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International Centre for Radio Astronomy Research

Spectral evolution of pulsar radio emission using SKA-Low precursor stations

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Overview

We demonstrate the early science capabilities of the SKA-Low precursor stations

This talk:

1. Background on pulsars and the SKA-Low stations
2. Shallow all-sky census of 100 known pulsars
3. Using the stations to sample the radio spectra of 22 pulsars
4. Spectral modelling and analysis using **pulsar_spectra**
5. Accounting for pulsar non-detections

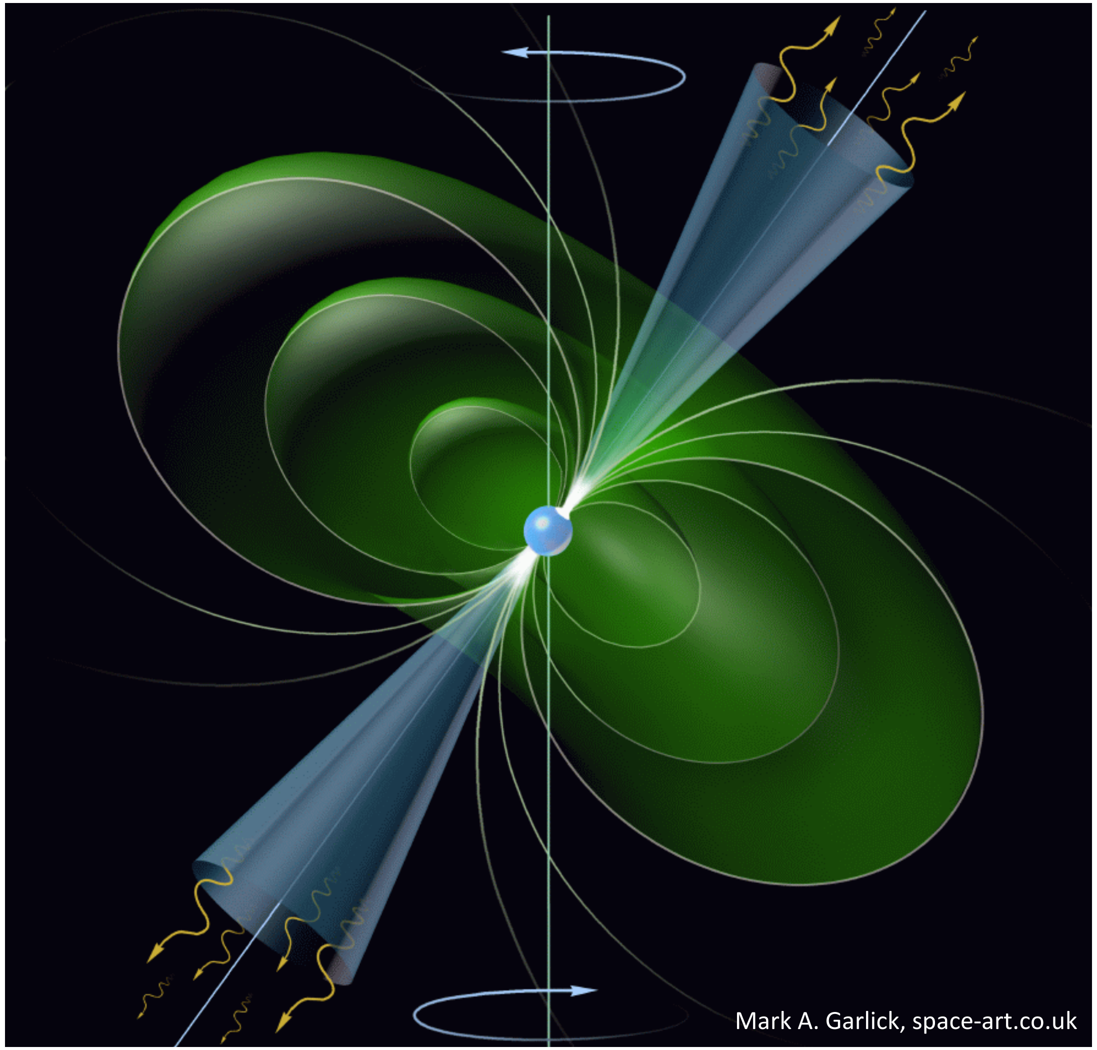
Pulsars – *Cosmic Lighthouses*

Left behind by massive stars (~8-25 $M_\odot$) after supernovae:

- Made of dense nuclear matter (~1.4 $M_\odot$ within ~20 km)
- Rapidly rotating (P~0.5 s)
- Very highly magnetised (B~10^{12} G)

Wide-ranging, ***high-profile*** applications:

- Pulsar timing arrays (detecting nanohertz gravitational waves)
- Performing the most precise tests of strong-field gravity


Mark A. Garlick, space-art.co.uk

Pulsar Radio Spectra

Currently ~70% of known pulsars with studied radio spectra are best-fit with ***(typically) steep*** simple power laws

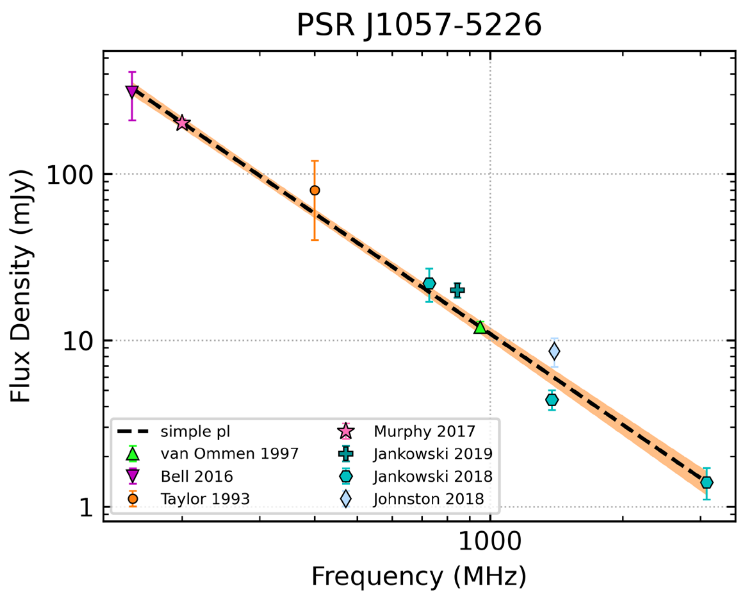
$$S \propto \nu^{\alpha}, \quad \langle\alpha\rangle = -1.6$$

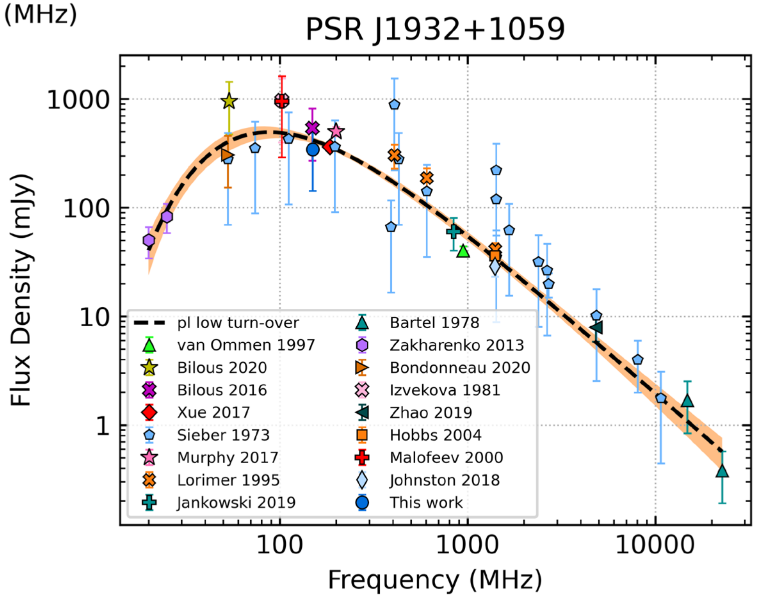
Long-period (non-recycled) pulsars sometimes show a spectral ***turn-over*** at ~100 MHz

Spectra with poor low-frequency coverage are often best-fit with simple power laws

Links to the underlying emission mechanism and the intervening ISM

Useful for pulsar population studies and survey planning





Spectral Features

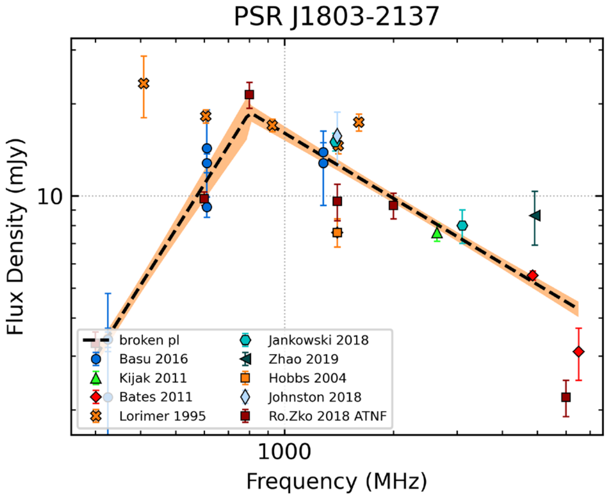
Common models are ***mostly empirical:***

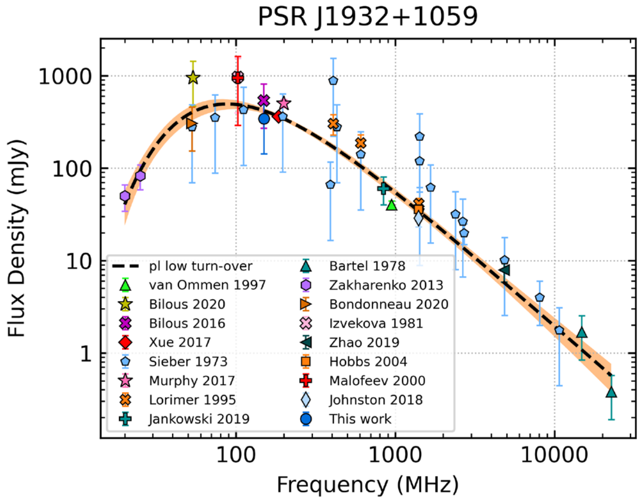
- Simple and broken power-law
- Log-parabolic spectrum

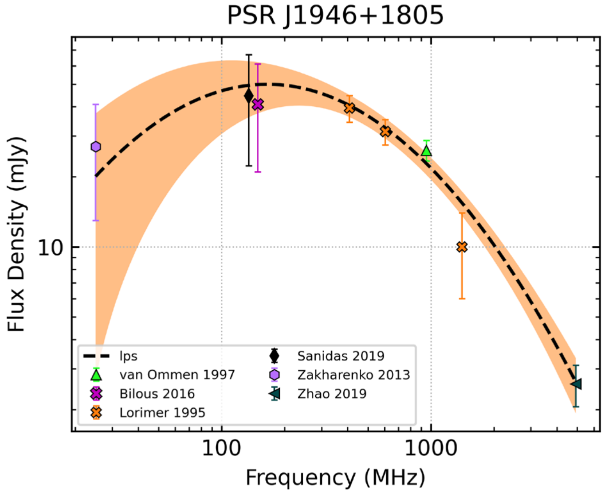
Some are ***physically motivated:***

- Power-law + low-freq. turn-over
  - Synchrotron self-absorption
  - Free-free absorption
- Power-law + high-frequency cut-off
  - Electrons accelerating in the pulsar's electric field

It is not clear whether spectral features are ***intrinsic*** or ***environmental*** in nature

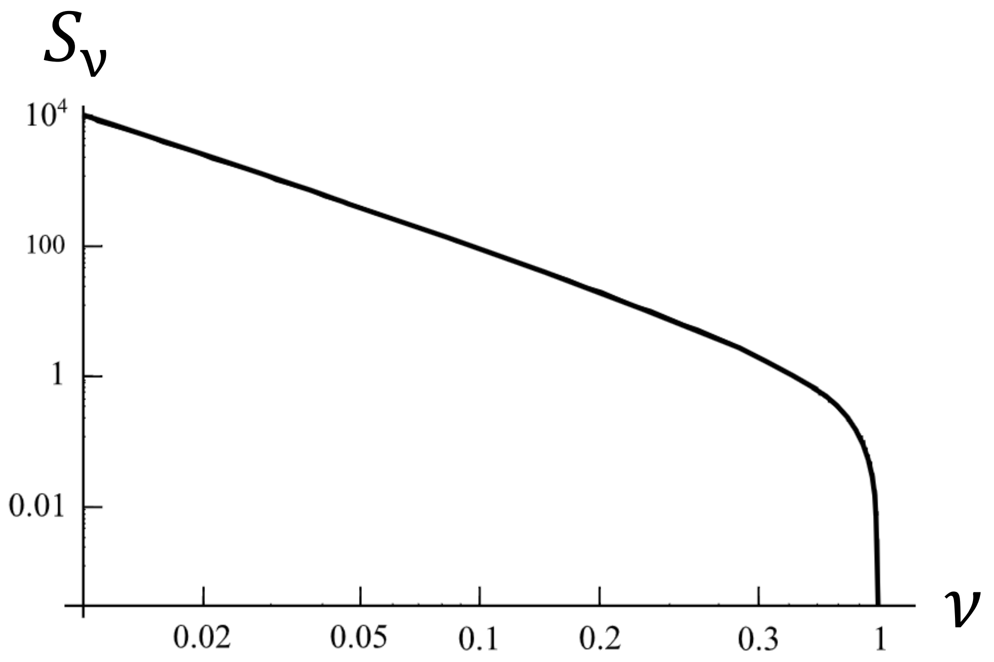






High-frequency Cut-off

- Observed since earliest studies of pulsar spectra [1]
- Has been attributed to acceleration of electrons by the pulsar's electric field [2]
- Electron acceleration goes to zero as the electrons approach the speed of light
- All radiated power located in the radio-frequency band
- Related to magnetic field strength and emission height



The Kontorovich & Flanchick model of high-frequency cut-off spectra [2]

[1] Sieber (1973)
[2] Kontorivich & Flanchik (2013)

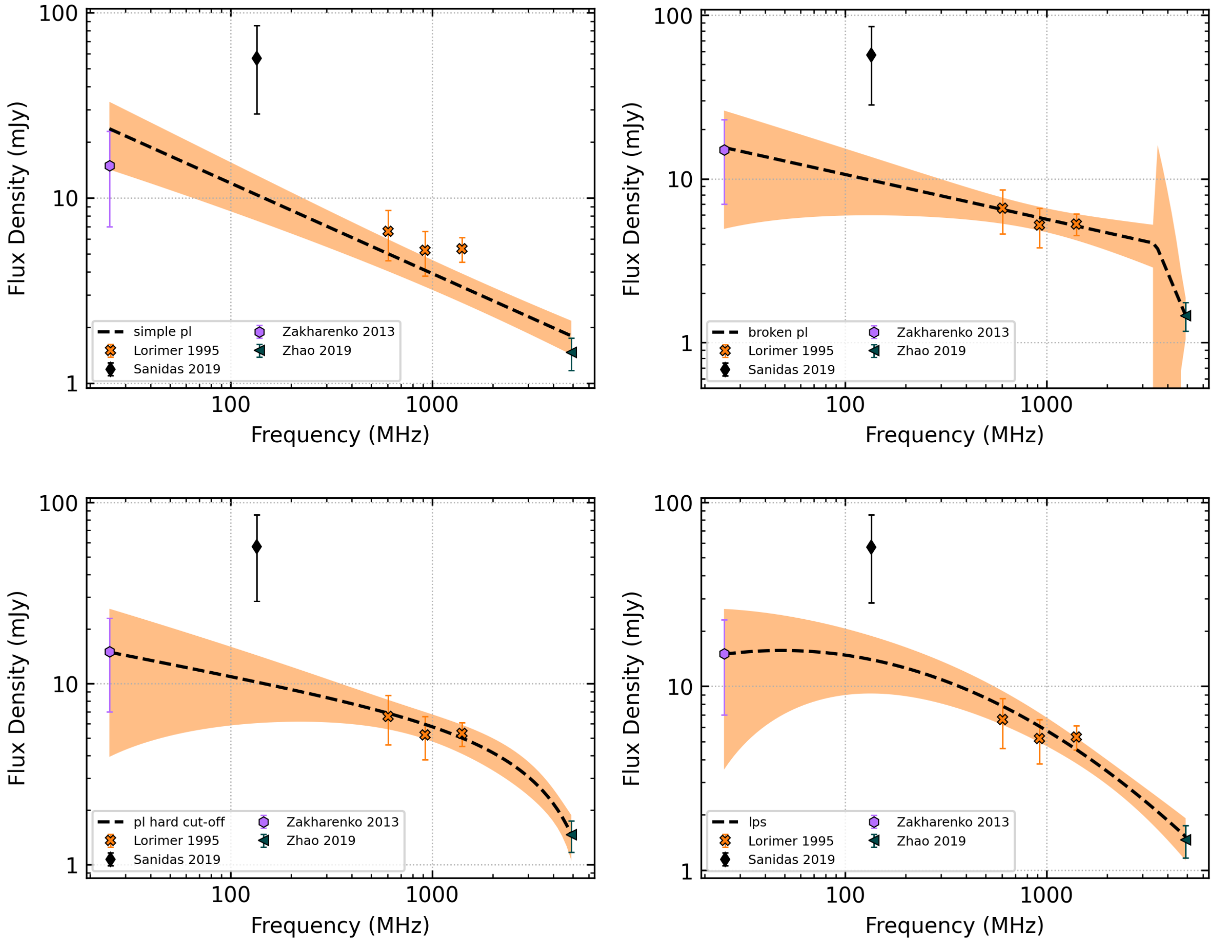
The Problem of Spectral Data

In the ATNF pulsar catalogue:

- There are >3300 known pulsars
- **~70%** have ***no spectral data*** available below 400 MHz
- **~85%** have ***no spectral data*** available above 2 GHz

Many flux density measurements have ***large uncertainties*** due difficulties in absolute flux density calibration for beamformed detections

More published spectral data is needed to better constrain spectral features



Example: A poorly constrained spectrum (PSR J1954+2923)

The SKA-Low Precursor Stations

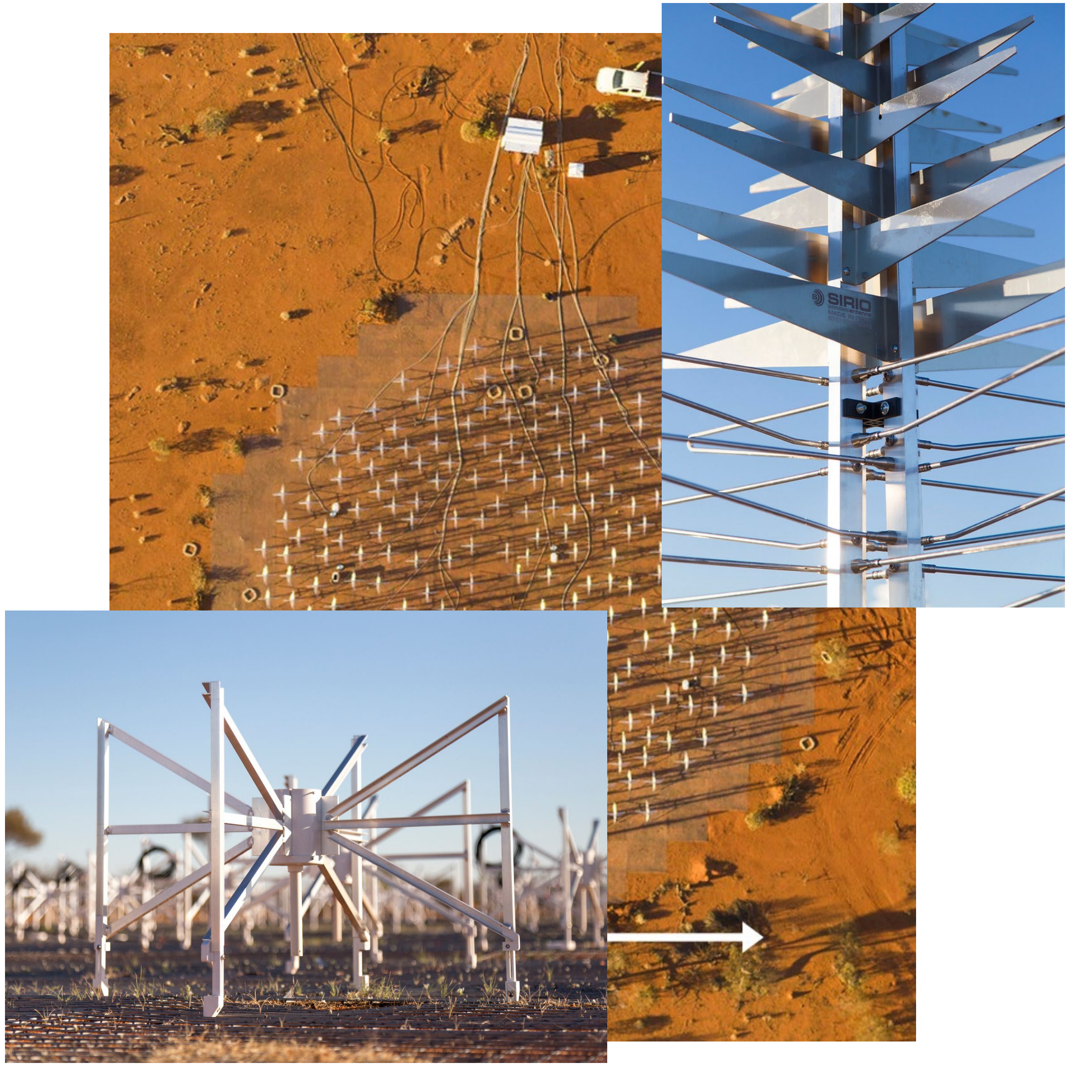
Prototype aperture array stations to the low-frequency Square Kilometre Array

- Aperture Array Verification System 2 (AAVS2)
- Engineering Development Array 2 (EDA2)

Used to test SKA technology and prepare for science with the SKA-Low

Frequency range:	50 – 350 MHz
Bandwidth:	~0.93 MHz*
AAVS2 antennas:	256 × SKALA-4.1
EDA2 antennas:	256 × MWA dipoles
Data recording rate:	**12 GB/hour***

*For the initial system employed for this work (single coarse channel)



Aerial view of AAVS2
Image credit: ICRAR/Curtin

SKA-Low Precursor Stations vs the MWA

	EDA2 (Initial system)	**MWA** (Phase II)	**Ratio** (MWA/EDA2)
Frequency range (MHz)	50 – 350	70 – 300	0.6[a]
Bandwidth (MHz)	0.93	30.72	33
Number of antennas	256	2048	8
Effective area @ 160 MHz (m^2)[b]	520	2690	5.2
Data volume (GB/h)	12	28000	2333

[a]based on beam simulations (Sokolowski et al., 2022)
[b]ratio of frequency ranges in log-space

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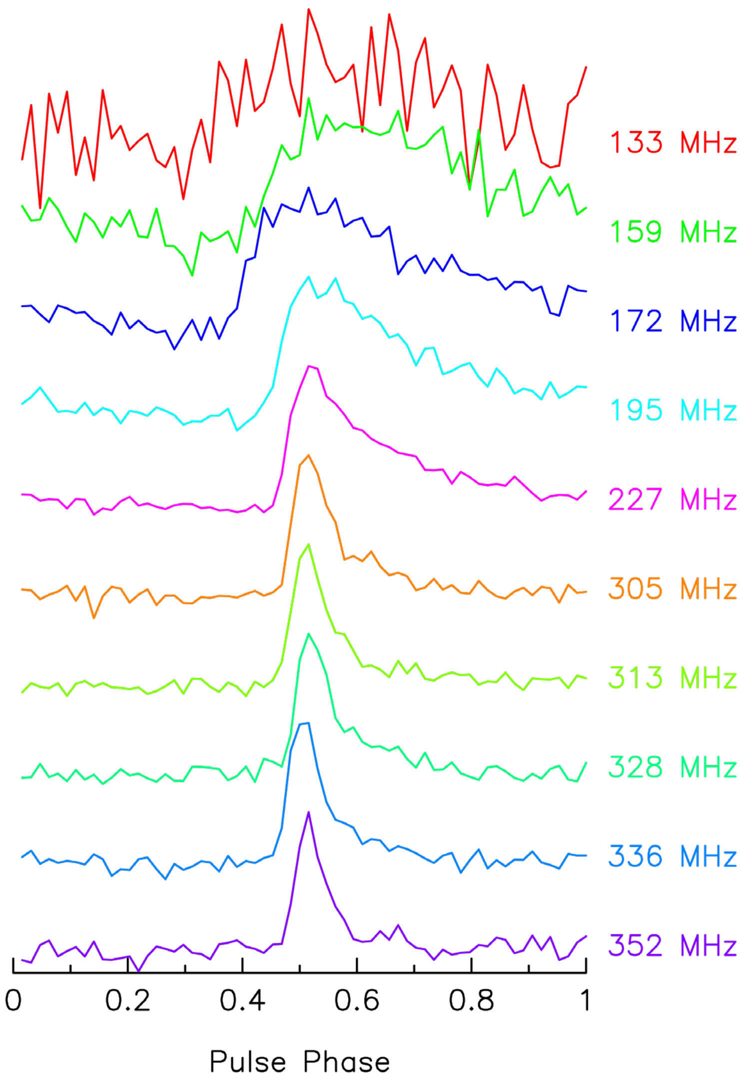
Testing Detection Capabilities

Census of 100 known southern-sky pulsars

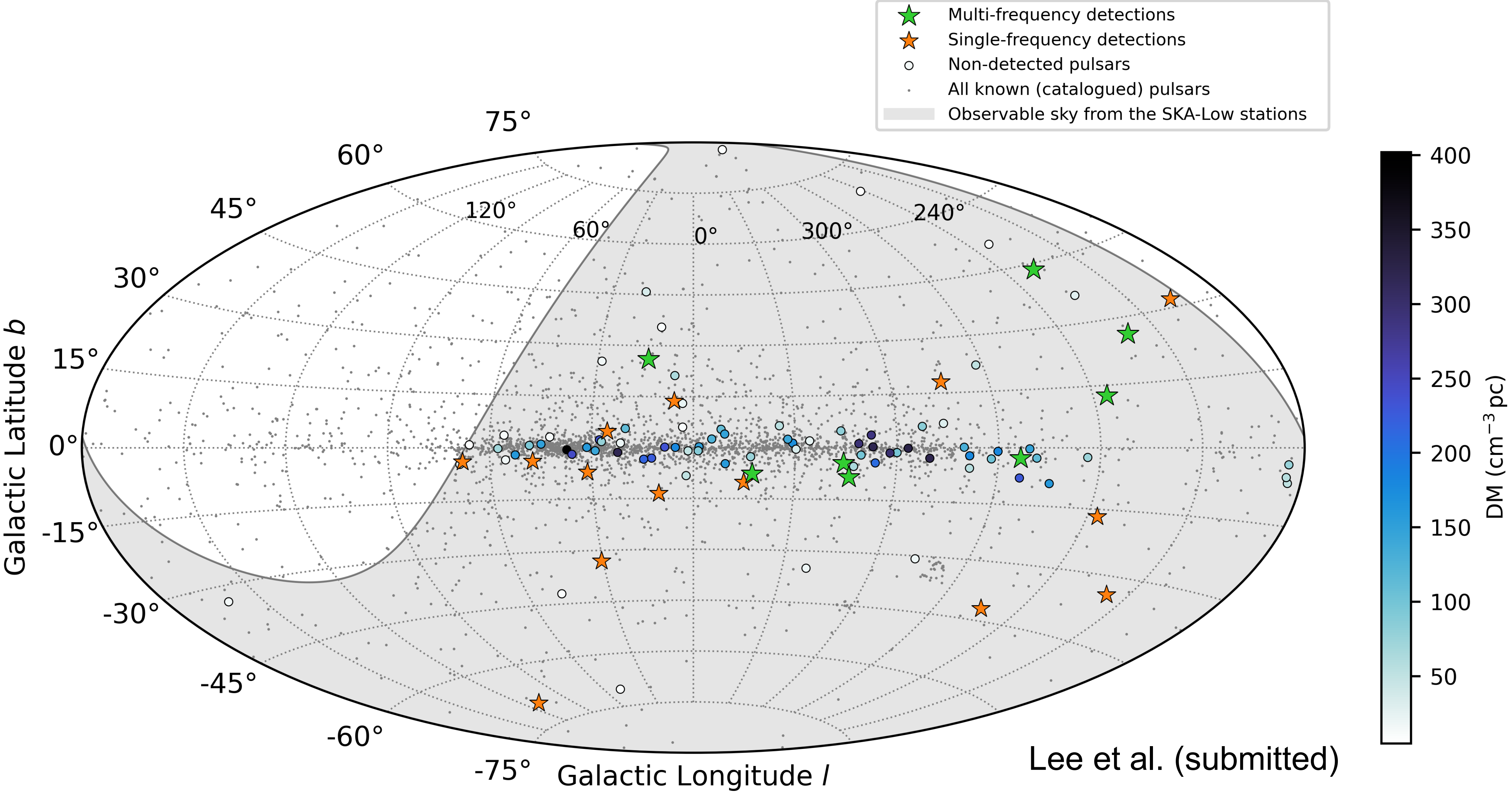
- Detected 22 pulsars (DMs between ~2 – 123 pc/cm^3)
- Simultaneous detections with stations for 17 pulsars
- Observed but did not detect 78 pulsars

Follow-up observations at 18 centre frequencies for 8 pulsars

- Made detections between ~70 – 352 MHz
- Most detections were near the centre of the frequency range (~150 MHz)

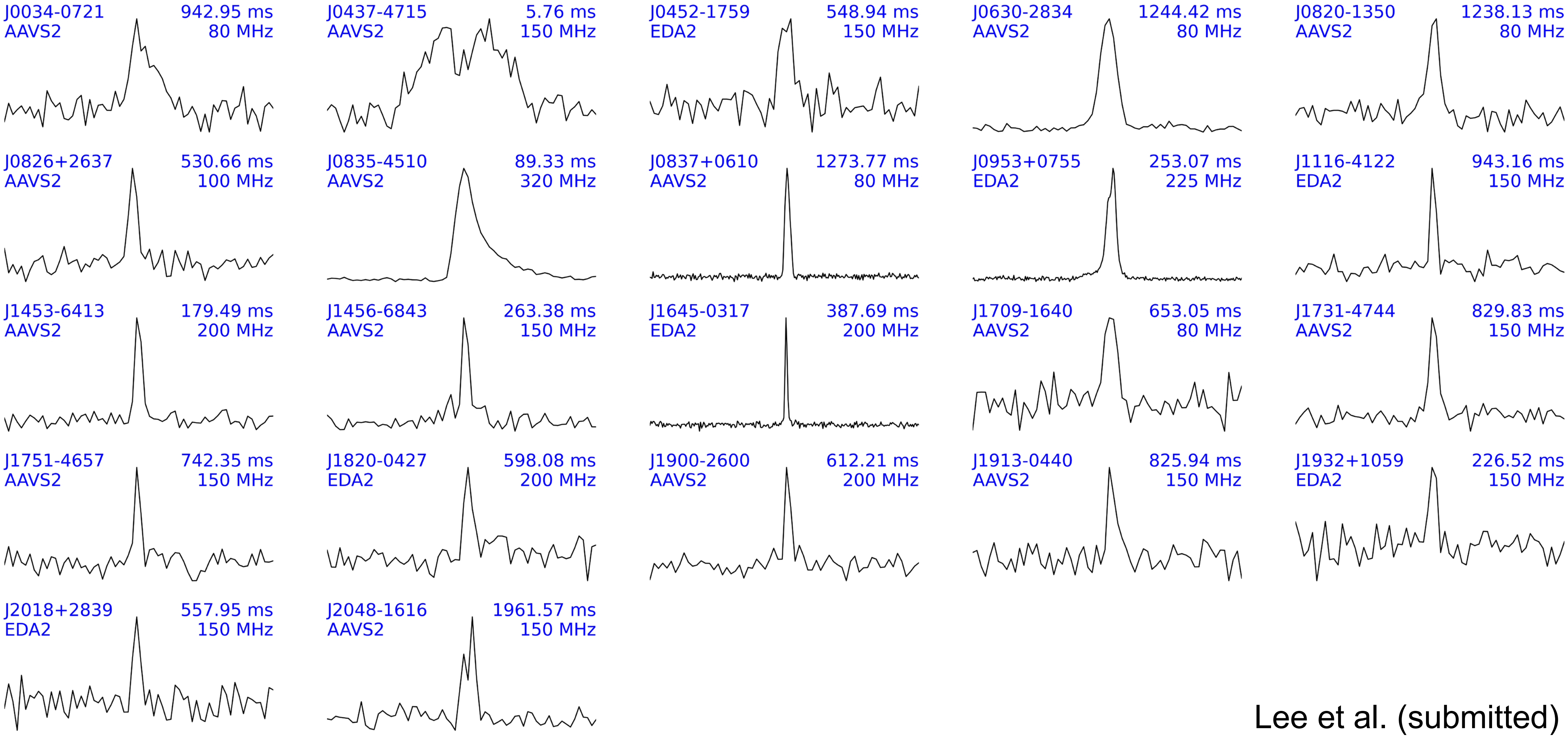


Galactic Sky Map



Lee et al. (submitted)

Integrated Pulse Profiles



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Mean Flux Densities

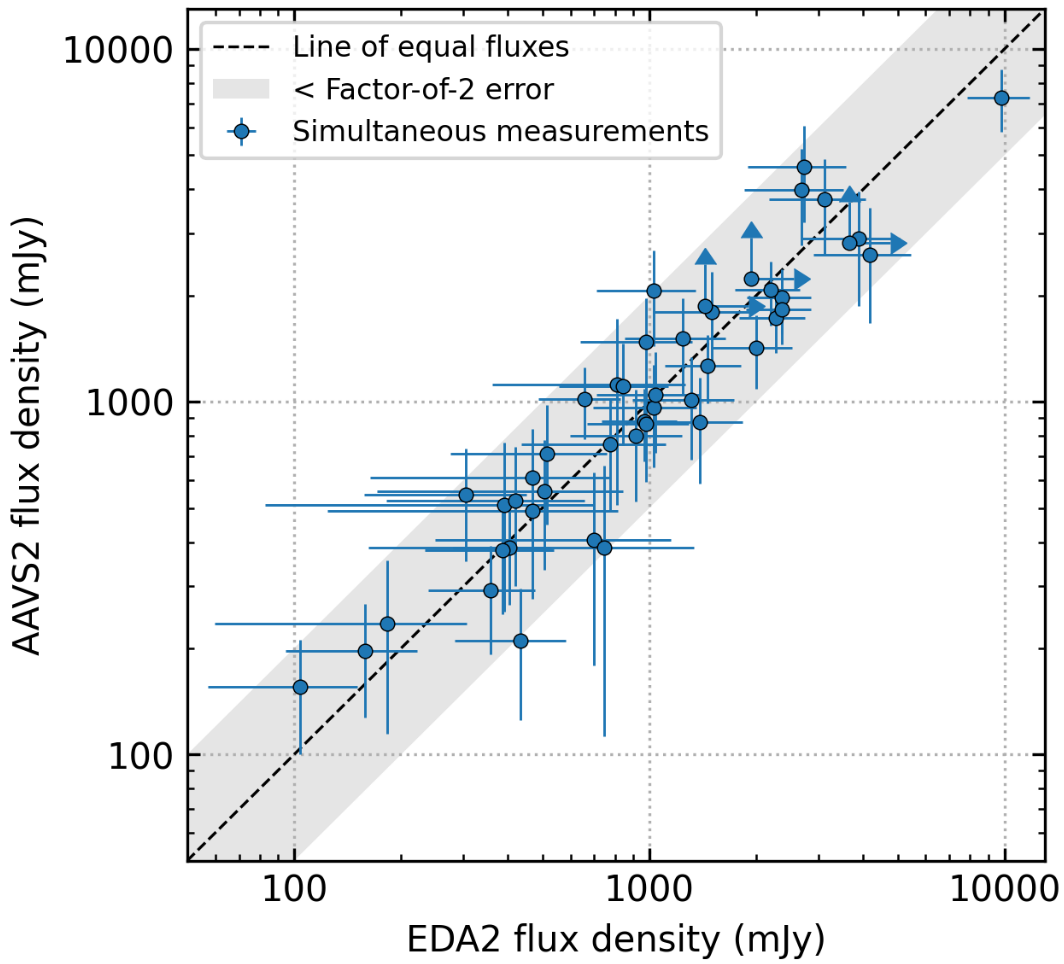
Measured phase-averaged flux density for each detection

Flux densities calibrated by comparing:
- Off-pulse RMS noise
- Estimated off-pulse RMS noise from station ***beam simulation*** [3]

Verified flux density calibration with electromagnetic simulations in FEKO

Verified agreement between flux densities measured with both stations

[3] Sokolowski et al. (2022)



Comparison of flux density measurements
Lee et al. (submitted)

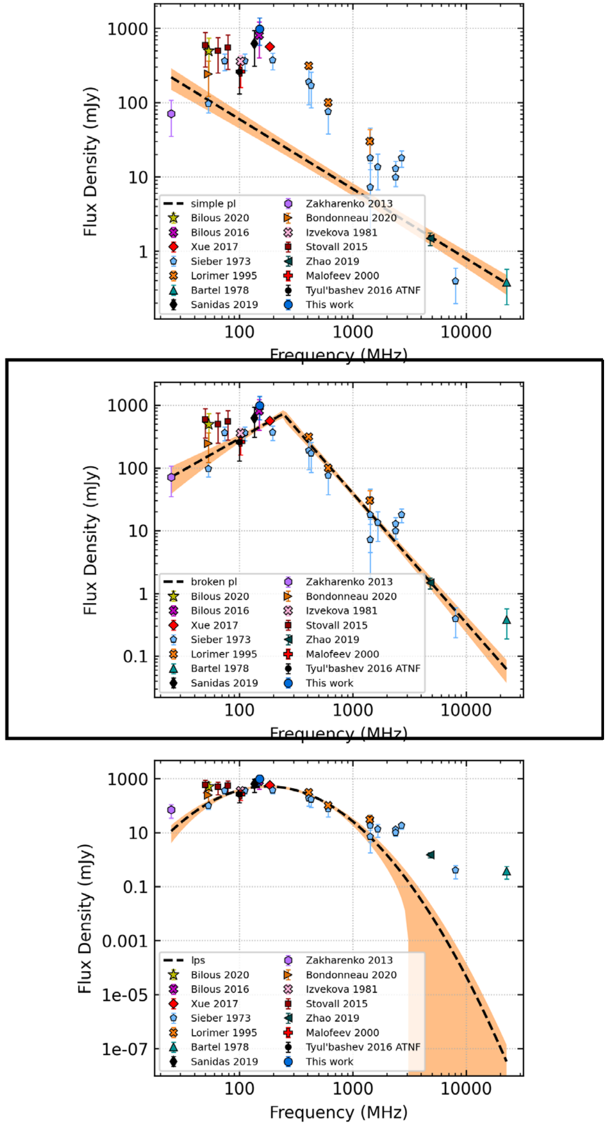
Spectral Modelling

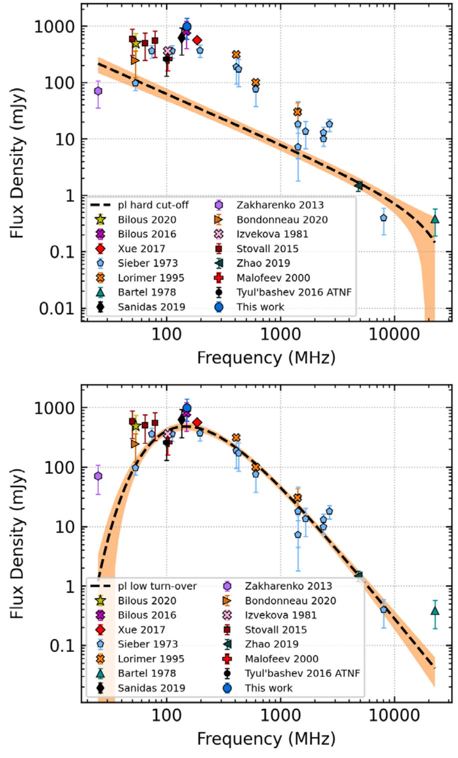
pulsar_spectra software used
(see Nick’s presentation + paper)

In summary:

- ***Open source*** flux density catalogue
- ***Automated*** spectral modelling:
  - Tests 5* spectral models
  - Robust against outlier data
- ***Spectral analysis*** tools:
  - Peak frequency (log-parabolic)
  - Emission height (high cut-off)

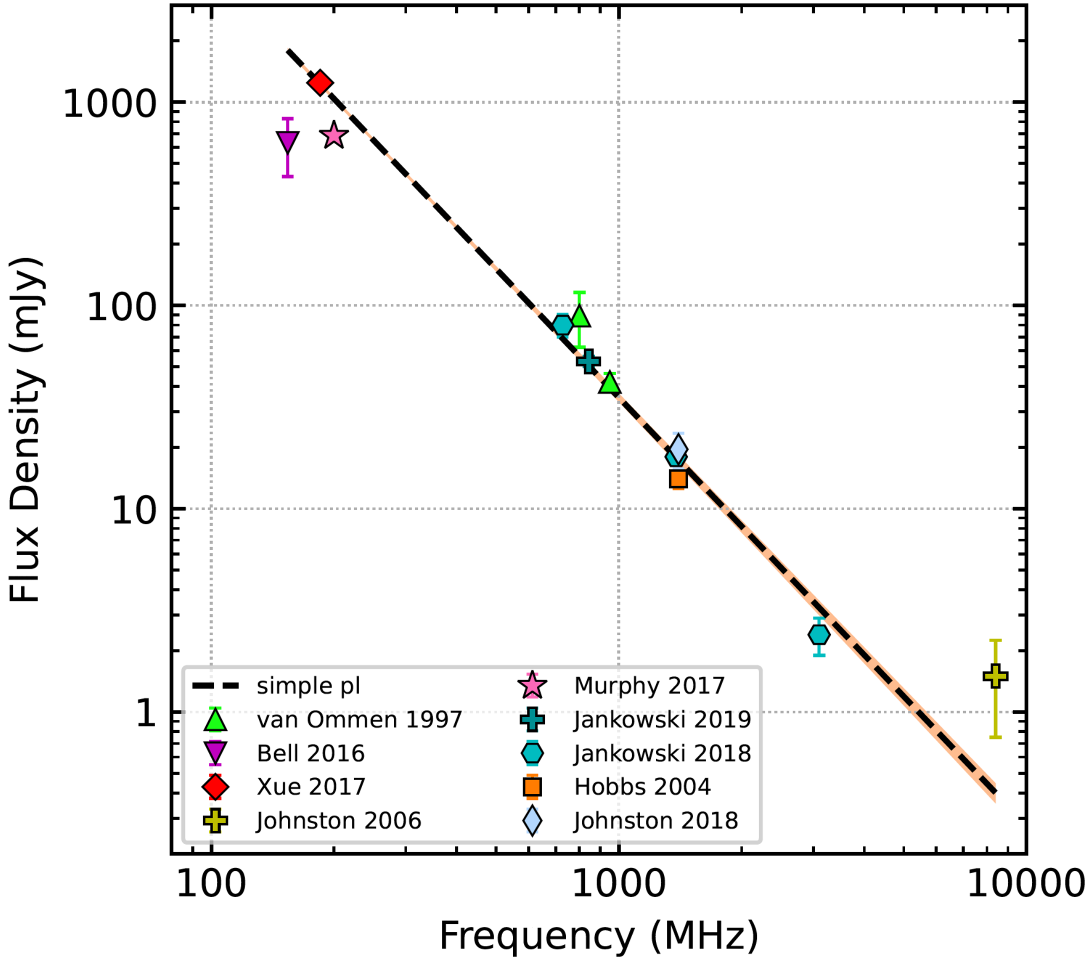
*Easy to add more models – e.g. triple power-law, double turn-over



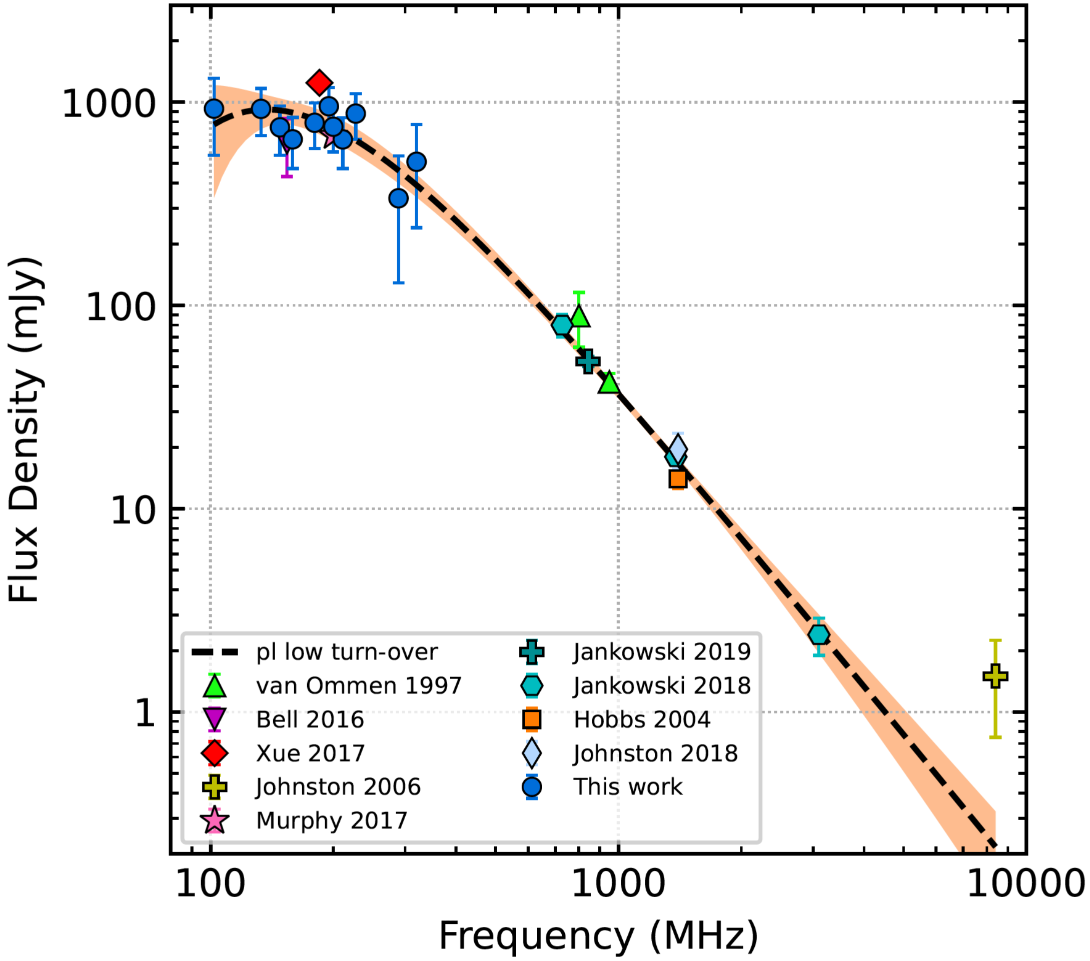


Example: Best-fit model is automatically selected

Example: PSR J1453-6413



Before: Simple power-law



After: PL + Low-frequency turn-over

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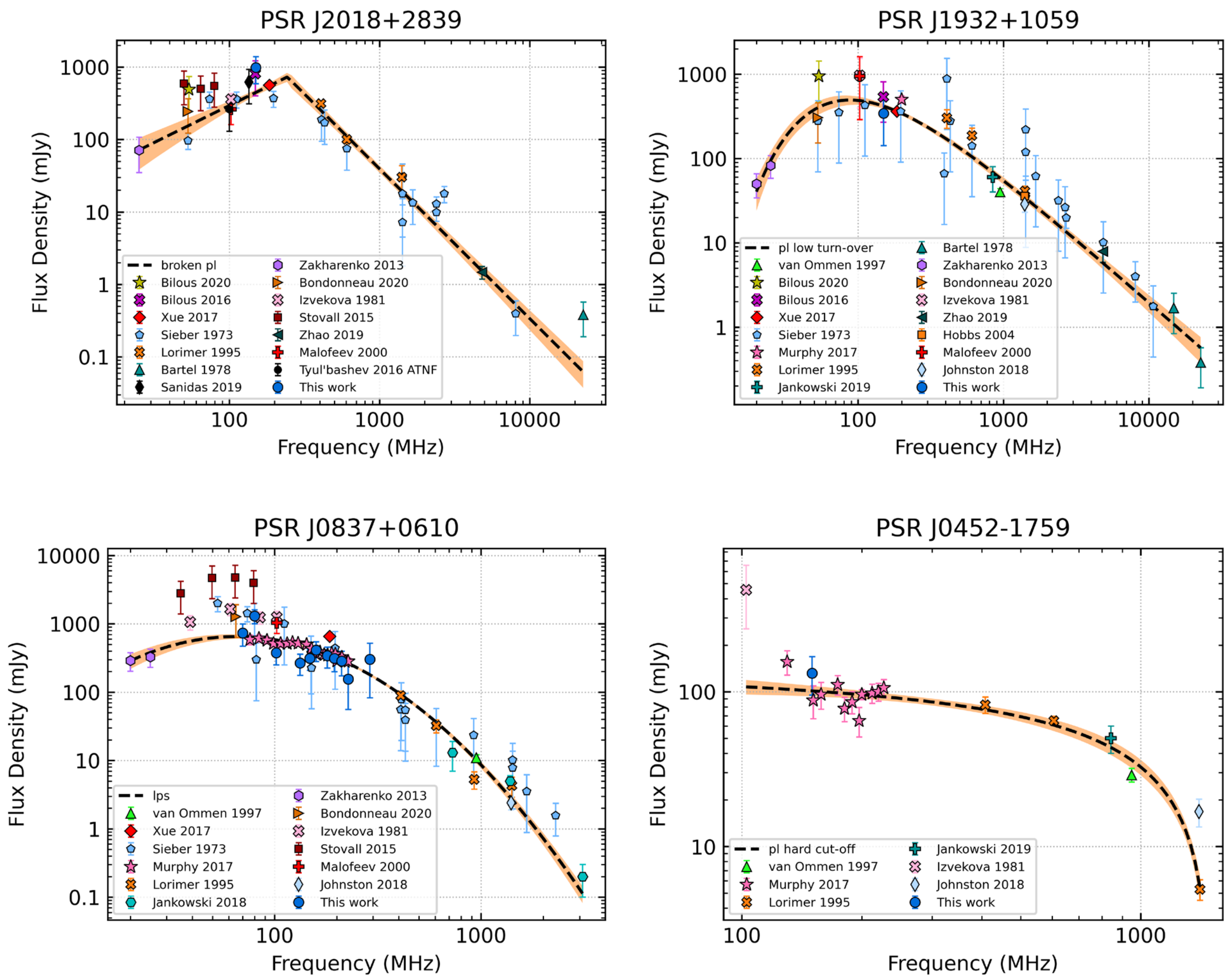
Results of Spectral Modelling

All but one out of the 22 pulsars showed ***spectral features***
(i.e. deviations from a simple power-law)

	# PSRs
Broken power-law	**7**
Low-frequency turn-over	**7**
Log-parabolic spectrum	**5**
High-frequency cut-off	**2**
<u>Updated best-fit models</u>	**16**



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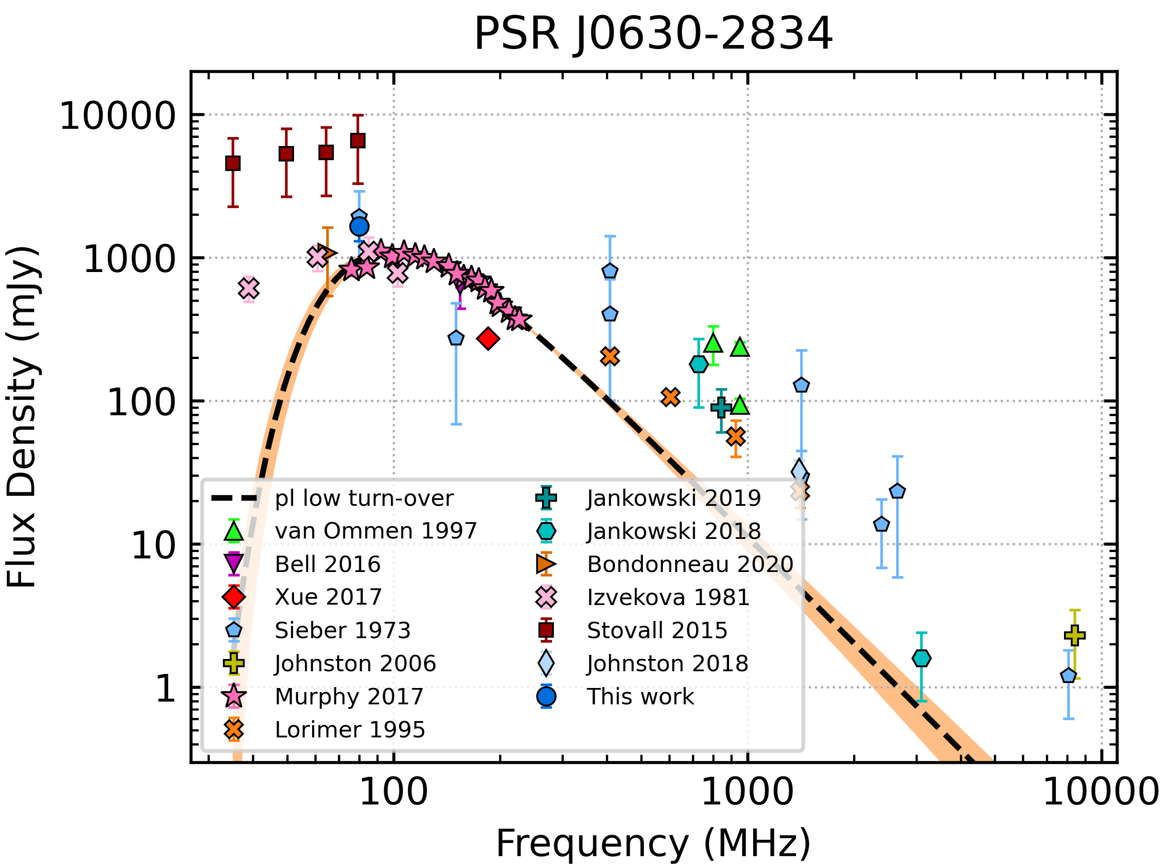
Continuum vs Beamformed Measurements



Best fit: All spectral data

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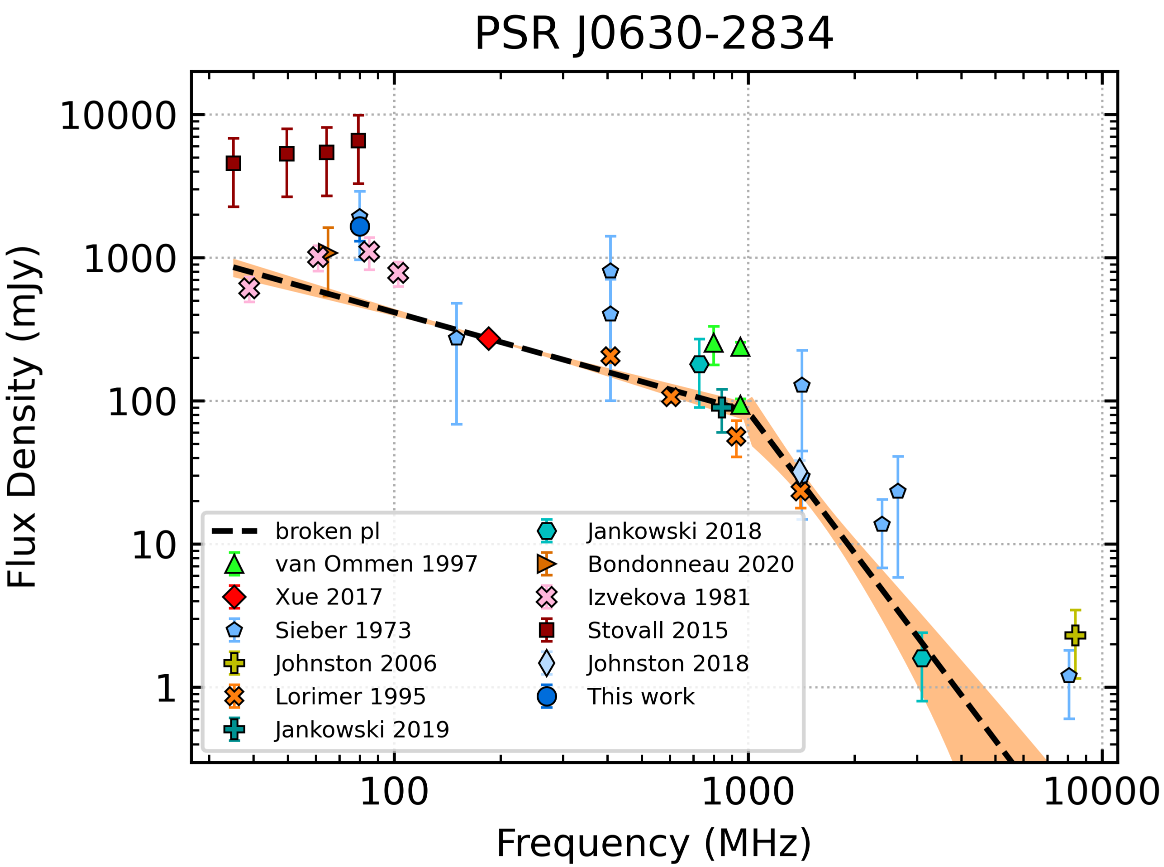

Best fit: Continuum flux density measurements excluded

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Relating Spectra to Physical Parameters

The cut-off frequency $\boldsymbol{\nu_c}$ is related to the magnetic field strength at the polar cap $\boldsymbol{B_{\mathrm{pc}}}$ and the pulsar period $\boldsymbol{P}$:

$$B_{\mathrm{pc}} \propto P \times \nu_c^2$$

Assuming a dipole magnetic field and a canonical $1.4\ \mathrm{M}_\odot$ neutron star, we can derive the emission height $\boldsymbol{z_e}$.

For PSR J0452-1759, we estimate:

$$B_{\mathrm{pc}} = (2.21 \pm 0.06) \times 10^{10}\ \mathrm{G}$$

$$z_e = 52 \pm 9\ \mathrm{km}$$

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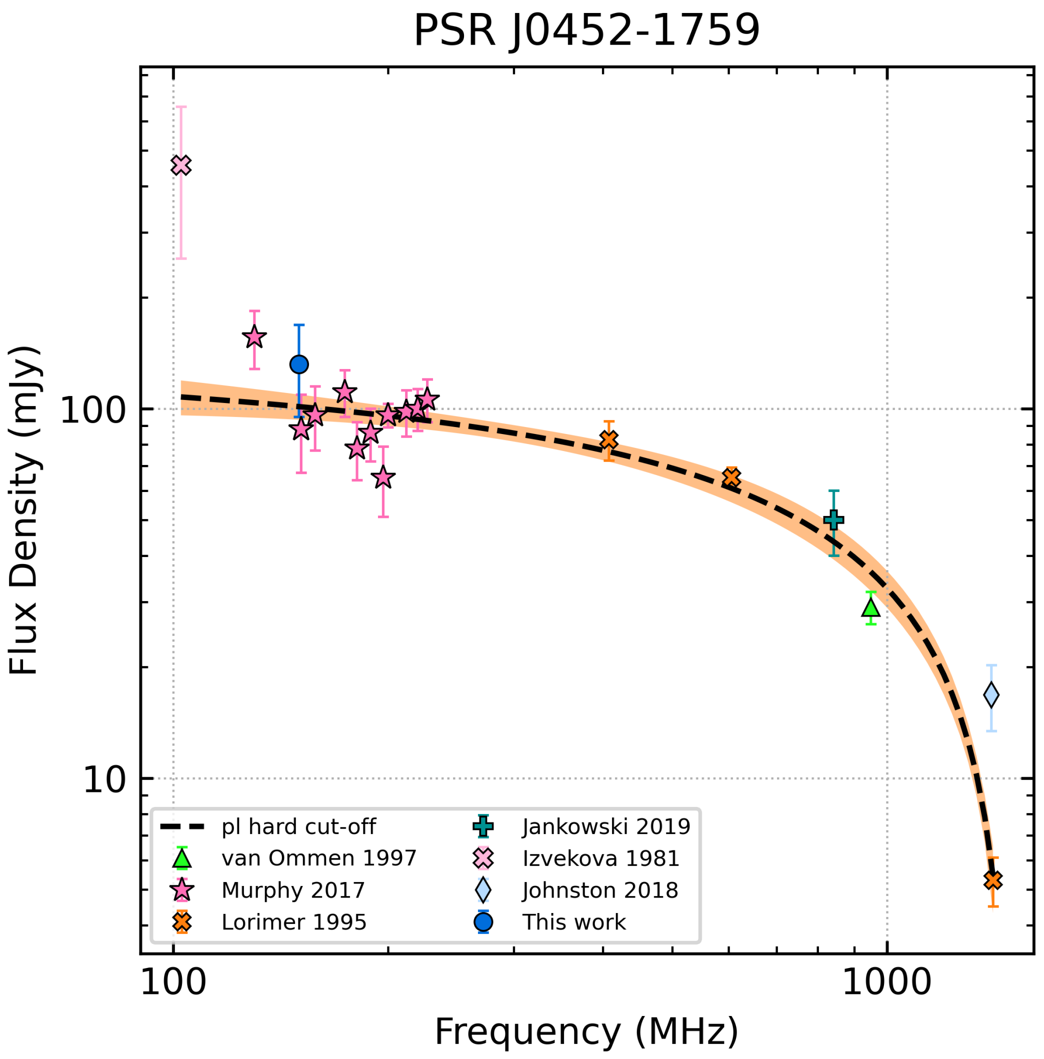
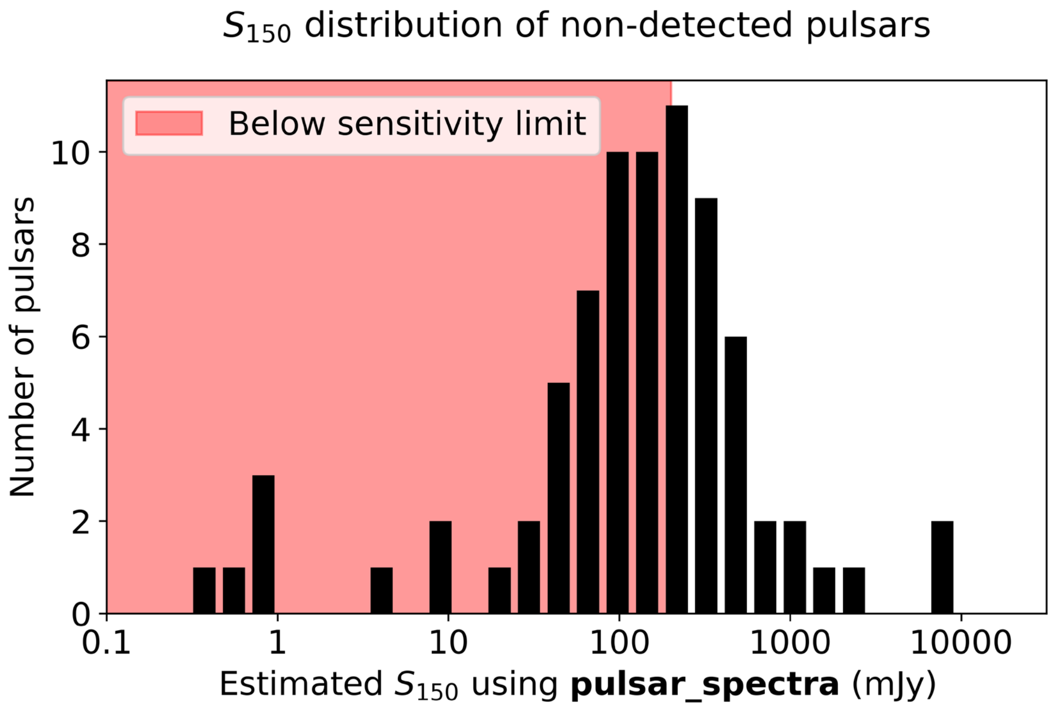
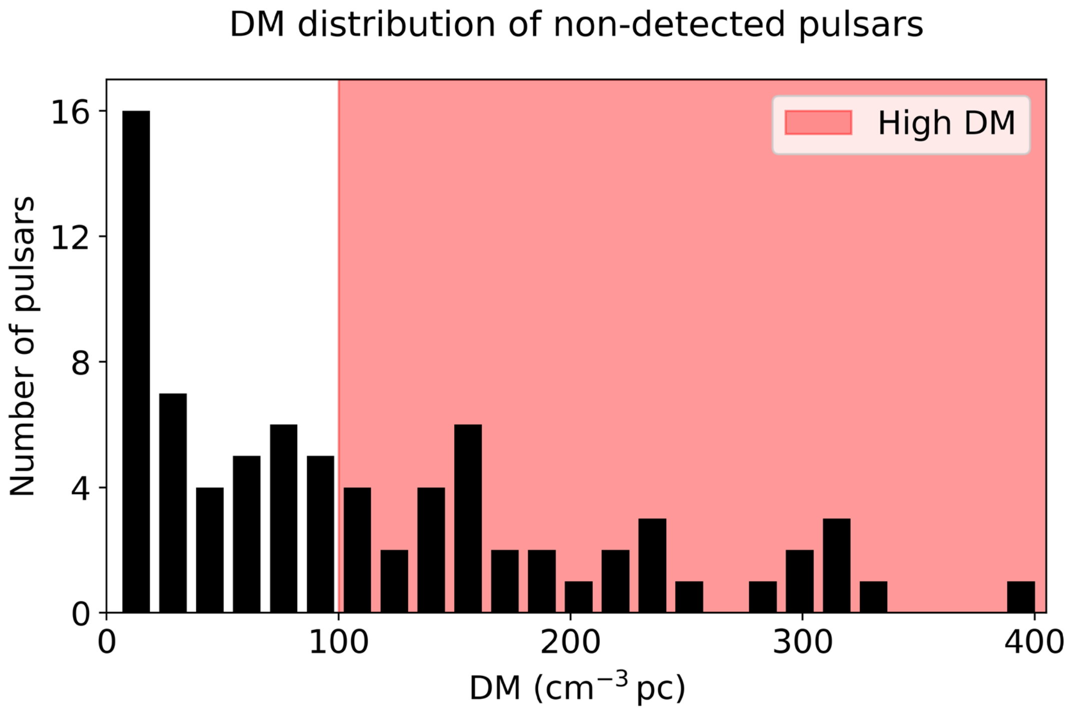


Non-detected pulsars

Most likely causes of non-detection:

1. Overestimated S_{150} $\longrightarrow$ true flux density below sensitivity limit of stations
2. High DM $\longrightarrow$ pulses more likely to be scattered by ISM

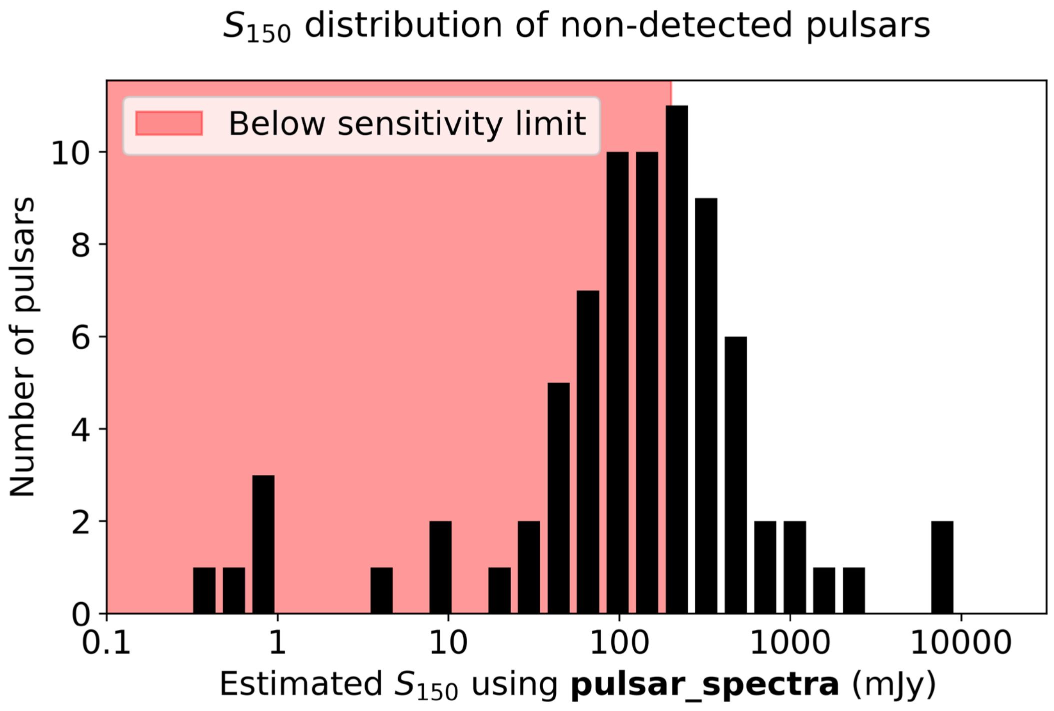


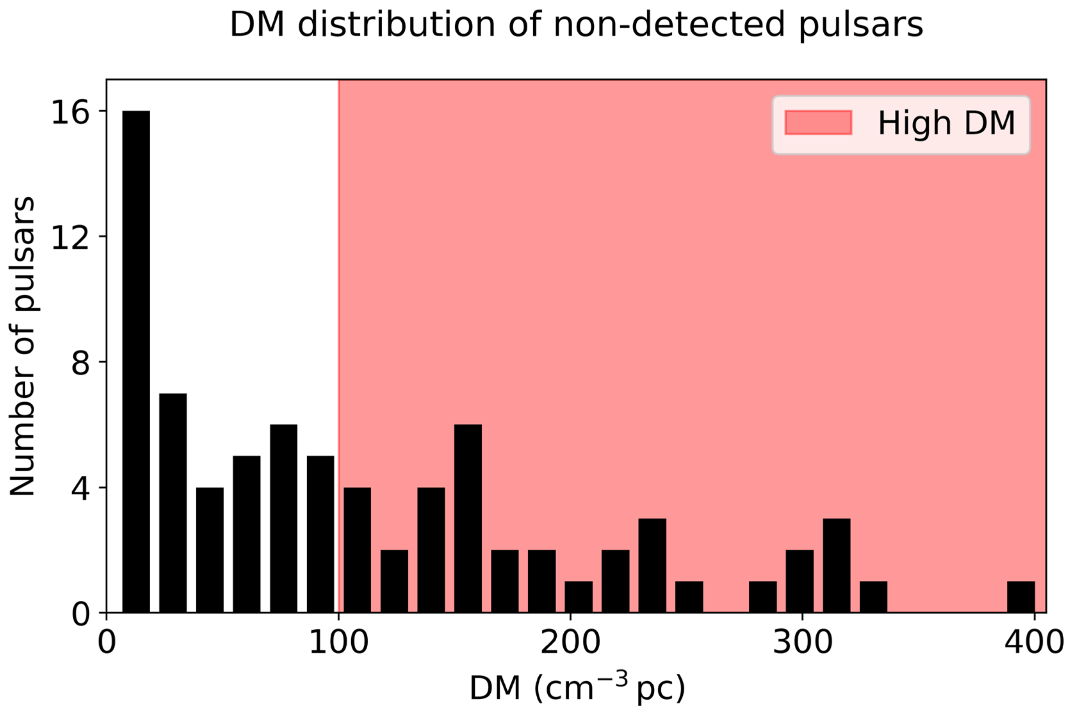


Non-detected pulsars

9 non-detected pulsars cannot currently be accounted for
i.e. they are bright enough ($S_{150} > 200\ \mathrm{mJy}$) and have a low DM ($< 100\ \mathrm{cm^{-3}\ pc}$)

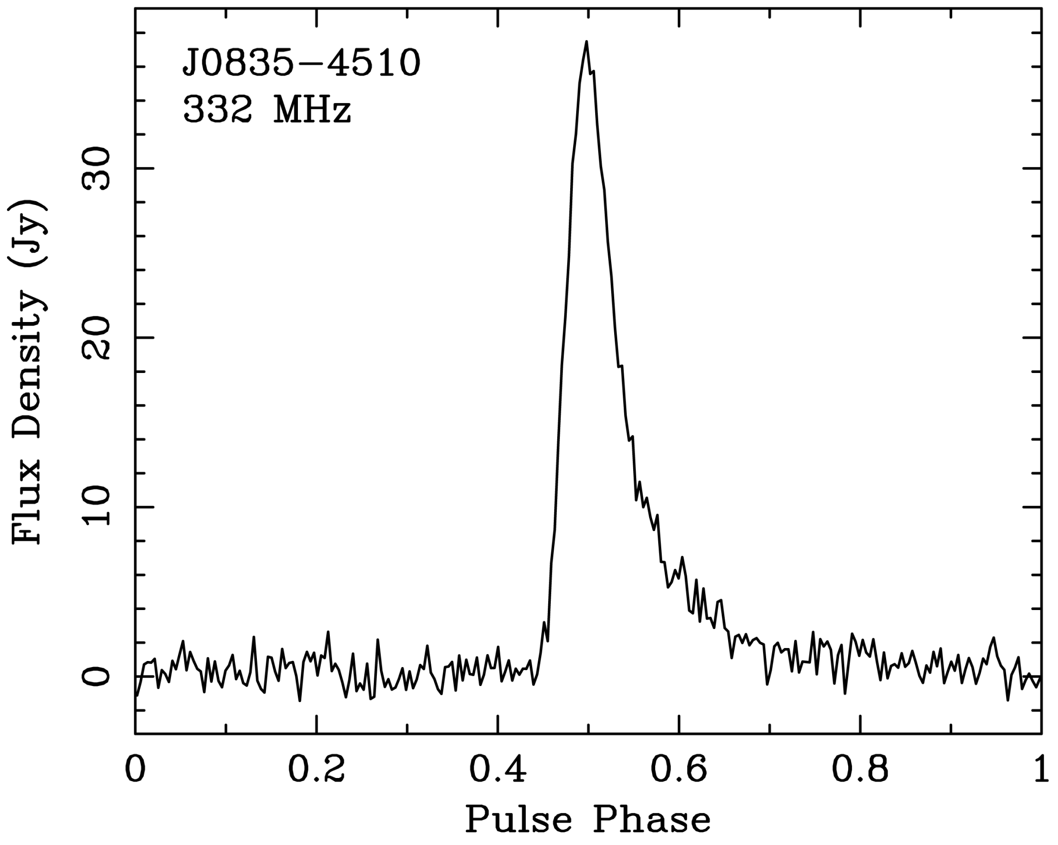
Some non-detections may be due to ***interstellar scintillation***



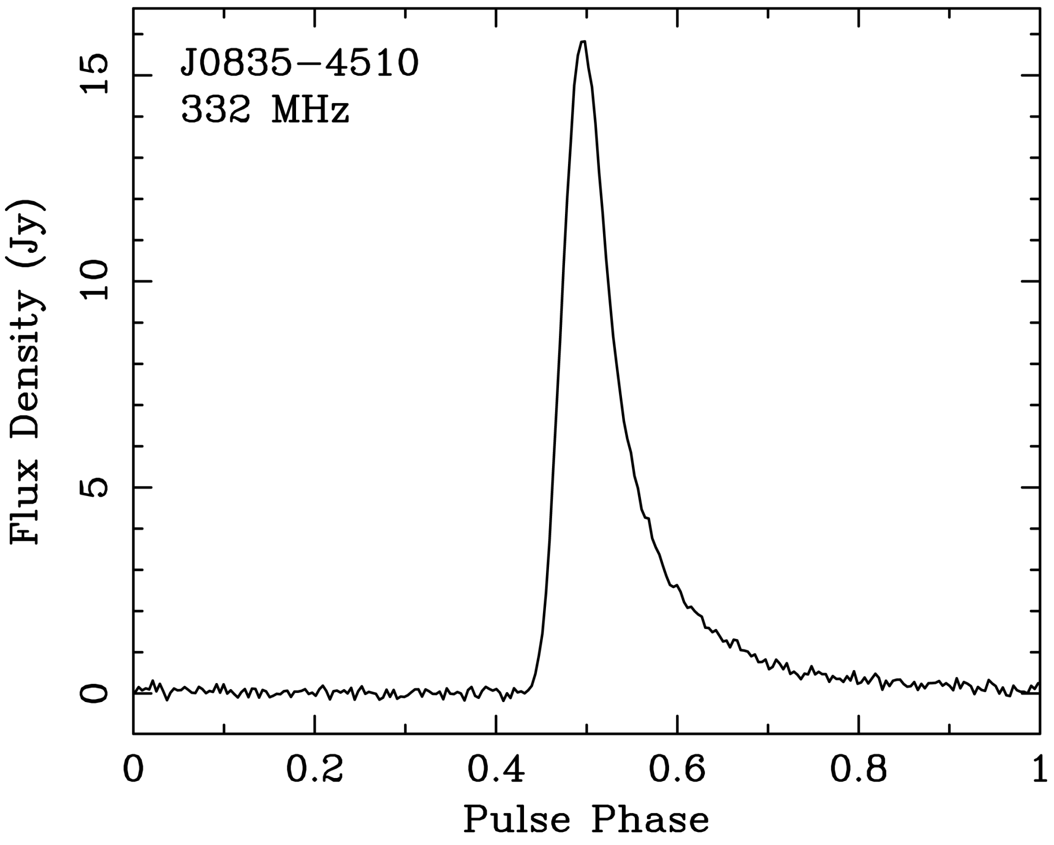


Station Bandwidth Upgrade

Ongoing bandwidth upgrade to > 32 coarse channels (i.e. $> 25\ \mathrm{MHz}$)



Single coarse channel



32 coarse channels

Summary and Conclusions

Demonstrated the ***pulsar detection capabilities*** of the initial setup of the SKA-Low stations AAVS2 and EDA2 (~1 MHz bandwidth):

- Observed 100 pulsars between ~70–350 MHz
  - 8 pulsars detected at multiple frequencies
  - 14 pulsars detected at single frequencies

Demonstrated how SKA-Low stations can ***meaningfully be used for science***, even with the modest sensitivity of the initial system:

- Measured flux densities for all detections
- Modelled and analysed the radio spectra of the detected pulsars
- Presented updated best-fit models for 16 pulsars

This work suggests a ***promising future of low-frequency pulsar astronomy***, even in the early-science phase of the SKA-Low.

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RESEARCH PAPER

Spectral analysis of 22 radio pulsars using SKA-Low precursor stations

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Abstract

We present the first observational study of pulsars performed with the second-generation precursor stations to the low-frequency component of the Square Kilometre Array (SKA-Low): the Aperture Array Verification System 2 (AAVS2) and the Engineering Development Array 2 (EDA2). Using the SKA-Low stations, we have observed 100 southern-sky pulsars between 70–350 MHz, including follow-up observations at multiple frequencies for a selected sample of bright pulsars. These observations have yielded detections of 22 pulsars, including the lowest-frequency detections ever published for 6 pulsars, despite the modest sensitivity of initial system where the recording bandwidth is limited to ∼ 1 MHz. By comparing simultaneous flux density measurements obtained with the SKA-Low stations and performing rigorous electromagnetic simulations, we verify the accuracy of the SKA-Low sensitivity simulation code presented in Sokolowski et al. (2022). Furthermore, we perform model fits to the radio spectra of the detected pulsars using the method developed by Jankowski et al. (2018), including 9 pulsars which were not fitted in the original work. We robustly classify the spectra into 5 morphological classes and find that all but one pulsar exhibit deviations from simple power-law behaviour. These findings suggest that pulsars with well-determined spectra are more likely to show spectral flattening or turn-over than average. Our work demonstrates how SKA-Low stations can be meaningfully used for scientifically useful measurements and analysis of pulsar radio spectra, which are important inputs for informing pulsar surveys and science planned with the SKA-Low.

Keywords: instrumentation: interferometers – methods: observational – pulsars: general – stars: neutron

1. INTRODUCTION

The radio spectra of pulsars offer unique insights into the nature of the mysterious pulsar emission mechanism, and for this reason have been the subject of extensive study for many decades (e.g. Sieber, 1973; Malofeev & Malov, 1980; Izvekova et al., 1981; Lorimer et al., 1995; Maron et al., 2000). Furthermore, studies of pulsar spectra are useful resources for planning surveys of the Galactic pulsar population with the Square Kilometre Array (SKA). In particular, spectral modelling can be

the MSP population have found that they do not turn over like long-period pulsars (e.g. Kramer et al., 1999; Kuzmin & Losovsky, 2001; Toscano et al., 1998), but rather continue as power-laws to the lowest observable frequencies (e.g. Erickson & Mahoney, 1985). Only a handful of MSPs have shown hints of turning over (e.g. Kuniyoshi et al., 2015; Dowell et al., 2013), all of which are predicted to peak well below 100 MHz, which suggests that turn-overs in MSPs may occur at much lower frequencies than long-period pulsars. Deviations from a simple power-law (such as spectral flattening and low-frequency

Lee *et al.*
(submitted to PASA)