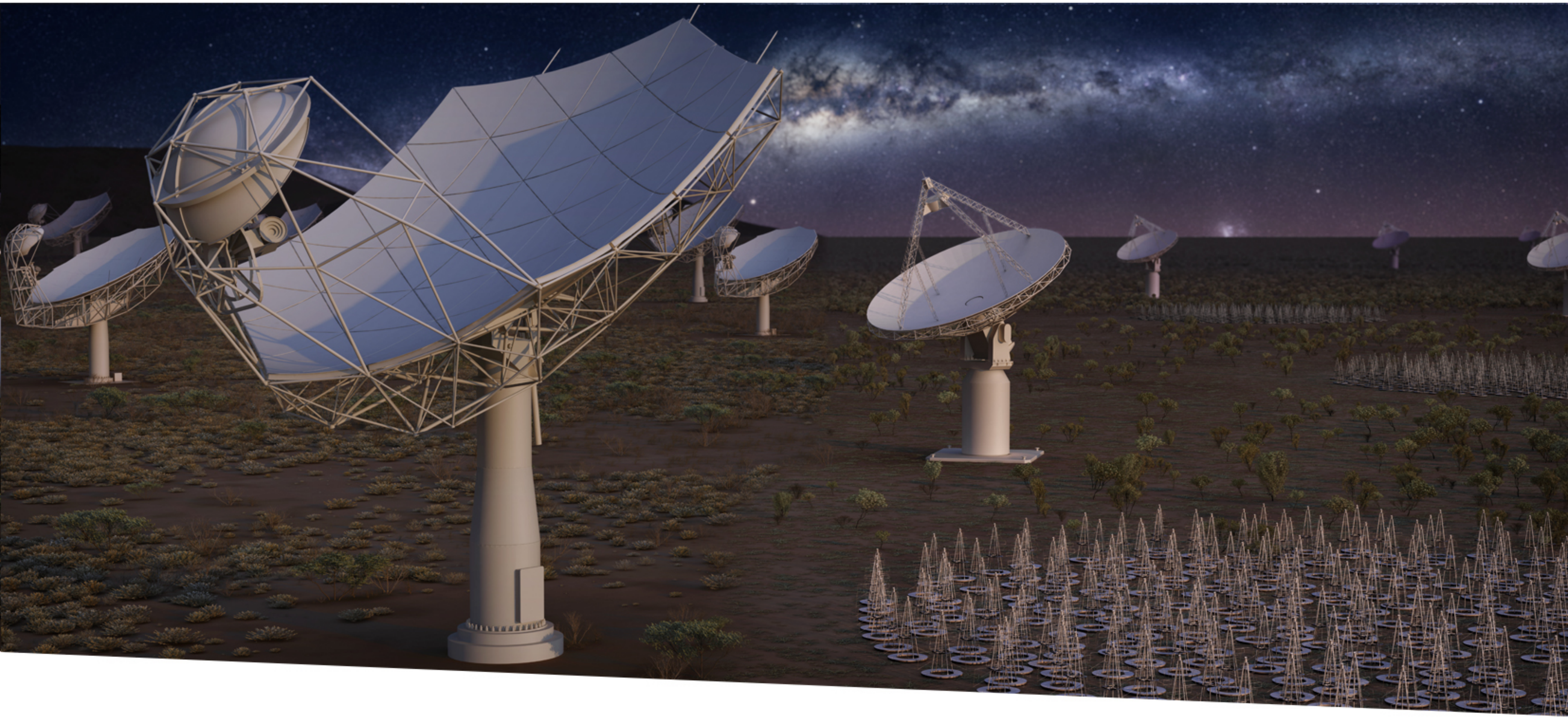
Radio Astronomy



SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

Robert Laing

CTA Science Symposium

Overview

- Technological opportunities in radio astronomy*
- The SKA, its pathfinders and precursors
- New science areas
- Synergies with CTA

* 10 MHz – 60 GHz / 30 m – 5 mm

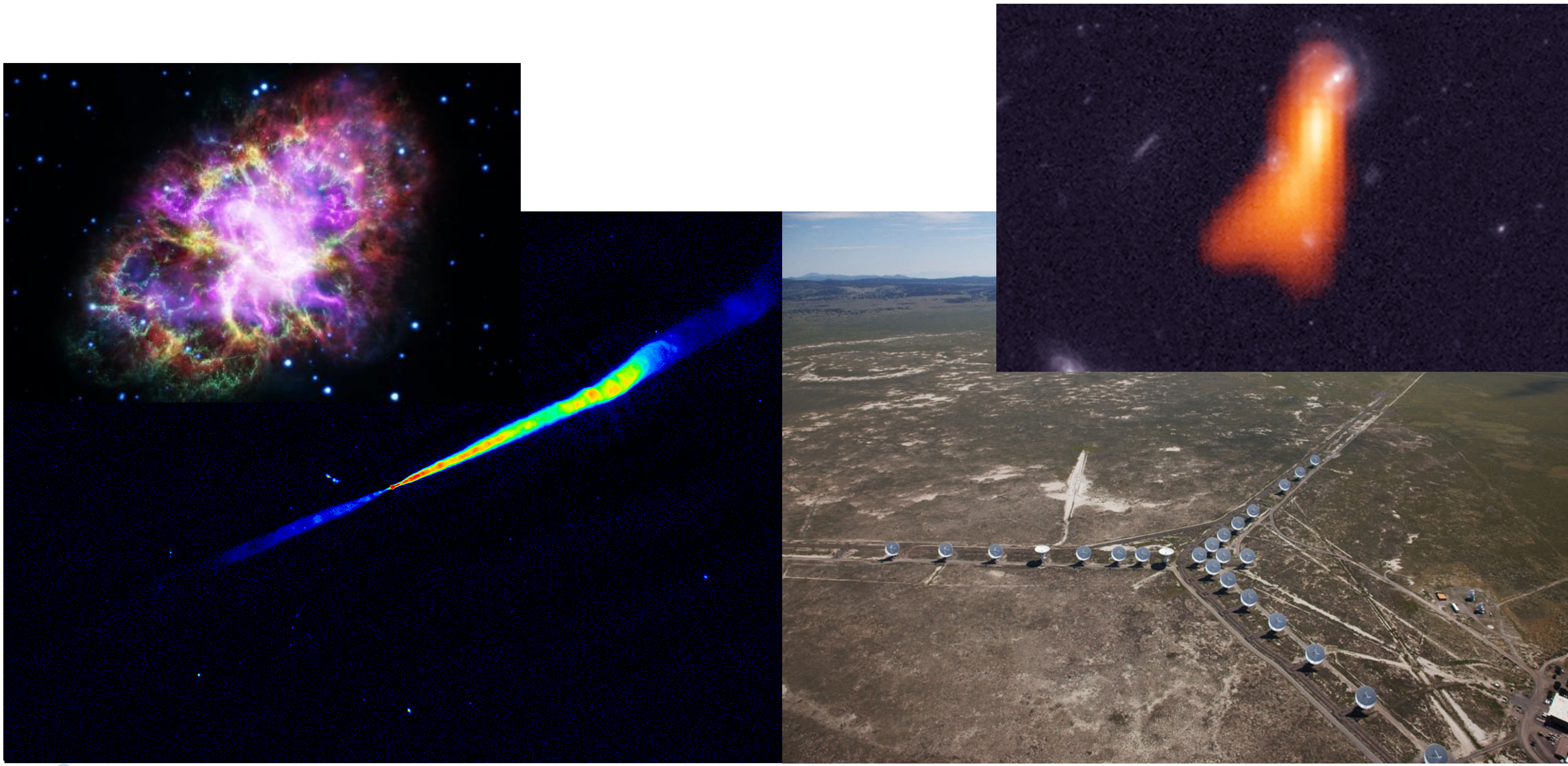
New Directions

- High frequencies: many small dishes
  - Large field of view
  - Excellent uv coverage
  - Offset Gregorian optics: lower sidelobes
  - Multi-beam (focal plane arrays; phased-array feeds)
- Low frequencies: aperture arrays
  - Huge field of view
  - Multiple beams, steered electronically

- Common features
  - Many frequency channels (avoid chromatic aberration; simultaneous line and continuum)
  - Wide bandwidth
  - Tied-array beam forming for pulsars, VLBI
  - Transients
- But ….
  - Complex trade-offs between field of view, frequency coverage and systematics
  - Troposphere and (especially) ionosphere are hard to correct
  - Noise temperatures are already close to theoretical limits
  - Big fields and many channels imply enormous data-processing challenges
  - Radio-frequency Interference
  - Cost

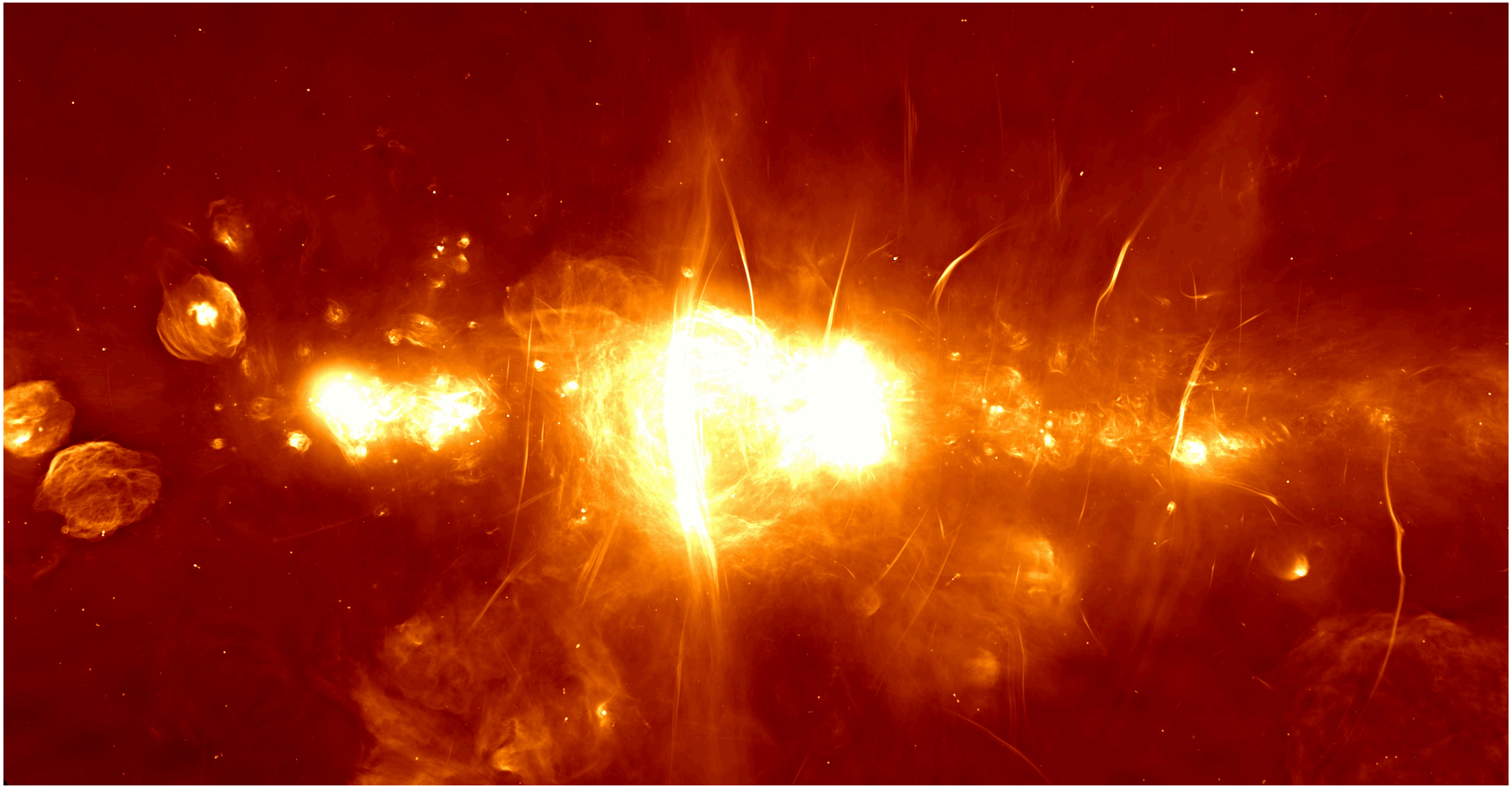
Jansky VLA

- Major upgrade to increase bandwidth
- Continuous frequency coverage 1-50 GHz
- Operational from 2011



MeerKAT

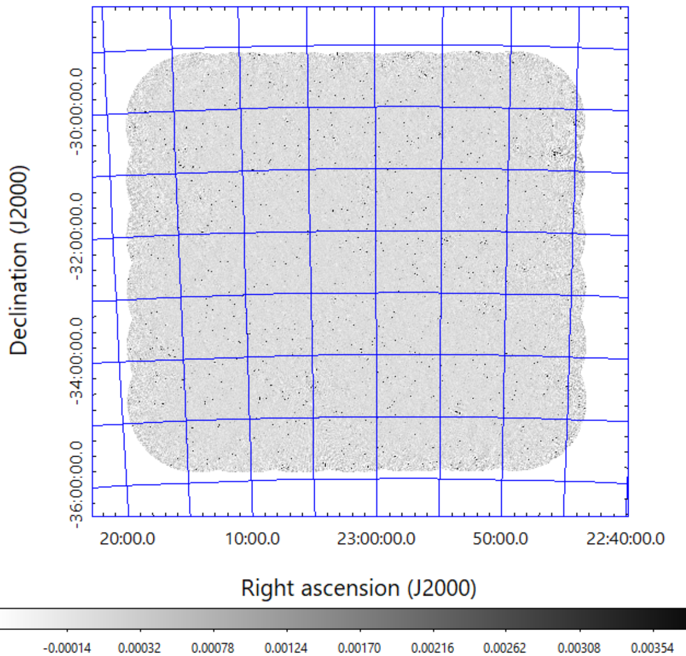
MeerKAT: Galactic Centre at 1.4 GHz

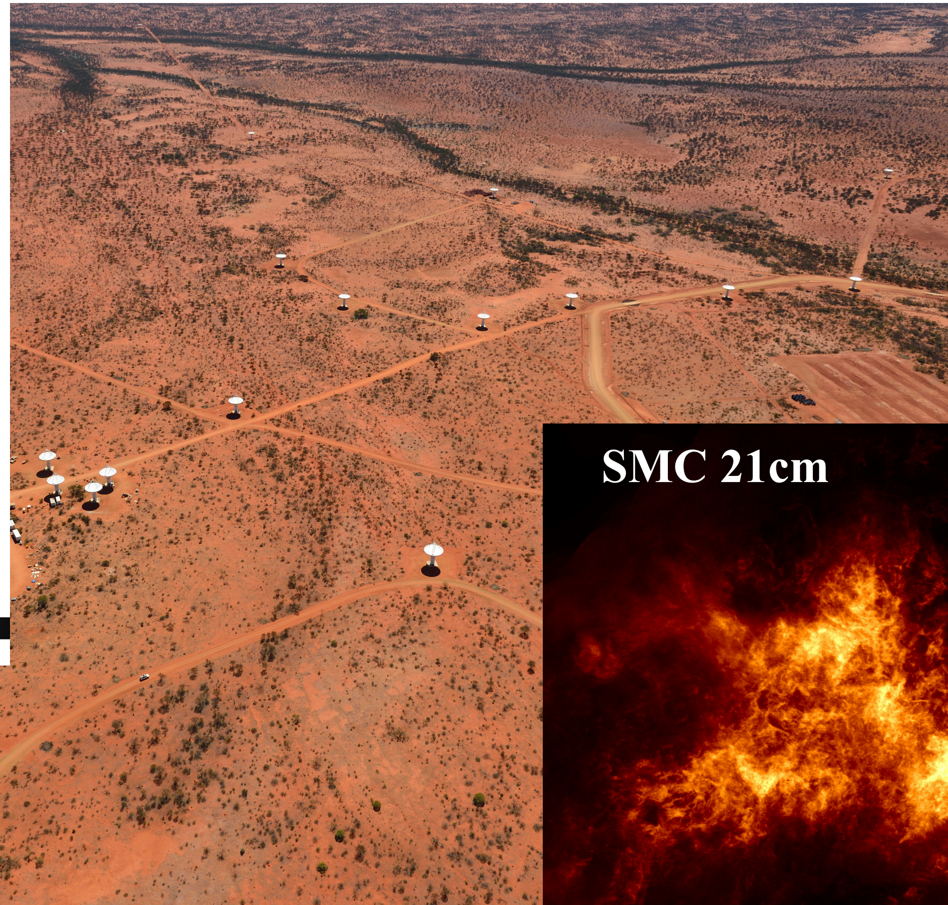


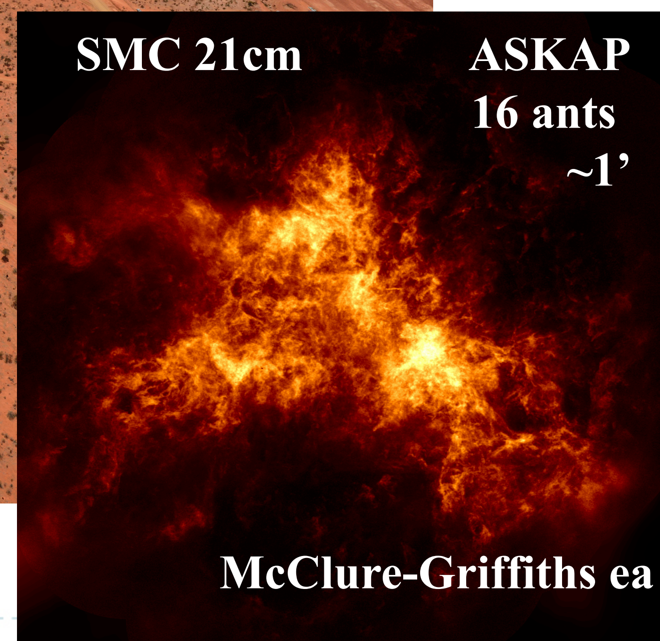
ASKAP

36 antennas, 36 PAF beams
700-1800 MHz
6km max baseline

GAMA 23 field (Leahy et al. 2019)



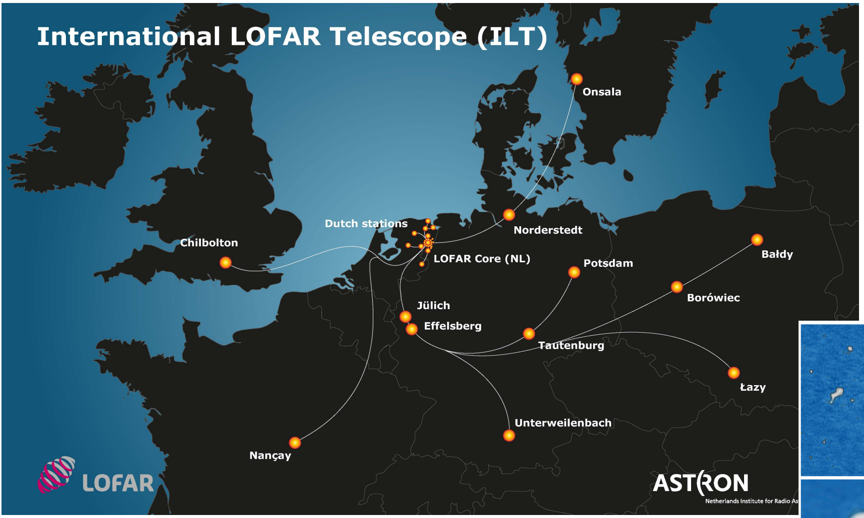




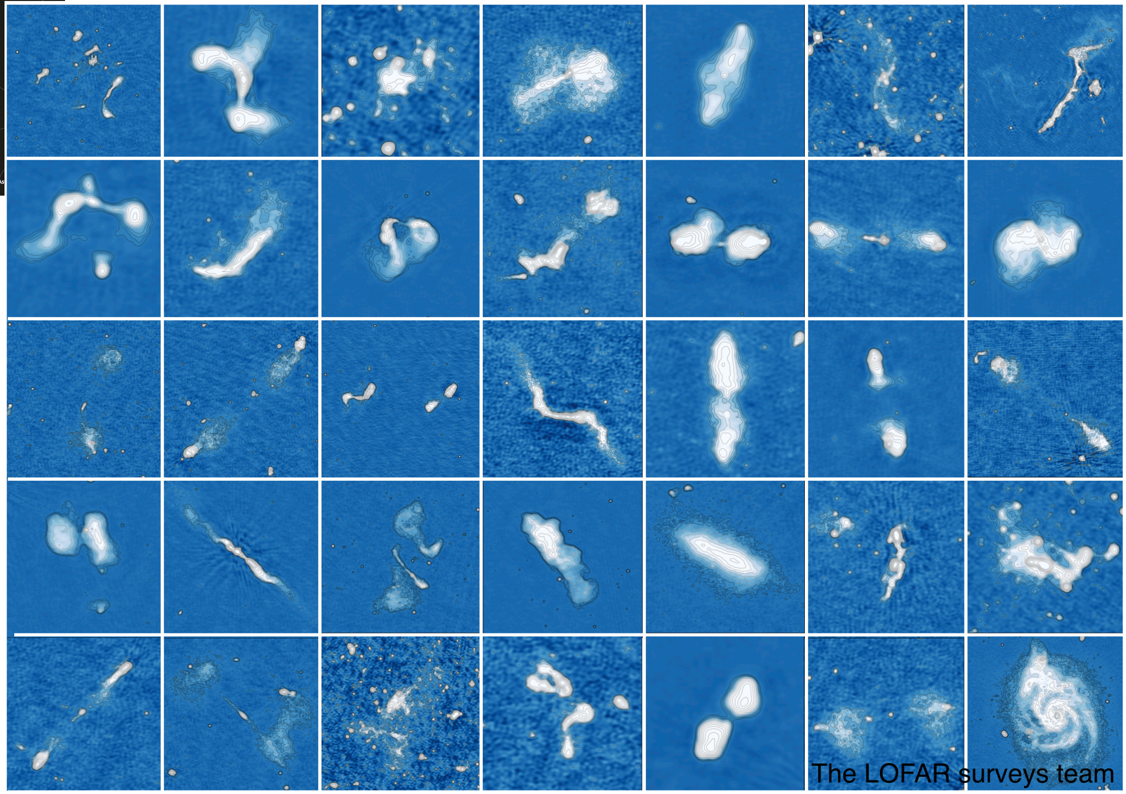
Murchison Widefield Array

- 128 tiles; dipole antennas (extending to 256)
- 3 km maximum baseline (6 km)
- 80-300 MHz
- GLEAM survey

LOFAR

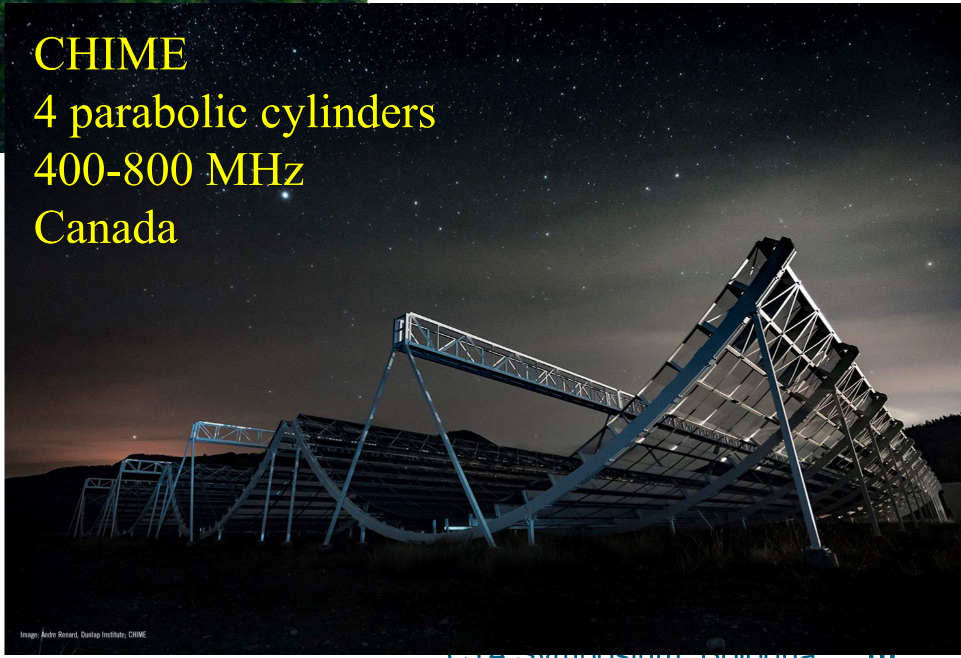


LoTSS Shimwell et al.



Dutch core + international stations
Maximum baseline >1000 km
30 to 80 and 120 to 240 MHz
32 MHz bandwidth

More pathfinders



Proposed: ngVLA: filling the gap between SKA1 and ALMA; emphasis on higher frequencies (protoplanetary disks, redshifted molecular lines)

SKA1

3 sites (AUS, RSA, UK-HQ) 2 telescopes (LOW, MID) **one Observatory (SKAO)**

Construction start: 2022

SKA1-Low: ~131,000 log-periodic antennas,
in 512 stations, 50 – 350 MHz
65 km max. baseline (>11" @ 110 MHz)
Murchison, Western Australia

SKA1-Mid: ~200 x 15m dishes,
0.35 – 15 (24) GHz
150 (120) km max. baseline
(>0.22" @ 1.7 GHz; >34 mas @ 15 GHz)
Karoo, South Africa

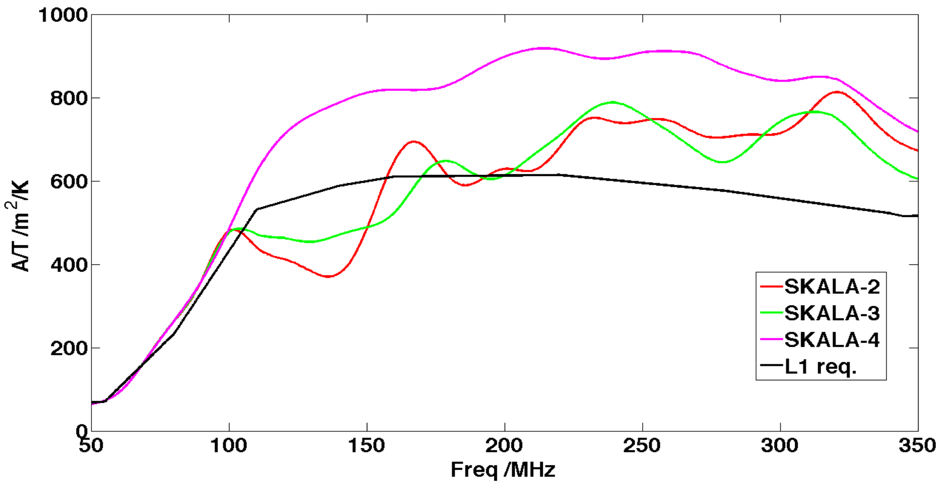
SKA1 Frequency Bands

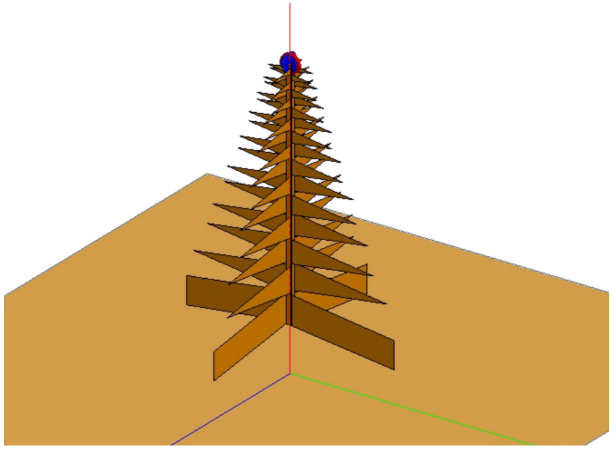
Band	Frequency Range	Bandwidth
Low	50 – 350 MHz	300 MHz
Mid Band 1	0.35 – 1.05 GHz	1 GHz
Mid Band 2	0.95 – 1.76 GHz	1 GHz
Mid Band 3	1.65 – 3.05 GHz	1 GHz
Mid Band 4	2.80 – 5.18 GHz	2.5 GHz
Mid Band 5a	4.6 – 8.5 GHz	2.5 GHz
Mid Band 5b	8.3 – 15.3 GHz	2 x 2.5 GHz

Dishes and Low-frequency Antennas

SKA-P First prototype antenna

SKALA-4 Antenna Design





Computing Challenges

SKA-LOW

~2 Pb/s

LOW-FREQUENCY APERTURE ARRAY

7.2 Tb/s

SKA-MID

8.8 Tb/s

SIGNAL AND DATA TRANSPORT

CENTRAL SIGNAL PROCESSOR (CSP)

~50 PFlops

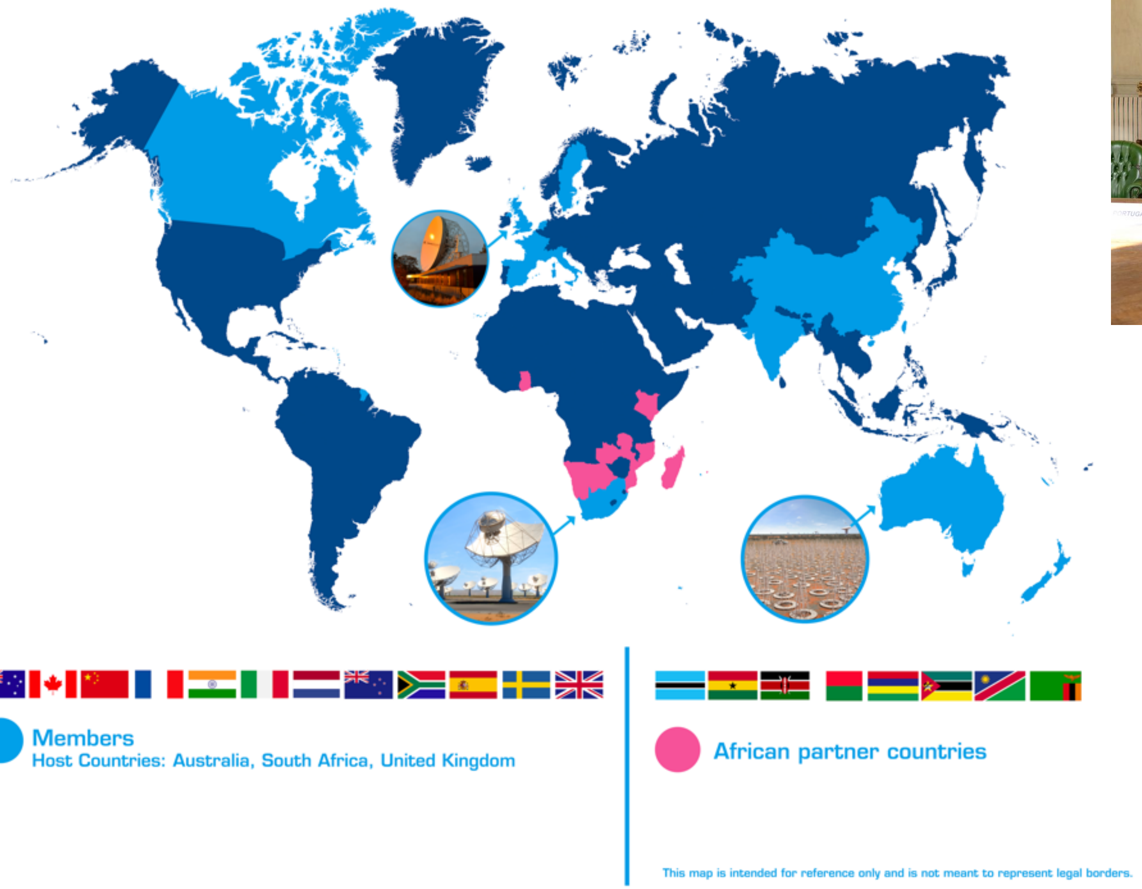
~5 Tb/s

SCIENCE DATA PROCESSOR (SDP)

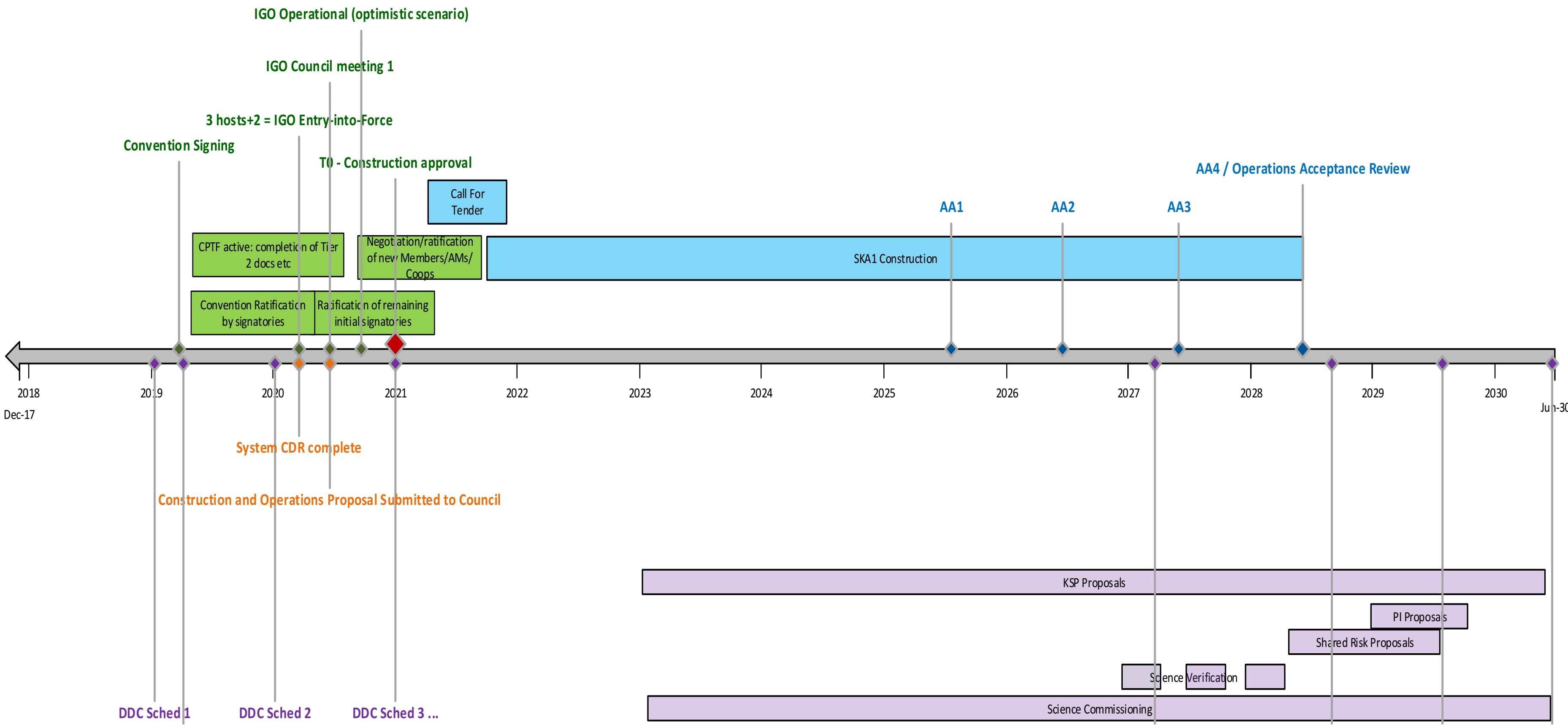
~250 PFlops

34 Gb/s ~130 PB/yr

SKA Countries

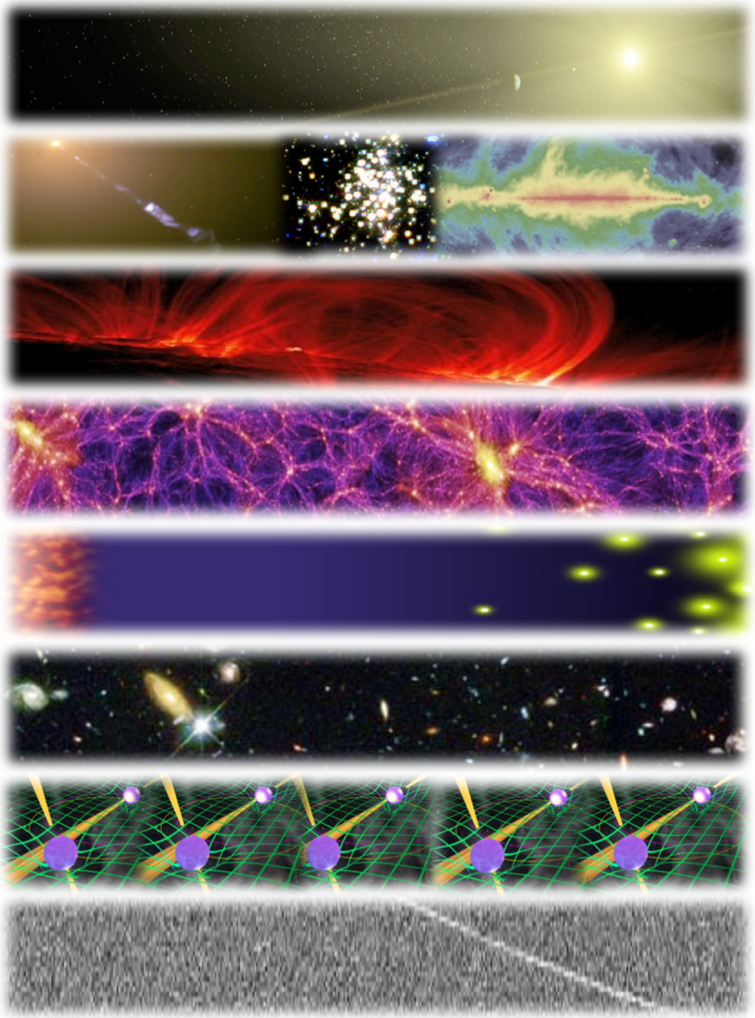


SKA1 Schedule



Science Drivers

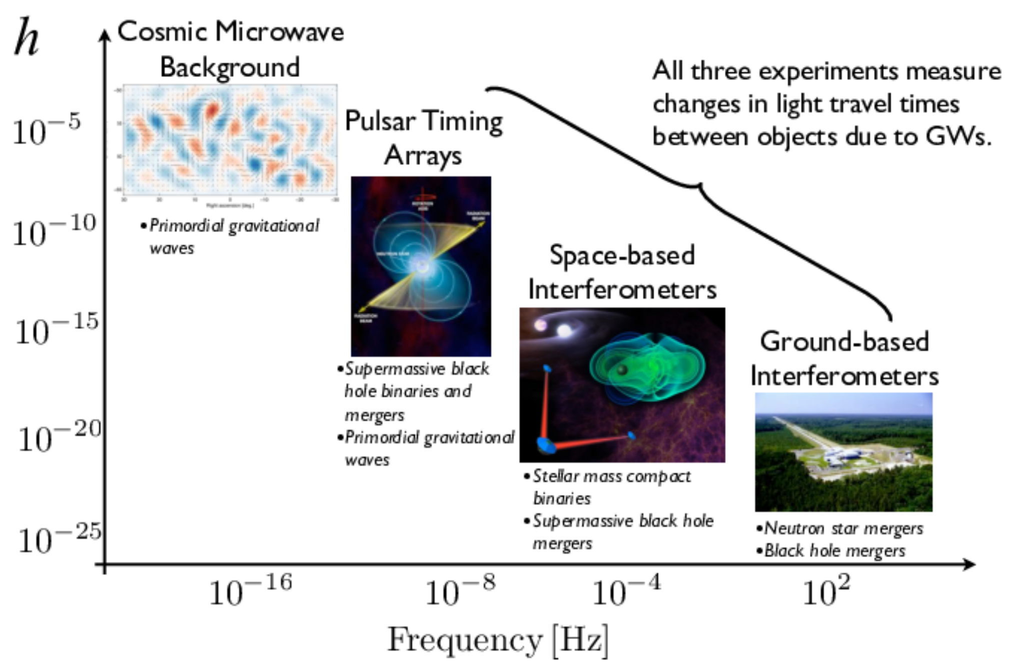
- Testing gravity
- Galaxy Evolution and Kinematics
- The Early Universe in HI
  - Astrobiology
  - Extragalactic continuum
  - Cosmic magnetism
  - Cosmology
  - Epoch of reionisation and Cosmic Dawn
  - Extragalactic spectral line (non-HI)
  - HI galaxies
  - Our Galaxy
  - Pulsars
  - Solar, heliospheric and ionospheric
  - Transients
  - VLBI

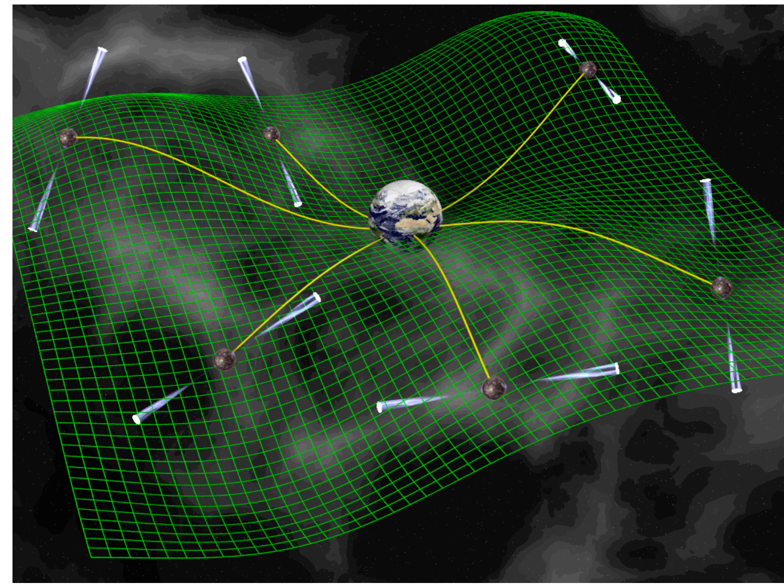


Pulsars and gravitational Wave Astronomy

NANOGrav

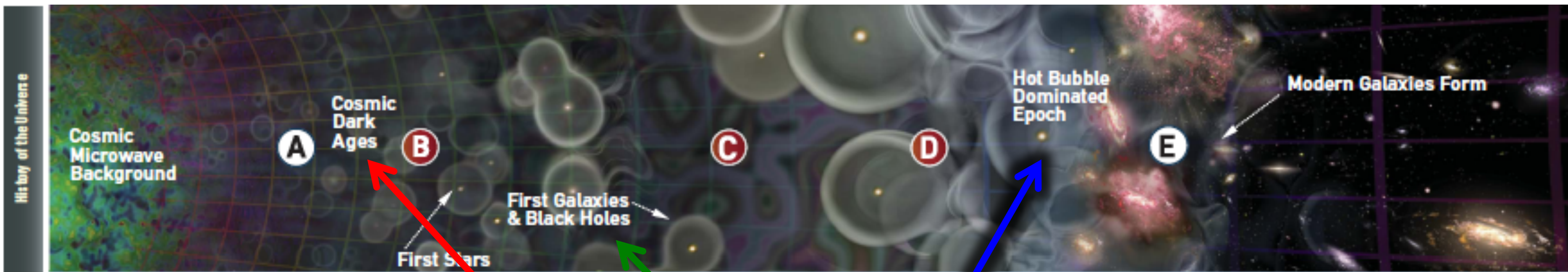
The spectrum of gravitational wave astronomy



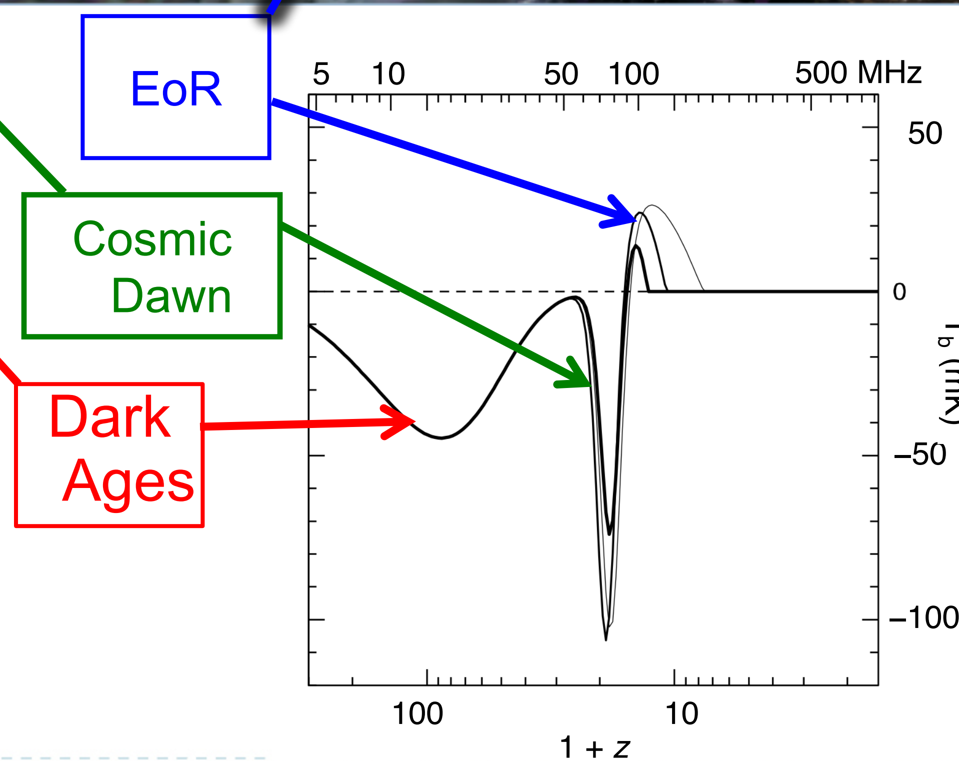


Measure correlations between millisecond pulsar timing residuals
SKA will be able to detect the nHz gravitational wave background
Detect ~16000 normal and ~2000 ms pulsars
~100 relativistic binaries
Pulsars in the Galactic Centre?

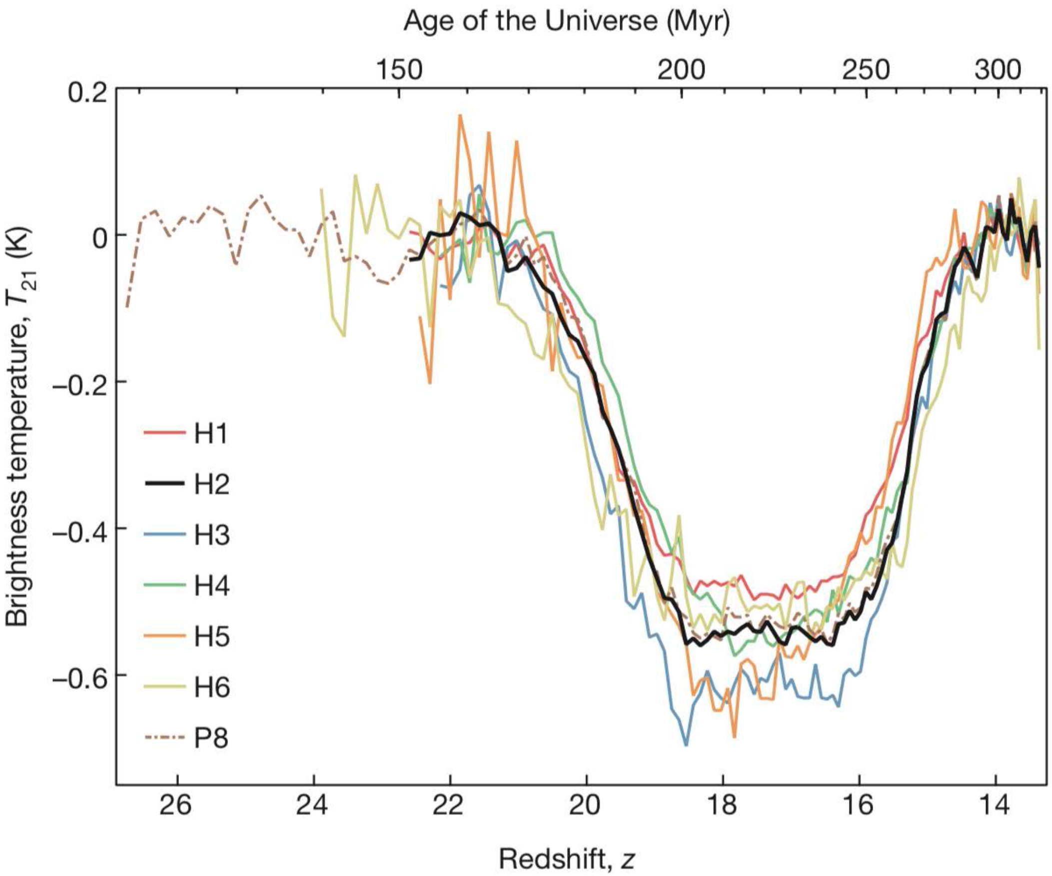
Epoch of Reionisation and Dark Ages

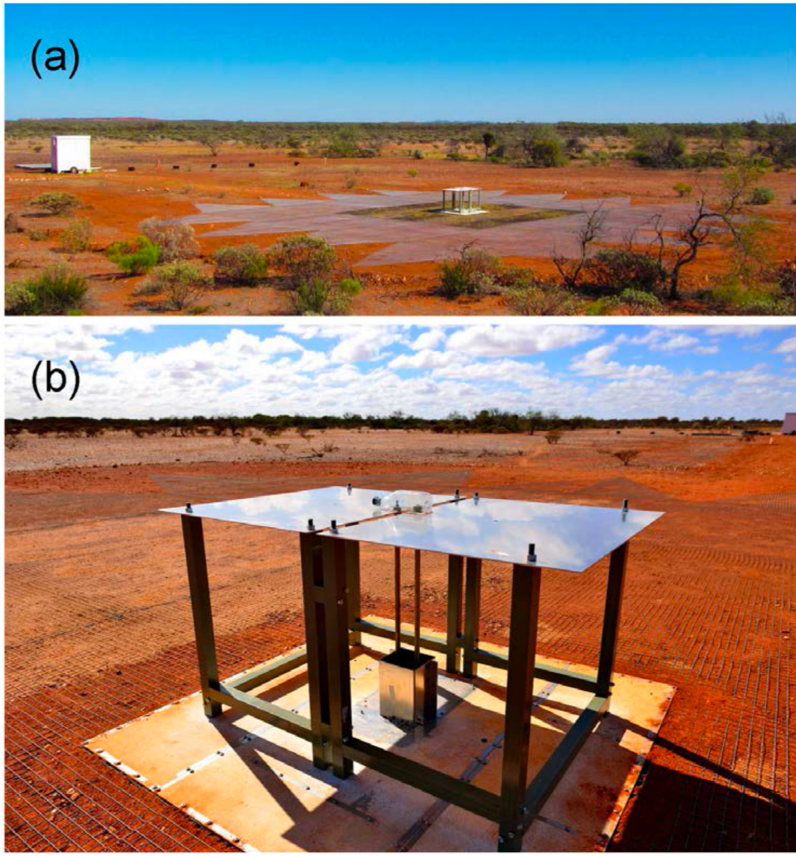


Neutral Hydrogen 21 cm spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars



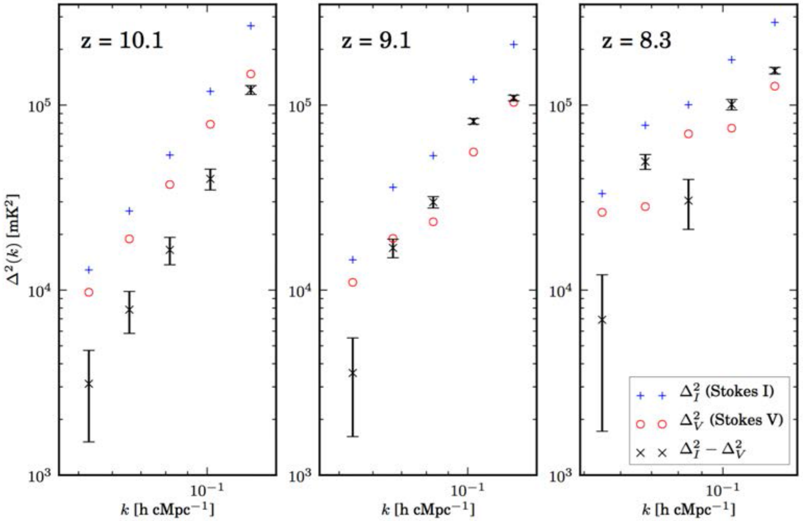
Stage 1: Global Signal





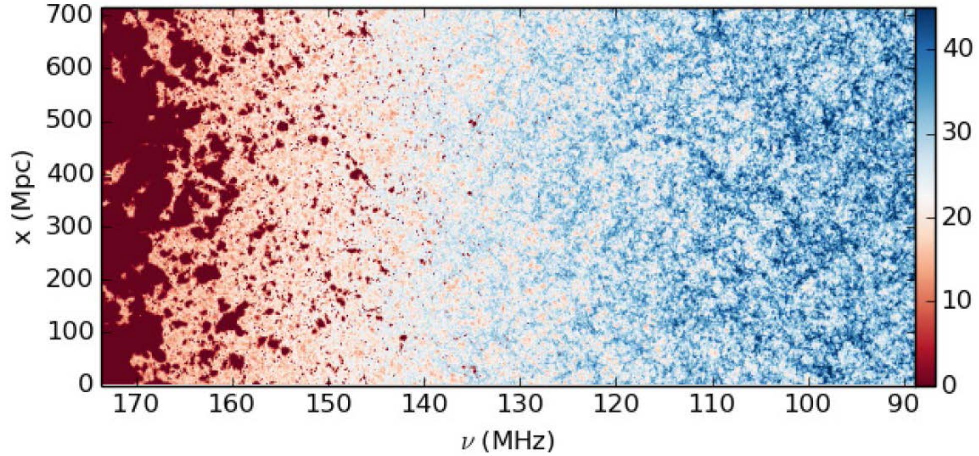
EDGES2, Bowman et al. (2018) Much deeper and flatter than expected.

Stage 2: Spatial/Spectral Fluctuations



2σ upper limit of Δ(k) < 80 mK for k = 0.05 Mpc^{-1} at z = 10.1 (Patil et al. 2017) LOFAR

Stage 3: Imaging/Tomography – SKA1-LOW

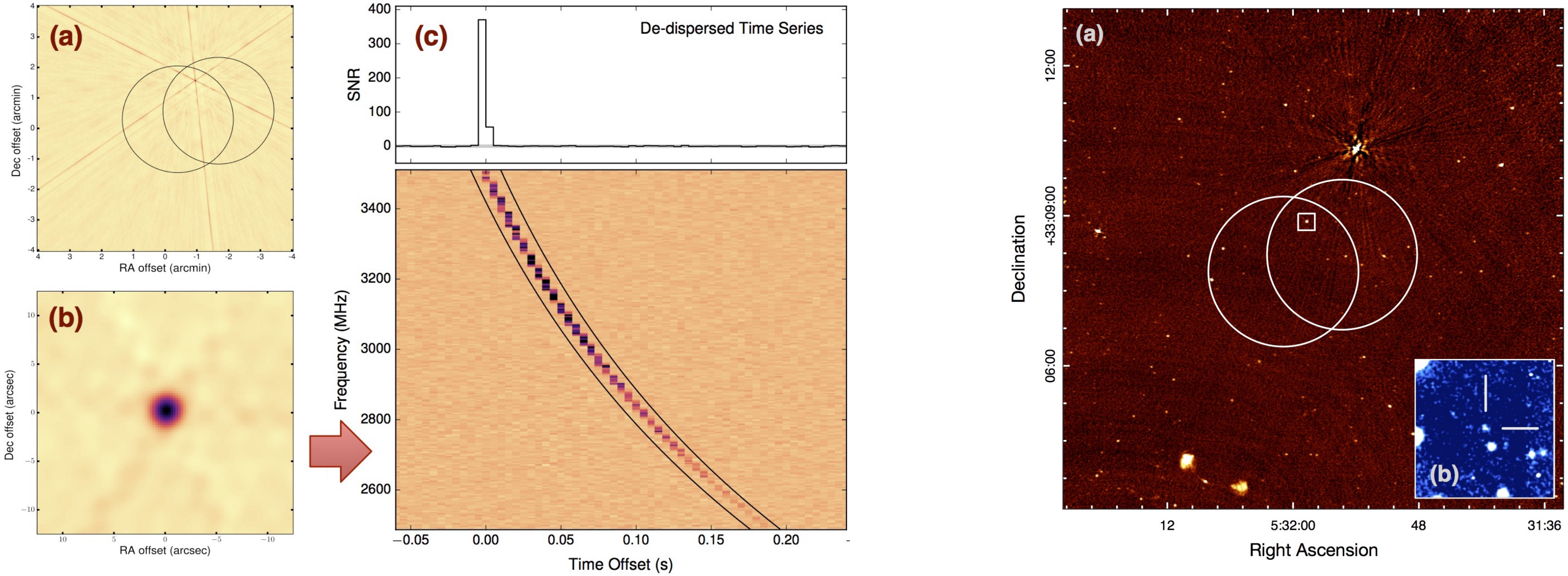


Transients: Fast Radio Bursts

Bright (50 mJy - 100 Jy), dispersed single pulses of emission, detected 400-8000 MHz with durations of a few ms or less.

>60 known, with 2 repeaters

Many models (mostly neutron stars); no conclusive evidence.

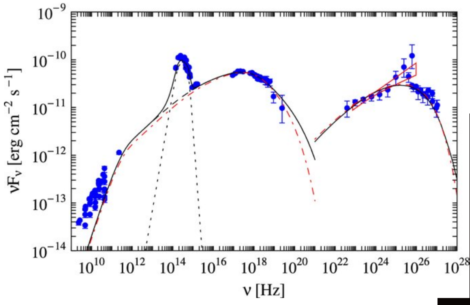


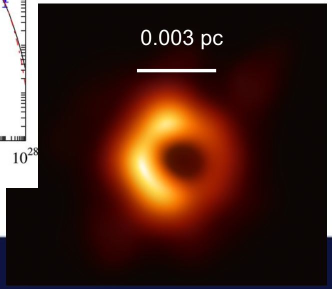
Localisation of one of the two known repeating Fast Radio Bursts (Chatterjee et al 2017)

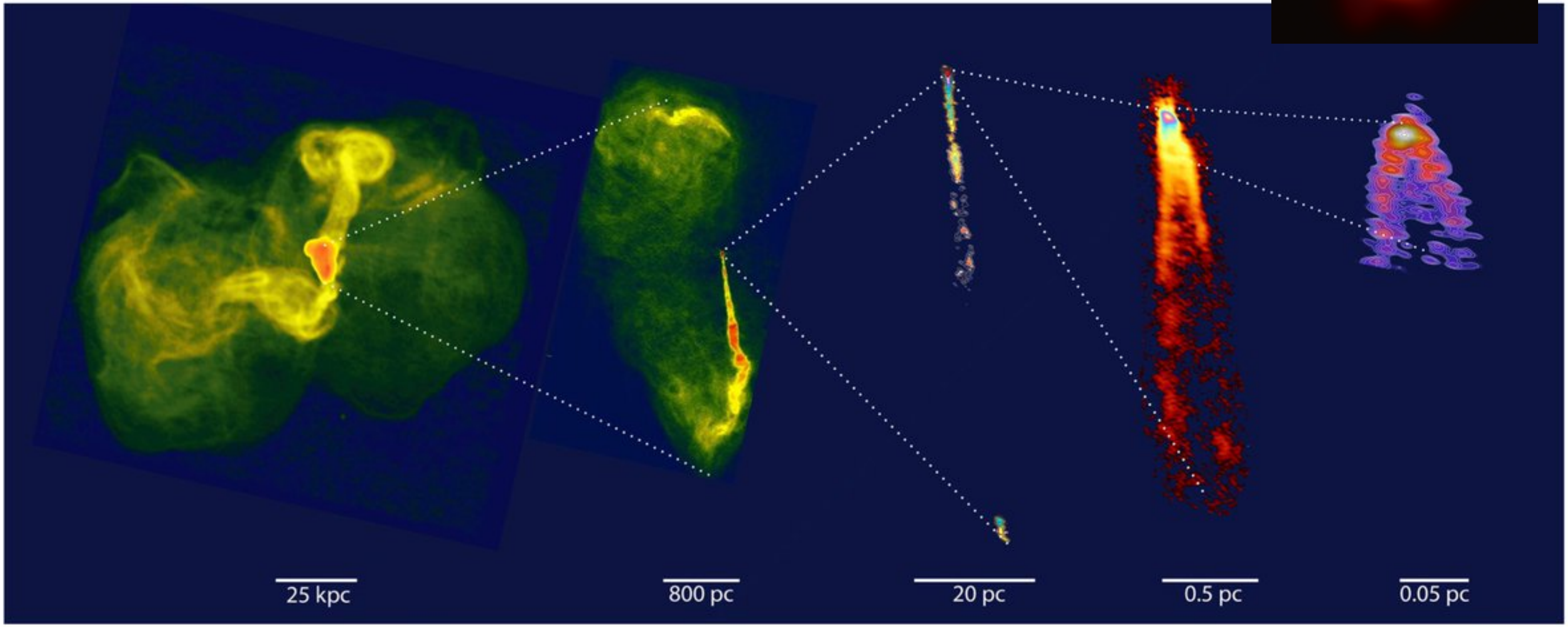
Relativistic Jets

Radio astronomy shows us the low-energy part of the electron energy distribution on all scales

VLBI allows exquisite resolution

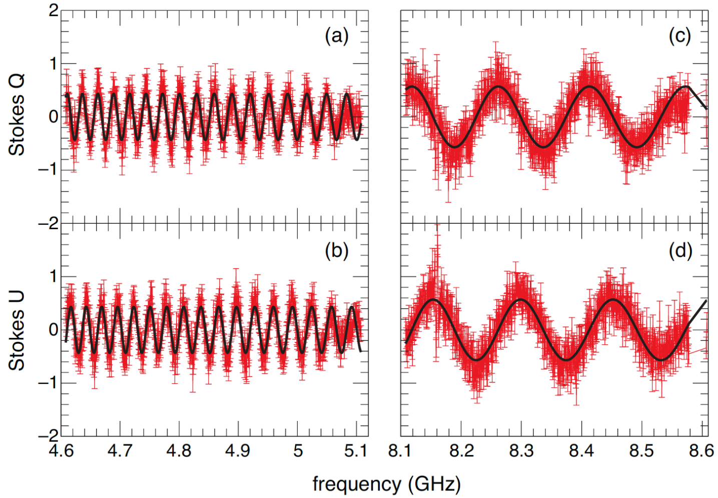




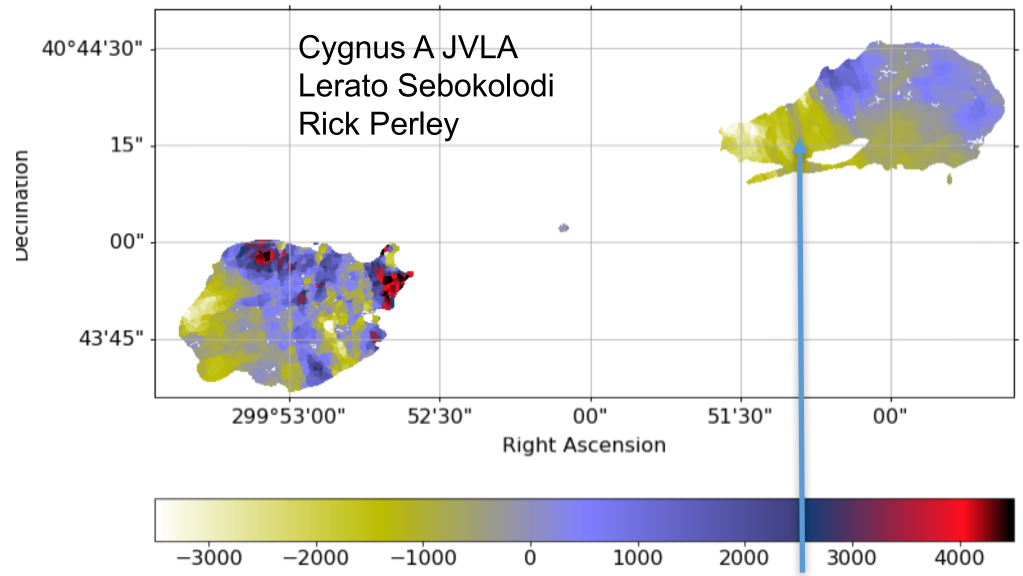


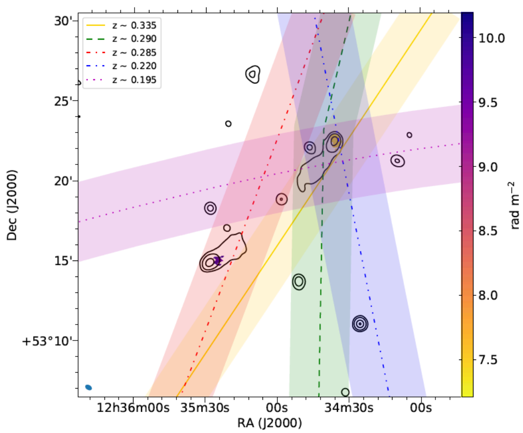
Magnetism: Faraday rotation

RM = -1043 rad m^{-2}



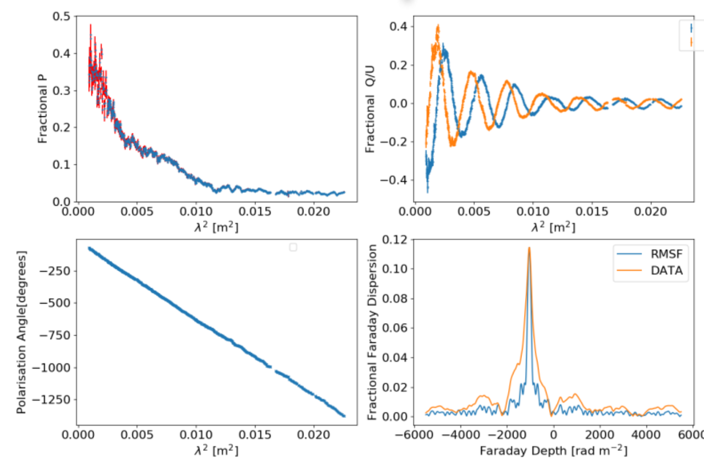
Galactic Centre magnetar
(Eatough et al. 2013)



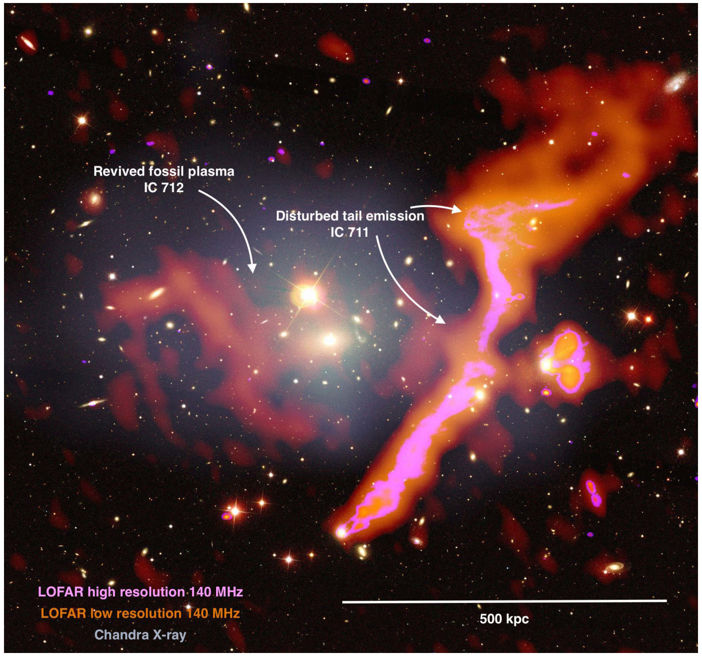


$\Delta\chi \propto \lambda^2 \int n_e B.dl$

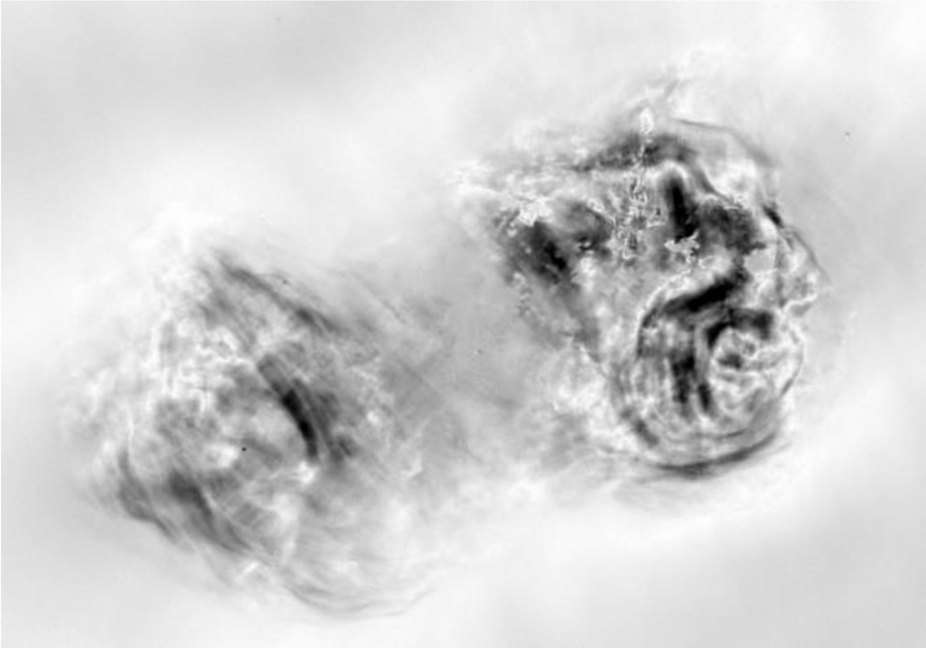
Faraday rotation from filaments in the Cosmic Web? O'Sullivan et al. (2019)



Magnetism: Synchrotron emission



A1314 LoTSS: diffuse emission from clusters of galaxies



Fornax A Polarised intensity (ASKAP, Craig Anderson)

CTA Science Cases

Theme		Question	Dark Matter Programme	Galactic Centre Survey	Galactic Plane Survey	LMC Survey	Extra-galactic Survey	Transients	Cosmic Ray PeVatrons	Star-forming Systems	Active Galactic Nuclei	Galaxy Clusters
Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of high-energy particle acceleration in the universe?		✔	✔✔	✔✔	✔✔	✔✔	✔	✔	✔	✔✔
	1.2	What are the mechanisms for cosmic particle acceleration?		✔	✔	✔		✔✔	✔✔	✔	✔✔	✔
	1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		✔		✔				✔✔	✔	✔
Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?		✔	✔	✔			✔✔		✔✔	
	2.2	What are the characteristics of relativistic jets, winds and explosions?		✔	✔	✔	✔	✔✔	✔✔		✔✔	
	2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	

1.1: Continuum radio surveys (Galactic/extragalactic) + transient searches and follow-up

1.2: Detailed radio imaging (polarisation) + VLBI

1.3: Radio continuum, HI and molecular lines

+ astrophysical contaminants in dark matter searches

2.1: VLBI; pulsar search and timing

2.2: Radio continuum imaging on all scales; transients

2.3: Faraday rotation in cosmic web/voids

- Many synergies
- Important radio techniques:
  - Wide-band polarisation
  - VLBI (cm, mm, sub-mm)
  - Wide-field continuum surveys
- Closer coordination
  - Survey planning
  - Transient detection and follow-up