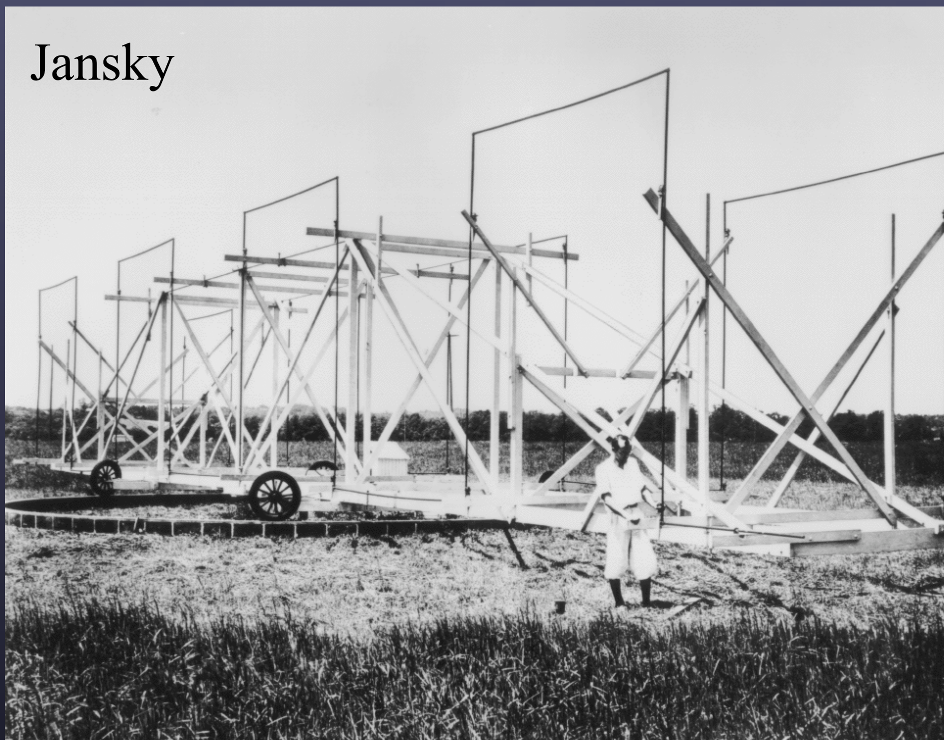
Low Frequency Interferometry

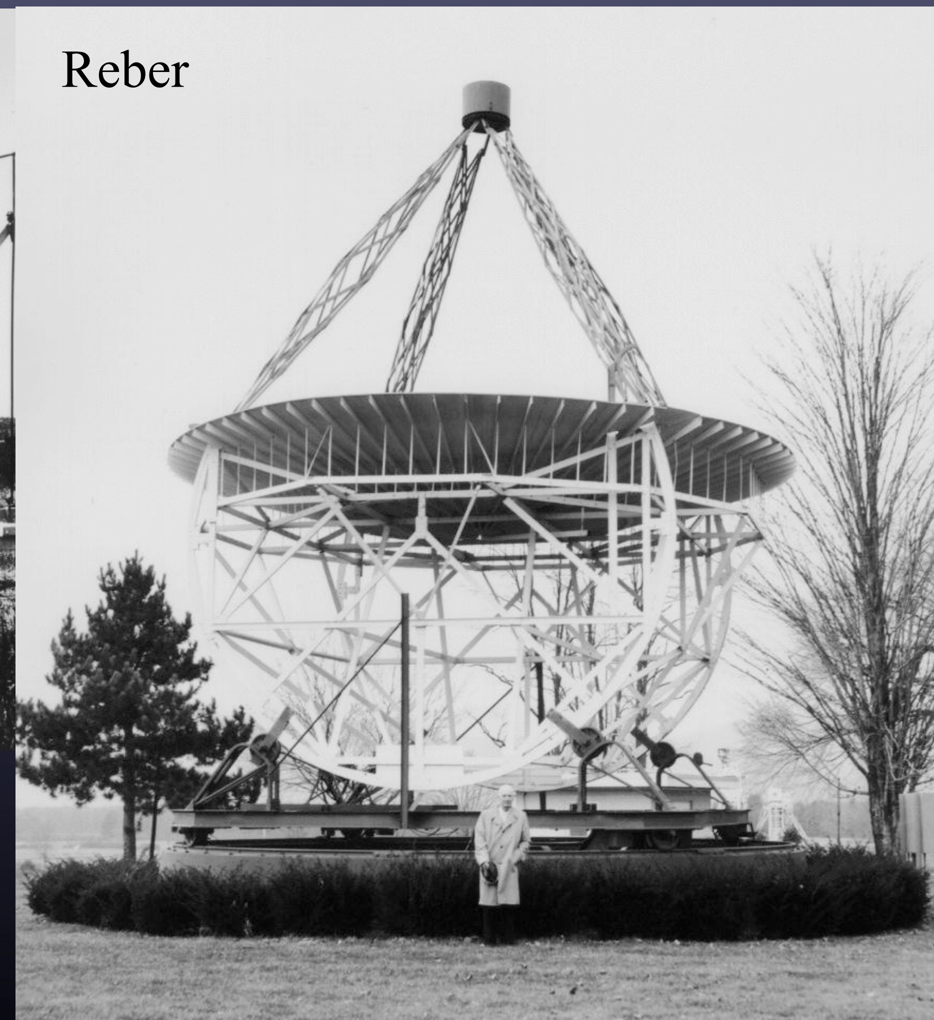
Tracy Clarke
(Naval Research Laboratory)

Eleventh Synthesis Imaging Workshop

Socorro, June 10-17, 2008

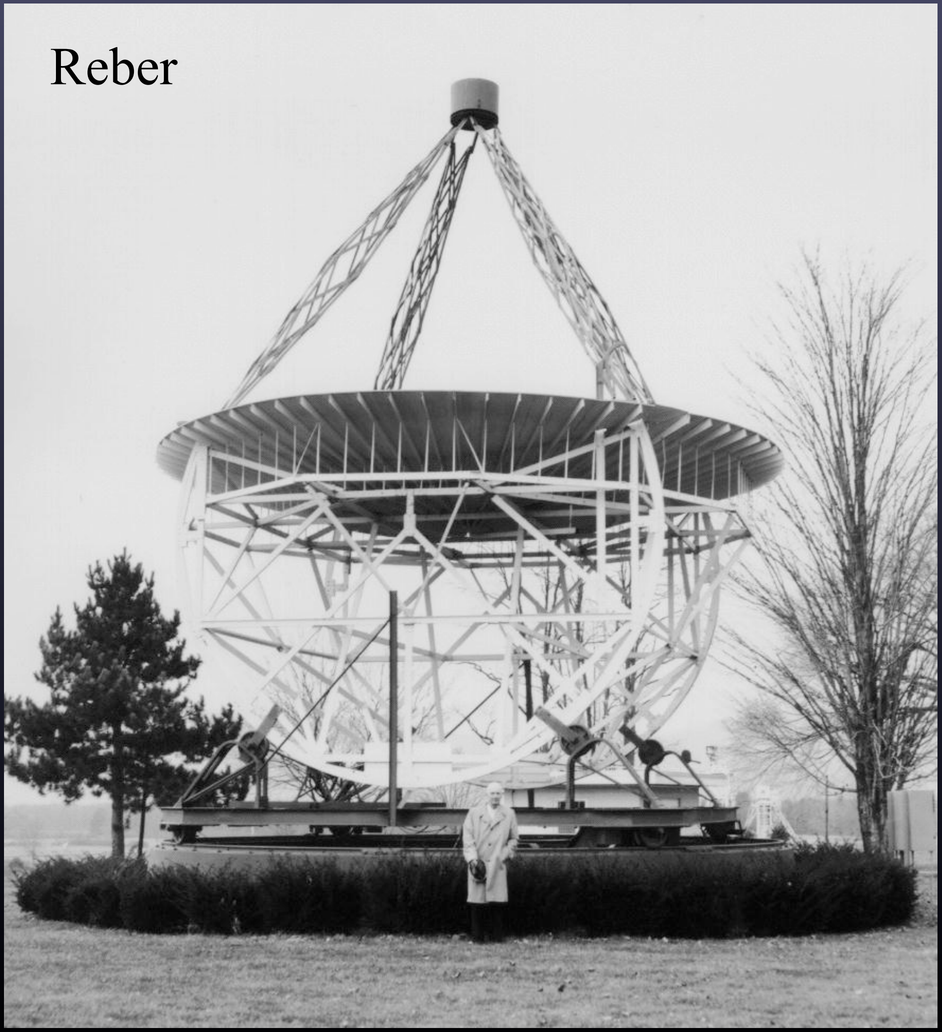
History of Radio Astronomy: Low Frequencies

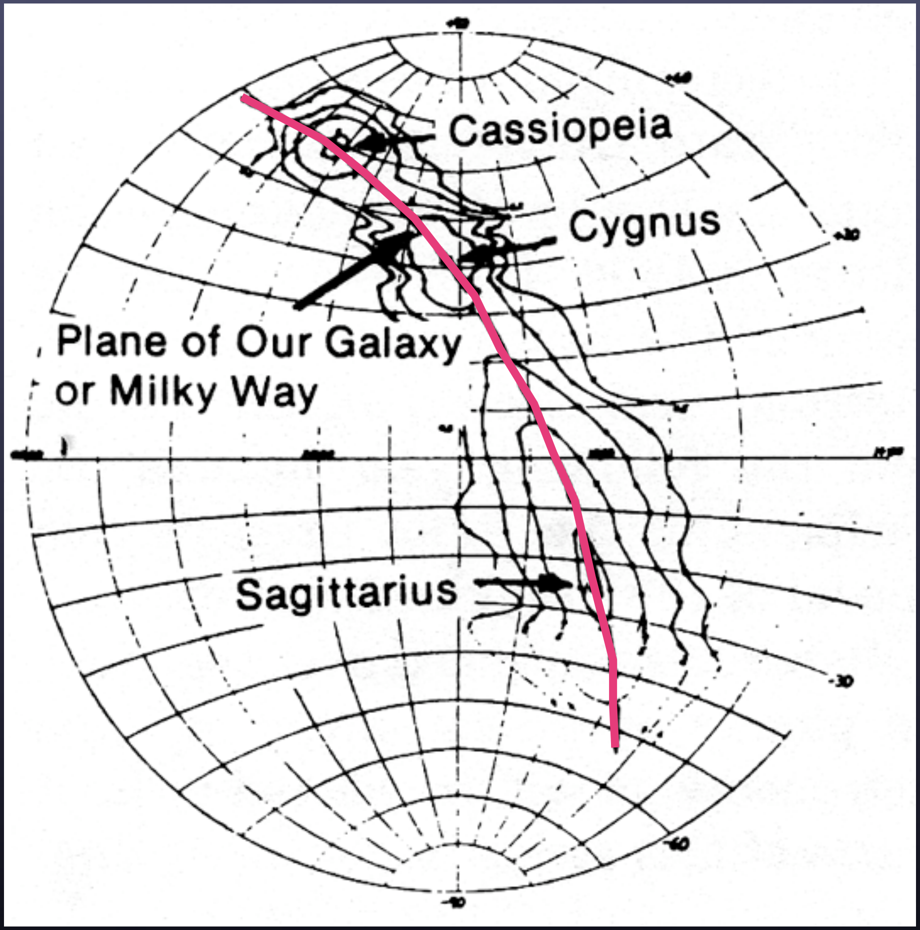




- Radio astronomy was born in the 1930's with Karl Jansky's work at 20.5 MHz (14.5 m) at Bell labs
- Reber continued radio astronomy work at 160 MHz (1.9 m) in his back yard

Reber's Radio Sky in 1944





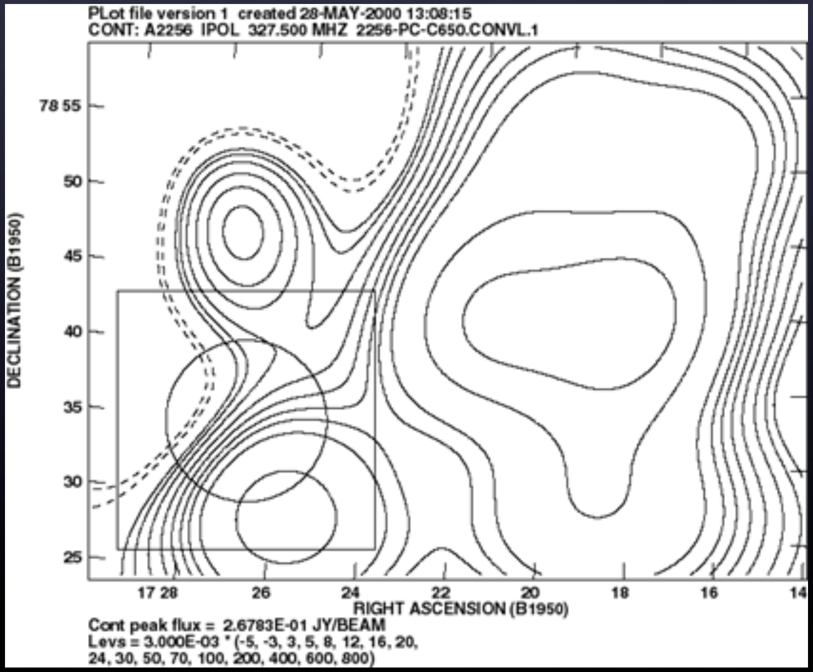
- 160 MHz sky image from Reber, resolution ~12 degrees

Fundamental Limitation

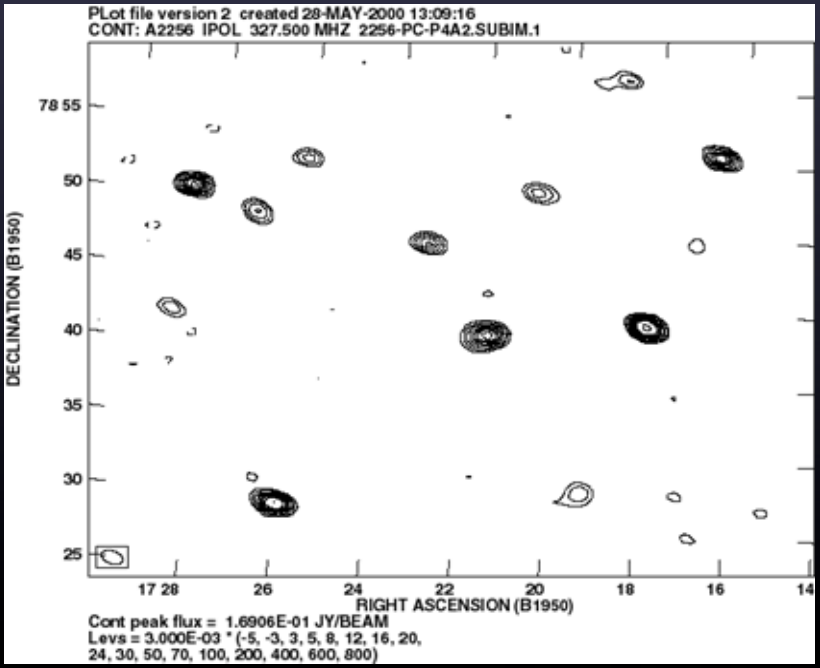
- Spatial resolution depends on wavelength and antenna diameter: $\theta \simeq \frac{\lambda}{D}$
- First long wavelength antennas had very low spatial resolution
- Astronomers pushed for higher resolution and moved to higher frequencies were the T_{SYS} is also lower: $T_{sys}(K) = 131000 \left(\frac{\nu}{15MHz}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

Confusion:

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



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



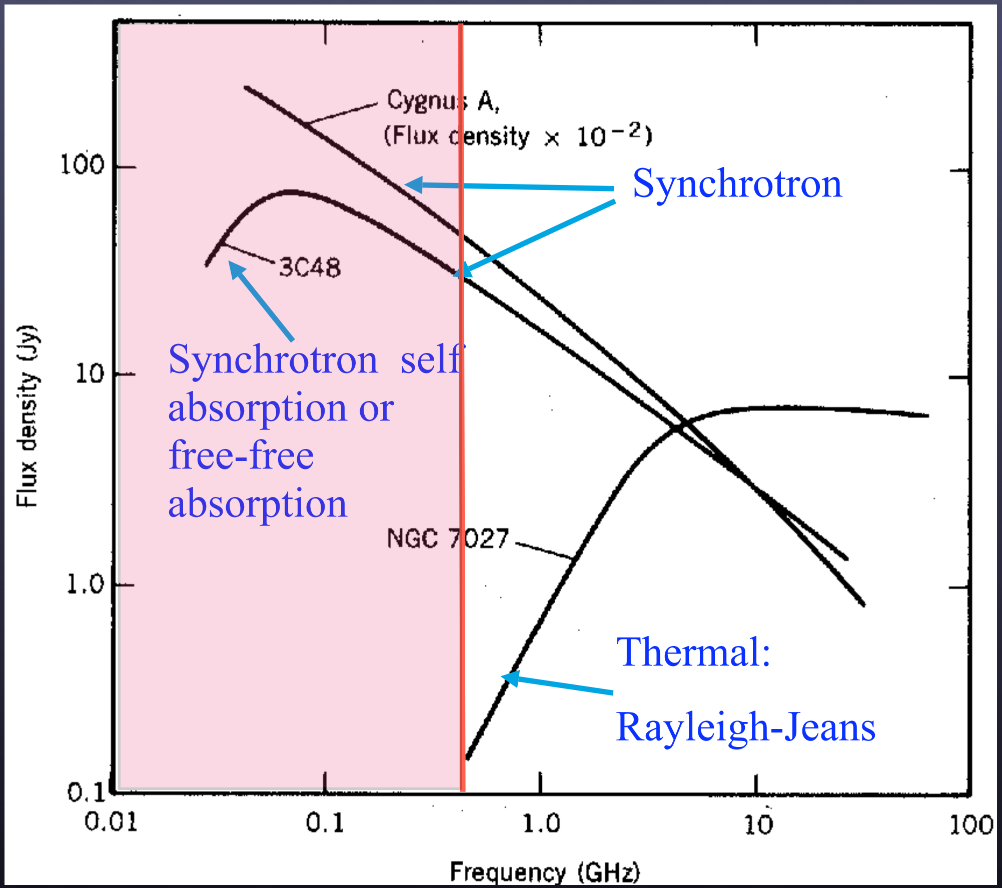
Emission Mechanism at Low Frequency

Synchrotron Emission: ***(Lang Lecture)***

- Best observed at m λ (ν < 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

Thermal Emission ***(Brogan Lecture)*** (Free-Free, Bremsstrahlung):

- Best observed at cm λ (ν > 1 GHz)
- Deflection of free electrons by positive ions in hot gas
- Depends on temperature of the gas



Thompson, Moran, & Swenson

Recombination Lines

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

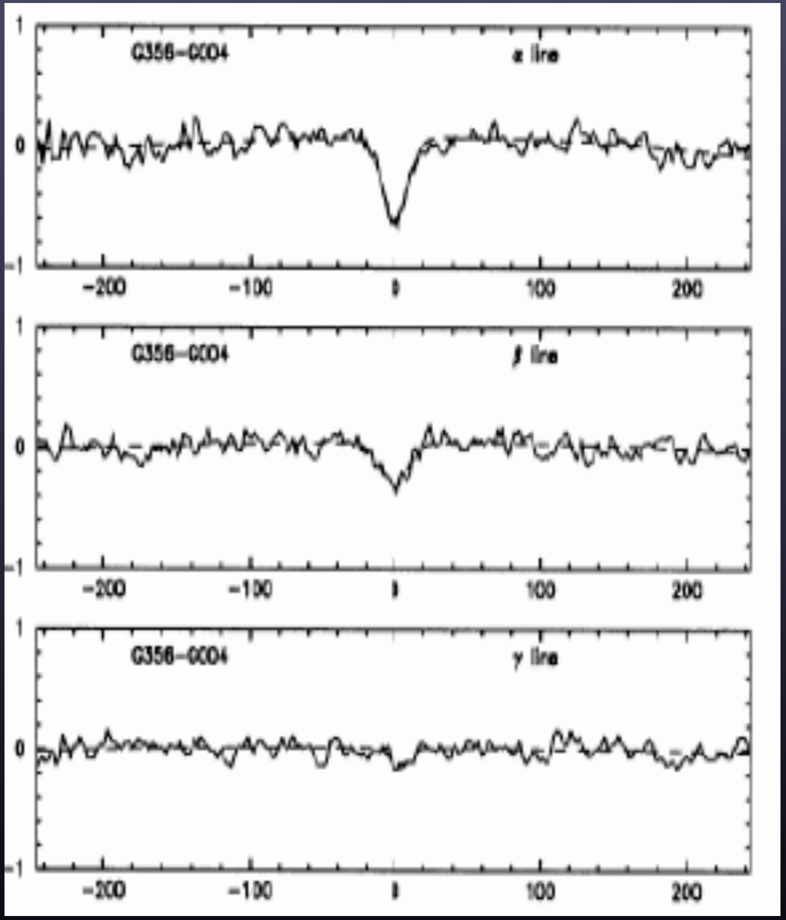
• High quantum number n state (n>100 for low frequencies), formed in transition region between fully ionized regions and neutral gas (PDRs)

• Nomenclature: $n+\Delta n \rightarrow n$, $\Delta n=1$ is $n\alpha$, $\Delta n=2$ is $n\beta$, $\nu_o \propto \Delta n/n^3$ (e.g. C441α)

• Largely observed toward the Galactic Plane and discrete source. Detected in H and (below 120 MHz) C in absorption

• Diagnostics of the physical conditions of the poorly probed cold ISM, e.g.

- temperature
- density
- level of ionization
- abundance ratios



Erickson et al. 1995

Low Frequency Science

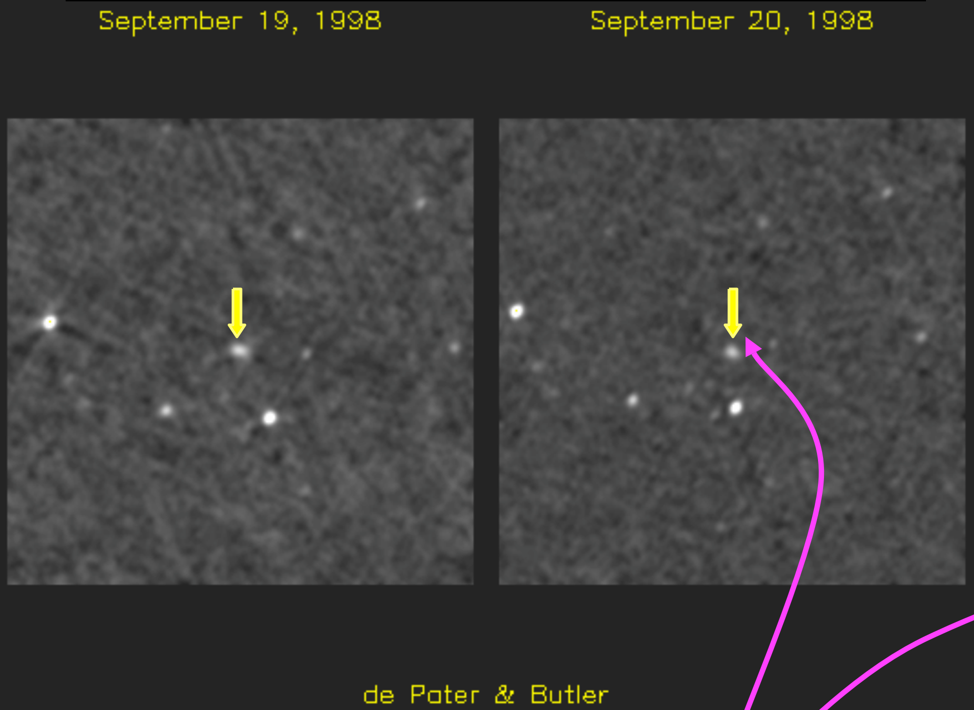
- Key science unique to low frequencies:
  - Dark Ages (spin decoupling)
  - Epoch of Reionization (highly redshifted 21 cm lines)
  - Early Structure Formation (high z RG)
  - Large Scale Structure evolution (diffuse emission)
  - Evolution of Dark Matter & Dark Energy (Clusters)
  - Wide Field (up 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)

Bursts From Jupiter & Extra-Solar Planets

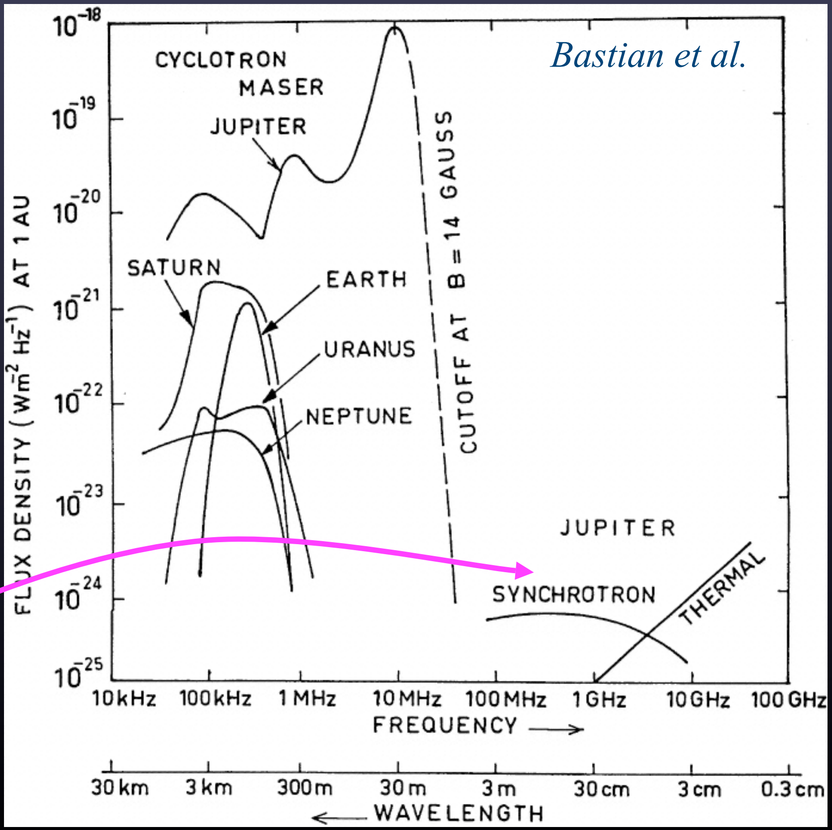
➢ Jupiter's coherent cyclotron emission: complex interaction of Jupiter's magnetosphere with Io torus *(Butler Lecture)*

POSSIBLE TO DETECT BURST EMISSION FROM DISTANT "JUPITERS"

VLA 74 MHz Jupiter images



VLA SYSTEM
CAN DETECT QUIESCENT EMISSION



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

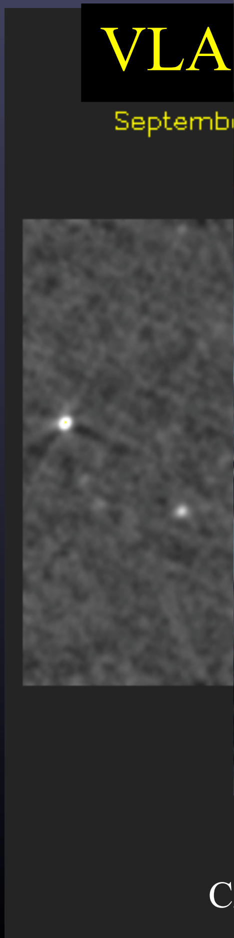
Bursts From Jupiter & Extra-Solar Planets

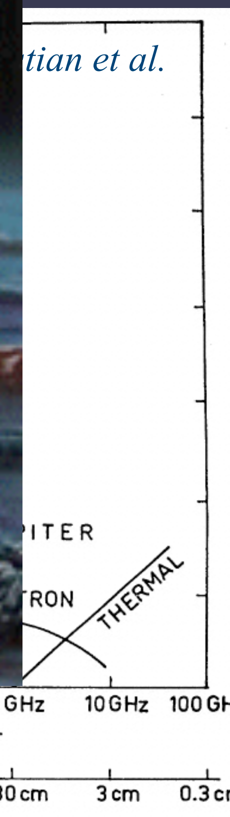
➢ Jupiter's coherent cyclotron emission: complex

interact

(Butler Le

TO
URST
ON
TANT
RS”

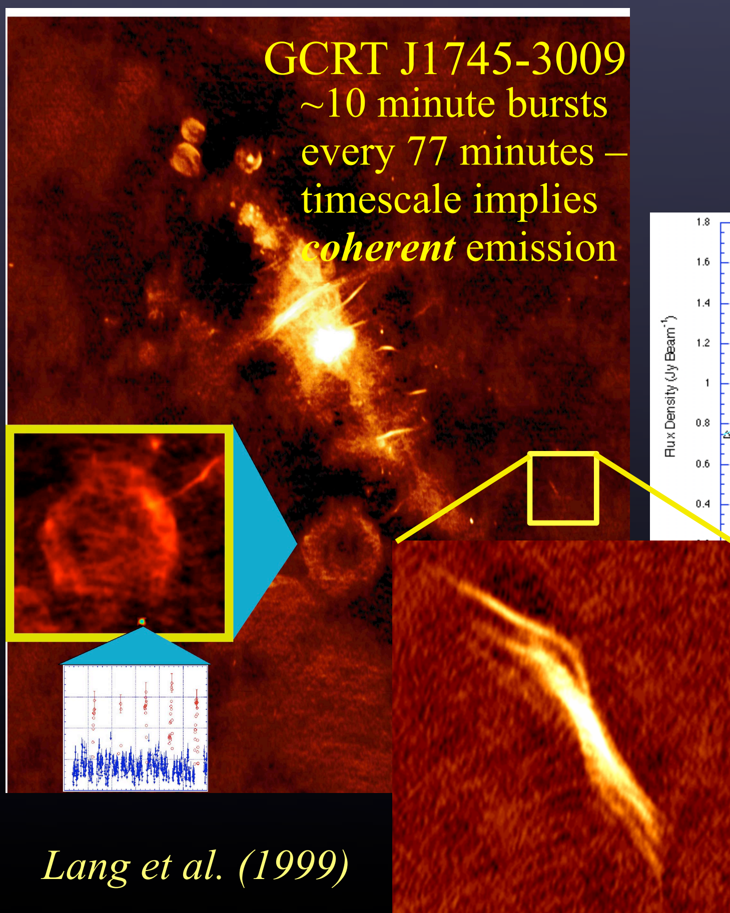




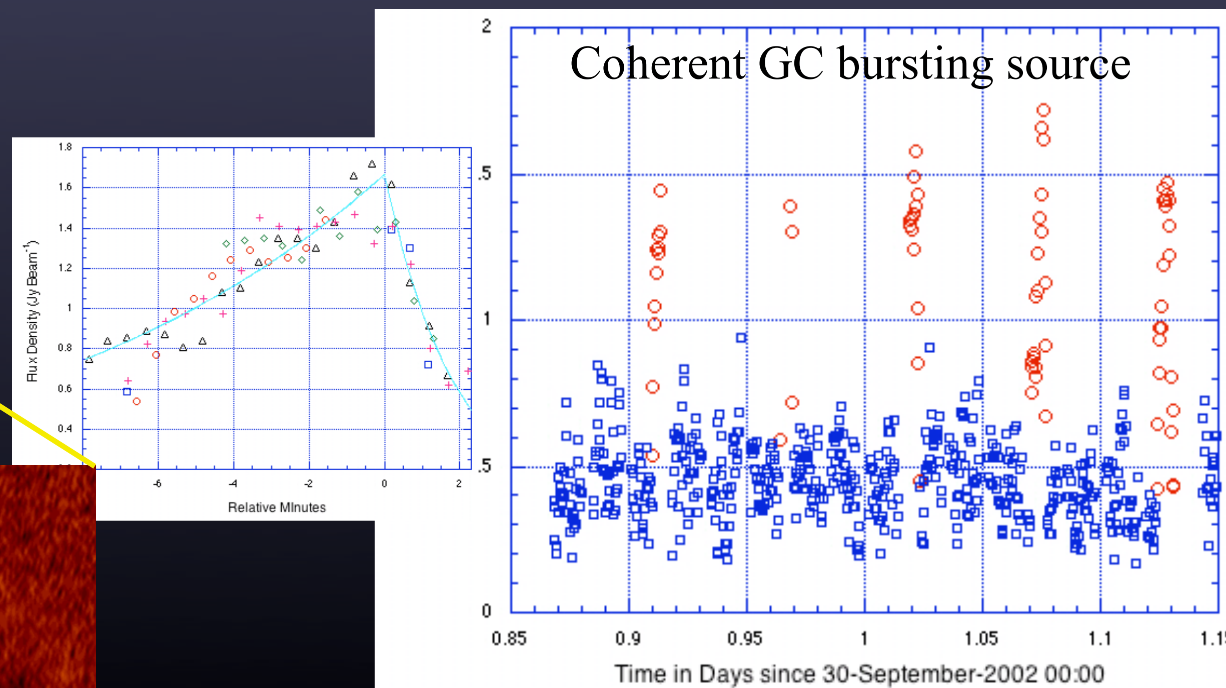
Future instruments will resolve Jupiter and may detect extra-solar planets

Galactic Center

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



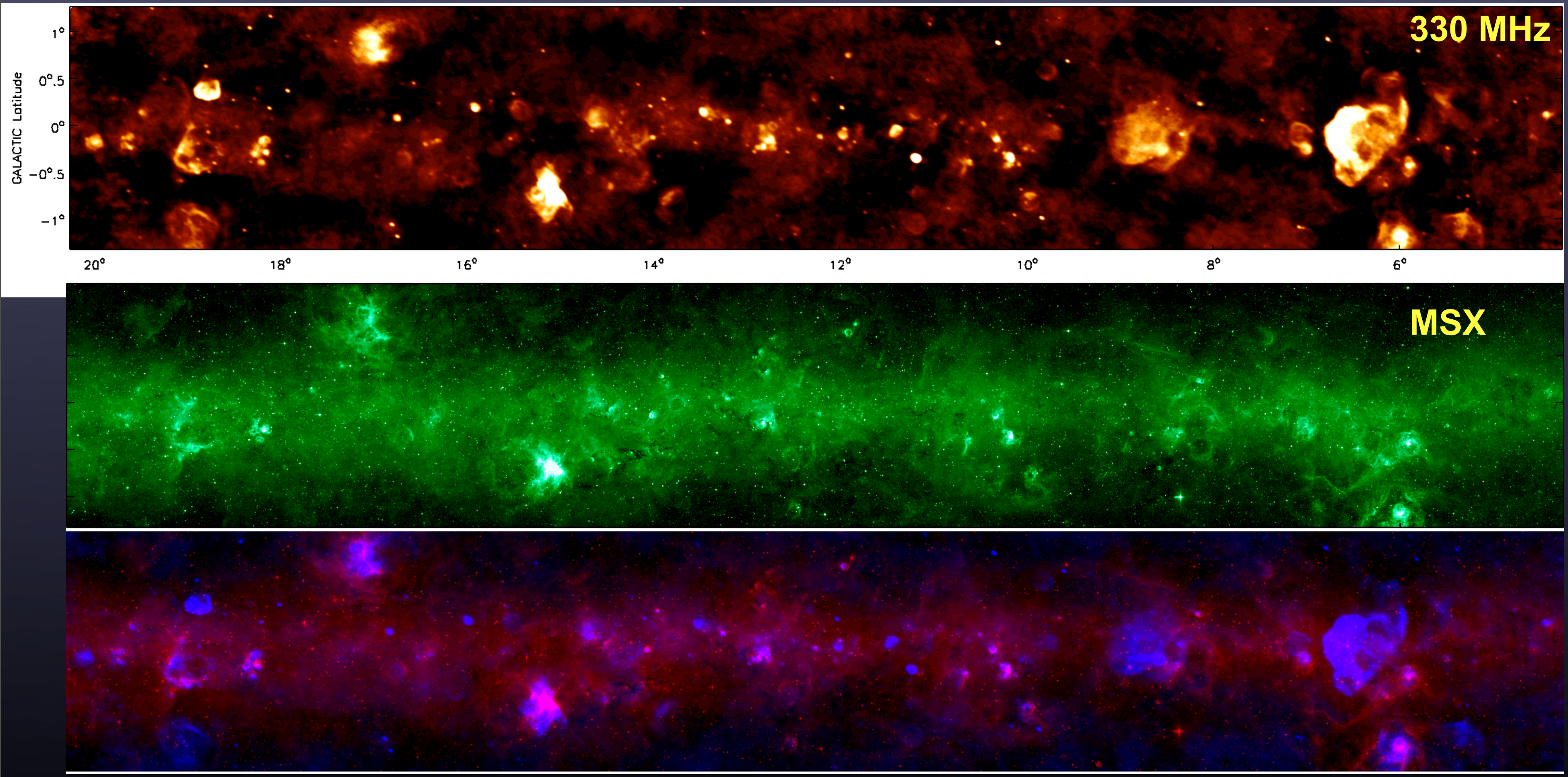
Lang et al. (1999)



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

Galactic Supernova Remnant Census

➢ Census: expect over 1000 SNR and know of ~230



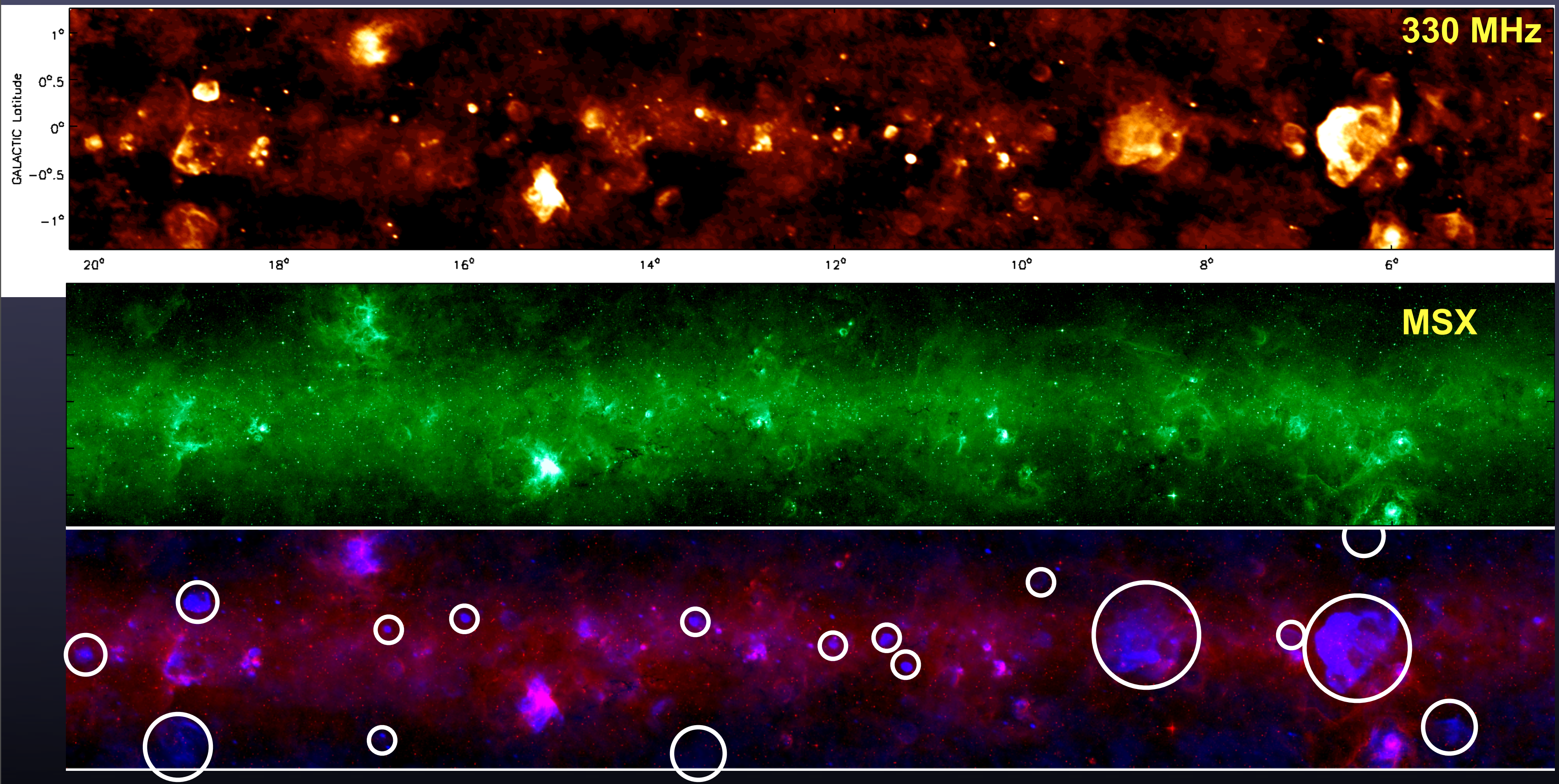
2 Color Image:
Red: MSXat 8 μm
Blue: VLA 330 MHz

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

Brogan et al. (2006)

Galactic Supernova Remnant Census

- ➢ Census: expect over 1000 SNR and know of ~230



2 Color Image:
Red: MSXat 8 μm
Blue: VLA 330 MHz

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

Brogan et al. (2006)

Pulsars

- Detecting fast (steep-spectrum) pulsars
  - – highly dispersed, distant PSRs
  - – tight binaries
- Probe PSR emission mechanism
  - – explore faint end of luminosity function
  - – spectral turnovers near 100 MHz
- New SNR/pulsars associations
  - -- Deep, high surface brightness imaging of young pulsars

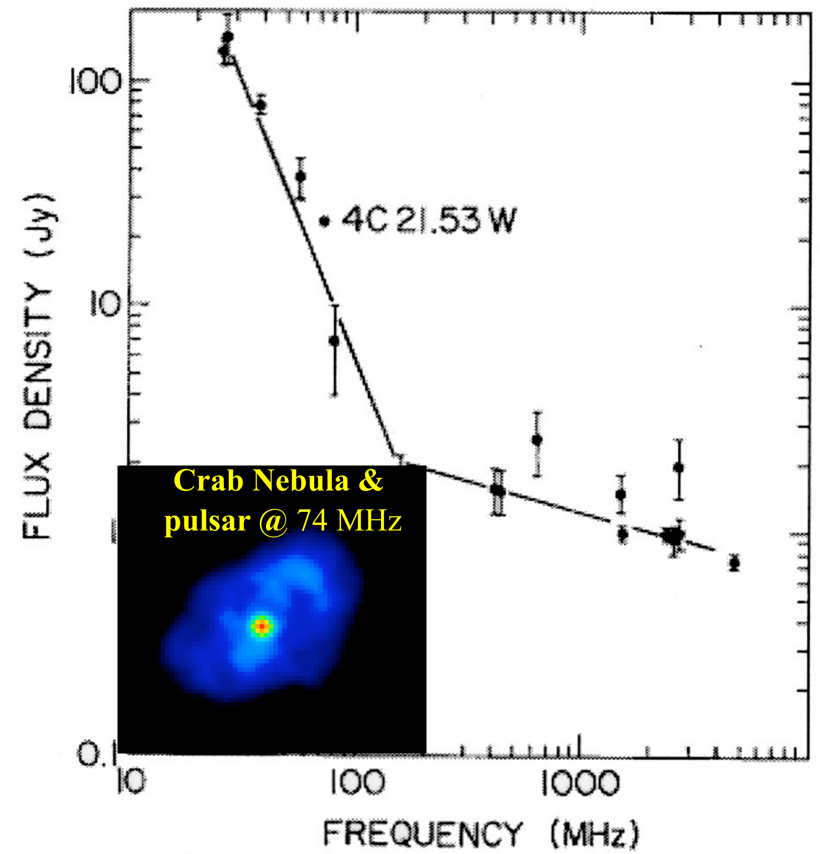
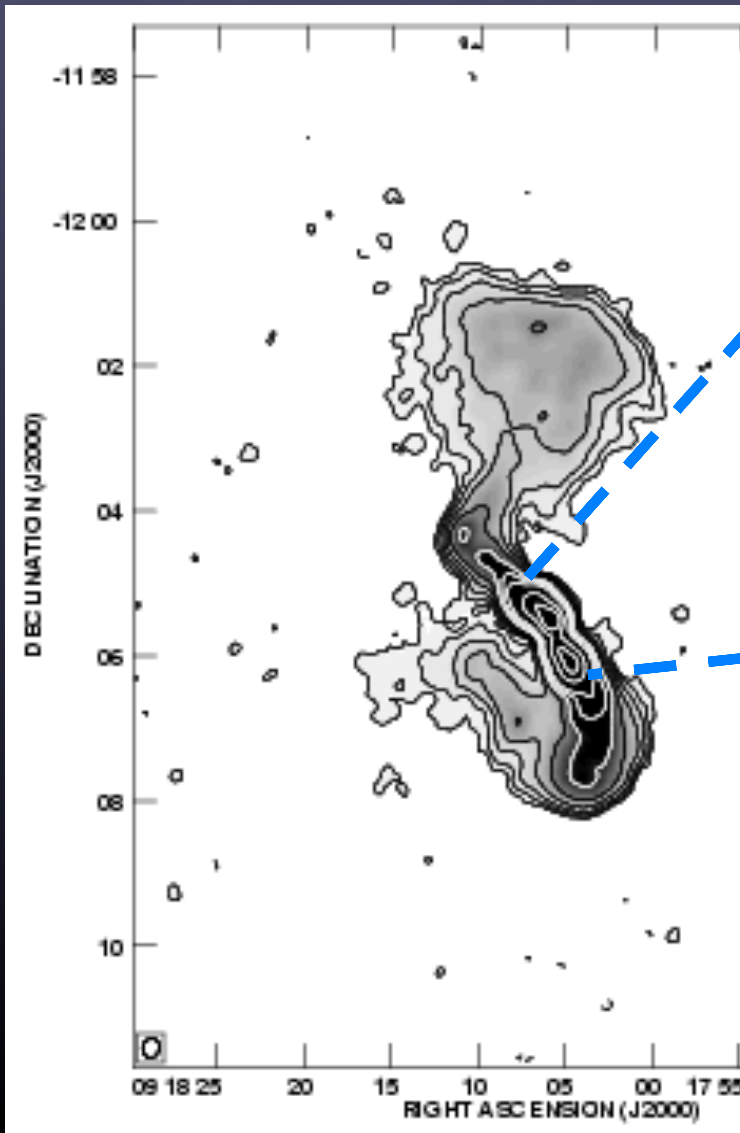


FIG. 2.—The radio spectrum of 4C 21.53W. Data are listed in Table 2. The solid lines correspond to spectral indices of −0.26 (ν > 150 MHz) and −2.44 (ν > 150 MHz).

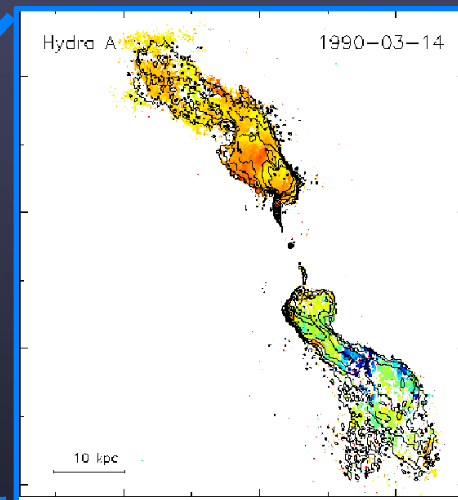
Spectrum of 4C21.53: 1st msec pulsar

Radio Galaxies: Outburst Lifecycle



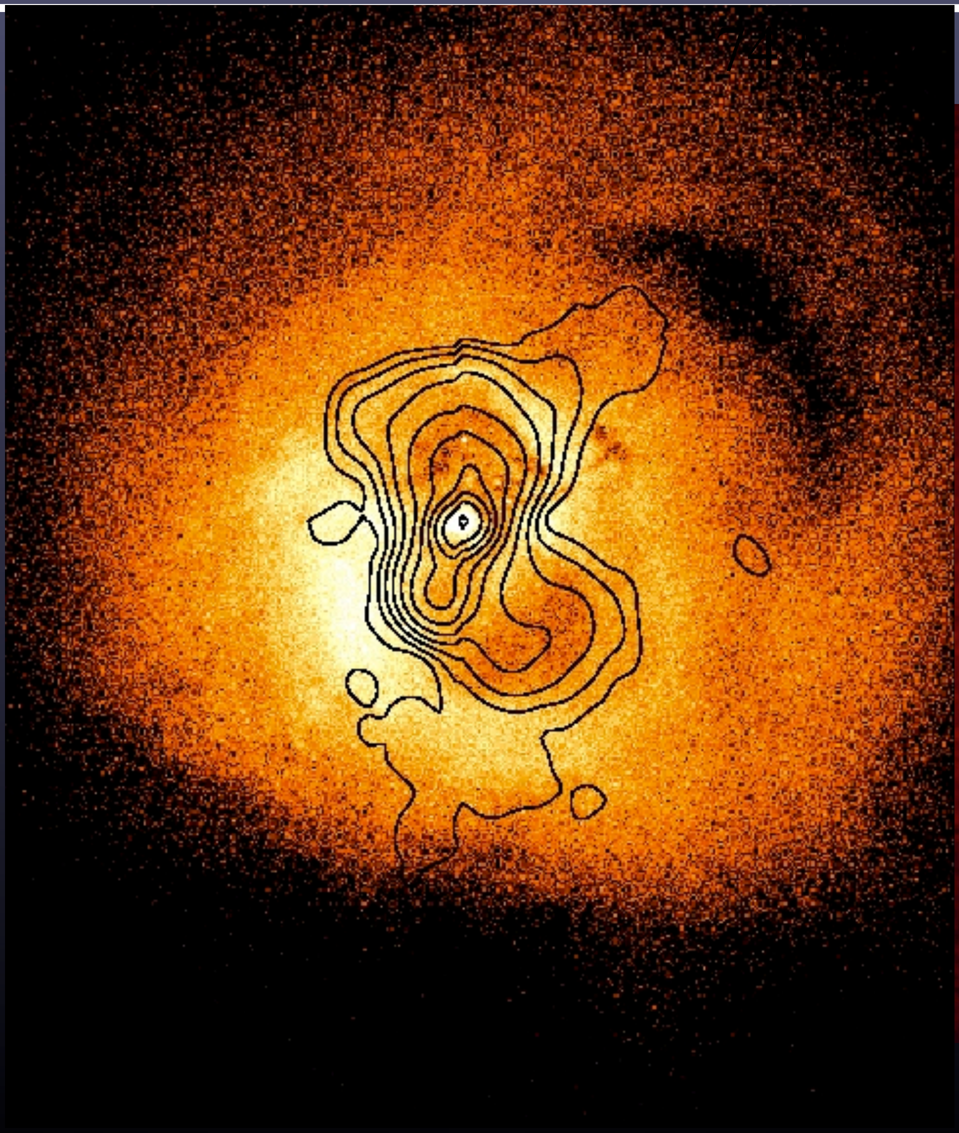
Lane et al. (2004)

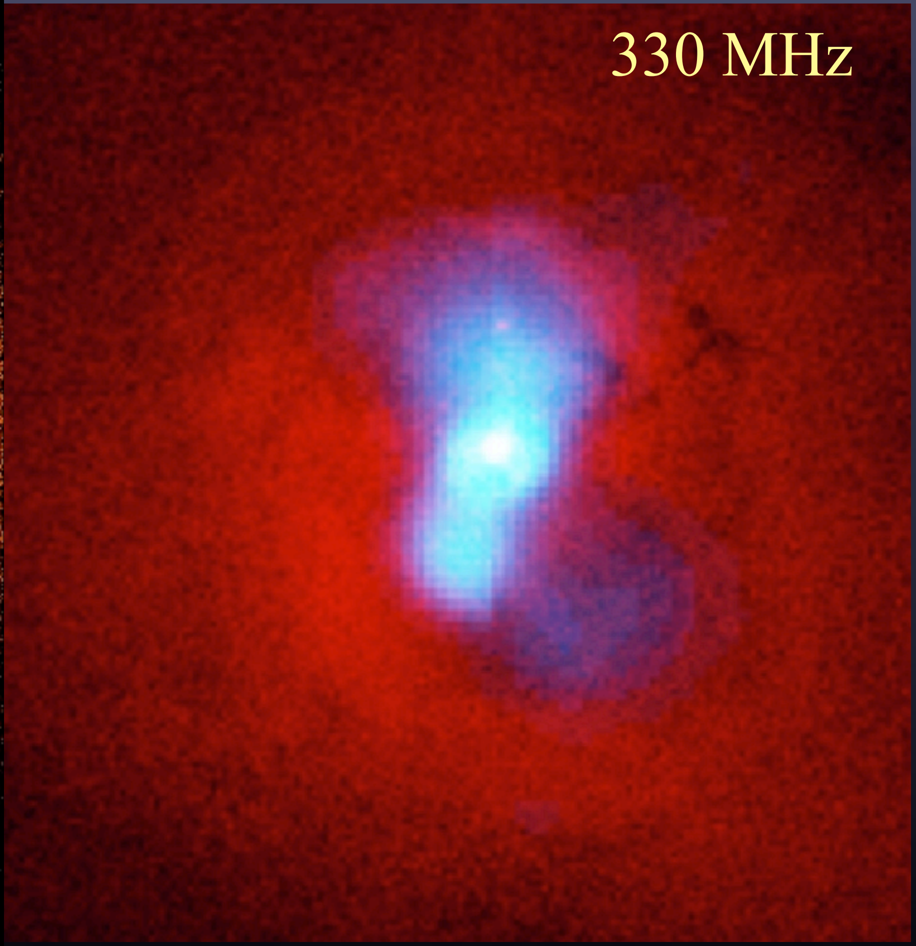
- Hydra A at 4500 MHz (inset) shows an FR-I morphology on scales of <1.5' (100 kpc)



- 74 and 330 MHz data show Hydra A is > 8' (530 kpc) in extent with large outer lobes surrounding the high frequency source
- Outer lobes have important implications for the radio source lifecycle and energy budget

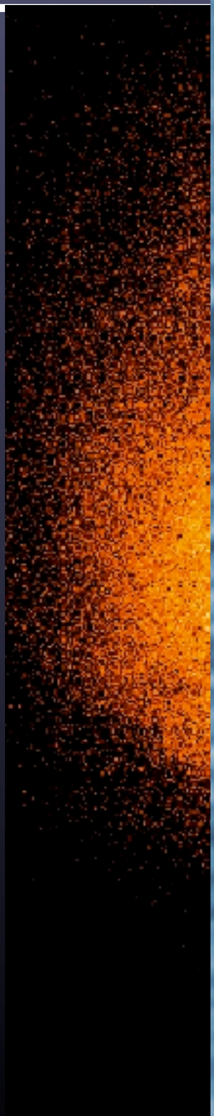
Galaxy Cluster Cores: AGN Feedback

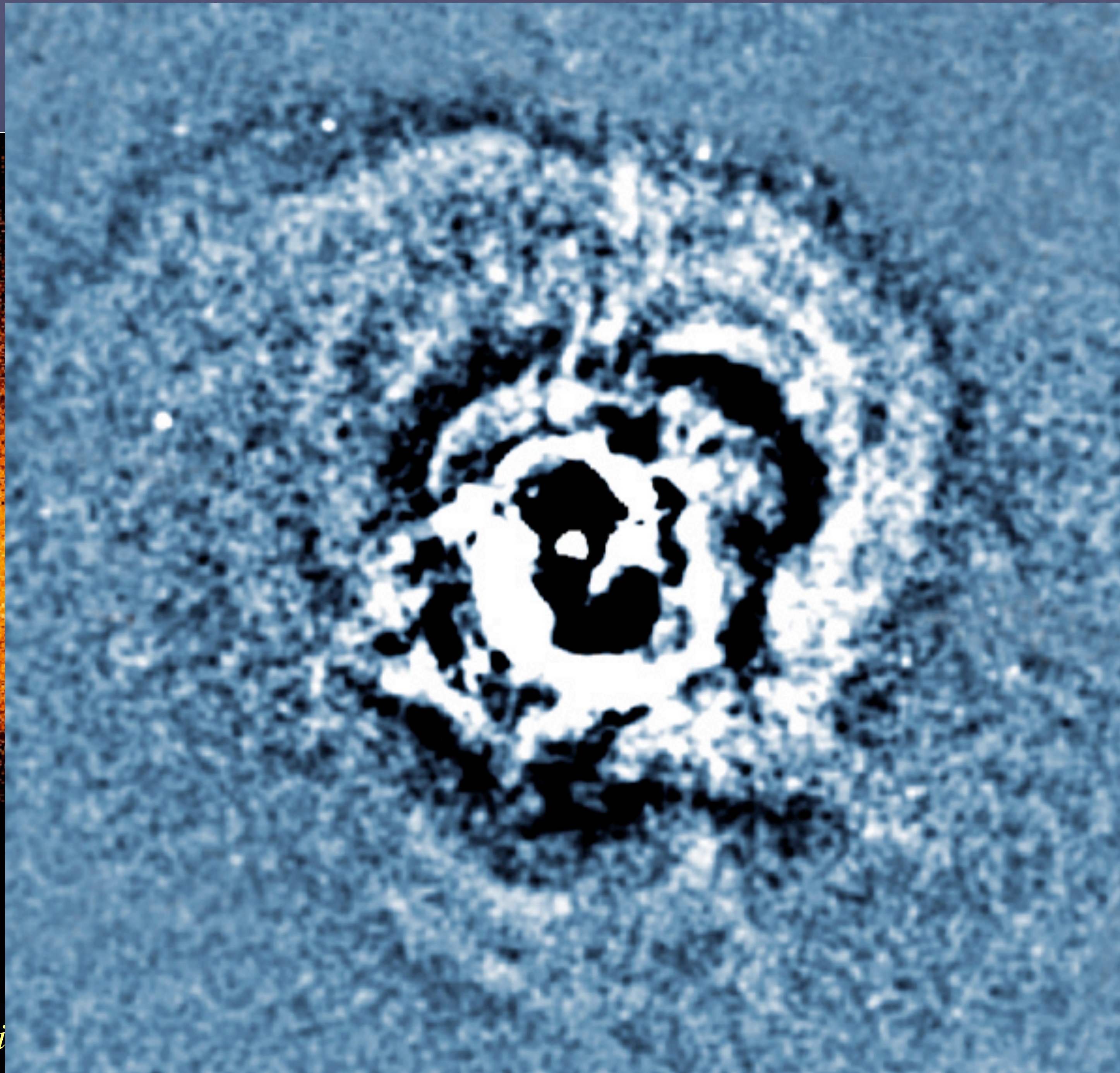


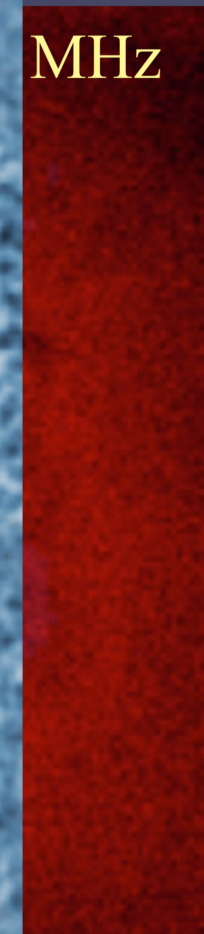


Fabian et al. (2002)

Condon Lecture

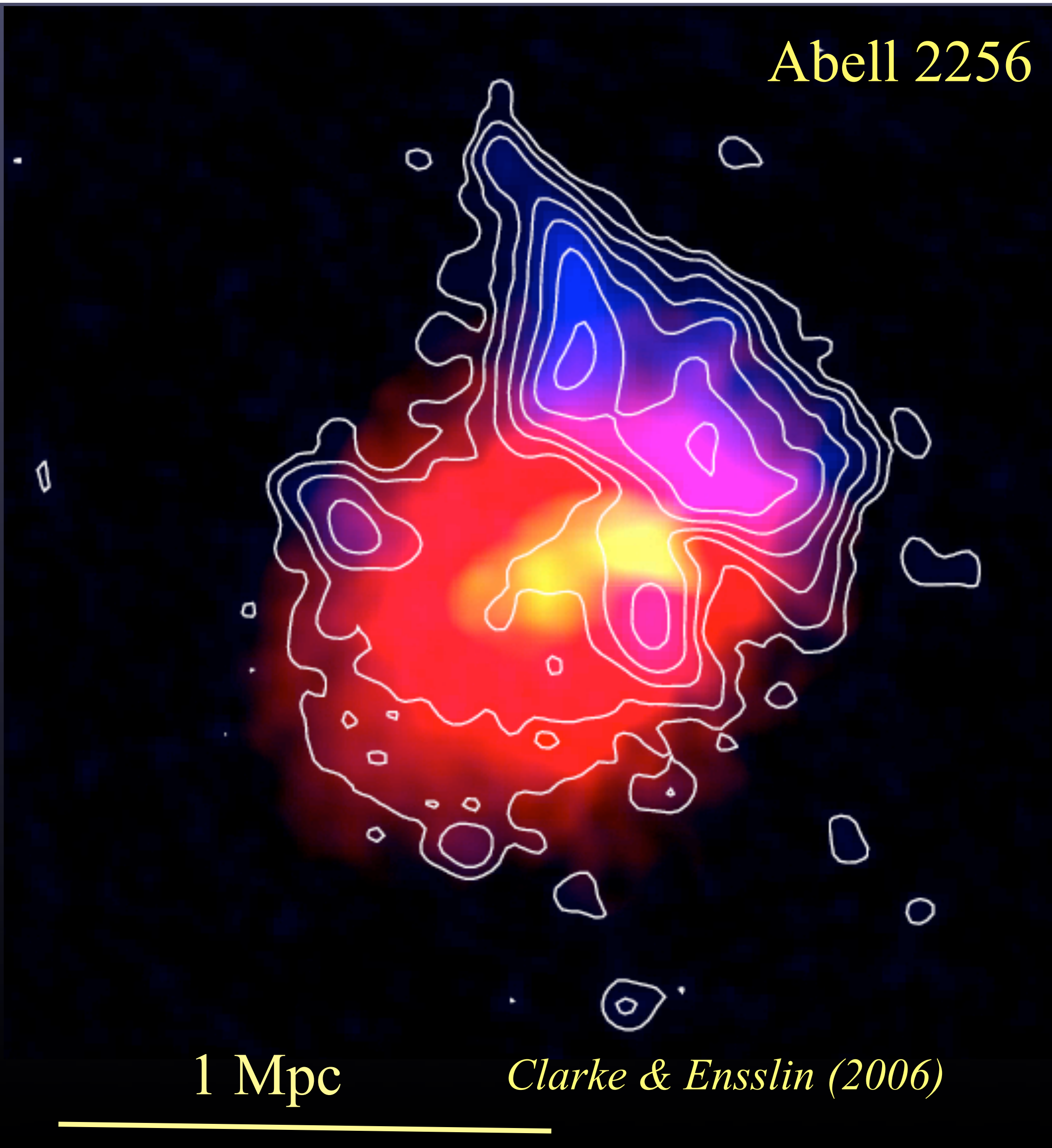






Fabi ... ***n Lecture***

Cluster Mergers: Diffuse Synchrotron Emission



Several clusters display large regions of diffuse synchrotron:

• 'halos' & 'relics' associated with merging clusters

• emission is generally steep spectrum

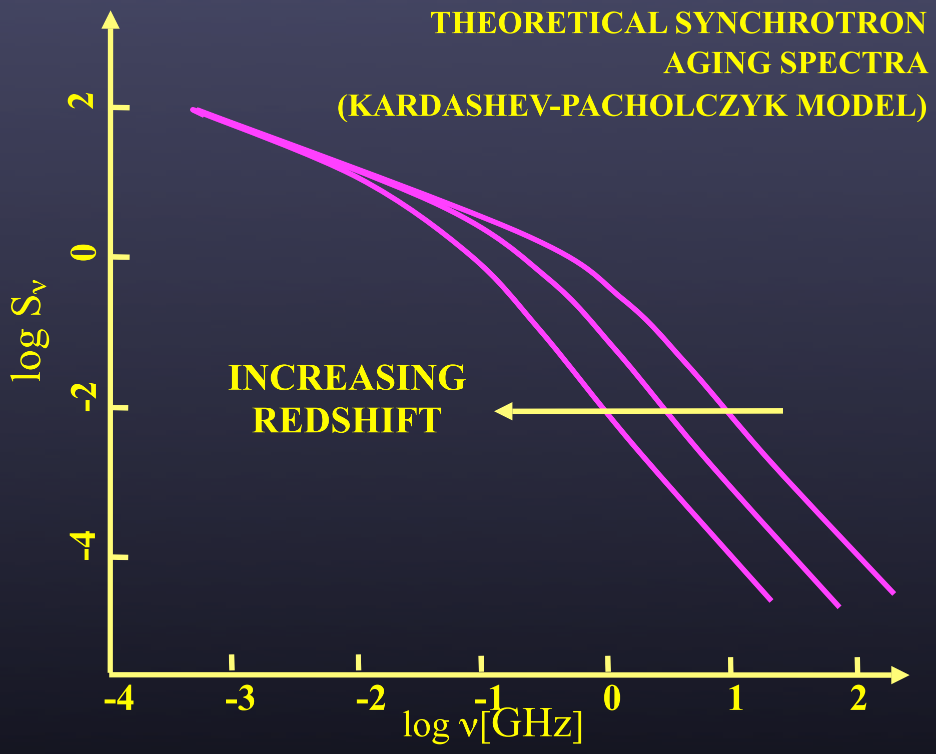
• location, morphology, spectral properties, etc... can be used to understand merger geometry

• ICM should be representative of the matter density in the Universe

• Dark Energy studies assume hydrostatic equilibrium that is violated by merging clusters

• low frequency studies can identify and remove contaminating clusters (Clarke et al. 2005)

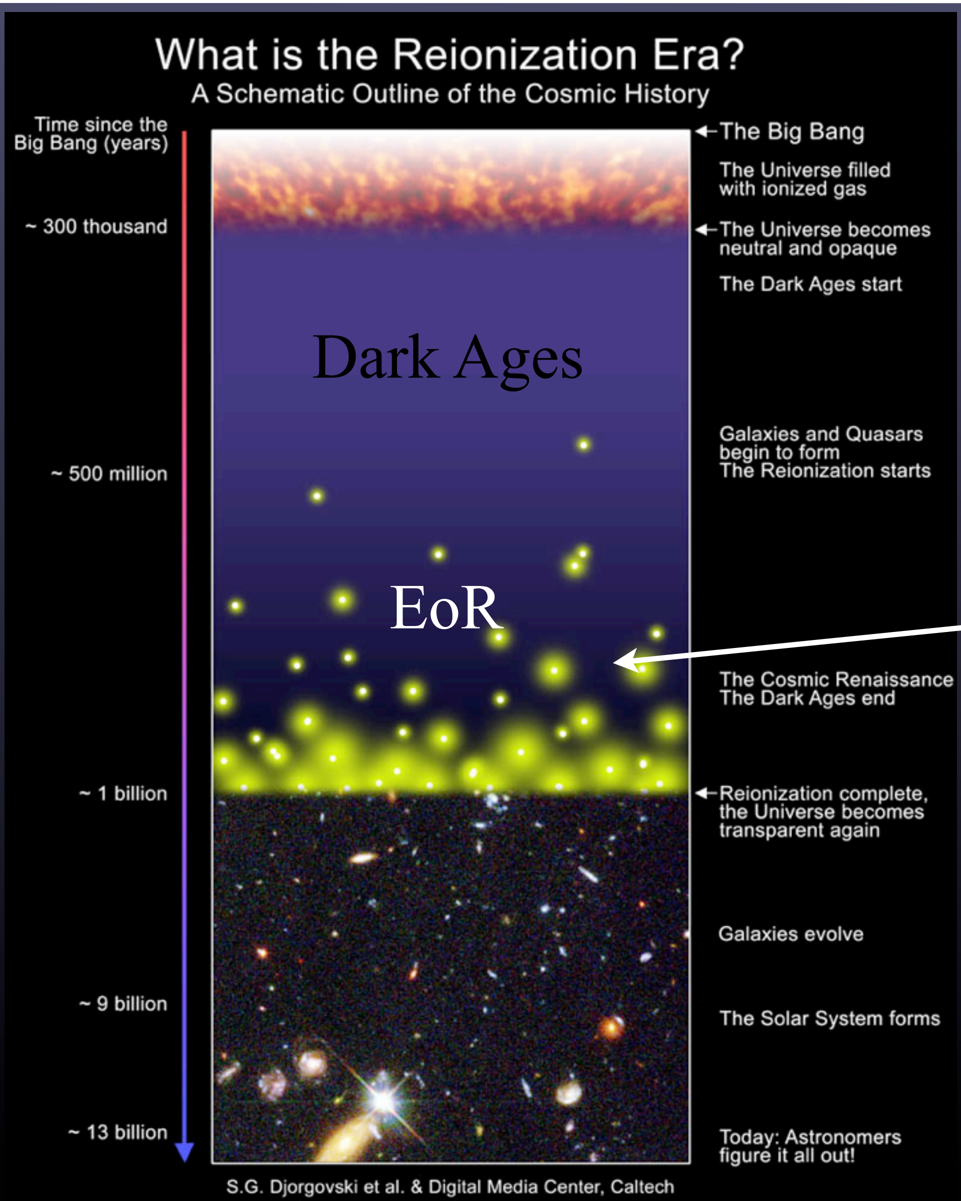
High Redshift Galaxies: Steep Spectrum



Observations of cosmic acceleration have led to studies of Dark Energy:

- Synchrotron losses steepen the spectrum of radio galaxies at high z
- Inverse Compton losses act similarly to steepen the spectrum, especially at high z since IC losses scale as z^4.
- Spectrum is also red shifted to lower frequencies so that the entire *observed* spectrum is steep.

Epoch of Reionization



- Detectable by highly-red shifted 21 cm H I line (ν< 200 MHz for z > 6) in absorption against first quasars, GRB's, SF galaxies …
- WMAP 5^{yr}: re-ionization epochs near z~10.8 (HI at 120 MHz)

Redshift range:
$6 < z < 11$
Frequency range:
$200 > \nu > 115$ MHz

EoR Intruments: MWA, LOFAR, 21CMA, PAPER

(Ulvestad Lecture)

Epoch of Reionization: $z > 6$ (H I @ 200 MHz)

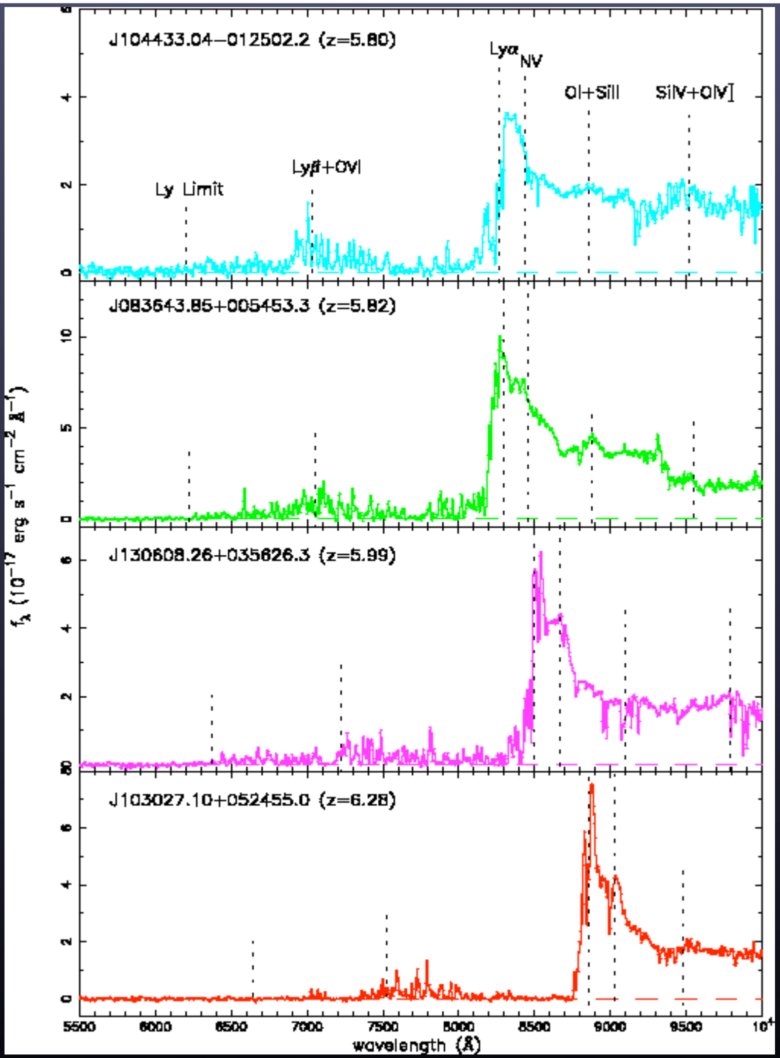
Universe made rapid transition from largely neutral to largely ionized

- Appears as optical Gunn-Peterson trough in high-z quasars, $z > 6$ trough indicating the end of re-ionization

- Also detectable by highly-red shifted 21 cm H I line ($\nu < 200$ MHz for $z > 6$) in absorption against first quasars, GRB's, SF galaxies …

- WMAP 5^{yr}: re-ionization epochs near z~10.8 (HI at 120 MHz)

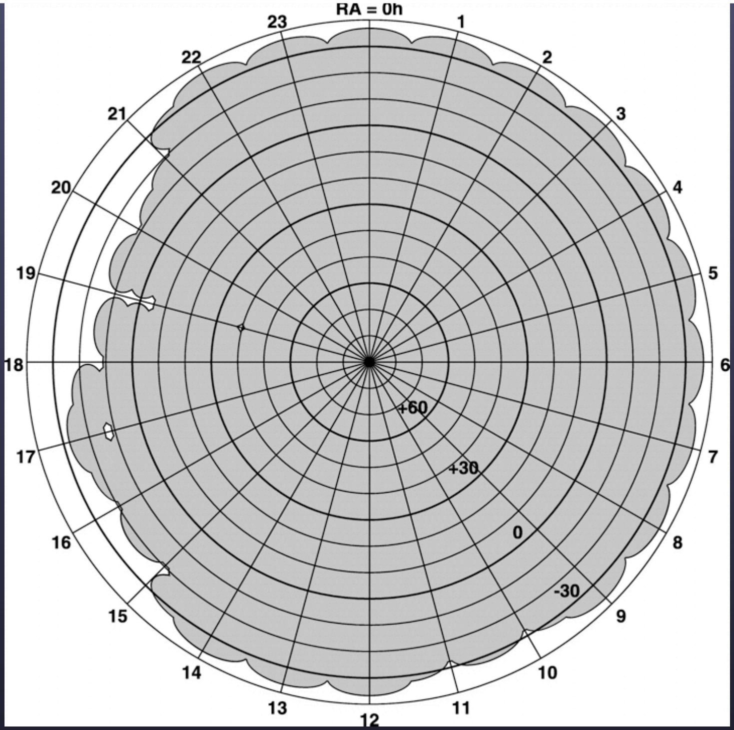
EoR Intruments: MWA, LOFAR, 21CMA, PAPER



SDSS: Becker et al. (2001)

VLA Low Frequency Sky Survey: VLSS

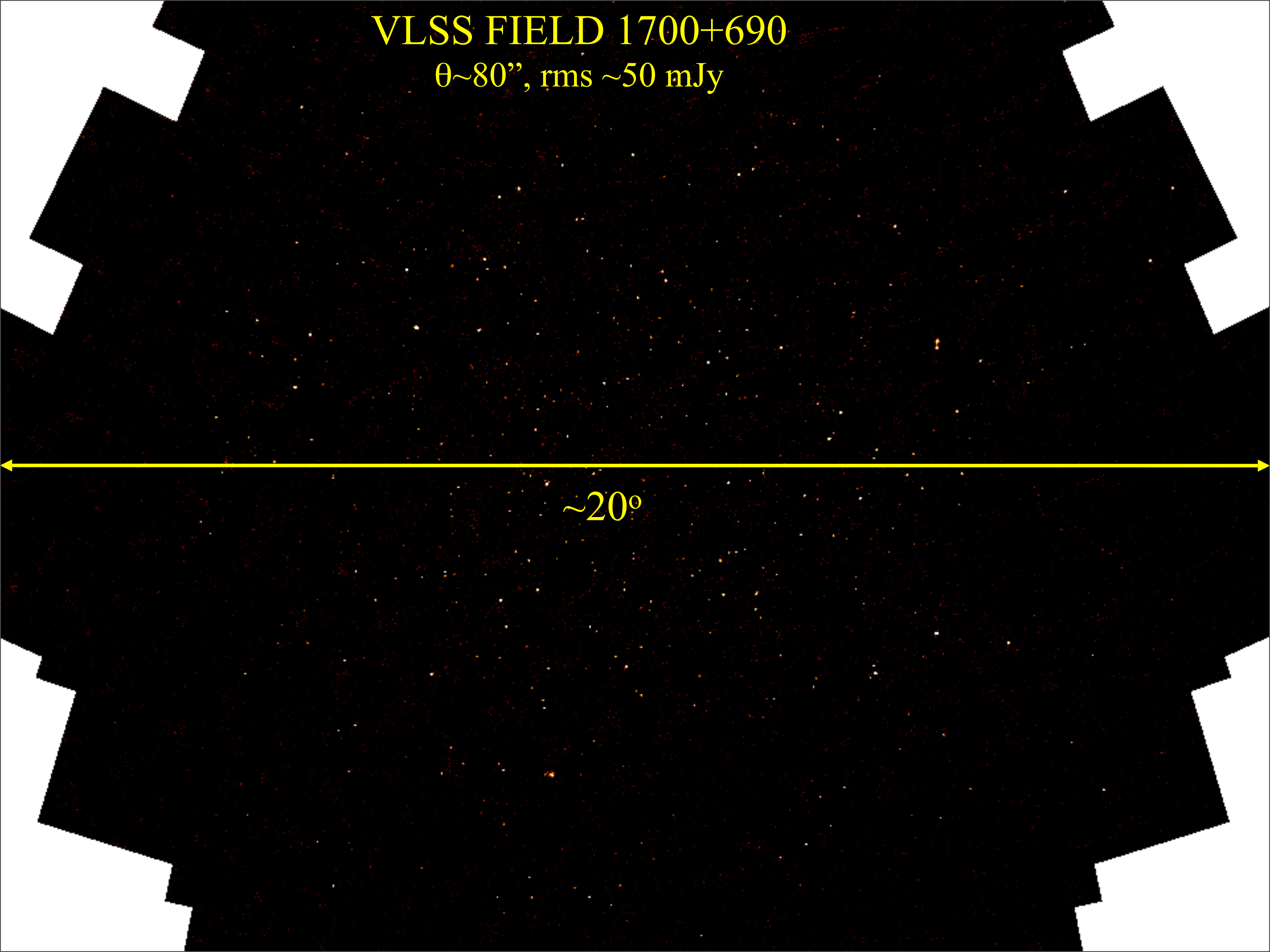
- **Survey Parameters**
  - 74 MHz
  - Dec. > -30 degrees
  - 80” resolution
  - rms ~100 mJy/beam

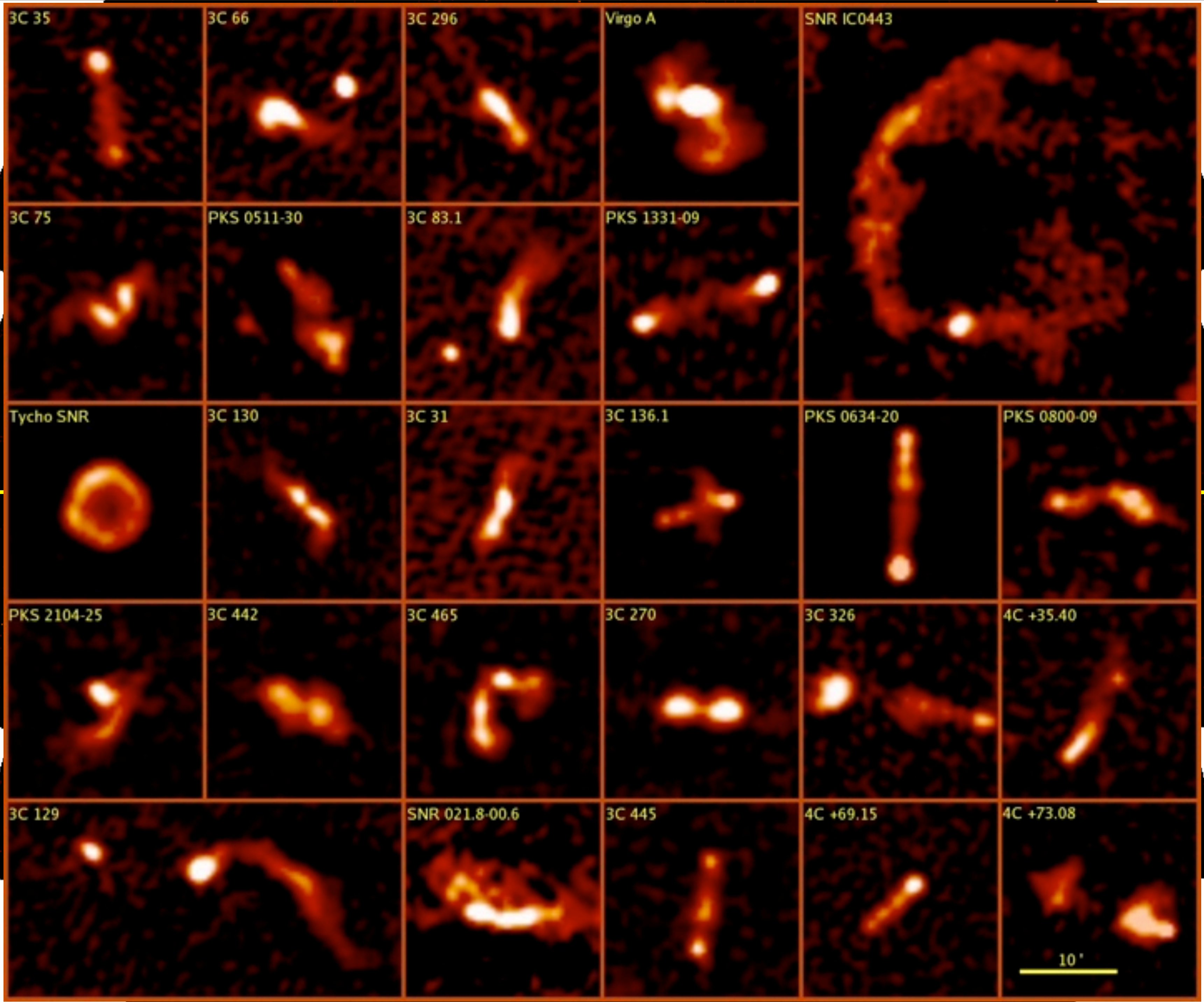


- **Deepest & largest LF survey**
  - N ~ 70 000 sources in ~ 95% of sky > -30°
  - Statistically useful samples of rare sources
    - => fast pulsars, distant radio galaxies, cluster radio halos and relics
  - Unbiased view of parent populations for unification models

- **Important calibration grid for VLA, GMRT, & future LF instruments**
- **Data online at:** http://lwa.nrl.navy.mil/VLSS

Cohen et al. 2007, AJ, 134, 1245


VLSS FIELD 1700+690
θ~80", rms ~50 mJy
~20°


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'

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 ***(Claussen Lecture)***

  - Wide-field imaging ***(Perley Lecture III)*** only recently (sort of) possible

  - RFI excision ***(Fomalont Lecture)***

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

Low Frequency In Practice: Not Easy!

- Phase coherence through ionosphere

  Corruption of coherence of phase on longer baselines

- Finite Isoplanatic Patch Problem: ***(Ulvestad Lecture)***

  Calibration changes as a function of position

- Bandwidth smearing: ***(Perley Lecture I)***

  Distortion of sources with distance from phase center

- Radio Frequency Interference: ***(Fomalont Lecture)***

  Severe at low frequencies

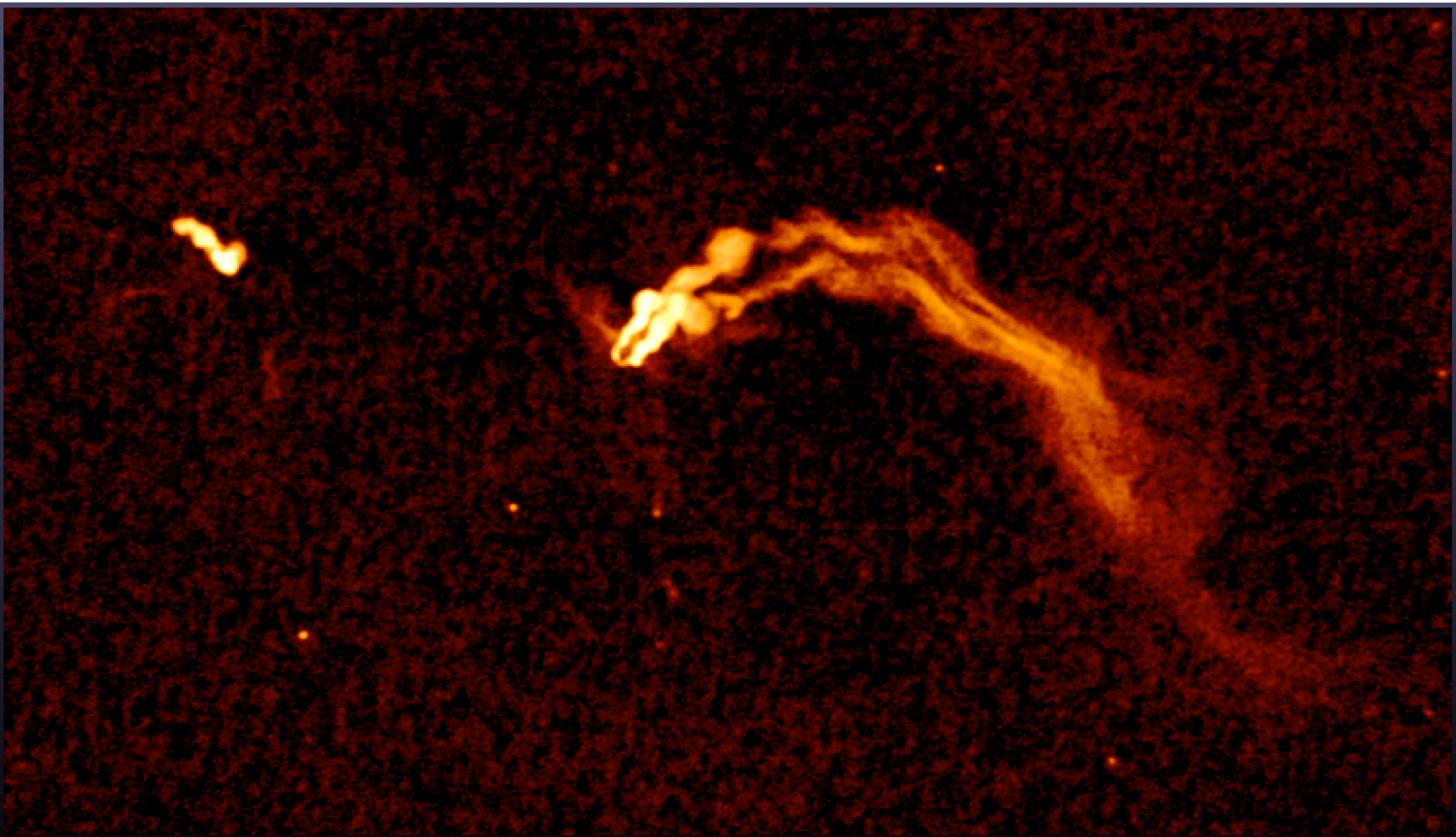
- Large Fields of View: ***(Perley Lecture III)***

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

  Large number of sources requiring deconvolution

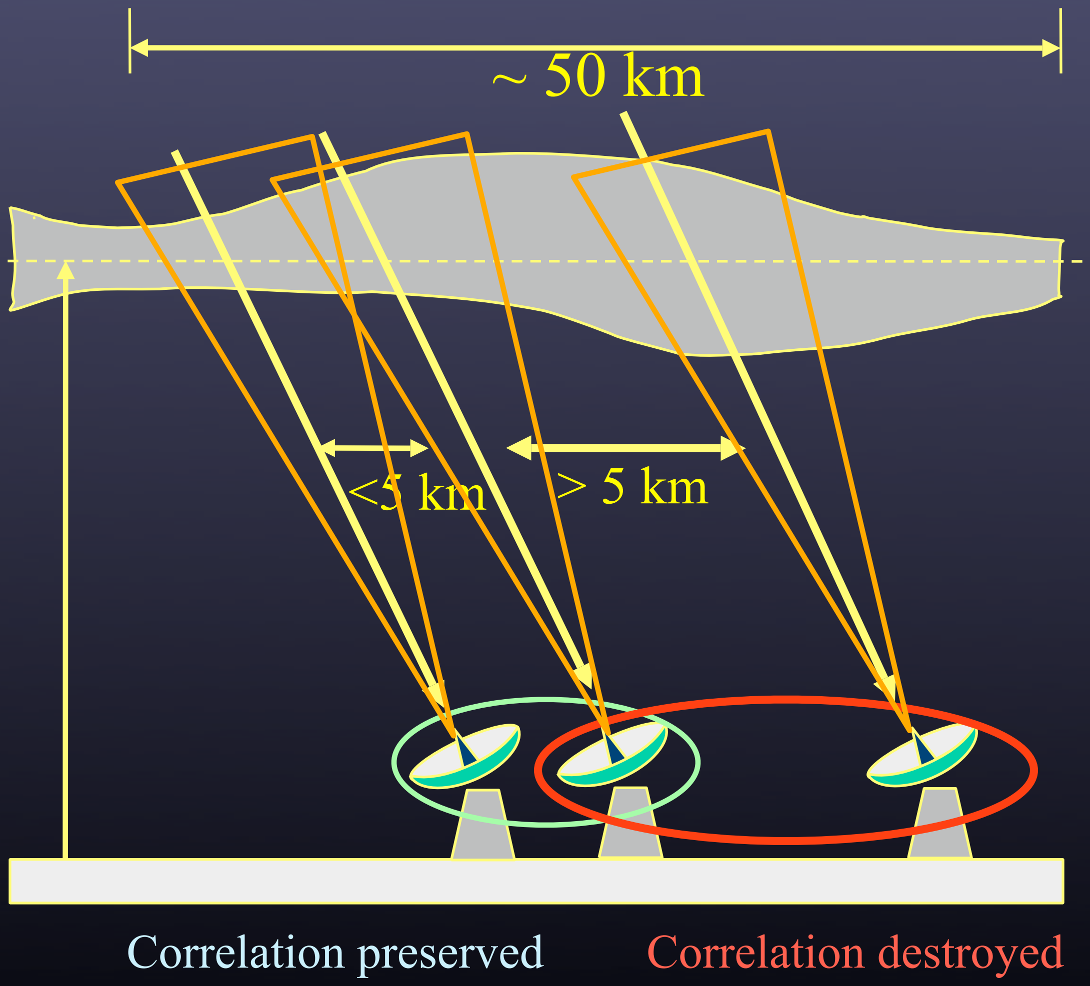
  Calibrators

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



Lane et al. (2001)

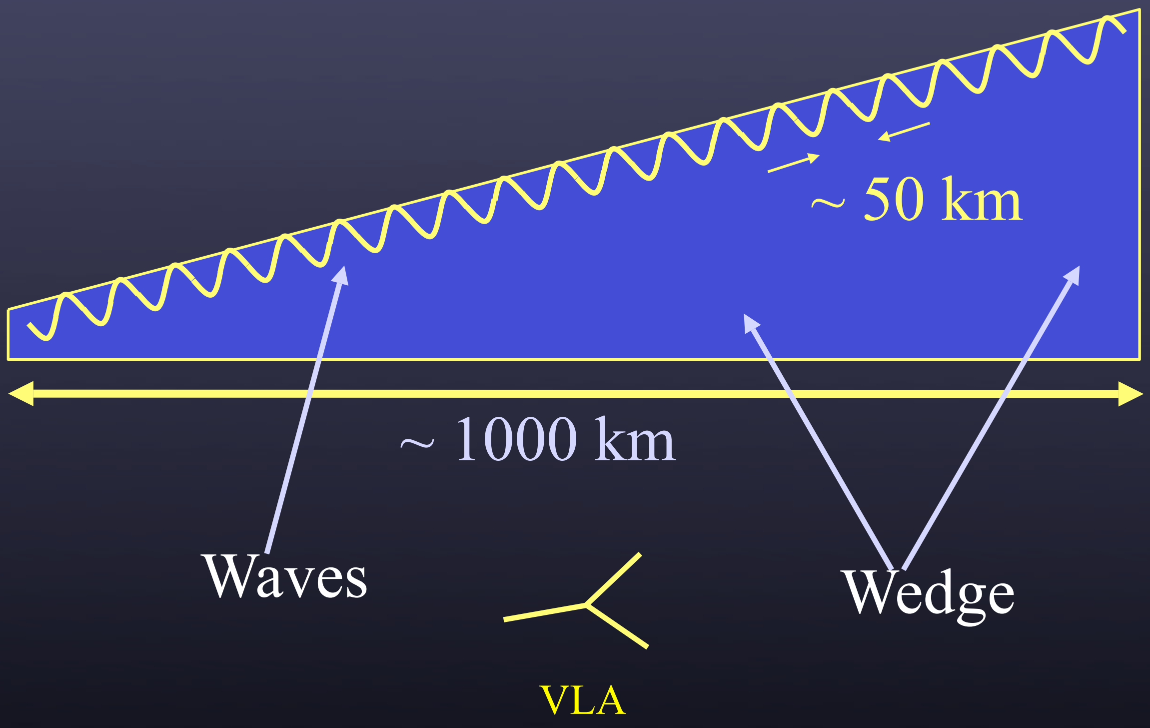
Ionospheric Structure:



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

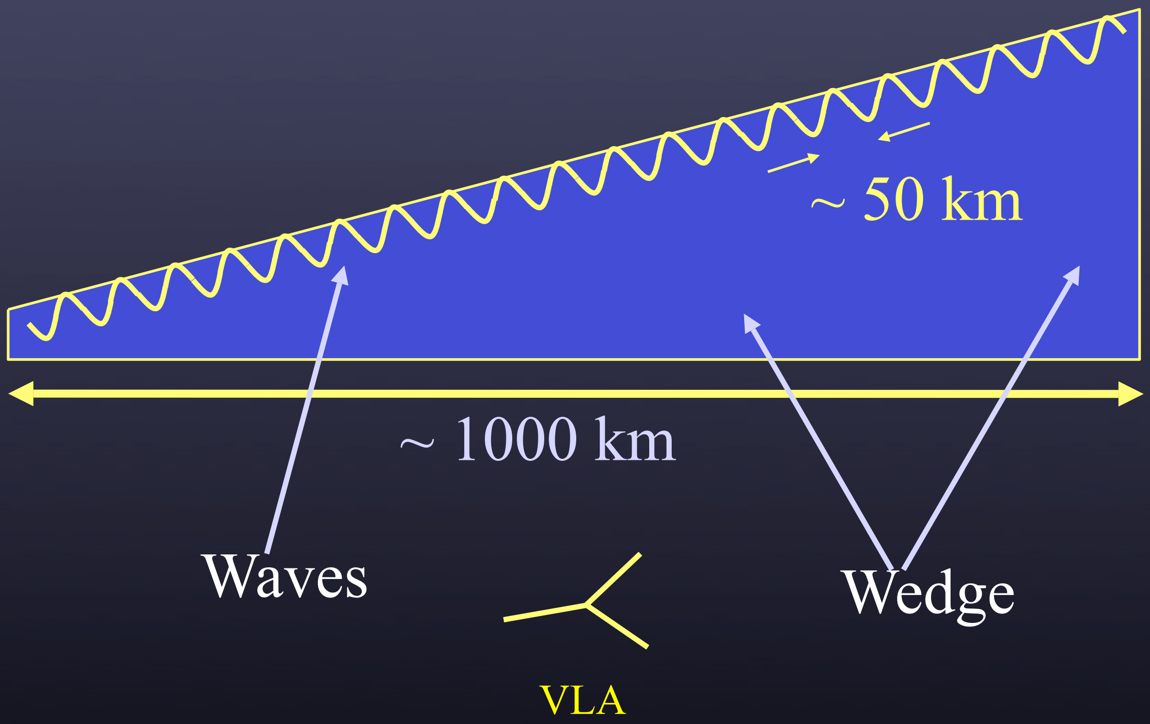
Ionospheric Effects

Wedge Effects: Faraday rotation, refraction, absorption below ~ 5 MHz (atmospheric cutoff)
Wave and Turbulence Effects: Rapid phase winding, differential refraction, source distortion, scintillations



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



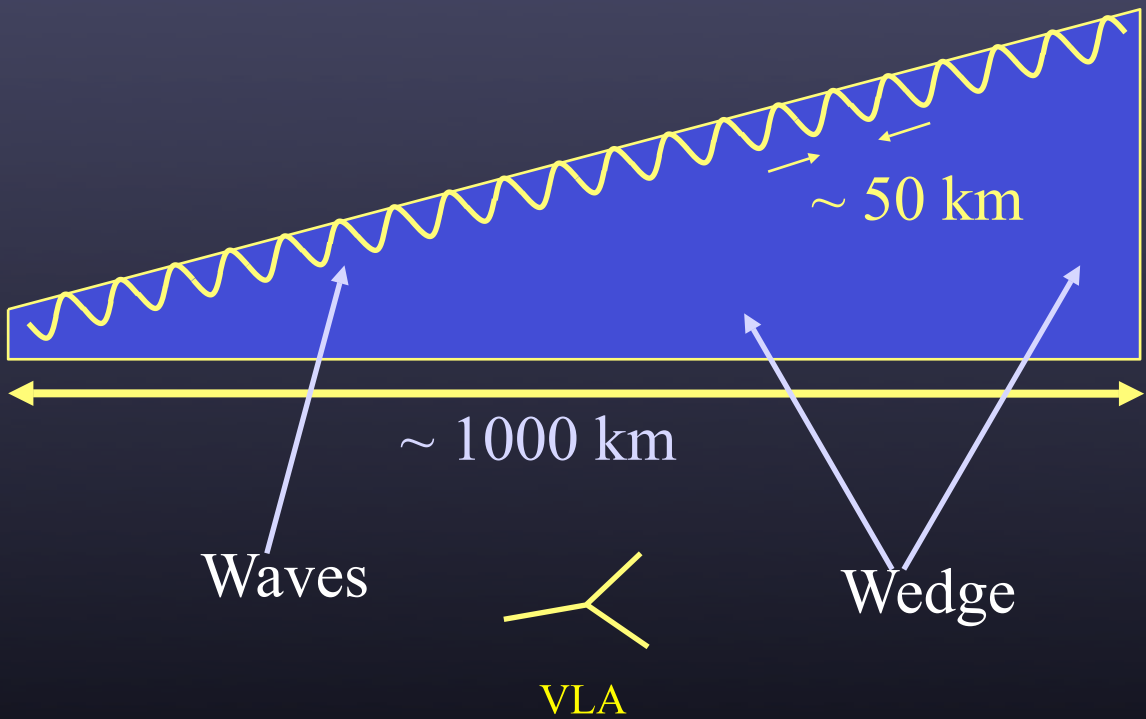
Wedge: characterized by
$TEC = \int n_e dl \sim 10^{17}\ m^{-2}$

Extra path length adds extra phase
$\Delta L \propto \lambda^2 * TEC$
$\Delta\phi \sim \Delta L/\lambda \sim \lambda * TEC$

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

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



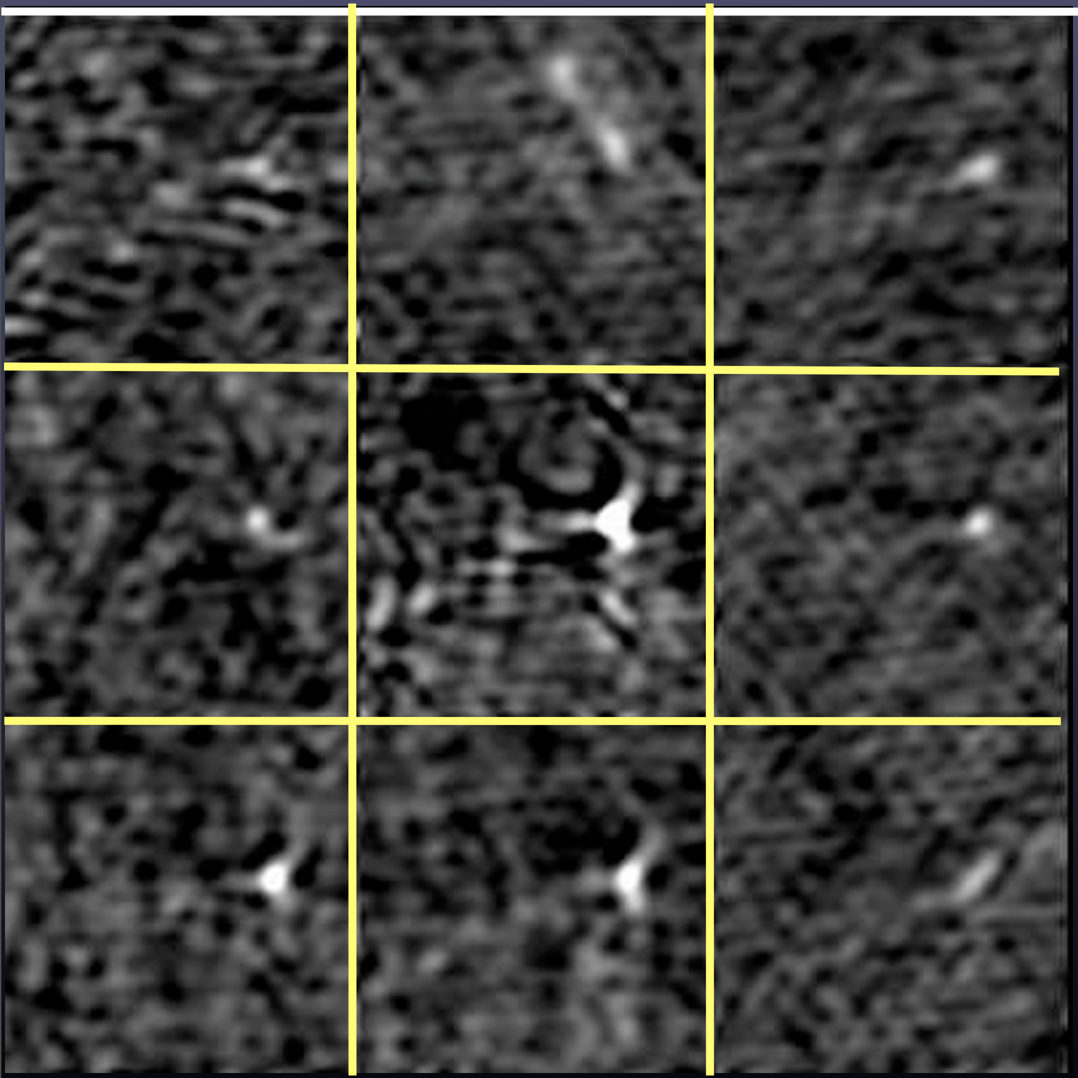
Wedge: characterized by
TEC = $\int n_e dl \sim 10^{17}$ m^{-2}

Extra path length adds extra phase
$\Delta L \propto \lambda^2 * TEC$
$\Delta\phi \sim \Delta L/\lambda \sim \lambda * TEC$

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

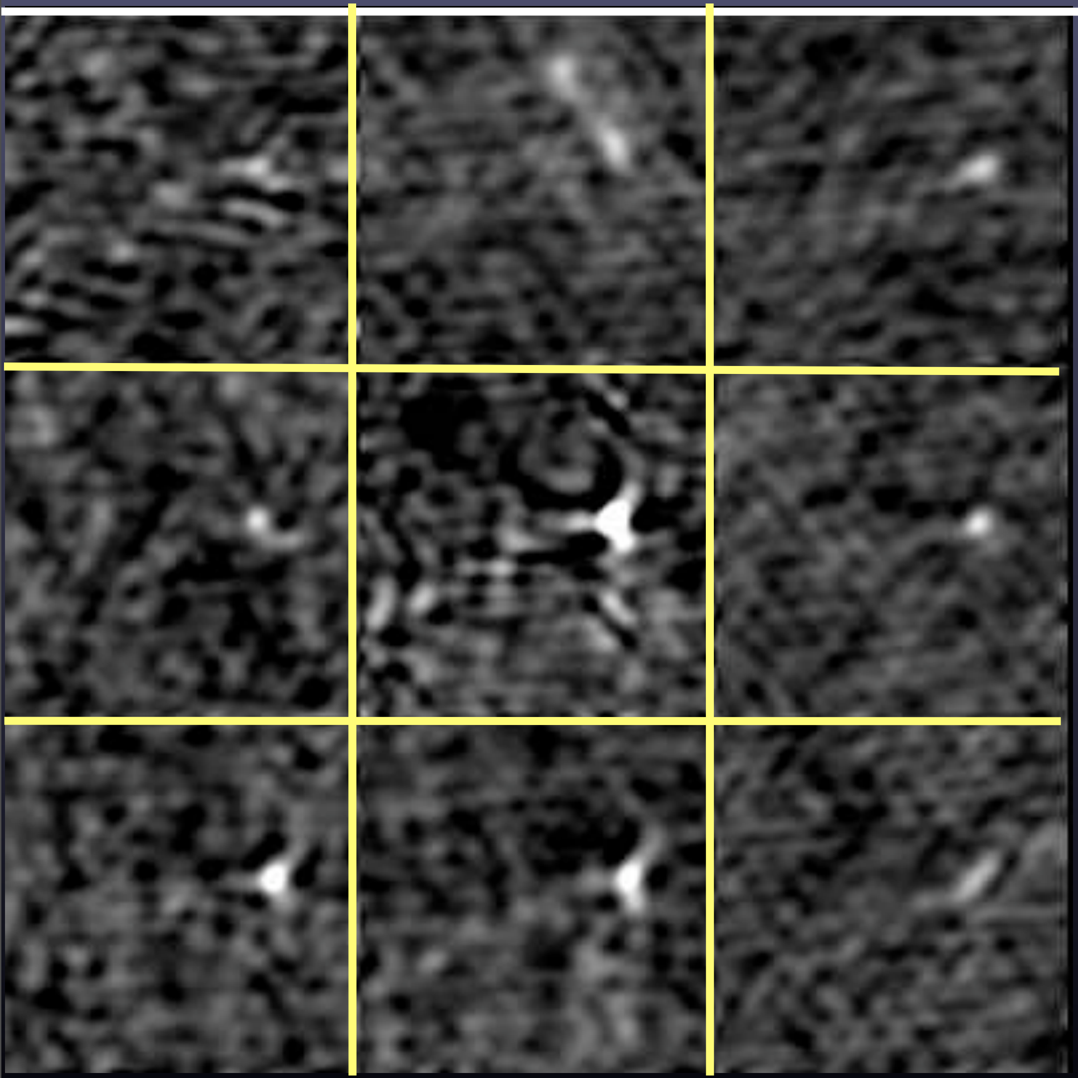
- The wedge introduces thousands of turns of phase at 74 MHz
- Interferometers are particularly sensitive to difference in phase (wave/turbulence component)

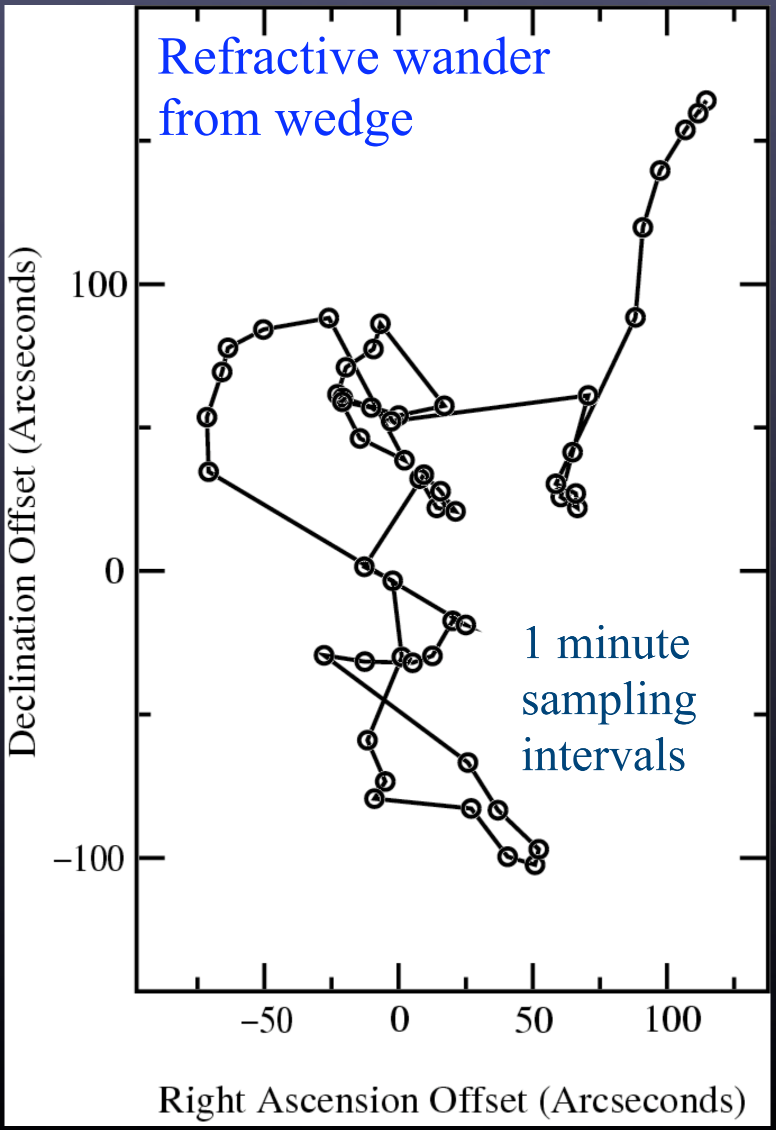
Ionospheric Refraction & Distortion



- Both global and differential refraction seen.
- Time scales of 1 min. or less.
- Equivalent length scales in the ionosphere of 10 km or less.

Ionospheric Refraction & Distortion



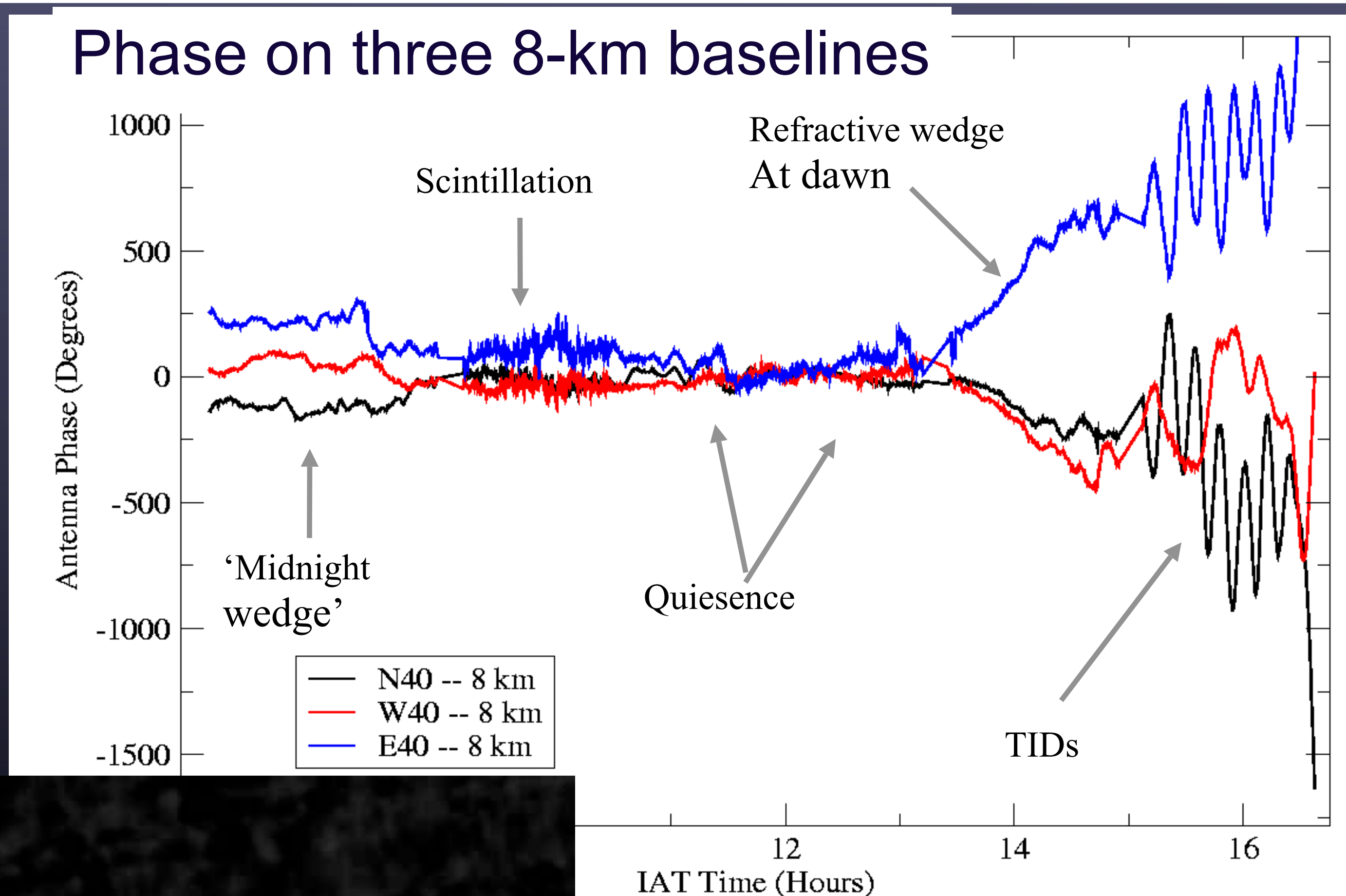


Antenna Phase as a Function of Time

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

=>

MYTH: Low freq. observing only at night. Often daytime (but not dawn) has very good conditions



Self-Calibration :'Dealing' with the Ionosphere

- Self-calibration models ionosphere as a time-variable antenna based phase: $\varphi_i(t)$
- Loop consisting of imaging and self-calibration ***(Claussen Lecture)***
  - model improves and S/N for self-cal increases
- Typical approach is to use a priori sky-based model such as NVSS, WENSS, or higher frequency source model (AIPS: SETFC, FACES, CALIB, IMAGR)
  - freezes out time variable refraction and ties positions to known sky-model
  - DOES NOT ALWAYS WORK – e.g. fails due to thermal absorption

- This method assumes a single ionospheric solution applies to entire FOV

- Problems remain with standard self-calibration:
  - – often fails if target is not brightest source in FoV
  - – also issues of differential refraction, image distortion, reduced sensitivity
  - – Ultimate solution: selfcal solutions with angular dependence

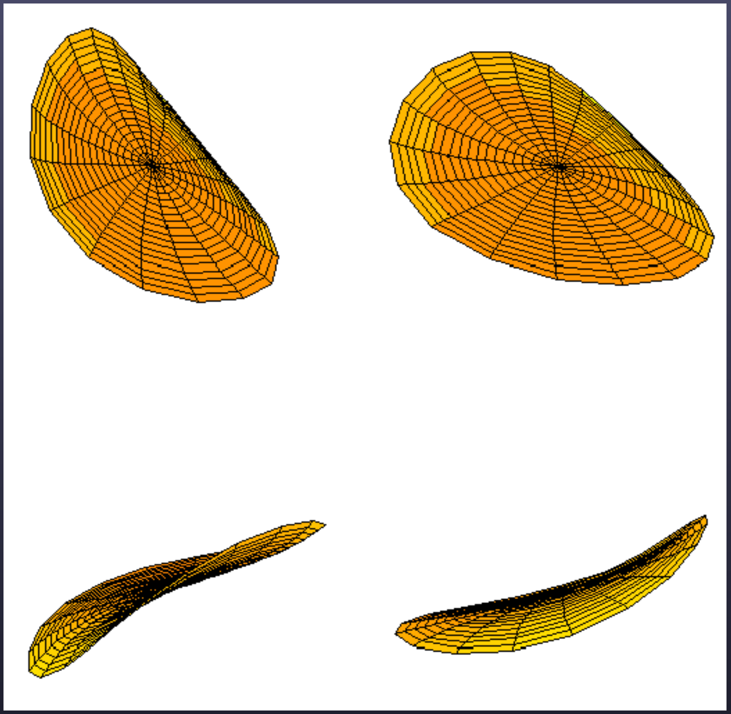
$$\varphi_i(t) \rightarrow \varphi_i(t, \alpha, \delta)$$

Field Based Calibration

- Zernike polynomial phase screen
  - – Developed by Bill Cotton (NRAO)
  - – Delivers astrometrically correct images
  - – Takes snapshot images of bright sources to compare to NVSS positions
  - – Fits phase delay screen rendered as a plane (3-D viewed from different angles)
  - – Apply time varying phase delay screens while imaging

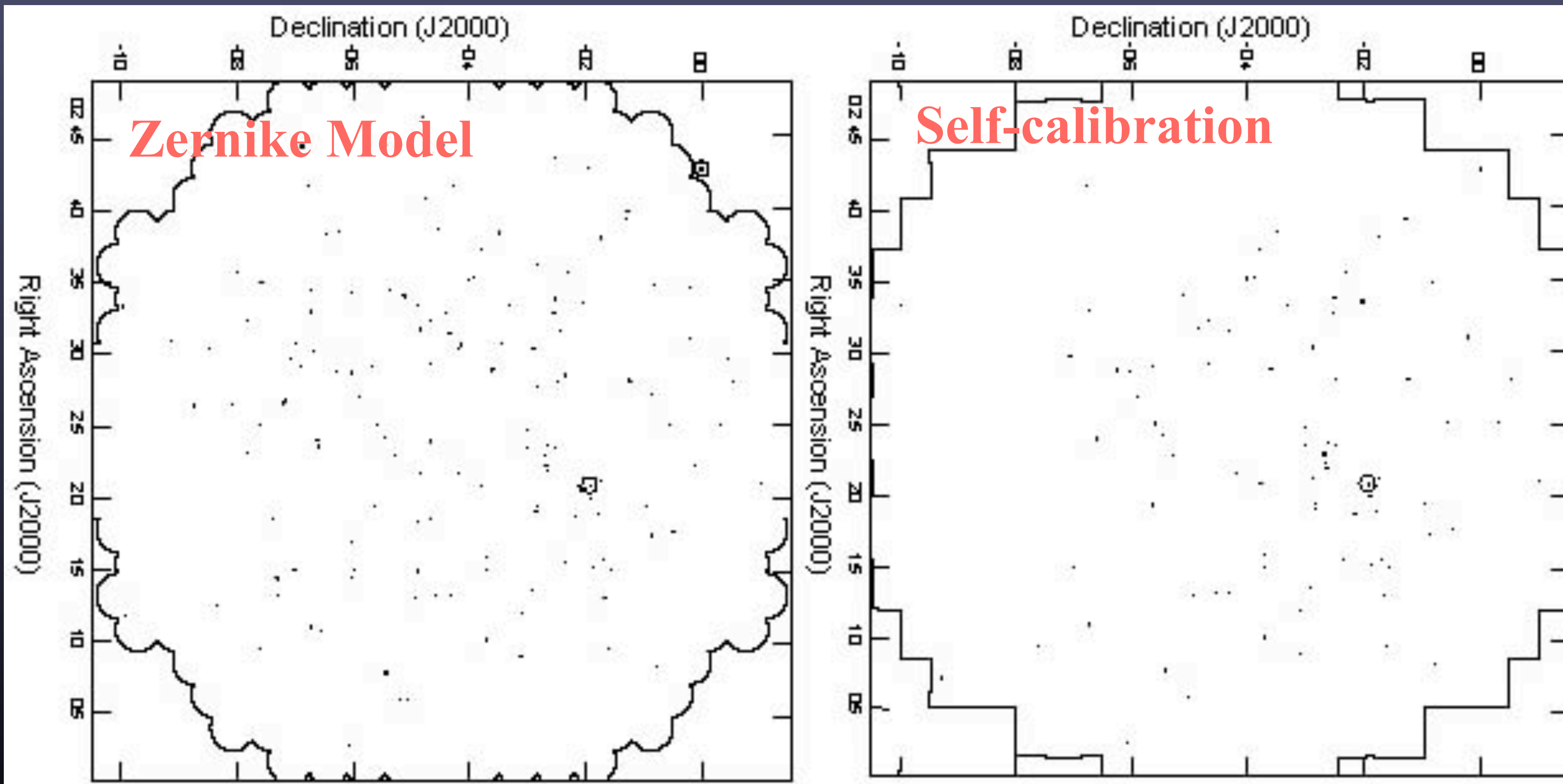
  Key handicaps:

  - – Need high S/N—significant data loss under poor ionospheric conditions
  - – Total flux should be dominated by point sources
  - – Good for baselines < 12 km



New tools needed for next generation of instruments with BL > 200 km

Field-Based Calibration vs Self-cal



Average positional error decreased from ~45” to 17”

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

Bandwidth Smearing

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

Freq. (MHz)	BW (MHz)	A-config. θ_{synth} (“)	Radius of PB_{FWHM} (‘)	θ_{MAX} (‘) for 50% degradation
74	1.5	25	350	41
330	6.0	6	75	11
1420	50	1.4	15	1.3

(Perley Lecture I)

Bandwidth Smearing

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

Freq. (MHz)	BW (MHz)	A-config. θ_{synth} (")	Radius of PB_{FWHM} (')	θ_{MAX} (') for 50% degradation
74	1.5	25	350	41
330	6.0	6	75	11
1420	50	1.4	15	1.3

Solution: spectral line mode (already essential for RFI excision)

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

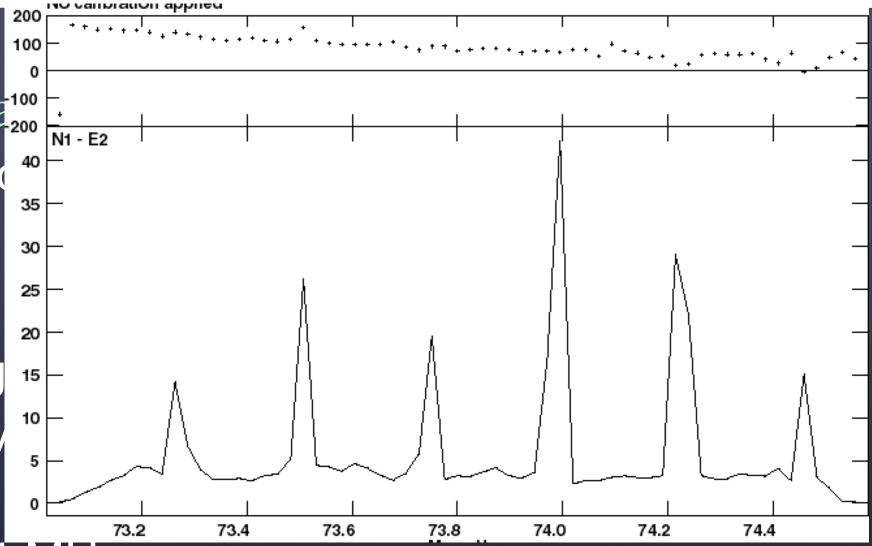
(Perley Lecture I)

Radio Frequency Interference: RFI

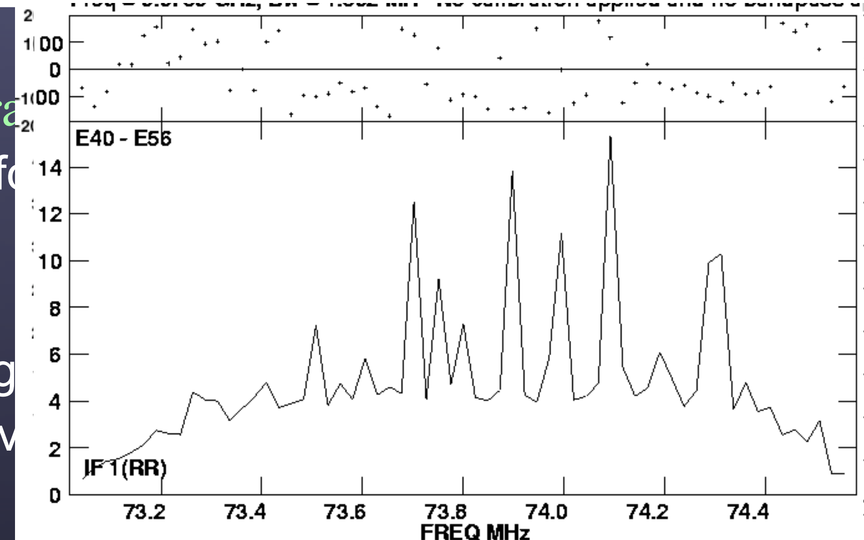
- As at cm wavelengths, natural and man-generated RFI are a nuisance
  - Getting "better" at low freq., relative BW for commercial use is low
- At VLA: many different signatures seen at 74 and 330 MHz
  - 74 MHz: VLA generated comb is mostly gone
  - signatures: narrowband, wideband, time varying, 'wandering'
  - Solar effects – unpredictable
    - Quiet sun 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
- Requires you to take data in spectral line mode
  - RFI can usually be edited out – tedious but "doable"

Radio Frequency Interference: RFI

- As at cm wavelengths, natural and man-genera
  - Getting “better” at low freq., relative BW fo
- At VLA: many different signatures seen at 74
  - 74 MHz: VLA generated comb is mostly g
  - signatures: narrowband, wideband, time v
  - Solar effects – unpredictable
    - Quiet sun 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
- Requires you to take data in spectral line mode
  - RFI can usually be edited out – tedious but “doable”



Radio Frequency Interference: RFI

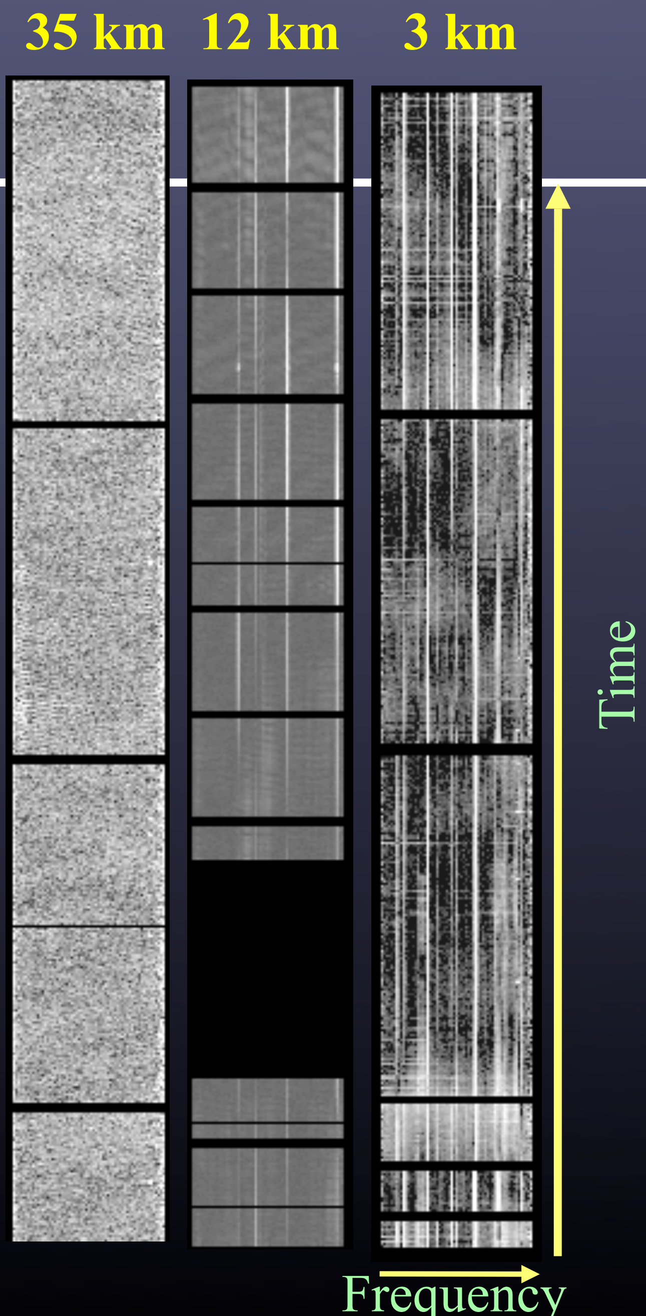


- As at cm wavelengths, natural and man-genera
  - Getting "better" at low freq., relative BW fo

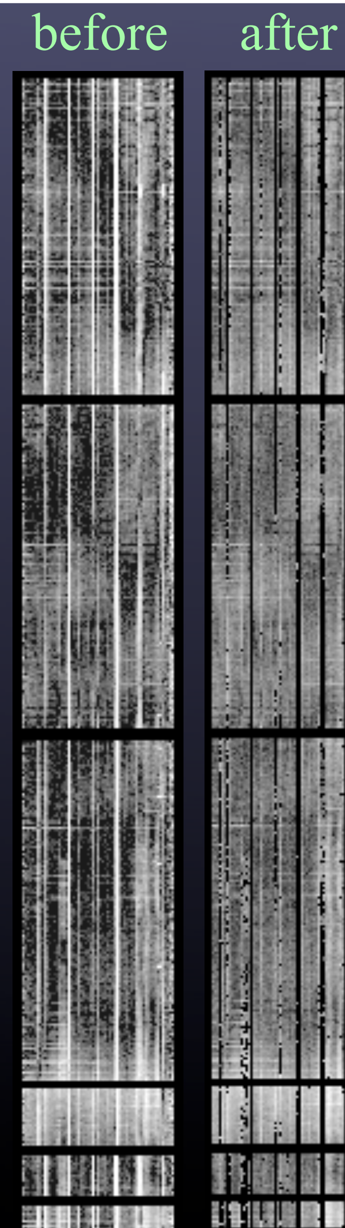
- At VLA: many different signatures seen at 74
  - 74 MHz: VLA generated comb is mostly g
  - signatures: narrowband, wideband, time v
  - Solar effects – unpredictable
    - Quiet sun a benign 2000 Jy disk at 74 MHz
    - Solar bursts, geomagnetic storms are disruptive => 10^9 Jy!
    - Powerful Solar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

- Requires you to take data in spectral line mode
  - RFI can usually be edited out – tedious but "doable"

RFI Excision



AIPS: SPFLG



RFI environment worse on short baselines

Several 'types': narrow band, wandering, wideband, ...

Wideband interference hard for automated routines

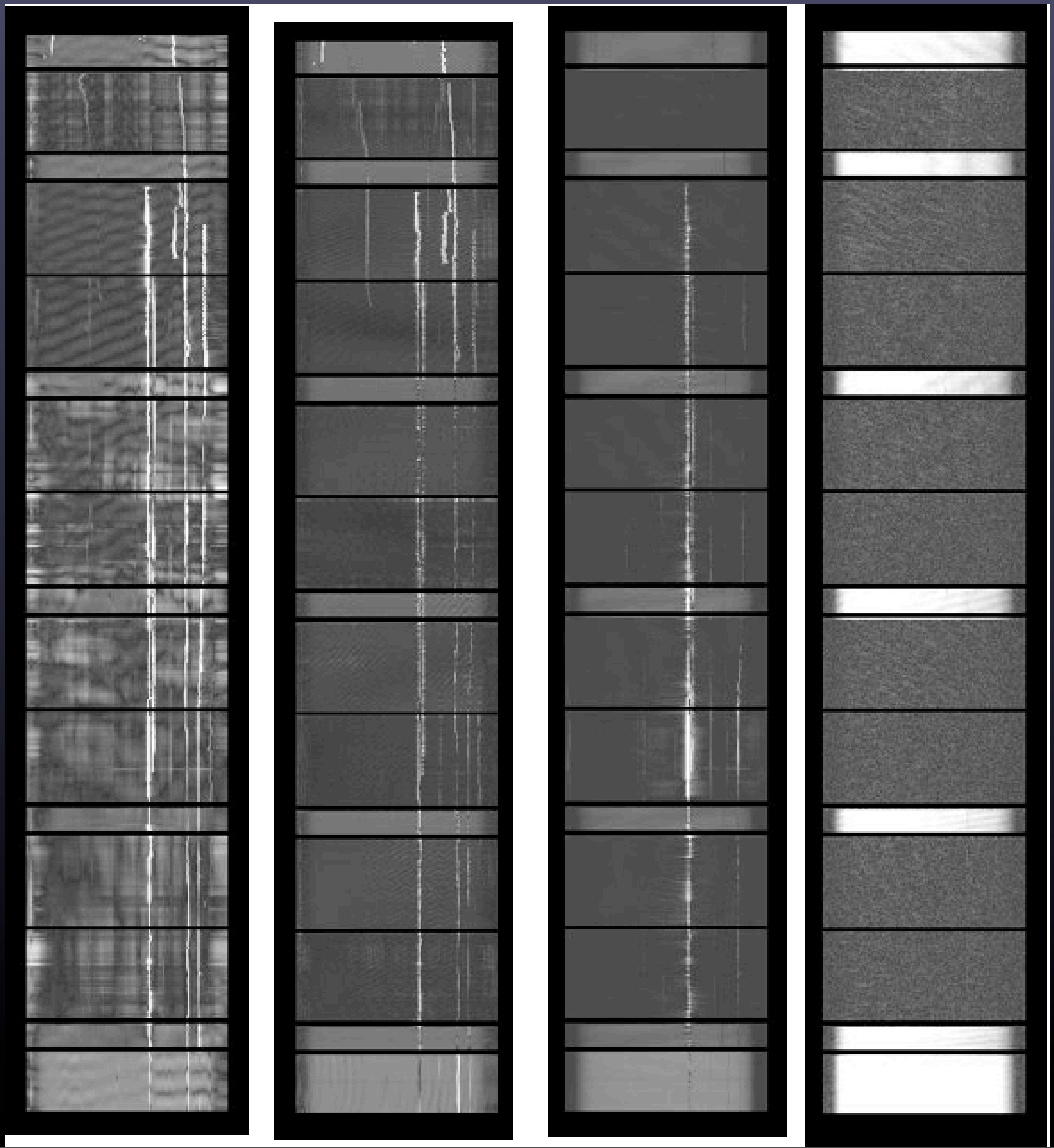
Example using AIPS tasks FLGIT, FLAGR, RFI

Unfortunately, still best done by hand!

(Fomalont Lecture)

RFI Excision II

Short baseline → Long baseline



GMRT RFI:

-- From poorly shielded RFI lines
-- Narrow band signals often bleed into adjacent channels
-- Wander in frequency

RFI Excision II

Short baseline → Long baseline

GMRT RFI:

-- From poorly shielded RFI lines
-- Narrow band signals often bleed into adjacent channels
-- Wander in frequency

RFI Excision in Practice

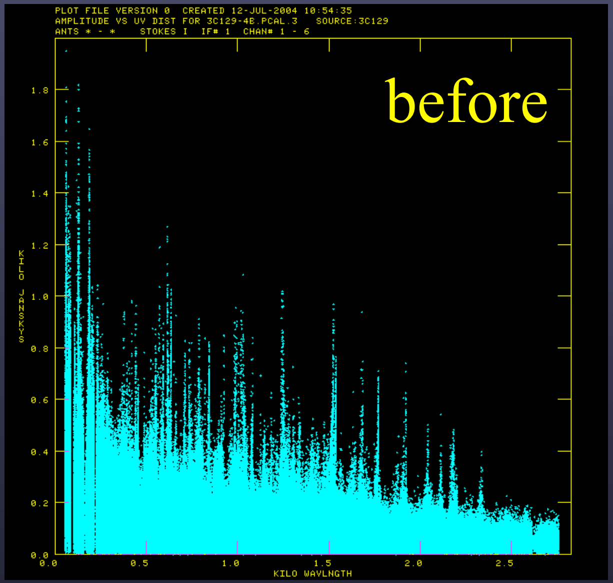
- Approach: averaging data in time and/or frequency makes it easier to isolate RFI, which averages coherently, from Gaussian noise, which does not

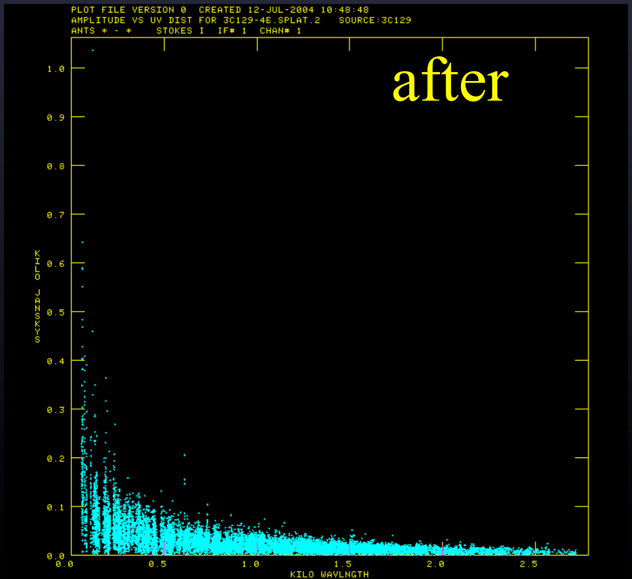
- Once identified, the affected times/baselines can be flagged in the un-averaged dataset

- Where to start?

<u>AIPS tasks</u>: QUACK, SPFLG, TVFLG, UVPLT, UVFND, UVFLG, UVSUB, CLIP, FLGIT, FLAGR, RFI, ...
<u>CASA tasks:</u> plotxy, flagdata
<u>Obit tasks:</u> AutoFlag, MednFlag

- Stokes V can be helpful to identify interference signals





Large Fields of View (FOV) I

Noncoplanar baselines: *(u,v, **and w**)* ***(Perley Lecture III)***

- Important if FOV is large compared to resolution (see Perley table)

  => in AIPS multi-facet imaging, each facet with its own θ_{synth}

  => in CASA *w*-projection or facets

- Essential for all observations below 1 GHz and for high resolution, high dynamic range even at 1.4 GHz

- Requires lots of computing power and disk space

- AIPS: IMAGR (DO3DIMAG=1, NFIELD=N, OVERLAP=2), CASA: *w*-projection

Example: VLA B array 74 MHz:

~325 facets

A array requires 10X more:

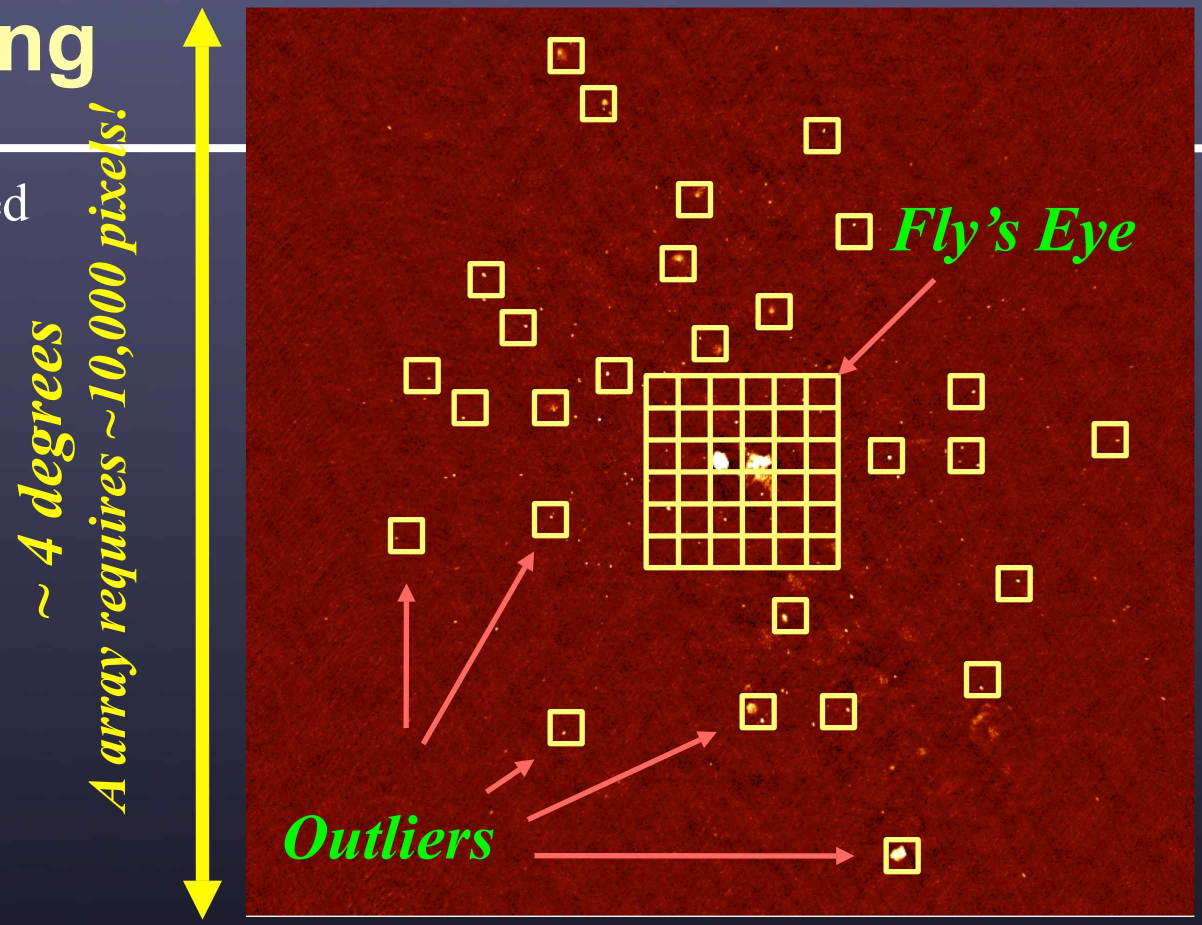
~ 3000 facets

~10^8 pixels

Targeted Faceting

- enormous processing required to image entire FOV
- reduce processing by targeting facets on selected sources (still large number!)
- overlap a fly's eye of the central region and add individual outliers

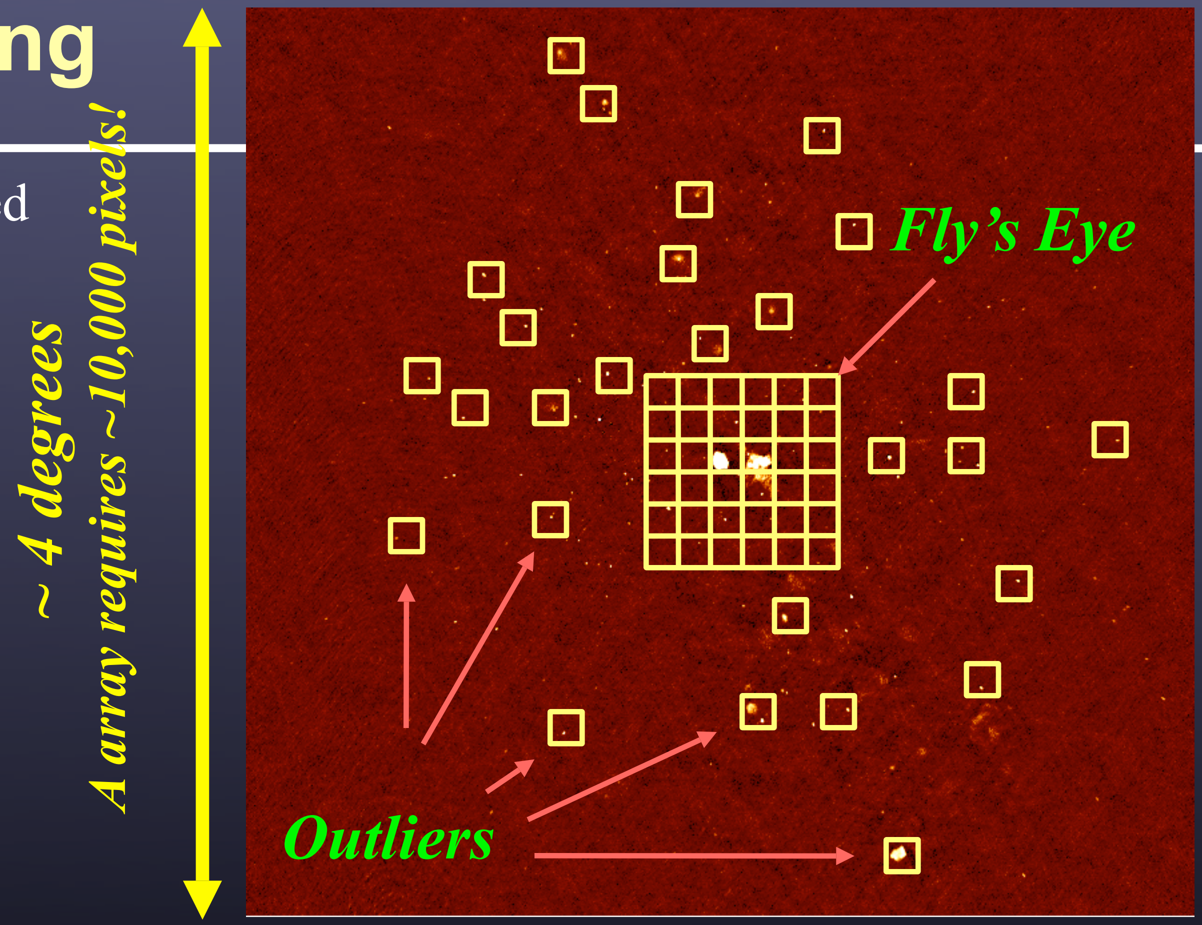
- AIPS: SETFC



Targeted Faceting

- enormous processing required to image entire FOV
- reduce processing by targeting facets on selected sources (still large number!)
- overlap a fly's eye of the central region and add individual outliers

- AIPS: SETFC



AIPS Tip:

- Experience suggests that cleaning progresses more accurately and efficiently if EVERY facet has a source in it.

- Best not to have extended sources spread over too many facets

=> often must compromise

Large Fields of View (FOV) II

Calibrators:

- Antenna gain (phase and amplitude) and to a lesser degree bandpass calibration depends on assumption that calibrator is a single **POINT** source
- Large FOV + low freq. = numerous sources everywhere
- At 330 MHz, calibrator should dominate flux in FOV: extent to which this is true affects absolute positions and flux scale

  => Phases (but not positions) can be improved by self-calibrating phase calibrator

  => Always check accuracy of positions

- Must use source with accurate model for bandpass and instrumental phase **CygA**, CasA, TauA, VirgoA

Large Fields of View (FOV) II

Calibra

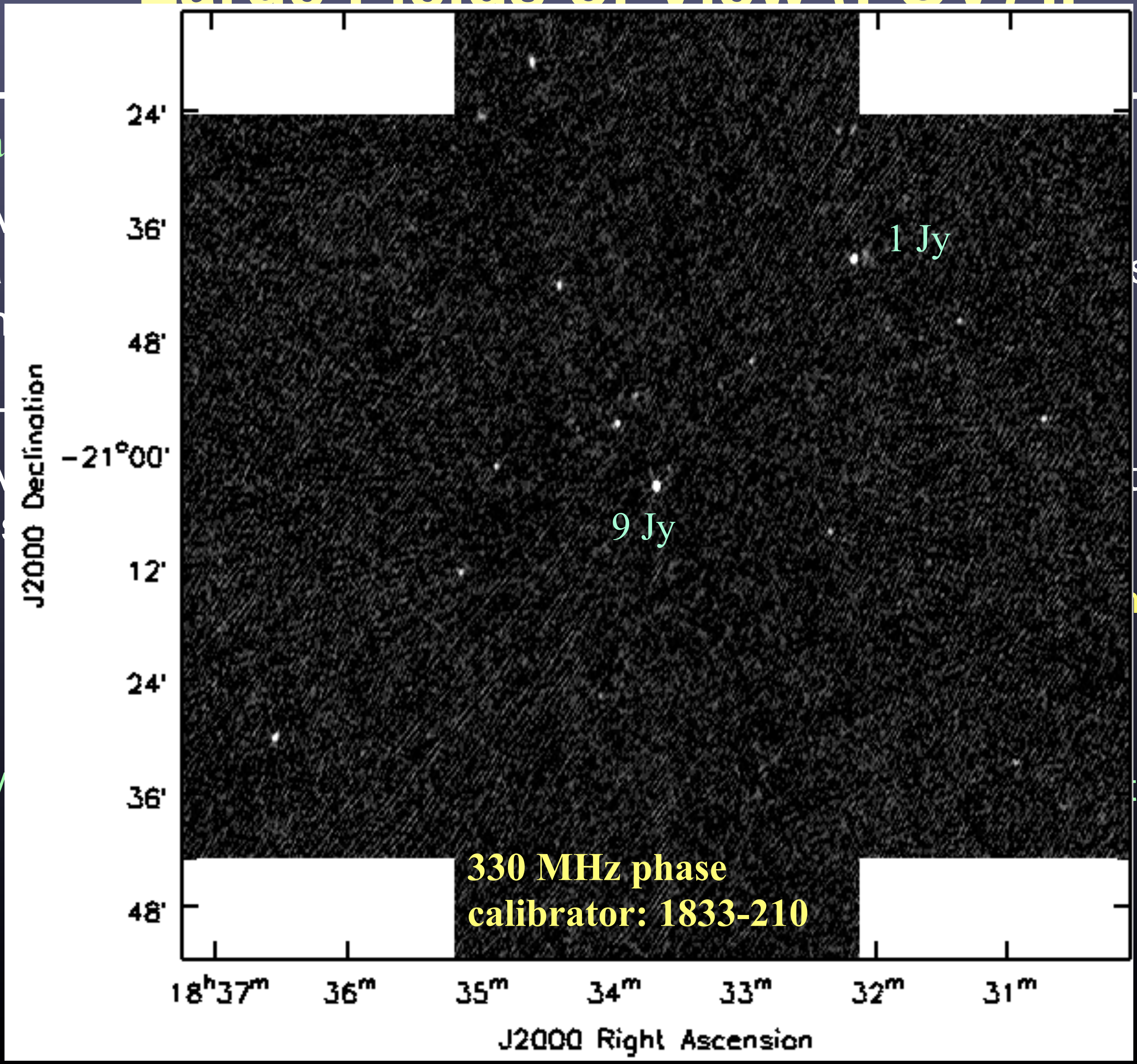
• A
ba … s a
sin

• L

• A … to which
thi

ng phase

• M … tal



Planning your Observing

- 4 band amplitude & bandpass calibration: Cyg A (few x 2 min)
  - Blows through RFI!
- P band amplitude & bandpass calibration: primary flux cal
- Phase calibration at 330 MHz: fairly easy
  - Sky is coherent across the array in C and D configurations
    - Observe one strong unresolved source anywhere in sky
  - Traditional phase calibration in A and B arrays
    - Being superseded by NVSS model – often no phase calibration required!
- Phase calibration at 74 MHz: more challenging
  - Cygnus A (or anything bright) is suitable in the C and D arrays
  - A and B arrays: Cyg A works for initial calibration, because enough short spacings see flux to start self-cal process
    - Selfcal can't overcome breakdown of isoplanatic patch assumption
    - Hourly scans on Cyg A => instrumental calibration for non-selfcal (Zernike polynomial) imaging
  - Calibration schemes continue to evolve rapidly with time!

Planning your Observing

- Avoid Sun particularly in compact configurations
- Observe in spectral line mode to avoid BW smearing and allow RFI excision
- Avoid time-averaging smearing by using an appropriate integration time
- Avoid sunrise (particularly at lowest frequencies)
  - often see very bad effects from ionospheric wedge near sunrise

Current Low Frequency Interferometers: VLA

- Two Receivers:

  330 MHz = 90cm

  PB ~ 2.5^{O} (FOV ~ 5^{O})

  74 MHz = 400cm

  PB ~ 12^{O} (FOV ~ 14^{O})

- Simultaneous observations

- Max 330 MHz resolution 6" (+ archival PT resolution ~3")

- Max 74 MHz resolution 25" (+ archival PT resolution ~12")

Current Low Frequency Interferometers: GMRT

- Five Receivers:

153 MHz = 190cm

PB ~ 3.8^{O} (res ~ 20")

235 MHz = 128cm

PB ~ 2.5^{O} (res ~ 12")

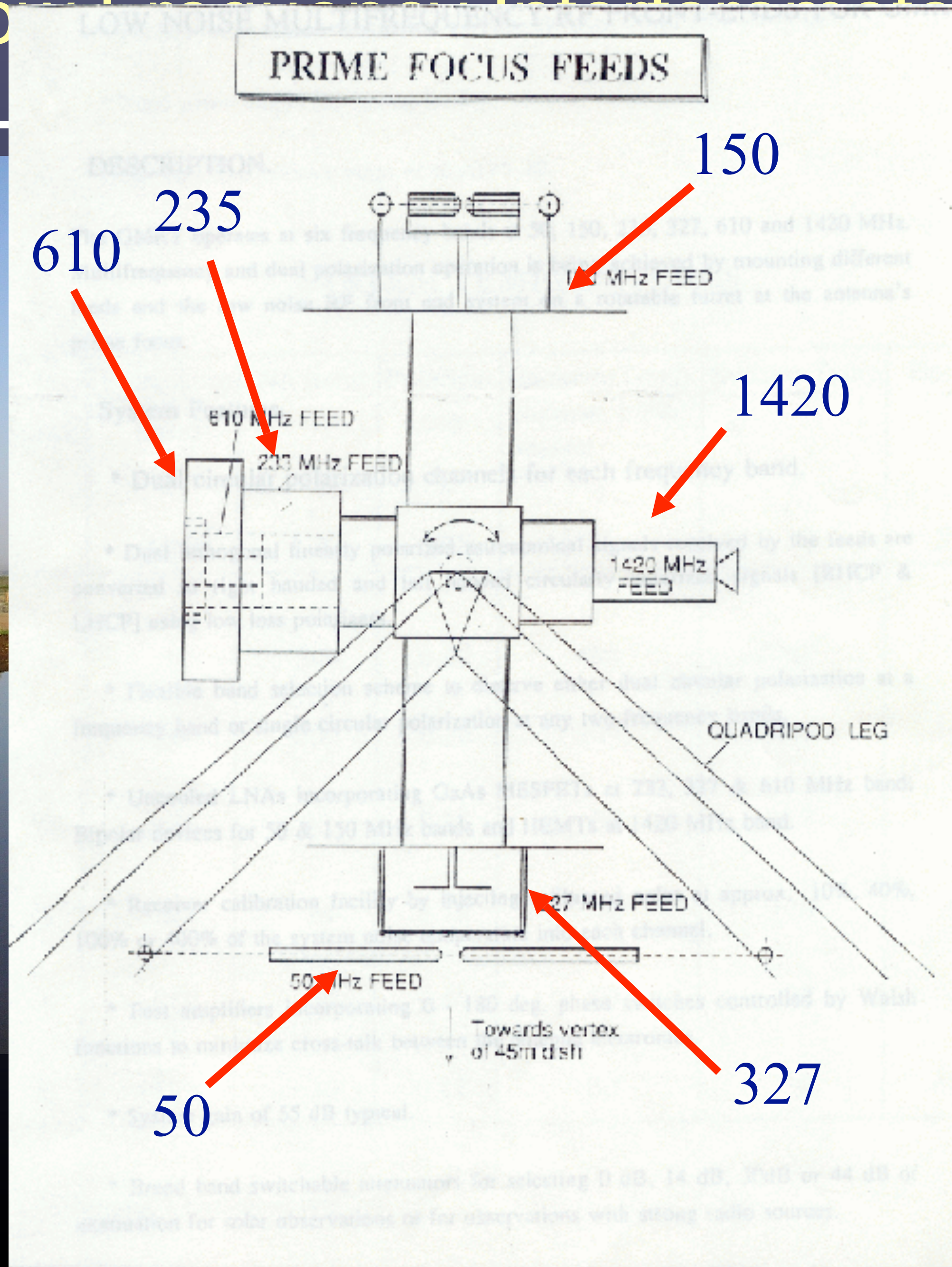
325 MHz = 90cm

PB ~ 1.8^{O} (res ~ 9")

610 MHz = 50cm

PB ~ 0.9^{O} (res ~ 5")

Current Lo… rs: GMRT



Receivers:

Hz = 190cm

3.8^{o} (res ~ 20")

Hz = 128cm

2.5^{o} (res ~ 12")

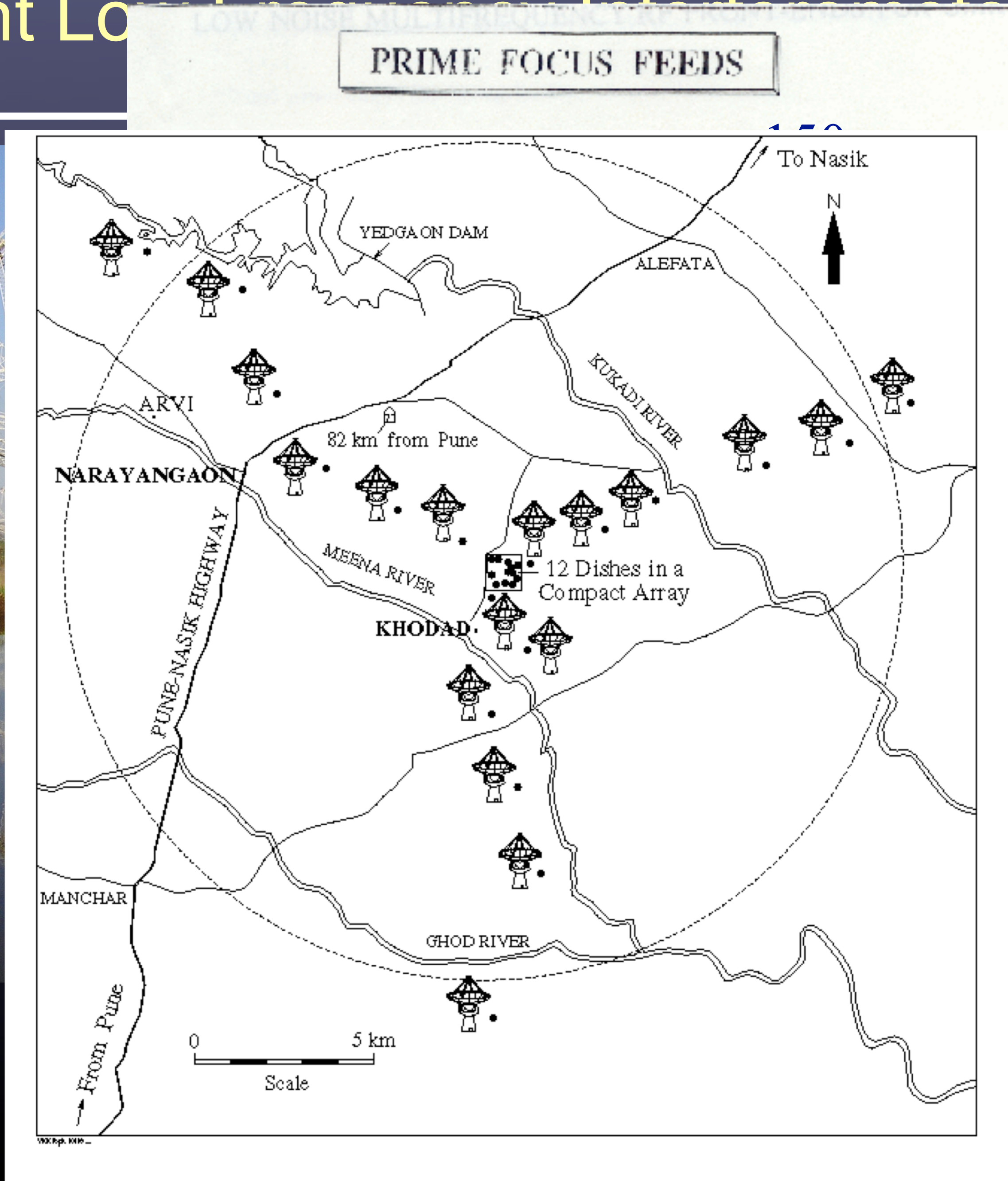
Hz = 90cm

1.8^{o} (res ~ 9")

Hz = 50cm

0.9^{o} (res ~ 5")

Current Lo rs: GMRT



Receivers:

Hz = 190cm

3.8° (res ~ 20")

Hz = 128cm

2.5° (res ~ 12")

Hz = 90cm

1.8° (res ~ 9")

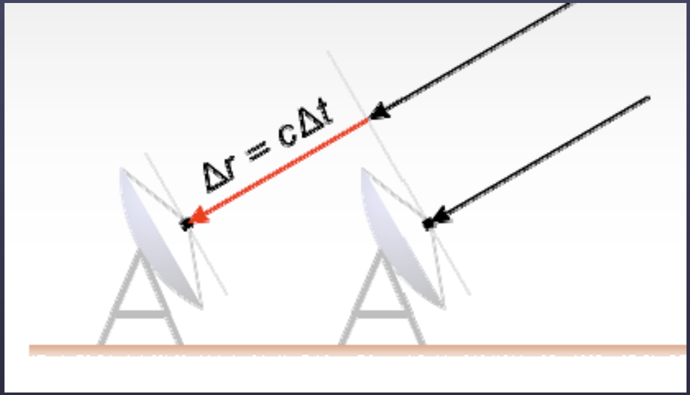
Hz = 50cm

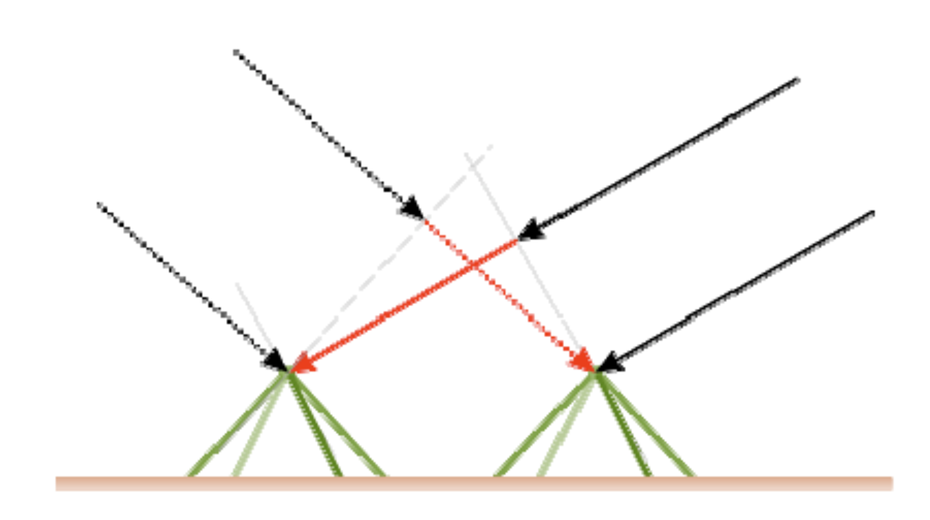
0.9° (res ~ 5")

Next Generation of Low Frequency Instruments

- Next generation low frequency telescopes will have no moving parts:

  - traditional interferometry uses delays to combine signals from different antennas
  - instantaneously limited to a single look-direction on the sky





- dipole arrays are sensitive to the entire sky
- different delays allow systems to simultaneously beamform in multiple different directions

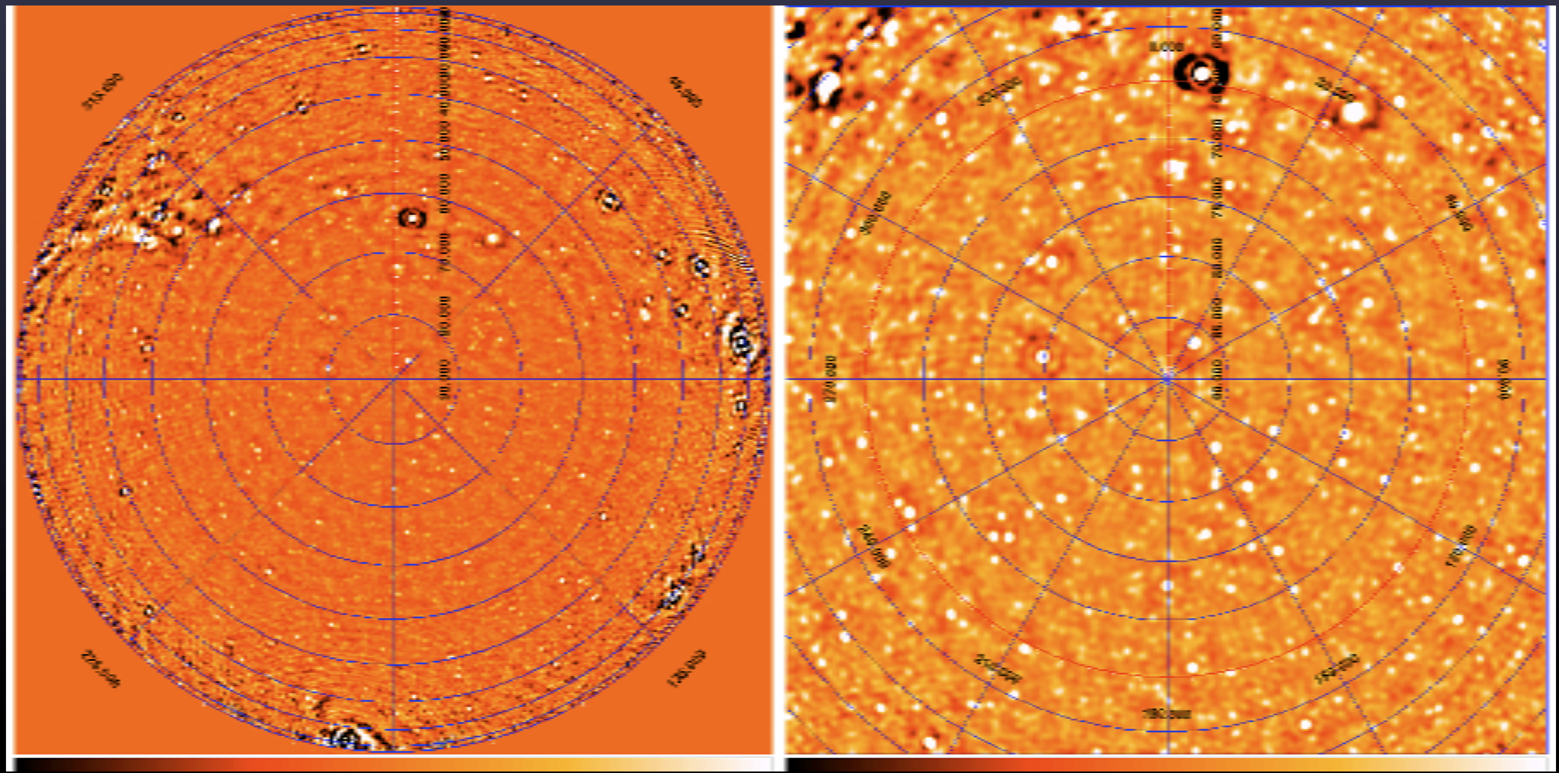
-*(McKinnon Lecture)*

Low Frequency Array (LOFAR)

- Under construction in the NL +
- Two frequency bands:
  - low band -- 30-80 MHz
  - high band -- 120-240 MHz
- Baselines to 100 km with European expansion to 1000 km
- Science Drivers:
  - Epoch of Reionization
  - Extragalactic Surveys
  - Transients and Pulsars
  - Cosmic Rays

Low Frequency Array (LOFAR)

- All-sky image from Core Station 1 centered on NCP
- Two brightest sources (Cas A and Cyg A) removed after self-calibration
- 50 MHz image from 3x24 hours, 30’ beam, nearly 1000 sources detected

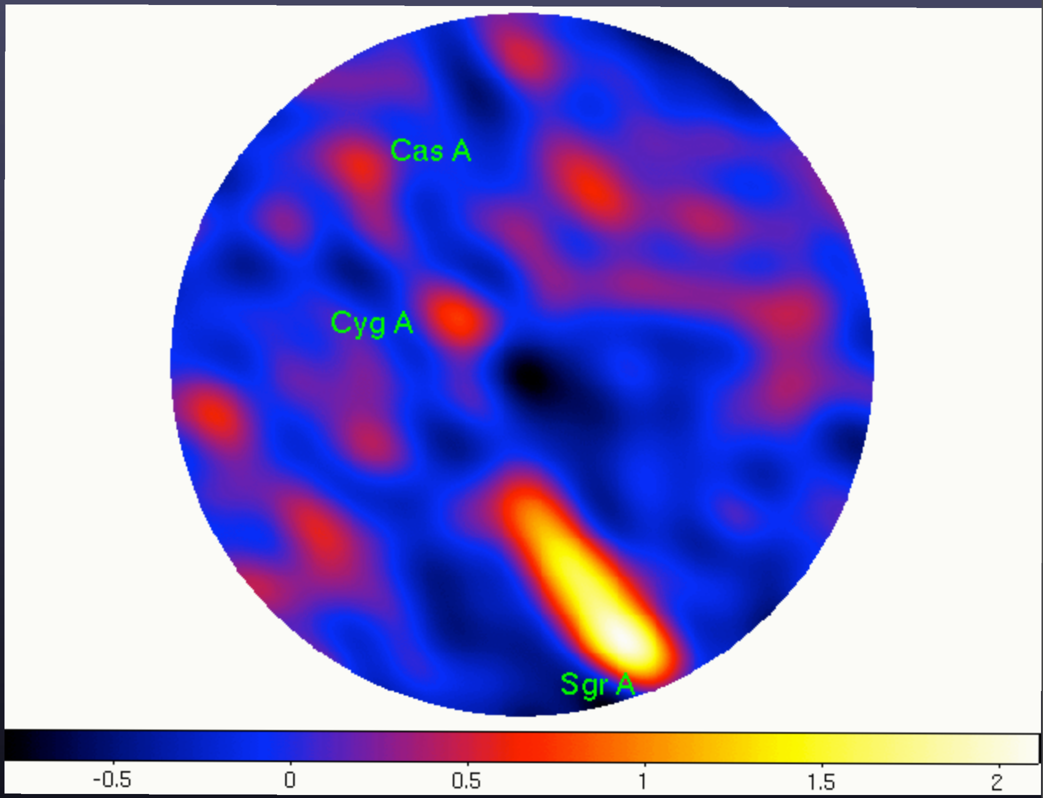


Long Wavelength Array (LWA)

- Under construction in New Mexico:
- Frequency range: 20-80 MHz, BL < 400 km
- Science Drivers:
  - Cosmic Evolution & The High Redshift Universe
    - pre-reionization – Dark Ages
    - 1st super-massive black holes
    - LSS - Dark Matter & Dark Energy
  - Acceleration of Relativistic Particles in:
    - SNRs in normal galaxies up to 10^{15} ev
    - Radio galaxies & clusters up to 10^{19} ev
    - Ultra high energy cosmic rays up to 10^{21} ev?
  - Plasma Astrophysics & Space Science
    - Ionospheric waves & turbulence
    - Solar, Planetary, & Space Weather Science
    - Acceleration, Turbulence, & Propagation
  - Exploration Science
    - Maximizes the opportunity for Discovery Science through flexibility

Long Wavelength Array (LWA)

- All-sky first-light image taken with the Long Wavelength Demonstrator Array centered at zenith
- Bright sources Cas A, Cyg A, Galactic Plane, Sun seen as well as NPS and Loop III
- 74 MHz image, 1.6 MHz of bandwidth, 50 ms snapshots taken every 5 minutes (total of 15 s of data in movie), 11 degree resolution

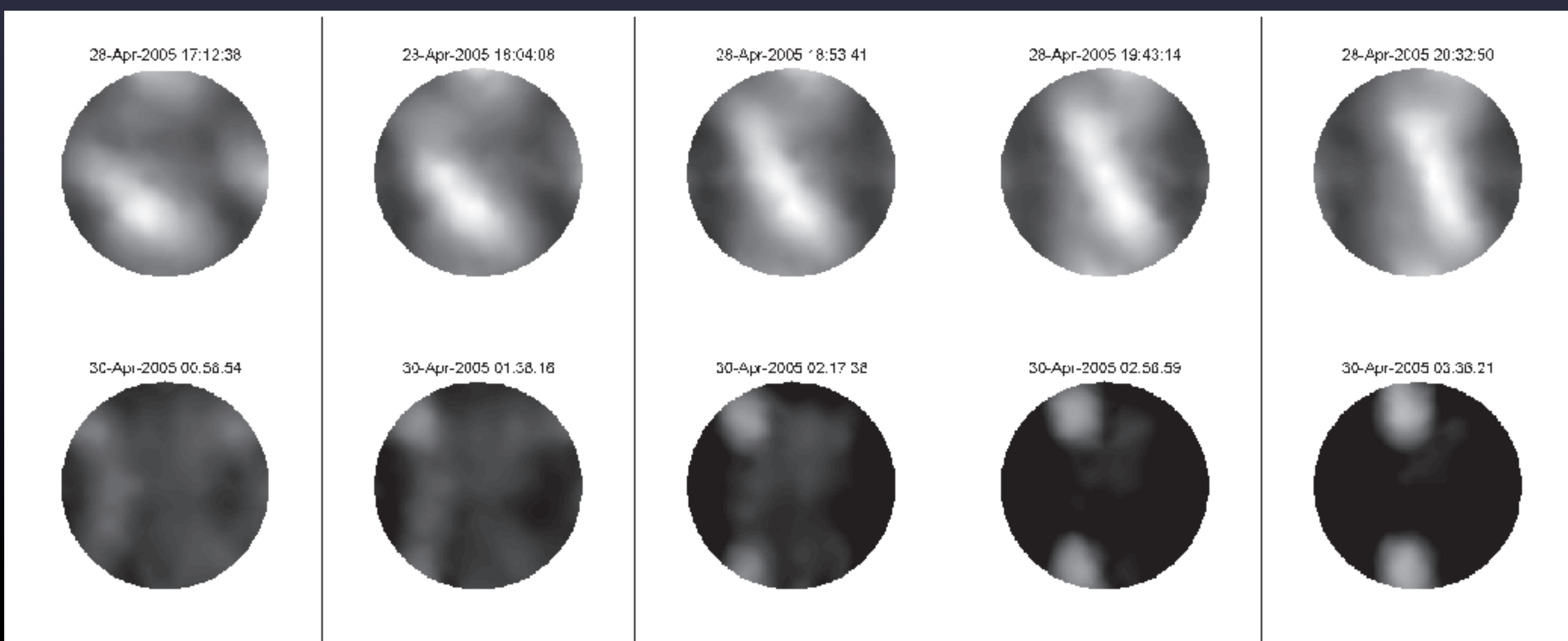


Murchison Widefield Array (MWA)

- Under construction in W. Australia:
- Frequency range: 80-300 MHz, BL < 3 km (most < 1.5 km)
- Science Drivers:
  - Epoch of Reionization
  - Solar, Heliosphere and Ionosphere

Murchison Widefield Array (MWA)

- Nearly all-sky maps (0˚-60˚ zenith angle) from the Murchison Widefield Array Low Frequency Demonstrator (MWA LFD, Bowman et al. 2007)
- Maps at 200 MHz made by scanning an antenna beam tile through a raster of pointing directions
- Top panel shows Galactic Center rising and transiting, bottom panel shows Sun rising (mirror image of Sun is due to diffraction-grating sidelobes)



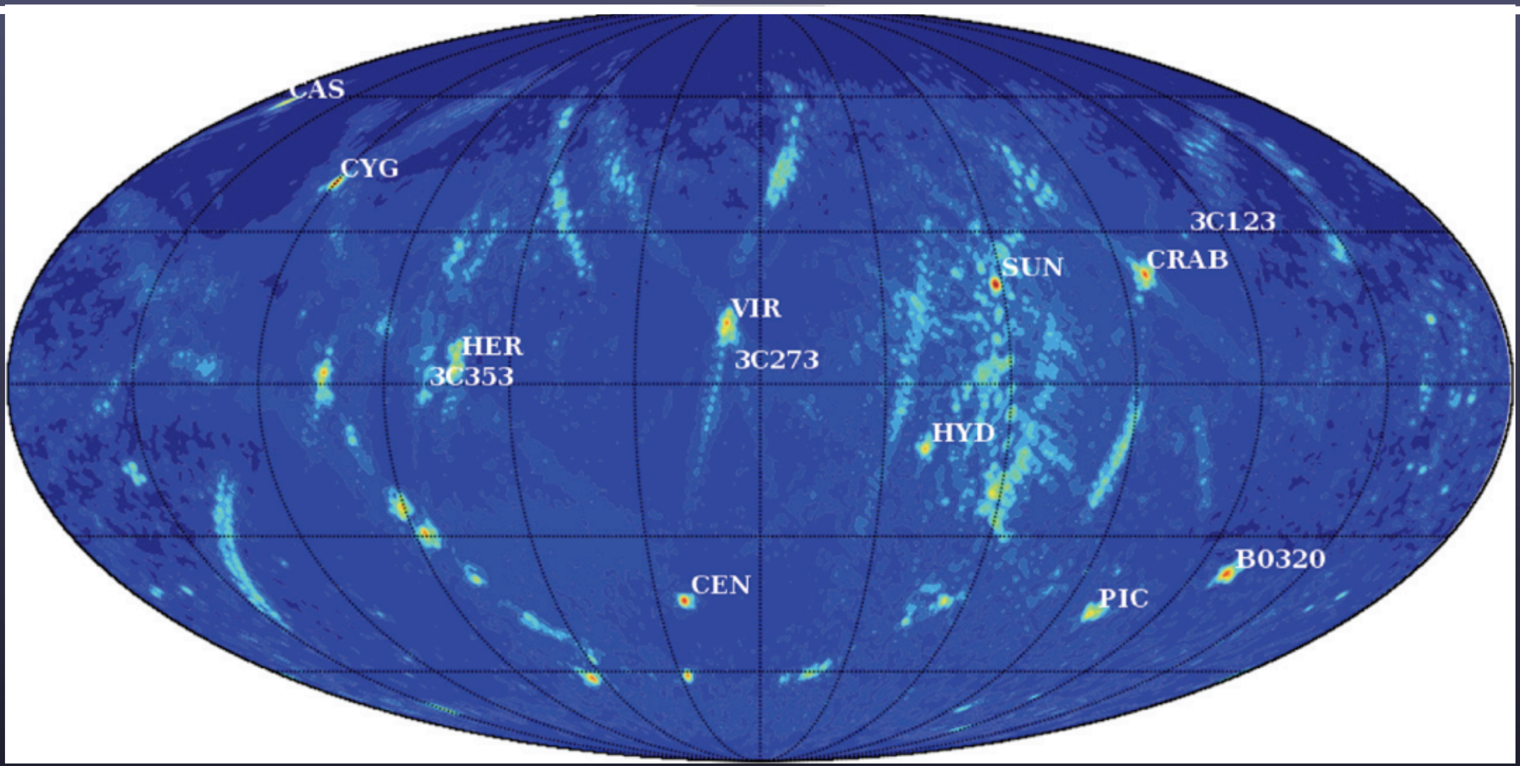
Precision Array to Probe Epoch of Reionization (PAPER)

- Under construction in W. Australia:

- Frequency range: 100-200 MHz,
BL < 0.3 km

- Science Driver:
  - Epoch of Reionization

Precision Array to Probe Epoch of Reionization (PAPER)



- All-sky image at 149.5 MHz from 4 single polz. dipole antennas
- Total bandwidth of 75 MHz, 24 hours of data

For more information:

Further reading:

White Book: Chapters 12.2, 15, 17, 18, 19, & 29

From Clark Lake to the Long Wavelength Array: Bill Erickson's Radio Science, ASP Conference Series 345

The 74 MHz System on the Very Large Array, Kassim et al. 2007, ApJS, 172, 686

Data Reduction:

http://www.vla.nrao.edu/astro/guides/p-band/

http://www.vla.nrao.edu/astro/guides/4-band/

Future Instruments: LWA, LOFAR, MWA, PAPER, ...

http://lwa.unm.edu http://www.lofar.org/ http://astro.berkeley.edu/~dbacker/eor/
http://www.haystack.mit.edu/ast/arrays/mwa/

Thanks to: C. Brogan (NRAO), N. Kassim, A. Cohen, W. Lane, J. Lazio (NRL), R. Perley, B. Cotton, E. Greisen (NRAO)