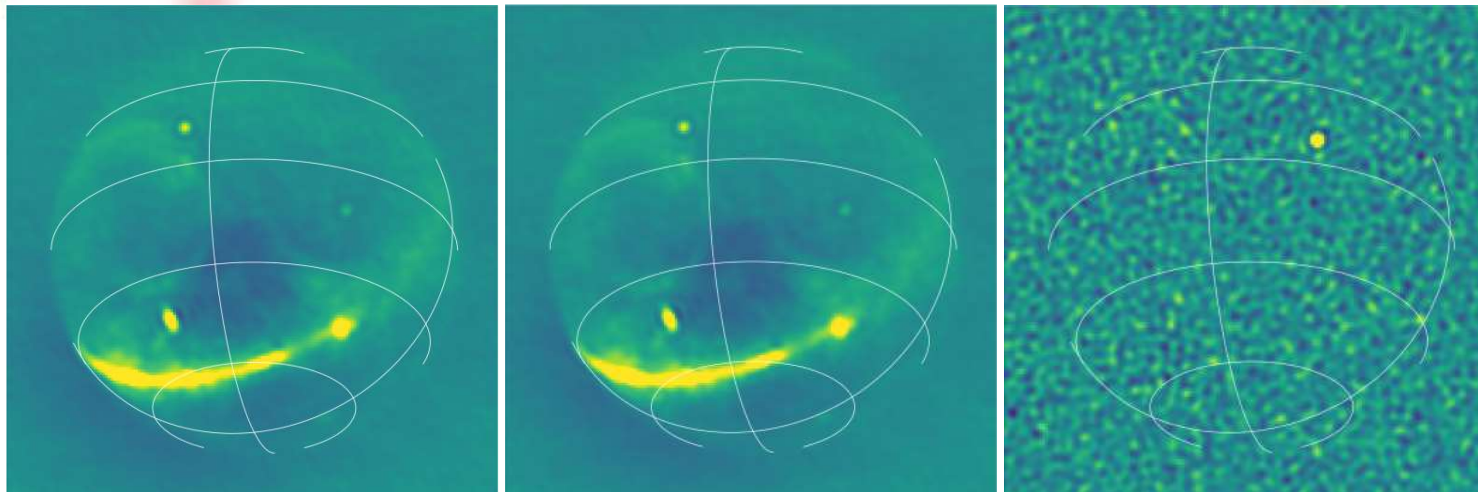
# All-sky high-time resolution monitoring of transient sky with SKA-Low stations

**Marcin Sokołowski, Danny Price, Randall Wayth**
**(ICRAR / Curtin University)**

ICRAR
International Centre for Radio Astronomy Research



Curtin University

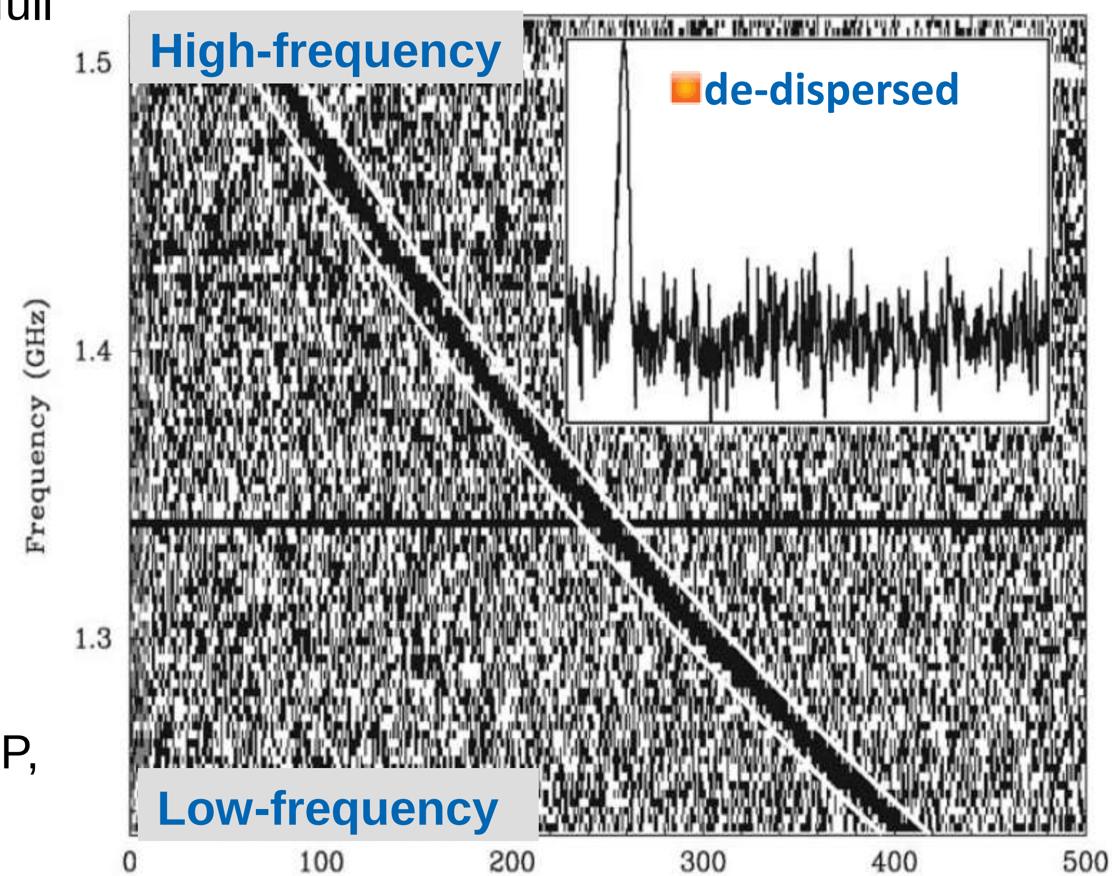
THE UNIVERSITY OF WESTERN AUSTRALIA

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

# Fast Radio Bursts (FRBs)

- **FRBs** are short (~millisecond) dispersed radio pulses
- Discovered 15 years ago and still awaiting full physical explanation
- Dispersed pulses at higher frequencies arrive earlier than at low frequencies
- Extragalactic origin confirmed by redshifts measurements of several host galaxies
- Extreme energies of the order of $10^{39}$ erg
- Require coherent emission mechanism
- By several radio-telescopes: Parkes, ASKAP, Areceibo, UTMOST, CHIME, GBT etc.
- ~5% FRBs repeat
- At 100 MHz ≤ ν ≤ 8 GHz , but only very few were detected ≤ 350 MHz)

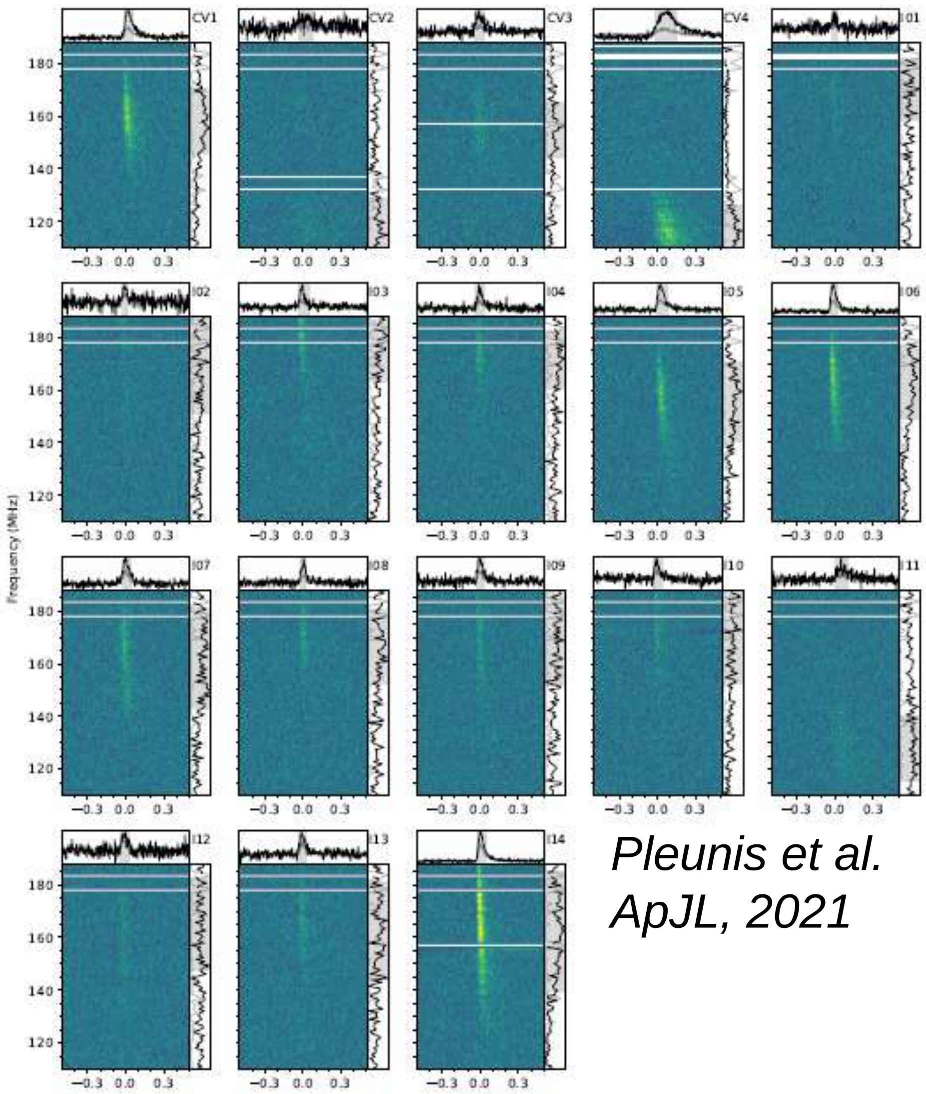
***The first FRB detected in archive data from Murriyang (Parkes) radio telescope by Lorimer et al (2007)***




$$t_2 - t_1 = \frac{e^2}{2\pi m_e c}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right) DM \quad \text{, where} \quad DM = \int_0^d n_e \, dl$$

# Detections of FRBs and alikes at low radio-frequencies (≤ 350 MHz)

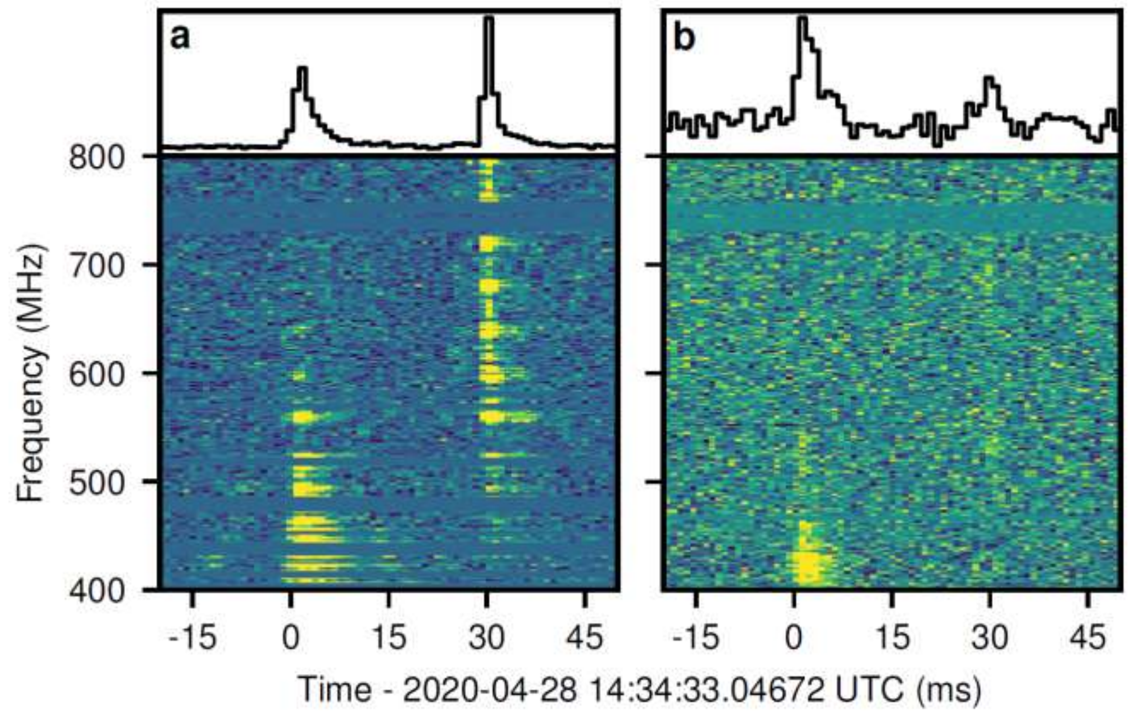
## LOFAR detections of the repeating FRB 20180916B



*Pleunis et al. ApJL, 2021*

*Also detected by Sardinia Radio Telescope (Pilia et al. ApJL, 2020)*

## CHIME detections of Galactic magnetar SGR 1935+2154 at 400 - 800 MHz

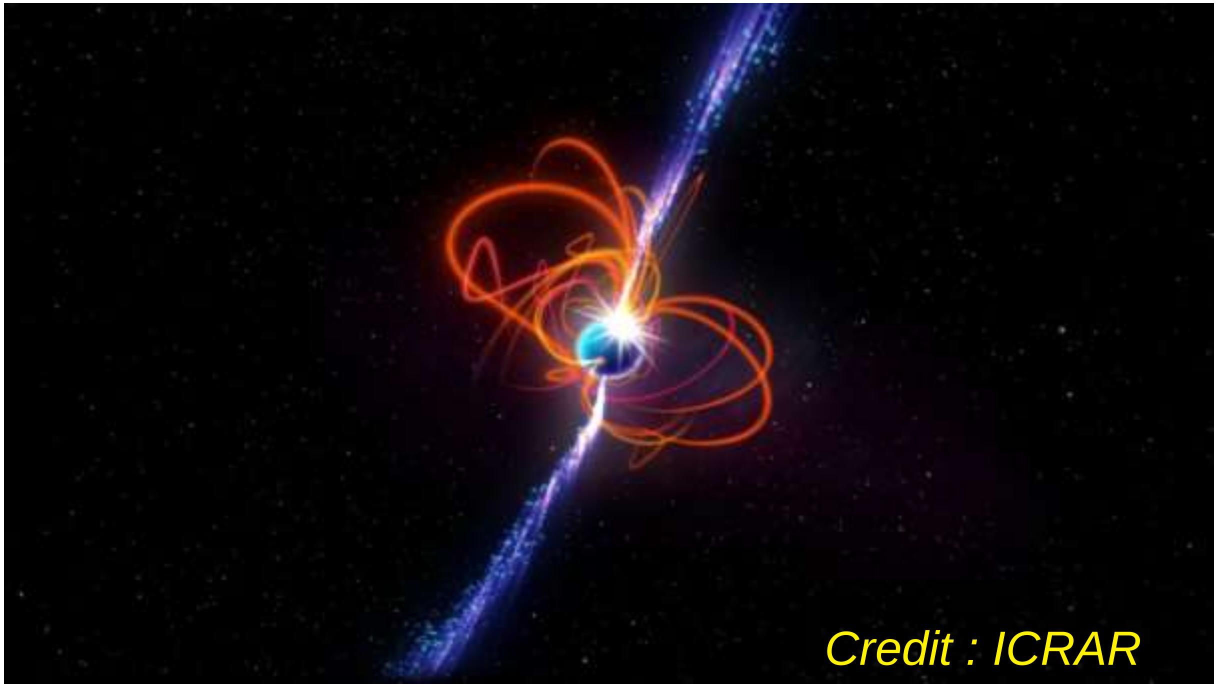


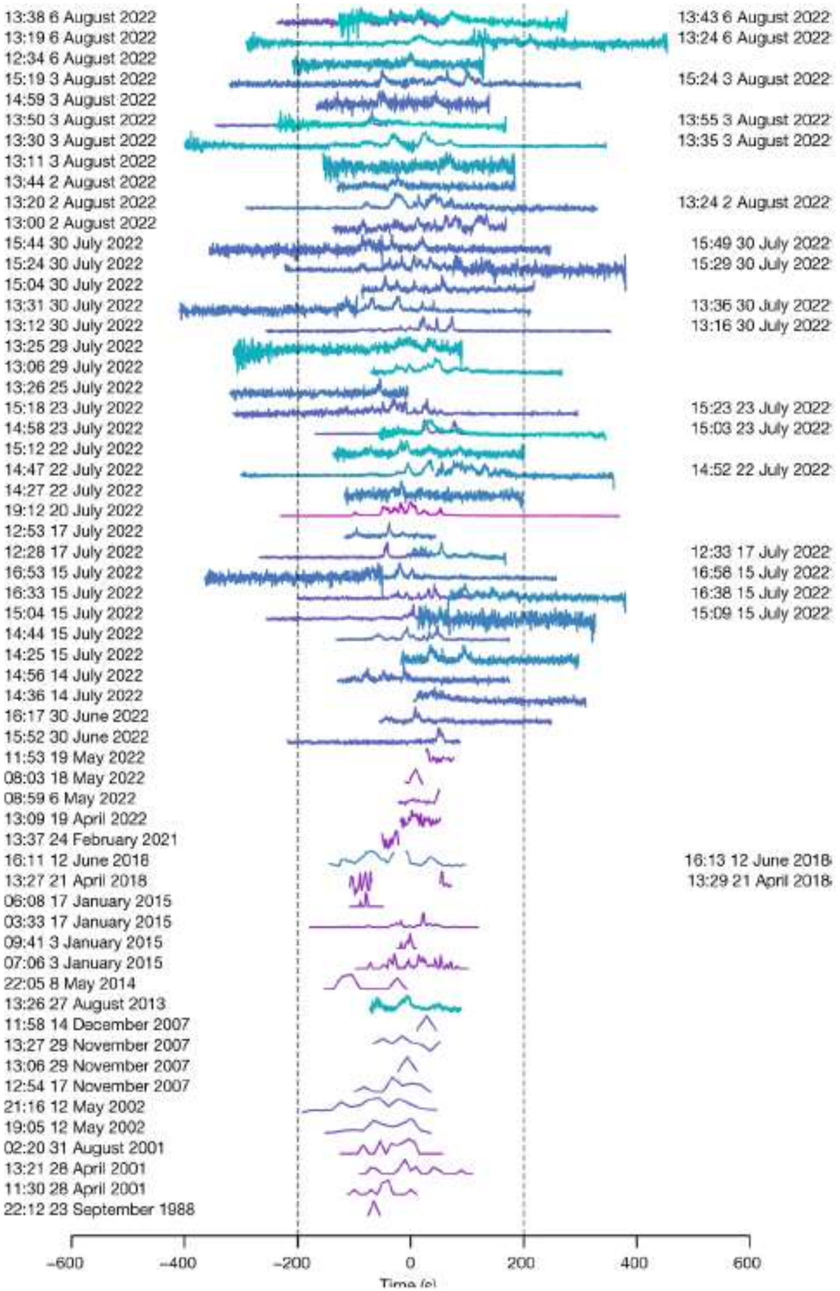

- Peak flux density 110 - 150 kJy ( fluence 220 - 480 kJy ms) and even MJys ms at higher frequencies (STARE2)
- Burst energy ~3 x $10^{34}$ erg

*CHIME/FRB Collaboration, Nature, 2020*

# Maybe ultra-long period magnetars or similar objects ?

- Two found by Natasha Hurley-Walker et al. (2023, 2022)
- Some may be sufficiently bright
- **Not immediate need for millisecond time resolution, but real-time imaging may be handy**



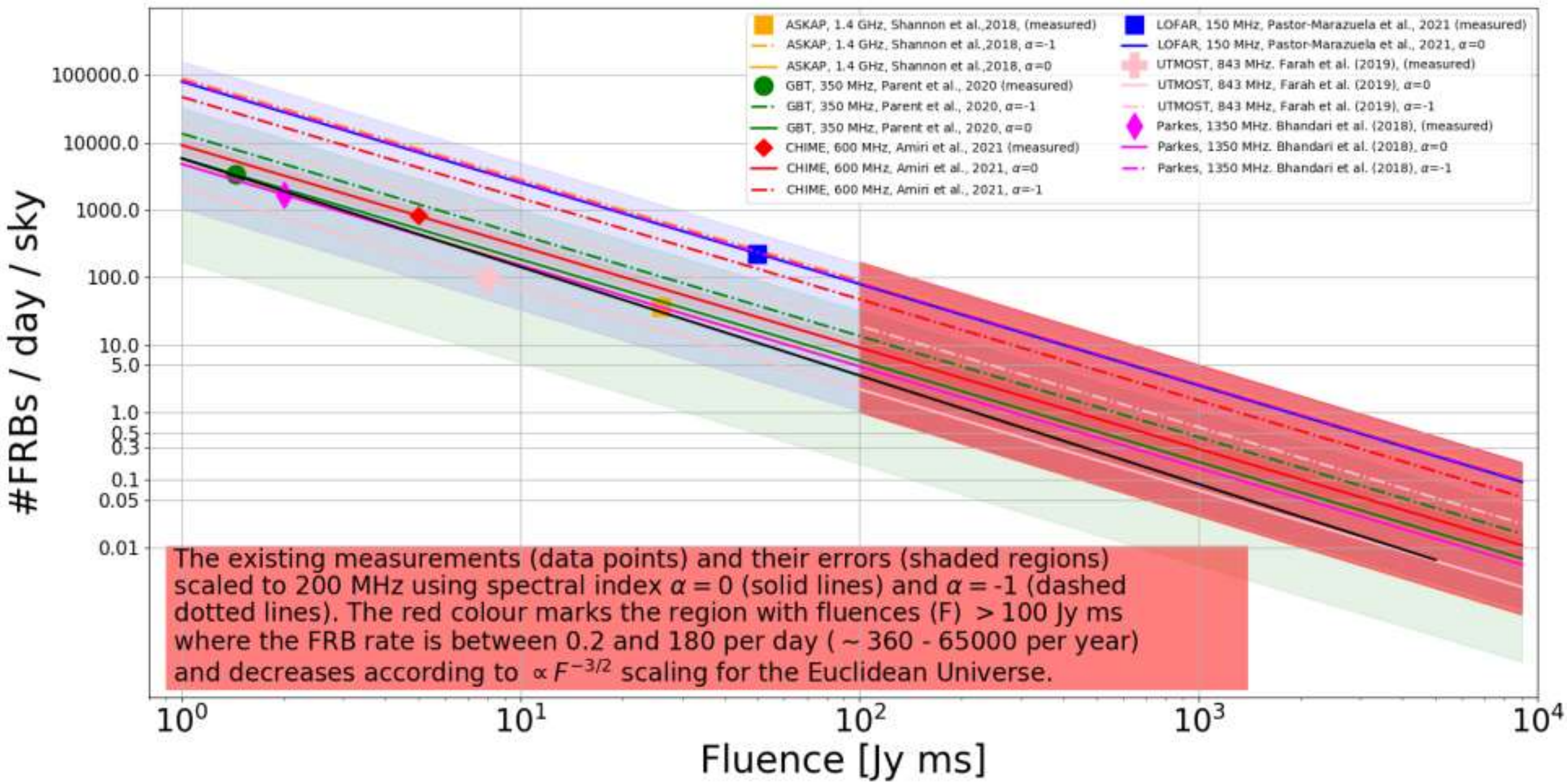
# The case for all-sky FRB detectors

| Survey | FoV [deg$^2$] | Observing Time (T) in [days] | Sensitivity (S) in [Jy ms] | Figure of merit (M) $N_{FRB}$ / year |
|---|---|---|---|---|
| Parent et al. (2020) - reference survey with GBT, detected one FRB at 350 MHz | $FoV_0 = 0.27$ | $T_0 = 173.6$ | $S_0 = 1.26$ | $M_0 = 2.1$ |
| Coenen et al. (2014) | 75 | 9.7 | 71 | 1.09 |
| Karastergiou et al. (2015) | 24 | 60.25 | 310 | 1.6 |
| Rajwade et al. (2020) | 0.61 | 58 | 46 | 0.62 |
| Rowlinson et al. (2016) | 452 | 3.3 | 223 500 | $2.4 \times 10^{-7}$ |
| Tingay et al. (2015) | 610 | 0.44 | 700 | 3.6 |
| **An all-sky FRB detector** | **12000** | **At least ~180 per year (planned )** | **200** | **142** |

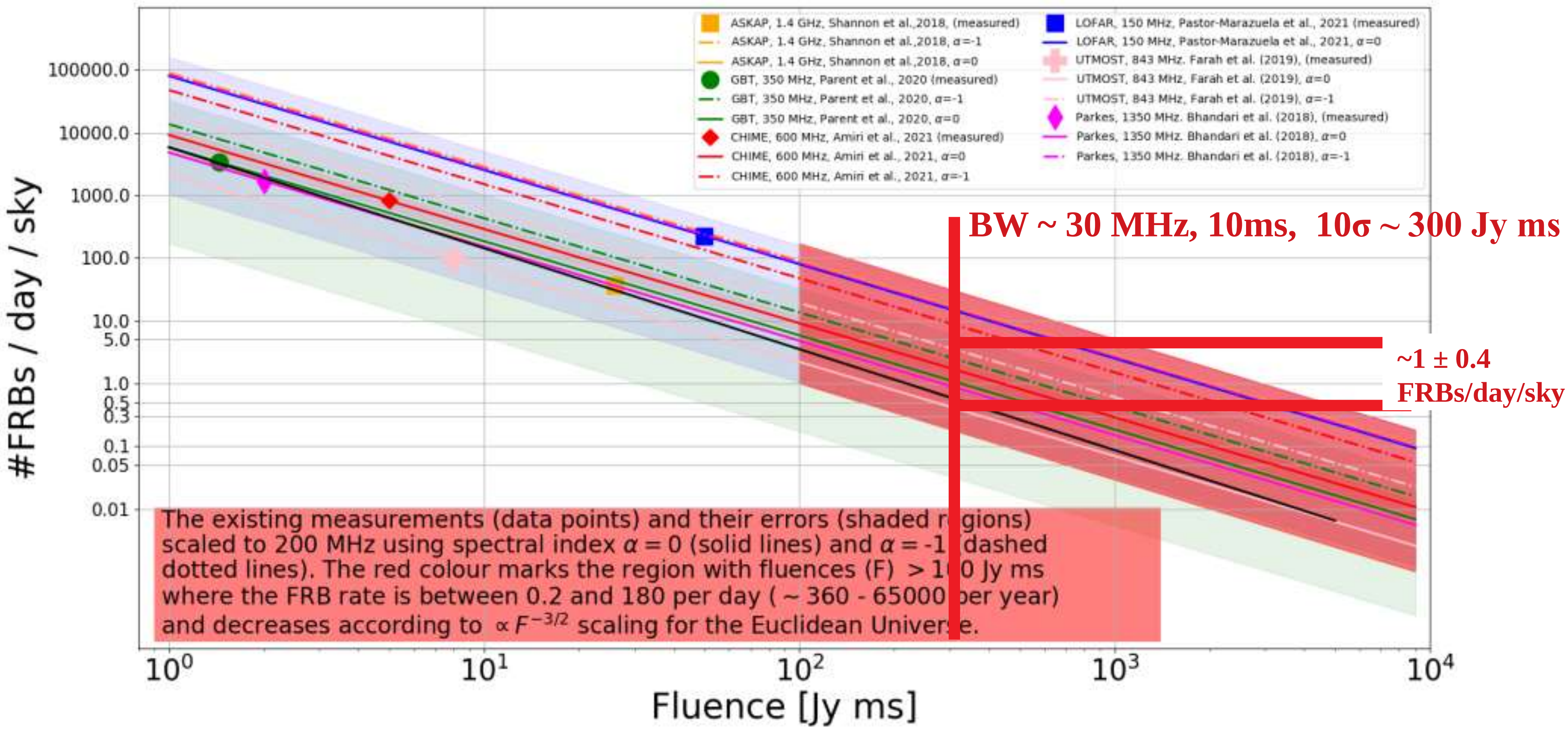
$$N_{FRB}/year = \frac{FoV}{FoV_0}\left(\frac{S}{S_0}\right)^{-3/2} \frac{365}{T_0[days]} \frac{\delta t_0}{\delta t}$$

where FoV is Field-of-View, S sensitivity (fluence threshold), T total observing time and $\delta t_0$ is time resolution of the survey in the table above. Subscript "0" stands for the parameters of the reference survey at 350 MHz Parent et al. (1st row in the table), which detected 1 FRB in 173.6 days of data.

# FRB rates at 200 MHz derived from higher frequency measurements assuming flat rate or rate ~ ν

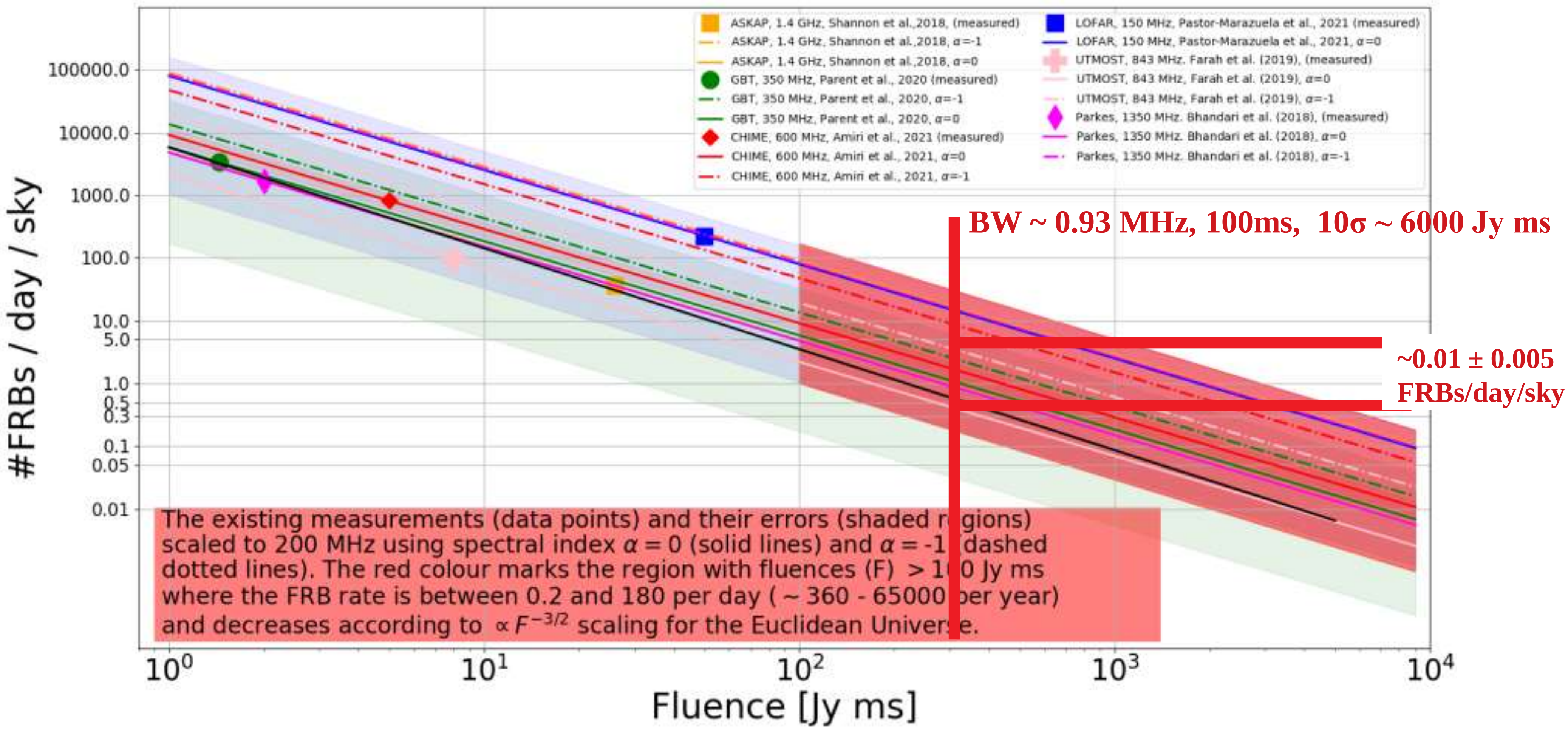


# FRB rates at 200 MHz derived from higher frequency measurements assuming flat rate or rate ~ ν




**Expected number of 10σ (≥ 300 Jy ms) detections ~ 10s - 100s FRBs / year mainly in the local Universe (redshift < 1)**

# FRB rates at 200 MHz derived from higher frequency measurements assuming flat rate or rate ~ ν




**With current system 10σ (≥ 6 kJy ms) detections ~ 4 ± 2 FRBs / year**

# SKA-Low (50 - 350 MHz) prototype stations

**Aperture Array Verification System 2 (AAVS2)**
**256 SKALA-4.1 antennas**
***( van Es et al, Proc. of SPIE, 2020, Macario et al, SPIE JATIS ,2022 )***

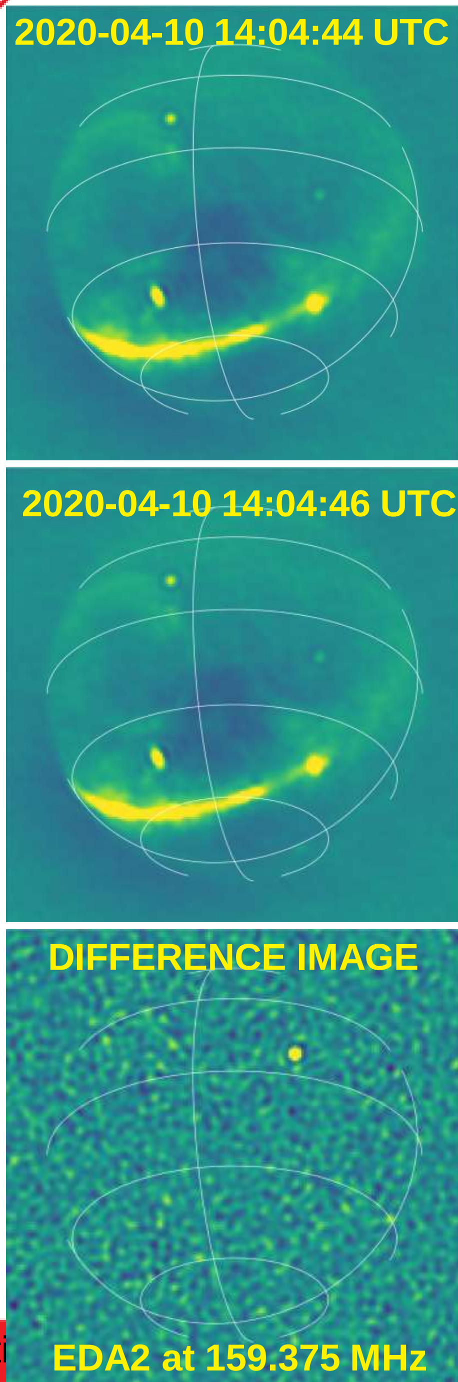
**Engineering Development Array 2 (EDA2)**
**256 MWA Dipoles**
***( Wayth et al., SPIE JATIS, 2022 )***

- Antennas individually digitised → 16 SmartBoxes → 5 km fibre → Tile Processing Units (TPMs)

- 16 TPMs per station (32 inputs per TPM) output data in 1.08 usec resolution :
  - Complex voltages from all antennas in 1 coarse channel (~0.93 MHz)
  - Station beam (~3.3˚ at 150 MHz) : complex voltages coherently added in the TPMs

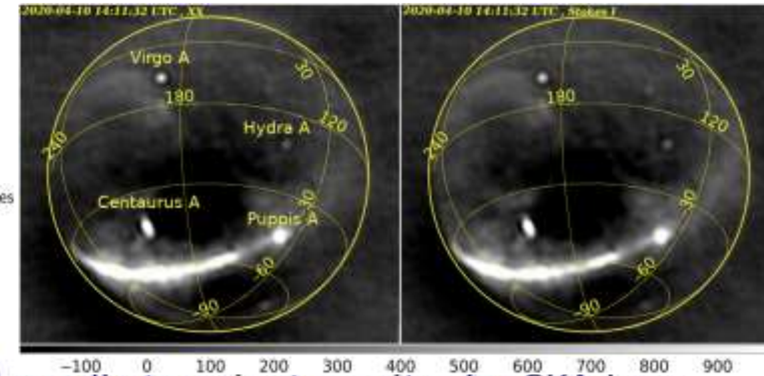
- Observing in 50 - 350 MHz band with the following modes available :
  - **Standalone interferometer: station antennas cross-correlated with xGPU correlator (all-sky images in 2s , 1 coarse channel ~0.93 MHz resolutions)**
  - Station beam : tested on drift scan observations and detections of multiple pulsars
  - High-time resolution voltages : 0.28s dumps and starting to get more

# Commissioning and test observations in 2019 and 2020 used to demonstrate transients monitoring capabilities





*Publications of the Astronomical Society of Australia* (2021), **38**, e023, 18 pages
doi:10.1017/pasa.2021.16


**Research Paper**

## A Southern-Hemisphere all-sky radio transient monitor for SKA-Low prototype stations


M. Sokolowski[1*], R. B. Wayth[1,2], N. D. R. Bhat[1], D. Price[1], J. W. Broderick[1], G. Bernardi[3], P. Bolli[3], R. Chiello[4], G. Comoretto[3], B. Crosse[1], D. B. Davidson[1], G. Macario[3], A. Magro[5], A. Mattana[6], D. Minchin[1], A. McPhail[7], J. Monari[6], F. Perini[6], G. Pupillo[3], G. Sleap[7], S. Tingay[1], D. Ung[1] and A. Williams[7]

[1]International Centre for Radio Astronomy Research, Curtin University, Bentley, WA 6102, Australia, [2]ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Bentley 6845, Australia, [3]Osservatorio Astrofisico di Arcetri, Istituto Nazionale di Astrofisica, Florence, Italy, [4]University of Oxford, Denys Wilkinson Building, Oxford OX1 2JD, UK, [5]Institute of Space Sciences and Astronomy, University of Malta, Msida, Malta, [6]Istituto di Radioastronomia, Istituto Nazionale di Astrofisica, Bologna, Italy and [7]Curtin Institute of Radio Astronomy, GPO Box U1987, Perth, WA 6845, Australia



**Abstract**

We present the first Southern-Hemisphere all-sky imager and radio-transient monitoring system implemented on two prototype stations of the low-frequency component of the Square Kilometre Array (SKA-Low). Since its deployment, the system has been used for real-time monitoring of the recorded commissioning data. Additionally, a transient searching algorithm has been executed on the resulting all-sky images. It uses a difference imaging technique to enable identification of a wide variety of transient classes, ranging from human-made radio-frequency interference to genuine astrophysical events. Observations at the frequency 159.375 MHz and higher in a single coarse channel (≈0.926 MHz) were made with 2 s time resolution, and multiple nights were analysed generating thousands of images. Despite having modest sensitivity (~ few Jy beam$^{-1}$), using a single coarse channel and 2-s imaging, the system was able to detect multiple bright transients from PSR B0950+08, proving that it can be used to detect bright transients of an astrophysical origin. The unusual, extreme activity of the pulsar PSR B0950+08 (maximum flux density ~155 Jy beam$^{-1}$) was initially detected in a 'blind' search in the 2020 April 10/11 data and later assigned to this specific pulsar. The limitations of our data, however, prevent us from making firm conclusions of the effect being due to a combination of refractive and diffractive scintillation or intrinsic emission mechanisms. The system can routinely collect data over many days without interruptions; the large amount of recorded data at 159.375 and 229.6875 MHz allowed us to determine a preliminary transient surface density upper limit of $1.32 \times 10^{-9}$deg$^{-2}$ for a timescale and limiting flux density of 2 s and 42 Jy, respectively. In the future, we plan to extend the observing bandwidth to tens of MHz and improve time resolution to tens of milliseconds in order to increase the sensitivity and enable detections of fast radio bursts below 300 MHz.

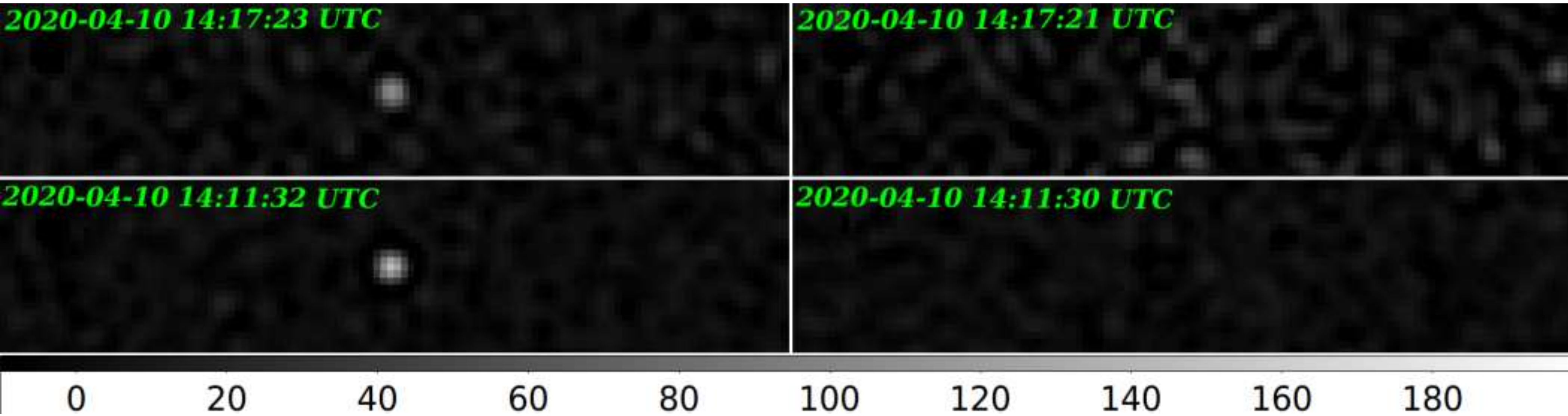


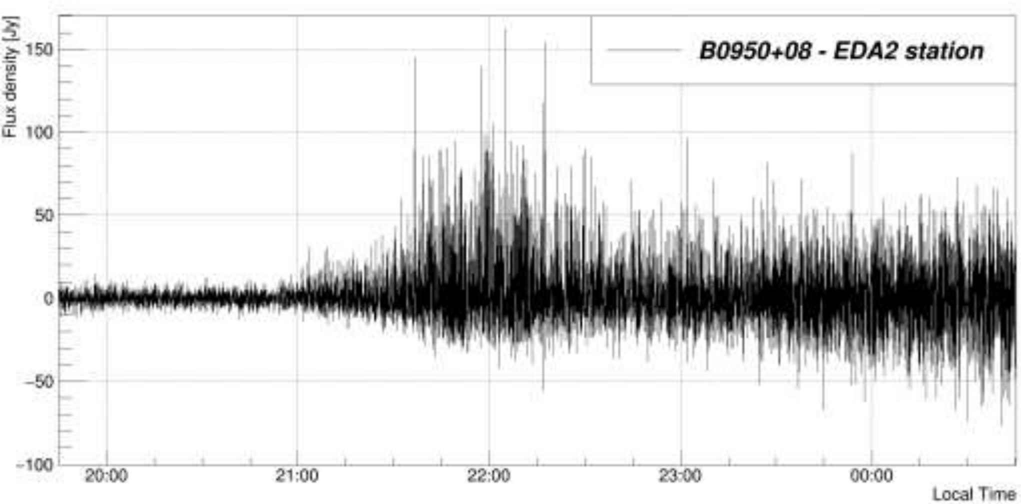
**Keywords:** instrumentation: interferometers – telescopes – methods: observational – pulsars: individual(PSR B0950+08) – radio continuum:transients

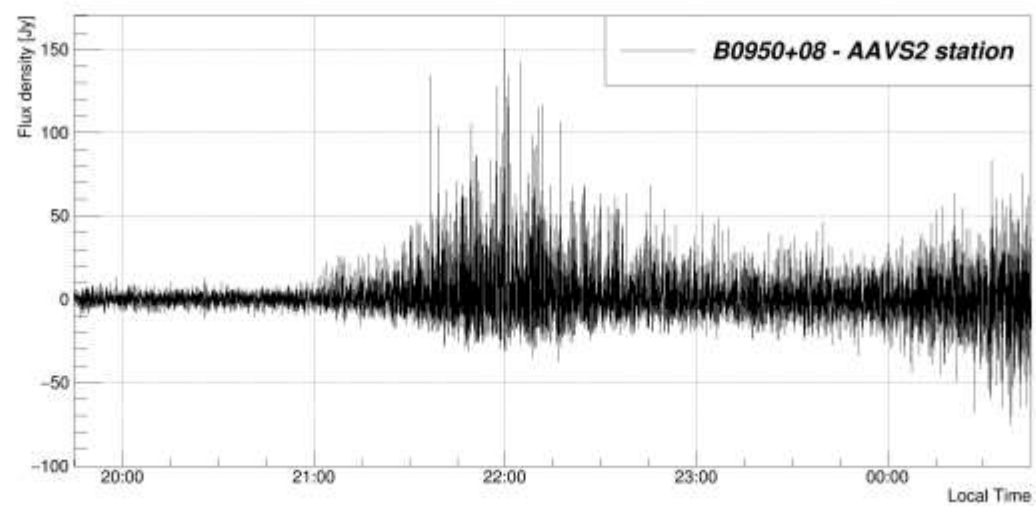
(Received 6 February 2021; revised 13 March 2021; accepted 29 March 2021)


[Sokolowski, Wayth, Bhat, Price et al. 2021, PASA](#)

# Detection of extreme activity of a nearby pulsar B0950+08 during the night 2020-04-10/11

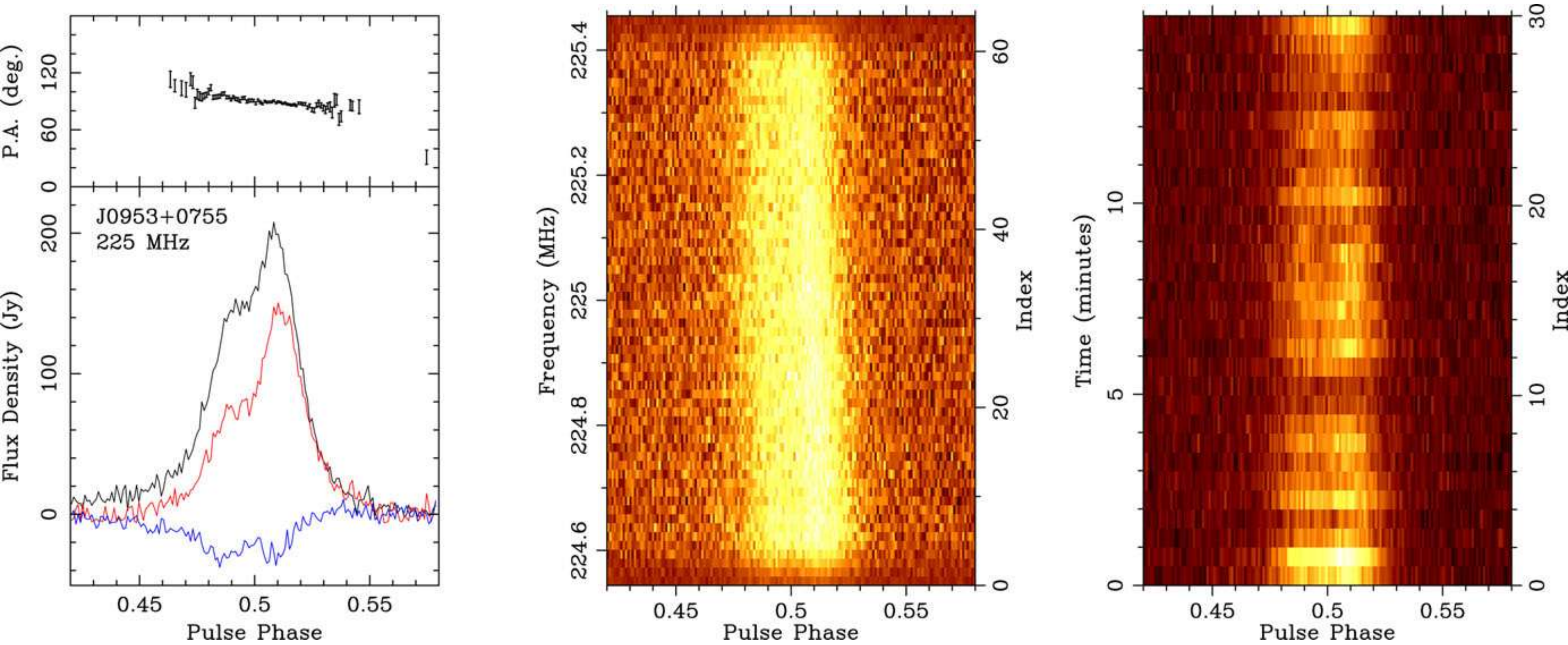



- Radio transients up to 160 Jy in 2 seconds images due to a combination of diffractive and refractive scintillation

# Pulsar detections in real-time station beam (up to 40 MHz of bandwidth)

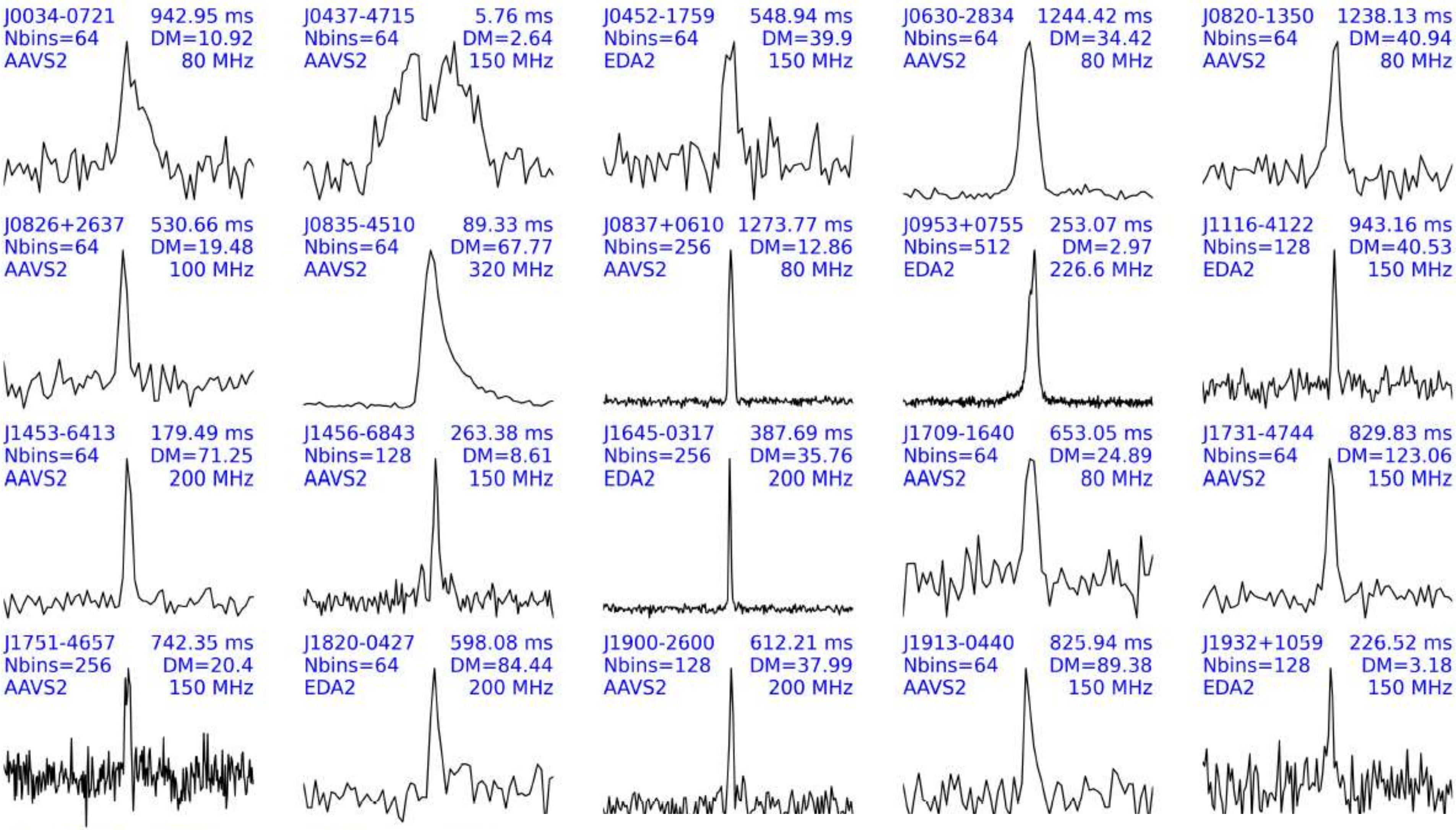



- 22 pulsars detected with both stations
- 6 lowest frequency detections ever
- 1 millisecond pulsar ( J0437-4715 )
- 8 bright pulsars used for multi-frequency studies

***Lee et al., PASA, 2022***

ICRAR

# Pulsar detections in real-time station beam (up to 40 MHz of bandwidth)



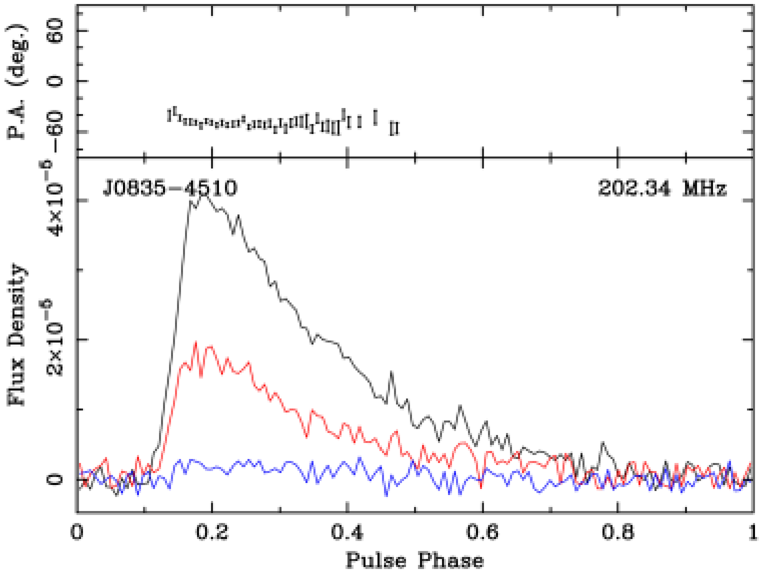


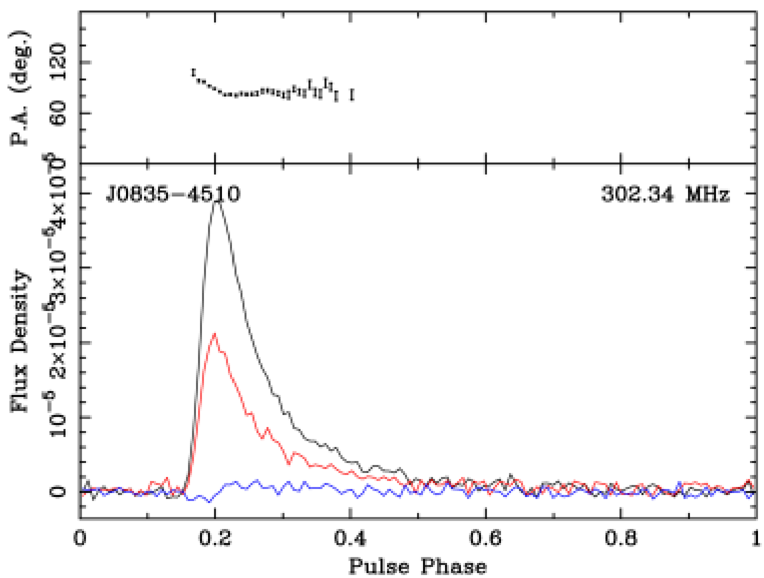
- 22 pulsars detected with both stations
- 6 lowest frequency detections ever
- 1 millisecond pulsar ( J0437-4715 )
- 8 bright pulsars used for multi-frequency studies

***Lee et al., PASA, 2022***

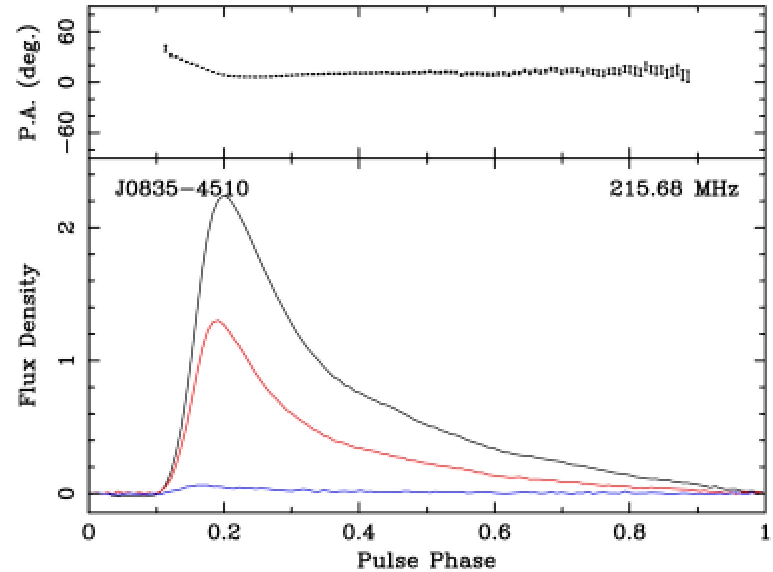
# Pulsar polarimetric measurements verified against MWA pulse profiles

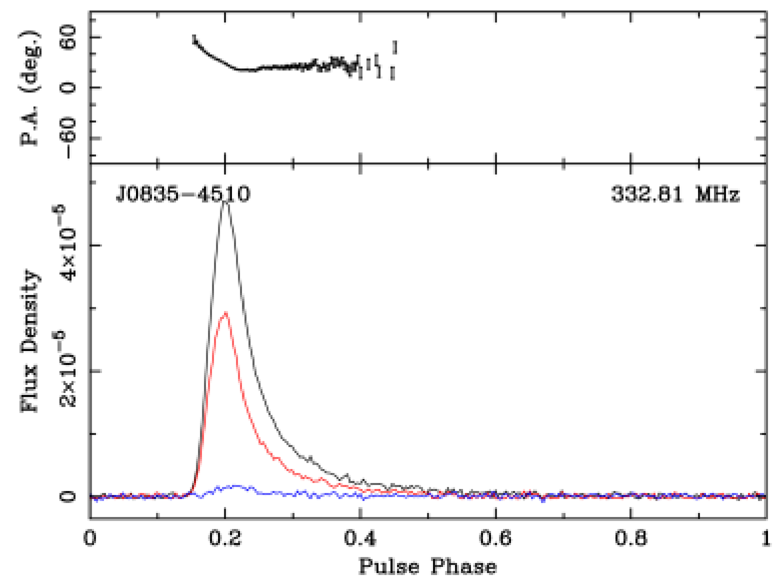
**AAVS2**



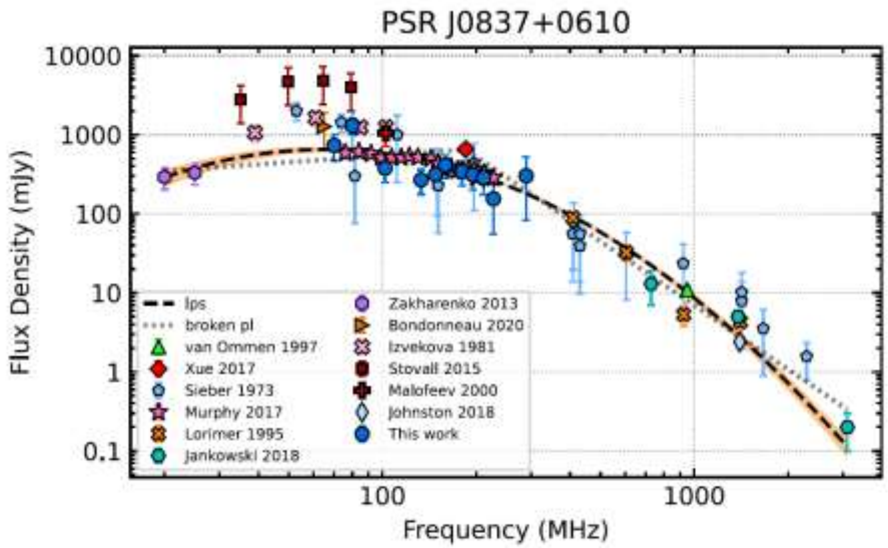

**MWA**

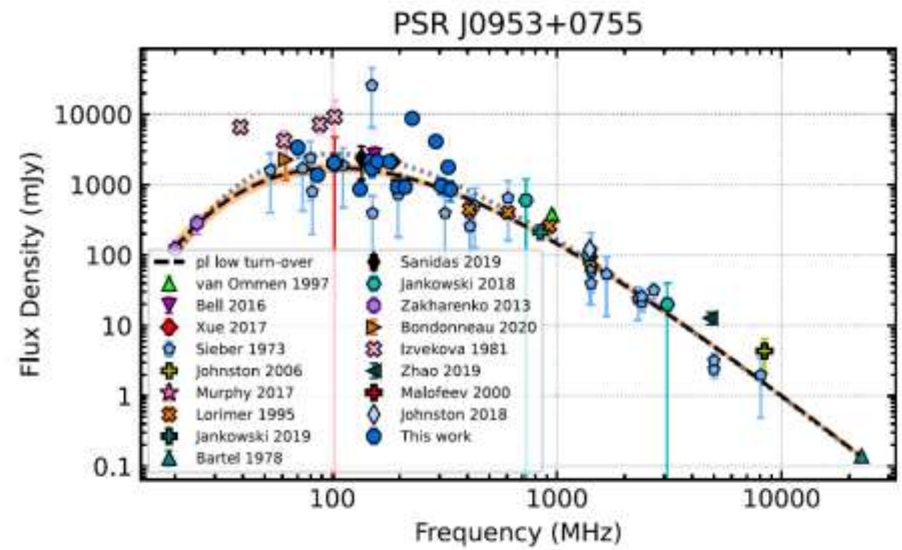


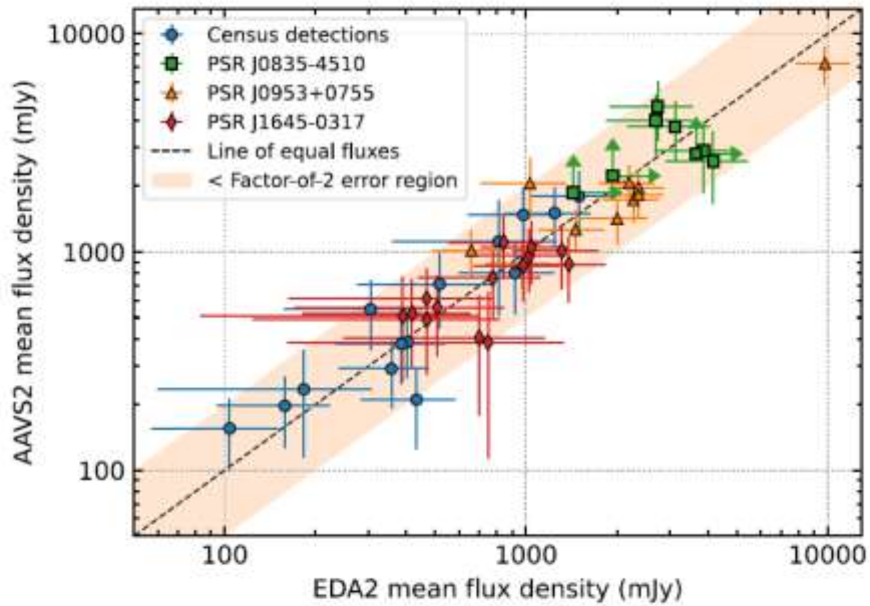




***Lee et al., PASA, 2022***

# Flux density measurements and modelling of 8 selected pulsars




***Lee et al., PASA, 2022***

# Fast Radio Bursts (FRBs) : upper limits on low-frequency counterparts of one ASKAP and two DWF FRBs

- No detections of low-frequency FRBs
- Observed when three FRBs were detected by ASKAP and Deeper Wider Faster (DWF)
- FRB 20191228 (ASKAP) ~40 Jy ms FRB, EDA2 and AAVS2 upper limit, but no ATEL for that one
- DWF FRBs 200914 and 200919 both stations observed → upper limits
- **Using 0.93 MHz bandwidth and 2s images upper limits on fluence ~30 Jy s (30 kJy ms)**
- Demonstrates that if transient, like gamma-ray burst or gravitational wave is detected by other instruments will have images before, during and after the event !
- **Larger bandwidth and better time resolution are needed to start detecting FRBs ...**

## Upper limits on low-frequency emission from FRBs 200914 and 200919 from SKA-Low prototype stations

ATel #14044; *M. Sokolowski, N. D. R. Bhat, R. B. Wayth, J. Broderick, D. Minchin, A. McPhail, D. Ung, B. Crosse, D. Davidson, T. Booler, S. Tingay, D. Price, B. Juswardy, A. Sutinjo (ICRAR/Curtin University) on behalf of the EDA2 Team. G. Bernardi, P. Bolli, J. Monari, A. Mattana, F. Perini, G. Comoretto, G. Macario, G. Pupillo, M. Schiaffino (INAF) on behalf of the AAVS2 Team. A. Magro (University of Malta), R. Chiello (University of Oxford), P. Benthem (ASTRON) and M. Waterson (SKA Organisation, Manchester)*
on **27 Sep 2020; 12:17 UT**
*Credential Certification: Marcin Sokolowski (marcin.sokolowski@curtin.edu.au)*

Subjects: Radio, Fast Radio Burst

Tweet

The Engineering Development Array 2 (EDA2; Wayth et al., in prep.) and the Aperture Array Verification System 2 (AAVS2; Bolli et al., in prep.) are two prototype stations of the low-frequency component of the Square Kilometre Array (SKA-Low). During the times of FRBs 200914 and 200919 (Gupta et al. ATEL #14040), both EDA2 and AAVS2 were performing test commissioning observations, and thus fortuitously, effectively co-observed the FRBs at low frequencies. The data were collected in a correlated mode using a single coarse (narrow-band) channel (approximately 0.926 MHz bandwidth), at central frequencies 159.4 (EDA2) and 229.7 MHz (AAVS2), which can be used to produce all-sky images in near real-time. The correlated data were analysed using an automatic transient detection algorithm (Sokolowski et al., in prep.), and the data around the vicinity of FRB locations and the times were also visually inspected.
Neither of these have revealed any low-frequency counterparts, resulting in the following (1 sigma) upper limits:

EDA2 at 159.4 MHz :
FRB200919 : ~25 kJy ms, implied spectral index limit > -4.0 (between 159.4 MHz and 1400 MHz)
FRB200914 : ~26 kJy ms, implied spectral index limit > -4.7 (between 159.4 MHz and 1400 MHz)

AAVS2 at 229.7 MHz :
FRB200919 : ~33 kJy ms, implied spectral index limit > -4.9 (between 229.7 MHz and 1400 MHz)
FRB200914 : ~32 kJy ms, implied spectral index limit > -5.8 (between 229.7 MHz and 1400 MHz)

Both the systems are currently in their early stages of development, and we note that both FRBs were observed at fairly low elevations. As a result, the sensitivities achieved are at ~10% level of the near-zenith (maximum). Improved sensitivities (and hence better constraints) will be possible in the future when more instantaneous bandwidth becomes available and for observations at more optimal elevations.

# For a start network upgrade

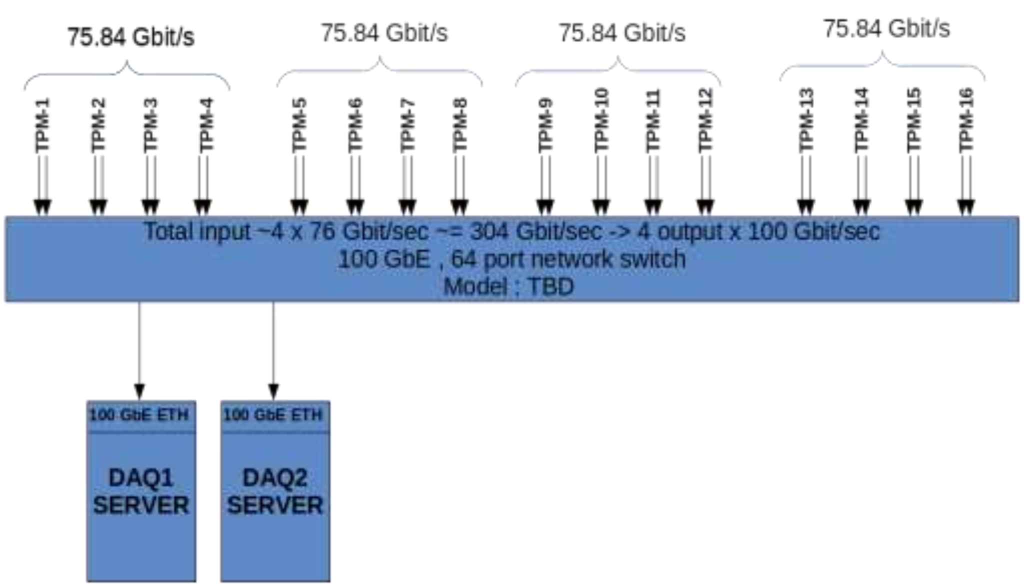
- High-throughput switch
  32 x 40 Gbit + 8 x 100 Gbit
- 1 data acquisition computer to capture a few MHz bandwidth
- Test capturing >1 coarse channel
- from all antennas
- Test real-time imaging


# Upgrade of EDA2 bandwidth and high-time resolution imaging capability

TPM output data rates:

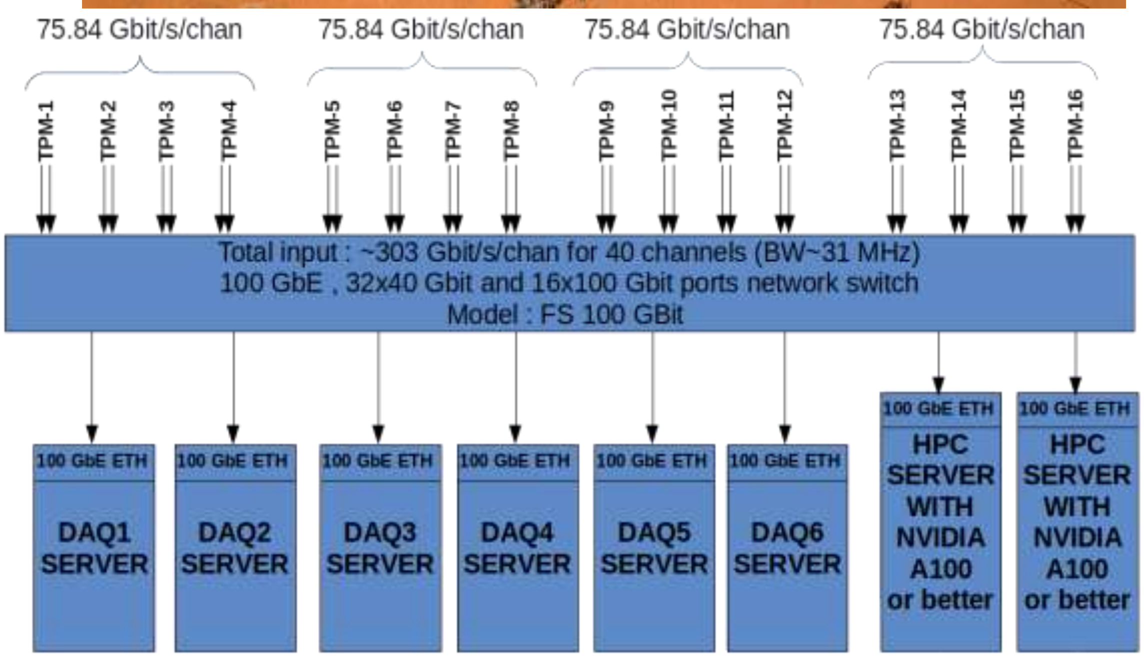
1 TPM, 1 channel -> 0.474 Gbit/s
4 TPMs, 1 channel -> 1.896 Gbit/s
4 TPMs, 40 channels -> 75.84 Gbit/s

16 TPMs , 1 channel -> 7.584 Gbit/s (current)
**16 TPMs, 10 channels -> 75.84 Gbit/s (CHASM1)**
**1 channel corresponds to 0.78125 MHz**




- High-throughput (100 Gbit) :
  - 32x40 Gbit TPM inputs
- - 1x100 Gbit output
- 1 data acquisition computers to capture ~50 Gbit/s per computer
- Data rate ~7.6 Gbit / s
- Enables capturing of up to 12 coarse (BW~10 MHz) channels from all antennas
- **New firmware and capturing software to be tested.**
- **Potentially ~ 26 FRBs / per year +/- 50%**

# Upgrade of EDA2 bandwidth and high-time resolution imaging capability




- High-throughput (100 Gbit) 64 port network switch
- 6 data acquisition computers to capture ~50 Gbit/s per computer, form 10-ms images and copy to FRB search servers (~10 GBit/s)
- FRB search servers with state of art GPUs (A100 or better) to perform de-dispersion and search for FRBs
- Software for 10ms all-sky
- imaging and FRB searches being developed under the PaCER project with PAWSEY (funding a two HDR positions)
- Sensitivity to FRBs ~200 Jy ms at frequencies ≤ 350 MHz
- **Even ~100s FRBs / year ?**

A High Time Resolution All-Sky Monitor for Fast Radio Bursts and Technosignatures, 2022 3rd URSI Atlantic and Asia Pacific Radio Science Meeting

# GPU-based high-time resolution imaging software (PaCER BLINK project)

**Image of the entire visible hemisphere at 160 MHz obtained with MIRIAD package**

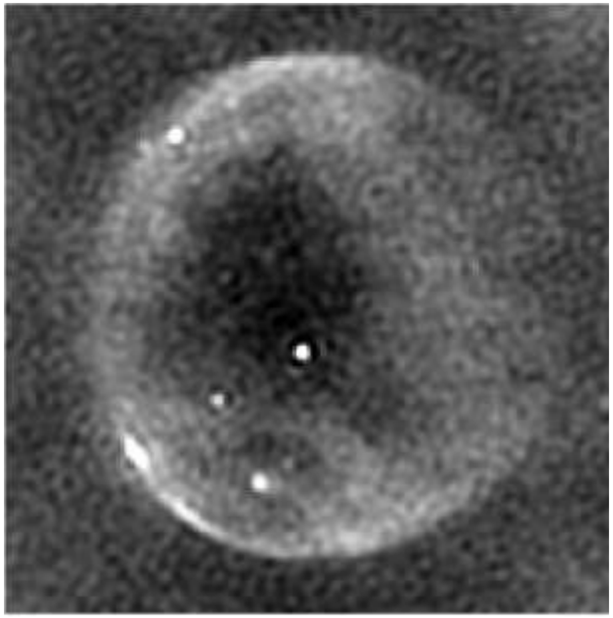


**Image of the entire visible hemisphere at 160 MHz obtained with CASA package**

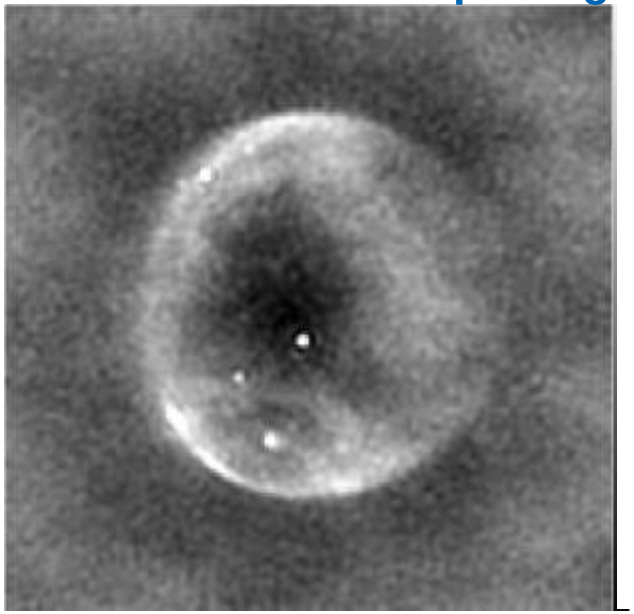
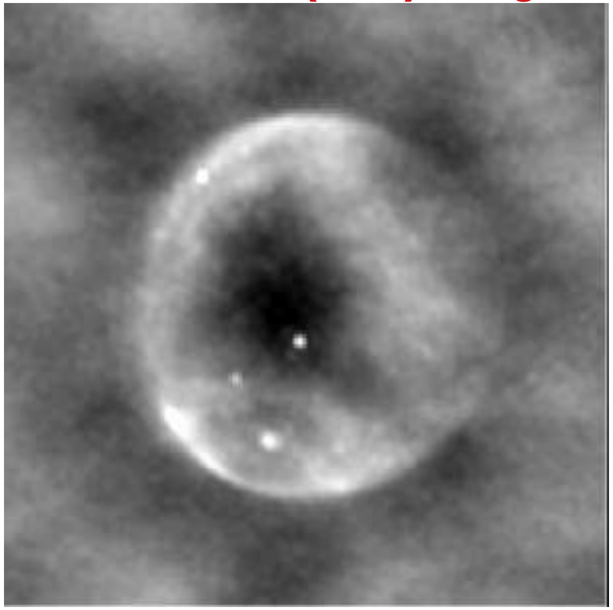


**Image of the entire visible hemisphere at 160 MHz obtained with BLINK (our!) imager**

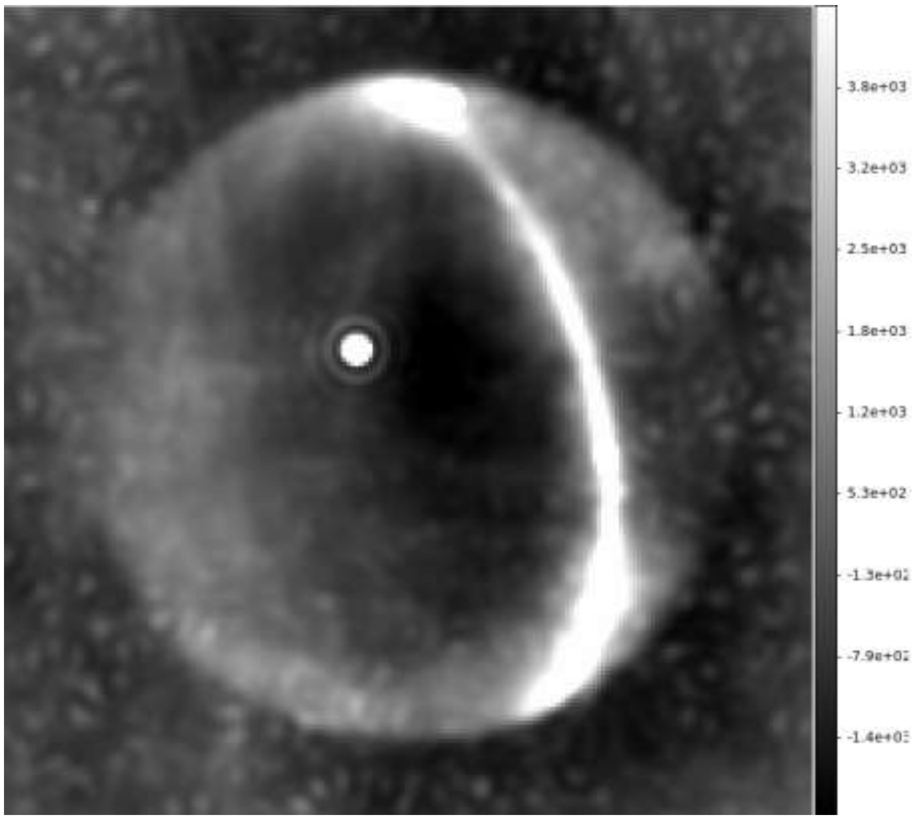


- **Validation of the code against standard radio astronomy packages on sample EDA2 data (2022_01_18_ch204_station_beam) at 160 MHz , 180x180 images**
- **Right : BLINK_pipeline program (correlation + imaging in 1-go)**
- **Production version of imaging pipeline under development**

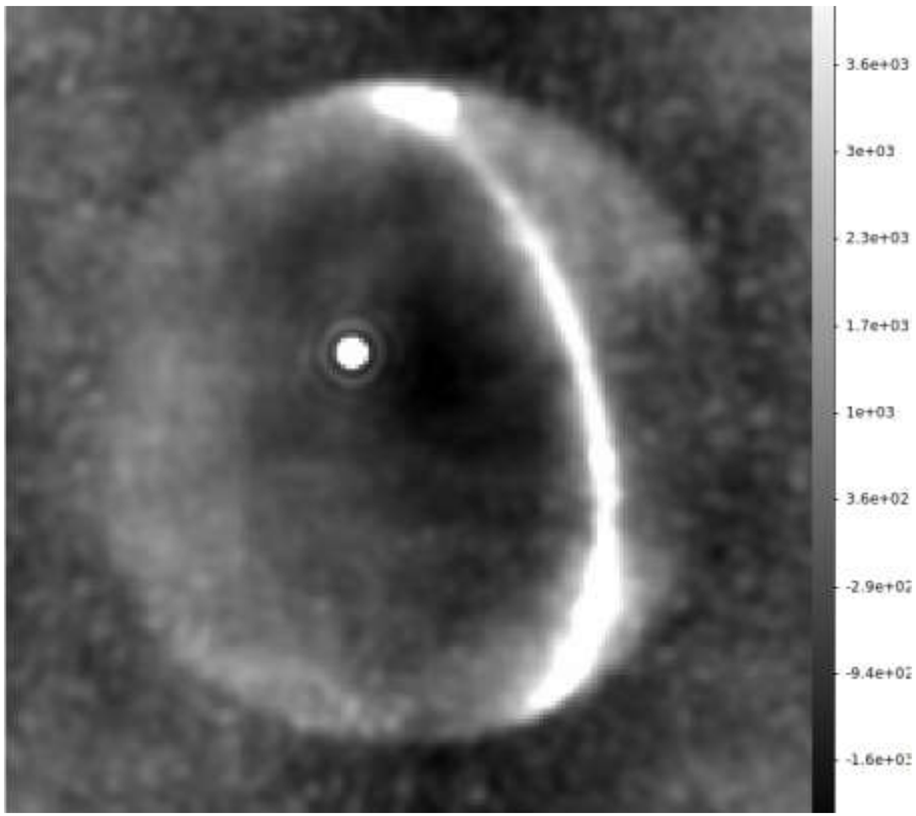
*Aniruddha, Sokolowski in preparation*

# GPU-based high-time resolution imager validation : EDA2 simulated data

**MIRIAD image of visitilities simulated for EDA2 at 160 MHz**




**BLINK image of visitilities simulated for EDA2 at 160 MHz**

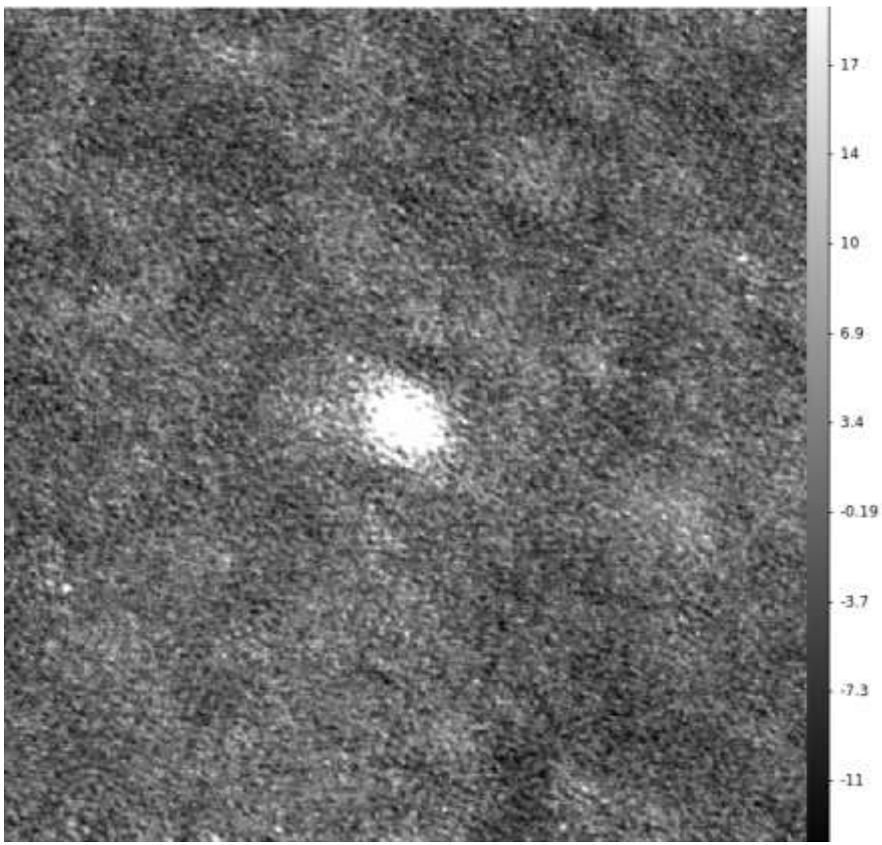



**Both images in natural weighting**

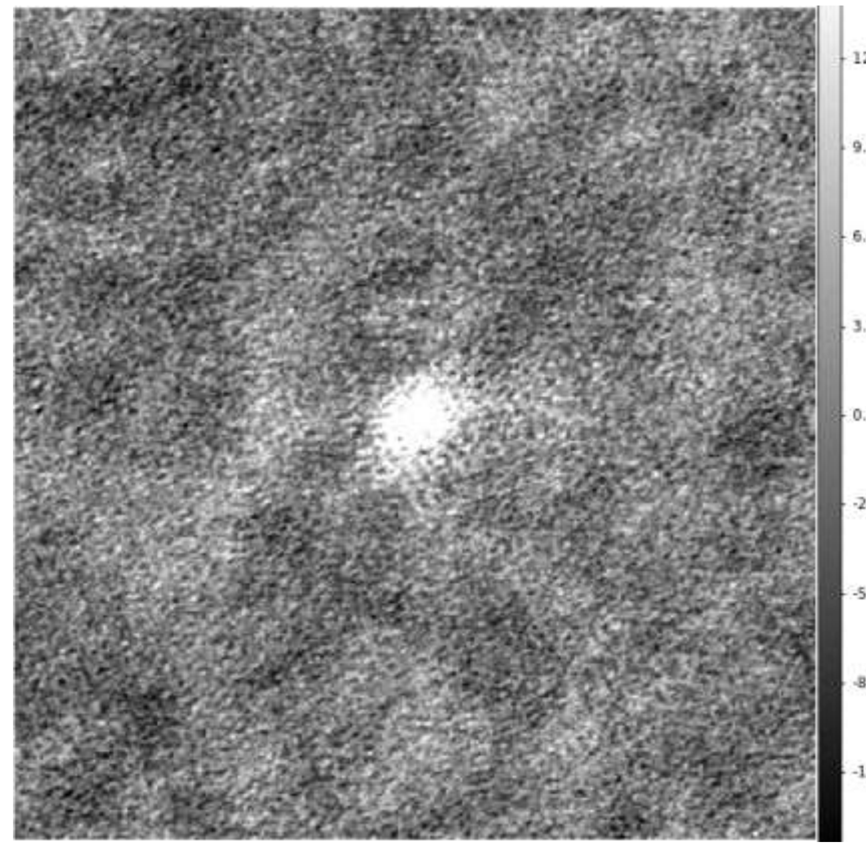
*Aniruddha, Sokolowski in preparation*

# GPU-based high-time resolution imager validation : MWA Hydra-A observation

**CASA image of MWA data from Hydra-A observation took ~2.2sec (including I/O)**




**BLINK image of MWA data from Hydra-A observation took ~0.17 sec (including I/O)**

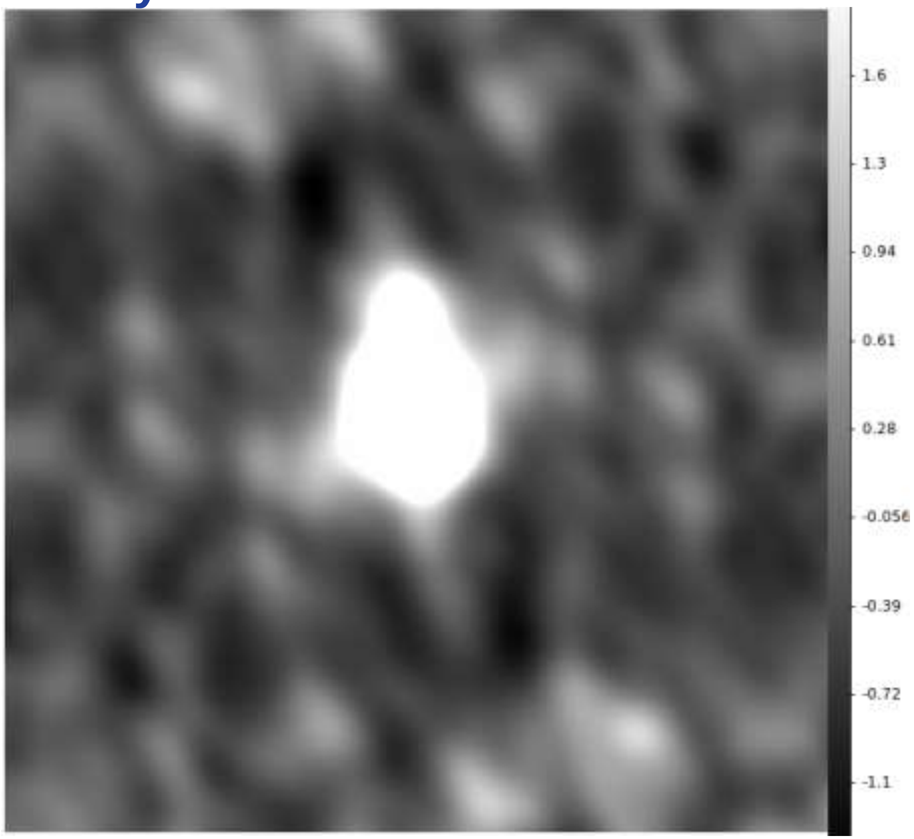



**Validation of the code against standard radio astronomy packages on sample MWA Hydra-A observation (obsID = 1419609943)**
**Both dirty images in natural weighting, same image size etc.**

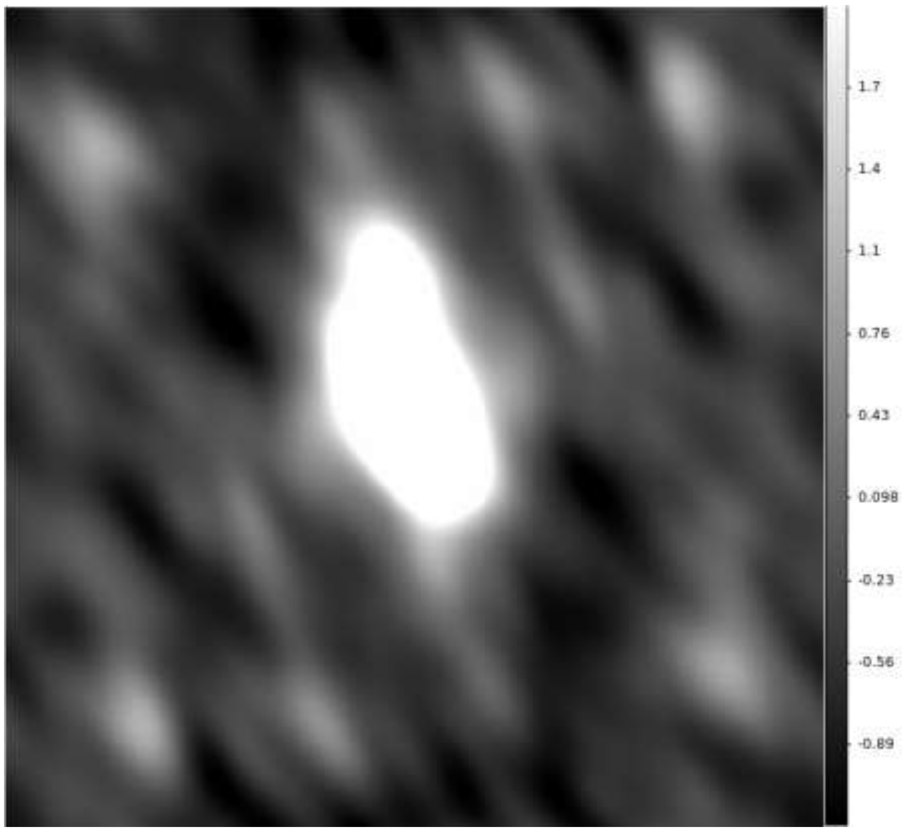
*Aniruddha, Sokolowski in preparation*

# GPU-based high-time resolution imager validation : MWA Hydra-A simulated data

**WSCLEAN image of MWA data of Hydra-A simulated visitilities**



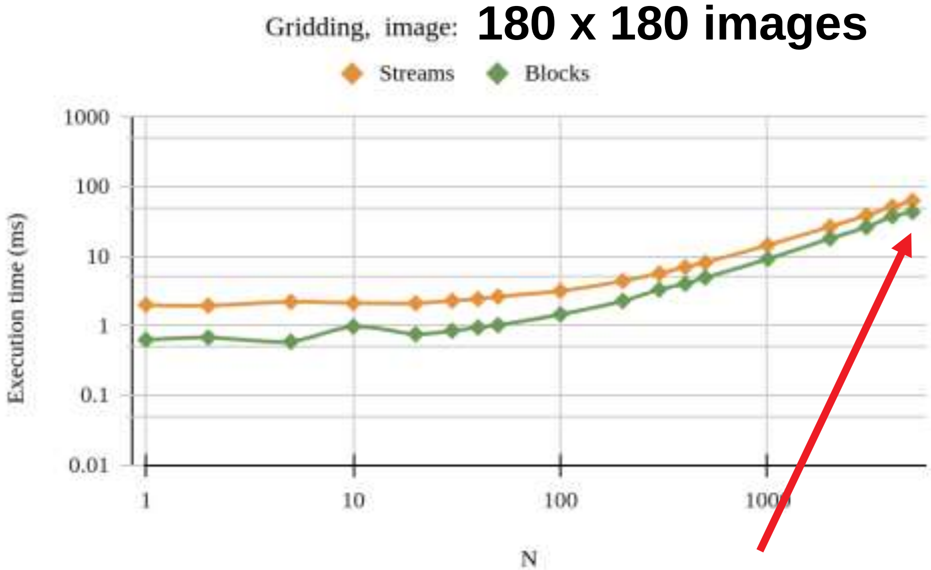

**BLINK image of MWA data of Hydra-A simulated visitilities**




*Aniruddha, Sokolowski in preparation*

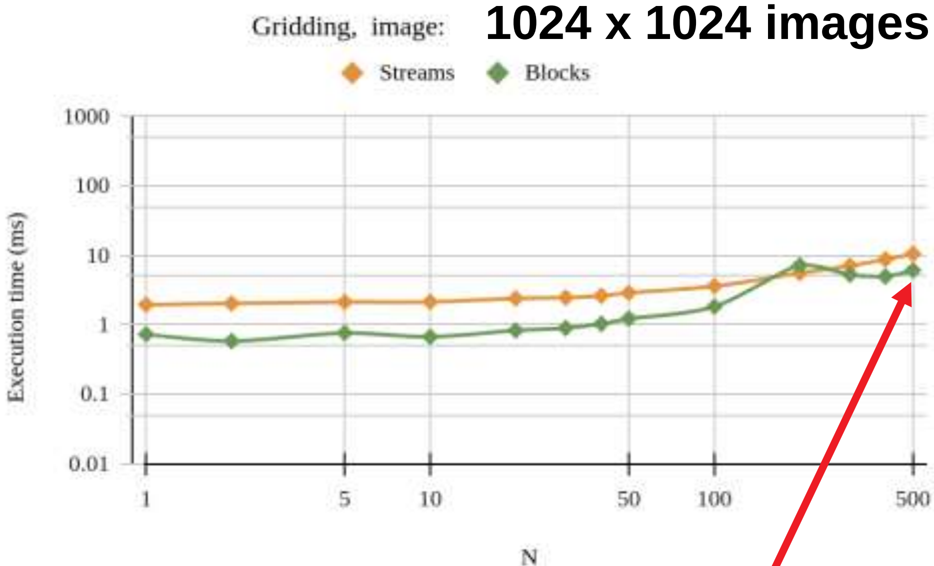
# GPU imager banchmarking on Pawsey HPC Setonix (AMD GPUs) and Topaz (NVIDIA GPUs)

**180 x 180 images**




**≈ 8.7 usec / image**

**1024 x 1024 images**

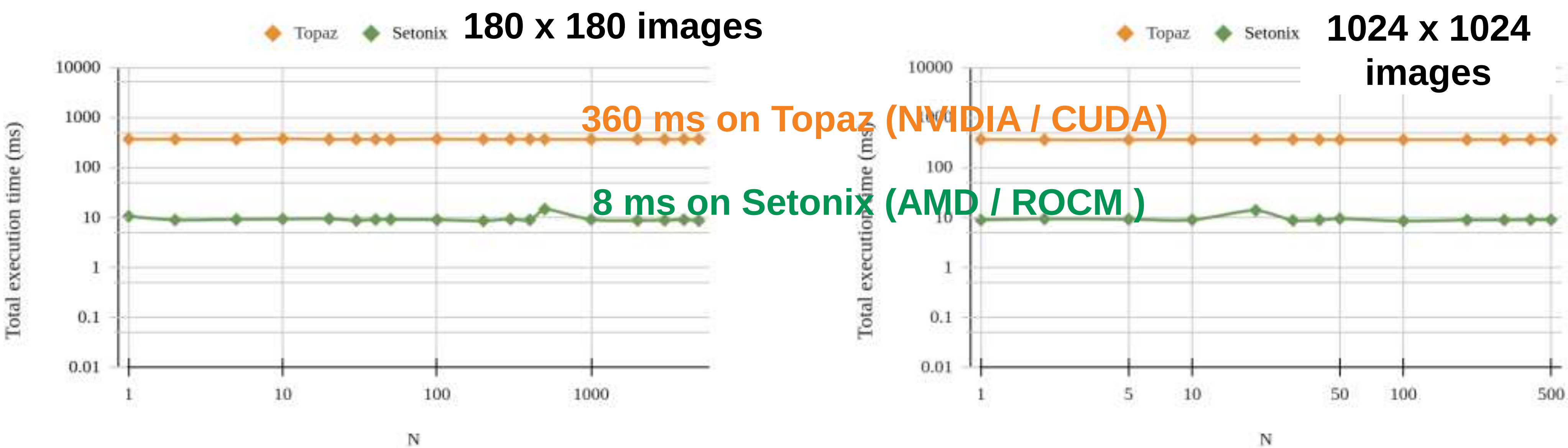



**≈ 12 usec / image**

## Parellel GPU gridding can be very fast ~10usec / image

*Aniruddha, Sokolowski in preparation*

# GPU imager banchmarking on Pawsey HPC Setonix (AMD GPUs) and Topaz (NVIDIA GPUs)

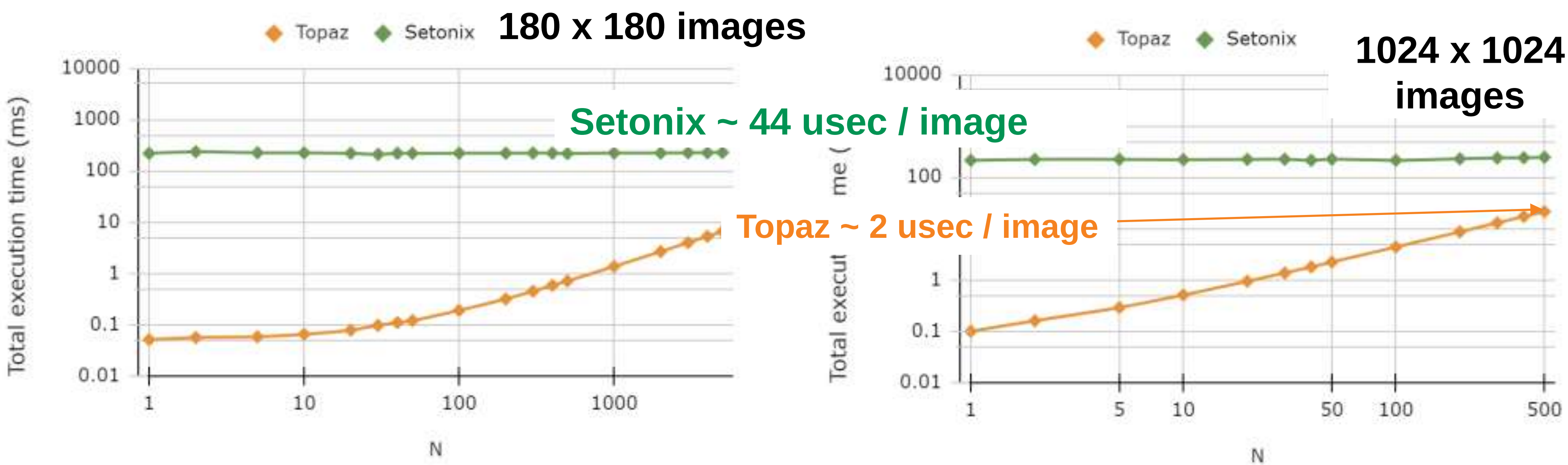



**GPU cuFFT - PlanyMany Creation (only once) is a constant contribution independent of image size**

*Aniruddha, Sokolowski in preparation*

# GPU imager banchmarking on Pawsey HPC Setonix (AMD GPUs) and Topaz (NVIDIA GPUs)

## GPU cuFFT - PlanyMany Execution




## GPU cuFFT : PlanyMany Creation + Execution for 5000 images

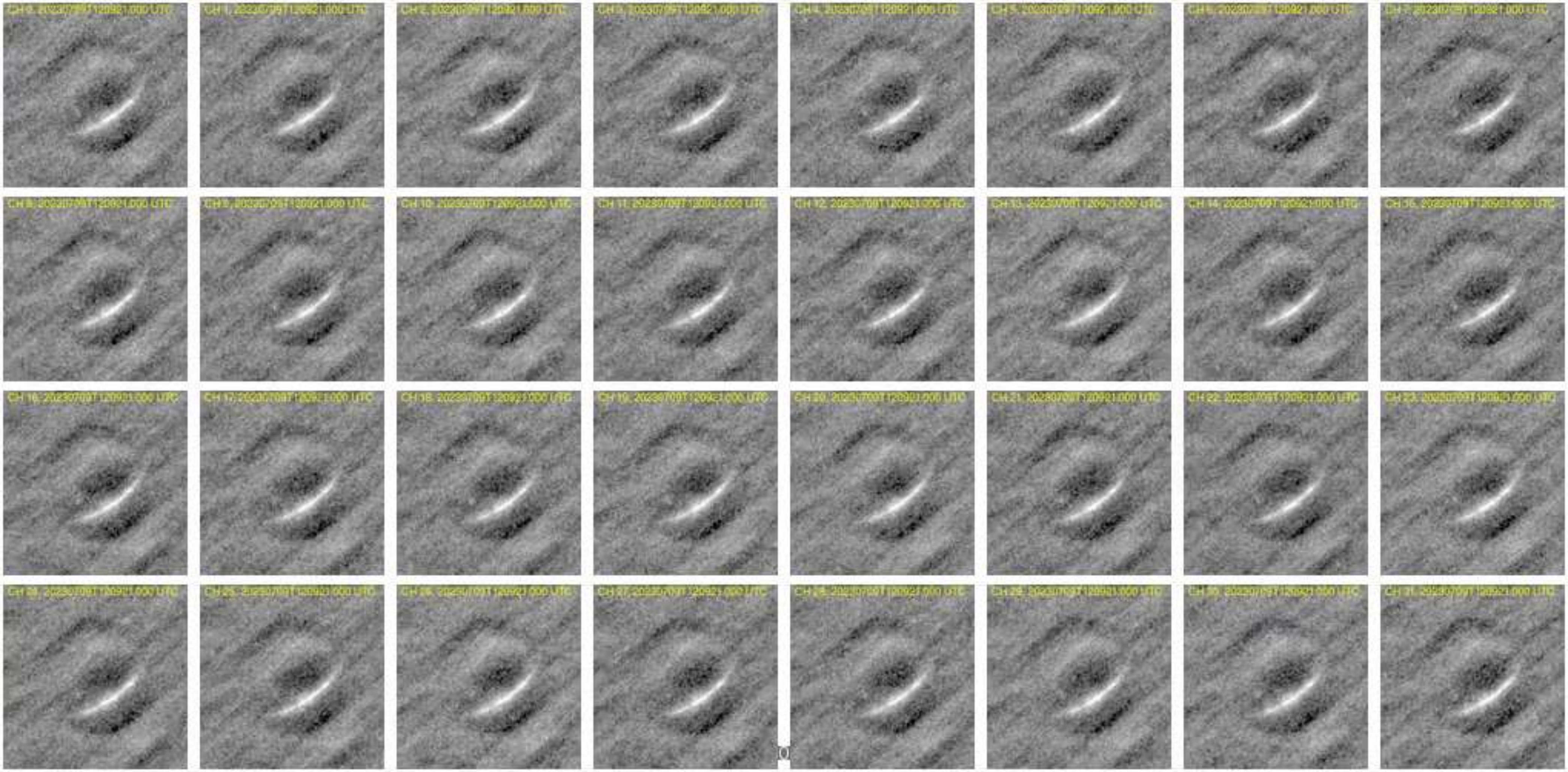
- Topaz (NVIDIA / CUDA) : ≈370 ms / 5000 images ≈74 usec / image
- **Setonix (AMD / ROCM ) : ≈228 ms / 5000 images ≈46 usec / image (~1.5 times faster)**

*Aniruddha, Sokolowski in preparation*

# Real-time and off-line GPU-imaging on EDA2 data acquisition server or Setonix

**Recorded ~2.5 hours of data for testing in 1 minute blocks**

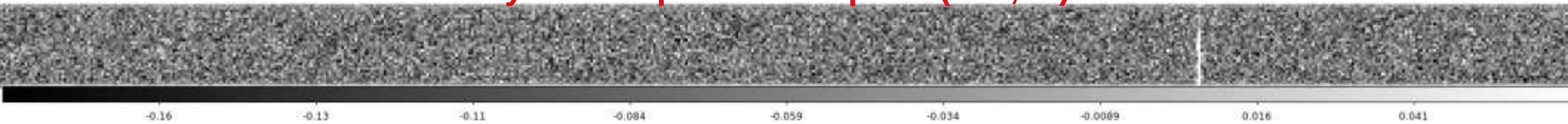
**Bandwidth ~1 MHz of data (32 channels) at 230 MHz, 100ms, start 20230709 12:09:21 UTC**



# Pilot off-line “FRB search” on Setonix

**For every pixel above horizon - create dynamic spectrum and look for dispersed pulses ...**

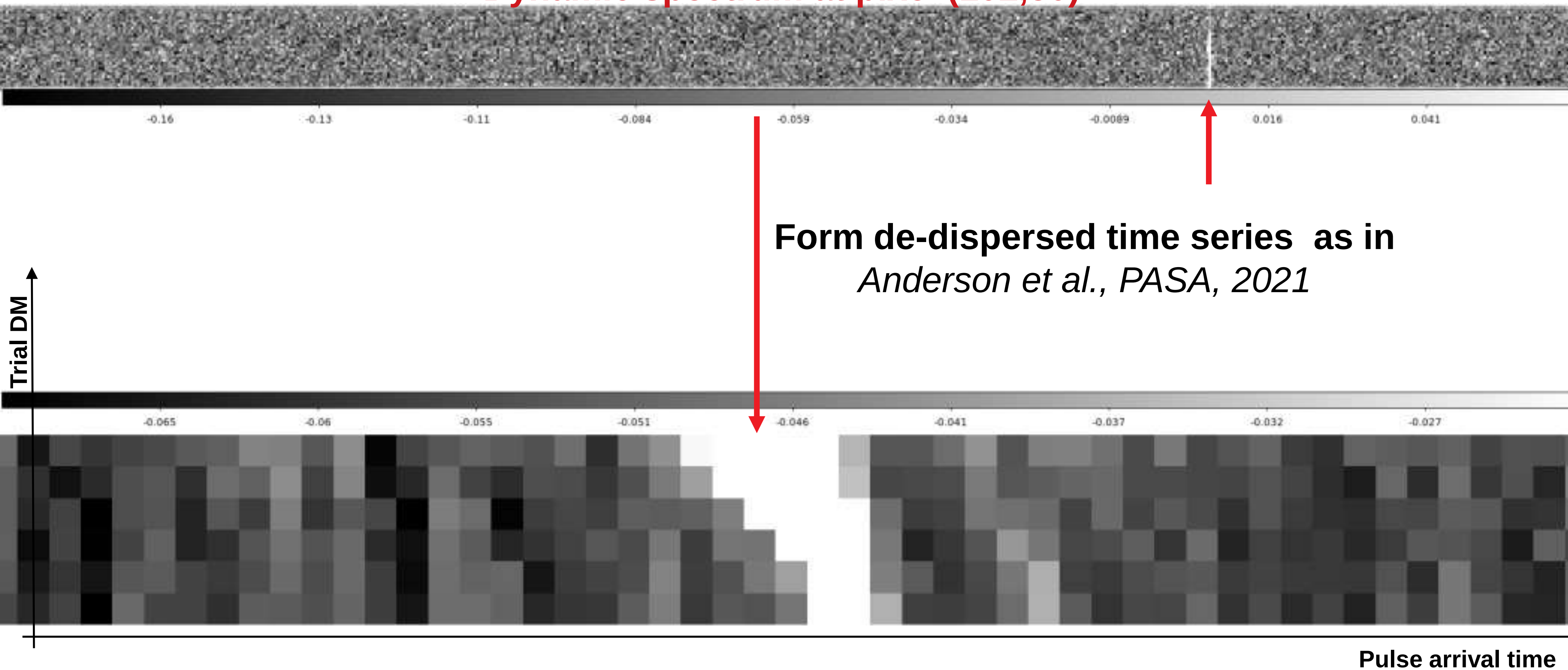
**Dynamic spectrum at pixel (102,50)**



# Pilot off-line “FRB search” on Setonix

**For every pixel above horizon - create dynamic spectrum and look for dispersed pulses ...**

**Dynamic spectrum at pixel (102,50)**

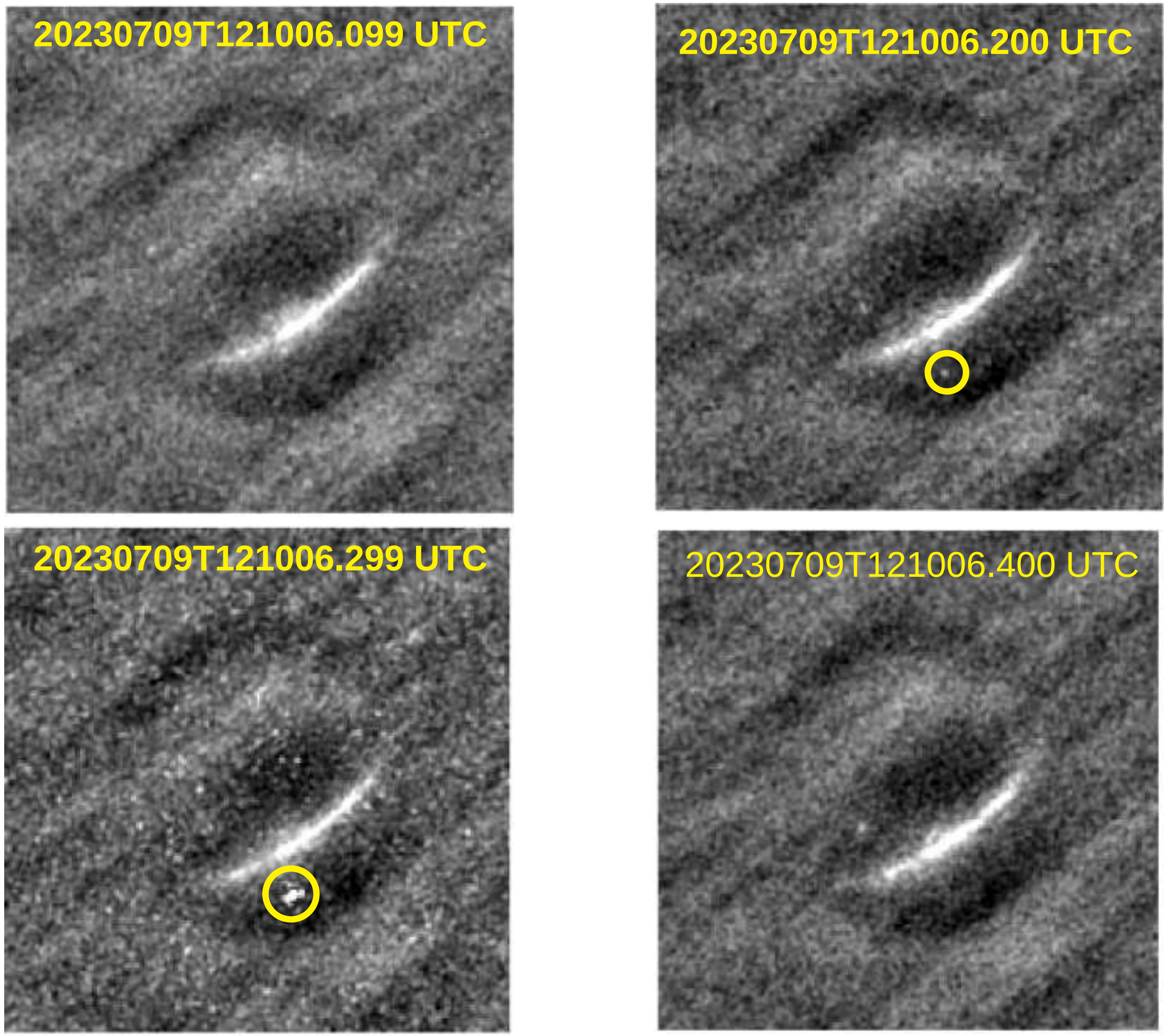



**6 DM ranges between 0 - 900 due to small BW ~ 1 MHz**

# Pilot off-line "FRB search" on Setonix

**Back to images to check what it is ?**

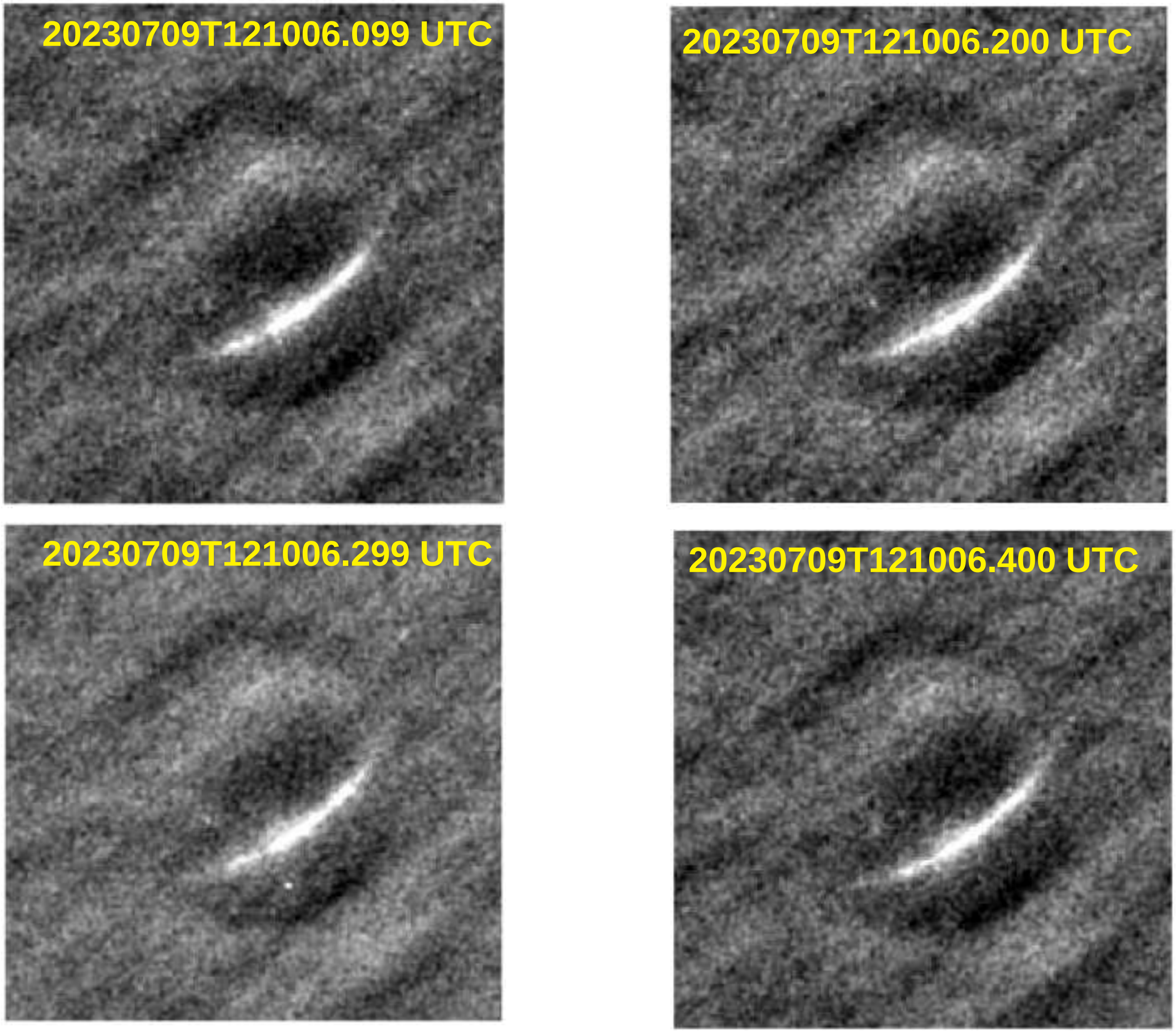
**Fine Channel 0**



# Pilot off-line “FRB search” on Setonix

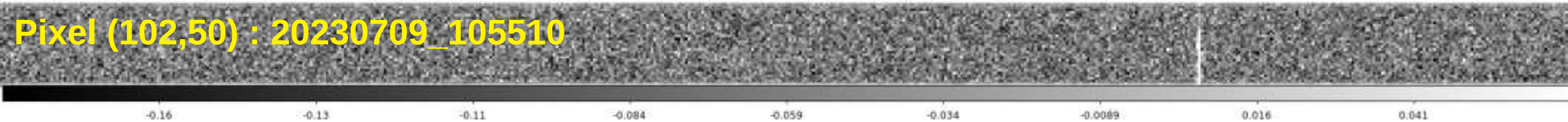
**Back to images to check what it is ?**

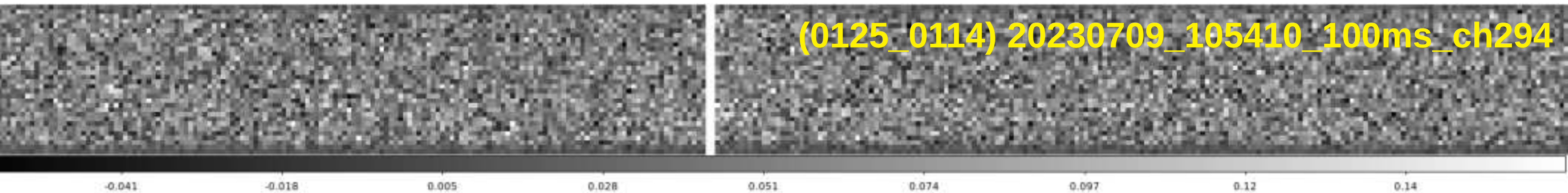
**Fine Channel 31**

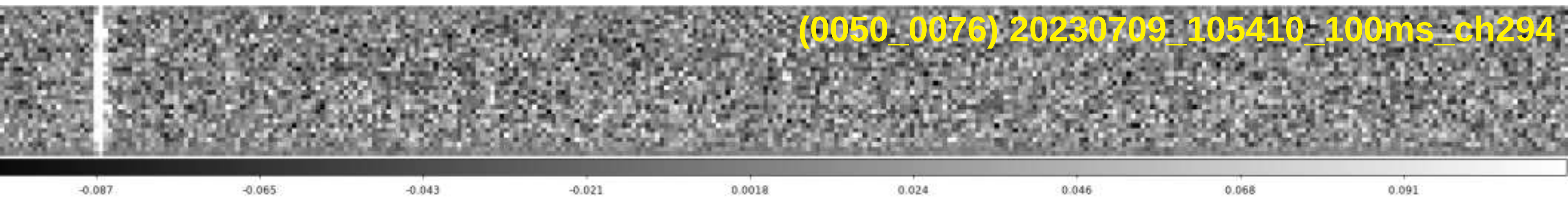


# Example of candidates (~9 in ~2 hours) : mostly similar RFI transients most likely from satellites or planes

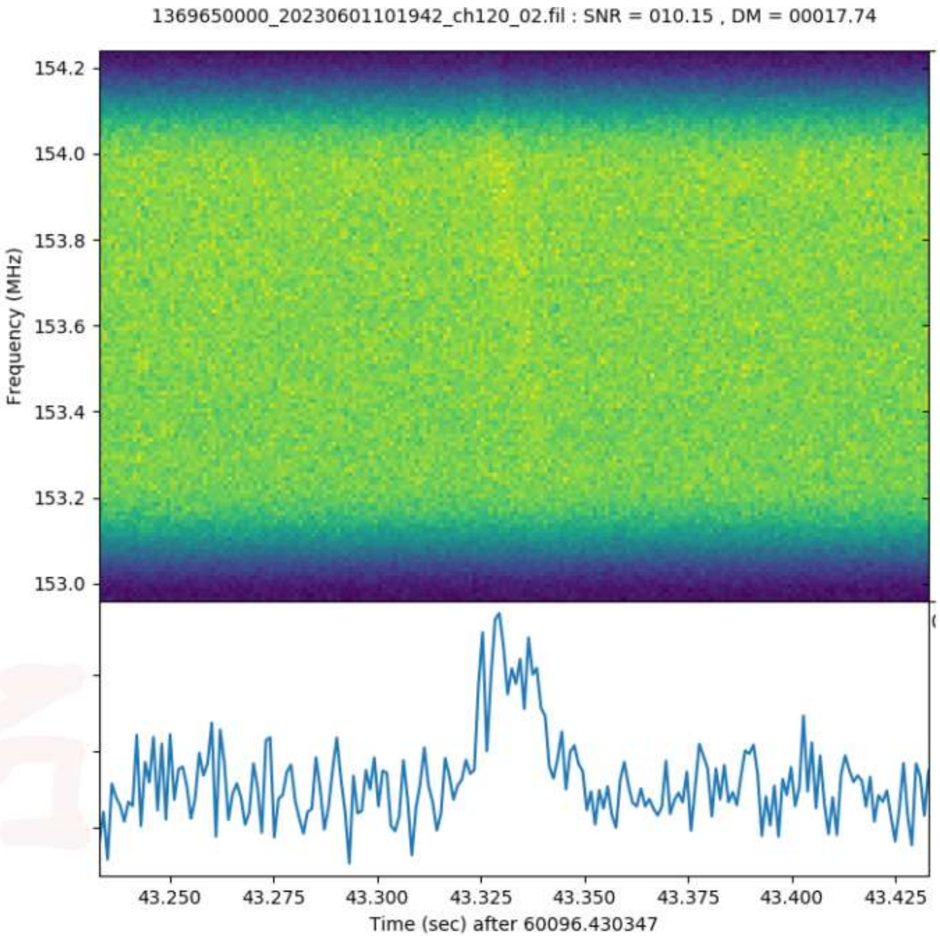
**For every pixel above horizon - create dynamic spectrum and look for dispersed pulses ...**



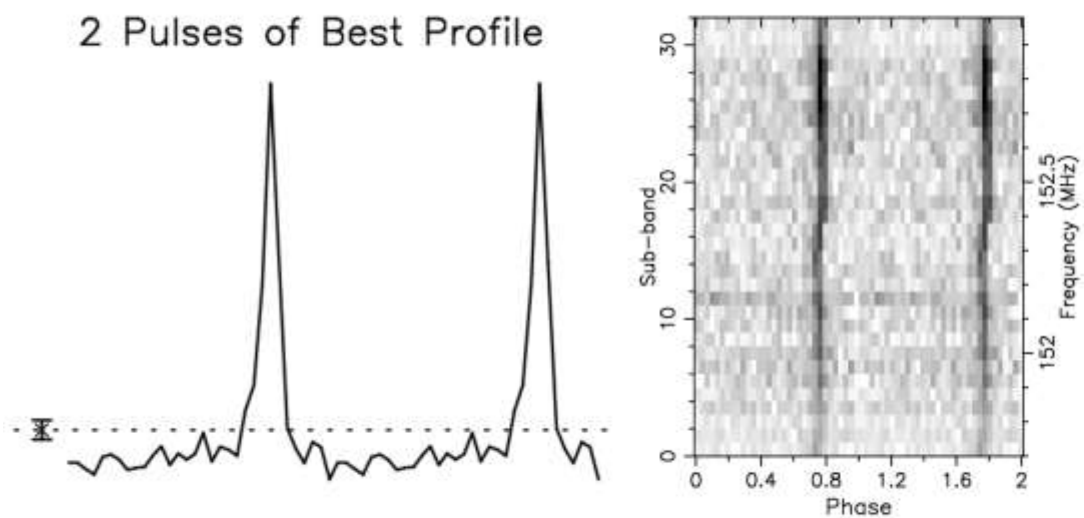



# Commensal FRB searches in the MWA incoherent beam using FREDDA ( Bannister et al., 2019)



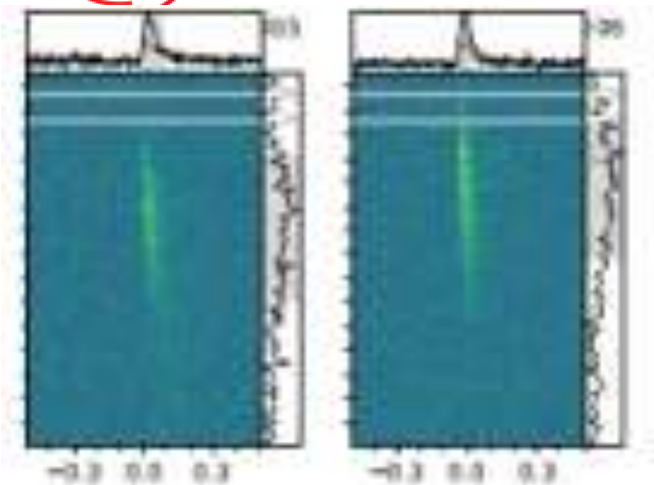

**FREDDA detection of a single pulse from the pulsar B0950+08 in 1ms time resolution**



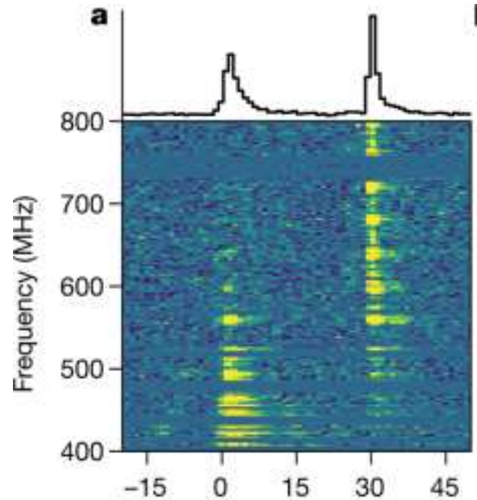

**Off-line SNR ~ 50 detection of B0950+08 in 290s at 152 MHz of real-time beamformed data in 1ms time resolution and 1.28 MHz bandwidth (single coarse channel)**

*Sokolowski et al., in preparation*

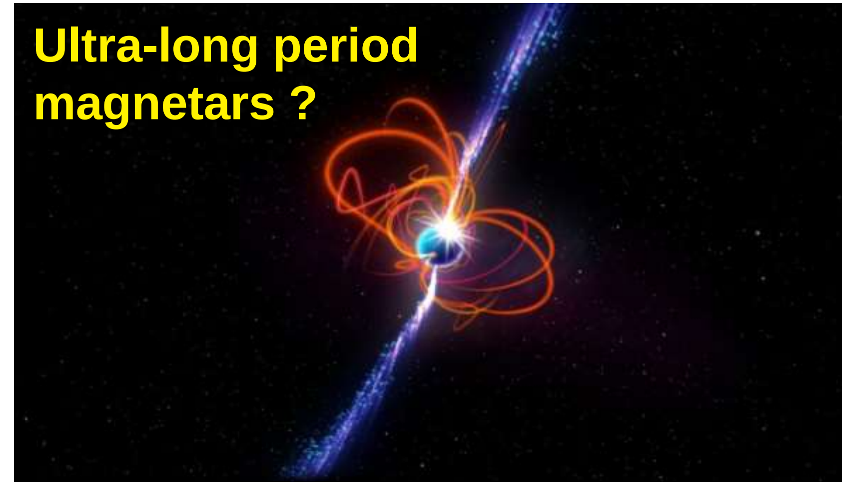
# Main targets for FRB science with the upgraded EDA2 ( CHASM'em )



How many FRBs there are at low frequencies ?



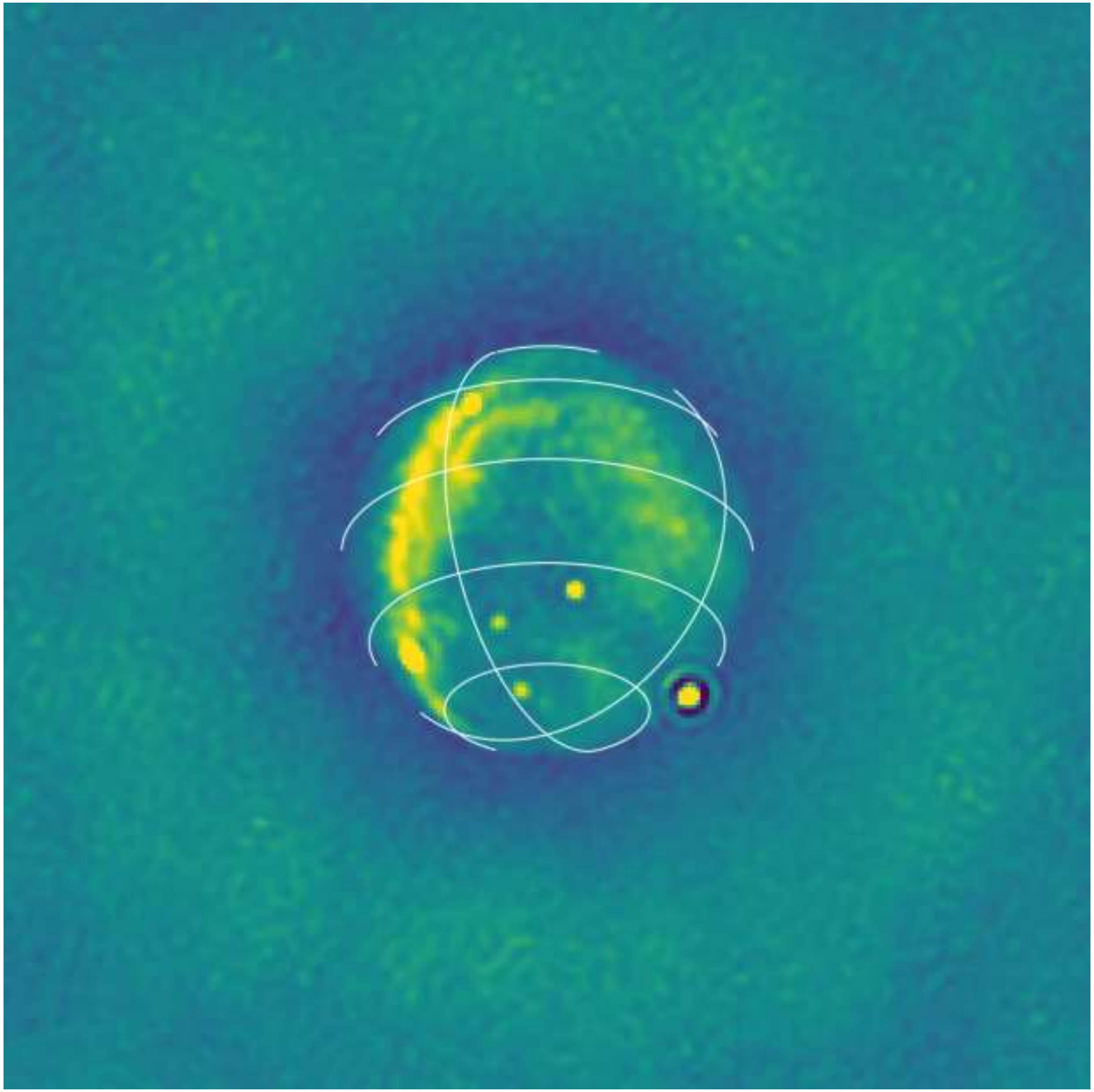

Nearby and local FRBs (like SGR 1935+2154)





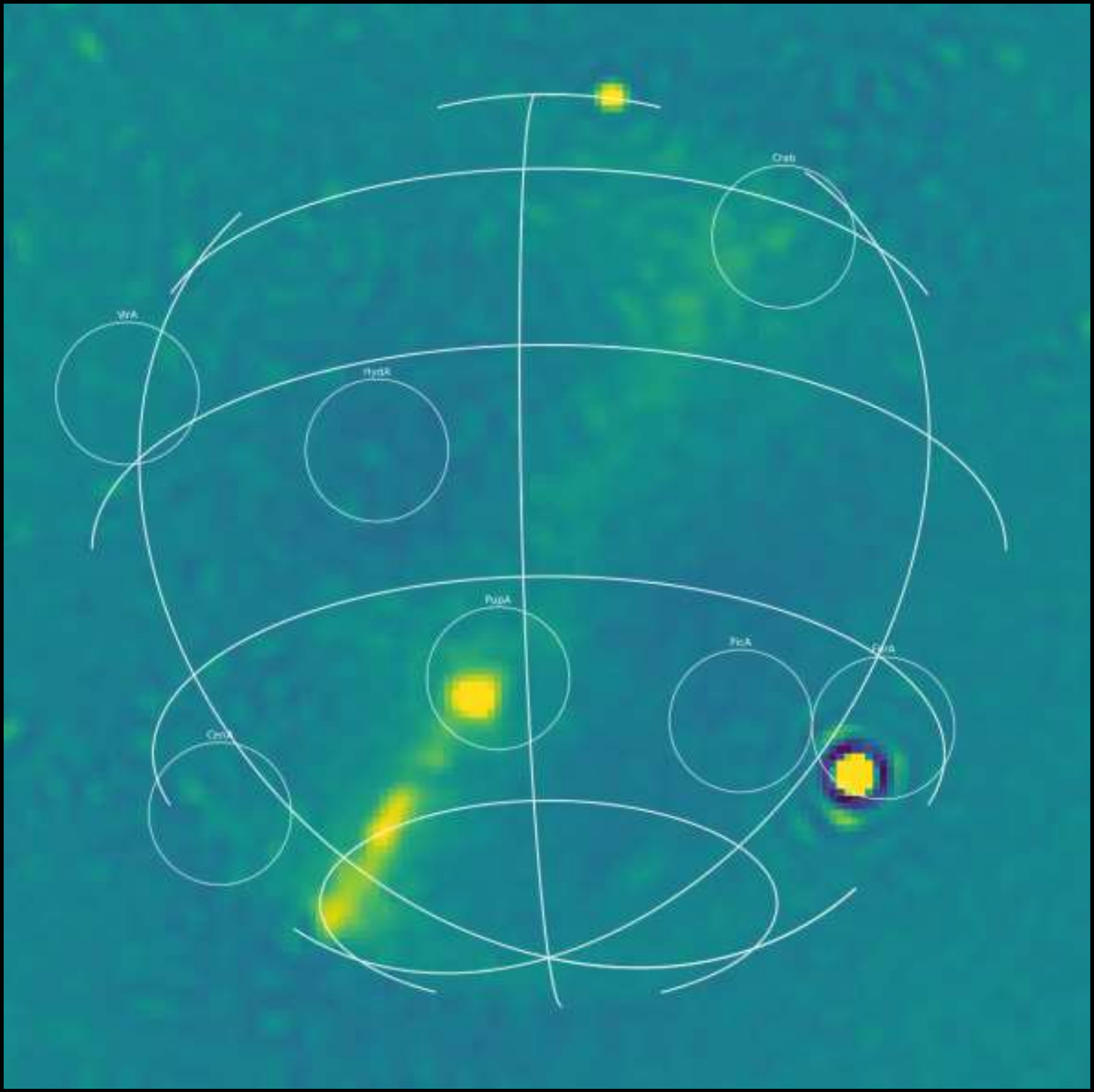

Space junk monitoring

# RFI and space debris monitoring (ISS pass at FM 98.4 MHz)

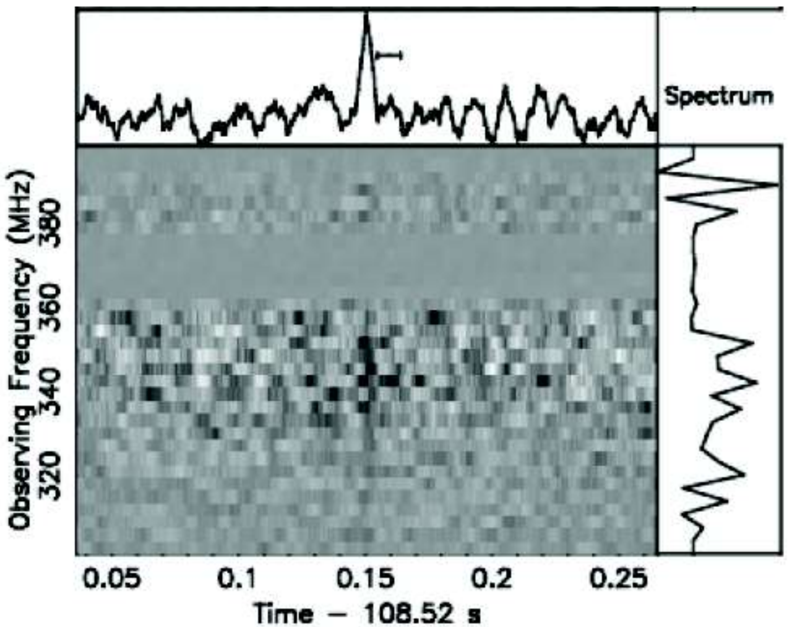


**Quiz : what frequency was EDA2 observing at ?**

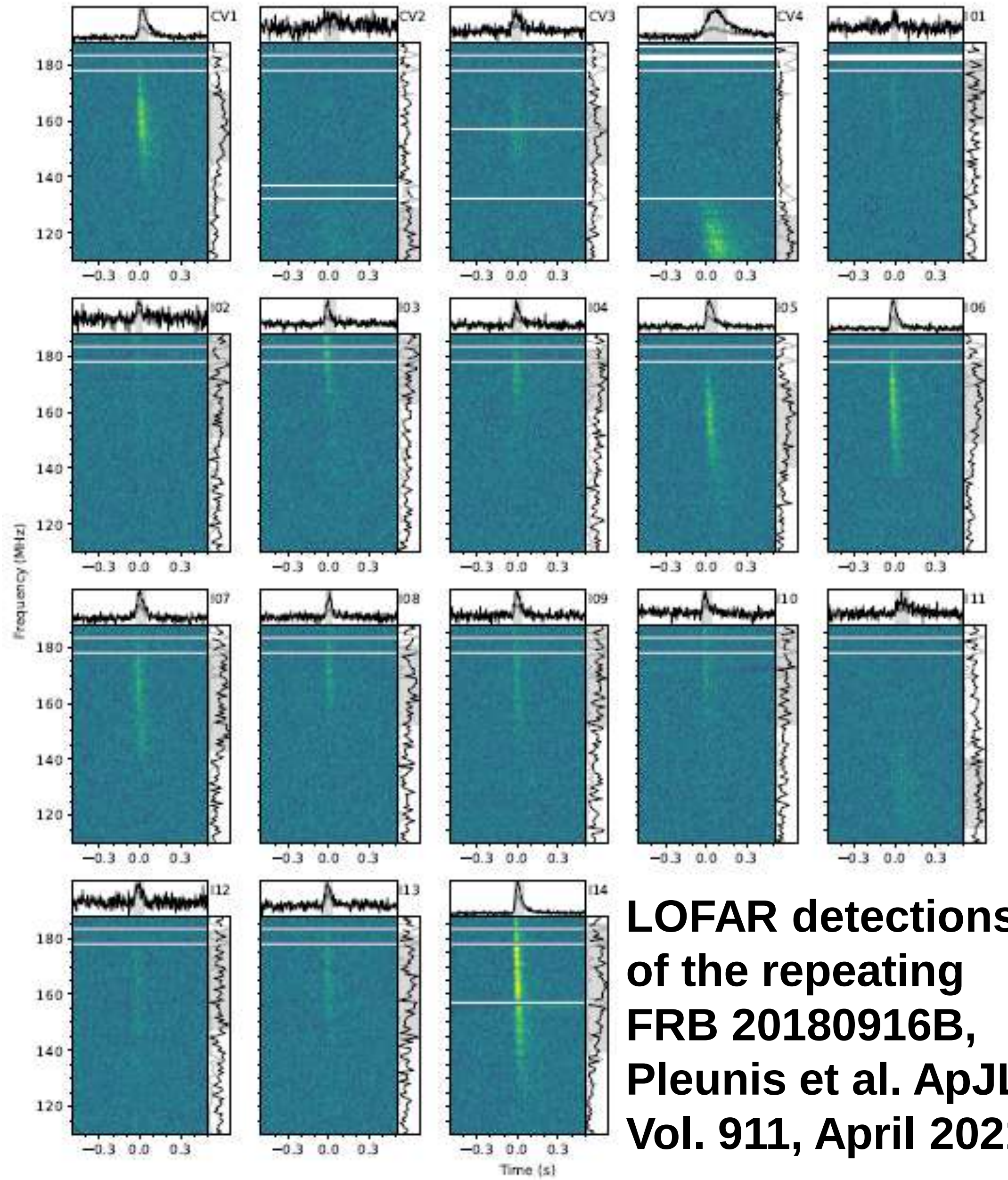
https://pollev.com/marcinsokolowski712



# Detections of FRBs and alikes at low radio-frequencies (≤ 350 MHz)




**FRB 200125A detected by GBT at 350 MHz ( Parent et al., ApJ, Dec 2020)**



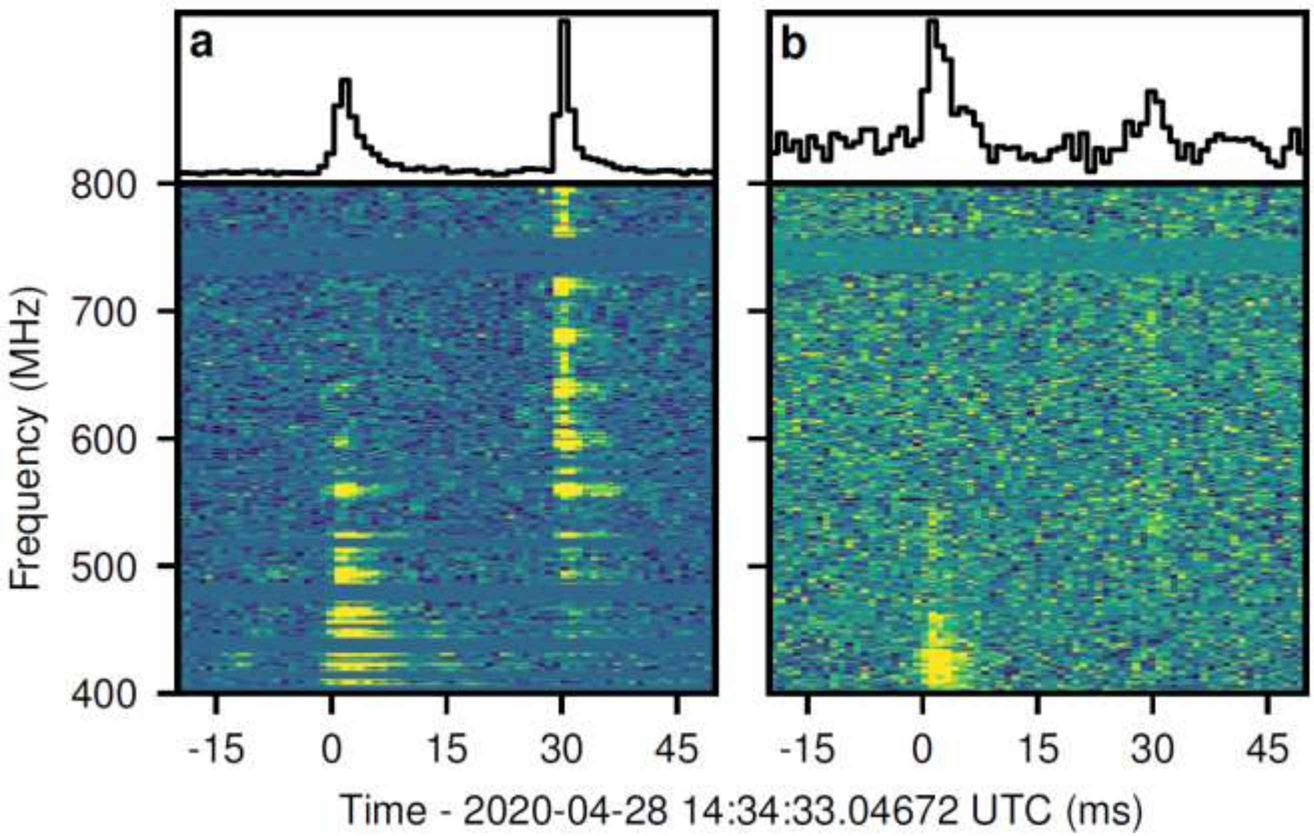

**LOFAR detections of the repeating FRB 20180916B, Pleunis et al. ApJL Vol. 911, April 2021**

Also detected by Sardinia Radio Telescope (Pilia et al. ApJL, 2020)

# Detections of Galactic Magnetar SGR 1935+2154 at DM ~ 332.7 $pc/cm^3$

**CHIME detection in 400 - 800 MHz band**

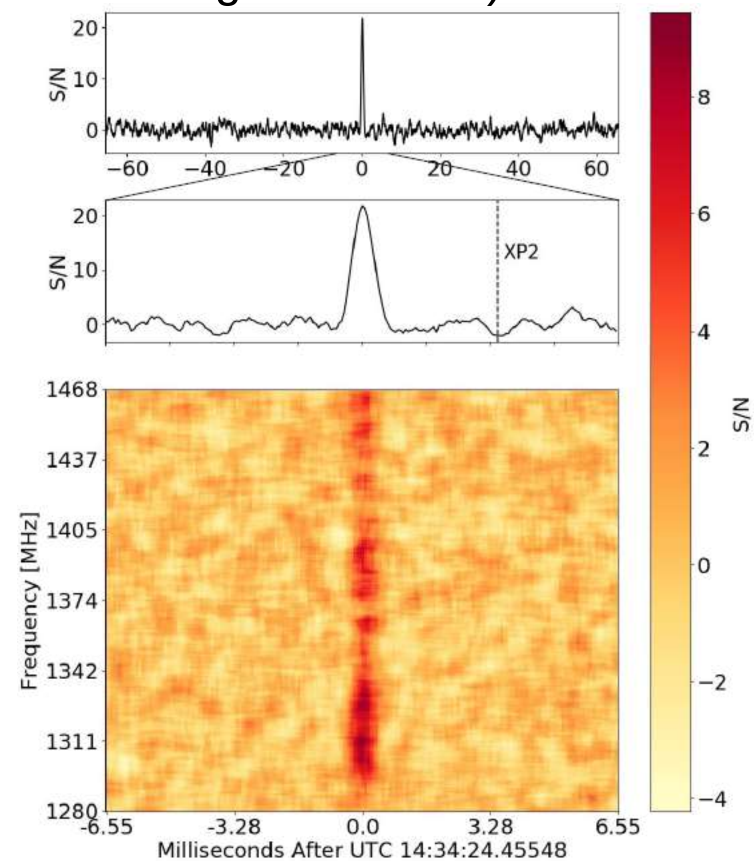
- Peak flux density 110 - 150 kJy ( fluence 220 - 480 kJy ms)
- Burst energy ~3 x $10^{34}$ erg
- Magnetars have extreme magnetic fields ~ $10^{15}$ G




*CHIME/FRB Collaboration, Nature, Vol. 587, Nov 2020*

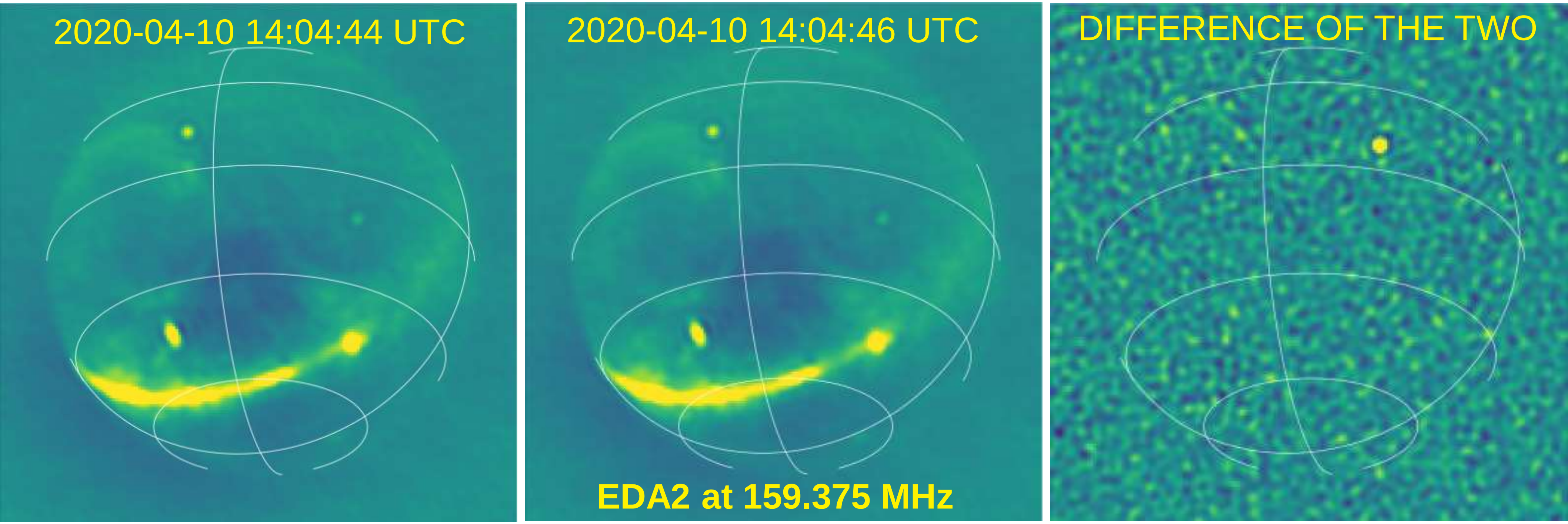
**STARE2 radio array at 1281 - 1468 MHz**

- Peak fluence ~1.5 mega-Jy ms
- Burst energy ~2.2 x $10^{35}$ erg
  (~ 40 fainter than the weakest extragalactic FRB)




Bochenek et al., Nature, Vol. 587, Nov, 2020

# Difference imaging technique was used to identify transient candidates in the 2 second all-sky images from both stations

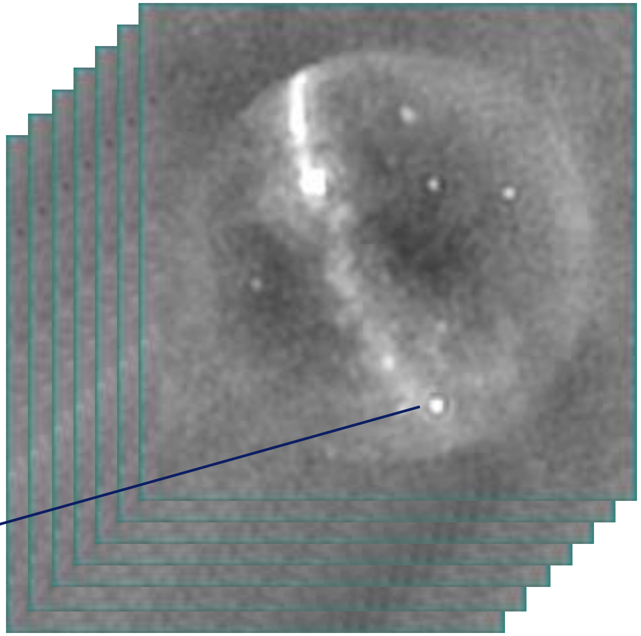


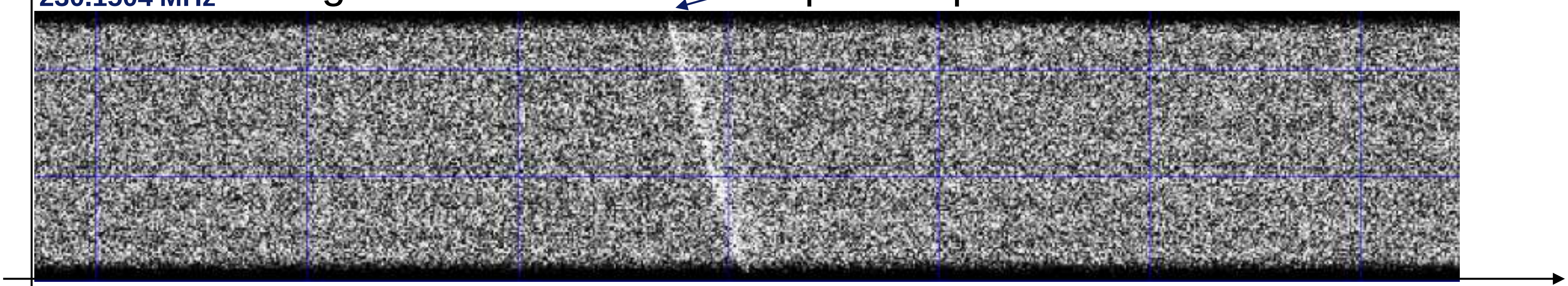

- Transient candidates identified in difference images from both stations
- Excluding regions around bright radio-sources to remove subtraction artefacts
- Time and spatial coincidence of the candidates from both stations required
- Filtering out candidates at positions known objects in the Earth orbit, airplanes, radio frequency-interference (RFI) from ground based FM and DTV transmitters

# A High-Speed All-Sky Monitor for Fast Radio Bursts and Technosignatures (CHASM)

- BW ~30 MHz imaging time resolution to ~10 ms
- **Sensitivity to FRBs by ~2 orders of magnitude to ~300 Jy ms (~ few Jy in 10ms images)**
- For DM=1000 pc/cm$^3$, 230 - 200 MHz band, e.g. dispersion delay ~ 24.7s * 0.64GB/s ~ 16 GB memory bandwidth ~1.6 TB/s for 200x200 images )
- This development will require algorithms for high-time resolution images and searches for dispersed pulses

**Time / frequency data cube**



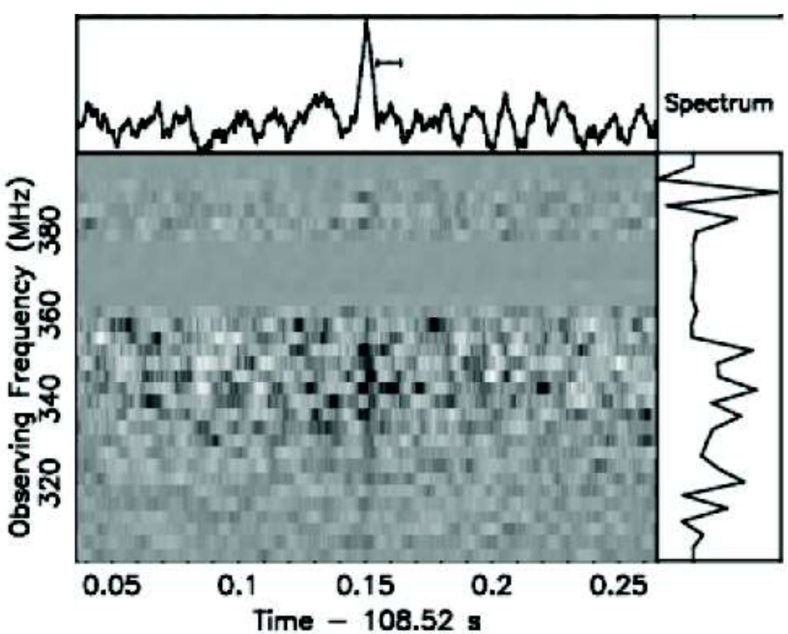



**Detection of giant pulse from Crab pulsar (B0531+21) in dynamic spectrum from EDA2 station bean data**

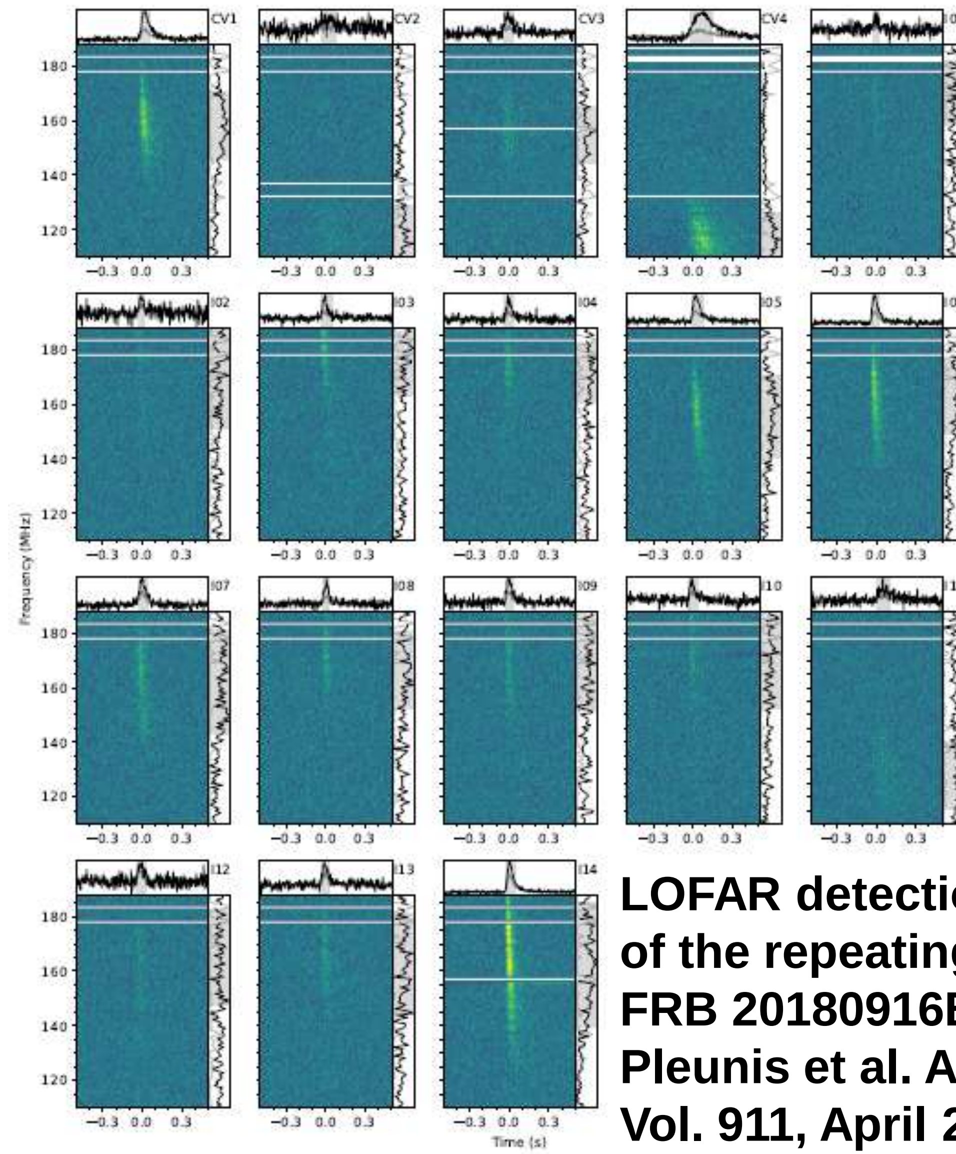
# Scattering considerations

**Low frequency FRBs are unscattered (probably selection effect), for example :**

- FRB 20180916B (Lofar FRB)
- FRB 20200125A (GBT FRB)



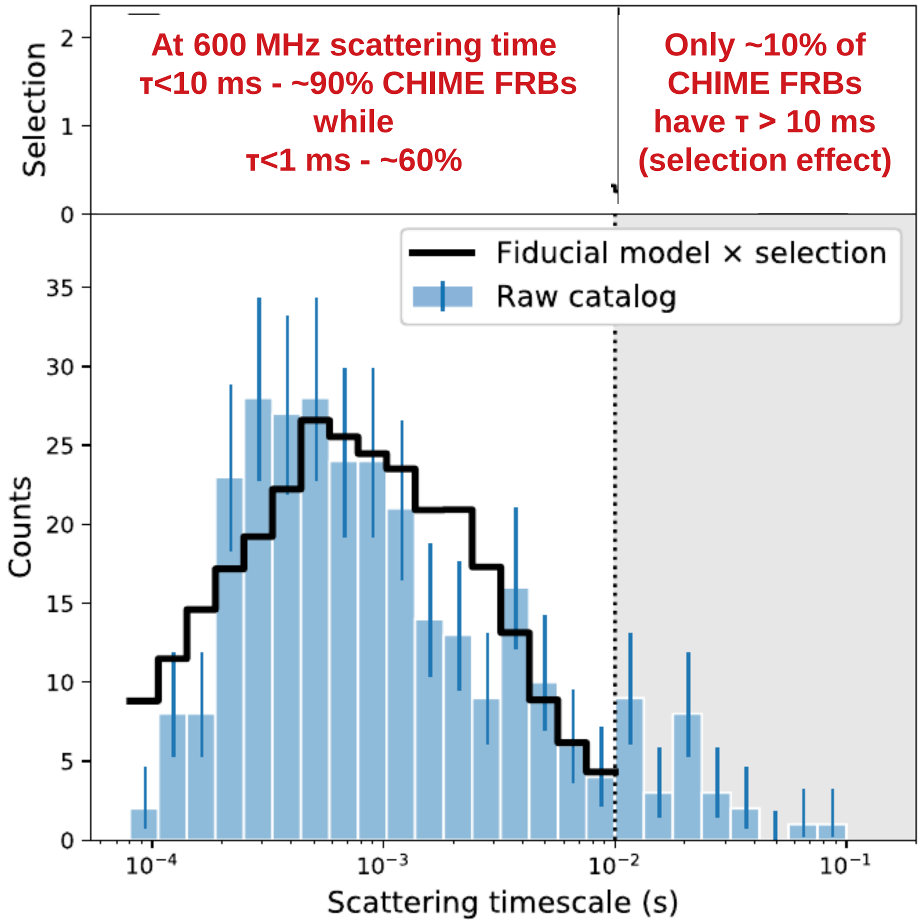

**FRB 200125A detected by GBT at 350 MHz ( Parent et al., ApJ, Dec 2020)**




**LOFAR detections of the repeating FRB 20180916B, Pleunis et al. ApJL, Vol. 911, April 2021**

# Scattering considerations

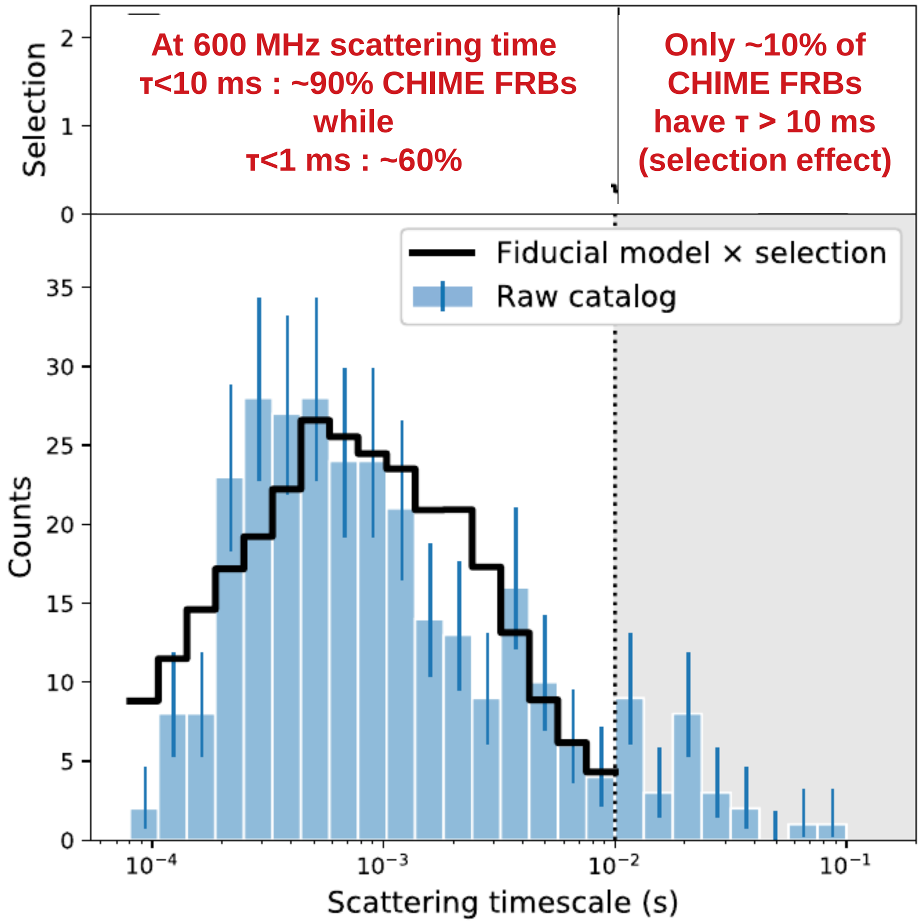
- **BASED ON CHIME FRB CATALOGUE (** ***Amiri et al. (2021)*** **) :**




| Scattering time [ms] | Fraction of FRBs (out of ~293) [ % ] |
|---|---|
| <10ms | 89.4 |
| **<1ms** | **58.7** |
| >10ms | 9.2 |

# Scattering considerations

**BASED ON CHIME FRB CATALOGUE at 600 MHz ( *Amiri et al. (2021)* ) :**



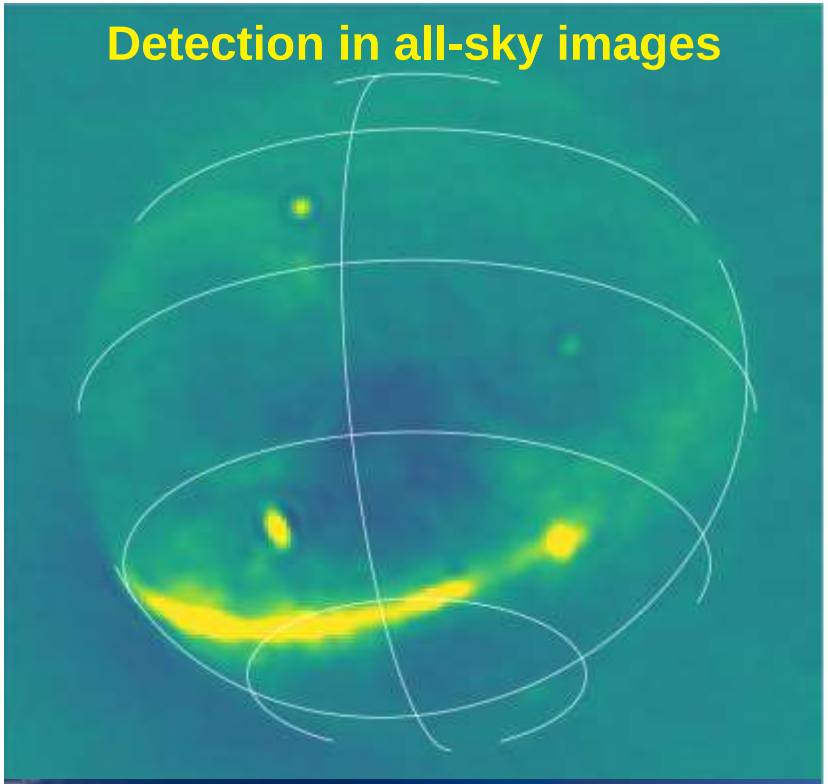

| Scattering time [ms] | Fraction of FRBs (out of ~293) [ % ] |
|---|---|
| <10ms | 89.4 |
| **<1ms** | **58.7** |
| >10ms | 9.2 |

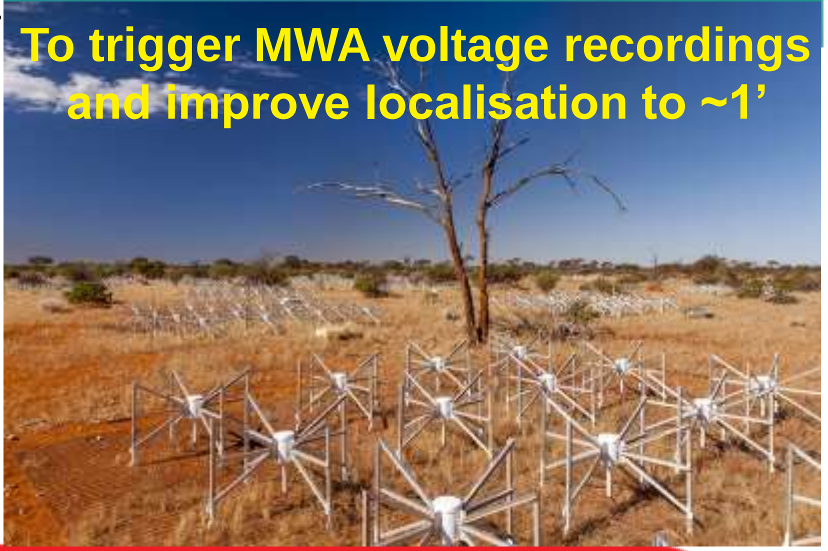
| Scattering power law index | Scattering time at 100 MHz [ms] | Scattering time at 200 MHz [ms] | Scattering time at 300 MHz [ms] | Scattering time at 350 MHz [ms] |
|---|---|---|---|---|
| -4 | 1296.0 | 81.0 | 16 | 8.63 |
| -4.4 | 2653.8 | 125.7 | 21.1 | 10.7 |
| Optimal imaging time resolution | a few seconds | ~100 - 200 ms | ~20 ms | ~10 ms |

- ~60% of CHIME FRBs with measured scattering (~293 of out 536 have scattering time <1ms
- This translates to scattering times between 10 - 130 ms at 350 and 200 MHz respectively
- Hence ~10 - 100ms time resolution is reasonable

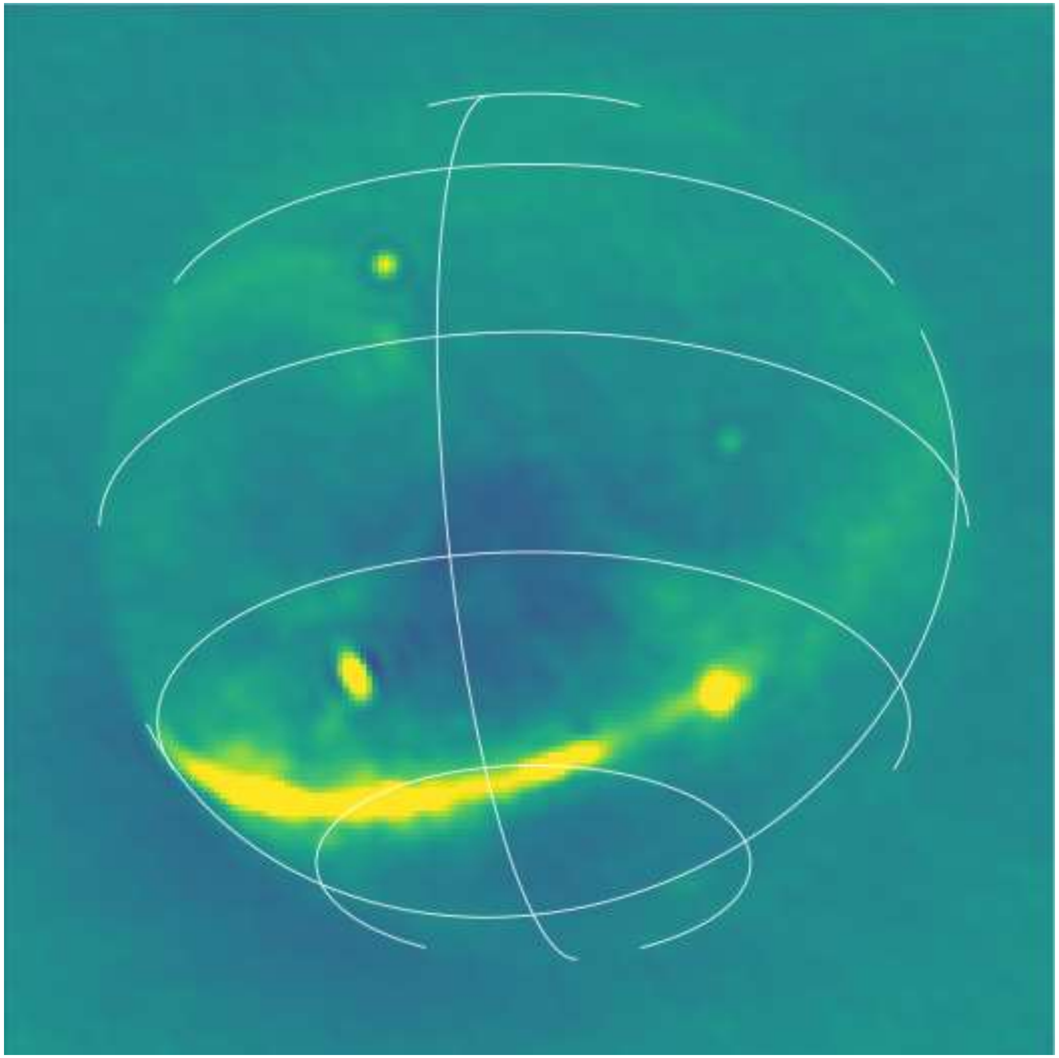
# FRB localisation with CHASM and MWA

- Localisation accuracy of all-sky images from EDA2 ~1 degree
- Detection at 300 MHz can trigger MWA high-time resolution observations at 200 MHz for example, DM=350 pc/cm$^3$ -> ~20s dispersion delay, DM=1000 pc/cm$^3$ ~60sec
  - sufficient to trigger MWA observations and refine localisations to ~1 arcmin
- Test SKA-Low station triggering capabilities using EDA2 detections to trigger AAVS2 (~15 arcmin accuracy)
- And later first SKA-Low stations improving localisation accuracy to sub-arcmin (maximim baselines a bit longer than MWA)



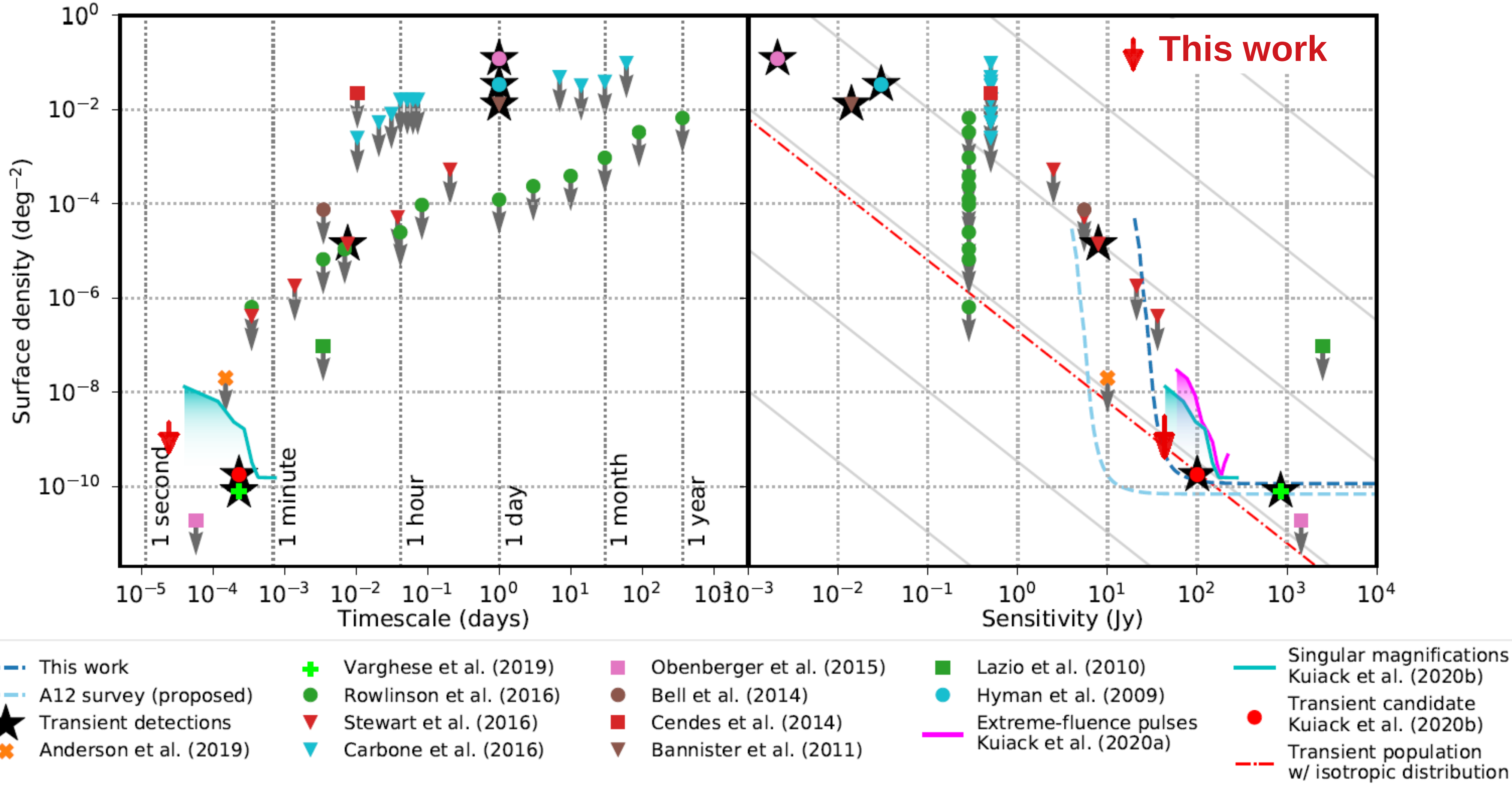



# Technosignatures with CHASM



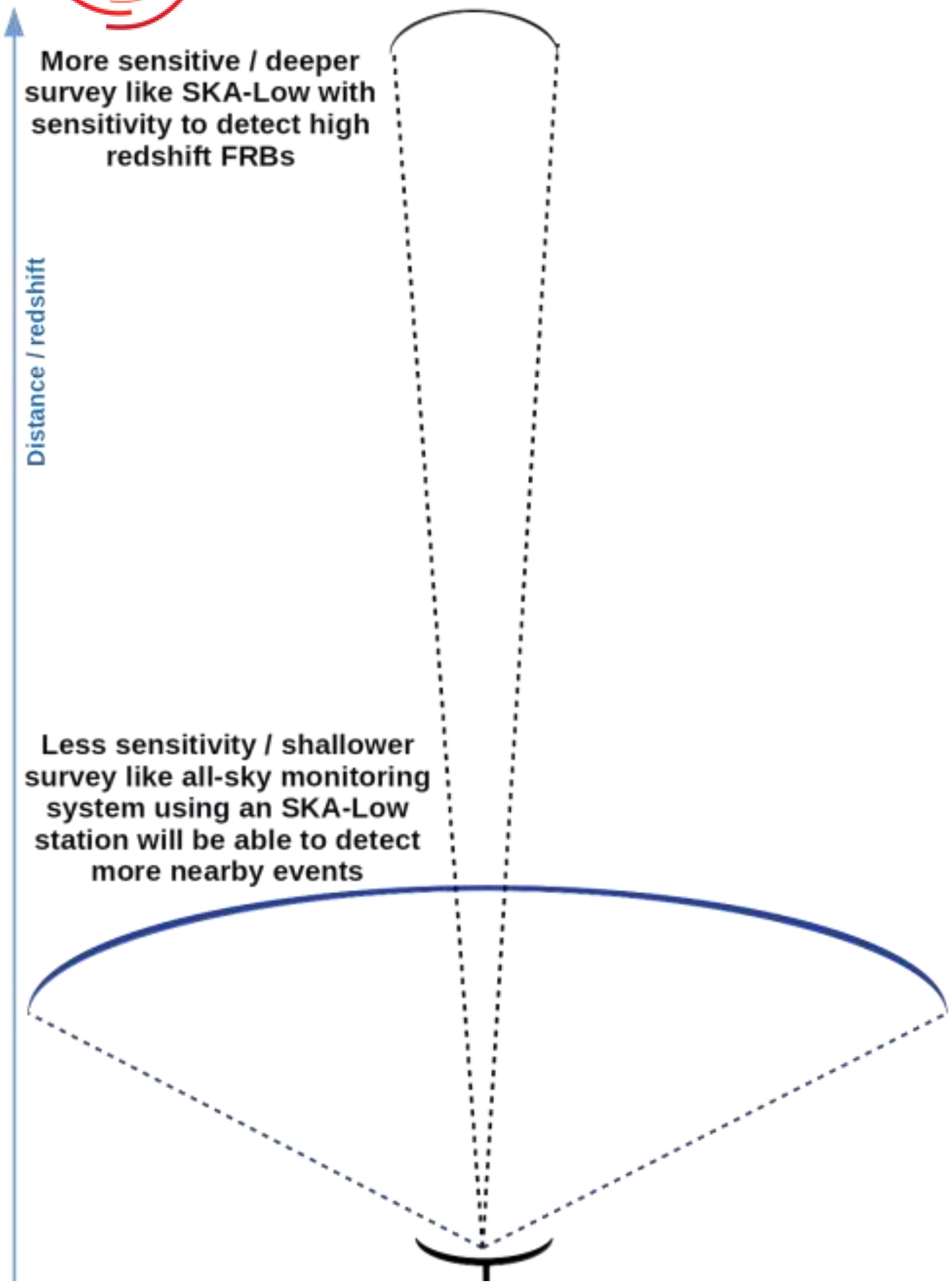
- CHASM will perform the first volume-complete SETI survey in the Southern hemisphere.
- Much less ambiguity in direction of arrival from all-sky image cubes.
- Will allow stringent constraints on periodic narrowband transmissions.
- High frequency resolution poses different challenges: data rate out of the correlator is larger than input!
- Solution is to store ‘hits’ only, or capture voltages to disk.

# Upper limit on surface density of transients vs. earlier results




*Kuiack et al. (2020) - submitted to MNRAS*

# Deeper and narrow FoV vs. shallow all-sky Fo




- **<u>FRB rate at cut-off fluence F :</u>**
  - $$R(F) = R_0 \left(\frac{F}{F_0}\right)^{\alpha}$$
- where $R_0$ is rate at the reference fluence cut-off $F_0$ and α is the source count index (see James et al. (2019)) α = -3/2 for Euclidean Universe
- **<u>SKA-Low case number of FRBs $N_{skalow}$:</u>**

$$N_{skalow} = R_{skalow} FoV_{skalow} \propto \sigma_{skalow}^{\alpha} \left(\frac{\lambda}{D}\right)^2$$

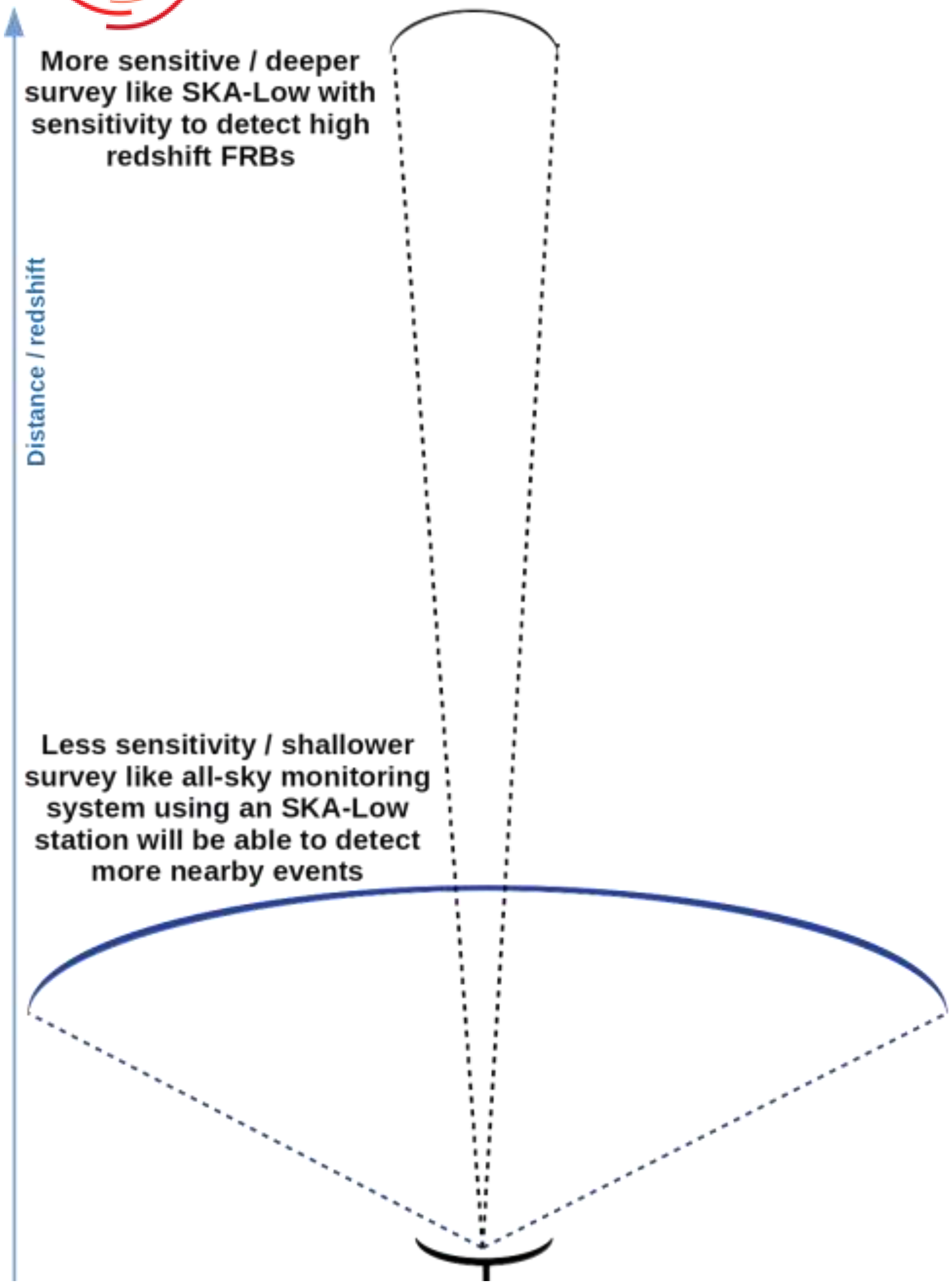
- **<u>Single SKA-Low station (st) case $N_{st}$ :</u>**

$$N_{st} = R_{st} FoV_{st} \propto 2\pi\sigma_{st}^{\alpha}$$

- **<u>Ratio between number of detections :</u>**

$$\frac{N_{skalow}}{N_{st}} = \left(\frac{\sigma_{skalow}}{\sigma_{st}}\right)^{\alpha} \frac{(\lambda/D)^2}{2\pi}$$

# Deeper and narrow FoV vs. shallow all-sky Fo




- **<u>Ratio between number of detections :</u>**

$$\frac{N_{skalow}}{N_{st}} = \left(\frac{\sigma_{skalow}}{\sigma_{st}}\right)^{\alpha} \frac{(\lambda/D)^2}{2\pi}$$

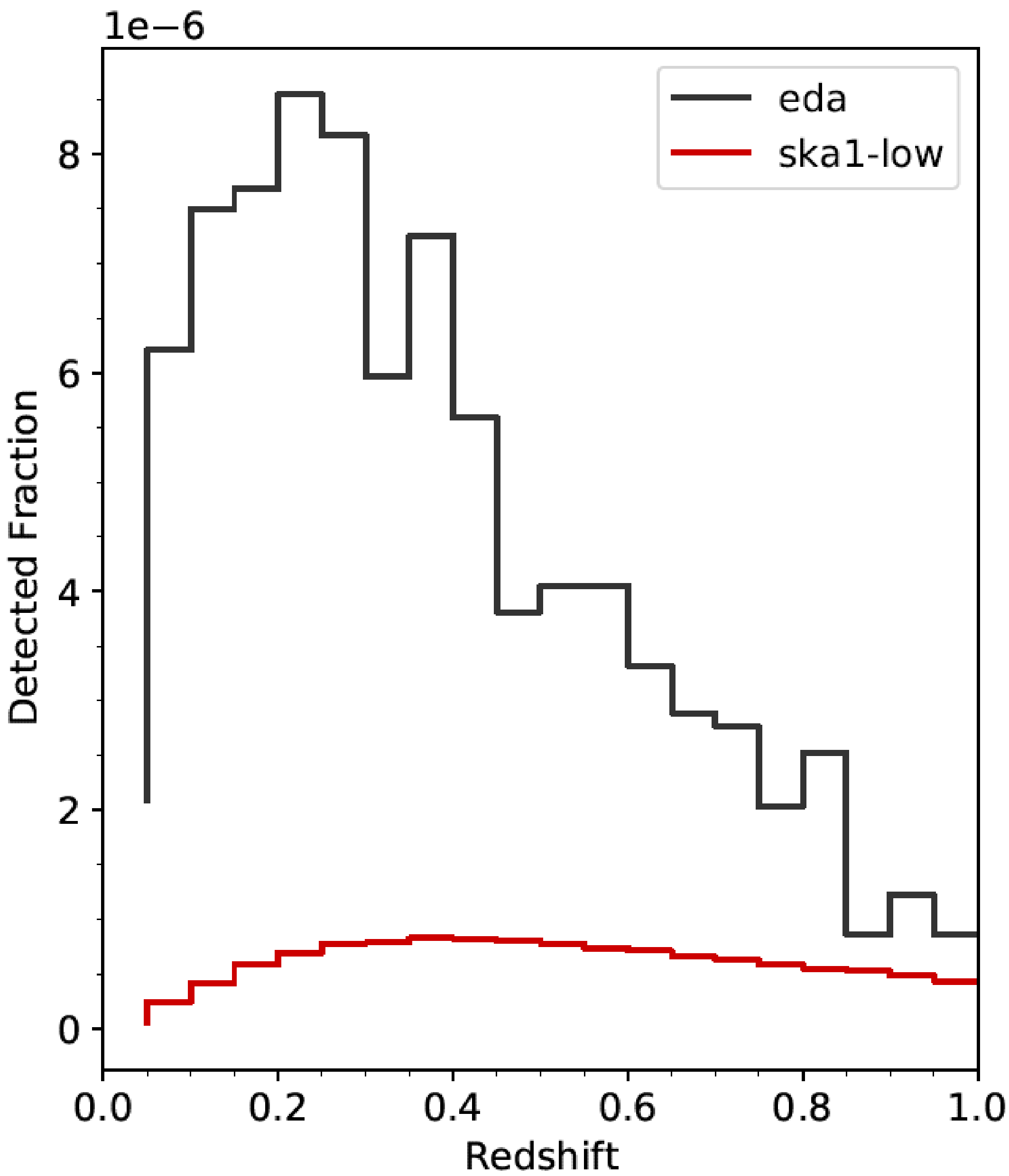
- where station diameter D=35m, λ=2m (at 150 MHz), and $\sigma_{skalow} = \sigma_{st} / N_{st}$ and hence :

$$r = \frac{N_{skalow}}{N_{st}} \approx 0.00051969 N_{st}^{-\alpha}$$

- With $N_{st}$ = 512 the ratio depends on source count index α , considering three cases :
  - **α = -2.2** (Shannon et al. (2018)) : r ~ 474
  - **α = -1.5** (Euclidean) : r ~ 6
  - **α = -1.18** (James et al.(2019)) : r ~ 0.82
  - **α = -1.00** : r ~ 0.27

- Single SKA-Low station can detect more FRBs for shallower source count distribution

# FRBpoppy predictions for SKA-Low station and SKA1-Low telescope




- We used **frbpoppy** (Gardenier et al) to simulate FRB surveys with the EDA2 and the full SKA1-low.
- In the SKA1-low, each station will be beamformed, limiting its field of view, then all stations correlated together.
- Surprisingly, a single SKA1-low station used as an all-sky system detects far more (nearby) FRBs than the narrow FoV SKA1-Low telescope.

# Establishing FRB rates with CHASM

- **LOFAR (Pastor-Marazuela et al., 2020)**
  Rate 3 – 450 FRBs/sky/day at fluence ≥50 Jy ms

- **GBT (Parent et al., 2020) :** $3400_{-3300}^{+15400}$
  FRBs/sky/day at fluence ≥0.42 Jy ms
  Scaled to fluence ≥50 Jy ms : $2.6^{+12}_{-2.5}$ FRBs/day/sky

  - Rate 3400 corresponds to: 2.6 FRBs/sky/day
  - Rate+1sigma → ~15 FRBs/sky/day
  - Rate+3sigma (49600 FRBs/sky/day) → ~38 FRBs/sky/day

  **Estimated low-frequency FRB rate ~ 3 - 38 FRBs / sky / day**

- Shannon et al. (2018) rate ~9 FRBs/sky/day **at fluence ≥50 Jy ms**

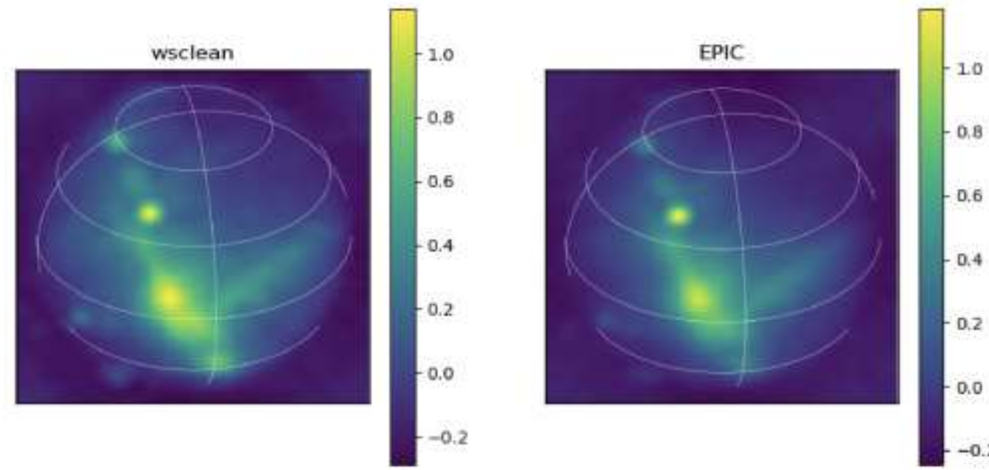
- **SKA-Low Station SEFD ~ 2500 Jy**

- Minimum observed elevation ~20$^{o}$ (might be relaxed)

- **Expected number of 10σ (≥ 200 Jy ms) detections : 10s - 100s / year**

# Leverage new algorithms + software

100 GbE + SPEAD2 + Infiniband verbs




E-field Parallel Imaging Correlator (EPIC)


Tensor core correlator

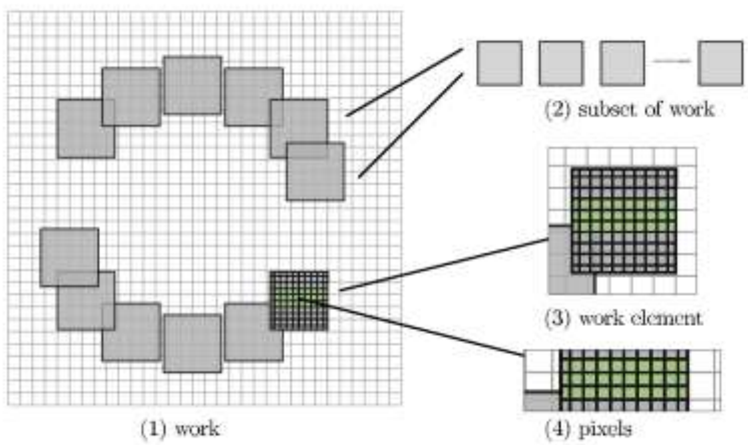
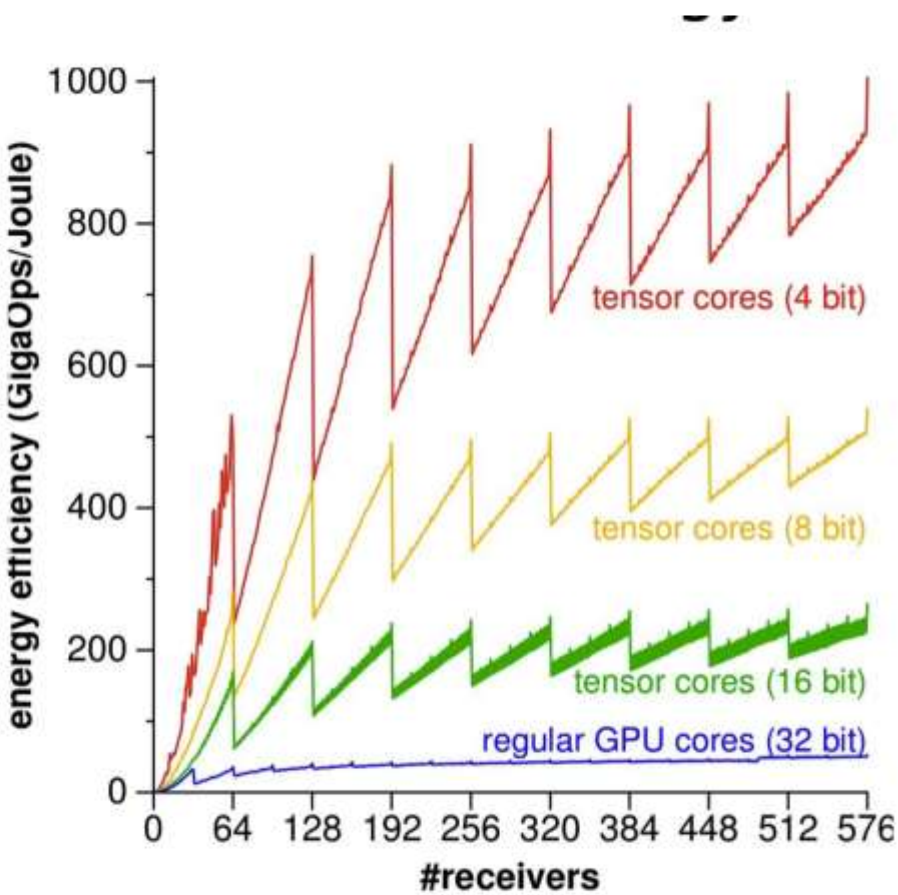



Image-domain gridding (IDG)

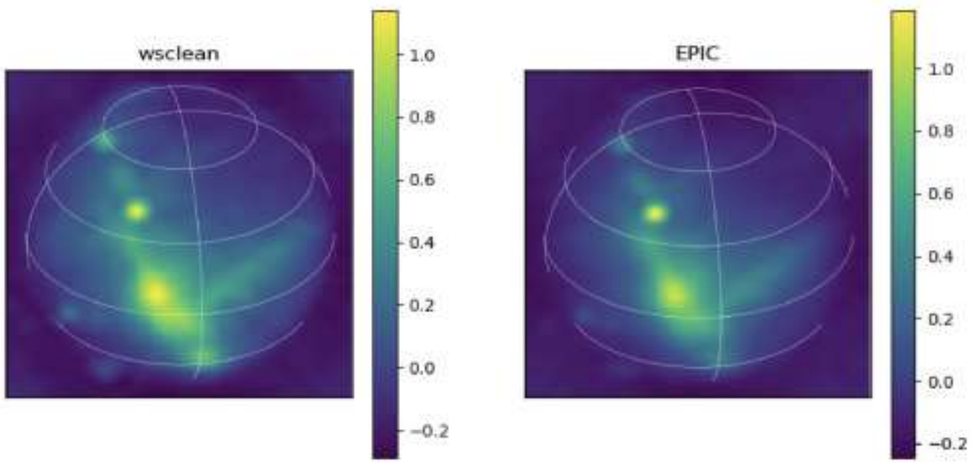
# Tensor Core Correlator




- Tensor cores (low-bitwidth instructions) have been added to NVIDIA GPUs as they are useful for deep learning.
- Romein (2020) showed dramatic improvement over floating-point (xGPU) correlator.
- 5-20x performance achievable over previous xGPU code by using tensor cores.

https://osf.io/b5se9/

# E-field Parallel Imaging Correlator (EPIC)

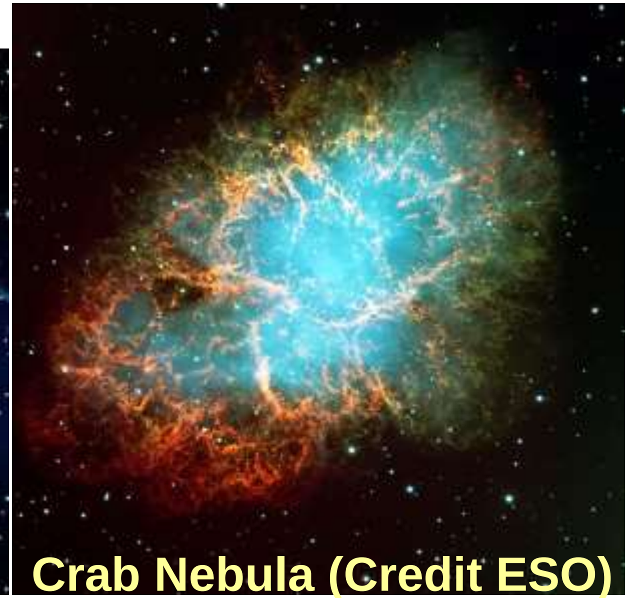


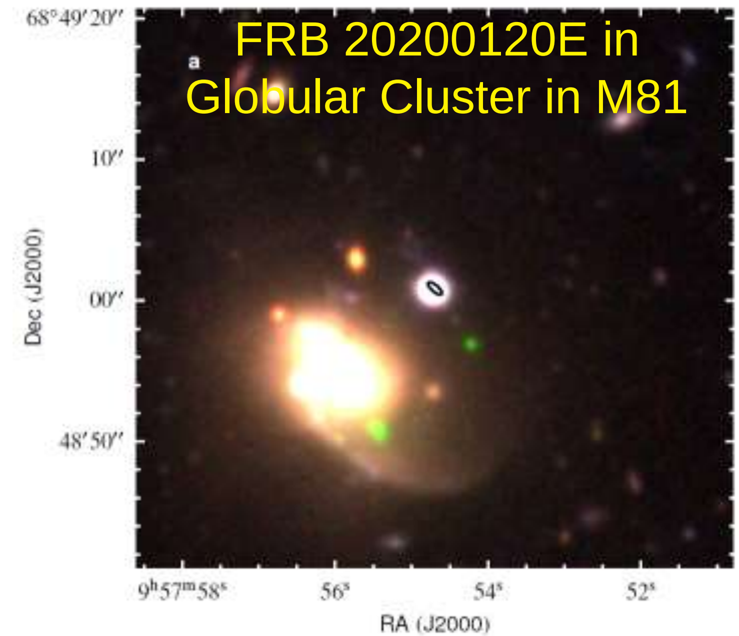

- For dense arrays, it can be computationally advantageous to skip antenna cross-correlation and go straight to images.
- EPIC algorithm brings imaging cost to *O(N log N)*, (from *O($N^2$)* for correlator)
  - Thyagarajan et al (2017)
  - Kent et al (2019)
  - Kent et al (2020)
- Already demonstrated an EPIC-based realtime 80 ms imaging pipeline at LWA-SV, using Bifrost pipeline.

https://github.com/epic-astronomy/LWA_EPIC

# FRB theoretical models


Artist's impression of a magnetar (Credit ESO)


Crab Nebula (Credit ESO)



FRB 20200120E in Globular Cluster in M81

- Young mili-second magnetars (neutron stars with extremely powerful magnetic fields ~ $10^{14}$ - $10^{15}$ Gauss) in dense environments (Metzger at al 2017)

- Giant pulses from young pulsars in nearby galaxies (Connor at al. 2016; Cordes & Wasserman 2016, Maijd at al. 2021)

- Binary neutron stars mergers (Totani 2016)

# Future upgrade

- Milli-second time resolutions (we can already get 0.1s images off-line)

- ~50 MHz bandwidth

- Observe 24/7

- Detect FRBs at low-frequencies !

- Other science cases :
  - Pulsars
  - Transients in general (Gamma-ray bursts, magnetars, gravitational wave events etc.)
  - Techno-signatures (Danny Price)
  - Cosmic-rays
  - Globel Epoch of Re-ionisation (see McKinley et al. (2020))
  - RFI monitoring
  - Space debris , Space Situational Awareness

# Earlier “blind” FRB surveys at low-frequencies

Table 1: Summary of non-targeted wide-field FRB searches conducted with various low-frequency telescopes around the world sorted from most sensitive to least. Parent et al. (2020) detected one FRB (1$^{st}$ line), and other surveys resulted in upper limits based on their detection thresholds.

| Reference | T[c] | Frequency range [MHz] | Sensitivity [Jy ms] | Timescale [ms] | Band-width [MHz] | FoV [deg$^2$] | Obs. Time [days] | DM range [pc cm$^{-3}$] |
|---|---|---|---|---|---|---|---|---|
| Parent et al. (2020) | G | 350 | 1.26 | 0.08192 | 100 | 0.27 | 173.6 | <3000 |
| Rajwade et al. (2020) | J | 332 | 46 | 0.256 | 64 | 0.61 | 58 | <1000 |
| Coenen et al. (2014) | L | 140 | 71[a] | 0.66 | 6 | 75 | 9.7 | <3000 |
| **CHASM (this proposal)** | C | 50 – 350 | 200 | 10 | 40 | 12000[b] | - | <1500[b] |
| Karastergiou et al. (2015) | L | 145 | 310 | 5 | 6 | 24 | 60.25 | <320 |
| Tingay et al. (2015) | M | 139 – 170 | 700 | 2000 | 30.72 | 610 | 0.44 | 170 – 675 |
| Rowlinson et al. (2016) | M | 170 – 200 | 223500 | 28000 | 30.72 | 452 | 3.3 | <700 |

[a] these surveys provided sensitivity in Jy and in these cases we converted them to Jy ms to be directly comparable.
[b] above elevation 25°, the preliminary DM upper limit is based on results of the FRBPOPPY simulations (Gardenier et al., 2021)
[c] Telescopes: G - GBT (100 m), J - Lovell telescope at Jodrell Bank (76 m), L - LOFAR, M - MWA (~60 m), C - this proposal (34 m at 100 MHz and 20 m at 200 MHz). The values in brackets are dish diameters or equivalent for the aperture arrays.