Using Pulsars to Study the Solar Wind

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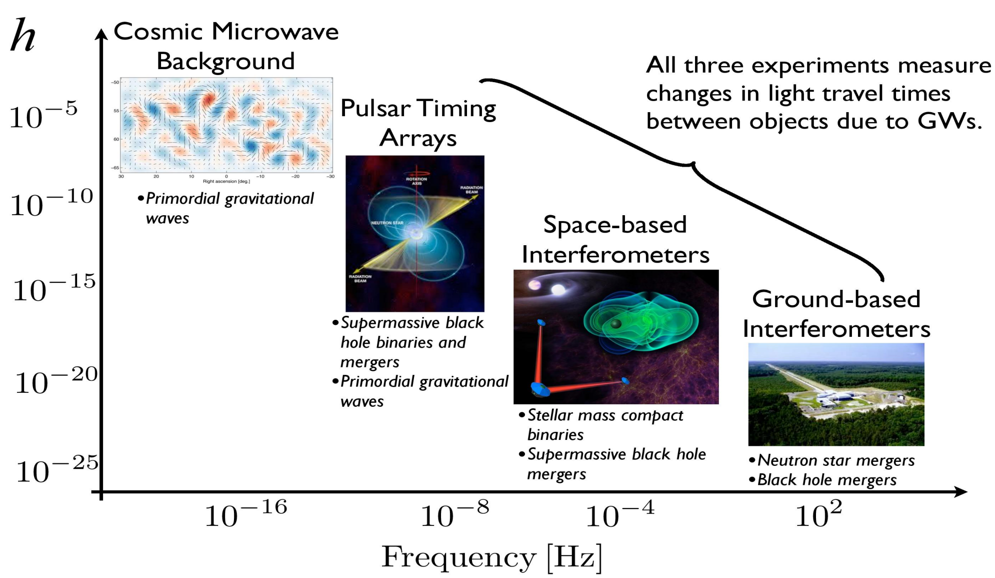
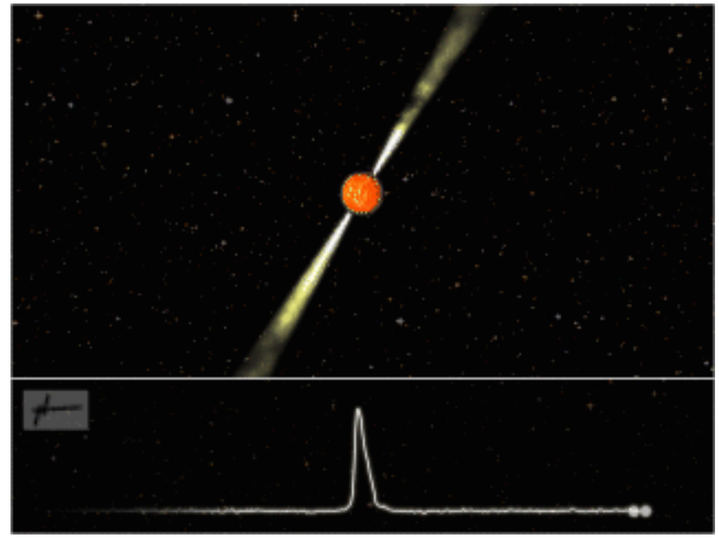
LWA Users Meeting 2021

Pulsars and Pulsar Timing

- Pulsars are rapidly rotating magnetized neutron stars
- One of the varied application include detection of Gravitational Waves from Supermassive black hole binaries

The spectrum of gravitational wave astronomy





Credit: Joeri van Leeuwen

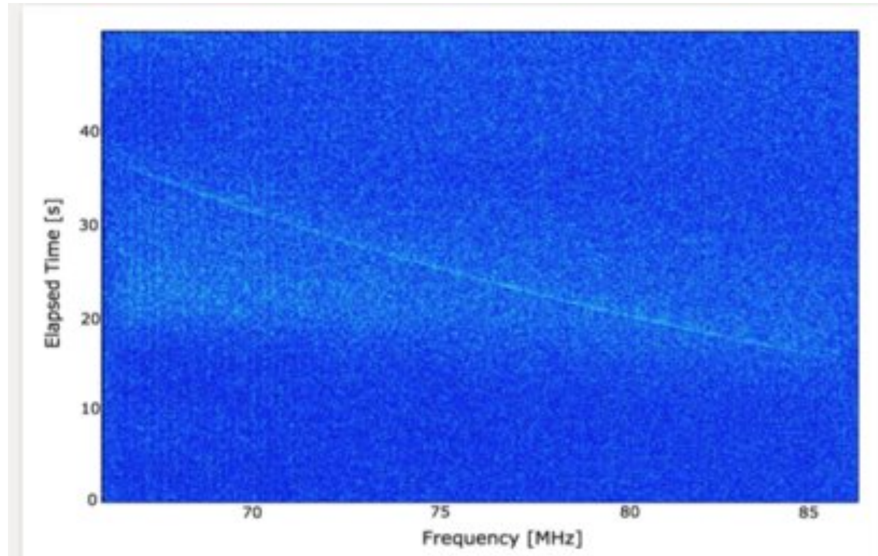
- To improve the detection limit: need to mitigate noise, such as noise due to the non-stationary behaviour of the intervening medium

Non-Stationary Interstellar Medium

- Integrated column density of free electrons between the observer and the pulsar.

$$\mathcal{DM} \equiv \int_0^d n_e \, dl$$

$$\Delta t = \frac{\mathrm{DM}}{2.41 \times 10^{-4}} \left(\frac{1}{\nu_{\mathrm{low}}^2} - \frac{1}{\nu_{\mathrm{high}}^2} \right)$$



Credit: Eftekhari et al. 2016

- Stronger effect at low frequencies
- Can be affected by
  - Proper motion of the pulsar through the ISM
  - Structures in the ISM: see Bansal et. al 2019
  - External factors such as solar winds
  - Variations from Ionosphere

Solar Wind Models (SWMs)

- One-phase model
  - Describes free electron density in the solar wind as purely spherical

$$n_e(R) = \frac{n_o}{R^2}$$

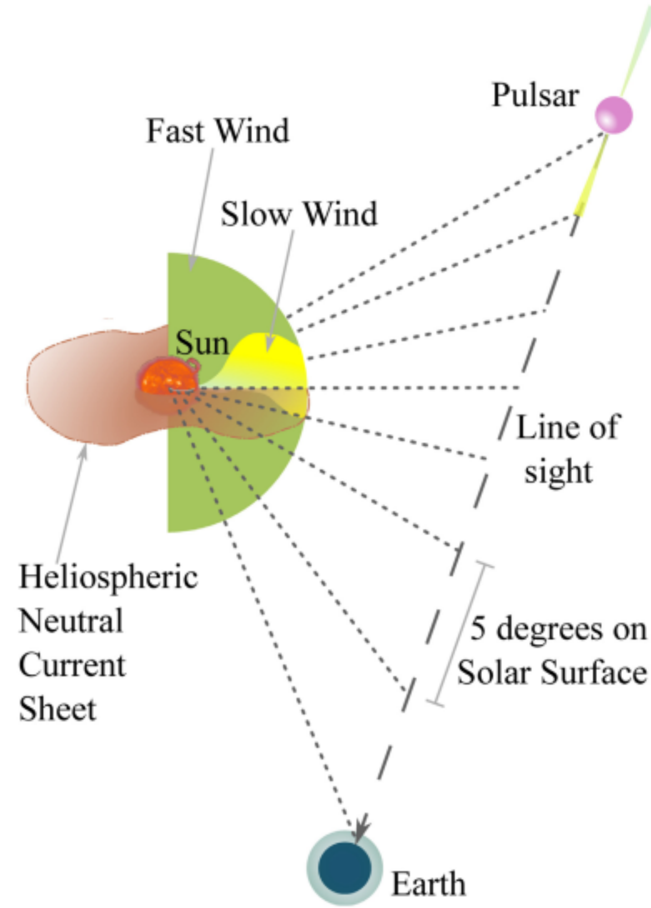
$n_0 = 10$ (T1)

$n_0 = 4$ (T2)

- Two-phase model
  - See You et. al. 2007
  - Separately describes the fast and slow wind phases of the solar wind

(FAST)
$$n_e(R) = 1.155 \times 10^{11} R^2 + 32.3 \times 10^{11} R^{4.39} + 3254 \times 10^{11} R^{16.25} m^{-3}$$

(SLOW)
$$n_e(R) = 2.99 \times 10^{14} R^{16} + 1.5 \times 10^{14} R^6 + 4.1 \times 10^{11} (R^2 + 5.74 R^{2.7}) m^{-3}$$

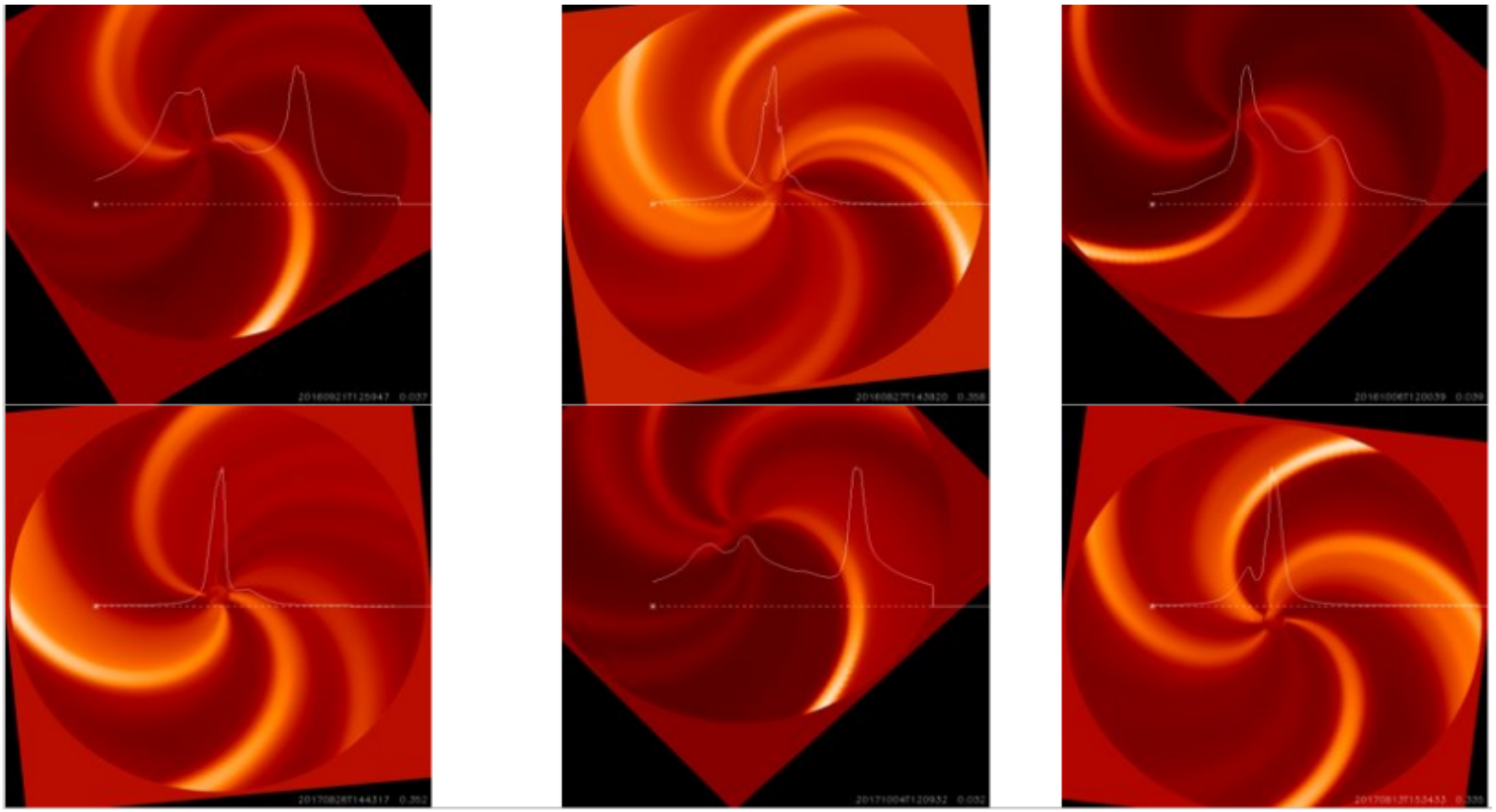


Credits: Tiburzi et. al. 2019

Solar Wind Models (SWMs)

Non-Stationary SWM

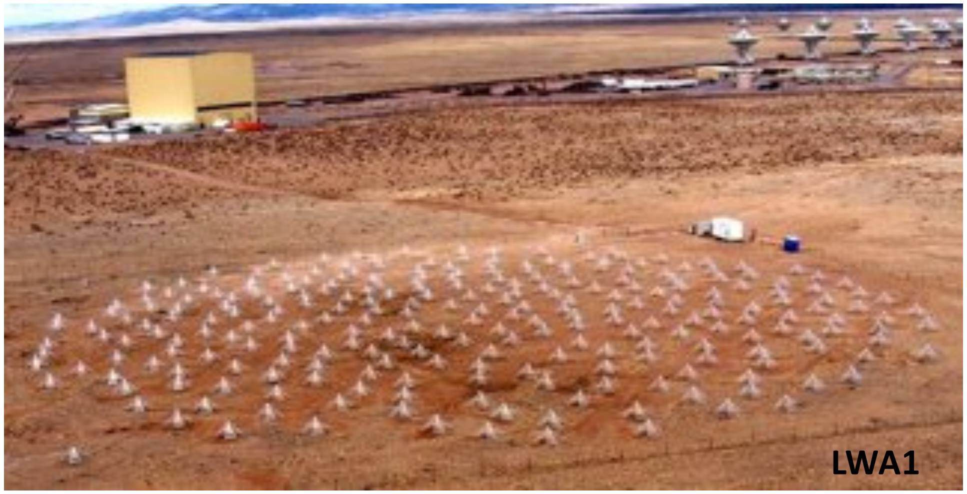
- WSA-Enlil

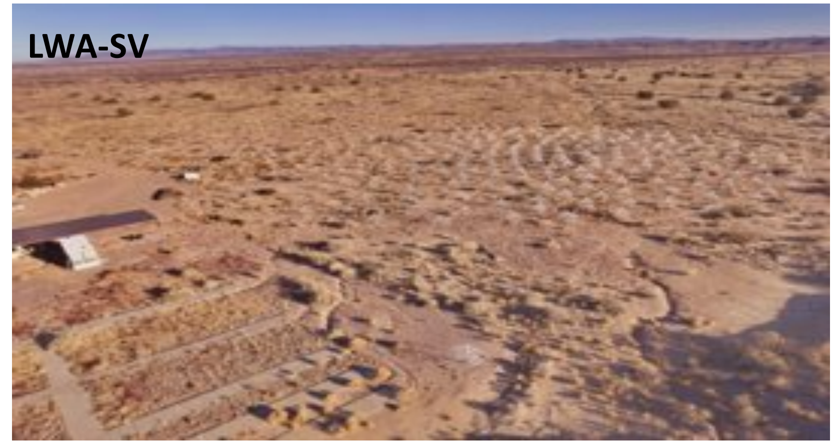


Credit: S. White

WSA density profile for a few different cases of PSR B0950+08

Long Wavelength Array (LWA)





Frequency Range: 3-88 MHz
First station ("LWA1") completed April 2011

Second NM station ("LWA-SV" completed July 2017

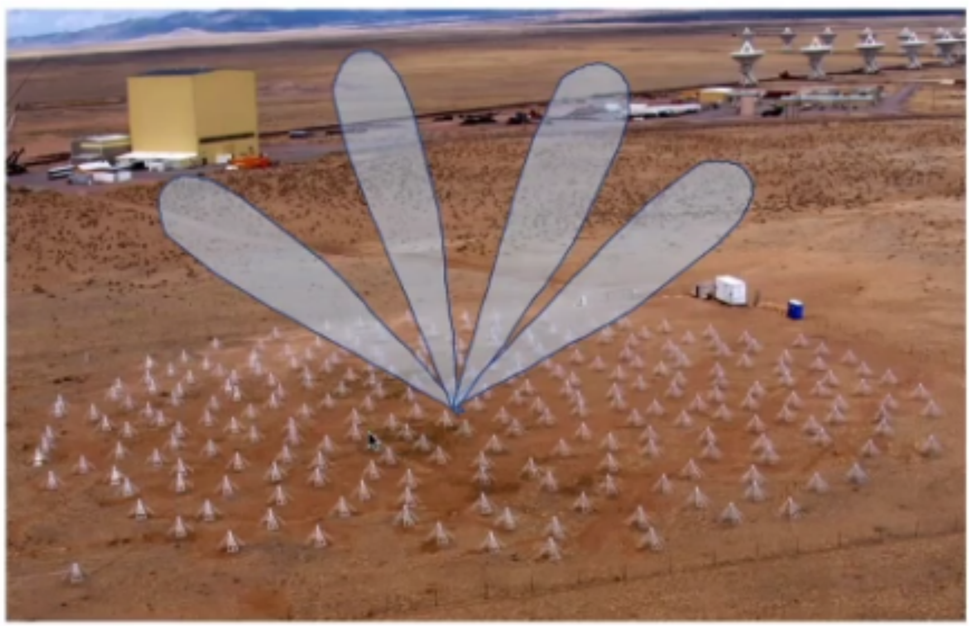
Next up: "LWA-NA" mini-station (64 dipoles) 2021 Construction

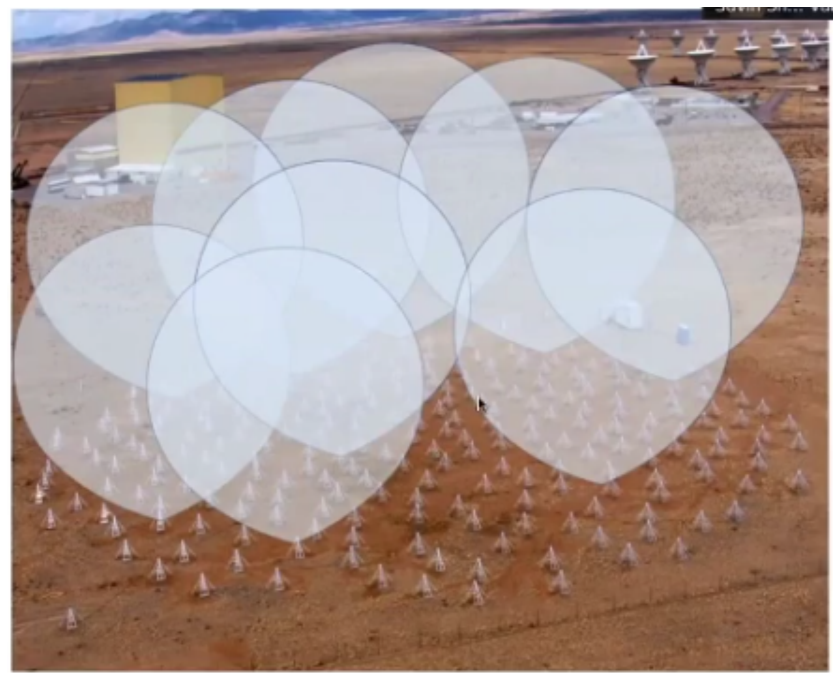
OVRO-LWA Imaging and Beamforming superstation

LWA swarm – 1" resolution

Observing Modes

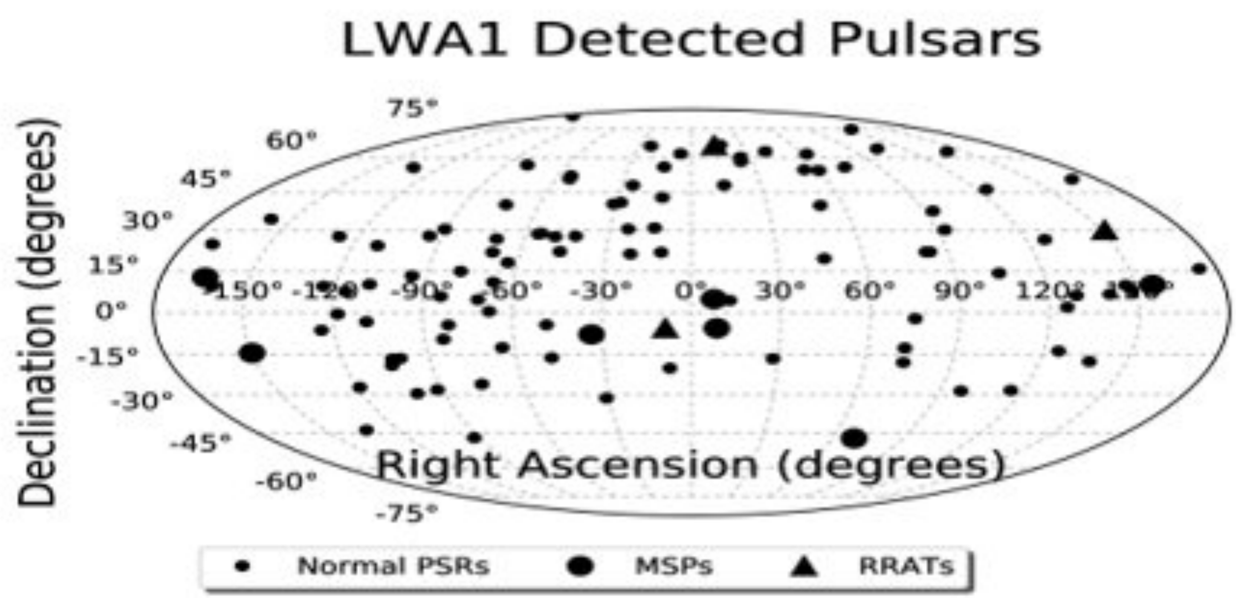
- 256 dual-polarization antennas
- Distributed within a 100 x 110 m ellipse
- Two primary observing modes: Digital Beamforming and All-sky mode





LWA Pulsar Monitoring and Reduction

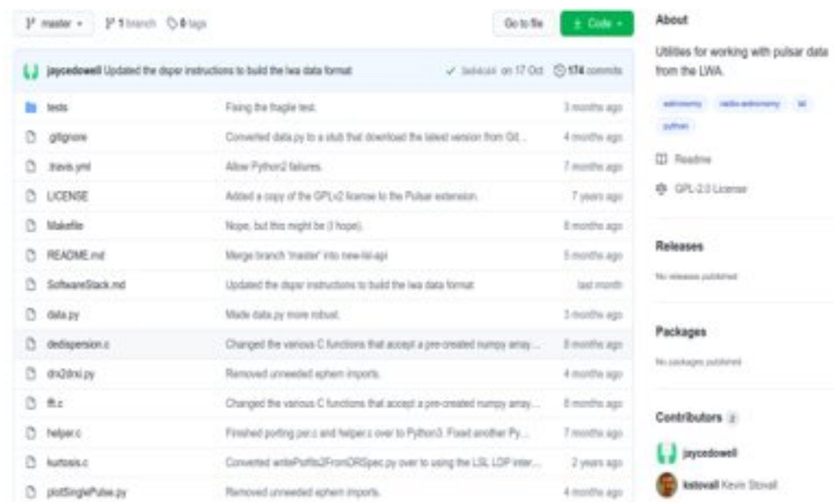
- Pulsar Observations Since 2013, Monitoring began in September 2015 (Stovall et. al. 2014)
- 108 Sources, including Pulsars, MSPs and RRATs
- Automated Robust observing with a Python based script
- Sources observed at a cadence of about 3 weeks
- Observations at 4 frequencies, 35.1 MHz, 49.8 MHz, 64.5 MHz and 79.2 MHz each with 19.6 MHz bandwidth



Credit: K. Stovall

LWA Pulsar Monitoring and Reduction

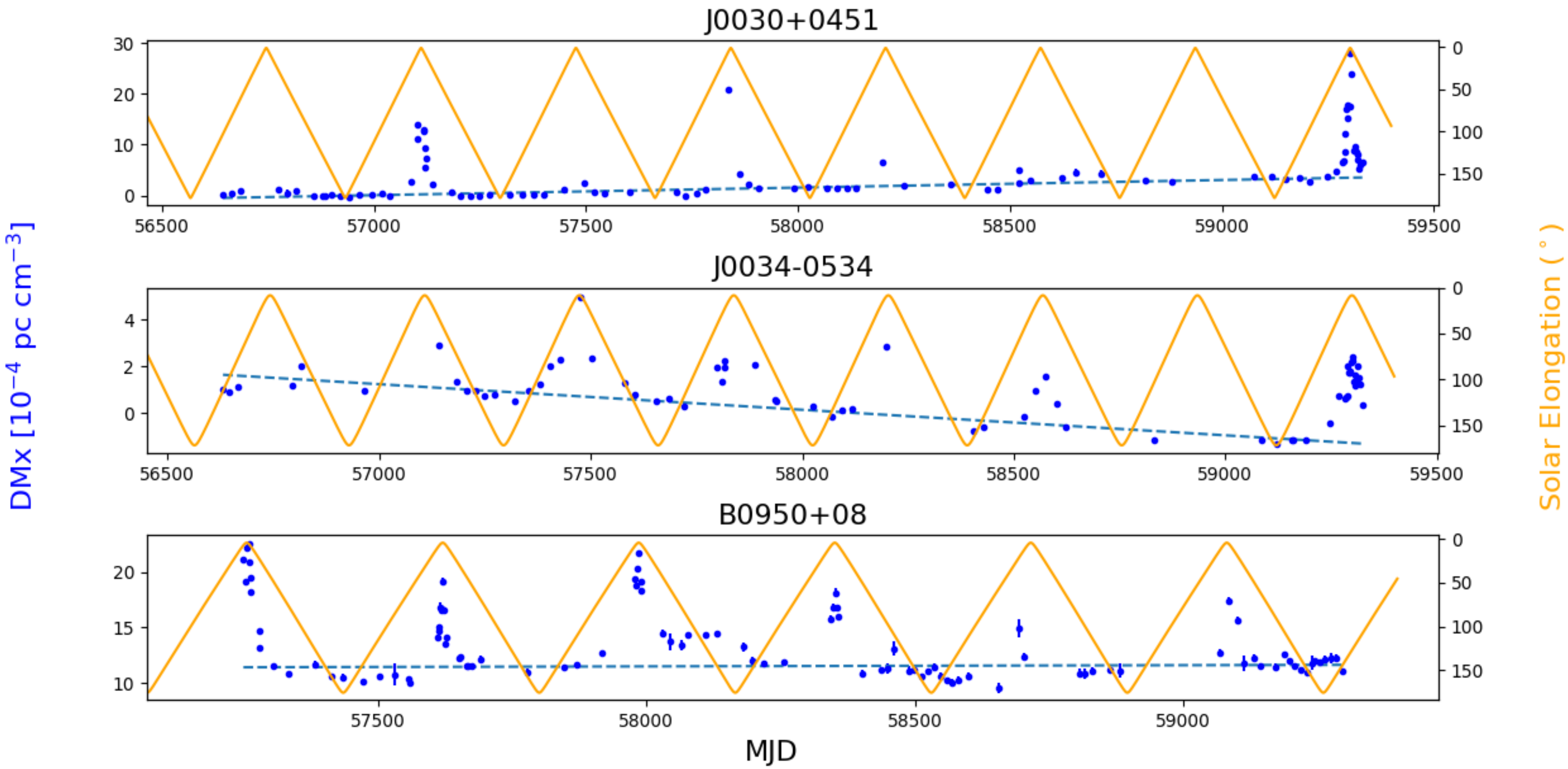
- Automated Data reduction incorporating standard pulsar software and LWA Software Library (Dowell et. al. 2012) tools.
- More than 4000 beam hours of reduced and archived data available publicly.



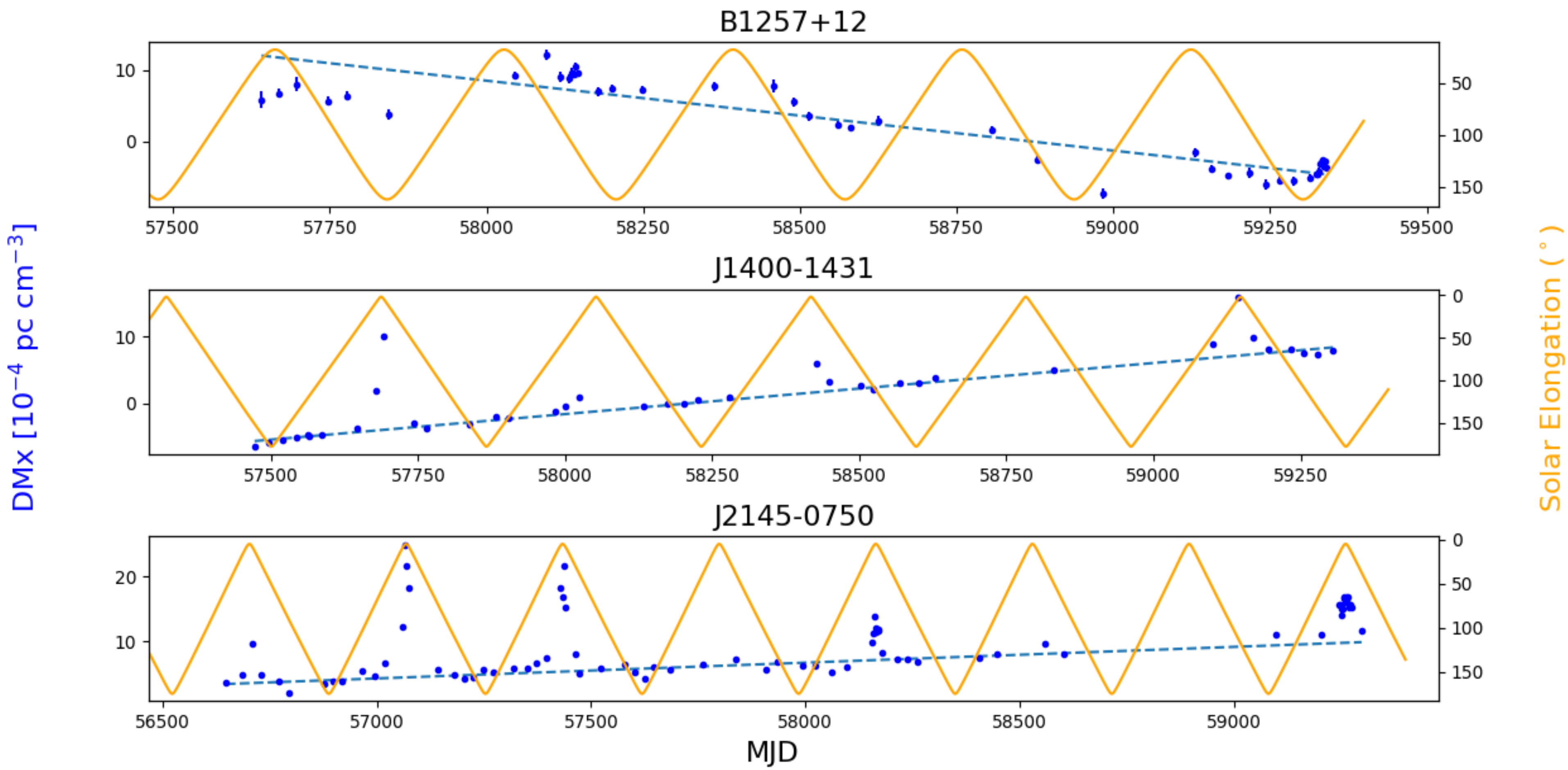
https://lda10g.alliance.unm.edu/PulsarArchive/

https://github.com/lwa-project/pulsar

Trends in Time



Trends in Time



Trends with Solar Elongation

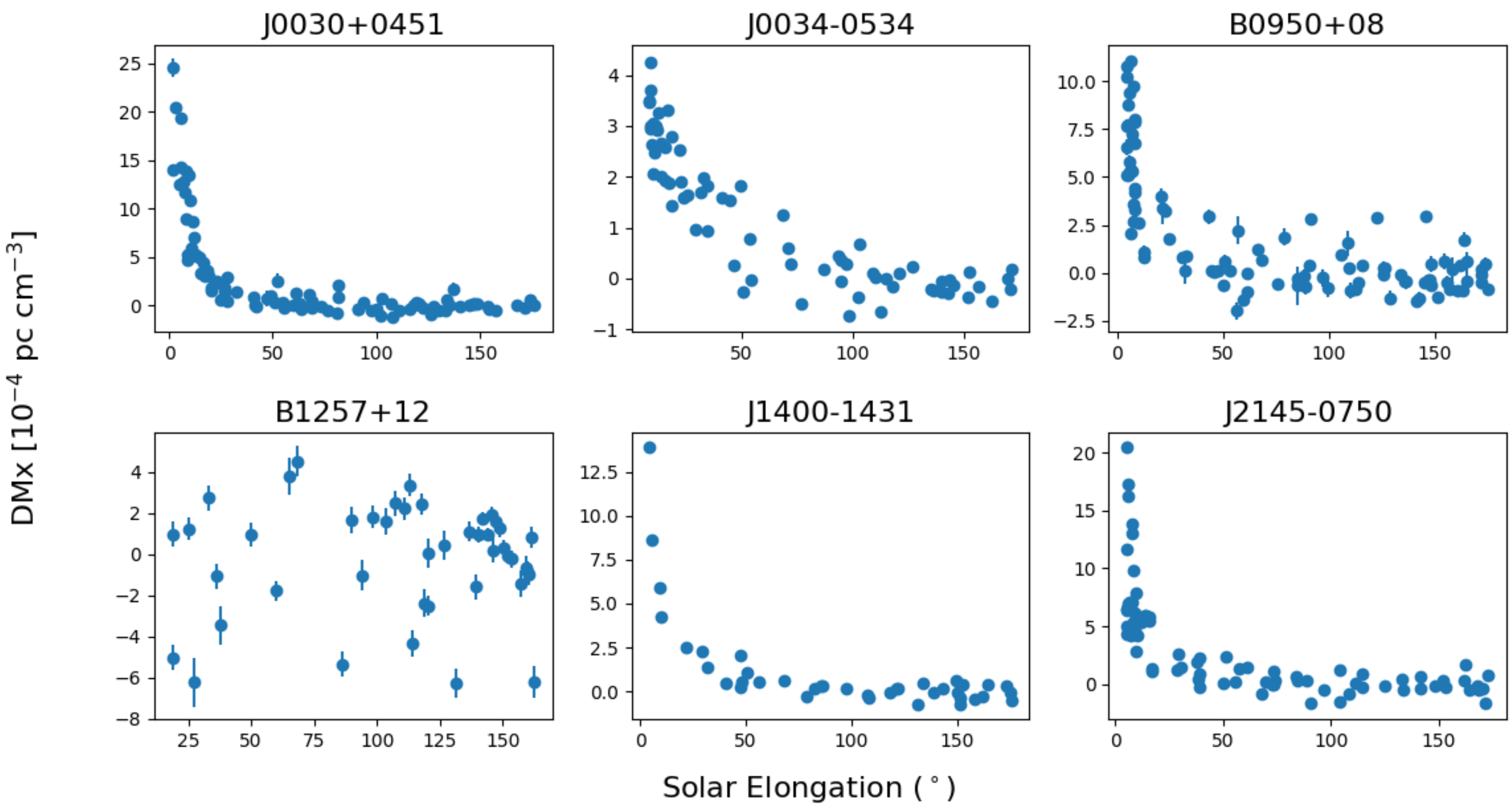
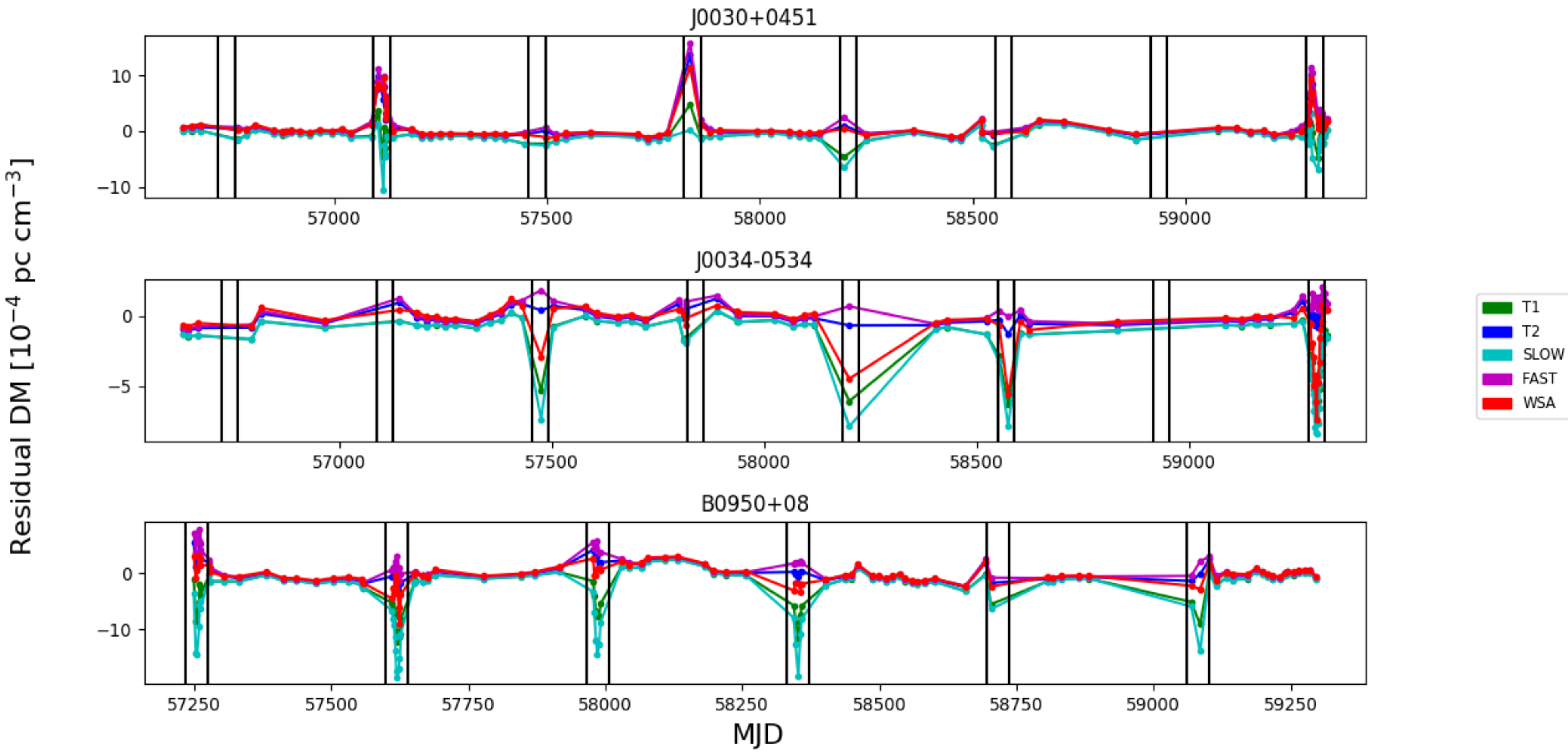


Figure shows the DMx vs Solar Elongation angle after subtraction of linear contribution.

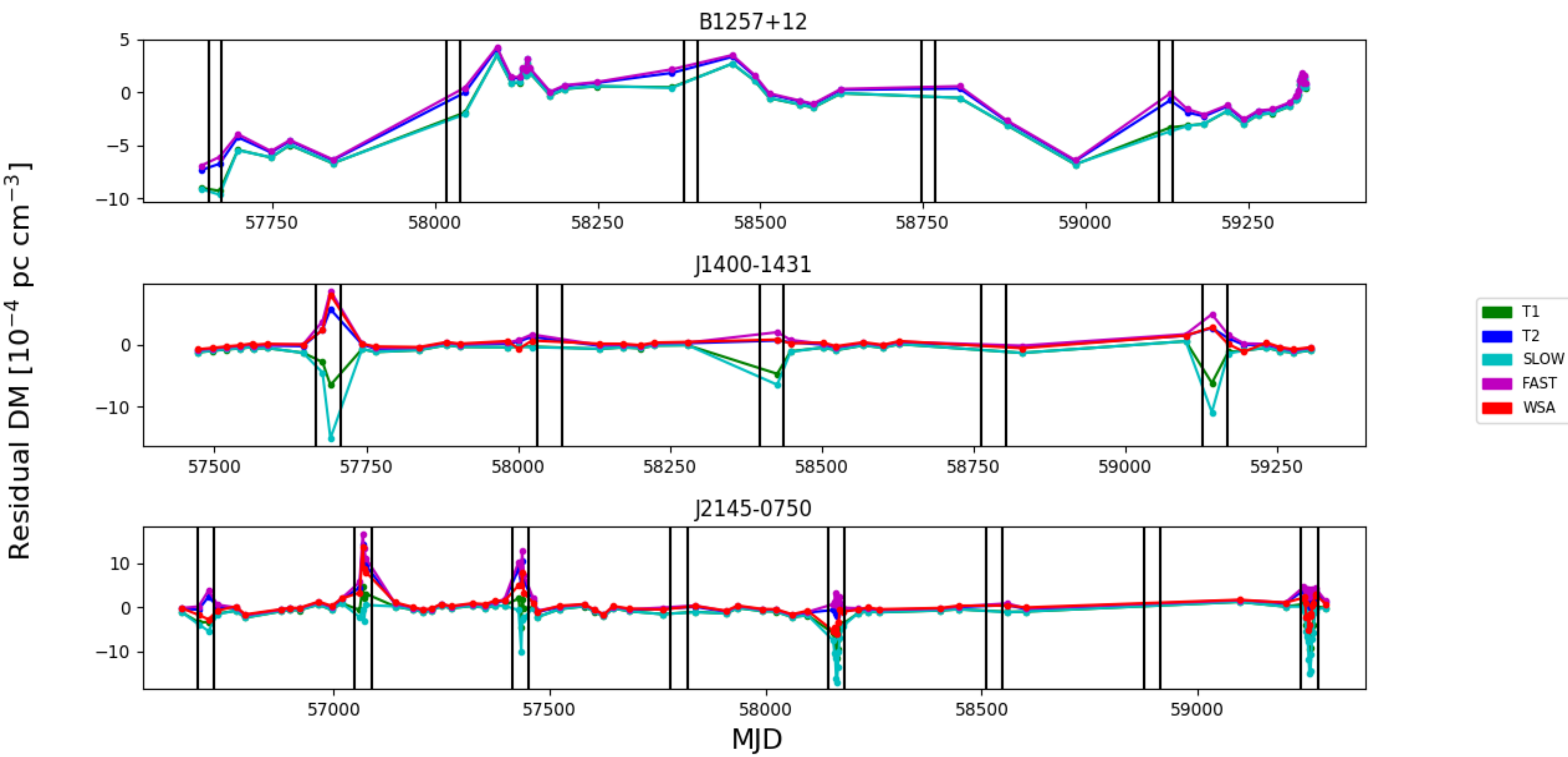
IISM modelling

- Slow variations, dominant term at large angular separations
- Modeled by polynomial fitting of data > 60-degree angular separations
- Current analysis shows that a linear function is sufficient to model these effects

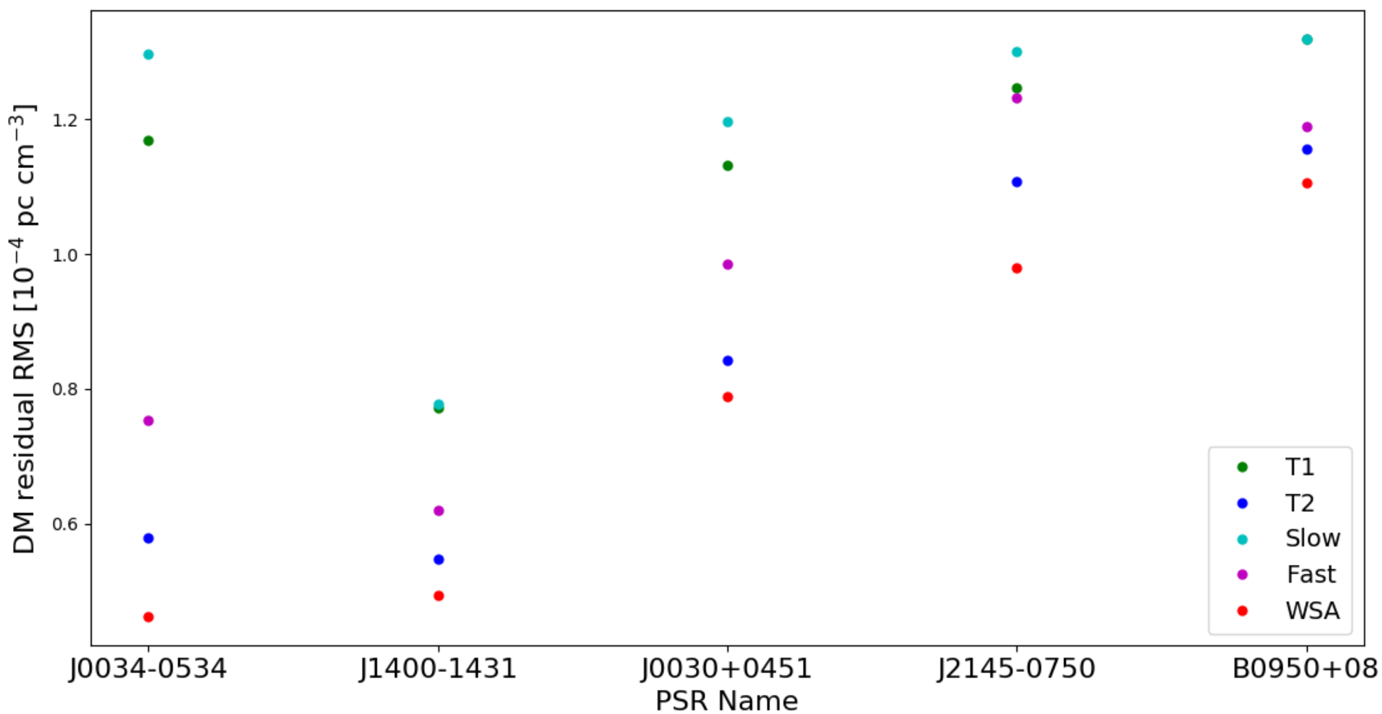
DM residuals



DM residuals



RMS values



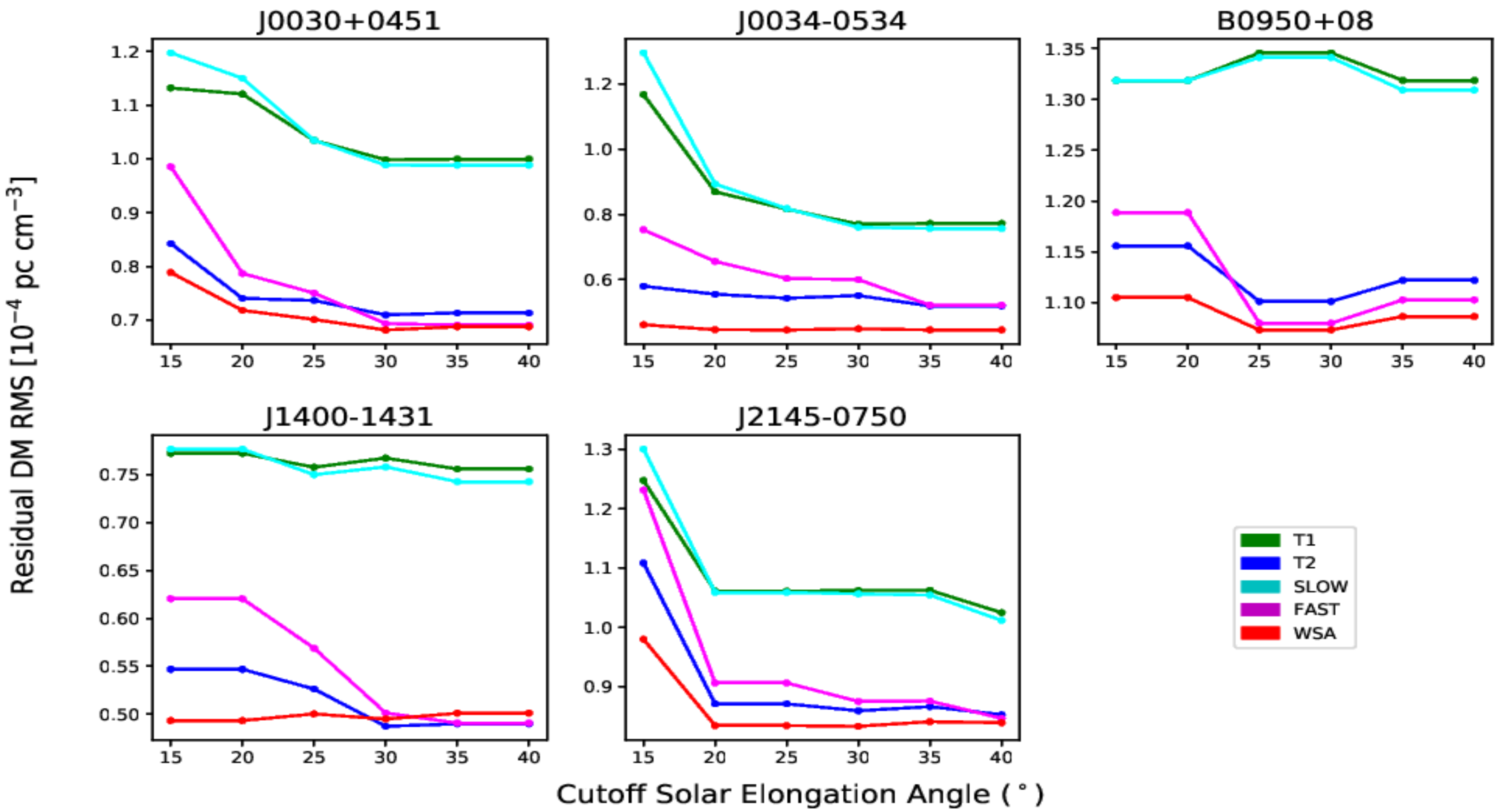
RMS of DM residuals for more than 15 deg separation from the Sun

Residual Delay at 1.4 GHz for WSA

	J0030+0451	J0034-0534	B0950+08	J1400-1431	J2145-0750
RMS_{15} (μs)	0.167	0.098	0.234	0.104	0.207
RMS_{40} (μs)	0.146	0.094	0.230	0.106	0.178

Tolerance?

How does the RMS change with separation from the sun?



Summary

- Low frequency monitoring observations of pulsar can test the existing models of SW
  - In general, non-spherical models of SW have a lower precision than corresponding spherical approximation.
  - WSA works better than other common models of SW correction for PTA: need non-stationary SW models
  - Efficacy of models degraded below 15–20-degree angular separations: need better models or an avoid observing window
    - 15-degree cutoff: ~ 25-30 days or ~8% of total observing time
    - 20-degree cutoff: ~ 35-40 days or ~11% of total observing time
- Our current estimates show that DM RMS of the order of 10^-5 pc cm^-3 can be achieved using low frequency observations of pulsar: could improve the noise floor of high precision pulsar timing
- Next step: Test with simultaneous high frequency data

Delay at 1.4 GHz for WSA for >15-degree separation