Low Frequency Science and Techniques

MWSkyII, Pune, India

Ron Ekers

21 March 2019

CSIRO ASTRONOMY AND SPACE SCIENCE
www.csiro.au

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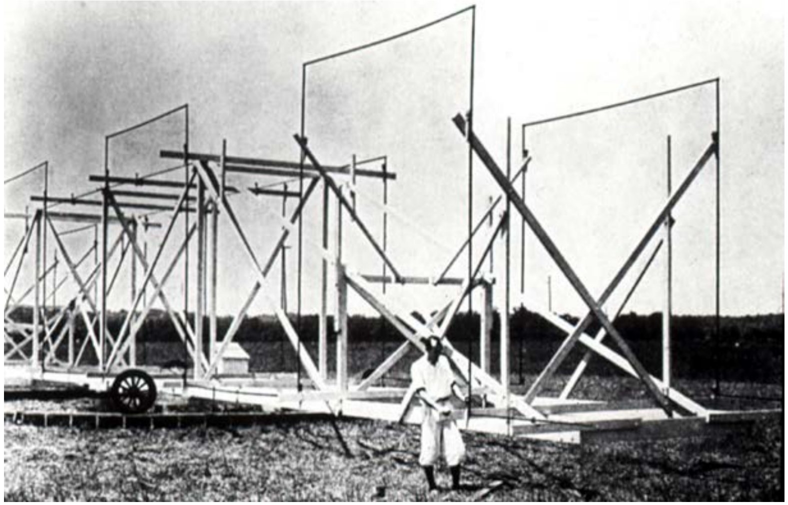
Outline

- The beginning
  - Radio astronomy started at low frequency
- Low Frequency radio astronomy re-emerges after many decades
  - Required adequate computer power to image large FoV
  - Need to correct for ionosphere
- SKA low frequency pathfinders
  - LOFAR
  - MWA
- New techniques
  - Wide FoV imaging, ionosphere, RFI mitigation, IPS
- New discoveries
  - EoR, Low brightness Universe, Surveys, FRB, Cosmic Rays

Beginning of Radio Astronomy

Low frequency-long wavelength science



- Jansky 1933 – 20MHz
  - Unexpected source of noise peaking each day
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  - not accepted by the astronomical community at the time

  – no theoretical framework

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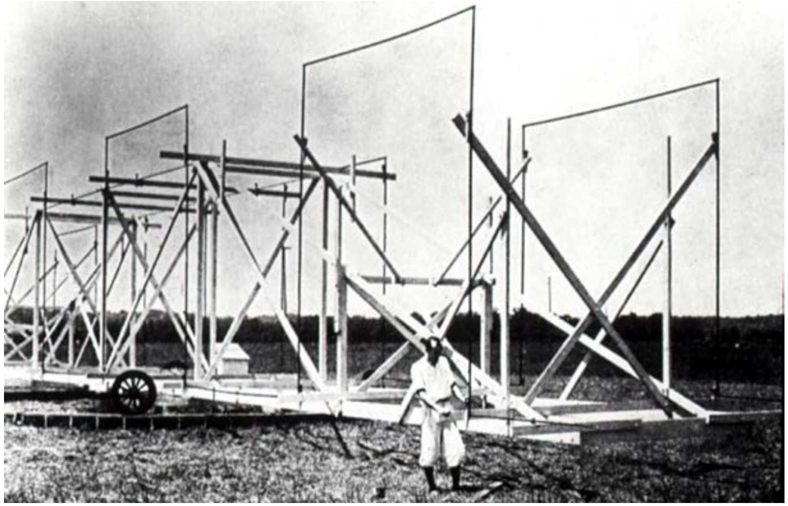

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- Pasteur
  - *"In the field of observation, chance favours the prepared mind"*

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Discovery of the Non-thermal Universe

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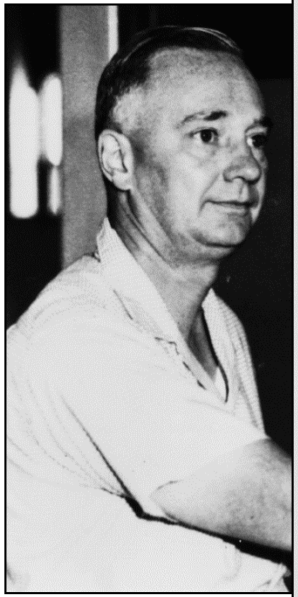

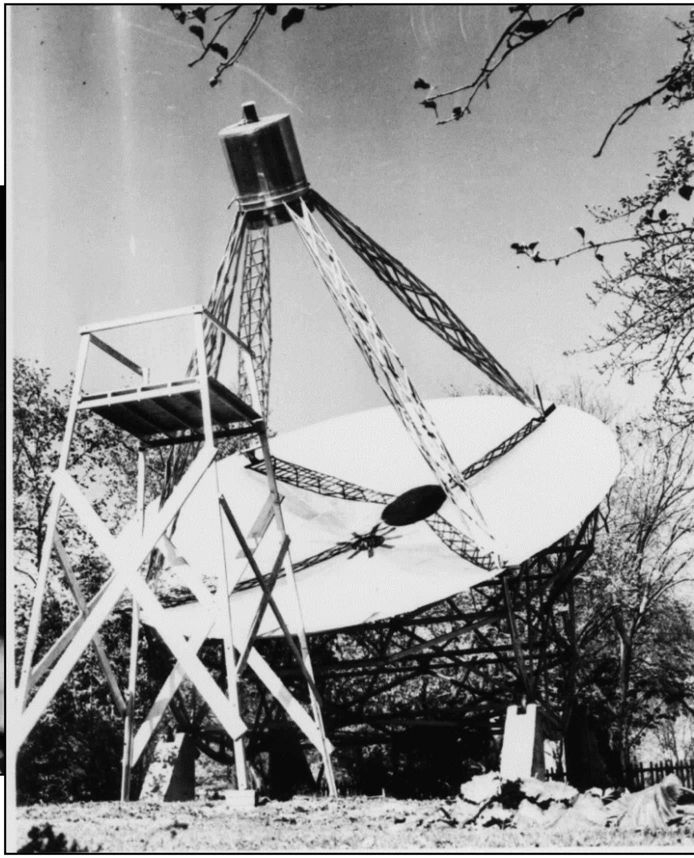

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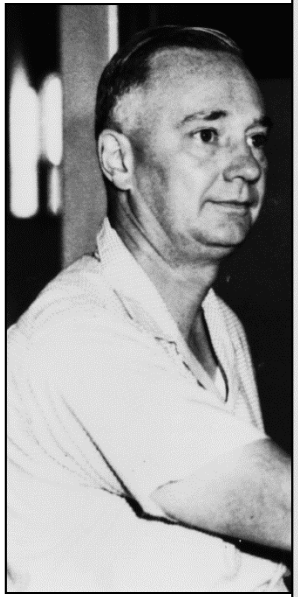
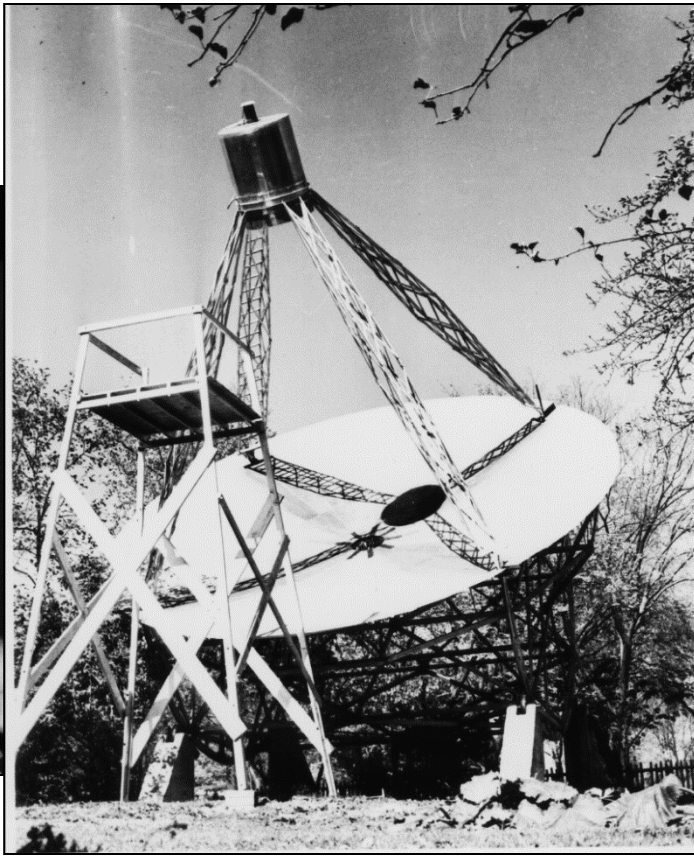
  - ✓ 160 MHz





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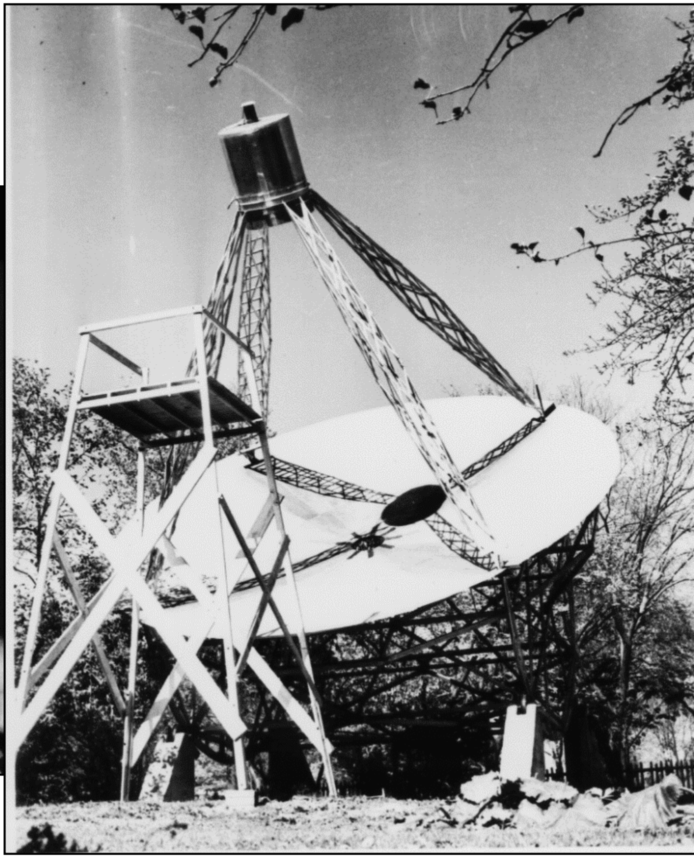

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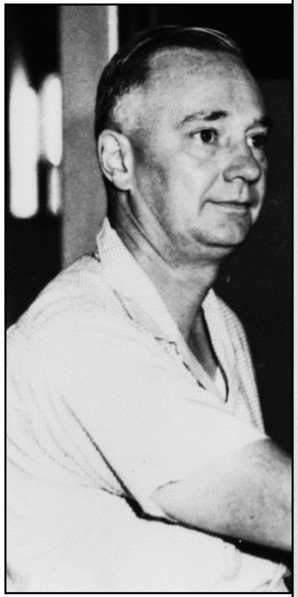

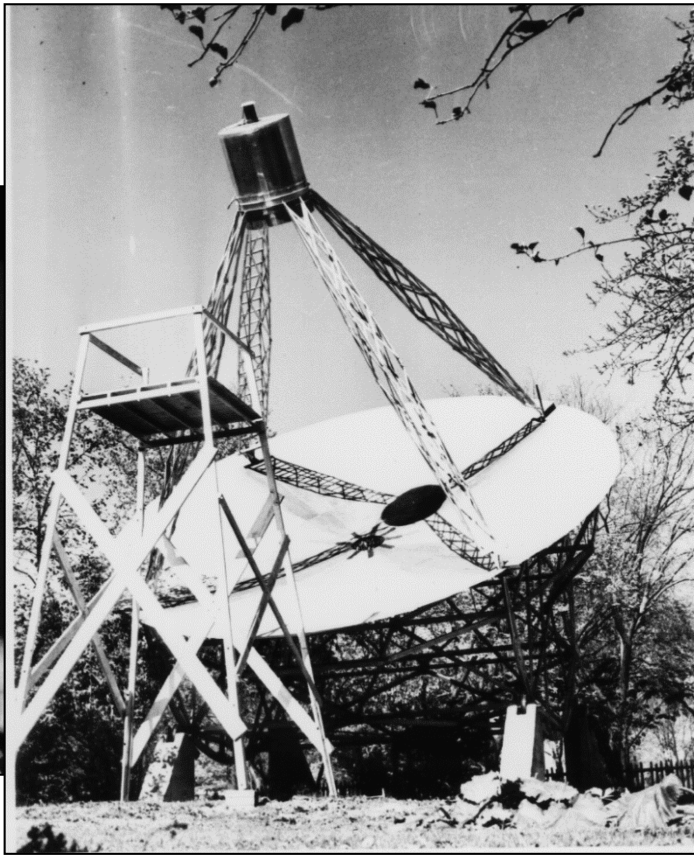

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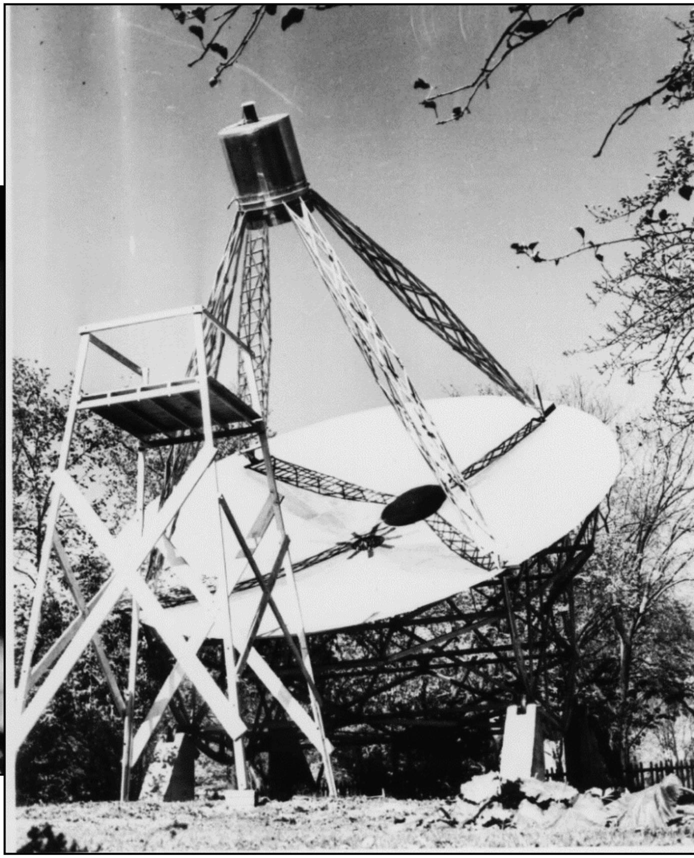
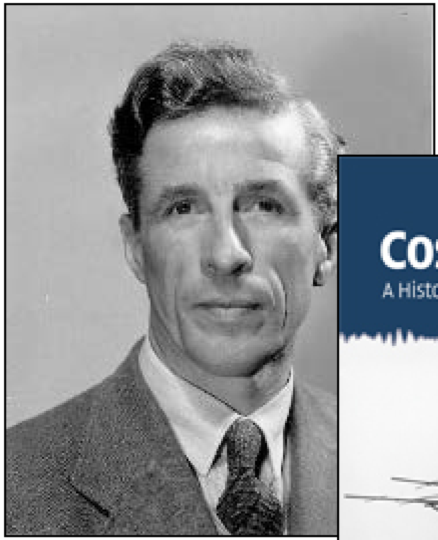
- Radiation was not thermal!
  - ➢ Had to be a non-thermal process
  - ➢ No theoretical basis at the time
  - ➢ 1950 Synchrotron radiation theory
    - 10 years after Reber's discovery
    - Linked comic rays, magnetic field and radio emission

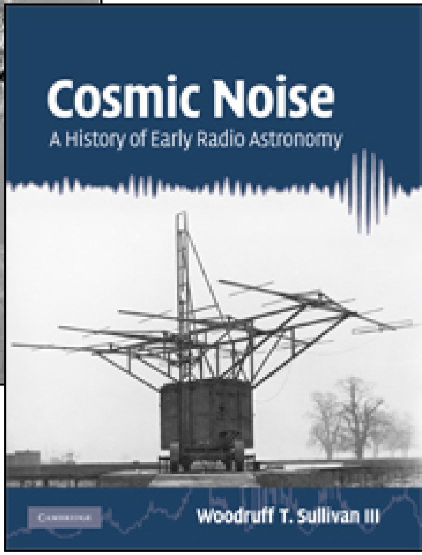


..for innovative contributions to radio astronomy

Strongest Radio Sources in Sky: Sun and Cygnus A

- Solar emission 1940
  - Multiple independent detections
- Hey 1946 detects Cygnus A
  - source with variable intensity
  - time scale of seconds to minutes
  - must be small diameter
  - the first “radio star”
- What was it?
  - no optical counterpart
  - was the whole galactic plane was made of such stars?
  - no theory linking diffuse galactic emission to cosmic rays





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Potts Hill Reservoir – 1955

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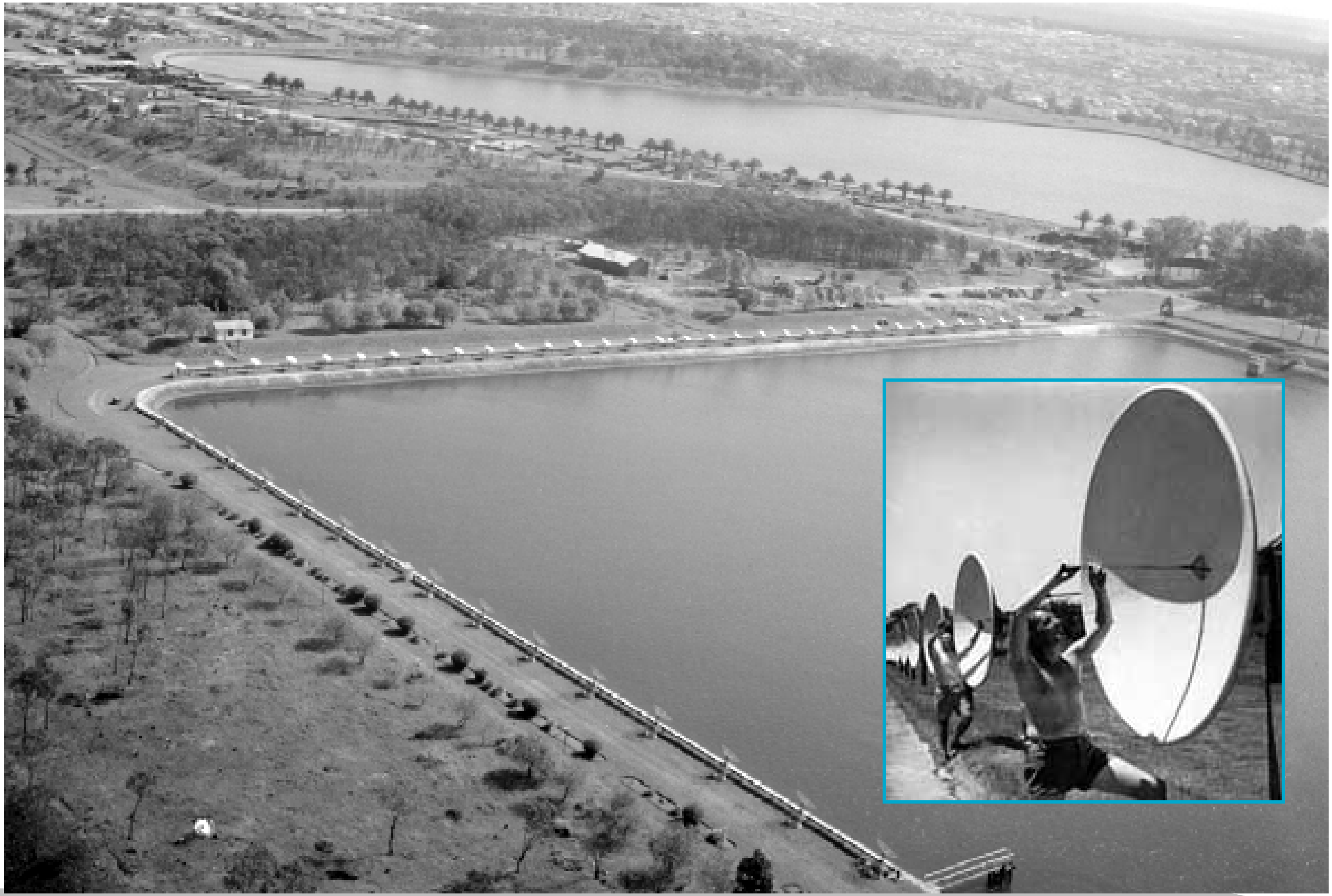

Potts Hill Reservoir – 1955

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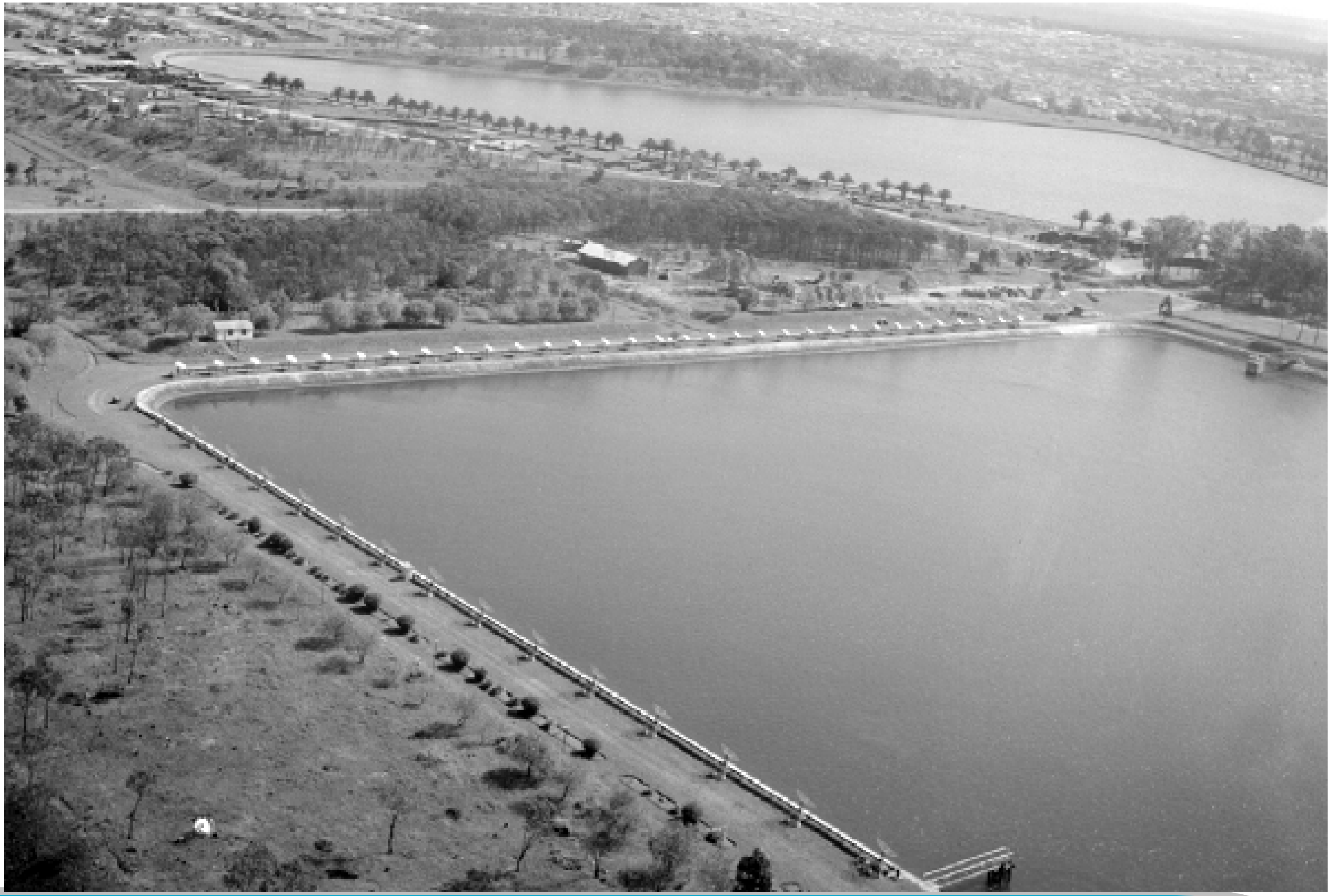
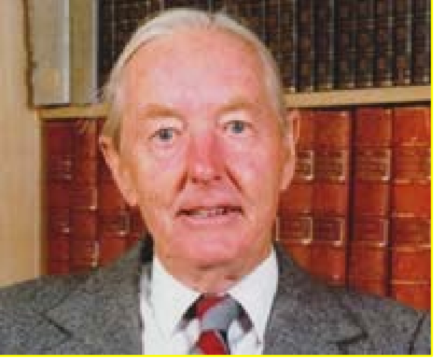
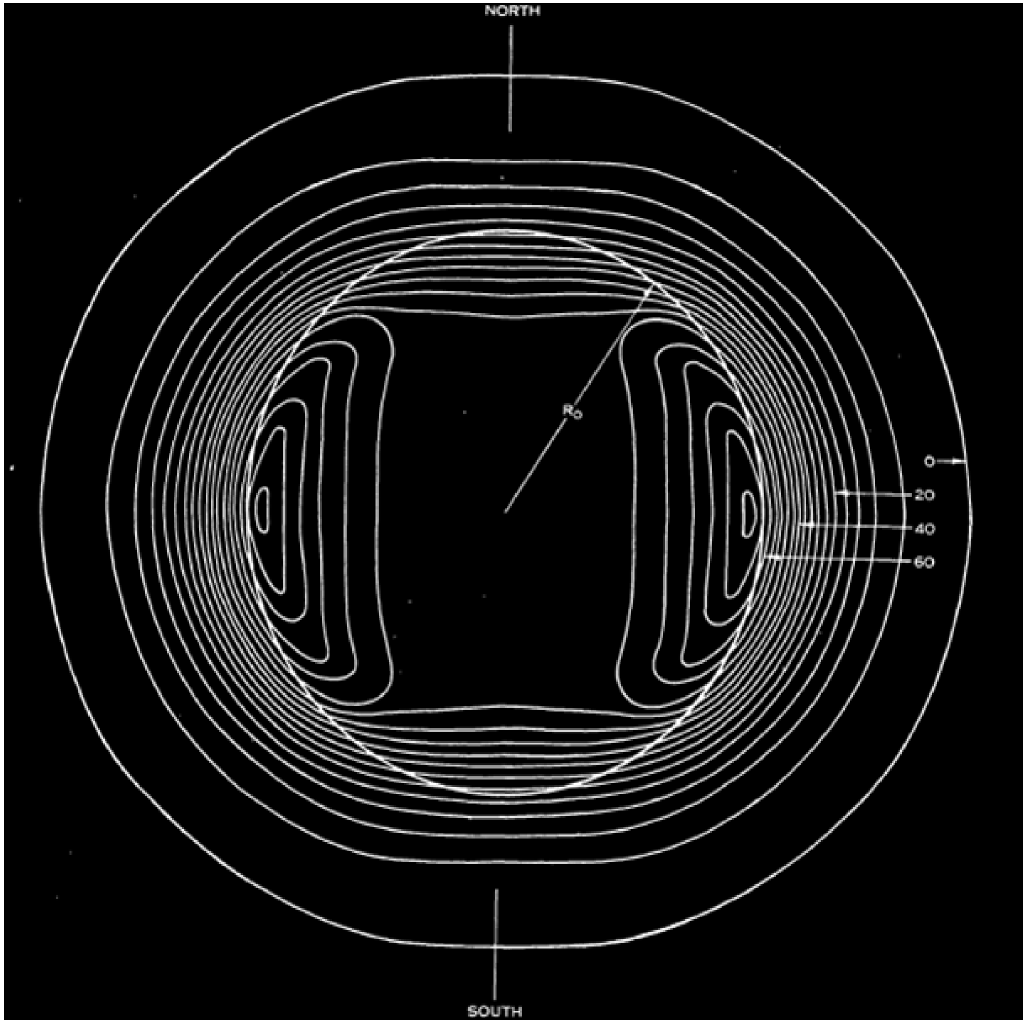




Christiansen and Warburton earth rotation synthesis (1955)

- Chris takes the 1D FT of each strip distribution & does a 2D Fourier synthesis using all strips
  - *The way in which a 2D radio brightness distribution may be derived from a number of 1D scans is not obvious. However rather similar 2D problems have arisen in crystallography and solutions for these problems, using methods of Fourier synthesis have been found.*
- Reference to O'Brian (Cambridge)
- Swarup calculates the Fourier Transforms
  - More than 1 month with electronic calculator

First earth rotation aperture synthesis image
The Sun at 21cm 1955



- Limb brightening observed
- Problem of correcting weights in back projections

Christiansen and Warburton, Aust J Phys 8, 474 (1955)

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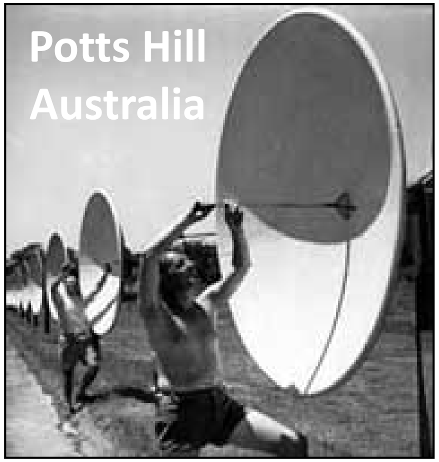

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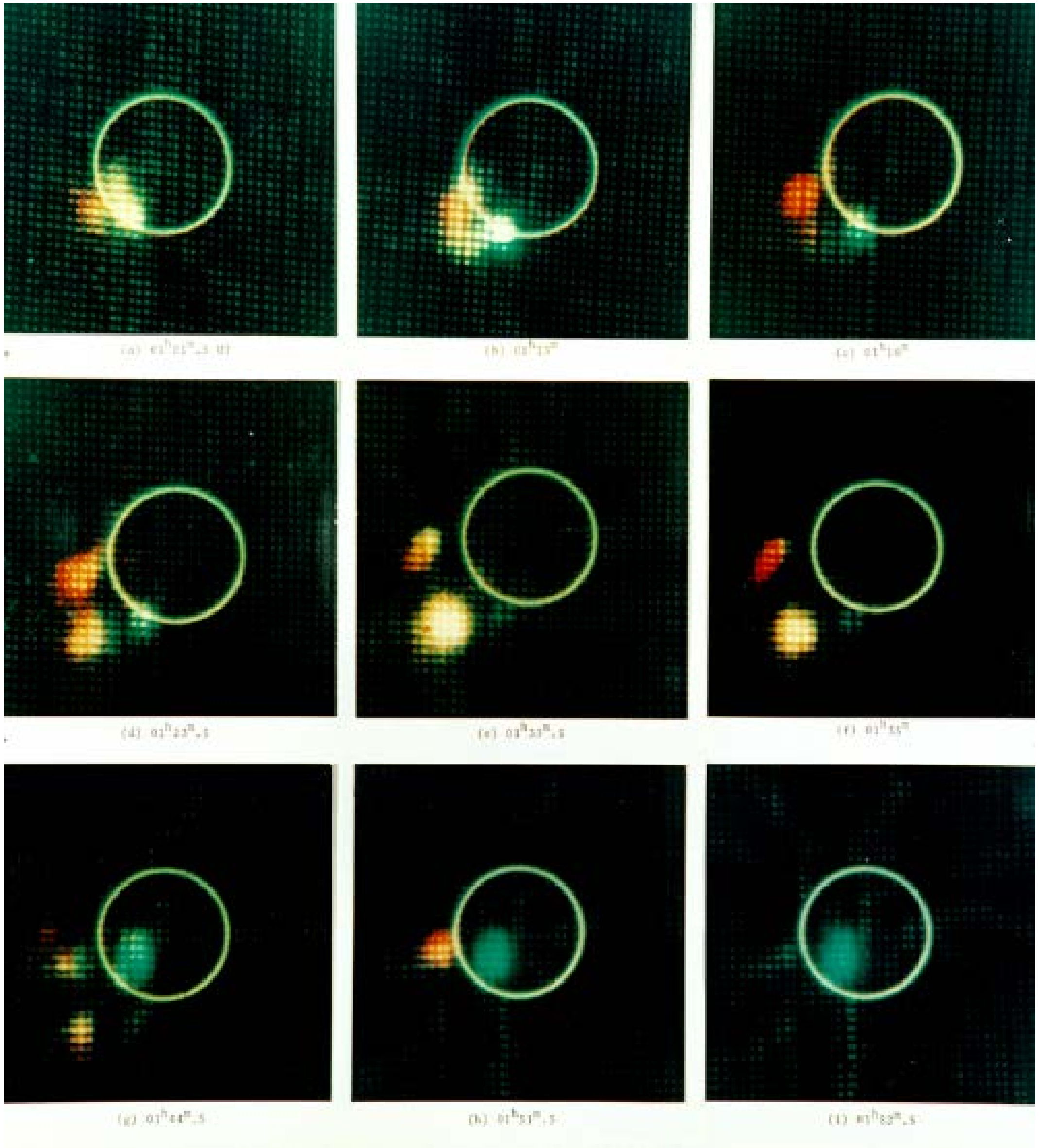
- 1955 Potts Hill array of dishes given to India
- 1956 Swarup joins Bracewell at Stanford
  - Invents round trip phase correction
  - Invents the back projection correction
  - Published by Bracewell in 1967!
  - Major impact on medical imaging

Solar Heliograph 1967-1984

- 1 dual pol 2D image per second
- 60 x 60 images
- J2 synthesis

- Left circular(red)
- Right circular (blue)

- Solved the problem of the evolution of type II and III solar bursts
- New understanding of type IV bursts



Computers and signal processing

- 1958
  - EDSAC II completed and applied to Fourier inversion problems
  - 360 38-point 1D transforms took 15 hours (Blyth)
  - Output was contours!


1960 user queue for programming the EDSAC 2

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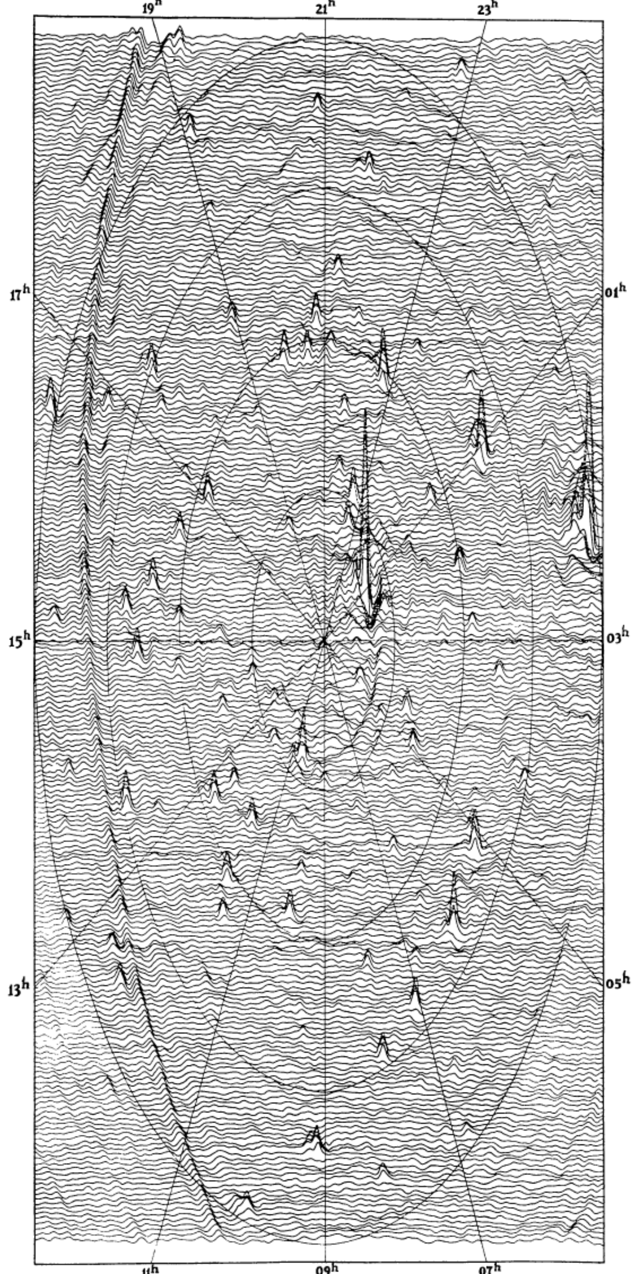
- 1965
  - Cooley & Tukey publish a *convenient* implementation of the FFT algorithm



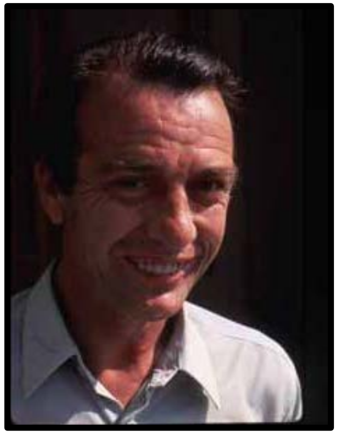
First Cambridge Earth Rotation Synthesis Image

- Ryle & Neville, MNRAS 1962
- North pole survey
- 4C aerials
- 178 MHz
- EDSACII
- 7 years after Christiansen
- No further developments of low frequency radio astronomy until LOFAR & MWA 50 years later!

3C 273 identification

Parkes lunar occultation

Cyril Hazard



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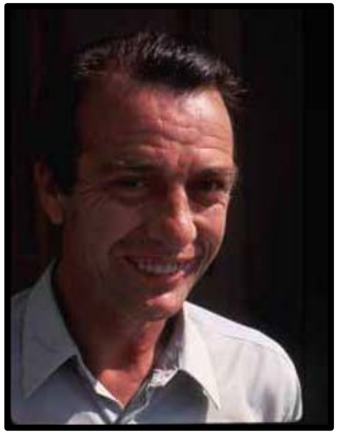

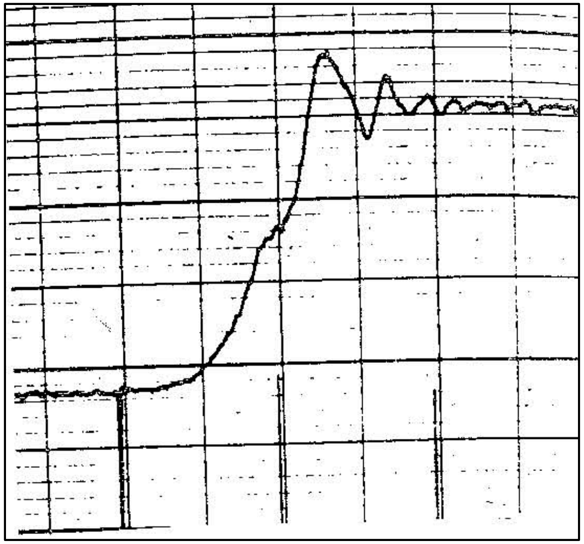

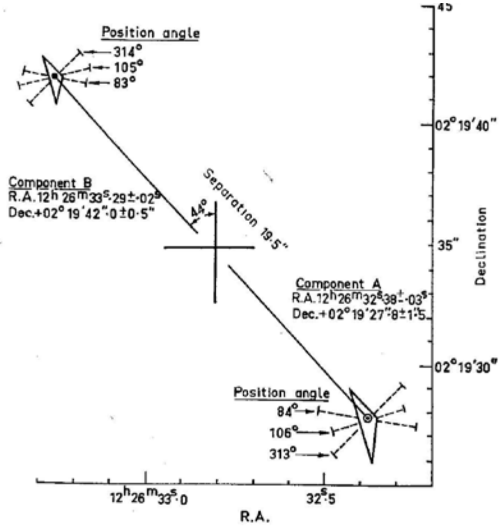

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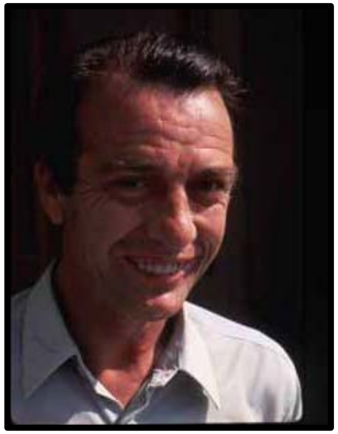
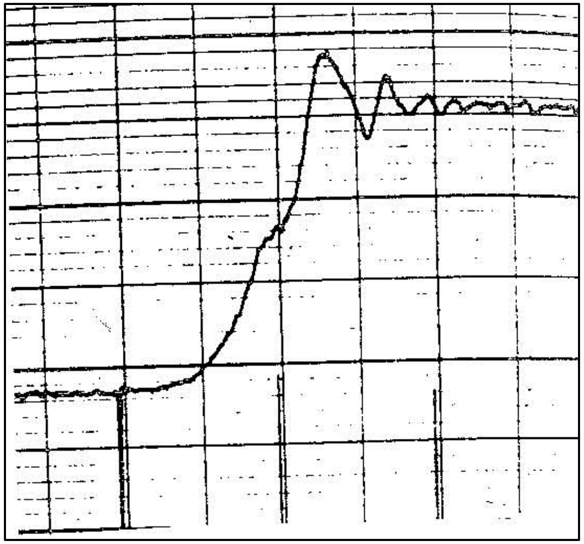
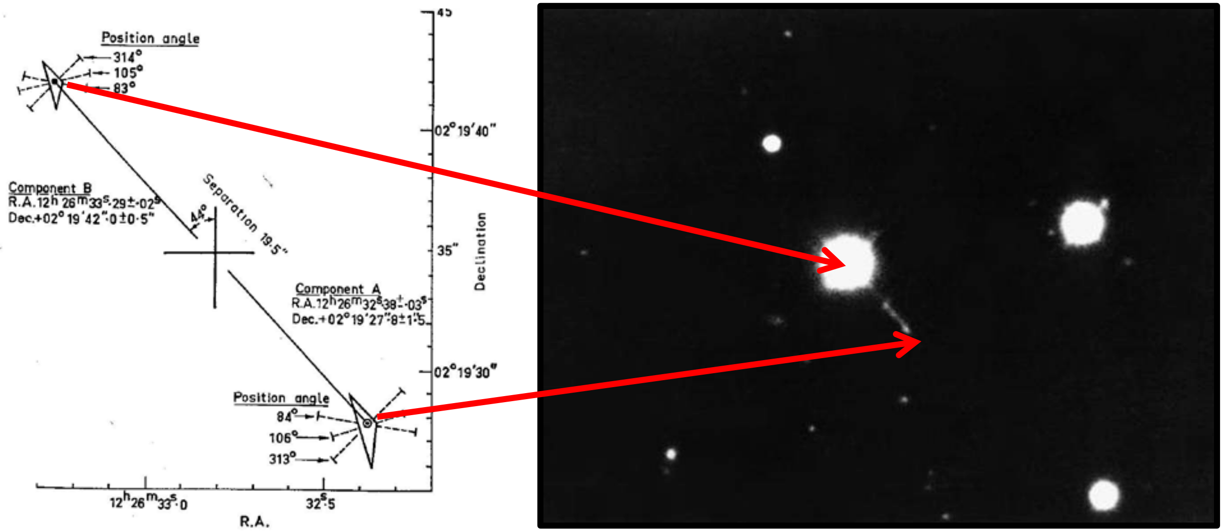
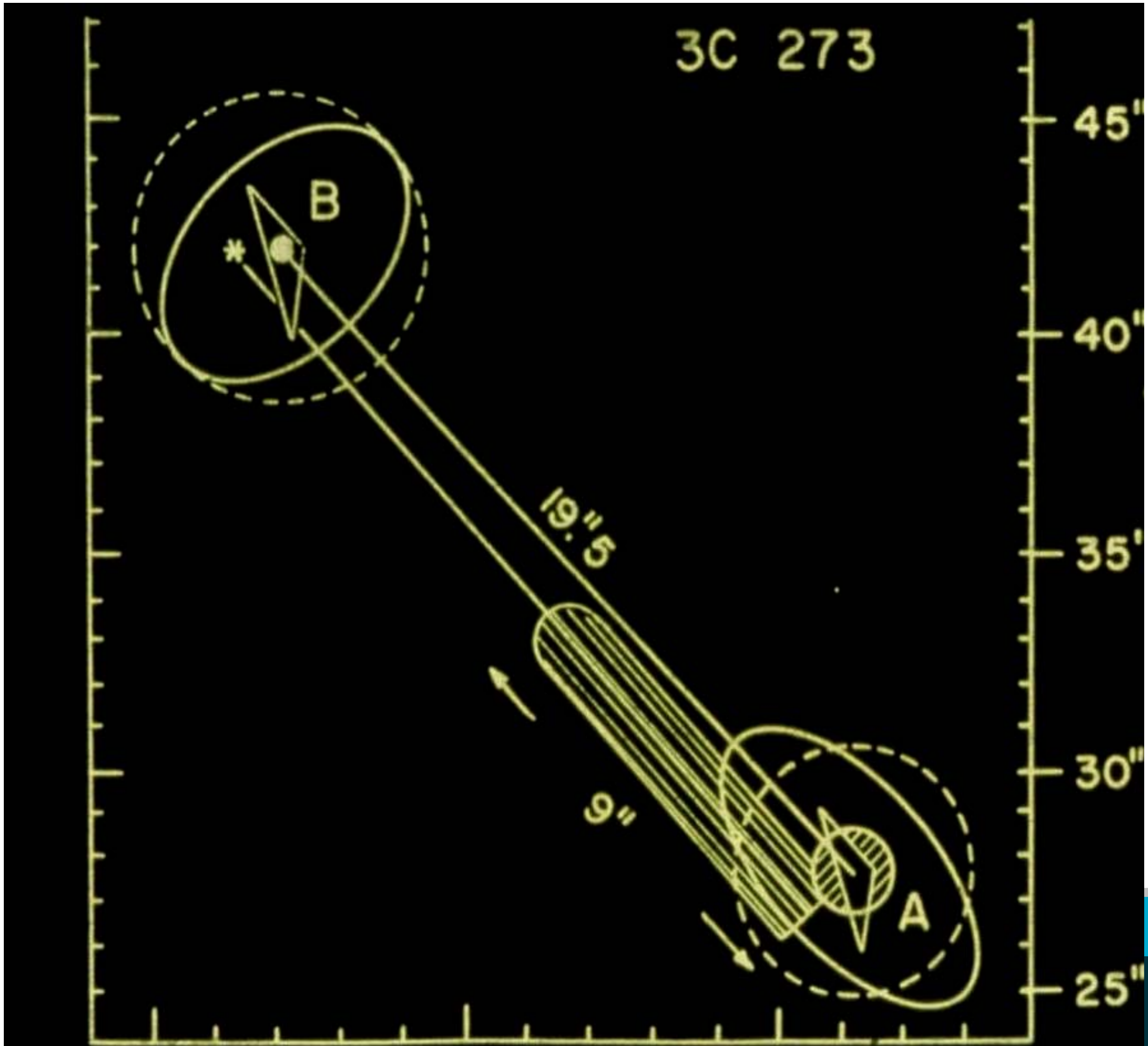




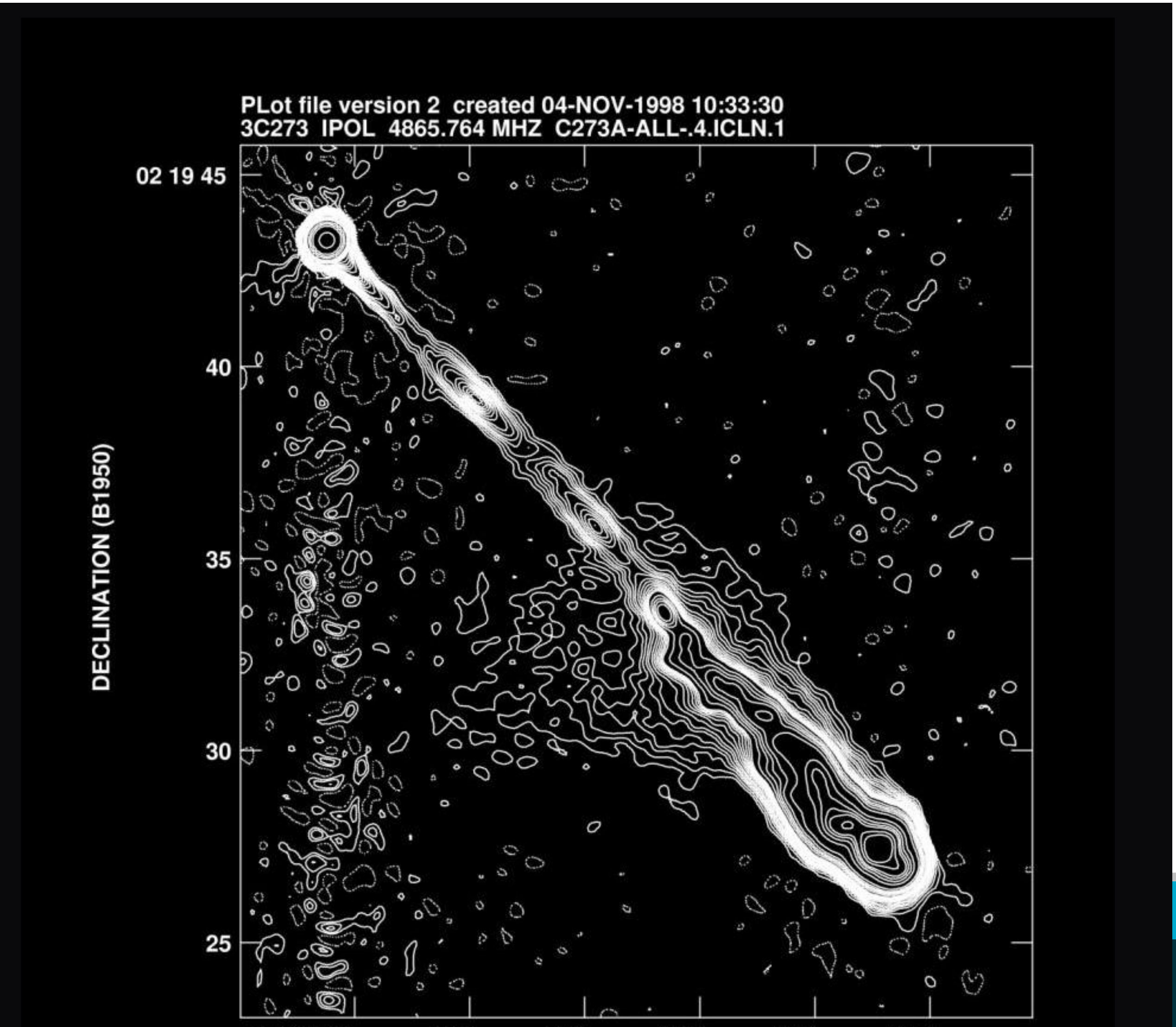


3C273
Parkes Occultation 1962



- Striking difference in radio spectra
- Component A
  $S = \nu^{-0.9}$
- Component B
  $S = \nu^{0.0}$

3C273
VLA 5GHz Rick Perley 1998



Radio Astronomy at TIFR

- 1963 Homi Bhabha (TIFR) forms a radio astronomy group in India
  - Expats return: Swarup, Menon, Kundu, T.Krishnan
- Swarup proposes an equatorially mounted cylinder to do fainter occultations ⇦ 3C273 impact

- Ooty operational 1970
- Ooty synthesis telescope 1984

Even bigger visions

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- 1982 GMRT concept

Giant Metre-wave Radio Telescope GMRT completed 2000

NCRA • TIFR

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Vijay Kapahi

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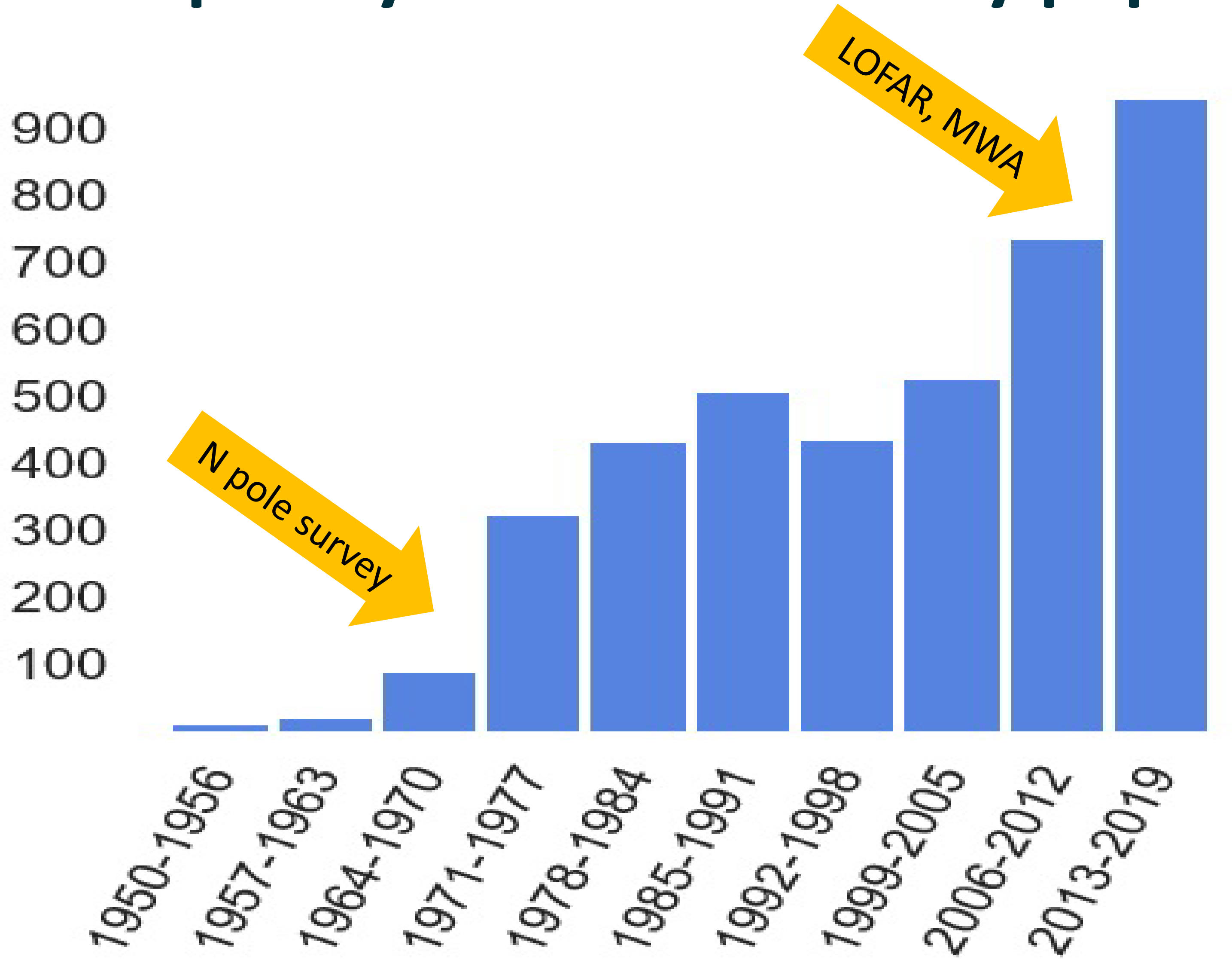
First LOFAR station complete - April 2009

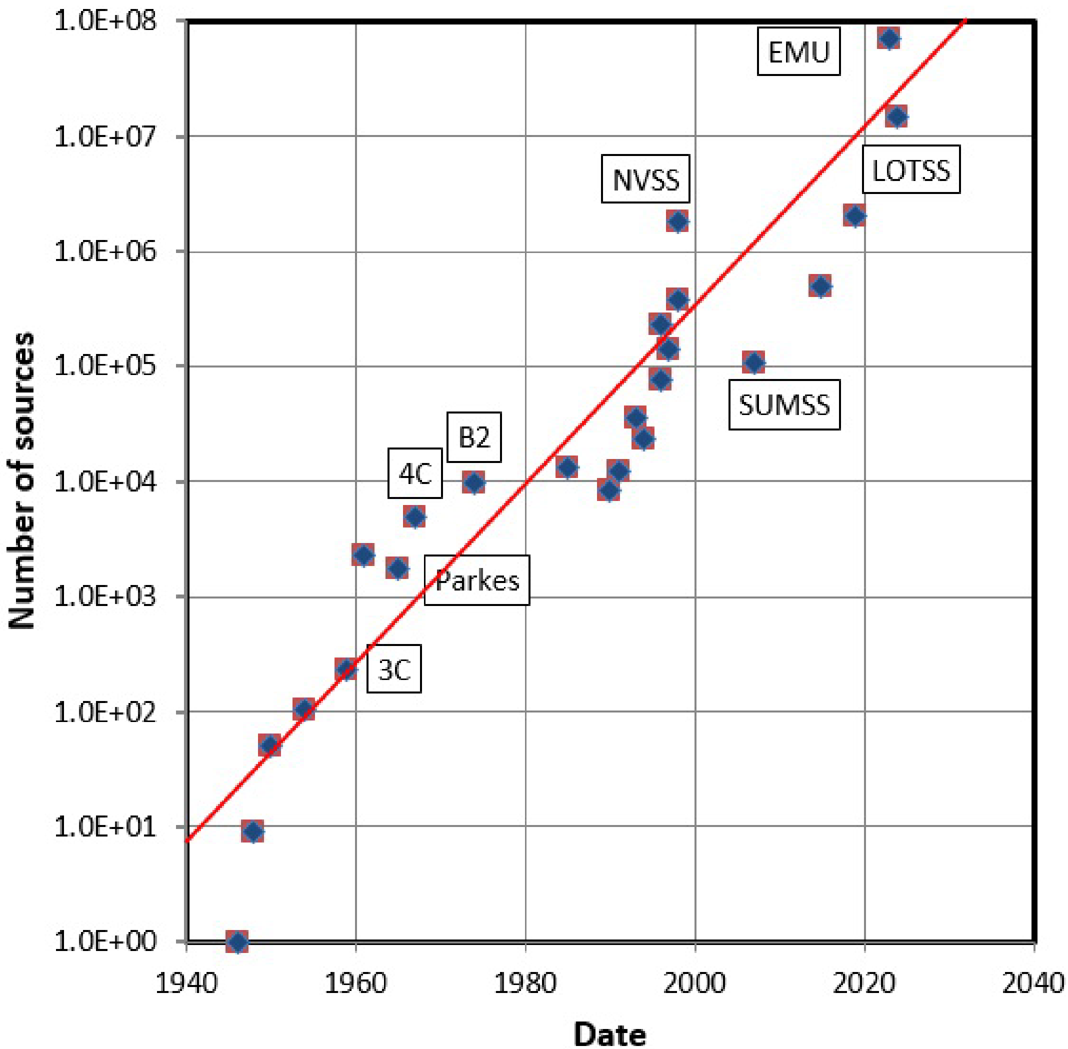

MWA
Survey the whole sky in a few nights
Image Credit: GLEAM Team

Low Frequency Radio Astronomy papers

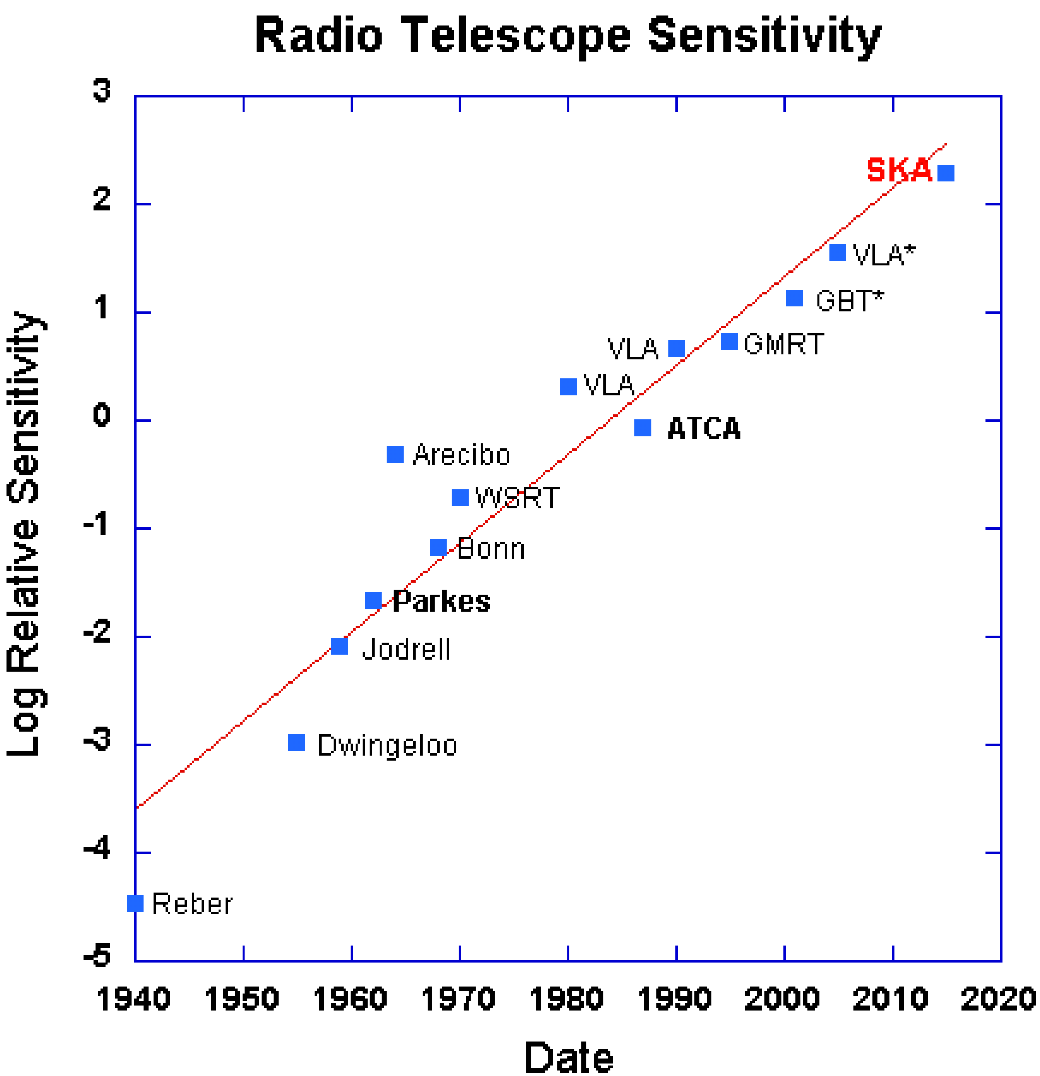


Evolution of radio surveys

- Increase by 10^5 in 60 yr
- 3 year doubling time for survey size
- Exponential?
- What happened from 1970 to 1990?
  - WSRT and VLA focus on individual objects
- Tracks telescope sensitivity evolution



Radio Telescope Sensitivity



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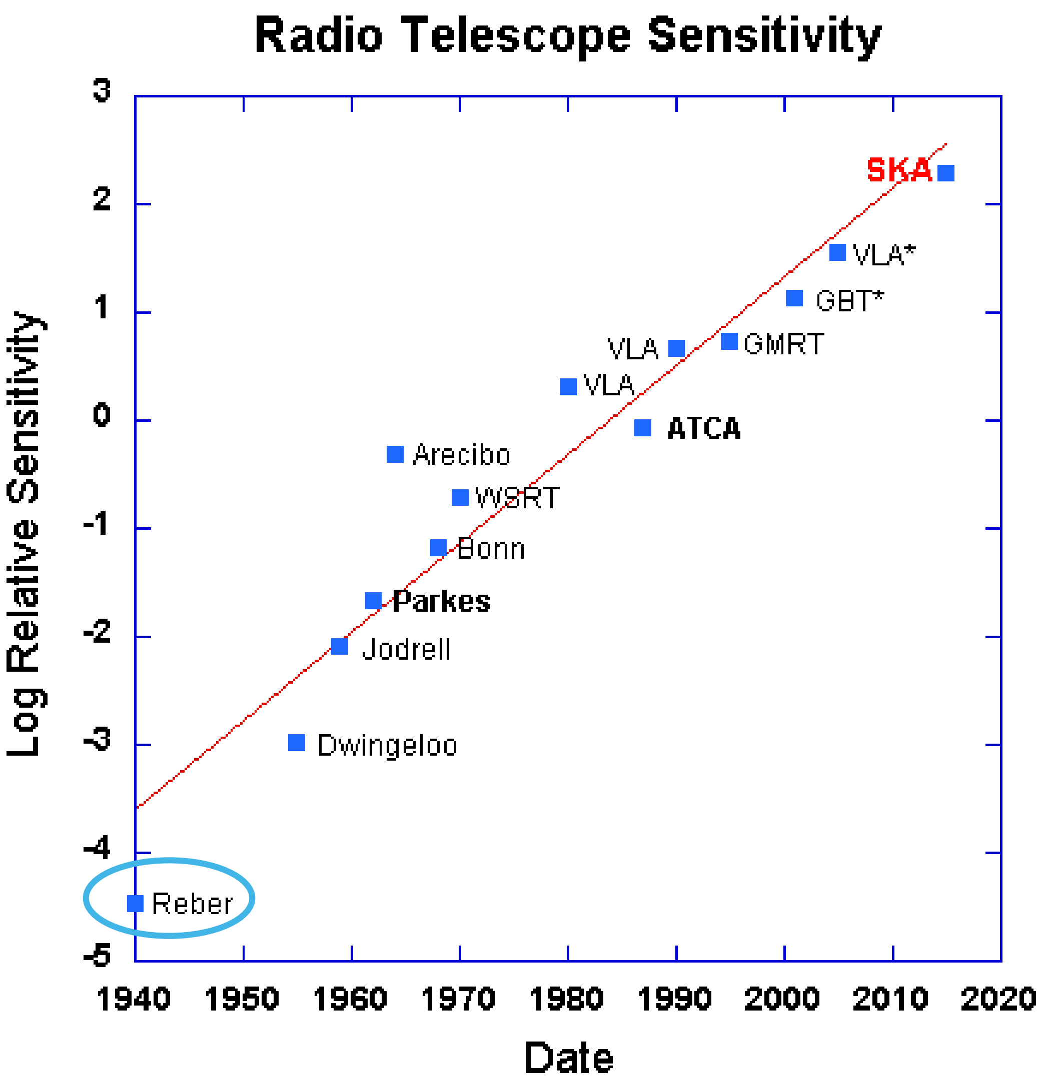

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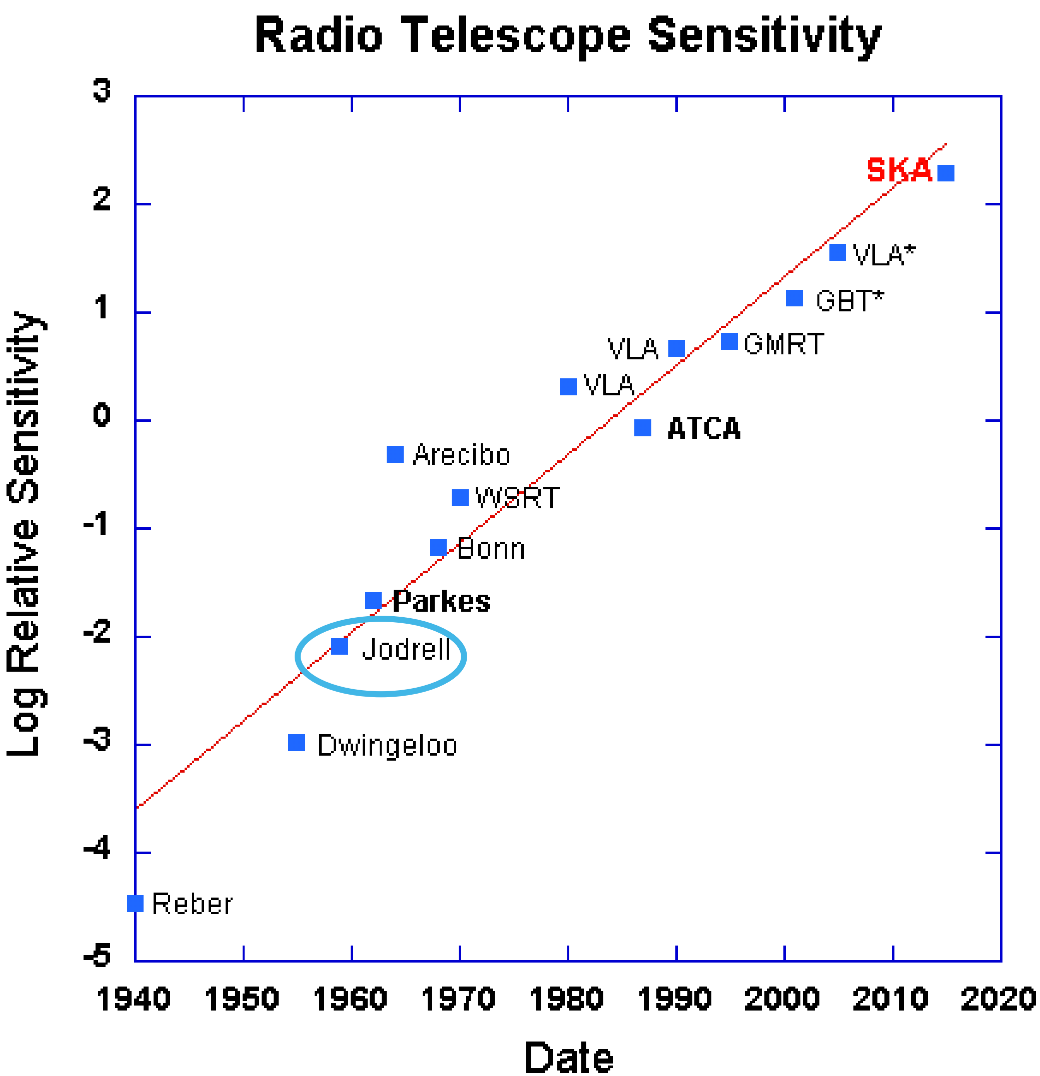

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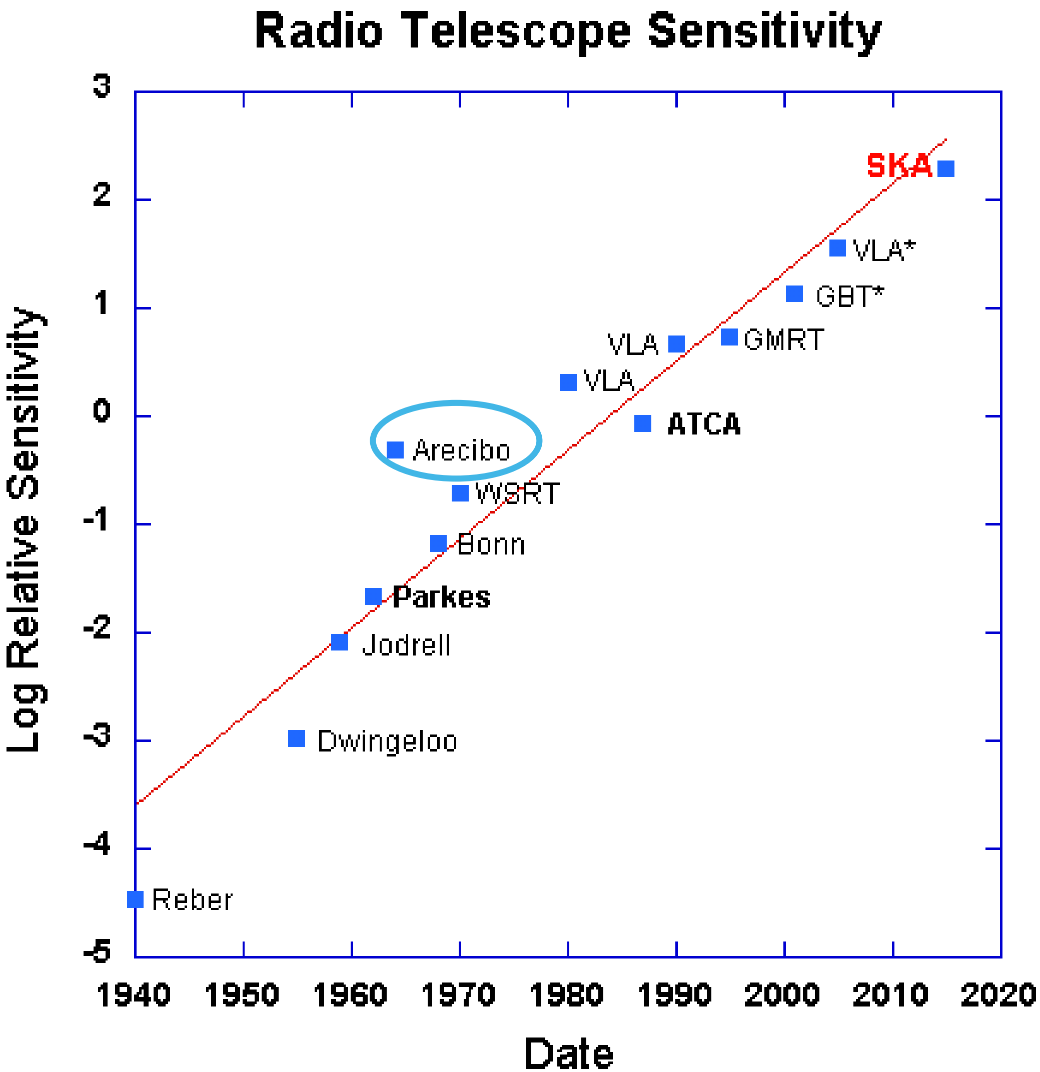

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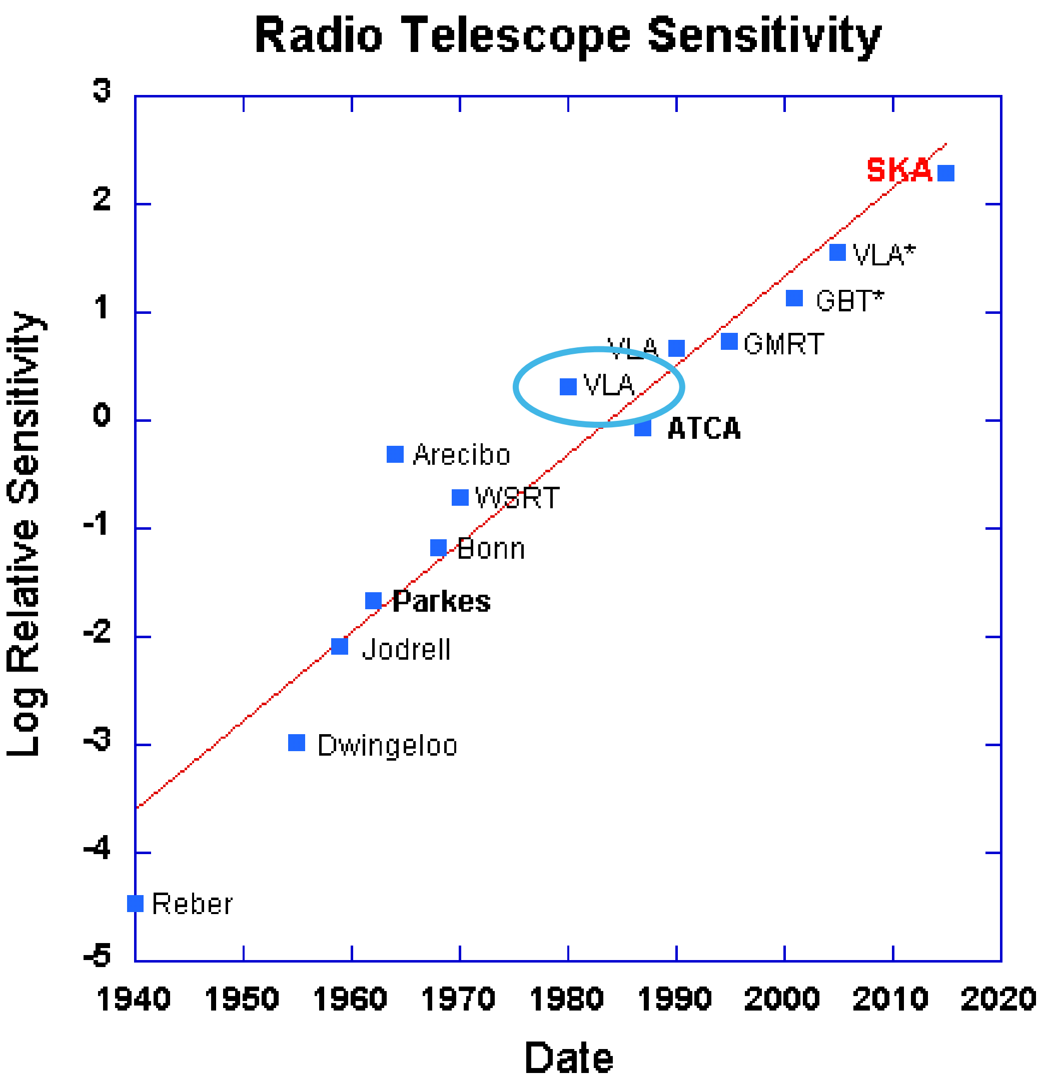

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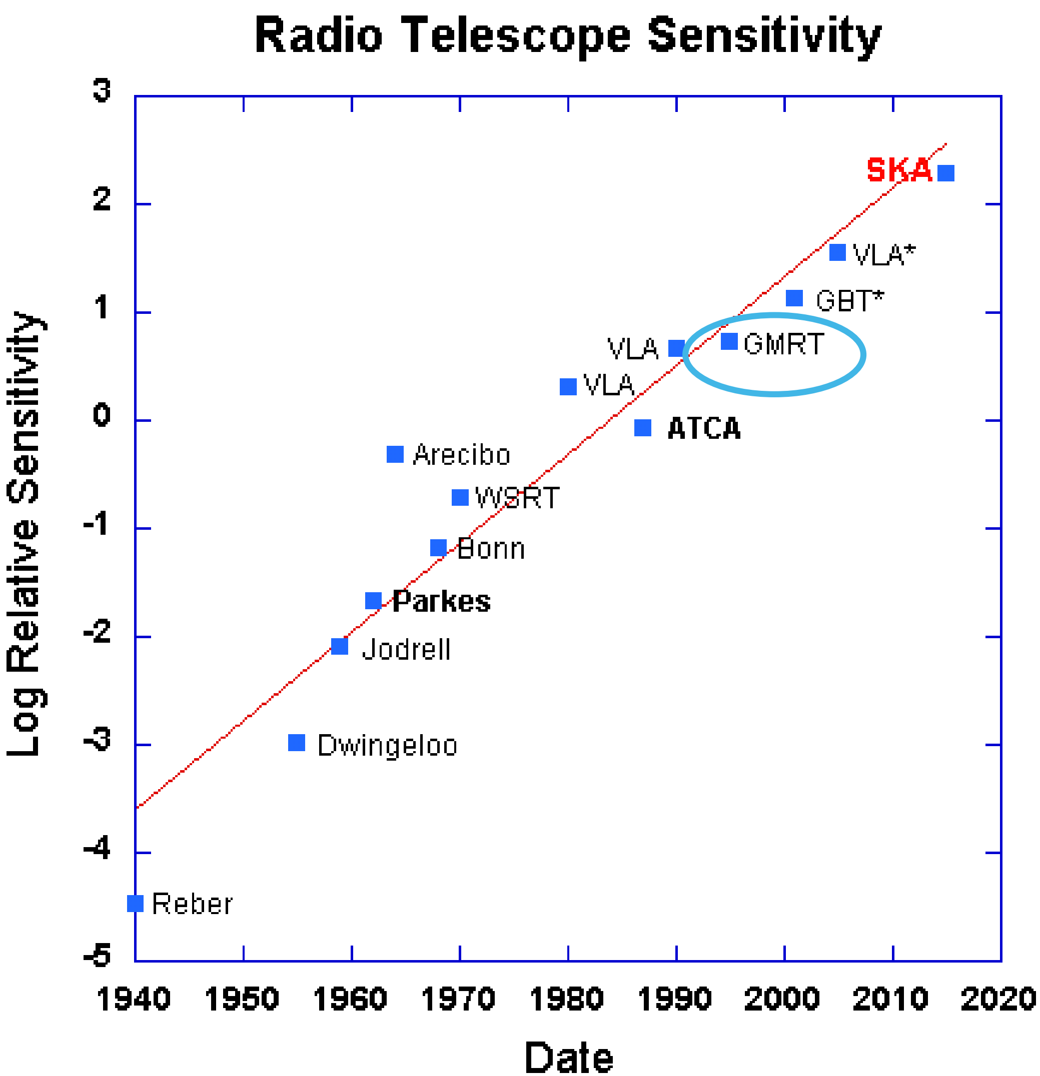

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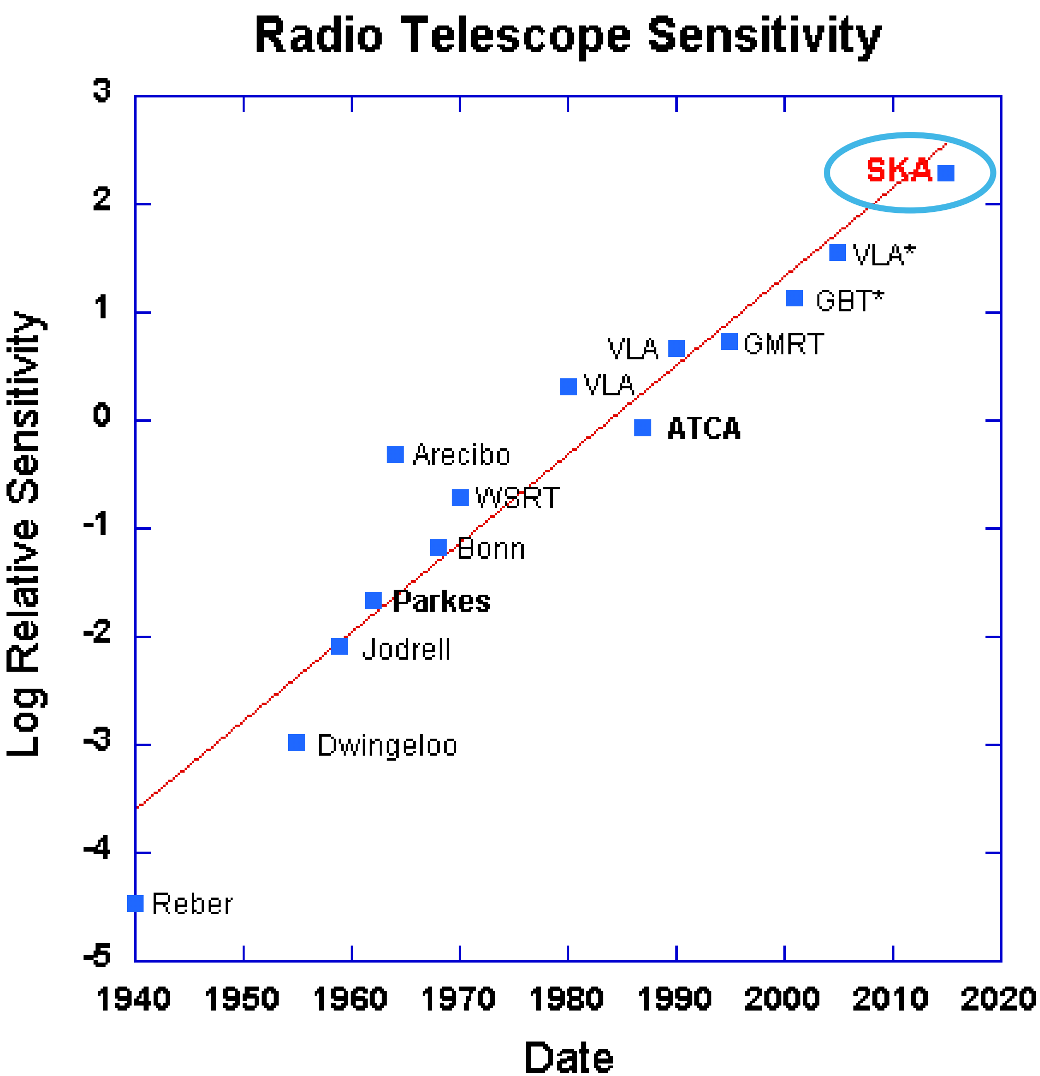
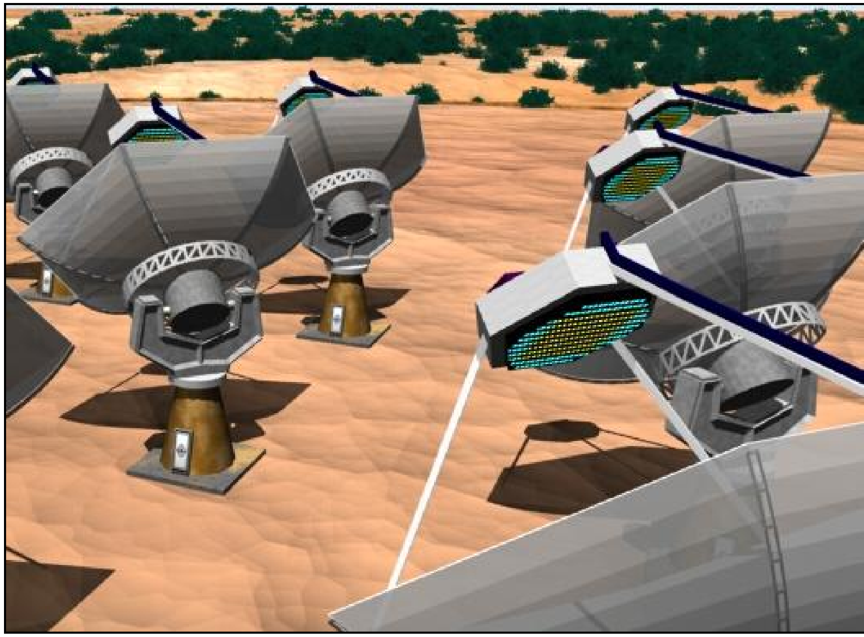
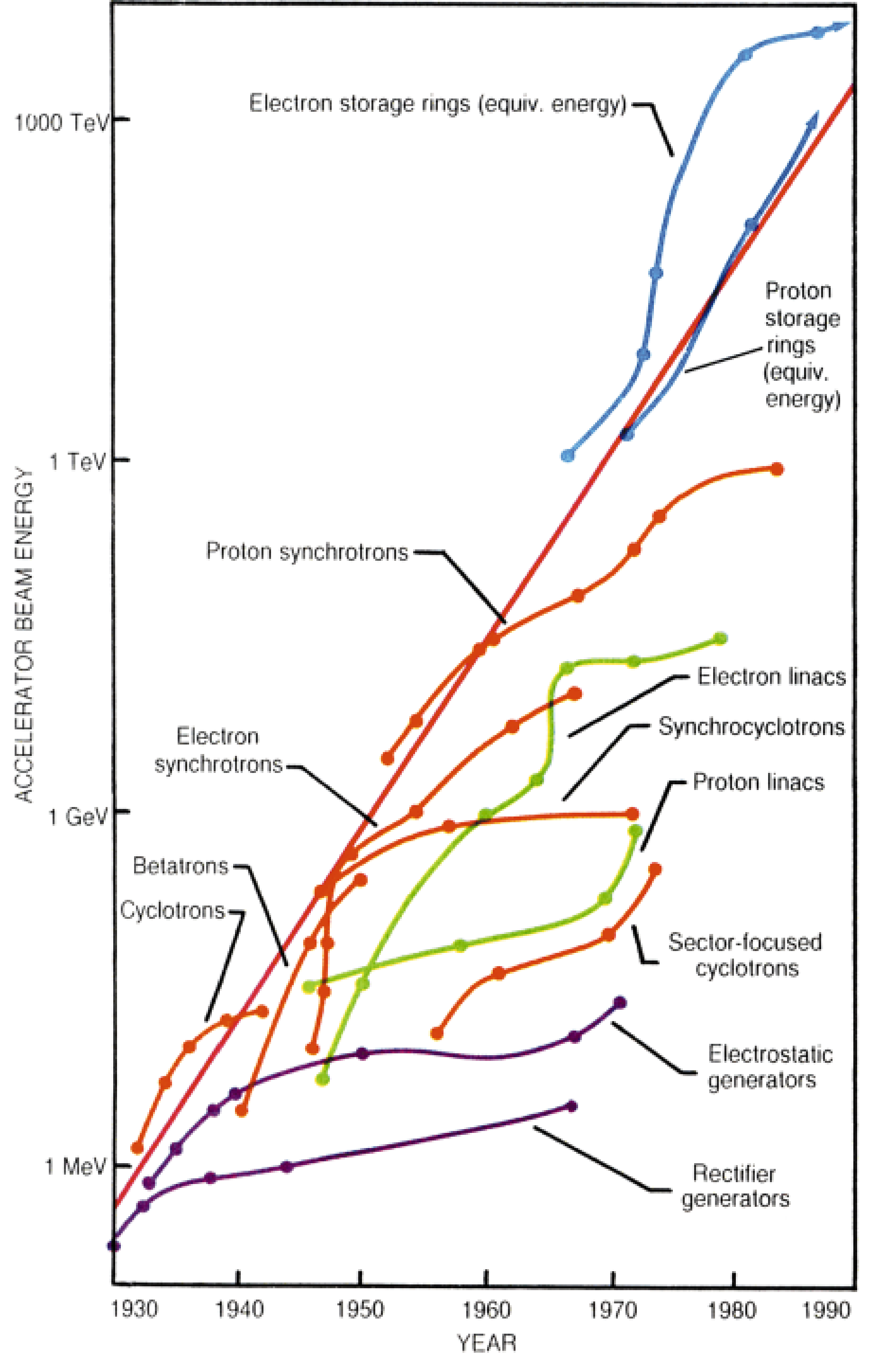


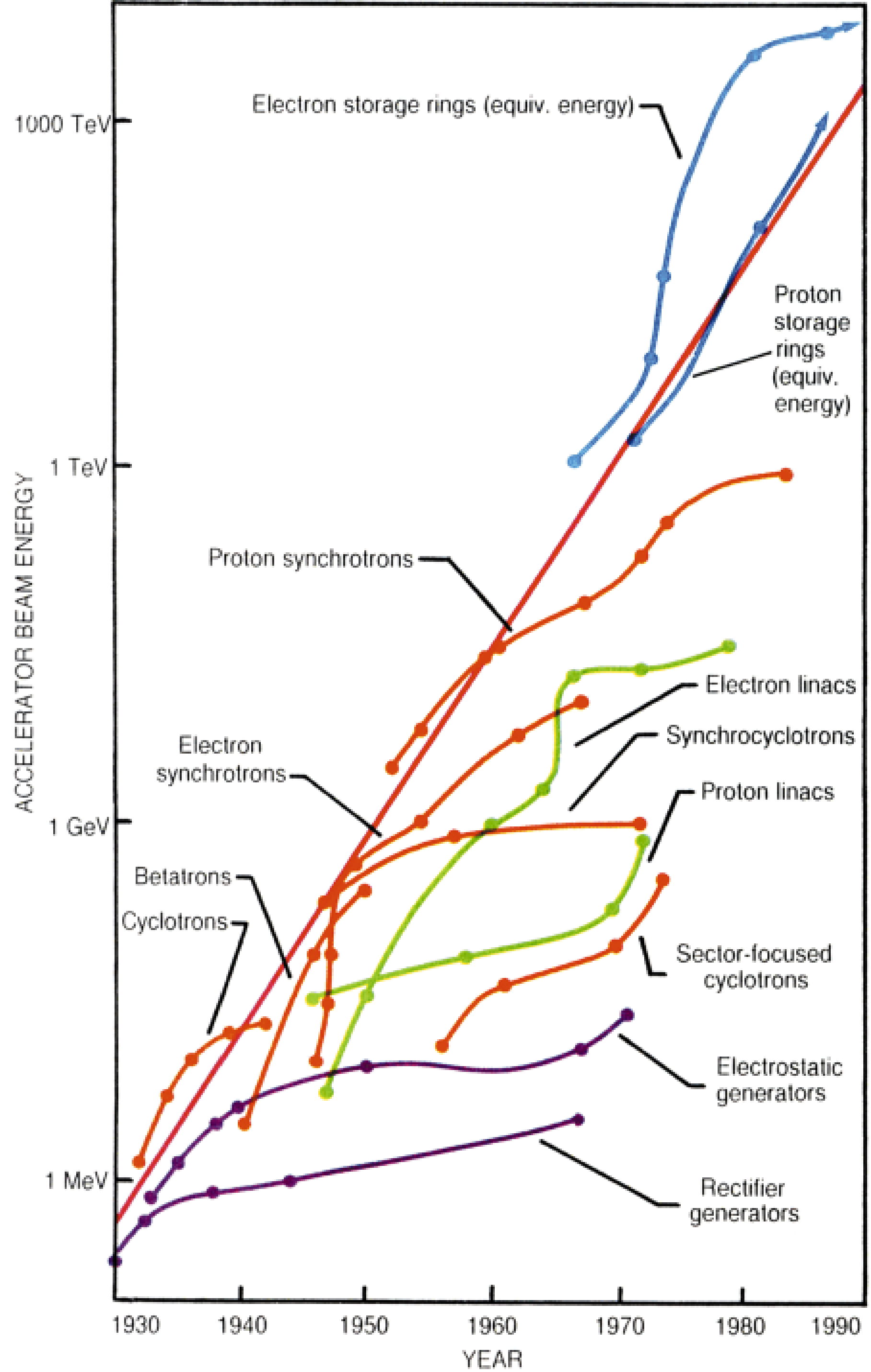


Exponential Grow



Exponential Grow

- Livingstone Curve
  - Blewett, Brookhaven 1950
  - Fermi 1954
  - Livingstone 1962



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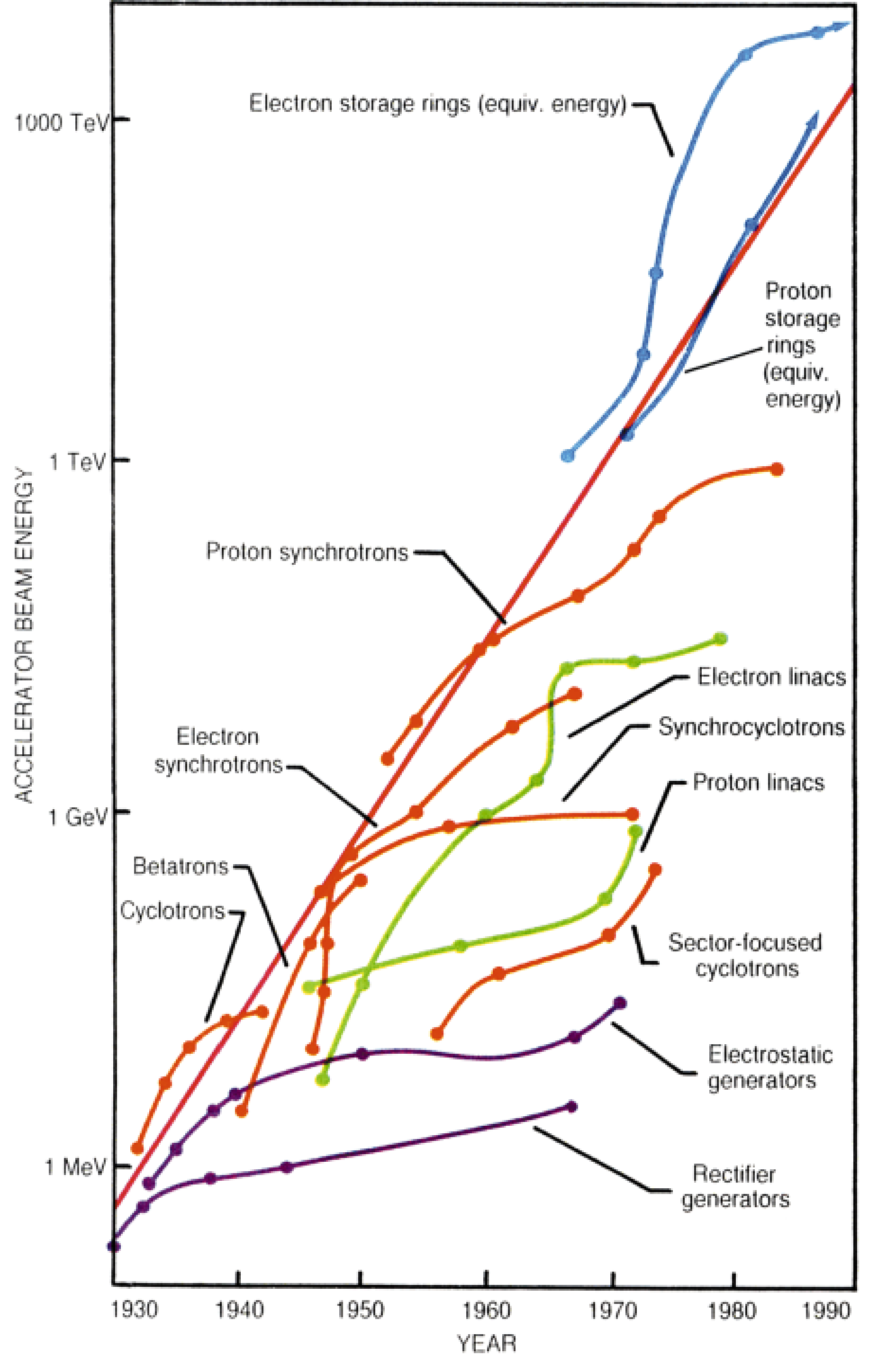

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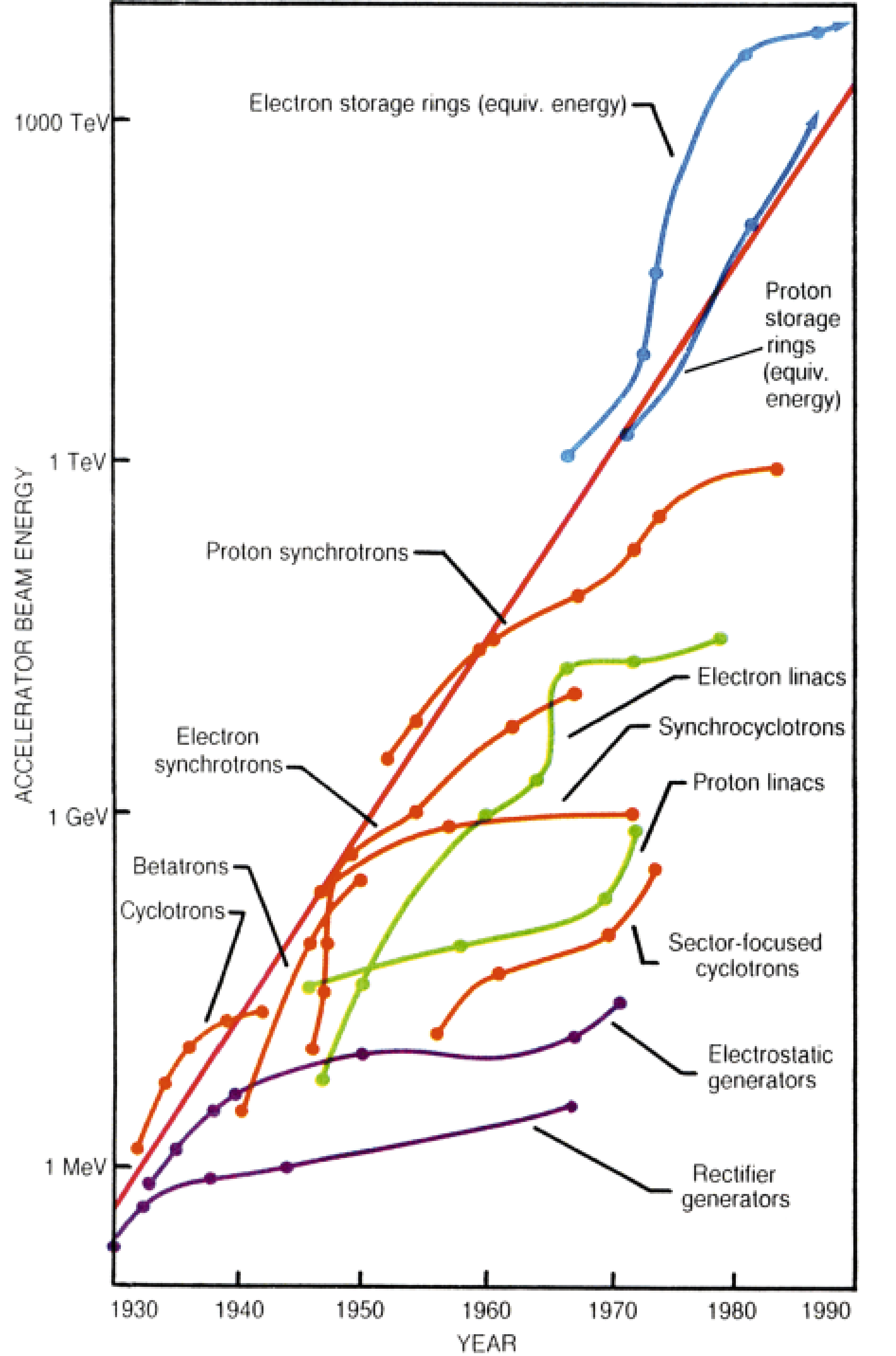
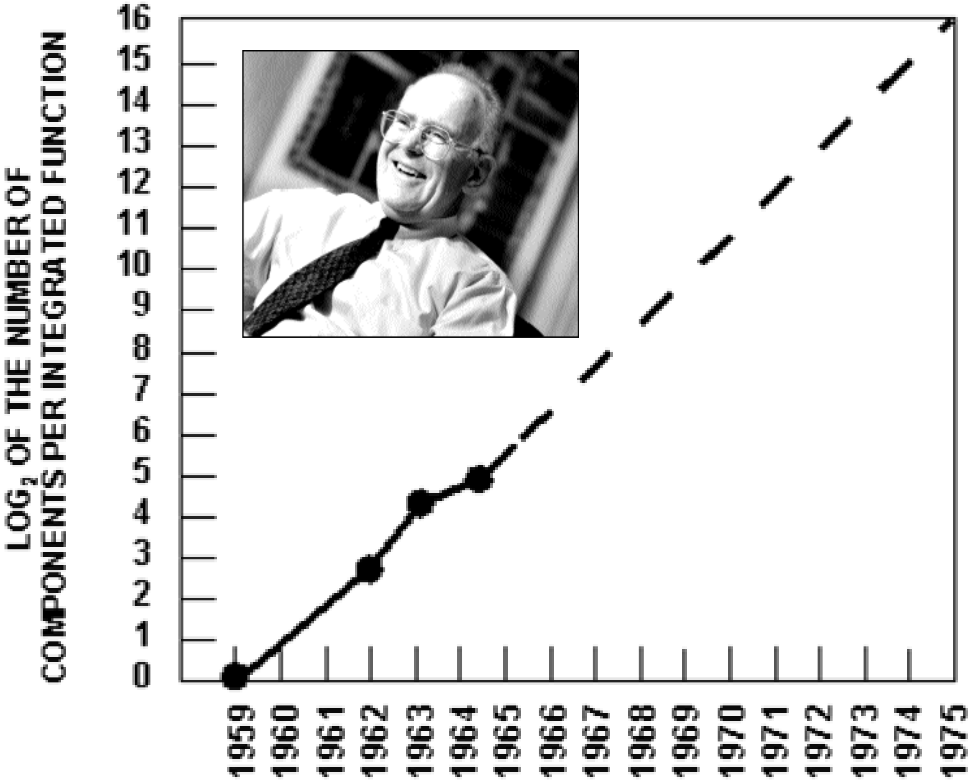
- Each technology saturates



The Original Moore's Law Plot

In 1965 Gordon Moore (co-founder of Intel) noted that the transistor density of semiconductor chips doubled roughly every 18 months.



Electronics, April 1965

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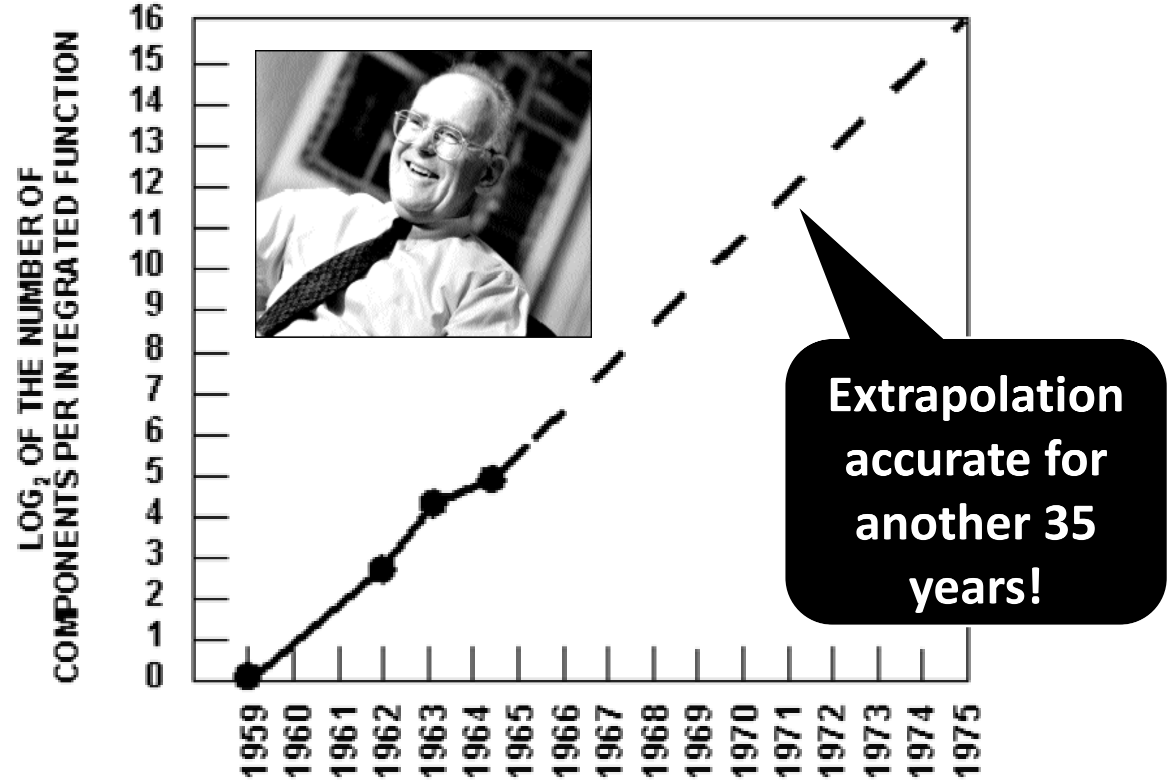
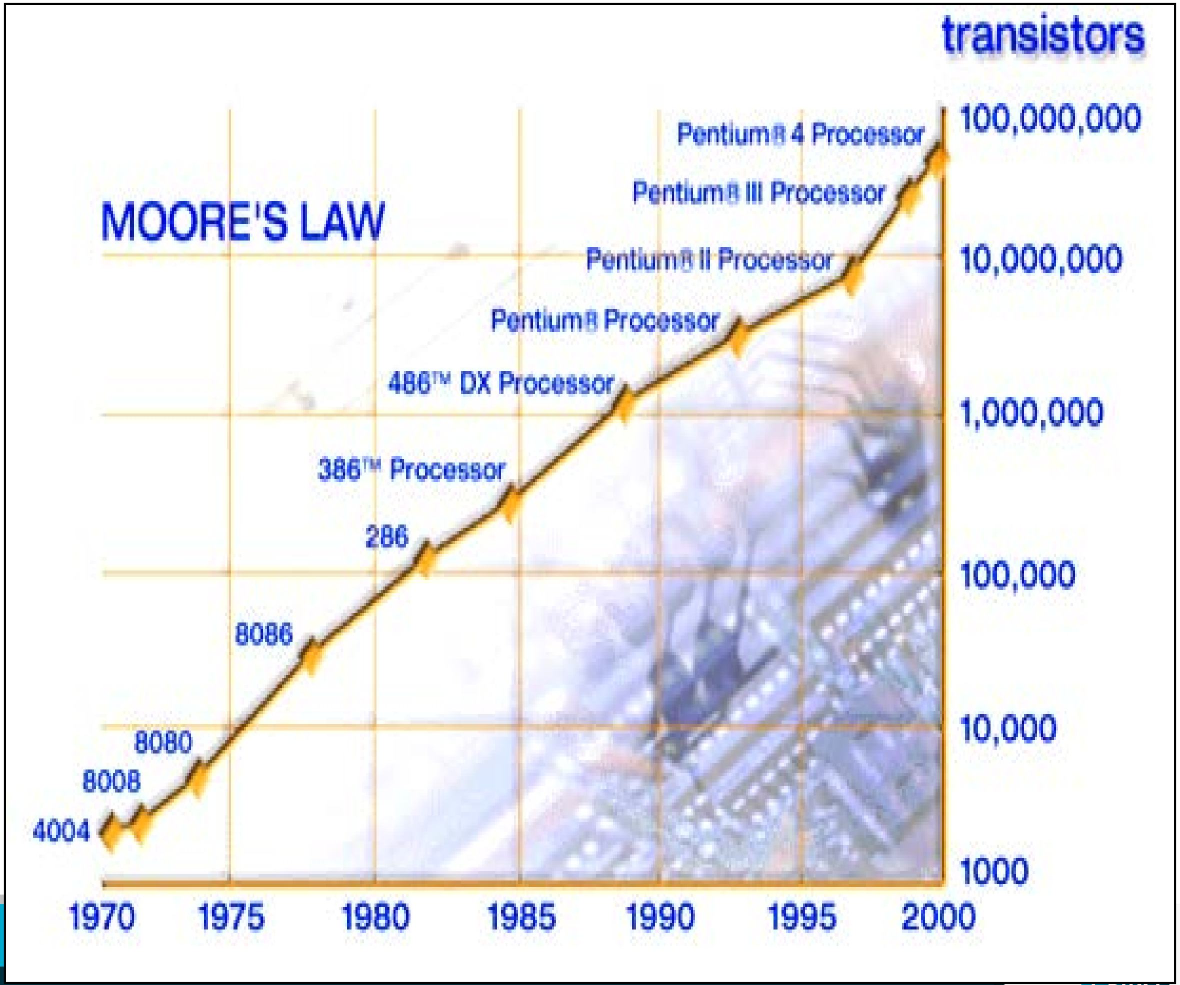


Electronics, April 1965

Microprocessor performance

- Moore's Law
  - Intel 2000



Technology leads scientific discoveries

- De Solla Price: *most scientific advances follow laboratory experiments*
- Martin Harwit: *most important discoveries result from technical innovation*
  - Discoveries peak soon after new technology appears
  - usually within 5 years of the technical capability
- Many examples from radio astronomy
  - Quasars, Pulsars, CMB….
- Successful telescopes are built by visionaries but often for the wrong reason

SKA beginnings

- 1971 Cyclops
- 1986-9 Canadian proposal for Radio Schmidt
  - Peter Dewdney 100x12m antennas
- 1988-1990 Dutch extragalactic HI telescope
  - Robert Braun, Ger DeBrujn and Jan Noordam
- 1988-1991 Swarup proposals
  - International Radio Astronomy telescope (ITRA)
  - 160 75m dishes, centrally concentrated and baselines to 200km
- 1990 URSI General Lecture Prague
  - exponential growth and discovery arguments

Technology

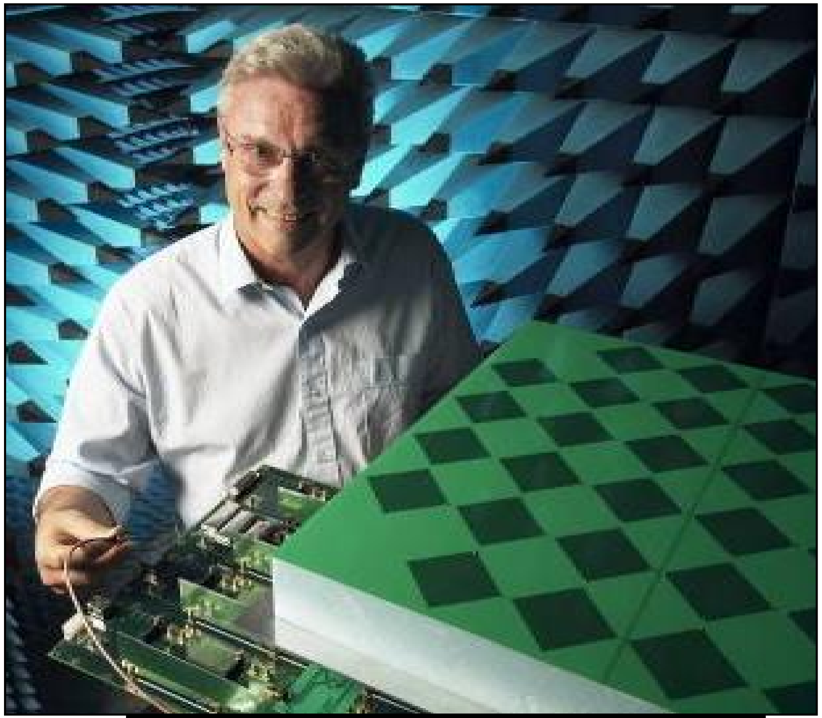
- New techniques
  - Wide FoV imaging
  - Ionosphere
    - Direction dependant calibration
  - RFI mitigation
    - Very clever excision algorithms
    - Limited development of adaptive filters

Aperture arrays and Phased Array Feeds

- Wide FoV at full sensitivity over whole field
  - FoV is fully sampled (key issue for fast transients)
  - Basis for all the low frequency arrays
  - Technical issues with aperture arrays
  - Perhaps time for more hardawere solutions

- Advantage of PAFs - not just spatially continuous
  - Aperture illumination control
  - Wide bandwidth (3:1)
  - No bandpass ripple
  - High aperture efficiency
  - RFI mitigation

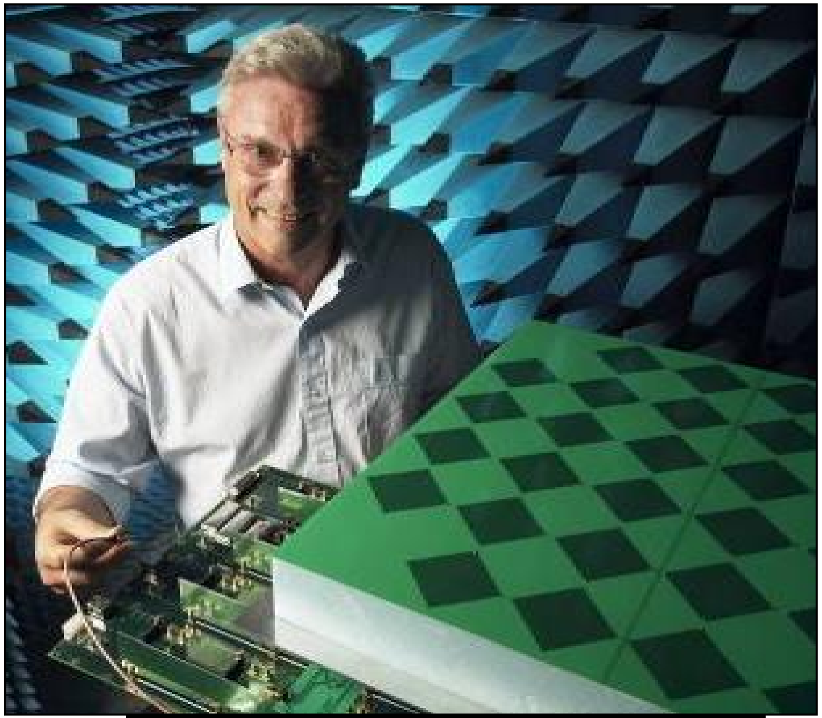
Some PAF designs



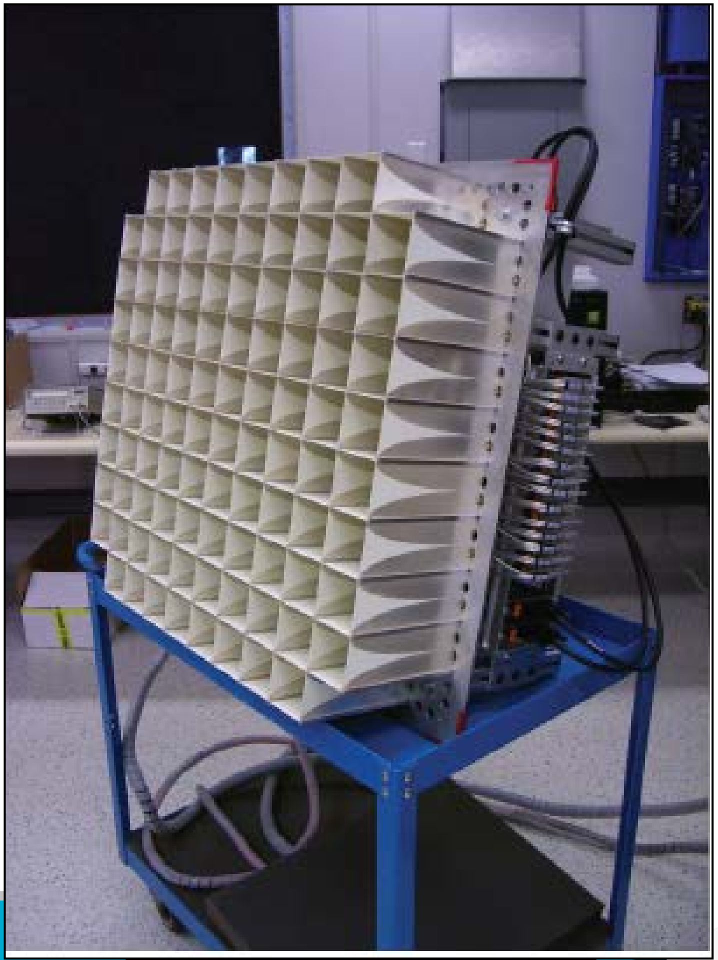
Checker board - ATNF

Vivaldi - DRAO

Some PAF designs



Checker board - ATNF



Vivaldi - DRAO

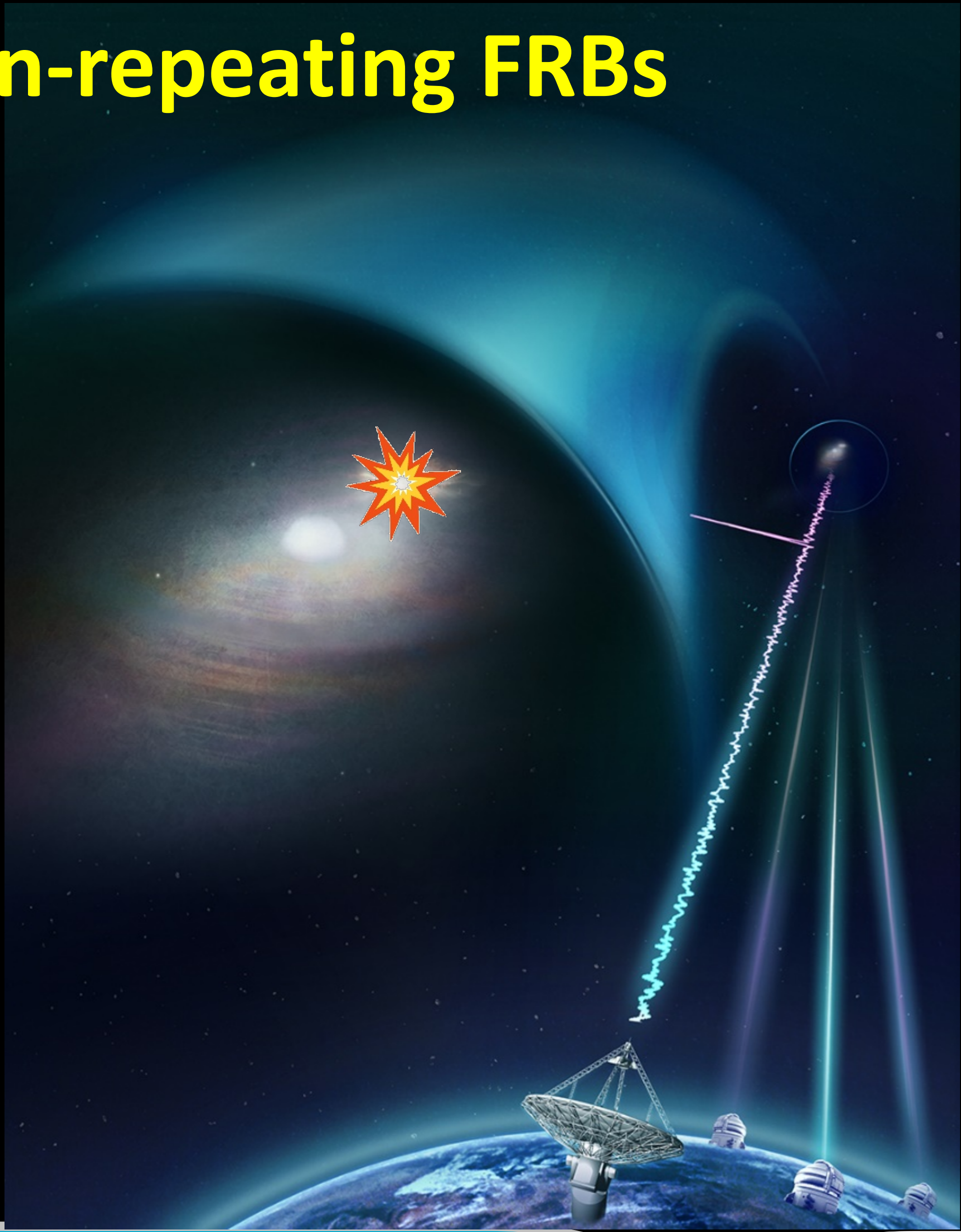
John Bolton discovers radio emission from the galactic centre

- Built his own “hole in the ground” antenna (without approval)
  - ➢ Dover Heights near Sydney
  - ➢ Now a football field
- Discovered radio emission from the nucleus of our galaxy
  - ➢ McGee and Bolton *Nature (1954)*

MeerKat enters the picture

ASKAP Positions of non-repeating FRBs

- Incoherent detection (full FoV)
- Voltage dump
- Correlation
- Image




Survey the whole sky in a few nights
Image Credit: GLEAM Team

Exceptional instantaneous imaging capability: 128 tiles and 8128 baselines

CSIRO

Cover Feb 2016

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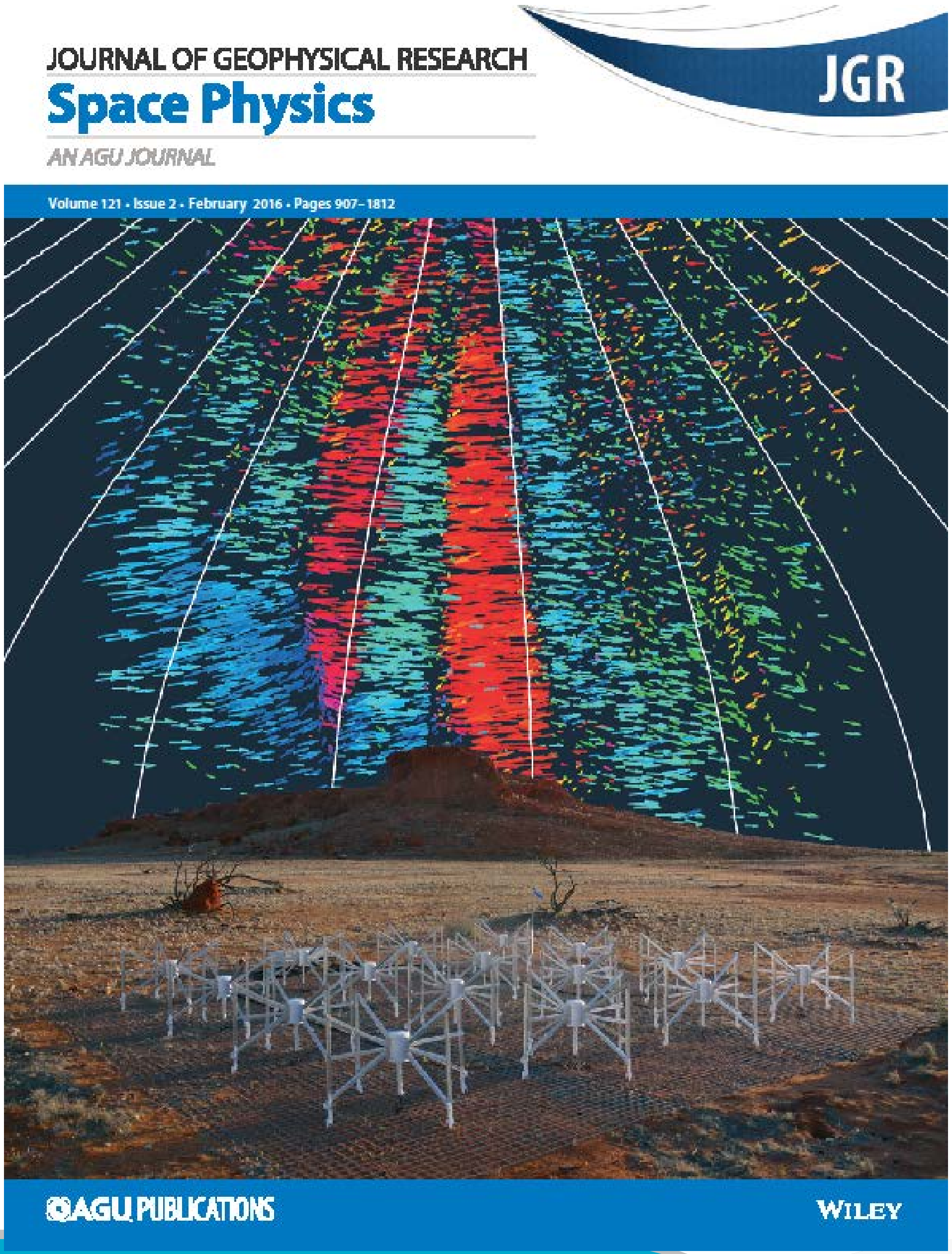
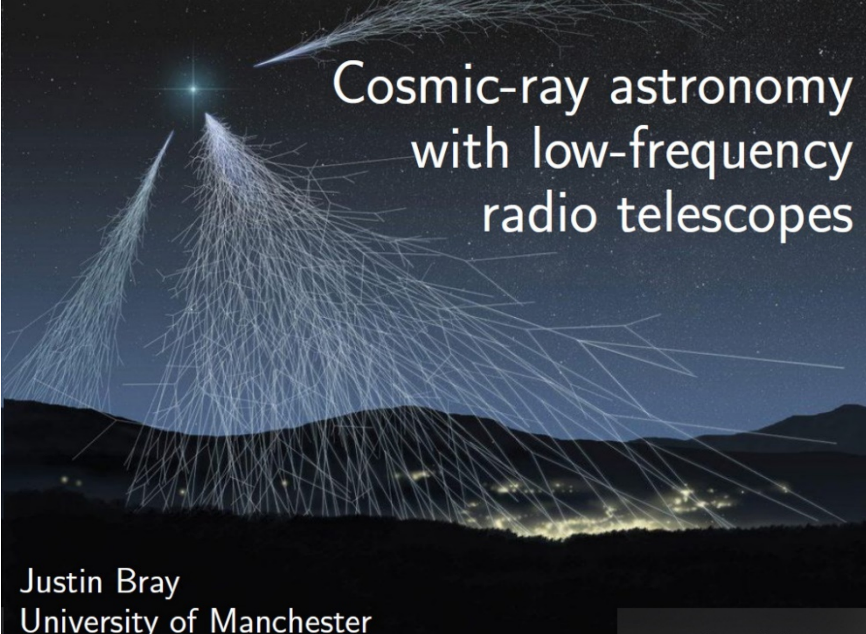
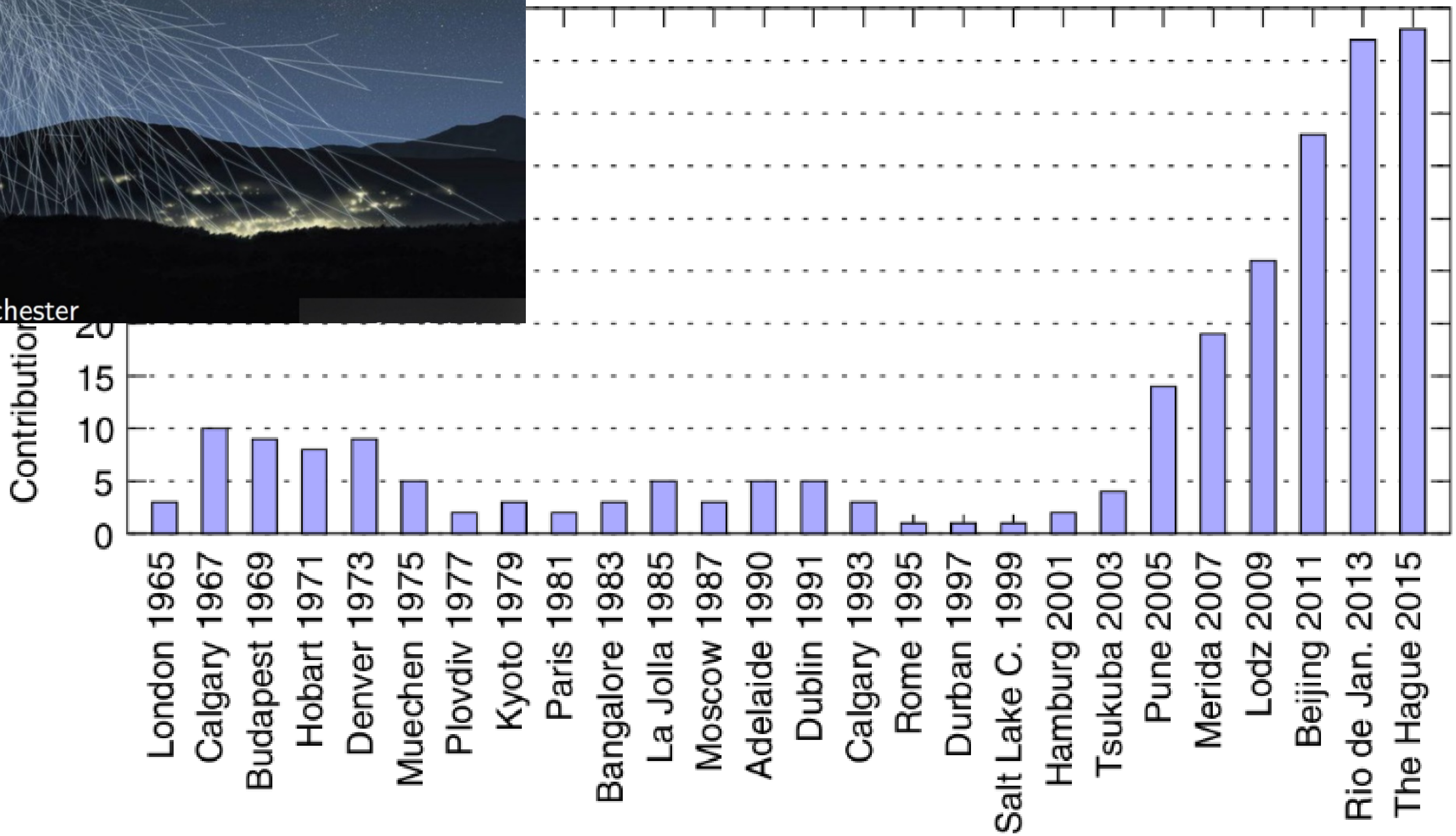
- Shyeh Tjing Loi (Cleo)
- Ionospheric ducts over the MWA

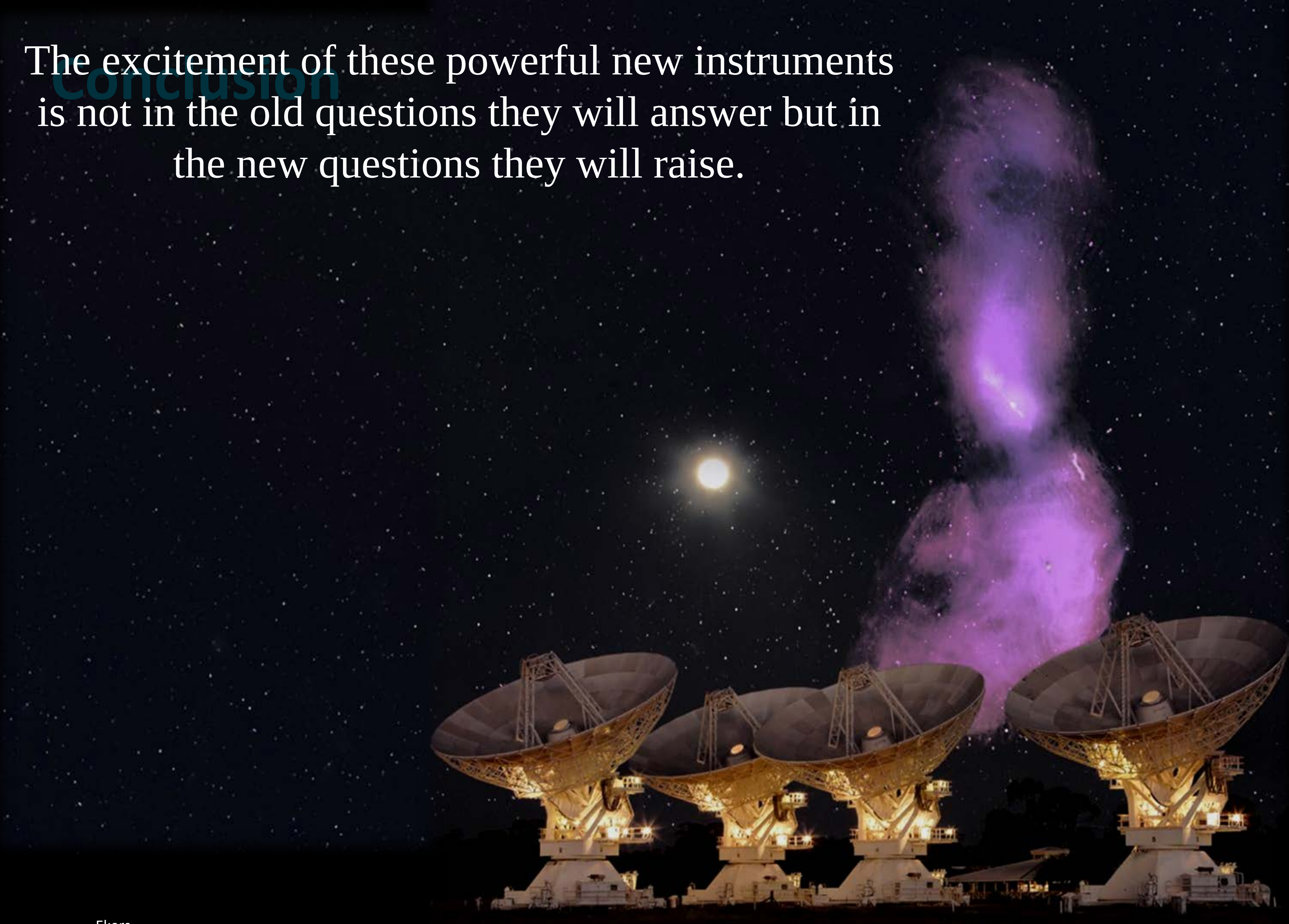



Cosmic-ray astronomy
with low-frequency
radio telescopes
Justin Bray
University of Manchester


Contribution
0
5
10
15
London 1965
Calgary 1967
Budapest 1969
Hobart 1971
Denver 1973
Muechen 1975
Plovdiv 1977
Kyoto 1979
Paris 1981
Bangalore 1983
La Jolla 1985
Moscow 1987
Adelaide 1990
Dublin 1991
Calgary 1993
Rome 1995
Durban 1997
Salt Lake C. 1999
Hamburg 2001
Tsukuba 2003
Pune 2005
Merida 2007
Lodz 2009
Beijing 2011
Rio de Jan. 2013
The Hague 2015

Conclusion

The excitement of these powerful new instruments is not in the old questions they will answer but in the new questions they will raise.



Conclusion

The excitement of these powerful new instruments is not in the old questions they will answer but in the new questions they will raise.

The power of science is its ability to make predictions but science itself will evolve in unpredictable ways