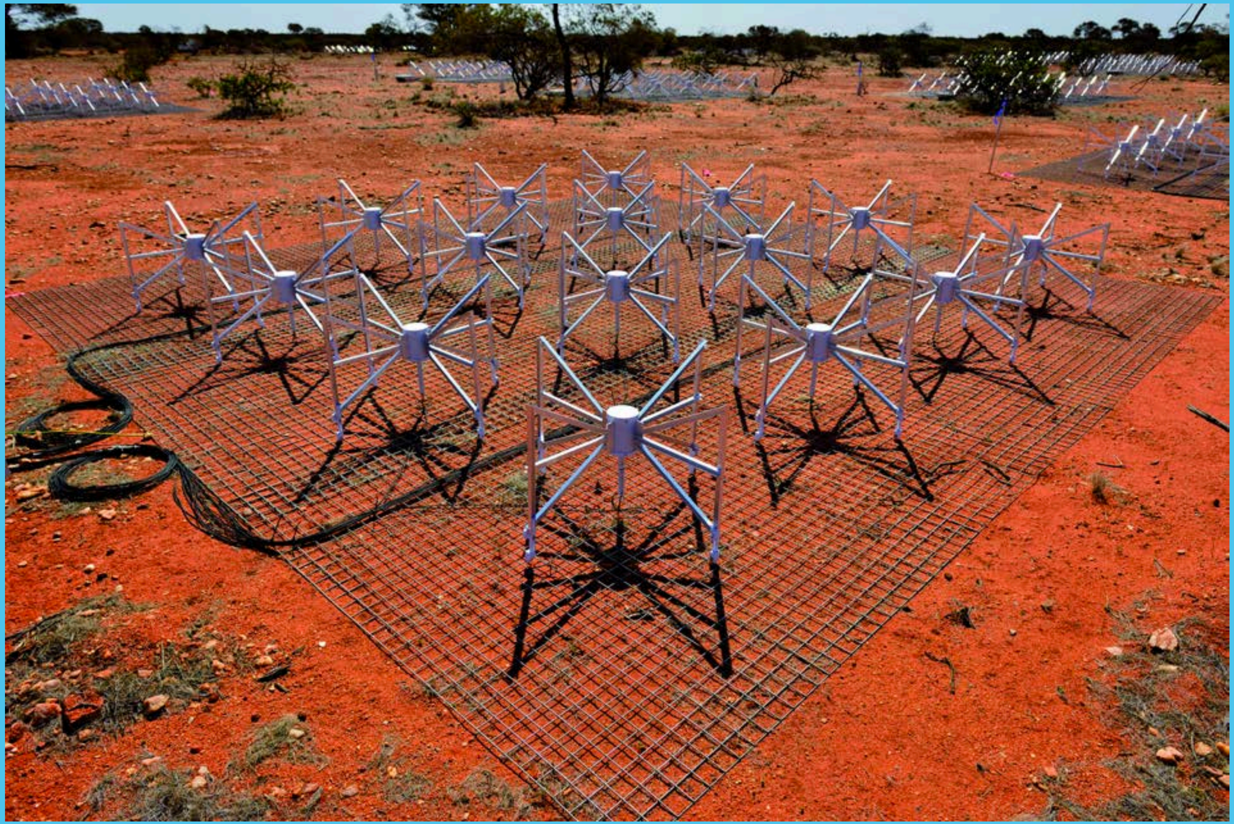

Pulsar science with (e)MWA

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Astronomy and Space Science
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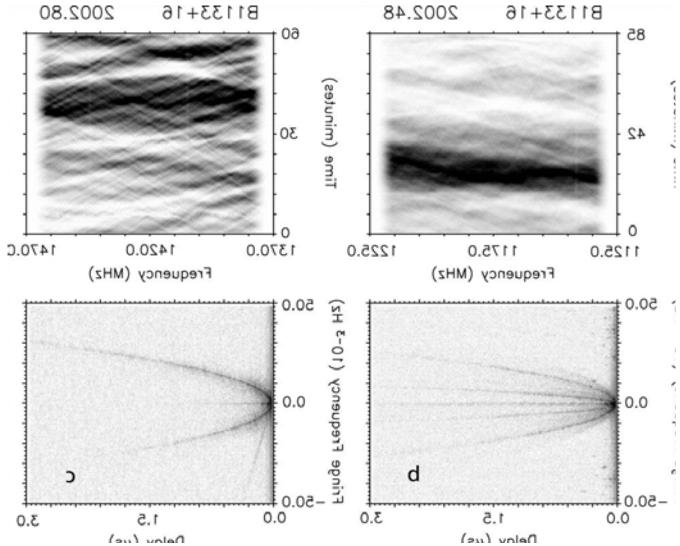
CSIRO

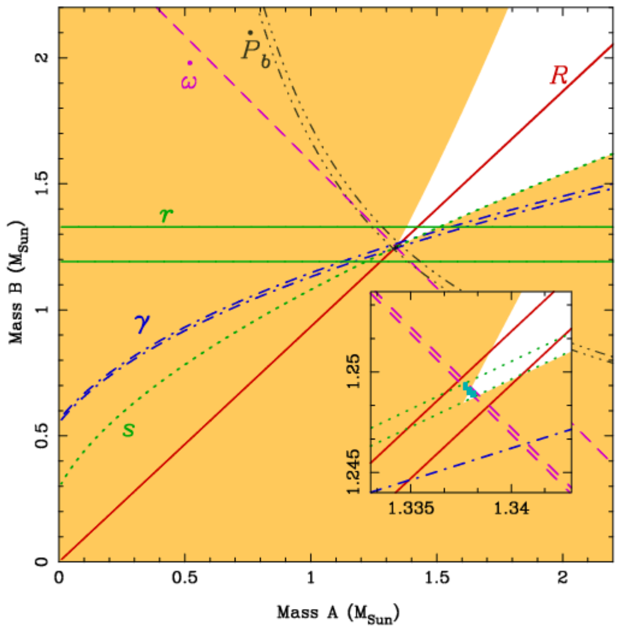
Why pulsars?

- **Plasma physics**
  - Pulsar magnetospheres are extreme places
  - We don't understand how coherent emission works!
  - Help us understand relativistic processes occurring in more distant places in the Universe (supernovae, gamma-ray bursts, fast-radio bursts)



- **Compact radio sources that probe the interstellar medium (ISM)**
  - The more we observe the ISM, the weirder it looks

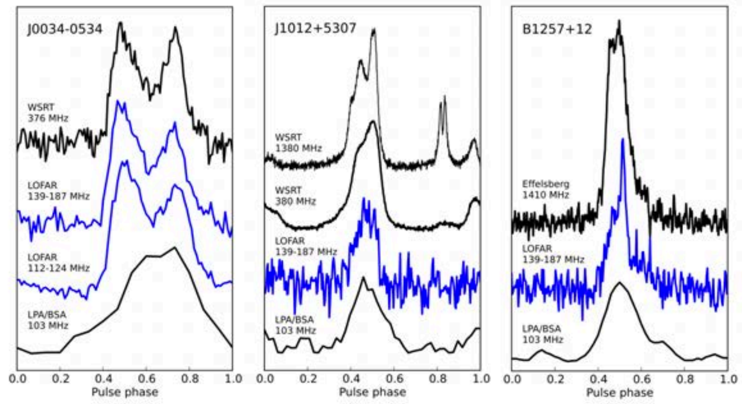
- **Clocks in space**
  - General Relativity, Nuclear Equations of State, Gravitational Waves



Why low frequency?

- Steep spectral indices
  - But does the spectrum peak?
- Wider beams
  - More action in the magnetosphere
  - More fractional bandwidth
- Multi-(radio) wavelength complementarity
- ISM studies
  - Scale strongly with frequency

Example LOFAR observations



Fluxes of PPTA pulsars (Dai et al. in prep)

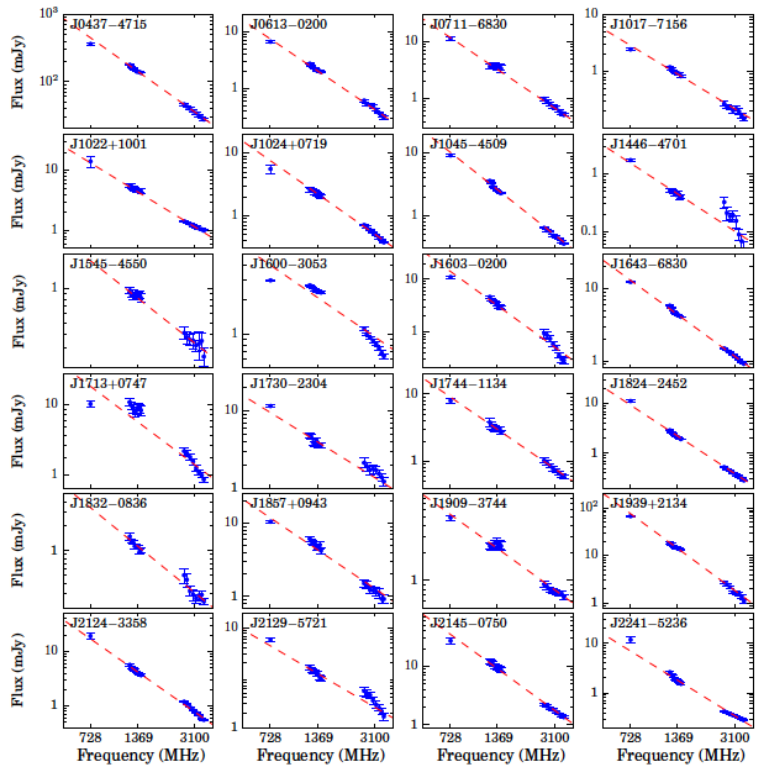
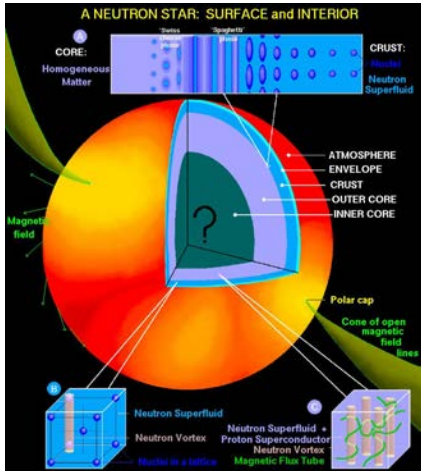
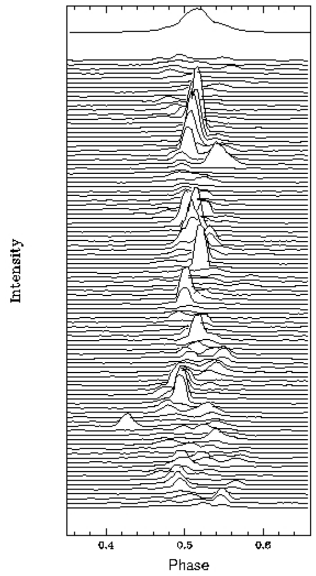


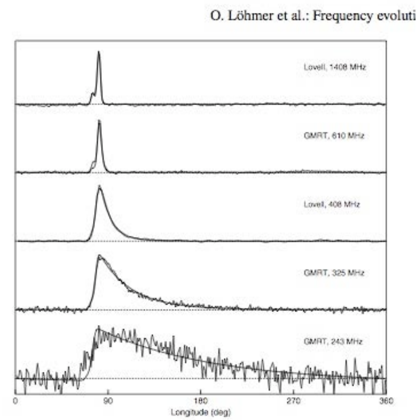
Figure 1. Flux density spectra for 24 MSPs. The fitted power-law spectra are indicated with red dashed lines

Outline

- Pulsar Emission and Variability
- Examining the interstellar medium
- Imaging pulsars and their fields
- 1
- What are the limitations to pulsars as clocks? What can low-frequency observations tell us about these limitations?
- Goal: present science through a series of example projects







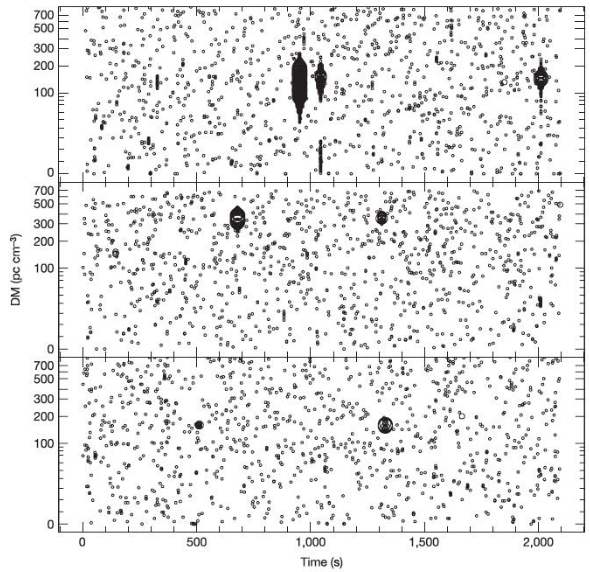
Unifying pulsar emission

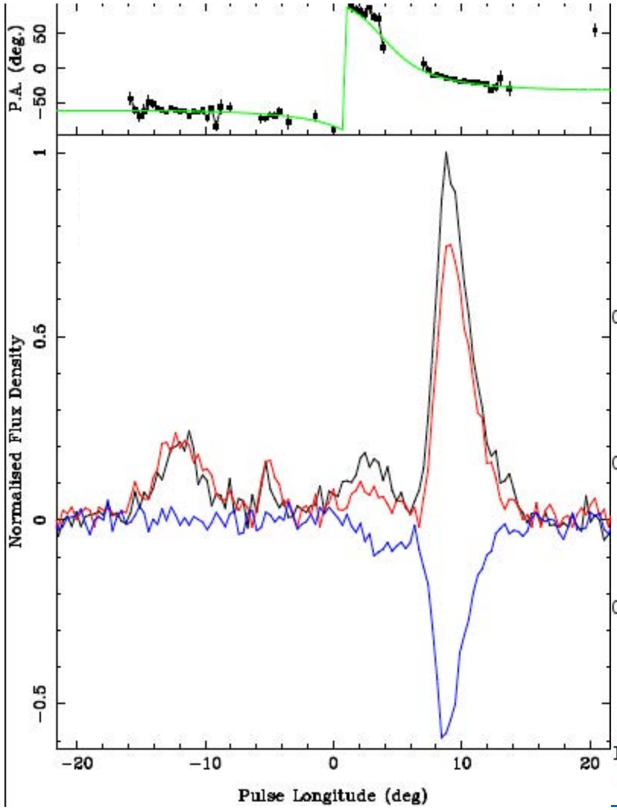
- Radio emission from neutron stars
  - **Rotating radio transients:** sporadic bright pulses
  - **Nulling:** occasional cessation of radio emission (1-1000s of pulses)
  - **Intermittency**: like nulling, but off-states last days to years
  - **State-changing:** like intermittency, but only see change in pulse shape
  - **Giant pulses:** extremely bright nano-second duration pulses
- Why the different *observed* emission?
  - Magnetosphere (Period, Period-derivative, magnetic axis)
  - Geometry (viewing angle)
  - Low frequency observations can help with both of these things.
- Find pulsars exhibiting multiple modes of emission at the same time

Example: PSR J0901-4624

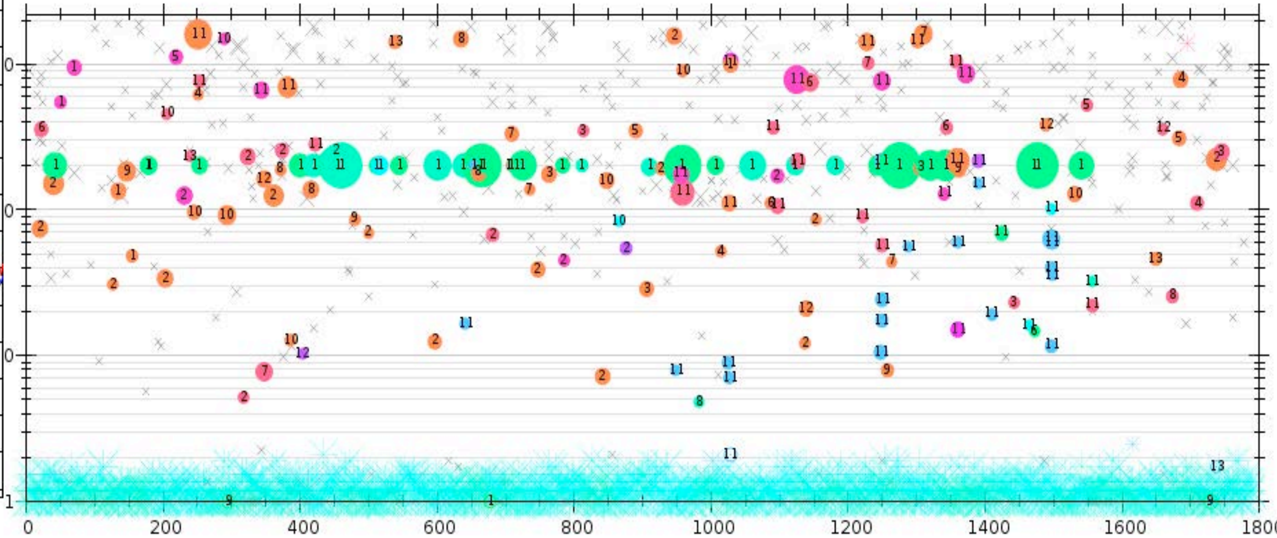
- An apparently normal pulsar
- RRAT-like mode occurs simultaneously with normal emission mode
  - Pulse widths
  - Power-law statistics?
- RRAT mode has different polarisation state
  - Different part of magnetosphere

RRAT (McLaughlin et al. 2006)



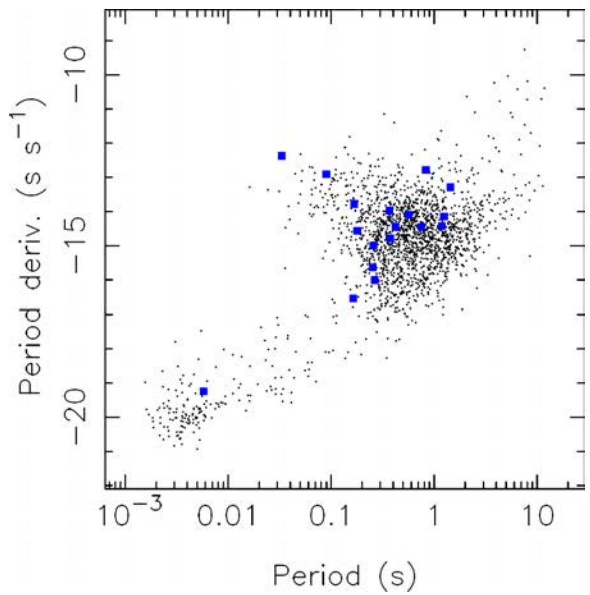


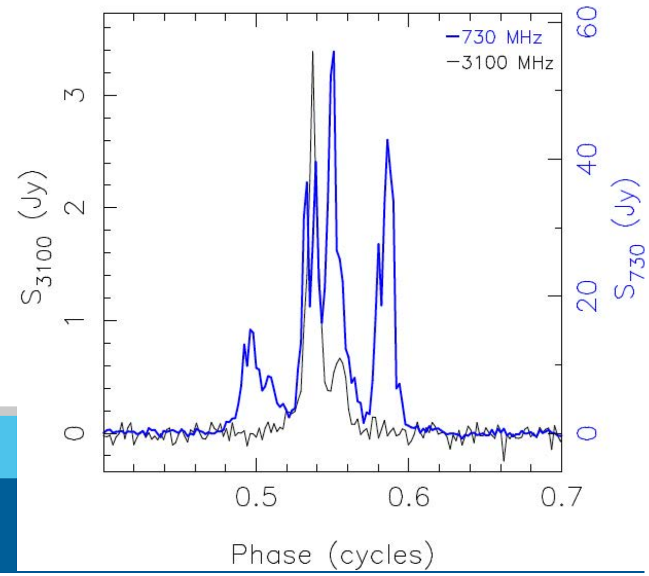
PSR J0901-4624 (Raithel et al, in prep).



Proposal: What is the bandwidth of pulsar emission?

- Over what range of frequencies (altitudes) is pulsar emission correlated?
- Survey 20 bright pulsars that are representative of the pulsar population
- Example MWA + Parkes
  - 150 MHz, 700-760 MHz, 2.5-3.5 GHz
  - Best and brightest pulsars
  - Measure polarisation of individual pulses
- Extension: monitoring programme
  - How do single pulse properties change with time?

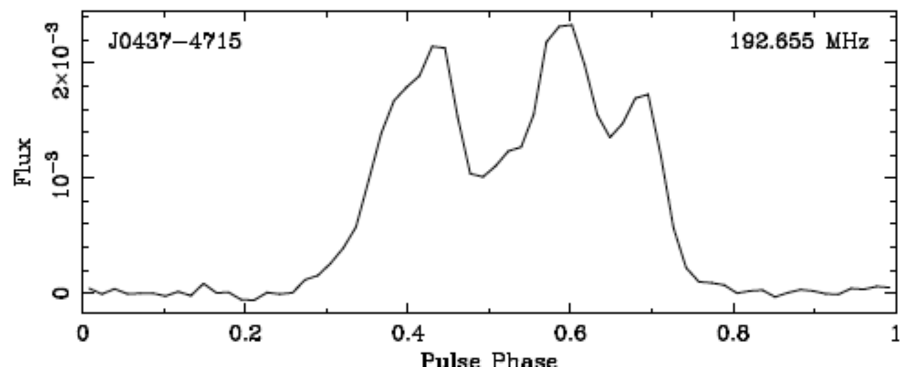




Pulse profile evolution

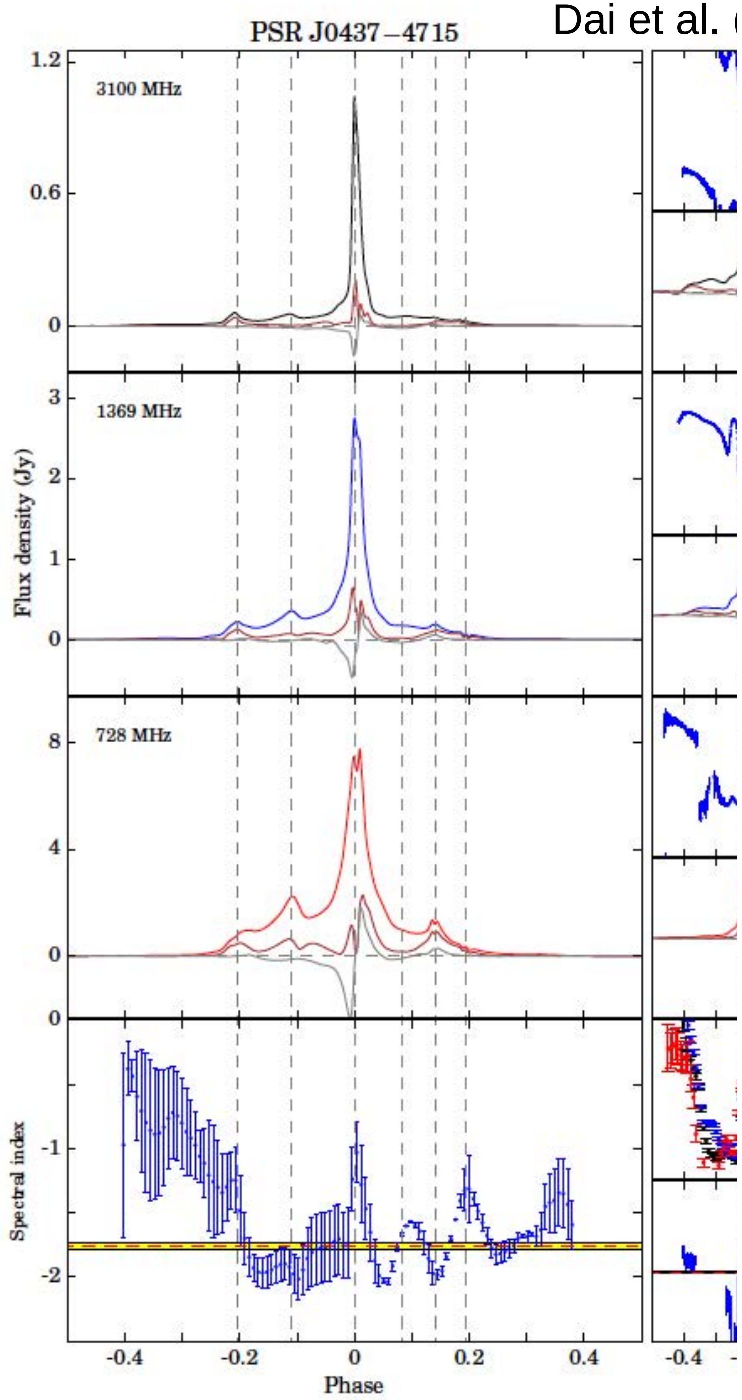
- Tomography of pulsar magnetosphere
  - Low-frequencies = higher altitude?
- Also important to understand profile evolution for precision timing
  - New algorithms for pulsar timing
- Example: observations of MSP J0437-4715 at 3100/1400/730 MHz with Parkes and 200 MHz with MWA (Bhat et al. 2014)

Bhat et al. (2014)



Need Higher time resolution

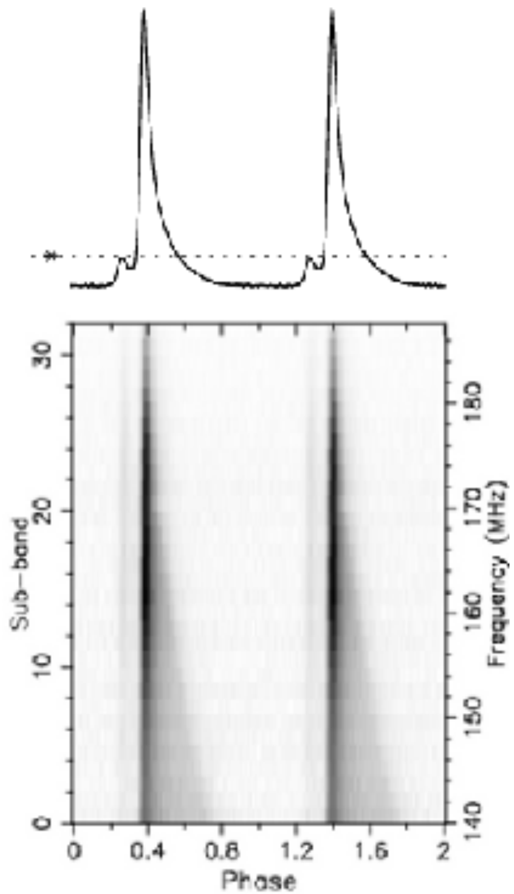
Dai et al. (



Integrated emission at low-frequency

- Question: What do southern pulsars look like at 100 MHz?
- Data: high-SNR profiles of a diverse sample of pulsars.
- Complement high quality high-frequency observations from Parkes
- Use continuum maps as finder chart for bright pulsars at 100 MHz

- Requirements:
  - High-fidelity polarimetry
  - 100 microsec time resolution may be sufficient for slow pulsars, insufficient for faster pulsars



LOFAR observations of a very bright pulsar

Continuum searches for pulsars

- Ultimate goal: Find pulsar-black hole binary

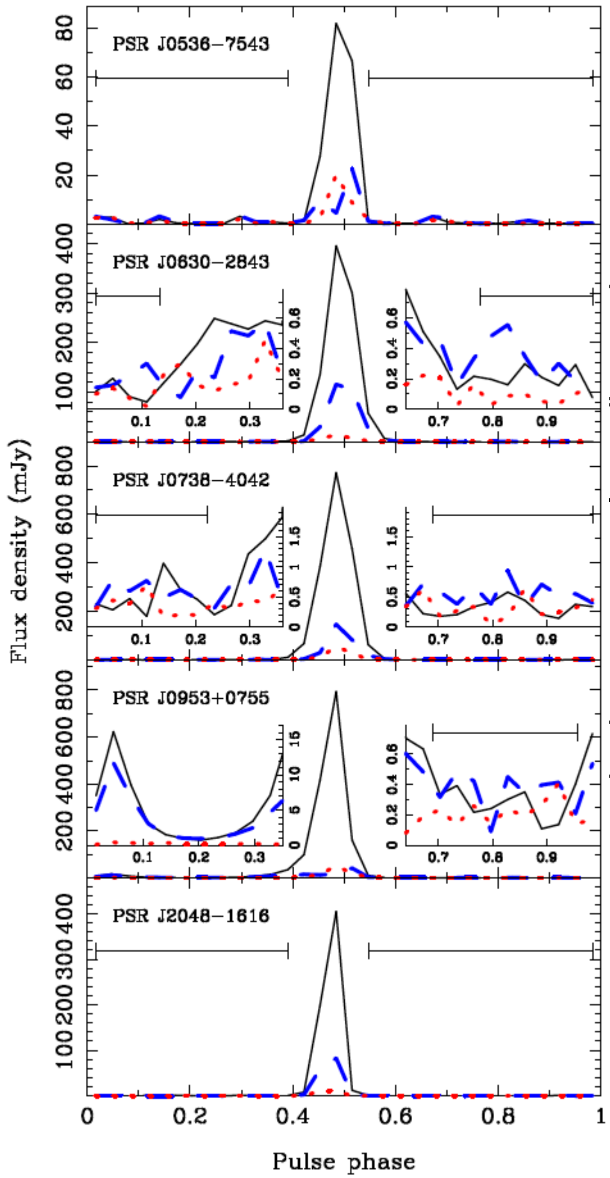
- Polarisation
  - High degree of circular polarization: Stokes V
  - Look for effects of RM variation in multi-frequency synthesis images of stokes Q and U (point sources turn into doughnuts)

- Scintillation
  - Search for the closest pulsars (do you need a bright source to benefit from higher order statistics)

- Complementarity to single dish searches
  - Narrow phase-space for periodicity searches
  - Highly accelerated systems (Pulsar-Black Hole Binary)
  - Intermittent/bursty pulsars

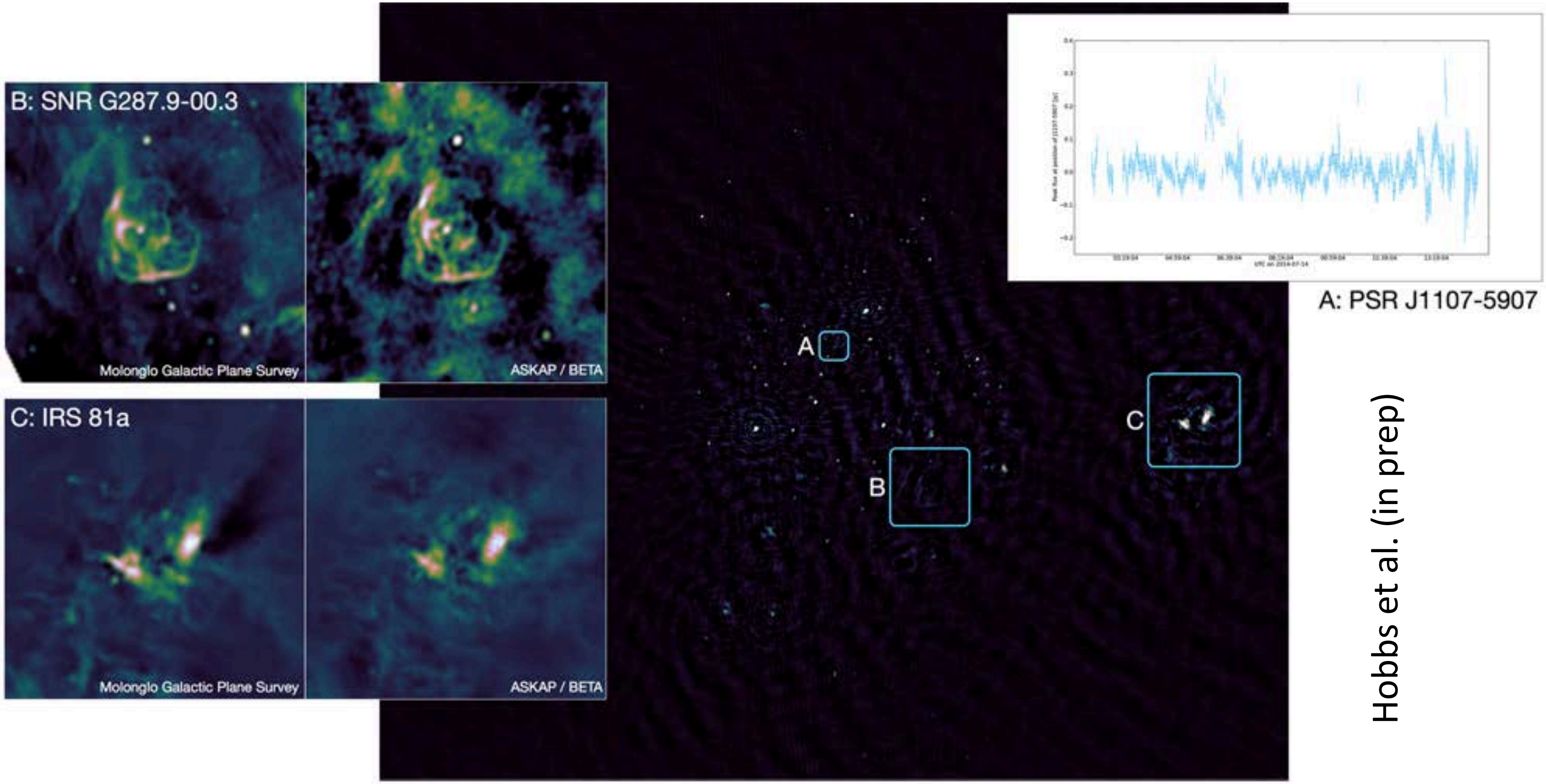
Continuum observations of pulsars

- Off-pulse emission
  - Is emission confined to regions around magnetic axis?
  - Claims of off-pulse emission at low frequency
  - Inconsistent with limits on off-pulse emission from ATCA observations at 20cm (Ravi, Shannon, & Melatos, in prep.)
  - Requires: Gating visibilities
- Pulsar wind nebulae
  - Gating to get rid of pulsar variability
  - Confusion an issue
- Bright intermittent pulsars
  - Gating not required, but could be beneficial
  - Example: PSR J1107-5907



Ravi, Shannon & Melatos (in prep)

BETA observations of field of J1107-5907



Hobbs et al. (in prep)

Bright state ~ 0.5 Jy in continuum at 730 MHz

Continuum observations of pulsars

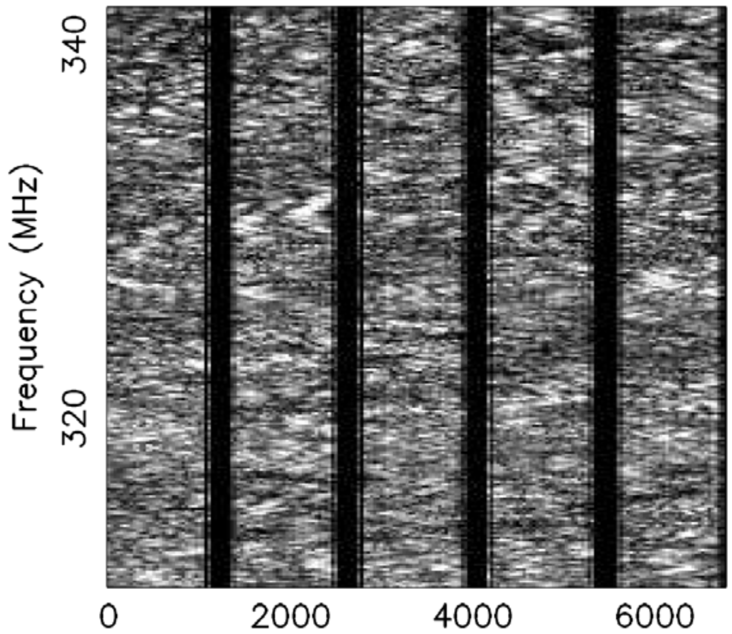
- Proposal 1: Continuum searches for pulsars (ongoing?)
  - Use existing/future all-sky surveys
  - Longer baselines to resolve out diffuse emission and reduce confusion

- Proposal 2: Known intermittent pulsars
  - Long-term baseline from current all-sky/transient surveys (ongoing?)
  - Targeted observations to bridge time-scales (12 hours per day)

- Proposal 3: Search for off-pulse emission/PWN from bright pulsars
  - Require gating of visibilities (decrease correlator cycle time, then average visibilities appropriately)

The Interstellar Medium

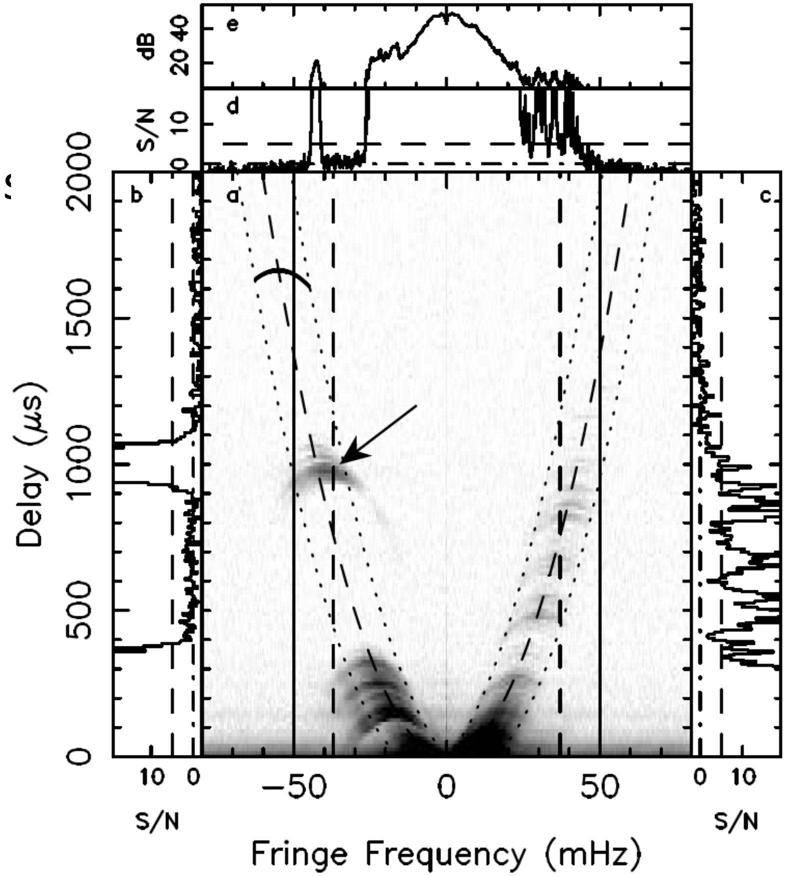
- Pulsars are effectively point sources
- Pulsars probe AU-scale structure in the ISM
- As pulsar-Earth baseline changes, sample different path through ISM
  - Earth's motion, binary motion, pulsar's space velocity
- Phenomena divided on time-scale that they occur on
  - Dispersion measure (DM) variations
  - Refractive Scintillation (flux variations/ refractive wander of pulsar position)
  - Diffractive Scintillation (intensity variations)



Pulsars + ISM at low frequencies

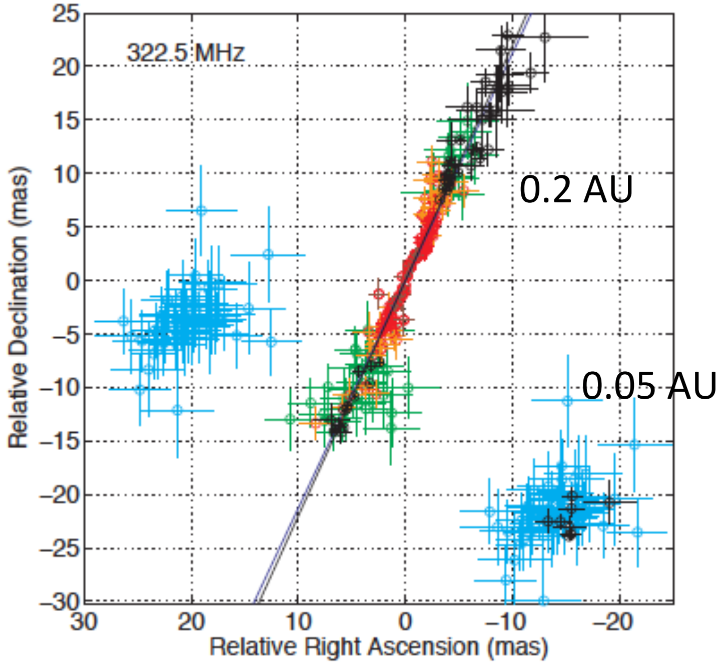
- Traditional model: Kolmogorov Turbulence
  - Turbulent cascade of density perturbations from large scales to small the scale

- The more we look, the more we see that this model
  - Long-living discrete structure
  - Anisotropic scattering



Pulsars + ISM at low frequencies

- Traditional model: Kolmogorov Turbulence
  - Turbulent cascade of density perturbations from large scales to small the scale
- The more we look, the more we see that this model
  - Long-living discrete structures
    - Track sources over ~ months of observation
  - Anisotropic scattering

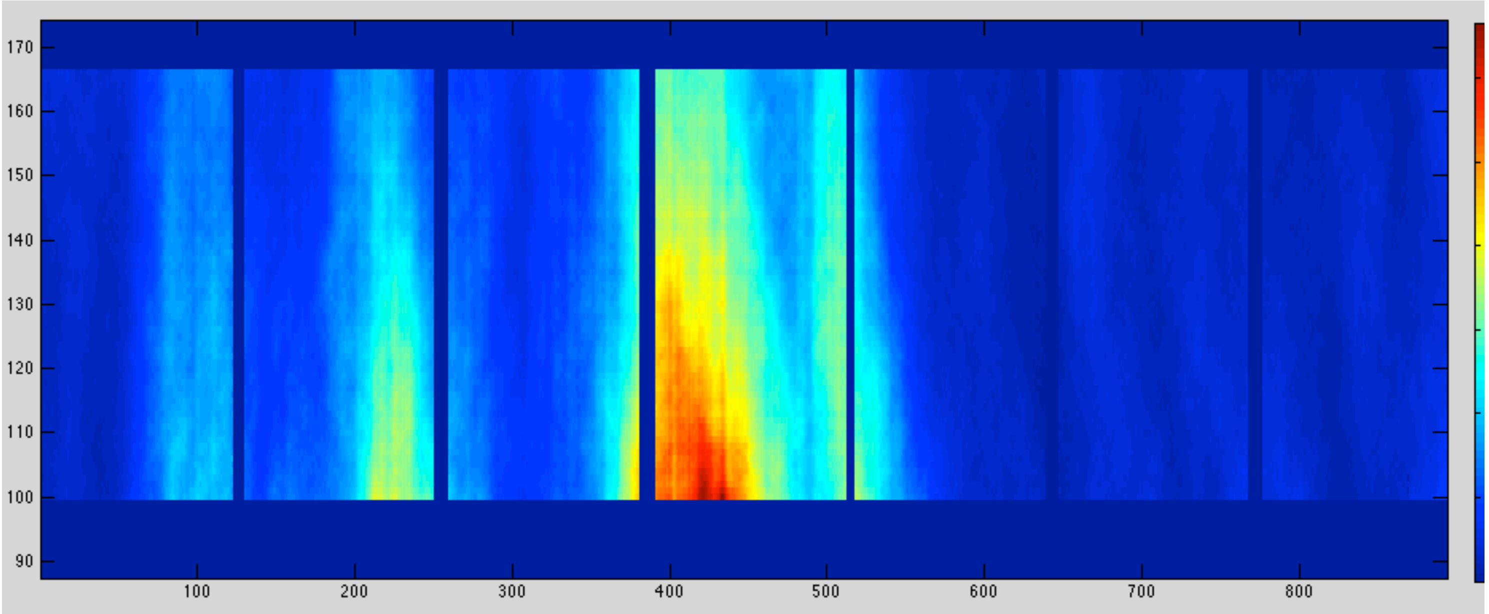


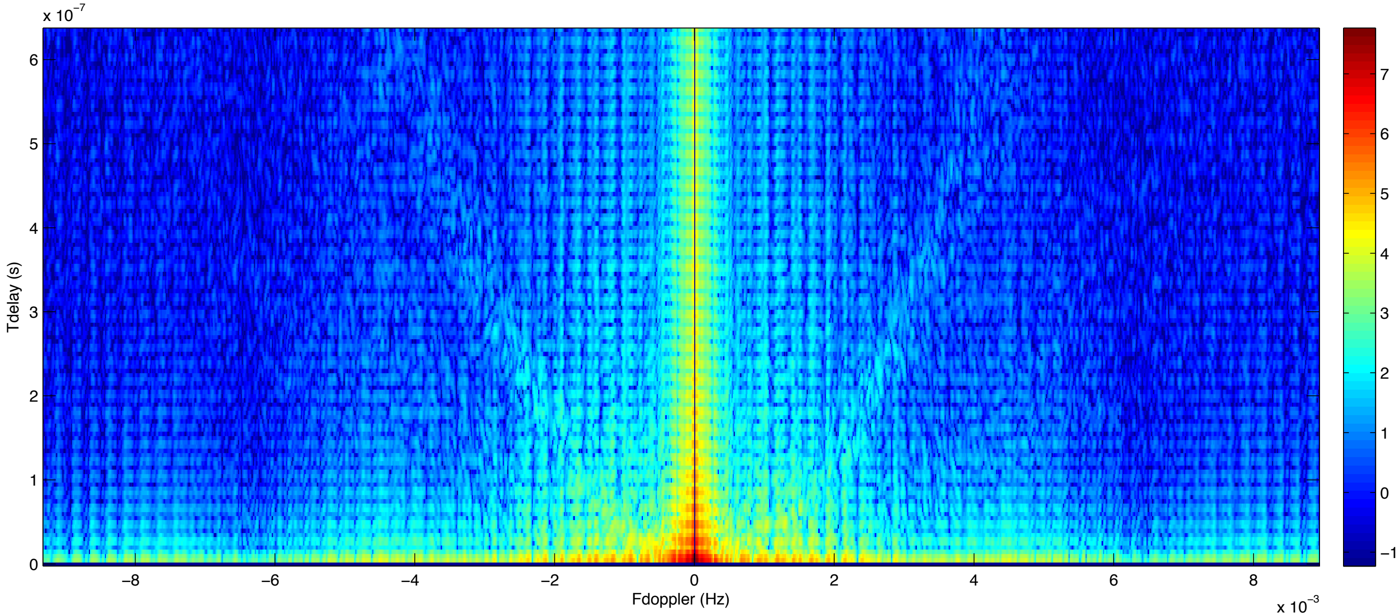
Brisken et al. (2010)

Scintillation and arcs of PSR J0437-4715: 50cm Parkes Observations

You don't need 10^5 scintles to see arcs

Observations conducted Saturday night, analysed Bill Coles

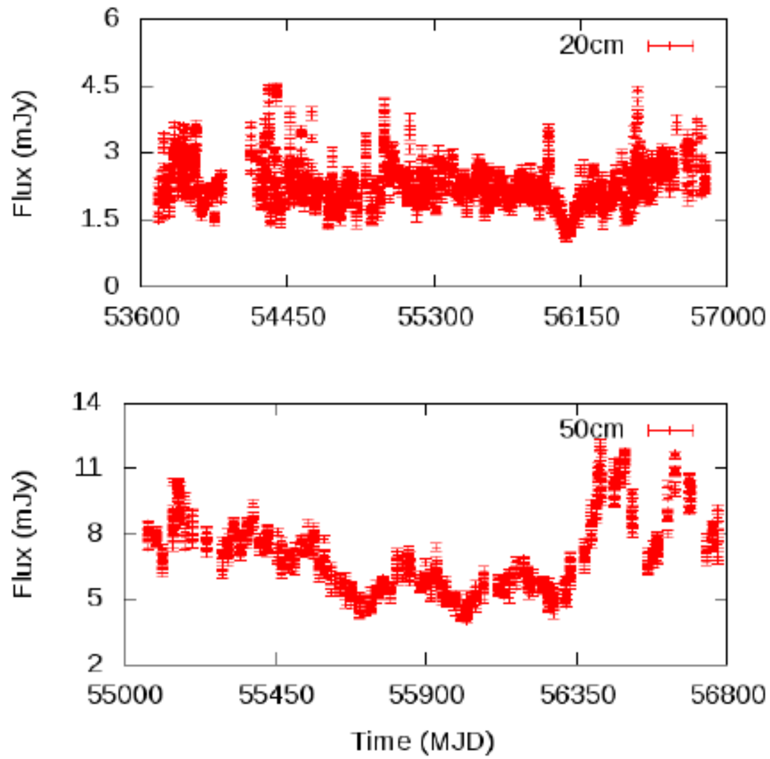




Do MWA observations agree?

Characterising the ISM at low frequency

- Question: What is the structure of the local ISM?
- Flux variations of pulsars for refractive scintillation (monitoring project; perhaps even in continuum observations)
- Diffractive scintillation/dynamic spectra
  - Start with short observations known interesting sources (PSR B0834+06)
  - Select pulsars with diffractive structure matching frequency resolution of system



Flux variations of J0613-0200
Renee Spiewak

DM Variations and Precision Timing

- Arrival times of pulses from millisecond pulsars can be inferred to high precision.
  - Best TOAs ~ 10 ns uncertainties.   Measure 10 metre differences in path length to kpc distant objects

- Can potentially detect gravitational waves with pulsar timings.   Current limits are ruling out astrophysically relevant models (Shannon et al. 2013)

- Largest source of noise in residuals is associated with variations in the total electron content (DM variations)

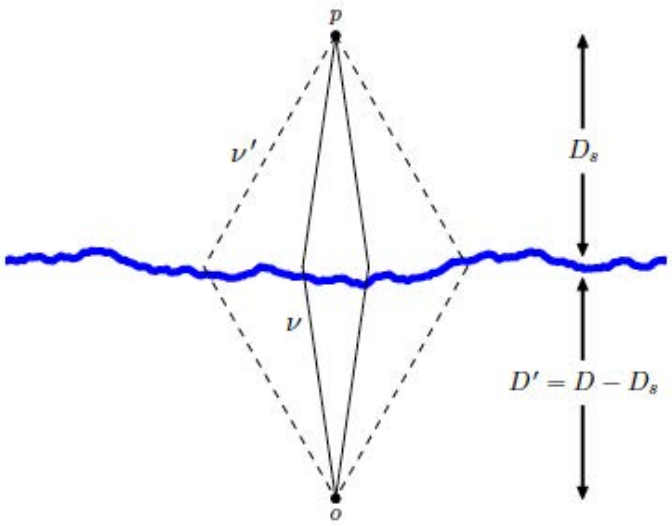
- We correct for this by measuring pulse arrival times at multiple frequencies.

- Lower frequencies: stronger propagation effects

Can you correct for DM variations with low-frequency observations?

Cordes & Shannon (2010)
Cordes, Shannon & Stinebring (in prep)

- Sampled volume of ISM ~ $\nu^{-4.4}$
- Turbulent ISM = "The Giant power-law on the sky"
  - Averaging over larger volumes causes random-walk away from LOS electron content

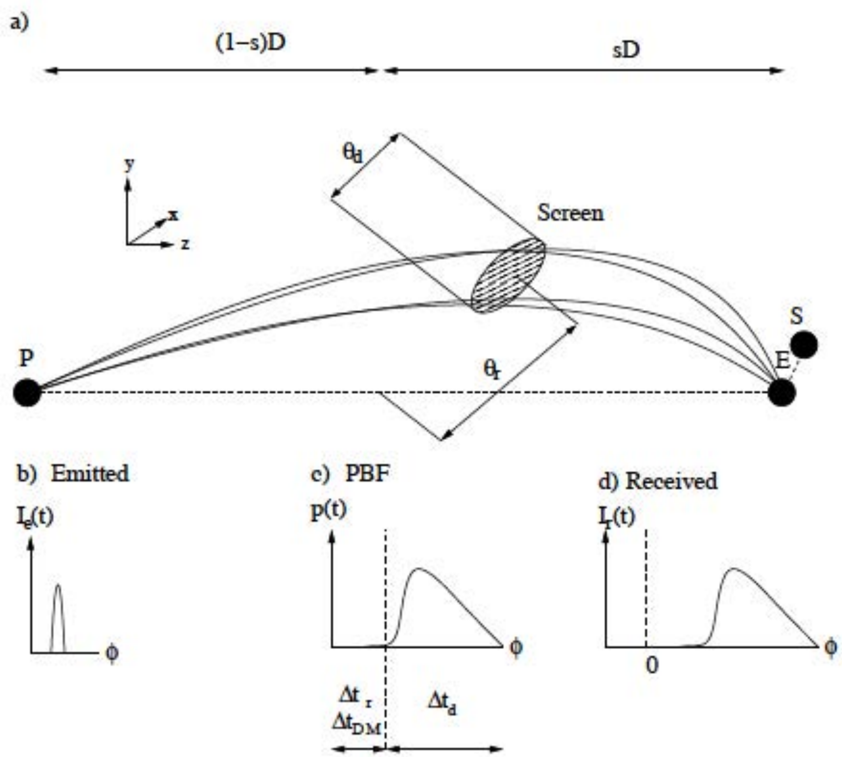


Can you correct for DM variations with low-frequency observations?

Shannon & Cordes (in prep)

- DM-induced delays at low-frequency should be smoother than those at high frequencies

- Of course, we need to find this out!
  - Measure DM variations
  - Combine with multi-frequency observations at Parkes

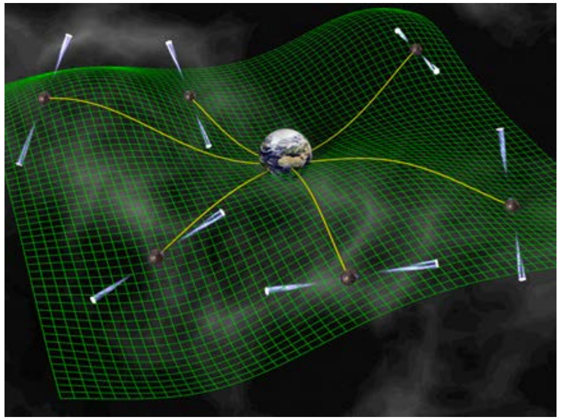


Low-frequency DM monitoring

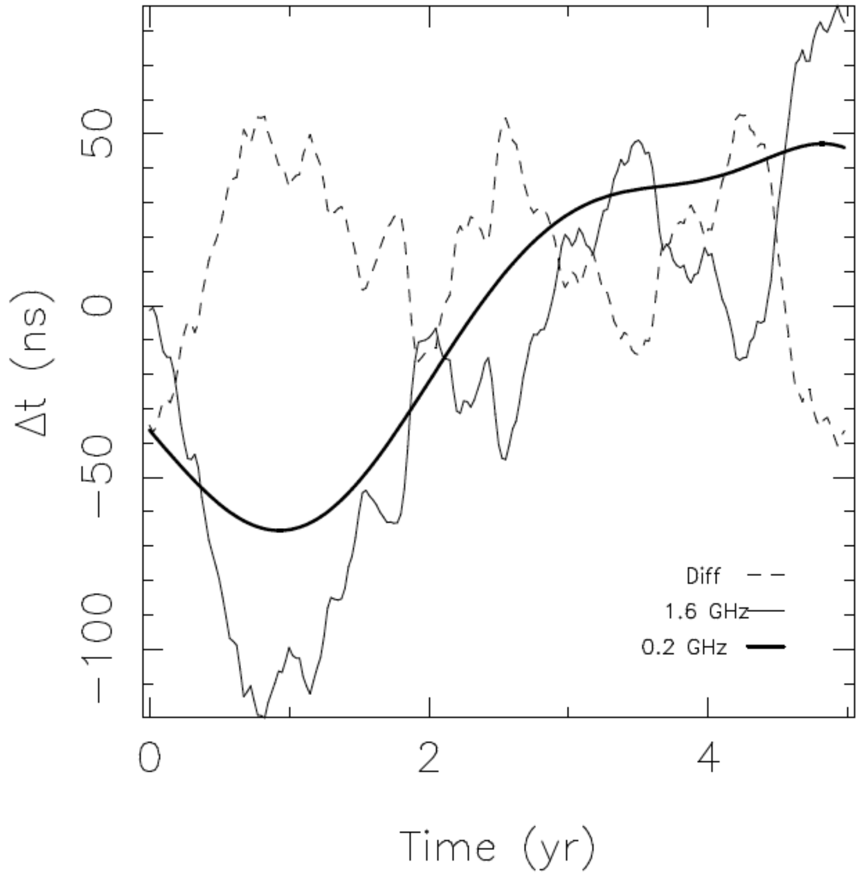
- Proposal: monitor dispersion measures of MSPs
  - Lowest DM pulsars in PPTA sample
  - Judicious choice of frequencies

- Systematic errors compounded by variations in pulse broadening.

- Need answer to this question before SKA-low



Shannon & Cordes (in prep.)



Requirements for Pulsar Observing

- **High time-resolution modes**
- Increased sensitivity
  - Collecting area, simultaneous processed bandwidth
- Coordinated multi-frequency observations
- High-fidelity polarisation
- Observing time/backend requirements
  - Large: Monitoring projects
  - Small: pulsar-emission studies/ snap-shot ISM studies
- Clock for timing observations

Conclusions

- Plenty of high-impact pulsar science ready to go with (e)MWA
  - Higher time resolution required to enable most but not all of this science
- Study the pulsar emission mechanism
- Study the ISM
- Tests for precision timing in an “extreme environment”
  - 10 ns TOA variations at 20cm are > 100 μs at 2 metres.
- Path towards the low-frequency SKA
  - Position Australian scientists to taking leading role in SKA-low pulsar science
- Thank you

Why the eMWA shouldn't observe pulsars

- Pulsars are dynamic
  - Show variations on every time scale we look at them
  - Huge strain on correlator; (tied array) beamformer; post-pr
- Pulsars are dispersed/scattered
  - ISM distorts emitted signal
  - Huge strain on correlator/backend to get frequency and time
- Pulsars involve complicated physics
  - Electrodynamics, Relativity, Condensed Matter, Nuclear Physics, Gravitational Waves