



# Using Pulsars to Study the Solar Wind

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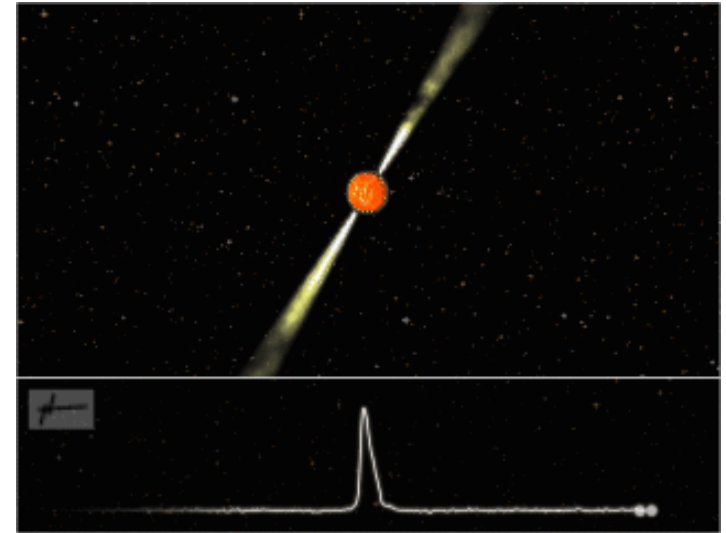
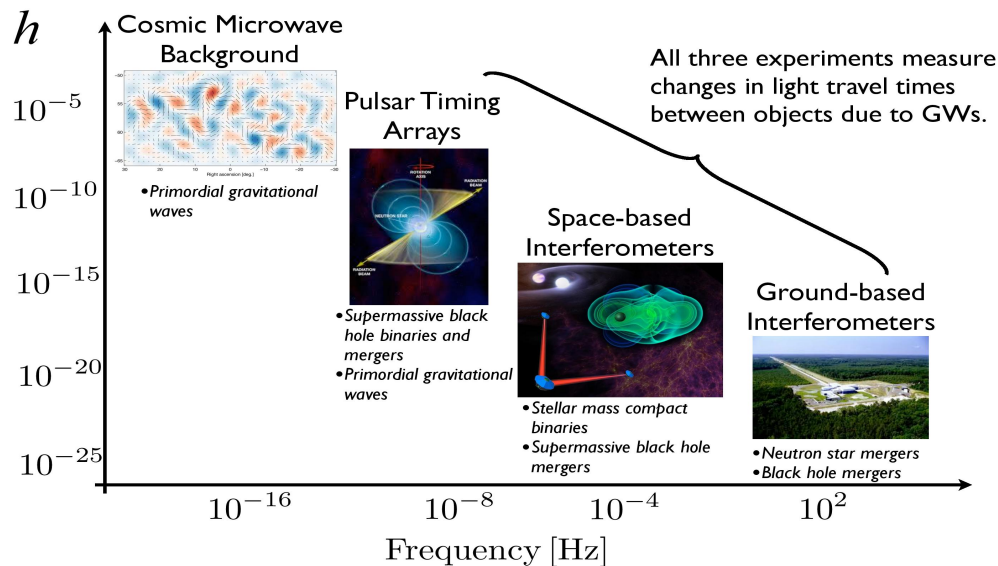
LWA Users Meeting 2021

# 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

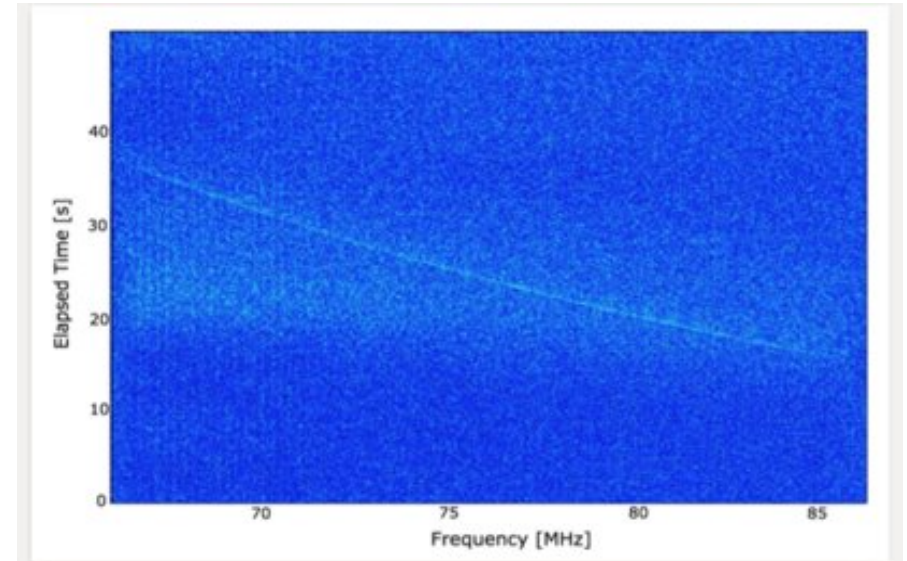
## Non-Stationary Interstellar Medium

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

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

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

- 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



Credit: Eftekhari et al. 2016

## Solar Wind Models (SWMs)

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

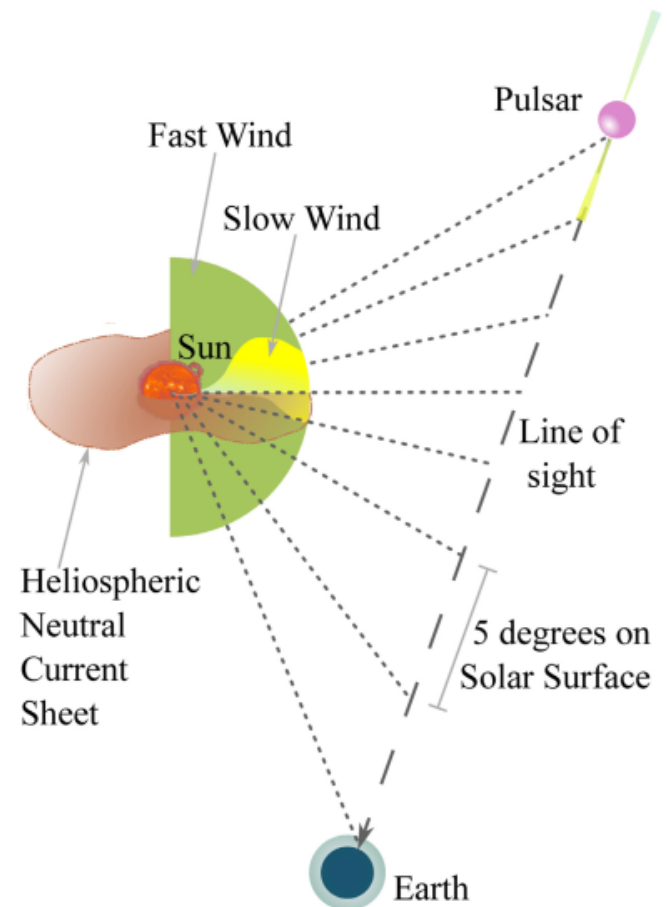
$$n_e(R) = \frac{n_0}{R^2} \quad n_0 = 10 \quad (T1)$$

$$n_e(R) = \frac{n_0}{R^2} \quad n_0 = 4 \quad (T2)$$

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

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

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

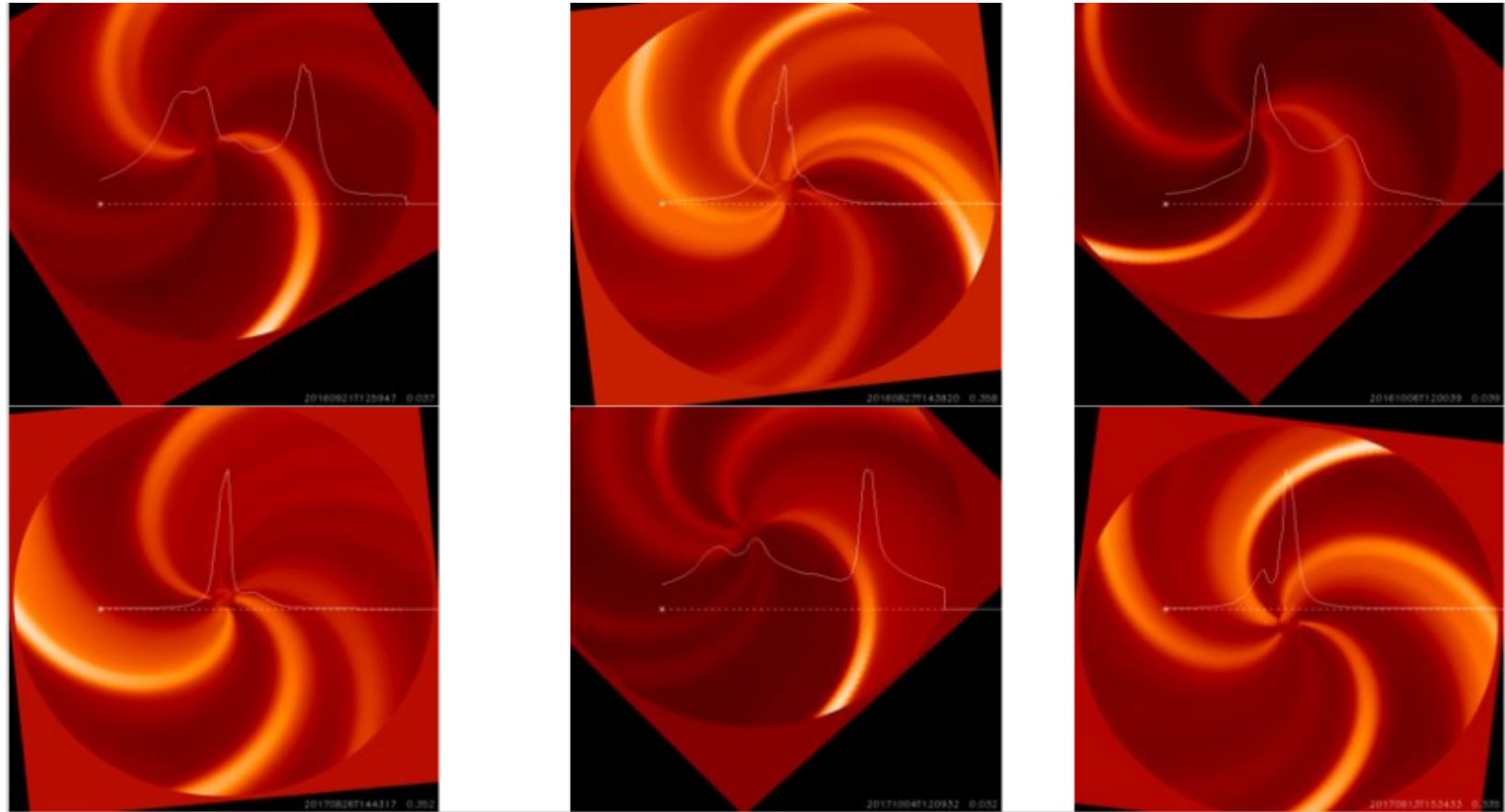


Credits: Tiburzi et. al. 2019

## Solar Wind Models (SWMs)

Non-Stationary  
SWM

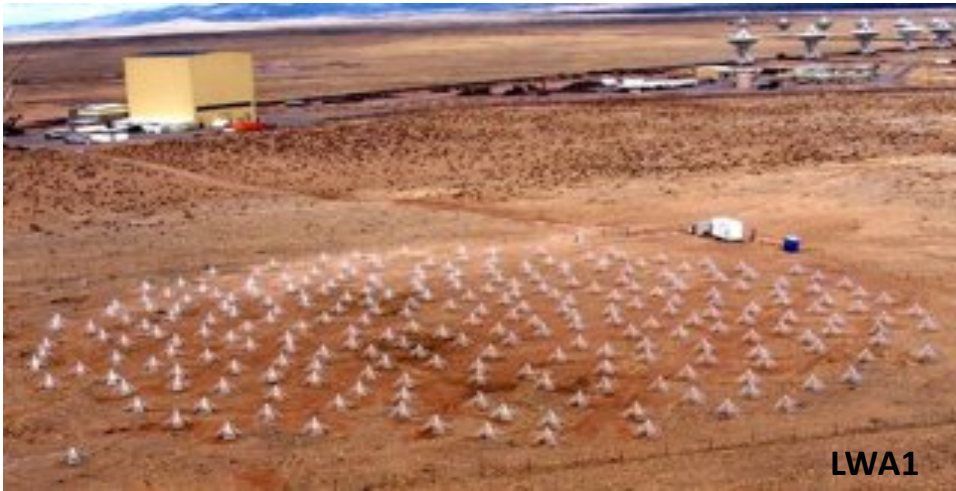
- WSA-  
Enlil



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

Credit: S. White

## Long Wavelength Array (LWA)



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

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

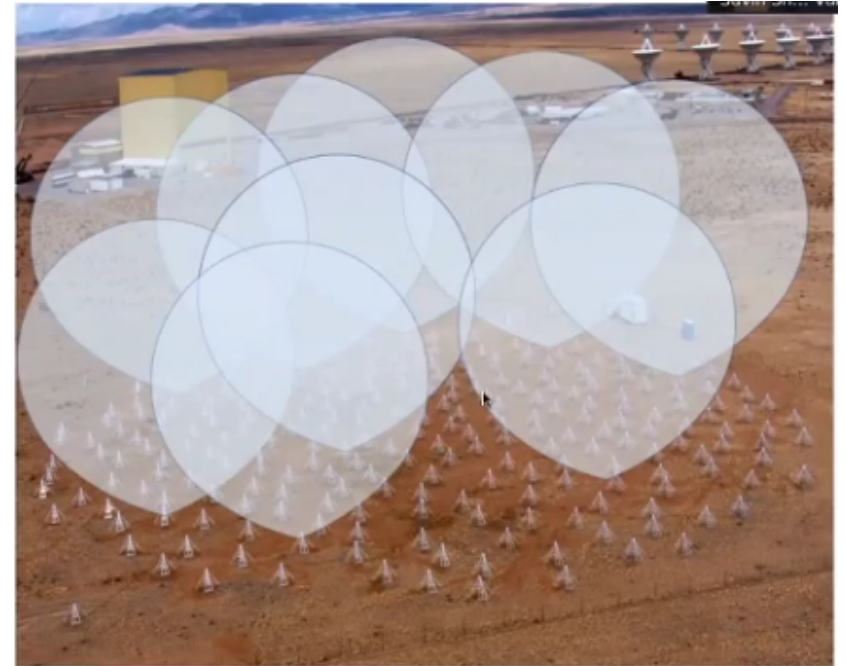
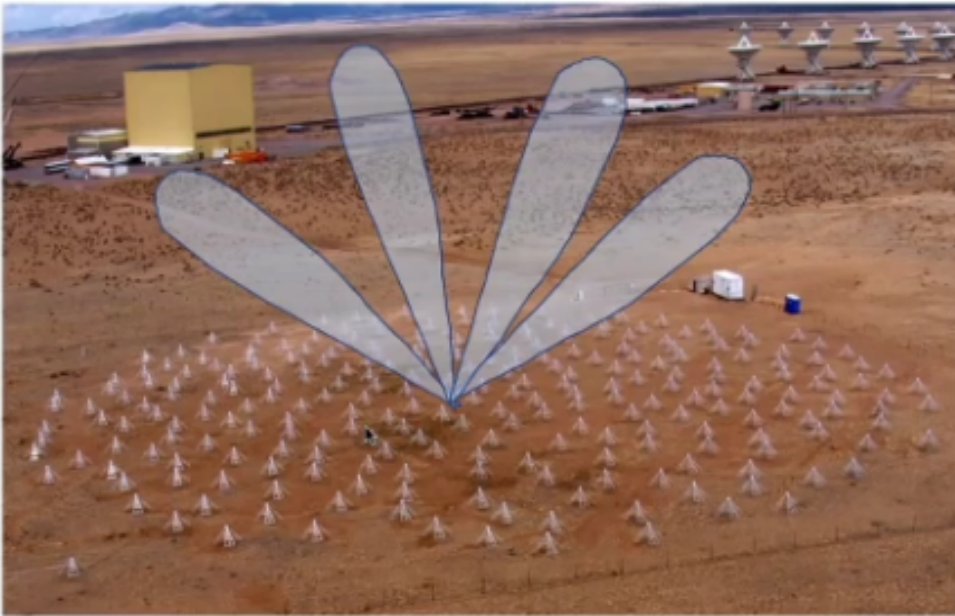
**Next up: "LWA-NA" mini-station (64  
dipoles) 2021 Construction**

**OVRO-LWA Imaging and Beamforming  
superstation**



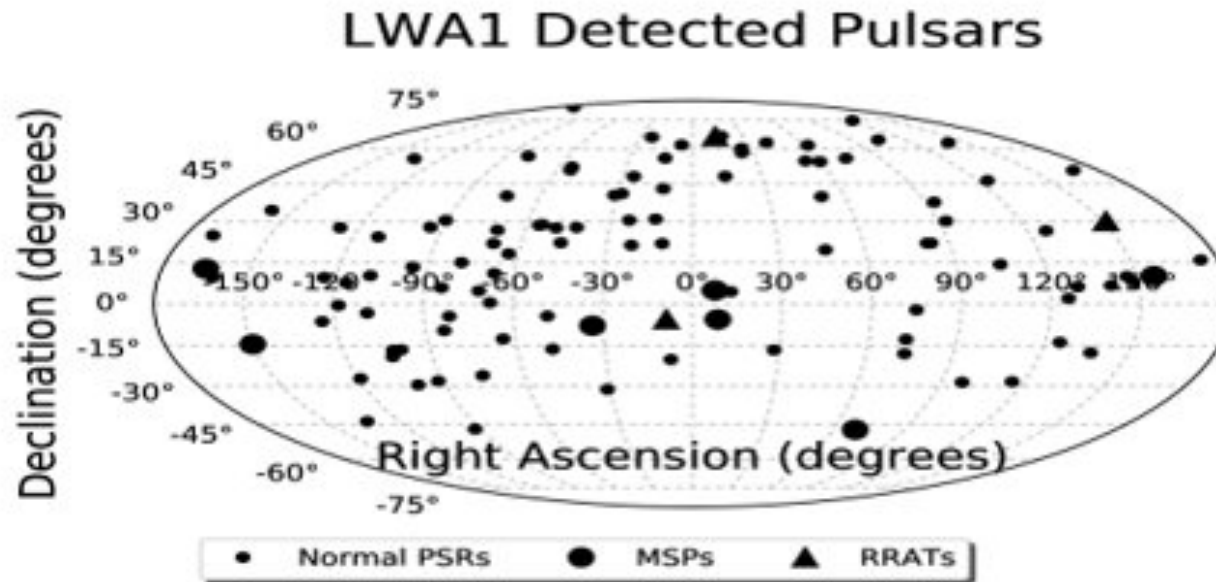
## Observing Modes

- 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.

## Index of /PulsarArchive

| Name                             | Last modified    | Size | Description |
|----------------------------------|------------------|------|-------------|
| <a href="#">Parent Directory</a> |                  | -    |             |
| <a href="#">B0031-07/</a>        | 2020-11-14 13:20 | -    |             |
| <a href="#">B0053+47/</a>        | 2020-10-17 20:02 | -    |             |
| <a href="#">B0105+05/</a>        | 2020-11-04 11:33 | -    |             |
| <a href="#">B0136+57/</a>        | 2020-11-19 12:59 | -    |             |
| <a href="#">B0138+59/</a>        | 2020-10-27 12:51 | -    |             |
| <a href="#">B0149-16/</a>        | 2020-10-24 11:57 | -    |             |
| <a href="#">B0201+19/</a>        | 2020-10-23 00:56 | -    |             |
| <a href="#">B0220+39/</a>        | 2020-11-05 14:54 | -    |             |
| <a href="#">B0229+54/</a>        | 2020-11-21 20:19 | -    |             |
| <a href="#">B0355+54/</a>        | 2020-10-31 18:45 | -    |             |
| <a href="#">B0402+01/</a>        | 2020-11-08 14:52 | -    |             |
| <a href="#">B0447-12/</a>        | 2020-11-07 12:15 | -    |             |
| <a href="#">B0450+55/</a>        | 2020-11-09 23:06 | -    |             |
| <a href="#">B0450-18/</a>        | 2020-11-11 17:53 | -    |             |
| <a href="#">B0525+21/</a>        | 2020-10-26 22:49 | -    |             |
| <a href="#">B0531+21/</a>        | 2020-04-21 02:03 | -    |             |
| <a href="#">B0628-28/</a>        | 2020-11-08 21:00 | -    |             |
| <a href="#">B0655+04/</a>        | 2020-11-18 02:38 | -    |             |
| <a href="#">B0656+14/</a>        | 2020-11-02 00:42 | -    |             |

The screenshot shows the GitHub repository page for 'lwa-project/pulsar'. The repository is owned by 'jaycedowell' and has 1 branch and 8 tags. The main content area lists files and their commit history:

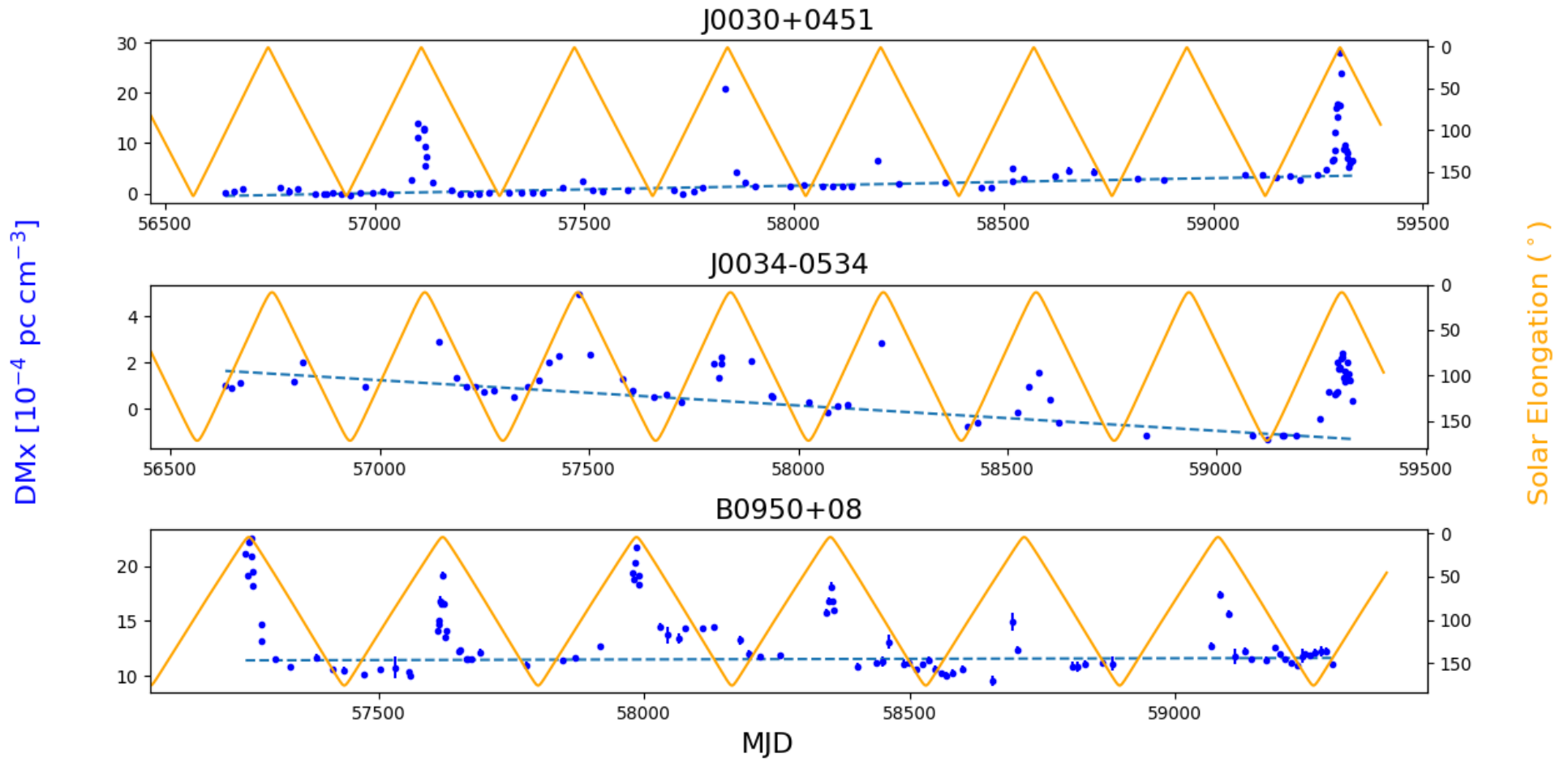
- tests: Fixing the fragile test. 3 months ago
- gitignore: Converted data.py to a stub that download the latest version from Git. 4 months ago
- setup.py: Allow Python2 failures. 7 months ago
- LICENSE: Added a copy of the GPLv2 license to the Pulsar extension. 7 years ago
- Makefile: Nope, but this might be (I hope). 8 months ago
- README.md: Merge branch 'master' into new-10-agi. 8 months ago
- SoftwareStack.md: Updated the duper instructions to build the lwa data format. last month
- data.py: Made data.py more robust. 3 months ago
- dedispersion.c: Changed the various C functions that accept a pre-created numpy array... 8 months ago
- fit2tbl.py: Removed unneeded sphinx imports. 4 months ago
- fit.c: Changed the various C functions that accept a pre-created numpy array... 8 months ago
- helper.c: Finished porting par2 and helper.c over to Python3. Fixed another Py... 7 months ago
- kurvas.c: Converted writePulsar2FromDRSpec.py over to using the LIL LOP inter... 2 years ago
- plotSinglePulse.py: Removed unneeded sphinx imports. 4 months ago

The right sidebar contains information about the repository, including 'About' (Utilities for working with pulsar data from the LWA), 'Releases' (No releases published), 'Packages' (No packages published), and 'Contributors' (jaycedowell, katovall Kevin Stovall).

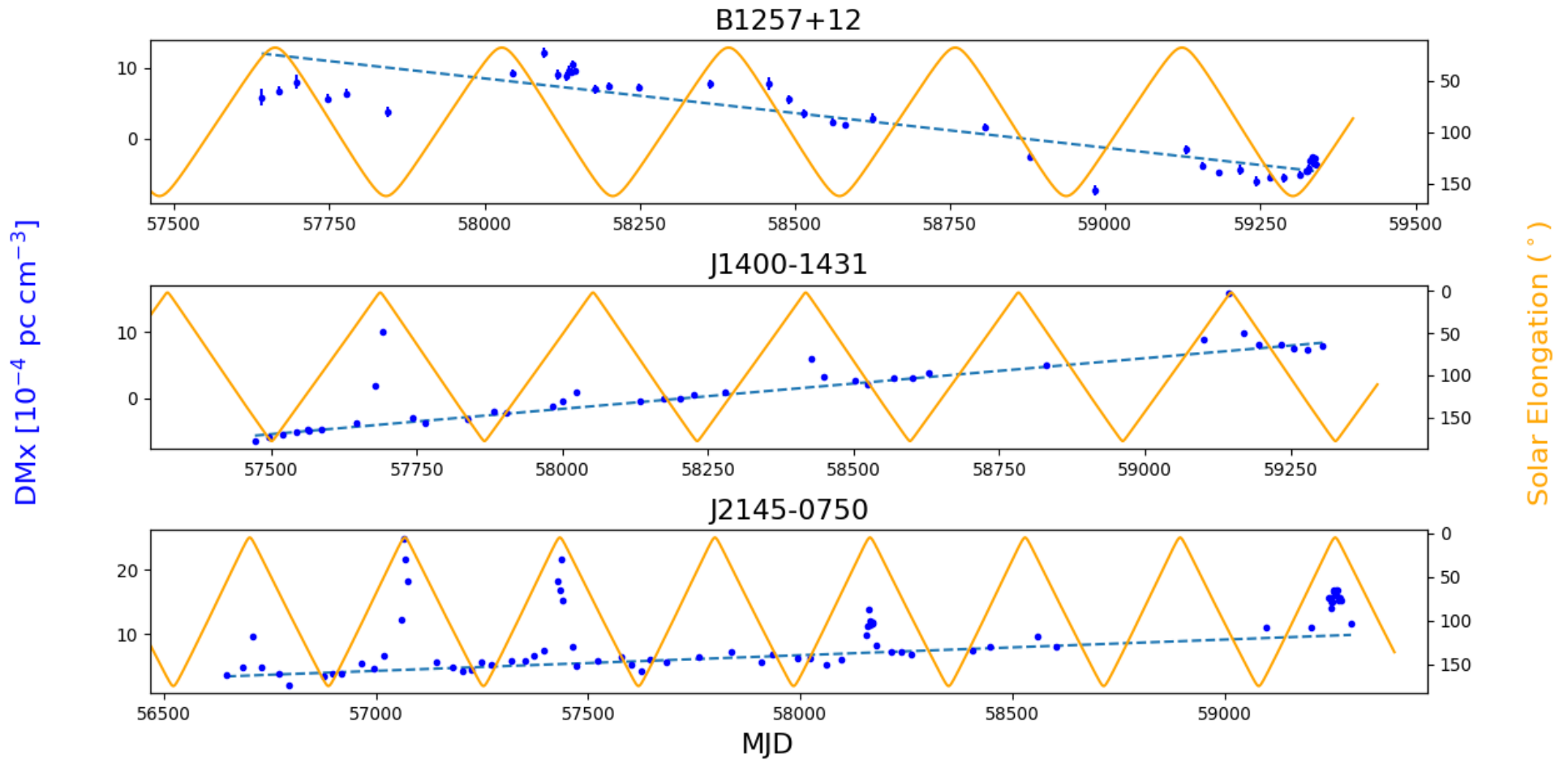
<https://lda10g.alliance.unm.edu/PulsarArchive/>

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

# Trends in Time



# Trends in Time



## Trends with Solar Elongation

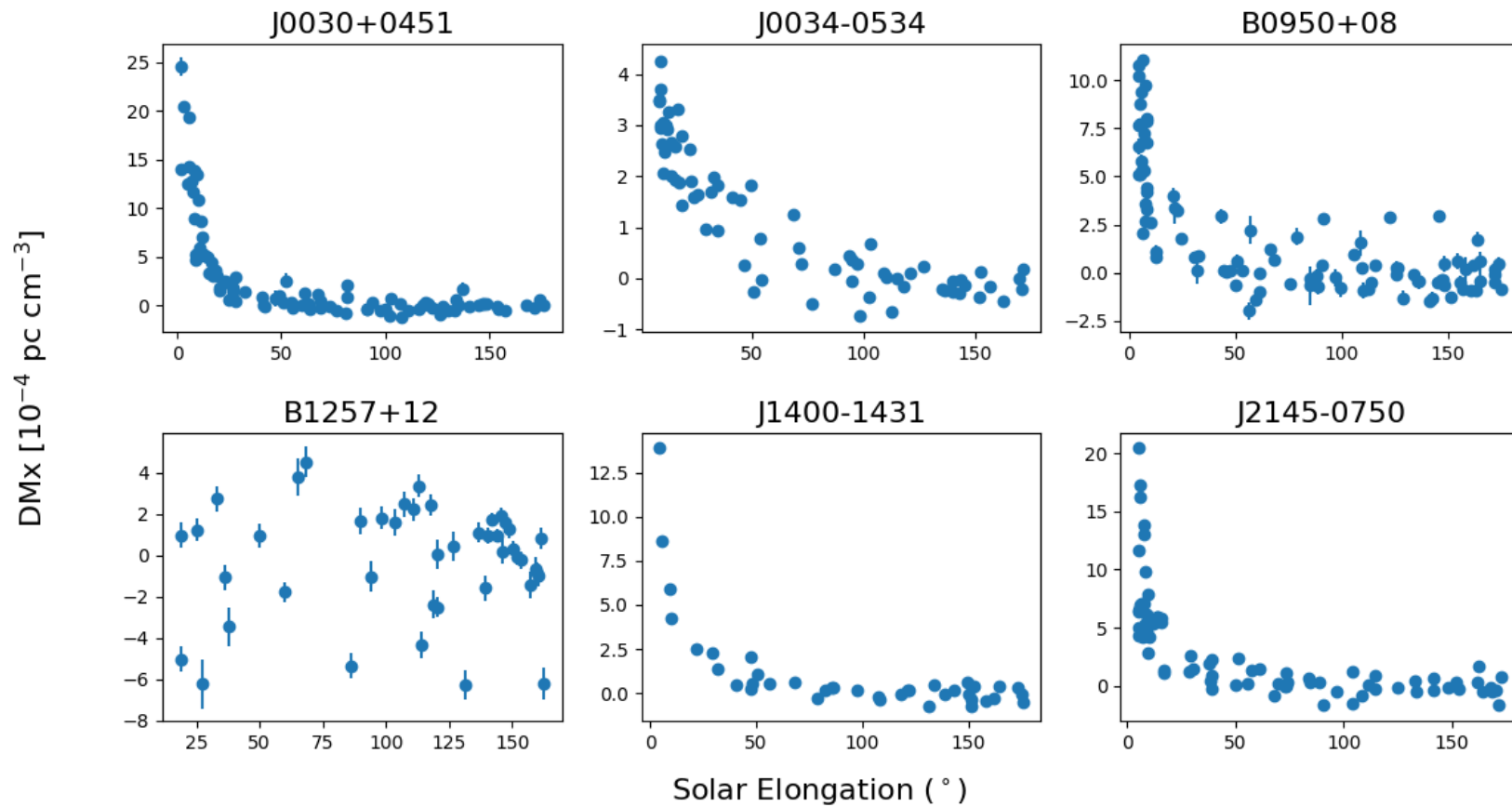
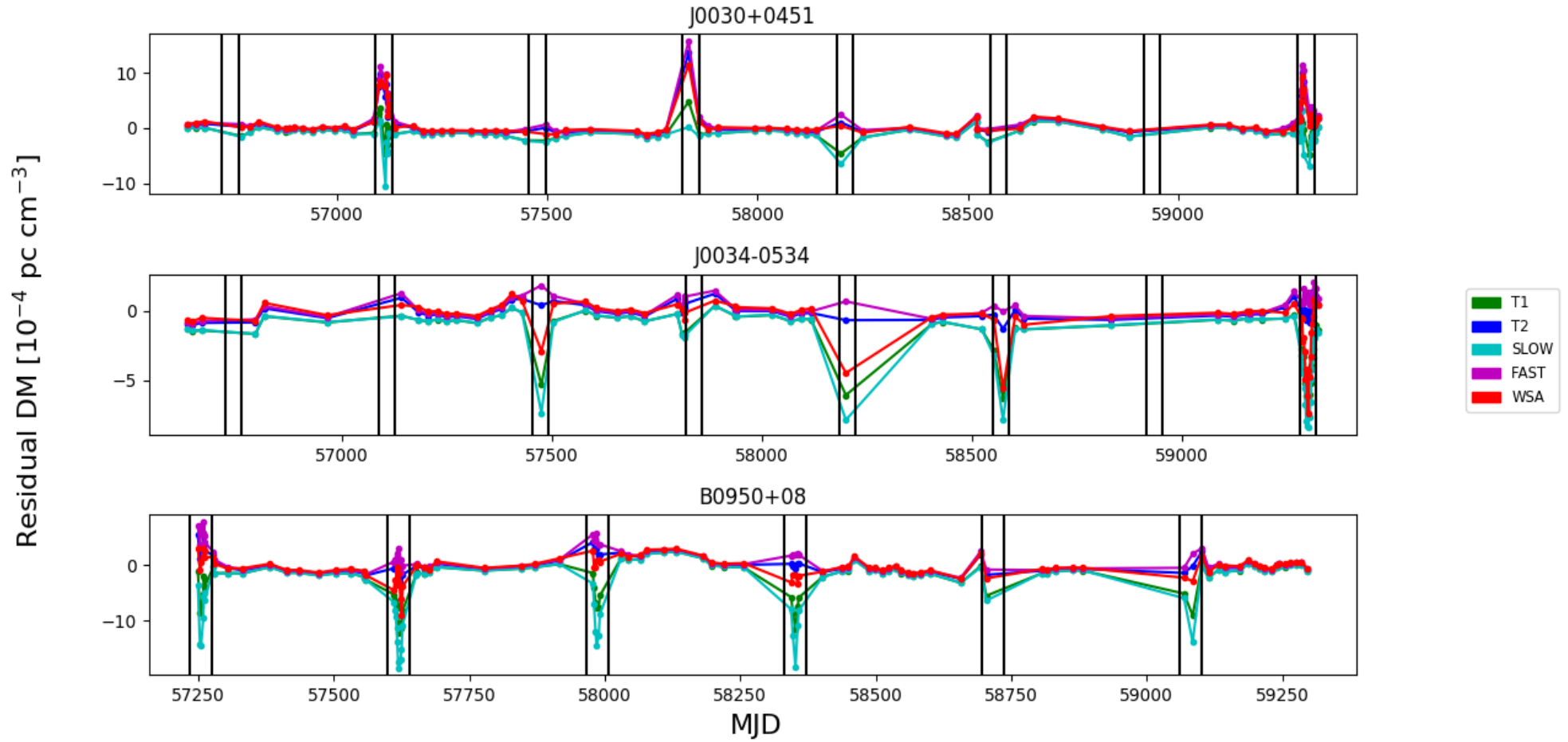


Figure shows the DMx vs Solar Elongation angle after subtraction of linear contribution.

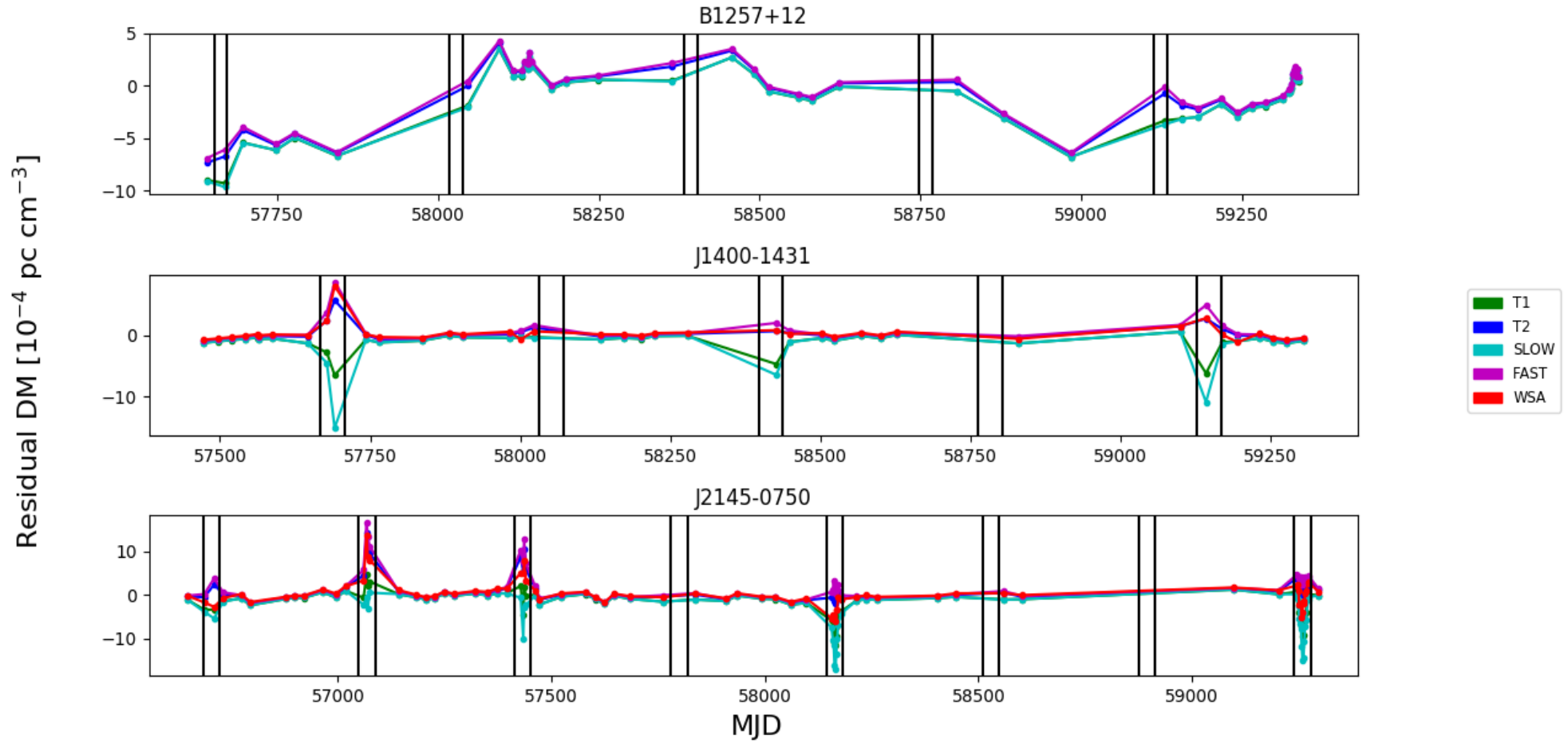
## IISM modelling

- 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

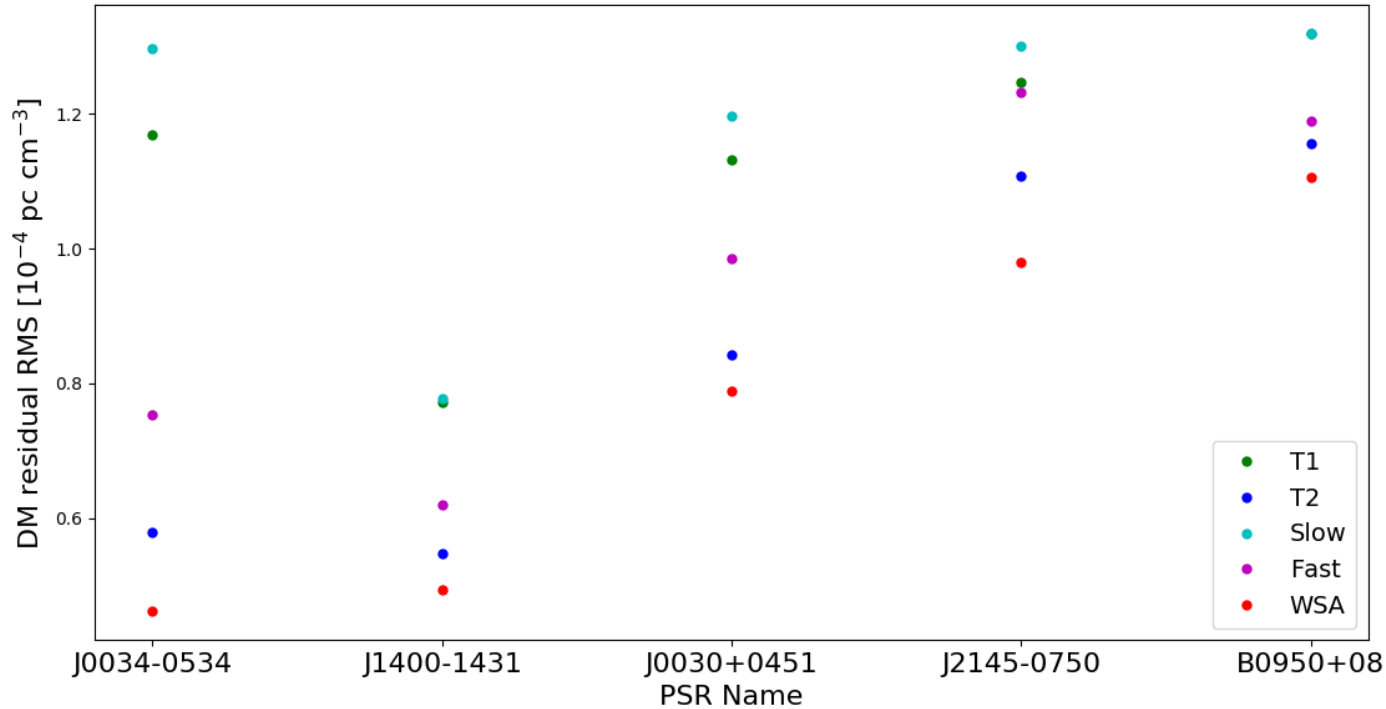
# DM residuals



# DM residuals



## RMS values



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

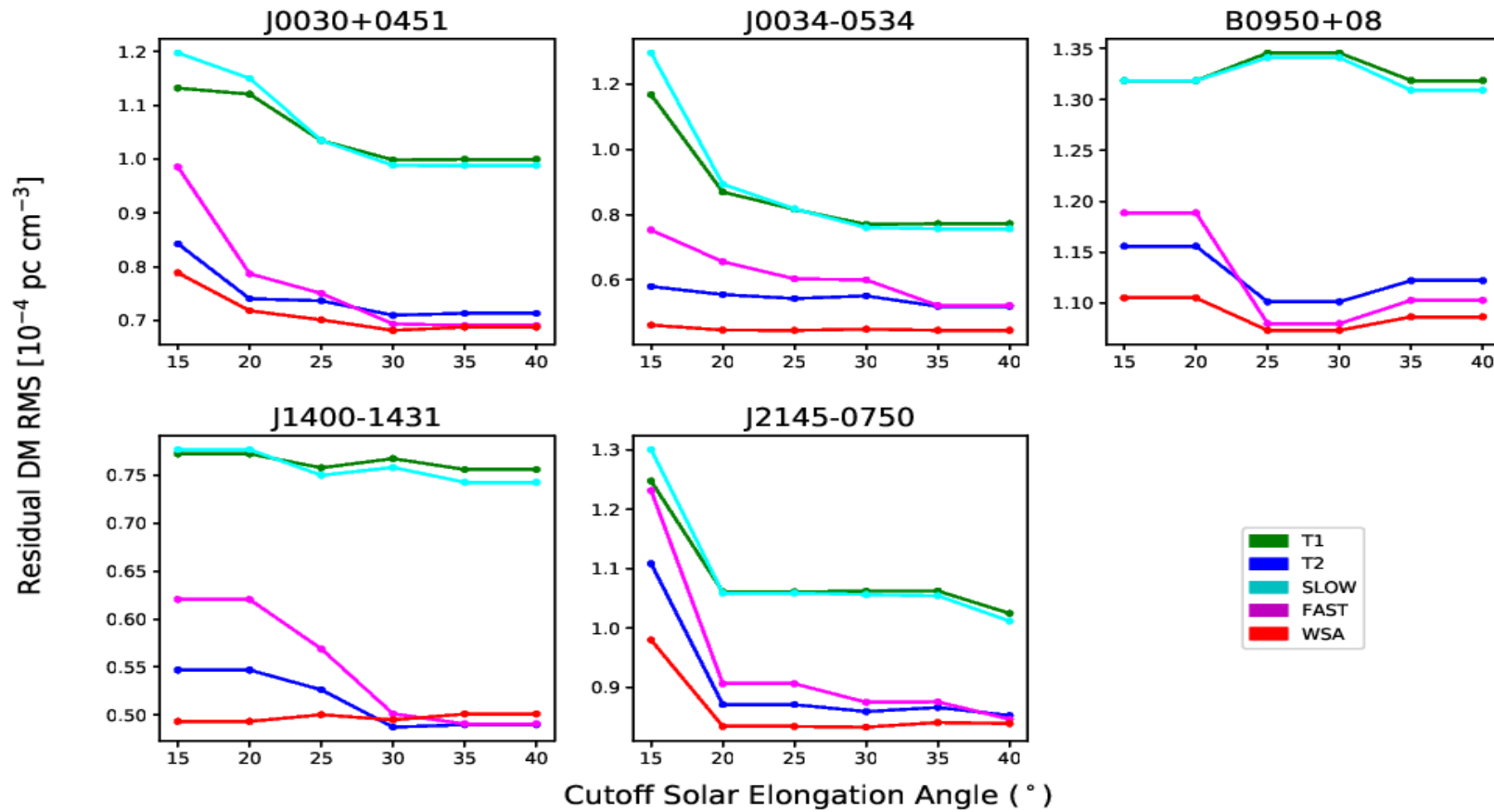
Residual Delay at 1.4 GHz for WSA

|                    | J0030+0451 | J0034-0534 | B0950+08 | J1400-1431 | J2145-0750 |
|--------------------|------------|------------|----------|------------|------------|
| $RMS_{15} (\mu s)$ | 0.167      | 0.098      | 0.234    | 0.104      | 0.207      |
| $RMS_{40} (\mu s)$ | 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<sup>-3</sup> 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

