MODERN RADIO INTERFEROMETERS

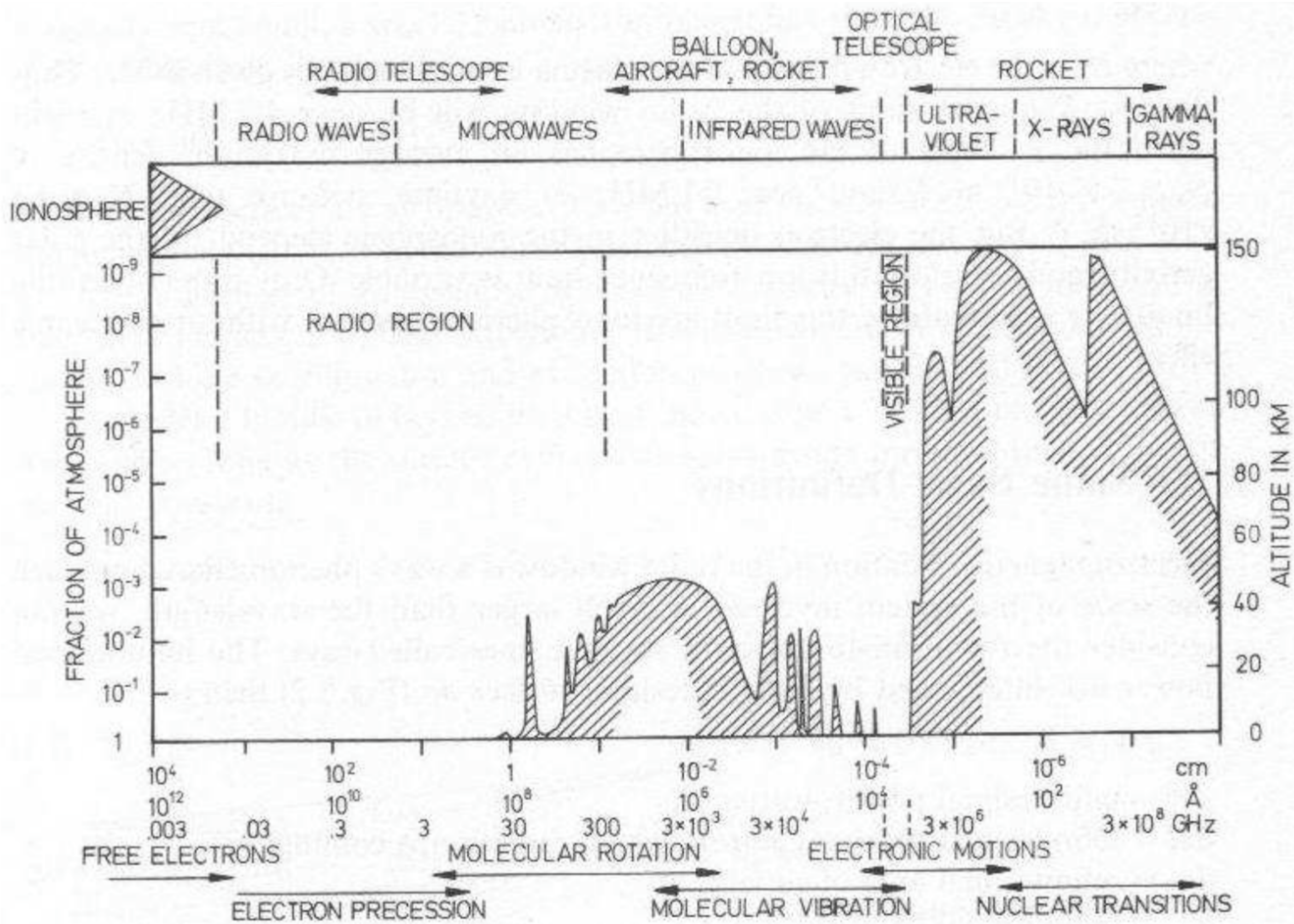
Adapted from ERIS2015 (Credit. J. McKean)

The Atacama Large Millimeter/Submillimeter Array (ALMA). Credit: ESO/C. Malin

Introduction

1. What is available?
2. What science can you do?
3. What does the future hold?

The Radio Sky



Rohlfs & Wilson, 2001

The Quest for the Perfect Interferometer

We pick an interferometer based upon:

i. Observing frequency

ii. Resolution
   - Defined as: $\theta_{\rm res}[\rm radians] \sim \dfrac{\lambda}{B}$

iii. Sensitivity
   - Sensitivity of (heterogeneous) array defined as:

$$S_{\rm rms} = \frac{1}{\eta_c} \frac{\rm SEFD}{\sqrt{n_{\rm pol} N(N-1) \Delta\nu \; t}}$$

where:

$$\mathrm{SEFD} = 2kT_{\rm sys}/A_{\rm eff}, \quad A_{\rm eff} = A \times \eta_{\rm ant}, \quad T_{\rm sys} \propto T_{\rm rec}$$

The Quest for the Perfect Interferometer

One interferometer cannot do all of this (despite SKA claims)!

For example:

- varying receiver technologies for different frequencies
- variable baseline lengths to achieve different resolutions
- sky coverage - one interferometer cannot see all the sky.

So what is available?

Receiver Technologies

Aperture Arrays


Credit: ASTRON

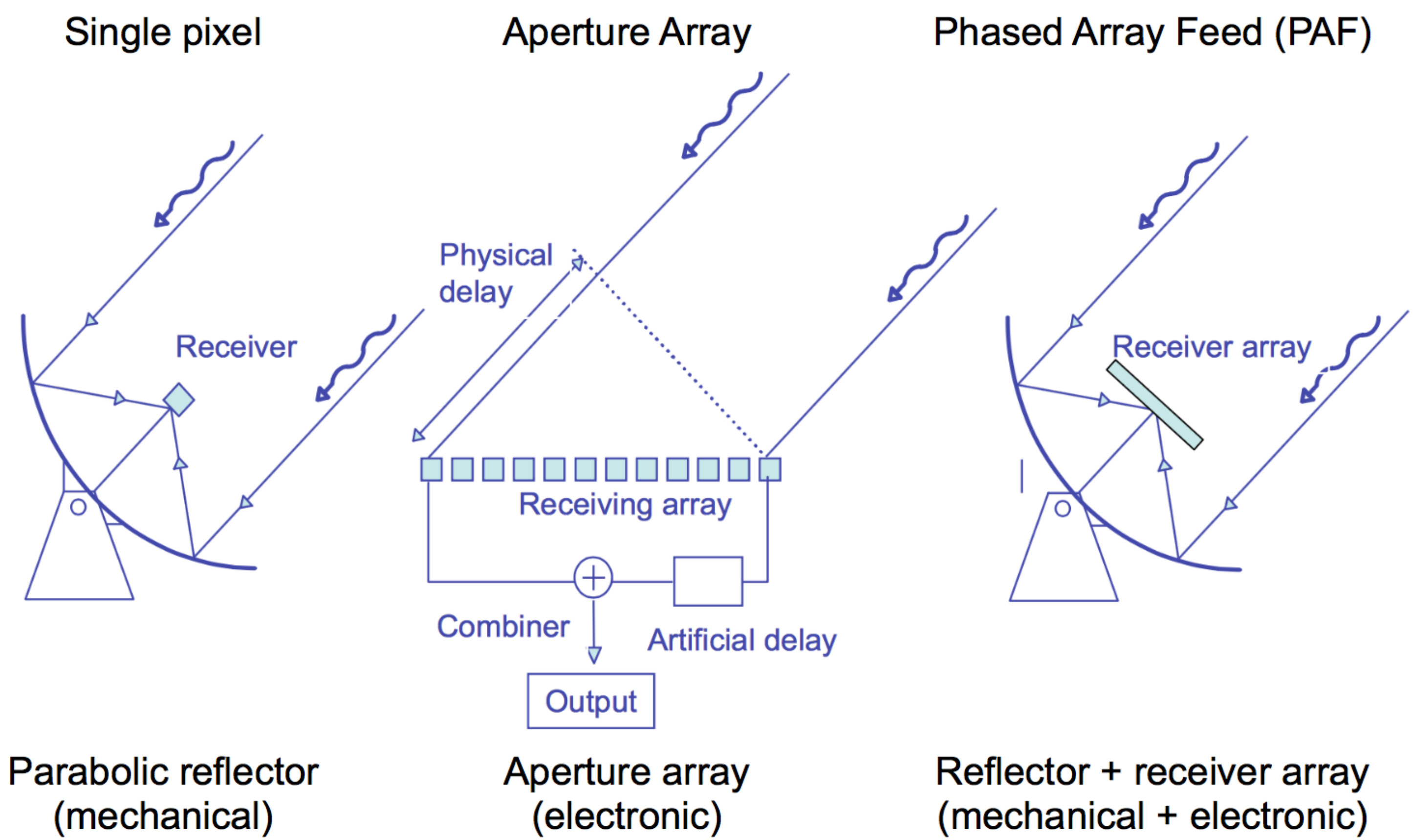
- Low cost
- Variable collecting area ($\sim\lambda^2/4\pi$)
- Large field of view
- Used at low frequencies
- Non-uniform directional response
- Beam poorly understood

Dishes


Credit: I. Morison

- High cost
- Fixed collecting area ($\sim A_{\text{geo}}$)
- Small field of view
- Used at high frequencies
- Uniform directional response
- Beam well understood

Receiver Technologies



The delay added will coherently add the different elements of an aperture array in one direction, and suppress emission from other directions

Low Frequency Arrays

Generally defined between 1000 MHz (loosely) and 10 MHz (due ionosphere), where free-electrons scatter low-frequency emission,

plasma frequency (5-10MHz)

$$\frac{\nu_p}{\mathrm{kHz}} = 8.97\sqrt{\frac{N_e}{\mathrm{cm}^{-3}}}$$

electron density (0.25-$1\times10^6\ \mathrm{cm}^{-3}$)

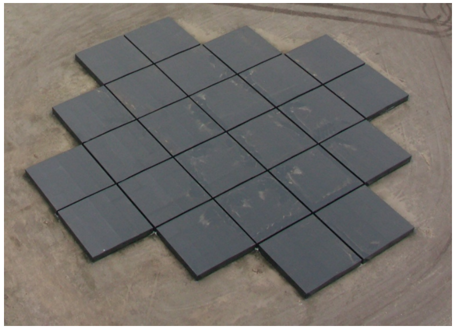
Challenges:

1. Wide fields-of-view (~degrees) and highly variable ionosphere.
   A. Observe during best conditions.
   B. Advanced calibration techniques (see Calibration lectures)

2. Radio frequency interference.
   A. Radio quiet locations.
   B. Advanced RFI mitigation techniques.
   C. Excellent frequency and time resolution.

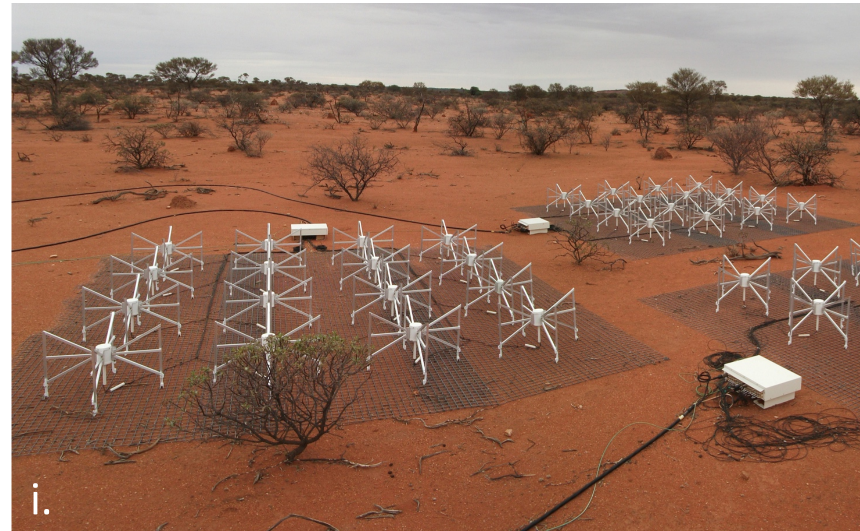
The **LO**w **F**requency **AR**ray: LOFAR

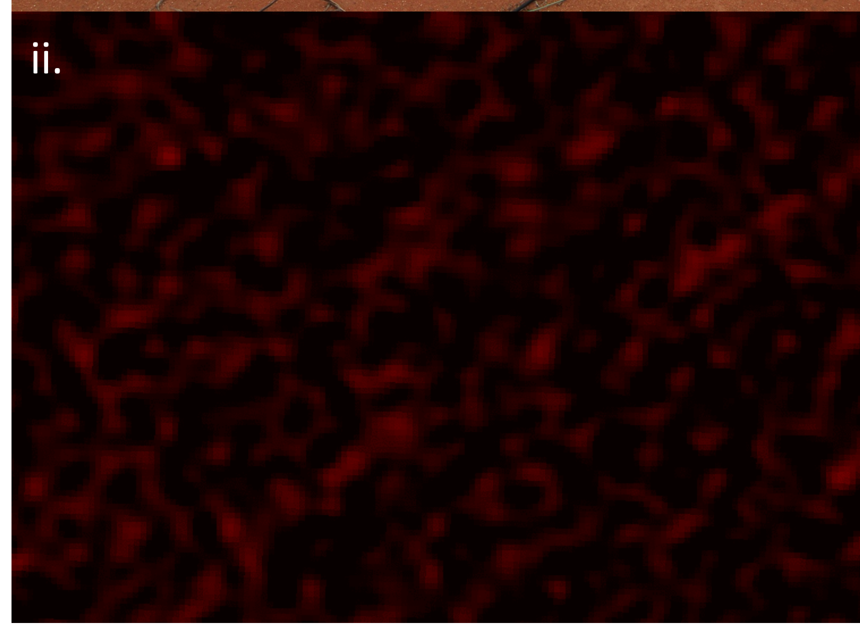
- International LOFAR Telescope being built by a consortium of institutes in the Netherlands, Germany, UK, France, Sweden and Poland.
- Low Band Antenna (LBA; 10--90 MHz) - simple dipoles.
- High Band Antenna (110-180 MHz, 210-240 MHz) - tiled array.
- 78 MHz bandwidth.
- 48 stations throughout Europe (~50 m to 1500 km baselines), resolution ~few degrees to sub-arcsec.



The Murchison Wide-field Array: MWA

- Low frequency pathfinder based in Australia (quiet-site).
- 80--300 MHz frequency coverage, with 31 MHz instantaneous bandwidth.
- 8000 dipoles, put into 4 x 4 dipole tiles, giving 512 tiles.
- Max baseline 1.5 km, with 3 km outriggers.
- Wide field-of-view (15-45 degrees)
- Resolution of 2.5 to 8.5 arcmin

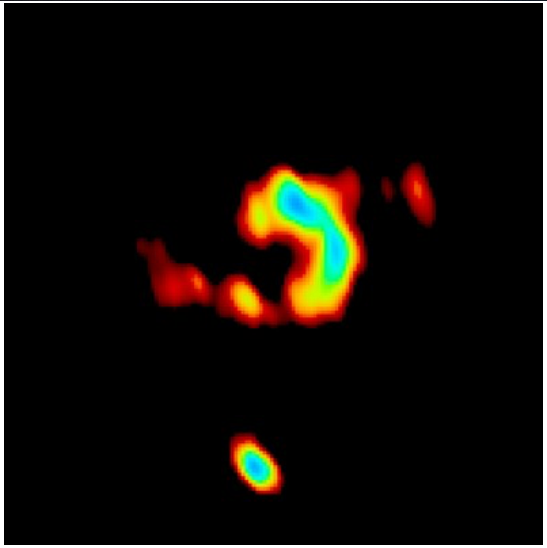




i. Photography by Paul Bourke and Jonathan Knispel. Supported by WASP (UWA), iVEC, ICRAR, and CSIRO.
ii. Credit: N. Seymour, N. Hurley-Walker (ICRAR/Curtin), B. McKinley (Melbourne) and the MWA team.

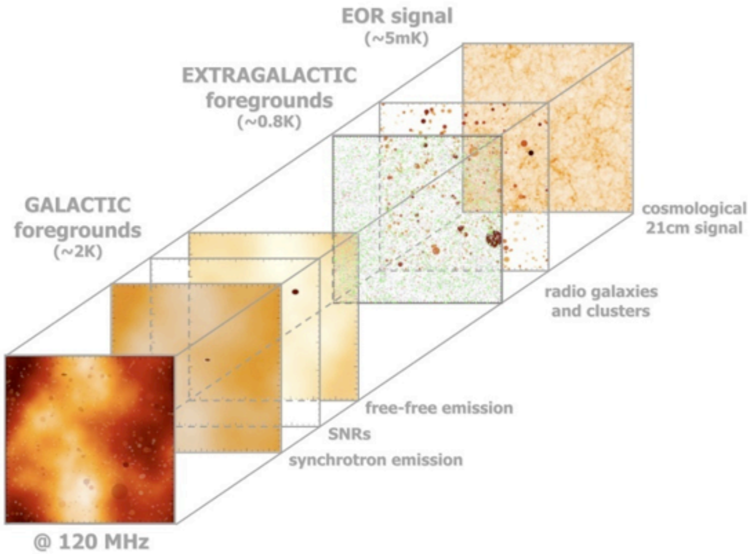
Giant Metrewave Radio Telescope: GMRT

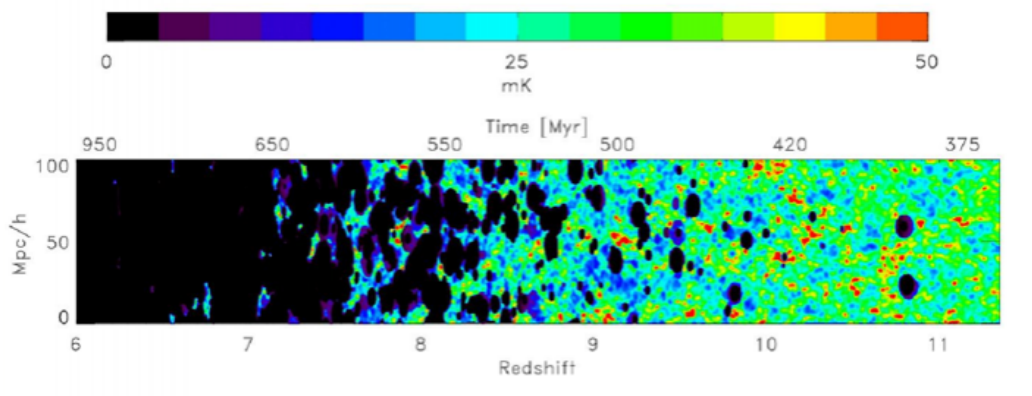
- 30 fully steerable 45m parabolic dishes of 45m diameter located in Pune, India
- Maximum baseline of 25 km gives 2-60 arcsec resolution.
- Five frequency bands at 50, 153, 233, 325, 610 and 1420 MHz
- New calibration pipeline SPAM (Intema et al. 2014) applies DD calibration - vastly improved performance!
- 1:1 subscription and just upgraded!



Roy et al. (2013)

Low Frequency Science: Epoch of Re-ionisation





- Universe was re-ionised around redshift 6 to 15 (from quasar spectra and CMB), by the first objects (stars, mini-black-holes).

- Can detect the signal of the EoR from observations of redshifted HI (21 cm) in the 100-180 MHz band of LOFAR, MWA, PAPER.

Low Frequency Science: Wide Area Surveys

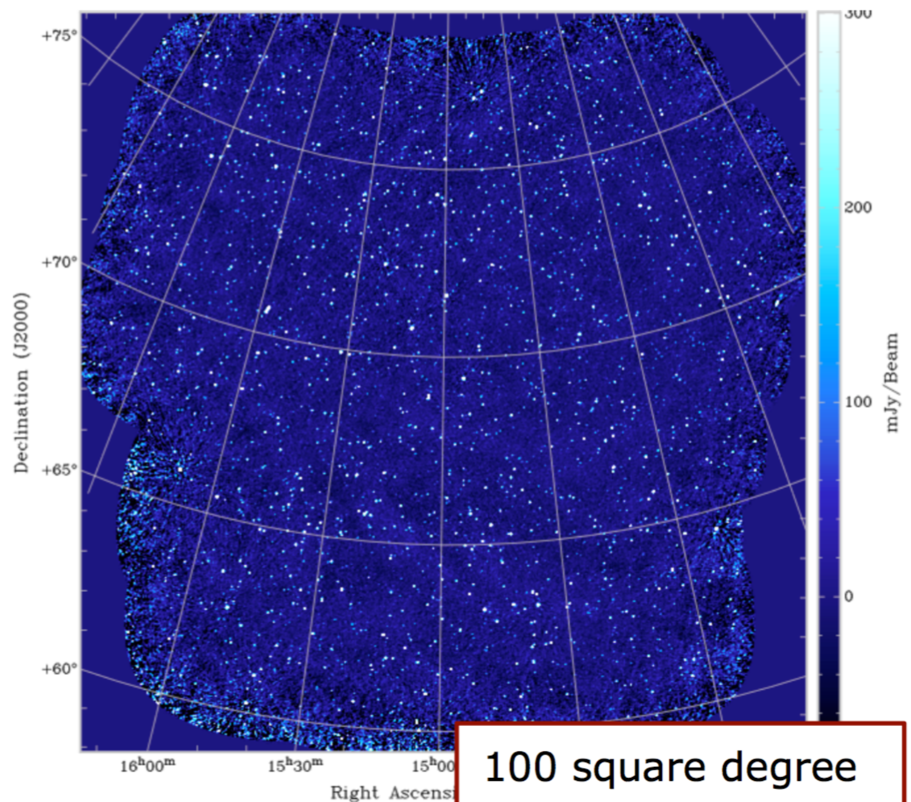
Imaging wide-fields is useful for,

1. An efficient all-sky survey.
2. Looking for rare objects.

Primary science goals:

i. Relic/halo emission from galaxy
ii. Clusters
iii. Census of AGN and star-formation
iv. over cosmic time.
v. Cosmic magnetism.
vi. Highest redshift radio sources
vii. Gravitational lenses
viii. Detailed studies of nearby AGN

LOFAR MSSS SVF; *George Heald*



100 square degree

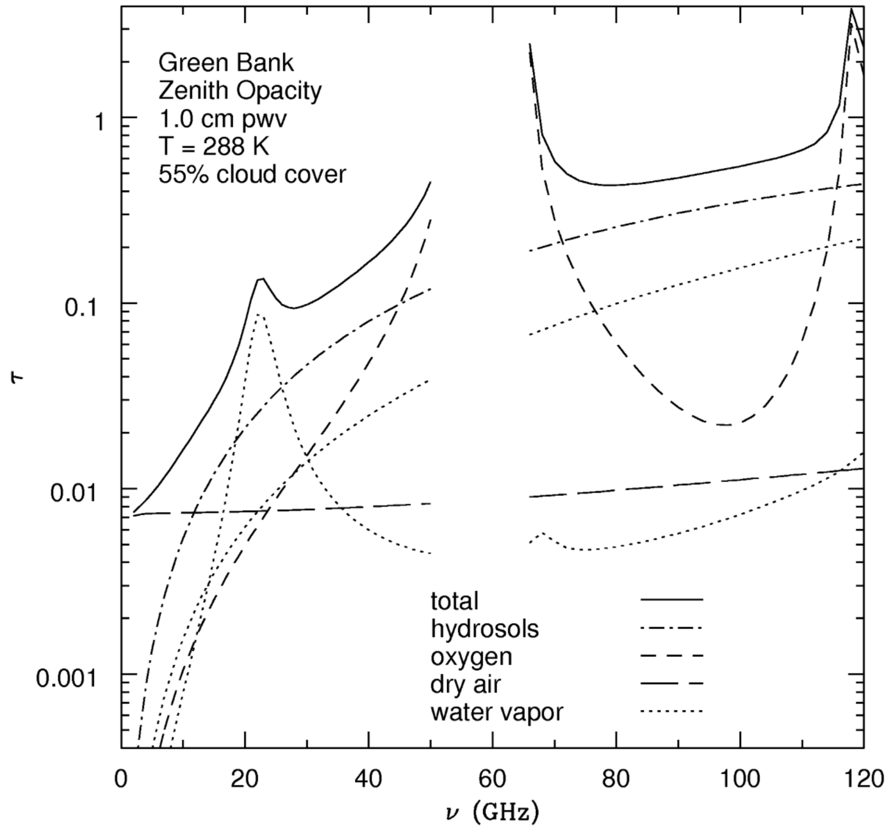
~10 mJy /beam [2 arcmin resolution]

The Centimetre Wavelength Sky

Generally defined between 1 GHz (loosely) and 50 MHz (due to atmospheric cut-off by 0_2), calibration limited by the ionosphere at low-freq and the troposphere at high freq.

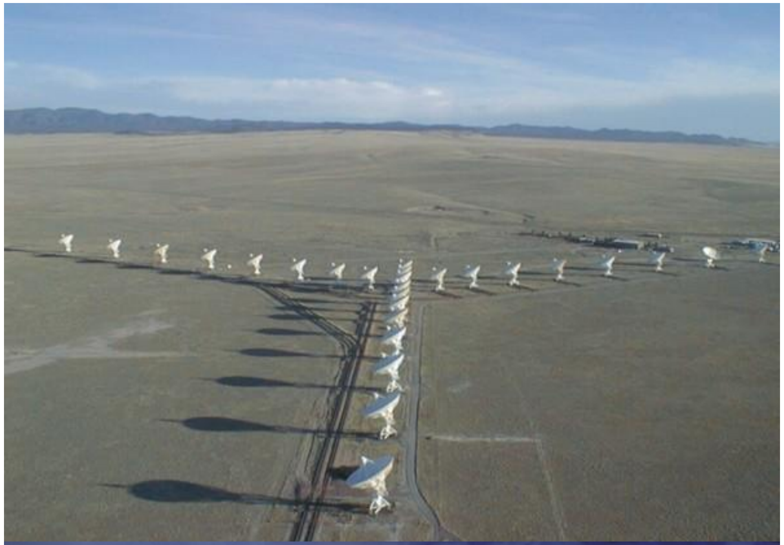
$$I_{\rm obs} = I_0 + I_{\rm atm}(1 - e^{-\tau})$$

- Atmosphere attenuates signal and also adds noise for high opacity.
- Calibration and systematics are well-understood.
- Science drivers:
  1. Synchrotron continuum
  2. Free-free continuum
  3. Spectral line (HI, OH, CH_3OH, H_2O, CO high-z).



Karl G. Jansky Very Large Array: JVLA

- Built in the 1960s (New Mexico, USA).
- 27x25m antennas (1 to 50 GHz).
- Four configurations (max. baselines: 1 to 36 km; resolution: 2 to 69 arcsec/ν[GHz]).
- Small field of view (45 arcmin /ν[GHz]).
- Heavily over-subscribed.
- Newly upgraded!

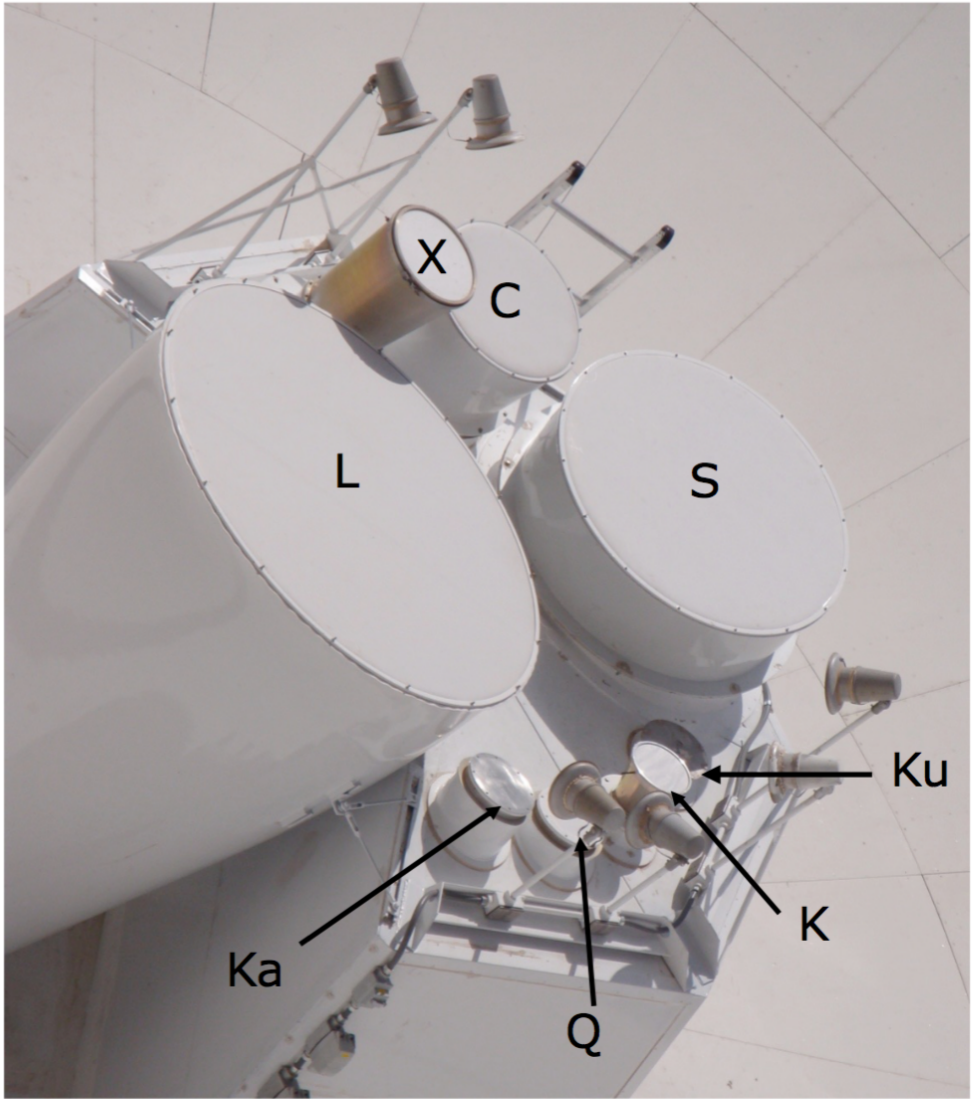


Images courtesy of NRAO/AUI

Karl G. Jansky Very Large Array: JVLA

Complete frequency coverage from 1 - 50 GHz!

Band (GHz)		T_{sys} / η_{ant} (best weather)
1-2	L	60 -- 80
2-4	S	55 -- 70
4-8	C	45 -- 60
8-12	X	45
12-18	Ku	50
18-26.5	K	70 -- 80
26.5-40	Ka	90 -- 130
40-50	Q	160 - 360



Karl G. Jansky Very Large Array: JVLA

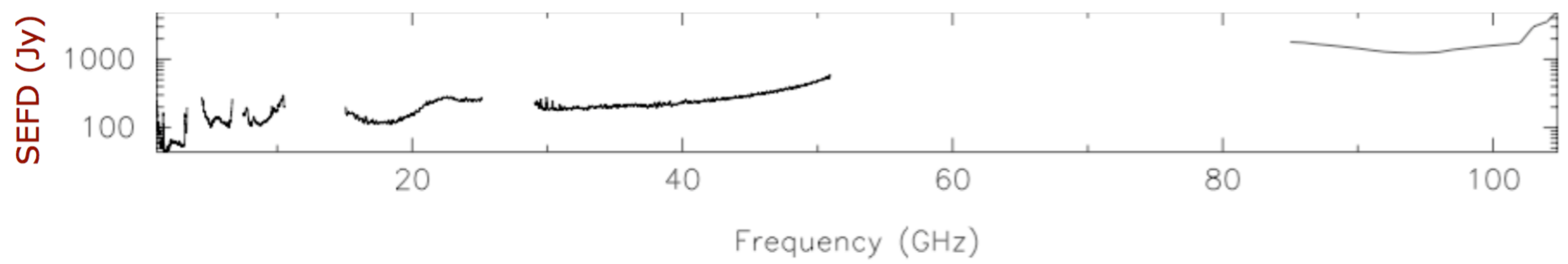
Bandwidth: Increase from 50 MHz to 1-8 GHz per spw.

1 sigma point-source sensitivity for 1 hour on-source (line: 1 kms^{-1}):

Band	Code	Effective BW	SEFD	σ(cont)	σ(line)
GHz		GHz	Jy	μJy	mJy
1 – 2	L	0.75	400	5.5	2.2
2 – 4	S	1.75	350	3.9	1.7
4 – 8	C	3.5	300	2.4	1.0
8 – 12	X	4	250	1.8	0.65
12 – 18	Ku	6	280	1.7	0.61
18 – 27	K	8	450	2.3	0.77
27 – 40	Ka	8	620	3.2	0.90
40 -- 50	Q	8	1100	5.6	1.4

The Australia Compact Telescope Array: ATCA

- 6 x 25 m telescopes (15 baselines).
- 4 movable configurations.
- Operates between 1--100 GHz
- Good overlap with ALMA.
- New broadband receivers installed (2 x 2 GHz bandwidth)

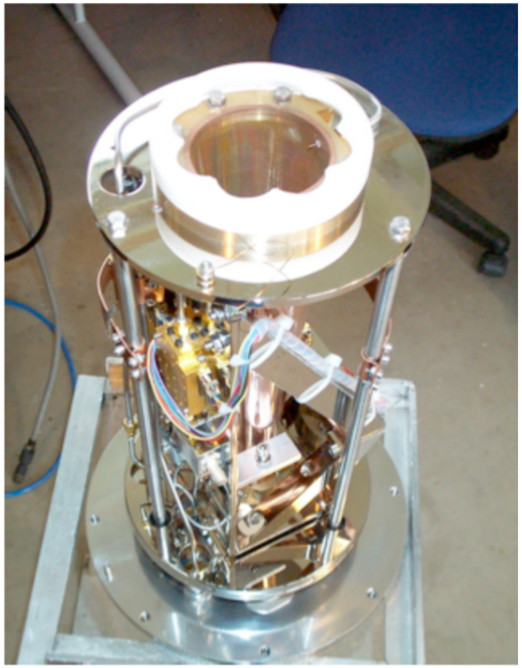


e-MERLIN

- (**e**nhanced) **M**ulti-**E**lement **R**adio **L**inked **I**nterferometer **N**etwork (e-MERLIN).
- Up to seven telescopes (~25 to 76 m) can be used
- New outrigger stations in UK, Sweden and Netherlands being considered.
- Max. baseline is 217 km.
- Excellent resolution (230 mas $/\nu$[GHz]).
- Link between VLA/ATCA and VLBI.

e-MERLIN

- New wide-band receivers (sensitivity, spectral line capability)
- Reaching the theoretical limit for receiver technologies Feeds, Low noise amplifiers, etc.
- Sampling and digital signal processing at 4 Gbits / s.



- L-band: 1.3---1.8 GHz
- C-band: 4.0--8.0 GHz
- (K-band: 22--24 GHz)

e-MERLIN

Technical Capabilities - FINAL ARRAY

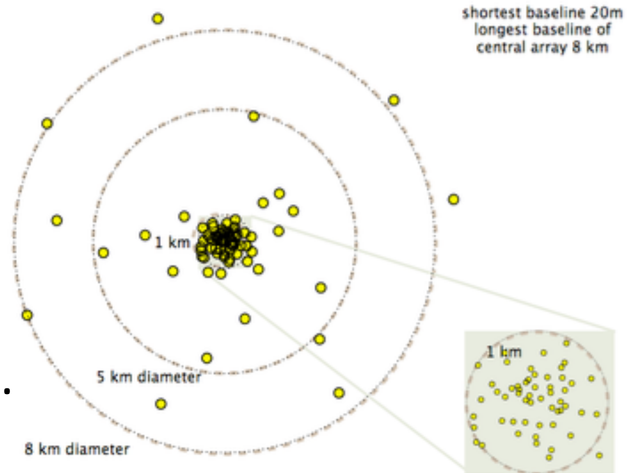
Table 1: Basic observing capabilities of e-MERLIN

	1.5GHz (L-band)	5 GHz (C-band)	22 GHz (K-band)	Comments
Resolution (mas)	150	40	12	Uniform weighting at central frequency
Field of View (arcmin)	30	7	2.0	FWHM of 25-m dishes; reduced when Lovell Telescope included at 1.5 or 5 GHz (1)
Freq. Range (GHz)	1.3-1.7	4-8	22-24	
Bandwidth (GHz)	0.4	2	2	Max. Bandwidth per polarization. Can use 4-GHz, single polzn, at 5 or 22GHz
Sensitivity (μJy/bm) in full imaging run	5-6	1.8-2.3	~15	Final performance will depend on useable bandwidth, final reciever optimization, Lovell Telescope performance. These figures are for e-MERLIN with the Lovell Telescope(1).
Surface brightness sensitivity (K)	~190	~70	~530	As above
Astrometric performace (mas)	~2	~1	~2	WRT the ICRF (typical 3-deg target-calibrator separation using VLBA Calibrator Survey)
	~0.5	~0.2	~1	Day-to-day repeatability using surveyed or in-beam sources, and assuming full imaging run.
Amplitude calibration	2%	1%	10%	Targets for day-to-day repeatability

Notes: (1) The Lovell telescope may be included in e-MERLIN at 1.5 and 5 GHz (L, C). Its inclusion increases the sensitivity by a factor of between 2 and 3 and reduces the field of view to approximately 20/(freq/1.4GHz) arcmin, depending on the data-weighting scheme adopted.

MeerKAT - South African SKA Pathfinder

- 64 x 13.6 m telescopes, concentrated in 1 km core, but extend to 8 km.
- Single pixel receivers operating at 0.6-1.8 GHz and 8-14 GHz (maybe) Up to 4 GHz bandwidth per polarization. Tsys ~ 30 K.
- Located in the Karoo desert of northern South Africa.
- Observations start (full array) by 2017/20 - test site is operational (KAT7)



Single Pixel Array Science

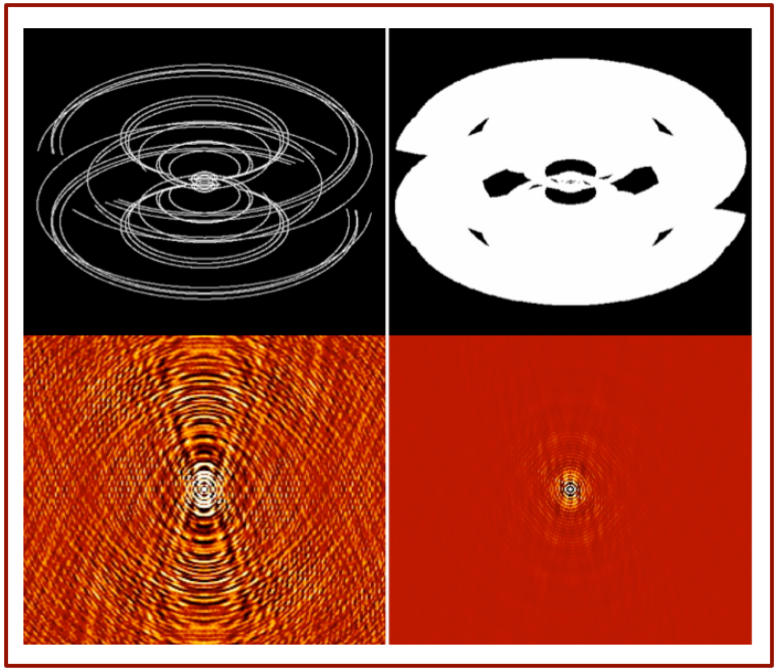
- **New science:** The JVLA, ATCA and e-MERLIN are accepting proposals - commissioning still allows cutting edge science - **Be inspired to do something spectacular**!

- Increasing the bandwidth -> increase the image sensitivity by √Δv.

- Also improves the uv-coverage.

- Better dynamic range, lower de-convolution errors.

- Better sensitivity to sources over different angular scales (need to know the spectral index...)



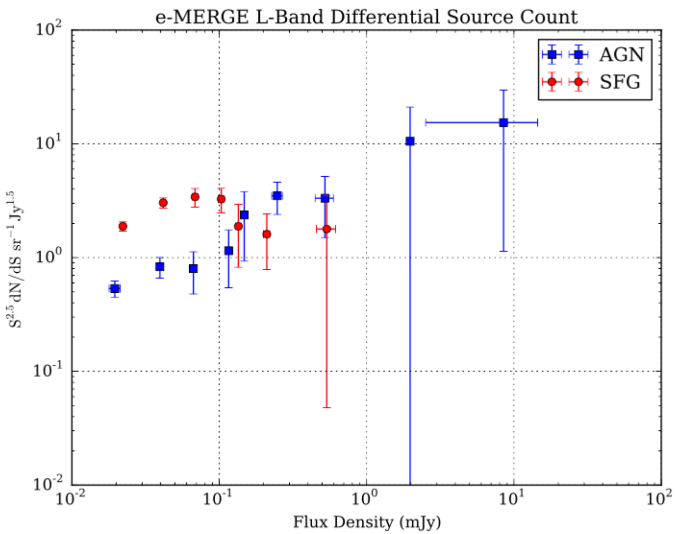
Single Pixel Array Science

μJy level sensitivities allow investigations of,

i. The star-forming population (radio-FIR correlation).

ii. Radio quiet-AGN

iii. AGN-starburst feedback



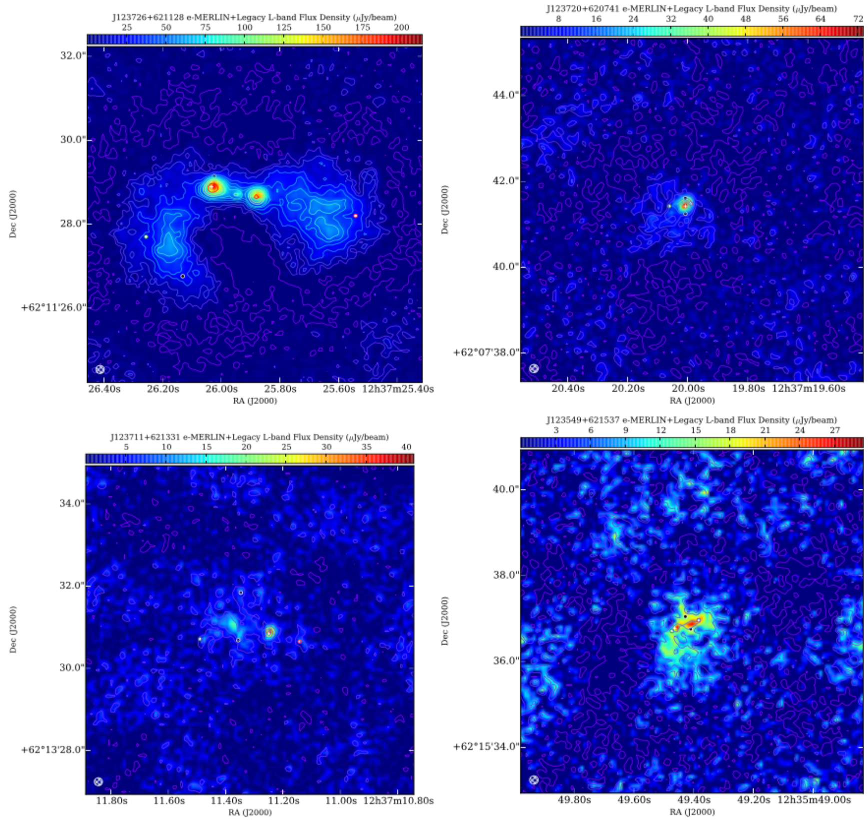
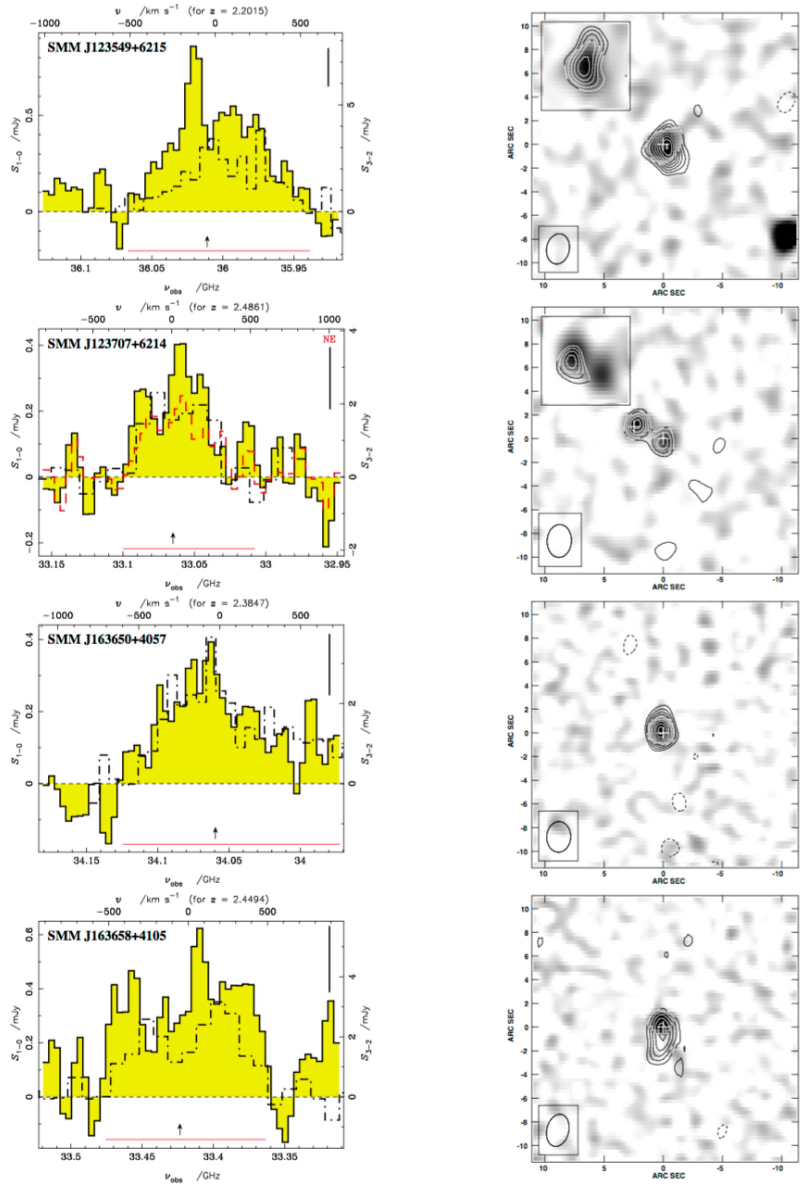


Figure 5.16: A selection of *e*-MERGE sources derived from *e*-MERLIN & Legacy Data. Top left: Wide Angled Tail exhibiting excellent image fidelity. Top right: An AGN embedded within a spatially extended region. Bottom left: A source with two components. Bottom right: A source at the edge of the field exhibiting extended spatial features.

Single Pixel Array Science

- Large bandwidths and flexible correlators will allow new spectral line studies to be carried out.
- In the 1-50 GHz band (OH, CH_3OH, H_2O) multiple line transitions can be detected allowing measurement of the temperature and density of the ISM.
- For higher redshift objects HI and CO will be detected and *imaged*.
- e.g., Ivison et al. (2010) find the CO molecular gas of star-forming galaxies is extended by ~16 kpc using the EVLA.
- **Just the beginning!**

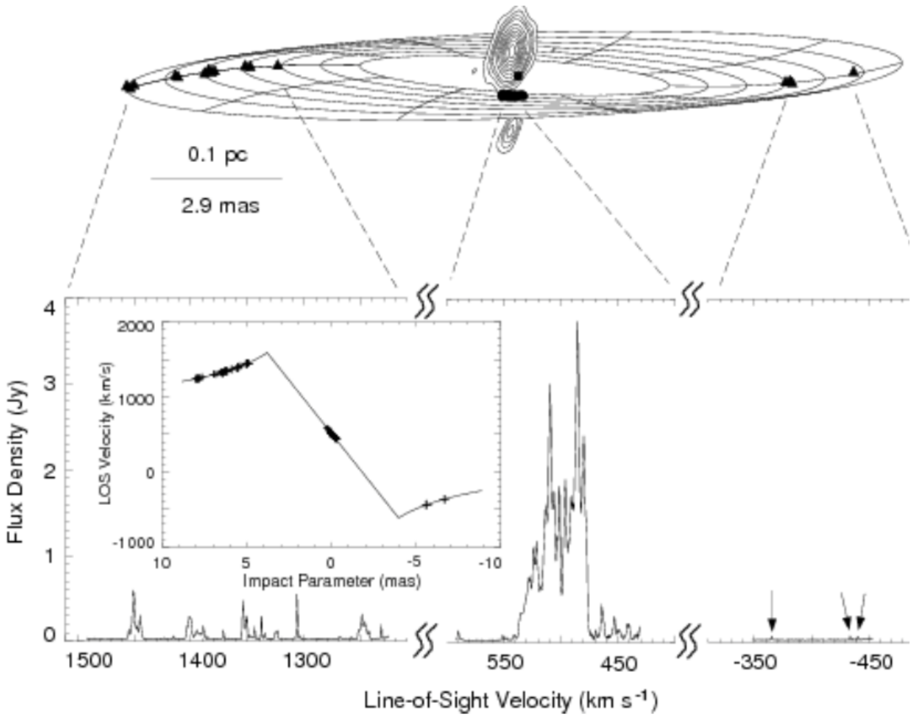


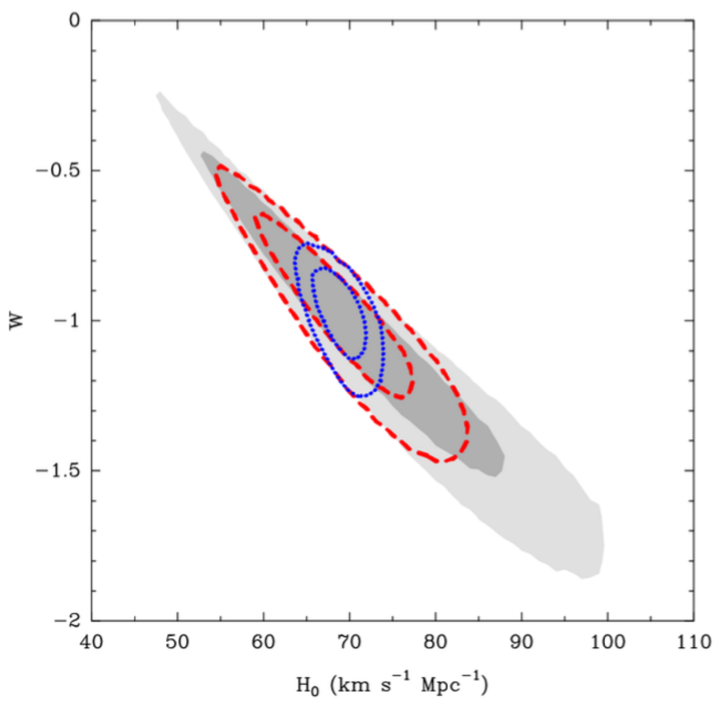
Very Long Baseline Interferometry

VLBI Science - Masers

22.245 GHz water masers can be used to probe the nuclear accretion disks of active galaxies.

1. Measure the rotations to determine the black hole mass (~within 10 percent).
2. Determine the geometric distance to test models for dark energy

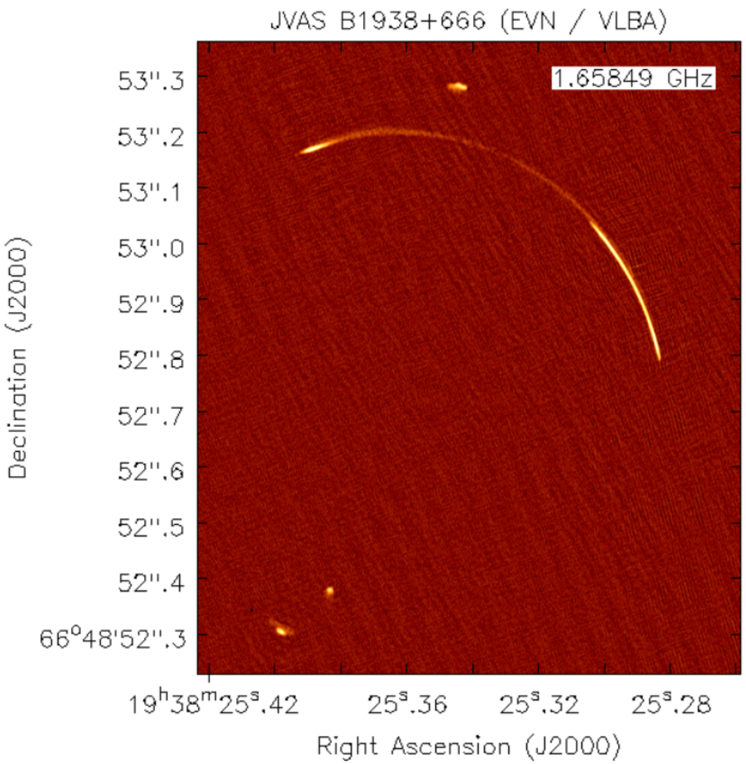


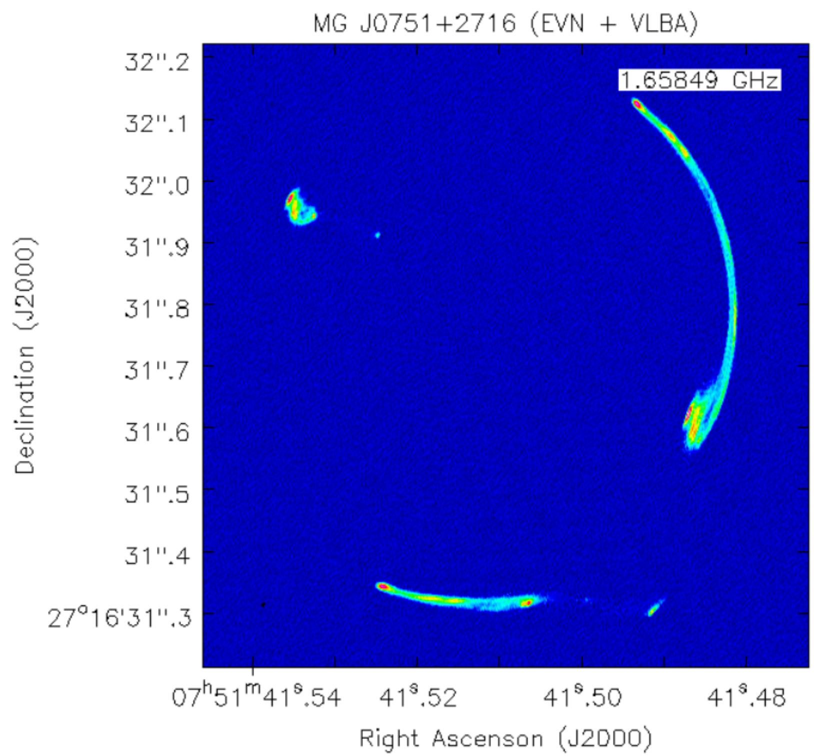


VLBI Science - Gravitational Lensing

Gravitational lenses can be used to study the structure of dark matter haloes.

1. Determine mass profiles and level of low mass substructure in haloes to test models for dark matter
2. Investigate the structure of high redshift active galaxies on parsec-scales





Cristiana Spingola

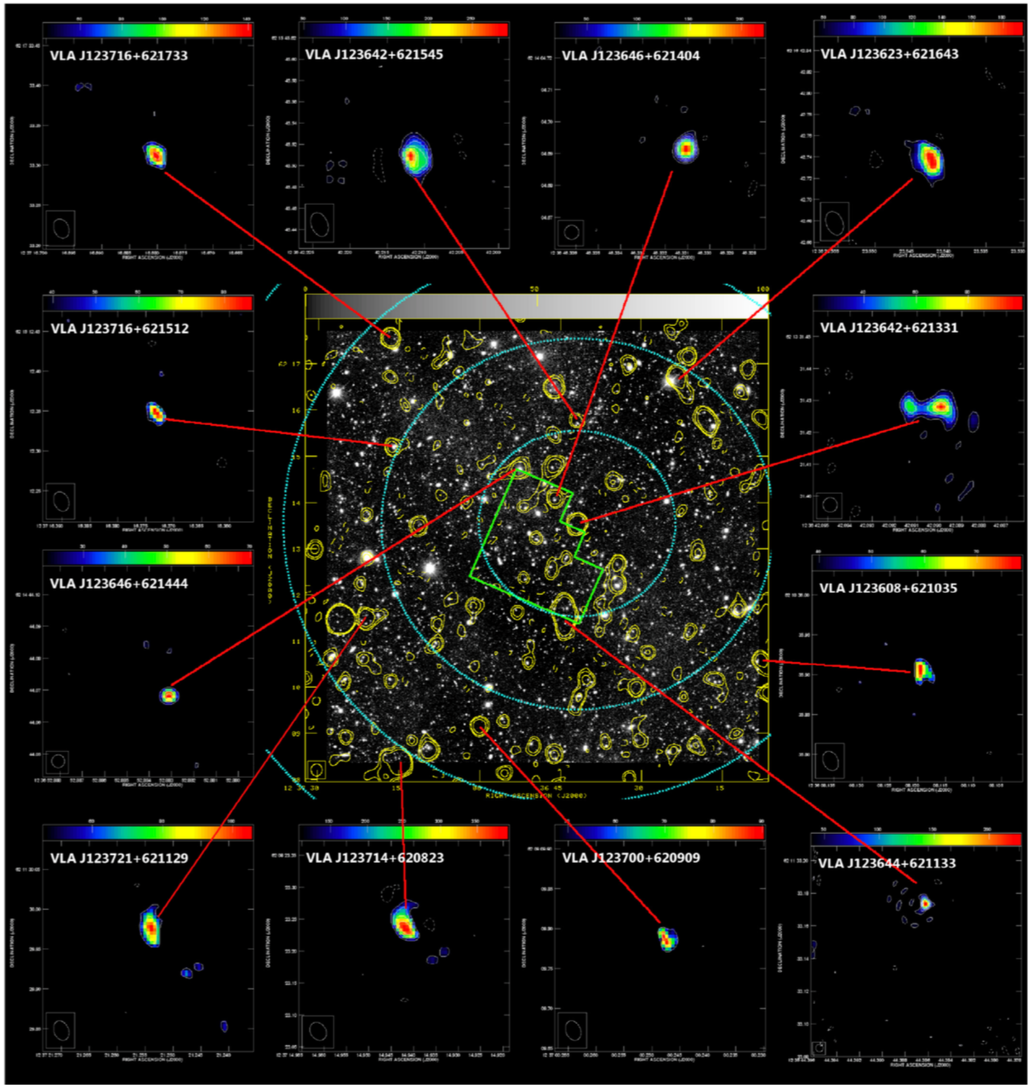
VLBI Science - High-z AGN/Starburst Connection

Wide-field VLBI can be used to observe multiple sources at once

Impact is huge,

- Detect radio quiet embedded AGN in starforming galaxies - symbiosis?
- Accurate AGN population densities - radio (GHz) is extinction free
- Clearer insight on the properties of AGN host galaxies at high-z

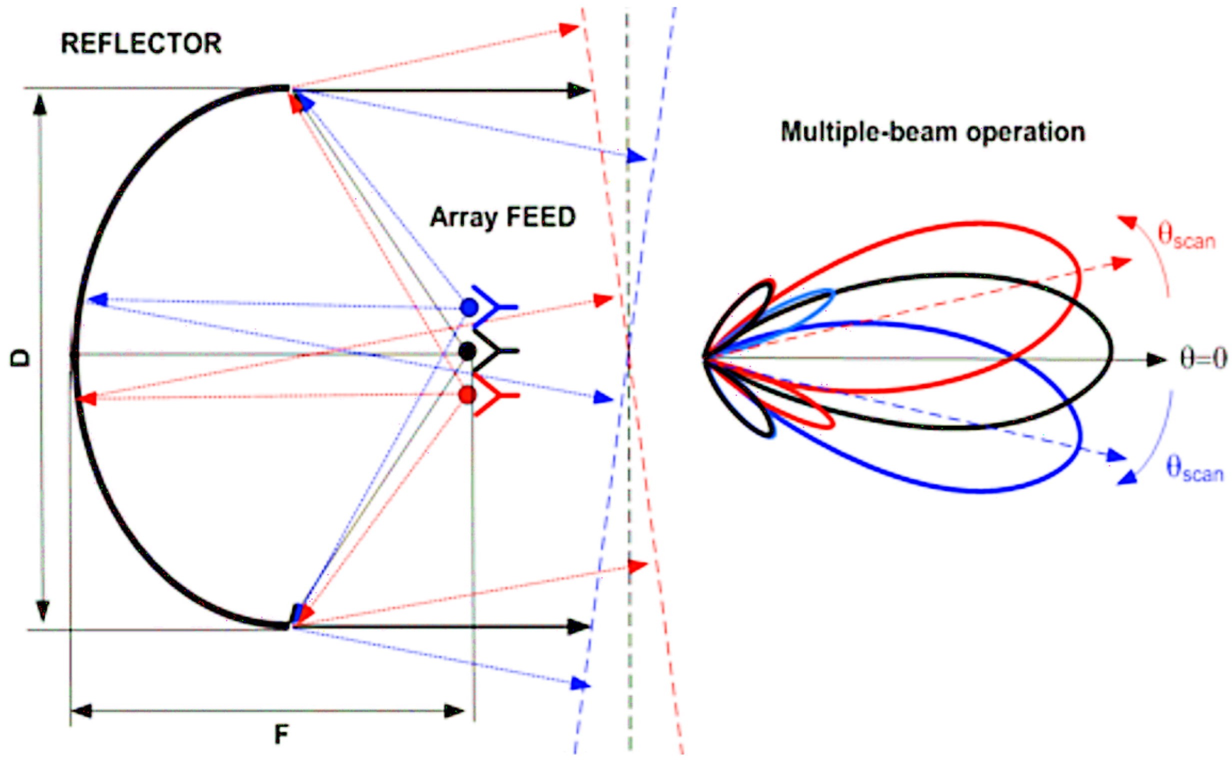
More on this in Jack's talk.



Phased Array Feeds

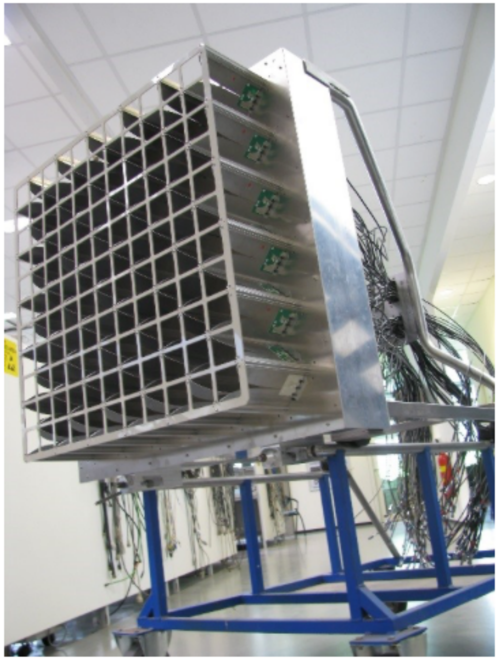
Large Focal plane array (Phased array feeds): Receivers off-set in the focal plane of the telescope see a slightly different part of the sky.

1. Can provide a much larger field-of-view.
2. Still limited by the mechanics of the telescope.
3. Combining different beams results in a uniform response to the sky.

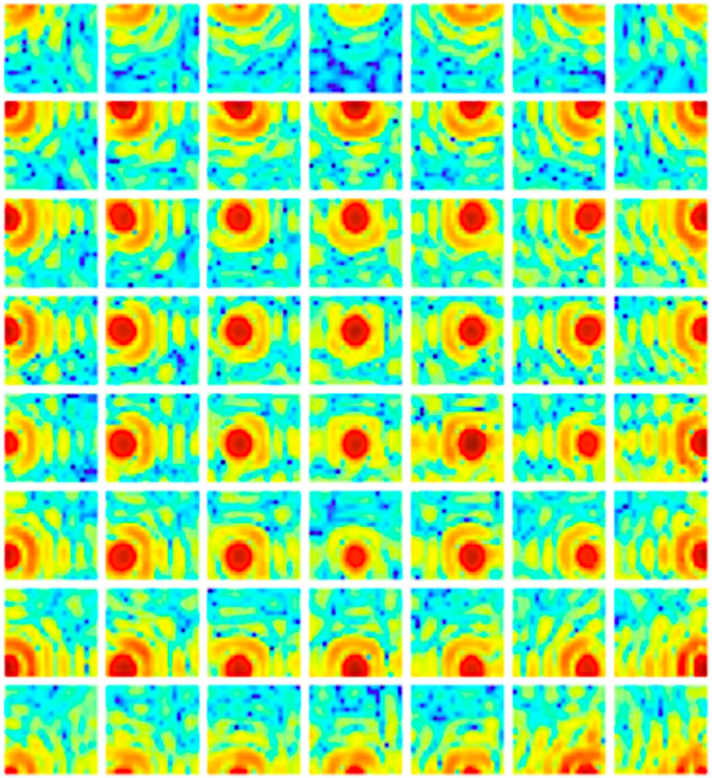


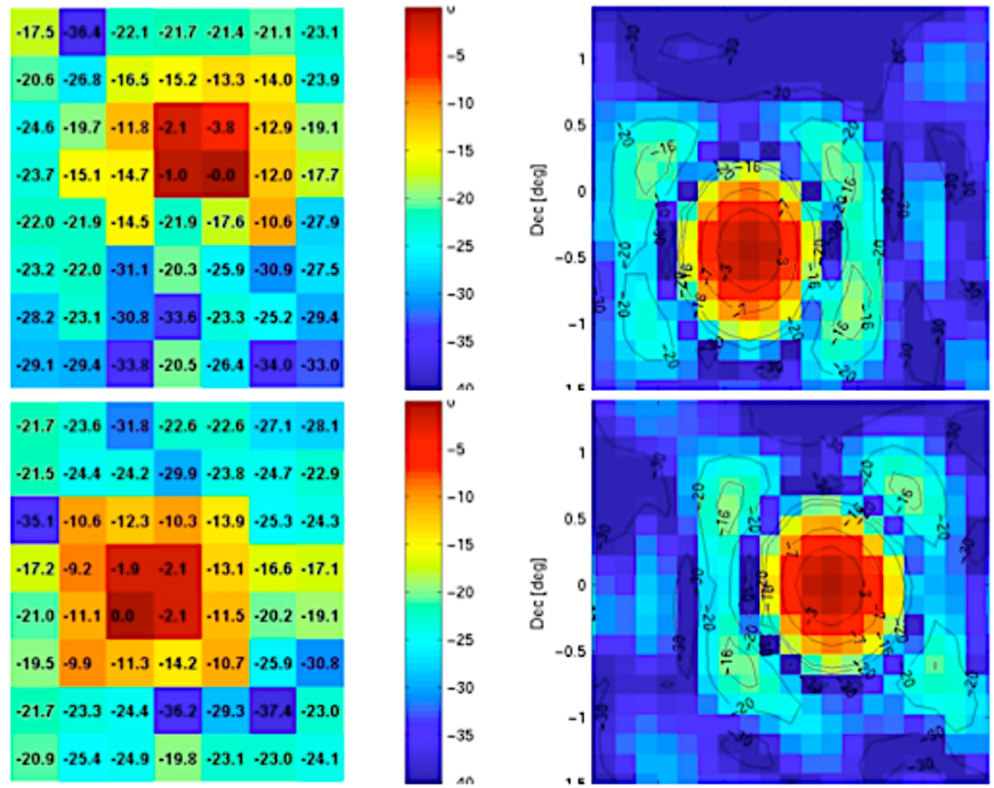
WSRT-APERITIF

- An E-W array in Netherlands (good for wide-field imaging) of 13 (10) Antenna x 25 m.
- Maximum baseline length of 3 km (similar to the EVLA in C-configuration).
- Resolution of 15 arcsec at 1.4 GHz.



PAF- Beam Forming





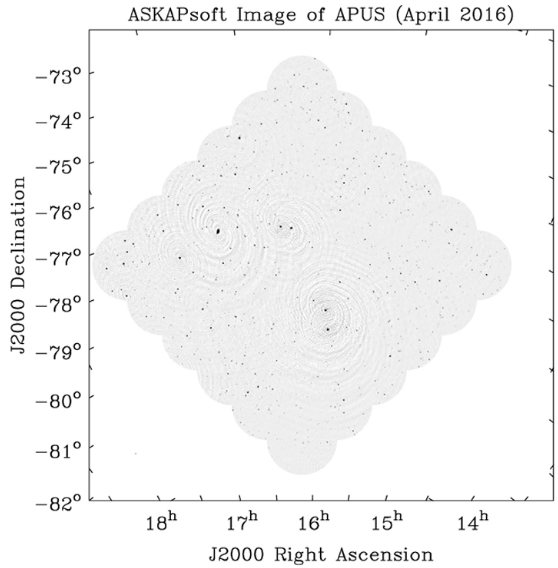
Individual element beams from the prototype Apertif PAH.

Each element observes a slightly different part of the sky.

Left: Weights used to form different tile beams.
Right: The resulting tile beams (same scale as before), with suppressed side-lobes.

ASKAP - Australian SKA Pathfinder

- 36 x 12 m telescopes being built in Western Australia.
- Baselines up 6 km.
- Phased array feed operating between 0.7-1.8 GHz.
- Tsys ~ 50 K.
- 30 beams giving a total FoV of 30 deg^2
- Instantaneous bandwidth up to 300 MHz
- Currently in construction / commissioning. BETA (6 antenna test array) operational!
- 75% of observing time already set aside for key projects.

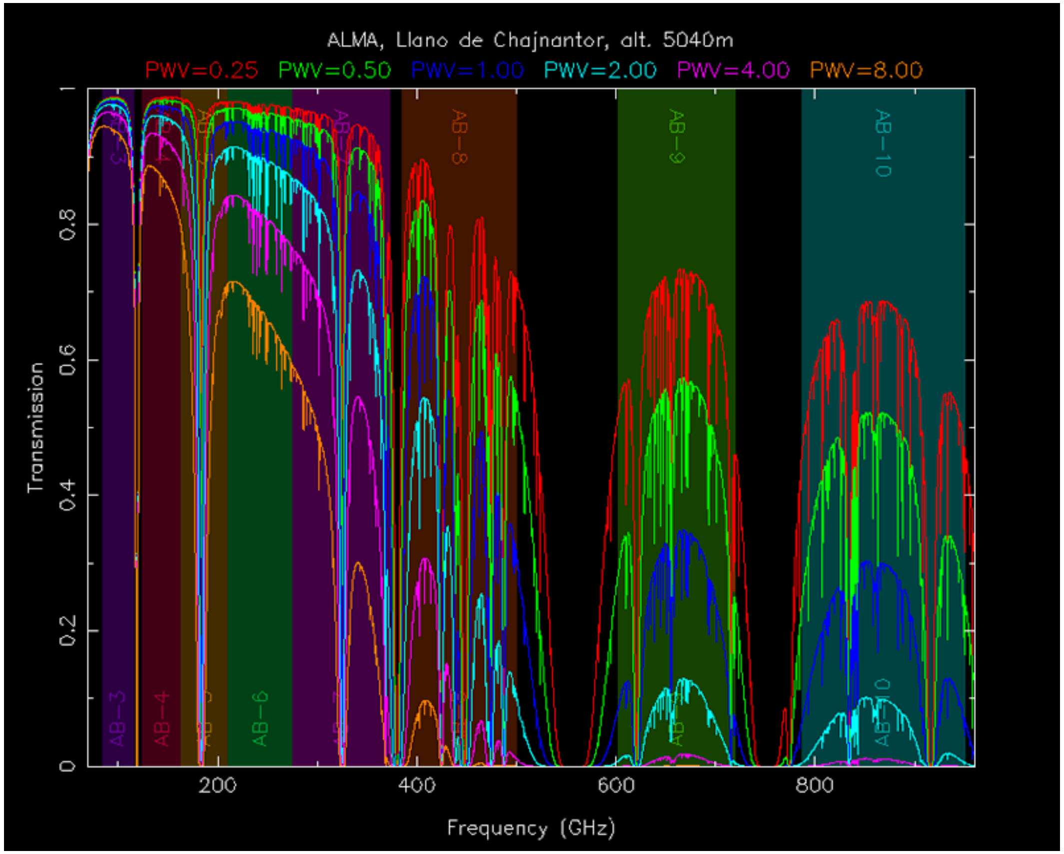


The continuum image, produced with ASKAPsoft, has an rms of around 300 uJy/beam and a field of view of 30 square degrees. The image, produced using 36 beams and representing the full ASKAP FoV of 30 square degress, contains over 1300 sources. Credit: ASKAP team.

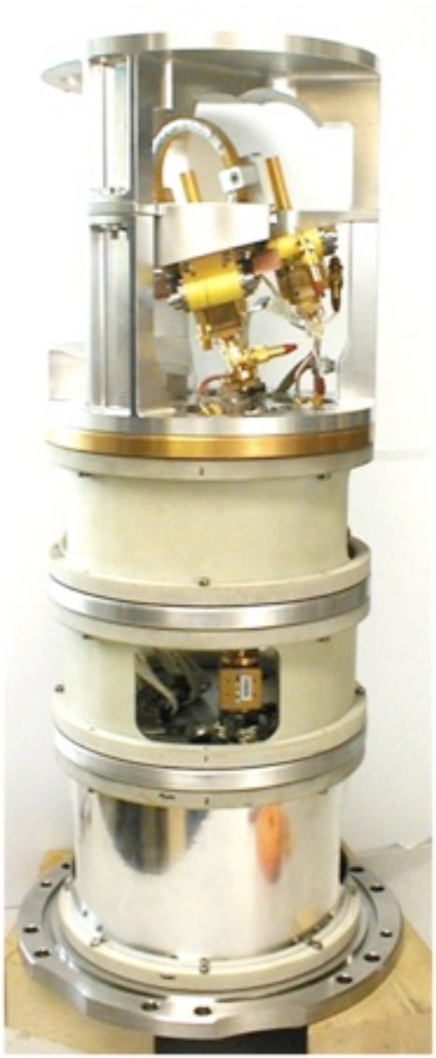
The Millimetre Wavelength Sky

- Generally defined between 60 GHz (loosely) and 1 THz (atmospheric cut-off), must observe from space to observe at a higher frequency (e.g. Herschel)

- Strong opacity due to water molecules in the atmosphere.
- Bands defined by gaps.
- Observatories located at high and dry locations
- Use water vapour radiometers to estimate the best atmospheric conditions for observations.



The Atacama Large Millimeter Array (ALMA)



- Altitude: 5058.7 m, Atacama desert, Chile
- 54x12m dishes
- 12x7m dishes
- Frequency range: 85 GHz to 1 THz
- Baselines 15 m to 15 km
- Sensitive to heated dust (star-formation) and molecular emission.

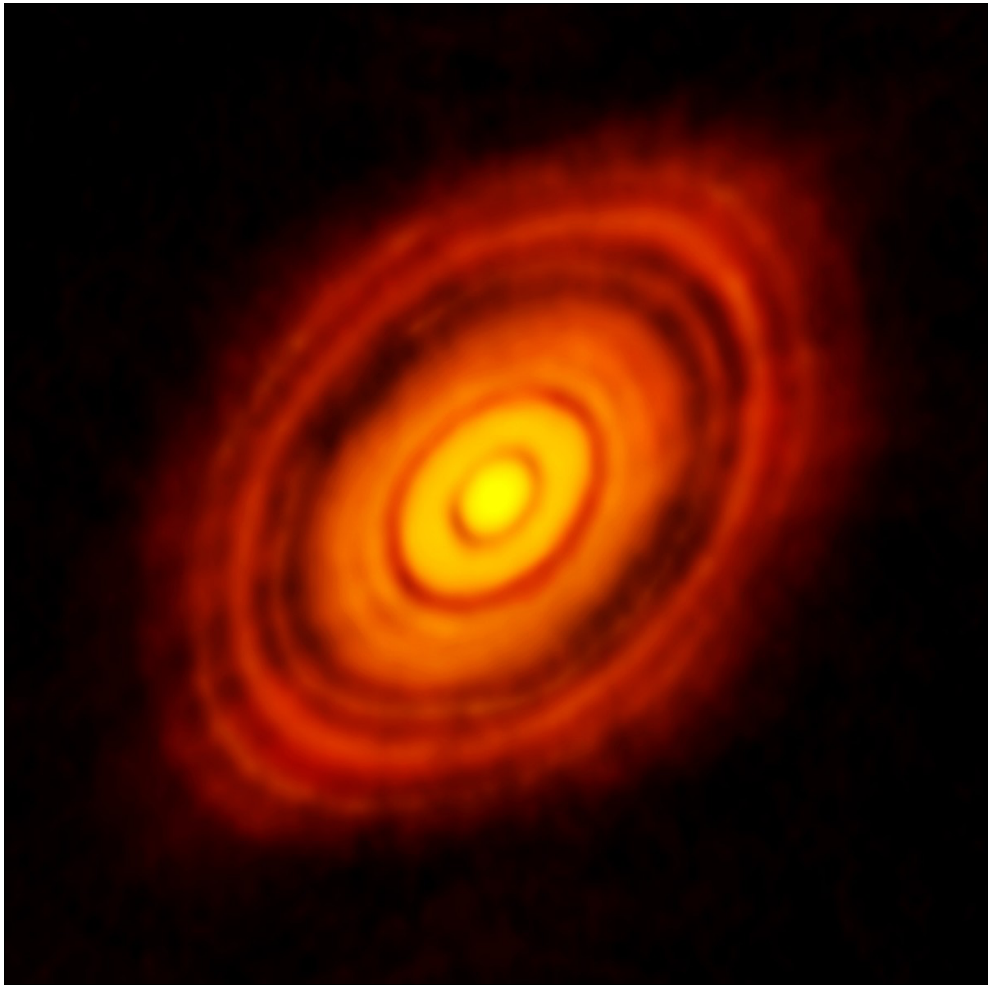
Plateau de Bure / NOEMA

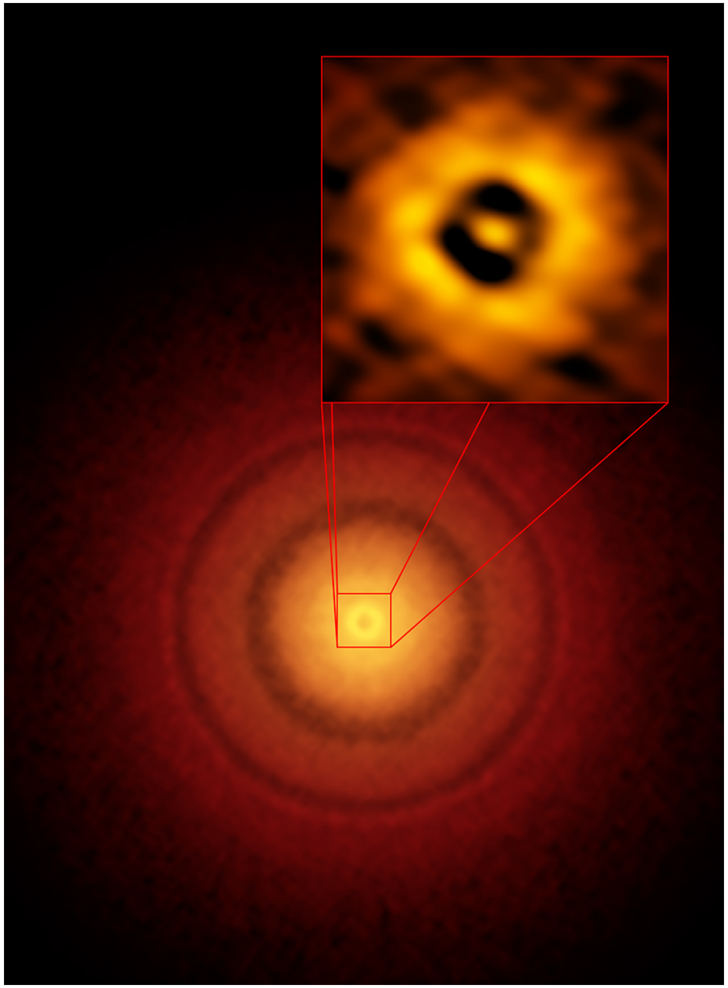
- NOEMA is the successor to Plateau de Bure with 6 more antennas
- Total twelve 15-meter antennas on a 2550-meter-high plateau in the French Alps (complete 2019)
- 2000 meters of track on which the antennas can be moved into different configurations
- 48 high technology reception systems with sensitivities close to quantum limit
- State-of-the-art electronic equipment designed to process the celestial data

	Plateau de Bure 2012	NOEMA 2016	NOEMA 2018
Number of antennas	6	10	12
Track length	1200 m	1200 m	2000 m
Collecting surface	1 060 m²	1 766 m²	2 120 m²
Best angular resolution	0.2 arc seconds	0.2 arc seconds	0.1 arc seconds
Bandwidth	120 GHz	1 440 GHz	2 112 GHz
Number of baselines	15	45	66

Millimetre Array Science

The detailed structure of the protoplanetary disc around HL Tau and young sun like star TW Hydrae mapped for the first time to show rings and gaps (where the planets are forming).



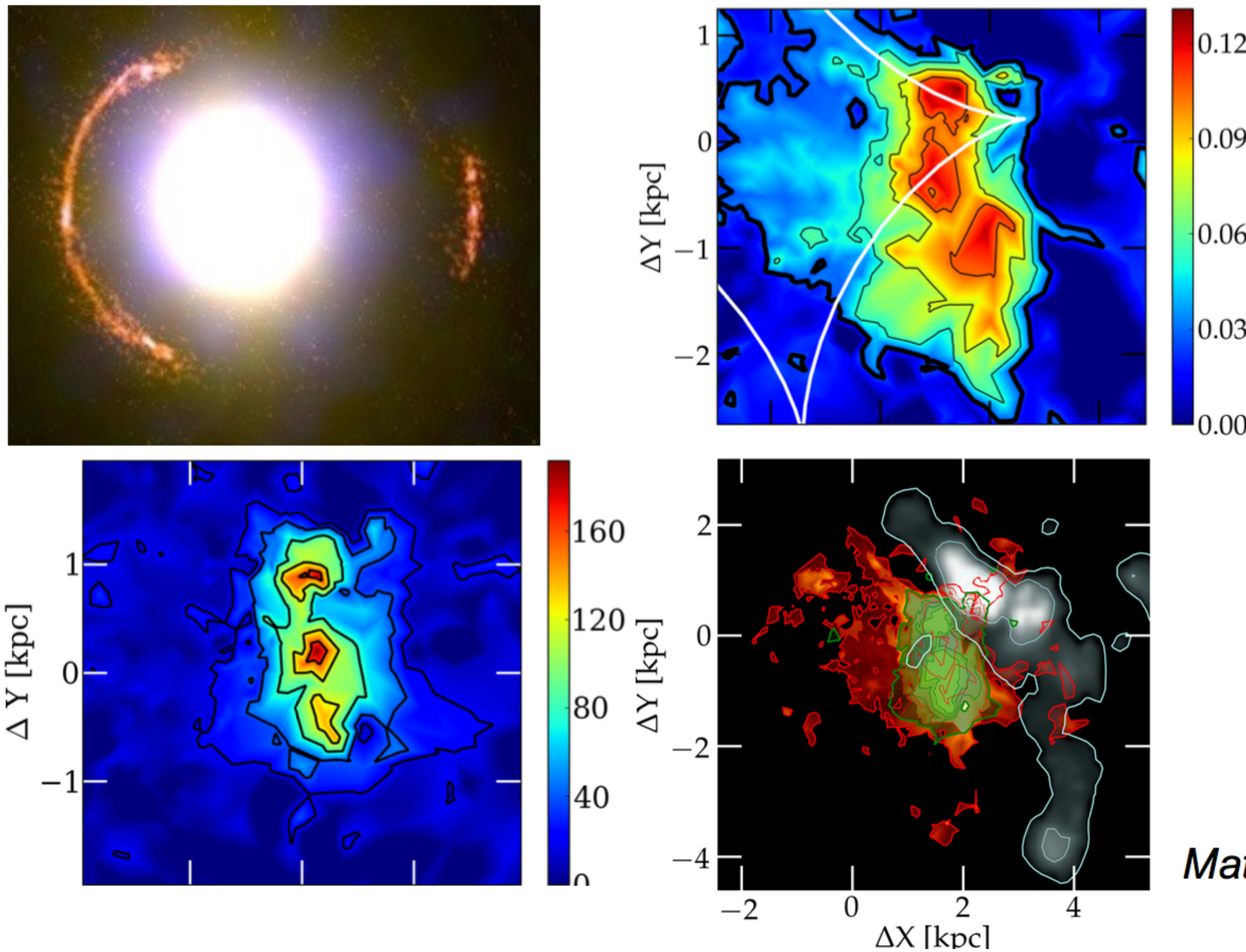


Credit: ALMA (ESO/NAOJ/NRAO)

Credit: S. Andrews (Harvard-Smithsonian CfA); B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)

Millimetre Array Science

Gravitational lensing and the long baseline capability of ALMA used to study the structure of star-forming galaxies on sub-50 parsec-scales.



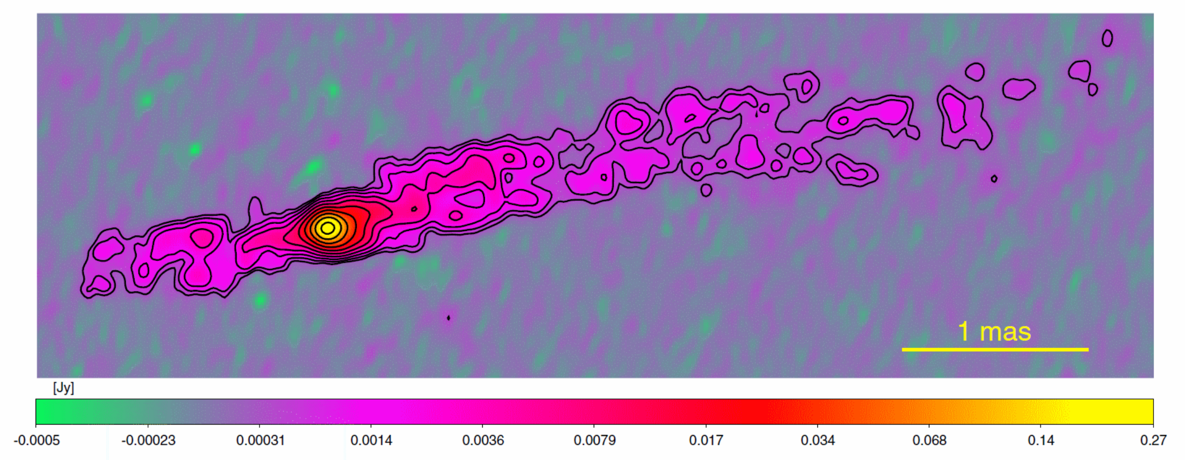
Matus Rybak

mm-VLBI

mm-VLBI is now able provide good quality images in the 3mm band, with an angular resolution of typically 50-70 micro-arcseconds (2mm & 1.3mm in development)

Some key objectives:

- Testing General Relativity
- Understanding accretion around a black hole
- Understanding jet genesis and collimation



VLBI image of the archetypal radio galaxy Cygnus A at the frequency of 86 GHz.

B. Boccardi, T.P. Krichbaum, U. Bach, M. Bremer, and J.A. Zensus A&A, 588, L9

The Event Horizon Telescope

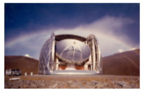
Aims to DIRECTLY image the event horizon of Sgr A* (and M87) using an ultra sensitive array of telescopes operating at 230-450 GHz


Arizona Radio Observatory/Submillimeter-wave Astronomy (ARO/SMT)

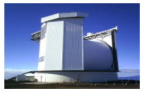

Atacama Pathfinder EXperiment (APEX)


Atacama Submillimeter Telescope Experiment (ASTE)

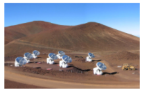

Combined Array for Research in Millimeter-wave Astronomy (CARMA)

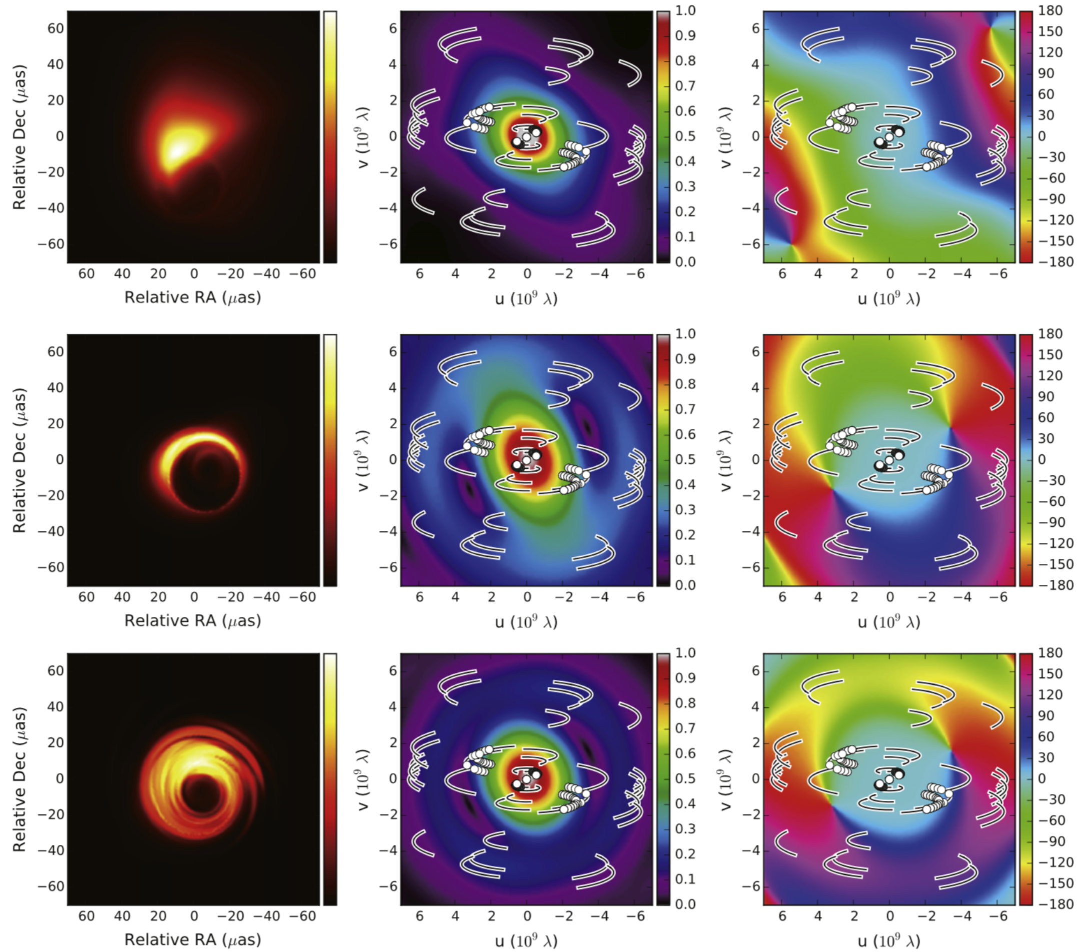

Caltech Submillimeter Observatory (CSO)


Institut de Radioastronomie Millimetrique (IRAM) 30m


James Clerk Maxwell Telescope (JCMT)


The L arge Millimeter Telescope (LMT)


The Submillimeter Array (SMA)



Akiyama et al. 2015

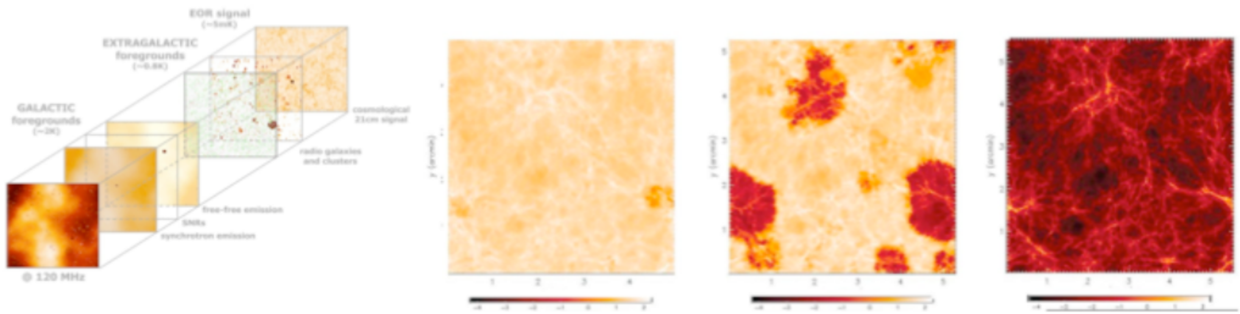
The Square Kilometer Array (SKA)

A large radio telescope for new ground breaking science:

- Up to 1 million m2 (hence, SKA) distributed over up to ~3000 km (VLBI like baselines) and between South Africa & Australia
- Operational between 50 MHz (maybe lower) to 13.8 GHz (maybe higher).
- Fibre network, computing power and raw power to put everything together.
- Constructed in 2 phases (SKA1 and SKA2).
- Cost cap of SKA phase 1 set at ~€650M

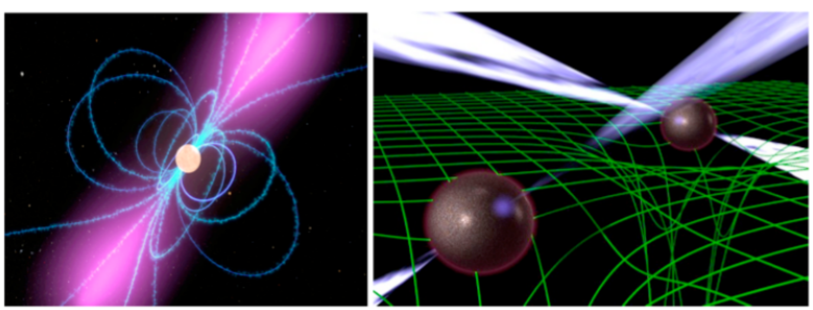
SKA Key Science Goals

The Epoch of Re-ionisation: Detect the faint signals from HI during the period when the Universe was re-ionised by the first stars and galaxies.
Important implications for galaxy formation



Vibor Jelic

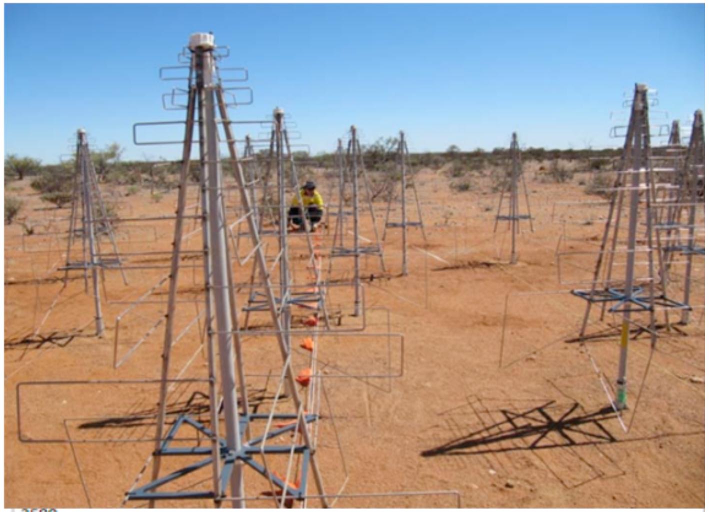
Pulsar Timing Array: Measure the small differences in the timing of Pulsars to search for gravitational waves.
Important implications for theories of gravity

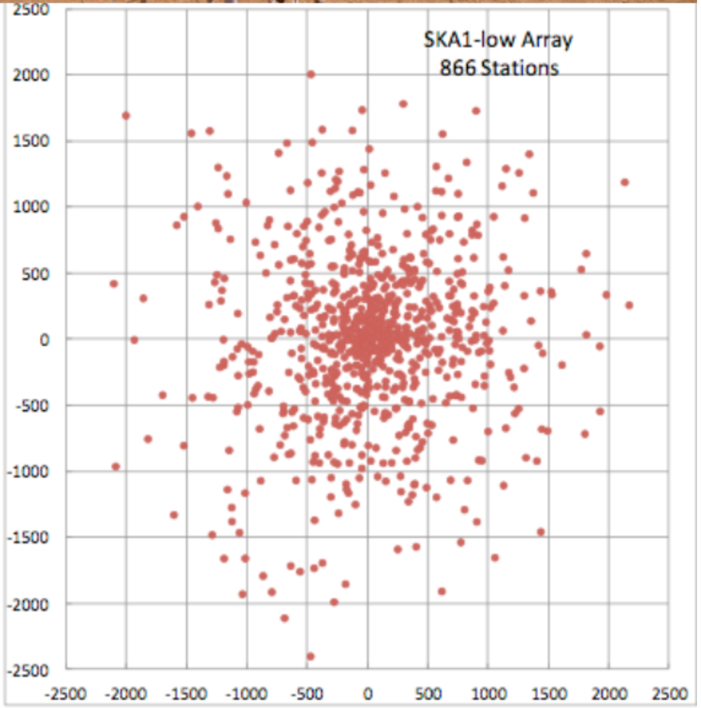


David Champion

SKA Low

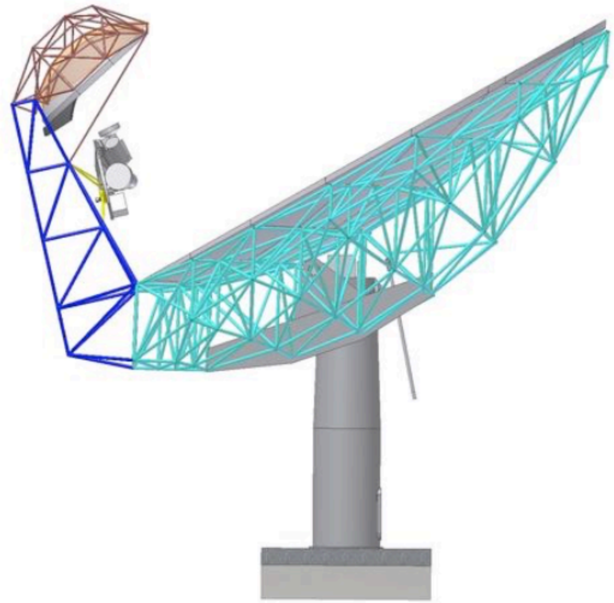
- Sparse dipoles (dual pol; similar to LOFAR).
- Freq: 50 to 350 MHz (300 MHz bandwidth).
- 130000 dipole antennas.
- 8 x more sensitive than LOFAR
- 50% collecting area at < 600 m, 75% at < 1 km.
- Spiral arms out to 50 km (100 km baselines), containing only ~4% of the collecting area.
- Dense core for EoR and Pulsar timing experiments (1 mK brightness temperature for 5 arcmin structures).
- Aeff/Tsys ~1000m^2 /K(>100MHz).

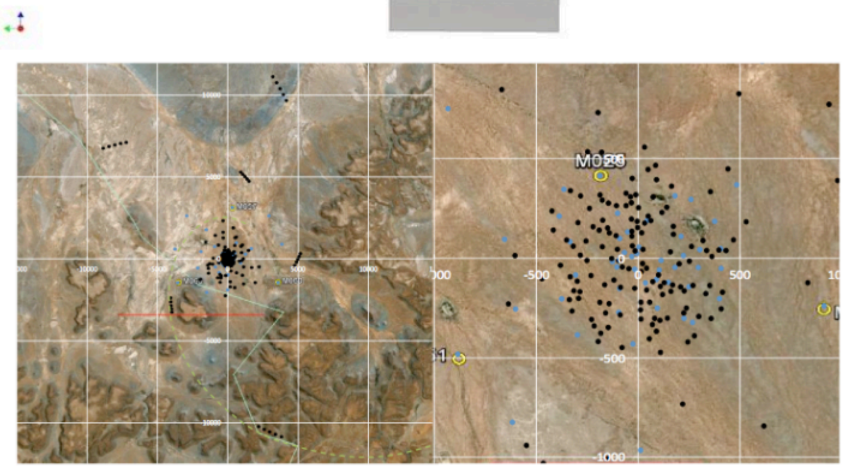




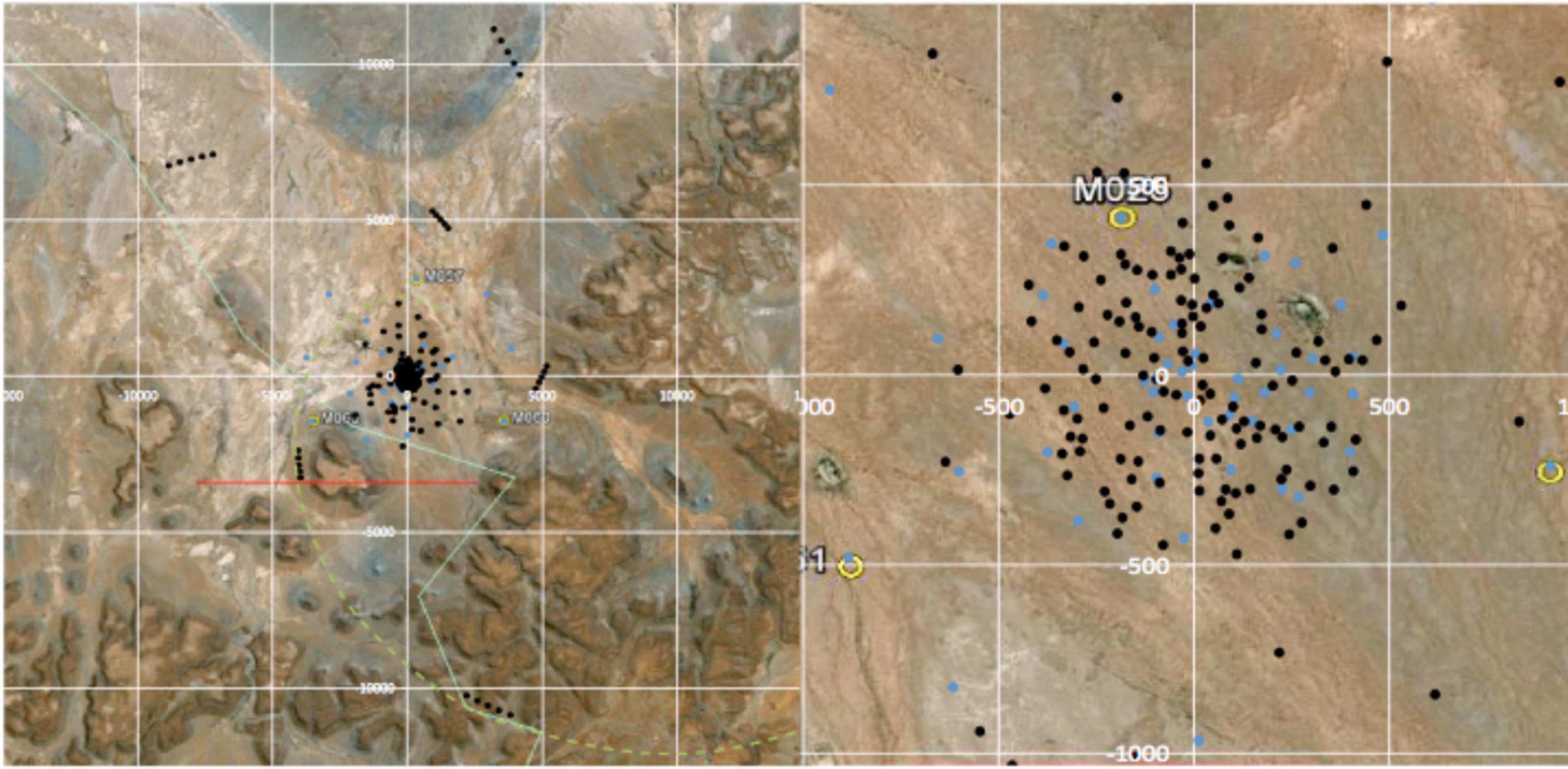
SKA Mid

- 130 x 15 m offset Gregorian dishes + 64 MeerKAT dishes (194 in total).
- Dual polarisation with 700 -- 9200 MHz bandwidth.
- Freq: 350 -- 13800 MHz (band 1 -- 5).
- 5 x more sensitive than the JVLA
- 4 x better resolution than the JVLA
- Wide-band single pixel feeds.
- Will have baselines out to 150 km.
- 85% collecting area within 4 km.
- Dense core for Pulsar timing, HI and continuum and polarisation experiments.
- Aeff/Tsys ~1000--1600m2 /K.





SKA Mid


10000
5000
-10000
-5000
0
5000
10000
-5000
-10000
-500
0
500
-500
-1000

Summary

- Radio astronomy spans a large-range in frequency and telescope type, allowing a wide range of science goals to be investigated - all based on the same basic principles of interferometry.

- A new generation of the interferometers (upgraded and new) are online now, and can be used from 10 MHz up to 1 THz

- In the future, the SKA will be a transformational telescope when it is complete (2020-2025).

The Golden Era of Radio Astronomy needs a Golden Generation of Radio Astronomers...