A Road Map to Mitigating Chromatic Timing Variations for NANOGrav

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NANOGrav's Goal: Mitigate Chromatic Effects of the Interstellar Medium on Pulsar Timing

Dispersion

Time delay between two frequency components of a pulse due to free electrons in the ISM:

$$\Delta t_{\rm DM} \approx 4.15 \times 10^6 {\rm ms} \times {\rm DM}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right)$$

$$\mathrm{DM}(t) = \int_0^{L(t)} n_e(s\hat{n}(t), t)ds$$

[1]

Birefringence

Time delay due to magnetized medium:

$$\pm\Delta t_{\rm RM} = 28.6{\rm ps} \times {\rm RM}/\nu^3$$

$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2 c^4}\int_0^L n_e B_{||} ds$$

[2]

Pulse Broadening

Multi-path scattering causes pulse broadening with mean delay:

$$\tau_d = 1/2\pi\delta\nu_d \propto \nu^{-4.4} \text{ (Kolmogorov)}$$

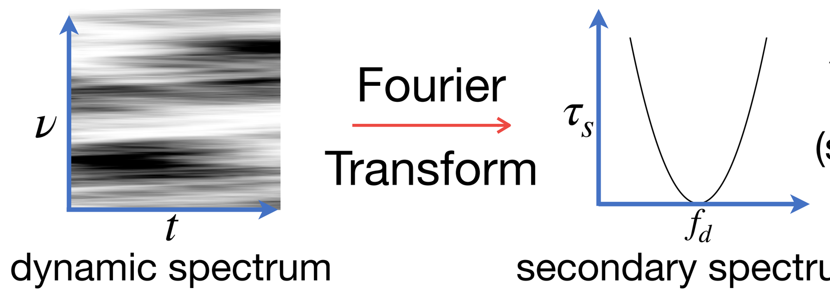
The pulse broadening function is:

$$\mathrm{PBF}(t) \propto e^{-t/\tau_d}$$

[3]

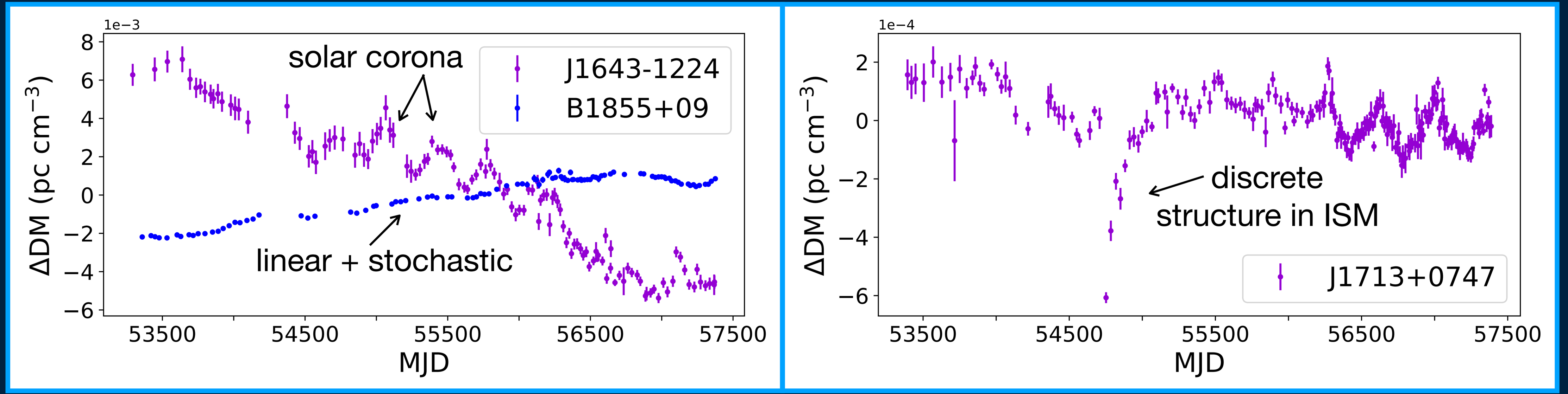
Scintillation

Scattering induced phase delays cause interference between ray paths. In the Fourier domain the interference pattern is a parabolic arc:



[4]

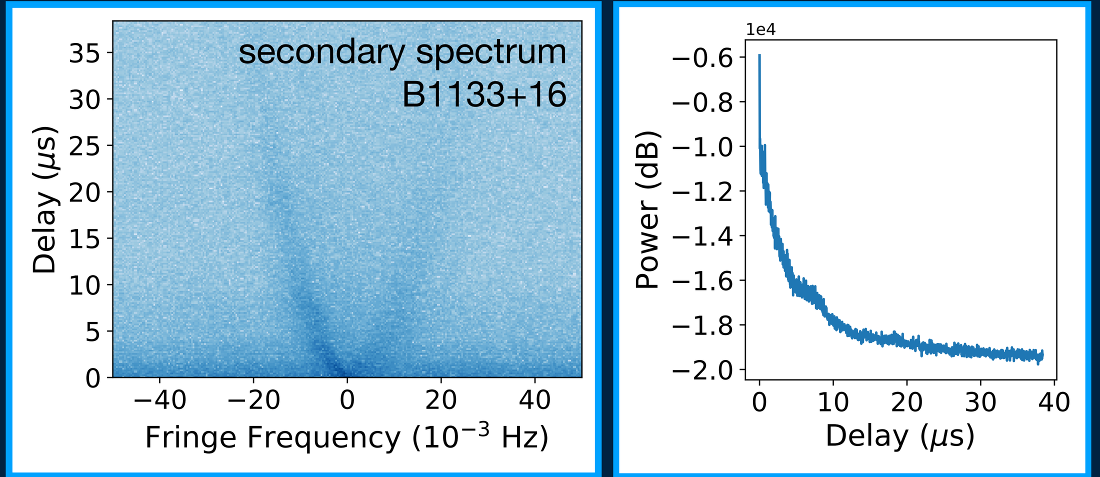
Time-Dependent Dispersion



[5]

Stochastic Impulse Response Effects

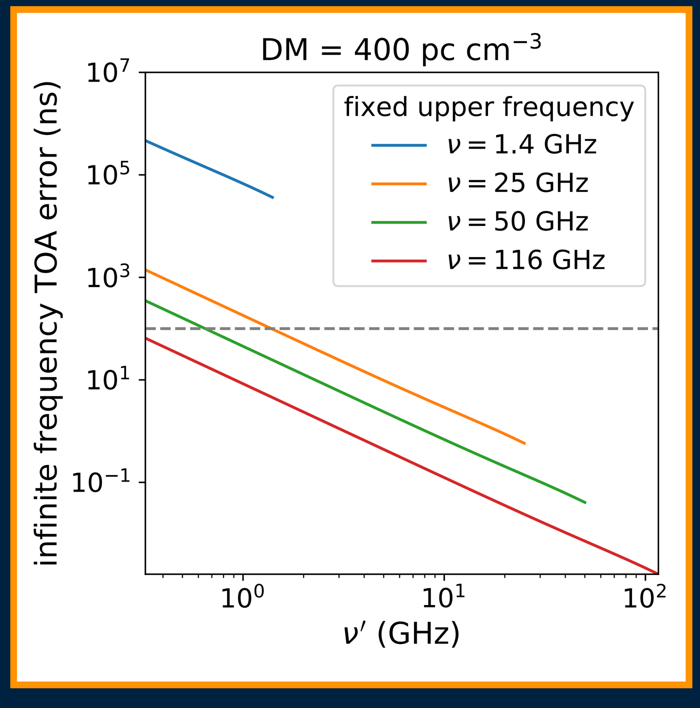
- Observed pulse is a convolution of emitted pulse & scattering impulse response PBF(t).
- Extent of scintillation arc in delay = width of PBF(t).
- Scattering might still be important in observations where pulse broadening seems small.



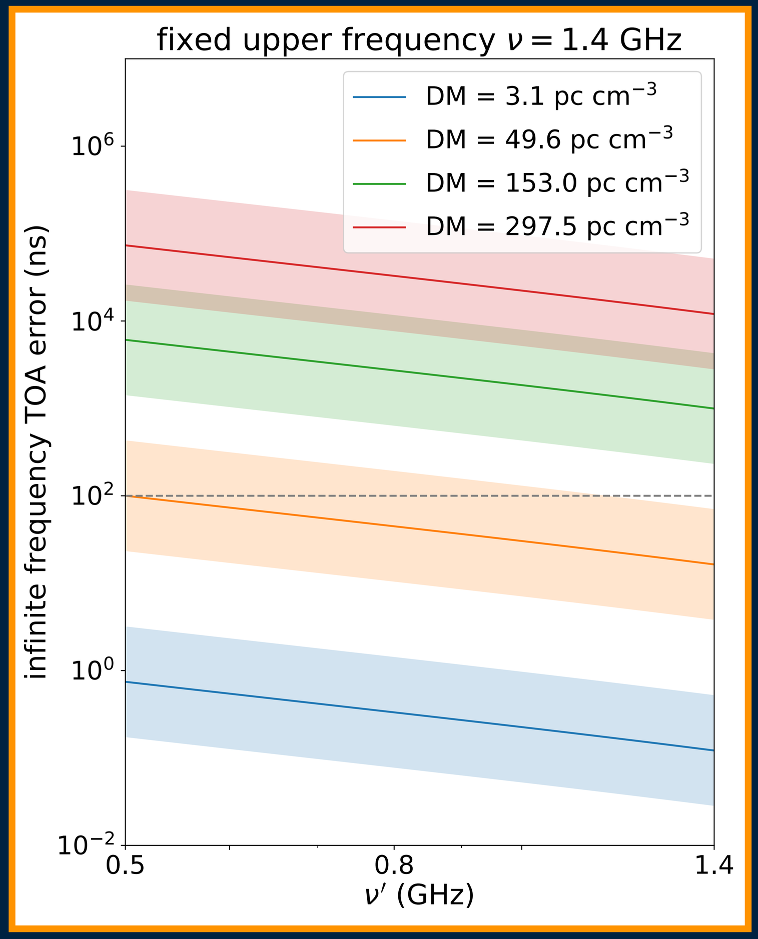
[6]

Frequency-Dependent Dispersion

- Multi-path propagation causes frequency-dependent DMs.
- This may ultimately limit the highest precision TOAs.
- Mitigation: higher frequencies (e.g., ngVLA)

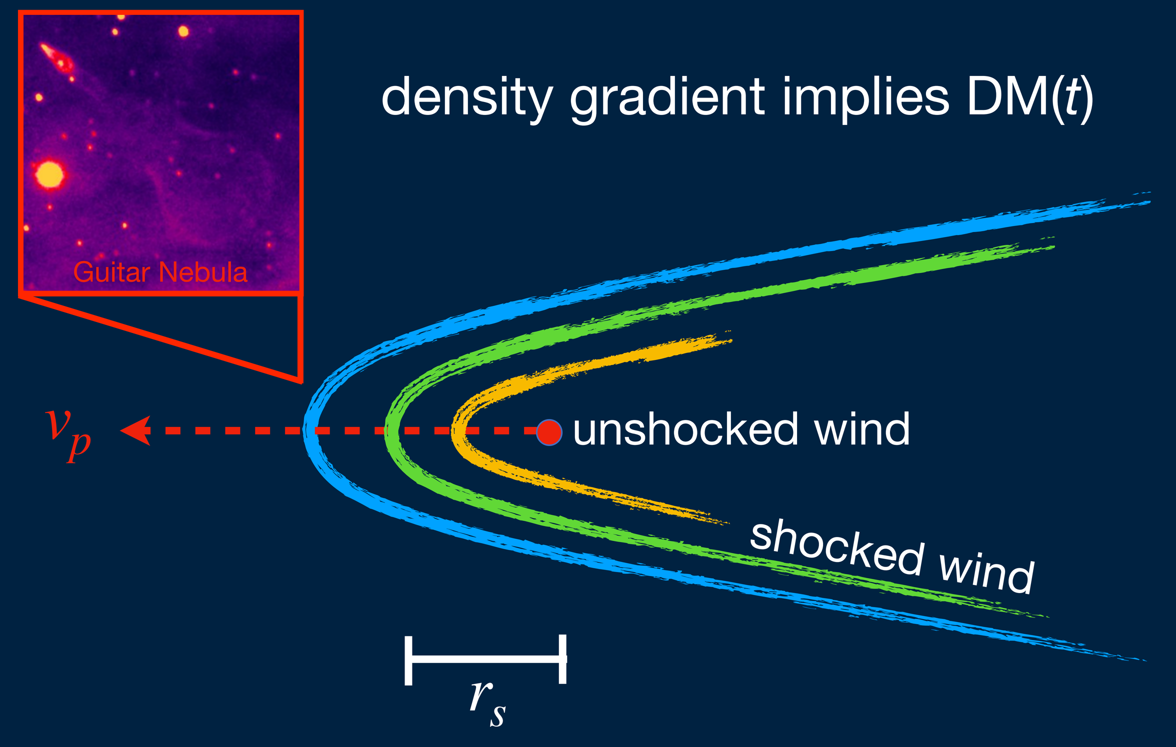


TOA error is lower for high upper frequencies and low DMs



[7]

Pulsar Bow Shocks & Wind Nebulae



$$r_s \sim L_{\rm wind} n_{\rm ISM}^{-1/2} v_{\rm NS}^{-1} \sim 50 - 100{\rm s\ AU}$$

$$L_{\rm wind} \sim B_{\rm NS}^2 R_{\rm NS}^2 c(\Omega R_{\rm NS}/c)^4$$

- forward shock
- contact discontinuity
- termination shock

[8]

Propagation Regimes

Physical Optics → Diffraction → pulse broadening, scintillation, DM(ν) → δTOAs

Geometric Optics → Refraction → SSBC, geom. delays, ESEs, DM(t) → δTOAs

$r_{\rm Fresnel}$

References: [1] Lam et al. 2016, ApJ, 821, 66 [2] Suresh & Cordes 2019, ApJ, 870, 29 [3] Rickett 1990, ARAA, 28, 561-605 [4] Stinebring et al. 2001, ApJ, 549, p. L97-L100 [5] Jones et al. 2017, ApJ, 841, 125 [6] Hemberger & Stinebring 2008, ApJ, 674 [7] Cordes et al. 2016, ApJ, 817, 16 [8] Barkov et al. 2019, MNRAS, 484, p.4760-4784

The NANOGrav Physics Frontiers Center is supported by NSF award number 1430284. The Green Bank Observatory and National Radio Astronomy Observatory are facilities of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The Arecibo Observatory is a facility of the National Science Foundation operated under cooperative agreement by the University of Central Florida in alliance with Yang Enterprises, Inc. and Universidad Metropolitana.

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