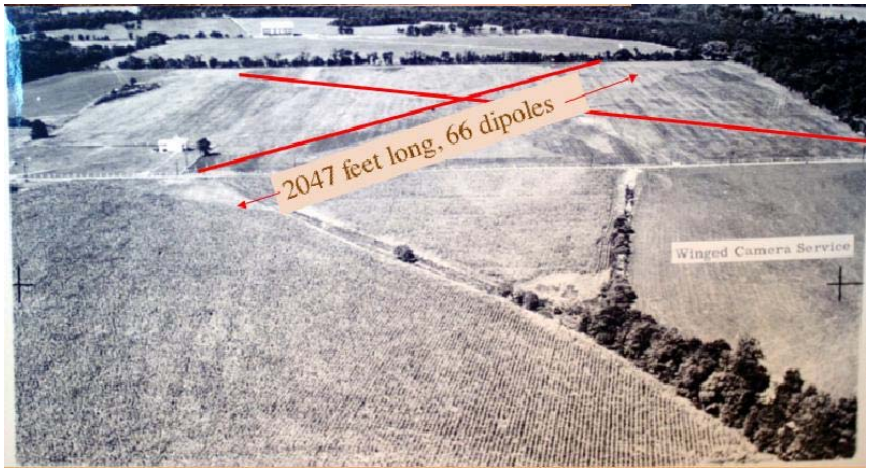
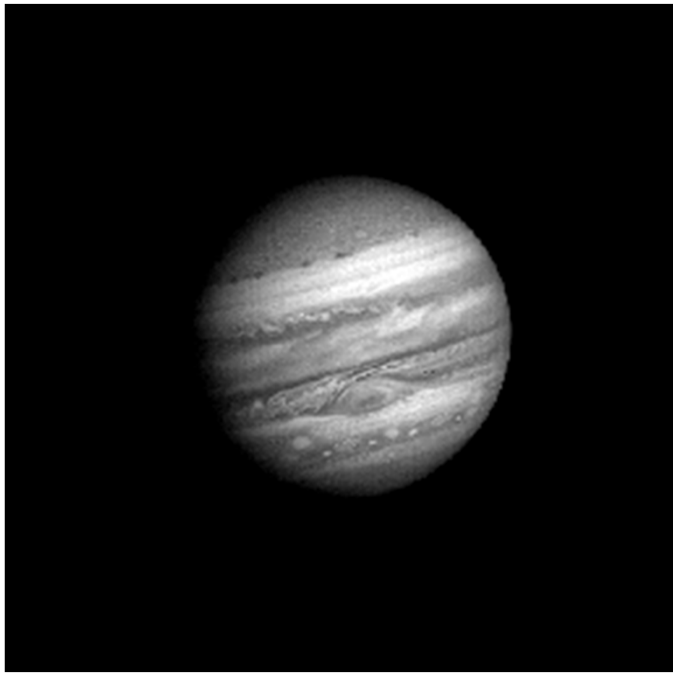
1955 - Radio Emission from Jupiter



Bernard Burke and Kenneth Franklin mistook radio signals from Jupiter for a Maryland farmhand driving home after a late date.

"Our identification of Jupiter as a radio source is not based directly on reasoning, but more on luck!" – Franklin



Importantly this radio emission confirmed that Jupiter had a magnetic field and firmly established its rotation rate of 9.925 hours.

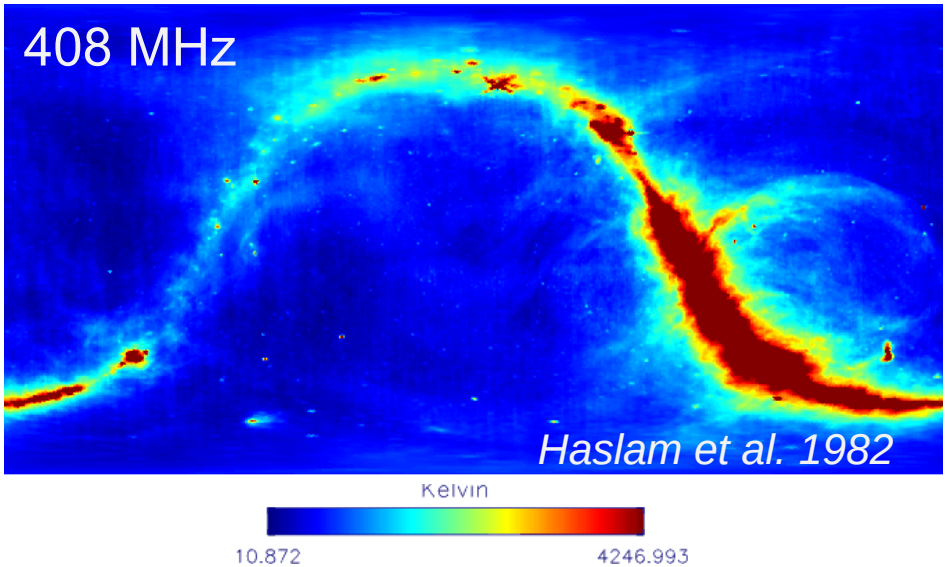
Fundamental limitations

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

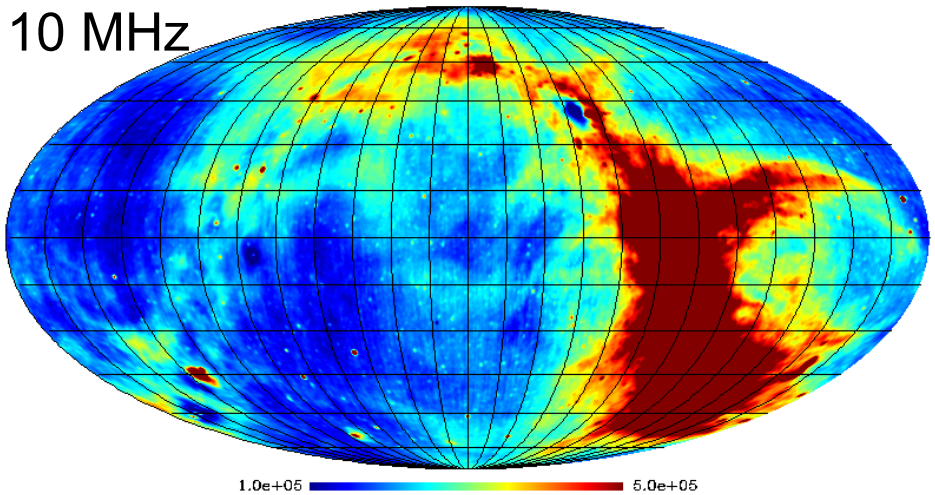
$T_{sys}=T_{Source}+T_{Ant}+T_{Rx}$

Sky brightness

$$T_{sys}(K) = 131000 \left(\frac{\nu}{15\ MHz}\right)^{-2.55}$$



Peak: 4200 K



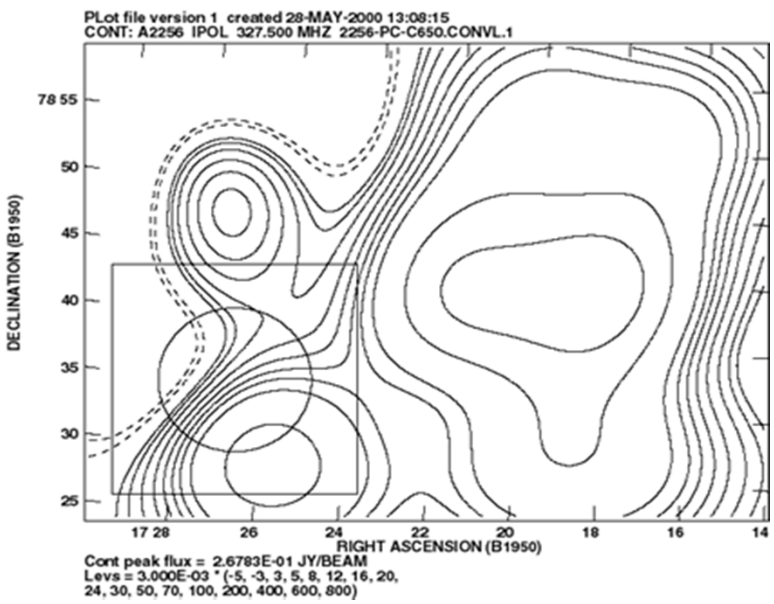
Peak: 500,000 K

from Costa et al. 2008

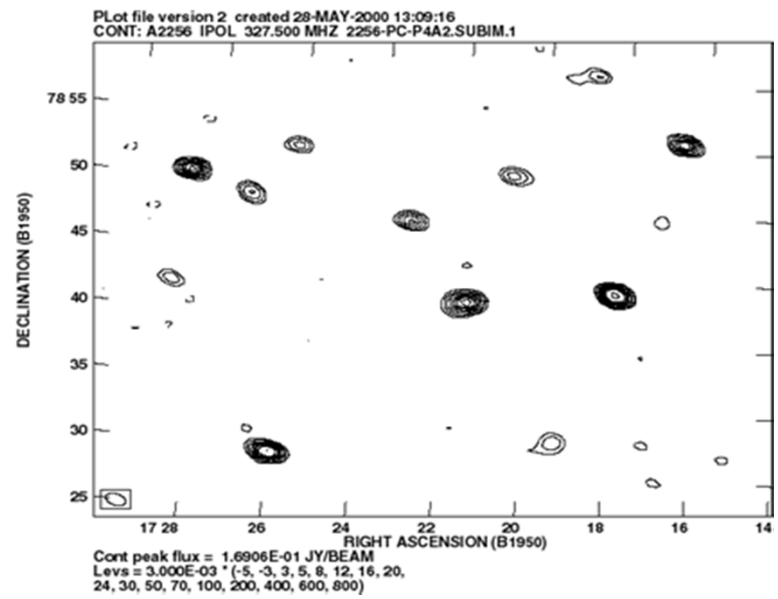
Confusion

- source counts rise to lower F_ν
- for any angular resolution θ
  - there is a confusion limit
  - individual weak sources blend
  - the resulting sky noise may exceed thermal noise
  - such cases are “confusion limited”
- $F_\nu \sim 3\ \mathrm{mJy}\ (\theta/2')(150\ \mathrm{MHz}\ /\ \nu)^{0.7}$ - (Bernardi et al. 2010)

~ 10’, rms ~ 30 mJy/beam

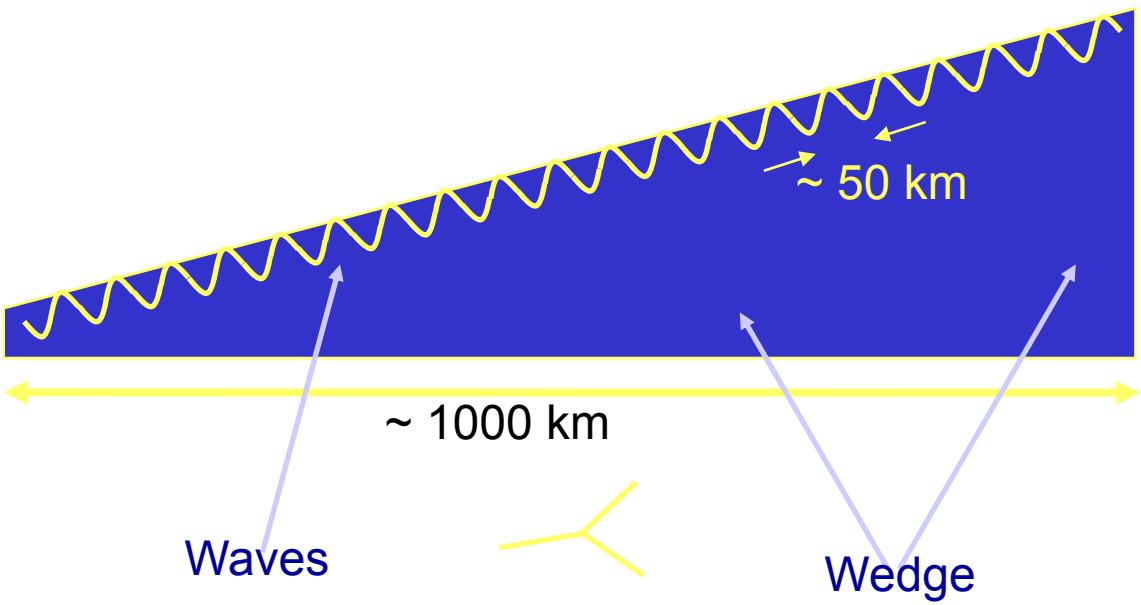


~ 1’, rms ~ 3 mJy/beam



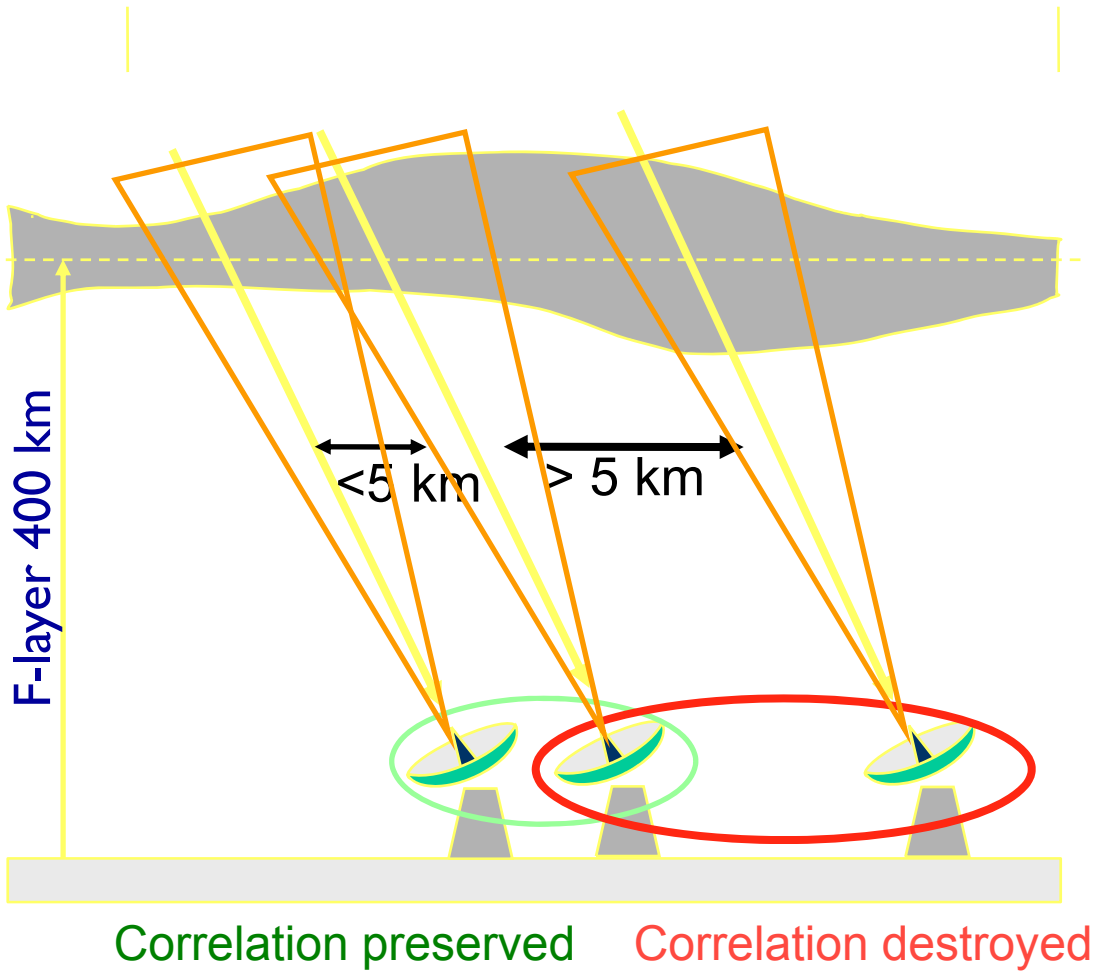
Ionospheric Effects

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



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

Ionosphere



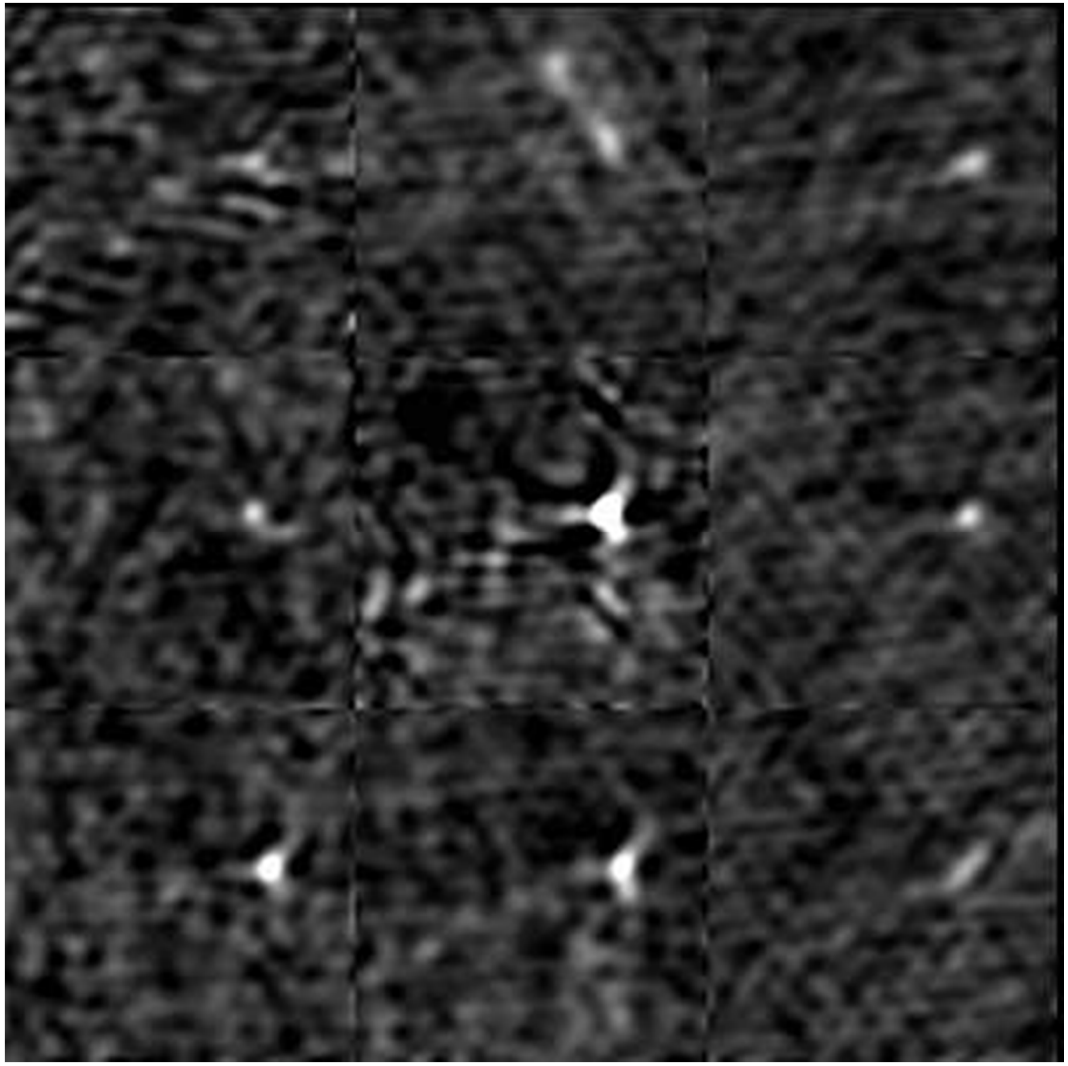
- Waves in the ionosphere introduce rapid phase variations (~1°/s on 35 km BL)

Phase coherence is preserved on BL < 5km (gradient)

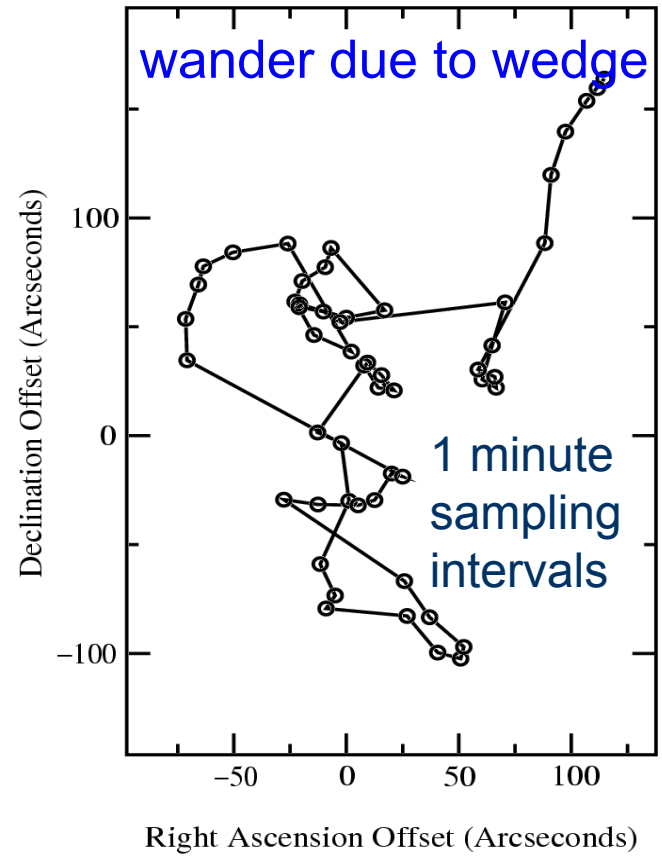
- BL > 5 km have limited coherence times

- Without proper algorithms this limits the capabilities of low frequency instruments

Ionospheric Refraction & Distortion

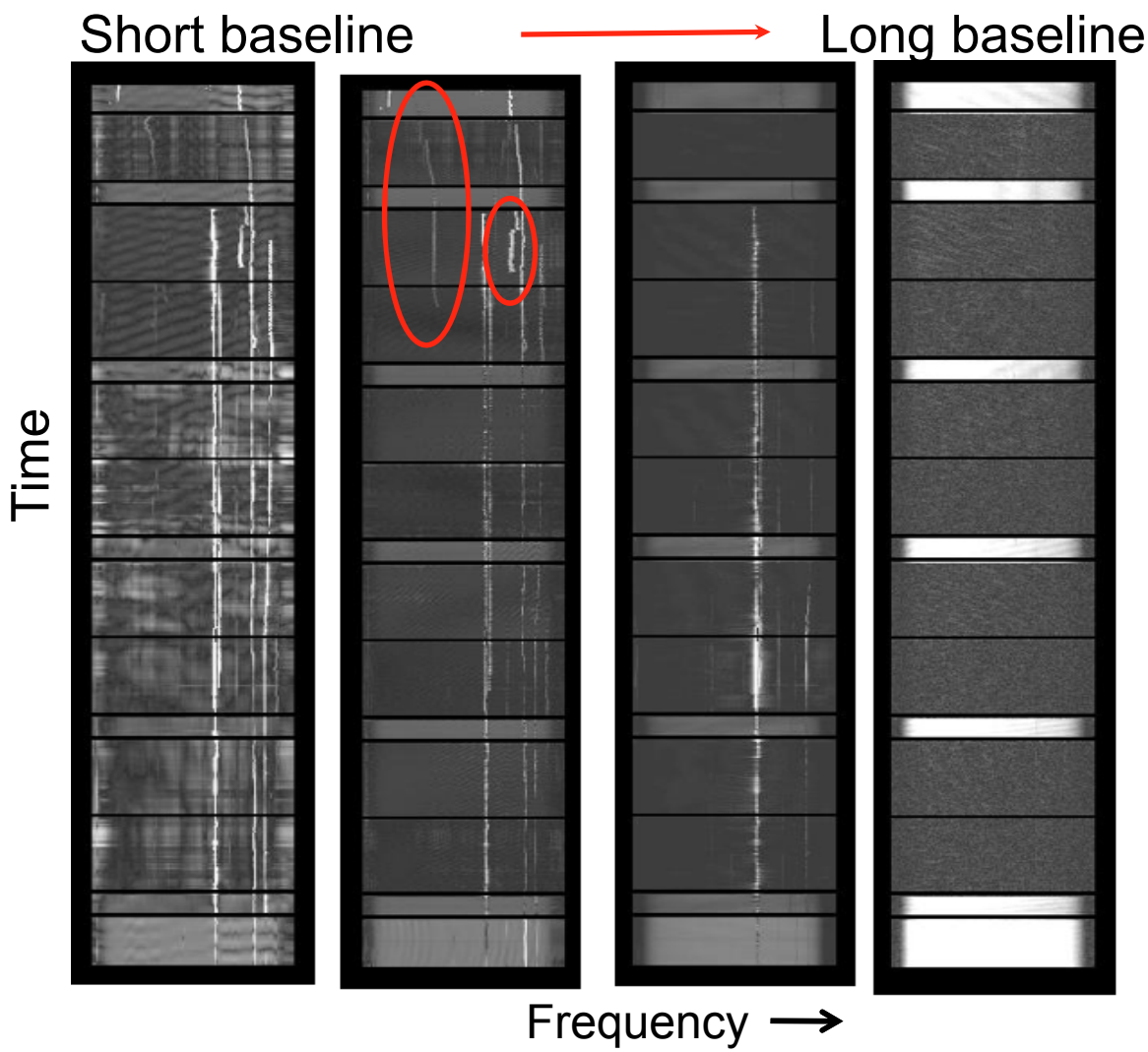


(credit: Namir Kassim)



- common mode & differential refrac'n
- variability over 1 min or less
- length scales @ altitude < 10km

RFI Examples



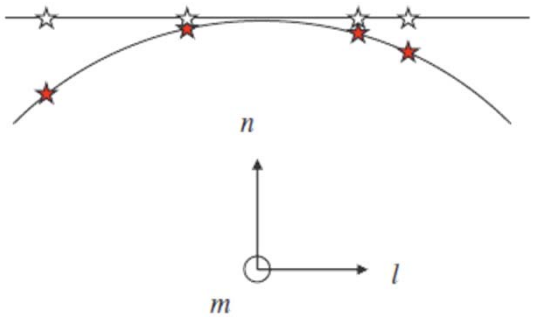
- RFI is worst on short baselines

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

- Wideband interference can degrade automated routines

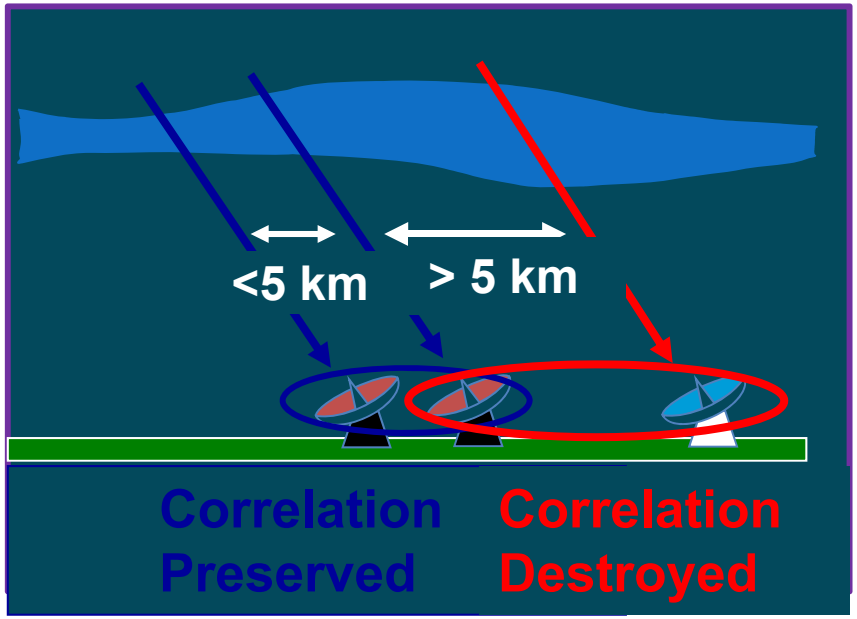
Wide FOV

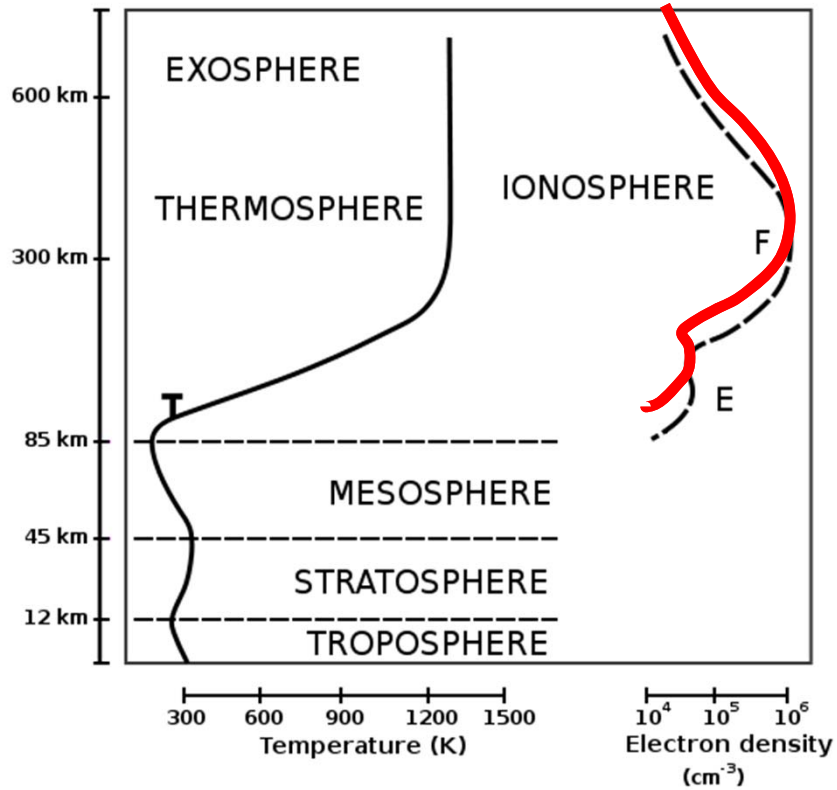
- dipoles: PAPER: 60°; MWA: 20°; LWA/LEDA: 130°
- dishes: VLA: 11° (74 MHz); GMRT: 3° (150 MHz)
- requires advanced techniques if non-coplanar
    - faceting (well understood)
    - w-correction + various (uv) deconvolution schemes
    - potentially computationally expensive
    - warped snapshot imaging



Why Low Frequencies 'Abandoned'?

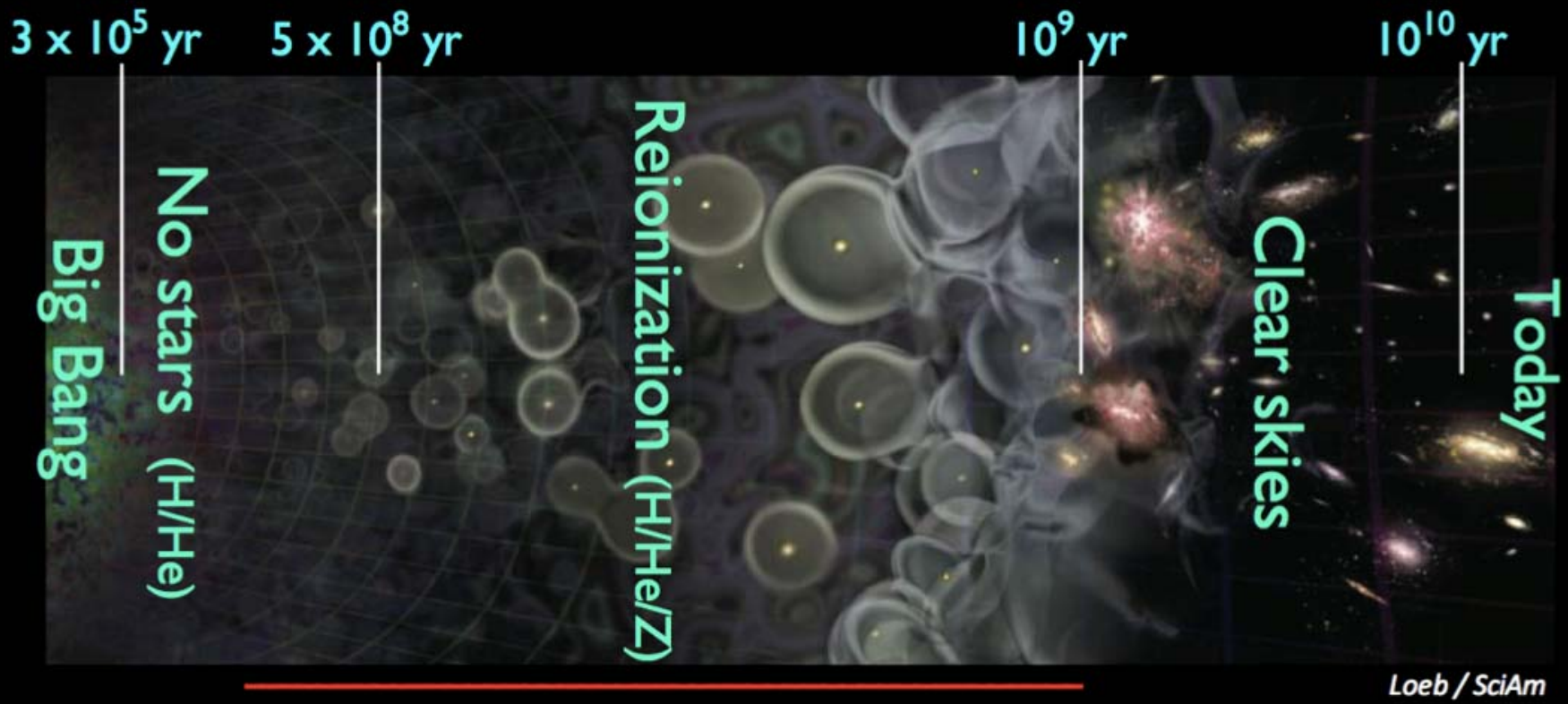
- **Low frequency instruments had limited aperture due to ionosphere (B< 5 km)**





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

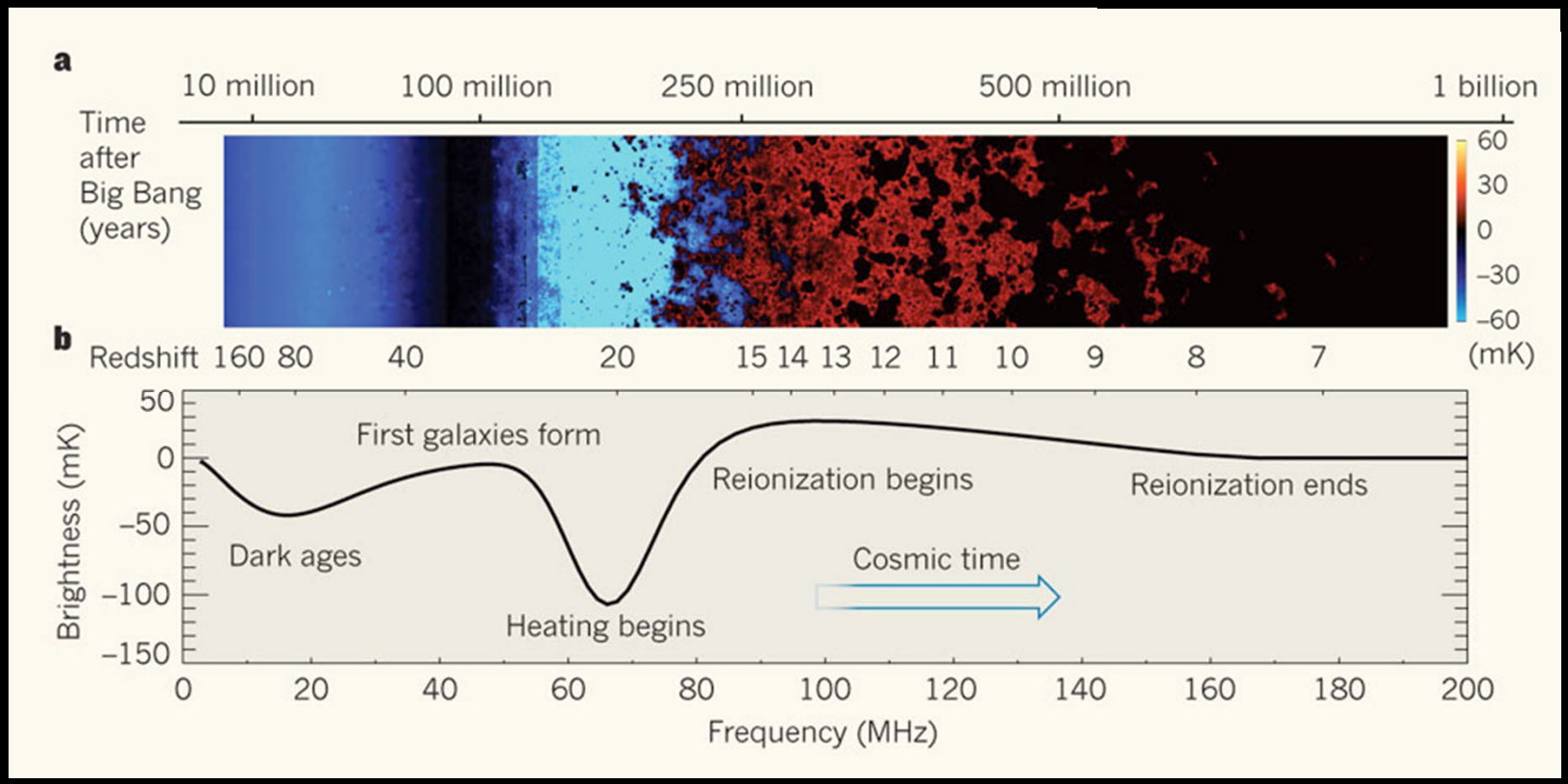
The Next Great Frontier of Cosmology



The Epoch of Reionization:
100 Myr – 1 Gyr after Big Bang
Formation of first stars, galaxies and black holes

Probing the EOR with Redshifted HI

Pritchett & Loeb 2010



- The race is on to detect the Epoch of Reionization (EOR)
- The study of redshifted 21cm hydrogen (21 cm HI) is the key
- EOR studies may eventually provide more insight on the early universe than even CMB studies

Overcoming the Resolution Problem

- A revolution is occurring – A new generation of telescopes is being built at low radio 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 (eg. Pearson and Readhead 1984)

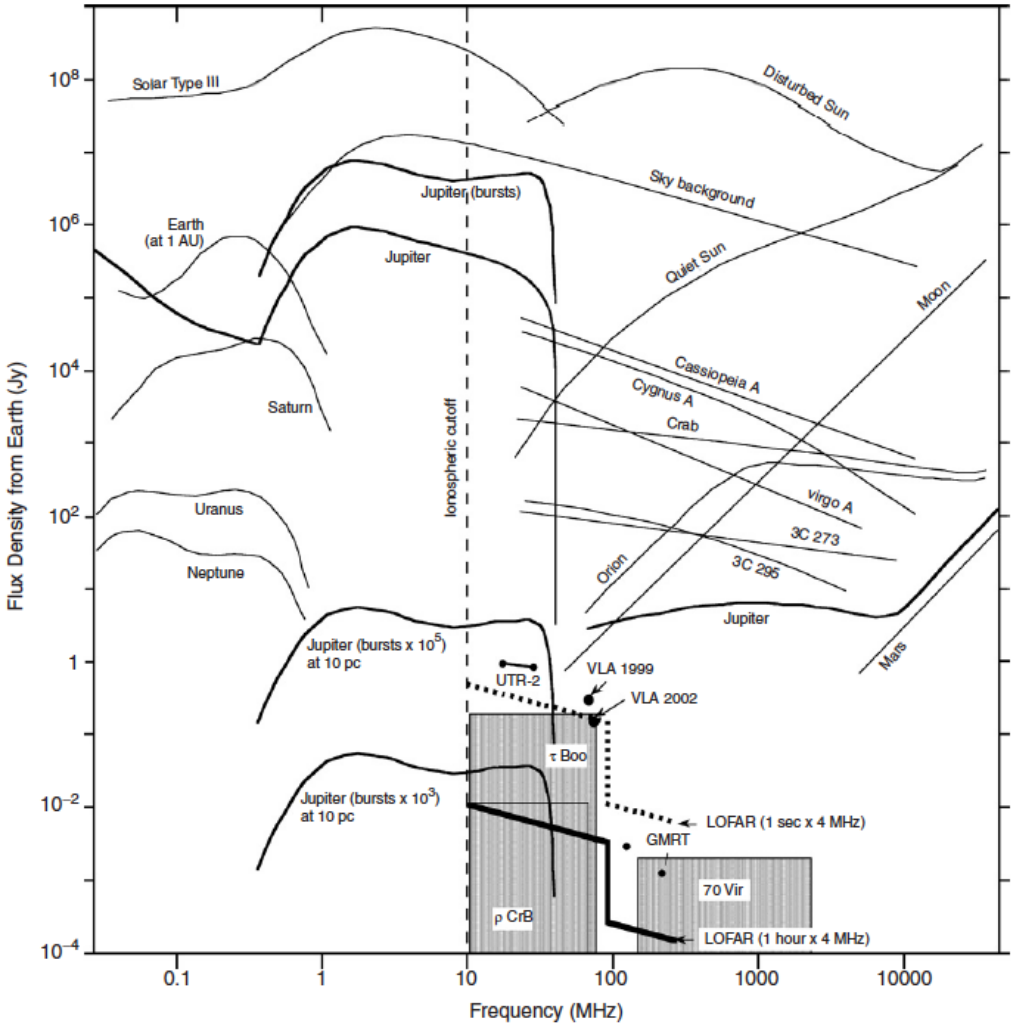
- Wide-field imaging only recently (sort of) possible

- RFI excision development

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

- Moore's Law has made computing power affordable

Jupiter's radio emission



-Jupiter average distance ~ 5 AU

- Average flux density ~ 10^6 Jy

- Let's consider at 2 pc = ~410000AU

Intensity = $10^6/(410000/5)^2$ = ~0.1 mJy

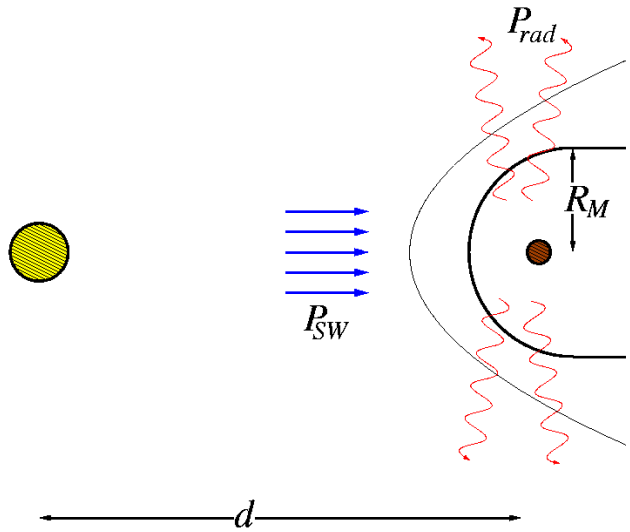
Fig. 1. Spectra of astronomical radiosources detected from the Earth's vicinity (1 Jansky = 1 Jy = $10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$). Galactic, extragalactic and solar spectra are adapted from (Kraus, 1986). Planetary spectra, corresponding to auroral radio emissions, are adapted from (Zarka, 1992). Jupiter's spectrum, which includes auroral and Io-induced decameter emissions, is from Zarka et al. (2004). Its average flux density is about 10^6 Jy, while peak flux densities reach or exceed 10^7 Jy during short-lived bursts. If all planetary emissions were normalized to the same observer distance of 1 AU, Jupiter's spectrum should be upscaled by $\times 20$, Saturn's by $\times 100$, Uranus' by $\times 400$, and Neptune's by $\times 900$, so that all are grouped within 2–3 orders of magnitude of each other. Jupiter's peak spectrum is reproduced with two different scalings to illustrate the possible radio spectrum of hot Jupiters (see text). Shaded boxes are predictions from (Farrell et al., 1999). Sensitivities of UTR-2, VLA, GMRT and future LOFAR observations are indicated. The Earth's ionospheric cutoff is indicated at 10 MHz.

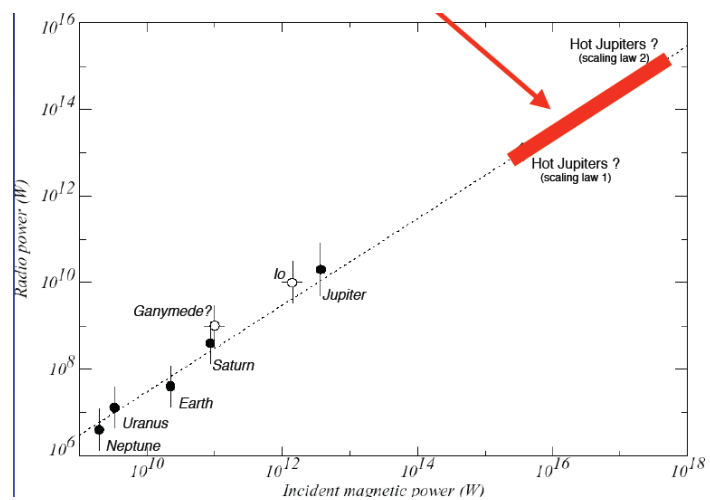
Expected Flux…

- Strong correlation between Solar Wind (P & V) and auroral radio emissions.

- The emitted power scales with the received stellar wind power - $P_{rad} \propto P_{SW}^{x}$

- The received stellar wind power depends on the distance and the cross-section of the magnetosphere - $P_{SW} \propto R_M^2 d^{-2}$





Zarka et al, ApSS. 2001

LOFAR

LOFAR: 6-station Superterp, a 24-station core array, a 40-station Dutch array, and a 48-station full array.

LWA

HJUDE – Hot Jupiter Detection Experiment with the LWA

-The Long Wavelength Array (LWA) in Socorro NM

- 512 dipoles

- 10-88 MHz

- Sensitivity of a few mJy

- Perfect for planet searches

- HJUDE has been allocated 5000 hours

HJUDE Team: Gregg Hallinan, Jake Hartman, Greg Taylor, Steve Ellingson & Chris Wolfe

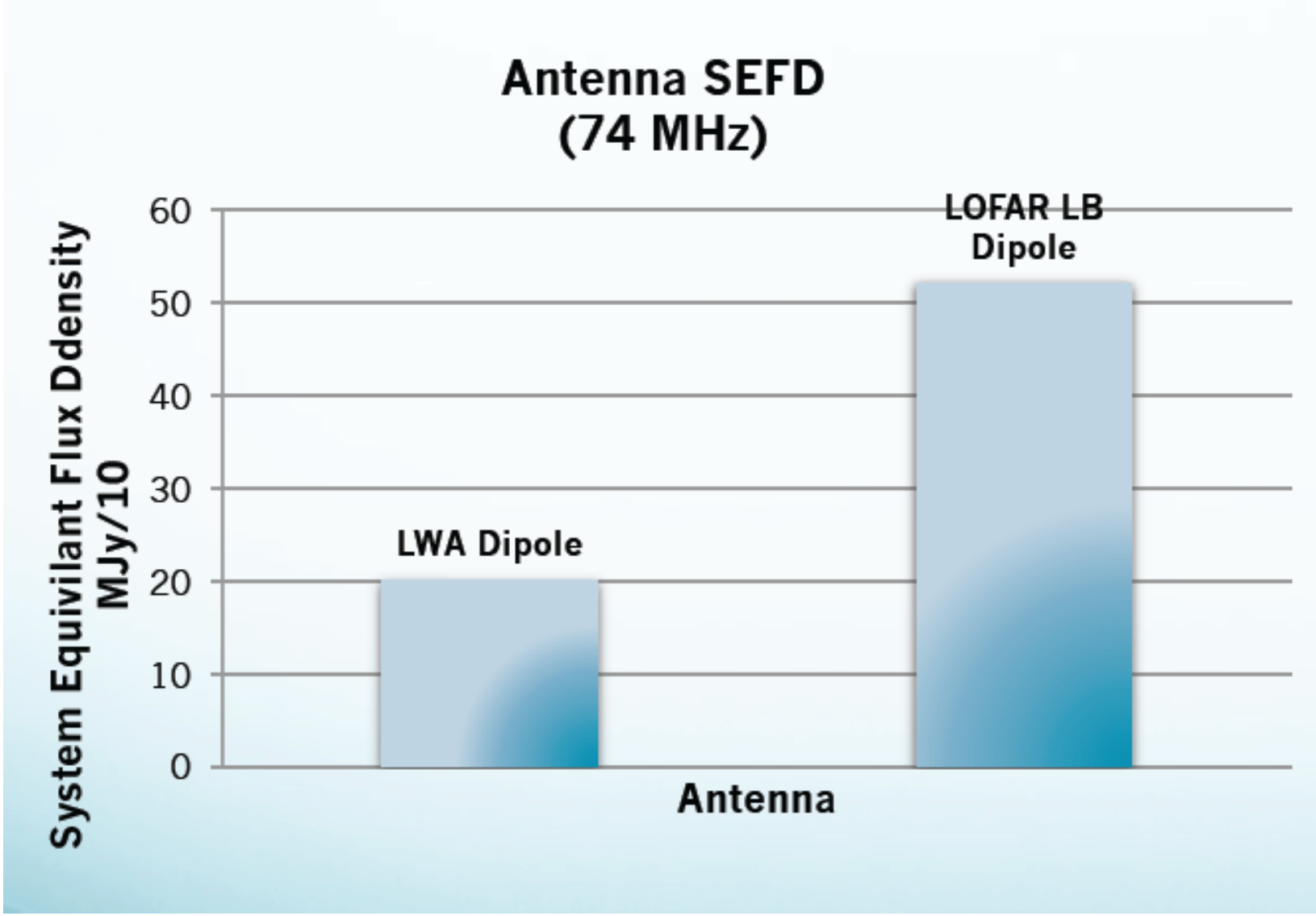
Sensitivities

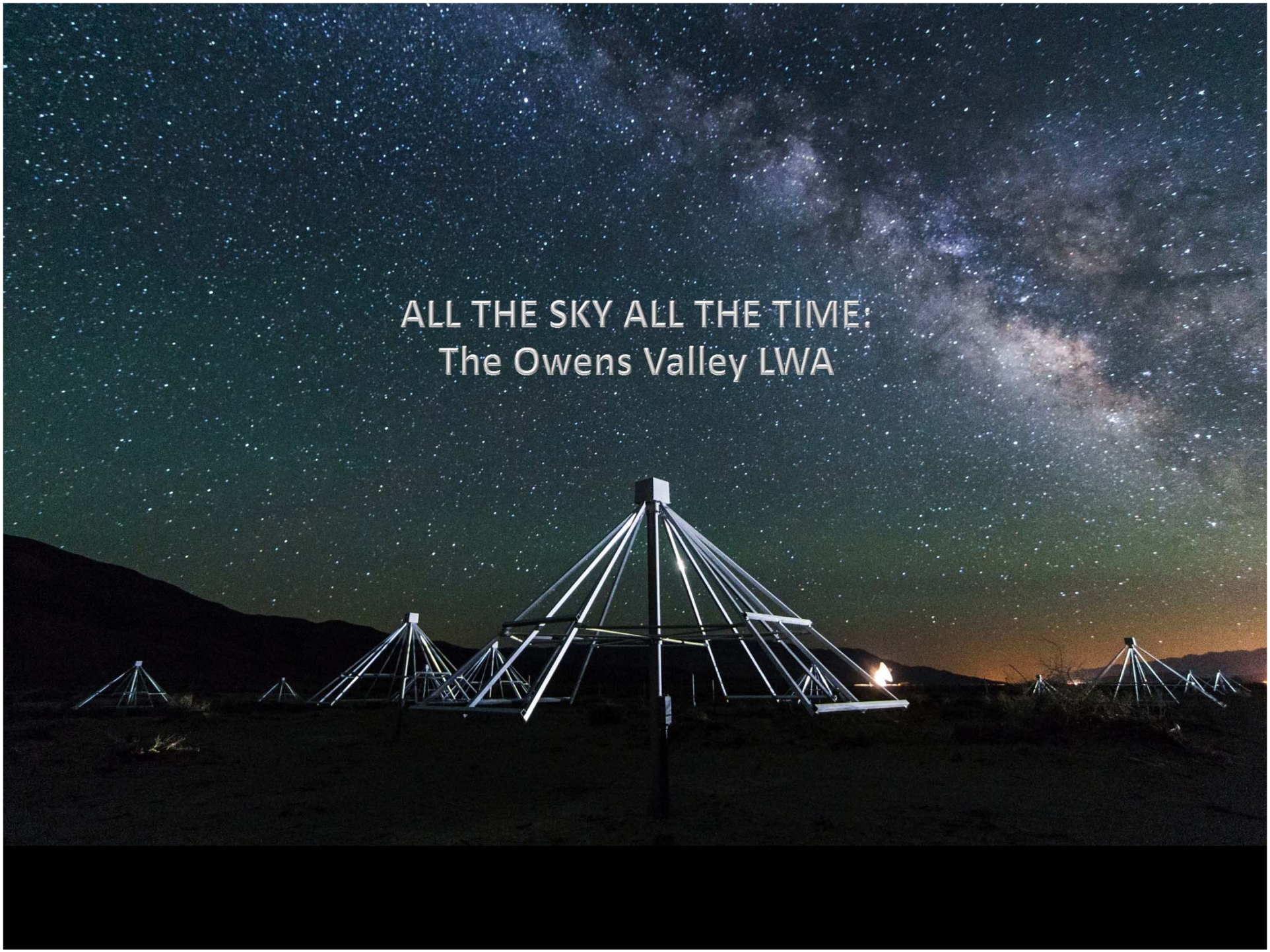
LOFAR Low Band

Freq. (MHz)	λ (m)	Sensitivity: Superterp (mJy)	NL Core (mJy)	Full NL (mJy)	Full EU (mJy)
15	20.0	...	...	...	...
30	10.0	36	9.0	5.7	3.8
45	6.67	29	7.4	4.7	3.1
60	5.00	25	6.2	3.9	2.6
75	4.00	44	10.8	6.8	4.5
120	2.50	1.5	0.38	0.30	0.20
150	2.00	1.3	0.31	0.24	0.16
180	1.67	1.5	0.38	0.30	0.20
200	1.50	(2.5)	(0.62)	(0.48)	(0.32)
210	1.43	(2.5)	(0.62)	(0.48)	(0.32)
240	1.25	(5.6)	(1.4)	(1.1)	(0.73)

Table 4: *LOFAR sensitivities. The different columns refer to the case of a 6-station Superterp, a 24-station core array, a 40-station Dutch array, and a 48-station full array.*

Sensitivities



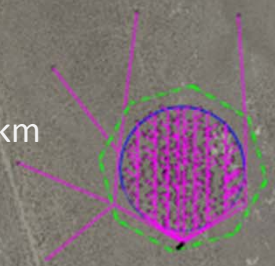

ALL THE SKY ALL THE TIME:
The Owens Valley LWA

Owens Valley Long Wavelength Array (LWA)

- 256 antennas in core array + 5 outliers

- 1000 m of fencing, 80,000m of cables

-Core aperture of 200m with outliers spaced at a distance of 250m from core center



- Future upgrade could include spiral arms out to 2km

-Baselines to improve resolution

- Operational from 28-88 MHz [2000 channels]

- Full cross correlation array (unlike sister array in New Mexico)

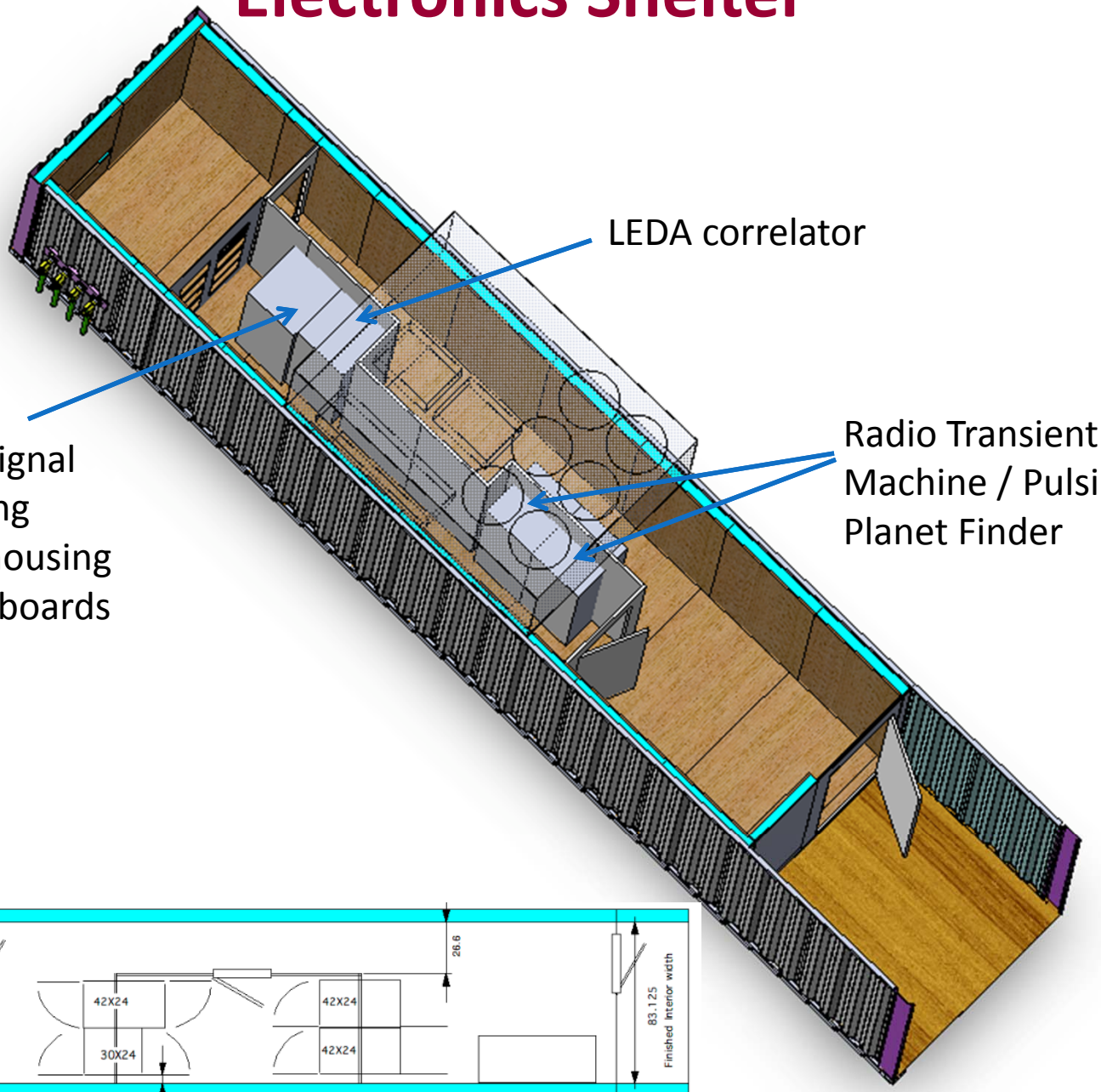
- Two powerful back-ends:

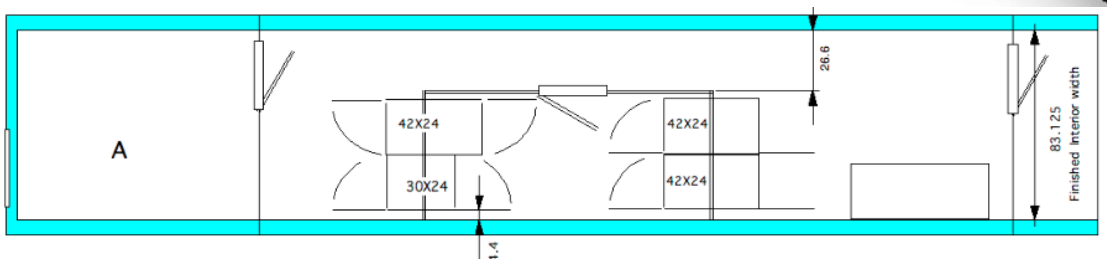
-***Cosmic Dawn:*** **Large Aperture to detect the Dark Ages (LEDA) [Harvard, Berkeley, UNM, VT] -** ***PI: Lincoln Greenhill***

-- ***Transient Science:*** **Real-time All-sky Transient Machine [Caltech & JPL] – focus on exoplanets -** ***PI: Gregg Hallinan***

Latest Status: Construction Completed

Electronics Shelter





Electronics Shelter

Connecting it all together…

Large Aperture Experiment to Detect the Dark Age (LEDA)

- PI: Lincoln Greehill, Harvard CFA
- Funded by NSF ($1.7 million)
- Uses Graphics Processing Units (GPUs) to achieve exceptionally high computing density and power efficiency
- Combines the signals from 256 antennas to image the entire visible sky instantaneously

All Sky Transient Monitor

160 CPU cores, 20 GPUs

1 TB of RAM

144 TB of high speed Lustre storage (up to 30 Gbps)

Data volume: 20 Gbps

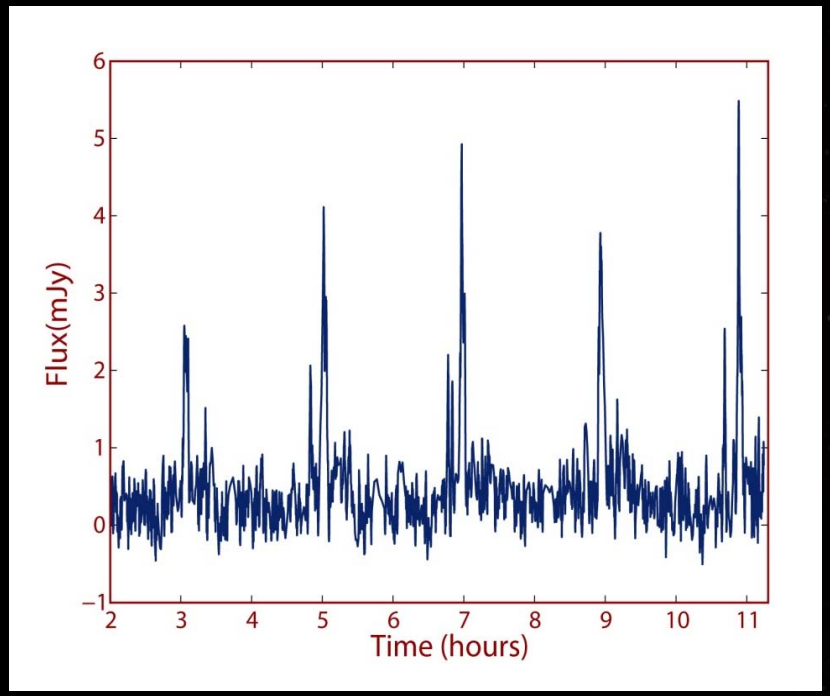
Data will be processed and archived in real time

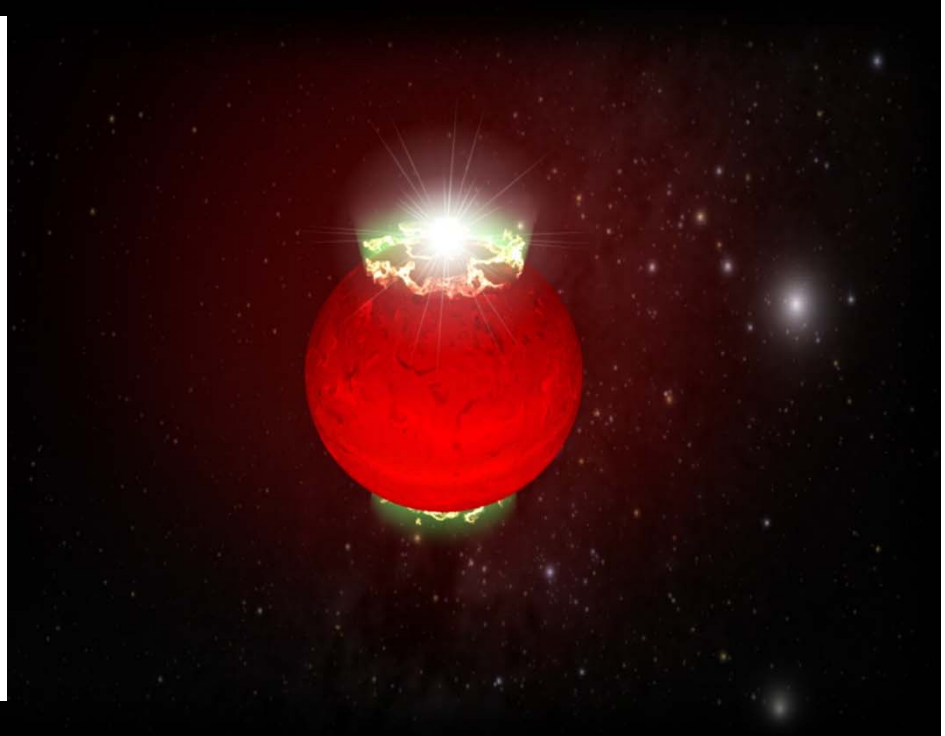
Can monitor the entire sky continuously to detect exoplaets

Square Kilometre Array

- 300,000 dipoles
- High gain antennas
- 400 μJy in 1 minute!

Brown Dwarfs can Pulse

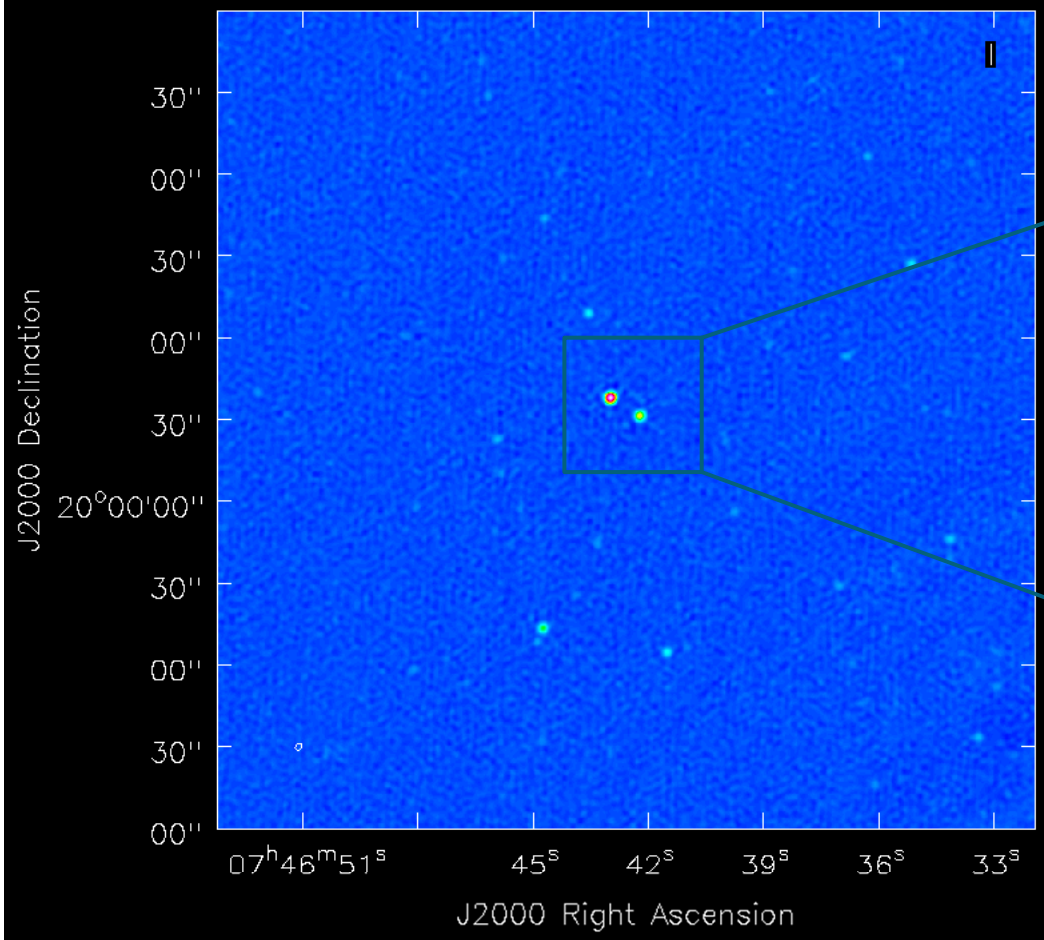


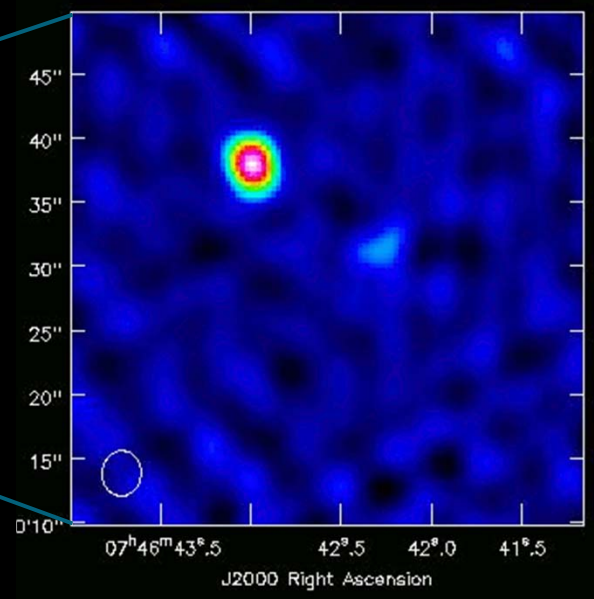


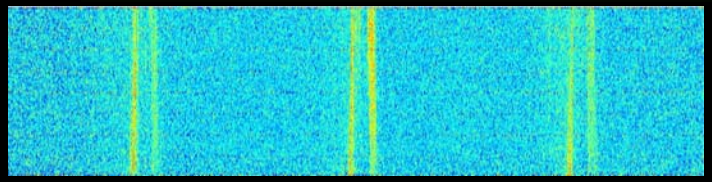
Brown dwarfs have been discovered to periodically pulse at GHz frequencies (Hallinan et al. 2007).

The radio emission is 100% circularly polarized with brightness temperature $> 10^{15}$ K

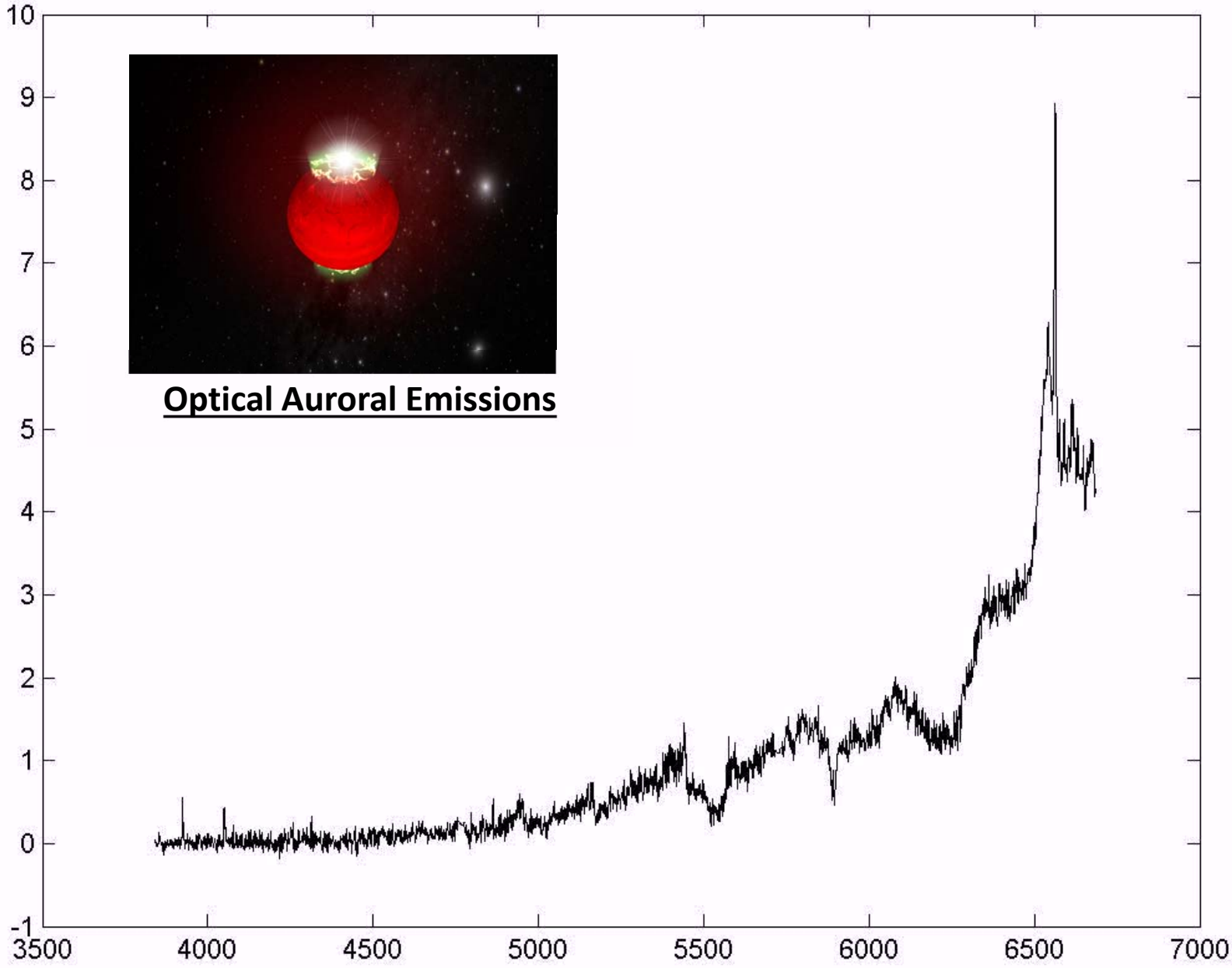
VLA: Brown Dwarfs





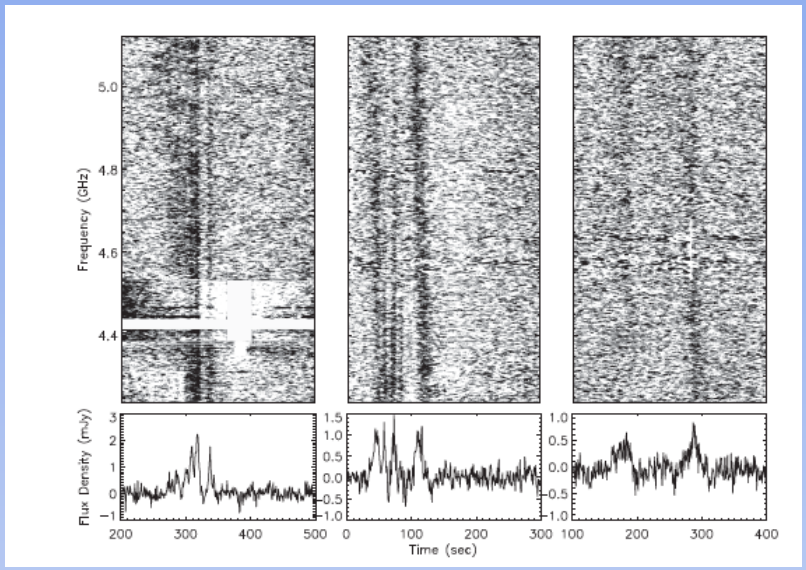


- **RMS noise ~1.6 μJy/beam**

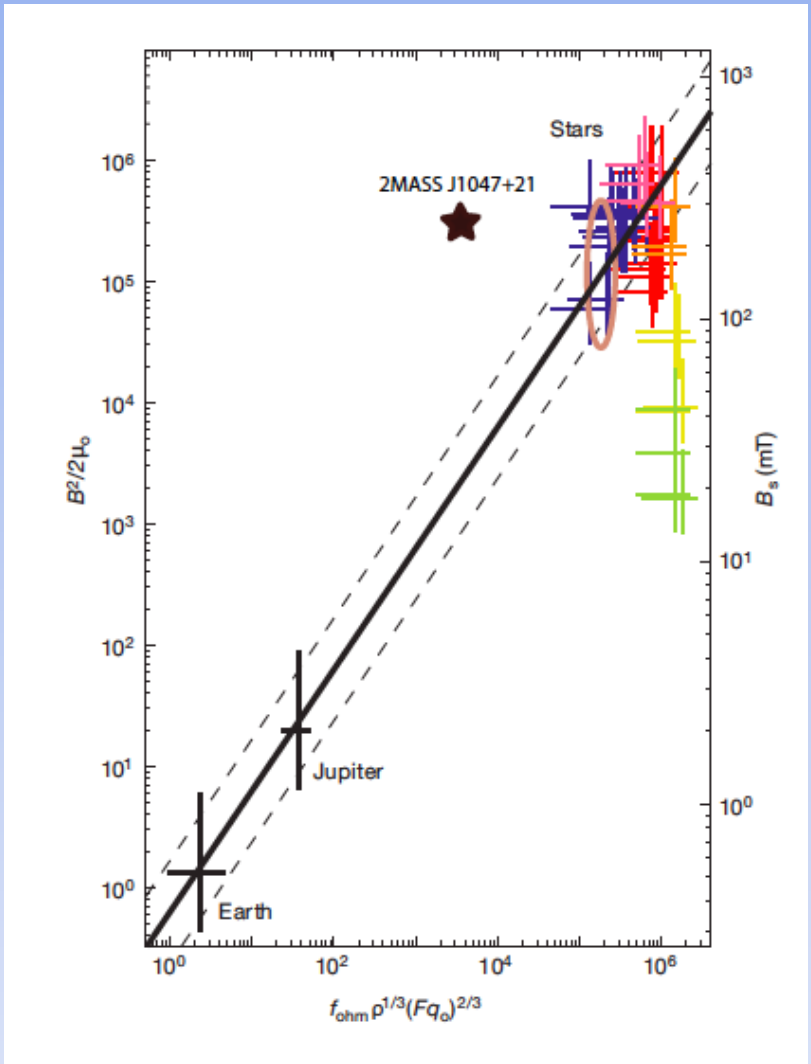

Optical Auroral Emissions
10
9
8
7
6
5
4
3
2
1
0
-1
3500
4000
4500
5000
5500
6000
6500
7000

The Radio Detection of a T6.5 Dwarf

Route & Wolszczan 2012



- Detected with Arecibo at 4.5 GHz
- Requires magnetic field strengths of 1.7 kG
- Christensen et al. 2009 propose a single dynamo model for rapidly rotating fully convective stars -> energy flux available for generating the magnetic field sets the field strength
- **Very challenging for current dynamo theories for fully convective objects**



Christensen et al. 2009, Nature, 457, 167