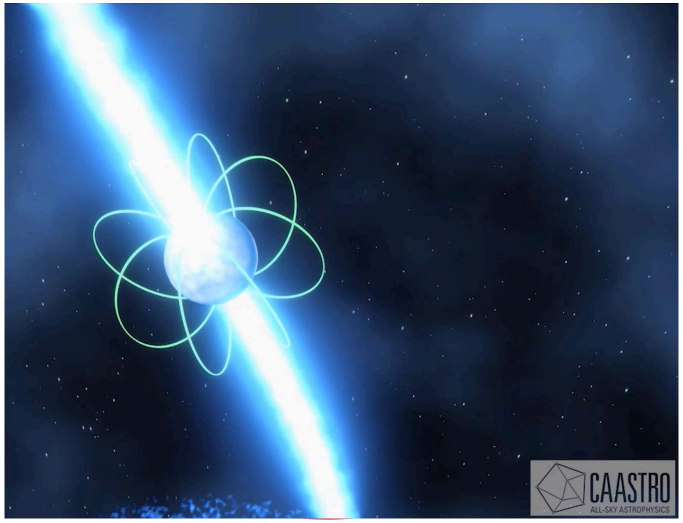


Pulsar Astronomy with the Murchison Widefield Array (MWA)

Ramesh Bhat

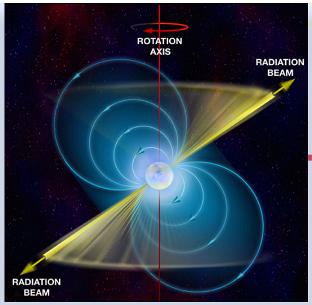
Curtin University

The Government of Western Australia

The University of Western Australia

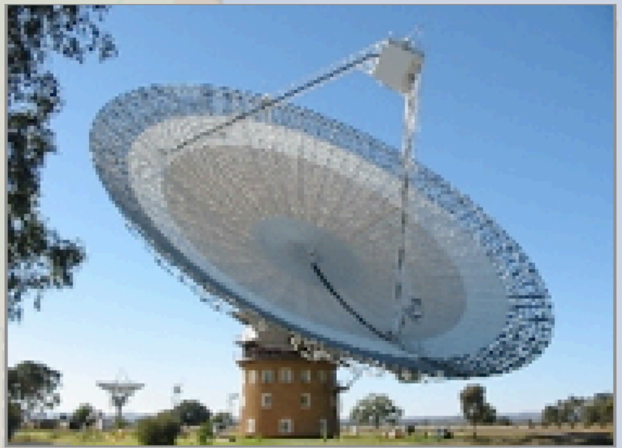
@ The Broad Impact of Low frequency Observing, Bologna, Italy, 19 – 23 June 2017

MWA – a new low-frequency window for pulsar astronomy in the southern hemisphere



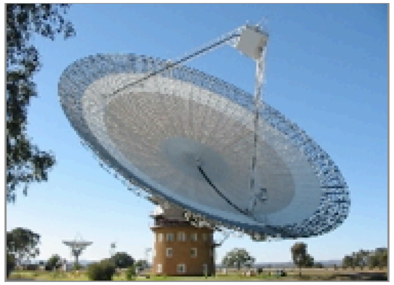
MWA 80-300 MHz

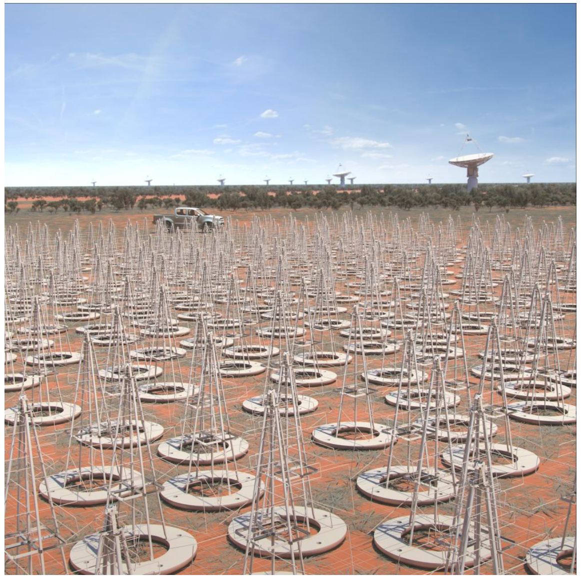
Parkes + UTMOST > 700 MHz



Pulsar astronomy in the SKA era

Transitioning from single dishes to multi-element interferometric arrays





- **Important considerations:**
  - Beam-forming (phasing up) – calibration and processing at high time and frequency resolutions; pixelisation of the FoV, multiple sub-arrays, multiple beams, etc.
  - Incoherent vs. coherent signal addition of signals, associated trade-offs, potential of non-traditional methods for searches
  - Single-dish dominance over the past ~5 decades – a major paradigm change!

MWA provides a great opportunity in the path forward, particularly SKA-low

Pulsar astronomy with the MWA

Pulsar astronomy – was NOT a key science drivers for the MWA!

- MWA correlator produces visibilities at 500 ms, 40 kHz cadence
- Pulsar astronomy needs much higher time (and high frequency) resolution; access to baseband (voltage) data for phase coherent de-dispersion)

The implementation of a "voltage capture" (VCS) functionality in the signal path – to access 100 us, 10 kHz raw "voltage" time series from **all** 128 tiles

- Challenges and limitations; e.g. data rates, transport to Pawsey, post-processing overhead
- Opportunities for exploring calibration and beam-forming strategies, data processing challenges, student training

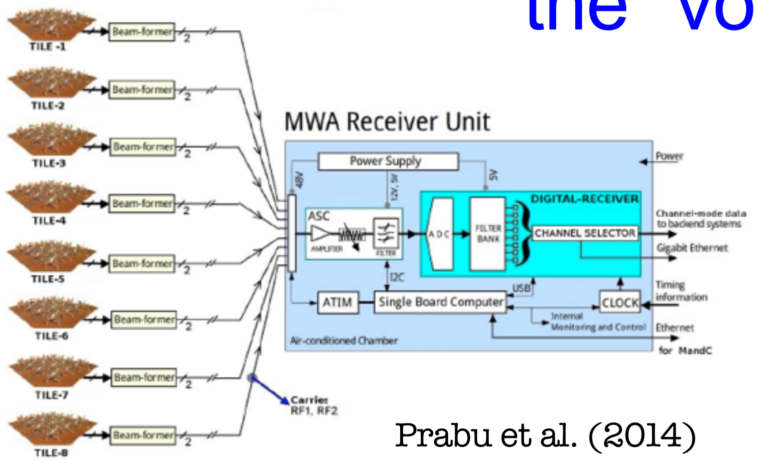
Outline

- Pulsar Observing @ MWA
- Recent Science Highlights
- Looking Ahead (Phase 2)

Pulsar observing with MWA

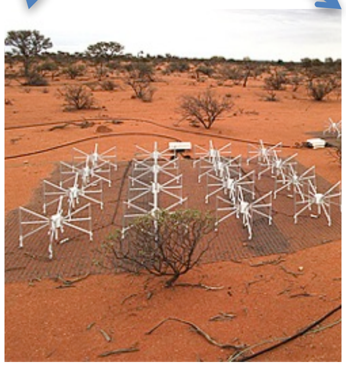
Pulsar observing @ the MWA

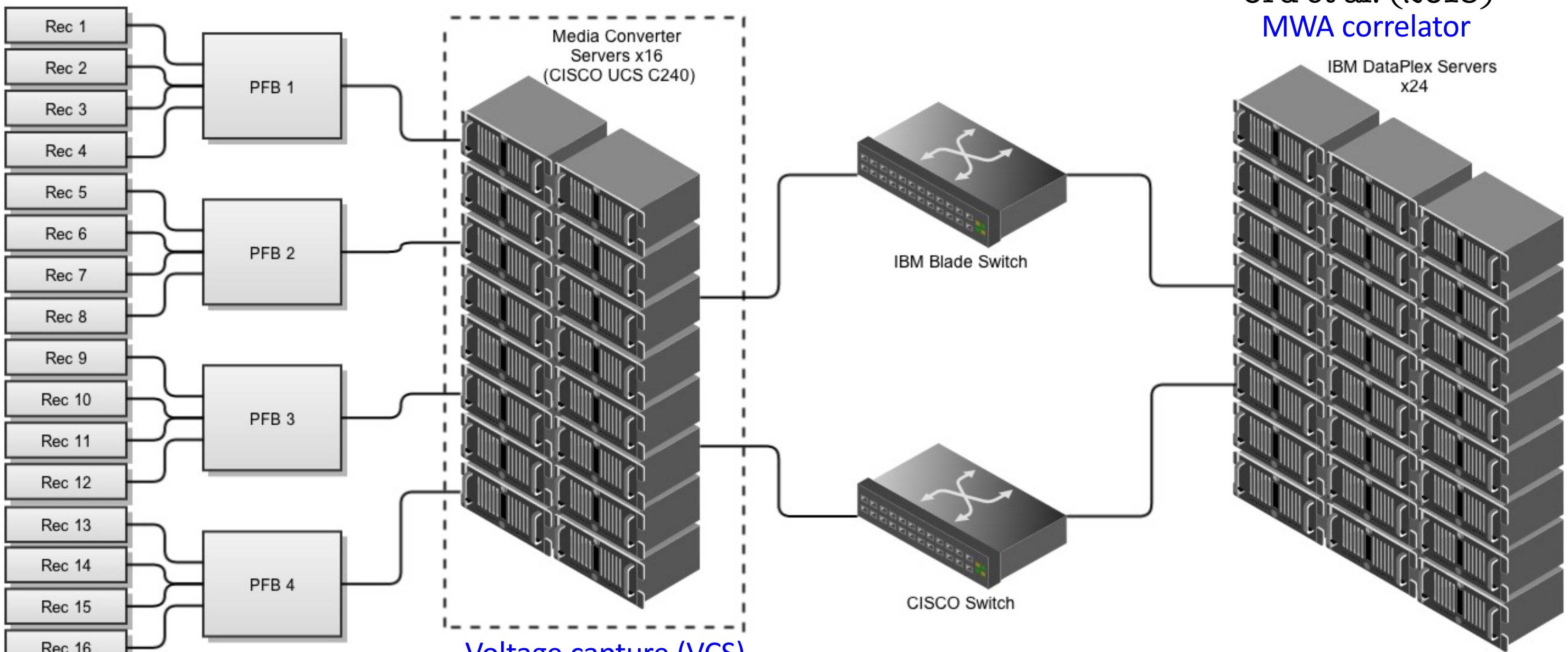
the “voltage capture” (VCS) way



Prabu et al. (2014)

- VCS mode: a **functionality to capture raw voltages** streaming into the correlator, from ALL 128 tiles, at 100-us, 10-kHz resolutions, over a BW = 30.72 MHz
- Aggregate data rate = 24 x 242 MBps (or 7.8 GBps) = 28 TB per hour!



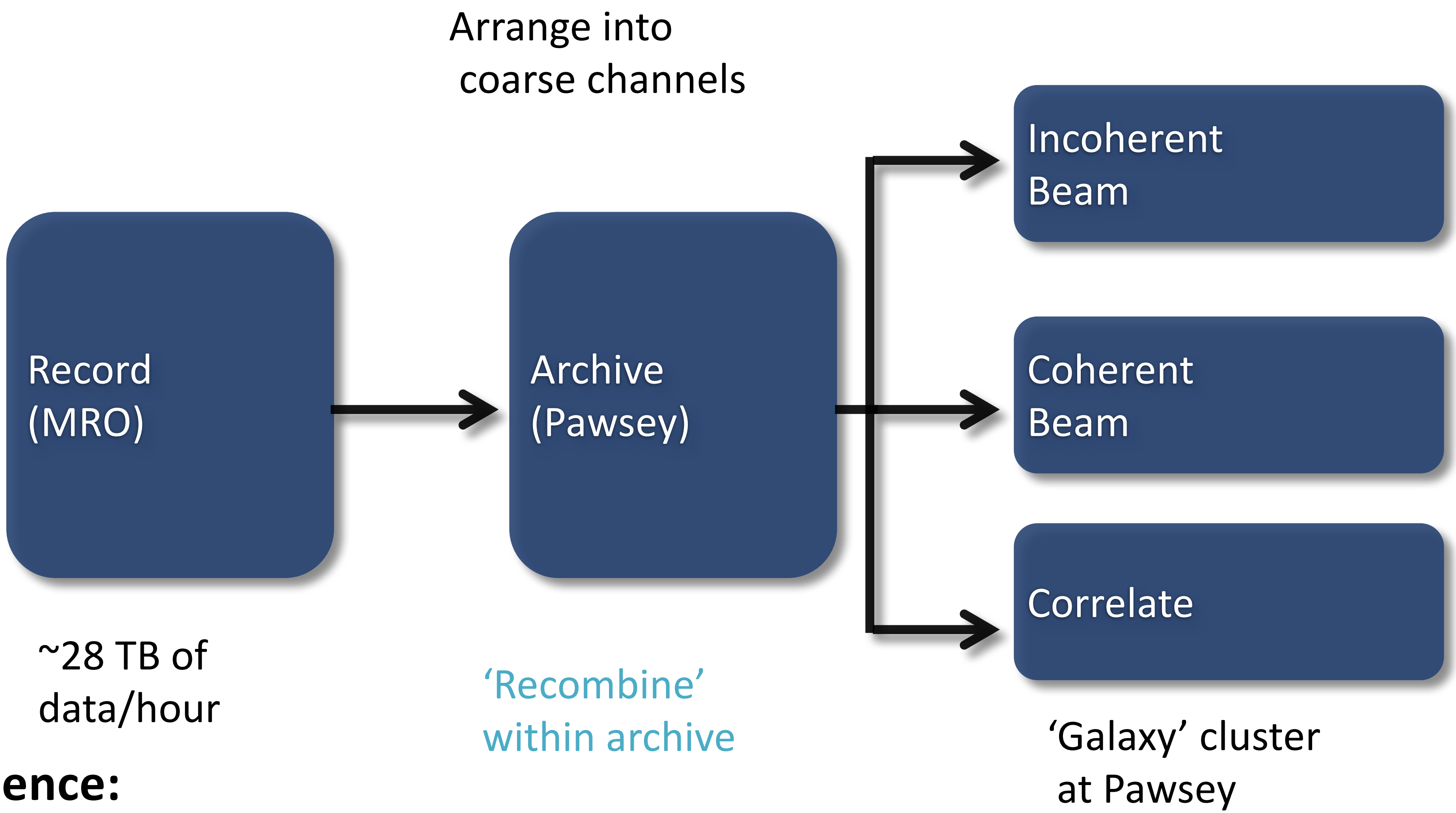


Ord et al. (2015)
MWA correlator

Voltage capture (VCS)

Tremblay et al. (2015)

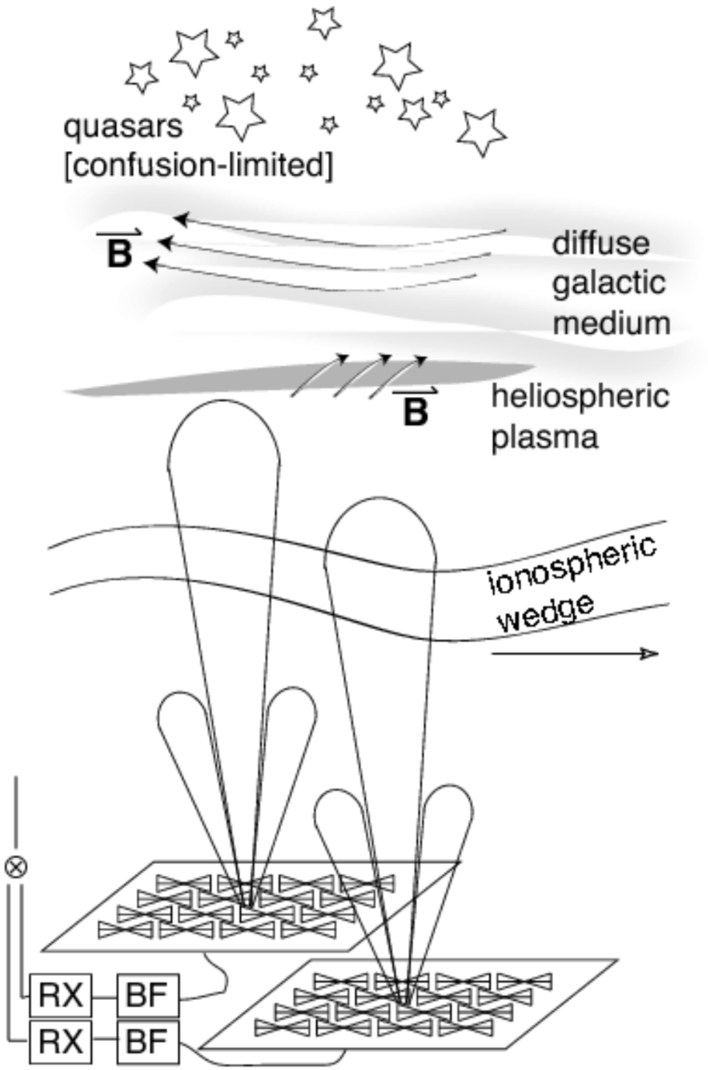
VCS Data Processing



Science:

Pulsars, Fast Transients, FRBs, spectral lines, SETI, passive radar. etc.

The MWA tied-array (coherent beam) pipeline



MWA voltage capture system (VCS) for data recording: baseband time series (at 10 kHz, 100 us resolutions) that stream out of the 2nd stage of PFB

Offline version of the MWA correlator: running on Galaxy @ Pawsey to generate visibility sets for calibration

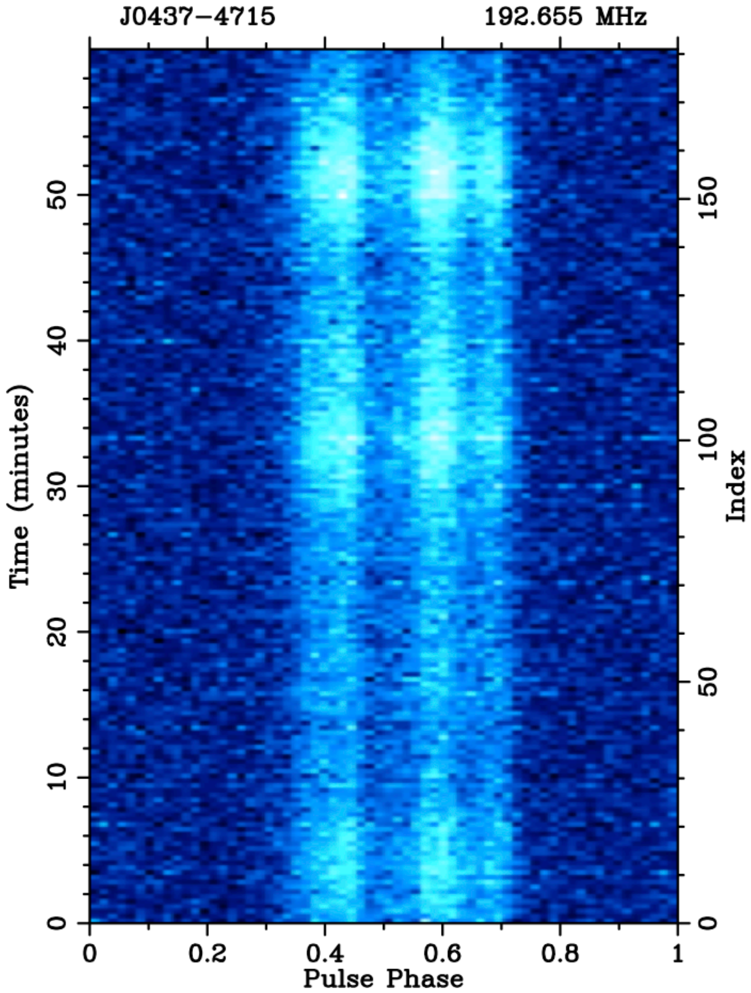
Generation of Jones matrix using a sky model with the MWA RTS (calibration + imaging) – e.g. Pic A for calibrating the 0437 field)

Beam forming toward the target of interest (pulsar) – apply the beam model to get the antenna Jones matrices

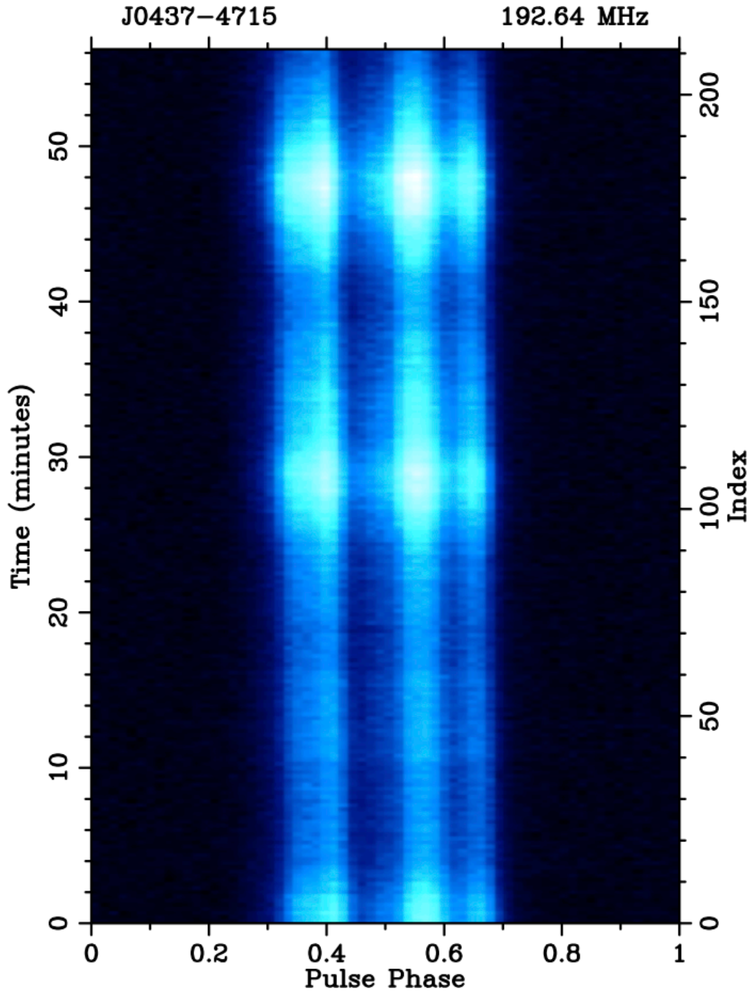
Pulsar processing software – DSPSR for baseband processing, and coherent de-dispersion (in VDIF or PSRFITS)

Signal improvement on phasing up

PSR J0437-4715 @ MWA 200 MHz



Incoherent addition of all 128 tiles

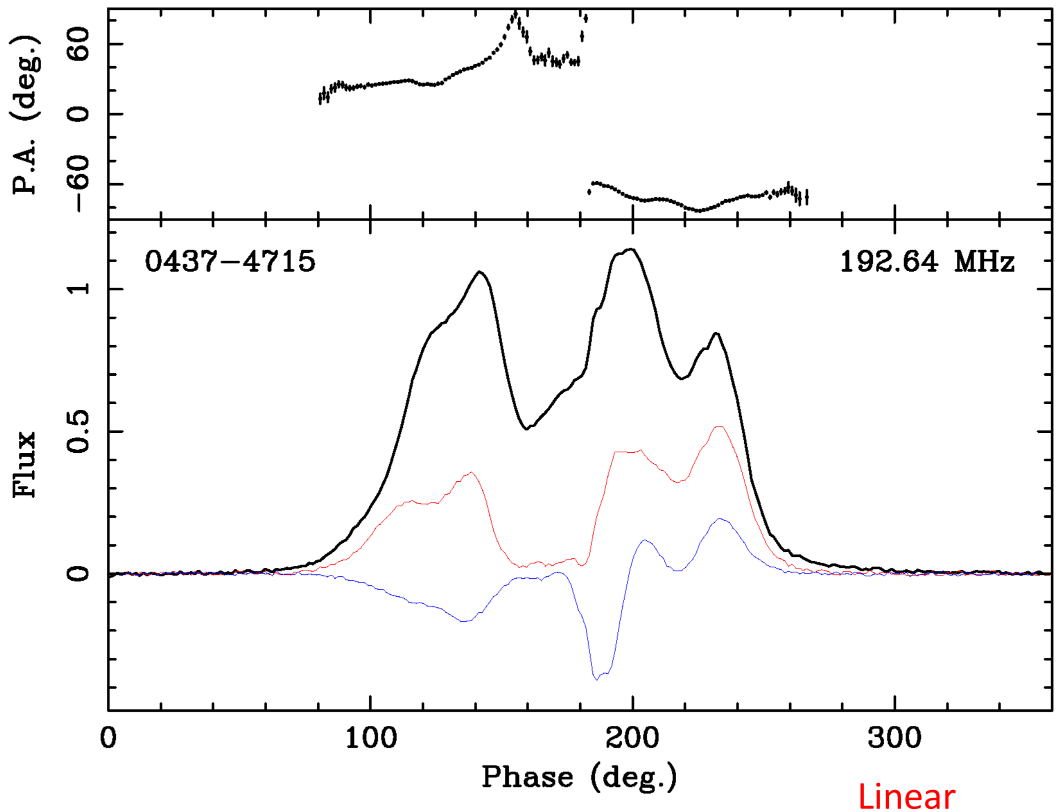


Coherent addition of 126 tiles

Bhat et al. (2016)

Coherently dedispersed Polarimetric *Tied-array* beam on J0437-4715

Ord et al. (2016) in prep.



Linear

Circular

Work in progress:

Verification exercise using common targets with Northern telescopes (e.g. GLOW stations, LOFAR, GMRT)

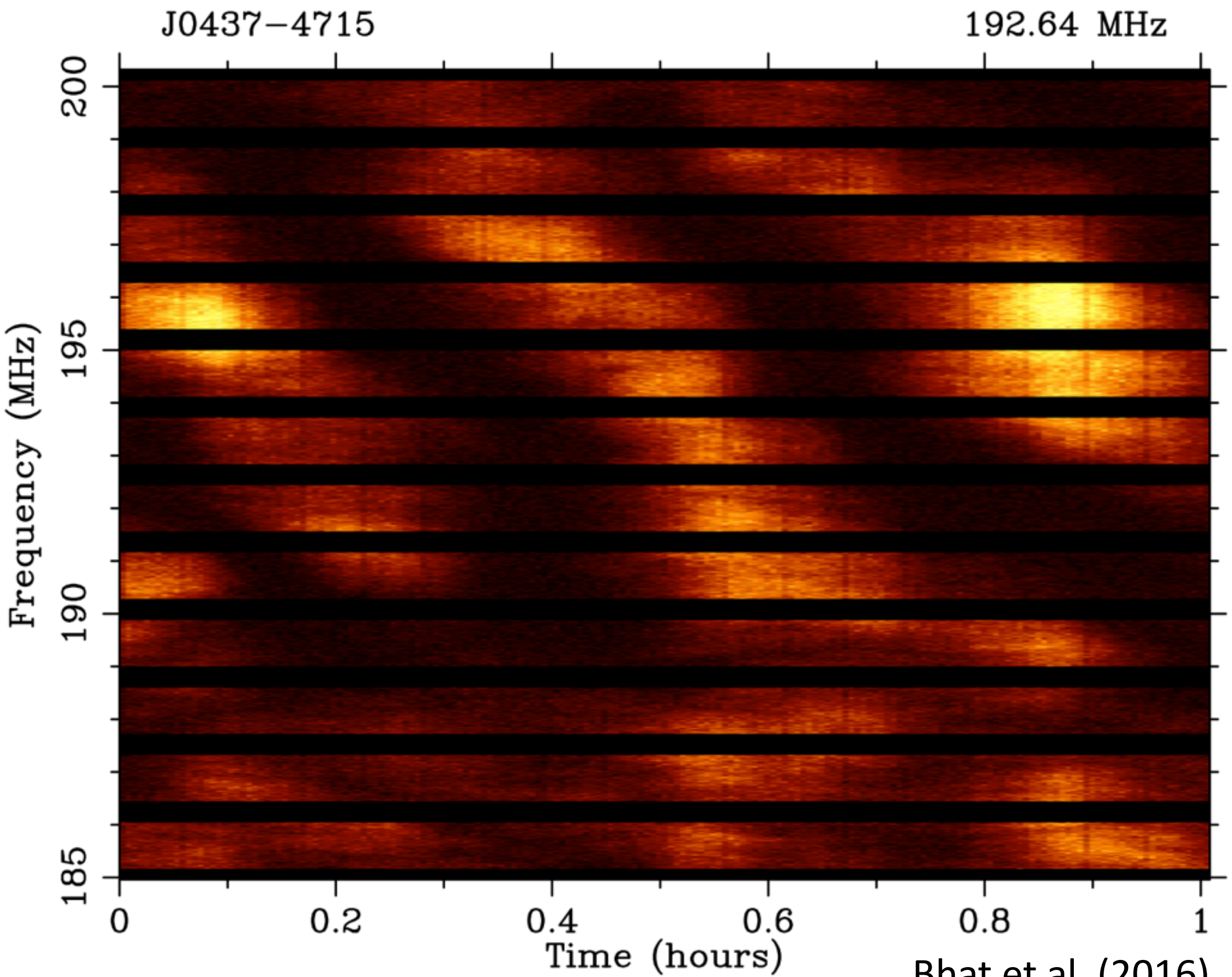
Ramping up Pulsars@MWA

- From Commissioning data:
  - *The low-frequency characteristics of PSR 0437-4715 with the MWA*
    Bhat et al. (2014)
  - *The high time and frequency resolution capabilities of the MWA*
    Tremblay et al. (2015)
  - *Simultaneous observations of Crab giants with the MWA and Parkes*
    Oronsaye et al. (2015)
  - *Scintillation arcs in the low-freq. observations of MSP J0437-4715*
    Bhat et al. (2016)
- New and upcoming publications:
  - *Low-frequency observaions of the sub-pulse drifter PSR J0034-0721*
    McSweeney et al. (2017)
  - *Evidence for a spectral flattening at low frequencies in Crab giants*
    Meyers et al. (2017) – under collaboration review
  - Wide-band observations of millisecond pulsars
    Bhat et al. (2017) – in prep.
  - *A census of southern pulsars at 185 MHz*
    Xue et al. (2017) – under collaboration review **(See Mengyao Xue's talk)**
  - First fringes between the MWA and the GMRT at 160 MHz
    Kirsten et al. (2017) – in prep. **(See Franz Kirsten's talk)**

Science Highlights

Scintillating MSP J0437-4715 @ MWA 200 MHz

- Phased-up MWA (126 tiles)   Spectral resolution = **10 kHz**

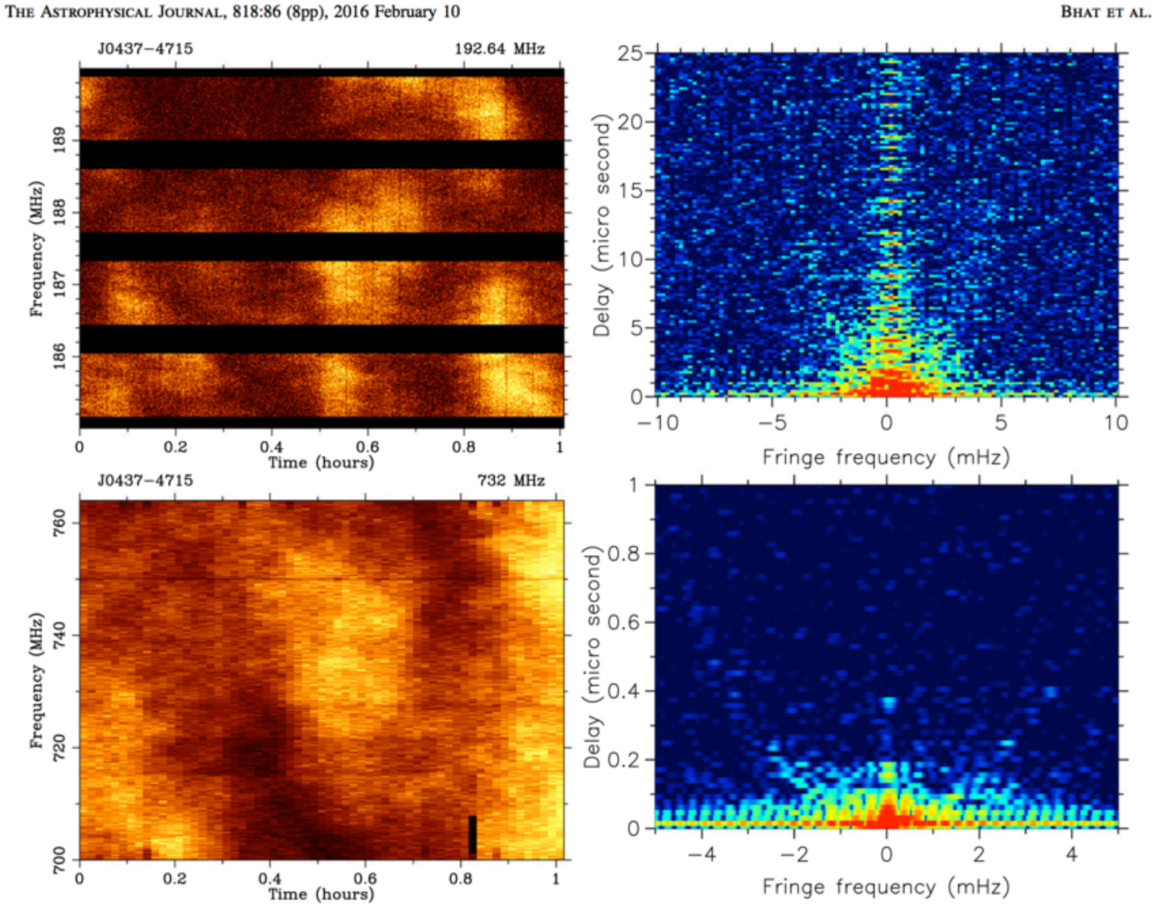


Bhat et al. (2016), ApJ, 818, 86

Scintillation arcs in MWA observations

Parabolic scintillation arcs seen in the "secondary spectra" of MSP J0437-4715

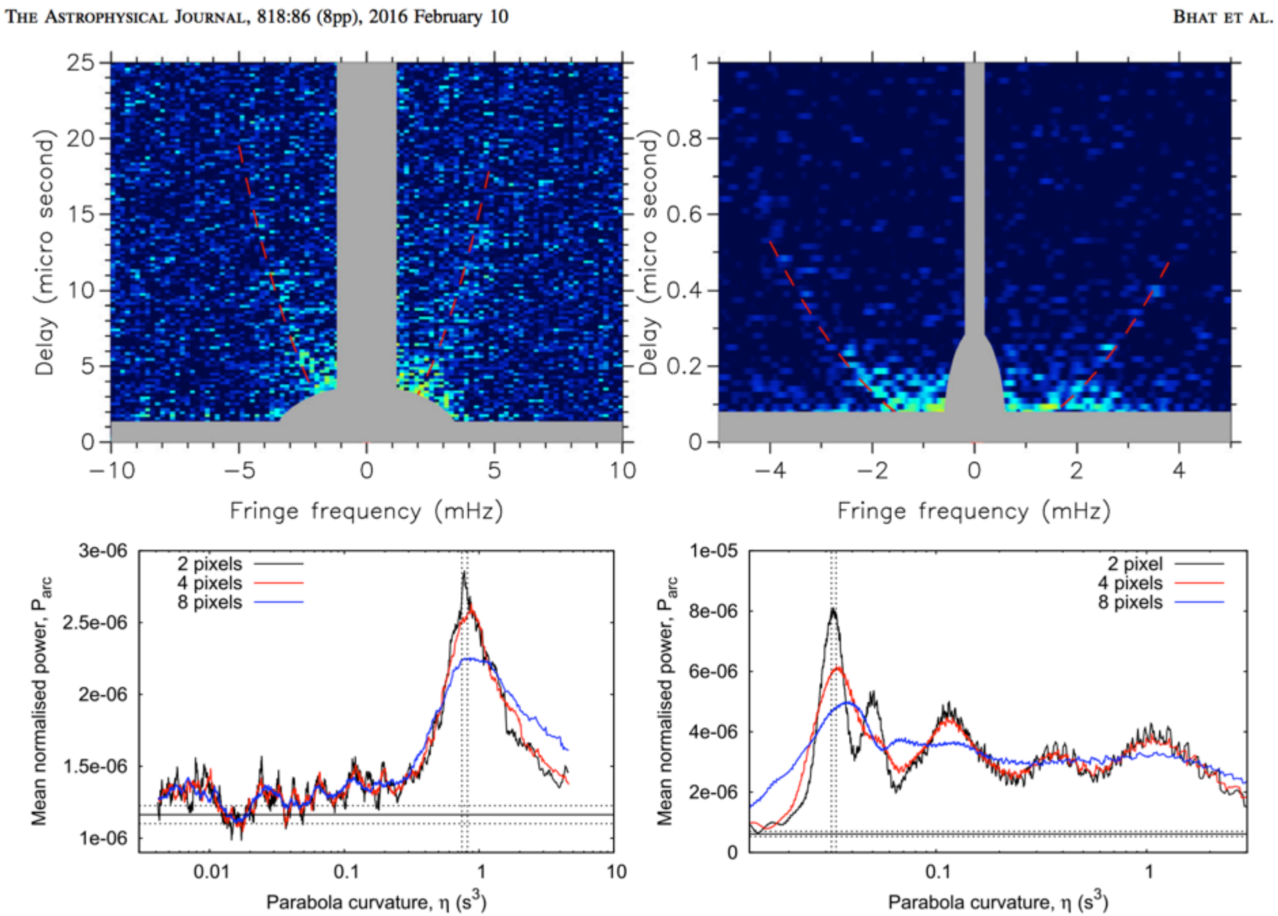
A "tiny" fraction of the scattered power appearing at large delays – discovered by Stinebring et al. (2001) in Arecibo observations; theoretical treatments by Cordes et al. (2006) and Walker et al. (2004)



Bhat et al. (2016), ApJ, 818, 86

Measuring the arc curvature

The arc curvature η scales as λ^2 once the pulsar's (and the Earth's) orbital motions are fully accounted for



MWA measurements:
s = 0.26 ± 0.01
Screen distance = 115 ± 2 pc

Parkes measurements:
s = 0.27 ± 0.01
Screen distance = 114 ± 2 pc

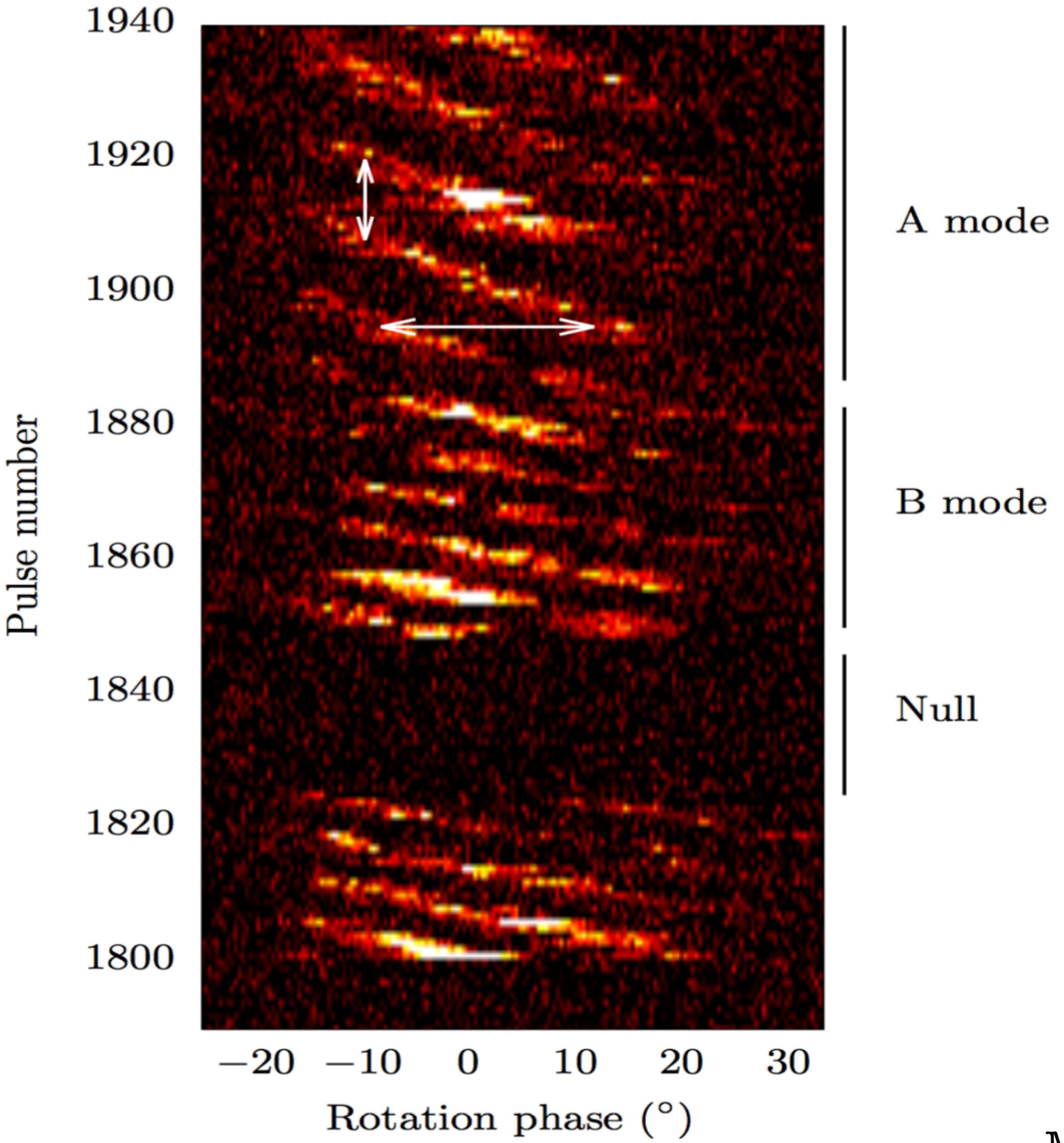
The Local Bubble located at ~100-120 pc in the pulsar's direction

$$P_{\mathrm{arc}}(\eta) = \frac{1}{N}\sum_{i=1}^{N} S_2(\eta f_{\mathrm{t,i}}^2\,,\ f_{\mathrm{t,i}}\,)$$

Bhat et al. (2016)

Sub-pulse Drifting in PSR J0034−0721

MWA observations at 185 MHz



Mode A

$P_3 \approx 13\ P_1$

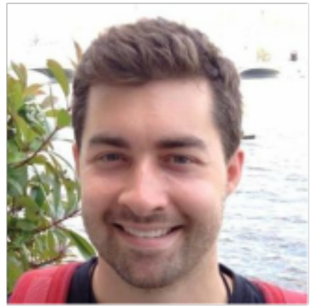
Mode B

$P_3 \approx 7\ P_1$

(Mode C)

$P_3 \approx 4\ P_1$

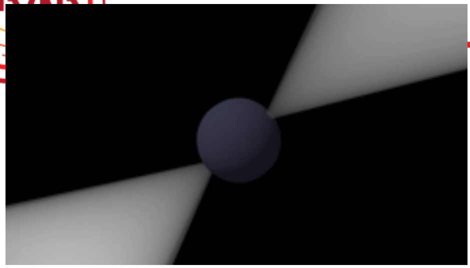
Mode B



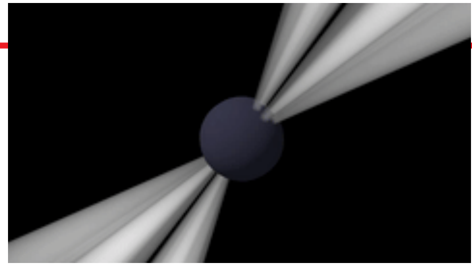
Sammy McSweeney
(PhD student)

McSweeney, Bhat, et al. (2017), ApJ, 836, 224

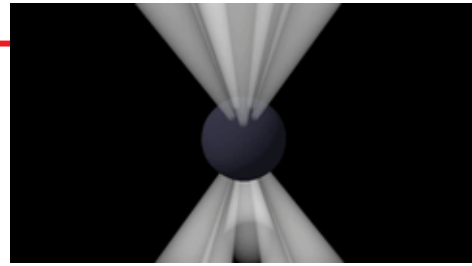
Sub-pulse Drifting in Pulsar Emission



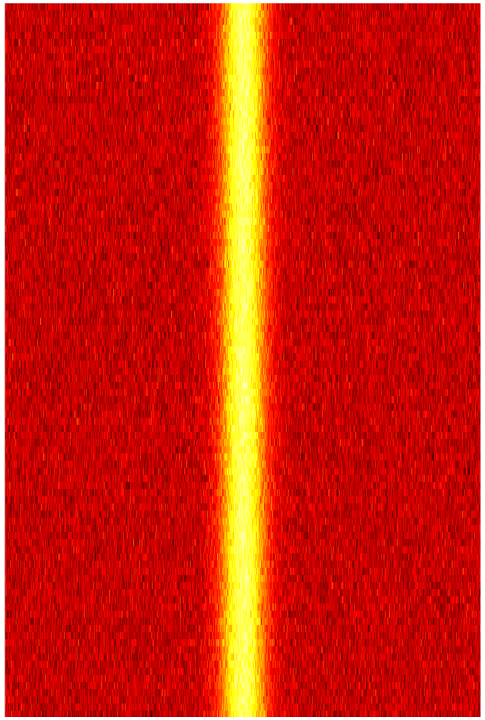
“Lighthouse”
Simulation



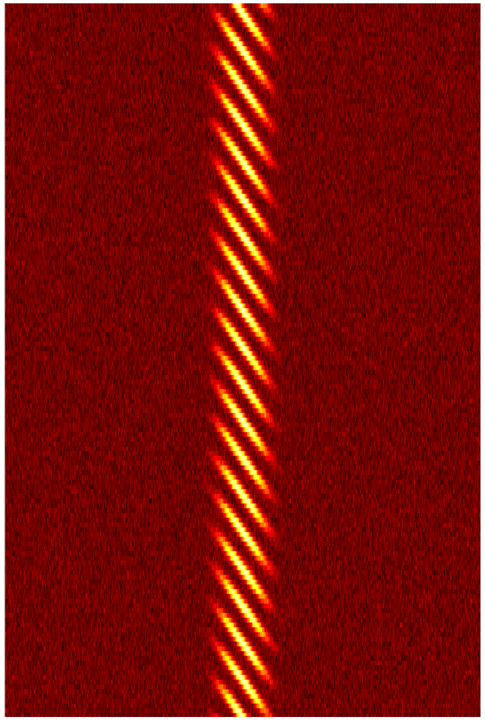
“Carousel”
Simulation

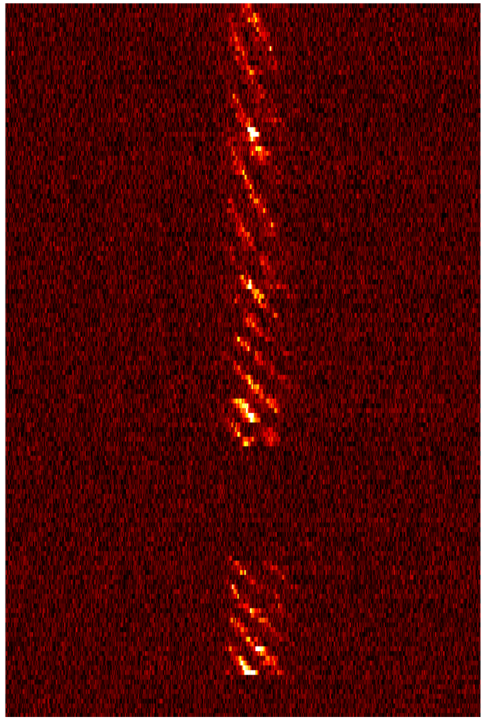


Real data (**MWA**)
(PSR J0034-0721)

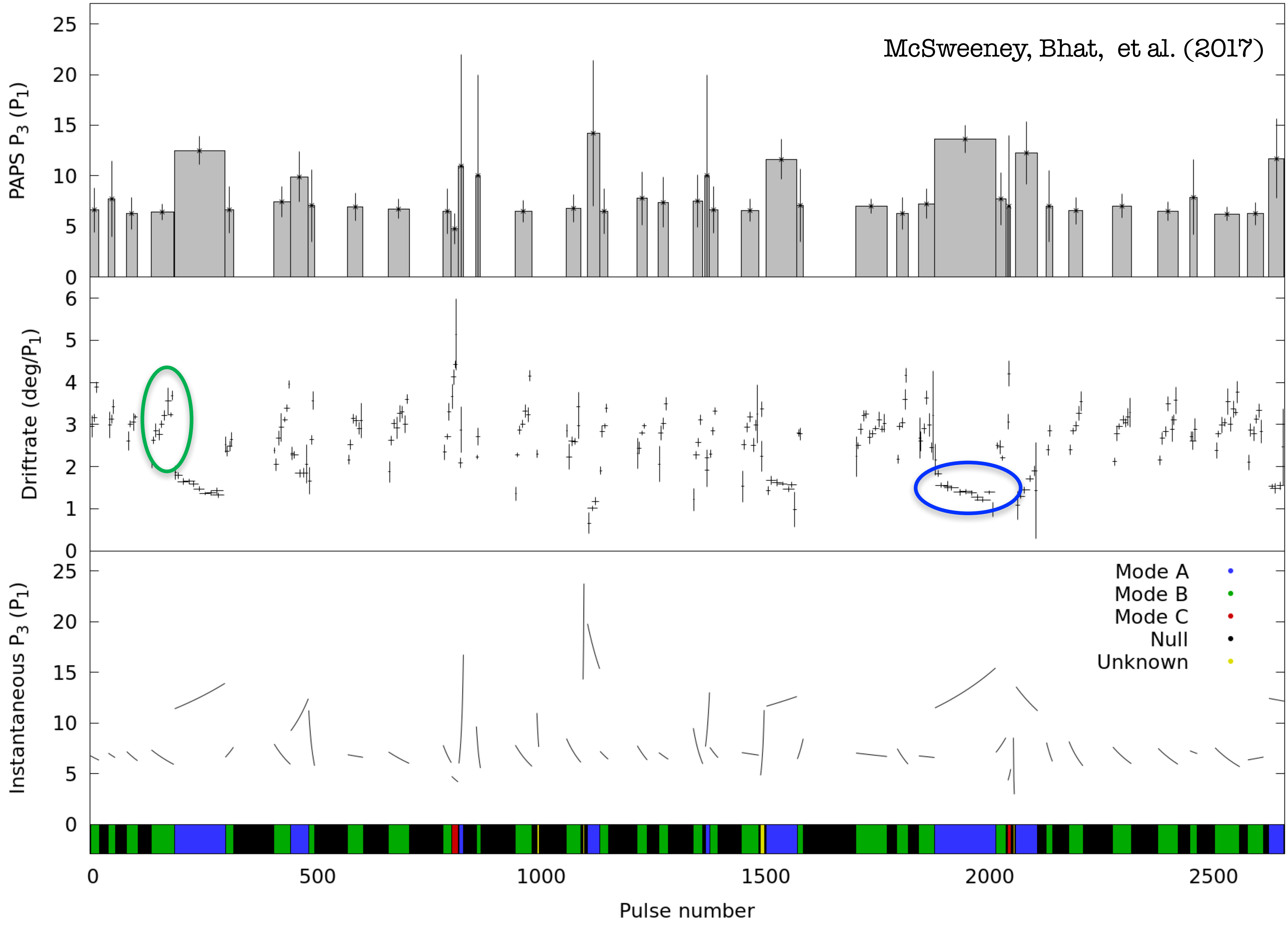


1 pulsar rotation



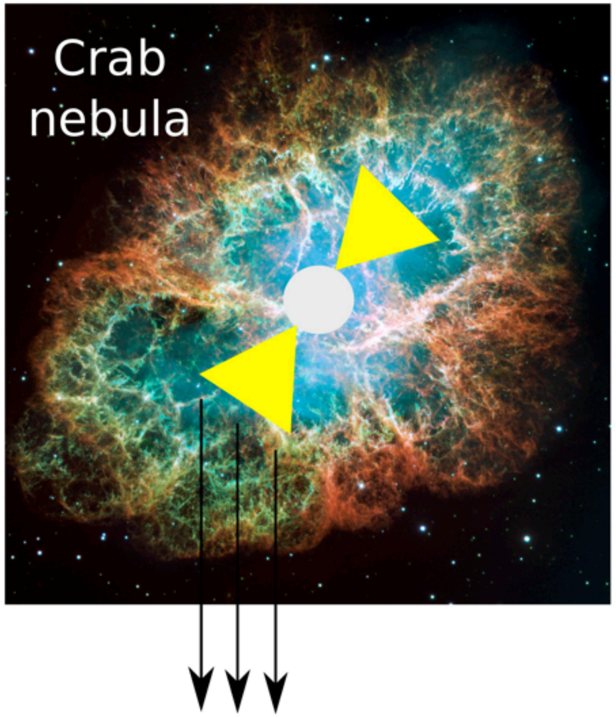


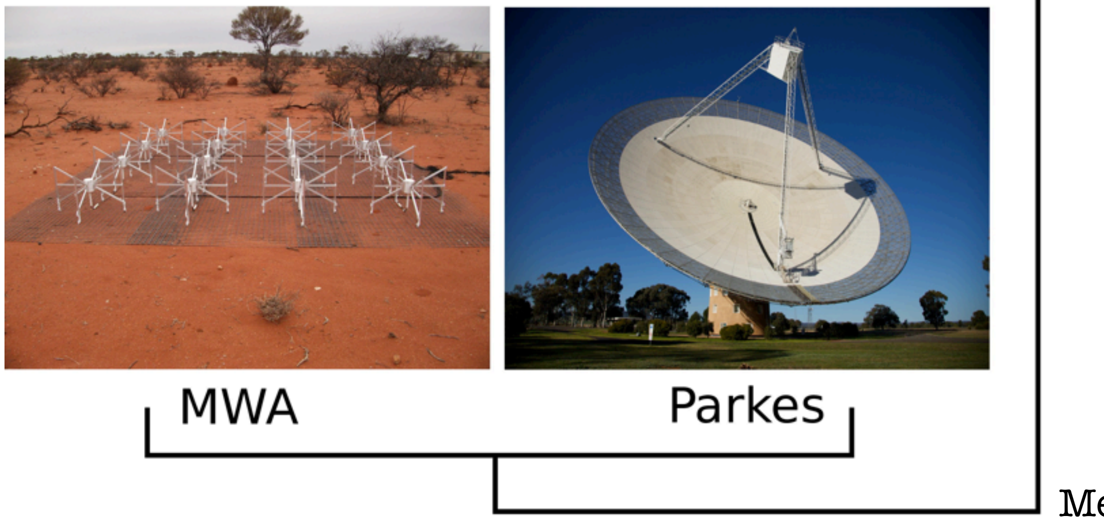
McSweeney et al.


McSweeney, Bhat, et al. (2017)
PAPS P3 (P1)
Driftrate (deg/P1)
Instantaneous P3 (P1)
Mode A
Mode B
Mode C
Null
Unknown
Pulse number

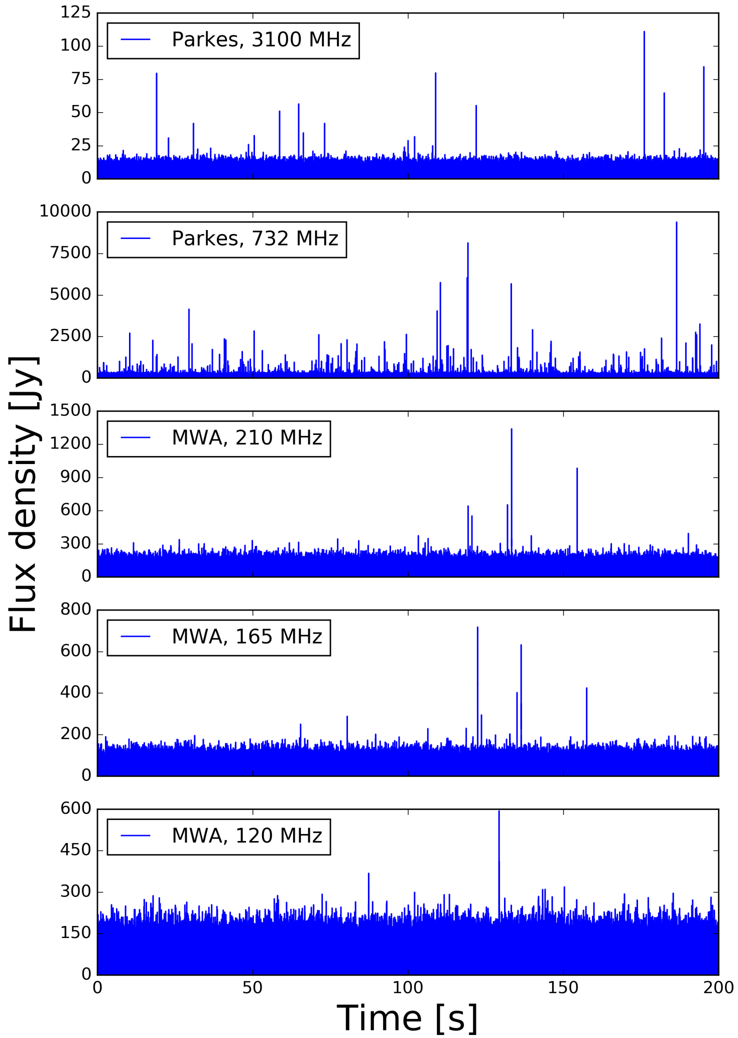
Giant-pulse emission from MHz to GHz bands

Bradley Meyers
(PhD student)





Simultaneous observations with the MWA and Parkes spanning ~100 to ~3100 MHz



Meyers, Tremblay, Bhat, et al. (collab. review)

Tied-array beam modelling

The tied-array beam pattern is expressed as

$$\boxed{P_{\mathrm{array}}(\theta,\phi)} = \boxed{P_{\mathrm{tile}}(\theta,\phi)}\boxed{|f(\theta,\phi)|^2}$$

array power pattern

tile power pattern

"array factor"

We want this...

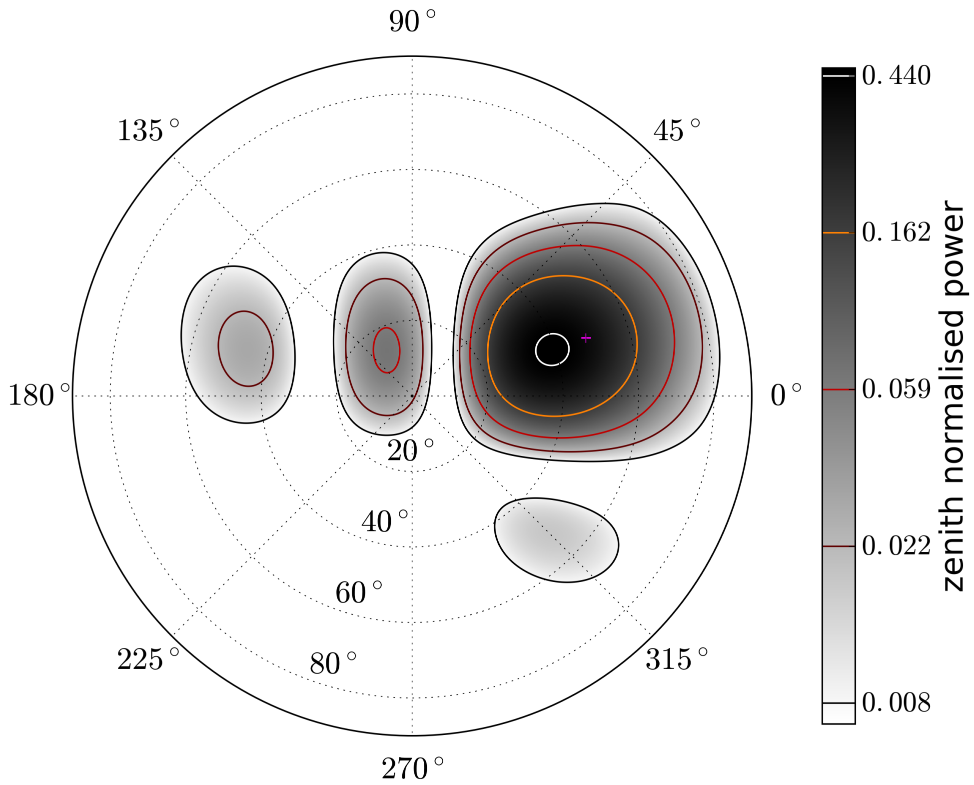
But need to calculate both of these...

We can already get $P_{\mathrm{tile}}(\theta,\phi)$ but need to also calculate

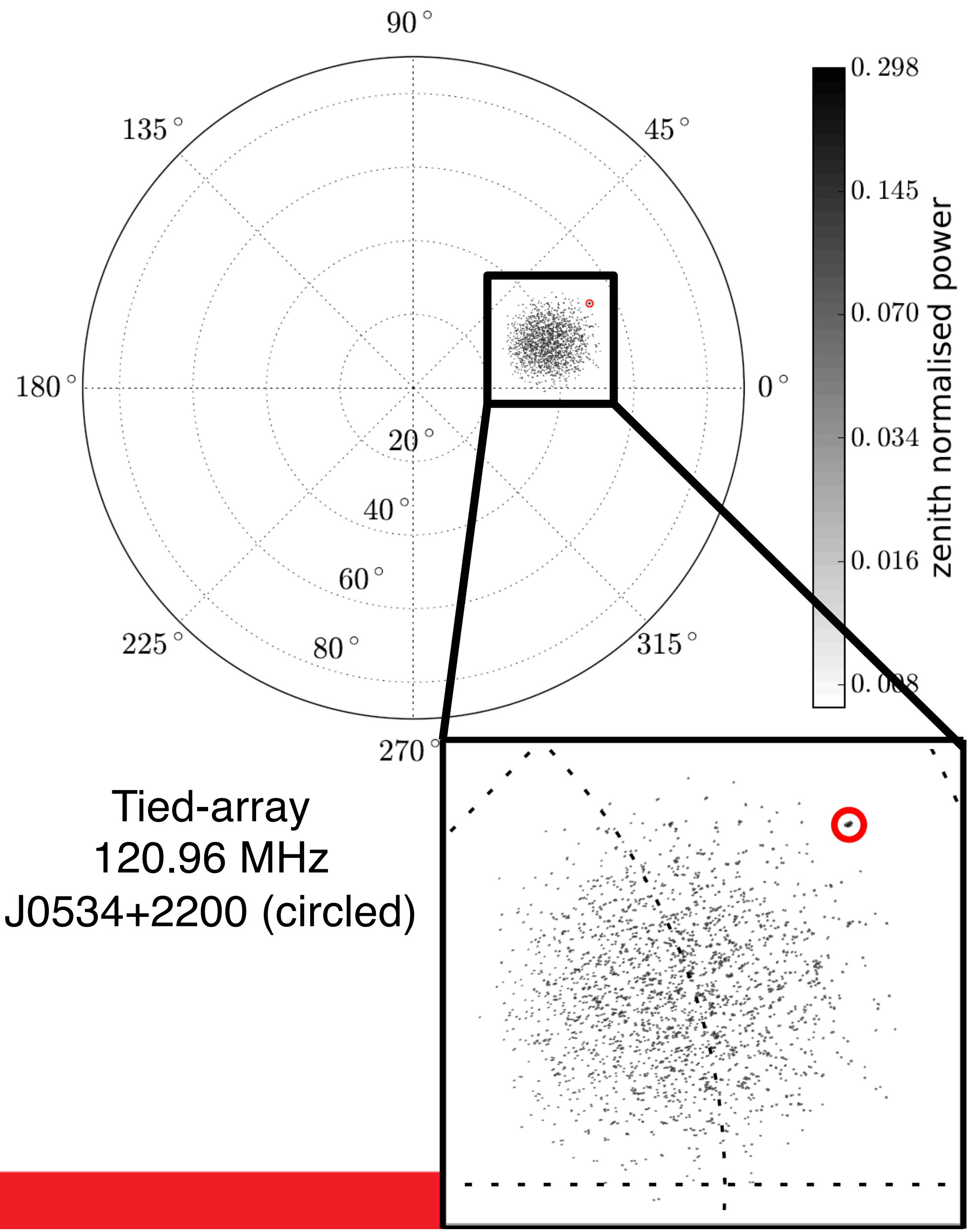
$$f(\theta,\phi) = \frac{1}{N}\sum_{n=1}^{N}\boxed{w_n}\exp\left(i\mathbf{k}\cdot\mathbf{r}_n\right)$$

weights to "steer" beam to target

Tied-array beam modelling



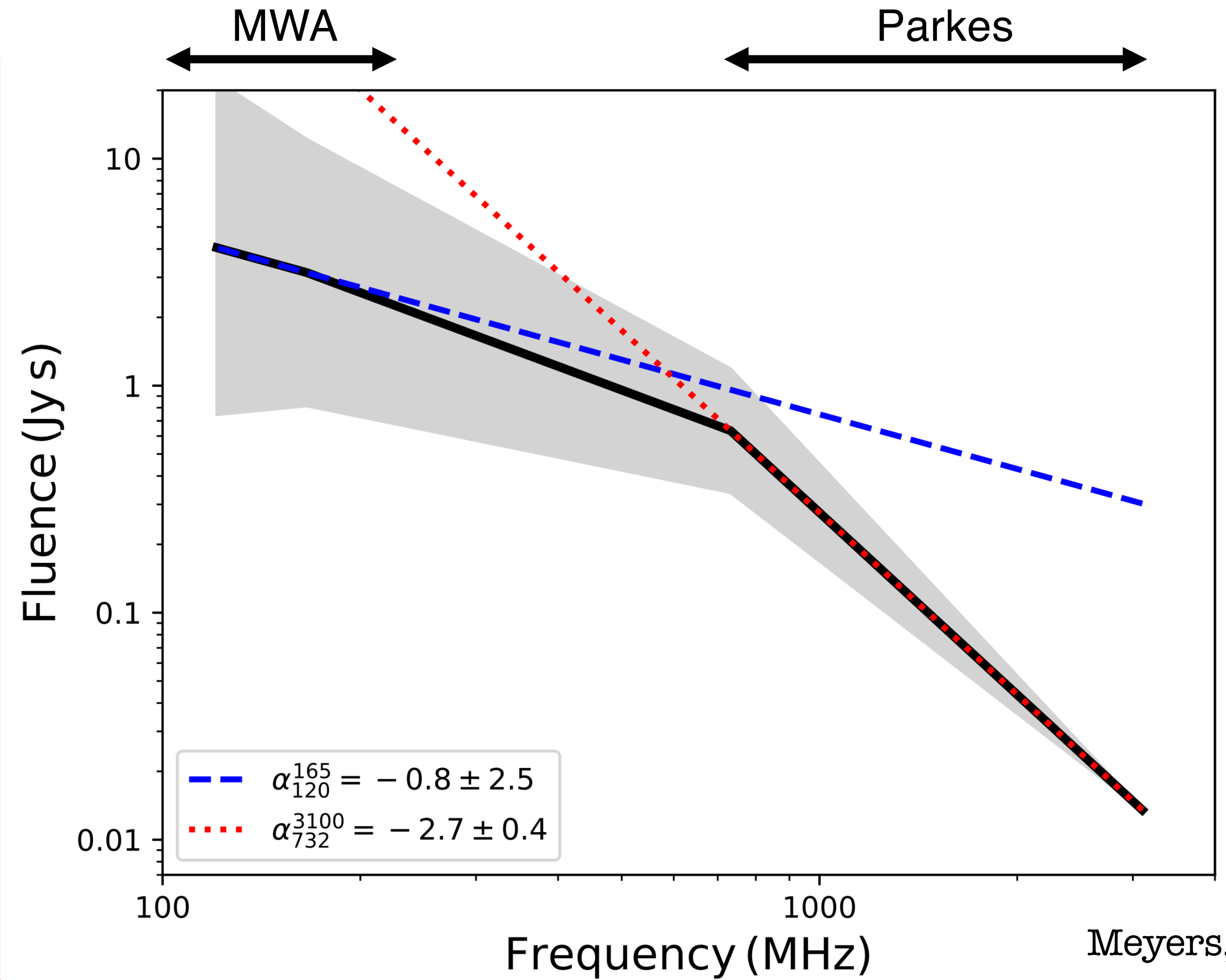
Tile beam (Embedded Element)
120.96 MHz
Az = 18.43, ZA = 41.42



Tied-array
120.96 MHz
J0534+2200 (circled)

Flattening Spectrum of Crab GPs

For **simultaneous** giant pulses, we see a flattening spectrum:



732 MHz: $\alpha \approx -2.7$

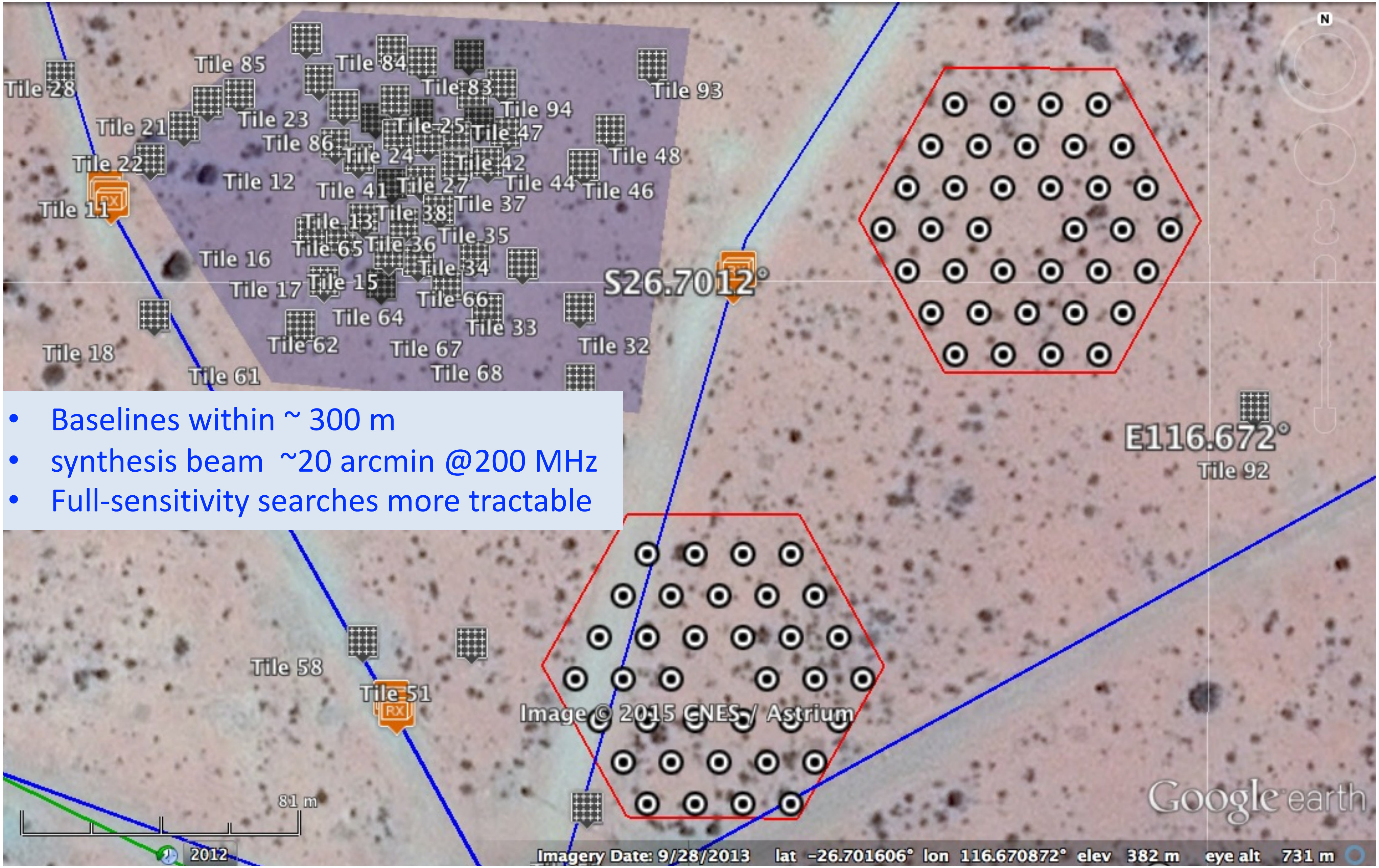
165 MHz: $\alpha \approx -1.0$

: $\alpha \approx -0.8$

If the spectrum remains steep at low frequencies, we expect >10 times more detectable giant pulses

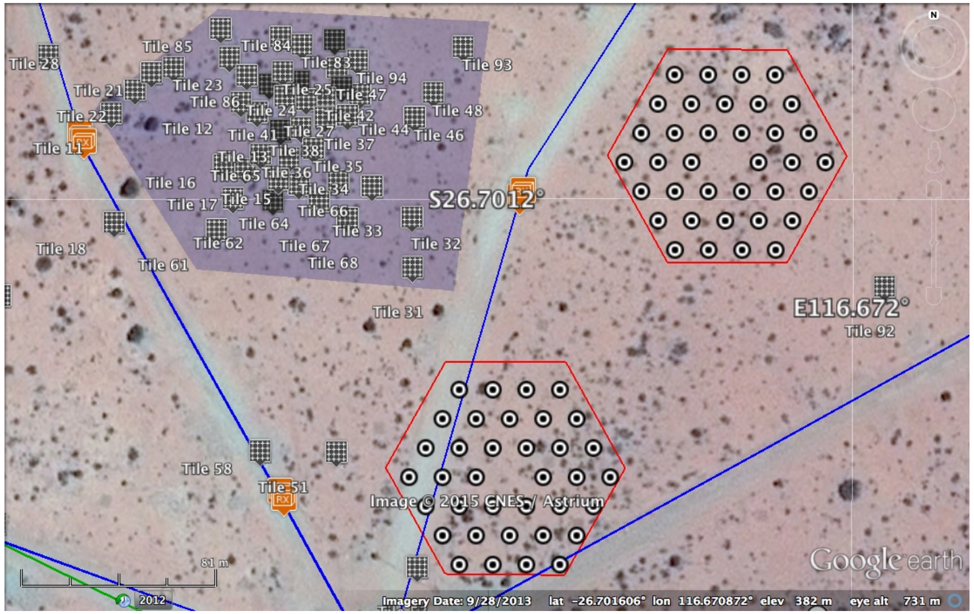
Meyers, Tremblay, Bhat, et al. (collab. Review)

Phase 2 MWA “EOR” Array



- Baselines within ~ 300 m
- synthesis beam ~20 arcmin @200 MHz
- Full-sensitivity searches more tractable

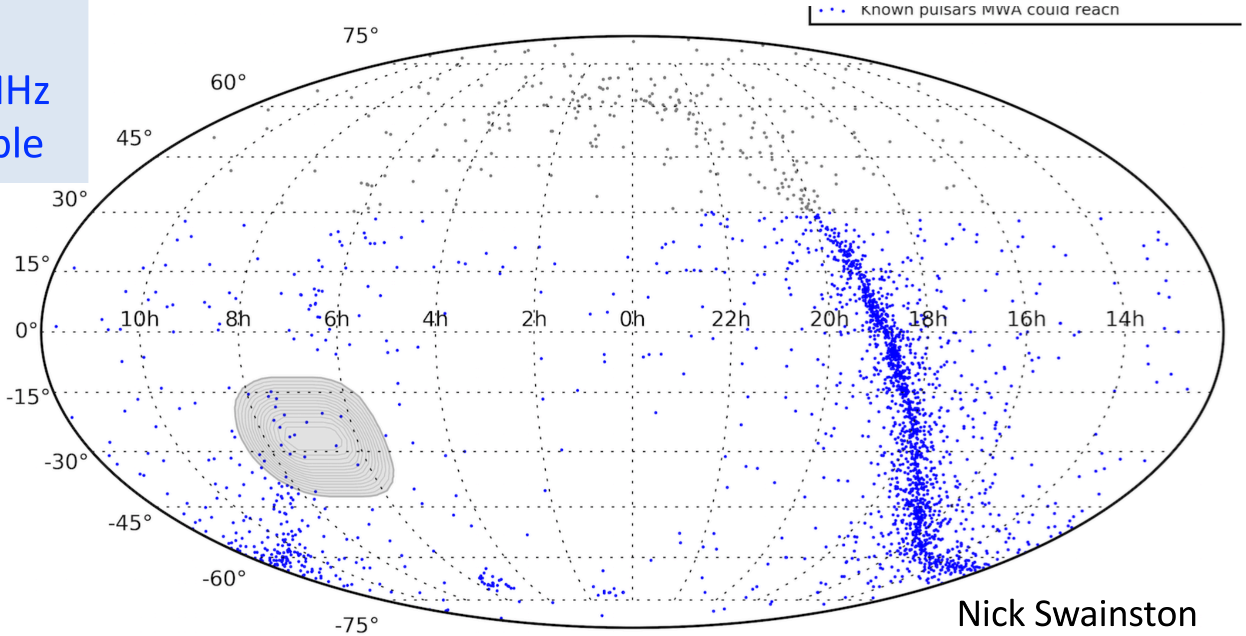
A Pilot Pulsar search with Phase 2



- Rapid localisation via imaging or gridding, or long baselines
- Accelerated convergence to the timing solutions
- Exploration of alternate (image-based) techniques for candidate targets

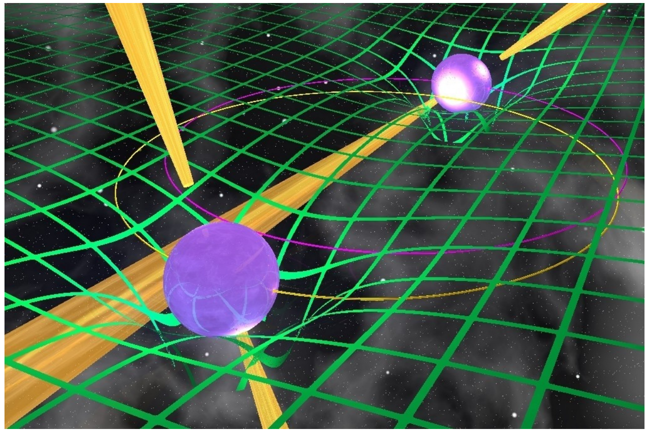
- Baselines within ~ 300 m
- synthesis beam ~20 arcmin @200 MHz
- Full-sensitivity searches more tractable

Test pulsars in the field beam-formed to check data quality and calibration performance



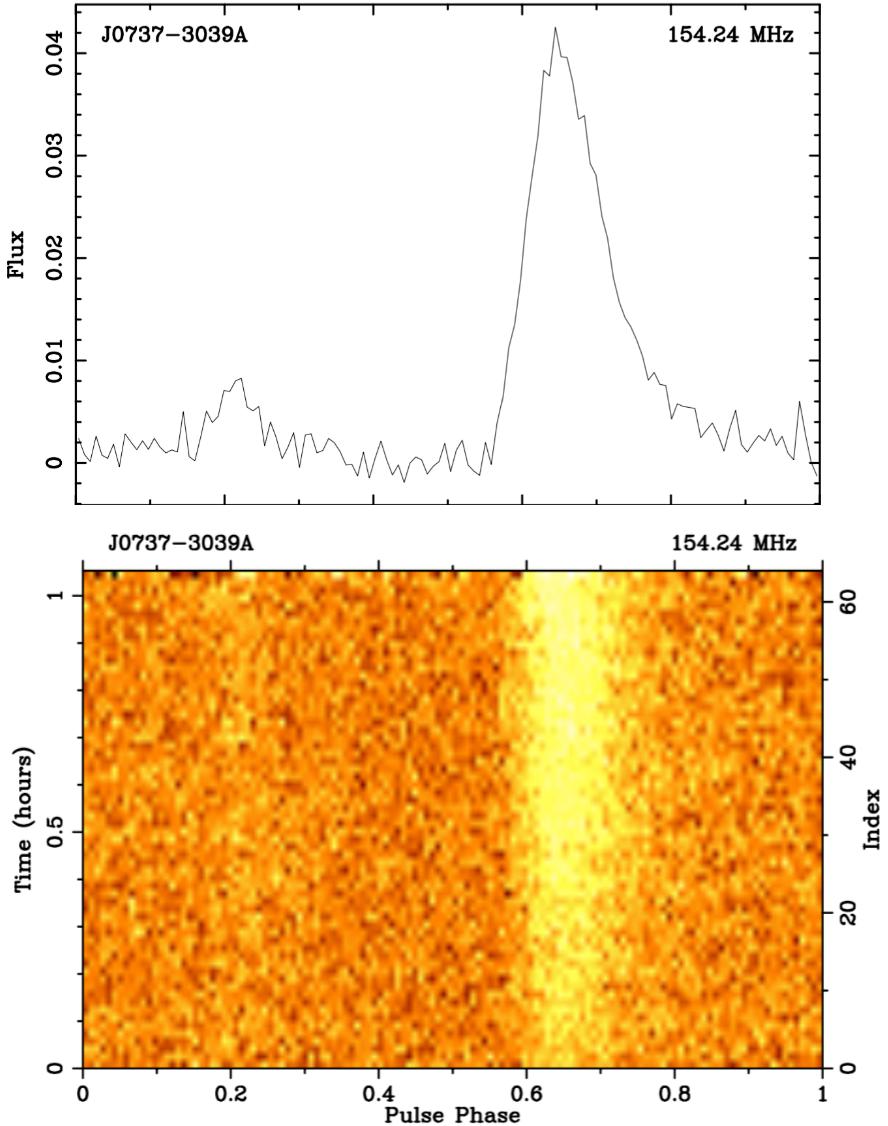
Nick Swainston

The Double Pulsar @ MWA 150 MHz



DM-smearing from 10 kHz channels; improved detection possible from reprocessing (coherent dedispersion)

Pulsar A @ MWA 140-170 MHz



The Engineering Development Array (EDA)

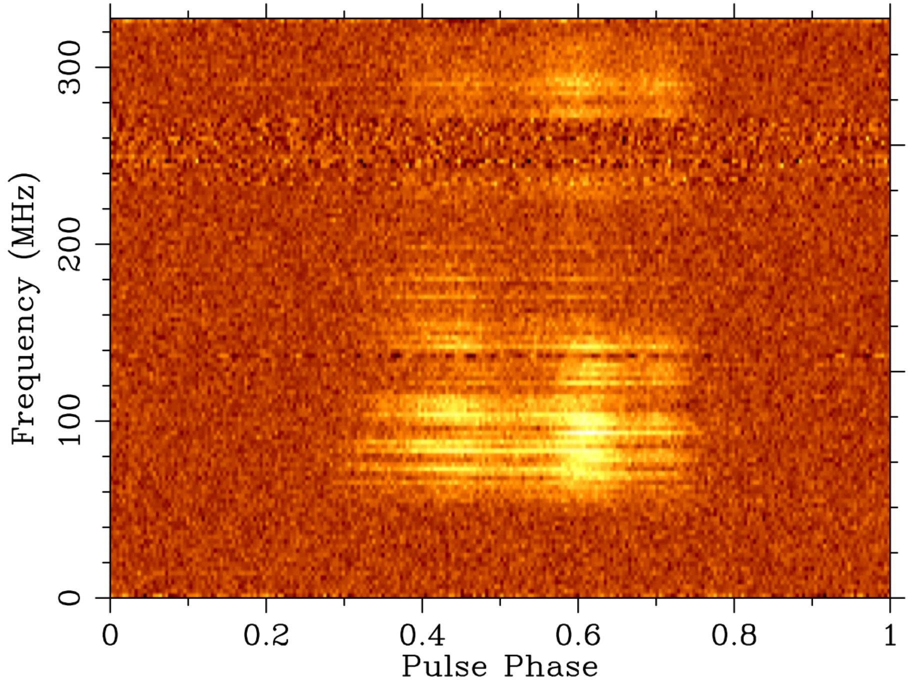
- A station comprised of 256 MWA dipoles (16-tile equivalent)
- Test & verification system aimed at MWA & SKA-Low prototyping
- Development for integration of external signals->MWA
- Direct baseband stream sampled at Nyquist 655.36 MHz

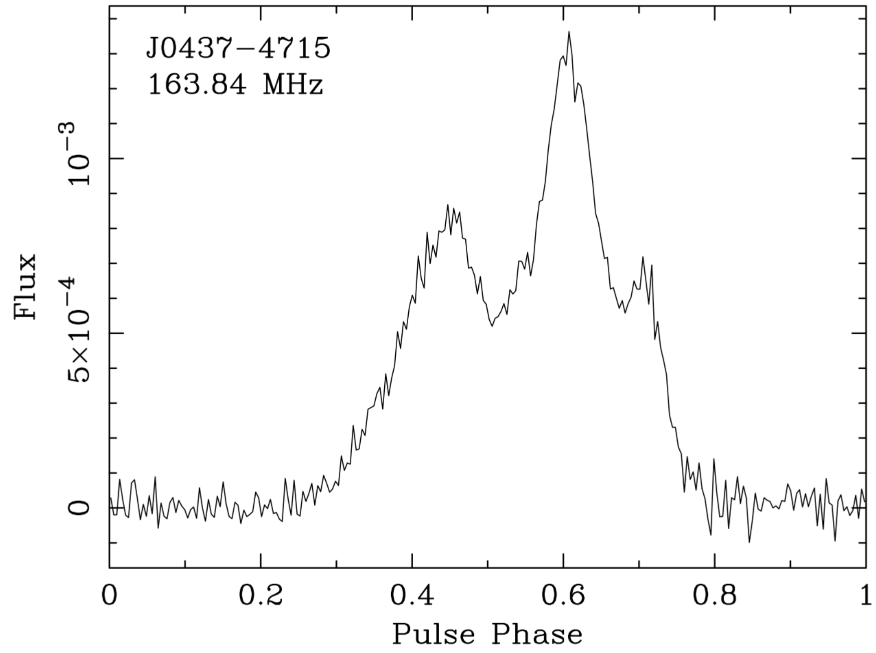
See Wayth et al. (2017), PASA (Submitted) for details

PSR J0437-4715 with the EDA

Access to full bandwidth baseband data and integration of the pulsar processing software

Development efforts by Marcin Sokolowski, Willem van Straten

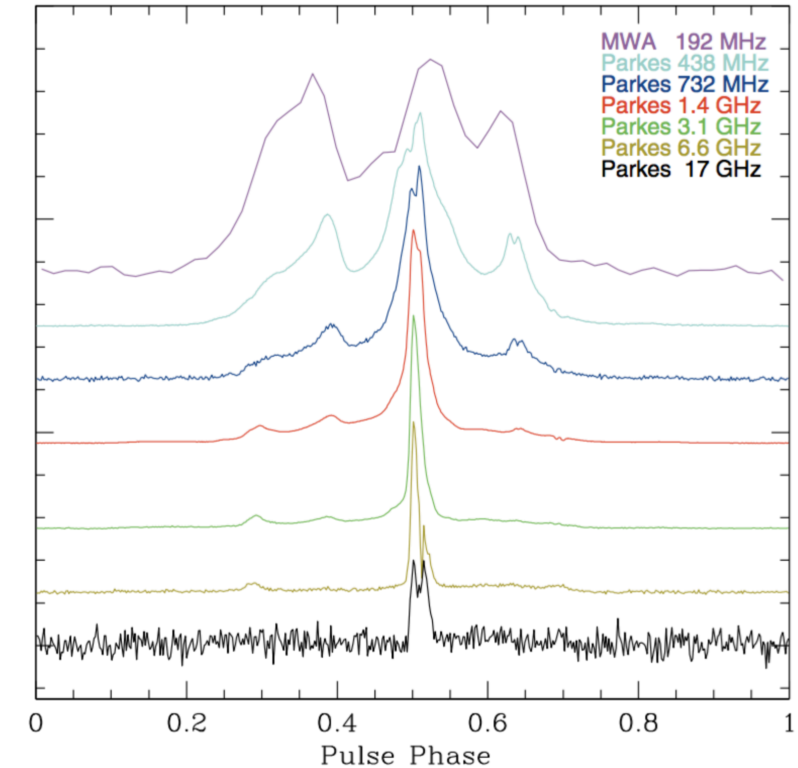




Millisecond Pulsar J0437-4715

MWA 200 MHz

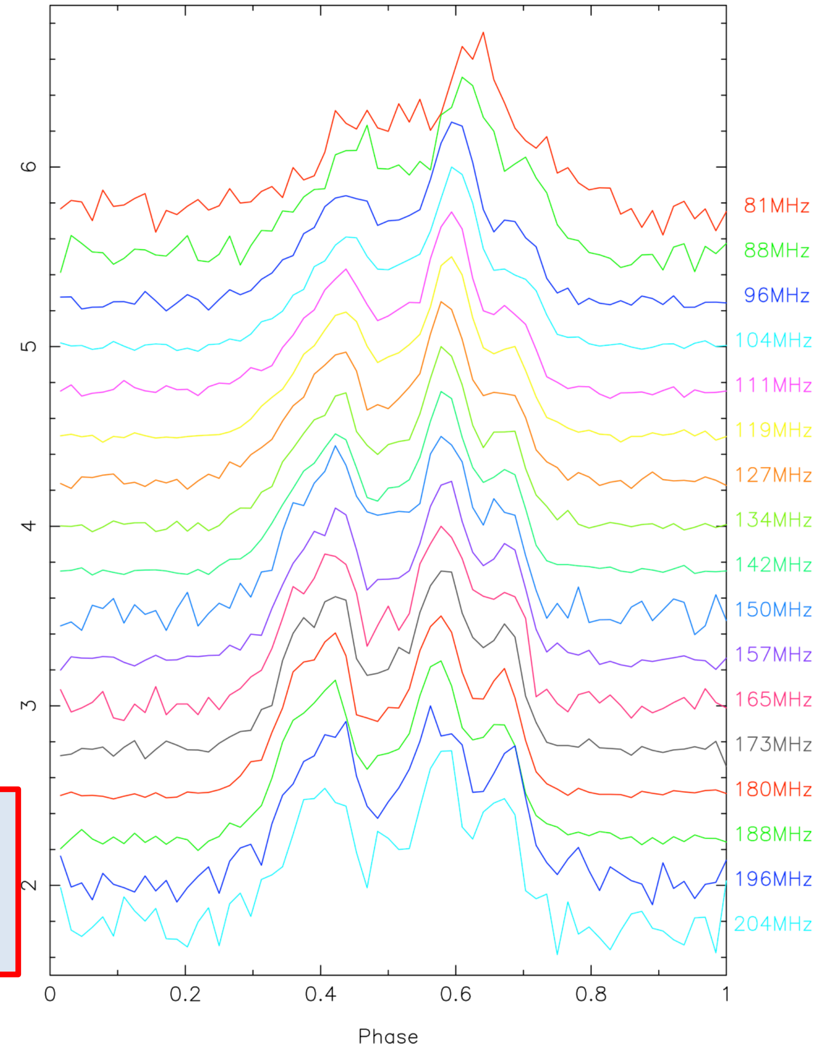
Bhat et al. (2014)



Parkes 438 MHz to 17 GHz

Simultaneous multi-band observations across the 80-300 MHz MWA band

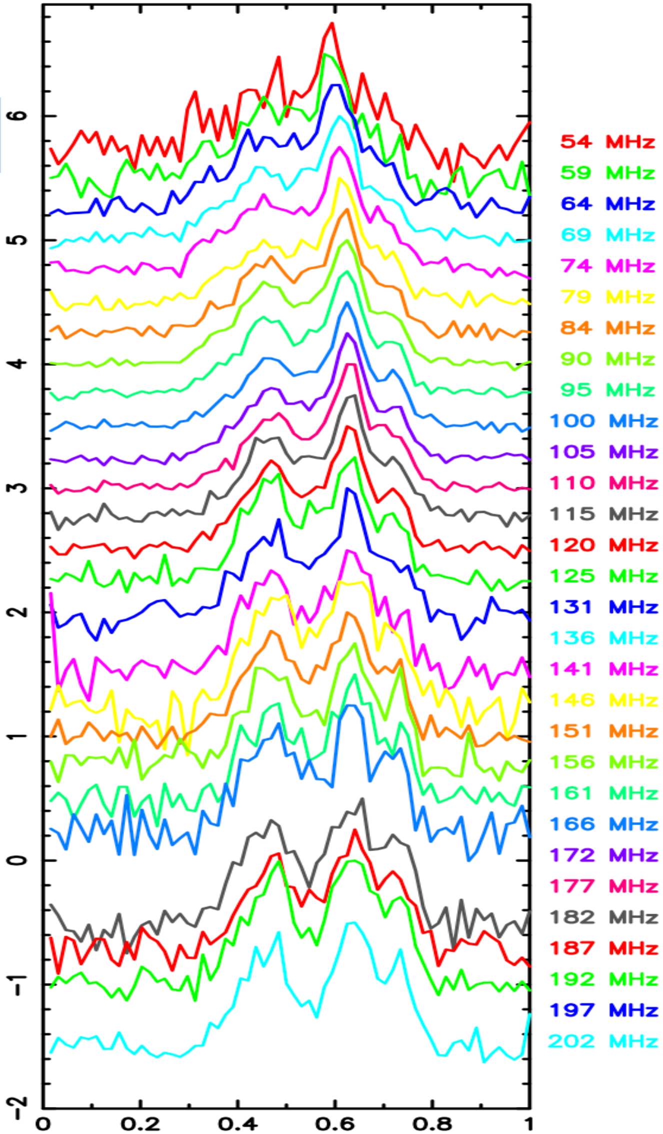
New MWA observations



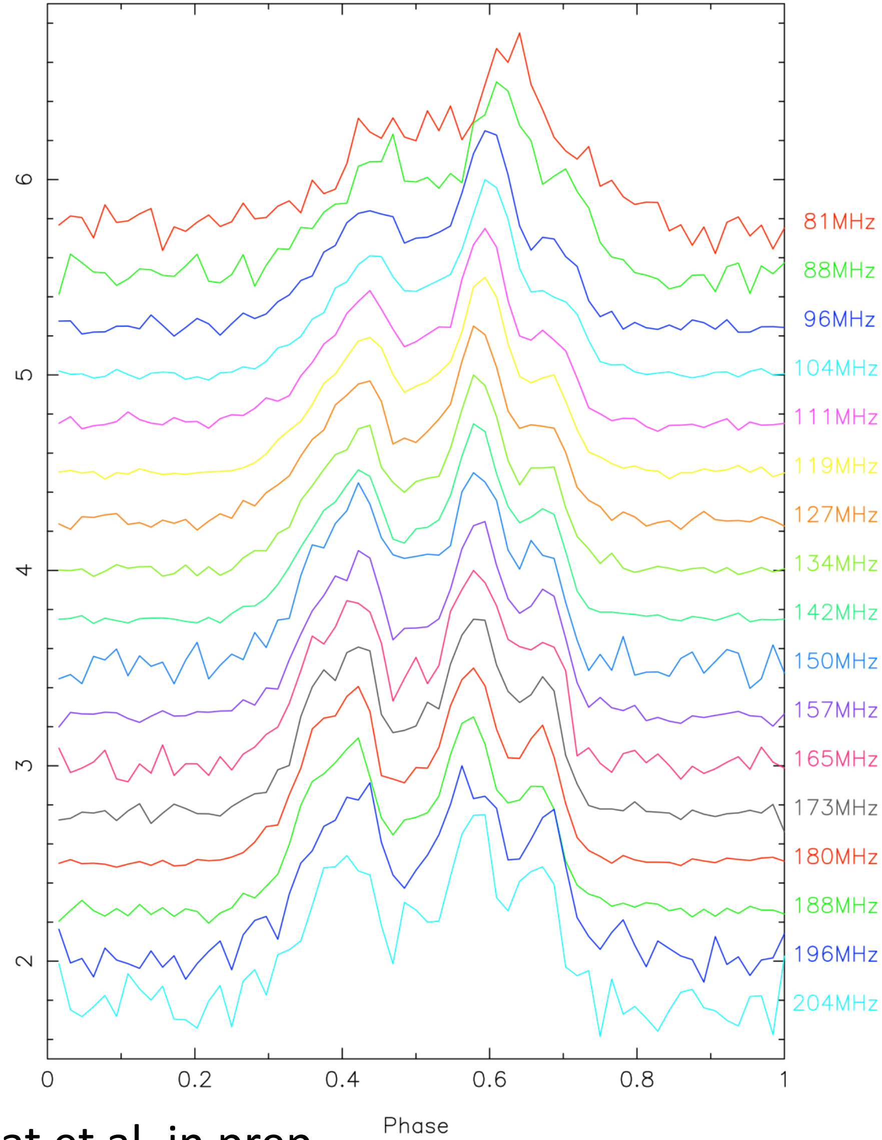
Bhat et al. in prep.

MSP J0437-4715

EDA from ~50 MHz to ~200 MHz



MWA from ~80 MHz to ~200 MHz



Bhat et al. in prep.

Pulsars@MWA: Looking Ahead

Phase 2+3 compact vs long-baseline arrays + planned new high time resolution backend will bring in a major boost to Pulsars@MWA

- Exciting prospects for large-area searches to be enabled by Phase 2 configurations – efficient tiling of the full FoV (compact array), rapid localization (long baselines)
- More routine observations (e.g. PTA pulsars) to be enabled by faster turn-around in processing (new hardware that connects the 100Gb link from MRO to Pawsey/CITS)
- Pulsar emission studies at finer time resolution to be enabled by direct access to coarse-channel (1.28MHz) data, initially for 1/3 bandwidth (e.g. micro-structure, MSP studies)
- Prospects of expanding ISM studies using either high-resolution dynamic+secondary spectral studies or application of CS (cyclic spectroscopy) and related techniques

Summary

- MWA is opening up a new window for pulsar astronomy in the southern hemisphere – compliments other facilities (e.g. Parkes, UTMOST)
- Pulsar science @ MWA via VCS; involves large data rates + transport to Pawsey + calibration and beam-forming for maximal sensitivity
- Coherent (tied-array) beam processing pipeline; polarimetry under development, verification using MWA and GLOW stations
- Science ramping up – projects that exploit both archival data + targeted observations, co-ordination with other facilities (e.g. Parkes, GMRT)
- Beginning to exploit simultaneous multi-band (picket fence) capability, and the new wide-band capability provided by the EDA
- Phase 2 + new high time res backend to bring a major paradigm shift in pulsar science @ MWA; e.g. wide-field searches; integration into global PTA efforts; science relating to emission mechanism and ISM studies.
- MWA is Precursor for SKA-low, and provides an excellent platform for development relating to pulsars with SKA-Low