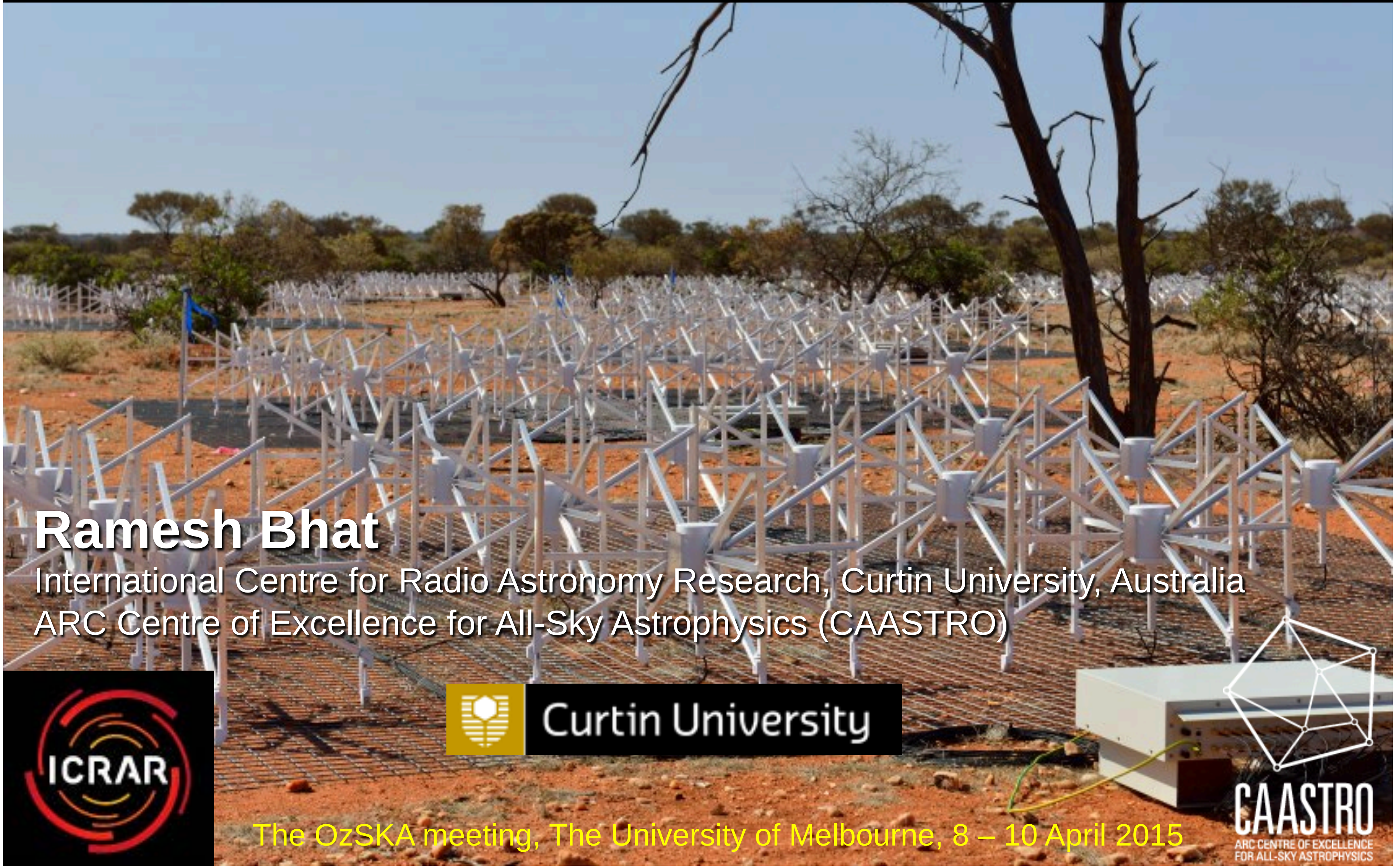
Low-frequency pulsar astronomy with the MWA and SKA-low



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CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

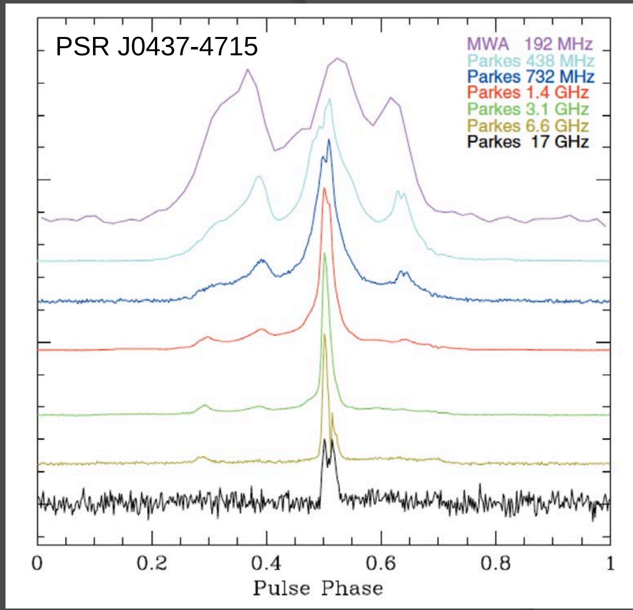
The OzSKA meeting, The University of Melbourne, 8 – 10 April 2015

Low-frequency pulsar astronomy in the SKA era

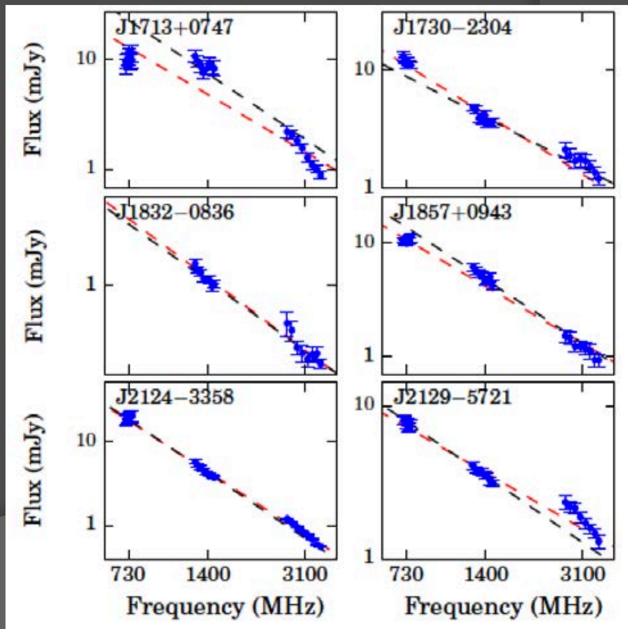
- Beam forming (phasing up) and processing for pulsar observations:
  - A major consideration for pulsar astronomy with array instruments – single-dish dominance over the past 4+ decades
  - Incoherent vs. coherent addition of signals (i.e. tied-array beams) and associated trade-offs
  - From MWA to SKA-low ➔ Going from 100+ elements, ~3km baselines to 500+ elements, distributed over ~80km baselines

Why Low Frequencies?

- Inherently steep spectrum objects, though some do exhibit a turn-over at LFs (can't say that for MSPs yet!)
- Wider beams (pulse profiles) at lower profiles, i.e. more action in the magnetosphere
- ISM propagation effects scale strongly with the observing frequency
  - Dispersion delay ~ λ^2
  - Scattering delay ~ λ^4
- Pulsar timing arrays– measuring (and correcting for) temporal DM variations and ISM effects, i.e. monitoring and compensating for "*interstellar weather*" – is critical for achieving the required timing precision



Bhat et al. (2014)



Dai et al. (2015)

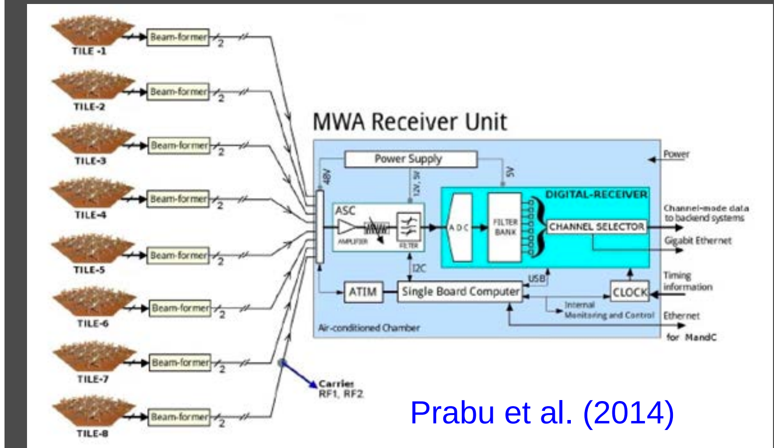
SKA science case – Pulsars

- ***Gravitational wave astronomy with the SKA*** (Janssen et al.)
- ***Testing gravity with pulsars in the SKA era*** (Shao et al.)
- ***A cosmic census of radio pulsars with the SKA*** (Keane et al.)
- Probing the neutron star interior and the equation of state of cold dense matter with the SKA (Watts et al.)
- Multi-wavelength, multi-messenger pulsar science in the SKA era (Antoniadis et al.)
- Understanding the neutron star population with the SKA (Tauris et al.)
- Understanding the pulsar magnetospheres (Karastergiou et al.)
- Pulsars in globular clusters with the SKA (Hessels et al.)
- Pulsar wind nebulae in the SKA era (Gelfand et al.)
- Three-dimensional tomography of the Galactic and extragalactic magneto-ionic medium with the SKA (Han et al.)

In this Talk:

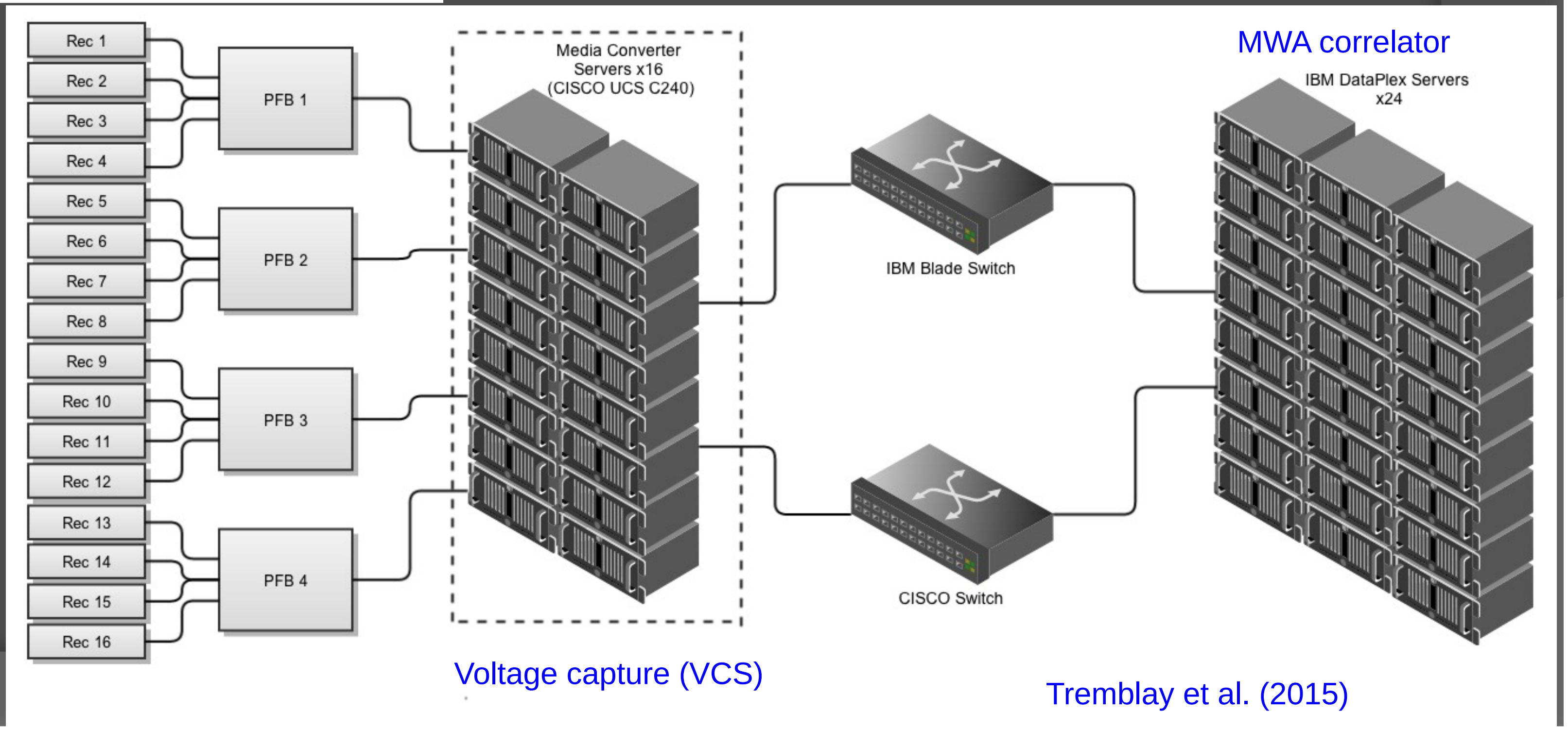
- MWA for high time resolution science
- New developments on the pulsar front
  - Coherent (phased-array) beam pipeline
  - Picket-fence mode for pulsar observing
- Planned observations (PTA pulsars)
- Connections to SKA-low

Gearing up the MWA for high time resolution: the voltage capture (VCS) mode



Prabu et al. (2014)

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

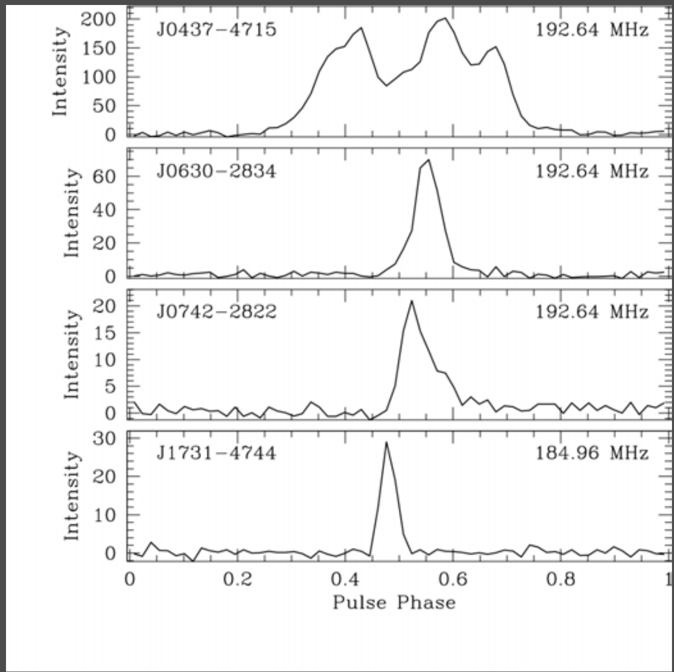


Voltage capture (VCS)

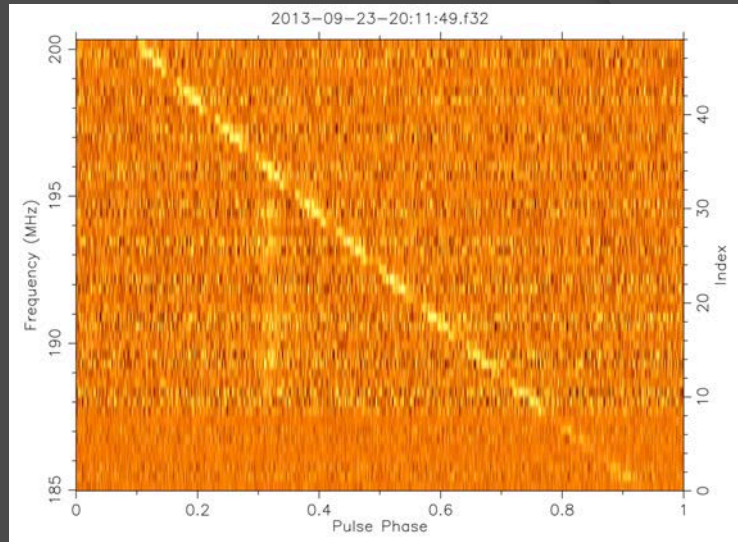
Tremblay et al. (2015)

Science applications of MWA VCS

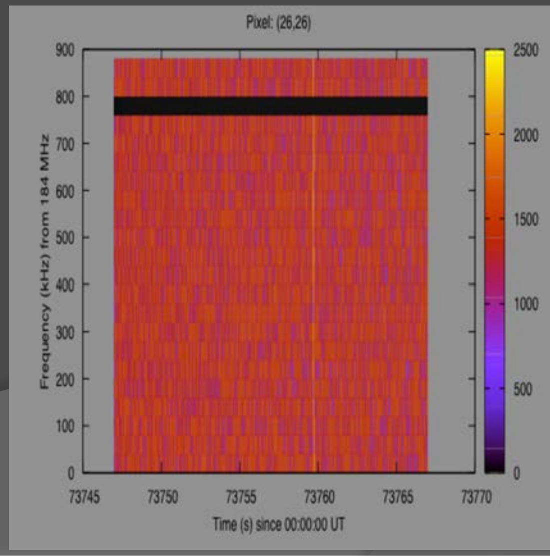
Pulsars



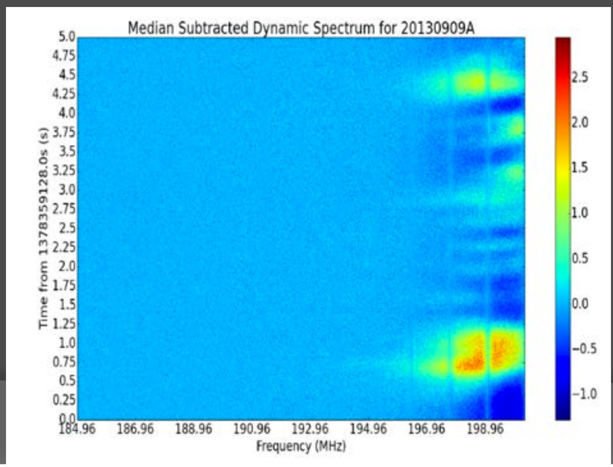
Fast transients (e.g. FRBs)



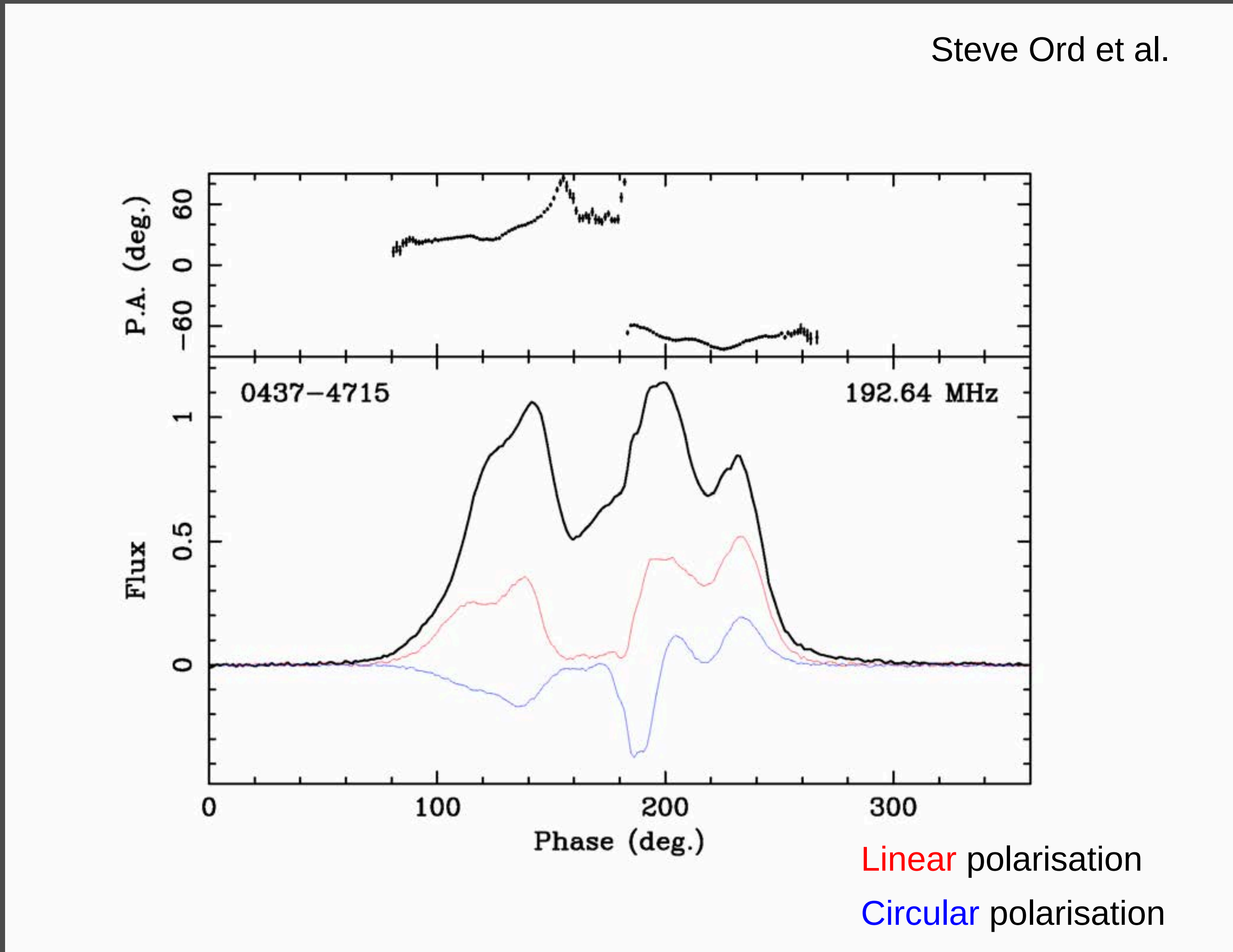
High time resolution imaging



Solar Observations



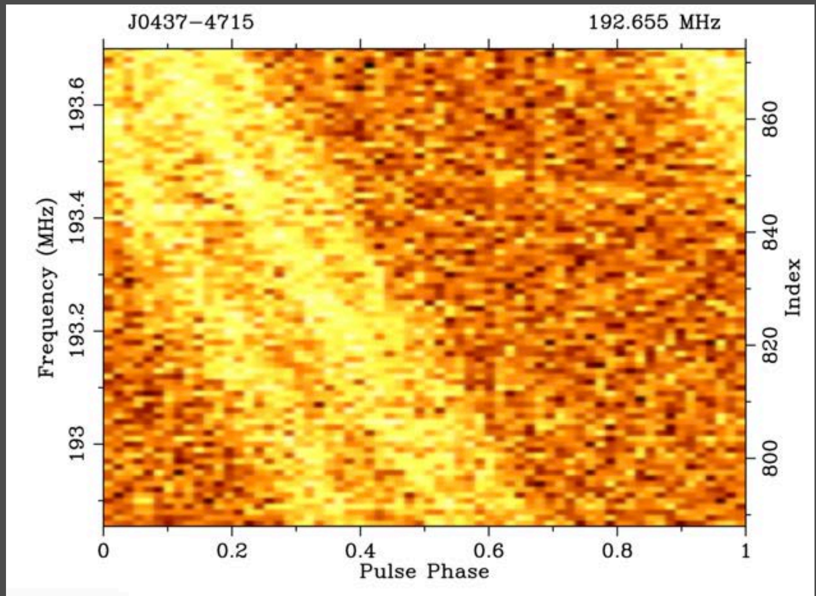
MWA coherently de-dispersed polarimetric tied array beam on MSP J0437-4715



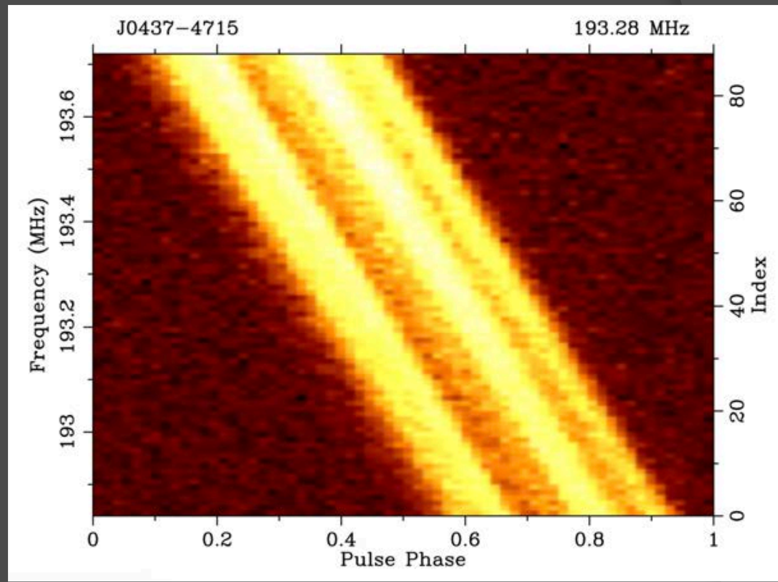
- Effectively ~ 12 μs time resolution, however there is “temporal” leakage (because of PFB)

Signal improvement on phasing up

Over a single coarse channel – effectively over a band of ~ 0.88 MHz



Incoherent detection (before phasing up)



Coherent beam (i.e. after phasing up)

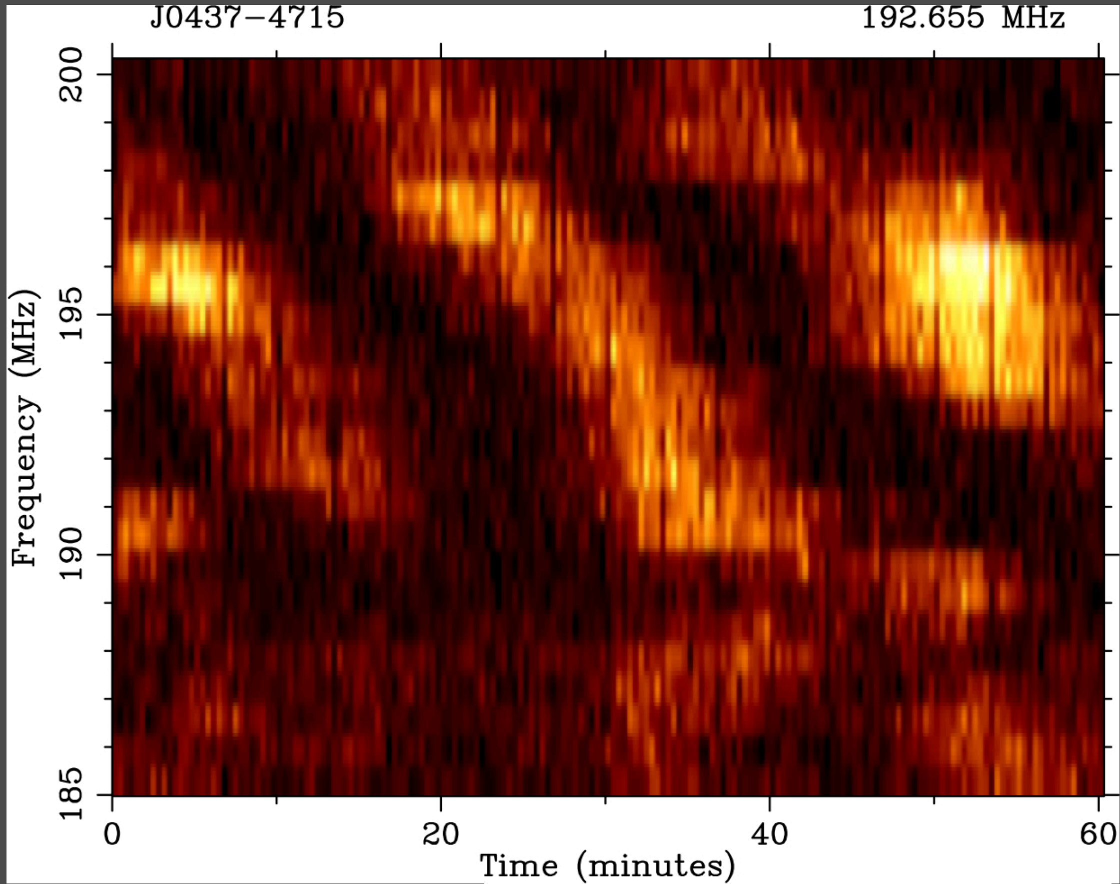
- Signal-to-noise improvement by approximately a factor of 10
- DM sweep ~ the pulse period (~5 ms) over a single coarse channel (~ 1 MHz)
- ~ 100 ms over the full 30 MHz MWA band @ 200 MHz, compared to ~ 20 ms between the 10 and 50 cm bands of PPTA data

MWA beamformer pipeline

- MWA voltage capture system 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, i.e. the real-time system (calibration using Pic A for 0437 observations)
- 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

Leverages a range of software developed by many people over the past decade!

Scintillating MSP J0437-4715 @ MWA 200 MHz

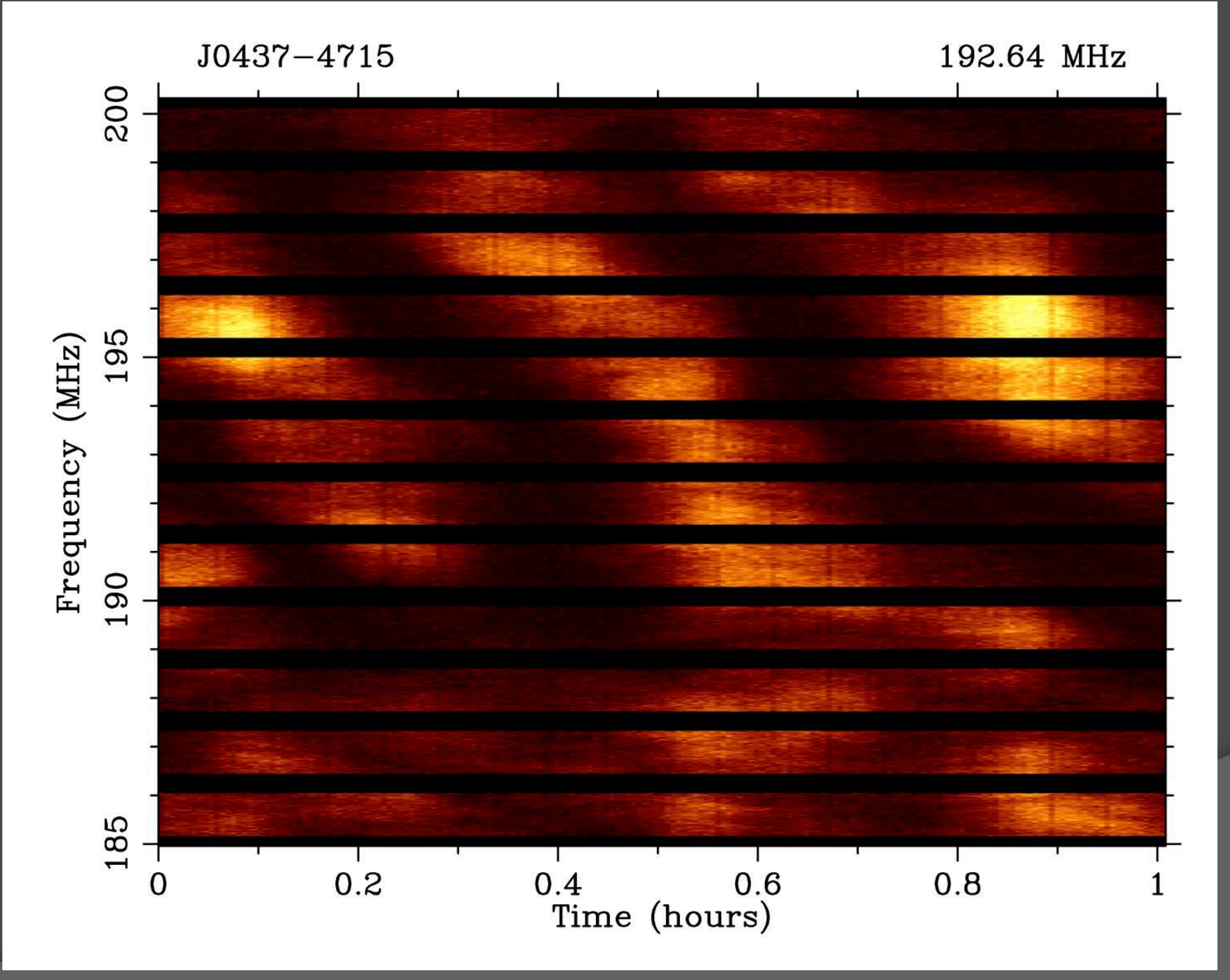


Bhat et al. (2014), **ApJL**, 791, L32

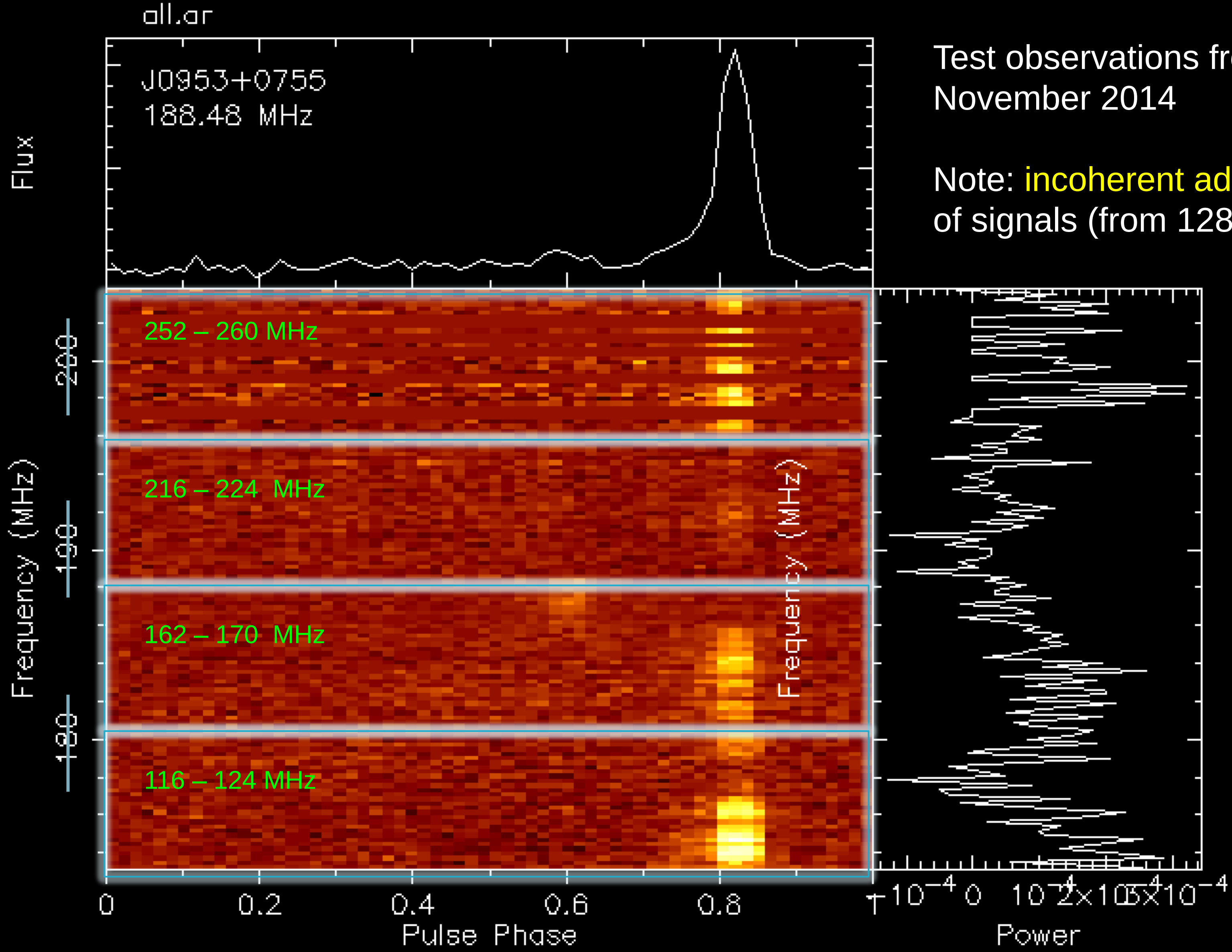
- Incoherent MWA (all 128 tiles)
- Spectral resolution = **640 kHz**
- MWA measurements ➔ transition frequency near ~ 1 GHz

Scintillating MSP J0437-4715 @ MWA 200 MHz

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



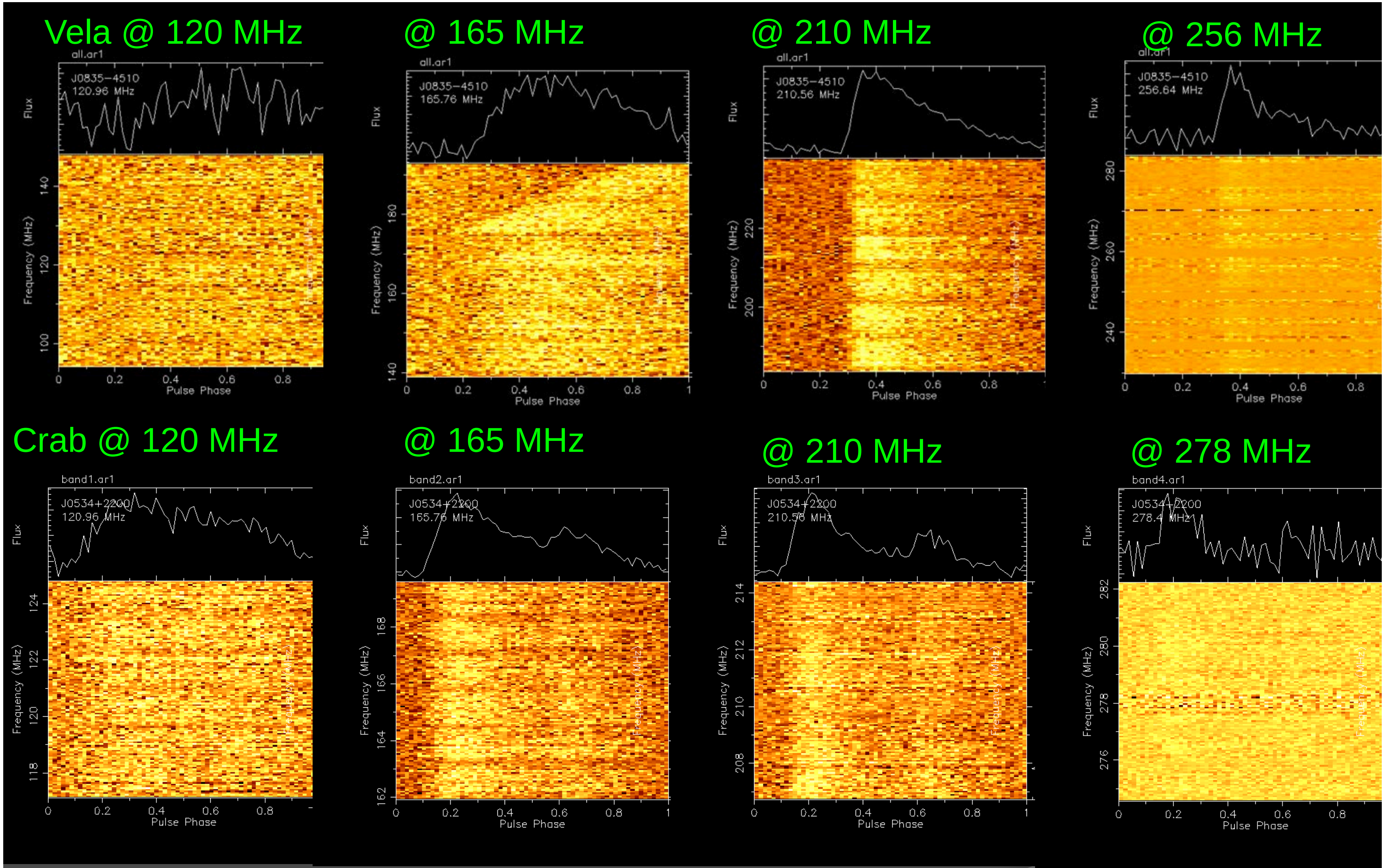
B0950+08 in the VCS “picket-fence” mode



Test observations from November 2014

Note: incoherent addition of signals (from 128 tiles)

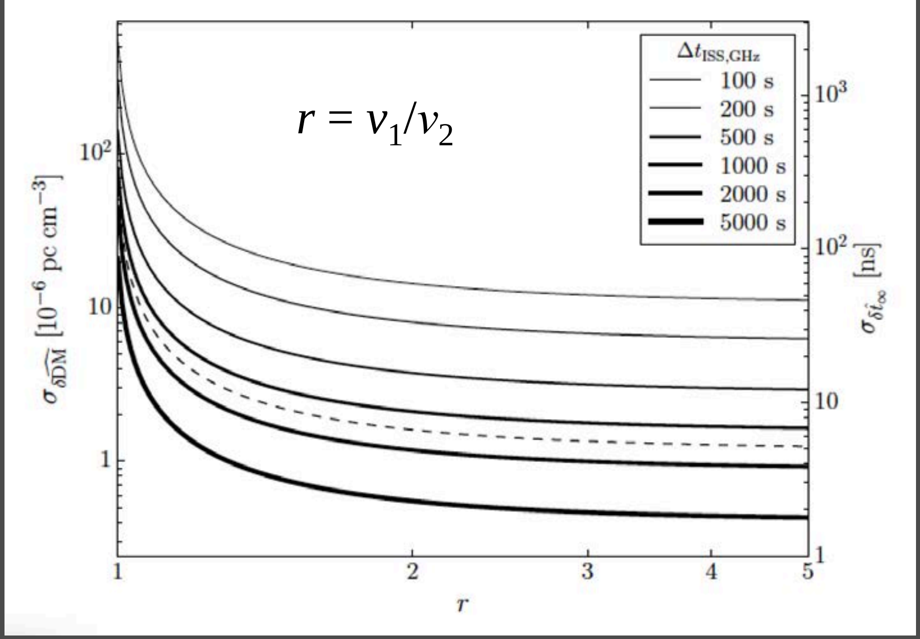
Distribute the 30.72 MHz bandwidth across the 80 – 300 MHz range as multiple sub-bands



Observations in the VCS picket-fence mode: simultaneously at **FOUR** frequency bands

From the VCS commissioning observations; **Incoherent addition** of signals from all tiles

On DM correction for PTAs



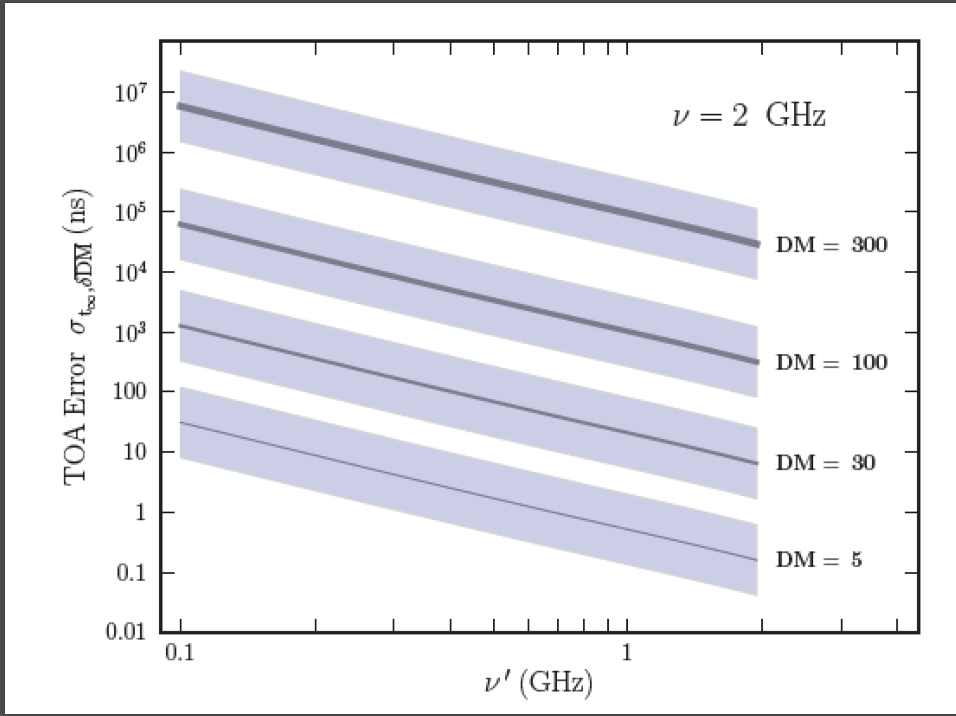
Lam, Cordes, et al. (2015), arXiv:1411.1764v2

- Measurements need to be made contemparaneously (within about ~1 day) for minimal error
- Improved timing precision (by a factor of two) from multiple (2-3) observations

- These considerations would naturally make the MWA (and SKA-low) the logical choice to support PTA experiments
- Need to demonstrate this using MWA + Parkes observations in the next ~ 2 years (i.e. before SKA-low)

On DM correction for PTAs

Cordes, Shannon, et al. (2015), arXiv:1503.0849

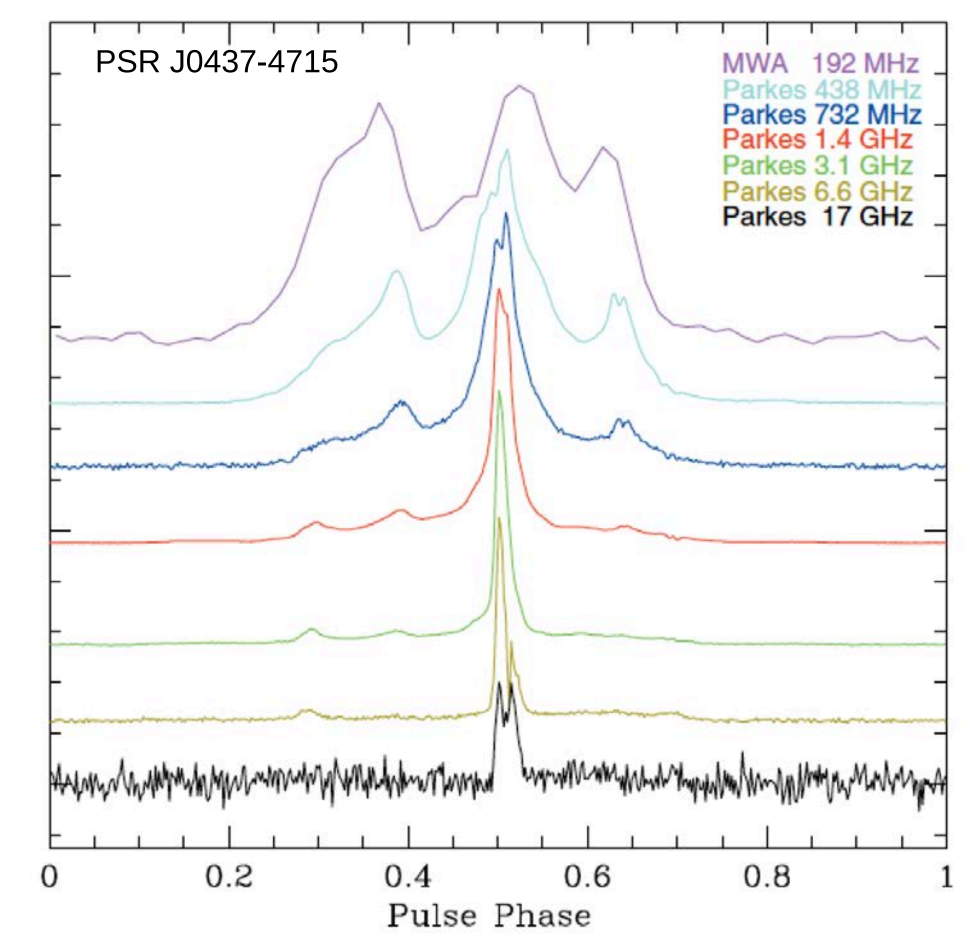


- The ISM sampled is frequency dependent ($\theta_{scatt} \sim \nu^{-2.2}$)
- TOA errors (from chromatic DMs) ~ a few 100 ns (DMs < 30 pc cm^{-3}) to ~ a few us (at larger DMs)
- Mitigatable using observations across an octave in frequency

The PPTA makes use of observations at 10cm and 50cm (700 MHz & 3100 MHz)

- Take advantage of the flexibility in the MWA system (e.g. VCS, picket fence)
- Independent DM determinations e.g. with MWA, with the ultra-wide band Rx

On DM correction for PTAs

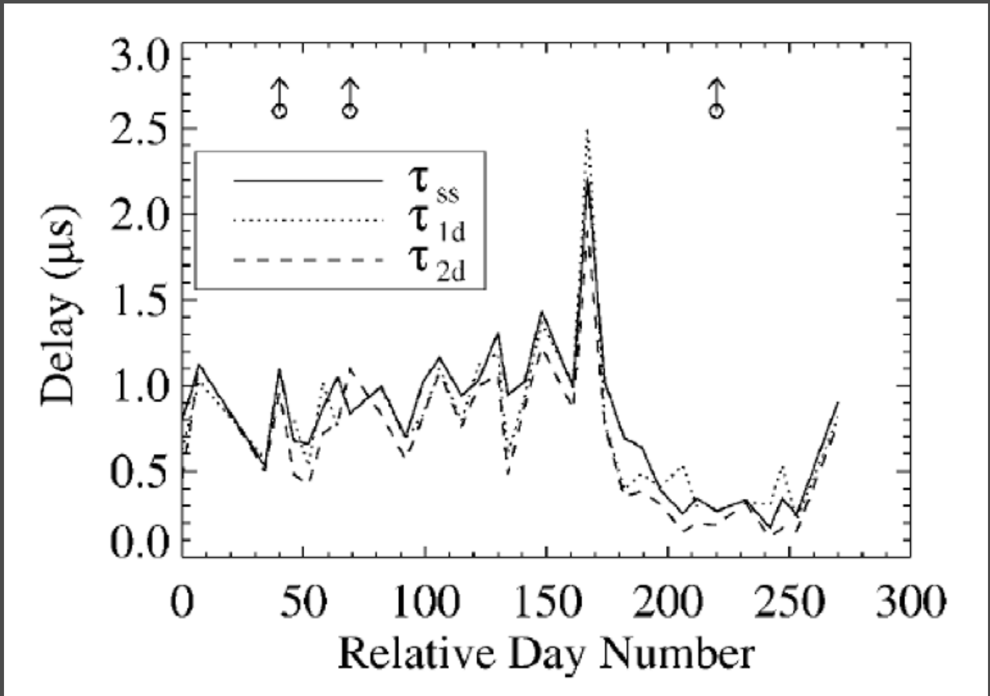


Bhat et al. (2014)

- Spectral evolution of the pulse profile is very important, particularly for measurements involving low-frequency observations (e.g. J0437-4715)

Scattering delays – how important is this?

Hemberger & Stinebring (2008) – Arecibo observations of B1737+13 **at 1380 MHz**



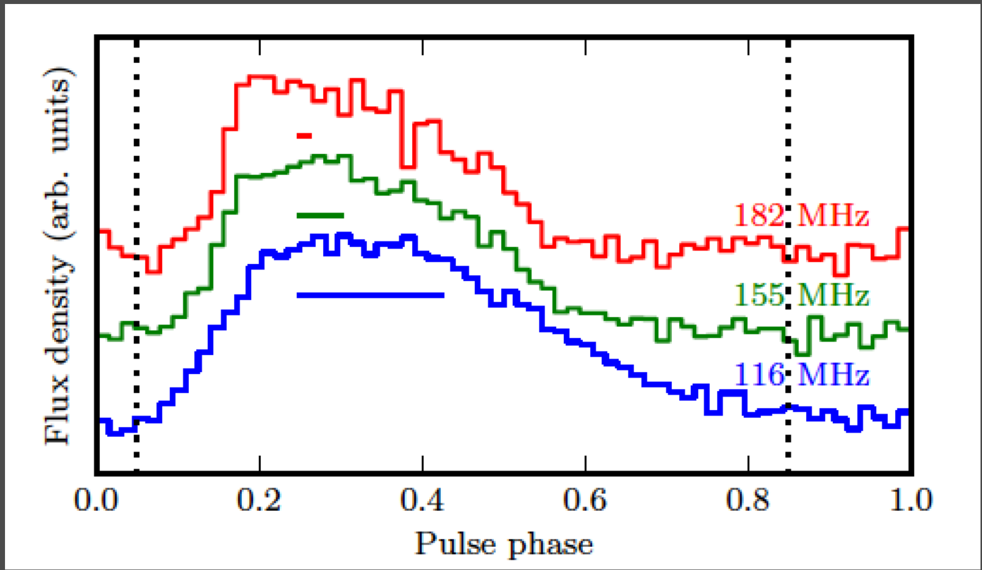
- PSR B1737+13 – a pulsar with DM = 48.6 pc cm^{-3}, location l = 37°, b = 22°
- Scattering delay varied from **0.2 μs to 2.2 μs** in observations over ~270 days
- Another source of significant "red noise" in timing data

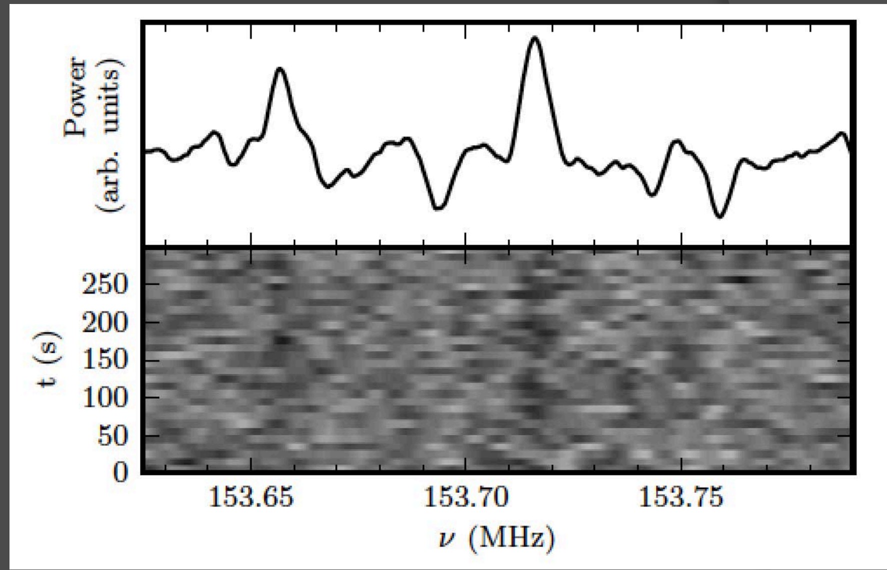
Scattering delay ~ $\nu^{-(3.6\pm0.2)}$

- MWA and SKA low bands are well suited for the chacterisation of scattering effects

Cyclic spectroscopy for ISM characterisation

- Newly developed techniques (Demorest 2011; Walker et al. 2013)
- Archibald et al. (2014) – demonstration with LOFAR observations

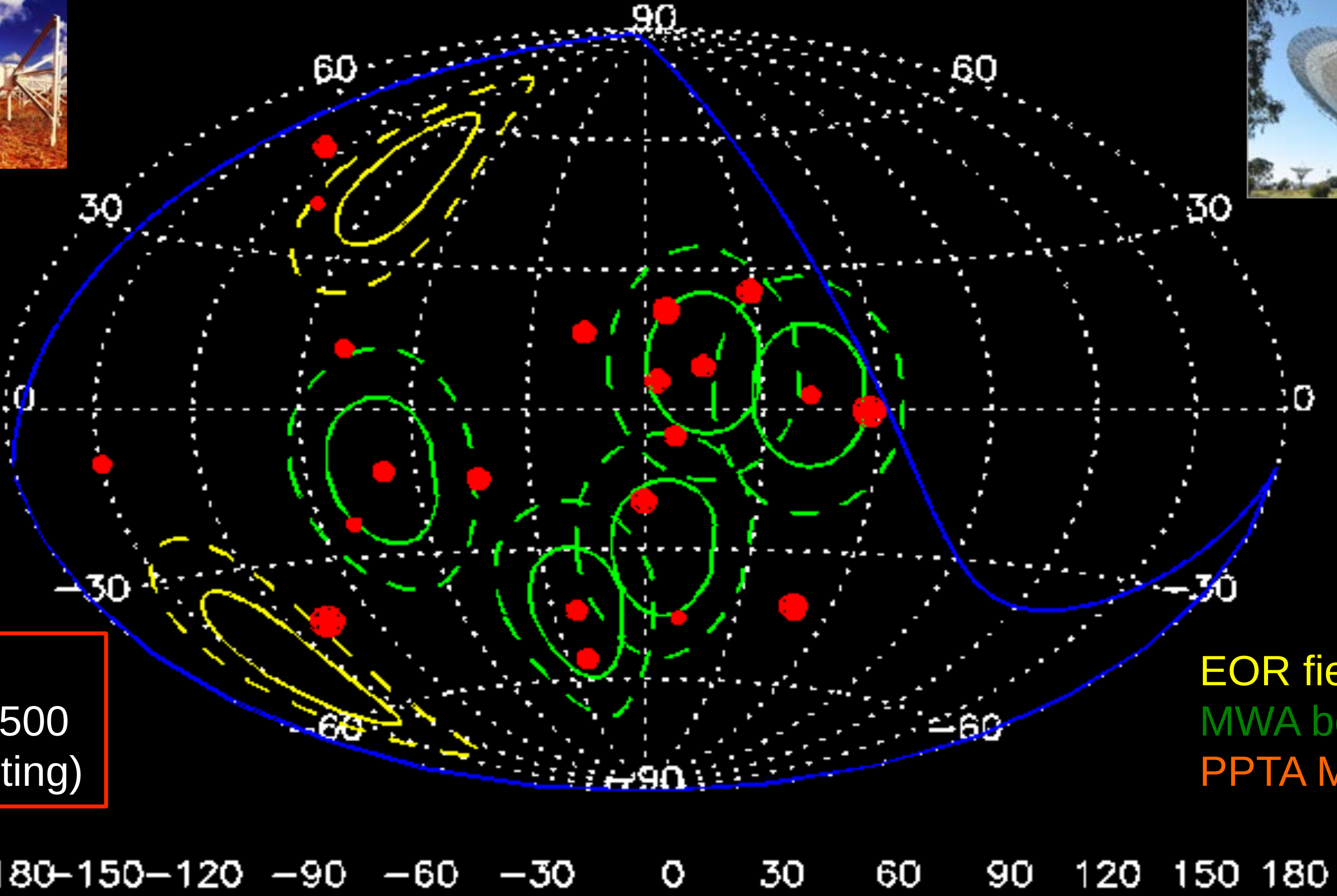




- For pulsars that require high spectral resolution (< 10 kHz) for scintillation analysis
- Combination of pulse phase resolution and high spectral resolution
- Scintillation analysis (in frequency) while also resolving scattering tail
- Powerful analysis technique if not limited by instrumental resolution

Taking advantage of the large Field of View

Observing PPTA pulsars with the MWA



Detectability:
S/N ~ 20 to 1500
(~1 hour pointing)

- Exploit the MWA's Large Field-of-View – e.g. Observations of multiple pulsars in a single pointing
- Modest observing time (~10 hr per month) to support a high profile science project in pulsar astronomy
- Commensal Observing? – e.g PSRs J0437-4715 and J1022+1001 are within the beams of EoR fields

MSP Observations @ MWA

- In the next few months (2015A):
  - Observations of MSPs from the PPTA project – all 20+ pulsars in the MWA frequency bands, regular observations of PSR J0437-4715
- In the near future (starting 2015B):
  - Commence regular observations of PTA pulsars, at a cadence similar to that of PPTA observations, contemporaneously as much as possible (i.e. within practical constraints)

Summary

- MWA is now (almost) ready for pulsar science! Commissioning of full polarimetric tied-array beam + its integration to baseband processing software. VCS mode is open for science proposals since 2015A
- MWA – the only low-frequency capable telescope for the full sample of PPTA pulsars; similarly SKA-low is the best instrument to support PTA experiments with SKA-Mid
- Recent work advocates contemporaneous, multiple measurements, across an octave in frequency for best possible DM corrections – the MWA and the new ultra-wideband receiver bring new avenues
- Not just DM corrections, but also other ISM effects (e.g. scintillation and scattering) – best studied at LFs (e.g. MWA and LOFAR work)
- Processing challenges – e.g. beam forming requirements, going from 100+ elements over ~3 km (MWA) to 500+ elements over ~60-80 km (SKA-low) – MWA makes an excellent test bed to move in this path