Probing Interstellar Turbulence and Precision Pulsar Timing with PSR J1903+0327

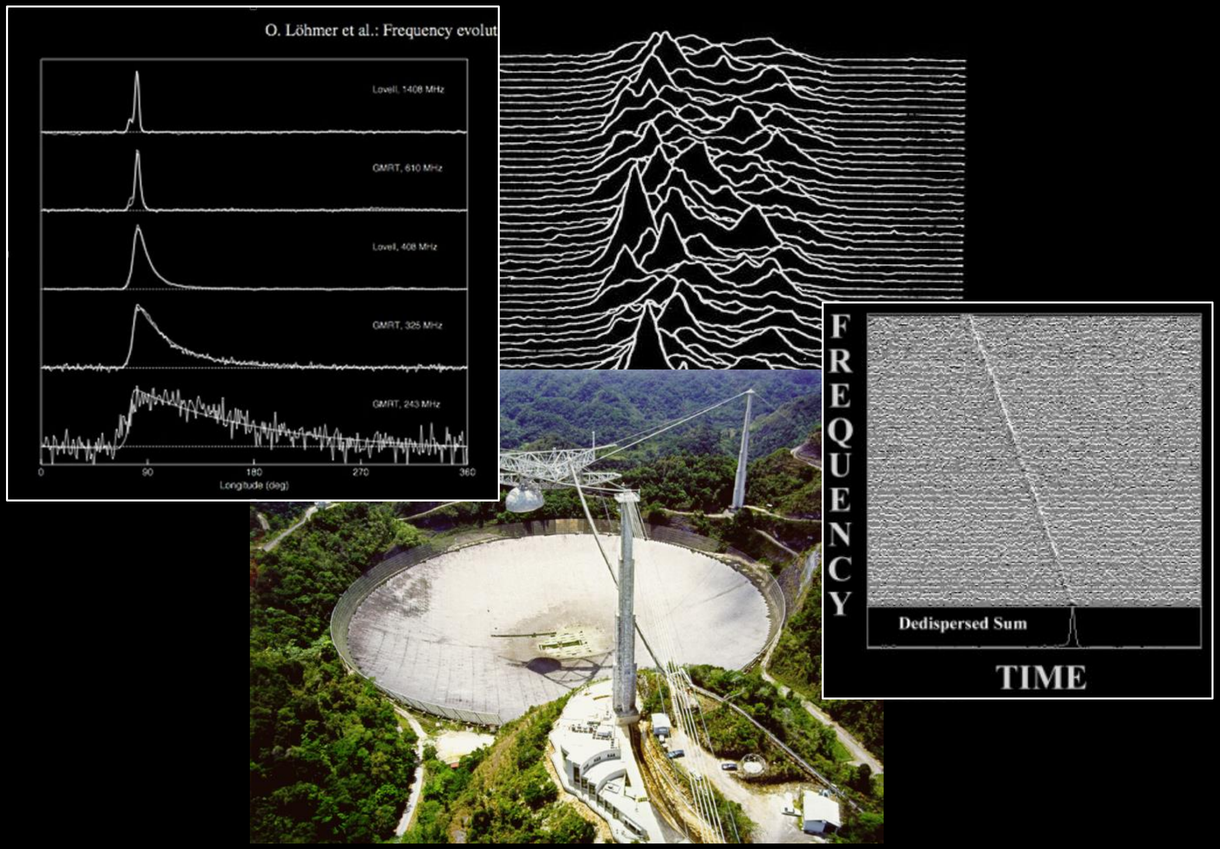
Abra Geiger

James Cordes, Michael Lam, Stella Ocker, Shami Chatterjee

NANOGrav Fall Collaboration Meeting 10/8/24

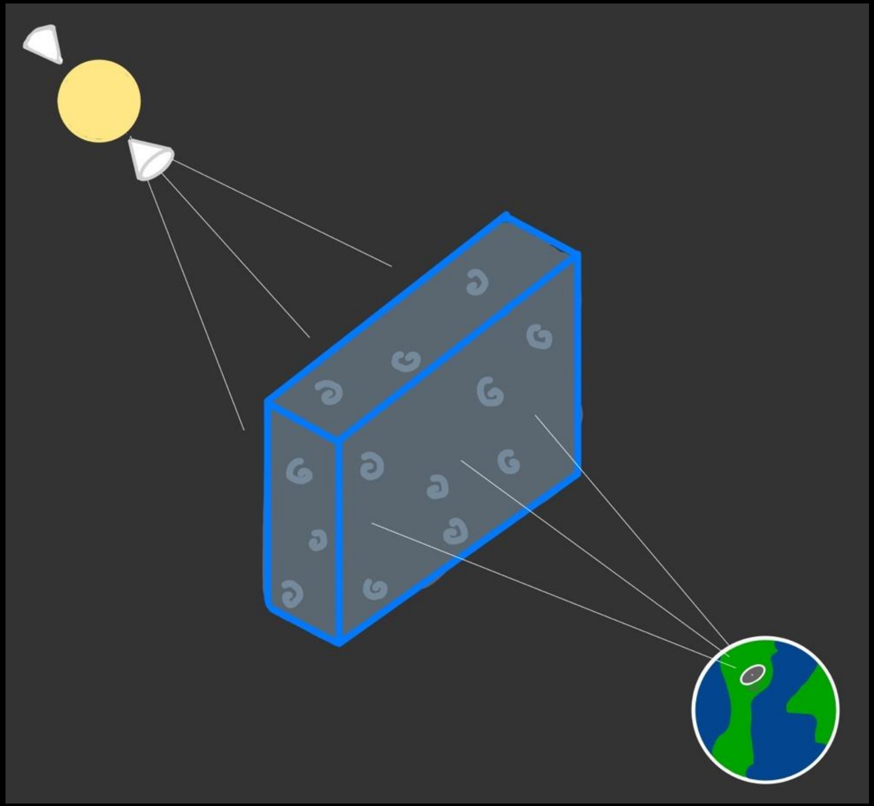
Noise in Pulsar Timing

Noise sources:
- Radiometer
- Pulse Jitter
- Interstellar Noise
- And more



Scattering

- Multipath propagation broadens the pulsar image



Scattering

- Multipath propagation broadens the pulsar image

$$I(t) = aU(t - t_0) * p(t, \tau)$$

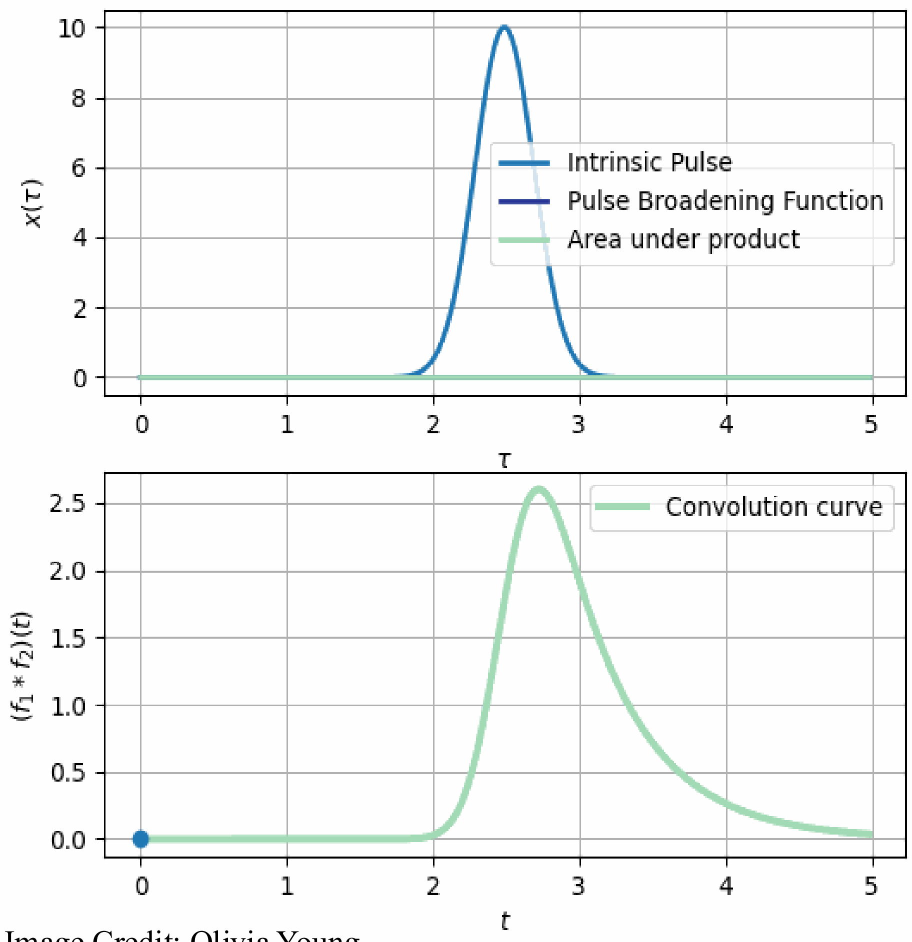
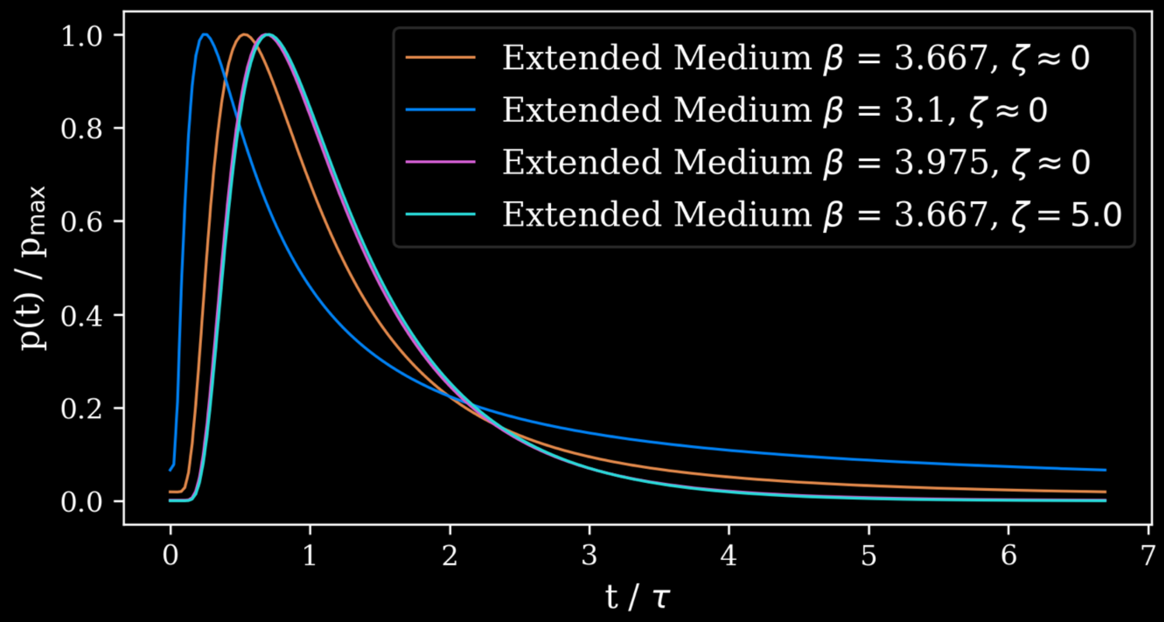
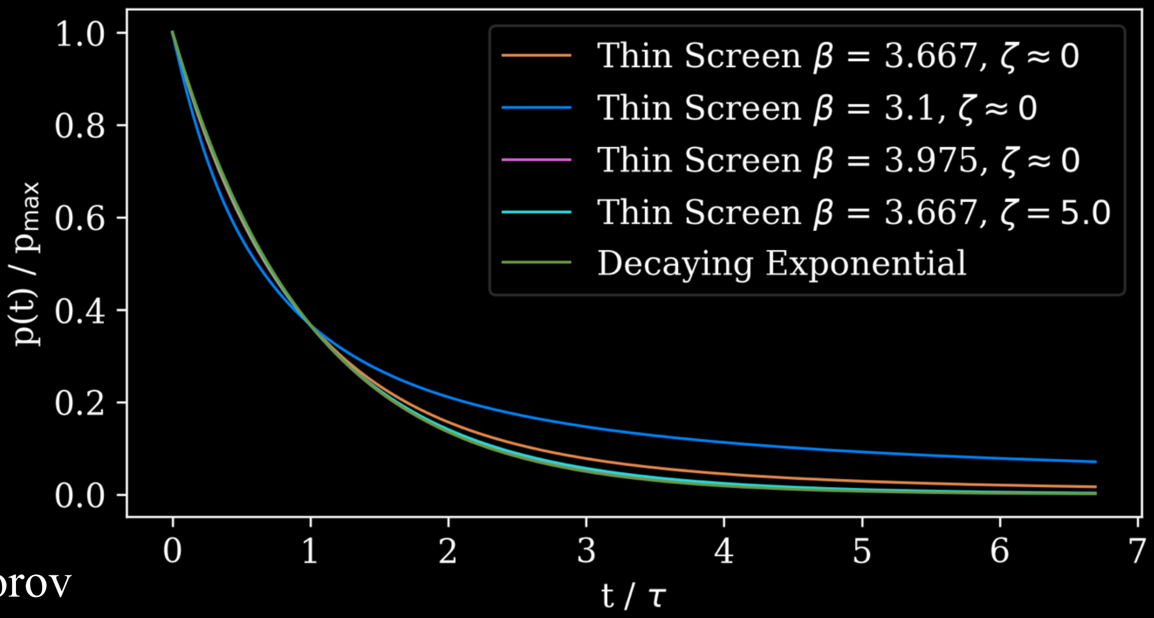


Image Credit: Olivia Young

Scattering





- Multipath propagation broadens the pulsar image

$$I(t) = aU(t - t_0) * p(t, \tau)$$

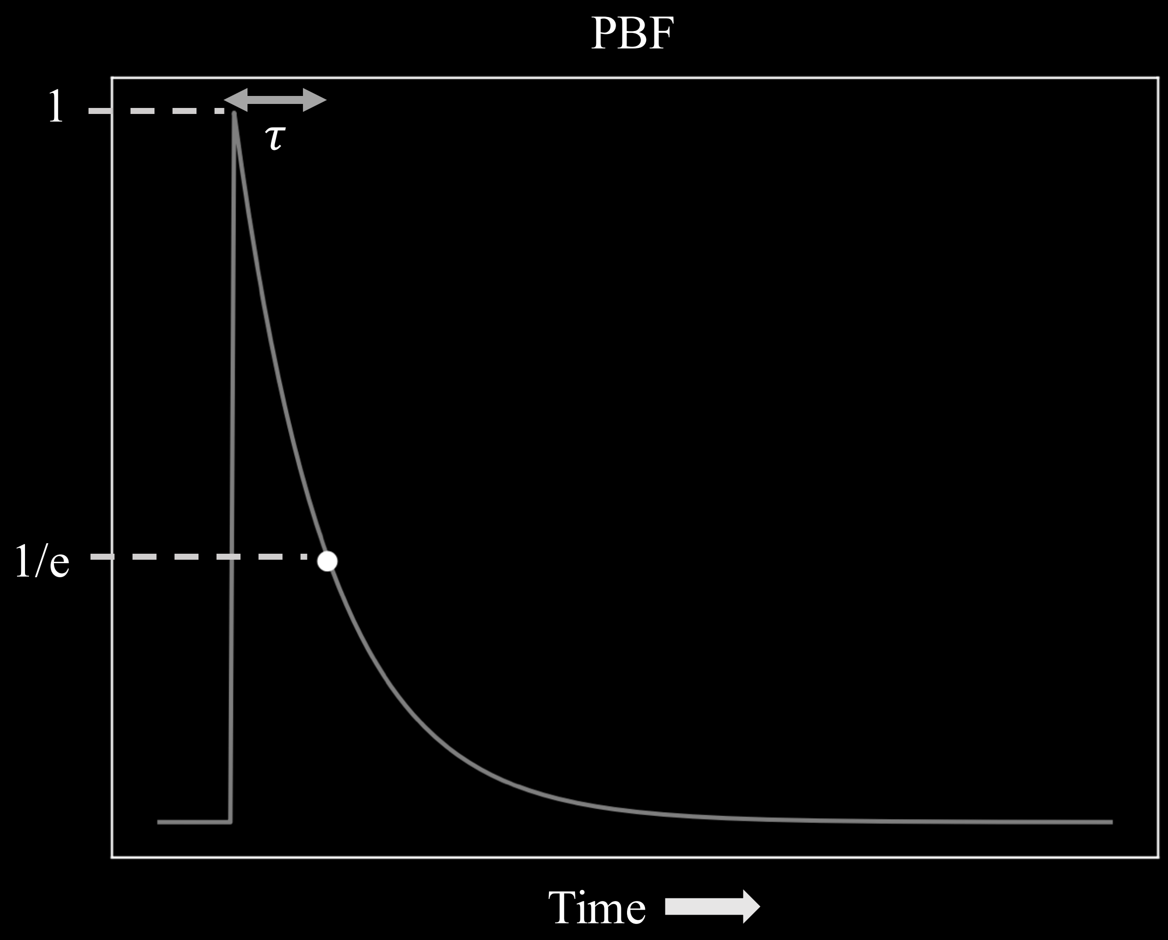
- The pulse broadening function (PBF) is dependent on the spectrum of turbulence and the extent of the intervening plasma

$$P_{\delta n_e}(q) = C_n^2 q^{-\beta} e^{-(q/q_i)^2}$$

$$q_i = 2\pi/l_i \quad \beta = 11/3 \rightarrow \text{Kolmogorov}$$

Scattering

- Scattering time is the time of decay of the PBF to 1/e of its max



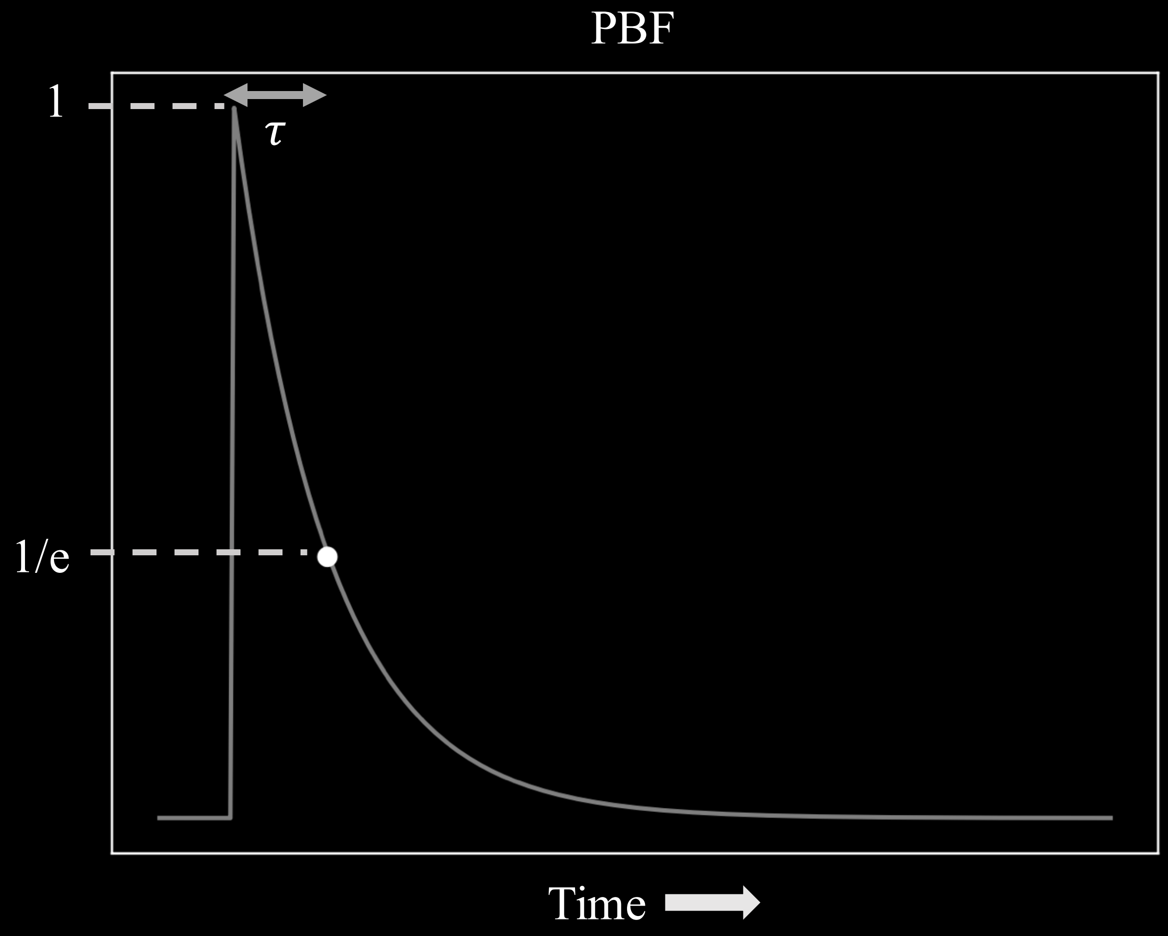
Scattering

- Scattering time is the time of decay of the PBF to 1/e of its max

- Scattering time is frequency-dependent

$$\tau(\nu) = \tau_0 \left(\nu/\nu_0\right)^{-X_\tau}$$

$$X_\tau = 2\beta/(\beta - 2)$$



Scattering

- Scattering time is the time of decay of the PBF to 1/e of its max

- Scattering time is frequency-dependent

$$\tau(\nu) = \tau_0 \left(\nu/\nu_0\right)^{-X_\tau}$$

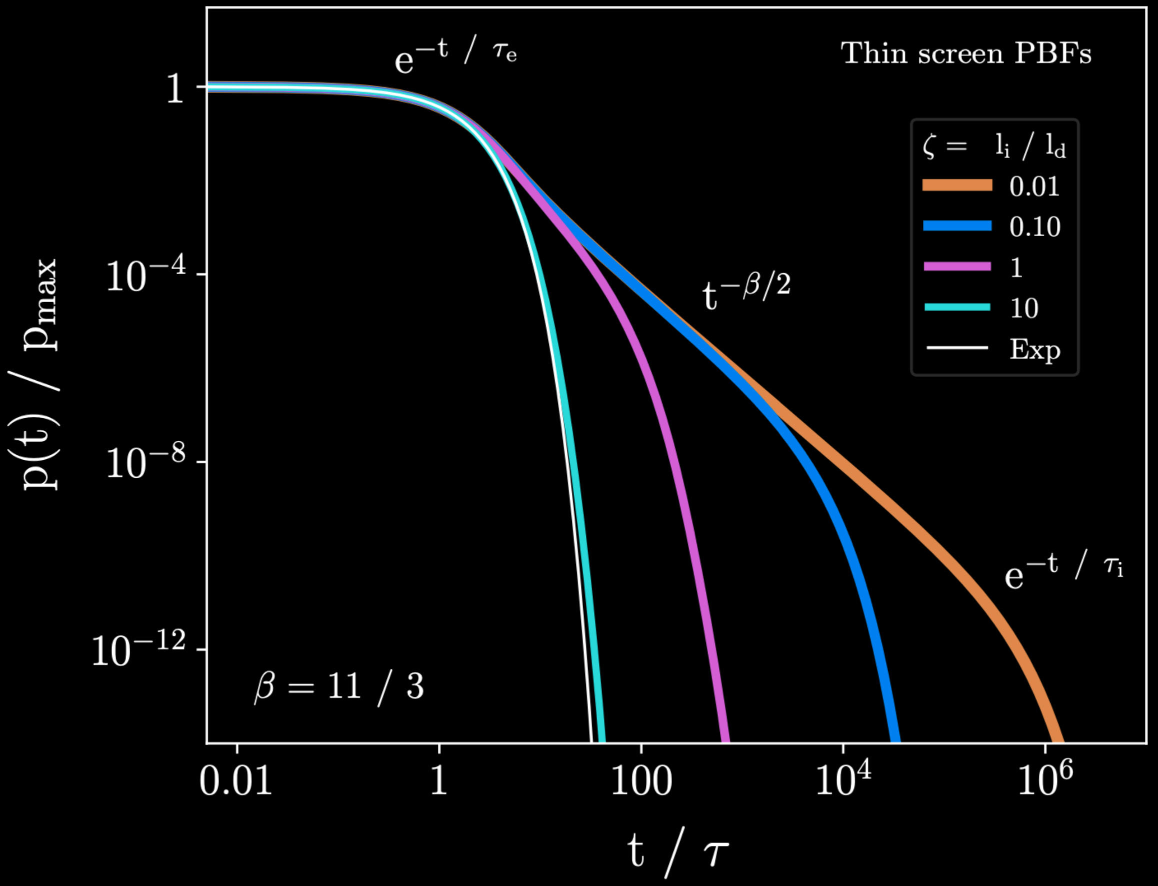
$X_\tau = 22/5$ → Kolmogorov

$$X_\tau = 2\beta/(\beta - 2)$$

BEWARE → exponential $X_\tau = 4$

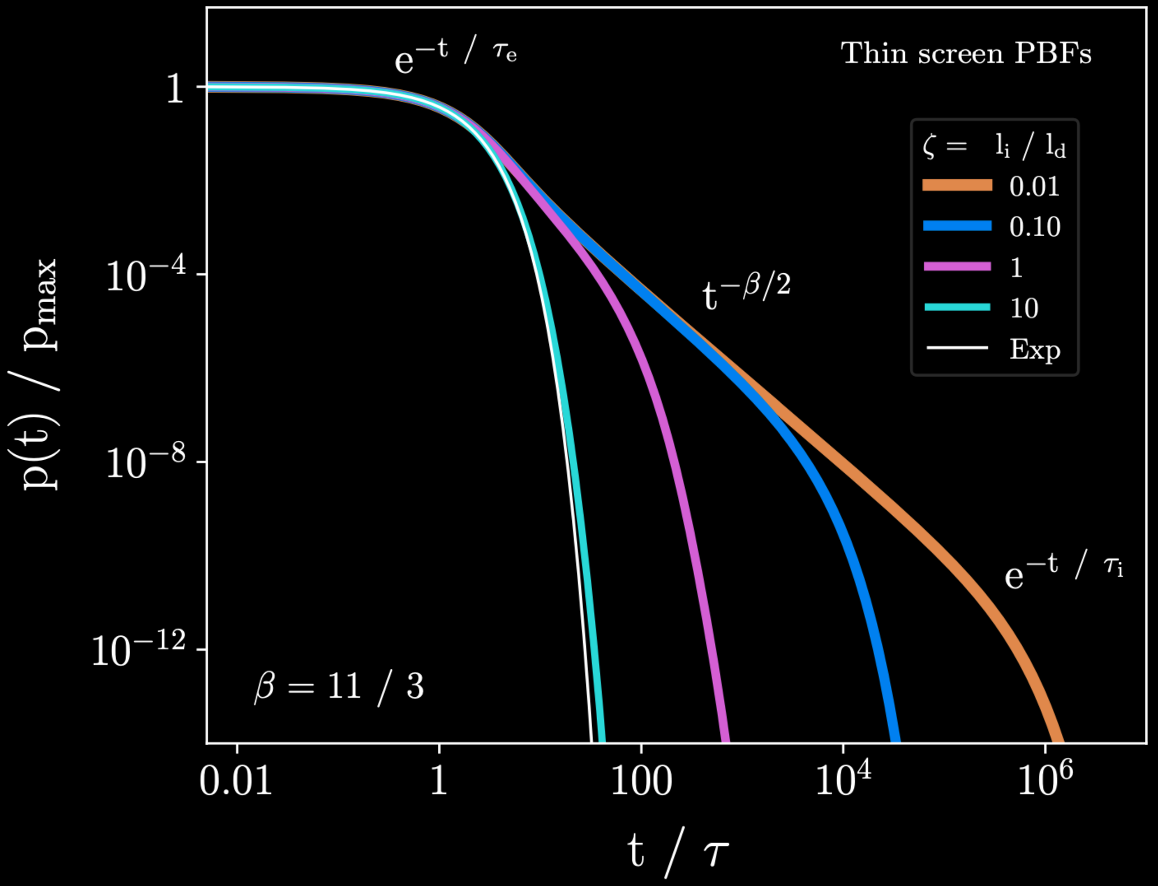
Modeling Scattering: PBFs

- Exponential PBF: thin screen, single characteristic scale of inhomogeneities, Gaussian image



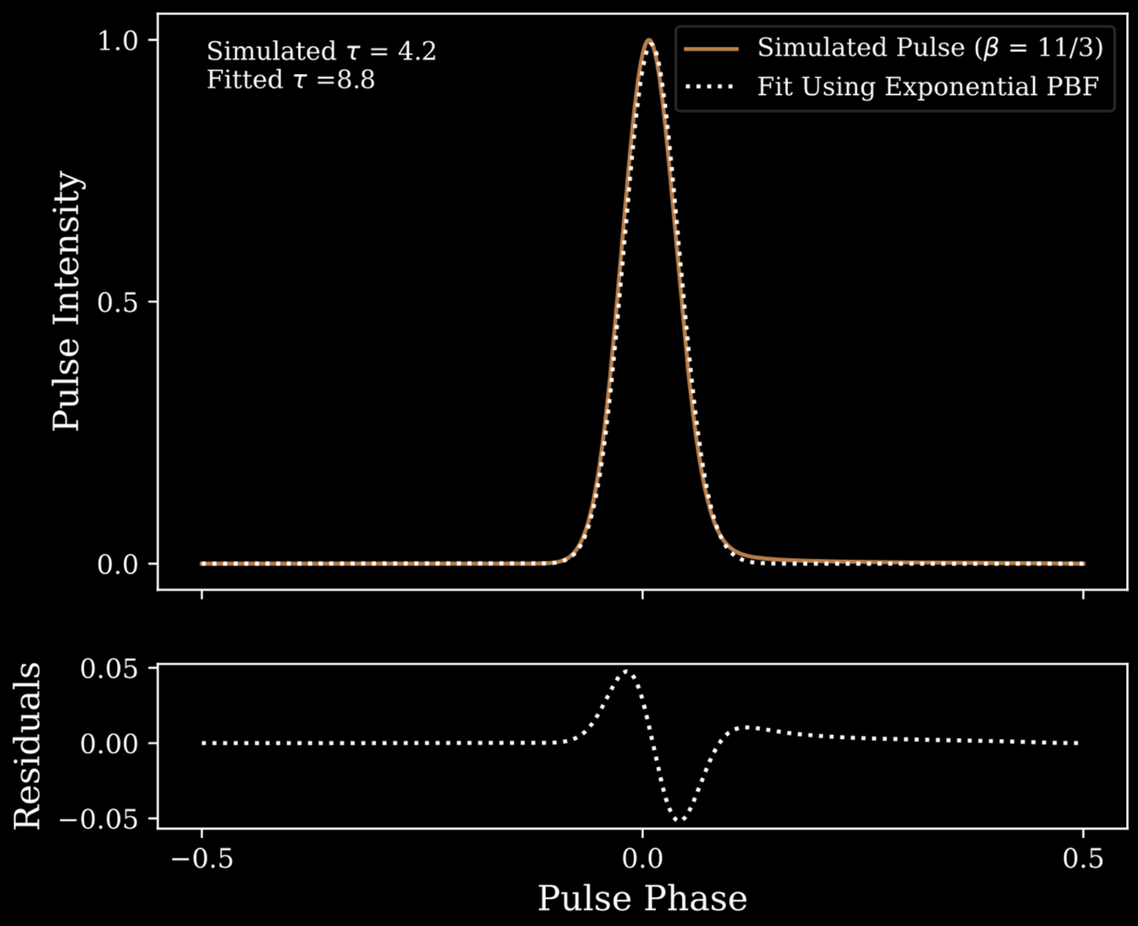
Modeling Scattering: PBFs

- Exponential PBF: thin screen, single characteristic scale of inhomogeneities, Gaussian image
- Generally, this is a poor assumption

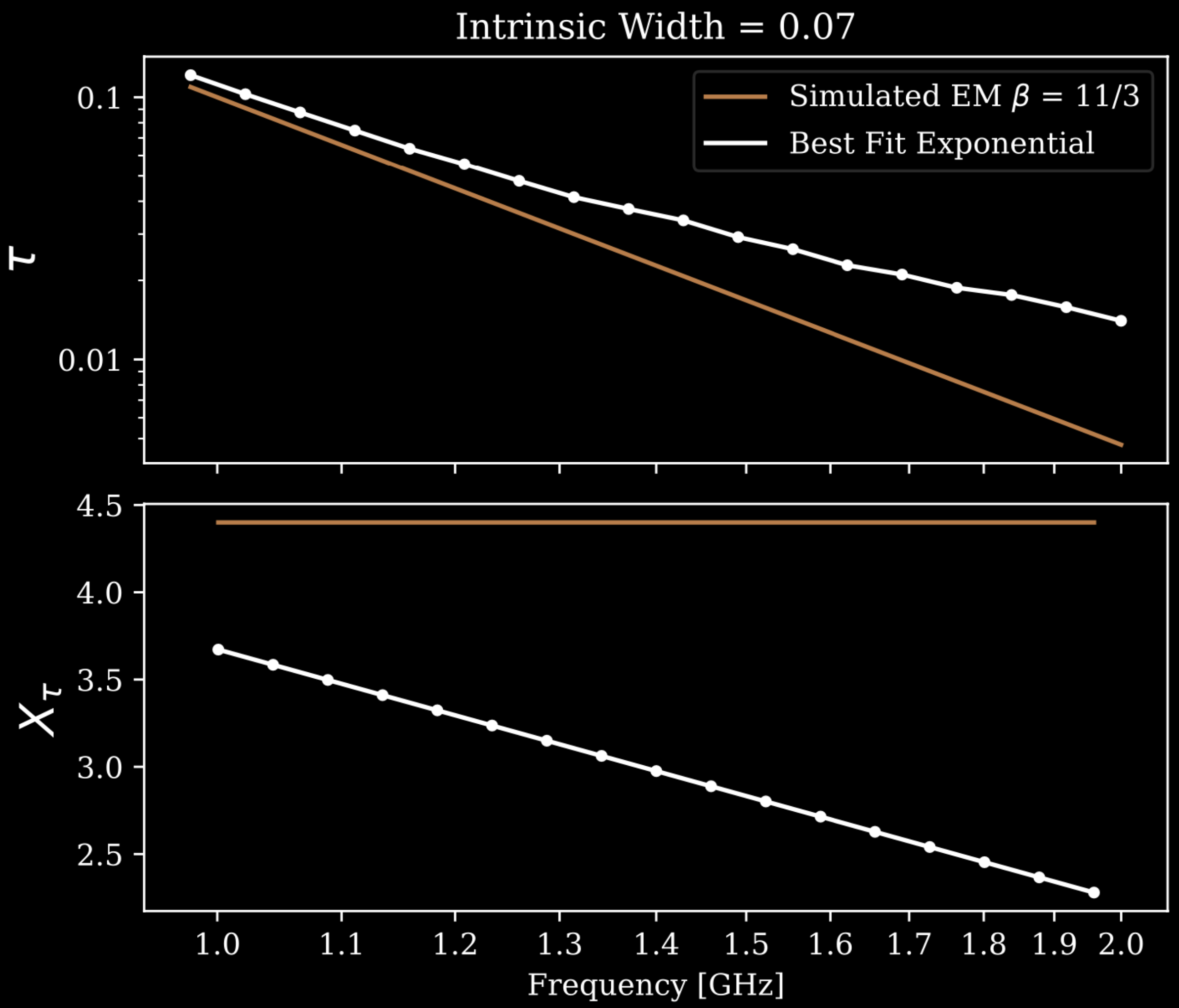


Modeling Scattering: PBFs

- Exponential PBF: thin screen, single characteristic scale of inhomogeneities, Gaussian image
- Generally, this is a poor assumption



Modeling Scattering: PBFs

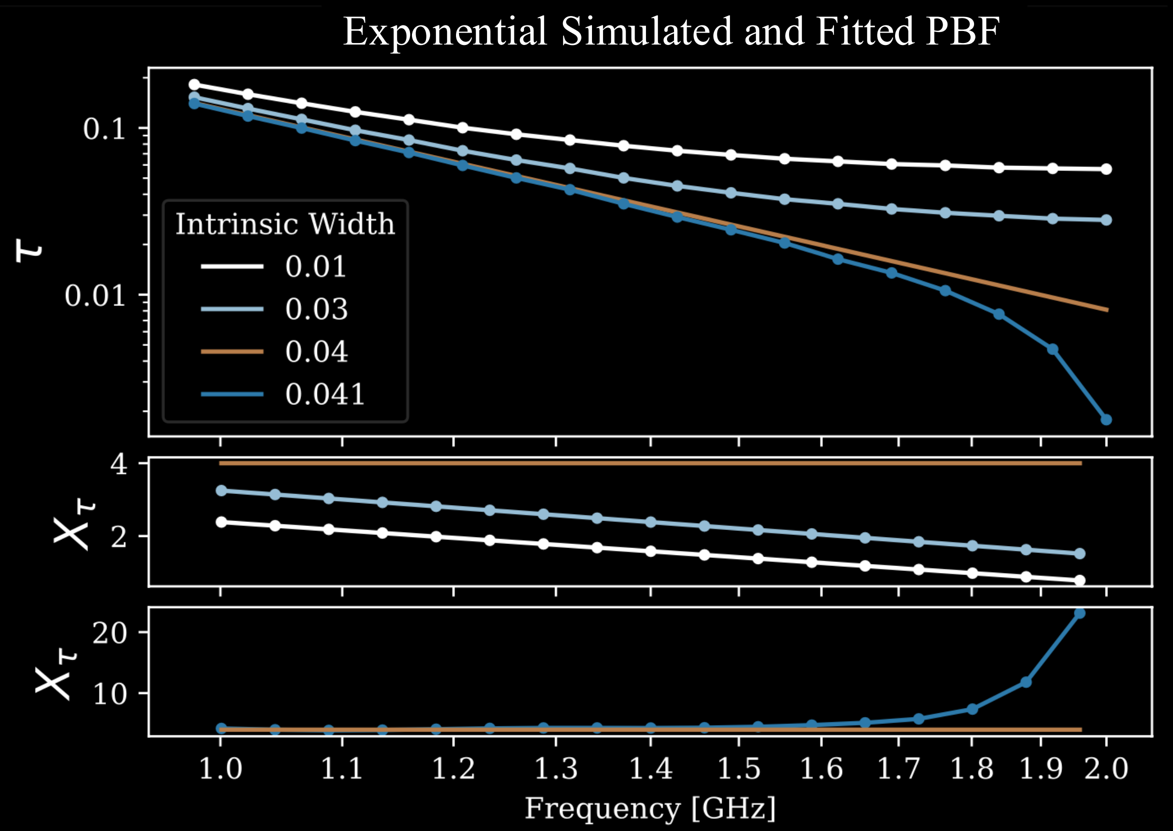


Modeling Scattering: Intrinsic Shapes

- Intrinsic pulse shapes evolve over frequency, often with multiple components

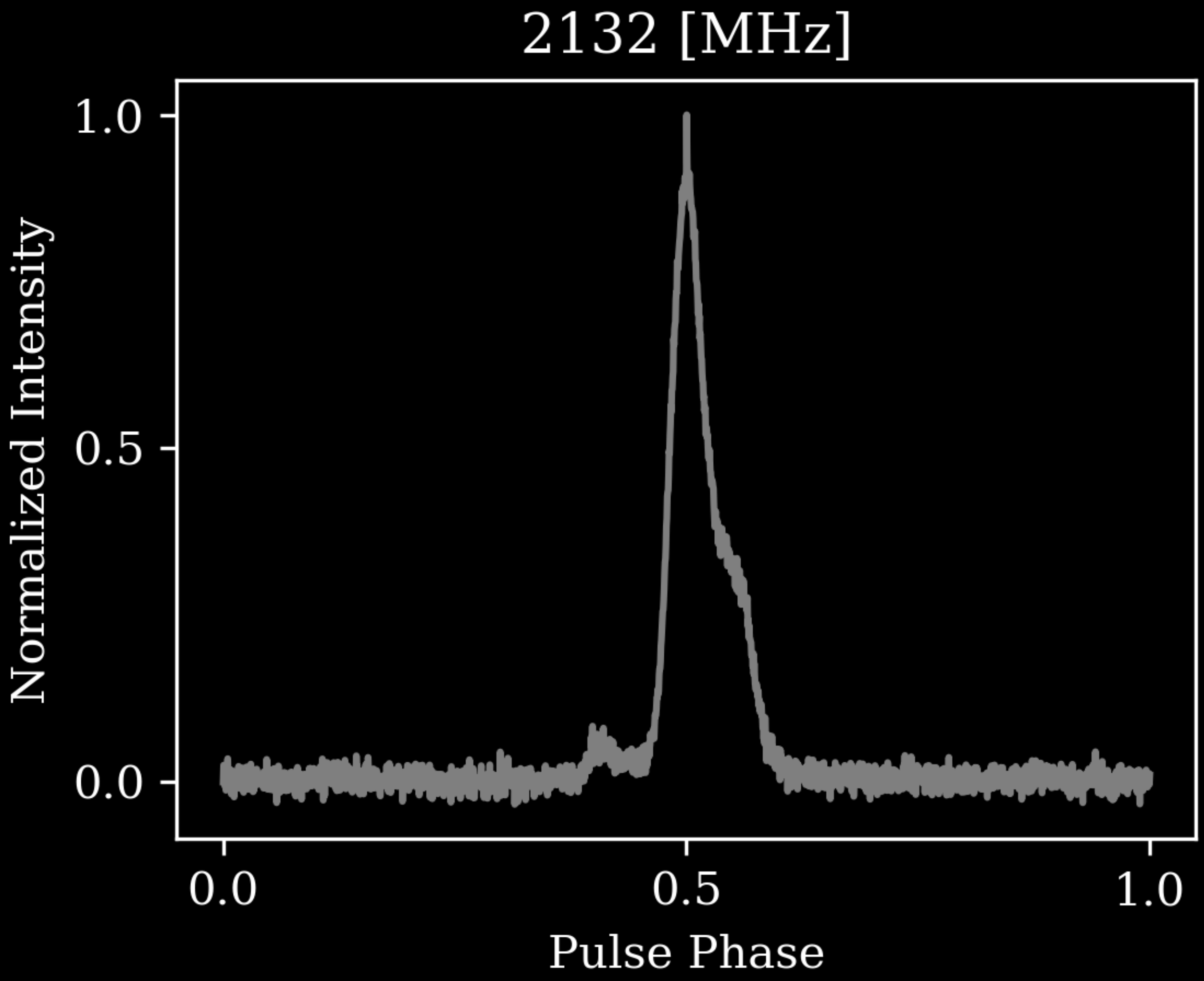
Modeling Scattering: Intrinsic Shapes

- Intrinsic pulse shapes evolve over frequency, often with multiple components
- Misestimation of the intrinsic width also biases $\tau(\nu)$



J1903+0327

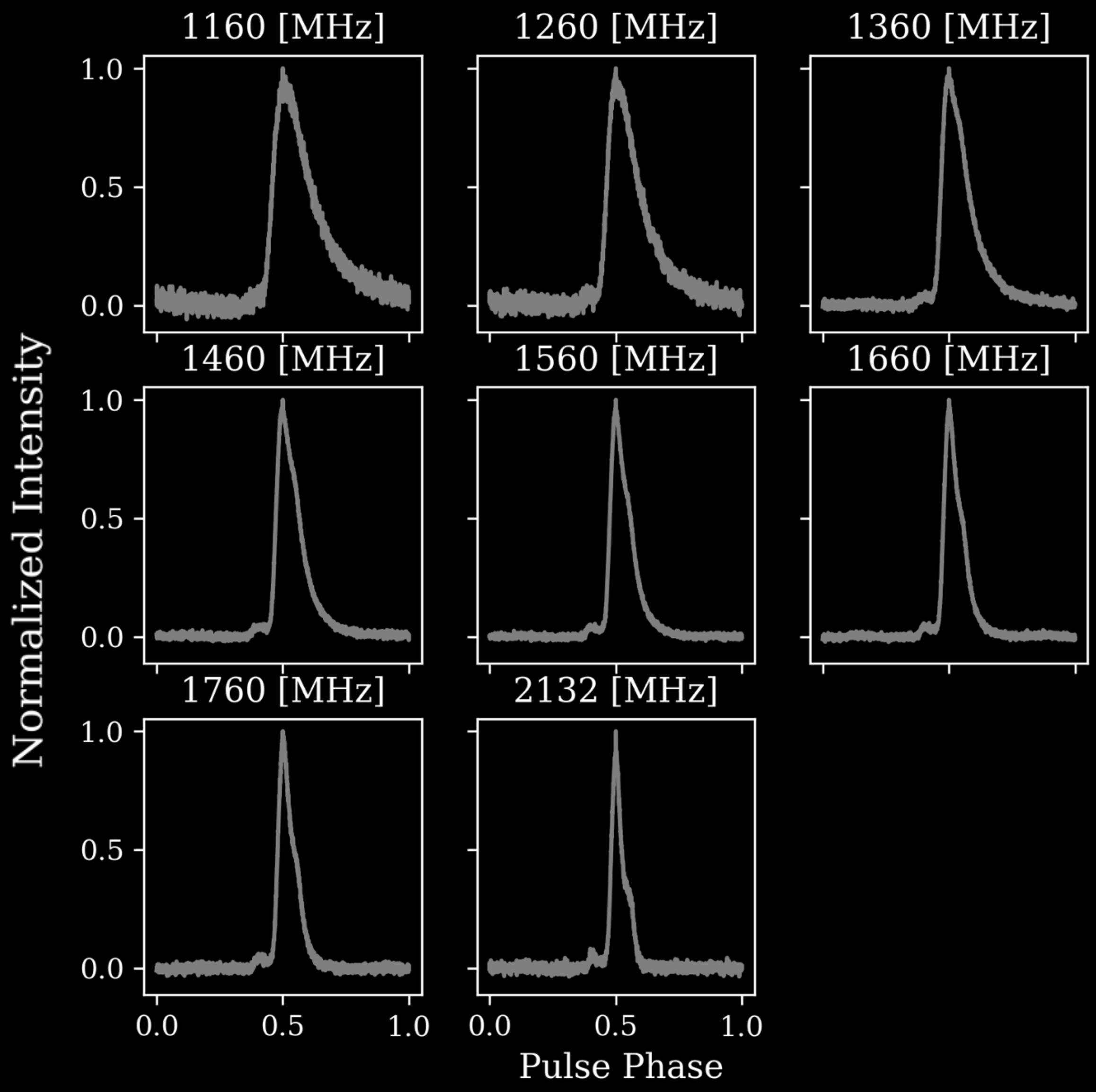
- Highest DM pulsar observed by NANOGrav: $297.53\,\mathrm{pc\ cm^{-3}}$



J1903+0327

- Highest DM pulsar observed by NANOGrav: $297.53\,\mathrm{pc\ cm^{-3}}$

- Heavily scattered and a poor timer

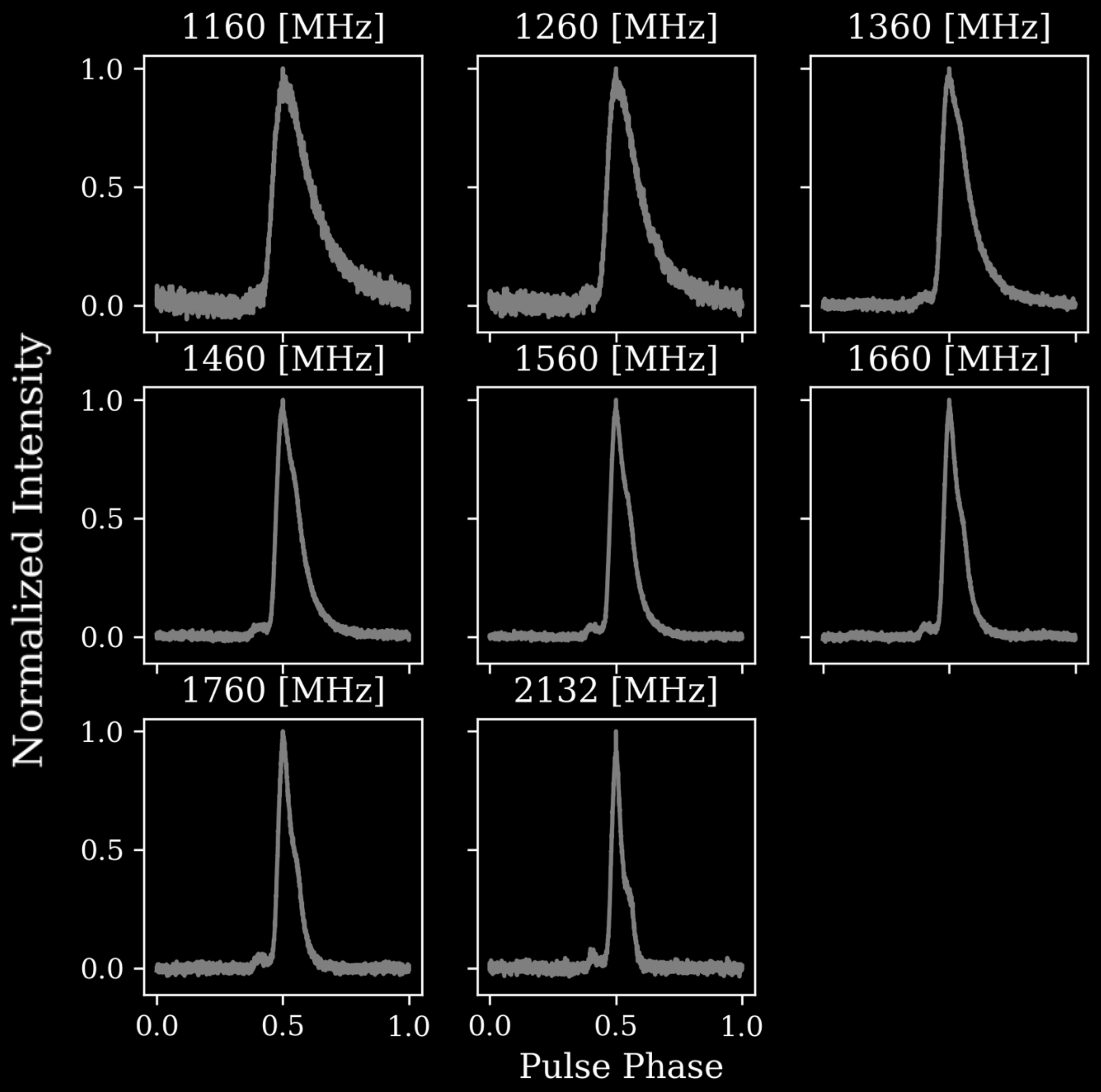


J1903+0327

- Highest DM pulsar observed by NANOGrav: $297.53\,\mathrm{pc\ cm^{-3}}$

- Heavily scattered and a poor timer

- 12.5-year dataset collected at Arecibo at L-band and S-band



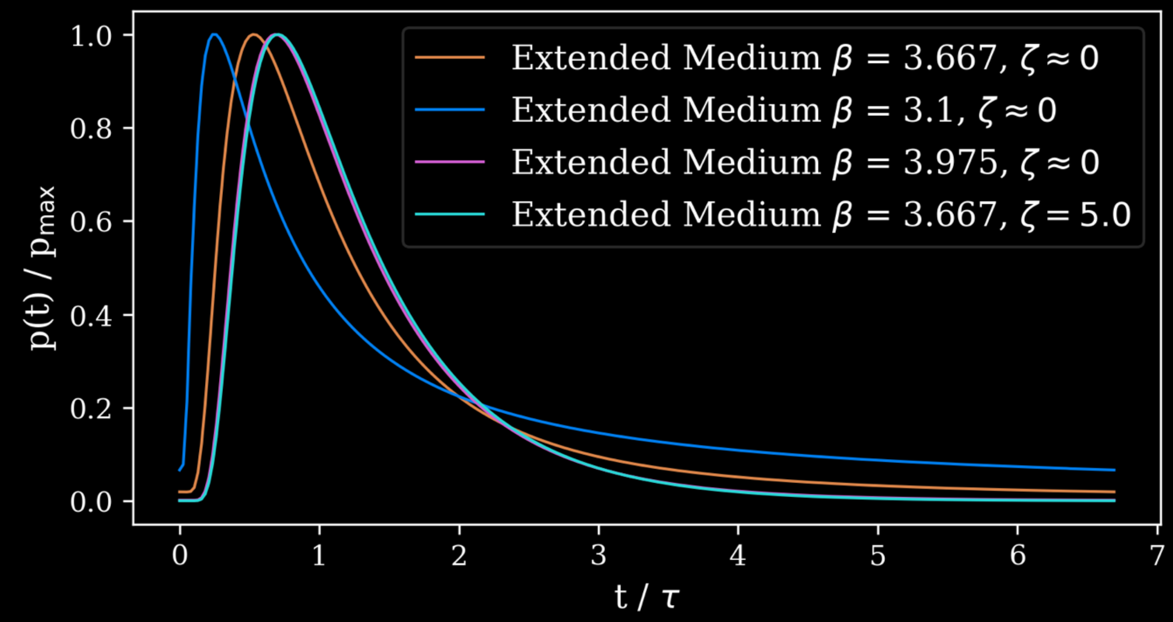
Methods

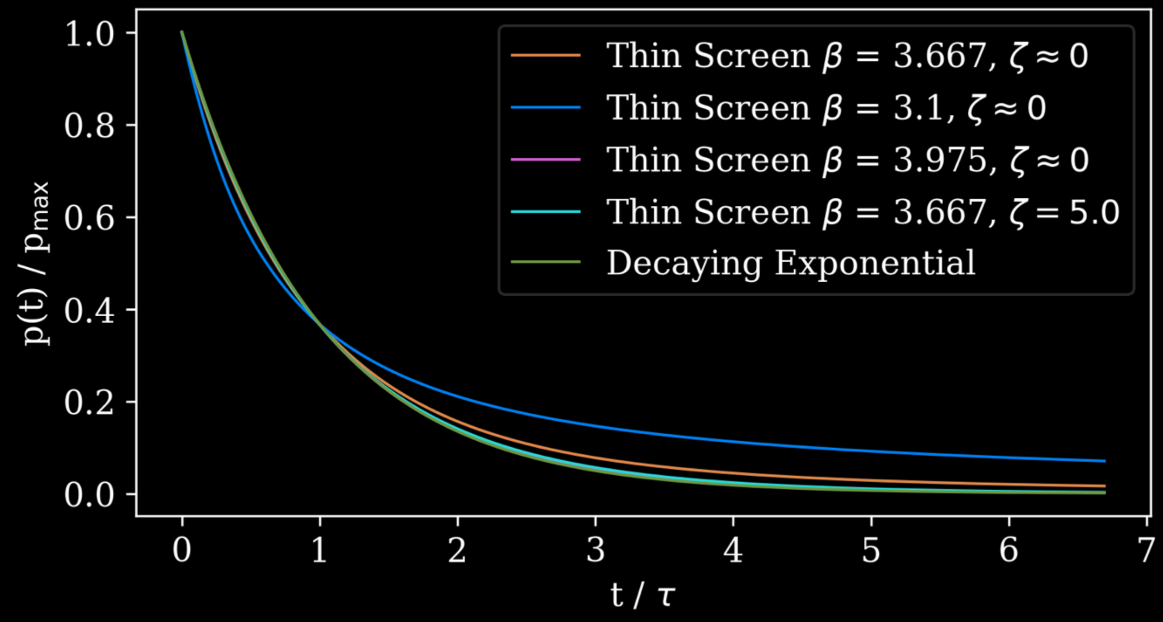
Naturally, reconciling the intrinsic and PBF shapes is a challenge

Methods

Naturally, reconciling the intrinsic and PBF shapes is a challenge

- Choose a PBF

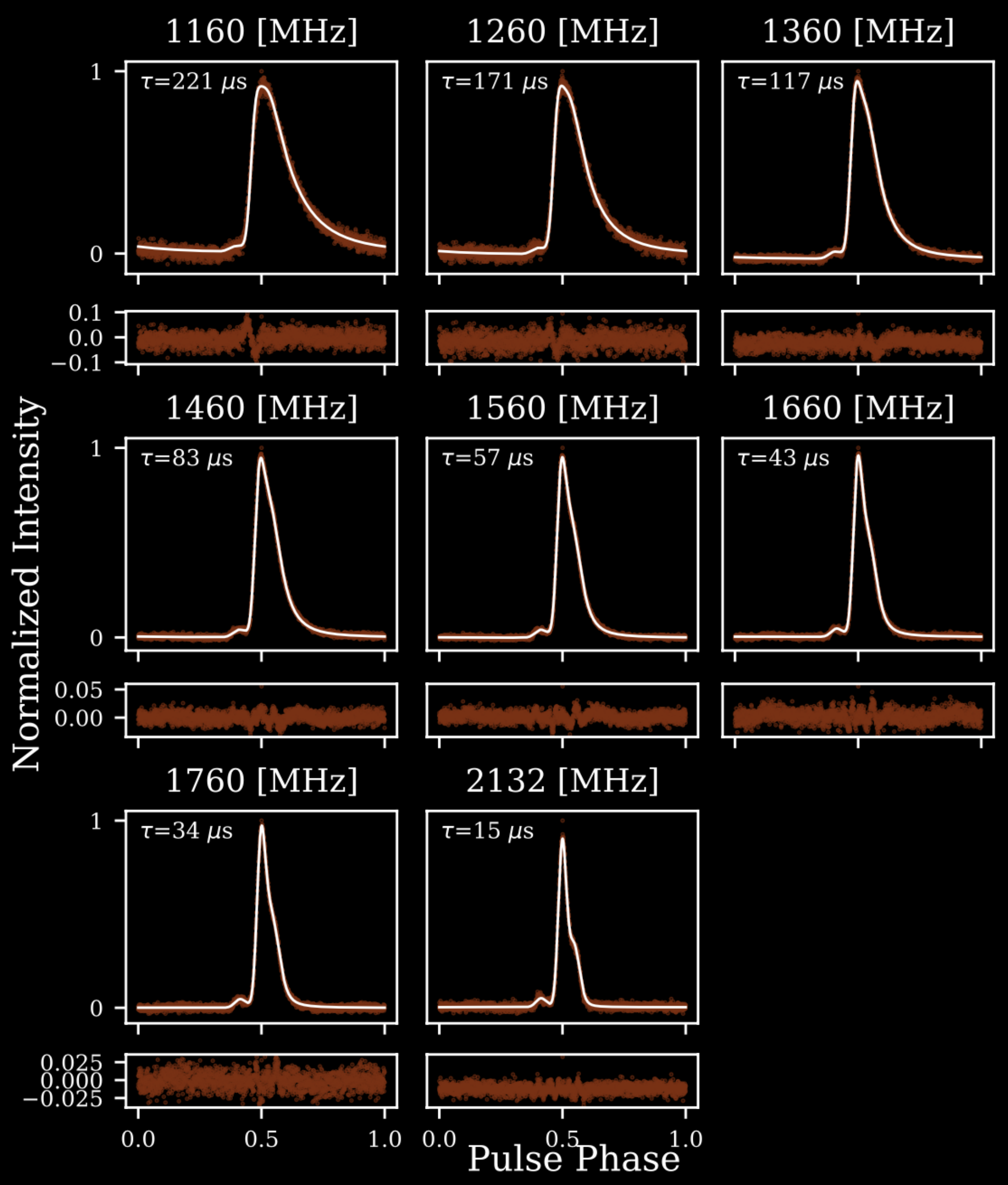




Methods

Naturally, reconciling the intrinsic and PBF shapes is a challenge

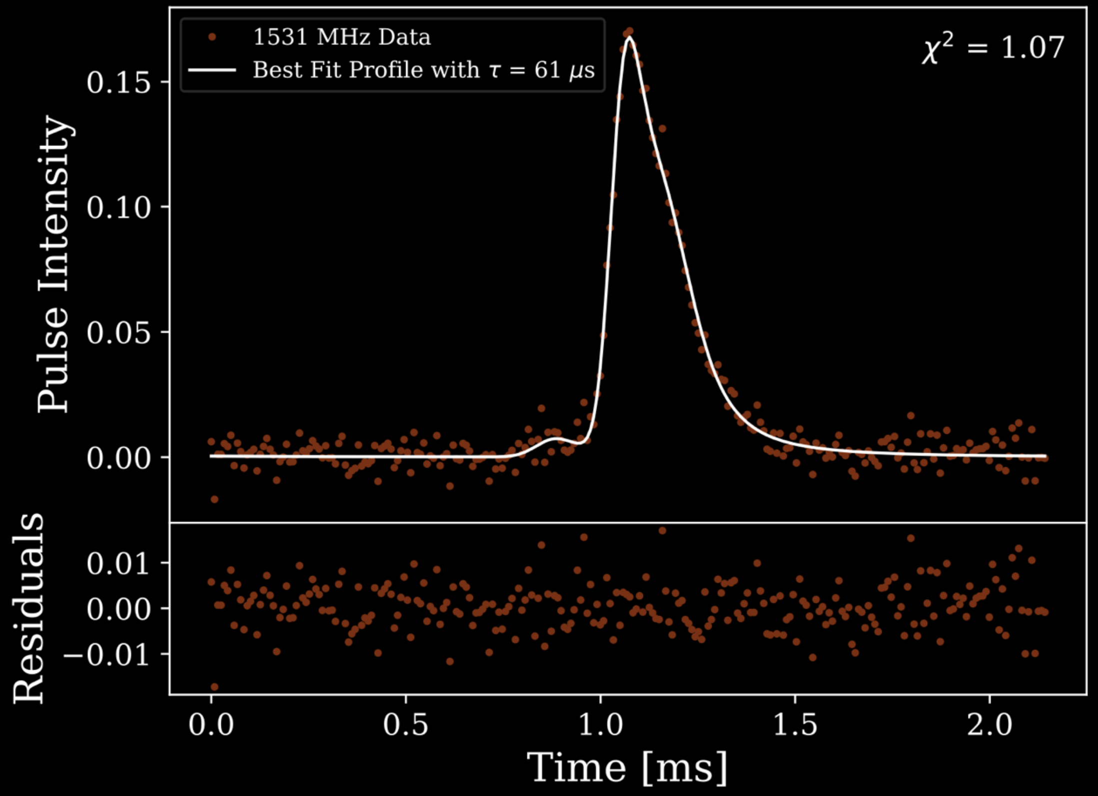
- Choose a PBF
- Model average intrinsic shape

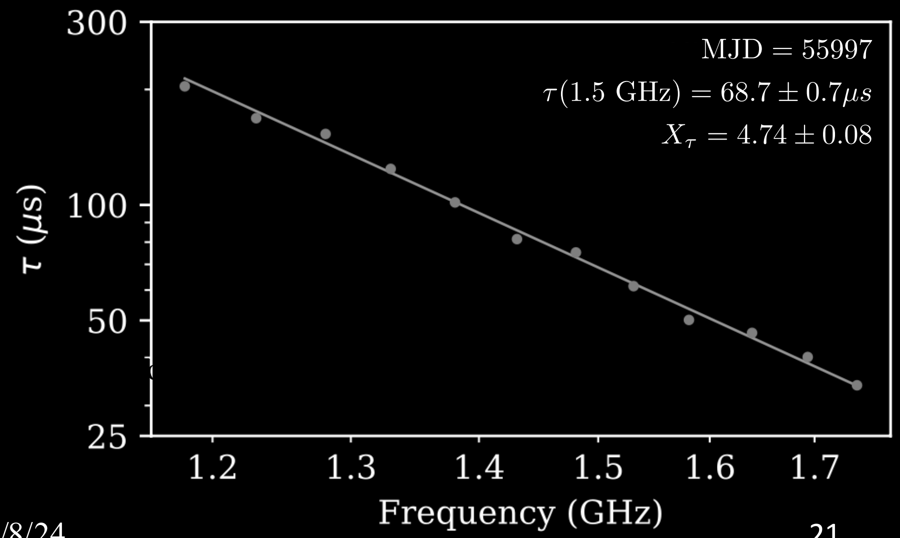


Methods

Naturally, reconciling the intrinsic and PBF shapes is a challenge

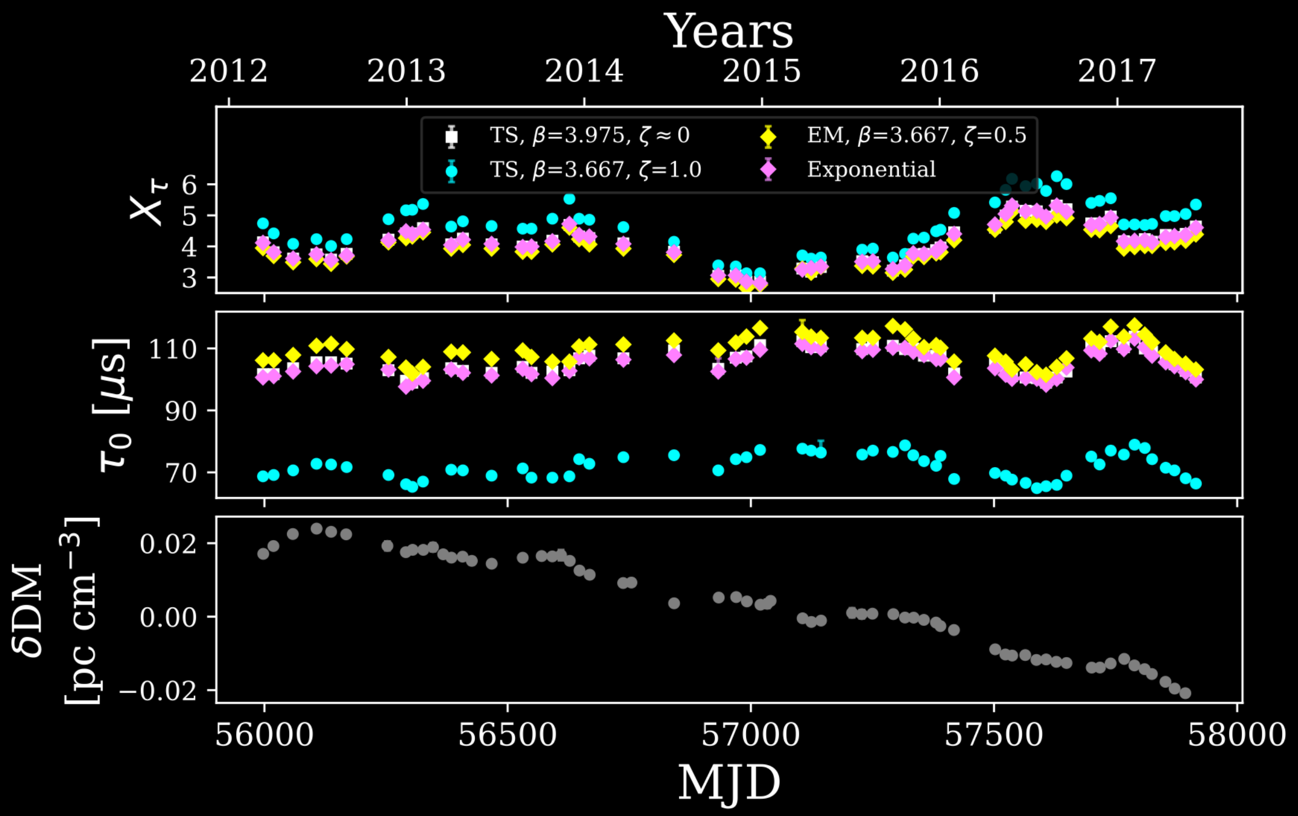
- Choose a PBF
- Model average intrinsic shape
- Fit for $\tau(\nu)$ at each epoch with this PBF and intrinsic shape

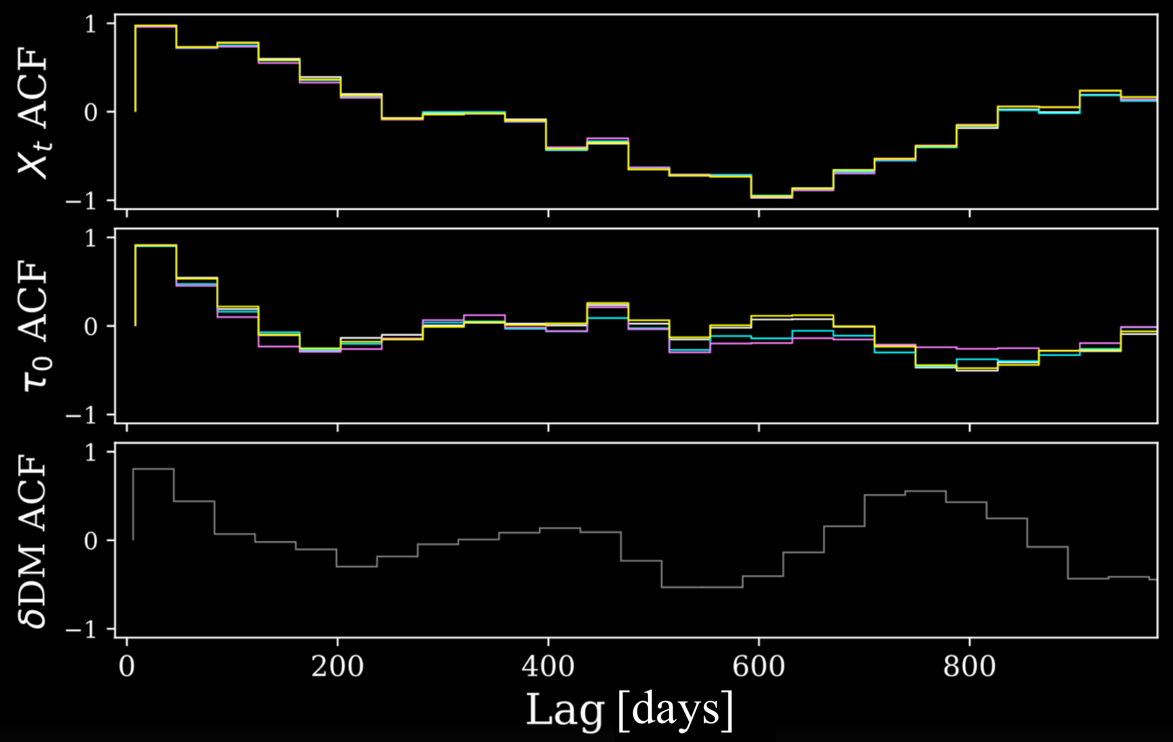




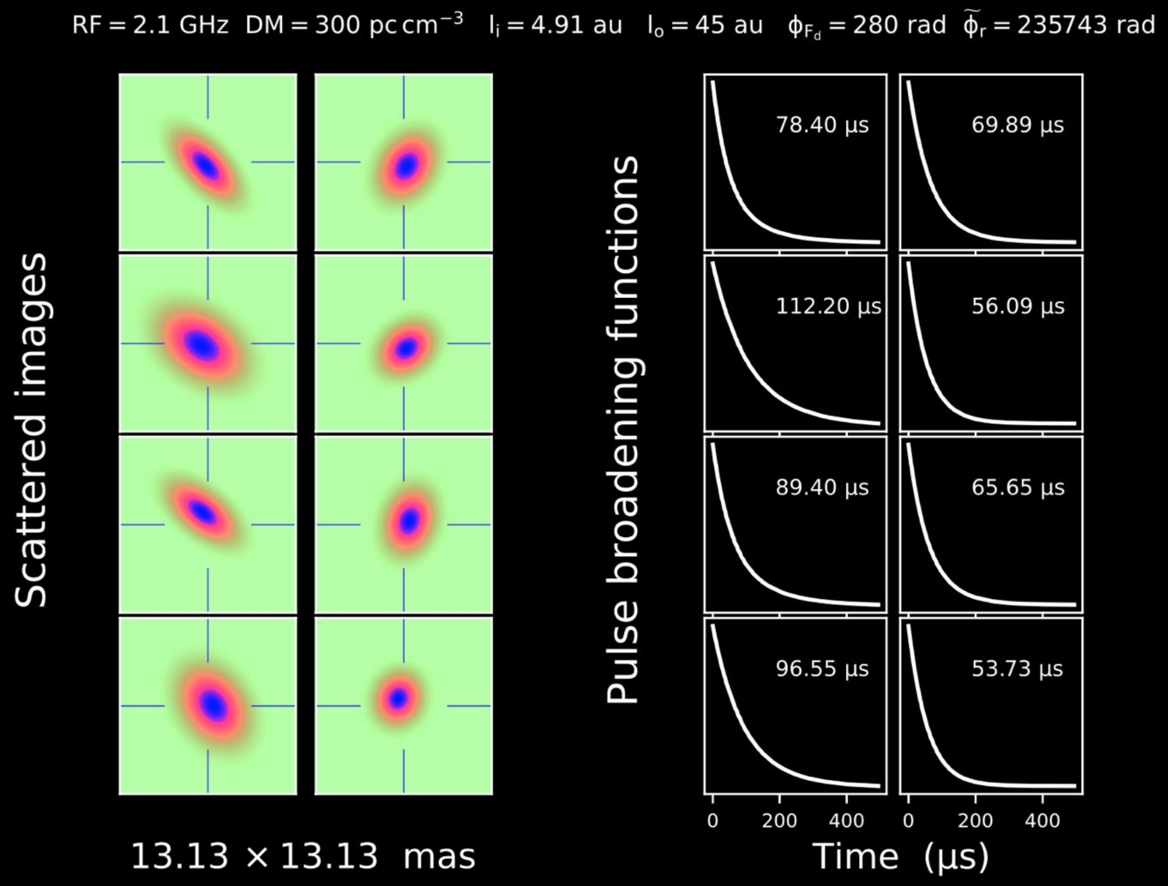
Scattering and DM Variability

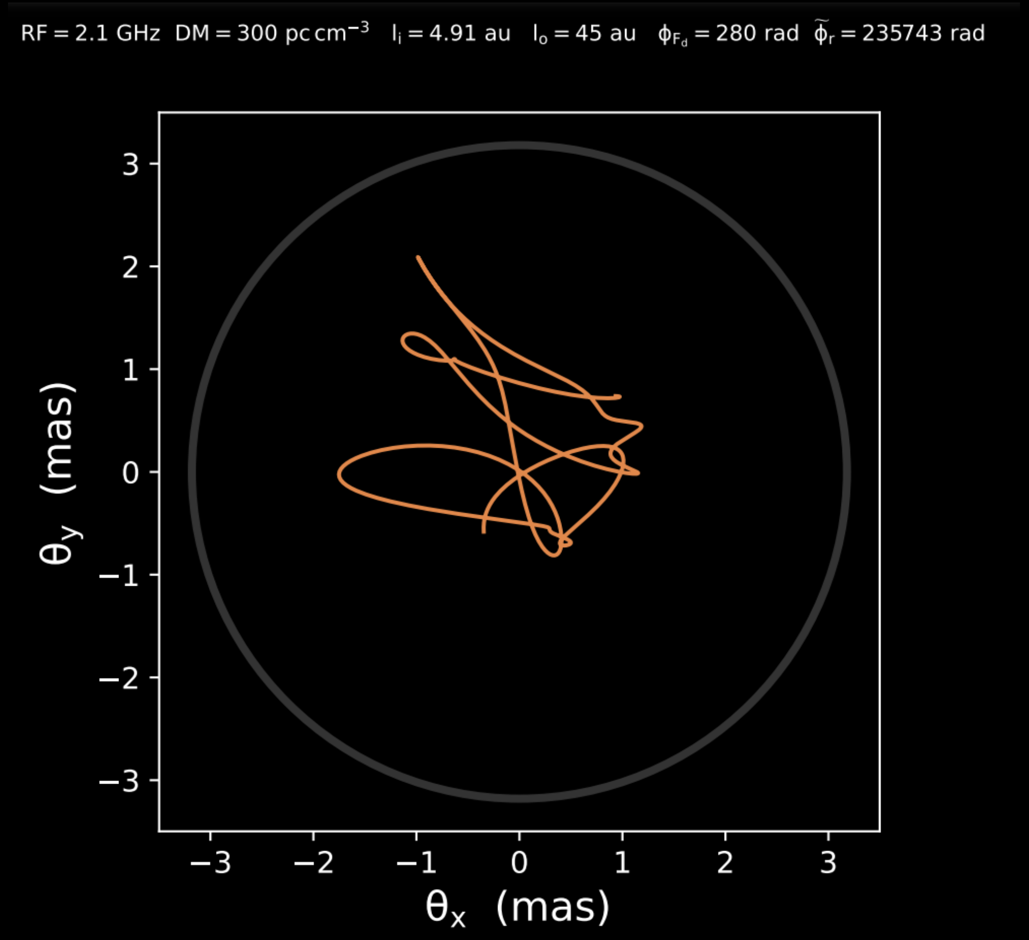
Best Fit PBF: Thin screen with
$\beta = 11/3, \zeta = 1.0 \longrightarrow l_i \approx 1400\text{km}$





Refraction: Underlying Cause of Variability



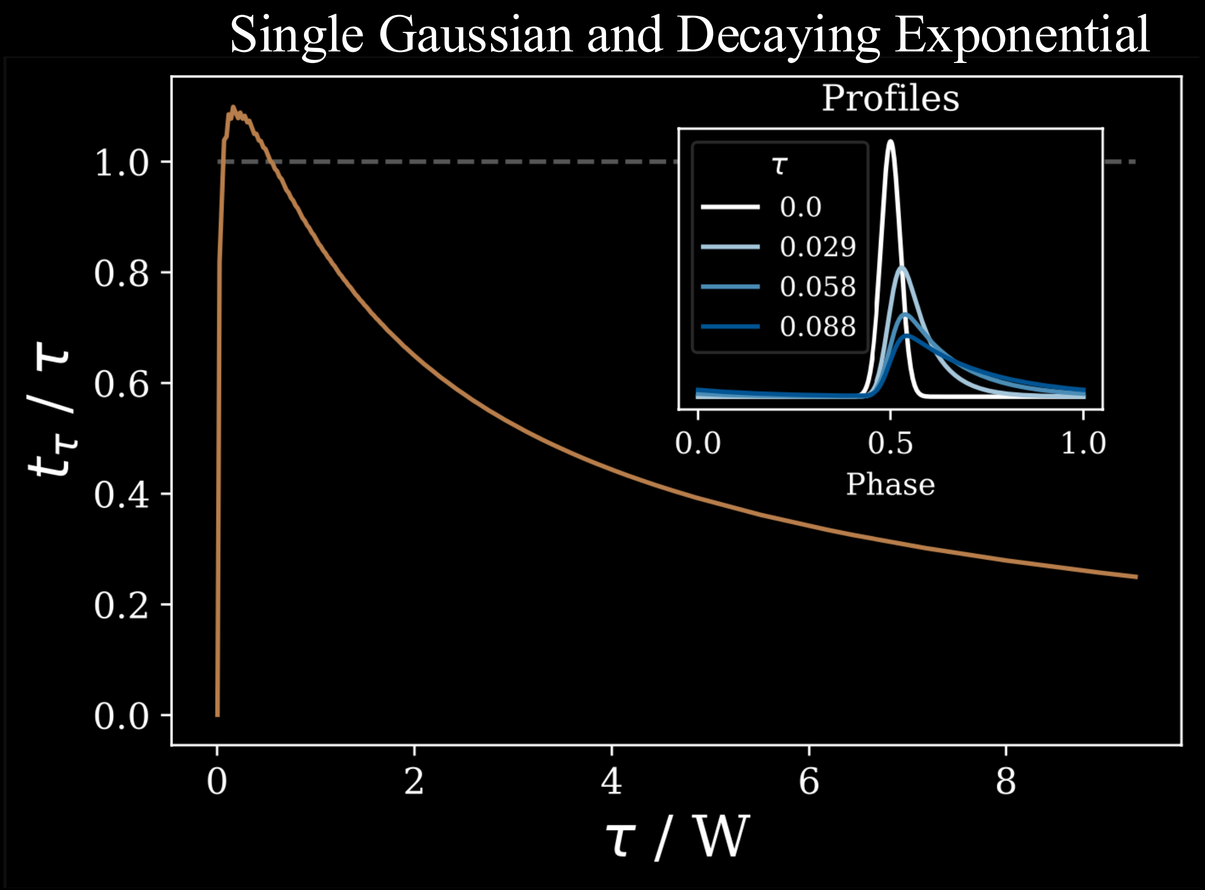


TOA Shifts and Application to Timing

- Scattering TOA shift: cross correlation of scattered pulse and intrinsic shape

TOA Shifts and Application to Timing

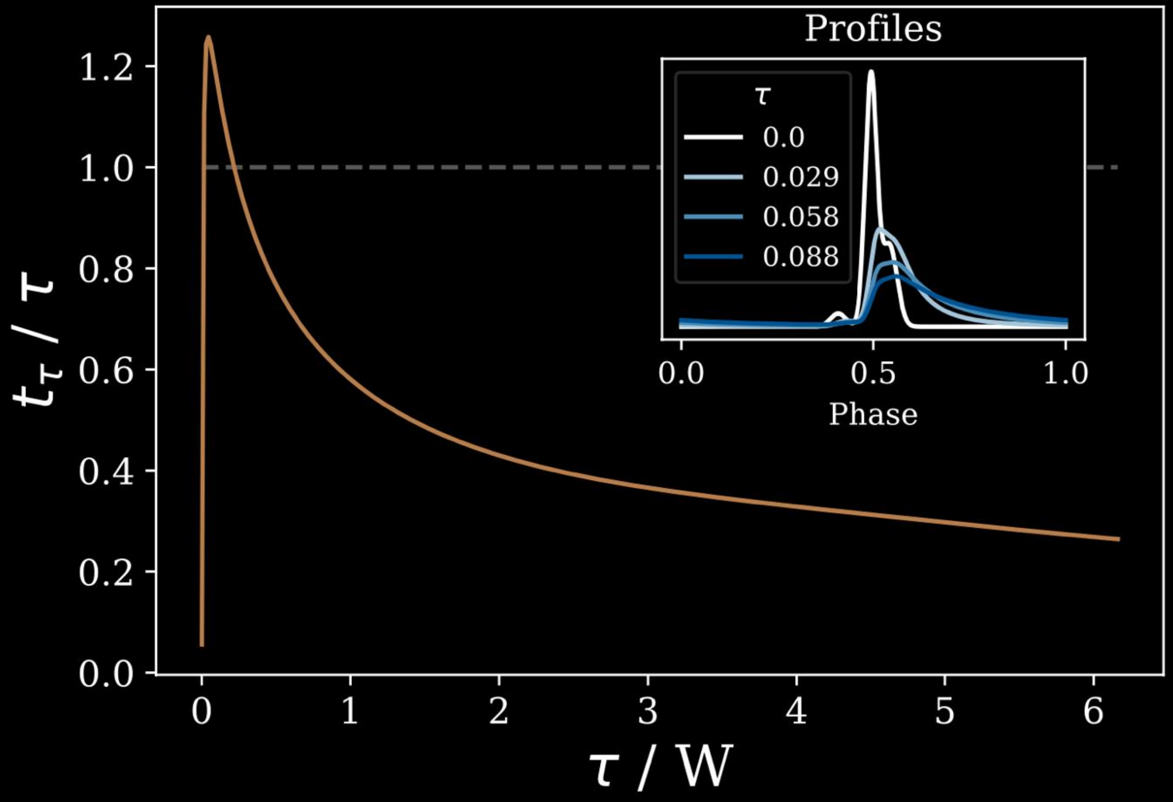
- Scattering TOA shift: cross correlation of scattered pulse and intrinsic shape
- Mean shift regime: $t_\tau = \tau$ only for exponential PBFs with $\tau << W_i$



TOA Shifts and Application to Timing

- Scattering TOA shift: cross correlation of scattered pulse and intrinsic shape
- Mean shift regime: $t_\tau = \tau$ only for exponential PBFs with $\tau << W_i$

Simulated J1903+0327 Thin $\beta = 11/3, \zeta = 1.0$



Discussion and Conclusions

- Assumptions of intrinsic and PBF shape are extremely important for scattering analysis
- J1903+0327 variable scattering is likely explained by a refraction timescale
- Application to timing is tricky

Paper circulated to Noise Budget and Timing and will be available to all soon!

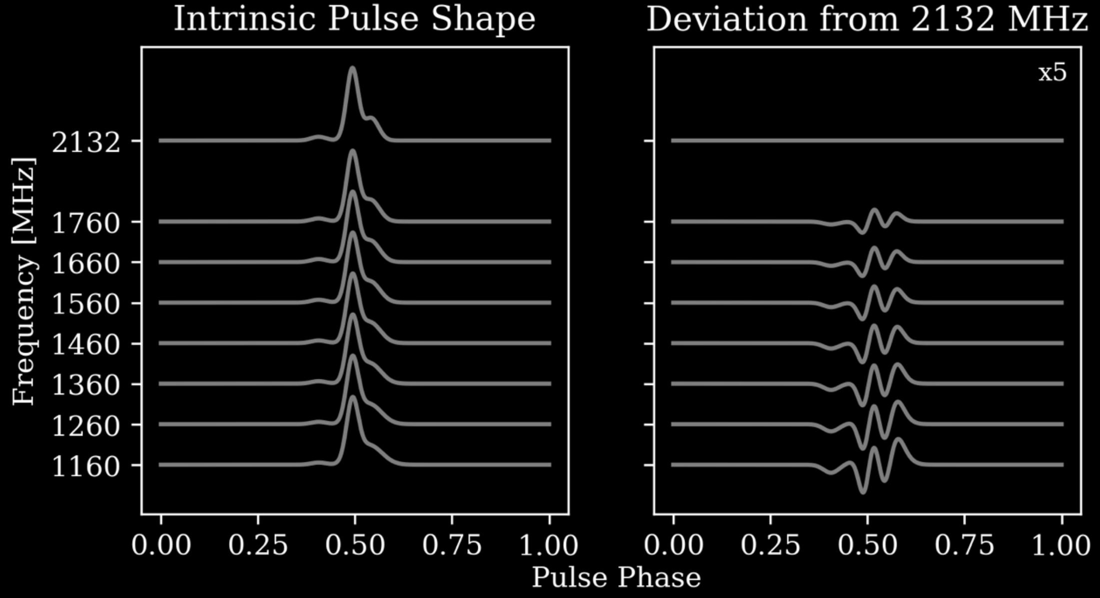
Thank You!

Questions?

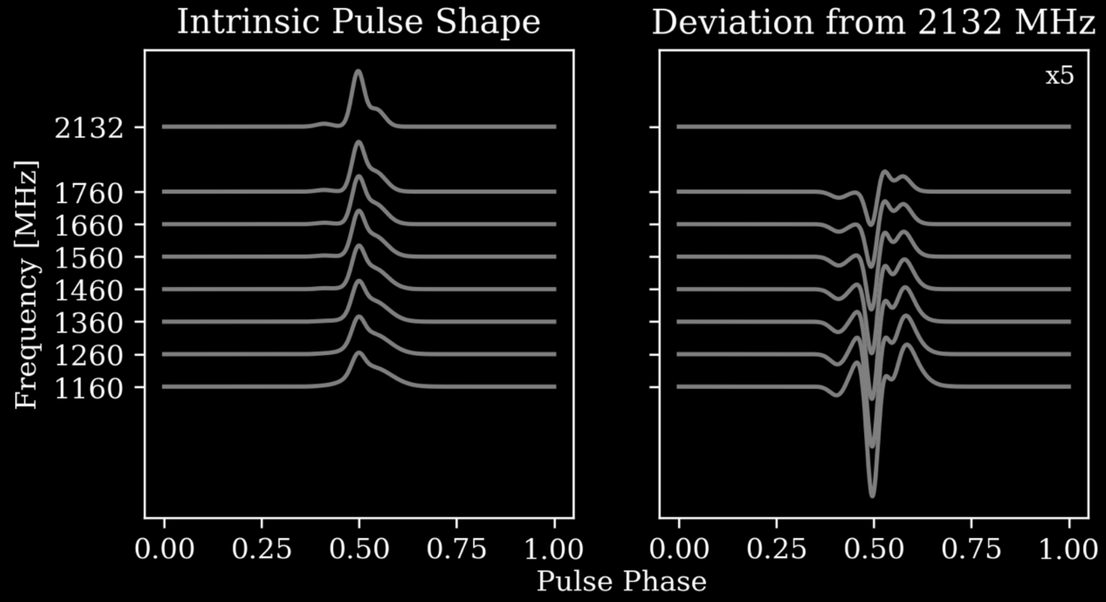
Find out more!

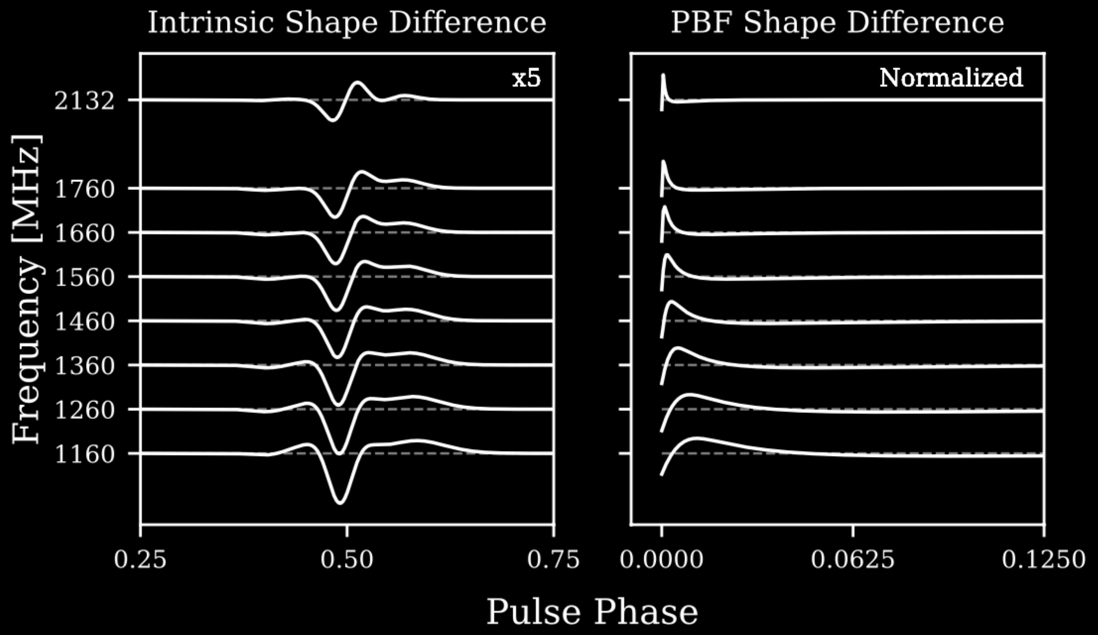
Special thanks to my supporters including the McNair Scholars Program, the Nexus Scholars Program, and my mentors and collaborators.

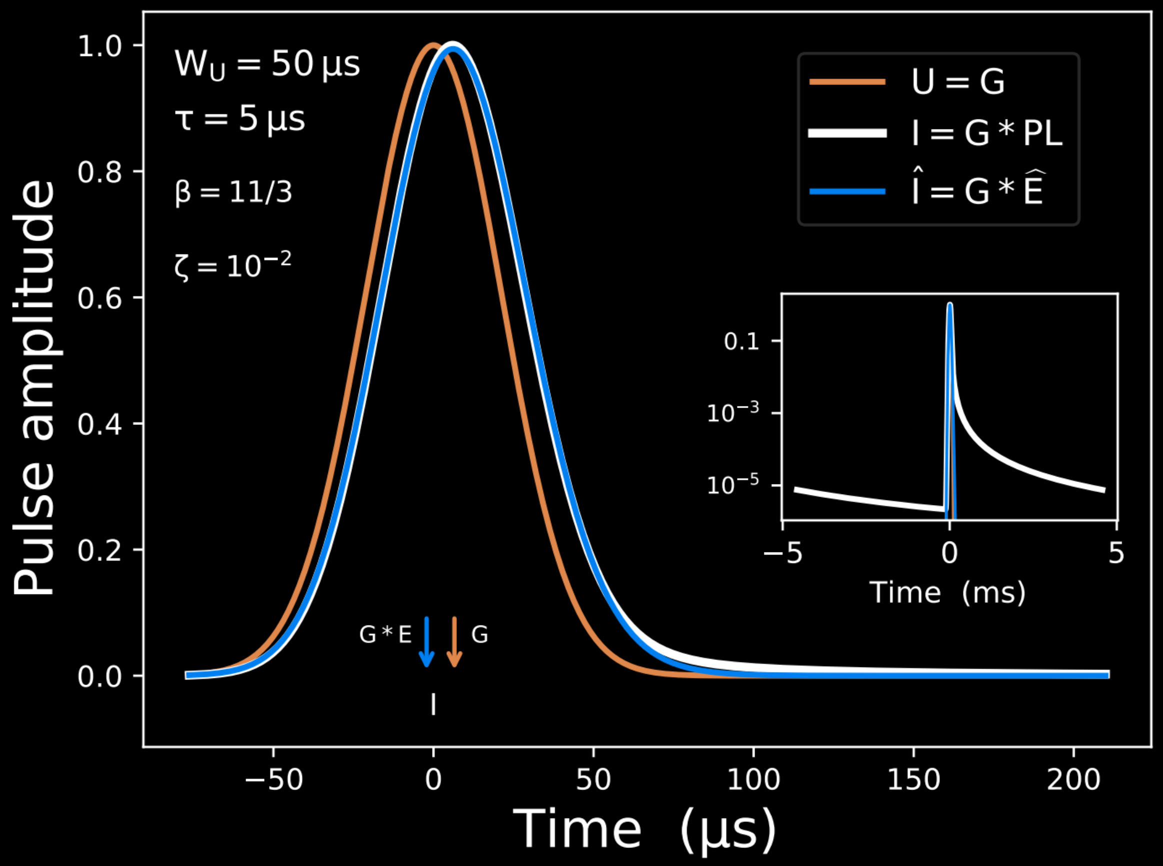
Thin Screen $\beta = 11/3, \zeta = 1.0$



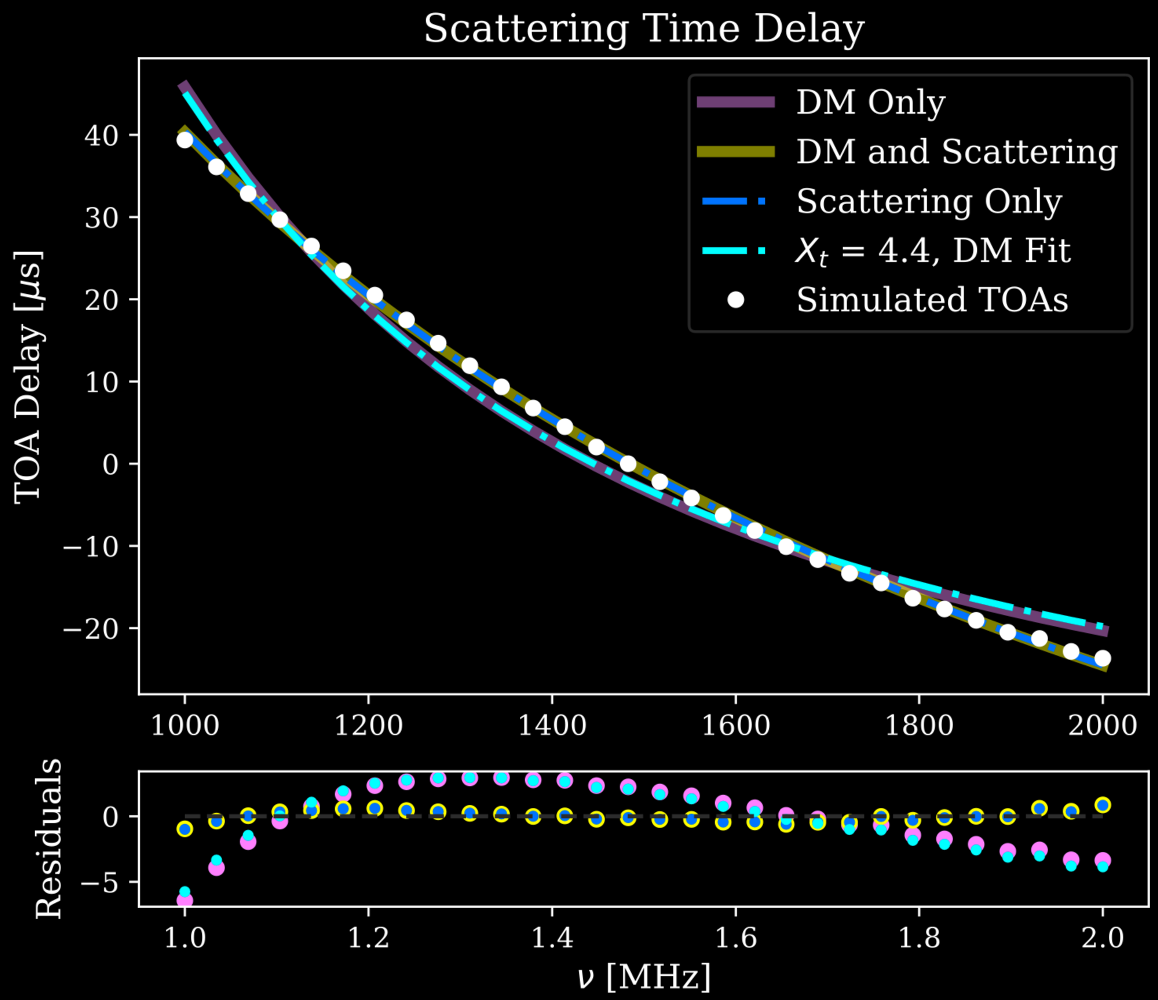
Extended Medium $\beta = 3.1, \zeta = 0.0$







$W_U = 50\,\mu s$
$\tau = 5\,\mu s$
$\beta = 11/3$
$\zeta = 10^{-2}$
U = G
I = G * PL
Î = G * Ê
G * E
G
I
Pulse amplitude
Time (μs)
Time (ms)



Scattering Time Delay
DM Only
DM and Scattering
Scattering Only
X_t = 4.4, DM Fit
Simulated TOAs
TOA Delay [μs]
Residuals
ν [MHz]