The SMART pulsar survey and its role in the SKA era

***ABOVE**: An artist's impression of one of 256 tiles of the Murchison Widefield Array radio telescope observing a pulsar – a dense and rapidly spinning neutron star sending radio waves into the cosmos.*
***CREDIT**: Dilpreet Kaur / ICRAR / Curtin University.*

Ramesh Bhat

ICRAR

MWA MURCHISON WIDEFIELD ARRAY

Curtin University

THE GOVERNMENT OF WESTERN AUSTRALIA

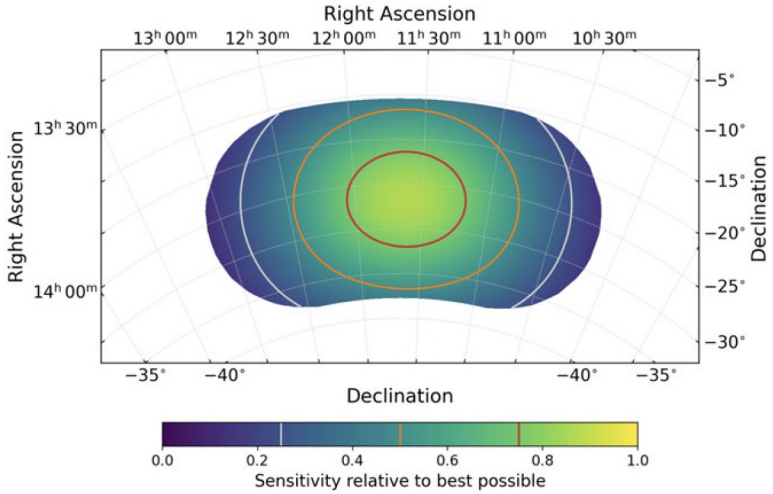
THE UNIVERSITY OF WESTERN AUSTRALIA

Swiss SKA Days, Geneva, 2 – 4 September 2024

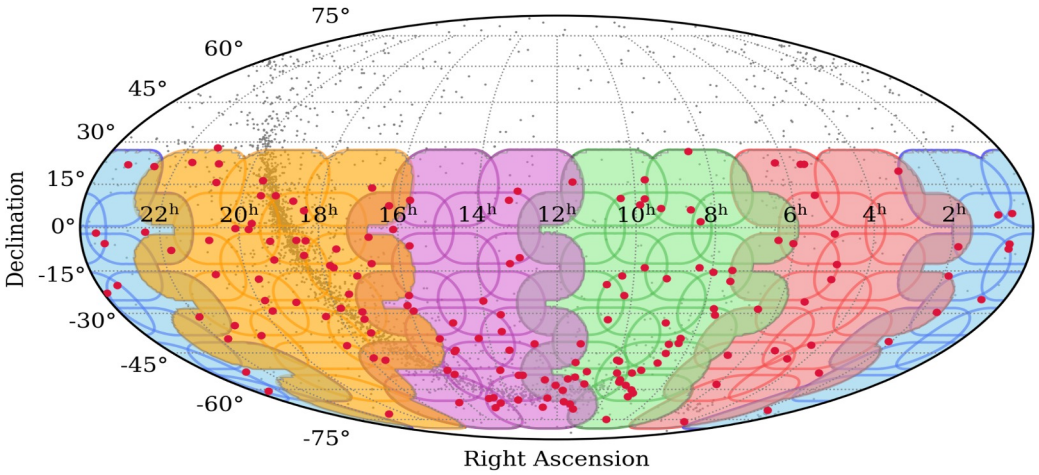
The Southern-sky MWA Rapid Two-metre (SMART) Survey

Leverages the MWA's large Field of View (FoV), the voltage capture system (VCS), and the compact configuration of the Phase II array

- Large FoV (~610 deg^2 at 150 MHz) and the VCS recording ➔ a **survey speed** of ~450 deg^2 hour^{-1}
- **First** southern-sky pulsar survey in the frequency band of SKA-Low
- Data collection **completed!** 4 PB of VCS (voltage) data from five dedicated campaigns (2018-2023)



(Bhat et al. 2023a/b, PASA, 40, e020/e021)



- Frequency band: 140-170 MHz
- Recording at 100-μs and 10-kHz resolutions
- **Long dwell times** (4800 second per pointing)
- *Tied-array* beam size ~23 arcminutes
- 6000-8000 beams per each observation
- 600,000 tied-array beams for the full survey
- **100 hours** to cover the full sky south of +30°
- **Large Data rate**: 42 – 84 TB per observation

Why search for more pulsars?

Populations
- Neutron Stars, Supernovae, Massive Stars
- Binaries, Milisecond Pulsars (MSPs)

Exotic Systems
- Triple Systems
- Double Pulsar, Pulsar-BH
- Double Neutron Stars (DNSs)

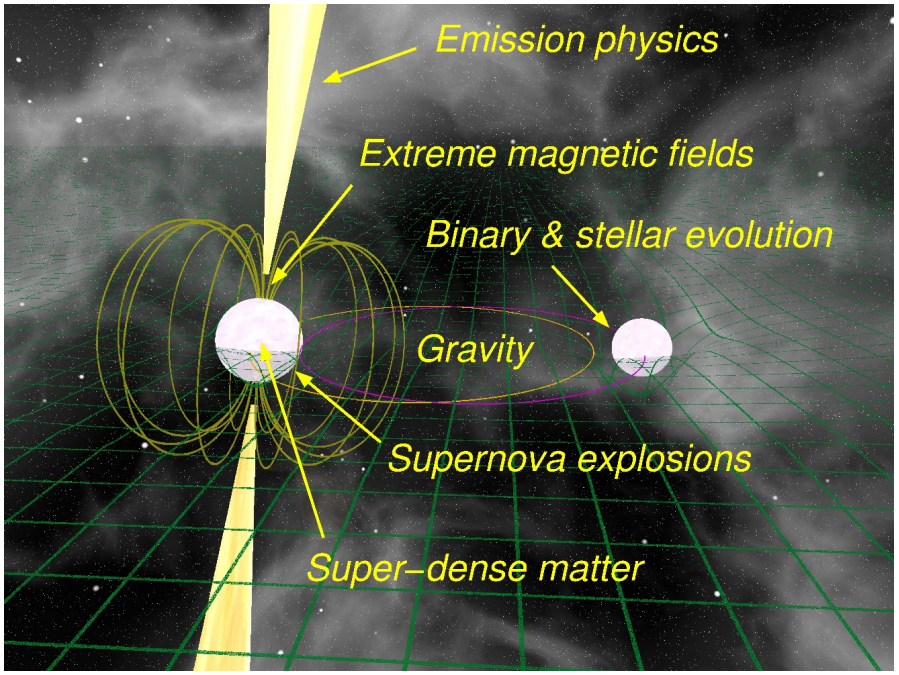
Clocks
- Time Standards

Interstellar Medium
- Dispersion, Faraday rotation
- Scattering and Scintillation

Extreme Environments
- Large B-field
- Neutron Star Interior
- Tight Binary systems
- Fast Spinning pulsars

Theories of Gravity
- Tests of General Relativity
- Tests of Alternative theories of gravity
- Gravitational Waves (pulsar timing arrays)

Pulsars & gravity is a key science for the SKA; and conducting a full Galactic census is high priority science objective for the SKA



Pulsars are natural laboratories for advancing physics, and are also unique tools for physical laboratories

SMART complements all other major surveys

LOFAR (LOTAAS)
Sanidas et al. (2019)

GBT (GBNCC)
Stovall et al. (2014)

Murriyang (HTRU)
Keith et al. (2010)

MWA (SMART)
Bhat et al. (2023)

GMRT (GHRSS)
Bhattacharyya et al. (2016)

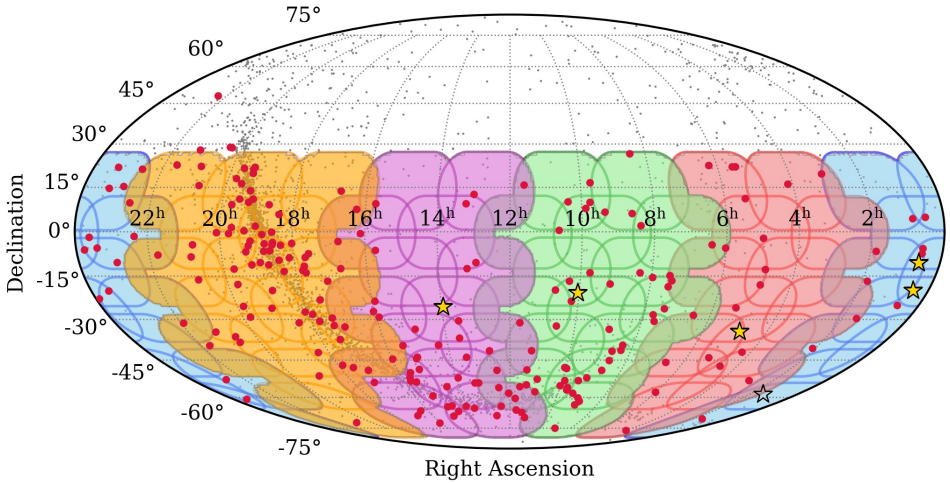
FAST (GPPS)
Han et al. (2021)

Survey	Telescope	Frequency Band (MHz)	Sky coverage	Time resolution (μs)	Frequency resolution (kHz)	Dwell time (s)	S_{min} † (mJy)
LOTAAS	LOFAR	119-151	$\delta > 0°$	491.52	12.21	3600	1-2
SMART	MWA	140-170	$\delta < +30°$	100	10	4800	2-3
GBNCC	GBT	300-400	$\delta > -40°$	81.92	24	120	1.1
GHRSS	GMRT	306-338	$-40° > \delta > -54°$	30.72-61.44	15.625-31.25	900, 1200	1.0
HTRU	Parkes	1182-1522	$\delta < +30°$	64	390	240, 540, 4200	0.2-0.6
GPPS	FAST	1100-1500	$-10° < b < +10°$	49.152	244.14	300	0.005

SMART is a survey with SKA precursor

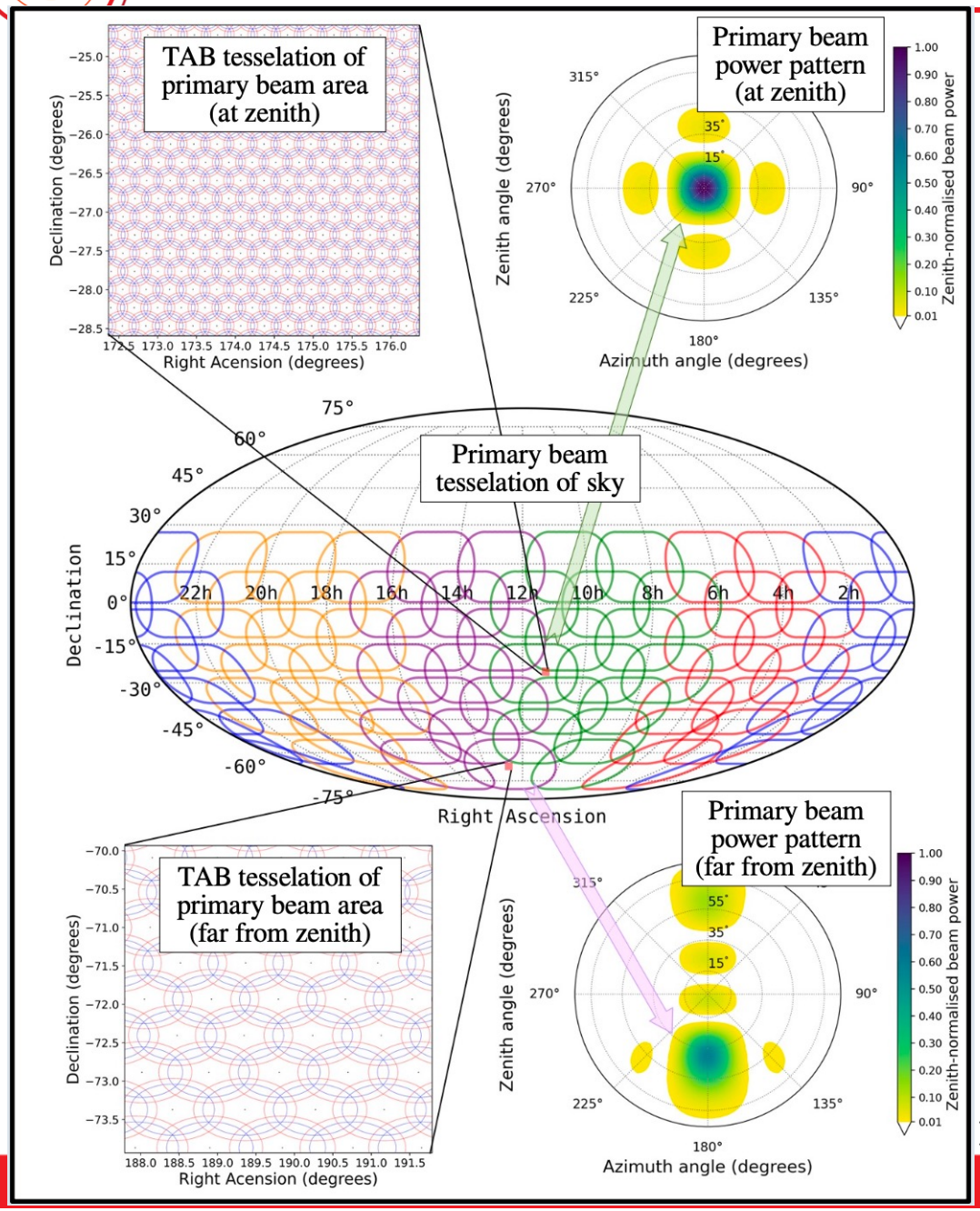
SMART is unique on several counts: e.g. novelty in data recording, and as a reference for pulsar surveys planned with the SKA-Low

- **SKA precursor pulsar survey**: synergistic overalp with calbration and beamforming methodologies likely relevent for SKA-Low
- **Reference survey for SKA-Low**, providing complete digital record of the southern sky
- **Voltage-capture mode for data recording** (as opposed to filterbank data format of all other surveys) ➔ a multitude of processing (and reprocessing) avenues for follow-ups and confirmation (inc timing/localisation)
- 3-5 times deeper than previous-generation low-frequency pulsar survey (Parkes 70cm from 1990s), and 2-3 times more sensitive compared to high-latitude Parkes HTRU
- Complementarity with ongoing surveys (e.g. LOFAR, GBT, GMRT, FAST) in terms of sky and/or frequency coverages



- *Search for pulsars (and fast transients) in the new parameter space opened up by the MWA*
- *Map out the pulsar population in the southern sky at the low frequencies*
- *Inform pulsar survey and science prep for the SKA-Low*

Survey strategy & beamforming



- **Each SMART observation** (~ 610 deg^2) is processed to form ~ 6000 to ~ 8000 tied-array (phased-array) beams

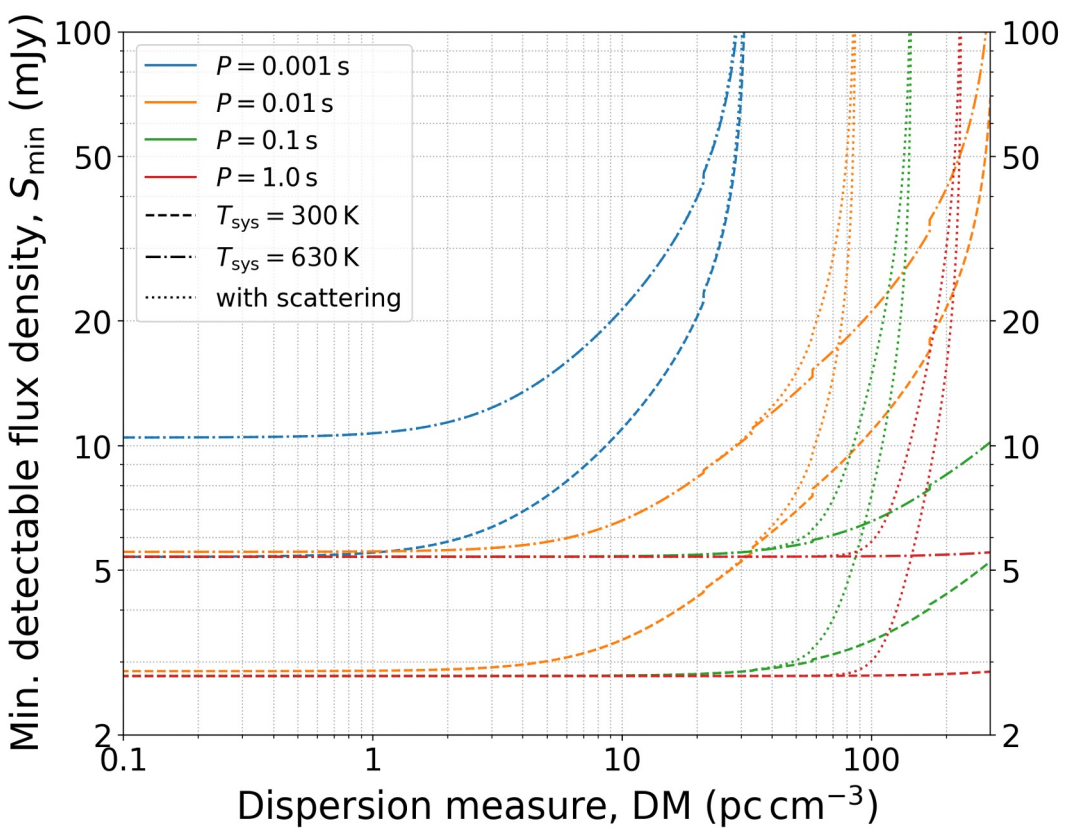
- **Multi-pixel beamformer** (Swainston et al. 2022) is the front-end workhorse for SMART search pipeline

- Raw voltage data archived for SMART observations
- Excellent data sets for trialing beamforming methodologies

Bhat et al. (2023), PASA, 40, e020

SMART Search sensitivity

At low frequencies, pulsar search sensitivity is a strong function of period, DM, and sky background



- For full observation (dwell time = 80 mins; the second pass processing)
- Comparable sensitivity to LOTAAS (LOFAR survey)
- Scattering is primarily an issue in the Galactic plane and near Galactic Centre
- Sensitive down to DM ~ 50 for MSPs and DM ~250 for long-period pulsars

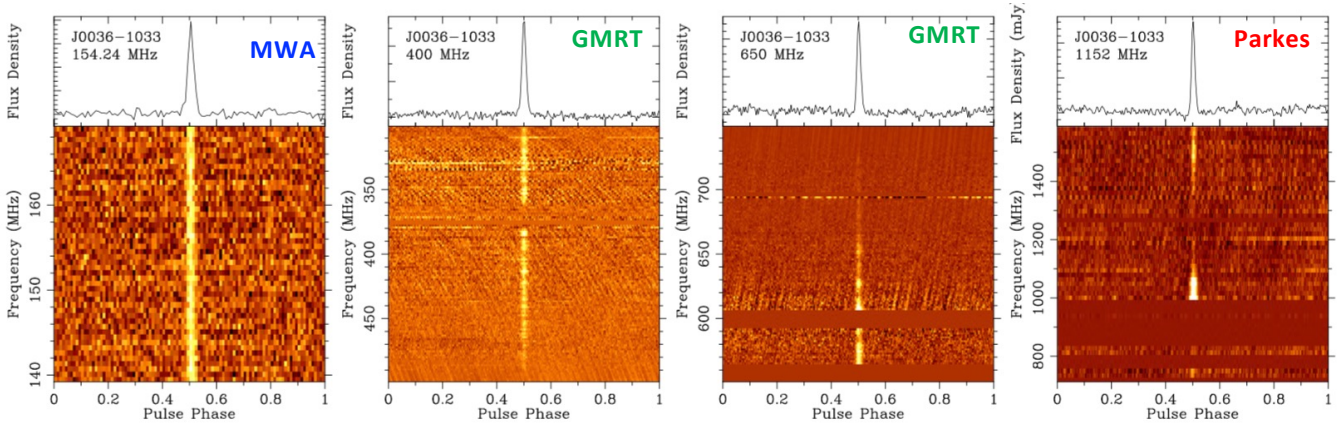
Limiting search sensitivity:

- ~2-3 mJy for long-period pulsars (P ~ 1 second or longer)
- ~5-10 mJy for short-period (MSPs) pulsars (P ~ 1- 10 ms)

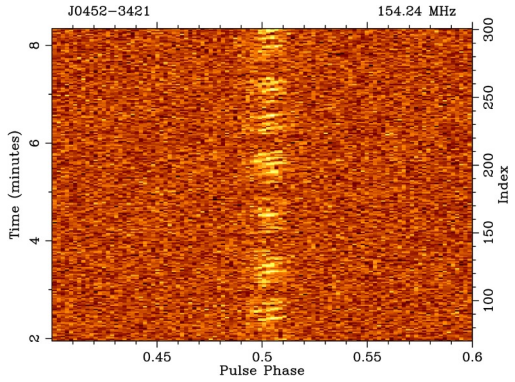
LOTASS (LOFAR) + SMART (MWA) will be the most sensitive pulsar surveys in the SKA-Low's frequency band

New Pulsars from the First pass

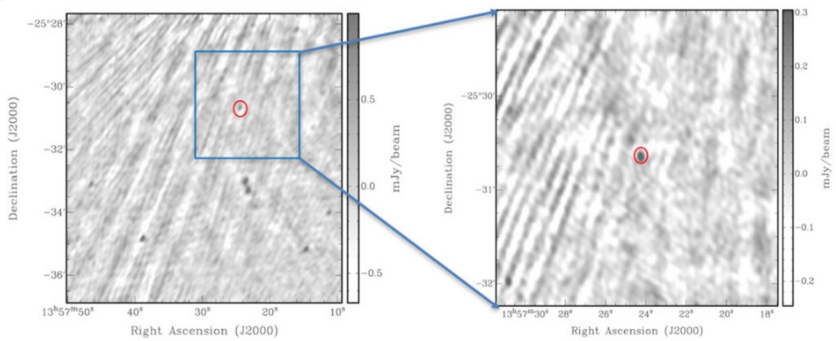
First pass processing: a shallow survey, limited to periodicity searches, DM < 250 pc cm^{-3}



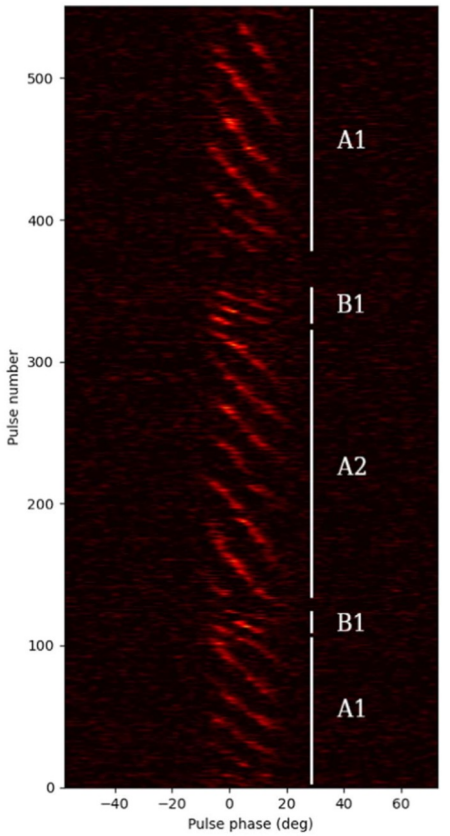
J0036-1033: steep spectrum, low-luminosity, and highly variable (a factor of ~ 5-6), high-|b|, so promising for scintillation analysis (Swainston, Bhat, et al. 2021, ApJL, 911, L26)



J0452-3418: subpulse drifting, nulling (Grover, Bhat, et al. 2024a, ApJ, **970**, 798)



J1357-2530: uGMRT imaging localisation from concurrent imaging + beamforming observation (Bhat et al. 2023b, PASA, 40, e020)



J0026-1955: sub-pulse drifting, nulling, high-|b| location (McSweeney, Bhat, et al. 2022, ApJ, **933**, 210)

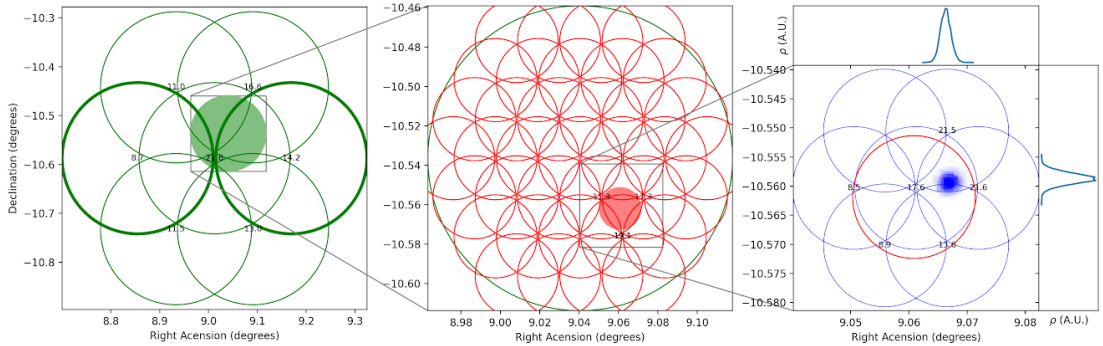
uGMRT Follow-up (Janagal et al. 2023b, MNRAS, **524**, 2684)

Beamforming + Imaging for Localisation

and hence an accelerated convergence to the full coherent timing solution

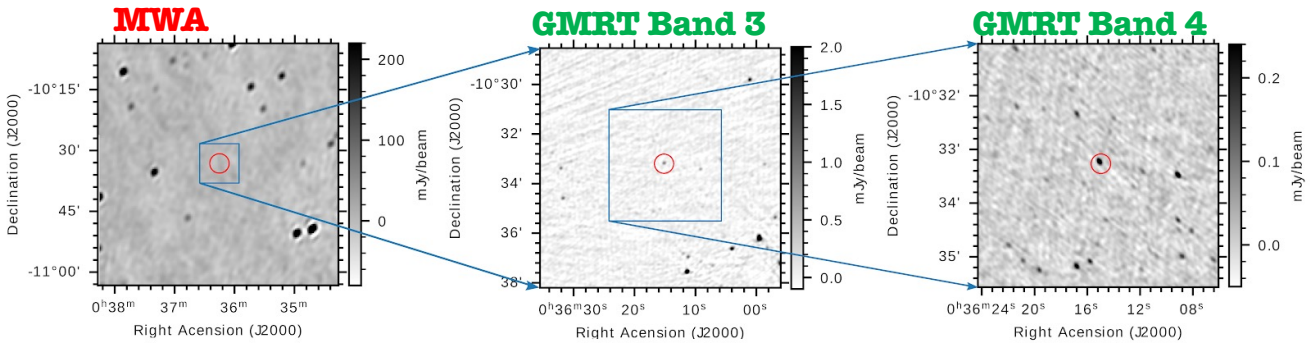
Step #1: from ~10' to ~10" using a combination of SMART and VCS archival data

Phase 2 compact (~300 m) **Phase 1 (~3 km)** **Phase 2 extended (~6 km)**



SMART Pulsar #1:
PSR J0036-1033
P = 0.900009 seconds
DM = 23.123 pc cm^{-3}

Step #2: Improved localisation (~arcsecond level) via uGMRT imaging observations

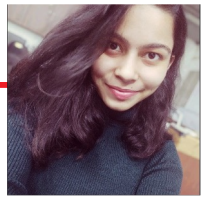


A similar strategy can be employed for SKA-Low discoveries, e.g. SKA-mid imaging for localisation

Swainston, Bhat, et al. (2021), ApJ, **911**:L26; Bhat et al. (2023b), PASA, **40**, e020

Step #3: faster convergence to timing solutions (in a few months); e.g. J0036, J0026

PSR J0026-1955: evolutionary sub-pulse drifting and nulling



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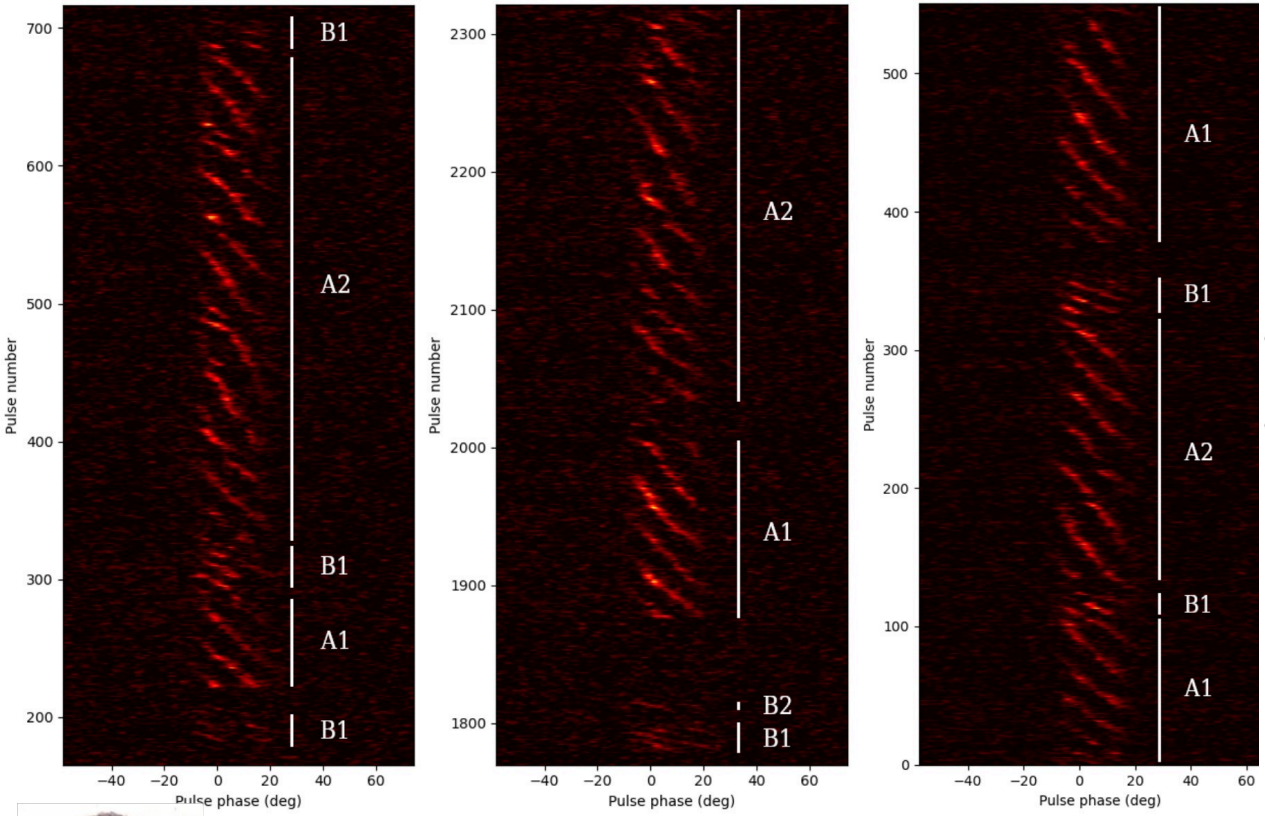
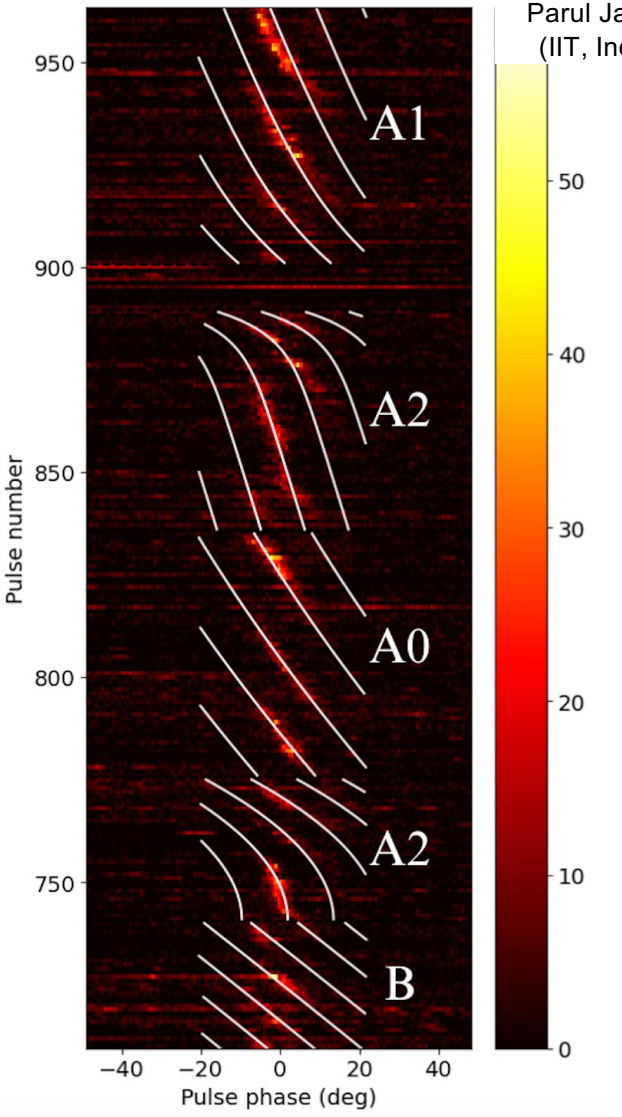
GMRT Follow-up
Janagal et al. MNRAS, **524**, 2684

A pulsar with unusual sub-pulse drifting (evolutionary and stable drift modes) and a very large nulling fraction (70%)

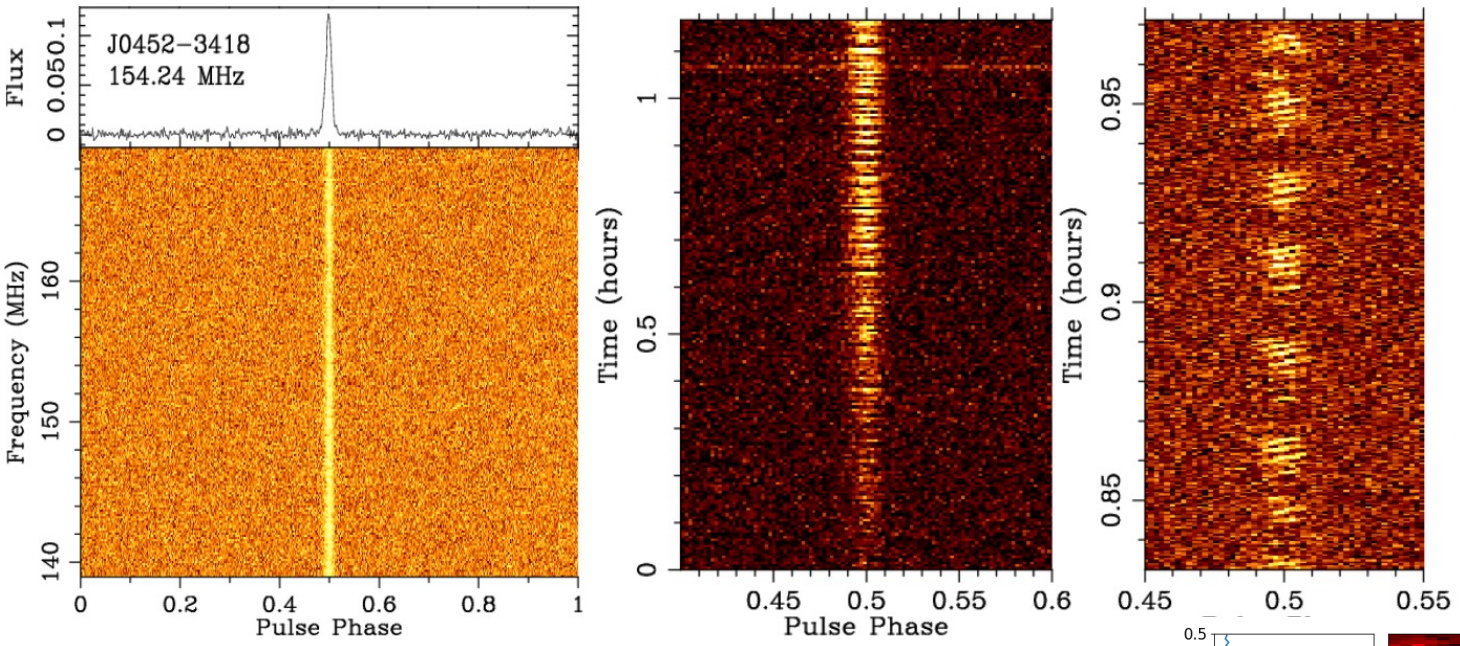




McSweeney et al. (2022), ApJ, ***933***, *210*
MWA Discovery and Follow-up

Sam McSweeney

PSR J0452-3418: regular sub-pulse drifting + quasi-periodic nulling



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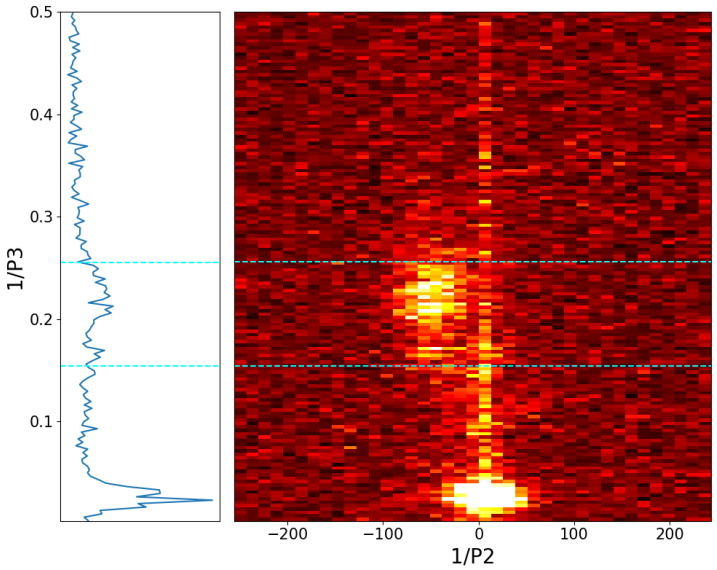
Grover, et al. 2024a, ApJ, **970**, 798

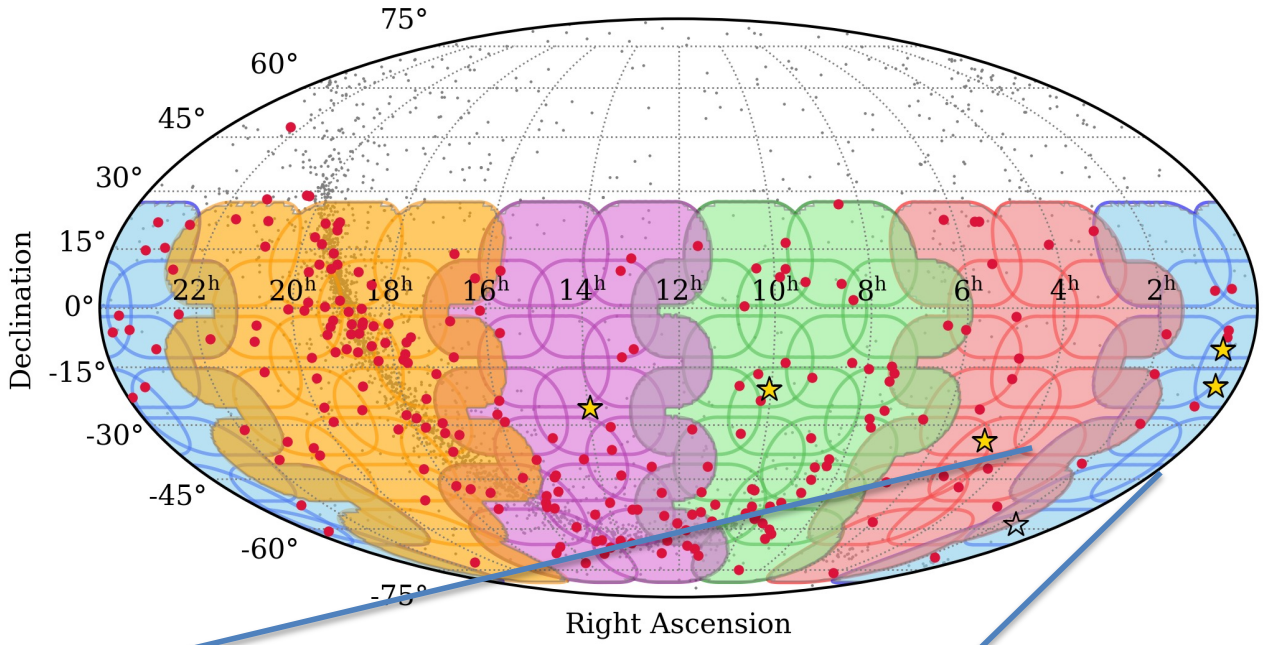


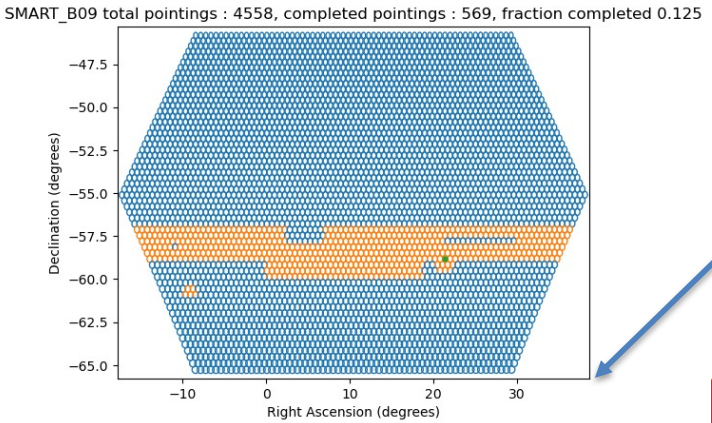
Pulsar **#5** from the first-pass SMART processing

- Period (P_1) = 1.67 seconds
- DM = 19.78 pc cm^{-3}
- Sub-pulse drifting periodicity, P_3 ~ 5 P_1
- Quasi-periodic nulling on time scale ~ 45 P_1
- Localization (~arcsecond) via uGMRT (Band 3) high-resolution imaging

Commencing the second pass

Second pass processing: full observation searches, FFT+FFA for periodicity searches, single-pulse (transient) searches, targeted searches for MSPs, etc.





Some Numbers (Chia Min Tan)

- Processing on NT (OzSTAR)
  (NT = Ngarrgu Tindebeek)

•Beamforming

- 300 hours with **24 GPUs** for 1/8th obs (or **2400 hours**, for one full SMART observation)

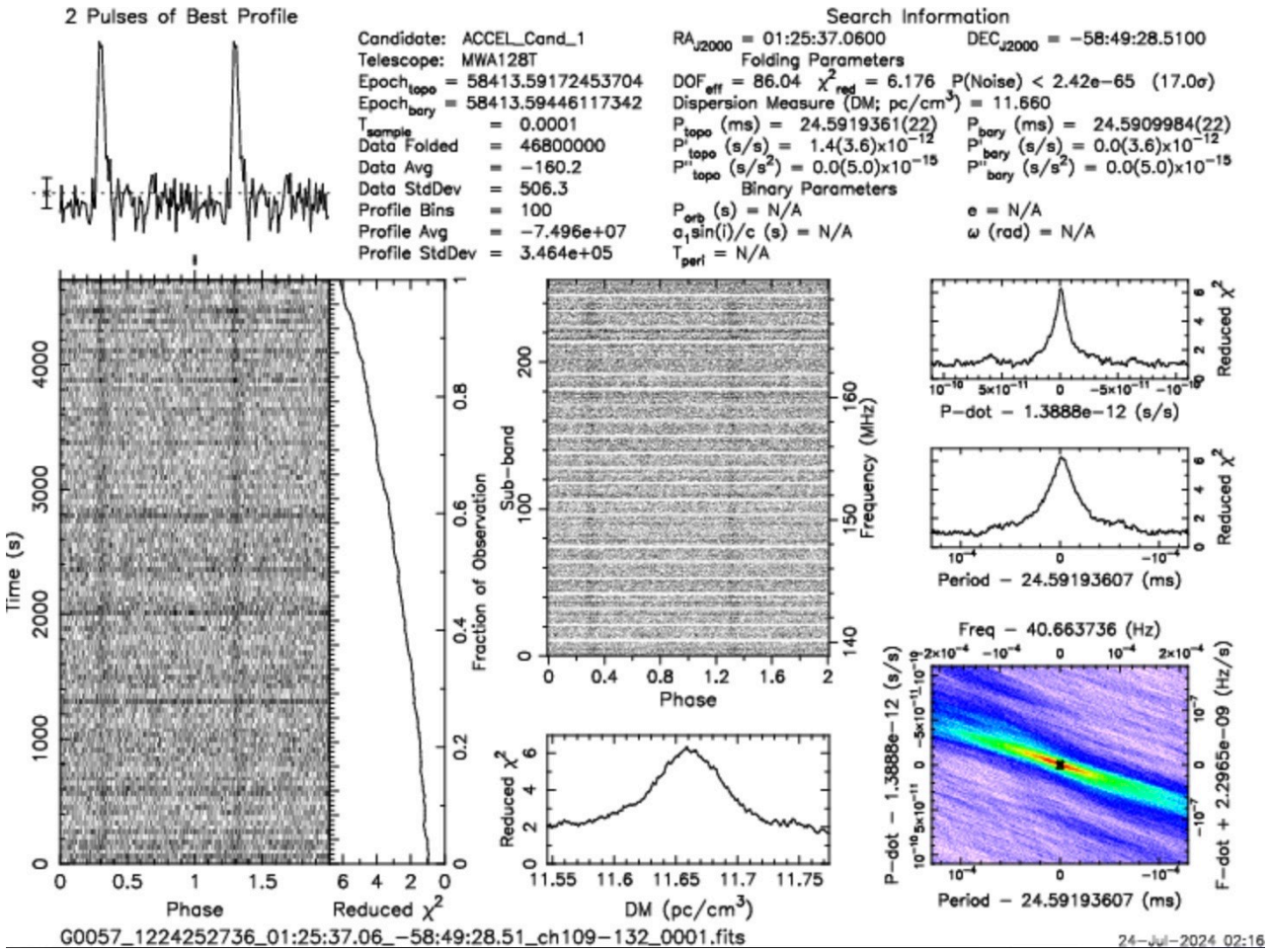
•Search pipeline :

- 4000 CPU hours for FFT+FFA search for 1/8th observation (or **31,500 CPU hours** for one SMART observation)

- Need to spread out the processing load; e.g. DUG (commercial HPC) + NT (OzSTAR) in the near future, alongside Pawsey (Setonix)

New pulsar candidate

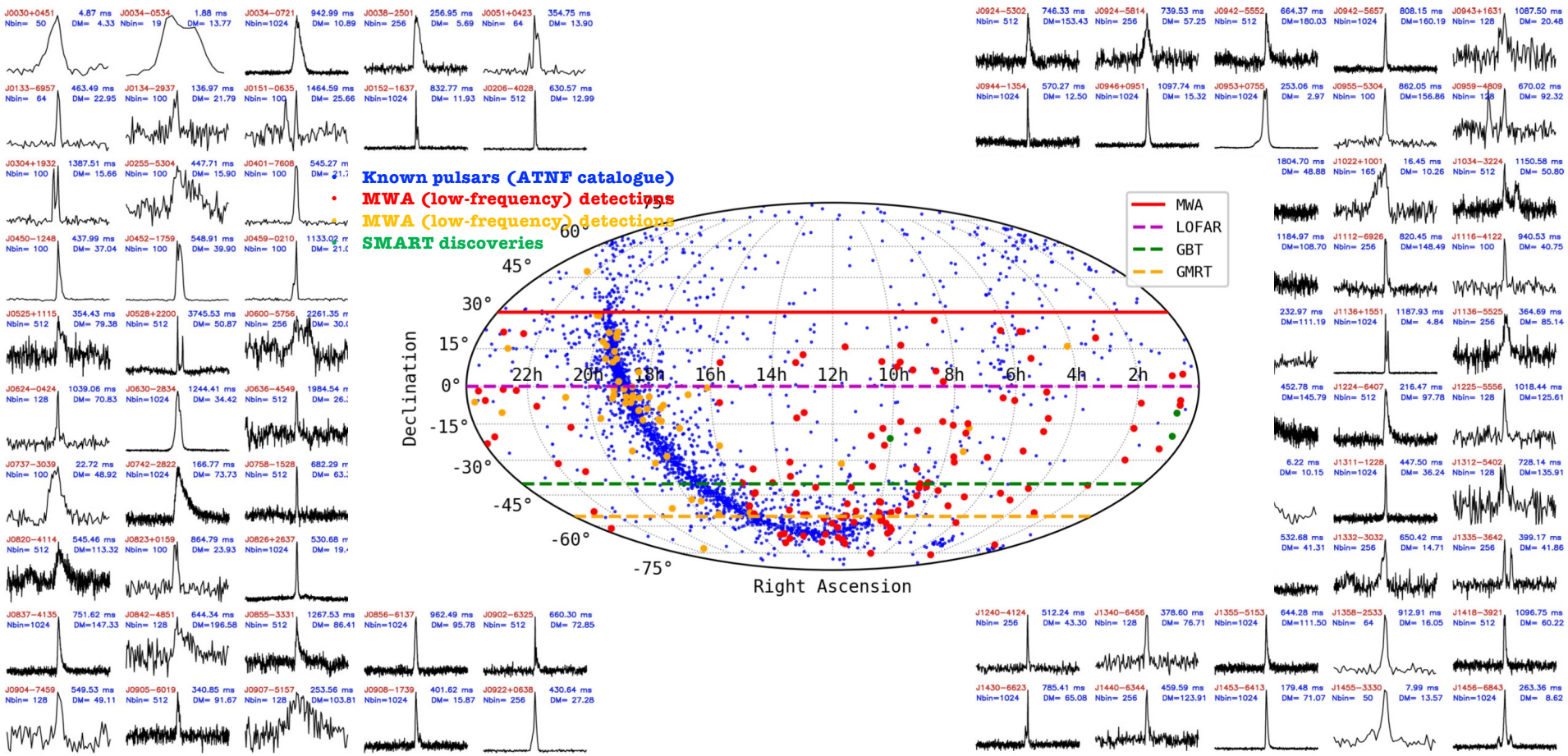
After processing 1/8th of first observation, i.e. 560 tied-array beams (out of 4500), or **~0.2%** of sky



- Period: 24.6 ms
- DM: 11.669 pc cm^{-3}
- S/N: 17 sigma in 80 min
- S_{150}: ~4-6 mJy (indicative)

- Confirmed in an adjacent SMART observation
- Detected in archival (VCS) observations
- Preliminary indications
  - Likely in a binary orbit (~days)
  - Possibly a partially recycled object

MWA (SMART) Pulsar Census

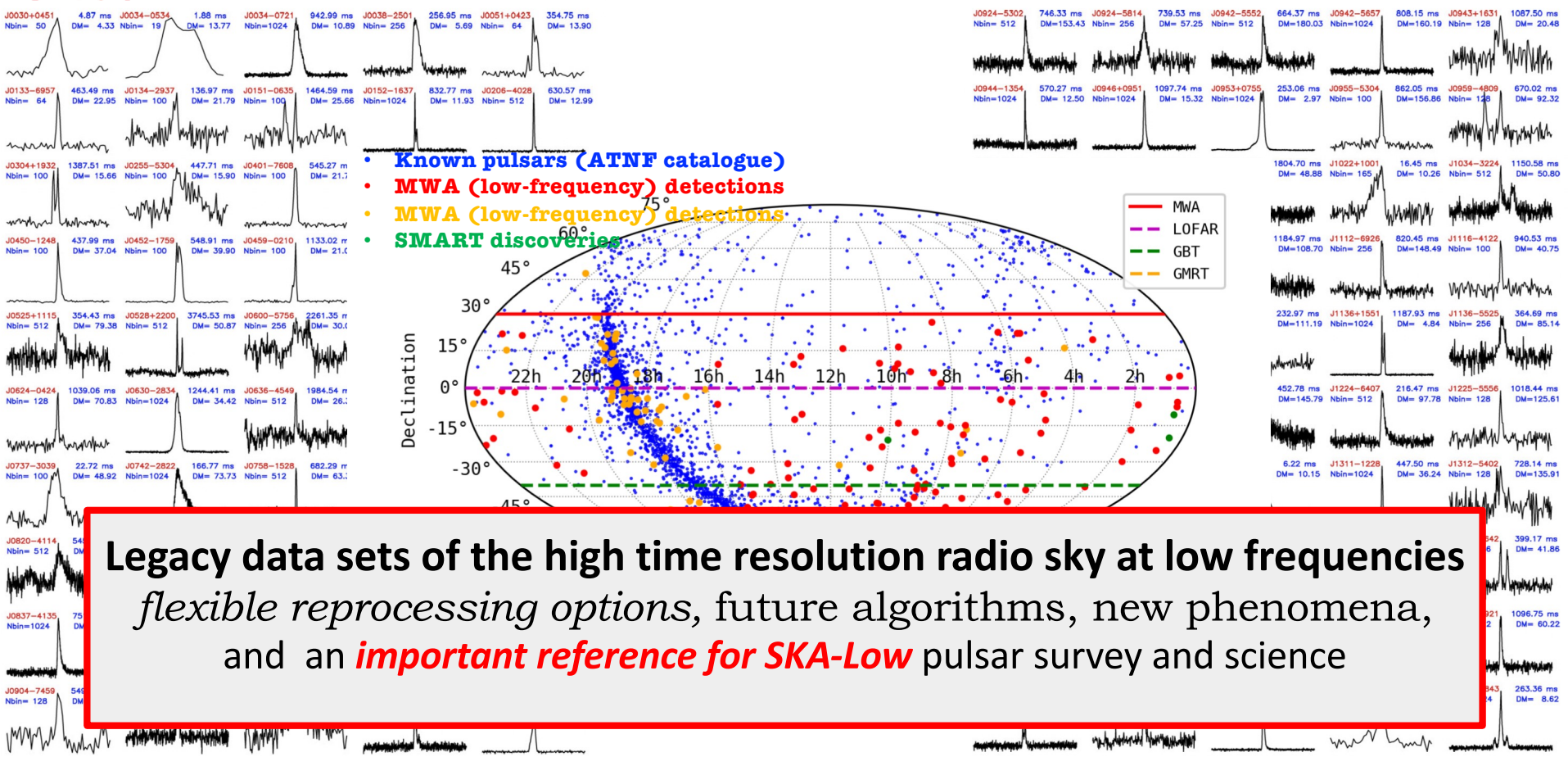


Bhat et al. 2023b, PASA, **40**, e020

SMART Pulsar Detections:

- Low-frequency detections of 230+ pulsars
- Five pulsar discoveries from analysis of < 5% of data
- Data release papers in prep (updated pulsar census + MSP census)

MWA (SMART) Pulsar Census



Legacy data sets of the high time resolution radio sky at low frequencies

flexible reprocessing options, future algorithms, new phenomena,

and an ***important reference for SKA-Low*** pulsar survey and science

Bhat et al. 2023b, PASA, **40**, e020

SMART Pulsar Detections:

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Summary

- The SMART survey exploits the MWA's large field of view (~610 deg^2) and the voltage capture system (VCS) capability for data recording
- SMART complements past/ongoing surveys in sky coverage & frequency band
- Data collection 100% completed (2018-2023); total data volume ~4 Petabytes
- ~10% processed for a "first-pass" search, ~10% of which scrutinised for cands; 5 new pulsars, Redetections of 230 pulsars (Bhat et al. 2023a,b; McSweeney et al. 2022; Swainston et al. 2021; Grover et al. 2024; Lee et al. in prep.; Bhat et al. in prep.)
- Second pass processing (dwell time ~80 minutes) has commenced; periodicity (FFT + FFA), single-pulse, CDMT + acceleration searches; New MSP candidate
- Legacy (voltage) data set for the low-frequency (southern) sky, an important reference survey for SKA-Low survey planning and verification