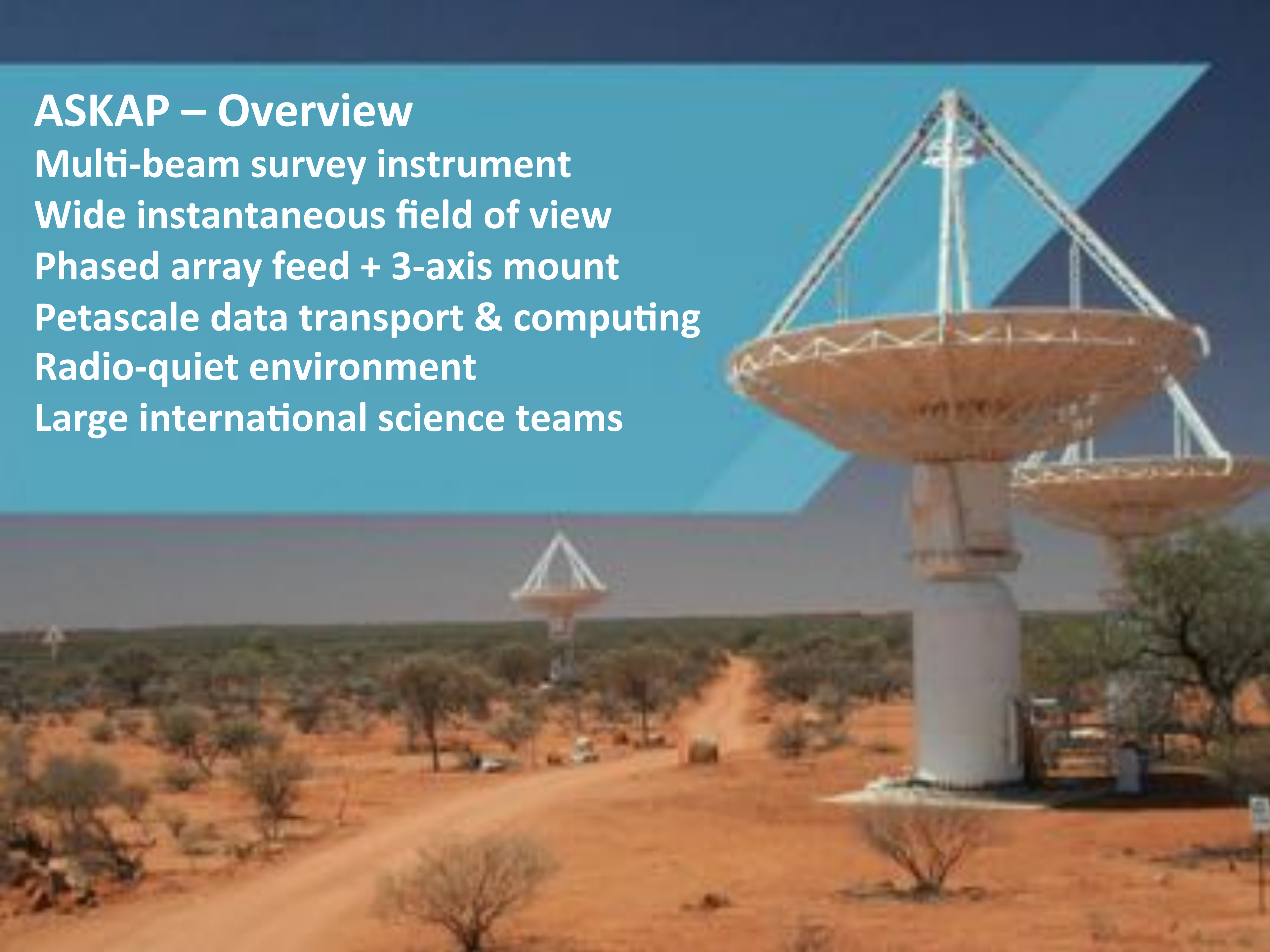
ASKAP: Australian SKA Pathfinder
EMU: Evolutionary Map of the Universe

Joshua Marvil | CSIRO Postdoc

SPARCS 2016 | Goa, India | 3 November 2016

ASKAP – Overview

- Multi-beam survey instrument
- Wide instantaneous field of view
- Phased array feed + 3-axis mount
- Petascale data transport & computing
- Radio-quiet environment
- Large international science teams



ASKAP - Details

36x 12-meter antennas

300 MHz instantaneous bandwidth

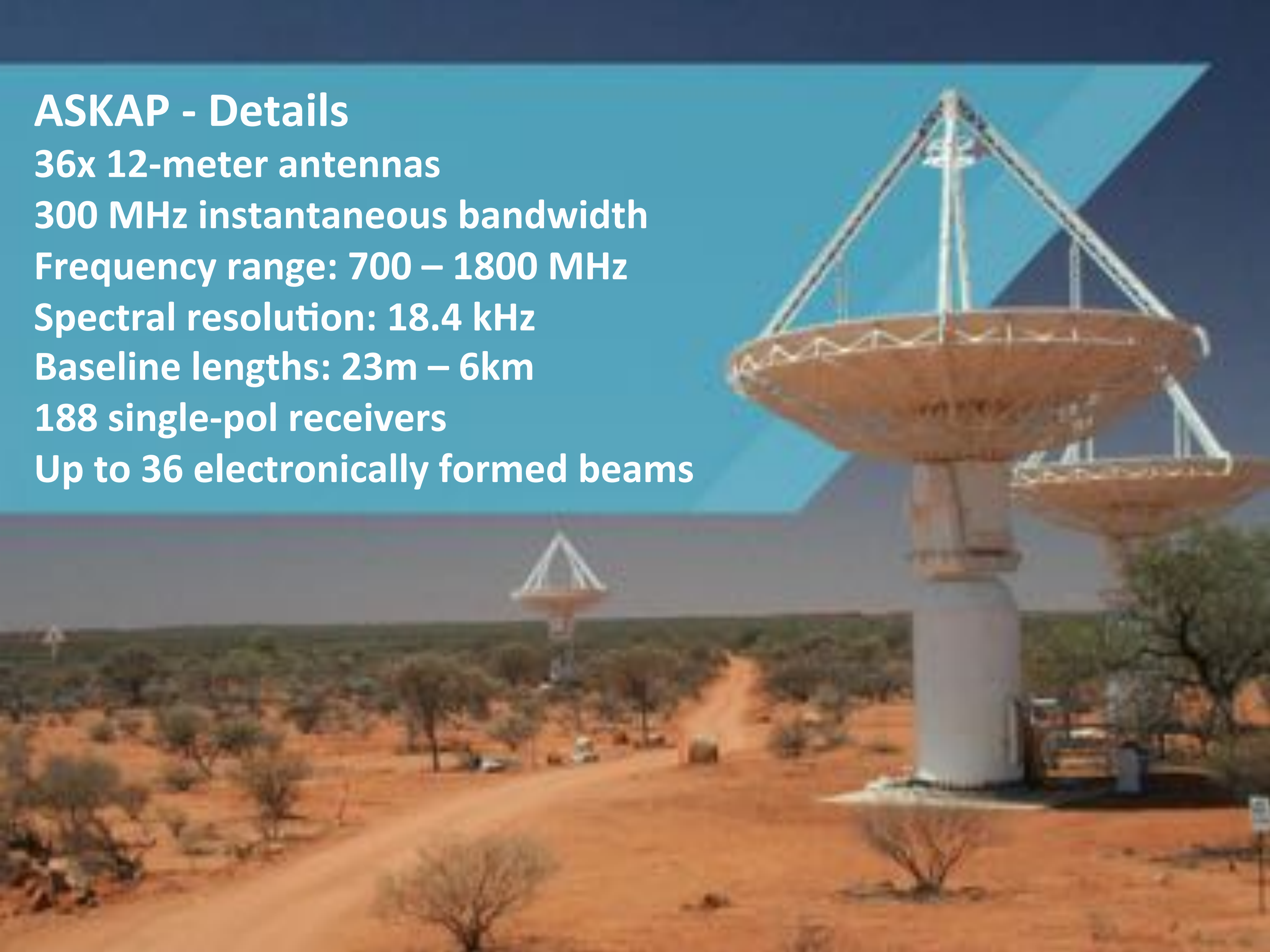
Frequency range: 700 – 1800 MHz

Spectral resolution: 18.4 kHz

Baseline lengths: 23m – 6km

188 single-pol receivers

Up to 36 electronically formed beams



ASKAP Science

38 proposals submitted to ASKAP

2 selected as being highest priority

- EMU all-sky continuum (PI Norris)
- WALLABY all-sky HI (PI Koribalski & Staveley-Smith)

8 others supported at a lower priority

- COAST pulsars etc
- CRAFT fast variability
- DINGO deep HI
- FLASH HI absorption
- GASKAP Galactic
- POSSUM polarisation
- VAST slow variability
- VLBI

EMU Overview

Observe 75% of the sky (to dec +30)

Frequency range: 1130-1430 MHz

40x deeper than NVSS — 10 uJy across the sky

5x better resolution than NVSS (10 arcseconds)

Improved sensitivity to extended structures

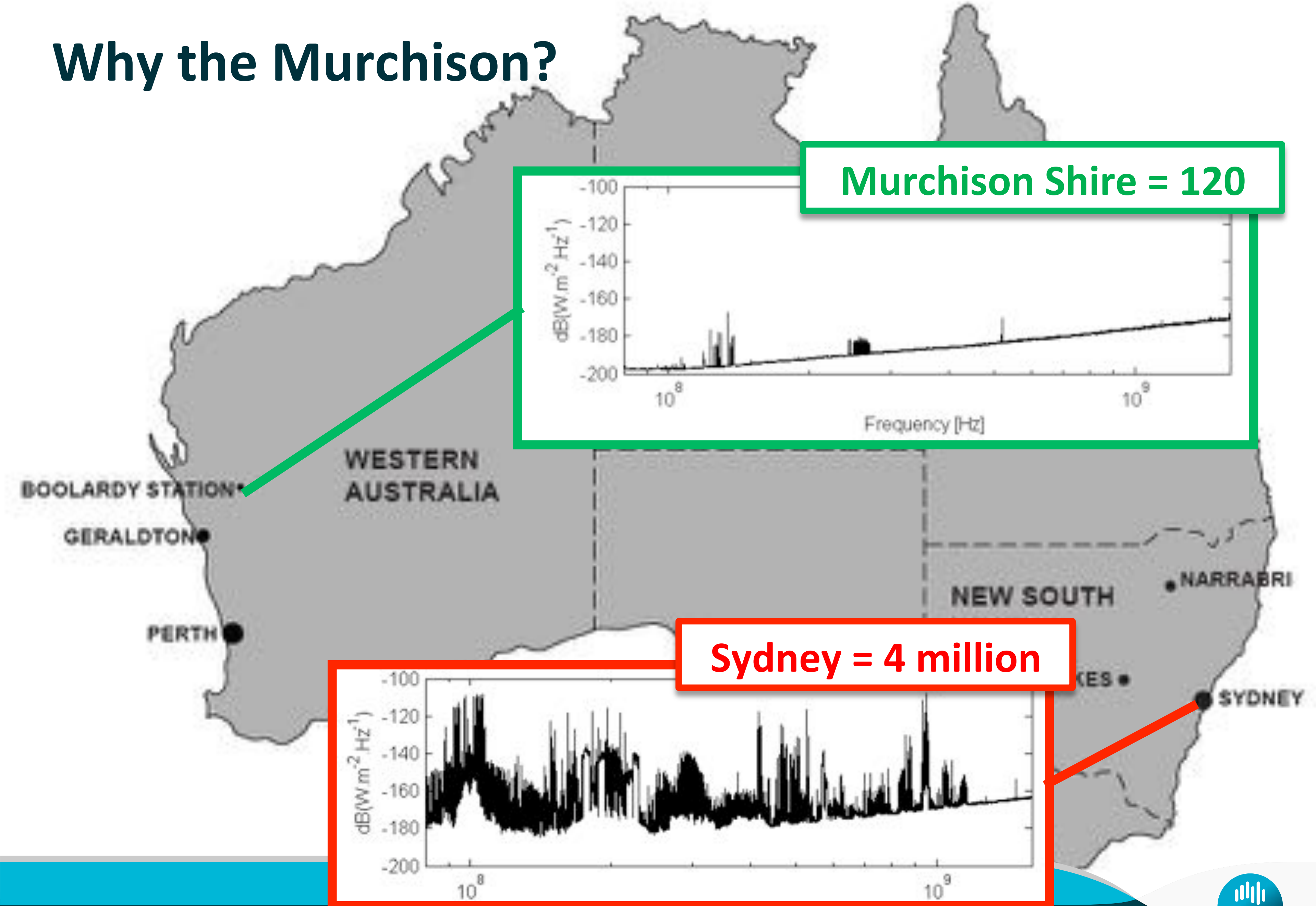
Will detect and image **70 million galaxies** at 20 cm

- Trace the evolution of SF galaxies from z=2 to the present
- Trace the evolution of massive black holes over cosmic time
- Explore large-scale structure and cosmological parameters
- Generate an atlas of the Galactic plane
- Investigate clusters and low surface brightness emission
- Explore uncharted parameter space - discover the unknown

Key technical aspects of ASKAP

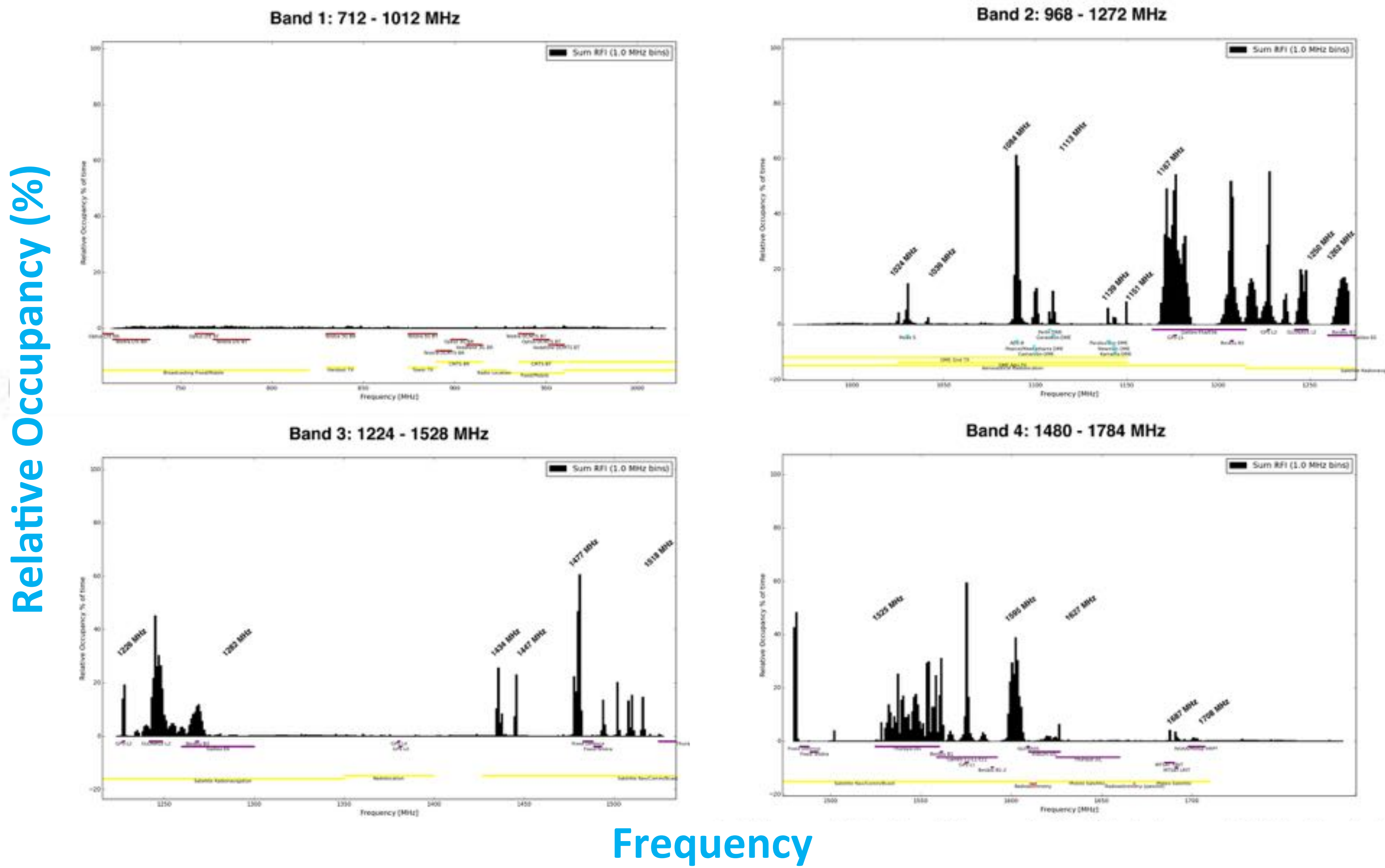
ASKAP location

Why the Murchison?



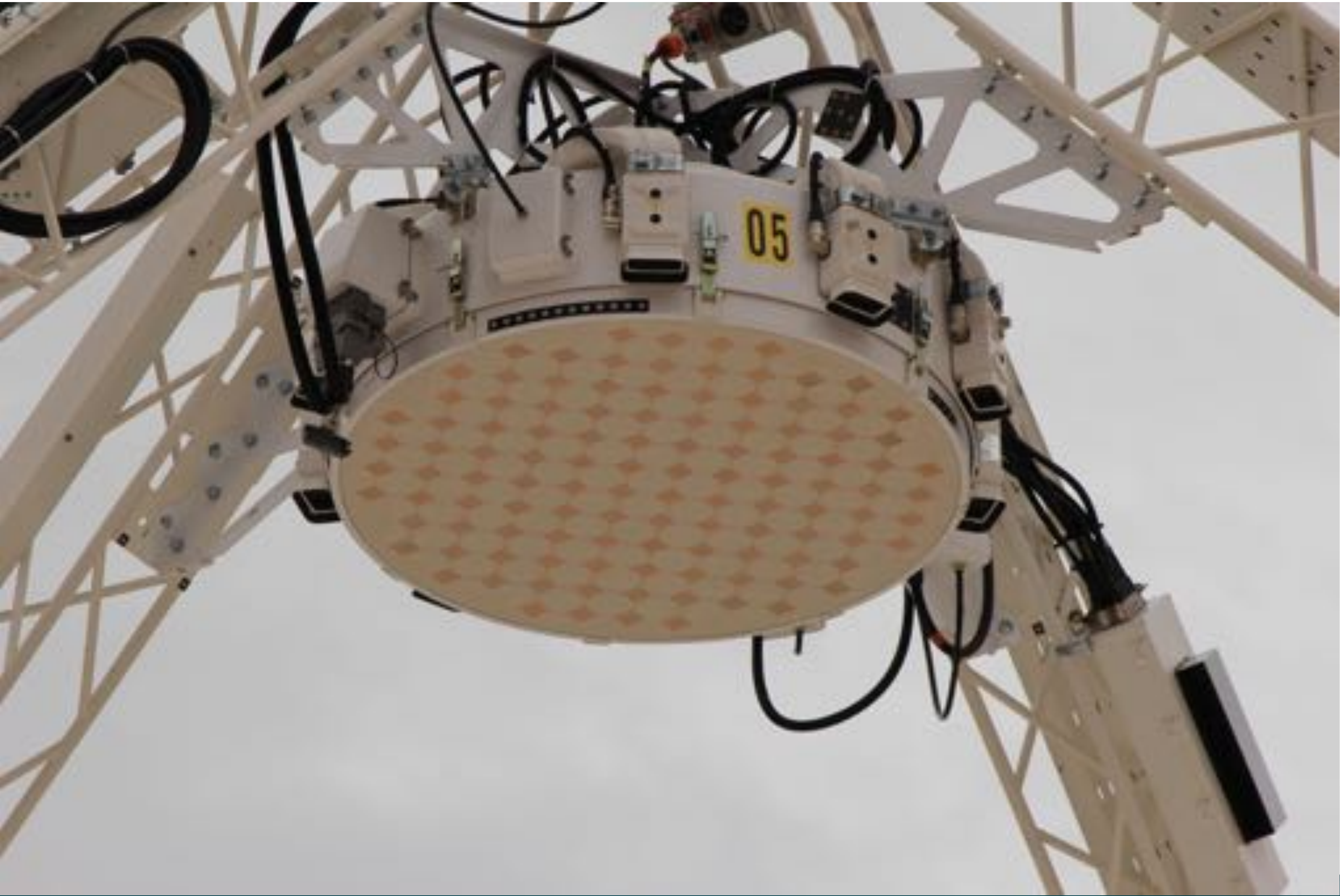
Slide courtesy of Antony Schinkel

Why the Murchison?

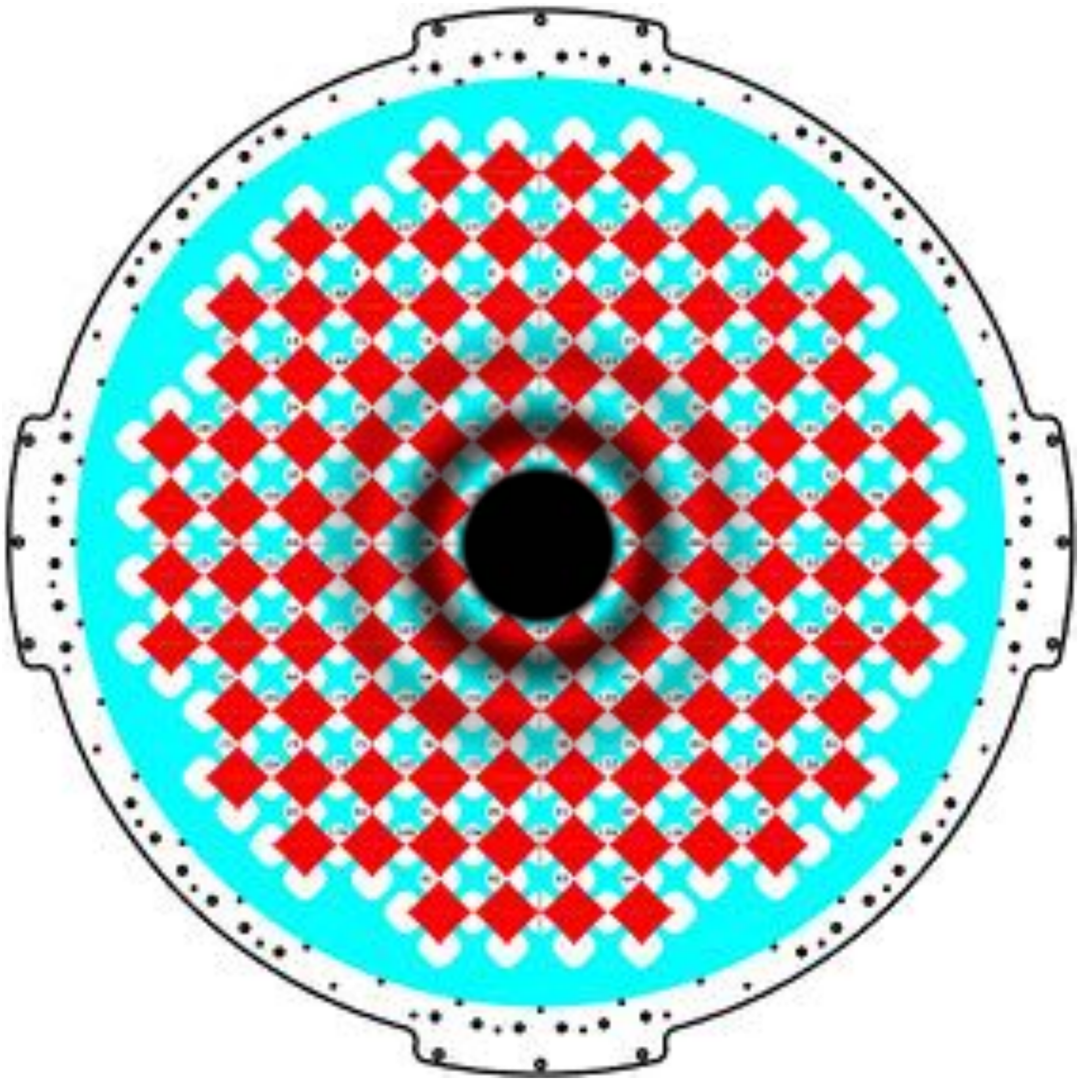



New Electronics
A better view of the skies
The Square Kilometre Array is set to provide astronomers with unprecedented views of what's out there – and opportunities for UK electronics.

Phased Array Feed – 188 single pol receivers

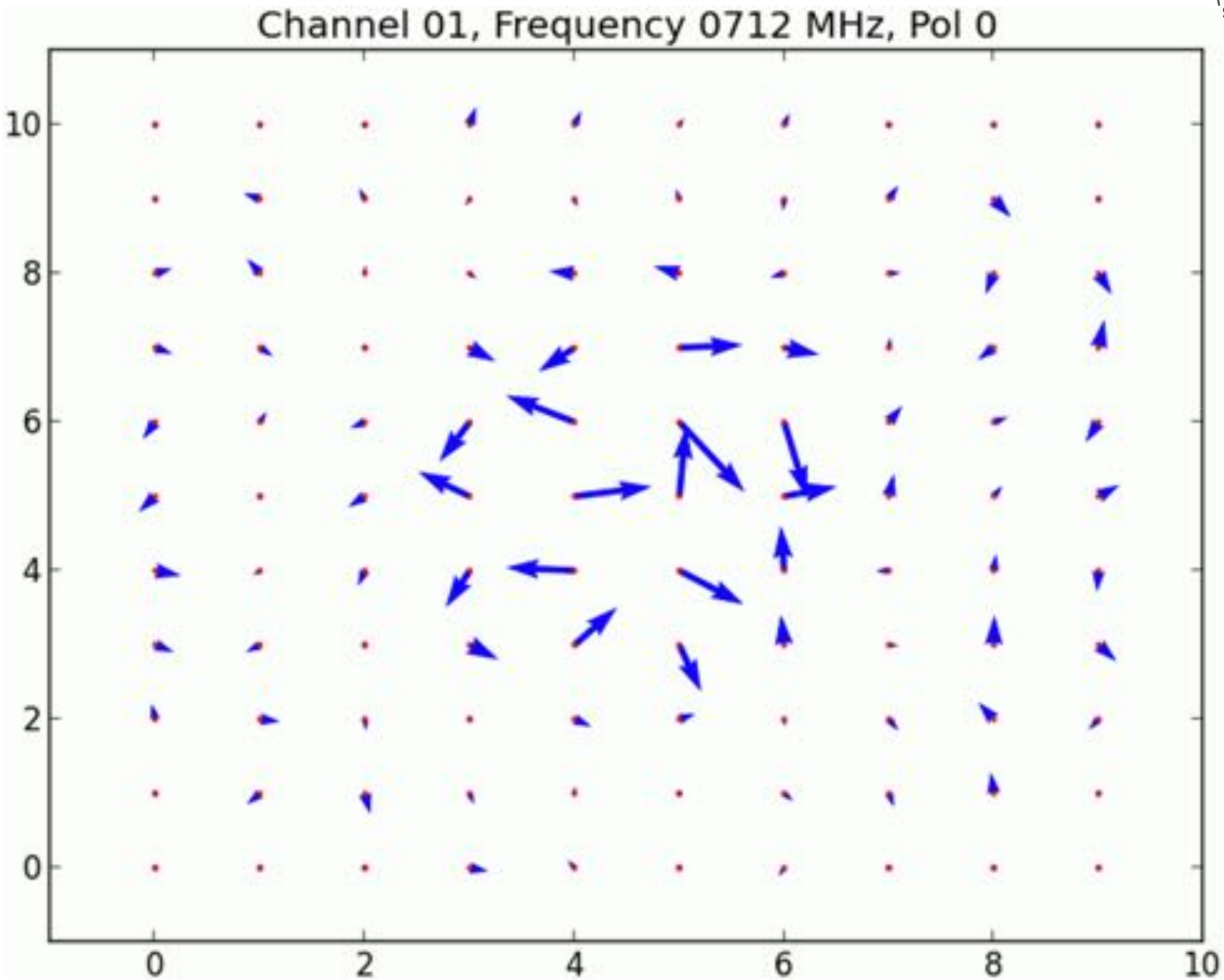


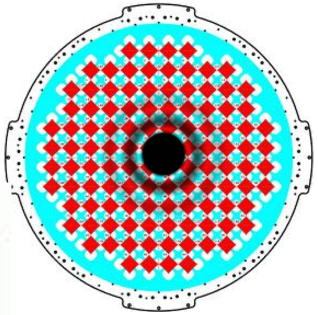
Beamforming from the PAF's perspective



Credit: Aidan Hotan

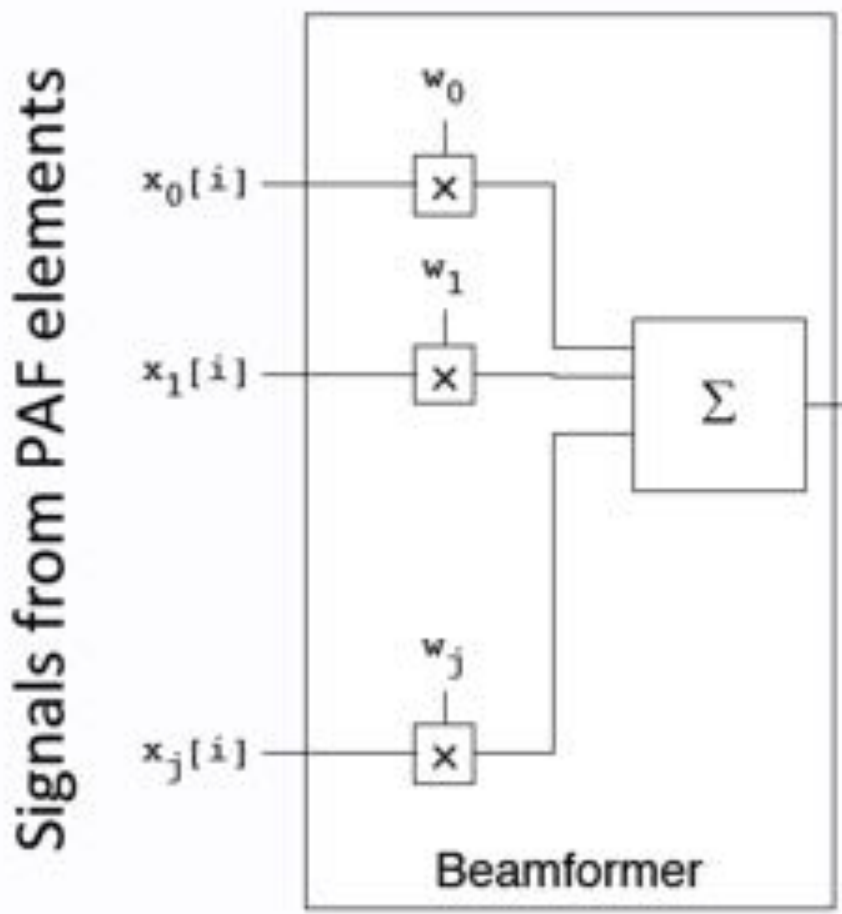
Maximum sensitivity beam weights





Credit: Aidan Hotan

Beamforming for ASKAP



$$y_k[i] = \mathbf{w}_k^T \mathbf{x}[i]$$

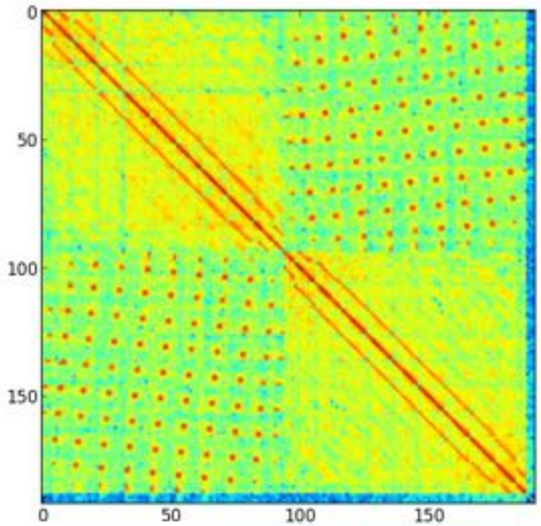
336 x 2 x 36 beamformers

frequencies pols beams

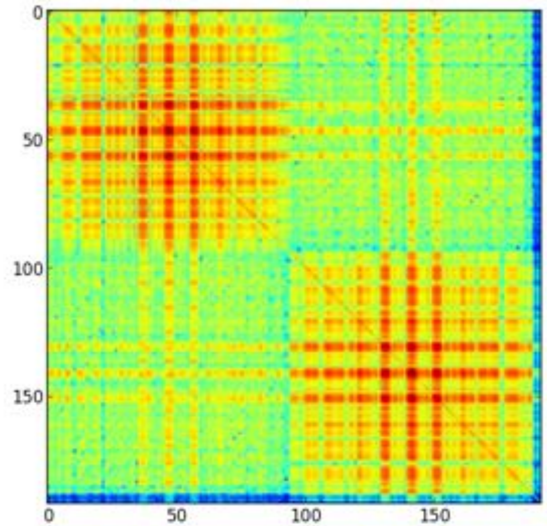
Beamformers currently have hardware for 336 MHz, upgradable to 384 MHz

Credit: Max Voronkov

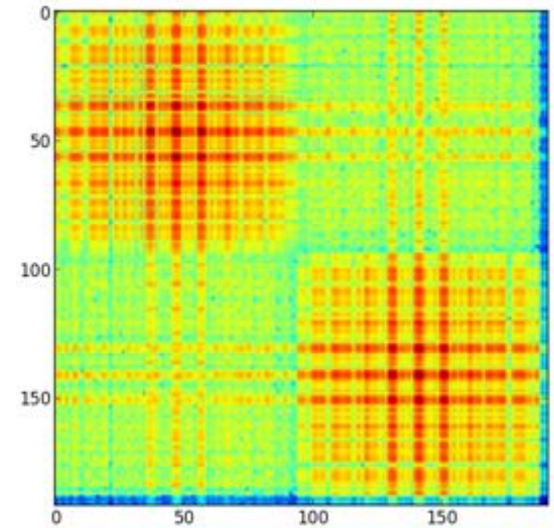
Max-SNR Beamforming on the Sun



$\mathbf{R}_n$



$\mathbf{R}_{s+n}$



$\mathbf{R}_{s+n} - \mathbf{R}_n$

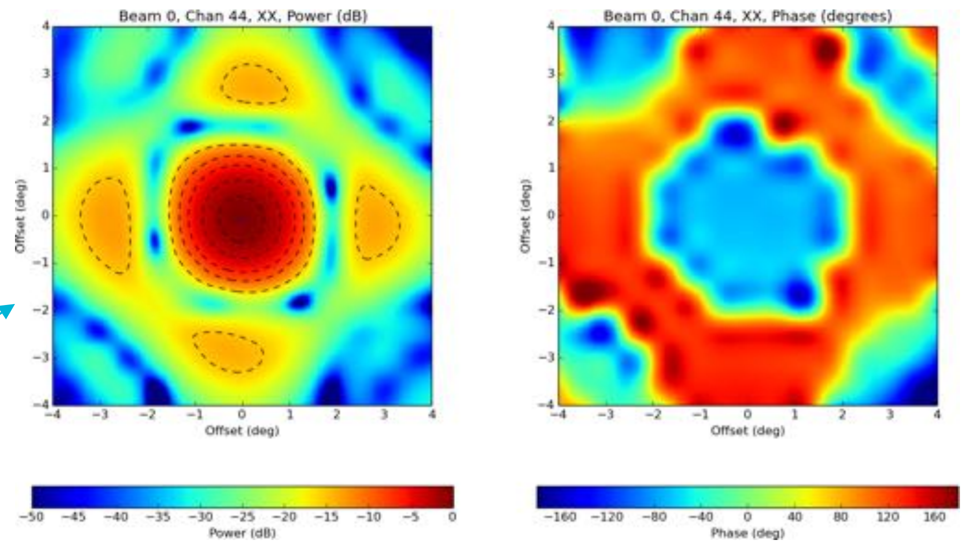
- Weight is the dominant Eigenvector of the difference above.
- The Sun dominates the noise in this example. Weaker sources have proven less effective.
- To make offset beams, point the antenna off-axis. Need one observation for each beam.

Credit: Aidan Hotan

Shape of maximum sensitivity beams

- Maximum sensitivity beam-forming does not constrain the shape of the beam, its symmetry, side-lobe levels, etc.
  - Good for detecting point sources, but may not be optimal for mosaicking.
  - Holography measurements can be used to study the beam shape.

Amplitude



Phase

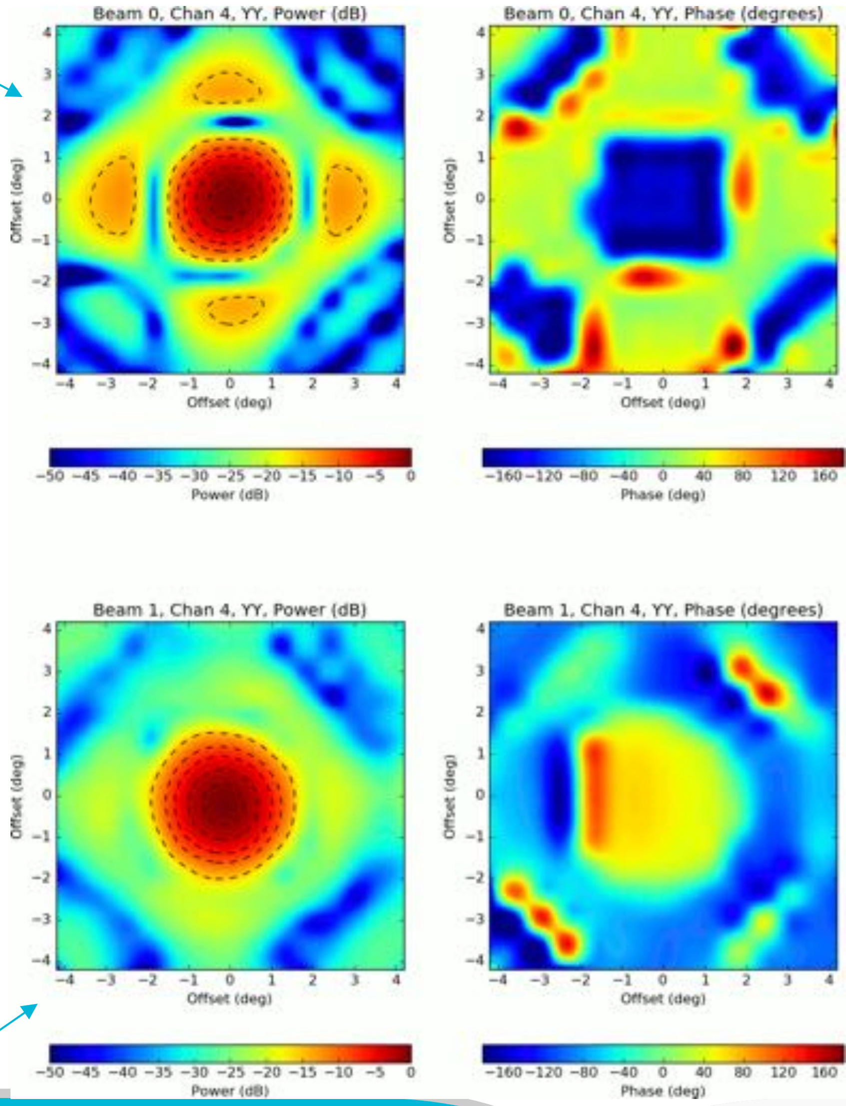
Asymmetry due to feed support structure

Beamforming is an active area of research

Max S/N

- Shape constrained beams and other beamforming algorithms
- Instrumental polarisation
- Interferometric beamforming
- On-dish radiators to stabilise beams
- Beam longevity (limited by hardware resets so far)
- Beam cross-talk
- Advanced topics, e.g. bad ports, RFI

- More efficient approaches (observation to form 36 max S/N beams takes about 2 hours)



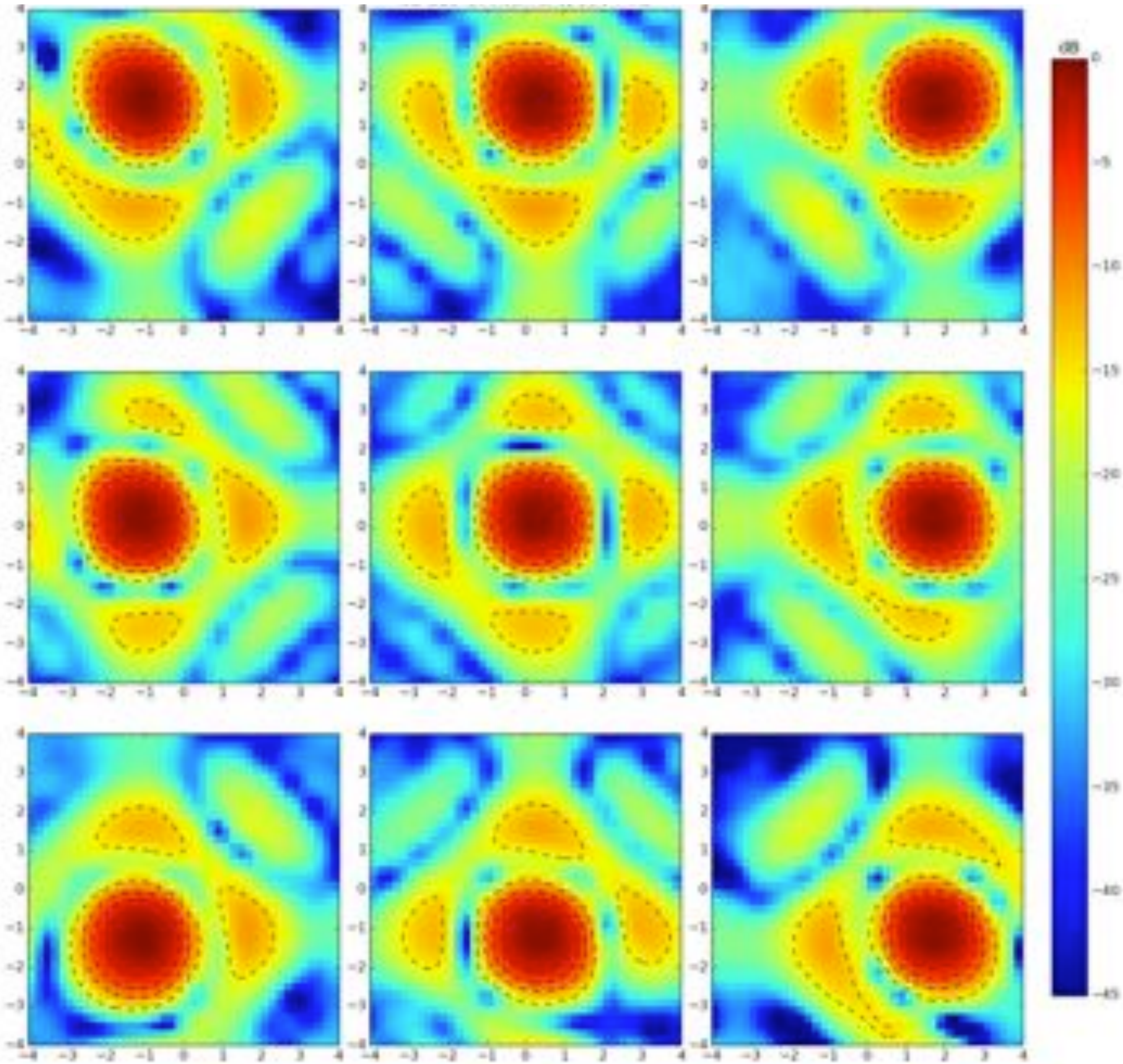
Shape constrained

Credit: Sarah Hegarty and Aidan Hotan

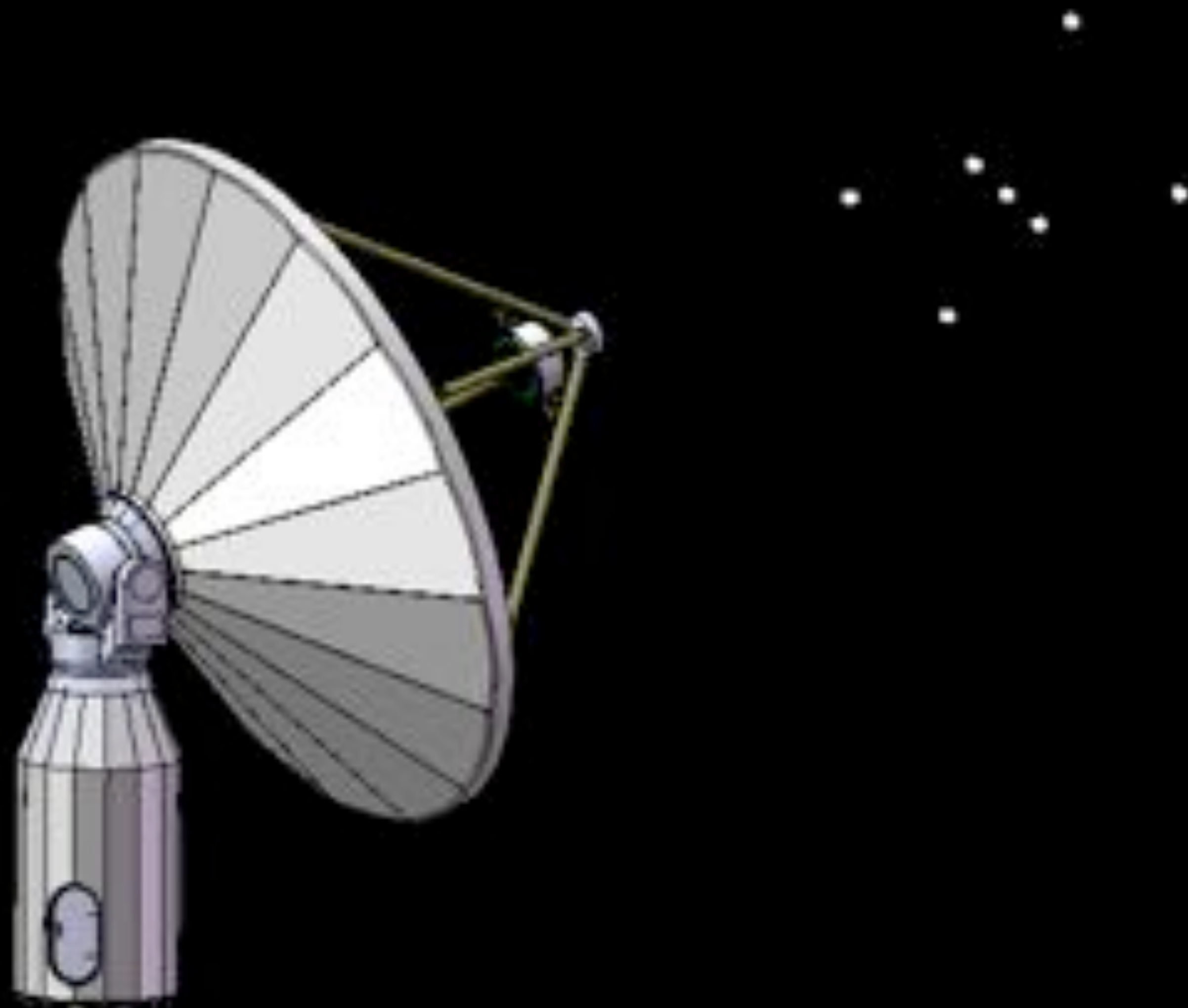
Holographic Beam Measurements - 3x3 Square Footprint

Axes:

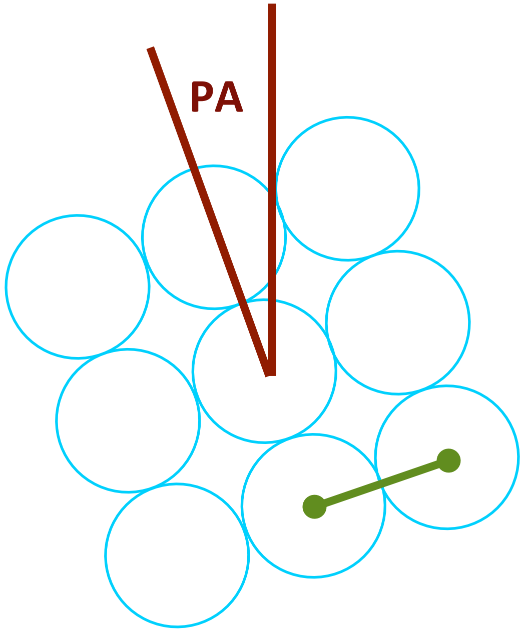
± 4 Degrees



ASKAP’s 3-axis Antenna



Beam footprint:



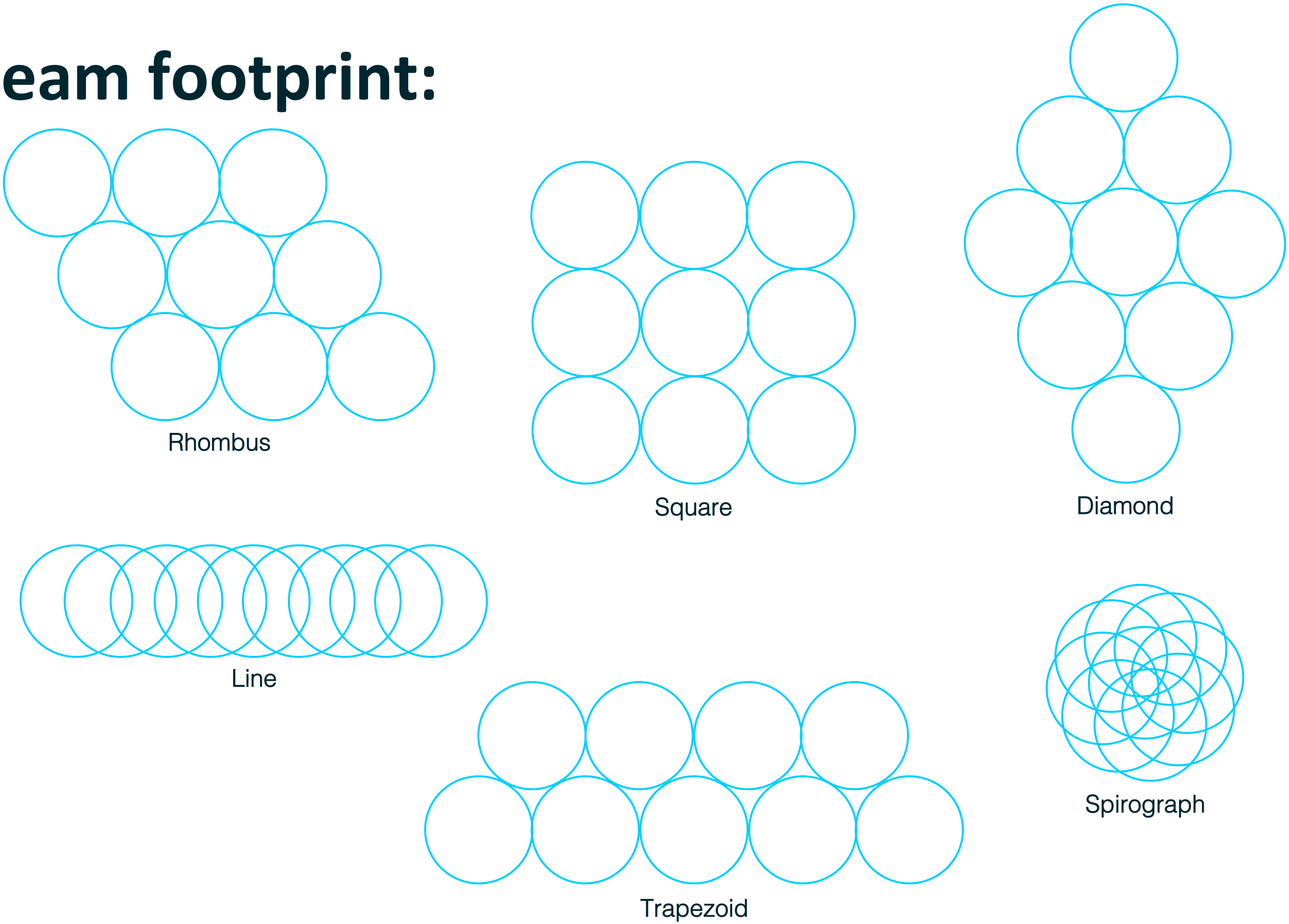
Square

Geometry

Pitch

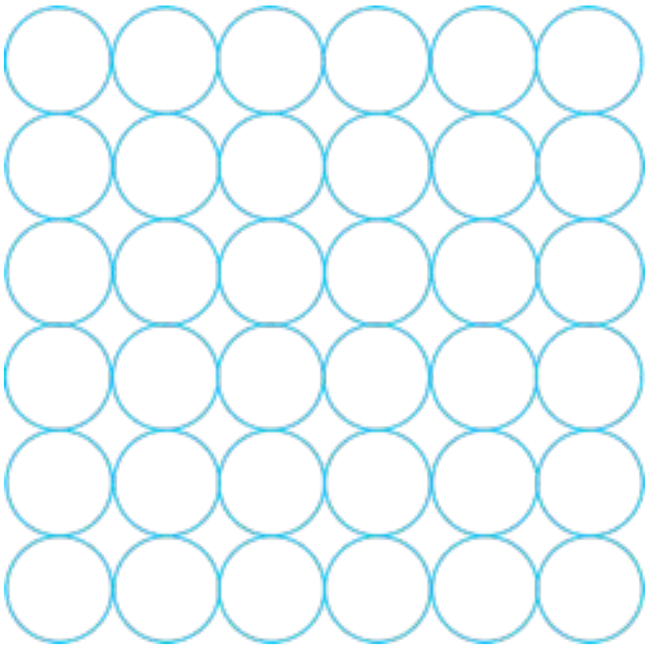
Position Angle

Beam footprint:



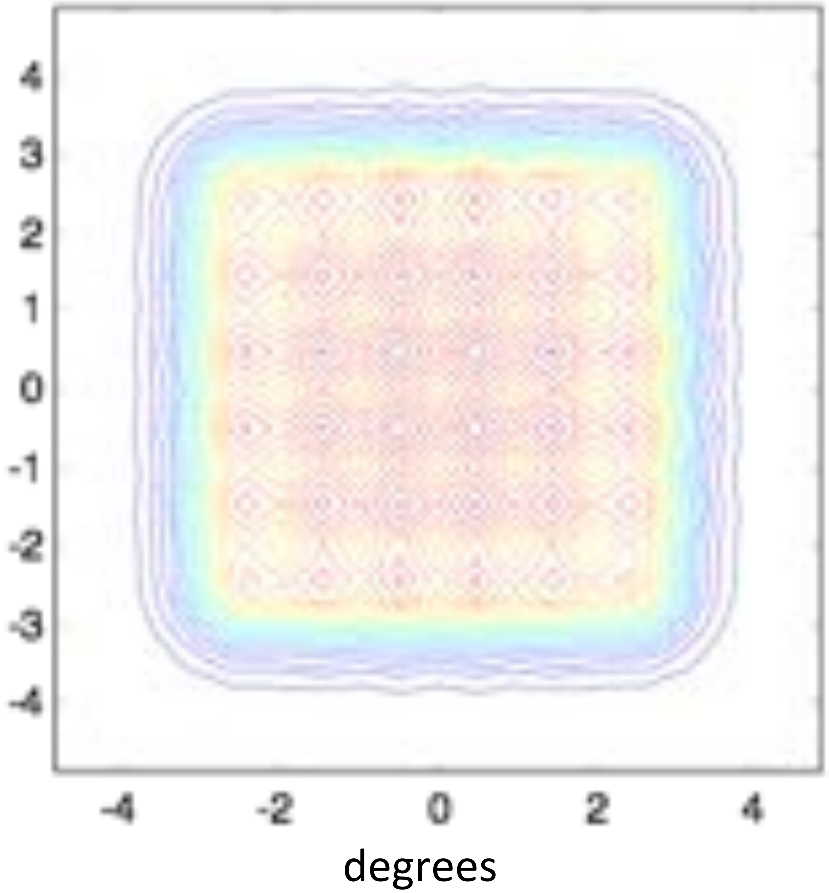
Interleaving:

36 beams



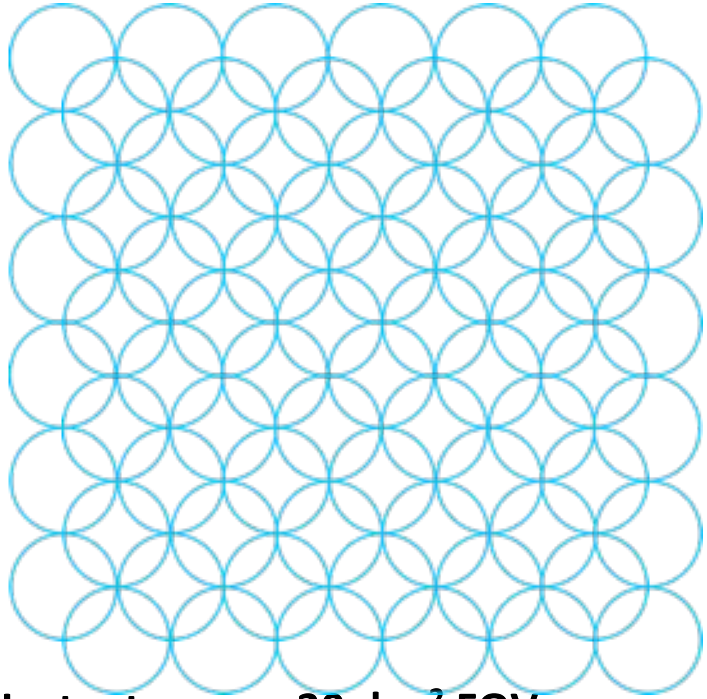
Instantaneous 30 deg^2 FOV

Sensitivity (5% contours)



Interleaving:

36 beams



Instantaneous 30 deg^2 FOV

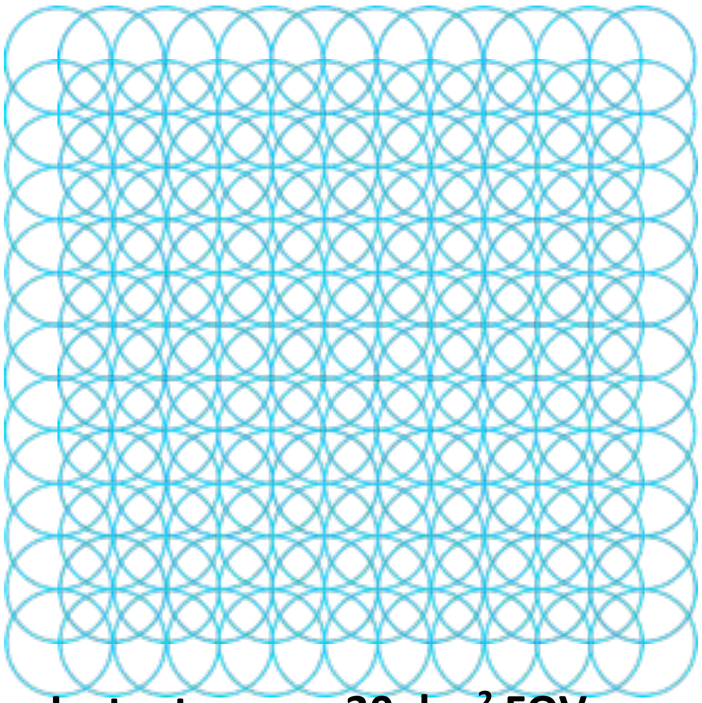
<u>2x interleaving:</u>

Observe a second field center, shifted by beam HWHM in both directions

Mosaic together all beams from both fields

Interleaving:

36 beams + 4x interleaving



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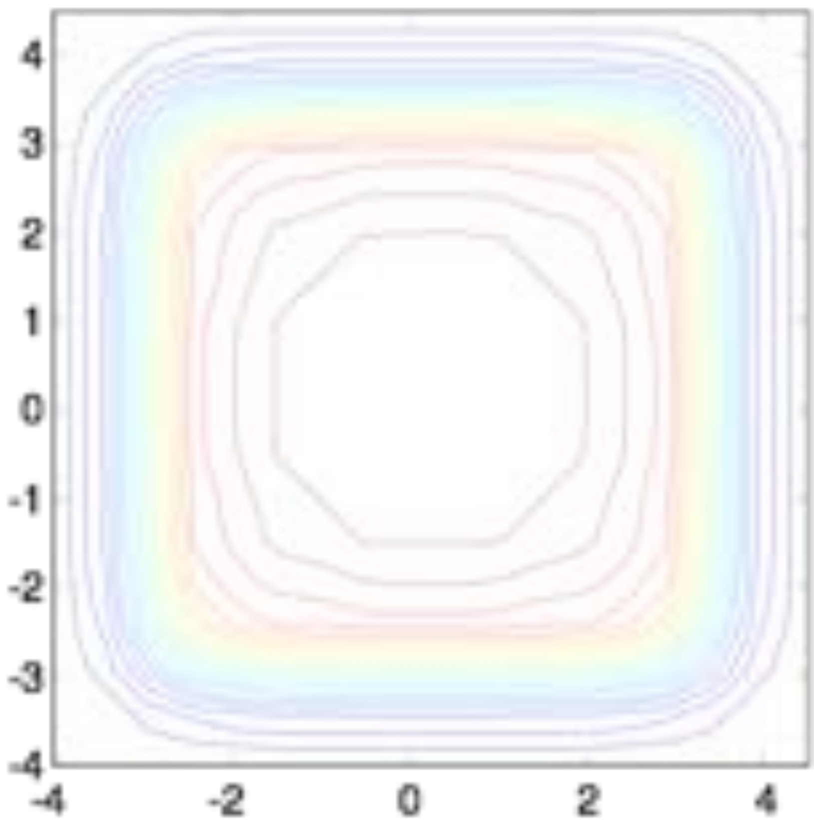
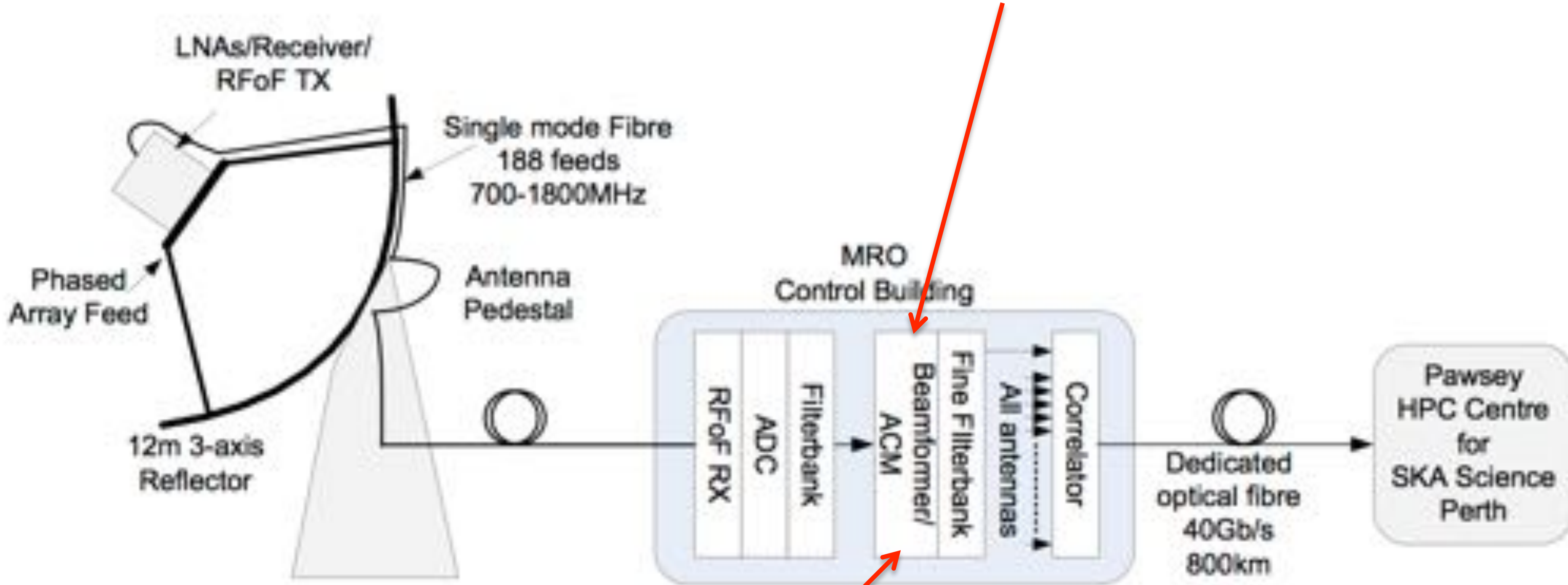


degrees

ASKAP – system architecture

Beamformer computes linear combinations of input signals

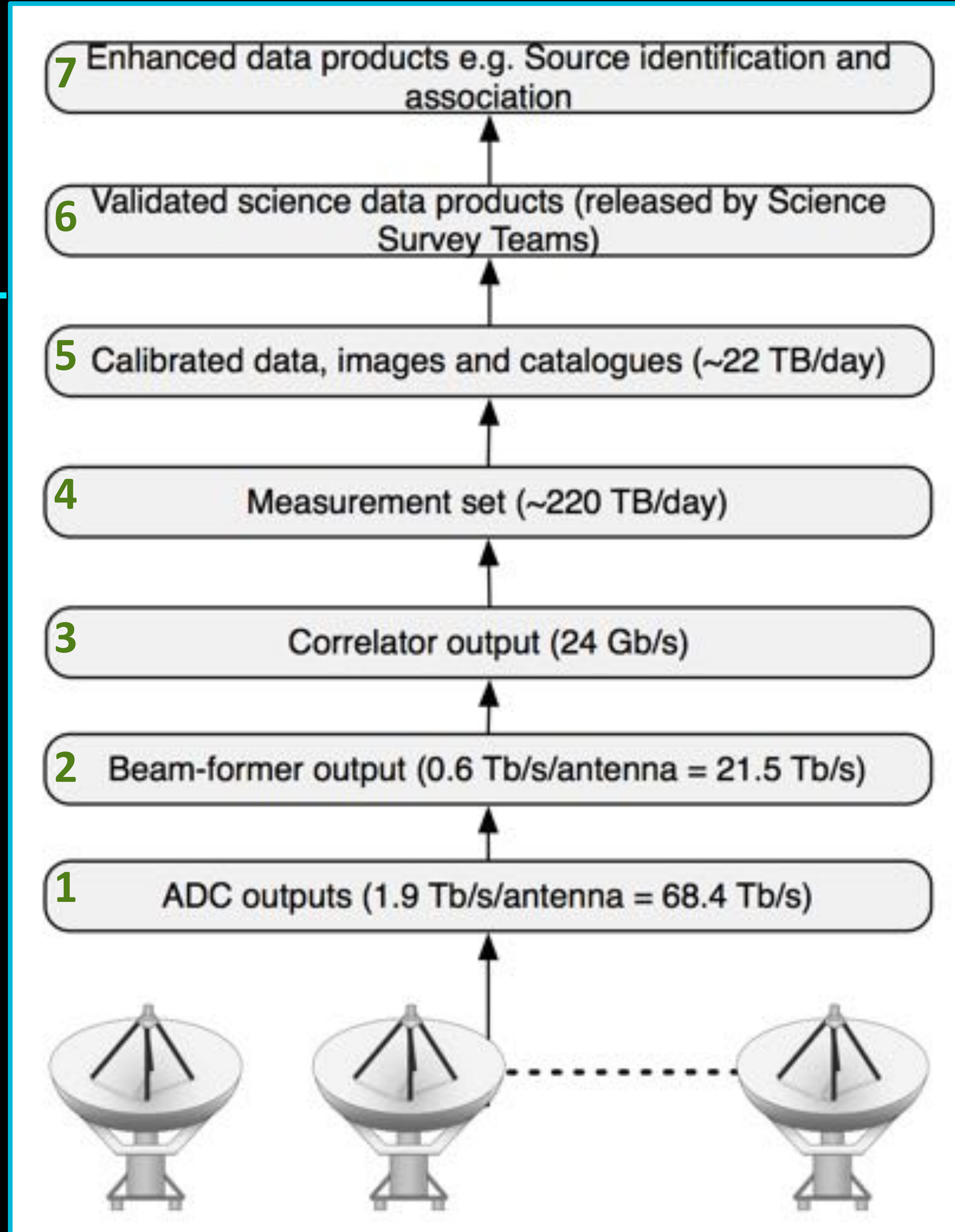


ACM = Array Covariance Matrix, i.e. correlation of every PAF element with every element

Credit: Max Voronkov

ASKAP Data

CSIRO | EMU



MRO | Pawsey

ASKAP Processing

ASKAP Processing Platform

Cray XC30 Series Supercomputer

472 Compute Nodes:
- 2 x 3.0 GHz Intel Xeon CPUs
- 10 Cores per CPU
- 64 GB DDR3-1866
- Cray Aries Interconnect
- Cray Dragonfly Topology
- 200 TeraFLOPS

1.4 Petabytes Lustre Data Storage

ASKAPsoft Data Pipelines

Pawsey Supercomputing Center

What is ASKAPSoft?

Processing software suite for ASKAP

Tailored to meet the peculiar requirements of ASKAP: very high data rates and quasi-real-time processing

Designed to run on high-performance computing systems

ASKAP processing approach described in detail in ASKAP-SW-0020

Covers all stages of processing:

- Ingest of data from correlator
- Calibration & Imaging
- Source extraction & cataloguing
- Archiving

New version of SW-0020 due out soon!

Credit: Matthew Whiting

The ASKAPsoft ecology

ASKAPsoft is a package of custom-written software for ASKAP

It uses a number of 3rd-party packages, including casacore, but all synthesis functions are written specifically for ASKAP

Written in C++, presenting stand-alone executables for running individual tasks (imaging, calibration, source-finding, …)

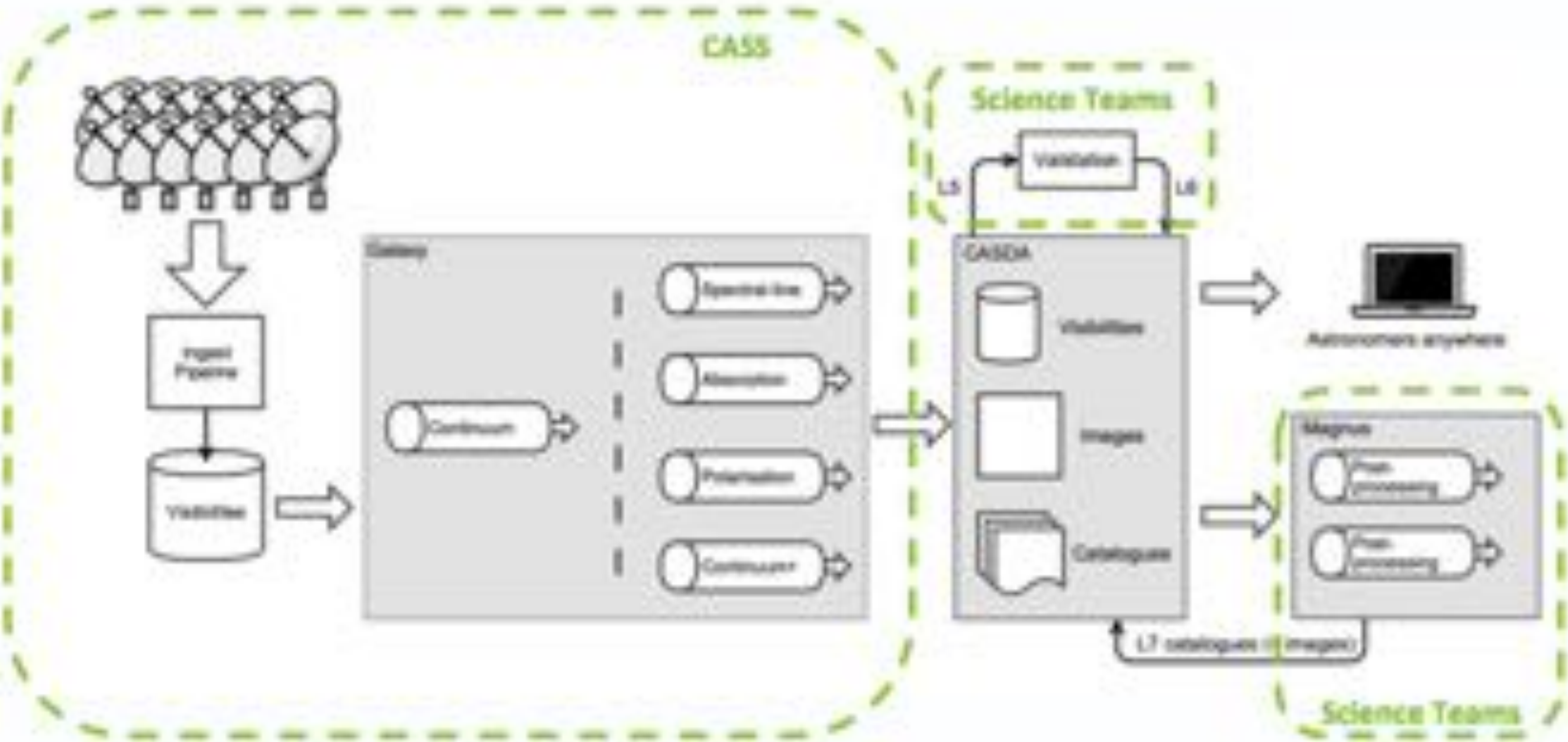
Modular tasks are tied together in a *pipeline*, a specific workflow with dependencies aimed at producing a set of data products

Makes use of casa-style data formats:

- Visibilities stored in measurement sets (MS)
- Calibration tables in CASA tables
- Images (currently) in CASA images – moving to direct output of FITS

Credit: Matthew Whiting

ASKAPsoft data pipelines



Credit: Matthew Whiting

Features and Constraints for full-ASKAP processing

Automated processing:

- Pipelines commence upon completion of observation
- Processing must finish in time for next observation to start
- Aim for *unsupervised* imaging

Sky model used for initial continuum subtraction

- Image the residuals, so less cleaning required (fewer major cycles)
- Sky model is kept up to date

Data sizes place limitations on what is possible

- Continuum at 10" resolution challenging (memory)
- Spectral-line limited to 30" resolution
- Cannot keep spectral-line visibilities indefinitely
- Particular solutions (e.g. preconditioning) chosen to minimise passes through the data

Note though the distinction between what ASKAPsoft pipelines *will* do for ASKAP-36, and what ASKAPsoft *can* do

Credit: Matthew Whiting

What's different for Early Science?

Smaller datasets!

- 1 TB/hr (ASKAP-12) vs 8.5 TB/hr (ASKAP-36)
- Larger natural resolution (maximum baseline = 2.18km)

Able to do manual processing – still hard (many beams, large cubes), but tractable

- Processing team will run pipelines manually upon completion of observation

Some features not available:

- Processing is not automated
- No Sky Model available, nor calibration service applied in ingest
- Transient pipeline not yet developed

Credit: Matthew Whiting

Magnus

General-purpose supercomputer

Compute:

- 1488 Cray XC40 compute nodes
- Each 2x12 core, with 64GB RAM

Storage:

- 3PB Lustre filesystem (/scratch)
- Peak I/O performance 70 GB/s

Open to entire research community through NCMAS & Partner programs

ASKAP early science post-processing project is based here

Credit: Matthew Whiting

Early science with ASKAP-12+

Priorities for ASKAP early science:

- Demonstrating the unique capabilities of ASKAP
- Providing data sets to the astronomy community to facilitate the development of analysis and interpretation techniques
- Providing a mechanism for feedback to CASS on the performance and characteristics of the system and opportunities for improvement
- Achieving high scientific impact

Early Science Observations

Two Primary 'observing streams' ~800 hours each

- Continuum: 700-1800 MHz, full Stokes

→ **EMU, POSSUM, FLASH**

- Spectral line: 1150-1450 MHz, 120 hours per field

→ **WALLABY, VAST, FLASH**

Additional observations / advanced modes

- HI stacking, zoom modes, fast transients.

→ **DINGO, GASKAP, CRAFT**

ASKAP EMU Early Science

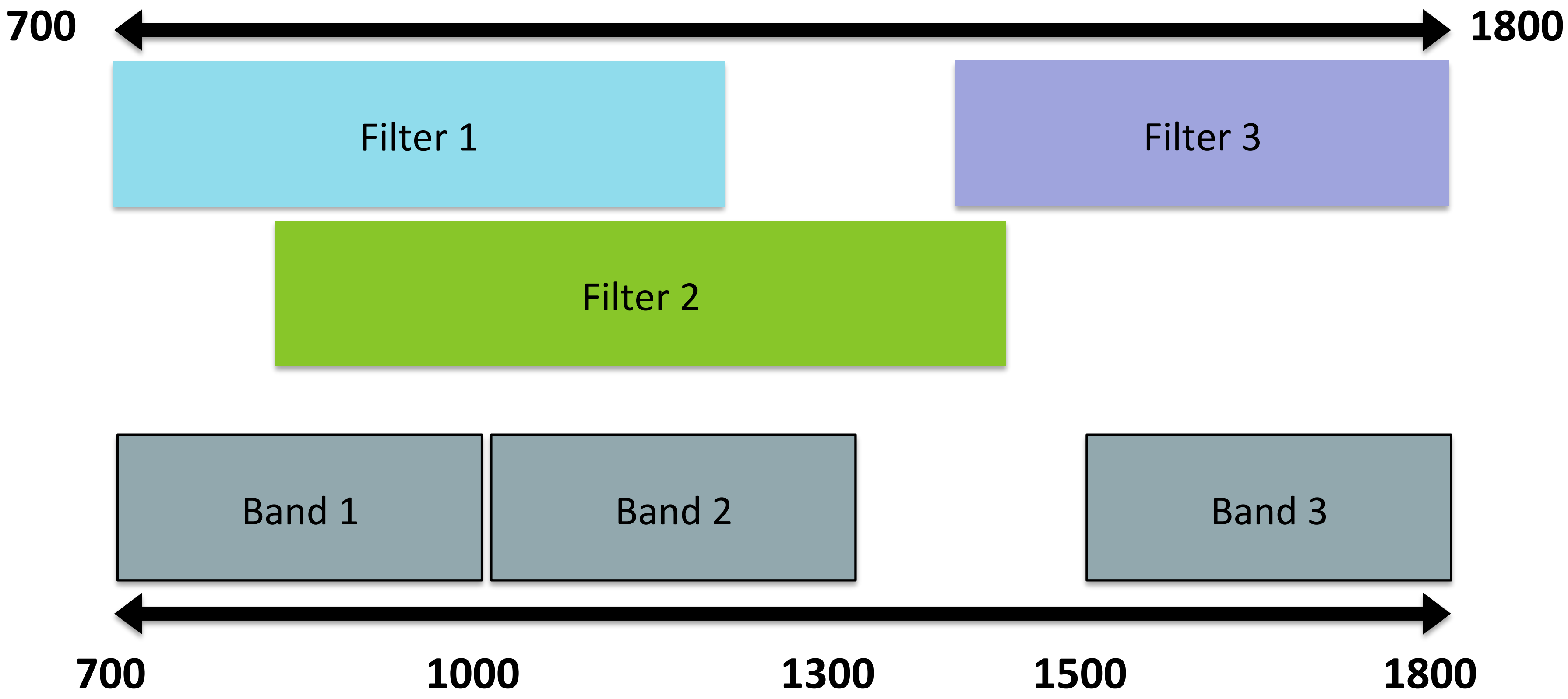
Evolutionary Map of the Universe

EMU's early science strategy:

- Full frequency coverage on each field (700-1800 MHz)
- 30 hours per field (total over all bands)
- Fields chosen to best align with early science priorities
- Fields of interest to multiple teams

Three Observing Bands

Continuum: 700-1800 MHz, full Stokes



EMU-ASKAP Early Science Observations:

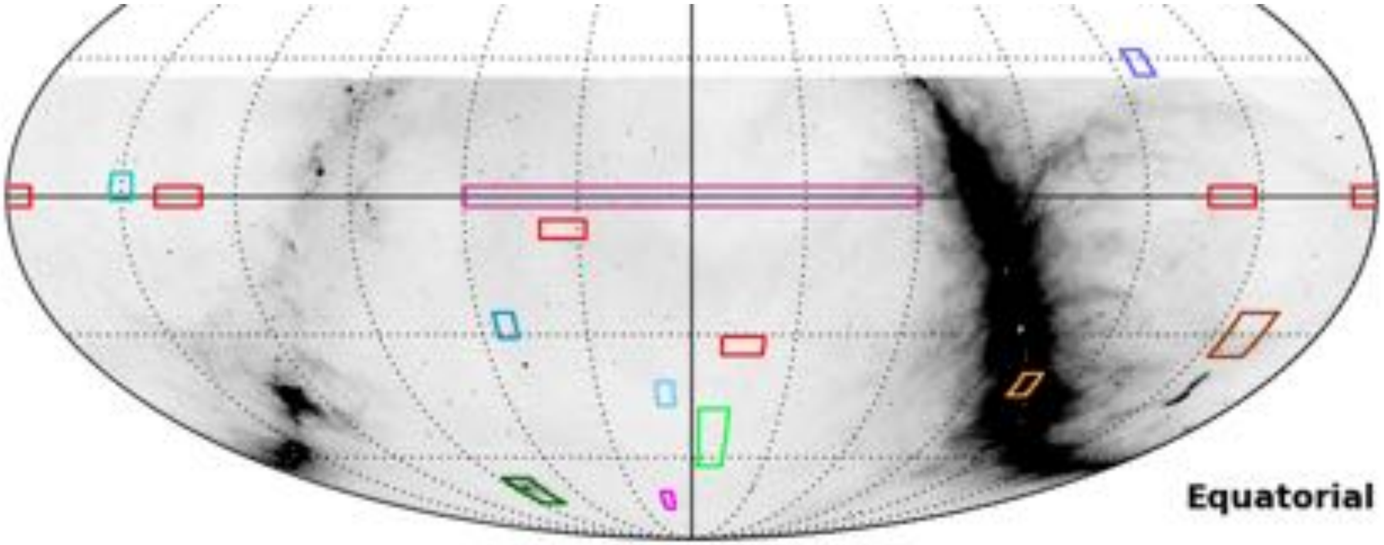
possible time distributions given approx. 30 hours per field

		Band 1	Band 2	Band 3
	Frequency (MHz)	700-1000	1000-1300	1500-1800
	Resolution	32”	24”	18”
	Confusion (uJy)	44 uJy	25 uJy	17 uJy
Uniform Time	Time	10 hours	10 hours	10 hours
	RMS	51 uJy	37 uJy	43 uJy
Uniform Sensitivity	Time	12 hours	8 hours	10 hours
	RMS	47 uJy	42 uJy	43 uJy
Scaled Sensitivity	Time	8 hours	8 hours	16 hours
	RMS	57 uJy	42 uJy	34 uJy

CSIRO

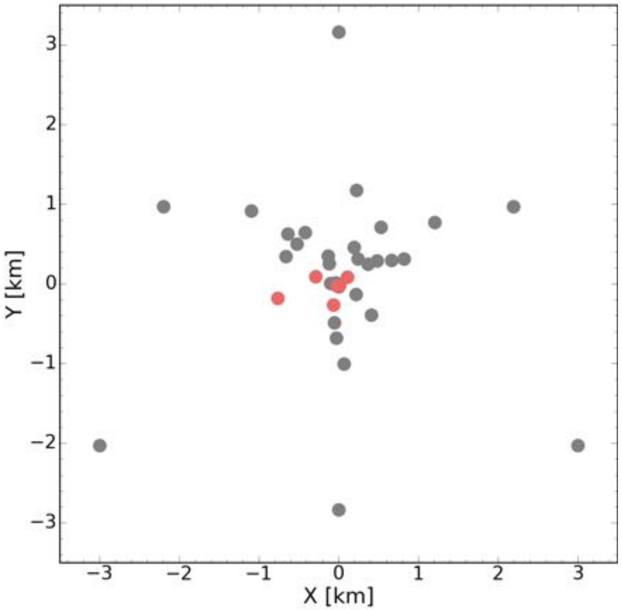
Early science fields include:

SPARCS	ELAIS-S1	Scorpio
GAMA	~~Stripe 82~~	Shapley
SPT	SMC	LMC



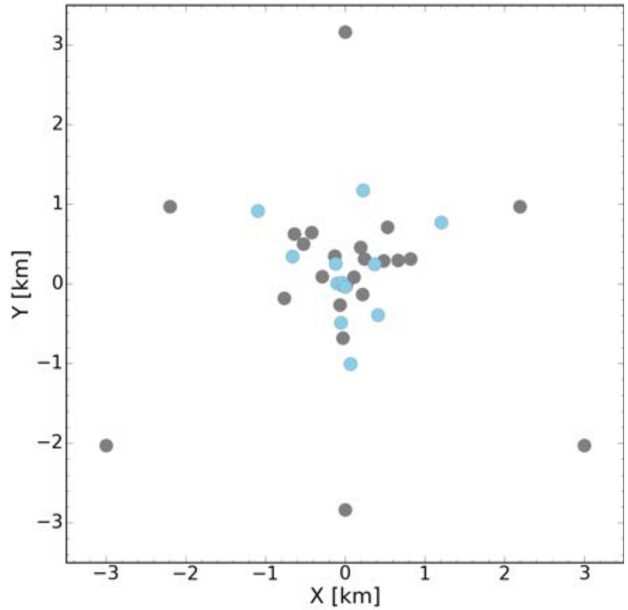
ASKAP status and imaging performance

BETA



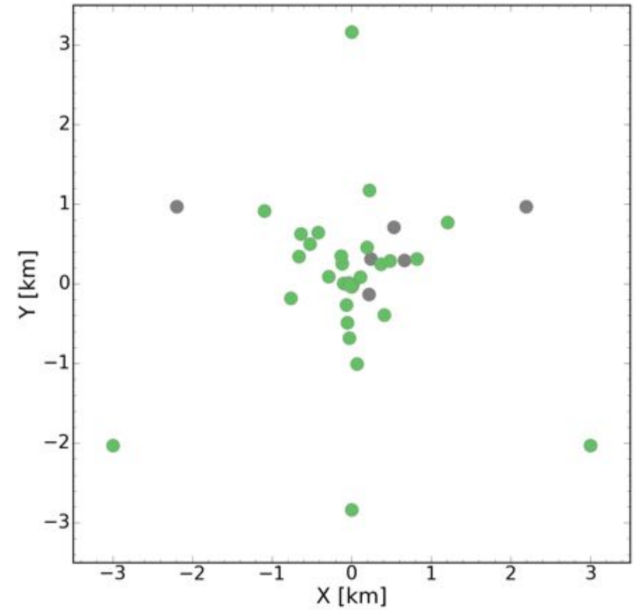
2014-2016

ASKAP-12



Present

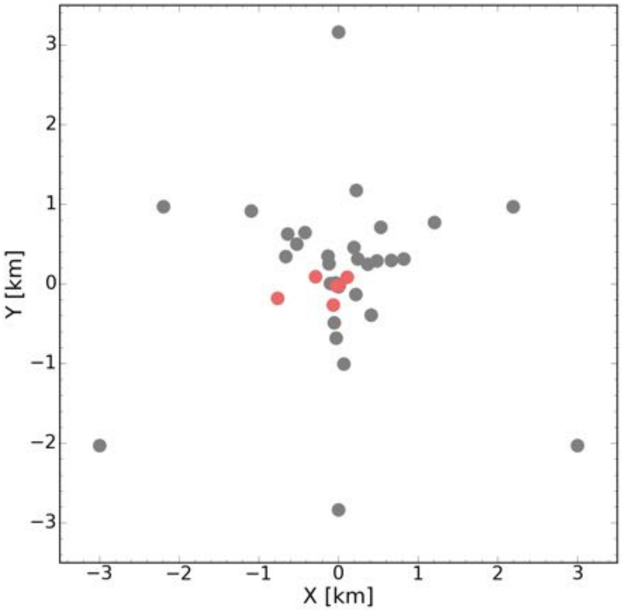
ASKAP-30



2017

ASKAP status and imaging performance

BETA

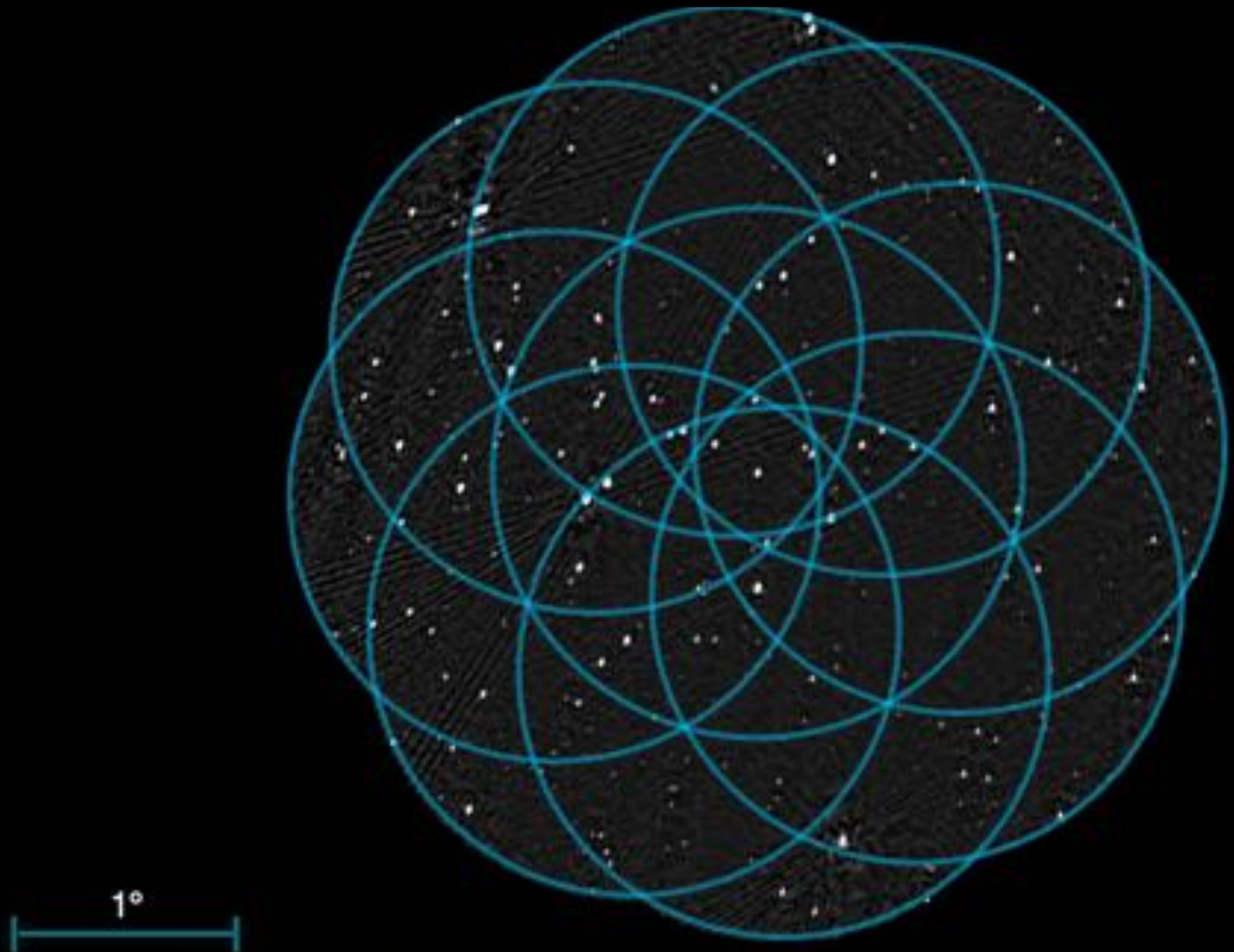


2014-2016

- 6 antennas
- First-generation PAFs
- Up to 9 formed beams
- 300 MHz Bandwidth

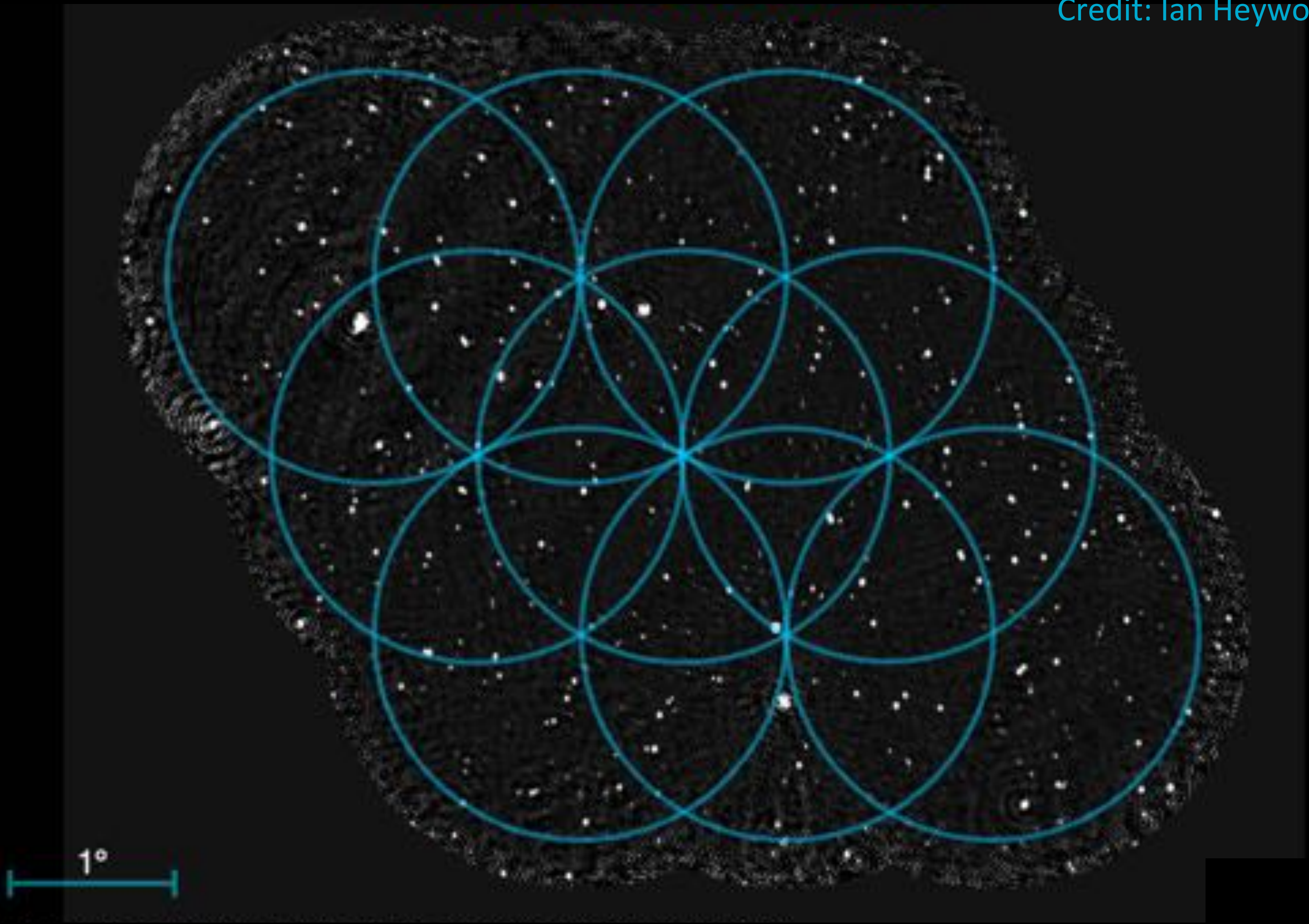
Spirograph

Credit: Ian Heywood



Rhombus

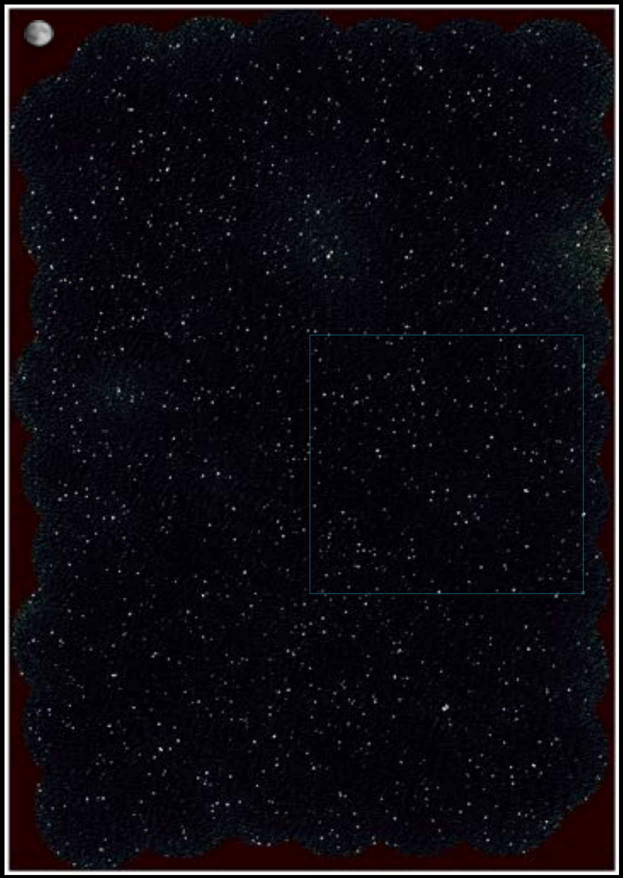
Credit: Ian Heywood



Square + interleaving + tiling

Credit: Ian Heywood

SB 1206



12 hours • 150 sq. deg. • 12 fields • <1 mJy RMS • ~2,000 sources >5σ

Repeated Observations

Credit: Ian Heywood

SB 1206

02 / 12 / 14

SB 1229

07 / 12 / 14

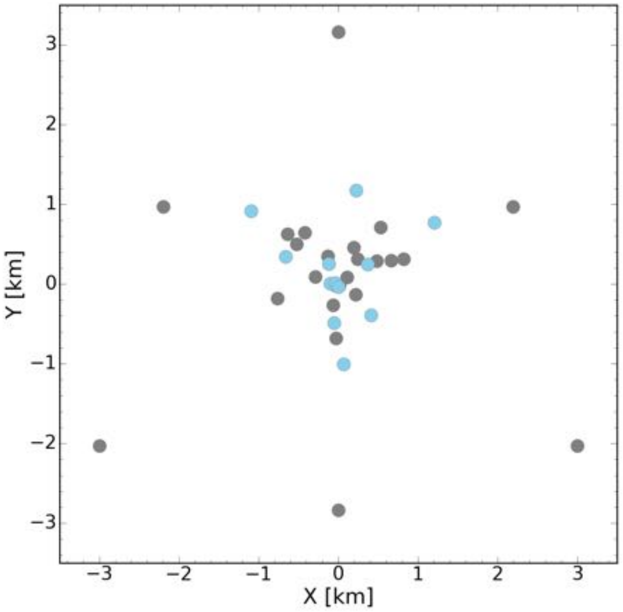
SB 1231

08 / 12 / 14

Same SB executed on three different nights • excellent stability

ASKAP status and imaging performance

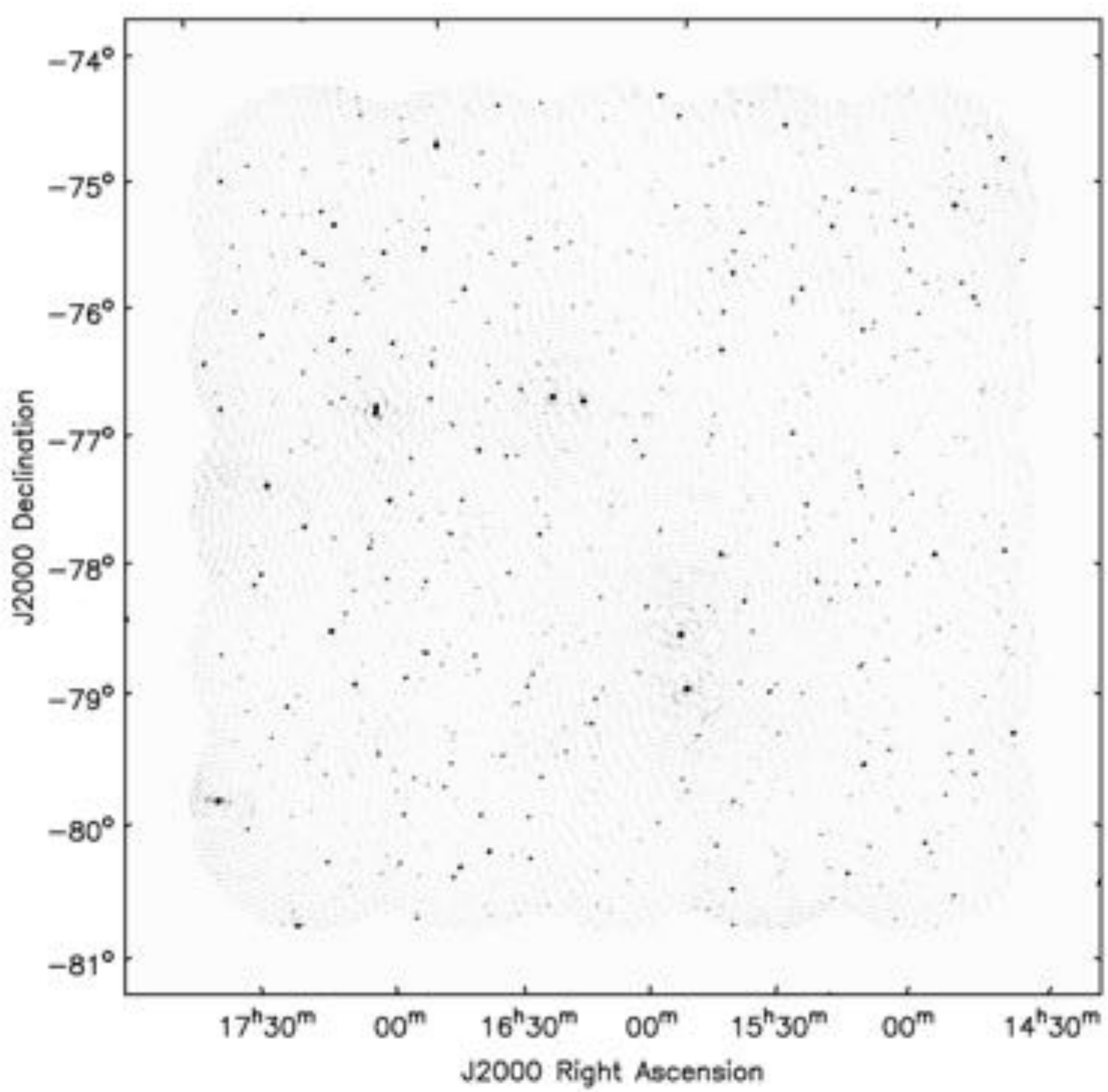
ASKAP-12



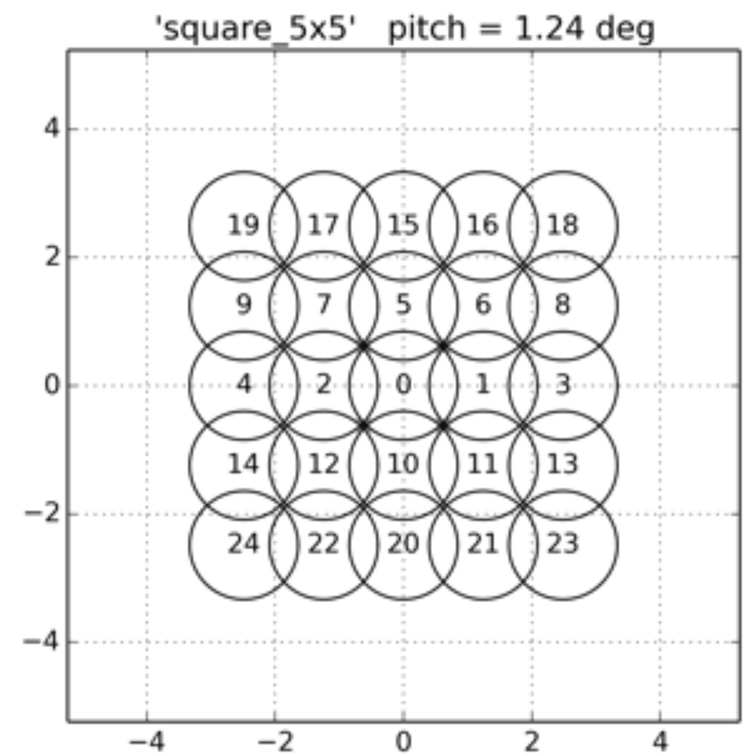
Present

- 12 antennas
- Second-generation PAFs
- Up to 36 formed beams
- Current bandwidth limitations

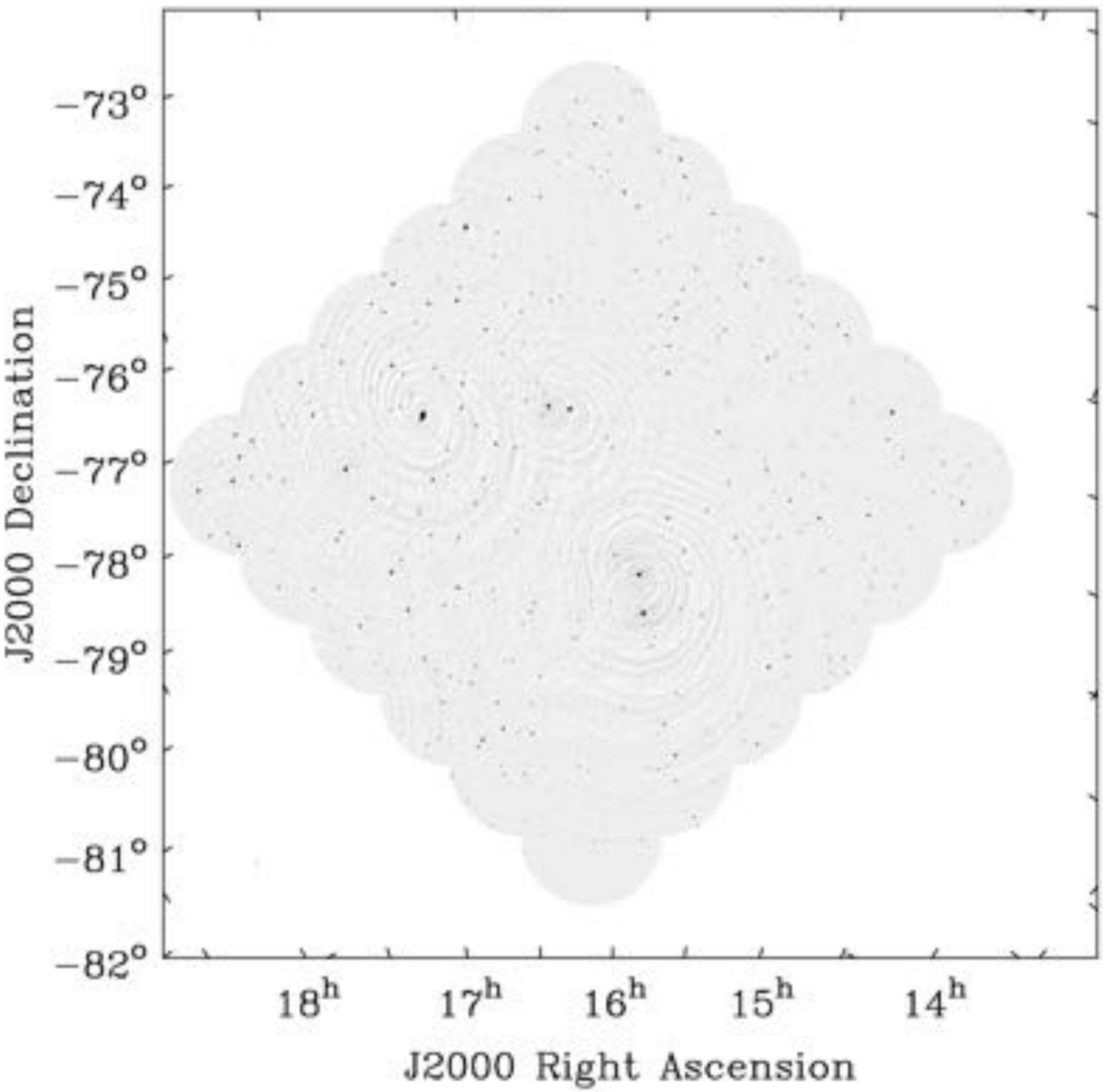
ADE Image of the Apus test field



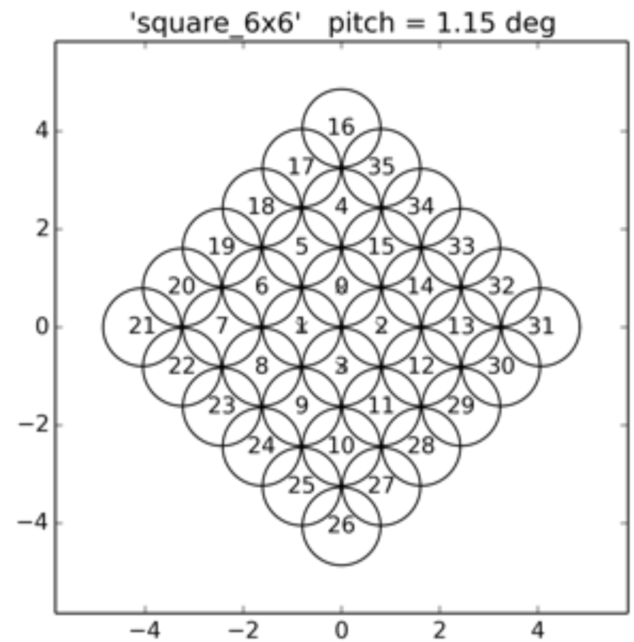
- 5 antennas with mkII PAFs
- 25 formed beams (max-SNR)
- 12 hours on source
- 939 MHz center frequency
- 48 MHz bandwidth
- ~ 1 mJy sensitivity
- ~ 70" resolution
- > 30 square degrees



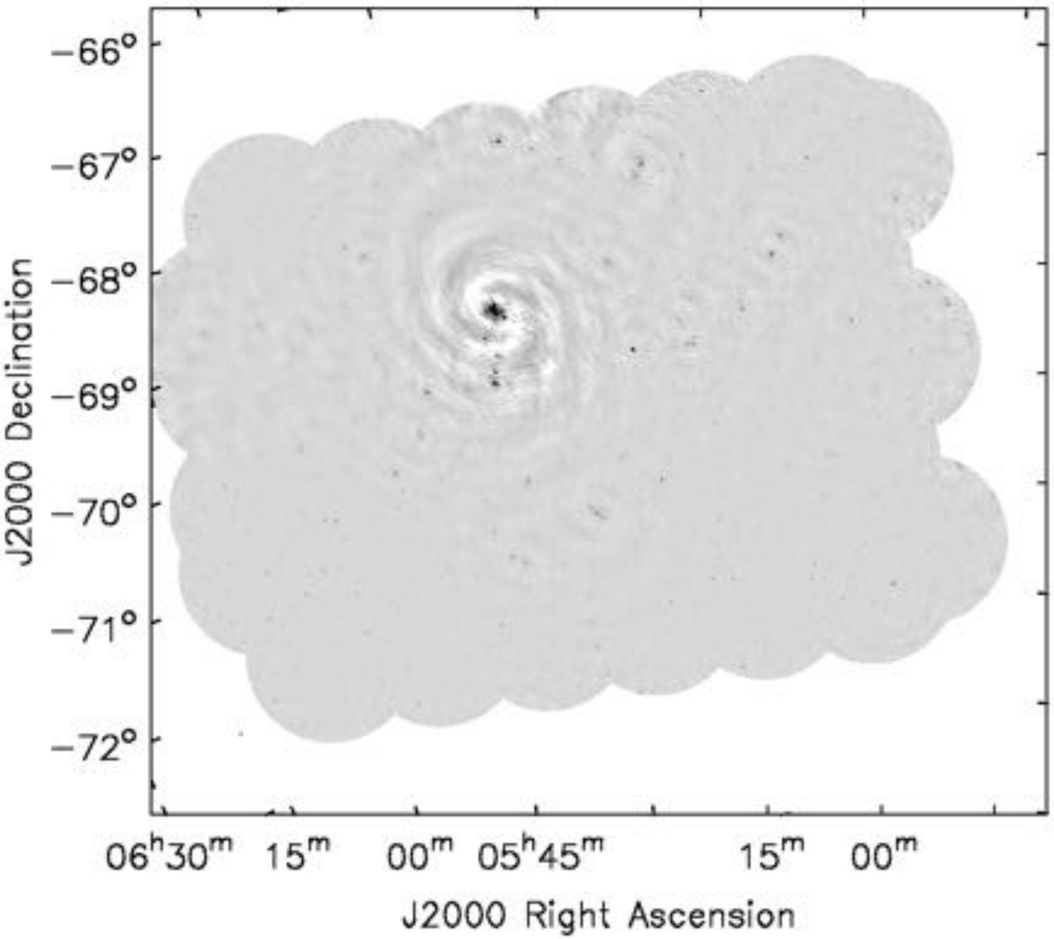
36-beam image of the Apus test field



- 9 antennas with mkII PAFs
- 36 formed beams (max-SNR)
- 11 hours on source
- 939 MHz center frequency
- 48 MHz bandwidth
- ~ 300 uJy sensitivity
- ~ 50” resolution
- ~ 30 square degrees



30-beam image of the LMC



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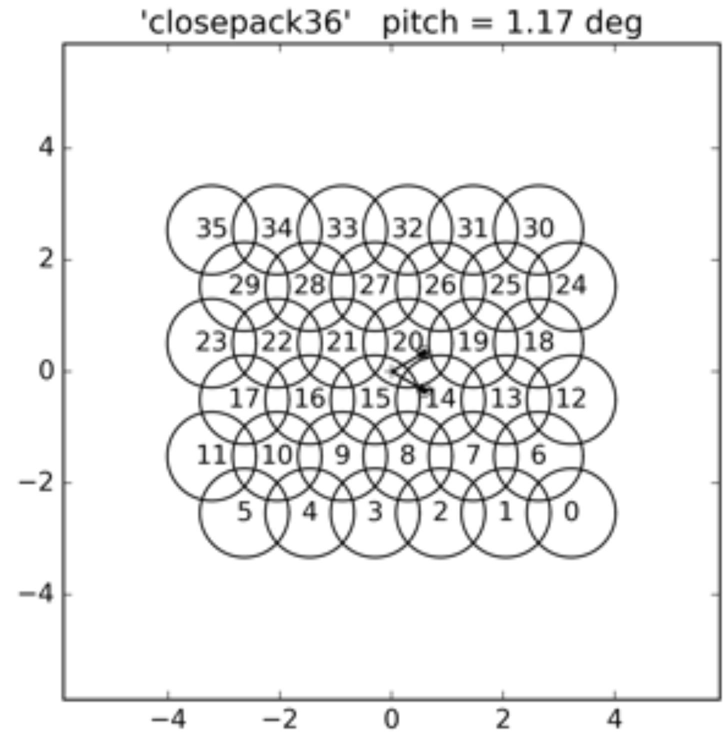
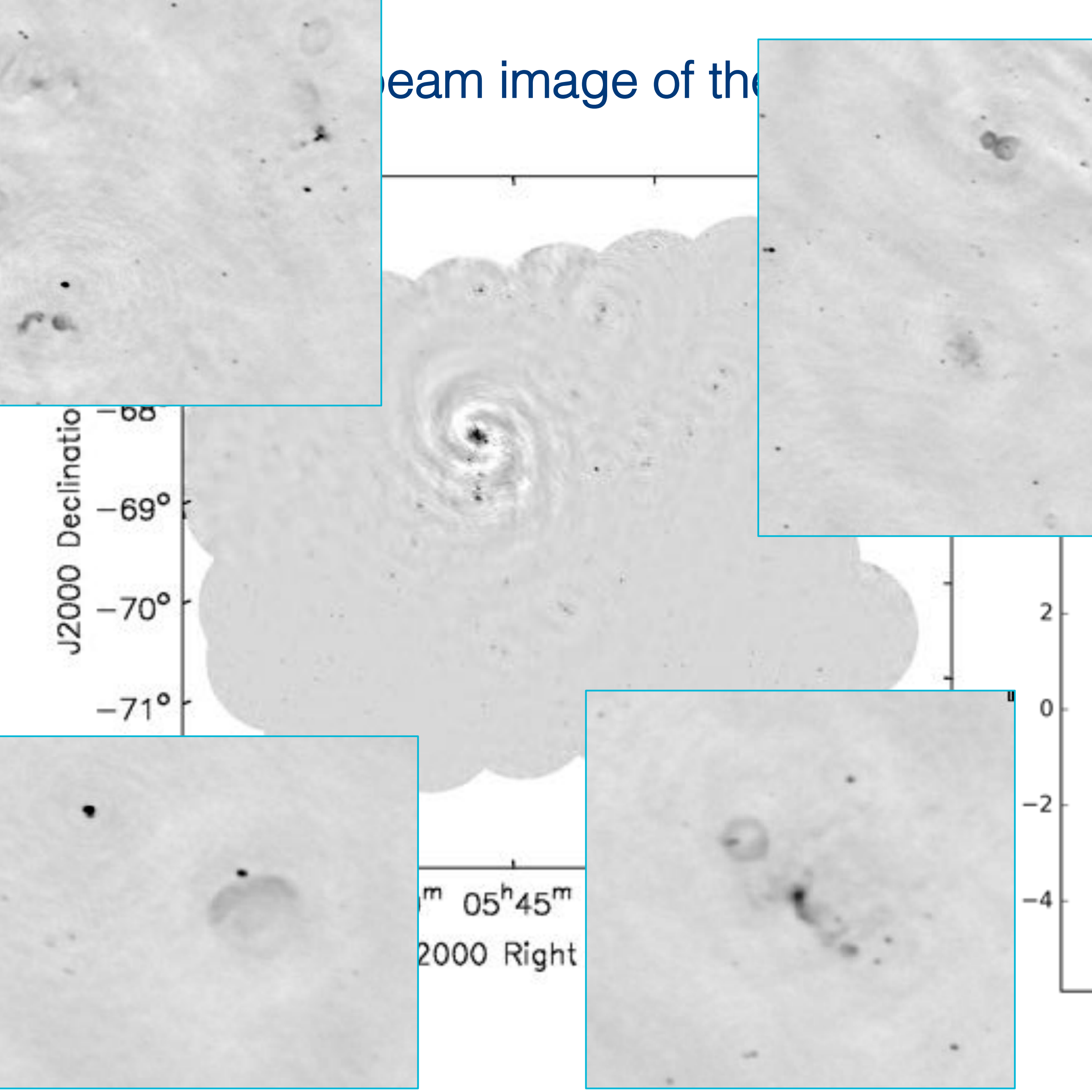


…eam image of the…



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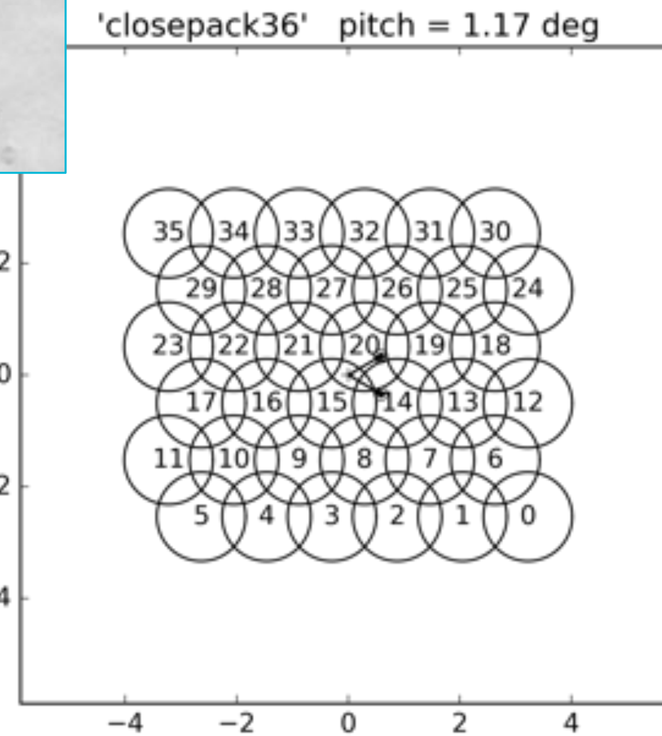
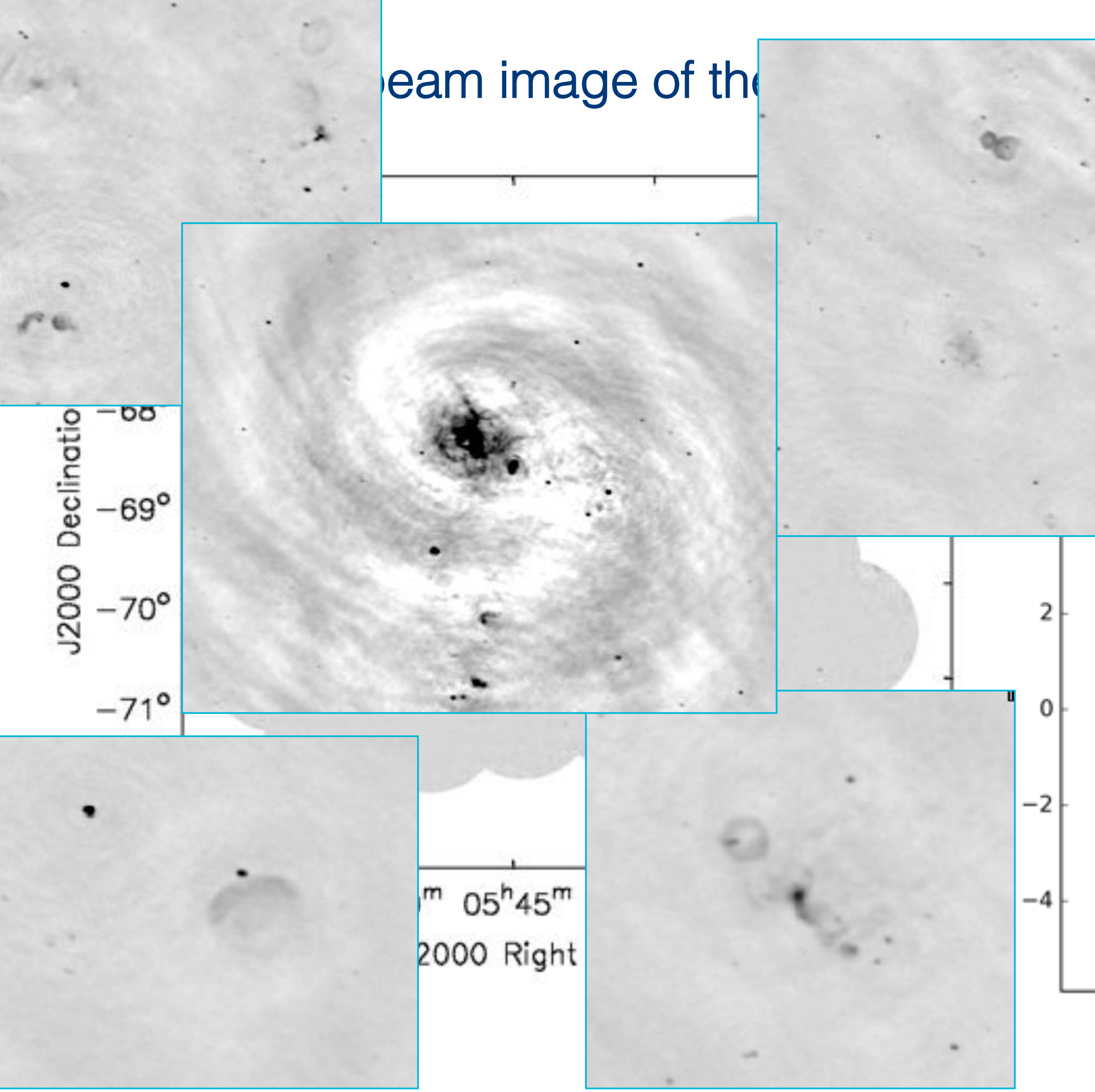


eam image of the



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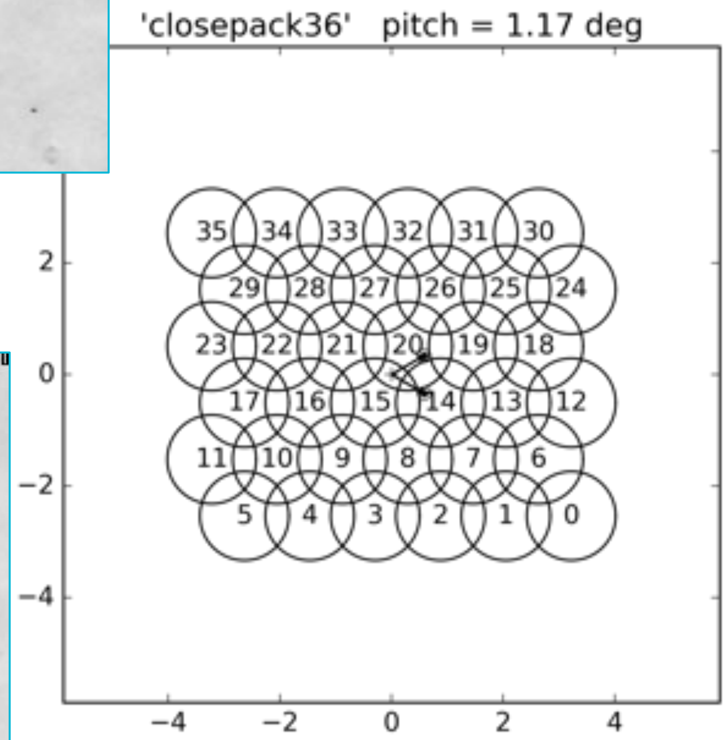
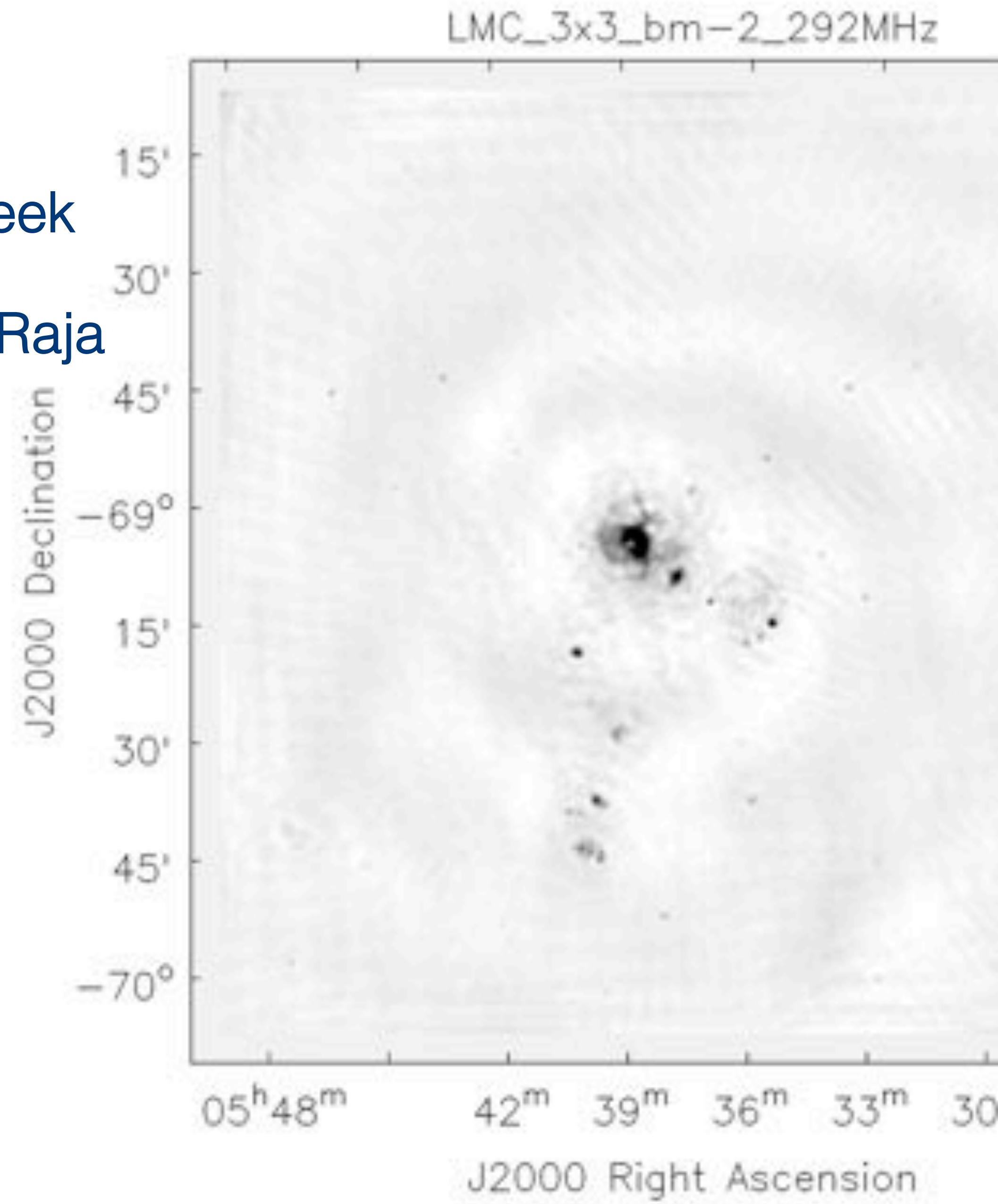


ASKAP-12 with192 MHz BW

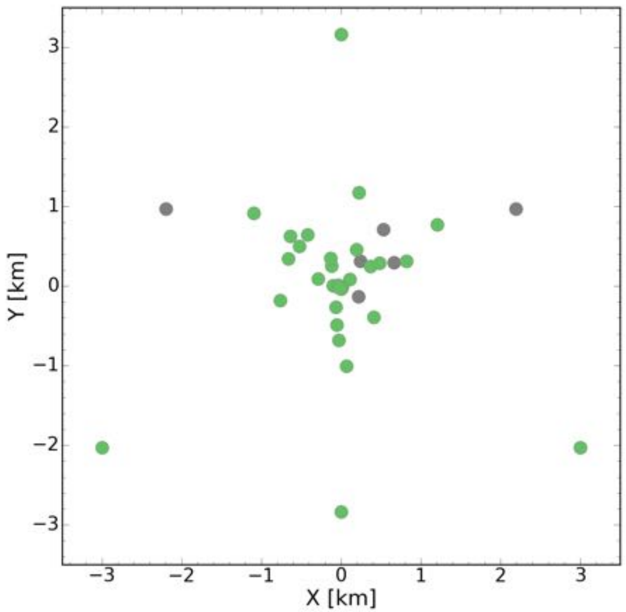
First observations earlier this week

Processed yesterday by Wasim Raja



ASKAP status and imaging performance

ASKAP-30



2017

- 30 antennas
- Up to 36 formed beams
- 300 MHz bandwidth
- Final 6 PAFs early 2018
- EMU/WALLABY surveys begin

We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site.

Challenges

- Survey Strategy
- Performance of PAF
    - uniformity, polarisation, sidelobes, etc.
- Image Processing
    - Dynamic range, calibration, sensitivity as function of scale size, etc.
- Source Extraction – the Grand Data Challenge
- Cross-identification
- Redshifts
- Data delivery (Value-added catalogue/VO)

Examples of EMU Development Projects

Developers earn co-authorship on key science papers

- Ensure the EMU database satisfies our storage and access needs (both CASDA and value–added, and interactions with other data centres/VO)
- Develop, set up, and implement the data quality/validation process
- Ensure ASKAPSOFT imaging satisfies EMU needs
- See what special imaging is needed for the Galactic Plane
- Ensure ASKAPSOFT source extraction satisfies EMU needs
- Develop algorithms for extraction of diffuse emission

For Level 6 data

For Level 7 data

- Develop the self-ID and cross-ID algorithms
- Develop an "optimum photo-z algorithm" for all EMU and an optimum photo-z strategy for those smaller areas of EMU covered by other surveys such as DES
- Develop techniques for Statistical redshifts & Spatial Cross-correlation redshifts
- Explore other EMU applications for Machine Learning

Improved PAF Sensitivity on ASKAP Dish