Future Ideas for Low Frequencies at the VLA (and in New Mexico)

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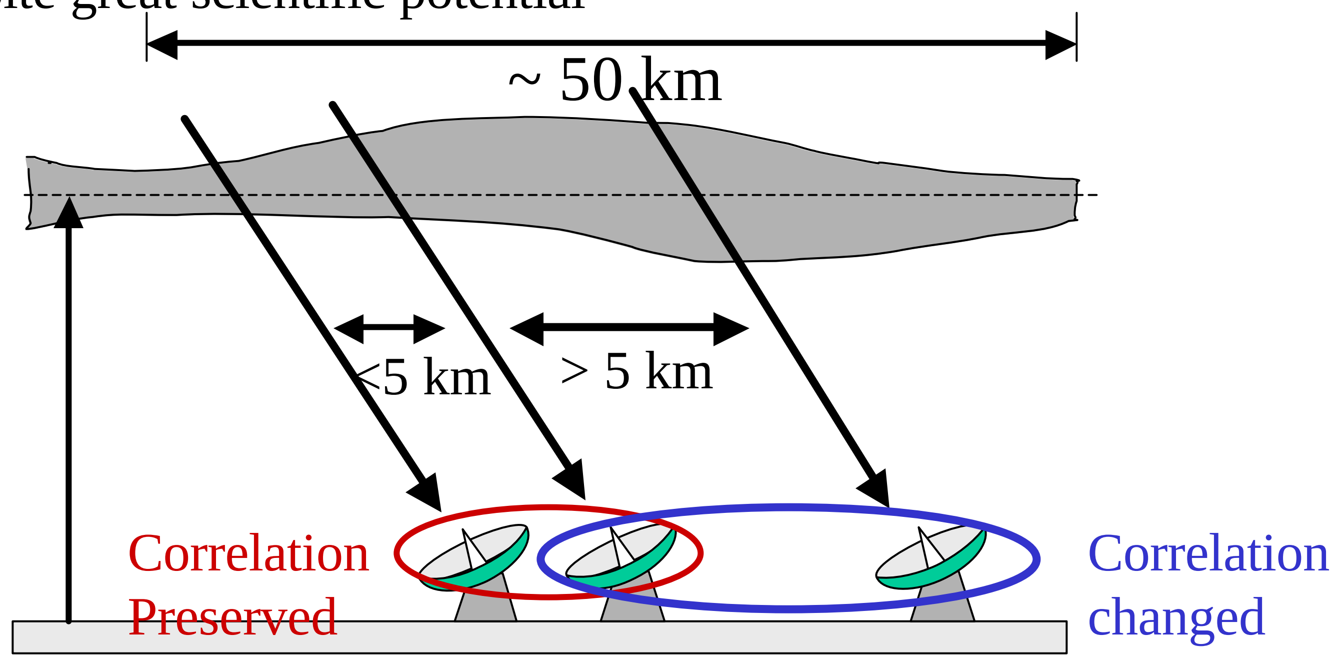
Background & Objectives

- Success of 74 MHz VLA demonstrates that modest investment of resources can result in significant progress in low frequency astronomy
- In light of recently awarded funding from NRL to pursue basic research in radio astronomy we are considering a modest program to gradually expand the performance of the VLA at low frequencies by utilizing mainly existing NRAO infrastructure in NM
  - This will also help develop and exercise new technology as part of NRL's responsibilities to the LOFAR project
- Philosophy – institute technical improvements:
  - without adversely impacting VLA/VLBA operations
  - so that they efficiently translate into concrete scientific enhancements of the instrument and can be readily realized by a growing user community

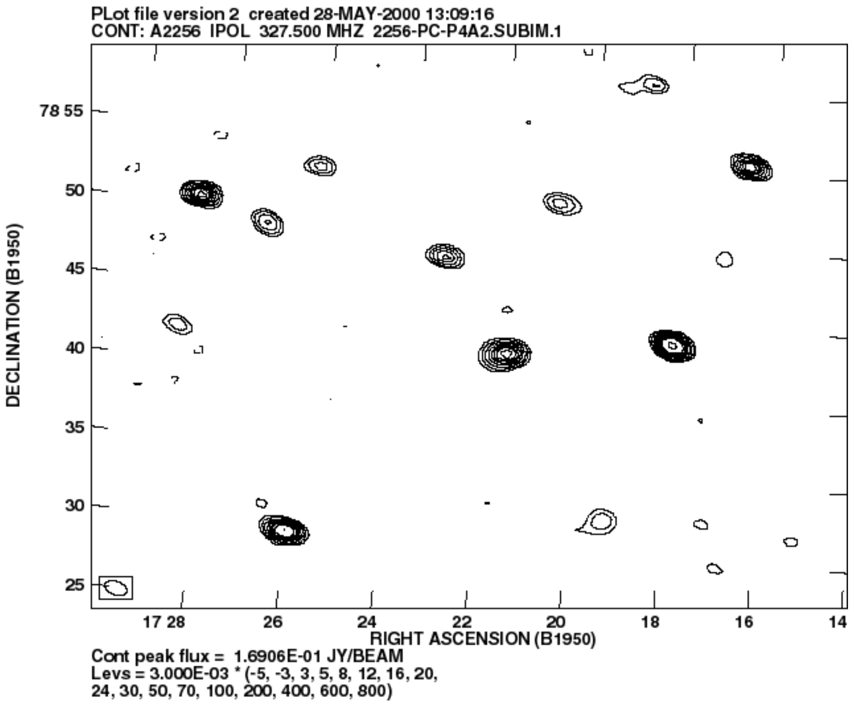
Background of Low Frequency Radio Astronomy: Mired in the Dark Ages

- Radio astronomy began at low frequencies: $\nu \sim 20$ MHz
- Until recently, ionospheric effects severely limited angular resolution & sensitivity
- Remains one of the most poorly explored regions of the EM spectrum despite great scientific potential

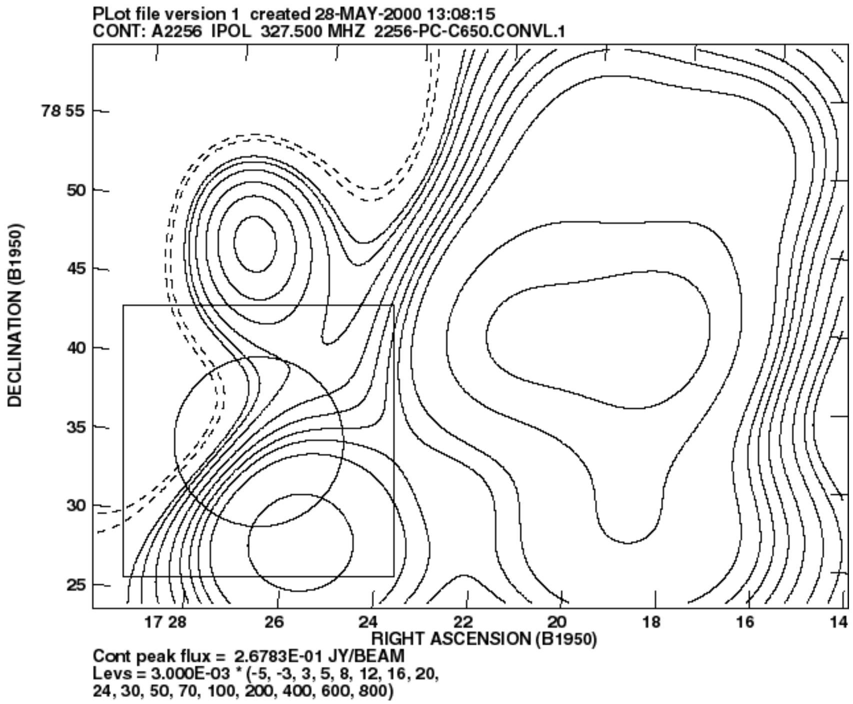


Low Angular Resolution: Limits Sensitivity Due to Confusion

θ ~ 1’, rms ~ 3 mJy/beam



θ ~ 10’, rms ~ 30 mJy/beam

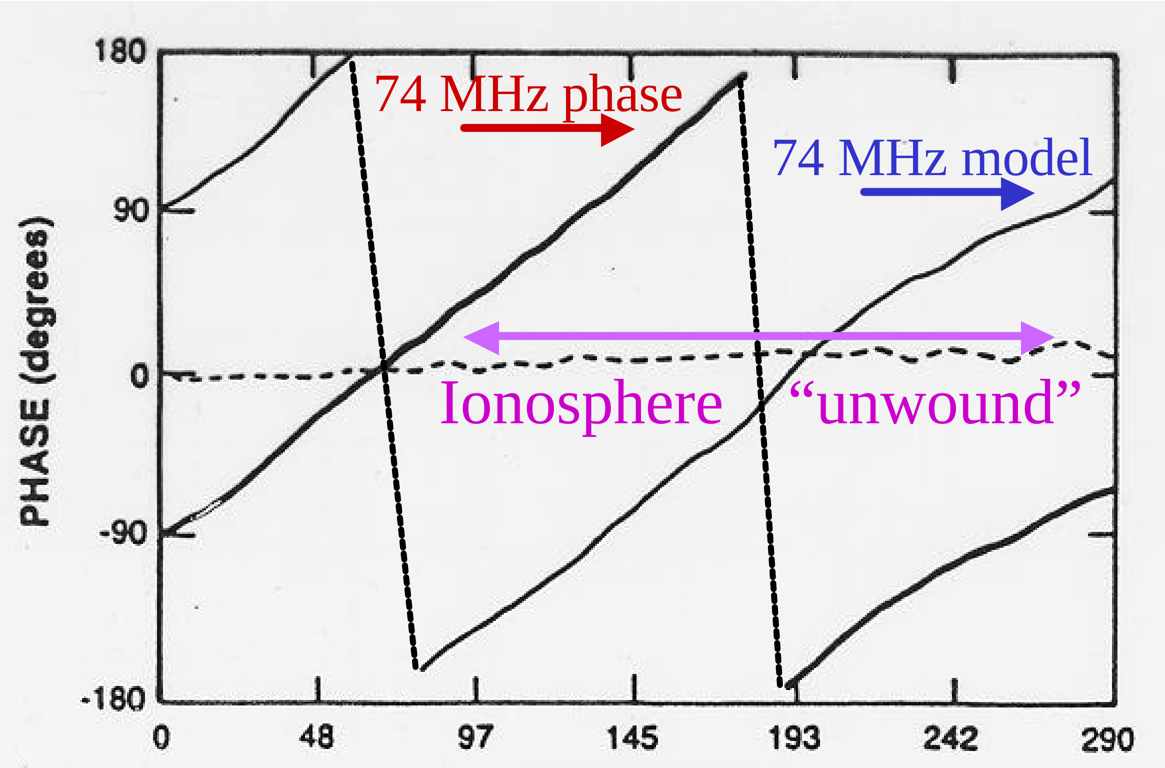


74 MHz VLA SYSTEM

- 74 MHz VLA imaging system implemented 1993–1997
- Demonstrated **self-calibration** can remove ionospheric effects
  - Over-determined problem manageable with high N array & initial model
    - Works well at VLA (N=27)
    - Originally motivated by recognition that *phase transfer* from higher frequencies can increase coherence times and S/N – rarely required
- VLA 74 MHz system is now the most powerful long wavelength interferometer in the world.

THE 74 MHz NRL-NRAO VLA SYSTEM

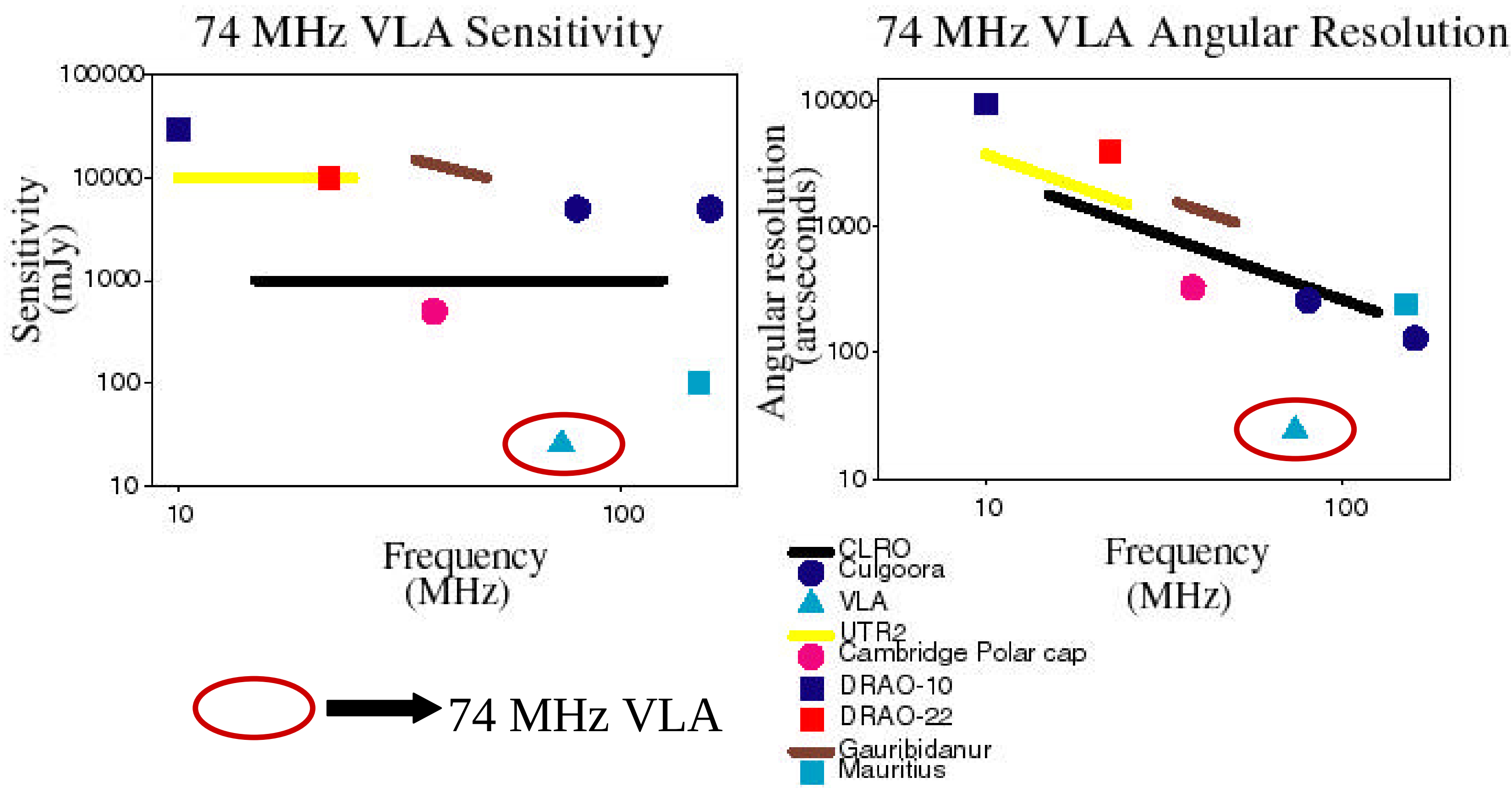
Phase Transfer: Enhancing S/N for Self-cal



(Kassim et al. 1993)

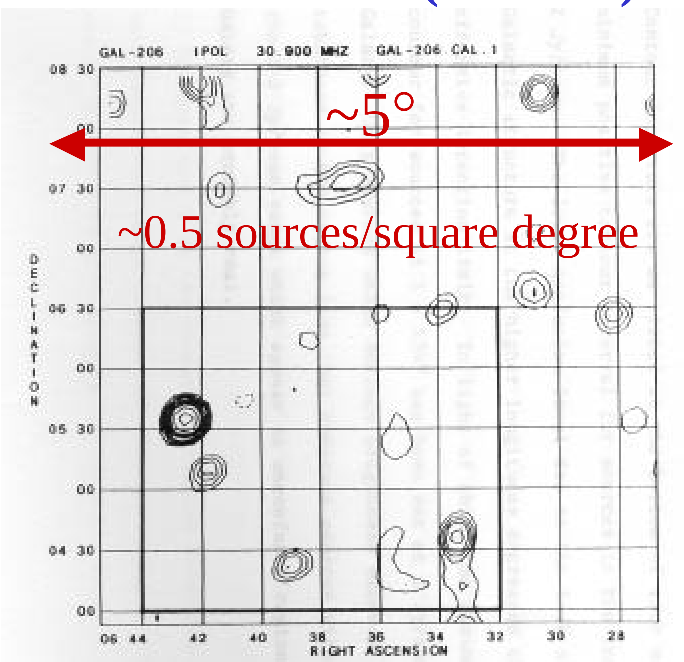
- Ionospheric waves introduce rapid phase variations
  - ~ 1°/sec for A–array (35 km) VLA.
- Disrupt phase measurements and limit coherence times
- Self-calibration can remove them to the level needed for normal synthesis observations.

74 MHz VLA: Significant Improvement in Sensitivity and Resolution



Comparison of Low Frequency Capabilities (past vs. present)

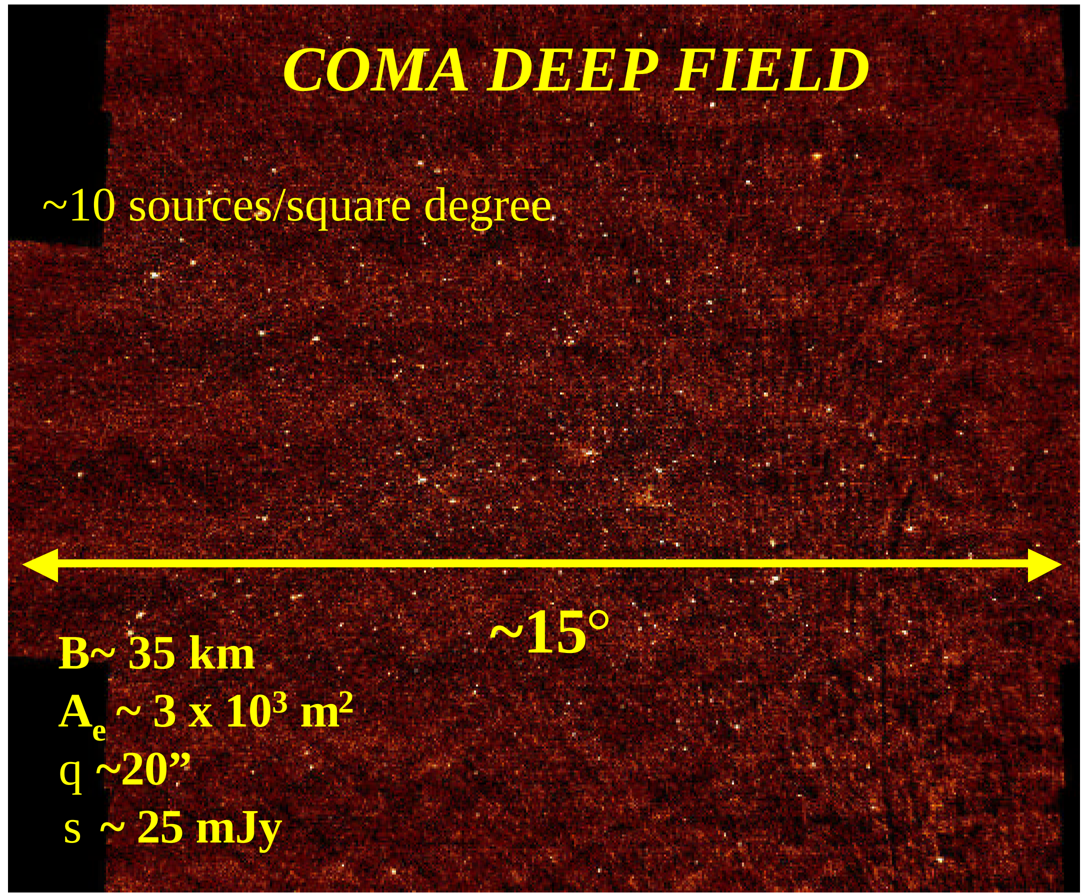
Clark Lake (30 MHz)



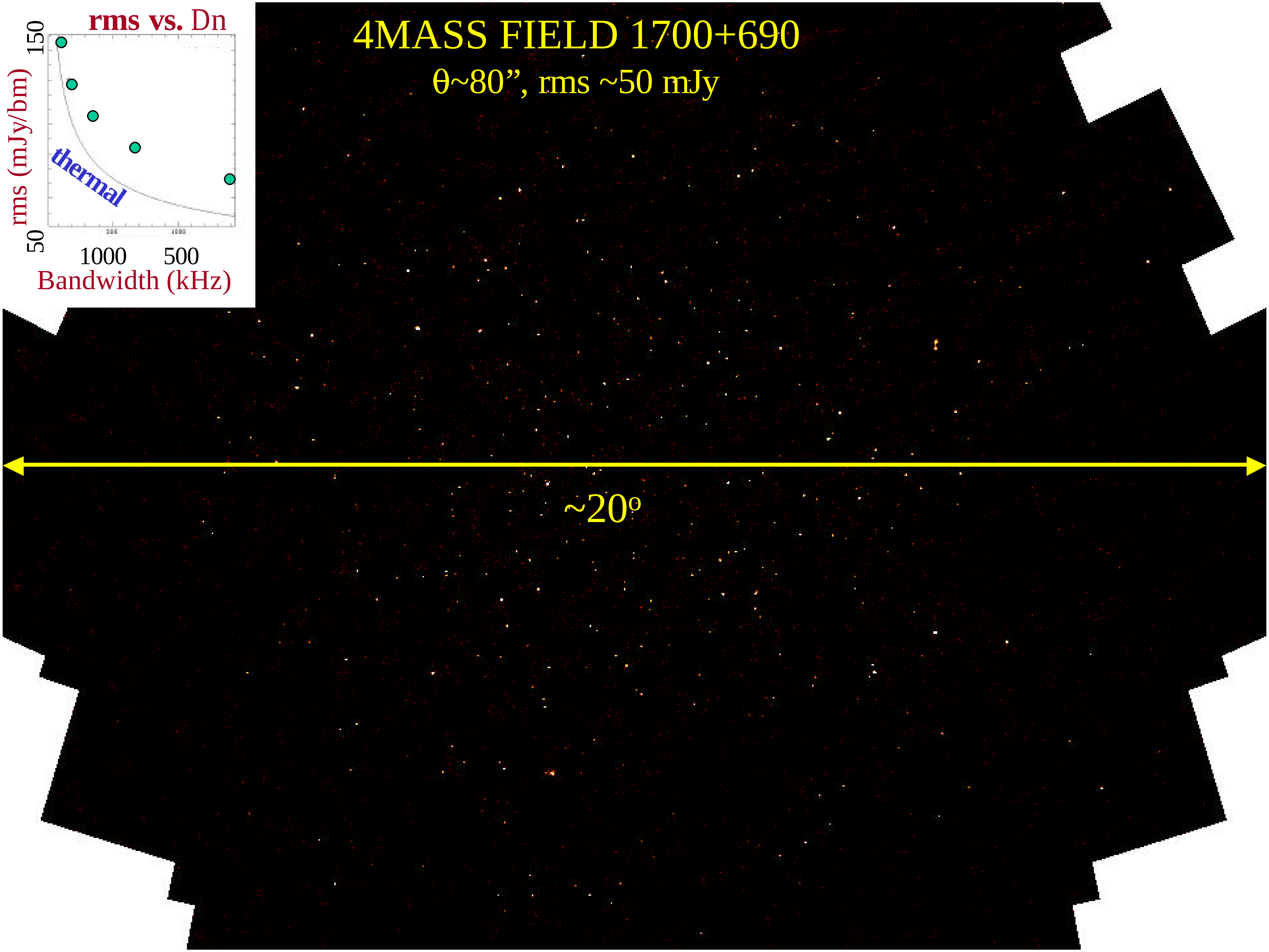
Kassim 1989

- B ~ 3 km
- A_e ~ 3 x 10^3 m^2
- θ ~ 15’ (900”)
- σ ~ 1 Jy

VLA (74 MHz)

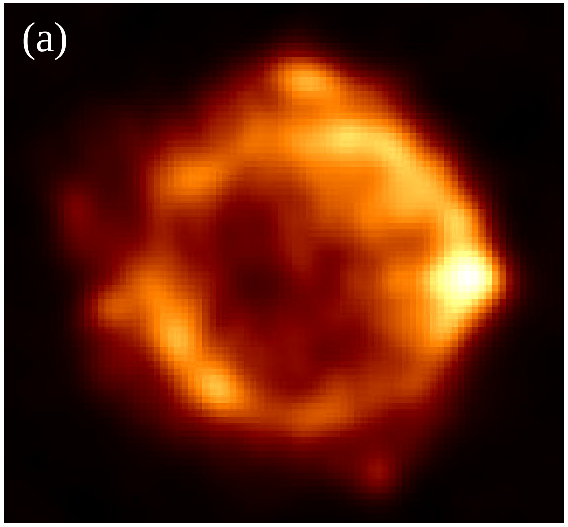


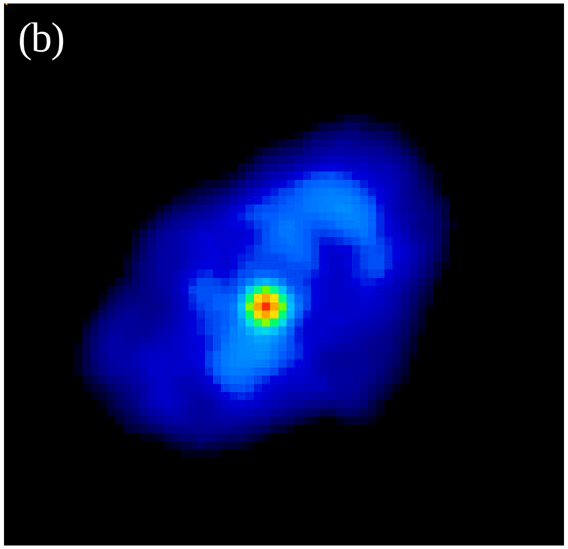
Enßlin *et al*. 1999

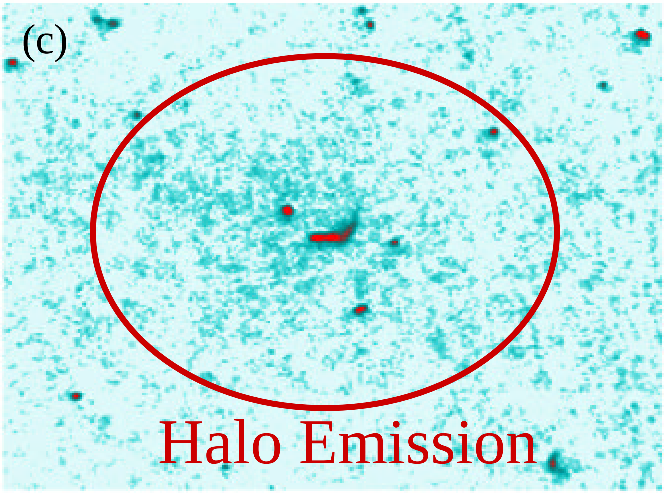


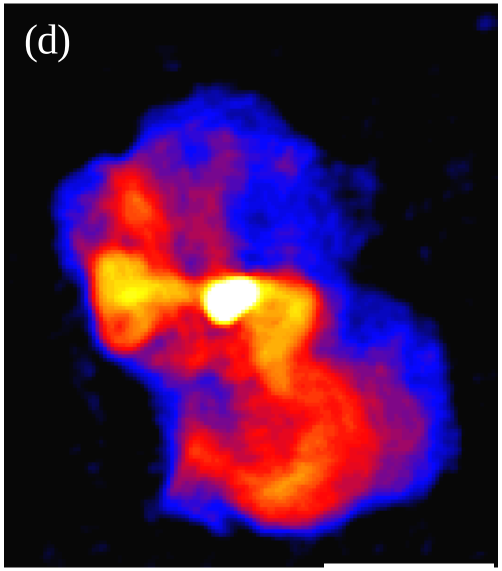
rms vs. Dn
150
50
rms (mJy/bm)
thermal
1000
500
Bandwidth (kHz)
4MASS FIELD 1700+690
θ~80”, rms ~50 mJy
~20º

Results from VLA 74 MHz System



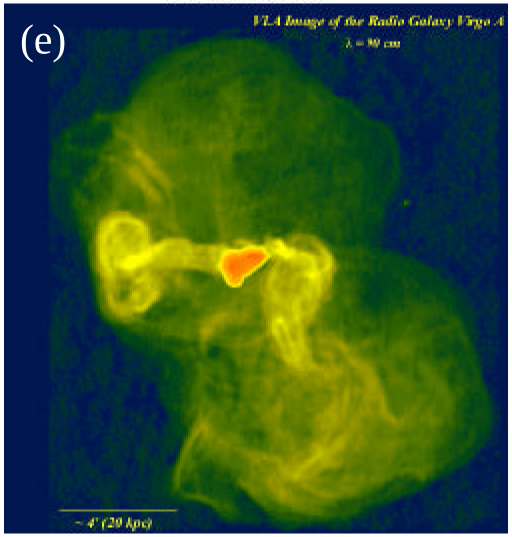






74 MHz

The Virgo Cluster and the M87 Radio Halo: Outflow, not Cooling Flow
Owen, Eilek, & Kassim 1999



327 MHz

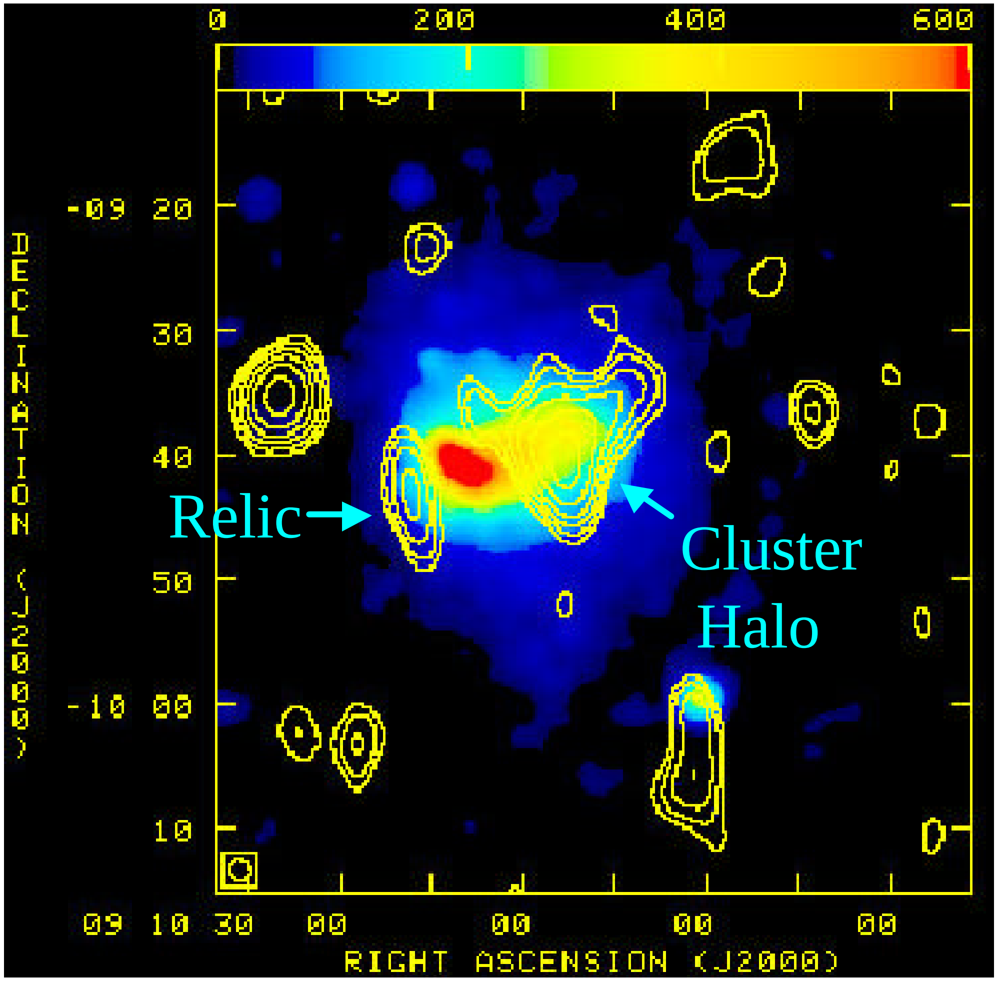
(a,b) internal absorption in supernova remnants (a: Cas A - Kassim *et al*. 1995; b: Crab Nebula - Bietenholz *et al*. 1997)

(c) emission from relics & clusters of galaxies (Enßlin et al. 1999, Kassim et al. 1999, 2000)

(d,e) radio galaxies & halos (Kassim et al. 1993, Owen et al. 1999, 2000)

VLA 74 MHz: New Cluster/Relic System

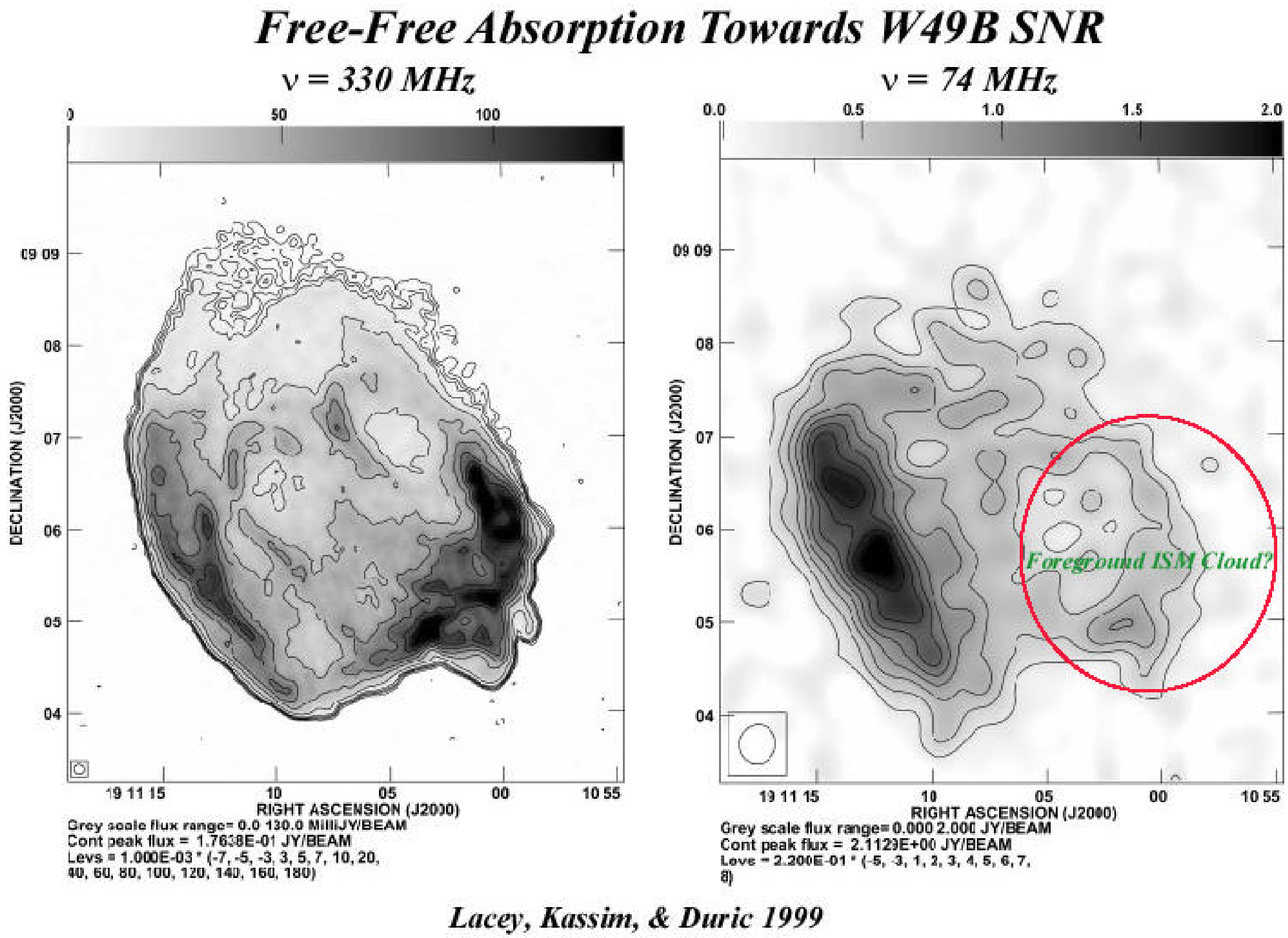
Kassim, Clarke, et al. 2001(ApJ, astro-ph/0103492)



A new halo-relic system in the Abell 754 cluster of galaxies recently discovered with the 74 MHz VLA

Color: ROSAT X-ray image
Contours: 74 MHz VLA image

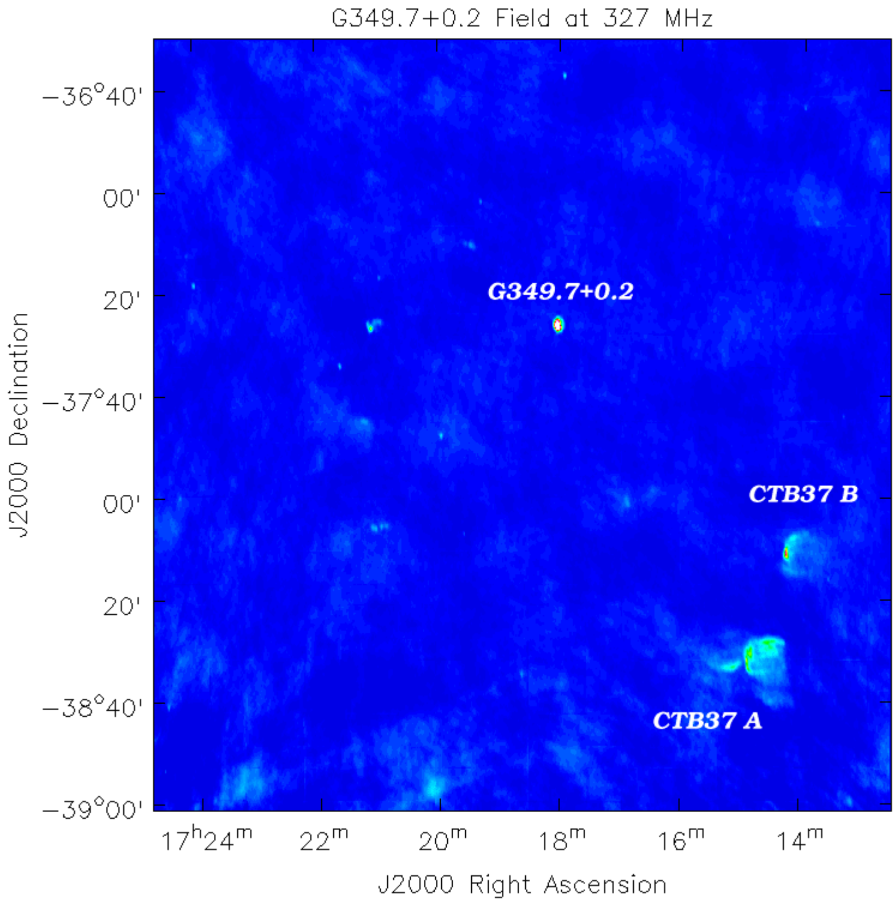
SNRs: Extrinsic ISM Absorption
(images courtesy C. Lacey)



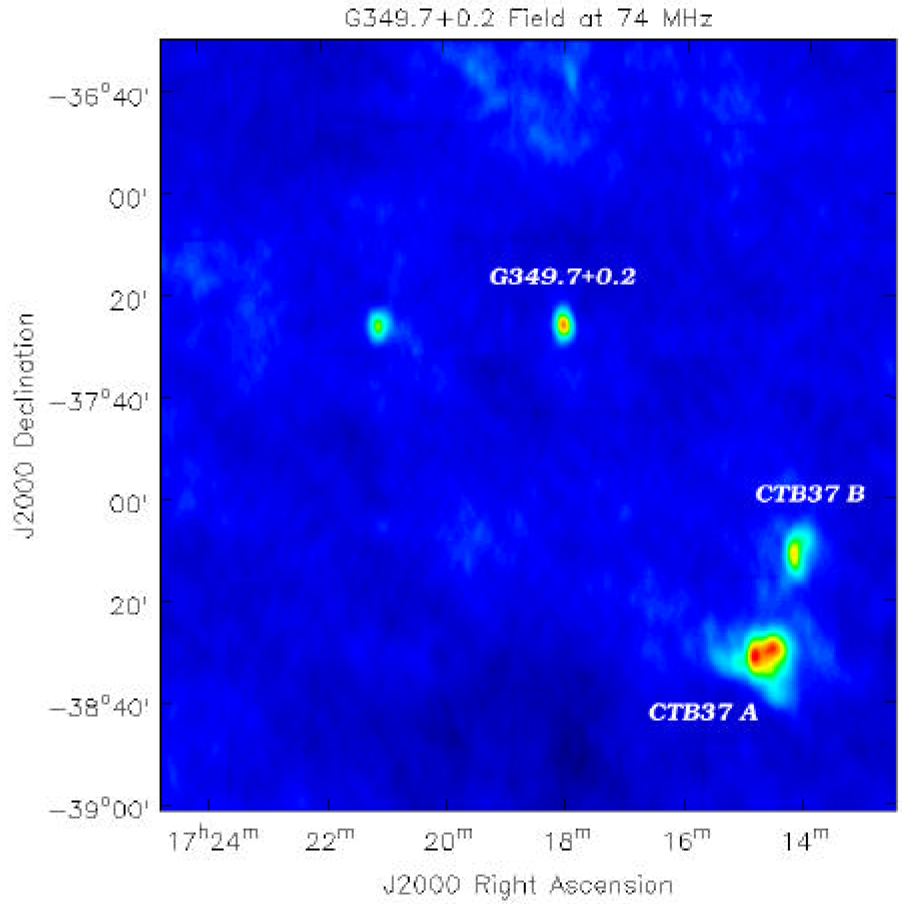
- First example of spatially resolved free-free absorption towards a Galactic SNR (Lacey et al. 2001)

Investigating SNRs and the ISM
(images courtesy C. Brogan)

G349.7+0.2 at 327 MHz



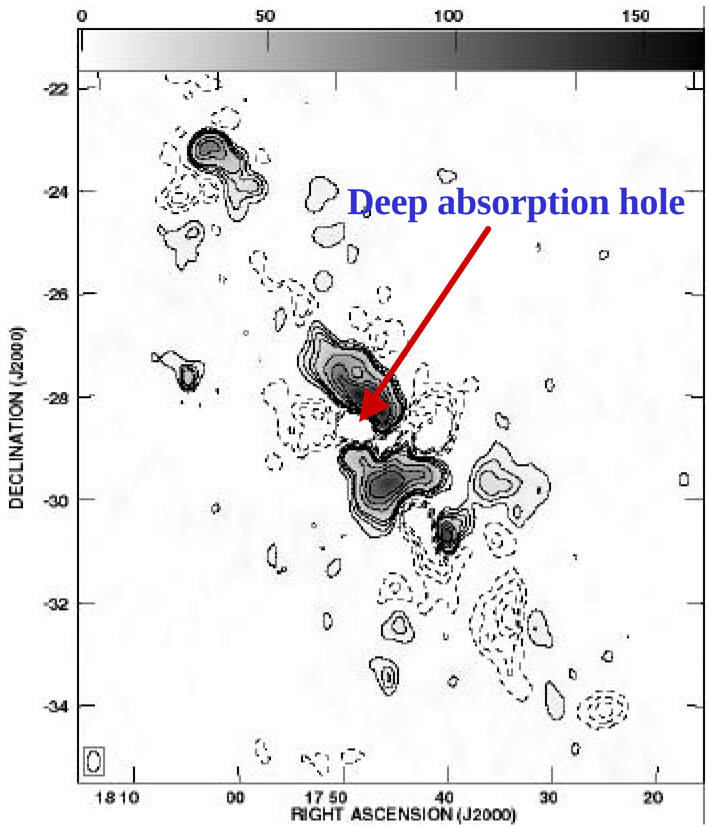
G349.7+0.2 at 74 MHz



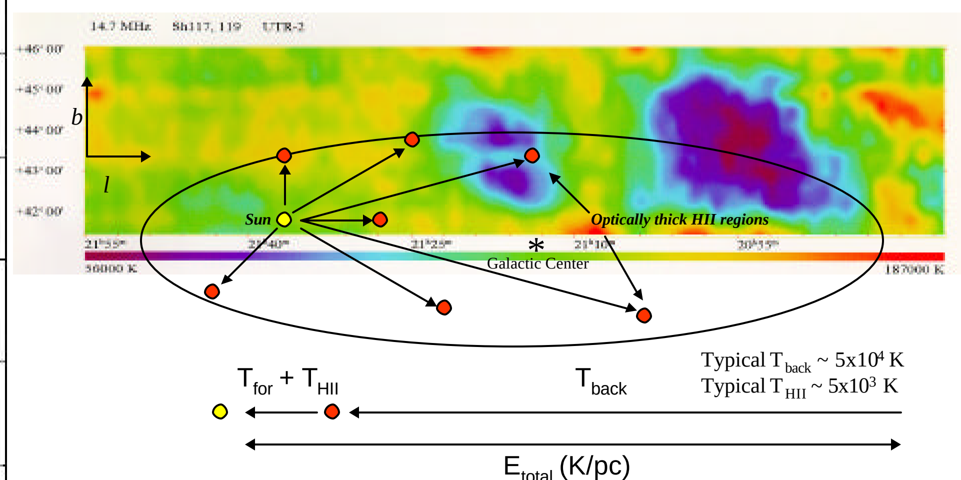
VLA 74 MHz: Galactic Center

Absorption Holes => Synchrotron Emissivity Vectors

74 MHz Galactic Center: Preliminary D-array Image – (θ~10’)
(courtesy Mike Nord – UNM-NRL PhD Thesis Project)



MAPPING OUT THE COSMIC RAY ELECTRON GAS



Typical 30 MHz absorption “hole” flux for 10” HII region: ~ 0.5 mJy (outer Galaxy)
~ 3 mJy (inner Galaxy)

(There are at least 1000 Galactic HII regions of this scale.)

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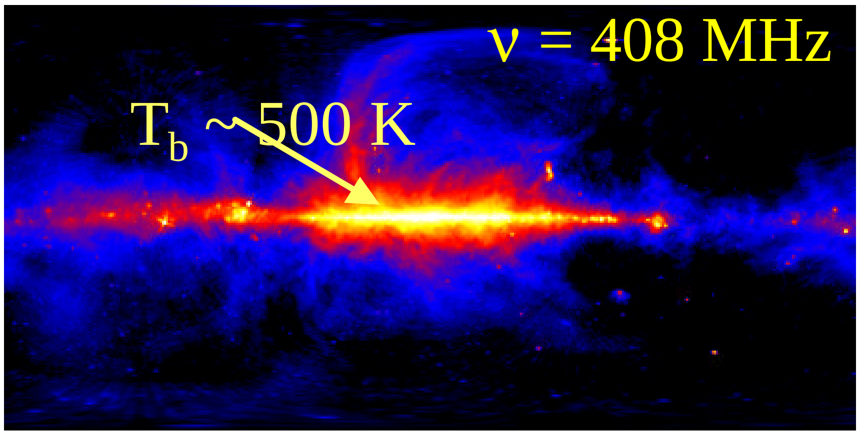
Possible Near Term Activities

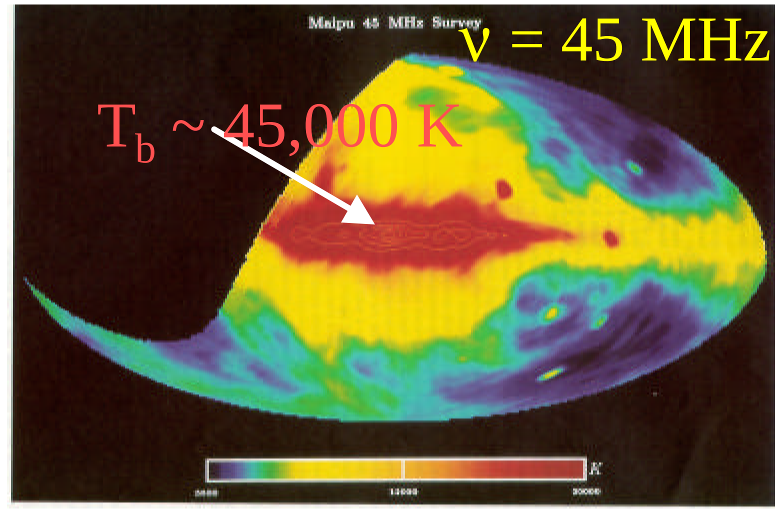
- Some room for improvement with current VLA system
  - New calibration/imaging algorithms being explored for use with current VLA system and in anticipation of LOFAR
    - New strategies being explored with NRAO on the 4MASS project
      - 4MASS – initial LOFAR calibration grid
- However, the main limitations of the present 74 MHz VLA are sensitivity and angular resolution
- Possible modest near term programs to address these:
  - Increase the available bandwidth at 74 MHz
  - Outfit PT at 74 MHz and implement 74/330 MHz PT link tests
  - Plan for a few inner VLBA 74 MHz campaigns
    - To constrain the practical limits of low frequency interferometry in anticipation of LOFAR and to do unique science

Possible Longer Term Activities

- The VLA was not designed to provide good sensitivity at these wavelengths: ε ~15%, sidelobes ~ 20dB, Tsys/Ae too high
  - It would be far better to use an array of broad-band antennas, electronically phased to act as a single dish
- We are designing a stand-alone low frequency (10-90 MHz) "station" consisting of several hundred antenna elements (for LOFAR)
- We would like to build two stations as prototypes for the low frequency part of LOFAR and use them to enhance the capabilities of the present VLA 74 MHz system
  - Station I – VLA center; Station II – VLA outlier (eg. A+ site)
    - Command & control systems compatible with present & future (EVLA) control systems
  - Two stations will allow us to explore LOFAR beam-forming at frequencies other than 74 MHz

SKY NOISE DOMINATED SYSTEM TEMPERATURE





Frequency	Band Name		System	Antenna	RMS (10 min)
(GHz)	approximate	letter	Temperature[1]	Efficiency[2]	Sensitivity
	wavelength	code	(K)	(%)	(mJy/beam)
0.073 – 0.0745	400 cm	4	1000–10000	20	150[3]
0.3 – 0.34	90 cm	P	150–180	40	1.4[3]
1.3 – 1.70	20 cm	L	35	55	0.056
4.5 – 5.0	6 cm	C	45	69	0.054
8.1 – 8.8	3.6 cm	X	35	63	0.045
14.6 – 15.3	2 cm	U	120	58	0.17
22.0 – 24.0	1.3 cm	K	150 – 180	40	0.31[4]
40.0 – 50.0	0.7 cm	Q	100 – 140	35	0.60[5]

$$\text{rms} \sim T_{sys}/A_e$$

Impact of Central Station:

Relaxing the finite Isoplanatic Patch assumption

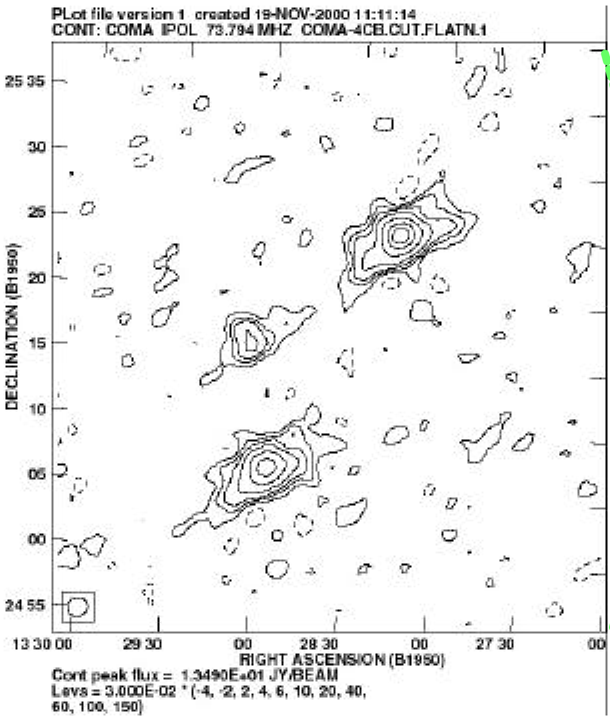
- Current self-calibration assumes single ionospheric solution across full field of view (FOV)
  - Assumption valid over a much smaller region than the full FOV
  - Problems: differential refraction, image distortion, reduced sensitivity
  - Solution: selfcal solutions with angular dependence

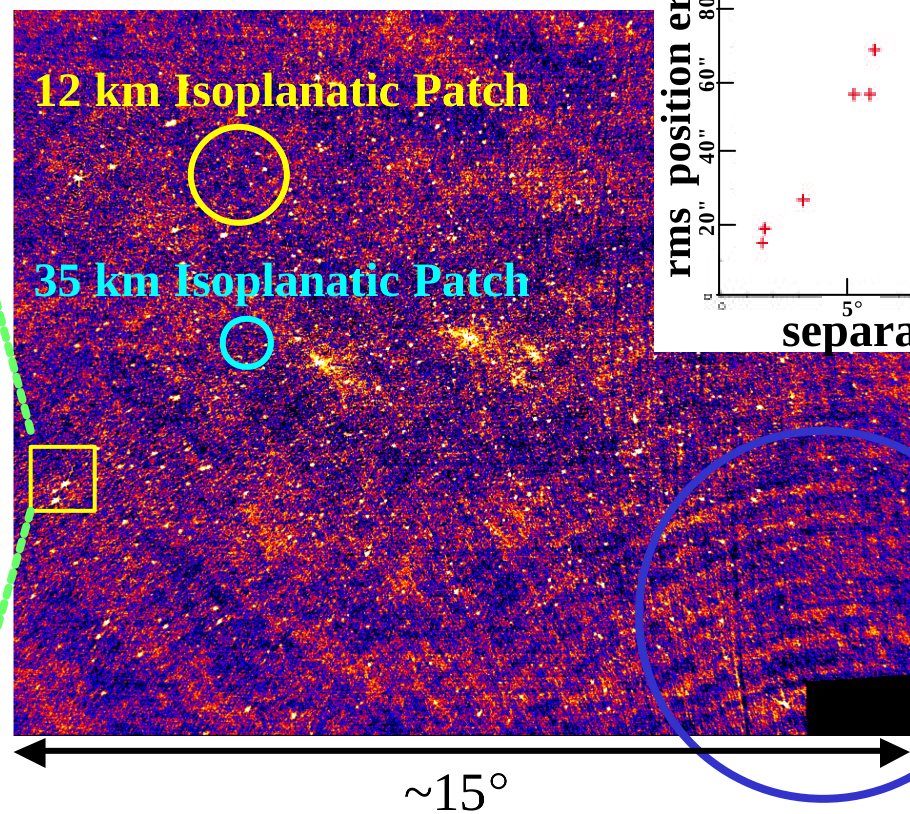
$$\varphi_i(t) \rightarrow \varphi_i(t, \alpha, \delta)$$

- Zernike polynomial phase screen correction now available prior to self-calibration
  - Non-selfcal reliant imaging code developed for 4MASS by Cotton
  - Key handicap – poor S/N – significant data loss except under very good ionospheric conditions

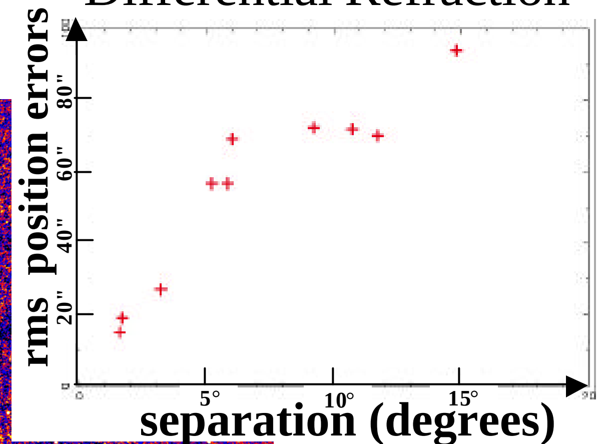
Breakdown of Finite Isoplanatic Patch Assumption

Image Distortion





Differential Refraction



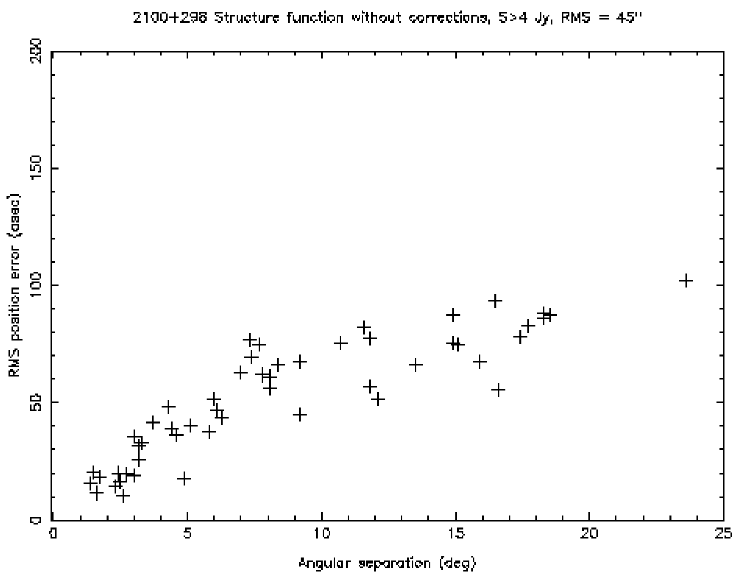
Sidelobe Confusion

Striping due to sidelobe confusion from a far-off source in a completely different IP

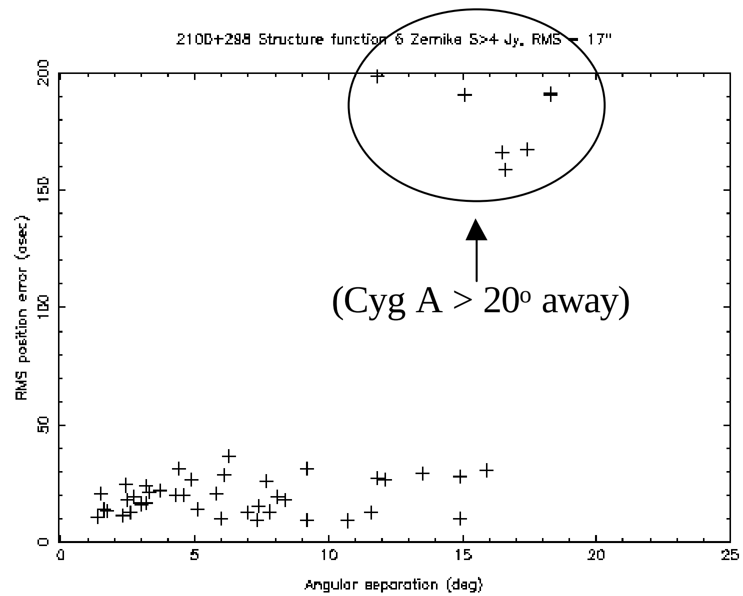
Phase Delay Screen Modeling

1D – phase structure function

Before Zernike Model

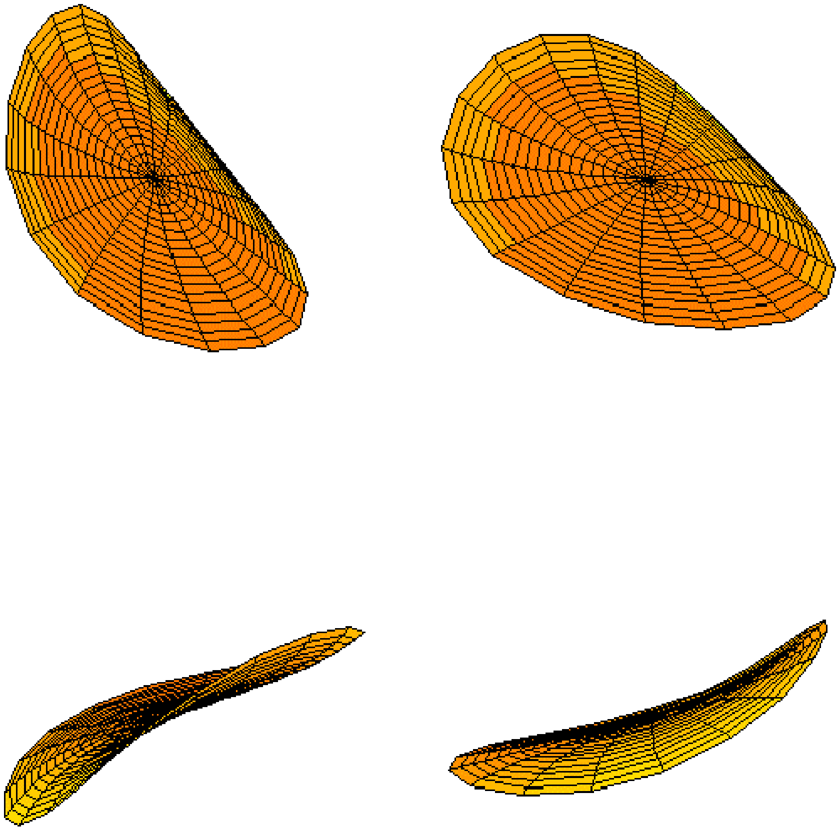


After Zernike Model



Phase Delay Screen Model

(Zernike polynomial models – courtesy B. Cotton, J. Condon)



Fitted model ionospheric phase Delay screen rendered as a plane in 3-D viewed from different angles.

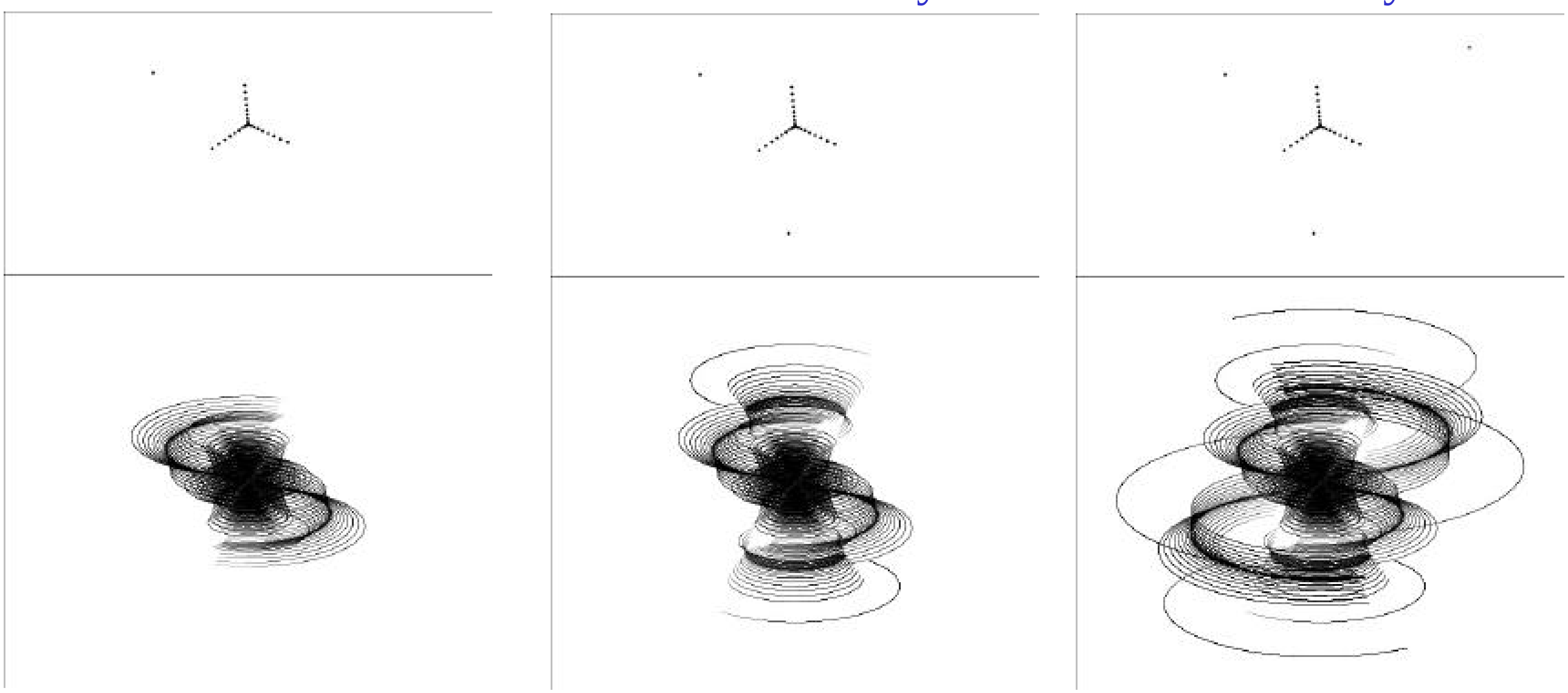
Impact of Central Station

- Will significantly increase the power and sophistication of 74 MHz VLA calibration
  - At least 10X the sensitivity of a VLA dish will aid calibration much as a large dish helps when initially calibrating VLBI data
    - Should greatly improve efficiency of VLAFM
    - Allow us to "map out" the larger FOV of the 25 m dish and aid in determining antenna based phases with an angular dependence
  - ~100 m diameter - sufficient room in central sector
  - Better calibration ➔ Better DR, image fidelity & sensitivity
- Useful for exploring proposed LOFAR calibration schemes which rely on a large "virtual core" of antenna elements

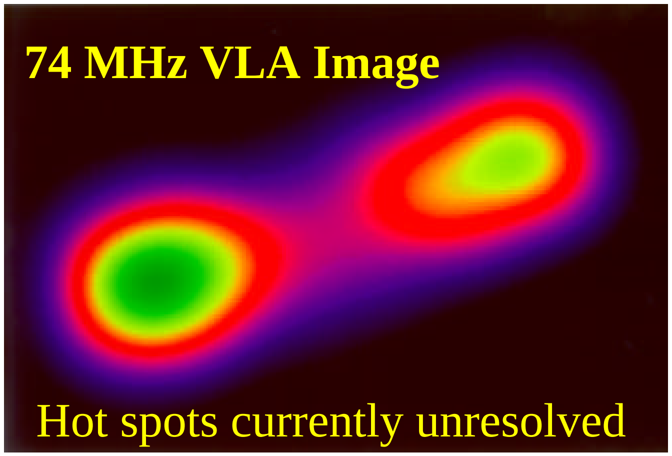
Outlier Station Objective
Extending resolution and uv coverage

$\delta = +20^{o}$

VLA+PT VLA+PT+Dusty VLA+PT+Dusty+Bernardo

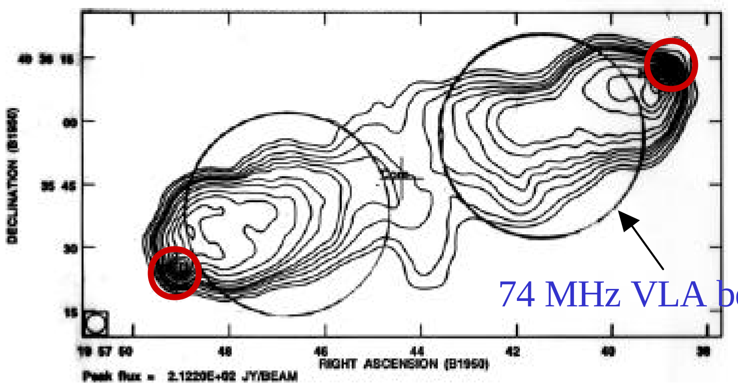


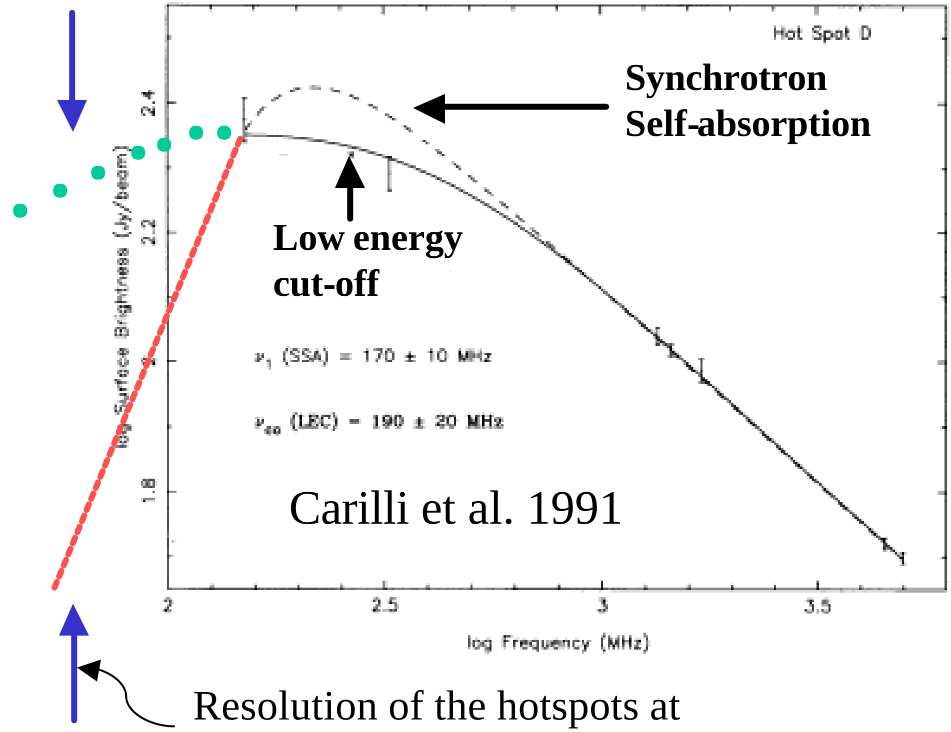
Benefits of Higher Angular Resolution



Kassim et al. 1996

330 MHz VLA Image





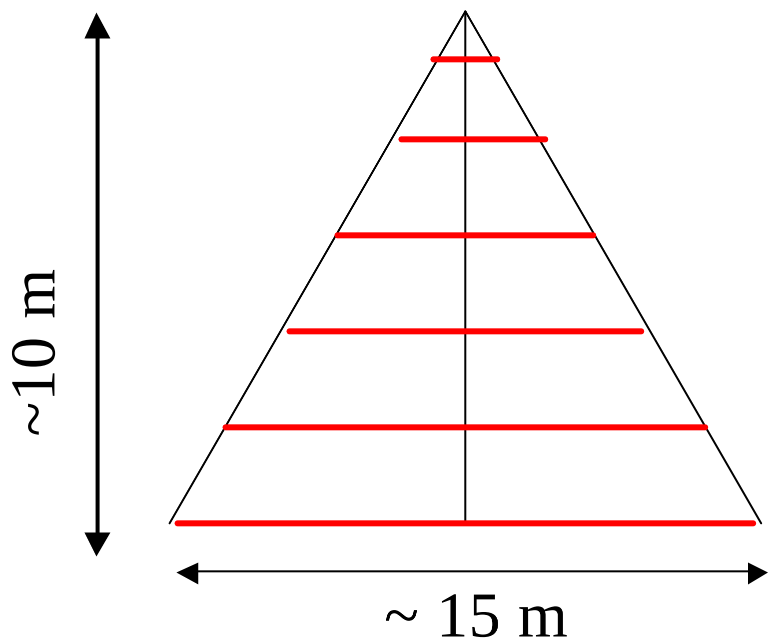
Resolution of the hotspots at
74 MHz will easily differentiate between
competing models for spectral turnover

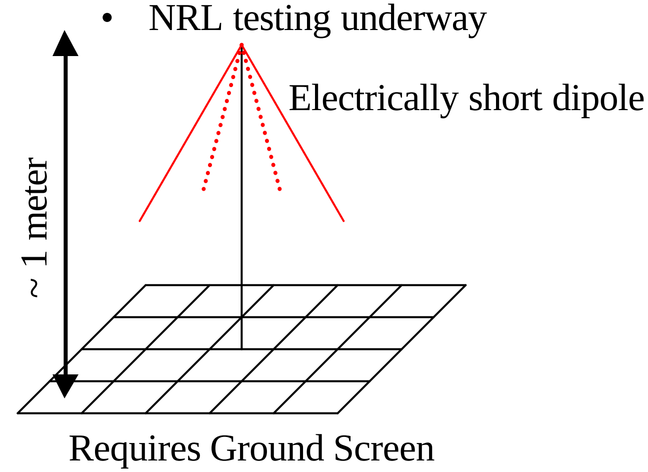
○ → "Hotspots"

Antenna Design

- Conventional approach:
  Log-Periodic Array
  - Advantages: well studied – good frequency & sky coverage
  - Disadvantages: large

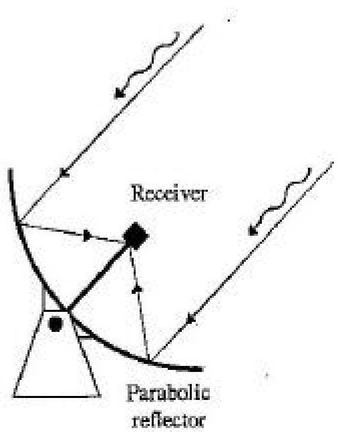
- New-technology approach:
  "Active" Dipoles
  - Advantages: small
  - Disadvantages: impedance matching, sensitivity, sky coverage, ground plane, strong inter-element coupling
    - exploring feasibility in consultation with Erickson & Fisher
    - NRL testing underway

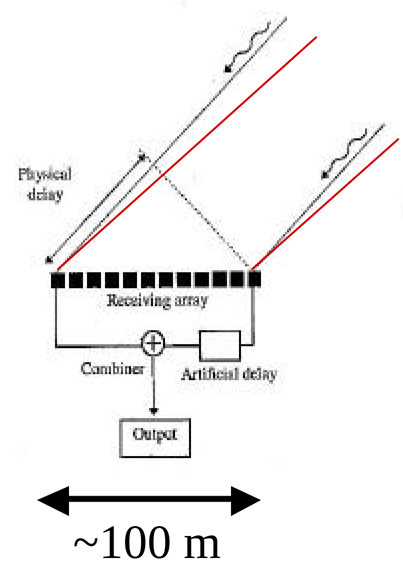




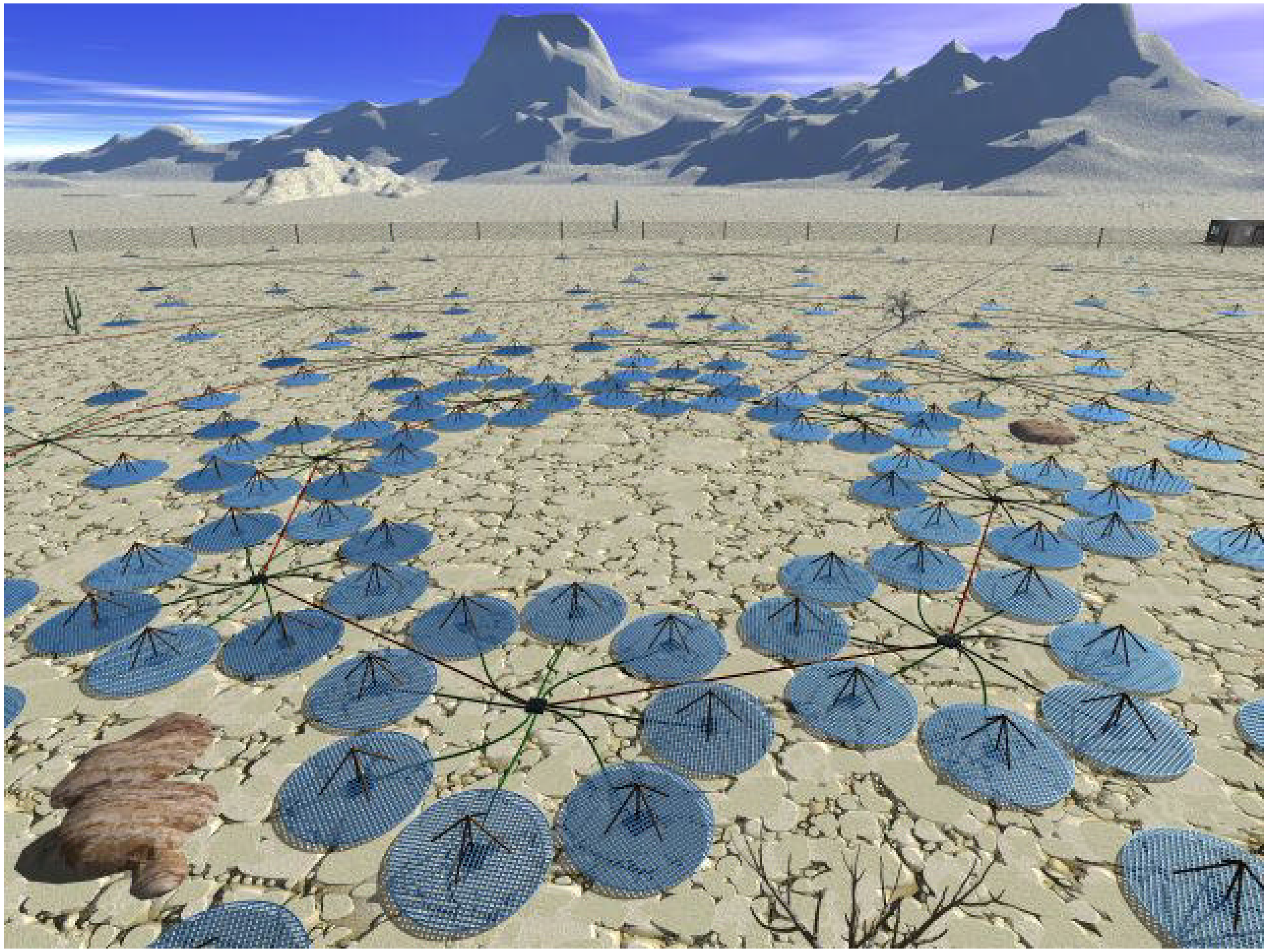
Station Design

- Consists of ~256-1000 broad-band wire antenna elements
- Phased array will deliver one signal which looks like the signal from a single VLA antenna (EVLA compatible)
  - Plug & play philosophy for VLA integration
  - Will serve as prototypes for LOFAR lower frequency antennas





High Sensitivity Station
Prototype for LOFAR Low Frequency Antennas



Analogous to one VLA antenna but with >10X the sensitivity

~100 meter diameter

@74MHz:

VLA antenna ~ 125 m^2

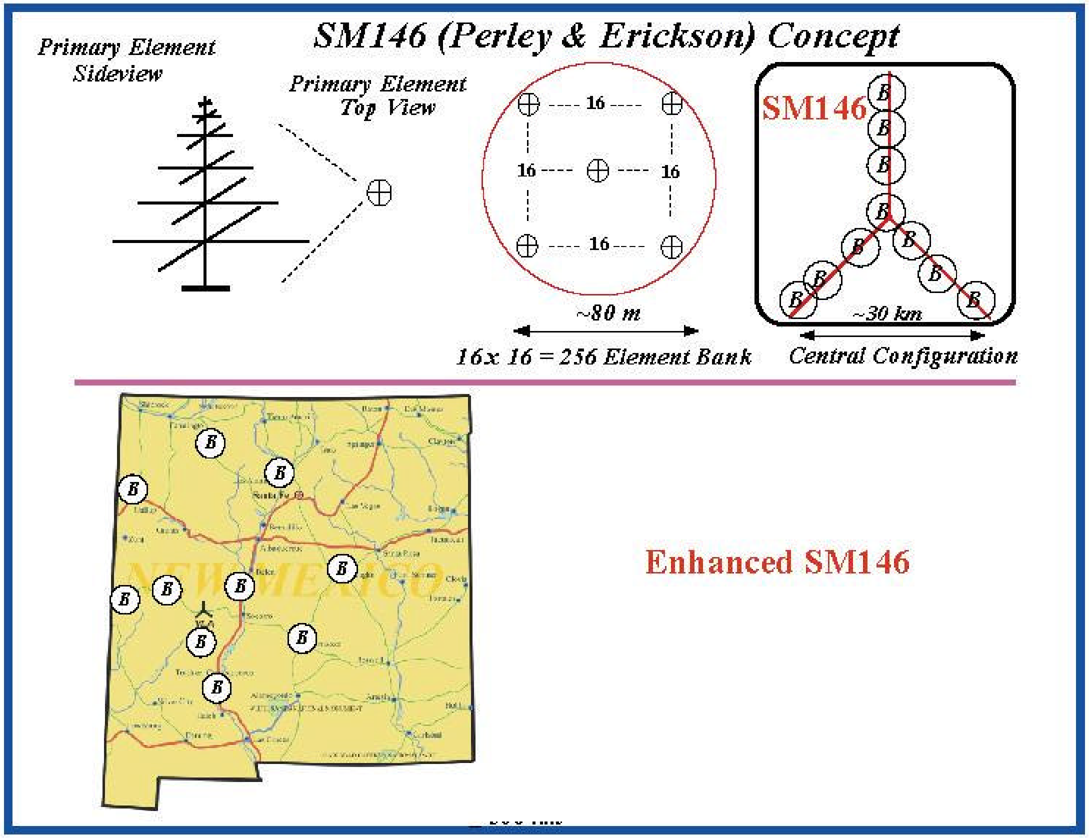
LWA Station ≥ 1500 m^2

(fractal element distribution shown here is not necessarily our favorite)

Future Prospects

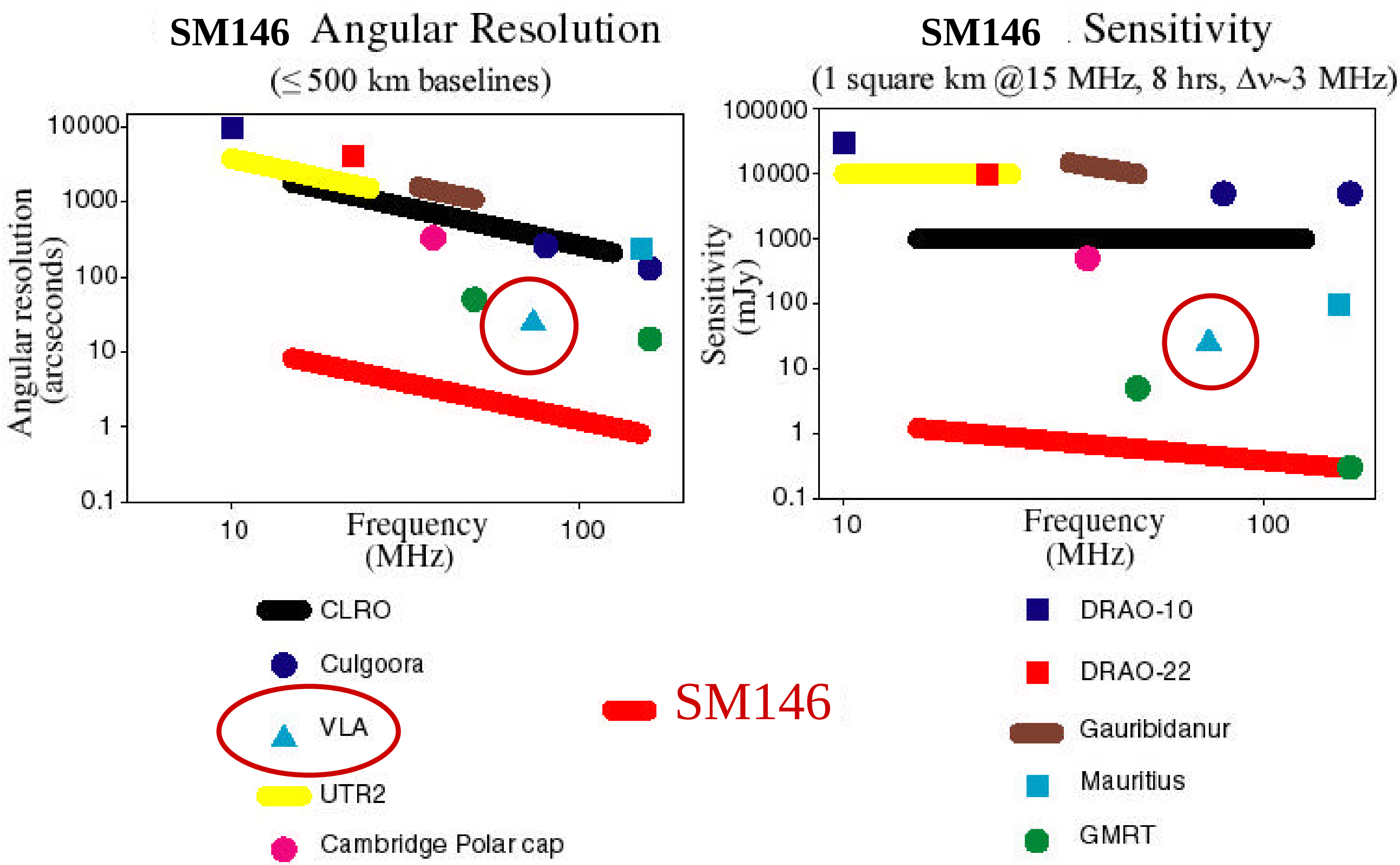
- The proposed near-term plans provide a significant increase in capabilities of an existing VLA system
- They also make it possible to prototype a future standalone, broad-band capability at the VLA
  - Permits eventual realization VLA SM146: “A proposal for a large, LF array located at the VLA” – Perley & Erickson, 1984
    - Partly implemented as 74 MHz system - after “phase transfer” insured self-cal convergence
- Everything we now know scientifically & technically ensures that SM146 would work beautifully and be a powerful instrument for both Galactic & EG work

SM146 Concept
(VLA Scientific Memorandum #146)

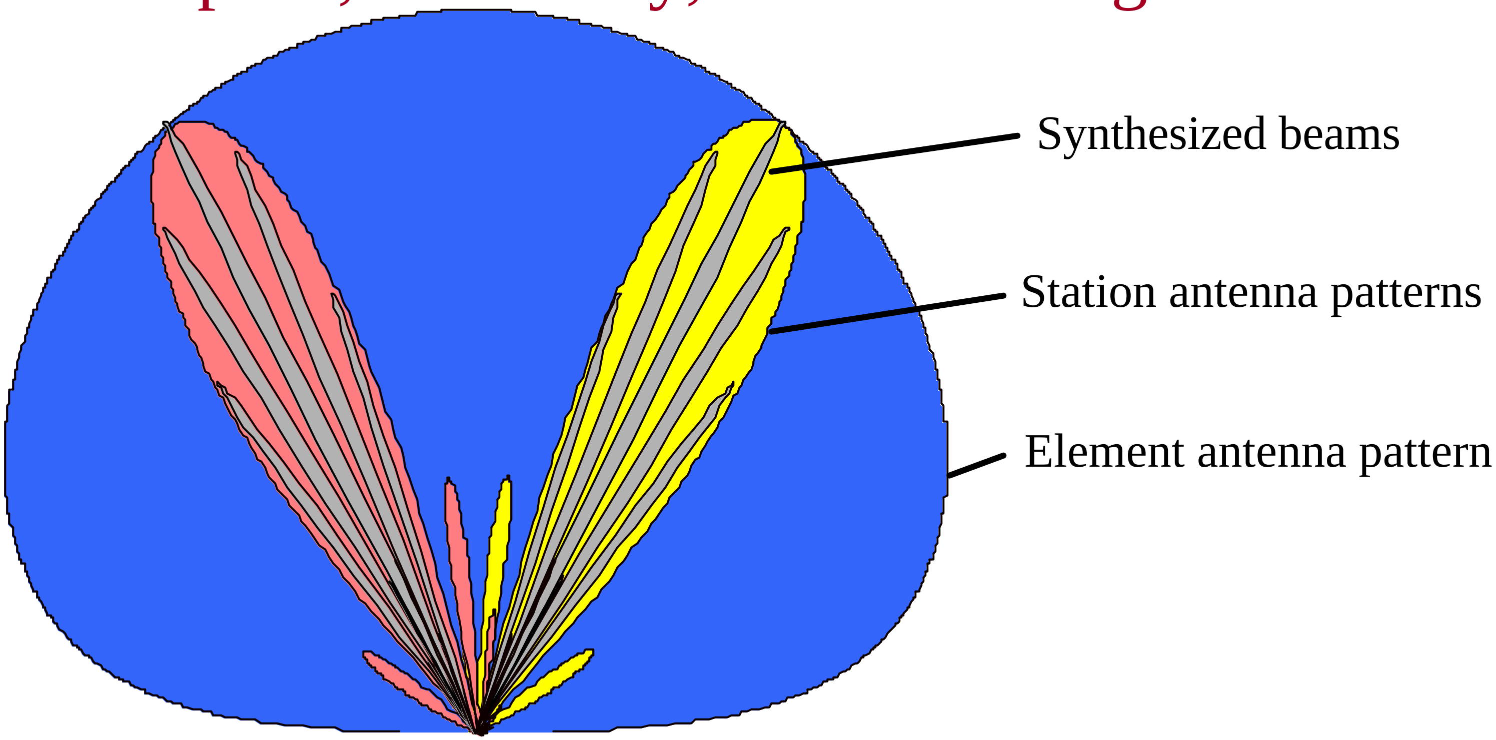


- Perley & Erickson concept
  - Standalone stations along VLA arms
    - VLA arm easement enough room for 100 m stations
    - Logistical issues remain – how will the cows like them?
  - Might proceed with EVLA-I
- Augmented SM146
  - Addition of A+ capability
  - Might proceed with EVLA-II

SM146 CAPABILITY



Advantages of New Technology Electronic Arrays: Speed, Flexibility, Multibeaming



Multiple, independent beams $\Rightarrow$ speed and flexibility
$\Rightarrow$ multiple, simultaneous science programs

Relationship to LOFAR

- LOFAR is much more complex than SM146
  - It has a substantial technology development element as well as purely scientific goals
    - Larger Freq. Range (LOFAR: 10-240 MHz; SM146: 10-90 MHz))
    - Much larger bandwidth (larger than EVLA)
    - Many more stations (>100)
    - Complex configuration (log spiral)
    - MUCH more software, etc …
- SM146 and LOFAR: parallel, mutually beneficial
  - SM146 development clearly meshes with LOFAR technical developments for low frequencies (< 100 MHz)
  - Might SM146 develop into the low frequency portion of LOFAR?
    - LOFAR site is not yet determined; there are other good candidates
    - Anything is possible
- Independent of LOFAR – VLA based SM146 makes sense

KEY LOFAR SCIENCE DRIVERS

- High Redshift Universe
  - unbiased sky surveys, select highest z galaxies
  - trace galactic & intergalactic B fields, infalling shocks around clusters
  - Epoch of Reionization: search for global signature, detect and map spatial structure
- Cosmic Ray Electrons and Galactic Nonthermal Emission
  - map 3D distribution, test expected origin and acceleration in SNRs
- Bursting and Transient Universe
  - broad-band, all-sky monitoring for variable/transient sources (GRBs, etc …)
  - search for coherent emission sources; e.g. from stars, quasars, & extra-solar planets
- Solar-Terrestrial Relationships
  - study fine-scale ionospheric structures
  - image Earth-directed CMEs (as radar receiver)
- LOFAR science plan was recommended by the NAS Astronomy Survey Committee in the new Decade Report.
- LOFAR Consortium (growing) – NRL-MIT/HO-ASTRON-UT
  - Science advisory board forming with growing US University membership

Summary

- We are considering a modest, incremental program for enhancing the scientific and technical performance of an existing VLA system
  - Some of these have synergetic overlap with planned EVLA activities – eg. development of a common A+ outlier site
  - Some of these satisfy NRL's responsibilities for developing new technology for LOFAR – eg. low frequency antennas/stations
- If it were possible to start down this road, our philosophy would be to
  - realize these enhancements in a manner that translates to immediate scientific benefits to the low frequency user community
  - implement them with minimum impact on VLA/VLBA operations
- These plans also lay the ground work for a broad-band standalone system as described in NRAO SM146
  - It could possibly proceed in parallel with EVLA I & II