Pulsar surveys with the GMRT

Metre-wavelength Sky-II conference
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NCRA • TIFR

Why do we care?

Already ~2600 pulsars including ~360 millisecond pulsars known
Predicted pulsar population ~10^5, 1% of which is known

- ✓ To probe Galactic neutron star populations
- ✓ Discovery of interesting individual objects for probing gravity in strong field regime (e.g. double pulsar testing GR, triple pulsar J0337+1715 testing universality of free-fall)
- ✓ Probing the recycling process of Radio MSPs with Low-mass X-ray Binary and Millisecond pulsar transitioning systems
  (e.g. J1227-4853 discovered by GMRT; Roy et al. 2015)
- ✓ Probing interaction between pulsars and companion in compact binaries in special evolutionary stage (e.g. J1544+4937 discovered by GMRT; Bhattacharyya et al. 2013)

Discovery of new pulsars limited by three factors

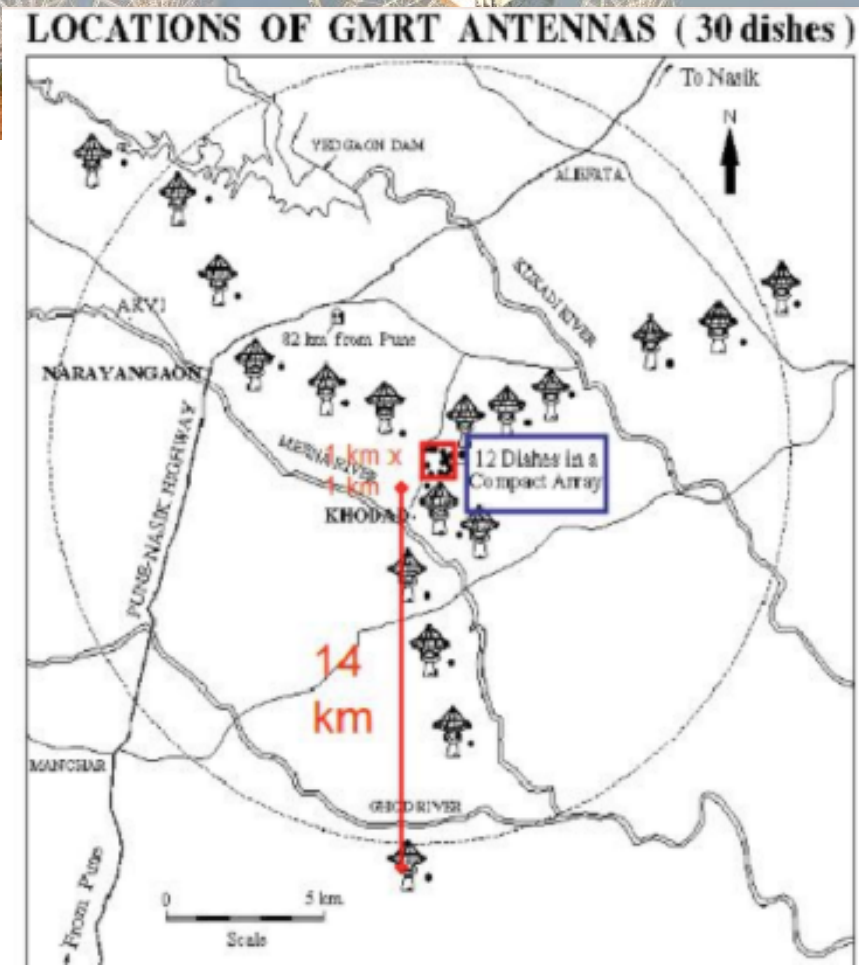
Sensitivity of survey

Available Compute power

Analysis technique

Why GMRT?

Time domain study with GMRT



✓ Largest array in metre-wavelengths:
GMRT is a radio interferometer with
30 antennas each of 45 m diameter

✓ Low radio frequency coverage

Band1: 120-240 MHz, Band2: 250-500 MHz,
Band3: 550-850 MHz, Band4: 1000-1460 MHz
Benefitted by spectra

✓ Pulsar surveys benefitted by wide field of view at low frequencies:

Simultaneous dual beam: incoherent beam with HPBW ~ 80'
coherent beam with HPBW~ 1'

Why GMRT?

Time domain study with GMRT

SMART (Stretched Mesh Attached to Rope Trusses)
Design of GMRT antennas allowing sensitive observations

- ✓ Sensitivity (Band width up to 400 MHz)

incoherent beam with **0.3 mJy** @ 200 MHz band width @10 mins
coherent beam with **0.1 mJy** @ 200 MHz band width @ 10 mins

- ✓ Post discovery precise localisation in the image plane and simultaneous time-domain and imaging study

Targeted and Blind searches with GMRT

Two popular ways to search for pulsars

- ✓ *Targeted search* : With a priori knowledge of position
  - Globular cluster (1 MSP) : Freire et al. 2004
  - Supernovae remnants (1 pulsar) : Gupta et al. 2005
  - **High energy sources (8 MSPs)** : Bhattacharyya et al. 2013

↓

Fermi directed targeted searches

- ✓ *Blind search* : Without a priori knowledge of position
  - ➢ 610 MHz Galactic plane (3 pulsars) : Joshi et al. 2009
  - ➢ **322 MHz off-Galactic plane (18 pulsars, including 2 MSPs)**: Bhattacharyya et al. 2016, 2019

↓

GHRSS survey :
GMRT High Resolution Southern Sky survey for pulsars and transients

Targeted search: Fermi directed searches with GMRT

Team: Bhattacharyya, Roy, Ray, Gupta, Bhattacharya, Ferrara +PSC

Discoveries from Fermi directed survey

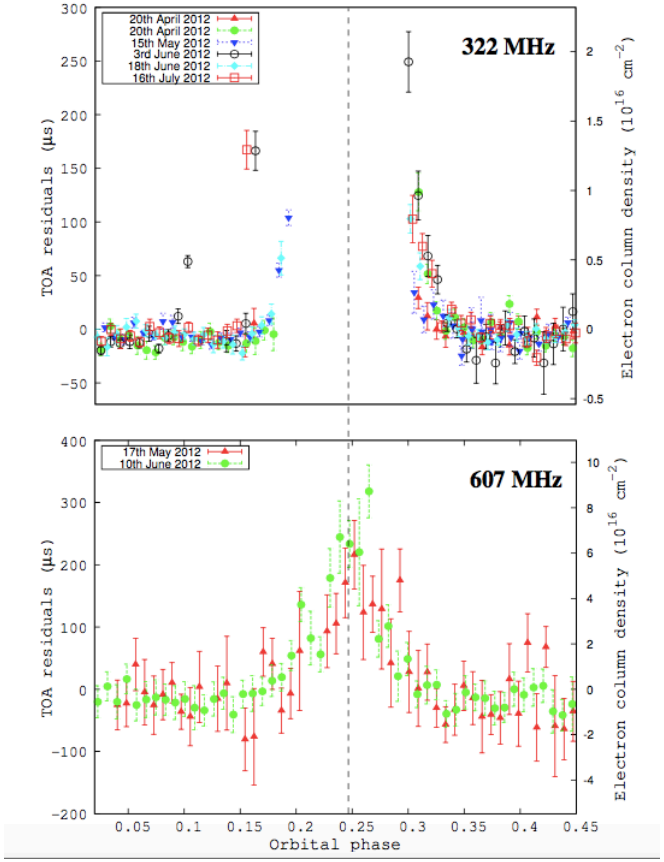
Pulsar name	Period (ms)	Dispersion measure (pc cm^{-3})	Type of pulsar/Orbital period (day)	Flux density‡ (mJy)
PSR J0248+4230	2.60	48.2	isolated	1.9
PSR J1120−3618	5.55	45.1	isolated	0.3
PSR J1207−5050	4.84	50.6	isolated	0.5
PSR J1227−4853	1.686	43.4	0.28	6.6
PSR J1536−4948	3.08	38.0	62.5	12
PSR J1544+4937	2.16	23.2	0.12	5.4
PSR J1646−2142	5.85	29.7	isolated	0.7
PSR J1828+0625	3.63	22.4	isolated	1.0

Ray et al. 2012
Bhattacharyya et al. 2013
Bhattacharyya et al. 2019 (in prep)

Targeted search: Fermi directed searches with GMRT

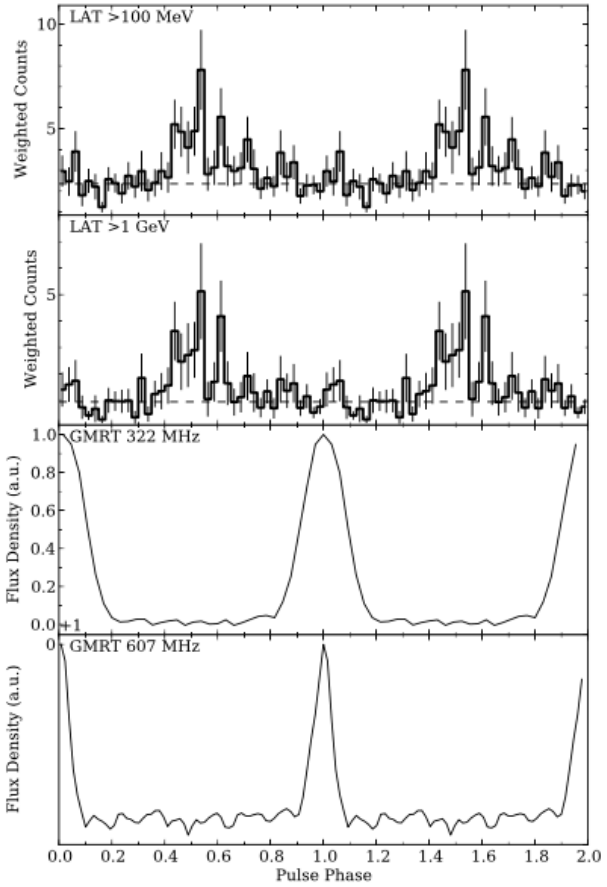
Team: Bhattacharyya, Roy, Ray, Gupta, Bhattacharya, Ferrara +PSC

Discovery of Black-widow millisecond pulsar J1544+4937 (Bhattacharyya et al. 2013, ApJL)



Frequency dependent eclipsing

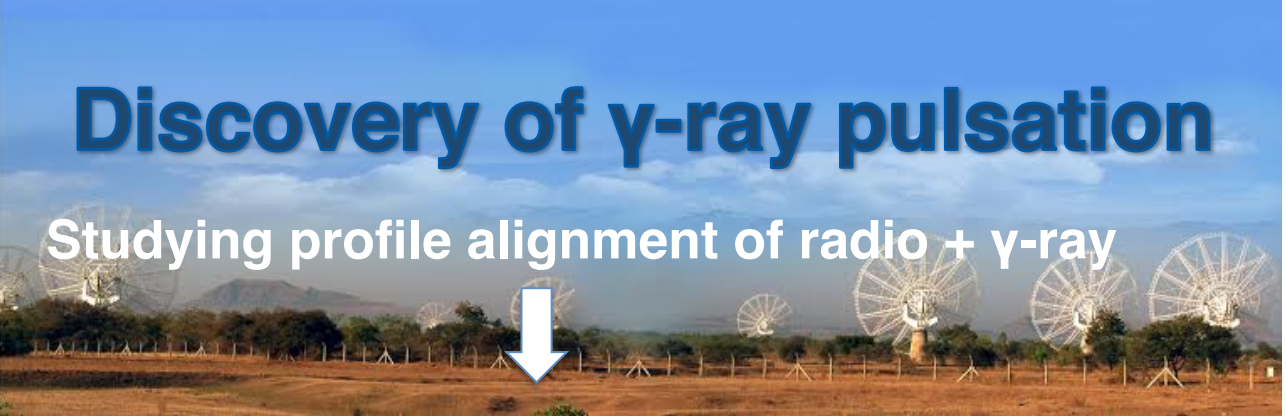
Study with uGMRT will be done by Devojyoti

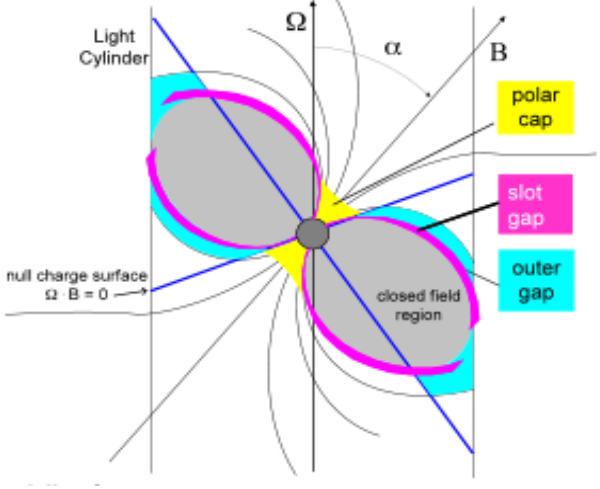


Aligned radio-gamma-ray profile

Discovery of γ-ray pulsation

Studying profile alignment of radio + γ-ray

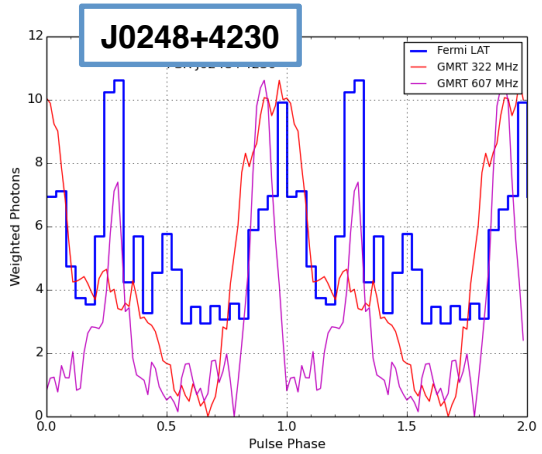


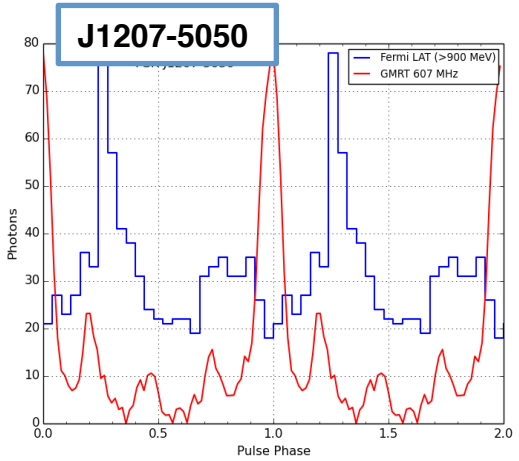


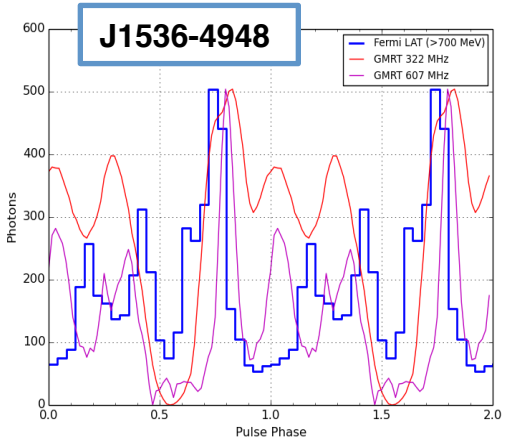
Radio emission: Polar cap model (low altitude)

Gamma-ray emission: Outer gap model, Slot gap model, Pair-starved polar cap (high altitude)

Aligned γ-ray (Fermi LAT) and radio (GMRT) profiles







Aligned: J0248+4230, J1536-4948 → Co-located Radio and γ-ray emission

Non aligned: J1207-5050 → Phase lag is predicted by radio, Y-ray models

Blind survey : GMRT High Resolution Southern sky (GHRSS) Survey

Team: Bhattacharyya, Roy, Stappers, Keith, McLaughlin, Ray, Ransom, Chengalur, Lyne, Sally, Mateusz, Sanjay

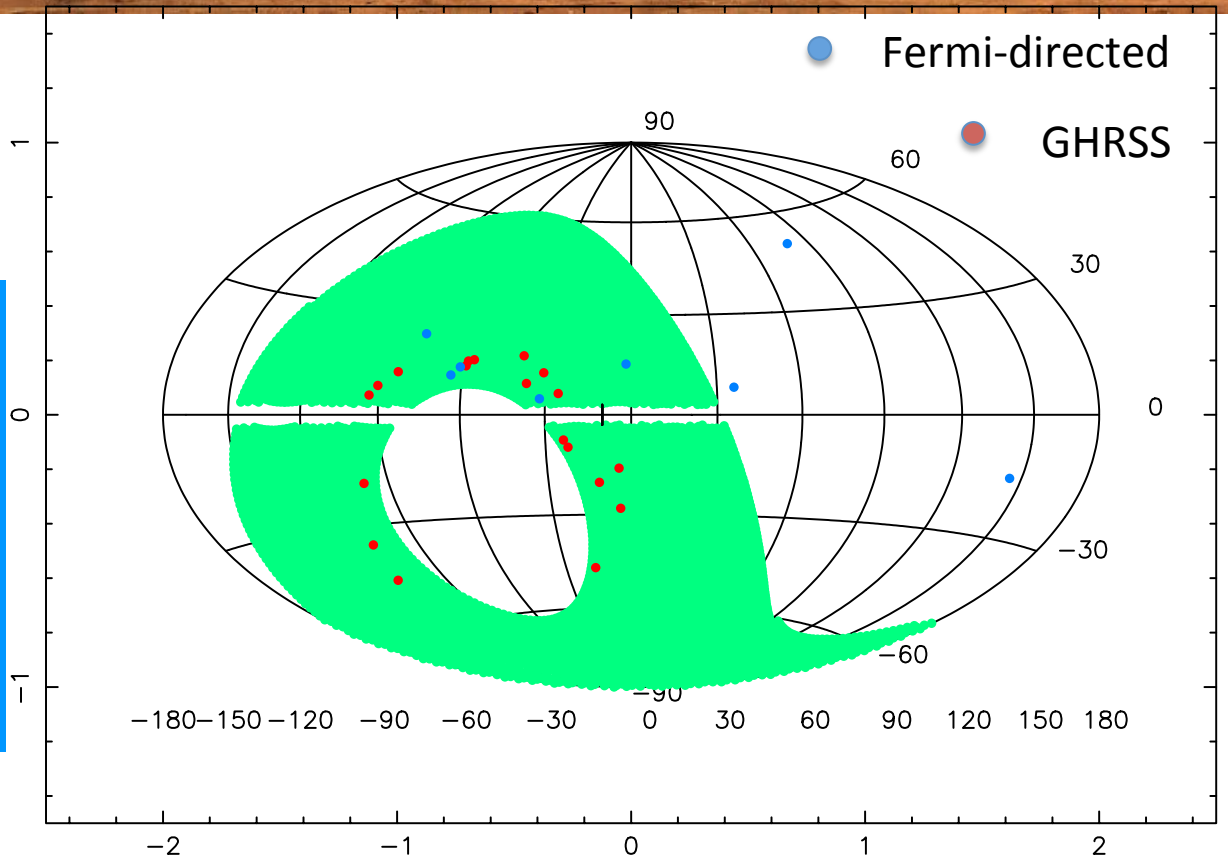
Target Sky

Entire southern sky visible to GMRT (Dec 0 to -54)

Periodicity Search

18 pulsars (started 2014)
2 MSPs
2 mildly recycled pulsars
1 with γ-ray emission

5 pulsars with uGMRT



1st MSP from uGMRT
1st RRAT from GMRT

Bhattacharyya et al. 2016, Astrophysical Journal, 817, 130

Bhattacharyya et al. 2019, (LAT review done, will be submitted soon)

Webpage :
www.ncra.tifr.res.in/ncra/research/research-at-ncra-tifr/research-areas/pulsarSurveys/GHRSS

(1) Parameter space for GHRSS Survey

Survey parameters

Phase-1

- Frequency : 322 MHz
- Bandwidth : 32 MHz
- Sensitivity : 0.5 mJy
- Sky coverage : 1800 square deg
- Compute cost : 10 Tera Ops

Discovery of 13 pulsars

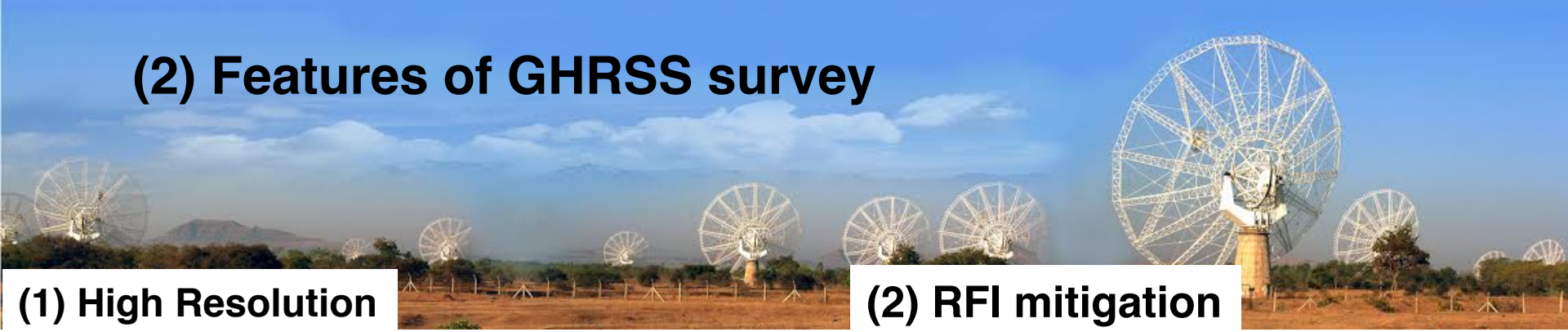
Phase-2

- Frequency : 400 MHz
- Bandwidth : 200 MHz
- Sensitivity : 0.3 mJy
- Sky coverage : 650 square deg
- Compute cost : 15 Tera Ops

Discovery of 5 pulsars
And 1 RRAT

First MSP with uGMRT
First RRAT with GMRT

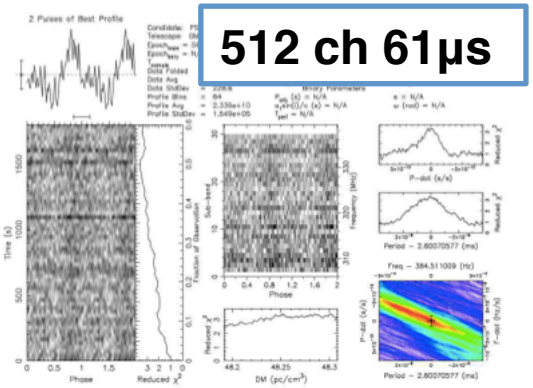
(2) Features of GHRSS survey



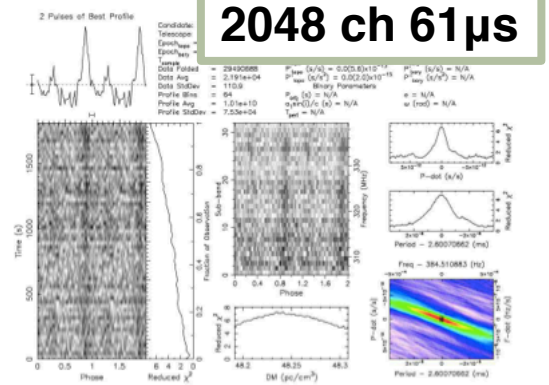
(1) High Resolution

High time resolution (81 μs)
Frequency resolution (~50 kHz): 2x of default

J0248+4230 (2.5x sensitivity gain)



512 ch 61μs



2048 ch 61μs

(2) RFI mitigation

Zero-DM RFI mitigation:
Improvement of SNR a factor of 3

RFI mitigation with Gptool
(developer : Aditya Chowdhury)

(3) Machine learning

Number of Candidates per GHRSS pointing

500 (less RFI)

> 5000 (in presence of RFI)

Large number of candidates
In GHRSS ~ 1.5 Million

Human investigation difficult

Solution : Machine Learning
(based on Weka software)
Developed by Lyon et al. 2016
Also applied to HTRU and LOFAR

Discoveries from GHRSS survey (one of the highest discovery rate)
Probing a different luminosity distribution?

	Pulsar name	Period (ms)	Dispersion measure (pc cm^{-3})	Detection significance (σ)	Flux density† (mJy)
	PSR J0418−4154	757.11	24.5	50	10.3
γ-ray pulsation →	PSR J0514−4407	320.7	15.4	42	9.7
	PSR J0702−4956	666.66	98.7	30	15.7
	PSR J0919−42	812.6	57	19	6.4
	PSR J0941−43	447.7	105.5	53	2.3
	PSR J1023−43	454.3	62.7	38	1.6
	PSR J1239−48	653.89	107.6	21	0.4
MSP →	**PSR J1243−47**	5.31	78.6	18	0.9
	PSR J1255−46	52.0	42.9	12	0.8
Mildly recycled →	**PSR J1428−42**	234.7	66.0	41	1.8
	PSR J1456−48	536.81	133.0	15	1.2
Mildly recycled →	PSR J1516−43	36.02	70.25	9	0.7
	PSR J1559−44	1169.89	122.0	8	1.7
	PSR J1708−52	449.62	102.6	9	1.4
	PSR J1845−40	324.18	68.4	11	1.5
	PSR J1726−52	631.84	119.7	8	0.7
	RRAT J1850-48		23	–	–
	PSR J1947−43	180.94	29.9	17	4.7
MSP →	PSR J2144−5237	5.04	19.0	9	1.6

GHRSS survey for last 5 years

GHRSS1 (0.5 mJy)
10% SKA1

GHRSS2 (0.3 mJy)
1/5th SKA1

SKA1 (0.05 mJy)

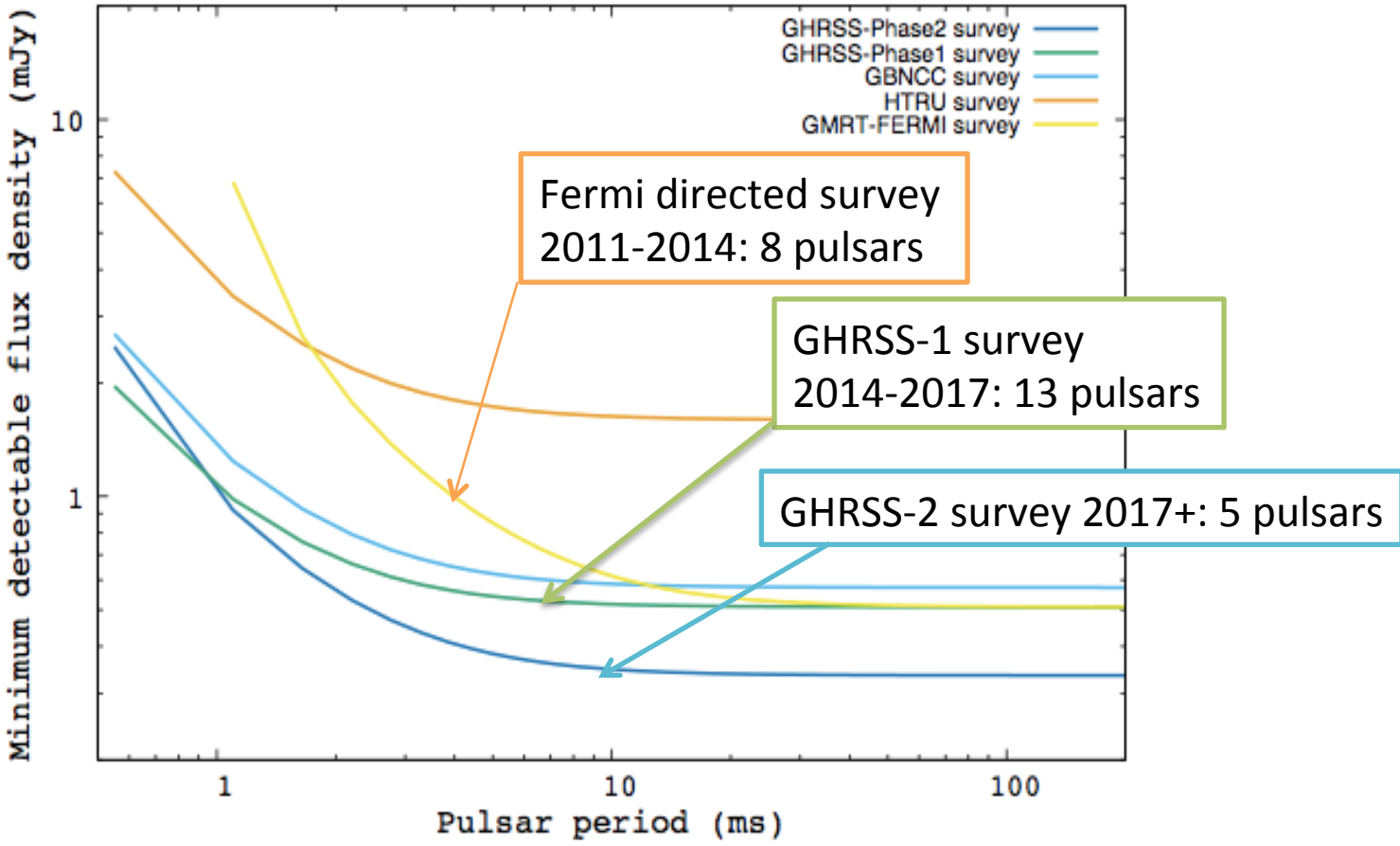
13 pulsars discovered
→ 1 pulsar per 20 hrs

5 pulsars discovered
→ 1 pulsar per 20 hrs

9000 pulsars (prediction)
→ 1 pulsar per 2 hours

Discovery rate:
0.008 per sq deg

Comparable to other surveys



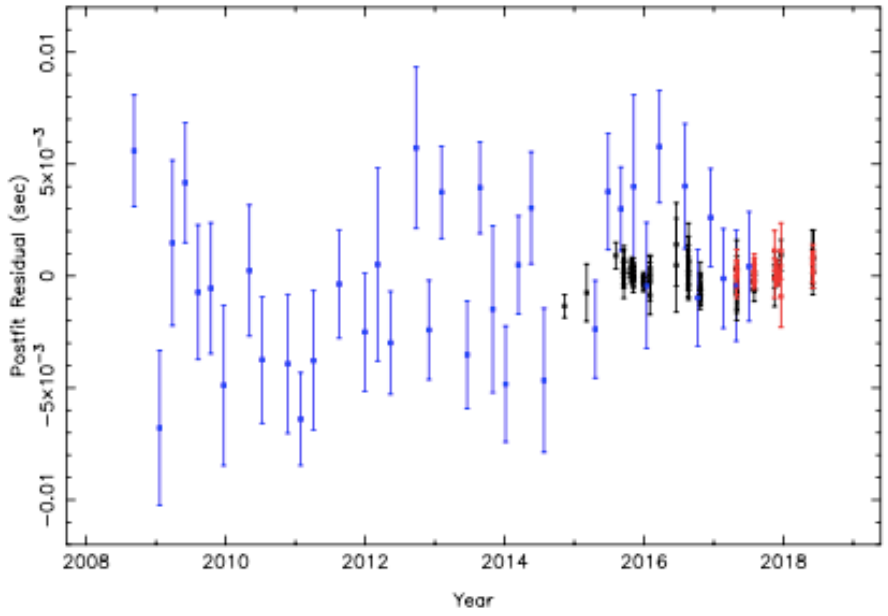
Fermi directed survey
2011-2014: 8 pulsars

GHRSS-1 survey
2014-2017: 13 pulsars

GHRSS-2 survey 2017+: 5 pulsars

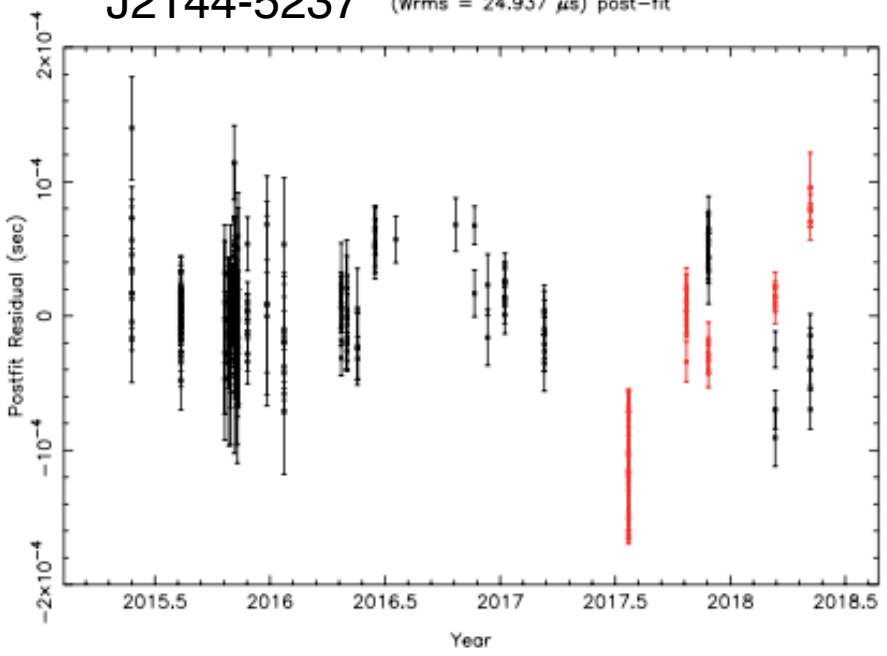
Follow up study of GHRSS pulsars : Timing

PSR J0514-4408 (Wrms = 459.369 μs) post-fit



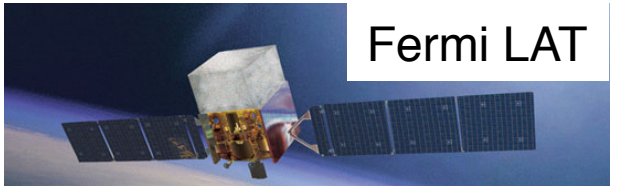
Combined radio-gamma ray timing residual for PSR J0514-4408

J2144-5237 (Wrms = 24.937 μs) post-fit



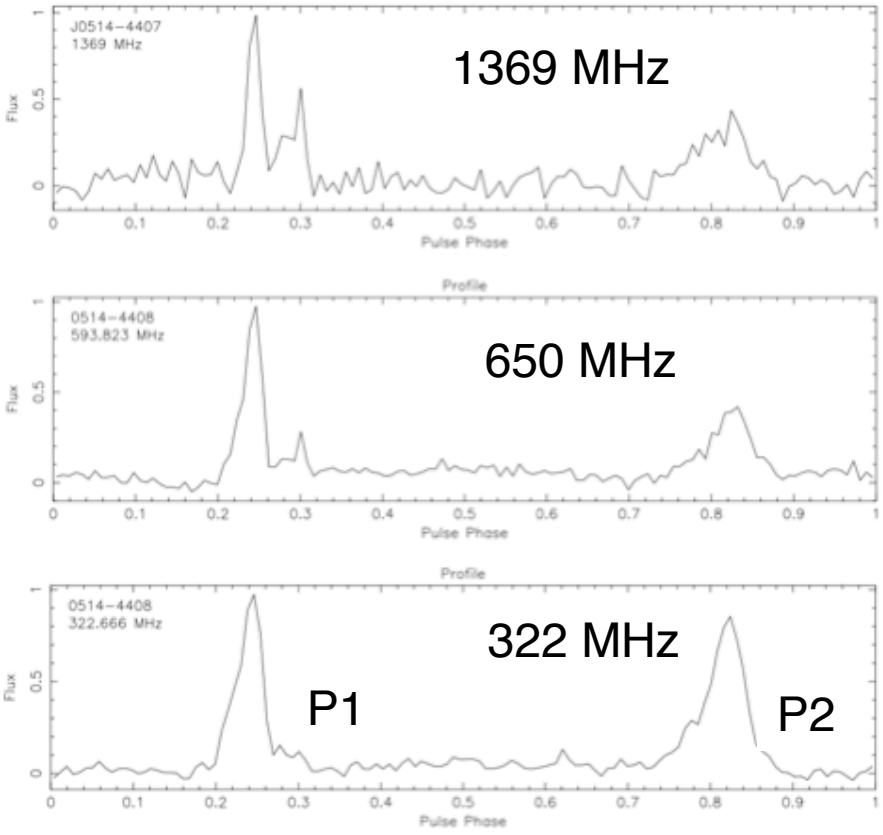
Timing residual for MSP J2144-5237

Black points : legacy system (32 MHz bandwidth)
Red points : uGMRT (200 MHz bandwidth)
Blue points : Gamma-ray residual with Fermi LAT

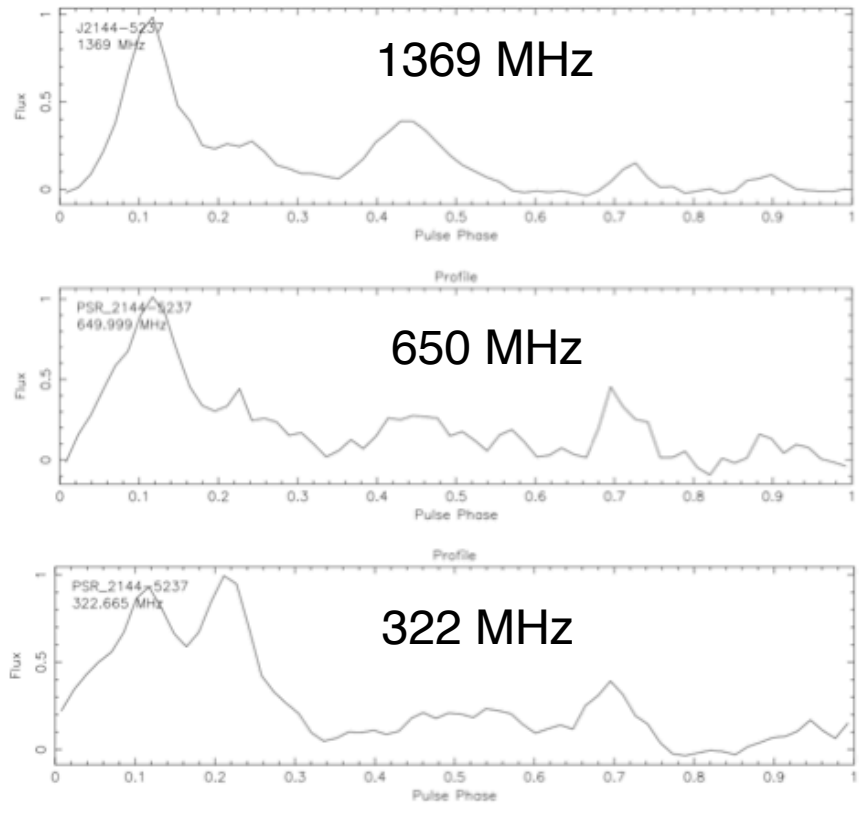


Follow up study of GHRSS pulsars : Profile evolution

PSR J0514-4408



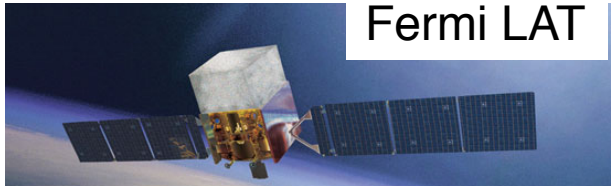
PSR J2144-5237

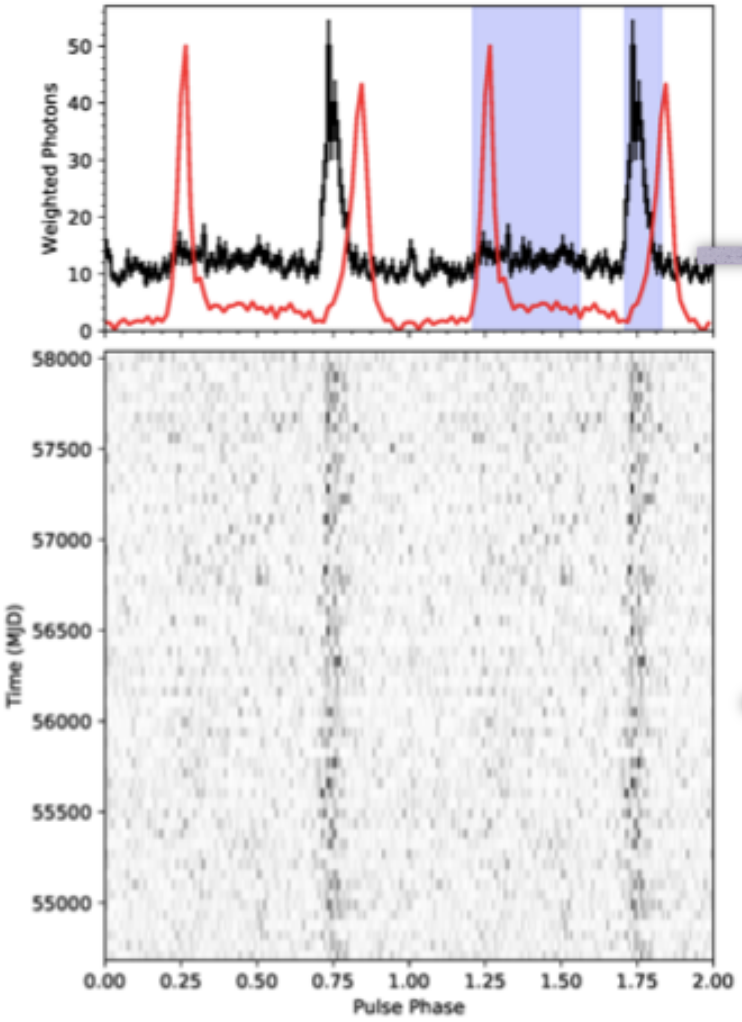


P2 is becomes weaker at higher frequencies
Detected strong single pulses aligned with P1

Very wide profile : almost no off pulse

Follow up study of GHRSS pulsars: Radio-γray profile





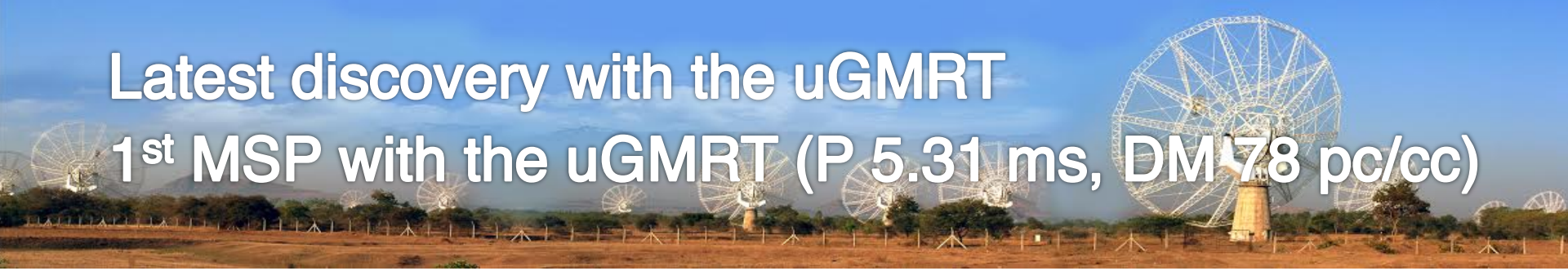
322 MHz radio profile (red) of PSR J0514–4408 plotted with the LAT γ–ray profile (using ~9.2 years of Fermi Large Area Telescope (LAT) Pass 8 data above 100 MeV)

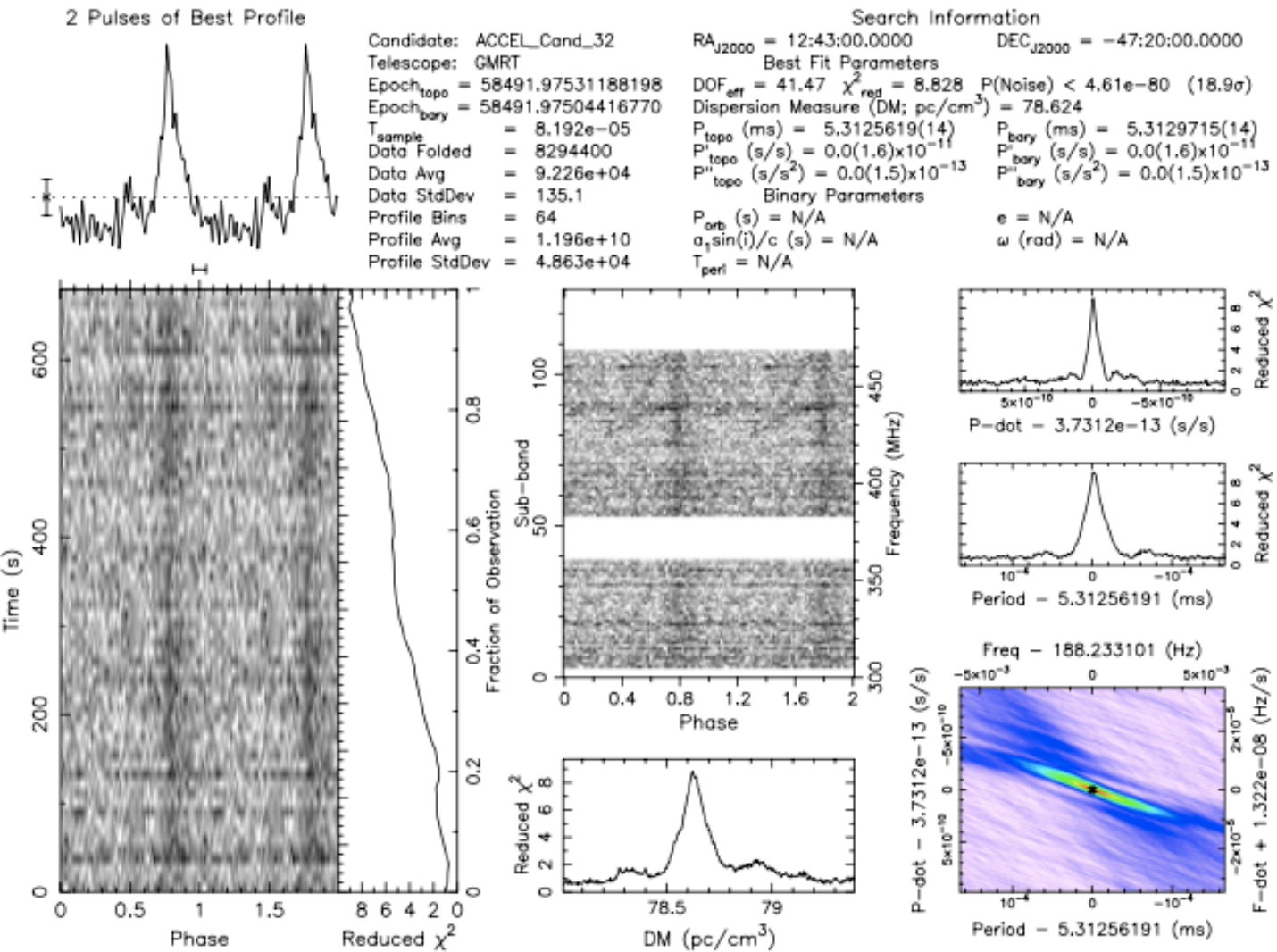
LAT phasogram of PSR J0514–4408

In the process of modeling the radio and γ-ray light-curves with combinations of emission height, and viewing angles

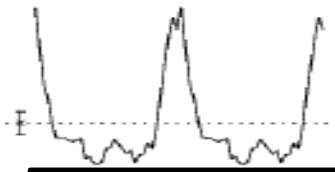
Latest discovery with the uGMRT

1st MSP with the uGMRT (P 5.31 ms, DM 78 pc/cc)

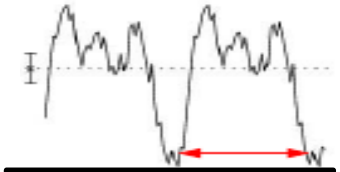




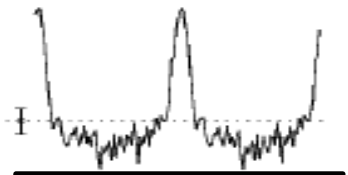
GMRT DISCOVERIES



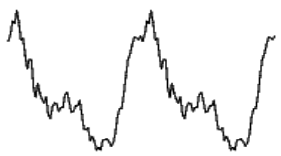
J1544+4937
2.16ms @ 23.2 DM



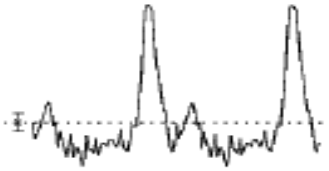
J1536-4948
3.16ms @ 38.0 DM



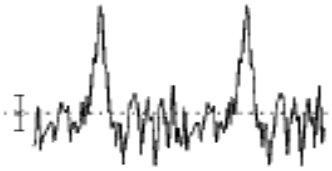
J1828+0625
3.07ms @ 22.4 DM



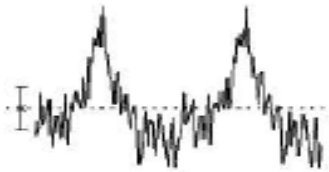
J0248+4230
2.60ms @ 48.2 DM



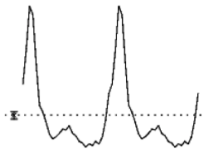
J1646-2142
5.84ms @ 29.7 DM



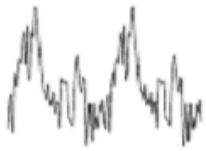
J1207-5050
4.84ms @ 50.6 DM



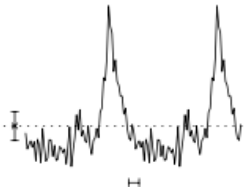
J1120-3618
5.55ms @ 45.1 DM



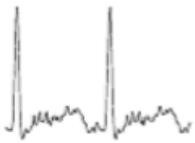
J1227-4853
1.69ms @ 43.2 DM



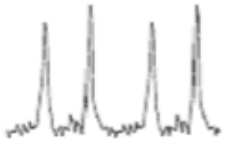
J2144-5237
5.04ms @ 19.0 DM



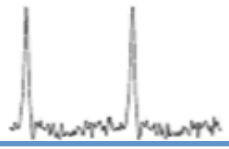
J1243-47
5.31ms @ 78.6 DM



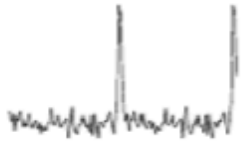
J0418-4154
757ms @ 24 DM



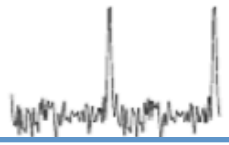
J0514-4408
320ms @ 15 DM



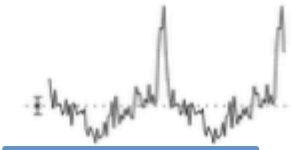
J0702-4906
666ms @ 98 DM



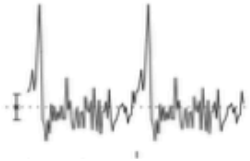
J0919-42
812ms @ 57 DM



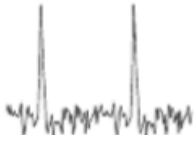
J1255-46
52.0ms @ 42 DM



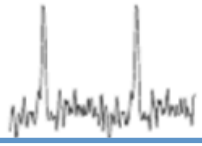
J1239-48
653ms @ 107



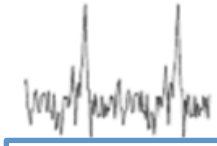
J1726-52
631ms @ 119



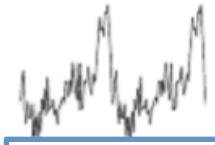
J1456-48
536ms @ 133



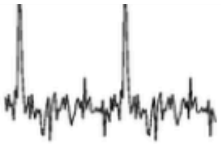
J1559-44
1169ms @ 122



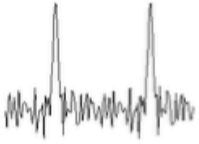
J1708-52
449ms @ 102



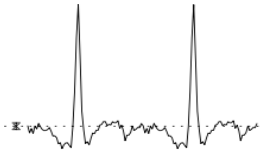
J1947-43
180ms @ 29



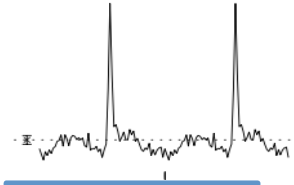
J1516-43
4.84ms @ 50.6



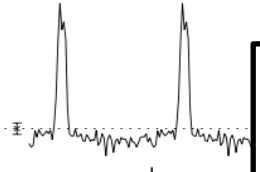
J1845-40
4.84ms @ 50.6



J0941-42
447ms @ 105



J1022-43
454ms @ 62



J1428-43
234ms @ 66

MSPs: 10

Pulsars: 16

Summary:

Pulsar per square degree
"0.008"

10 MSPs, 1 RRAT, 16 normal pulsars

1st MSP with the uGMRT

1st RRT with uGMRT

Faster analysis with GPU based pipeline at NCRA

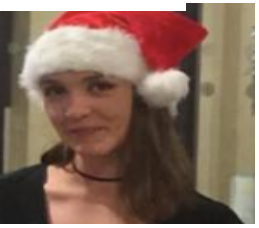
Improved RFI mitigation

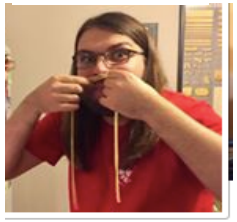
More RRATs and new FRBs

Jerk search for pulsars in compact binaries

FFA based search for long period pulsars

Thank you

Cristina 

Mateusz 

Sally 

Sanjay 

Arpit 

Rajeev 

Devojyoti 

Discoveries in P-Pdot diagram