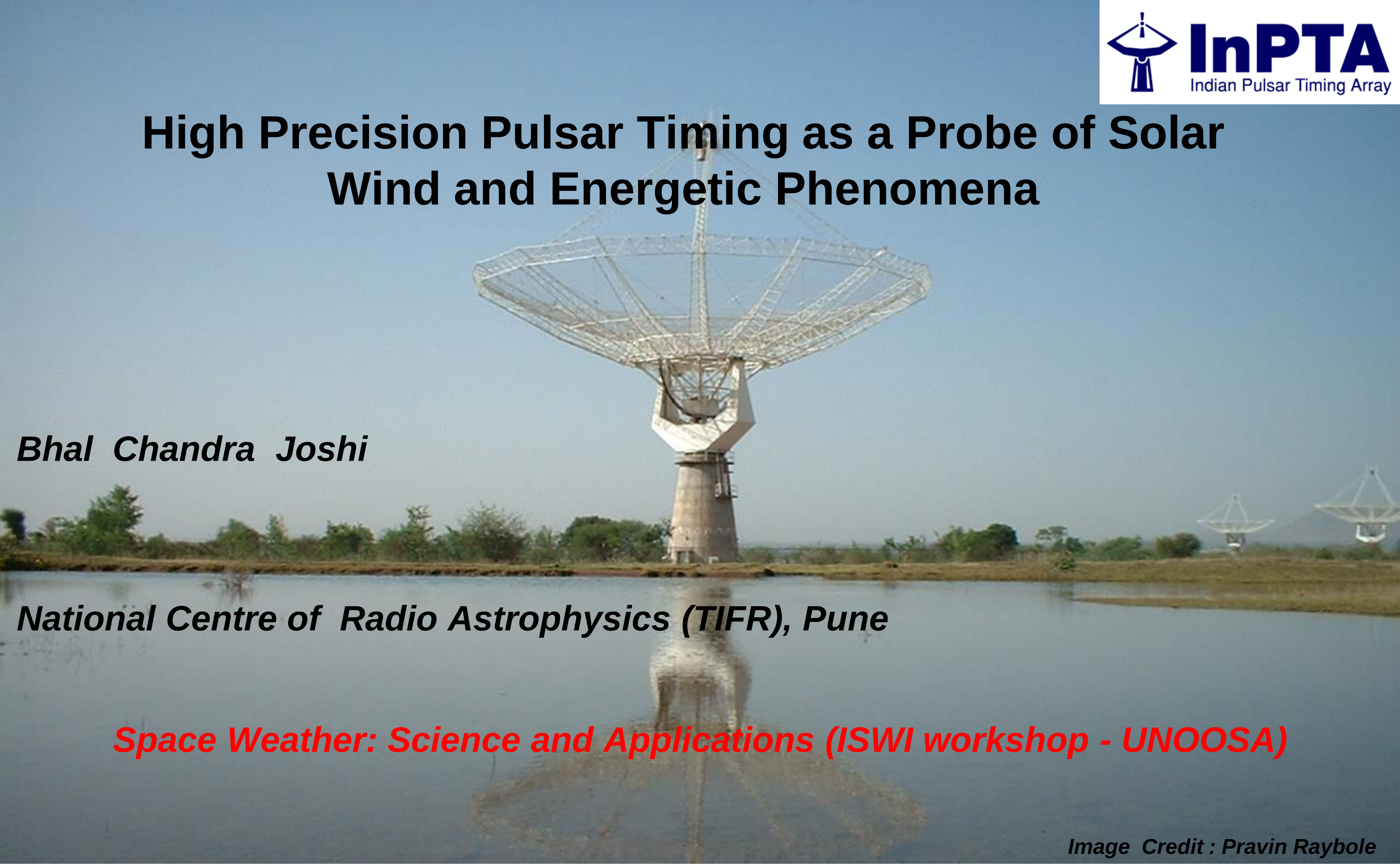
InPTA
Indian Pulsar Timing Array

High Precision Pulsar Timing as a Probe of Solar Wind and Energetic Phenomena



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Space Weather: Science and Applications (ISWI workshop - UNOOSA)

Image Credit : Pravin Raybole

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Introduction

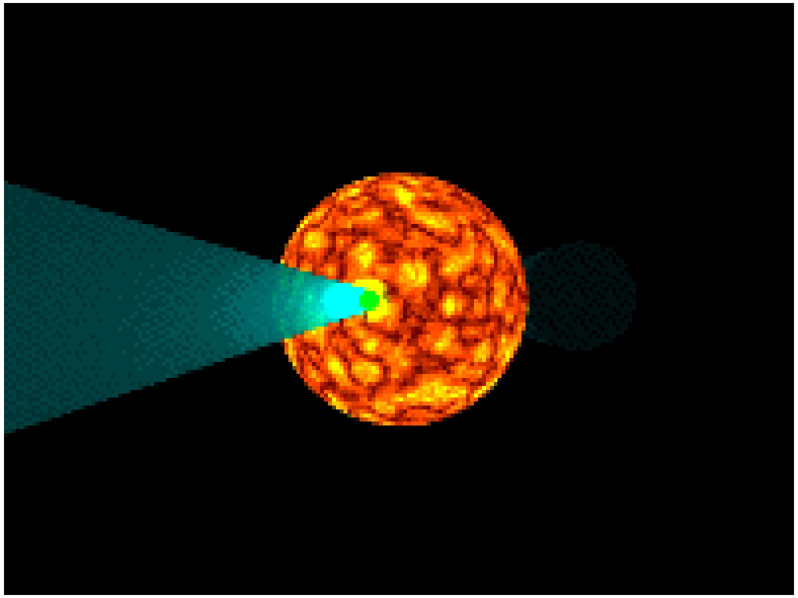
- Space weather can be directly probed by several methods
- Indirect probes
  - Observations directed at other targets
  - Space weather is a nuisance, yet needs to be accounted for

- Precision pulsar timing for discovery of nano-Hz gravitational waves (GWs)
- Radio pulsars - the celestial clocks
- Pulsar Timing Arrays (PTAs) - the celestial instrument using pulsars

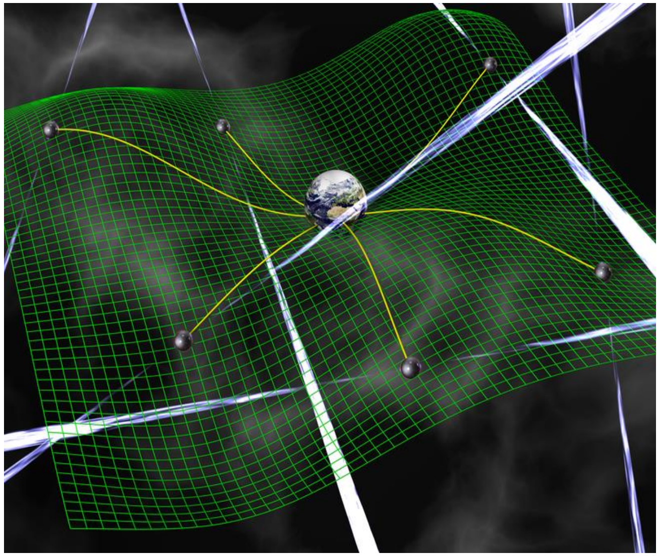
- High precision measurements with low frequency telescope the upgraded GMRT
- Review of PTA experiments relevant to space weather
- Detection of CME-solar wind interaction by InPTA experiment
- Conclusion and discussion

Radio Pulsars

- Radio pulsars are massive compact neutron star (M ~ 1 Mo; R ~ 10 km)
- Emission is a train of narrow highly periodic pulse (1.3 ms to 77 s)
- Narrow rotating radio beam - celestial light houses
- Stability is due to large kinetic energy reservoir - 10 billion times
- Useful celestial clocks for detecting ultra-low frequency GWs



Ensemble of pulsars – PTA GW detector



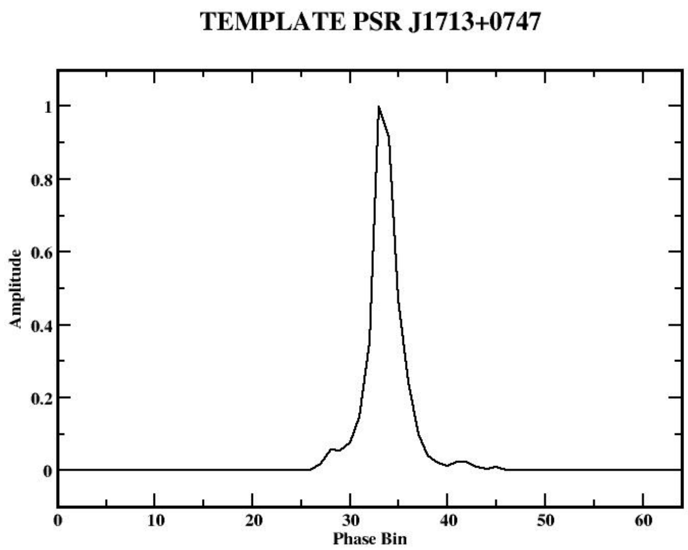
- GWs are small propagating perturbation of space-time
- GWs manifest themselves as systematic "noise" in pulse frequency measurement
- Detection of GWs requires correlated deviation across an ensemble of pulsars.

Image Credit : MPIfR, David Champion
https://www.mpifrbonn.mpg.de/research/fundamental/forces

- Pulsar Timing Array (PTA)
  - A celestial detector of pulsars uniformly distributed across the sky
- GW source
  - super massive black hole binary system
  - typical orbital period of decades (frequency ~ nano-Hz)
  - signature varies slowly over years
- GW is like a common "red noise" process
- Required precision ~ ns

Pulsar Timing

- **Measured ToA - time on the average pulse based on atomic clocks**
- **Predicted ToA - based on a rotational model of pulsar**
  - **Pulsar positional parameter**
  - **Spin parameters**
  - **Solar system ephemeris**
  - **Binary Keplerian and post-Keplerian parameters**



$$t_{SSB} = t_{topo} + t_{clock} + \Delta_p + \Delta_{RO} + \Delta_{SO} + \Delta_{EO} + \Delta_A + \Delta_{DMO} - D/f^2 + \Delta_R + \Delta_S + \Delta_E + \Delta_B$$

- **Assumed model of pulsar rotation ($t = t_{SSB}$)**

$$\nu(t) = \nu_0 + \nu_{dot}(t-t_0) + ½\, \nu_{ddot}(t - t_0)^2$$

- **Calculate pulse number from the above two relations**

$$N = \nu * (t - t_1)$$

- **Timing residual - difference between measured and predicted time-of-arrival**
- **GW is unmodeled systemic deviations with a "red noise" signature**

Pulsar Timing in action

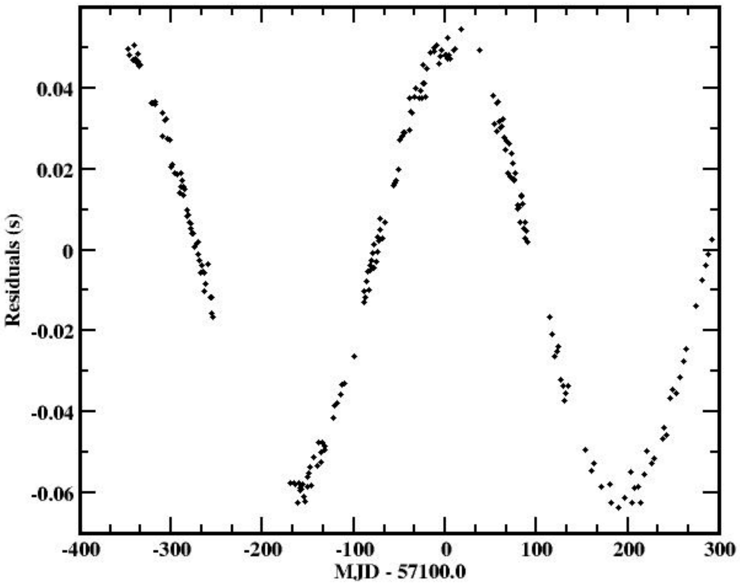
- Determining position of GMRT discovery pulsar – PSR J2208+5500

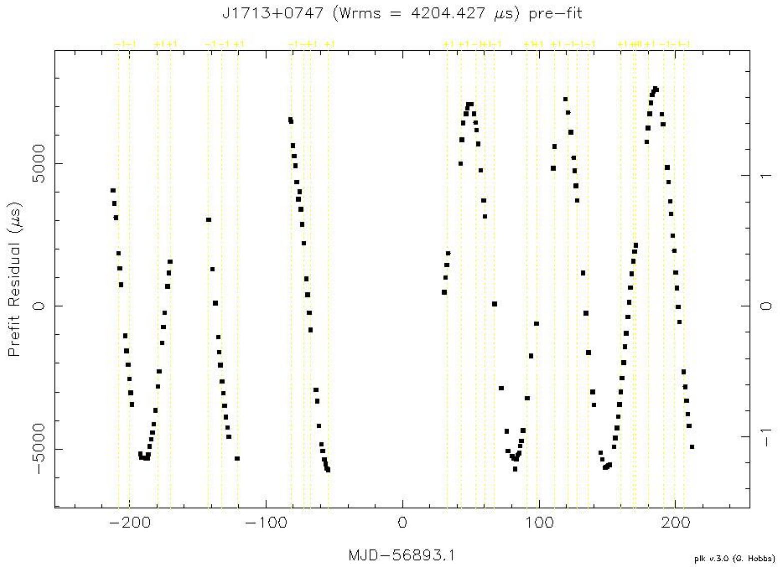
68 day Orbital period

PSR J1713+0747

observed at ORT

Phase Residual for PSR J2208+5500

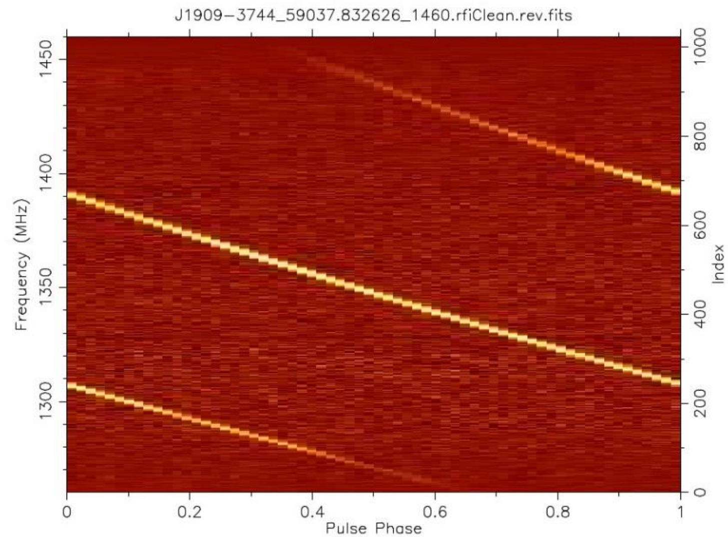




(Joshi et al. 2009, MNRAS, 398, 943; Surnis, Joshi et al. 2019,ApJ,870,8)

Pulsed signal and medium

- **Pulsed signal is dispersed in ISM and IPM**



$$\Delta\tau = 4.15\ [(\nu_{lo}/\mathrm{GHz})^{-2} - (\nu_{hi}/\mathrm{GHz})^{-2}]\ \mathrm{DM}$$

$$\mathrm{DM} = e^3/(2\pi m_e^2 c^4)\int_0^d n_e\, dl$$

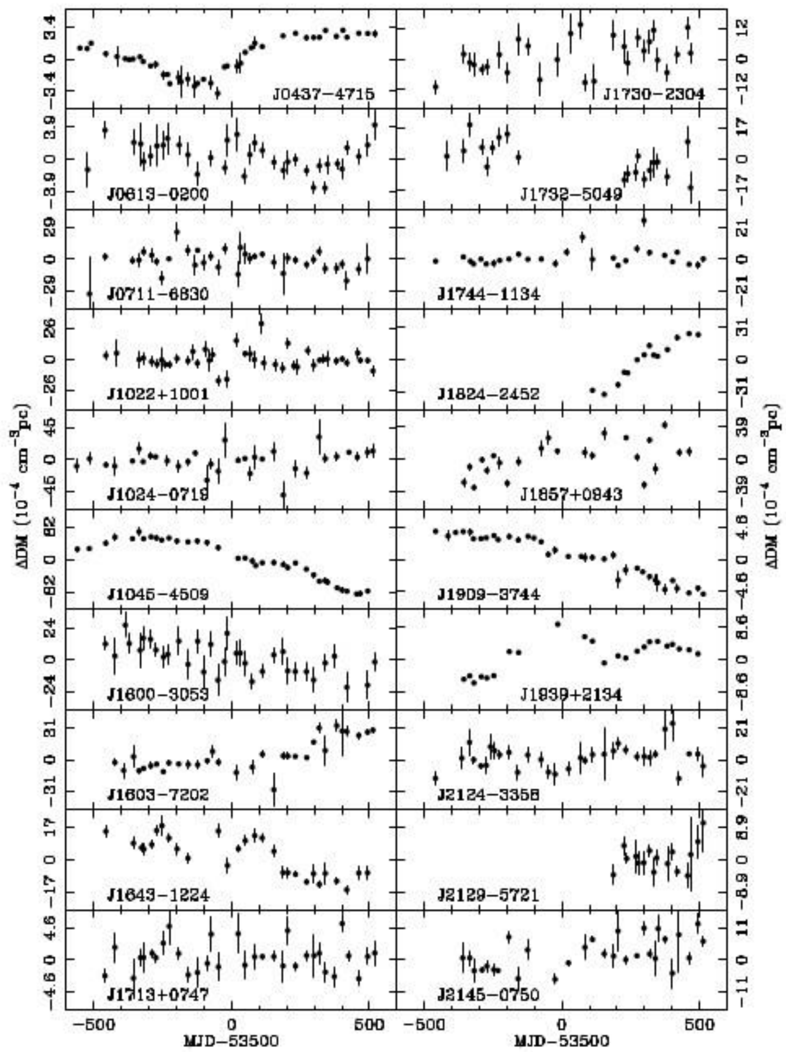
- **Dispersion delay is predominantly due to ISM**
- **ISM : n_e ~ 0.03 per cm^{-3} ;L ~ 1 kpc ~ 30 pc-cm^{-3}**
- **IPM : n_e ~ 10 per cm^{-3}; L ~1 au ~ 0.001 pc-cm^{-3} (3 order of magnitude small)**
- **Dispersion delay is a strong function of frequency**
- **Higher precision measurements possible at lower frequencies**

Sensitivity to solar phenomenology

- **No significant variations in DM measured or reported in 1970-2000**
- **The requirement of ns timing in PTA experiment motivated measurements up to 3rd decimal place**
- **Slow variations of DM reported by 2007 in PTA data sets**

(You et al. MNRAS, 378,493)

- **Changes in SW or events such as CMEs enhance ne in IPM by 1000 times**
- **Line of sight of many PTA pulsars come close to few degrees every year**
- **Pulsar astronomers have to take solar wind into account**



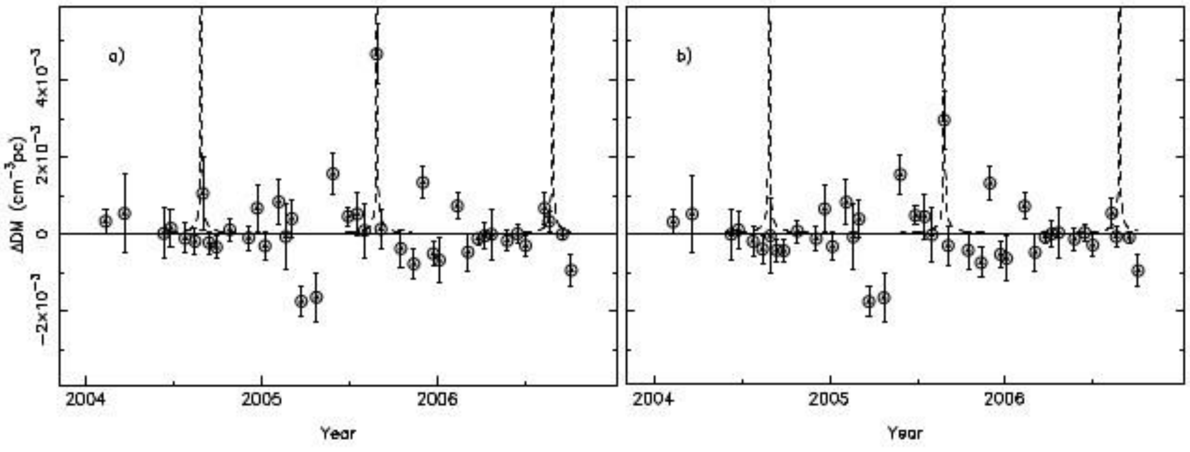
Past investigations - I

- **Sporadic studies of solar phenomenology before 2000**

Counselman et al, 1968, Sci, 162,352; Counselman et al, 1972, ApJ, 175,843;Archibald et al. 2018, Nat, 559,73

- **First systematic study of the effect of solar wind** You et al. 2007, MNRAS, 378, 493
- **Solar wind needs to be accounted for high precision timing**
- **Simplest solar wind model - spherically symmetrical electron density**
- $n_{esw} = A_{sw} \, [1AU/r]^2$ **(Δ_{DMO} term in timing formula)**

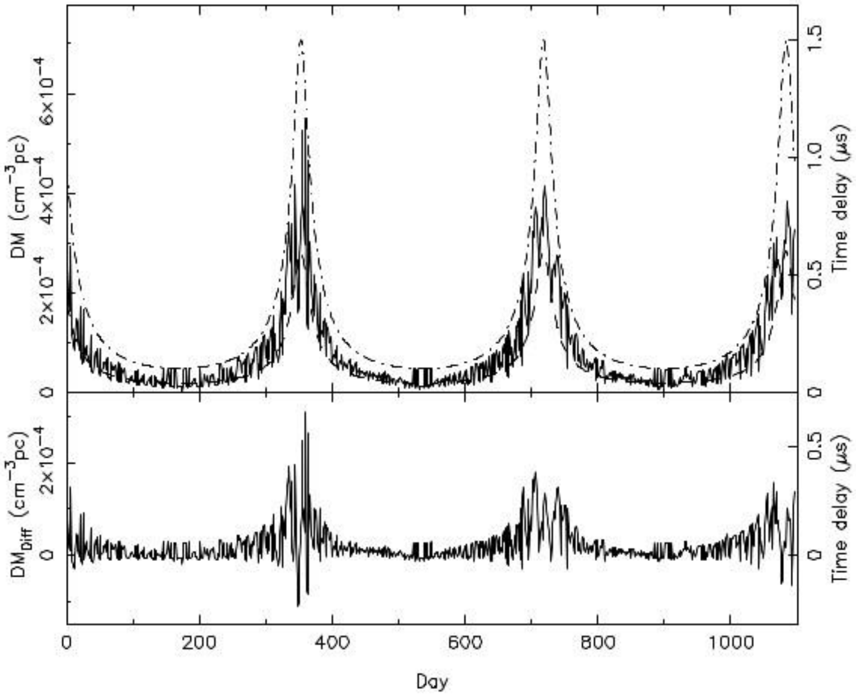
Edwards et al. 2006, MNRAS, 372, 1549;Madison et al. 2019, ApJ, 872, 150



- **This model fails to explain PTA data**

Past investigations - II

- **Electron density distribution is more complex**
- **Solar wind is bimodal at minima**
  (Schwenn 2006, Living reviews in solar physics)
- **High velocity (600 to 800 km/s) low density (3 per cm^-3) "fast wind"**
- **Slower ((<400 Km/s) wind is denser (10 per cm^-3)**
  (Tokumaru et al. 2010, J. Geo. Res, 115, A04102;
  Manoharan et al. 2003, Lect in Phy, p299)
- **Interaction of "slow" and "fast" wind can produce over dense regions**
- **Nature and bimodality of SW varies with solar cycle** (Schwenn 2006)
- **Modeling data with two component model** (You et al 2007, ApJ, 671, 907)

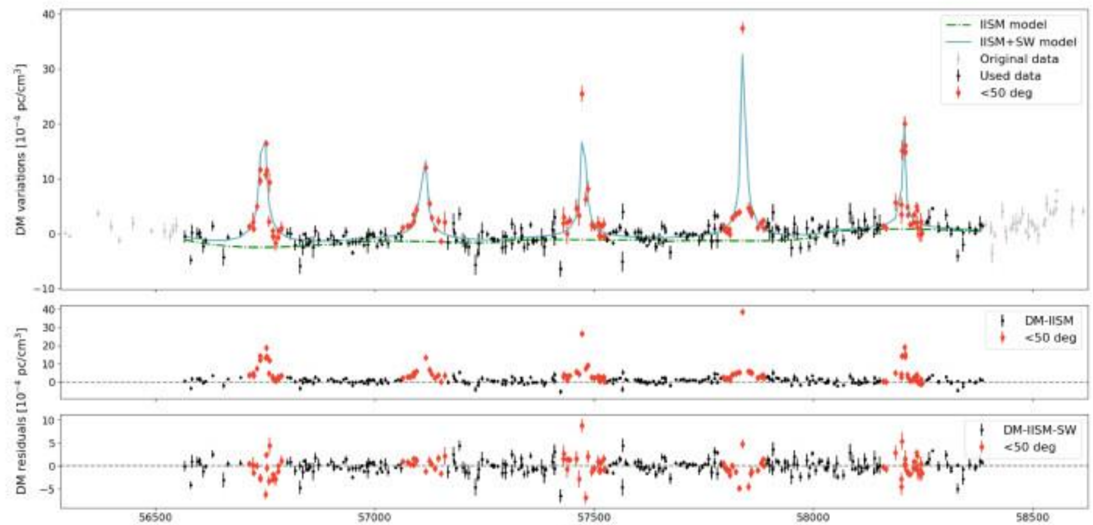


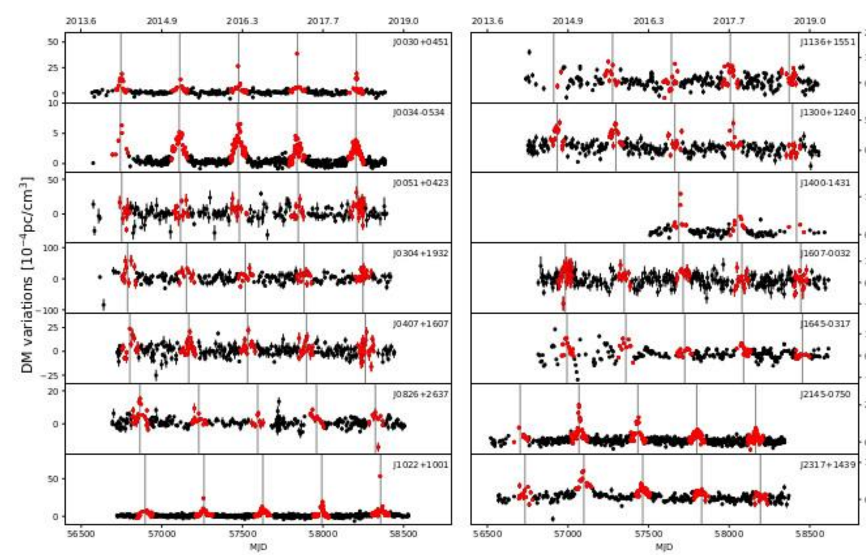
Variability of Solar wind

- **More detailed studies have shown an yearly variability in the solar wind**

  (Tiburzi et al. 2021, A&A, 647, A84)

- **Suggest a more complicated model of solar wind needed for PTAs**
- **A useful by-product can be measurements of solar wind variability**
- **PTA measurements at low frequency provide useful complimentary measurements**
  - **To confirm the results of other probes**
  - **To provide additional inputs**

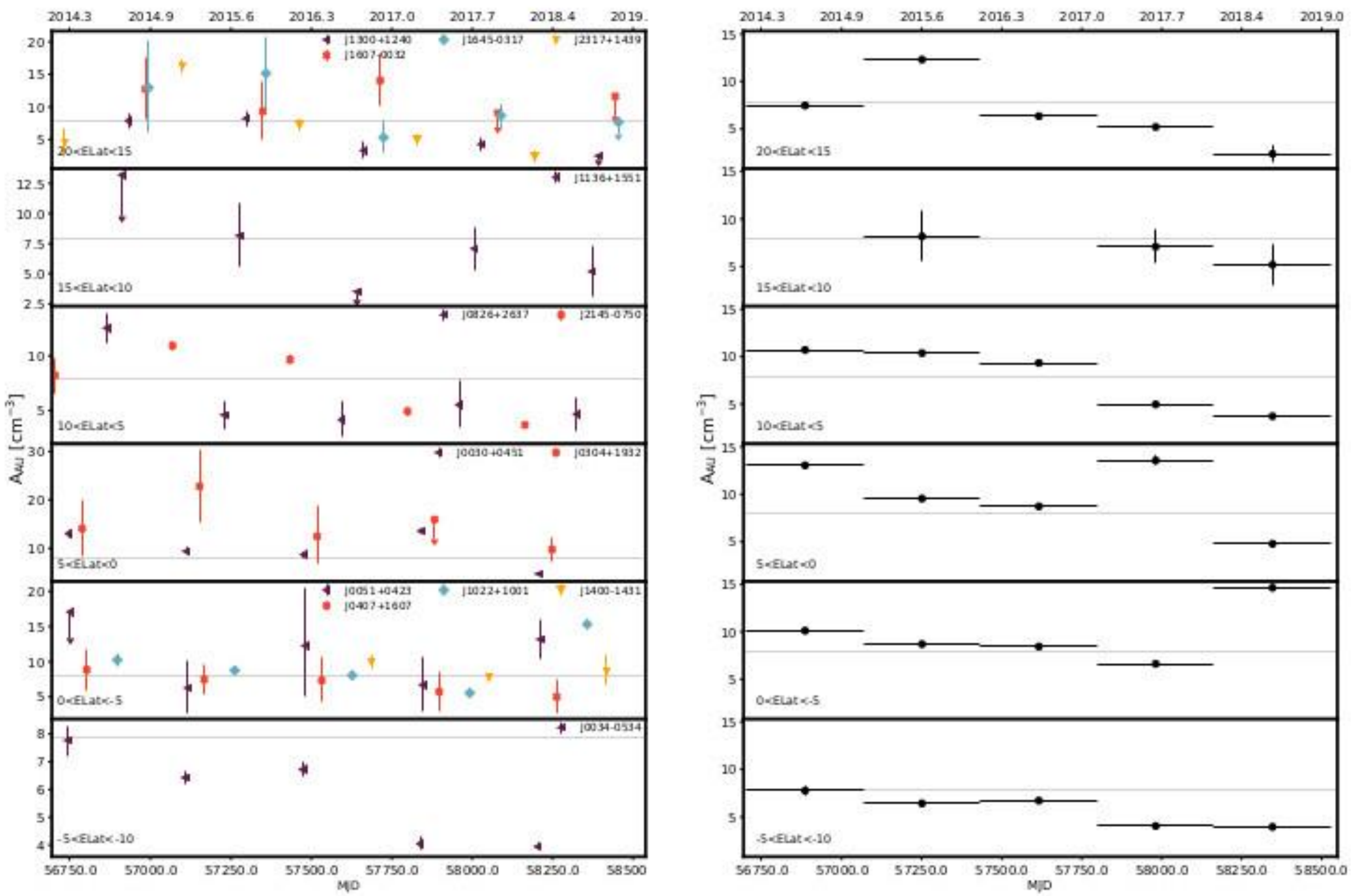




Variability of Solar wind

- **Solar wind varies with time and ecliptic latitude**

(Tiburzi et al. 2021, A&A, 647, A84)

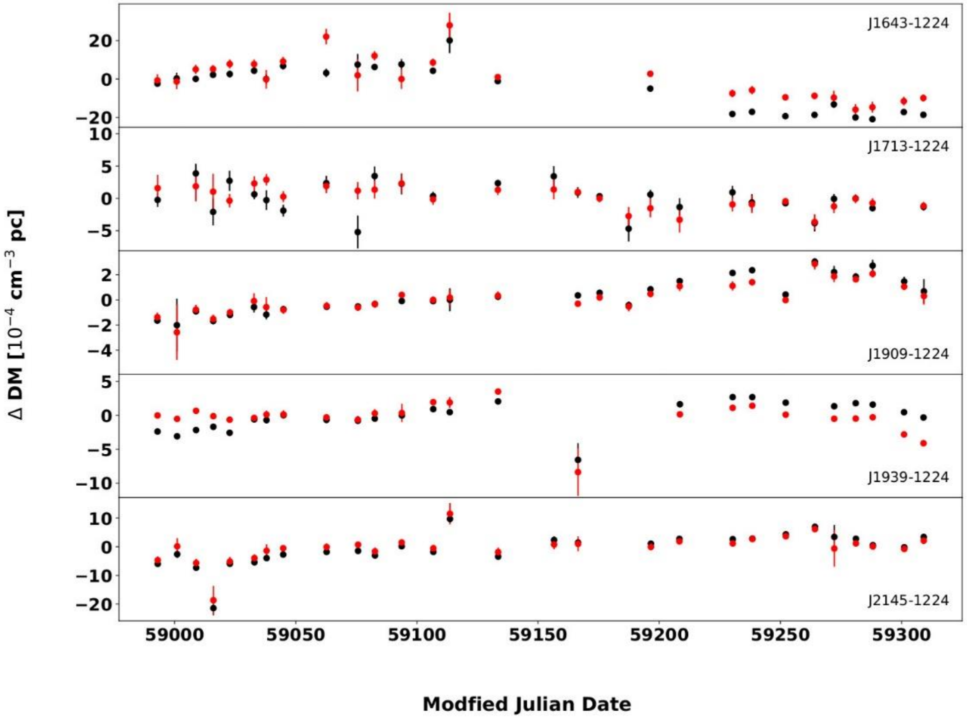


Detecting solar energetic events with InPTA

- **PTA measurements can also probe transient events**
- **February 2019 event detected in by InPTA**
- **InPTA monitors 20 pulsars once every 15 days**
- **Unprecedented precision on 0.0001 to 0.00001 pc-cm^{-3} (0.1-1.0 per cm^{-3}) due to measurements at 300-500 MHz**

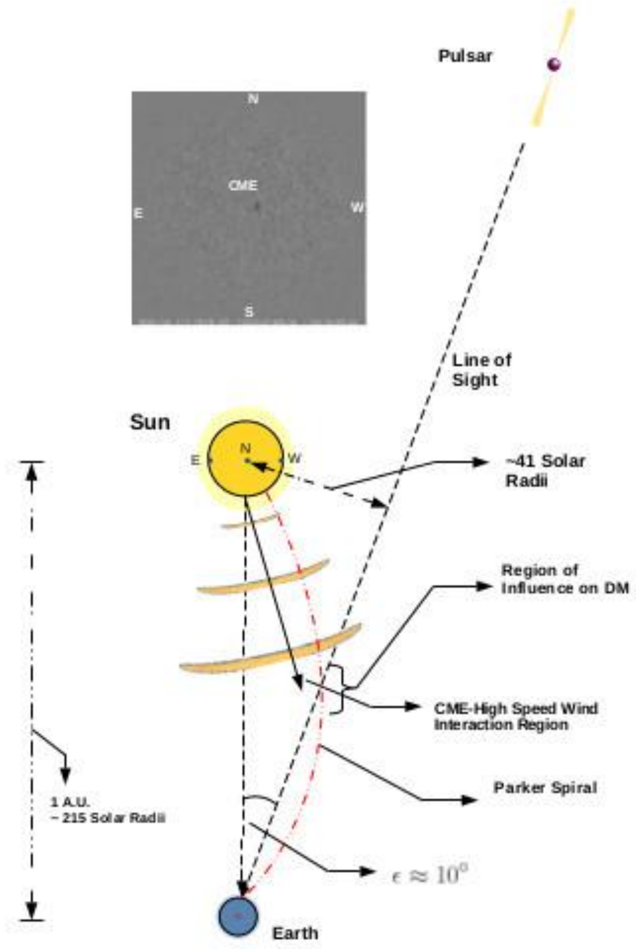
  (Nobleson et al. 2021, in prep)

- **PSR J2145-0750 approaches Sun ~ 5 deg between January to March**

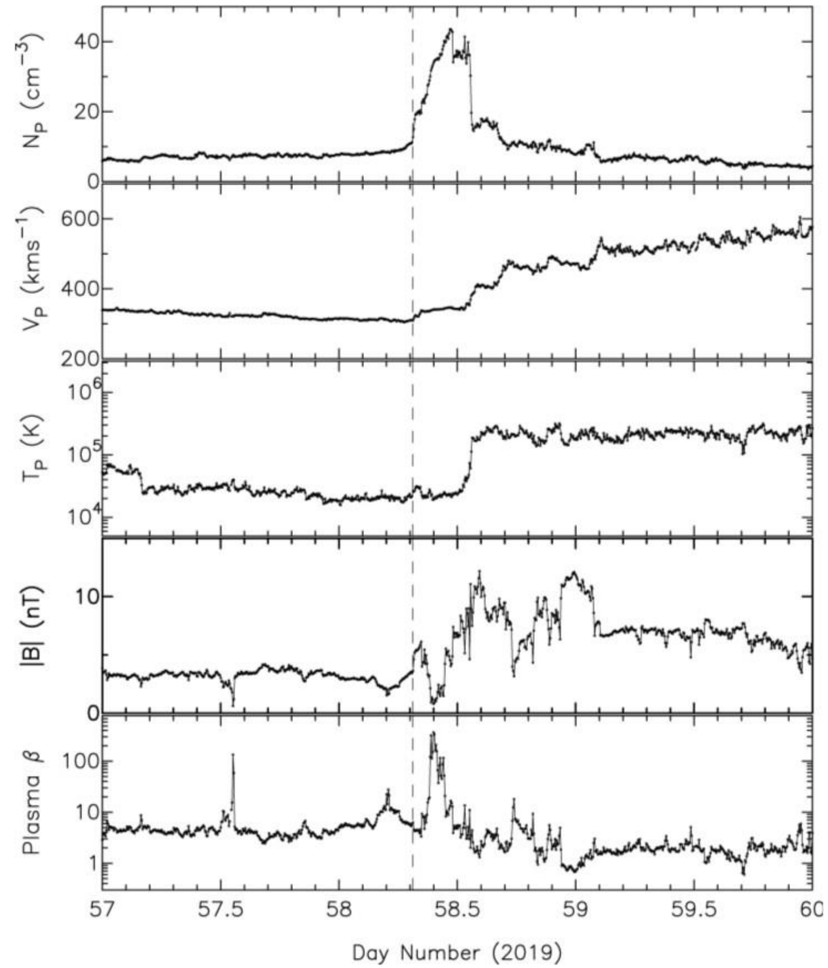


ICMEs on February 23, 2019

Geometry of passage of shock region in line-of-sight of the pulsar



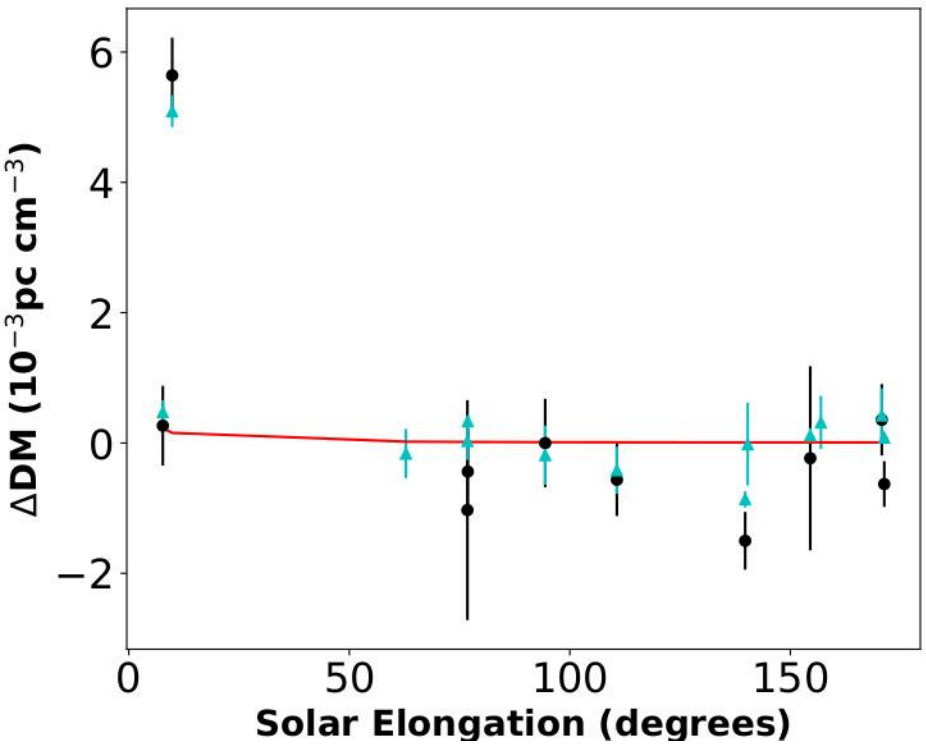
Density enhancement from interaction of slow and fast solar wind with CMEs



Krishnakumar et al. 2021, A&A, 651, A5

Our measurements

- **An enhancement in DM of the order of 0.006 pc-cm^{-3} is seen**



- **This corresponds to density enhancement to 5000 per cm^{-3}**
  - **Steeper gradient of R$^{-2.5}$ implied**
  - **compact transverse region implied**

Krishnakumar et al. 2021, A&A, 651, A5

Conclusions

- **High precision is required by Pulsar Timing Arrays for GW detection**
- **This motivates measurement precision of 1 part in 4 or 5 for DM**
- **This corresponds to measurement of column density enhancements of 0.1 per cm^{-3}**
- **Thus, measurements of solar wind and its variability across solar cycle is possible with PTAs**
- **PTAs are capable of detecting density enhancement in transient shocks in ICMEs or solar wind interaction region**
- **Thus, PTA can provide complimentary probes of space weather**

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Thank you for your attention