Low-frequency radio astronomy and wide-field imaging

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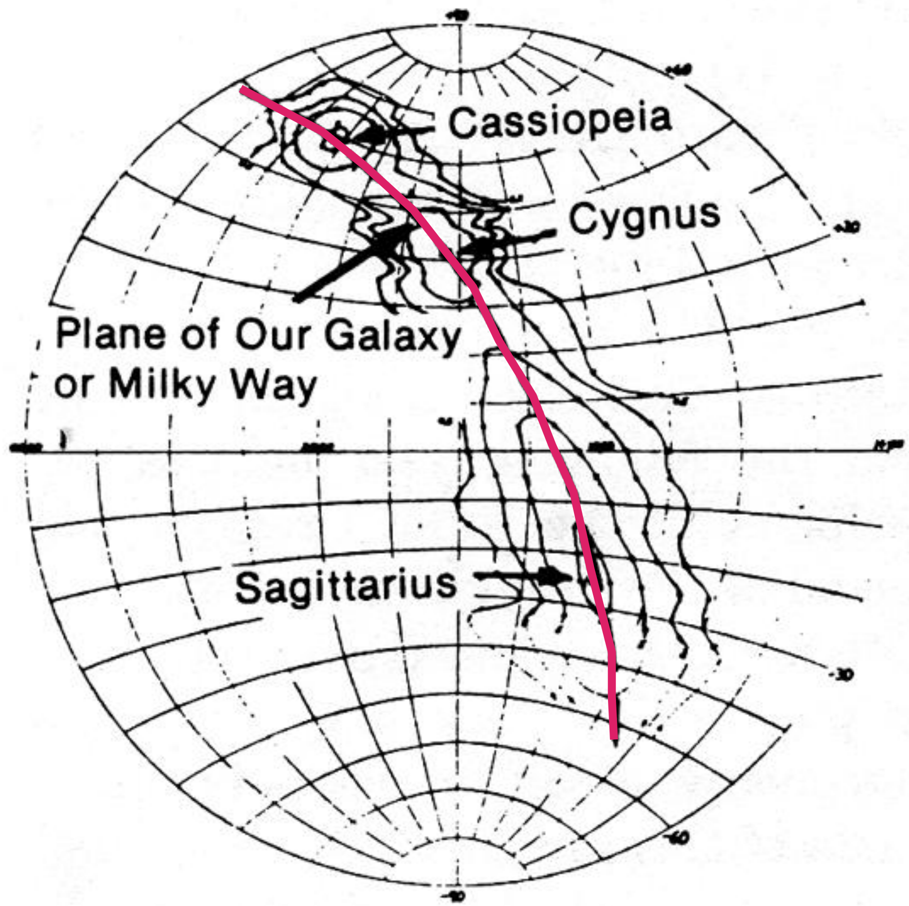
ITN 215212: Black Hole Universe

Many slides taken from NRAO Synthesis Imaging Workshop (Tracy Clark talk) (http://www.aoc.nrao.edu/events/synthesis/2010/)

Low-frequency radio astronomy

- Wavelength range 10 MHz – 1 GHz
- HF, VHF, UHF bands
- Long wavelengths, low frequencies, low photon energies
- Ionosphere places a cut-off at 10 MHz
- Frequencies where radio astronomy began
  - Jansky's work at 20.5 MHz
  - Reber's work at 160 MHz



160 MHz sky image from Reber, resolution ~12 degrees

Fundamental limitations

- Resolution of an interferometer $\theta = \frac{\lambda}{b_{\max}}$
- Field of view $\theta = \frac{\lambda}{D}$
- Sensitivity $\sigma_S = \frac{2k_B T_{sys}}{A_{eff}\sqrt{N(N-1)t_{\mathrm{int}}\Delta\nu}}$

- Low-frequency radio astronomy is inherently
  - low-resolution
  - wide field-of-view
  - low fractional bandwidth

  with respect to similar centimetre-wavelength observations

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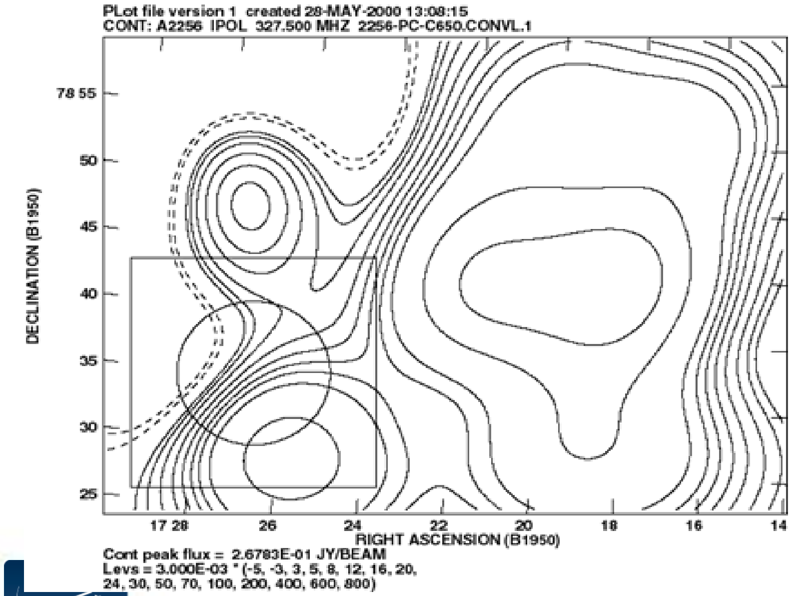
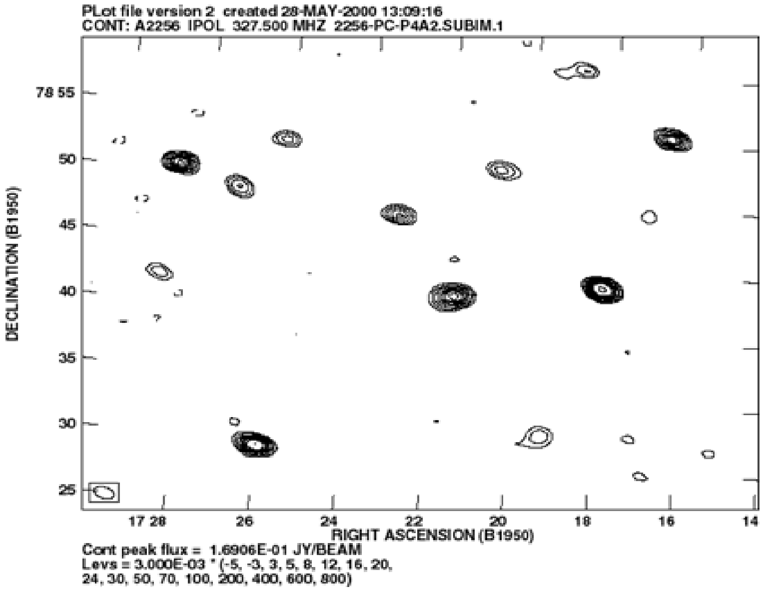
Fundamental limitations: Confusion

- Low resolution coupled with high sensitivity = confusion
  - Unresolved sources place a fundamental limit on the theoretical noise limit

θ ~ 10’, rms ~ 30 mJy/beam



θ ~ 1’, rms ~ 3 mJy/beam

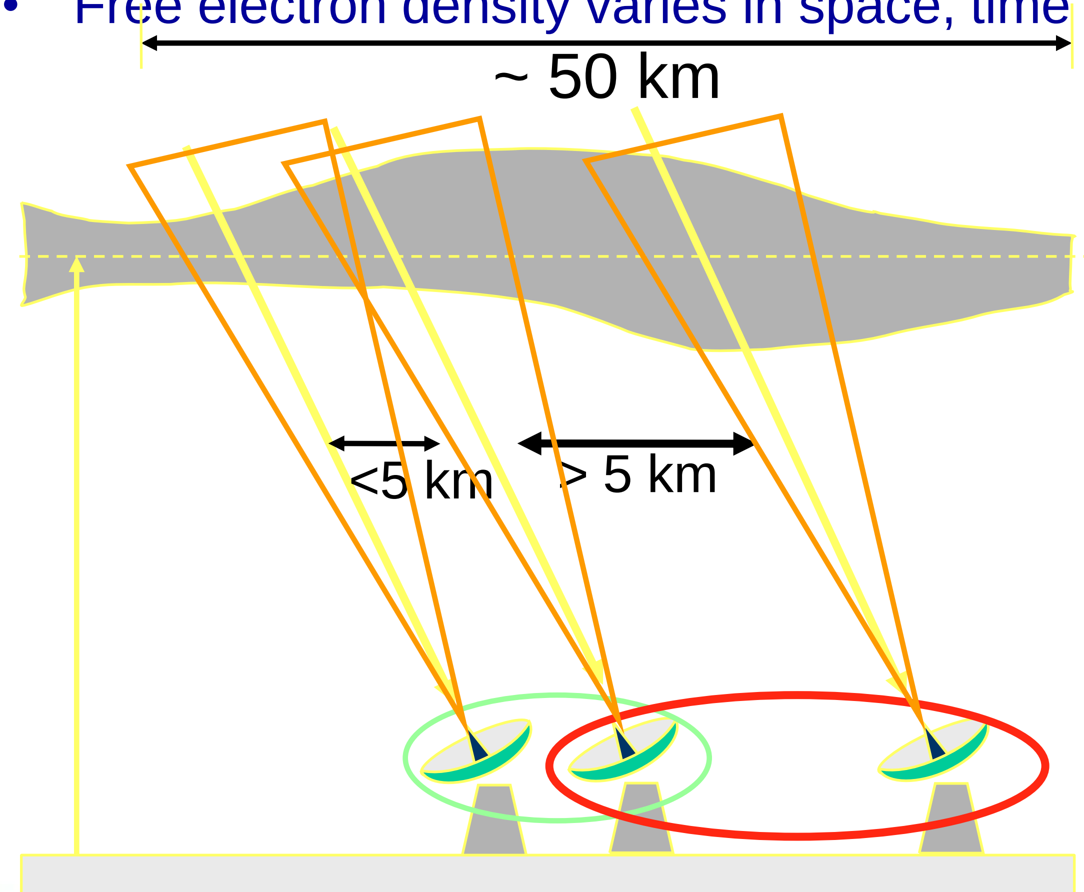


Other low-frequency problems

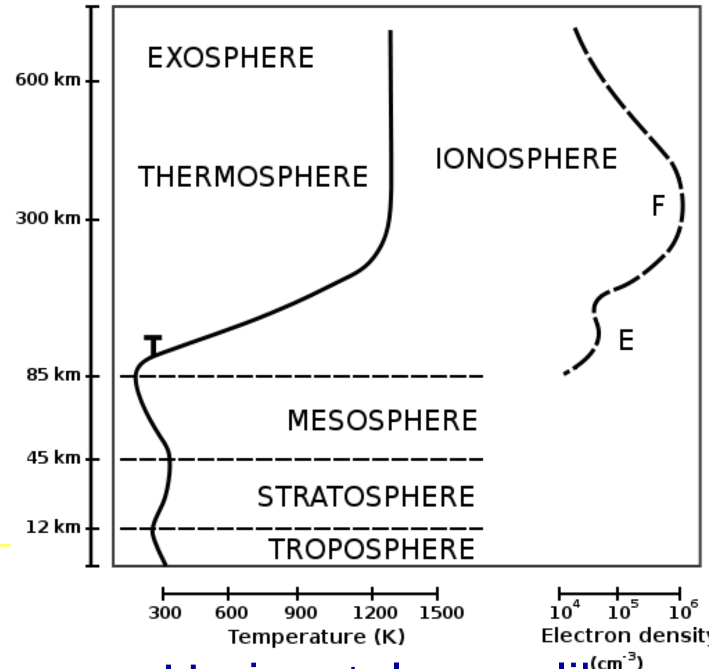
- Ionosphere affects signal propagation
  - Refraction, source “wander”, decorrelation
- RFI swamps astronomical signals
- Wide field of view
  - Field of view exceeds size of isoplanatic patch
    - Direction-dependent self-calibration
  - Bandwidth smearing requires small channel widths
  - Time smearing requires rapid correlator dumps
  - Imaging must use multiple facets to cover field of view
    - Imaging large fields of view requires enormous computing power

The ionosphere

- Partially ionized gas layer 50-300km up
- Free electron density varies in space, time



Correlation preserved   Correlation destroyed

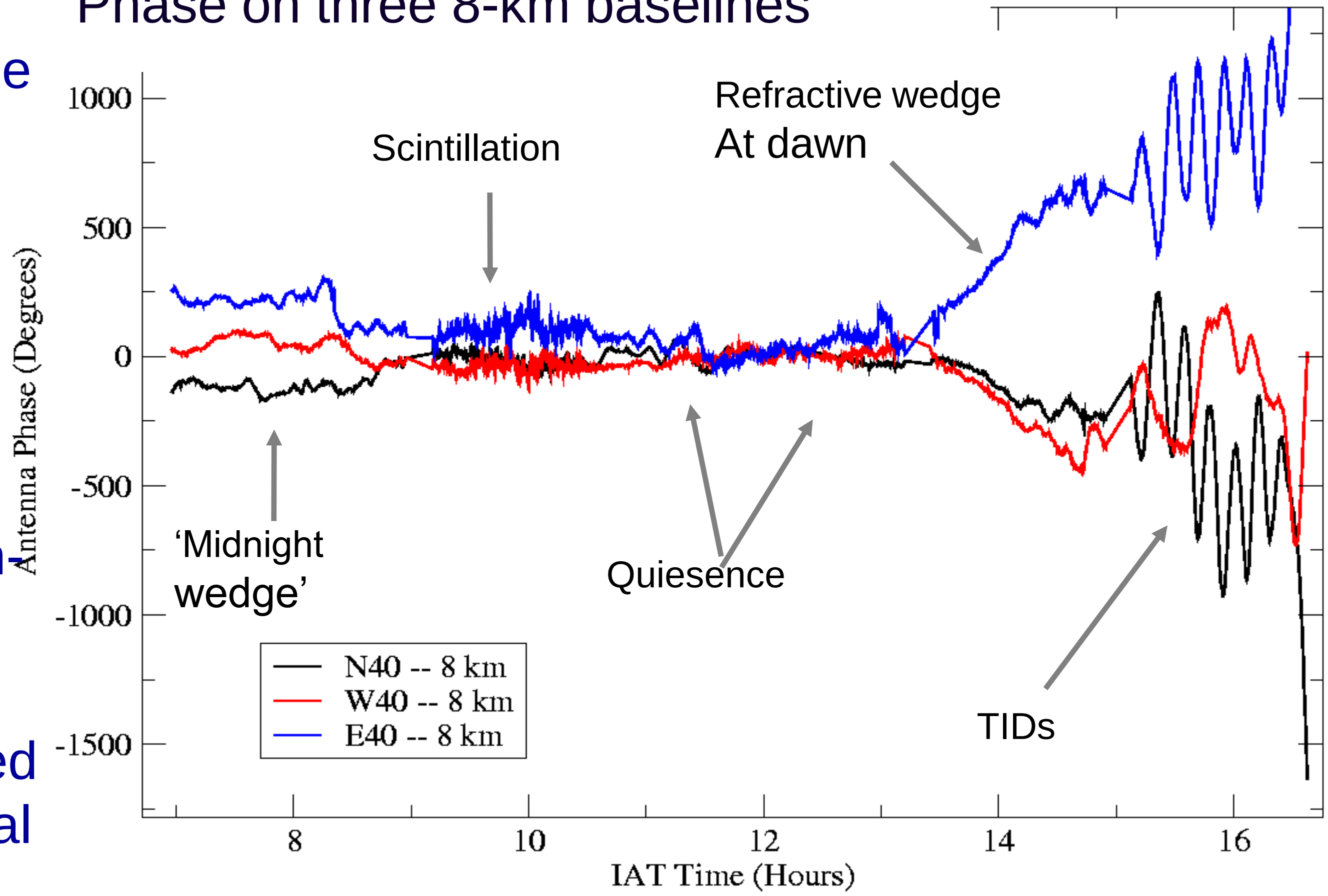


- Horizontal, wavelike bulk motions (TIDs)
- Smaller-scale turbulence

The ionosphere

- Radio waves experience variable refractive index
- Extra path length adds extra phase
- Interferometers sensitive to phase changes
- Time and direction-dependent phase error per antenna
- Cannot be removed by standard self-cal

Phase on three 8-km baselines



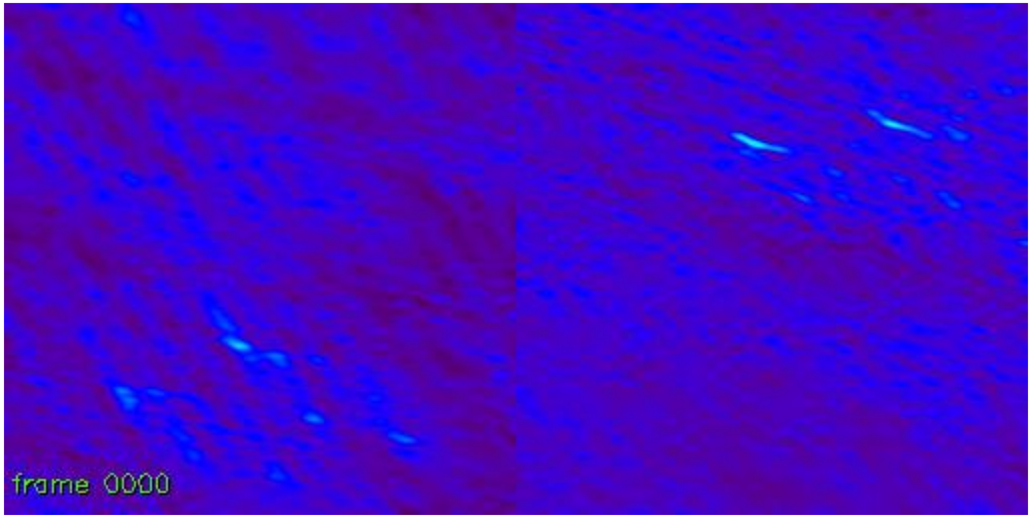
Avoid dawn!

The ionosphere

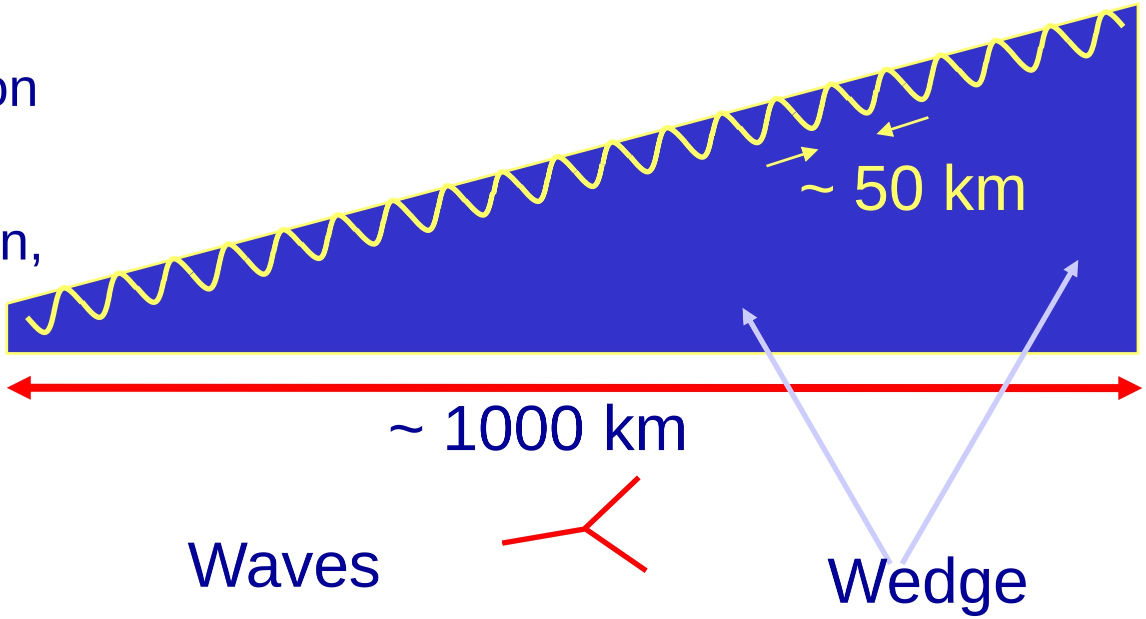
- Ionosphere affects signal propagation

$$\phi_{ion} = \frac{e^2}{4\pi\varepsilon_0 m\nu}\int n_e dl$$

- Wedge:
  - Faraday rotation, absorption, refraction
- Waves:
  - Differential refraction, source distortion, scintillation

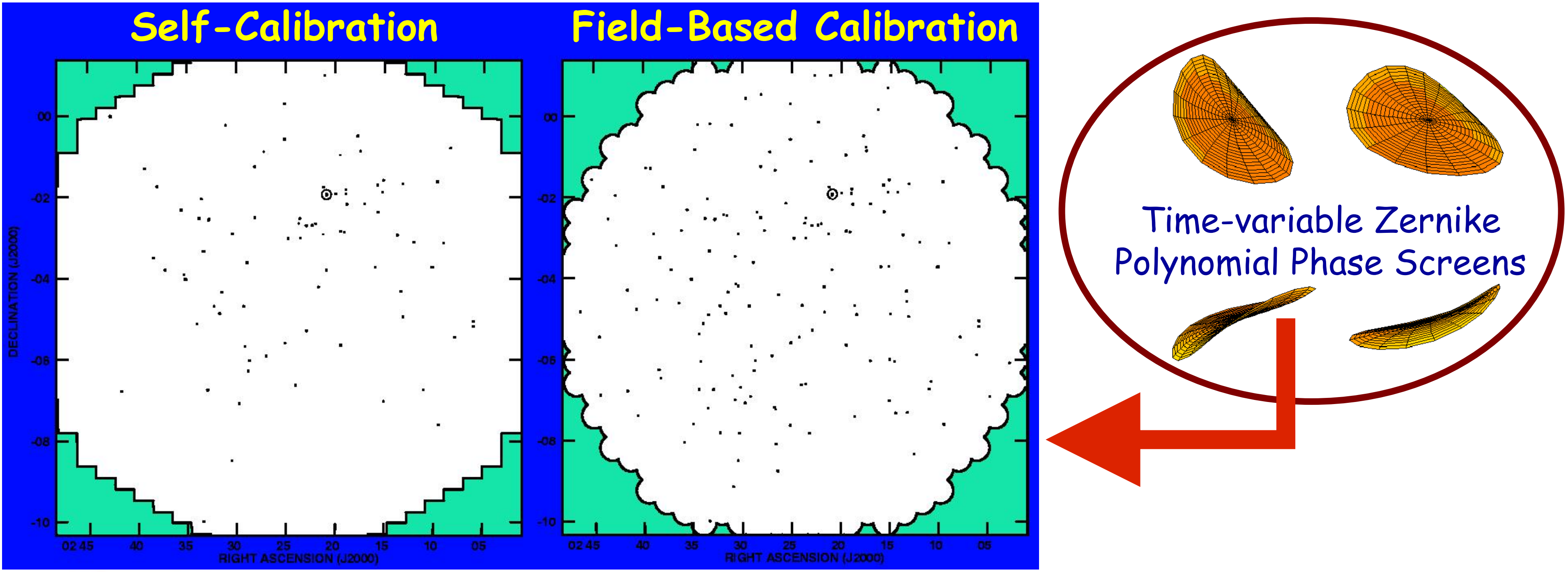


Credit: Dharam Vir Lal



Compensating for the ionosphere (I)

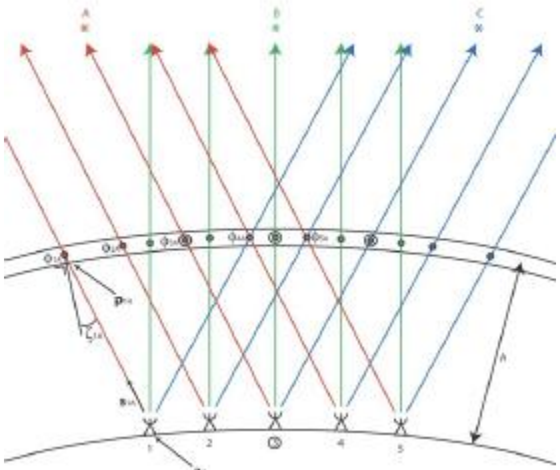
- Field-based calibration
  - Rapid images of bright sources to compare to known positions
  - Fit Zernike polynomial phase delay screen for each time interval.
  - Apply time variable phase delay screen to produce corrected image

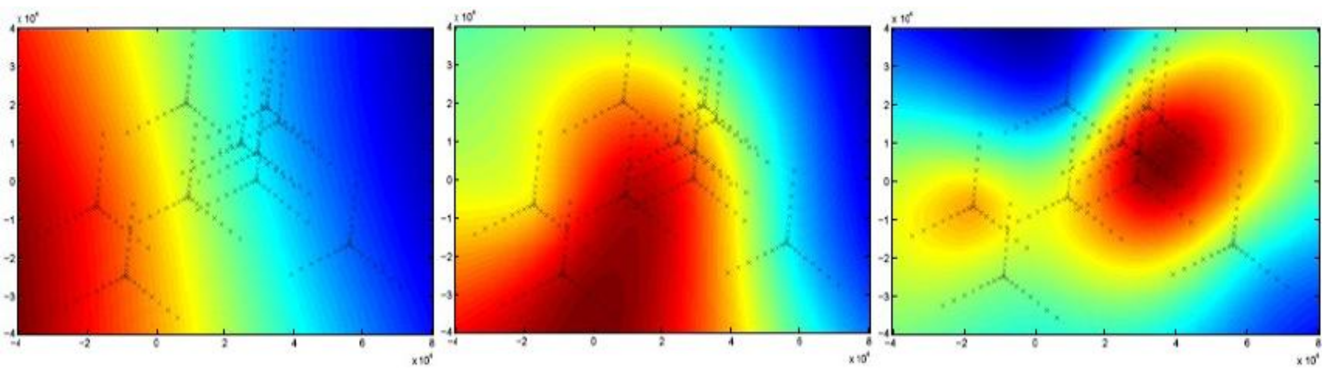


Average positional error decreased from ~45” to 17”

Compensating for the ionosphere (II)

- Source Peeling and Atmospheric Modelling (SPAM; H. Intema)
  - Iteratively self-calibrate on and subtract bright sources from uv-data
  - Fit global ionospheric model to peeling solutions
  - Calculate model phase solutions for each facet of wide-field image
  - Apply solutions, image and deconvolve as usual
    - 10-50% reduction in background noise
    - Peak fluxes and astrometric accuracy increased





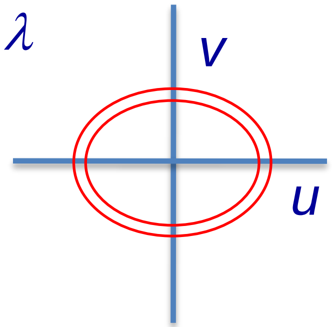
Credit: Huib Intema

Bandwidth smearing

- Recall field of view given by λ/D
- But bandwidth smearing affects point source response

$$\frac{\Delta\nu}{\nu} \approx \frac{\Delta\theta}{\theta_s}$$

- At low frequencies:
  - Field of view is large
  - Fractional bandwidth is high
- Solution
  - Split the bandwidth into many spectral channels
  - Each channel is not affected by bandwidth smearing
  - Fourier transform each spectral channel separately
    - Recall (*u*,*v*,*w*) are components of **b** measured in λ
    - Grid each channel separately



Radio Frequency Interference

- The other benefit of narrow channels: RFI excision
  - Most man-made RFI is narrow-band
  - MUCH brighter than most astronomical data
  - We need to edit out visibilities affected by interference
  - Sensitivity $\sigma_S = \dfrac{2k_B T_{sys}}{A_{eff}\sqrt{N(N-1)t_{\text{int}}\Delta\nu}}$
- Remove few affected channels rather than entire integration
- RFI can also be natural (lightning, solar effects...)

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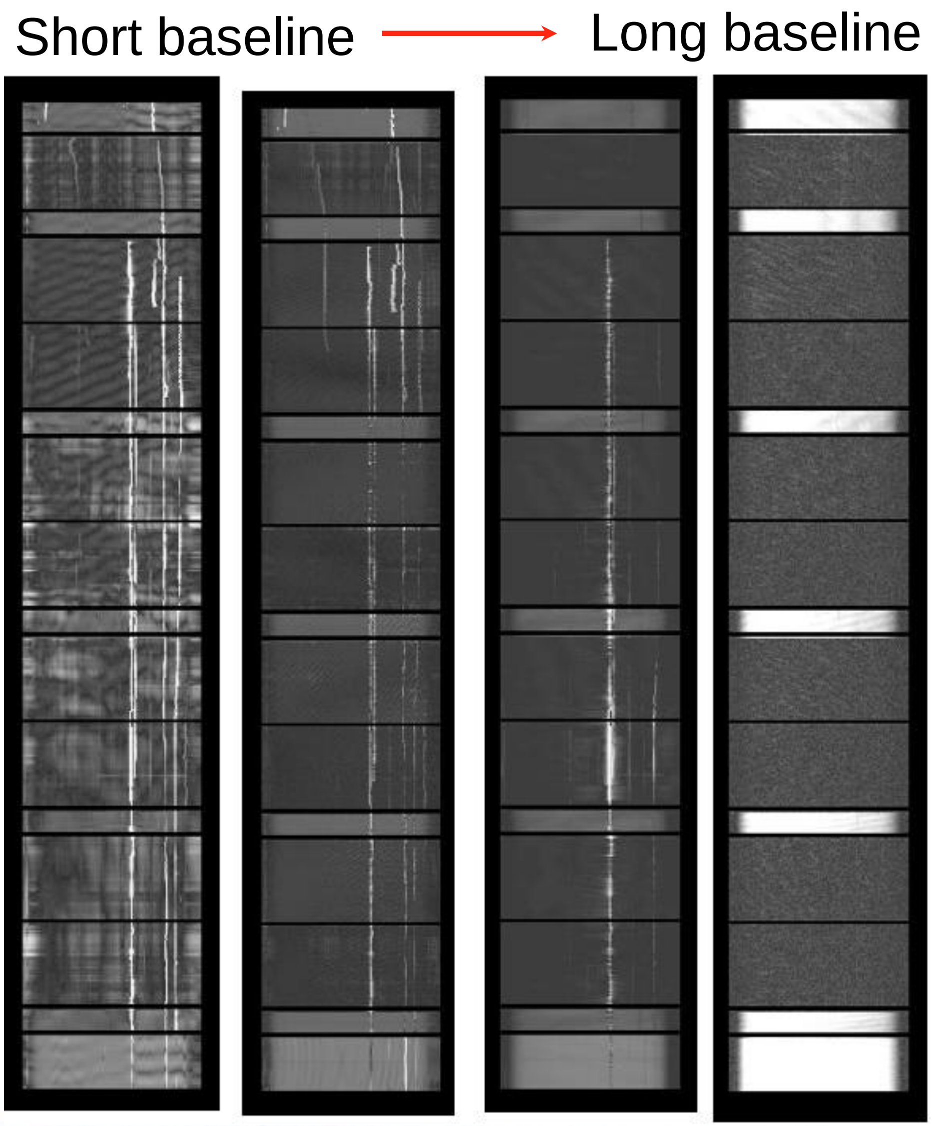
Radio Frequency Interference

- Worst on short baselines
- Tends to be narrow-band
- Care about internal generation
- Automated algorithms
  - Thresholding
  - Median window filters
  - Deviation in complex plane
  - High Stokes *V*
  - Pattern recognition
  - *u=0* (fringe rate is zero on *v* axis)



Non-coplanar arrays

- Recall the relation between visibility and sky brightness

$$V_\nu = \int I_\nu(\mathbf{s}) \exp\left(-2\pi i \frac{\mathbf{b.s}}{\lambda}\right) d\Omega$$

$$V_\nu(u,v,w) = \iint \frac{I_\nu(l,m)}{\sqrt{1-l^2-m^2}} \exp\left[-2\pi i(ul+vm+wn)\right] dl dm$$

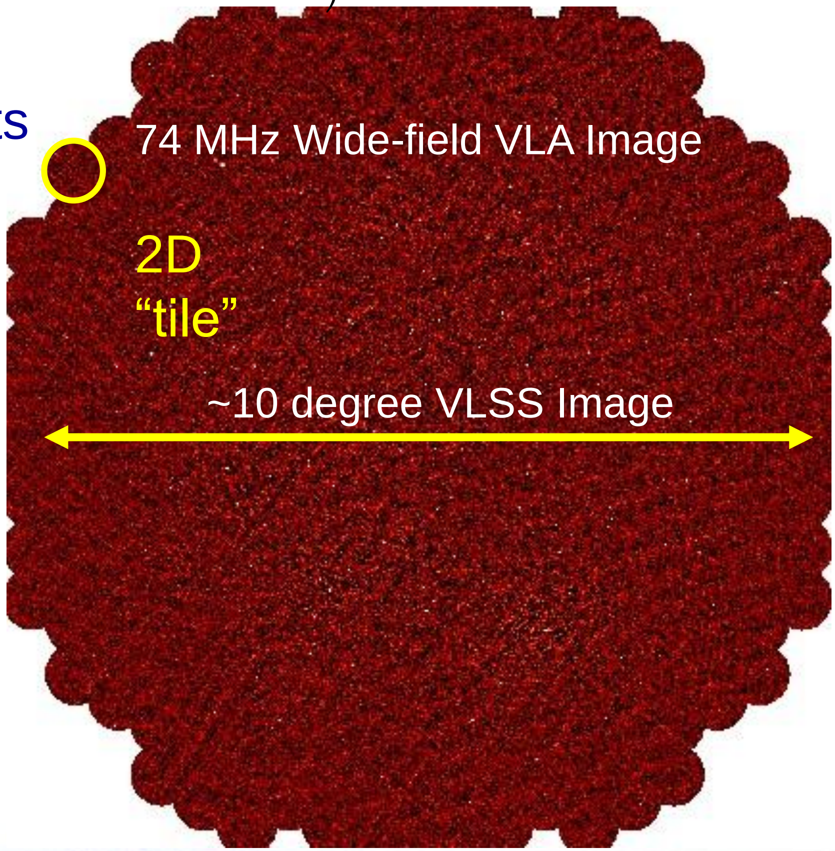
- Not a Fourier transform relation unless:
  - 1) All baselines lie in a plane (E-W interferometers, snapshots)
  - 2) Emission from a small region of sky (narrow-field imaging)

- At low frequencies, FOV = λ/D, i.e. large
  - We can only recover FT relation for snapshots or E-W interferometers

Non-coplanar arrays: facetting

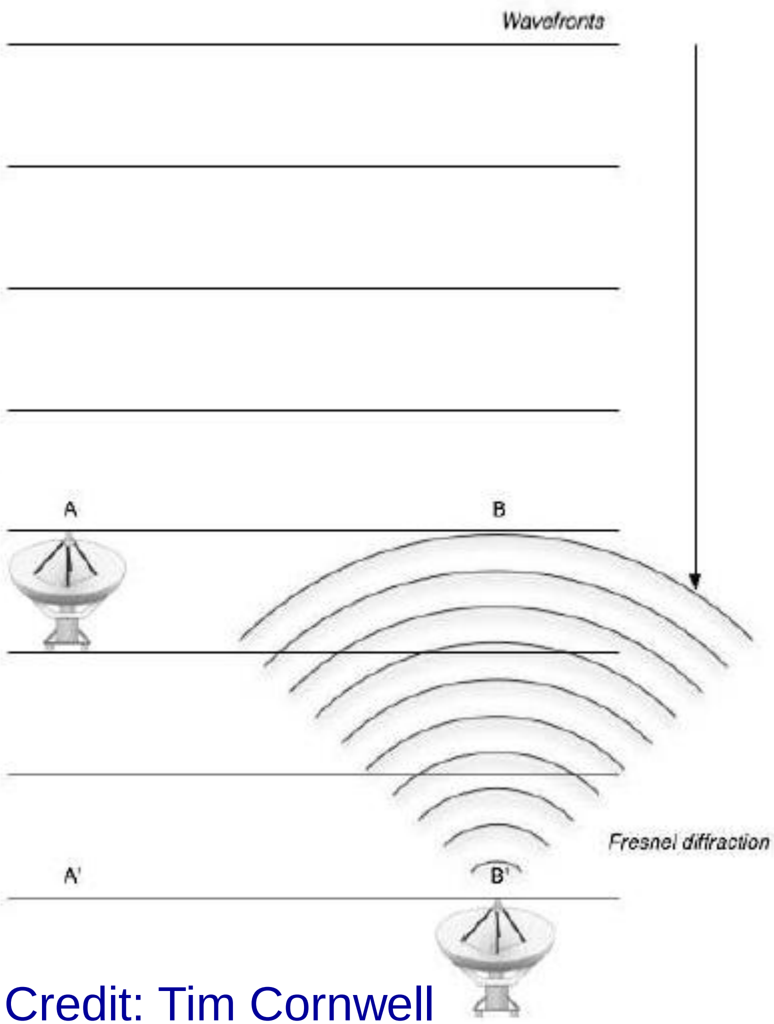
$$V_\nu(u,v,w) = \iint \frac{I_\nu(l,m)}{\sqrt{1-l^2-m^2}} \exp\left[-2\pi i\left(ul+vm+w\left\{\sqrt{1-l^2-m^2}-1\right\}\right)\right] dl\,dm$$

- We can't perform an FT unless $2\pi w\left(\sqrt{1-l^2-m^2}-1\right)<1$
- Facetted approach:
  - Split full FOV into many small facets
  - For each facet, *w* term < 1
  - Image/deconvolve each facet separately
  - Separate PSFs for each facet
  - Reconcile different facets in a "major cycle"
  - Stitch facets together at the end



Non-coplanar arrays: w-projection

- Correlation of electric field at A and B is 2-D FT of sky brightness
- We sample at B' not B
- Propagating from B to B', the electric field diffracts
- Use reciprocity theorem and consider transmission
- If BB' is small, use Fresnel diffraction theory



Credit: Tim Cornwell

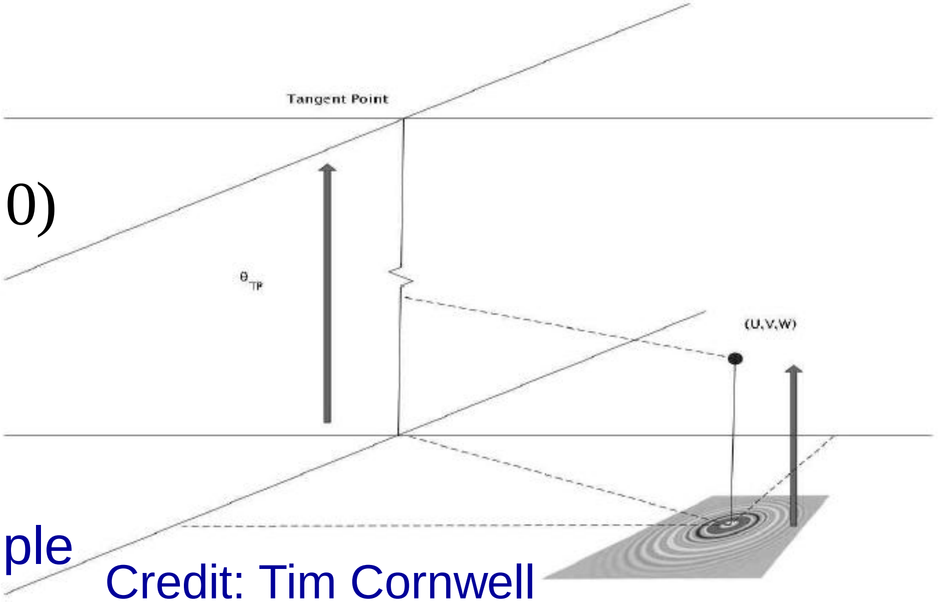
Non-coplanar arrays: w-projection

- Project visibility at a point (*u,v,w*) to the plane (*u,v,w*=0)
- *w*-term disappears, we recover 2D FT relation

$$V_\nu(u,v,w) = \iint \frac{I_\nu(l,m)}{\sqrt{1-l^2-m^2}} G(l,m,w) e^{-2\pi i(ul+vm)} dl dm$$

$$G(l,m,w) = e^{-2\pi i w\left(\sqrt{1-l^2-m^2}-1\right)}$$

$$V(u,v,w) = \tilde{G}(u,v,w) * V(u,v,w=0)$$



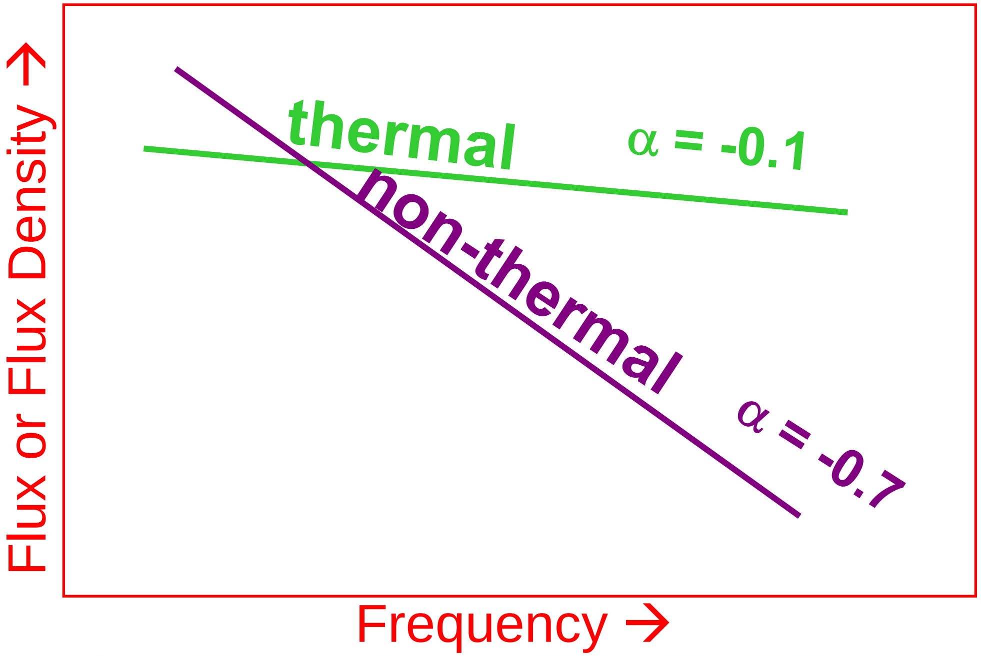
- Convolution relation between *V(u,v,w)* and *V(u,v,w=0)*
- No longer probe a single spatial frequency with a single (*u,v*) sample
-

Credit: Tim Cornwell

Low frequencies = bright sources!

- Typical synchrotron spectral indices: α ~ -0.7
- Brighter at lower frequencies
- Deconvolution even beyond the primary beam
- Many clean iterations
- Sensitivity to extended structure (short uv-spacings)
- Multi-scale clean

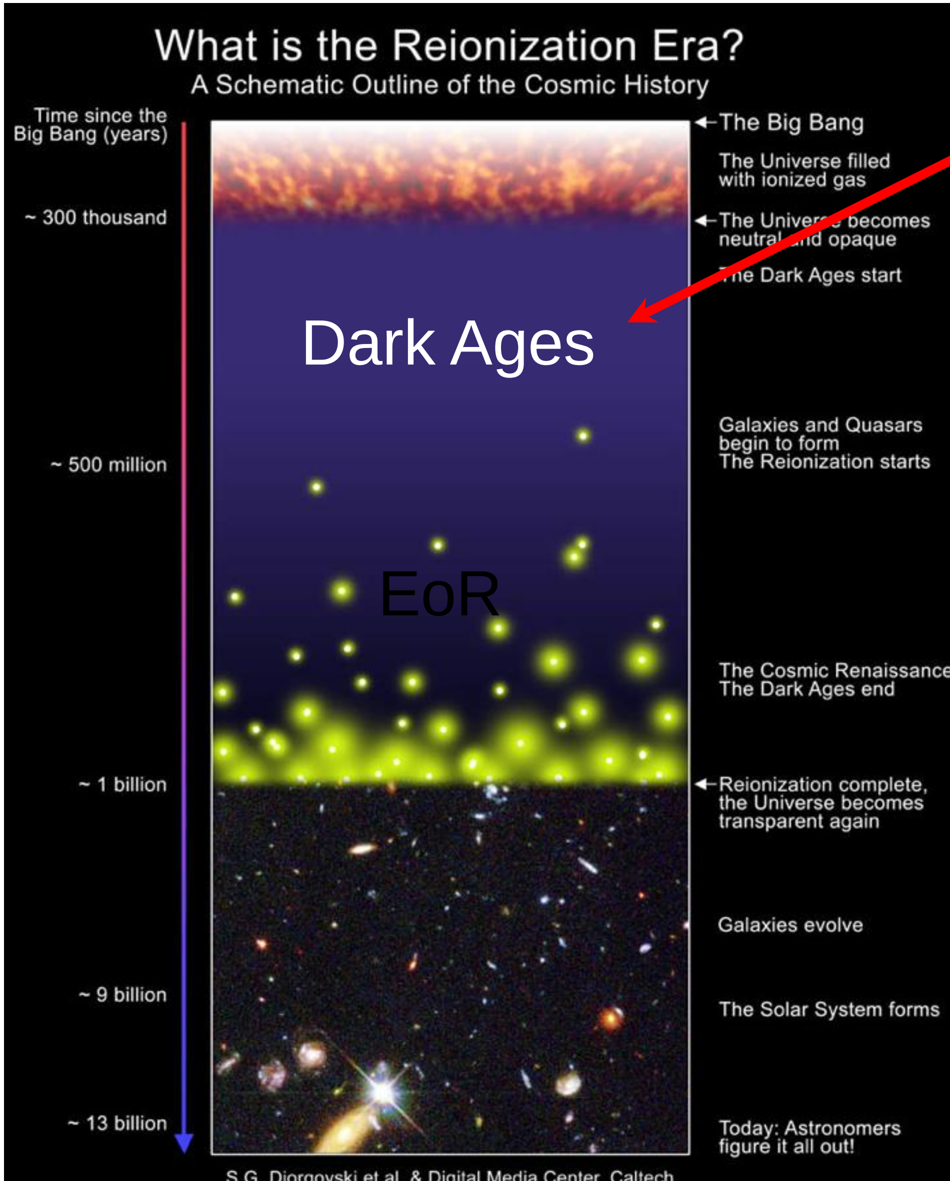
- Cygnus A
  - 5 kJy at 330 MHz
  - 17 kJy at 74 MHz
  - Dynamic range issues

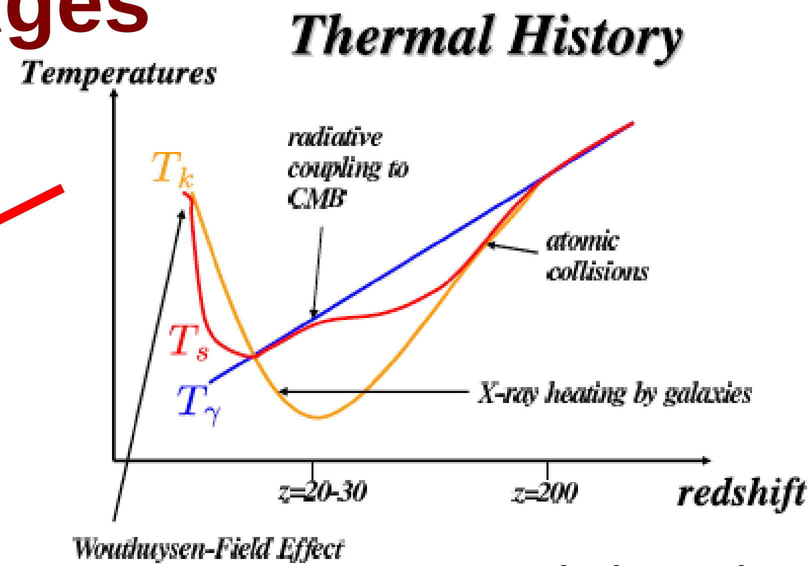


Low-frequency science: why bother?

- 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

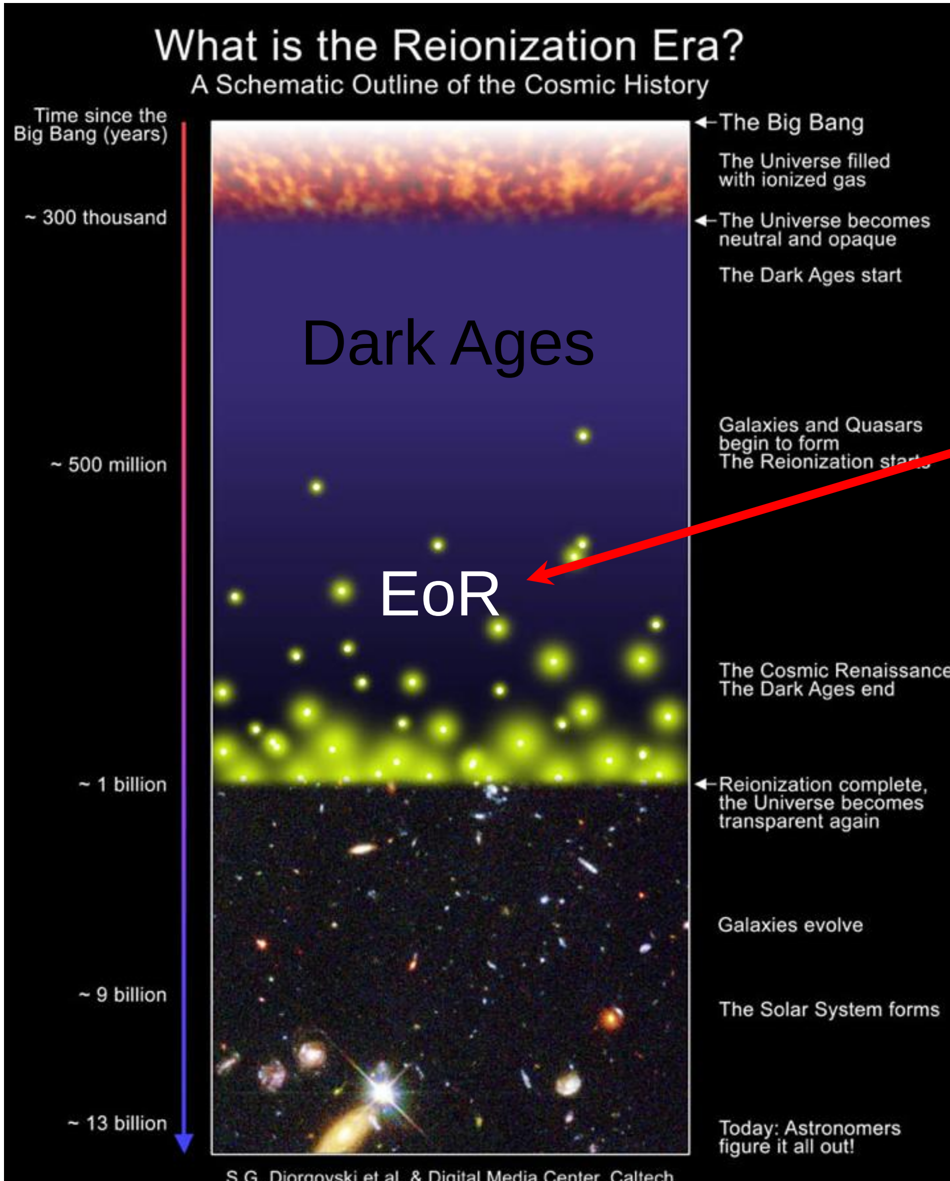


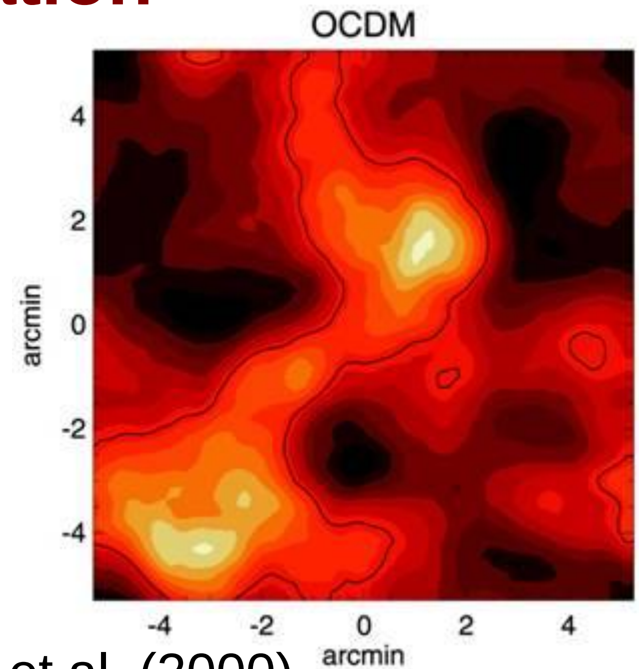


Loeb (2006)

- 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



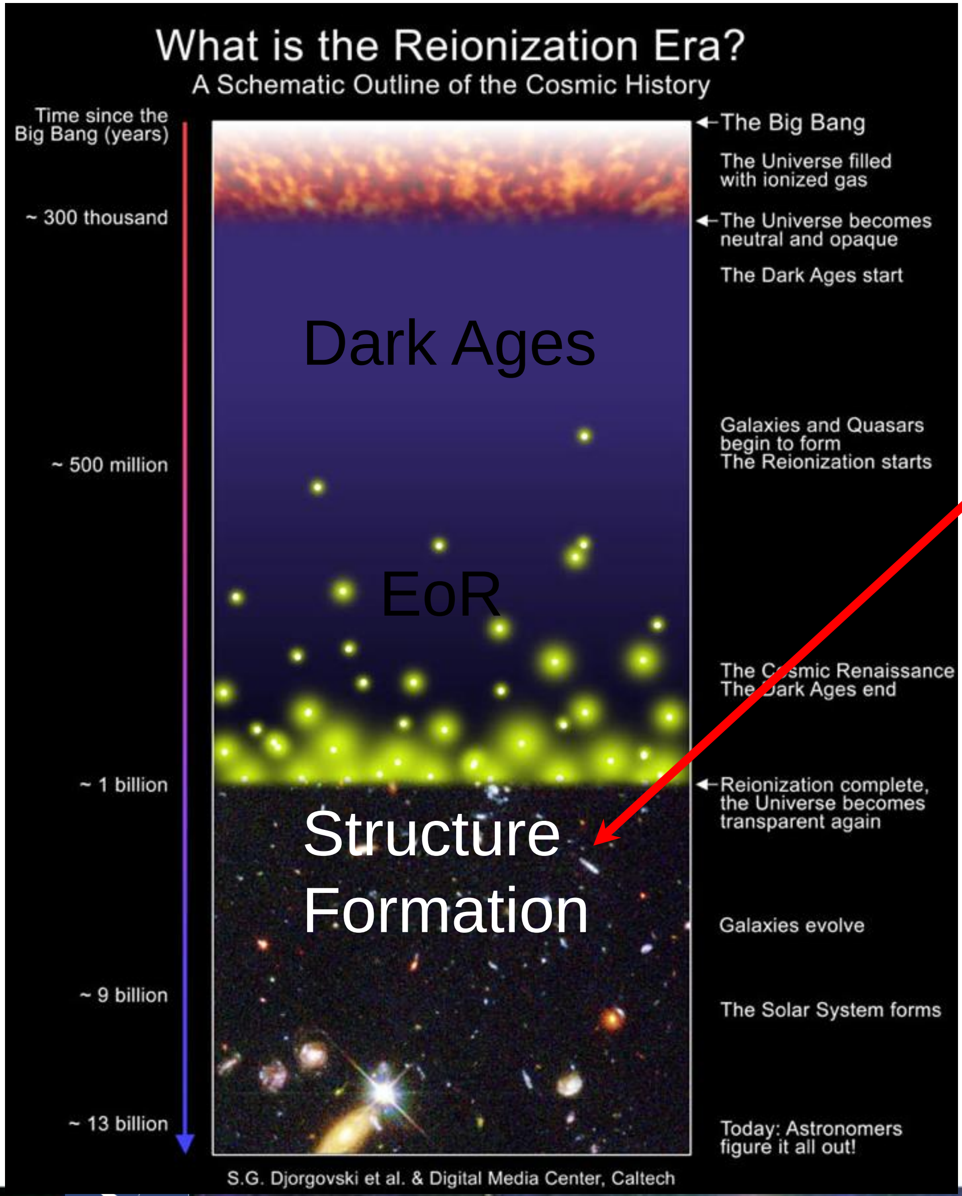


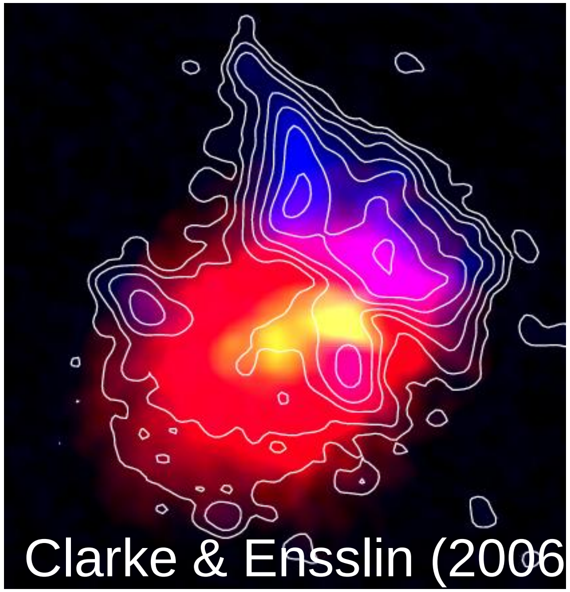
Tozzi et al. (2000)

- 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

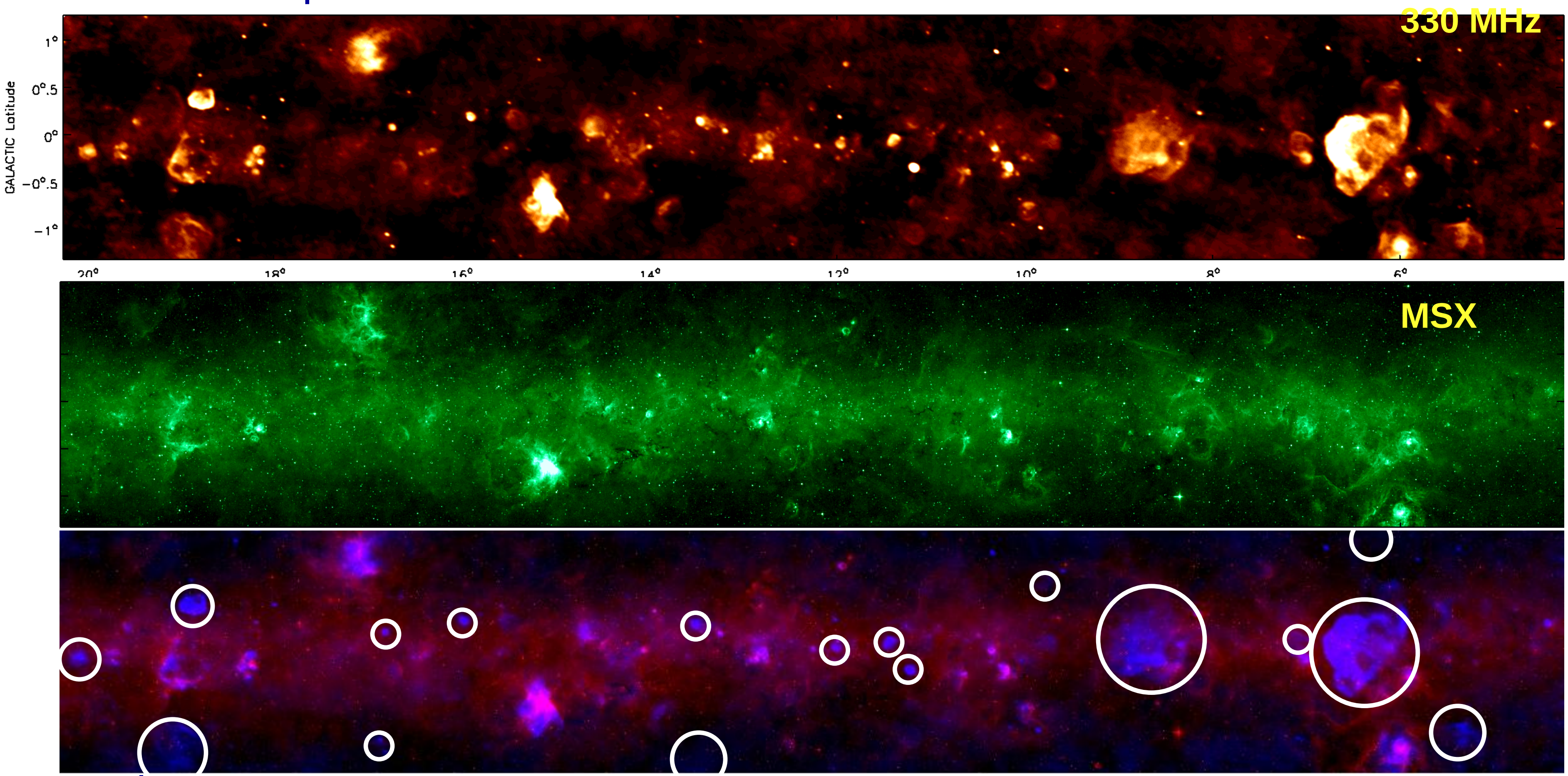




- Galaxy clusters form through mergers and are identified by large regions of diffuse synchrotron emission (halos and relics)
- Important for study of plasma microphysics, dark matter and dark energy

Galactic Supernova Remnant Census

Census: expect over 1000 SNR and know of ~230



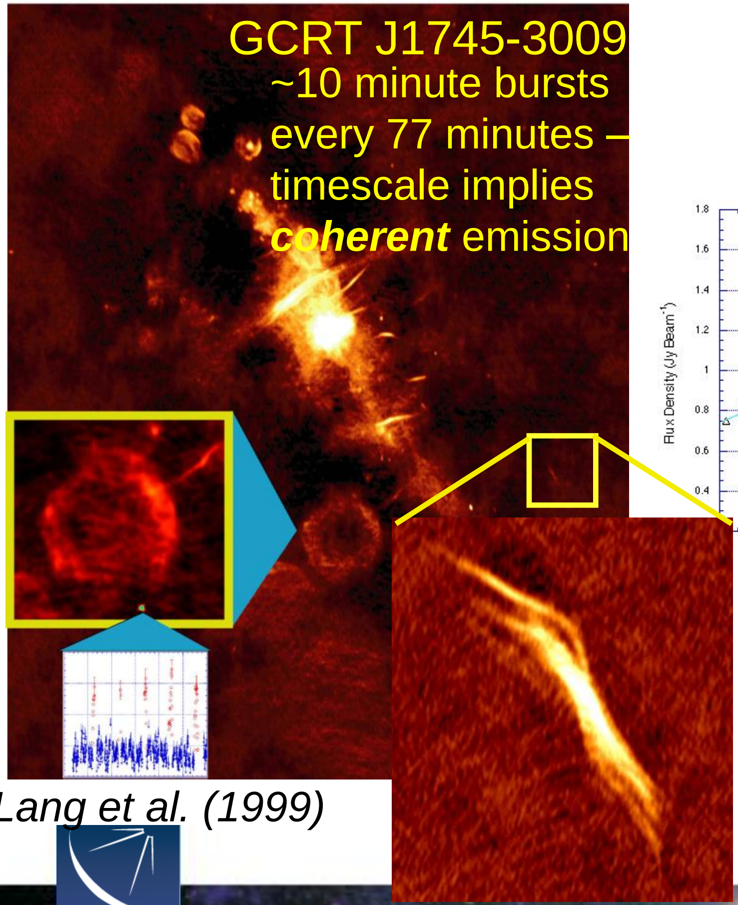
2 Color Image:
Red: MSXat 8 ⌠m
Blue: VLA 330 MHz

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

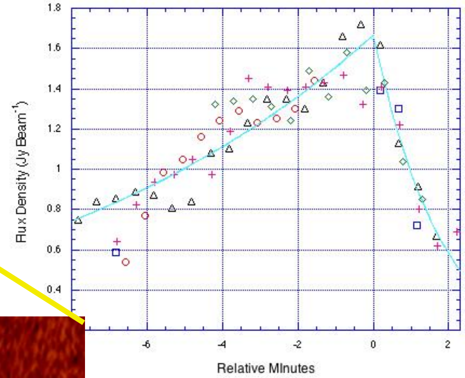
Brogan et al. (2006)

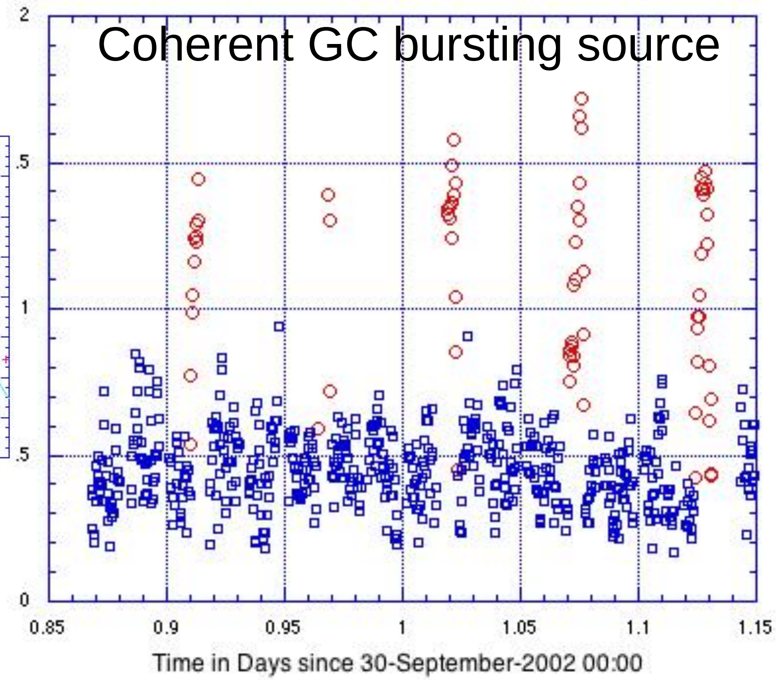
Transients: Galactic Center

- ➢ 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)

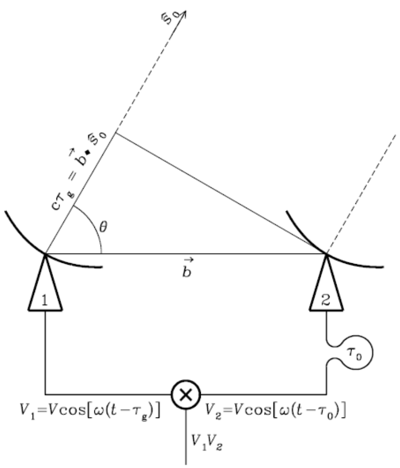




Hyman, et al., (2005) - Nature;
Hyman et al. (2006, 2007)

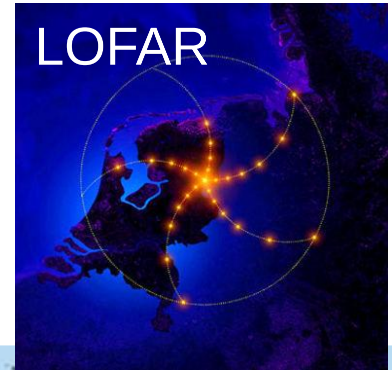
Simplicity and complexity

- Average collecting area of a lossless antenna $\langle A_e \rangle = \frac{\lambda^2}{4\pi}$
- Very simple receivers possible
  - Dipoles
- Complexity is in computing power
  - Electronic “software telescopes”

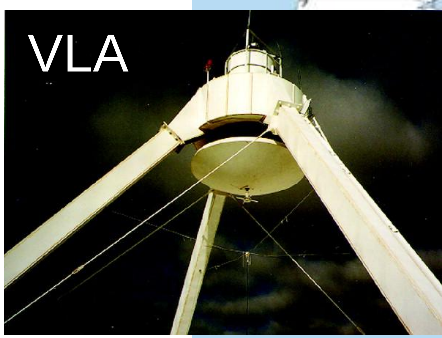


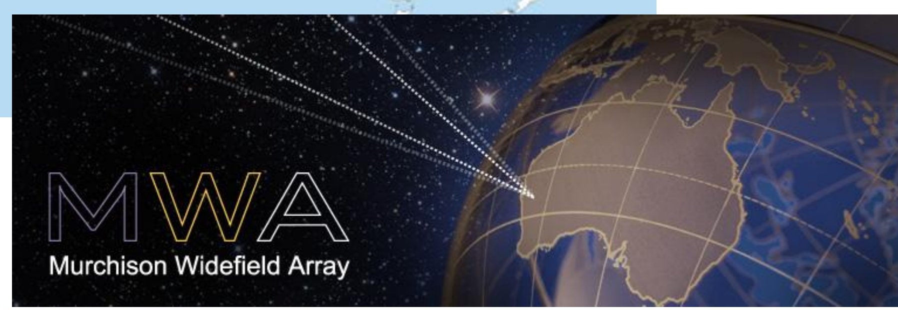
$$\tau_g = \frac{\mathbf{b} \bullet \mathbf{s}}{c}$$

Low-frequency arrays



LWA
Long Wavelength Array





Low frequency summary

- Challenging but rewarding region of the EM spectrum
- Technical, algorithmic and computational challenges
- Advances in computing power have opened up the era of low-frequency
  - LOFAR, MWA, LWA, PAPER
- Fundamental science
  - EOR
  - Rapid all-sky surveys
  - Transient science and the unknown
  - Cosmic magnetism
  - Solar physics
  - UHECRs