# Radio Astronomy
# Then Now and Future

CASS Radio Astronomy School

Narrabri

1826 Sep 2017

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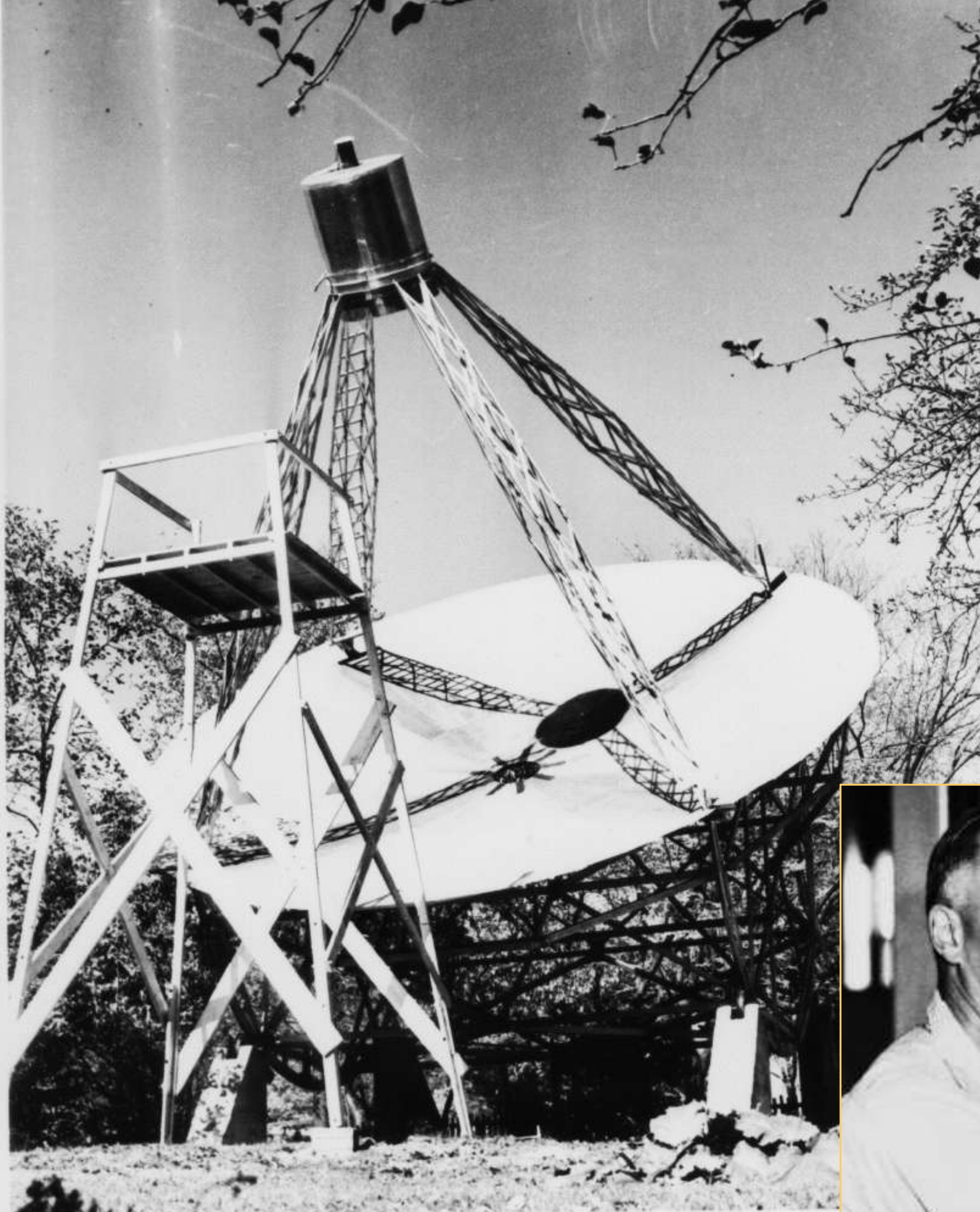
# Outline

- History with emphasis on technical innovation in radio astronomy
- Most advances and discoveries in radio astronomy are a direct consequence of technology development
- How some of these innovative steps have occurred
  - pushing boundaries
  - cross fertilization between fields
  - sophisticated end users (i.e. the astronomers)
  - most depended on external developments
- The future
- George Santayana:
  - *Those who cannot remember the past are condemned to repeat it*



# Grote Reber

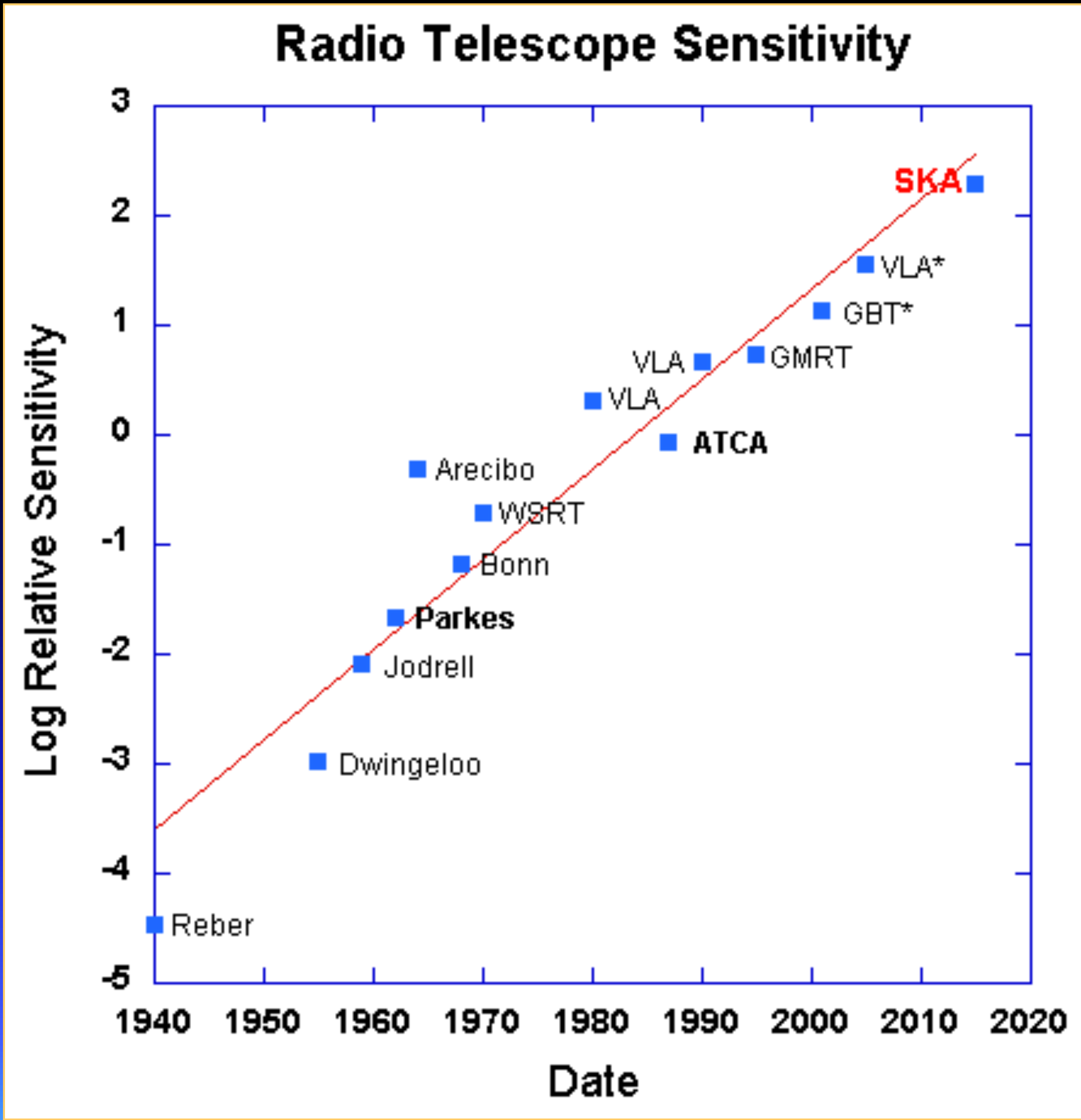
Wheaton, Illinois 1937
- Parabolic dish for frequency flexibility
- 32’ antenna, privately funded - $2K

# The Discovery of the Non-Thermal Universe

- 1939 detected cosmic static by going to **longer** wavelengths
  - ✗ 3300 MHz
  - ✗ 900 MHz
  - ✓ 160 MHz
- Radiation had to be non-thermal
  - – No theoretical basis at the time
  - – 1950 Synchrotron radiation theory
    - 10 years after Reber
- First radio map of sky
  - – Great difficulty getting published

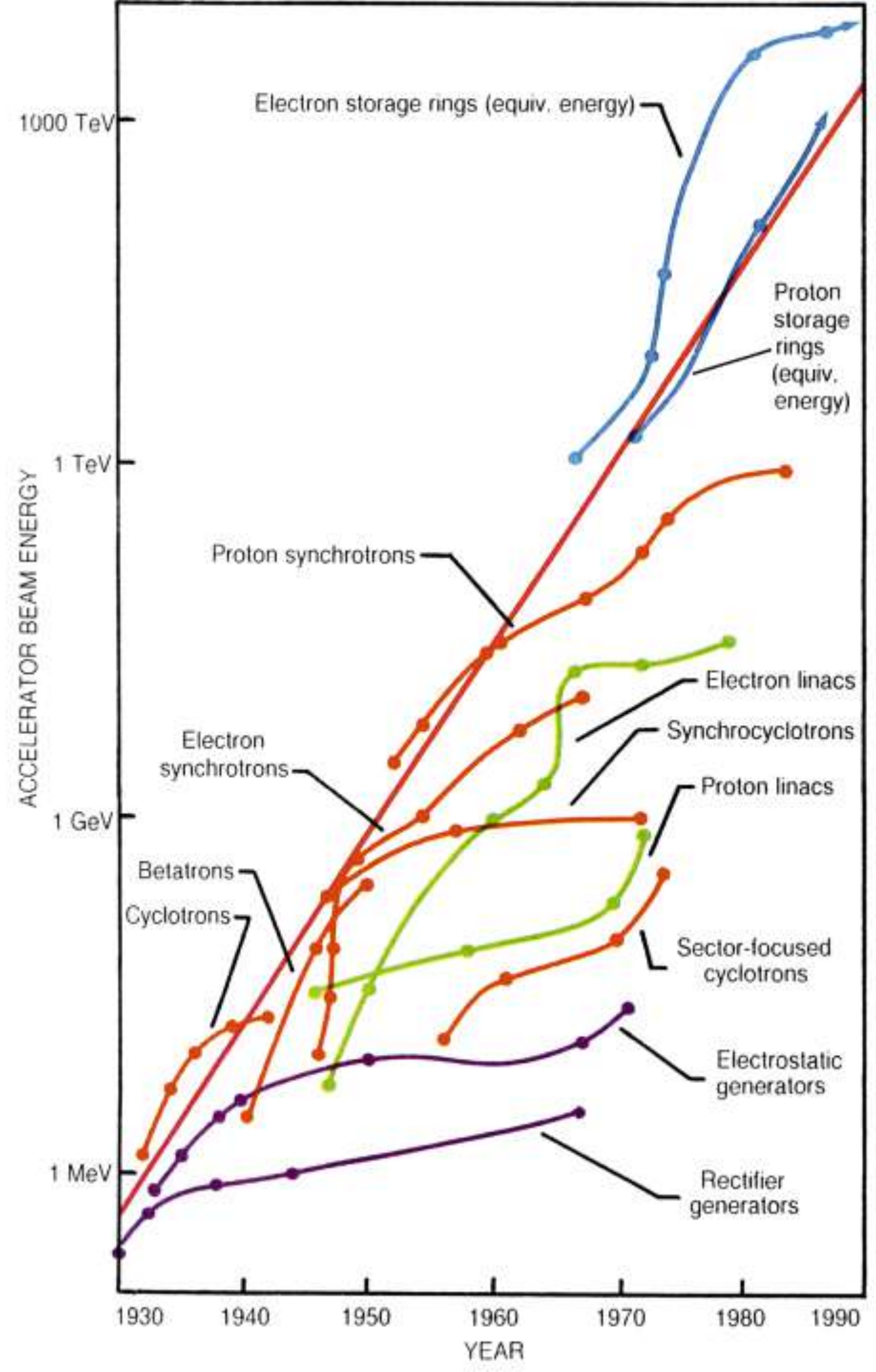
# Radio Telescope Sensitivity

- Earlier version shown at the URSI GA Prague 1990
  - General lecture
- Exponential increase in sensitivity x $10^5$ since 1940 !
  - 3 year doubling time for sensitivity



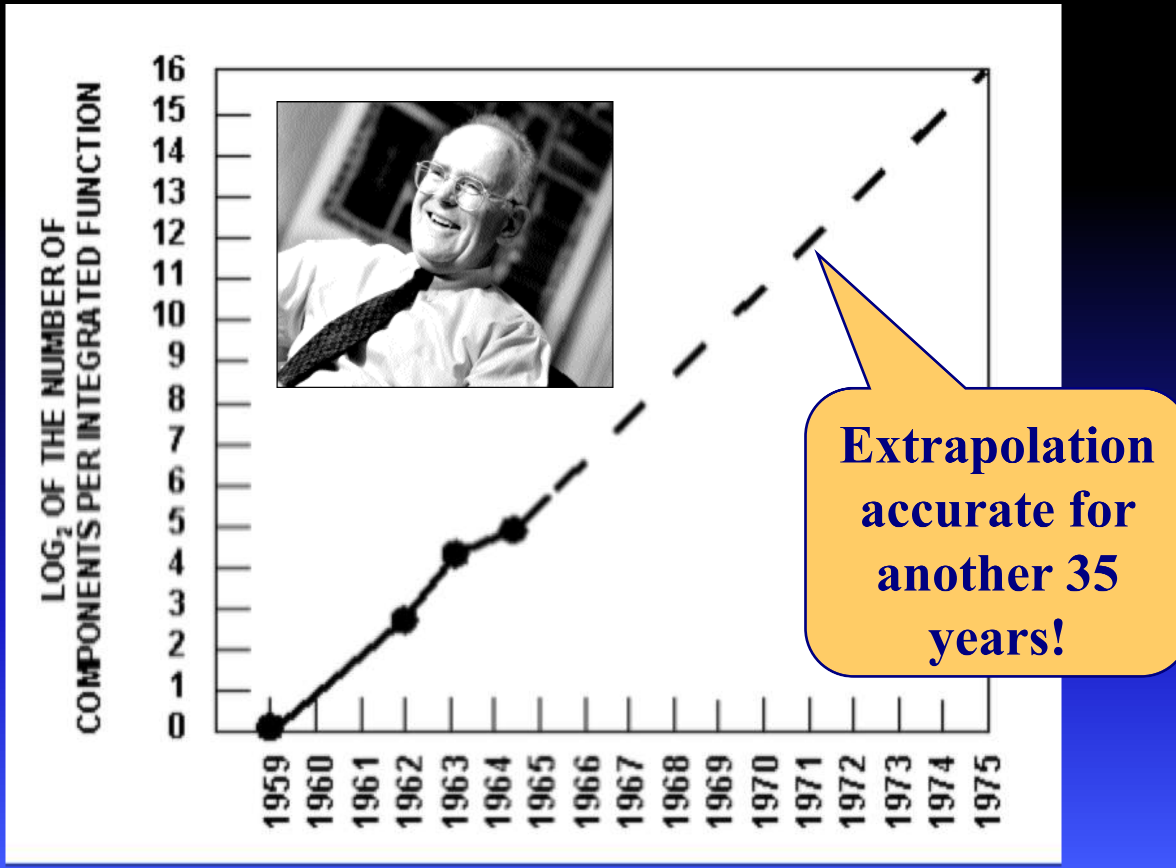
# Exponential Growth

- Livingstone Curve
  - Blewett, Brookhaven 1950
  - Fermi 1954
  - Livingstone 1962
- Envelope is exponential
- Each technology saturates



# The Original Moore's Law Plot

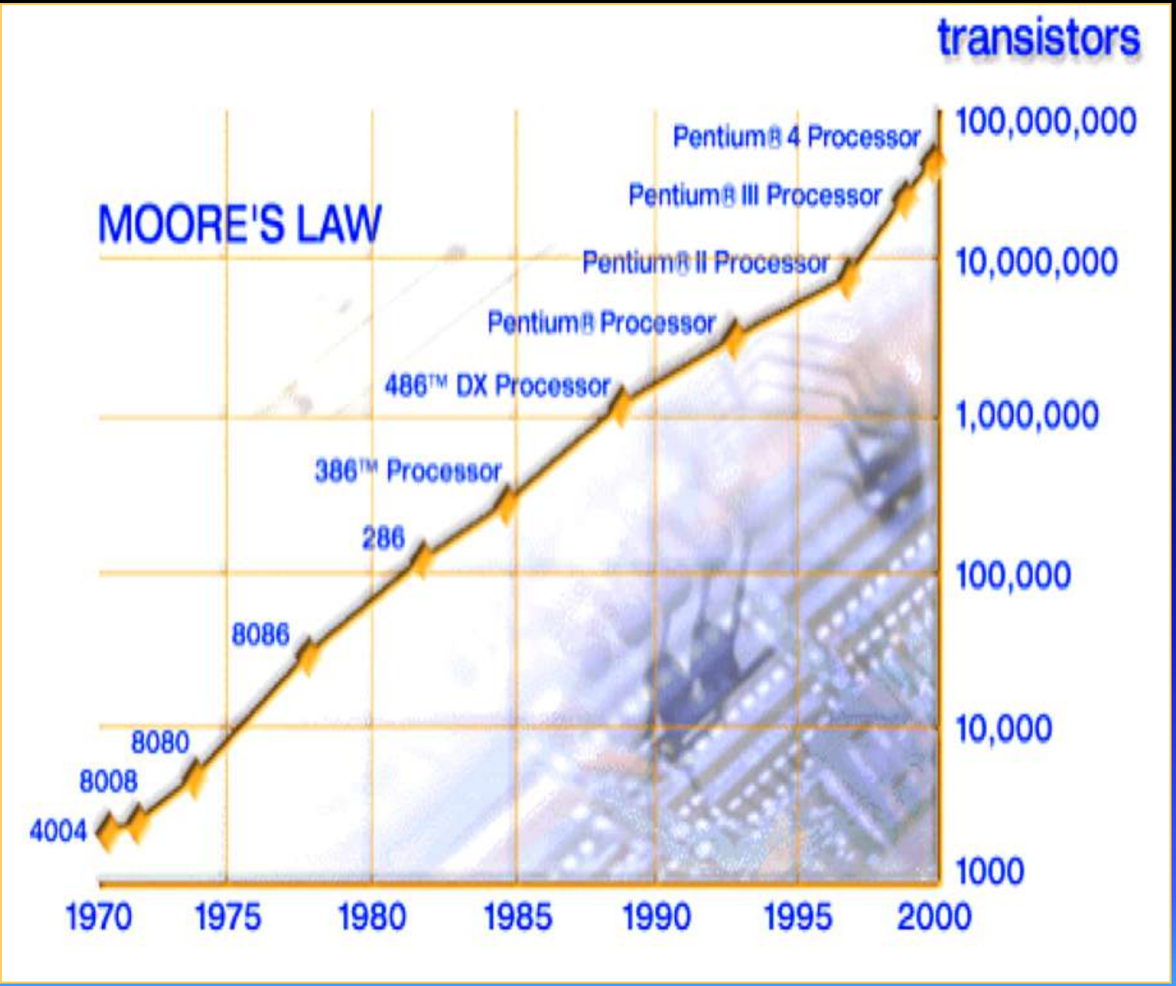
In 1965 Gordon Moore (co-founder of Intel) noted that the transistor density of semiconductor chips doubled roughly every 18 months.




*Electronics*, April 1965

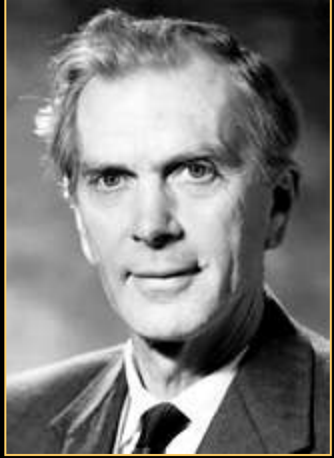
# Microprocessor performance

- Moore's Law
  - Intel 2000
- Enables all processing intensive radio astronomy



# Technology leads scientific discoveries

- De Solla Price (1963):
  - *most scientific advances follow laboratory experiments*
- Martin Harwit (1981):
  - *Most important discoveries result from technical innovation*
- Discoveries peak soon after new technology appears
  - Usually within 5 years of the technical capability
- Radio window is now old but survey parameter space can still be enlarged
  - Bandwidth (x10 – 50)
  - Field of View (x 100)
  - Sensitivity and FoV lead to discovery of new rare objects



# Nobel Prize 1974
# Sir Martin Ryle

*from the presentation*

*"The radio-astronomical instruments invented and developed by Martin Ryle, and utilized so successfully by him and his collaborators in their observations, have been one of the most important elements of the latest discoveries in Astrophysics."*

# 1938 van Cittert-Zernike theorem

- The spatial coherence over a space illuminated by an incoherent extended source is described by the Fourier transform of the intensity distribution over the source.
- Now considered the basis of Fourier synthesis imaging
- Played no role in the early radio astronomy developments but appears in the literature after Born & Wolf *Principles of Optics* (1960)

# The discovery of aperture synthesis

- 1935: Pawsey PhD with Ratcliffe at Cambridge
  - Learns about the Fourier Transform (ionospheric reseach)
- 1936
  - Fourier synthesis calculations routine in X-ray crystallography
- 1946: Ryle and Vonberg
  - Michelson interferometer to measure size of sunspots
- 1947: McCready, Pawsey & Payne-Scott
  - *It would be possible in principal to determine the brightness distribution by Fourier synthesis*
- 1952: Ryle invents the phase switch $(A+B)^2 - (A-B)^2 \rightarrow AxB$
  - Now practical to observe weak sources
- 1954: X-ray crystallographers
  - introduce Ryle's group to EDSAC-1 for Fourier transforms
- 1960: Ryle & Hewsish
  - Synthesis of large radio telescopes

# McCready, Pawsey & Payne-Scott 1947

- Proc Roy Soc, Aug 1947 - received July 1946!
- Used the phase of the sea interferometer fringes (lobes) to co-locate solar emission with sunspots
- They note that its possible in principal to determine the actual distribution by Fourier synthesis using the phase and amplitude at a range of height or wavelength.
- They consider using wavelength as a suitable variable as unwise since the solar bursts are likely to have frequency dependent structure.
- They note that getting a range of cliff height is clumsy and suggest a different interference method would be more practical.

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Joe Pawsey NRAO 1961

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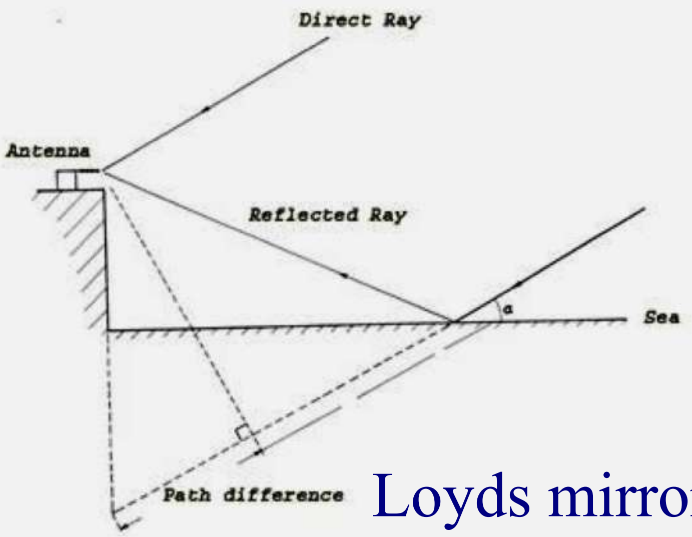
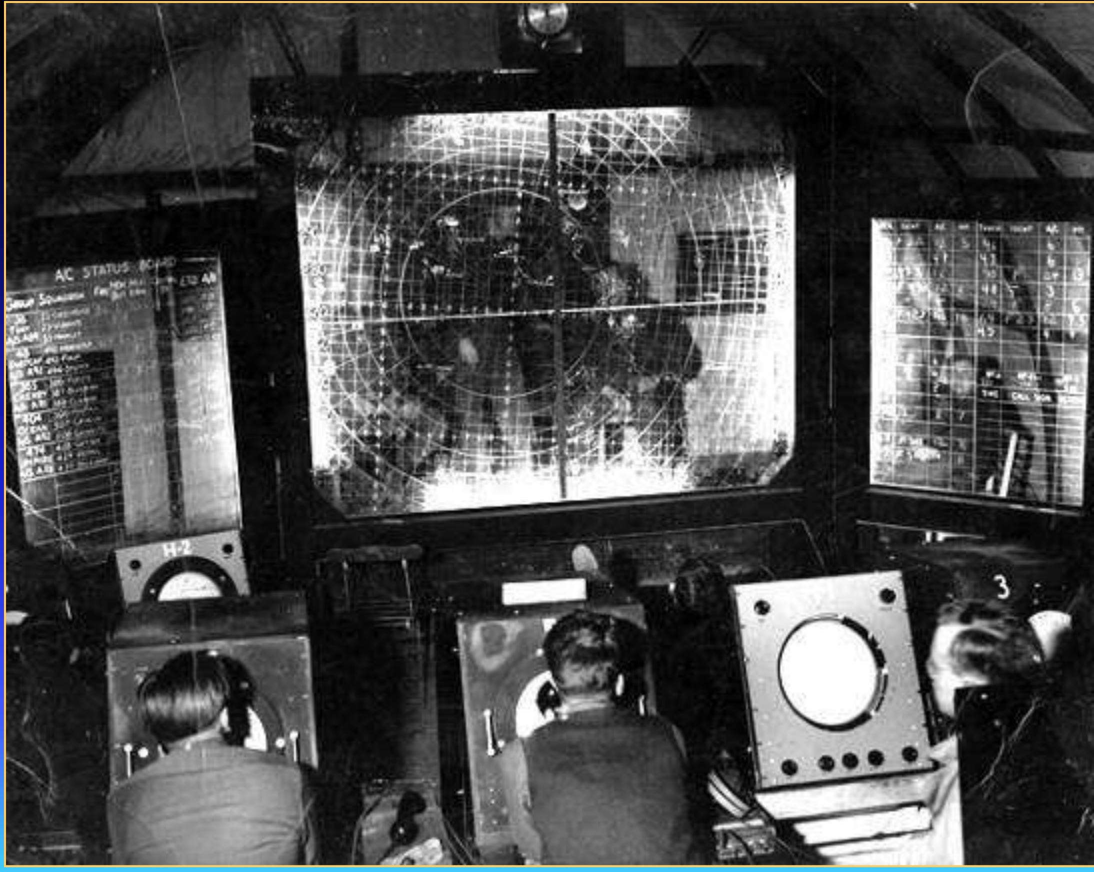
Ruby Payne-Scott

# Why a Cliff Interferometer?

- Concept from coastal radars in WW2




Loyds mirror

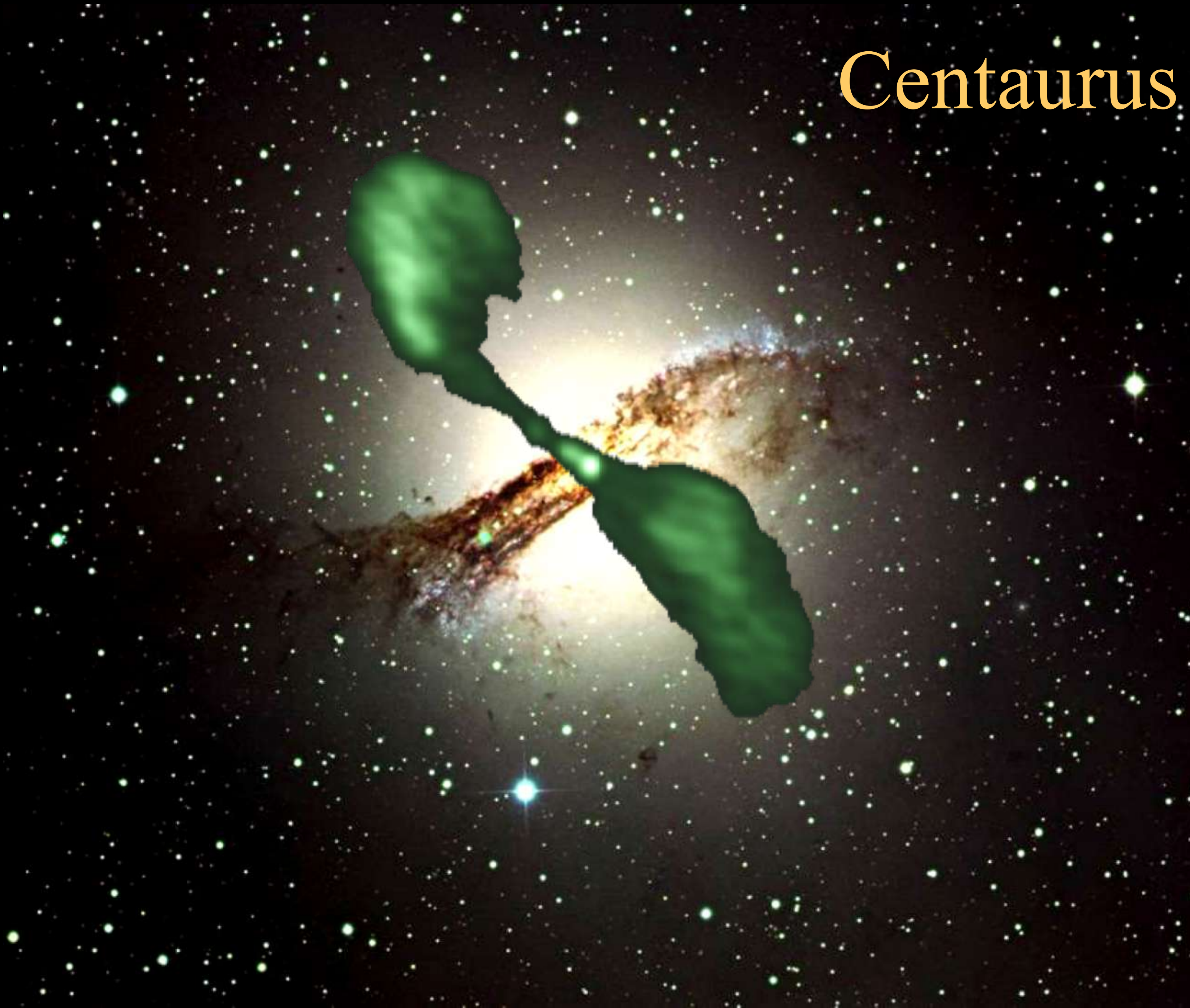


# Dover Heights 1952

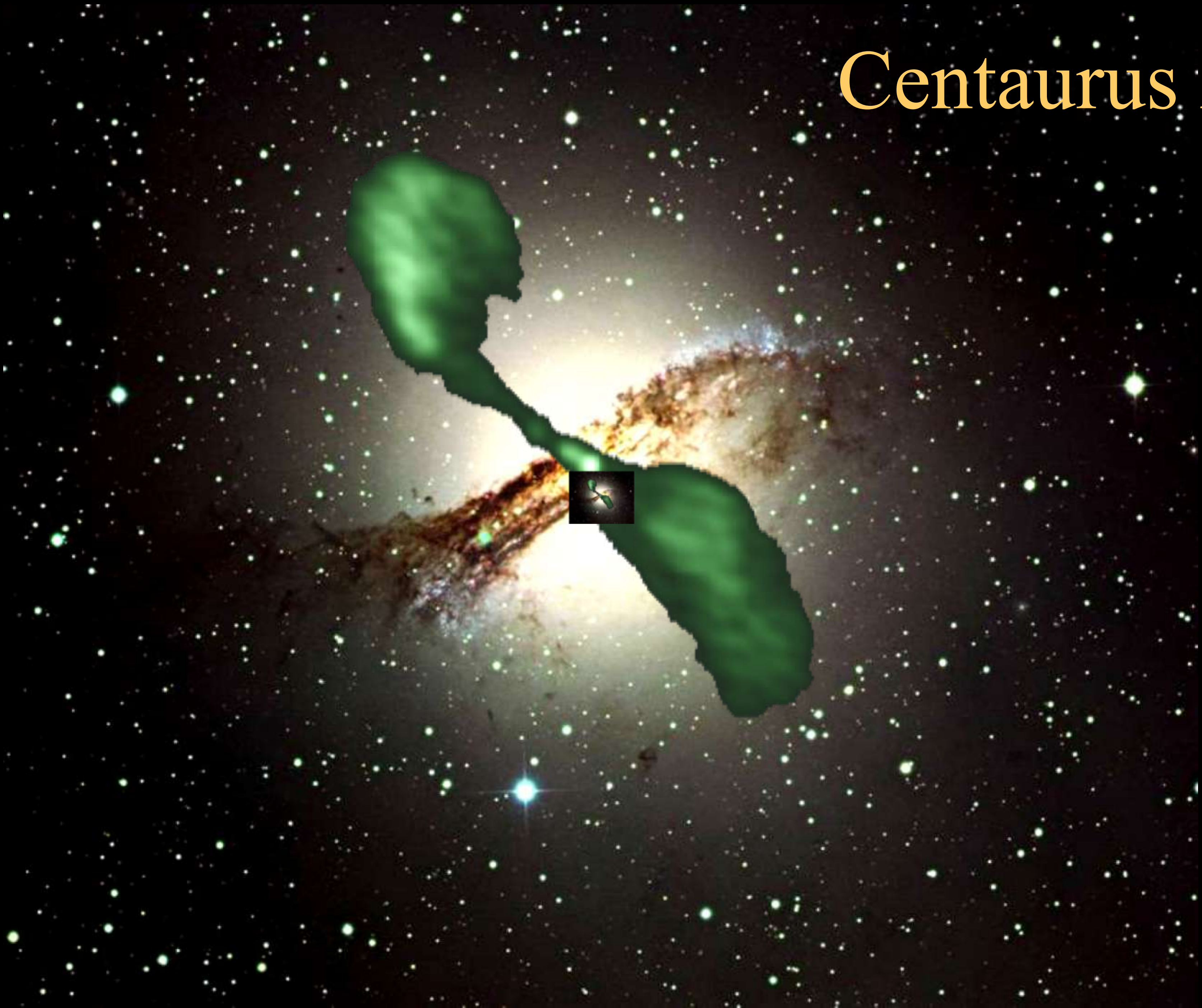
Cliff interferometer CSIRO, Australia (1948)

- Built to identify the radio stars (John Bolton)
- Idea from multiple path interference in ship borne radar
- Discovery of extragalactic radio sources at great distances
  - Centaurus A , Virgo A, Cygnus A, Fornax A
- Had to hedge on extragalactic origin to get paper published

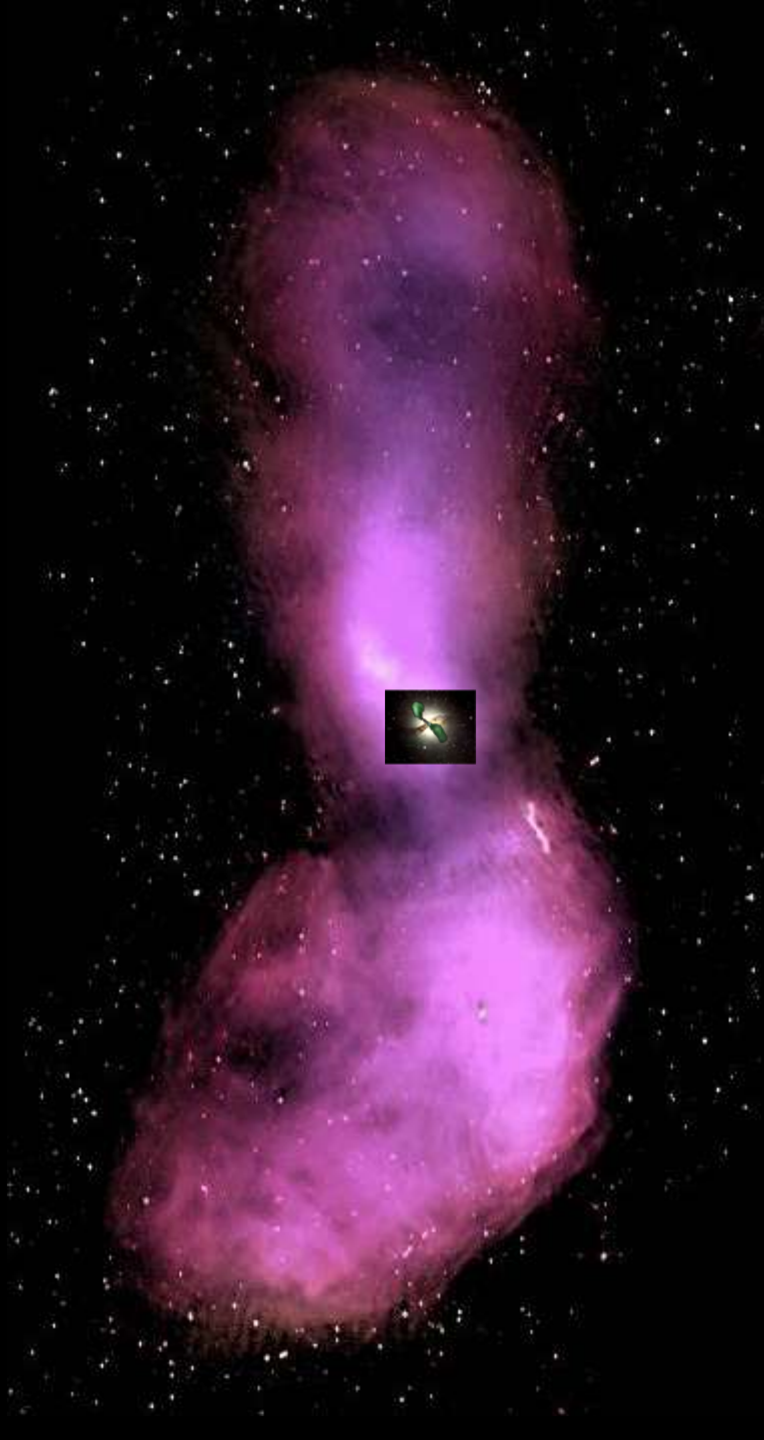
# Centaurus A



# Centaurus A

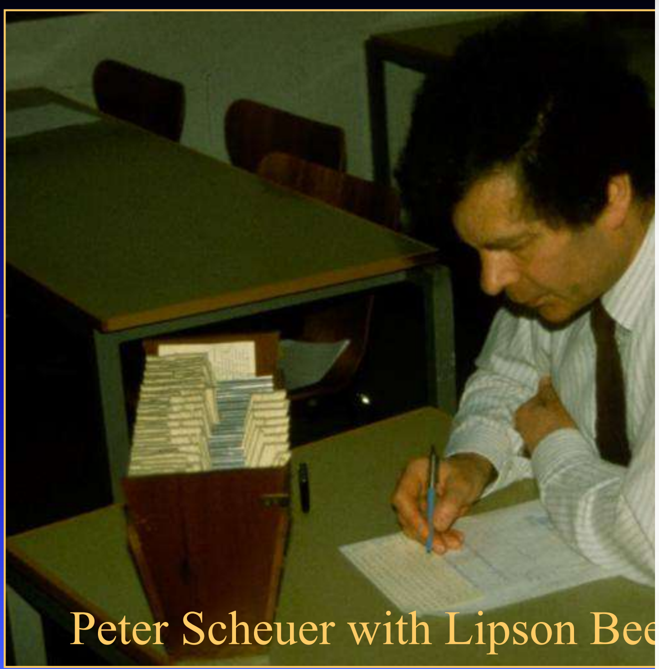


# Centaurus A
## ATCA Mosaic

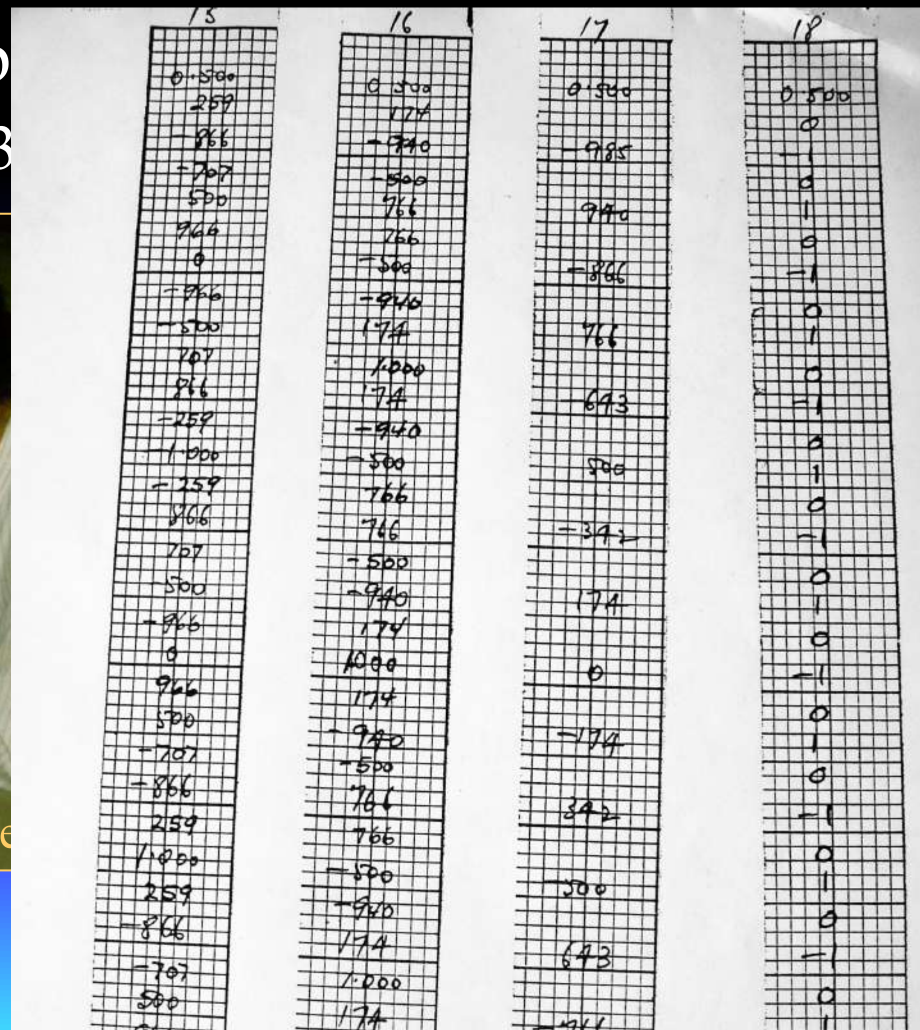


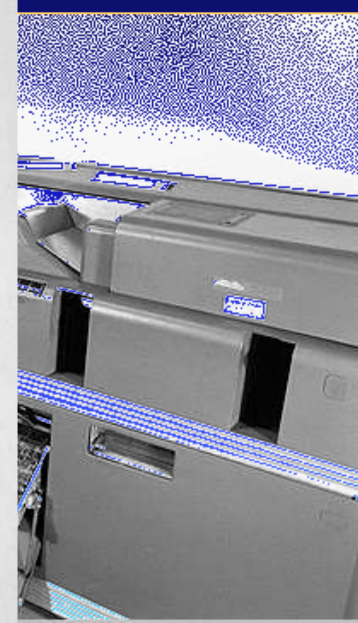
# Fourier Transforms - 1953

- Lipson-Beevers strips
  - 25x25 array to 2 digits 1 person in 24 hours
- Punched card tab
  - 25x25 array to 3



Peter Scheuer with Lipson Bee



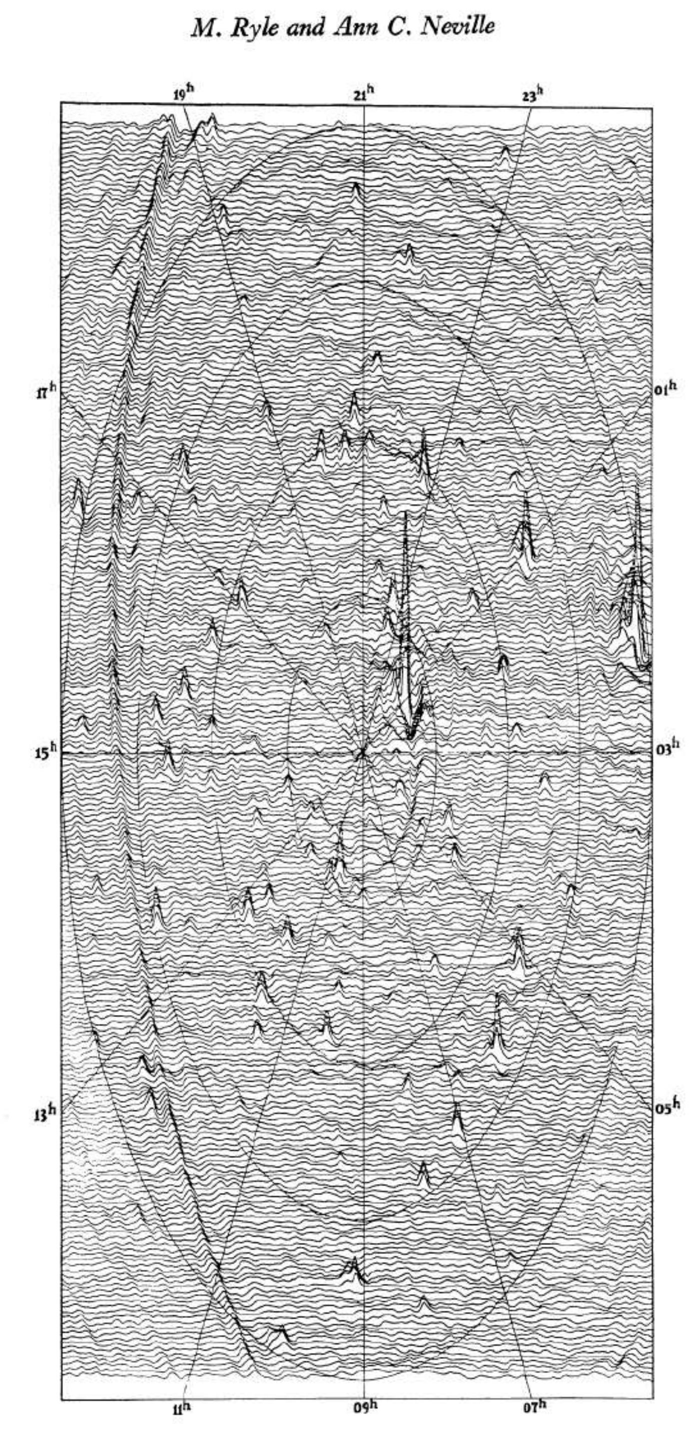
# Fourier synthesis imaging - 1954

- Bracewell and Roberts: *Arial smoothing*
  - introduces *invisible* distributions and the principal solution
- Scheuer: *Theory of interferometer methods*
  - PhD chapter 5 (unpublished)
  - Full analysis of Fourier synthesis including *indeterminate* structure
- Independent developments, but all acknowledge Ratcliffe's lectures

# 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!
- 1961
  - Jennison had acquired F
    Fourier transform and p
    Transform
  - Sandy Weinreb builds t
- 1965
  - Cooley & Tukey publis
    the FFT algorithm

1960 user queue for programming the EDSAC 2




# First Cambridge Earth Rotation Synthesis Image

- Ryle & Neville, MNRAS 1962
- North pole survey
- 178 MHz
- 200x200 pixels took a full night on EDSACII
- Now Moore's law and the massive improvements in computing power give us LOFAR and MWA

# MWA Radio Continuum 80-300MHz


False colour spectrum

- Thermal
- Non thermal

Luke Hindson, University of Wellington

# The early Australian arrays

- A time variable sun needs instantaneous coverage
- 1951
  - Christiansen build the P
    - 32 steerable paraboloids
    - No computer – hand calc
    - First earth rotation synth
- 1953
  - Chris Cross (Fleurs)
  - Mills cross
- 1967
  - Paul Wild solar heliogr
  - Uses J2 synthesis
    - electronic summation o

# Dishes v Arrays circa 1957

- Parkes 64 … oss
- The dish … low frequencies
- At high f… hermal emission which is …
- The array… frequency and you can map …
- Bolton – build an interferometer with large dishes

# Westerbork: 1970

- Oort 1961 vision
- Bennelux Cross  an International project
  – Hogbom (Cambridge)

    +

  – Christiansen (Sydney)

⇨ WSRT

- 12 x 25m dishes 1.5km
  – Two moveable
  – 10 redundant spacings
  – Self calibration
- HI and dark Matter (1978)

# WiFi
# IEEE 802.11

- **European Inventor Award 2012**
- **Inventors**: Dr John O'Sullivan et al
- **Country**: Australia
- **Invention**: Wireless LAN for high speed data transfer

# WiFi - IEEE 802.11 wireless network standard

- 1970's John O'Sullivan PhD using Fleurs Synthesis Telescope
- 1974 John O'Sullivan searches for Exploding Black Holes – *"there has to be a better way!"*
- 1977 explanation of why adaptive optics works
  - Noordam, Hamaker, O'Sullivan
  - Paper based on redundant calibration in radio astronomy
- 1980's Fourier Transform on a chip
- 1996 CSIRO obtains US patent #5,487069
  - O'Sullivan, Daniels, Percival, Ostry, Deanne
- 2001 Skellern develops a wireless chip meeting IEEE standard

# The IEE 802.11 and Redundant Spacing analogy

- Redundant spacing interferometers
  - Redundant spacings measure the same Fourier component
  - If corrupted by the atmosphere they will not be equal and the peak image intensity must decrease
  - S/N is maximised when the atmosphere is correct
- A broad band wireless link is corrupted by multiple reflections
  - Individual narrow Fourier components are not corrupted because delays are small
  - Each has a redundant low time resolution copy of the modulated signal
  - The S/N on the link is maximised when all these Fourier components are correctly aligned.
- A 1D real time Fourier transform has to be implemented in the communication chip

# The Hydrogen Epoch of Reionization Array (HERA)

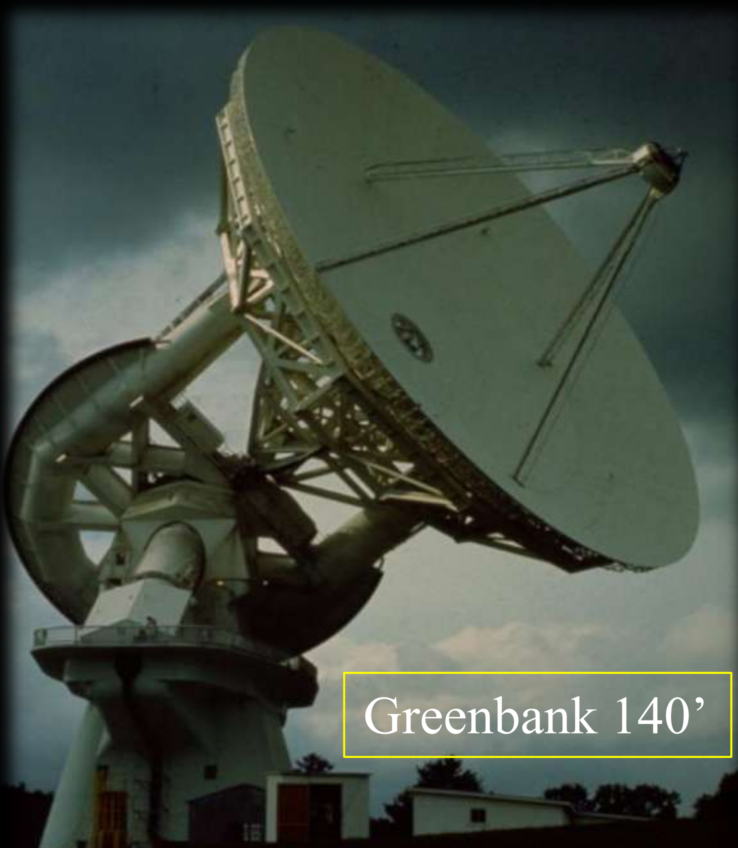
- Maximum redundancy for calibration

South African Karoo

# Equatorial v Alt-Az 1950s debate

Barnes Wallis
Master
Equatorial

- Coordinate conversion
- Drive motor difficult with Alt-Az
  - Merle Tuve, Director DTM, Carnegie Institute



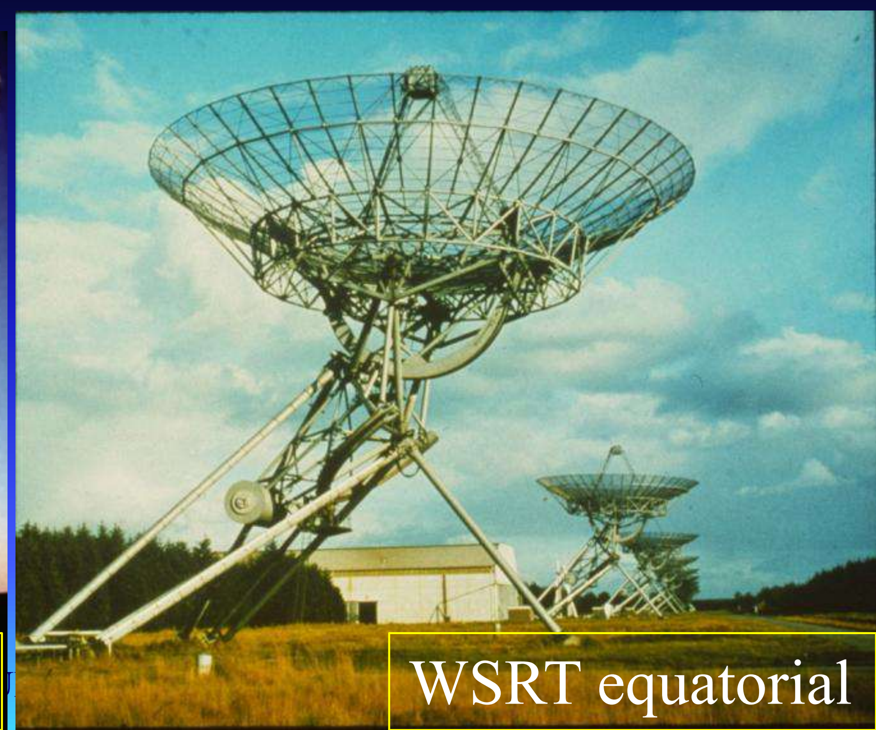
Greenbank 140’

Parkes 210’ (64m)

# Equatorial v Alt-Az 1960s debate

- Coordinate conversion no longer the issue
- Alt-Az are cheaper but beams and sidelobes rotate on the sky limiting dynamic range

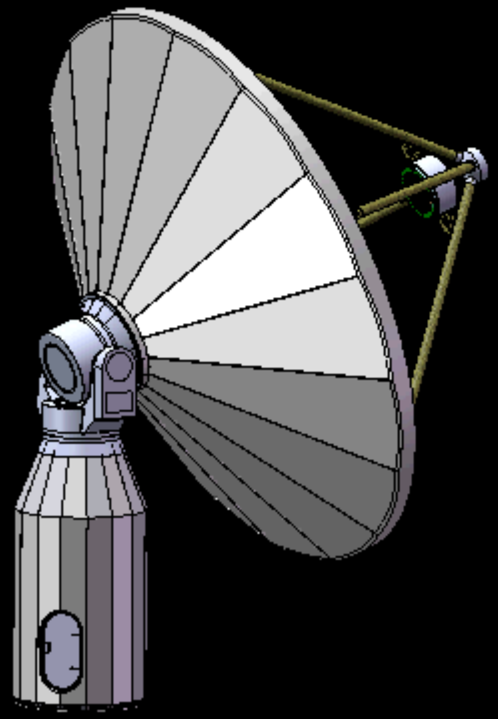
VLA alt-az

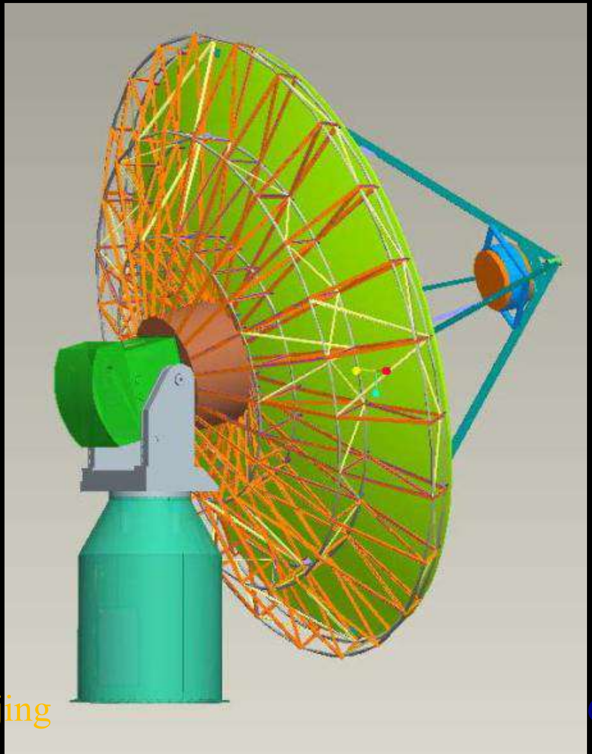


WSRT equatorial

# Roll axis

- ASKAP antenna
- CETC54
- 10% incremental cost for 3 axis mount

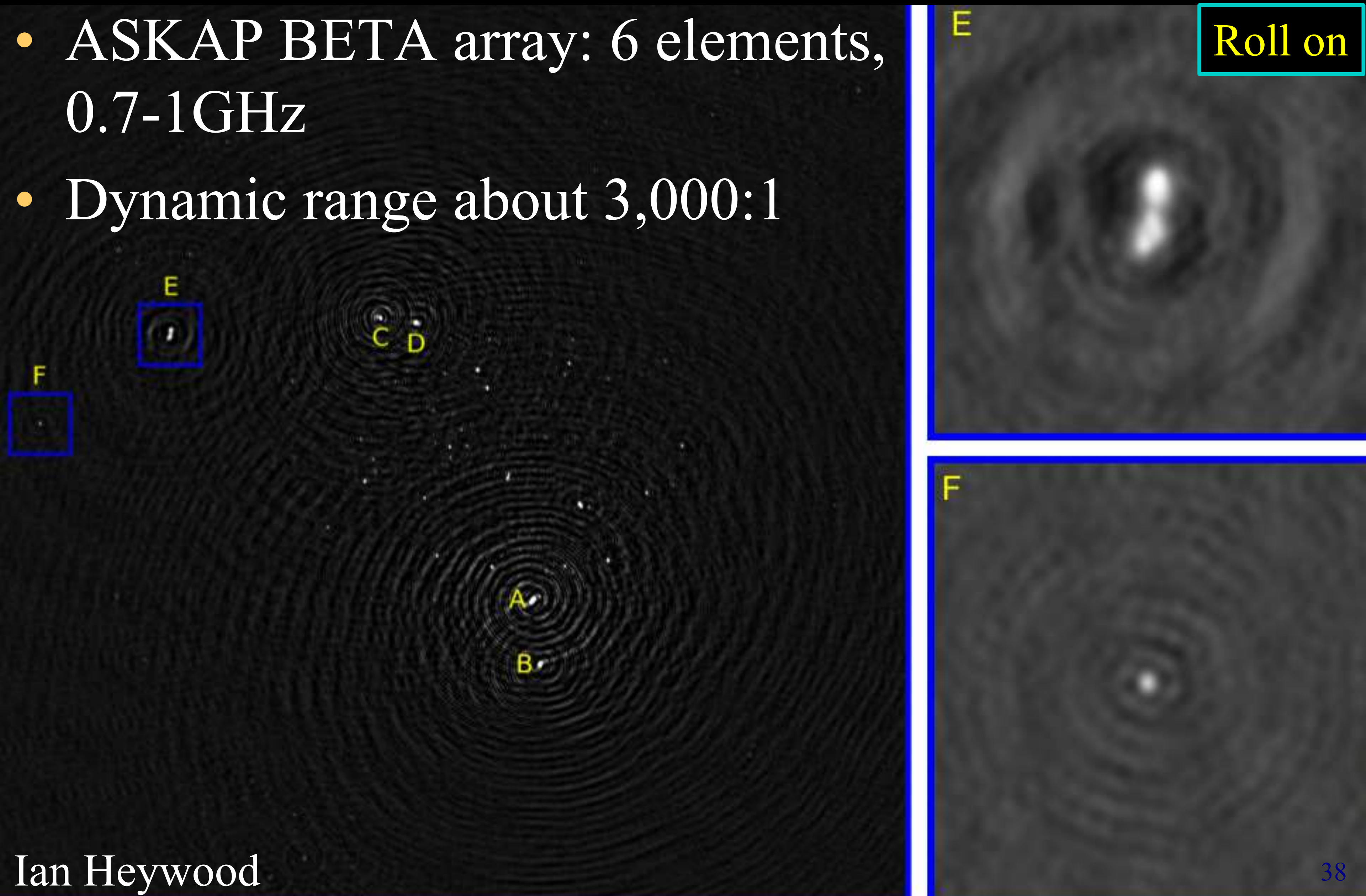




# ASKAP antennas

# Effect of roll axis on image quality

- ASKAP BETA array: 6 elements, 0.7-1GHz
- Dynamic range about 3,000:1




Ian Heywood

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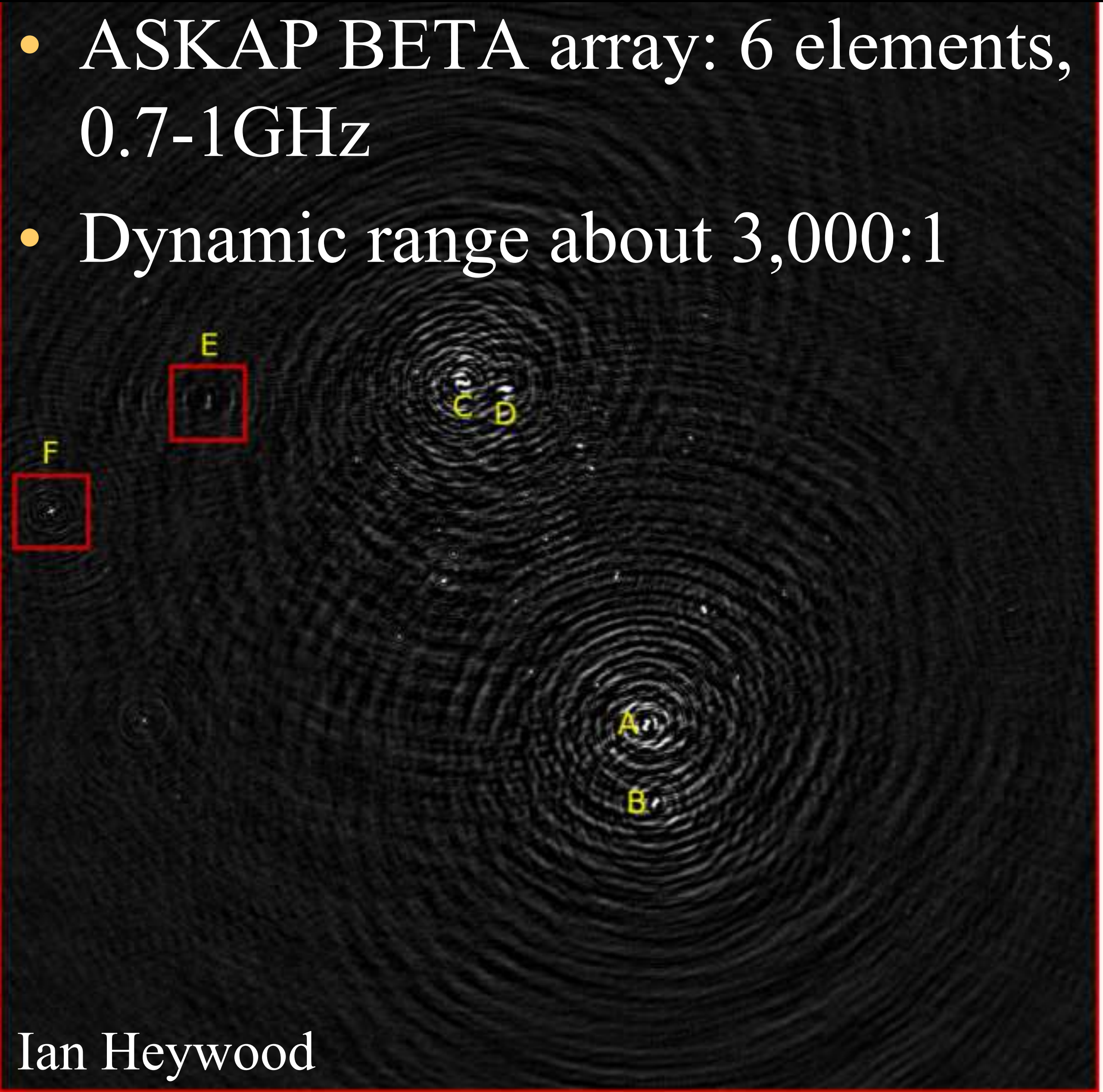


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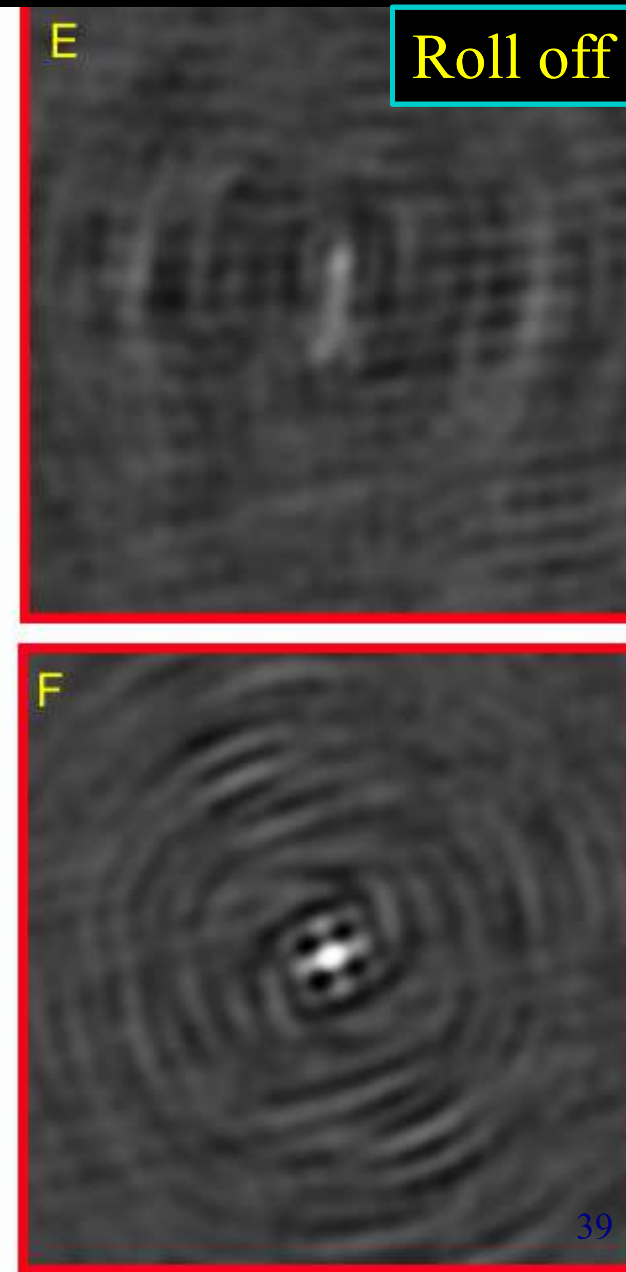
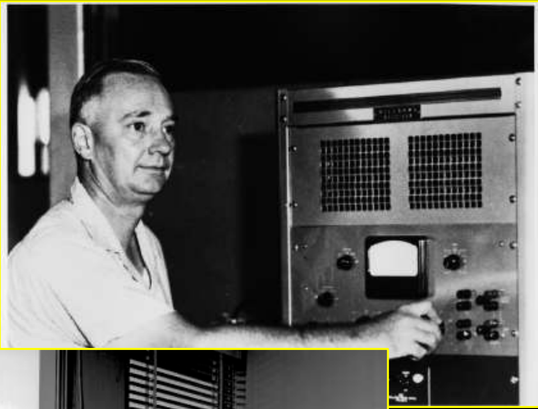
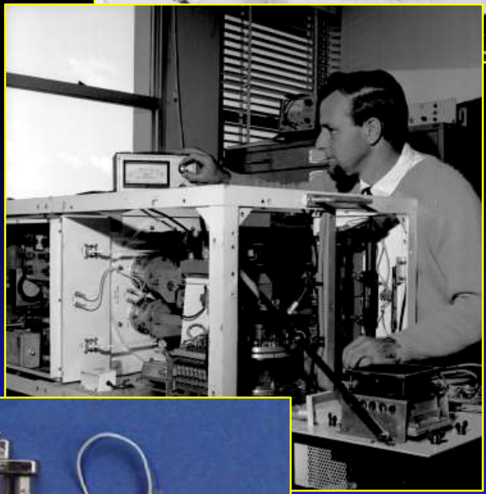


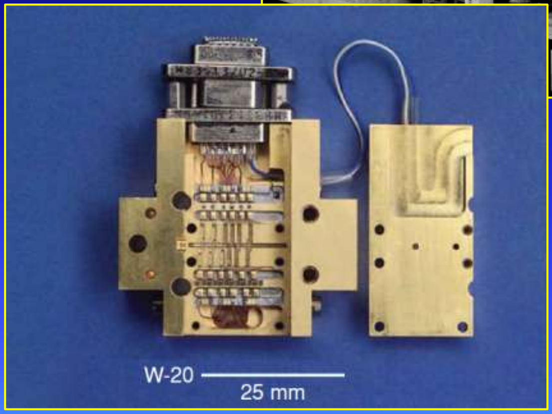

Ian Heywood

# Receiver developments (Radio Astronomy)

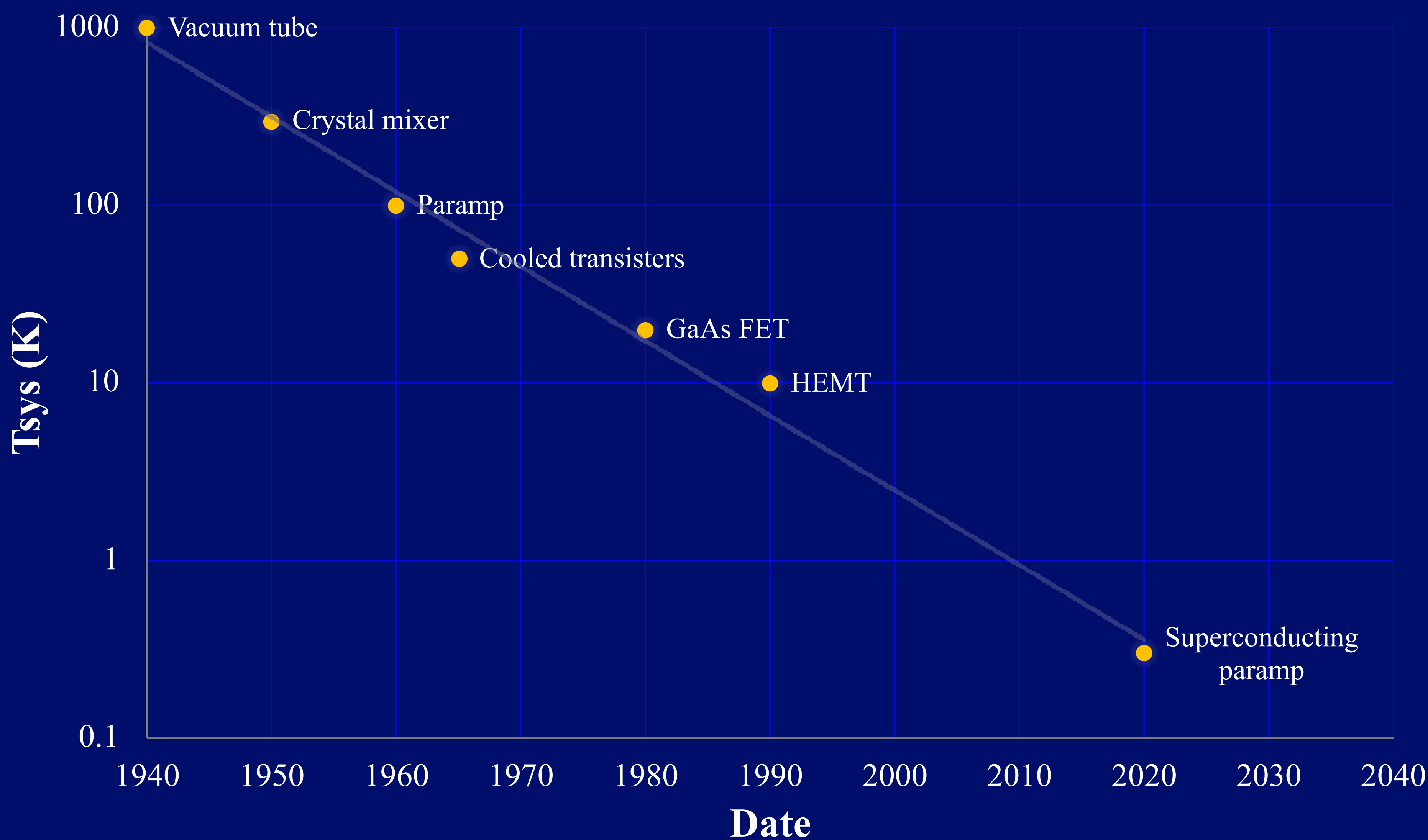
- 1940 Vacuum tubes (>1000K)
- 1950 Crystal mixers (300K)
- 1960 Parametric amplifiers (100K)
- 1960 Masers (65K)
- 1960 Diode mixers
- 1965 Cryogenically cooled transistors (50K)
- 1980 GaAs FETs (20K)
- 1990 HEMT (10K)
- 2000 SIS (high frequency)
- 2020 Superconducting paramp (0.3K)







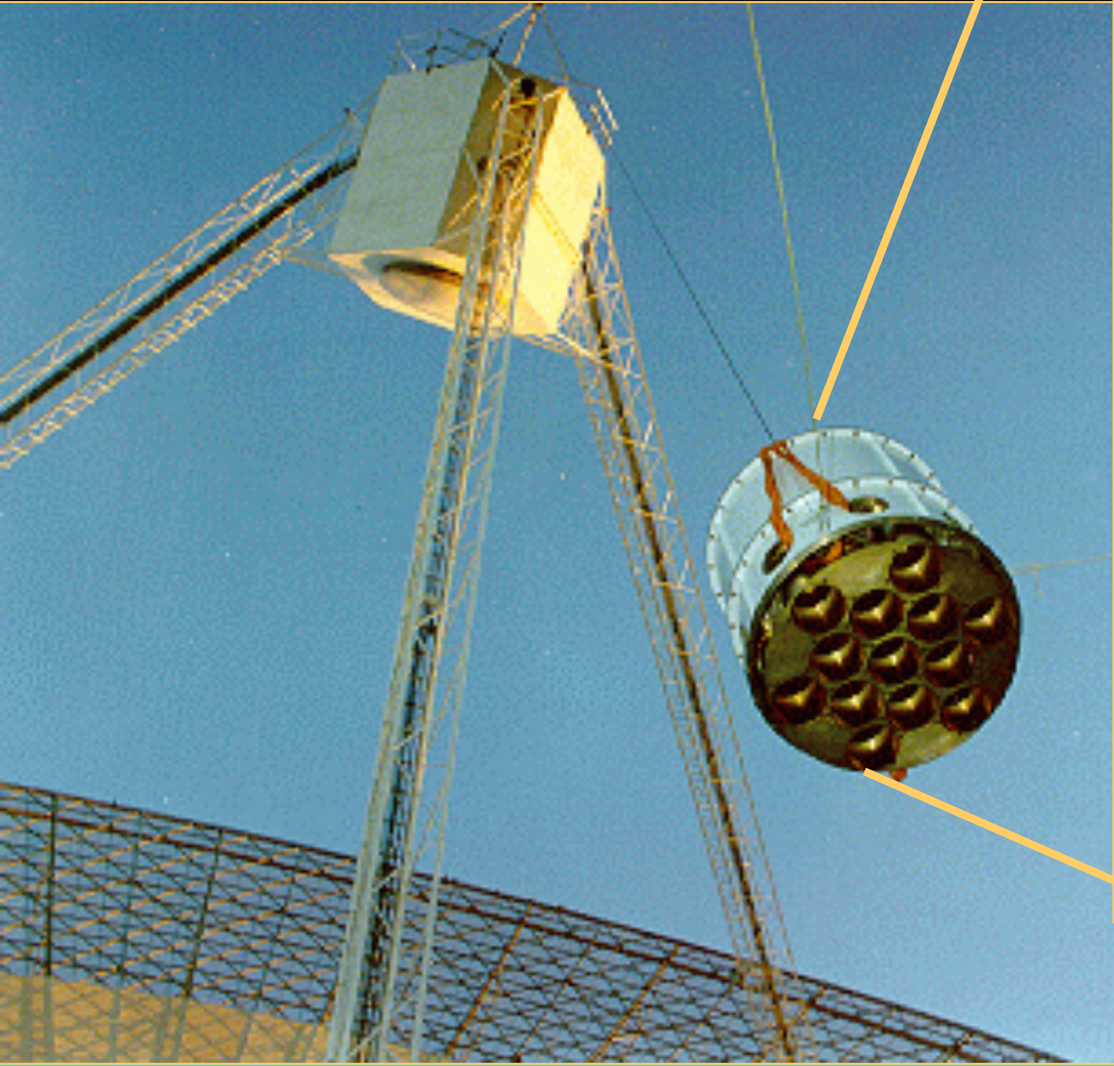
# Receiver Sensitivity exponentials again!



# MMIC (Transistors)

- GAs -> InP
  - Extend frequency range 1GHz - > 150 GHz
  - Wide instantaneous bandwidth
- Large scale integration
  - Complete receiver system on one chip
- Focal plane arrays
- Receivers embedded in feed structure
- Integrated photonics

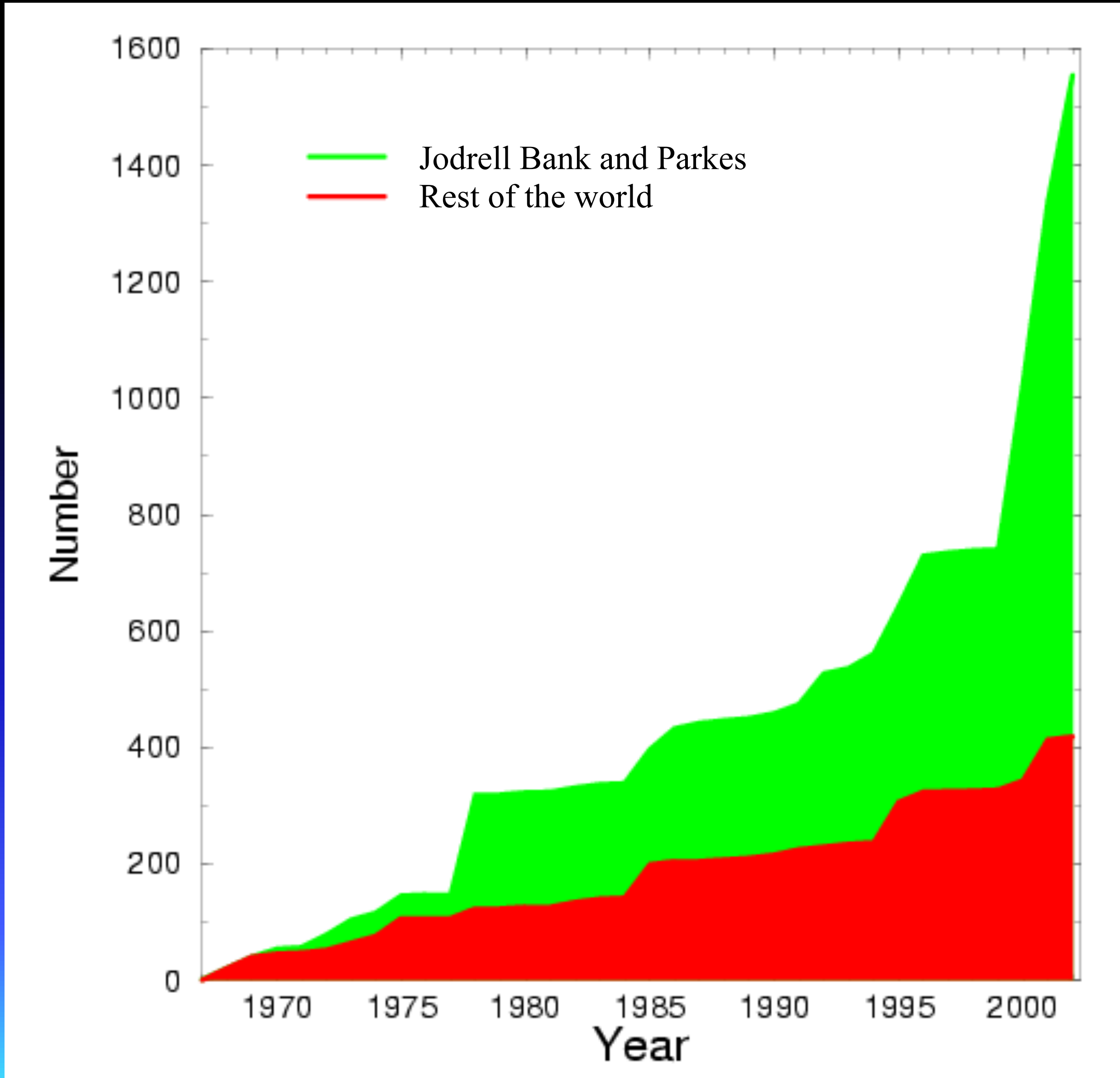
# Parkes Mult



# Parkes Multi-beam receiver brief history

- 1975 Arecibo multi-beam survey (Condon et al)
- 1987 Multi element receiver for Green Bank 300’
- 1988 Receiver shipped to Parkes for PMN survey
  - Condon & Burke
  - Overcame local engineering conservatism
- 1996 Parkes 13 beam receiver
  - Digital signal processing opportunity created by a high yield for ATCA correlator chips
  - Very competent engineering (Warwick Wilson)
  - Science case was for a blind HI survey
  - Major impact was on pulsar survey science
- 2005 Copy installed on Arecibo

# Pulsar discovery rate



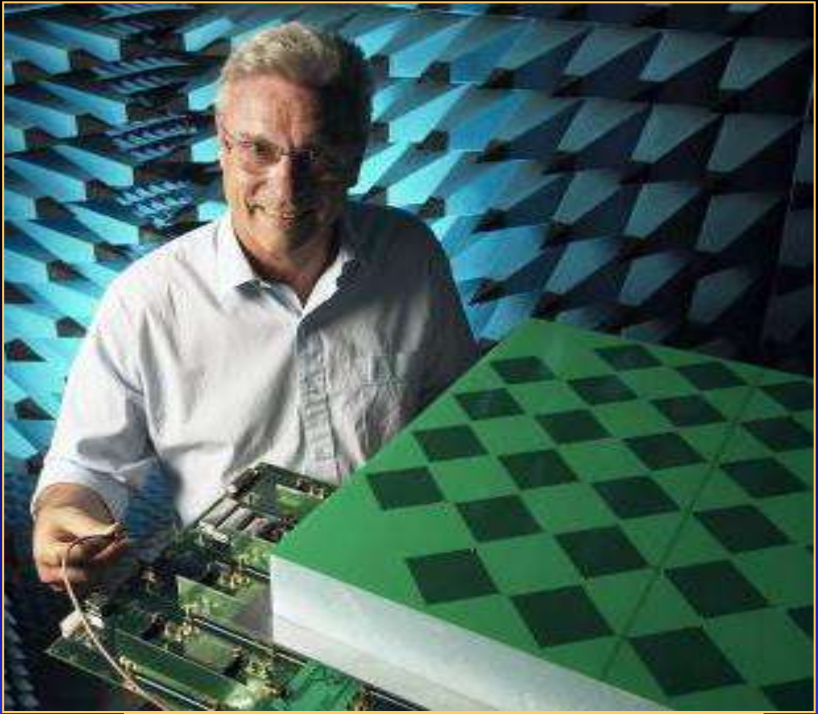
# Phased Array Feeds

- Wide FoV at full sensitivity over whole field
- Not just spatially continuous
- Aperture illumination control
- RFI mitigation
- Can measure the very low spatial frequencies
  - Fourier transform into aperture plane
  - Corresponds to patches on surface of dish
  - Highly redundant
  - No shadowing
- Eg large scale HI statistics at high z

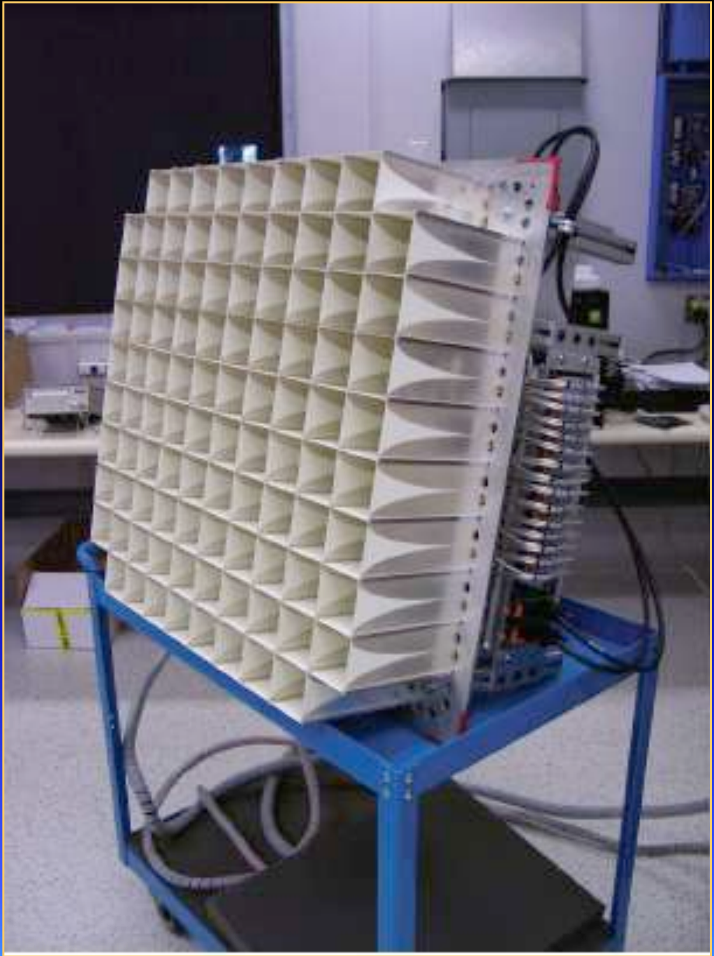
# PAF in Radio Astronomy brief history

- 1982 NRAO workshop
  - Weinreb discusses aperture correction using PAF
- 1985 Ekers discusses analogies between focal and aperture plane arrays
- 1988 Cornwell and Napier (Radio Science)
  - PAF can be placed anywhere between the aperture and the focus
- 1993 PAF design considered and rejected for Parkes multi-beam (Trevor Bird)
- 1995 Rick Fisher PAF element design
- 2004 PAF proposed for SKA survey
  - Van Ardenne and others also working on dense aperture arrays during this period
- 2006 Australian proposal for array using PAFs (ASKAP)

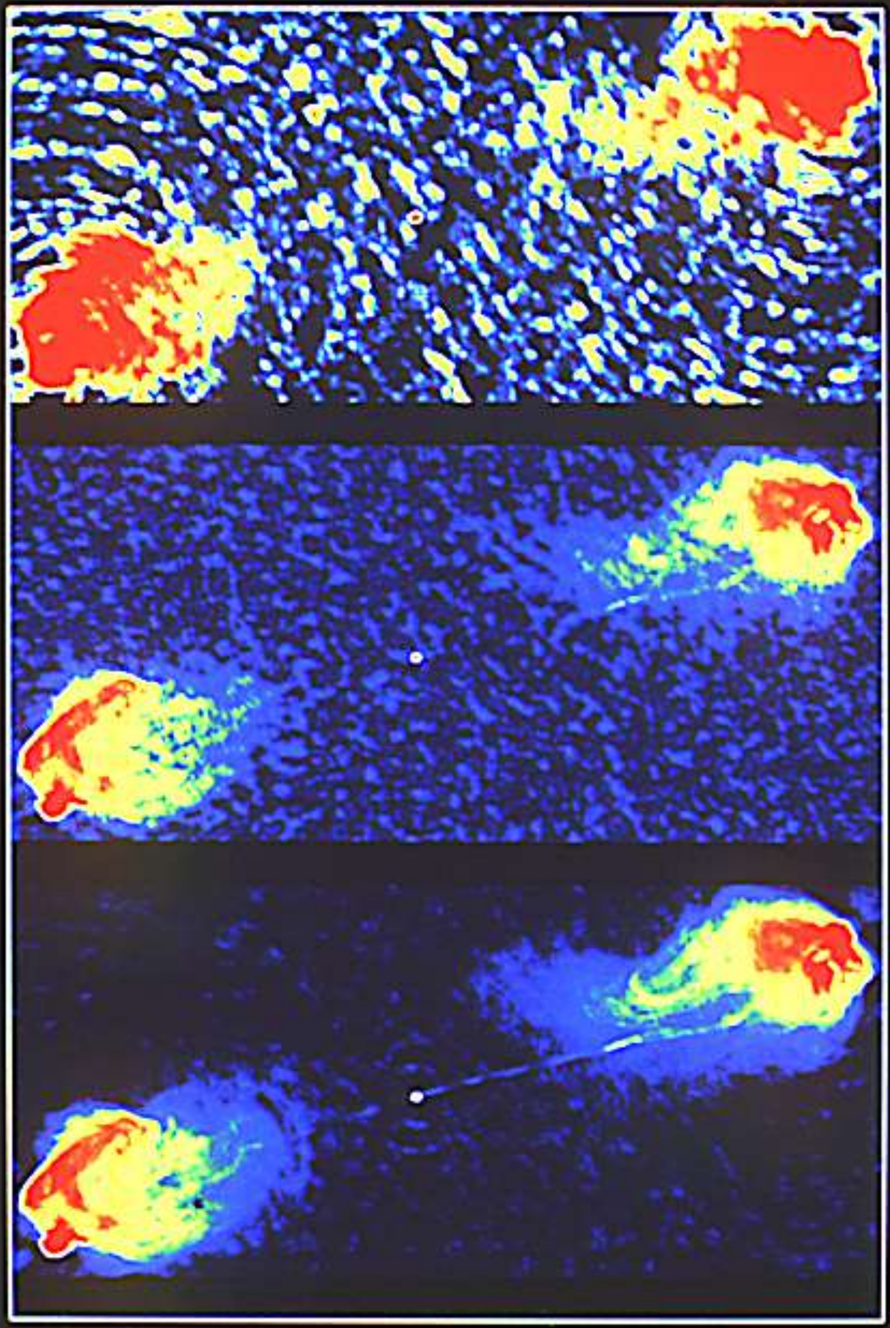
# Some PAF designs



Checker board - ATNF



Vivaldi - DRAO



# Algorithms

- Deconvolution
- Self Calibration
- Mosaicing
- Bandwidth Synthesis
- Rotation Measure Synthesis
- .......

# Deconvolution

- 1962: Moffet using model fitting (OVRO)
  - Ekers (Parkes), Fomalont (OVRO)
- 1968: Hogbom does first clean experiments
  - NRAO 3 element data
    - Bad UV coverage
  - First cleaned image published in 1970
    - Rogsstad and Shostak (OVRO HI image)
- 1974
  - Hogbom publishes the CLEAN algorithm
  - Ables introduces Max Entropy Method (MEM)
  - Idea introduced from geophysics
- Use of deconvolution very controversial in the 1970's
  - Super resolution

# Self Calibration

- 1958: Phase and amplitude closure
  - Jennison (Jodrell Bank)
- 1977: Redundant spacing interferometry
  - Hamaker , O'Sullivan, Noordam (Westerbork)
  - Equivalence to adaptive optics
- 1974-79: Phase closure in VLBI imaging
  - Rogers, Yee, Readhead, Cotton….
- 1980: Antenna based calibration
  - Clark, Schwab (VLA)
- 1983: Cornwall: Self cal ≡ phase closure ≡ adaptive optics
  - Triple correlation
- 1985: Nobel prize (chemistry) to Hauptman & Karles
  - Structural invariance ≡ phase closure

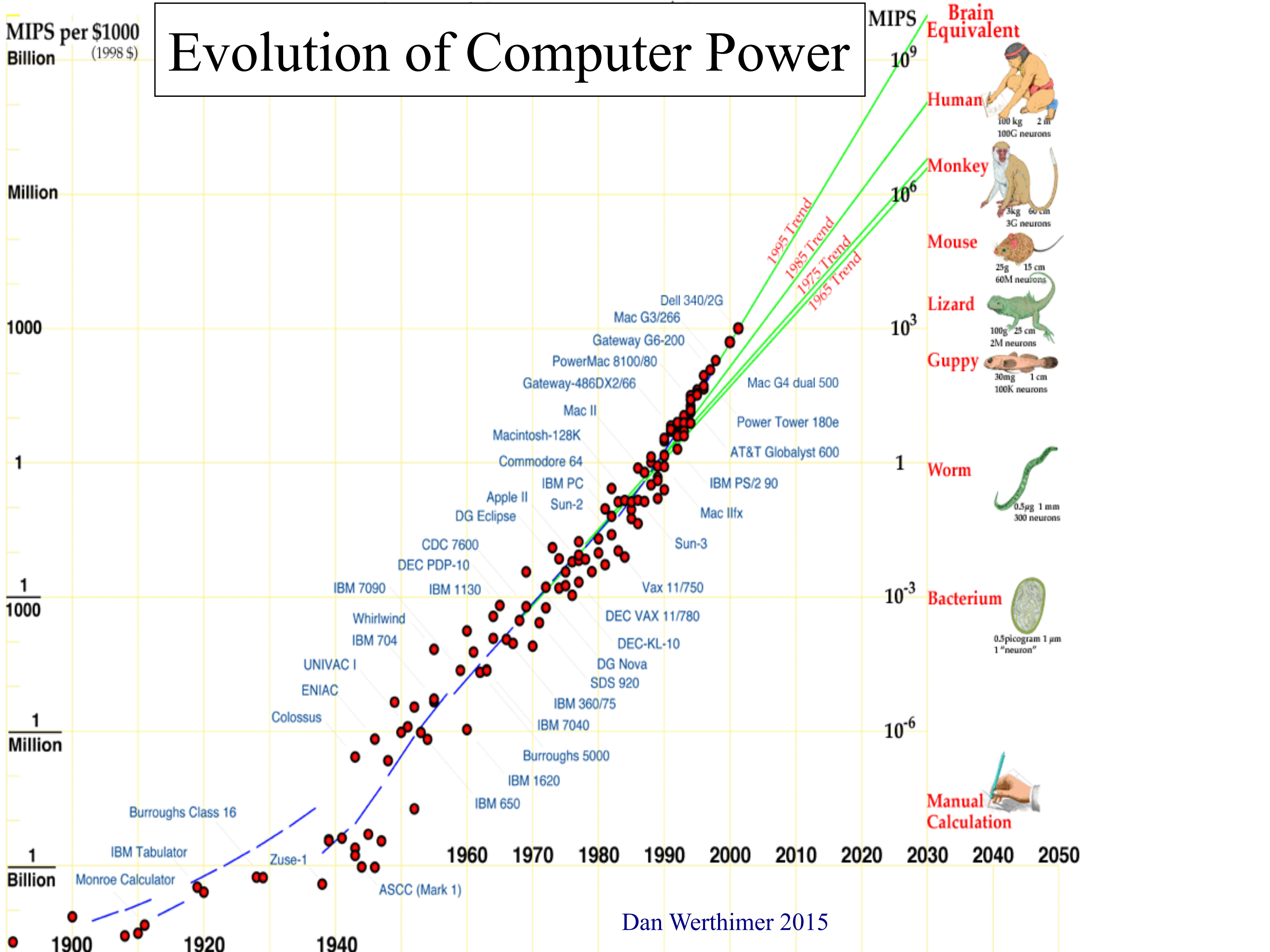
# Mosaicing

- 1975 WSRT
  - Needed short spacing for spectral line synthesis
  - Difficulty in obtaining adequate single dish data
  - Primary beam scanned interferometer invented
    - *Ekers & Rots IAU-C49 76 , 61 (1979)  see Astroph 1212.3311*
- 1983-1988 VLA (VTESS)
  - Cornwell explores algorithms for mm arrays
    - *Cornwell A&A 202 , 316 (1988)*
  - MEM  joint deconvolution algorithm (VTESS)
- 1990  ATCA (MOSMEM, MOSSDI)
  - routine use results from  an effective implementation

# Computational Issues

- software
  - treat as capital investment not an operating cost
  - prepare software before the survey starts
  - involve science teams early
- hardware
  - exponential growth of digital electronics (MMIC)
  - ASIC ⇔ FPGA ⇔ GPU ⇔ general purpose computer
  - treat as operating cost and make continual upgrades

# Evolution of Computer Power




Dan Werthimer 2015

# Two Impressions

- Chris Christiansen (Sydney) *"The further development of this technique required a faster way to make the Fourier Transforms and this discouraged use of this technique in Australia. The turning point took place in Cambridge when digital computers revolutionised the speed of computation. The importance of the Cambridge work is well known and perhaps this is why the more humble first use of the technique in a distant land tends to be ignored."*

  *Q.J. RAS (1989) 30, 357*

- Graham Smith (Cambridge) *"We took very little notice of any publications, either in journals or textbooks, and relied on Ryle's insight. We were indeed guilty of underestimating, for example, Pawsey, McCready & Payne-Scott's work on Fourier analysis. But we were in the full flood of discovery, and we were self-propelled."*

  *1988*

# Impact of Digital Computing

- After Christiansen it was two decades before a non-solar synthesis image was computed in Australia!
  – Brouw (FST) and Schwartz (Parkes interferometer)

- Australia's first digital computer, CSIRAC, was operating in the same building at this time but the radio astronomers took no advantage of the new computer age.

- Cambridge went on to exploit aperture synthesis using digital electronic computers

# Examples


VLA

New Mexico

# Performance Design Goals for VLA

| | Goal (1967) | Achieved(1980) | Factor |
|---|---|---|---|
| Resolution | 1" | 0" .1 | 10 |
| Sensitivity | $10^{-3}$-$10^{-4}$ Jy | 5 x $10^{-5}$ Jy | 2 |
| Sidelobes | -20 dB | -30 dB | 10 |
| FoV | 1' to 10' | 1' to 30' | 3 |
| Wavelengths | 5, ll cm | 1.2, 2, 6, 20cm | 2 |
| Speed | 3 images/day | 100 images/day | 30 |
| Spectral Line | Not excluded | 256 channels | |
| Map Size | -100 x 100 | 512 x 512 (routine) | 25 |

# VLA Science

- Funding Proposal (1967)
  - Key scientific drivers (8 pages)
    - » radio galaxies, quasars, cosmology
  - Other science which may benefit
    - » planets, galactic studies, 21cm Hydrogen line

- Science being done (1980-1991)
  - stars (16%)
  - galaxies (14%)
  - ✓ radio galaxies (13%)
  - ✓ Quasars (9%)
  - star formation (9%)
  - solar system (6%)
  - AGN (5%)
  - Supernovae (4%)
  - Interstellar medium (4%)
  - ✓ cosmology (4%)
  - molecules (3%)
  - galactic centre (3%)
  - VLBI (3%)
  - pulsars (2%)
  - X-ray etc (1%)
  - Astrometry (1%)

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

SKA
SQUARE KILOMETRE ARRAY