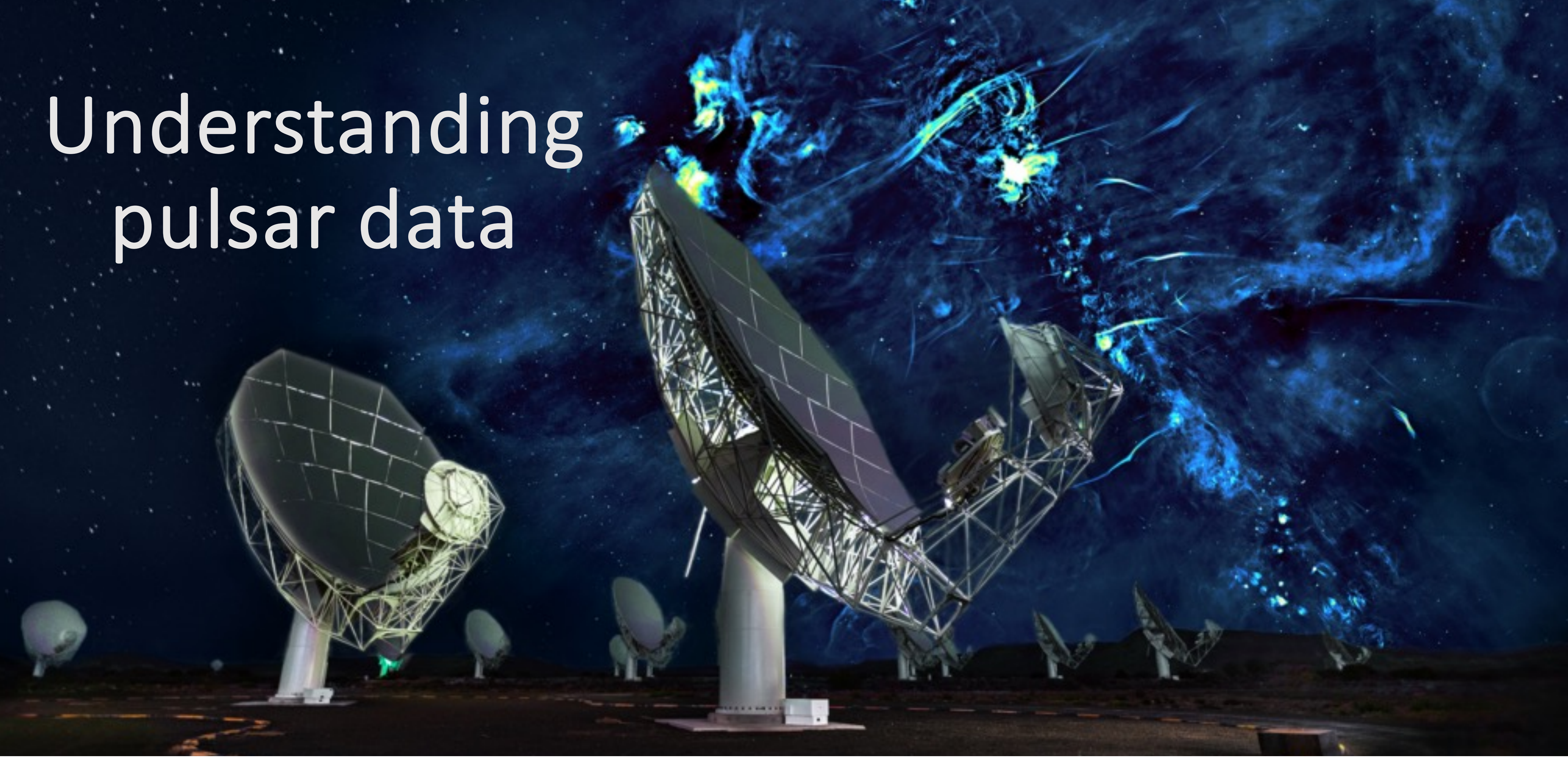


Understanding pulsar data

Daniel Reardon (Swinburne/OzGrav)

Many slides from Ryan Shannon and James McKee

About me

- Postdoctoral researcher at Swinburne University
  - Precision pulsar timing
  - Searching for gravitational waves
  - Studying the ionised interstellar medium
- I like to run and ride bikes fast and far
  - Ironman triathlons
  - Ultra marathons
- Also known for getting magnets stuck in my nose
  - Neodynium magnets
  - ~0.6 T magnetic field strength!

Astrophysicist gets magnets stuck u
nose while inventing coronavirus de

Australian Dr Daniel Reardon ended up in hospital after inserting magnets in his nostrils while building a necklace that warns you when you touch your face

- **Sign up for Guardian Australia's daily coronavirus email**
- **Follow Australia coronavirus live news and updates**
- **Follow live global coronavirus updates**

▲ Astrophysicist Daniel Reardon was playing around with powerful neodymium magnets while trying t
coronavirus safety device and managed to get them stuck in his nose. Photograph: Supplied by Daniel

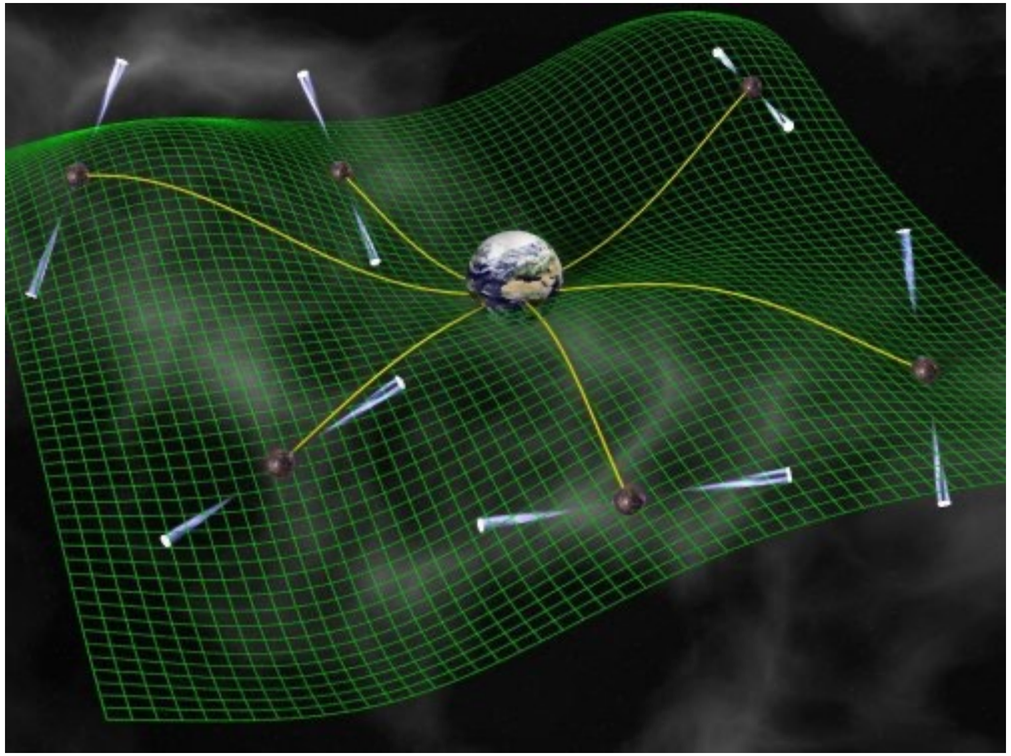
Motivation

- Pulsars enable tests of physics
  - Gravitational waves
  - General relativity
  - Matter at extreme density
  - Interstellar plasma, neutron star interior and magnetosphere, solar system and solar wind, stellar astrophysics

- We want to do the bests tests possible
  - Need the best telescopes
  - Need the best instrumentation
  - Need the best data sets and tools to analyse them

- Q: What does the data actually look like?

Schematic representation of Pulsar Timing Array



Credit: David Champion

Telescope -> Receiver -> Backend -> Pulse profiles -> Time-tagging -> Timing residuals -> Physics

Telescopes

- **Pulsars are faint**
- Large size = large sensitivity
- Historically: Large aperture single-dish telescopes
  - Don't need angular resolution
- Now: Interferometers
  - MeerKAT/LOFAR/VLA/SKA
- Sites chosen for low radio-frequency inference
- Works at observing frequencies of choice


MeerKAT, South Africa


Parkes/Murriyang, Australia

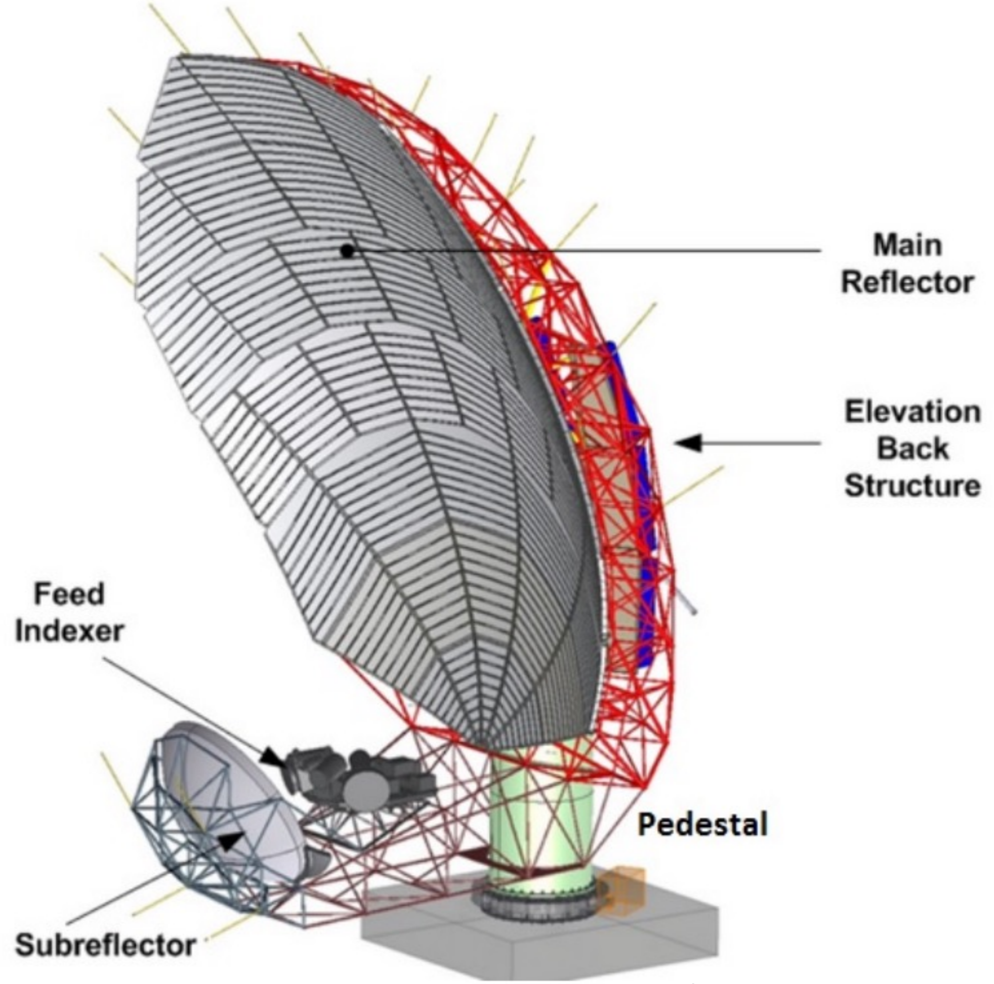

FAST, China

Receivers

- "Frontend" – turns radio waves into electricity (voltages)

- **Choosing observing frequencies**
  - Pulsars are brighter at lower frequency
  - The sky background is brighter at low frequency
  - The ionized gas in the interstellar medium affects low frequencies.
  - Precision pulsar timing done between 600 MHz - 3 GHz (50 cm - 10 cm)

- **System temperature**
  - Adds randomness, "noise", to the data
  - The lower the better
  - Can't build expensive cooling systems for large arrays



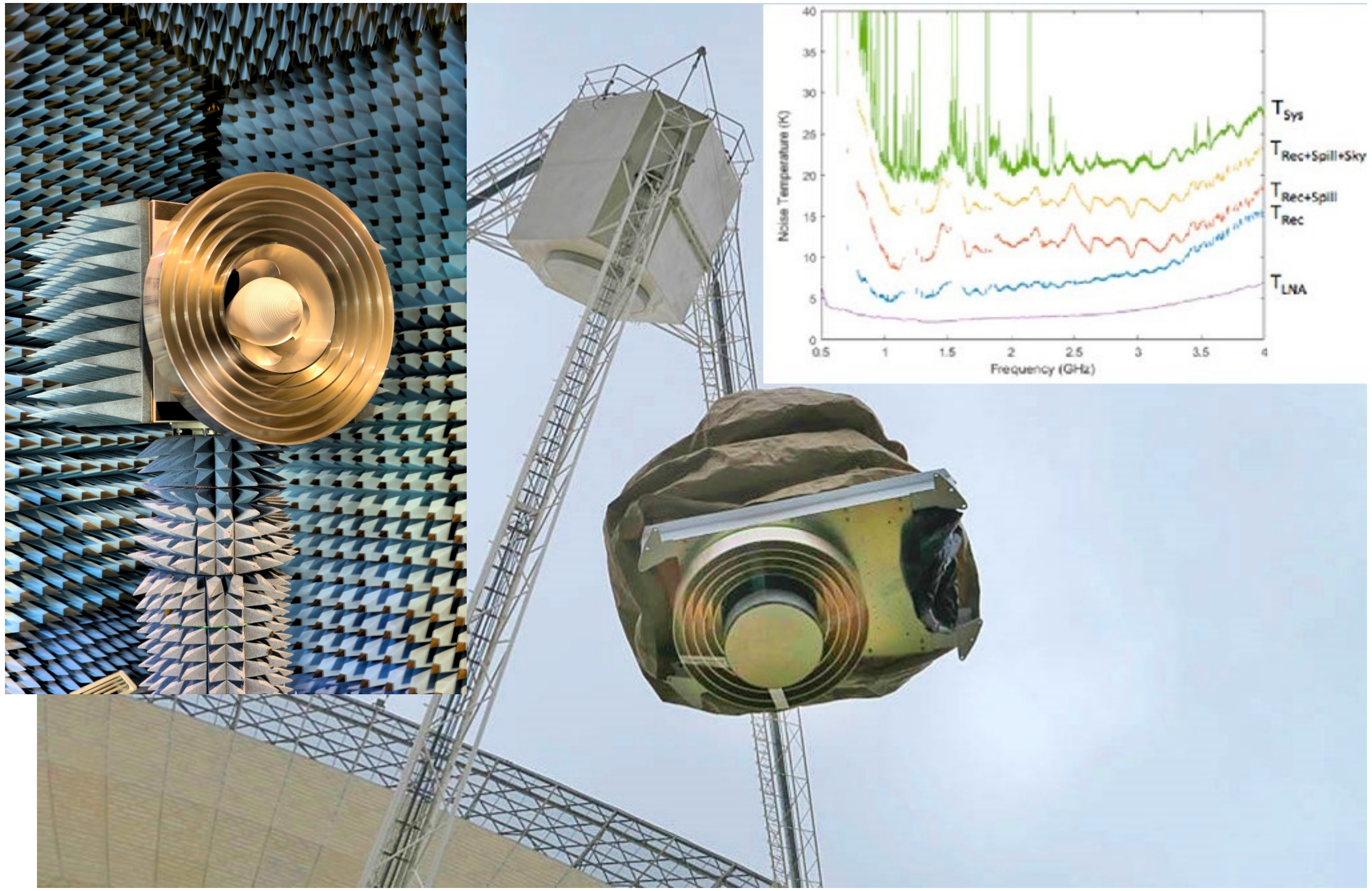
Credit: Jonas et al. 2016

$$\boxed{\Delta S_{\rm sys} = \frac{T_{\rm sys}}{\sqrt{n_{\rm p} t_{\rm obs} \Delta f}}}$$

$T_{\rm sys}$ = system temperature (20 K)
$n_{\rm p}$ = number of polarisations (2)
$t_{\rm obs}$ = integration time (1 hour)
Δf = bandwidth (500 MHz)

Receivers

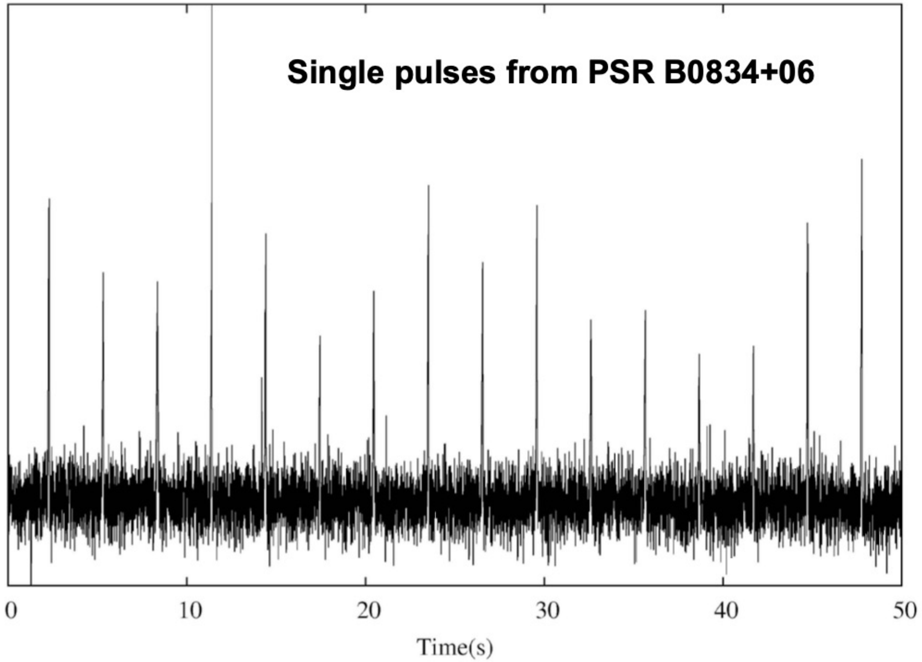
- **Bandwidth**
  - Range of radio frequencies
  - MeerKAT:
    - UHF: 544 MHz - 1088 MHz
    - L-band: 856 MHz - 1712 MHz
    - S-band: 1750 – 3500 MHz
- **Polarization**
  - Detect both polarization bases of the field

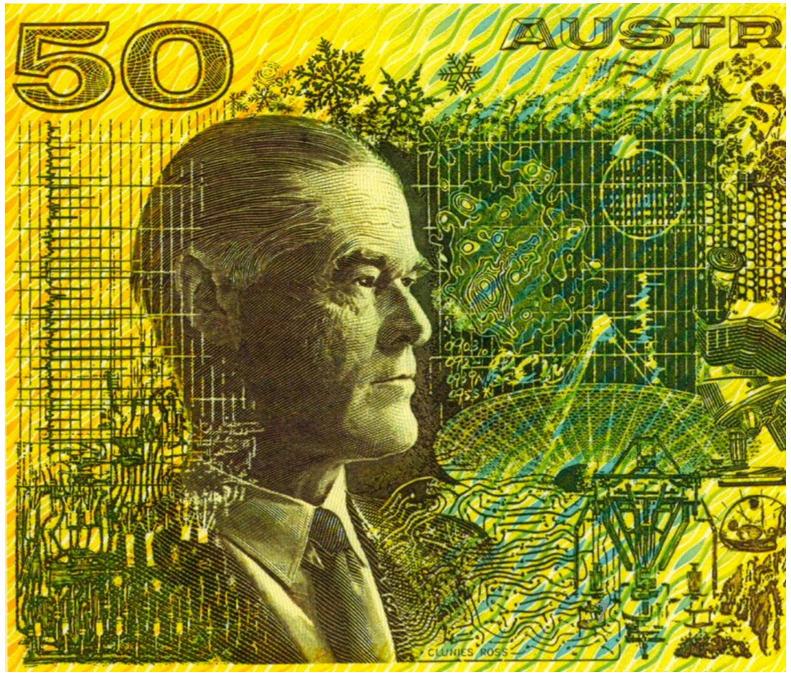


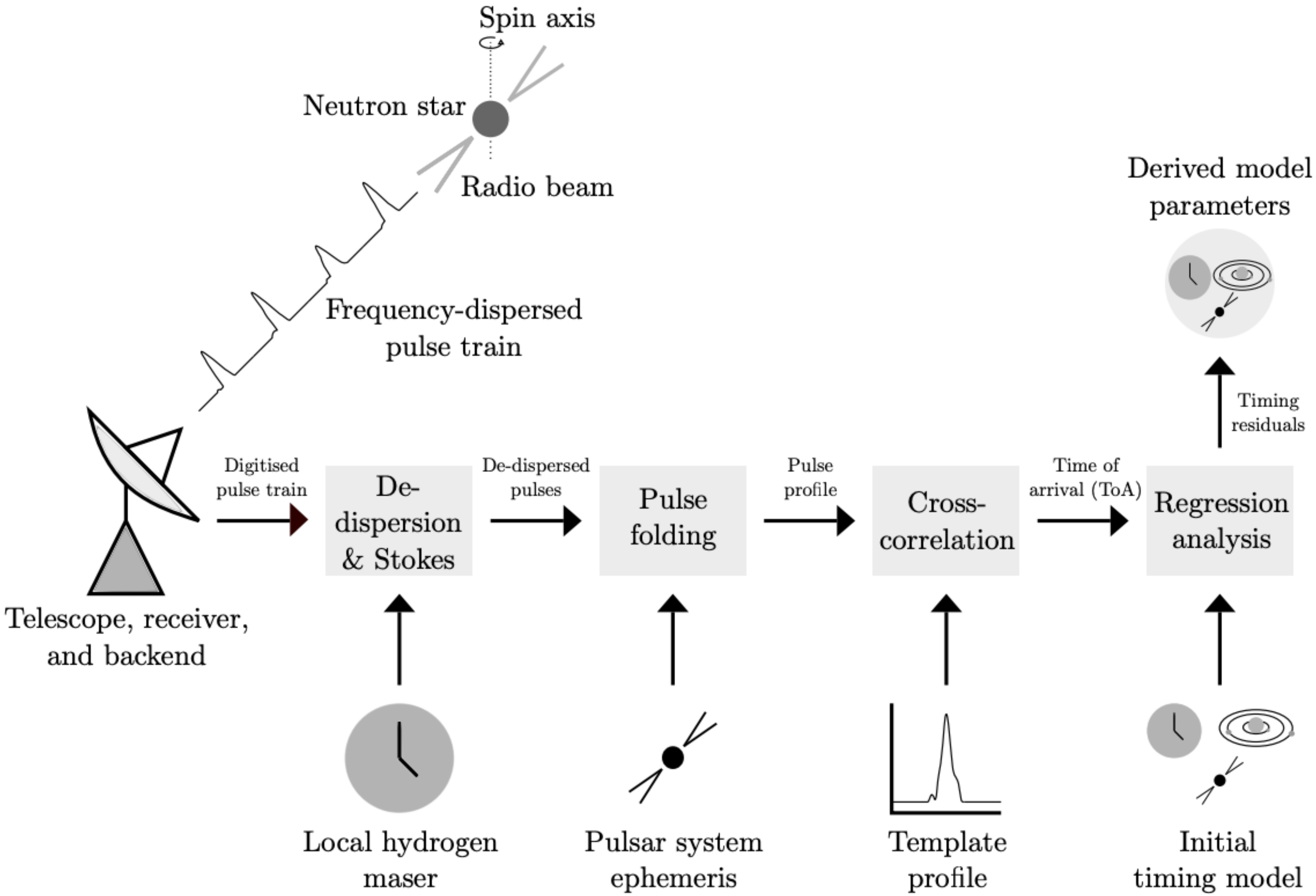
Above: Parkes ultrawide band system:
Should work from 700 MHz -4.2 GHz

Backends

- Digitise the electric signal (voltages)
  - time series from the frontend
- Channelise into many small frequency channels
  - Isolate narrow-band radio-frequency interference
- Data types:
  - Voltages -> Save everything and process later
  - Search mode -> Channelised high time resolution
  - ***Fold mode -> compact data cube for known pulsars. High time resolution in pulse phase***







Spin axis

Neutron star

Radio beam

Frequency-dispersed pulse train

Telescope, receiver, and backend

Digitised pulse train

De-dispersion & Stokes

De-dispersed pulses

Pulse folding

Pulse profile

Cross-correlation

Time of arrival (ToA)

Regression analysis

Timing residuals

Derived model parameters

Local hydrogen maser

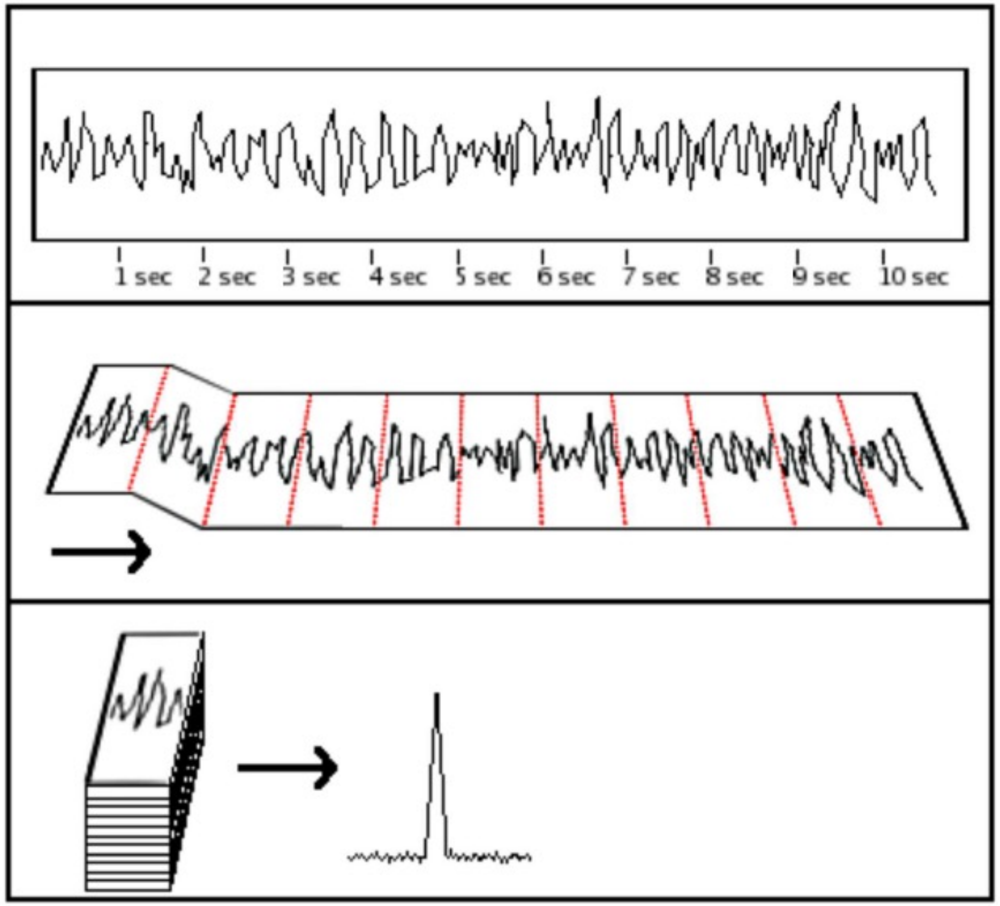
Pulsar system ephemeris

Template profile

Initial timing model

Pulsar folding

- **Pulsars are faint**
  - For most pulsars observed with most telescopes, individual pulses are indistinguishable from the noise
  - Average together many pulses to get a clearer signal
- In pulsar timing, we are studying known pulsars
  - We have a good model for the rotation of pulsar



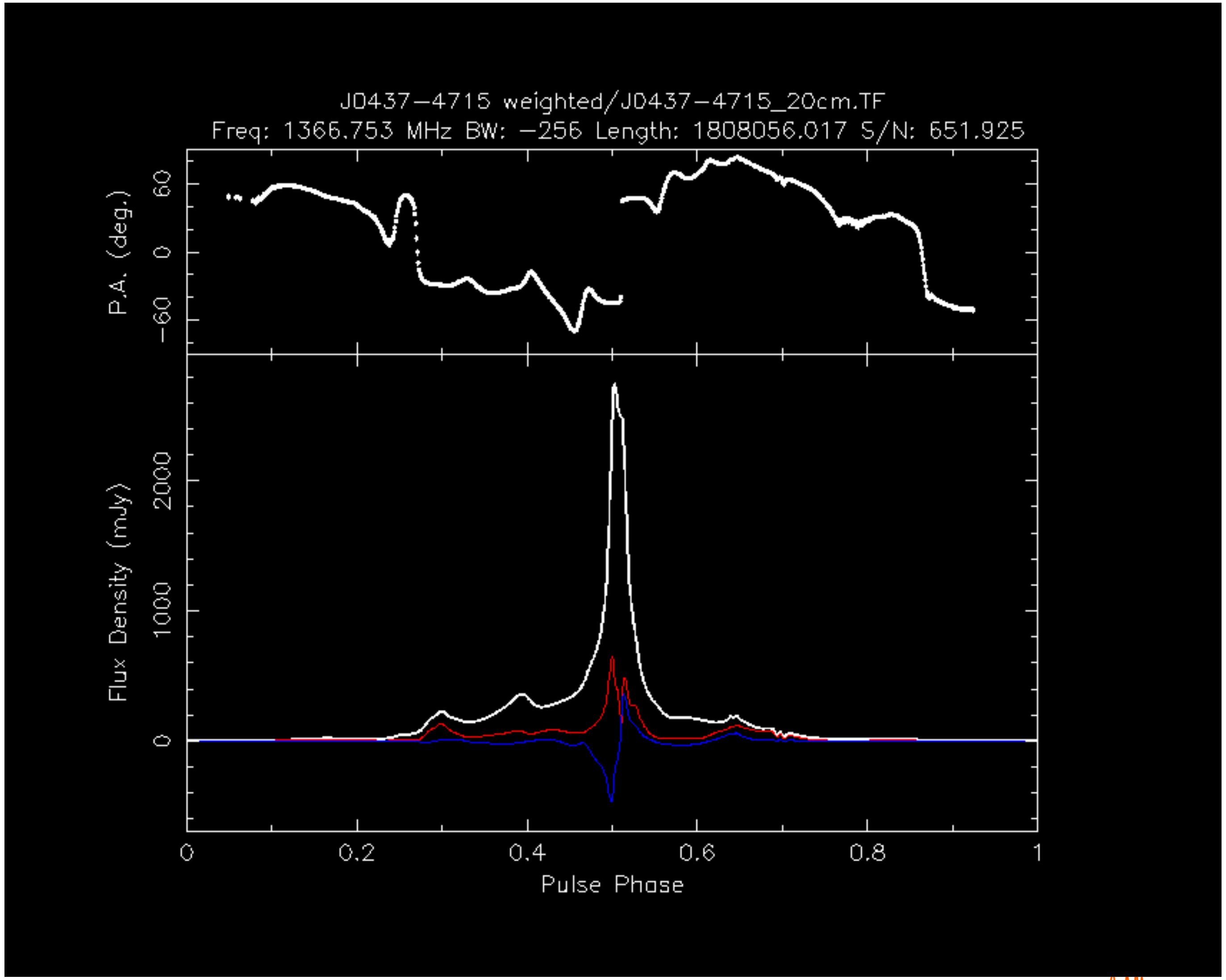
Credit: R. Lynch

Pulse profile

- **Linear polarization position angle**

- **White: total intensity**
- **Red: linear polarization**
- **Blue: circular polarization**

- Profiles can have *microsecond* time resolution



Dai et al. (2015)

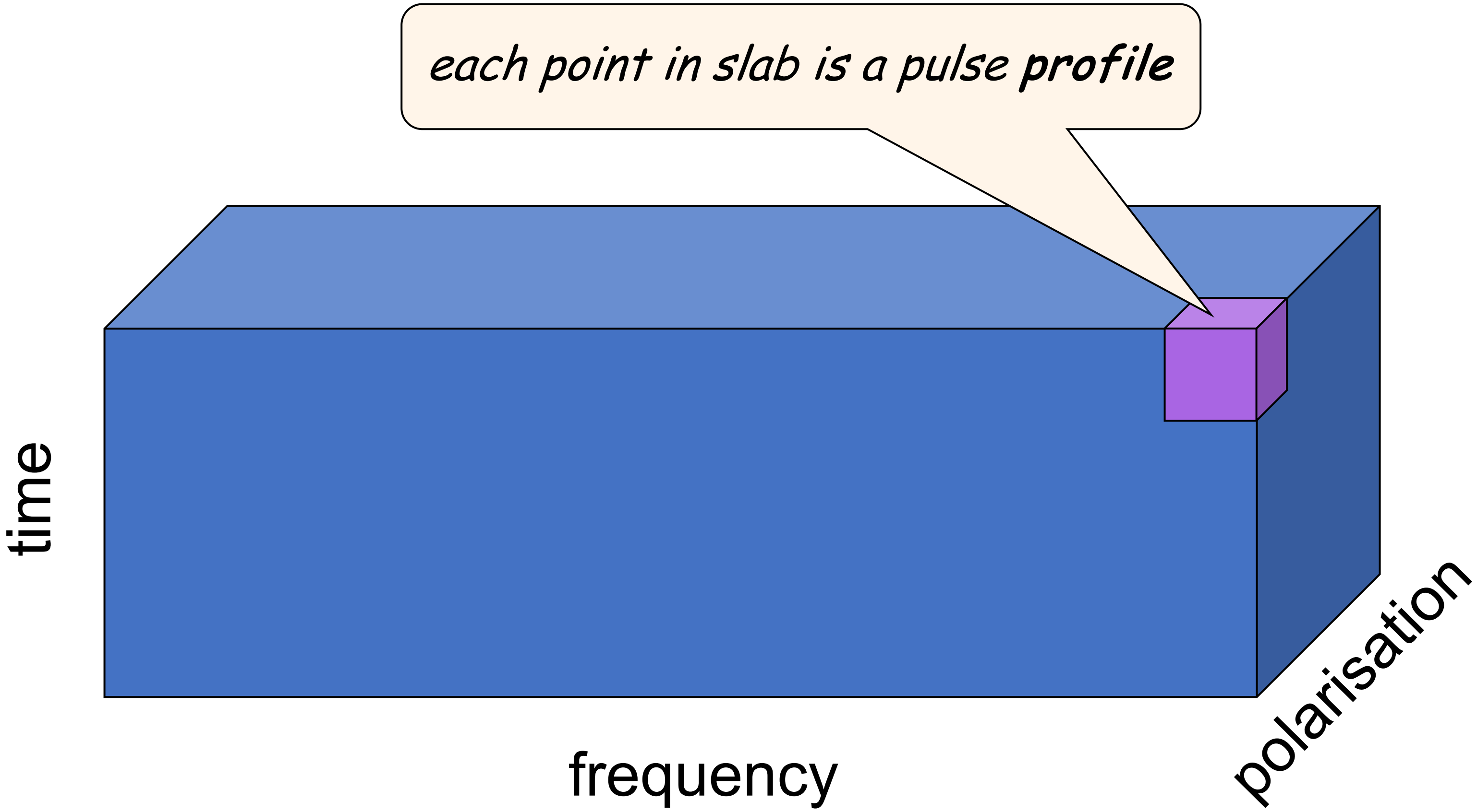
Fold mode data cube

- **One pulse profile per:**
  - Frequency channel
  - Time sub-integration
  - Polarisation

- Sum over polarisation to get to total intensity “Stokes I”

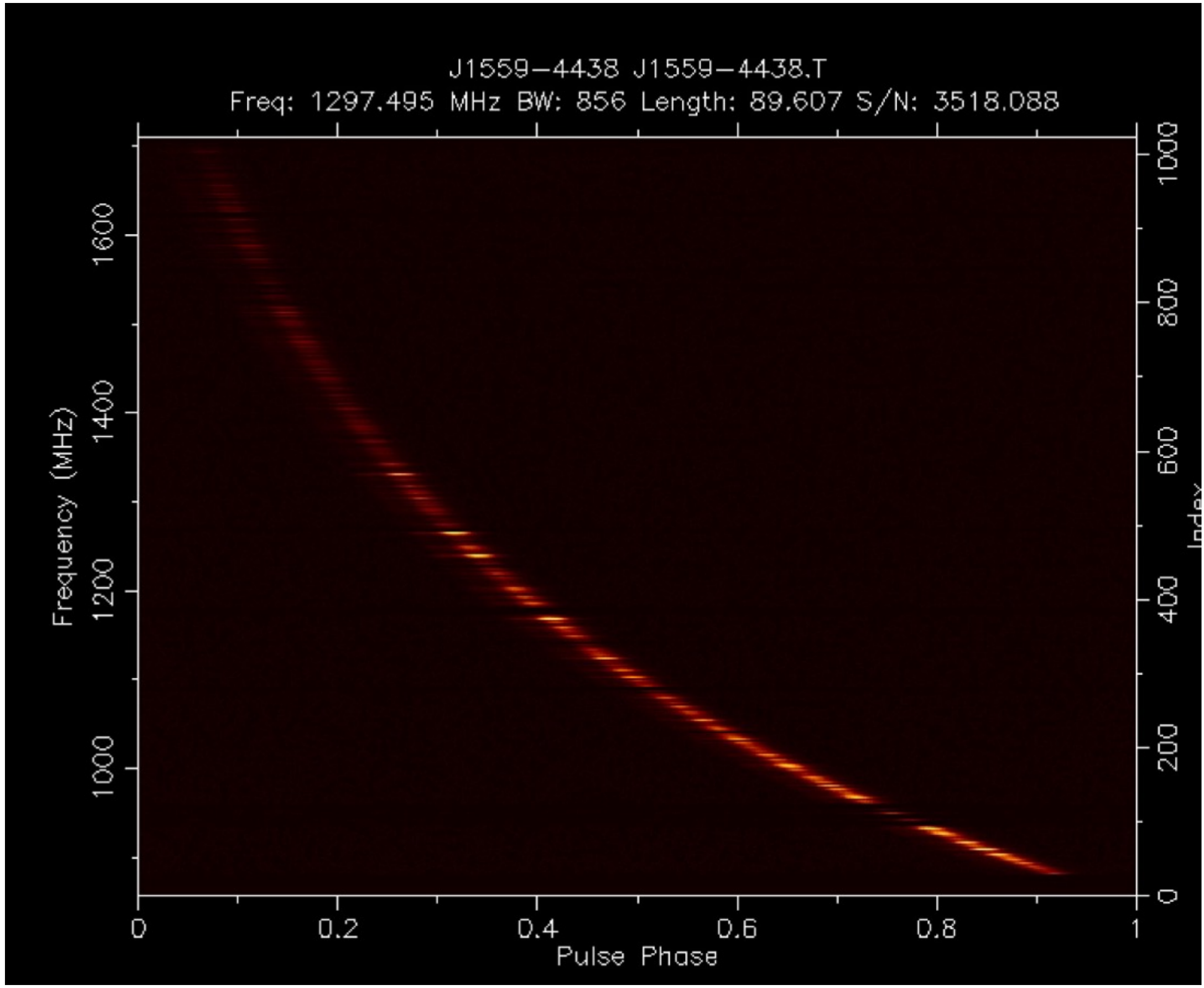
- Let’s look at some real data!

***psrchive* is used to process these data**



Profiles with frequency

- Physics!
  - Dispersion
    - Interstellar medium disperses radio waves
    - Low frequencies arrive later than high
  - Scattering / scintillation
    - Density fluctuations in the interstellar medium cause propagation and interference
  - Pulsar intrinsic spectrum
    - Pulsars typically brighter at low frequency
  - Pulse width changes
    - High frequencies come from lower in the magnetosphere
- Radio-frequency interference (RFI)



Profiles with frequency

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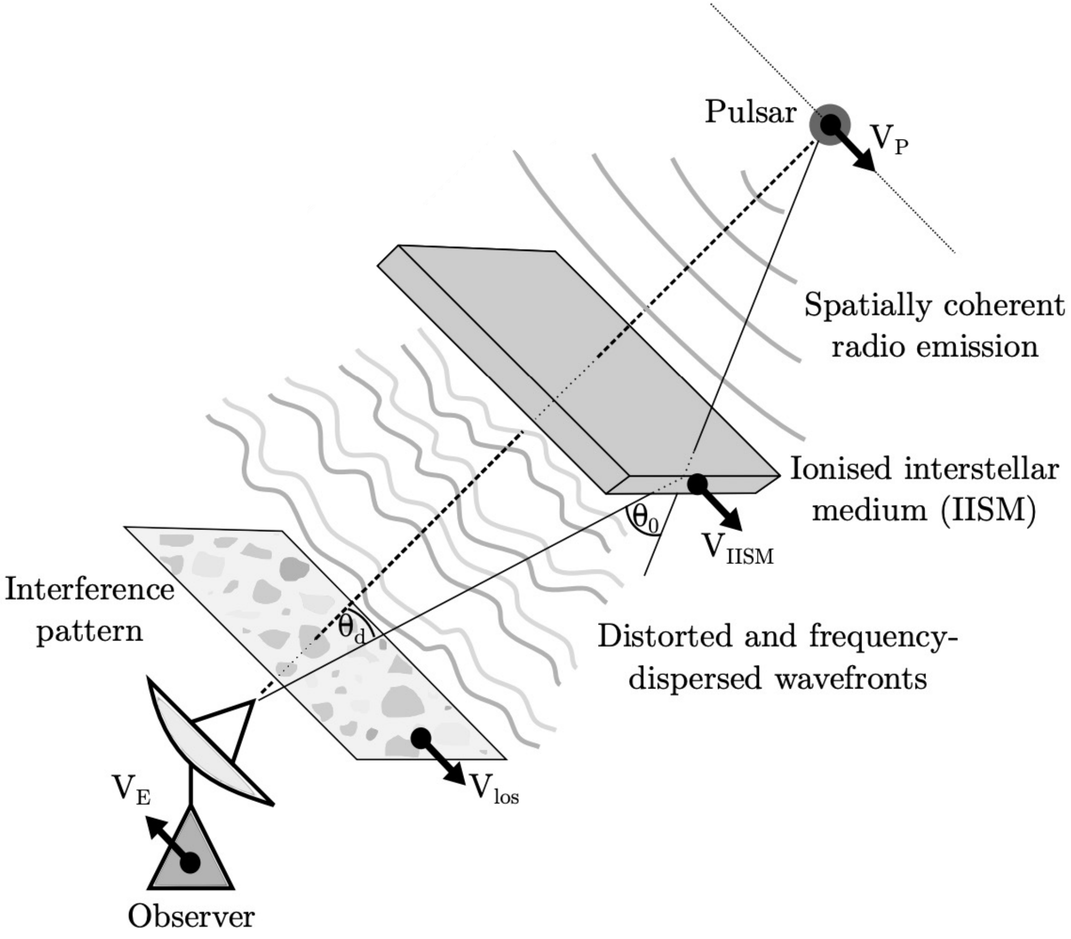
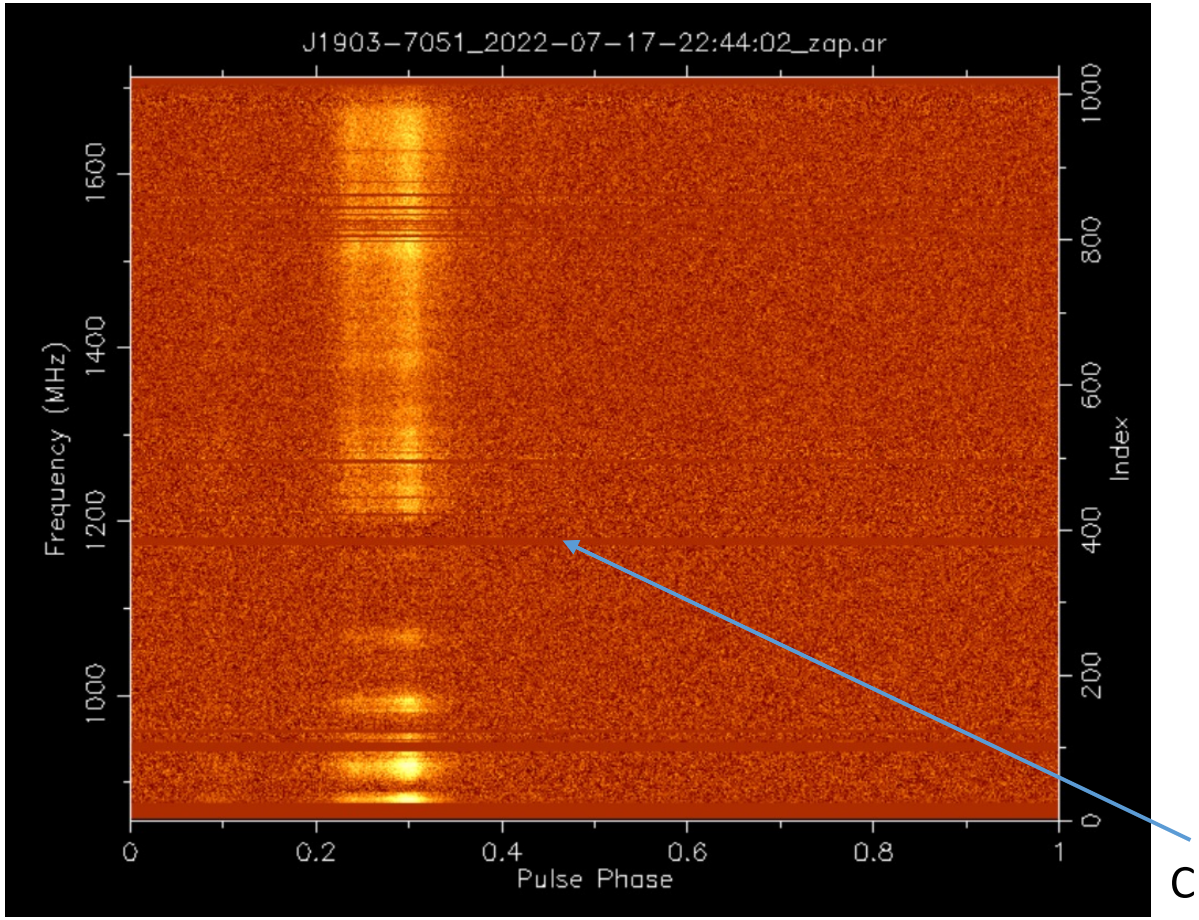
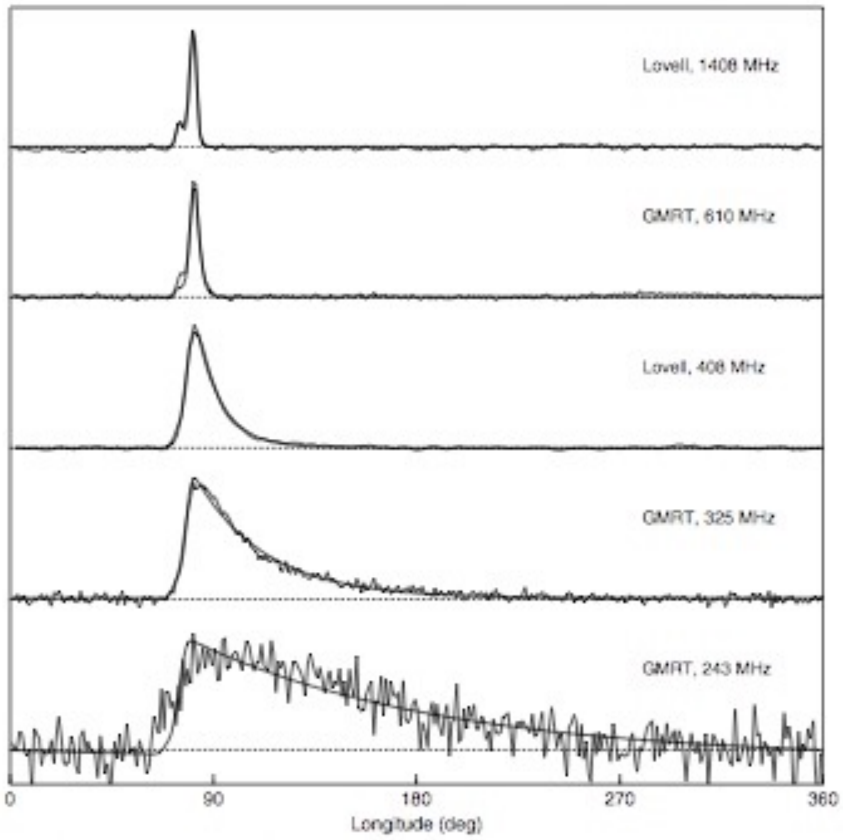


Profiles with frequency

- Another pulsar profile versus frequency



O. Löhmer et al.: Frequency evoluti

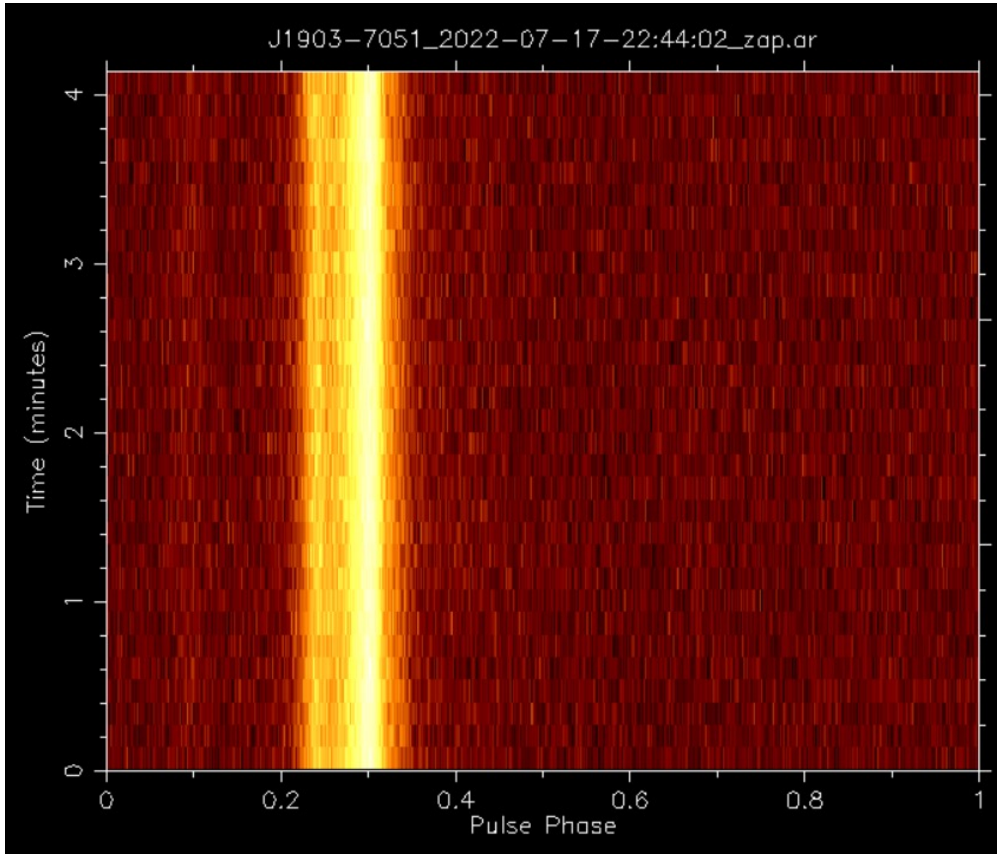


- the effect of scattering

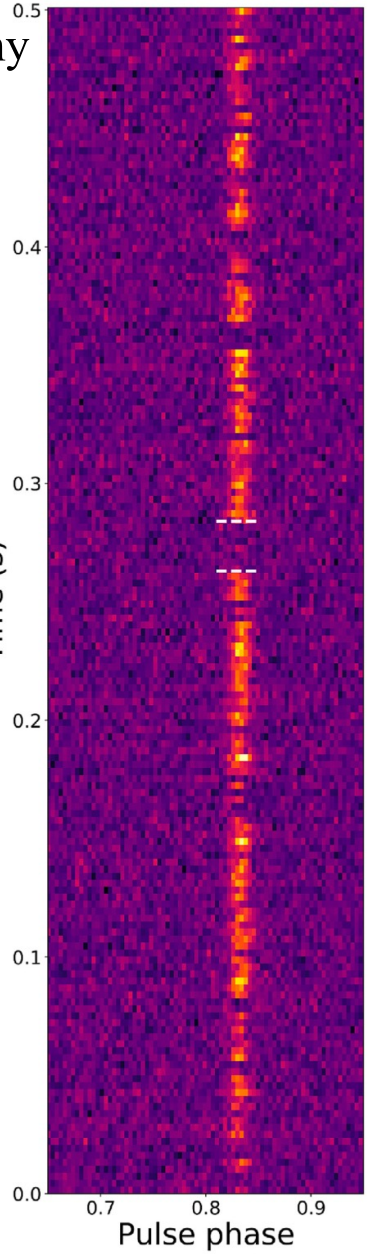
Channels removed because of interference

Profiles with time

- Physics!
  - Scintillation
    - Interference pattern moves as the Earth/pulsar/ interstellar medium move
  - Mode changing
    - The pulsar emission changes
  - Jitter
    - Random pulse shape and intensity variations make the brightness vary randomly
  - Bursts of RFI

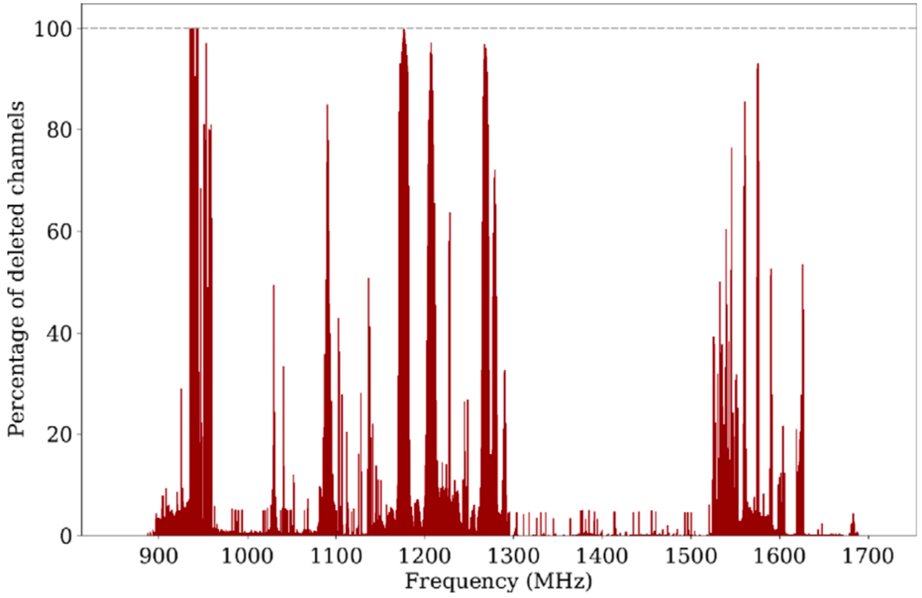


Right: Parthasarathy et al. (2021)

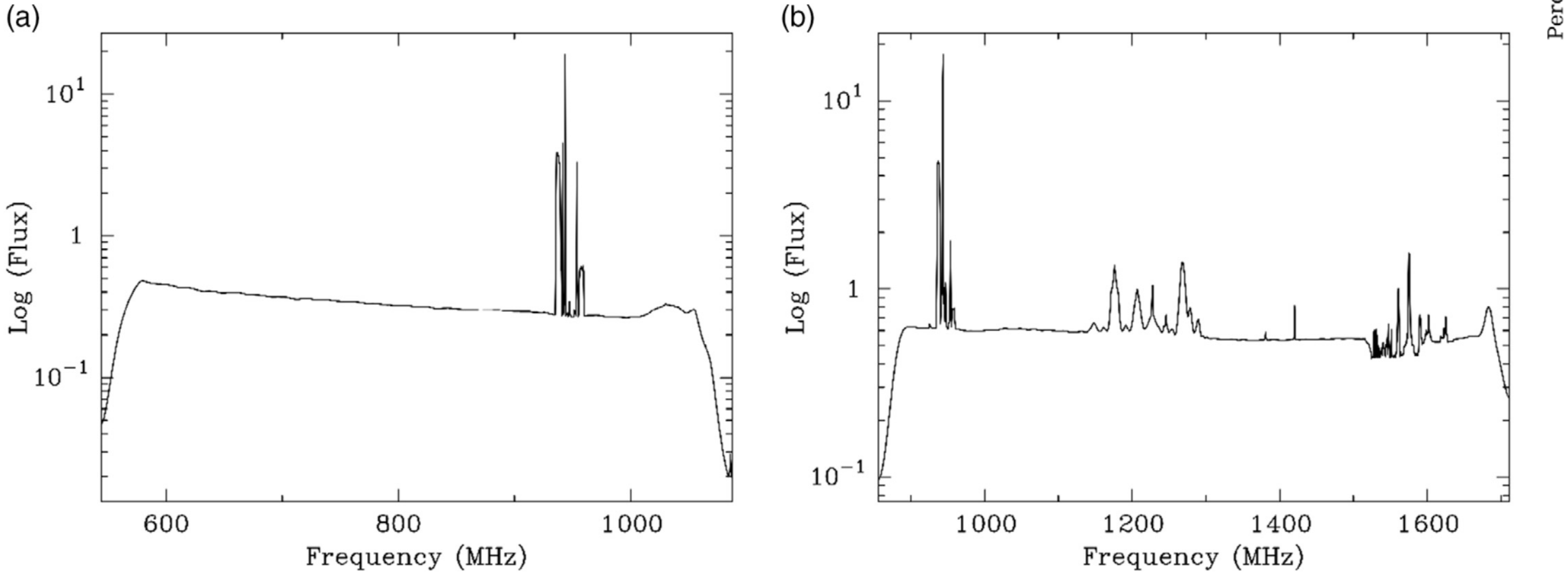


Radio-frequency interference

- MeerKAT is at a relatively radio-quiet site.
  - But RFI is everywhere
- Satellites, cell phone, wifi, planes, radio broadcast, lightning, microwaves

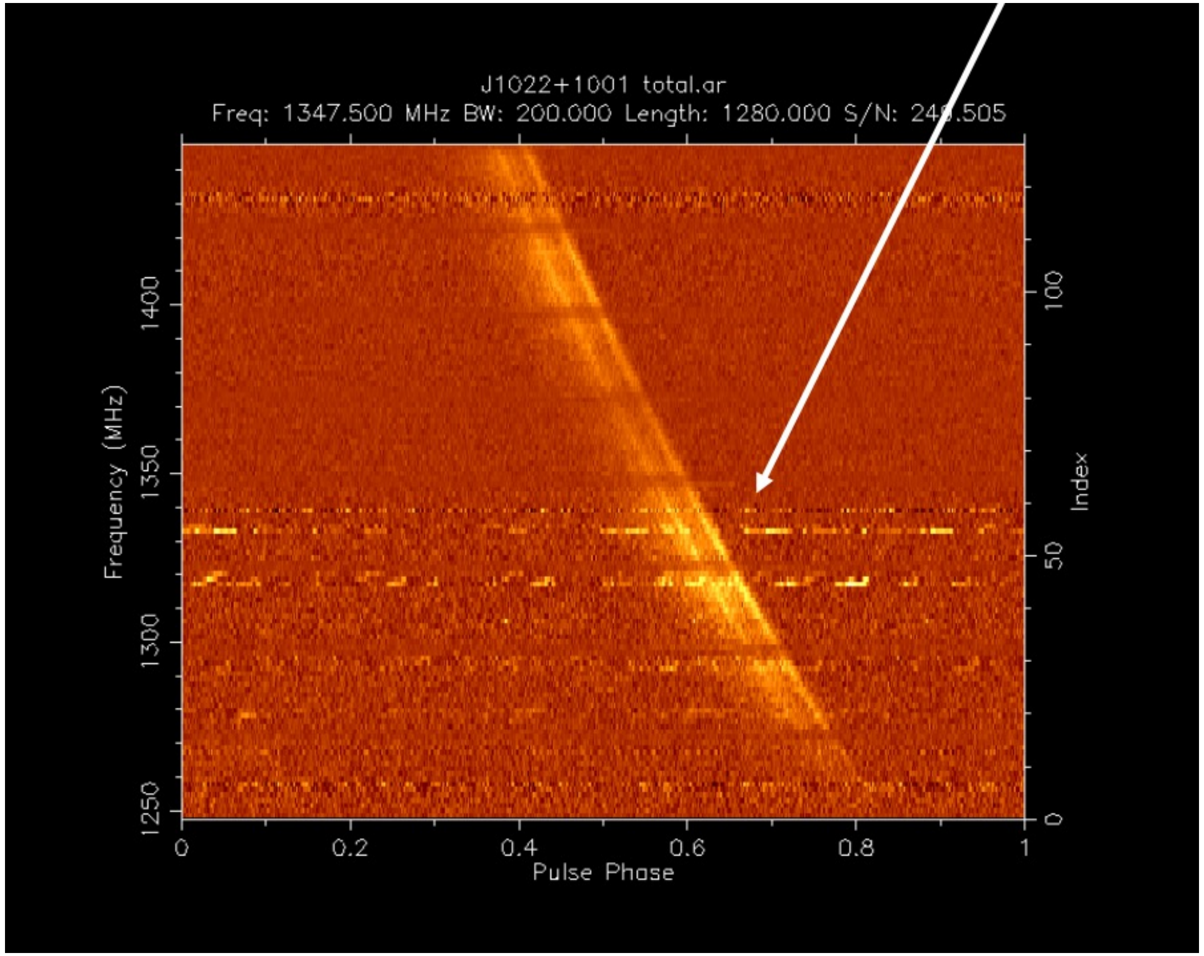


Above: Fraction of time a channel has RFI

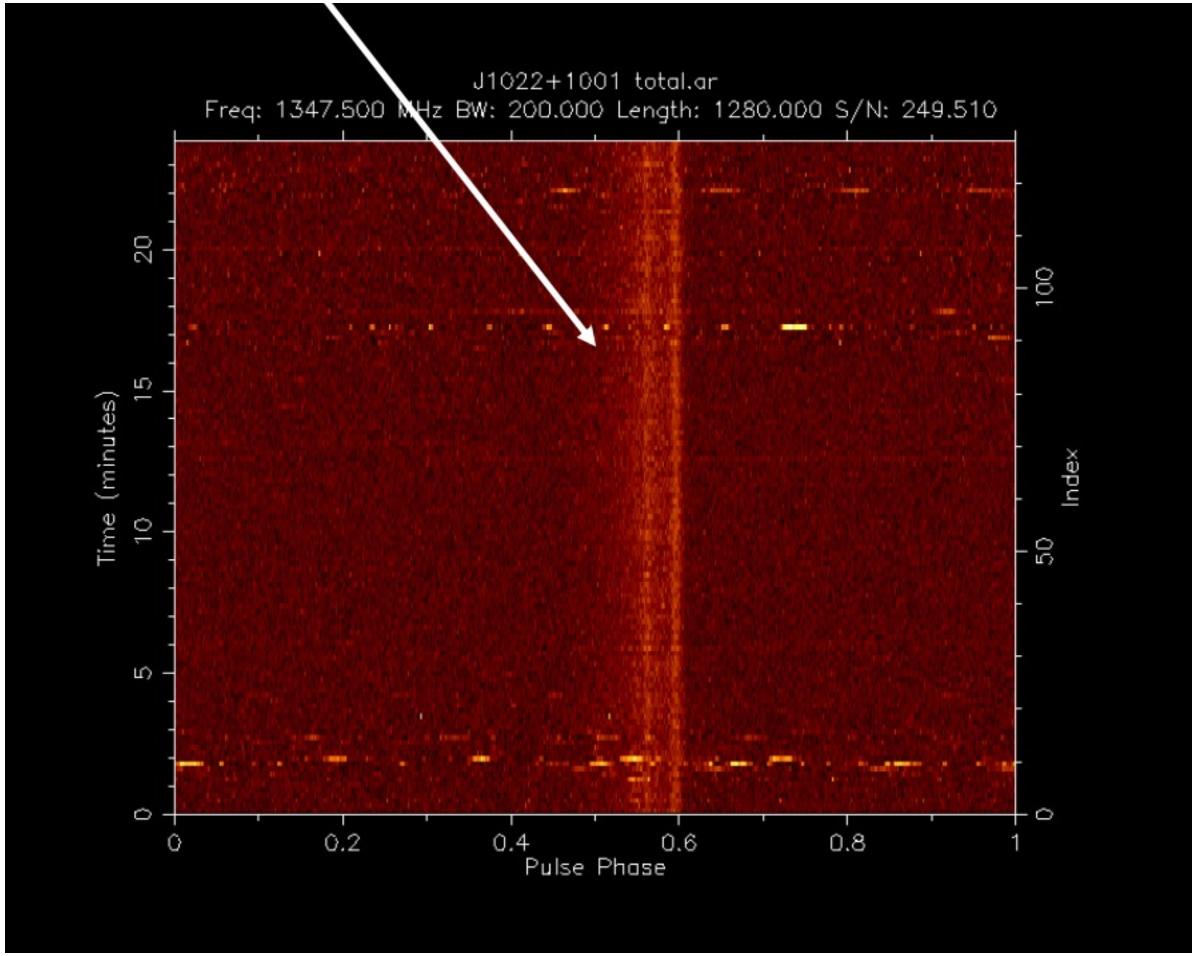


UHF receiver bandpass for Stokes I (544–1088 MHz). L-Band receiver bandpass for Stokes I (856–1712 MHz)

Radio-frequency interference in data



Narrow-band



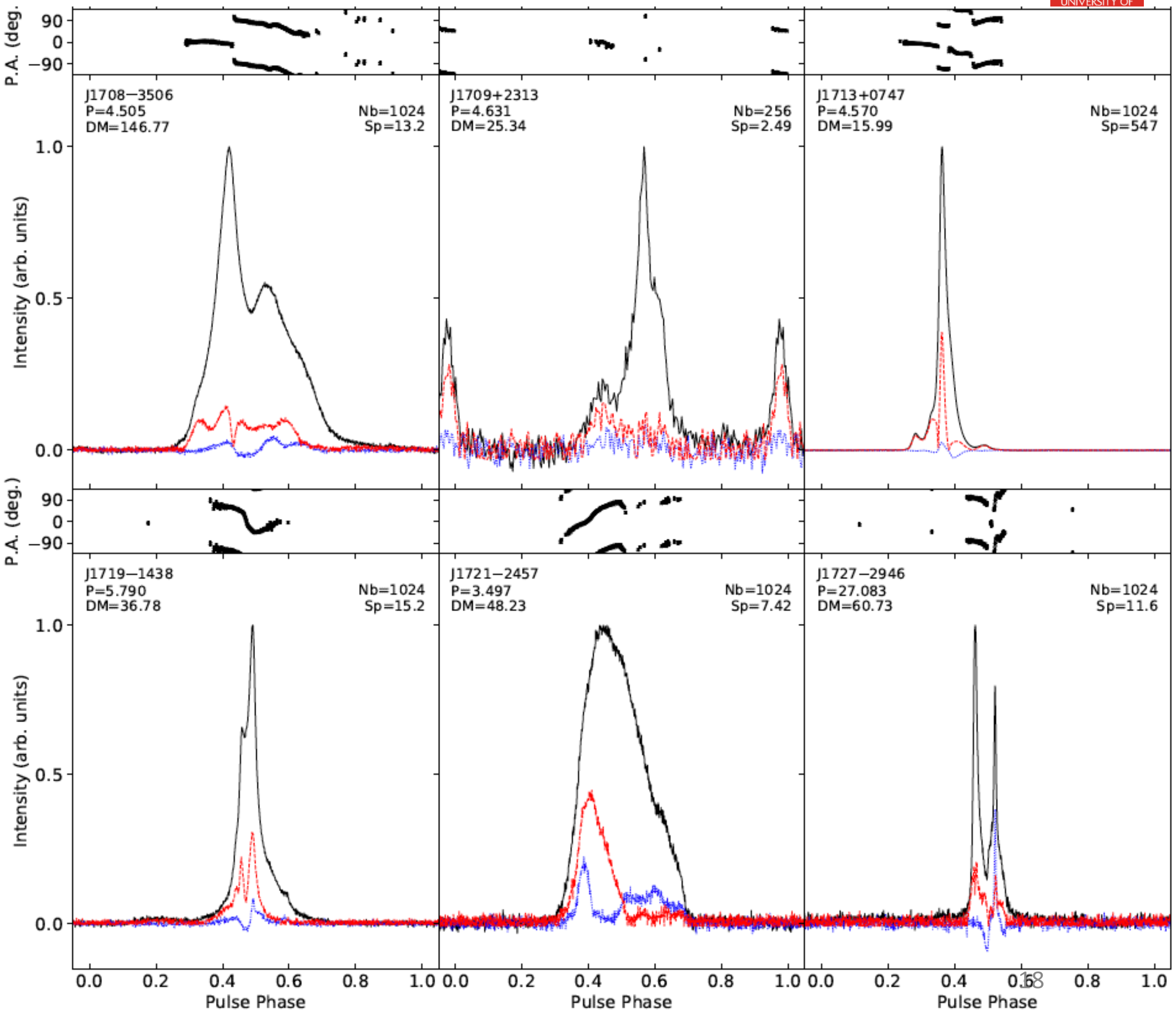
Bursts

More profiles

- Average over time and frequency
- Pulsars have different shapes
  - Depends on spin properties of pulsars
  - Depends on viewing angle of pulsar beam
  - Depends on shape of emission region
  - Narrow pulses provide higher timing precision

- Example: MeerKAT profiles of millisecond and recycled pulsars

Spiewak et al. (2022)



Pulsar timing

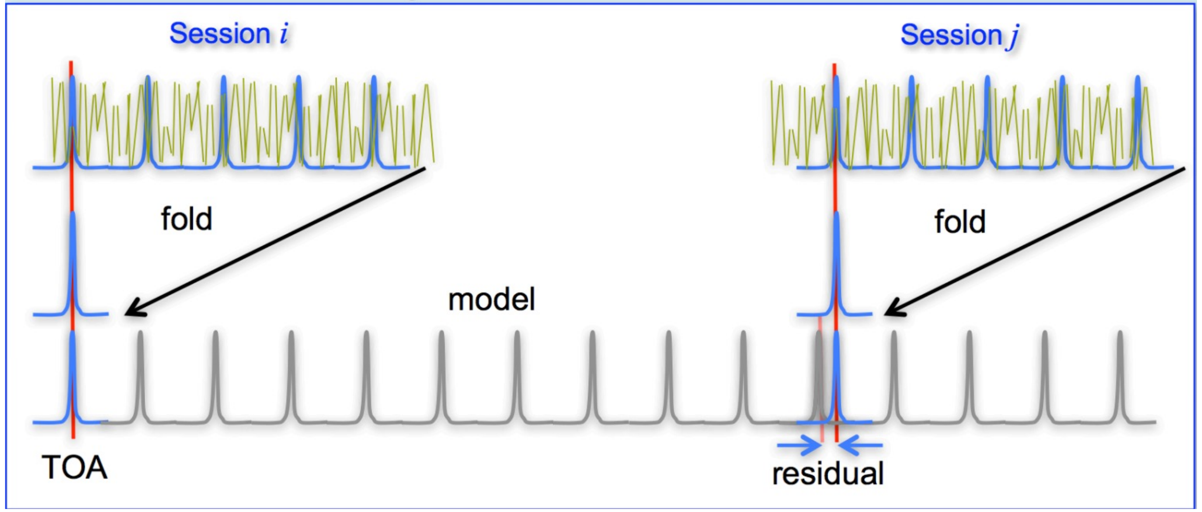
- We have nice profiles… Now what?
- Time-tagging! When did the pulses arrive?

- Power of pulsar timing technique:
  - Account for ***every rotation*** of pulsar over data set

- Assumptions:
  - Radio emission is “anchored” to neutron star
  - Radio emission is stable: emission will converge to same profile at each epoch
    - Notable exceptions: in precessing relativistic binaries
  - Signals of scientific interest alter arrival times of pulses and don’t distort pulse shape

Phase-connected timing solution:

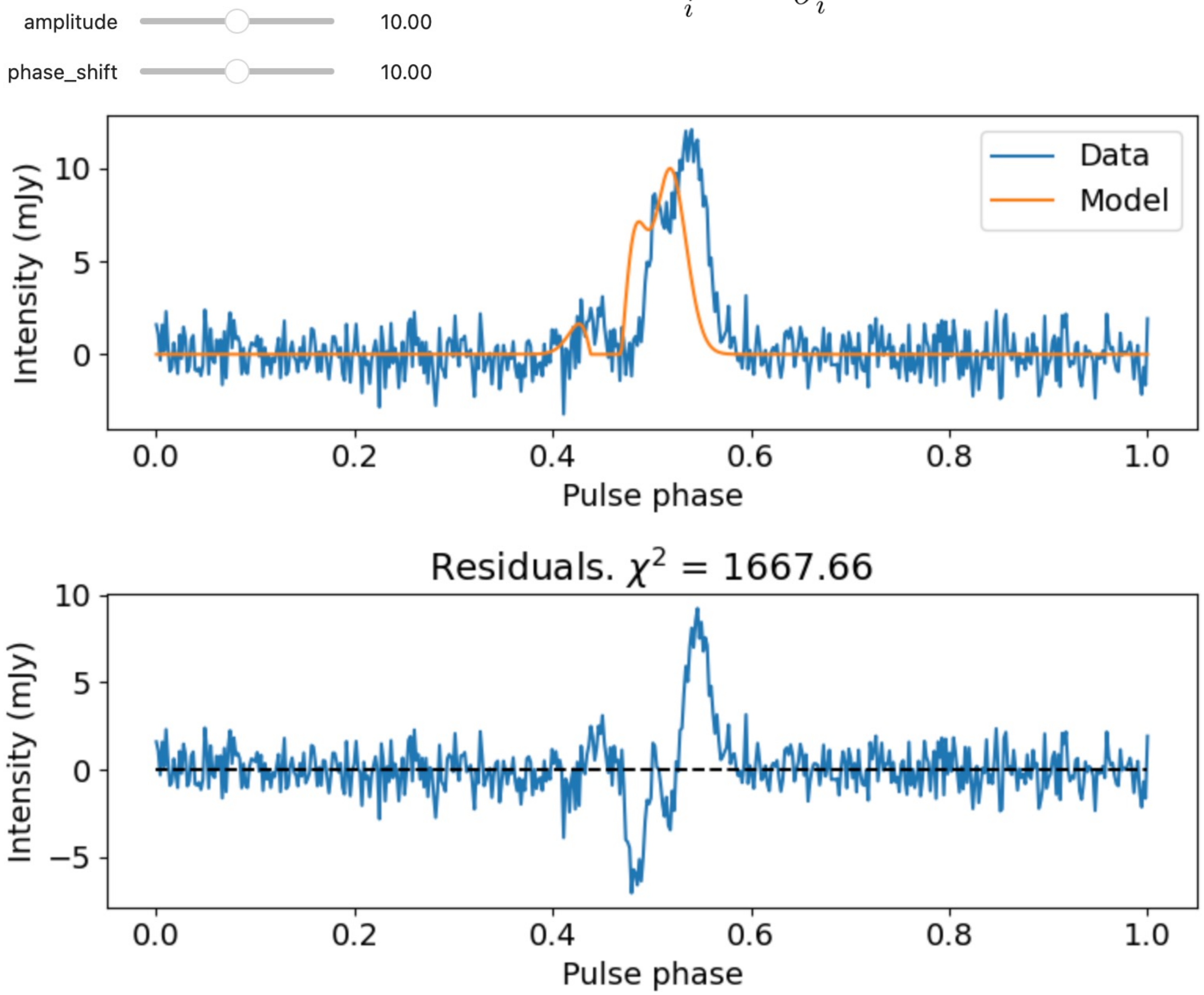
Credit: D. Champion



Time tagging

- Match a template to the pulse profile observation
    - Shift the template in phase until it best matches the data
- Relative to timing model arrival times varied show excess white noise
- Millisecond pulsars easily measured to less than 1 microsecond

$$\chi^2 = \sum_i \frac{(x_i - m_i)^2}{\sigma_i^2}$$



amplitude 10.00

phase_shift 10.00

Time tagging

$$\chi^2 = \sum_i \frac{(x_i - m_i)^2}{\sigma_i^2}$$

- Match a template to the pulse profile observation
  - Shift the template in phase until it best matches the data
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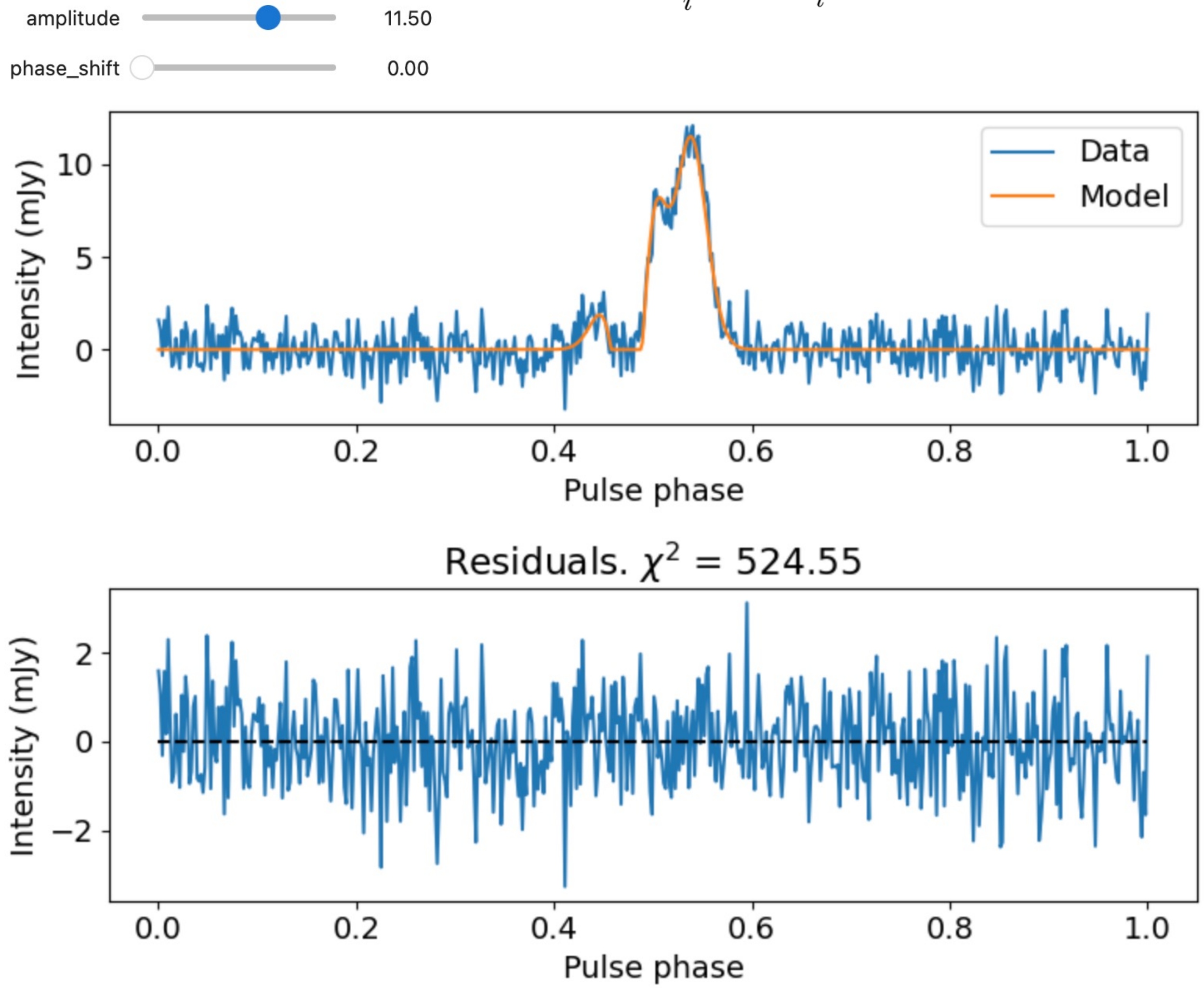


amplitude 11.50

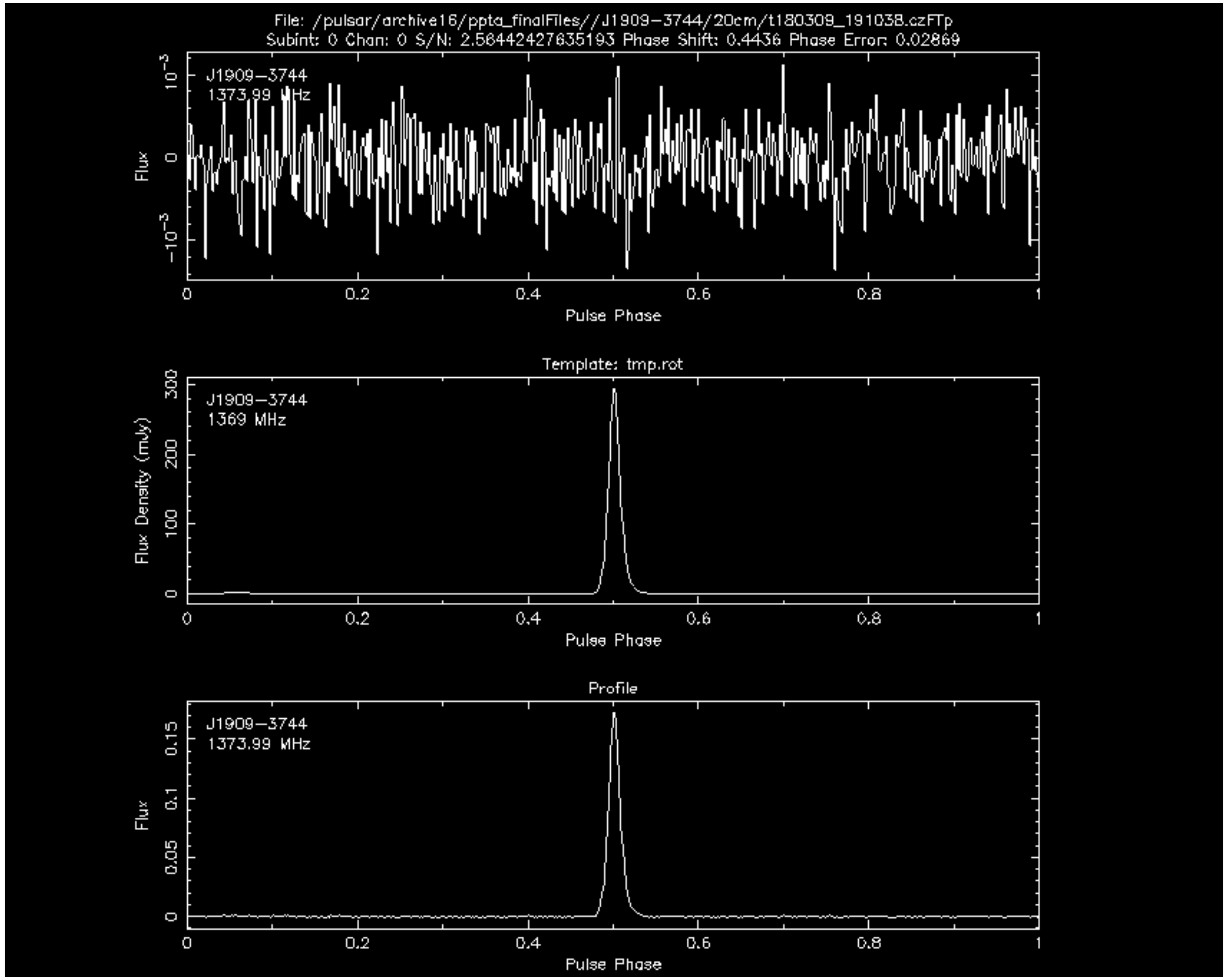
phase_shift 0.00

This interactive demonstration is available in the virtual machine!

Time tagging

- Cross correlate observation with noise-free template
  - Shift the template in phase until it matches the data

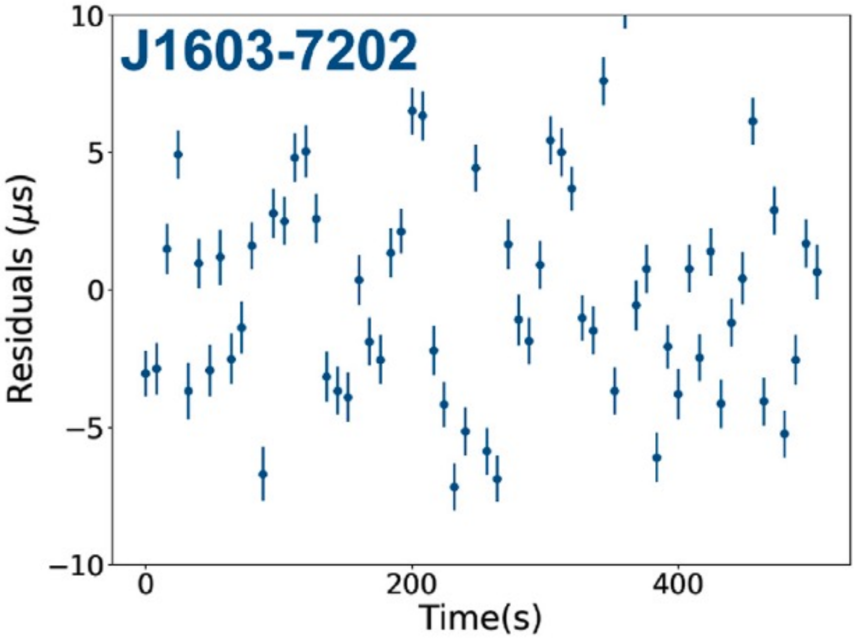
- Relative to timing model arrival times varied show excess white noise
- Millisecond pulsars easily measured to less than 1 microsecond



TOA (MJD) 58186.821751361541342
Error (microsec) 0.029

ToA uncertainty

- What properties of telescope/receiver/pulsar give the best ToAs?
- Best millisecond pulsars can be time-tagged to ***10 nanoseconds*** uncertainty!
- However, measurements often show excess noise



Jitter noise in J1603-7202
(Parthasarathy et al. 2021)

$$\Delta S_{\rm sys} = \frac{T_{\rm sys}}{\sqrt{n_{\rm p} t_{\rm obs} \Delta f}}$$

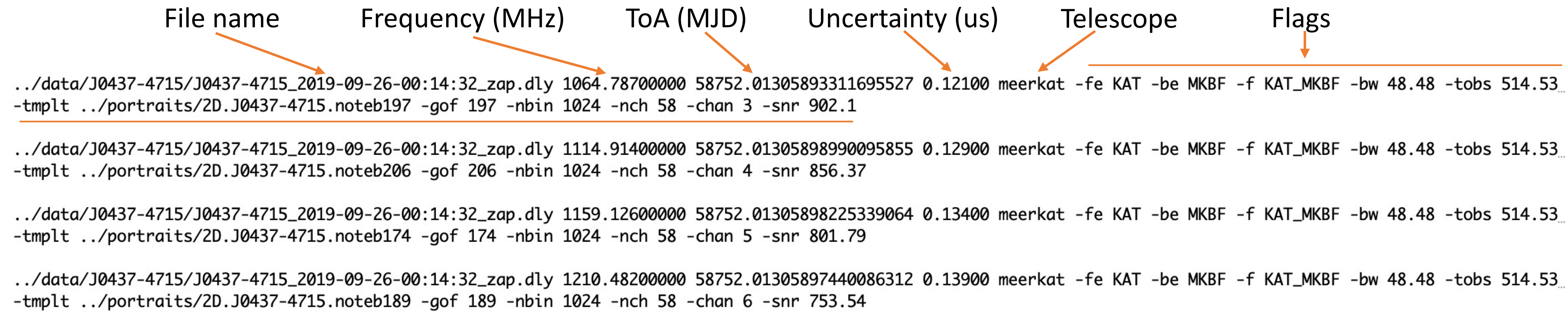
$T_{\rm sys}$ = system temperature (20 K)
$t_{\rm obs}$ = integration time (1 hour)
$n_{\rm p}$ = number of polarisations (2)
Δf = bandwidth (500 MHz)

$$\sigma_{\rm TOA} \simeq \frac{S_{\rm sys}}{\sqrt{t_{\rm obs}\Delta f}} \frac{P\delta^{3/2}}{S_{\rm mean}}$$

$S_{\rm mean}$ = mean pulsar flux density
δ = duty cycle (pulse width/pulse period)
P = pulse period

Saving times of arrival (ToAs)

- Measured ToAs are saved to a text file (.tim file) with flags describing the observation



File name

Frequency (MHz)

ToA (MJD)

Uncertainty (us)

Telescope

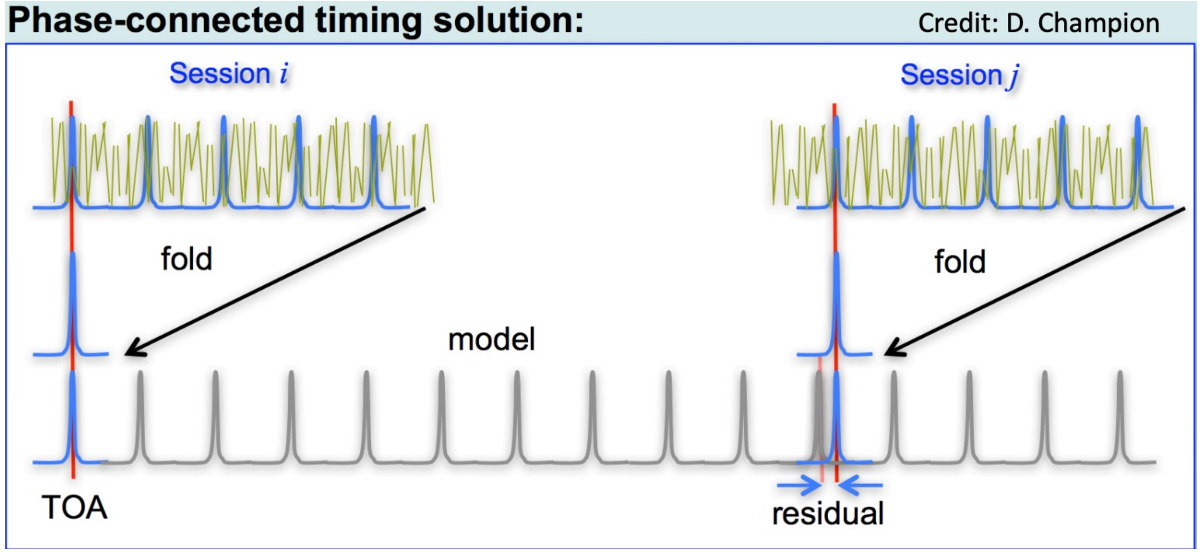
Flags

```
../data/J0437-4715/J0437-4715_2019-09-26-00:14:32_zap.dly 1064.78700000 58752.01305893311695527 0.12100 meerkat -fe KAT -be MKBF -f KAT_MKBF -bw 48.48 -tobs 514.53
-tmplt ../portraits/2D.J0437-4715.noteb197 -gof 197 -nbin 1024 -nch 58 -chan 3 -snr 902.1

../data/J0437-4715/J0437-4715_2019-09-26-00:14:32_zap.dly 1114.91400000 58752.01305898990095855 0.12900 meerkat -fe KAT -be MKBF -f KAT_MKBF -bw 48.48 -tobs 514.53
-tmplt ../portraits/2D.J0437-4715.noteb206 -gof 206 -nbin 1024 -nch 58 -chan 4 -snr 856.37

../data/J0437-4715/J0437-4715_2019-09-26-00:14:32_zap.dly 1159.12600000 58752.01305898225339064 0.13400 meerkat -fe KAT -be MKBF -f KAT_MKBF -bw 48.48 -tobs 514.53
-tmplt ../portraits/2D.J0437-4715.noteb174 -gof 174 -nbin 1024 -nch 58 -chan 5 -snr 801.79

../data/J0437-4715/J0437-4715_2019-09-26-00:14:32_zap.dly 1210.48200000 58752.01305897440086312 0.13900 meerkat -fe KAT -be MKBF -f KAT_MKBF -bw 48.48 -tobs 514.53
-tmplt ../portraits/2D.J0437-4715.noteb189 -gof 189 -nbin 1024 -nch 58 -chan 6 -snr 753.54
```

Pulsar timing data sets often have thousands of ToAs

Timing residuals

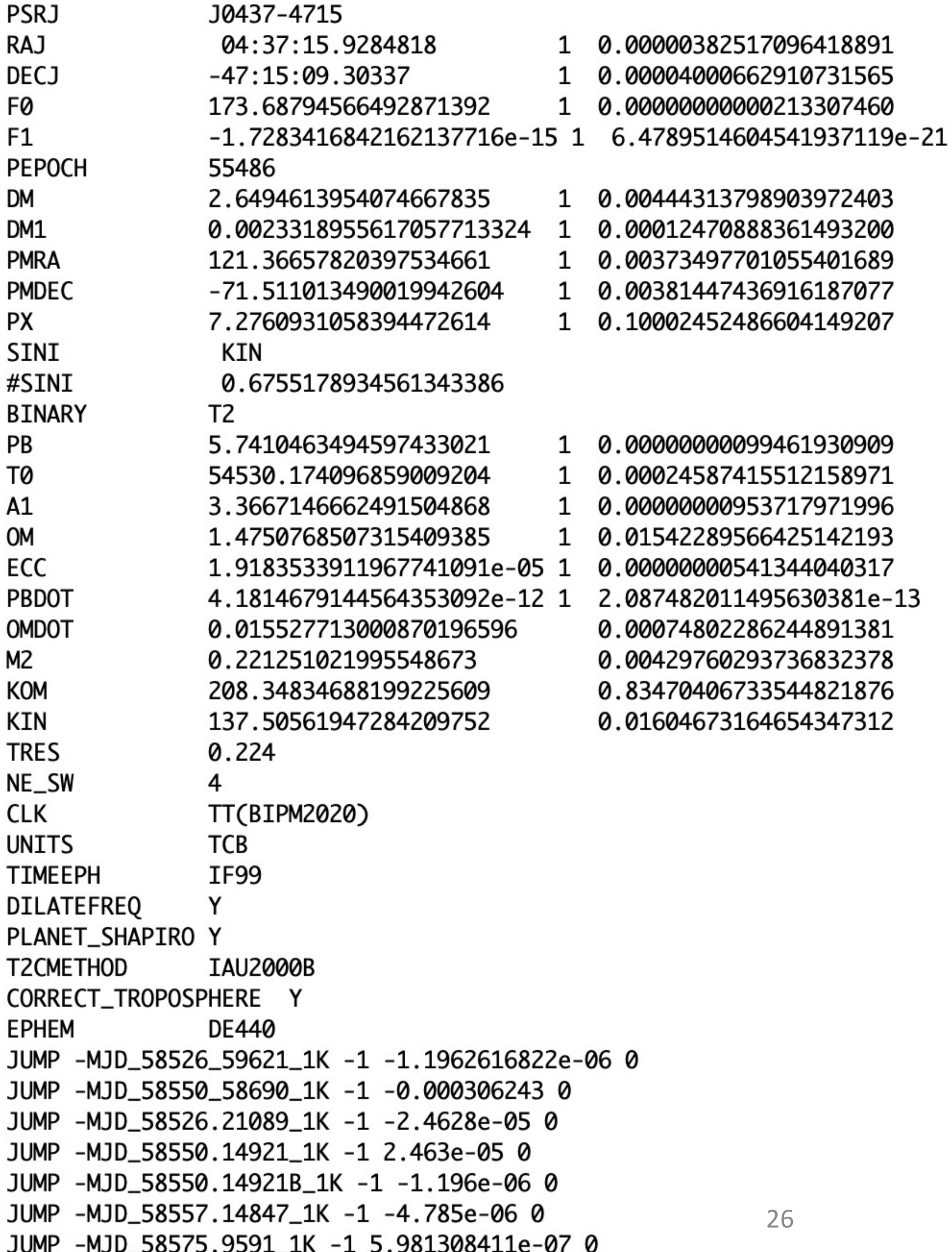
- A model is used to predict the arrival times
- The model is developed following the discovery of a pulsar
- It is always improving with more data collected
- Timing residuals = ToAs – model
    - Timing residuals reveal ***physics*** missing from the model.



The timing model

- Text file of parameters and uncertainties (.par file)

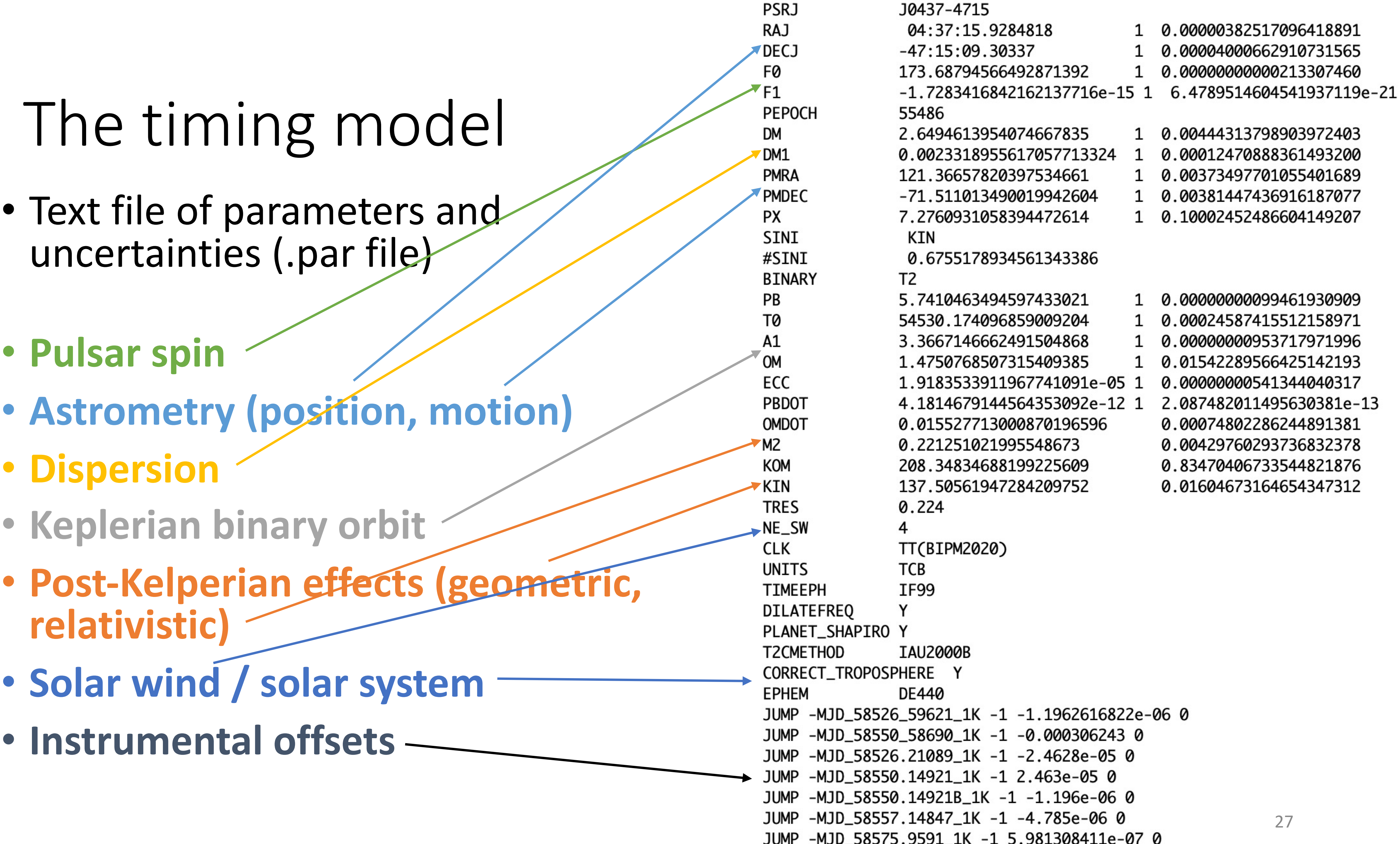
- **Pulsar spin**
- **Astrometry (position, motion)**
- **Dispersion**
- **Keplerian binary orbit**
- **Post-Kelperian effects (geometric, relativistic)**
- **Solar wind / solar system**
- **Instrumental offsets**



```
PSRJ           J0437-4715
RAJ             04:37:15.9284818         1  0.00000382517096418891
DECJ           -47:15:09.30337           1  0.00000400662910731565
F0             173.68794566492871392     1  0.00000000000213307460
F1             -1.7283416842162137716e-15 1  6.4789514604541937119e-21
PEPOCH         55486
DM             2.6494613954074667835     1  0.00444313798903972403
DM1            0.0023318955617057713324  1  0.00012470888361493200
PMRA           121.36657820397534661     1  0.00373497701055401689
PMDEC          -71.511013490019942604    1  0.00381447436916187077
PX             7.2760931058394472614     1  0.10002452486604149207
SINI            KIN
#SINI           0.67551789345613 43386
BINARY         T2
PB             5.7410463494597433021     1  0.00000000099461930909
T0             54530.174096859009204     1  0.00024587415512158971
A1             3.3667146662491504868     1  0.00000000953717971996
OM             1.4750768507315409385     1  0.01542289566425142193
ECC            1.9183533911967741091e-05 1  0.00000000541344040317
PBDOT          4.1814679144564353092e-12 1  2.0874820114956303 81e-13
OMDOT          0.015527713000870196596      0.00074802286244891381
M2             0.221251021995548673         0.00429760293736832378
KOM            208.34834688199225609        0.83470406733544821876
KIN            137.50561947284209752        0.01604673164654347312
TRES           0.224
NE_SW          4
CLK            TT(BIPM2020)
UNITS          TCB
TIMEEPH        IF99
DILATEFREQ     Y
PLANET_SHAPIRO Y
T2CMETHOD      IAU2000B
CORRECT_TROPOSPHERE  Y
EPHEM          DE440
JUMP -MJD_58526_59621_1K -1 -1.1962616822e-06 0
JUMP -MJD_58550_58690_1K -1 -0.000306243 0
JUMP -MJD_58526.21089_1K -1 -2.4628e-05 0
JUMP -MJD_58550.14921_1K -1 2.463e-05 0
JUMP -MJD_58550.14921B_1K -1 -1.196e-06 0
JUMP -MJD_58557.14847_1K -1 -4.785e-06 0
JUMP -MJD_58575.9591_1K -1 5.981308411e-07 0
```

The timing model

- Text file of parameters and uncertainties (.par file)



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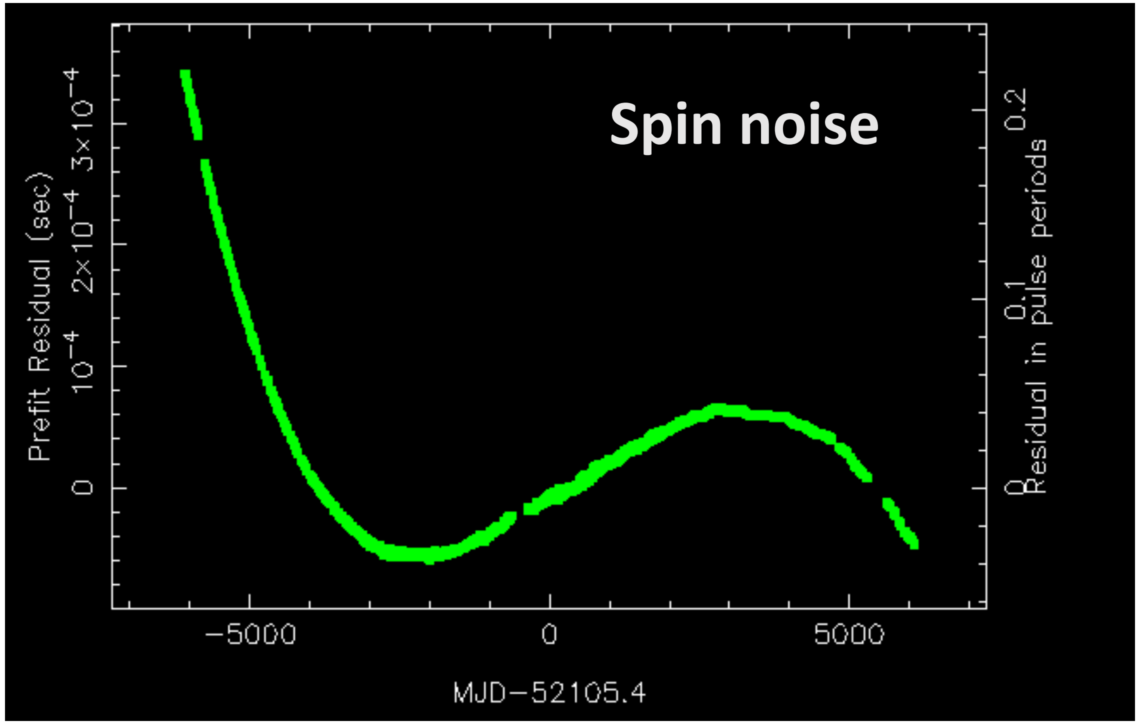
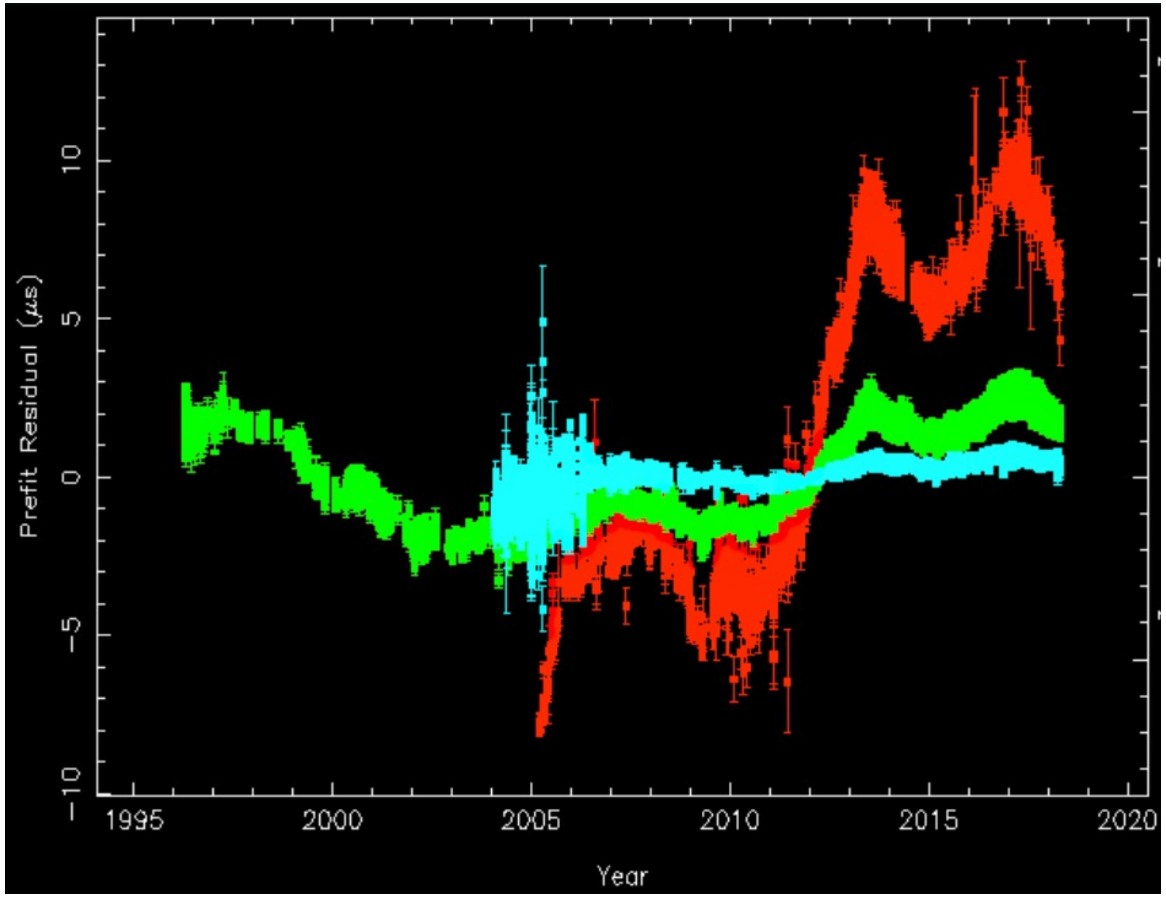
```
PSRJ           J0437-4715
RAJ             04:37:15.9284818         1  0.00000382517096418891
DECJ           -47:15:09.30337           1  0.00000400662910731565
F0             173.68794566492871392     1  0.00000000000213307460
F1             -1.7283416842162137716e-15 1  6.4789514604541937119e-21
PEPOCH         55486
DM             2.6494613954074667835     1  0.00444313798903972403
DM1            0.0023318955617057713324  1  0.00012470888361493200
PMRA           121.36657820397534661     1  0.00373497701055401689
PMDEC          -71.511013490019942604    1  0.00381447436916187077
PX             7.2760931058394472614     1  0.10002452486604149207
SINI            KIN
#SINI           0.6755178934561343386
BINARY         T2
PB             5.7410463494597433021     1  0.00000000099461930909
T0             54530.174096859009204     1  0.00024587415512158971
A1             3.3667146662491504868     1  0.00000000953717971996
OM             1.4750768507315409385     1  0.01542289566425142193
ECC            1.9183533911967741091e-05 1  0.00000000541344040317
PBDOT          4.1814679144564353092e-12 1  2.087482011495630381e-13
OMDOT          0.015527713000870196596      0.00074802286244891381
M2             0.221251021995548673          0.00429760293736832378
KOM            208.34834688199225609        0.83470406733544821876
KIN            137.50561947284209752        0.01604673164654347312
TRES           0.224
NE_SW          4
CLK            TT(BIPM2020)
UNITS          TCB
TIMEEPH        IF99
DILATEFREQ     Y
PLANET_SHAPIRO Y
T2CMETHOD      IAU2000B
CORRECT_TROPOSPHERE   Y
EPHEM          DE440
JUMP -MJD_58526_59621_1K -1 -1.1962616822e-06 0
JUMP -MJD_58550_58690_1K -1 -0.000306243 0
JUMP -MJD_58526.21089_1K -1 -2.4628e-05 0
JUMP -MJD_58550.14921_1K -1 2.463e-05 0
JUMP -MJD_58550.14921B_1K -1 -1.196e-06 0
JUMP -MJD_58557.14847_1K -1 -4.785e-06 0
JUMP -MJD_58575.9591_1K -1 5.981308411e-07 0
```

Noisy timing residuals

Observations of millisecond pulsar B1937+21



Last observation (2018): 674,489,762,880 pulse periods after first observation (1984)

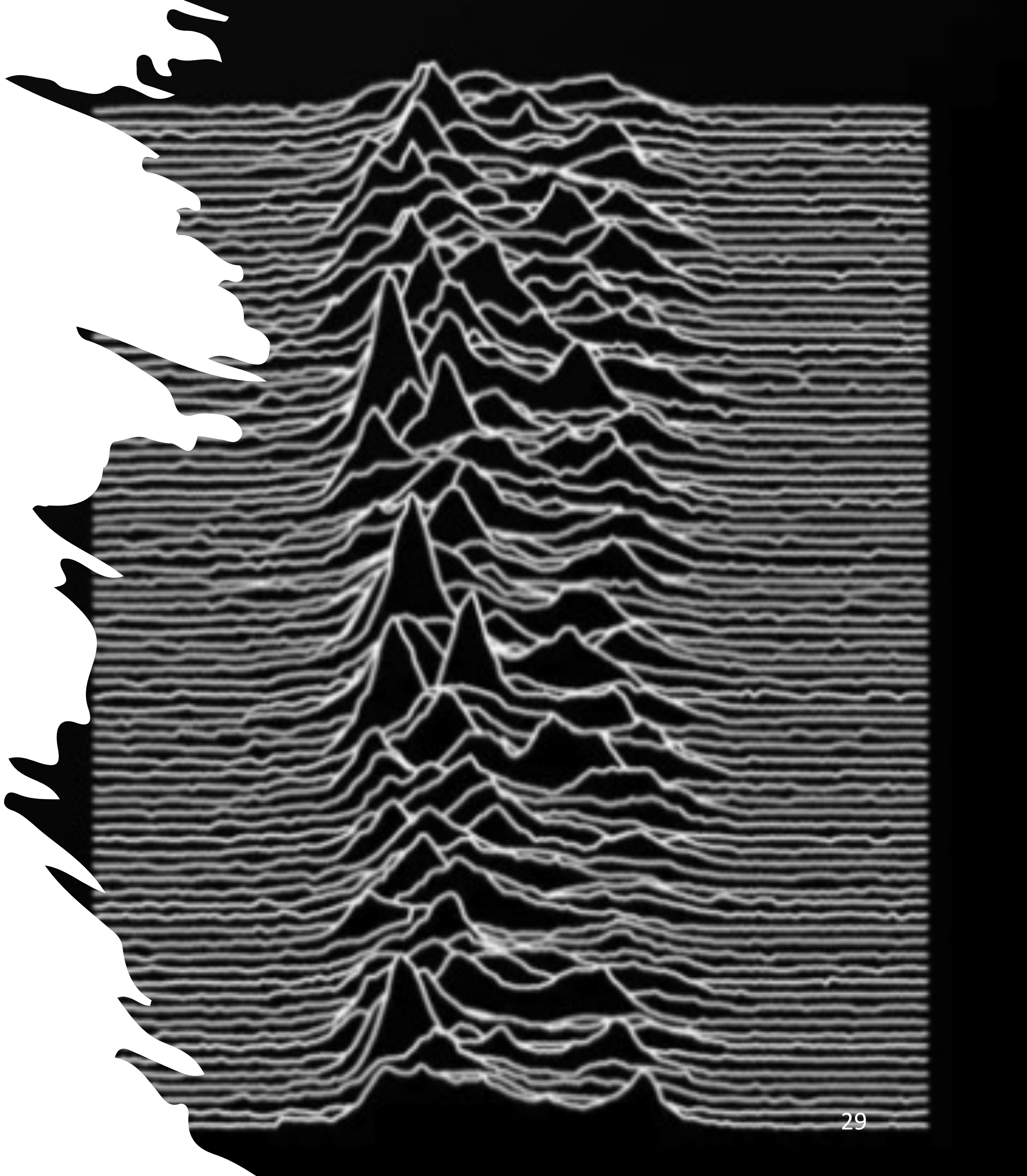


Dispersion measure variations in PSR J0437-4715

Summary

The journey of pulsar timing data

- Big radio telescopes in radio-quiet regions observe pulsars for minutes to hours
- Receivers transform radio waves to voltages
- A backend system folds data at the pulsar period and saves profiles as a function of frequency, time, and polarisation
- Radio-frequency interference (RFI) is removed
- Profile is summed over frequency, time, polarization
- Profile is tagged with a time of arrival by matching a template
- Time of arrival is compared with a model prediction
- Timing residual is analysed for interesting physics missing in the model
- Gravitational waves?!
- **Pulsars are awesome**



Bonus: Software to use

- Voltages processed (e.g. folded) with *dspsr*
- Search mode searched for new pulsars with *presto*
- Pulse profiles analysed with *psrchive*
- Timing residuals and (least squares) timing model fit in *tempo2* or *pint*
- Stochastic (random) processes, and timing model fit with Bayesian inference with *temponest* or *enterprise*
- Gravitational wave detection *enterprise*