The Development of Focal Plane Arrays in Radio Astronomy

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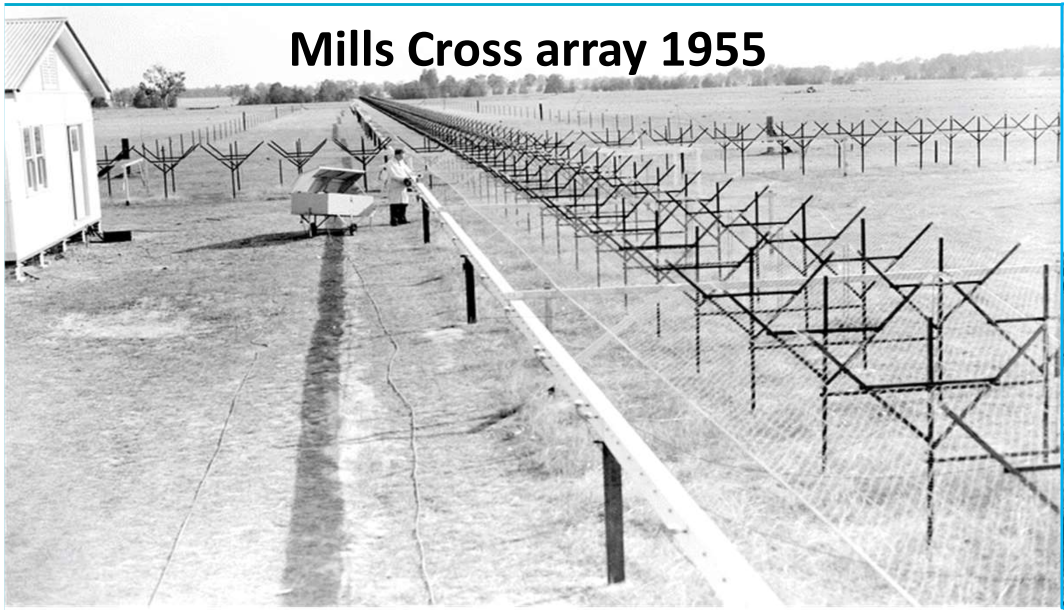
Summary

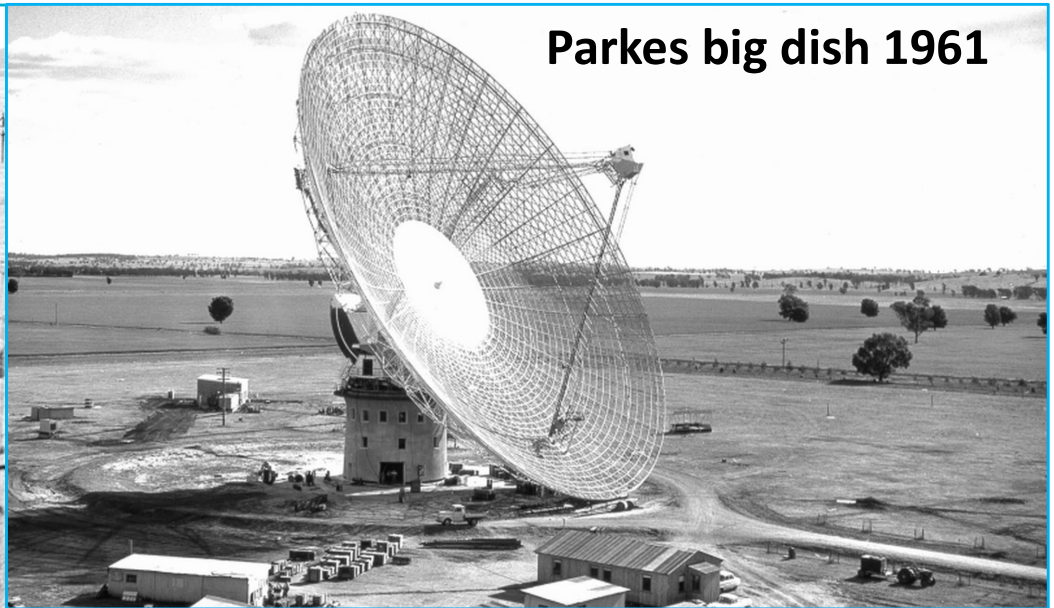
- Multi-beam receivers in Radio Astronomy
  - The single pixel feed culture
  - The case for focal plane sampling
  - Bolometer arrays at mm and sub mm wavelengths
  - Multi-beam receivers on Arecibo and Parkes
- Phased Array Feeds (PAFs) developments
  - NRAO
  - CSIRO
  - NFRA
  - DRAO
- Why use PAFs
  - FoV
  - Fully sampled
  - RFI mitigation
  - Higher spectral dynamic range
- Some PAF enabled science
  - ASKAP
  - Cryo PAF on Parkes

John O'Sullivan and WiFi
European Inventor Award 2012

Aperture Arrays and Big Dishes
The early days in Radio Astronomy established a culture

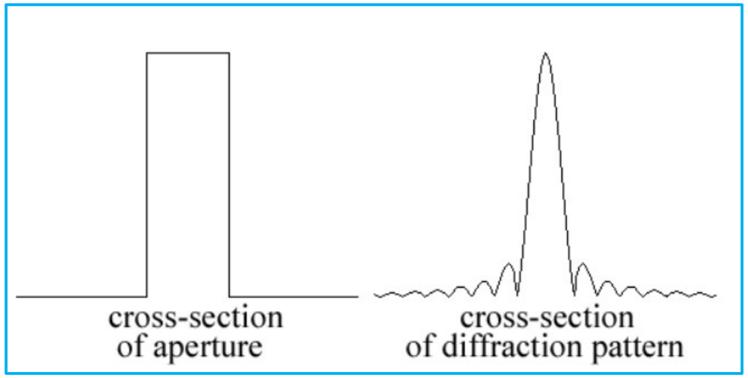
- In the beginning aperture arrays were ubiquitous
- But big dishes with one receiver had significant advantages
  - ➢ Frequency agility, better receiver performance, higher frequencies
- A single receiver at the focus of a dish became the norm

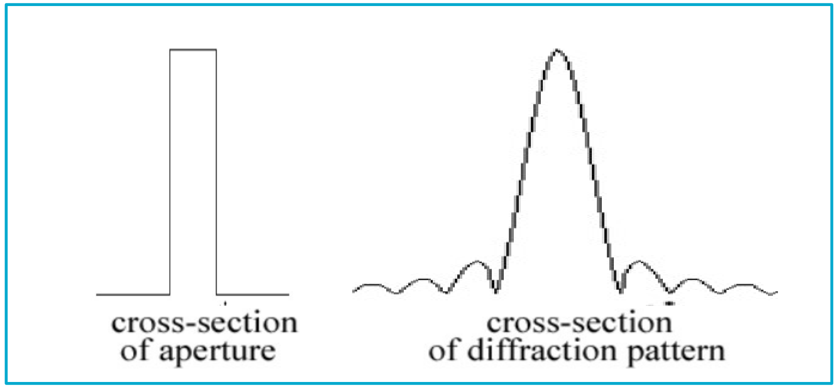

Mills Cross array 1955


Parkes big dish 1961

The case for PAFs and dense aperture arrays

- Heisenberg's uncertainty principal
  - ➢ You can have both large collecting area and large FoV
  - ➢ Must have multiple information channels (coherent beams)





- Digital beamforming dominates cost and power
- To minimise beam number for given collecting area and FoV the tightest non-redundant packing is needed
- Design must include mutual coupling/connected array elements

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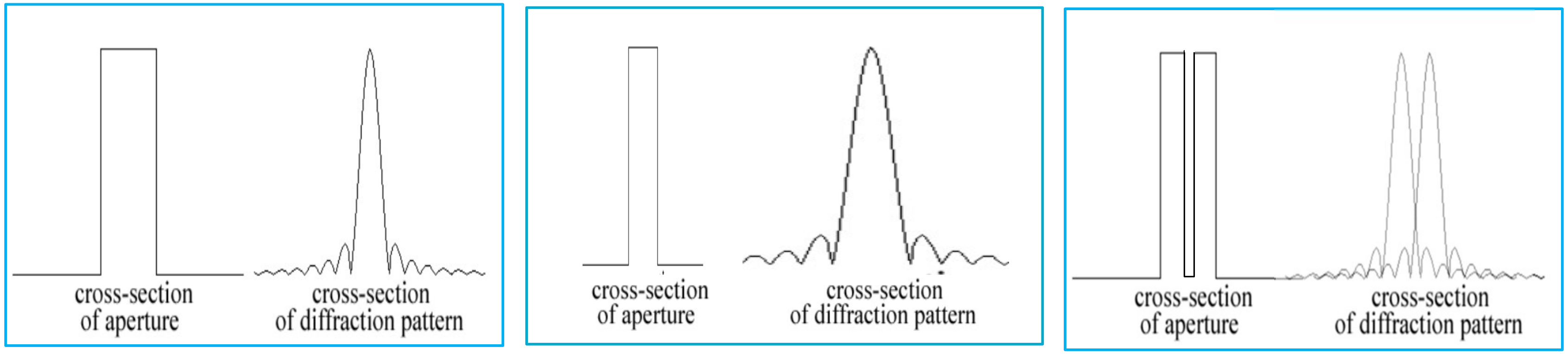

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The origins of focal plane sampling

- Beginning of time
  - Optical and later infrared – 2D power detectors/bolometers at focus
  - Dual/quadruple feed systems for satellite ground station
- Circa 1975
  - Ron Ekers and V Radhakrishnan
  - Does the focal plane have all information
  - Interferometer vs lens at beam waist

- 1978 - Ron Ekers on sabbatical at CSIRO fails to interest antenna engineers in fully sampling focal plane

Development of multibeam receivers

- 1975 – Jim Condon using multibeam receiver on Arecibo
- 1983 – Arnold van Ardenne does heterodyne multibeam mm receiver study
- 1987 – NRAO 7-beam 5.85 GHz receiver on 300’ and later Parkes
- 1987 – Arnold van Ardenne starts work on 350 GHz array for JCMT
- 1988 – NRAO 8-beam Schottky mixer 230 GHz receiver

Bolometer arrays for mm/submm astronomy

✓A bolometer is a simple thermal or total power detector

- Optimum continuum sensitivity above 100GHz
- Note different physics above and below the peak in the black body spectrum

✓High sensitivity (cryogenics)

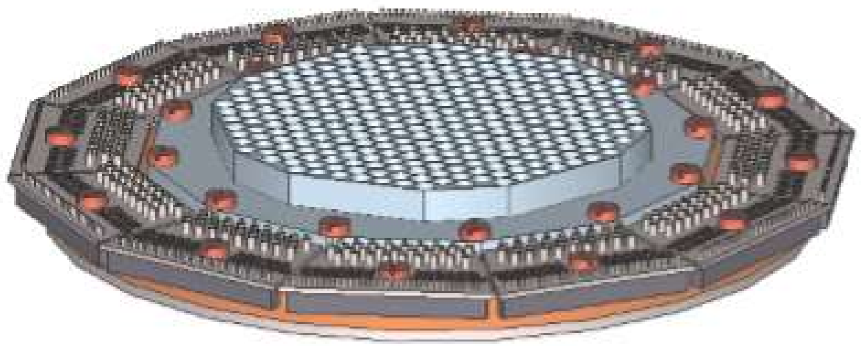
✓Wide bandwidth

✓Simple to construct

✗Not coherent

✗No frequency resolution

✗No interferometry

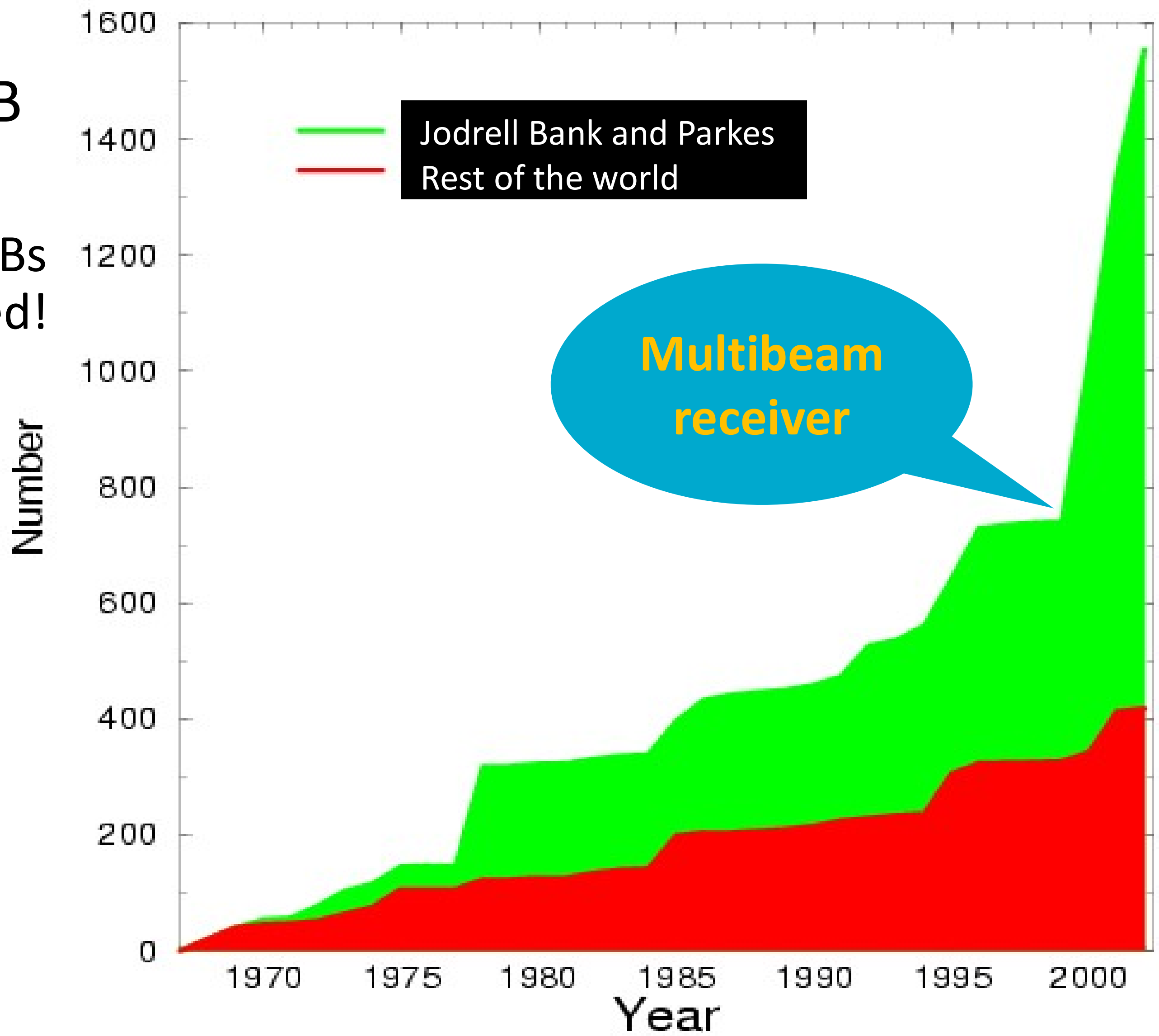


LABOCA -870 microns (350GHz),
313 pixels
APEX mm telescope 2015

Parkes Multibeam Receiver
21 Jan 1997

Impact on pulsar discovery rate

- Discovery of the first FRB
  - Lorimer burst in 2006
  - Without the multibeam FRBs would not yet be discovered!



Parkes Multi-beam receiver brief history

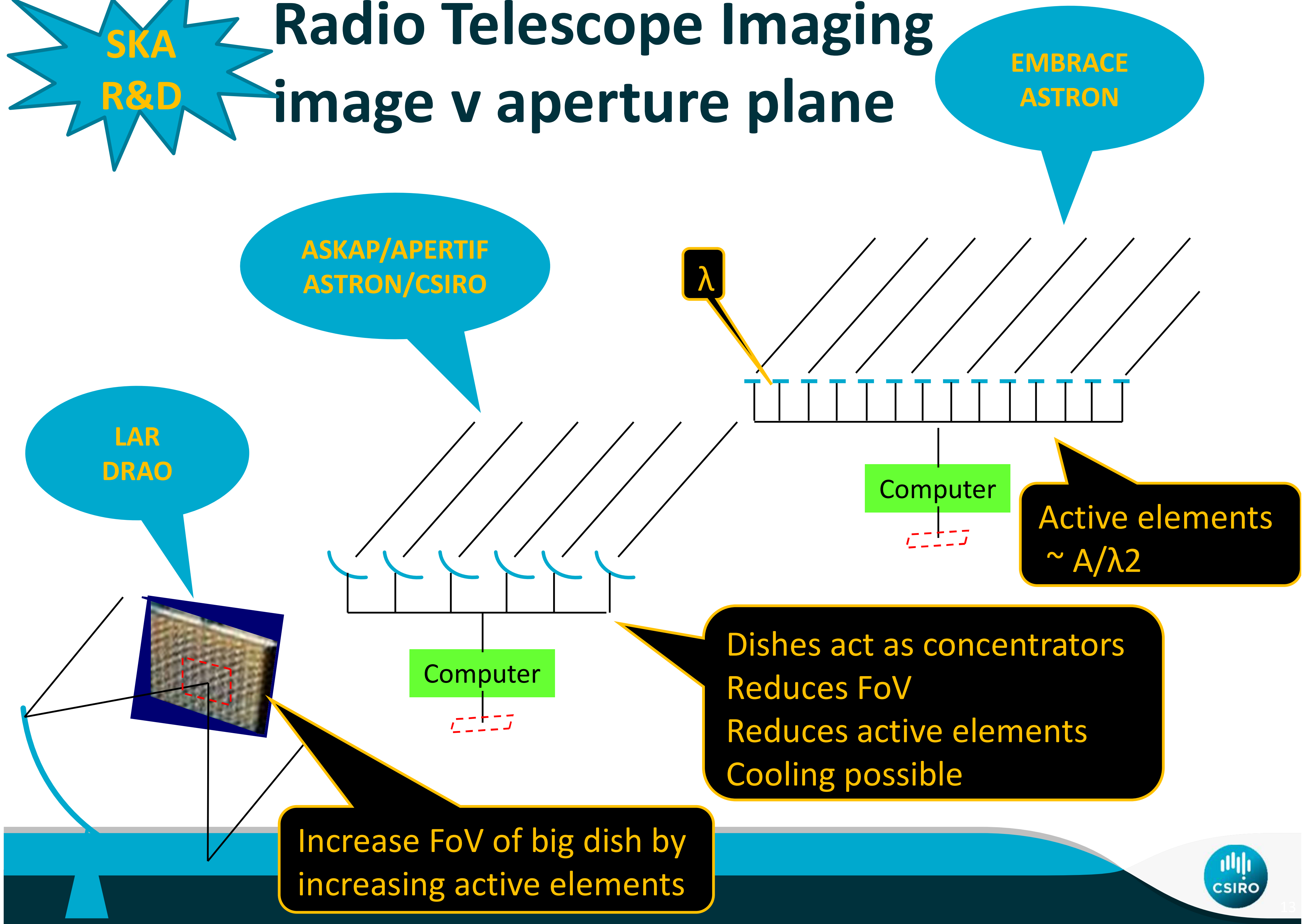
- 1975 Arecibo multi-[illegible]y (Condon et al)
- 1987 Multi element receiver for Green Bank 300’
- 1988 Receiver shipped to Parkes for PMN survey
  - Condon (NRAO) & Burke (MIT)
  - Overcame local engineering conservatism
- 1996 Parkes 13 beam receiver
  - Digital signal processing opportunity created by a high yield for ATCA correlator chips
  - Very competent engineering (Trevor Bird and Warwick Wilson)
  - Science case was for a blind HI survey
  - Major impact was on pulsar survey science
- 2005 Copy installed on Arecibo
- 2018 19 beam copy on FAST

From multi-beam to Phased Arrays

- 1988 – Cornwell and Napier publish on theory of focal plane coherence to correct aberrations, distortions etc.
- 1988 - Ron Ekers joins CSIRO and tries again with MMIC designers for AT Compact Array
  - ➢ runs into shaped dual reflector problems!
- 1993 – Trevor Bird and Geoff Poulton multi-feed onboard satellite "illuminator"
  - ➢ WA beam - CSIRO + Hughes
- 1993 – Parkes 13 beam 21 cm receiver (Bird, Ekers, Stavely-Smith, …)
- 1995 – Conference on multi-feed systems for radio telescopes at NRAO

SKA R&D

Radio Telescope Imaging image v aperture plane



Motivations for PAFs in Radio Astronomy

- Increased FoV
  - Survey speed $$S \propto \left(\frac{A_{eff}}{T_{sys}} \right)^2 \Omega$$
  - Simultaneous look directions (transient detection, interference rejection)
  - Cost reduction through re-use of dish
  - One-off transient discovery space – probability linear with FoV
- Full sampling of image space
  - Aberration and reflector distortion, pointing correction
    - Potential dish cost reduction
  - Adaptive interference rejection and spillover reduction
  - Increased self calibration potential (multiple sources in FoV)
  - Near instantaneous large field imaging

But must hold the line on Aeff/Tsys (JOS 2005)!

ASKAP failed!

But Phased Array Feeds can do much more!

- Aperture illumination control – reduced spill-over
- Higher dynamic range (eg dish pointing errors cancel)
- RFI mitigation – adaptive nulling
- Reduced spectral ripple
  - no reflections from focal plane region
- Can transfer calibration
  - You cant point an aperture array without changing gain/beam
- Can measure the very low spatial frequencies (mosaicking)
  - Fourier transform into aperture plane
  - Corresponds to patches on surface of dish
  - Highly redundant
  - No shadowing
  - Eg large scale HI statistics at high z

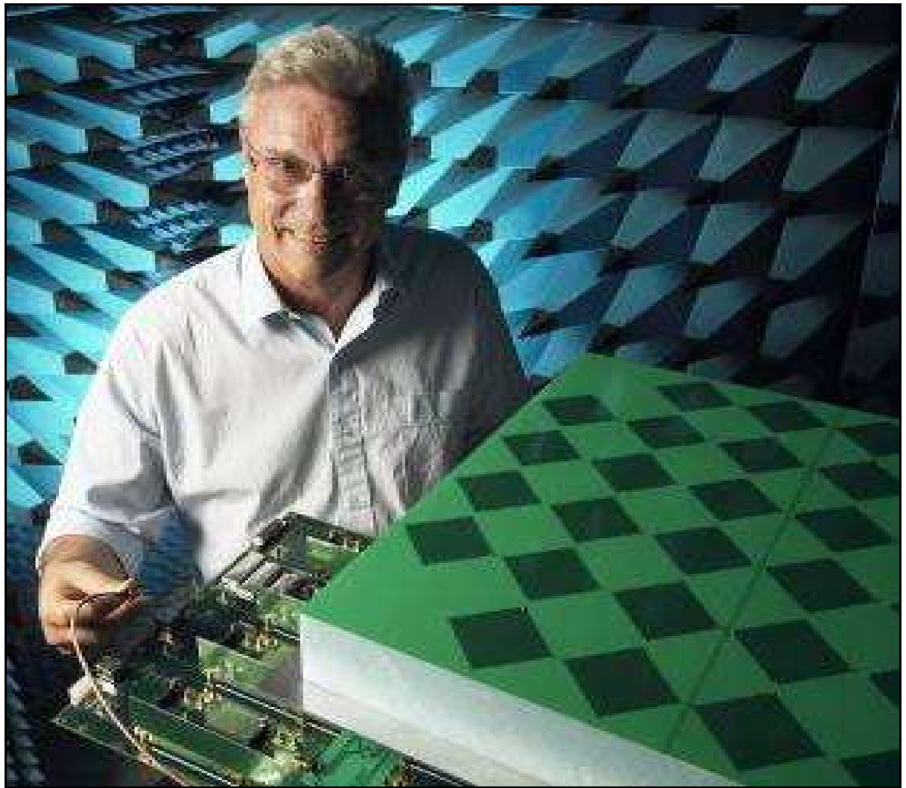
PAF in Radio Astronomy - brief history

- 1982 Weinreb aperture correction using PAF (NRAO workshop)
- 1988 Cornwell and Napier publish on theory of focal plane coherence to correct aberrations, distortions etc.
  - PAF can be placed anywhere between the aperture and the focus
- 1993 PAF design considered and rejected for Parkes multi-beam
  - Trevor Bird and Geoff Poulton multi-feed onboard satellite (CSIRO + Hughes)
  - Decision to use interlaced observations instead of full instantaneous sampling
- 1995 Rick Fisher PAF element design
- 2000 Arnold van Ardenne commissions Vivaldi design with Dan Schaubert (U Mass.)
- 2001 3 focal plane array options considered for SKA design
  - Peter Dewdney et al propose large reflector (LAR) with PAF on aerostat
  - John Bunton's cylinder with 1D line feed - implemented in CHIME
  - Ron Ekers pushes dish concentrators with PAF – implemented as ASKAP

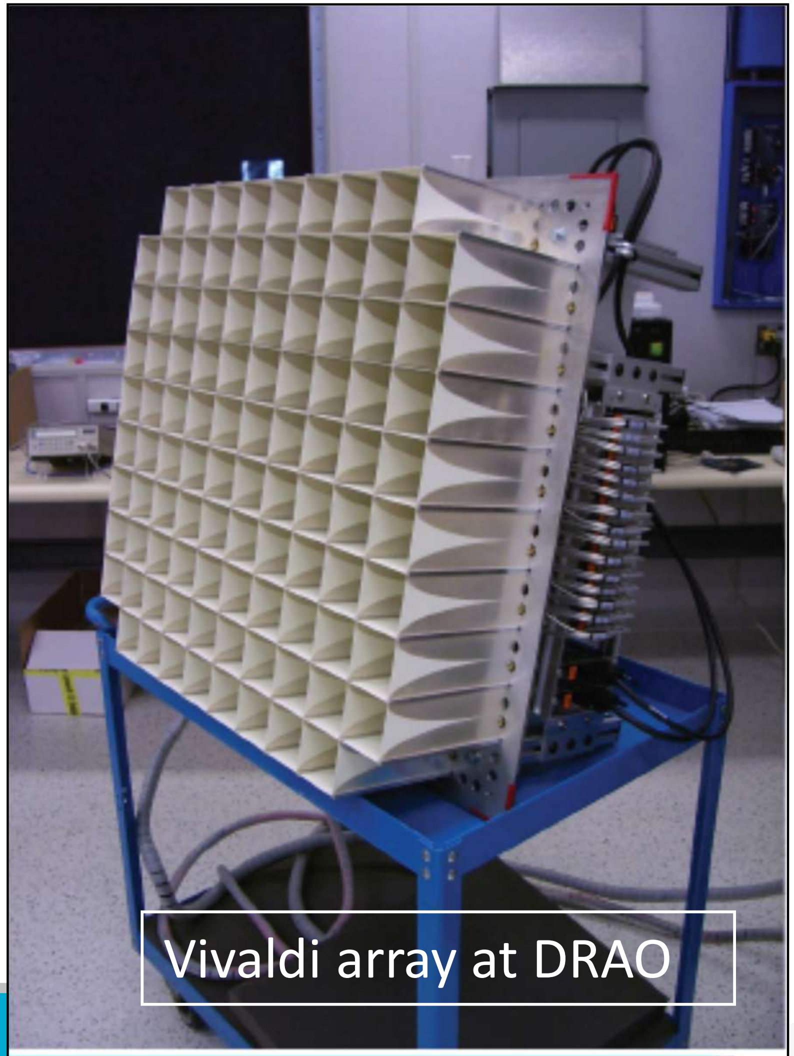
PAF in Radio Astronomy - brief history

- 2003 – Arnold van Ardenne and Marianne Ivashina (Astron) test first Astron Vivaldi array tile at CSIRO
- 2005 – Peter Hall requests clarification of FPA v PAF nomenclature
  - All parties agree to use “PAF”
- 2005 - Stuart Hay proposes connected dipole
  - Design evolves into a more broadband checkerboard array design
- 2006 Australian proposal for array using PAFs (ASKAP)
  - 2012 ASKAP opened, fully operational 2022
- 2007 – Rick Fisher (NRAO), Karl Warnick (BYU) et al proposed dipole phased array feed for GBT
- 2019 APERTIF installed in WSRT, operational 2019
- 2022 Parkes CryoPAF (see Alex Dunning talk #11)

Some PAF designs – circa 2005



Checker board - ATNF



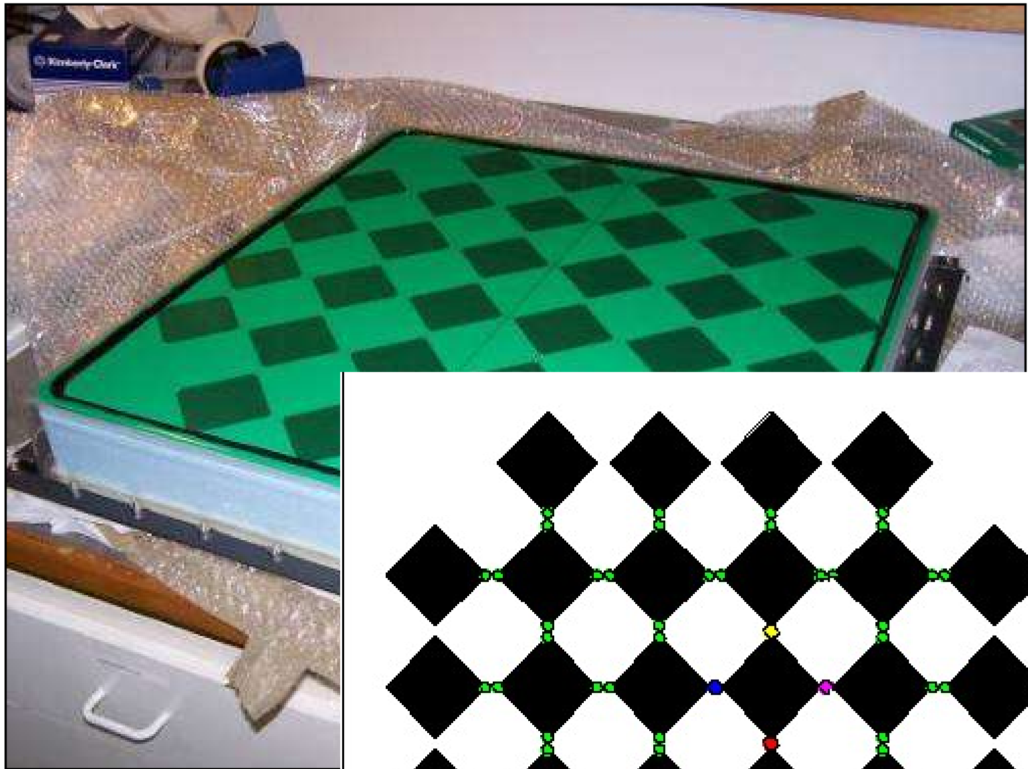
Vivaldi array at DRAO

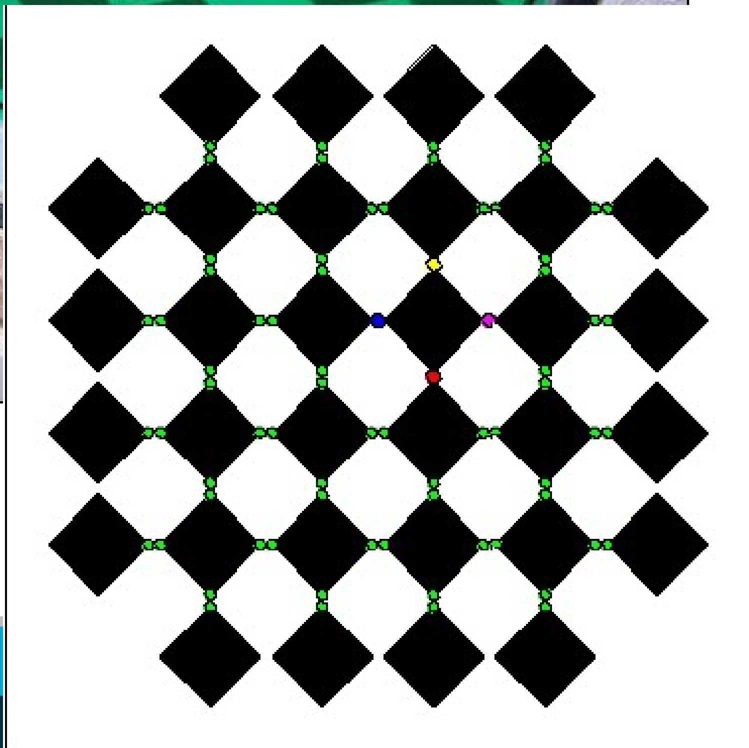
Vivaldi - DRAO

Toward SKA

- 1995 – AvA drives research into aperture array for SKAI in ASTRON
- 1996 – Rick Fisher paper on fundamentals of phased array feeds on parabolic reflectors
- 1996 – Delft SKAI conference
  - AvA pushes dense aperture array based on growth projections of computing/processing.
- 1997 – 1KT Technical Workshop Sydney
  - Harvey Butcher – arrays and focal plane arrays as Dutch focus
  - Arnold van Ardenne – comprehensive talk on arrays, station heirarchy, element types etc.
  - Rick Fisher – arrays and array beamforming principles.

Checker Board Focal Plane Array

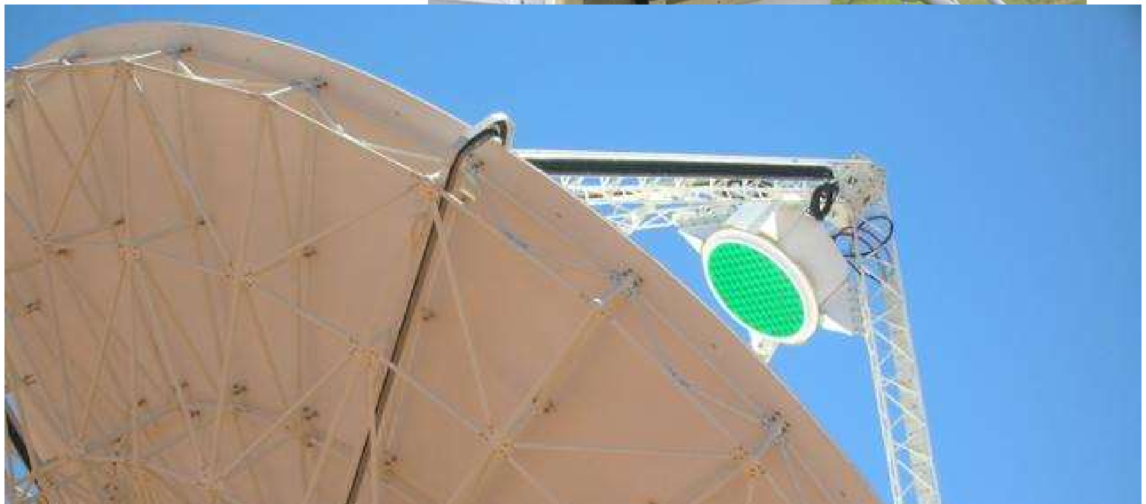




- Self-complementary antenna
- Frequency independent free space impedance
  - 380 ohms
- Babinets Principal
- Differential amplifiers at vertices
- Accurate modelling possible

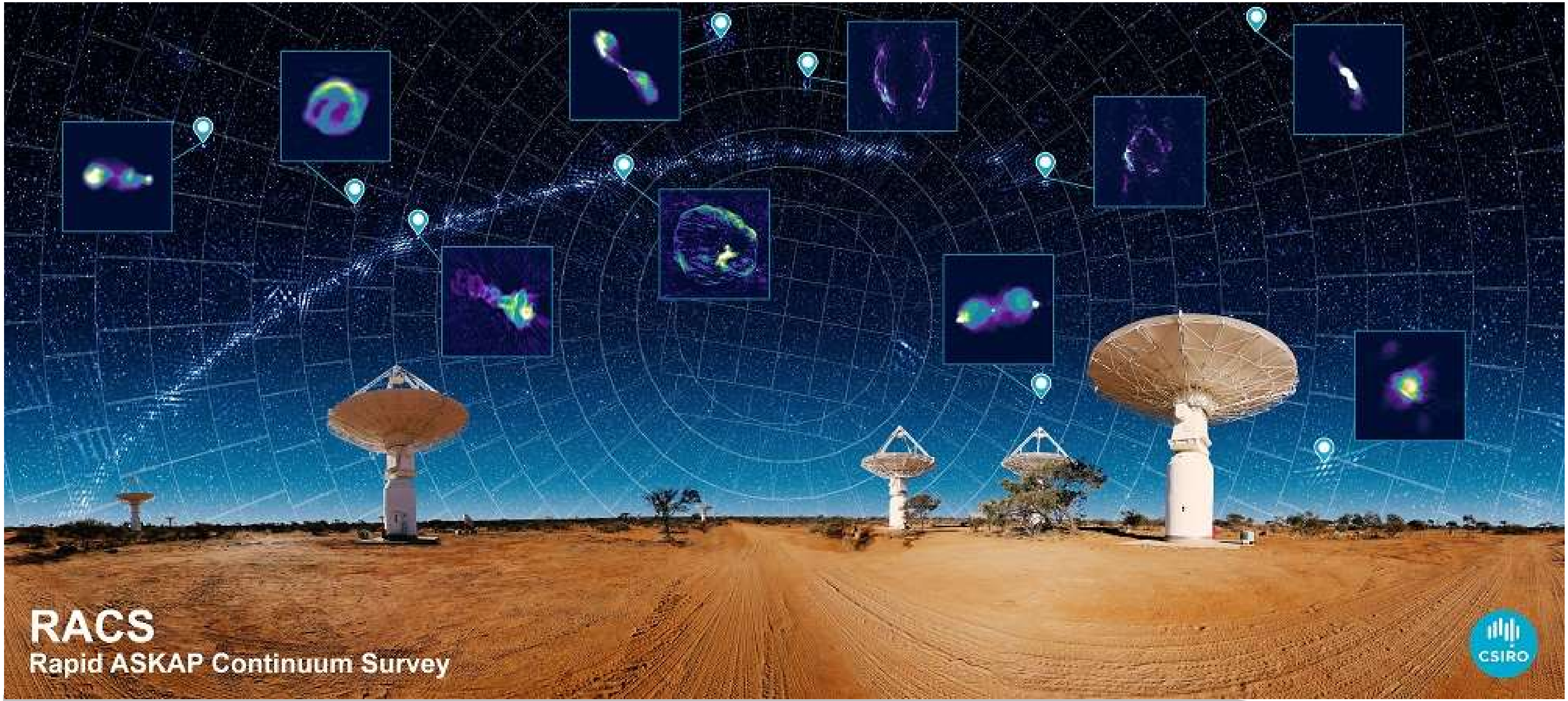
Some working PAFs

- Apertif
  - 121 element,
- ASKAP
  - 188 element
- NRAO/BYU
  - 17 element
- PHAD
  - Several hundred



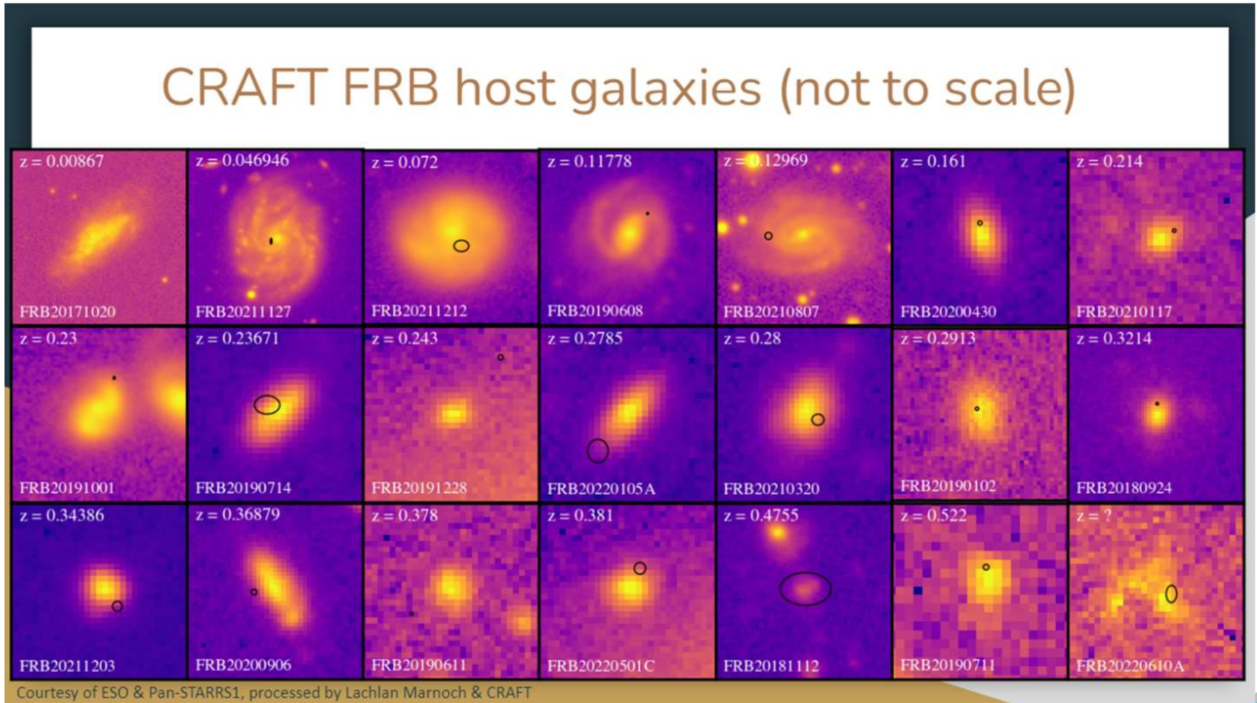
ASKAP – FoV enabled science
Mapping the entire sky

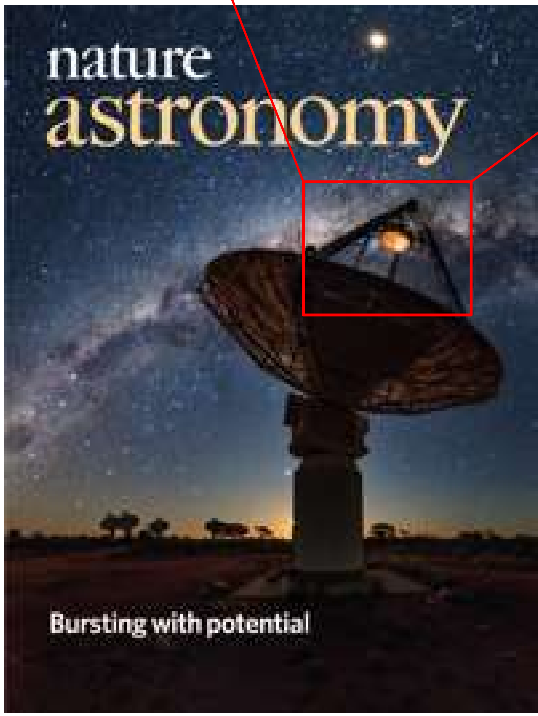
- ASKAP: 36 antennas with 36 beam FPA in each antenna
- 30 sqd FoV enables rapid all sky surveys



ASKAP – FoV enabled science transient discovery space

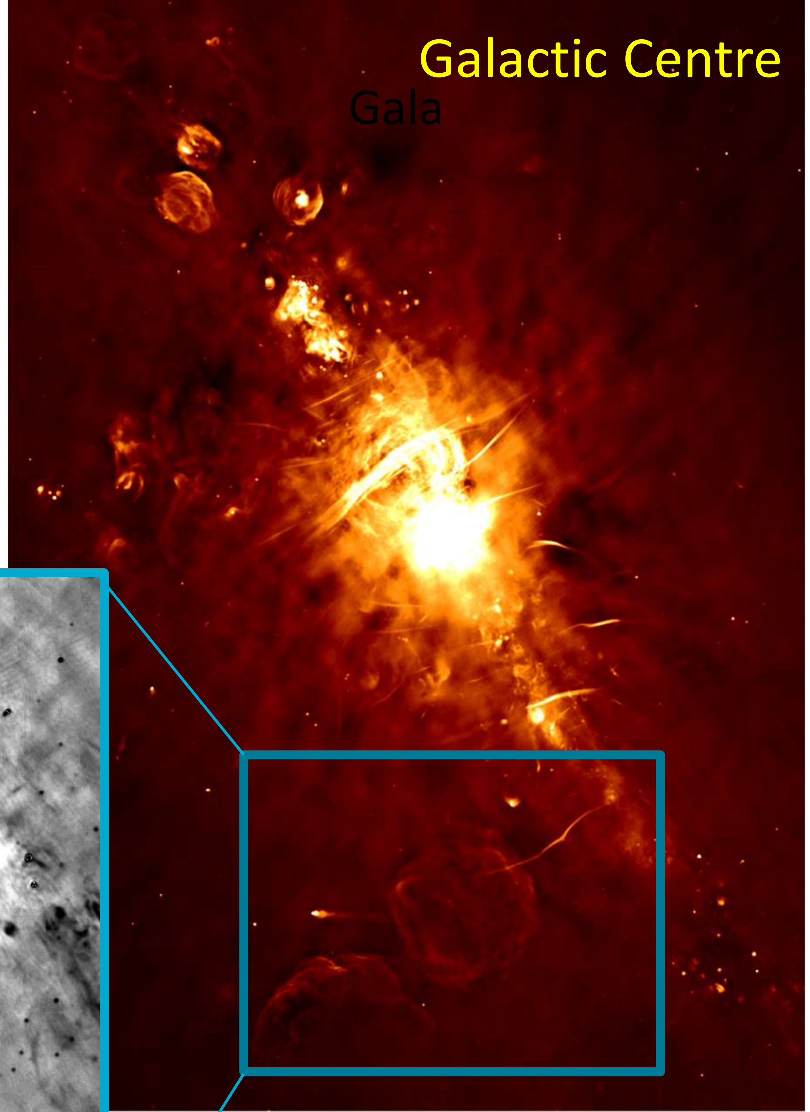
- Large discovery FoV triggers voltage dump for positions
- 90% of all localised non-repeating FRBs
- Highest redshift FRB and Hubble constant

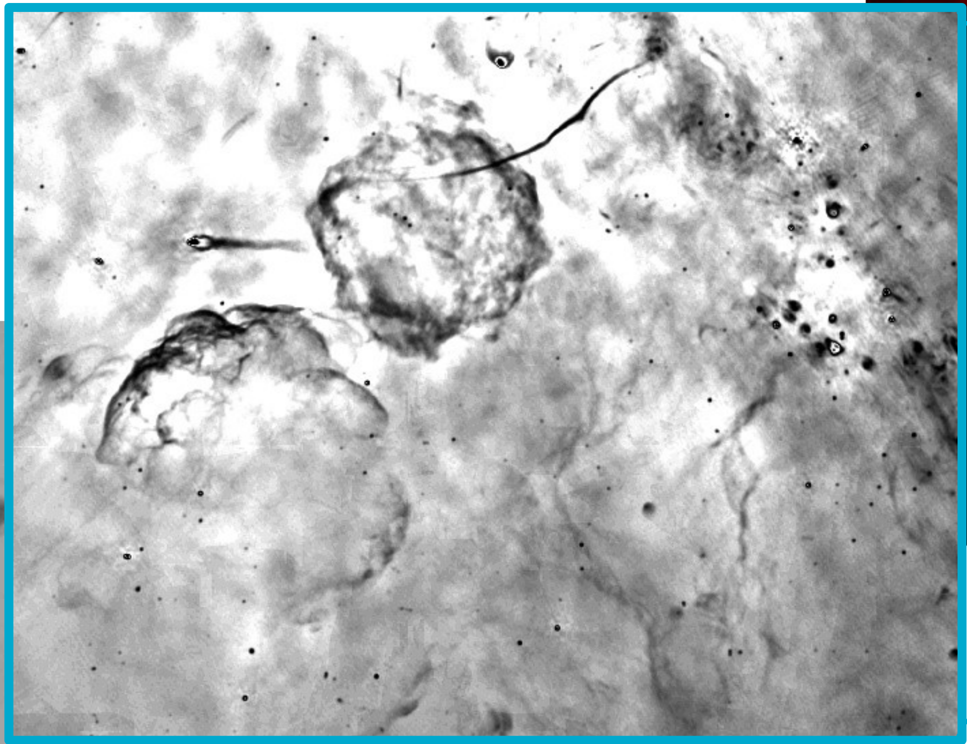


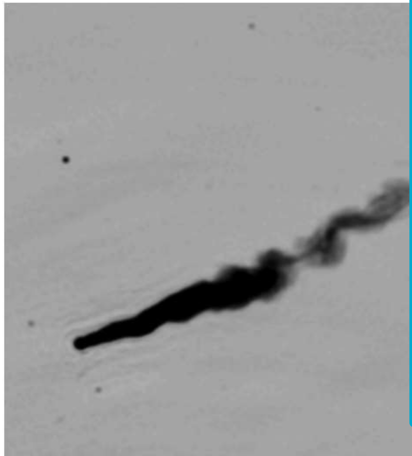


ASKAP – FoV enabled science
Large scale structure

- Full range of spatial scales from maximum baseline to sub dish diameter.



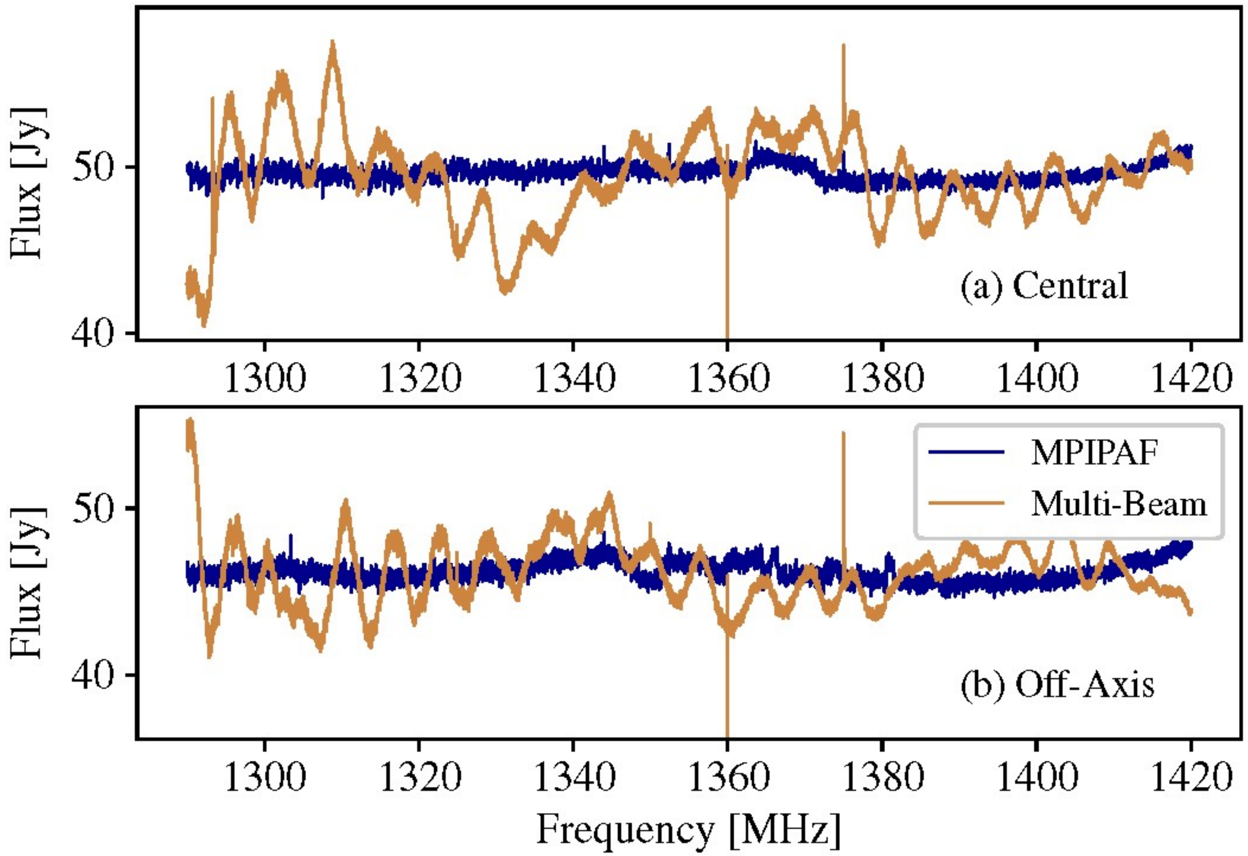




Tail radio source in Norma galaxy cluster

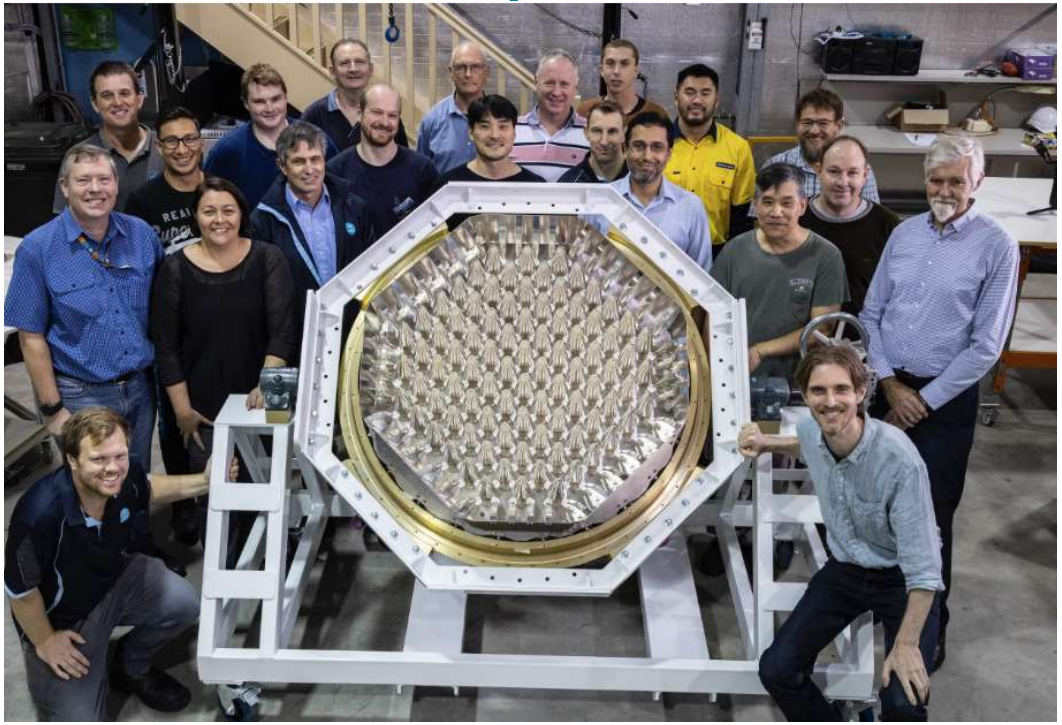
Reduced spectral ripple
MPI PAF on Parkes

- Ideal for HI intensity mapping, positronium, dark matter

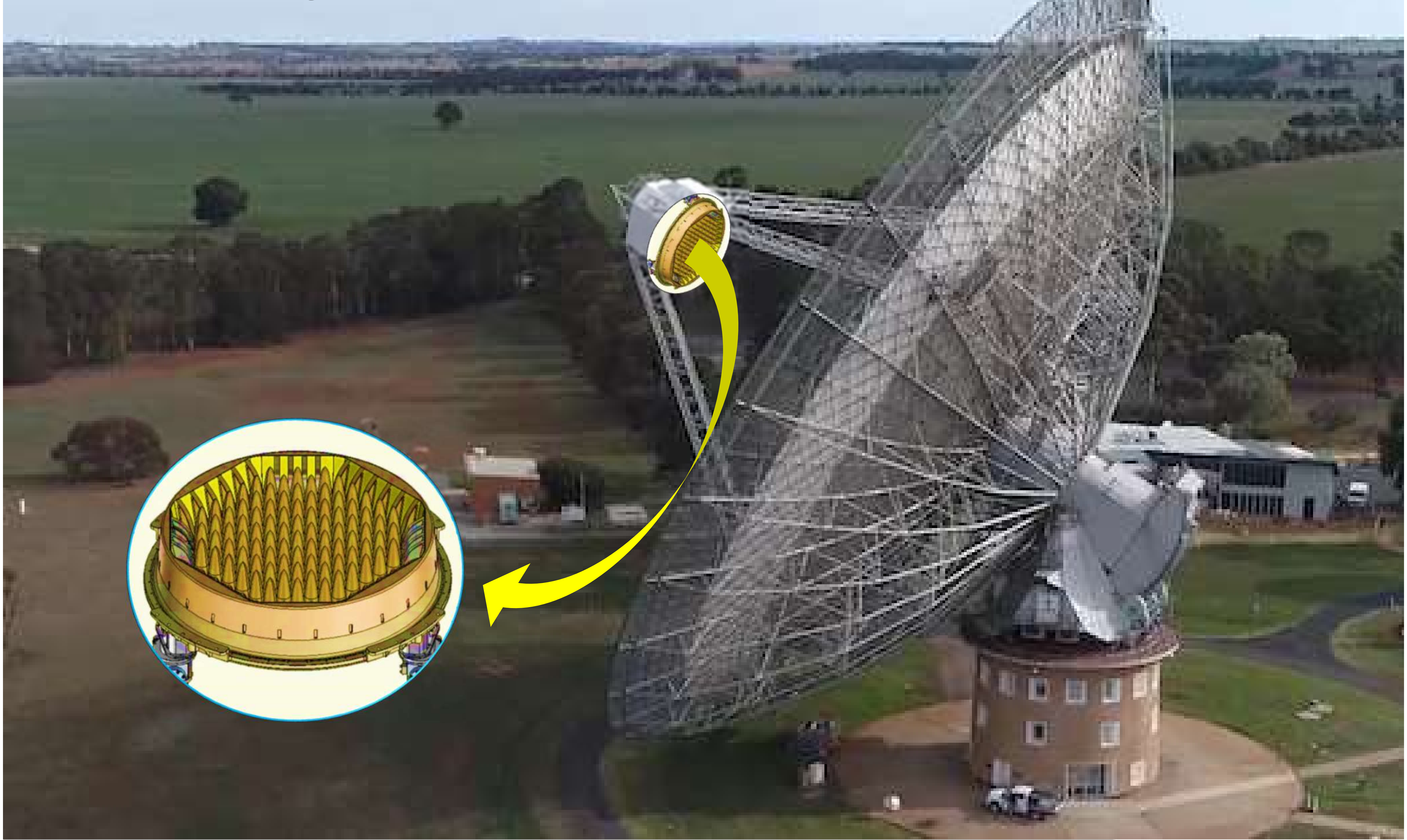


PAF Future - the "Rocket" cryo PAF

Talk # 11 by Alex Dunning

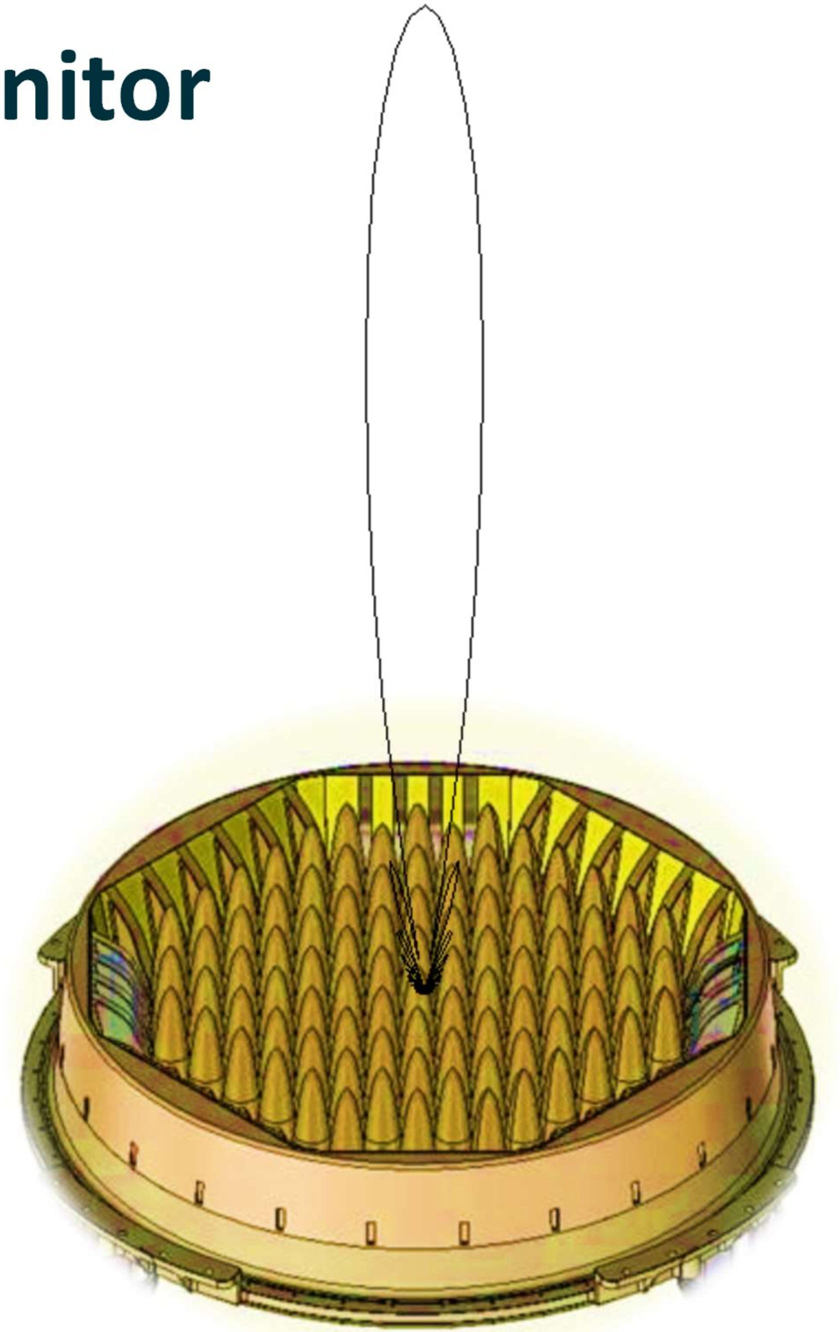


Parkes Cryo-PAF



PAF all-sky dishless monitor

- Combine all 98 elements to make each beam
  - Total collecting area sum of all elements



PAF all-sky dishless monitor

- Combine all 98 elements to make each beam
  - ➢ Total collecting area sum of all elements
- Form 72 separate beams covering whole hemisphere
  - ➢ FoV 10,000 sqd
  - ➢ 30x larger than CHIME!
- But is it still a PAF?
  - What do we call it?
- PAF design v dense aperture arrays