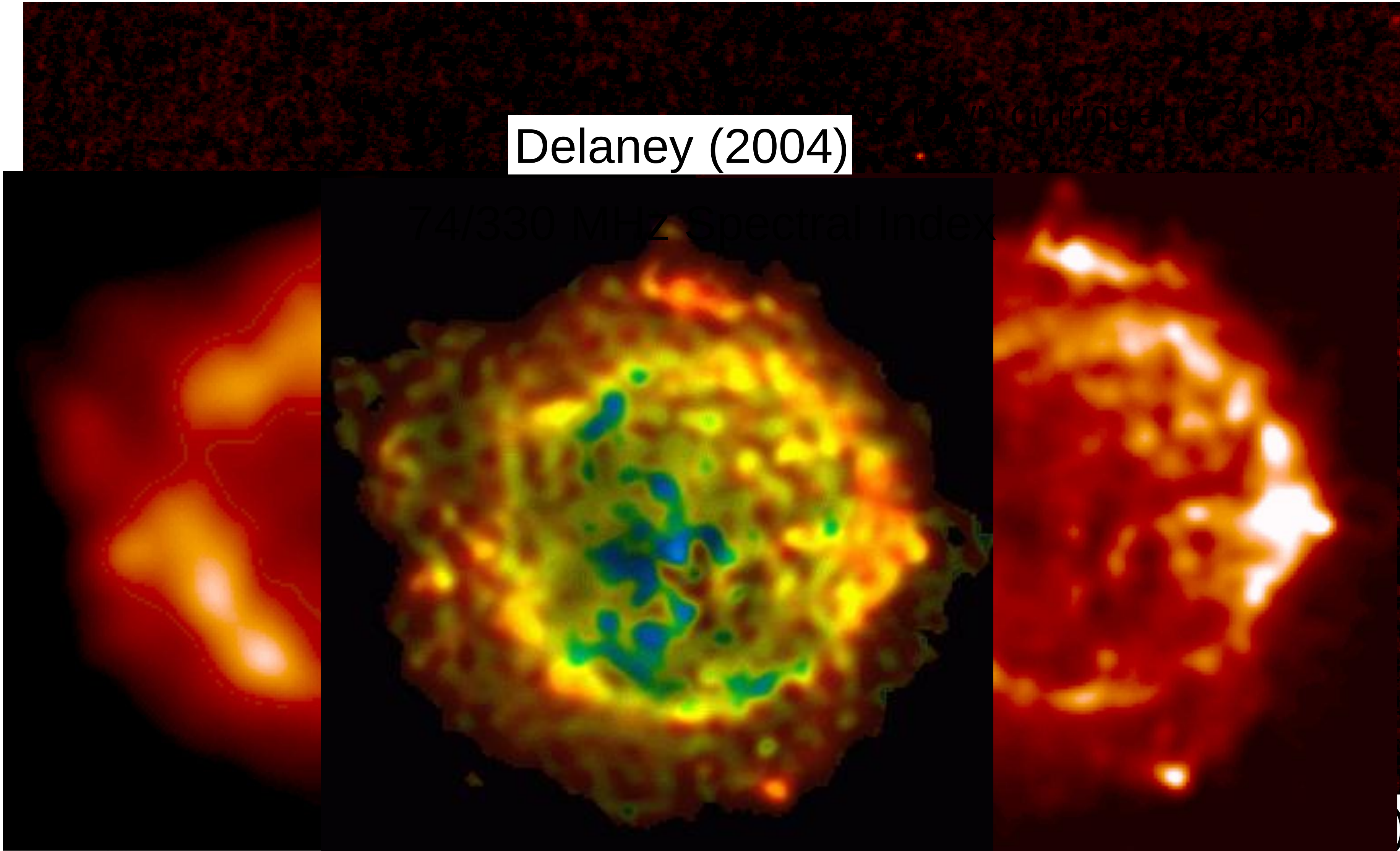
- Data online at NED & http://lwa.nrl.navy.mil/VLSS


3C 35
3C 66
3C 296
Virgo A
SNR IC0443
3C 75
PKS 0511-30
3C 83.1
PKS 1331-09
Tycho SNR
3C 130
3C 31
3C 136.1
PKS 0634-20
PKS 0800-09
PKS 2104-25
3C 442
3C 465
3C 270
3C 326
4C +35.40
3C 129
SNR 021.8-00.6
3C 445
4C +69.15
4C +73.08
10'

Low Frequency In Practice: **Not Easy!**

- Phase coherence through ionosphere
  - Corruption of coherence of phase on longer baselines
- Finite Isoplanatic Patch Problem:
  - Calibration changes as a function of position
- Bandwidth smearing:
  - Distortion of sources with distance from phase center
- Radio Frequency Interference:
  - Severe at low frequencies
- Large Fields of View:
  - Non-coplanar array (*u*,*v*, & *w*)
  - Large number of sources requiring deconvolution
  - Calibrators

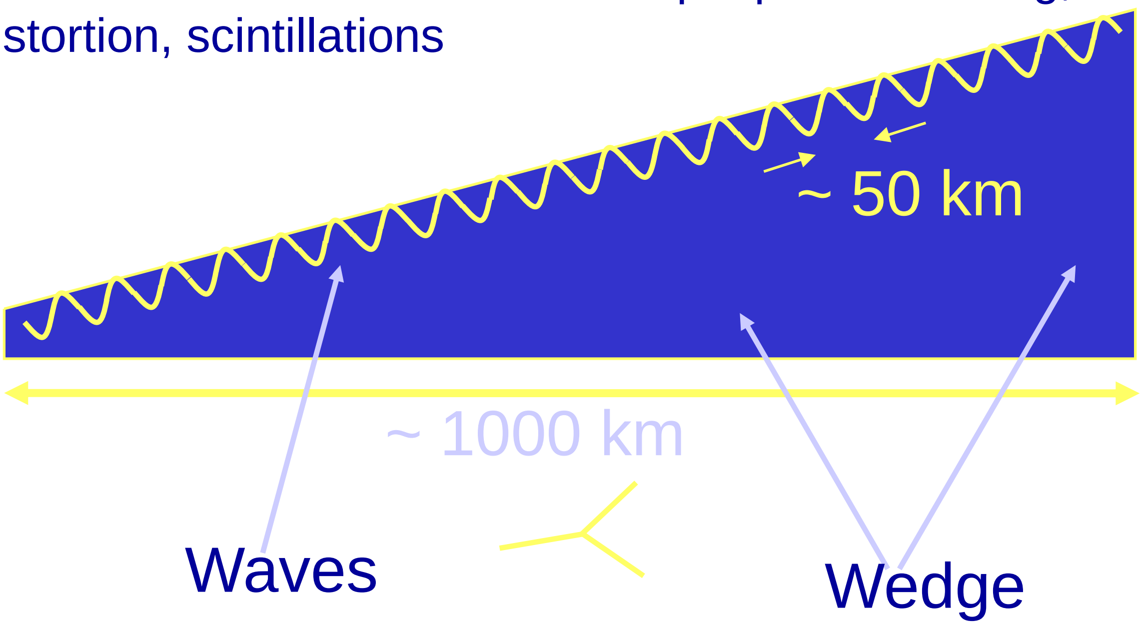
Not Easy but <u>certainly possible!</u>



Ionospheric Effects

Wedge Effects: Faraday rotation, refraction, absorption below ~ 5 MHz (atmospheric cutoff)

Wave and Turbulence Effects: Rapid phase winding, differential refraction, source distortion, scintillations



Wedge: characterized by

TEC = +$n_e$dl ~ 10^{17} m^{-2}

Extra path length adds extra phase

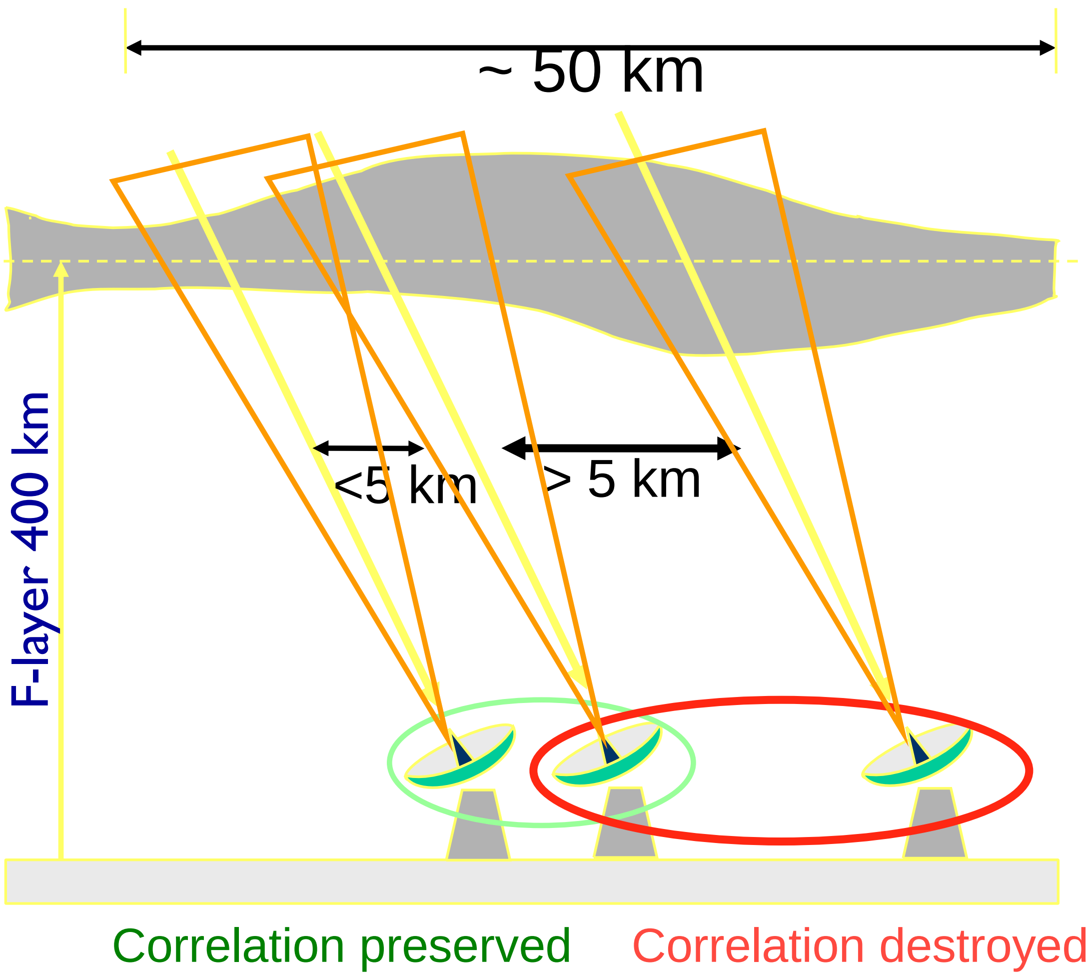
⊗L 〈 ⌊^{2} □ TEC

⊗⎞ ~ ⊗L∆⌊ ~ ⌊ * TEC

Waves: tiny (<1%) fluctuations superimposed on the wedge

- ➢ The wedge introduces thousands of turns of phase at 74 MHz
- ➢ Interferometers are particularly sensitive to difference in phase (wave/turbulence component)

Ionosphere



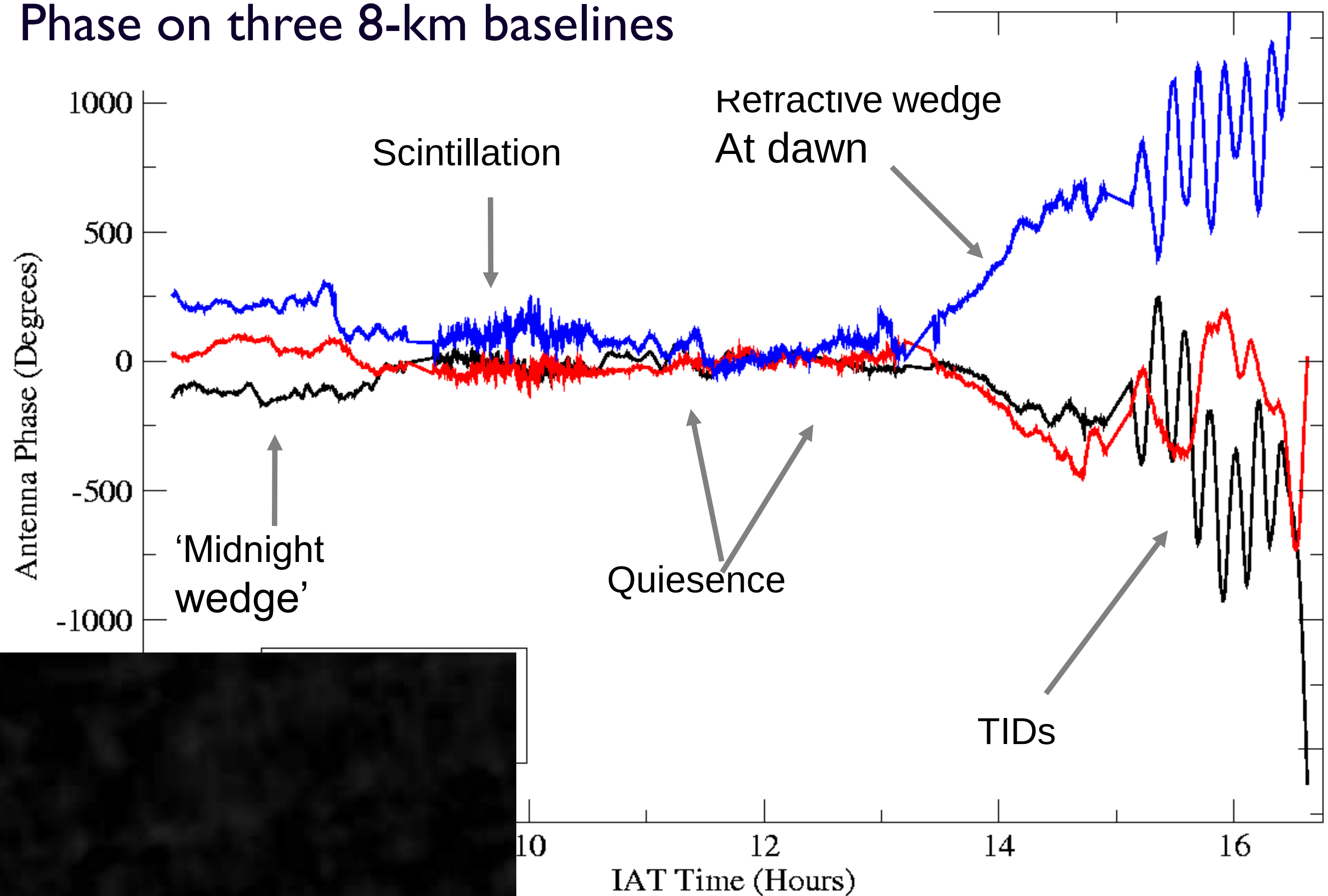
- Waves in the ionosphere introduce rapid phase variations (~1°/s on 35 km BL)
- Phase coherence is preserved on BL < 5km (gradient)
- BL > 5 km have limited coherence times
- Without proper algorithms this limits the capabilities of low frequency instruments

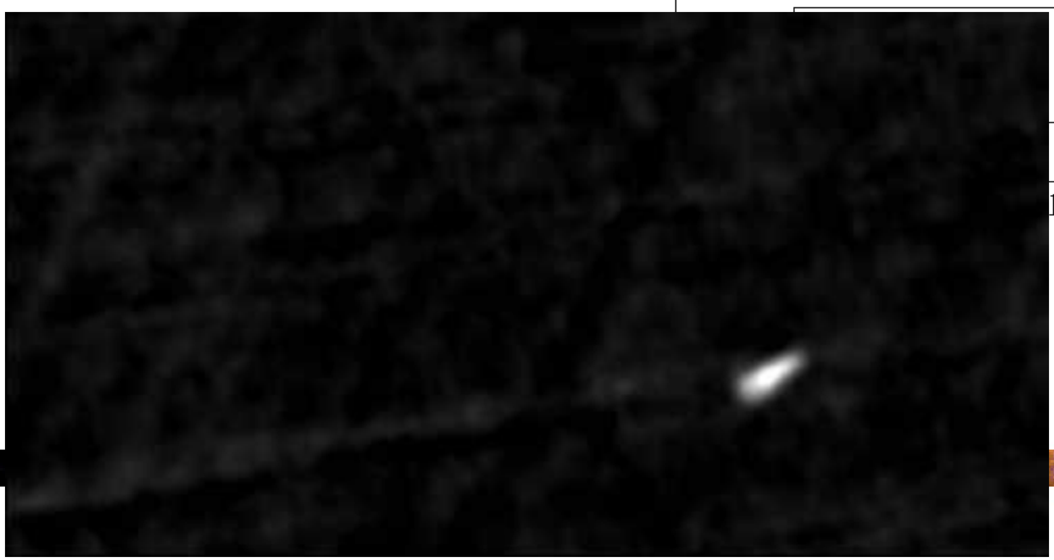
Antenna Phase as a Function of Time

- A wide range of phenomena were observed over the 12-hour observation

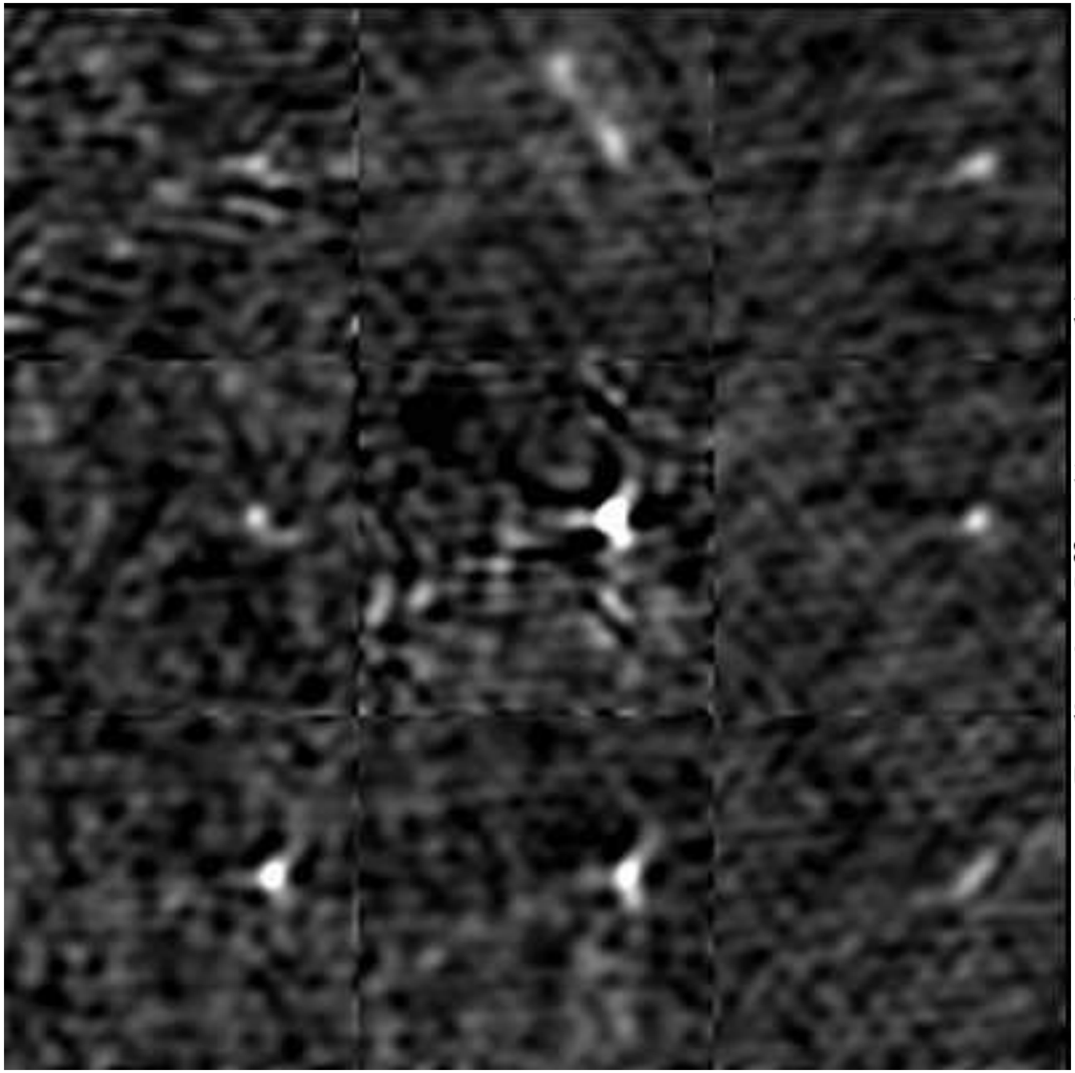
- Often daytime (but not dawn) has very good conditions

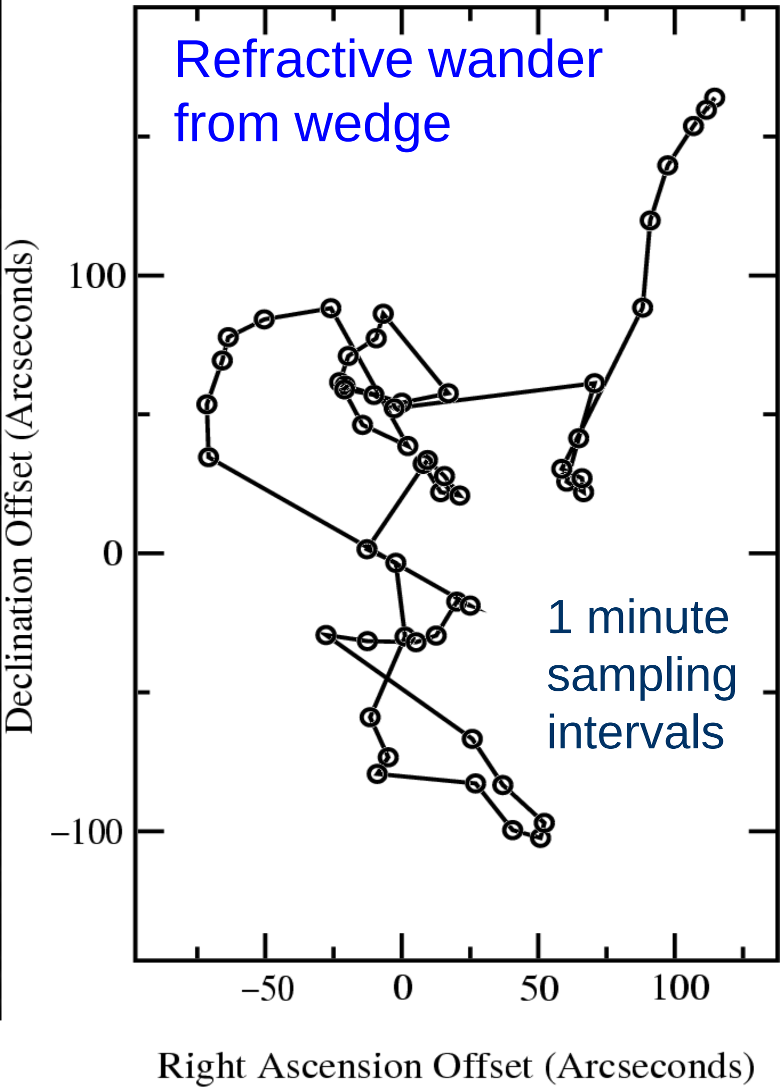
Phase on three 8-km baselines



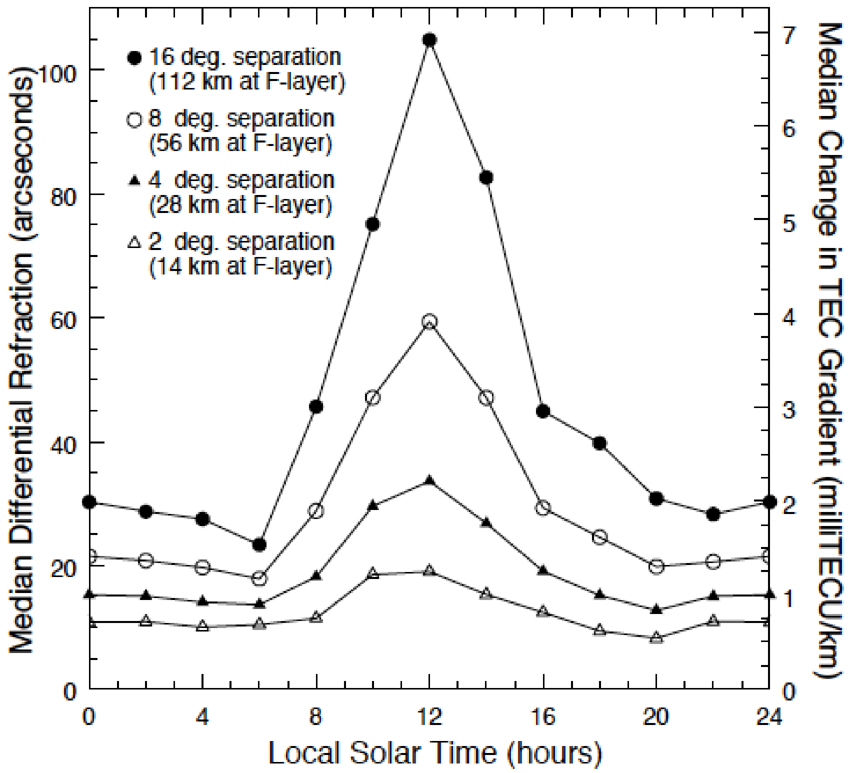


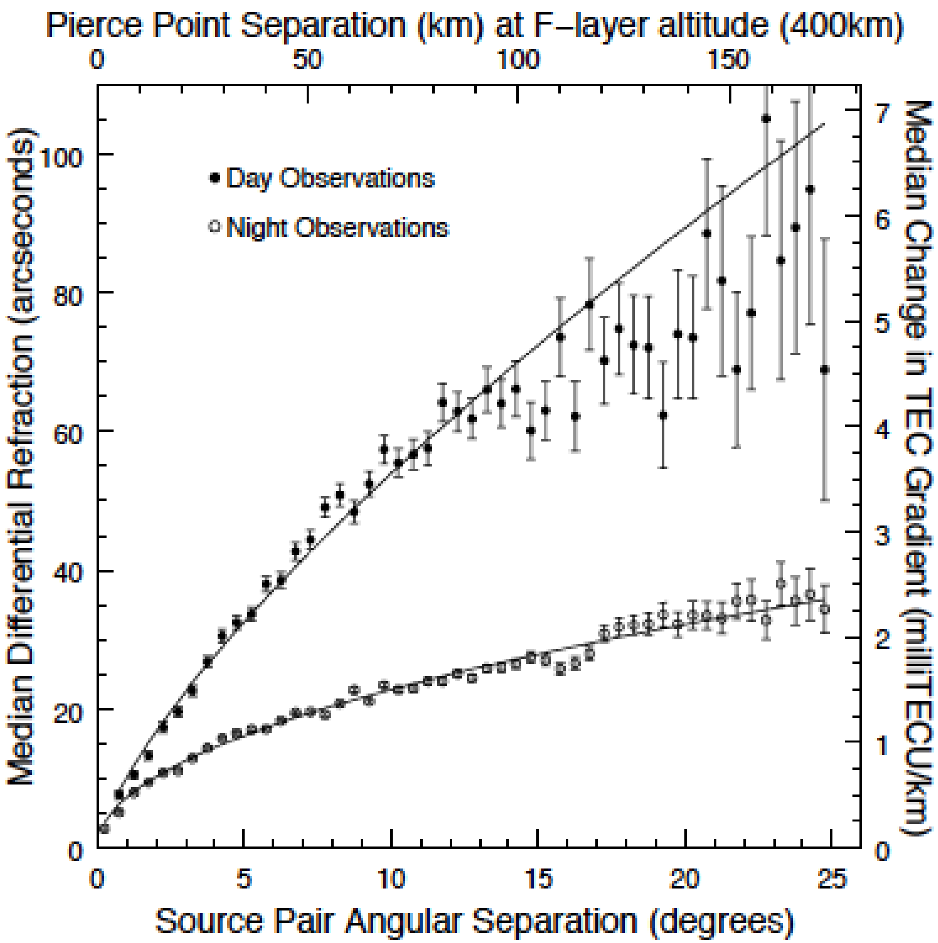
Ionospheric Refraction & Distortion





Ionospheric Differential Refraction

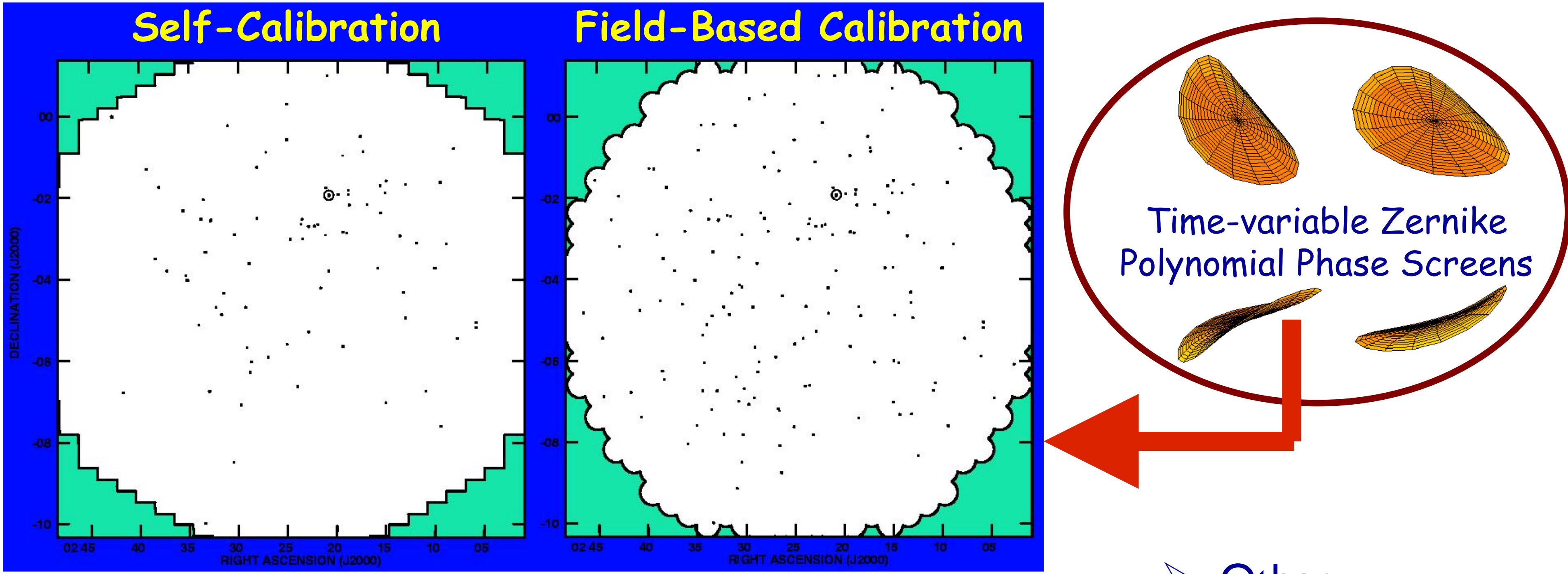




Cohen et al (2009)

Field-Based Calibration

- Rapid images of bright sources to compare to known positions
- Fit Zernike polynomial phase delay screen for each time interval.
- Apply time variable phase delay screen to produce corrected image.



Average positional error decreased from ~45” to 17”

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

- Other methods are under development

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Bandwidth Smearing

- Averaging visibilities over finite BW results in chromatic aberration worsens with distance from the phase center => radial smearing $(\otimes\{/\{_{|})x(\backslash_{|}/\backslash_{synth}) \sim 2 \Rightarrow I_o/I = 0.5$ => worse at higher resolutions

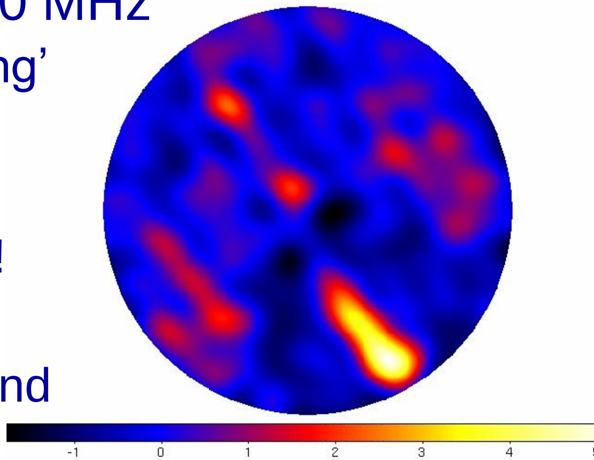
- Rule of thumb for full primary beam targeted imaging in A config. with less than 10% degradation:

74 MHz	channel width < 0.06	MHz
330 MHz	channel width < 0.3	MHz
1420 MHz	channel width < 1.5	MHz

Radio Frequency Interference: RFI

- Natural & man-generated RFI are a nuisance
  Getting "better" at low freq., relative BW for commercial use is low

- At VLA: many different signatures seen at 74 and 330 MHz
  signatures: narrowband, wideband, time varying, 'wandering'
  Solar effects – unpredictable
  Quiet sun is a benign 2000 Jy disk at 74 MHz
  Solar bursts, geomagnetic storms are disruptive => 10^9 Jy!
  Powerful Solar bursts can occur even at Solar minimum!
  Can be wideband (C & D configurations), mostly narrowband



- Best to deal with RFI at highest spectral resolution before averaging for imaging.

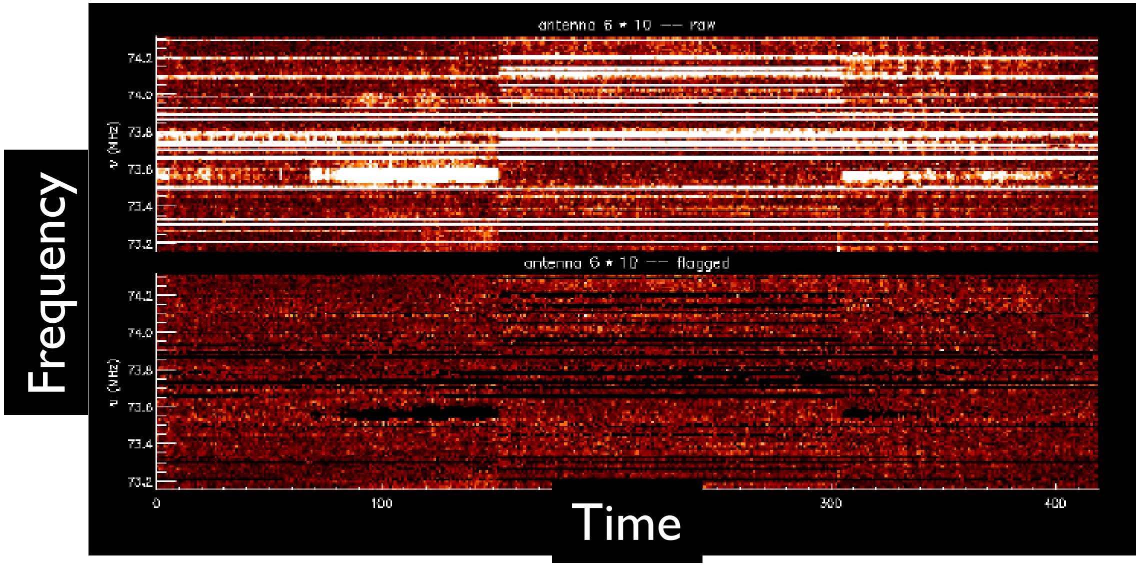
RFI Examples

Short baseline → Long baseline

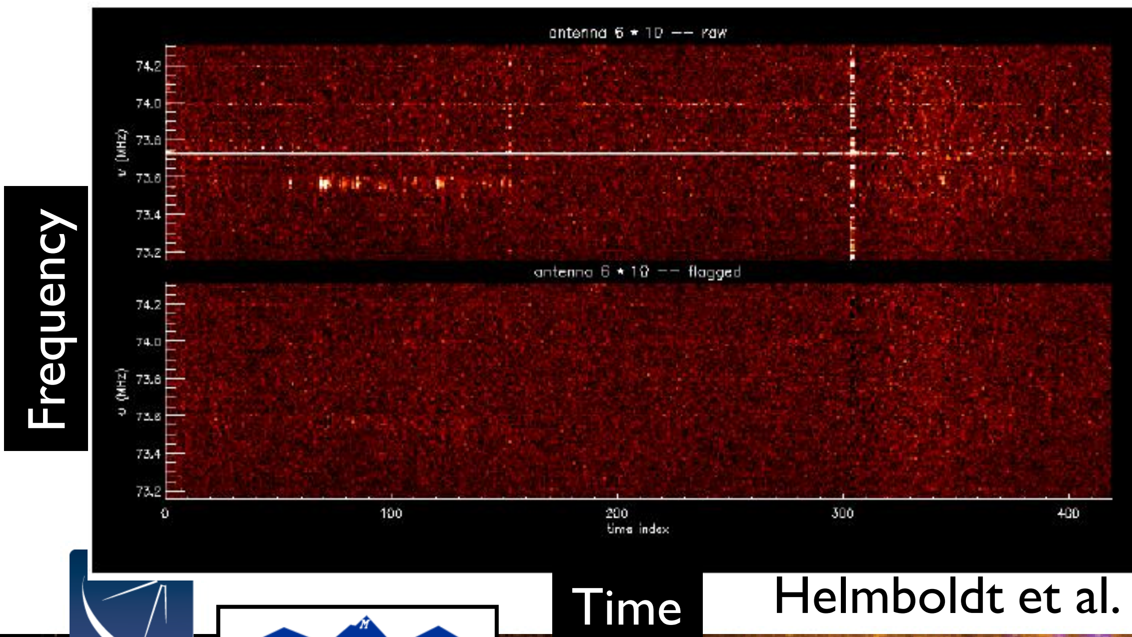
- RFI environment worse on short baselines
- Several 'types': narrow band, wandering, wideband, ...
- Wideband interference hard for some automated routines
- Example using AIPS tasks FLGIT, FLAGR, RFI, <u>*NEW:* </u>UVRFI

(Pen Talk)

RFI Excision vs Cancellation



- Many algorithms handle RFI through excision
  - OK if you have little RFI or lots of data
- Ideally we want to remove RFI and leave the data



- Current development aimed at cancellation
- Fringe stopping works well for constant RFI but not moving or time variable
- Full removal will likely require algorithms using multiple techniques

Helmboldt et al. (in prep.)

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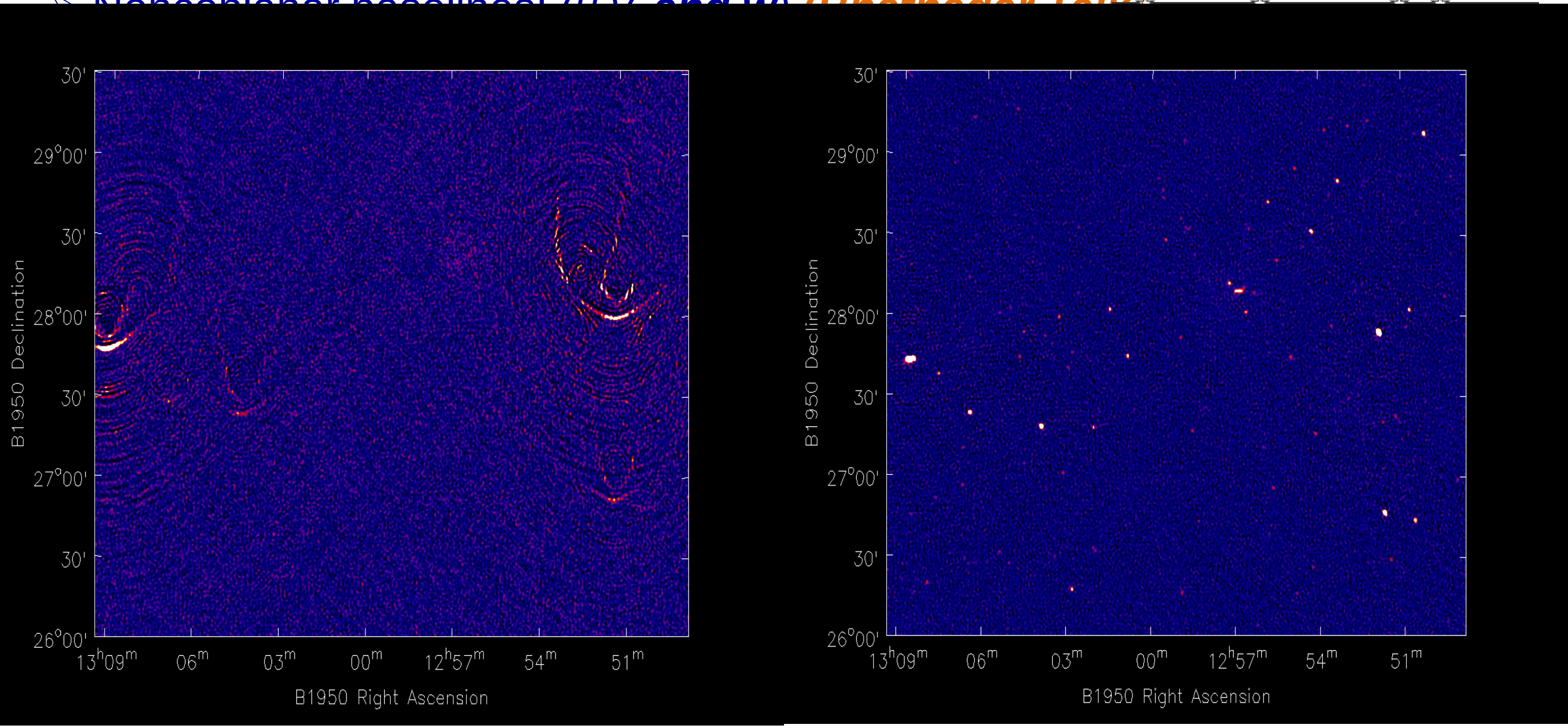
Large Fields of View: Imaging

- Noncoplanar baselines: (u,v, *and w*) *(Bhatnagar Talk)*

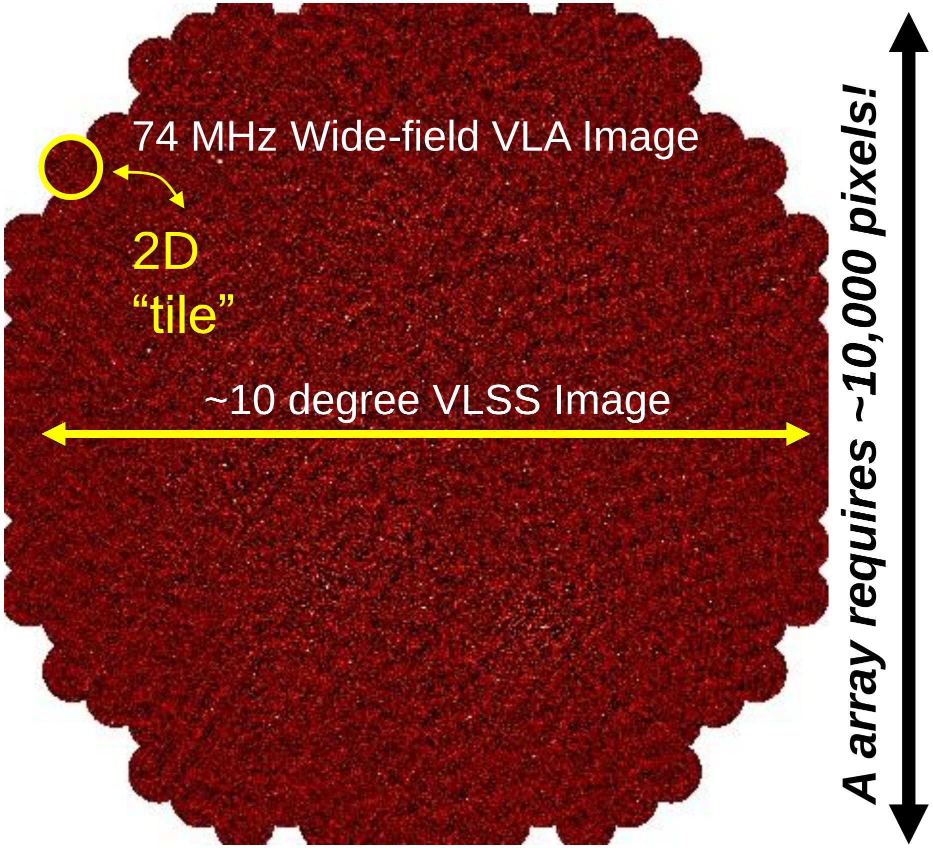


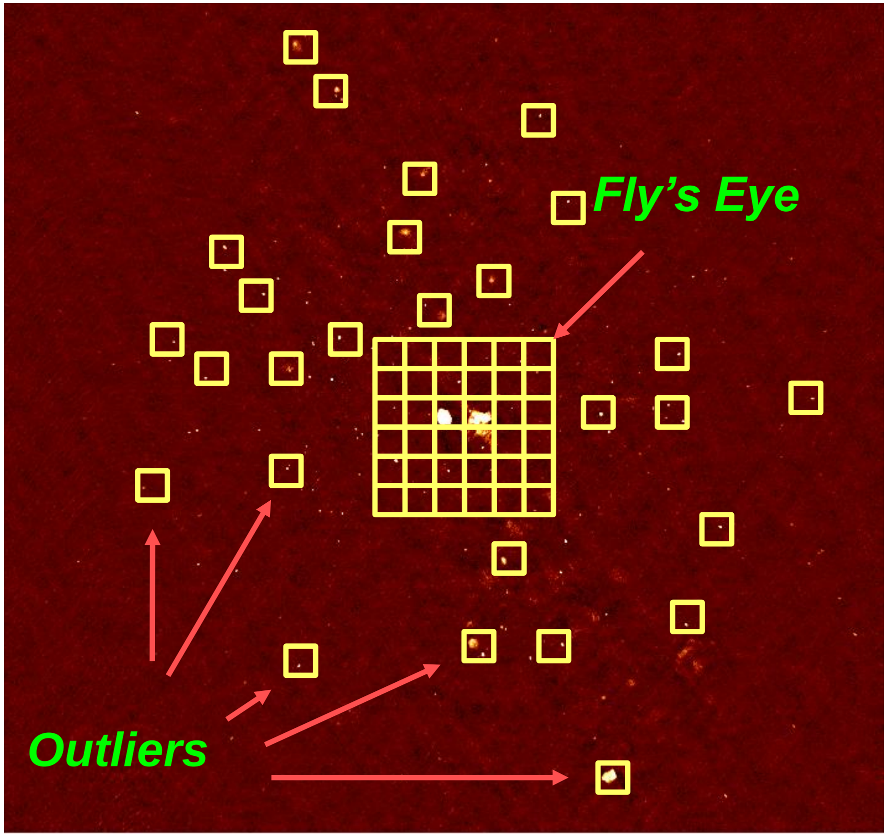
A array requires 10X more:

~ 3000 facets

~10^8 pixels

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

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Large Fields of View: Calibration

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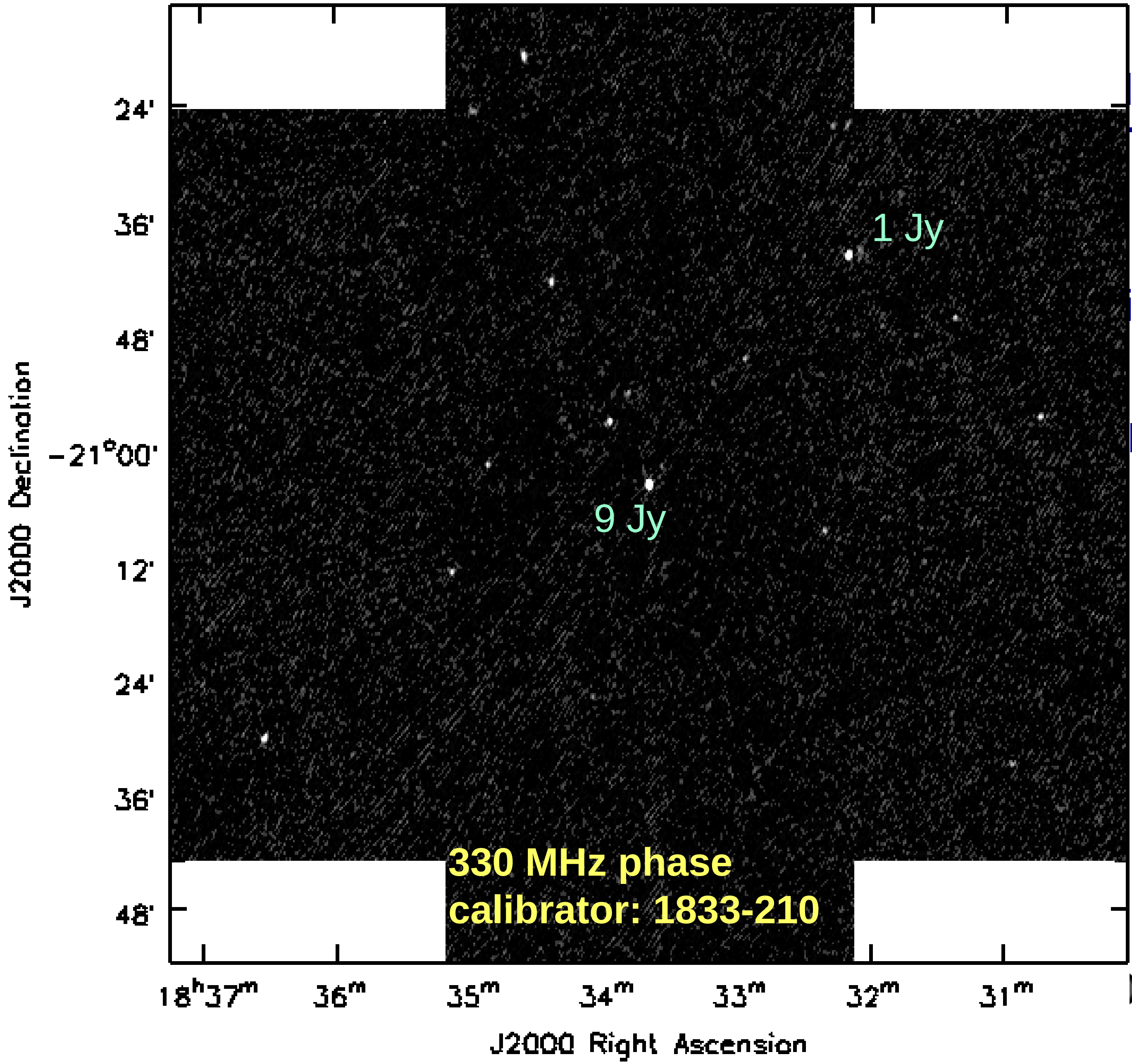

Summary

- Recent progress in wide-field imaging, RFI excision/cancellation, and ionospheric calibration are opening the low frequency spectrum to arcsecond resolution and mJy sensitivities – stay tuned for latest developments
- Advances will lead improved scientific capabilities for studies from Dark Ages to the ionosphere
- Next generation of low frequency instruments is being built while current instruments (such as the EVLA) are being upgraded
    - NRAO plans testing of the 4 band system in the upcoming C configuration and hopes to re-deploy it in B/BnA/A configs
    - Development of new P band system anticipates having new receivers ready by Nov. 2011
    - Initially observations will likely continue to use the old feeds but ideally new broadband feeds will be developed