Principles of Interferometry

Hans-Rainer Klöckner

IMPRS Black Board Lectures 2014

acknowledgement

- Mike Garrett lectures
- NRAO Summer School lectures
- Ken Kellerman talk at the Modern Radio Universe 2013
- Ian Heywood talk at the Modern Radio Universe 2013
- google provides you with 2.8 Million hits enjoy it

Synopsis

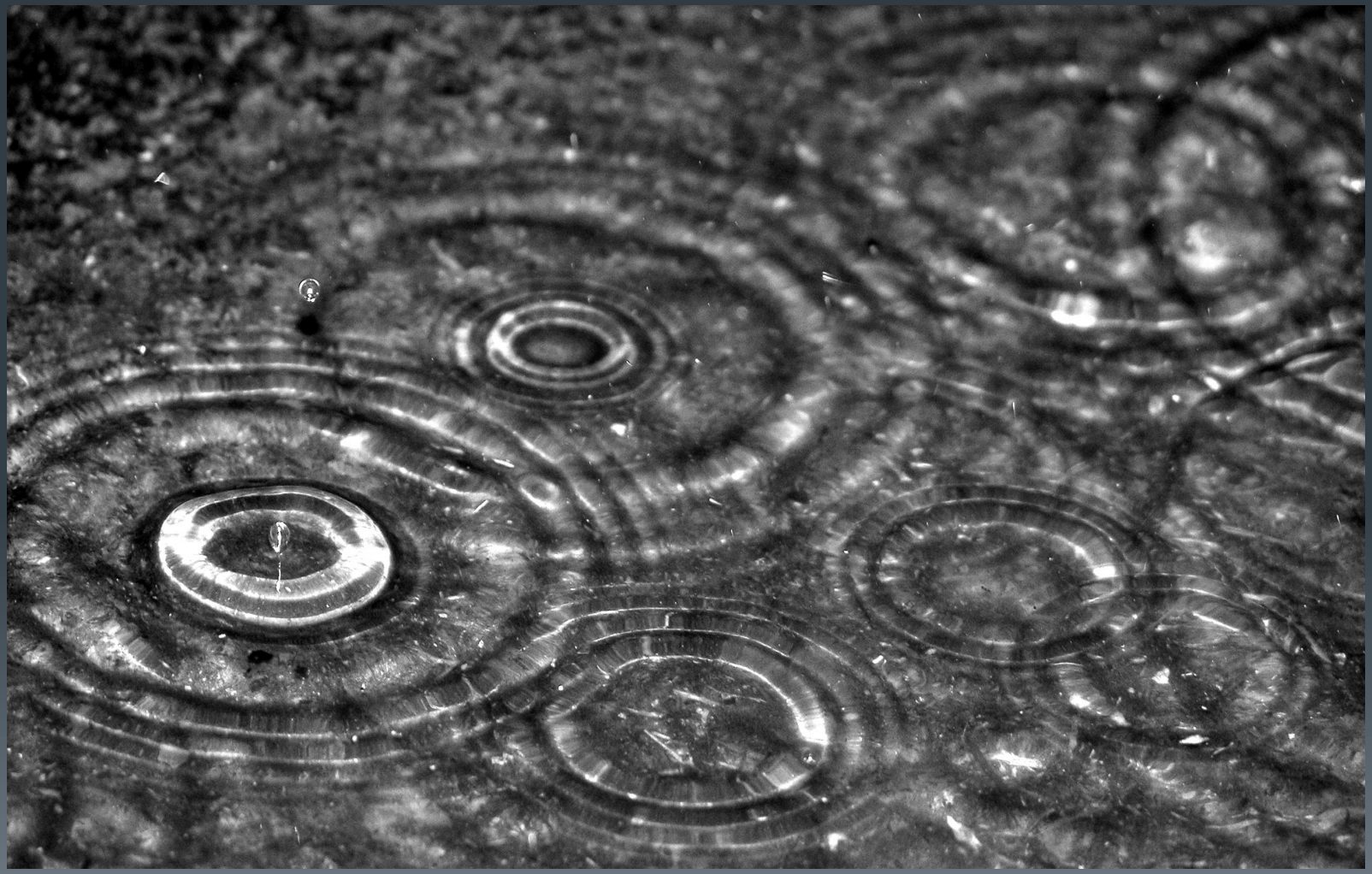
- Radio Interferometry and Synthesis Imaging is the art to synthesise a very large effective aperture from a number of "smaller" antennas. Combining the signals of these antennas will result in a meaningful property that can be used as a diagnostic tool to investigate the original state of the received radio waves.

- In this light the lectures will explain the theory and the technical requirements needed to successfully measure extra-terrestrial radio emission.

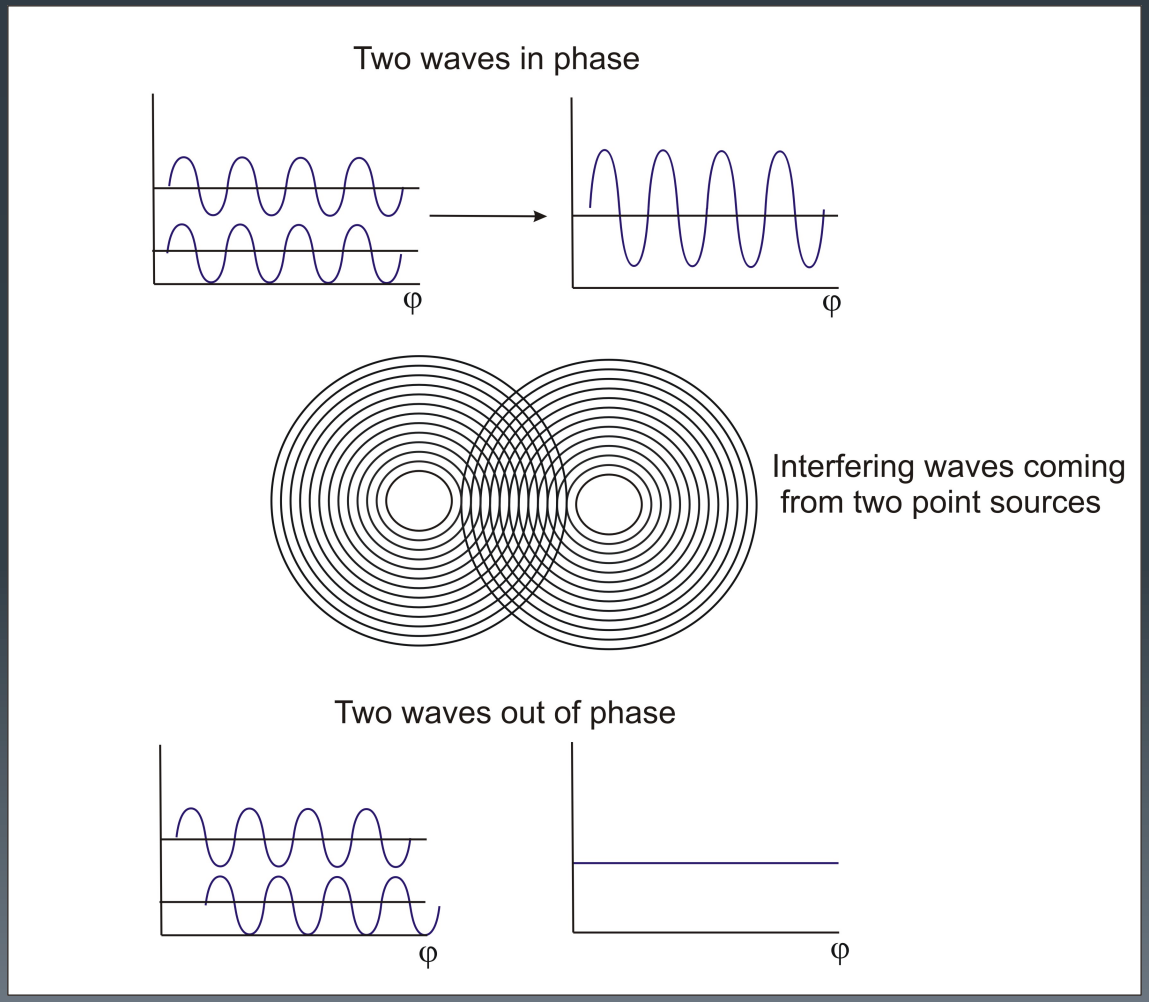
Lecture 1

- concepts of interferometry
- early history of radio astronomy
- cosmic radio emission
- radio telescopes
- interferometers

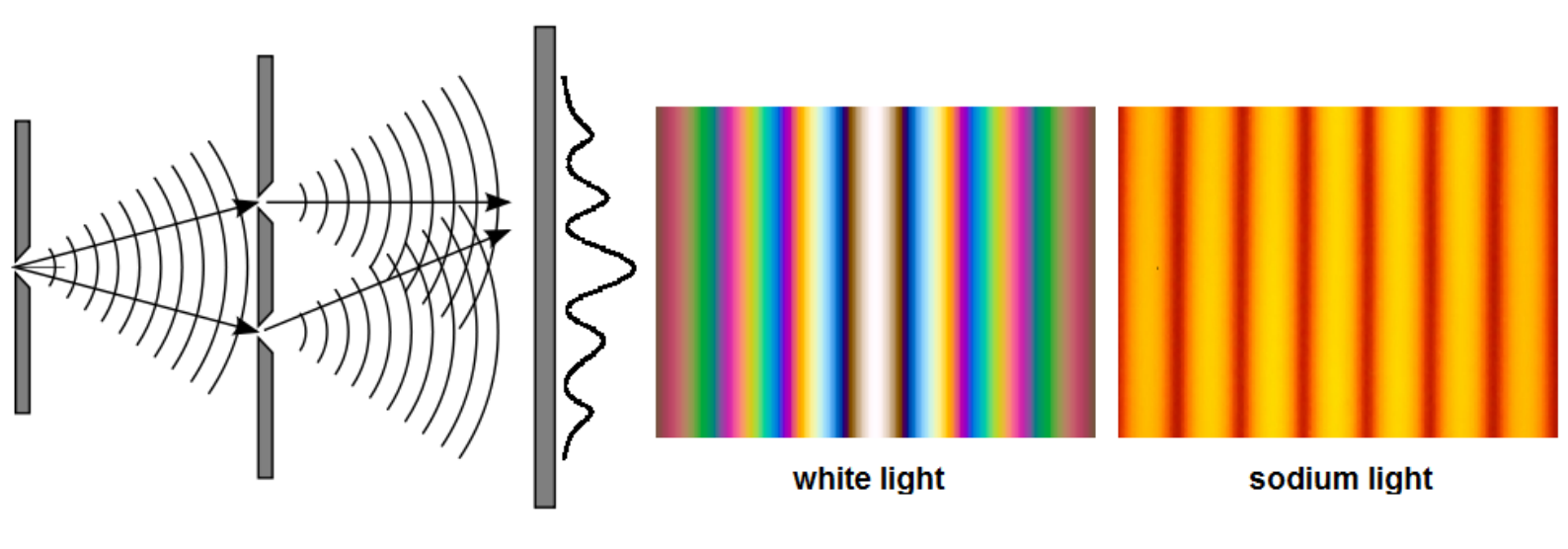
the basics



fringe pattern

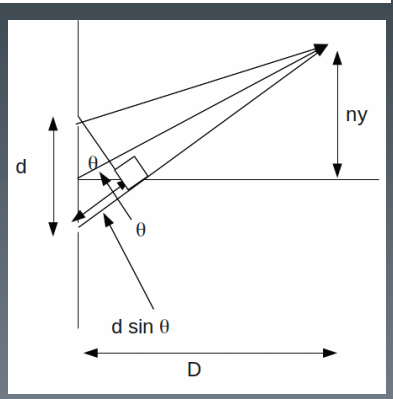


Young's two-slit experiment

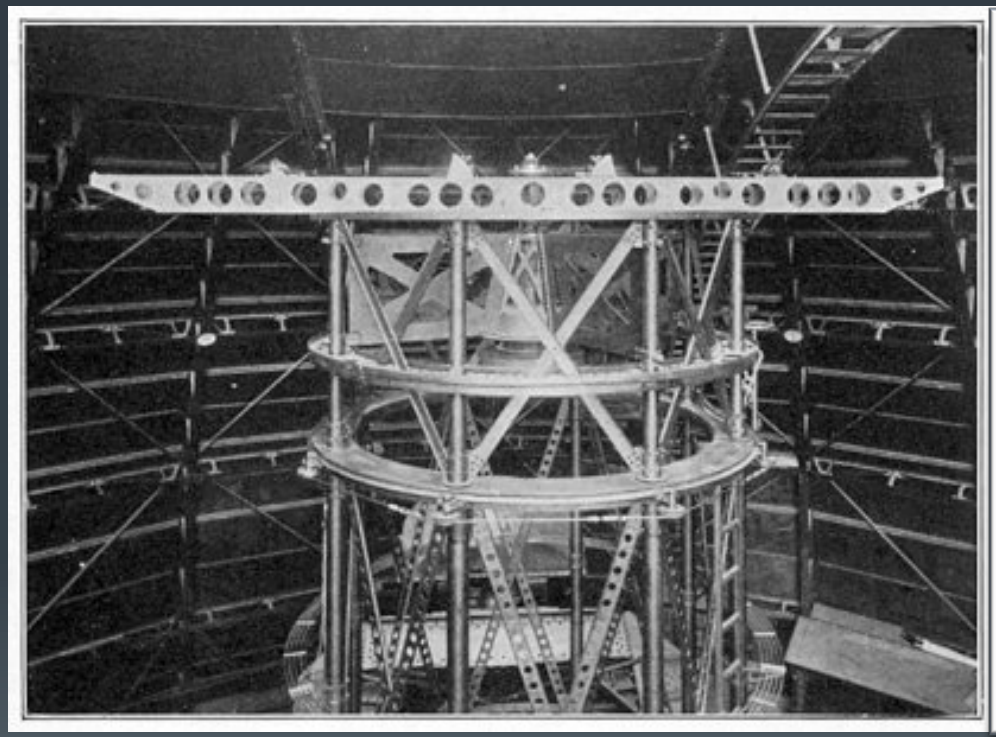


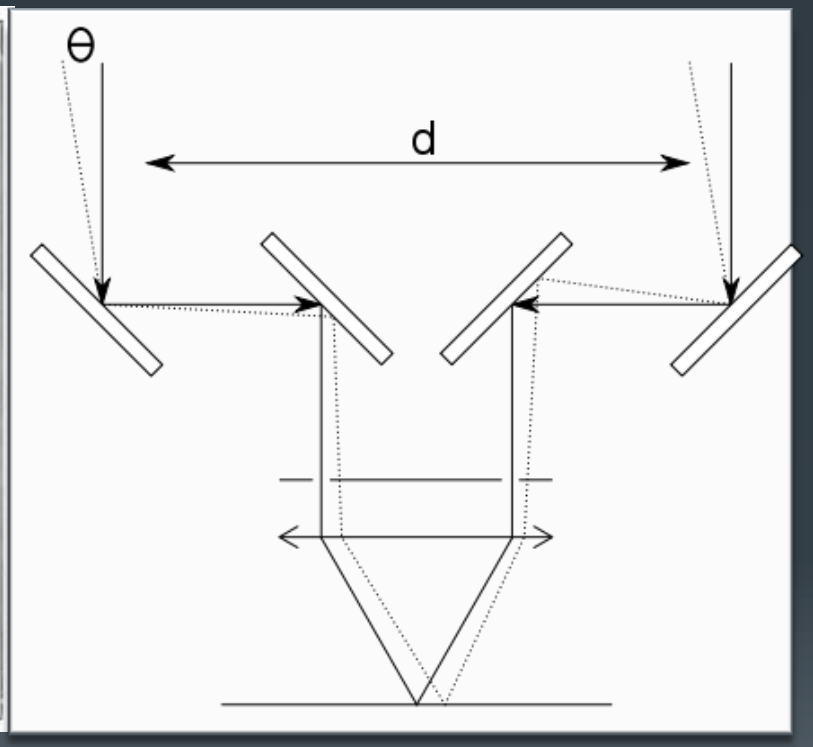
bright fringes (maxima): $y = n \lambda D / d$

angular measure $\theta \sim \lambda / d$



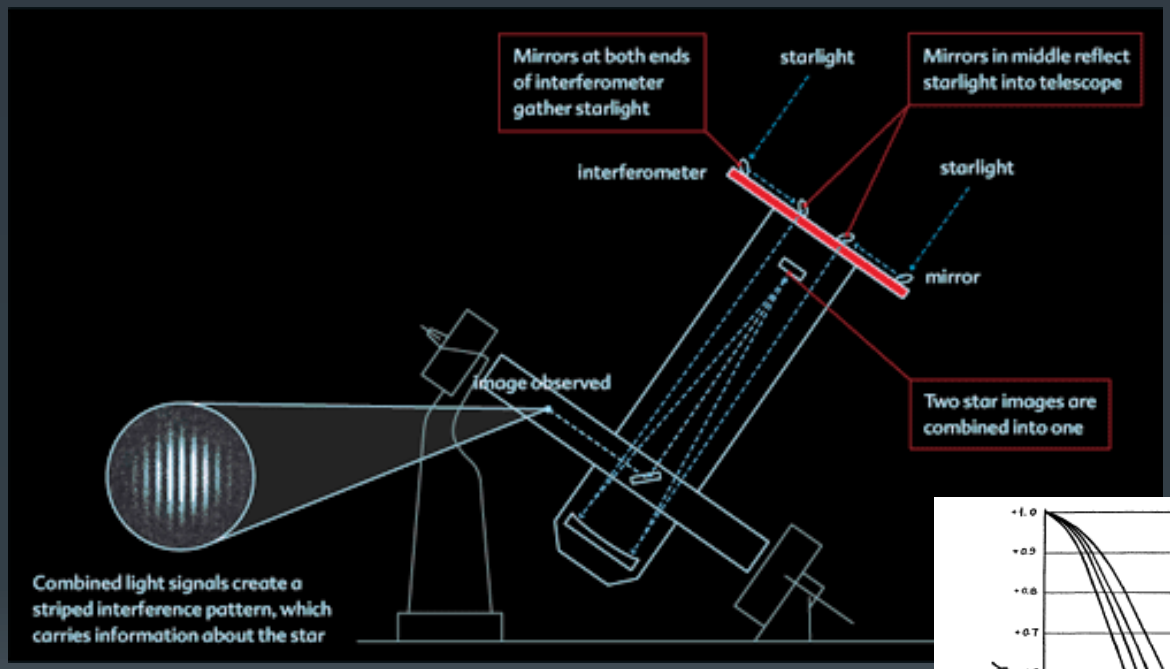
Michelson Stellar Interferometer





Mount Wilson 100 inch Mirror

Michelson Stellar Interferometer



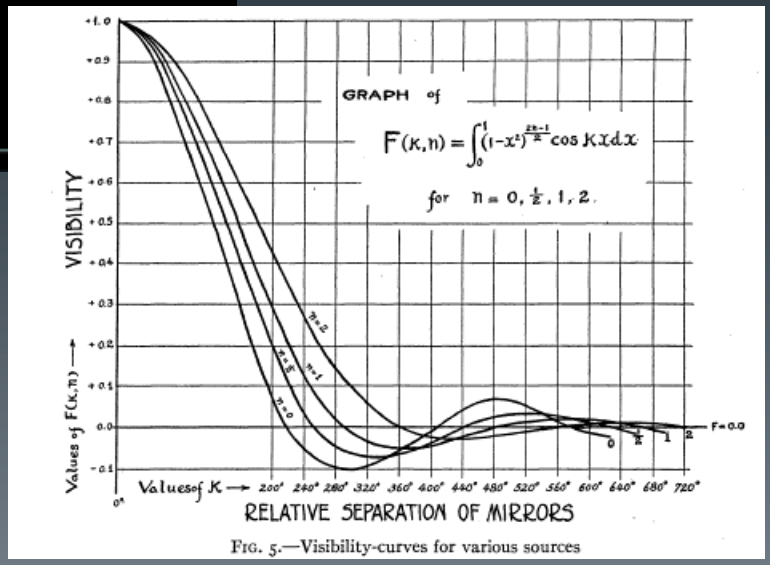


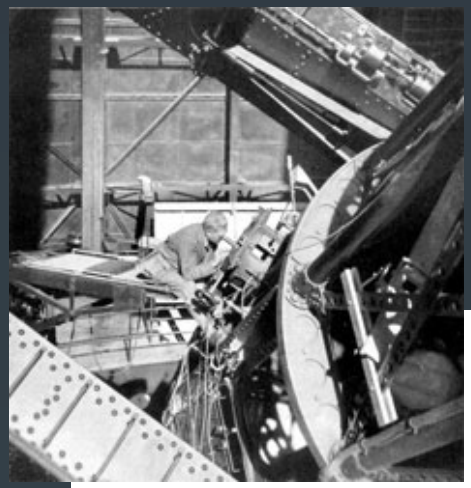
FIG. 5.—Visibility-curves for various sources

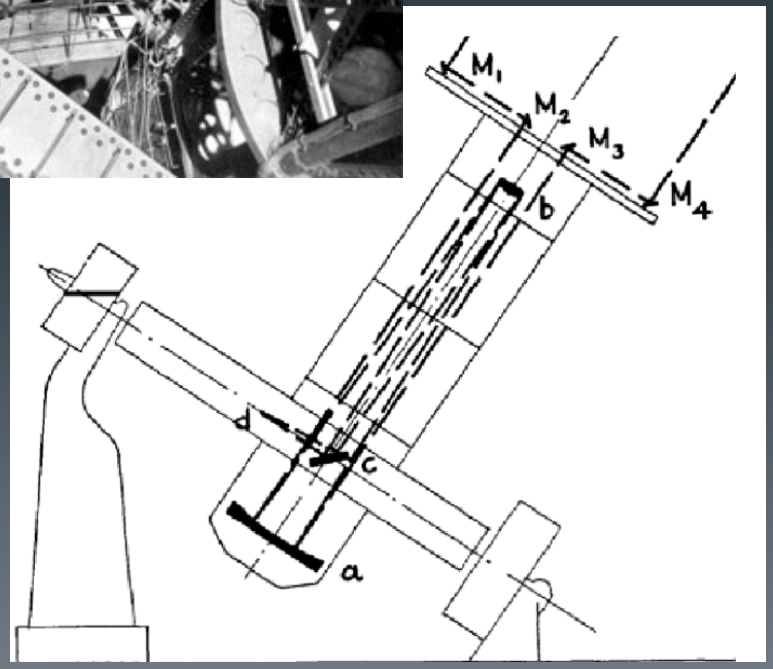
Betegeuse diameter of 380 Million km

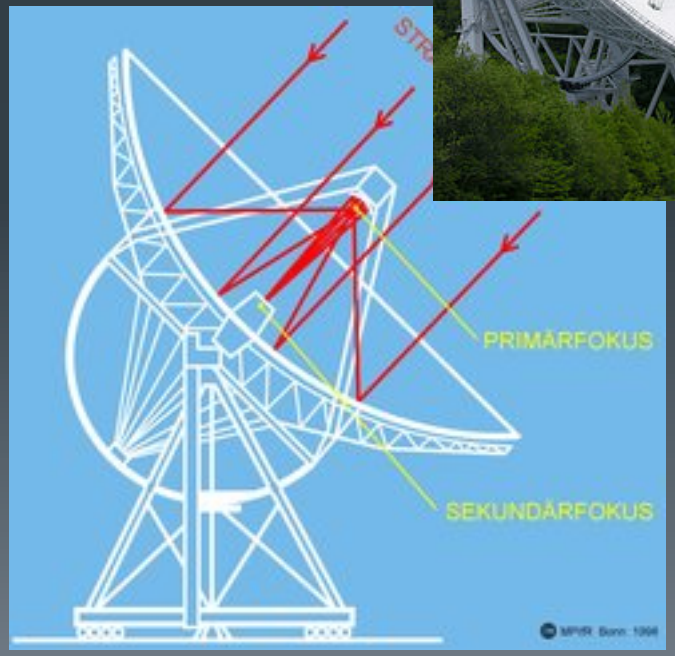
Michelson, A. A. & Pease, F. G., 1921, ApJ, 1921, 53, 249

geometrical optics

collect the cosmic rays
by mirror or parabola



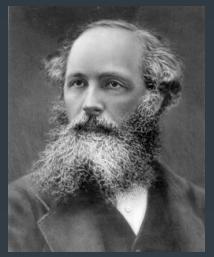




radio emission

- The whole information content (amplitude and phase) of the incoming radiation can only be recorded at radio frequencies and processed either real time or after observation
- Radio waves largely unaffected by dust.
- Can observe day and night.
- The power received from a (rather strong) 1 Jy radio source over a 100 m radio telescope is only 0.000000000000001 (10−15) Watts but still it is very easy to detect.

Historical Background



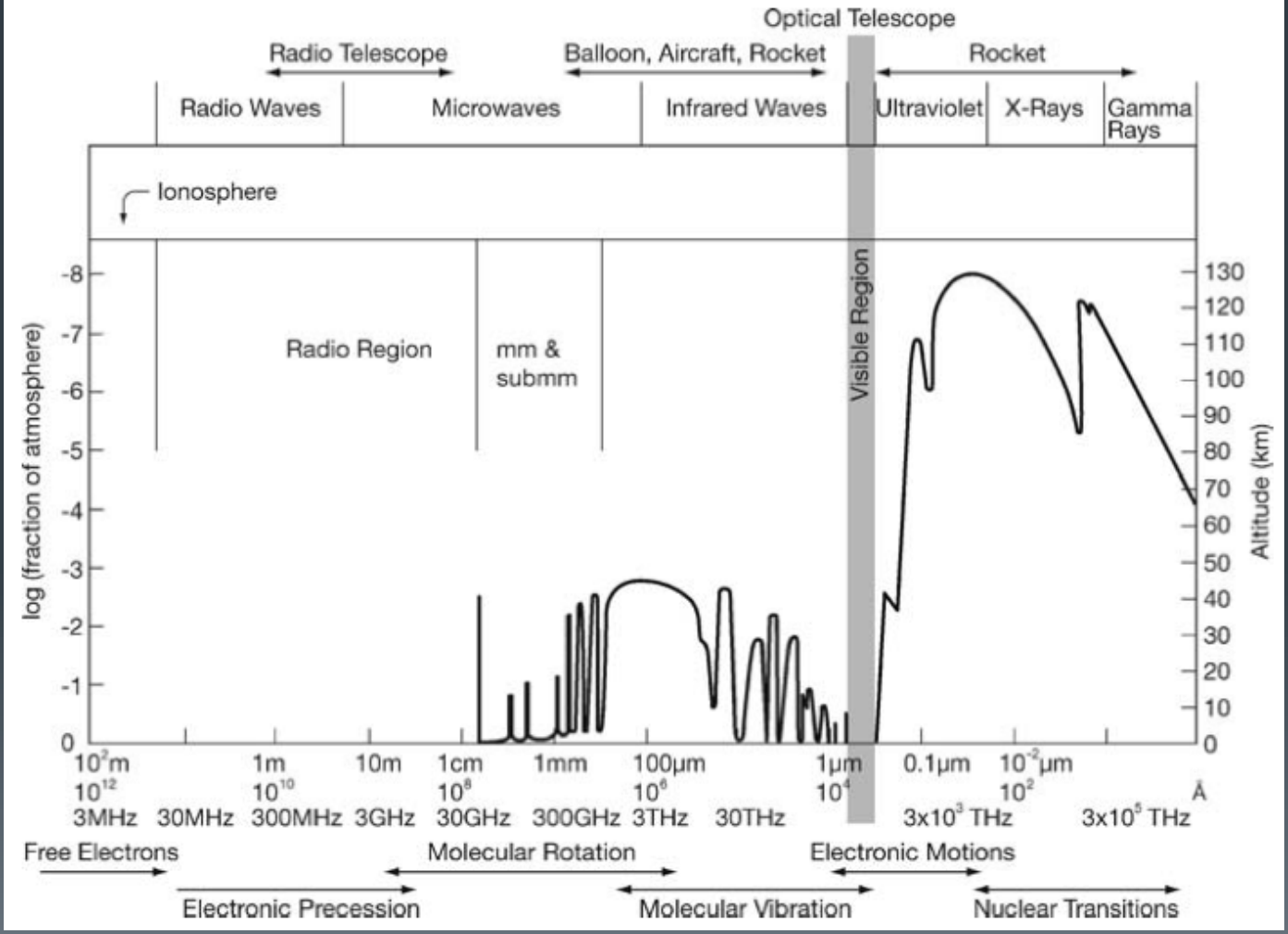
- James Clerk Maxwell develops the laws of electro-magnetism (Maxwell's laws 1861).
- Maxwell's equations describe light as a wave-like phenomenon in which the electric field (E) and the magnetic field B are at right angles to each other, as well as to the direction of the propagation of the wave.
- Energy alternates periodically between the electric and magnetic fields. The disturbance propagates at a constant speed (c) in a vacuum.
- Maxwell's laws also show that electro-magnetic radiation can span a wide-range of wavelengths and that light is just a subset of the electro-magnetic spectrum.

$$\nabla \cdot \mathbf{E} = 0 \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \nabla \times \mathbf{B} = \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}.$$

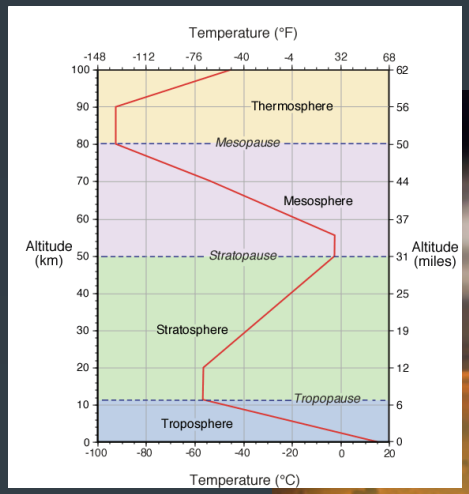
vacuum equations

atmospheric window

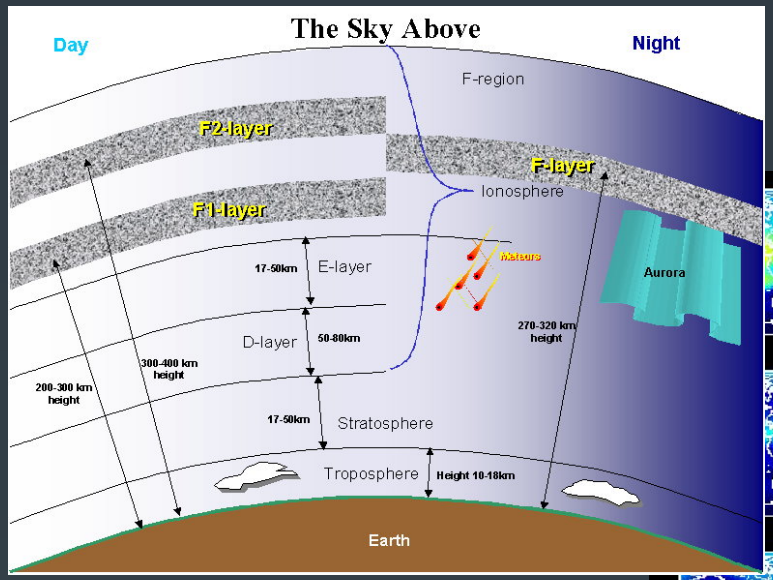


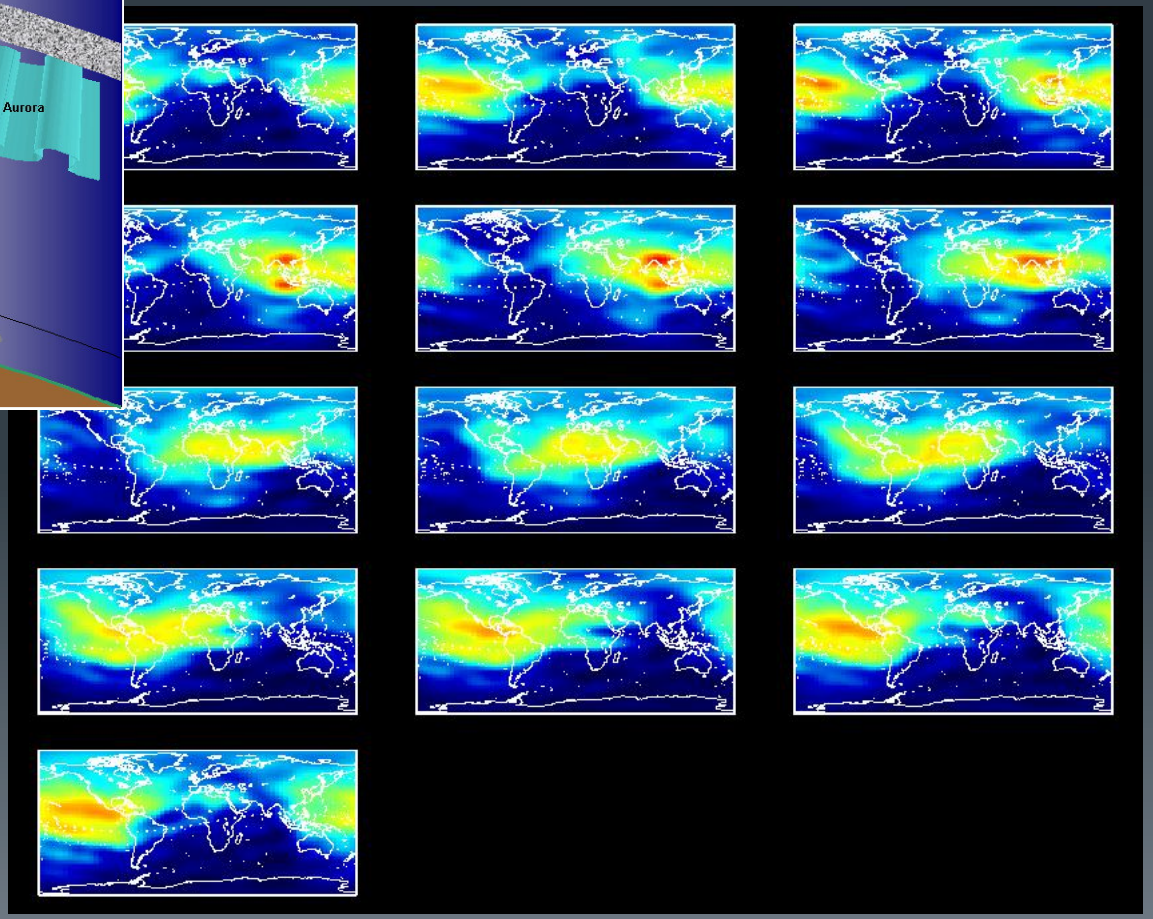
transparent between 15 MHz to 1.5 THz

Troposphere



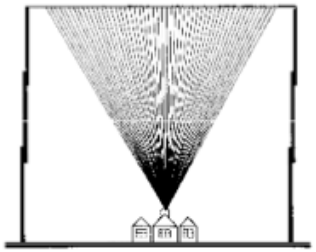
Ionosphere


The Sky Above
Day
Night
F-region
F2-layer
F1-layer
F-layer
Ionosphere
17-50km
E-layer
Meteors
Aurora
D-layer
50-80km
270-320 km height
300-400 km height
200-300 km height
17-50km
Stratosphere
Troposphere
Height 10-18km
Earth



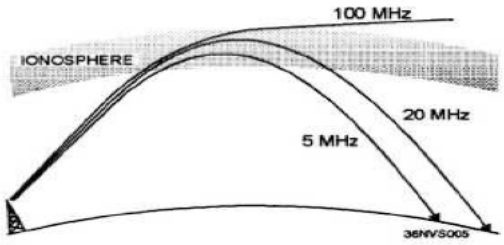
refracting ionosphere

Marconi invented the ground antenna and experimented with antenna arrays. He realised that the directivity (gain) of his array was as important as the total power radiated. Images: Marconi's array at Poldhu Corwall where the first transatlantic signals were transmitted and received (Newfoundland).



Below: Receiving antenna borne by a kite in St. Johns, Newfoundland, Canada

Marconi's success led to the discovery of the ionosphere (right) & its reflective and refractive properties w.r.t. (low-frequency) radio wave propogation:



1909 shared Nobel Prize in Physics – in recognition of their contribution to the development of wireless telegraphy

the beginnings

Alexander Graham Bell invents the telephone - Bell telephone Company created in 1877 - it will play a significant role in radio astronomy over the next 100 years:

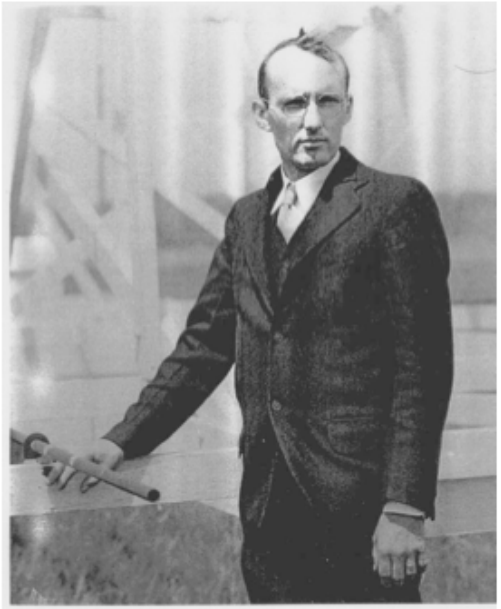


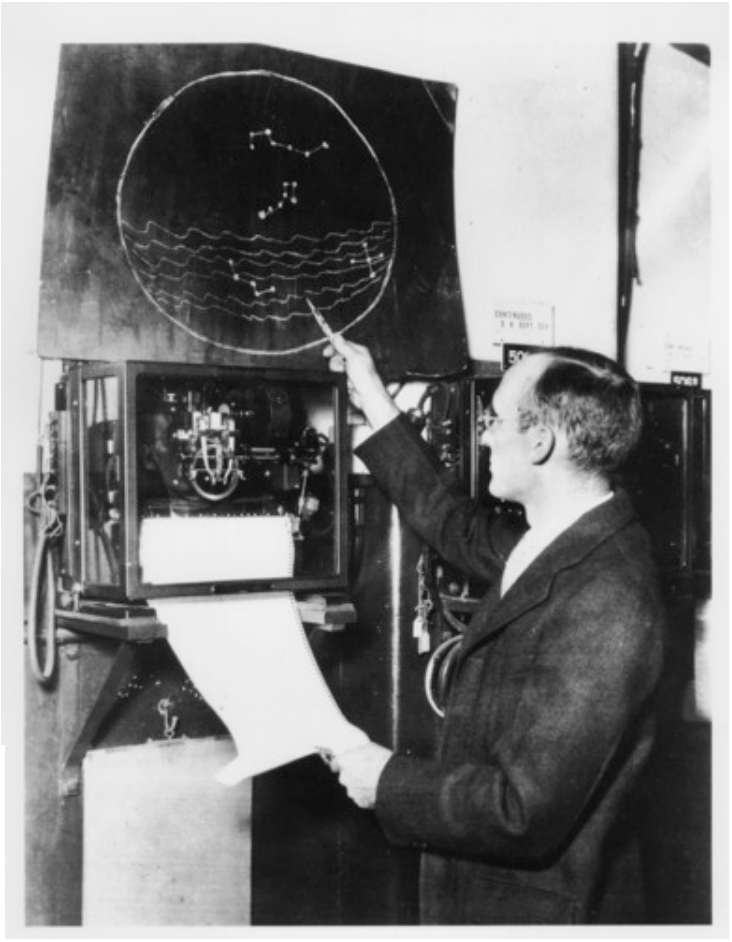
FIG. 1—Karl Guthe Jansky, about 1933.

1930's Karl Jansky - communication engineer at Bell Laboratory begins to investigate sources of radio noise that adversely affected communications - cross-country, transatlantic etc.

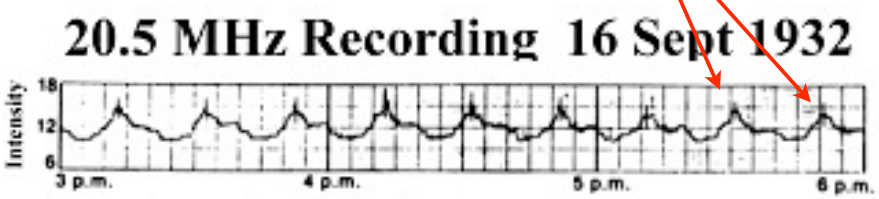
Identified thunderstorms (near and far) and something else....

Early History of Radio Astronomy

1932 Discovery of cosmic radio waves (Karl Jansky):

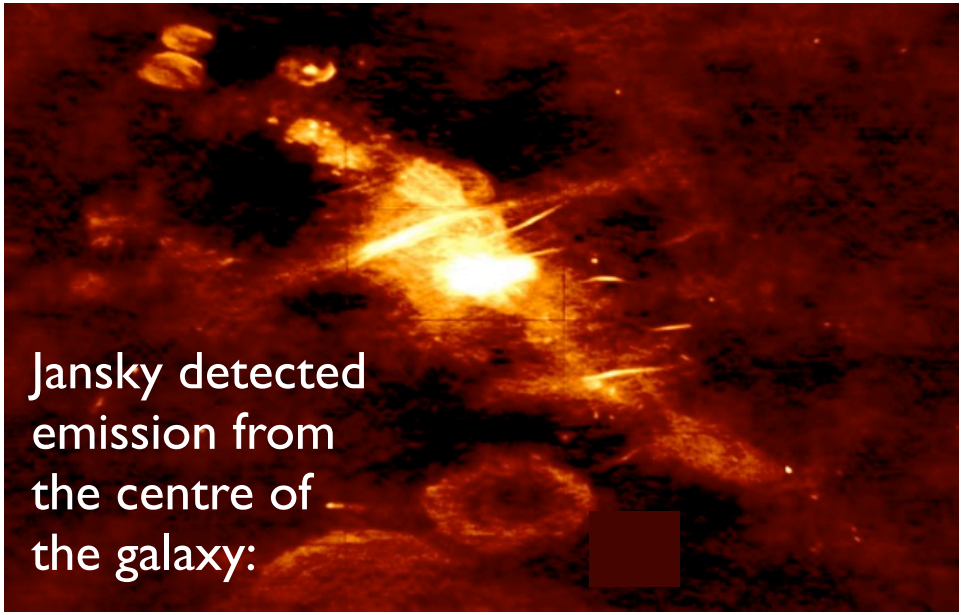


Galactic centre



... mostly ignored

New York Times:



Jansky detected emission from the centre of the galaxy:

"*There is no indication of any kind, that these results are the form of some 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."

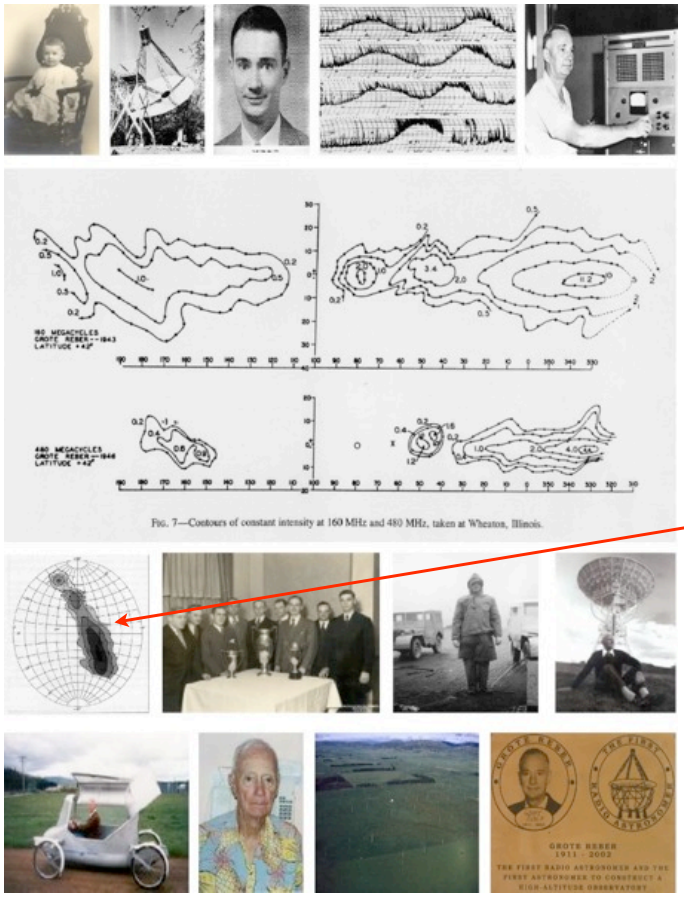
There is no indication of any kind, Mr. Jansky replied to a question, that these galactic radio waves constitute some kind of interstellar signalling, or that they are the result of some form of intelligence striving for intra-galactic communication.

Radio Entertains the Children With Crime, drama Mass in May Scribner's.—Advt.

80 Years of Discoveries

1933 Cosmic radio emission
1938 Non-thermal radiation
1942 Solar radio bursts
1949 Radio galaxies
1951 HI
1955 Cosmic evolution
1955 Jupiter bursts
1959 Jupiter radiation belts
1963 Quasars and AGN
1963 Interstellar molecules
1965 Pulsars
1965 CMB
1965 Mercury rotation
1965 Cosmic masers
1979 Gravitational lensing
1982 Gravitational radiation
1992 Extra solar planets

The first radio astronomer (Grote Reber)



Built the first parabolic radio telescope:

- "Good" angular resolution

- Good visibility of the sky

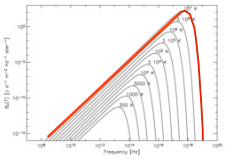
- Detected Milky Way, Sun, Cas-A, Cyg-A, Cyg-X @ 160 & 480 MHz (ca. 1939-1947).

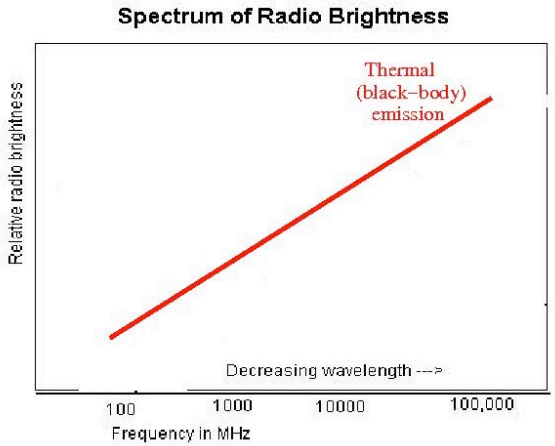
- Published his results in ApJ

- Multi-frequency observations

non – thermal radio emission

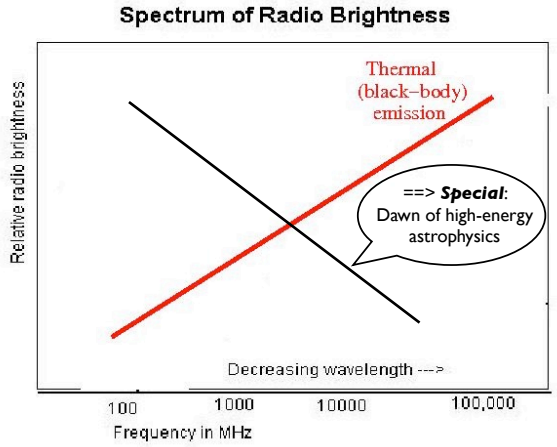
Reber's multi-frequency observations revealed the non-thermal nature of radio emission:





The things that make radio astronomy "special":

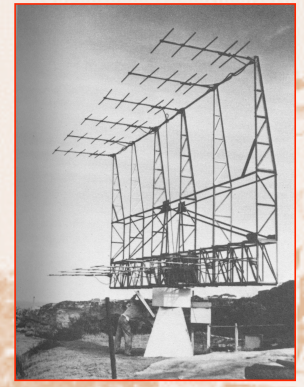
Reber's multi-frequency observations revealed the non-thermal nature of radio emission (UNEXPECTED!)





Radio galaxies

"Positions of Three Discrete Sources of Galactic Radio-Frequency Radiation"
Bolton, Stanley, and Slee, 1949, Nature 164, 101



"NGC 5128 and NGC 4486 (M87) have not been resolved into stars, so there is little direct evidence that they are true galaxies. … would indicate that they are [within our own Galaxy]."



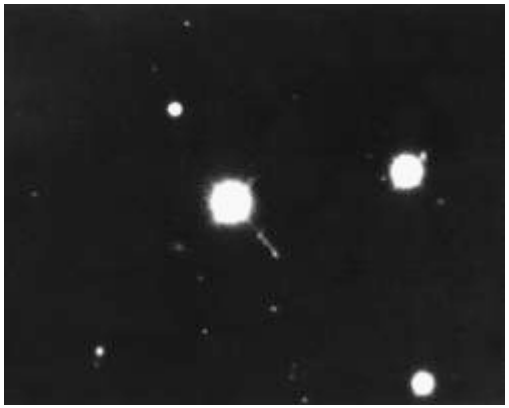
The first Quasar: 3C 48

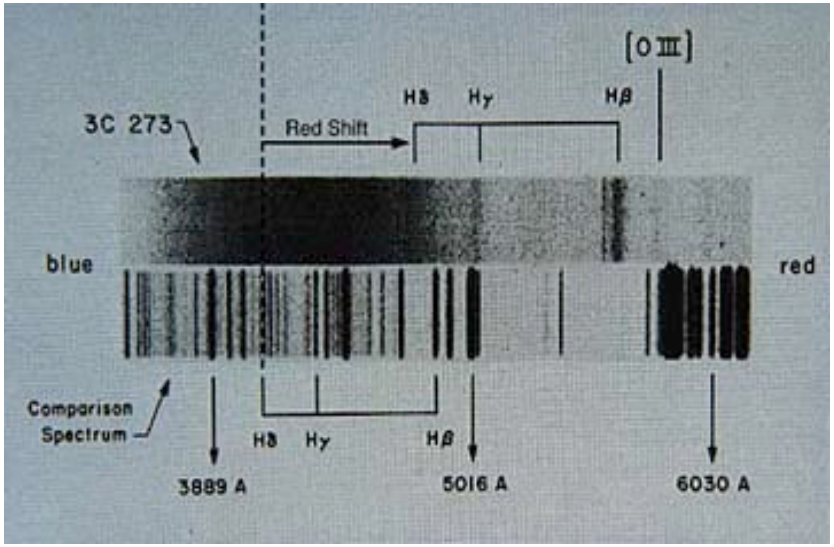
- November 1960: Bolton and Matthews identify 3C 48 with star-like object
  - Bolton claims z= 0.37
  - Greenstein and Bowen dismiss redshift
  - 3C 48 declared “first true radio star”
- Bolton returns to Australia
  - Concentrates on constructing Parkes 210-ft
  - Forgets about 3C 48

Discovery of Quasars -1963

In the 1950s/60s the great challenge was to identify radio sources with optical counterparts.

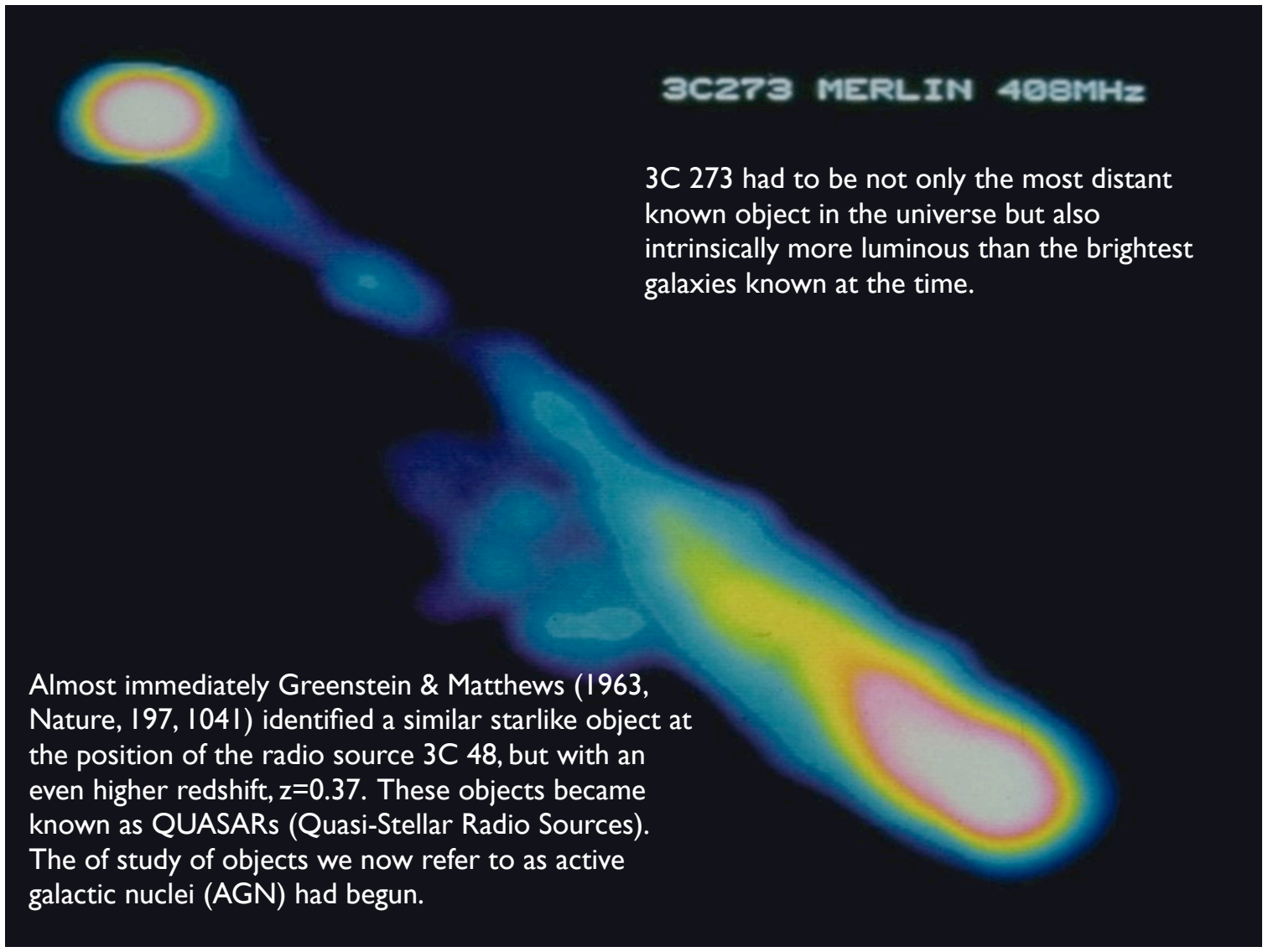
In 1963 one of the brightest radio sources then known, 3C273, was identified with a faint blue 13th mag star-like source (Hazard et al. Nature)...





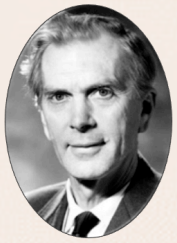
Maarten Schmidt (1963, Nature, 197, 1040) examined a visible spectrum of this "star" and identified the characteristic spectrum of emission lines in the Balmer series of hydrogen Doppler-shifted to longer wavelengths by 16 percent!

$z = 0.16$



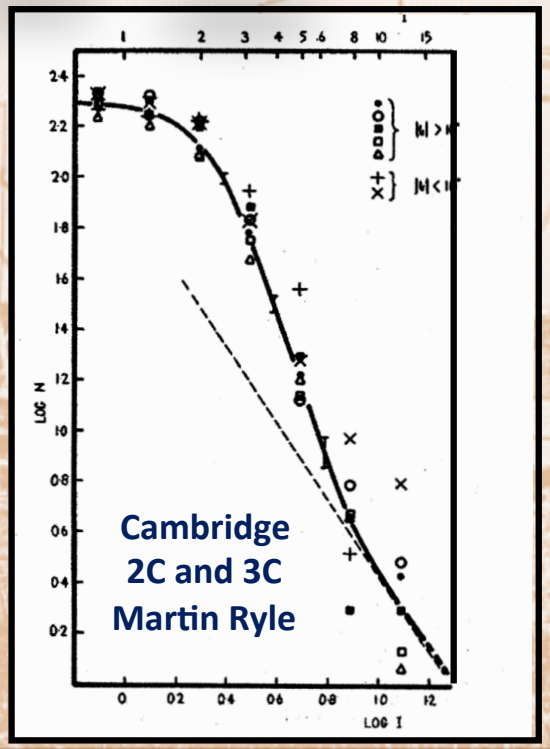
3C 273 had to be not only the most distant known object in the universe but also intrinsically more luminous than the brightest galaxies known at the time.

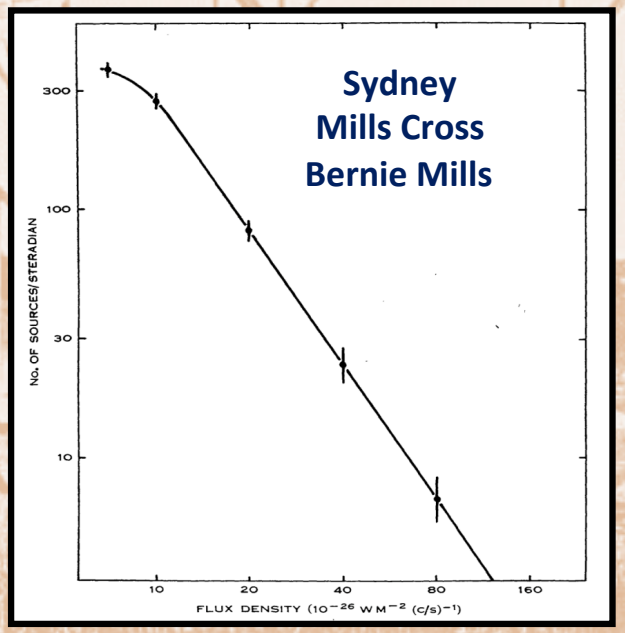
Almost immediately Greenstein & Matthews (1963, Nature, 197, 1041) identified a similar starlike object at the position of the radio source 3C 48, but with an even higher redshift, z=0.37. These objects became known as QUASARs (Quasi-Stellar Radio Sources). The of study of objects we now refer to as active galactic nuclei (AGN) had begun.



Radio Source Counts and Cosmic Evolution

$N(S)=KS\_1.5$



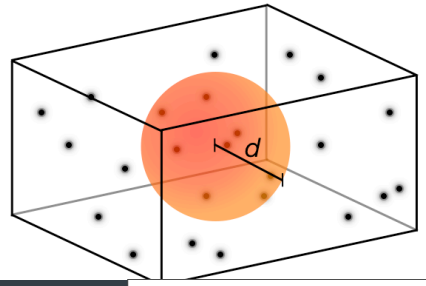


source count

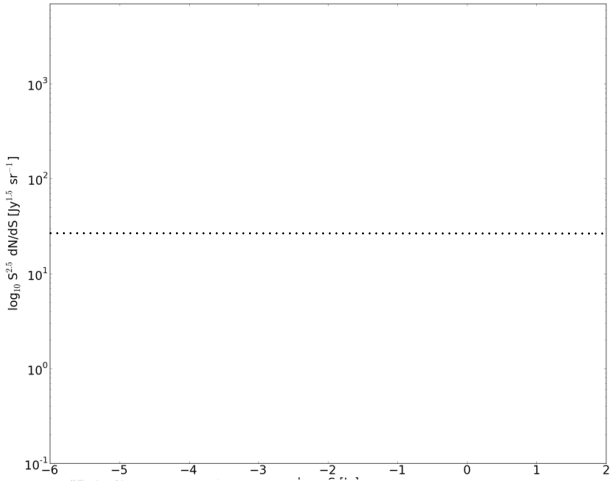
A non-expanding Euclidean (i.e. zero curvature) universe filled with luminosity L sources with number density n contains $N = 4\pi n d^3/3$ sources out to distance d.

Since the flux density $S = L / 4\pi d^2$

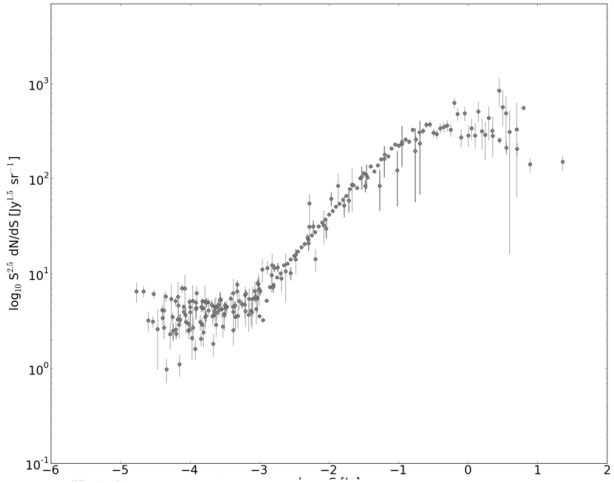
the source counts $N(S) \propto S^{-3/2}$ and $dN/dS \propto S^{-5/2}$.

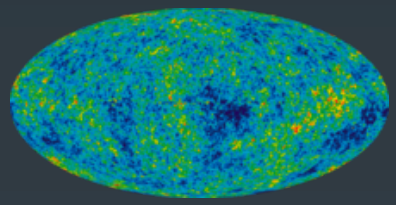


Differential source counts in a non-expanding Euclidean universe



Observed Euclidean-normalised differential source counts





Cosmic Microwave Background: an Ignored or Forgotten Prediction

- Discovered by Penzias and Wilson
  - Working at same Bell Labs as Jansky
- Predicted by George Gamov in 1946
- Bob Dicke re-predicted CMB
- Beaten by Penzias and Wilson in 1965
  - Prediction not known to Penzias and Wilson
  - Penzias and Wilson did not set out to discover the CMB
  - Did not understand the implications of their discovery
- 4 Nobel prize winners (Penzias, Wilson, Mather & Smoot)
- CMB actually detected 1941 from CN excitation of 2.3K

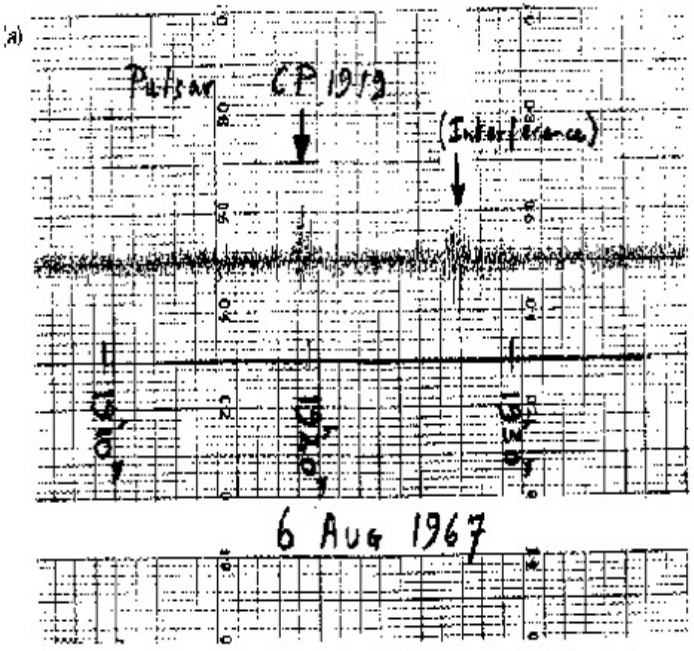
Discovery of Pulsars -1967

Pulsars discovered by Jocelyn Belll-Burnell (PhD student) and Anthony Hewish, as a by-product of Interplanetary Scintilation Studies (ISS) in Cambridge.

The signal was recorded on chart paper - telescope produced about 30 metres per day!

Jocelyn carefully waded through the paper (and interference), and started to notice an unusual source that appear to be periodic (T ~ 2 secs) she called this "scruff".

By 1968, four periodic sources had been discovered.

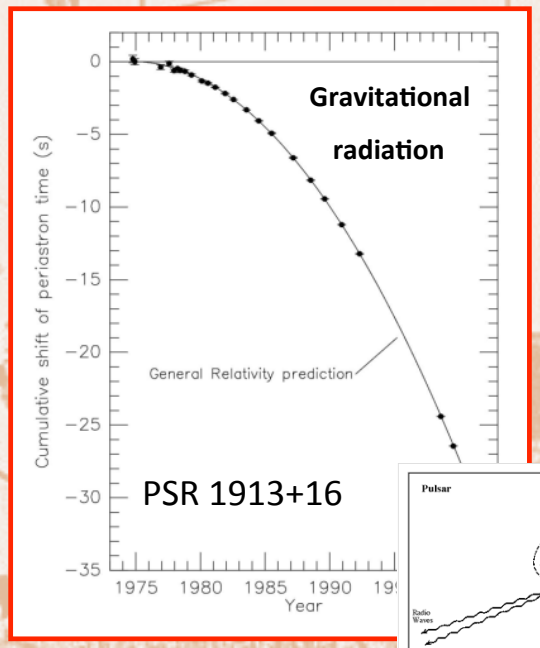


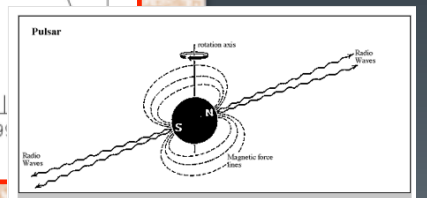
After instrumental causes were ruled out, other physical explanations were considered - including that the signal were being beamed to us by other intelligent life-forms in the galaxy.

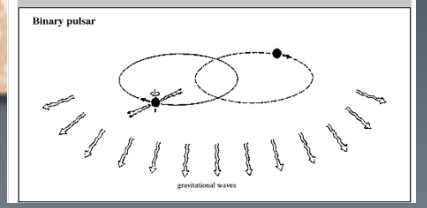
See youtube "**2009: Pulsars (Bell Burnell)**"

Gravitational radiation

R.A. Hulse & J.H. Taylor, Jr



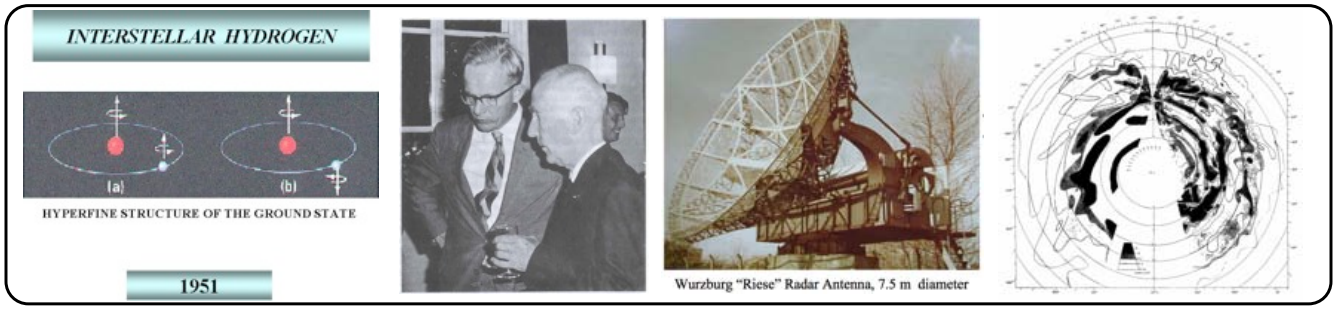




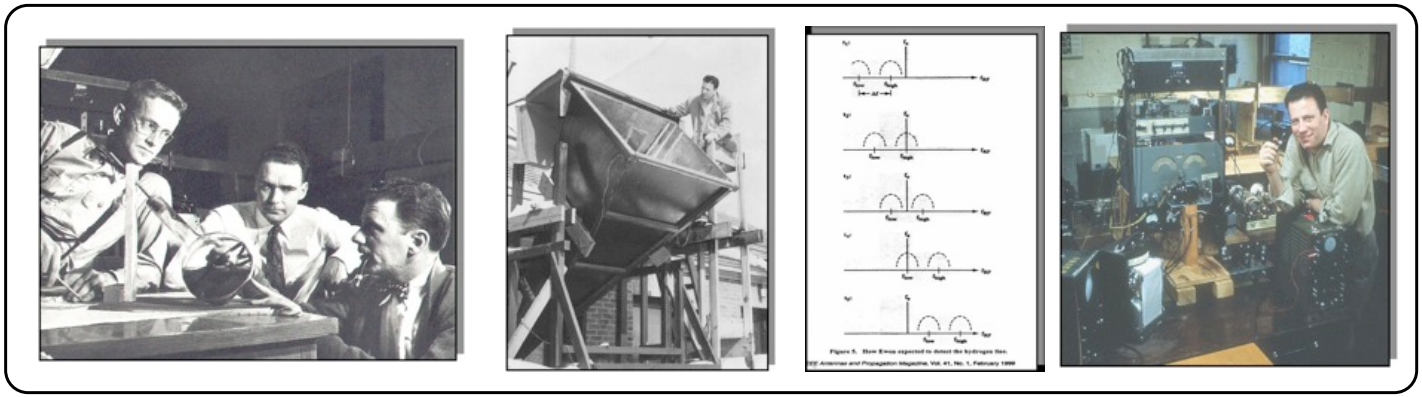
distance gets smaller by 3m / year

Radio Spectral Lines - neutral hydrogen

1944: van der Hulst predicts discrete 1420 MHz (21 cm) emission from neutral Hydrogen (HI).



1951: HI detected by Ewen & Purcell and Oort & Muller.



Special: Radio astronomy traces the FIRST and most ABUNDANT element in the Universe.

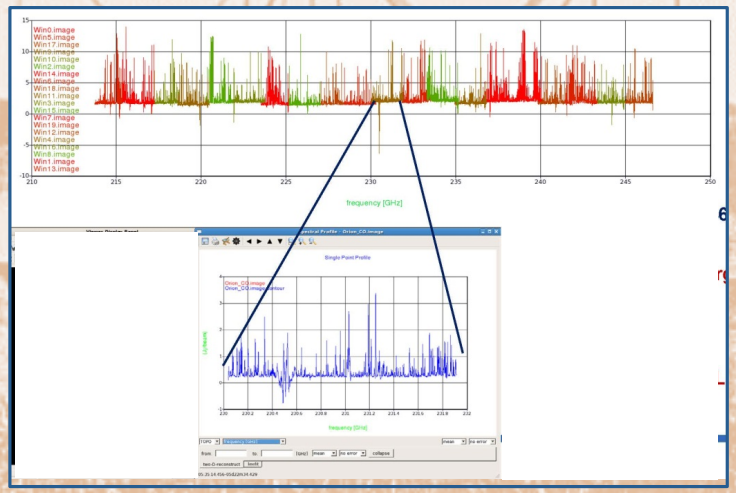



Molecular spectroscopy

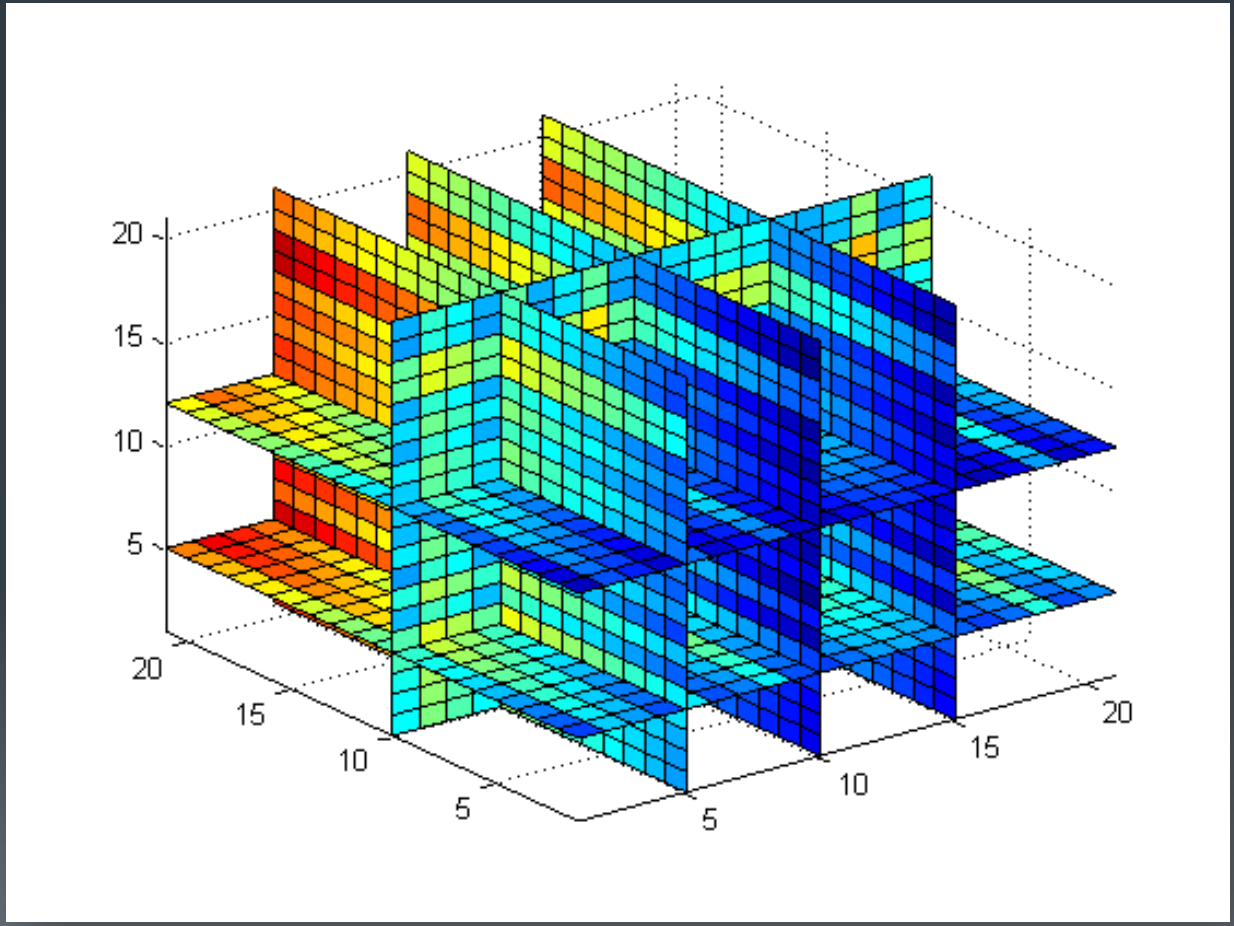
- OH - 18 cm
  - Townes & Shklovsky
  - Detected by Weinreb et al.
- Berkley
  - Mysterium (OH) (1965)
  - HN_3 – 1.3 cm (1968)
  - H_2O – 1.4 cm (1968)
- H_2CO – 6 cm (1969)
- CO - 2.8 mm (1970)

Molecular Spectroscopy

> 4000 lines known from >170 molecules



and there is lots more

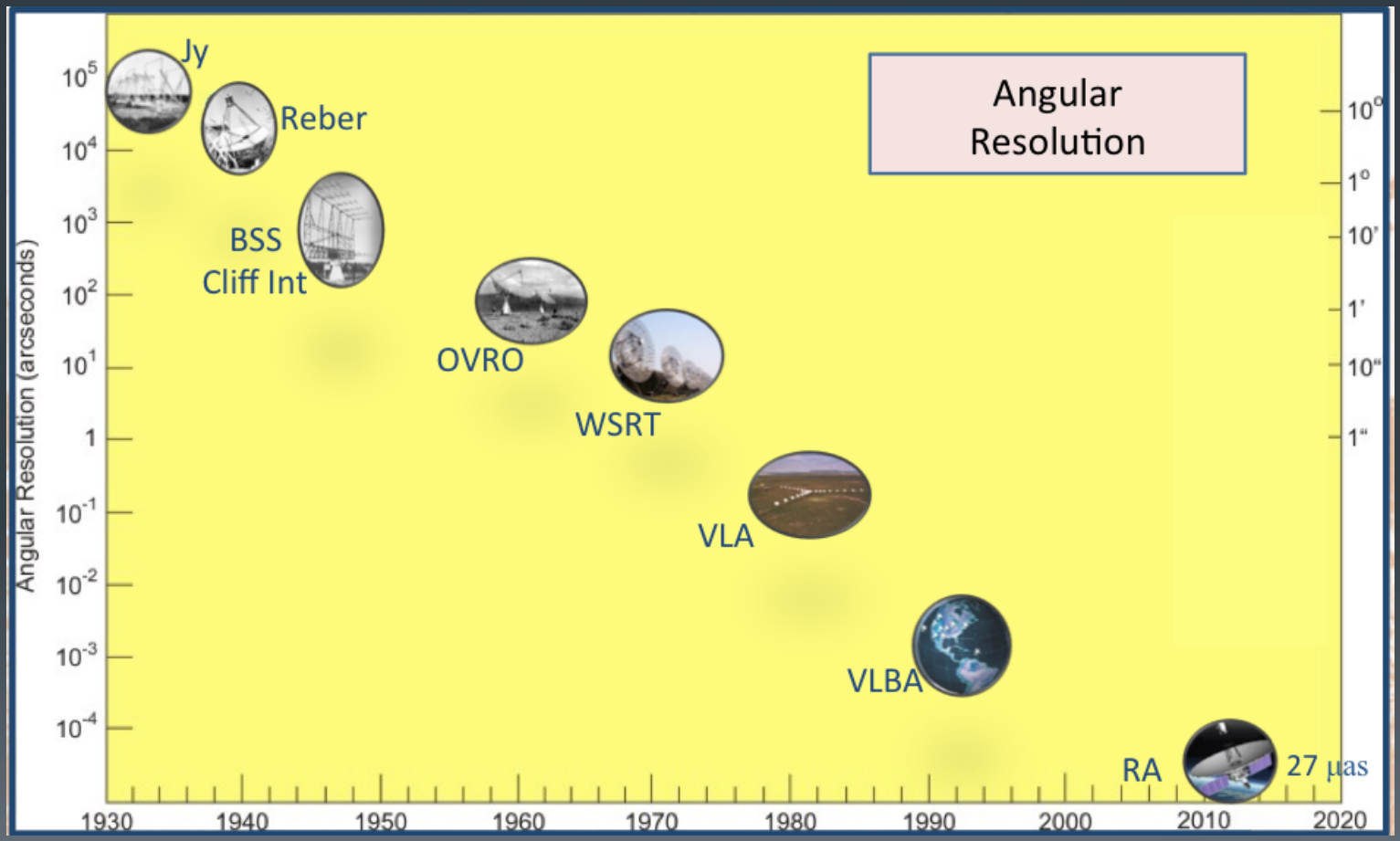


data = cube(freq,time)

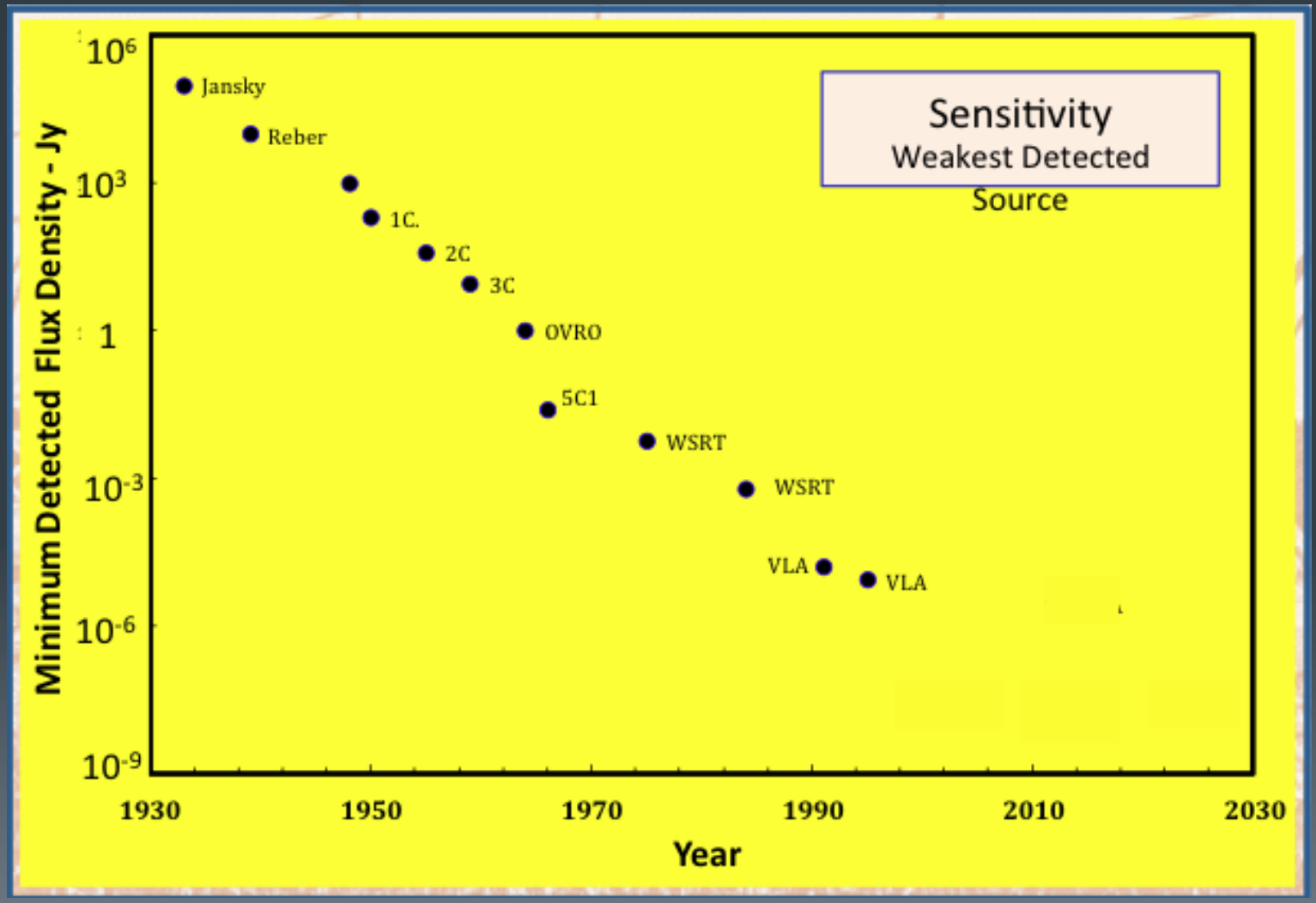
Inventions that changed the course of radio astronomy

Years	Invention
1930s	Horn fed parabolic reflector
1940s	**Cliff Interferometer**
1940s	Dicke Receiver
1950s	**Two element interferometer**
1960s	**Aperture Synthesis**
1960s	Autocorrelation spectrometer
1960s	**Computer assisted data analysis**
1960s	**Independent-oscillator-tape-recording-interferometry**
1960s	Cryogenically cooled radiometers
1970's	**CLEAN and Self Calibration**
1980s	**Space VLBI**

angular resolution



Telescopes & Instrumentation



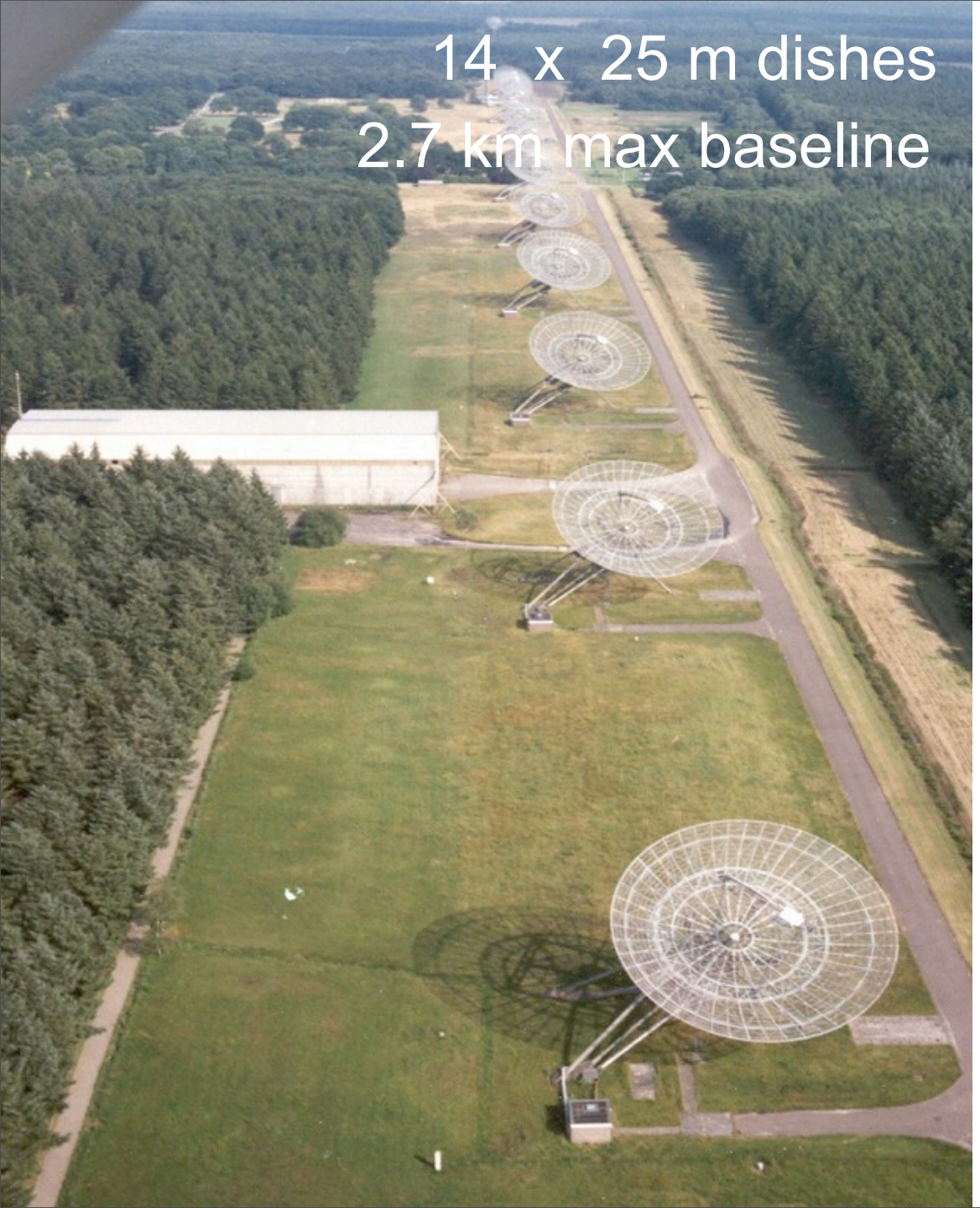
4 big dishes

Lovell Telescope 76 m

Effelsberg 100 m

Green Bank ~100 m

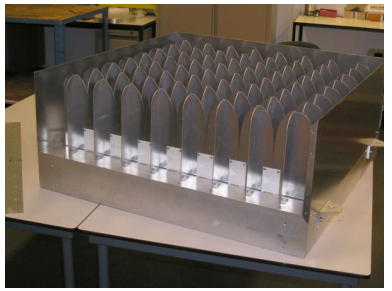
Arecibo 305 m



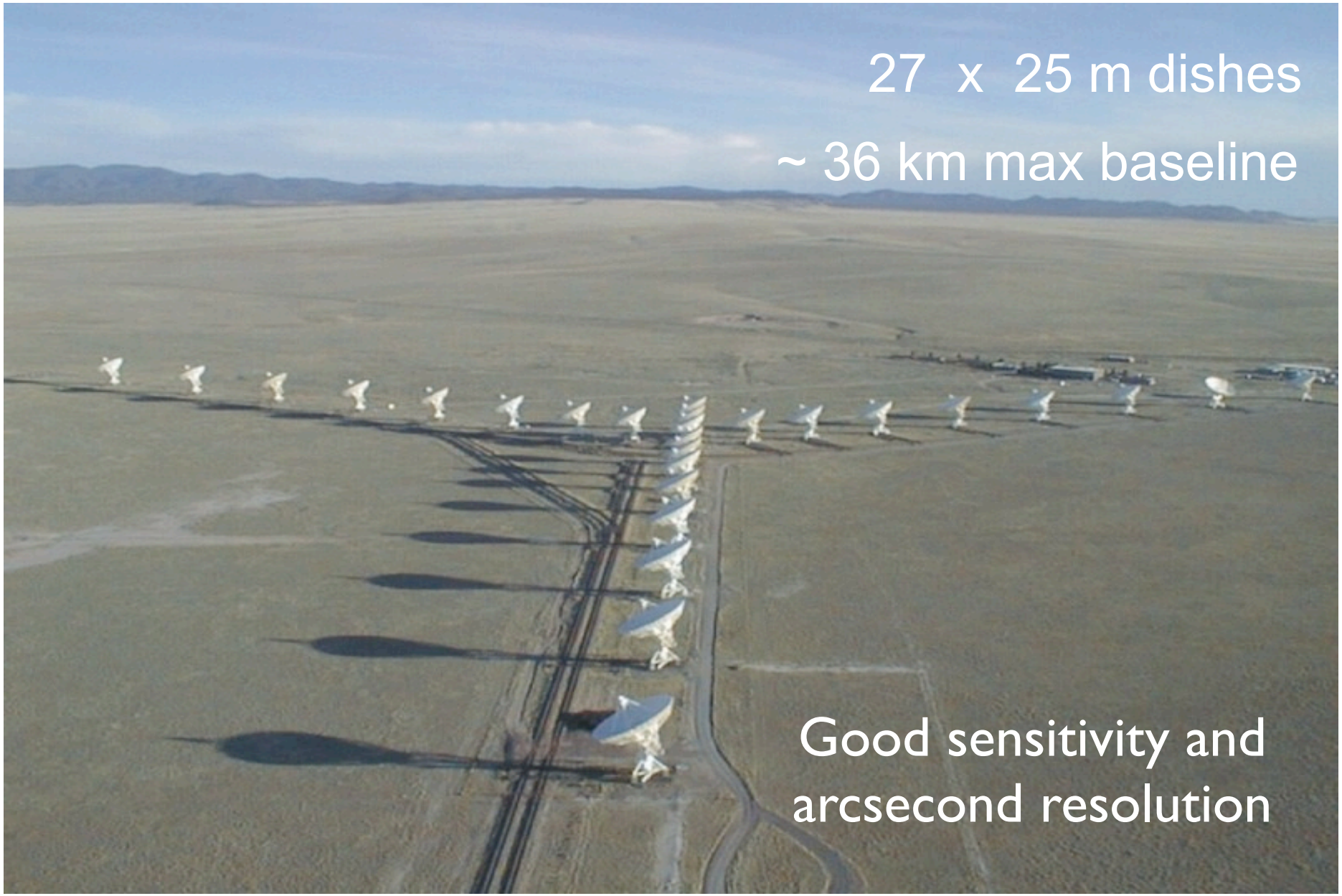
Westerbork built - 1970

Good sensitivity and tens of arcsecond resolution

WSRT upgrade
Apertif (FPA)



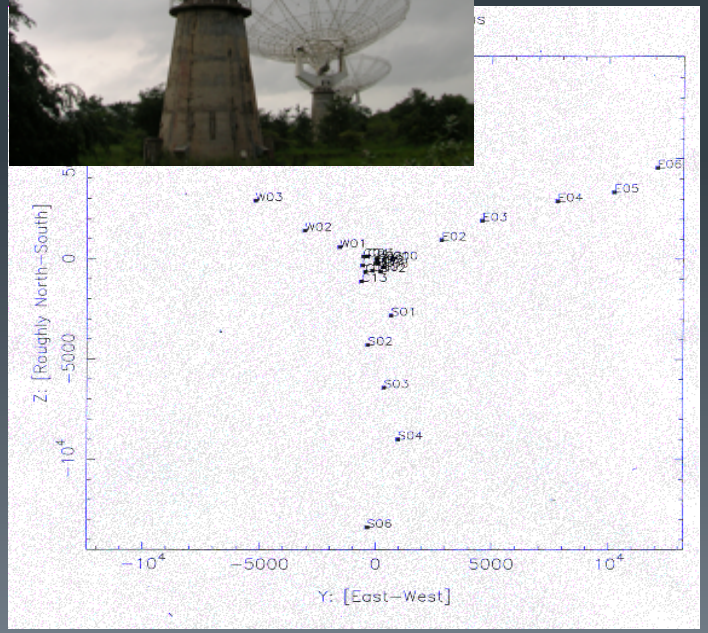
Very Large Array (VLA) operational - 1980

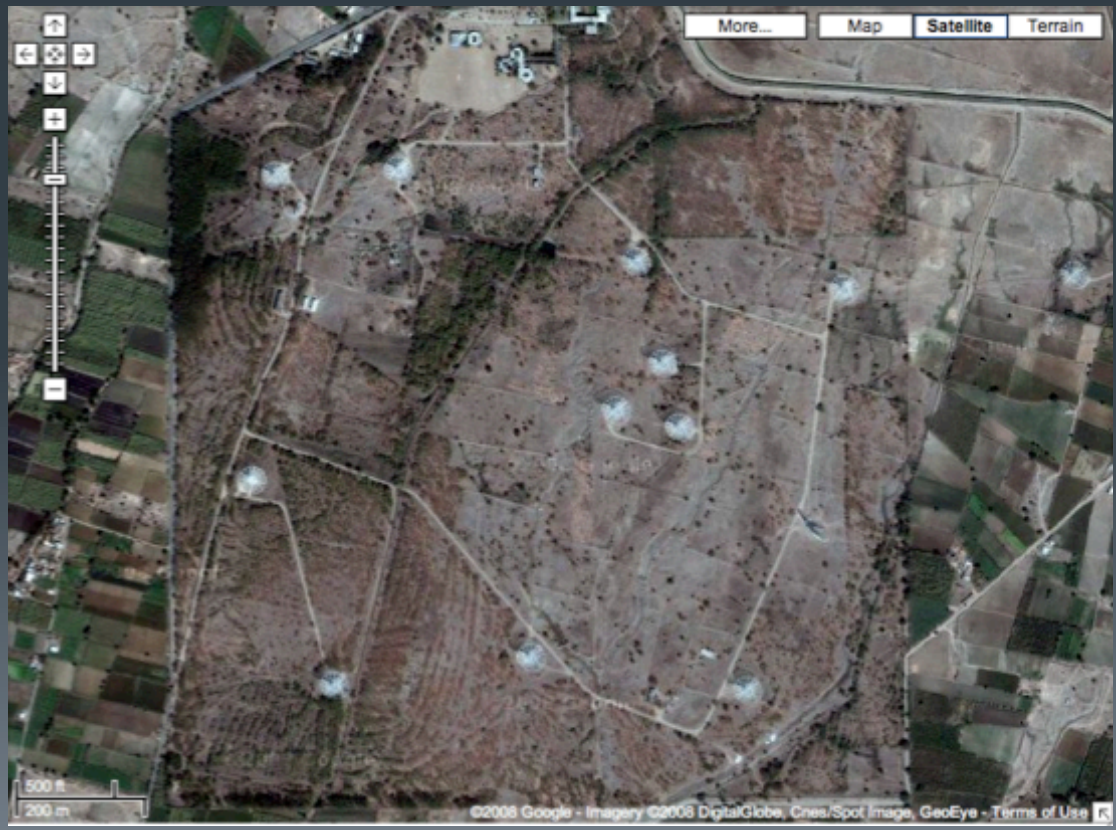


Giant Metrewave Radio Telescope

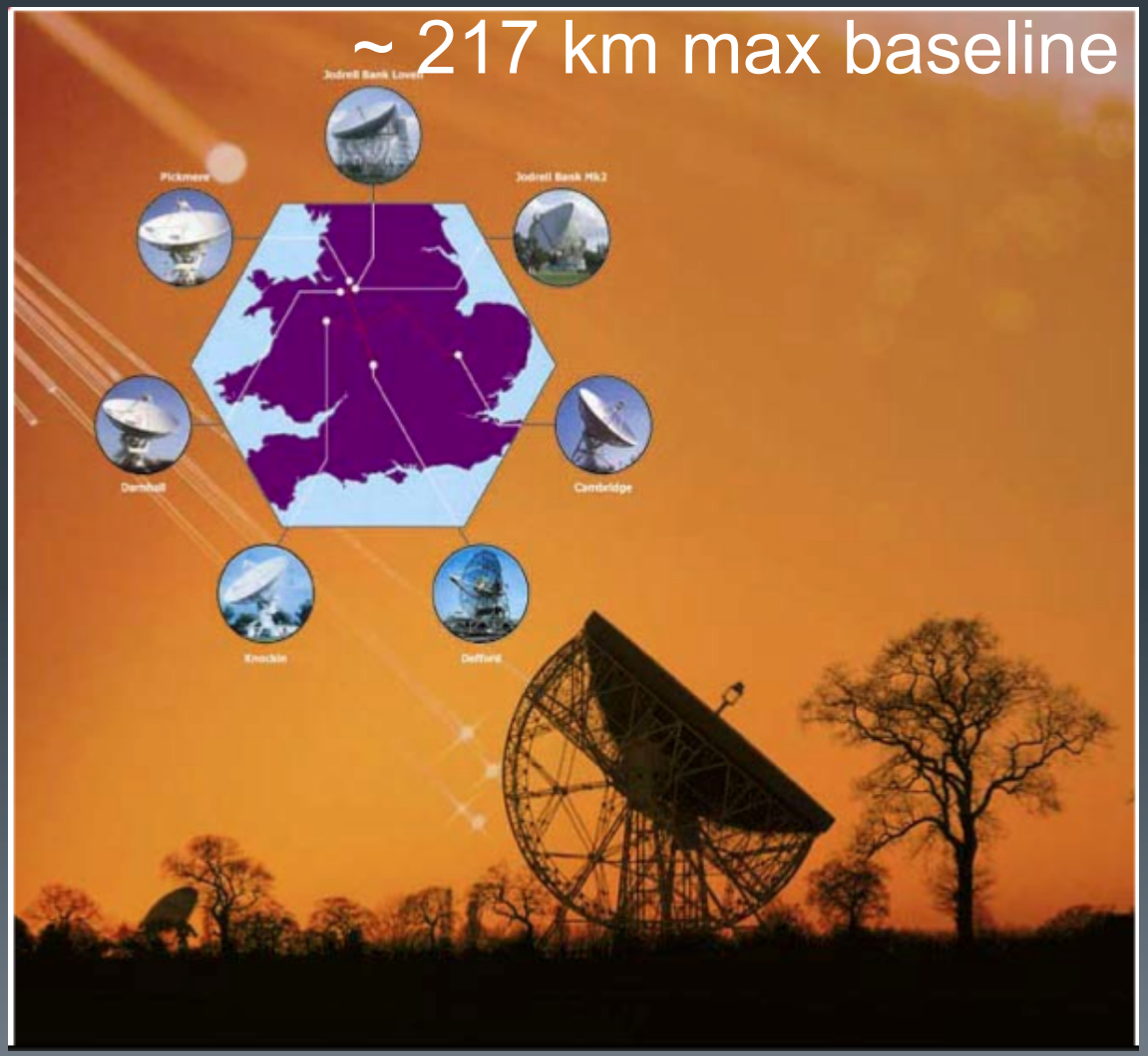
30 x 40 m dishes

~ 25.5 km max baseline



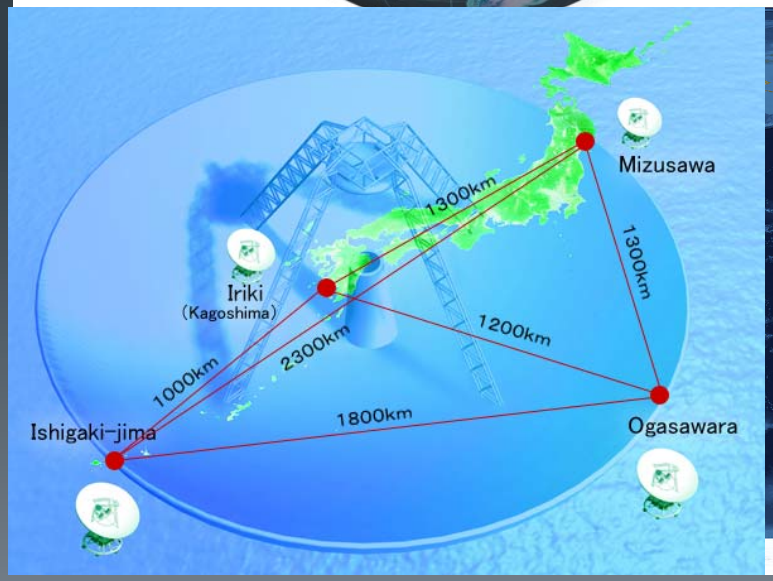


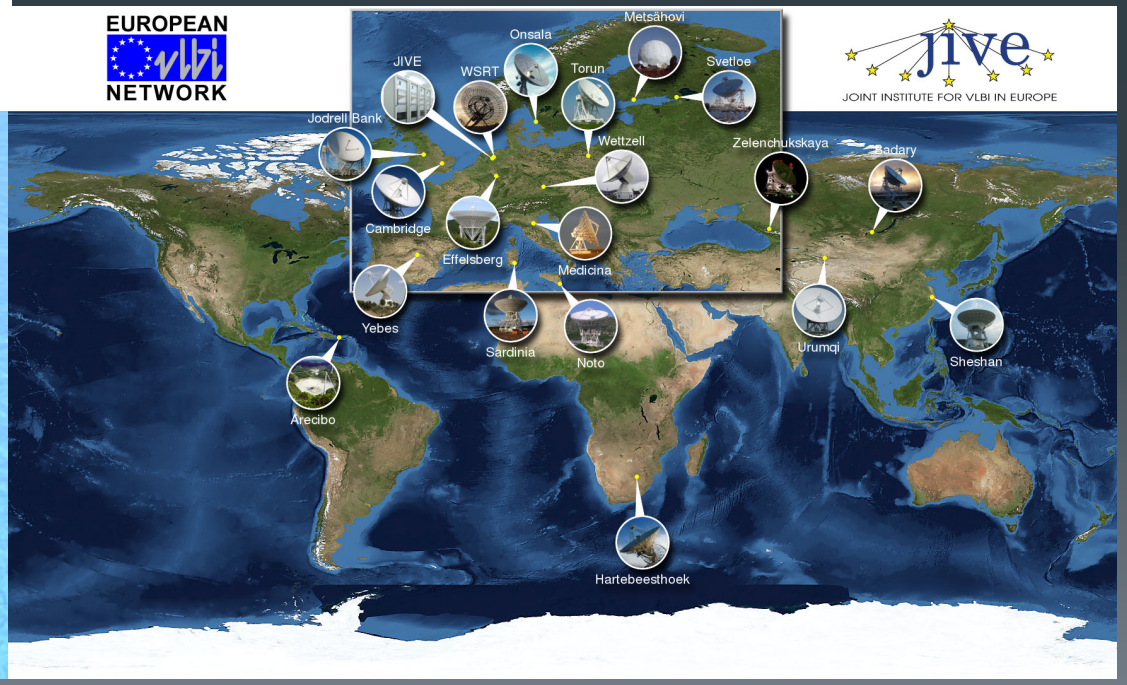
eMERLIN


~ 217 km max baseline
Jodrell Bank Lovell
Pickmere
Jodrell Bank Mk2
Darnhall
Cambridge
Knockin
Defford

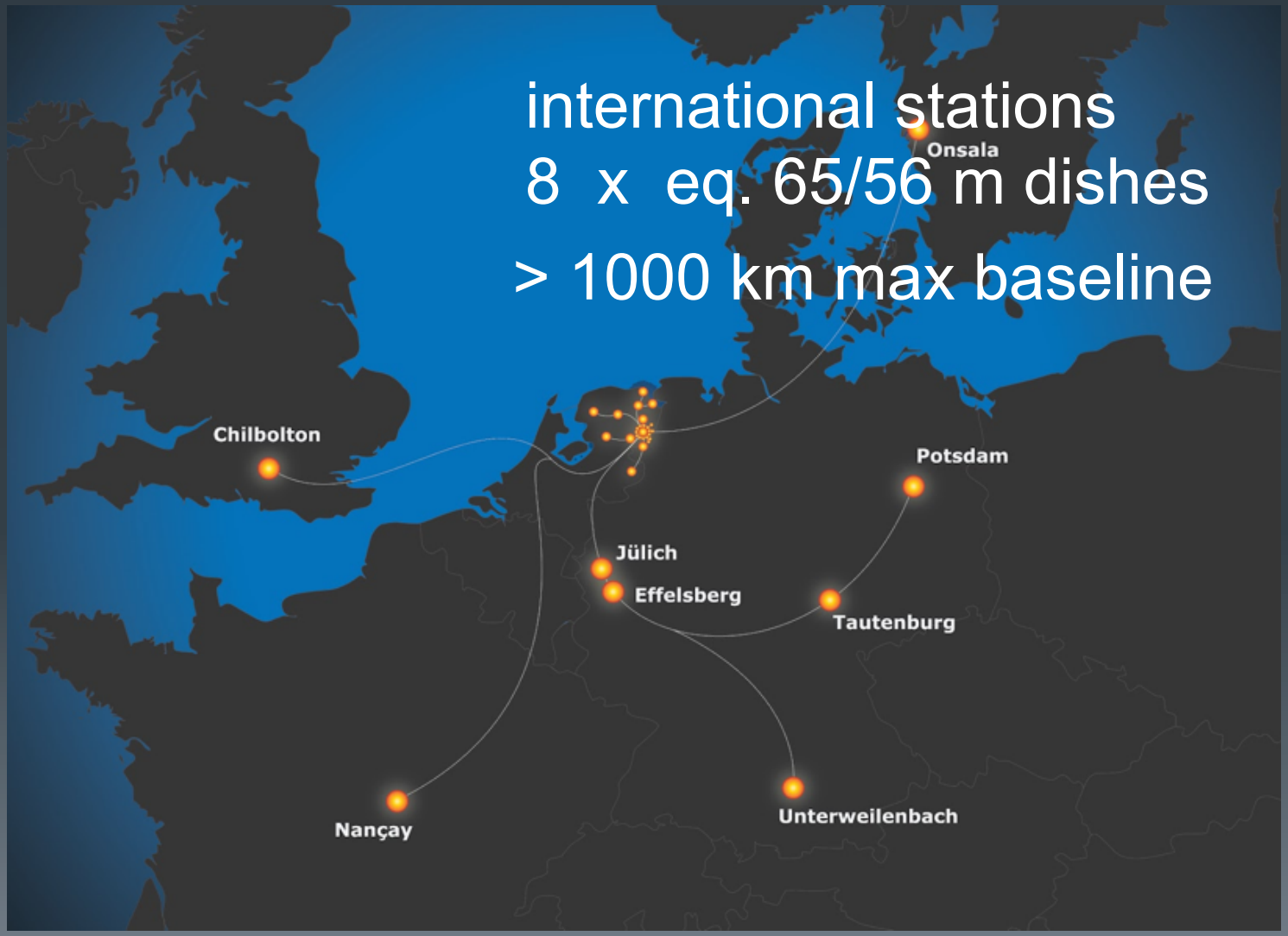
very long baseline Interferometry

thousands of km max baseline





LOFAR

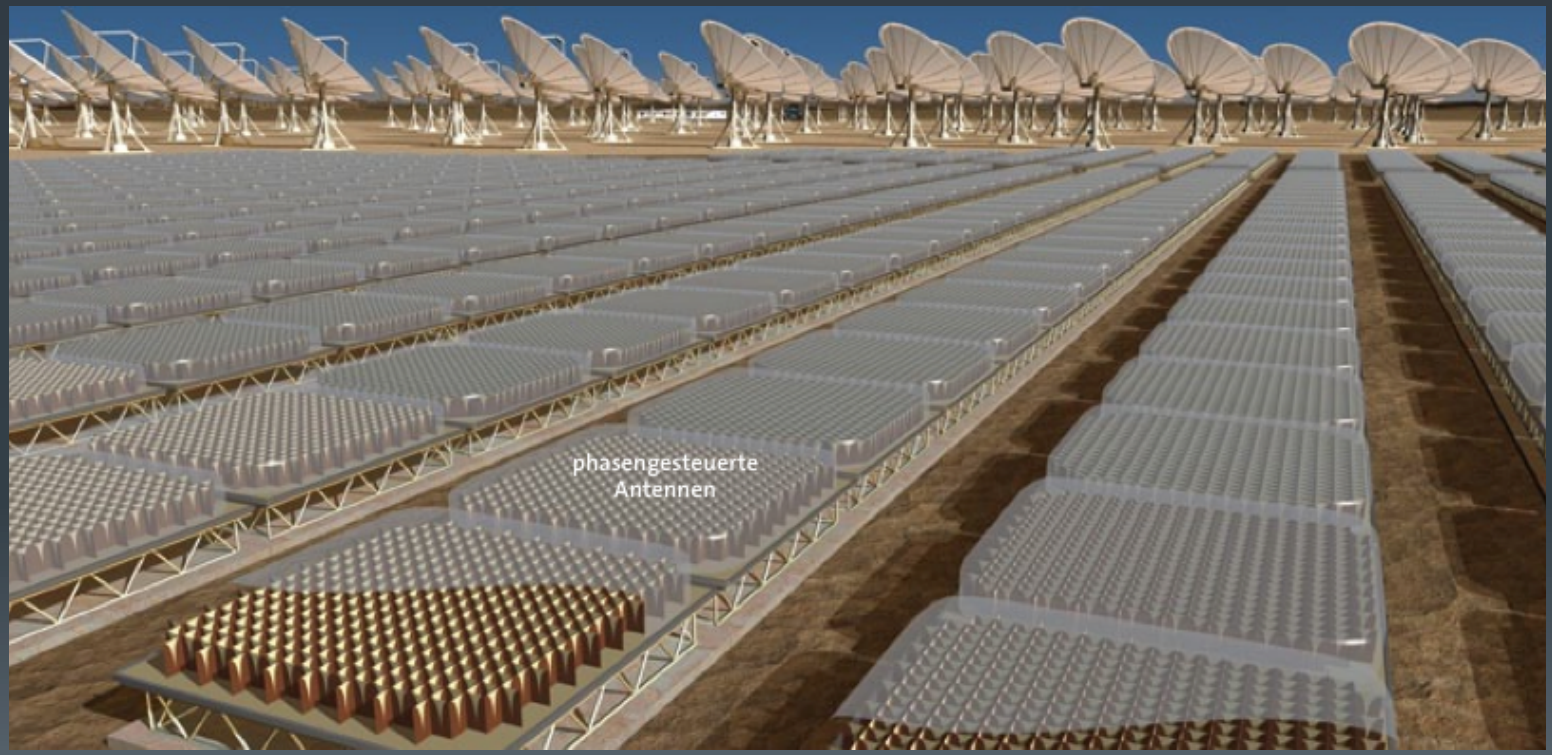

international stations
8 x eq. 65/56 m dishes
> 1000 km max baseline
Onsala
Chilbolton
Potsdam
Jülich
Effelsberg
Tautenburg
Nançay
Unterweilenbach

ALMA


currently 36 x 12 m dishes
currently 9 x 7 m dishes
~ 14 km max baseline

SKA

tons of dishes
phased arrays dense and sparse



we are in the
the golden age of
radio astronomy