PhD program in
Astronomy, Astrophysics and Space Science

2021/22 teaching activities

25 November 2021

# Sardinia Radio Telescope
# &
# Square Kilometer Array


Dr. Francesca Panessa
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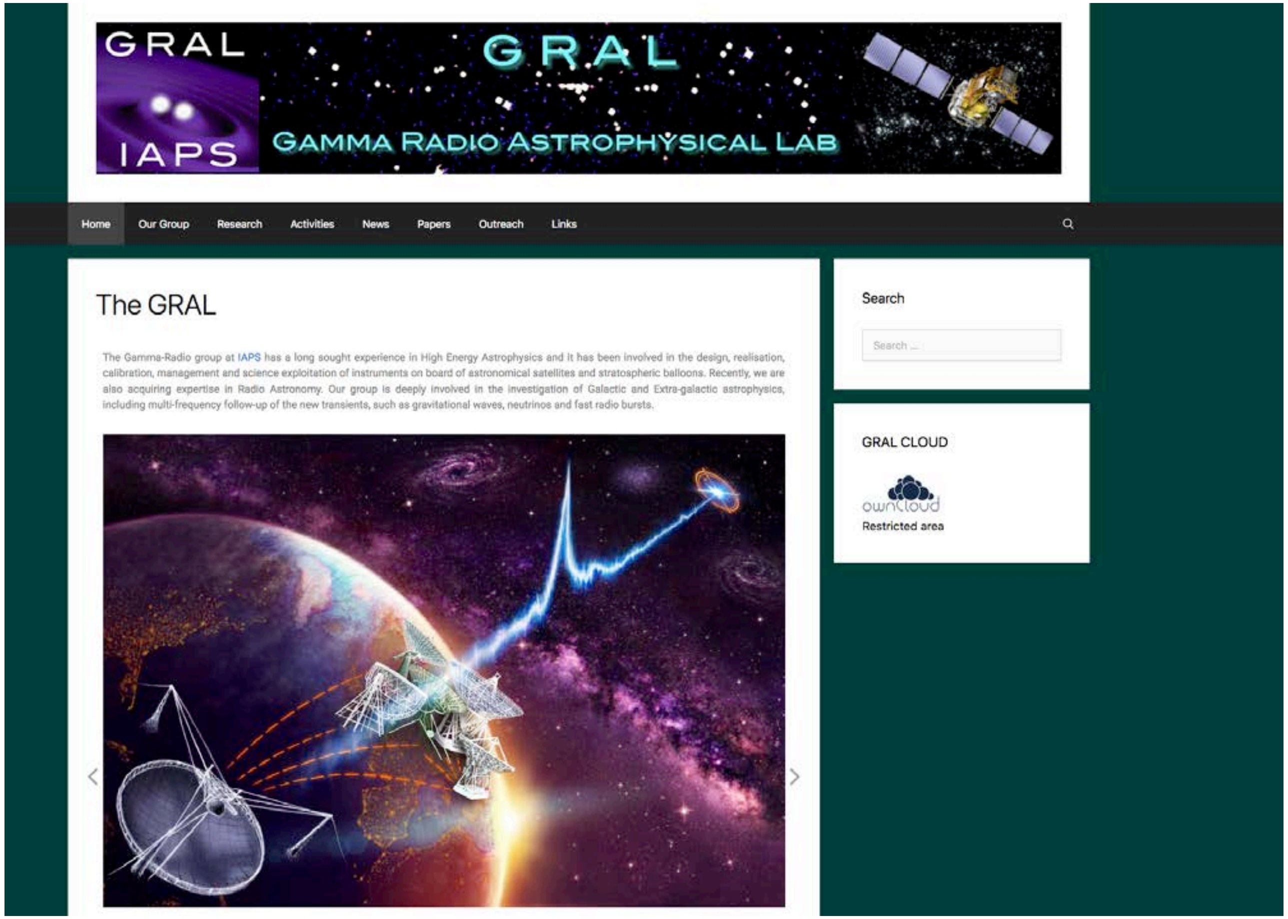
Istituto di Astrofisica e Planetologia Spaziali




## Francesca Panessa

Staff researcher at INAF-IAPS

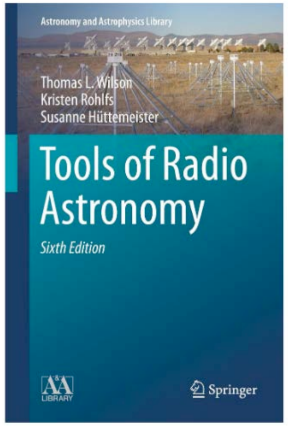
- Expertise: accretion/ejection physics in AGN, radio & X-rays
- SKA VLBI core member
- SRT, LOFAR-it, EVN, eMERLIN Time Allocation Committee

francesca.panessa@inaf.it

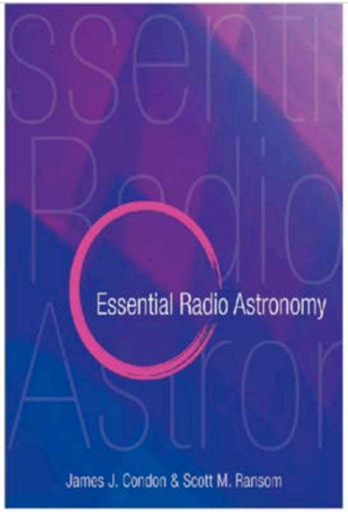
**GRAL research group:**

http://gral.iaps.inaf.it/

# Material




Wilson, Rohlfs & Huettemeister: Tools of Radio Astronomy




*Essential Radio Astronomy*
Condon & Ransom

Princeton University Press, 2016

https://science.nrao.edu/opportunities/courses/era/

**Useful notes:**
http://www.ira.inaf.it/Library/e-books/Fanti&Fanti-Papers.pdf

**School of radioastronomy:**
https://www.chalmers.se/en/researchinfrastructure/oso/events/ERIS2019/Pages/default.aspx

Credits to: Sergio Poppi, John McKean, Robert Braun, Phil Diamond, Robert Laing, Grazia Umana

## COURSE OVERVIEW

- Brief introduction to radioastronomy
- Sardinia Radio Telescope (SRT)
- Square Kilometer Array (SKA)

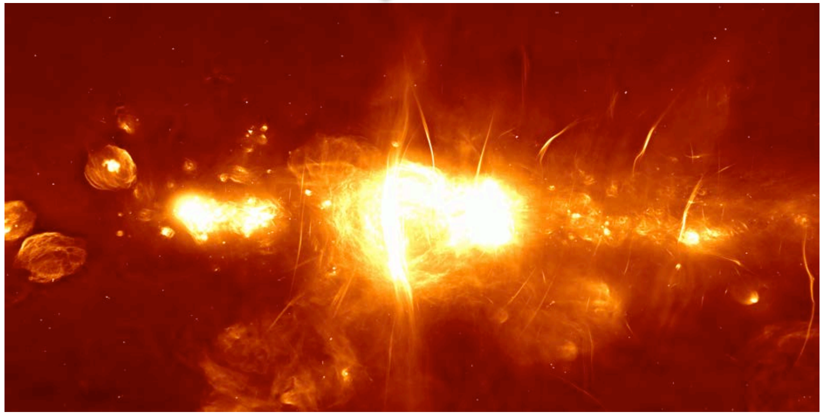
Institute for Space Astrophysics and Planetology
Istituto di Astrofisica e Planetologia Spaziali

GRAL
GAMMA RADIO ASTROPHYSICAL LAB

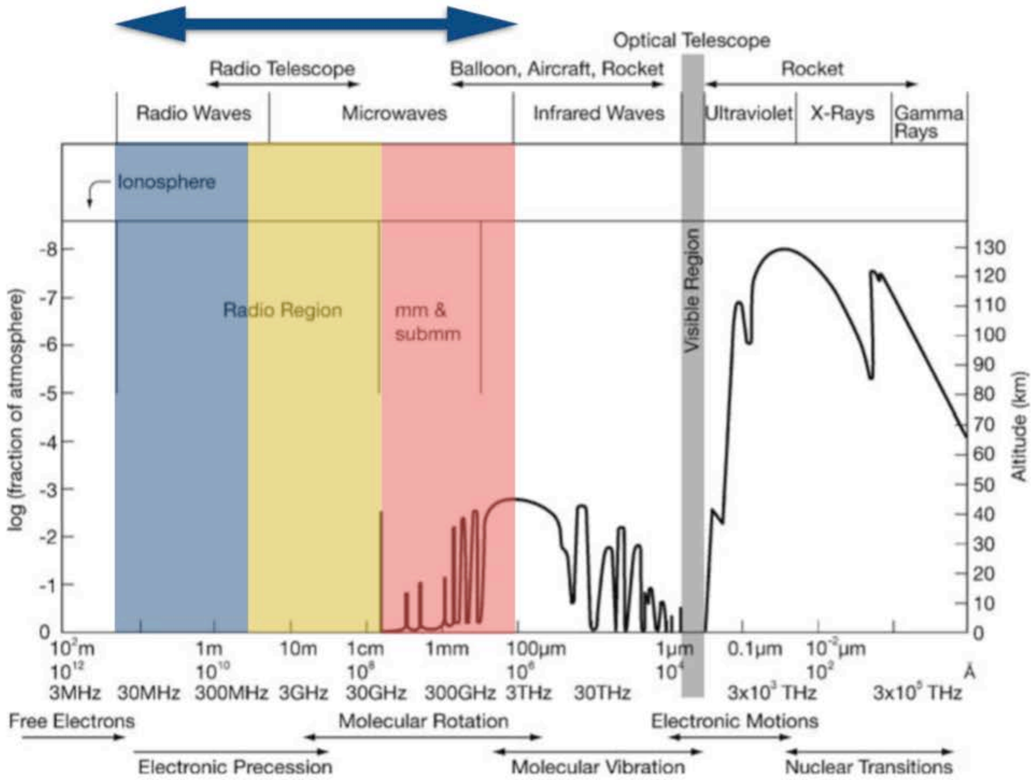

National Radio Astronomy Observatory / Associated Universities, Inc. / National Science Foundation

← if our eyes were able to see radiowaves

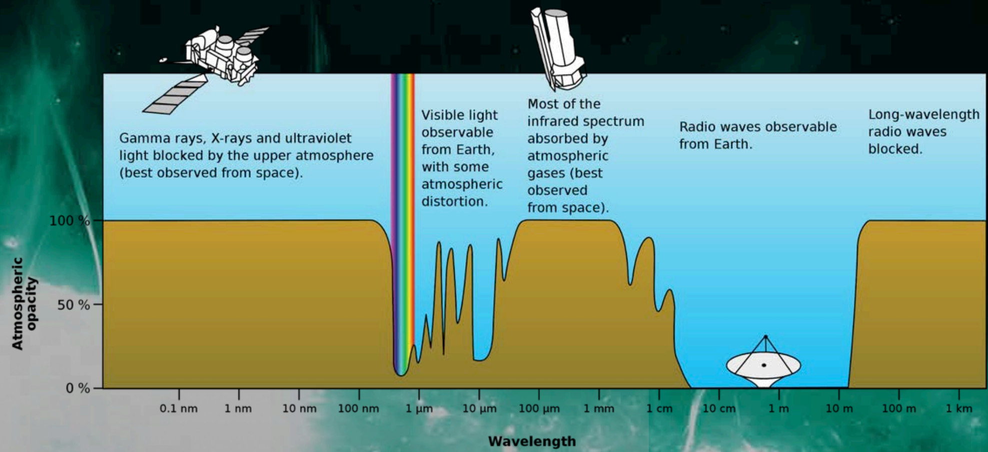
looking toward the center of our galaxy


MeerKAT image of the Milky Way center at 1.4 GHz

- Radio Astronomy is the study of radiation from celestial sources at frequencies between $\nu \sim$ 10 MHz to 1 THz ($10^7$ Hz to $10^{12}$ Hz).

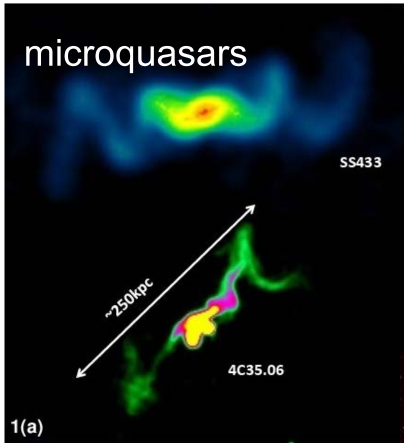


# Why radio astronomy?

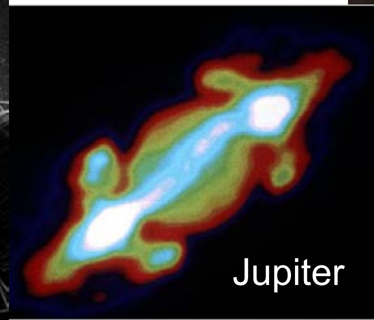



- Radio waves reach the ground
- Can observe objects or phenomena that are difficult or impossible to detect in other wavelength ranges
- Used for quantitative physical diagnostics of object parameters
- Discovery of new sources (e.g., fast radio bursts)

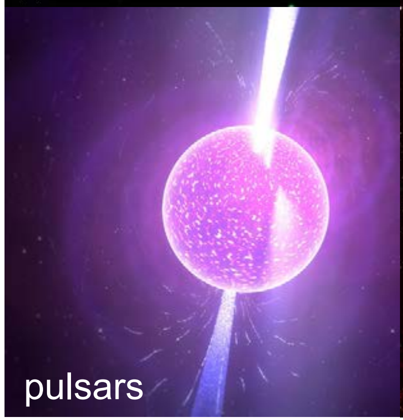
# Radio sources

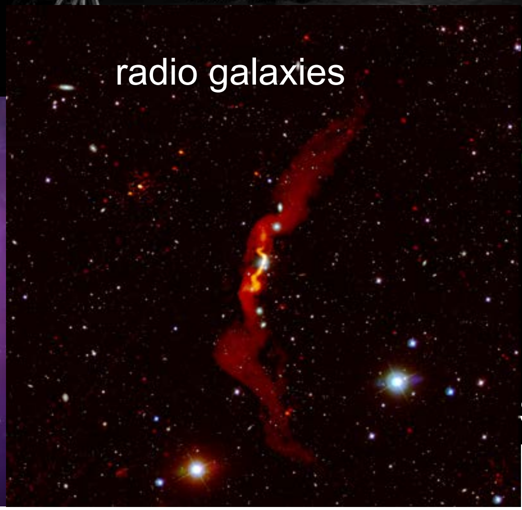


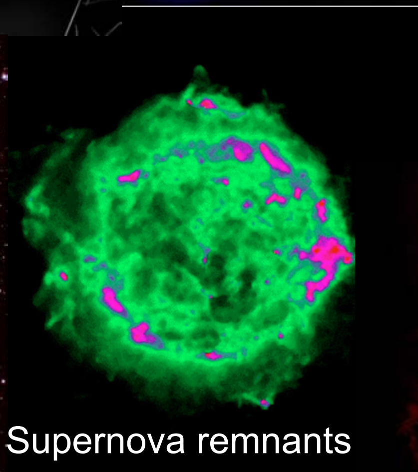


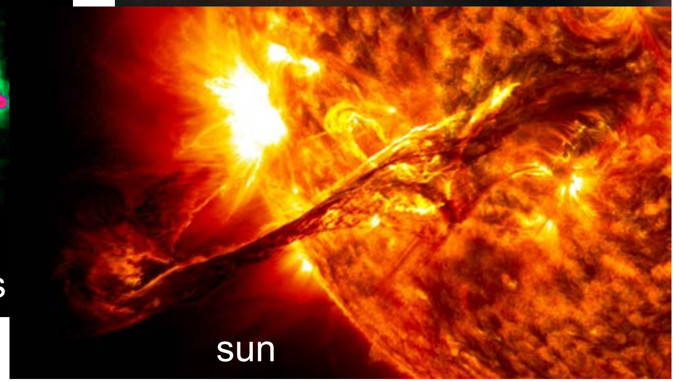


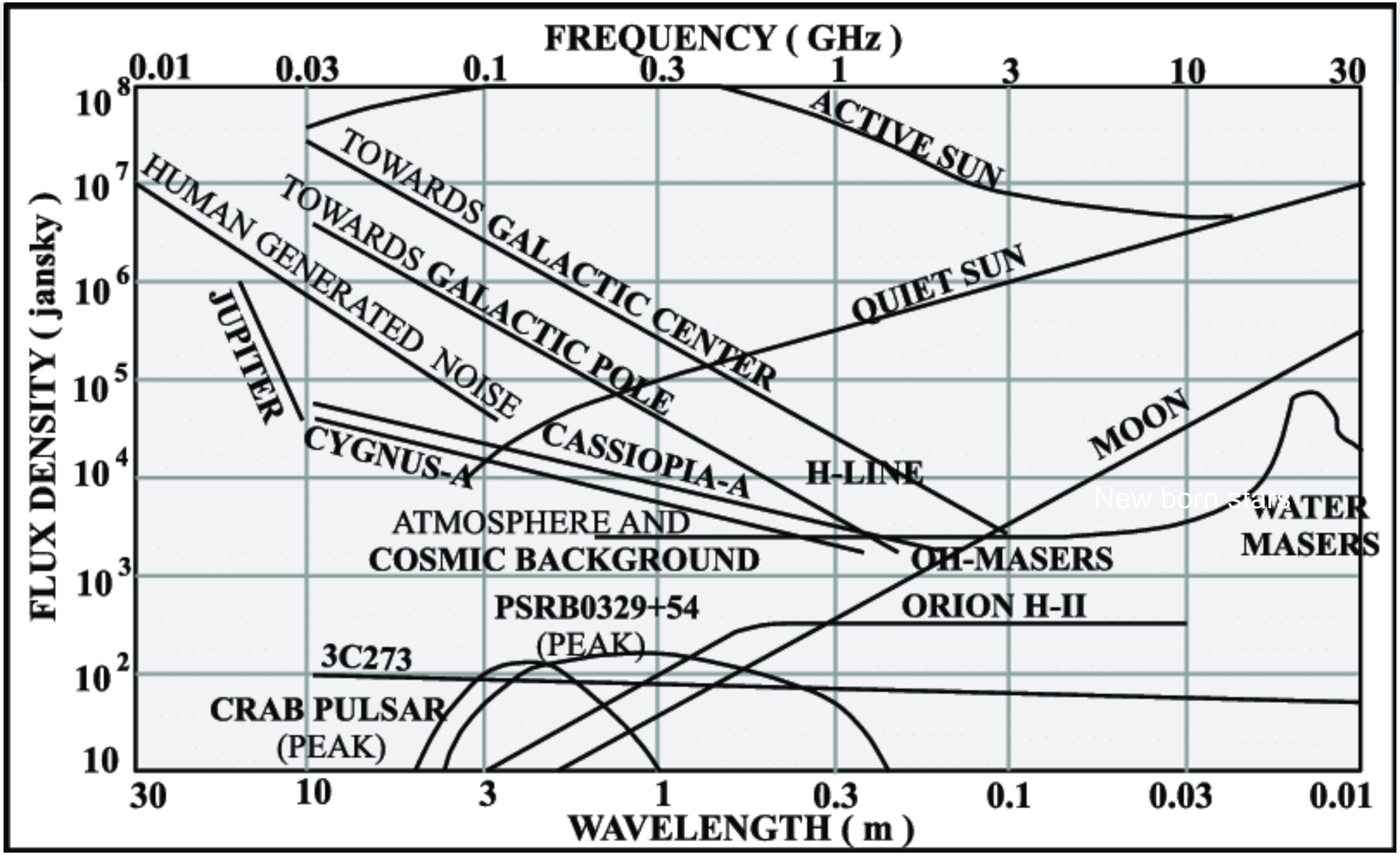




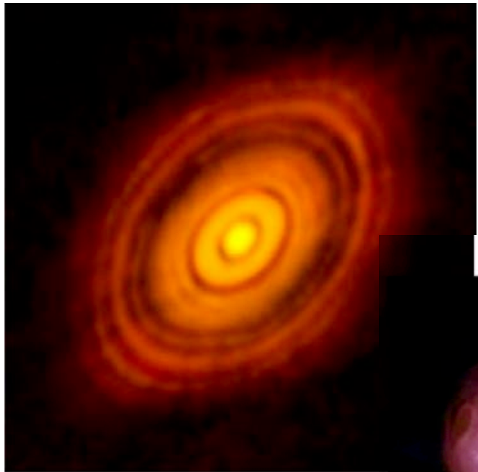




FREQUENCY ( GHz )
0.01
0.03
0.1
0.3
1
3
10
30
FLUX DENSITY ( jansky )
$10^8$
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
10
ACTIVE SUN
TOWARDS GALACTIC CENTER
TOWARDS GALACTIC POLE
HUMAN GENERATED NOISE
QUIET SUN
JUPITER
CYGNUS-A
CASSIOPIA-A
H-LINE
MOON
New born stars
WATER MASERS
ATMOSPHERE AND
COSMIC BACKGROUND
OH-MASERS
ORION H-II
PSRB0329+54
(PEAK)
3C273
CRAB PULSAR
(PEAK)
30
10
3
1
0.3
0.1
0.03
0.01
WAVELENGTH ( m )

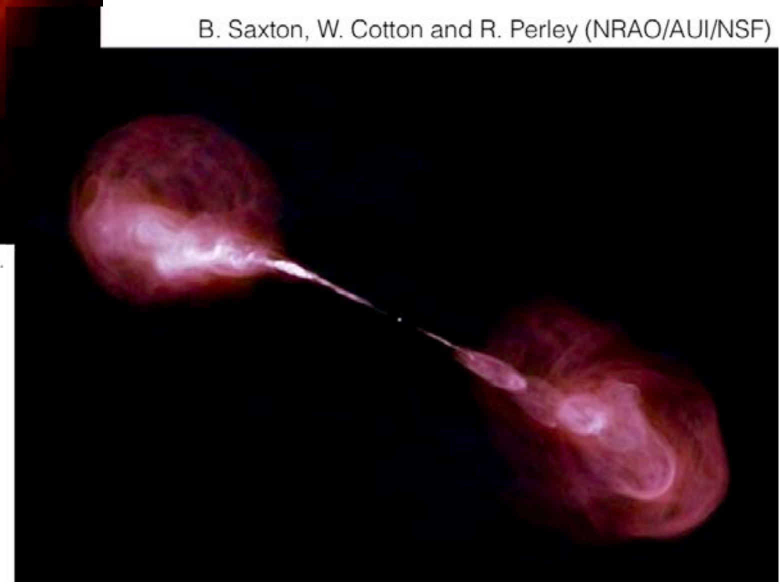
# Radiation mechanisms?

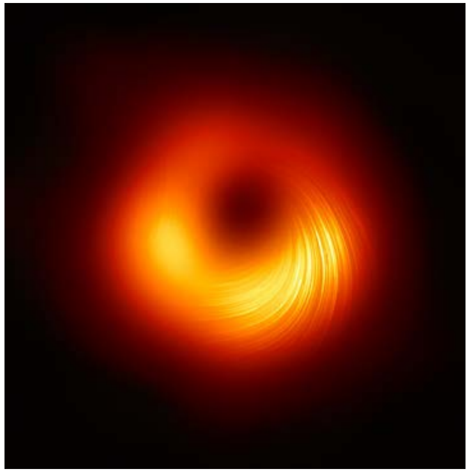


ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF)

Radio emission from celestial objects can be both
thermal and non-thermal

B. Saxton, W. Cotton and R. Perley (NRAO/AUI/NSF)





EHT Collaboration

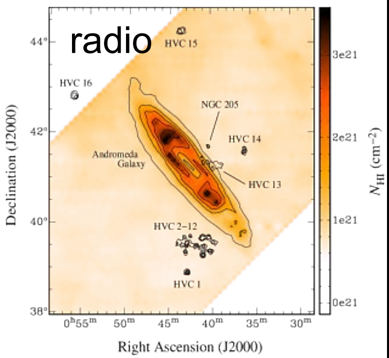
Radio emission is produced in a large number of ways

→ one must first determine which radio emission mechanism is responsible for the emission

# Multi-frequency

the radio range of wavelengths is as essential as gamma ray, X-ray, UV, optical, and IR for providing a complete picture of the physical nature of astronomical sources

→ MULTI-FREQUENCY ASTROPHYSICS !



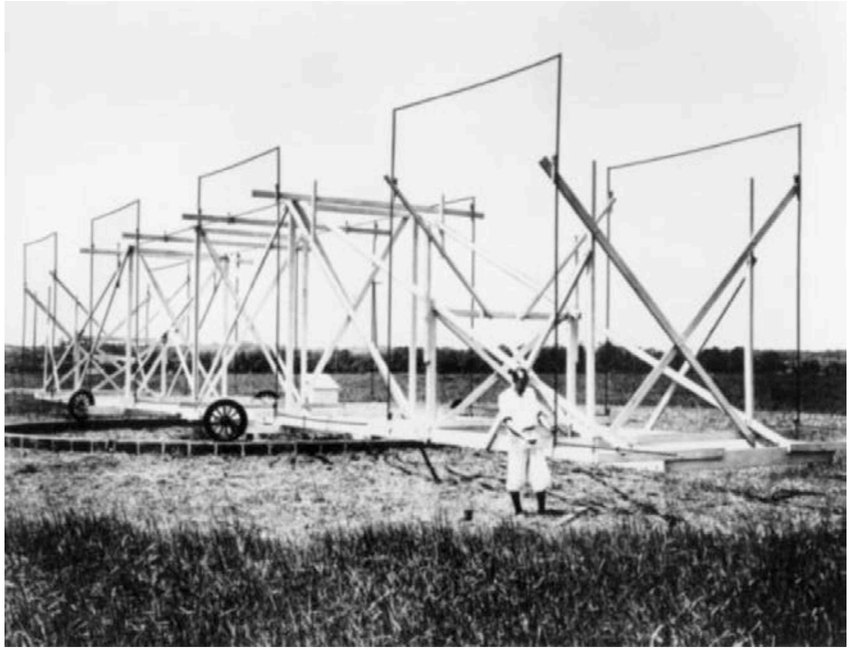

# Early Radio Astronomy

- The first detection of radiation at radio wavelengths was not made until 1932 due to:
  - ➢ limitations of technology (our eyes), but then the communication era started
  - ➢ the expectation that celestial objects would be too faint

- Long distance communication developed by Marconi & Ferdinand Braun - Nobel Prize 1909

- Karl Jansky (1933, published) discovered a radio signal at 20.5 MHz that varied steady every 23 hours and 56 minutes (Sidereal day).

→ "The data give for the co-ordinates of the region from which the disturbance comes, a right ascension of 18 hours and declination -10 degrees."
He had detected the Galactic Centre.



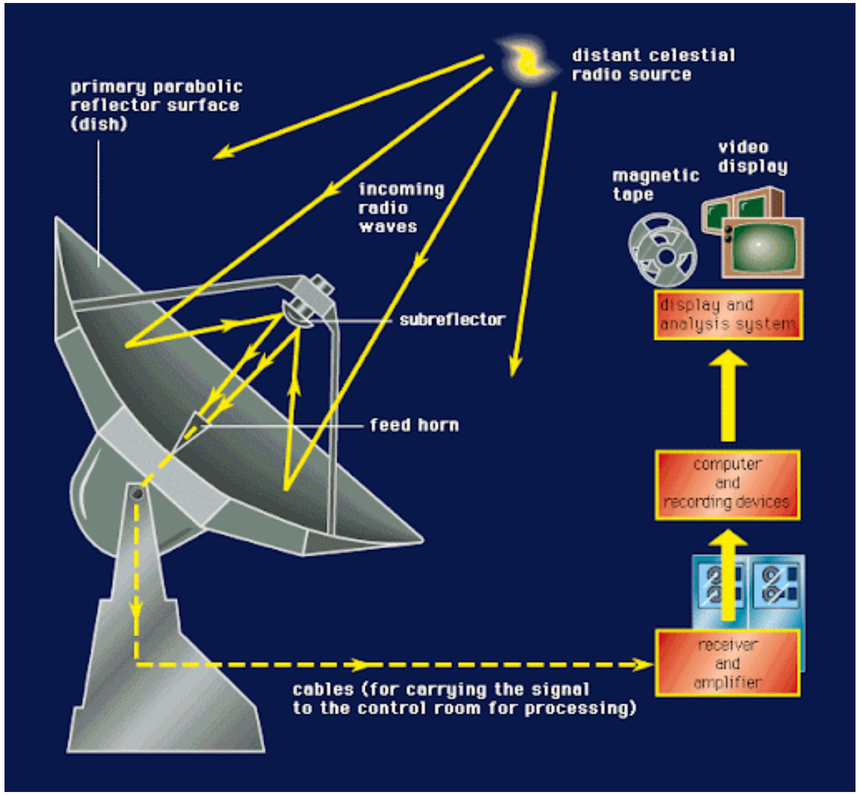
# Radio telescopes

- Radio telescopes are designed in a different way to optical telescopes, and the radio range is so broad (5 decades in frequency) that different telescope technologies can be used

- Because radio waves are so long and cosmic radio sources are extremely weak, radio telescopes are the largest telescopes in the world, and only the most sensitive radio receivers are used inside them

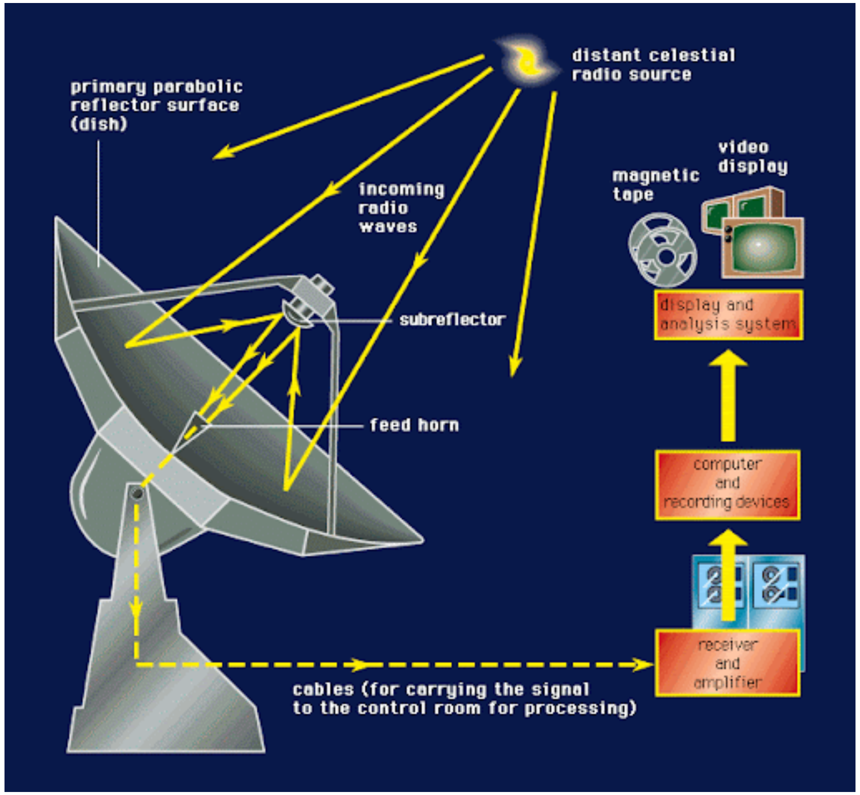
- Dish antennae bounce many different wavelengths at once, and we need different receivers to tune to different frequency channels for the different kinds of research

- To observe a specific wavelength range, we select a specific size funnel to grab the radio waves we want. These funnels are called feed horns.



# Radio telescopes

- To incoming radio waves from space, the dish surface acts in the same manner as a smooth mirror
- The waves are reflected and focused into a *feedhorn*
- The weak radio signals are channeled by the *feedhorn* into a *receiver*
- Radio receivers amplifies the incoming signal ~ million times
- The amplified signals are carried by fibre optic cable from the receivers down into where they are stored on computer disks



# Radio telescopes and interferometers

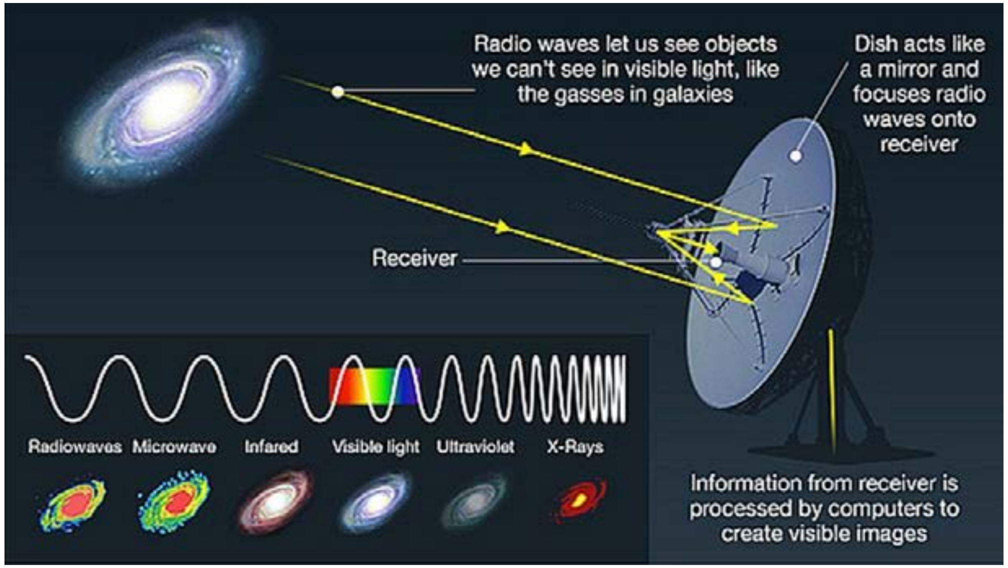
Large single-element radio telescopes can be constructed cheaply, but have limited spatial resolution

$$\theta \approx \lambda/D$$

Resolution (radians)

Observing wavelength (m)

Diameter of telescope (m)




Single dishes have limited resolution but can achieve excellent sensitivity ($A_e \sim D^2$)

**Worked example:** What is the spatial resolution (in arcseconds) of the $D$ = 300 m Arecibo telescope, operating at $\nu$ = 5 GHz?

$$\lambda = \frac{c}{\nu} = \frac{3 \times 10^8 \text{ m}}{5 \times 10^9 \text{ Hz}} = 0.06 \text{ m}$$

$$\theta \sim \frac{0.06 \text{ m}}{300 \text{ m}} = 0.0002 \text{ radians} \equiv 41 \text{ arcsec}$$

Arecibo, Puerto Rico: 300 m

Green Bank Telescope: 110 m

# Radio interferometry

- Interferometric techniques have been developed to combine several single-element telescopes into a multi-element array
- Now, the resolution is limited by the distance between the elements

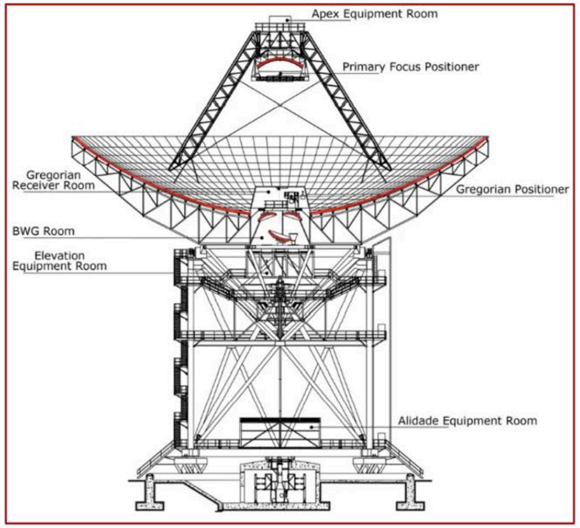
$$\theta \approx \lambda / D$$

Resolution (radians)

Observing wavelength (m)

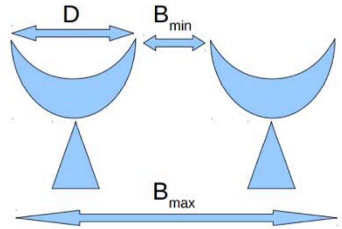
Distance between telescopes (m)

**Single Dish**




Resolution = $\lambda/D$

**Interferometer**




Resolution=$\lambda/B_{max}$
Sensitive to this range of angular sizes $\lambda/B_{max} < \theta < \lambda/B_{min}$

Single dish minimum separation is zero so they can, in principle, recover the total flux of extended sources

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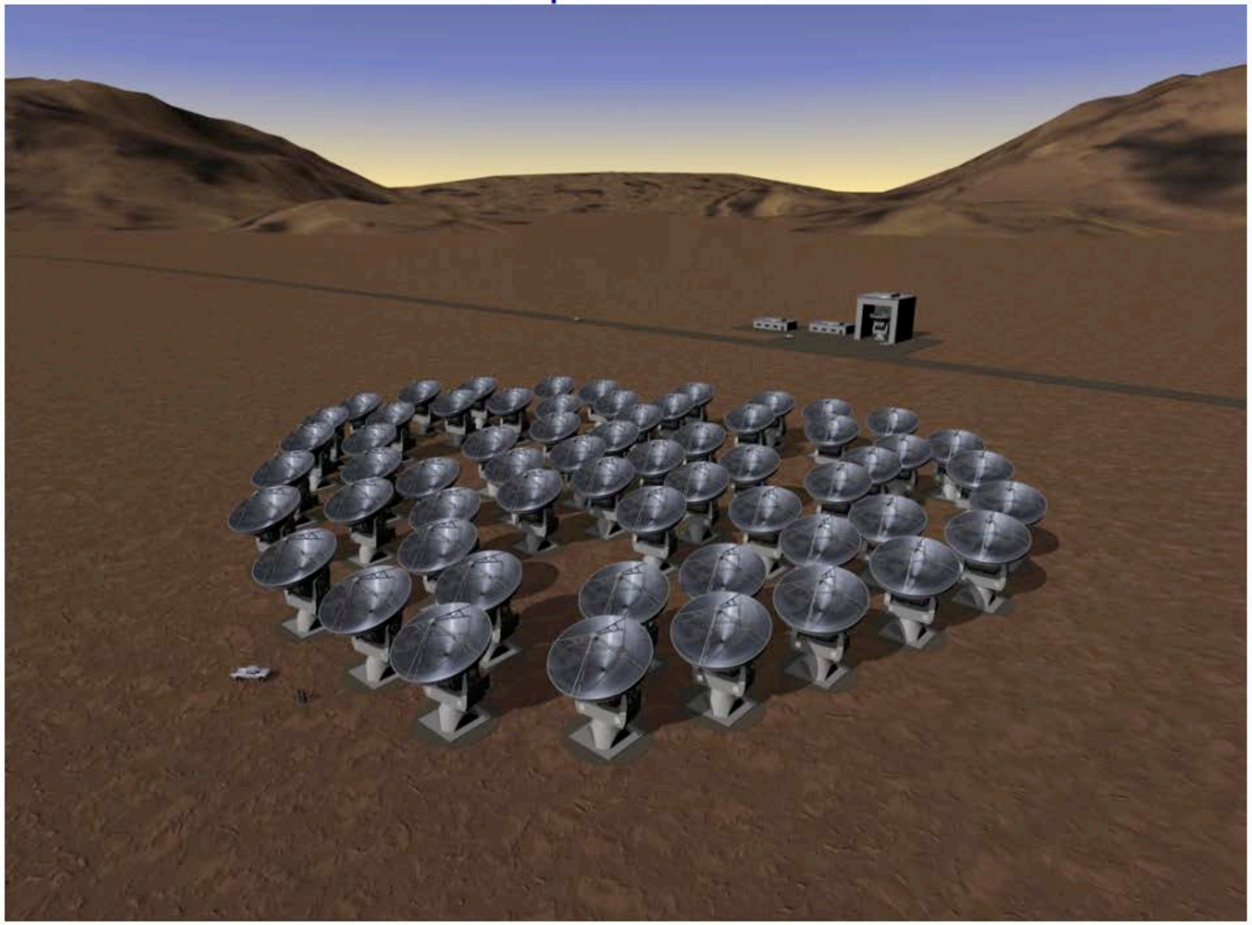
# Radio interferometry

**Single dish:** diameter is responsible for sensitivity, field of view, resolution

**Interferometer:** takes this apart



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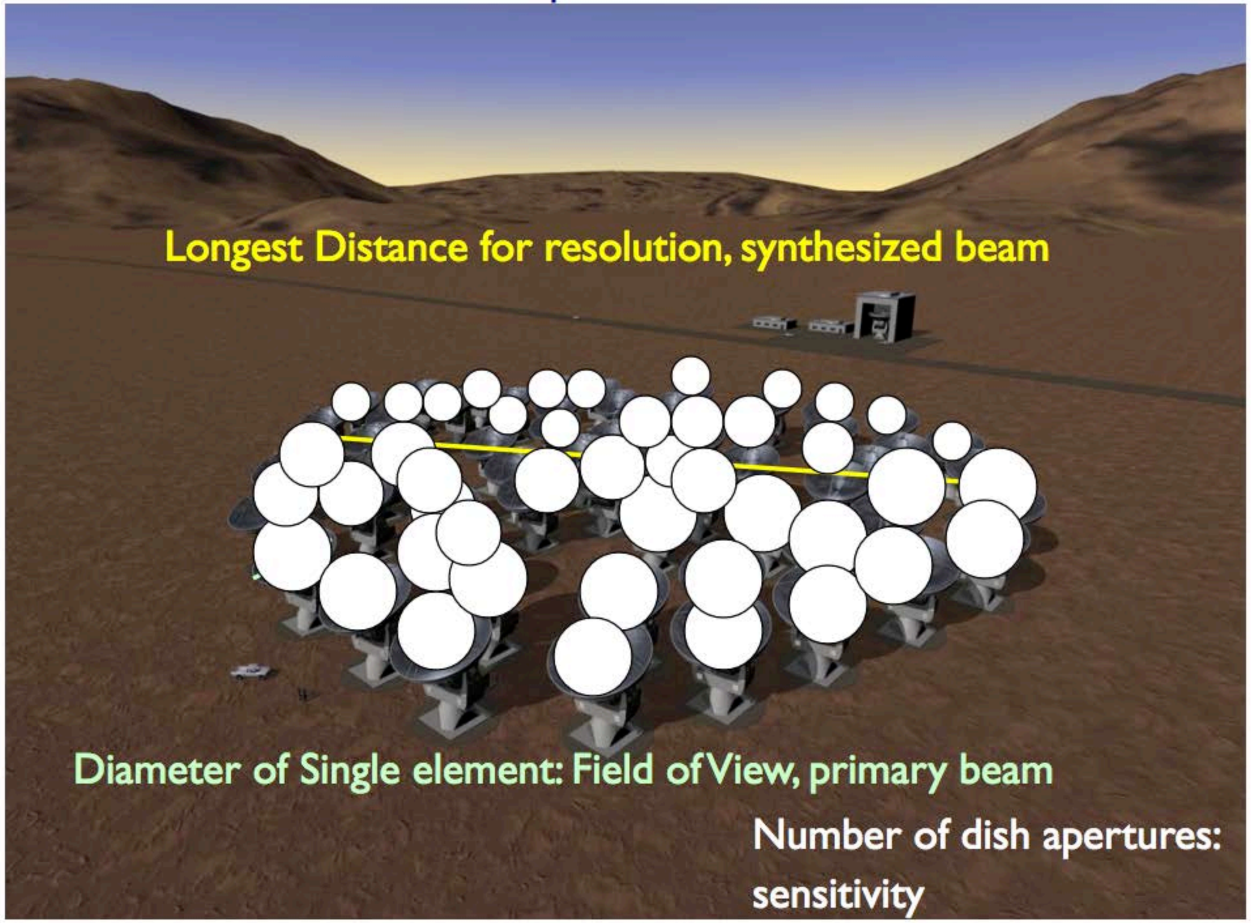
Istituto di Astrofisica e Planetologia Spa

# Radio interferometry

**Single dish:** diameter is responsible for sensitivity, field of view, resolution

**Interferometer:** takes this apart



# Radio interferometry

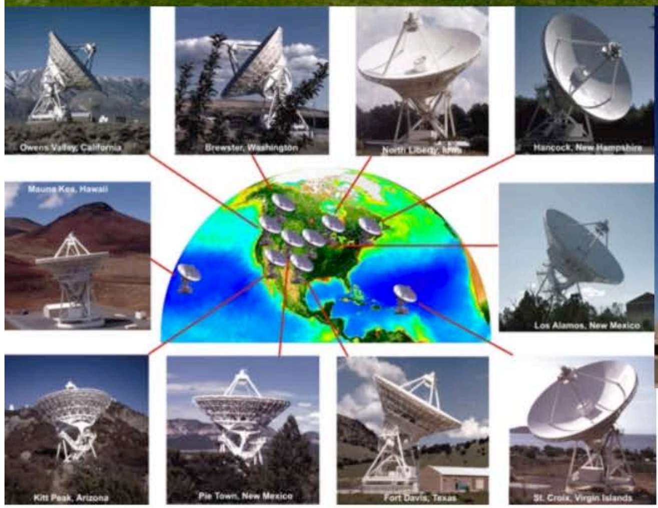
**Worked example:** What is the spatial resolution (in arcseconds) of the Very Long Baseline Array operating at $\nu = 5$ GHz? The longest distance between telescopes is $D_{max}$ = 8611 km.

$$\theta \sim \frac{0.06 \text{ m}}{8.611 \times 10^6 \text{ m}} = 7 \times 10^{-9} \text{ rad}$$

$$\frac{180}{\pi} * 3600 * 7 \times 10^{-9} = 0.00144 \text{ arcsec}$$

The Low Frequency Array: $D_{max} \sim 1500$ km

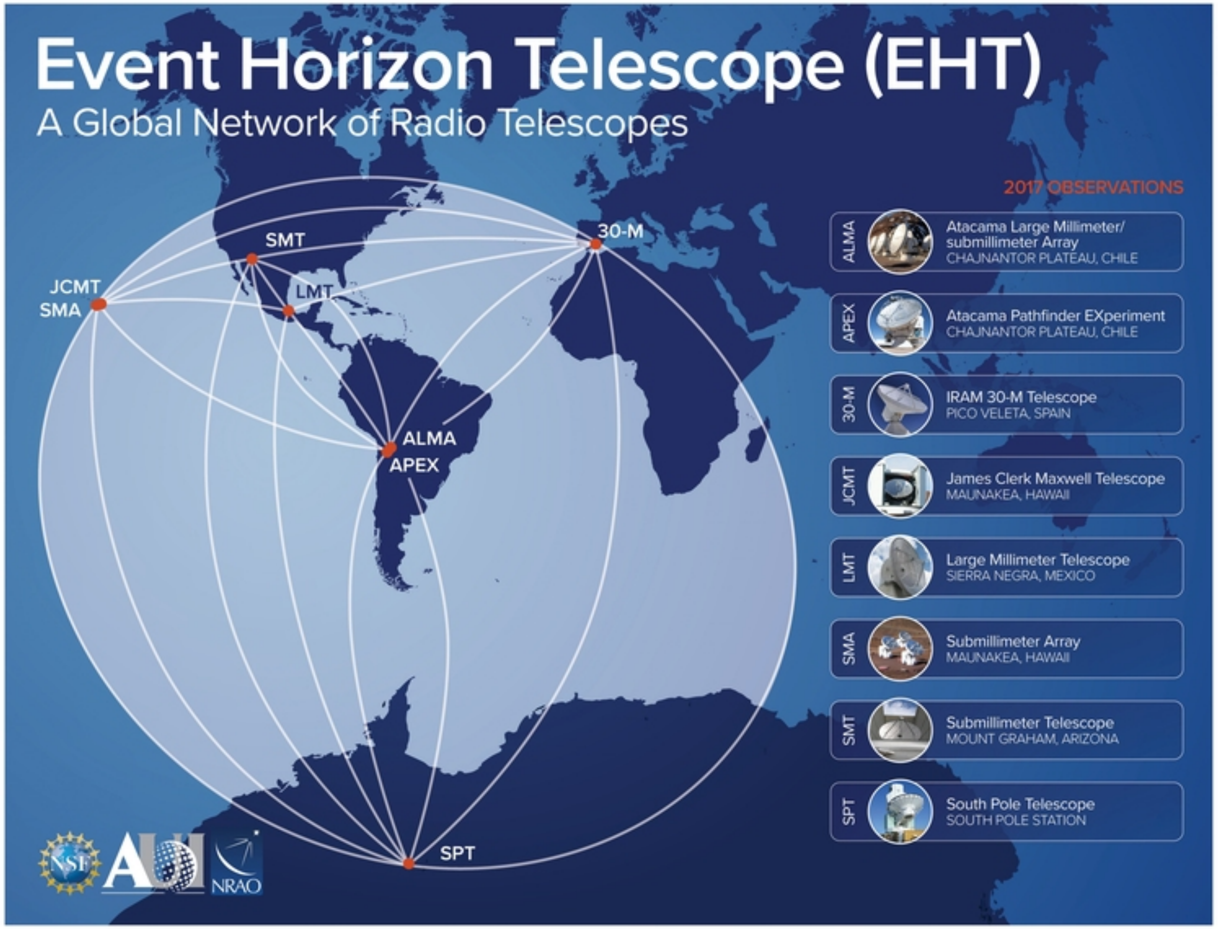
The Very Large Array: $D_{max} \sim 36$ km

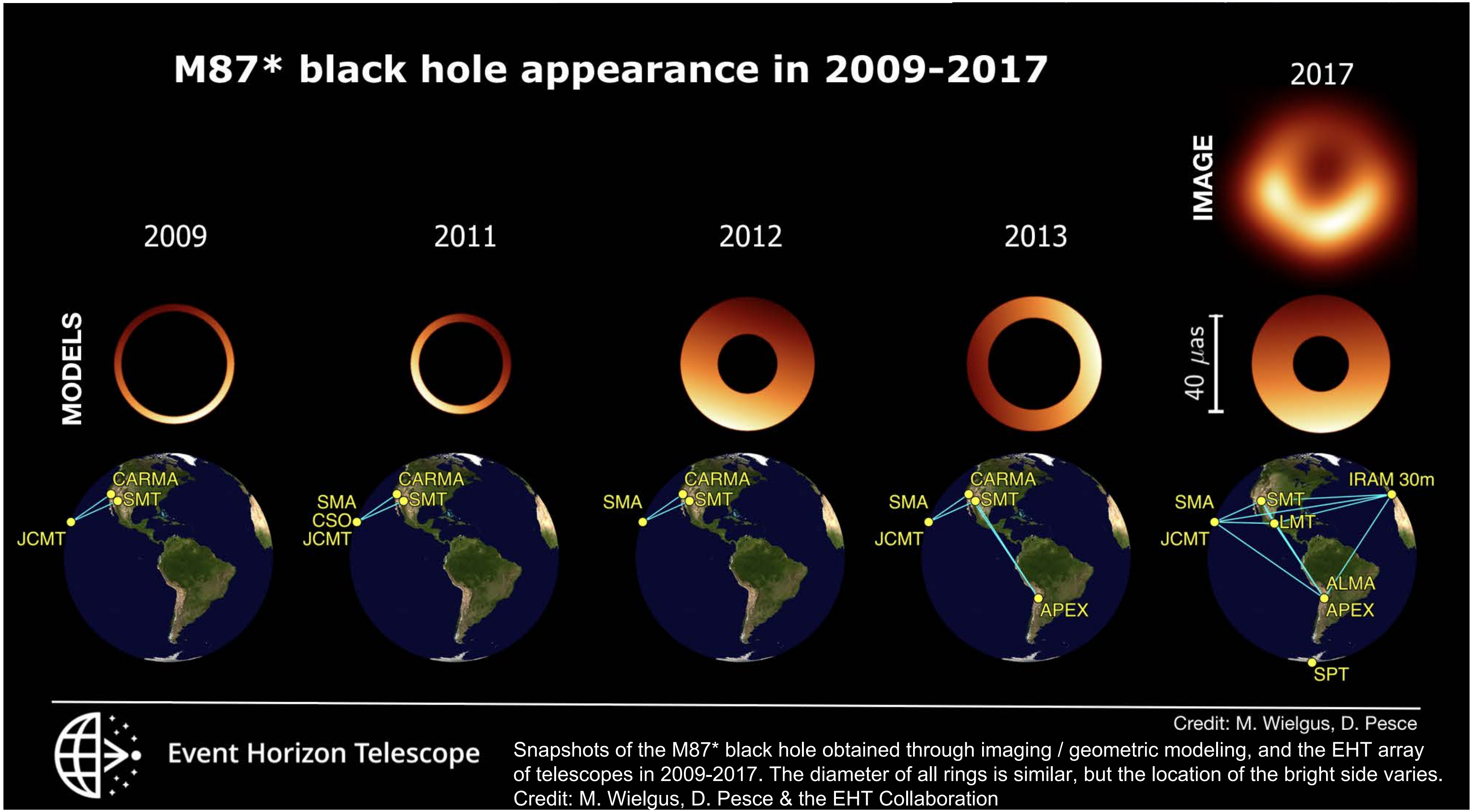



Atacama Large Millimetre Array: $D_{max} \sim 16$ km

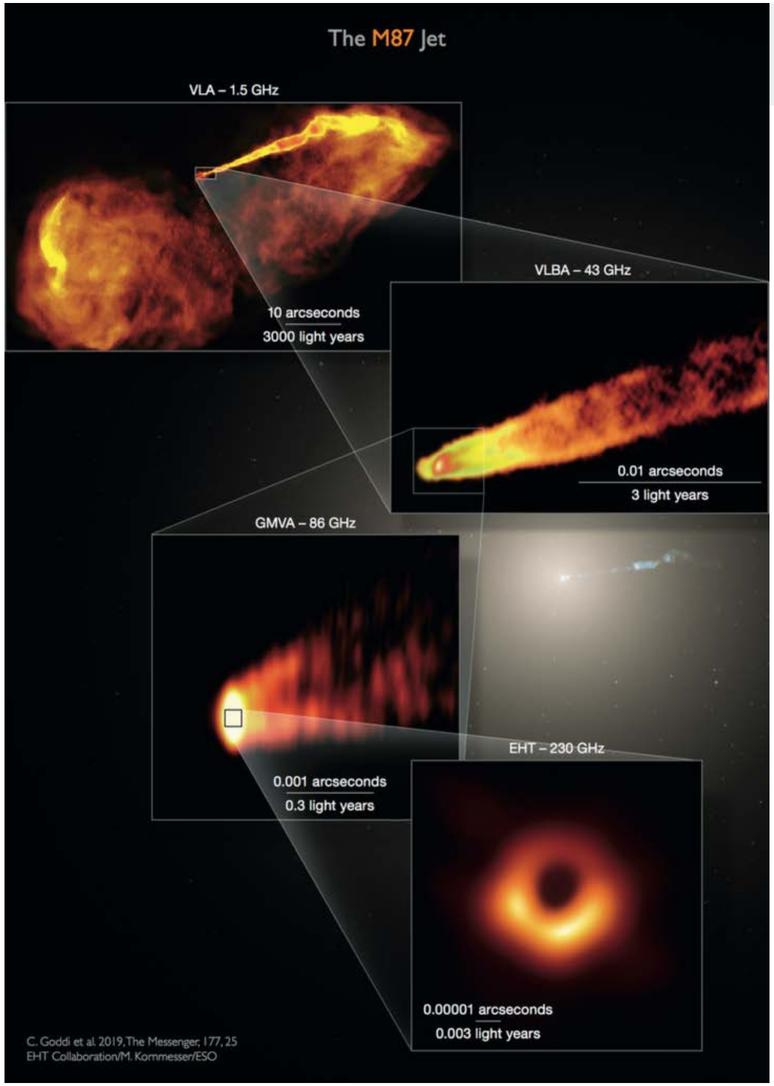
The Very Long Baseline Array: $D_{max} \sim 9000$ km

Radio interferometry can provide the highest angular resolution imaging possible in astronomy


Event Horizon Telescope (EHT)
A Global Network of Radio Telescopes
2017 OBSERVATIONS
SMT
30-M
JCMT
SMA
LMT
ALMA
APEX
SPT
ALMA Atacama Large Millimeter/ submillimeter Array CHAJNANTOR PLATEAU, CHILE
APEX Atacama Pathfinder EXperiment CHAJNANTOR PLATEAU, CHILE
30-M IRAM 30-M Telescope PICO VELETA, SPAIN
JCMT James Clerk Maxwell Telescope MAUNAKEA, HAWAII
LMT Large Millimeter Telescope SIERRA NEGRA, MEXICO
SMA Submillimeter Array MAUNAKEA, HAWAII
SMT Submillimeter Telescope MOUNT GRAHAM, ARIZONA
SPT South Pole Telescope SOUTH POLE STATION
NRAO

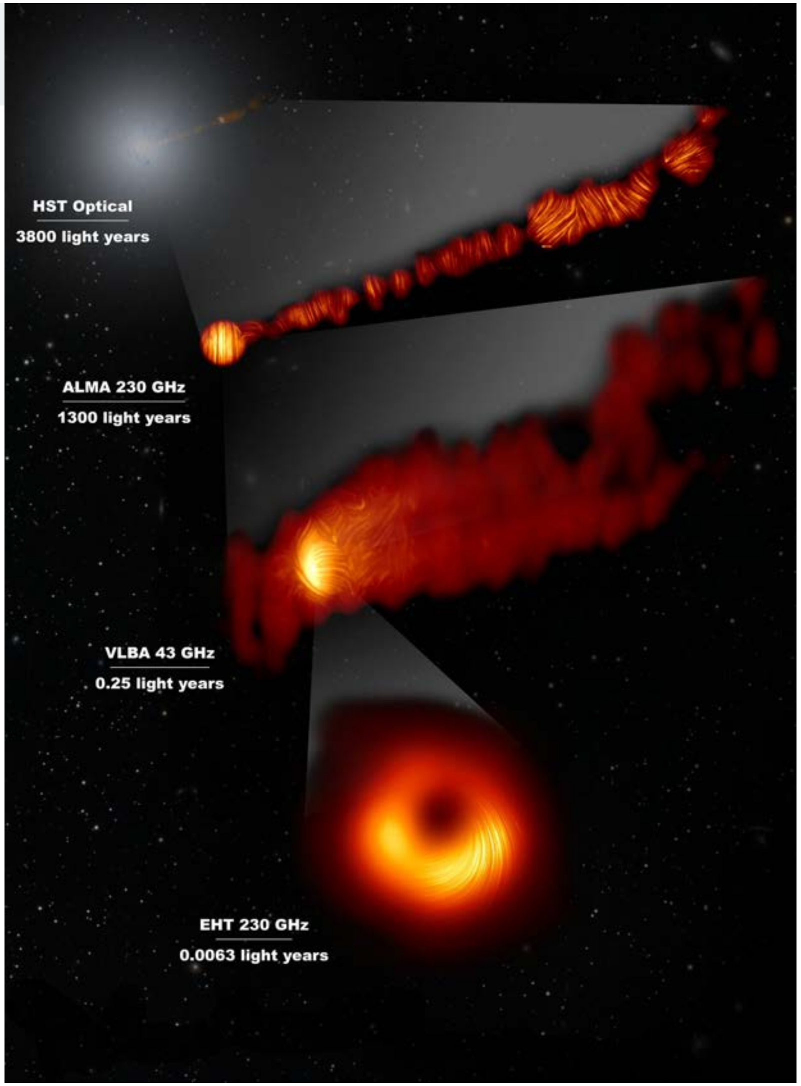



Snapshots of the M87* black hole obtained through imaging / geometric modeling, and the EHT array of telescopes in 2009-2017. The diameter of all rings is similar, but the location of the bright side varies. Credit: M. Wielgus, D. Pesce & the EHT Collaboration




Optimization of the scientific output:

Resolution
&
Frequency



# The Sardinia Radio Telescope (SRT)


Some userful links:

- SRT Commissioning paper http://bit.ly/srt_bolli
- Italian Radio Telescopes https://www.radiotelescopes.inaf.it/

# The Sardinia Radio Telescope (SRT)

SRT is an observing infrastructure operated by INAF,
result of a scientific and technical collaboration among three
INAF research units:

- the Cagliari Astronomical Observatory (OACa),
- the Institute of Radio Astronomy (IRA),
- the Arcetri Astrophysical Observatory (OAA)

The telescope:

- 64-metre radio telescope
- fully steerable
- Frequency range: 0.3 - 116 GHz

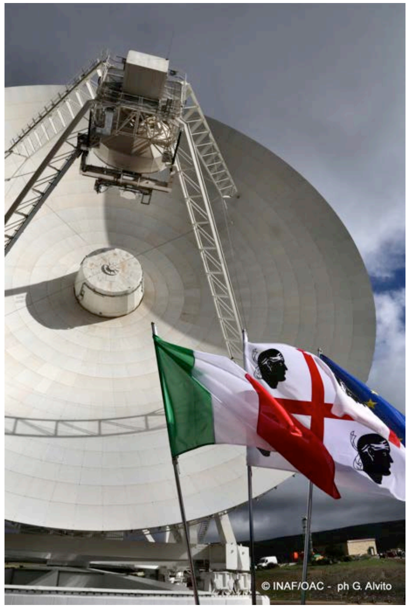
Funding Bodies:

- MIUR
- Italian Space Agency
- Regional Government of Sardinia

# The Sardinia Radio Telescope (SRT): timeline

# The Sardinia Radio Telescope (SRT): timeline

- **June 2012 – October 2013**:
  Technical commissioning;
- **September 2013**:
  Opening Ceremony;
- **February 2012 - January 2016**:
  Astronomical Validation;
- **February - August 2016**:
  Early Science Program;
- **2017**:
  Refurbishment of active surface; Buildings and infrastructures completed;
- **2018**:
  Re-commissioning;
- **From Dec. 2018**
  Call for proposals together with Italian Radio Telescopes

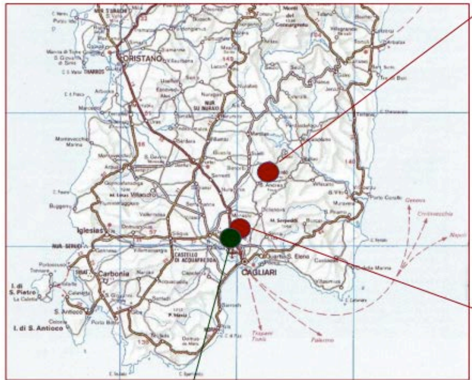


# The Sardinia Radio Telescope (SRT): location

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

OAC Osservatorio Astronomico di Cagliari

SRT (San Basilio / Gerrei)



New Headquarters (Selargius)

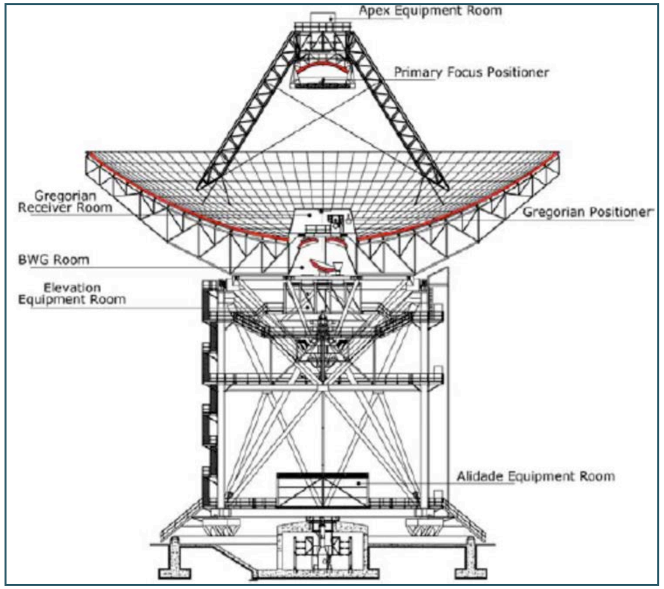
Physics Department of the University of Cagliari

**SRT**

- Location: Pranu Sanguni, San Basilio (SU), Italy
- Longitude: 9°14’42”East
- Latitude: 39°29’34’’North
- Altitude: 650 m. a.s.l.

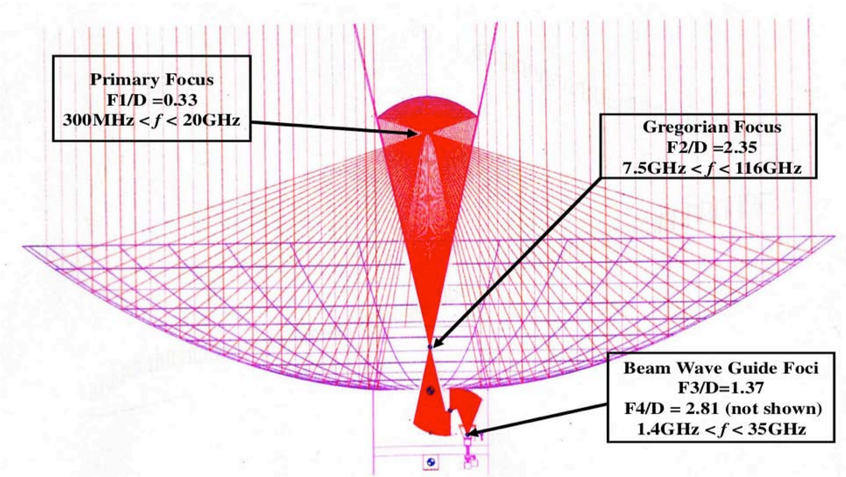
# The Sardinia Radio Telescope (SRT): structure

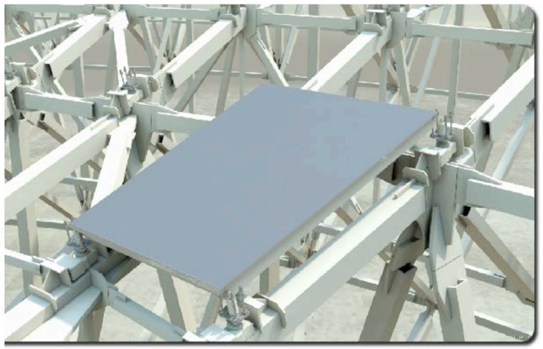
- 64m primary mirror with **active surface**
- Gregorian **shaped** configuration
- 7.9 m secondary mirror.
- 6 focal positions, **frequency agility**
- Frequency range: 0.3 – 26.5 GHz (now!)
- Elevation range: 5°-90°
- Azimuth range: ± 270°
- Azimuth slewing speed:51°/min
- Elevation slewing speed: 30°/min



# The Sardinia Radio Telescope (SRT): unique features

1. Active Surface (Stable beam (PSF) shape during the observation)
2. Shaped Profile (SRT outstanding spectral machine)
3. L-P Band Receiver (Outstanding pulsar machine)
4. K-Band Multibeam receiver (unique high sensitivity spectral survey capabilities)



# The Sardinia Radio Telescope (SRT): reicevers

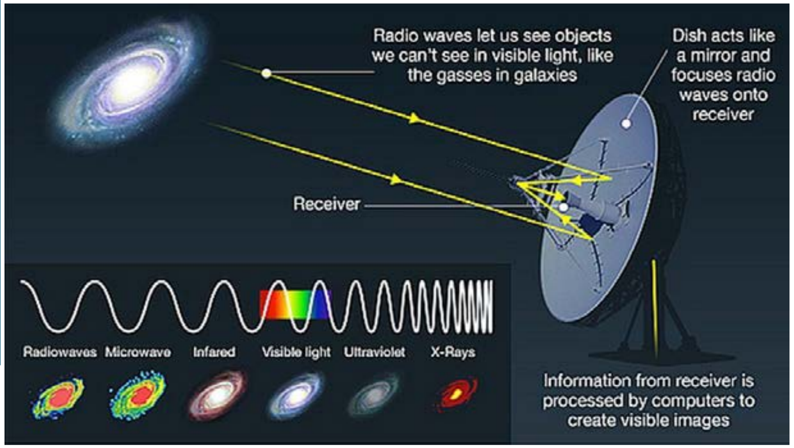
**Available**

- **L-P band:** 305-410 MHz (P), 1.3-1.8 GHz (L), cryogenic, primary focus;
- **K band:** 18-26.5 GHz, cryogenic, 7-beam array, Gregorian focus;
- **C-band:** 5.7-7.7 GHz, cryogenic, BWG;

**Forthcoming**

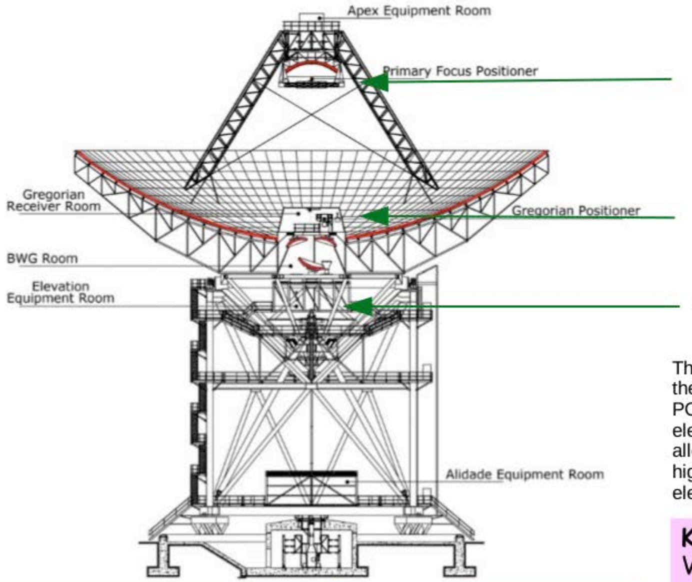
- **Low-C band:** 4.2-5.6 GHz, cryogenic single feed dual-circular pol. - BWG focus;

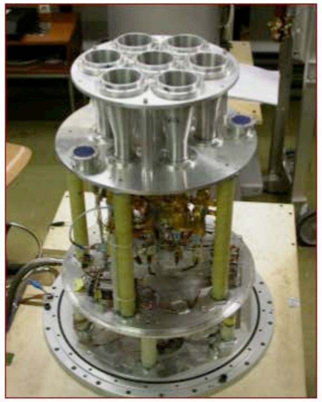
- **S band:** 3.0-4.5 GHz, cryogenic 7-beam dual-linear pol. - primary focus;



# The Sardinia Radio Telescope (SRT): reicevers

## *Sardinia Radio Telescope - RECEIVERS*



The recently completed upgrade of the active surface and the possibility of upgrading the infrastructure provided by this PON represent a great opportunity to equip SRT with all the electronic, mechanical and software systems necessary to allow the observation of radioastronomical sources at the highest radio frequencies, opening a window of the electromagnetic spectrum not yet explored by SRT.

**P-band** 305-425 MHz

**L-band** 1.3-1.8 GHz

**C-band** 5.7-7.7 GHz

**S-band** 3.0-4.5 GHz

**Clow-band** 4.2-5.6 GHz

**K/Q/W band** VLBI

**W-band** Camera 80-116 GHz

**K-band** multibeam 18-26 GHz

**Q-band** multibeam 33-50 GHz

**W-band** multibeam 75-116 GHz

# The Sardinia Radio Telescope (SRT): backends

Backend system, as a part of the radio telescope, receives the radio signal which is amplified by the receiver, lays its emphasis on signal digitization and processing and sends the processed data into storage system.

- **Total Power**, single band backend for continuum observations. Seven beams.
- **XARCOS**, a digital spectrometer. Seven beams.
- **SARDARA**, a ROACH2-based spectro-polarimeter. (2.3 GHz BW)
  Single beam => seven beams soon.
  2 GHz bandwidth, 16384 ch
  spectroscopy, spectropolarimetric/continuum
  soon: zoom modes + pulsar modes
- **DFB3**, Digital Filter Bank mark 3, for pulsar observations. Dual beam.
- **ROACH1: 128 MHz**

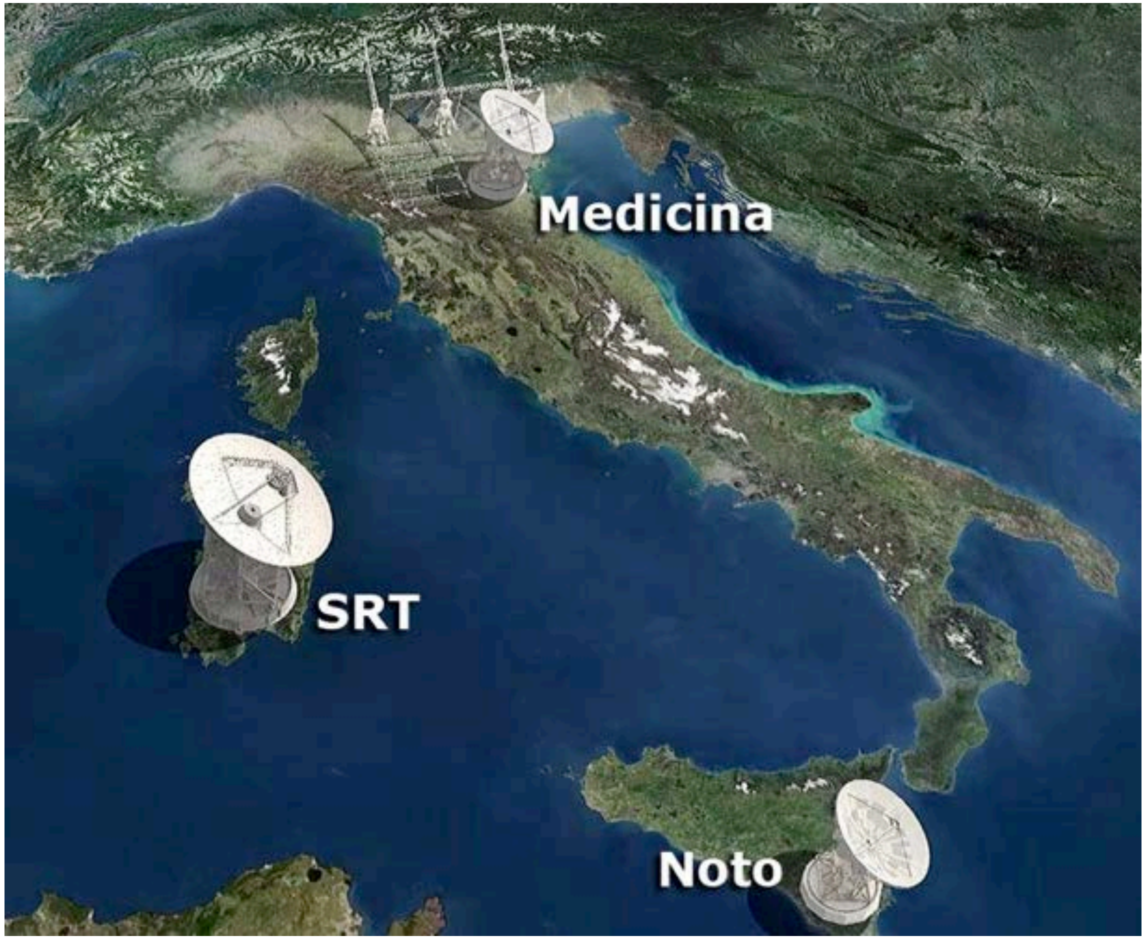
# The Sardinia Radio Telescope (SRT): performances

- **Sensitivity:**
  - 1 mJy within seconds integration time

- **Beam Size:**
  - 1 deg$^2$ at 300 MHz
  - 15'x15' at 1.4 GHz
  - 2.5'x2.5' at 7 GHz
  - 7X 1'x1' at 20 GHz

- **Time sampling:**
  - Down to 10 ms with spectropolarimeters
  - 100 us in pulsar mode

# The italian antennas



# Italian Radio telescopes

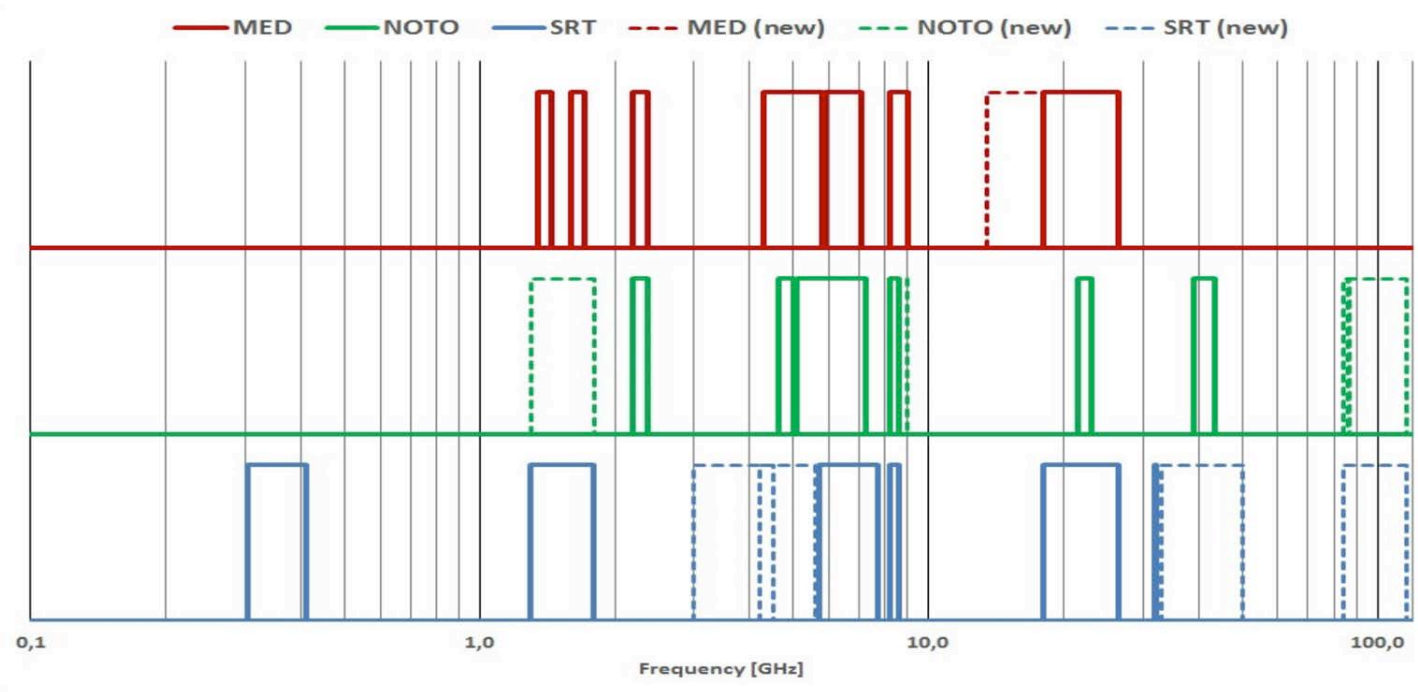
INAF manages three single-dish radio telescopes. Observations can be run either in single-dish or in a network for interferometric observations (VLBI):

- Sardinia Radio Telescope (64m)
- Medicina Radio Telescope (32m)
- Noto Radio Telescope (32m)

Network which Italian Radio telescopes join to:

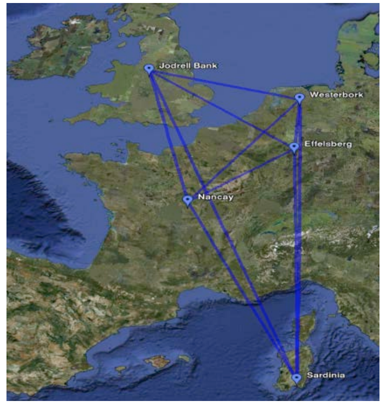
- European VLBI EVN
- Italian VLBI
- East Asia to Italy Near Global VLBI (EATING VLBI)

# The Sardinia Radio Telescope (SRT): frequency coverage



# Science with SRT and the Italian VLBI

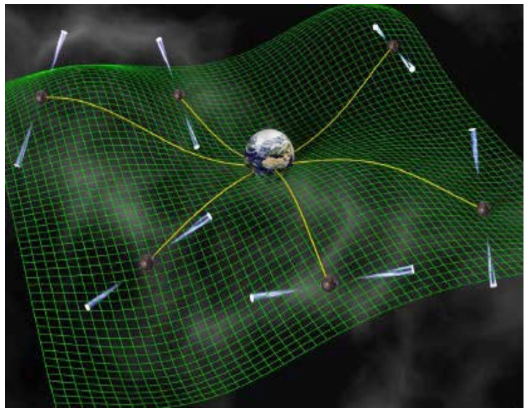
# The Sardinia Radio Telescope (SRT): pulsars




## SRT is part of the European Pulsar Timing Array (EPTA)

- 100m Effelsberg Telescope (Germany)
- 94m-equivalent Nançay Radio Telescope (France)
- 94m-equivalent WSRT (The Netherlands)
- 76m Lovell Telescope (UK)
- 64m Sardinia Radio Telescope (Italy)

## Large European Array for Pulsars (LEAP): “Pulsar VLBI”



- Simultaneous monthly pulsar observations at all 5 telescopes at L-band
- Record baseband data at each telescope
- Coherently combine baseband data from the 5 telescopes to form a phased array
- LEAP has a sensitivity equivalent to a 194m dish, similar to SKA Phase 1. Pathfinder for next generation of radio telescopes.

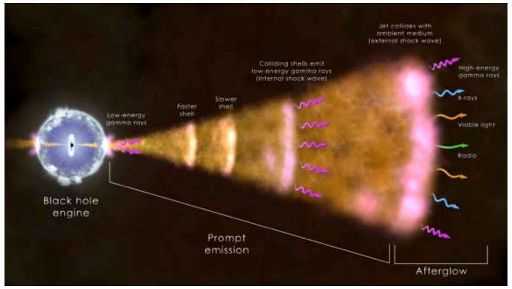
Scientific aim: direct detection of the gravitational wave background from merging supermassive black holes using pulsars

# The Sardinia Radio Telescope (SRT): GRB afterglows

Radio GRB (gamma-ray burst) ejecta produce a relativistic blast wave shock as they expand into their ambient environment. This shock accelerates electrons and produces synchrotron radiation, which is visible as long-lasting X-ray to radio “afterglow” emission.

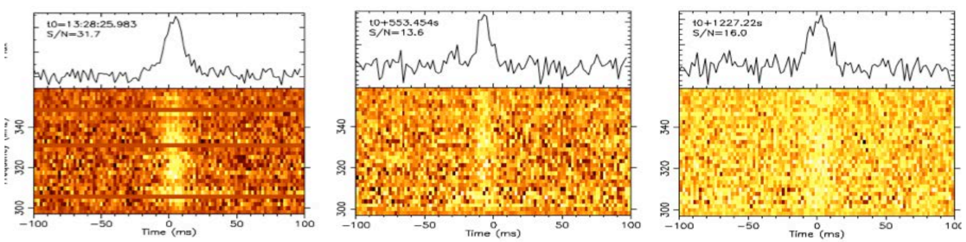
Observations of GRB afterglows with SRT are challenging since flux density < 1 mJy (Marongiu, Pellizzoni, Egron et al. 2020).

They are essential to constrain the models of GRBs and understand the physics of relativistic blast waves.



# The Sardinia Radio Telescope (SRT): FRB

→ Fast radio bursts (FRBs) are fast, millisecond-duration, extremely bright (~Jy) bursts that have so far only been observed at radio wavelengths




**Lowest frequency detection of Fast Radio Bursts**

The Lowest-frequency Fast Radio Bursts: Sardinia Radio Telescope Detection of the Periodic FRB 180916 at 328 MHz


M. Pilia[1], M. Burgay[1], A. Possenti[1,2], A. Ridolfi[1,3], V. Gajjar[4], A. Corongiu[1], D. Perrodin[1], G. Bernardi[5,6,7], G. Naldi[5], G. Pupillo[5], F. Ambrosino[8,9], G. Bianchi[5], A. Burtovoi[10,11], P. Casella[12], C. Casentini[8,13], M. Cecconi[14], C. Ferrigno[15], M. Fiori[16], K. C. Gendreau[17], A. Ghedina[14], G. Naletto[11,16], L. Nicastro[18], P. Ochner[11,16], E. Palazzi[18], F. Panessa[8], A. Papitto[12], C. Pittori[12,19], N. Rea[20,21], G. A. Rodriguez Castillo[12], V. Savchenko[15], G. Setti[5,22], M. Tavani[8,23], A. Trois[1], M. Trudu[1,2], M. Turatto[11], A. Ursi[8], F. Verrecchia[12,19], and L. Zampieri[11]


− Hide full author list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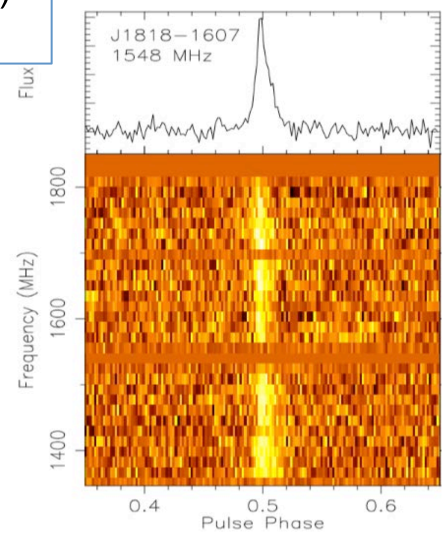
The Astrophysical Journal Letters, Volume 896, Number 2


A VERY YOUNG RADIO-LOUD MAGNETAR


P. Esposito,[1,2] N. Rea,[3,4] A. Borghese,[3,4] F. Coti Zelati,[3,4] D. Viganò,[3,4] G. L. Israel,[5] A. Tiengo,[1,2,6] A. Ridolfi,[7,8] A. Possenti,[7,9] M. Burgay,[7] D. Götz,[10] F. Pintore,[2] L. Stella,[5] C. Dehman,[3,4] M. Ronchi,[3,4] S. Campana,[11] A. Garcia-Garcia,[3,4] V. Graber,[3,4] S. Mereghetti,[2] R. Perna,[12,13] G. A. Rodríguez Castillo,[5] R. Turolla,[14,15] and S. Zane[15]

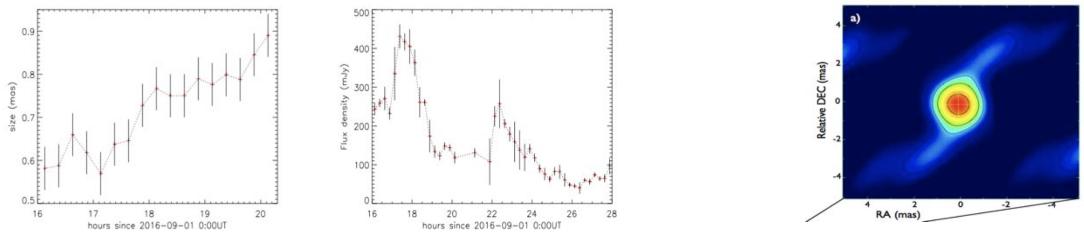
# The Sardinia Radio Telescope (SRT): microquasars

## Multi-wavelength programs from radio to gamma-rays

=> simultaneous observations to better understand the connections between accretion and ejection processes and explore the fast variability in radio, X-rays and gamma-rays.

## Single-dish and VLBI observations

=> allow us to follow the evolution of the radio emission, in particular the fast, strongly variable flux density and structural changes during the transition from compact to transient jets moving away from the core of on time scales of hours or days.



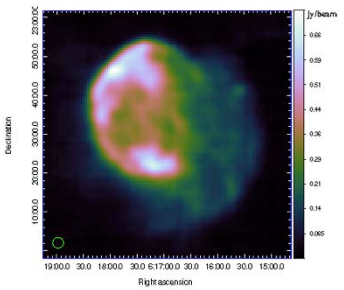

VLBI observations of Cyg X-3 during a mini-flare (Egron, Pellizzoni, Giroletti et al. 2017)

# The Sardinia Radio Telescope (SRT): SNRs

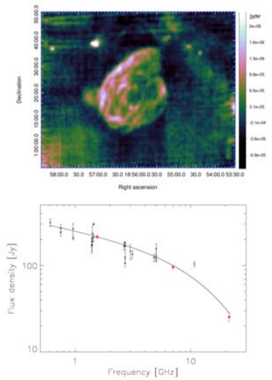
- **A powerful laboratory to study the Cosmic-Ray acceleration processes** at the shocks and their relation to the properties of the circumstellar medium: **spatially-resolved multi-frequency investigation of the energy distribution of accelerated electrons and the magnetic field conditions.**

- Innovative exploitation of on-the-fly single-dish **imaging techniques and data analysis.**

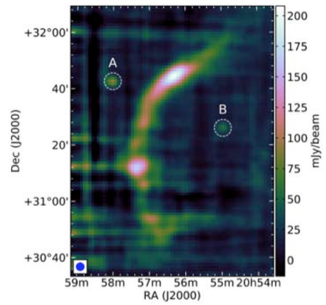
**W44, IC443 L/C bands**
Egron, Pellizzoni, Iacolina et al. 2017



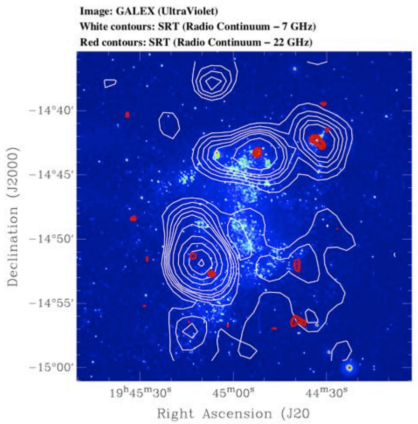

**multi-feed receiver K ban**
Loru, Pellizzoni, Egron et al. 2019




**new challenges with the Cygnus Loop**
Loru, Pellizzoni, Egron et al. 2020



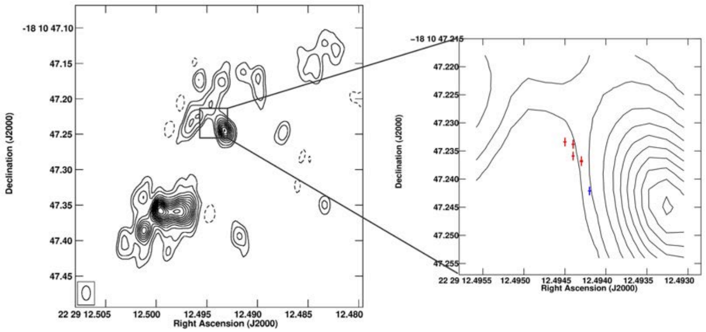
# The Sardinia Radio Telescope (SRT): masers




**Sardinia Radio Telescope observations of Local Group dwarf galaxies – I. The cases of NGC 6822, IC 1613, and WLM**

**(Monthly Notices of the Royal Astronomical Society, Volume 492, Issue 1, p. 45-57, 2020)**

by A. Tarchi, P. Castangia, G. Surcis, A. Brunthaler, C. Henkel, M. Pawlowski, K. M. Menten, A. Melis, S. Casu, M. Murgia, A. Trois, R. Concu and J. Darling



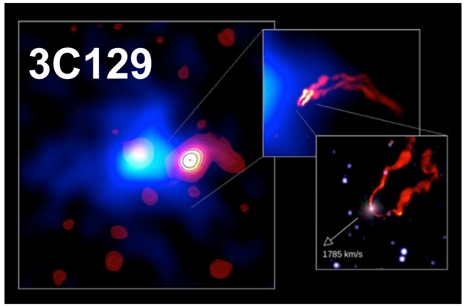

**VLBI observations of the H2O gigamaser in TXS2226-184** by G. Surcis, A. Tarchi and P. Castangia

**Astronomy and Astrophysics, Volume 637, id.A57, 12 pp. ,2020)**

# The Sardinia Radio Telescope (SRT): radio galaxies

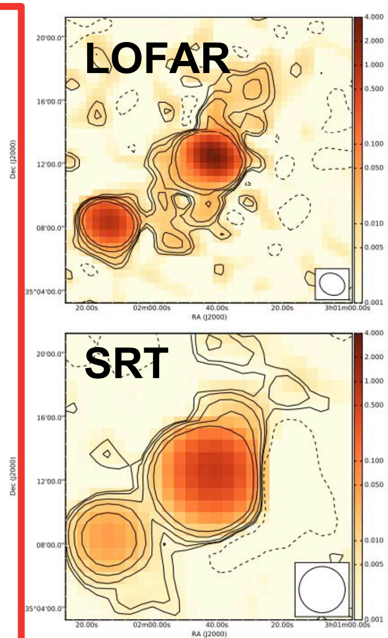
Scientific motivation: to determine the age of the synchrotron plasma in cluster radio sources

First SRT scientific publication



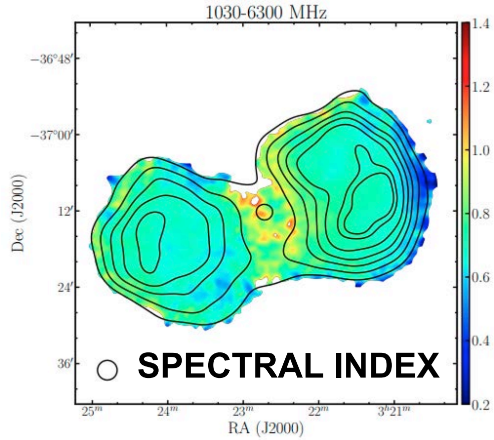

3C129 - Murgia et al. (2016)

**Single-dish Spectral-polarimetry Software (SCUBE)**




B2 0258+35 - Brienza et al. (2018)

MeerKAT - SRT




Fornax A - Maccagni et al. (2019)

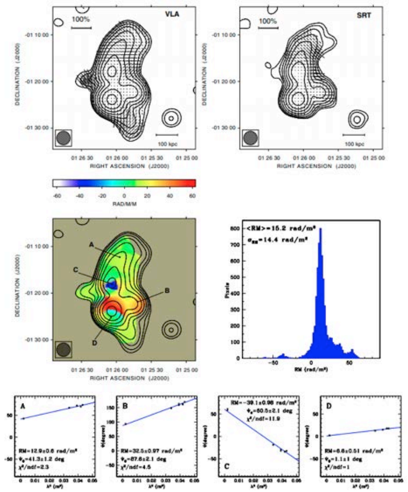
multiple episodes of nuclear activity must have formed the extended radio lobes.

# The Sardinia Radio Telescope (SRT): intra-cluster medium

Scientific motivation: to study the intra-cluster magnetic field properties

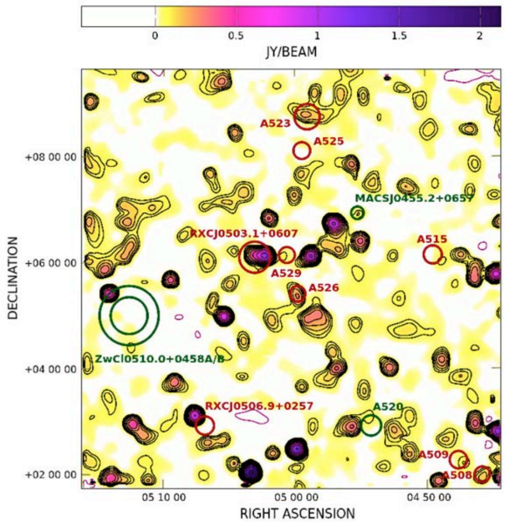
**ROTATION MEASURE**

**VLA** **SRT**



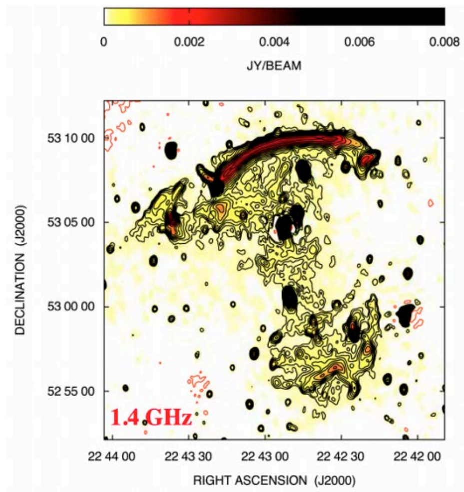
**A194 - Govoni et al. (2017)**

**DIFFUSE EMISSION**




**Supercluster - Vacca et al. (2018)**

**WSRT - SRT**



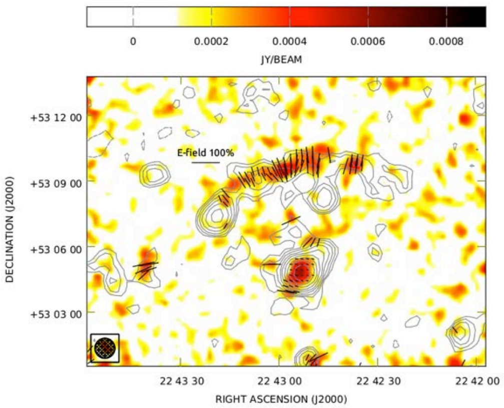

**CIZA J2242.8+5301 - Loi et al. (2017)**

Early Science Program SMOG (PI M.Murgia) – 323h at L, C, and K bands

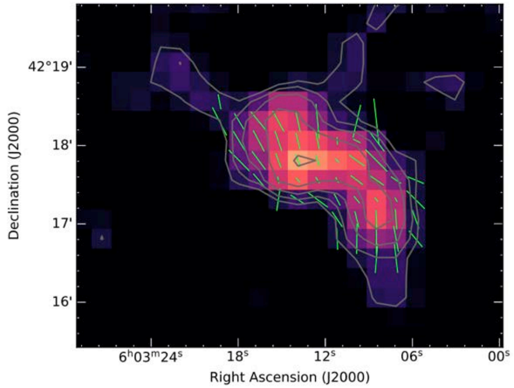
# The Sardinia Radio Telescope (SRT): intra-cluster medium

Scientific motivation: to understand the mechanism sustaining these sources and the intra-cluster magnetic field

First image in polarization of these sources at these frequencies and first polarimetric image with the SRT K-BAND receiver




**CIZA J2242.8+5301 - Loi et al. (2020)**




**1RXS J0603.3+4213 - Rajpurohit et al. (2020)**

K-BAND multifeed observations at 18.6 GHz

# The Sardinia Radio Telescope (SRT): other

- Space Weather applications
- Solar radio images and related parameters are published
- European Surveillance and Tracking Bistatic radar for LEO debris tracking
- Radio frequencies monitoring

Institute for Space Astrophysics and Planetology
Istituto di Astrofisica e Planetologia Spaziali

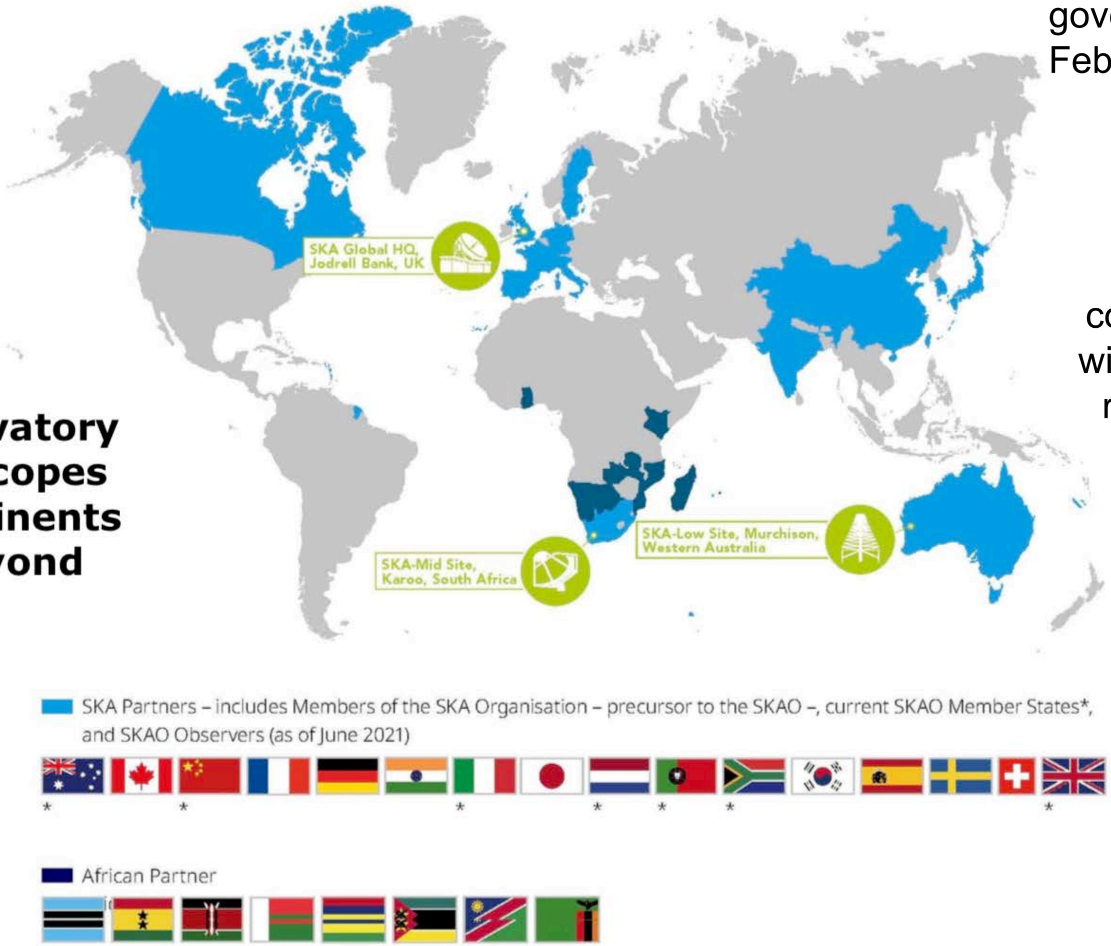

# The Square Kilometer Array (SKA)

# The Square Kilometer Array (SKA)

SKA Observatory (SKAO), a new Inter-Governmental Organisation governed by a treaty, was born on 4 February 2021.

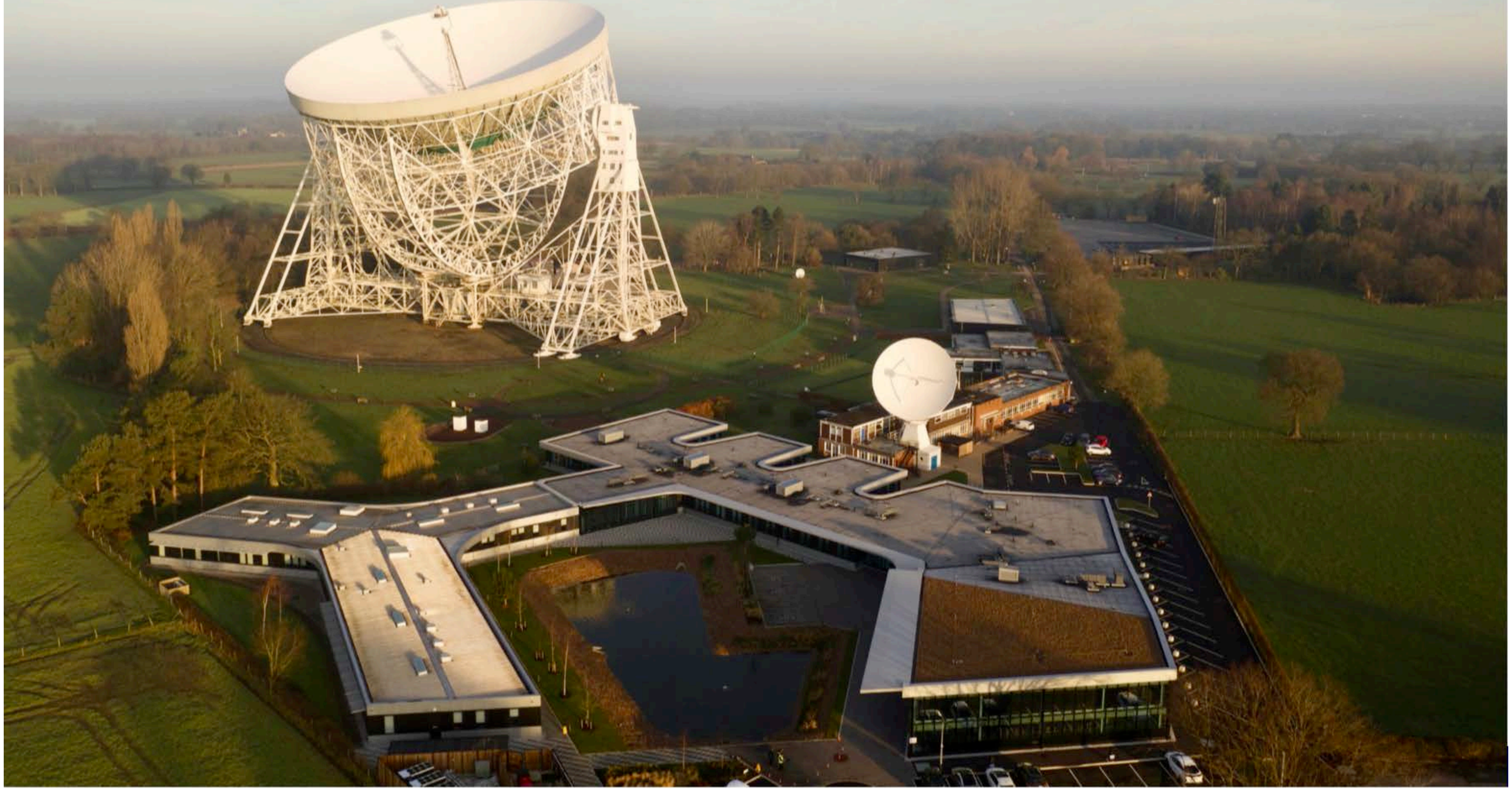
A global collaboration of 16 countries which is building and will operate the next-generation radio astronomy observatory

**One Observatory**
**Two Telescopes**
**Three Continents**
**...and beyond**



## SKAO HQ: Jodrell Bank, UK

Headquartered at Jodrell Bank (near Manchester)
United Kingdom



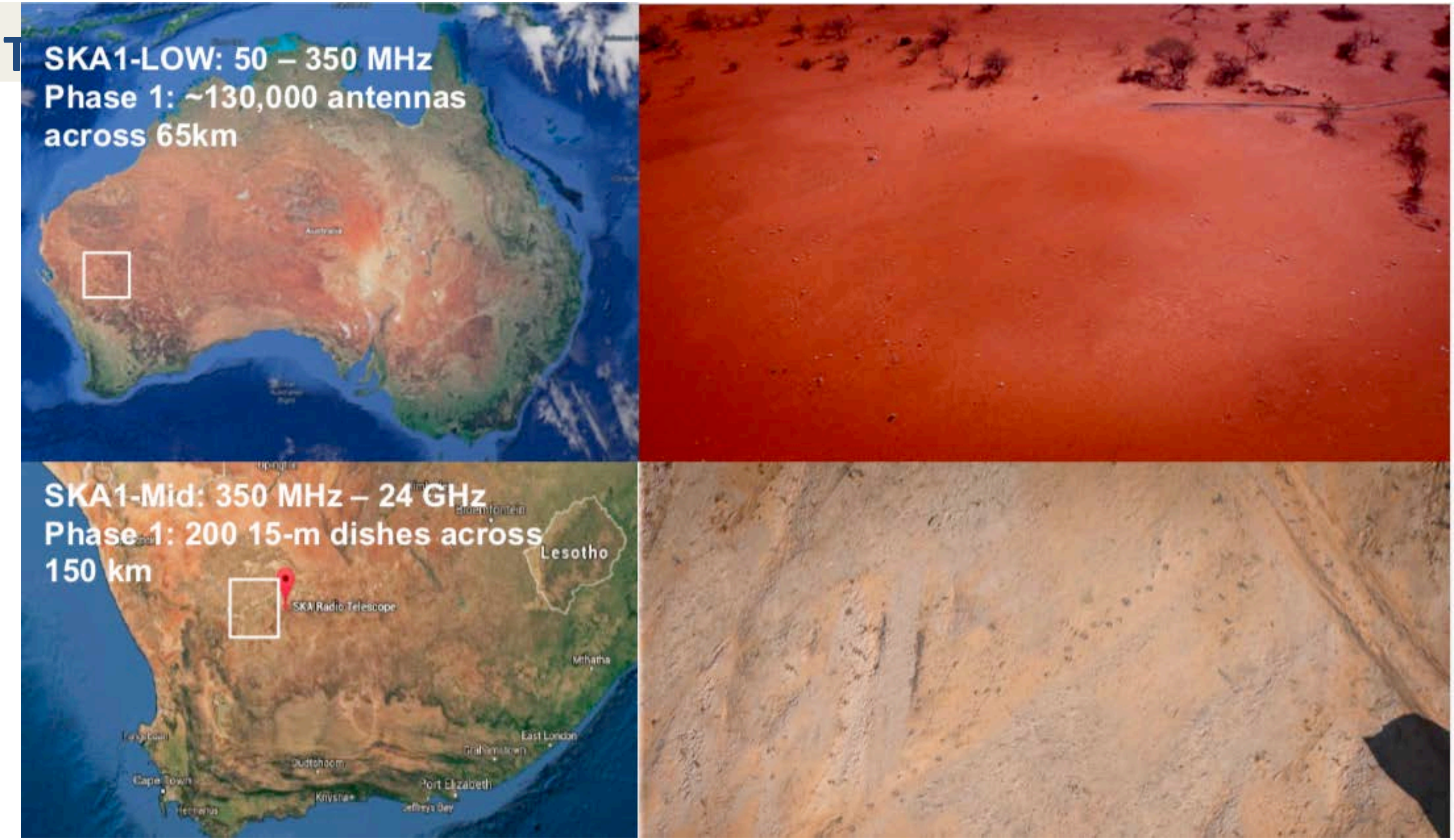
# A short history of SKA


## Construction timeline: underway

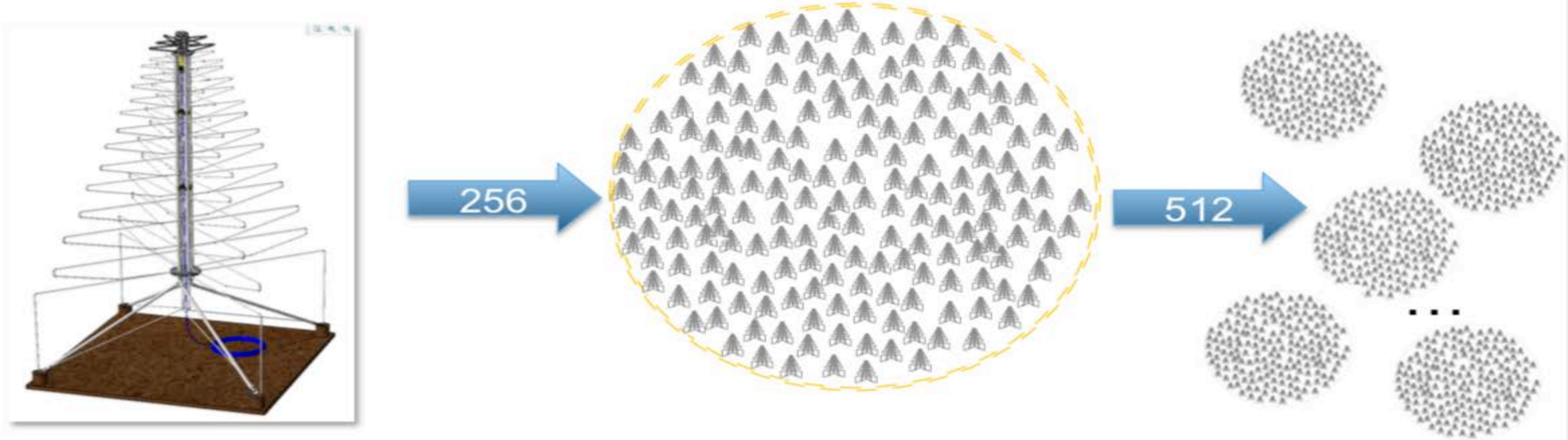
- First contracts (software) have been let
- ITTs for construction camps about to be issued
- Good progress on heritage & ecological surveys; permitting underway.

| | SKA-Low | SKA-Mid |
|---|---|---|
| Start of construction (T0) | 1ST JULY 2021 | 1ST JULY 2021 |
| Earliest start of major contracts (C0) | AUGUST 2021 | AUGUST 2021 |
| Array Assembly 0.5 finish (AA0.5)<br>SKA-Low = 6-station array<br>SKA-Mid = 4-dish array | FEBRUARY 2024 | MARCH 2024 |
| Array Assembly 1 finish (AA1)<br>SKA-Low = 18-station array<br>SKA-Mid = 8-dish array | FEBRUARY 2025 | FEBRUARY 2025 |
| Array Assembly 2 finish (AA2)<br>SKA-Low = 64-station array<br>SKA-Mid = 64-dish array, baselines mostly <20km | FEBRUARY 2026 | DECEMBER 2025 |
| Array Assembly 3 finish (AA3)<br>SKA-Low = 256-station array, including long baselines<br>SKA-Mid = 133-dish array, including long baselines | JANUARY 2027 | SEPTEMBER 2026 |
| Array Assembly 4 finish (AA4)<br>SKA-Low = full Low array<br>SKA-Mid = full Mid array, including MeerKAT dishes | NOVEMBER 2027 | JUNE 2027 |
| Operations Readiness Review (ORR) | JANUARY 2028 | DECEMBER 2027 |
| End of construction | JULY 2029 | JULY 2029 |

T


SKA1-LOW: 50 – 350 MHz
Phase 1: ~130,000 antennas
across 65km
SKA1-Mid: 350 MHz – 24 GHz
Phase 1: 200 15-m dishes across
150 km
Lesotho
SKA Radio Telescope
Bloemfontein
Mthatha
East London
Grahamstown
Oudtshoorn
Port Elizabeth
Knysna
Jeffreys Bay
Cape Town
Hermanus

# SKA1-Low: Array of Arrays




SKA1-Low
Antenna/Receptor

**Antenna Beam**

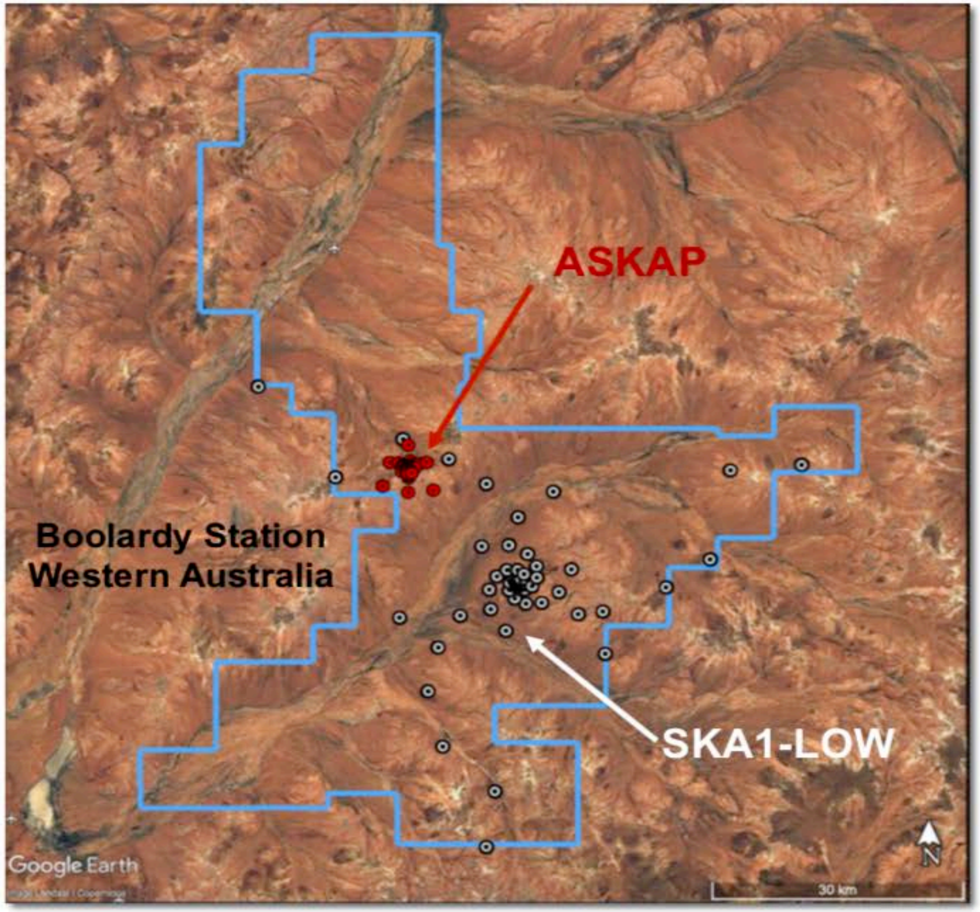
SKA1-Low
*"Station"*

**Station Beam**

SKA1-Low
"Array"

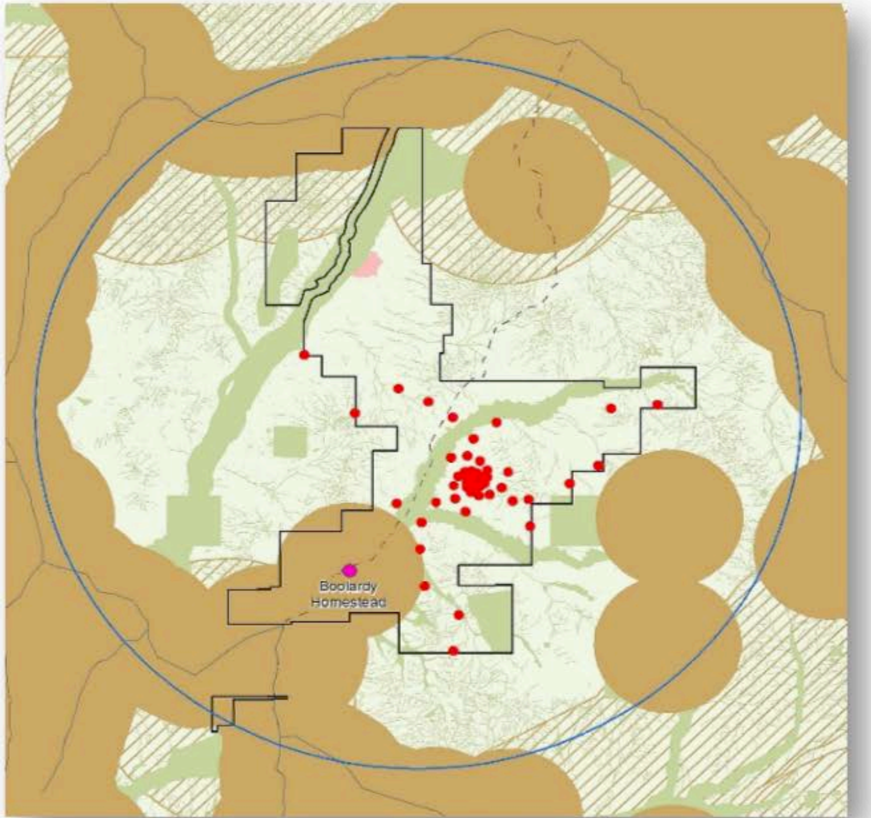
**Correlation and**
***Tied-array Beams***

# SKA1 – Low: Layout



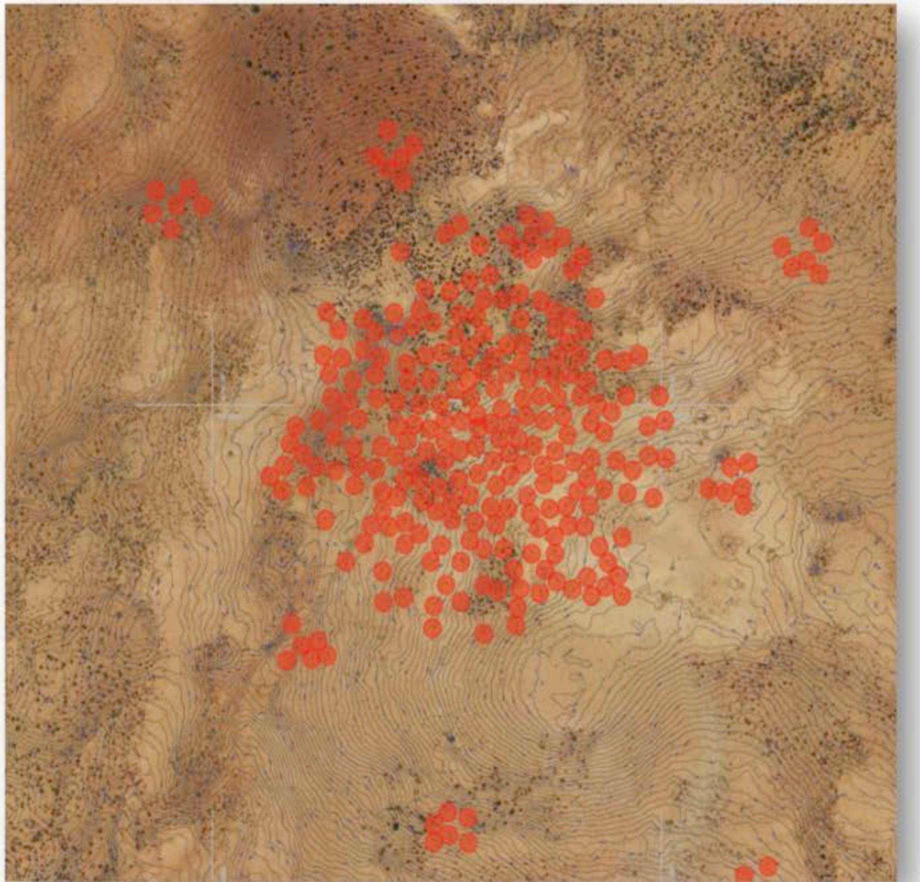

- 512 aperture array stations
- Maximum baseline 65 km
- 3 modified spiral arms

# SKA1 – Low: Layout




- 512 aperture array stations
- Maximum baseline 65 km
- 3 modified spiral arms
- Respect site constraints

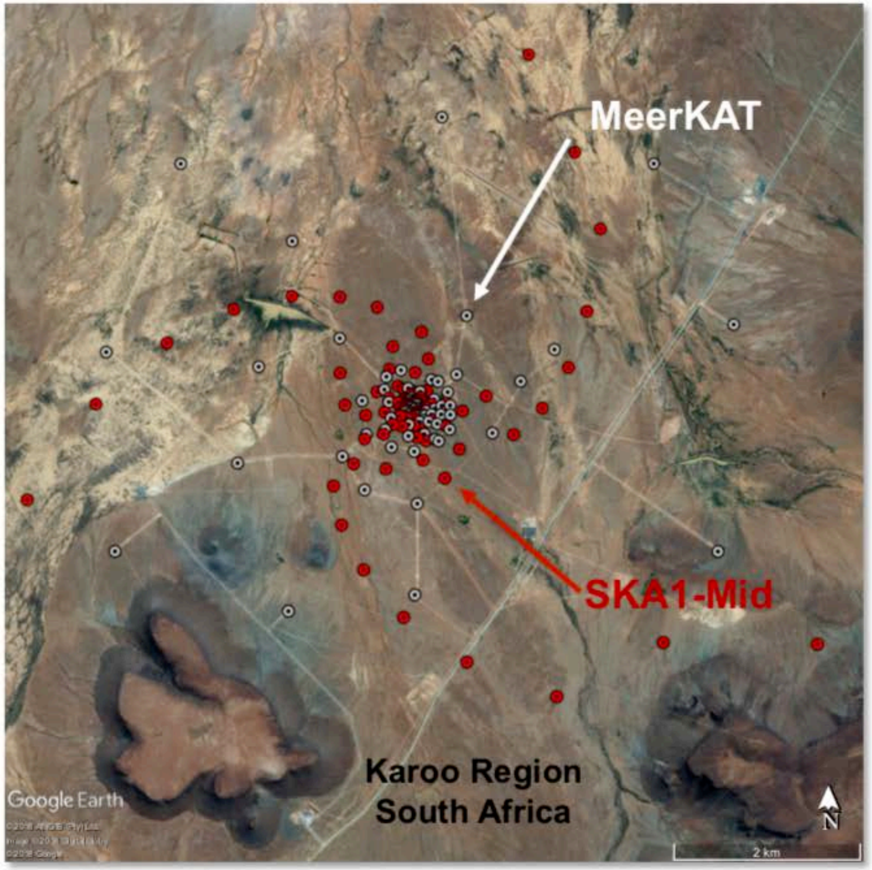
# SKA1 – LOW: Layout



- 512 aperture array stations
- Maximum baseline 65 km
- 3 modified spiral arms
- Respect site constraints
- ~ 50% within ~1 km randomly distributed
- Others in clusters of 6 stations arranged randomly over an area 100 to 150 m in diameter

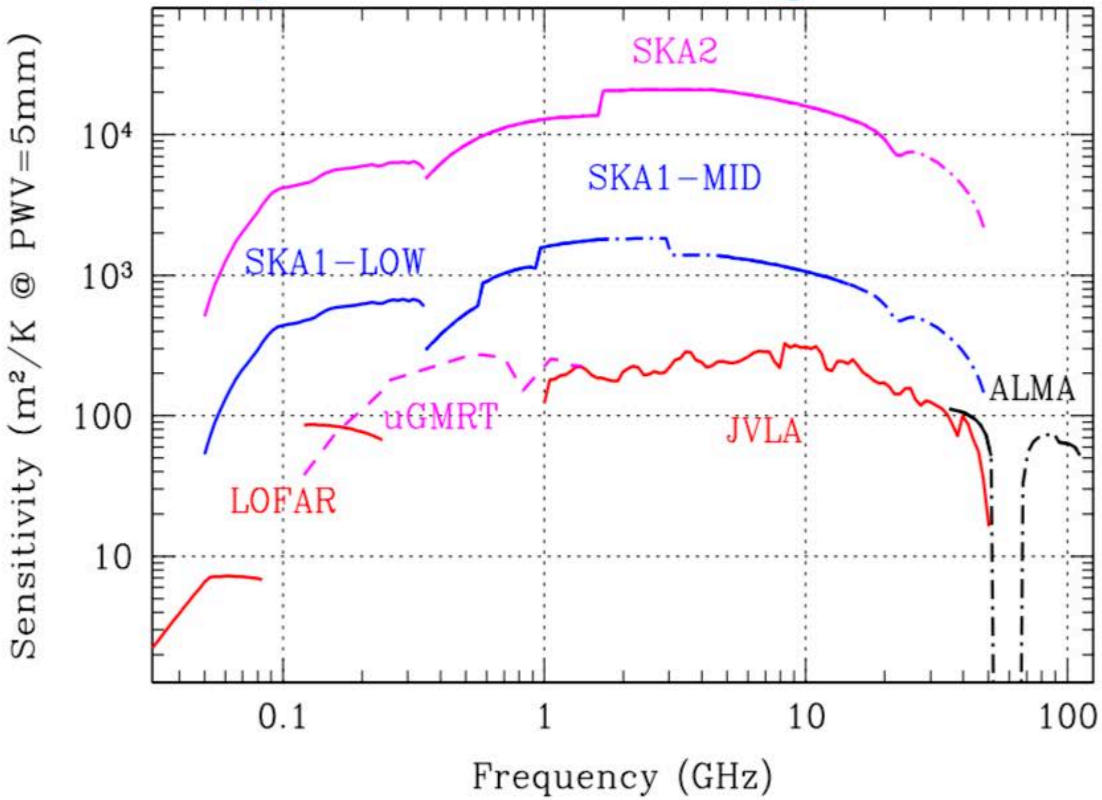
- 256 antennas per station
- 38m station diameter

# SKA1 –Mid: Layout



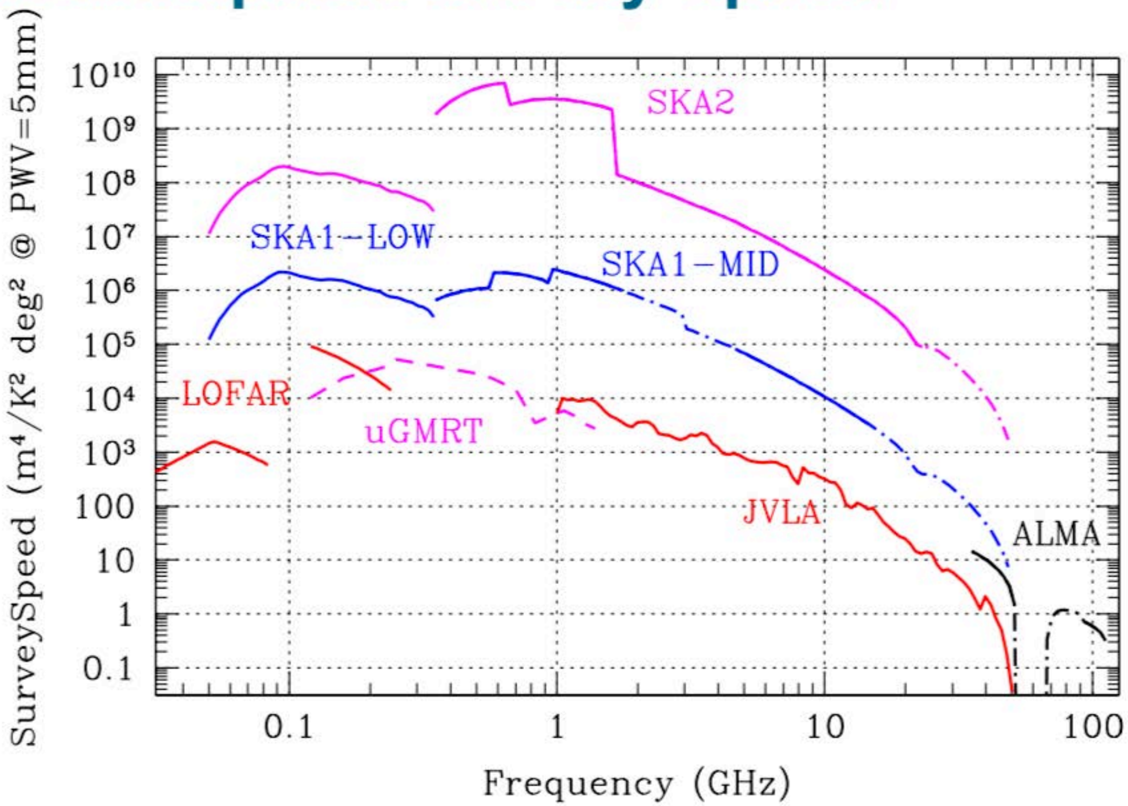

- 133 SKA 15m dishes
- 64 MeerKAT 13.5m dishes
- Maximum baseline 150 km
- 3 logarithmic spiral arms
- ~ 50% within ~2 km randomly distributed

# SKA1 Anticipated Sensitivity



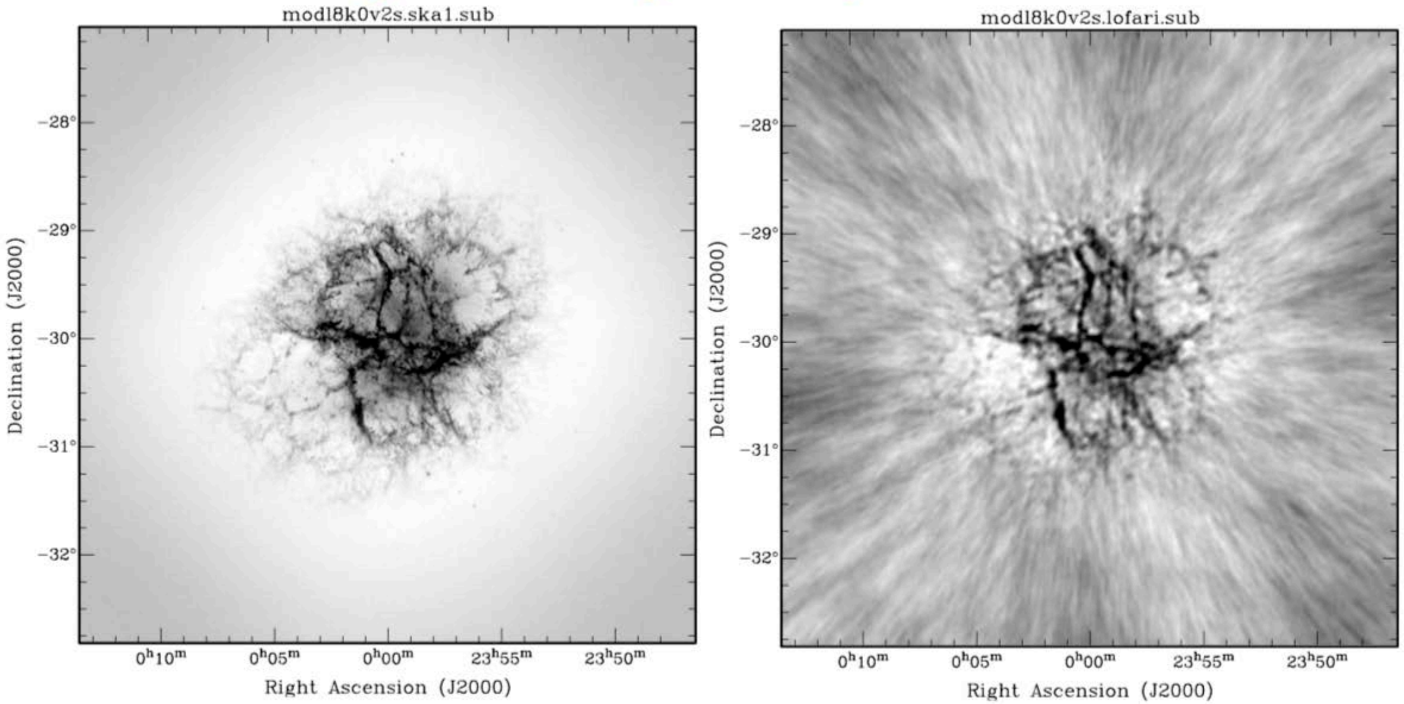

- Improved performance predictions now available at all frequencies
- Opportunity for seamless interface of SKA to ALMA capabilities

# SKA1 Anticipated Survey Speed



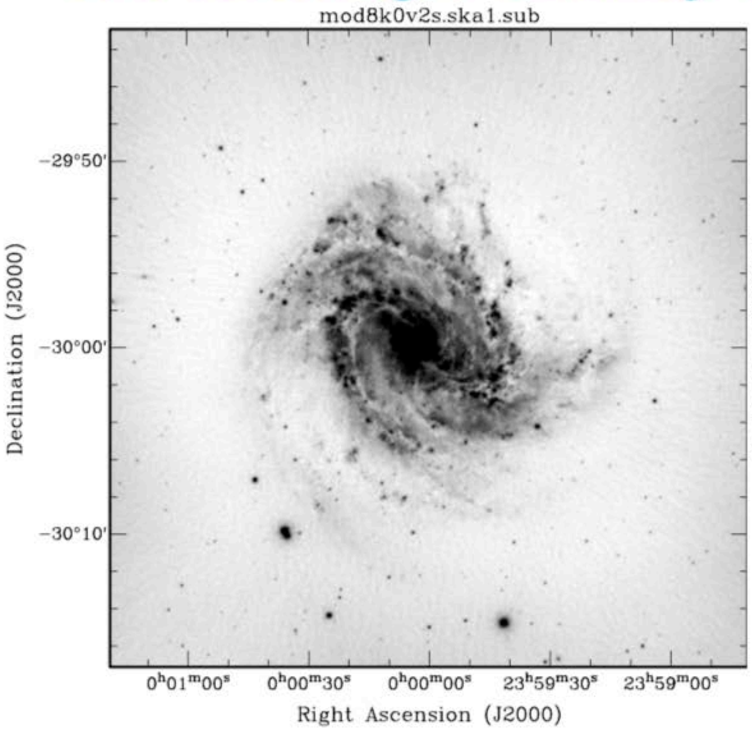

- Improved performance predictions now available at all frequencies
- Opportunity for seamless interface of SKA to ALMA capabilities

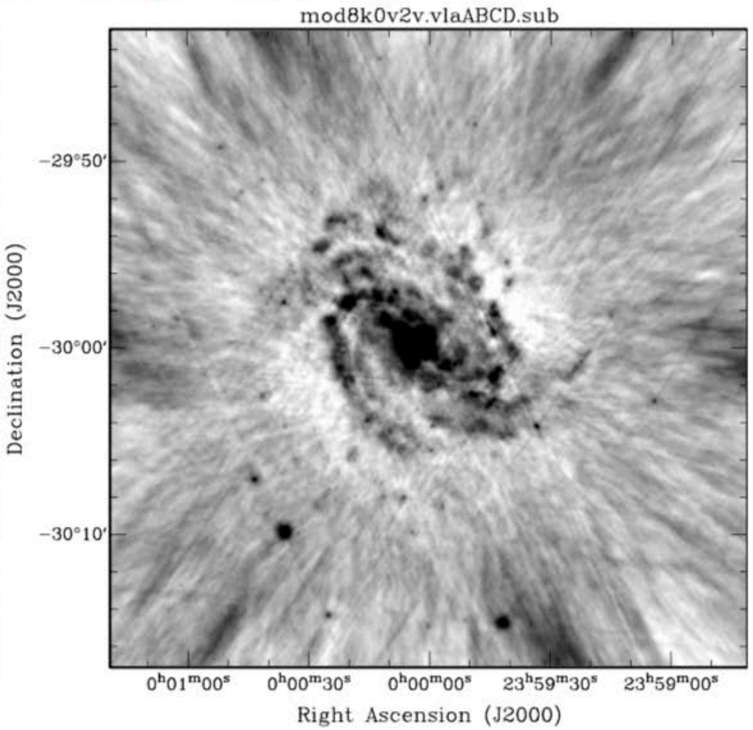
# SKA1 Image Quality Comparison




- Between 10 and 100 times the image quality of current facilities
- Single SKA1-Low “dirty” snap-shot compared to LOFAR “dirty” snap-shot

# SKA1 Image Quality Comparison



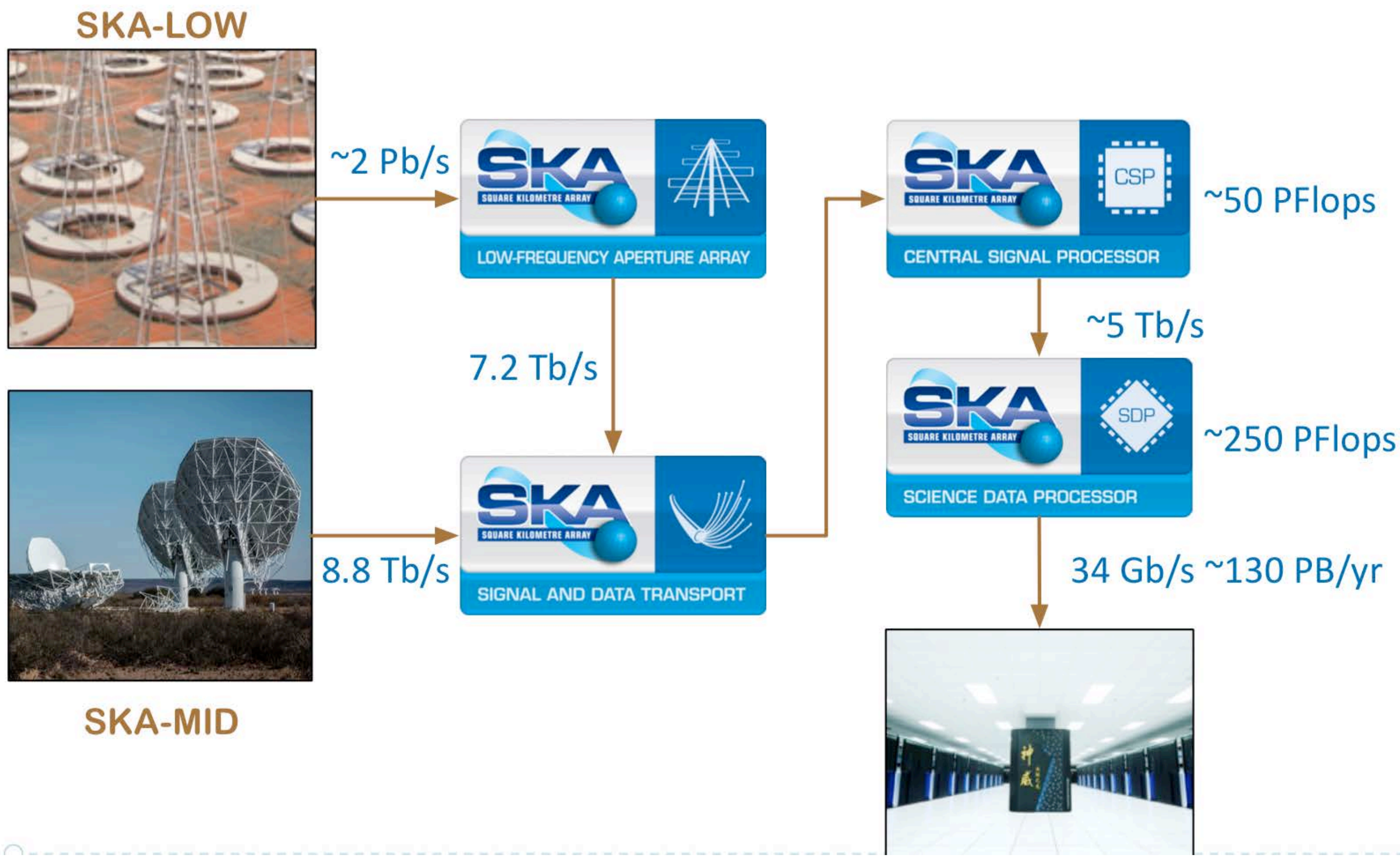




- Between 10 and 100 times the image quality of current facilities
- Single “dirty” SKA1-Mid snap-shot compared to combination of four “dirty” snap-shots, one in each of VLA A+B+C+D

# Cost Estimate

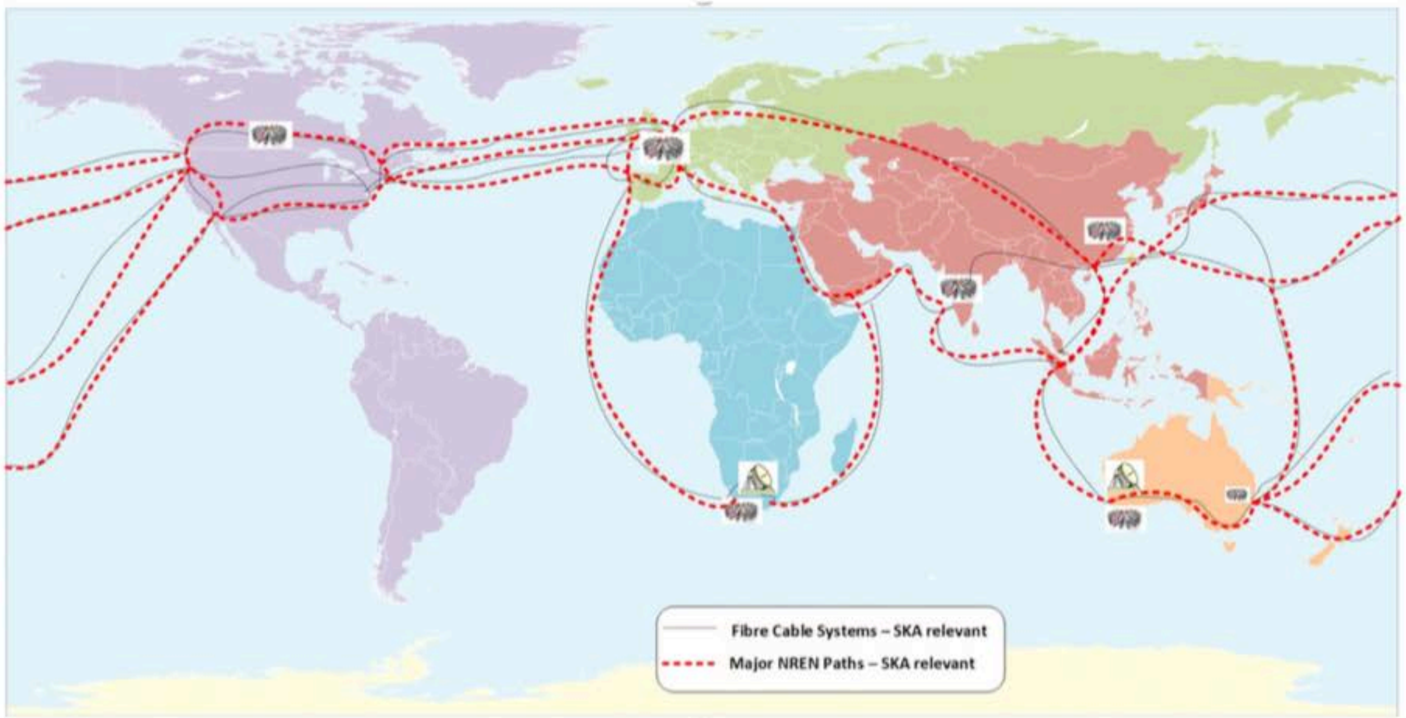
| Design Baseline | Sept 2020 submitted | Provided through annual contributions | | | |
|---|---|---|---|---|---|
| Total Value (€M) (Aug 2020) | Capital cost of construction (€M) | Construction Support Budget (€M) | Observatory Operations & Business-Enabling Functions (€M) | Observatory Development Programme (€M) | Funding Period |
| | 1054 | 228 | | | |
| 1986 | 1282 | | 664 | 40 | 2021-2030 |

# Computing Challenges



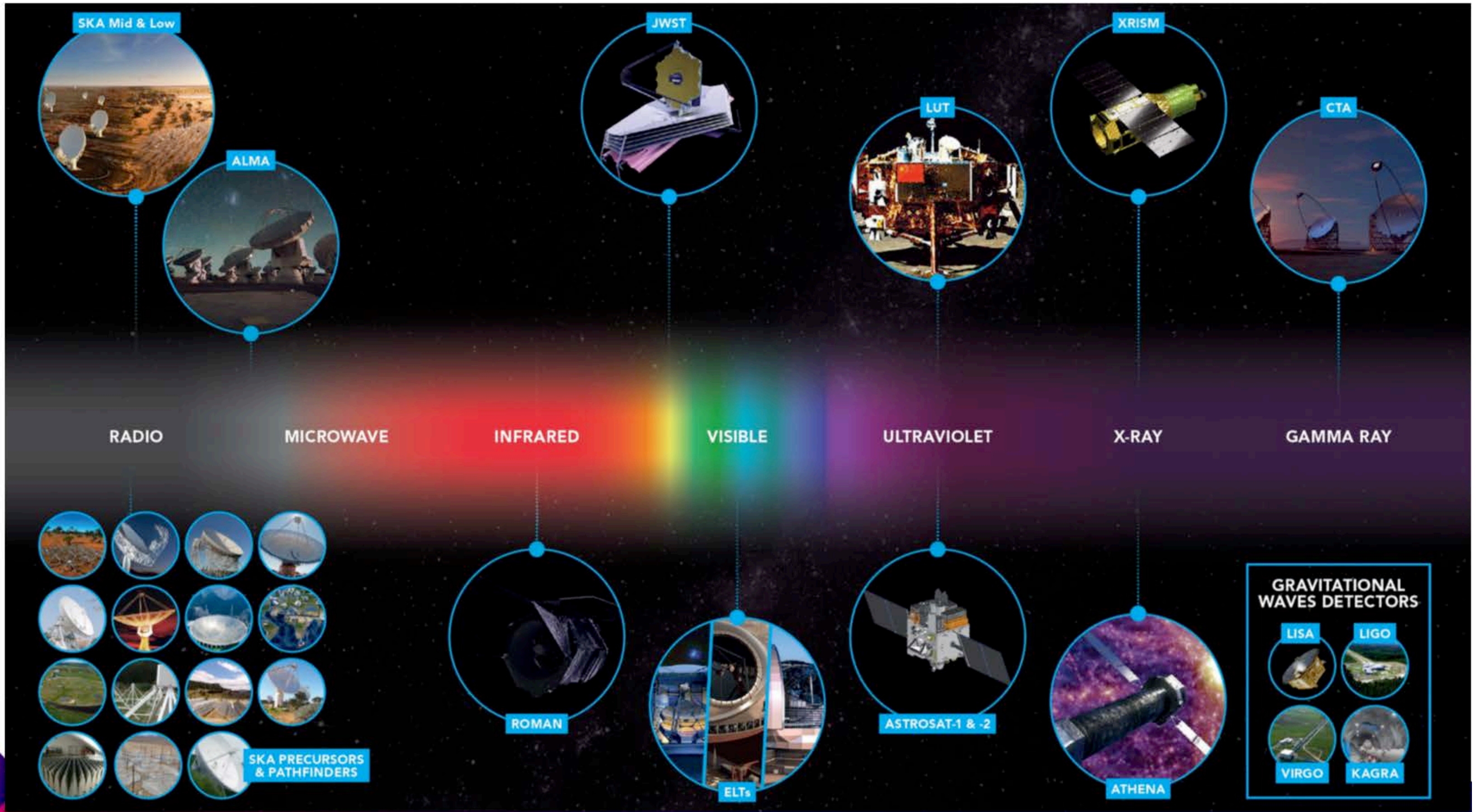
# The SKA Data Flow Challenge

# SKA Regional Centres (SRCs)




- Planning a network of SRCs around globe hosting SKA Science Archive
- Users may access SKA Science Archive via SRC network
- SRCs will provide resources for further processing and analysis
- Working groups developing SRC network design

# 21st Century Astronomy



# The Square Kilometer Array (SKA) Pathfinders & Precursors

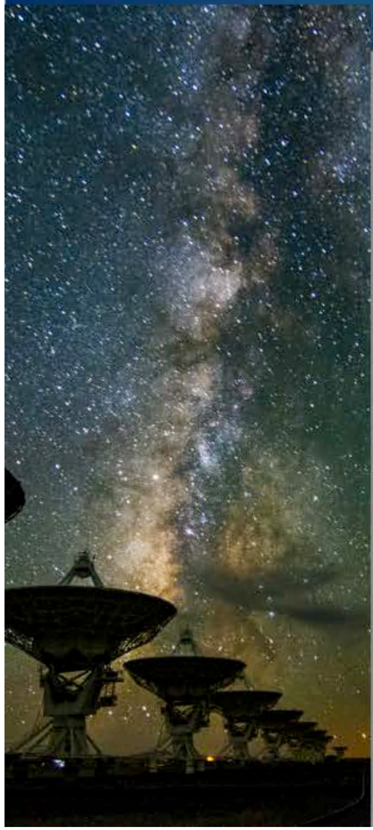
# SKA Pathfinders: JVLA



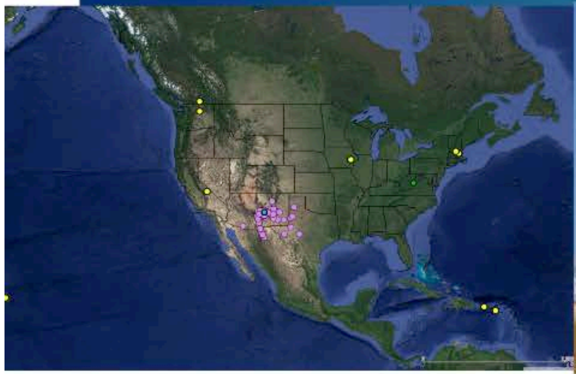
**Specifications**

27 antennas (25m)
Max baseline= 37 km
Frequency coverage: 1-50 GHz
Bandpass: 1000 MHz
Sensitivity: 20 μJy/hr @ 1.4 GHz

Open Sky: 2 call/yr, ToO, DDT



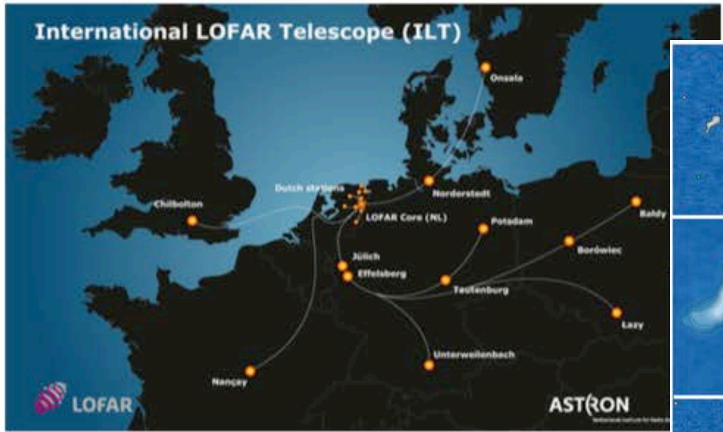
# ngVLA



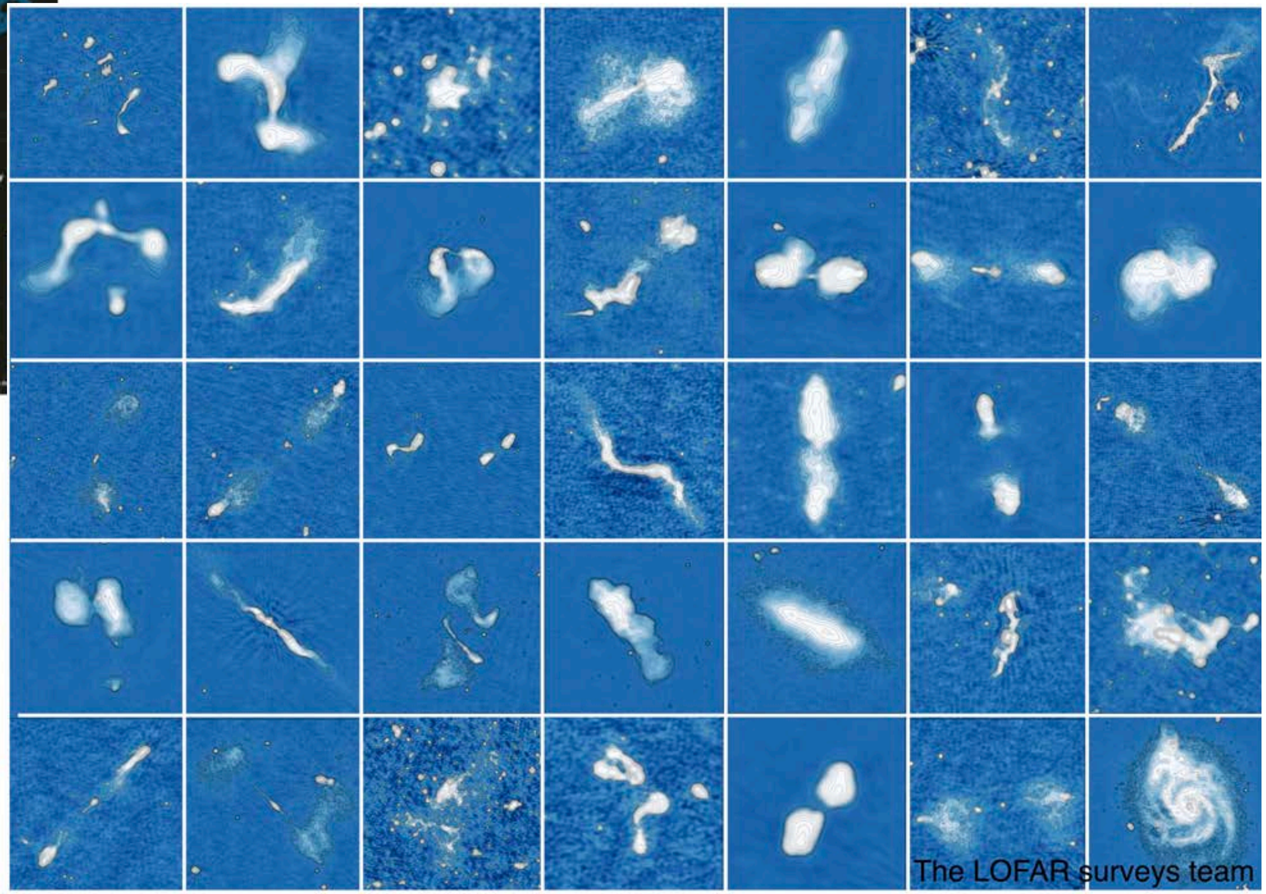
- **1.2 - 116 GHz** Frequency Coverage (bridging SKA-ALMA)
- **Main Array**: 214 x 18m offset Gregorian Antennas.
  - Fixed antenna locations across NM, TX, AZ, MX.
- **Short Baseline Array**: 19 x 6m Antennas
  - to fill in (*u*, *v*) hole.
- **Long Baseline Array**: 30 x 18m antennas located across continent for baselines up to ~8860 km.

Sensitivity/Resolution Goal: ***10x sensitivity & resolution of JVLA/ALMA***

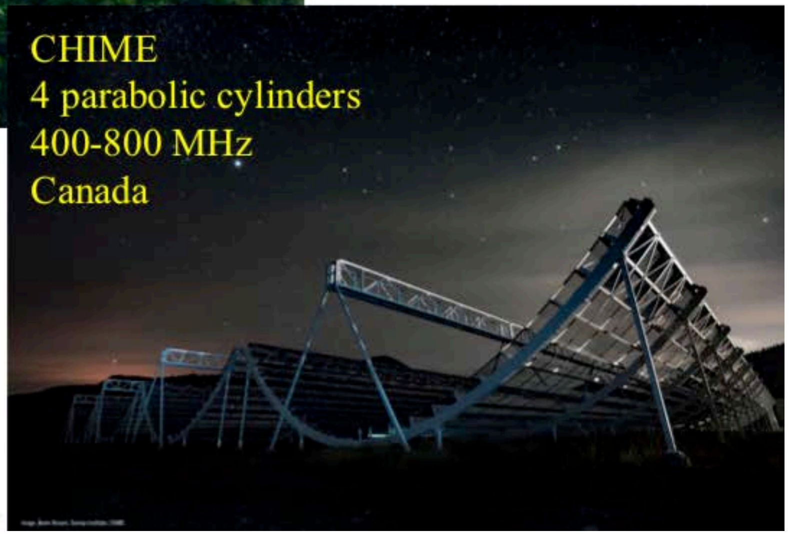
# LOFAR




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

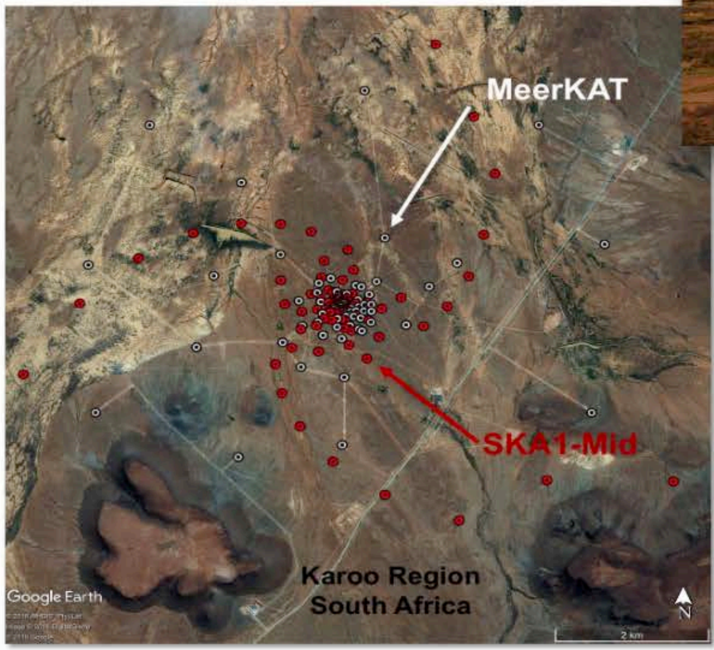


# More pathfinders


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

# MeerKAT as SKA-mid precursor




**MeerKAT**:
Operated by SARAO
64, 13.5-m dishes over 7.7 km
580-3500 MHz

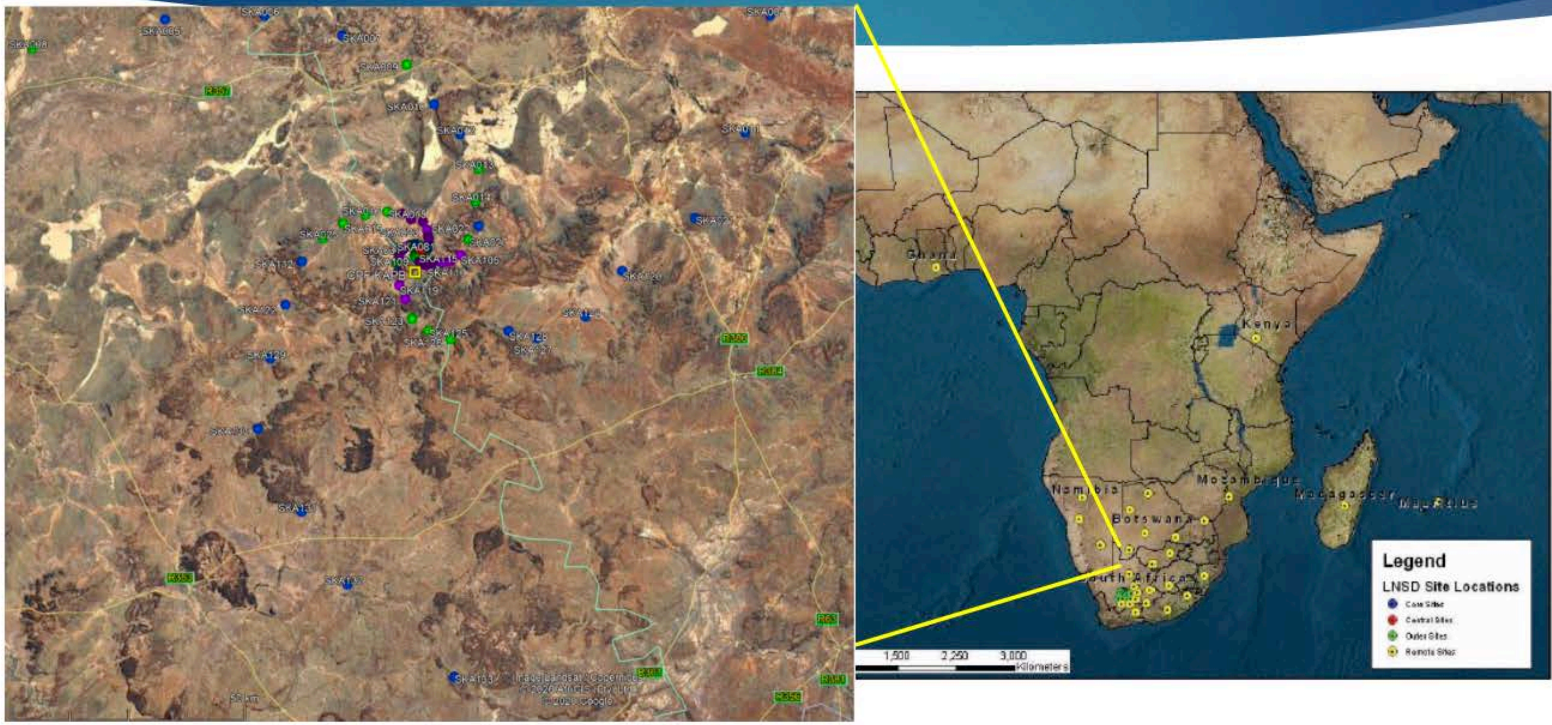
**SKA1_Mid:**
133 SKA 15m dishes
64 MeerKAT 13.5m dishes
Maximum baseline 150 km
3 logarithmic spiral arms
~ 50% within ~2 km randomly distributed

| Specifications | |
|---|---|
| L Band | 900-1670 MHz |
| UHF | 580-1015 MHz |
| *S Band* | 1750-3500 MHz |

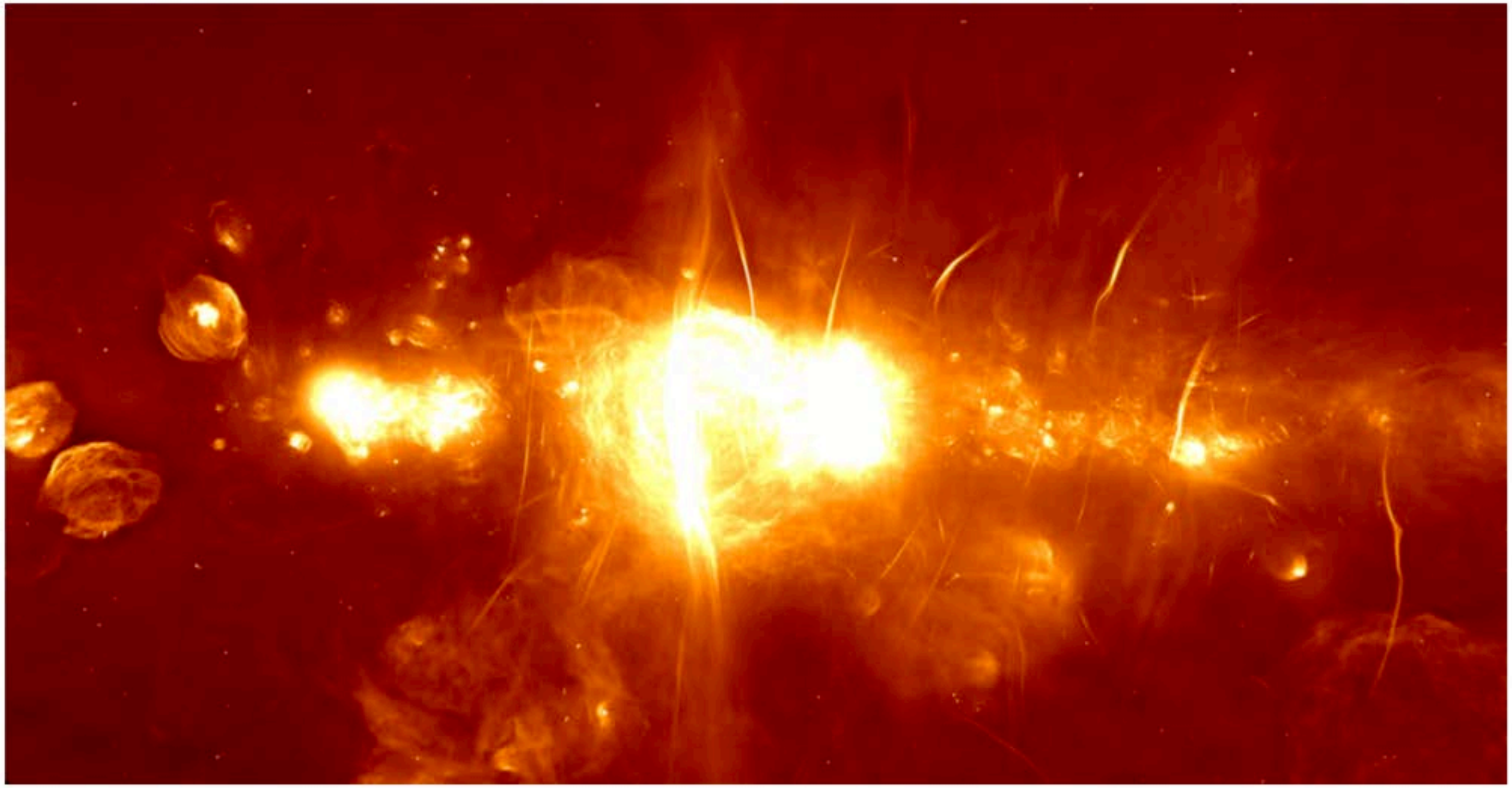
**L-Band sensitivity**

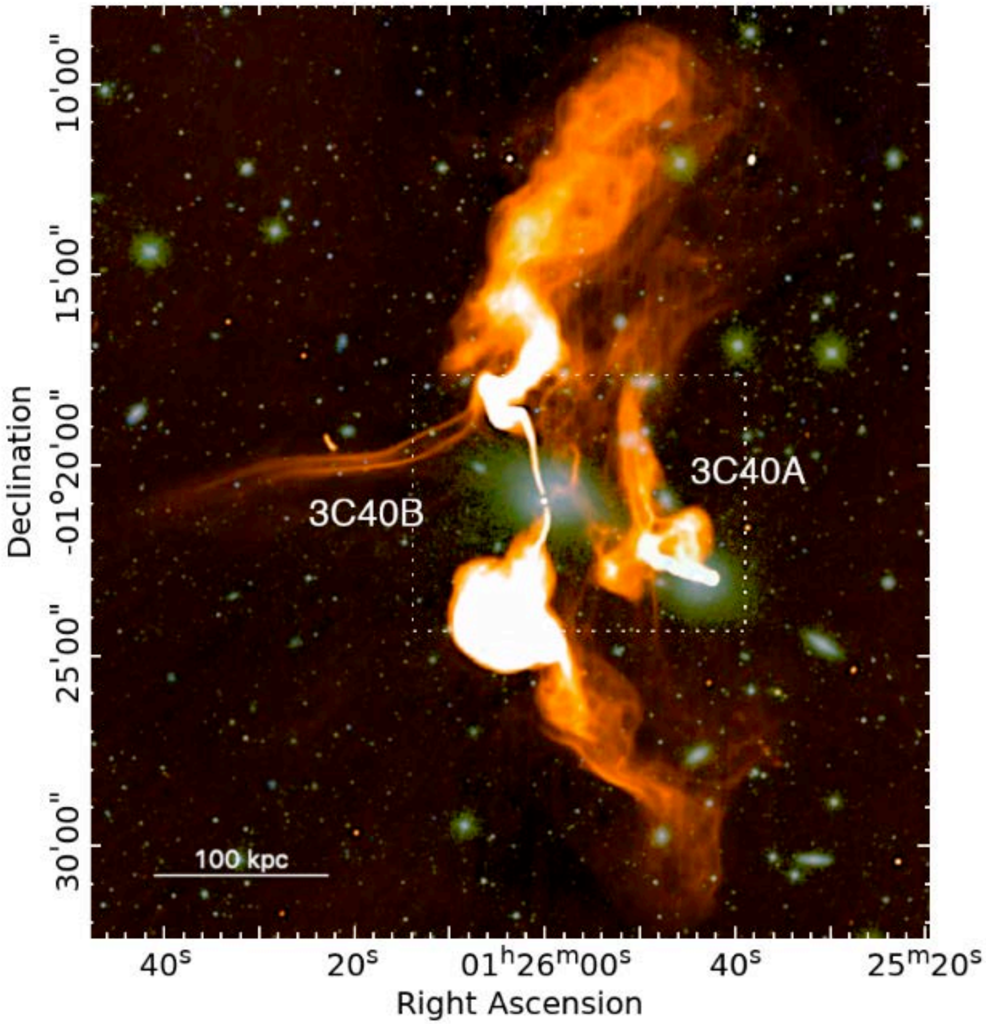
| | |
|---|---|
| Continuum | 12 μJy (1 hr) |
| Line | 184 μJy (1 hr, 209 kHz channel) |

# MeerKAT –> MeerKAT+ → SKA1-Mid



# MeerKAT: Galactic Centre at 1.4 GHz

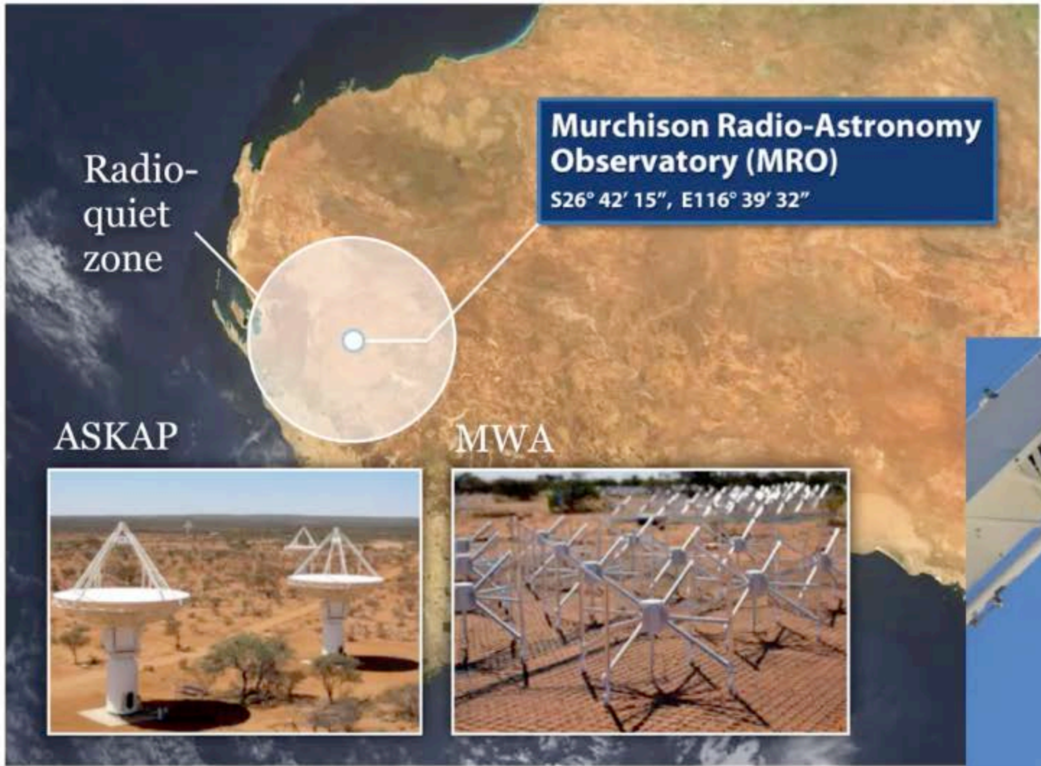





*Two giant radio galaxies with MeerKAT*
*(K. Knowles et al 2021)*

image credit: SARAO, SDSS

# The ASKAP telescope




- 36 12m antennas; baselines 22m - 6km
- Phased Array Feeds (PAFs)
- ~700-1800 MHz (288 MHz instantaneous bandwidth)
- Resolution up to ~10 arcsec

## SKA Precursors: **ASKAP**

Specifications

36 antennas (12 m)
Max baseline: 6 km
Frequency coverage: 0.7- 1.8 GHz
Bandpass: 300 MHz
Sensitivity: 25 $\mu$Jy/hr @ 1.4 GHz
Angular resolution= 10 arcs
FOV (PAF)= 30 deg$^2$
Survey Speed= 220 deg$^2$/hr (0.1 mJy)

Large surveys, ToO, DDT

**Unique capability:**
The Phased Array Feed
Innovative technology, allows a FOV of 30 deg$^2$


# The ASKAP telescope©

ASKAP Early Science observations of the Small Magellanic Cloud

(+Single dish data from Parkes)

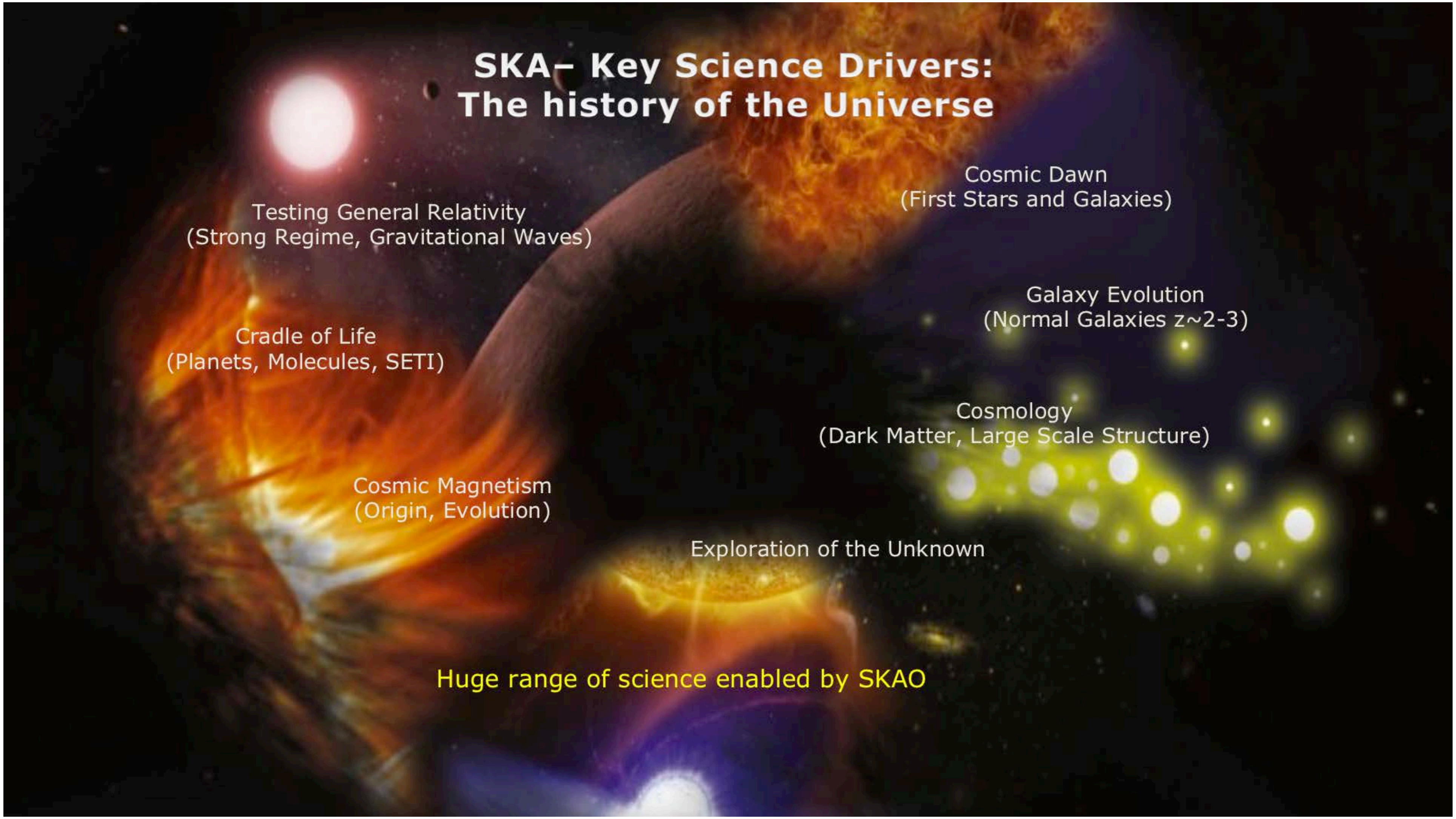
ASKAP:
FoV ~ 25 $deg^2$

30” resolution

Data taken in only 20 hours!

# Murchison Widefield Array

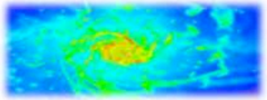
- 128 tiles; dipole antennas (extending to 256)
- 3 km maximum baseline (6 km)
- 80-300 MHz
- GLEAM survey

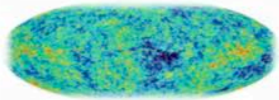

SKA– Key Science Drivers:
The history of the Universe
Testing General Relativity
(Strong Regime, Gravitational Waves)
Cosmic Dawn
(First Stars and Galaxies)
Galaxy Evolution
(Normal Galaxies z~2-3)
Cradle of Life
(Planets, Molecules, SETI)
Cosmology
(Dark Matter, Large Scale Structure)
Cosmic Magnetism
(Origin, Evolution)
Exploration of the Unknown
Huge range of science enabled by SKAO

# SKA Big Questions

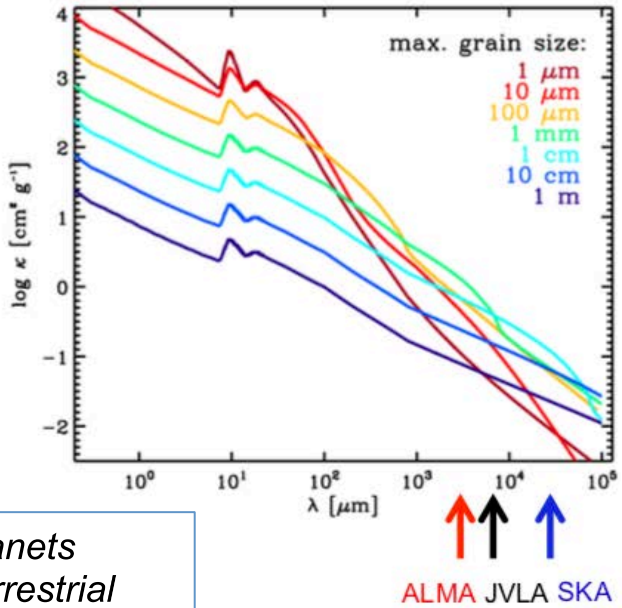
- **The Cradle of Life & Astrobiology**
  - *How do planets form? Are we alone?*
- **Strong-field Tests of Gravity with Pulsars and Black Holes**
  - *Was Einstein right with General Relativity?*
- **The Origin and Evolution of Cosmic Magnetism**
  - *What is the role of magnetism in galaxy evolution and the structure of the cosmic web?*
- **Galaxy Evolution probed by Neutral Hydrogen**
  - *How do normal galaxies form and grow?*
- **The Transient Radio Sky**
  - *What are Fast Radio Bursts? What haven't we discovered?*
- **Galaxy Evolution probed in the Radio Continuum**
  - *What is the star-formation history of normal galaxies?*
- **Cosmology & Dark Energy**
  - *What is dark matter? What is the large-scale structure of the Universe?*
- **Cosmic Dawn and the Epoch of Reionization**
  - *How and when did the first stars and galaxies form?*

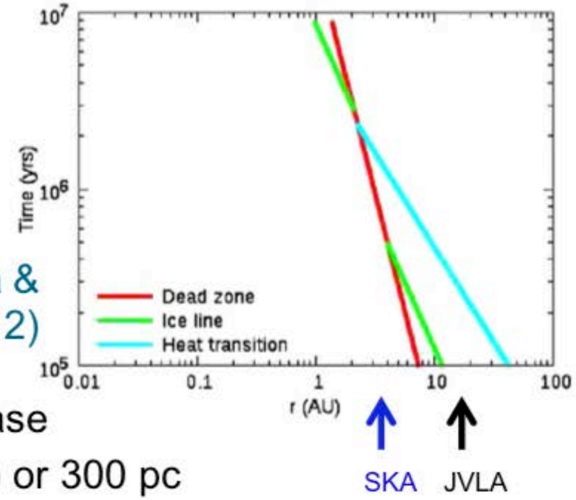



# The Cradle of Life: Understanding planet formation



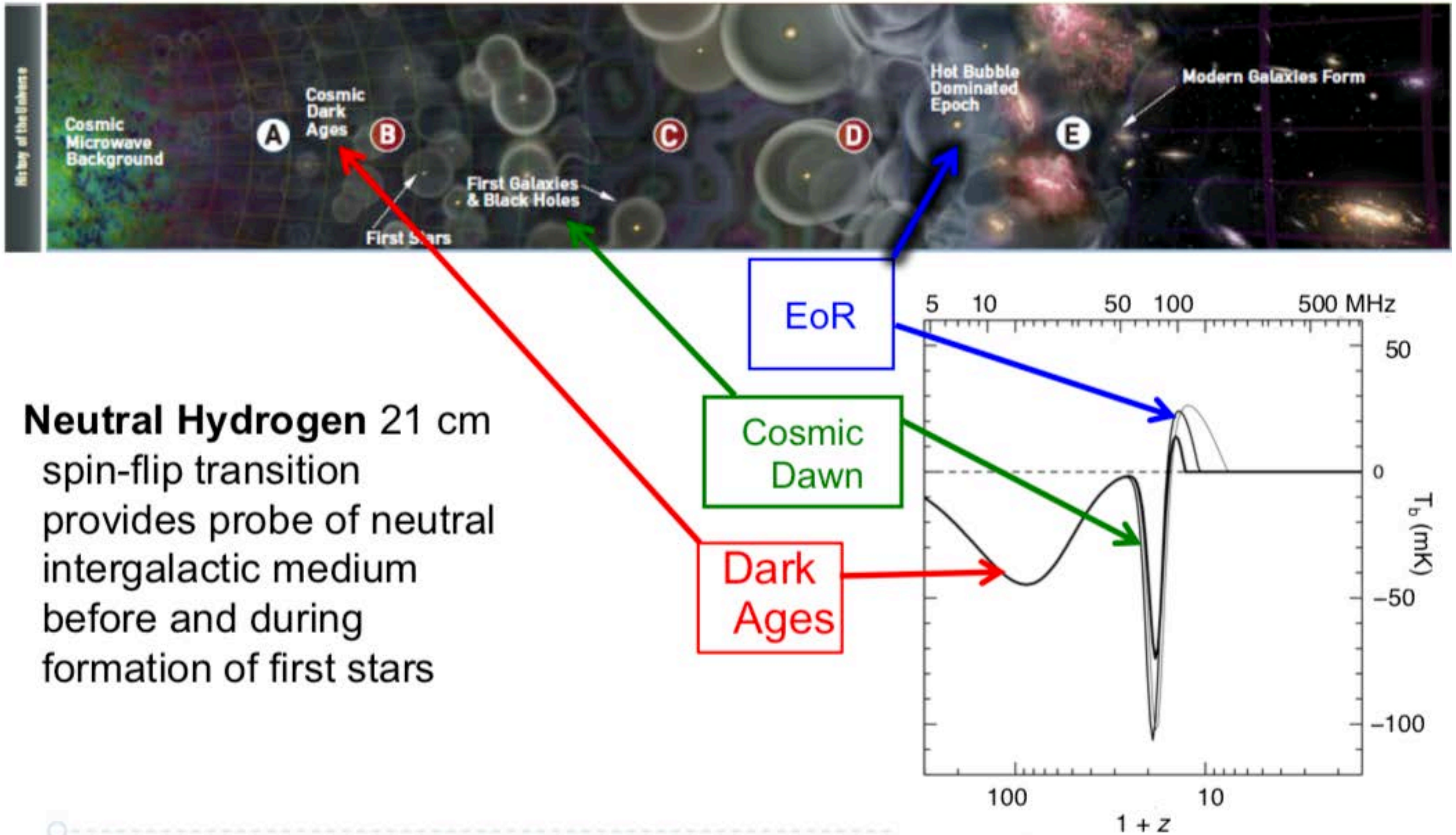




(Hasegawa & Pudritz 2012)

*Search for terrestrial planets*
*Radiation from ExtraTerrestrial Intelligence (ETI)*

- Measuring grain growth through planetesimal phase
- Resolving proto-planetary disks at 100 pc (SKA1) or 300 pc (SKA2) inside the snow/ice line, sub-AU scales with SKA2

# Epoch of Reionisation and Dark Ages

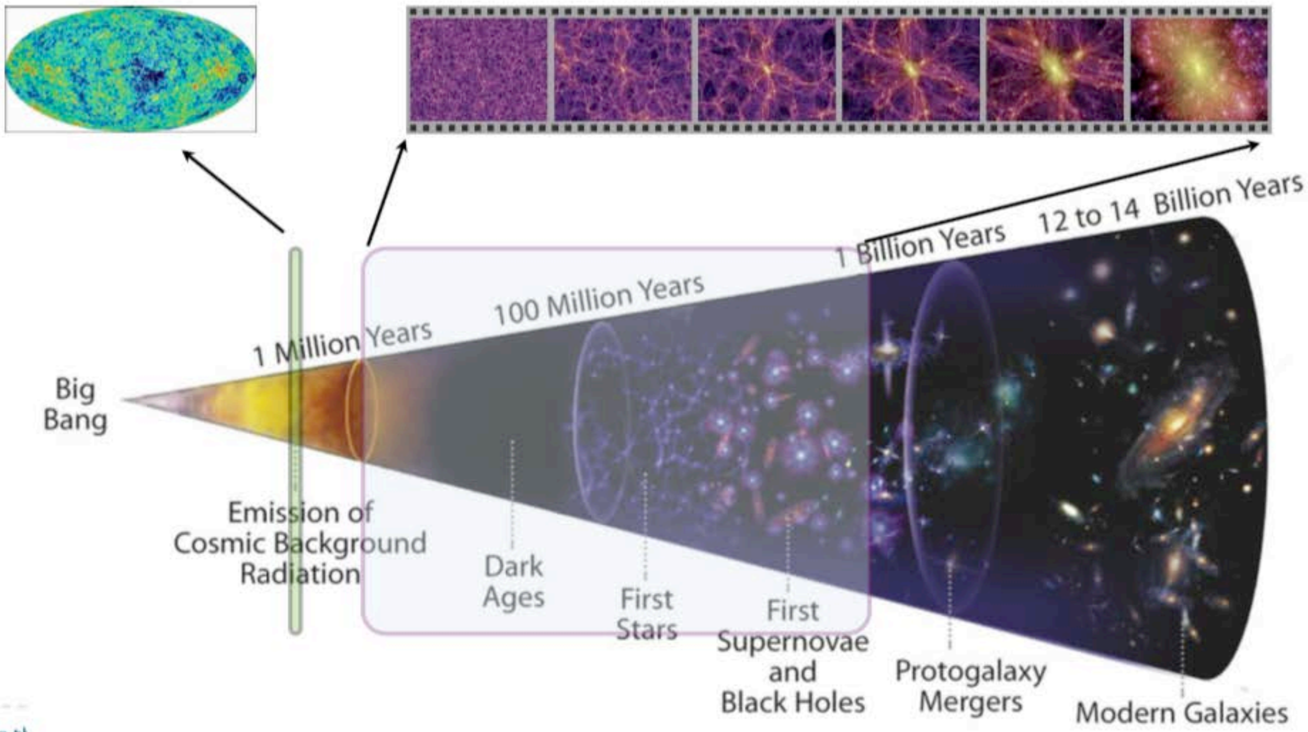



**Neutral Hydrogen** 21 cm spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars

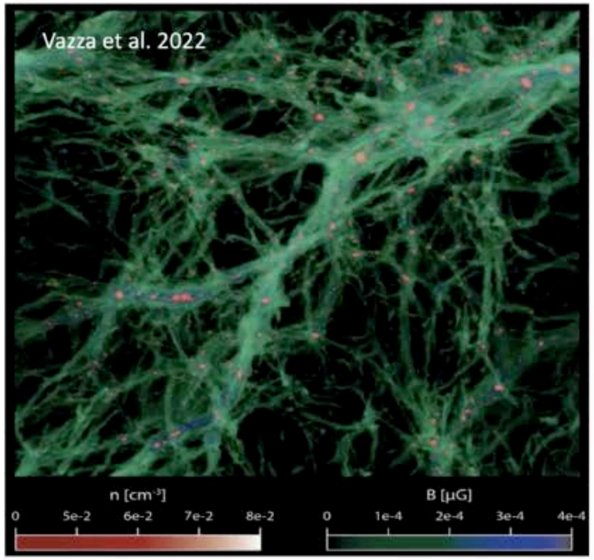
# HI surveys of the Dark Ages, Cosmic-Dawn & EoR

CMB displays a single moment of the Universe. Its initial conditions at ~400,000 yrs

HI emission from the Dark Ages, Cosmic Dawn & EoR traces an evolving "movie" of baryonic and DM structure formation at $t_{univ} < 10^9$ years.

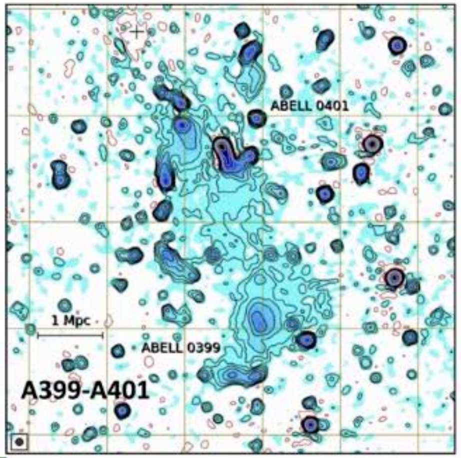


# Main SKA challenge: radio detection from the cosmic web



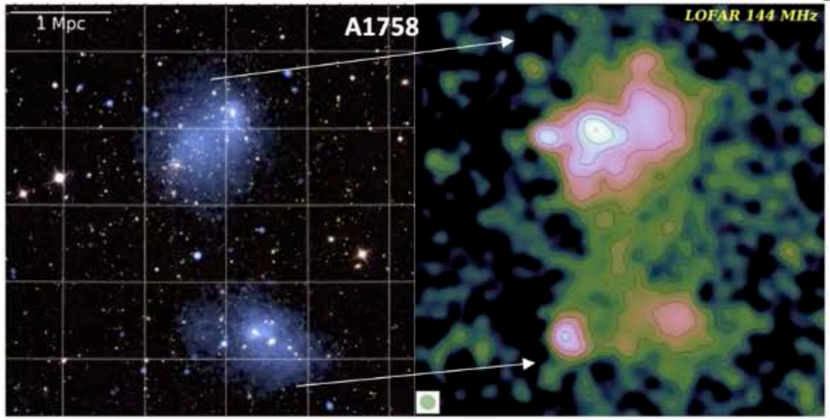

Only very few cases of detection of radio emission beyond the cluster scale, so far at low frequencies

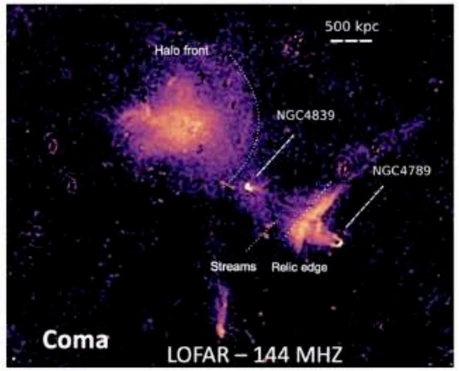
- Coma cluster (Kim+,1989, Bonafede+, 2021)
- A1758 (Botteon+ 2020)
- A399-A401 (Govoni+ 2019)



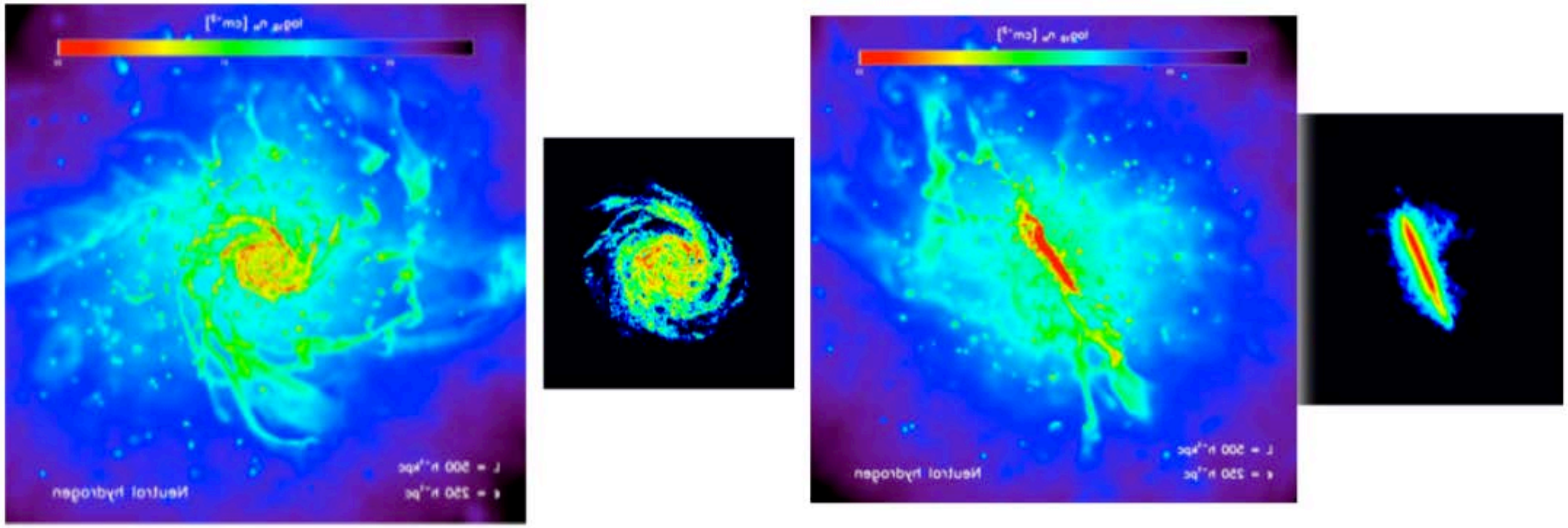

Key question – **detection of radio emission on scales beyond galaxy clusters**, in regions where $B_{eq} \lesssim 0.1$ μG to explore the **origin of primordial magnetic fields.**

Strong **synergy among observations, simulations, HPC**



## Galaxy HI Evolution:
## out to z ~ 1 with SKA1 and z ~ 5 with SKA2

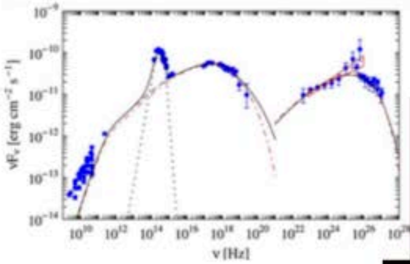


(Simulations: Schaye et al. 2010, Images: Oosterloo 2014)

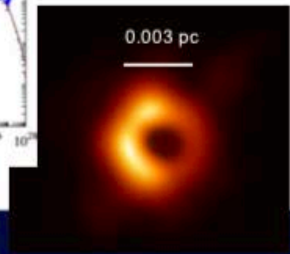
- Understanding galaxy assembly and the baryon cycle
  - Determine the impact of galaxy environments
  - Probe gas inflow and removal, diffuse gas $N_{HI} < 10^{17}$ cm$^{-2}$
  - Measure angular momentum build-up

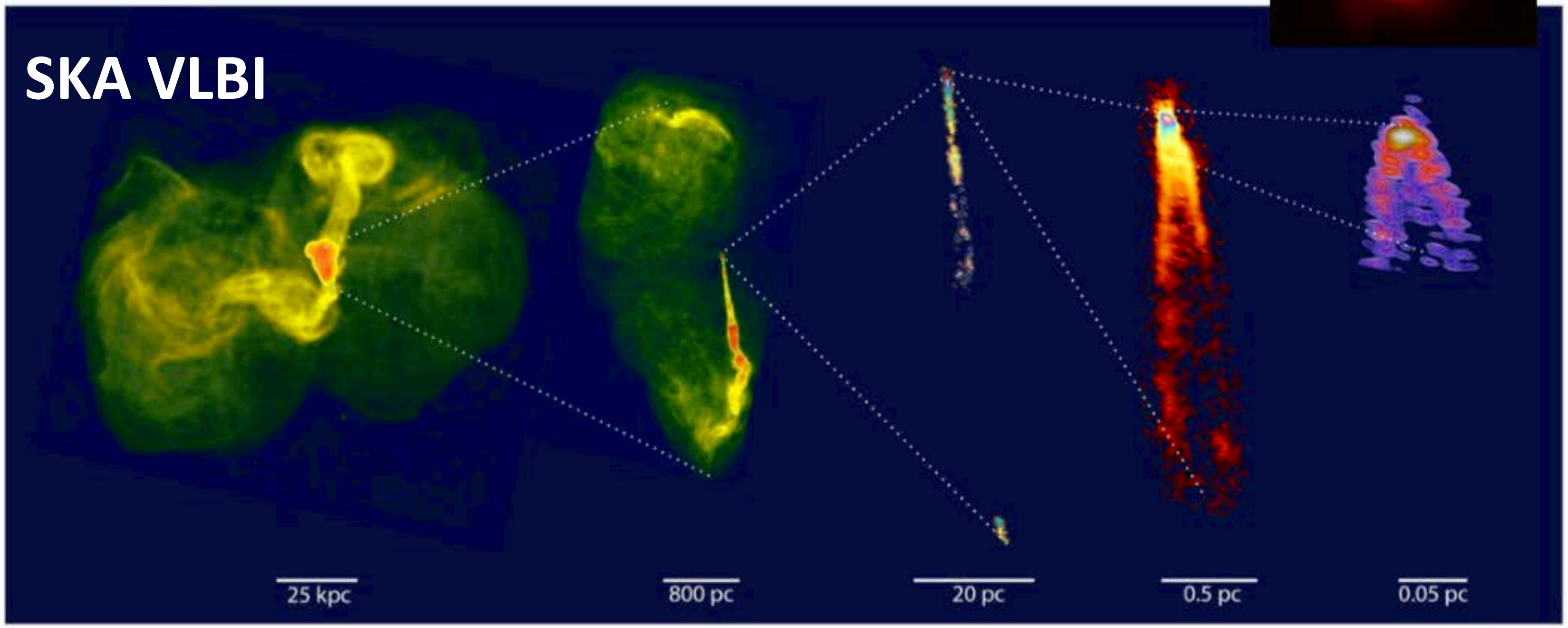
# Relativistic Jets

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

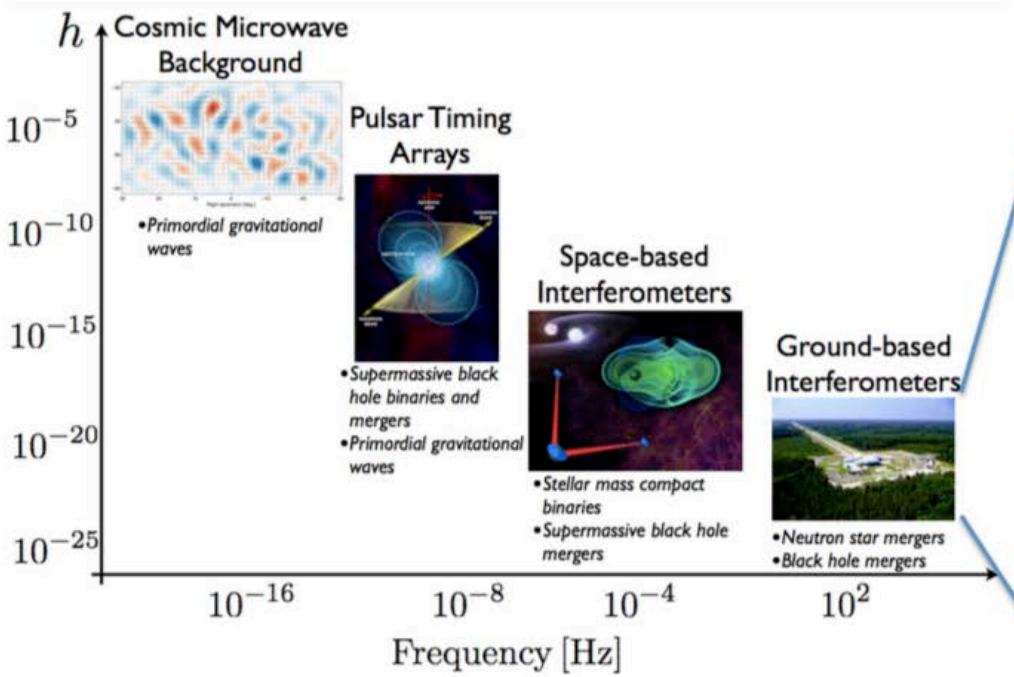


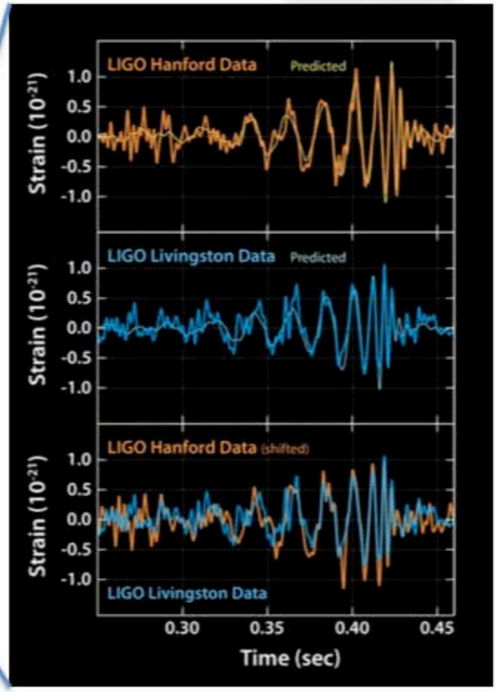

VLBI allows exquisite resolution



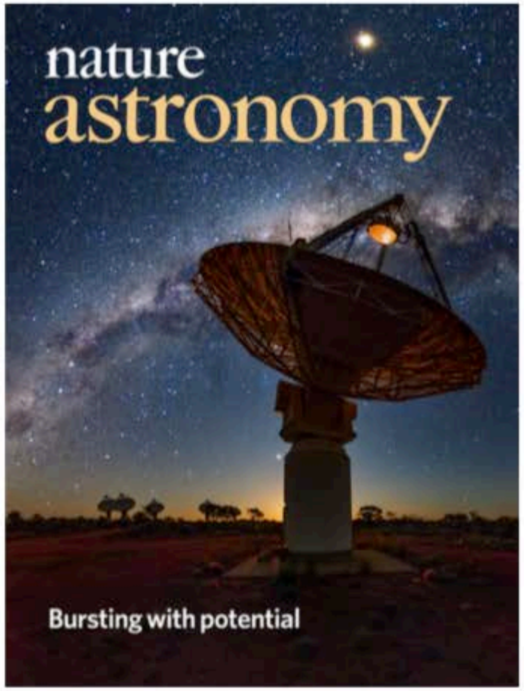
# Finding all the pulsars in the Milky Way…

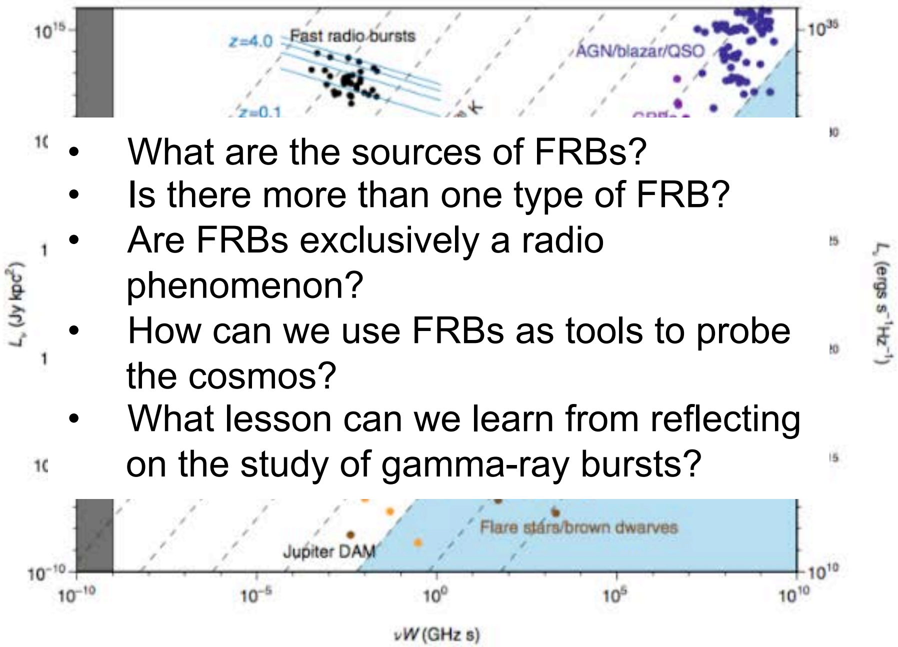



- Timing precision is expected to increase by factor ~100: nHz Grav. Waves
- Rare and exotic pulsars and binary systems: including PSR-BH systems!
- Testing cosmic censorship and no-hair theorem
- **Current estimates are ~50% of population with SKA1, 100% with SKA2**

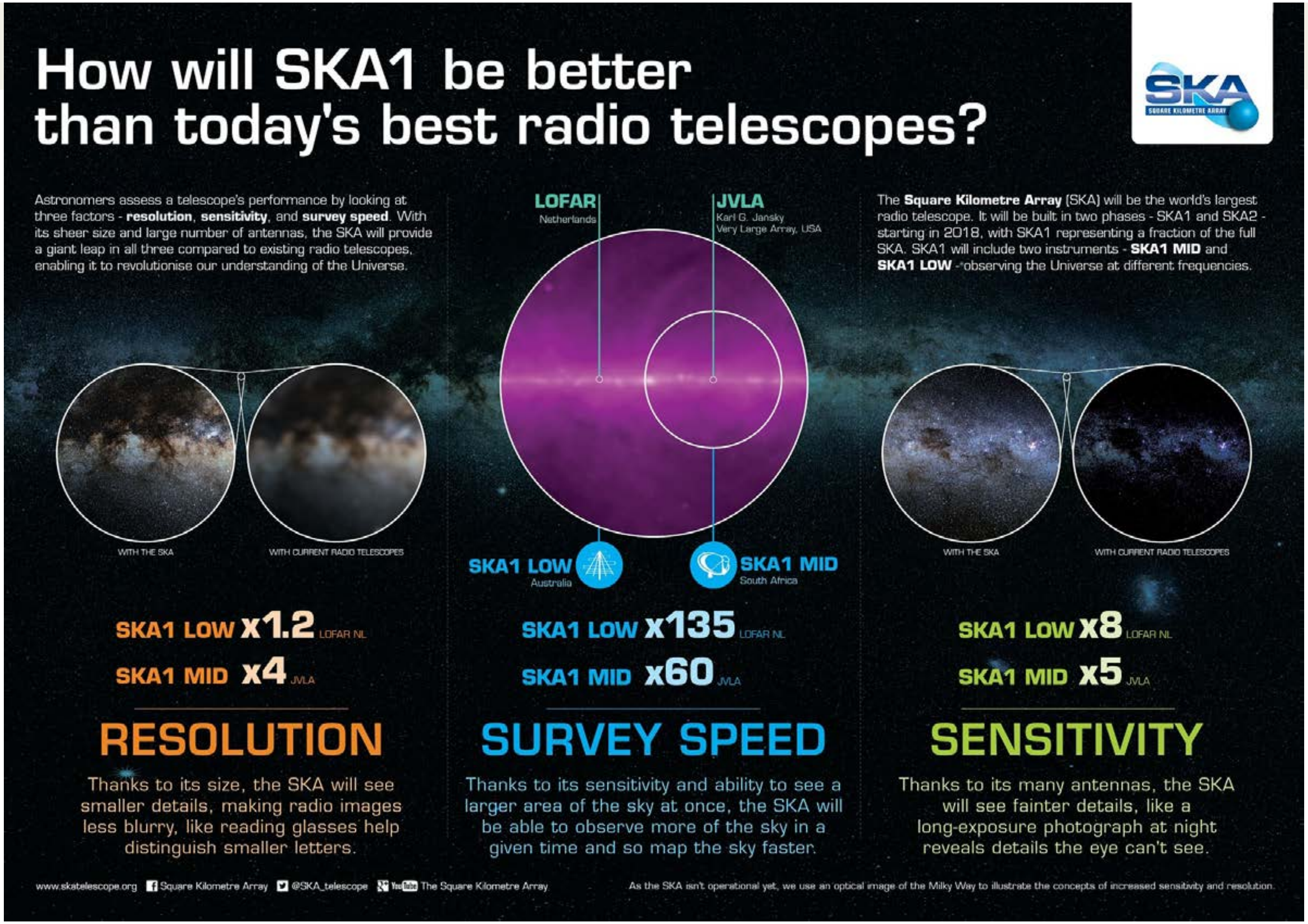
# The Transient radio sky




- What are the sources of FRBs?
- Is there more than one type of FRB?
- Are FRBs exclusively a radio phenomenon?
- How can we use FRBs as tools to probe the cosmos?
- What lesson can we learn from reflecting on the study of gamma-ray bursts?

- More than 60 celestial “FRB” events now detected (after first “Lorimer” burst): S = 0.5 – 2 Jy, Δt = 1 – 6 msec, DM = 500 – 2000 cm$^{-3}$ pc
- Estimated event rate: 3x10$^3$ sky$^{-1}$ day$^{-1}$
- Unknown origin – some, probably all at cosmological distances


How will SKA1 be better than today's best radio telescopes?
SKA SQUARE KILOMETRE ARRAY
Astronomers assess a telescope's performance by looking at three factors - **resolution**, **sensitivity**, and **survey speed**. With its sheer size and large number of antennas, the SKA will provide a giant leap in all three compared to existing radio telescopes, enabling it to revolutionise our understanding of the Universe.
LOFAR
Netherlands
JVLA
Karl G. Jansky Very Large Array, USA
The **Square Kilometre Array** (SKA) will be the world's largest radio telescope. It will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - **SKA1 MID** and **SKA1 LOW** - observing the Universe at different frequencies.
WITH THE SKA
WITH CURRENT RADIO TELESCOPES
SKA1 LOW
Australia
SKA1 MID
South Africa
WITH THE SKA
WITH CURRENT RADIO TELESCOPES
SKA1 LOW x1.2 LOFAR NL
SKA1 MID x4 JVLA
RESOLUTION
Thanks to its size, the SKA will see smaller details, making radio images less blurry, like reading glasses help distinguish smaller letters.
SKA1 LOW x135 LOFAR NL
SKA1 MID x60 JVLA
SURVEY SPEED
Thanks to its sensitivity and ability to see a larger area of the sky at once, the SKA will be able to observe more of the sky in a given time and so map the sky faster.
SKA1 LOW x8 LOFAR NL
SKA1 MID x5 JVLA
SENSITIVITY
Thanks to its many antennas, the SKA will see fainter details, like a long-exposure photograph at night reveals details the eye can't see.
www.skatelescope.org Square Kilometre Array @SKA_telescope YouTube The Square Kilometre Array
As the SKA isn't operational yet, we use an optical image of the Milky Way to illustrate the concepts of increased sensitivity and resolution.


How does SKA1 compare with the world's biggest radio telescopes?
SKA
SQUARE KILOMETRE ARRAY
SKA1 LOW
Australia
419,000m²
~130,000 antennas
SKA1 MID
South Africa
33,000m²
~200 dishes
MWA
Murchison Widefield Array, Australia
2,500m²
2048 antennas
LOFAR
Low Frequency Array for Radio astronomy, Netherlands
52,000m²
34,000 antennas
GMRT
Giant Metrewave Radio Telescope, India
48,000m²
30 dishes
At 110 MHz
LOW FREQUENCIES
ASKAP
Australian SKA Pathfinder, Australia
4,000m²
36 dishes
MeerKAT
South Africa
9,000m²
64 dishes
JVLA
Karl G. Jansky Very Large Array, USA
13,200m²
27 dishes
ARRAYS
NRT
Nancay Radio Telescope, France
7,000m²
300m x 35m antenna
Lovell
UK
4,500m²
76m dish
Effelsberg
Germany
7,800m²
100m dish
Parkes
Australia
3,200m²
64m dish
GBT
Green Bank Telescope, USA
7,800m²
100m dish
FAST
Five Hundred Meter Aperture Spherical Telescope, China
71,000m²
500m dish
Arecibo
Puerto Rico
42,000m²
305m dish
SINGLE DISHES
NON-STEERABLE
MID FREQUENCIES
ALMA
Atacama Large Millimeter/submillimeter Array, Chile
6,500m²
66 dishes
HIGH FREQUENCIES


A CURA DEL CUG INAF
INAF
NOV 25, 2021
INTERNATIONAL DAY FOR THE ELIMINATION OF VIOLENCE AGAINST WOMEN
CREDITI: UN WOMEN | GRAFICA: DAVIDE COERO BORGA
"Violence against women is perhaps the most shameful human rights violation, and it is perhaps the most pervasive. It knows no boundaries of geography, culture or wealth. As long as it continues, we cannot claim to be making real progress towards equality, development and peace"
Kofi Annan, 7th UN secretary
SOME STATISTICS:
HOW TO TALK ABOUT IT:
ANOTHER FUTURE WITHOUT VIOLENCE AGAINST WOMEN IS POSSIBLE WITH EDUCATION, ESSENTIAL SERVICES ACROSS POLICING, JUSTICE, HEALTH, AND SOCIAL SECTORS, AND SUFFICIENT FINANCING DEDICATED TO WOMEN'S RIGHTS.

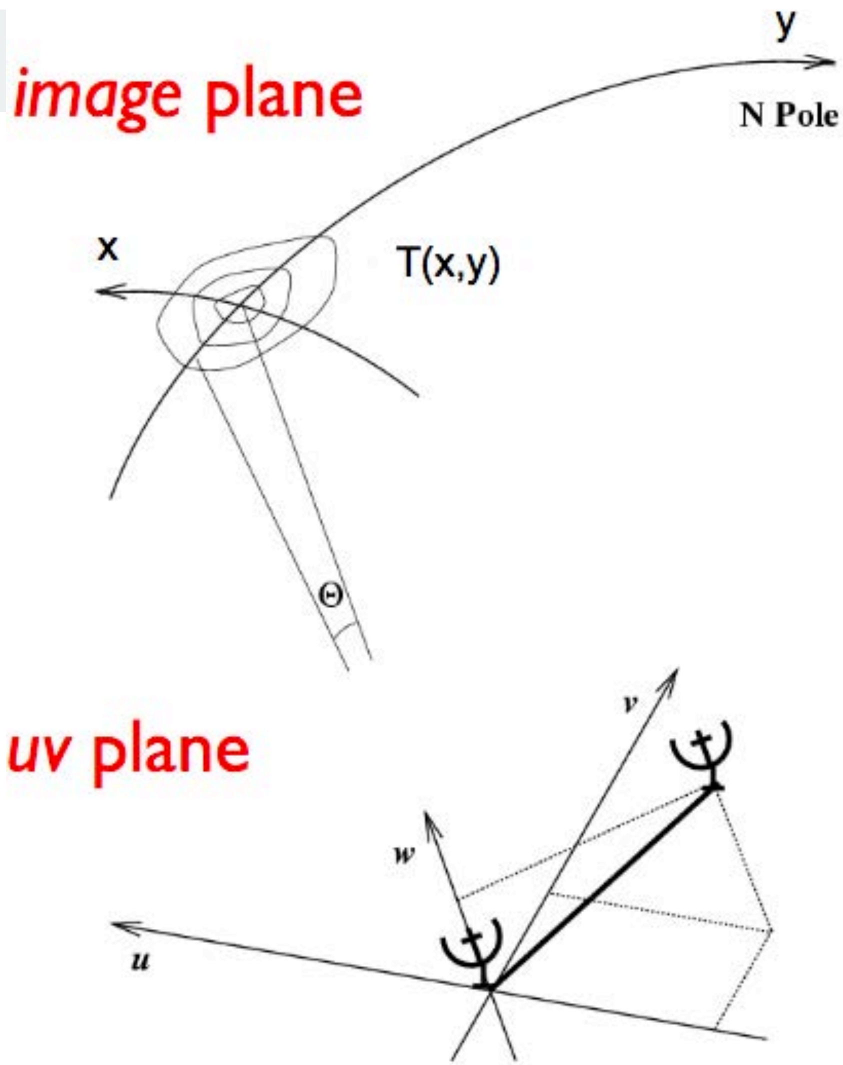
Thank you!

# Radio interferometry

Radiotelescopes measure the visibility function V(u,v) ∈ C which is the FT of the sky brightness distribution B(θ,φ) ∈ R

1. An interferometer measures the interference pattern observed by pairs of apertures

2. The interference pattern is directly related to the source brightness.
In particular, for small fields of view the complex visibility, V(u,v), is the 2D Fourier transform of the brightness on the sky, T(x,y)



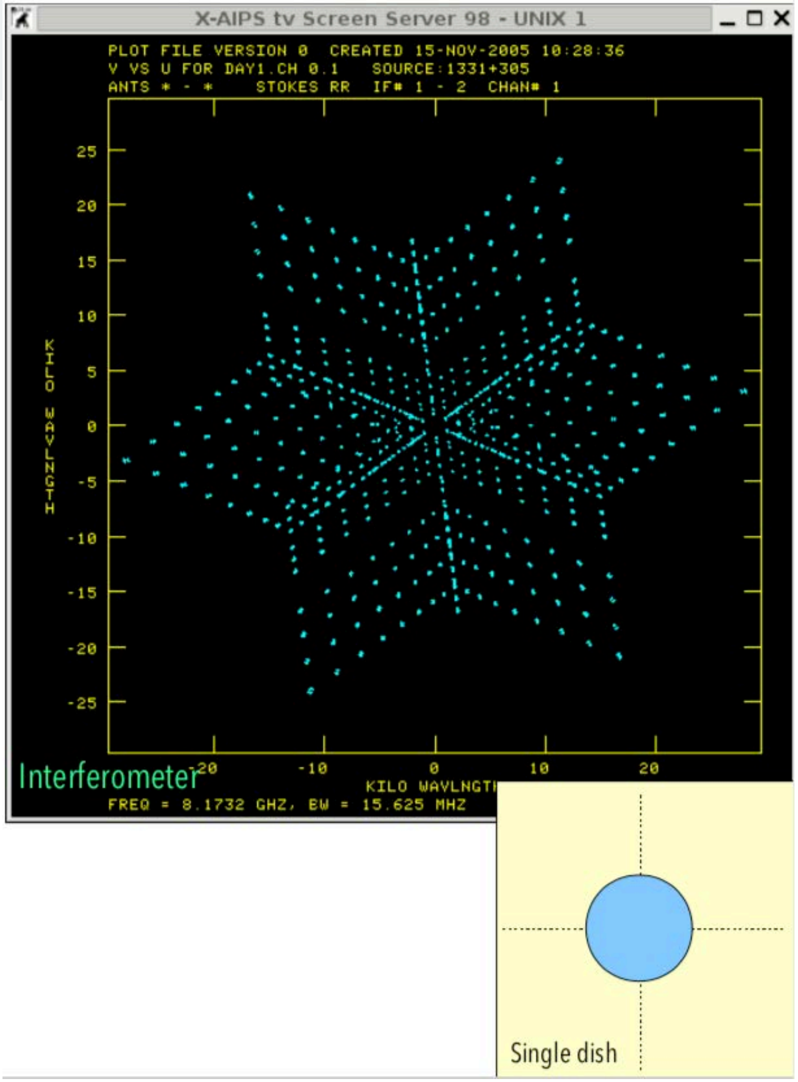
# Radio interferometry

● A simple interferometer brings in a limited amount of information and does not sample the total power

● Ideal interferometers are made up of as many elements as possible and provide excellent (simultaneous) sampling of the u-v plane

● The interferometer samples V(u,v) in the spatial frequency space over a range of baselines

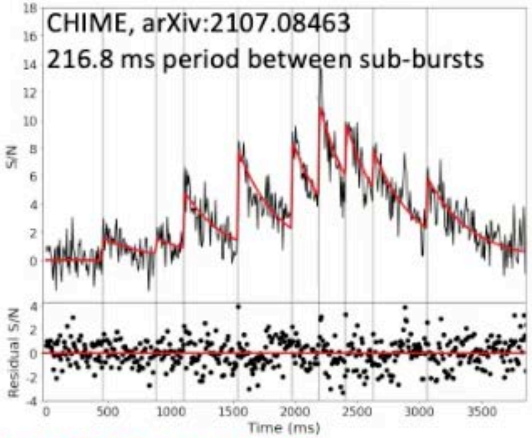
● The u-v sampling determines the PSF = beam = $P_n$ $(\theta,\varphi)$



# Science: burst sub-structure

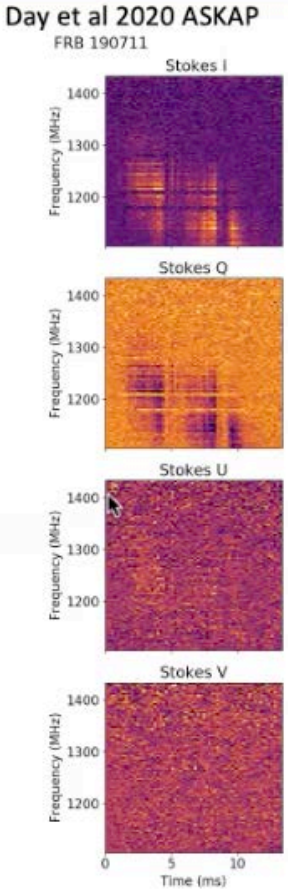
## Time-frequency structure

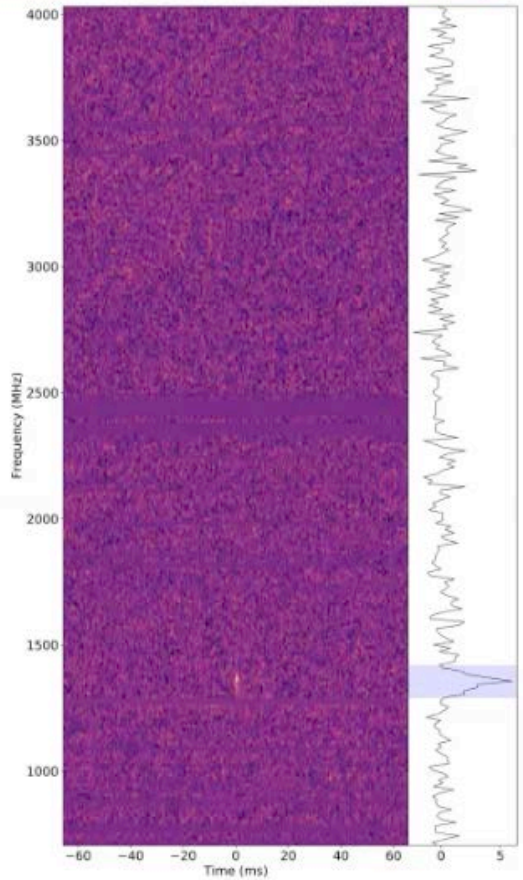
- Key to understanding emission mechanism
- Huge variation in observations!




## Key SKA message

- Broad-bandwidth observations, high time resolution
- Need many FRBs to characterize population




Parkes: Kumar et al, MNRAS 500 (2020) 2525