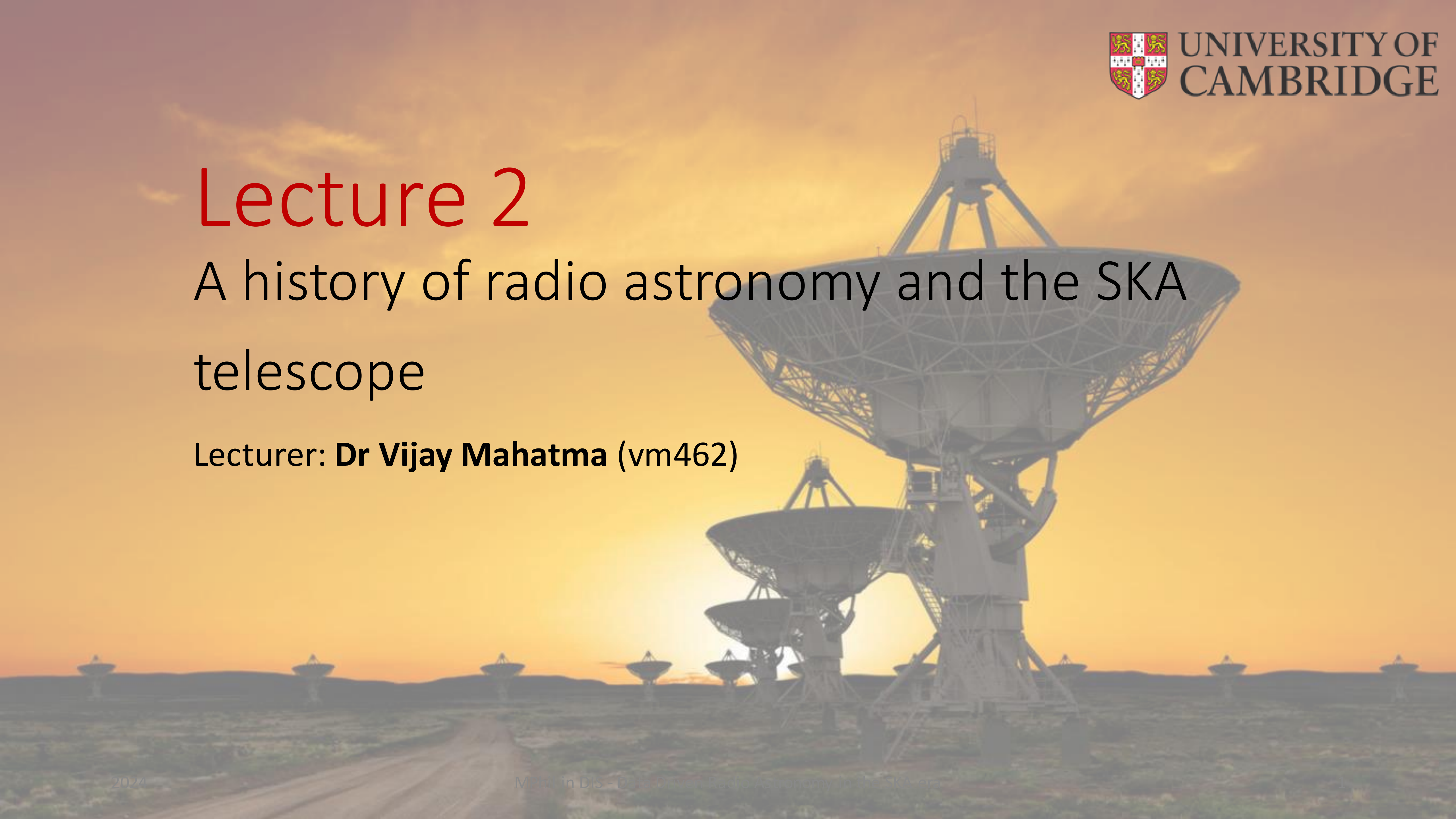


Lecture 2

A history of radio astronomy and the SKA telescope

Lecturer: **Dr Vijay Mahatma** (vm462)

UNIVERSITY OF CAMBRIDGE

Syllabus Overview

- Introduction to Big Data Radio Astronomy and Key Science Projects
  - Lecture 1: SKA Key Science Projects
  - Lecture 2: Brief history of radio astronomy and the SKA telescope
  - Lecture 3: The modern "large-N" radio interferometers
- Instrument simulations and design tools
  - Lecture 4: Intro into numerical methods for electromagnetic modelling
  - Lectures 5 and 6: Mutual coupling in antenna arrays
- Science Data Processing
  - Lecture 7: Calibration of radio observations
  - Lecture 8: Imaging techniques
  - Lecture 9: Advanced imaging techniques
  - Lecture 10: Time-domain radio astronomy
- Computing infrastructure
  - Lecture 11: Federation and scaling approaches for exascale data
  - Lecture 12: Data centre challenges and opportunities
- Advanced ML and Bayesian methods for data analysis and science extraction
  - Lecture 13: Nested sampling and MCMC
  - Lecture 14: Applications of Bayesian analysis
  - Lecture 15: Signal emulation for astrophysics and cosmology
  - Lecture 16: Simulation-based inference in astrophysics and cosmology

UNIVERSITY OF CAMBRIDGE

Syllabus Overview

- Introduction to Big Data Radio Astronomy and Key Science Projects
  - ~~Lecture 1: SKA Key Science Projects~~
  - Lecture 2: Brief history of radio astronomy and the SKA telescope
  - Lecture 3: The modern "large-N" radio interferometers
- Instrument simulations and design tools
  - Lecture 4: Intro into numerical methods for electromagnetic modelling
  - Lectures 5 and 6: Mutual coupling in antenna arrays
- Science Data Processing
  - Lecture 7: Calibration of radio observations
  - Lecture 8: Imaging techniques
  - Lecture 9: Advanced imaging techniques
  - Lecture 10: Time-domain radio astronomy
- Computing infrastructure
  - Lecture 11: Federation and scaling approaches for exascale data
  - Lecture 12: Data centre challenges and opportunities
- Advanced ML and Bayesian methods for data analysis and science extraction
  - Lecture 13: Nested sampling and MCMC
  - Lecture 14: Applications of Bayesian analysis
  - Lecture 15: Signal emulation for astrophysics and cosmology
  - Lecture 16: Simulation-based inference in astrophysics and cosmology

UNIVERSITY OF CAMBRIDGE

A brief history of radio astronomy

- Overview of the important events in the timeline
- Emphasis on instrumentation rather than scientific results
- A true historical account likely involves a number of other disciplines; antenna engineering, radio communications, data transport, Fourier analysis, Matrix optimizations and more

UNIVERSITY OF CAMBRIDGE

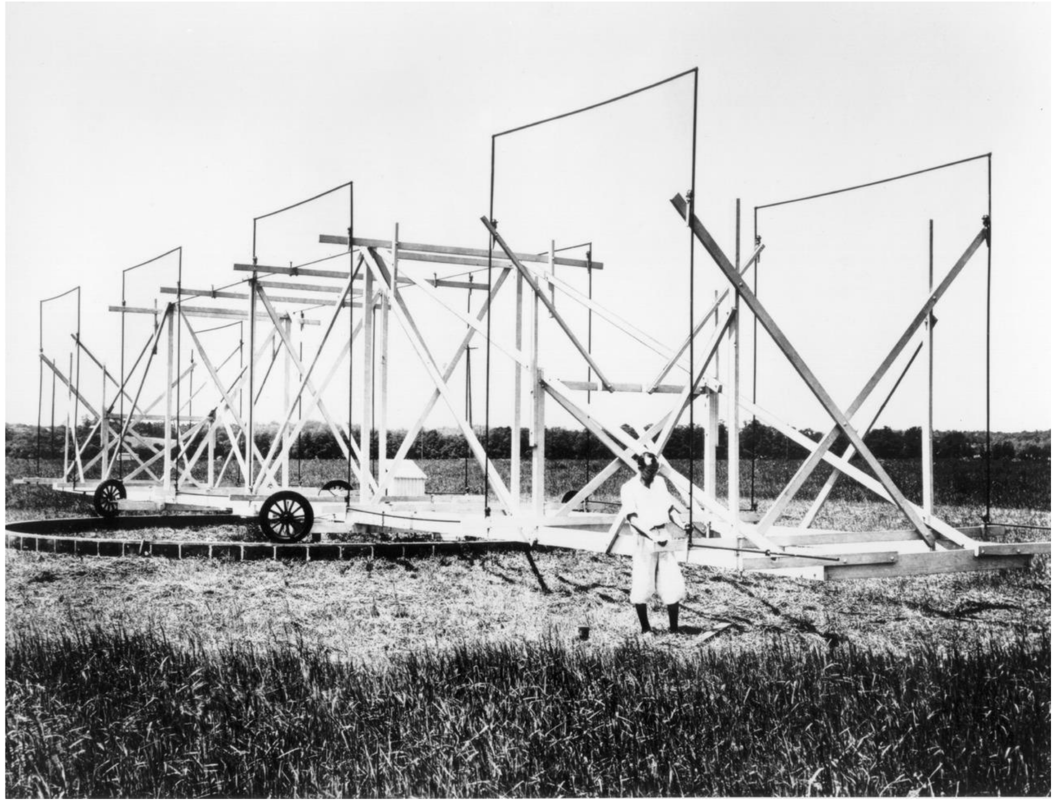
Pre-1930s

- 1860s – James Clerk Maxwell develops the foundation for classical electromagnetism – radio waves are propagating EM waves
- Late 1890s – first attempts to detect radio waves from the Sun, but unsuccessful
- 1902 – physicists are convinced that it is unlikely radio emission from space can be detected, due to the radio-reflecting ionosphere

UNIVERSITY OF CAMBRIDGE

1932

- A young engineer working for Bell Laboratories was trying to understand the problem of noisy static that was interfering with trans-atlantic voice communications
- The noise level was not uniform – it shifted across the sky

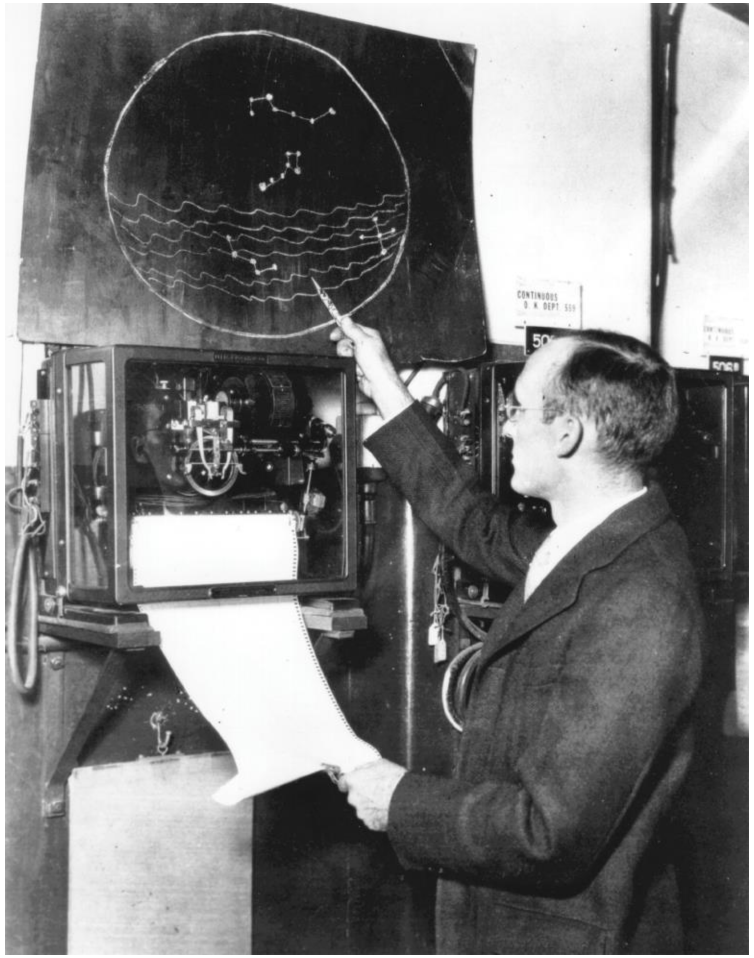


20.5 MHz antenna in New Jersey. Credit: NRAO

UNIVERSITY OF CAMBRIDGE

1932

- “I have taken more data which indicated definitely that the stuff, whatever it is, comes from something not only extraterrestrial, but from outside the solar system. It comes from a direction that is fixed in space and the surprising thing is that ...[it] is in the direction towards which the solar system is moving in space. According to Skellett...there are clouds of “cosmic dust” in that direction...”



Karl G. Jansky

UNIVERSITY OF CAMBRIDGE

1932

66 NATURE JULY 8, 1933

Radio Waves from Outside the Solar System

IN a recent paper[1] on the direction of arrival of high-frequency atmospherics, curves were given showing the horizontal component of the direction of arrival of an electromagnetic disturbance, which I termed hiss type atmospherics, plotted against time of day. These curves showed that the horizontal component of the direction of arrival changed nearly 360° in 24 hours and, at the time the paper was written, this component was approximately the same as the azimuth of the sun, leading to the assumption that the source of this disturbance was somehow associated with the sun.

Records have now been taken of this phenomenon for more than a year, but the data obtained from them are not consistent with the assumptions made in the above paper. The curves of the horizontal component of the direction of arrival plotted against time of day for the different months show a uniformly progressive shift with respect to the time of day, which at the end of one sidereal year brings the curve back to its initial position. Consideration of this shift and the shape of the individual curves leads to the conclusion that the direction of arrival of this disturbance remains fixed in space, that is to say, the source of this noise is located in some region that is stationary with respect to the stars. Although the right ascension of this region can be determined from the data with considerable accuracy, the error not being greater than ± 30 minutes of right ascension, the limitations of the apparatus and the errors that might be caused by the ionised layers of the earth's atmosphere and by attenuation of the waves in passing over the surface of the earth are such that the declination of the region can be determined only very approximately. Thus the value obtained from the data might be in error by as much as ± 30°.

The data give for the co-ordinates of the region from which the disturbance comes, a right ascension of 18 hours and declination of − 10°.

A more detailed description of the experiments and the results will be given later.

KARL G. JANSKY.

Bell Telephone Laboratories, Inc.,
New York, N. Y.
May 8.

[1] Karl G. Jansky, "Directional Studies of Atmospherics at High Frequencies", *Proc. Inst. Rad. Eng.*, **20**, 1920; 1932.

are made from one sheet of paper, it will only be necessary to calibrate one of them. The change in weight, after transferring from 40 per cent humidity, expressed as a percentage of the weight at 40 per cent, will be the same for all the hygrometers exposed to any particular humidity.

There are many applications for this method of hygrometry. It is possible to measure the humidity at the surface of a leaf, or among vegetation, without disturbing the air.

KENNETH MELLANBY.

Department of Entomology,
London School of Hygiene
and Tropical Medicine,
Keppel Street, W.C.1.
May 26.

Co-operative Industrial Research

THE leading article in NATURE of June 10 on this subject appears to me to be of profound significance. It brings into prominence the fundamental issues in regard to industrial research and the application of science to industry, which are so seldom taken into consideration.

I do not write in any critical spirit, but I feel that the end of the War left us—statesmen, administrators, scientific workers, and the nation at large—obsessed with the idea that the benefits to be derived from the application of science to industry were mainly external to the human mind and purely materialistic. We were very confident then that the so-called rationalisation of industry, the elimination of hand labour, the development of machinery and processes and the standardisation of mass-produced articles, were going to make us all happy and prosperous. A good many industrialists have learned since then that cheapness and efficiency in production are by no means everything; it is what is produced that matters most.

The vital thing about any manufactured product is the purpose it serves in the life of man, not the processes of its manufacture. Consideration of purpose leads to the investigation of design. Design is usually stated to include three factors, beauty, distinctiveness and utility. The relative importance of these factors will vary with the product, but it seems to me that to concentrate almost all industrial progress on utility, which is at present mainly affected by industrial research, may not give the

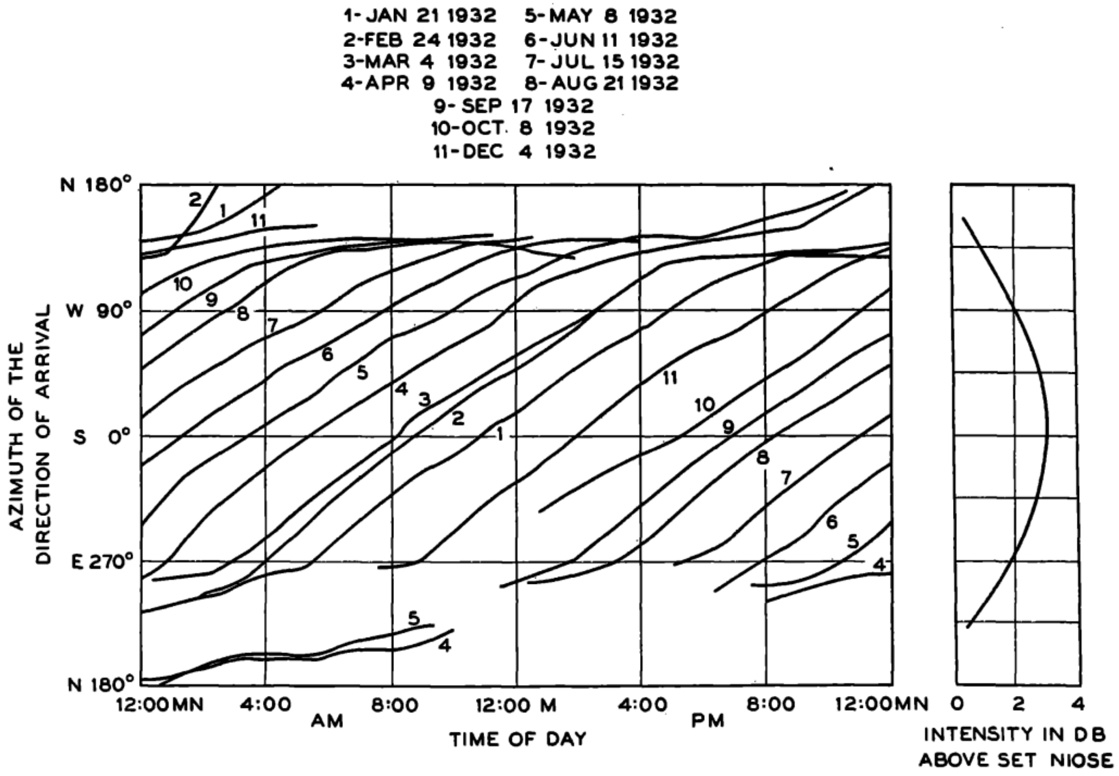


FIGURE 2.
AZIMUTH OF THE DIRECTION OF ARRIVAL OF WAVES OF INTERSTELLAR ORIGIN PLOTTED AGAINST TIME OF DAY.

Jansky (1933)

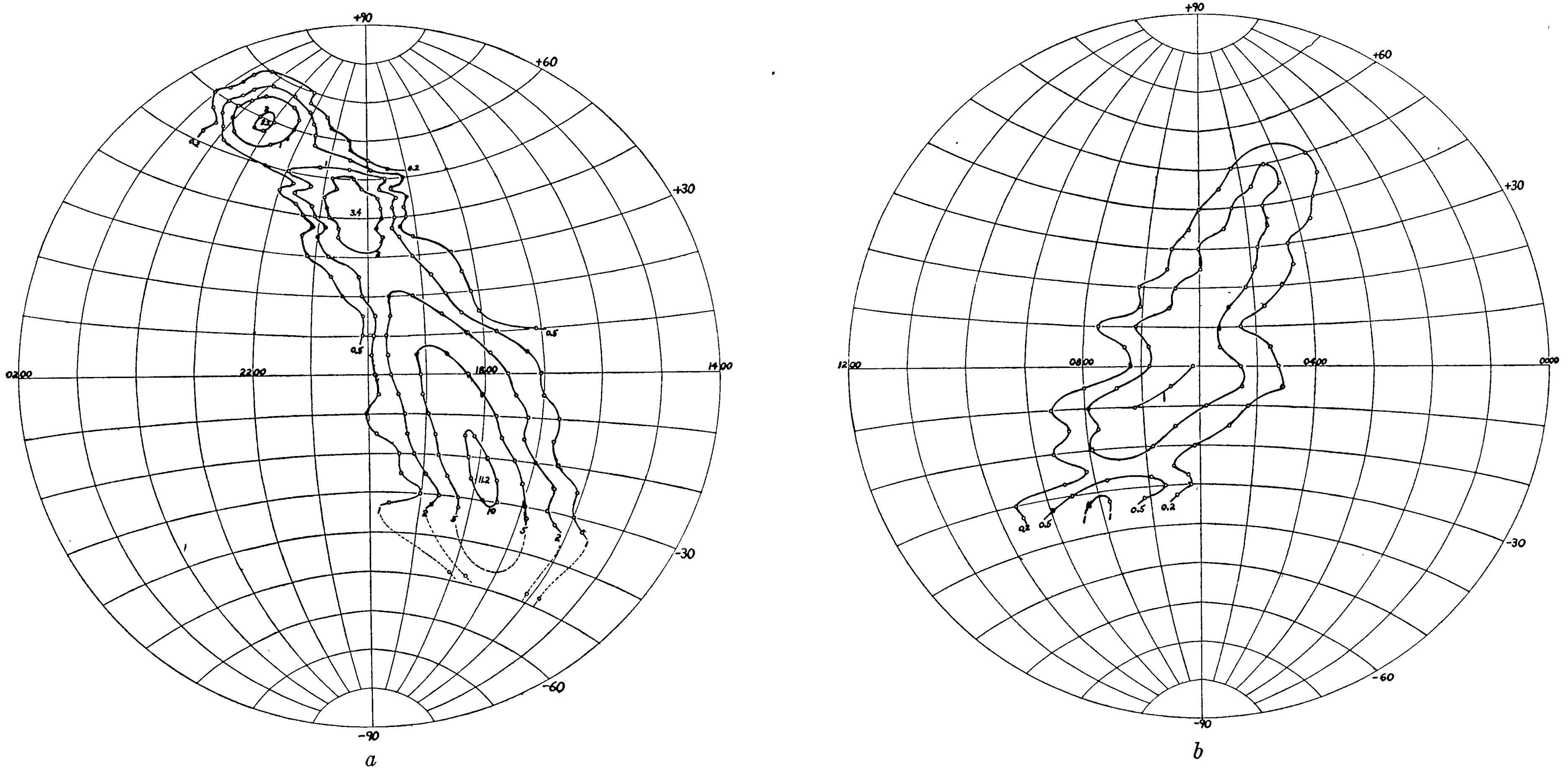
UNIVERSITY OF CAMBRIDGE

1937-1944

- Grote Reber, inspired by Janskys findings, built the first radio telescope in his back garden
- Made the first radio map of the sky -- "cosmic static"
- James Hey detects the radio waves from the Sun. Independent solar detections in USA, New Zealand, Austrailia during WWII

Rebers 9.5m parabolic radio dish

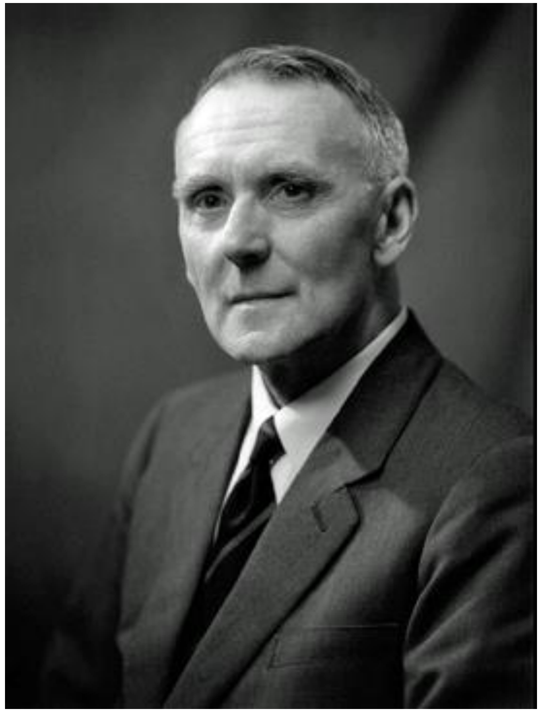
1937-1944



The first radio map of the sky, showing the three brightest radio sources in the plane of the Milky Way (Reber, 1944)

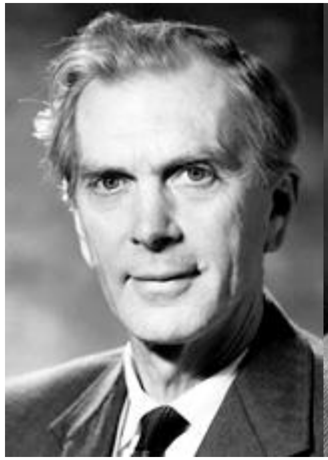
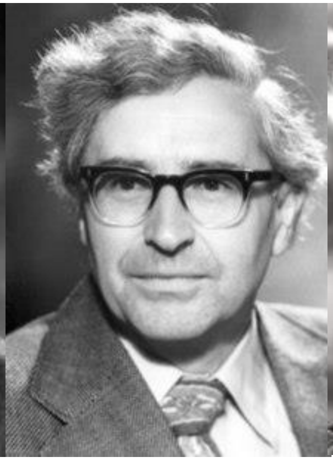
1937-1944

- Ionospheric studies take place at the Cavendish Laboratory before WWII
- Radio experts join the Telecommunications Research Establishment (TRE) to aid war efforts
- After WWII, transition from radar to radio astronomy
- Radio experts from the TRE became interested in extraterrestrial radio waves
- J.A. Ratcliffe forms a radio physics group at the Cavendish Laboratory, University of Cambridge
- Supervised Martin Ryle, Antony Hewish and Bernard Lovell – became the leaders of UK radio astronomy



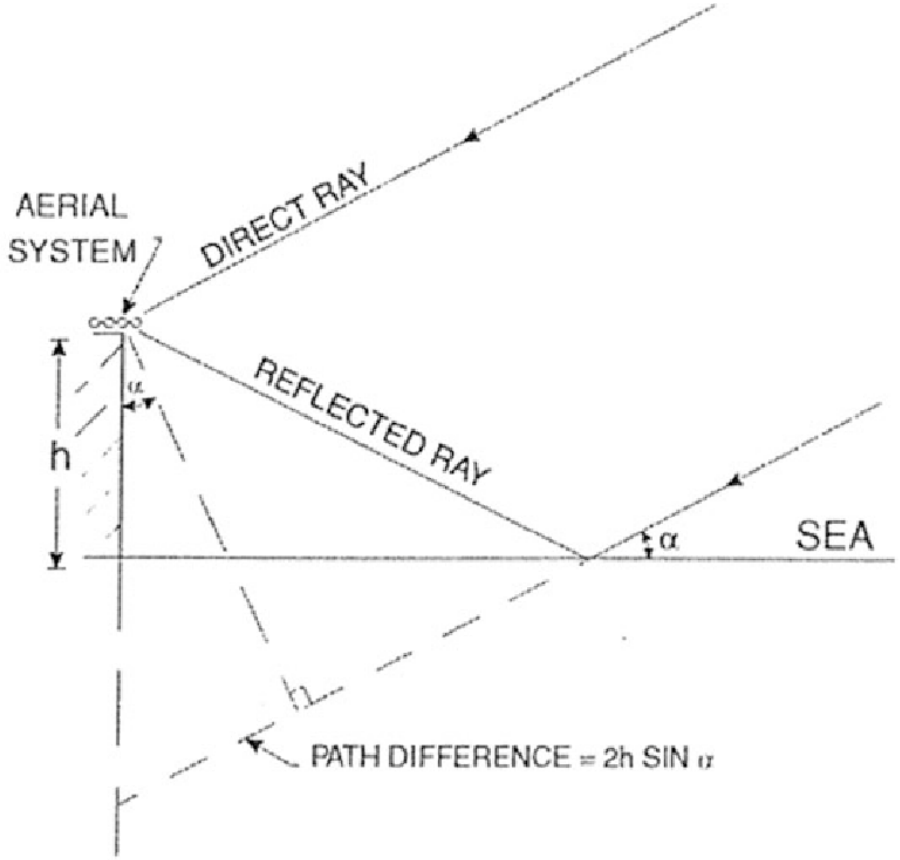
John A. Ratcliffe

Below, left to right:
Martin Ryle,
Anthony Hewish,
Bernard Lovell


1945-1948

- Technique of sea-interferometry is used in Australia
- Radio waves reflected off the sea allow for extra signals to be detected
- Notable detections of sunspots, sources in the constellations of Cygnus and Cassiopeia.



Schematic of sea-cliff interferometry (Goss+2023)

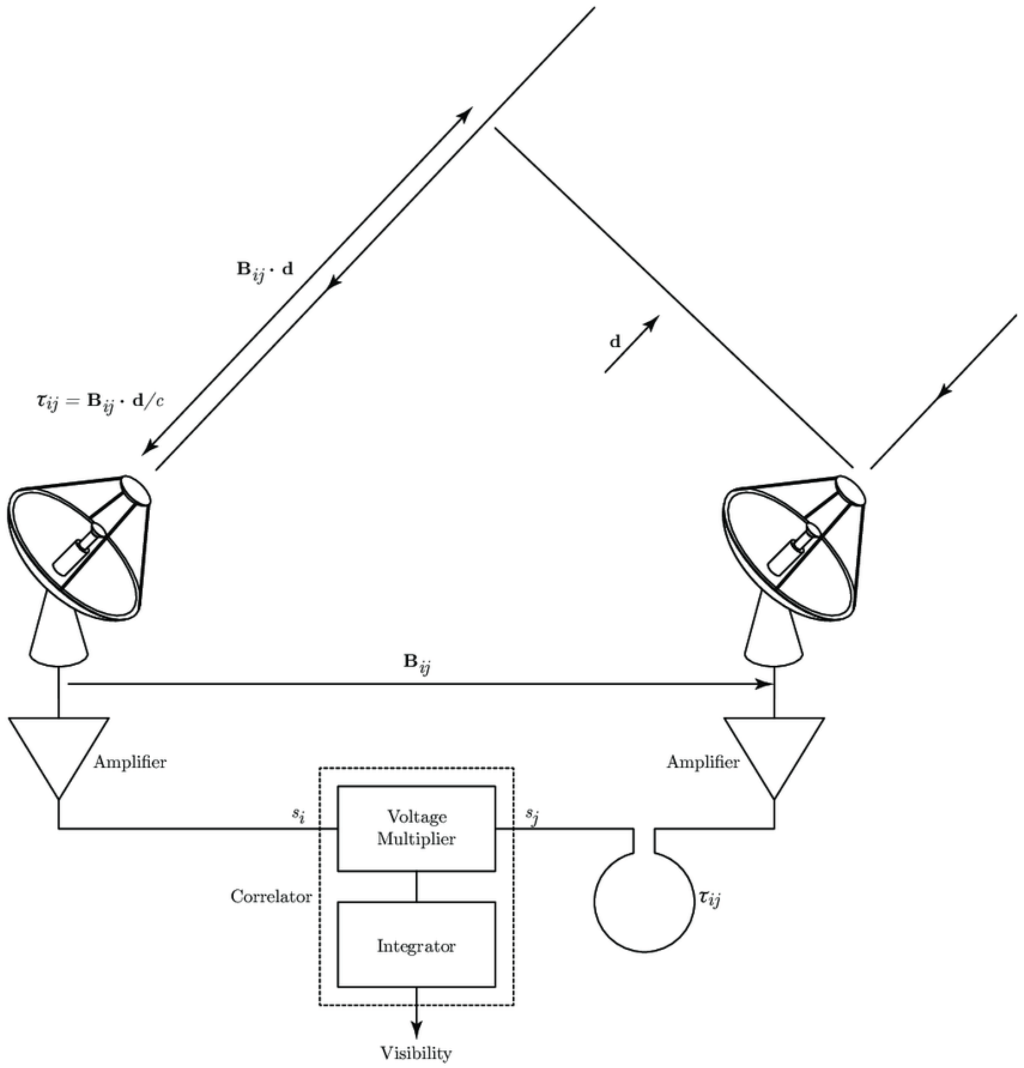
Early 1950s

- Ratcliffe split the radio research into ionospheric studies and radio astronomy, headed by Martin Ryle
- Discrete radio sources were starting to be discovered by Australian radio astronomers
- Martin Ryle, Graham Smith and Antony Hewish started to develop radio interferometers in Cambridge

UNIVERSITY OF CAMBRIDGE

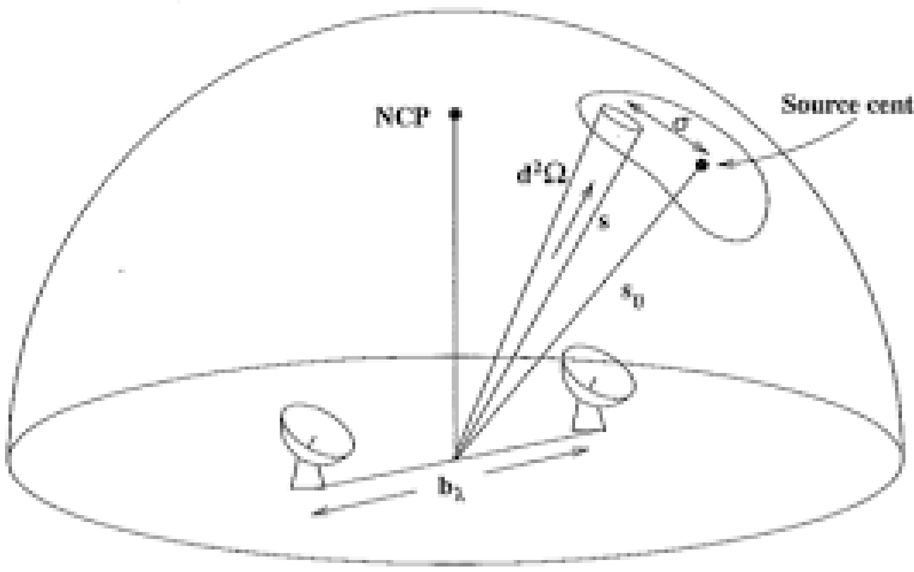
Early 1950s

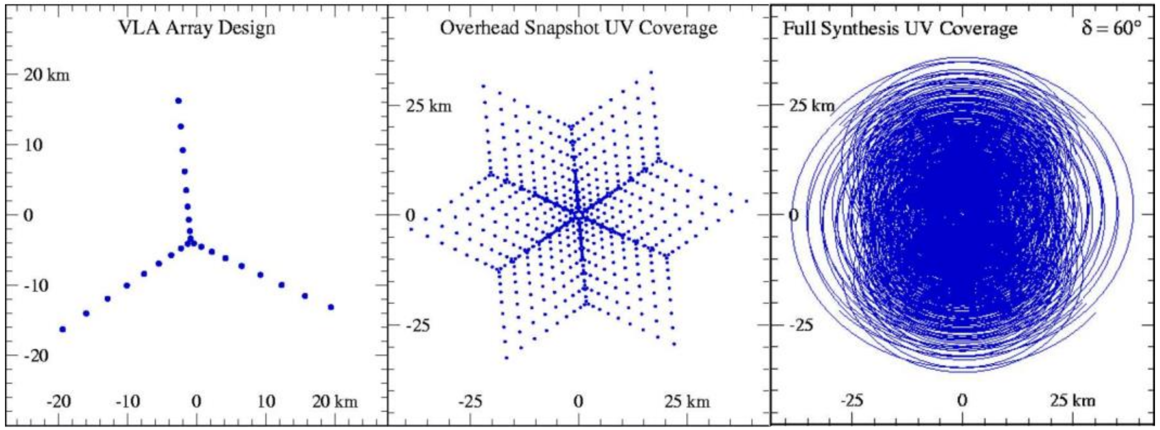
- Ryle and others developed technique of radio aperture synthesis – the basis for modern radio telescopes
- Rather than a single dish, use a number of dishes connected electronically
- 1 pair of dishes = 1 *uv* sample (Fourier transform of the sky)
- N dishes = N(N-1)/2 samples per unit time and frequency
- Fill *uv* plane by making use of Earth rotation (Ryle, 1974 Nobel prize in physics)



Early 1950s

- Ryle and others developed technique of radio aperture synthesis – the basis for modern radio telescopes
- Rather than a single dish, use a number of dishes connected electronically
- 1 pair of dishes = 1 *uv* sample (Fourier transform of the sky)
- N dishes = N(N-1)/2 samples per unit time and frequency
- Fill *uv* plane by making use of Earth rotation (Ryle, 1974 Nobel prize in physics)





Credit: NRAO

UNIVERSITY OF CAMBRIDGE

Early 1950s

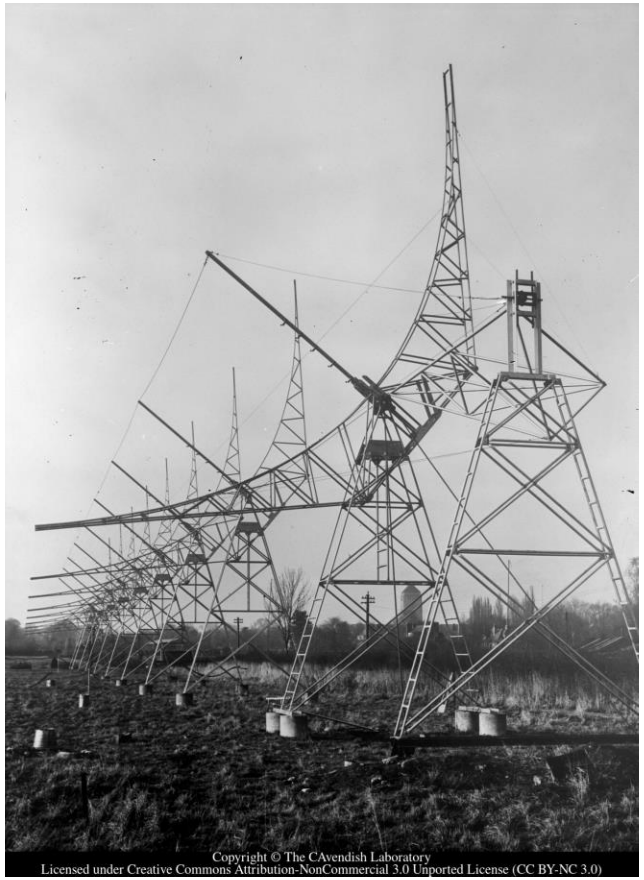
- Ryle built the Long Michelson interferometer in West Cambridge
- The first Cambridge survey of radio 'stars' (1C survey)
- 50 discrete radio sources found
- Developed the 'phased-switching' technique for radio astronomy (shifting the phases of the signals to 'point')

Ryle's 2-element Long Michelson radio interferometer

UNIVERSITY OF CAMBRIDGE

Early 1950s

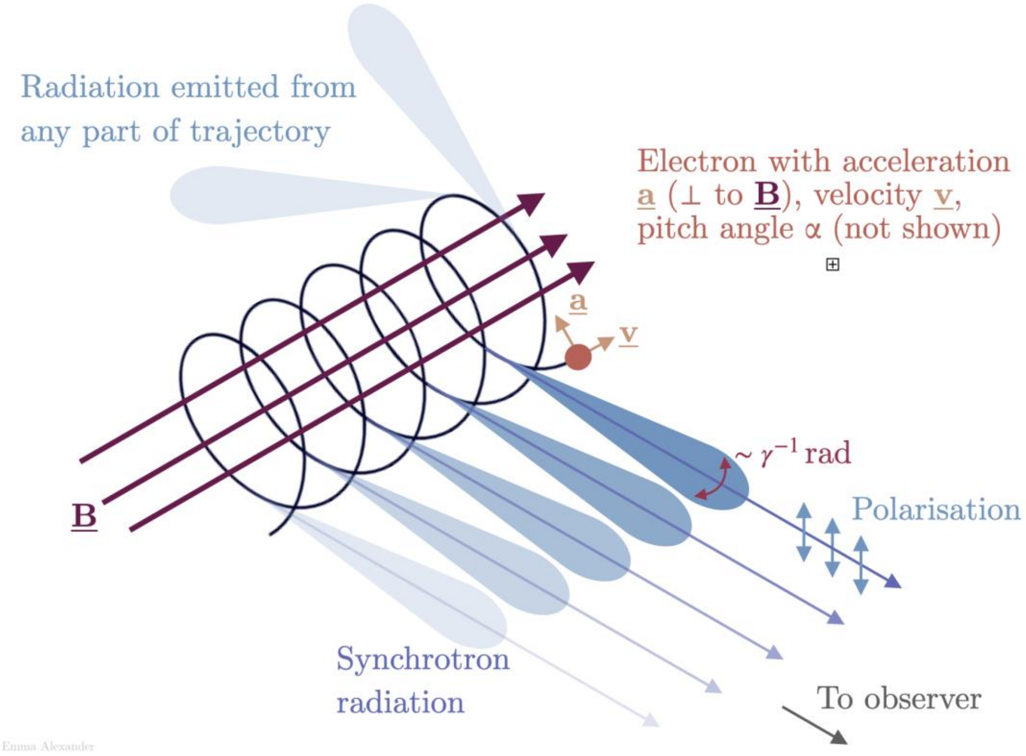
- More advanced Cambridge interferometer was built, producing the Second and Third Cambridge catalogue of radio sources (2C and 3C surveys)
- 3C survey (and its variations) is still the most widely used catalogue of radio sources today



4-element Cambridge interferometer

Early 1950s

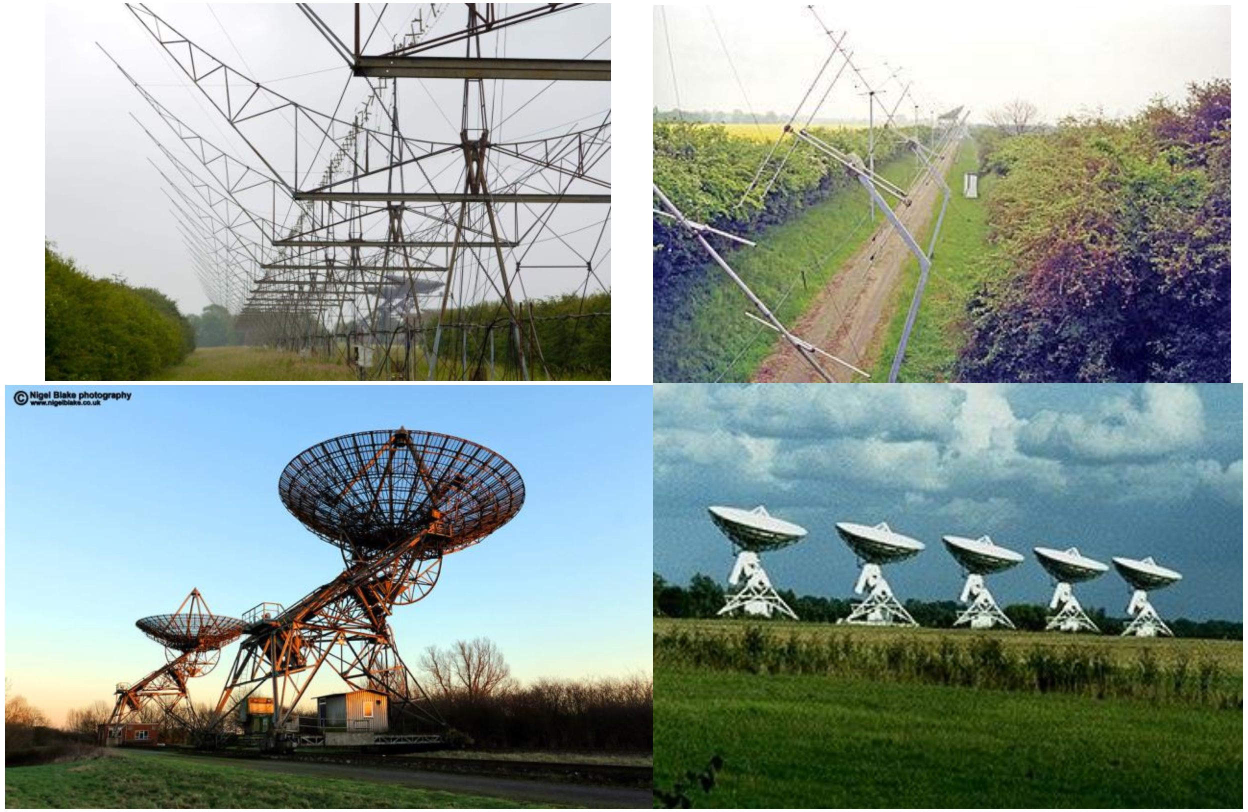
- It was discovered that the radio emission being detected was synchrotron radiation – non-thermal radiation released when electrons gyrate around magnetic fields
- Radio sources, such as Cygnus A, were identified as extragalactic (outside our Galaxy) -- this means that the energies observed must be enormous – billions of times more energetic than stars



Credit: Emma Alexander

Late 1950s

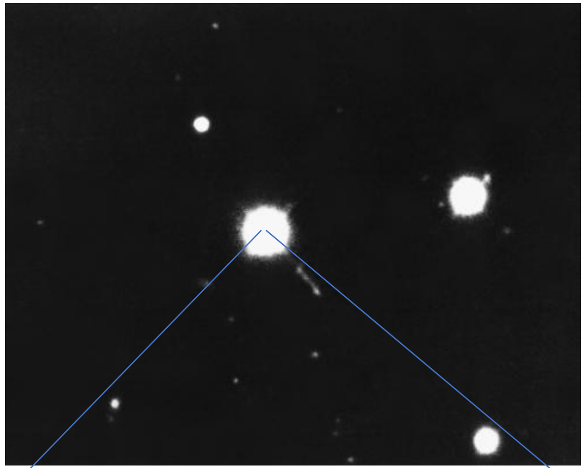
- Radio astronomy drove the development of High Energy Astrophysics
- Ryle had plans for even more advanced radio interferometers so that more radio sources could be identified
- Telescopes moved to a new, larger site – Lord's Bridge
- Mullard Radio Astronomy Observatory (MRAO) opens



The Cambridge telescopes developed by Ryle

1960s

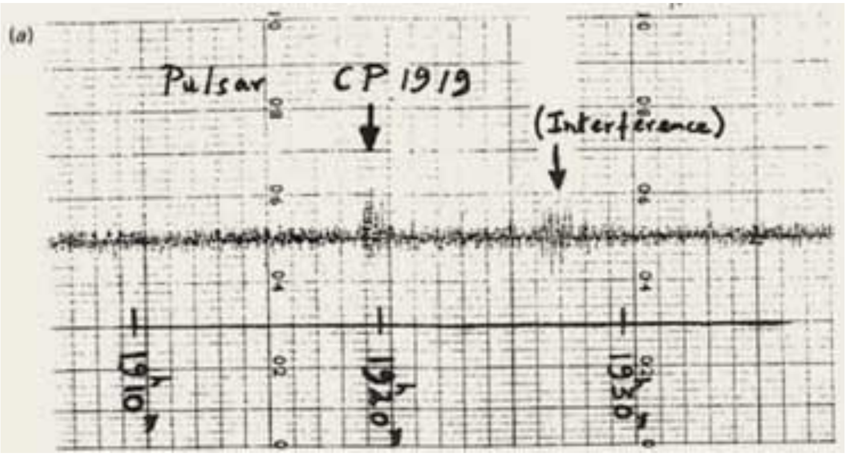
- The identification of 3C radio sources with quasars – extremely luminous galaxies with active supermassive black holes
- Measuring the redshifts of 3C quasars showed that they are very distant and very powerful, with radio powers of > 10^38 W!

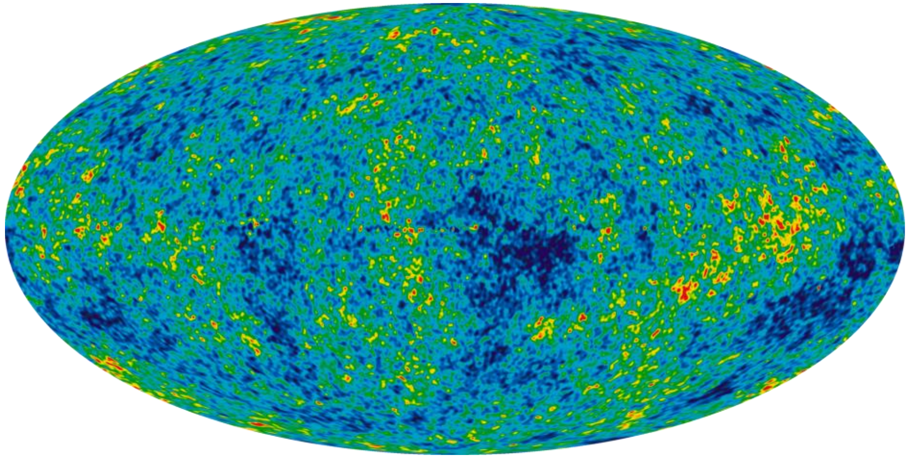


Top: Optical image of 3C 273 quasar. Bottom: Artists impression of an active black hole releasing a radio jet

1960s

- Antony Hewish dedicates new funding to building a new low frequency array to study compact radio sources
- Mapping the whole sky once a week
- His graduate student, Jocelyn Bell, found some sources with repeating pulses – discovery of pulsars
- Penzias and Wilson, at Bell Phone Laboratories, accidentally detect the Cosmic Microwave Background with a radio telescope – the relic of the Big Bang





Top: Bell's pulsar detection. Bottom: CMB map of the sky, credit: NASA/WMAP

UNIVERSITY OF CAMBRIDGE

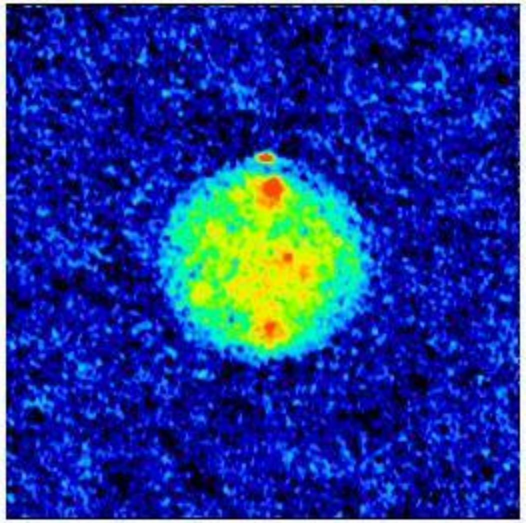
1970s-1990s

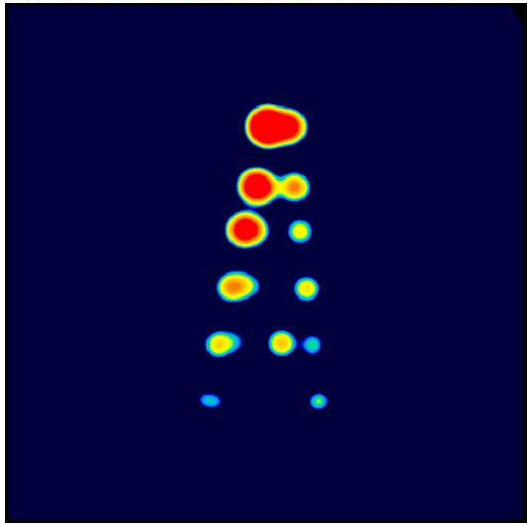
- Construction of the then next generation radio telescope begins – the Very Large Array in New Mexico
- Changed the game in terms of image fidelity – very sensitive images at high resolution
- Cambridge's 3C survey was followed up – all sources were radio galaxies

1970s-1990s

VLA:

- Discovers ice caps on Mercury
- Transforms science on stellar atmospheres
- Detects "microquasars" in our own Galaxy
- Unravels the complex gas in the center of our Galaxy
- Discovers the first Einstein Ring
- Reveals the extraordinary structures in the 3C radio survey





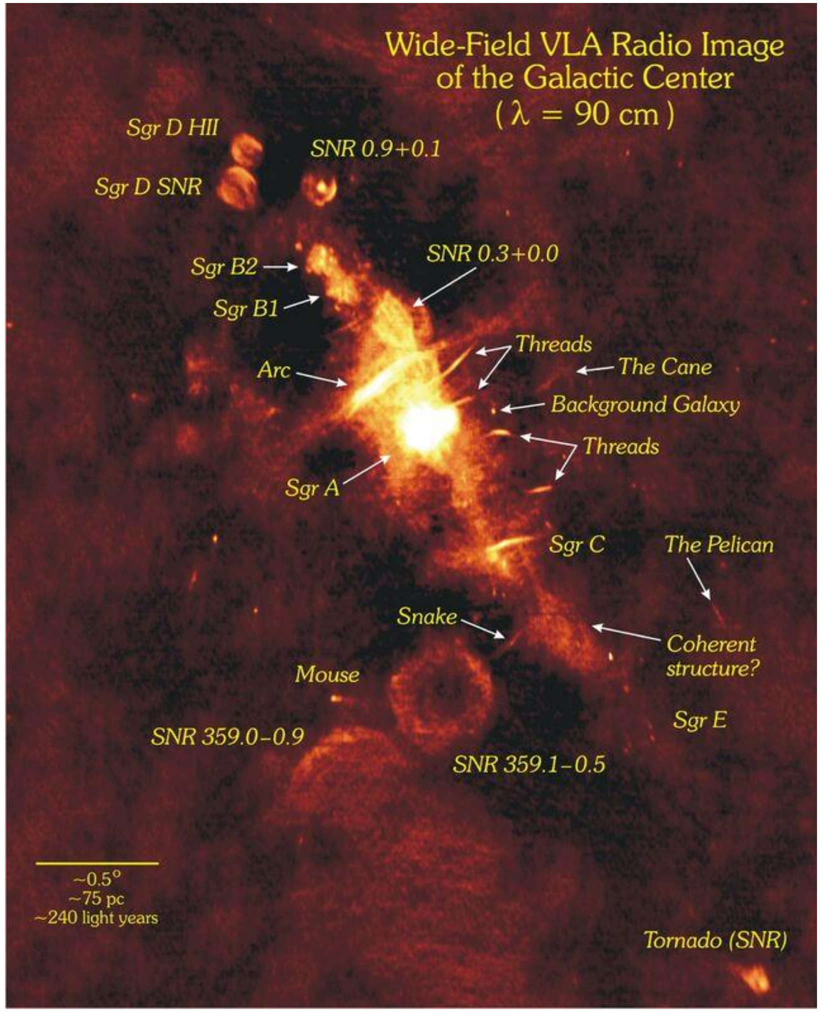
Top: Ice-poles of Mercury reflecting radio emission.
Bottom: Jets of a microquasar. Credit: NRAO

UNIVERSITY OF CAMBRIDGE

1970s-1990s

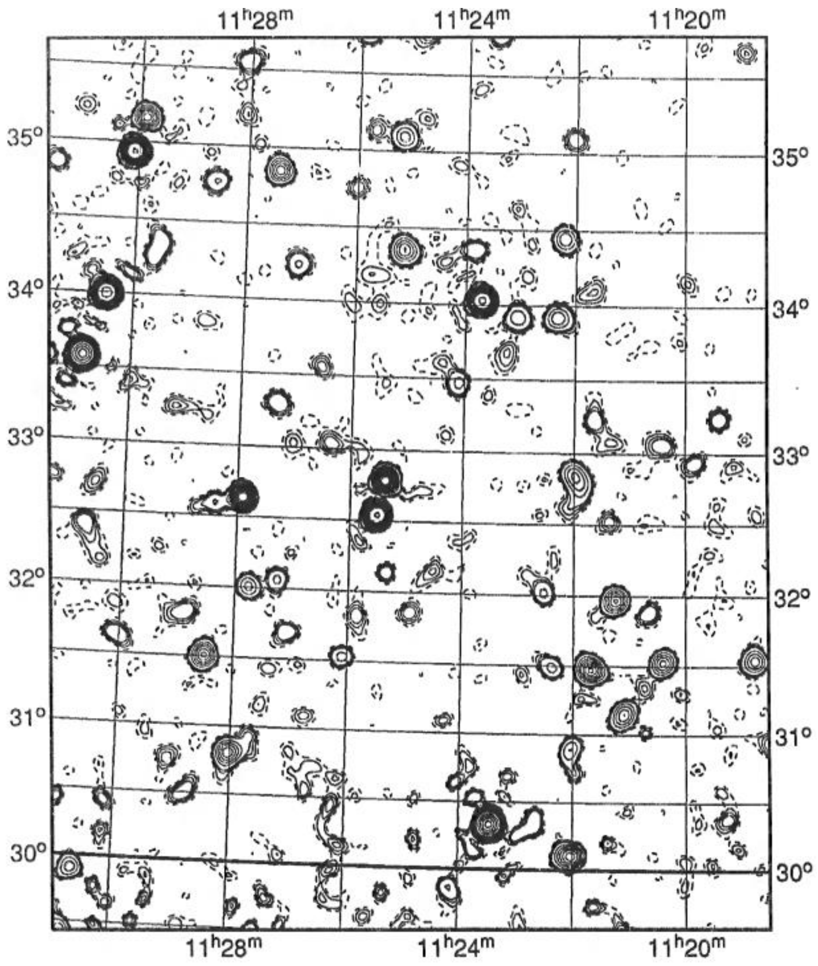
VLA:

- Discovers ice caps on Mercury
- Transforms science on stellar atmospheres
- Detects "microquasars" in our own Galaxy
- Unravels the complex gas in the center of our Galaxy
- Discovers the first Einstein Ring
- Reveals the extraordinary structures in the 3C radio survey



VLA image of the Milky Way. Credit: NRAO

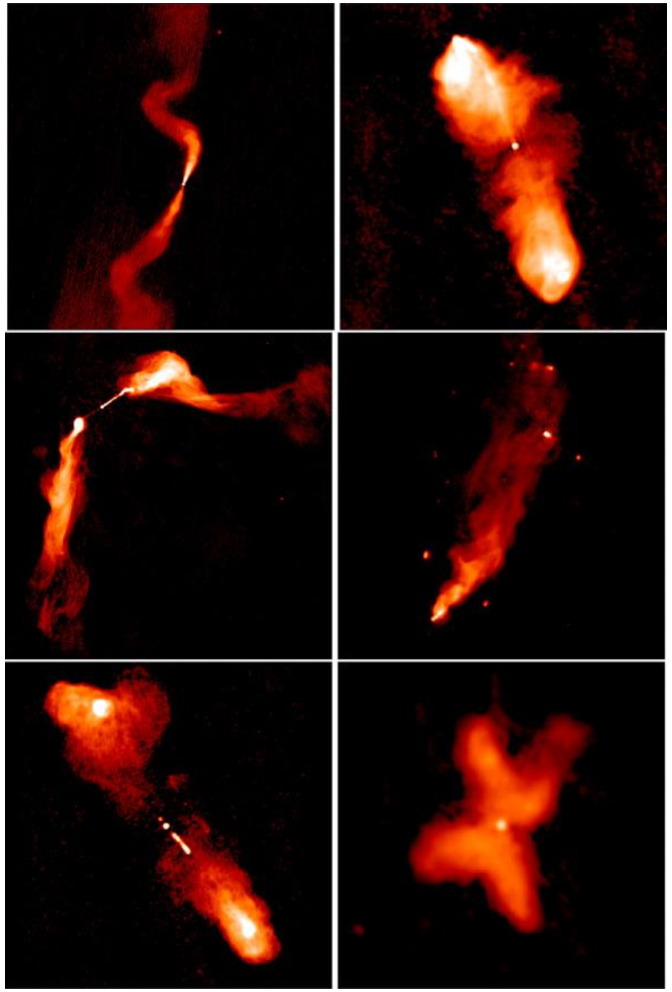
1970s-1990s



Before

The 6C survey. Hales (1988)

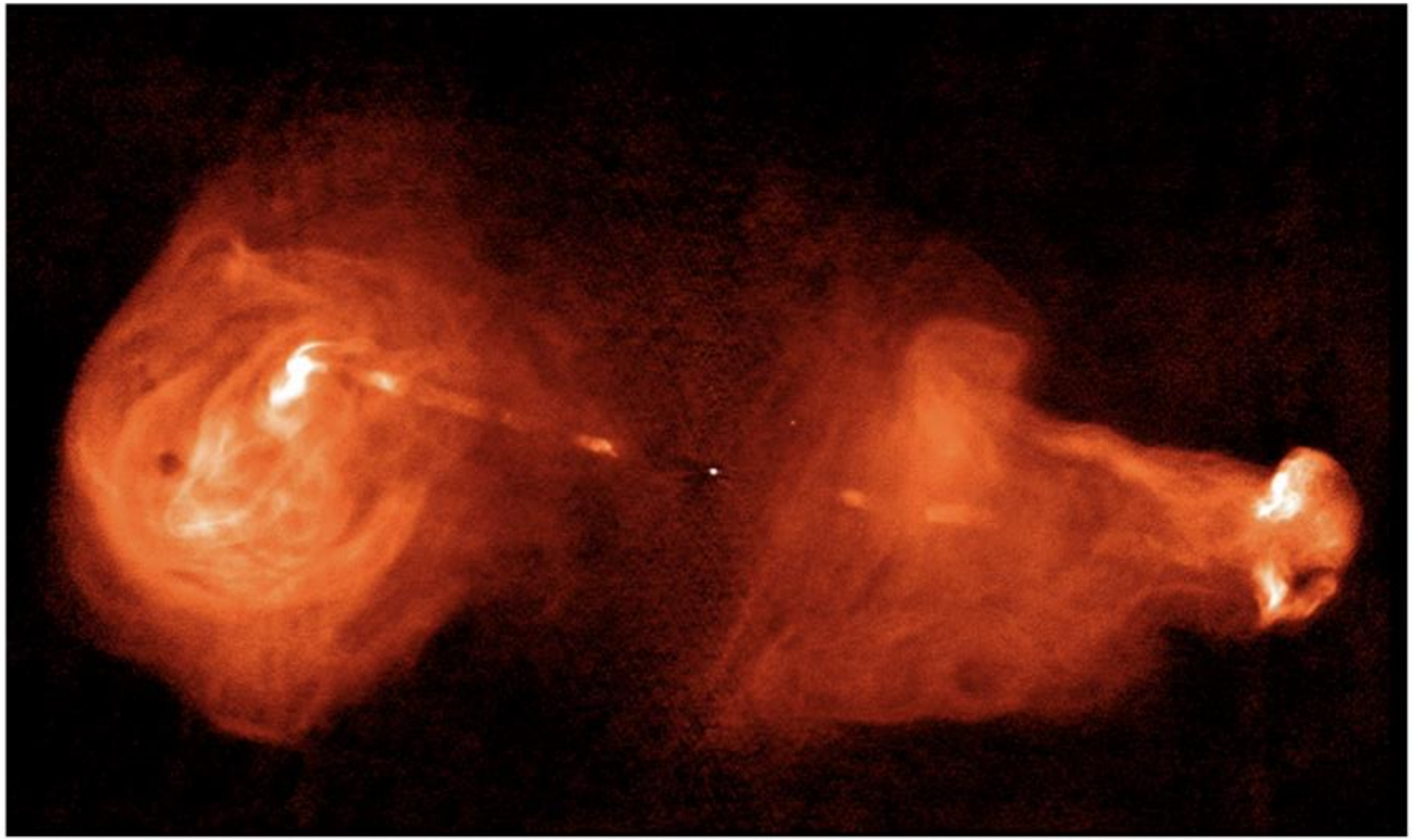
1970s-1990s



Now

VLA images of the 3C survey radio sources (Hardcastle & Croston 2020)

1970s-1990s

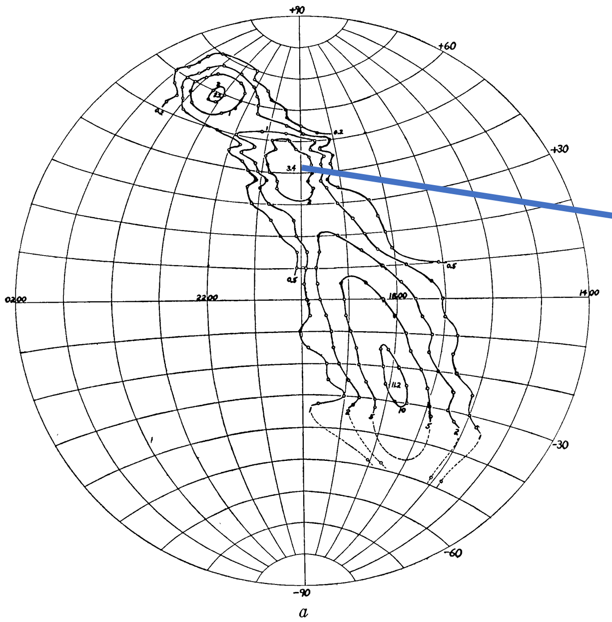


Now

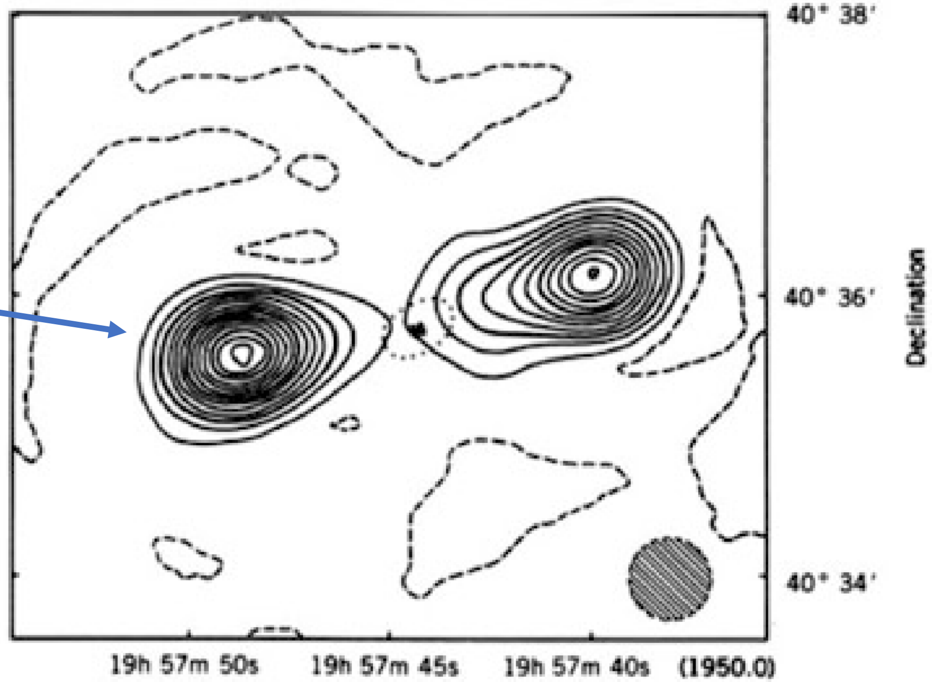
VLA image of the radio galaxy 3C 353. Credit: NRAO

UNIVERSITY OF CAMBRIDGE

1970s-1990s



The first radio map of the sky (Reber, 1944)

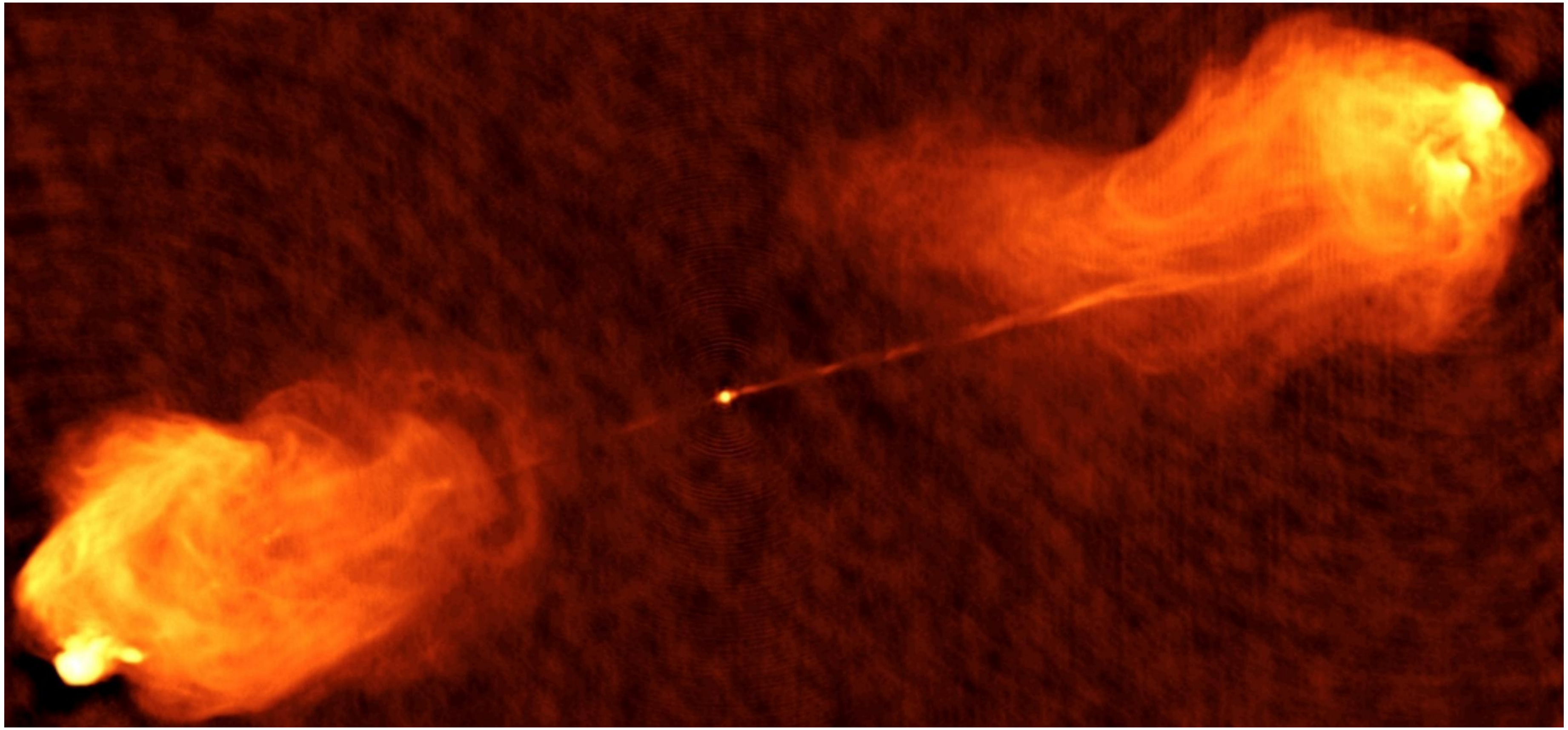


1965

The first 'resolved structure' image of Cygnus A with the Cambridge One-Mile Telescope

Before

1970s-1990s



VLA image of Cygnus A. Credit: NRAO

Now

2000s-2020s

- The Jansky VLA (JVLA; upgraded with better hardware) remains one of the most important radio telescopes
- Other newly established radio telescopes with pioneering hardware and software provided alternatives; the Low Frequency Array, MeerKAT, uGMRT, e-MERLIN, FAST (the modern radio interferometers – Lecture 3)
- Very Long Baseline Interferometry (VLBI) -- M87 Black Hole image
- Beginning of "the software telescope"

LOFAR

uGMRT

MeerKAT

FAST

UNIVERSITY OF CAMBRIDGE

2030s – the SKA era

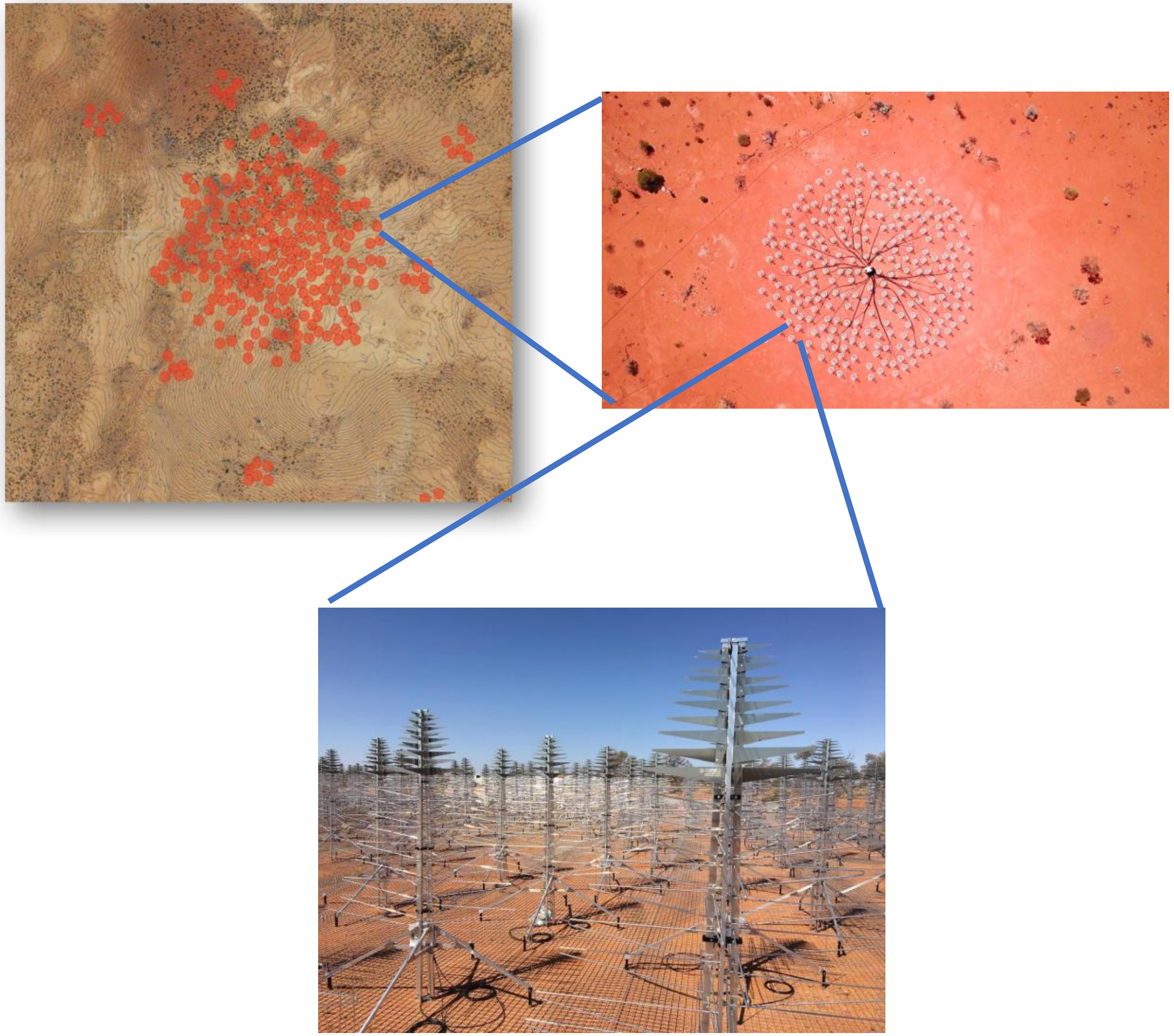
- A new paradigm is beginning – the Square Kilometer Array (SKA) era.
- Two revolutionary radio telescopes are being built: SKA-LOW (50 MHz-350 MHz) and SKA-MID (350 MHz to 15 GHz)
- Decades of experience and knowledge from existing telescopes are the foundation for the construction (hardware and software)
- 50 times more sensitive than other telescopes – achieving Key Science Objectives (Lecture 1)
- Governed by an international treaty
- Cost ~ $3 billion
- Phase 1 currently in construction – end 2028

Artists impression. Credit: SKAO

UNIVERSITY OF CAMBRIDGE

2030s – SKA -LOW

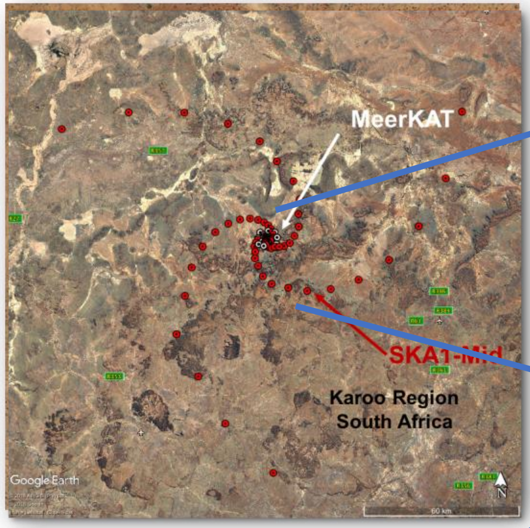
- 131,072 antennas spread between 512 stations (each station has 256 antennas)
- Design from institutions in Australia, China, Italy, Malta, the Netherlands and the UK
- Using the 'phased-array' design of LOFAR – pointing done by software
- Signals transmitted via optical fiber at 7.2 TB/s
- Signals digitized and combined at off-site correlator
- 8 times more sensitive and 135 times faster at observing than the current best low frequency telescope



UNIVERSITY OF CAMBRIDGE

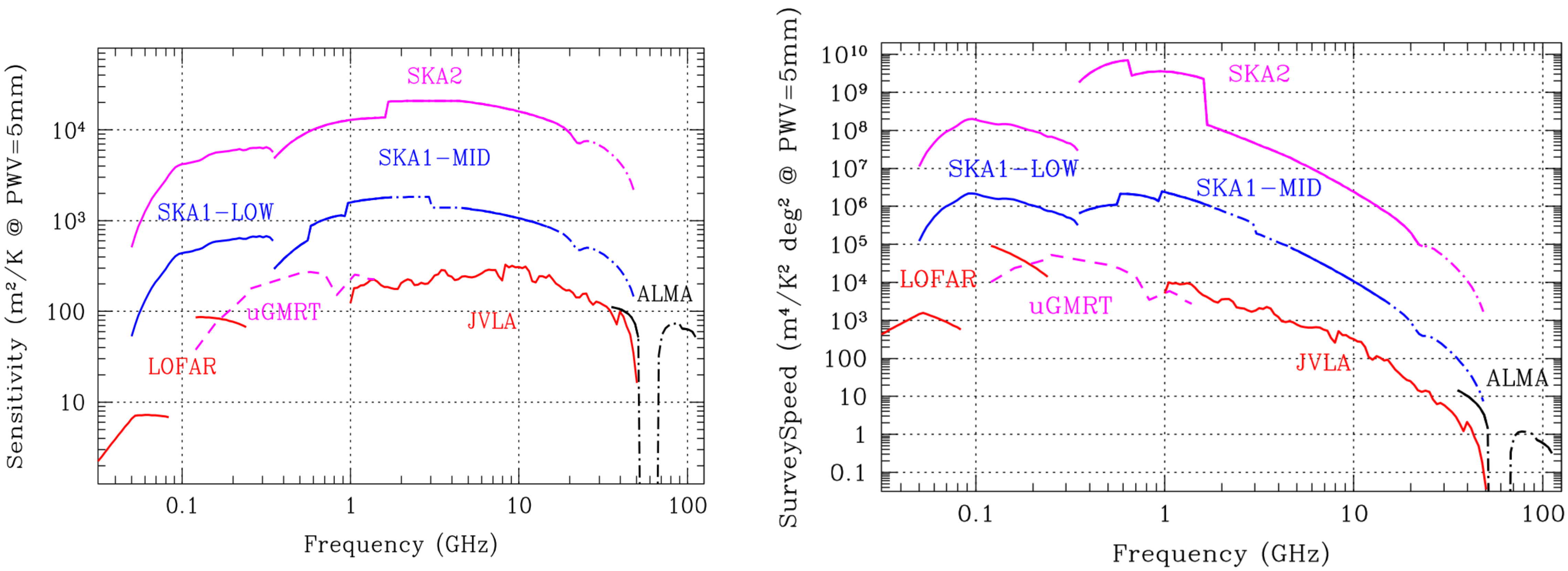
2030s – SKA -MID

- 197 fully steerable dishes, built over the current MeerKAT telescope in South Africa
- Designed by institutions in China, Australia, Canada, France, Germany, Italy, South Africa, Spain, Sweden and UK
- 4 times better resolution, 5 times better sensitivity and 60 times faster at observing than the current best: the JVLA



UNIVERSITY OF CAMBRIDGE

2030s – SKA anticipated performance



UNIVERSITY OF CAMBRIDGE

2030s – SKA anticipated performance

* Data rates approximate

UNIVERSITY OF CAMBRIDGE

2030s – SKA anticipated performance