Pulsars and transients with GMRT

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Broad impact of Low Frequency Observing
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NCRA • TIFR

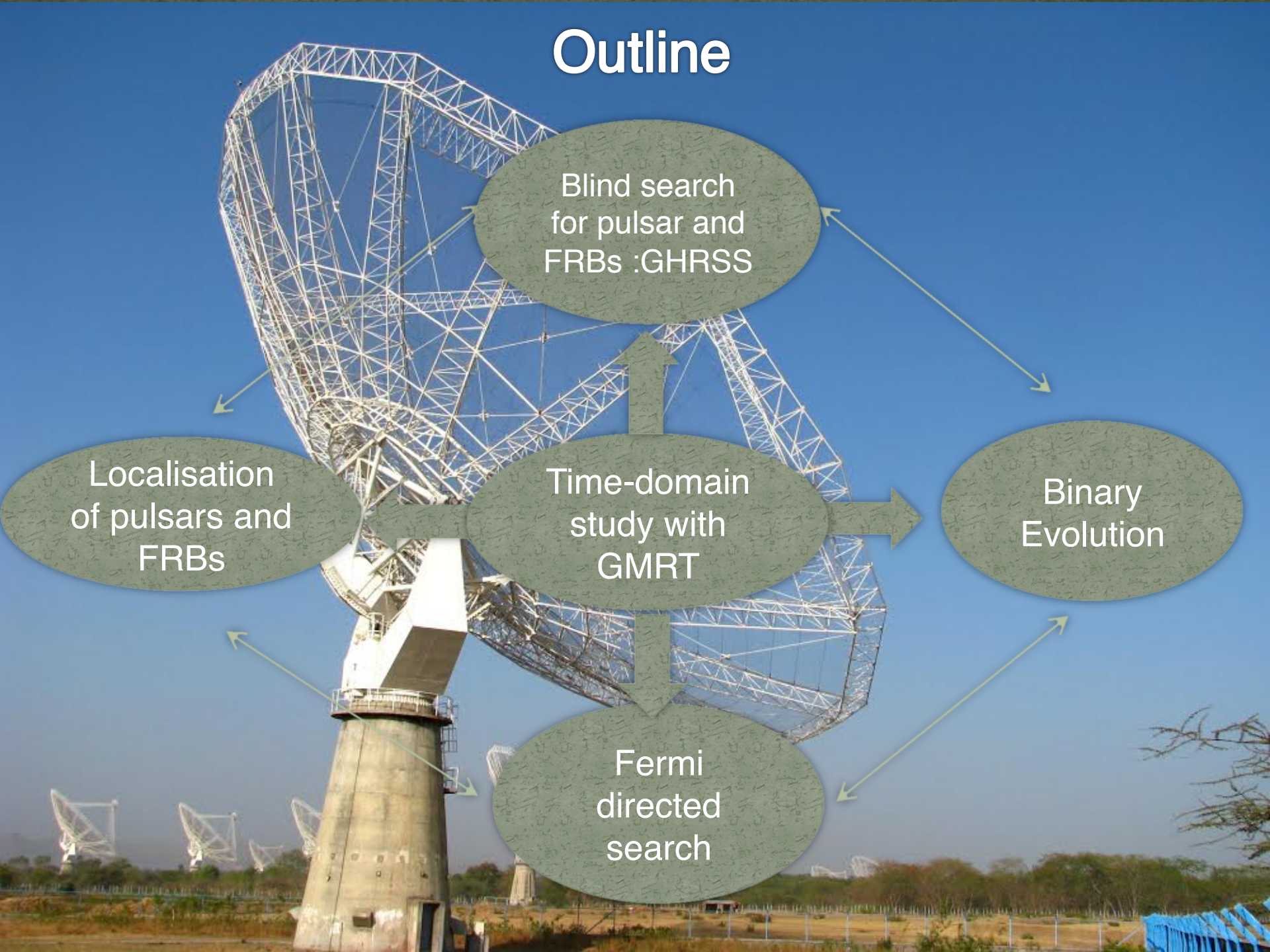
Time domain study with GMRT

- ✓ Largest array in metre-wavelengths: Giant metre-wave Radio Telescope (GMRT) is a radio interferometer with 30 antennas each of 45 m diameter
- ✓ Low radio frequency coverage: 150, 244, 322, 607, 1060 to 1450 MHz
  (Low-frequency pulsar study is benefitted by spectra)
- ✓ Pulsar surveys benefitted by wide field of view at low frequencies:

  Simultaneous dual beam: incoherent beam with HPBW ~ 40' (0.5 mJy @ 32 MHz band width)
  coherent beam with HPBW~ 1' (0.2 mJy @ 32 MHz band width)
- ✓ Localisation: Synchronous time-domain and imaging study
- ✓ Sensitivity improvement with upgraded GMRT (Band width up to 400 MHz)

  incoherent beam with HPBW ~ 30' (0.2 mJy @ 200 MHz band width)
  coherent beam with HPBW ~0.8' (0.08 mJy @ 200 MHz band width)

Outline


Blind search for pulsar and FRBs :GHRSS
Localisation of pulsars and FRBs
Time-domain study with GMRT
Binary Evolution
Fermi directed search

Pulsar Search

Two popular ways to search for pulsars

- ✓ *Targeted search* : With a priori knowledge of position
  - Globular cluster : Freire et al. 2004
  - Supernovae Remnants : Gupta et al. 2005
  - High energy sources : Bhattacharyya et al. 2013

Fermi directed targeted searches

- ✓ *Blind search* : Without a priori knowledge of position
  - 610 MHz Galactic plane : Joshi et al. 2009
  - 322 MHz off-Galactic plane : Bhattacharyya et al. 2016

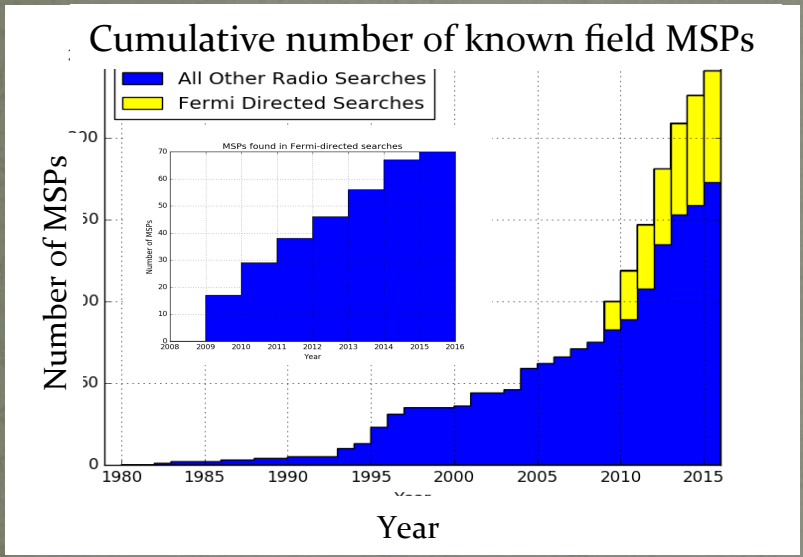
GHRSS survey :
GMRT High Resolution Southern Sky survey for pulsars and transients

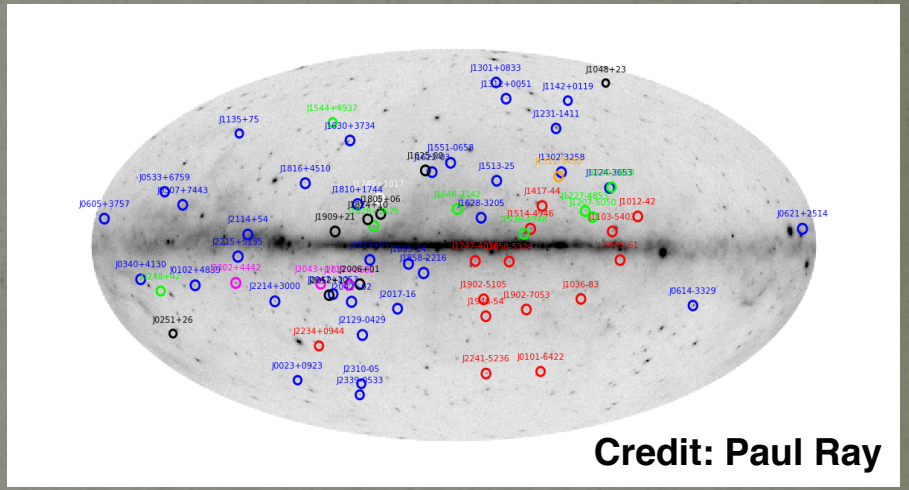
Targeted search: Fermi directed searches with GMRT

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

Fermi Pulsar Search Consortium efforts ⟶ 85 new MSPs

GMRT discovery (2011 to 2013) ⟶ 7+1 MSPs





Nançay

GMRT

GBT

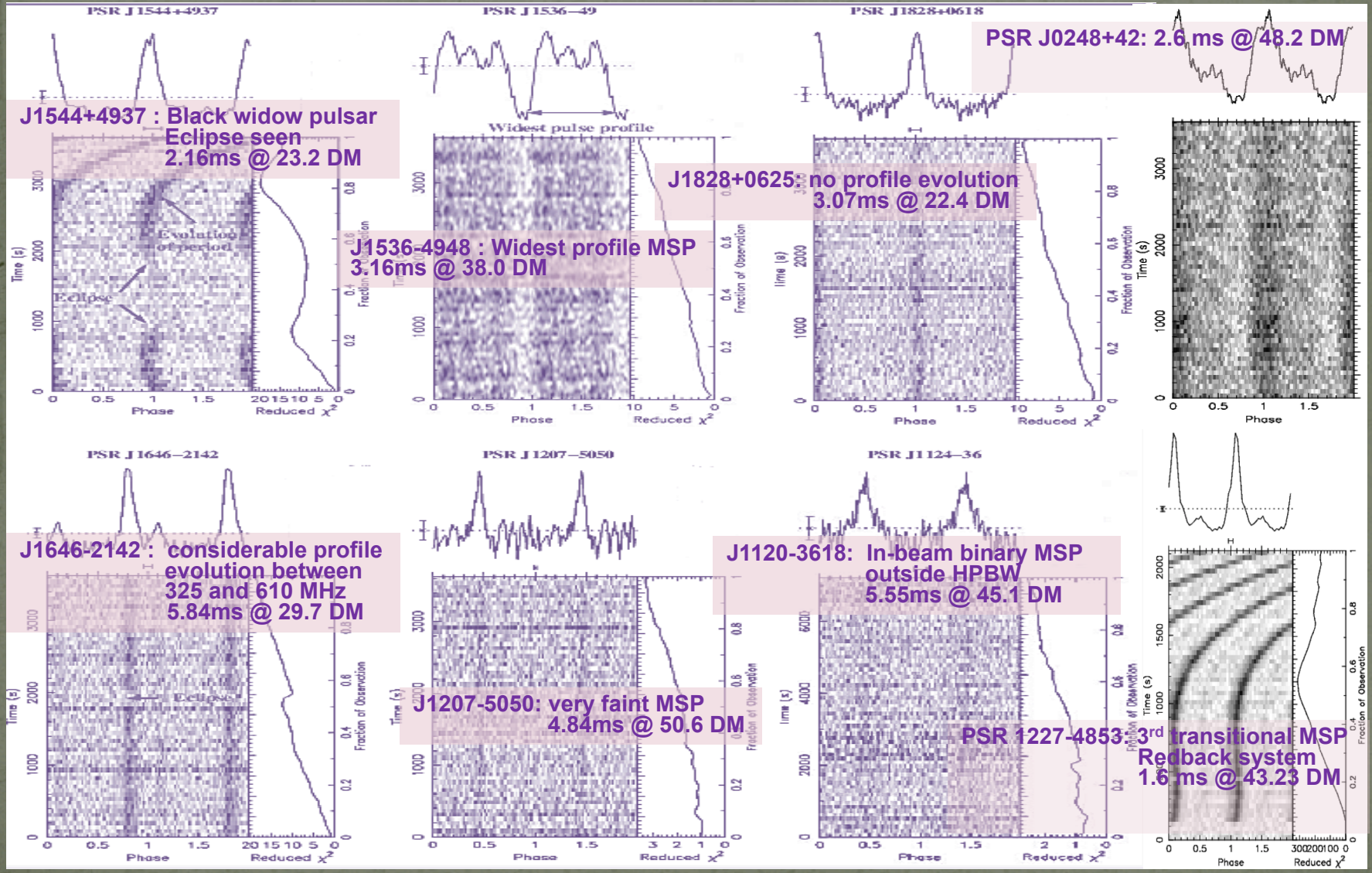
Parkes

Effelsberg

LOFAR

Seven MSPs discovered at GMRT from 2011-2013

Discovery of first galactic millisecond pulsation from GMRT
Bhattacharyya et al. 2013, ApJL



PSR J0248+42: 2.6 ms @ 48.2 DM

J1544+4937 : Black widow pulsar
Eclipse seen
2.16ms @ 23.2 DM

J1828+0625: no profile evolution
3.07ms @ 22.4 DM

J1536-4948 : Widest profile MSP
3.16ms @ 38.0 DM

J1646-2142 : considerable profile evolution between 325 and 610 MHz
5.84ms @ 29.7 DM

J1120-3618: In-beam binary MSP outside HPBW
5.55ms @ 45.1 DM

J1207-5050: very faint MSP
4.84ms @ 50.6 DM

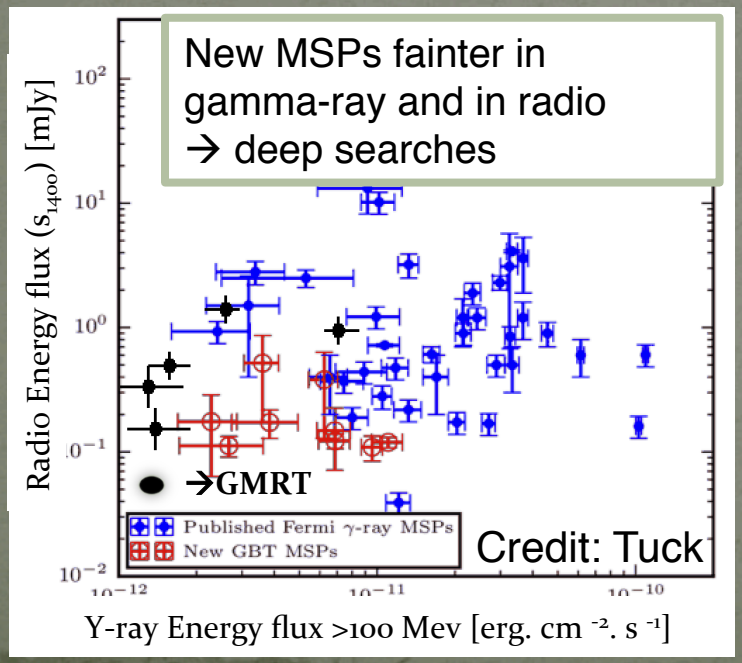
PSR 1227-4853: 3rd transitional MSP
Redback system
1.6 ms @ 43.23 DM

Fermi directed radio survey

- ✓ LAT pulsation detected for →56 out of 70 Fermi MSPs (4 unassociated)

  (info is not updated for last 6 months)

Gamma ray Vs Radio energy flux



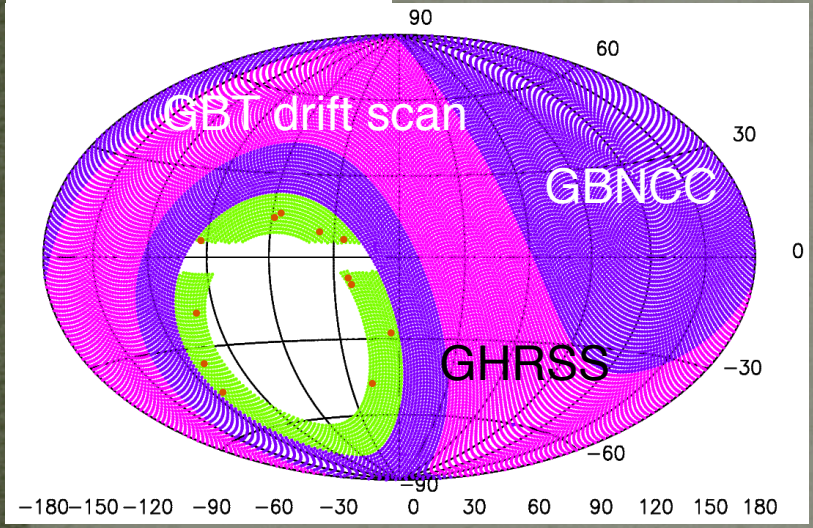
- ✓ LAT pulsation not yet found for 10 MSPs (includes one GMRT MSP J1646-2142)

2014 - 2017: LAT pulsation detected from 5 GMRT MSPs using radio timing

Blind search: GMRT High resolution Soutnern Sky (GHRSS) survey

Team: *Bhattacharyya*, Cooper, Malenta, Roy, Chengalur, Keith, Kudale, McLaughlin, Ransom, Ray, Stappers

Sky coverage



Survey parameters

Survey	MGL with HiRes1	HGL with HiRes2
Galactic region	$5<\|b\|<20°$	$\|b\| > 20°$
Declination	$-54°<\text{Dec}<-40°$	$-54°<\text{Dec}<-40°$
Integration time	1200 s	900 s
Sampling time	61.44 μs	30.72 μs
Bandwidth	32 MHz	32 MHz
Number of channels	2048	1024
Frequency Resolution	15.625 kHz	31.25 kHz
Number of pointings	682	911
Sky coverage	1227 deg^2	1639 deg^2
Data/pointing	37 GB	28 GB
Total data	25 TB	25 TB
No of DM trials	10000	6000

Parameter space of GHRSS

- ✓ Frequency overlap with SKA1 Mid and Low
- ✓ Frequency resolution~15 kHz, Time resolution~ 64 µs
- ✓ GHRSS sky 2900 square deg
- ✓ GHRSS compute cost 10 Tera Ops

GHRSS Survey

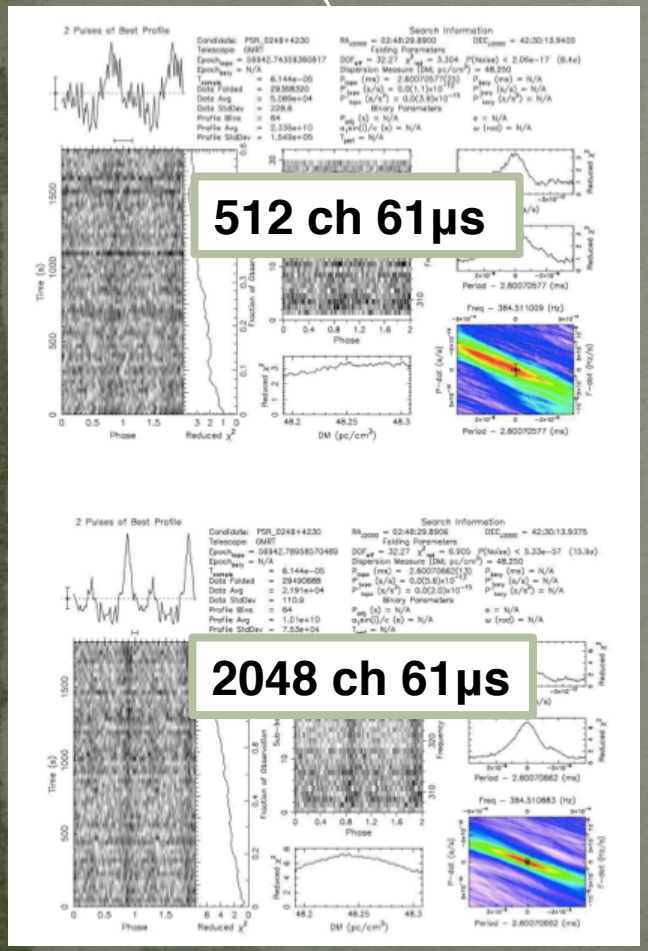
Major ongoing or recently completed off-Galactic plane surveys

Survey name – Telescope	Frequency of search (MHz)	Sky coverage	Discoveries	Sensitivity† (mJy)
HTRU[1] – Parkes	1352	$-120° < l, l < 30°$ $\lvert b\rvert < 15°$ 4500 deg^2	104 PSR, 26 MSP	1.5
HTRU–N – Effelsberg	1360	$\lvert b\rvert > 15°$, Dec $> -20°$	12 PSR	1.5
GBNCC[2] – GBT	350	Dec$>-40°$ 19500 deg^2	108 PSR, 12 MSP (158 PSR 20 MSP)	0.6
GBTdriftscan[3] – GBT	350	$-21°$ <Dec <$26°$	26 PSR, 7 MSP	0.9
AO327[4] – Arecibo	327	$0°$ <Dec< $28°$	24 PSR, 3 MSP	0.3
LOTAAS[5] –LOFAR	135	Dec >0 °	30 PSR	0.3
GHRSS‡[6] – GMRT	322	$-20°$ <Dec < $-54°$ 2900 deg^2	13 PSR, 1 MSP 2 mildly recycled	0.5

GHRSS features

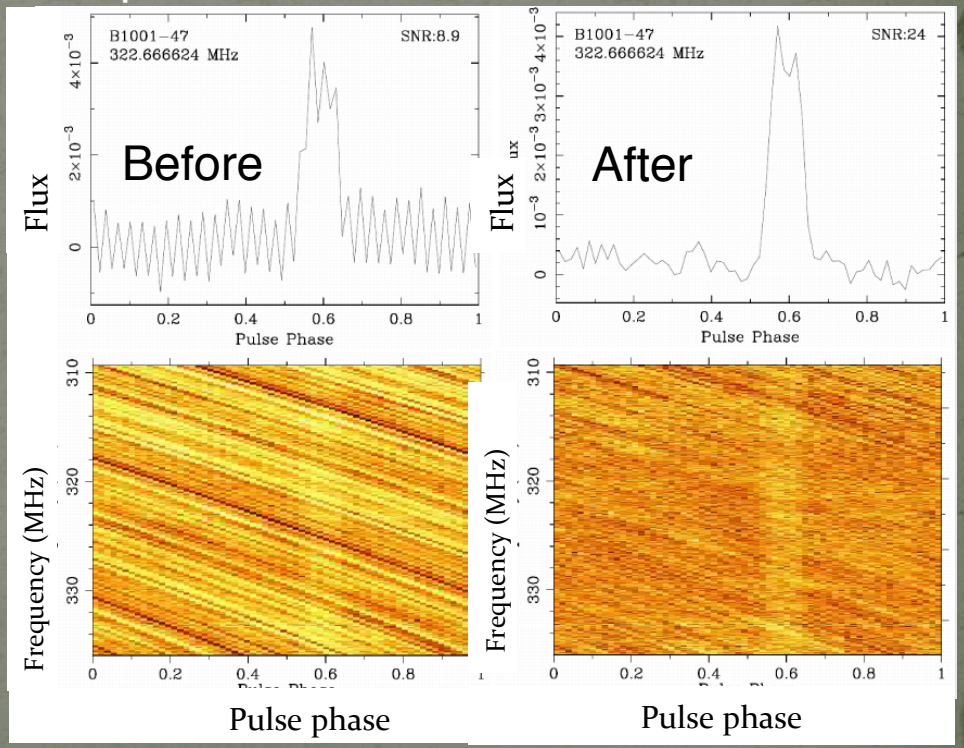
(1) High resolution mode

J0248+4230 (2.5x sensitivity gain)



(2) RFI mitigation

Zero-DM RFI mitigation:
Integrated profile, phasogram of B1007–47
→ Improvement of SNR a factor of 3



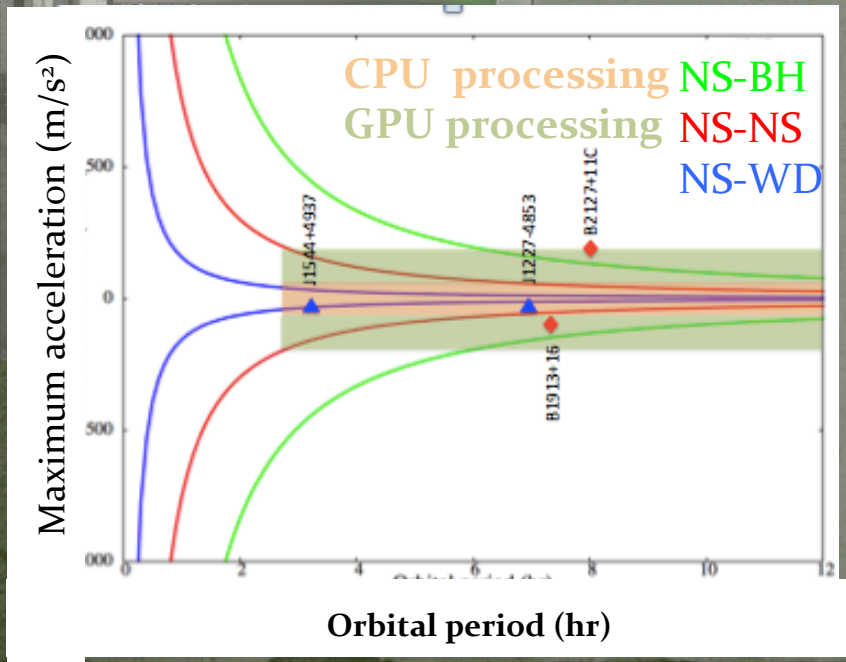
GHRSS features

(3) Processing

GPU pipeline (`BIFORT' developed by Mateusz)

✓ Acceleration parameter 4x increased for GPU

✓ Dedispersion range increases 500 pc cm^{-3} to 2000 pc cm^{-3}



(4) Machine Learning

Number of Candidates per GHRSS pointing

500 (less RFI)

> 5000 (in presence of RFI)

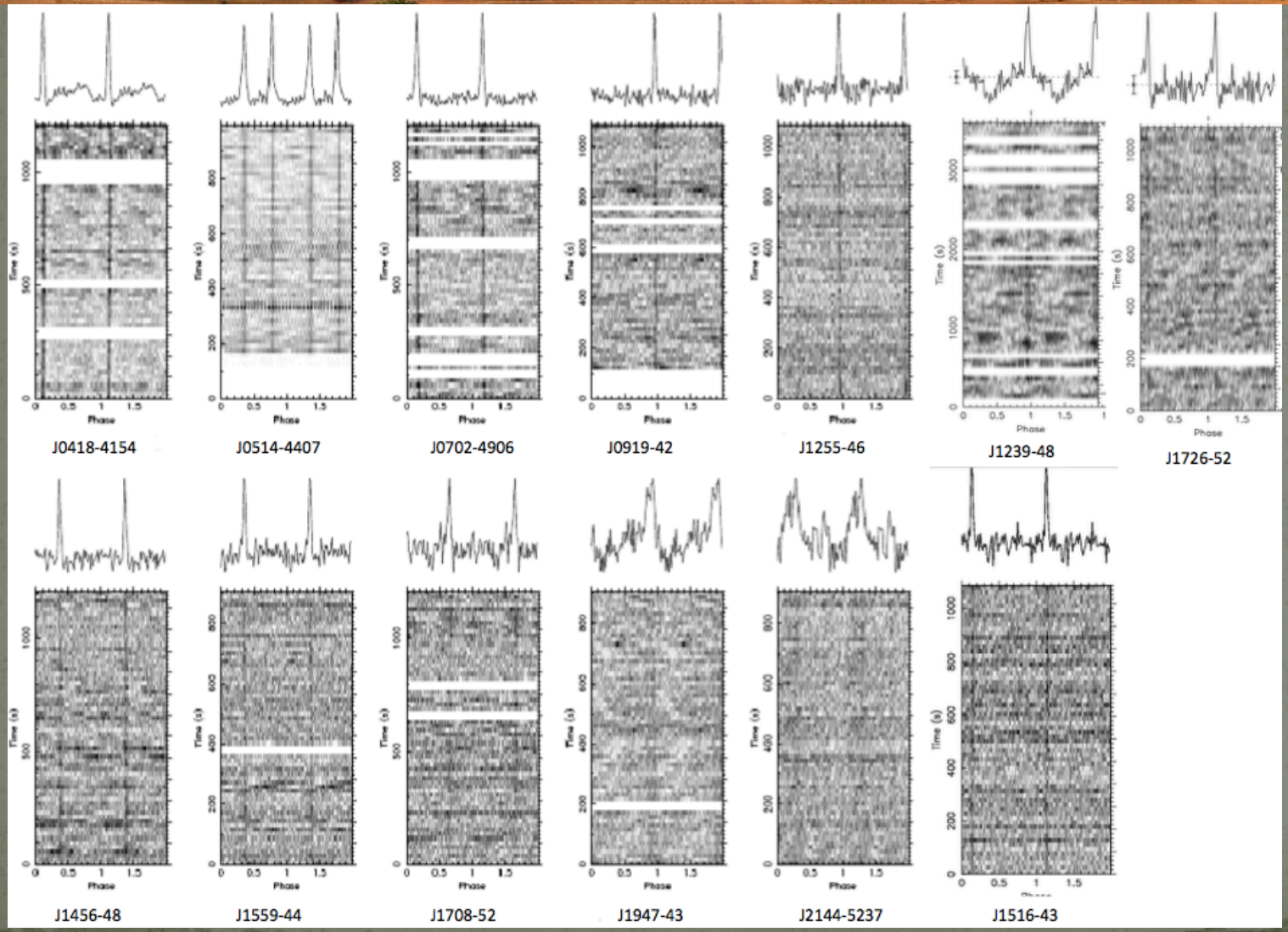
Large number of candidates in 50 % of GHRSS ~ 1.5 Million

Human investigation difficult

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

Thirteen pulsars discovered in GHRSS survey 2014-2017

(Including 1 MSP and 2 mildly recycled pulsars)



Total 21 discoveries from targeted & blind surveys with GMRT

Pulsar name	Period (ms)	Dispersion measure (pc cm^{-3})	Orbital period (day)	Flux density† (mJy)
PSR J0248+42	2.60	48.2	isolated MSP	1.9
PSR J0418−4154	757.11	24.5	normal PSR	10.3
PSR J0514−4407	302.2	15.4	normal PSR	9.7
PSR J0702−4956	666.66	98.7	normal PSR	15.7
PSR J0919−42	812.6	57.8	normal PSR	6.4
PSR J1120−3618	5.55	45.1	–	0.3
PSR J1207−5050	4.84	50.6	isolated MSP	0.5
PSR J1227-4853	1.686	43.4	0.287	6.6
PSR J1239−48	653.89	107.6	mildly recycled	0.4
PSR J1255−46	52.0	42.9	12	0.8
PSR J1456−48	536.81	133.0	15	1.2
PSR J1516−43	36.03	70.2	mildly recycled	0.7
PSR J1536−4948	3.08	38.0	62.5	12
PSR J1544+4937	2.16	23.2	0.12	2.6
PSR J1559−44	1169.89	122.0	normal PSR	1.7
PSR J1646−2142	5.85	29.7	isolated MSP	0.7
PSR J1708−52	449.62	102.6	normal PSR	1.4
PSR J1726−52	631.84	119.7	normal PSR	0.7
PSR J1828+0625	3.63	22.4	–	1.0
PSR J1947−43	180.94	29.9	normal PSR	4.7
PSR J2144−5237	5.04	19.0	10.58	1.6

Blue : MSP,
Red : Normal PSR,
Magenta : mildly recycled

MSP in special evolutionary phase
Redback MSP

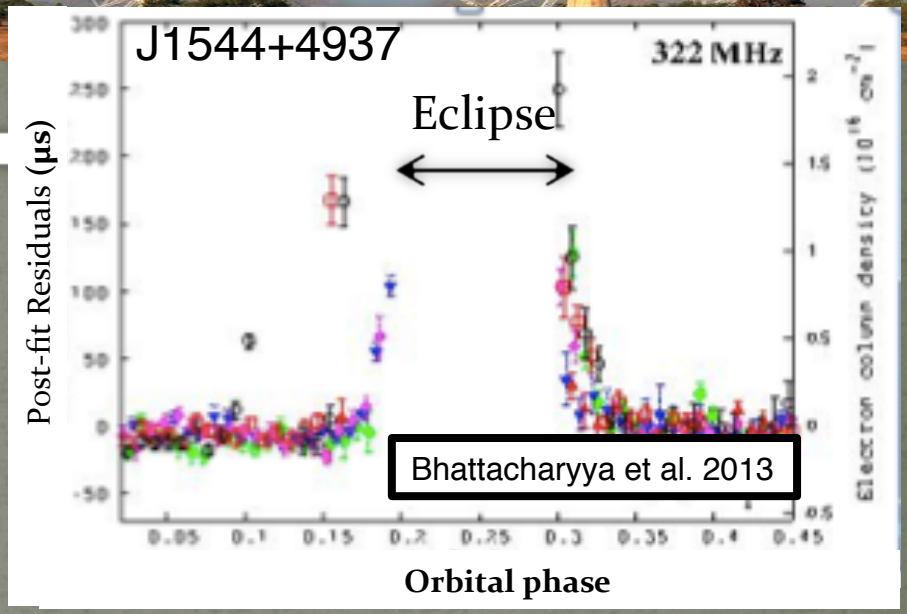
Black Widow MSP

Binary Evolution

1st published Fermi Black widow
P_b ~ 2.8 hrs
Companion mass ~ 0.017 $M_\odot$
Eclipses ~ 13% of orbit

Timing study

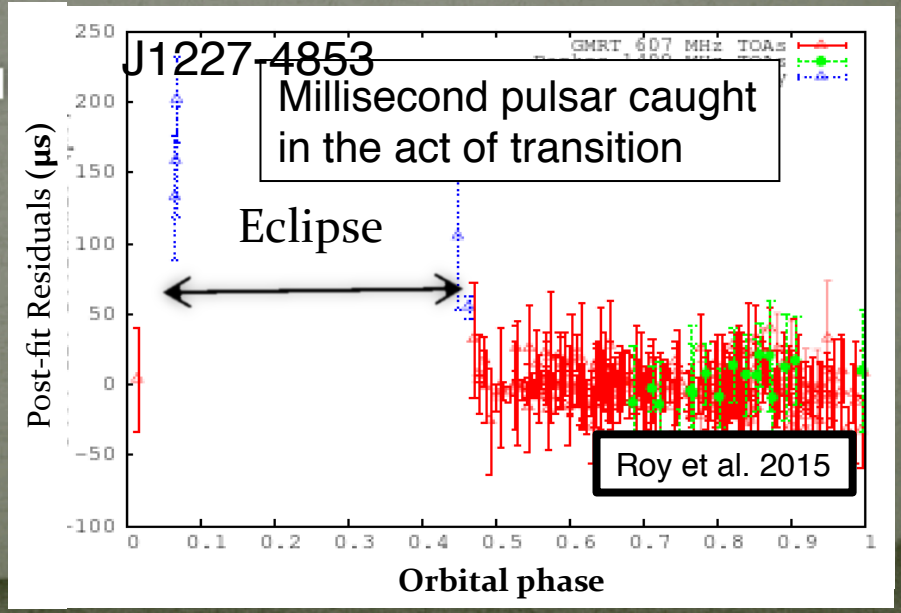
Cause of eclipse: Absorption



3rd transitioning MSP
Redback P_b ~ 6.9 hrs
Companion mass ~ 0.4 $M_\odot$
Eclipses ~ 50% of orbit

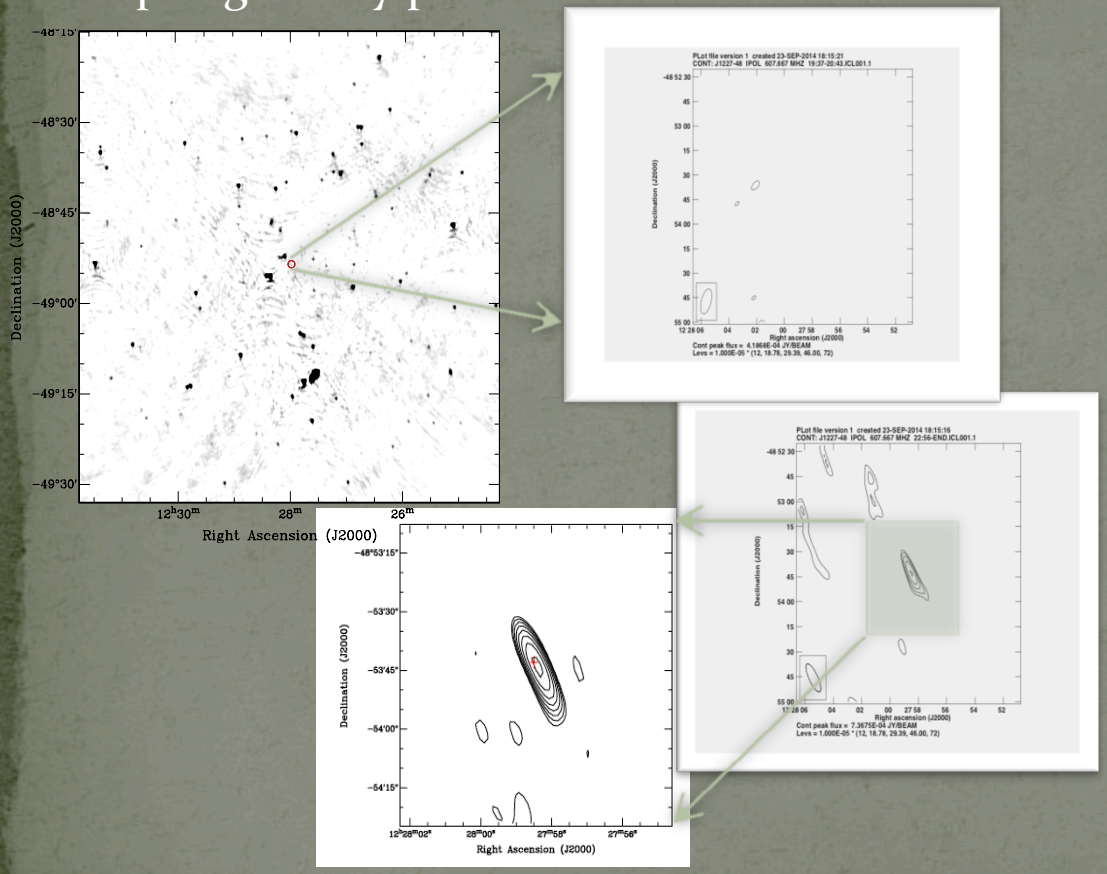
Simultaneous timing-imaging

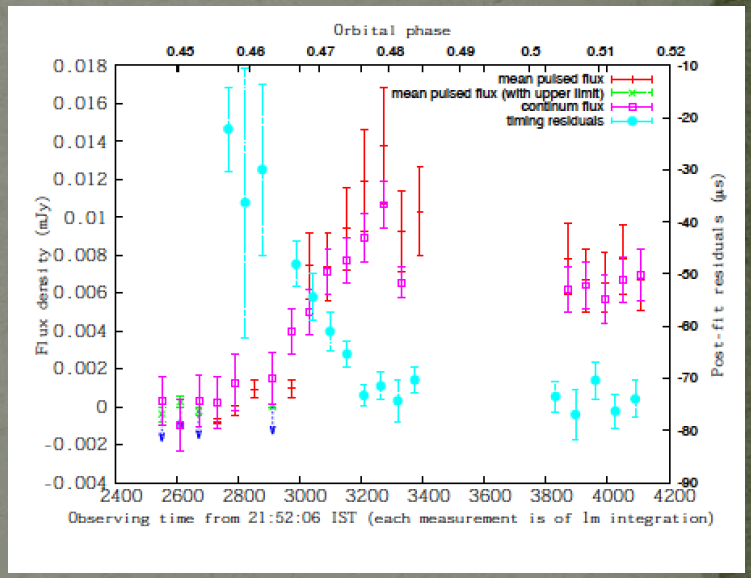
Cause of eclipse: Absorption not interstellar effects



Simultaneous timing and imaging study for J1227-4853

Eclipsing Binary phase





absorption of radio waves might be causing radio eclipse

Non-Eclipsing Binary phase

Radio transients (FRB & RRAT) : No discoveries yet

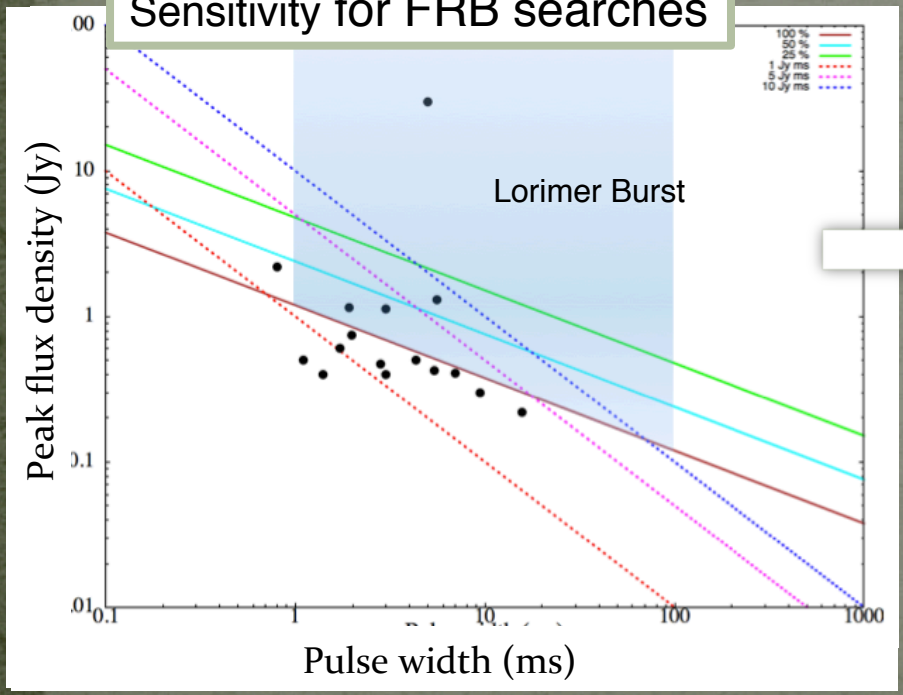
- ✓ FRB detection for GHRSS survey completion (500 hrs on-source time)
  → 4^{+2}_{-1} at 3 Jy-ms fluence (according to Champion et al. 2016)

GHRSS → FRB survey with Interferometer

↓

Simultaneous localisation & identify the origin

Sensitivity for FRB searches



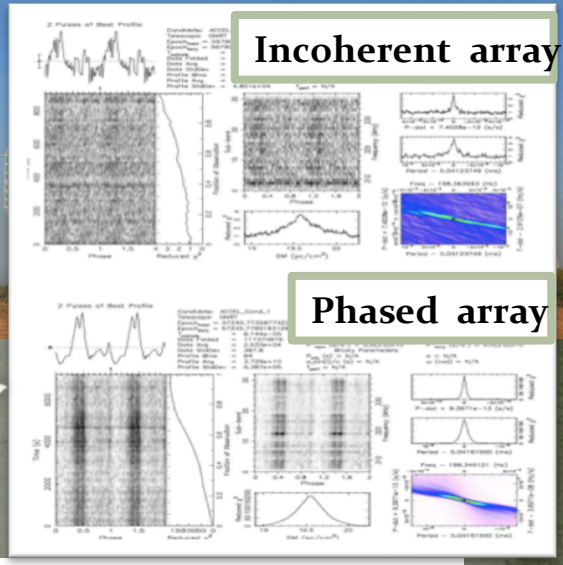
GHRSS Sensitivity 1.6 Jy for 10σ for 5ms
→ parameter space of 4 known FRBs

Full 500 hrs of GHRSS survey probe ~30% of FRB parameter space.
Gives a non detection limit of < 2100 $sky^{-1}day^{-1}$

Localisation with GMRT

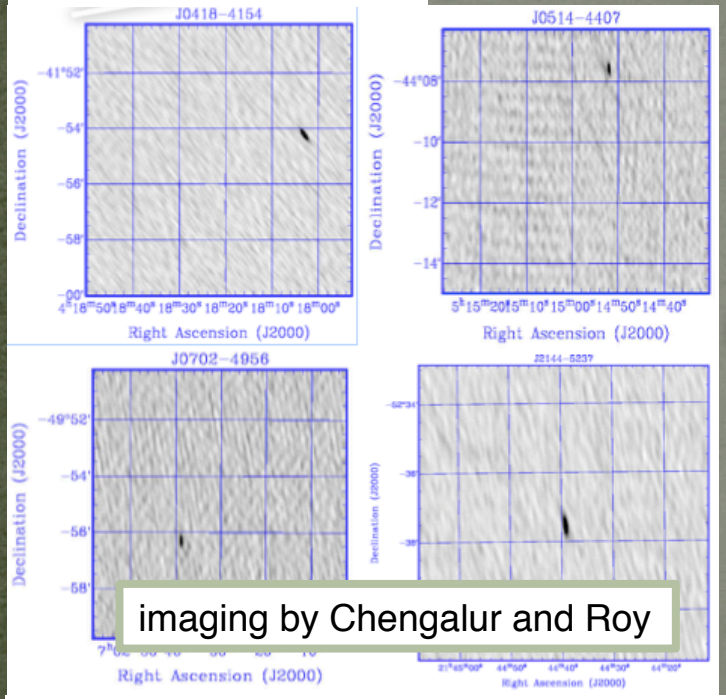
Pulsars : Discover → Localise → Time

FRBs : Discover → Localise → Identify host galaxy



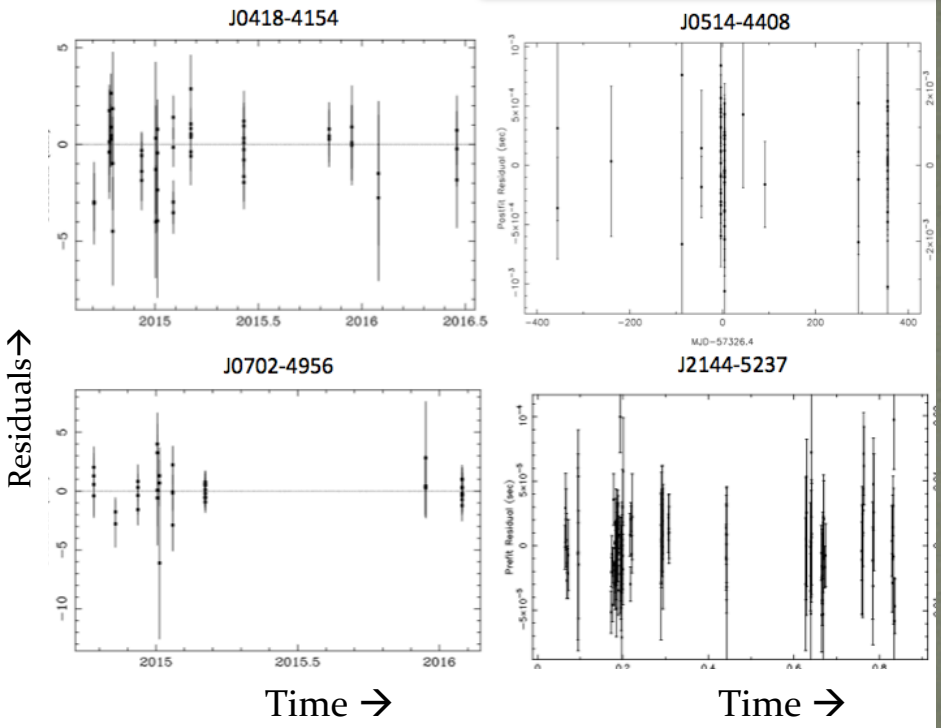
Enabling phased array observations

10” Localisation



imaging by Chengalur and Roy

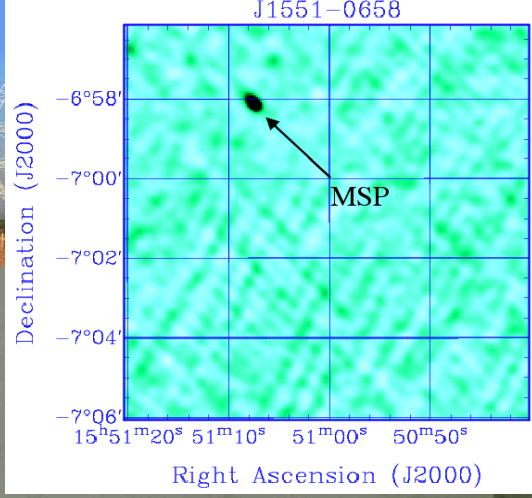
Timing Residuals

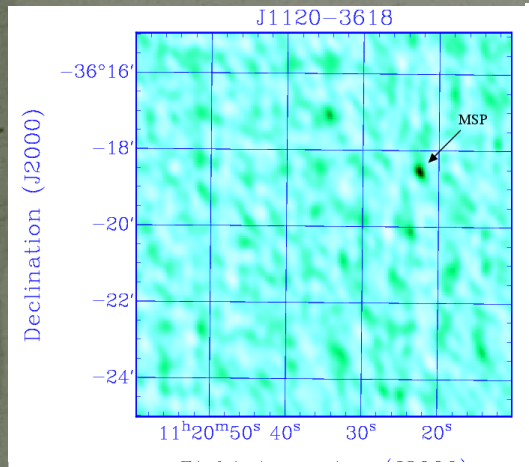


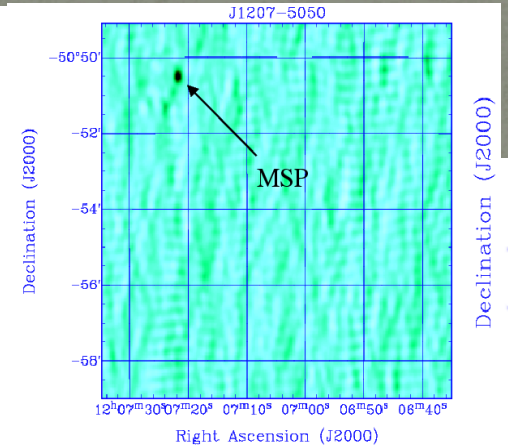
Convergence in timing with a priori arc-sec position

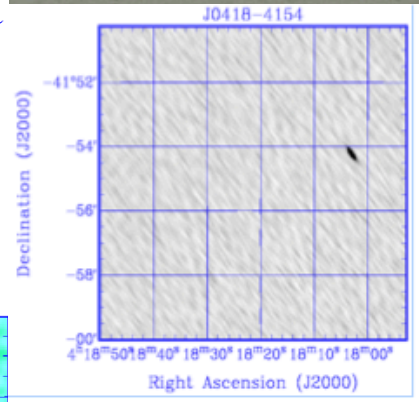
Pulsars discovered with SKA will have positions known up to 50”

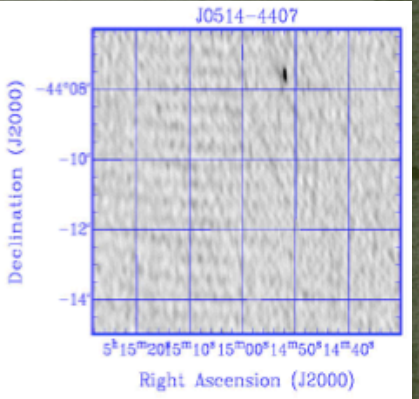
Localised pulsars

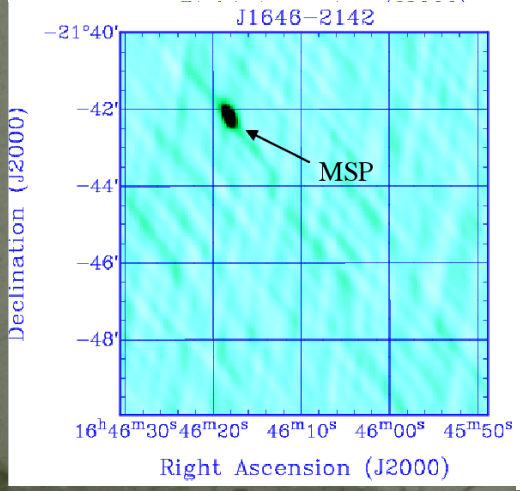


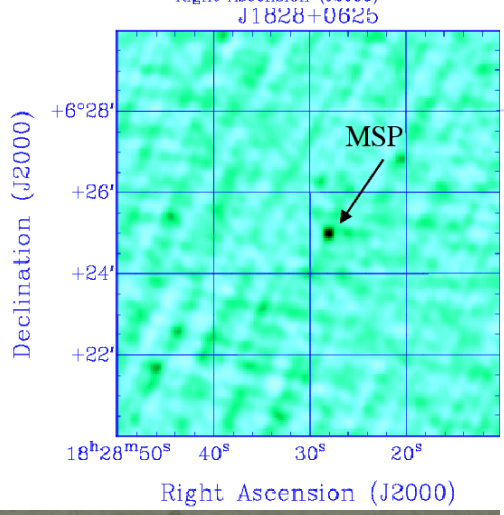


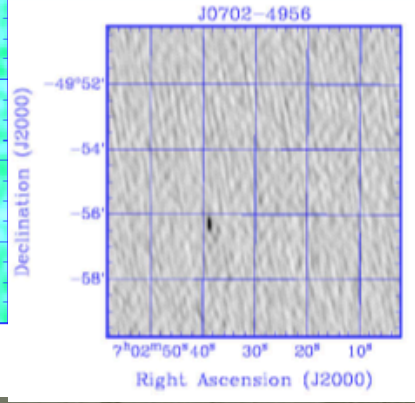


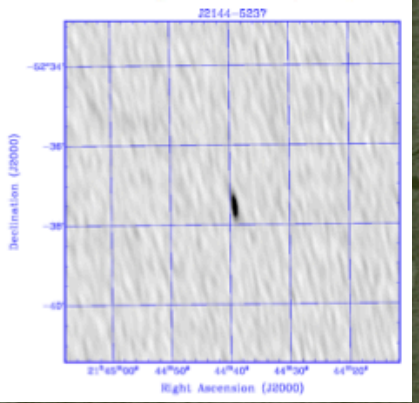




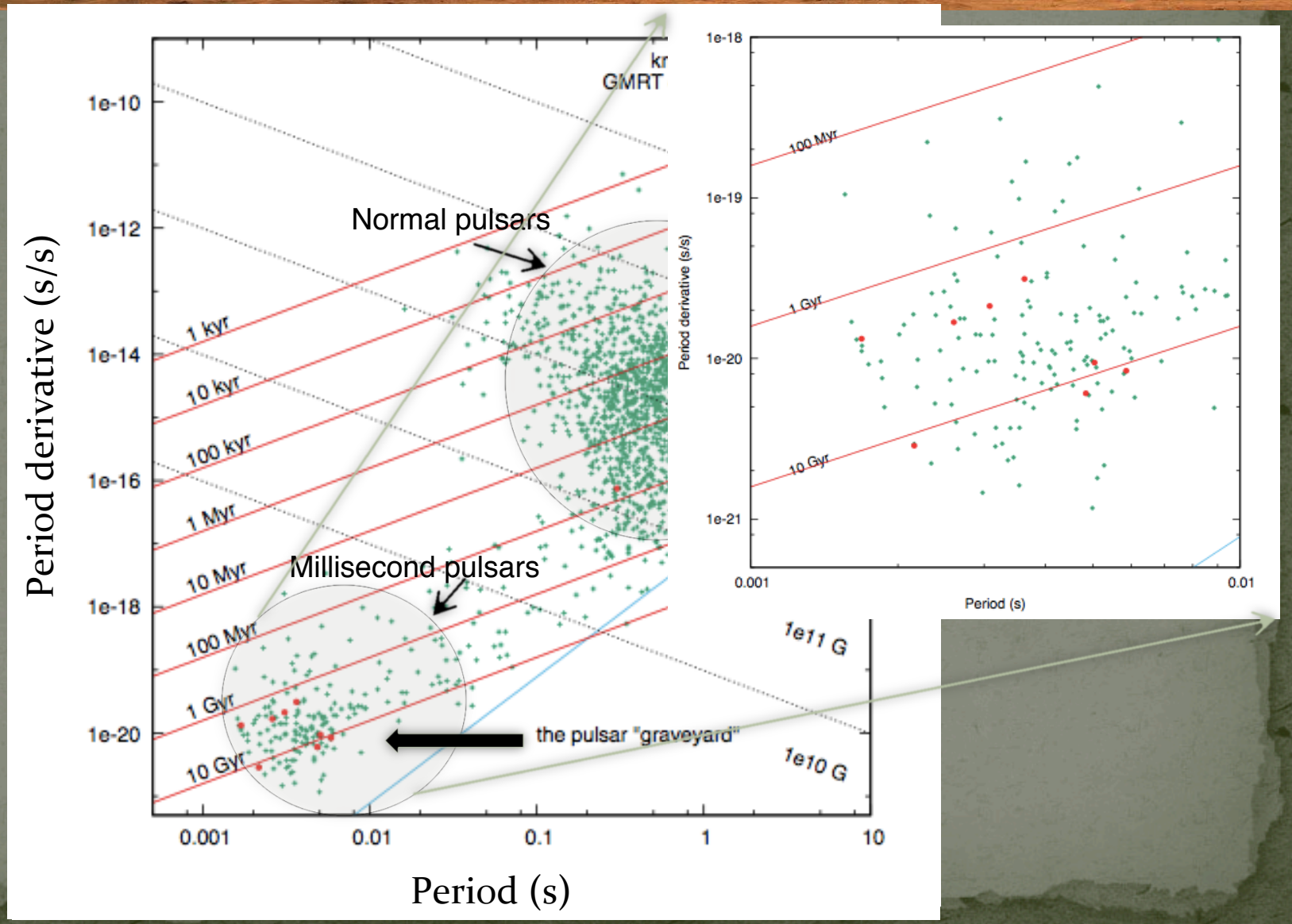








GMRT discoveries in P-Pdot



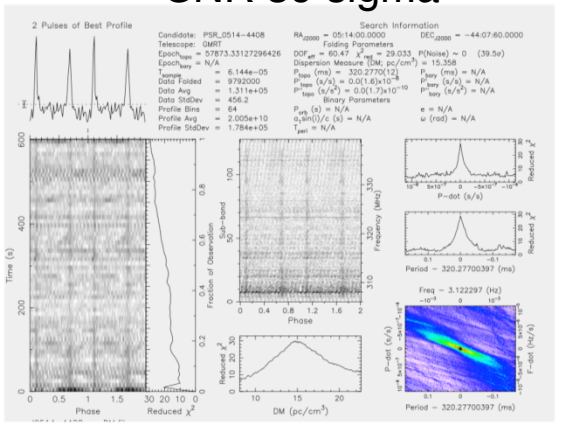
GHRSS in uGMRT era

GHRSS (0.5 mJy) 10% SKA1 → uGMRT (0.2 mJy) 1/4th SKA1 → SKA1 (0.05 mJy)

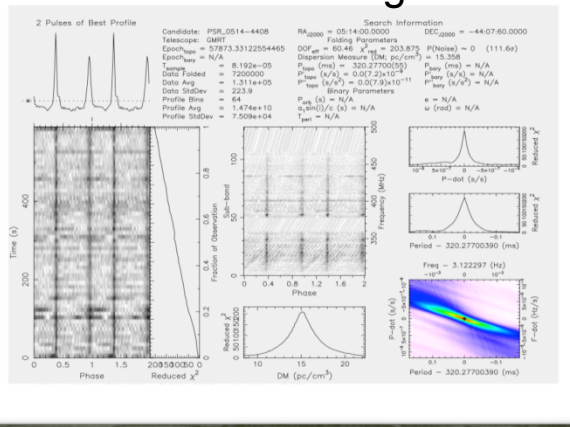
Parameter space

Galactic region	$\|b\| > 5°$
Declination	Dec>−54°, Dec<−20°
Integration time	600 s
Sampling time	64 μs
Bandwidth	250 MHz
Number of channels	8192 − 16384
Frequency Resolution	15 − 30 kHz
Data rate	125 − 250 MB/s
Pulsar Sensitivity	0.2 mJy at 5σ
Single pulse Sensitivity	0.5 Jy at 10σ for 5 ms
Single pulse fluence	1 Jy-ms
Data/pointing	75 − 150 GB
Total data	300 − 600 TB
Predicted discovery pulsar	120 PSR and 20 MSP
Predicted discovery FRB	40^{+15}_{-10}
Predicted discovery RRAT	> 10

SNR 39 sigma



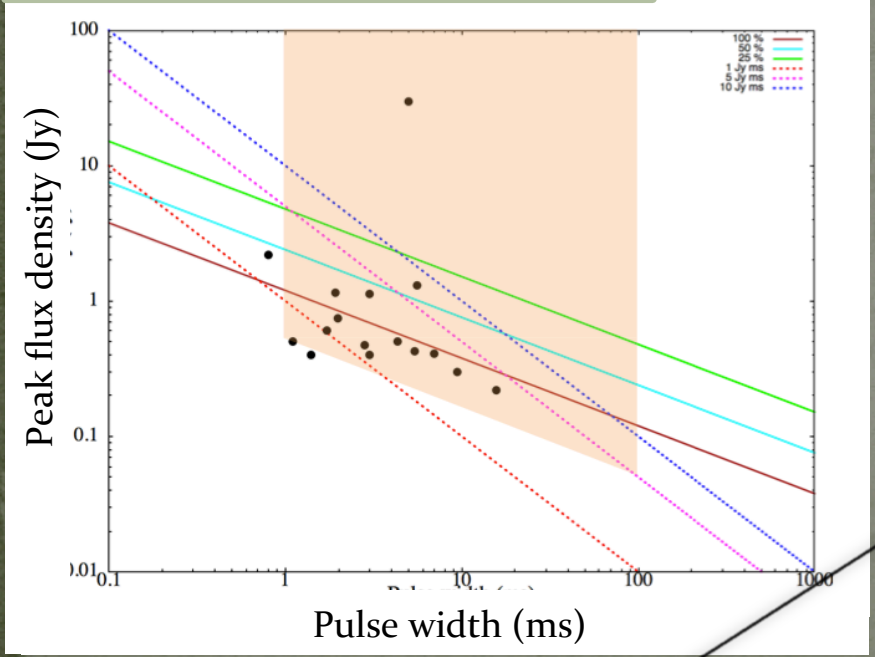
SNR 116 sigma



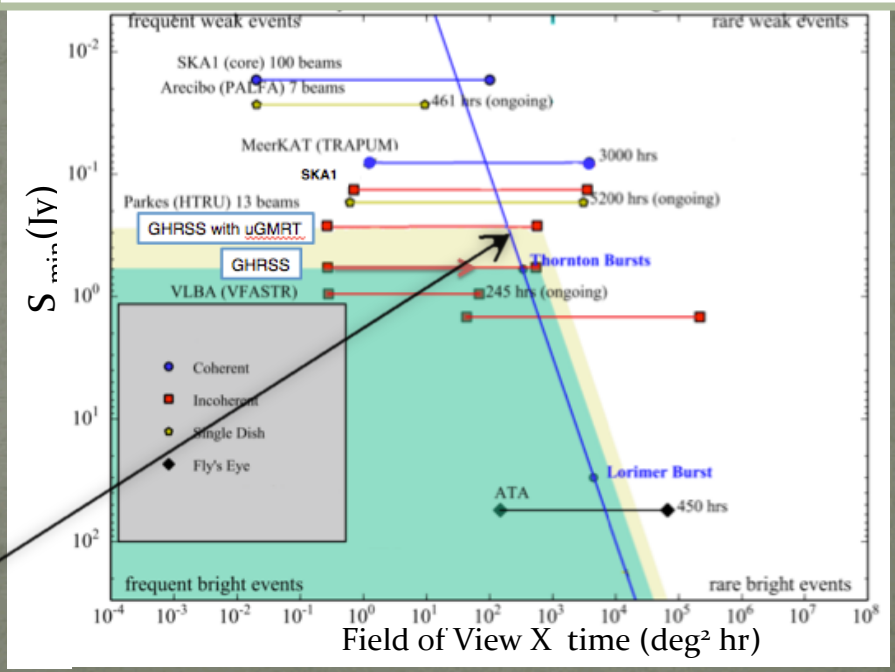
FRBs with uGMRT

No FRB detected < 800 MHz
Low frequency search important

Sensitivity for FRB searches



GHRSS with uGMRT on FRB parameter space



100 hrs of GHRSS with uGMRT cross single FRB detection line

Conclusion

Blind search for pulsar and FRBs :GHRSS

Discovery of 13 pulsars (including 1 MSP and 2 mildly recycled pulsars)
One of the highest pulsar per square degree discovery rate
Bhattacharyya et al. 2016

Localised the pulsars discovered in Fermi directed survey and GHRSS survey

Thanks for your attention

Localisation of pulsars and FRBs

Time-domain study with GMRT

Binary Evolution

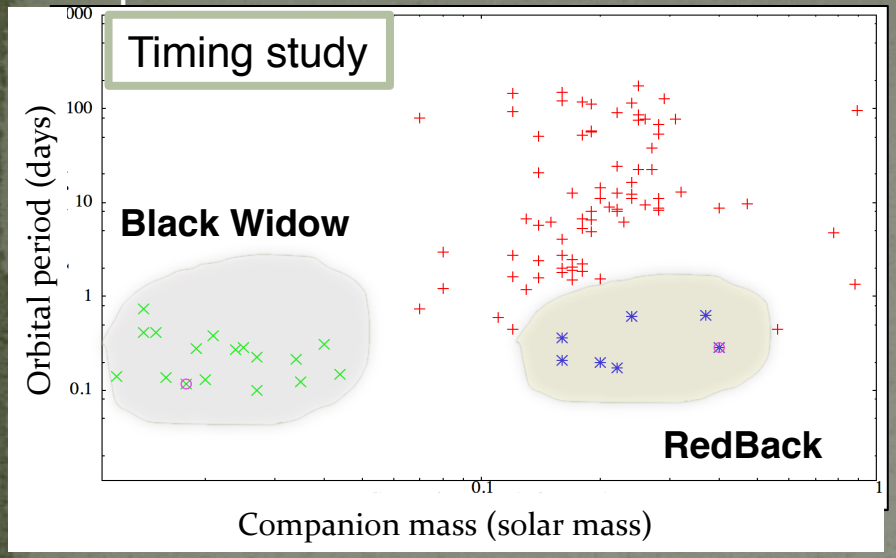
Discovered 8 pulsars
In Fermi directed survey.
Gamma-ray counterpart for all except one.

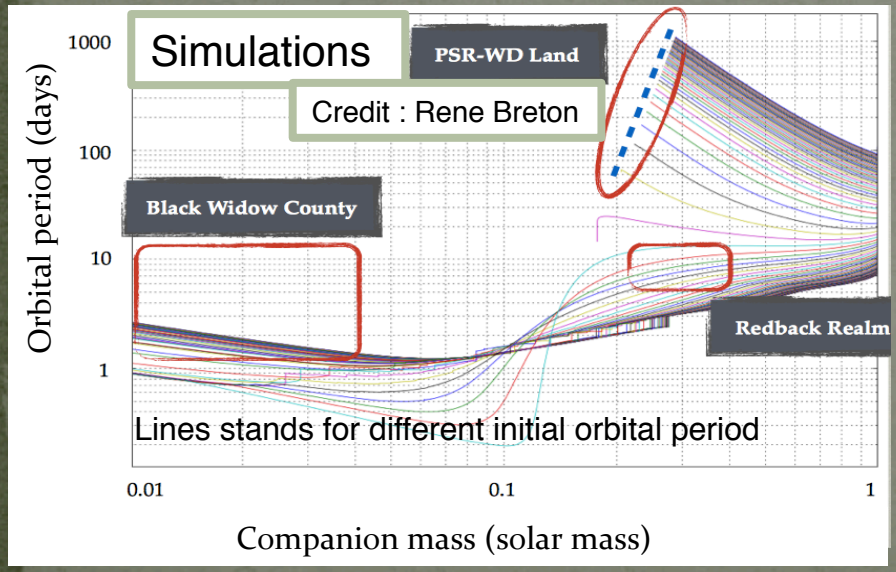
Spider MSPs with very low -mass companions
(1) Bhattacharyya et al. 2013
(2) Roy et al. 2015

Fermi directed search

Binary Evolution : list of Black Widows and Redbacks

Companion mass vs Orbital Period





Pulsar[1]	P_s (ms)	$\dot{E}/10^{34}$ [2] (erg/s)	d_{NE2001} (kpc)	P_B (hr)	M_c [3] (solar)	ref.
Old Black Widows						
B1957+20 F	1.61	11	2.5	9.2	0.021	Fruchter *et al.* (1990)
J0610−2100	3.86	0.23	3.5	6.9	0.025	Burgay *et al.* (2006)
J2051−0827	4.51	0.53	1.0	2.4	0.027	Stappers *et al.* (1996)
New Black Widows						
J2241−5236 F	2.19	2.5	0.5	3.4	0.012	Keith *et al.* (2011)
J2214+3000 F	3.12	1.9	3.6	10.0	0.014	Ransom *et al.* (2011)
J1544+4937 F	2.16	1.2	1.2	2.8	0.018	Bhattacharyya *et al.* (2012)
J1446−4701 F	2.19	3.8	1.5	6.7	0.019	Keith *et al.* (2012)
J1301+0833 F	1.84	6.8	0.7	6.5	0.024	Ray *et al.* (2012)
J1124−3653 F	2.41	1.6	1.7	5.4	0.027	Hessels *et al.* (2011)
J2256−1024 F	2.29	5.2	0.6	5.1	0.034	Boyles *et al.*(2011)
J2047+10 F	4.29	1.0	2.0	3.0	0.035	Ray *et al.* (2012)
J1731−1847	2.3	??	2.5	7.5	0.04	Bates *et al.*(2011)
J1810+1744 F	1.66	3.9	2.0	3.6	0.044	Hessels *et al.* (2011)
New Redbacks						
J1628−32 F	3.21	1.8	1.2	5.0	0.16	Ray *et al.* (2012)
J1816+4510 F	3.19	5.2	2.4	8.7	0.16	Kaplan *et al.* (2012)
J1023+0038 F	1.69	$\sim 5-10$	0.6	4.8	0.2	Archibald *et al.* (2009)
J2215+5135 F	2.61	6.2	3.0	4.2	0.22	Hessels *et al.* (2011)
J1723−28	1.86	??	0.75	14.8	0.24	Crawford *et al.* (2010)
J2215+5135 F	7.61	3.9	0.9	15.2	0.37	Hessels *et al.* (2011)

Total of 18 BWs and 8 RBs in Galactic field

Credit: Mallory Roberts

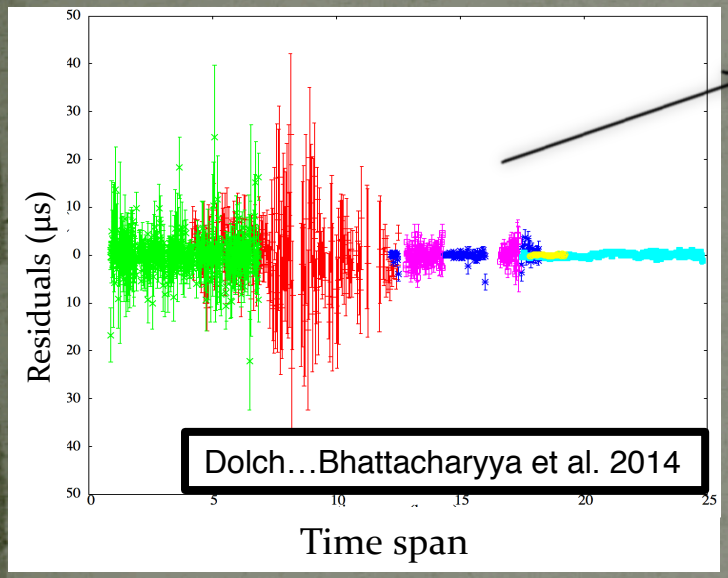
Black widow vs Red back depending on efficiency (Chen et al. 2013)

Probing Gravity

Team: Dolch, Ellis, Chatterjee, Cordes, Lam, Bassa, *Bhattacharya* et al.

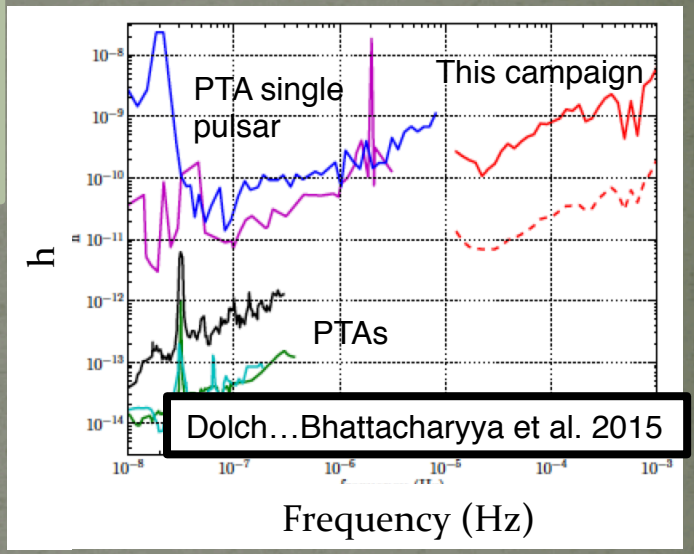
A day in life of millisecond pulsar J1713+0747 : one of the highest precision timer

L-band timing residual



Parkes → green
GMRT → red
Effelsberg → blue
WSRT → magenta
Arecibo → yellow
GBT → cyan

Single-source GW limits

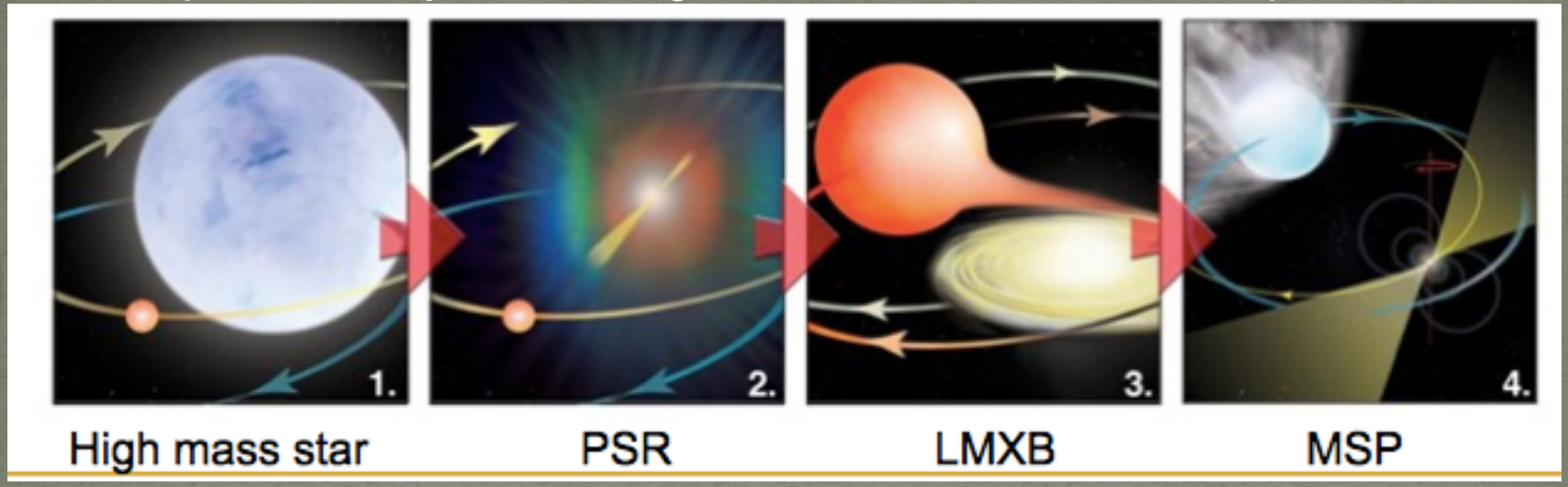


- ✓ All Telescope TOAs are aligned with clock offsets
- ✓ GMRT TOAs comparable with Parkes, except scintillation ~ 8 hrs
- ✓ Sensitive to GWs at 10^{-5} to 10^{-3} Hz.
- ✓ Best single source GW limit.
  At 10^{-5} Hz GW limit
  ~ 10^{-11} in PSR direction.

GMRT discoveries in PTAs : Two millisecond pulsars discovered with GMRT are candidate for inclusion in the IPTA.

Binary Evolution

Normal pulsars recycled through accretion → millisecond pulsars



Radakrishnan and Srinivasan 1982, Bhattacharya & van den Heuvel (1991)

Black Widow : Orbital period ~ few hrs
Companion mass ~ 0.02 $M_\odot$ → Missing link between Binary and Isolated MSPs

Redback : Orbital period ~ few hrs
Companion mass ~ 0.2 $M_\odot$ → LMXB-radio MSP transition
Pulsars are Redbacks

Probing Gravity

Team: Dolch, Ellis, Chatterjee, Cordes, Lam, Bassa, Bhattacharya et al.

Telescope	Offset from Global timing (ms)	verification
Parkes	0.54	J1227-4853
GBT	0.83	J1544+4937
Arecibo	0.76	-
WSRT	-1.82	-
Lovell	-1.72	-
Effelsburg	1.59	-

Dolch …Bhattacharyya…et al. ApJ 2014