Introduction to Pulsar Timing

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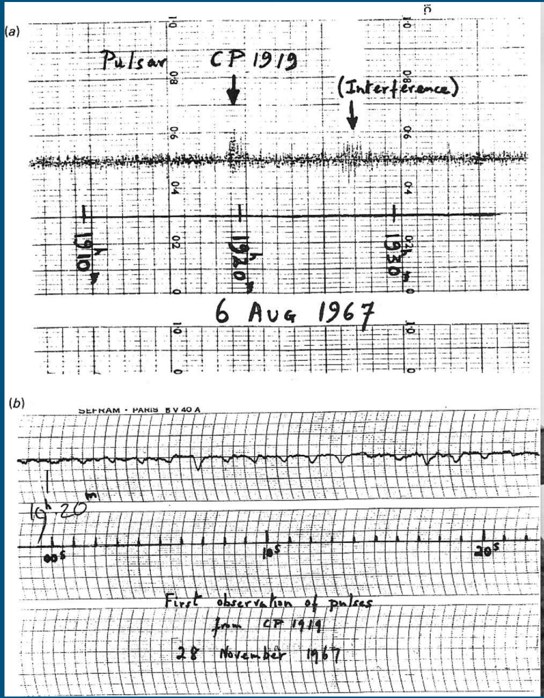
What are pulsars?



“A bit of scruff”
https://blog.csiro.au/pioneer-pulsars-pops-into-parkes/

- Pulsating sources with very stable pulse periods.
- Discovered in 1963 by Dame Jocelyn Bell-Burnell.
- Rotating neutron stars — predicted by Zwicky & Baade in 1933

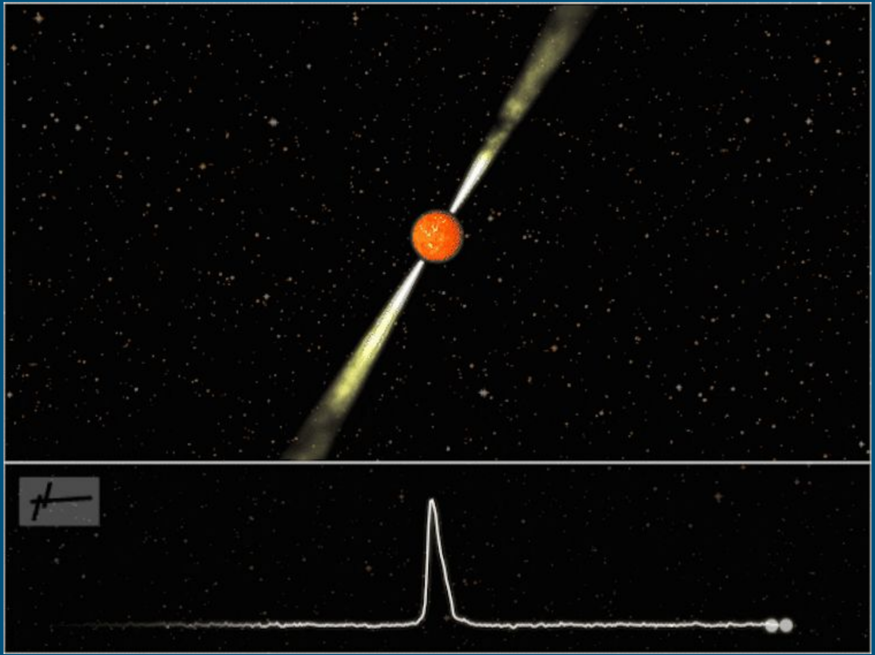
Neutron Stars

- Formed from supernova events
  - Death of a massive star (~ 10–25 $M_\odot$)
  - From accreting or merging white dwarfs (Type 1A supernova)
- Mass ~ 1.4 $M_\odot$ (Up to 3 $M_\odot$)
- Radius ~ 10 km (6 mi)
- Mostly made of neutrons — supported by neutron degeneracy pressure
  - (Probably) has a solid crust and superfluid neutrons + superconducting protons inside
  - Exact structure is unknown.
- Angular momentum conservation → Rapid rotation (Period ~ 10 s – 1 ms)
- “Magnetic flux freezing” → Large magnetic fields (B ~ 10^8–10^{14} T)

How do we know pulsars are neutron stars?

- Short pulse duration — Whatever it may be, it should be small
  - Not a “normal” star; White dwarfs or neutron stars?
- Clock-like accuracy – something massive
- Pulse period shows 1-year Doppler modulations
  - Not within the solar system
- Too many pulsars found, broadband signals ⇒ not other civilizations.
- If it’s orbital motion, it will merge very soon due to GW emission.
- Periods have too much spread (~4 orders of magnitude) — too much for oscillations
- If it’s rotation, it is too fast for a white dwarf — centrifugal force will rip it apart
- Hence, it must be a rotating neutron star.

- They don’t actually pulse! — Lighthouse effect
    - Radiation emitted from magnetic poles
    - Magnetic axis misaligned from rotational axis



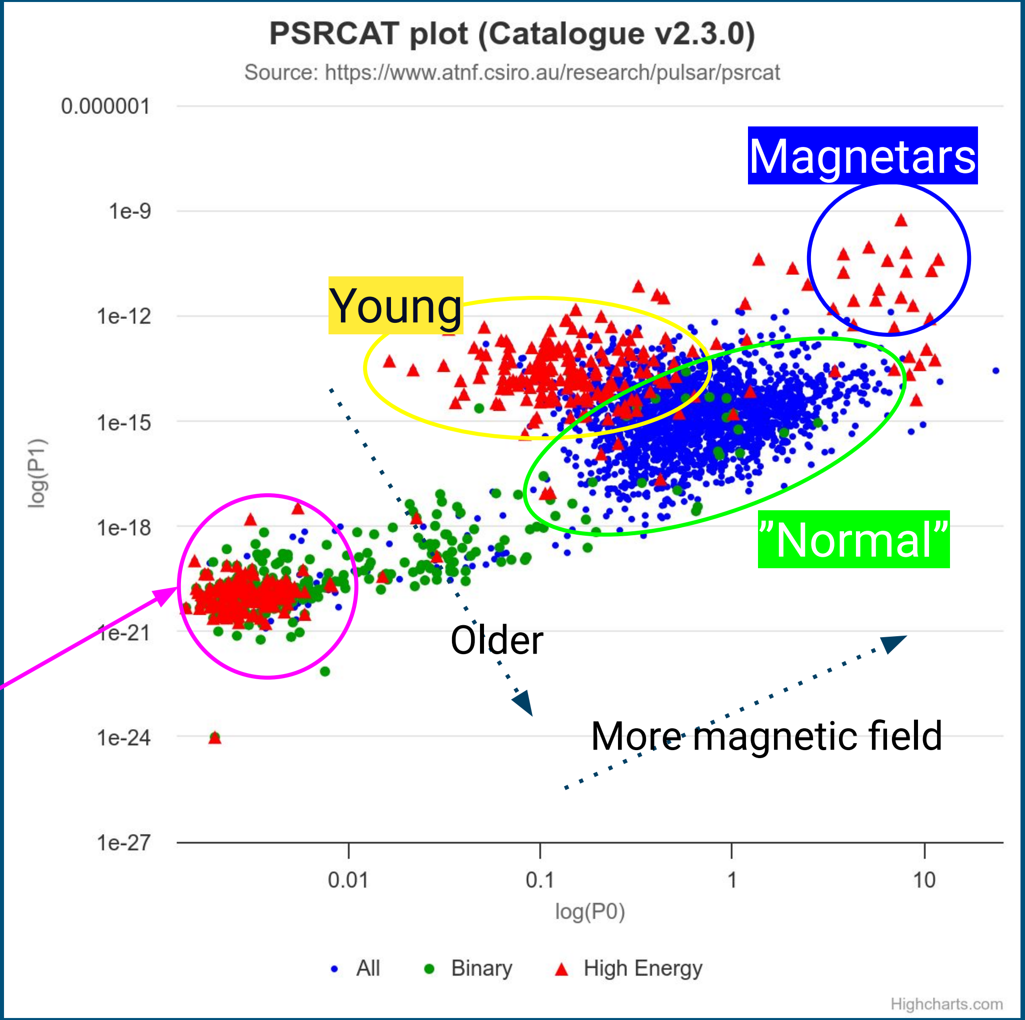
https://www.astron.nl/pulsars/animations/

Optical image of the crab pulsar

https://www.cieletespace.fr/actualites/nouveau-une-camera-ultra-sensible-pour-les-astronomes-amateurs

Where does the energy come from?

- **Rotation-powered pulsars — Rotational kinetic energy (spinning down)**
- Accretion-powered pulsars — Accretion from a companion star (spinning up)
- Magnetars — Decay of the strong magnetic field

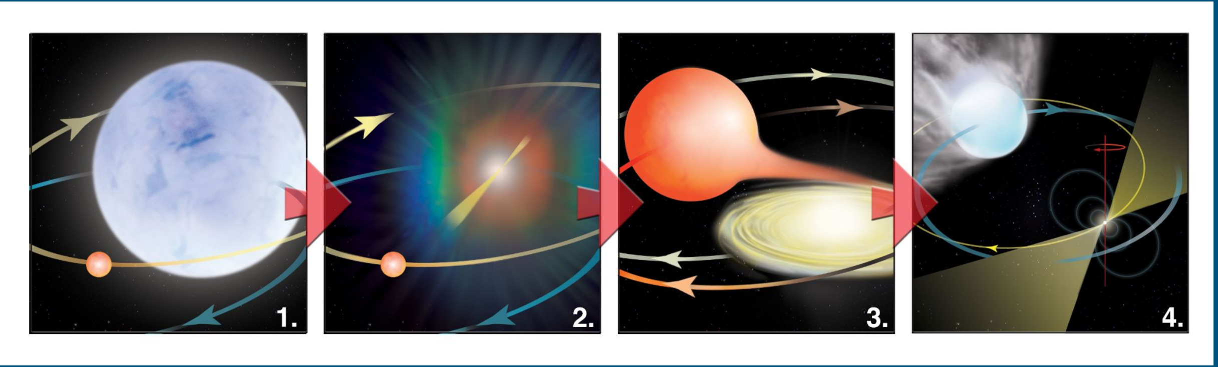


Millisecond pulsars

3600+ pulsars discovered so far.

Millisecond pulsars

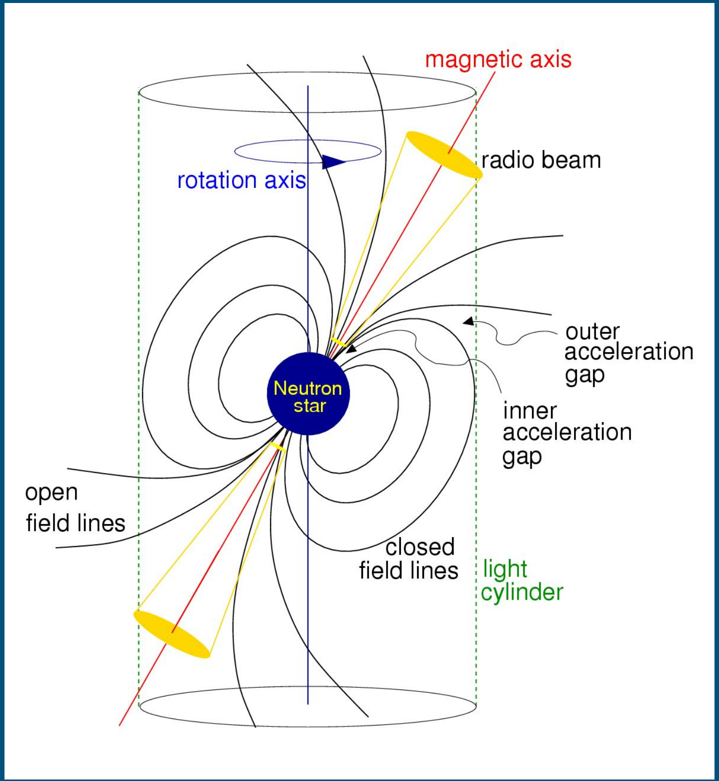
- ~ a few ms rotational period.
- Older pulsars spun up by accretion from a binary companion (“recycled”).
- Usually found in binary systems.
- More rotationally stable than slow pulsars ⇒ good clocks!



https://www.nrao.edu/pr/2006/mspulsar/mspulsar.graphics.shtml

Radio Emission mechanism

- Rotating magnetic dipole induces large electric fields – Rips electrons out of the surface
- Electrons cannot cross magnetic field lines ⇒ They travel along them “like beads on a string”
- The rotational speed equals c at the light cylinder ⇒ No co-rotation outside it
- Magnetic fields crossing the light cylinder cannot close.
- Electrons accelerated along open field lines → Curvature radiation → pair production → particle cascade to lower energies → radio emission

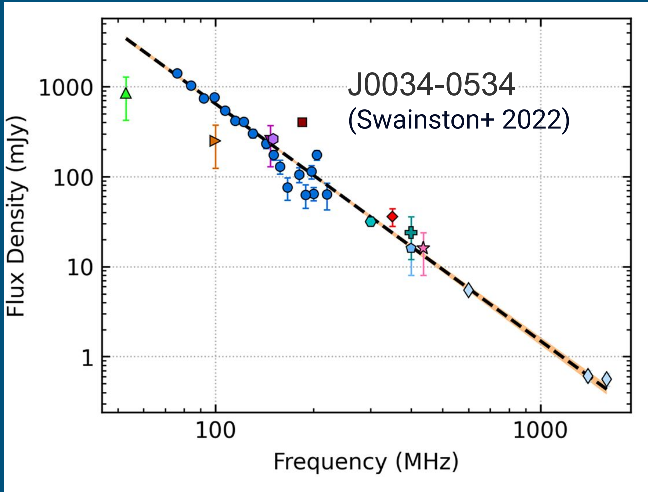


https://www.cv.nrao.edu/~sransom/web/Ch6.html

Pulsar Observations

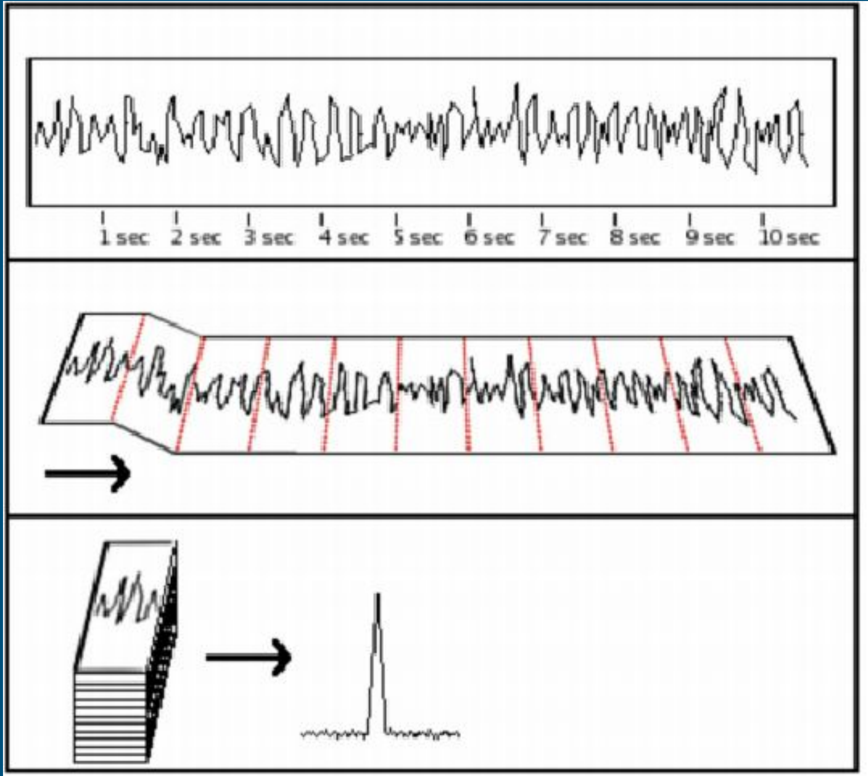
Pulsar Observations

- Most pulsars are seen in radio and gamma rays.
  - Some are seen in X rays.
  - Very few are seen in IR, Vis, or UV.
- Radio observations — ~100 MHz to several GHz
- Brighter in lower radio frequencies — Steep spectrum sources
- But lower frequencies are affected more by the interstellar medium (more on that later).
- Single pulses are too weak to see in most pulsars

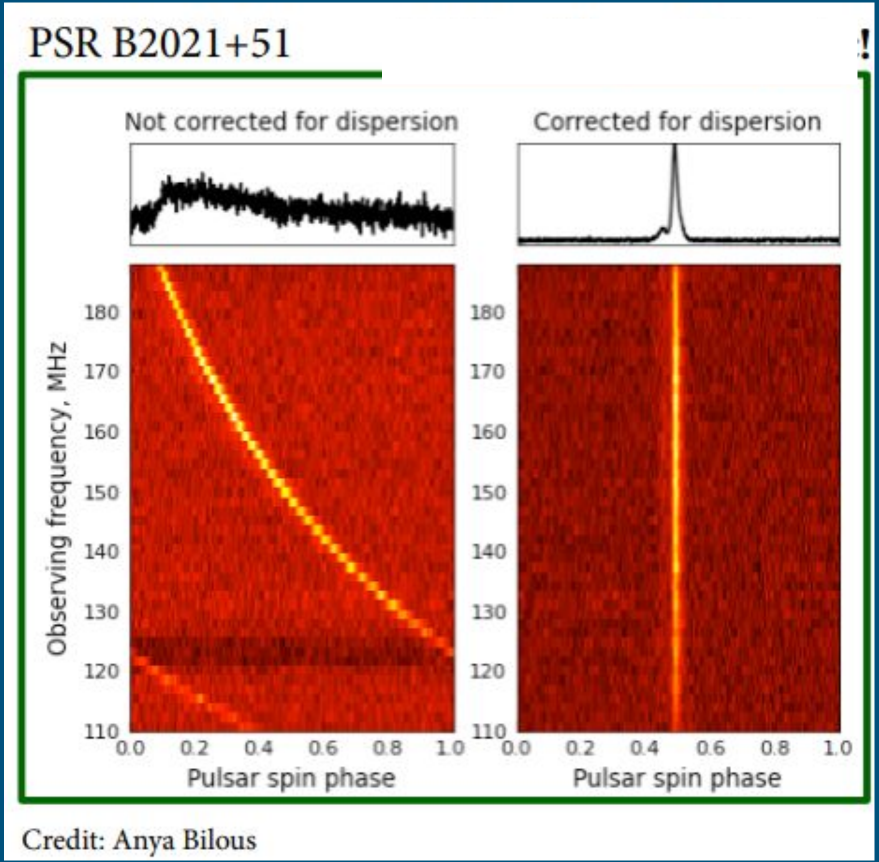


Folding

- Add multiple noisy pulses in phase.
- Signal adds coherently, but noise adds incoherently ⇒ Signal wins.
- If we add N pulses, the S/N $\propto N^{1/2}$
- Works even if we can't see individual pulses.
- A folded pulse is called an "integrated pulse profile"
- Pulse shape can vary a lot pulse-to-pulse, but the integrated pulse profile is stable.

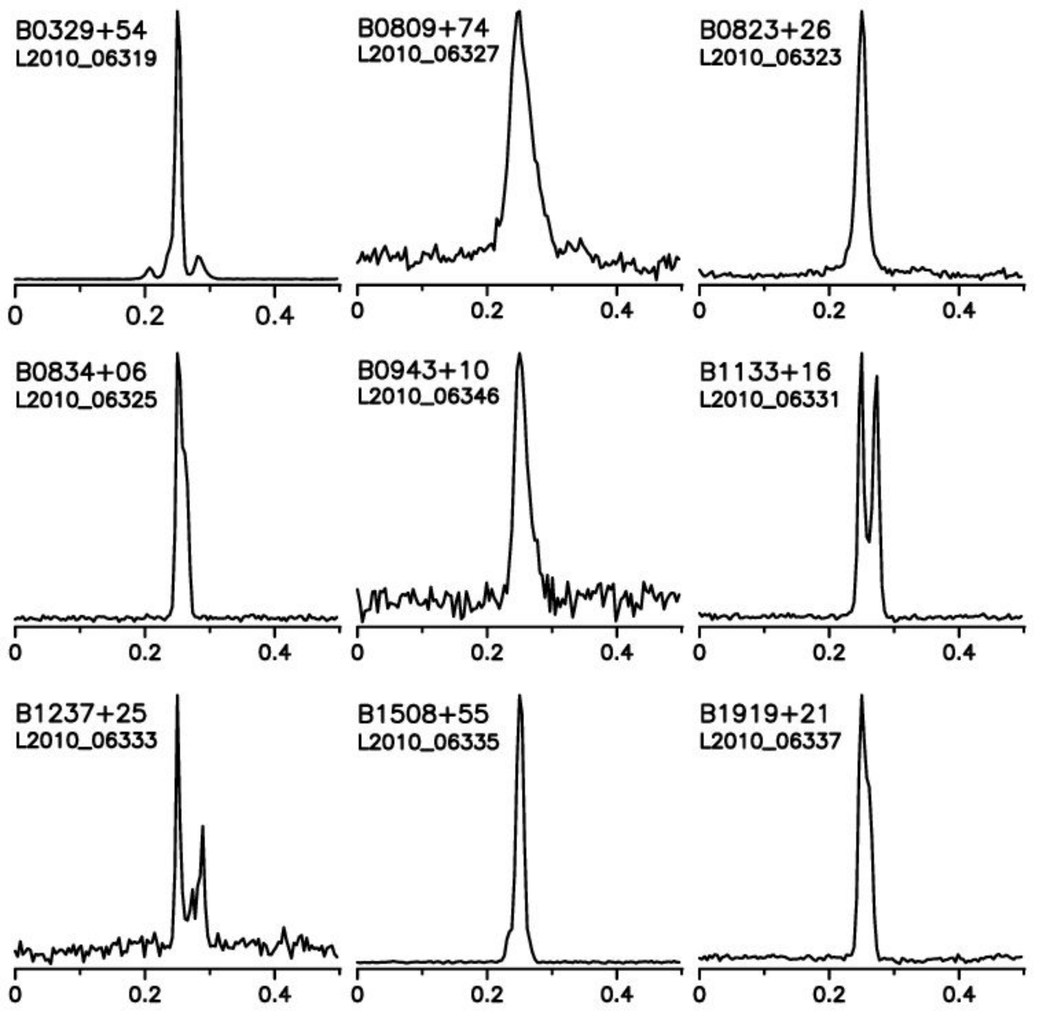


https://www.jsr.org/hs/index.php/path/article/view/1467



An integrated pulse profile as a function of phase and frequency

https://www.astron.nl/lofarschool2021/Documents/T4_Processing_beamformed_data_Pulp.pdf

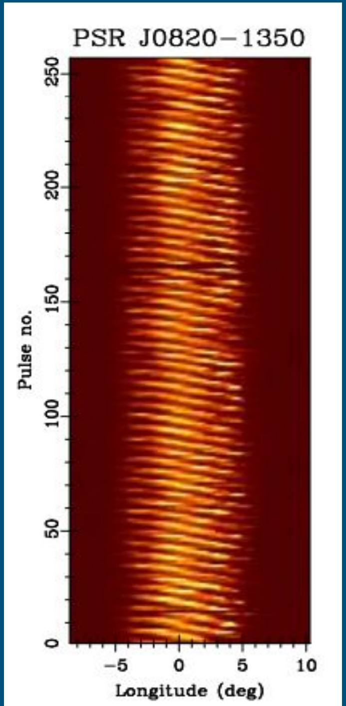


https://arxiv.org/abs/1009.1758

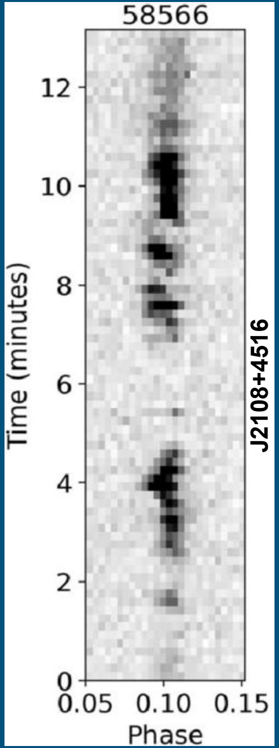
The integrated pulse profile is a pulsar’s fingerprint

… most of the time.

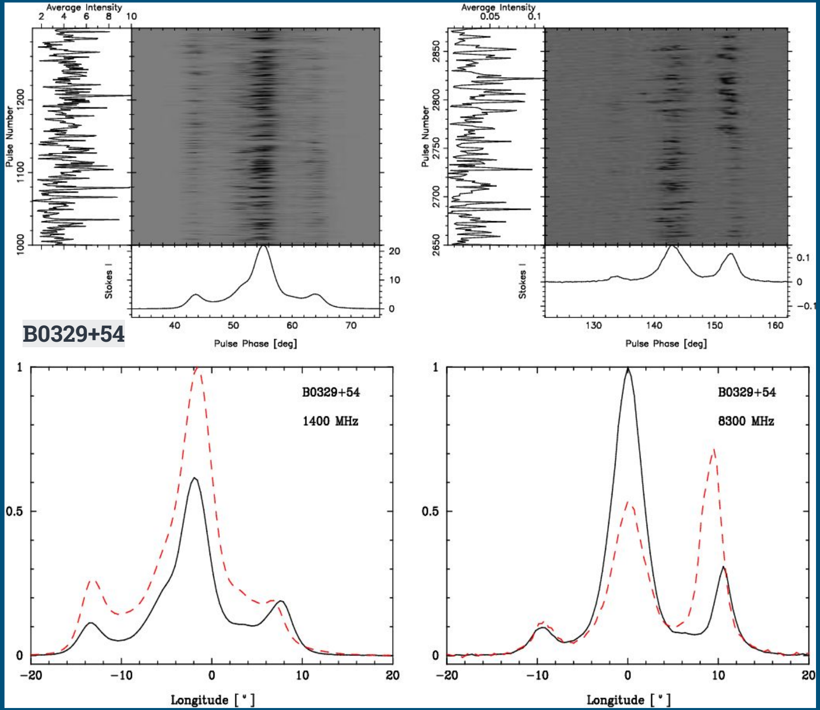
Some Phenomenology



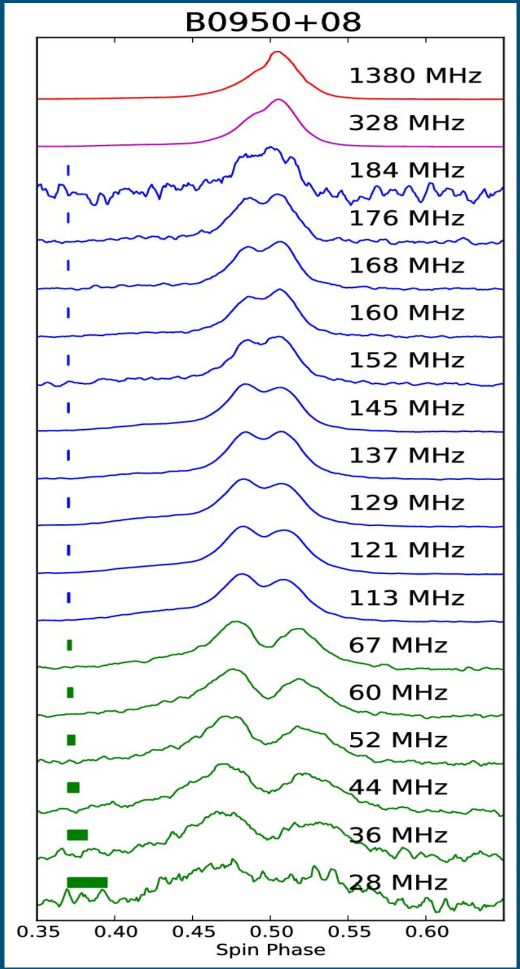
Subpulse drifting
(Basu & Mitra 2018)



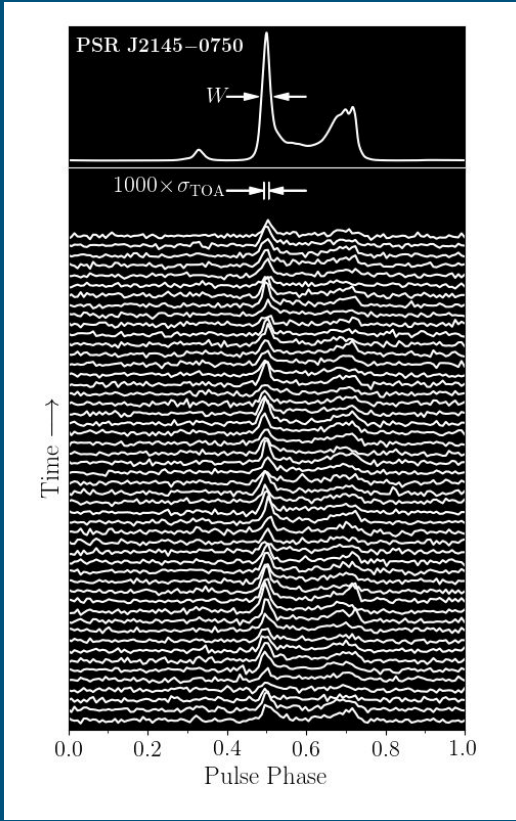
Pulse nulling
(Andersen+ 2023)



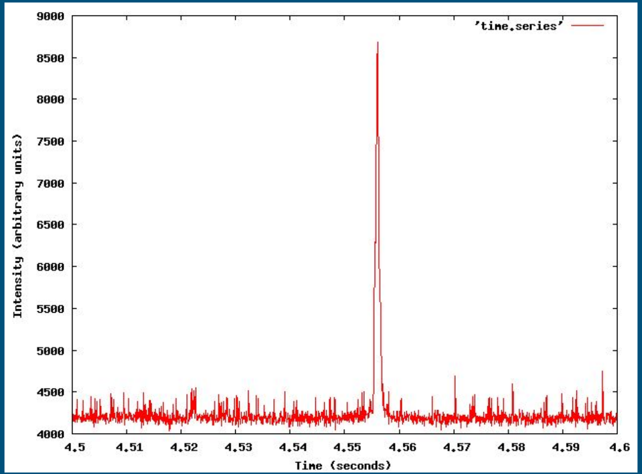
Mode changing
(Brinkman+ 2019)



Frequency-dependent profile evolution
(Pilia+ 2014)



Pulse jitter
(https://arxiv.org/abs/1810.06594)



Giant pulses
(https://safe.nrao.edu/wiki/bin/view/CICADA/WvuGiantPulse)

Some terminology

- “Subband” / “Channel” — A small portion of the observing radio frequency band
- “Sub-integration” — A portion of the total observing time
- “Phase Bin” — A bin of the rotational phase
- “Scrunch” — Reduce the number of subbands / sub-integrations / phase bins
- “Collapse” — Scrunch the profile into a single subband and a single sub-integration.
- “Total Intensity Profile” — A profile that only has intensity information.
- “Full Stokes Profile” — A profile that has both intensity and polarization information.
- “PSRFITS” — The standard file format for storing pulsar profiles (other formats are Timer, PRESTO, etc.)
- “RFI” — Radio frequency interference

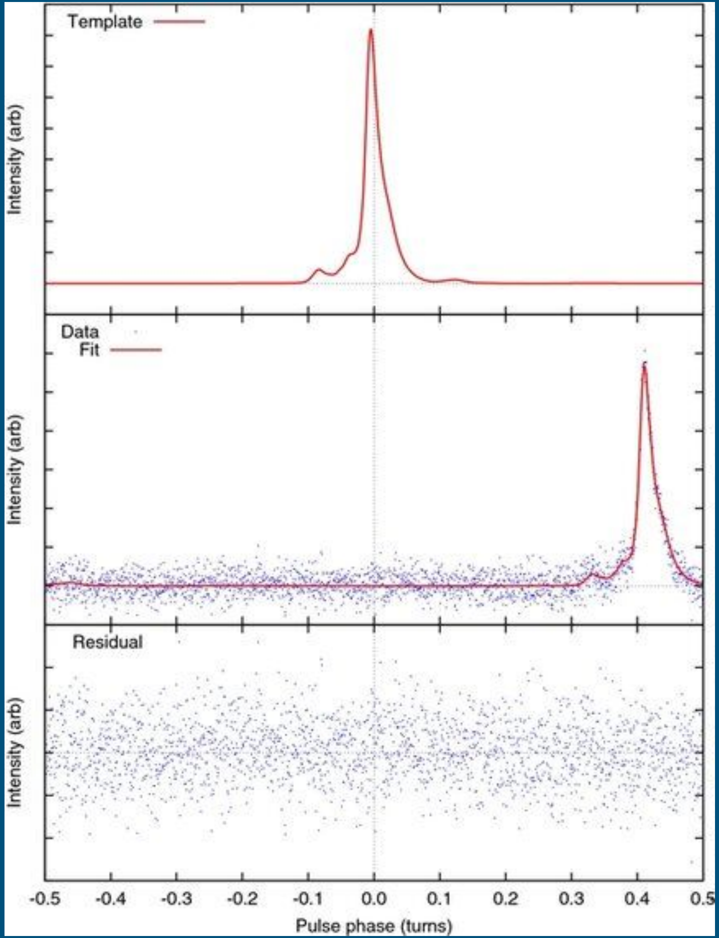
Relevant software

- sigproc — Old software for folding, pulsar searching, etc.
- PRESTO — Folding, pulsar searching, RFI mitigation, etc.
- DSPSR — Coherent dedispersion, filterbank formation, folding, etc.
- PSRCHIVE — Analysis of integrated pulse profiles.
- PyPulse — Analysis of integrated pulse profiles.
- PsrSigSim — Simulation of pulsar signals
- psrcat — The ATNF Pulsar catalogue
- psrqpy — Python interface for psrcat
- PSRPOPPy — Pulsar population synthesis
- nanopipe, CoastGuard, MeerPipe, pinta, … — Pulsar data reduction pipelines for specific telescopes and experiments

…………

Pulsar Timing

- Pulsar timing is the technique of tracking a pulsar's rotation using the **times of arrival (TOAs)** of its pulses
- We measure TOAs by comparing the measured profiles against a template profile.
- Usually done in the Fourier domain.
- Narrowband timing — measure TOAs in each subband
- Wideband timing — Measure a single TOA from the entire band using a 2D template.



(Lommen & Demorest 2013)

```
C Updated by replace_toas.py on Thu Jan 22 16:01:44 2015
C Converted by make_release.py on Tue Jun 17 16:36:57 2014 by pdemores
MODE 1
FORMAT 1
53358.000056.3.000.000.9y.x.ff 424.000000 53358.767912764015642   1.277  ao  -fe 430 -be ASP
-f 430_ASP -bw 4 -tobs 903.18 -tmplt B1855+09.430.PUPPI.9y.x.sum.sm -gof 1.09 -nbin 2048
-nch 1 -chan 1 -subint 0 -snr 142.71 -wt 15 -proc 9y -pta NANOGrav -to -0.789e-6
53358.000056.3.000.000.9y.x.ff 428.000000 53358.767912759999400   0.858  ao  -fe 430 -be ASP
-f 430_ASP -bw 4 -tobs 903.18 -tmplt B1855+09.430.PUPPI.9y.x.sum.sm -gof 1.13 -nbin 2048
-nch 1 -chan 2 -subint 0 -snr 207.92 -wt 15 -proc 9y -pta NANOGrav -to -0.789e-6
53358.000056.3.000.000.9y.x.ff 432.000000 53358.767912757814541   0.897  ao  -fe 430 -be ASP
-f 430_ASP -bw 4 -tobs 903.18 -tmplt B1855+09.430.PUPPI.9y.x.sum.sm -gof 1.16 -nbin 2048
-nch 1 -chan 3 -subint 0 -snr 200.42 -wt 15 -proc 9y -pta NANOGrav -to -0.789e-6
53358.000056.3.000.000.9y.x.ff 436.000000 53358.767912757364087   0.812  ao  -fe 430 -be ASP
-f 430_ASP -bw 4 -tobs 903.18 -tmplt B1855+09.430.PUPPI.9y.x.sum.sm -gof 0.981 -nbin 2048
-nch 1 -chan 4 -subint 0 -snr 225.19 -wt 15 -proc 9y -pta NANOGrav -to -0.789e-6
53358.000056.3.000.000.9y.x.ff 440.000000 53358.767912758637828   1.083  ao  -fe 430 -be ASP
-f 430_ASP -bw 4 -tobs 903.18 -tmplt B1855+09.430.PUPPI.9y.x.sum.sm -gof 1.13 -nbin 2048
-nch 1 -chan 5 -subint 0 -snr 166.03 -wt 15 -proc 9y -pta NANOGrav -to -0.789e-6
.
:
:
```

- TOAs are usually stored as “tim” files.

TEMPO2 format

```
FORMAT 1
53358.000056.3.000.000.9y.x.ff 424.000000 53358.767912764015642   1.277  ao  -fe 430 -be ASP
-f 430_ASP -bw 4 -tobs 903.18 -tmplt B1855+09.430.PUPPI.9y.x.sum.sm -gof 1.09 -nbin 2048
-nch 1 -chan 1 -subint 0 -snr 142.71 -wt 15 -proc 9y -pta NANOGrav -to -0.789e-6
```

Name of the profile file

Observing frequency

TOA Measurement

TOA uncertainty

Telescope

Flags (more info about observation & prodessing)

- We can use pulsars as clocks by timing them.
    - Not quite as good as the best atomic clocks, but still pretty good.
- To do this, we must model ALL the processes affecting the TOAs.
    - Some are deterministic, some are stochastic.
    - Some are astrophysical, some are instrumental.
    - This is called a timing (& noise) model.

Things that affect the measured TOAs

- Pulsar rotation and rotational irregularities
- Pulsar binary motion
- Interstellar dispersion
- Interstellar scattering
- Gravitational waves
- Solar system dynamics
- Solar wind
- Earth's troposphere
- Earth's rotation
- Signal propagation delays at the observatory
- Observatory clock
- Radiometer noise
- Pulse jitter
- Frequency-dependent profile evolution
- Mode changes
- …….

The Timing Model

Arrival time

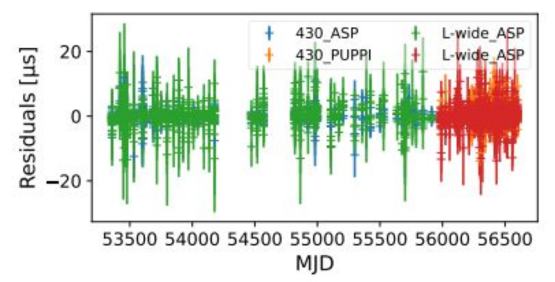
$$t_{em} = t_{arr} - \Delta_{clock} - \Delta_{SS} - \Delta_{DM} - \Delta_{B} - \Delta_{GW} - \ldots$$

Rotational phase

$$\phi = \phi_0 + F_0(t_{em} - t_0) + \tfrac{1}{2} F_1(t_{em} - t_0) + \ldots$$

Timing residual: **Observed TOA – Predicted TOA**

$$R = (\phi - N[\phi]) / F$$



B1855+09 (Susobhanan+ 2024)

```
PSR                              B1855+09
EPHEM                               DE421
CLK                          TT(BIPM2019)
UNITS                                 TDB
START                53358.727464829469664
FINISH               56598.871995360779606
INFO                                   -f
TIMEEPH                              FB90
DILATEFREQ                              N
DMDATA                                  N
NTOA                                 4005
CHI2                     3937.220640314035
CHI2R                   0.9937457446527095
TRES                 1.1777815379478908387
LAMBDA               286.863489323[illegible]774 1 0.00000001657953284211
BETA                  32.3214877320705[illegible] 1 0.00000002779903880471
PMLAMBDA              -3.2840650020131[illegible] 1 0.01376025362828431
PMBETA                -5.0668952989490[illegible] 1 0.02865604158640752
PX                     0.5790630771865302 1 0.16679442127718846
ECL                              IERS2003
POSEPOCH             54978.0000000000000000
F0                   186.49408127078641617 1 4.873395846479998781e-13
F1              -6.204449052502248315e-16 1 5.5047510586676844085e-21
F2              -3.585109440420168386e-28 1 1.9754604252581479131e-28
F3                                    0.0
PEPOCH               54978.0000000000000000
CORRECT_TROPOSPHERE                        N
PLANET_SHAPIRO                          N
SOLARN0                               0.0
SWM                                     0
DM                   13.316795424119637609 1 0.0035083995045182628236
DM1              0.00036027629492739770147 1 6.150894144672941194e-06
DM2              -8.2217228765829223776e-06 1 6.3115302370453797275e-05
DM3                                   0.0
DMEPOCH              54978.0000000000000000
BINARY                                 DD
PB                   12.327171191320784791 1 2.011299228313052724e-10
PBDOT                -5.203711571846227e-13 1 6.356825345079494e-13
A1                        9.230780614051401 1 6.754900583254921e-08
A1DOT                                 0.0
E                    2.1625774704251383e-05 1 1.4004524732604183e-08
EDOT                                  0.0
T0                   54975.5106592406134531 1 0.0016832371001023985636
OM                   276.47166849152344564 1 0.04915697274758697166
OMDOT                                 0.0
M2                      0.22662716528794766 0 0.008426744726114163
SINI                    0.9995500705086225 0 0.00012734672840277543
A0                                    0.0
B0                                    0.0
GAMMA                                 0.0
DR                                    0.0
DTH                                   0.0
FD1                  0.00016729910260593694 1 3.371501586428578e-05
FD2                 -0.00019513142148630134 1 4.113497231845879e-05
```

Parameter name

Parameter value

1 = Fit this parameter
0 = Don’t fit
Optional: Default is 0

Measured uncertainty
(Optional)

Timing models are stored as “par” files.

Fitting a timing model to TOAs

- Weighted least-squares fitting: When there is no correlated noise

$$\chi^2 = \sum_i \left(\frac{r_i}{\sigma_i}\right)^2 = \boldsymbol{r}^T \boldsymbol{N}^{-1} \boldsymbol{r}$$

Scaled TOA uncertainties

- Generalized least-squares fitting: When correlated noise is present

$$\chi^2 = \boldsymbol{r}^T \boldsymbol{C}^{-1} \boldsymbol{r}$$

$$\boldsymbol{C} = \boldsymbol{N} + \boldsymbol{U}^T \boldsymbol{\Phi} \boldsymbol{U}$$

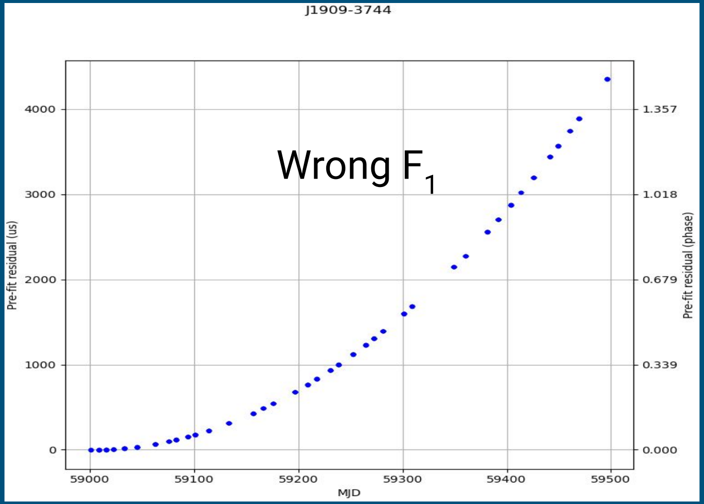
Reduced rank approximation

Now let’s understand the timing model components one-by-one

Pulsar rotation

- The pulsar is spinning down because it is converting its rotational kinetic energy into electromagnetic radiation
  - … and gravitational radiation?

$$\Phi = \Phi_0 + F_0(t_{em} - t_0) + ½\, F_1(t_{em} - t_0) + \ldots$$

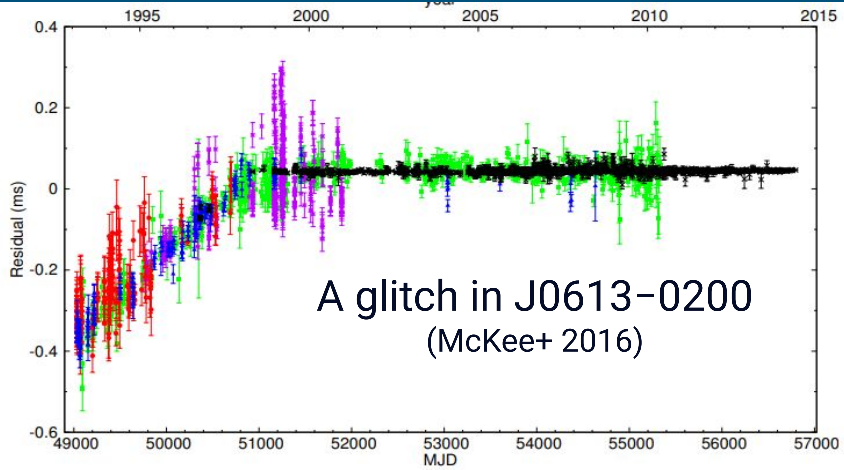


Glitches

- Sometimes a pulsar abruptly changes its rotational frequency.

$$\Phi = \Phi_0 + F_0(t_{em} - t_0) + \frac{1}{2} F_1(t_{em} - t_0) + \ldots + \Phi_{glitch}$$

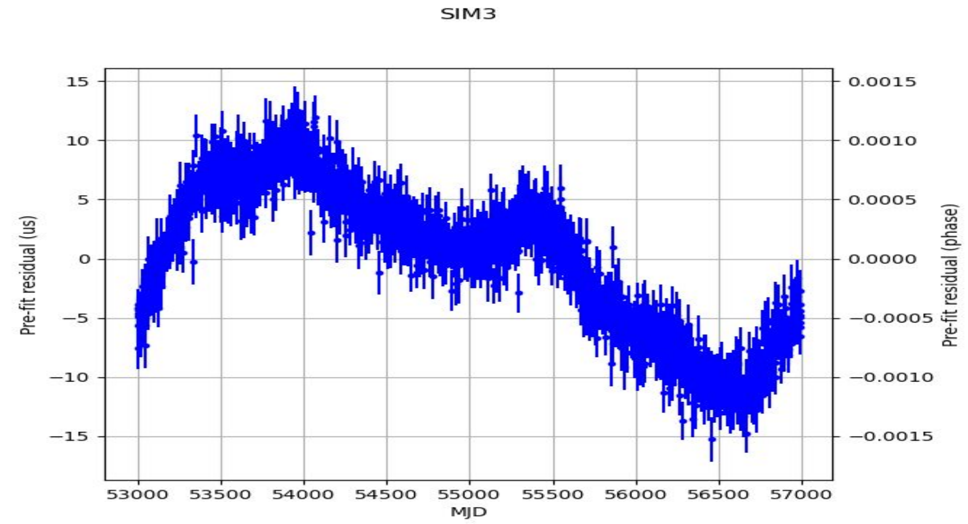
- Rare in millisecond pulsars



A glitch in J0613−0200
(McKee+ 2016)

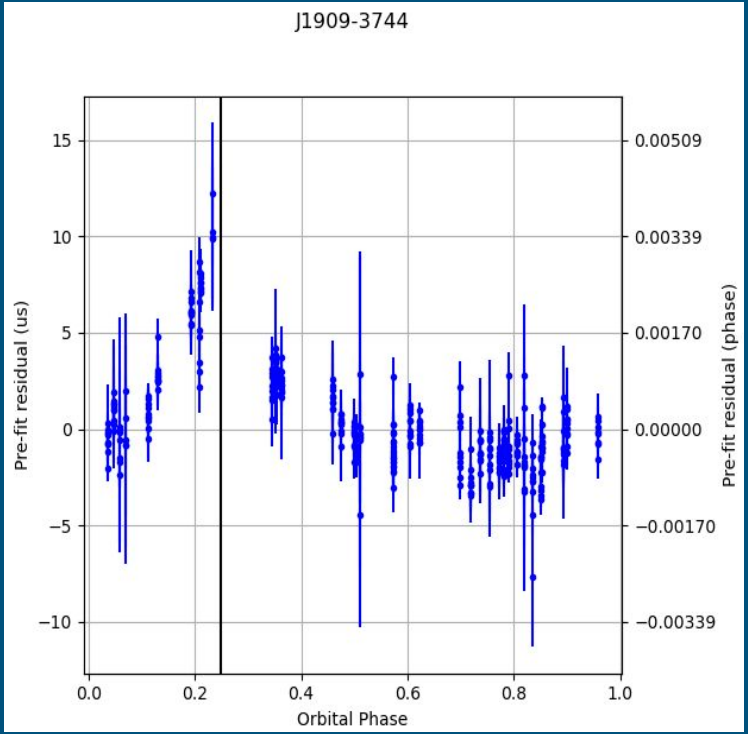
Spin noise (Achromatic red noise)

- Slow stochastic wandering of the spin frequency.
- Usually modeled as a Gaussian process with a power law spectrum.

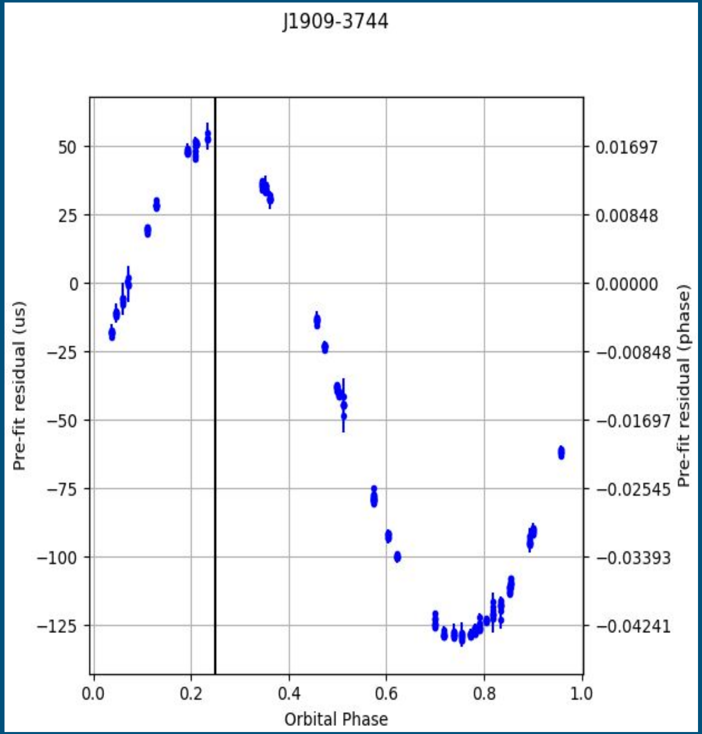


Pulsar binary motion

- Three effects
  - Rømer delay — Geometric delay due to the changing position of the pulsar.
  - Shapiro delay — Due to the spacetime curvature induced by the binary companion
  - Einstein delay — Time dilation due to motion (special relativity) and gravitational field (general relativity)
- Different types of binaries need different binary models
  - DD — Relativistic binary with significant eccentricity
  - ELL1 — Binary with small eccentricity
  - …



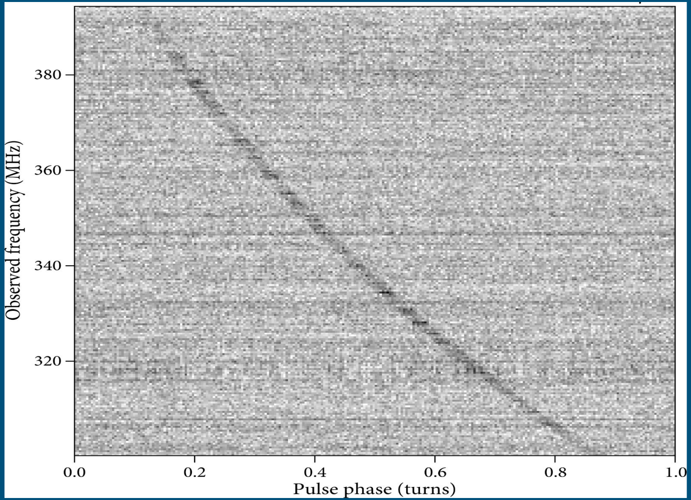
Unmodeled binary Shapiro delay



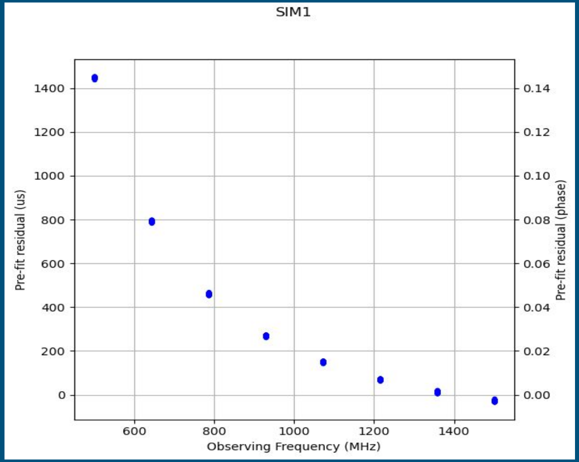
Wrong projected semi-major axis

Interstellar dispersion

- The free electrons in the ISM disperses radio waves.
- Refractive index of the ionized ISM $\propto n_e \nu^{-2}$
- Electron column density along the line of sight is called the dispersion measure (DM)
- Higher frequency signals reach faster than lower frequency signals.

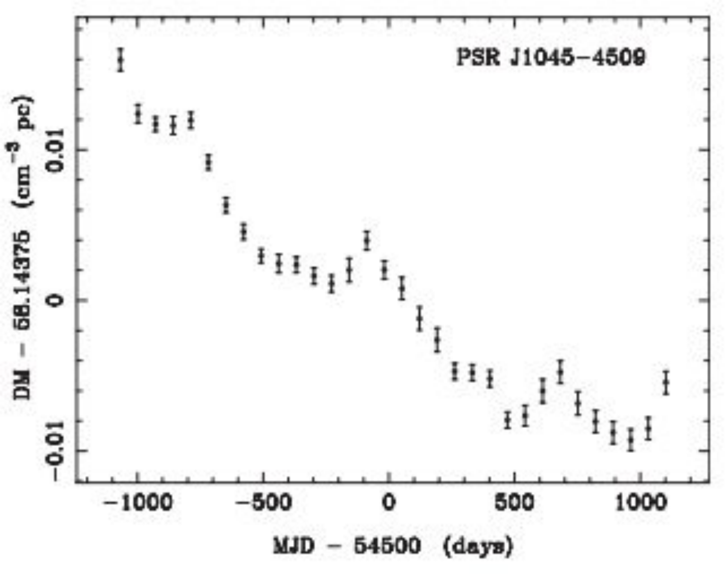


https://www.cv.nrao.edu/~sransom/web/Ch6.html



Interstellar dispersion variations

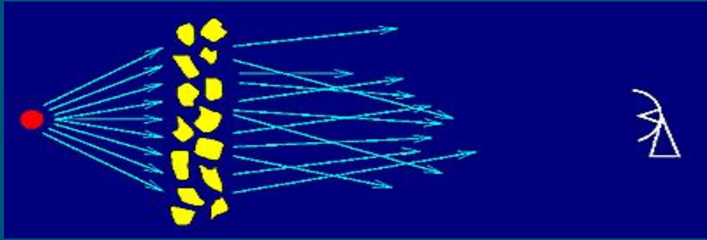
- Electron density in the ISM varies with both time and position.
- The pulsar and the Earth are in relative motion with each other.
- The line of sight passes through different parts of the ISM at different times.
- The DM is not a constant in time — stochastic variations.
- Usually modeled as a piecewise-constant function (DMX) or as a Gaussian process (DMGP).



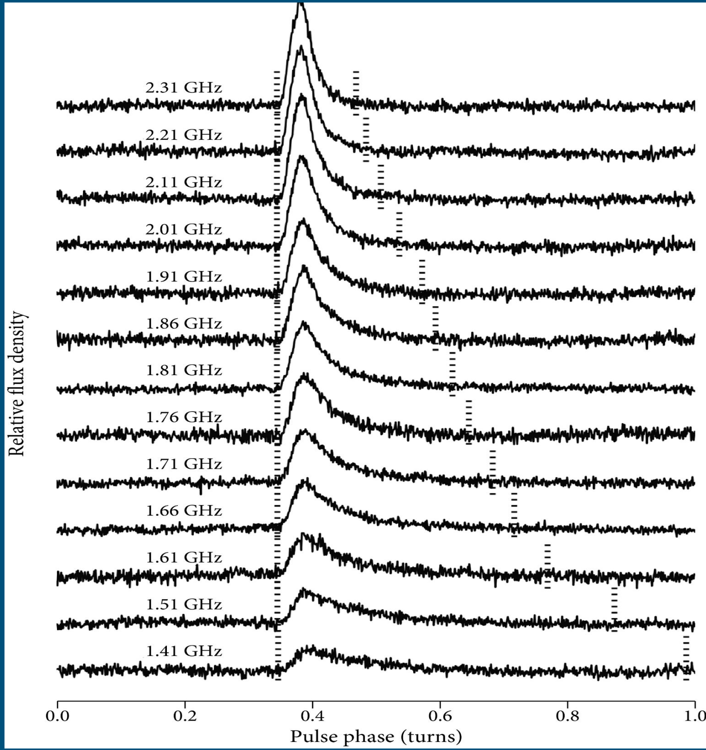
(Manchester+ 2012)

Interstellar scattering

- Inhomogeneities in the ISM causes multi-path propagation of the pulsar signal.
- The same pulse will reach us at different times through different paths.
- This smears out the pulse shape
- The smearing is more at lower frequencies.
- This also varies with time.
- The effect of scattering is modeled as a stochastic process with a $\nu^{-\alpha}$ dependence.
  - Not the best model



https://www.jb.man.ac.uk/distance/frontiers/pulsars/section6.html



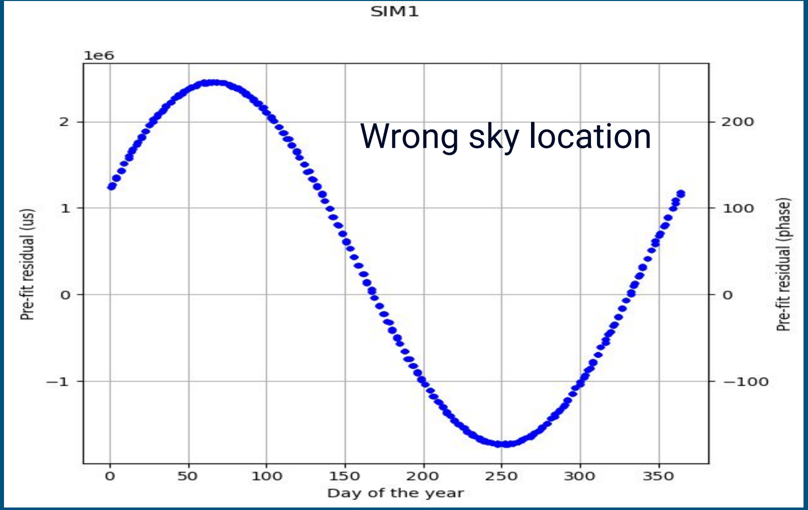
https://www.cv.nrao.edu/~sransom/web/Ch6.html

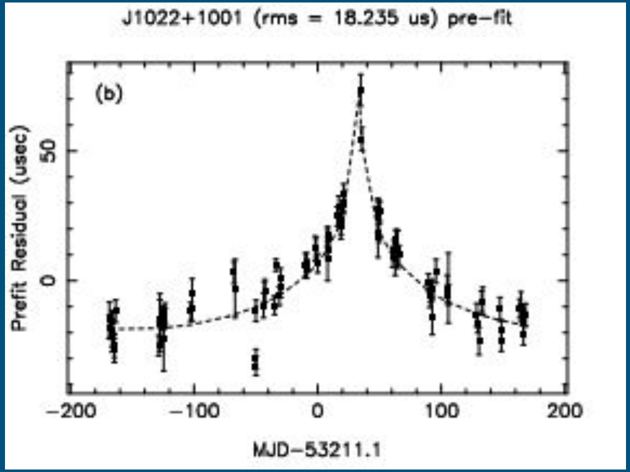
Gravitational waves

Steve's lecture after this

Solar system dynamics

- Like the pulsar binary system, the solar system also introduces Roemer, Shapiro, and Einstein delays.
- We know the position of the solar system objects from the solar system ephemerides published by space agencies
- These delays also depend on the sky location of the pulsar.





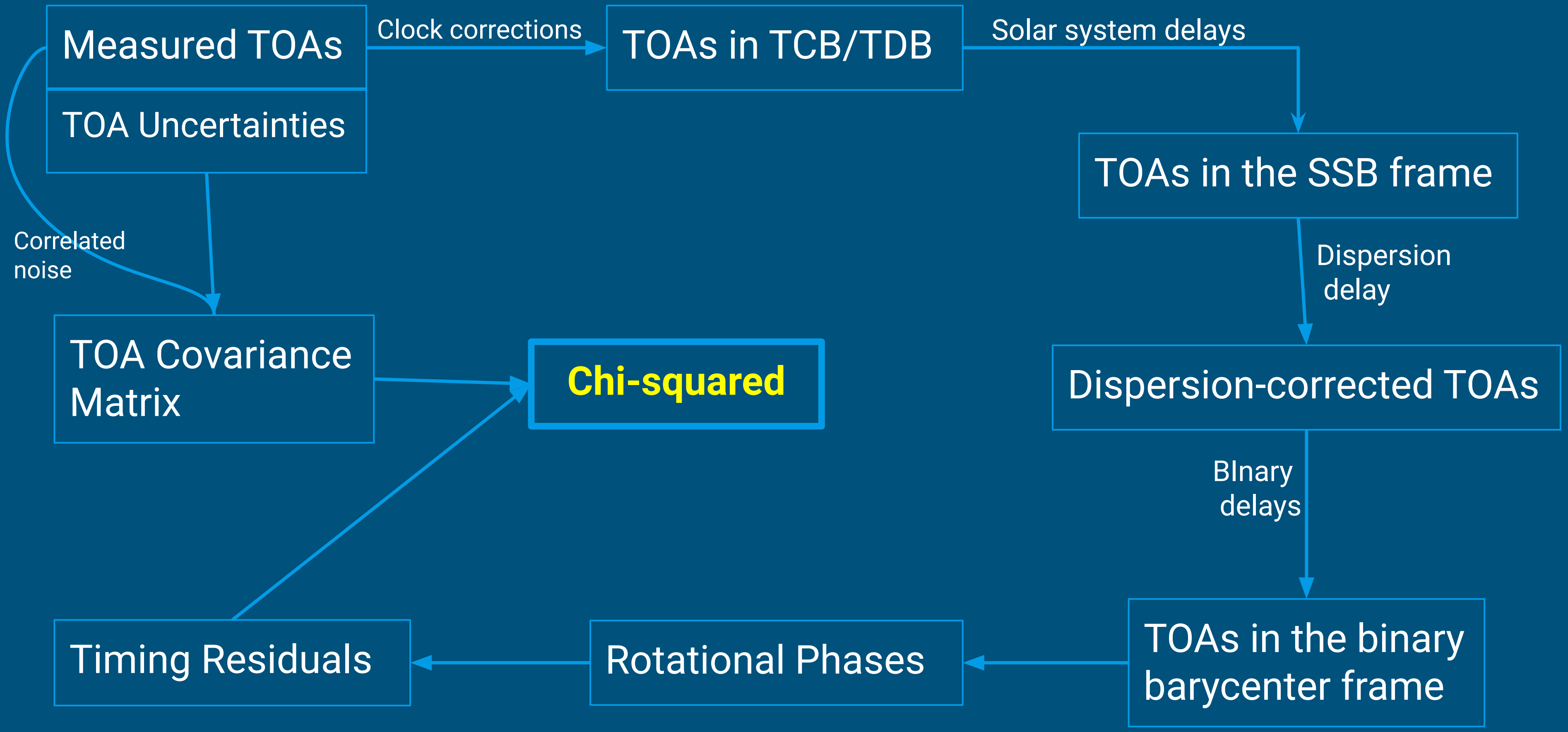
Unmodeled Solar system Shapiro delay
(Hobbs+ 2006)

Clock corrections

- The TOAs are measured against the observatory clock.
- These clocks have good short-term stability, but long-term stability is poor.
- We must transform them to an international timescale before doing any computations.
- Clock corrections are measured by comparing two clocks. E.g., observatory clock vs GPS clock.
- Ultimately, we transform the TOAs to the Barycentric Coordinate Time (TCB) or the Barycentric Dynamic Time (TDB).

Radiometer noise

- Instrumental noise of the telescope
- Represented by the TOA measurement uncertainties σ_i
- Uncorrelated
- Usually assumed to be Gaussian.


Measured TOAs
TOA Uncertainties
Clock corrections
TOAs in TCB/TDB
Solar system delays
TOAs in the SSB frame
Dispersion delay
Dispersion-corrected TOAs
BInary delays
TOAs in the binary barycenter frame
Rotational Phases
Timing Residuals
Chi-squared
TOA Covariance Matrix
Correlated noise

Pulsar timing packages

- TOA Generation — PSRCHIVE, PulsePortraiture, …
- Frequentist timing — tempo, tempo2, libstempo, PINT
- Bayesian timing / noise analysis — TEMPONEST, ENTERPRISE, …
- PTA-specific timing pipelines — pint_pal, …

Pulsar Timing with PINT

PINT 101

- Python package for pulsar timing
- Built using numpy, scipy, and astropy
- Can be used in different ways
  - GUI
  - Command line
  - Jupyter notebooks
  - Python scripts / pipelines

- TOAs (.tim)
- Initial timing model (.par)
- Solar System Ephemeris
- Clock Corrections

PINT

- Timing residuals
- Updated timing model

PINT Demo