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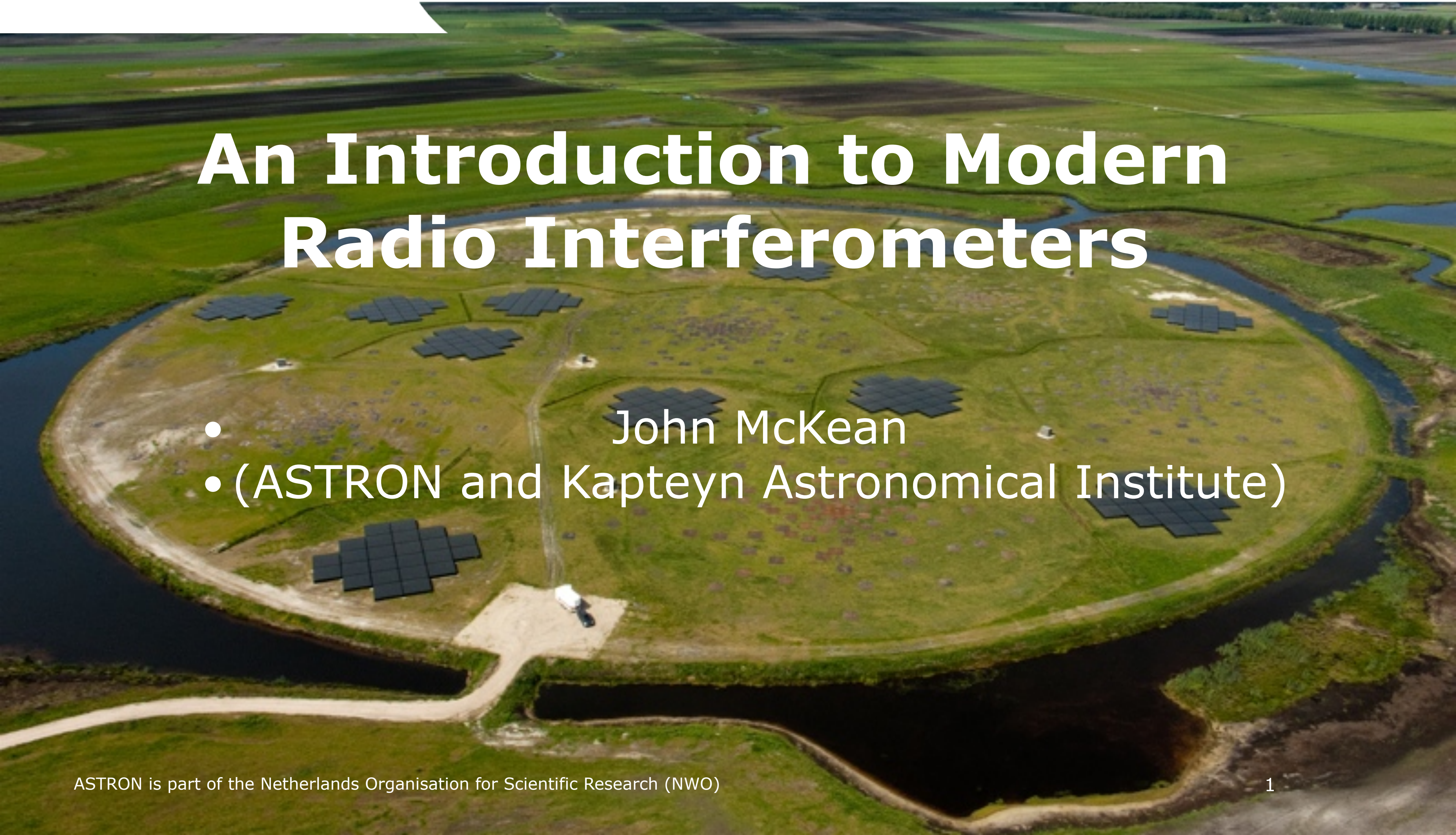
Netherlands Institute for Radio Astronomy



An Introduction to Modern Radio Interferometers

- John McKean
- (ASTRON and Kapteyn Astronomical Institute)

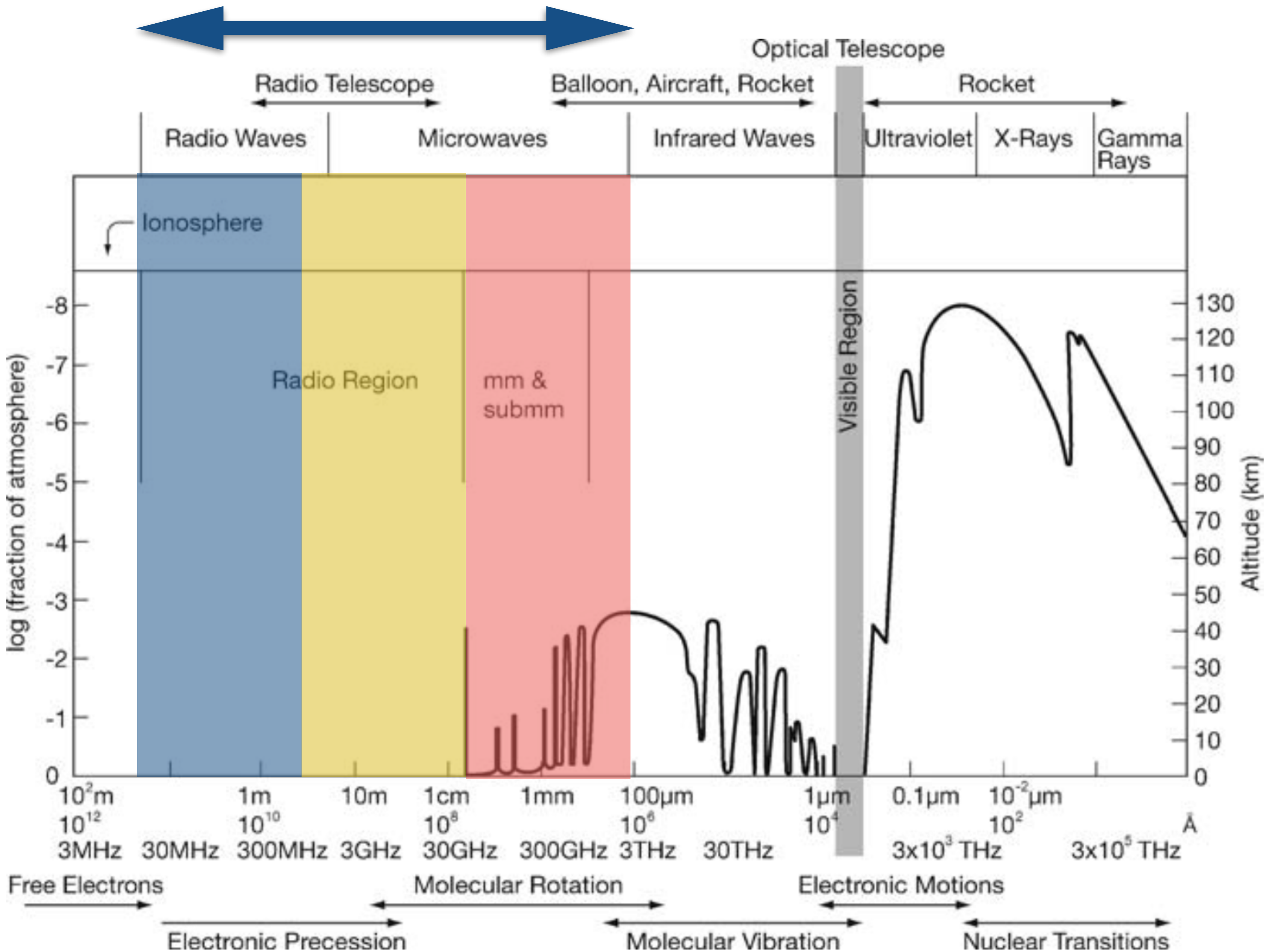
Preamble

- **AIM:** This lecture aims to give a general introduction to modern interferometers
    1. *What's available?*
    2. *What can they do?*
    3. *What's the future?*

- **OBJECTIVES:**
    1. Review the radio window (low, mid and high frequencies).
    2. Capabilities and limitations of the next generation of the interferometers.
    3. Science highlights (bias towards imaging and spectral line).
    4. The Square Kilometre Array (SKA).

- **NOTE:** There will be specific lectures on VLBI and low frequency techniques later in the school (Campbell, McKean).

The radio window (10 m - 100 μm)



The quest for sensitivity and resolution

- The resolution is defined as,

$$\theta_{\rm res}(\text{radians}) \sim \frac{\text{wavelength}}{\text{baseline length}}$$

- The System Equivalent Flux-Density (SEFD) is defined as,

$$\text{SEFD} = 2\,k\,T_{\rm sys}/A_{\rm eff}, \qquad A_{\rm eff} = \text{Area} \times \eta_{\rm ant}, \qquad T_{\rm sys} \propto T_{\rm rec}$$

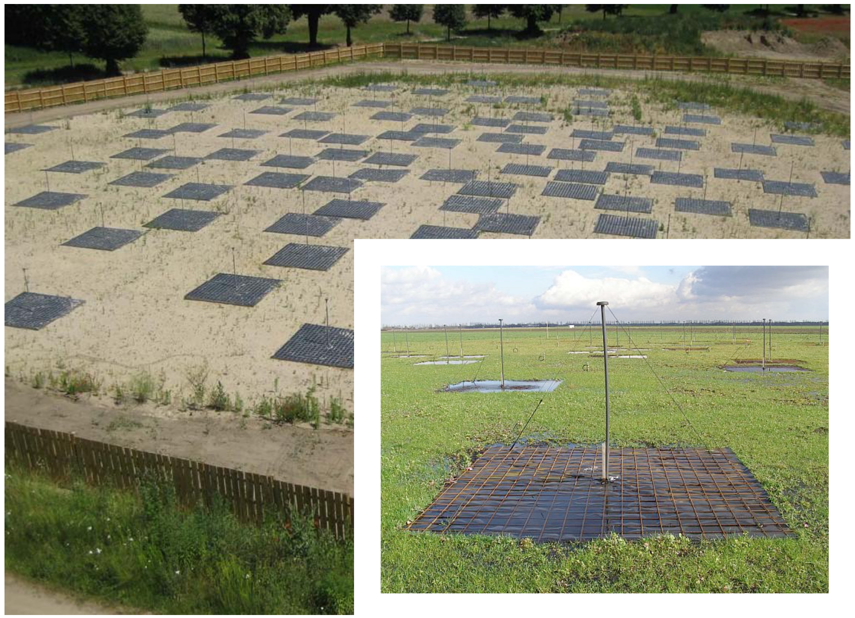
- The sensitivity of an array is defined as,

$$S_{\rm rms} = \frac{1}{\eta_{\rm c}} \frac{\text{SEFD}}{\sqrt{n_{\rm pol}\,N(N-1)\,\Delta\nu\,t}}$$

- Need to increase effective collecting area or bandwidth, decrease receiver temperature.

Varying technologies

Aperture Arrays



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

Dishes

- High cost.
- Fixed collecting area ($\sim A_{geo}$).
- Small field-of-view.
- Used at high-frequencies.
- Uniform directional response.
- Well understood beam pattern.

Varying technologies (receivers)

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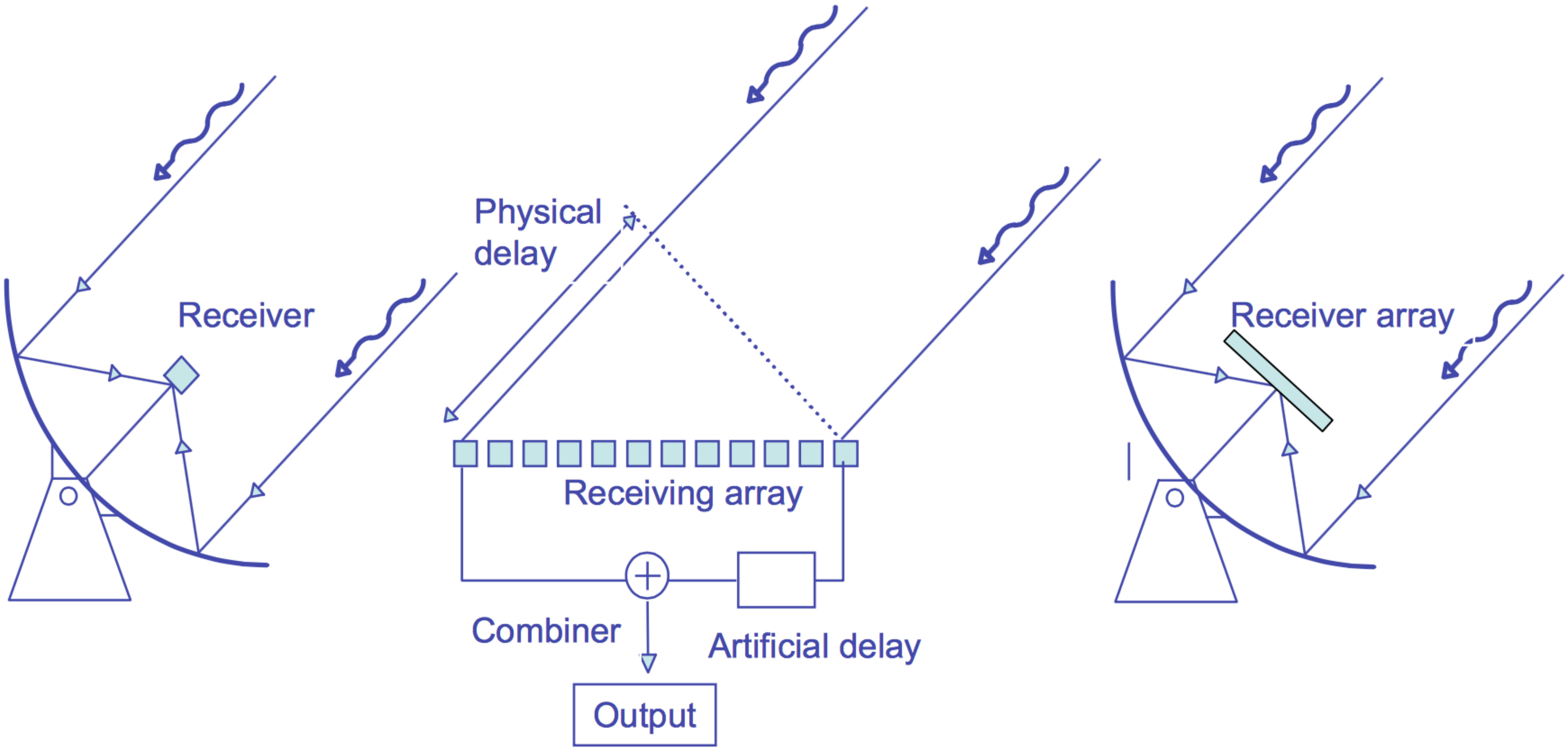
Single pixel	Aperture Array	Phased Array Feed (PAF)



Parabolic reflector (mechanical)	Aperture array (electronic)	Reflector + receiver array (mechanical + electronic)

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

The metre-wavelength sky

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

Plasma frequency (5 - 10 MHz)

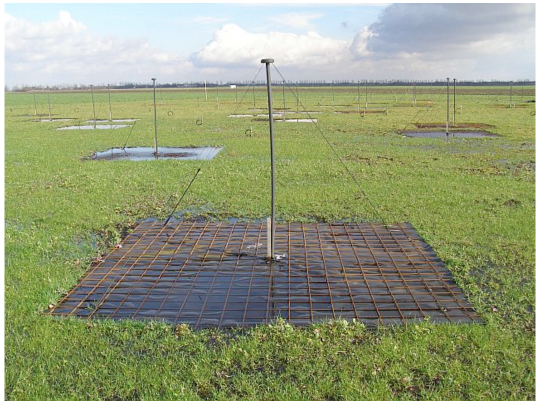
$$\frac{\nu_{\rm p}}{\rm kHz} = 8.97\sqrt{\frac{N_{\rm e}}{\rm cm^{-3}}}$$

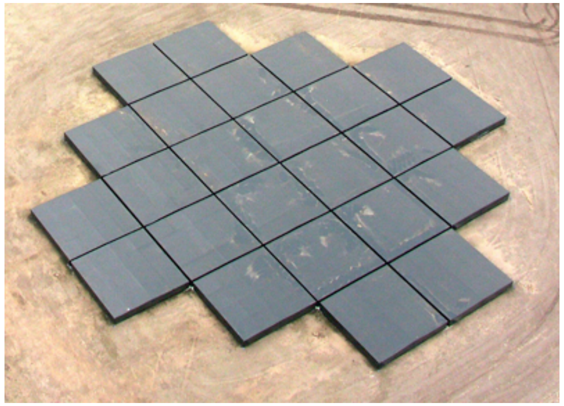
electron density ($\sim 0.25 - 1 \times 10^6$ cm^{-3})

- **Challenges:**
    1. Wide fields-of-view (~degrees) and highly variable ionosphere.
        A. Observe during best conditions.
        B. Advanced calibration techniques (see Calibration and Low Frequency Interferometry lectures).
    2. Radio frequency interference.
        A. Radio quiet locations.
        B. Advanced RFI mitigation techniques.
        C. Excellent frequency and time resolution.

The Low Frequency Array

- 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.
- More details in the LOFAR lecture.



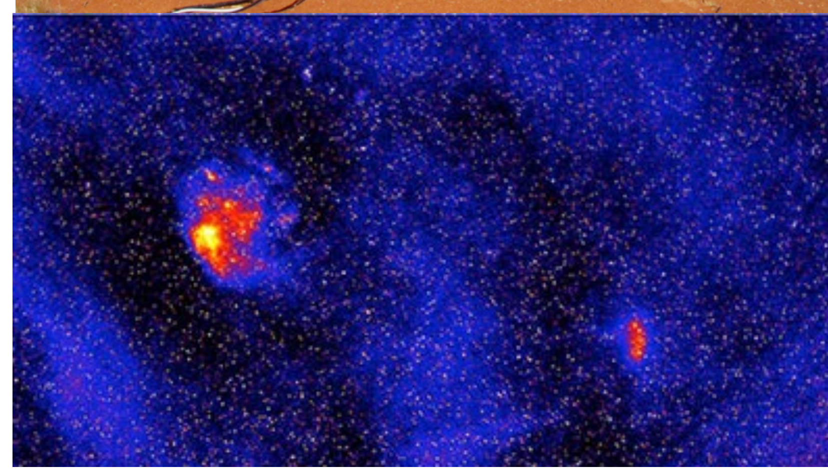


The Murchison Wide-field Array

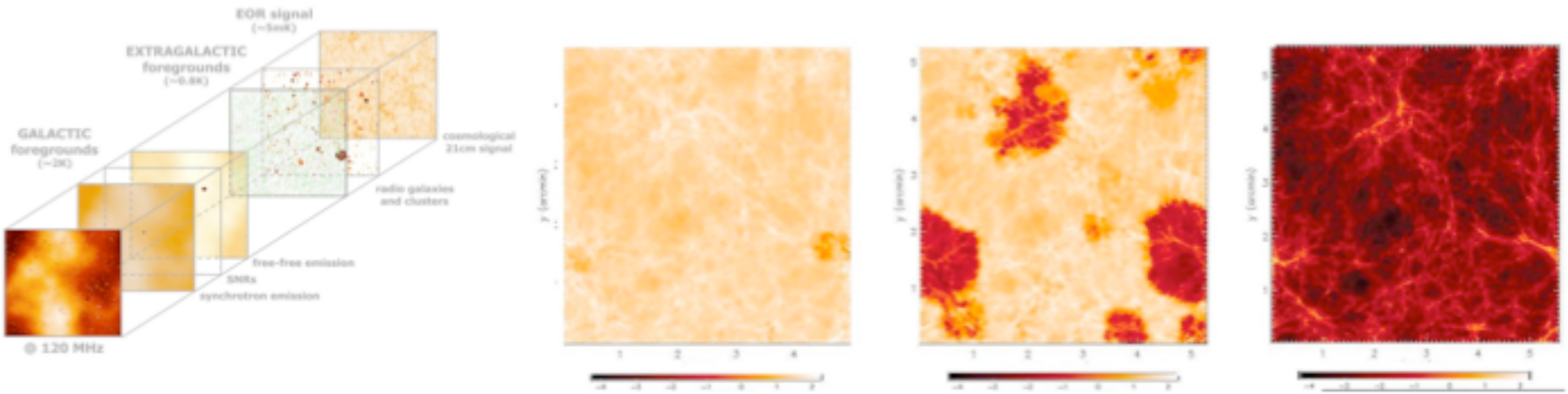
- Low frequency pathfinder based in Australia (quiet-site).

- 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



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.

Wide area surveys

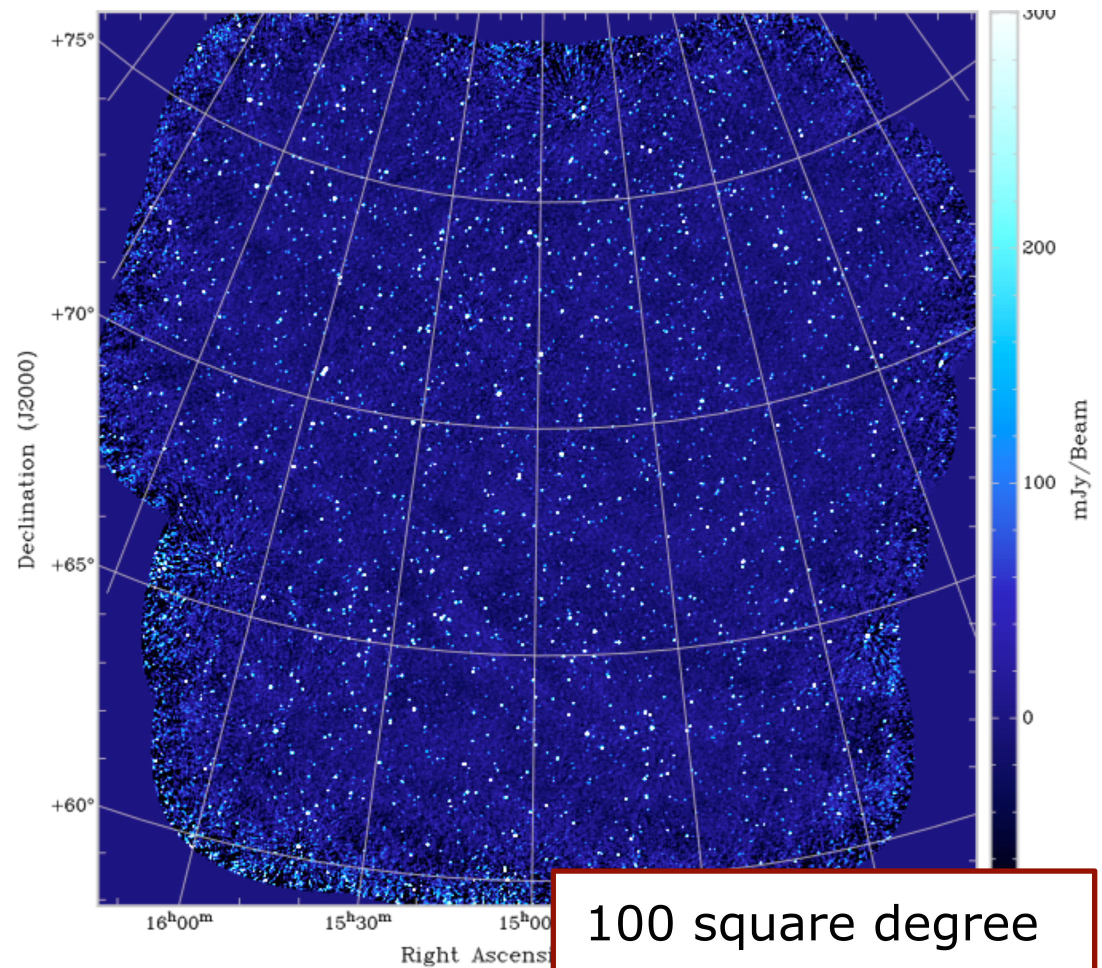
Imaging wide-fields is useful for,

1. Efficient all-sky survey.
2. Looking for rare objects.

Primary science goals:

1. Relic/halo emission from galaxy clusters
2. Census of AGN and star-formation over cosmic time.
3. Cosmic magnetism.
4. Highest redshift radio sources
5. Gravitational lenses
6. Detailed studies of nearby AGN.

LOFAR MSSS SVF; *George Heald*

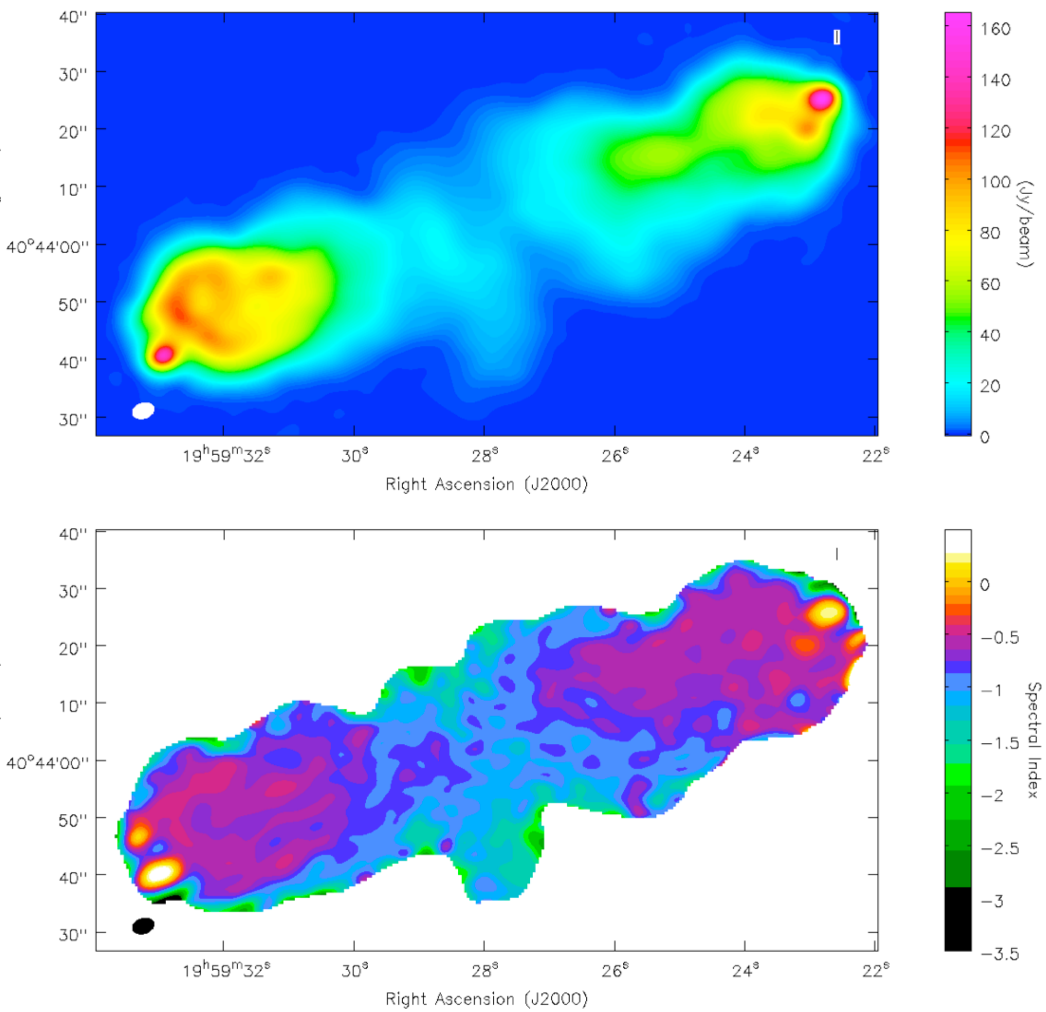


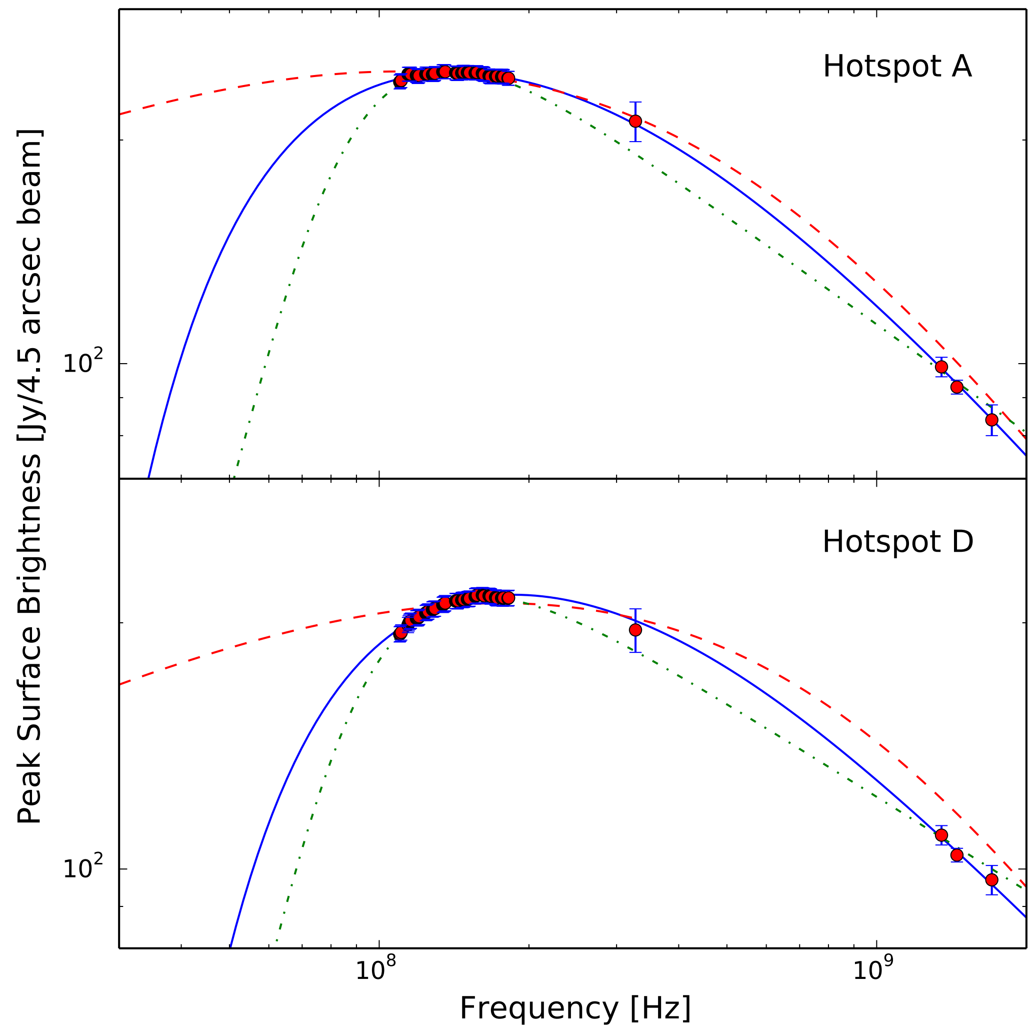
100 square degree

~10 mJy /beam [2 arcmin resolution]

Energetics of AGN

Sensitivity (~100 μJy / beam), resolution (4 arcsec) and bandwidth (78 MHz) allows studies of the low energy properties of active galaxies.



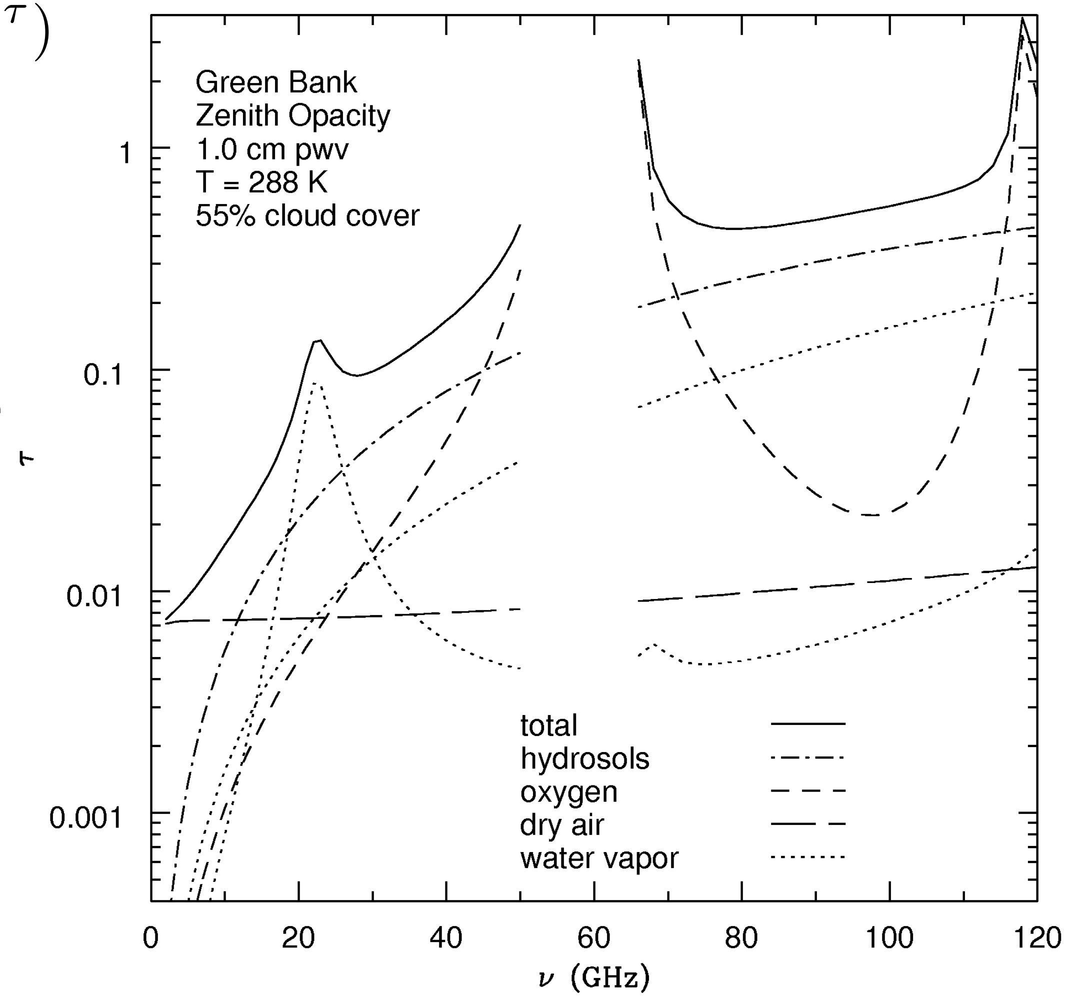


The cm-wavelength sky

- Generally defined between 1 GHz (loosely) and 50 MHz (due to atmospheric cut-off by O_2), calibration limited by the ionosphere at low-freq and the troposphere at high freq.

$$I(\text{obs}) = I(0)e^{-\tau} + I(\text{atm})(1 - e^{-\tau})$$

- 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).



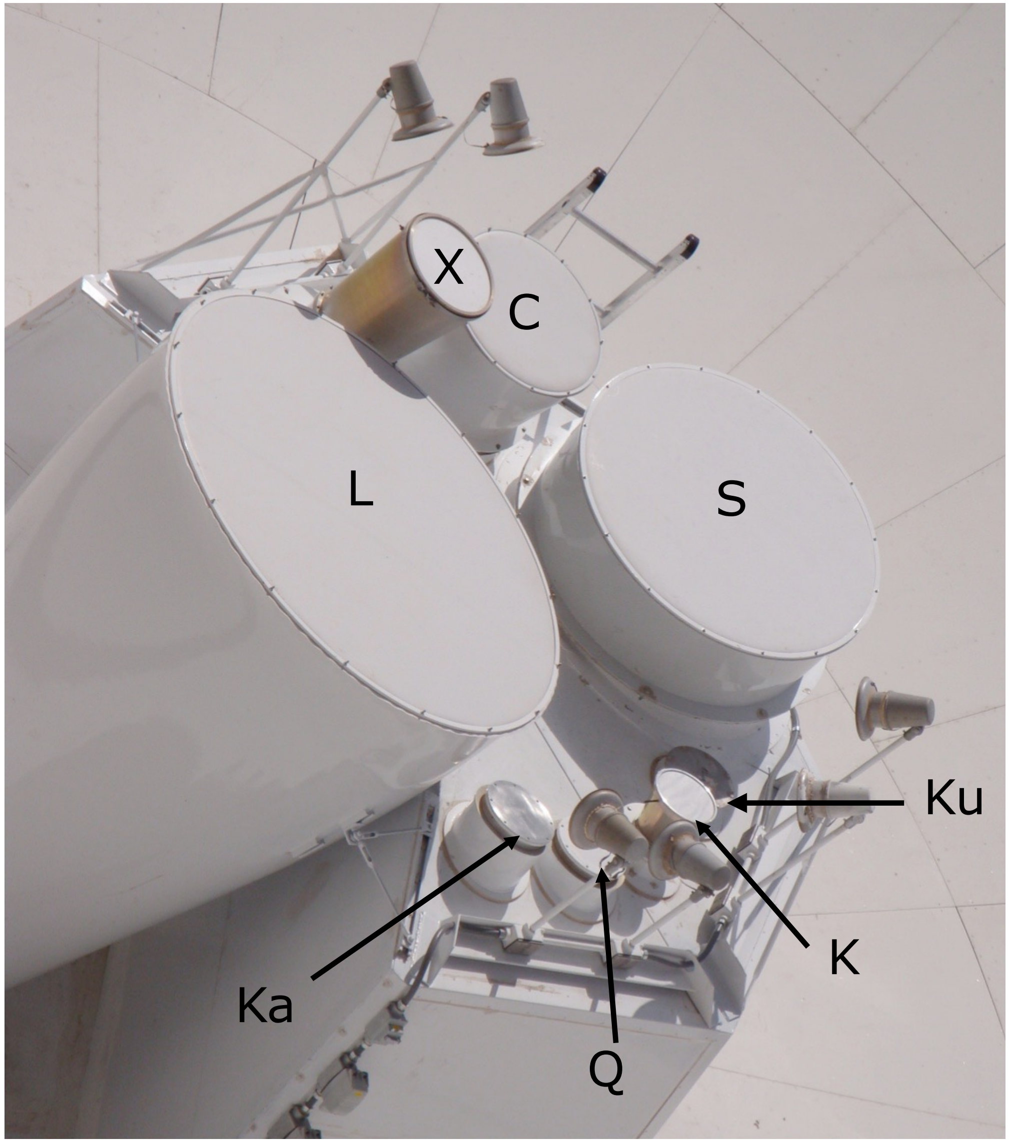
The Karl G. Jansky Very Large Array

- Built in the 1960s (New Mexico, USA).
- 27 x 25 m 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.

The Karl G. Jansky Very Large Array

- New receiver upgrade now completed.
- 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



The Karl G. Jansky Very Large Array

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

Jim Condon

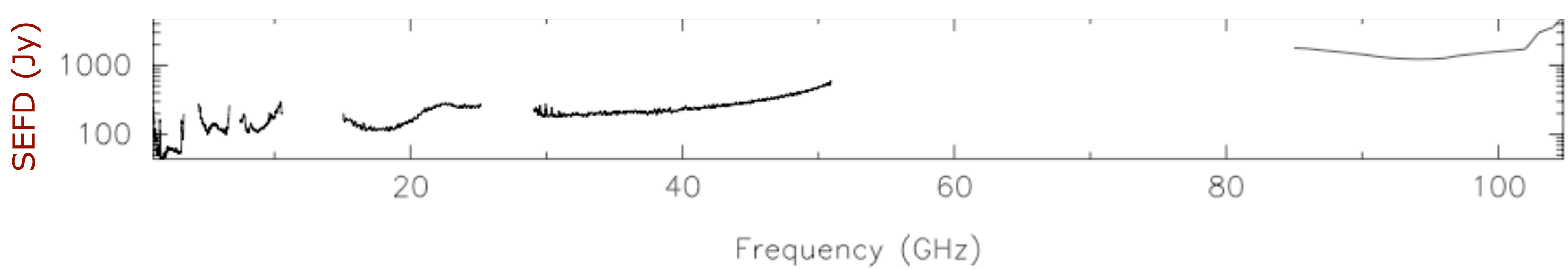
Band	Code	Effective BW	SEFD	σ(cont)	σ(line)
GHz		GHz	Jy	μJy	mJy
1 – 2	L	0.75	400	5.5	2.2
2 – 4	S	1.75	350	3.9	1.7
4 – 8	C	3.5	300	2.4	1.0
8 – 12	X	4	250	1.8	0.65
12 – 18	Ku	6	280	1.7	0.61
18 – 27	K	8	450	2.3	0.77
27 – 40	Ka	8	620	3.2	0.90
40 -- 50	Q	8	1100	5.6	1.4

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

The Australia Telescope Compact Array

- 6 x 25 m telescopes (15 baselines).
- 4 movable configurations.
- Operates between 1--100 GHz
- Good overlap with ALMA.

- New broad band receivers installed (2 x 2 GHz bandwidth).



e-MERLIN

- Multi-Element Radio Link Interferometer Network (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 / ν_{GHz}).
- Link between VLA/ATCA and VLBI.

e-MERLIN

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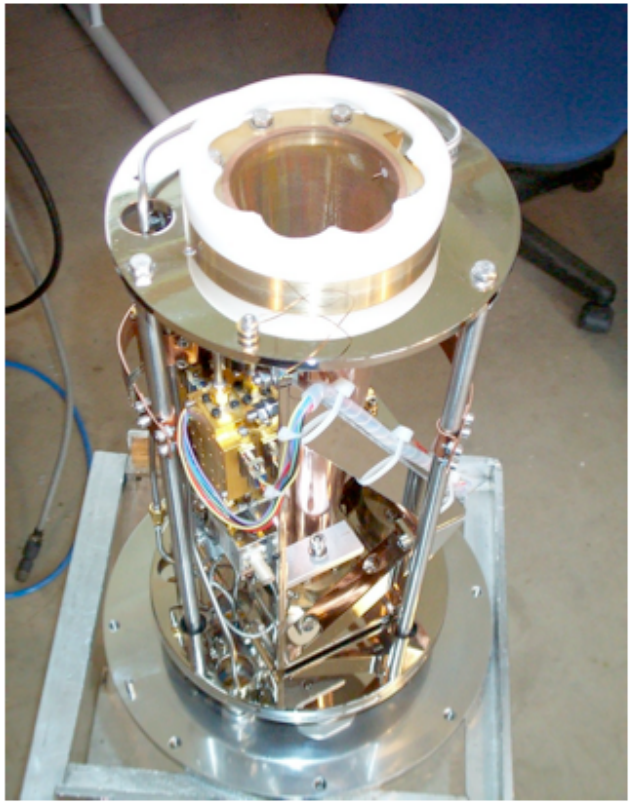
- New wide-band receivers (sensitivity, spectral line capability).



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

- Reaching the theoretical limit for receiver technologies

  Feeds, Low noise amplifiers, etc.

- Sampling and digital signal processing at 4 Gbits / s.

e-MERLIN

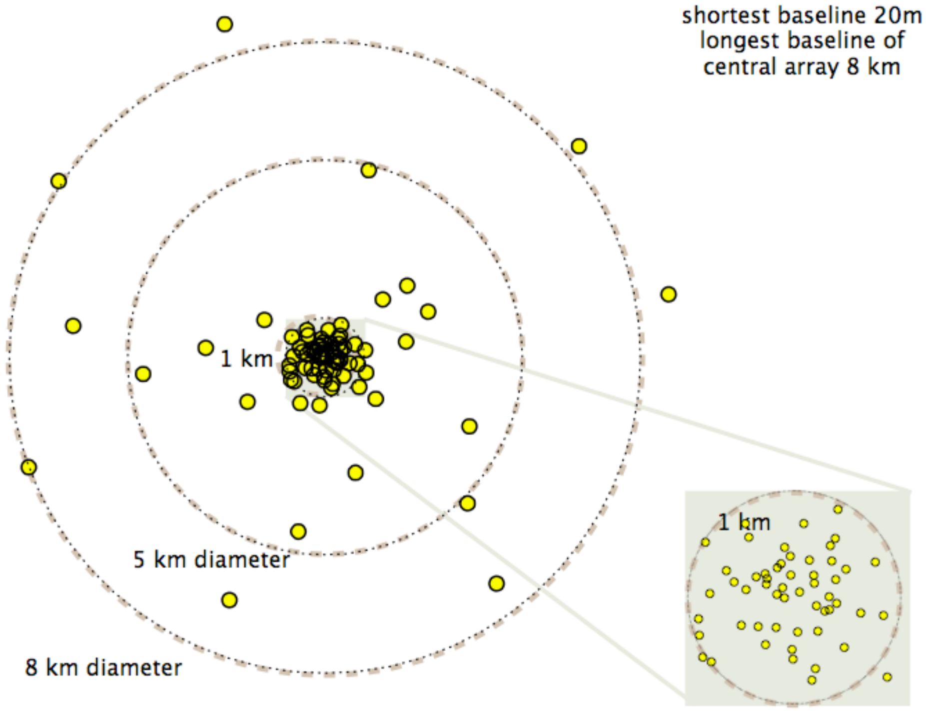
Table 1: Basic observing capabilities of e-MERLIN

	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 - Southern Africa 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.
- T_{sys} = 30 K.
- Located in the Karoo desert of northern South Africa.
- Observations start (full array) by 2017/20 - test site is operational (KAT7)



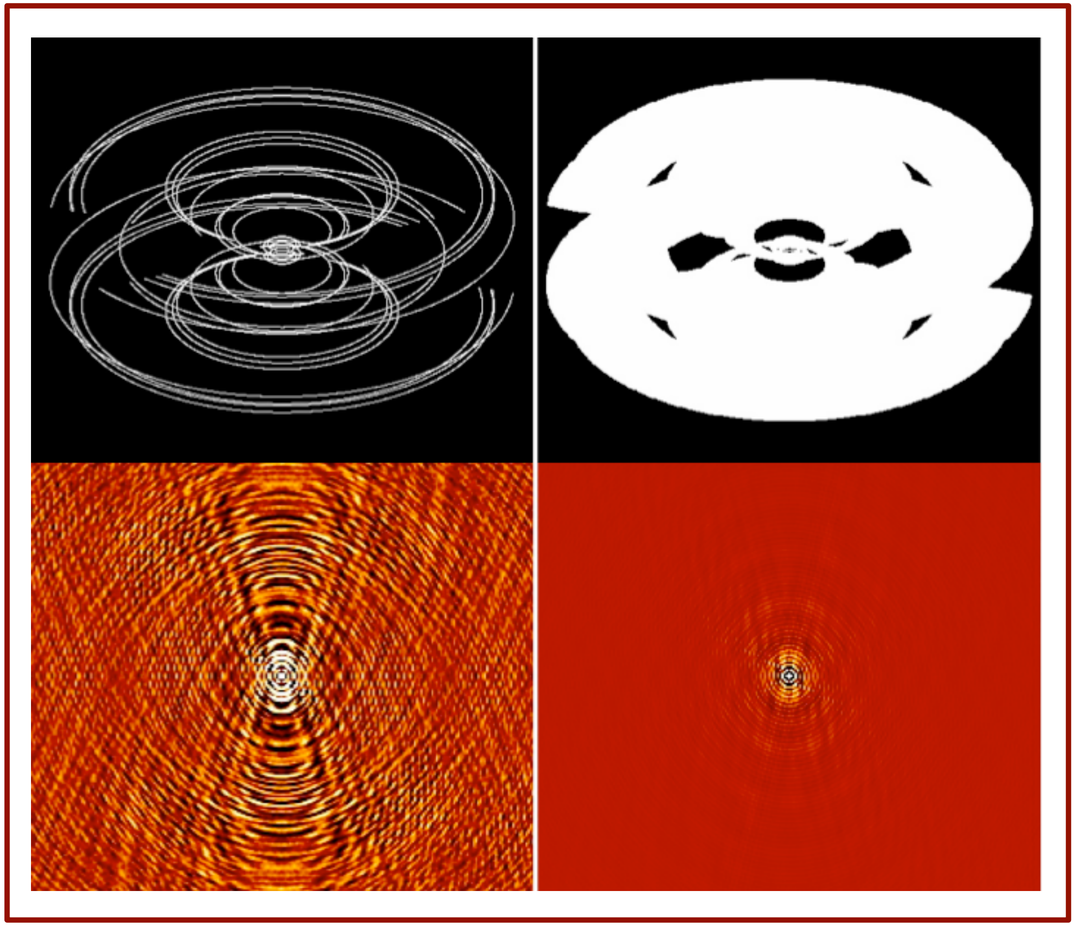
Science with the new single pixel arrays

- **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 $\sqrt{\Delta\nu}$.
- Also improves the uv-coverage.

- Better dynamic range, lower de-convolution errors.

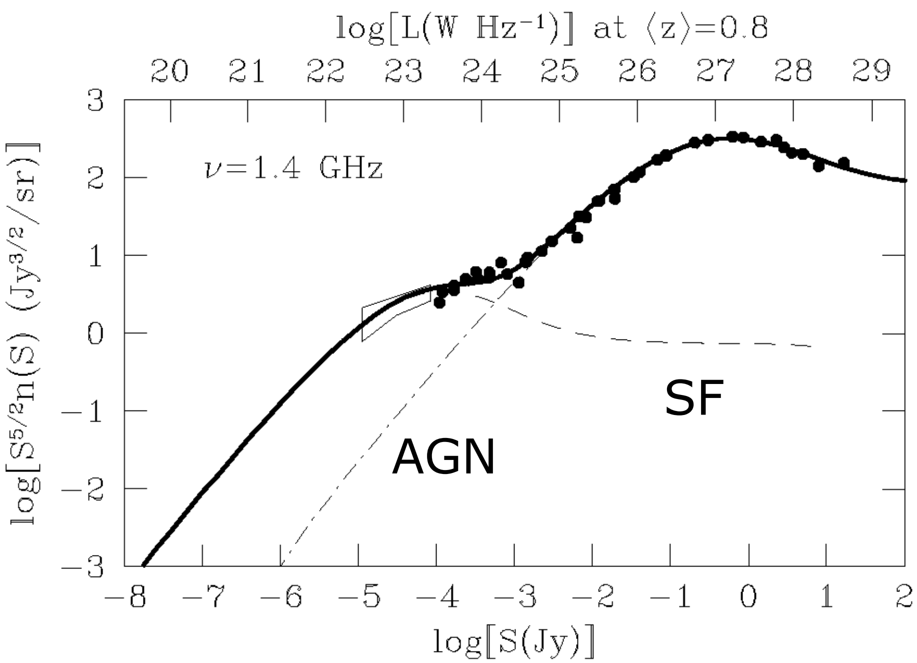
- Better sensitivity to sources over different angular scales (need to know the spectral index...)

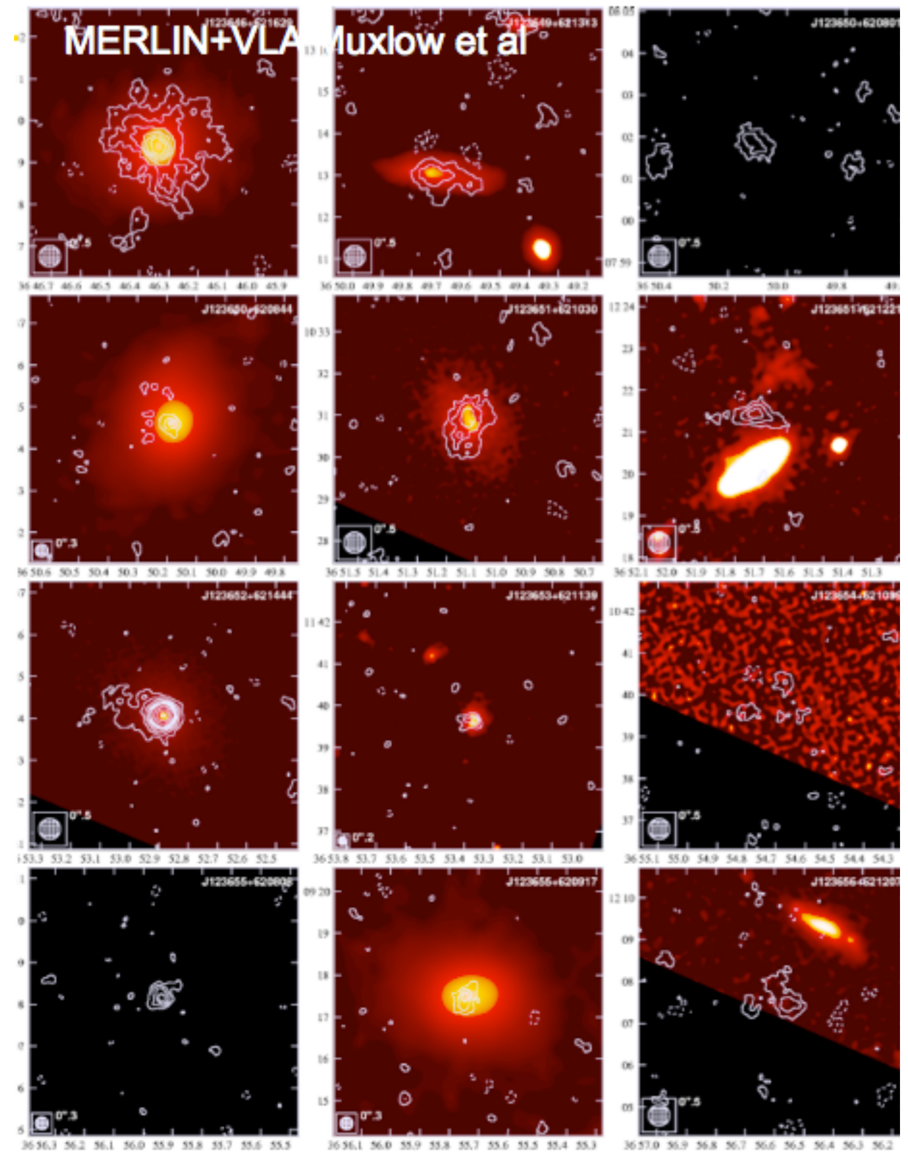


Simon Garrington

Science with the new single pixel arrays

- uJy level sensitivity will allow investigations of,
  - i) the star-forming population (radio-FIR correlation).
  - ii) radio quiet-AGN.





Science with the new single pixel arrays

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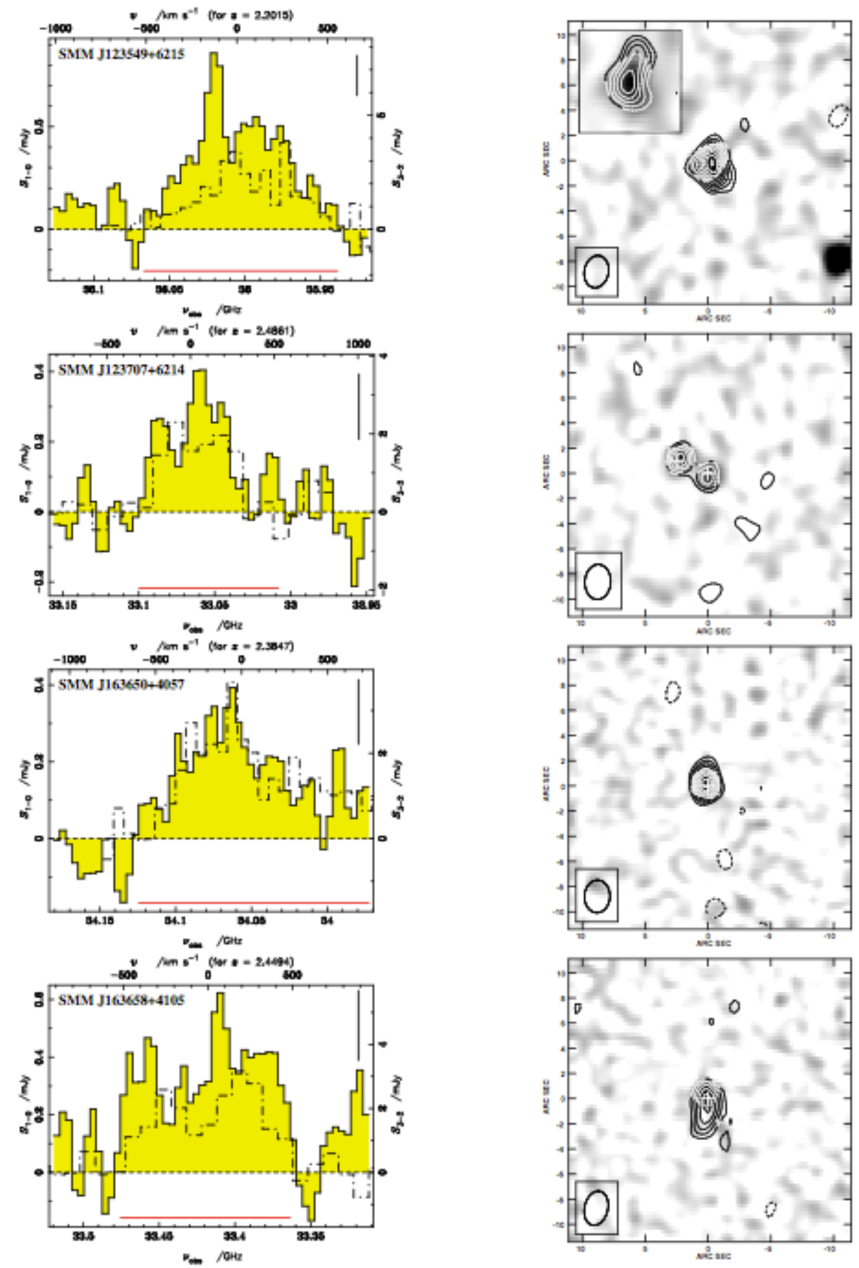
- Large bandwidths and flexible correlators will allow new spectral line studies to be carried out.
- In the 1-50 GHz band (OH, CH_3OH, H_2O) multiple line transitions can be detected allowing measurement of the temperature and density of the ISM.
- For higher redshift objects HI and CO will be detected 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!



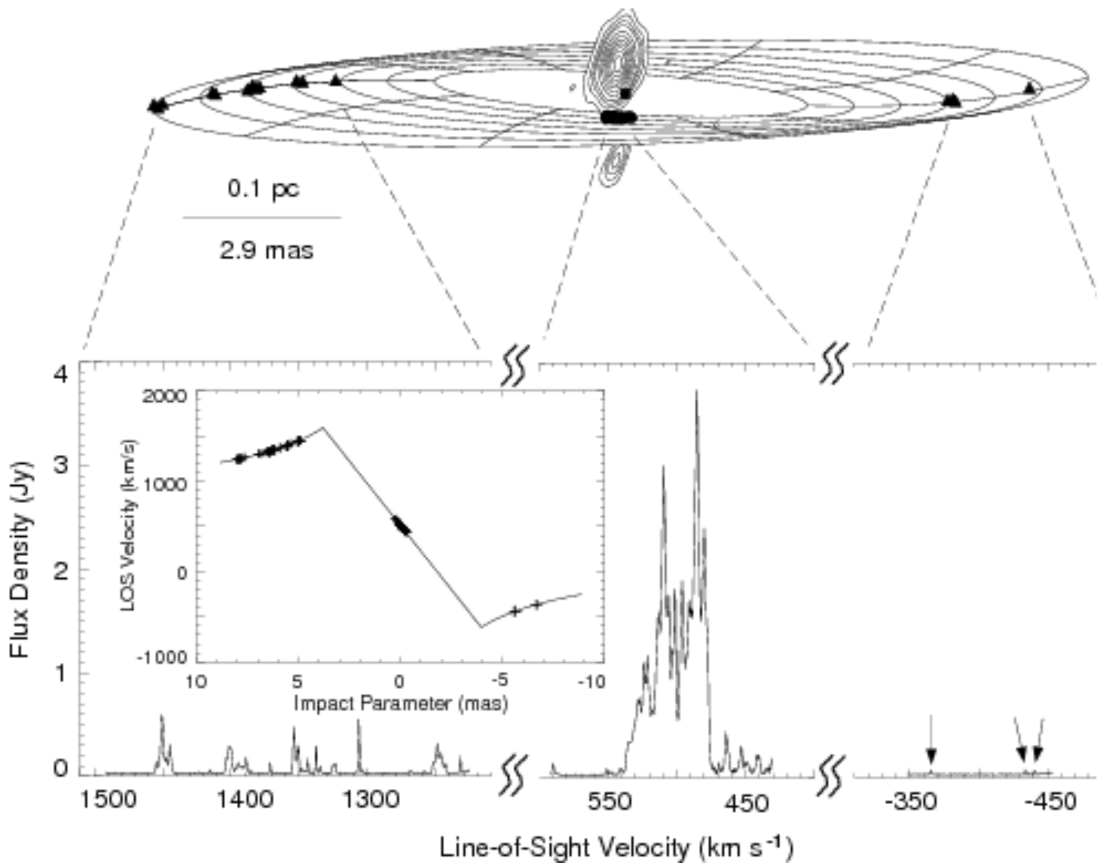
Rob Ivison

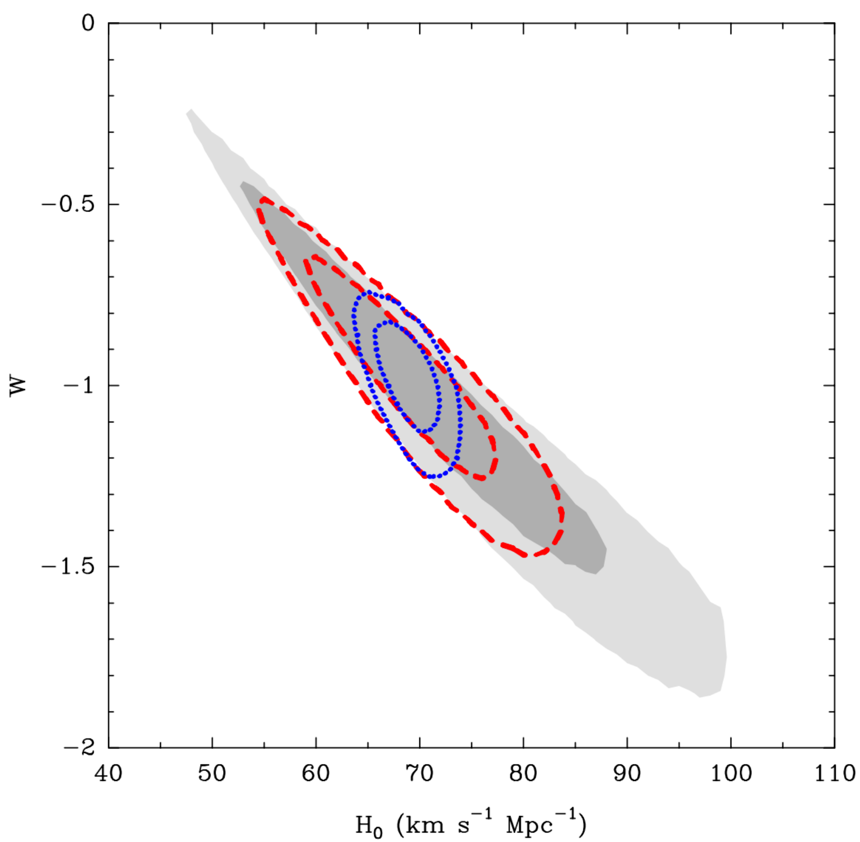
Very Long Baseline Interferometry

Science with VLBI

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

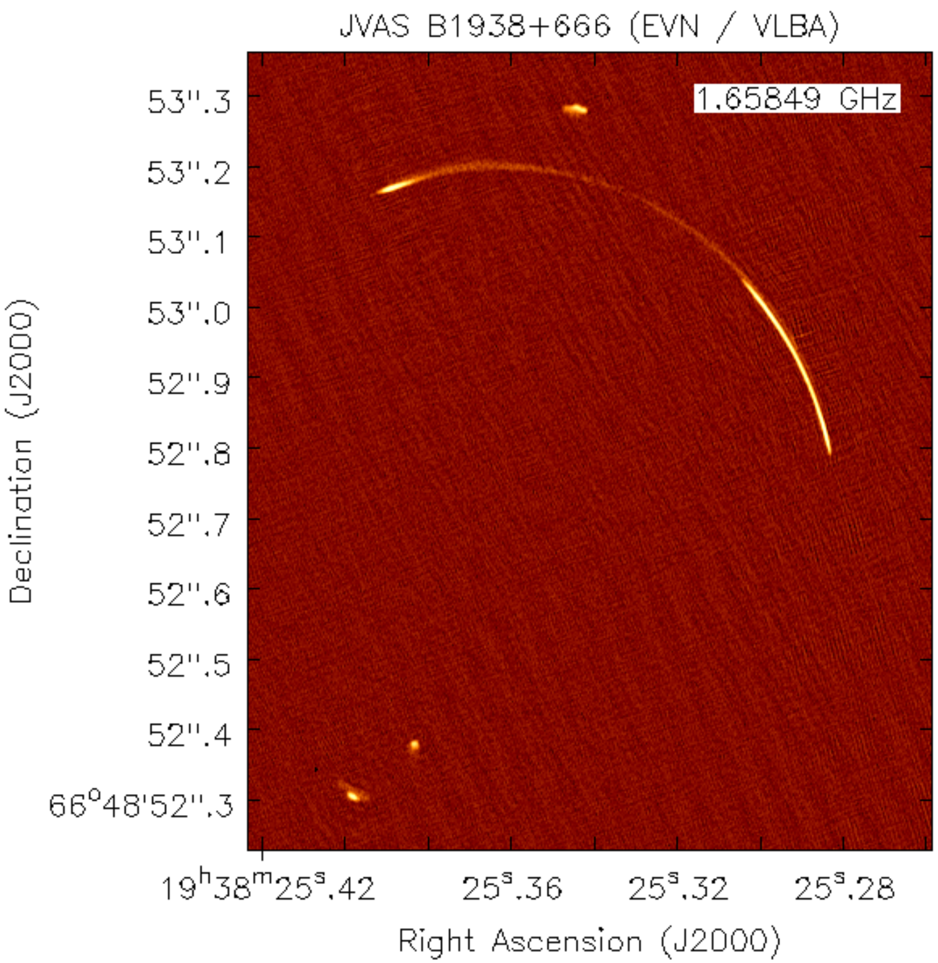


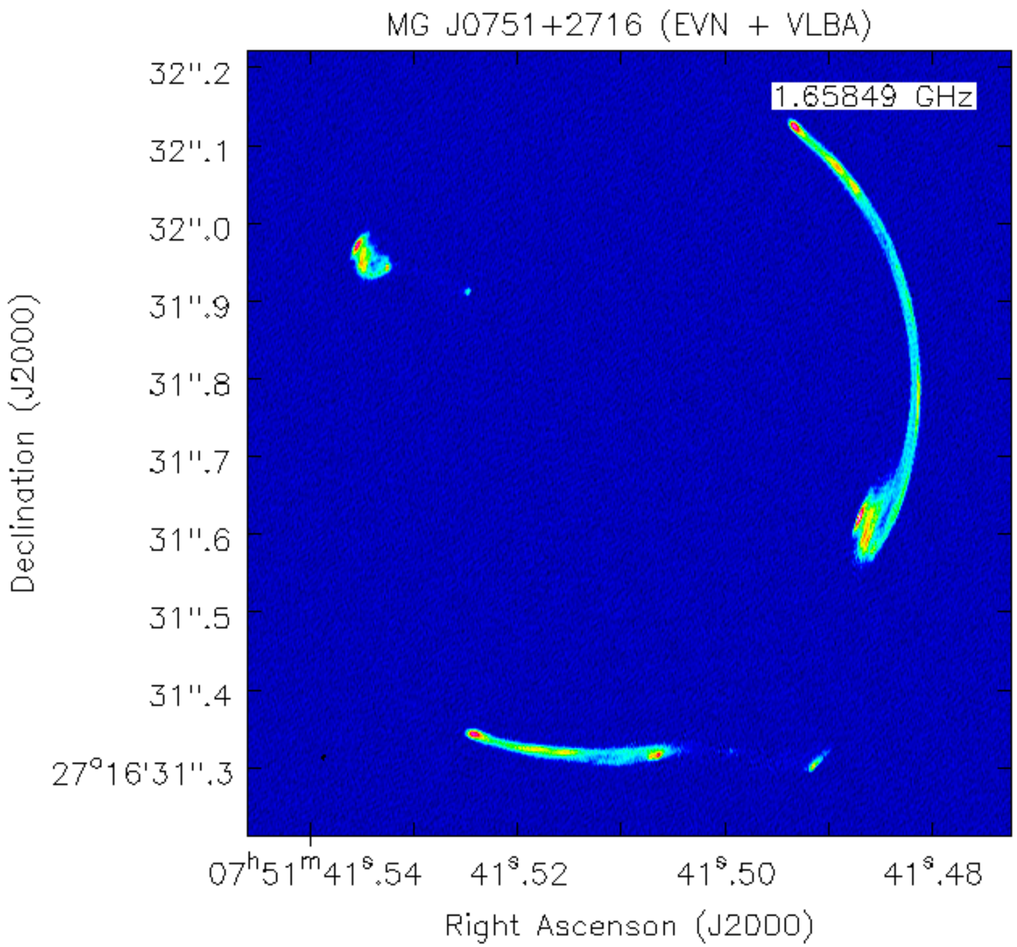


Science with VLBI

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

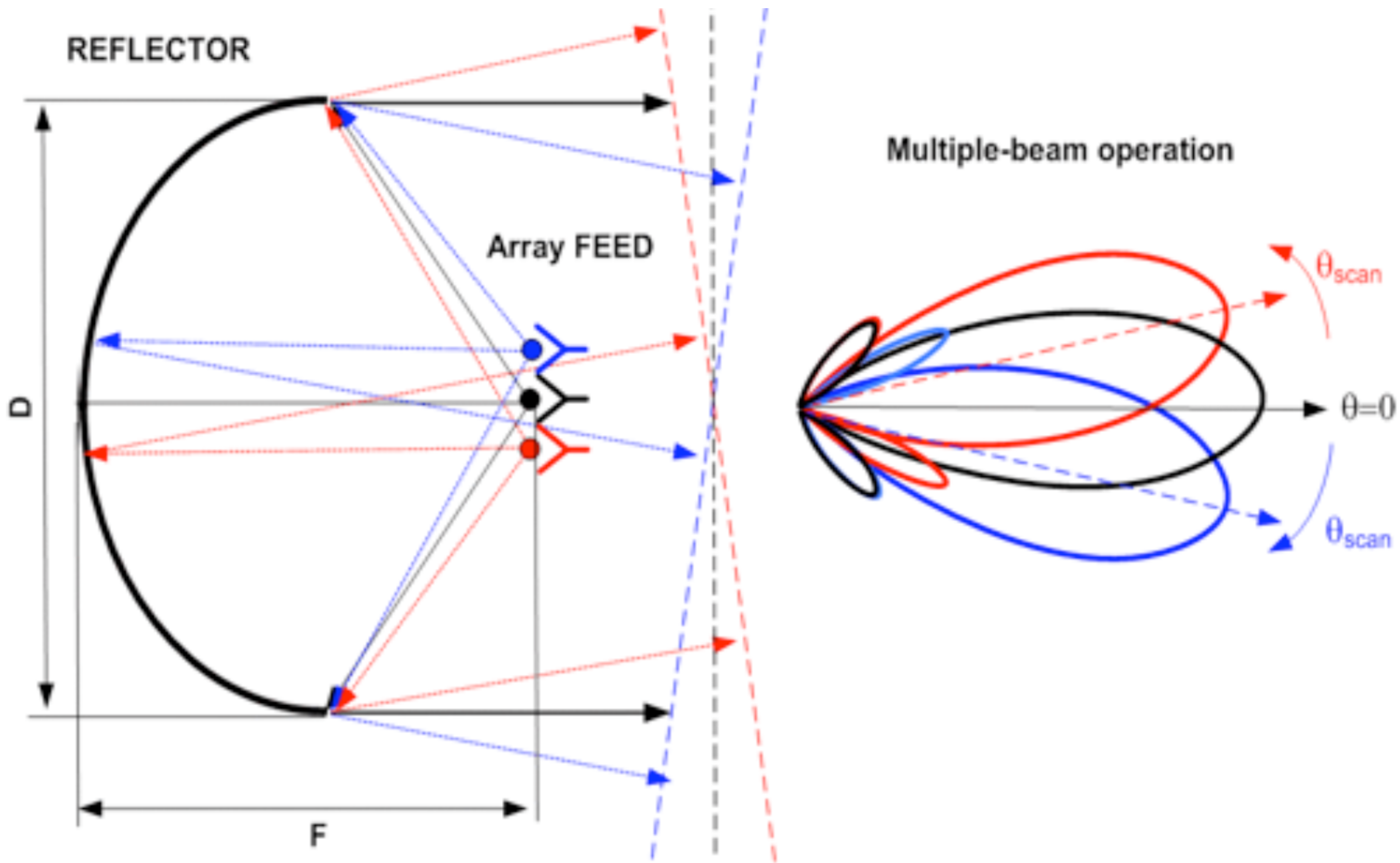




Cristiana Spingola

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-APERTIF

- 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.
- Aperture Tile in Focus (Apertif) will be installed in 2013.

	WSRT	Apertif
# receiving elements	1 horn (full pol)	121 Vivaldi (full pol)
# beams on sky	1	37
field of view	0.3 deg^2	8 deg^2
frequency range	115 - 8650 MHz	1000 - 1750 MHz
T_{sys}	30-35 K	50-55 K
aperture efficiency	55%	75%
bandwidth	160 MHz	300 MHz
# channels	1024	16384

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.
- T_{sys} ~ 50 K.
- 30 beams giving a total fov of 30 deg^2
- Instantaneous bandwidth up to 300 MHz

- Currently in construction / commissioning.
- 75% of observing time already set aside for key projects.

Beam forming a Phased Array Feed

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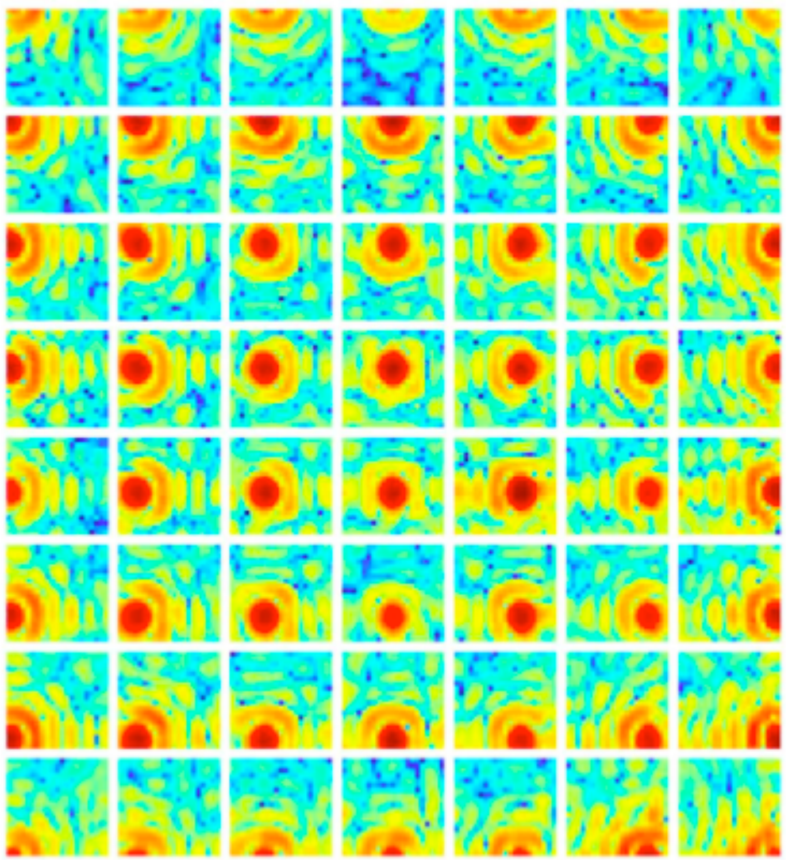
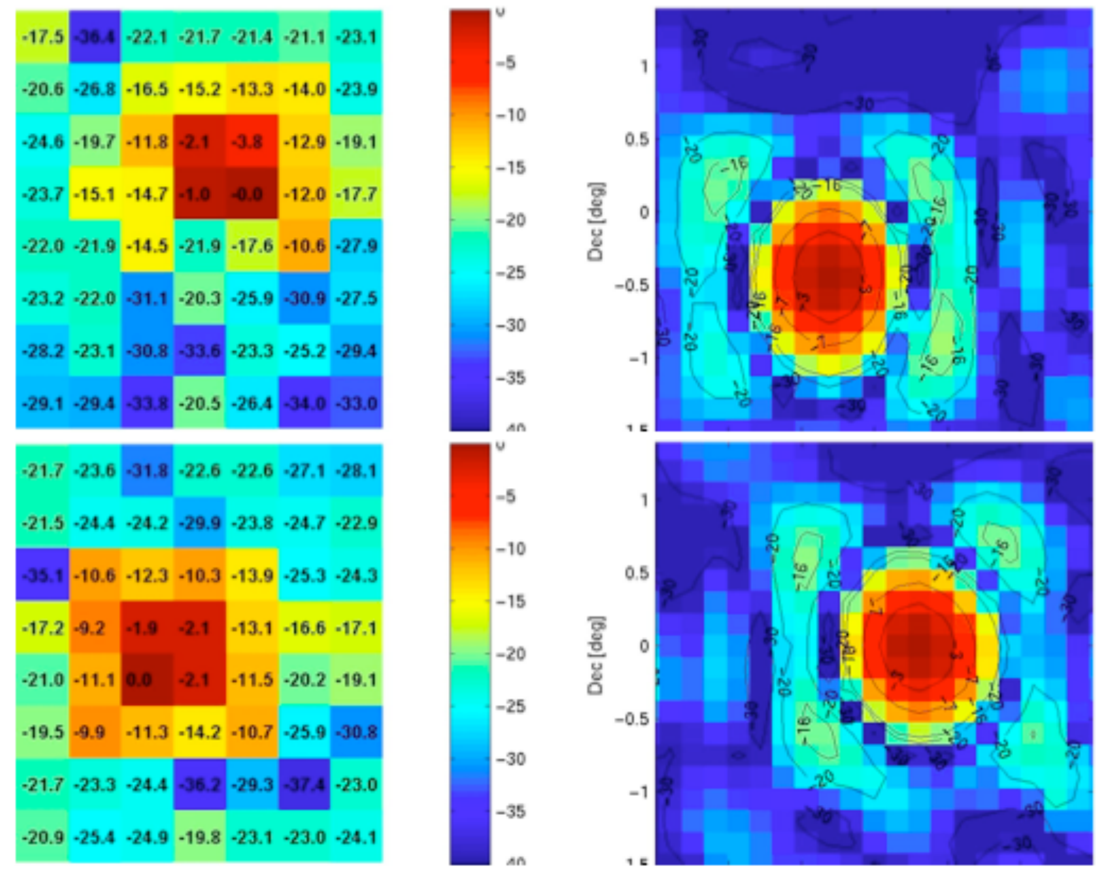


Individual element beams from the prototype Apertif PAH.

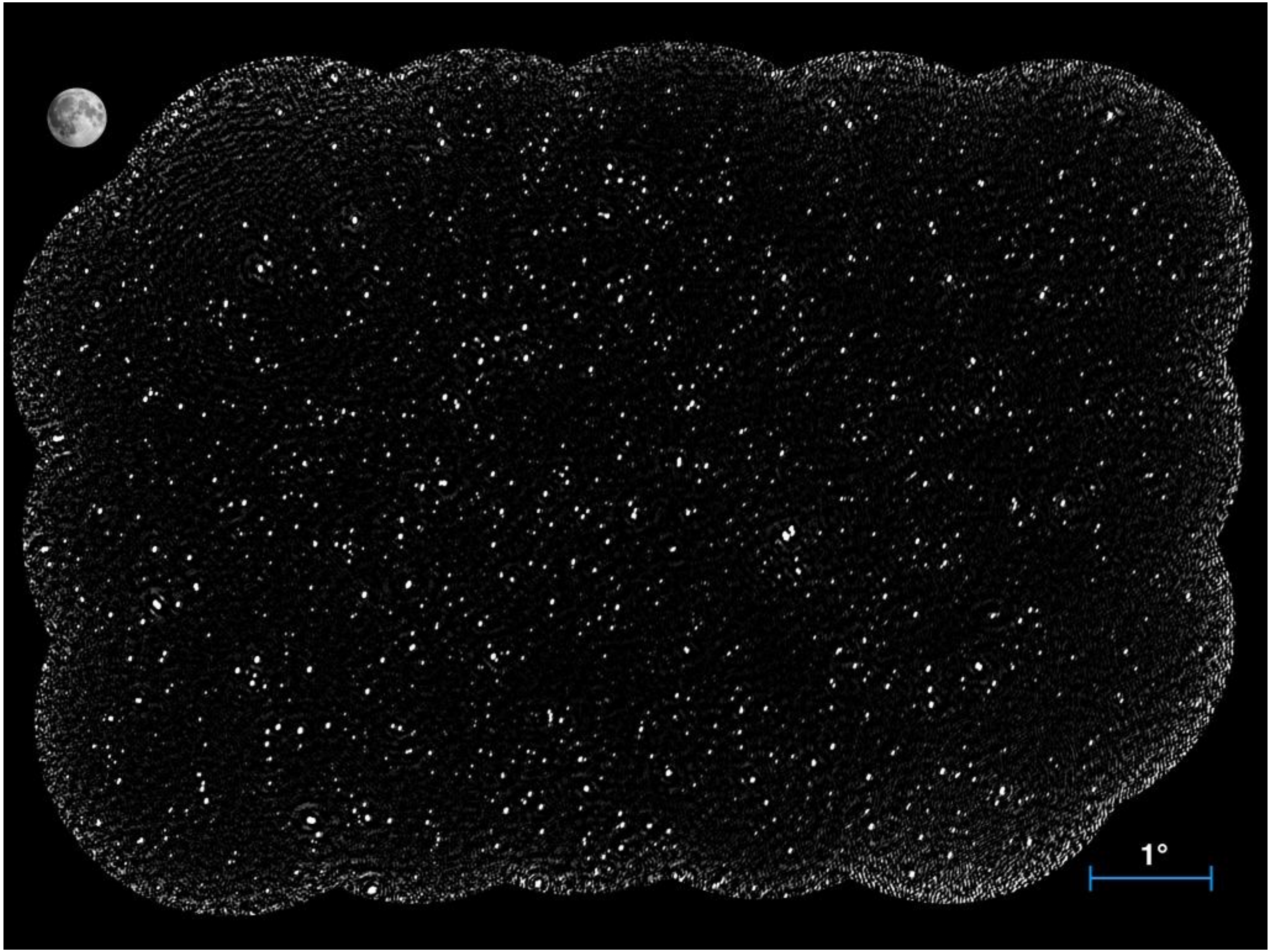
Each element observes a slightly different part of the sky.



Left: Weights used to form different tile beams.

Right: The resulting tile beams (same scale as before), with suppressed side-lobes.

Imaging with a Phased Array Feed



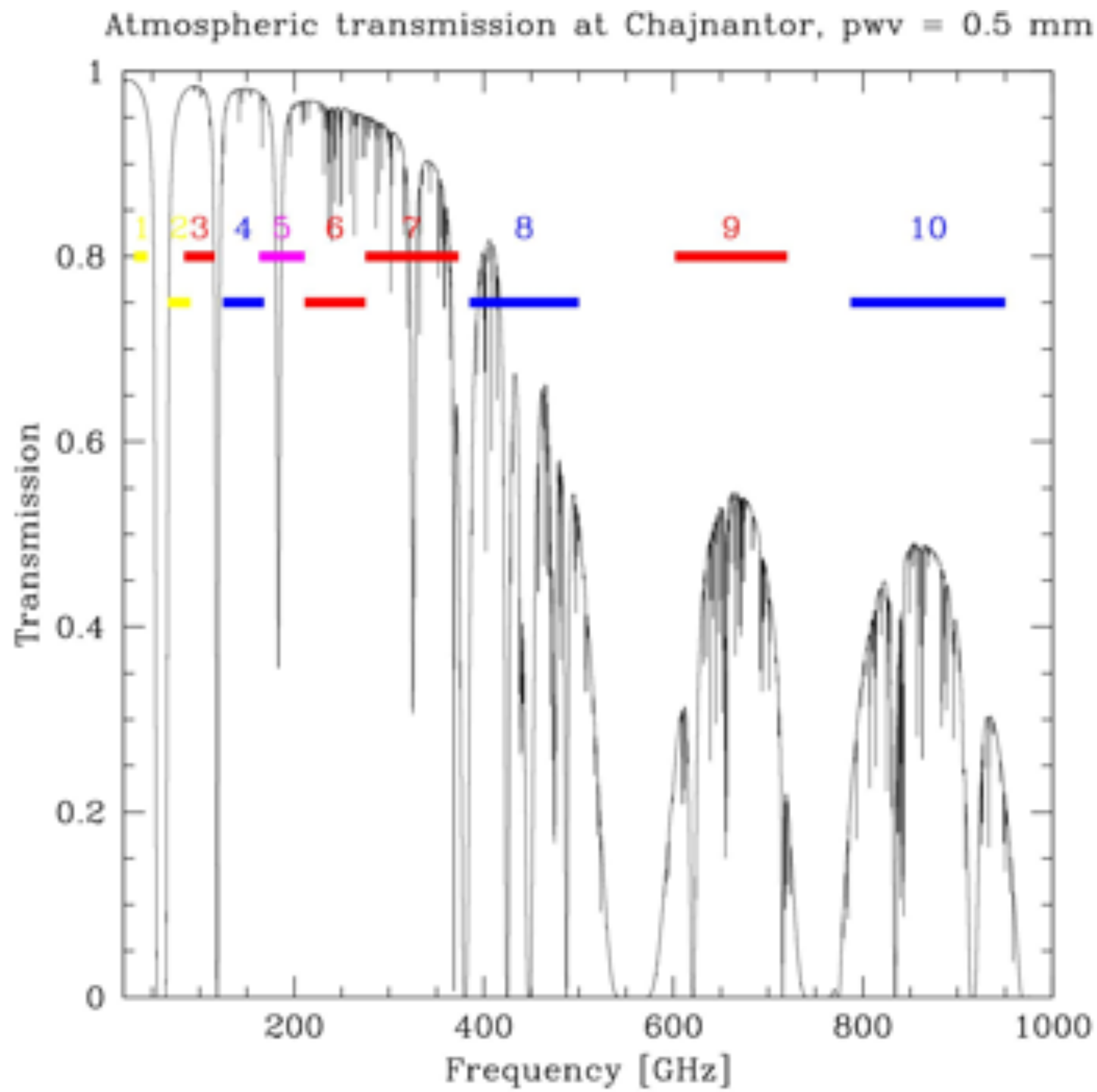
Ian Heywood

The mm-wavelength sky

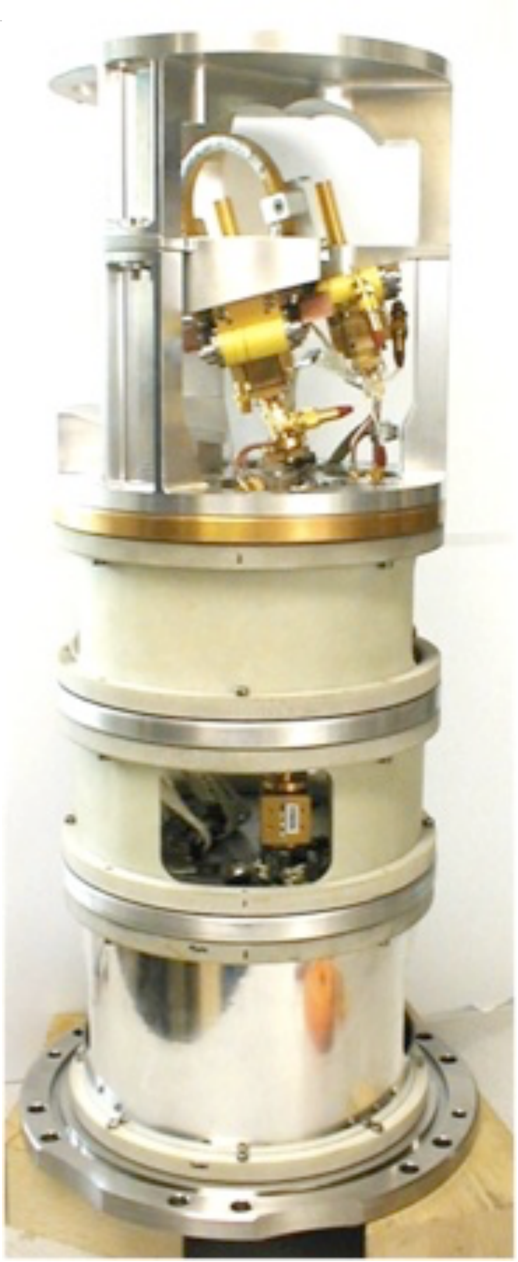
- Generally defined between 60 GHz (loosely) and 1 THz (atmospheric cut-off), must observe from space to observe at a higher frequency (e.g. *Herschel*)

- 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 Millimetre Array



- Atacama Large Millimeter Array (ALMA)
- Altitude: 5058.7 m, Atacama desert, Chile
- 54 x 12 m dishes
- 12 x 7 m dishes
- Frequency range: 85 GHz to 1 THz
- Baselines 15 m to 15 km

- Sensitive to heated dust (star-formation) and molecular emission.

The Atacama Large Millimetre Array

ALMA Band	Frequency Range (GHz)	Receiver Noise (K) over 80% of the RF band	Temperature (K) at any RF Frequency	To be produced by	Receiver Technology
1	31 - 45	17	26	tbd	HEMT
2	67 - 90	30	47	tbd	HEMT
3	84 - 116	37	60	HIA	SIS
4	125 - 163	51	82	NAOJ	SIS
5*	162 - 211	65	105	OSO	SIS
6	211 - 275	83	136	NRAO	SIS
7	275 - 373	147	219	IRAM	SIS
8	385 - 500	196	292	NAOJ	SIS
9	602 - 720	175	261	NOVA	SIS
10	787 - 950	230	344	NAOJ	SIS

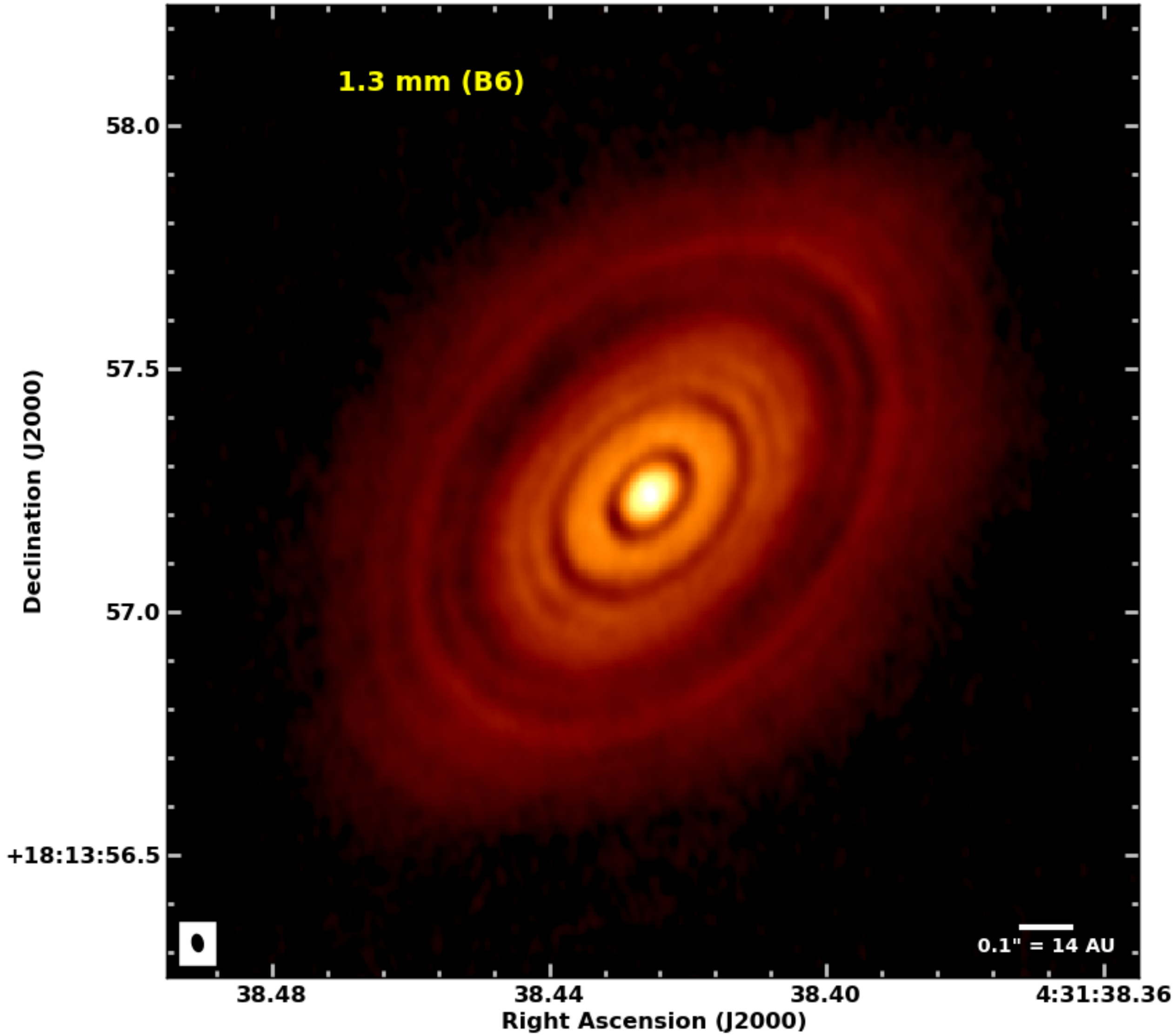
- HEMT (High electron mobility transistor)
- SIS (Superconductor-Insulator-Superconductor)

The Plateau de Bure interferometer

	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 m^2	1 766 m^2	2 120 m^2
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

Science with mm-arrays

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

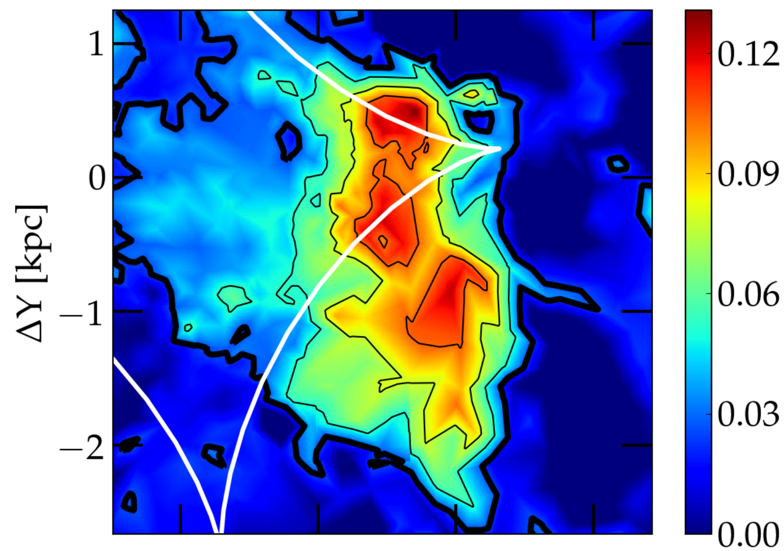


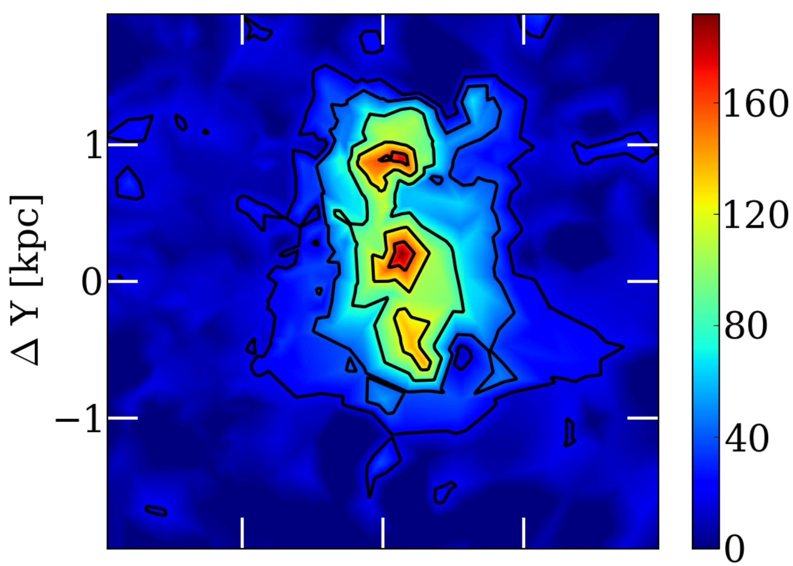
Science with mm-arrays

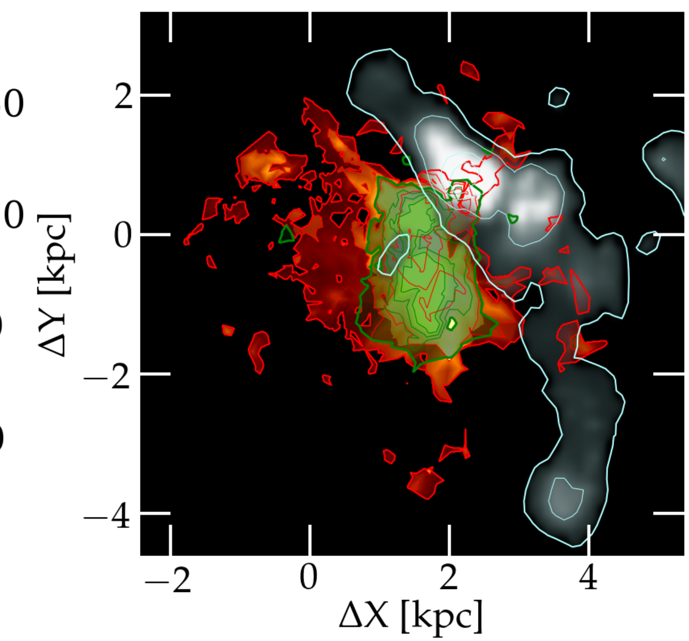
The mixture of dust, gas and stars can be mapped on parsec-scales in nearby mergers, like in the case of the ultra-luminous infrared galaxy, the Antennae.

Science with mm-arrays

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

The Square Kilometre Array

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- **A large radio telescope for new ground breaking science:**
- Up to 1 million m^2 (hence, SKA) distributed over up to ~3000 km (VLBI like baselines).
- 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

- **Final designs being discussed by the community right now!**

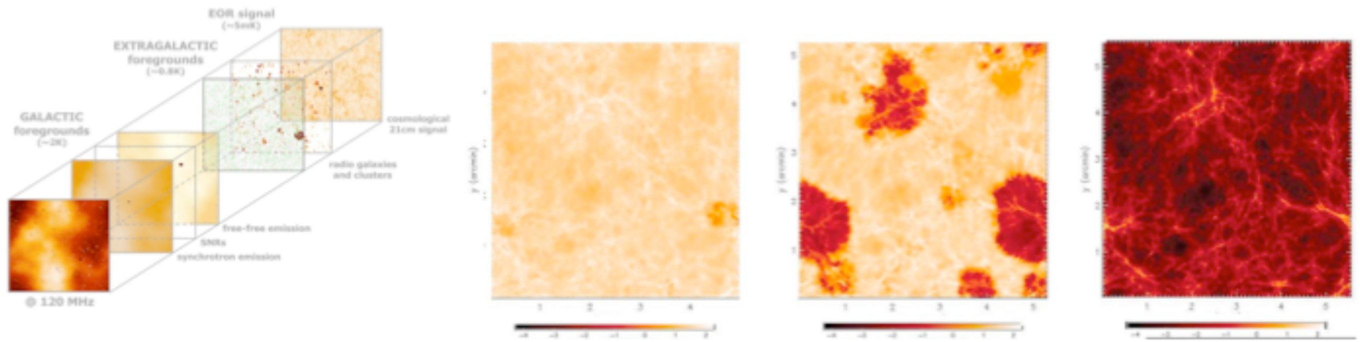
Key science goals

ASTRON

- **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.

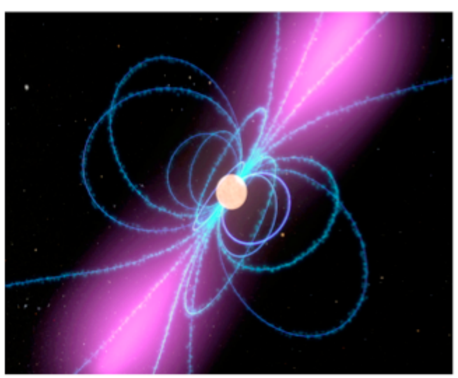
Important implications for galaxy formation

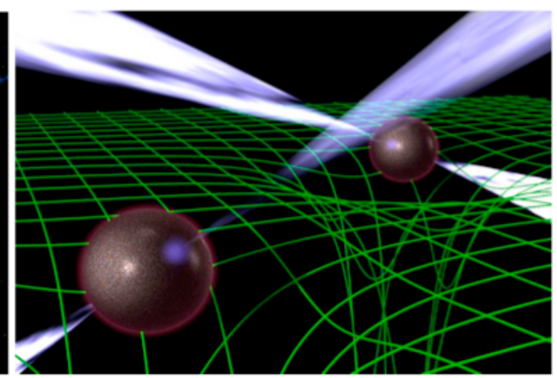
Vibor Jelic



- **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

Location, Location, Location

ASTRON

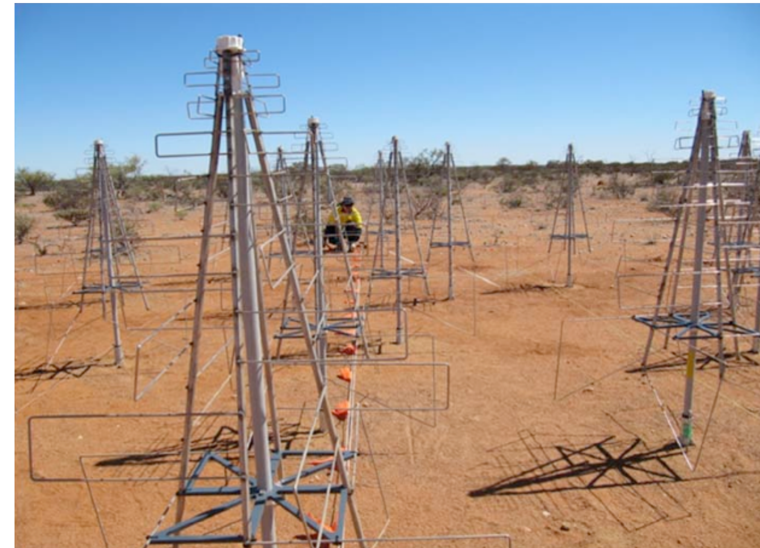
Southern Africa - SKA MID

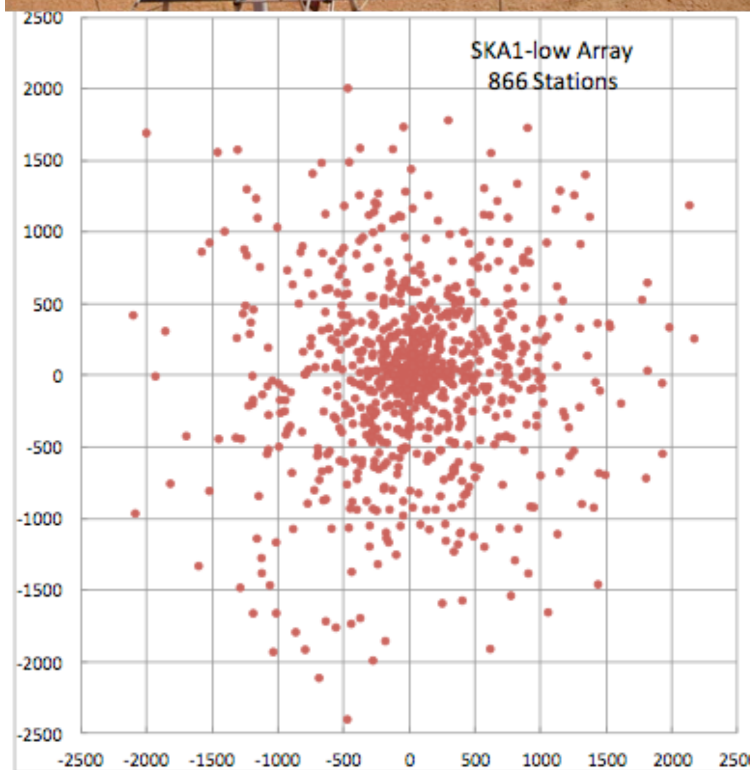
Australia and New Zealand - SKA LOW

SKA LOW

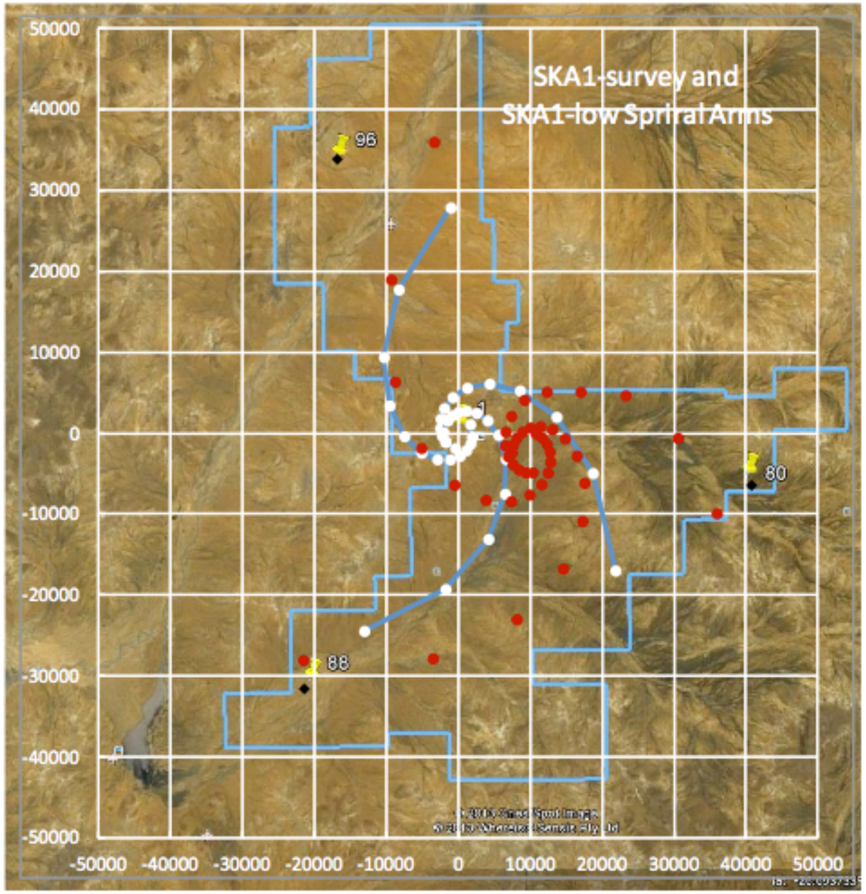
ASTRON

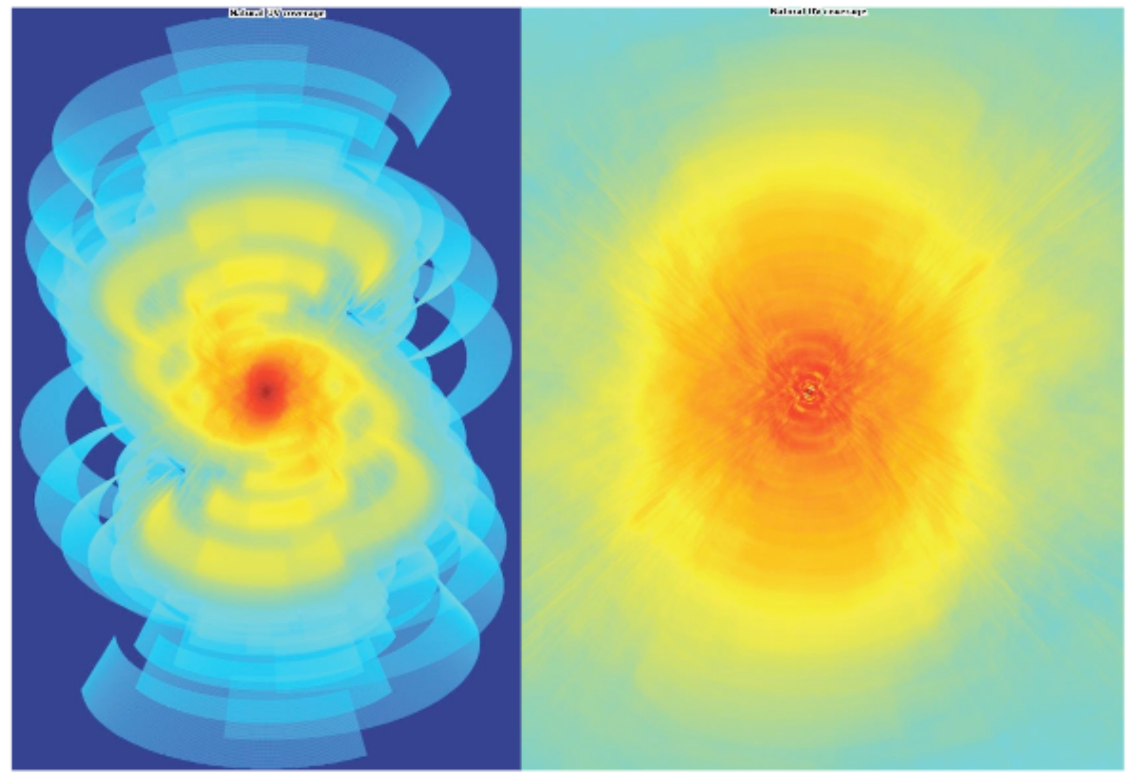
- Sparse dipoles (dual pol; similar to LOFAR).
- Freq: 50 to 350 MHz (300 MHz bandwidth).
- 130000 dipole antennas.
- 8 x more sensitive than LOFAR
- 50% collecting area at < 600 m, 75% at < 1 km.
- Spiral arms out to 50 km (100 km baselines), containing only ~4% of the collecting area.
- Dense core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





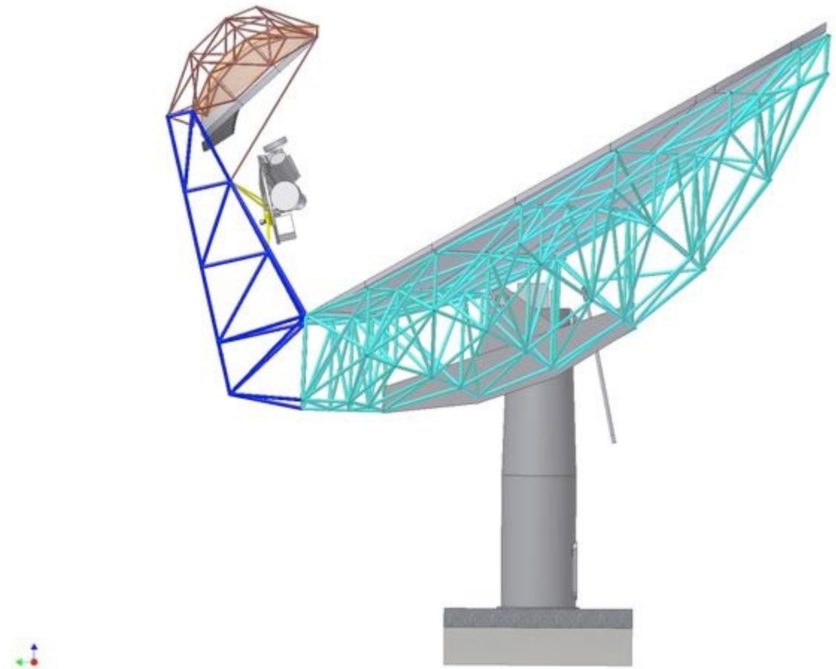
SKA LOW

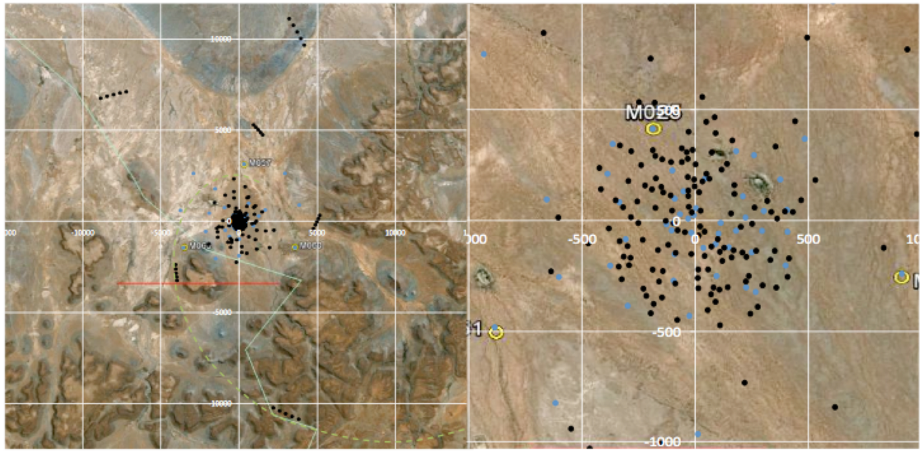

SKA1-survey and
SKA1-low Spriral Arms
96
80
88
50000
40000
30000
20000
10000
0
-10000
-20000
-30000
-40000
-50000
-50000 -40000 -30000 -20000 -10000 0 10000 20000 30000 40000 50000



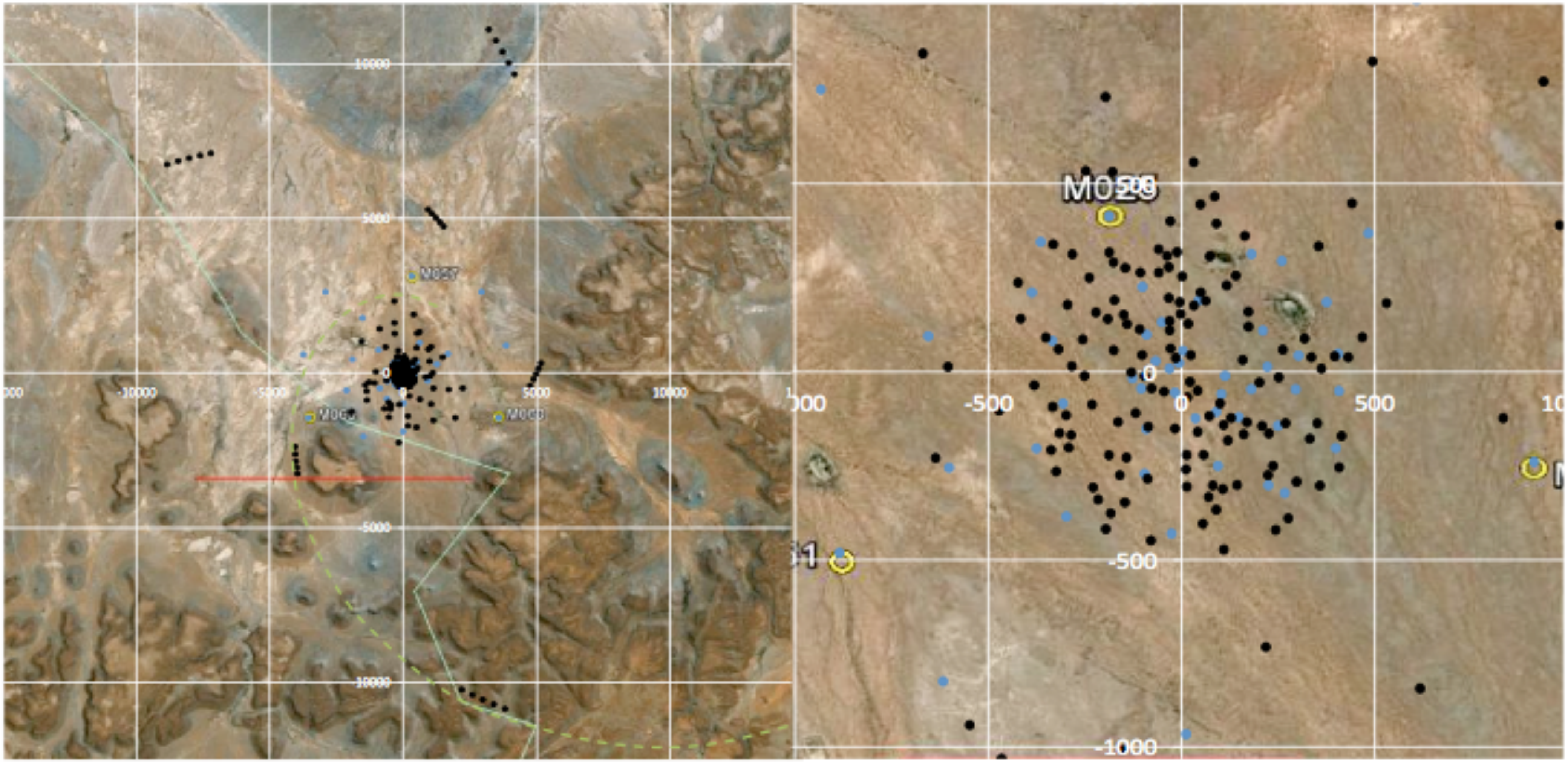
SKA MID

- 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.
- A_{eff} / T_{sys} ~ 1000 -- 1600 m^2 / K.

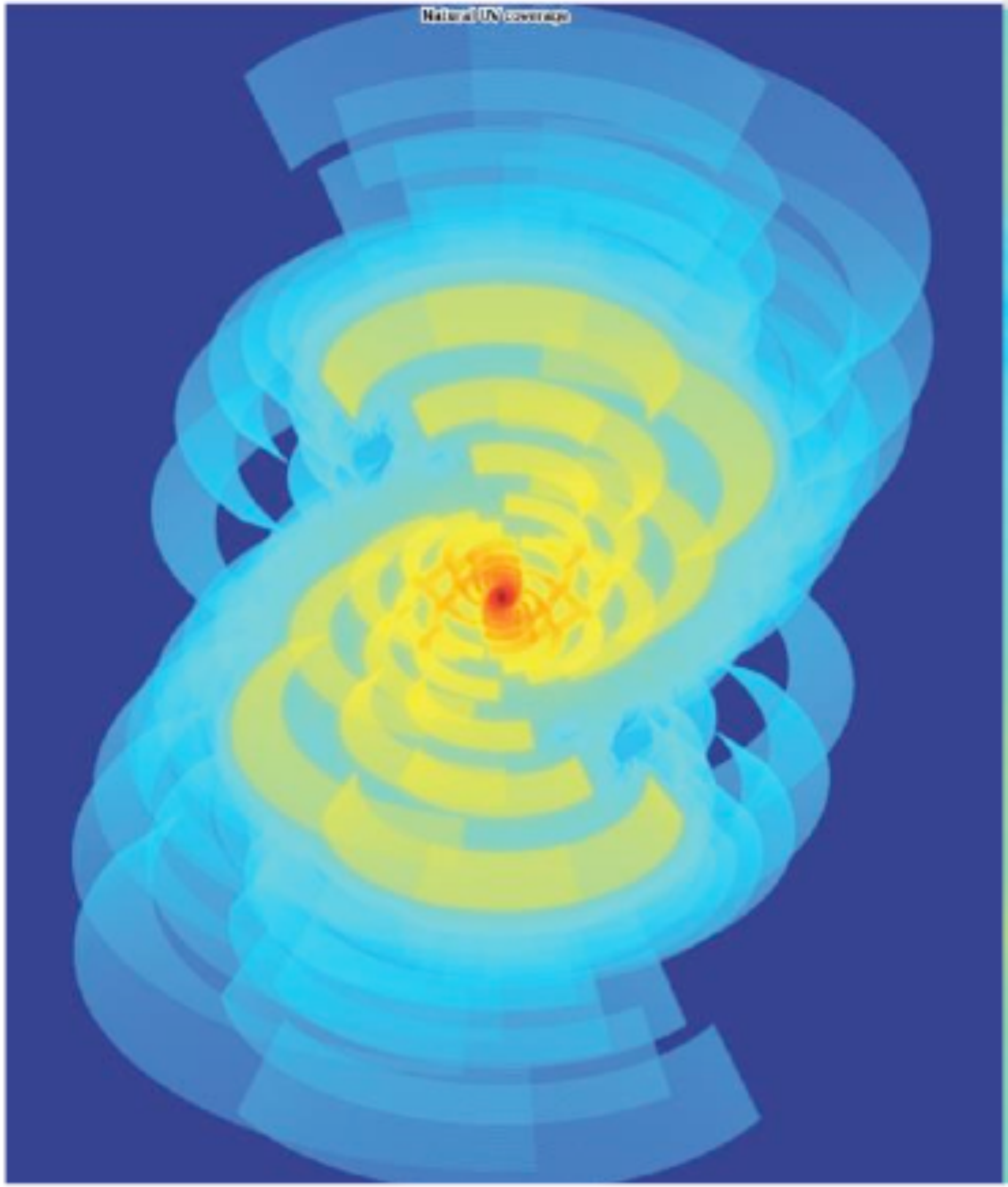


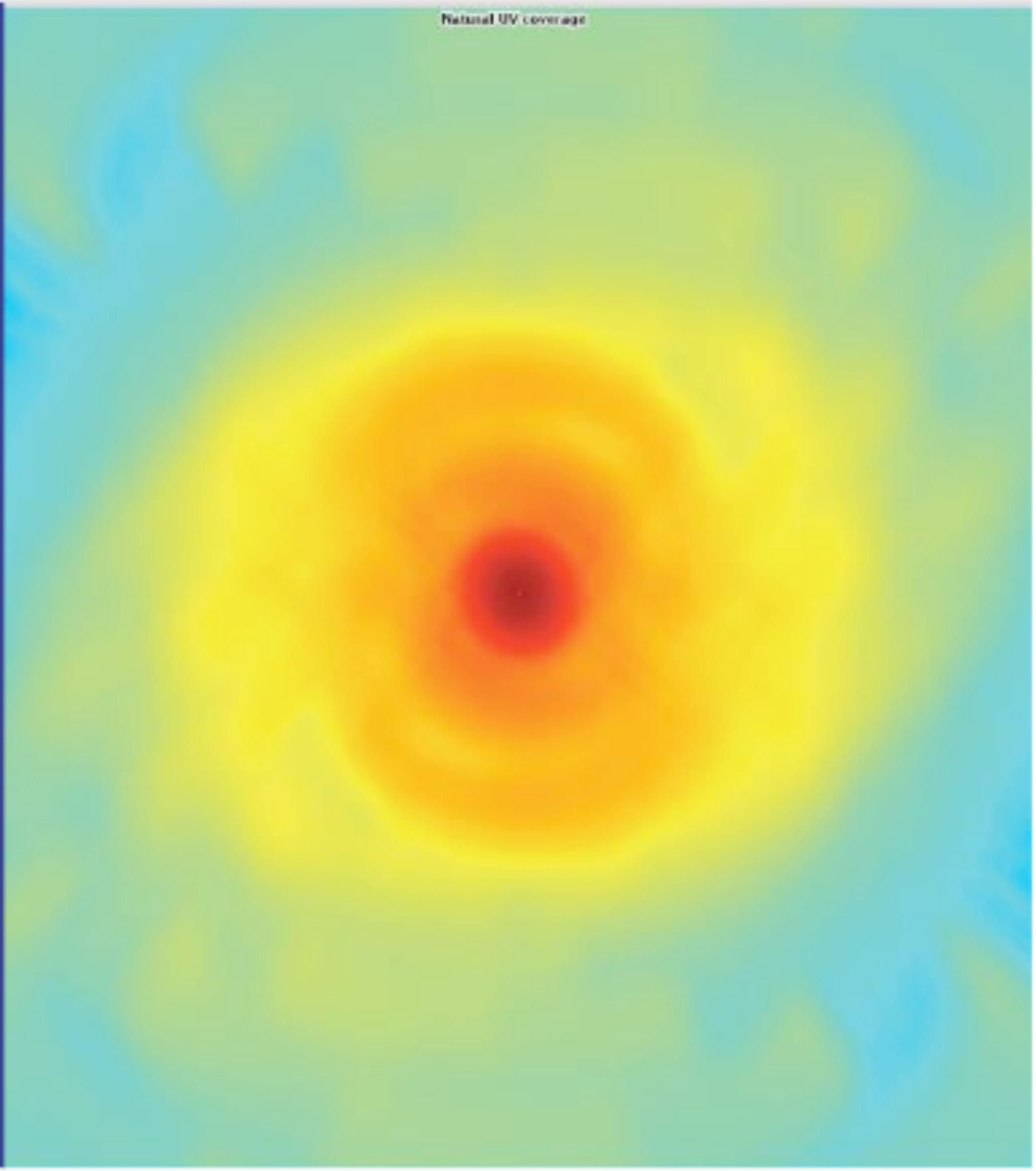


SKA MID



SKA MID





Square Kilometre Array

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...