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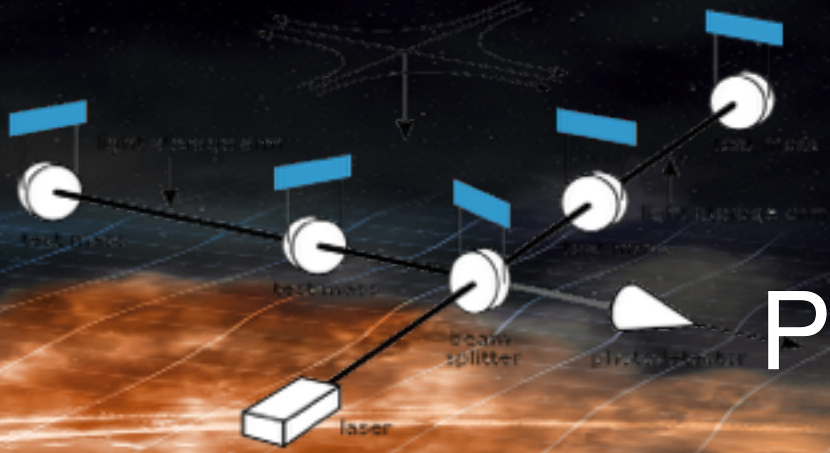

Precision timing and scintillation of binary radio pulsars

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Swinburne University of Technology · Australian National University · Monash University · The University of Adelaide · The University of Melbourne · The University of Western Australia · AAO · CSIRO

Part 1: Pulsar Timing

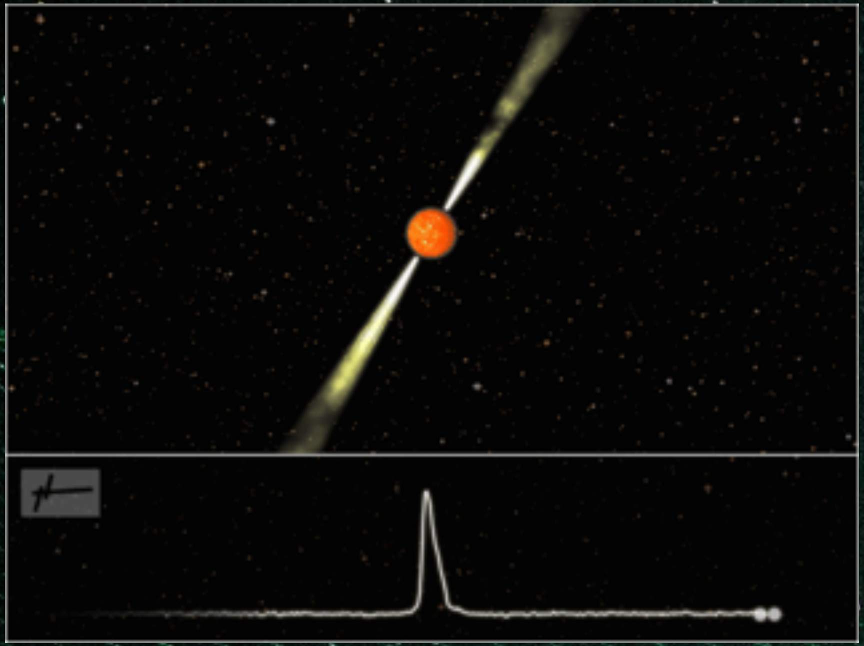
Introduction

Pulsars
Pulsar evolution
Binary Pulsars
Pulsar timing

Research

New timing analysis of PSR J0437-4715 for equation of state constraints

Pulsars



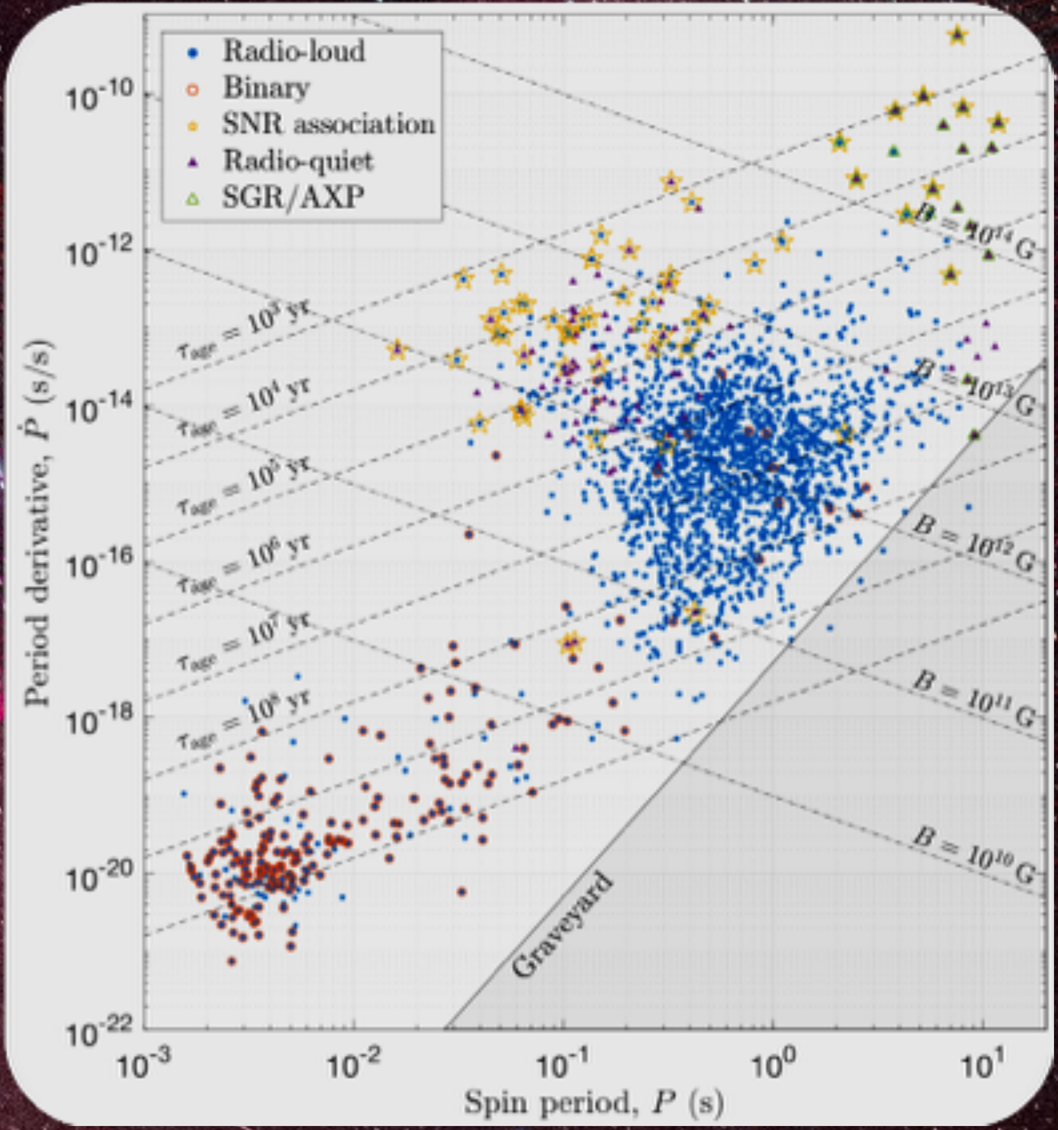
Credit: Joeri van Leeuwen

- Neutron stars
  - Dense with powerful magnetic fields
  - ~ 10km radius with ~ 1.4 solar mass
- Beamed radio emission
  - From magnetic poles
  - Powered by rotation
- Rapid and stable rotation
  - Observed as regular lighthouse-like flashes

Next: Pulsar evolution

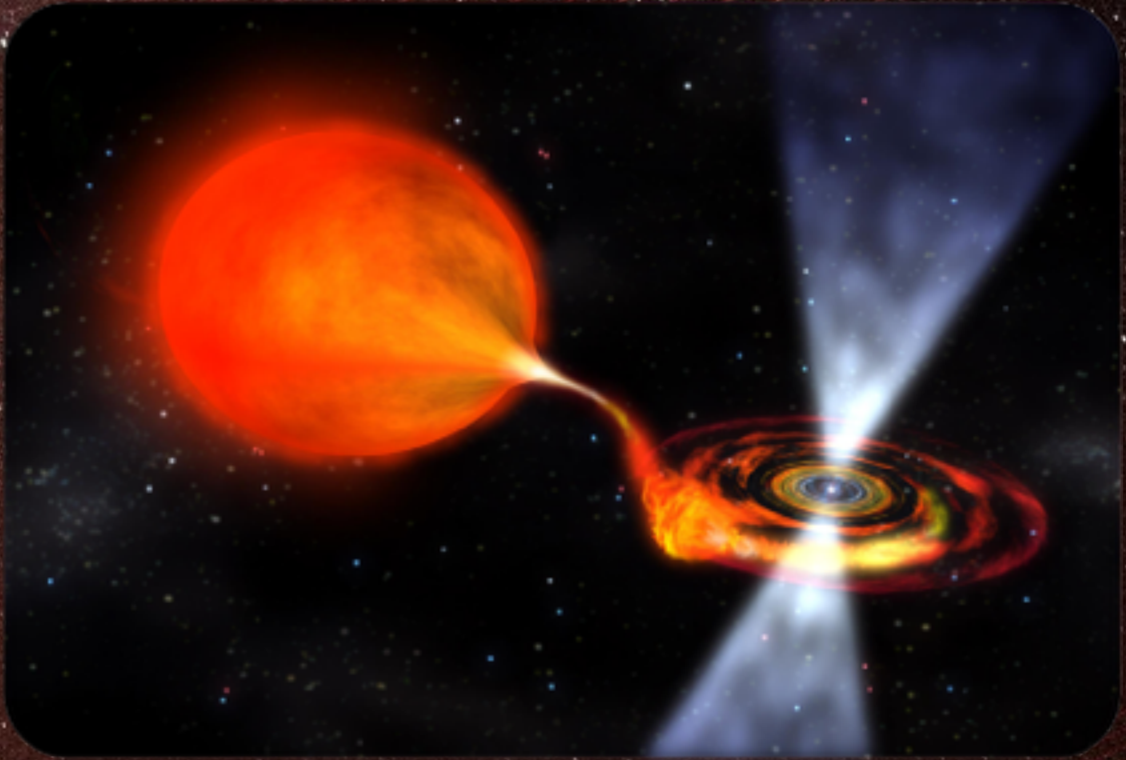
Pulsar Evolution

- Pulsar “P – Pdot” diagram
- Pulsars born in core-collapse supernova
  - ~ 0.1 – 1 second periods
  - High spin-down date
- Evolve through cluster of “normal” pulsars
- Lose rotational energy until emission shuts off.
  - Enter the **graveyard**



Next: Binary pulsars

Binary Pulsars



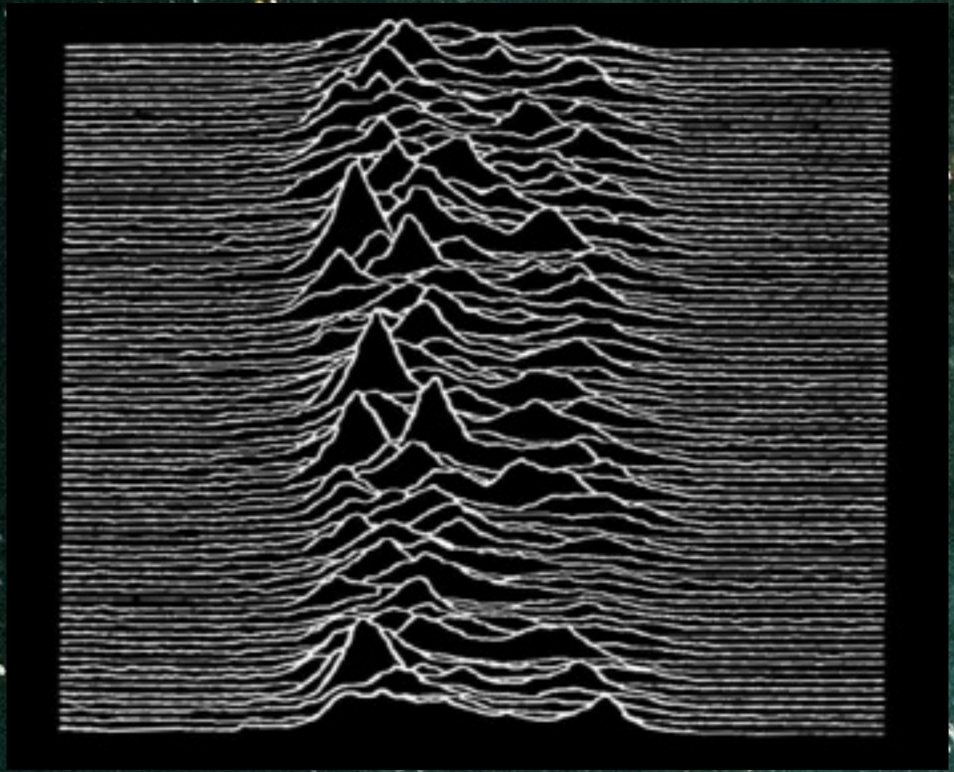
Credit: University of Southampton

- Pulsars can be ***recycled!*** With Roche-lobe overflow
- **Millisecond** pulsars are "spun up"
  - Often observed in binary with white dwarf companion
  - As fast as a ***blender***
- Relativistic binaries, e.g.
  - Neutron star – Neutron star
  - PSR J1141-6545: White dwarf companion formed first

Next: Pulsar timing

Pulsar Timing

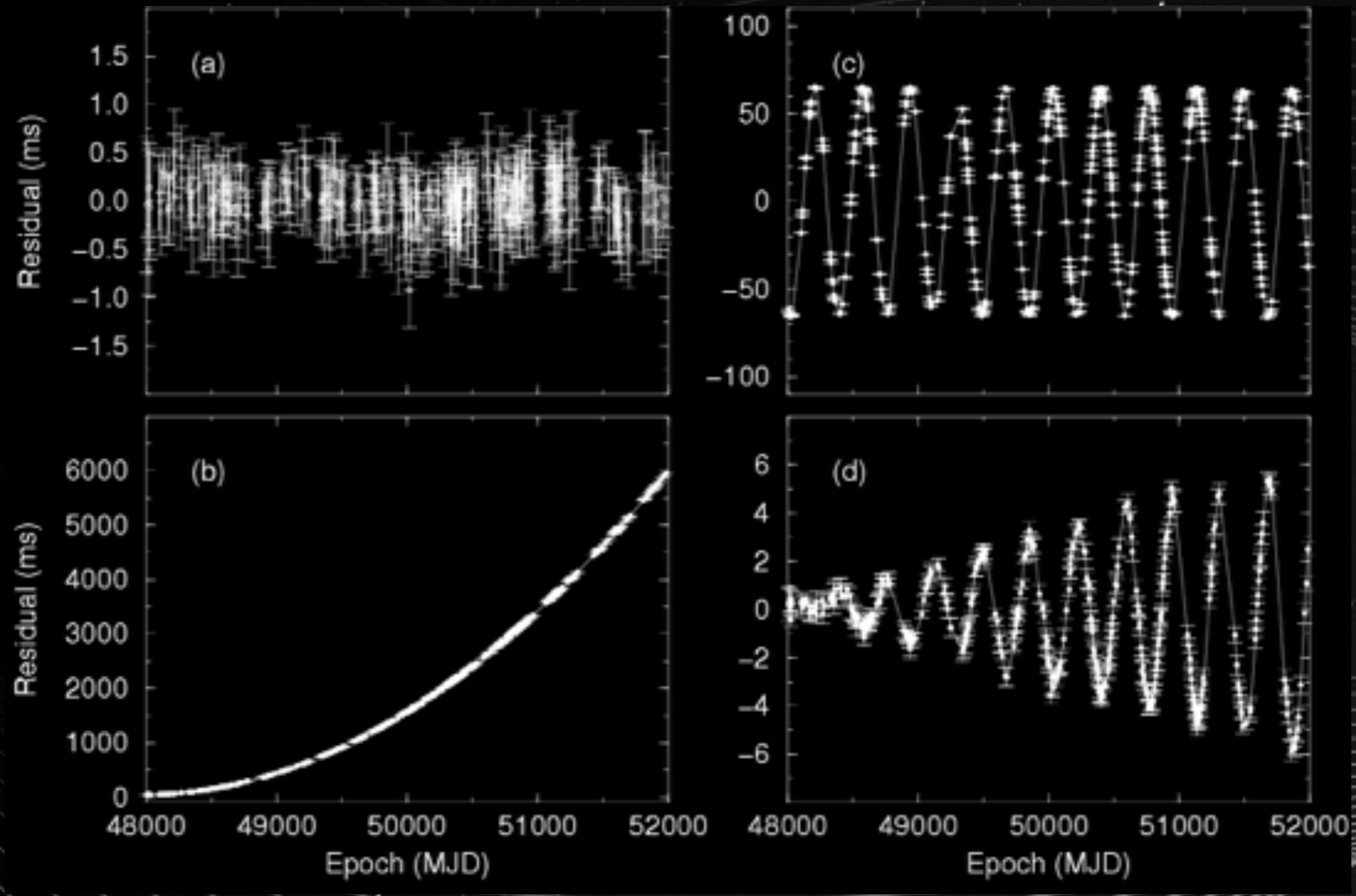
- Timing model predicts pulse arrival times. Includes:
  - Spin (period, period-derivative)
  - Astrometry (Position, proper motion, parallax)
  - Binary orbit
  - Dispersion measure (frequency-dependent delay from electrons in interstellar plasma)
  - Solar system ephemeris
- Timing residuals
  - Difference between model and observation
- Pulsar Timing Arrays (PTAs) used as Galactic-scale gravitational wave detectors



Joy Division: Unknown Pleasures album cover (Single-pulses from PSR B1919+21)

Next: Timing Residual

Pulsar timing residuals



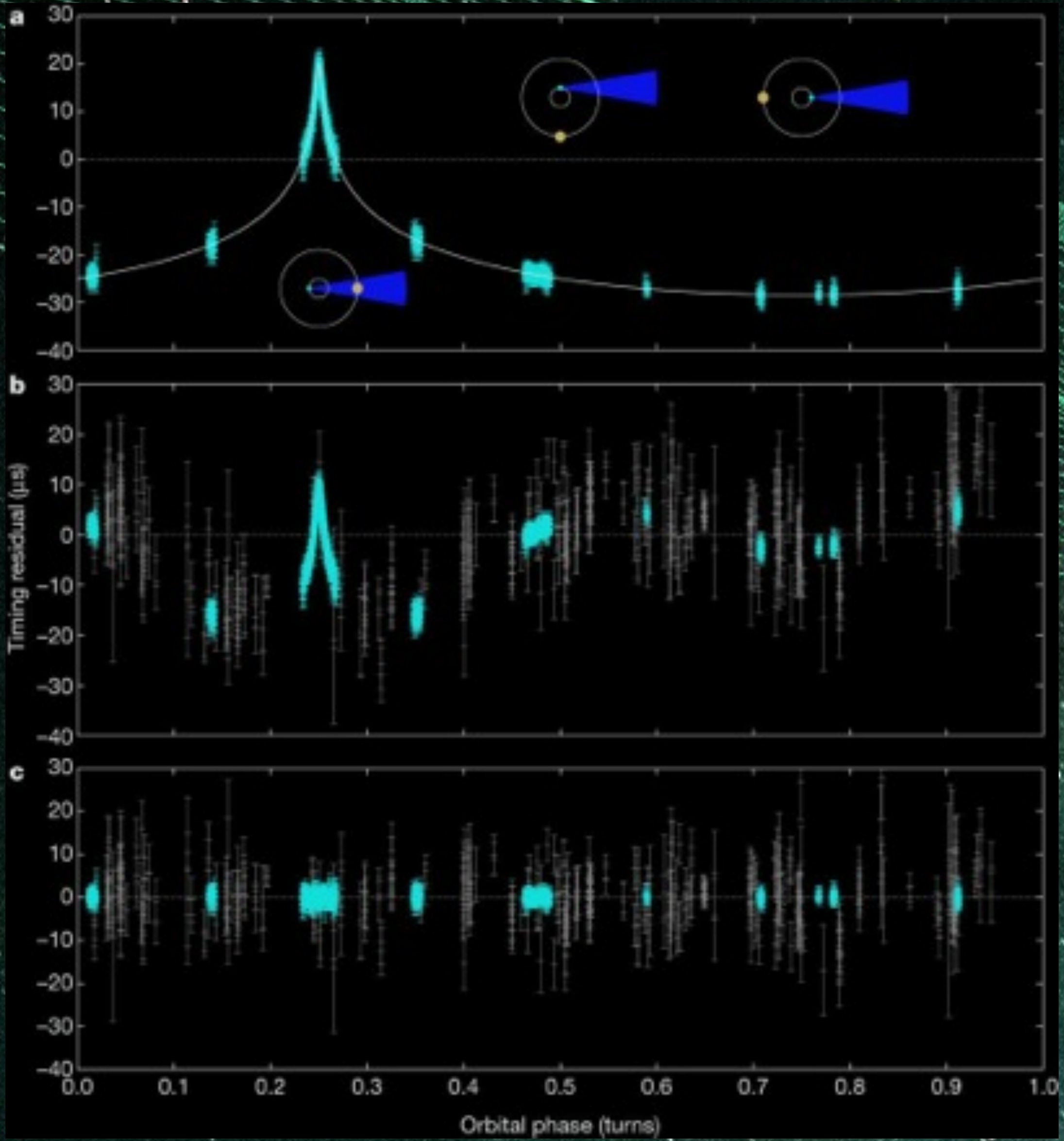
- Any errors in timing model appear in residuals
- We fit to the data to update timing model

Lorimer and Kramer (2005)

Next: Shapiro Delay

Shapiro Time Delay

- Gravitational time delay effect
  - Increased path length
- Useful measure of companion mass and orbital inclination
  - Can then find pulsar mass

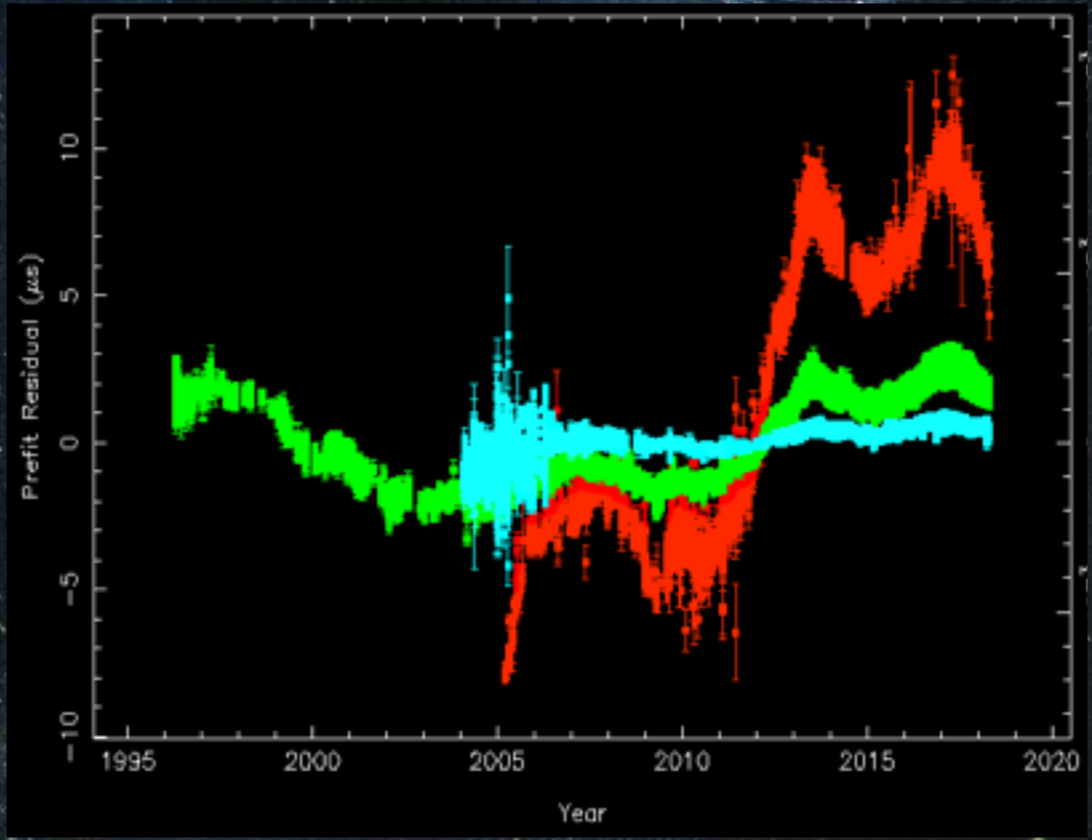


Demorest et al. (2010)

Next: Timing of J0437-471

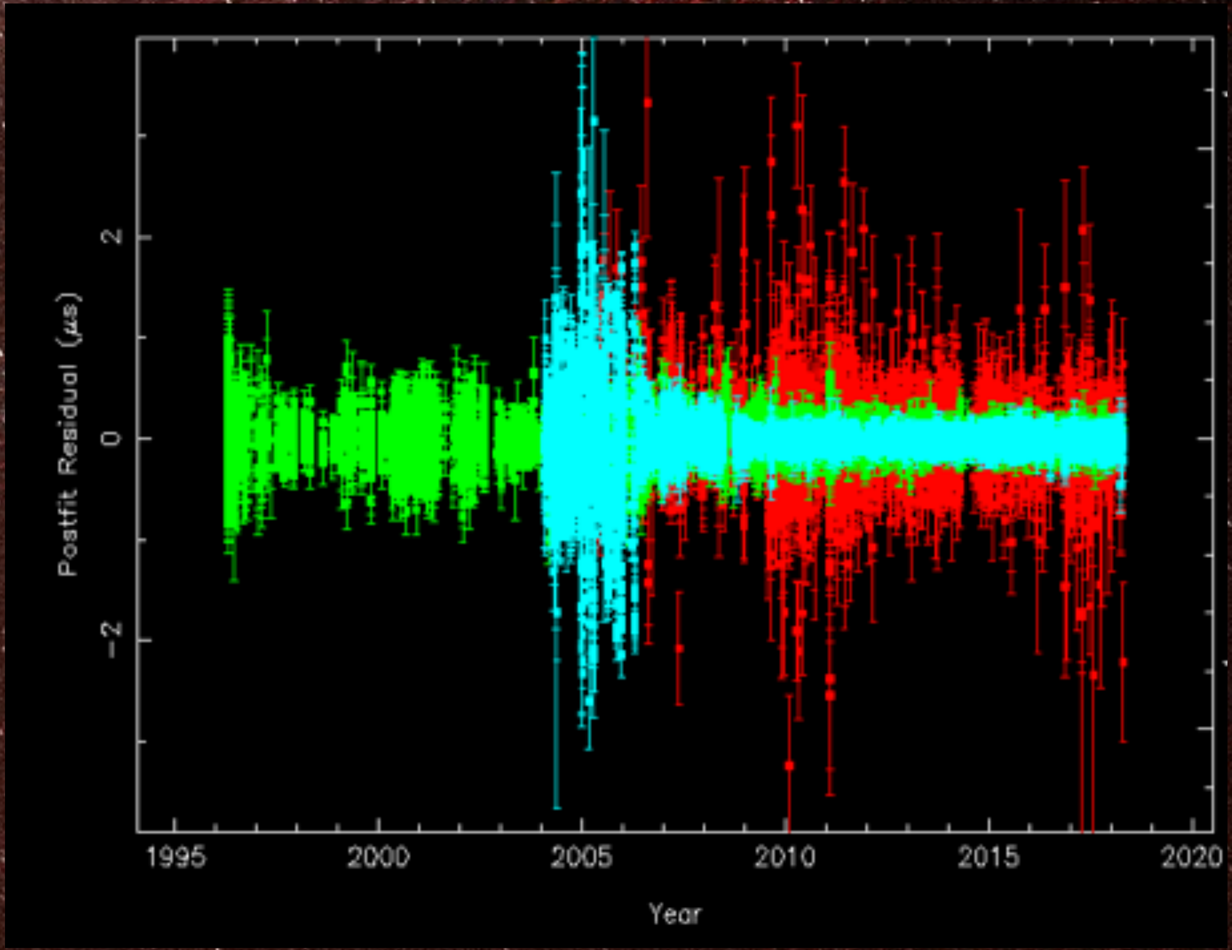
Timing of Millisecond Pulsar, PSR J0437-4715

- **Nearest** and **brightest** millisecond pulsar
- **~22 years** of regular timing observations with Parkes 64m radio telescope
- PPTA second data release
- Requires complex timing model
- Has ***lots*** of noise!!
  - Dispersion measure (electron column density) variations
  - Intrinsic spin noise
  - Pulse shape variability
  - Pulse shape change event
  - Instrumental noise
- Characterise noise simultaneously with timing model



Timing residuals (difference between data and model)
Red: 700 MHz
Green: 1400 MHz
Blue: 3100 MHz

PSR J0437-4715 Timing Precision



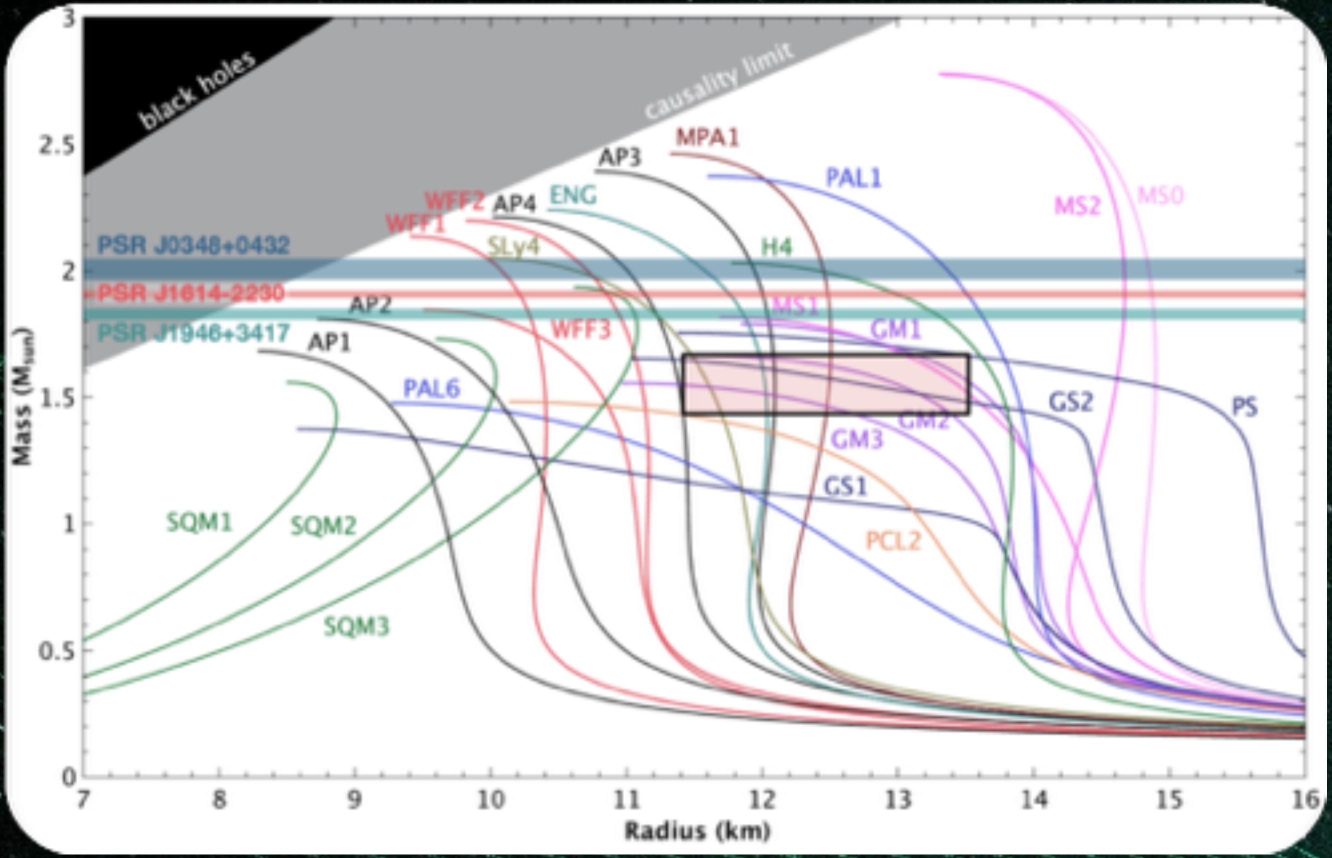
Timing residuals after removing the long-timescale noise.

~***100 nanosecond*** weighted rms residual
over ~***22 years***

Red: 700 MHz
Green: 1400 MHz
Blue: 3100 MHz

Next: Why do we care?

Q: Why do we care about this pulsar?



From OzGrav telecon presentation by Theo Motta (University of Adelaide)

- **One of our best opportunities for measuring the neutron star equation of state**
- *"A two-solar-mass neutron star measured using Shapiro delay"* - Demorest et al. (2010) 2500+ citations
- *"A Massive Pulsar in a Compact Relativistic Binary"* - Antoniadis et al. (2013) ~ 1500 citations
- *"GW170817: Measurements of Neutron Star Radii and Equation of State"* - Abbott et al. (2018) ~250 citations

Next: NICER

Neutron star Interior Composition ExploreR (NICER)

- NASA mission to explore neutron star interiors
  - X-ray timing and spectroscopy

- Measures neutron star radii
- Modelling x-ray light curves
- Require **distance**, pulsar **mass**, and orbital **inclination** from radio pulsar timing
- **Primary target is PSR J0437-4715**

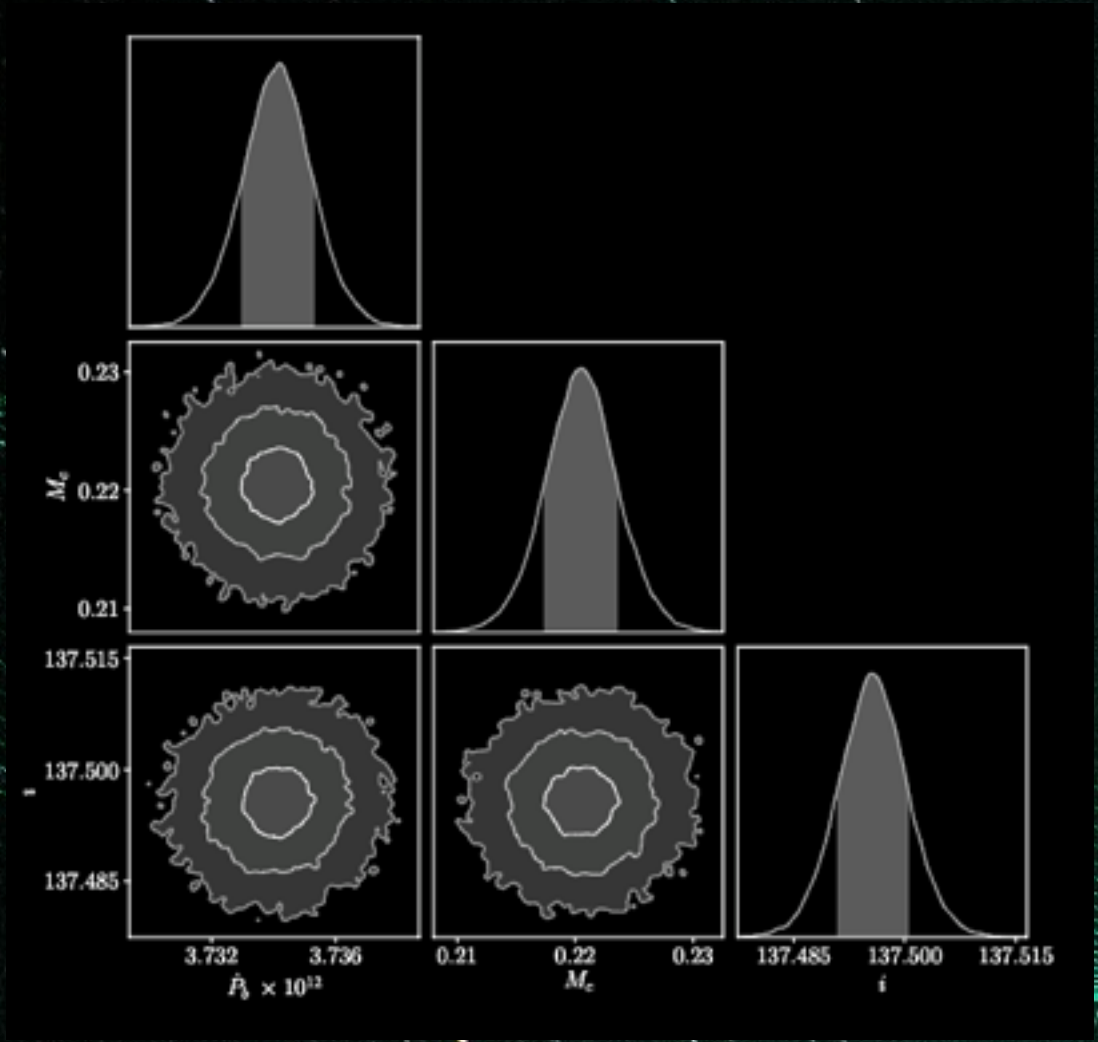
Credit: NASA

“If the *mass* of a neutron star and the pattern of radiation from its surface are known accurately a priori, NICER observations will achieve an accuracy of ~ 2% in the measurement of radius (Gendreau et al., 2012; Bogdanov, 2013). In practice, the measurement will be limited by uncertainties in these two requirements. The uncertainty in the mass measurement of NICER’s primary target, the bright pulsar PSR J0437–4715, is ~5% (Reardon et al., 2016).”

-- Watts et al. (2016)

Next: New timing result

New Timing Results for PSR J0437-4715



- Measured noise and timing model parameters simultaneously in a Bayesian analysis
- Companion mass measured with **Shapiro delay**

- Inclination angle: 137.496 ± 0.005 degrees
- Companion mass: 0.2205 ± 0.029 solar mass

- **Pulsar mass: 1.411 ± 0.030 solar mass**

Next: Distance and radial veloci

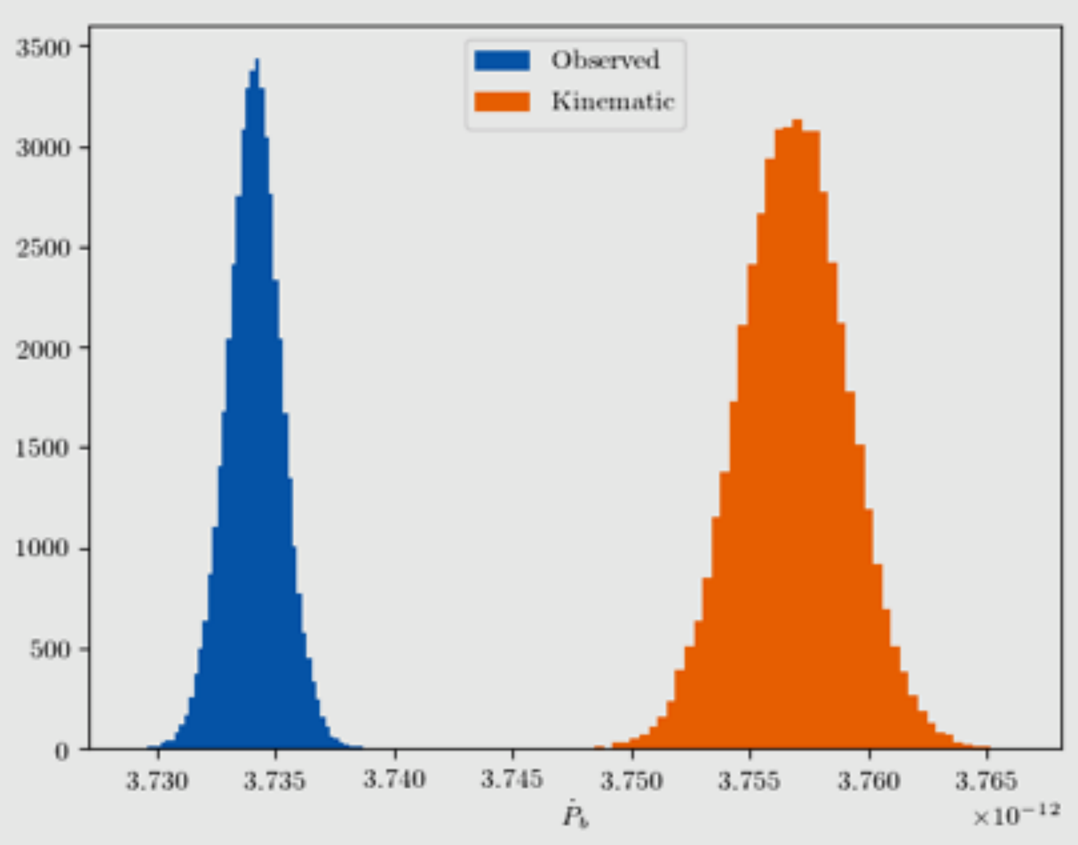
Deriving *distance* and *radial velocity(!)*

- Shklovskii effect

- Remarkably precise distance measurement from orbital period-derivative
  - D = 157.01 ± 0.10 pc
  - Useful for single-source gravitational wave searches

- First-ever radial velocity from second spin period-derivative
  - V_r = -75 ± 15 km/s

$$\dot{P}_b^{\rm obs} - \dot{P}_b^{\rm GR} - \dot{P}_b^{\rm Gal} \simeq \dot{P}_b^{\rm kin} = \frac{\mu^2 D}{c} P_b$$



Next: Scintillation

Part 2: Scintillation: The dynamic spectrum

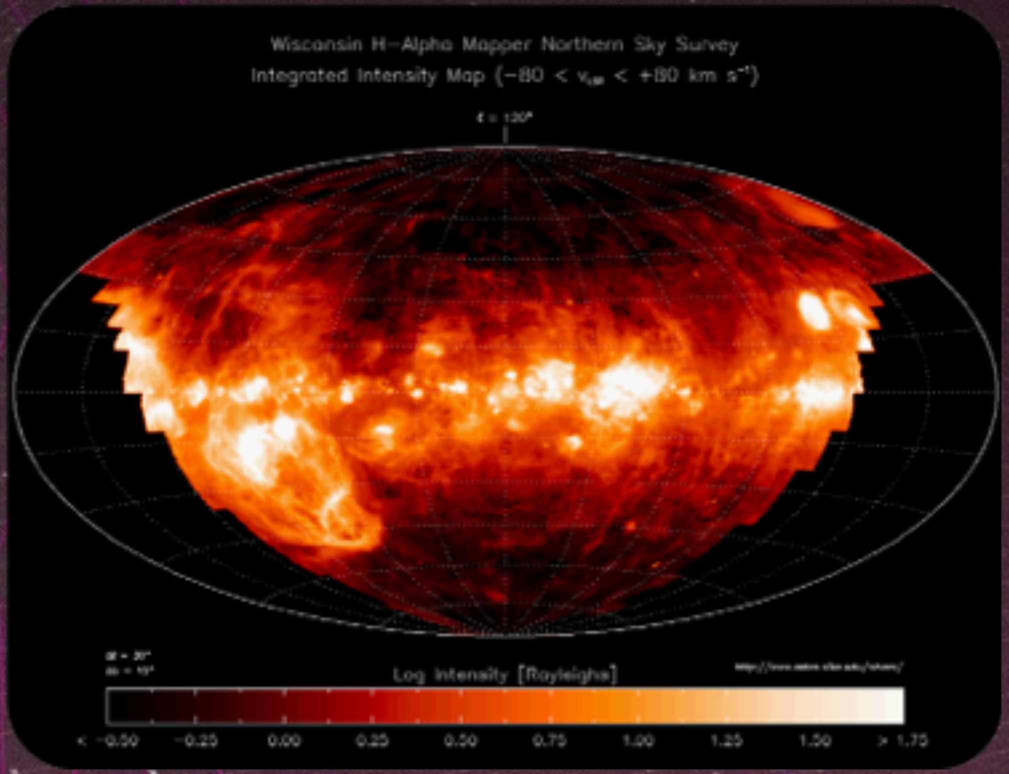
Introduction

Ionised Interstellar Medium (IISM)
Interstellar scintillation
Observing pulsar scintillation

Research

Modelling long-term scintillation of
relativistic binary PSR J1141-6545

Ionised Interstellar Medium (IISM)



Wisconsin H-Alpha Mapper (WHAM)

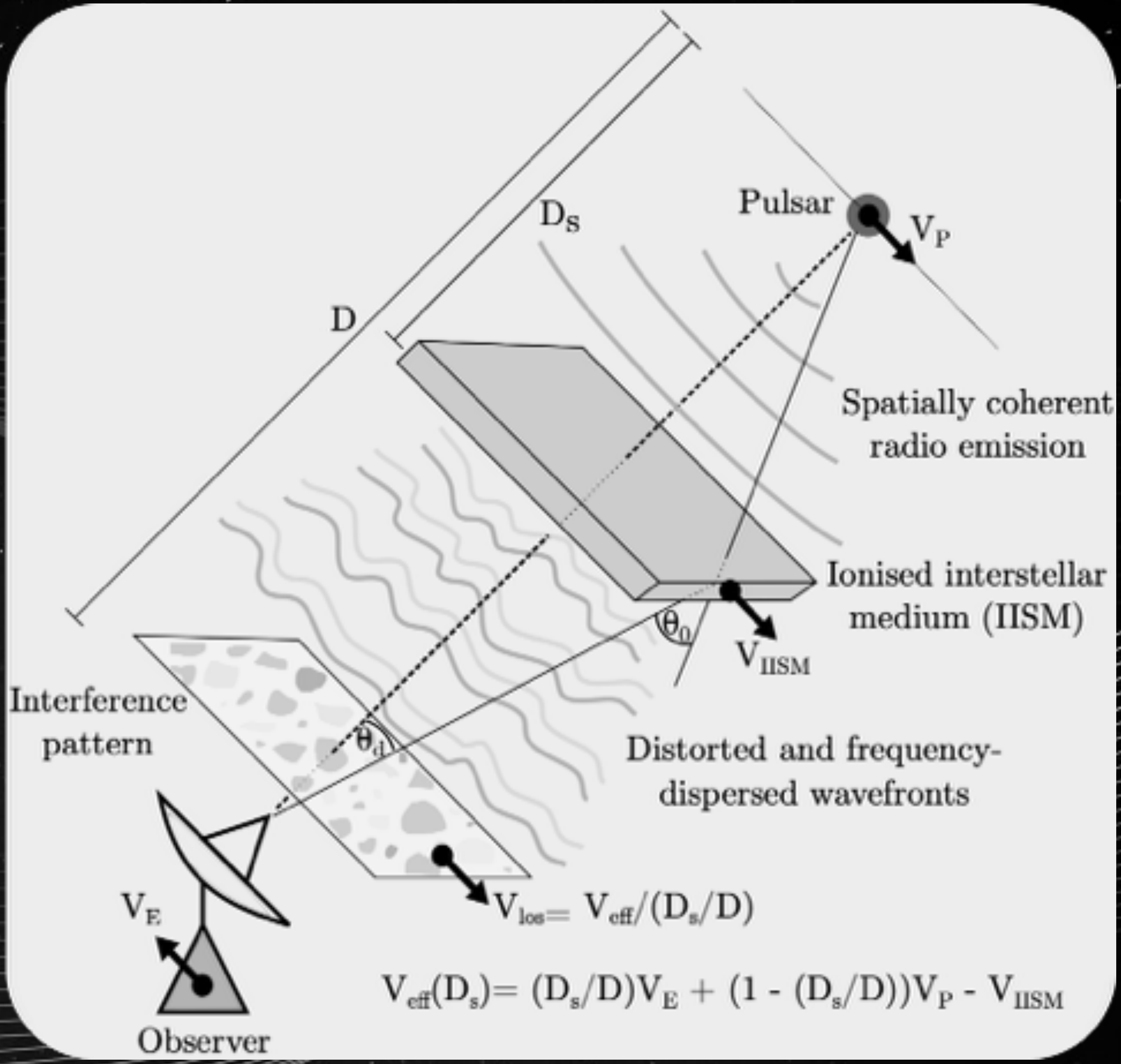
- Warm plasma phase
- Turbulent
  - Energy cascades from large to smaller spatial scales
- Free electrons scatter radio waves
- Diffraction occurs on small spatial scales
- Refraction occurs on larger spatial scales
- *Scattering often dominated by one, or a few, intensely turbulent regions*
- Extreme scattering events (ESEs) (interstellar tornados with ~AU scales)

Next: Interstellar Scintillati

Interstellar scintillation

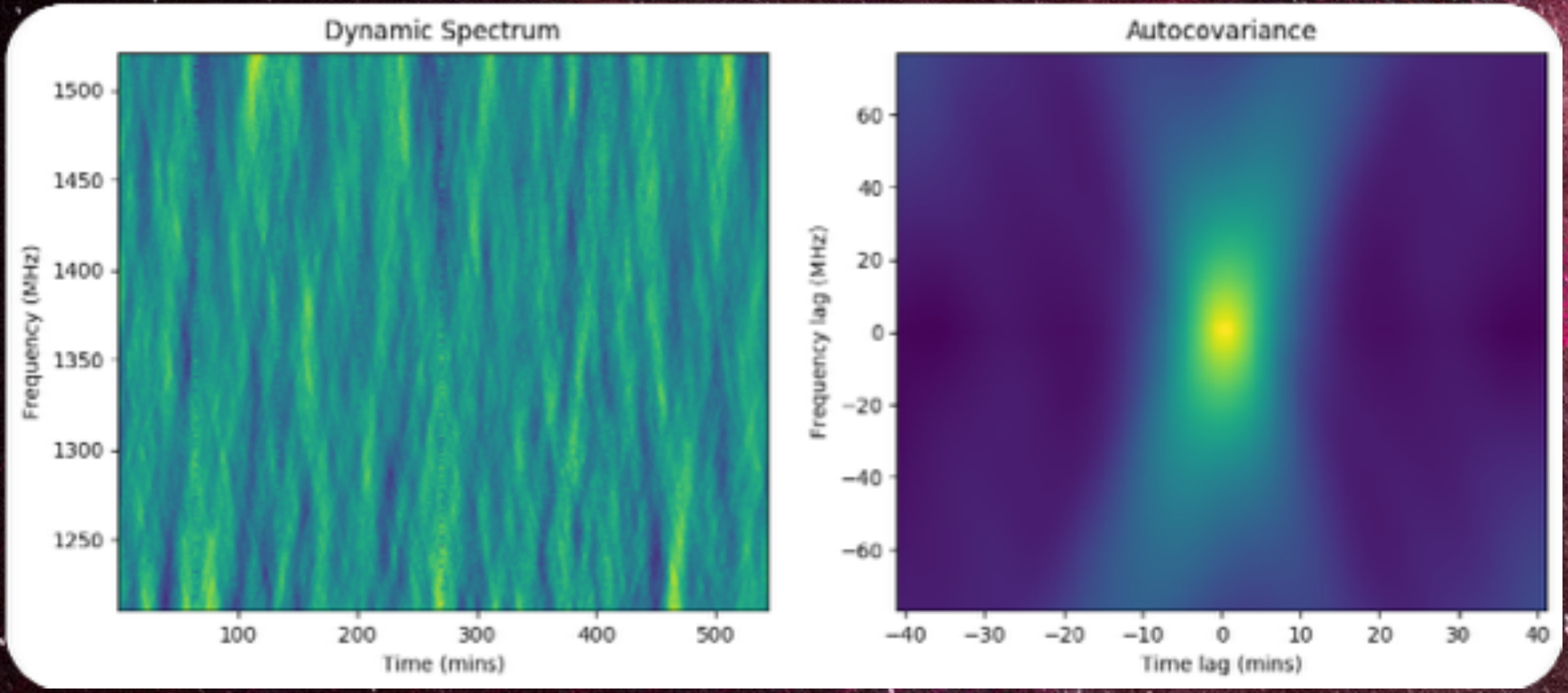
- Scattered wavefronts interfere
- Scattering is frequency-dependent
- Interference pattern drifts across telescope
- Drift velocity depends on line-of-sight velocity through scattering region
- ***Transverse*** velocities of **pulsar**, **IISM**, and **observer**

- Pulsar timing sensitive to radial motions



Next: Observing Scintillatio

Observing pulsar scintillation



Dynamic spectrum of PSR J0437-4715

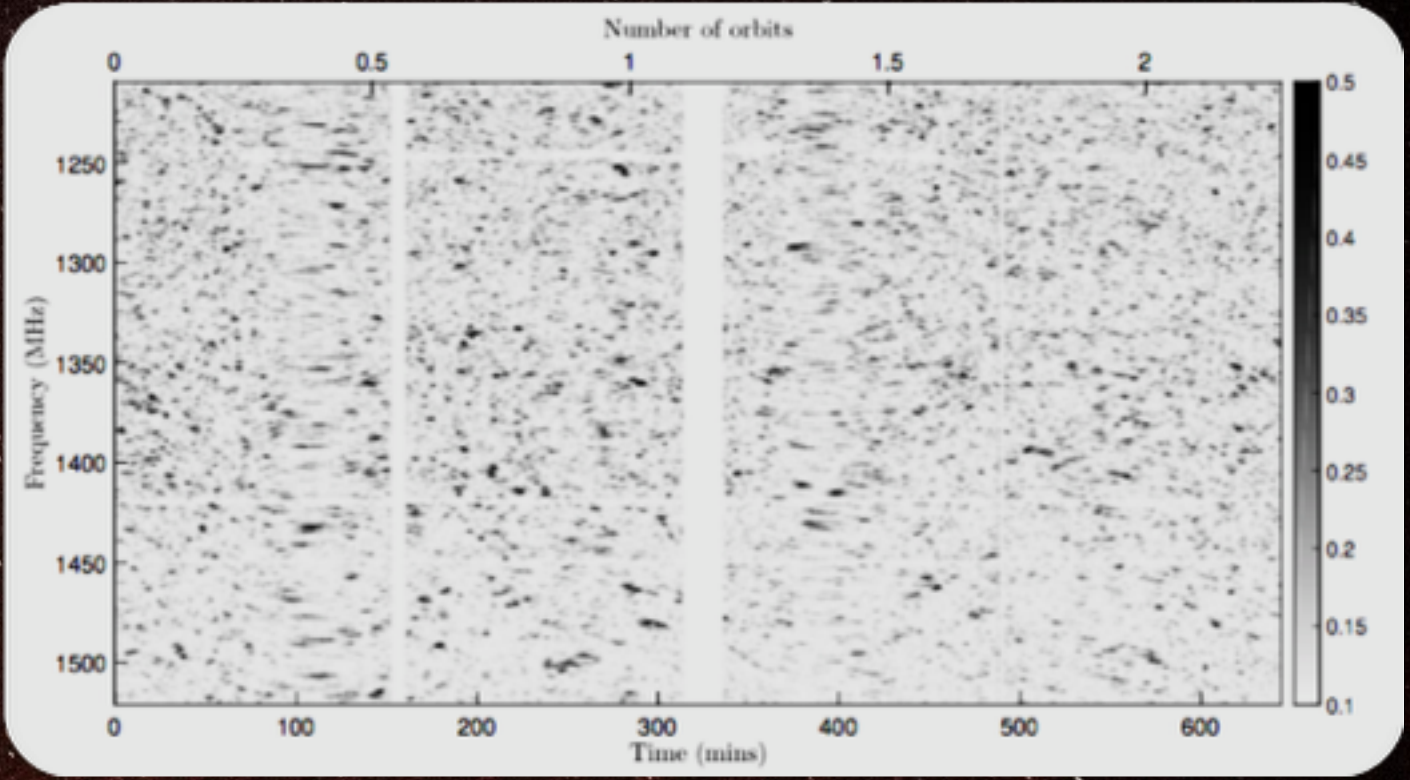
- Pulsar flux changes as a function of observing ***frequency*** and ***time***
- Characteristic scintle from autocovariance function
- Decorrelation bandwidth (of order MHz)
  - Depends on spatial scale, scattering angle and strength
- Scintillation timescale (of order mins)
  - Depends on spatial scale and velocity of the line-of-sight.

Next: Scintillation of PSR J1141-65

Scintillation of relativistic binary PSR J1141-6545

- Ord et al. (2002) modelled a single 10-hr observation of this pulsar
  - Measured inclination for the first time
  - New constraint for testing general relativity and estimate of mass
- Scintillation velocity ∝ 1/timescale
  - Modelling with line-of-sight velocity

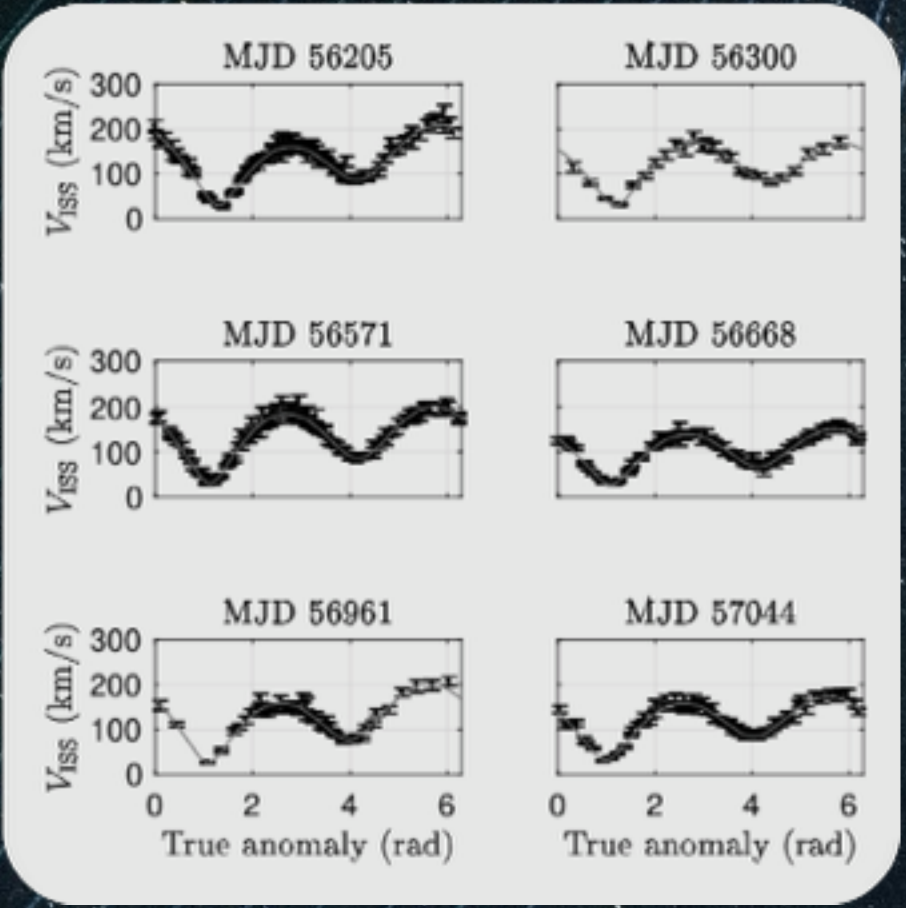
$$V_{\mathrm{ISS}} = A_{\mathrm{ISS}} \frac{\sqrt{D\Delta\nu_{\mathrm{d}}}}{f\tau_{\mathrm{d}}}$$



Reardon et al. (2019)

Next: Long-term Scintillatio

Long-term scintillation of PSR J1141-6545



Reardon et al. (2019)

- Measured scintillation parameters over ~6 years for PSR J1141-6545
- Scintillation velocity: $V_{\rm ISS} = A_{\rm ISS} \frac{\sqrt{D \Delta \nu_{\rm d}}}{f \tau_{\rm d}}$
- Sensitive to anisotropy in the scattering
  - Assuming isotropy introduces biases
- Observed ***annual*** and ***relativistic*** variations in scintillation timescale
  - More degrees of freedom in data!
  - More measured parameters!!

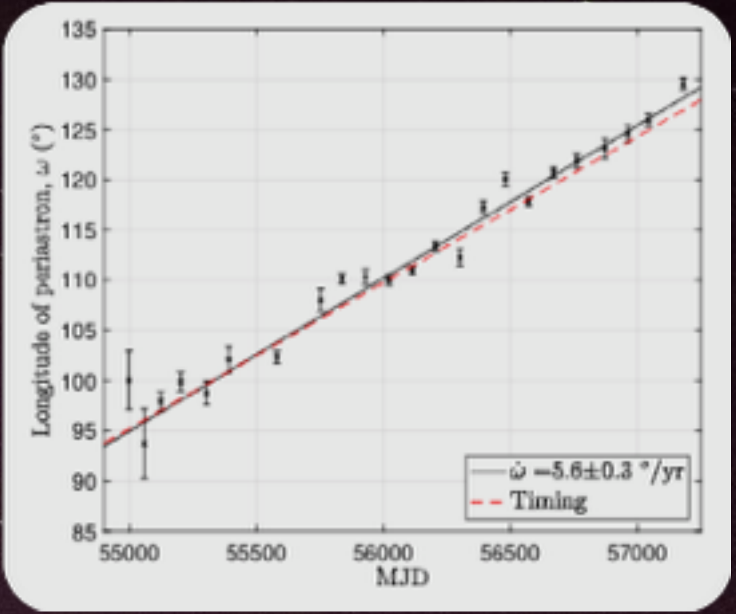
$$V_{\rm eff}(s) = (1-s)(V_{\rm p} + V_{\mu}) + sV_{\rm E} - V_{\rm IISM}(s),$$

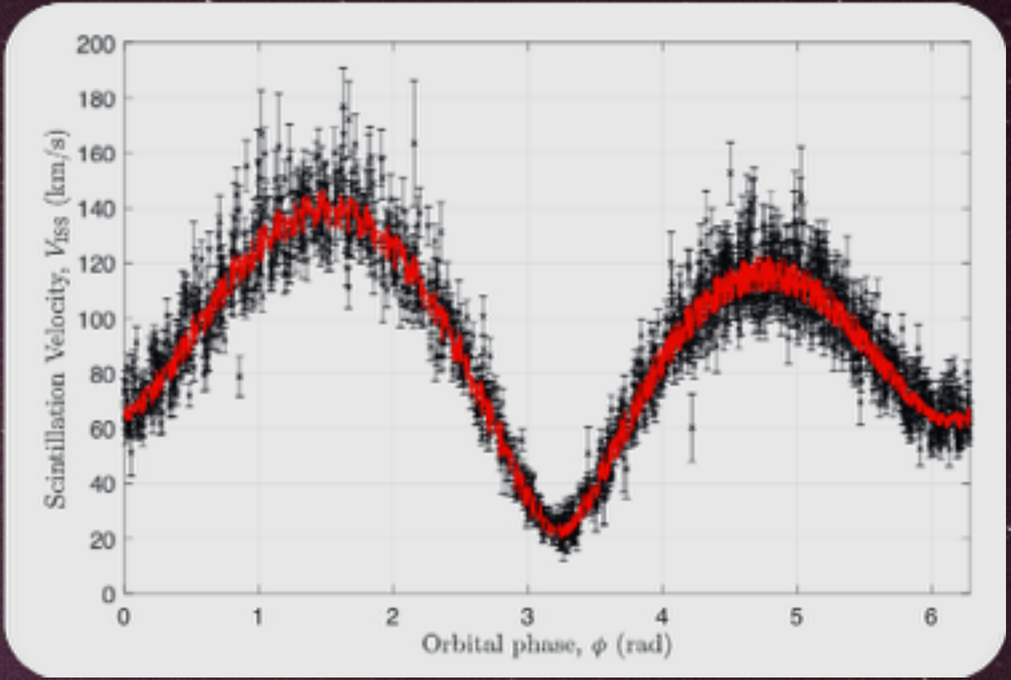
Next: Long-term mode

Long-term scintillation model

- Near-independent measurement of relativistic periastron advance!
- New method for estimating distance
- Improved measurement of transverse velocity
- Firsts (**only** possible with long-term study):
  - Estimate of proper motion in (RA/DEC)
  - Sense of inclination (< 90 degrees)
  - Longitude of ascending node Ω
  - Prediction for contamination in relativistic orbital period-derivative measurement from Shklovskii effect (only 1%)

Technique applicable to almost any binary pulsar – not just relativistic ones





Reardon et al. (2019)

Part 3: Scintillation: The secondary spectrum

Introduction

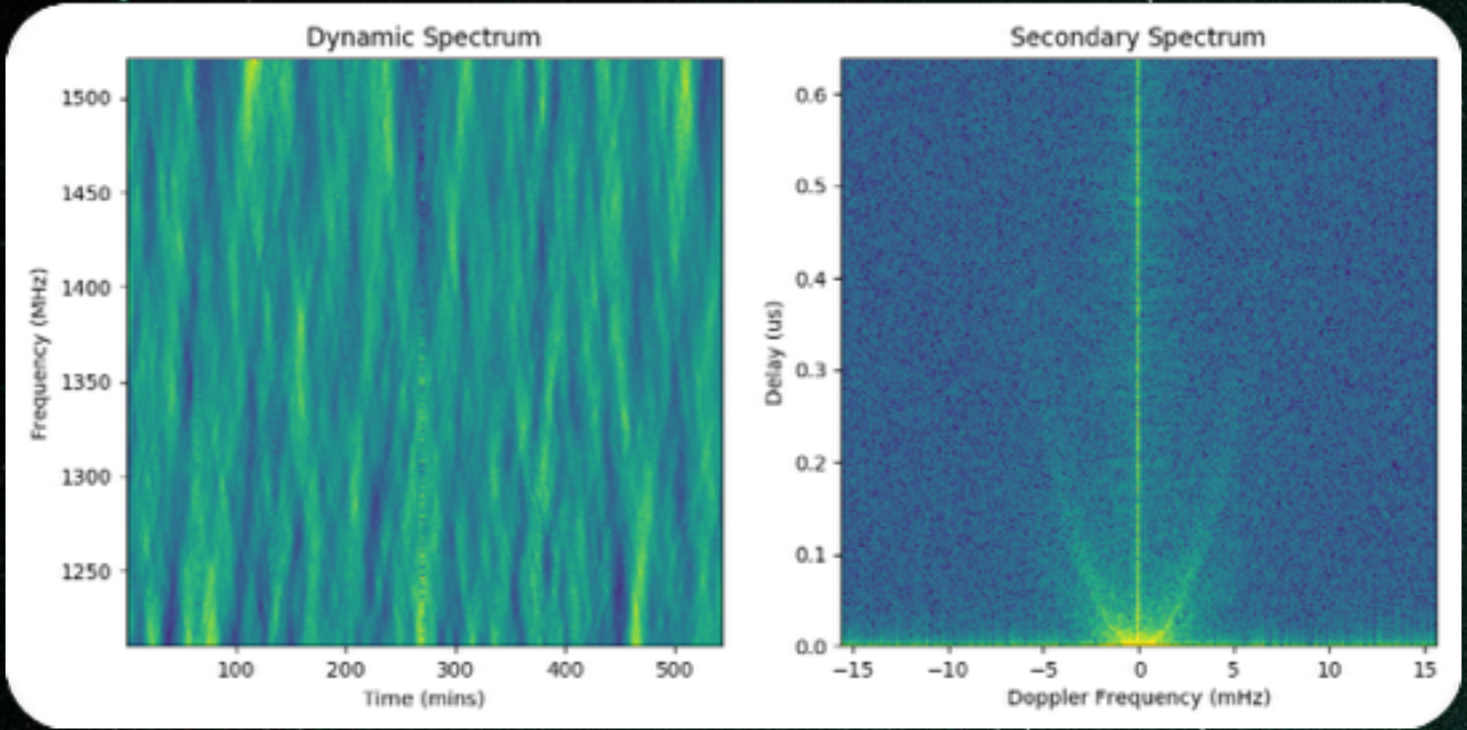
Delay-Doppler distribution and arcs

Arc curvature variations

Research

Long-term scintillation of PSR J0437-4715 *the* ***other*** *precise pulsar science*

The secondary spectrum / Delay-Doppler distribution



Dynamic spectrum of PSR J0437-4715

- Scintillation arcs discovered by Stinebring et al. (2001)
- Fringe pattern in dynamic spectrum becomes a ***parabola*** in secondary spectrum
- Curvature is simple to model!

$$\tau_{\mathrm{del}} = \frac{D(1-s)}{2cs}(\theta_2^2 - \theta_1^2)$$

$$f_{\mathrm{dop}} = \frac{f_c}{cs} V_{\mathrm{eff}} \cdot (\theta_2 - \theta_1),$$

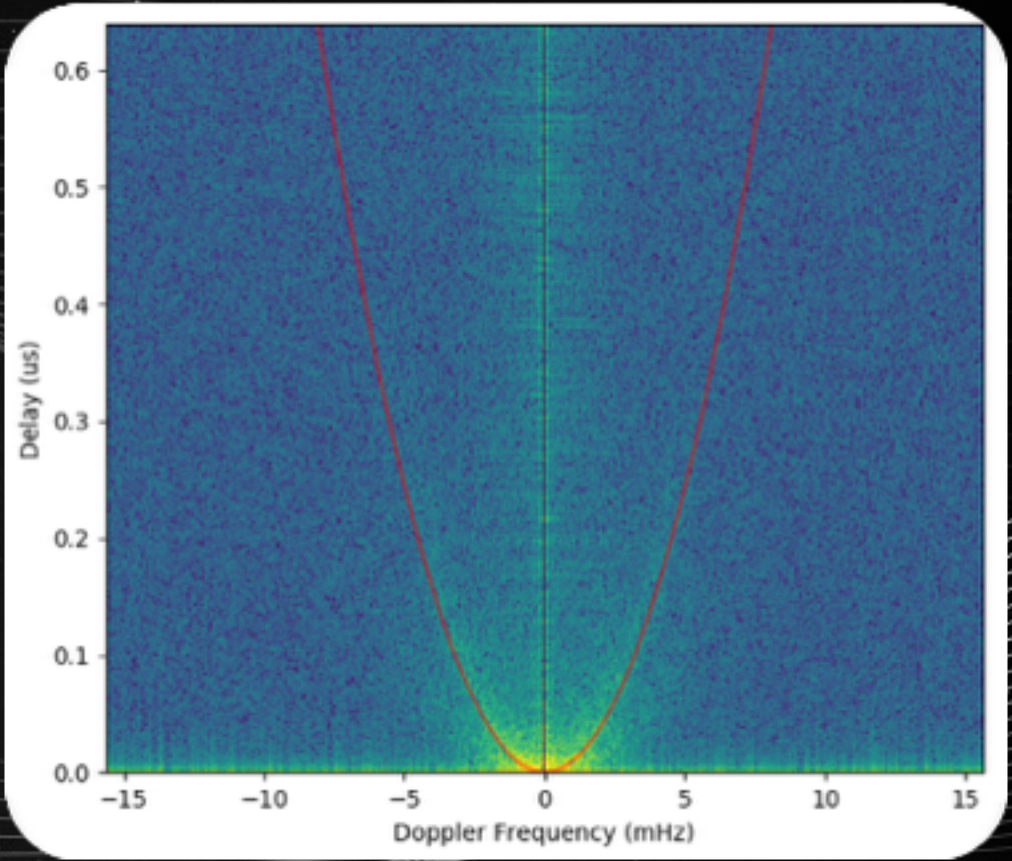
Next: Curvature measurement

Curvature Measurements

$$\eta = \frac{cDs(1-s)}{2f_c^2 V_{\mathrm{eff}}^2 \cos^2\psi}$$

- Independent of strength of scattering variations
- Much more **stable** with time than the "scintillation velocity" technique

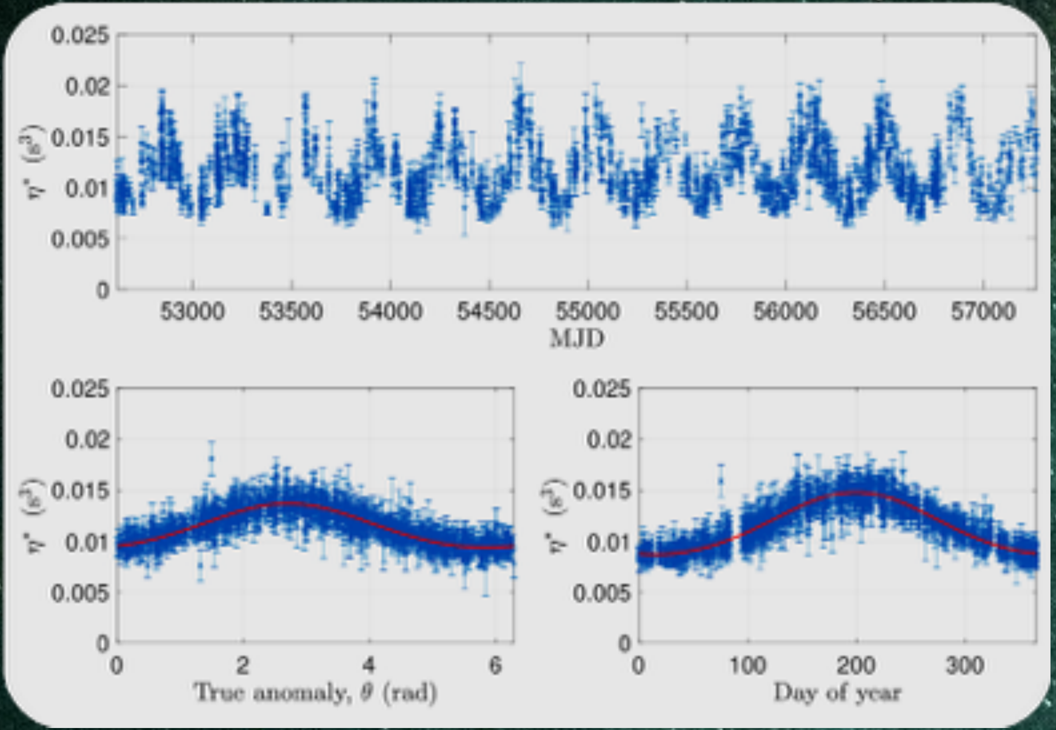
- For PSR J0437-4715, this is the **only** method we can use to model the scintillation
- Measured for ~1500 arcs over ~13 years!!



Next: Modelling curvature for J0437-471

Velocity model

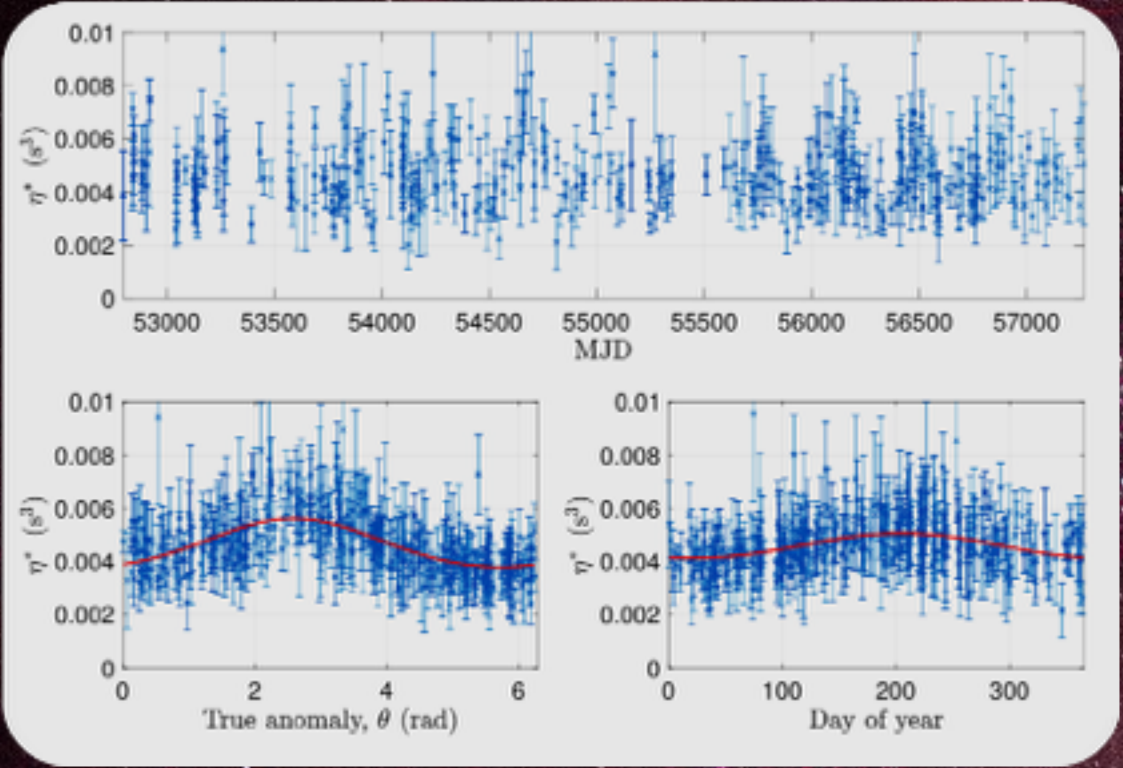
- Previously-unknown application of the Parkes Pulsar Timing Array (PPTA) data
- Competes with timing precision for **longitude of ascending node**
  - Ω = 207.2 ± 0.7 degrees (arcs)
  - Ω = 207.0 ± 1.2 degrees (Timing; Reardon et al. 2016)
- Impressive inclination angle precision:
  - i = 136.1 ± 0.5 degrees (arcs)
- Distance and velocity of scattering plasma:
  - D = 90.6 ± 0.7 pc
  - V_α = - 10.9 ± 0.8 km/s
  - V_δ = - 31.7 ± 0.7 km/s



Reardon (2018, PhD thesis)

Next: Another screen

...And a second arc!



- Second thin scattering screen!
- D = 122 ± 3 pc
- V_α = - 4 ± 9 km/s
- V_δ = - 47 ± 8 km/s

- Some evidence for at least one more scattering screen
- Precise measures of distance and velocity allow us to search for the source of the scattering.

Next: Summaries

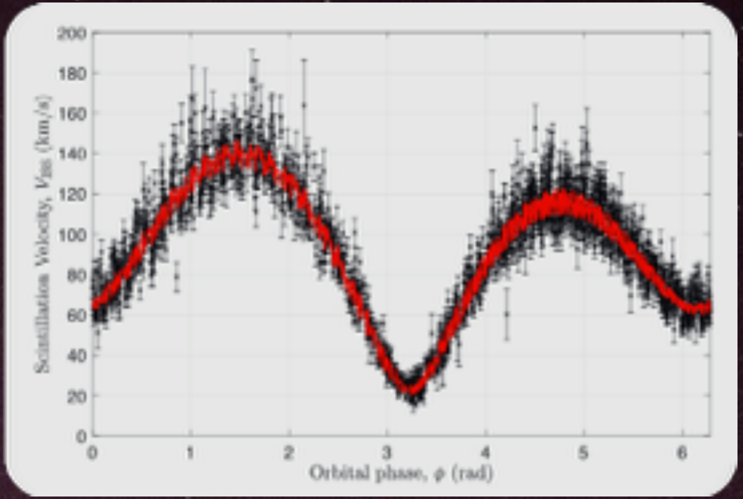
Scintillation Modelling Summary

- Long-term is key!
  - Annual variations
  - Time-variations in properties of IISM
  - inclination angle (mass constraints), proper motion, and 3D orbital geometry

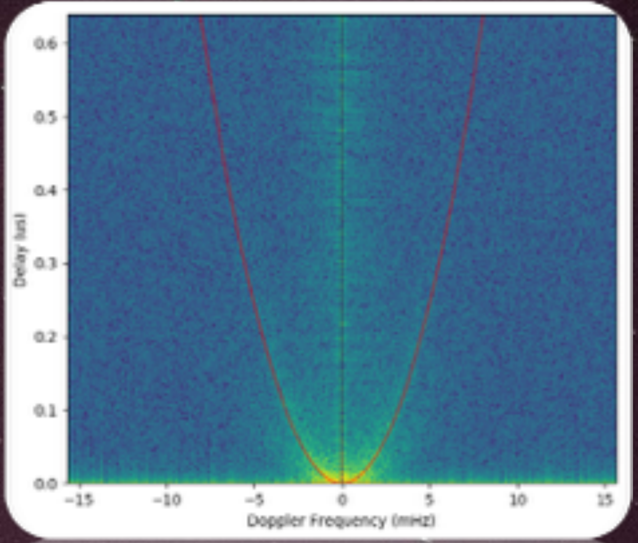
- Dynamic spectrum:
  - All radio pulsars scintillate.. Most have useful dynamic spectra
  - Widely applicable, but sensitive to changes in IISM

- Secondary spectrum:
  - Arc curvature precise and stable!
  - Independent of scattering strength
  - Applicable to fewer pulsars (but still many!)
  - May require tuning of observations
  - Can image the scattering medium

These are brand new techniques that can be used on *existing* data. Almost every pulsar I've looked at is



Scintillation velocity



Arc curvature

Summary: Synergy and Future Prospects

Pulsar Timing – known as a precise science
(New mass of PSR J0437-4715 measured to 2% for equation of state constraints)

Pulsar Scintillation – more sensitive to transverse motions
(proven to give precise measurements of IISM, binary, and astrometric parameters)

Timing + Scintillation – Ability to model full 3D geometry of binary orbits (e.g. PSR J1141-6545), and best chance for measuring astrometry (proper motion)

Future – Wide observing bandwidth instruments like ultra-wideband receiver on Parkes, and MeerKAT telescope are *ideal* for scintillation studies

With *thousands* of scintillating pulsars, and *hundreds* with existing data spanning years..
..This is sure to reveal some exciting and unexpected results!