Frequency-dependent dispersion measure towards the millisecond pulsar J2241-5236

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I acknowledge the Wadjuck people, past, present and future, as the original custodians of this land

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Detection of Frequency-dependent Dispersion Measure toward the Millisecond Pulsar J2241–5236 from Contemporaneous Wideband Observations

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Abstract

Making precise measurements of pulsar dispersion measures (DMs) and applying suitable corrections for them is among the major challenges in high-precision timing programs such as pulsar timing arrays (PTAs). While the advent of wideband pulsar instrumentation can enable more precise DM measurements and thence improved timing precision, it also necessitates doing careful assessments of frequency-dependent (chromatic) DMs that were theorized by Cordes et al (2016). Here we report the detection of such an effect in broadband observations of the millisecond pulsar PSR J2241−5236, a high-priority target for current and future PTAs. The observations were made contemporaneously using the wideband receivers and capabilities now available at the Murchison Widefield Array, the upgraded Giant Metrewave Radio Telescope, and the Parkes telescopes, thus providing an unprecedentedly large frequency coverage from 80 MHz to 4 GHz. Our analysis shows the measurable changes in DM that scale with the observing frequency (ν) as $\delta \mathrm{DM} \propto \nu^{2.5\pm0.1}$. We discuss the potential implications of such a frequency dependence in the measured DMs and the likely impact on the timing noise budget and comment on the usefulness of low-frequency observations in advancing PTA efforts.

Unified Astronomy Thesaurus concepts: Millisecond pulsars (1062)

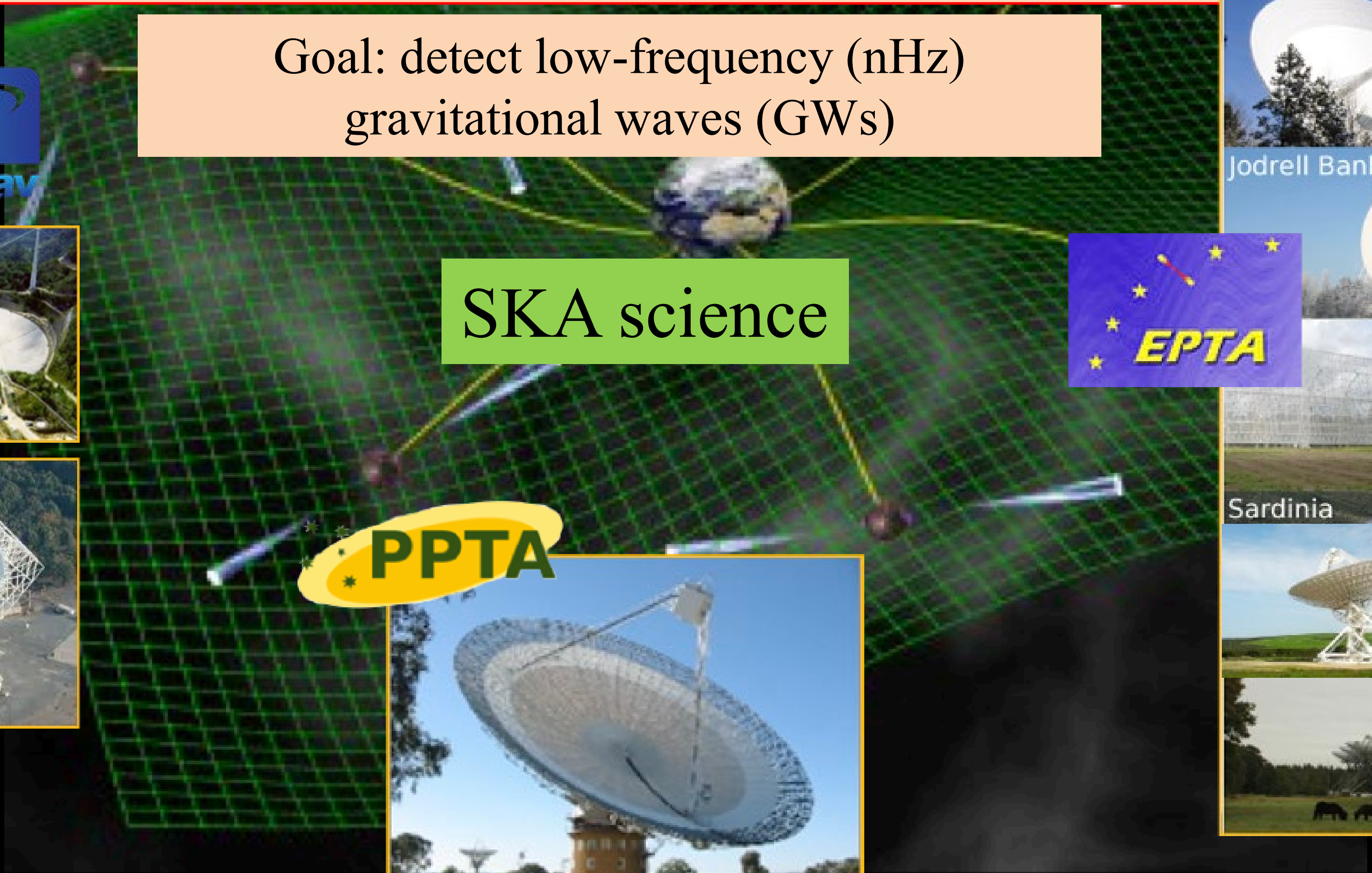
Kaur et al. (2022)

Pulsar Timing Arrays (PTAs)

Pulsar Timing Array (PTA): an experiment of regular, high precision timing observations of widely distributed array of MSPs to search for ultra low frequency gravitational waves (GWs)

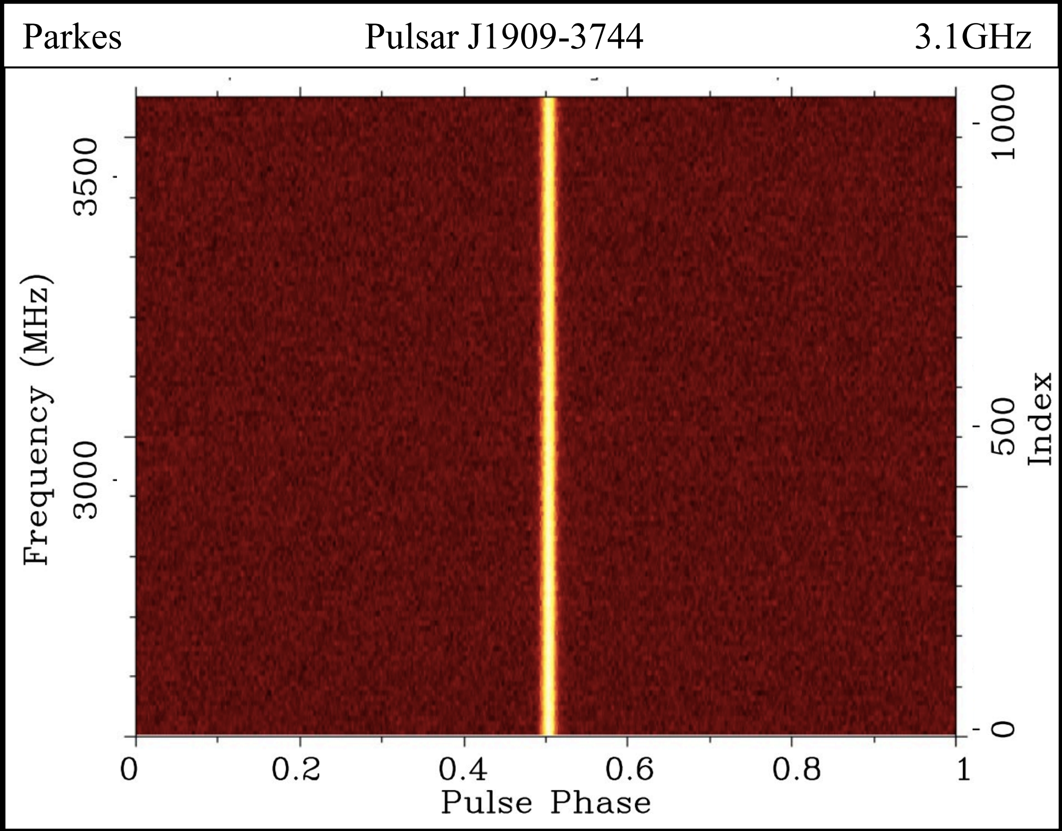
Goal: detect low-frequency (nHz) gravitational waves (GWs)

SKA science



credit: David J. Champion

ISM effects: Dispersion



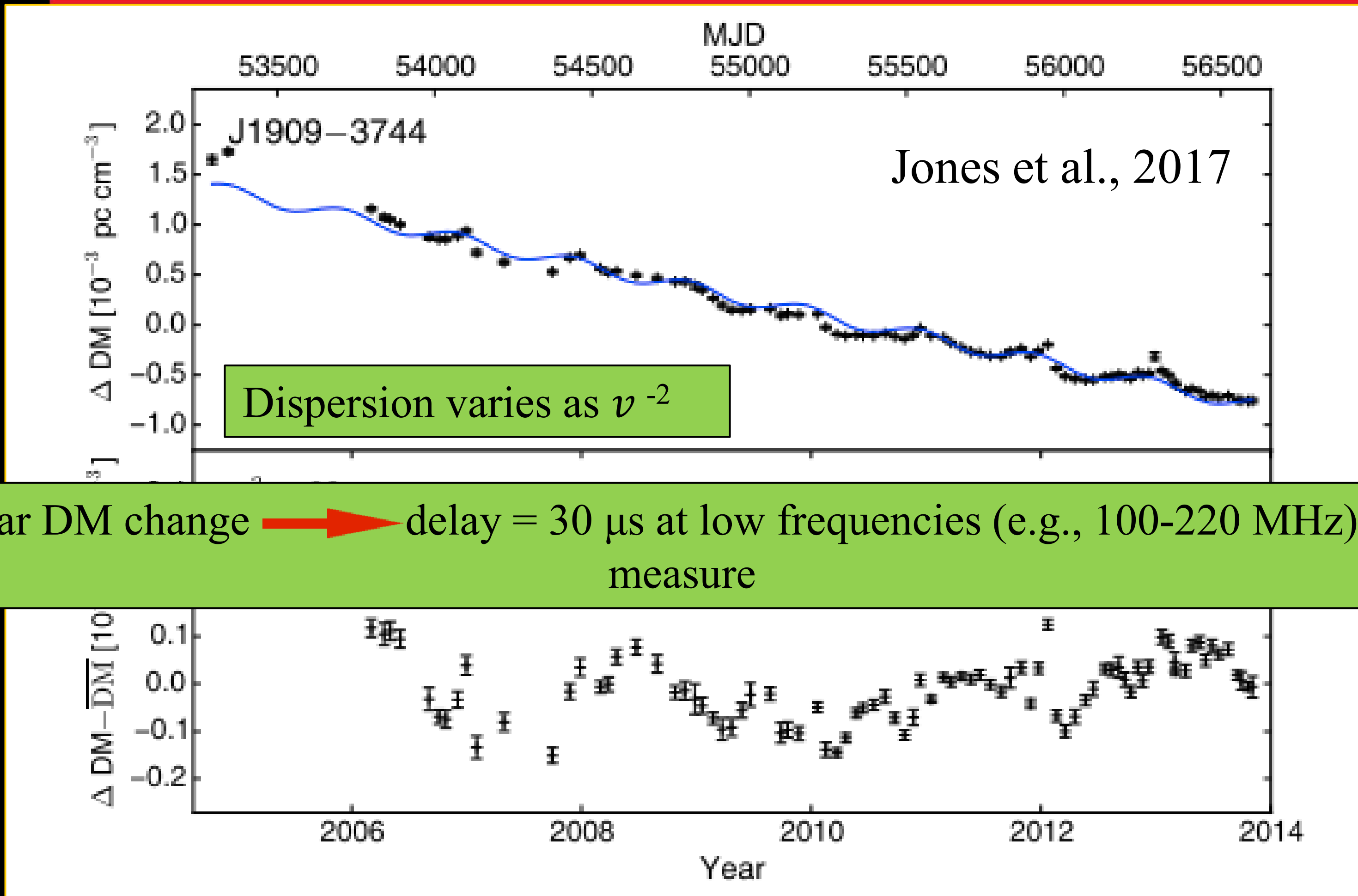
$$\Delta t \simeq 4.15 \times 10^6 ms \times (\nu_{high}^{-2} - \nu_{low}^{-2}) \times DM$$

Pulsar signal is dispersed by free electrons in interstellar medium.

$$\mathrm{DM} = \int_0^d n_e(l)dl$$

- Even very small changes in DM can effect timing.
- PTA- years of data.
- Need to be tracked at every observing epoch. (Keith et al. 2013; Lee et al. 2014; Jones et al. 2017)

DM variations in the PTA data



Similar DM change → delay = 30 μs at low frequencies (e.g., 100-220 MHz) – can measure

Delta DM ~ (0.02 – 3.1) × 10^{-4} pc cm $^{-3}$

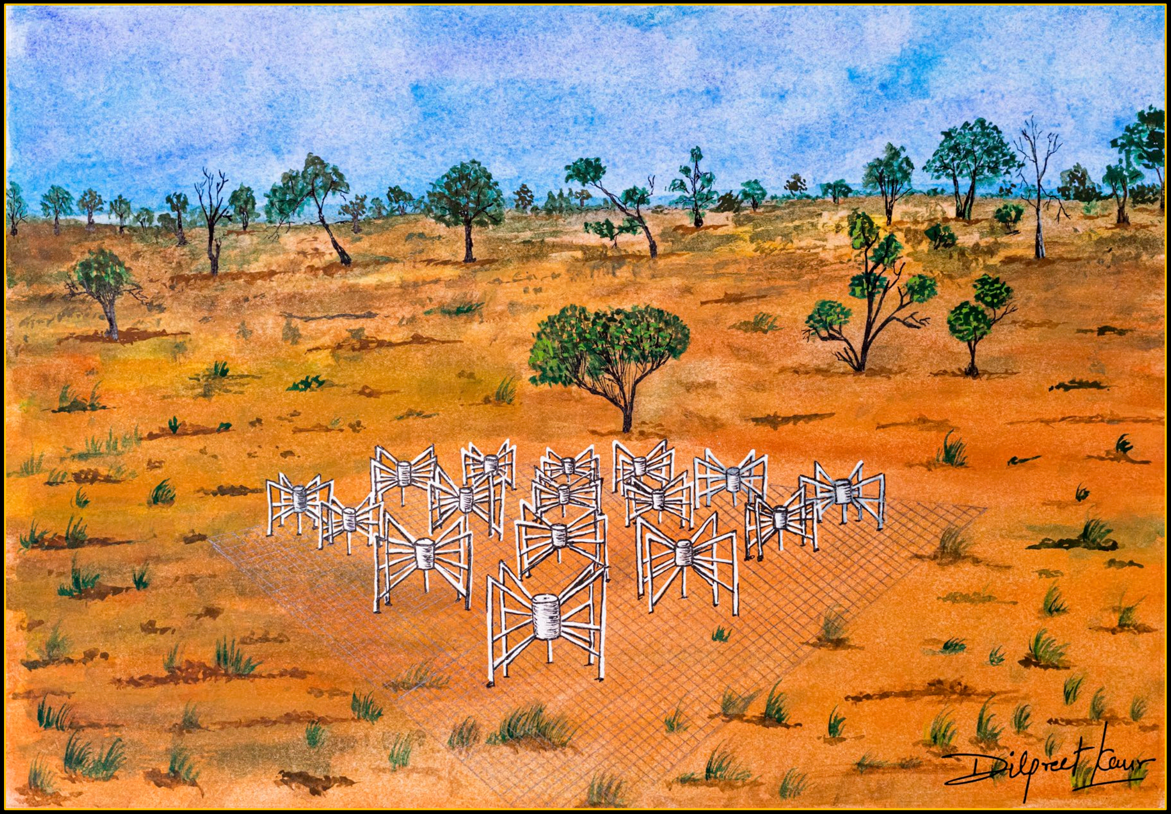
Change in DM ~ 0.0001 pc cm^{-3} → delay = 300 ns at timing frequencies (~1-2 GHz) – hard to measure

The Murchison Widefield Array

MWA
MURCHISON WIDEFIELD ARRAY

- Operating frequency range: 80-300 MHz
- SKA precursor

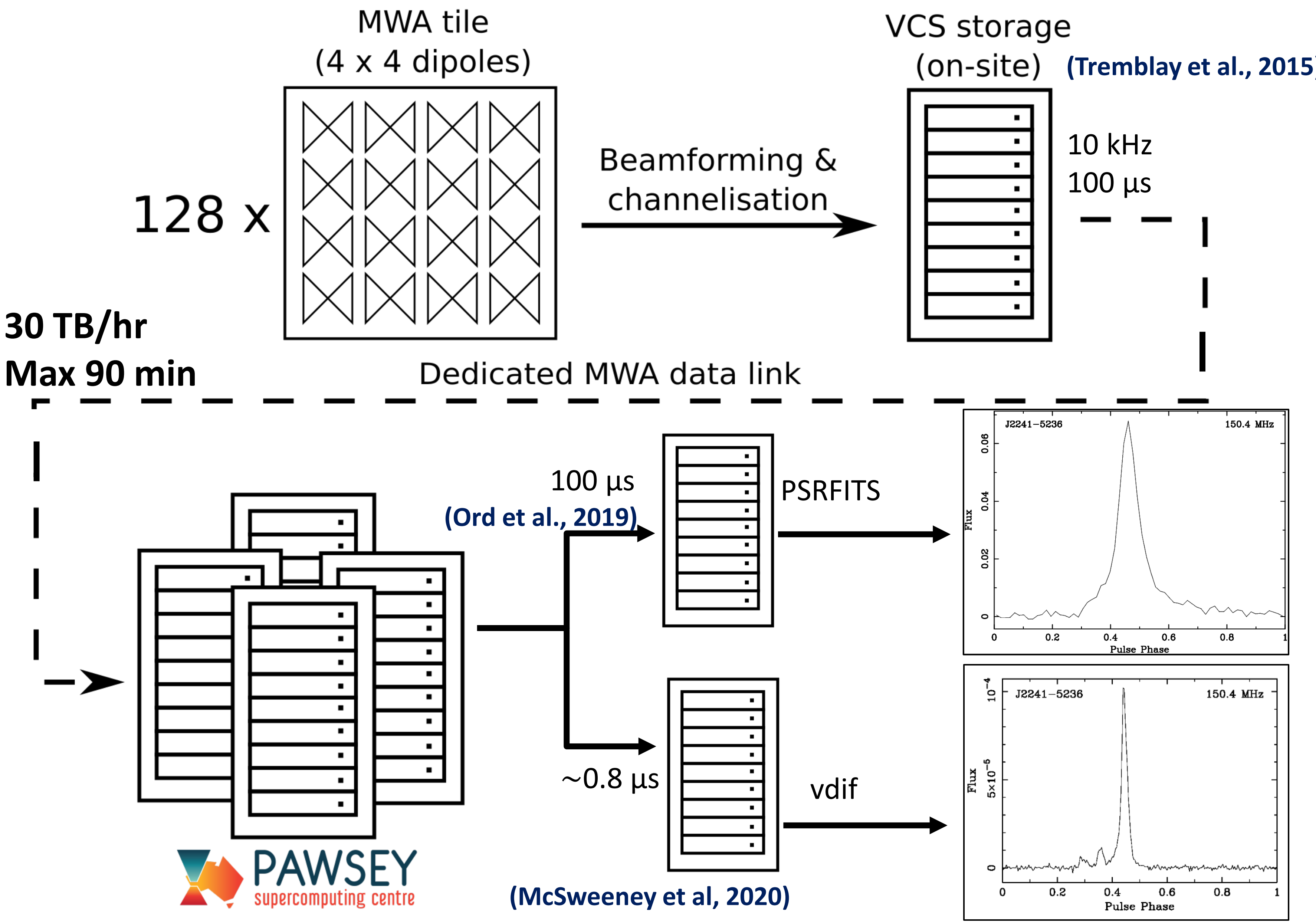
Tingay et al. (2013), Wayth et al. (2018)



Dilpreet Kaur

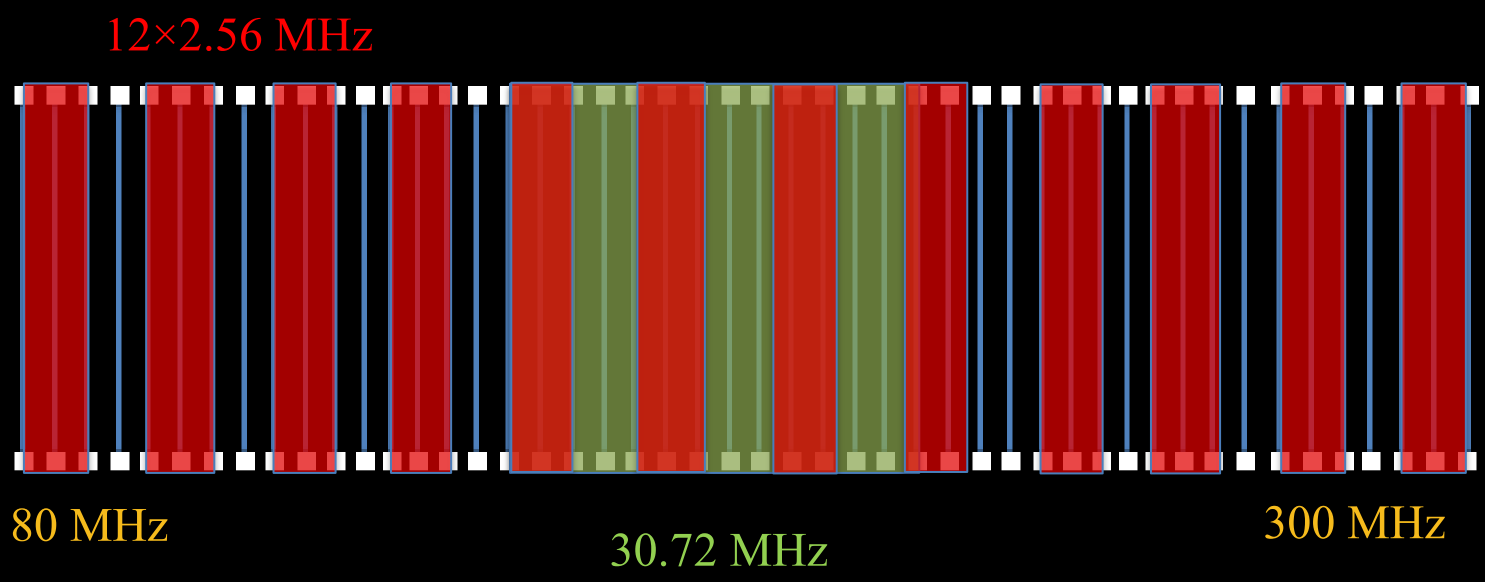
- 256 tiles (128 at a time, each consists 16 dipoles, 4×4 dual polarisation array)
- Frequency channels: 24 coarse channels (1.28 MHz), 30.72 MHz in total 128 fine channels (10 kHz) for each coarse channel
- Phase 3 upgrade in progress: new correlator & signal path

MWA’s Pulsar signal path

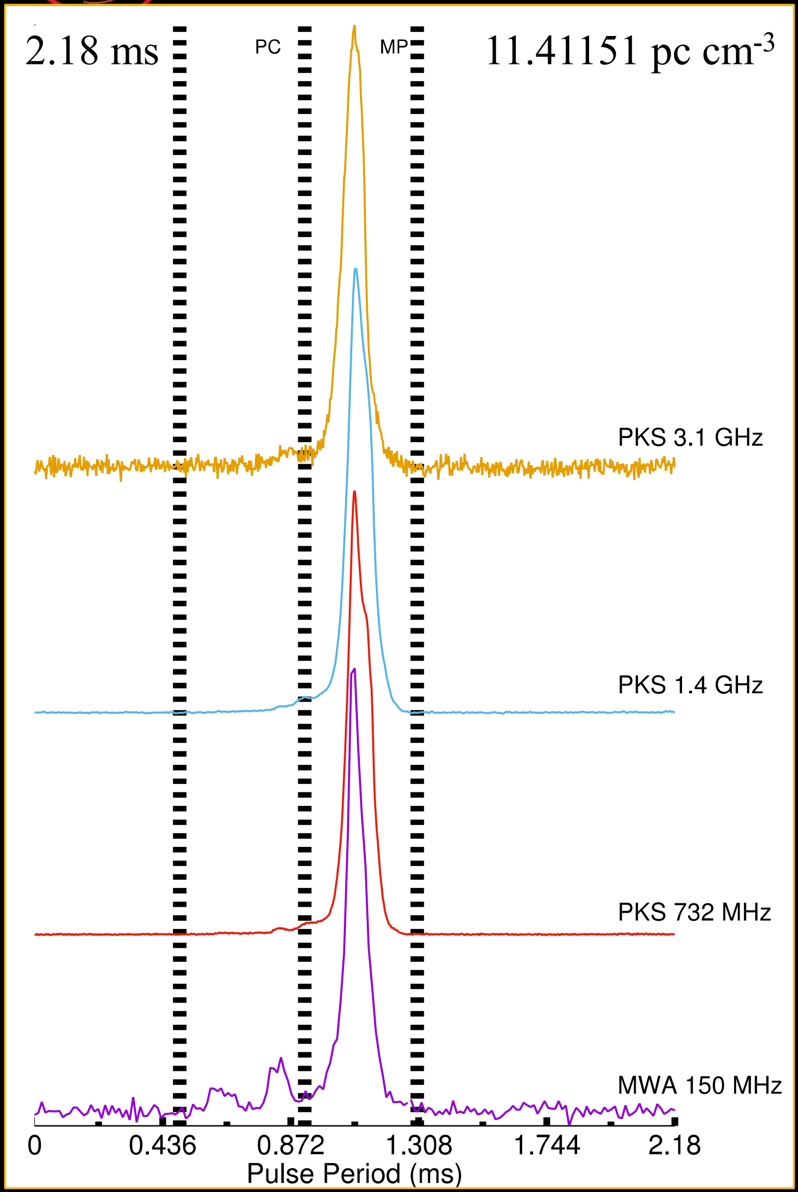


Picket fence mode observations with the MWA

- Frequency coverage from ~ 80 - 300 MHz: To study ISM effects
- Frequency lever arm
- 30.72 MHz maximum bandwidth
- “Picket-fence” mode of observation



J2241-5236: MWA and Parkes profiles

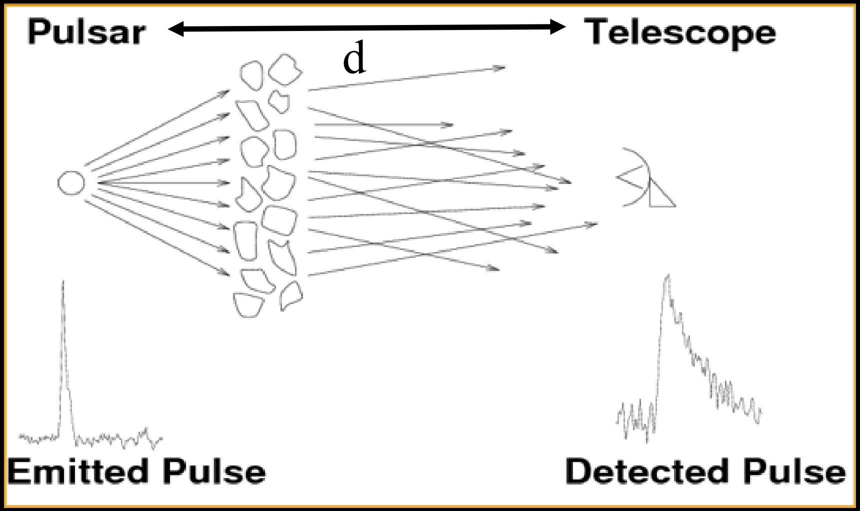


- Pulse profiles of J2241-5236
  - 3.1 GHz
  - 1.4 GHz
  - 732 MHz
  - 150 MHz
- Narrow pulse width ~150 μs

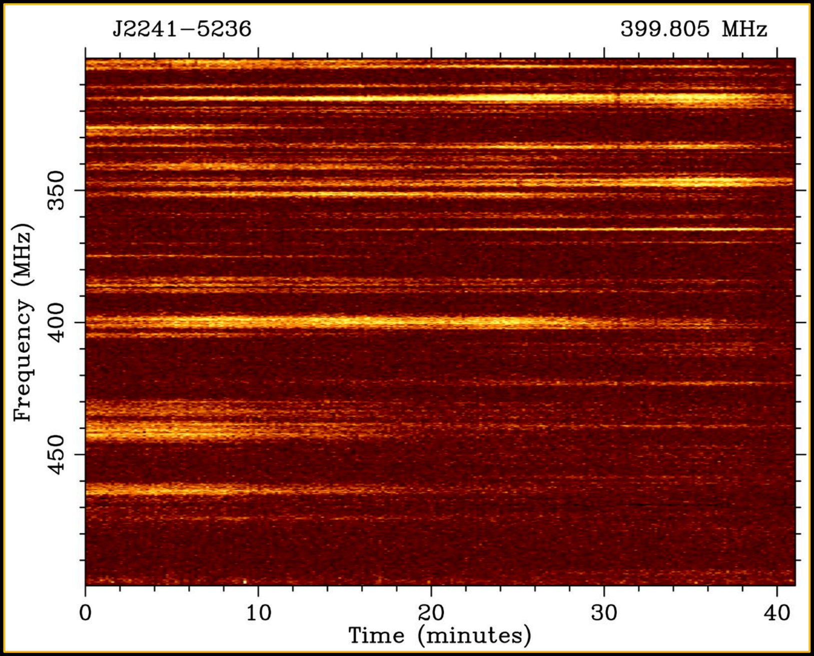
Large frequency lever arm, improved **timing precision** of the order of ~1 μs = excellent precision in dispersion measure (DM) measurements ~2 x 10^{-6} pc cm^{-3}

Kaur et al. (2019)

ISM effects: Scintillation and Scattering



Credit: pulsar handbook



$$\theta_s \propto \nu^{-2}$$

$$2\pi\, \tau_d\, \nu_d \sim 1$$

$$\tau_d \propto \nu^{-4}\, d^2$$

- Density fluctuations from ~ 1000s km to 100s AU
- Small scale - Diffractive scintillation - modulation of signal
- Large scale - Refractive scintillation - focusing/defocusing - flux variation, change of scintillation pattern

Frequency-dependent dispersion measure

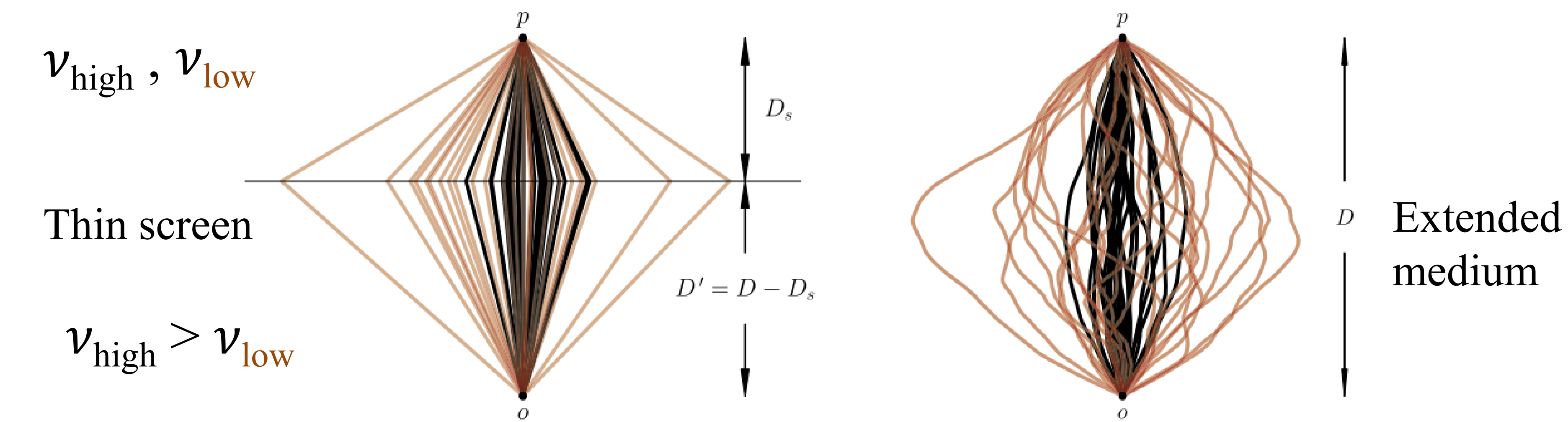


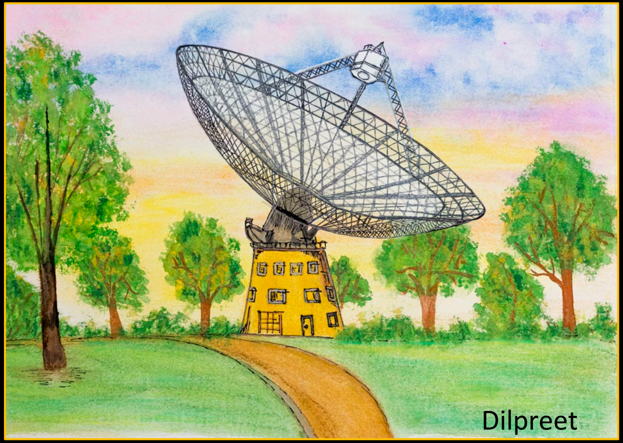
Figure 1. Geometries for scattering from a thin screen (left) and filled medium (right). Black lines show simulated ray paths at frequency ν and red lines are for frequency $\nu' = \nu/2$. The pulsar-observer distance is D. The thin screen is at a distance D_s from the pulsar at p and $D' = D - D_s$ from the observer at o.

Cordes et al. (2016)

$$\theta_s \propto \nu^{-2}$$

- Chromatic DMs result from multipath propagation caused by diffraction and refraction from interstellar electron density variations.
- First discussion by Cordes et al. (1990)
- Some studies so far Ramachandran et al. (2006), MSP B1937+21; Donner et al. (2019) , 50-200 MHz, long-period PSR J2219+4754

Observations with the MWA, uGMRT, and Parkes



Artwork by Dilpreet Kaur

MWA = 80-220 MHz

Band 3 = 300-500 MHz
Band 4 = 550-750 MHz

Parkes = UWL
700 MHz-4000 MHz

- Contemporaneous observations of two MSPs (J2241-5236 and J2145-0750)
- November 2019, multiple observing campaigns
- Three sessions spanning a full month
- Coverage from 80 MHz (MWA) to 4 GHz (Parkes UWL)
- Coordinated observations with the PPTA observing sessions

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Before investigating frequency dependence

1. Temporal DM variations ✓
   Contemporaneous observations (within 24 hours)

2. Orbital DM variations

3. Profile evolution with frequency

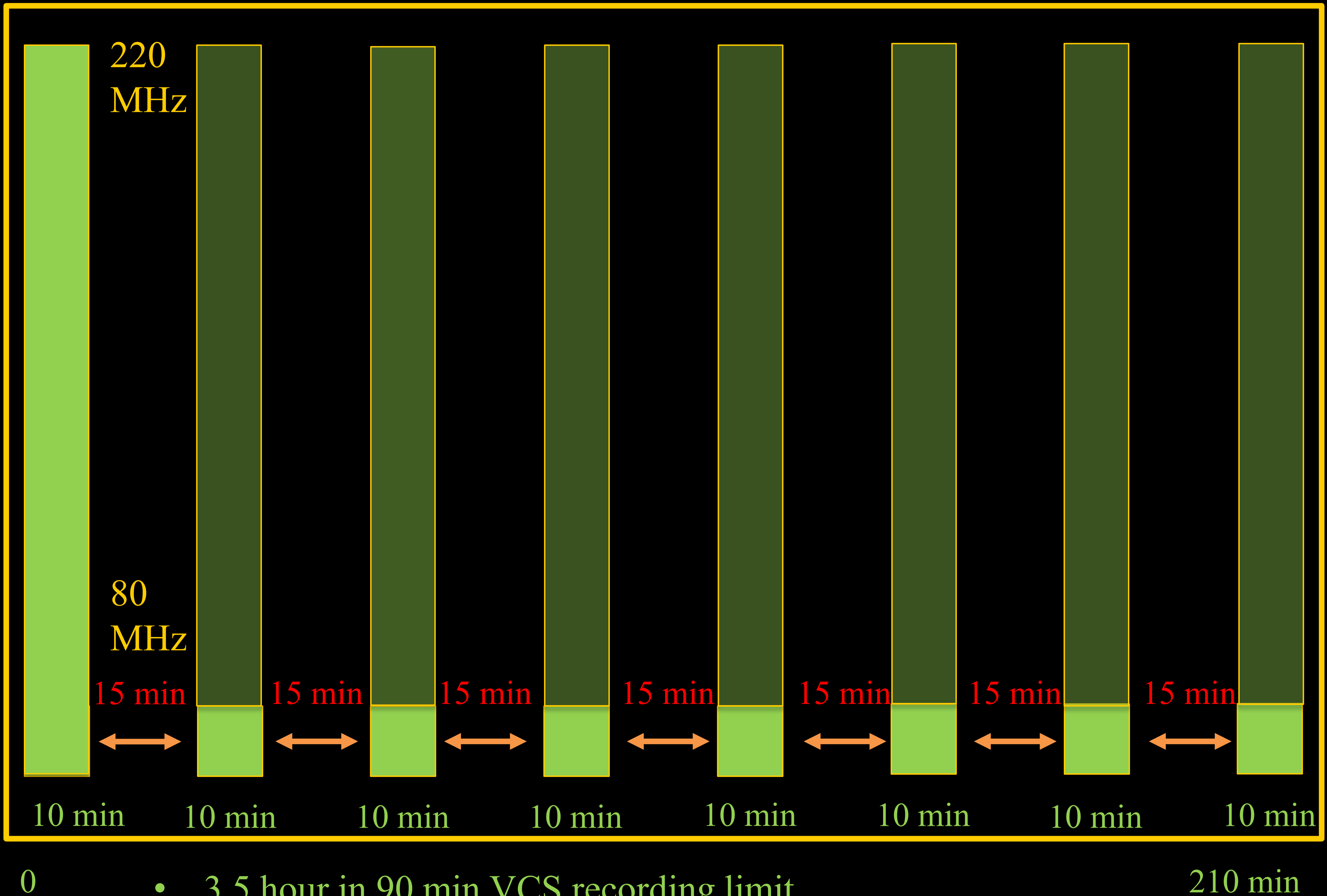
Before investigating frequency dependence

1. Temporal DM variations ✓

   Contemporaneous observations (within 24 hours)

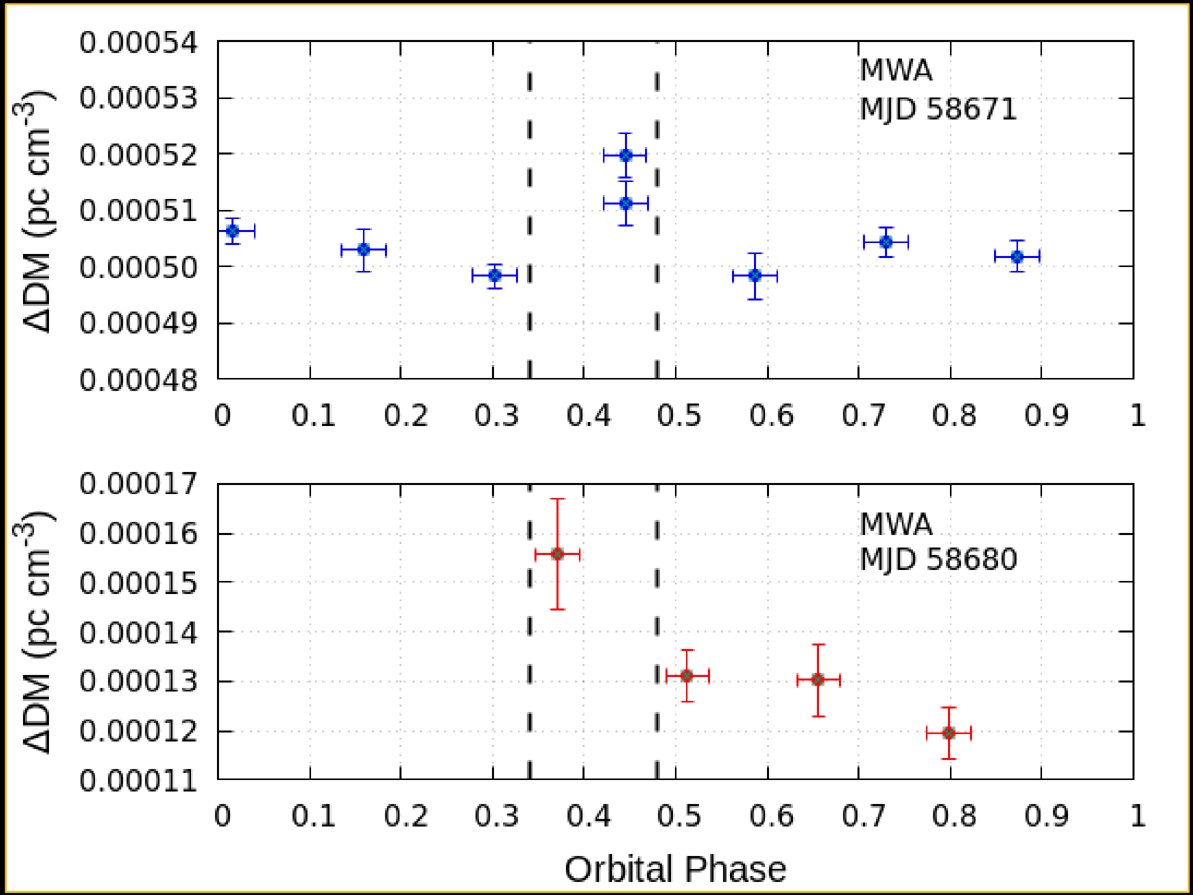
2. Orbital DM variations
   - 3.5 hour binary system with black widow type companion: Non-eclipsing
   - An et al 2018: modulations in gamma-ray studies
   - VCS maximum recording: 90 min, 50 TB

3. Profile evolution with frequency



- 3.5 hour in 90 min VCS recording limit
- More complicated observation to plan and calibrate

Orbital DM variations: J2241-5236

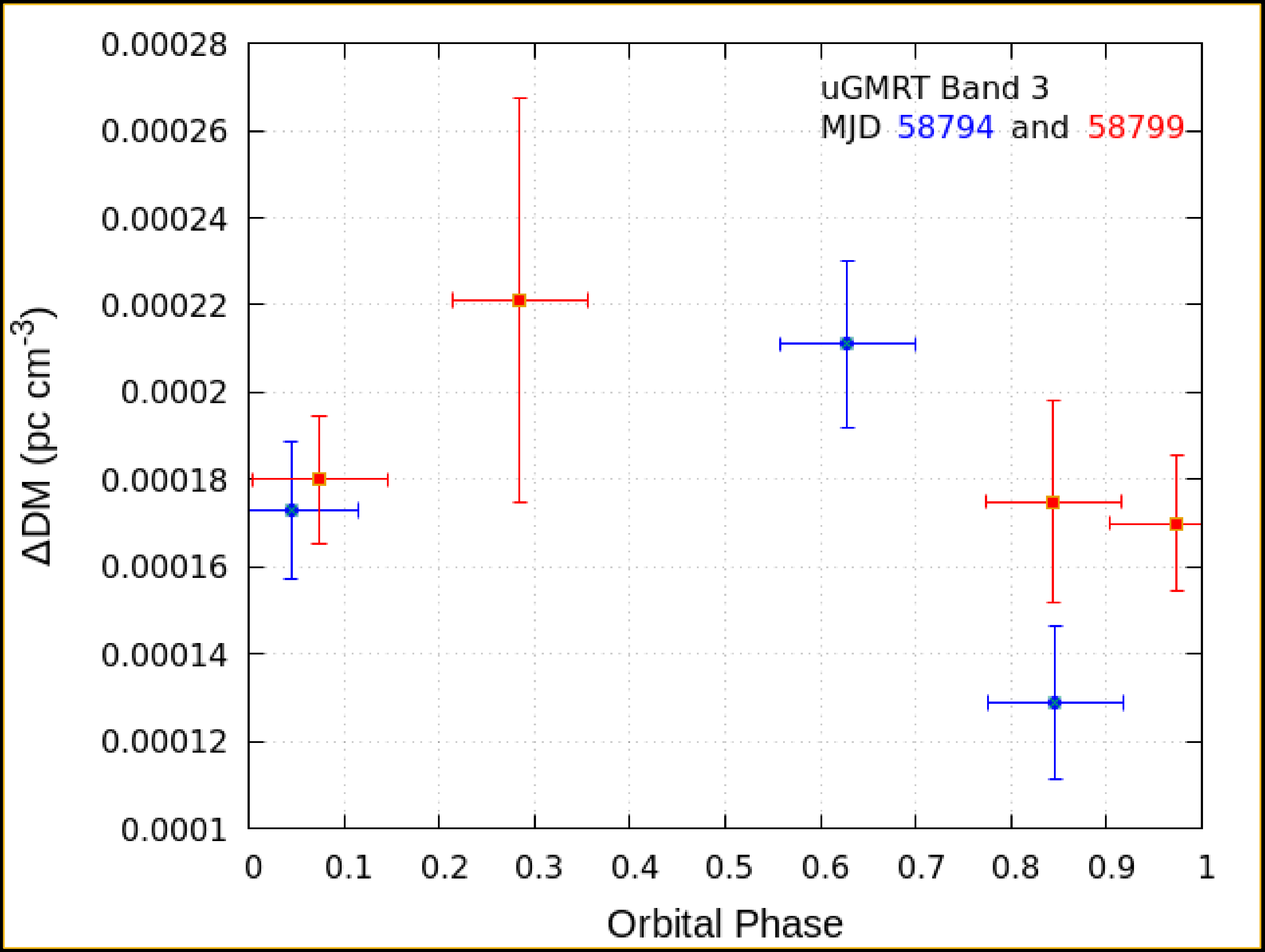


DM excess of $(1.4 \pm 0.6) \times 10^{-5}$ pc cm^{-3}

- 110 ± 50 ns at timing frequencies (~1-2 GHz)

Kaur et al. (2022)

Orbital DM variations: J2241-5236



Kaur et al. (2022)

Before investigating frequency dependence

1. Temporal DM variations

   Contemporaneous observations (within 24 hours)

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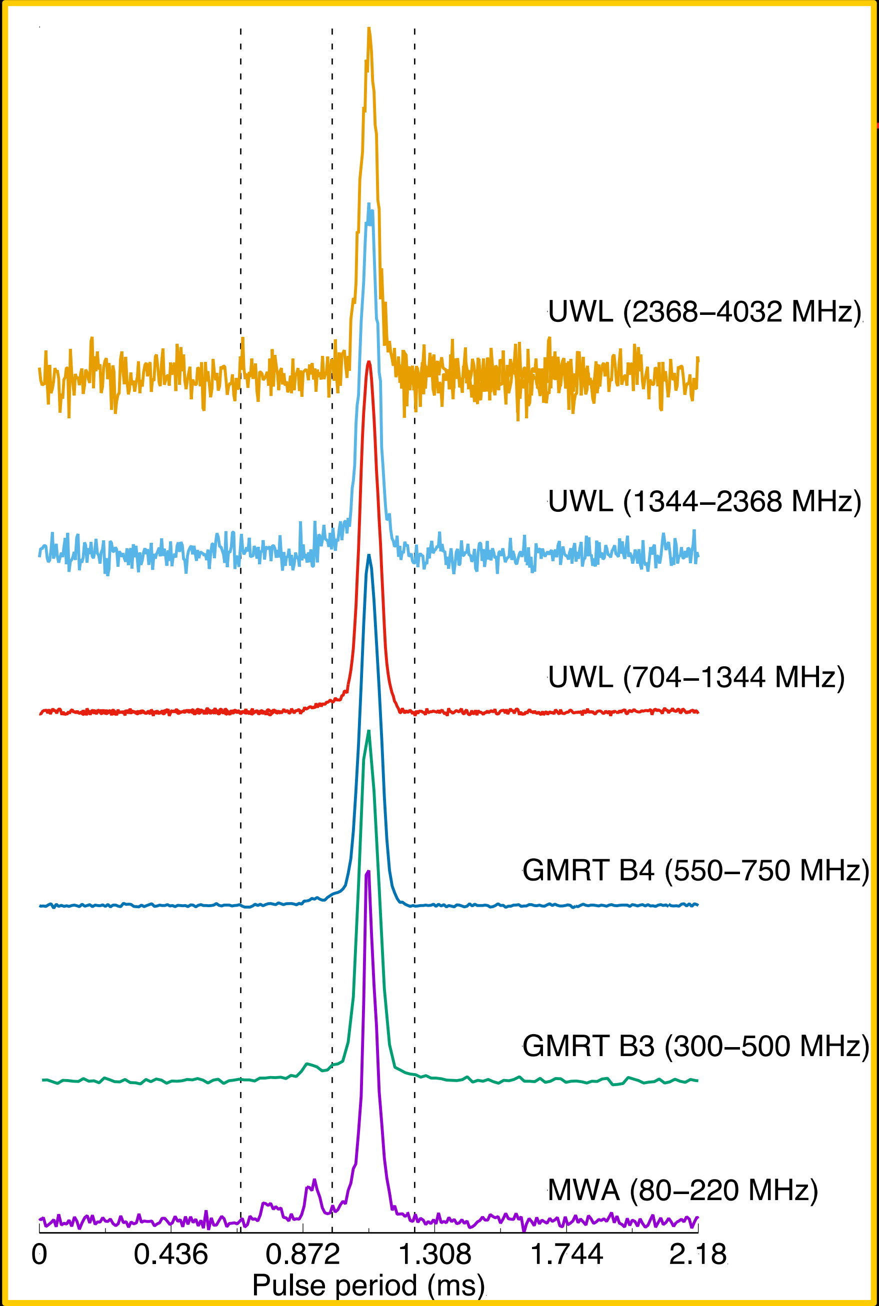
   - 3.5 hour binary system with black widow type companion: Non-eclipsing
   - An et al 2018: modulations in gamma-ray studies
   - VCS maximum recording: 90 min, 50 TB

3. Profile evolution with frequency

PSR J2241-5236



- Choice of good target
- Profile evolution is not large
- pulse width changes by 2% (uGMRT bands) to 10% (MWA, UWL)
- Analytic templates for each band
- Wideband timing using PulsePortraiture

Kaur et al. (2022)

Before investigating frequency dependence

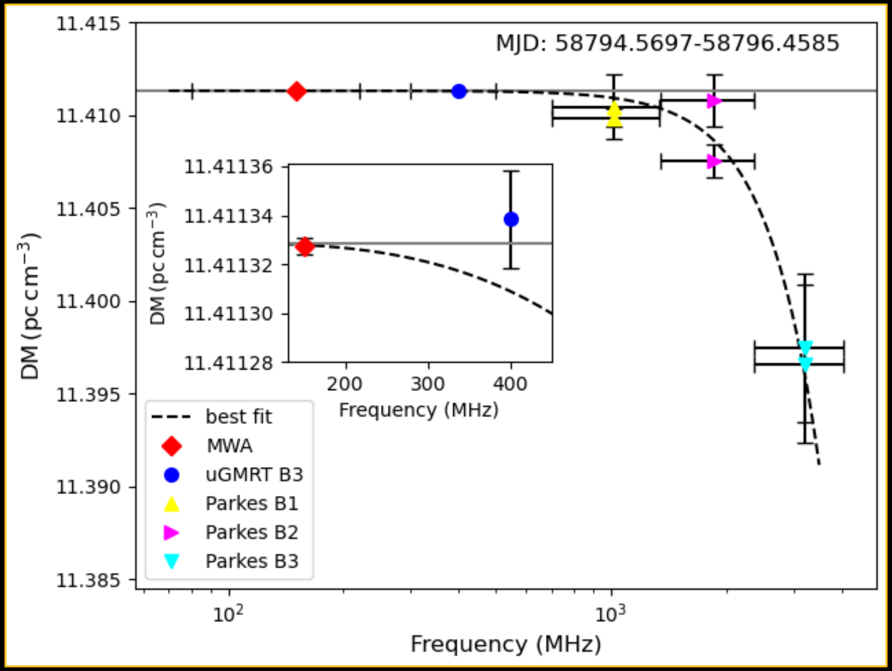
1. Temporal DM variations ✓
   Carefully planned contemporaneous observations

2. Orbital DM variations ✓
   Very small variations but measurable

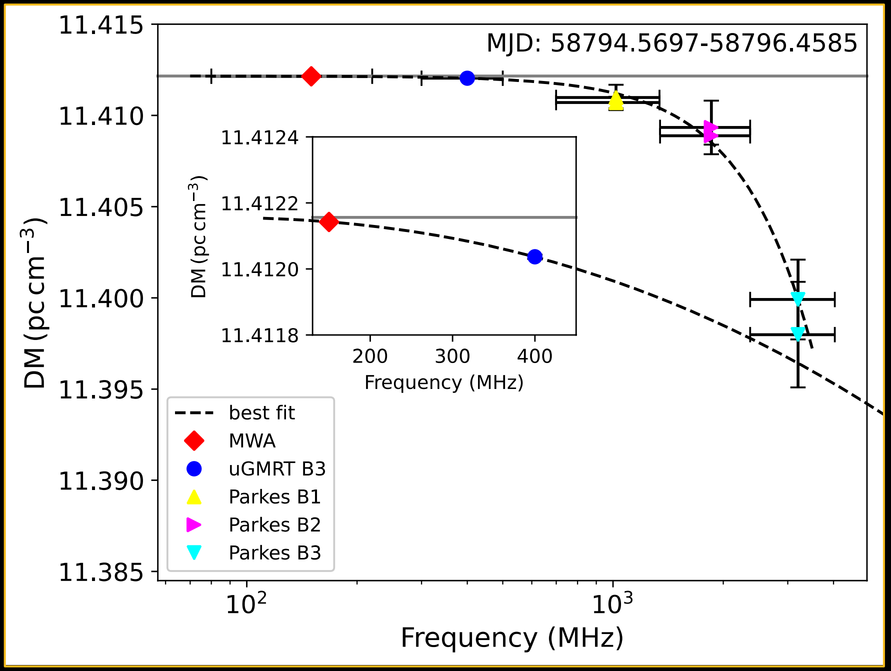
3. Profile evolution with frequency ✓
   Minimal (10%) profile evolution from ~100 MHz to 4 GHz

Frequency-dependence of DM: J2241-5236

Narrow band timing



Wide band timing



$1.5 \pm 0.3 \times 10^{-2}$ pc cm^{-3}

0.1 GHz 3 GHz

$1.2 \pm 0.2 \times 10^{-4}$ pc cm^{-3}

0.1 GHz 0.5 GHz

Delta DM $\propto \nu^{\alpha}$

E1 = 3.2±0.6

E2 = 4.1±0.4

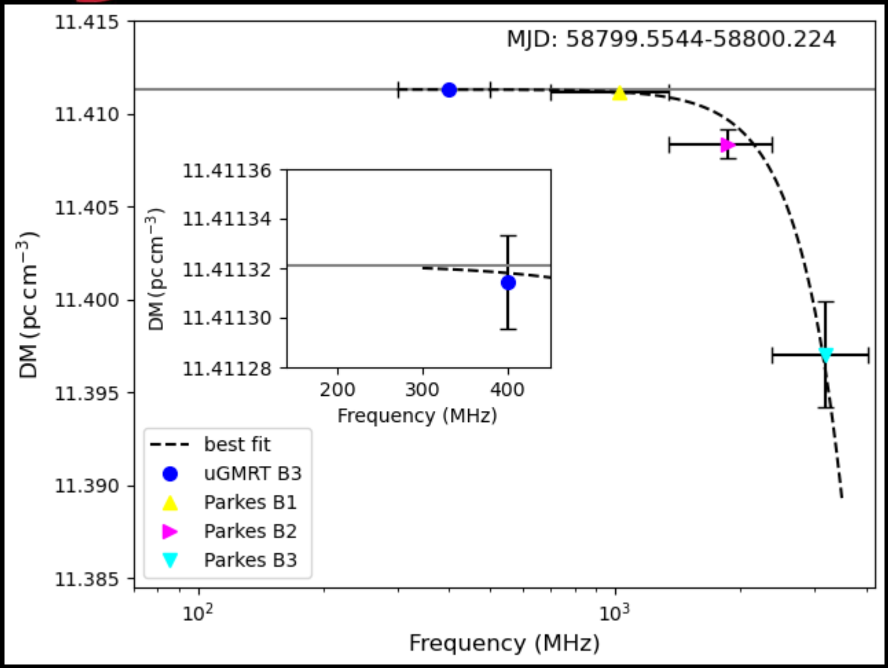
E3 = 2.9±0.4

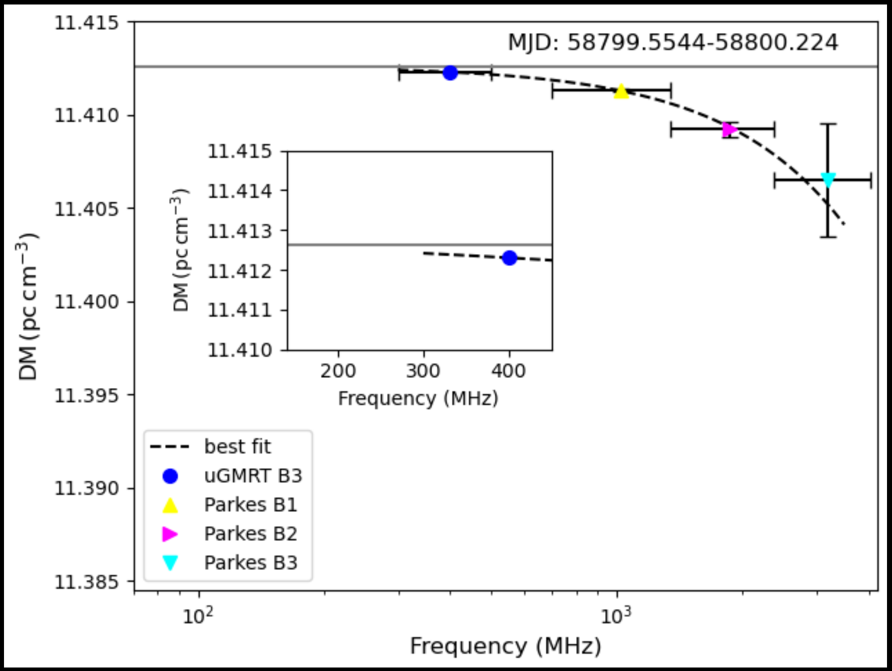
Kaur et al. (2022)

Summary

- High precision $\sim 2 \times 10^{-6}$ pc cm^{-3} DM measurements with the MWA
- DM excess of the order of $(1.4 \pm 0.6) \times 10^{-5}$ pc cm^{-3} as a function of orbital phase: 100 ±50 ns timing noise in timing bands
- Compelling observational evidence that the measured DM varies with the observed frequencies, consistently seen at three different observing epochs
- Empirical estimation of the scaling index $\delta\mathrm{DM} \sim \nu^{2.5\pm0.1}$
- Both the magnitude and scaling observed are discrepant with the expectations from Cordes at al.
- More details in Kaur et al. (2022), ApJ, 930:L27

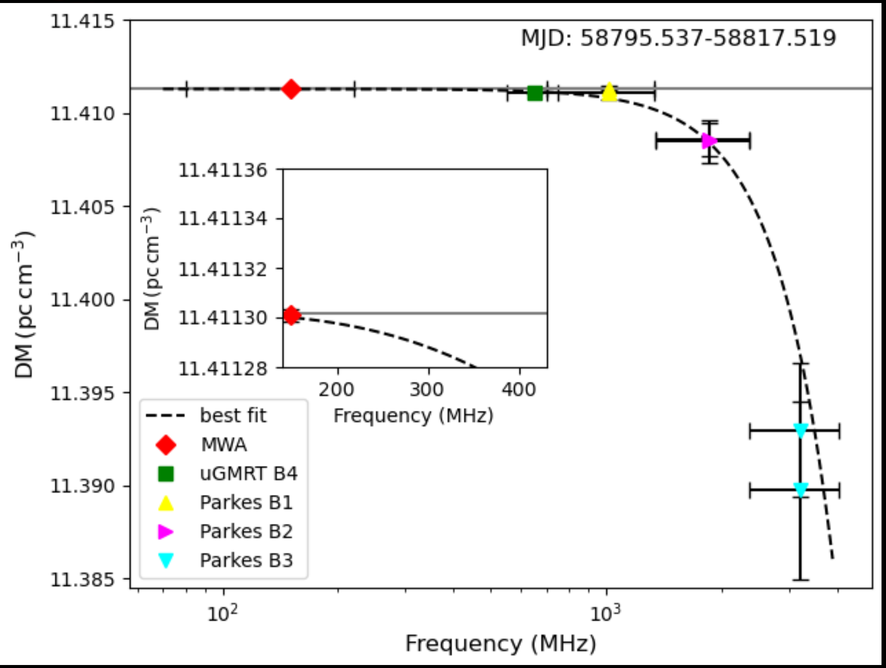
Epoch: 2

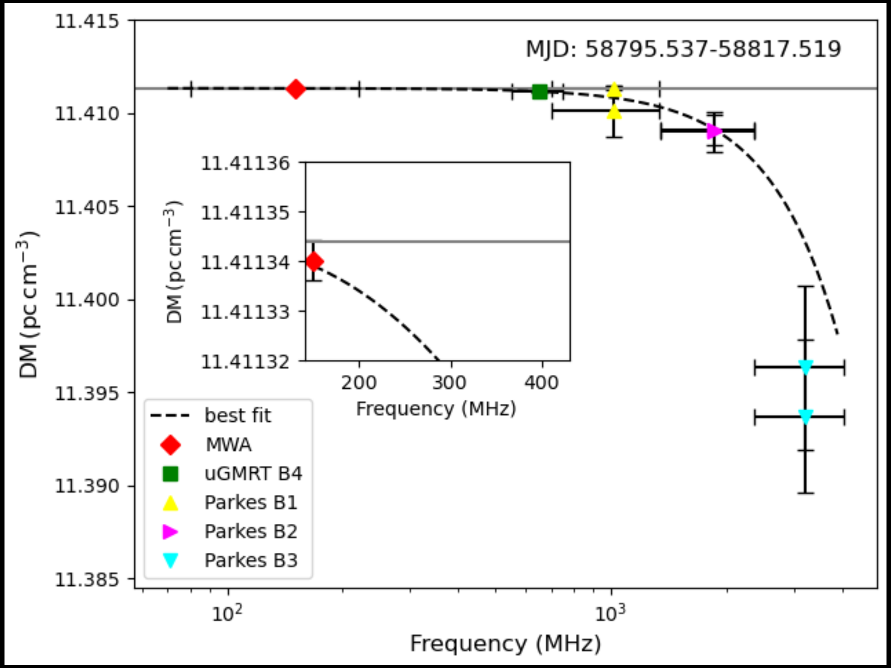




Kaur et al. (2022)

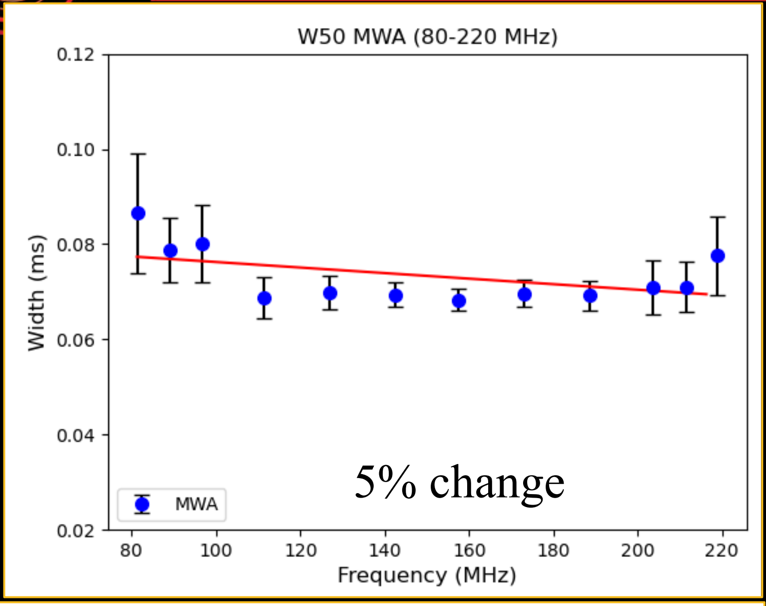
Epoch: 3

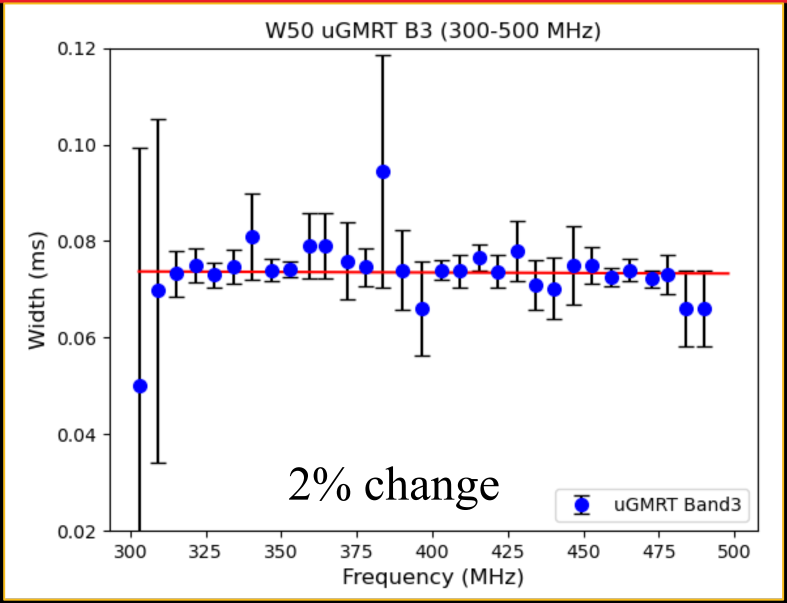


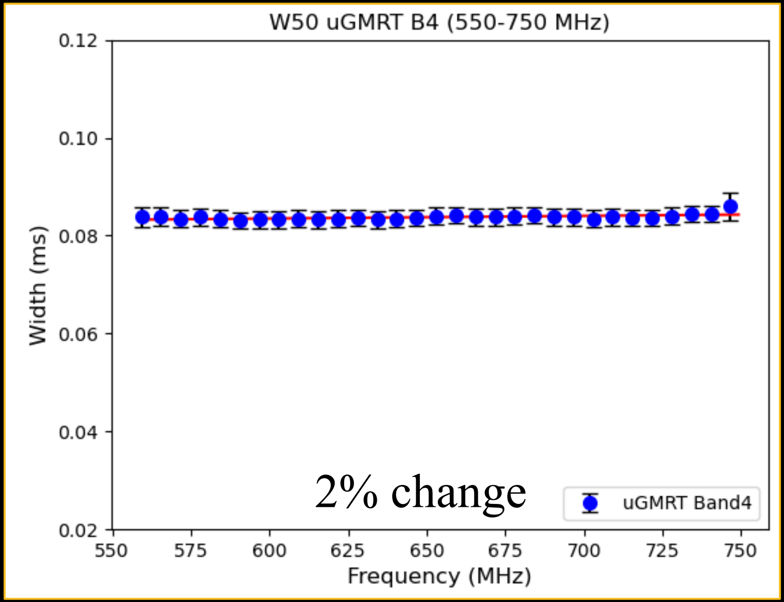


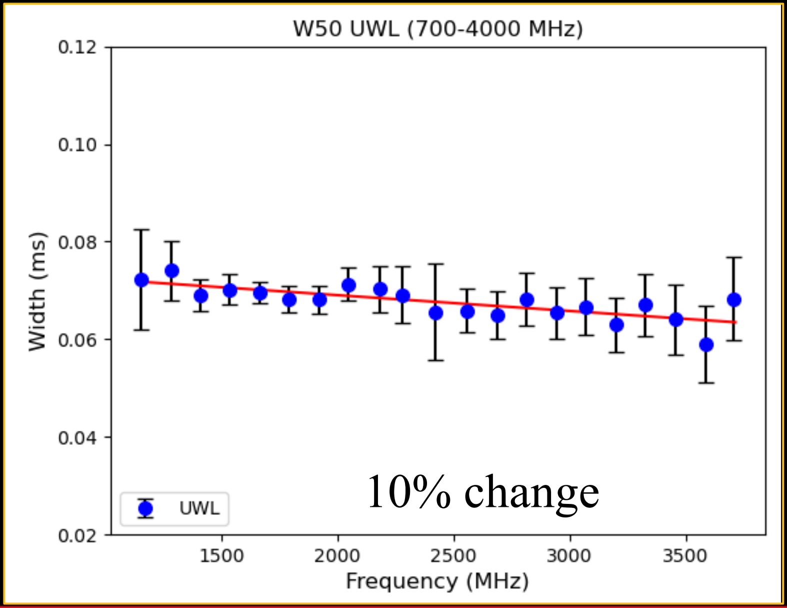
Kaur et al. (2022)

W_{50} for each band

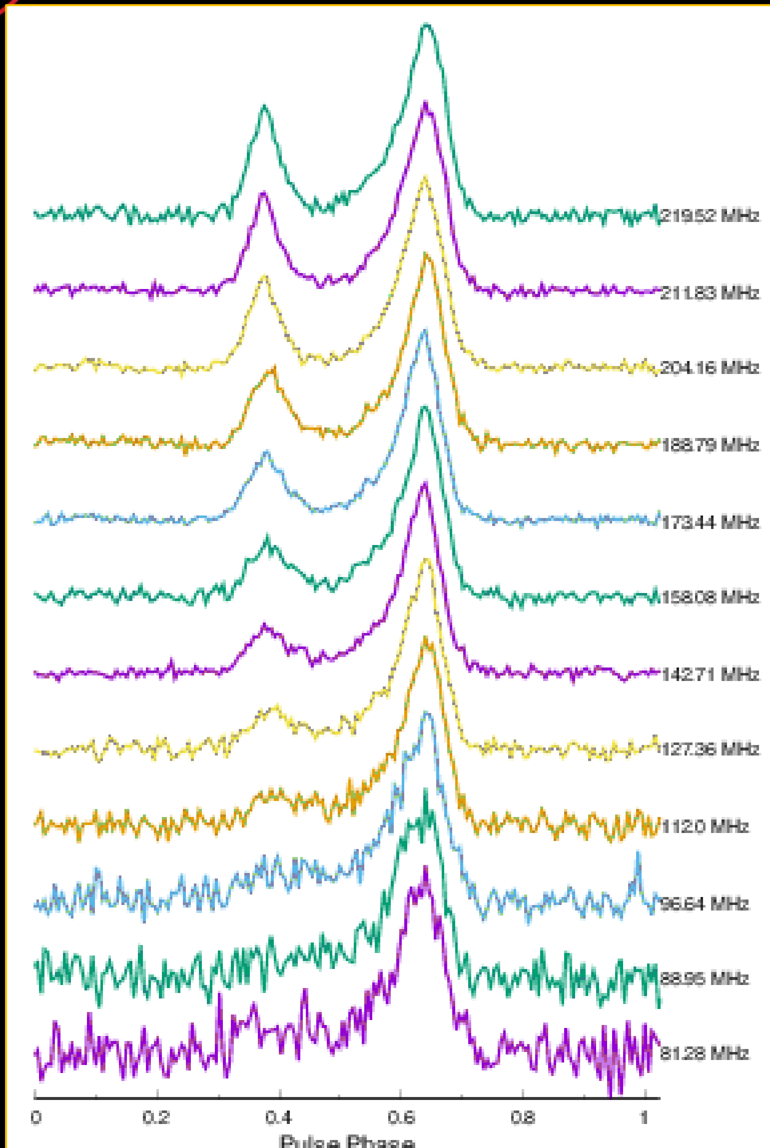


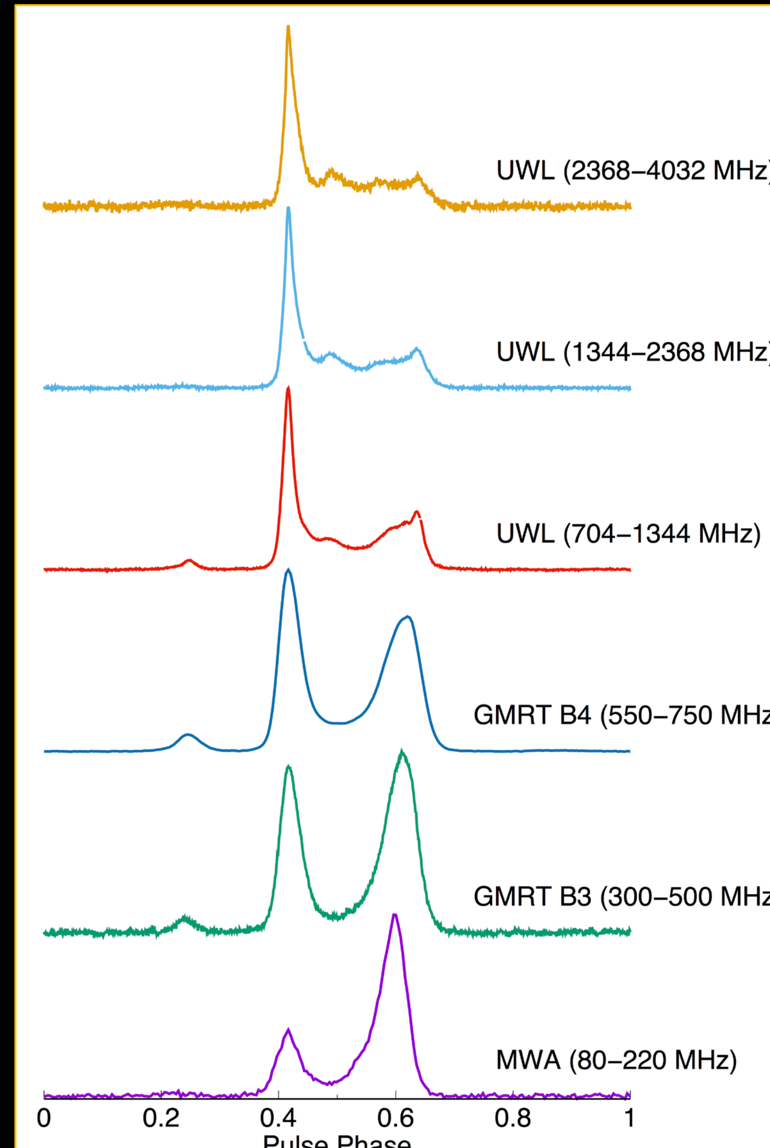






J2145-0750


219.52 MHz
211.83 MHz
204.16 MHz
188.79 MHz
173.44 MHz
158.08 MHz
142.71 MHz
127.36 MHz
112.0 MHz
96.64 MHz
88.95 MHz
81.28 MHz
0
0.2
0.4
0.6
0.8
1
Pulse Phase


UWL (2368–4032 MHz)
UWL (1344–2368 MHz)
UWL (704–1344 MHz)
GMRT B4 (550–750 MHz)
GMRT B3 (300–500 MHz)
MWA (80–220 MHz)
0
0.2
0.4
0.6
0.8
1
Pulse Phase