Massive scale pulsar timing with the Molonglo Observatory Synthesis Telescope

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CSIRO

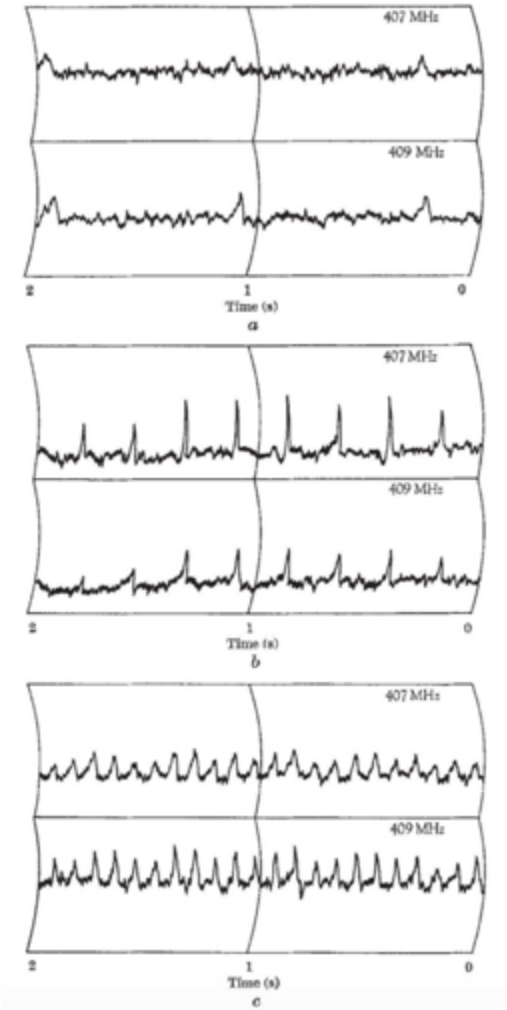
The MOST

- Located ~40 km east of Canberra.
- 1.6km long interferometer.
- 835 MHz, 31.25 MHz bandwidth.
- Single polarization (RHC).
- 2.5 x 4 degree field of view.

Tharindu Welikala (Instagram: @tharindu)

Early years of pulsar astronomy

- Pulsars discovered via single pulses (e.g. Large et al. 1968).
- >100 found via periodicity searches (e.g. Manchester et al. 1978).
- ~50% of pulsars discovered by the 1980s were found by MOST.



Large et al. (1968)

PSR J1731-4744

PSR J1932+1059

PSR J0835-4510 (Vela)

Pre-discovery of fast radio bursts?

- Amy et al. (1989) – radio transient survey.
- Limited bandwidth (3 MHz).
- Excess of short unexplained events.
- No clustering in time or location.

Table 1: Characteristics of MOTER records[a]

1. Explained Records	
No events	4%
Few events (1, 2 or 3)	7%
Known pulsars	3%
Instrumental effects	8%
2. Unexplained Records	
"Notable" events	11%
Events (> 3) with $\tau \leq 1$ ms	54%
Events (> 3) with $\tau > 1$ ms	20%

The UTMOST* project

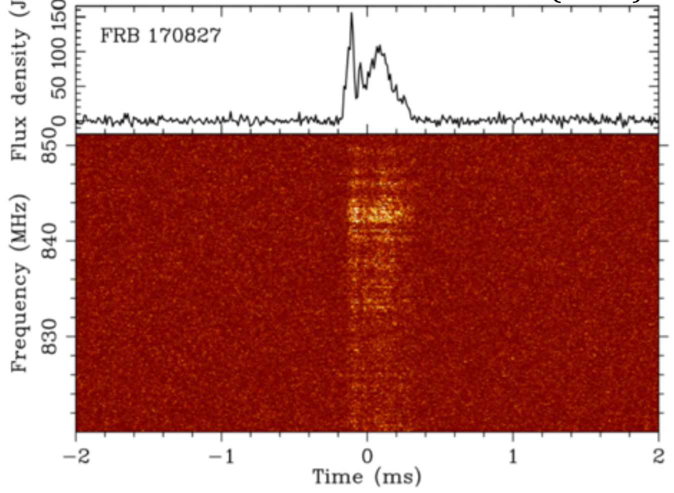
- MOST reborn: a transient detecting machine.
- Doubled the field of view of MOST.
- 10x the original bandwidth.
  - 3 MHz to 30 MHz
- Fully autonomous scheduling system.
- Transit instrument from mid-2017.

*Not an acronym.

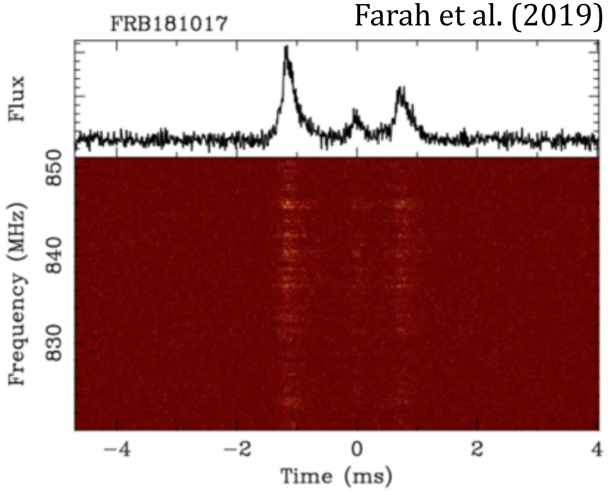
UTMOST fast radio bursts

- Real-time detection pipeline saves ‘voltage’ data.
- Interesting high-resolution structures.
- Good localization in RA, poor in DEC.

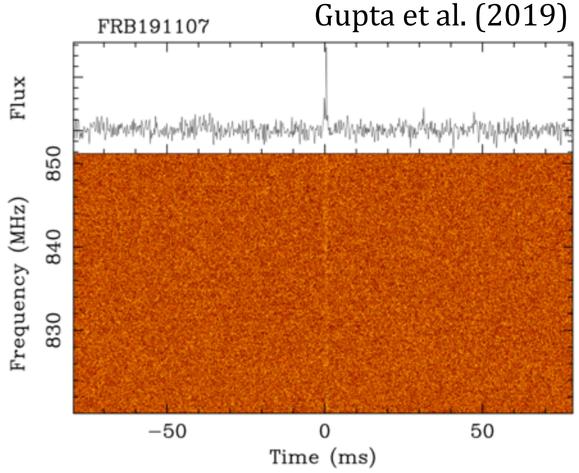
Farah et al. (2018)



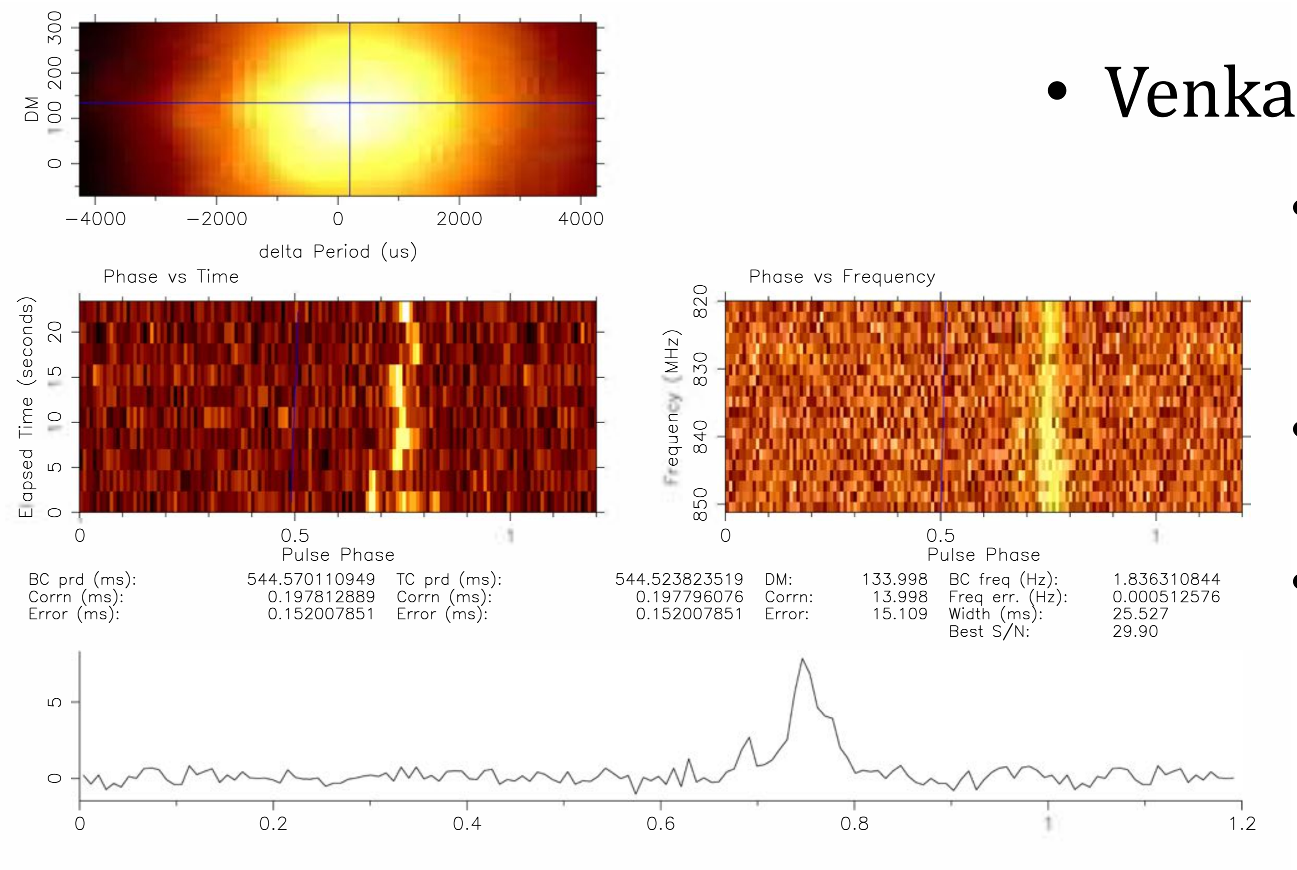
Farah et al. (2019)



Gupta et al. (2019)

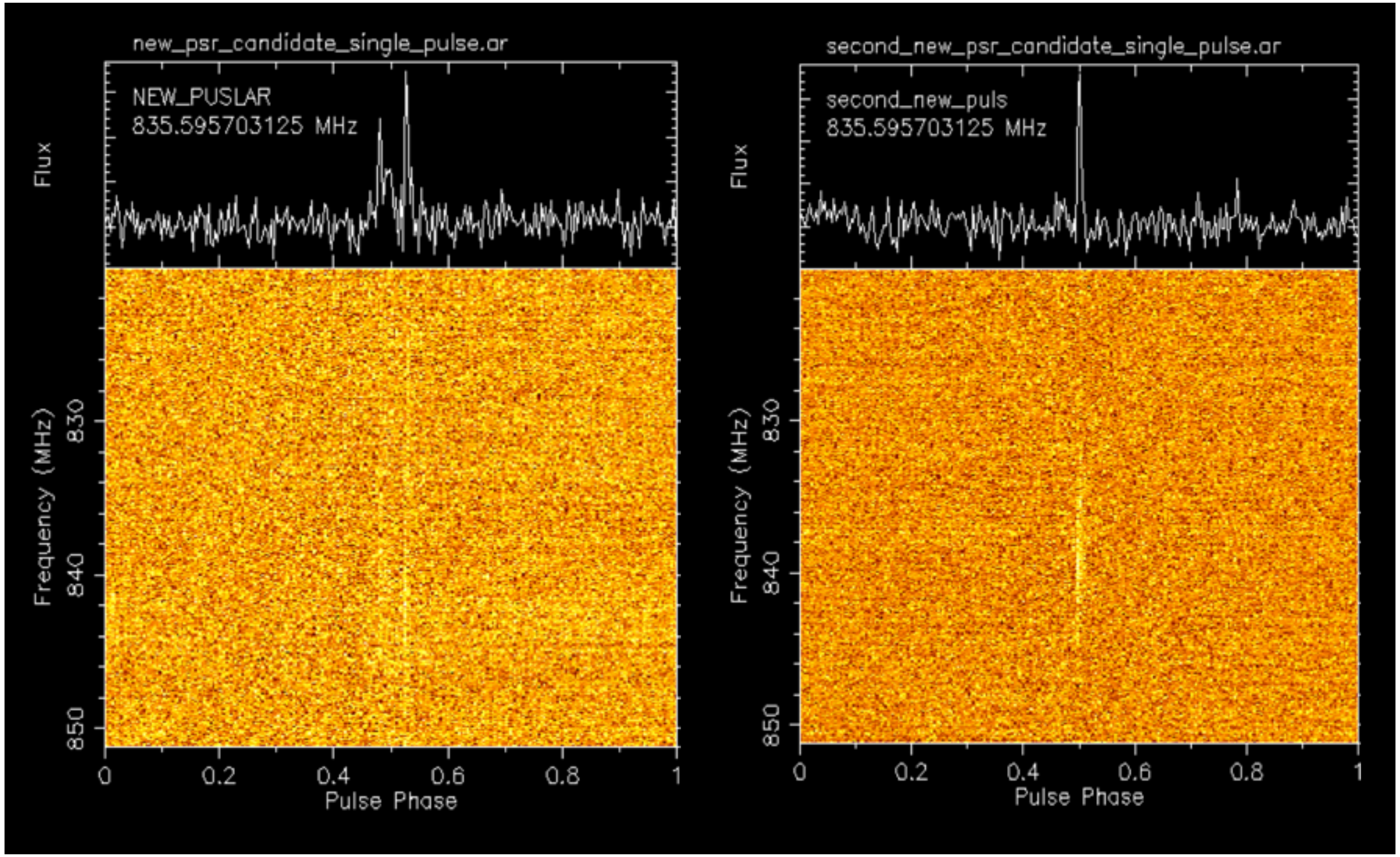


New intermittant pulsar!

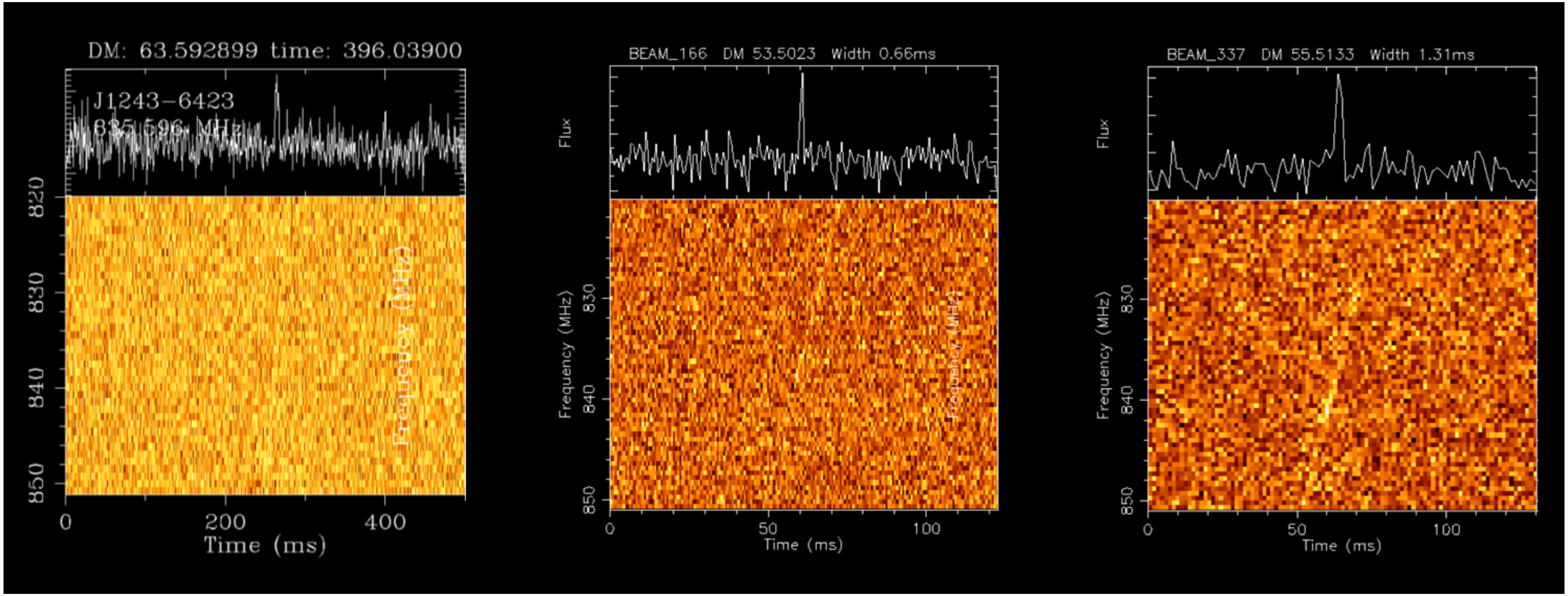


- Venkatraman Krishnan et al. (2020a):
  - UTMOST Survey for magnetars, intermittent pulsars, RRATs & FRBs (SMIRF).
  - One new intermittent pulsar candidate: PSR J1659-54.
  - P = 0.54 s, DM = 134 pc cm^-3.

Another new intermittent pulsar?

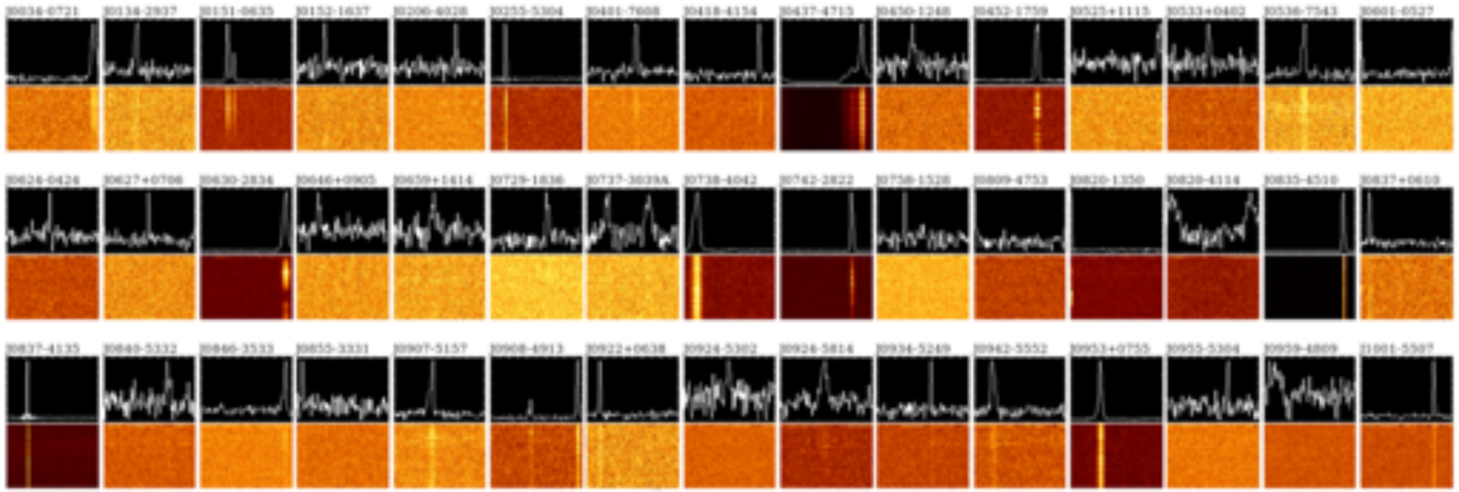


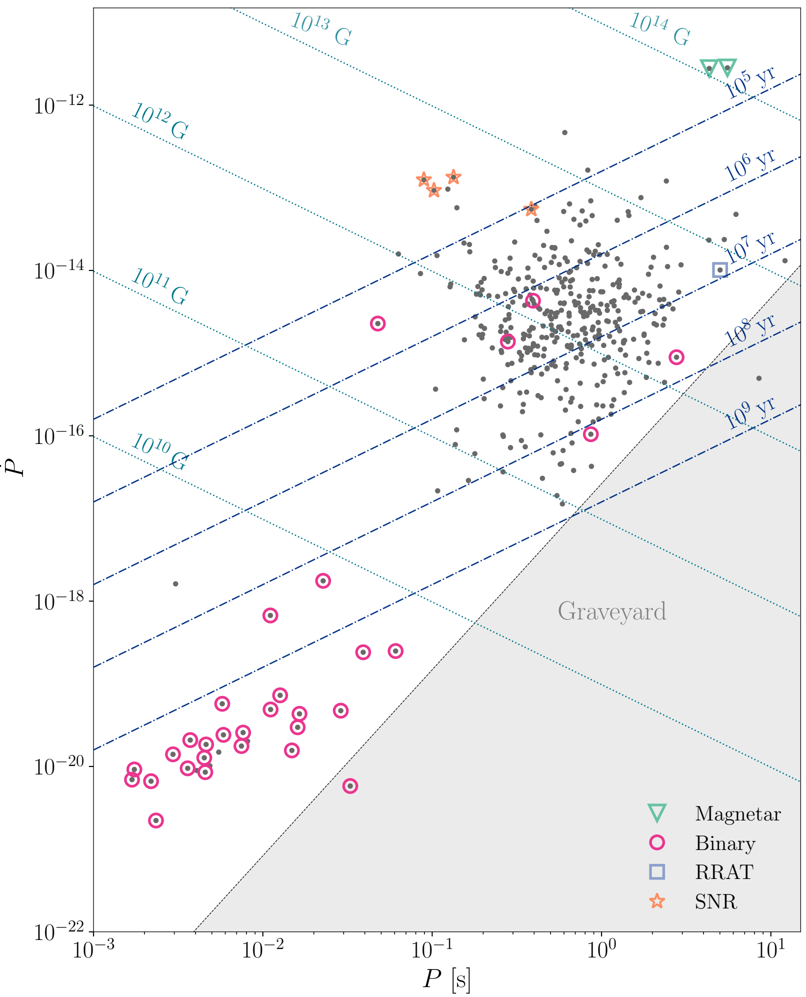
Orphan pulses



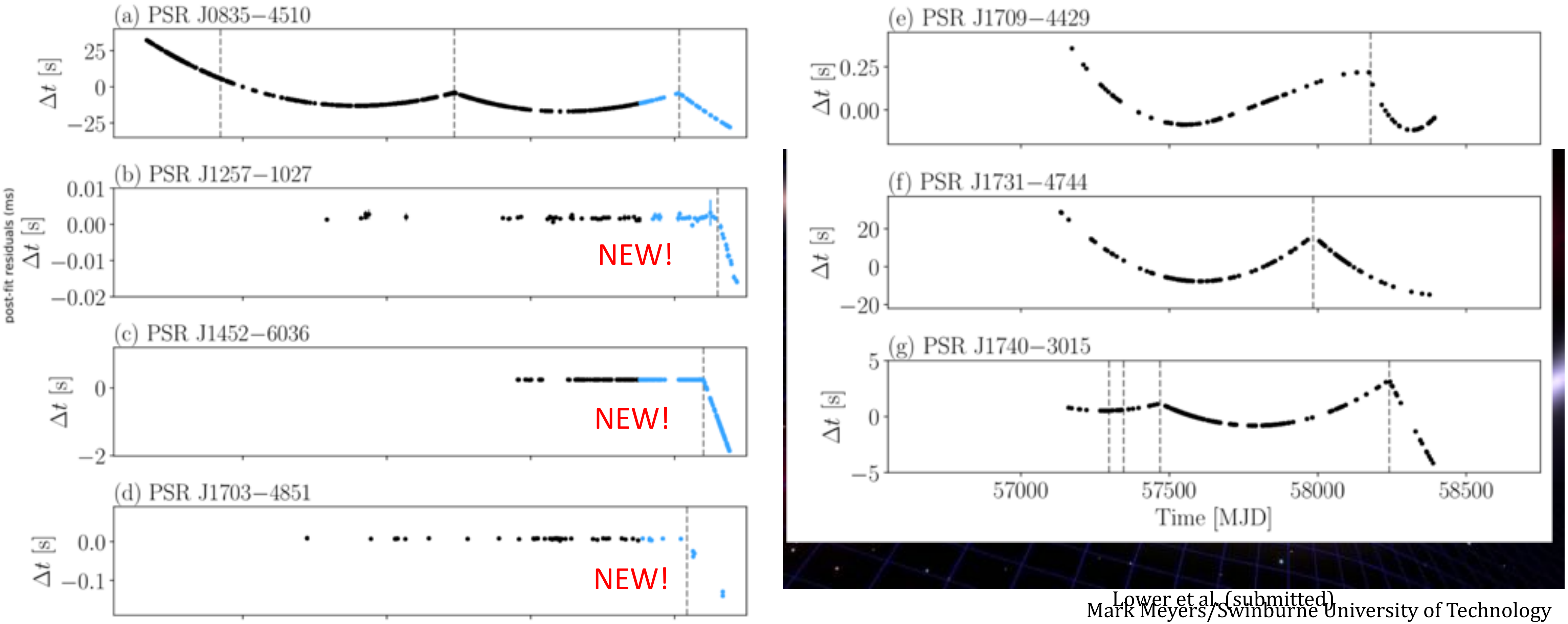
Pulsar timing programme

- 417 pulsars monitored for 5 years.
- ~300 pulsars observed every 10 days.
- Cadences of 3-7 days.





Why time so many pulsars?

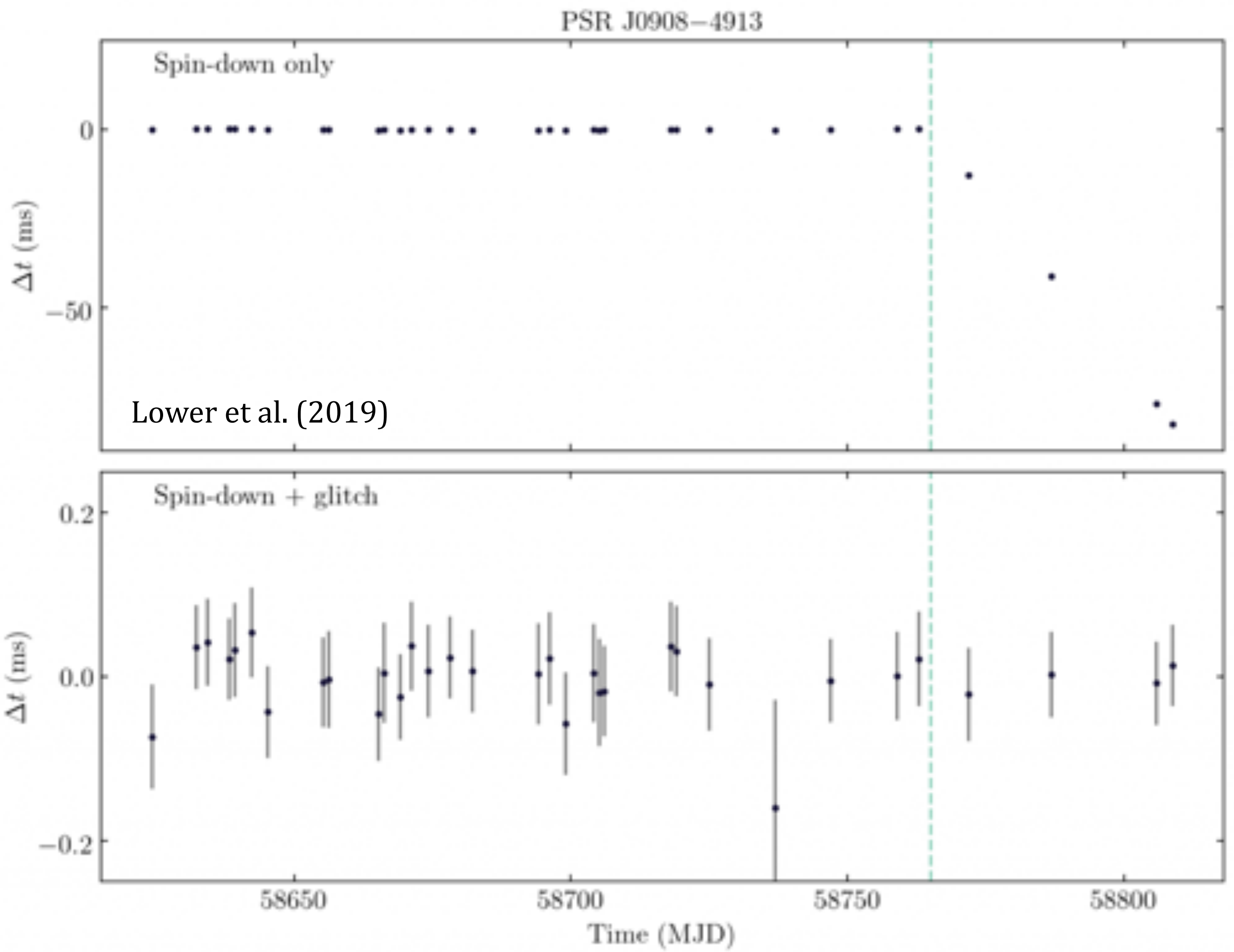


Lower et al. (submitted)

Mark Meyers/Swinburne University of Technology

First detected glitch in PSR J0908-4913

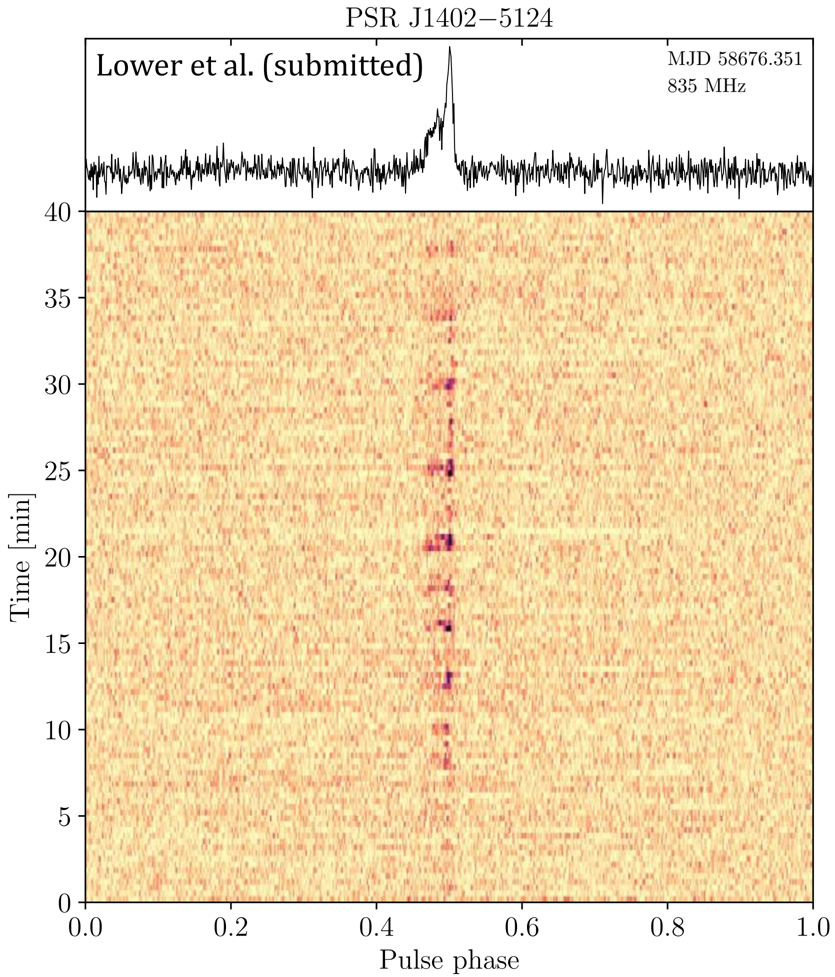
- Observed for ~20 years by Parkes – no glitches.
- Also seen in Parkes P574 data.



Lower et al. (2019)

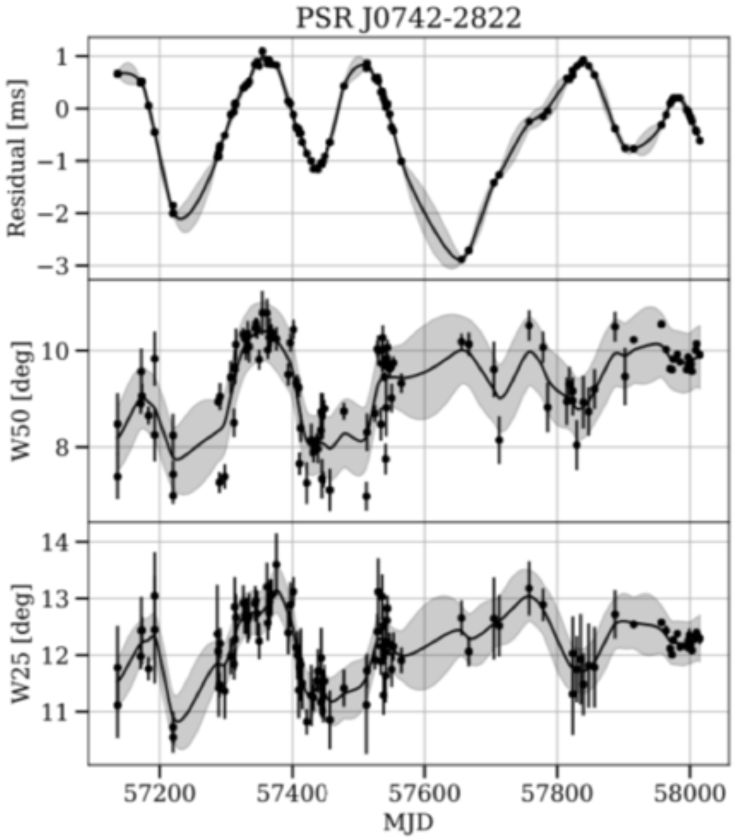
Re-discover long-lost friends

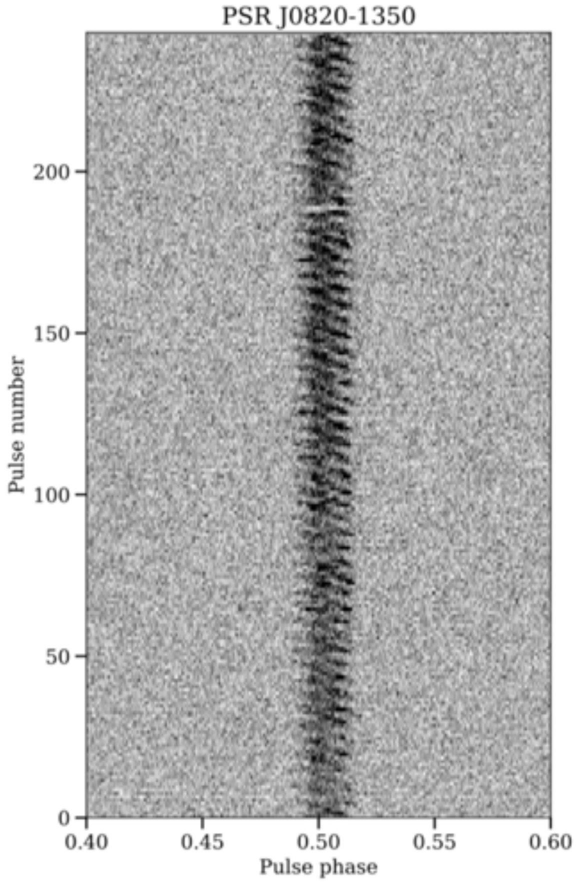
- Discovered by MOST in 1969.
- Catalogue position incorrect by ~ 1 degree (Manchester et al. 1978).
- Missing in timing observations.
- New position (J2000):
  - RA = 14:02:56.0(2)
  - DEC = –50:21:43(49)



Updated pulsar properties

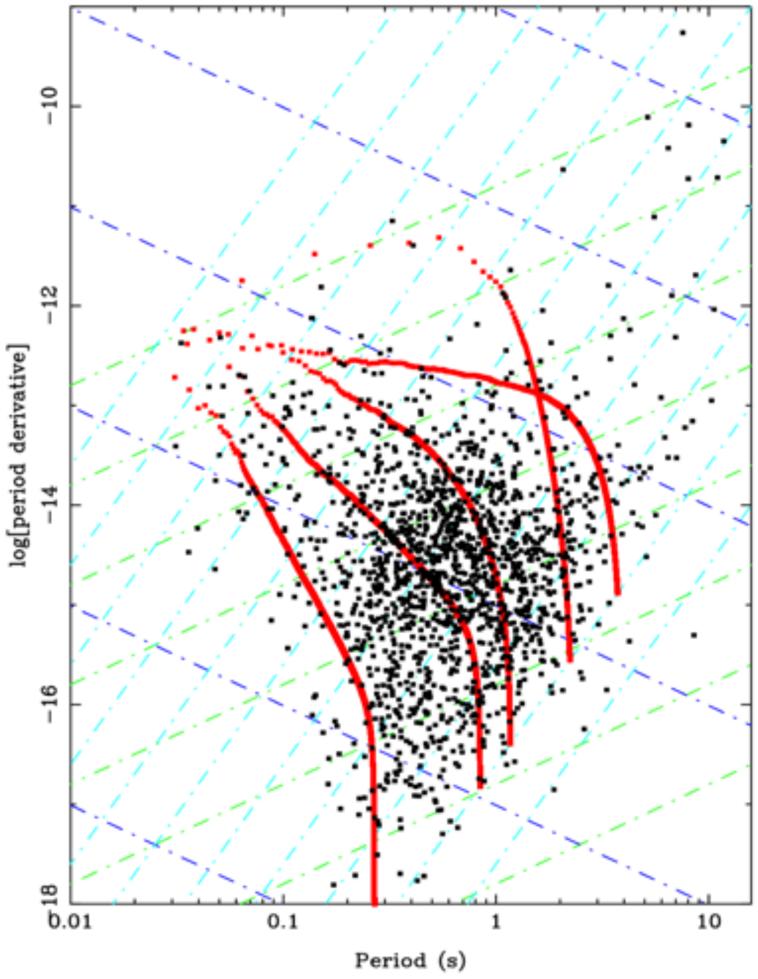
- Jankowski et al. (2019):
  - Updated properties of 200 pulsars.
  - Flux densities & pulse widths at 843 MHz.
  - Proper-motions.
  - Case studies for 2 pulsars.





How do pulsars evolve over time?

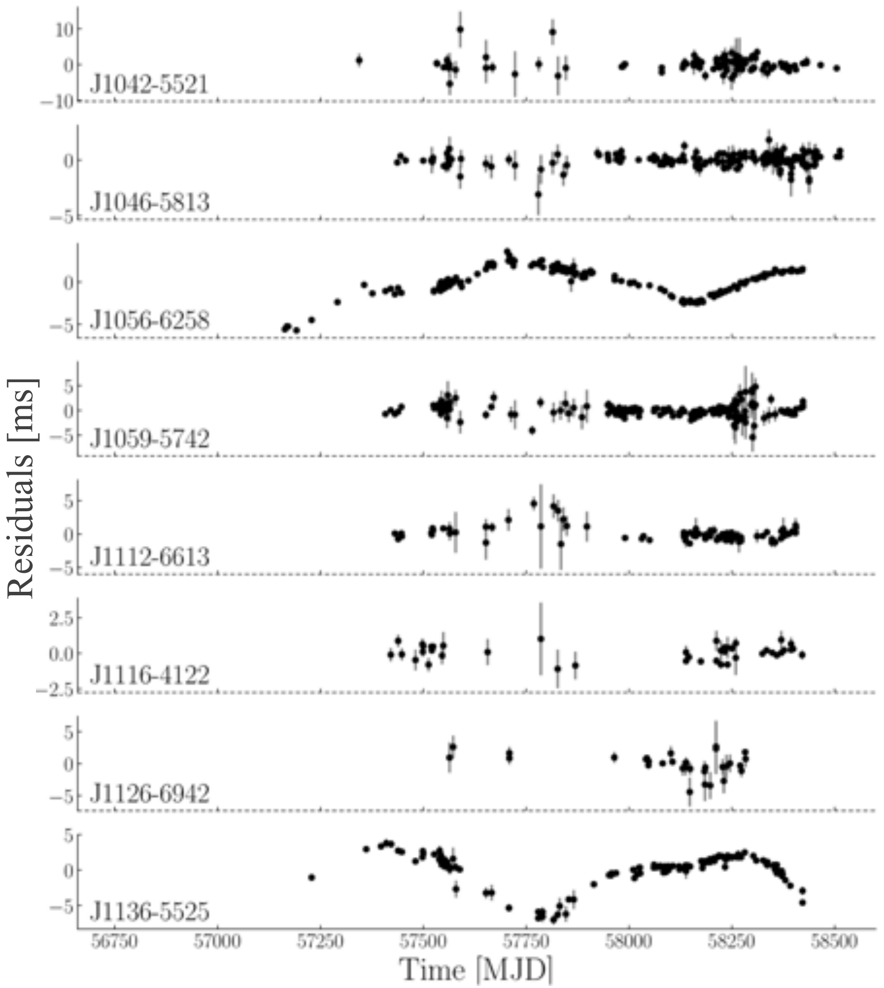
- Problem: pulsar lifetime >> human lifetime.
- Solution: look at lots of pulsars.



Johnston & Karastergiou (2017)

“Red noise” in pulsar timing residuals

- Red noise – wandering in pulse arrival times.
- Potential origins:
  - Propagation effects.
  - Discrete emission/spin-down states.
  - Free precession.
  - Spin noise.
  - Gravitational waves.
- May tell us something about neutron star interiors…



How do we model red noise?

- Fourier transform the residuals, fit the power spectrum with a power law:

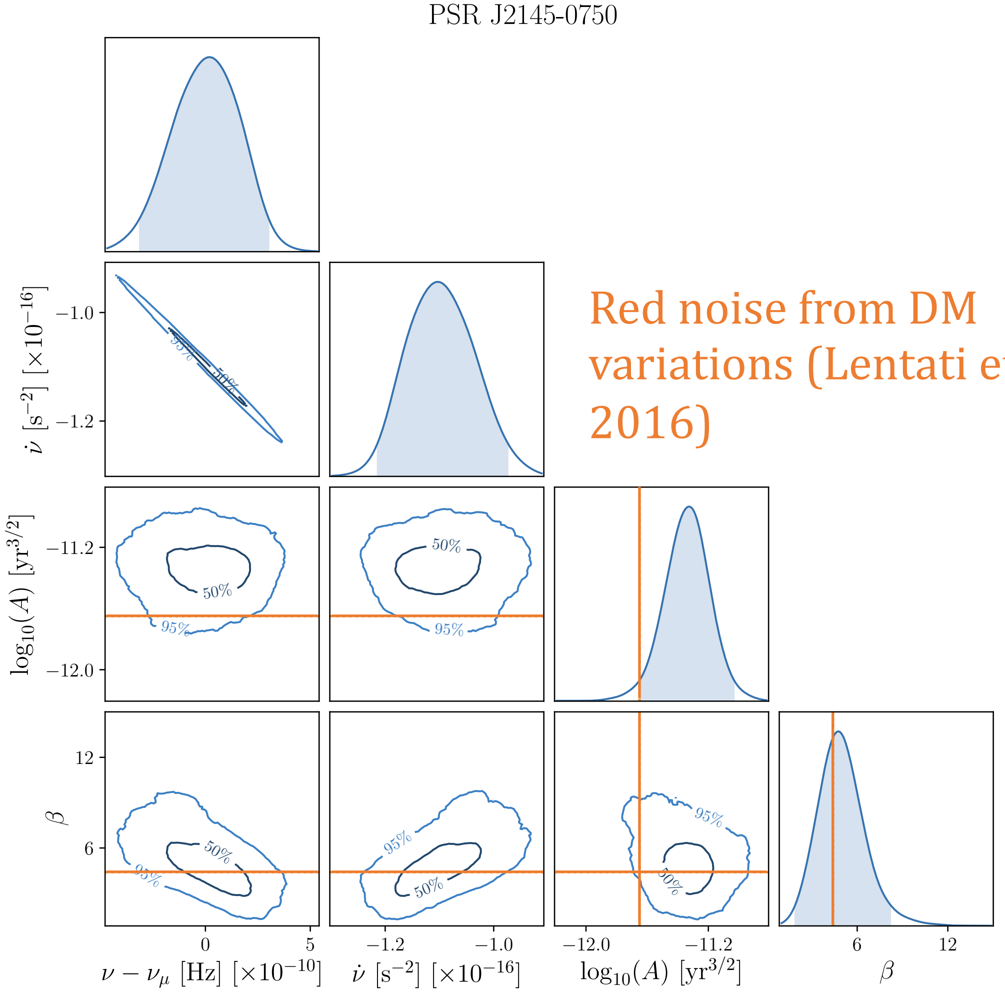
$$P_r(f) = \frac{A^2}{12\pi^2}\left(\frac{f}{f_{\mathrm{yr}}}\right)^{-\beta}$$

- Modelled alongside pulsar properties with TempoNest (Lentati et al. 2014).
- Effective red noise strength:

$$\sigma^2_{\mathrm{RN}} = A^2\, T^{\beta-1}$$

Results for individual pulsars

- DM variations dominate in millisecond pulsars.
- 112 normal pulsars favour the red noise model.
- Also looked for higher-order frequency derivatives.
  - None detected…

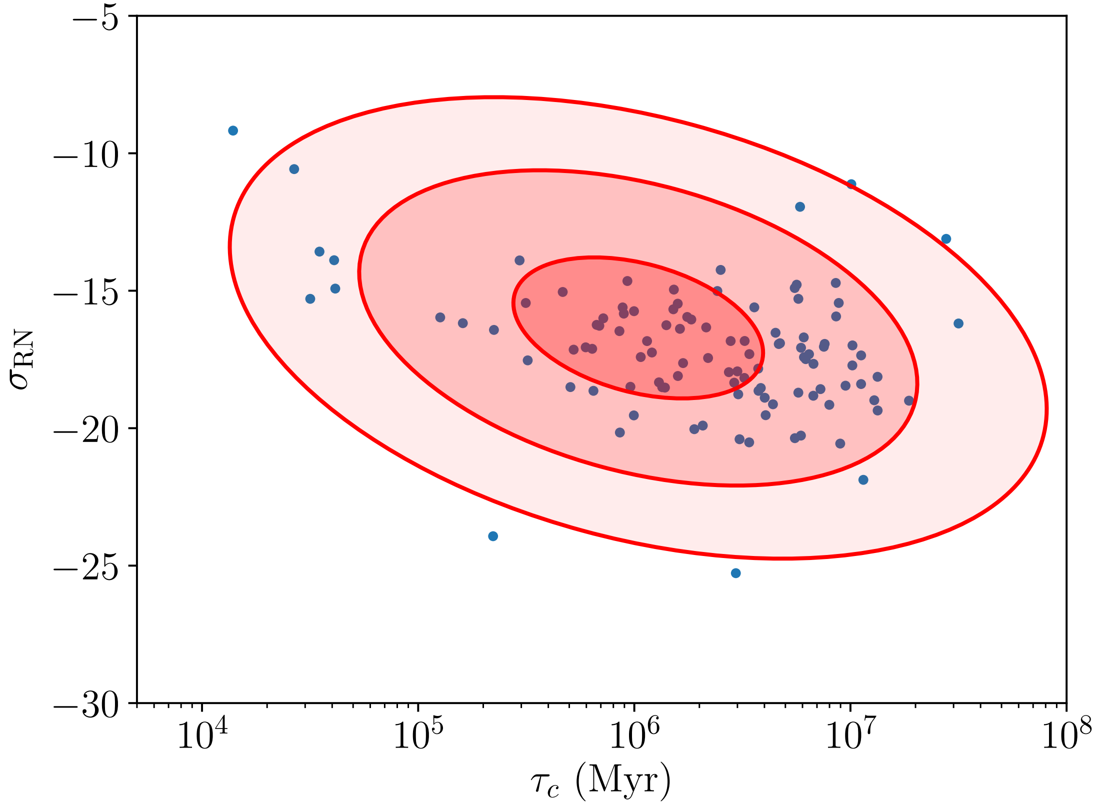


Red noise from DM variations (Lentati et al. 2016)

Red noise correlations?

- Estimate pulsar properties from spin & spin-down.
- Assume measurements drawn from a bivariate Gaussian.
- Sample hyper-parameters with Bilby: $\{\mu_\sigma, \mu_\chi, \sigma_\sigma, \sigma_\chi, \rho\}$
- Strongest correlations with spin-down & characteristic age.

Not actual fitted result



https://git.ligo.org/lscsoft/bilby

Red noise scaling across the population

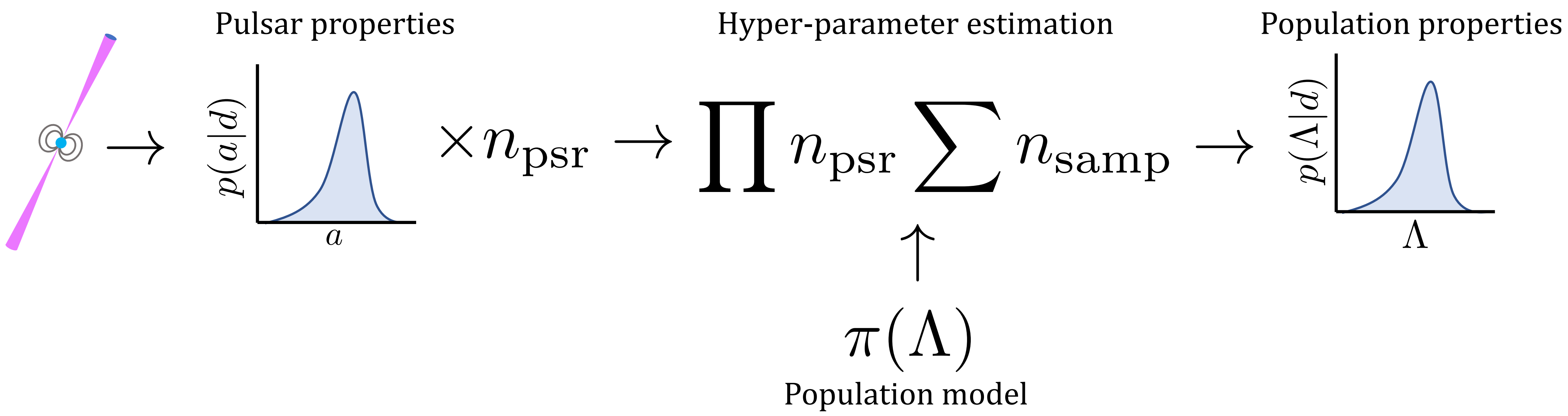
- Red noise scaling model from Shannon & Cordes (2010):

$$\chi_{\mathrm{RN}} = \xi\, \nu^a |\dot{\nu}|^b T^\gamma$$

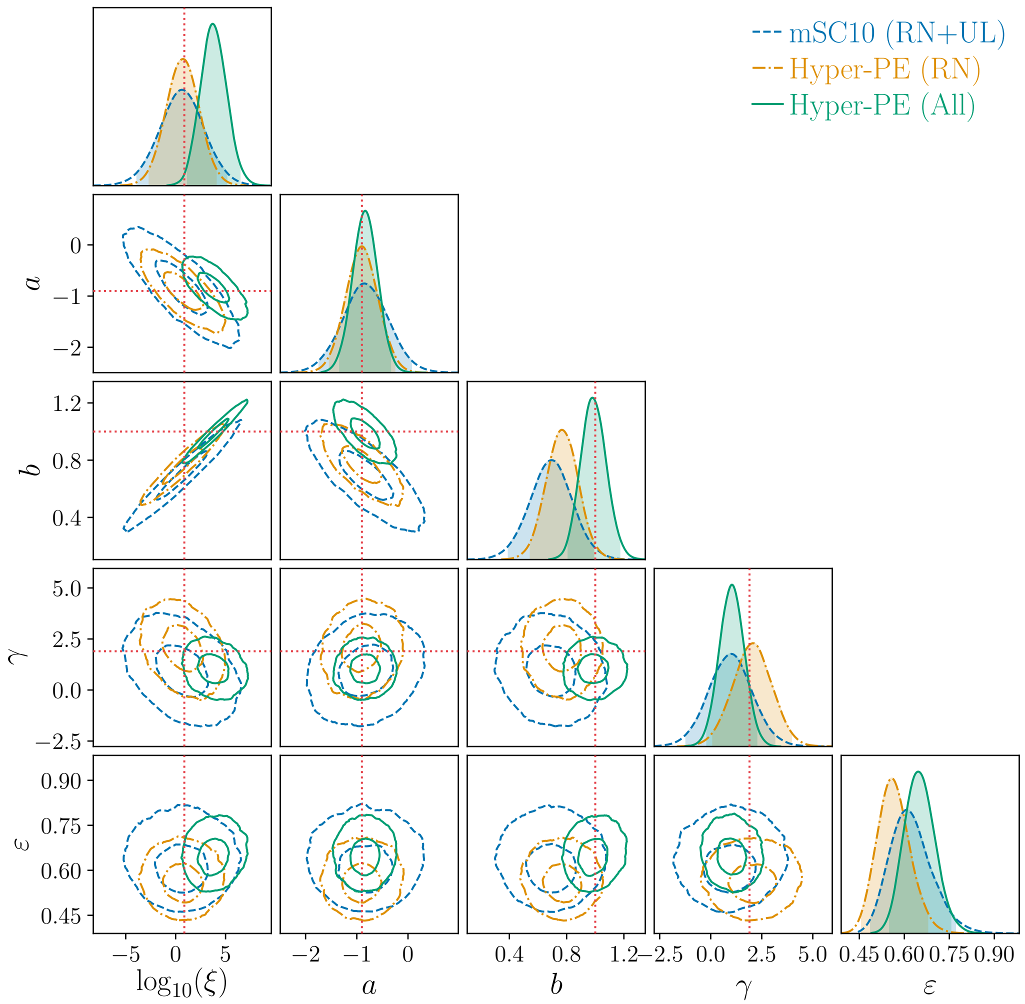
- Tried a modified version of their maximum likelihood framework.
- Doesn't take into account all available information – use hierarchical inference!

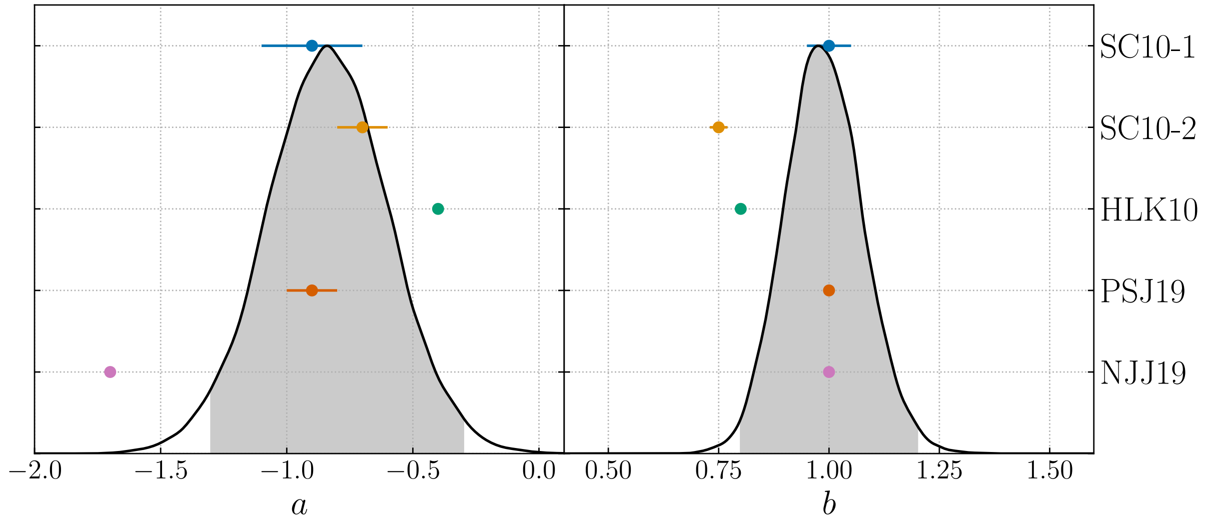
Hierarchical inference

- Combining posterior samples from individual pulsars to infer underlying population properties.



Population results

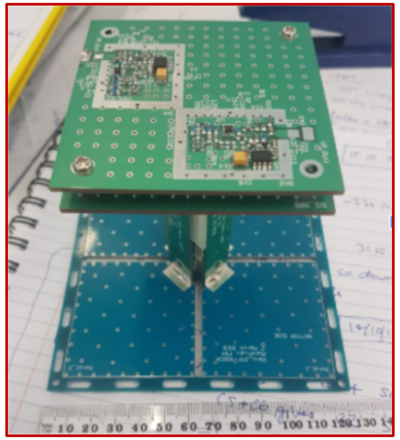


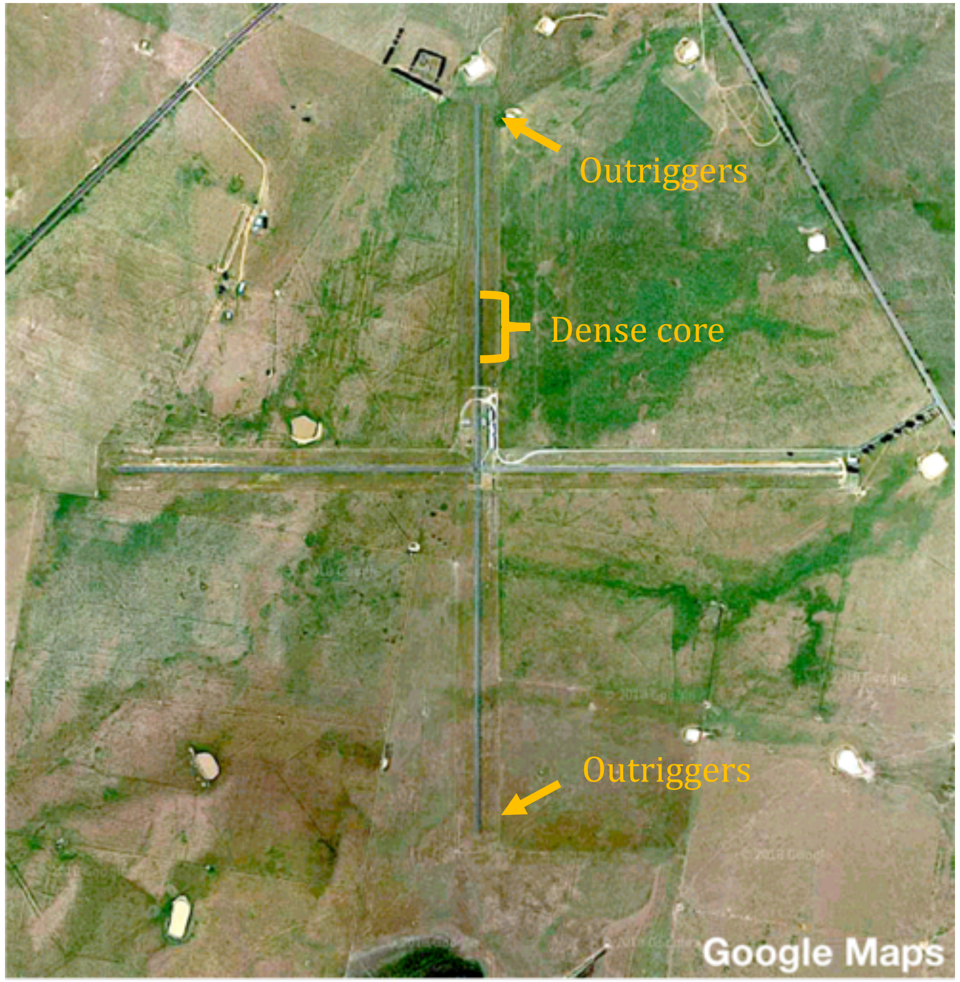


- Will improve with addition of longer data sets/more pulsars.
- Easily extended to physically motivated models (if available).

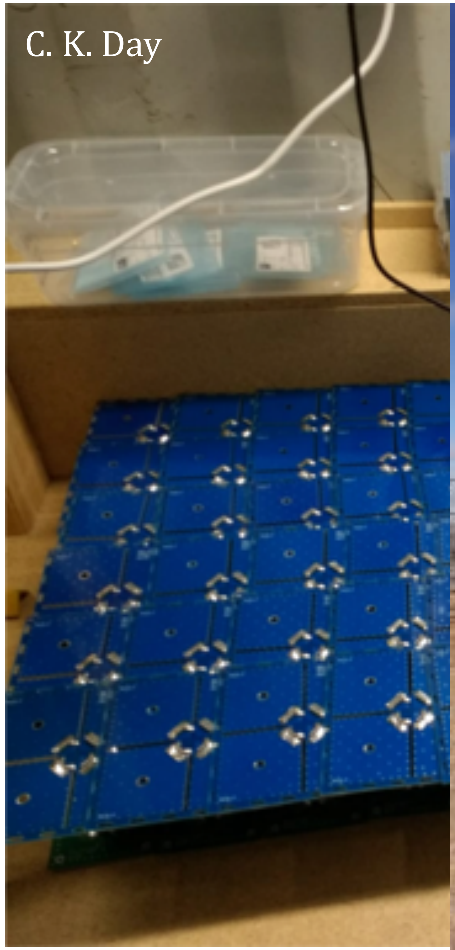
UTMOST-2D

- Re-fitting the north-south arm.
- Outriggers at far ends of NS-arm.
- 100 m dense core ≈ EW-arms.
- 12.7 x 2.5 degree field of view.
- Dual polarization.
- Electronic beam-forming.
  - 500 pulsar observations per day





UTMOST-2D: current progress



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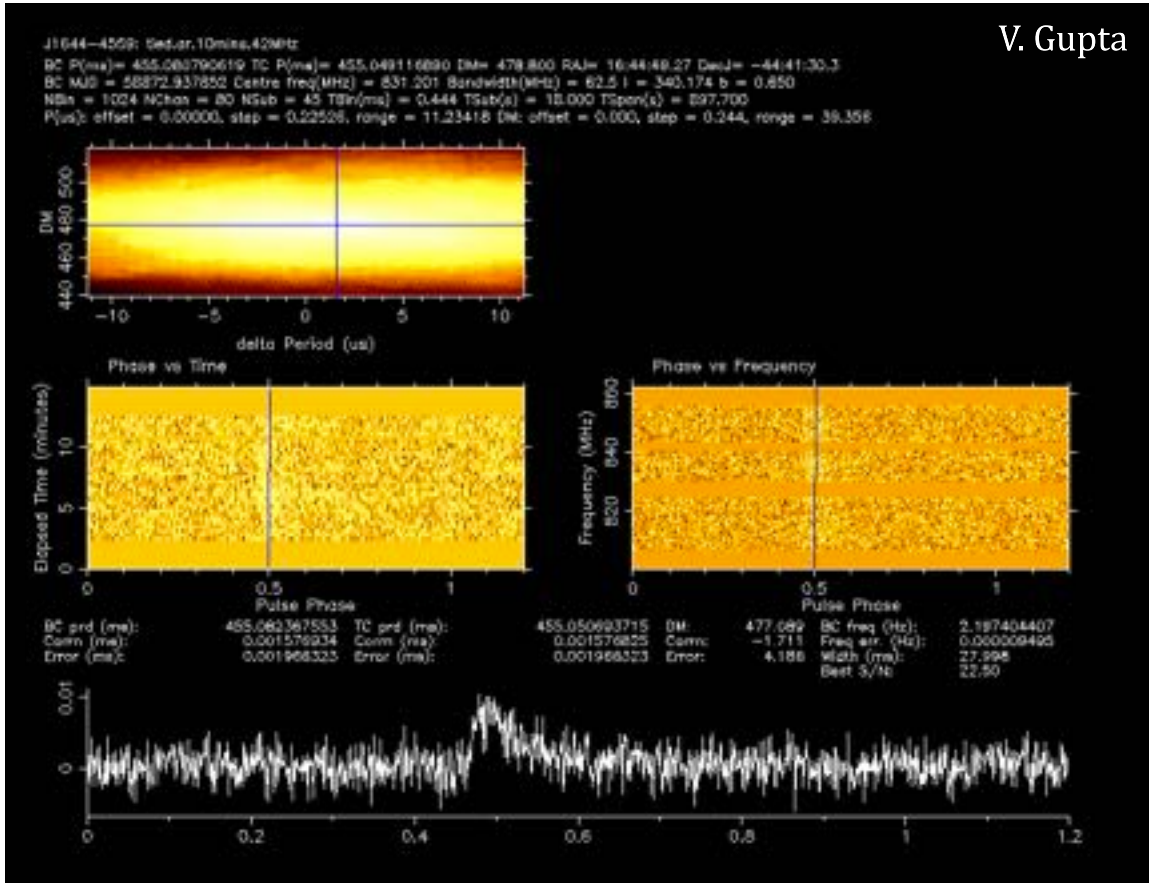

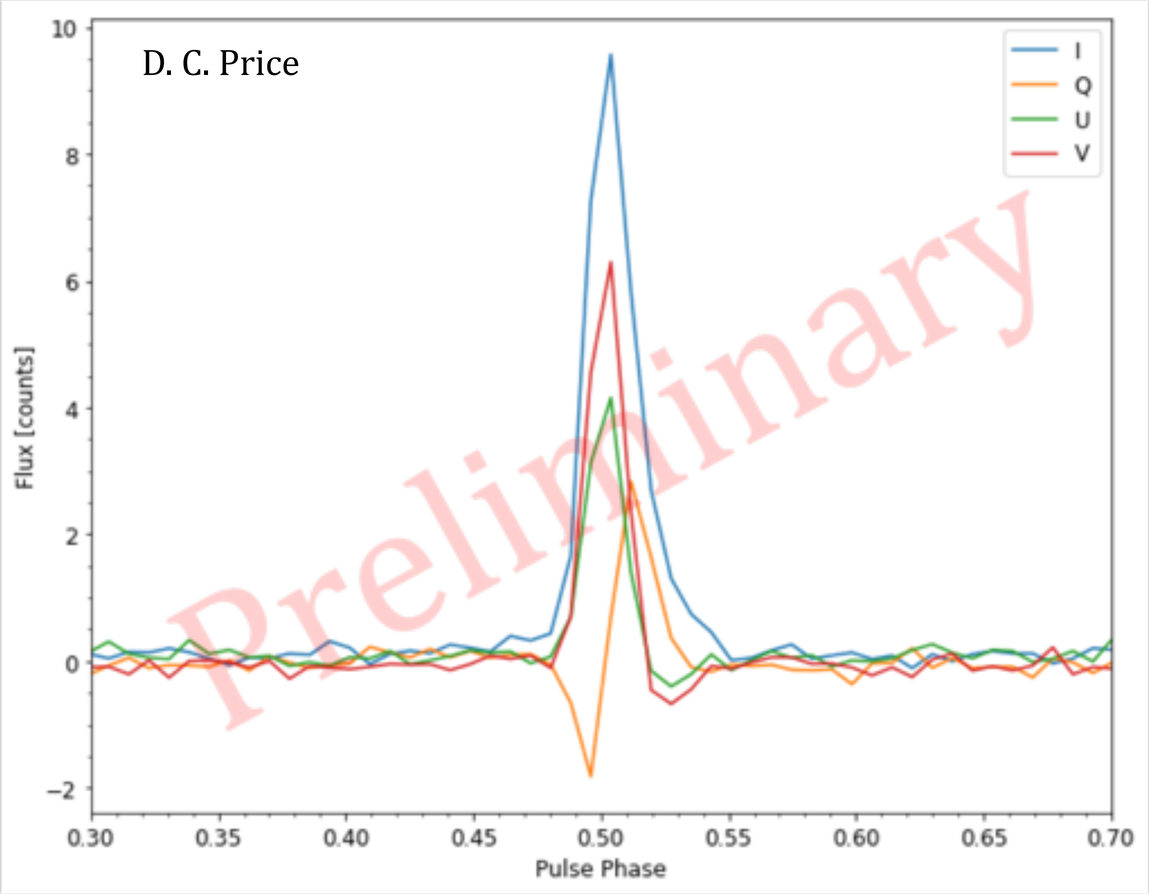

UTMOST-2D: potential upgrades

- Phase 2
  - Outfit the entire NS-arm with new antennas.
  - Massively increased sensitivity.
  - Timing observations of > 1000 pulsars every day.
  - $\sim$1 FRB detected per day.
- Phase 3?
  - Outfit EW-arms with new antennas.
  - Multiple FRB detections per day.
  - Increased rate of FRB localisations.
  - Even more pulsar observations.

Summary

- MOST has been transformed into UTMOST: a pulsar timing, FRB detecting machine.
- Observed 13 glitches to date (found 9).
- Equivalent red noise scaling measurements to other large timing programmes via hierarchical inference framework.
- Upgrade to the UTMOST-2D system ongoing: first localised FRBs later this year.
- Potential future upgrades would enable timing of 1000’s of pulsars with daily cadences.

Extra slides