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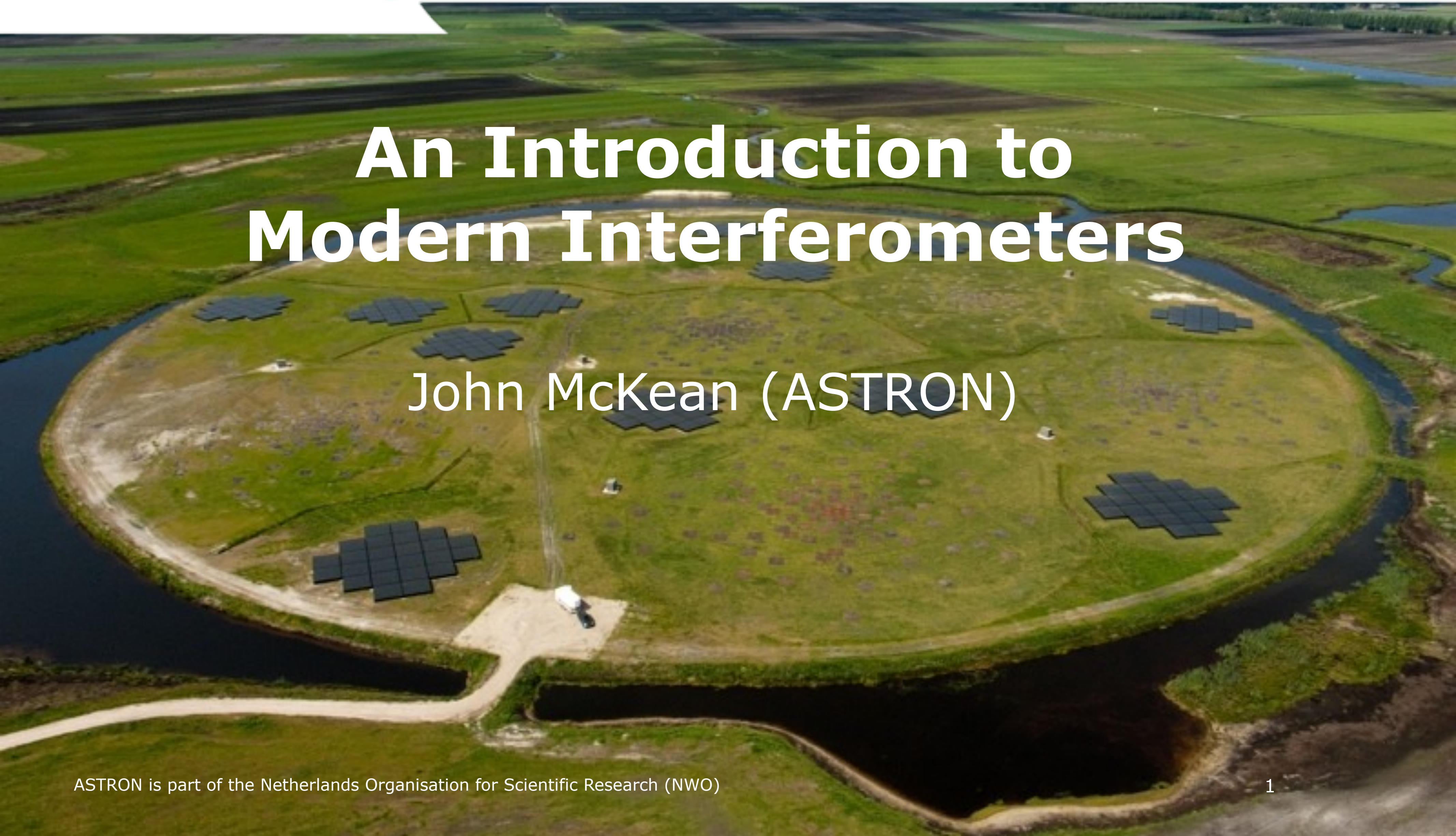
Netherlands Institute for Radio Astronomy



An Introduction to Modern Interferometers

John McKean (ASTRON)

Start at the end...

- The radio astronomy community is driving towards a new Great Observatory - the SKA!.
- Currently developing the technologies to make the SKA a reality.

Preamble

http://www.astron.nl/~mckean/ERIS-2013-1.pdf

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

- **OBJECTIVES:**

  i) The capabilities and limitations of newly upgraded radio astronomy facilities (JVLA, ATCA, e-MERLIN).

  ii) New technologies being developed for the pathfinders of the Square Kilometre Array (MeerKAT, ASKAP, EMBRACE, LOFAR, MWA).

  iii) The Square Kilometre Array (SKA).

- **NOTE:** There will be detailed introductions to the VLBI, ALMA and LOFAR arrays in other Lectures by Campbell, Bremer & McKean.

Overview

- The next generation of upgraded and new single pixel interferometers.
- Aperture Arrays (AAs) and Phased Array Feeds (PAHs)
- The Pathfinders
- The Square Kilometre Array
- Summary

How to upgrade your array

- **Single Pixel Receiver:** Telescopes with a single receiver in the focal plane at any given time - See Focal Plane Arrays later for multiple pixel receivers.

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

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

- The sensitivity of an array is defined as,

$$S_{\mathrm{rms}} = \frac{1}{\eta_c}\ \frac{\mathrm{SEFD}}{\sqrt{n_{\mathrm{pol}}\ \Delta\nu\ t}}$$

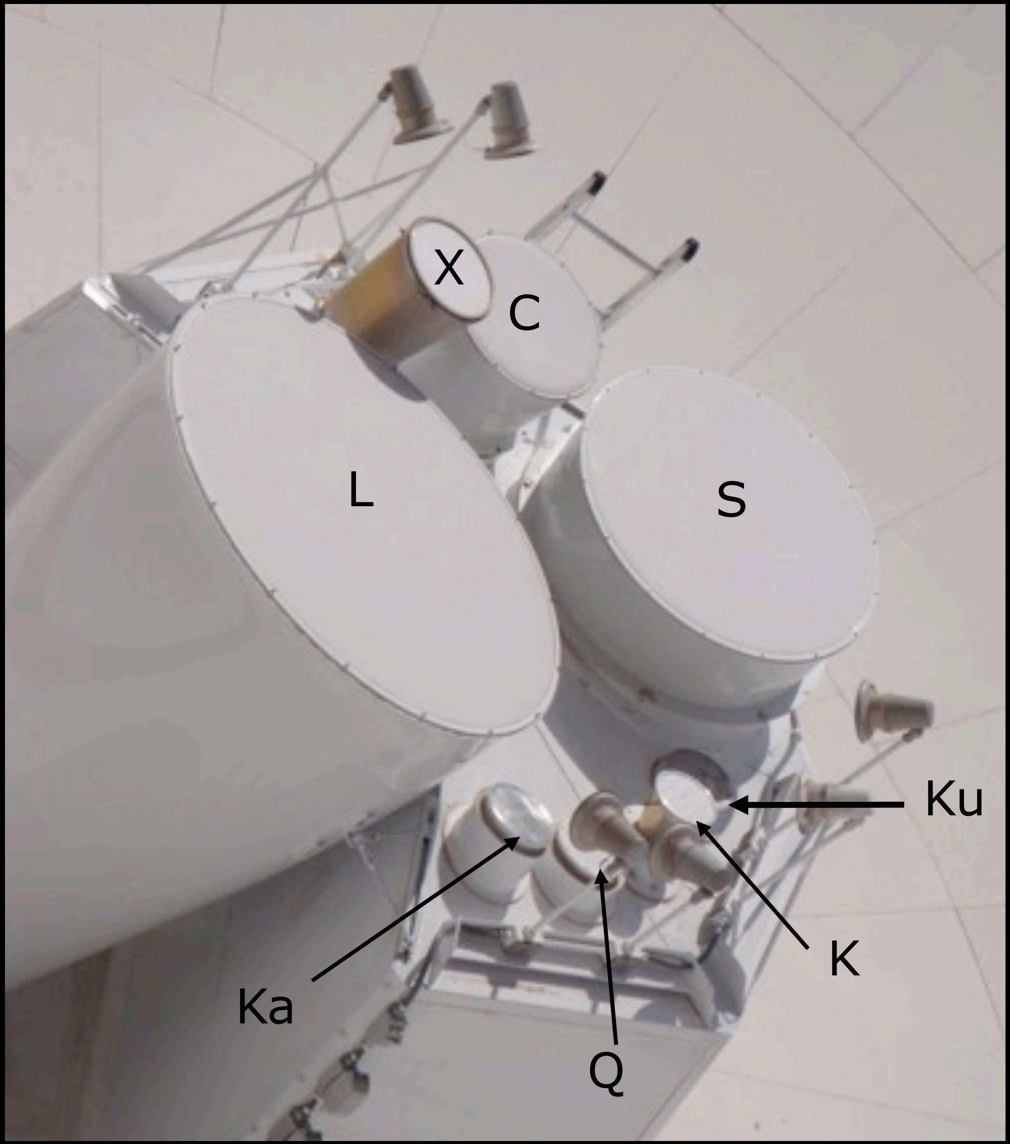
- Increase effective collecting area or bandwidth, decrease receiver temperature.

The Expanded Very Large Array

- Built in the 1960s.
- 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.

New receivers and feeds

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 WIDAR Correlator

- New WIDAR correlator allows full polarisation, large bandwidth, 10^5 spectral channels.
- For dual polarization (RR, LL) [* 10 second averaging],

Jim Condon

	Freq.	IF BW	SW Width	# SWP	Freq. Res.	Vel. Res.	Nch per	Nch	Data rate*
	GHz	GHz	MHz		kHz	km/s	spctrm	total	MB/s
L	1—2	1.024	16	64	15.6	3.1	1024	131072	50
S	2—4	2.048	32	64	62	6.3	512	65536	25
C	4—8	4.096	64	64	250	12.5	256	32767	12
X	8—12	4.096	64	64	250	7.5	256	32767	12
U	12—18	6.144	128	48	1000	20	128	12288	4.8
K	18—26.5	8.192	128	64	1000	13	128	16384	6.2
A	26.5—40	8.192	128	64	1000	9	128	16384	6.2
Q	40--50	8.192	128	64	1000	6.5	128	16384	6.2

Improved sensitivity

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

Jim Condon

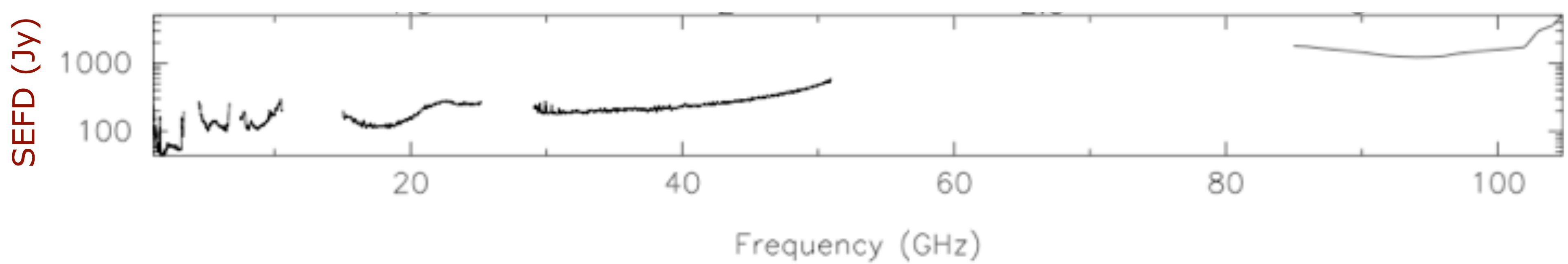
Band	Code	Effective BW	SEFD	σ(cont)	σ(line)
GHz		GHz	Jy	μJy	mJy
1 – 2	L	0.75	400	5.5	2.2
2 – 4	S	1.75	350	3.9	1.7
4 – 8	C	3.5	300	2.4	1.0
8 – 12	X	4	250	1.8	0.65
12 – 18	Ku	6	280	1.7	0.61
18 – 27	K	8	450	2.3	0.77
27 – 40	Ka	8	620	3.2	0.90
40 -- 50	Q	8	1100	5.6	1.4

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.

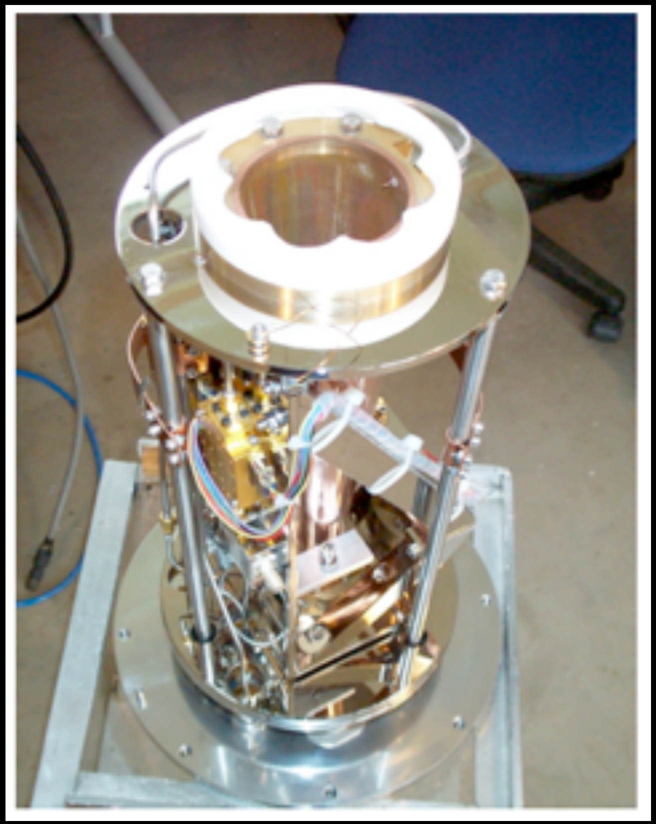
- New broad band receivers installed (from 2 x 123 MHz to 2 x 2 GHz).



e-MERLIN

- Multi-Element Radio Link Interferometer Network (MERLIN).
- Up to seven telescopes (~25 to 76 m) can be used.
- Upgrade:
  - New receivers
  - Fibre link
  - Larger observable bandwidth
- Max. baseline is 217 km.
- Excellent resolution (230 mas / ν_{GHz}).
- Link between VLA/ATCA and VLBI.

New wide-band receivers



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

- Lenses used to fast switch between different bands.

- Reaching the theoretical limit for receiver technologies

  Feeds, Low noise amplifiers, etc.

- Sampling and digital signal processing at 4 G samples / s.

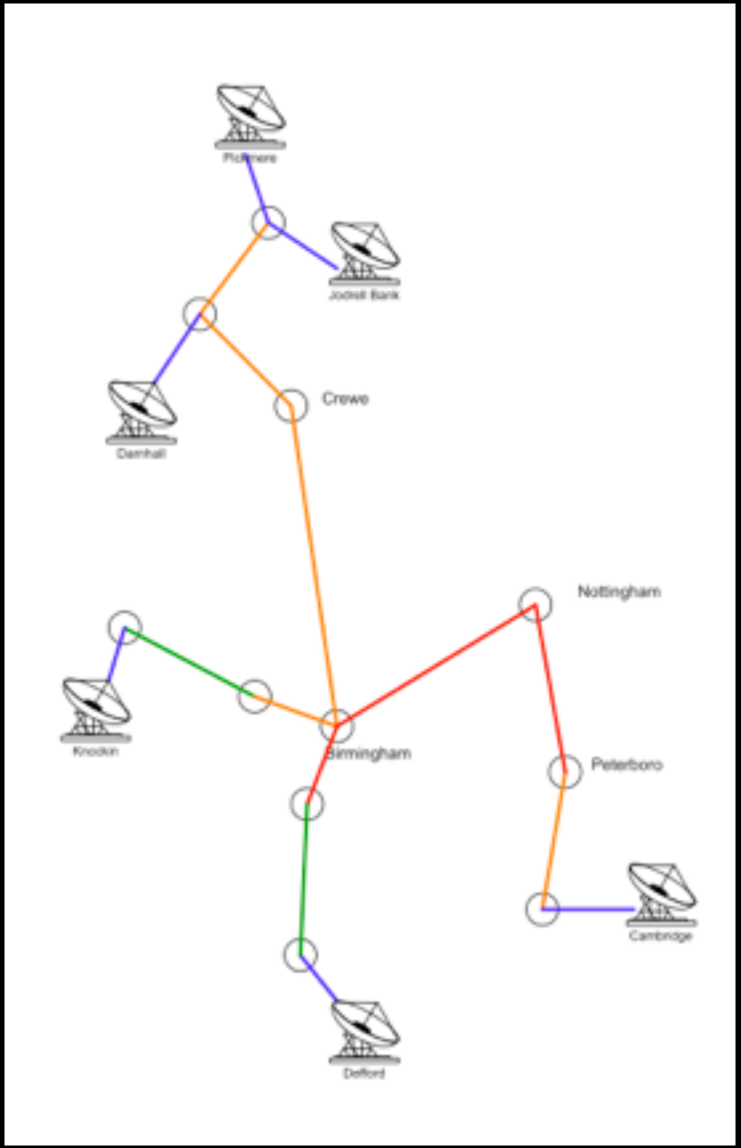
Fibre linked to the correlator

- The array is no longer ‘radio linked’, but is connected via optical fibres.
- Need to sustain a data rate of 30 Gb/s from each telescope.
- Pushing fibre technology (along with eVLBI).

- Data processed in a new correlator - similar to the new EVLA correlator.
- 2/4 GHz output (dual/single polarization) [from 16/32 MHz]
- 16 placeable subbands; independent width and channelization.

    0.25--128 MHz BW

    512--131072 channels



Capabilities

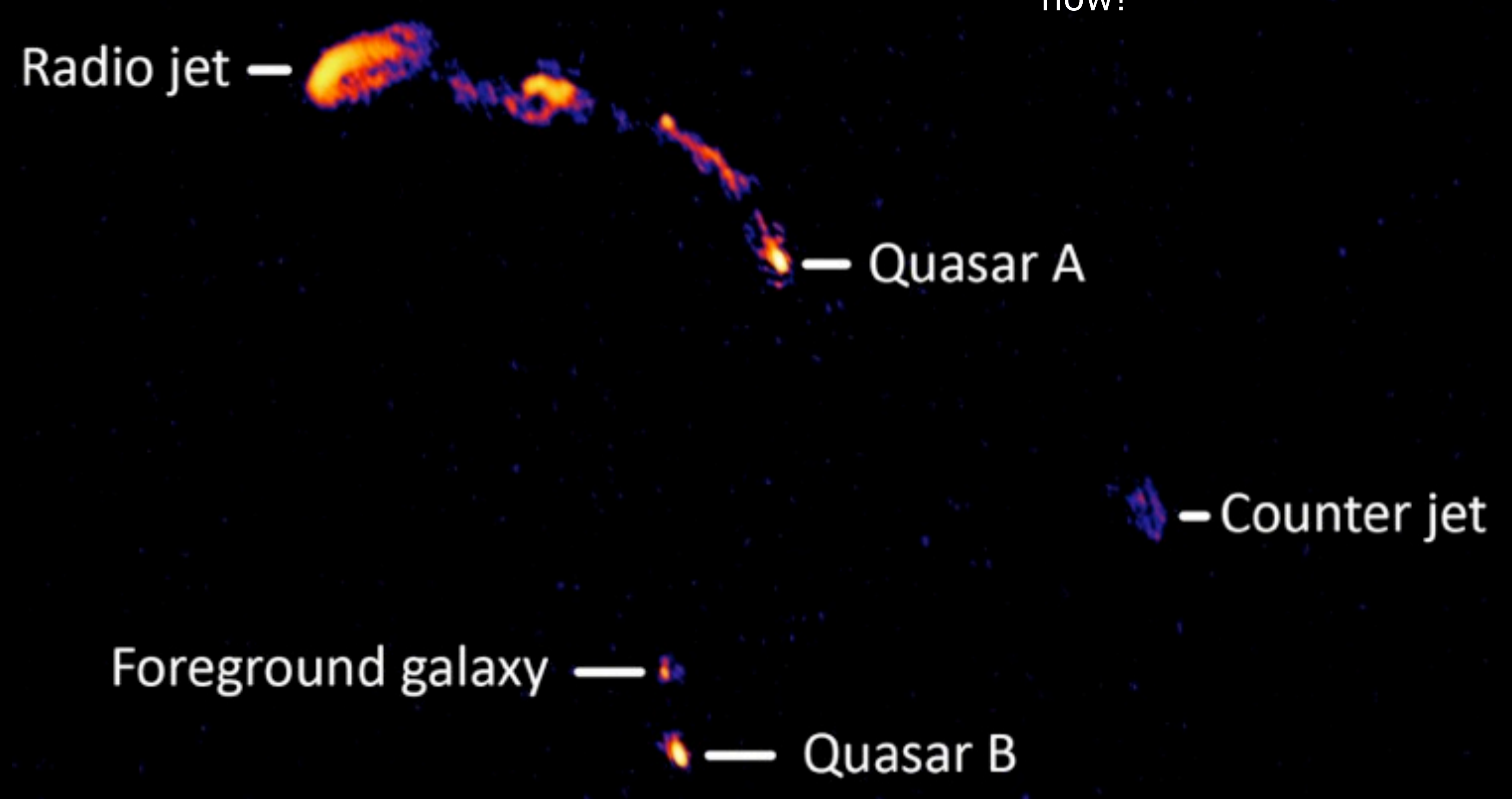
Table 1: Basic observing capabilities of e-MERLIN

	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.

e-MERLIN: First Images

Commissioning right now!



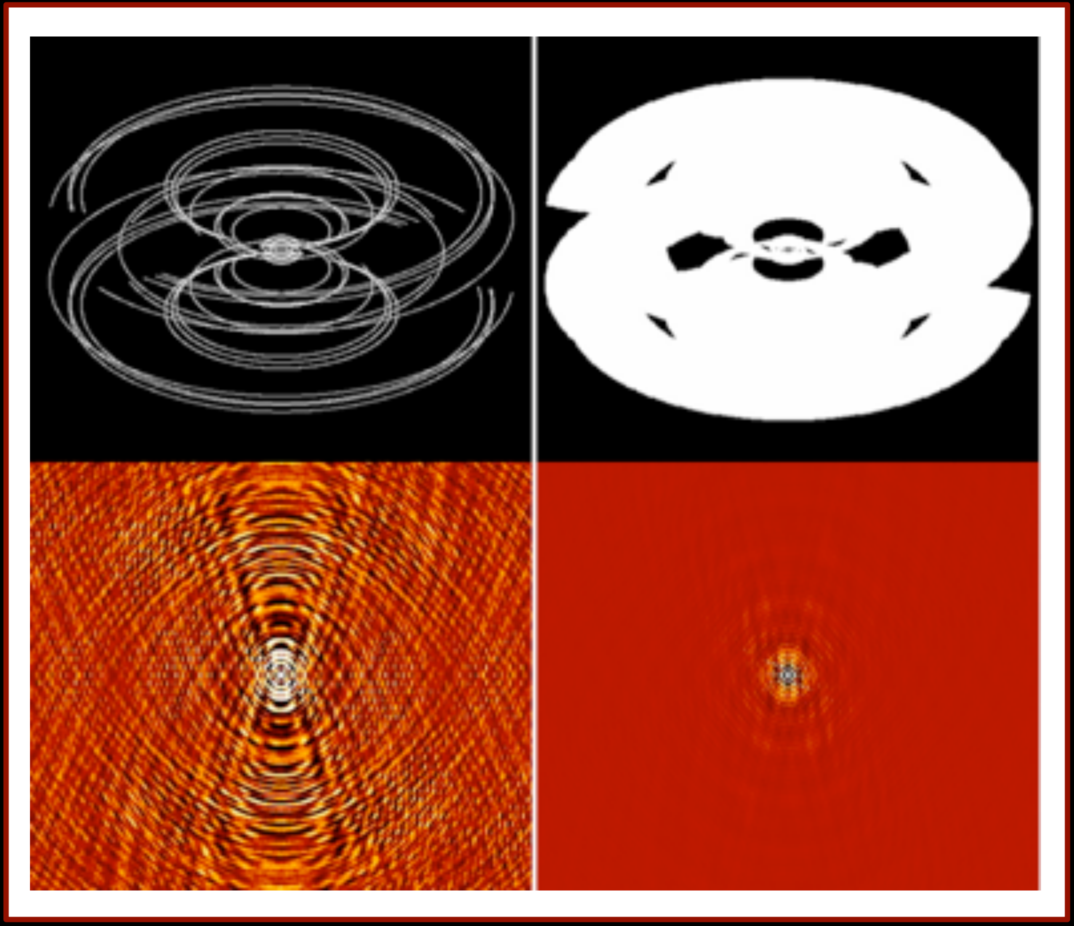
Science with the new single pixel arrays

- **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.

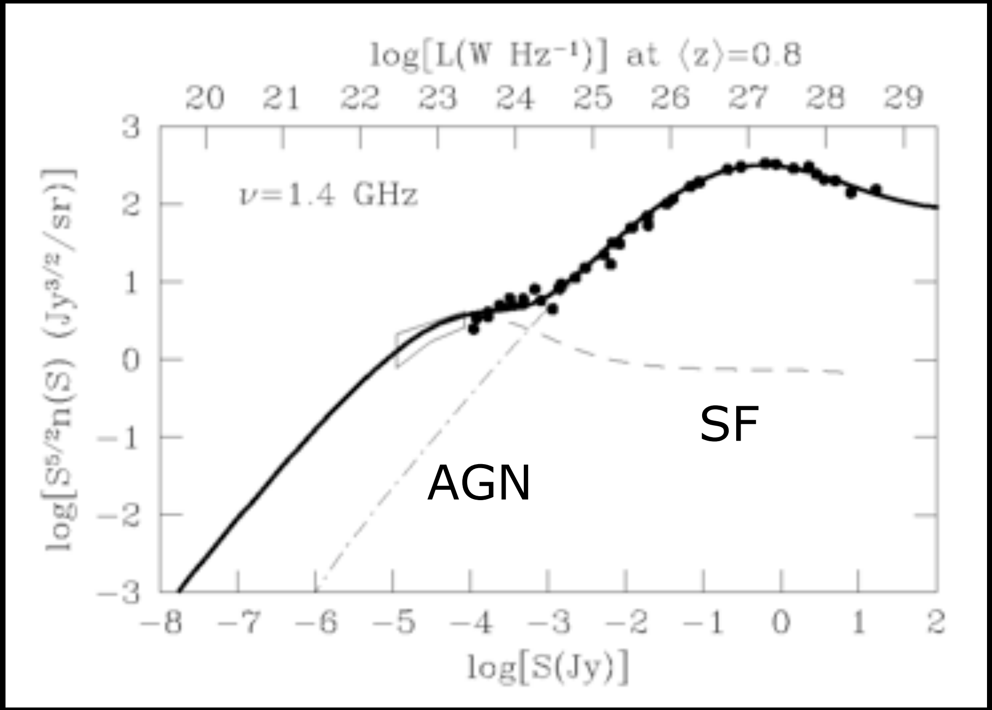
- Better sensitivity to sources over different angular scales (need to know the spectral index...)

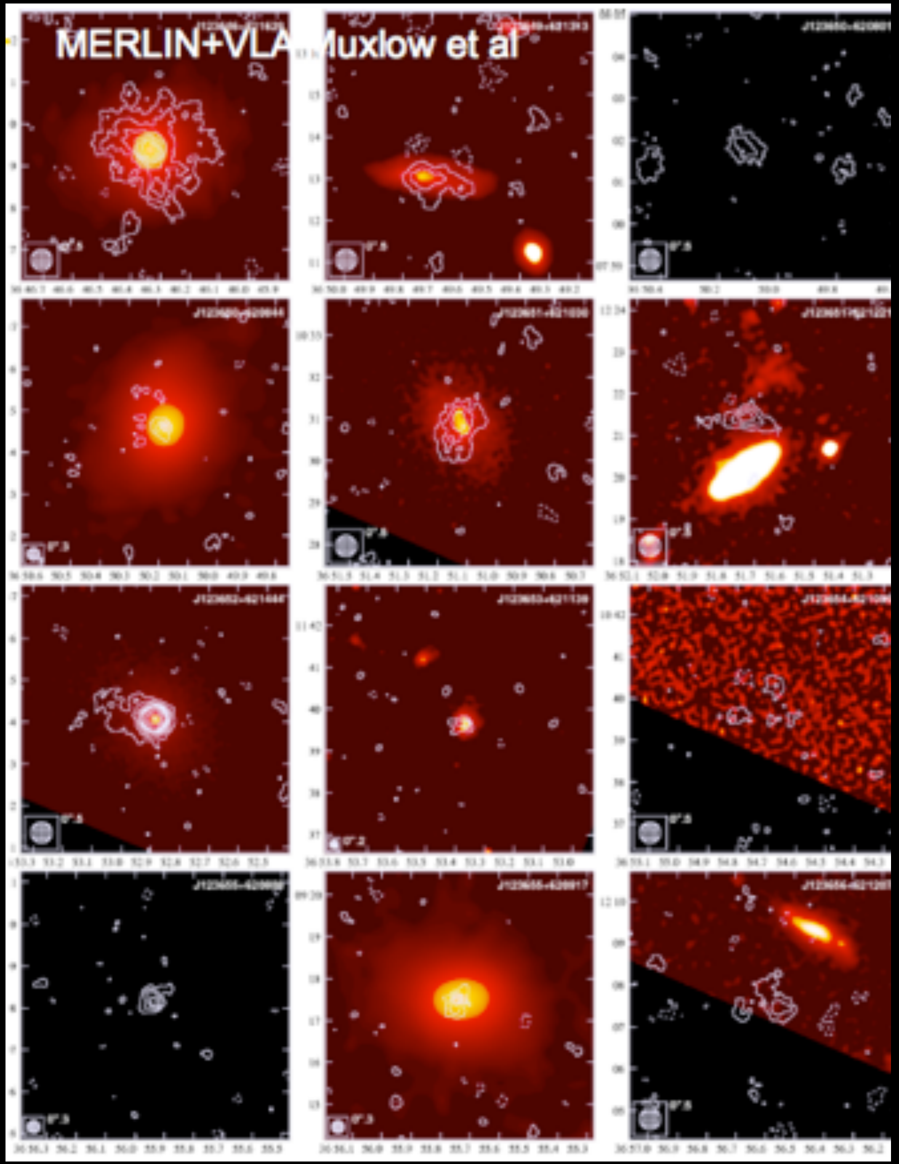


Simon Garrington

Very deep imaging surveys

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





Spectral line

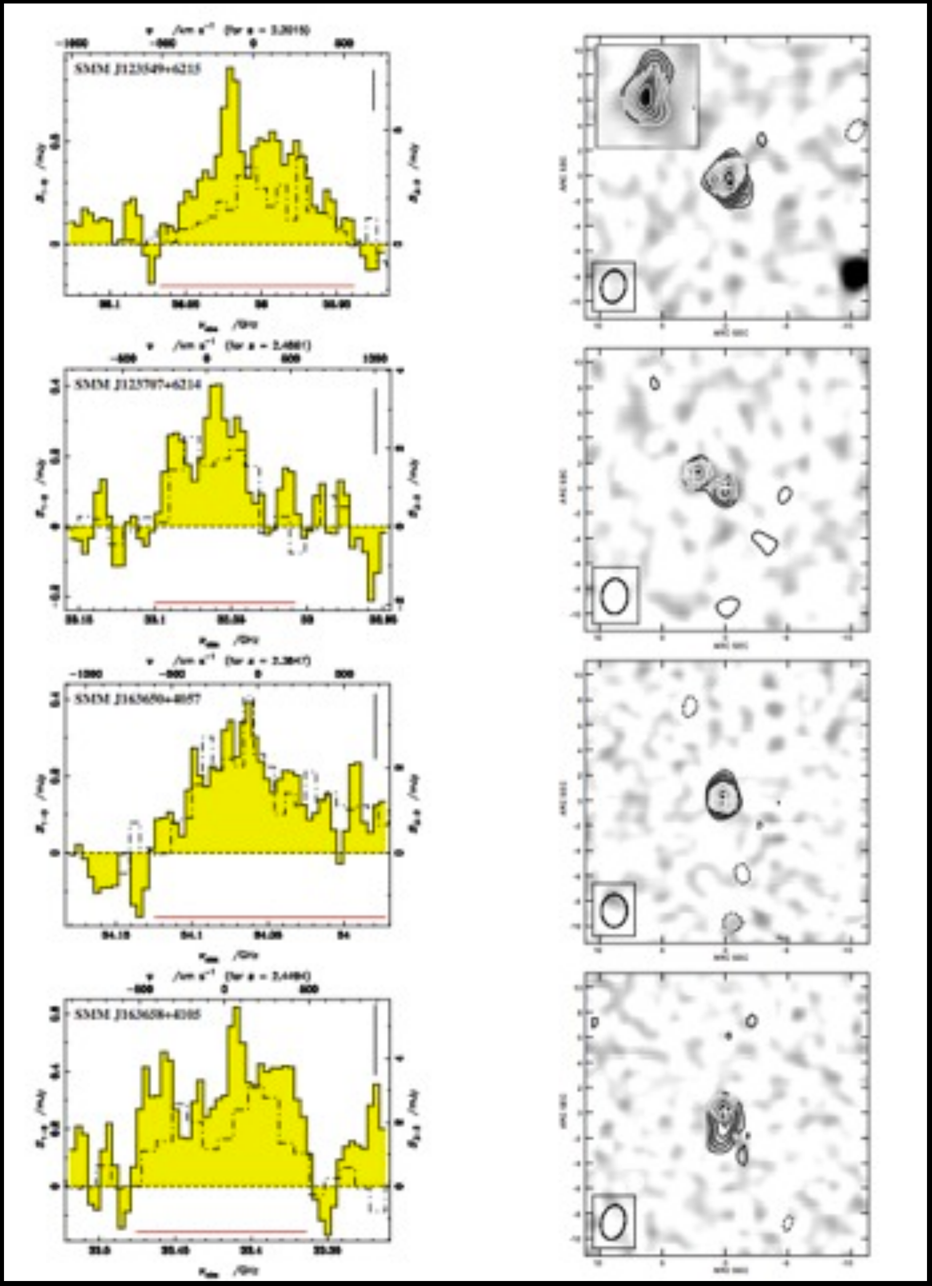
- Large bandwidths and flexible correlators will allow new spectral line studies to be carried out.

- 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 begining!



Overview

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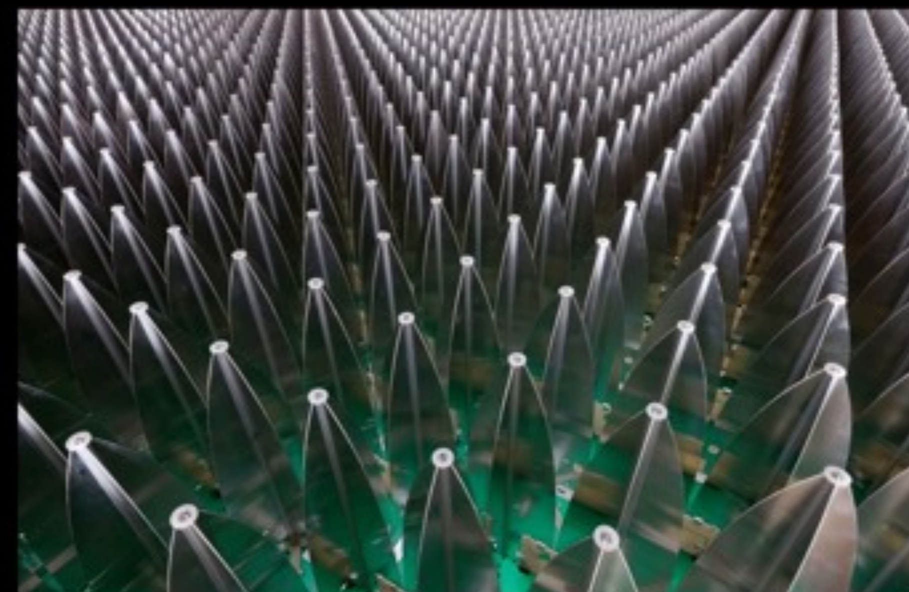
Aperture Arrays

- Technology for the SKA will need flexible imaging at low frequencies (10 MHz to ~1.0 GHz), with large collecting areas.
- No longer need the surface accuracy of dishes.



EMBRACE Aperture Array

- **Advantages:**

  Cheap, large fields-of-view, multiple beams, fast beam switching.

- **Dis-advantages:**

  lower instantaneous bandwidth? lower A_{eff} / T_{sys}? ν_{obs} < 1.5 GHz?

Beam-forming

- Unlike standard telescopes, aperture arrays have no moving parts.
- The operation of forming a weighted sum of the dipole, tile, or antenna signals is called beam-forming.
- Goal is to add (maximise) the signals from a specific direction and frequency coherently, while suppressing all other signals.

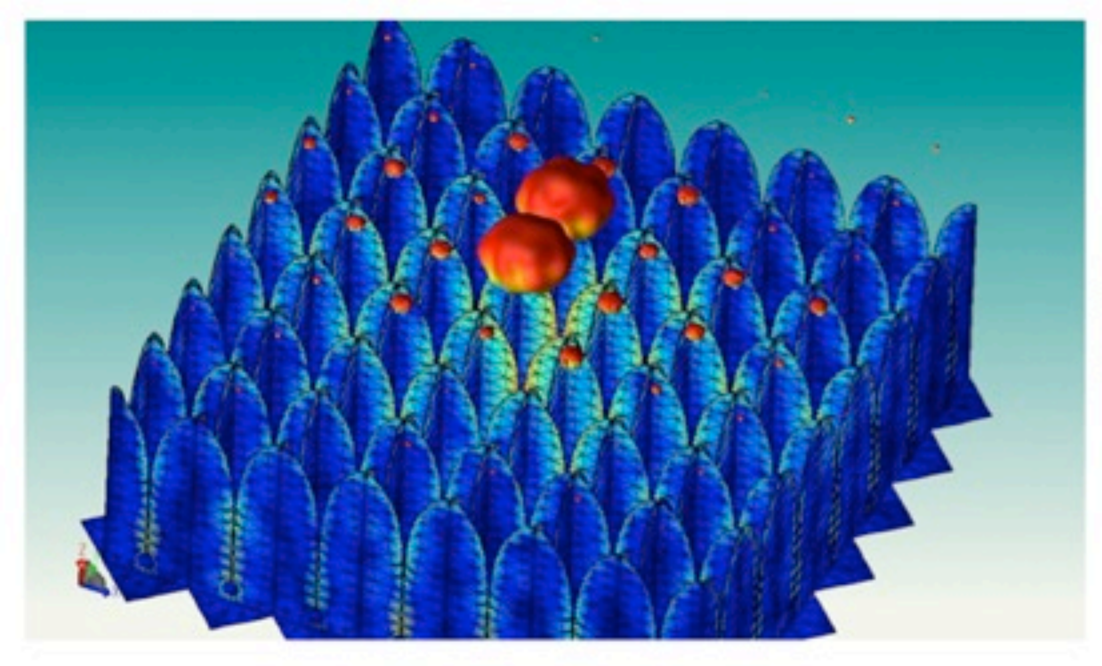
Voltage output

Array response function toward I_S

$$y(t) = w^H(I_0)a_s(I_s)s_s(t)$$

Conjugate of the weighting function toward I_0.

Source intensity distribution.



Beam-forming

Power: Multiple beams can be formed at the same time!

Important for surveys or fast transients, etc.

EMBRACE (mid-frequency AA)

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- Electronic Multi Beam Radio Astronomy ConcEpt.
- Mid-frequency range (~0.5 to 1.5 GHz) aperture array system.
- Aim is for,

  300 tiles, with 64 antennas / tile.

  2 beam system.

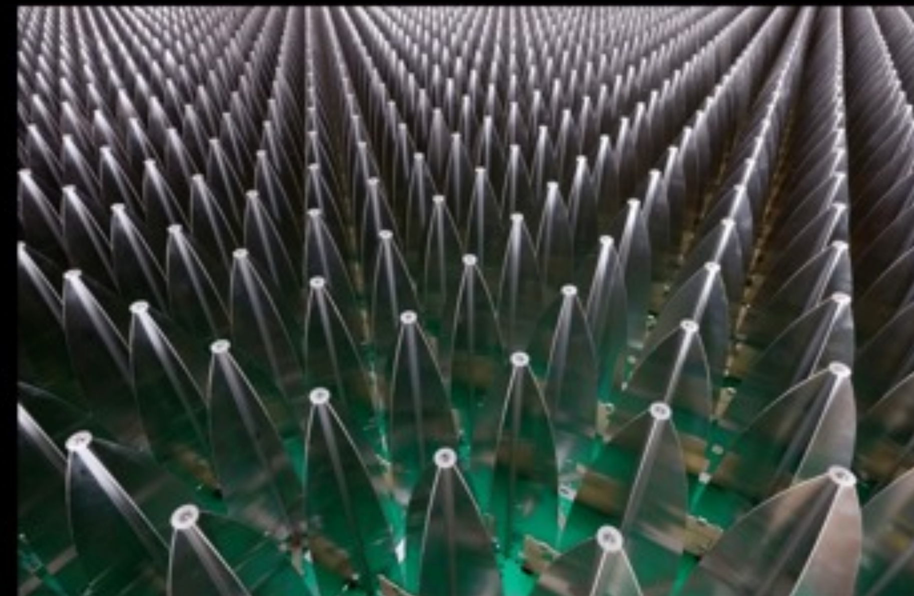
  36 MHz bandwidth.

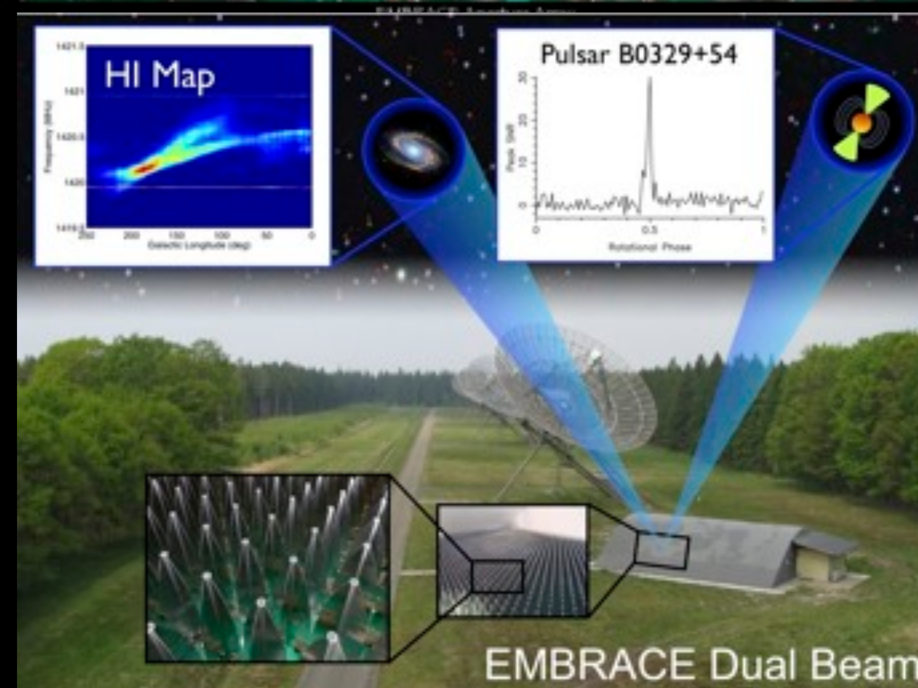
  Single polarization.
- Current test observations using,

  25 tiles (28 m^2 collecting area).

  2 subarrays separated by 10 m.

  3 x 12 MHz bandwidth
- Simultaneous HI from the galactic plane and Pulsar observations.





The Low-Frequency Array

- International LOFAR Telescope being built by a consortium of institutes in the Netherlands, Germany, UK, France and Sweden.

- Low Band Antenna (LBA; 10--90 MHz) - simple dipoles.
- High Band Antenna (110-240 MHz) - tiled array.

- 48 Stations throughout Europe.

- More details in the LOFAR lecture.

The Murchison Widefield 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

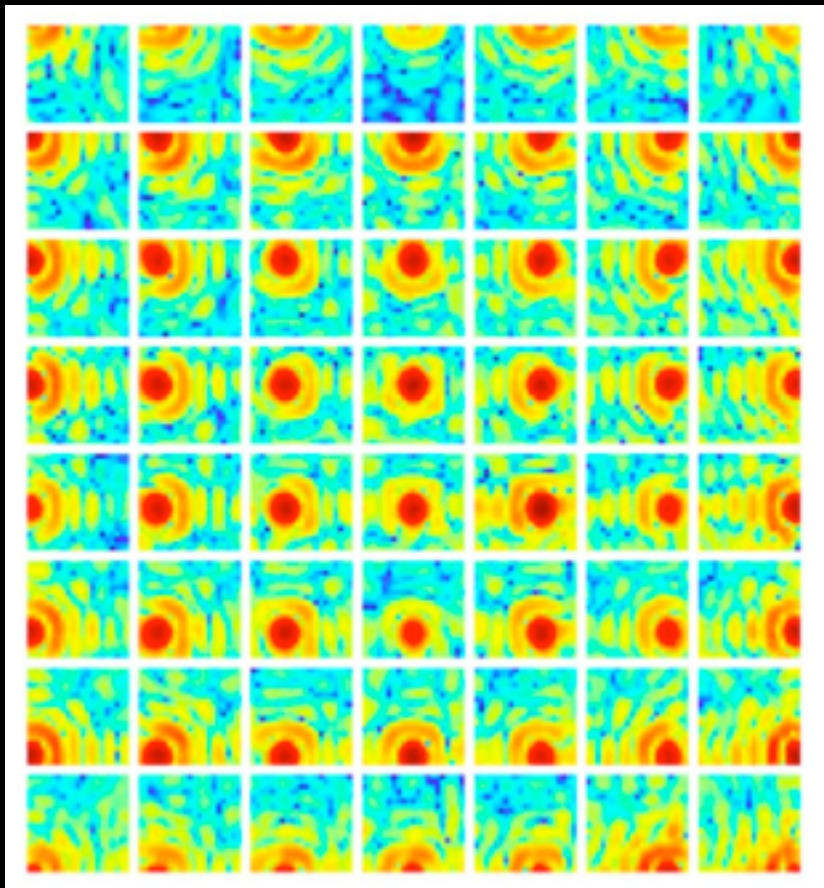
- Science goals:
  - Epoch of re-ionization + transients.

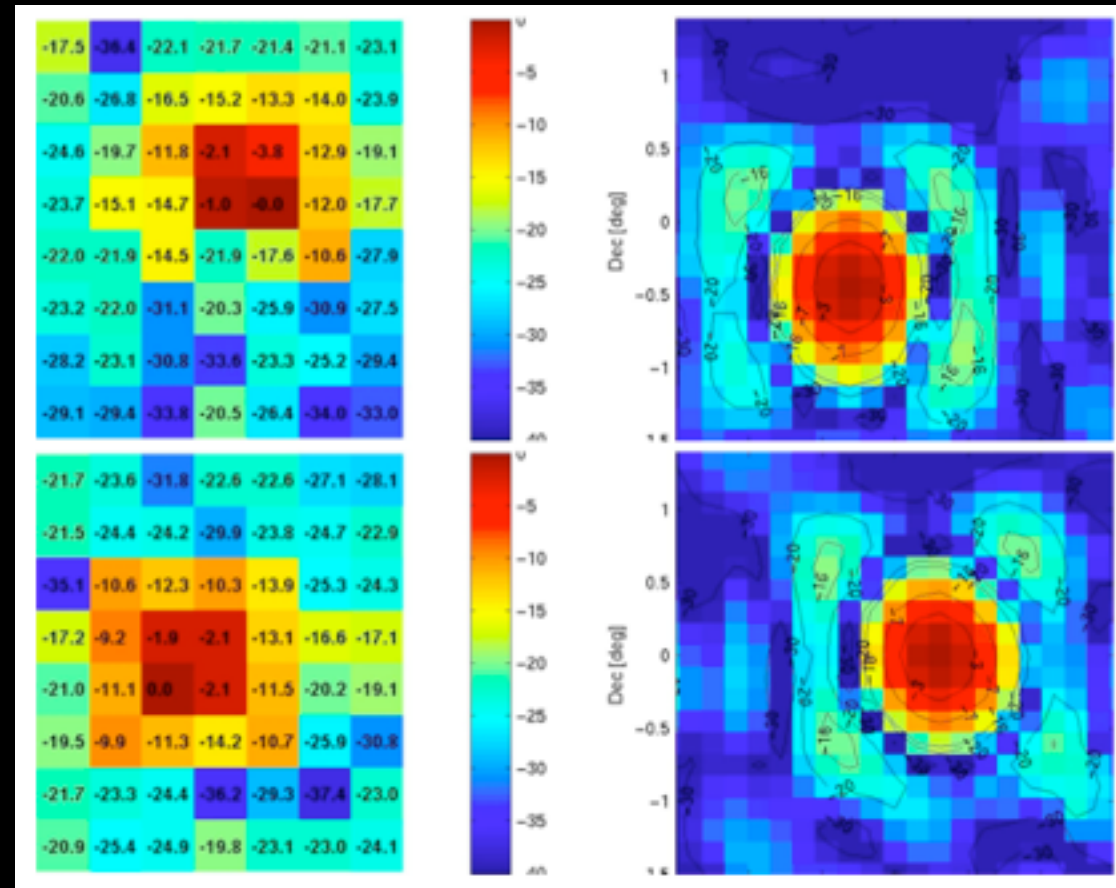
WSRT-APERTIF

- An E-W array (good for wide-field imaging) of 13 (12) 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

Beam forming a Phased Array Feed





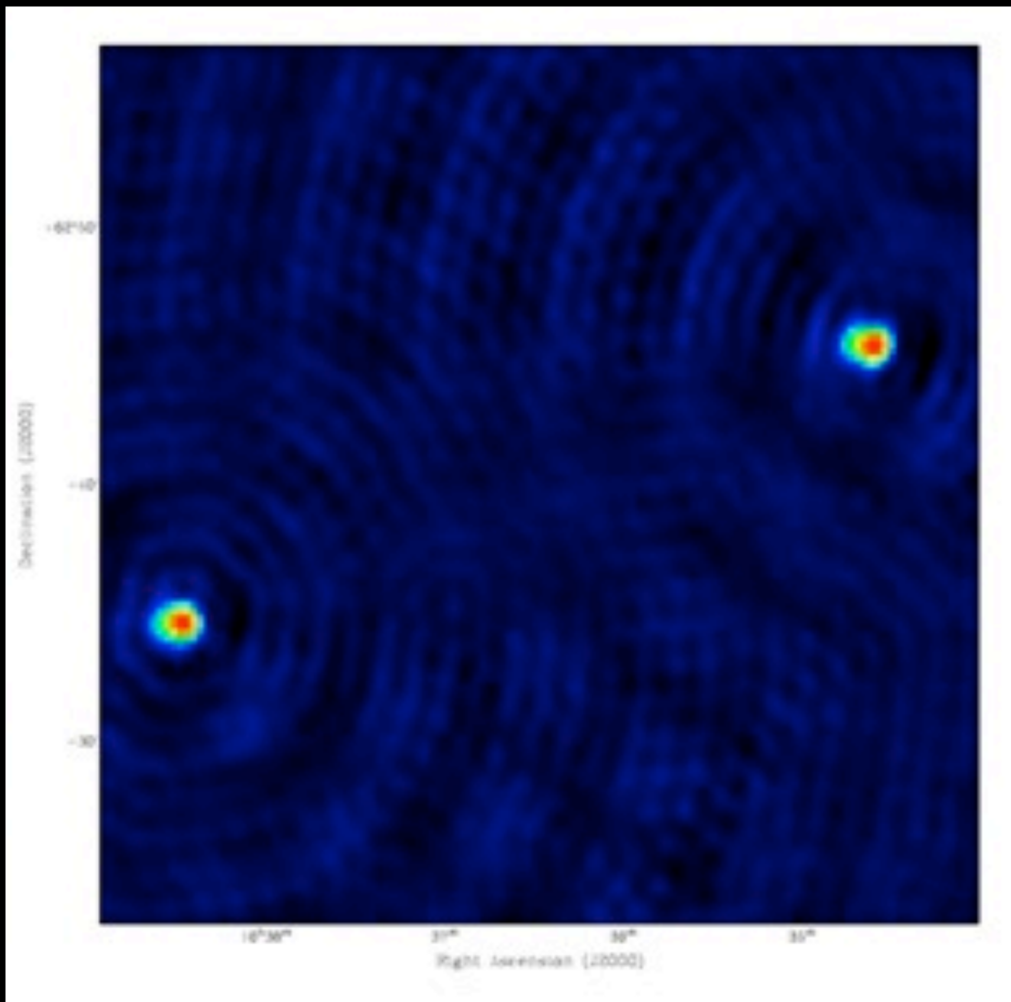
Individual element beams from the prototype Apertif PAH.

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.

First image from a Phased Array Feed



George Heald

- Apertif prototype fitted to 1 WSRT telescope and used with 3 single pixel WSRT telescopes to make an image of 3C343 and 3C343.1
- Separation of 40 arcminutes between the components.

Overview

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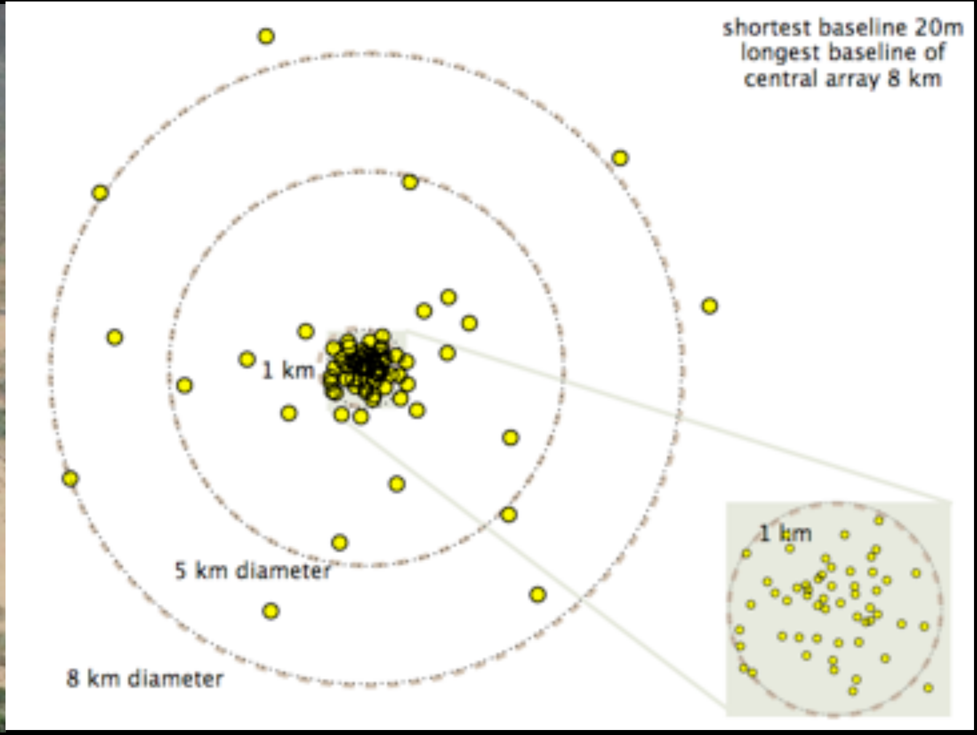
MeerKAT - Southern Africa SKA Pathfinder

- 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
- 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)



MeerKAT - Southern Africa SKA Pathfinder

- **Timeline (recent re-scope)**
  - 2011-2013: Design phase
  - 2013: Antenna prototype
  - 2013-2014: Construction of A2-A20
  - 2014-2016: Construction of A21-A64
  - 2015: Science with the first sub-array
  - 75% of the time for Key Projects

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.
- Operations >2014.

- 75% of observing time already set aside for key projects.

Science with the Pathfinders

- **HI (21 cm):** ASKAP, MeeKAT and WSRT-Apertif all have L-band receivers capable of detecting HI (in emission and absorption) out to z ~ 0.3.
  - Wide area / shallow surveys are planned to map the distribution of cold gas.
  - Narrow area, deeper surveys hope to detect HI out to z ~ 1 (perhaps statically).
- **OH:** ~1.67 GHz Masers can be found within our Galaxy and out to reshift ~ 1.2.
  - Investigate intense star forming regions, magnetic fields, evolution of the fine structure constant (absorption systems).
- **CO (1-0):** ~115 GHz line redshifted into the MeerKAT 8-14 GHz band for z ~ 9 galaxies.
  - Molecular gas studies of the first galaxies, additional proble of the EoR.
- **Deep continuum surveys:** The whole radio sky (ASKAP+Apertif) will be surveyed down to a sensitivity of 10 uJy / beam, with additional deeper fields at 5 uJy / beam.
  - Legacy catalogue of ~10s millions star-forming galaxies and AGN.

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The specification

- **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 3 GHz (maybe higher).
- Fibre network, computing power and raw power to put everything together.
- Constructed in 2 phases (SKA_1 and SKA_2).
- Cost cap of SKA_1 set at ~€600M

- **Capbilities:**
- 40 x the sensitivity of the EVLA.
- up to 10000 x the survey speed of the EVLA.

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

Key science goals

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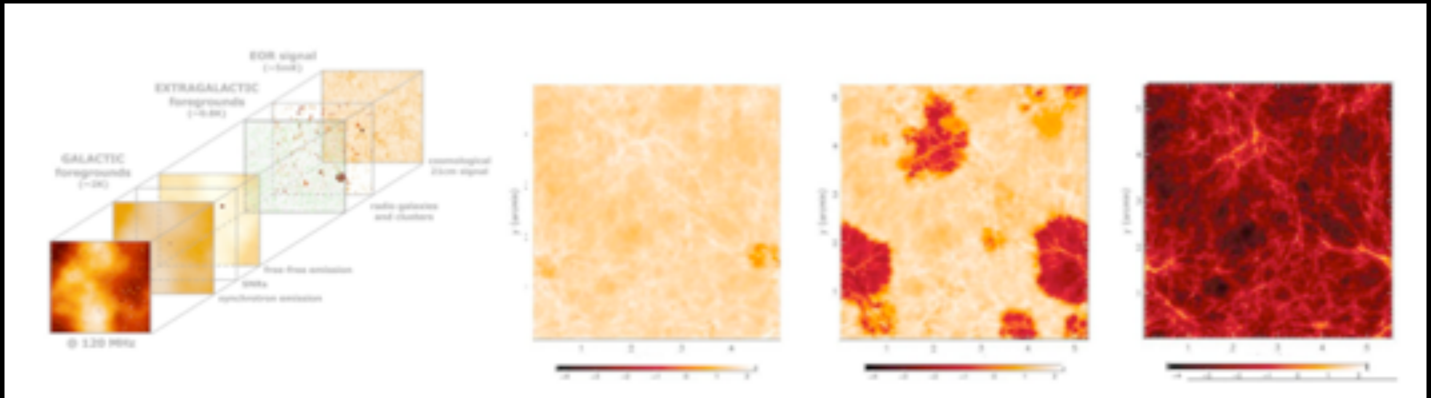
- **The Epoch of Re-inoization:** Detect the faint signals from HI during the period when the Universe was re-ionised by the first stars and galaxies.

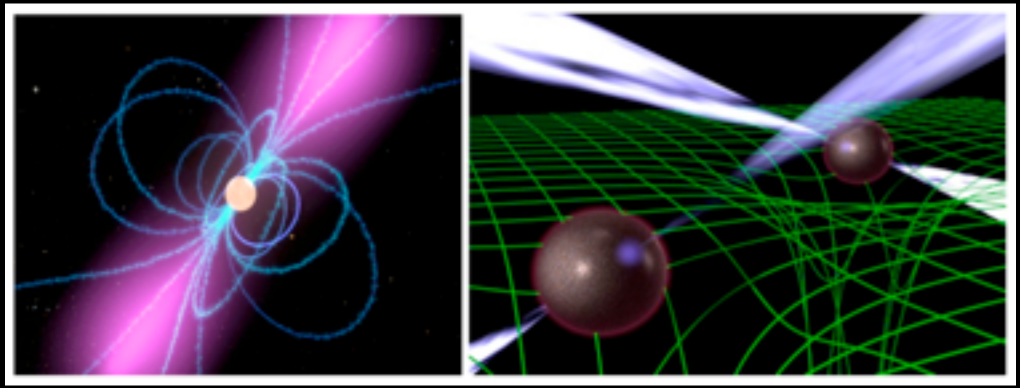
Important implications for galaxy formation

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

Australia and New Zealand

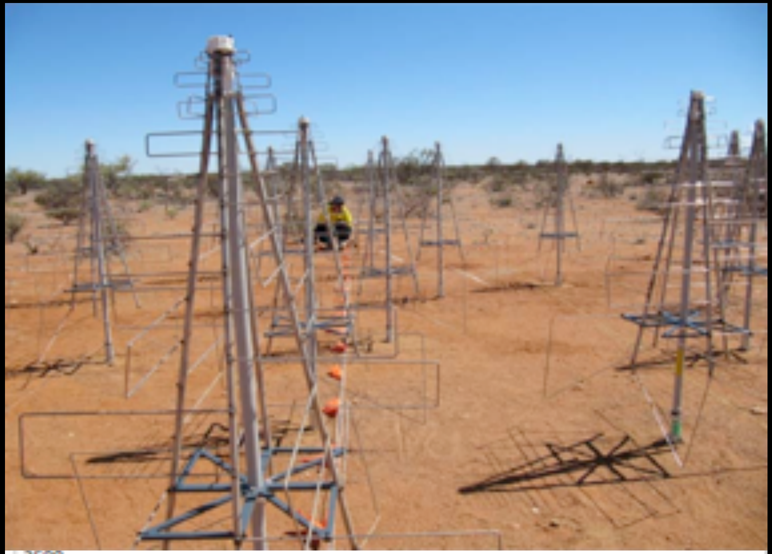
A split decision!!!

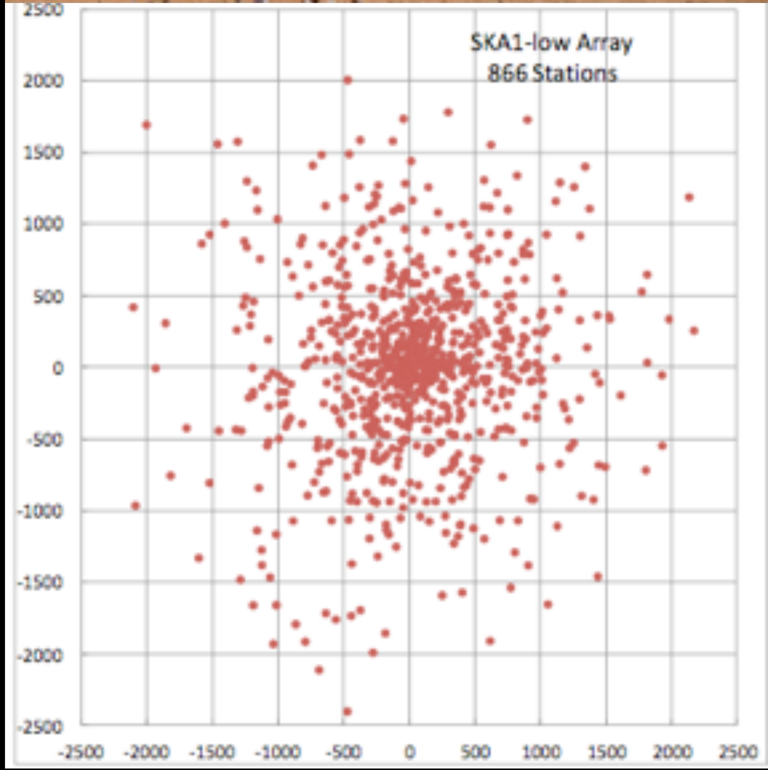
SKA_2 mid and SKA dishes

SKA low and SKA_1 Survey

SKA_1 LOW

- Sparse dipoles (dual pol; similar to LOFAR).
- Freq: 50 to 350 MHz (300 MHz bandwidth).
- 289 dipoles / station -- 911 stations.
- 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} ~ 1000 m^2 / K (>100 MHz).

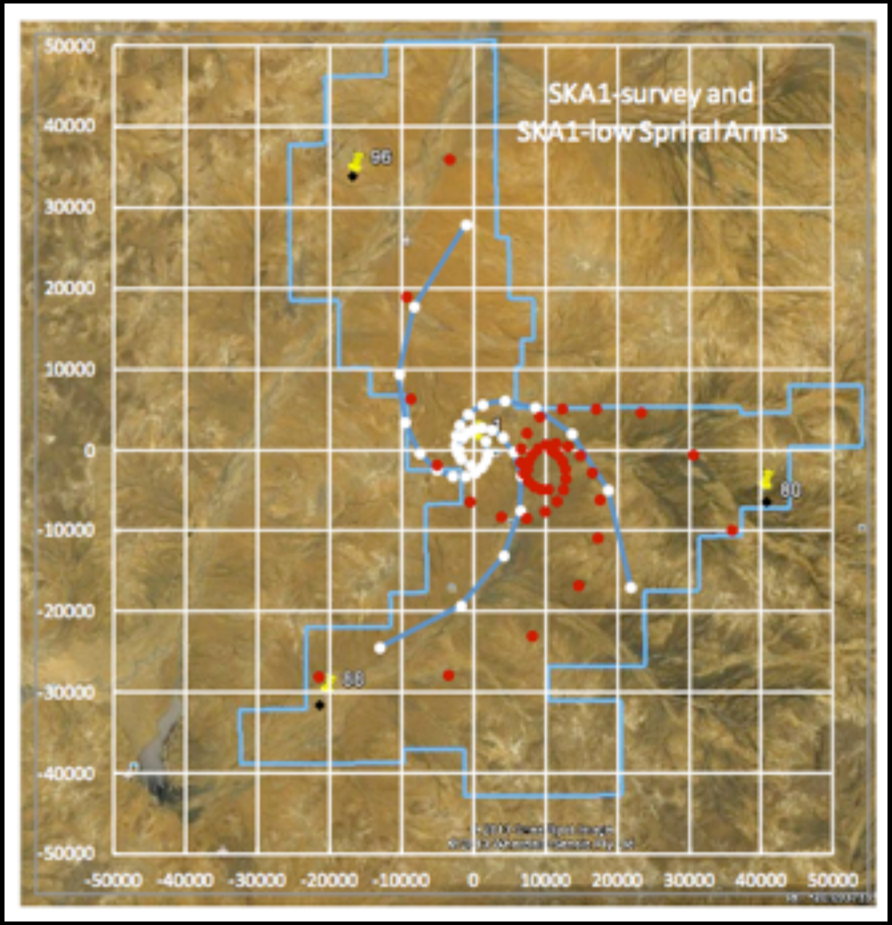


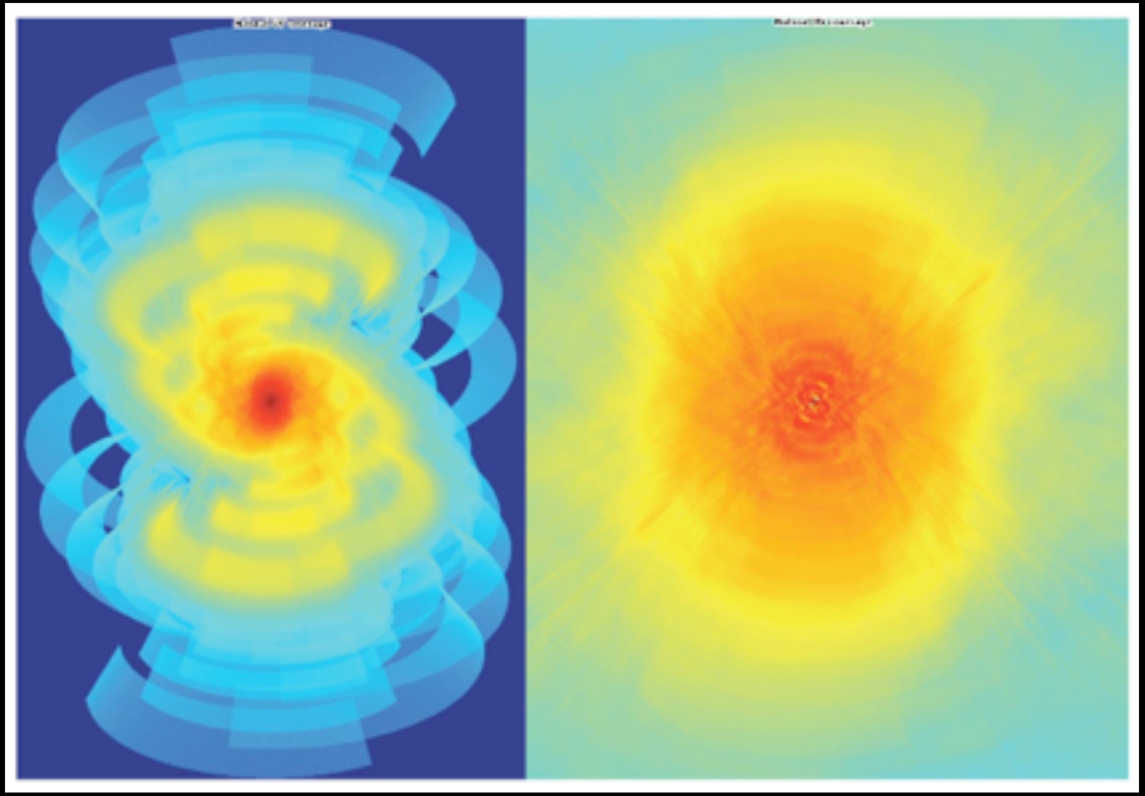


SKA$_1$ Survey

- 60 x 15 m offset Gregorian dishes (similar to MeerKAT) and 36 x 12 m symmetric dishes (from ASKAP).
- Dual polarisation with 500 MHz bandwidth.
- Freq: 650 -- 1670 MHz (band 2).
- 36 PAF beams
- Will have baselines out to 50 km.
- 75% collecting area within 4 km.
- Dense core for Pulsar timing, HI and continuum and polarization experiments.
- $A_{eff} / T_{sys} \sim 391\ m^2 / K$.

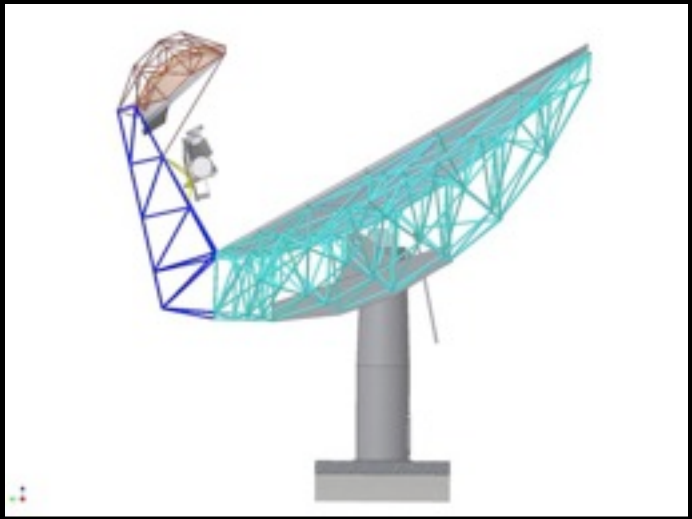
SKA$_1$ LOW and Survey

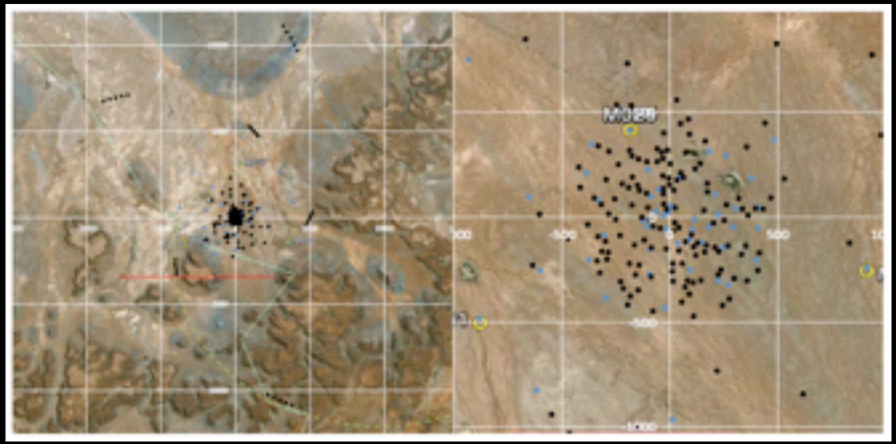




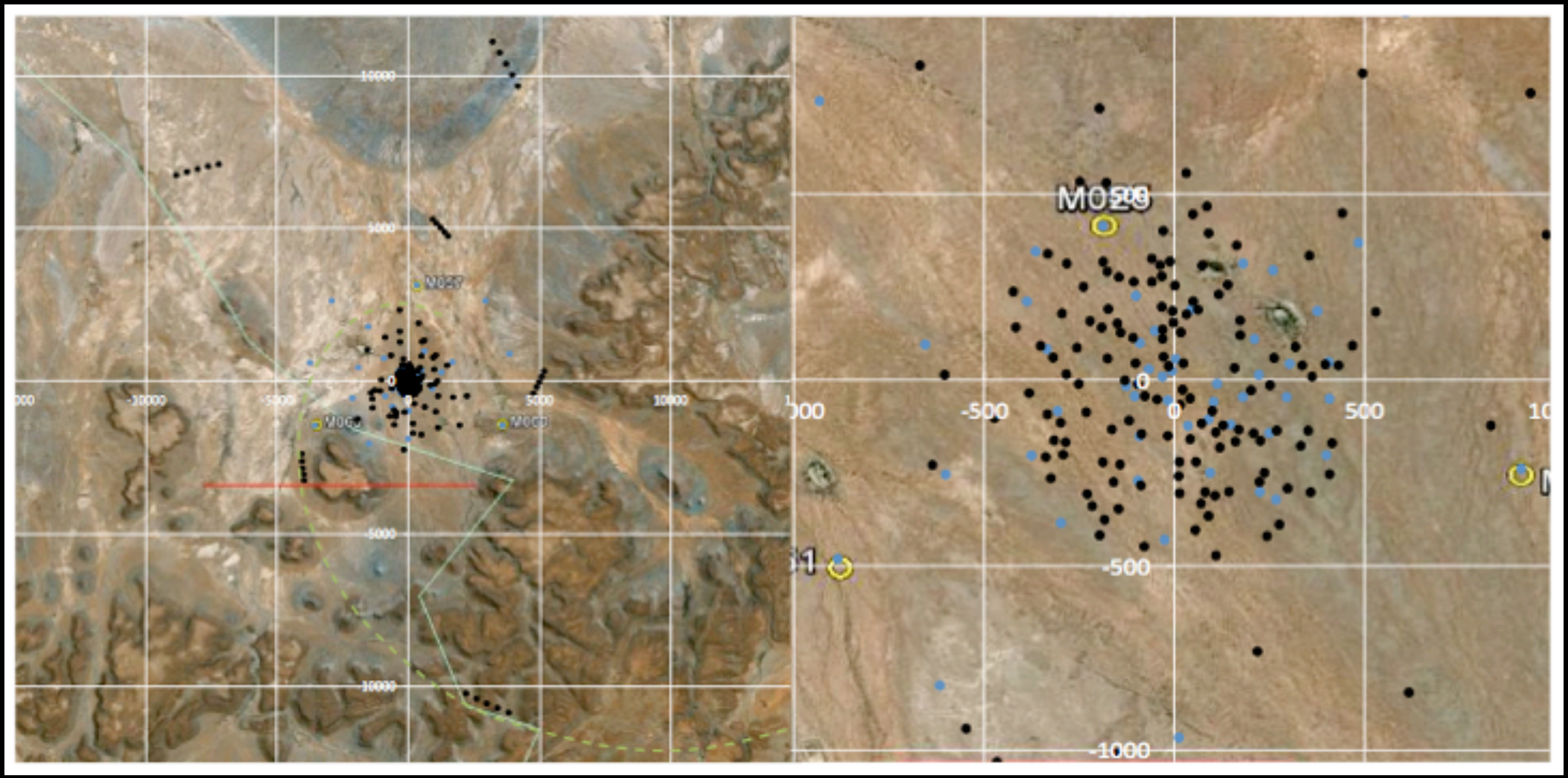
SKA$_1$ Mid

- 190 x 15 m offset Gregorian dishes + 64 MeerKAT dishes (254 in total).
- Dual polarisation with 700 -- 9200 MHz bandwidth.
- Freq: 350 -- 13800 MHz (band 1 -- 5).
- Wide-band single pixel feeds.
- Will have baselines out to 100 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.

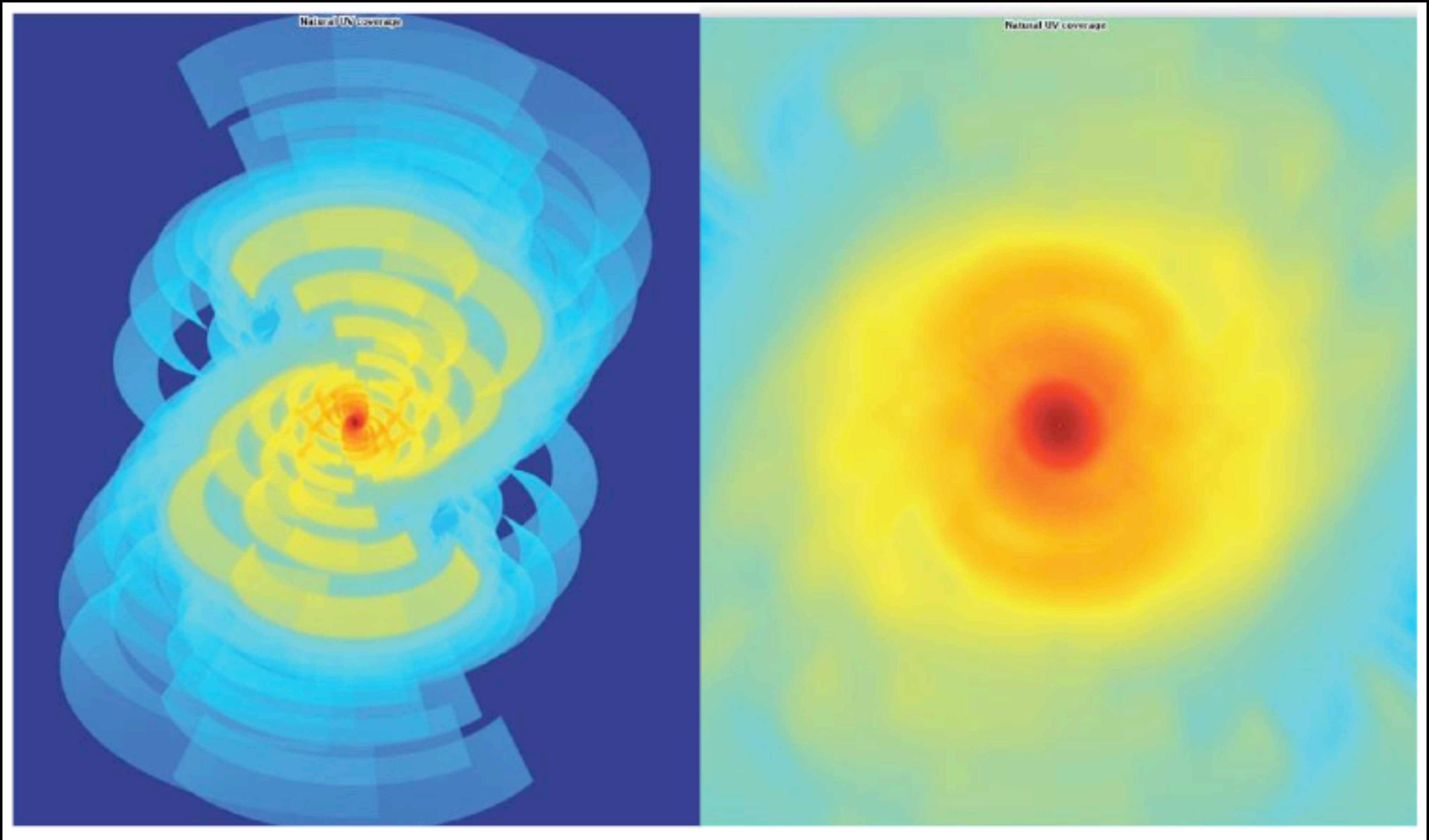




SKA$_1$ Mid



SKA$_1$ Mid

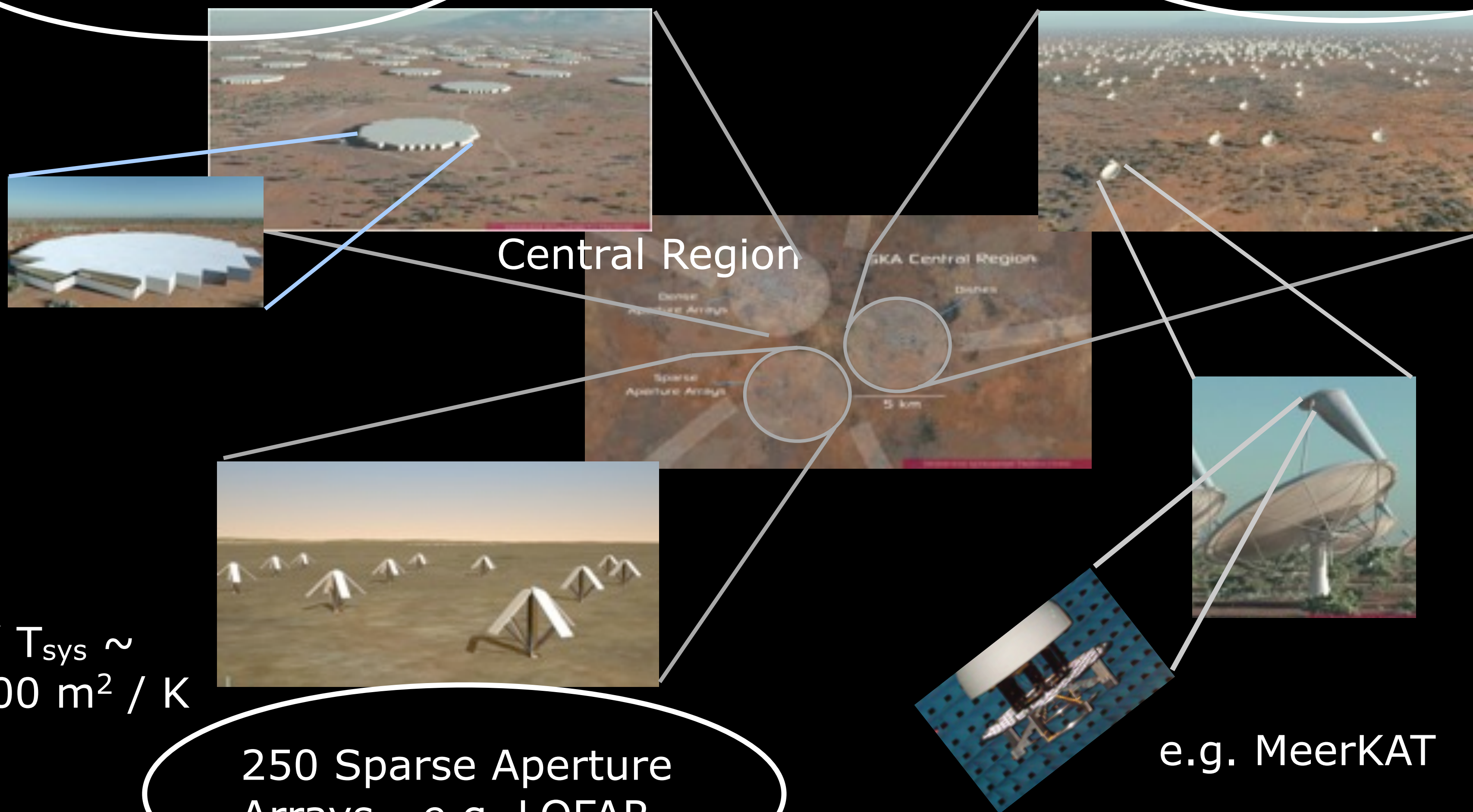


SKA$_2$ (>2020?)

250 Dense Aperture Arrays, e.g. EMBRACE

A_{eff} / T_{sys} ~ 12000 m^2 / K

3000 x 15 m Dishes



Central Region

A_{eff} / T_{sys} ~ 10000 m^2 / K

250 Sparse Aperture Arrays - e.g. LOFAR

e.g. MeerKAT

And >1000 km baselines...

But I want it now...

Overview

- The next generation of upgraded and new single pixel interferometers.
- Aperture Arrays (AAs) and Phased Array Feeds (PAHs)
- The Pathfinders
- The Square Kilometre Array
- Summary

Summary

ASTRON

- Recent upgrades have been made to common user facilities (EVLA, eMERLIN ATCA) allowing new science to be done.
- Pathfinder technologies / arrays being constructed over the next 5 years will provide new science opportunities - good time to be a radio astronomer.
- The SKA will be a transformation telescope when it is complete (2020-2025).

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