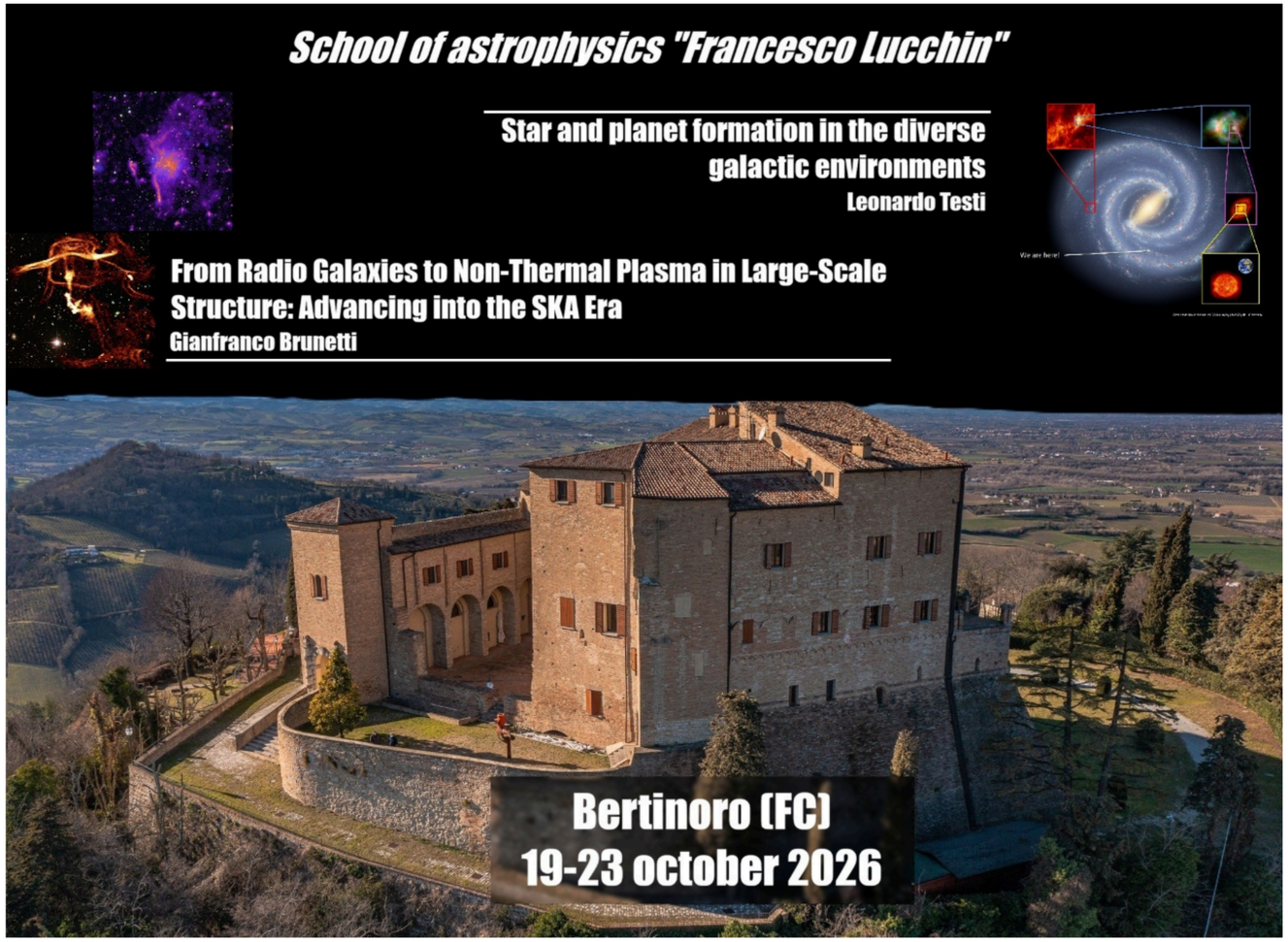
SOC

L. Testi (UniBO-DIFA),

G. Brunetti (INAF-IRA),

V. Roccatagliata (UniBO-DIFA),

M. Brienza (INAF-IRA)



LOC

Tabellini (INAF-IRA),

D. Govoni (INAF-IRA),

V. Roccatagliata (UniBO-DIFA),

M. Brienza (INAF-IRA),

R. Partisani (Ceub)

From radio galaxies to non-thermal plasma in large-scale structure: advancing into the SKA era

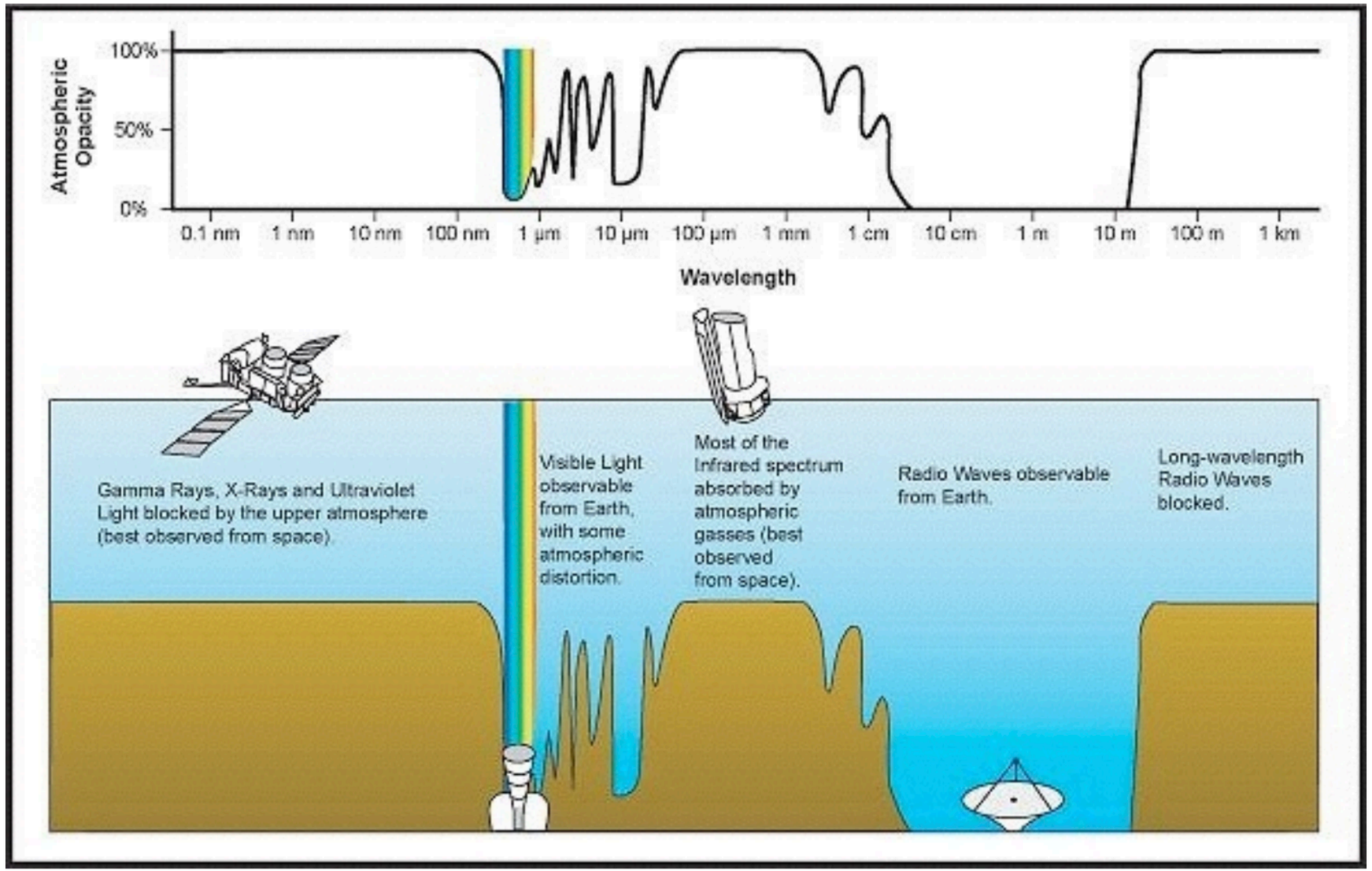
Welcome!

Introduction to radio observations and SKA

Marisa Brienza
IRA-INAF, Bologna, Italy

INAF PhD School “Franchesco Lucchin”, Bertinoro, October 2026

The radio window



http://coolcosmos.ipac.caltech.edu/cosmic_classroom/ir_tutorial/irwindows.html

0.02 mm to ~30 m (10 MHz)

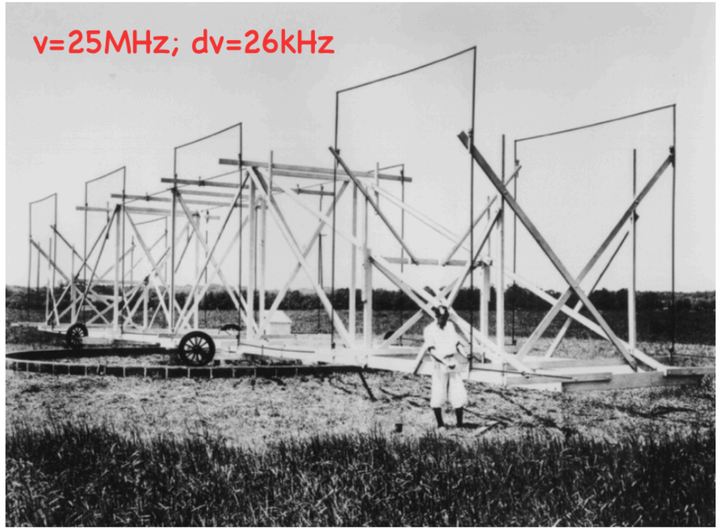
Atmosphere absorbs photons with wavelengths lower than 0.02 mm and, because of free electrons of the ionosphere, reflects back into space photons with wavelengths longer than 30 m.

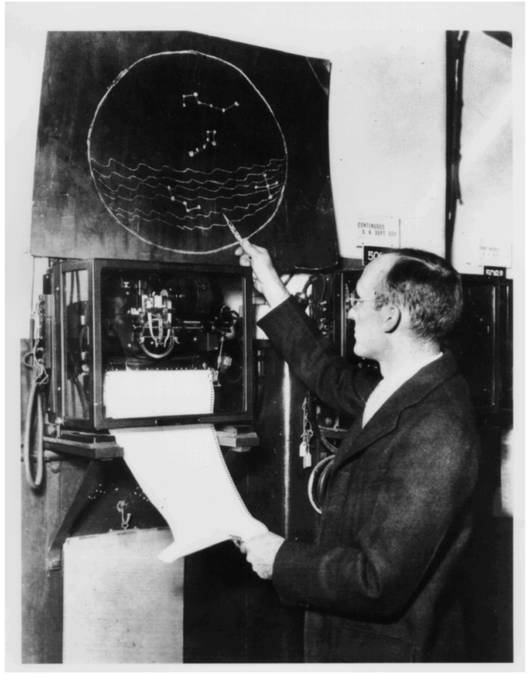
What can we observe at radio frequencies?

- (Polarized) Synchrotron radiation
  - Cosmic rays and magnetic fields, pulsars, galaxies, clusters, ...
- Thermal radiation (black body, bremsstrahlung)
  - Ionized gas, dust
- Cyclotron radiation
  - Planetary magnetic fields
- Spectral lines
  - Neutral hydrogen (21cm)
    Radio recombination lines, molecules, masers

Where it all began..

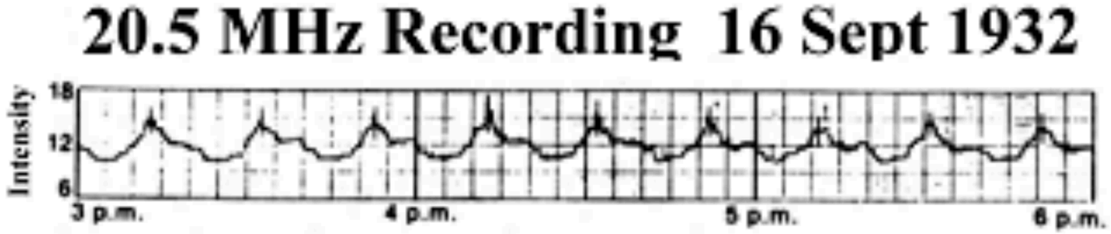
- Discovery of cosmic radio waves - Karl Jansky, 1932





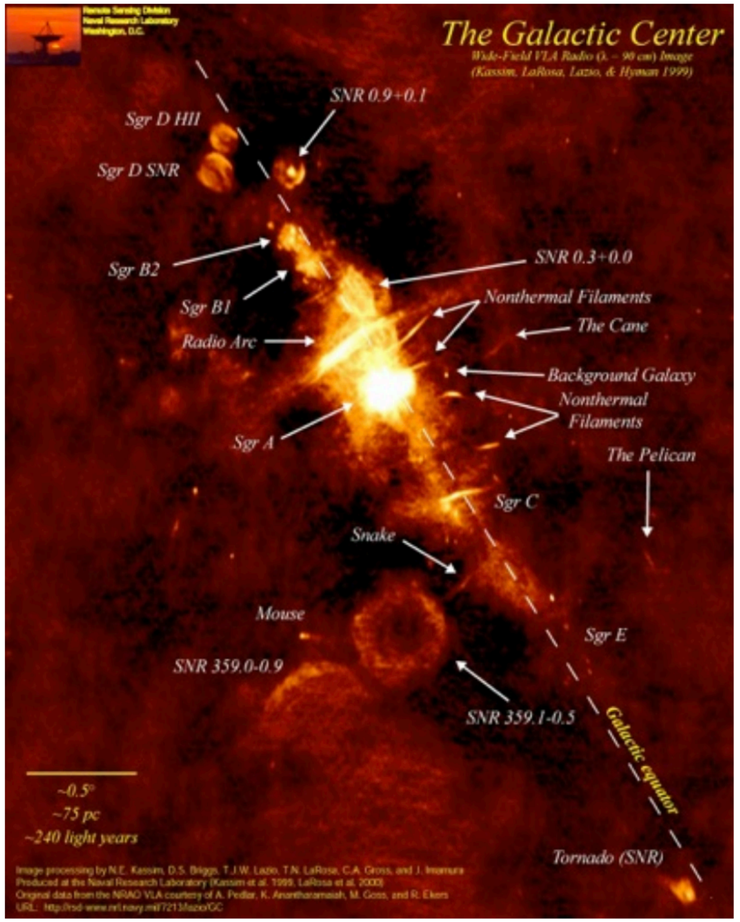
Karl Jansky - communication engineer at Bell Laboratory (USA) begins to investigate sources of radio noise that affects communications.

He identified thunderstorms and something else...



Where it all began..

- “There is no indication of any kind [...] that these galactic radio waves constitute [...] some form of intelligence striving for intra-galactic communication.”





NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N. J., and was described by him in a paper delivered before the International Scientific Radio Union in Washington.

The galactic radio waves, Mr. Jansky said, differ from the cosmic rays and also from the phenomenon of cosmic radiation, described last week before the American Philosophical Society at Philadelphia by Dr. Vesto M. Slipher, director of the Lowell Observatory at Flagstaff, Ariz.

Unlike the cosmic ray, which comes from all directions in space, does not vary with either the time of day or the time of the year, and may be either a photon or an electron, the galactic waves, Mr. Jansky pointed out, seem to come from a definite source in space, vary in intensity with the time of day and time of the year, and are distinctly electro-magnetic waves that can be picked up by a radio set.

New Waves Have High Frequency.

The cosmic radiation discovered by Dr. Slipher is a mysterious form of light apparently radiated independently of starlight, originating, Dr. Slipher concluded, at some distance above the earth's surface, and possibly produced by the earth's atmosphere.

The galactic radio waves, the announcement says, are short waves, 14.6 meters, at a frequency of about 20,000,000 cycles a second. The intensity of these waves is very low, so that a delicate apparatus is required for their detection.

Unlike most forms of radio disturbances, the report says, these newly found waves do not appear to be due to any terrestrial phenomena, but rather to come from some point far off in space—probably far beyond our solar system.

If these waves came from a terrestrial origin, it was reasoned, then they should have the same intensity all the year around. But their intensity varies regularly with the time of day and with the seasons, and they get much weaker when the earth, moving in its orbit, interposes itself between the radio receiver and the source.

A preliminary report, published in the Proceedings of the Institute of Radio Engineers last December, described studies which showed the presence of three separate groups of static: Static from local thunderstorms, static from distant thunderstorms, and a "steady hiss type static of unknown origin." Further studies this year determine the unknown origin of this third type to be from the direction of the centre of the Milky Way, the earth's own home galaxy.

Direction of Arrival Fixed.

The direction from which these waves arrive, the announcement asserts, has been determined by investigations carried on over a considerable period. Measurements of the horizontal component of the waves were taken on several days of each month for an entire year, and by an analysis of these readings at the end of the year their direction of arrival was disclosed.

"The position indicated," it was explained, "is very near to the point where the plane in which the earth revolves around the sun crosses the centre of the Milky Way, and also to that point toward which the solar system is moving with respect to the other stars.

"Further verification of this direction is required, but the discovery, like that of the cosmic rays and of cosmic radiation, raises many cosmological questions of extreme interest."

There is no indication of any kind, Mr. Jansky replied to a question, that these galactic radio waves constitute some kind of interstellar signalling, or that they are the result of some form of intelligence striving for intra-galactic communication.

Radio Entertains the Children With Crises.
Arthur Mass in May Scribner's.—Adv.

NY Times

Radio telescopes

Use the wave formalism -> not enough energy for photoelectric effect as in CCDs!

3.6 eV needed to photoionize silicon
at 1.4GHz E = 4e-6 eV

Detectors sensitive to electric field of incoming electromagnetic wave

-> weak signal = amplification

Radio telescopes

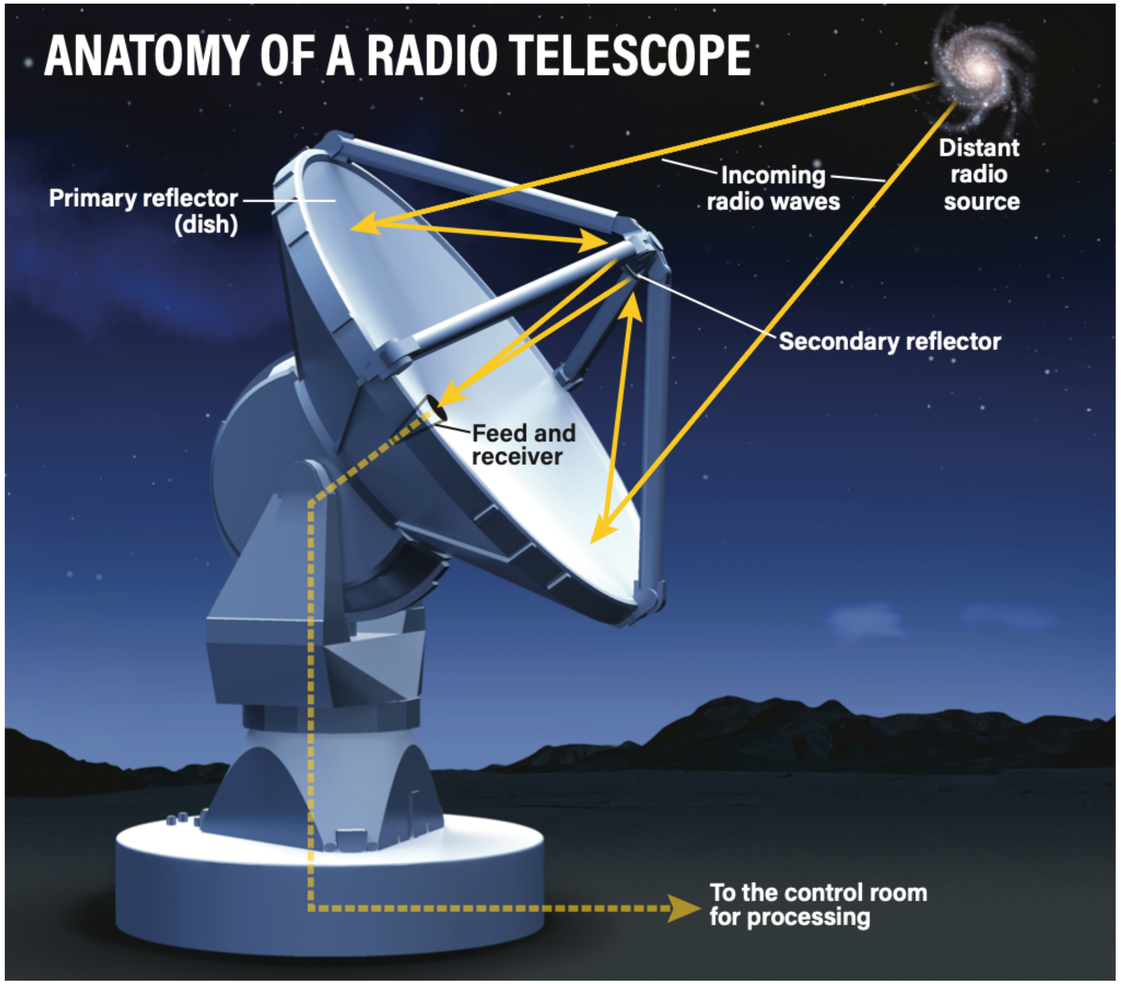
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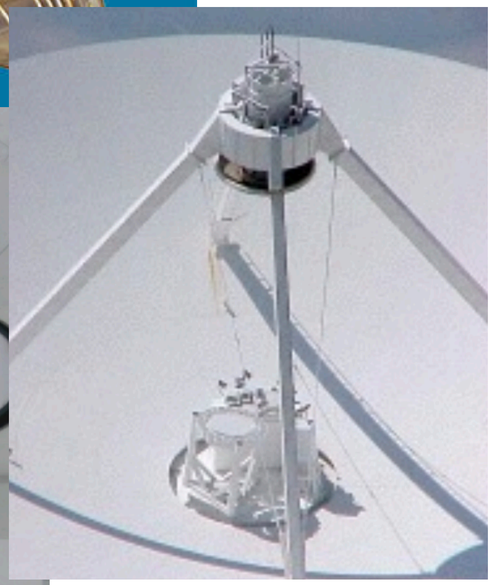
The simplest radio telescope is a parabolic reflector = a single dish.

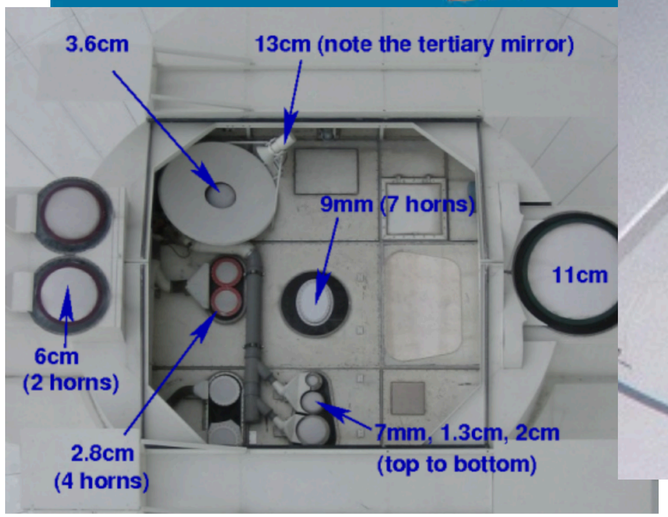


Radio telescopes

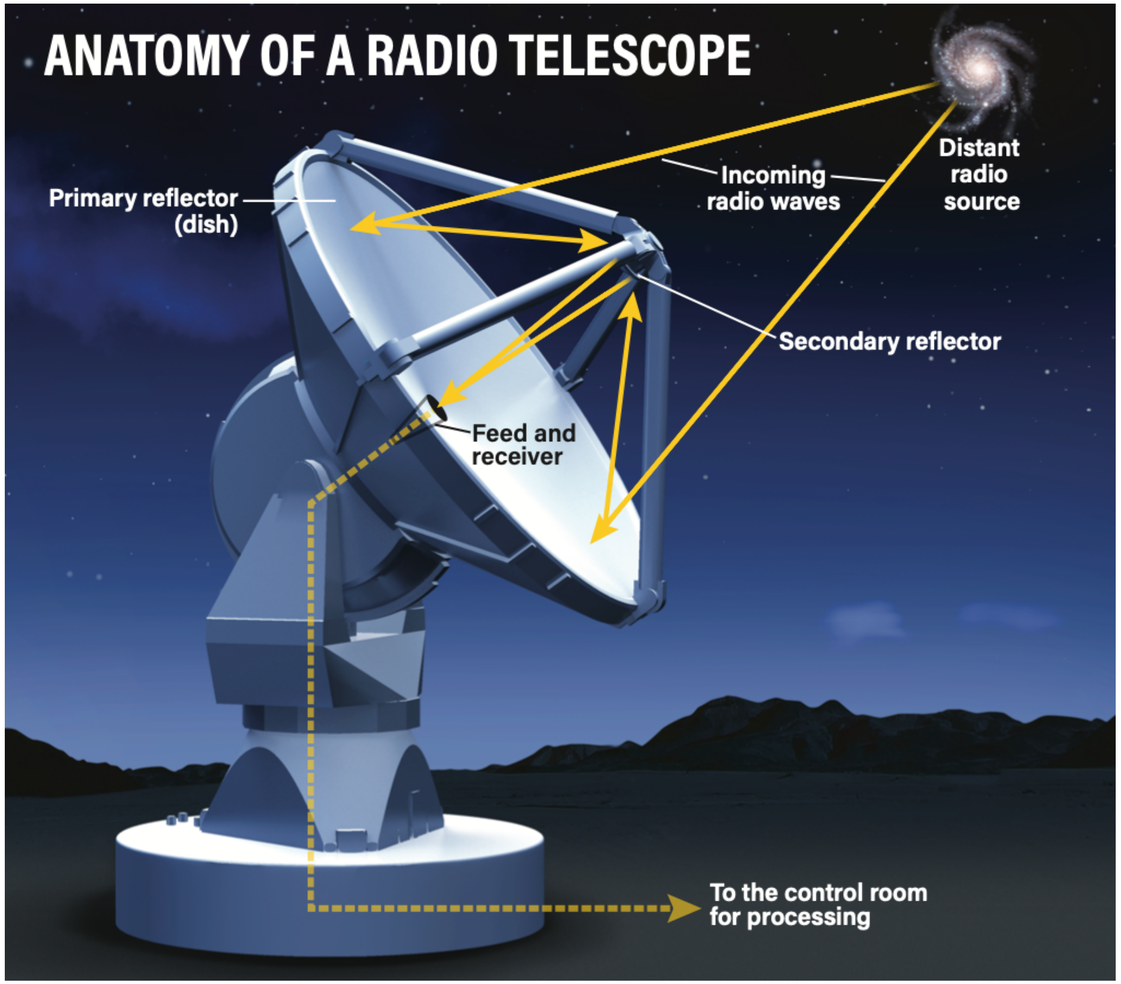


Feeds



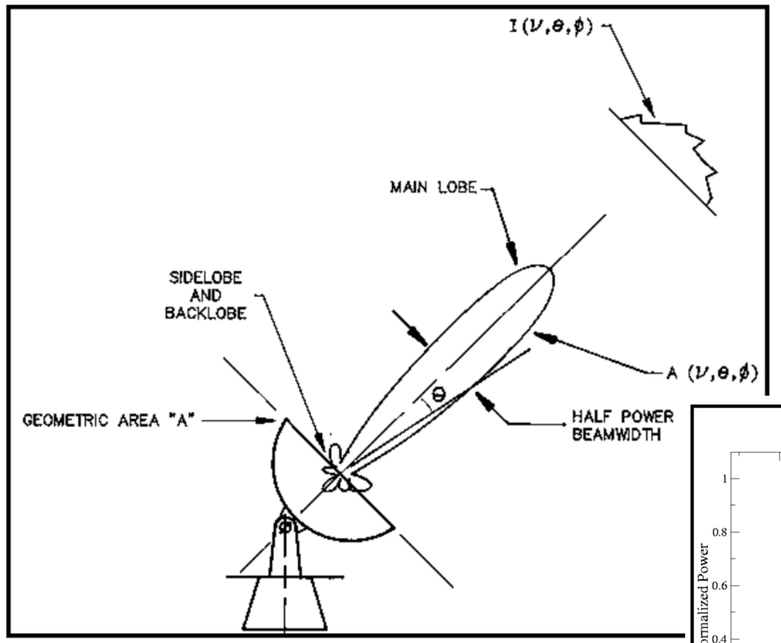


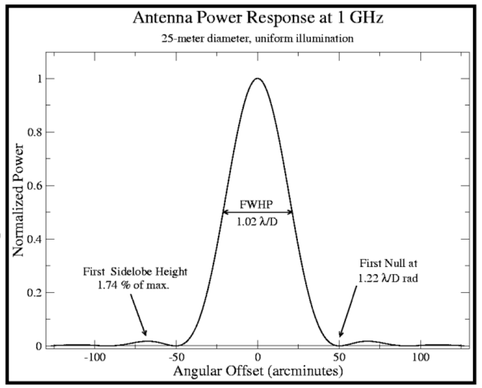
Effelsberg secondary focus

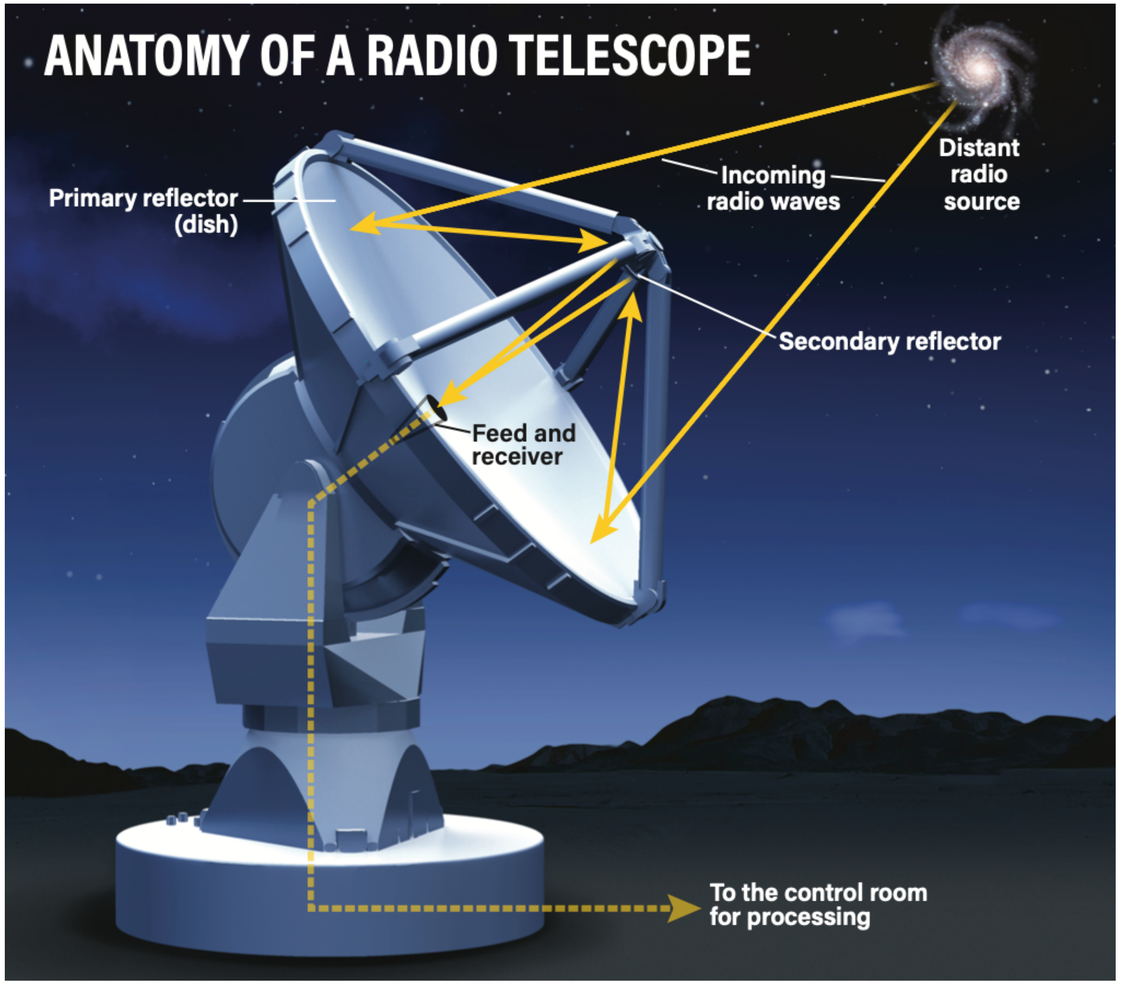


Radio telescopes

This has a directional gain + sidelobes = finite response at large angle from the pointing center







Biggest single dishes

100 m

FULLY STEERABLE

Effelsberg, Germany



Green Bank, West Virginia, US



FAST, Guizhou, China



500 m

PARTIALLY STEERABLE

Angular resolution ~ λ/Diameter

Resolution of single dish poor! e.g. 9 arcmin at 1.4GHz (21cm) with D=100

To get arcsec resolution at 1.4 GHz need ~ 43km dish… not easy!

Solution

↓

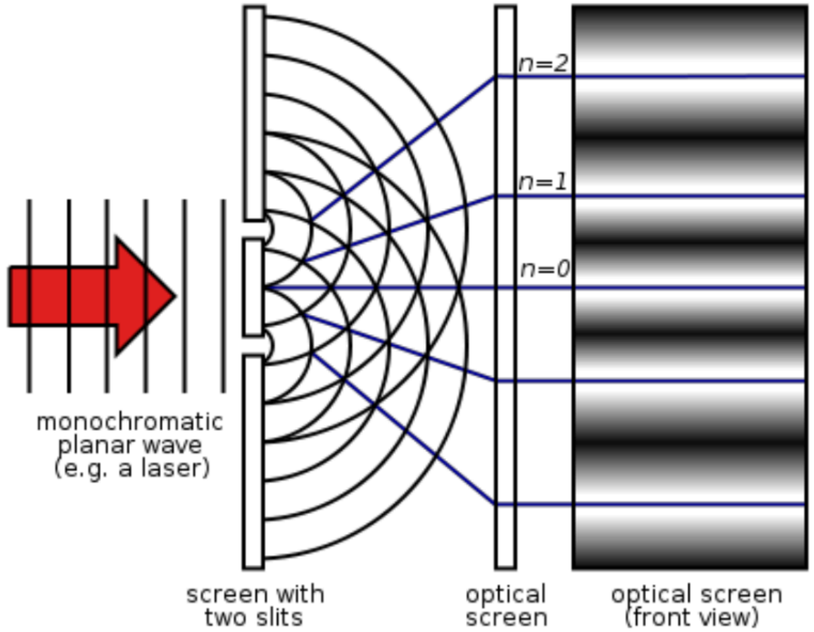
Synthesise an equivalent aperture by combining elements = arrays of antennas

Interferometry!

(Nobel prize Martin Ryle & Antony Hewish 1974!)

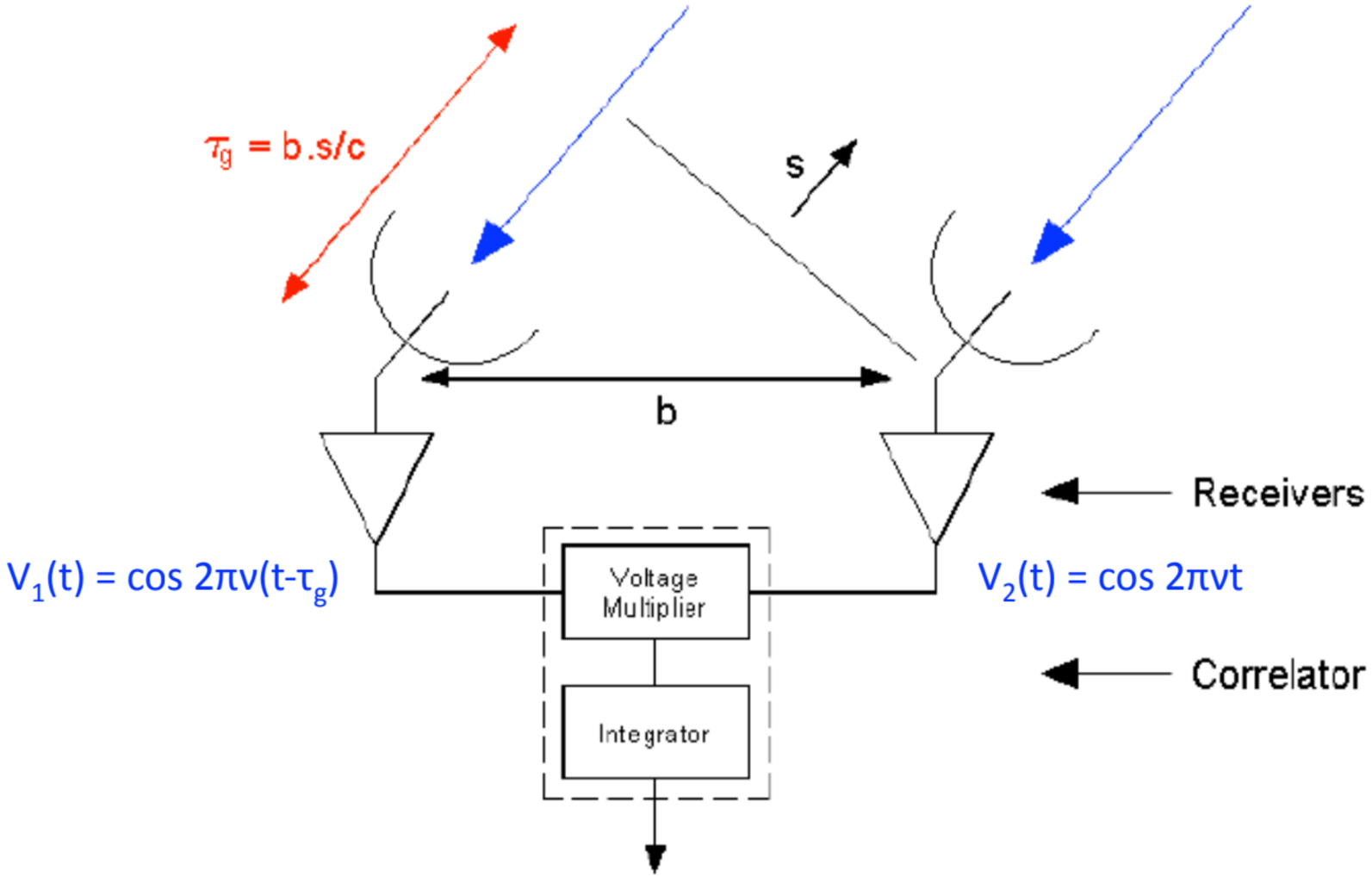
Interferometry

An *interferometer* measures the interference pattern produced by multiple apertures



The inverse Fourier transform of the measured interference pattern yields the radio brightness distribution on the sky.

Interferometry



Low pass filtered output $R_{12} = \langle V_1 V_2 \rangle = V_1 V_2 \cos 2\pi\nu\tau_g = V_1 V_2 \cos 2\pi \mathbf{b.s}/\lambda$

Interferometry

- Combines signals from multiple antennas (in phase!) to achieve higher angular resolution

Angular resolution ~ λ/Max Baseline

- Each pair of antennas measures a complex visibility, which encodes information about the source brightness distribution on a particular spatial scale and orientation.

- As the Earth rotates, the projected baselines change, sampling different spatial frequencies and building up the *uv coverage*.

$$V(u,v) = \iint I_\nu(l,m) e^{-i2\pi(ul+vm)}\, dl\, dm$$

- The sampled visibilities are Fourier-inverted and deconvolved to reconstruct an image of the sky.

- The minimum baseline dictates the largest scale the interferometer is sensitive to

LAS ~ λ/Min Baseline

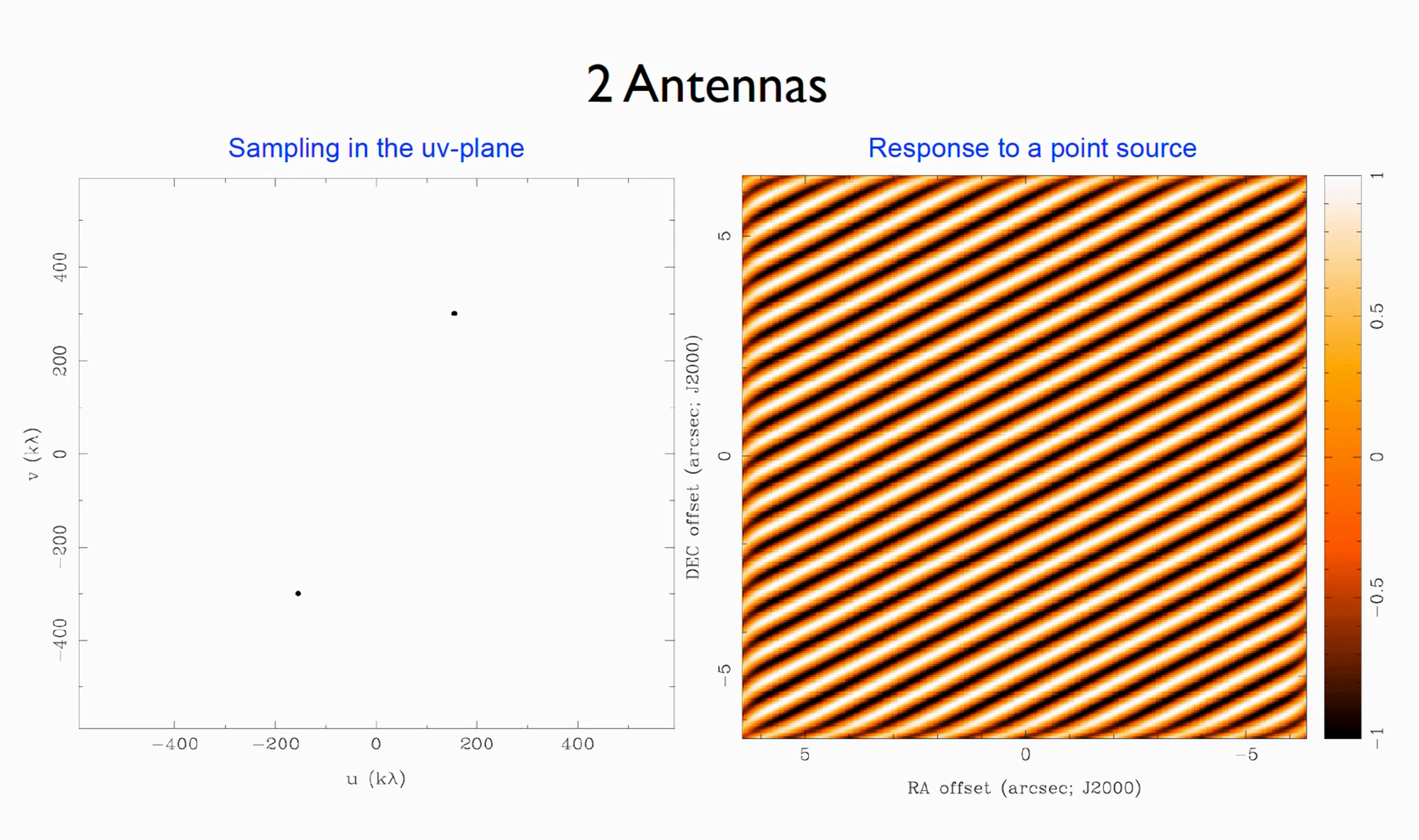
- Sensitivity

$$\sigma \propto \frac{}{\eta_c \sqrt{N(N-1) \cdot n_{\text{pol}} \cdot \Delta\nu \cdot t_{\text{int}}}}$$

N = number antennas t_int = integration time
n_pol = number of polarisations Δv = bandwidth η_c = Correlator efficiency

Interferometry

The angular resolution, sensitivity and image fidelity depend on the baseline number & distribution (uv coverage)

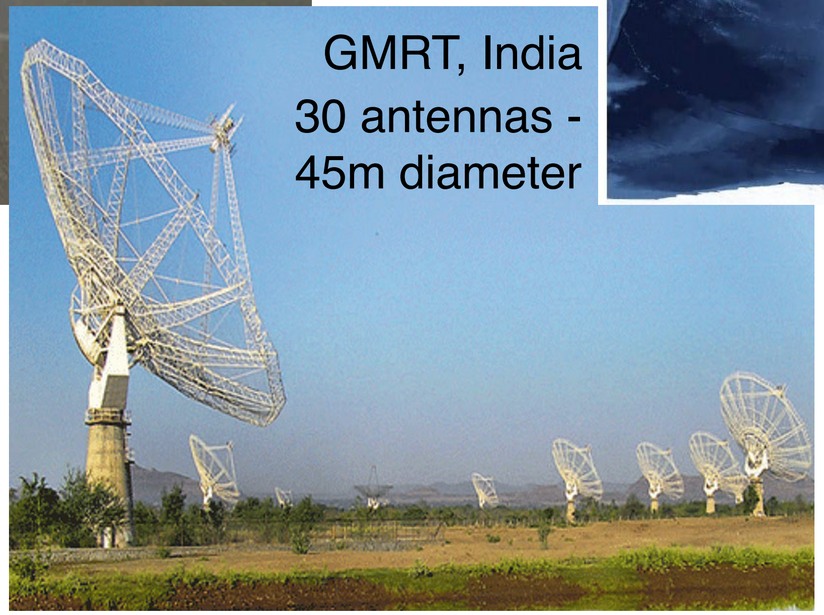


Wilner NRAO presentation

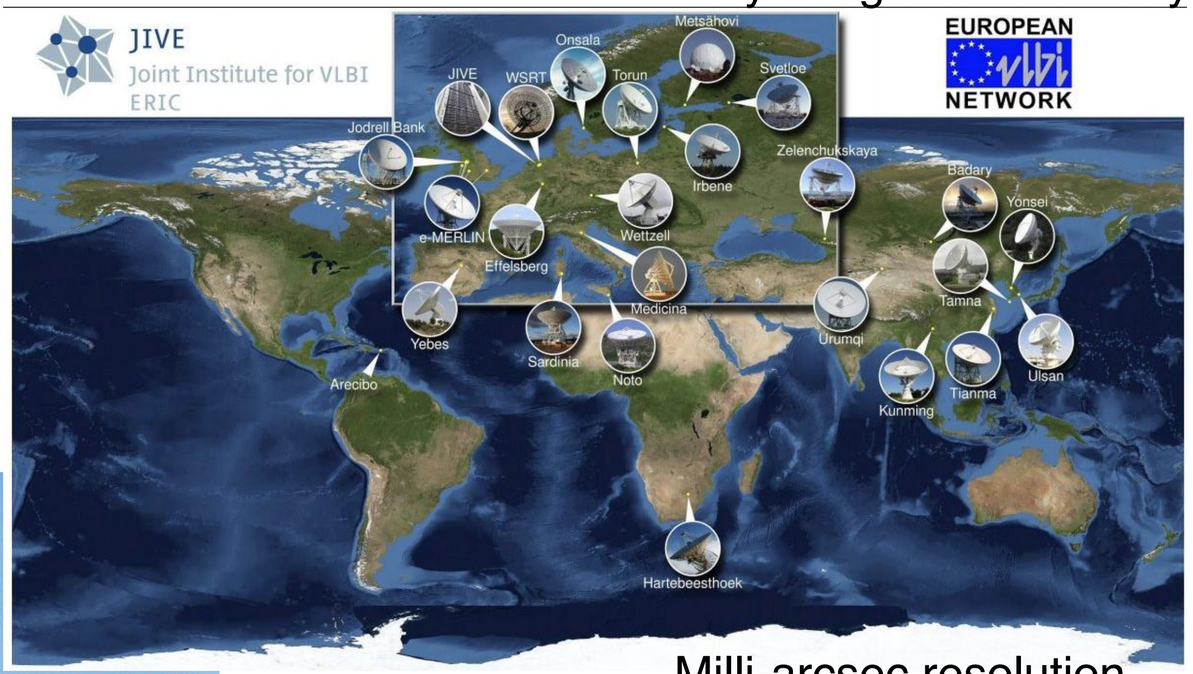
Interferometers



Arcsec resolution



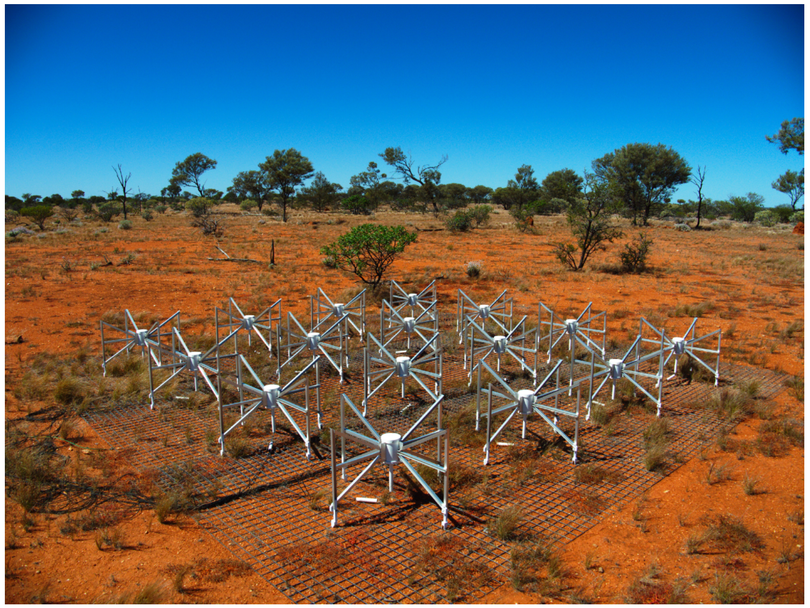
Very Long Interferometry



Milli-arcsec resolution

Interferometers

MWA



LOFAR LBA



Phased-array telescopes = arrays of dipole antennas

‘Software telescopes’

Not movable - potential all sky coverage - pointed electronically by introducing phase delays in the signal after digitalization = beam-forming technique

Interferometry

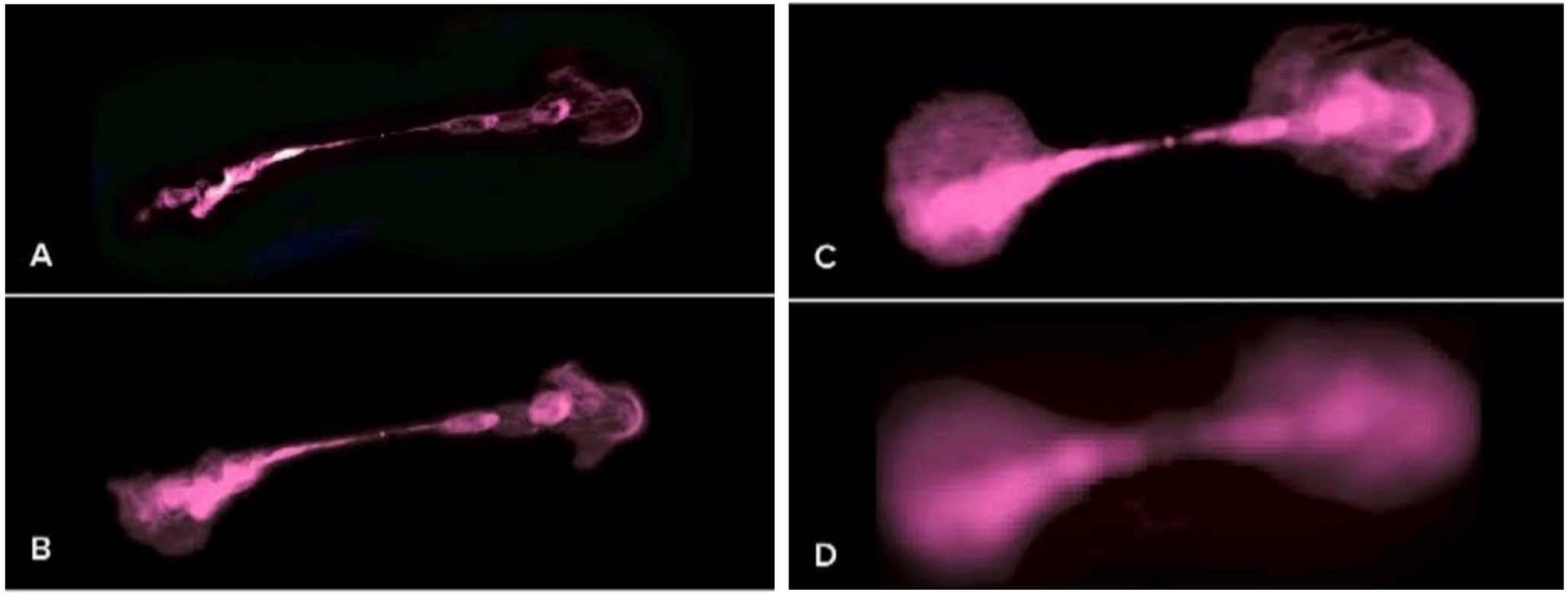
Hercules A as seen by VLA different array configurations

A = long max baseline but sparse core

D = short max baseline but dense core

36-0.7 km

11-0.21 km



3.4 0.035 km

1 0.035 km

Credit: NRAO

Interferometry



Credit: NRAO

Radio telescopes in Italy



In Italy there are four radio telescopes that have contributed to major astronomical discoveries in the last decades:

Radio telescopes in Italy



In Italy there are four radio telescopes that have contributed to major astronomical discoveries in the last decades:

- The Northern Cross interferometer in Medicina, Bologna





Involved in the European Space Surveillance and Tracking project for radar observations of space debris.

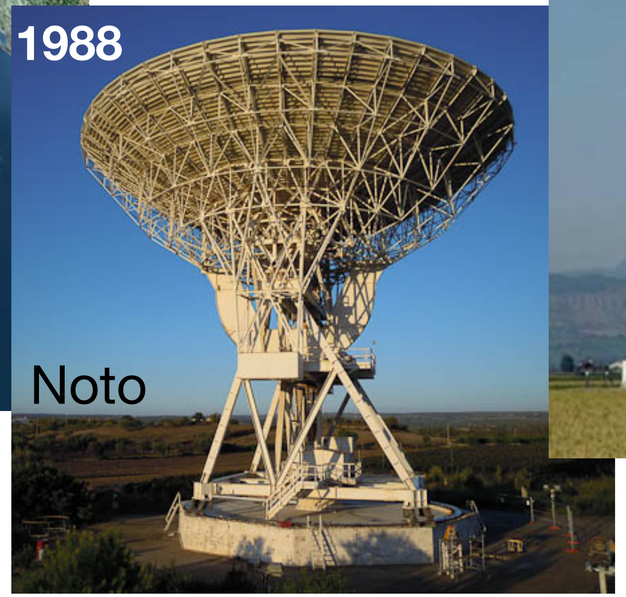
Radio telescopes in Italy



In Italy there are four radio telescopes that have contributed to major astronomical discoveries in the last decades:

- The two 32-m dish antennas in Medicina (Bologna) and Noto (Siracusa)





Used as single dish + VLBI networks

Radio telescopes in Italy

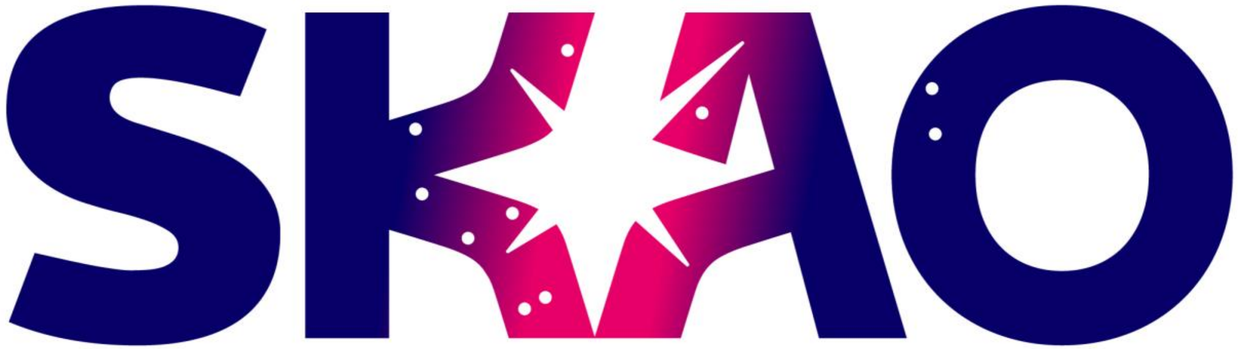


In Italy there are four radio telescopes that have contributed to major astronomical discoveries in the last decades:

- The 64-m dish antenna in San Basilio (Cagliari)



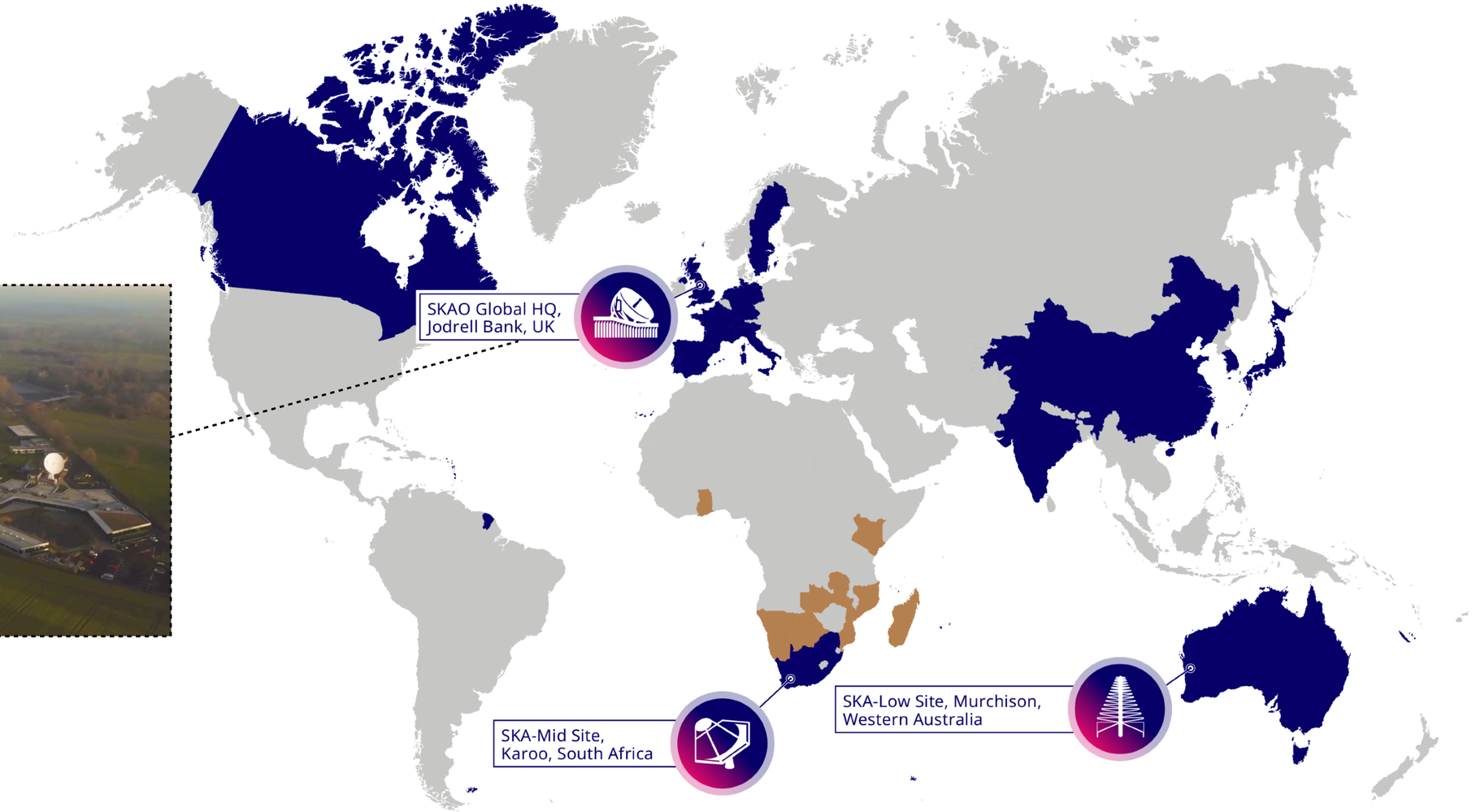
Used as single dish + VLBI networks



The Square Kilometer Array Observatory

SKAO membership map - June 2026





SKAO Partnership - includes SKAO Member States* and SKAO Observers (as of June 2026)

16

African Partner Countries

8

Credit: SKAO

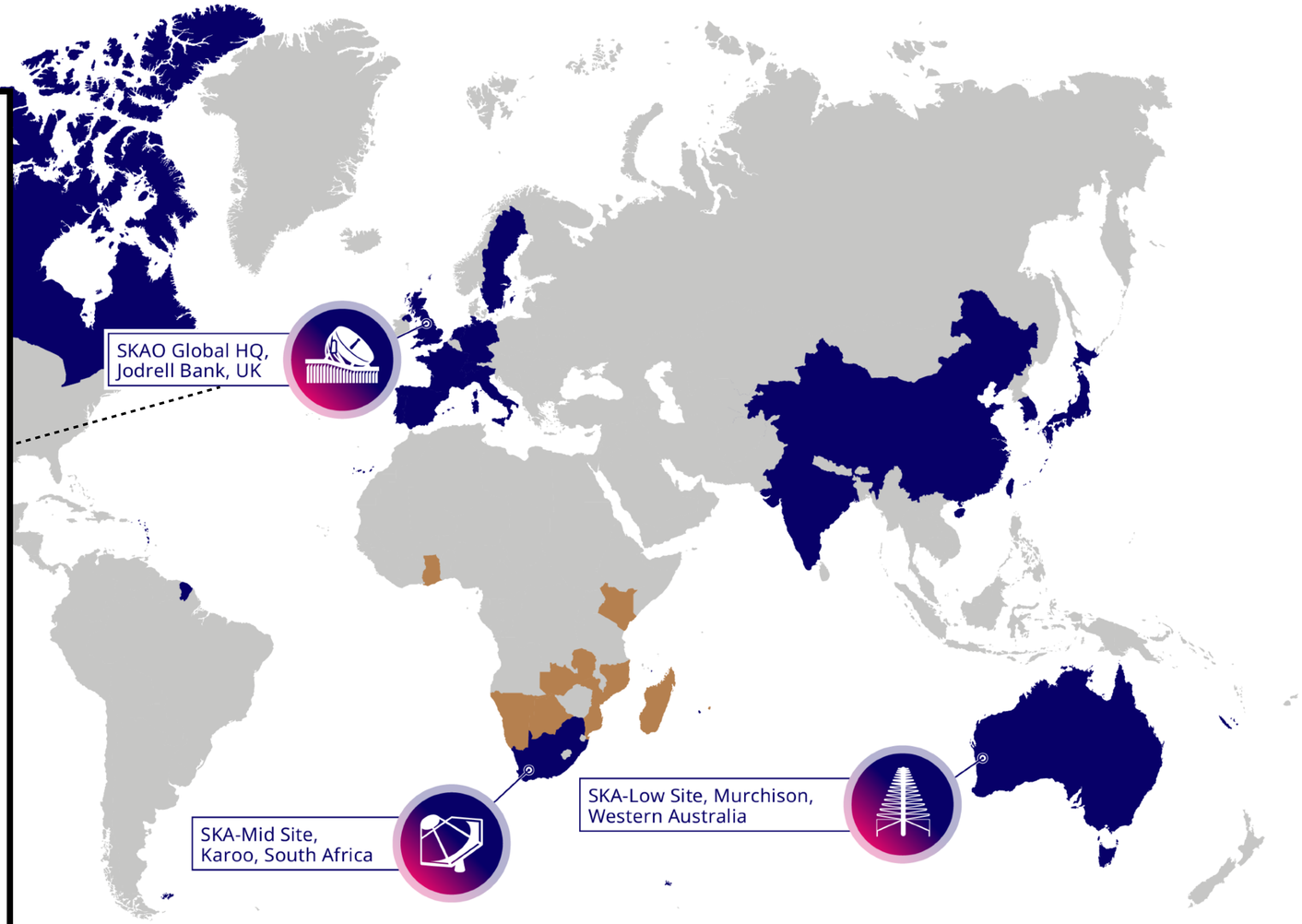
SKAO membership map - June 2026

Two **telescope sites** have been chosen due to their **radio quietness** (low radio frequency interference, RFI).

In South Africa, the SKA-Mid site is within the Karoo Central Astronomy Advantage Area.

In Western Australia, the SKA-Low site is within CSIRO's Murchison Radio-astronomy Observatory, on the traditional lands of the Wajarri Yamaji.

The recent boom in **satellite mega-constellations** poses additional challenges.



16

8

Credit: SKAO

A technological project (Hardware + software)



Credit: SKAO

Italian Leadership

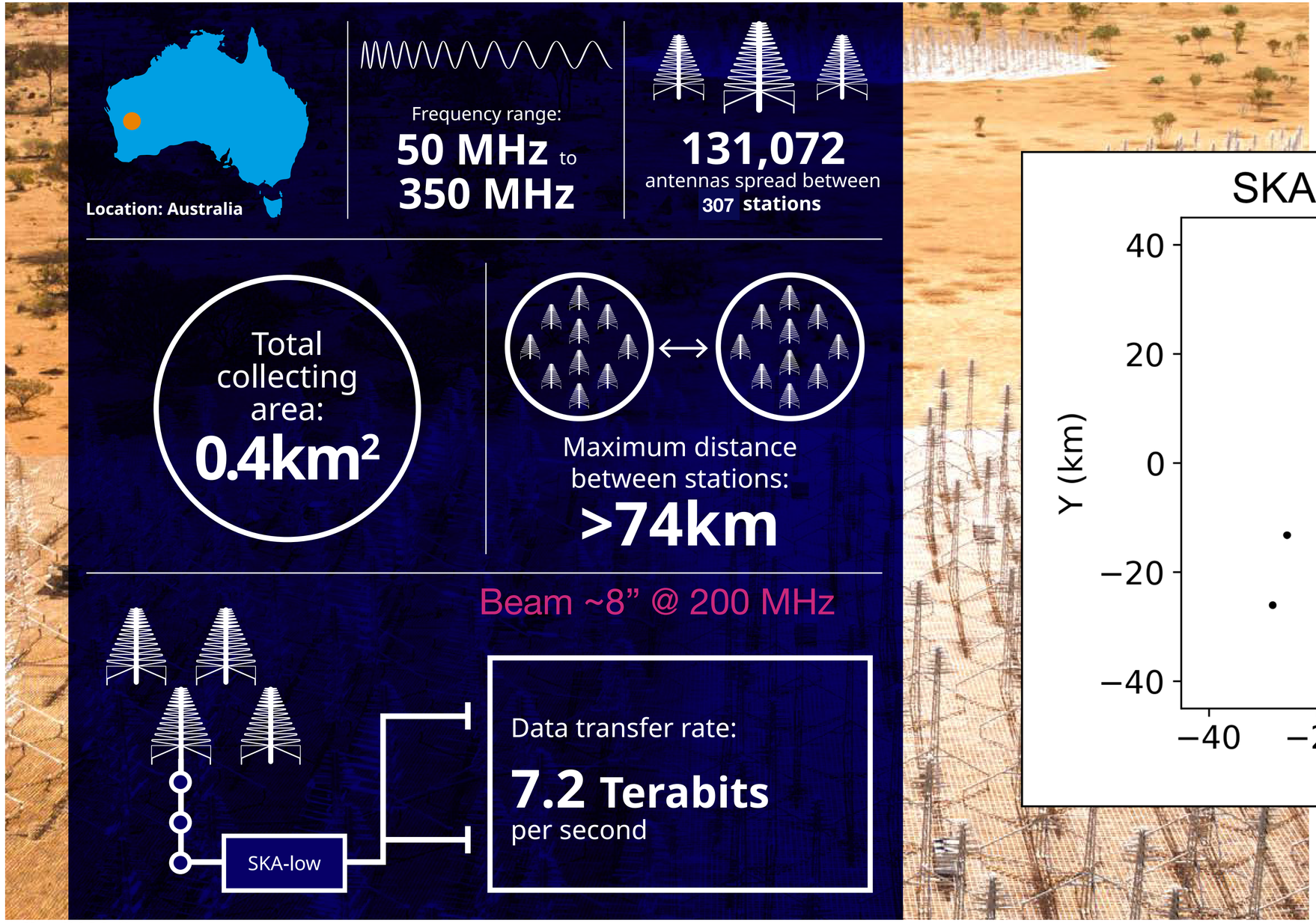
★Design of antennas, receivers & signal acquisition chain for SKA-Low

★ Observatory Monitoring and Control (OMC) Software for SKA-Mid

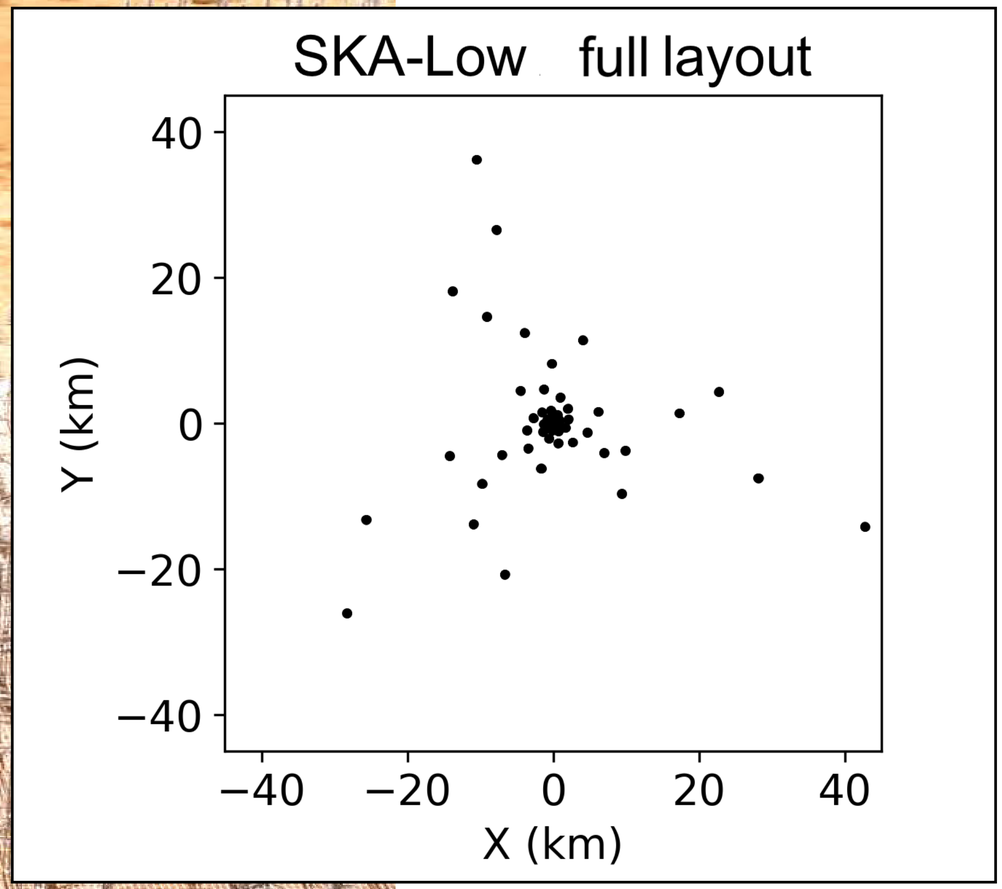
★ Development of software for pulsar search and timing

★ Development of phased array feed (PAF) receivers

SKA-low

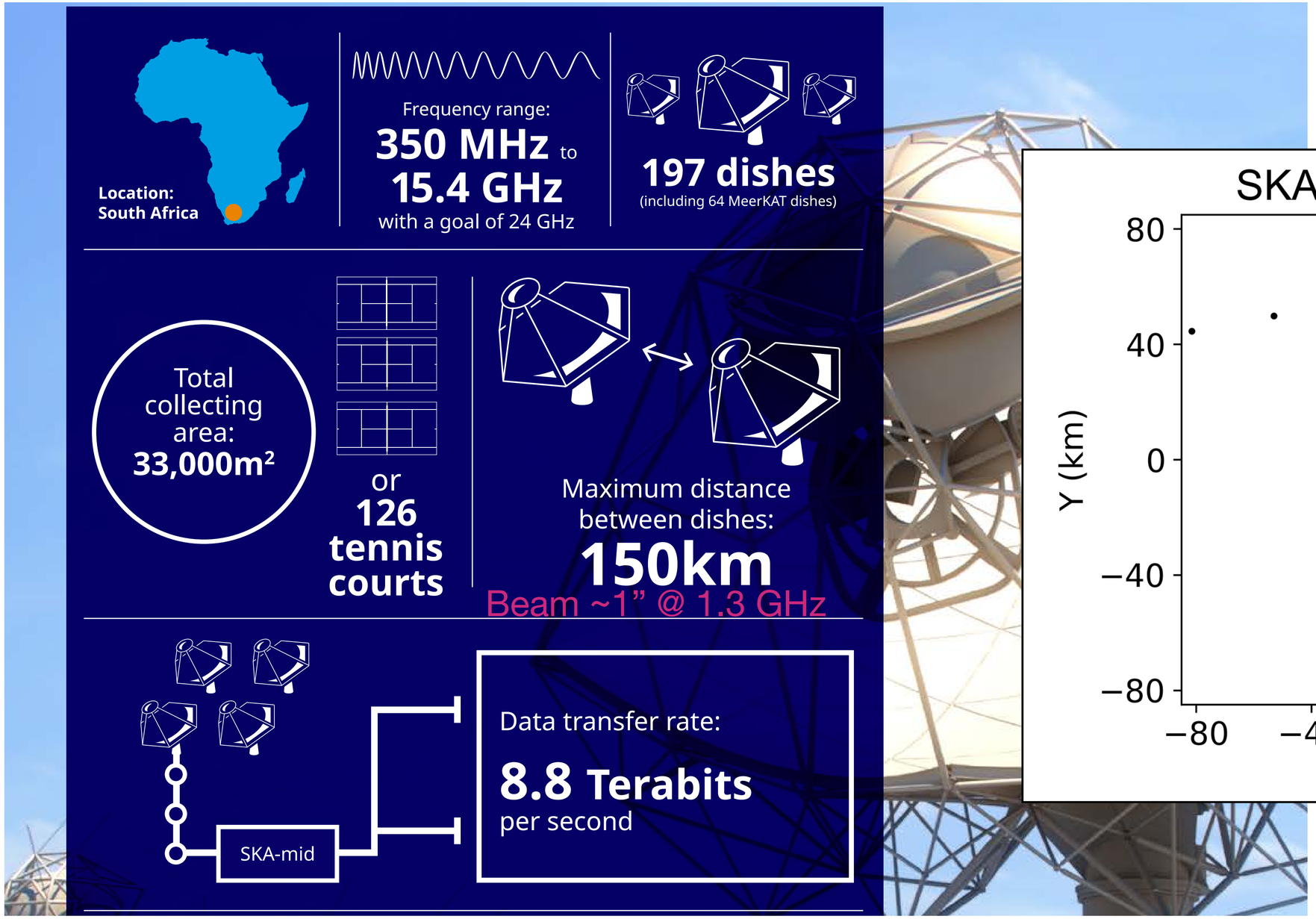


Large arms and dense core!

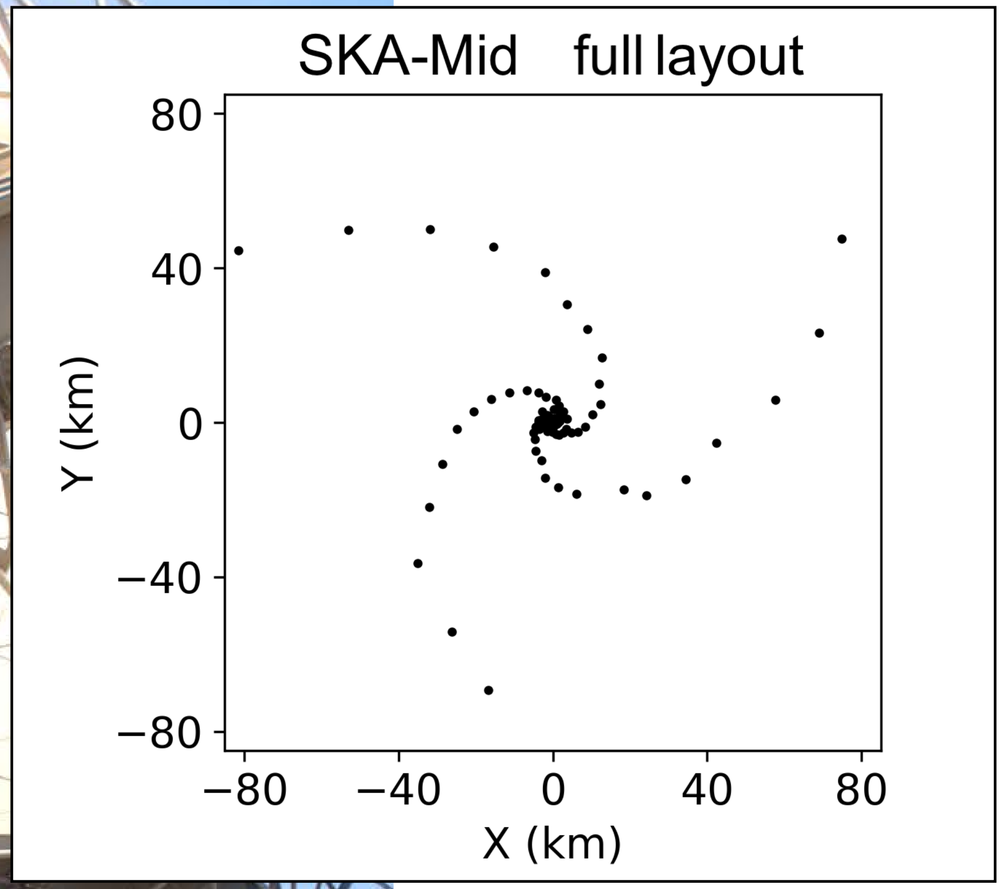


Credit: SKAO

SKA-mid



Large arms and dense core!



Credit: SKAO

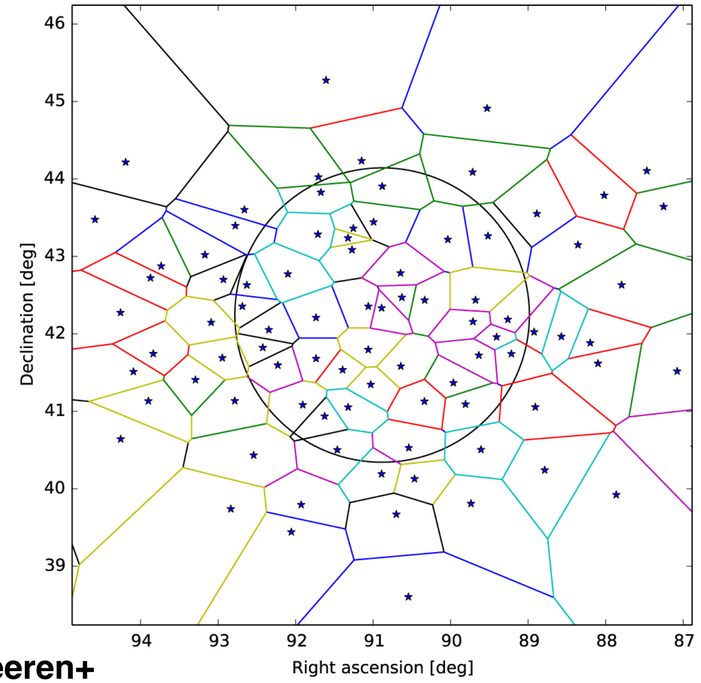
The era of Big Data…

- Broad bandwidth (hundreds of MHz to GHz)
- High spectral resolution (up to few kHz)
- Short integration times (0.1-1s)
- Large number of antennas
- Large fields of view

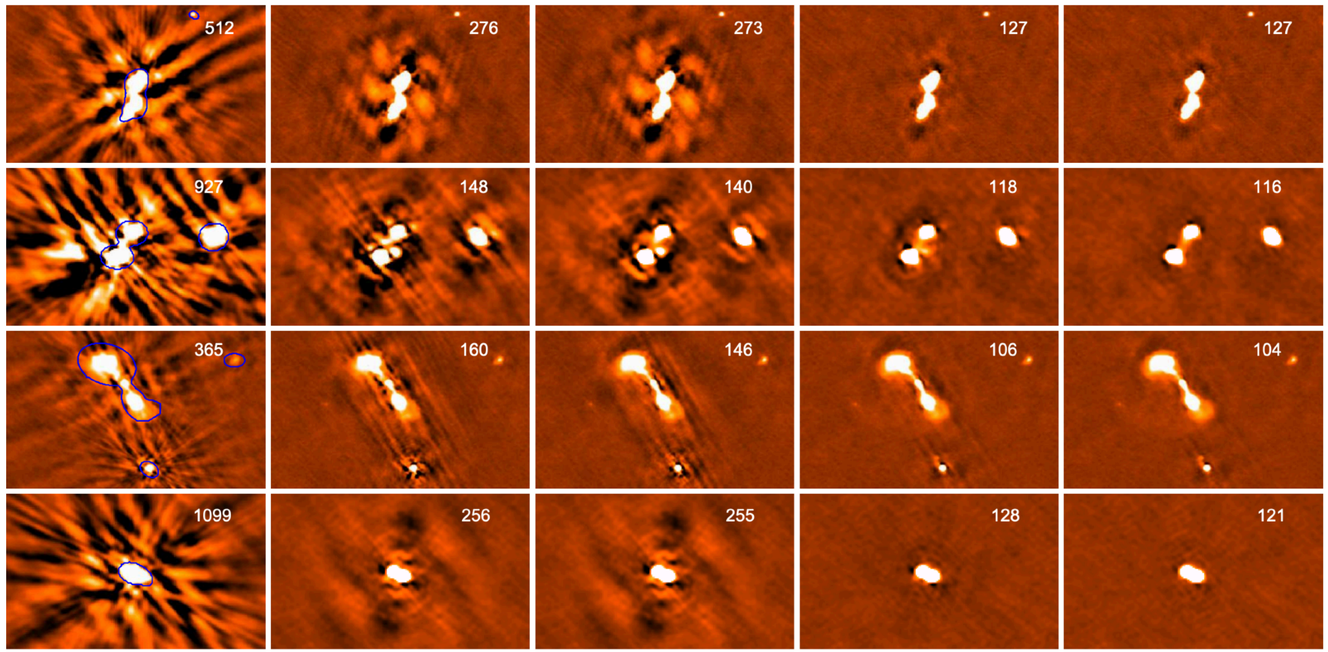
Processing + Archival challanges..

Wide field imaging challenges

- For wide fields of view (some degrees), the flat-sky approximation breaks down.
- Visibility calibration complex (amplitude and phase) -> The ionosphere, antenna beams and instrumental responses vary across the field, requiring direction-dependent calibration.



van Weeren+



Requires exascale, GPU-accelerated, data-parallel computing

The era of Big Data… guess who?

menti.com
1414 2600



Credit: SKAO

The era of Big Data… guess who?

menti.com
1414 2600

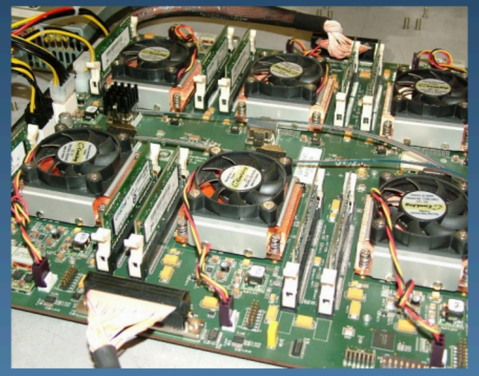


Credit: SKAO

Data flow and HPC

CSP: Central Signal Processor

Real-time channelisation, correlation, beamforming, and initial averaging



e.g. FPGAs in the ASKAP correlator

5 + 9 Tb/s data buffer of 2 minutes





5 Tb/s data buffer of 2 weeks

SDP: Science Data Processor



e.g. SDP prototype, Cambridge

300 PB/yr data persistence

Observatory automatic pipelines for RFI excision, calibration, wide-field imaging, continuum and spectral-line processing, quality assessment

SRC: SKA Regional Centre network

SRC

SRC

SRC

SRC

SRC

SKA portal

Distributed facilities

Calibrated data, images, catalogues are subsequently transferred to the SRC where users access value-added products, reprocessing tools, and scalable compute resources.



USERS

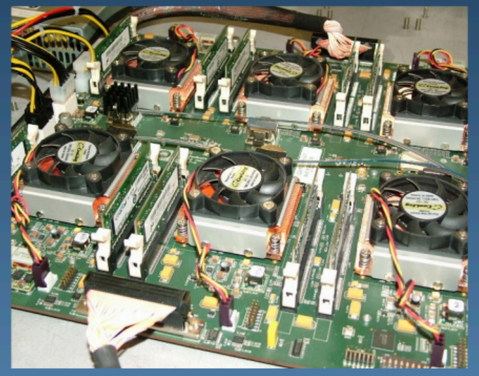
it SRC
SKAO Regional Centre Italy

Adapted from Philippa Hartley (SKAO) and Andrea Possenti (INAF)

Data flow and HPC

CSP: Central Signal Processor

Real-time channelisation, correlation, beamforming, and initial averaging



e.g. FPGAs in the ASKAP correlator

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e.g. SDP prototype, Cambridge

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5 + 9 Tb/s
data
buffer of
2 minutes





300 PB/yr
data persistence

SRC
SRC
SRC
SRC
SRC

SKA portal

Distributed facilities



USERS

Italy joined SRC Network in 2021 (ITSRC) in partnership with CINECA. Data archival and HPC resources at Tecnopolo in Bologna.

it | SRC
SKAO Regional Centre Italy

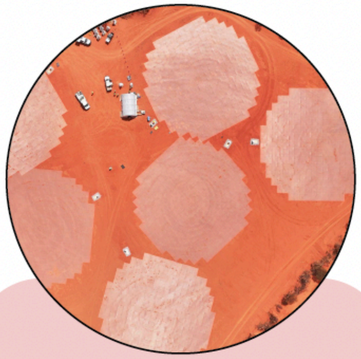
Adapted from Philippa Hartley (SKAO) and Andrea Possenti (INAF)

Timeline

SKAO milestones

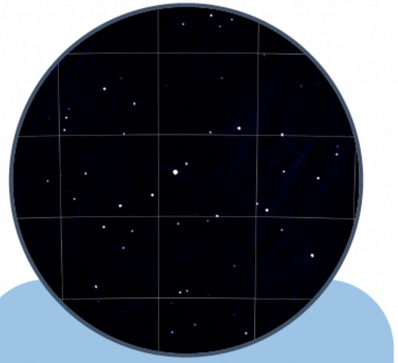
Community involvement starts

Credit: I. Heywood, SARAO



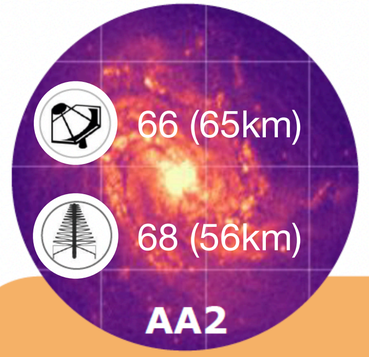
Construction

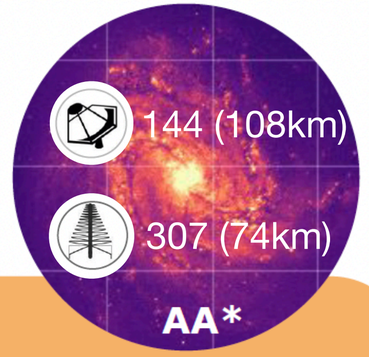
- Building antennas, dishes, roads etc!
- Followed by Assembly, Integration and Verification



Commissioning

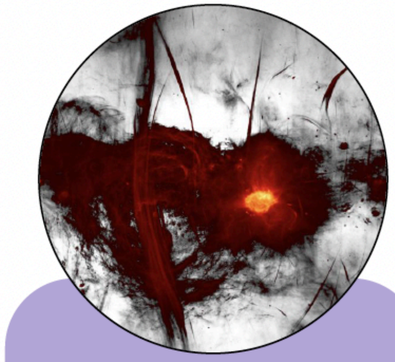
- SKAO activity
- Collaborative across system verification and science commissioning





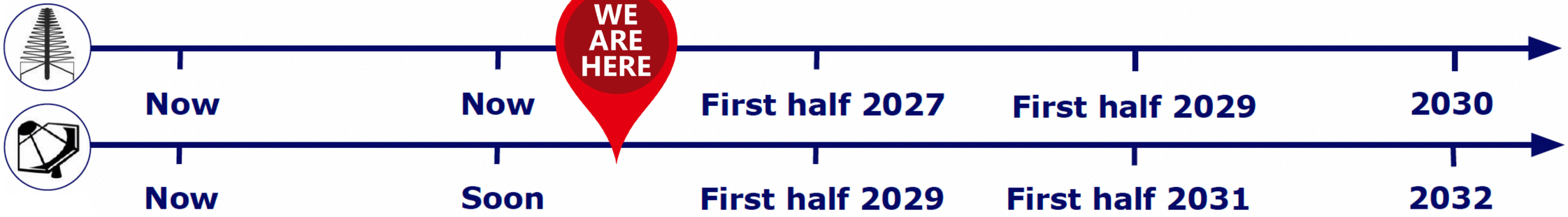
Science Verification

- A full dress rehearsal of the end-to-end system for every mode of operation
- Once modes and pipelines are working, the community can submit target ideas
- Data will be publicly available for scrutiny
- Build trust and fostering an early science return



Cycle 0

- Shared-risk PI projects
- SRCNet resources ready for user
- Proprietary periods



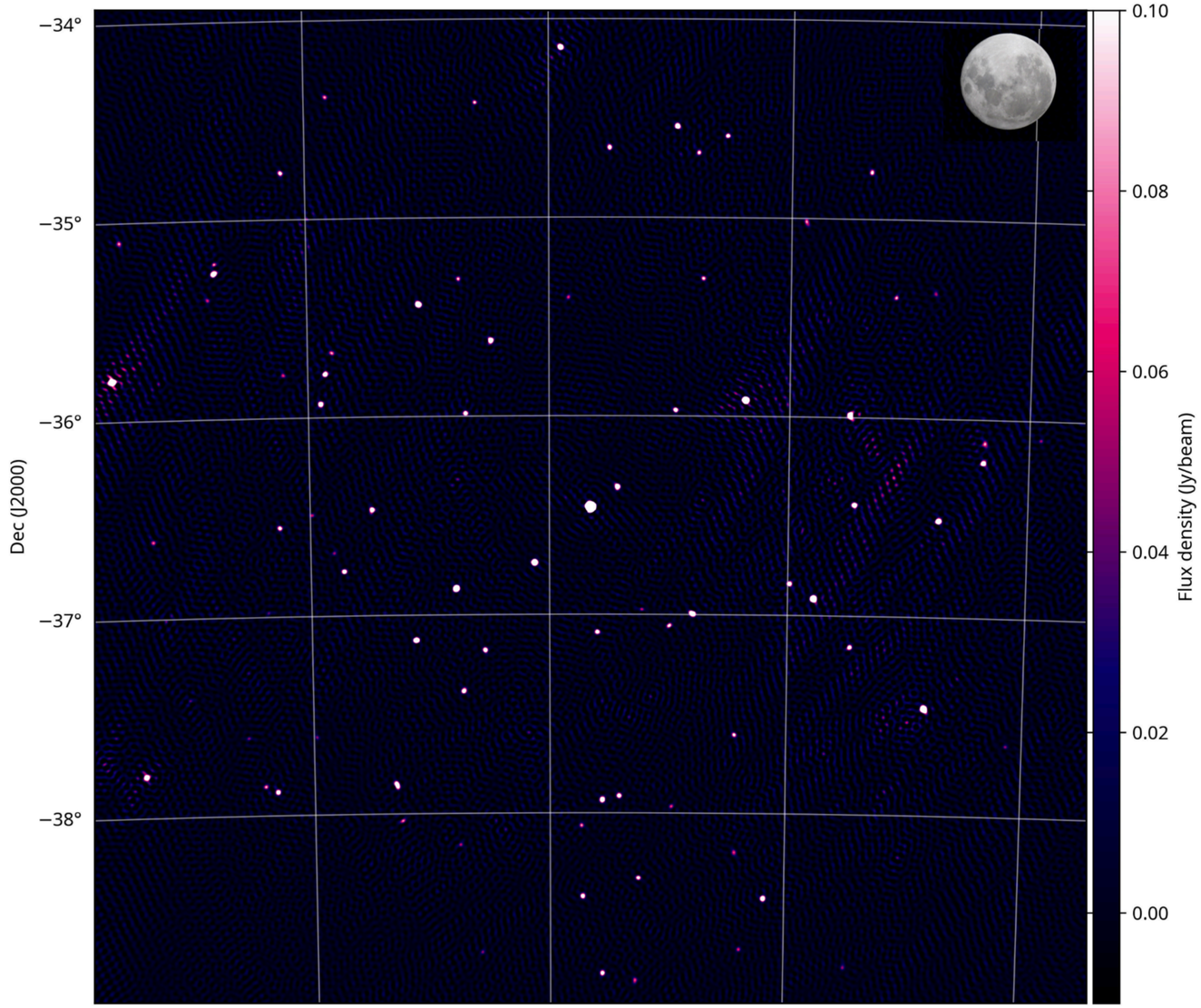
Credit: SKAO

The first SKA-Low AA0.5 image

March 2025

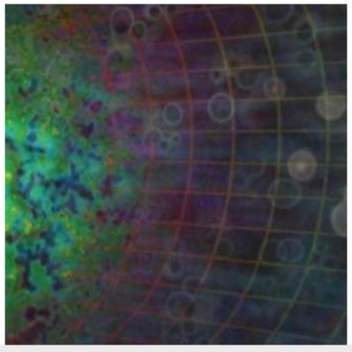
4 stations

- Field surrounding PKS 0521-36 (~56 Jy at 150 MHz)
- 150-175 MHz BW
- ~7h effective int.
- Image noise: ~5-6 mJy/beam at 70” final resolution
- 85 sources detected
- Very good match to GLEAM-X catalog (with mostly unguided self-cal!)



Credit: SKAO

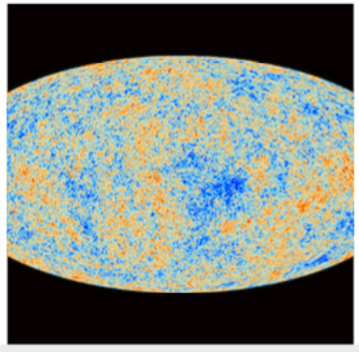
Science drivers



Cosmic Dawn and the epoch of reionisation

WHERE DID IT ALL BEGIN?

HOW AND WHEN DID THE FIRST STARS, GALAXIES AND BLACK HOLES FORM?



Cosmology and dark energy

CAN WE UNCOVER THE MYSTERIOUS NATURE OF DARK ENERGY?

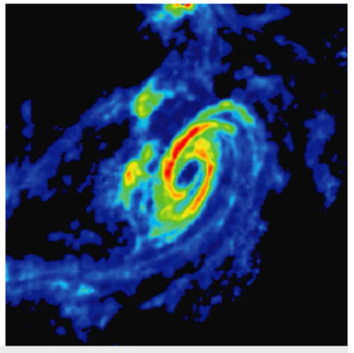
HOW AND WHY HAS IT BECOME THE MAJOR PLAYER IN OUR UNIVERSE?



Forming stars through cosmic time

HOW AND WHEN WERE THE FIRST STARS BORN?

HOW HAS THE RATE OF STAR FORMATION CHANGED OVER TIME, AND WHY?

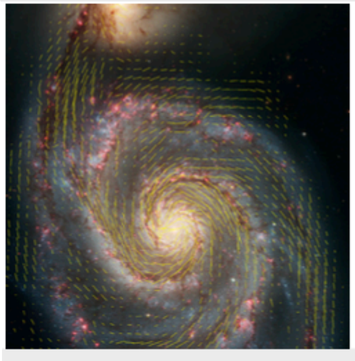


Galaxy evolution

WHAT IS THE LIFE-CYCLE OF A GALAXY?

WHERE DO THEY COME FROM, WHERE DO THEY GO?

WHAT ARE THE PROPERTIES OF THE MYSTERIOUS DARK ENERGY?

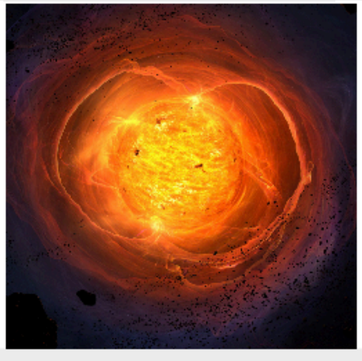


Cosmic magnetism

HOW DID THE UNIVERSE BECOME MAGNETIC?

WHERE AND WHEN DID MAGNETISM ORIGINATE?

HOW HAS IT EVOLVED?



The bursting sky

WHAT ARE THE COUNTERPARTS OF THE FAST AND FURIOUS BURSTS OF RADIO WAVES?

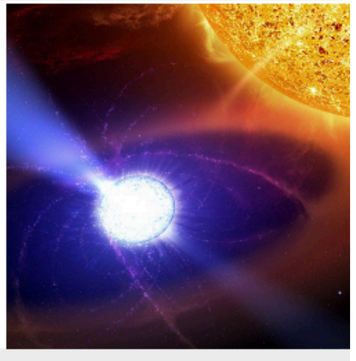
WHAT CAN THEY TELL US ABOUT THE CONSTITUENTS OF THE UNIVERSE?



The cradle of life

HOW DO YOU MAKE A PLANET FROM SPACE PEBBLES?

ARE WE ALONE IN THE UNIVERSE?



Challenging Einstein: gravitational waves

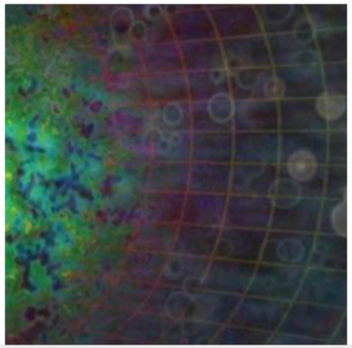
WAS EINSTEIN RIGHT ABOUT GRAVITY?

CAN WE FIND AND UNDERSTAND WHERE GRAVITATIONAL WAVES COME FROM?

Credit: SKAO

Credit: SKAO

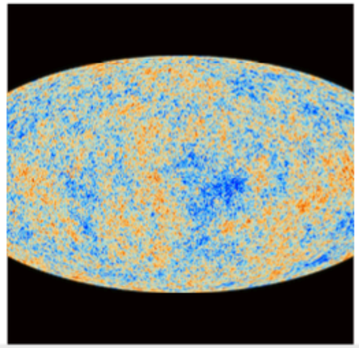
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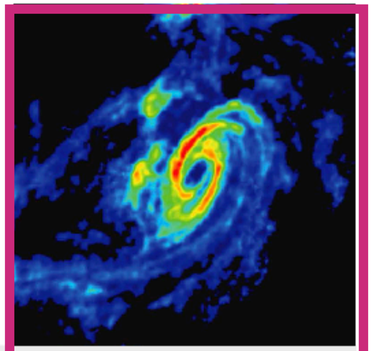
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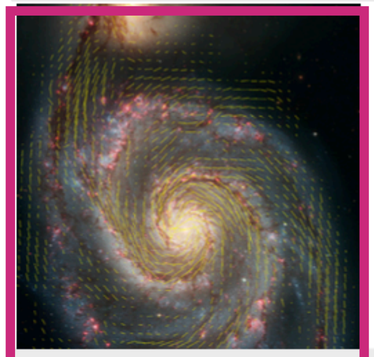


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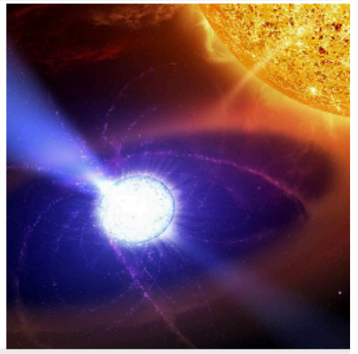
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Challenging Einstein: gravitational waves

WAS EINSTEIN RIGHT ABOUT GRAVITY?

CAN WE FIND AND UNDERSTAND WHERE GRAVITATIONAL WAVES COME FROM?

Credit: SKAO

AGN, CLUSTERS, COSMIC WEB & MAGNETIC FIELDS with SKA

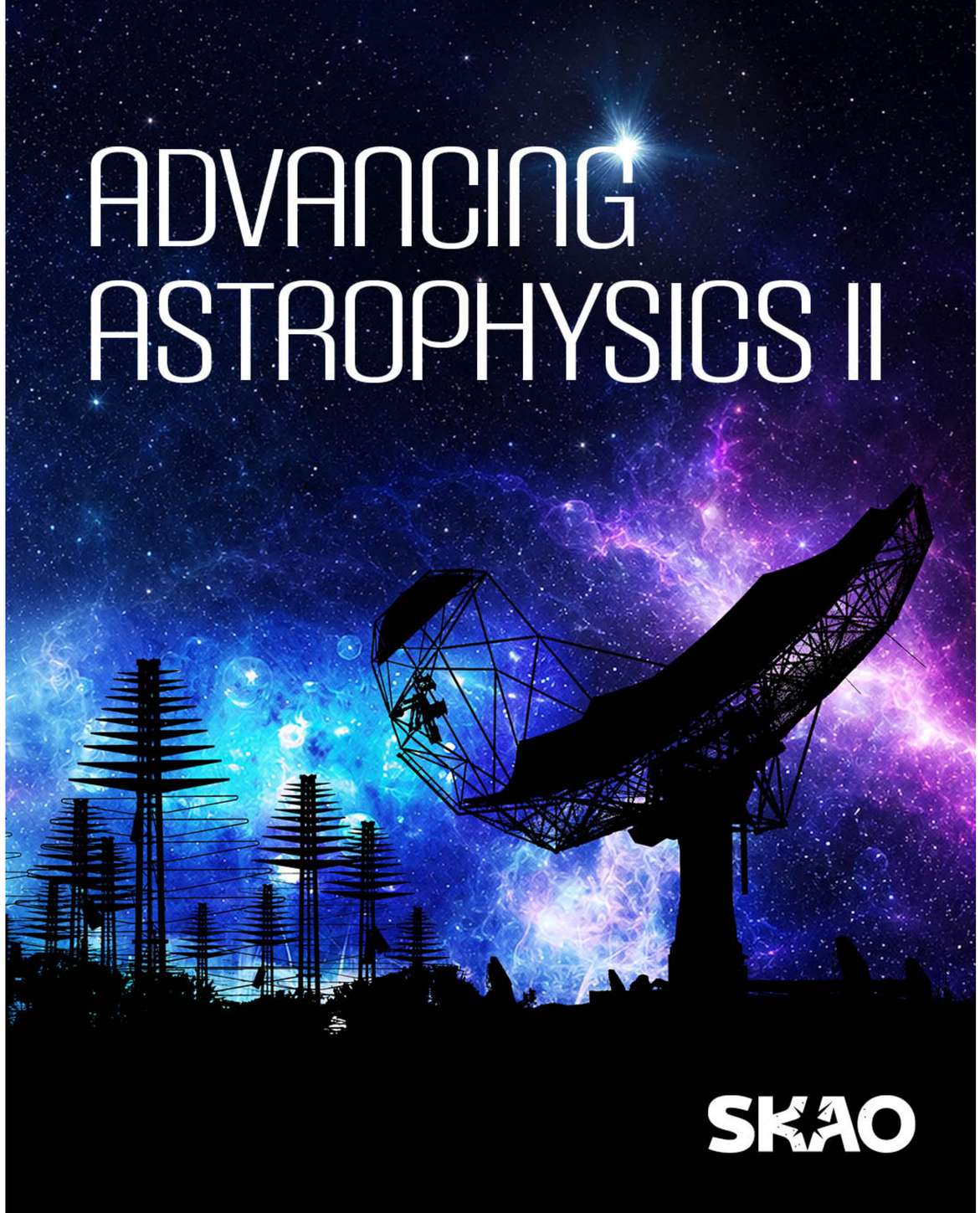
Synchrotron emission

✳ Sensitivity & sensitivity to various spatial scales (rich uv-coverage)
-> Morphology at different scales, from AGN nuclear regions up to diffuse emission on scales of the cosmic web
-> Magnetic field characterisation within individual sources, also fainter emission and substructures (e.g. filaments)

✳ Many bands with consistent uv coverage -> Broad band spectral analysis (resolved) = study particle (re-)acceleration and ageing

✳ Large field of view and fast survey speed -> large samples to test models, population studies, also at higher redshift
-> Dectability of large number of polarised sources (e.g. for RM studies)

✳ High spectral resolution -> higher precision on measurements of Faraday rotation and improved constraints on complex Faraday structures through RM synthesis

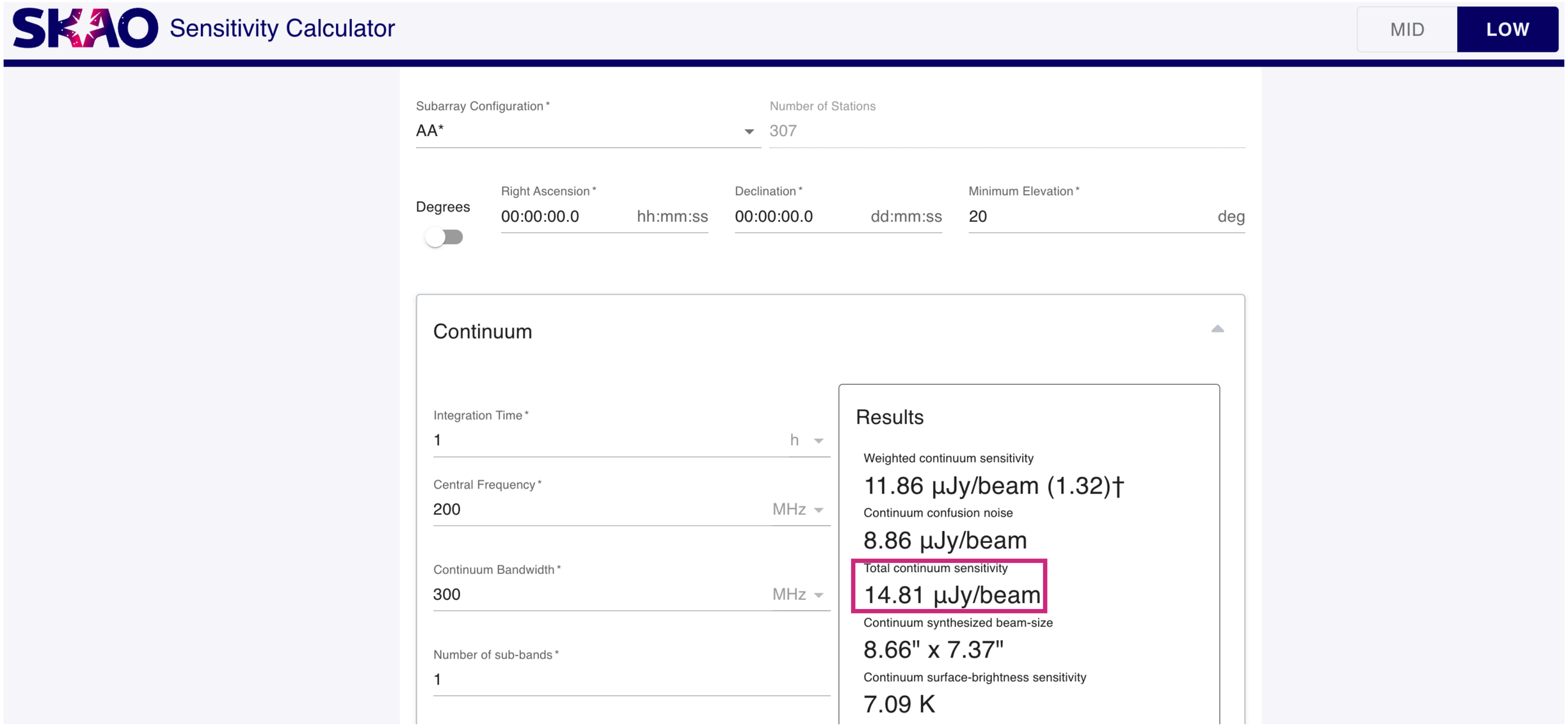


SKA White book 2026..

221 chapters

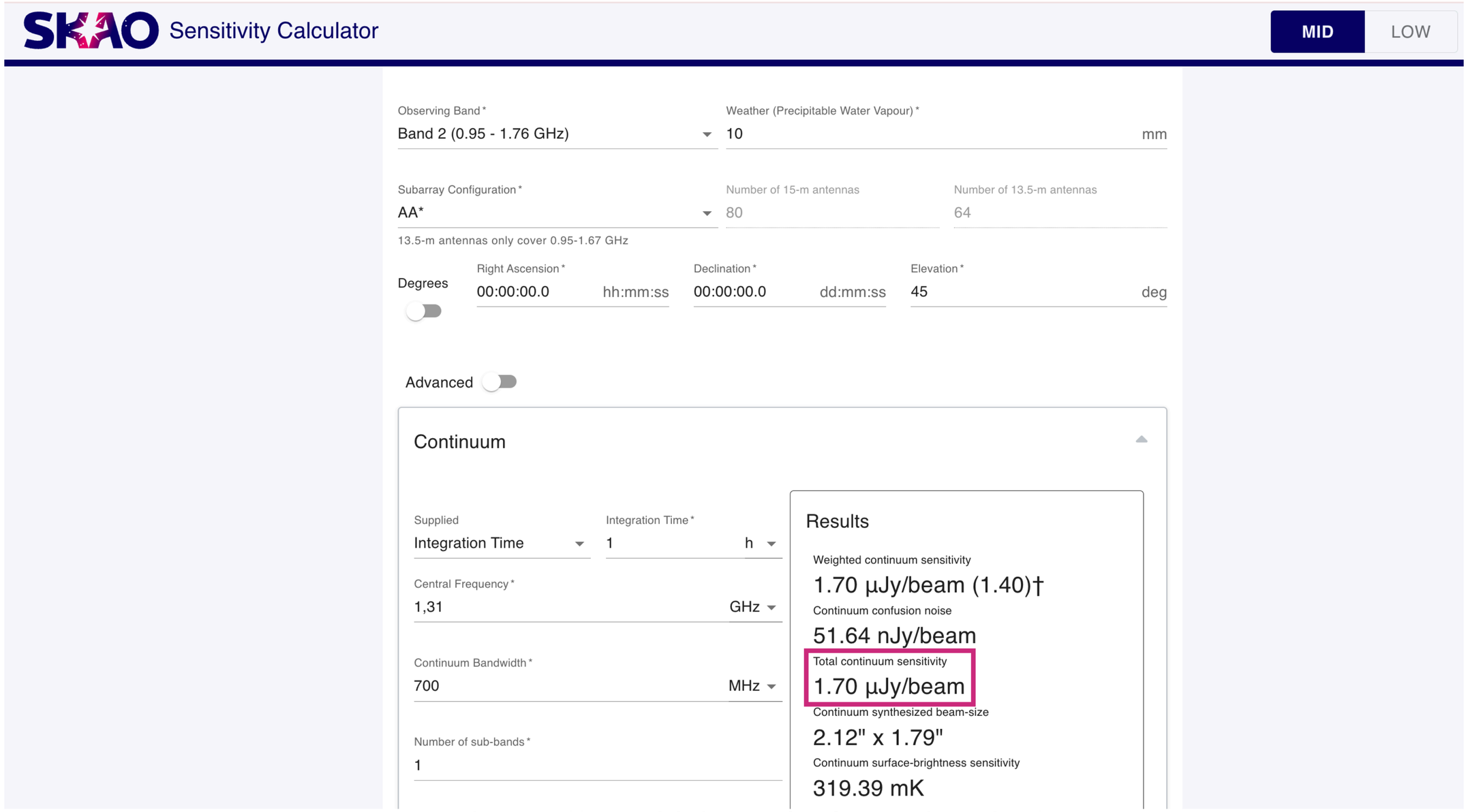
check out for many
science cases!

SKA Tools



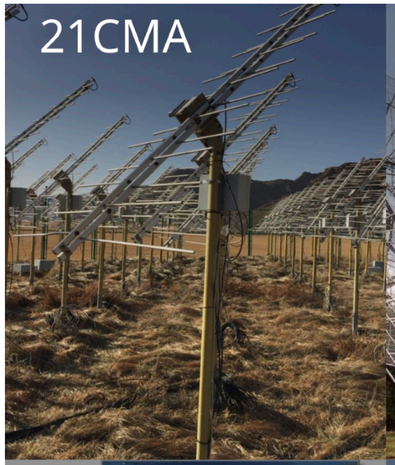
https://sensitivity-calculator.skao.int/

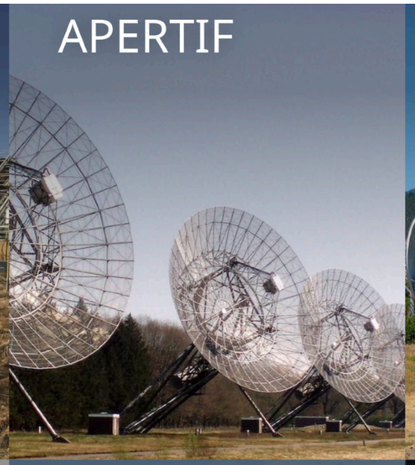
SKA Tools



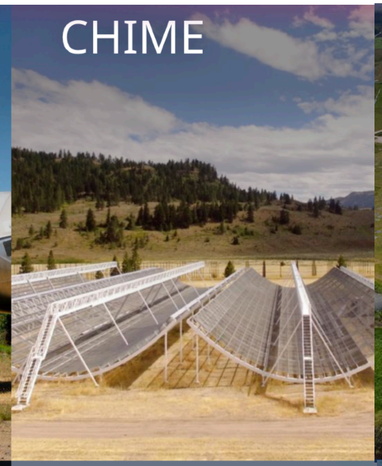
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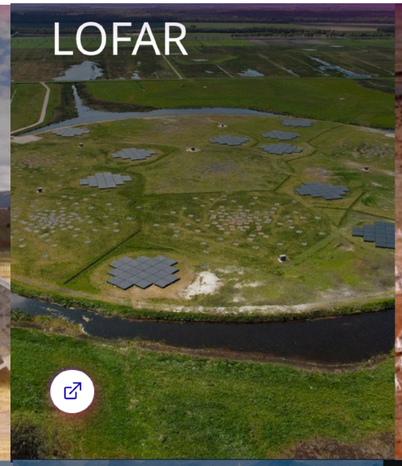
Waiting for the SKA … PRECURSORS



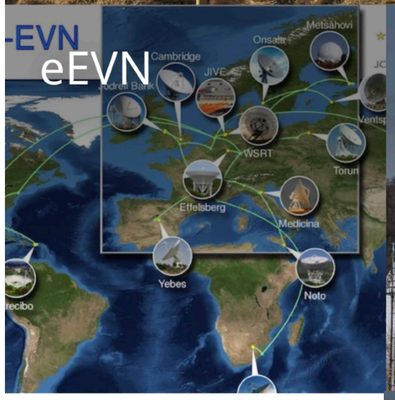








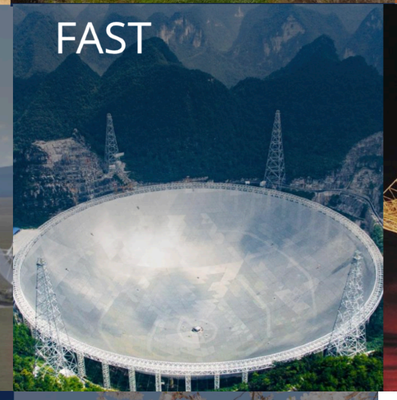




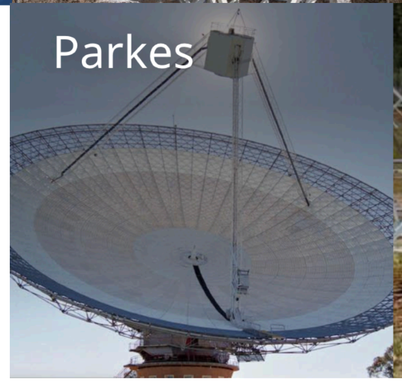


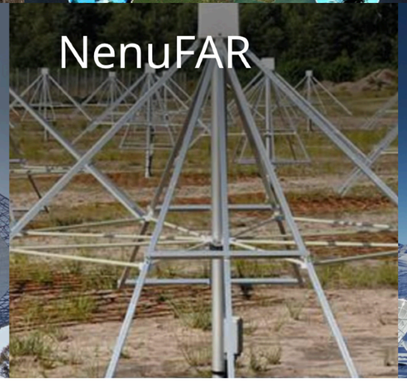


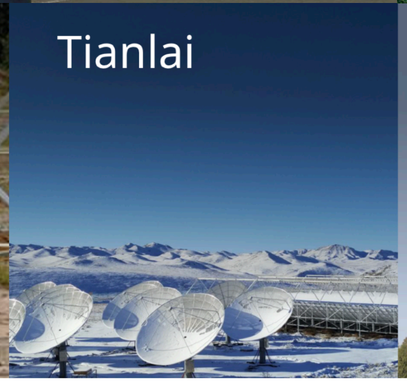














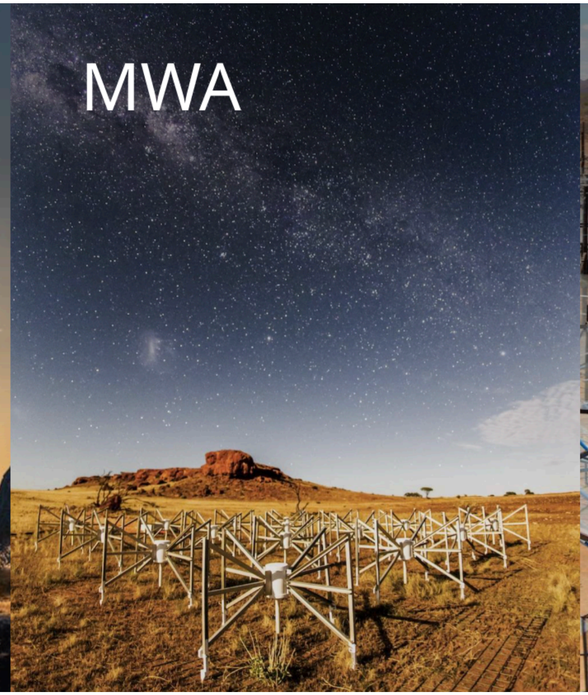
Waiting for the SKA … PATHFINDERS



Australia



South Africa



Australia



South Africa

Already facing technical challenges and science transformative!

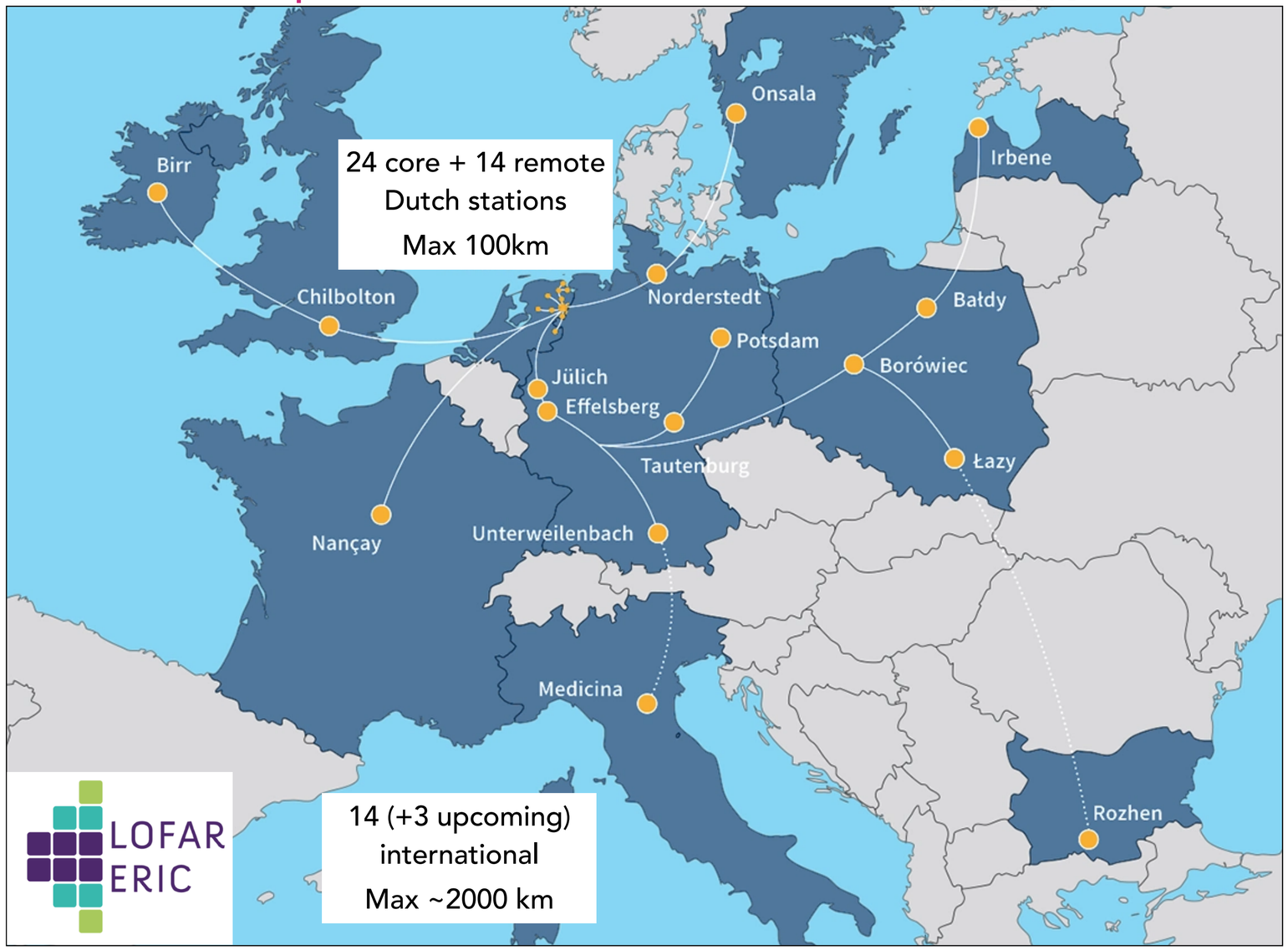
van Haarlem+2013

LOFAR

11 Countries (NL, D, Pl, It, Ir, UK, F, Sw, Bul, Latvia, Czech)

Since 2018

SKA-low pathfinder

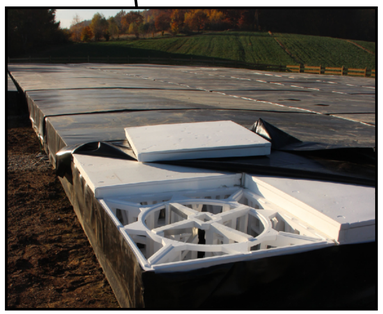




Low-band
antennas
10-90 MHz



Digital
aperture
array



High-band
antennas
120-200 MHz

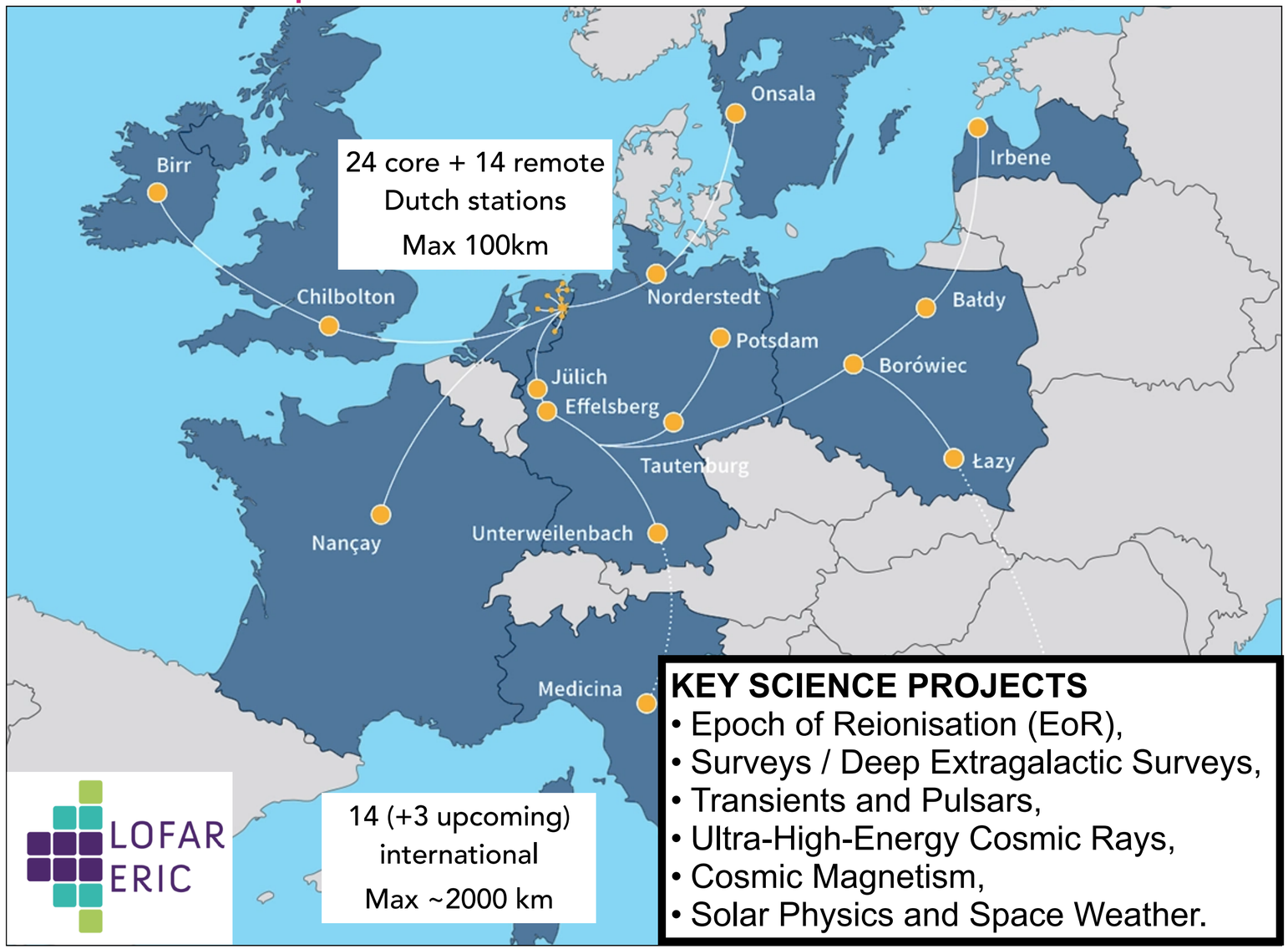
van Haarlem+2013

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KEY SCIENCE PROJECTS

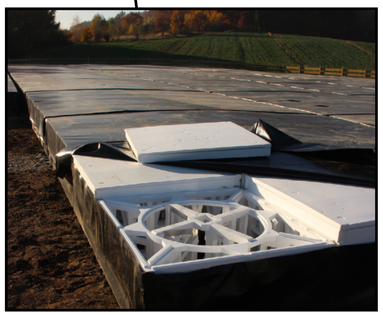
- Epoch of Reionisation (EoR),
- Surveys / Deep Extragalactic Surveys,
- Transients and Pulsars,
- Ultra-High-Energy Cosmic Rays,
- Cosmic Magnetism,
- Solar Physics and Space Weather.



Low-band antennas 10-90 MHz

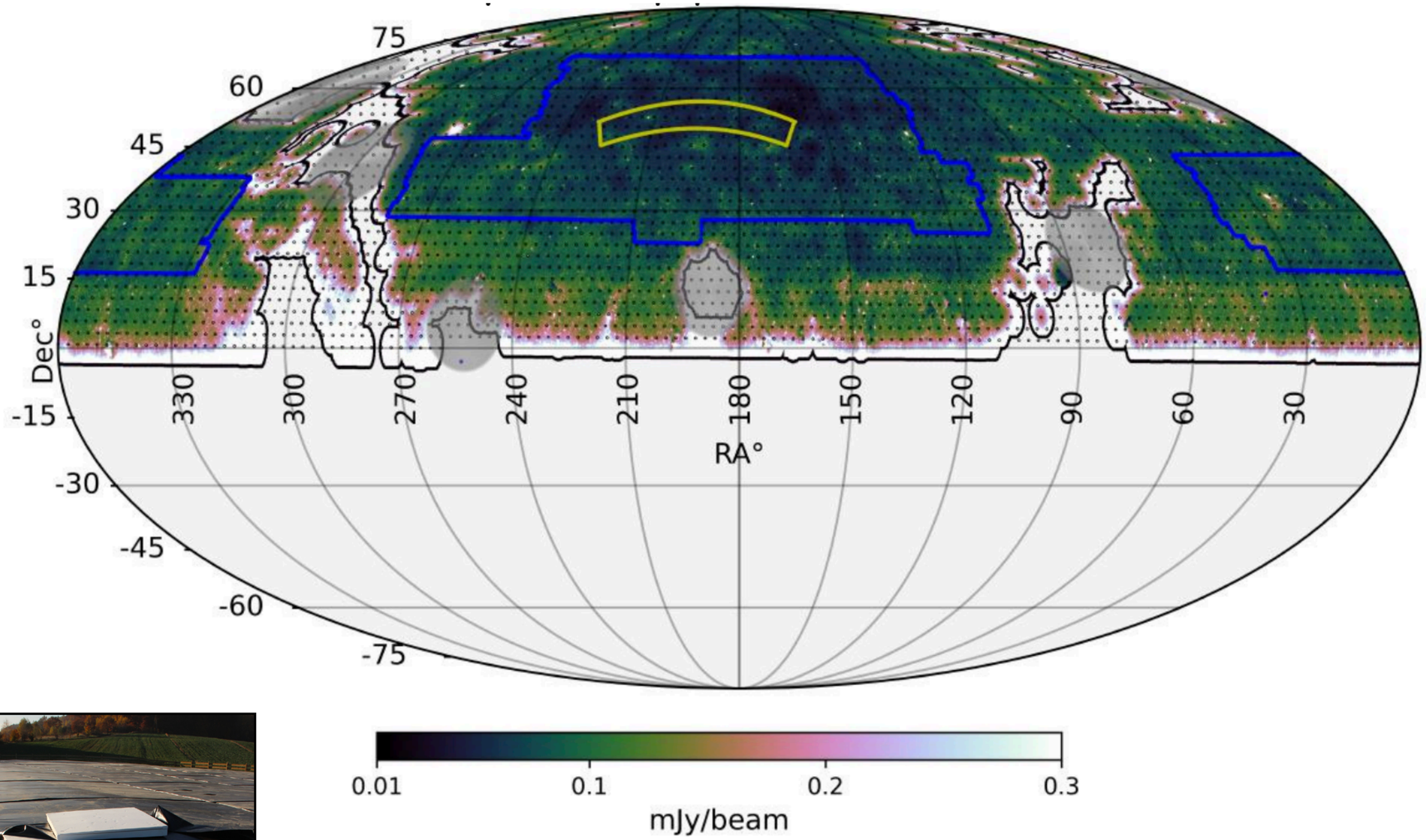


Digital aperture array

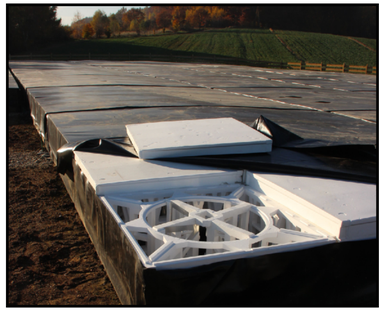


High-band antennas 120-200 MHz

LOFAR Two Meter Sky Survey (LoTSS) DR3 (Shimwell+2025)



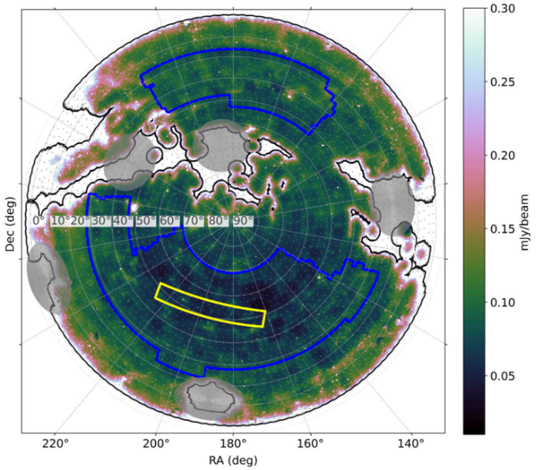
- 88% of the northern sky
- 2913 pointings
- 144 MHz continuum mosaic
- Only Dutch stations = 6″ beam
  (9″ below DEC 10deg)
- median RMS = 92 μJy/beam
- 14million sources
- 12,950 hrs of data over 10.5 years
- 18.6 PB
- 20 million core hours of processing



LOFAR SURVEYS

DR3: public data release

In this data release from the LOw-Frequency ARray (LOFAR) Two-metre Sky Survey (LoTSS) we present 120-168 MHz images covering 88% of the northern sky. The individual pointing images (at 6" and 20" resolution) were derived from 12,950 hrs (18.6 PB) of LOFAR High Band Antenna data which were processed through fully automated direction-independent and direction-dependent calibration pipelines that correct for instrumental effects as well as spatially and temporally varying ionospheric distortions. The Stokes I images were then combined, accounting for the rms noise level and telescope beam, to form the final Stokes I mosaic images at 6" and 20" resolution, with a central frequency of 144 MHz. From the 6" resolution Stokes mosaics we derived a catalogue of 13,664,379 radio sources (consisting of 16,943,656 Gaussian components), the majority of which have never been detected at radio wavelengths before. The 6" resolution mosaics have a median rms sensitivity of 92 μJy/beam; a random and systematic flux density scale accuracy of approximately 6% and 2%, respectively; an astrometric accuracy of 0.24"; and we estimate that we detect more than 95% of sources with integrated flux densities exceeding nine times the local root mean square noise. Below we provide access to the catalogues and all Stokes I 6" and 20" resolution mosaic products. The individual pointing products, including calibrated uv data (measurement sets and direction-dependent calibration solutions) to allow for re-imaging or post-processing; Stokes I images at 6" and 20" resolution (with associated scaling factors required to reproduce the mosaic images); Stokes V images at 6" resolution for each observing epoch; and Stokes Q and U image cubes at 20" and 4' resolution are available upon request (please e-mail lotss-dr3-infrastructure@strw.leidenuniv.nl).



LoTSS-DR3 is described in detail by Shimwell et al., 2026. Please cite the survey paper and any other relevant LoTSS description paper and give the acknowledgements listed on our credits pages if using these images for science.

Data repository

- The full DR3 data repository (including calibrated visibilities) is available at ASTRON.

Source catalogue

PyBDSF source and Gaussian catalogues are available. v1.0 is the catalogue released with and described by the DR3 paper. Updated versions will be released as necessary.

- Version 1.0 source catalogue and Gaussian catalogue.

Interactive images

HIPS images of the 6" or 9" high-resolution mosaics and the 20" low-resolution mosaics can be viewed at https://lofar-surveys.org/public_hips/LoTSS_high_hips_latest/ and https://lofar-surveys.org/public_hips/LoTSS_low_hips_latest/ respectively. These links can be viewed in the web browser or, for best results, in the Aladin app.

Raw fields

For the raw (pre-mosaic) images see the dedicated page. We do not recommend using these images unless you are interested in features that cannot be studied in the mosaics, such as source variability.

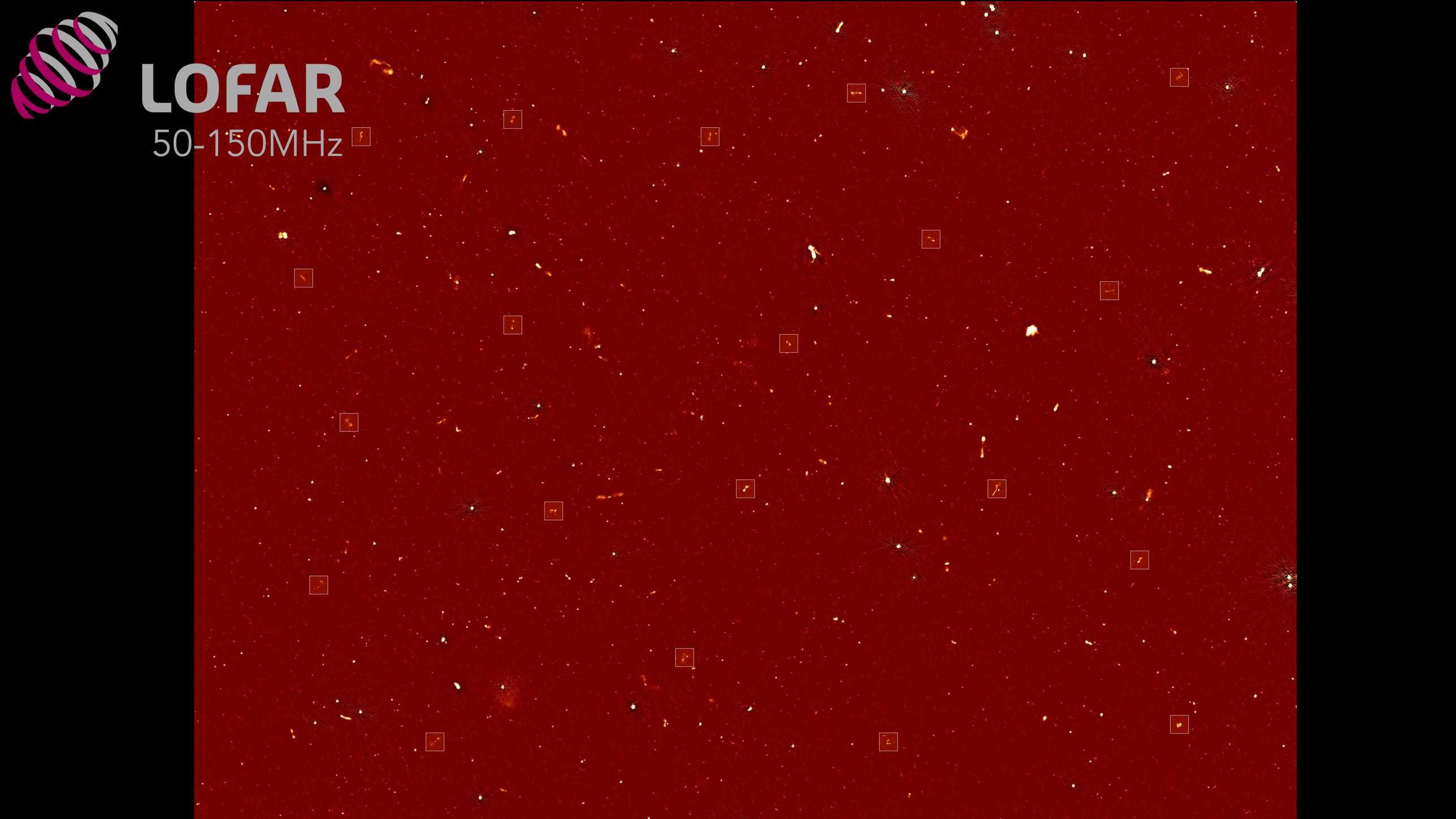
Mosaic position search

Enter object name or position to search for the nearest mosaics: Submit

Mosaic cutout service

- Enter object name or position and size in arcmin for cutout: size = 30 arcmin Submit
- Or see details of the API for scriptable downloads

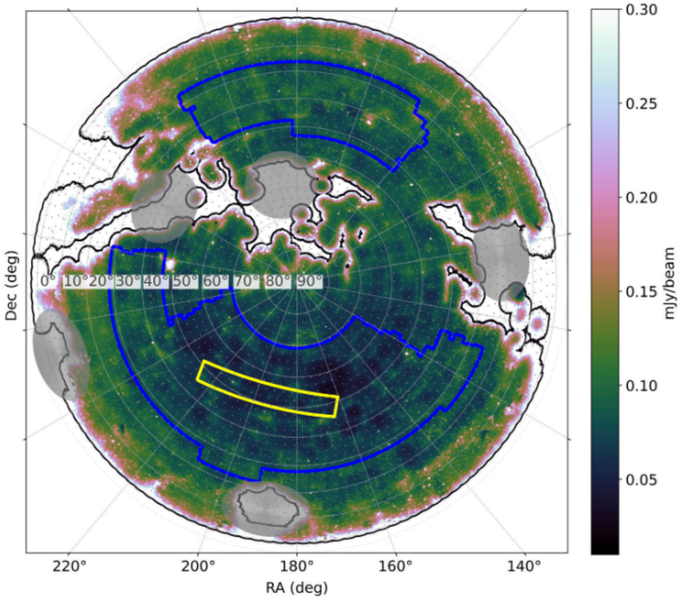
https://lofar-surveys.org/dr3.html


LOFAR
50-150MHz

LoTSS Data Release 2 (DR2)

In this data release from the ongoing LOw-Frequency ARray (LOFAR) Two-metre Sky Survey (LoTSS) we present 120-168 MHz images covering 27% of the northern sky. Our coverage is split into two regions centred at approximately 12h45m +44○30' and 1h00m +28○ 00' and spanning 4178 and 1457 square degrees respectively. The images were derived from 3,451 hrs (7.6 PB) of LOFAR High Band Antenna data which were corrected for the direction-independent instrumental properties as well as direction-dependent ionospheric distortions during extensive, but fully automated, data processing. A catalogue of 4,396,228 radio sources is derived from our total intensity (Stokes I) maps, where the majority of these have never been detected at radio wavelengths before. At 6" resolution, our full bandwidth Stokes I continuum maps with a central frequency of 144 MHz have: a median rms sensitivity of 83 μ Jy/beam; a flux density scale accuracy of approximately 10%; an astrometric accuracy of 0.2"; and we estimate the point-source completeness to be 90% at a peak brightness of 0.8 mJy/beam. By creating three 16 MHz bandwidth images across the band we are able to measure the in-band spectral index of many sources, albeit with an error on the derived spectral index of > ±0.2 which is a consequence of our flux-density scale accuracy and small fractional bandwidth. Our circular polarisation (Stokes V) 20" resolution 120-168 MHz continuum images have a median rms sensitivity of 95 μ Jy/beam, and we estimate a Stokes I to Stokes V leakage of 0.056%. Our linear polarisation (Stokes Q and Stokes U) image cubes consist of 480 97.6 kHz wide planes and have a median rms sensitivity per plane of 10.8mJy/beam at 4' and 2.2mJy/beam at 20"; we estimate the Stokes I to Stokes Q/U leakage to be approximately 0.2%. Here we publicly release our Stokes I, Q, U and V images in addition to the calibrated uv-data to facilitate the thorough scientific exploitation of this unique dataset.

The data are described by Shimwell et al (2022). Below we provide links to various ways to access the data and catalogues. Please cite the survey paper and any other relevant paper and give the acknowledgements listed on our credits pages if using these images for science.



Main repository and Virtual Observatory resources

- The main DR2 image and uv data repository
- ASTRON VO Mosaic image search
- ASTRON VO Source catalogue search
- ASTRON VO Gaussian catalogue search

HIPS previewer

- High-resolution preview (view in the Aladin app or in a web browser)
- Low-resolution preview (20 arcsec)

Radio catalogues

- Non-redundant source catalogue v1.1 (with source mask information)
- Non-redundant Gaussian catalogue v1.1

Radio-optical crossmatch catalogue

The catalogues in this section are described by Hardcastle et al (2023; A&A 678 151). The v1.2 catalogue is identical to the v1.1 catalogue but contains redshifts from the fi

- Value-added source catalogue v1.2 and README file
- Value-added source catalogue v1.1 and README file
- Component catalogue v1.1 and README file
- Zooniverse tags dictionary

Spectroscopic classifications

The spectroscopic classifications for DR2 are described by Drake et al. (2024) and Arnaudova et al. (2026). Currently available for download are:

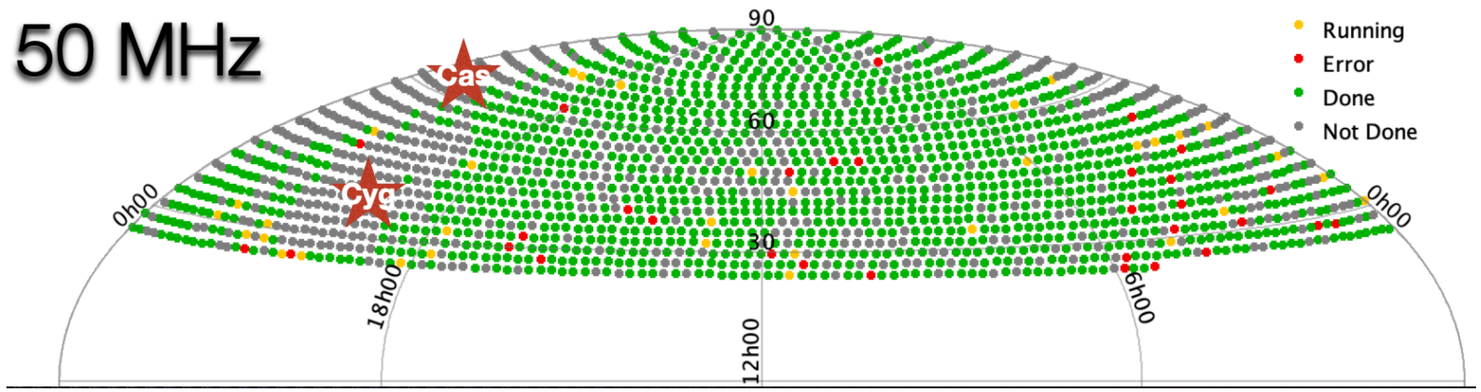
- Drake et al Classification catalogue v1.2 and README v1.2
- Arnaudova et al Classification catalogue v1.0 and README v1.0
- Arnaudova et al spectral stacks for HERGs, LERGs, radio-excess sources that cannot be classified at high probability, and all radio-excess sources, and README file

AGN selection

AGN selection for DR2 was carried out by Hardcastle et al (2025). You can currently download:

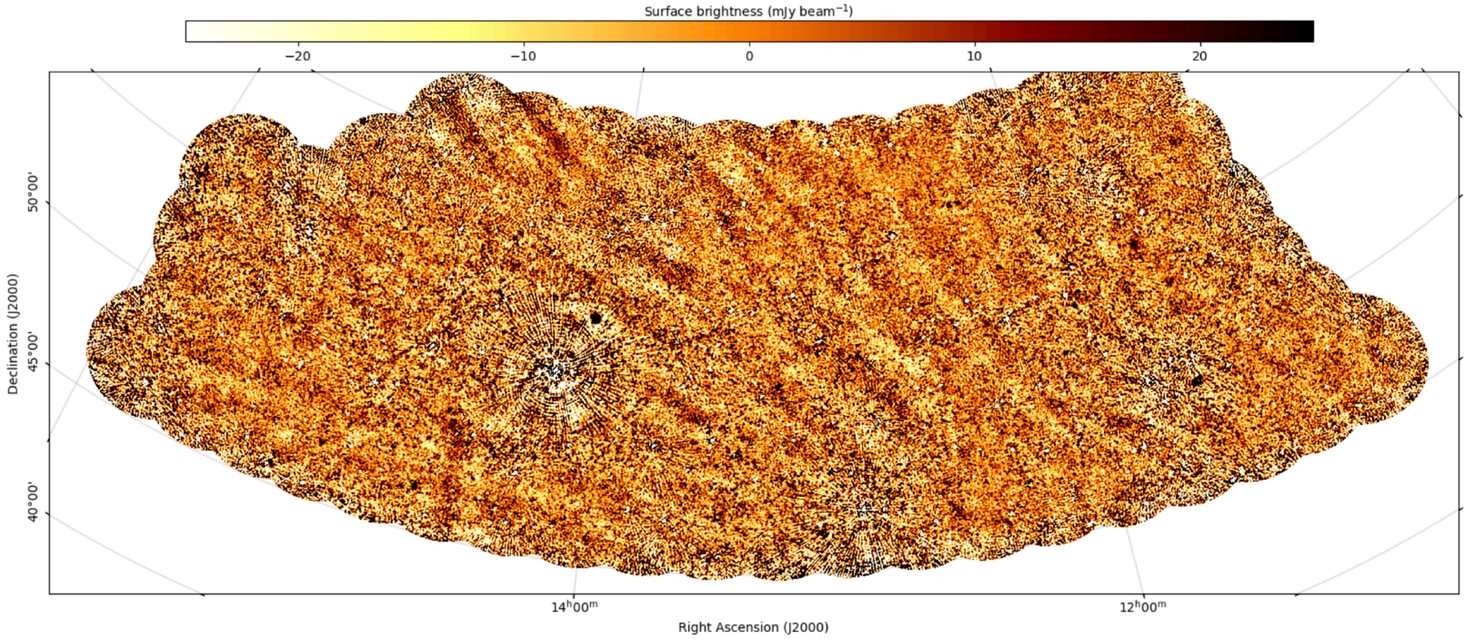
- The AGN catalogue based on the value-added catalogue with DESI DR1 redshifts (version 1.1)
- The full classified catalogue of sources with flux > 1.1 mJy, based on the value-added catalogue v1.2 with DESI DR1 redshifts (version 1.1)
- The AGN catalogue described in the paper (version 1.0)
- The full classified catalogue of sources with flux > 1.1 mJy described in the paper (version 1.0)

The LOFAR LBA Sky Survey (LoLLS) (de Gasperin+2023, more in prep.)





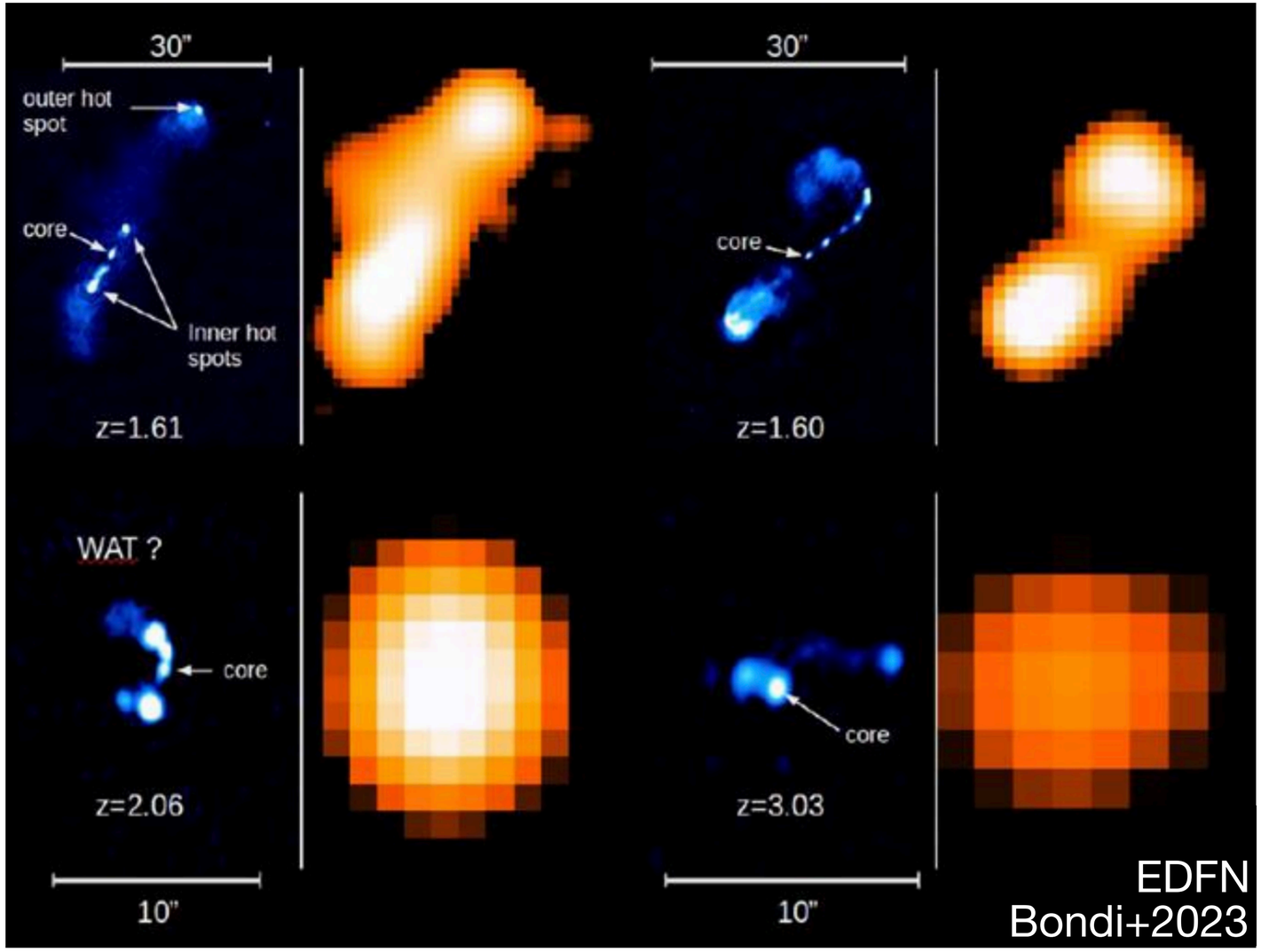
- >70% of the northern sky
- 1973 pointings
- 50 MHz continuum mosaic
- Only Dutch stations 15” beam
- median RMS = 1-2 mJy/beam
- 2400 hrs of data



https://lofar-surveys.org/lolss.html

LOFAR ILT (VLBI)

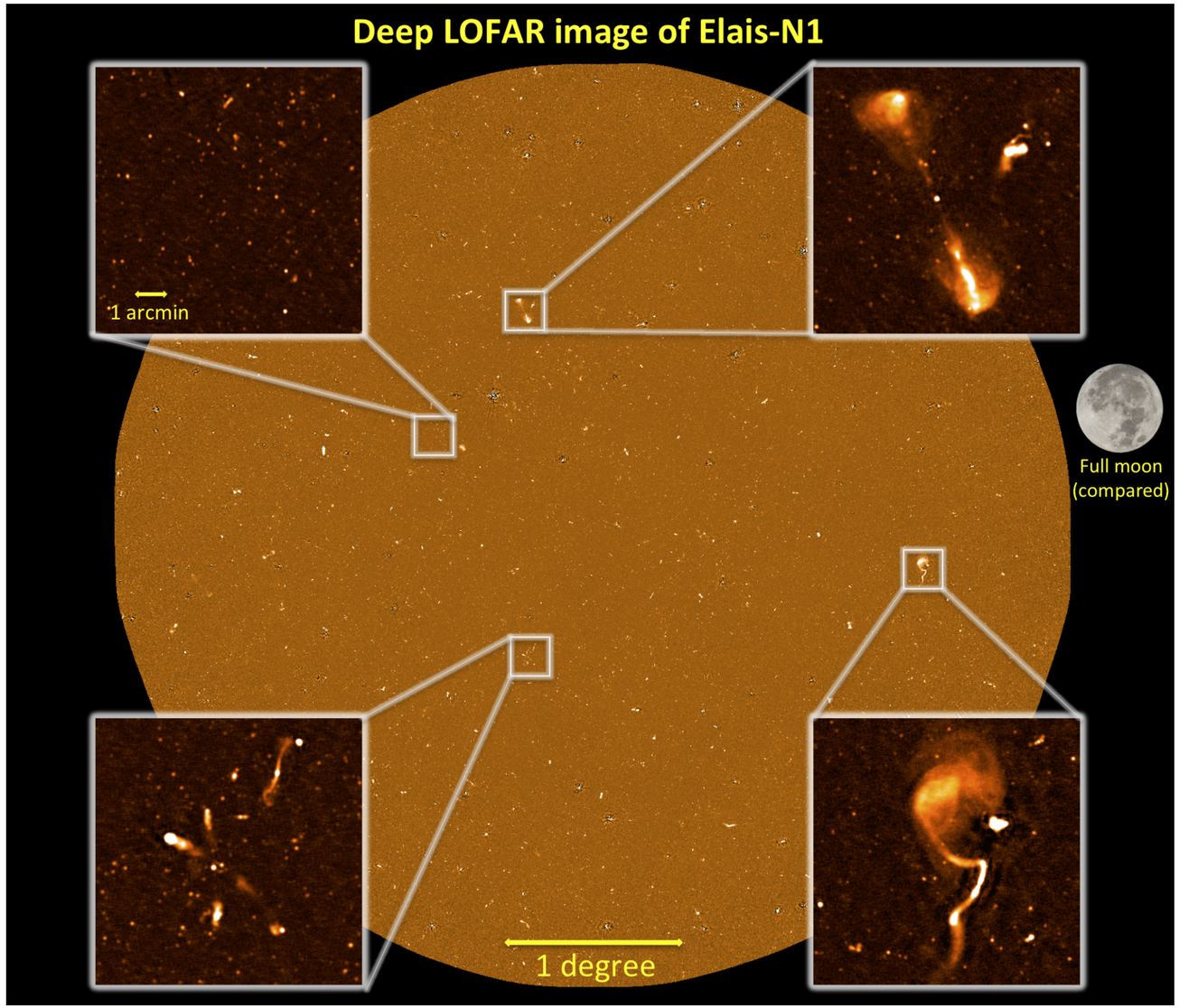
144 MHz - 0.3”



Lockman Hole field
300,000 core hours to image ~5 deg^2 observed with 8 hrs at 0.3 arcsec resolution (e.g. Sweijen+ 2022, Nat Astr)

Will remain unique also in SKA era!

LoTSS Deep Fields



- 120-168 MHz continuum mosaic
- angular resolution of 6″

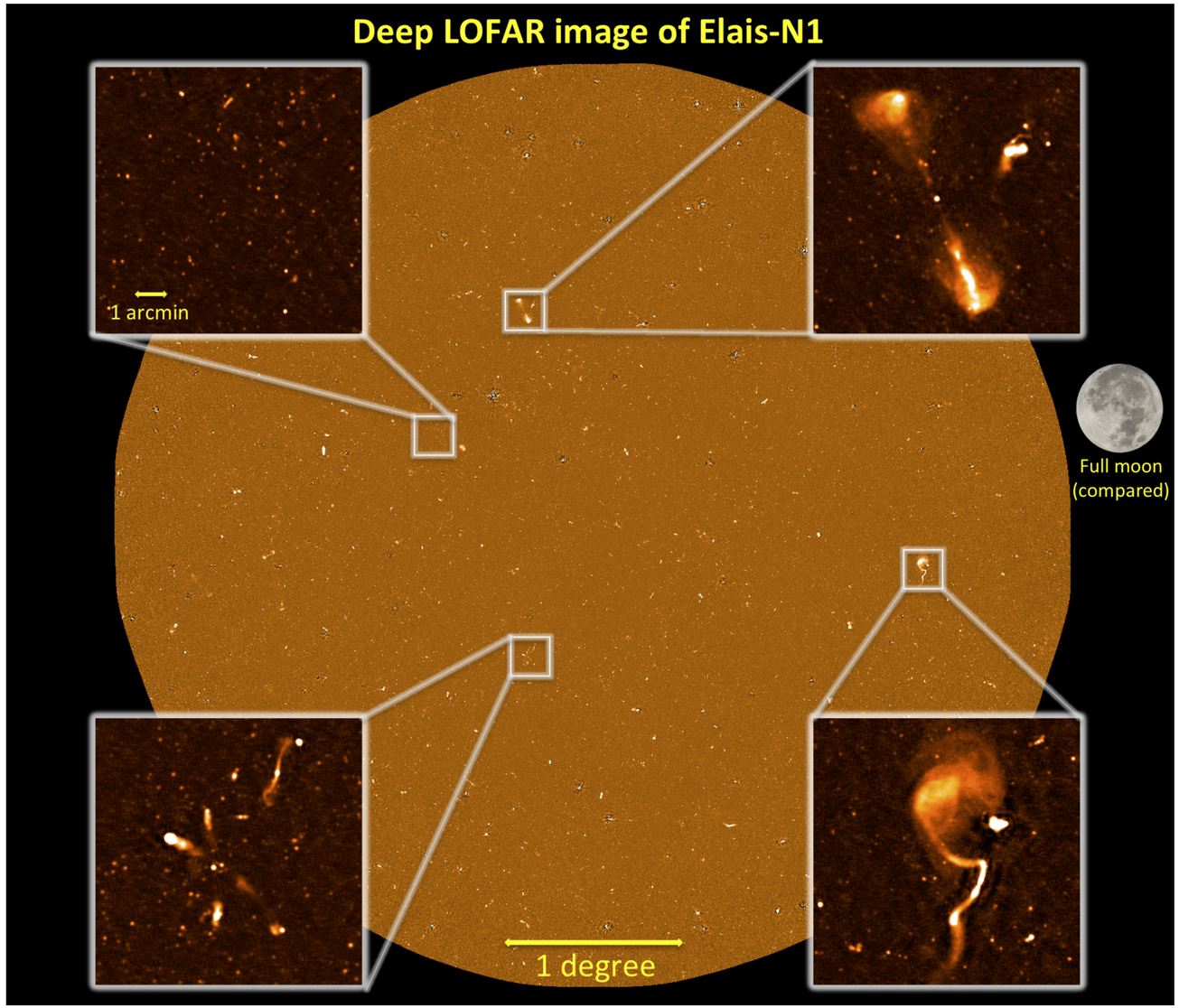
Boötes	80h	32 μJy/b
Lockman Hole	112h	22 μJy/b
NEP-EDFN	70h	30μJy/b
ELAIS-N1	500h	11μJy/b
Abell2255	336h	24 μJy/b

→ ~150k sources in 24.5 deg^2
= ~6000 sources/deg^2
vs
~700 sources/deg^2 in LOTSS

Shimwell+2025

LoTSS Deep Fields

SKA-low 14 μJy/b
@ 200 MHz in 1h!



- 120-168 MHz continuum mosaic
- angular resolution of 6″

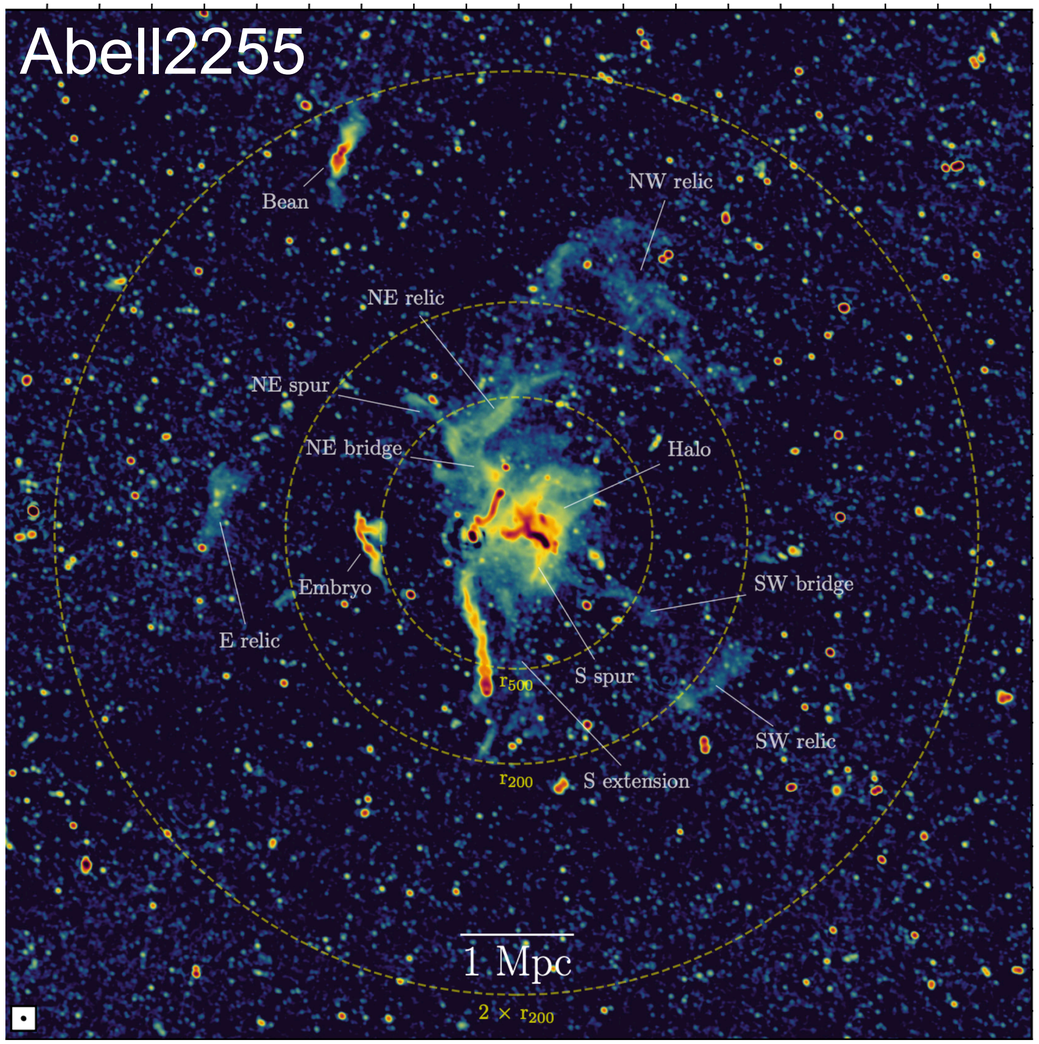
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Shimwell+2025

LoTSS Deep Fields

Botteon+2022,2026

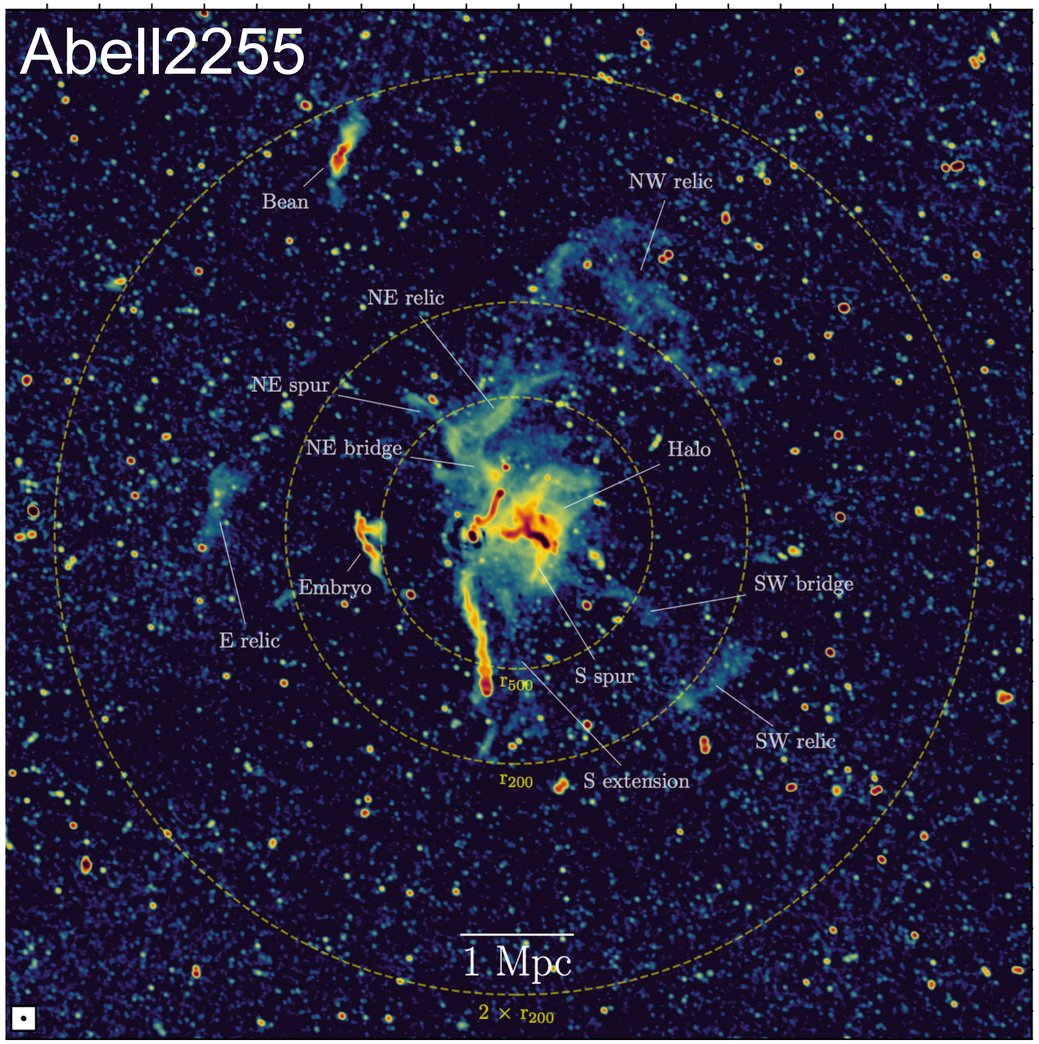


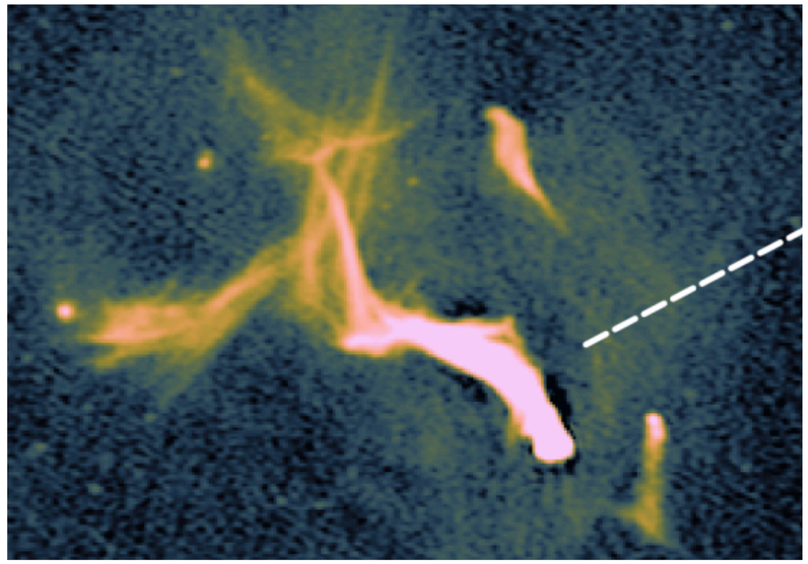
Abell2255 -> 336h = 24 μJy/b

	Initial data volume	Final data volume	Time
DOWNLOAD DATA FROM LOFAR ARCHIVE	200 TB	–	weeks/months
DIRECTION-INDEPENDENT CALIBRATION	200 TB	2 TB	weeks
DIRECTION-DEPENDENT CALIBRATION	2 TB	20 TB	months
TAILORED CALIBRATION ON THE TARGET	20 TB	1.5 TB	weeks
IMAGING AND ANALYSIS	1.5 TB	100s GB	weeks

LoTSS Deep Fields

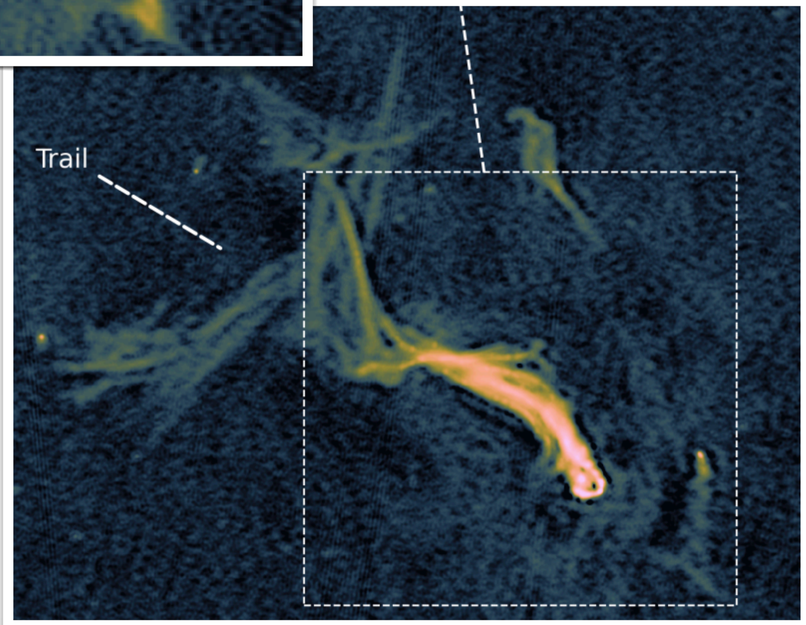
Botteon+2022,2026





6” LOFAR

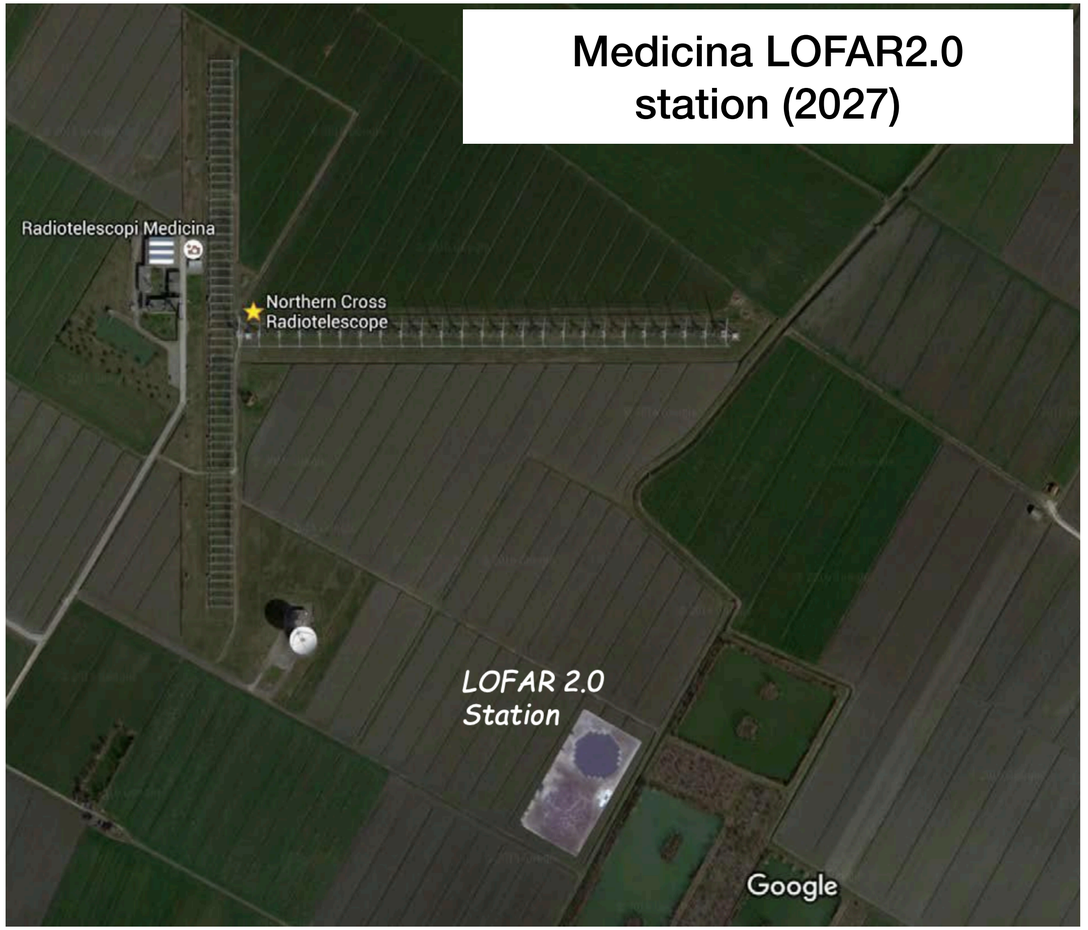
0.3” LOFAR VLBI
De Rubeis + 2025, 2026



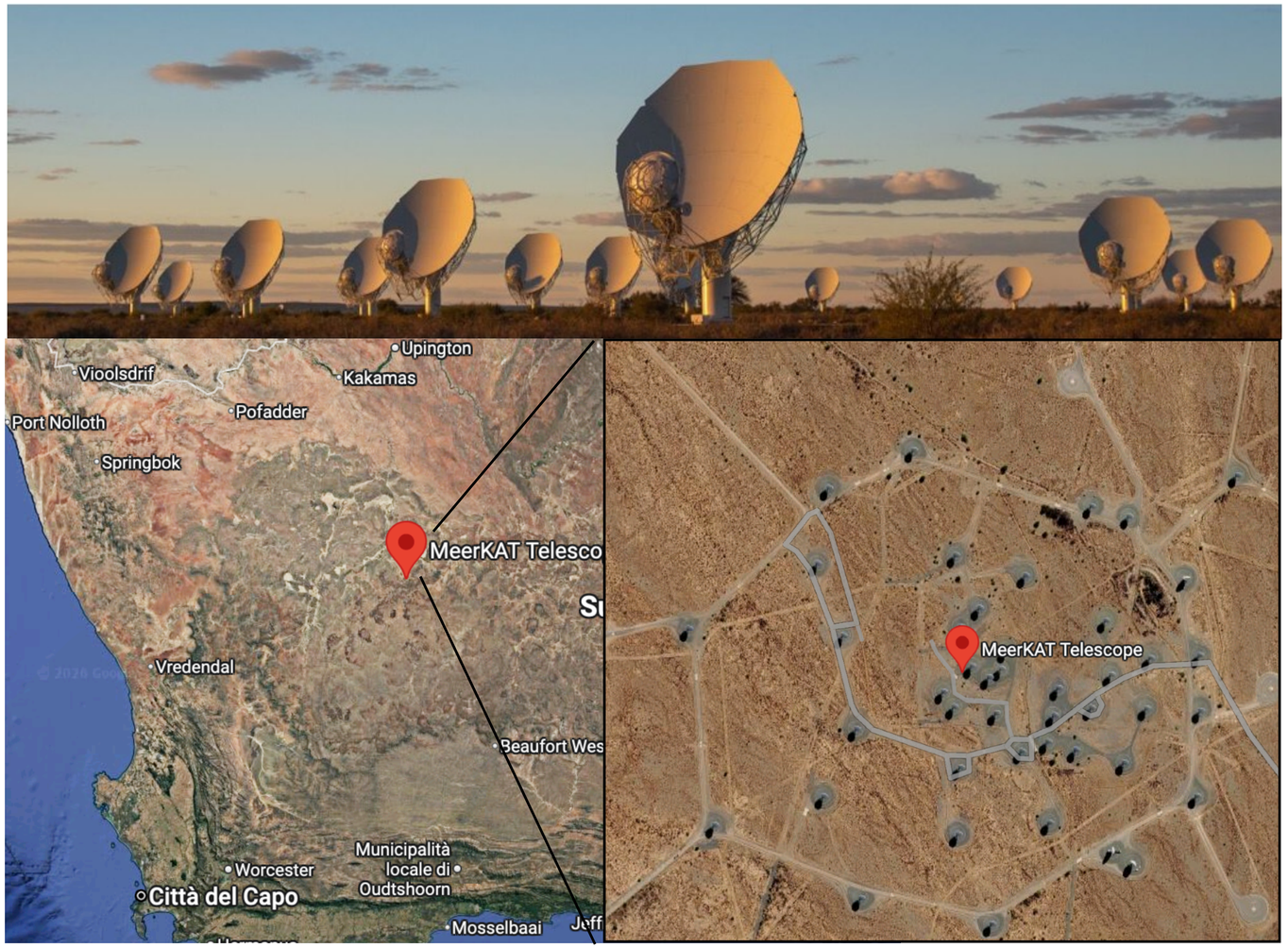
LOFAR2.0 upcoming

DIGITAL UPGRADE

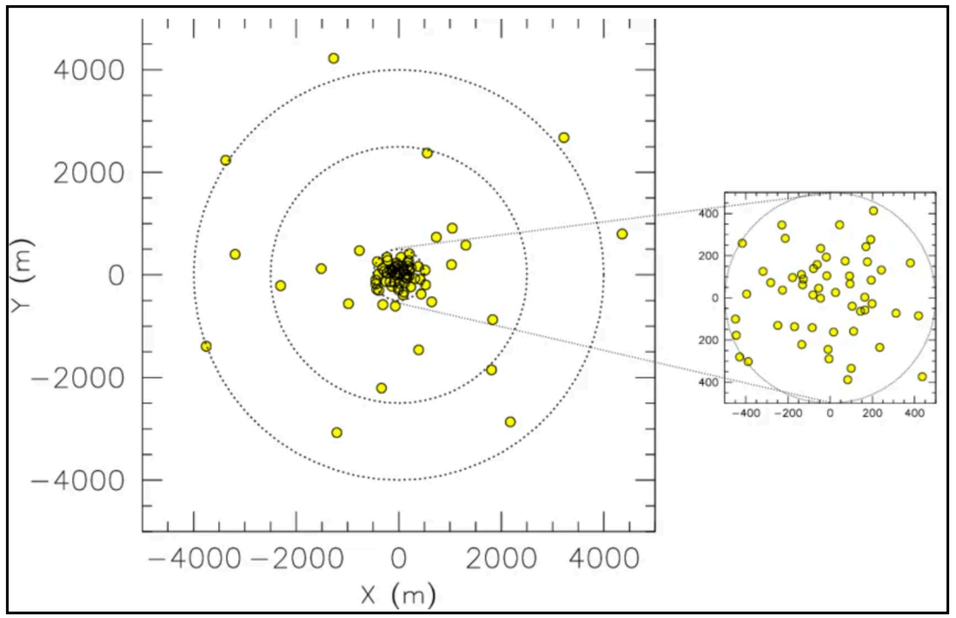
- Dutch stations 48 → 96 LBA dipoles = higher sensitivity!
- Receiver upgrade: parallel observations in LBA and HBA
- Dual band: from 96 MHz to 192 MHz (multi-beam)
- Clock distribution
- Ionospheric-based scheduling to improve telescope efficiency
- New beam model



MeerKAT (SKA-mid precursor)



- Observes sky below DEC~30deg
- B+C+D VLA configurations at the same time
- 64 dishes with 13.5 m fov
- Maximum baseline 7.7 km
- UHF band 580-1015MHz / Lband 900-1670MHz / Sband 1750-3500MHz
- 4k/32k channels, frequency resolution
- Lband 8”, 12μJy/b/h (continuum) & 184 (line)

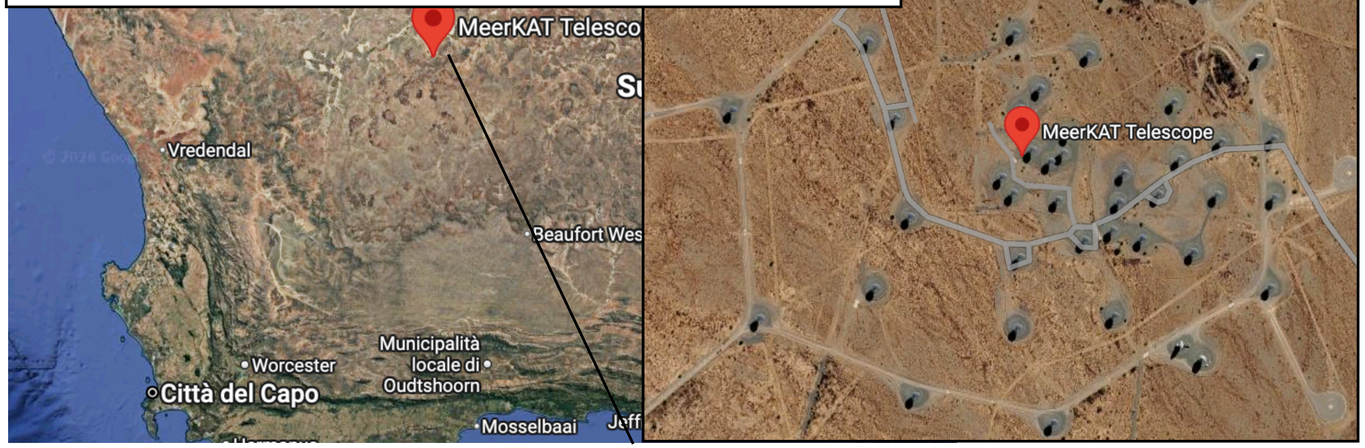


MeerKAT (SKA-mid precursor)

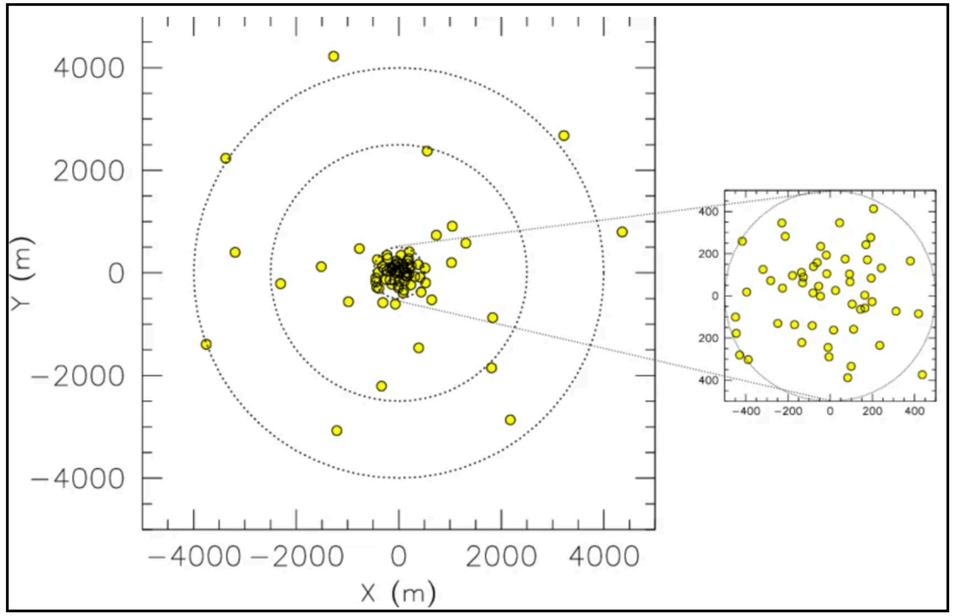
ONGOING SURVEYS • **LADUMA** – Looking at the Distant Universe with MeerKAT Array • **MALS** – MeerKAT Absorption Line Survey • **MeerKAT Fornax Survey** • **MeerTime** – MeerKAT KSP on Pulsar Timing • **MHONGOOSE** – MeerKAT HI Observations of Nearby Galactic Objects • **MIGHTEE** – MeerKAT International GHz Tuned Extragalactic Exploration • **ThunderKAT** – Dynamic and explosive transients • **TRAPUM** – Transients and Pulsars with MKAT • **MGCLS** – MeerKAT Galaxy Clusters Legacy Survey (scientific commissioning) • **SMGPS** – SARAO MeerKAT Galactic Plane Survey

For all-sky survey at GHz freq need ASKAP -> RACS, EMU





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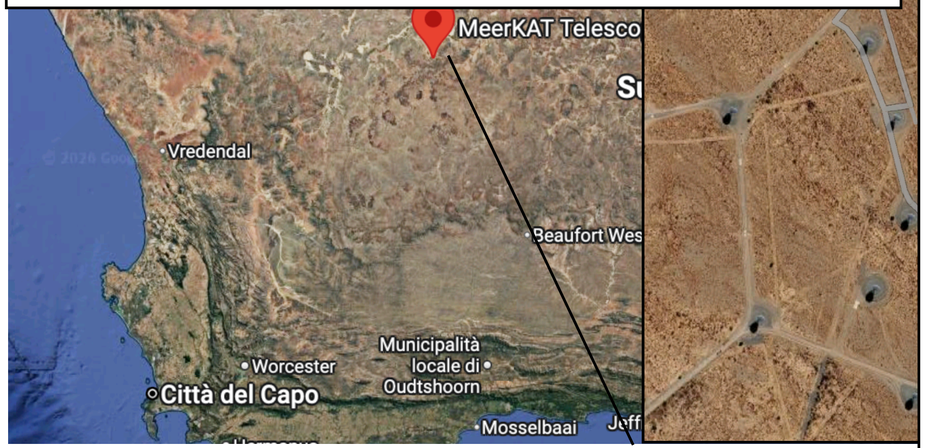
MeerKAT (SKA-mid precursor)

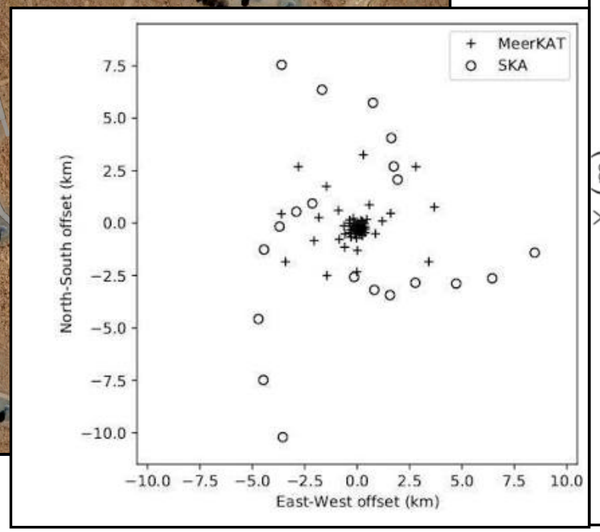
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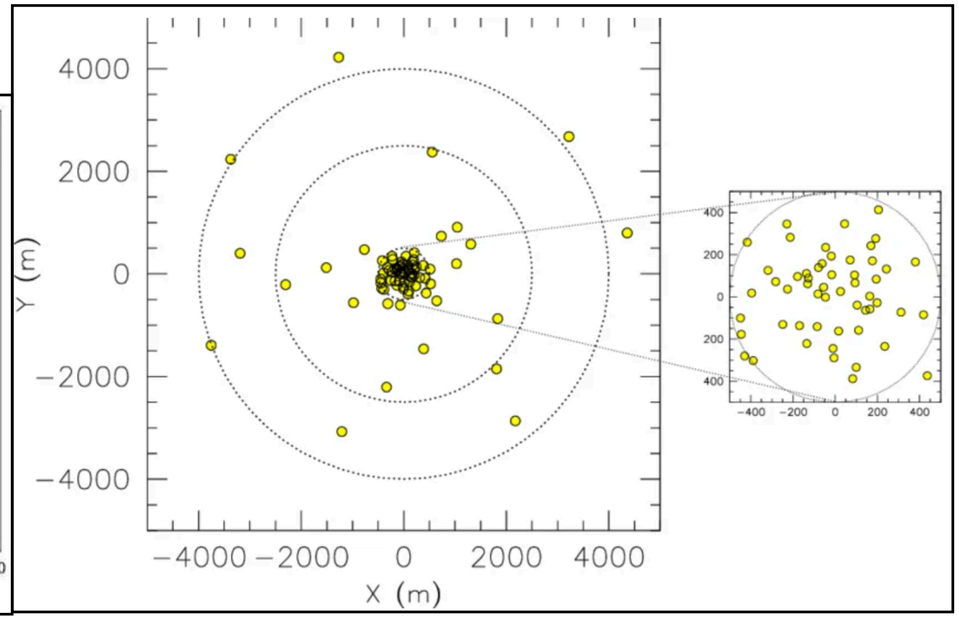




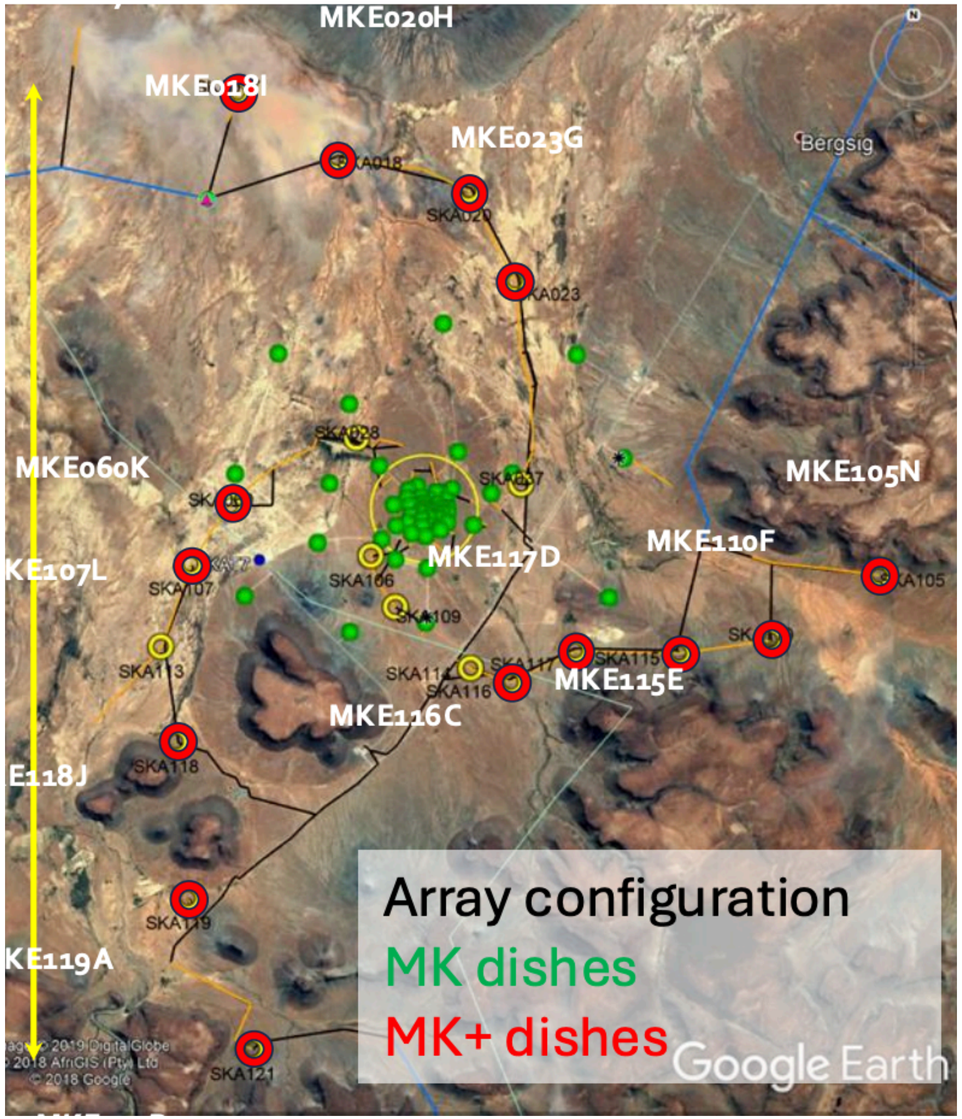




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MeerKAT+



Extending MeerKAT with 14 SKA-compliant dishes:

- South African Radio Observatory (SARAO)
- Max-Planck Gesellschaft (MPG)
- INAF

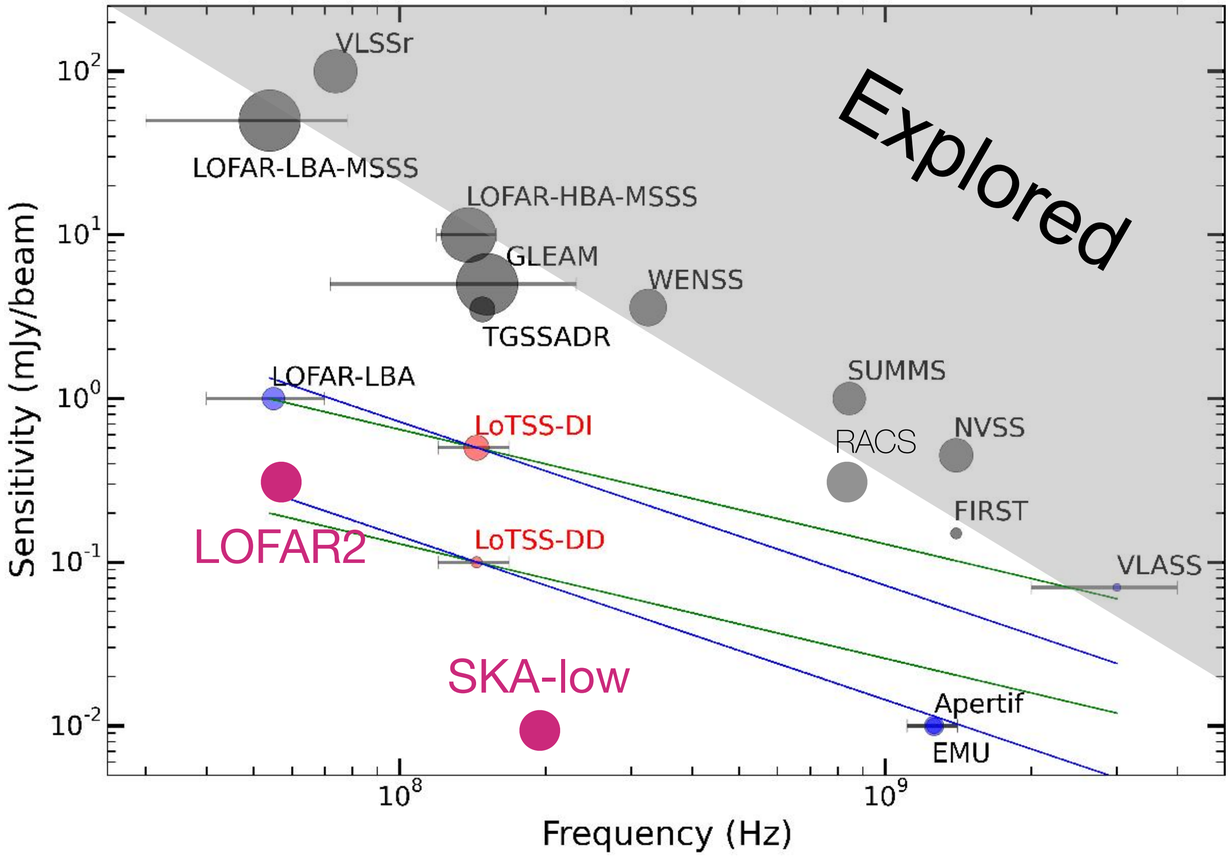
- Collecting area +30% (14 antennas)
- Sensitivity (1 hr): 12μJy/b → 9μJy/b
- L-band angular resolution: 8” → 3.4”
- L & S-band + band5b receivers
- Backend to process all 78 antennas simultaneously
- Initial wideband correlator mode with 8k channels
- Full polarisation



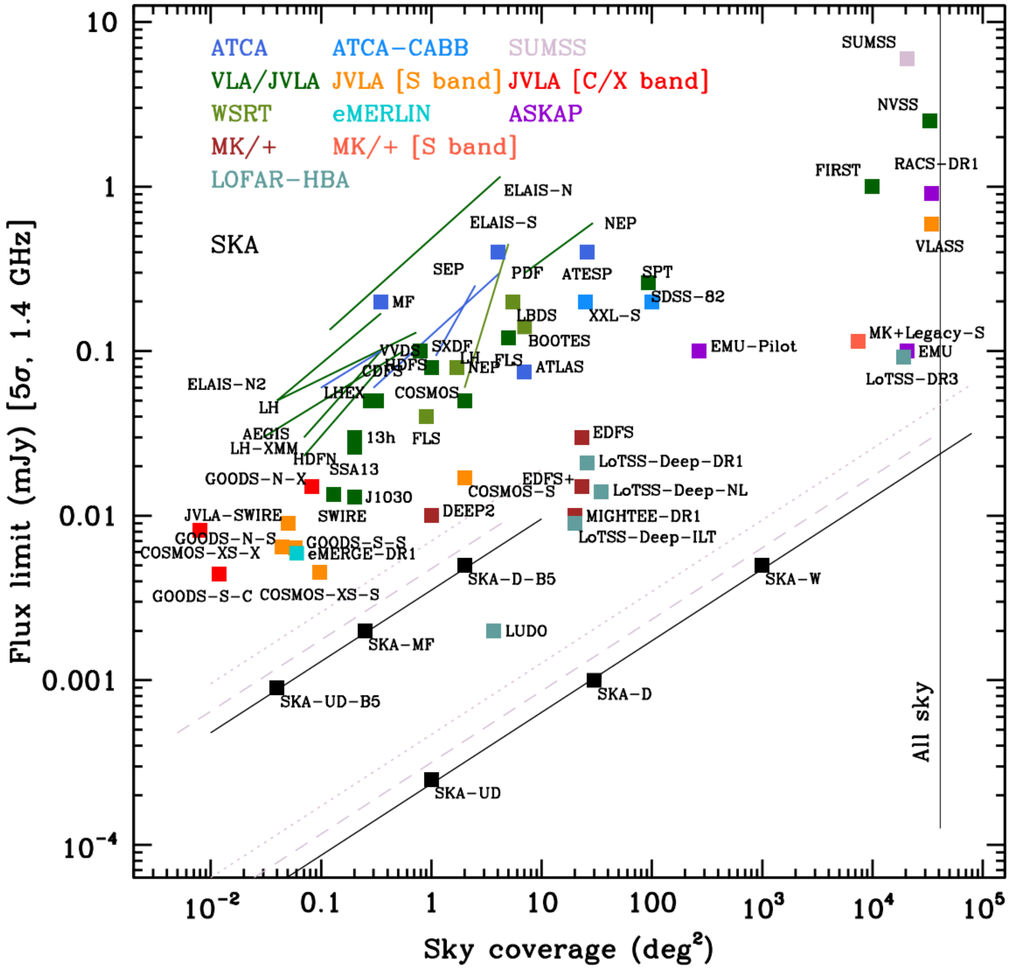
Upgrade ongoing

Current and future continuum surveys

WIDE



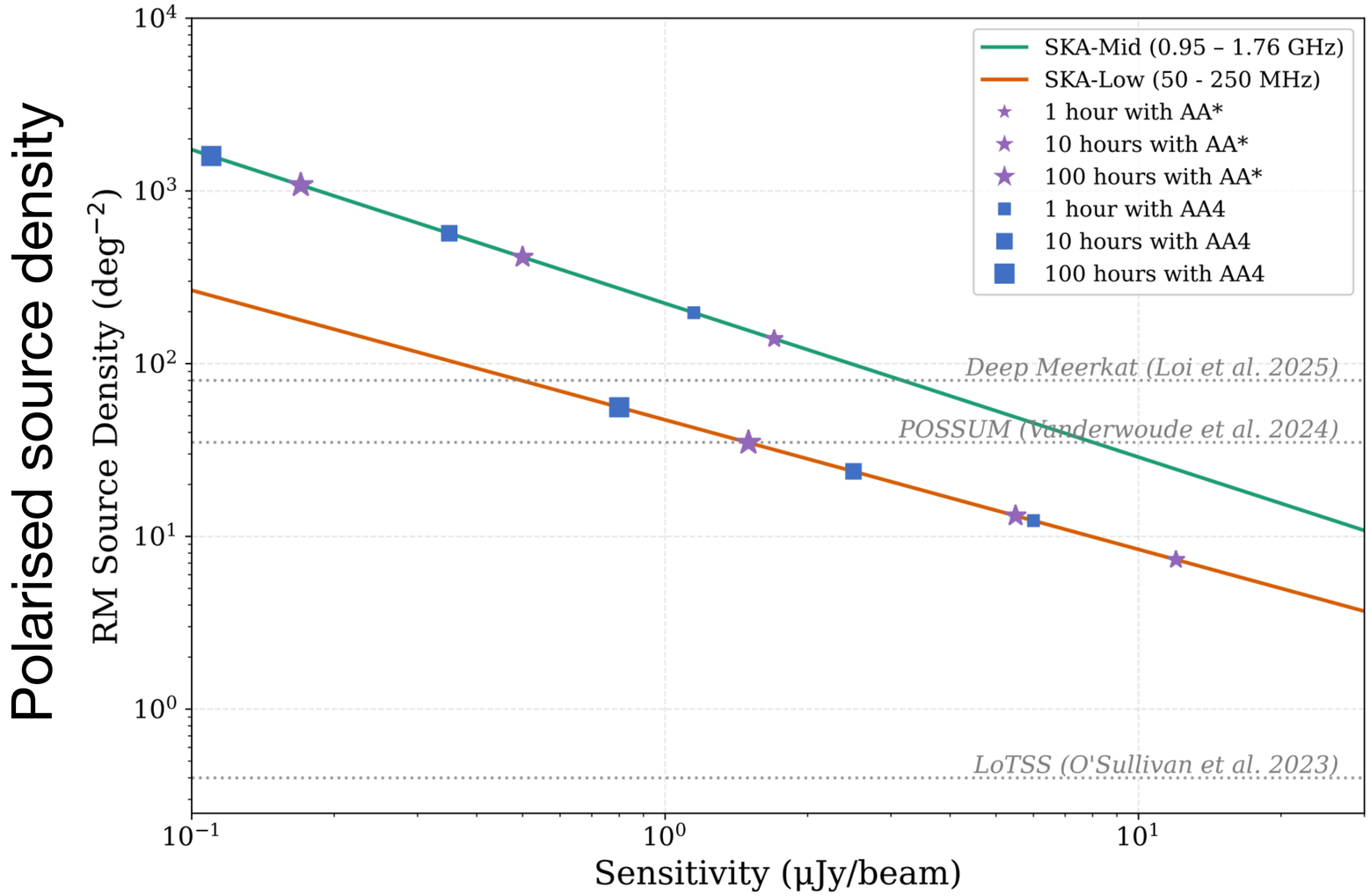
DEEP



Adapted from Shimwell+2025

Prandoni+2026

Current and future polarisation surveys



Crucial for large-scale magnetic field characterisation

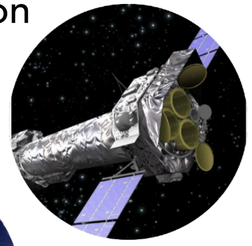
Vernstrom+2026

Synergies with multi-wavelength facilities

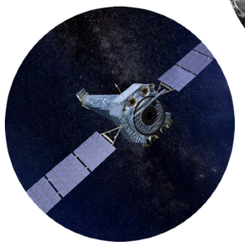
X-ray

Thermal emission from intracluster/group medium + non-thermal emission from AGN

XMM-Newton



Chandra



eROSITA





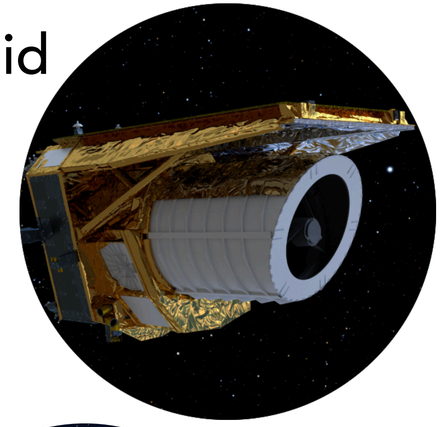
newATHENA in the future



Optical/IR

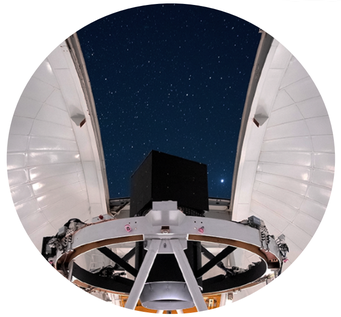
Emission from host galaxy and AGN + galaxy clustering and cosmic web

Euclid



Vera Rubin





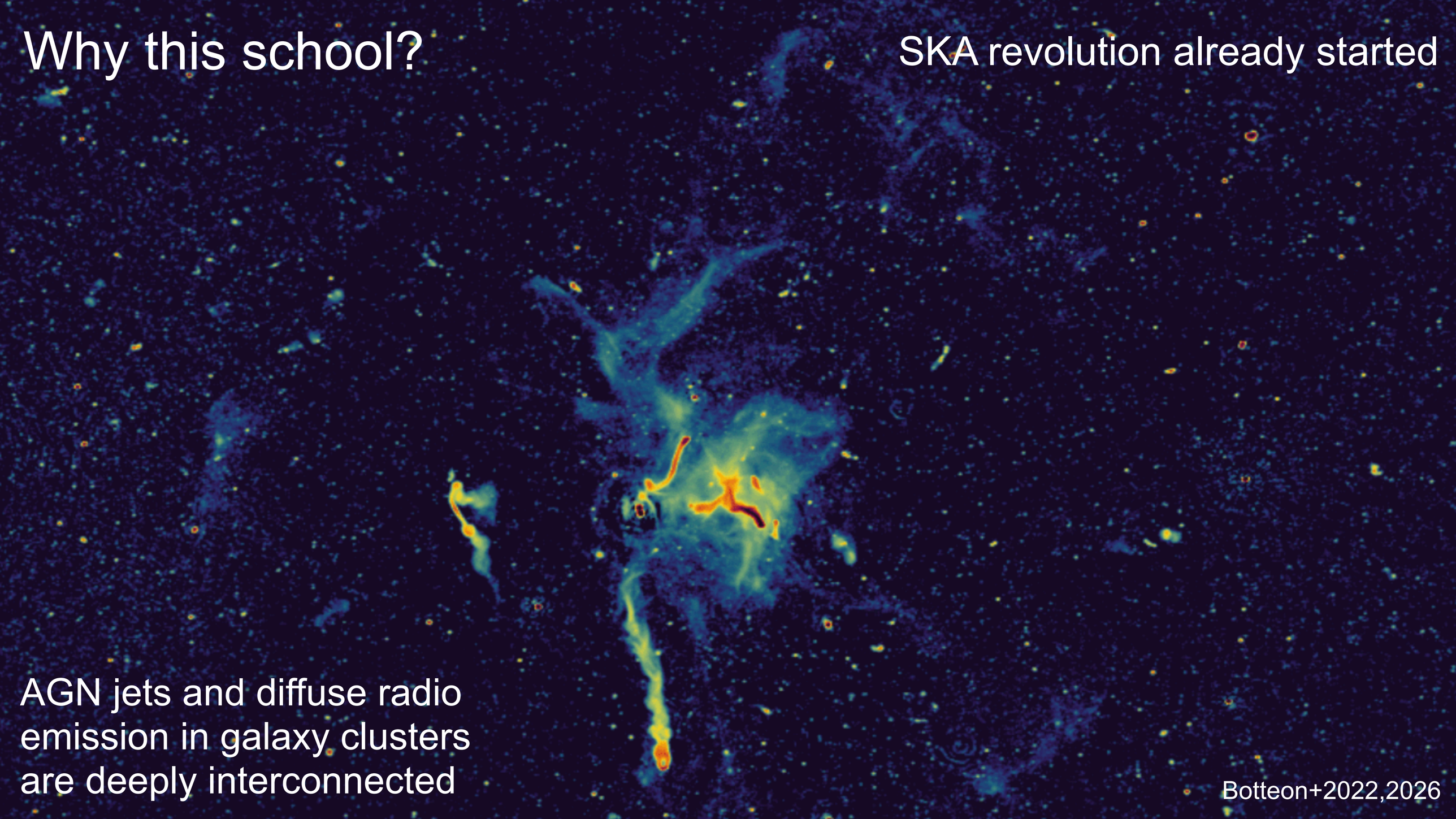
WEAVE - WHT



DESI

Why this school?

SKA revolution already started



AGN jets and diffuse radio emission in galaxy clusters are deeply interconnected

Botteon+2022,2026