The peculiar Interstellar Scintillation of PSR B1508+55

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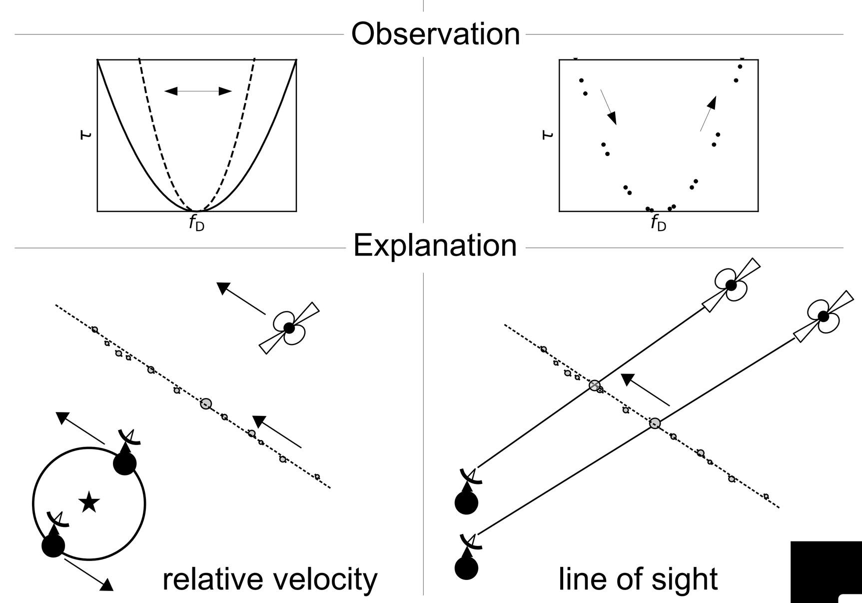
PSR B1508+55 (J1509+5531)

Located in the constellation Draco, this bright pulsar is moving away from the galactic plane at a speed of 963 km/s, which is one of the largest known pulsar velocities.

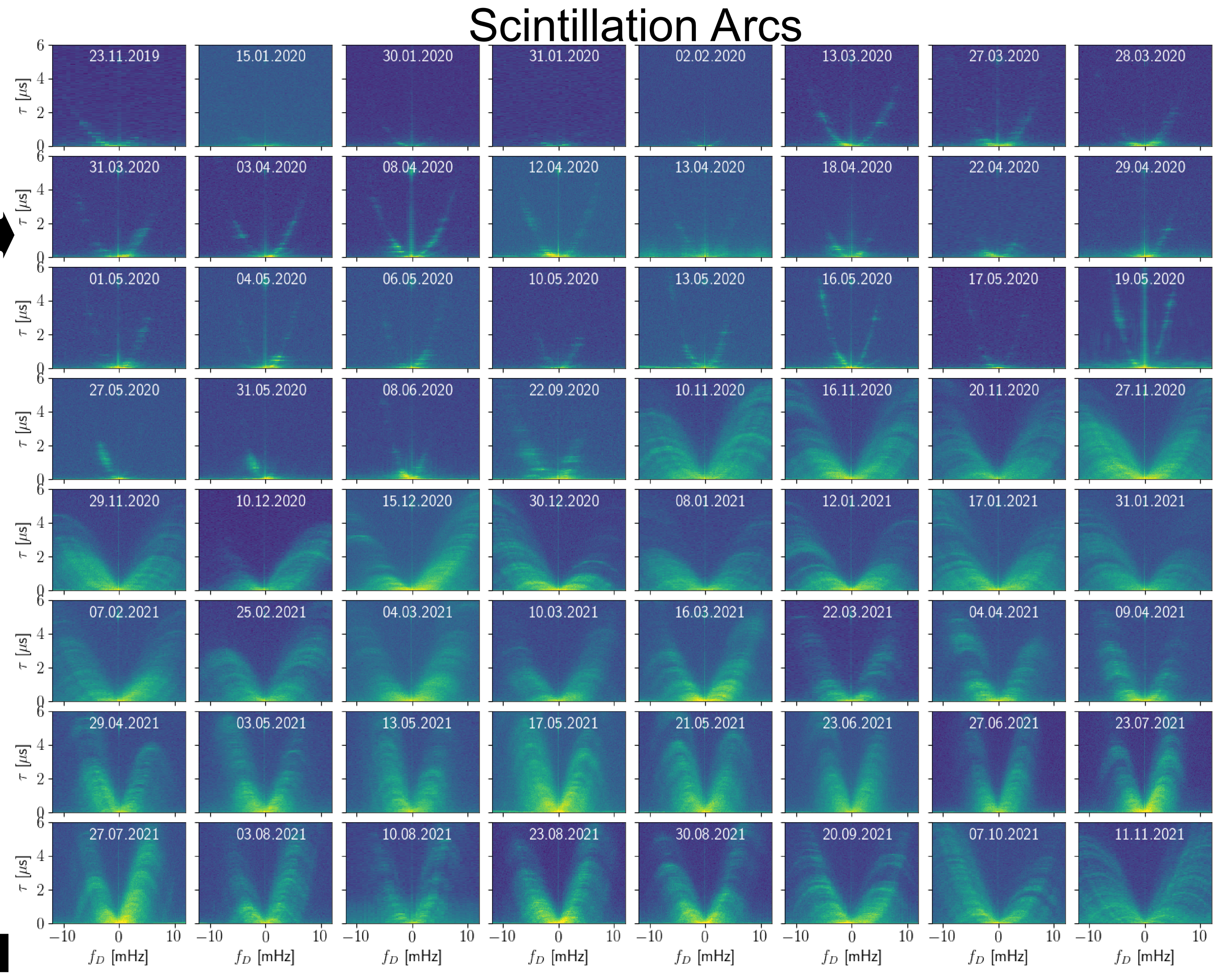
spin period	P	0.739681922904(4) s	Hobbs et al. 2004
dispersion measure	DM	19.6191(3) pc cm^{-3}	Stovall et al. 2015
distance	d_{PSR}	$2.10^{+0.13}_{-0.14}$ kpc	Chatterjee et al. 2009
proper motion (R.A.)	μ_α	$-73.64^{+0.05}_{-0.04}$ mas yr^{-1}	"
proper motion (Decl.)	μ_δ	$-62.65^{+0.09}_{-0.08}$ mas yr^{-1}	"

Observations at Effelsberg (100-m telescope)
- Circumpolar source
- Bandwidth 1.27-1.45 GHz
- 64 observations, 214 hours in total
- Dynamic spectra: brightness of pulses over time and frequency, used to produce
- Secondary spectra: 2D Fourier transformation

Scintillation Arc Variation / Feature Movement

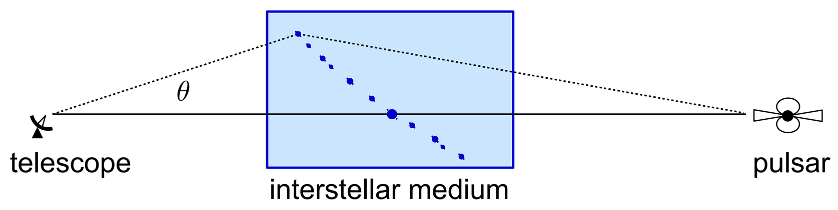


Scintillation Arcs



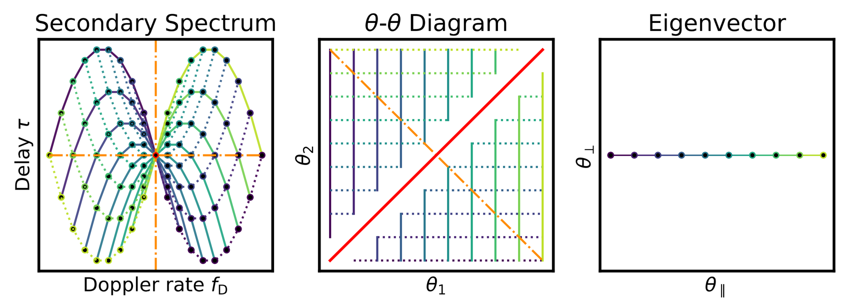
Motivations for this study

Stripes:
- Unusual parallel features known since Stinebring 2007.
- Not predicted by single thin anisotropic scattering screen consisting of plasma:



Echo crossing:
- Trailing pulse components visible at 150 MHz (LOFAR).
- Localized by Wucknitz 2019 using VLBI to be up to 0.5 arcseconds away on a screen of 120 pc distance.
- Crossing of the main pulse predicted for 2021.

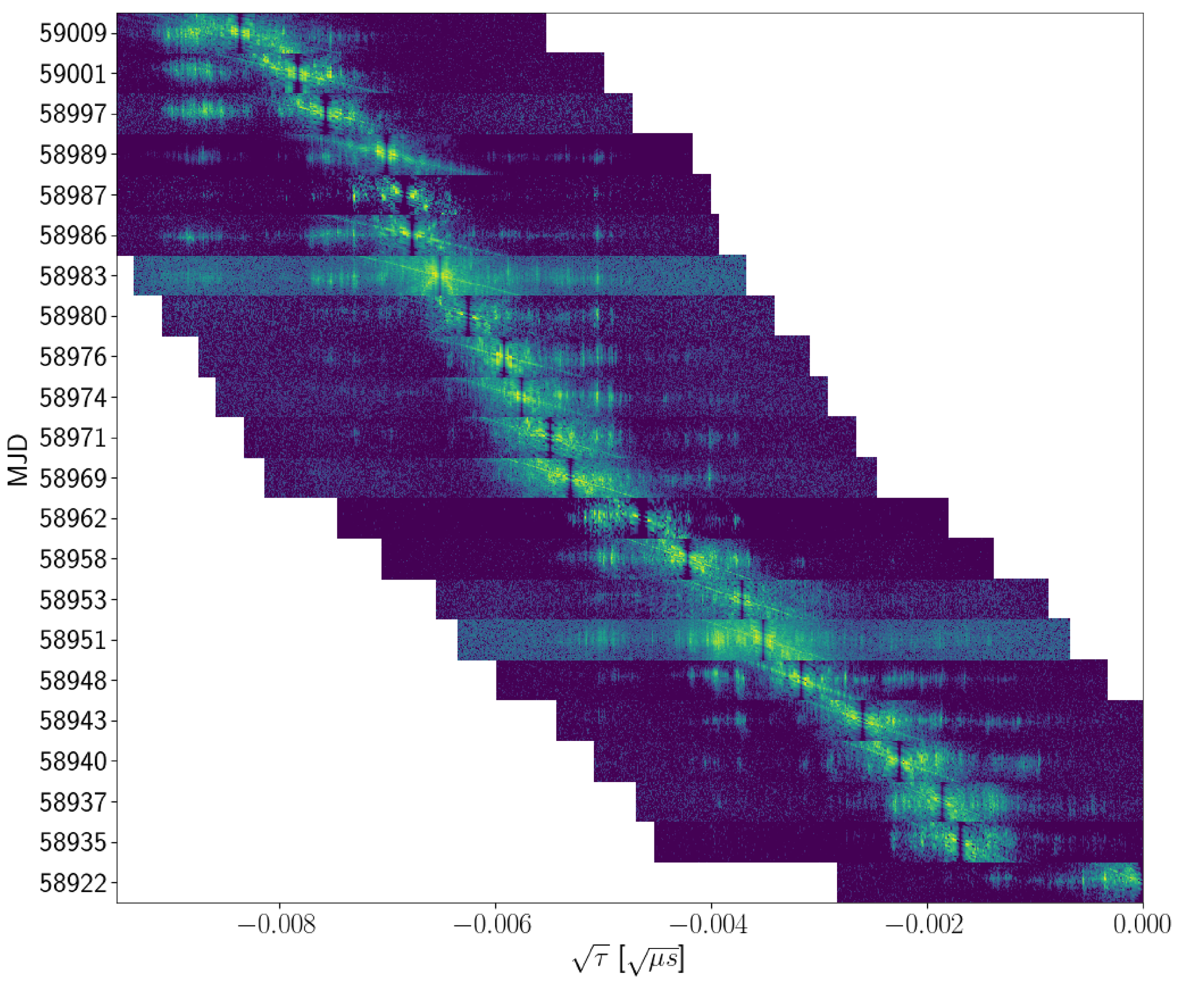
Eigenvector Decomposition



- Requires a one-dimensional distribution of images.
- Secondary spectrum can be transformed to space of interfering paths (Sprenger et al. 2021).
- Eigenvector gives brightness distribution of images.
  - Can be used to measure parabolic curvature (Baker et al. 2021).

Feature Alignment

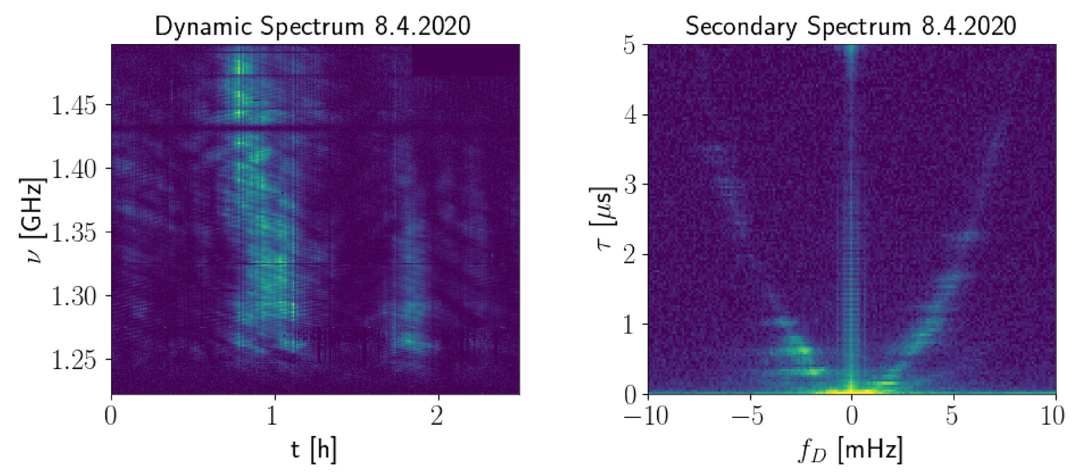
- Transform secondary spectra along arc to angular coordinates.
- Align the features visible in these plots.
- Stripes are at constant angular position and allow precise correlation method.
  - One data point for each pair of observations.
  - Contains the same information as parabolic curvature.
- Strong scintillation data needs manual alignment.
- Alignment of data from March 13 to June 8 in 2020 shown below.
  - X-axis: angular coordinates on the screen in model independent units.
  - Y-axis: modified Julian date of observation.



Transition

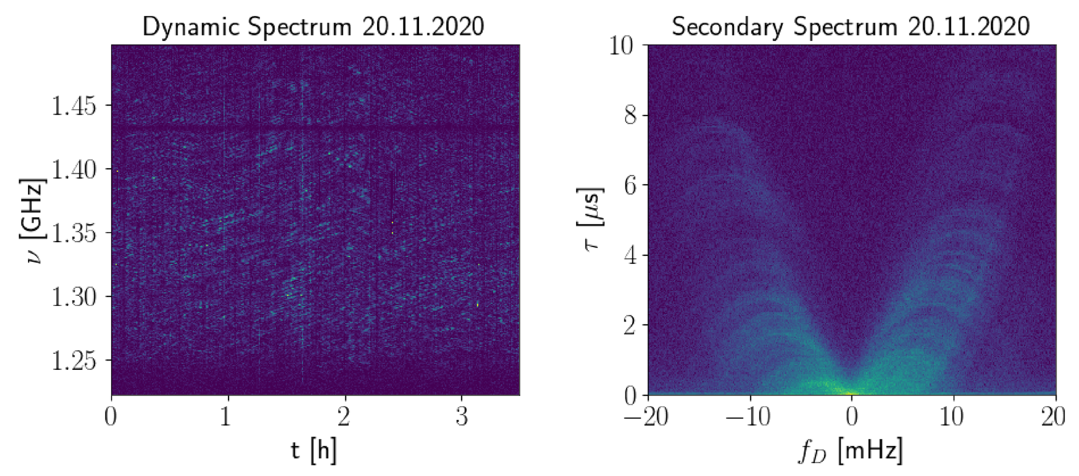
Until September 2020:

- Dynamic spectra are dominated by vertical modulations.
- Secondary spectra show a thin arc and parallel stripe-like features.
- Many observations contain a second weaker arc.

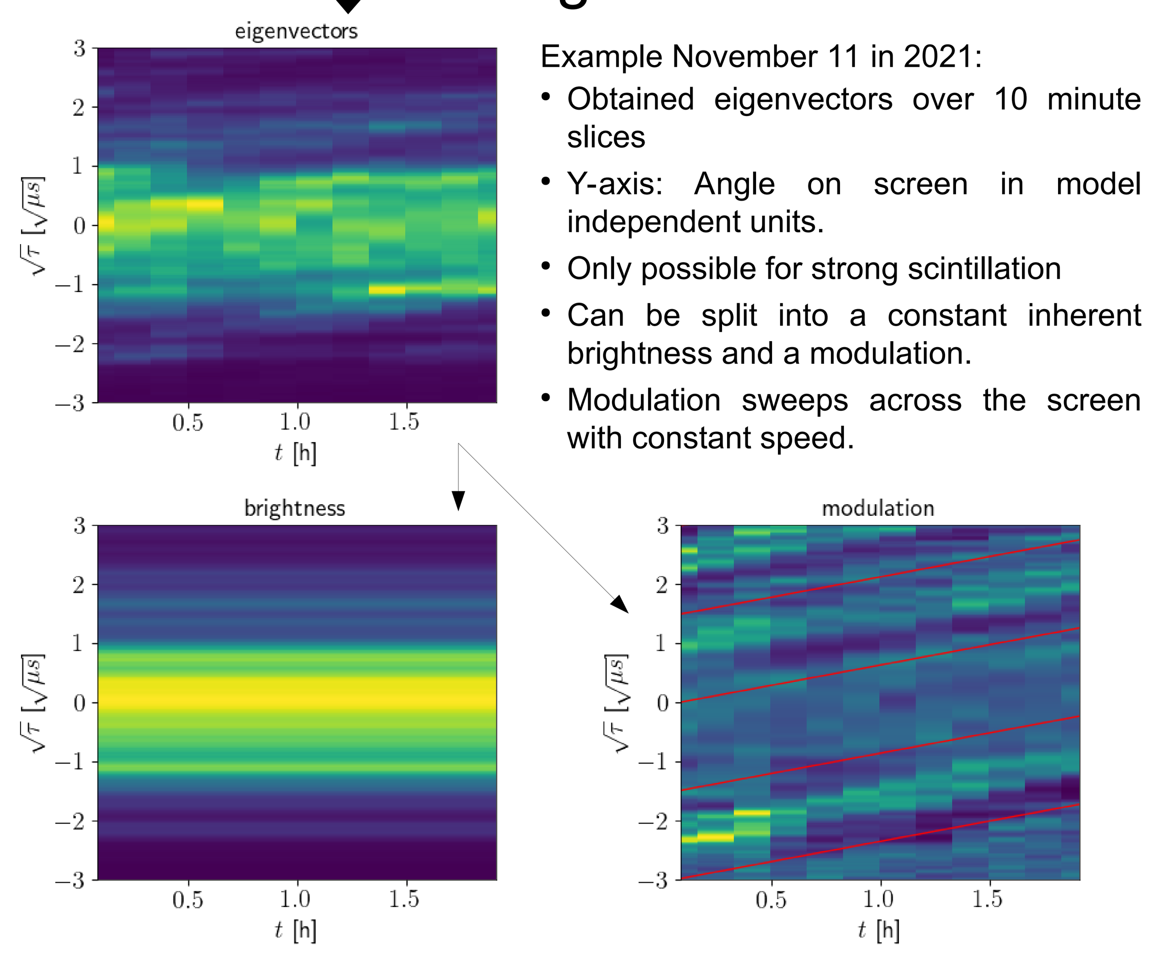


Since November 2020:

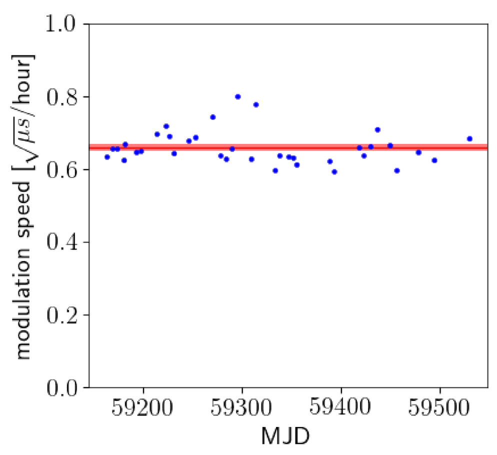
- Full transition from **weak scintillation** (thin arc) to **strong scintillation** (parabolic arclets).
- Vertical modulations and second arc disappeared.
- Stripes weakly remained in some observations.



Eigenvector Modulation



Example November 11 in 2021:
- Obtained eigenvectors over 10 minute slices
- Y-axis: Angle on screen in model independent units.
- Only possible for strong scintillation
- Can be split into a constant inherent brightness and a modulation.
- Modulation sweeps across the screen with constant speed.



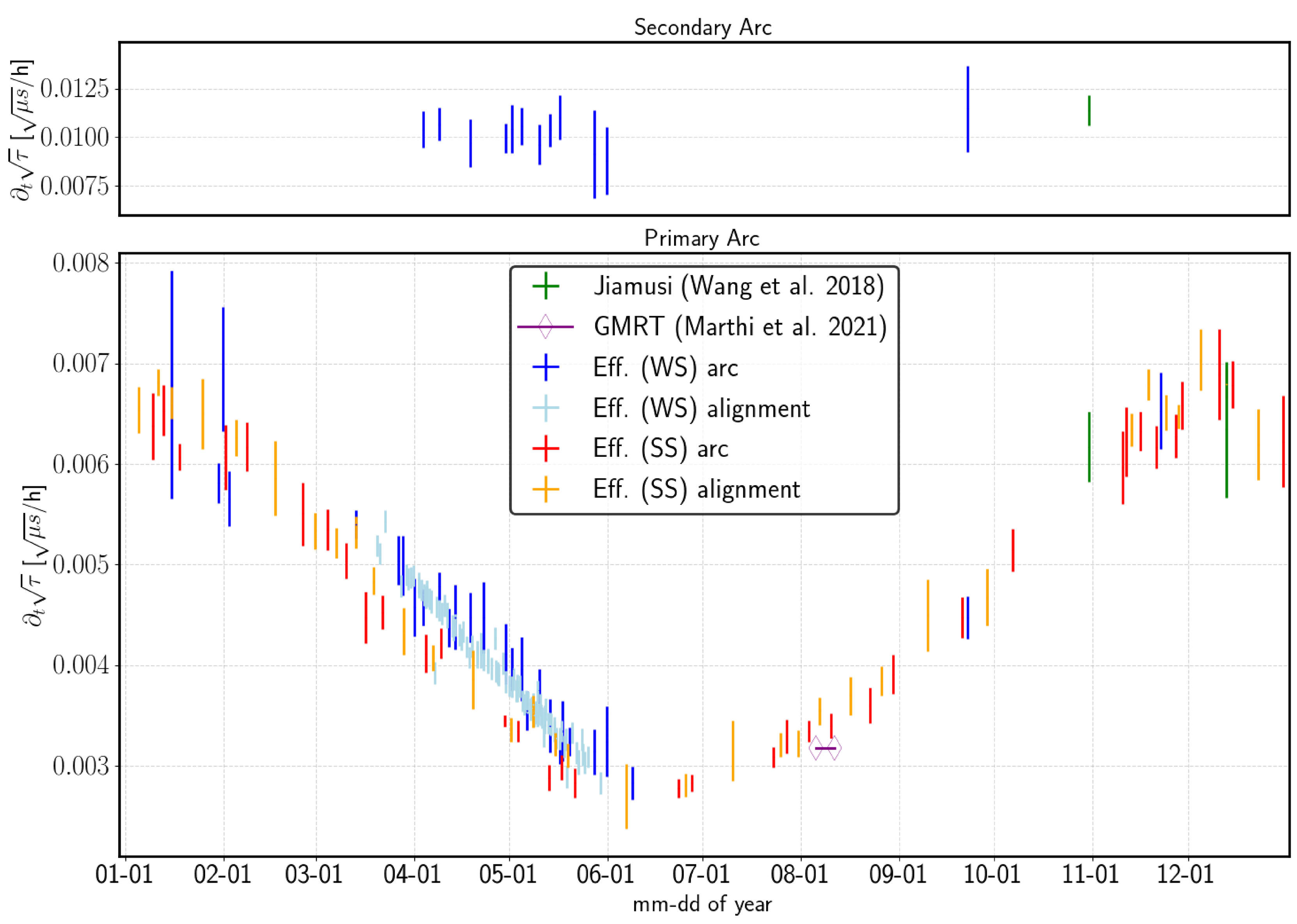
Modulation speed can be measured via the Hough transform.
- Mean measured value is constant over all observations.
- Distances on the screen are on the scale of astronomical units.
  - Modulation cannot originate from the same screen.
- Very constraining result:

$$0.6597(77)\ \sqrt{\mu s}/\mathrm{hour}$$

Annual Variation

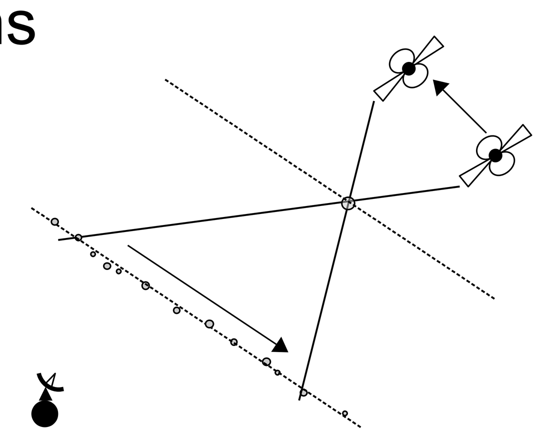
The plots below show the collected data of the alignment as well as the arc curvature translated into the shift it corresponds to in the feature alignment. The variation of the primary arc is obviously dominated by the earth's motion around the sun while the secondary arc only allows for low accuracy measurements and is compatible to a constant. This means its screen is much farther away than the primary screen.

The separation between weak (WS) and strong (SS) scintillation is necessary since the phase of the annual variation slightly changed. A possible explanation for this is a slight shift in the orientation of anisotropy of the primary screen. The obtained geometrical parameters from fits to this data are consistent with the screen distance and orientation found by Wucknitz 2019. Future study will also contain data obtained at LOFAR during the same time.

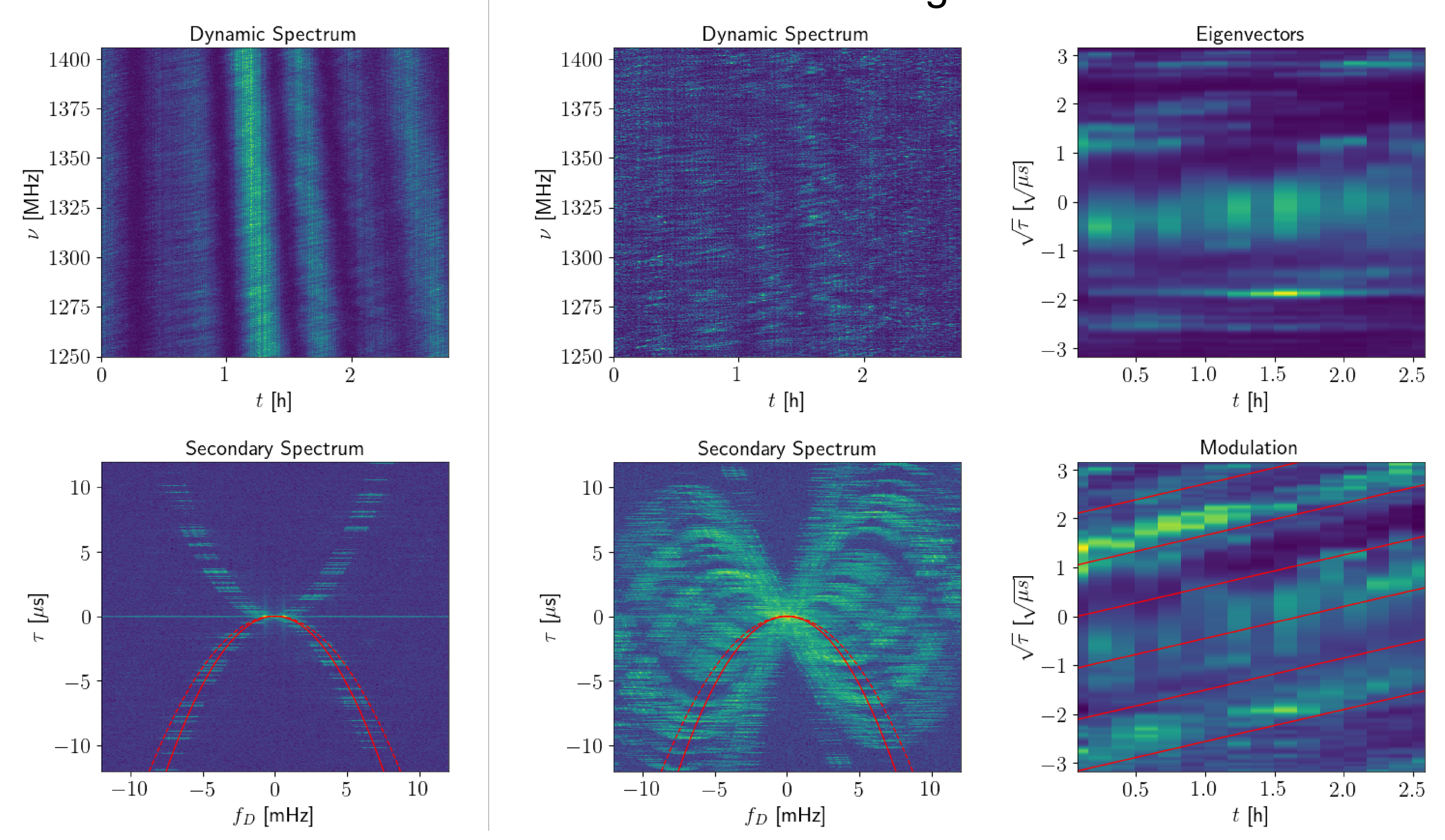


Simulations for two Screens

- Eigenvector modulation is very strong evidence for a second screen.
- Point of same lensing magnification is sweeping along screen
- We derived a double screen theory using wave optics and starting from these assumptions inferred from the data:
  - **Anisotropy**: Phase factors on the screen only depend on one coordinate.
  - **Stability**: Only along this axis, images stay at a fixed coordinate.
- Simulations below show that this theory can be used to model all observed phenomena.
- Red lines show the prediction of single (dashed) and double (solid) screen theory.



Weak Scintillation / Strong Scintillation



References Baker D., et al., 2021, arXiv:2101.04646 ; Chatterjee S., et al., 2009, ApJ, 698, 250 ; Hobbs G., et al., 2004, MNRAS, 353, 1311 ; Marthi V. R., et al., 2021, MNRAS, 506, 5160 ; Sprenger T., et al., 2021, MNRAS, 500, 1014 ; Stinebring D., 2007, AstronomicalSociety of the Pacific Conference Series Vol. 365, p. 254 ; Stovall K., et al., 2015, ApJ, 808, 156 ; Wang P. F., et al., 2018, A&A, 618, A186