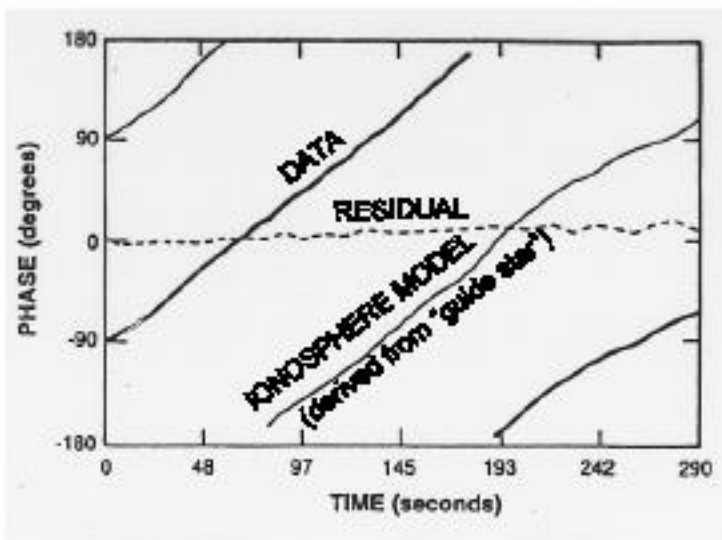
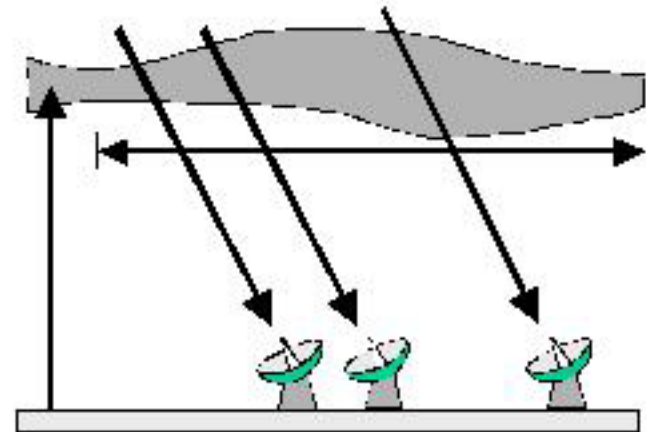


THE LOW-FREQUENCY ARRAY (LOFAR) BACKGROUND AND SCIENCE OVERVIEW

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Historical Background

- At low ν (<150 MHz), imaging limited primarily by ionospheric phase distortions.
 - Low angular resolution, confusion-limited sensitivity
 - Other barriers: RFI, 3D; computational tedium

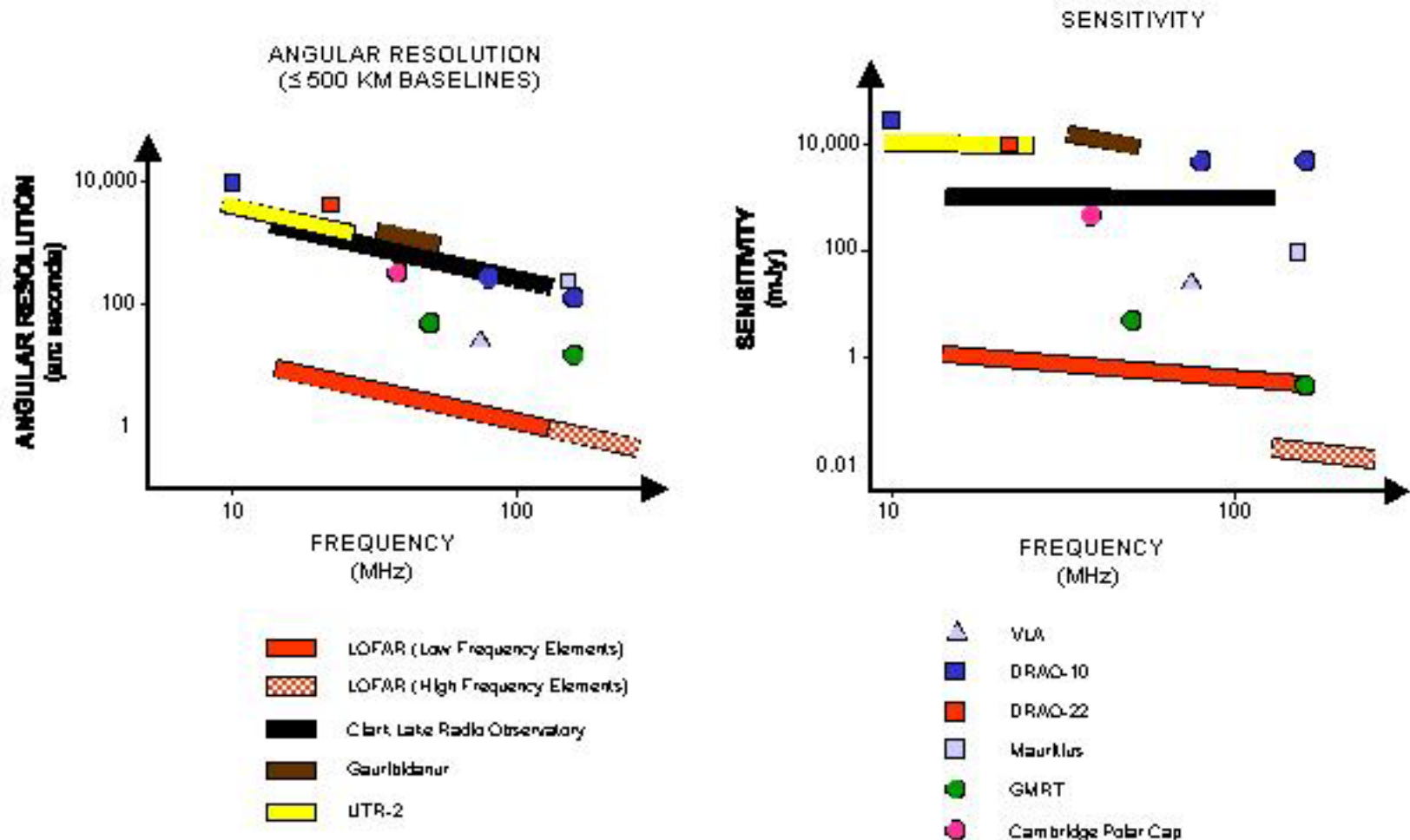


- NRL-NRAO (74/330 MHz imaging) and GMRT demonstrated removal of ionospheric effects, and solutions to most problems (e.g., 3D, RFI)
- **We now know how to extend our angular resolution and sensitivity far beyond what we have done to date, with major scientific impact.**

THE 74 MHz NRL-NRAO VLA SYSTEM



Opening a New Window on the Universe

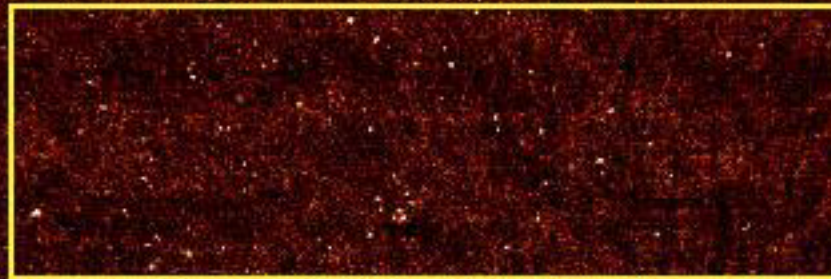


Key Science Drivers

- **High Redshift Universe**
 - unbiased sky surveys
 - select high z galaxies, natural steep spectrum sources
 - trace galactic & intergalactic **B** fields, infalling shocks around clusters
- **Epoch of Reionization**
 - search for the 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 monitoring for variable and transient source phenomena (GRBs, etc ...)
 - coherent emission from extra-solar planets
- **Solar-Terrestrial Relationships**
 - study fine-scale ionospheric structures
 - image Earth-directed CMEs

The High Redshift Universe

COMA CLUSTER
DEEP FIELD



UNBIASED
SURVEYS

CLUSTER
HALO
EMISSION



STEEP SPECTRUM
(HIGH z) SOURCES

$\lambda = 74 \text{ MHz}$

$\sigma \sim 25 \text{ mJy}$

$\theta \sim 25''$

$A_e \sim 3 \times 10^3 \text{ m}^2$

$\sim 15 \text{ degrees}$

LOFAR All-sky Survey

- LOFAR will combine very wide field capability with multibeaming to enable deep surveys conducted simultaneously with other science activities.
- Survey mapping sensitivity (4 MHz BW, 2 beams \approx 1 steradian):
 - Full hemisphere in 3 days 7 mJy (100 channels, 1% relative BW)
 - After one year 0.7 mJy (“ ”)
 - After 3–5 years 70 μ Jy (10 channels)
- The LOFAR very wide field capability at low frequencies will provide high sensitivity to transient events.
 - Event detection sensitivity (4 MHz BW): 0.25 Jy in 1 second

VLA 74 MHz: New Cluster Relic in A754

Clusters and relics probe relativistic particles and magnetic fields in intergalactic space and constrain theories of large-scale structure formation in the Universe

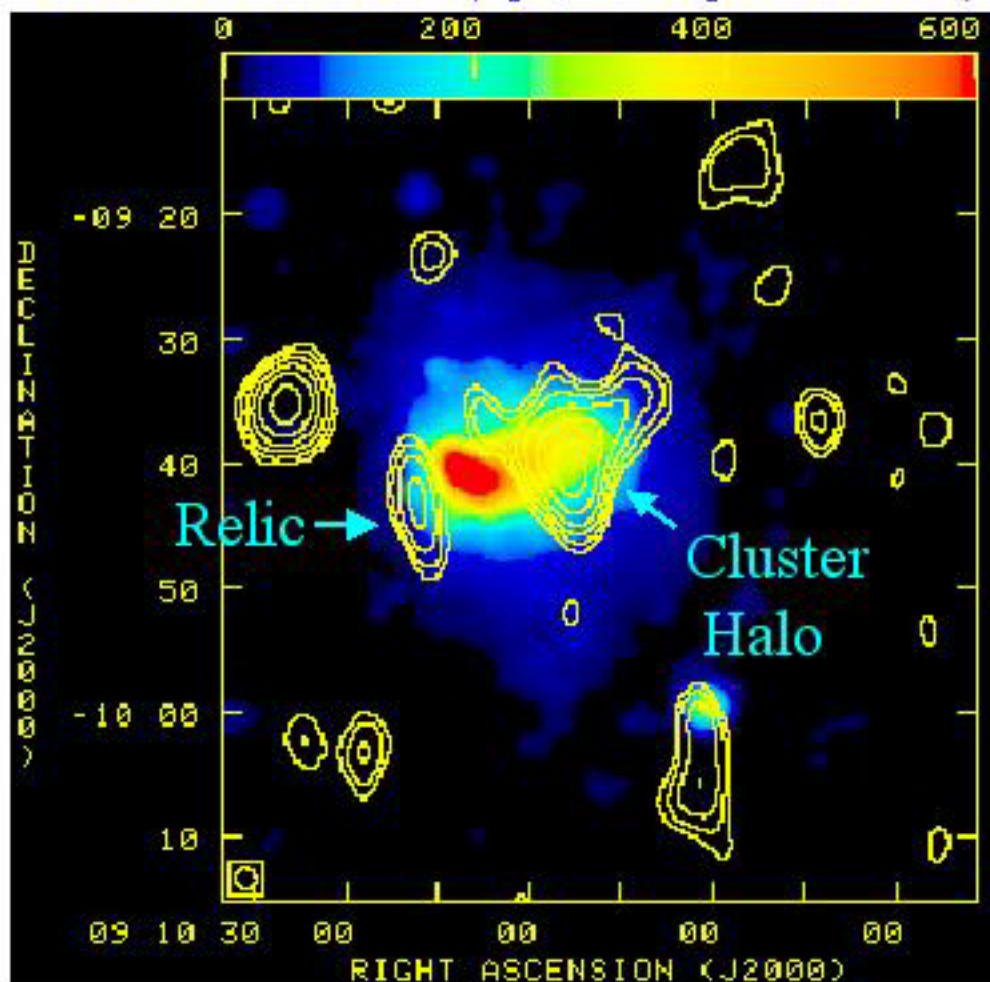
A new halo-relic system in the Abell 754 cluster of galaxies has just been discovered with the 74 MHz VLA. 4MASS should find numerous similar systems.

⇒ LOFAR may find 10,000 relics!

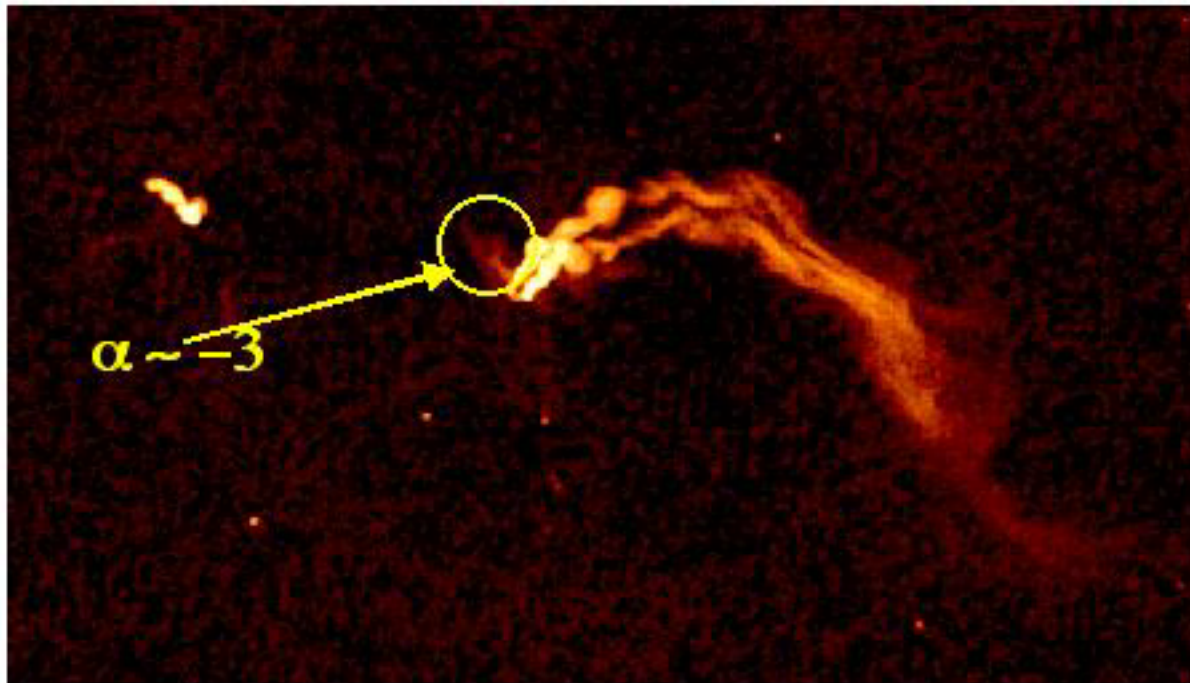
Color: ROSAT X-ray image

Contours: 74 MHz VLA image

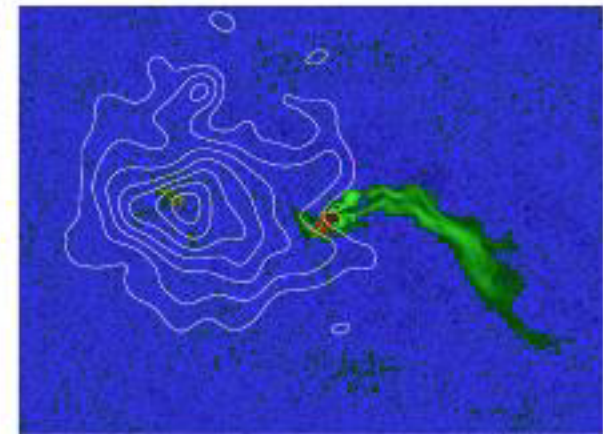
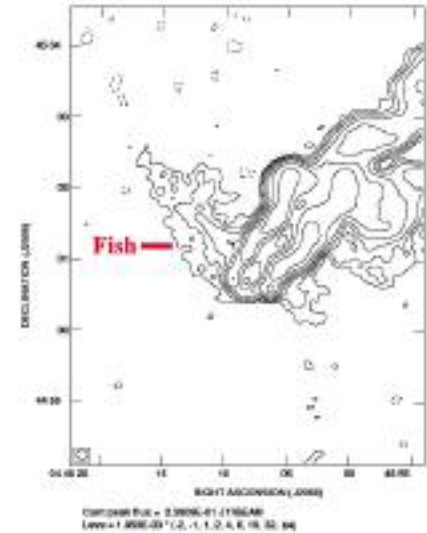
Kassim et al. 2001 (ApJ, astro-ph/0103492)



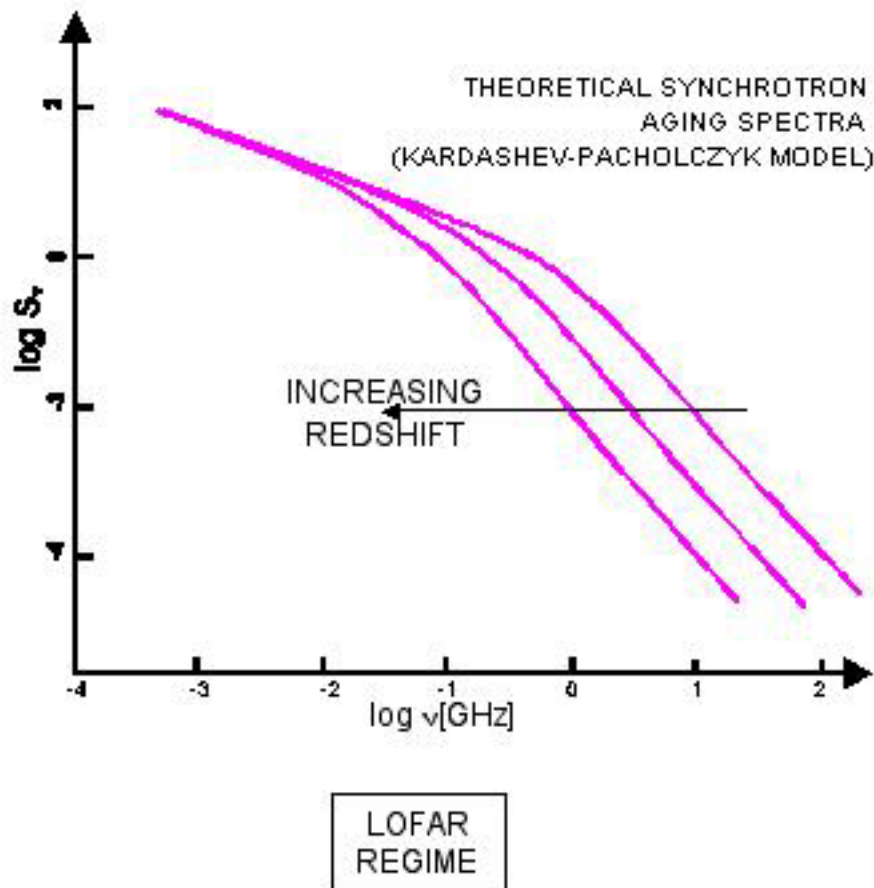
3C 129 – Ultra-Steep Spectrum Relic?



Lane et al. 2001

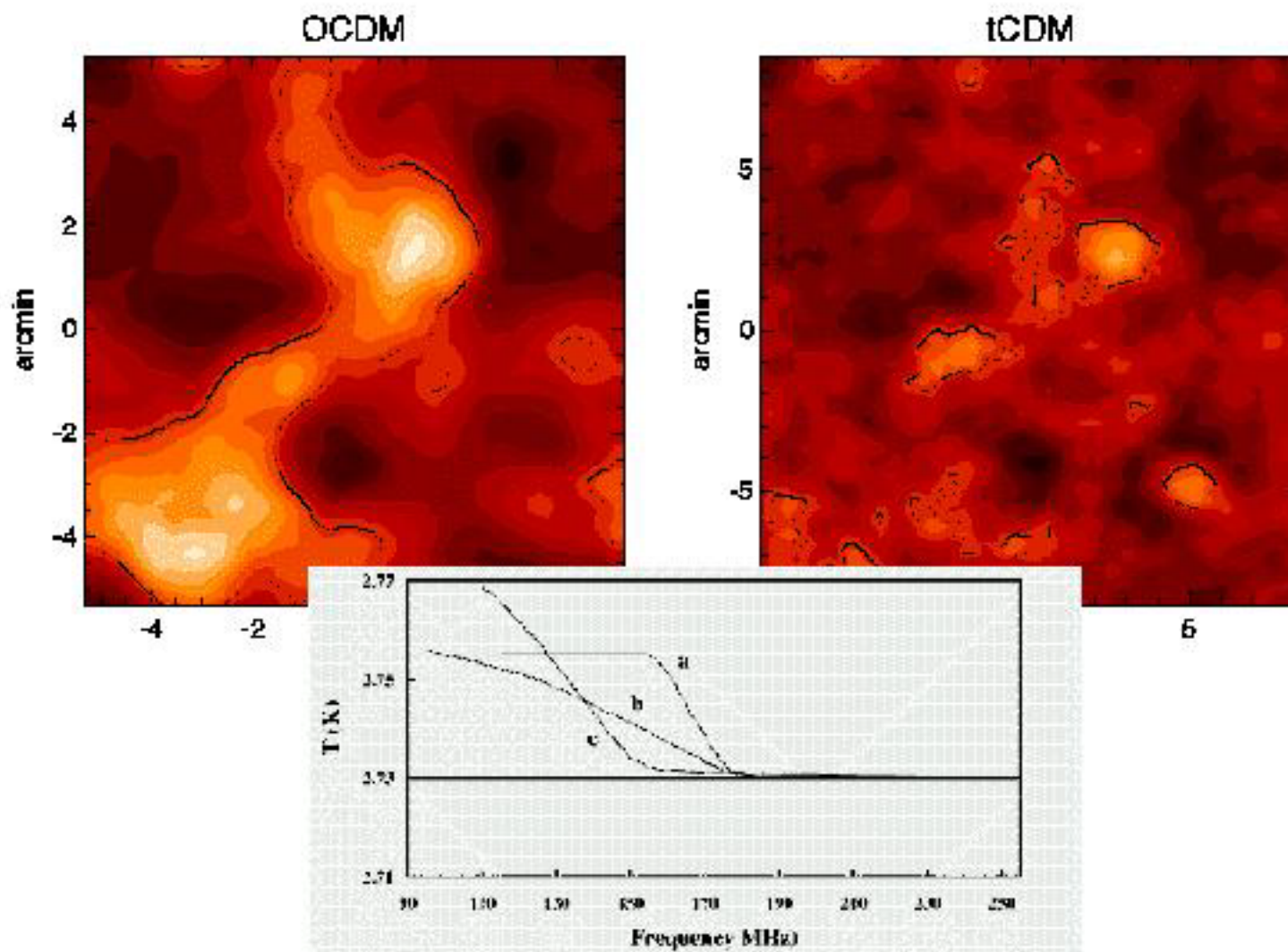


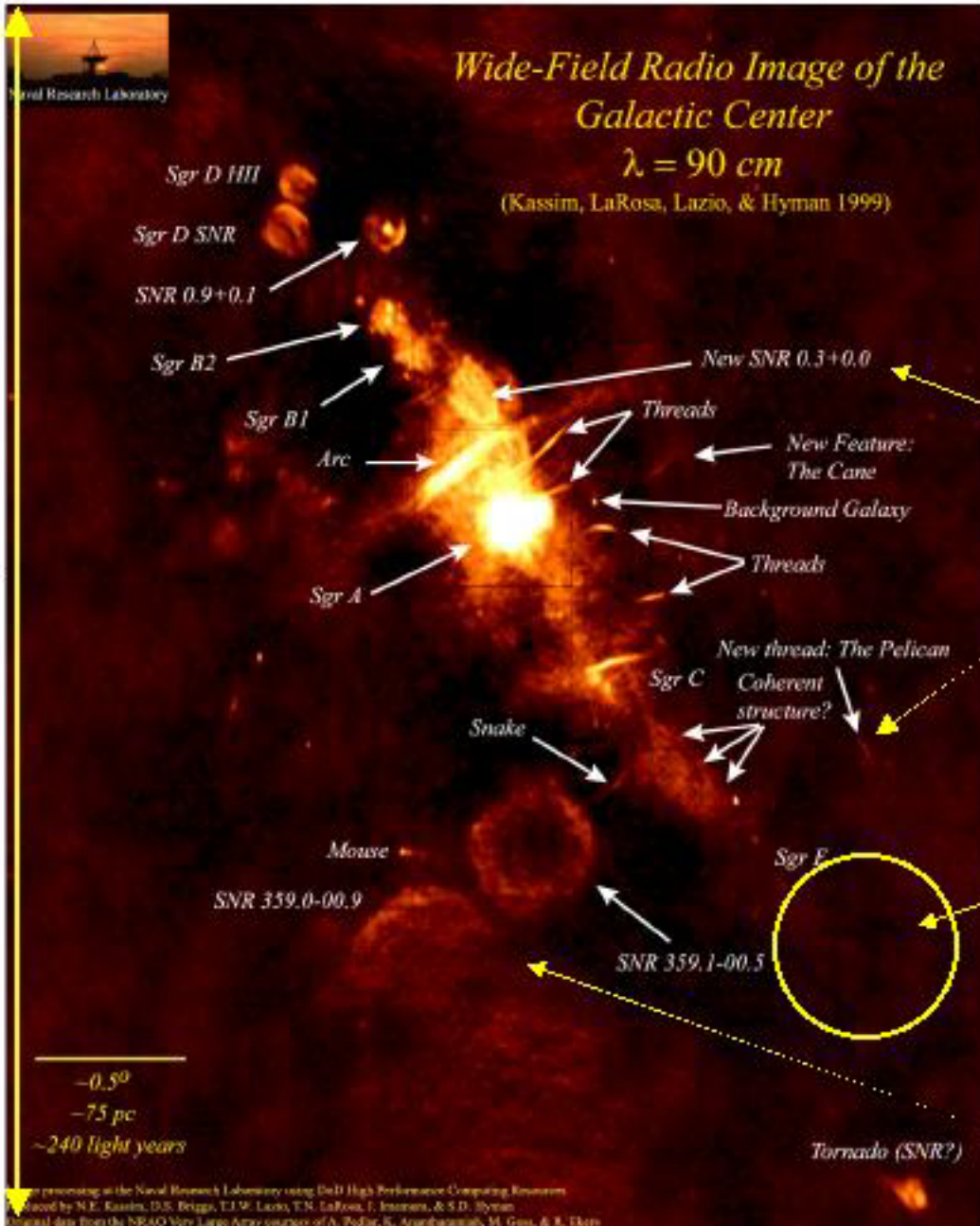
High Redshift Galaxies



- High redshift galaxies will be natural steep spectrum sources.
- Synchrotron losses steepen the high frequency spectrum of radio galaxies above ~ 1 GHz
- At high z the spectrum is shifted to lower frequencies so that the entire *observed* spectrum is steep
- Inverse Compton losses act similarly to steepen the spectrum, especially at high z since IC losses go as z^4

The Epoch of Reionization





Galactic Plane Studies

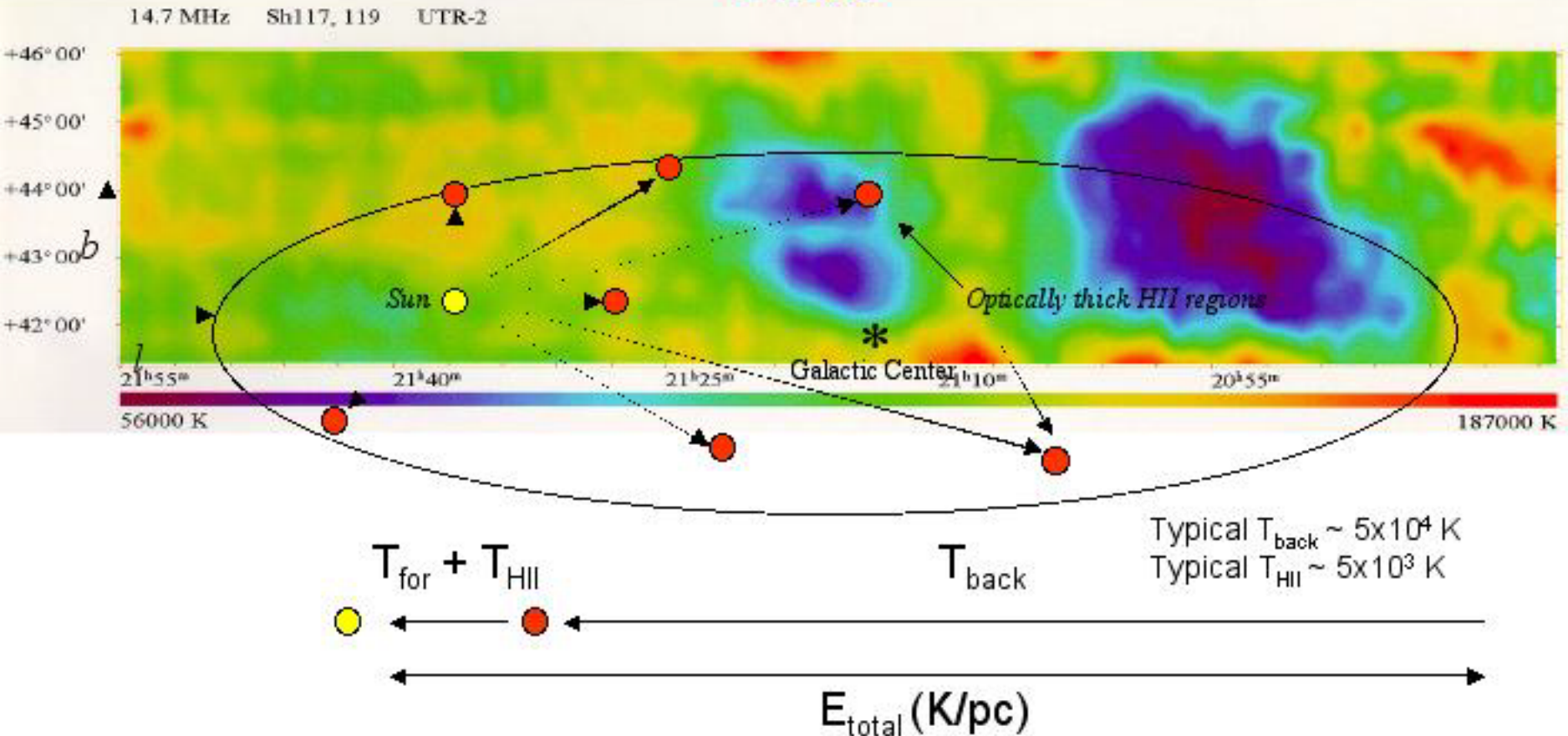
SEPARATION OF THERMAL AND NONTHERMAL EMISSION

TRANSIENT MONITORING

SEARCH FOR STEEP SPECTRUM PULSARS

OLD SUPERNOVA REMNANTS

Mapping Out the Cosmic Ray Electron Gas



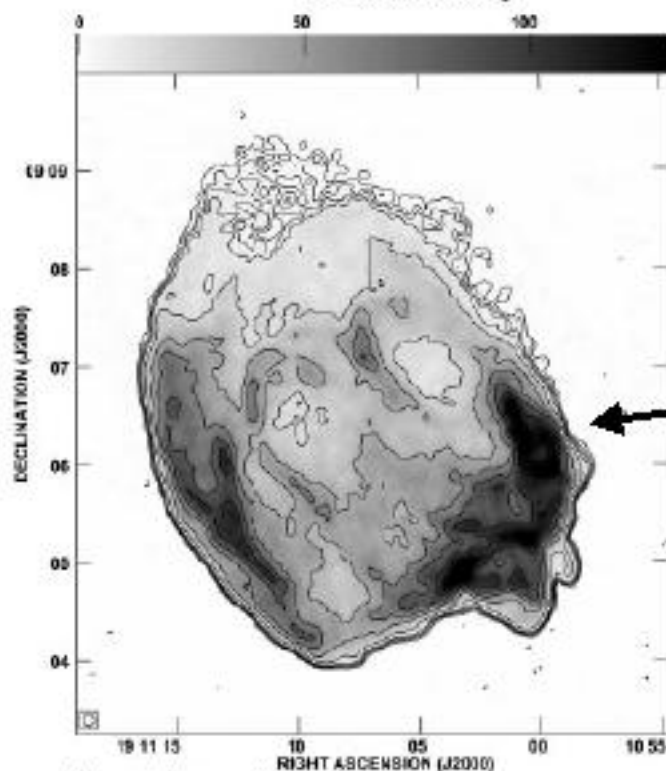
Typical 30 MHz absorption "hole" flux for $10''$ H II region: ~ 0.5 mJy (outer Galaxy)
 ~ 3 mJy (inner Galaxy)

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

Exploitation of Absorption Phenomena

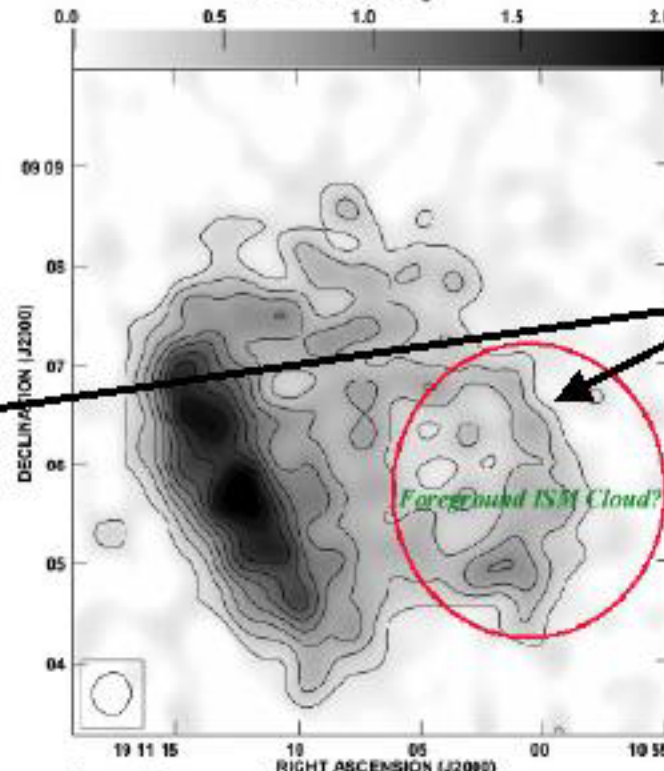
Free-Free Absorption Towards W49B SNR

$\nu = 330 \text{ MHz}$



Grey scale flux range = 0.0 130.0 MJY/BEAM
Cont peak flux = 1.7638E-01 JY/BEAM
Levels = 1.000E-03 (-7, -5, -3, 3, 5, 7, 10, 20,
40, 60, 80, 100, 120, 140, 160, 180)

$\nu = 74 \text{ MHz}$



Grey scale flux range = 0.000 2.000 JY/BEAM
Cont peak flux = 2.1123E-00 JY/BEAM
Levels = 2.304E-01 (-2, -1, 1, 3, 4, 5, 6, 7,
8)

Lacey, Kassim, & Duric 1999

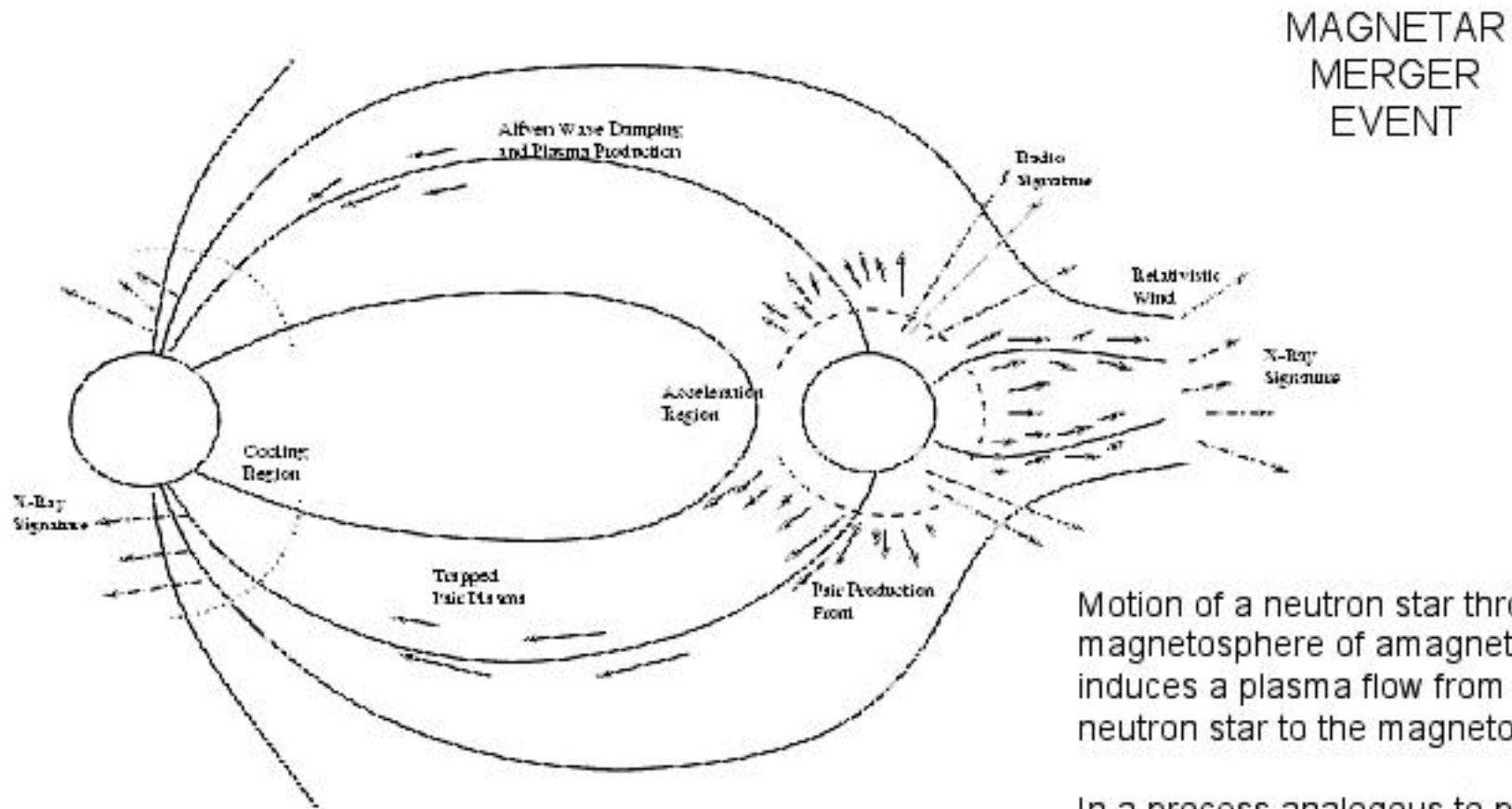
LOFAR enables the unique exploitation of interstellar absorption effects.

For example, the patchiness of the free-free absorption towards the W49B SNR, made apparent by the comparison of 74 and 330 MHz images, provides the first direct evidence of spatial structure in the diffuse ionized component of the interstellar medium.

The Bursting and Transient Universe

- LOFAR's all-sky monitoring capability enables it to discover transient and bursting phenomena.
 - Large collecting area
 - Large field of view
 - Ability to buffer data and detect and process events after cueing
 - Directional and frequency agility
 - Interference mitigation
- These observations could enhance our understanding of the physics of collapsed and collapsing objects.
 - Supernovae
 - Giant pulses
 - Gamma Ray Burst (GRB) afterglows
 - LIGO events??
 - Prompt GRB radio bursts??

Sources of Transient Emission

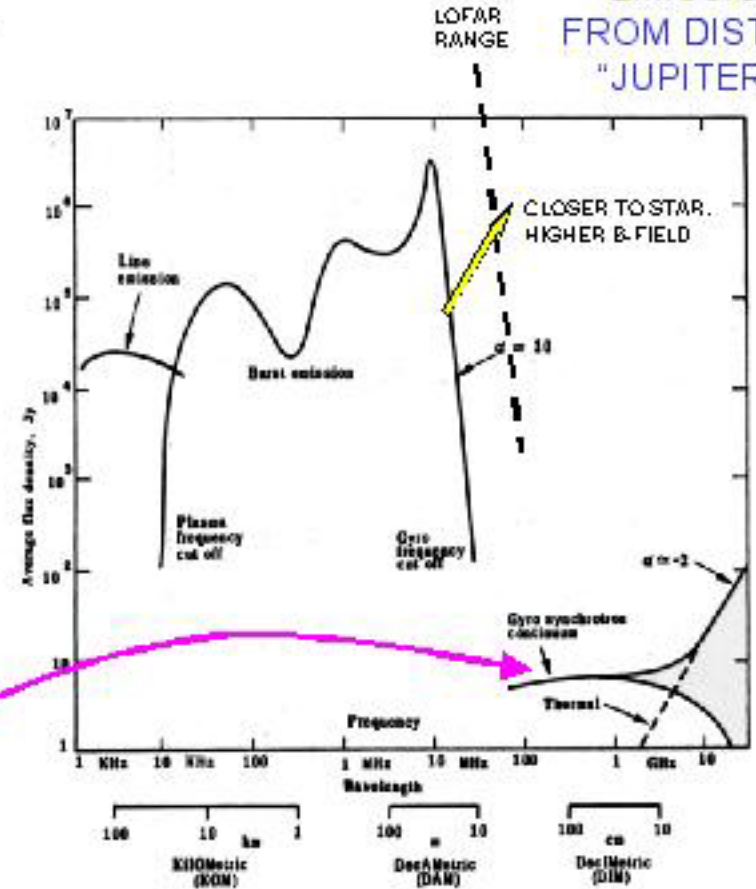
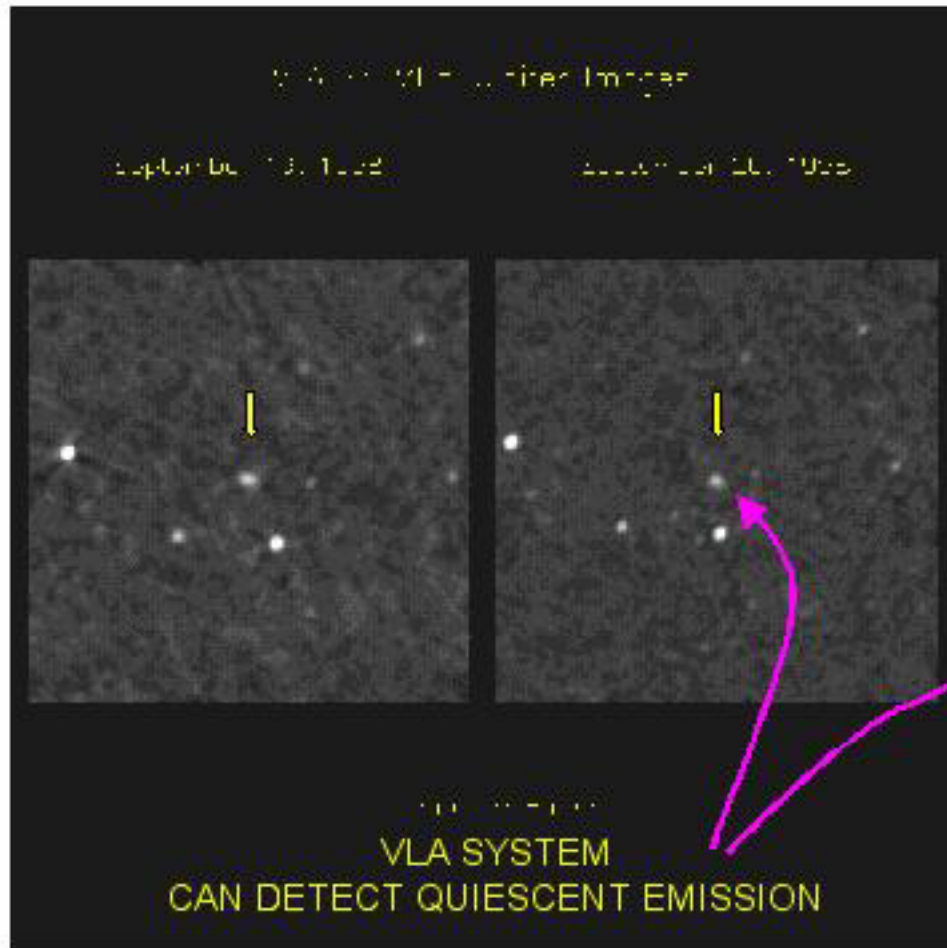


MAGNETAR
MERGER
EVENT

Motion of a neutron star through the magnetosphere of a magnetar induces a plasma flow from the neutron star to the magnetosphere.

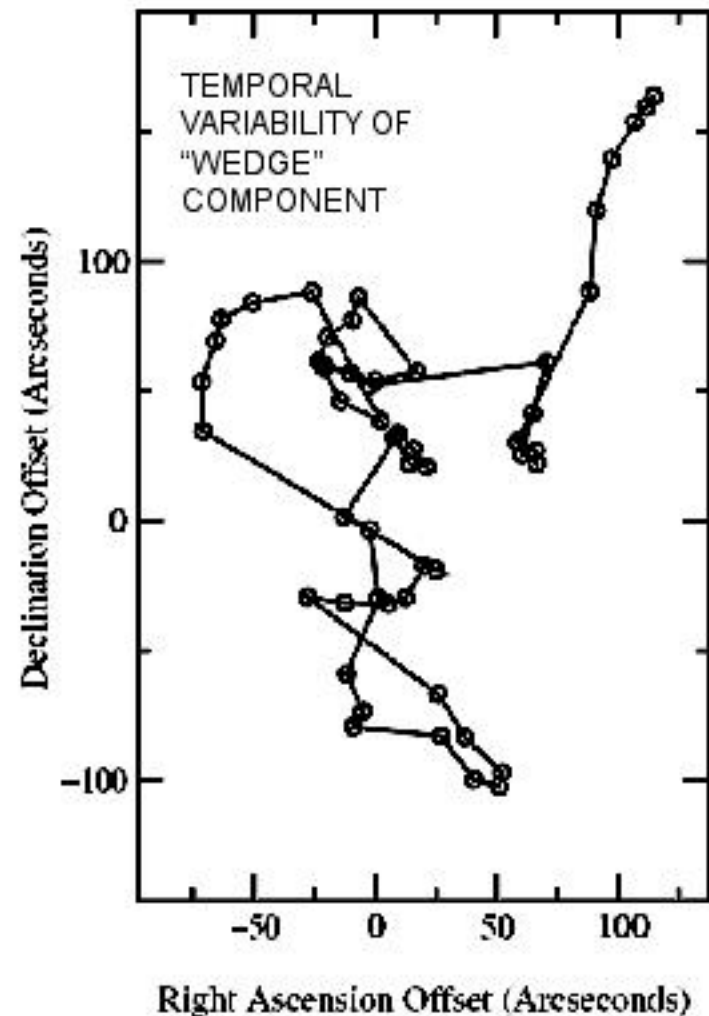
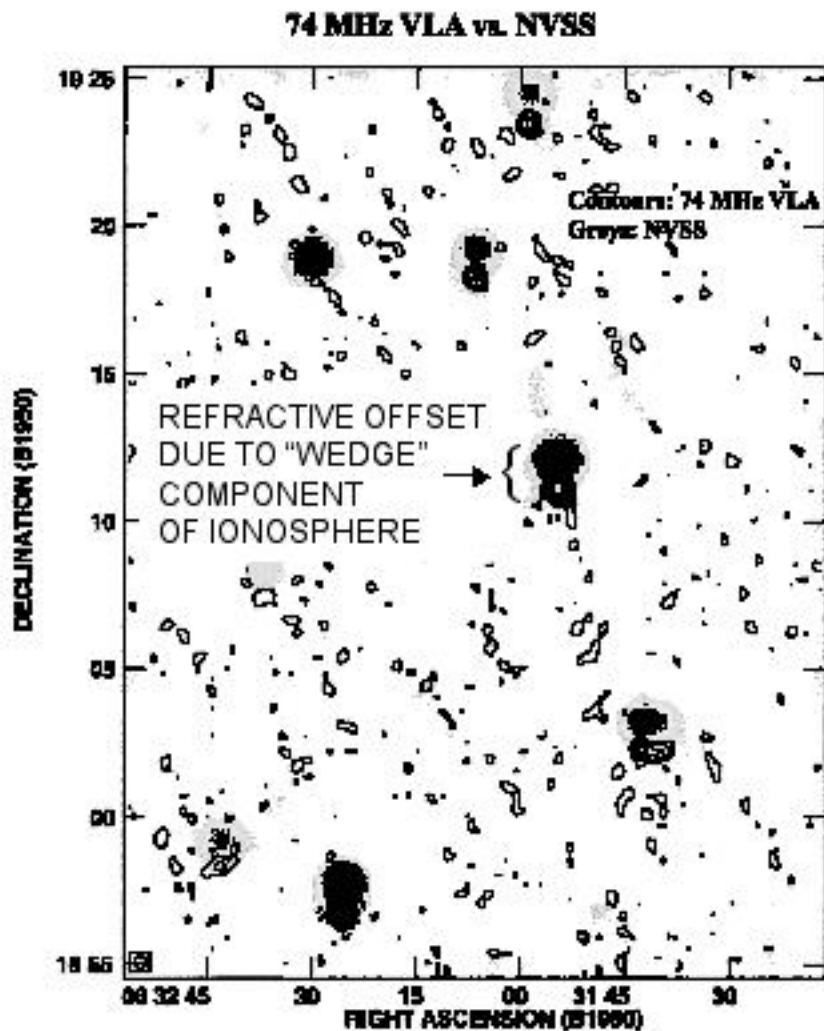
In a process analogous to pulsar emission, radio emission can be produced.

Decametric Bursts from Extrasolar Planets

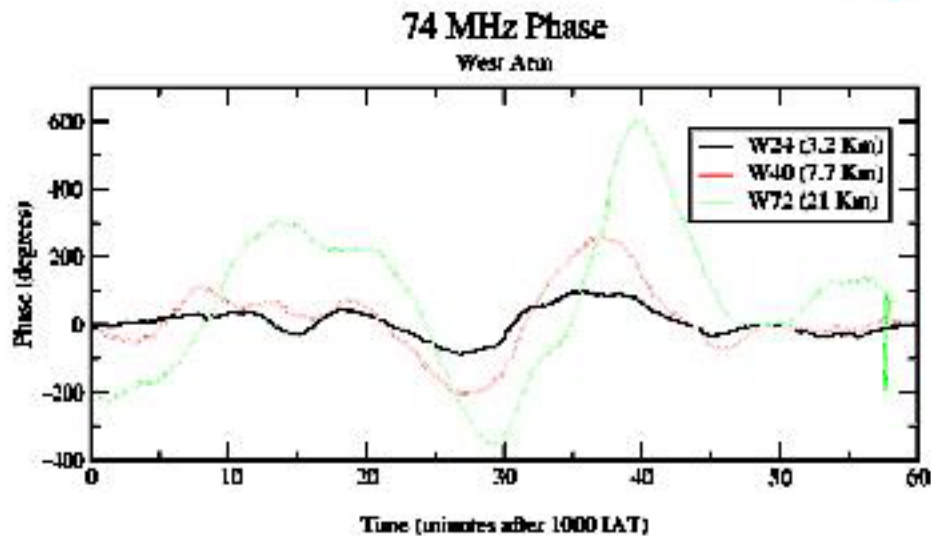


LOFAR COULD
DETECT BURST
EMISSION
FROM DISTANT
"JUPITERS"

Ionospheric Measurements

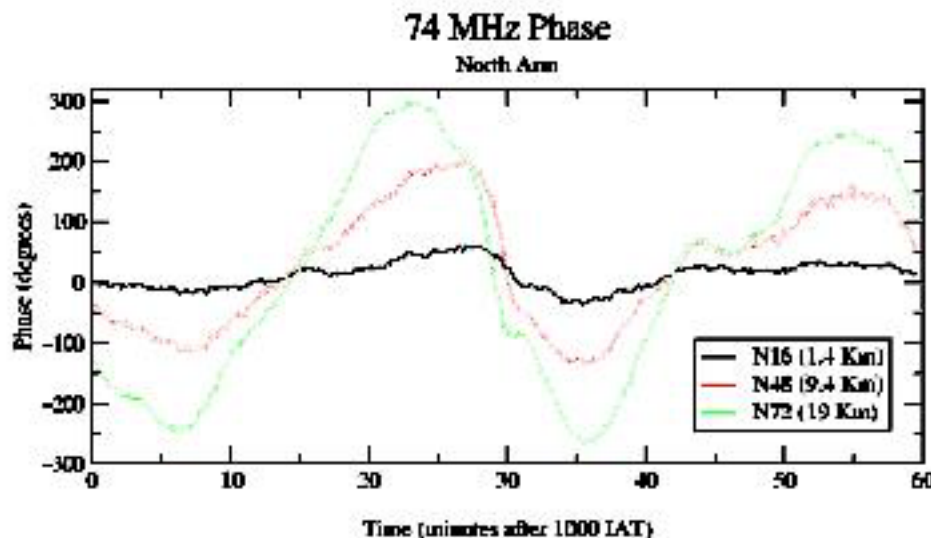


Fine-scale Ionospheric Structure



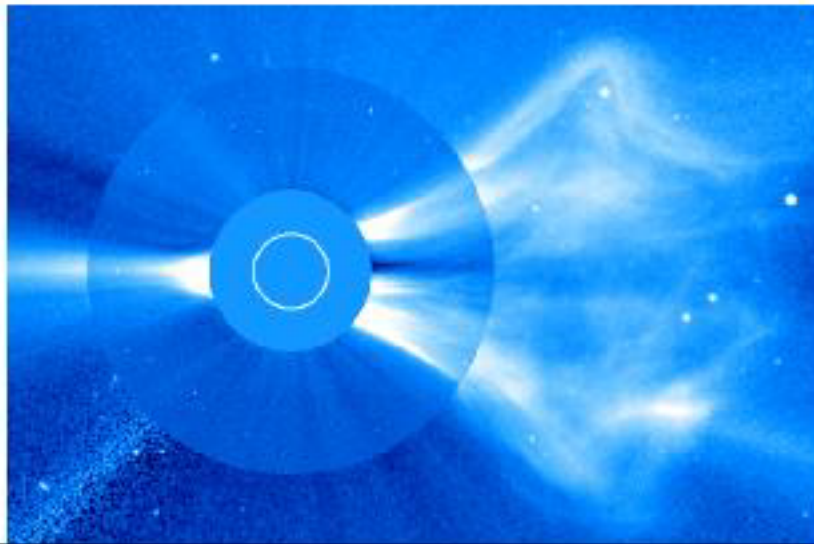
Traveling ionospheric disturbances (TIDs) can be seen in the phase offsets of 74 MHz VLA data. The waves are of larger scale than the VLA, so they are seen better on the largest spacings. The SNR and precision of the phase measurement are very high.

LOFAR should provide measurements with 1° phase precision every fraction of a second.



LOFAR will also provide ~ 100 penetration paths, for each of many simultaneous look directions. Thus, as a byproduct of calibration, it will generate a vast ionospheric tomography dataset. LOFAR will generate 3D ionospheric movies with extraordinary resolution and precision.

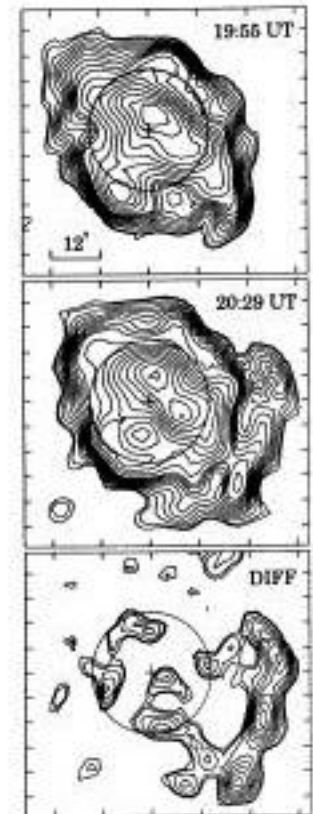
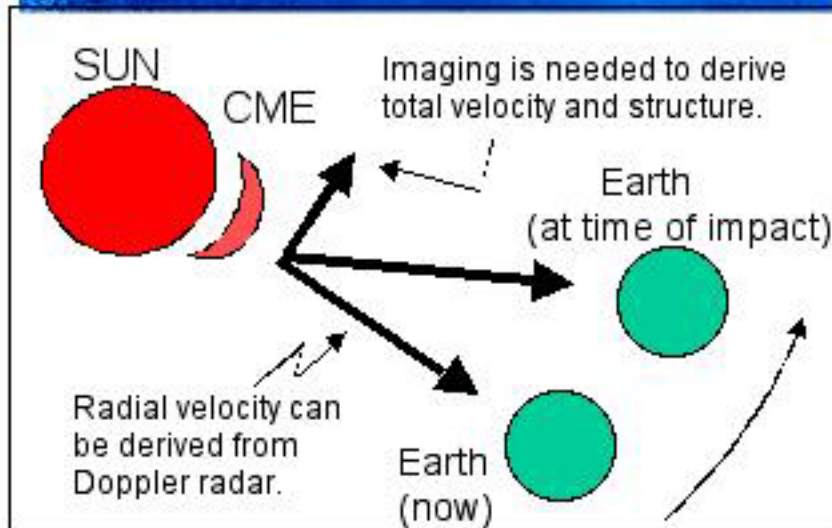
Coronal Mass Ejections



Coronal Mass Ejections (CMEs) are both significant science problems for solar physics and significant dangers for DoD and commercial space missions.

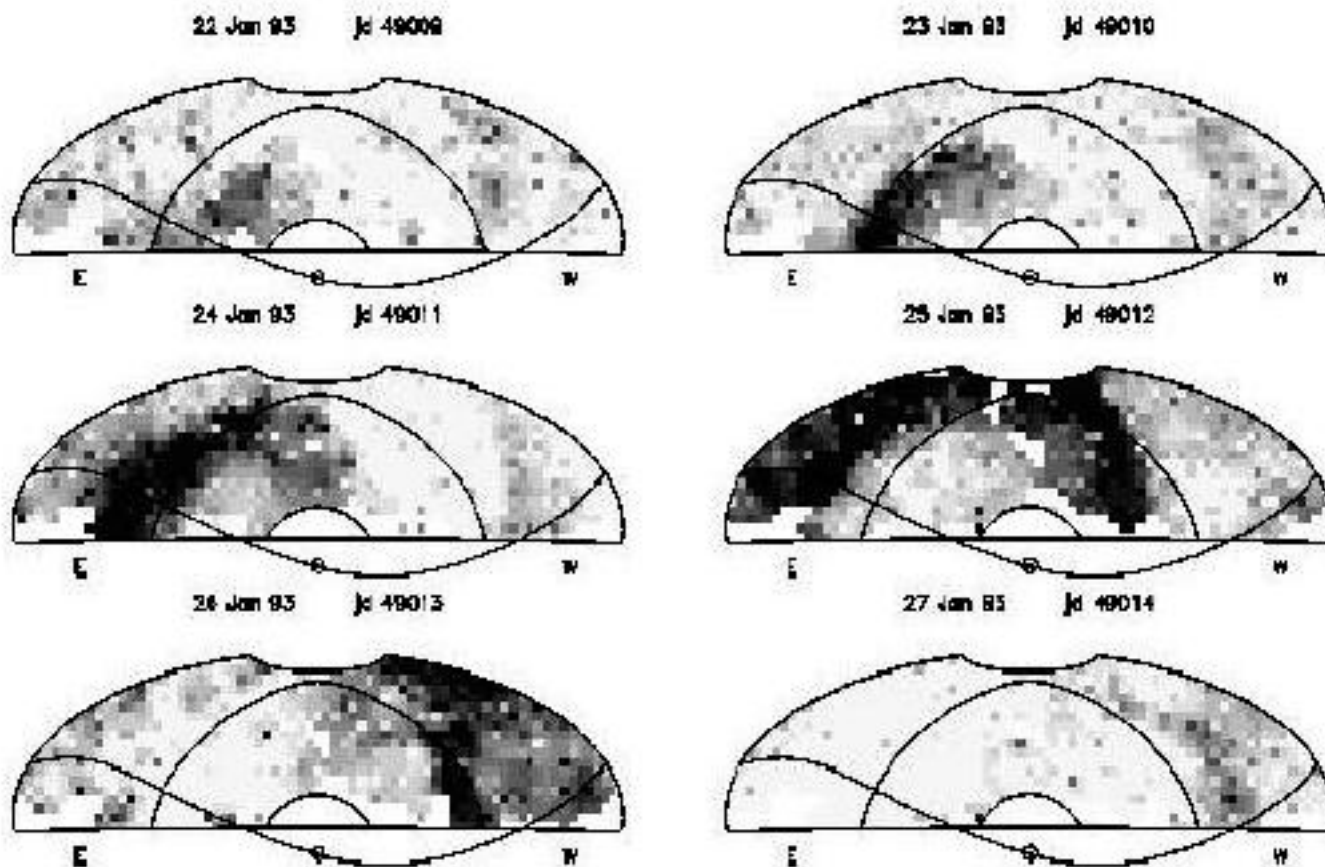
LOFAR could map out the structure of CMEs and determine space velocities to predict their impacts.

Although LOFAR is a passive instrument, it could also be used in combination with a suitably located radar transmitter to completely probe the density structure and space velocity.



Clark Lake
(73.8 MHz)

Solar Wind Studies



Plots of the intensity of scintillation of background radio sources reveal the structure and dynamics of the interplanetary plasma. With rapid, wide field of view measurements of large numbers of background sources, LOFAR will enable detailed studies of the solar wind.

Broad Range of Scientific Applications

- Steep spectrum clusters and fossil galaxies, including polarization studies using background sources
- Surveying (Galactic & extragalactic), studies of variable source populations
- Transient source detection
- Pulsars—detecting, finding new steep spectrum fast pulsars
- Supernova remnants and their interaction with pulsars and the ISM
- Thermal absorption from low density, ionized gas in ISM
- Recombination lines (carbon lines) from the cool ISM
- Propagation and scattering, in the solar wind, the IPM, the ISM (and the IGM?)
- Steep spectrum emission from Flare Stars
- Passive emission from solar flares, storms, CMEs, quiet sun
- Planetary radar
- Tracking Ionospheric TIDs, real-time ionospheric modelling from self-cal solutions
- Magnetospheric, ionospheric sounding

Summary

- LOFAR will open one of the last and most poorly explored regions of the electromagnetic spectrum.
- Key Science Drivers:
 - High redshift universe
 - The epoch of reionization
 - Mapping the cosmic ray electron gas
 - Bursts and transients
 - Solar-Terrestrial relationships
- **The LOFAR science plan was recommended by the NAS Astronomy Survey Committee in the new Decade Report.**
- Serendipity is a factor! New discoveries are likely in this unexplored regime.
- Sophisticated, multi-beam, multi-frequency electronic array will herald revolutionary new approach to astronomical observations.
- LOFAR Consortium “on track”