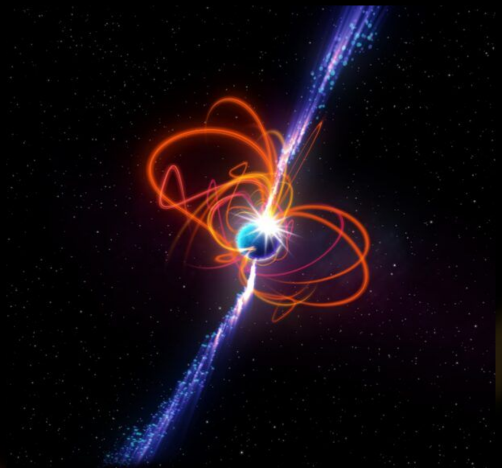
Celebrating 10 years of Transient Science with the MWA



Gemma Anderson (on behalf of the MWA Transient SWG)

ICRAR-Curtin University

MWA Project Meeting - 28 July 2023

ICRAR
International Centre for Radio Astronomy Research

Curtin University

The University of Western Australia

Government of Western Australia
Department of the Premier and Cabinet
Office of Science

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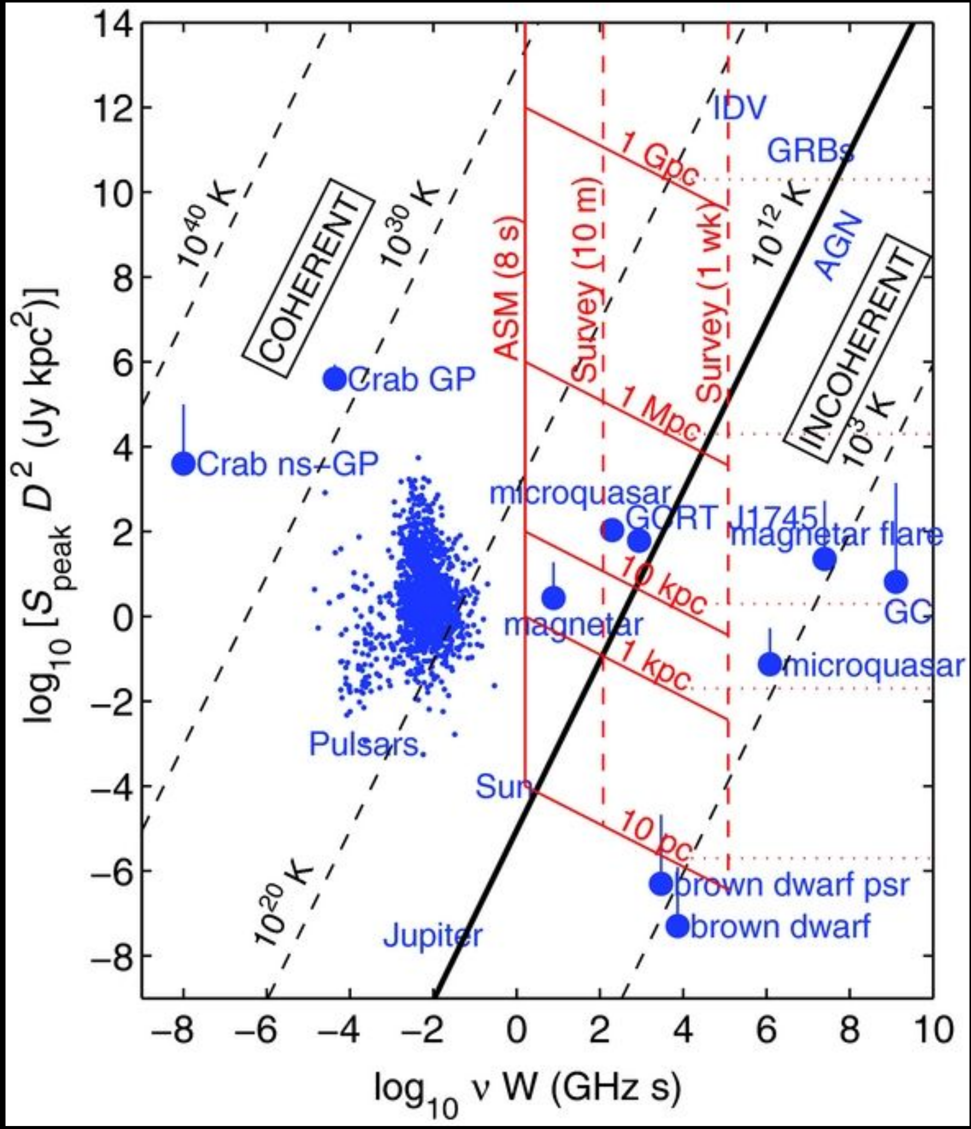
Image credit: ICRAR

MWA transient predictions in 2013

"The potential sources of radio transient emission fall into five broad categories:

1. coronal emission from nearby stars/substellar objects
2. emission from compact objects such as neutron stars and accreting black holes
3. explosive events such as gamma-ray bursts (GRBs) and radio supernovae
4. *(exo)*planetary emission from nearby systems
5. and new phenomena discovered through the opening of new regions of observational phase space."

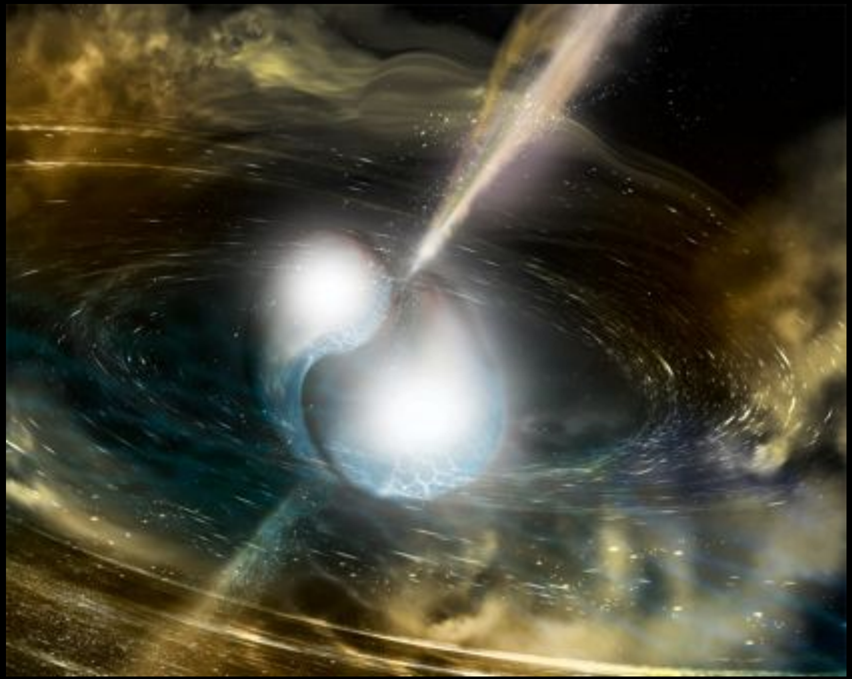
Bowman et al. (2013), Science with the Murchison Widefield Array, PASA, 30, e031



MWA 10 year transient journey

Themes

1. Fast radio burst (FRB) searches
   - Blind and targeted
2. Rapid-response triggering
   - GRBs, GWs and FRBs
3. Space Situational Awareness
4. Targeted transient searches (image plane)
   - Exoplanets
   - Flare stars
   - Pulsars
   - X-ray binaries (XRBs)
   - gravitational wave (GW) events and explosive transients
5. Blind transient searches
   - Searches and discoveries



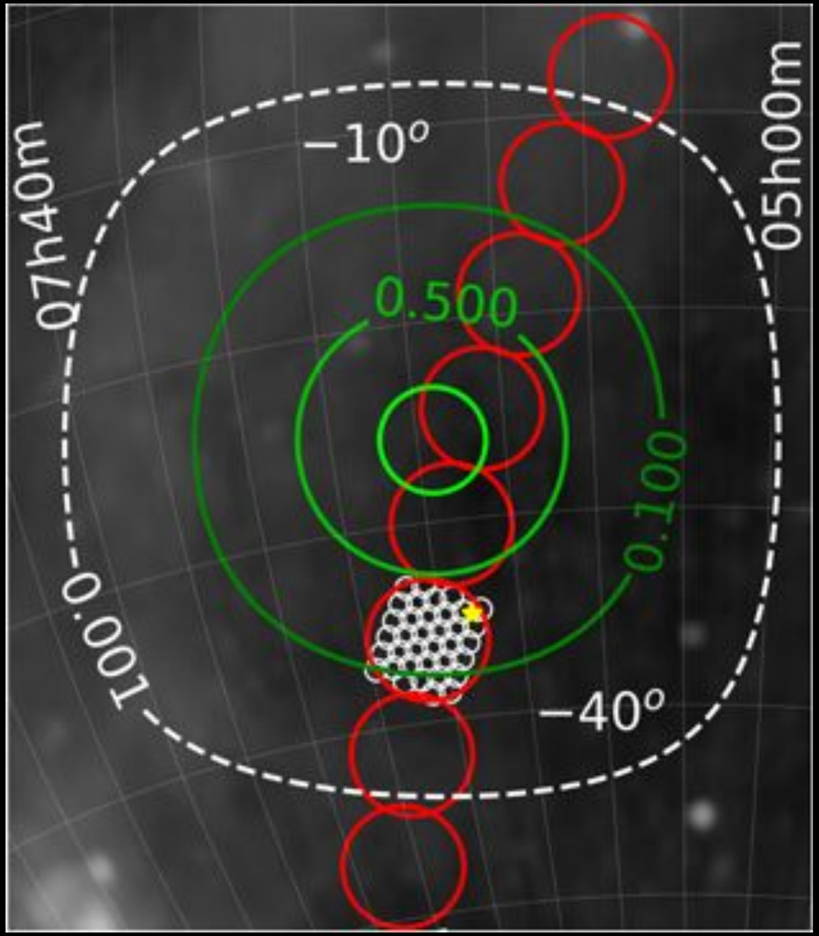
Artist's impression of GW170817/GRB 170817A
(binary neutron star merger)
Credit: NSF/LIGO/Sonoma State University/A. Simonnet

Also Cosmic-rays! but not covered here (see Clancy James's talk)

FRB searches

- Blind FRB search: image dedispersion, 10hr EoR field, 154 MHz, 2s/1.28MHz (Tingay et al. 2015, ApJ, 150, 199)
- Blind FRB search: 30s snapshots, 100hr EoR field, 182 MHz (Rowlinson et al. 2016, MNRAS, 458, 3506)
- ASKAP shadowing: MWA limits on 3 FRBs (of 7), image dedispersion (0.5s/1.28MHz), no low frequency detection
  - Most likely explanation is low frequency spectral turn-over (Sokolowski et al. 2018, ApJL, 867, 12)
- VCS archival search of known repeaters: see Ramesh Bhat's talk (Tian et al. 2023, MNRAS, 518, 4278)

Reference	Obs (hr)	Freq (Mhz)	Time/Freq res	Sensitivity (Jy ms)
Tingay et al. (2015)	10.5	156	2s/1.28MHz	700
Rowlinson et al. (2016)	100	182	28s/30.72MHz	7980
Sokolowski et al. (2018)	3.5	185	0.5s/1.28MHz	450-6500
Tian et al. (2023)	23.3	144-215	400us/1.28MHz	32-1175
Kemp et al. (2023)	100	156-197	4s/1.28MHz	840



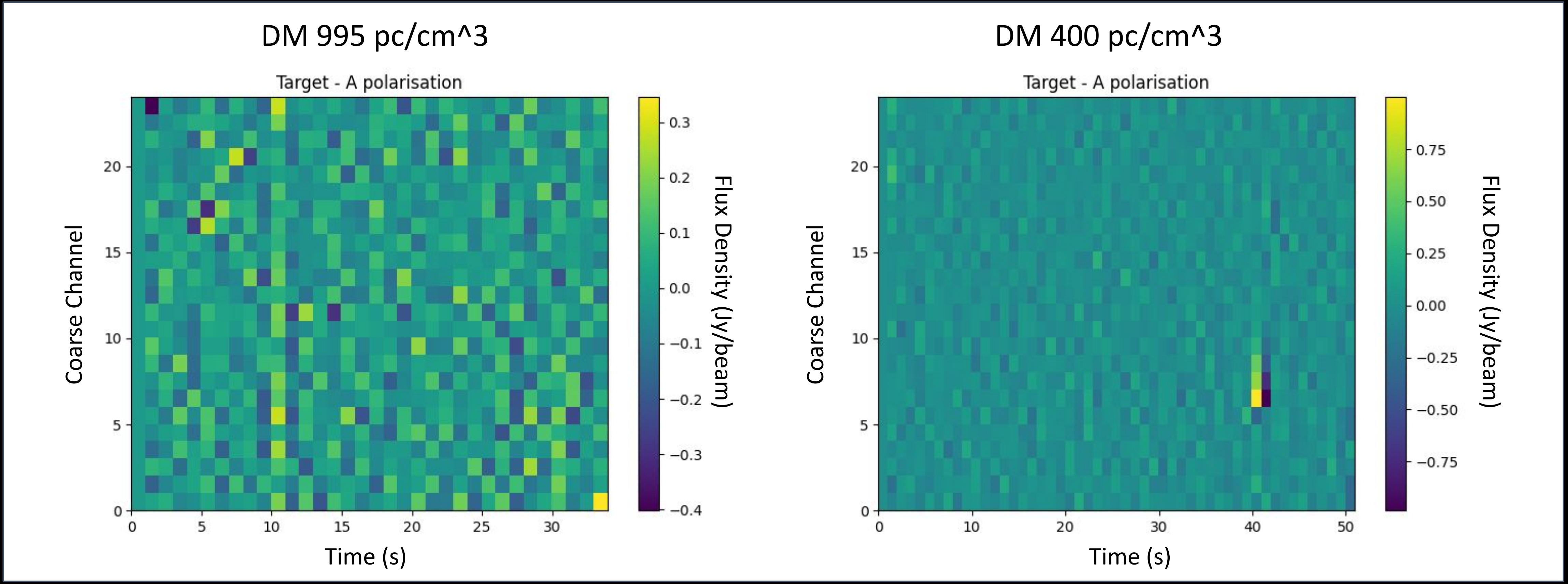
MWA shadowing strategy for FRB 180324

- Red circles ASKAP antenna beams
- White circles individual 36 antenna beams
- Contours MWA beam

FRB searches - New!

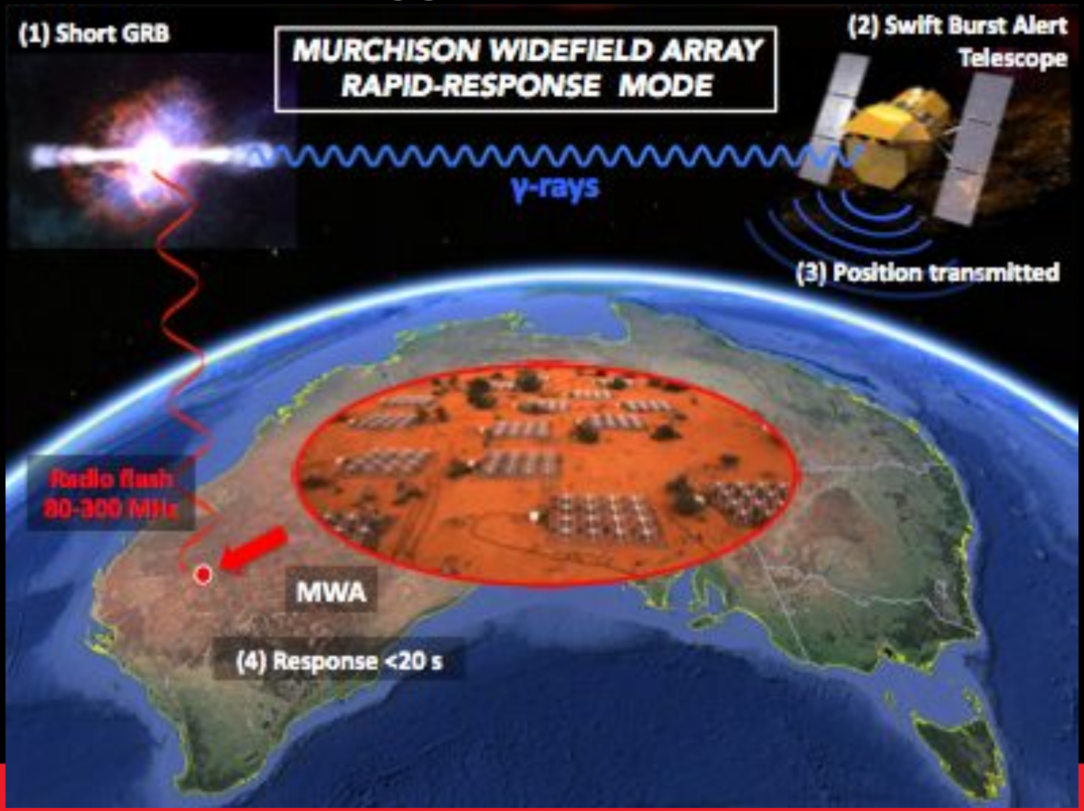
Ian Kemp’s PhD Thesis work

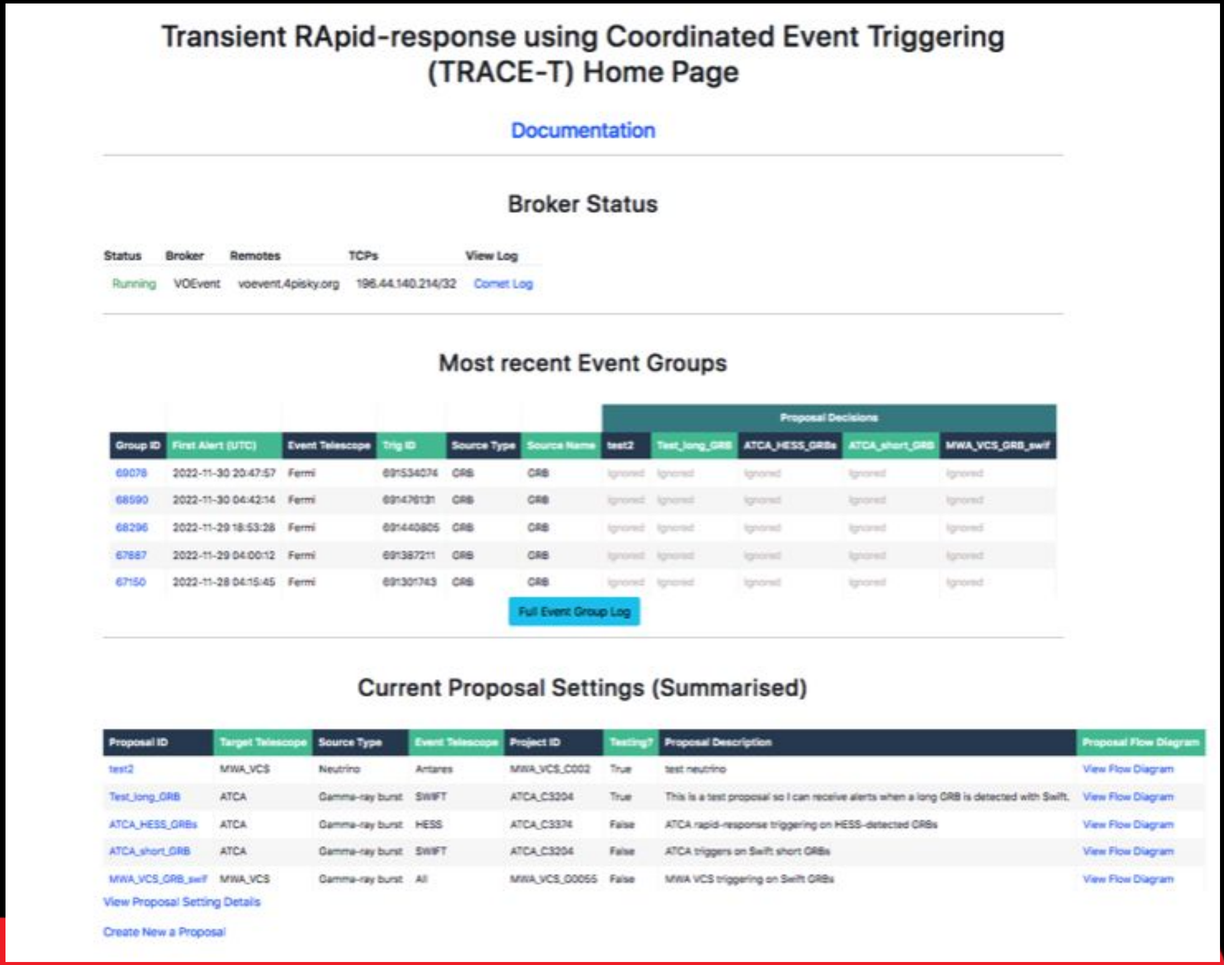
- Blind FRB search: image dedispersion, 100hr EoR field, 139-170 MHz, 7 sigma sensitivity 800 Jyms
- Expanding on analysis by Tingay et al. (2015, same EoR field)
- 3 candidates! Waterfall plots of 2 below (2 s/1.28 MHz)



MWA rapid-response triggering mode

- MWA triggering response <10-30s, VCS and standard correlator (FASTEST IN THE WORLD!)
- Recent upgrade to strategy and triggering functionality (Hancock et al. 2019, PASA, 36, e046)
- Search for prompt, coherent (FRB-like) signals associated with GRBs, GWs, FRBs, neutrinos
- TRACE-T (**ADACS developed**) parses alerts and sends triggers to MWA (and ATCA)





Transient RApid-response using Coordinated Event Triggering (TRACE-T) Home Page

Documentation

Broker Status

Status	Broker	Remotes	TCPs	View Log
Running	VOEvent	voevent.4pisky.org	196.44.140.214/32	Comet Log

Most recent Event Groups

						Proposal Decisions				
Group ID	First Alert (UTC)	Event Telescope	Trig ID	Source Type	Source Name	test2	Test_long_GRB	ATCA_HESS_GRBs	ATCA_short_GRB	MWA_VCS_GRB_swif
69078	2022-11-30 20:47:57	Fermi	691534074	GRB	GRB	Ignored	Ignored	Ignored	Ignored	Ignored
68590	2022-11-30 04:42:14	Fermi	691476131	GRB	GRB	Ignored	Ignored	Ignored	Ignored	Ignored
68296	2022-11-29 18:53:28	Fermi	691440805	GRB	GRB	Ignored	Ignored	Ignored	Ignored	Ignored
67887	2022-11-29 04:00:12	Fermi	691387211	GRB	GRB	Ignored	Ignored	Ignored	Ignored	Ignored
67150	2022-11-28 04:15:45	Fermi	691301743	GRB	GRB	Ignored	Ignored	Ignored	Ignored	Ignored

Full Event Group Log

Current Proposal Settings (Summarised)

Proposal ID	Target Telescope	Source Type	Event Telescope	Project ID	Testing?	Proposal Description	Proposal Flow Diagram
test2	MWA_VCS	Neutrino	Antares	MWA_VCS_C002	True	test neutrino	View Flow Diagram
Test_long_GRB	ATCA	Gamma-ray burst	SWIFT	ATCA_C3204	True	This is a test proposal so I can receive alerts when a long GRB is detected with Swift.	View Flow Diagram
ATCA_HESS_GRBs	ATCA	Gamma-ray burst	HESS	ATCA_C3374	False	ATCA rapid-response triggering on HESS-detected GRBs	View Flow Diagram
ATCA_short_GRB	ATCA	Gamma-ray burst	SWIFT	ATCA_C3204	False	ATCA triggers on Swift short GRBs	View Flow Diagram
MWA_VCS_GRB_swif	MWA_VCS	Gamma-ray burst	All	MWA_VCS_D0055	False	MWA VCS triggering on Swift GRBs	View Flow Diagram

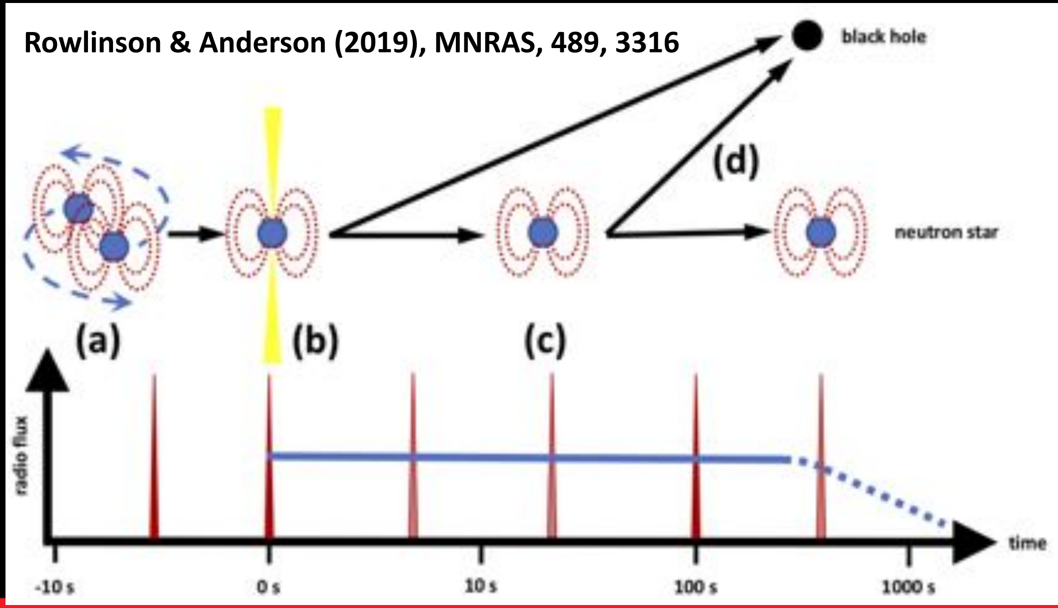
View Proposal Setting Details

Create New a Proposal

GRB triggering at MHz frequencies

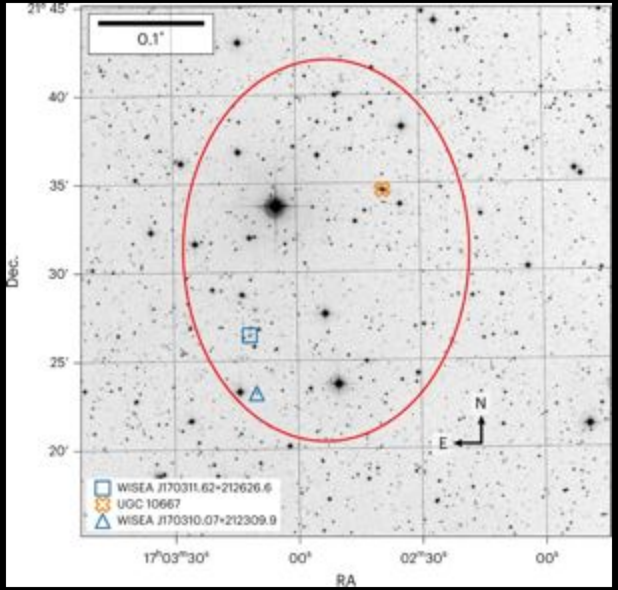
Links between GRBs, BNS mergers and FRB-like signals

- Dispersion delay at low frequencies (MWA <200 MHz)
- BNS mergers and long GRBs may have a (short lived) magnetar remnant
- Models predict coherent radio signals
- Models (EoS of nuclear matter)
  - Prompt (FRB-like)
  - Persistent (dipole radiation) from magnetar remnant



Rowlinson & Anderson (2019), MNRAS, 489, 3316

a) B field interactions
b) GRB jet-ISM interactions
c) Remnant dipole radiation
d) Collapse to BH



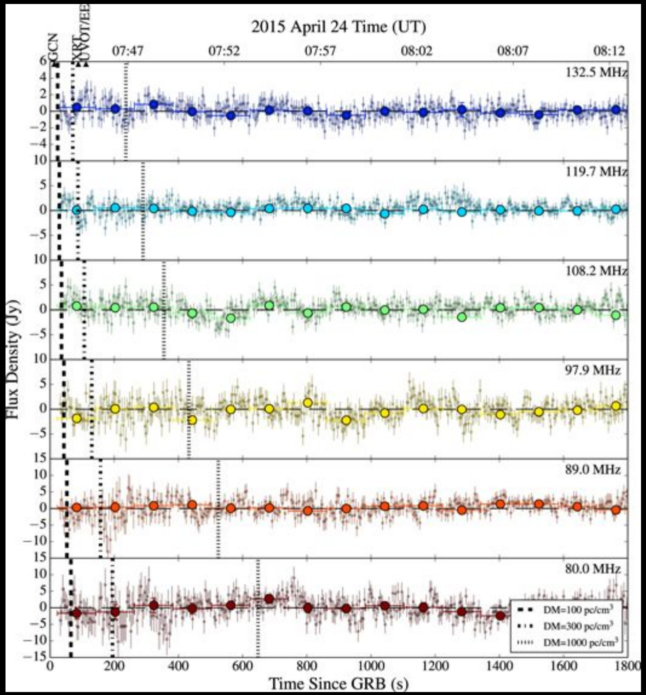
Potential host association for CHIME FRB 20190425A– GW 190425 (2.8σ) at 2.5 hrs post-merger:

Magnetar collapse into BH

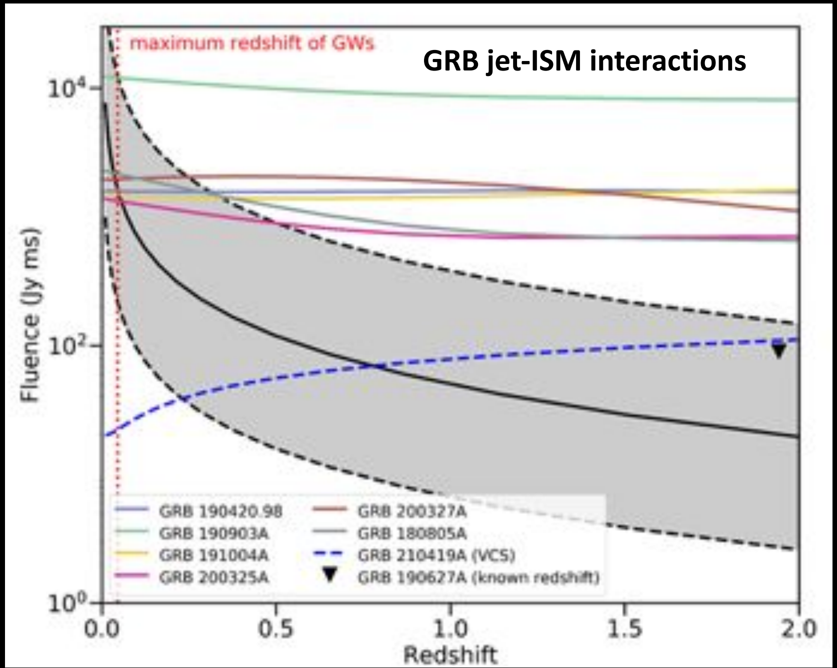
(Moroianu et al. 2023, Nature Astronomy, 7, 579)

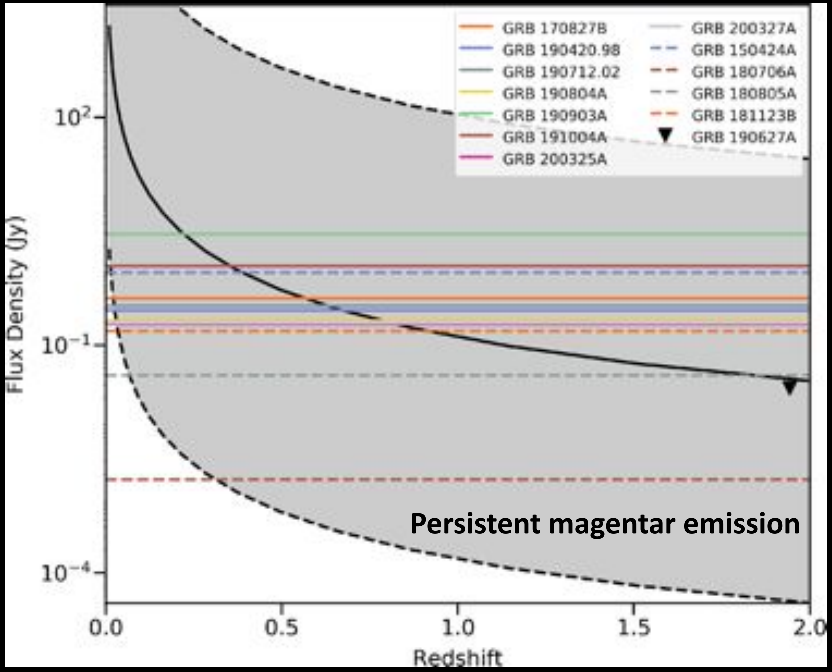
GRB triggering at MHz frequencies

- First MWA short GRB trigger (Kaplan et al. 2015, ApJL, 814, 25)
- First MWA short GRB trigger with updated system using image dedispersion (Anderson et al. 2021, PASA, 38, e026)
- 9 short GRBs (largest to date at low frequencies) using image dedispersion (Tian et al. 2022, PASA, 39, e003)
- First VCS trigger (long) GRB (Tian et al. 2022, MNRAS, 514, 2756)



Kaplan et al. (2015)





Anderson et al. (2021), PASA, 38, 26

Tian, Anderson et al. (2022), PASA, 39, 3

Tian, Anderson et al. (2022), MNRAS, 514, 2756

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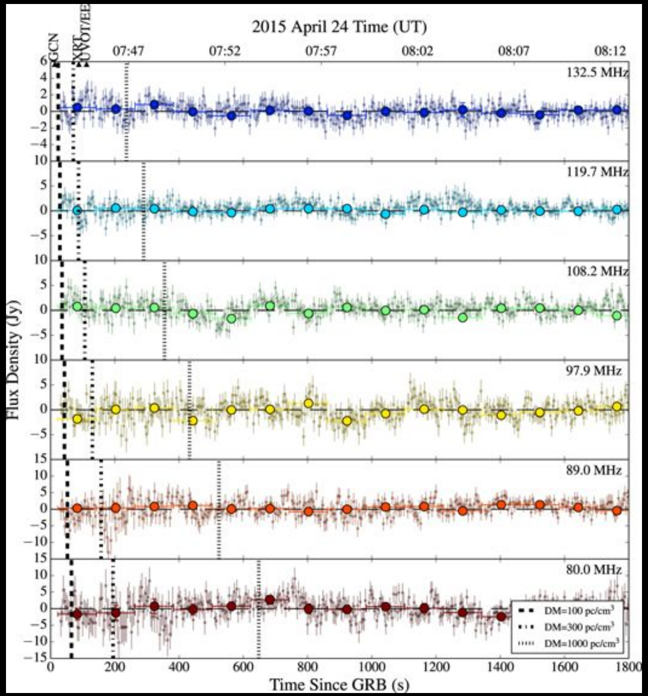
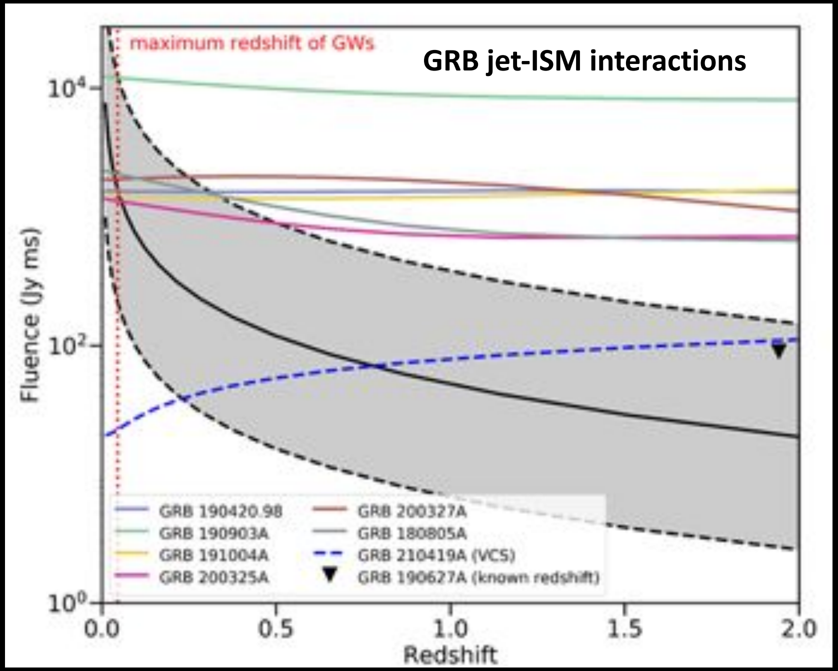
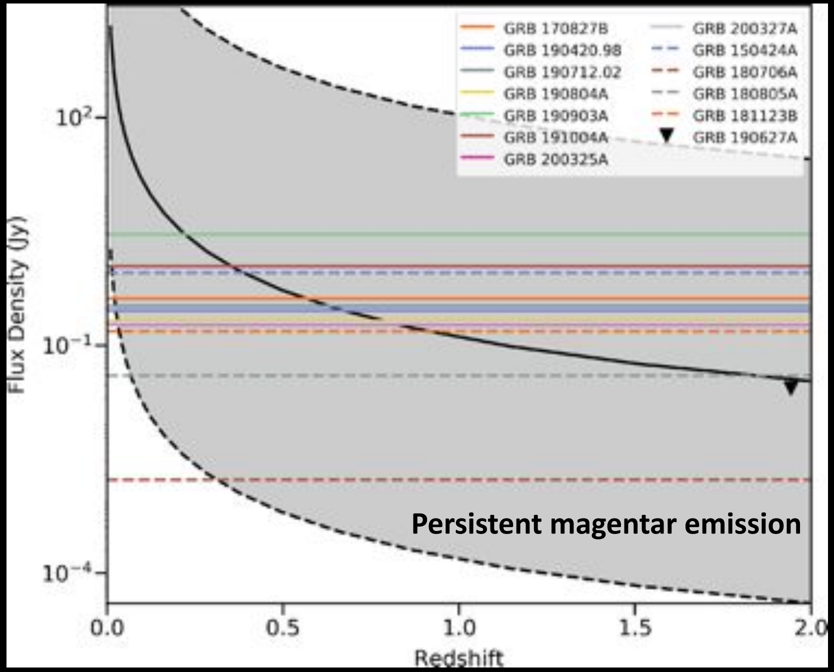


Kaplan et al. (2015)





What about GW events?

See Jun Tian's talk!

Early strategies see Kaplan et al. (2016), PASA, 33, e050 and James et al. (2019), MNRASL, 489, 75

Anderson et al. (2021), PASA, 38, 26

Tian, Anderson et al. (2022), PASA, 39, 3

Tian, Anderson et al. (2022), MNRAS, 514, 2756

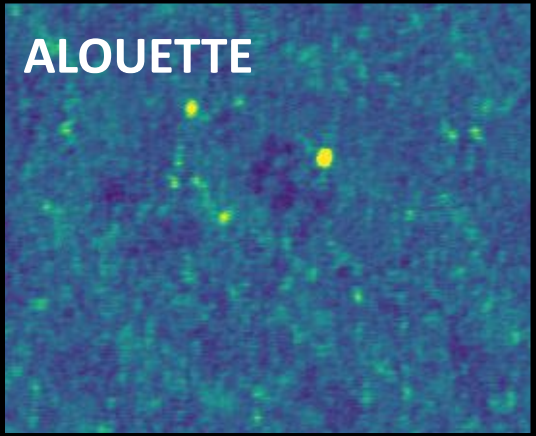
Space Situational Awareness

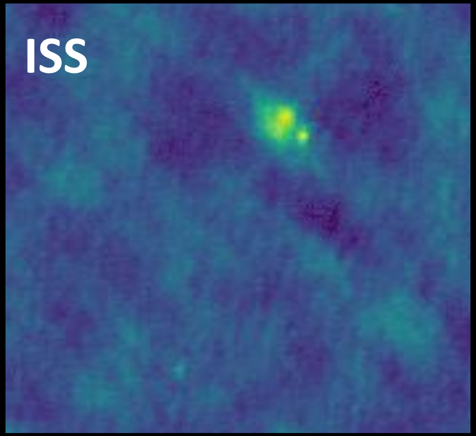
Using MWA as a passive radar for SSA (Tingay et al. 2013, AJ, 146, 4)

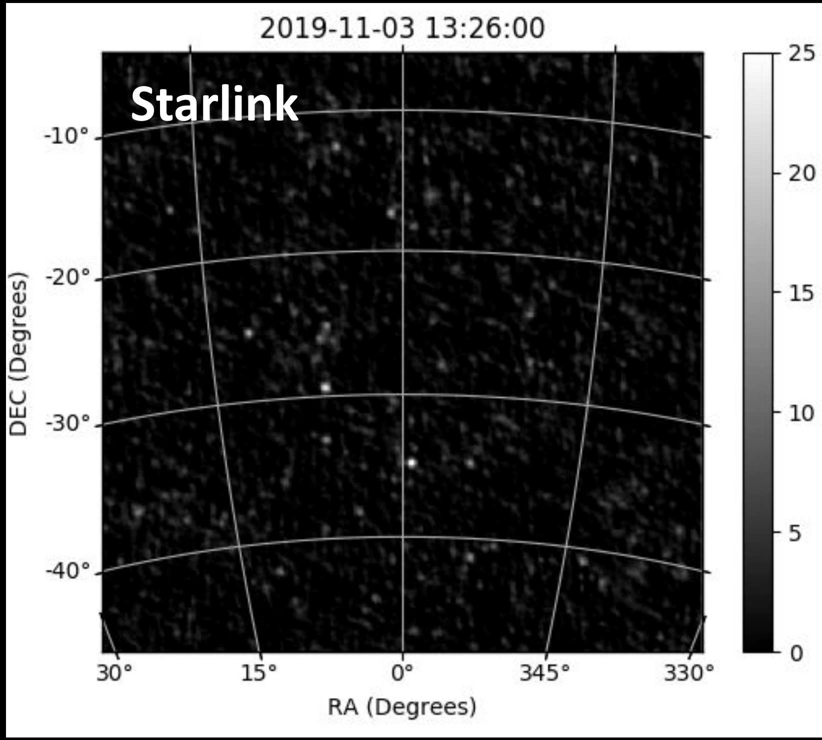
- RFI reflection of FM band (so don't flag)
- Detecting many objects in low Earth orbit

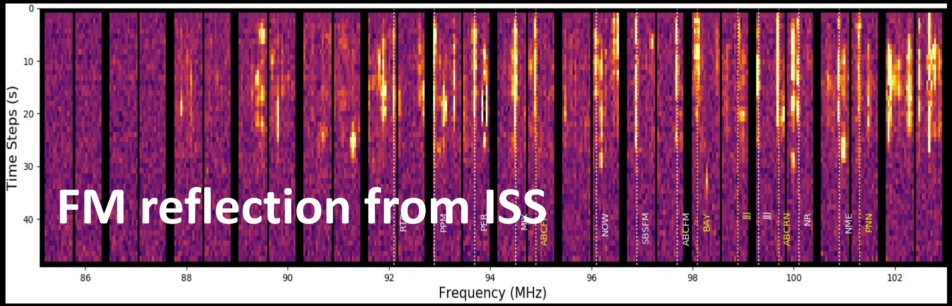
Prabu et al. (2020) PASA, 37, e010; Prabu et al. (2020), PASA, 37, e052)

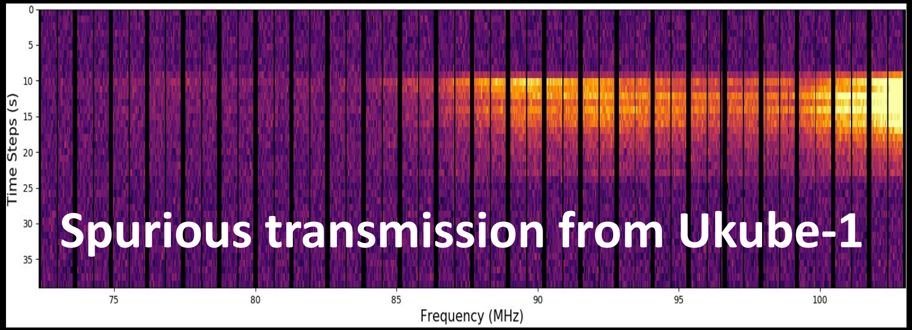
- Limits on Meteors (72-103 MHz) Zhang et al. (2018), MNRAS, 477, 5167







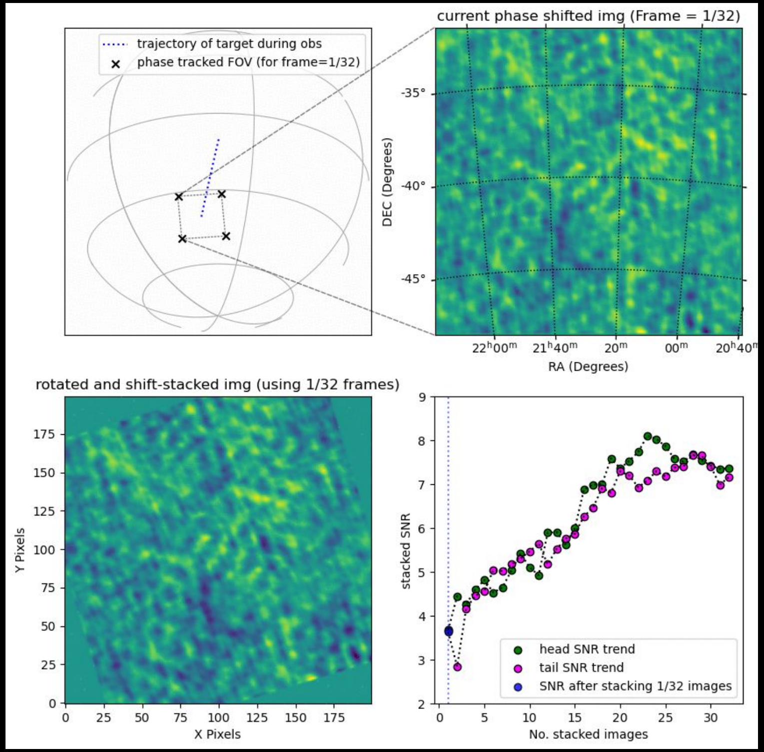




Space Situational Awareness - New!

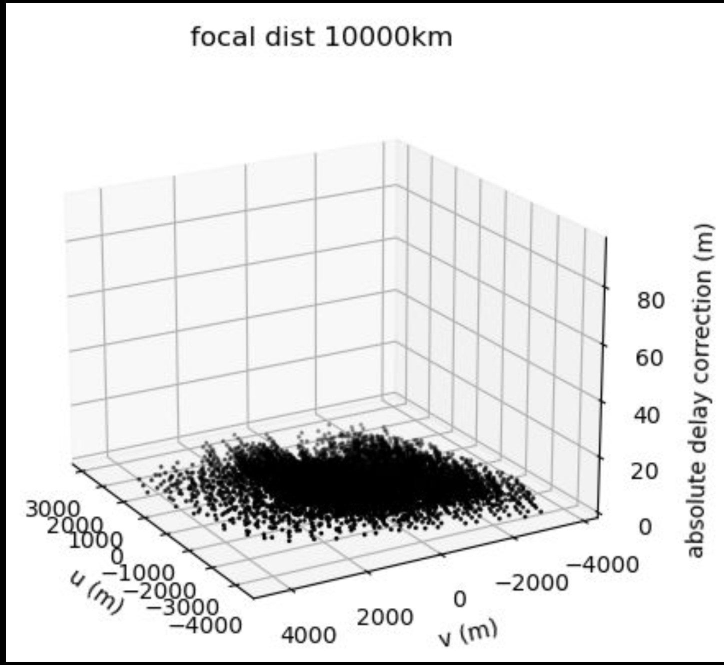
Improving sensitivity to Resident Space Objects (RSO)

- Method 1: Shift stacking search - stacking images along RSO's trajectory (Prabu et al. 2022, AdSpR, 70, 812)
- Method 2: Re-focus MWA to the near-field RSO position - applying complex phase correction to each visibility to account for curved wave-front (Prabu et al. 2023, PASA, under review)

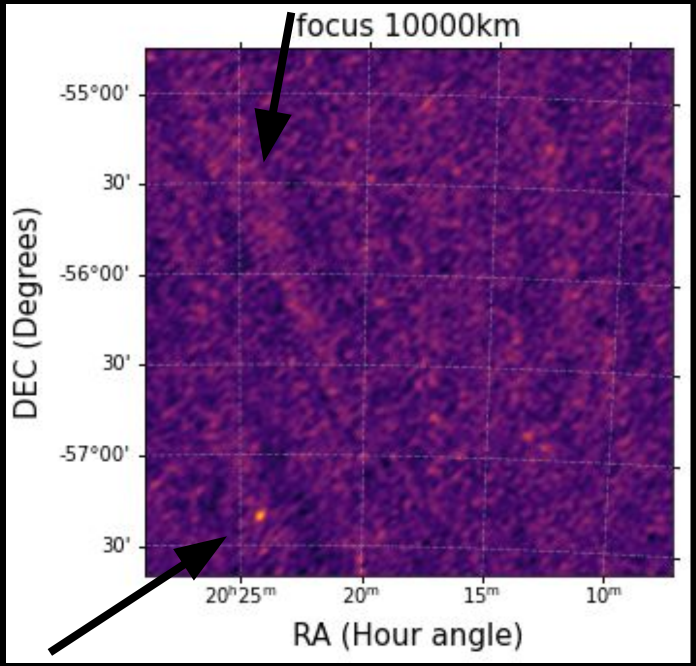


Method 1: Shift-stacking

Method 2: Aperture Plane ISS



Aperture Plane

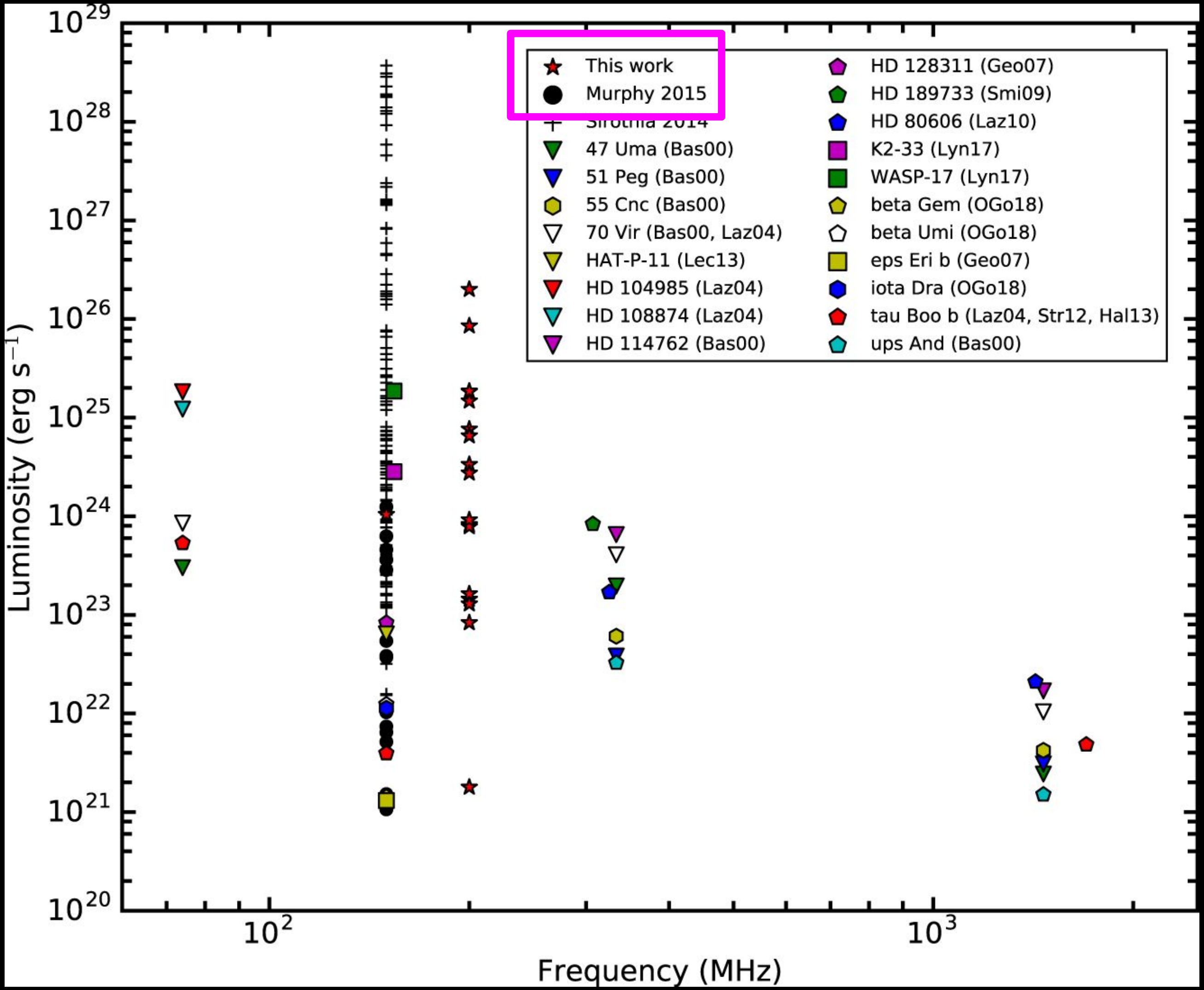


Point source

MWA Phase III

Targeted - Exoplanets

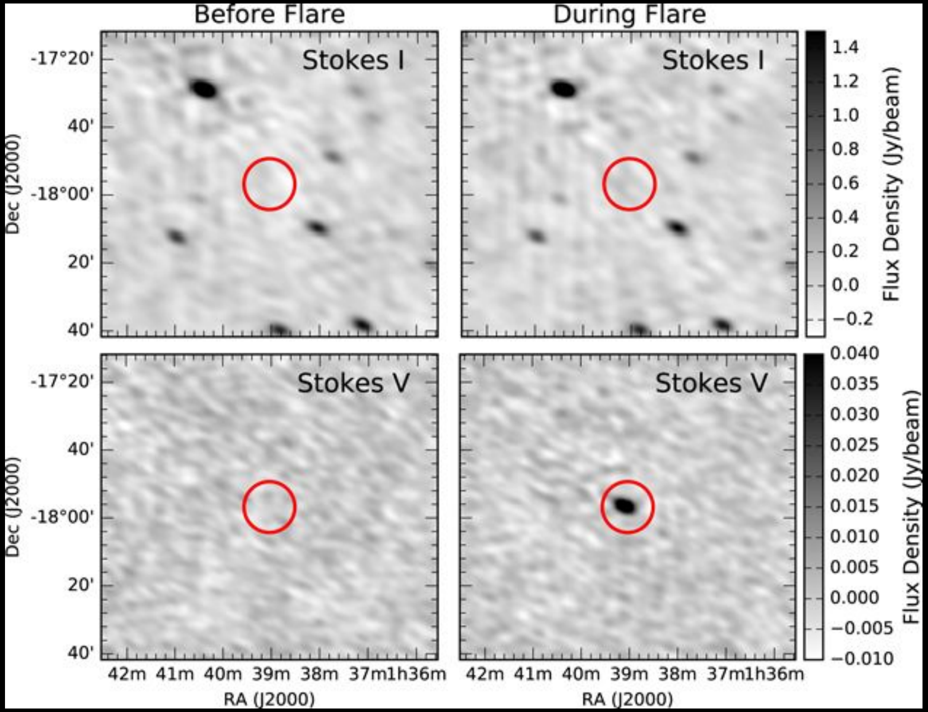
- Prediction (from Solar System objects)
  - Low frequency, coherent radio emission via electron-cyclotron maser instability
  - High circular polarisation (not confusion limited with MWA)
- Target known exoplanets around main sequence, dwarf type stars
  - Jupiter sized, strong magnetic fields.
- Targeted searches at 154 MHz (Murphy et al. 2015, Lynch et al. 2017)
- Targeted searches at 200 MHz (Lynch et al. 2018) using the MWA all-sky circular polarisation survey (Lenc et al. 2018)
  - 3 sigma limits 4.0-45.0 mJy, some of the most constraining at the time

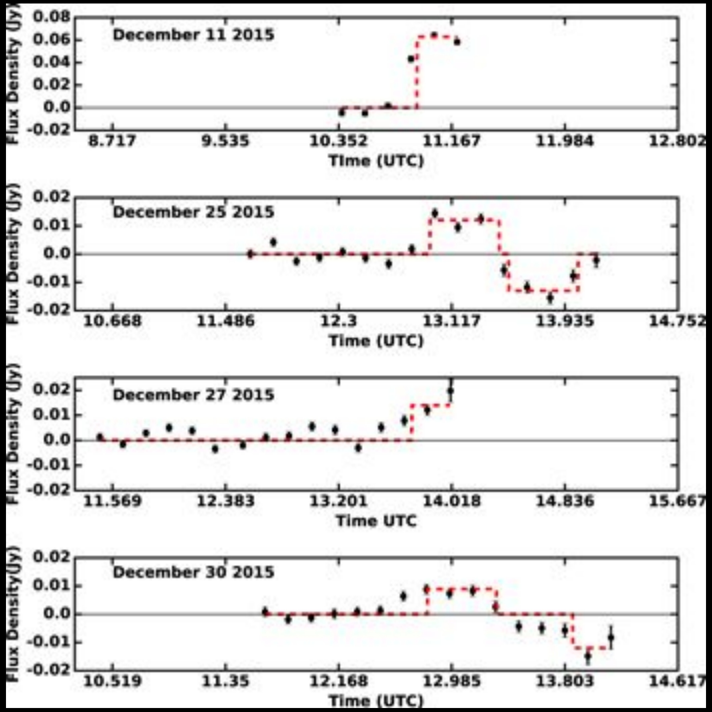


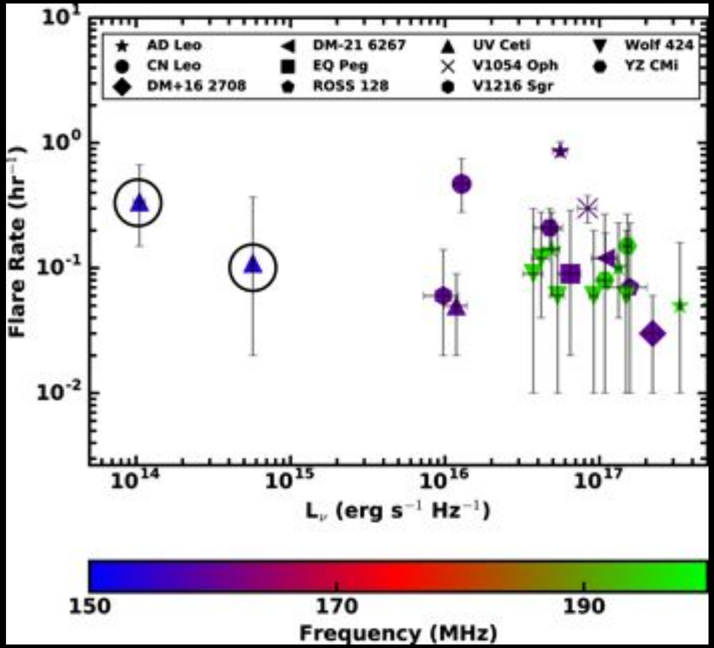
Lynch et al. (2018), MNRAS, 478, 1763

Targeted - Flare stars (M dwarfs)

- Low frequency, coherent radio emission via electron-cyclotron maser instability
- High circular polarisation
- UV Ceti at 154 MHz
  - Detection of polarised flares 10-65 mJy (100 x fainter than any in literature)
  - Flares may occur on same timescale as UV Ceti’s rotational period
  - M dwarf flare rate comparisons





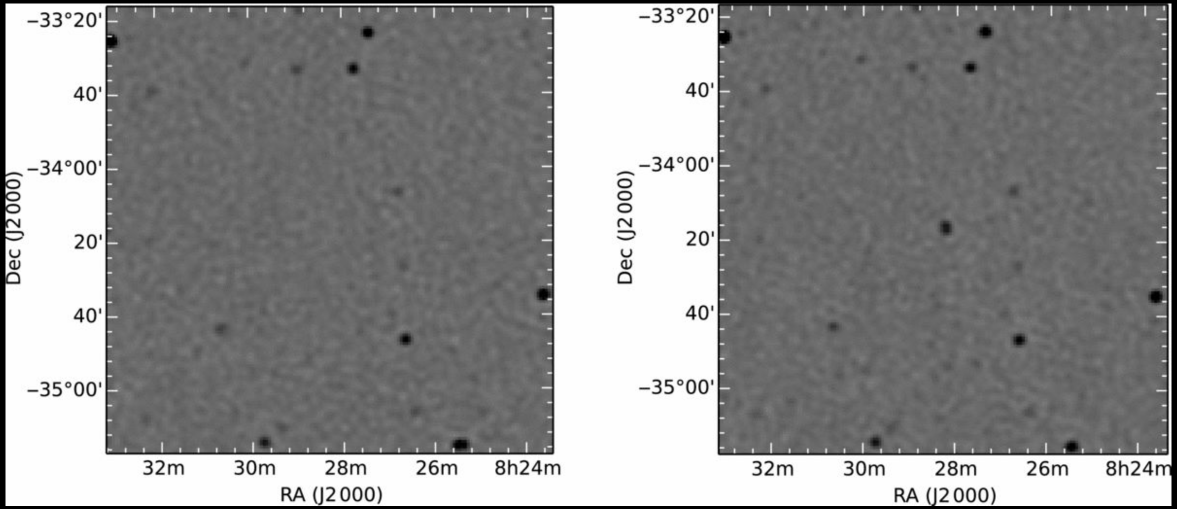


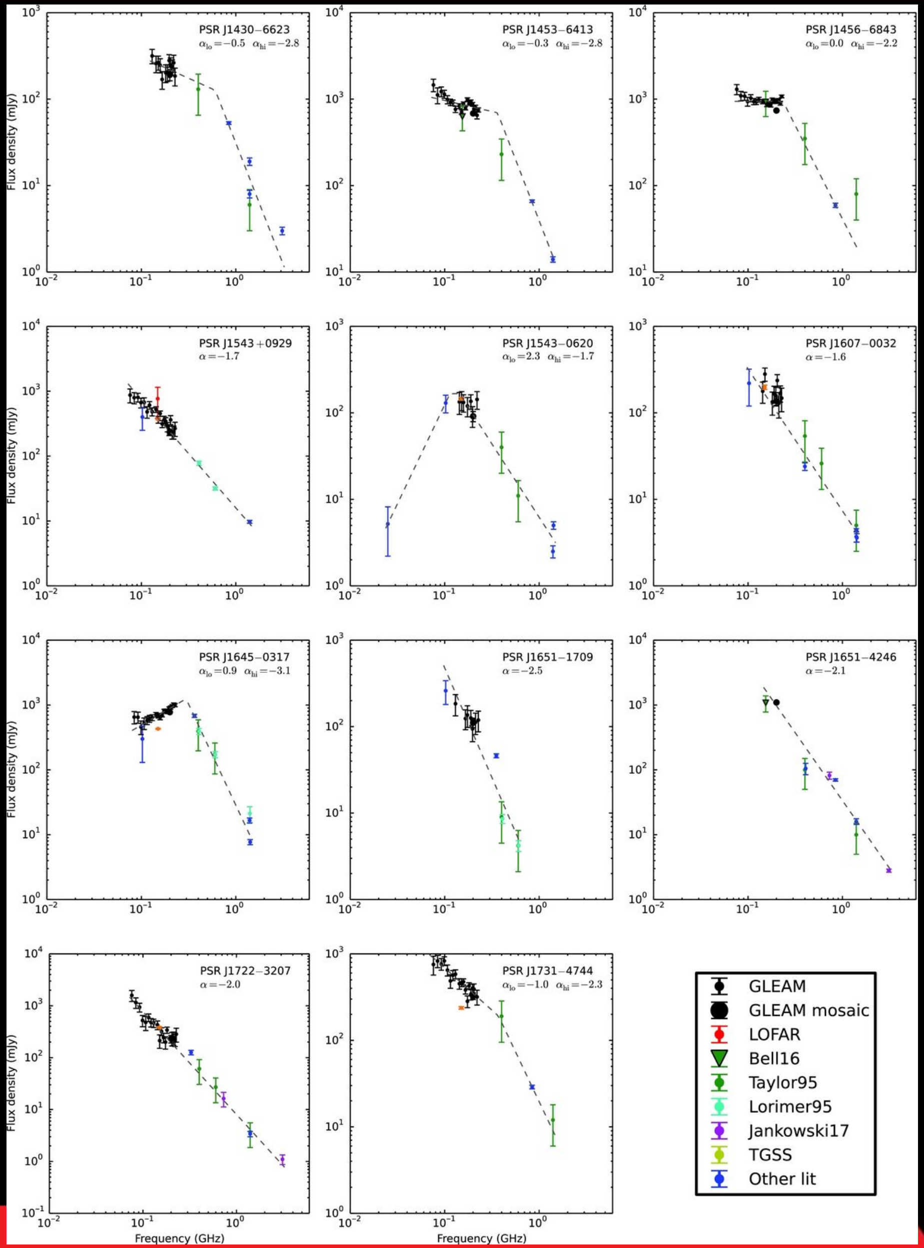
Lynch et al. (2017), ApJL, 836, 30

Targeted - Pulsar image plane searches

Characterising pulsars in the image plane

- 17 known pulsars at 154 MHz, scintillation detections (Bell et al. 2016)
- Variance image detections of scintillating pulsars (Dai et al. 2016)
- Low-frequency spectral energy distributions of 60 pulsars 72-231 MHz using GLEAM (Murphy et al. 2017, PASA, 34, e020)



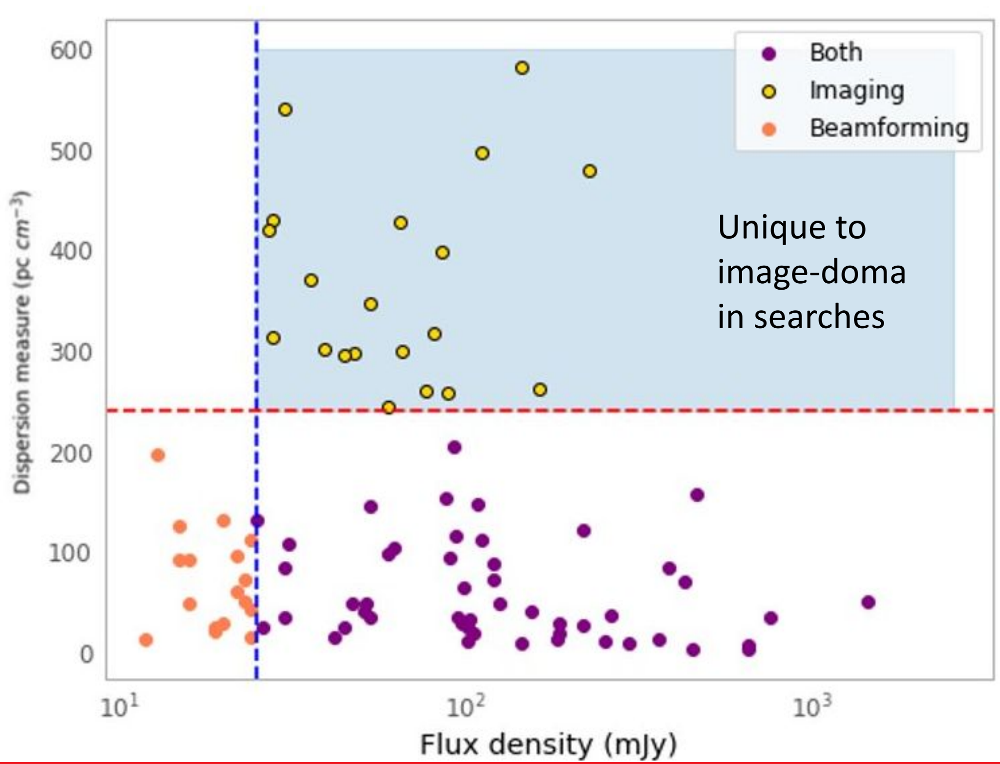


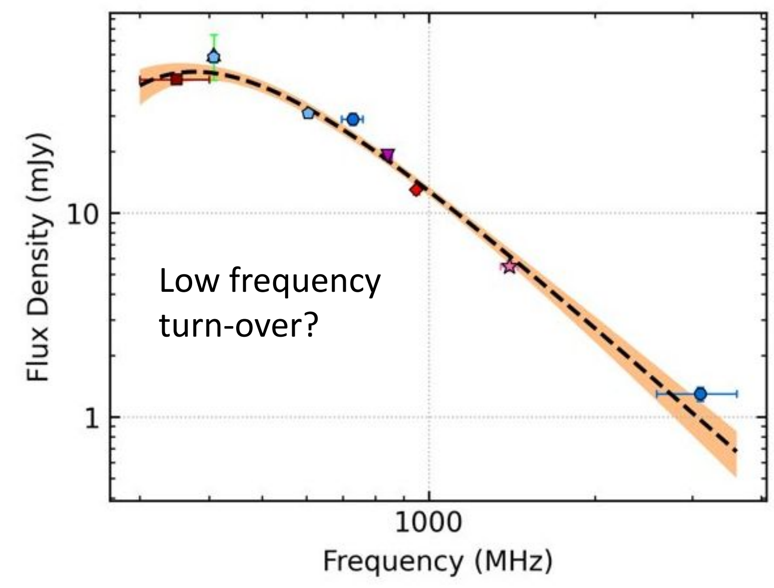
Murphy et al. (2017): 154 MHz PSR J0828-3417 (6 min separation) and SEDs

Targeted - Pulsar image plane searches - New!

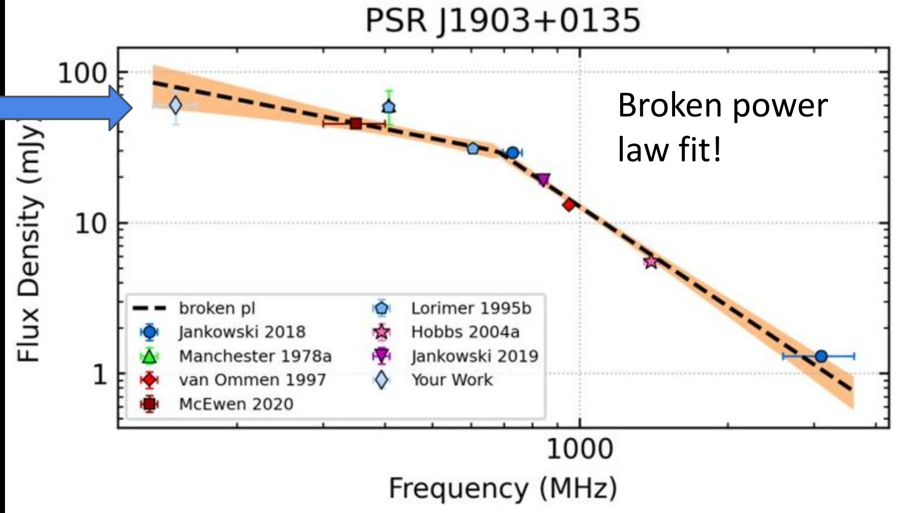
Susmita Sett's PhD work: Image-based pulsar searches in VCS data

- Detected 83 known pulsars, including 14 that were previous undetected at <400 MHz
- Highlighting a parameter space not accessible to time domain searches at low frequencies.
- Insight into low frequency pulsar spectral modelling.





MWA VCS data point shows there is no low frequency turn over!

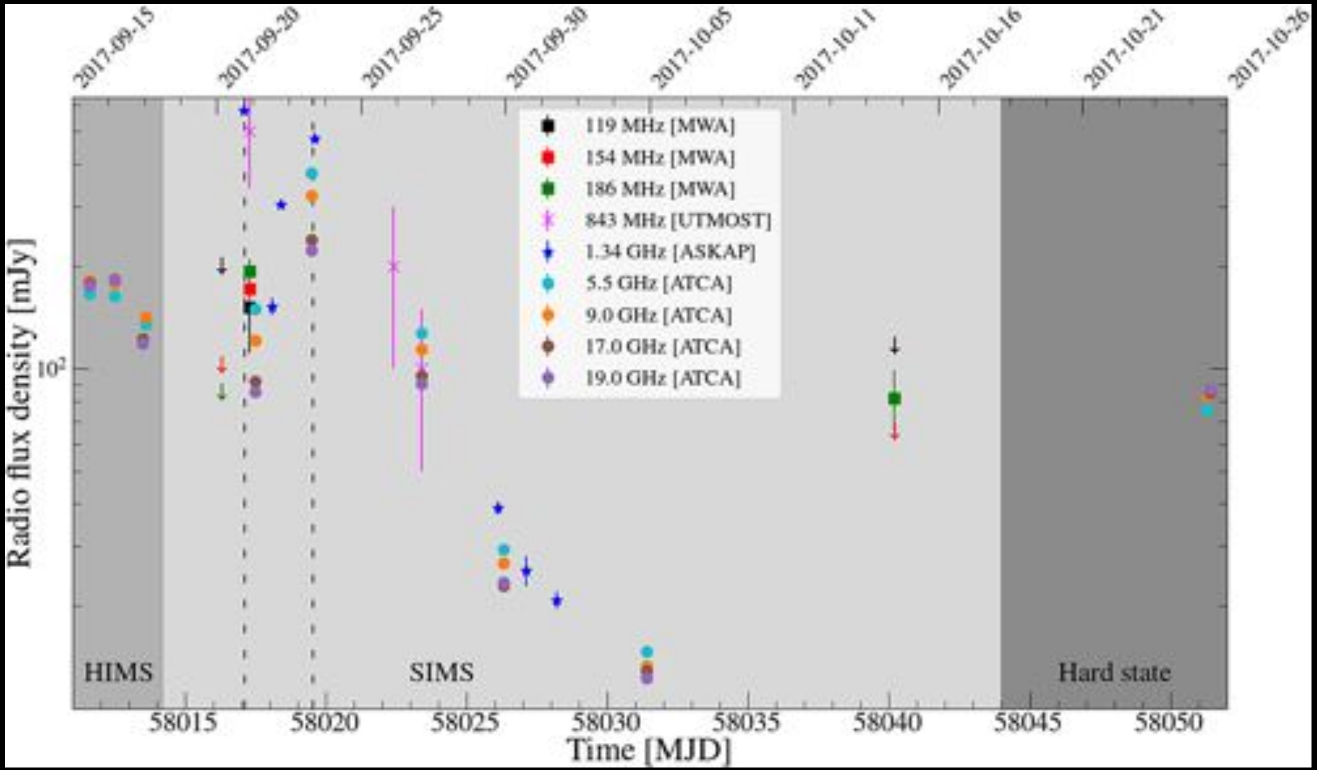


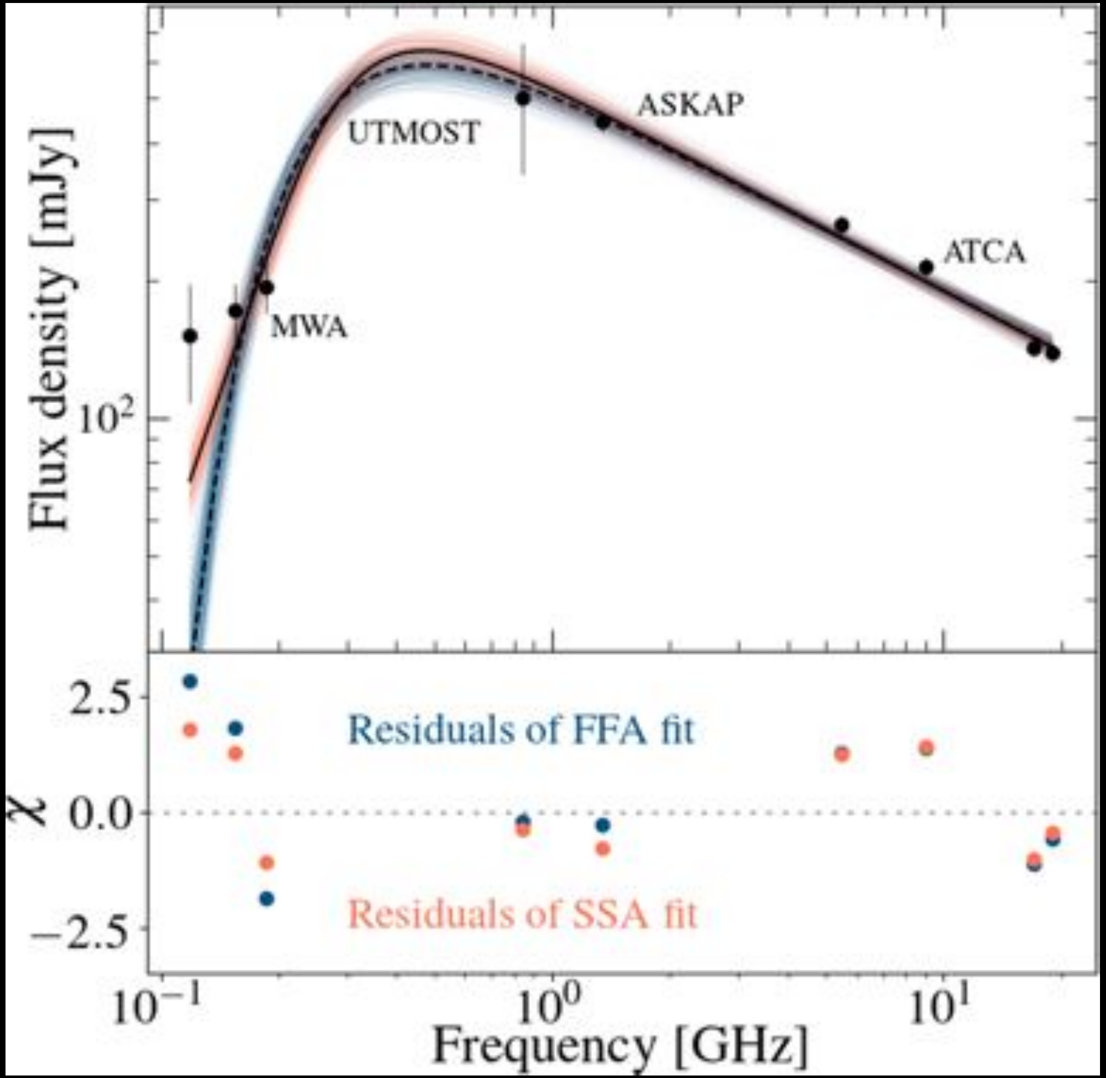
Sett et al. (2023), PASA, 40, e003, Sett et al. in prep

Targeted - Black hole X-ray Binaries

MAXI J1535-571 outburst: transient jet detection

- Quasi-simultaneous observations 0.84-19 GHz
- MWA, UTMOST, ASKAP, ATCA, LBA
- SSA turn-over: jet opening angle, B field

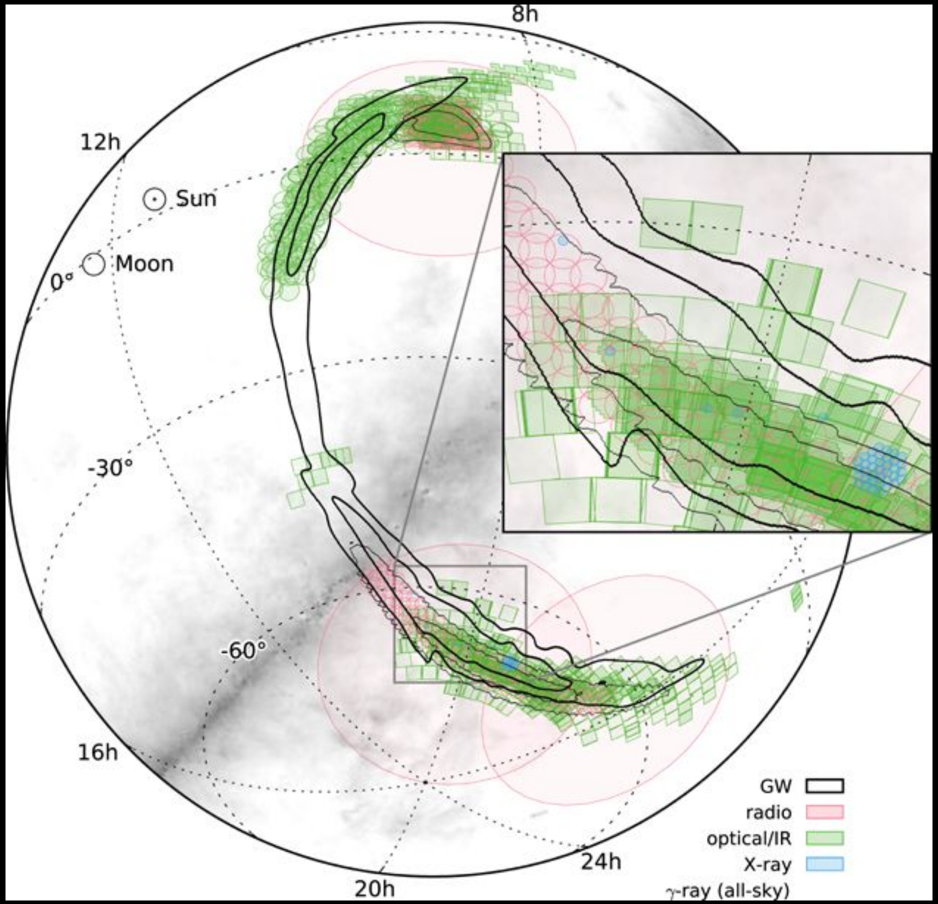




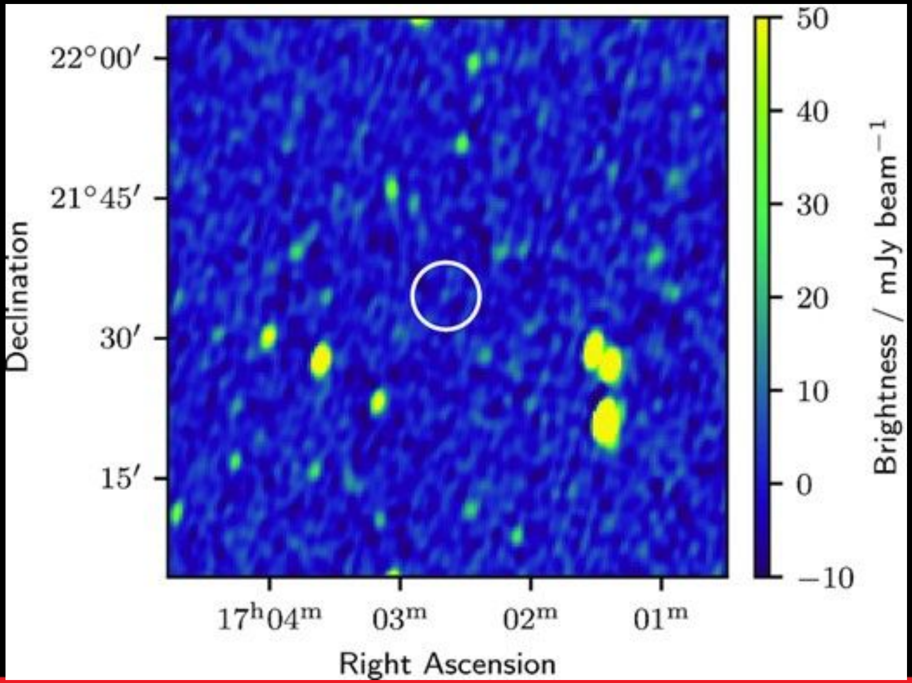
Jia Chauhan et al. (2021), PASA, 38, 45

Targeted - Gravitational wave events

- MWA follow-up of GW 150914 (Abbott et al. 2016, ApJL, 826, 13 - left figures)
- MWA follow-up of GW 170817 (Andreoni et al. 2017, PASA, 34, e069)



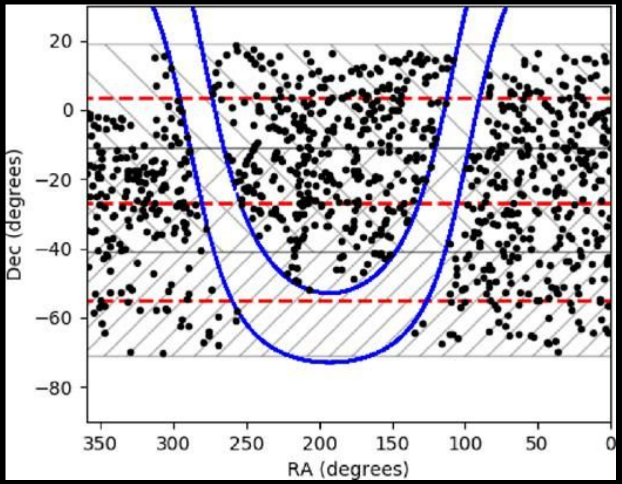
- MWA 154 MHz image centred on likely host of FRB 20190425A taken ~3 months post-burst (Panther et al. 2022, 519, 2235), which is possible associated with BNS merger GW 190425 (Moroianu et al. 2023, NatAs, 7, 579)



Blind transient searches and variability studies

Surface density upper-limits (extragalactic), timescales seconds - years

- 32-Tile prototype (154 MHz) transient search on Hyd A field, transient surface density upper limit, 26 min and 1yr (Bell et al. 2014, MNRAS, 438, 352)
- EoR field, 100 hours, 182 MHz, 28s - ~1 year (Rowlinson et al. 2016, MNRAS, 458, 3506)
- GLEAM and TGSS search for long timescale transients (Murphy et al. 2017, MNRAS, 466, 1944)
    - Timescale 1-3 yrs, 1 transient candidate detected in TGSS (not GLEAM)
- Kepler 2 mission fields (MWA and GMRT) (Tingay et al. 2016, AJ, 152, 82; Tingay et al. 2019, AJ, 158, 31)
    - Timescales days to weeks, 155 and 186 MHz
    - Continues to support low frequency radio transients rare
- Matched filter technique for transient searches to combat confusion noise
    - 182 MHz, timescales hour(s) to month (Feng et al. 2017, AJ, 153, 98)
- MWA Transient Survey (MWATS) Variability analysis of 944 >4Jy, 15 variable due to scintillation (timescales of decades; Bell et al. 2019, MNRAS, 482, 2484)



Extragalactic sources monitored in MWAS (Bell et al. 2019)

Blind transient searches and variability studies

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- GLEAM and TGSS search for long timescale transients (Murphy et al. 2017, MNRAS, 466, 1944)
  - Timescale 1-5 yrs, 1 transient candidate detected in TGSS (not GLEAM)
- Kepler 2 mission fields (MWA and GMRT) (Tingay et al. 2016, AJ, 152, 82; Tingay et al. 2019, AJ, 158, 31)
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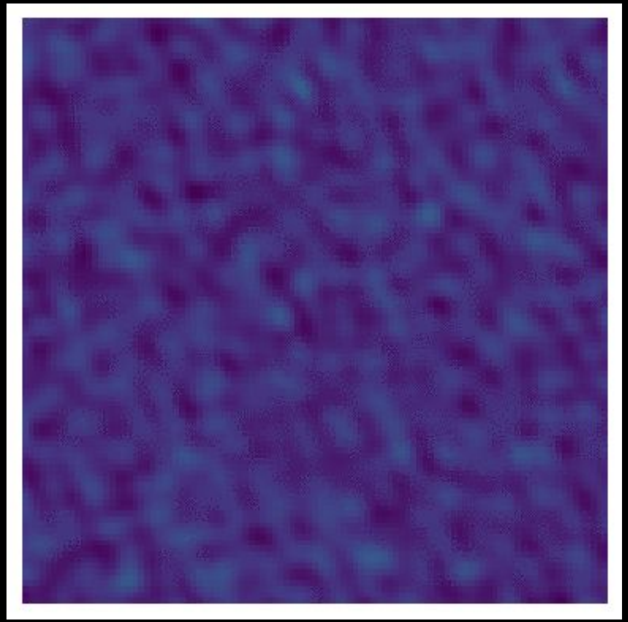
Extragalactic sources monitored in MWAS (Bell et al. 2019)

WHERE ARE ALL THE TRANSIENTS?

CAN WE FIND ANY IN BLIND SEARCHES?

(Unusual) Galactic Plane Transients!



Conducting "Fast" imaging searches in

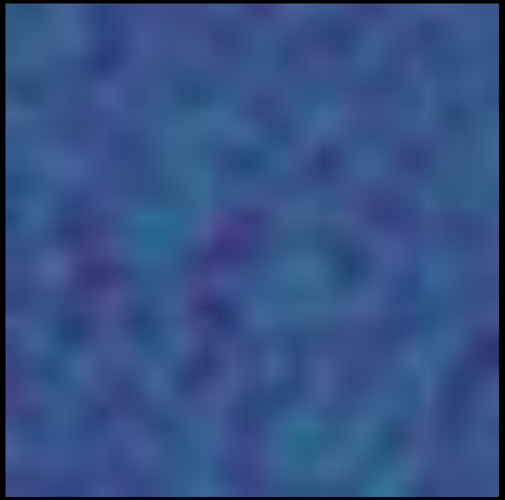
- Continuum-subtracted data (near Gaussian noise)
- Search via matched-filters
- GLEAM-X: 300 hrs search for second-minute timescale transients

(Credit: Natasha Hurley-Walker, Csanad Horvath, Tim Galvin)

Ultra long period transients (18 mins!)
Hurley-Walker et al. (2022a), Nature, 601, 526
See Natasha's talk!

Unexpected nighttime interplanetary scintillation

Arcminute localisation of RRATs and pulsars

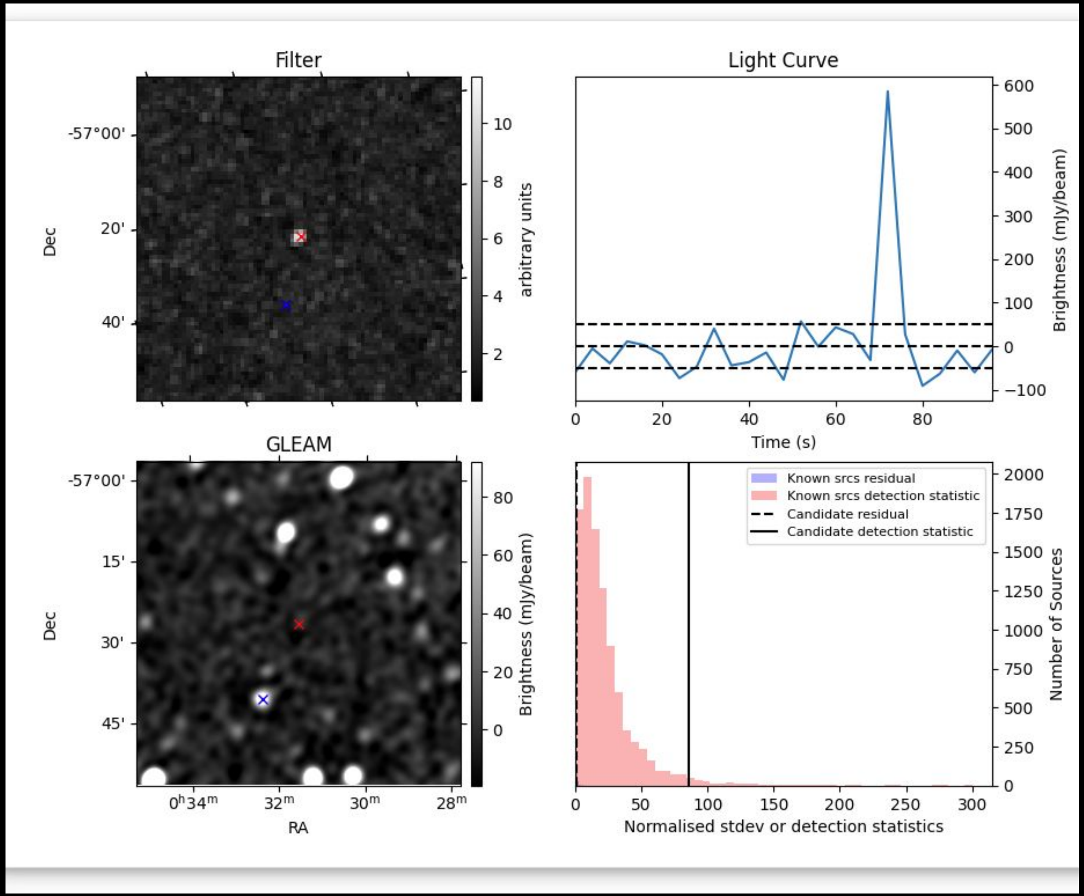


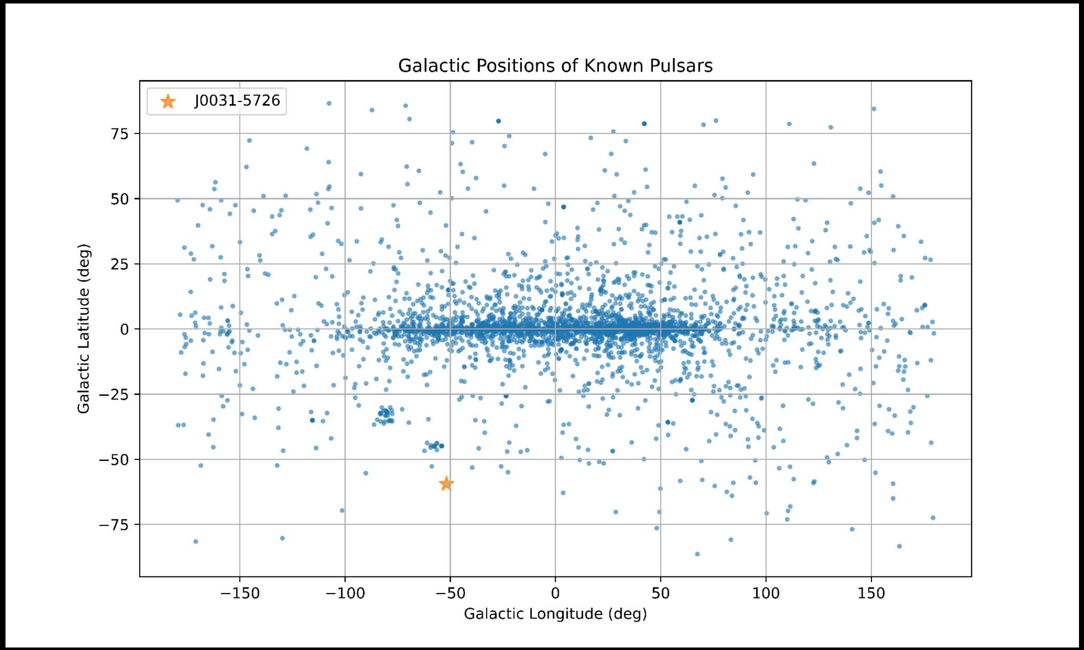
And more… see Natasha's talk

Discovery of pulsar in image plane - New!

High Galactic latitude

Discovery: Natasha Hurley-Walker, Csanad Horvath, Tim Galvin

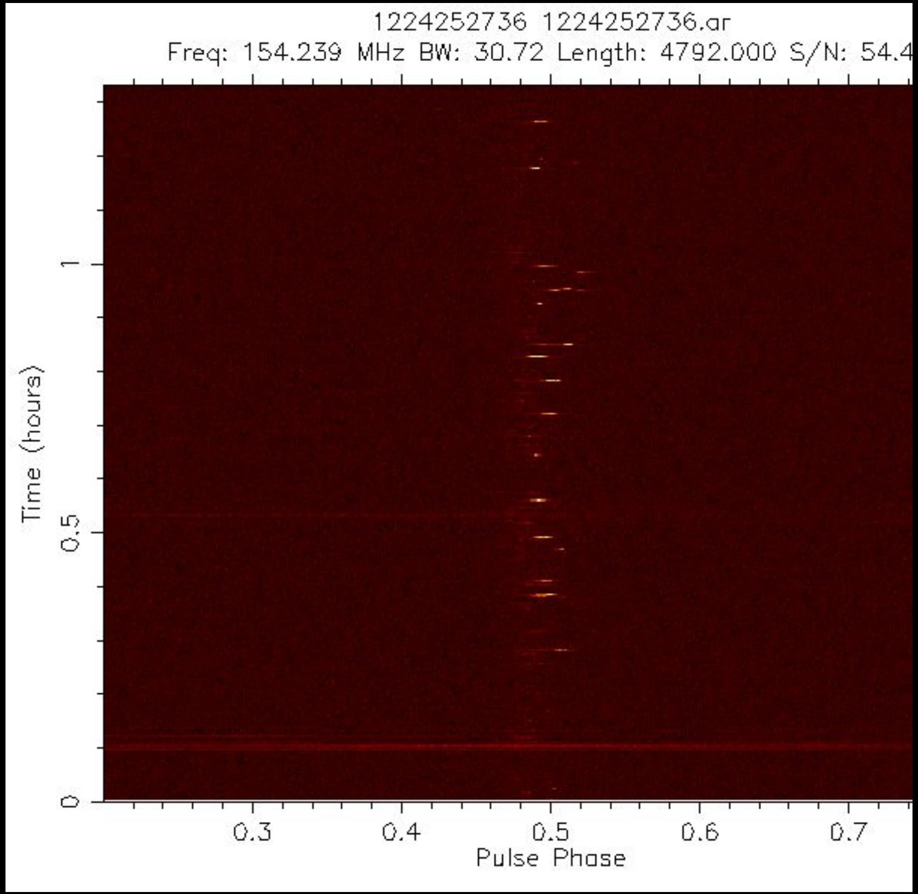


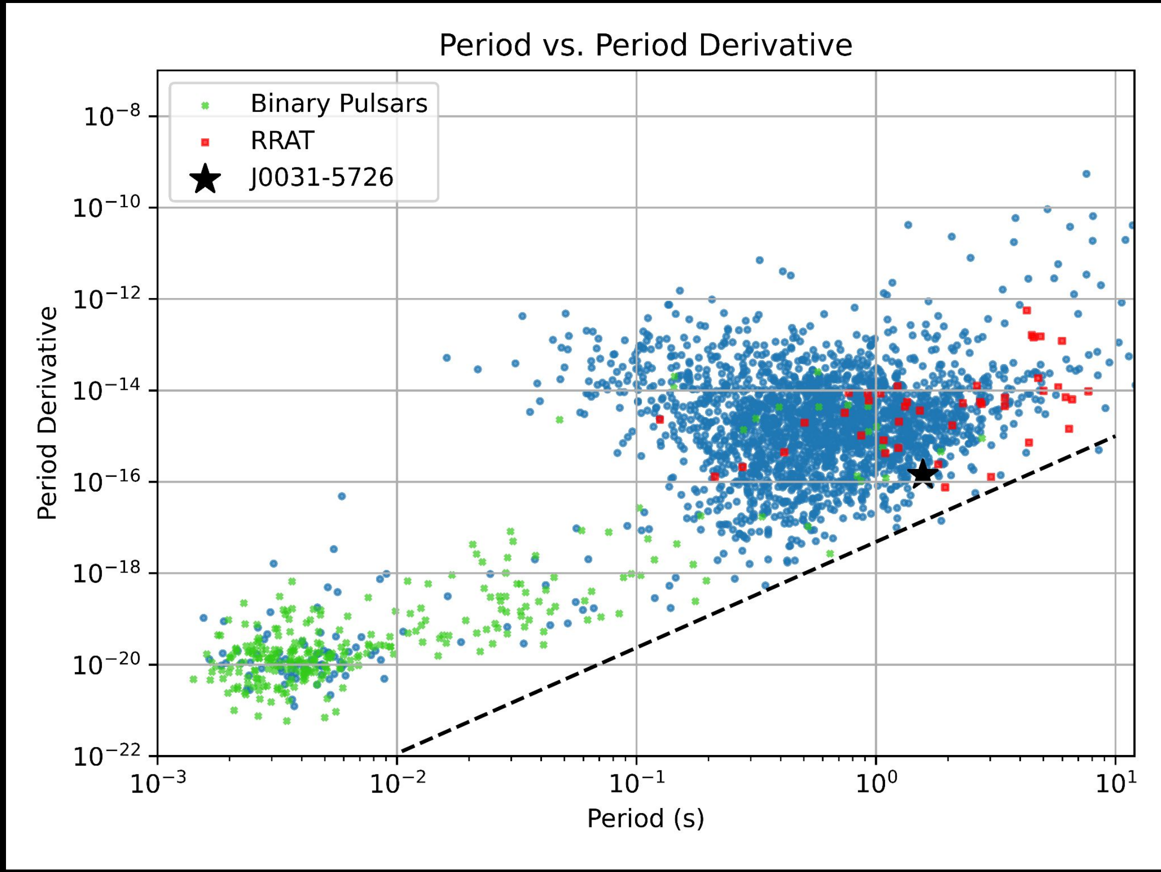


Discovery of pulsar in image plane - New!

VCS follow-up

- Sporadic bursts with leading faint yet continuous pulse
- Timing over 6 months - “old and dying” part of the P/Pdot diagram
- Credit: Jared Moseley (Hons), Sam McSweeney, Natasha Hurley-Walker





So how did we go?

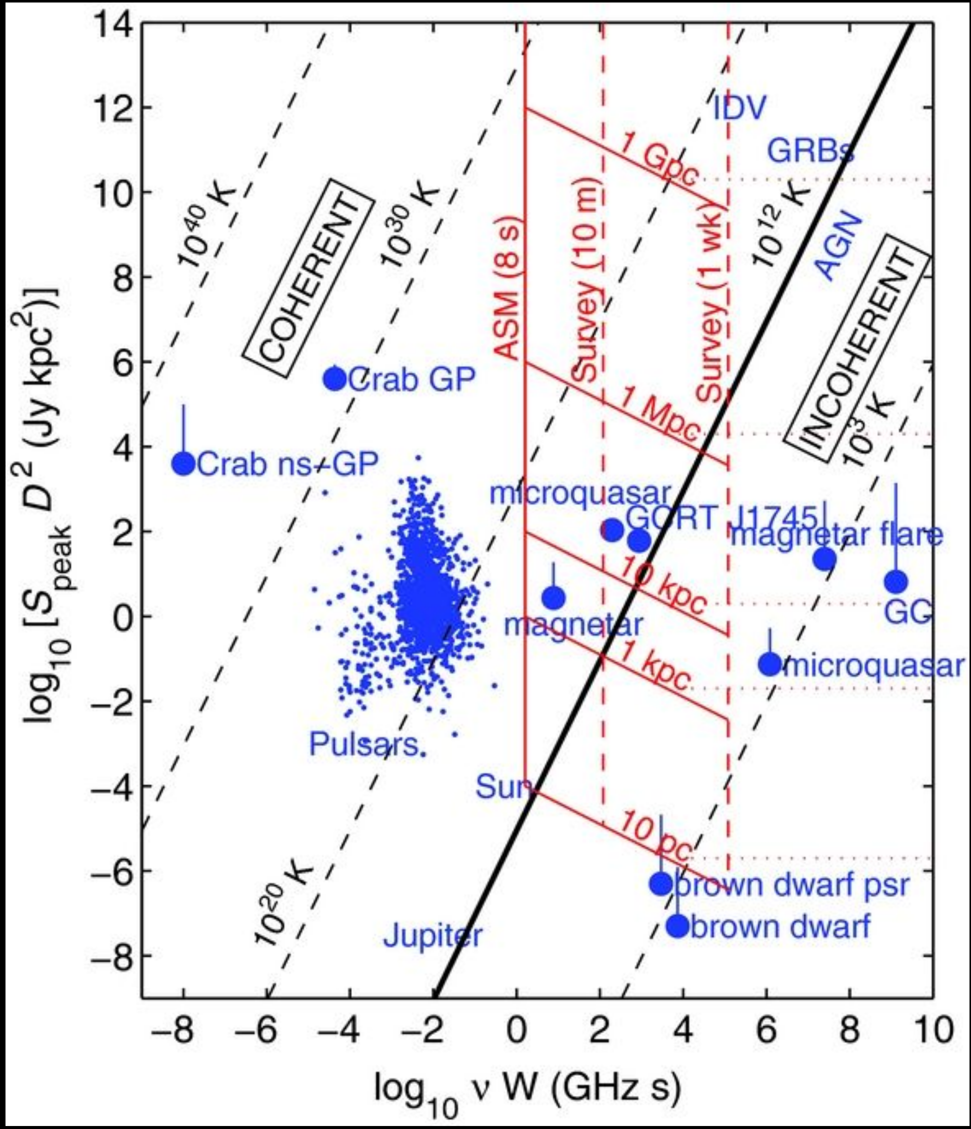
"The potential sources of radio transient emission fall into five broad categories:

1. coronal emission from nearby stars/substellar objects
2. emission from compact objects such as neutron stars and accreting black holes
3. ~~explosive events such as gamma-ray bursts (GRBs) and radio supernovae~~ Prompt/coherent?

? 4. *(exo)*planetary emission from nearby systems

5. and new phenomena discovered through the opening of new regions of observational phase space." ~~Extragalactic~~ Galactic

Bowman et al. (2013), Science with the Murchison Widefield Array, PASA, 30, e031



Conclusions

What have we learned? We need to

1. Play to the **MWA strengths**
   - MWA is the fastest pointed telescope (transient triggering)
   - MWA has a wide field of view and good view of the Galactic Plane.
   - Sensitivity limited
2. Acknowledge the **physics**
   - Great for Space Situational Awareness! (Also Cosmic Rays - Clany James's Talk)
   - Extragalactic, synchrotron (**incoherent**) transients (GRBs, supernovae…) are too faint
   - Focus on **coherent** extragalactic transients (e.g. FRBs)
     - Rapid-response triggering on explosive events for prompt/FRB-like (see Jun Tian's talk)
     - All sky monitoring for FRBs and SETI (see Marcin Sokolowski's talk)
     - Blind FRB searches using image dedispersion (and archival/new VCS)
   - Focus on the Galactic Plane for (new and unusual) transients
     - Ultra-long period transients (coherent - see Natasha Hurley-Walker's talk)
     - Pointed follow-up of (e.g.) flare stars and pulsars (coherent)
     - Galactic plane synchrotron transients (XRBs)

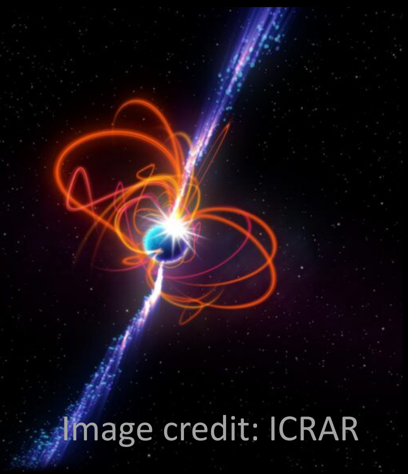


Image credit: ICRAR