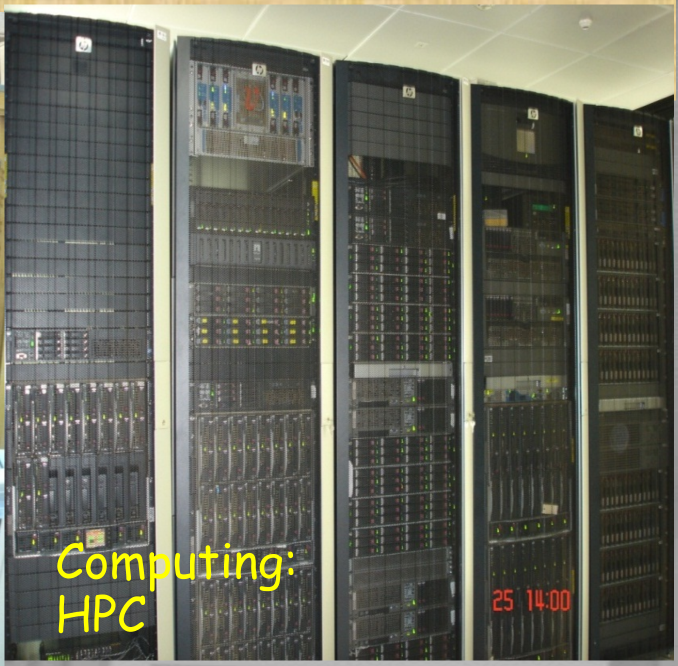
Probing neutron star laboratories using pulsars

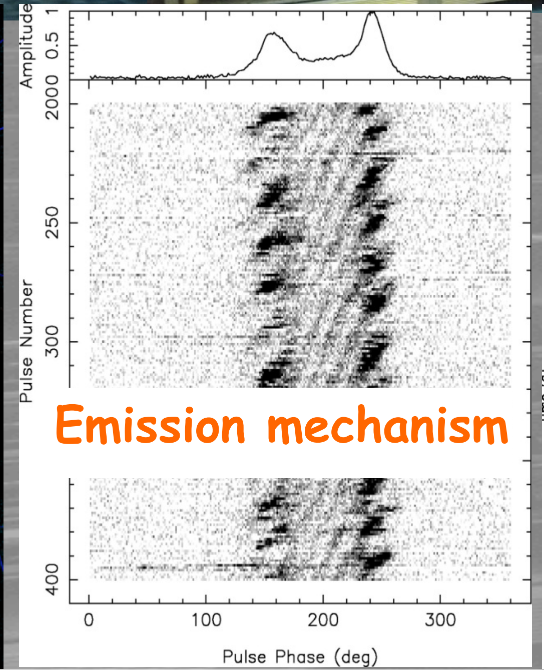
Observations:
GMRT

Backend:
GSB + GWB

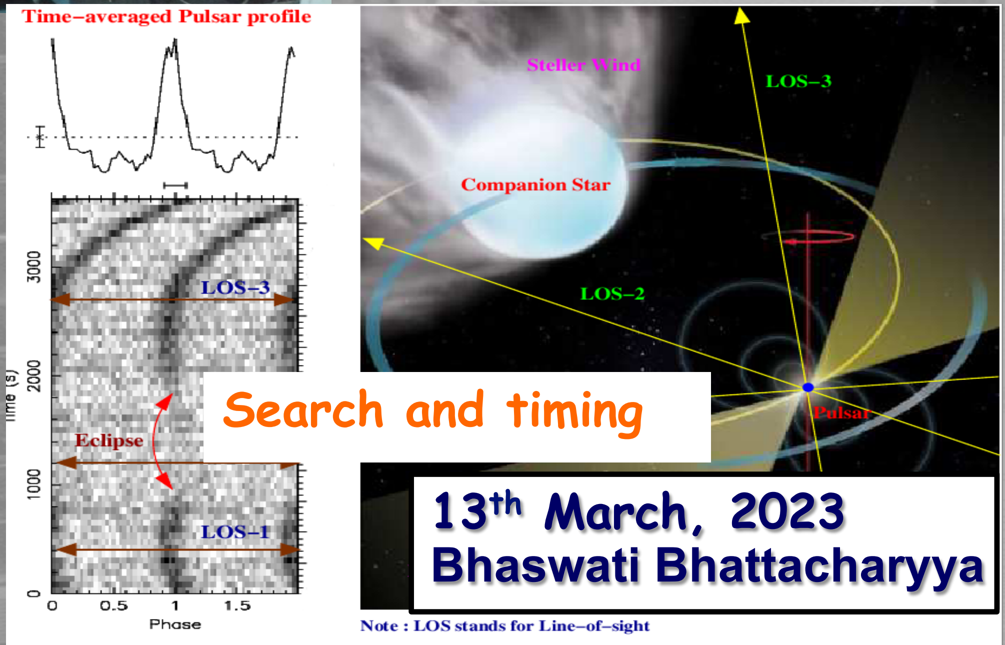


Computing:
HPC

Pulsar Research



Emission mechanism



Search and timing

Note : LOS stands for Line–of–sight

Artistic impression of a Black Widow system with real data of the discovered MSP

13th March, 2023
Bhaswati Bhattacharyya

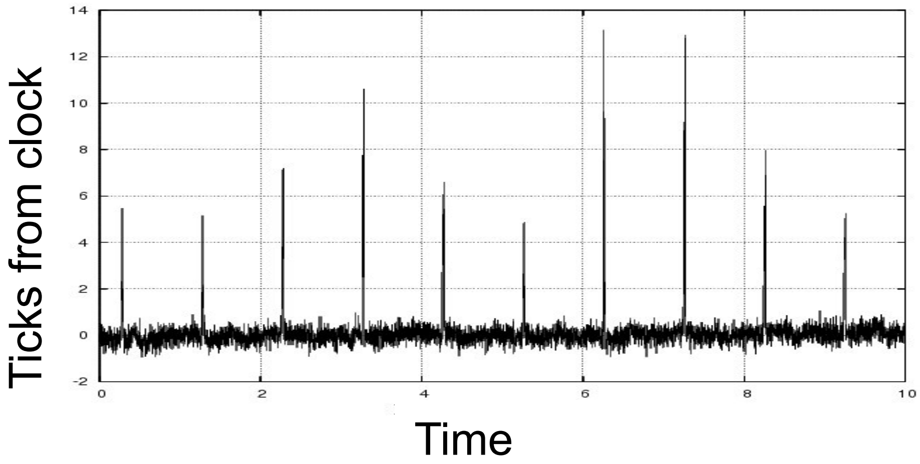
Let us start by checking our clocks

Take a look and tell me how precise is your clock?

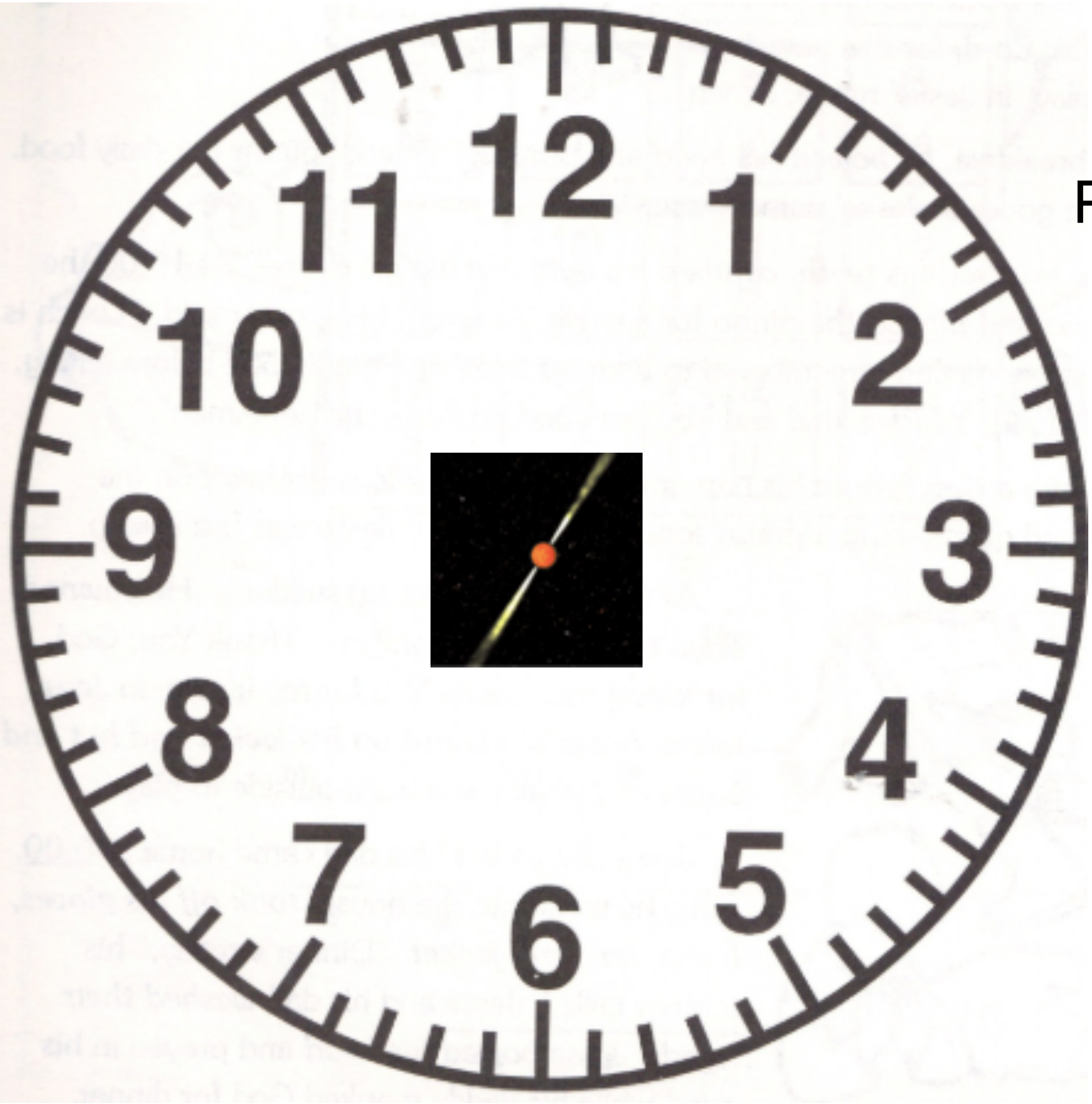
Let us start by checking our clocks

Take a look and tell me how precise is your clock?

a) 1s
b) 0.5s
c) 0.1s
d) None of above

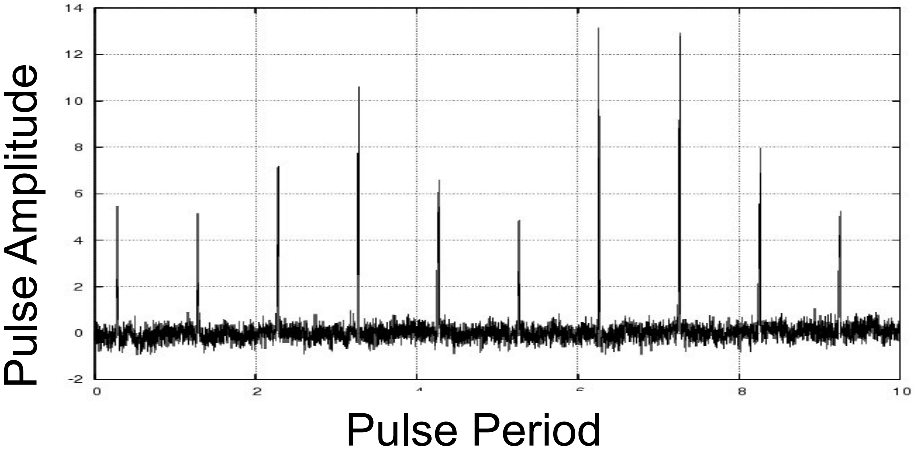


Pulsars are extremely precise clocks
Time keepers in sky



Ticks of a pulsar clock

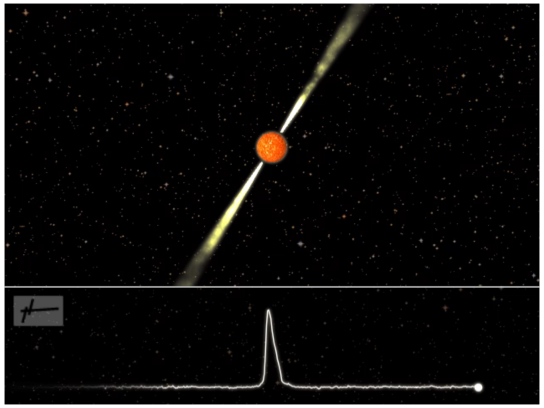
Pulses received from the pulsars



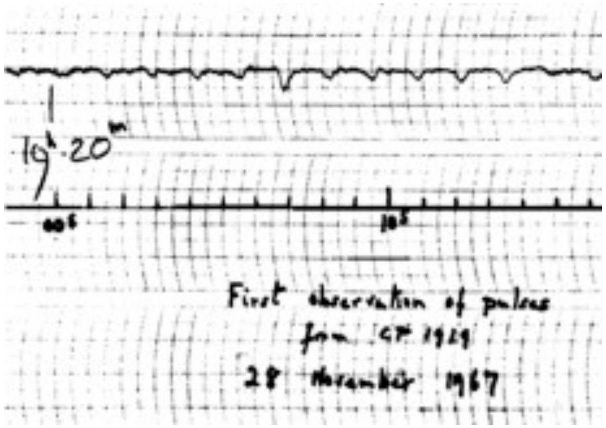
Plan of Talk

- ✓ Pulsars in a nutshell
- ✓ Neutron stars and pulsars – Early History 1930-1970
- ✓ Formation of pulsars
- ✓ Introduction to pulsars
  - Radio pulsars
  - Interstellar dispersion effect
  - Pulsar classification: normal pulsars and MSPs
  - Pulsars as astrophysical tools
- ✓ Search of pulsars
  - Targeted and Blind Radio surveys
- ✓ Timing of pulsars
- ✓ Investigation of emission mechanism
- ✓ Transient emission from neutron stars : RRATs

Pulsars in a Nutshell



Radio
Observations

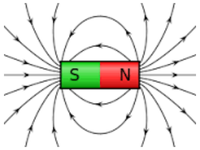


Light Houses

Pulsars are interstellar light houses

Pulsars are

Rapidly rotating – 1ms to 76s -- faster than kitchen blender

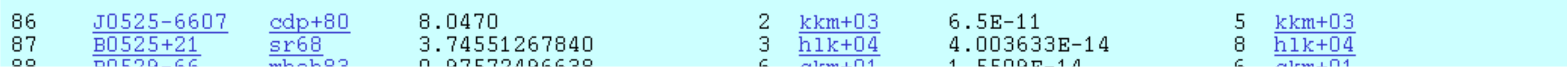


Strongly magnetised - 10^8 to 10^{15} G –100 billion times earth

Neutron stars – stellar undead of mass ~ 1.4 $M_\odot$ compressed to ~15 km

Very dense :500,000 earth masses in < 2 times Pune University

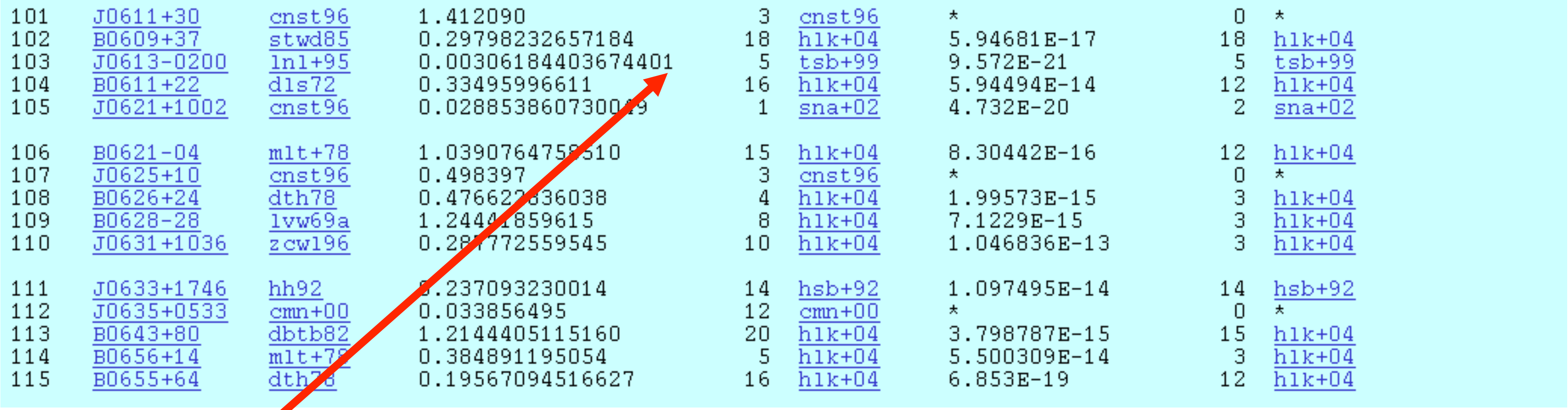
How precisely one can measure pulsar period?



86	J0525-6607	cdp+80	8.0470	2	kkm+03	6.5E-11	5	kkm+03
87	B0525+21	sr68	3.74551267840	3	hlk+04	4.003633E-14	8	hlk+04

Pulsar PSR J0613-0200:

- ✓ Rotation period: 0.003061844036744 01 +/- 0.00000000000000005 sec
- ✓ The precission we know it's period allows us to predict the arrival times of all incoming pulses for long (the next 10 million years)!
- ✓ It is the order of magnitude simillar to the best atomic clocks used on Earth!



101	J0611+30	cnst96	1.412090	3	cnst96	*	0	*
102	B0609+37	stwd85	0.29798232657184	18	hlk+04	5.94681E-17	18	hlk+04
103	J0613-0200	lnl+95	0.00306184403674401	5	tsb+99	9.572E-21	5	tsb+99
104	B0611+22	dls72	0.33495996611	16	hlk+04	5.94494E-14	12	hlk+04
105	J0621+1002	cnst96	0.028853860730049	1	sna+02	4.732E-20	2	sna+02
106	B0621-04	mlt+78	1.0390764758510	15	hlk+04	8.30442E-16	12	hlk+04
107	J0625+10	cnst96	0.498397	3	cnst96	*	0	*
108	B0626+24	dth78	0.476622836038	4	hlk+04	1.99573E-15	3	hlk+04
109	B0628-28	lvw69a	1.24441859615	8	hlk+04	7.1229E-15	3	hlk+04
110	J0631+1036	zcwl96	0.287772559545	10	hlk+04	1.046836E-13	3	hlk+04
111	J0633+1746	hh92	0.237093230014	14	hsb+92	1.097495E-14	14	hsb+92
112	J0635+0533	cmn+00	0.033856495	12	cmn+00	*	0	*
113	B0643+80	dbtb82	1.2144405115160	20	hlk+04	3.798787E-15	15	hlk+04
114	B0656+14	mlt+78	0.384891195054	5	hlk+04	5.500309E-14	3	hlk+04
115	B0655+64	dth78	0.19567094516627	16	hlk+04	6.853E-19	12	hlk+04

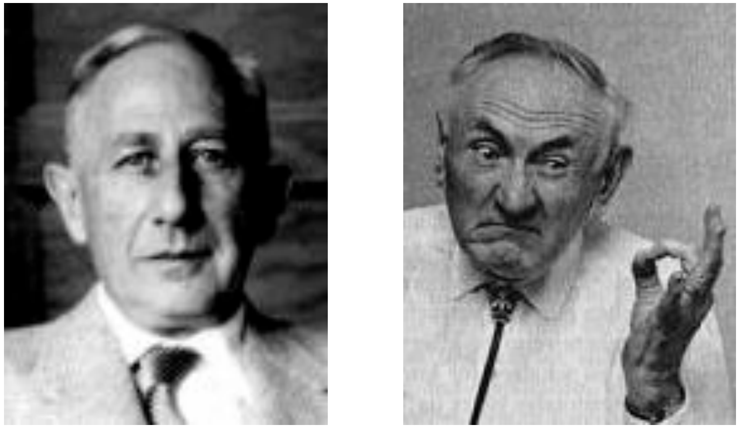
From ATNF pulsar catalogue:
http://atnf.csiro.au/research/pulsar/psrcat/

Seventeenth significant digit!!!

The fastest pulsar is PSR J1748-2446ad, which is rotating 713 times per second.

Neutron Stars and Pulsars – Early History
Time line : 1930 - 1970

Neutron Stars and Pulsars – Early History



Walter Baade & Fritz Zwicky 1934

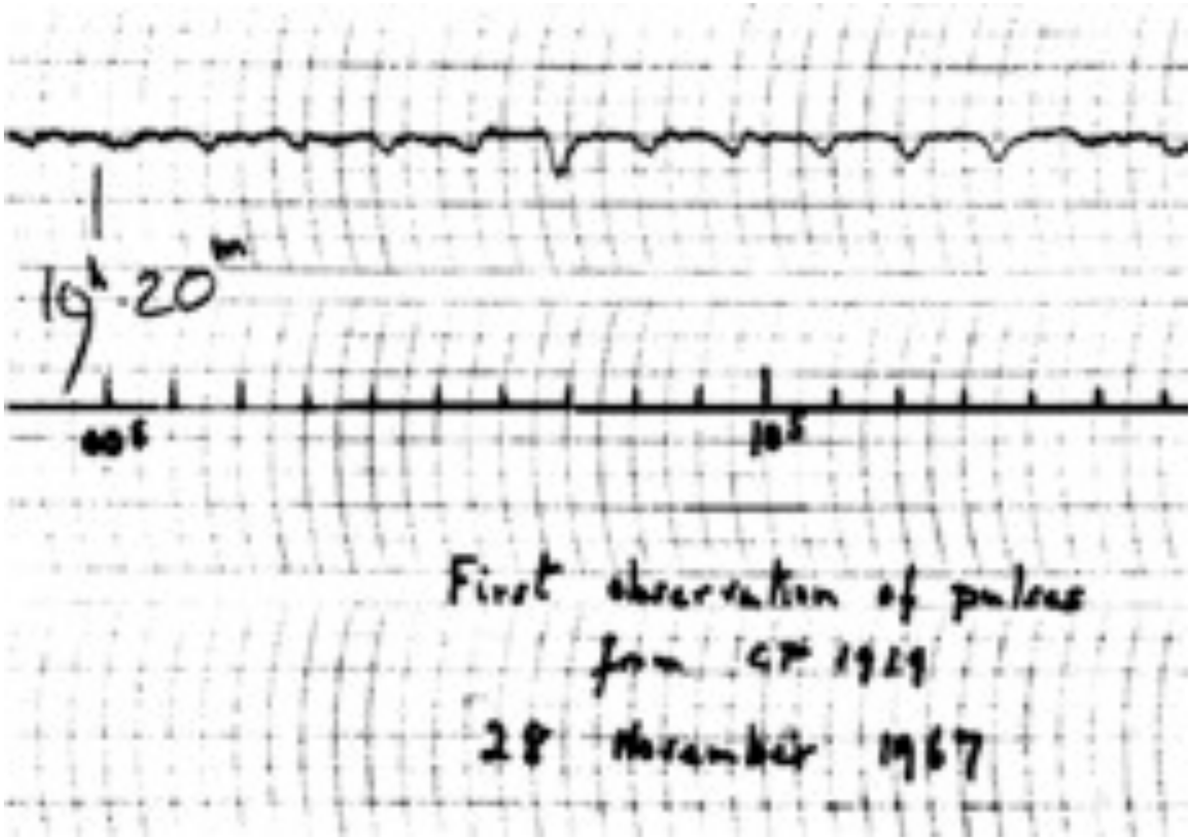
Proposed existence of a new form of star : **neutron star**

Franco Pacini 1967

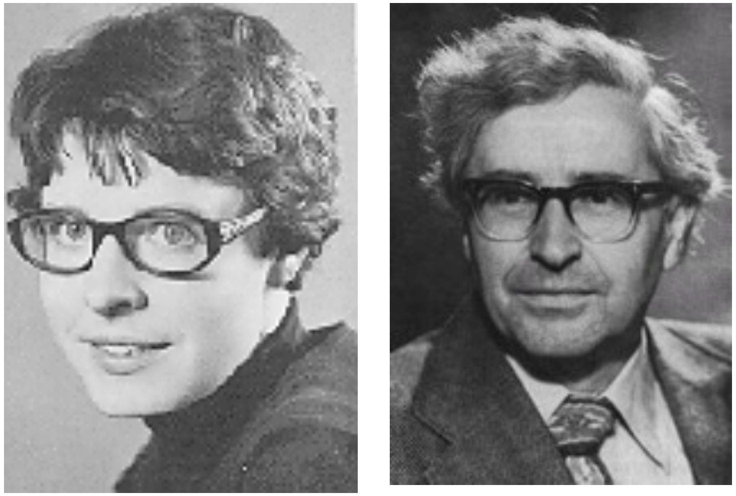
Rapid rotation of highly magnetised neutron star as the energy source

Neutron Stars and Pulsars – Early History

Jocelyn Bell (graduate student), Antony Hewish et al. 1967



First observation of pulsar
from CP 1919
28 November 1967

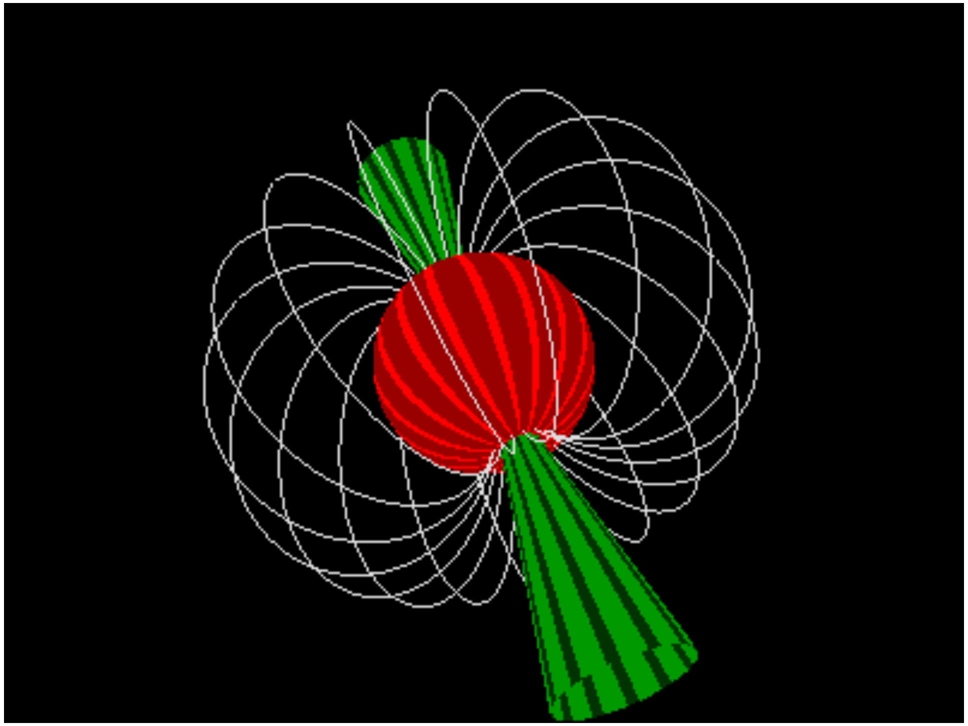


Discovery of radio pulsars → **Nobel Prize in 1974**

Neutron Stars and Pulsars – Early History

Franco Pacini 1968

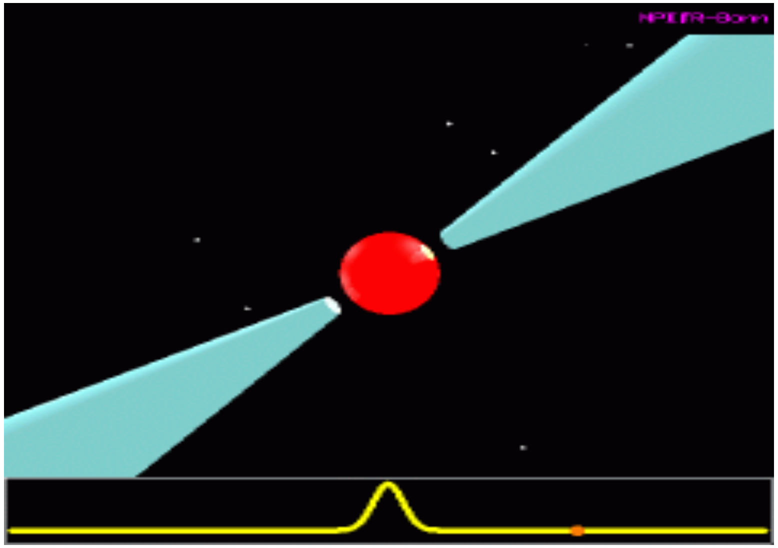
✓"Pulsars" are formed after supernovae explosion !



Neutron Stars and Pulsars – Early History

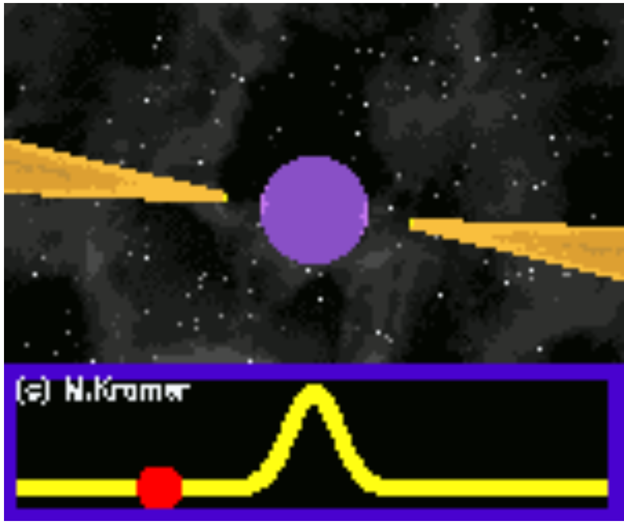
Tommy Gold 1968
: Pulsars are rotating neutron stars

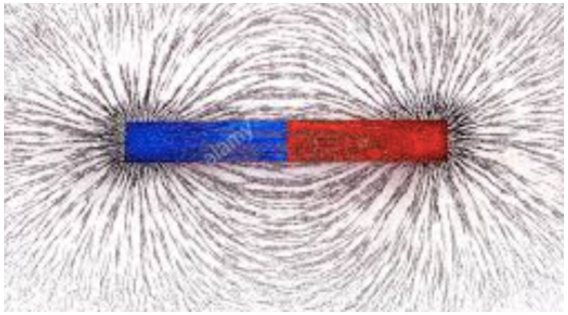
Lighthouse model of pulsations



Radio pulsars

Pulsars : Rapidly rotating strongly magnetized neutron stars





Magnetic field of refrigerator = ?

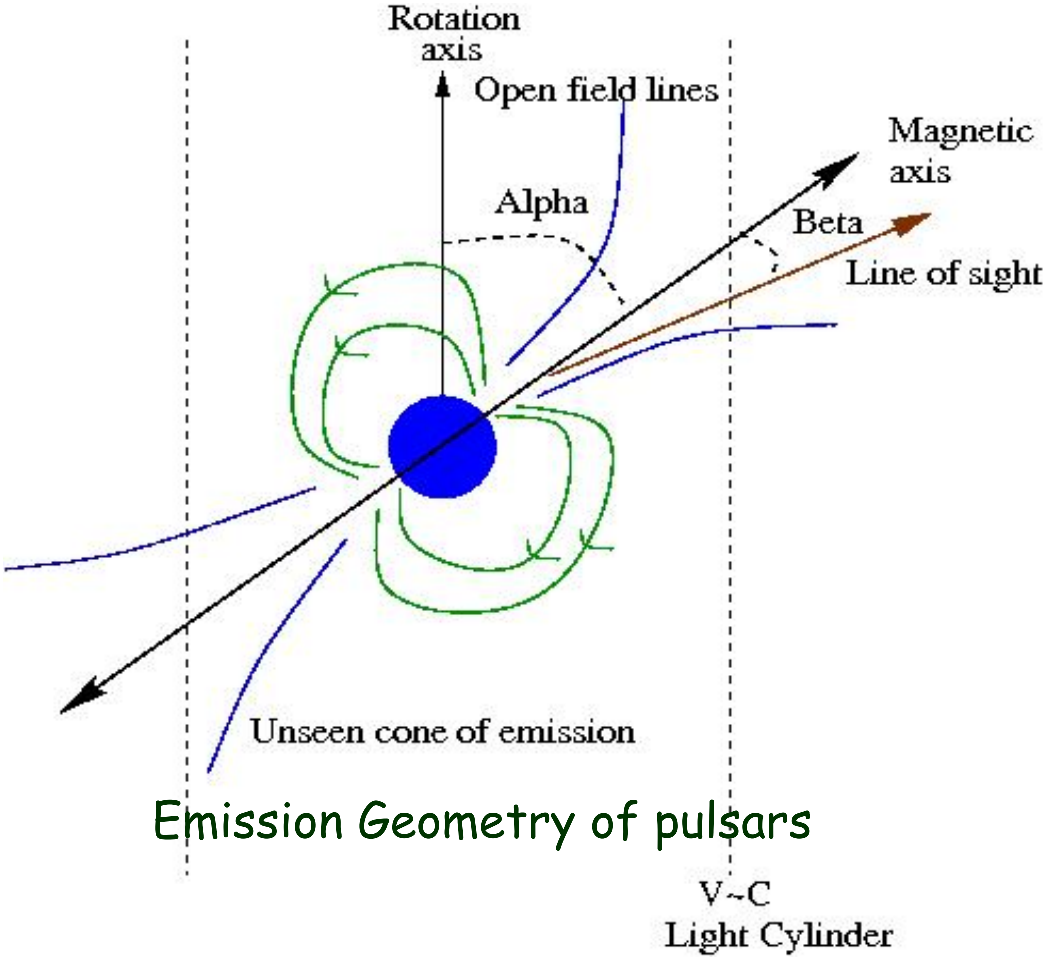
Magnetic filed of typical bar magnet = ?

Magnetic field of Earth = ?

Magnetic field of Sun = ?

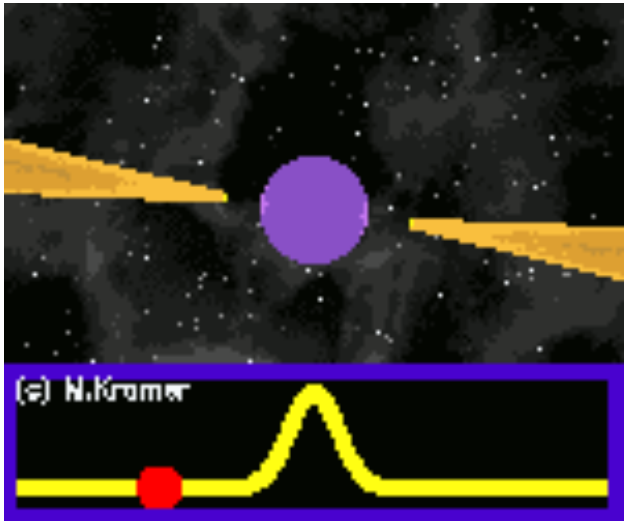
Strongest magnet in Earth = ?

Magnetic field of Neutron star = ?

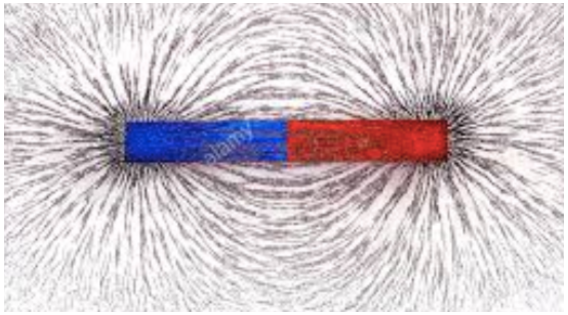


Emission Geometry of pulsars

Pulsars : Rapidly rotating strongly magnetized neutron stars



Neutron stars : Highly magnetized laboratories in sky



Magnetic field of refrigerator = 100 G

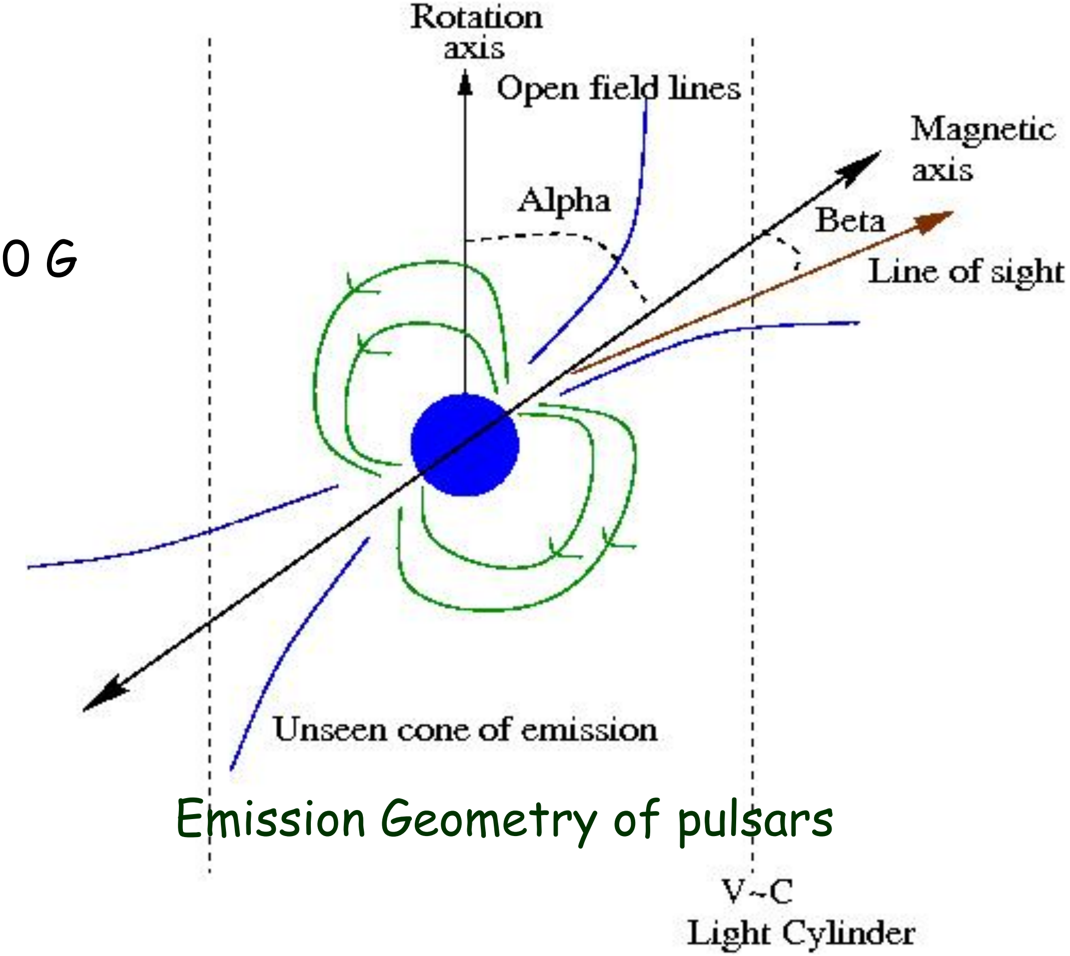
Magnetic filed of typical bar magnet = 10-100 G

Magnetic field of Earth = 0.5 G

Magnetic field of Sun = 0.3 G

Strongest magnet in Earth = 25,0000 G

Magnetic field of Neutron star 10^8 to 10^{15} G –100 billion times Earth



Emission Geometry of pulsars

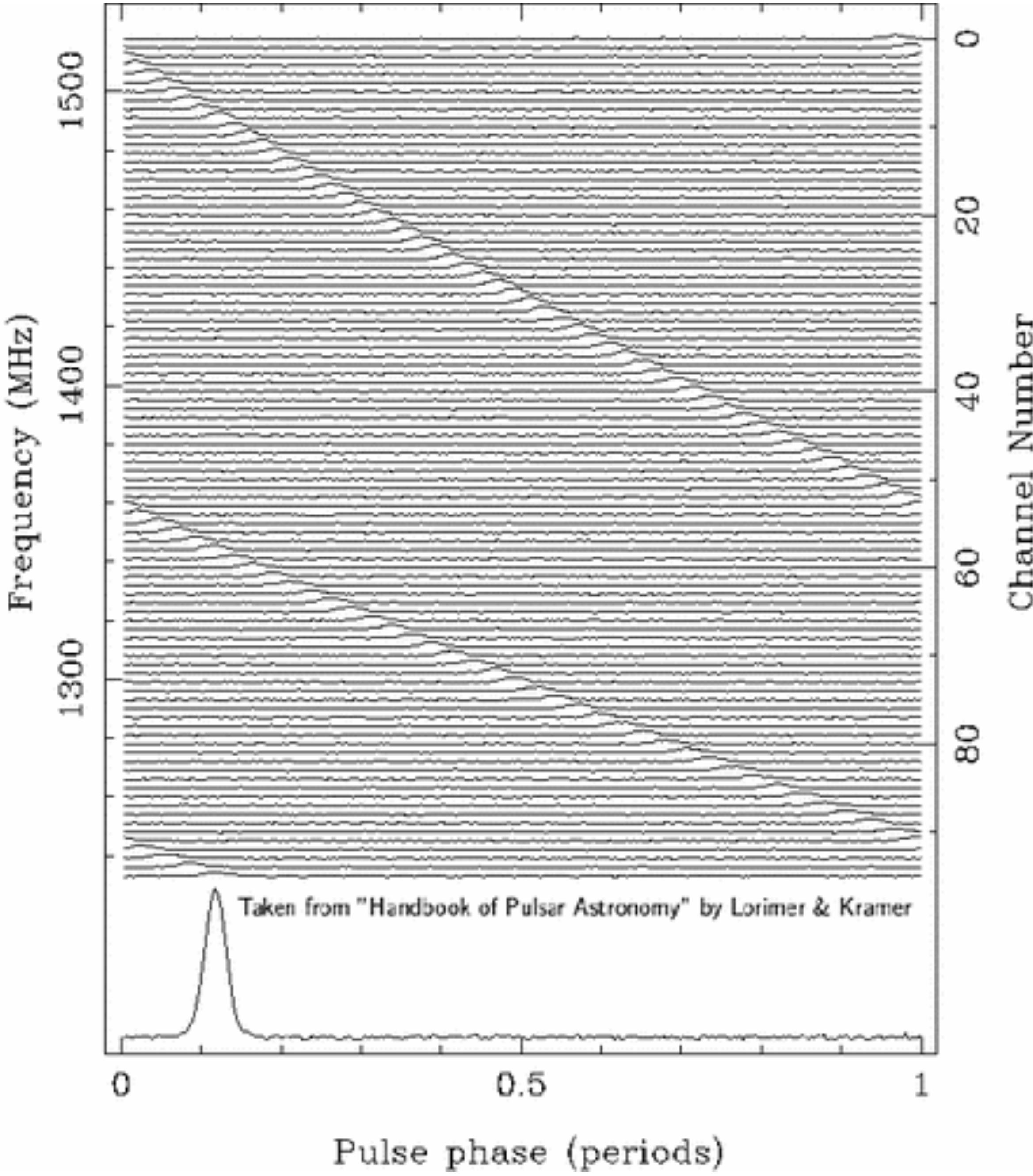
Interstellar dispersion effect:

Interstellar medium

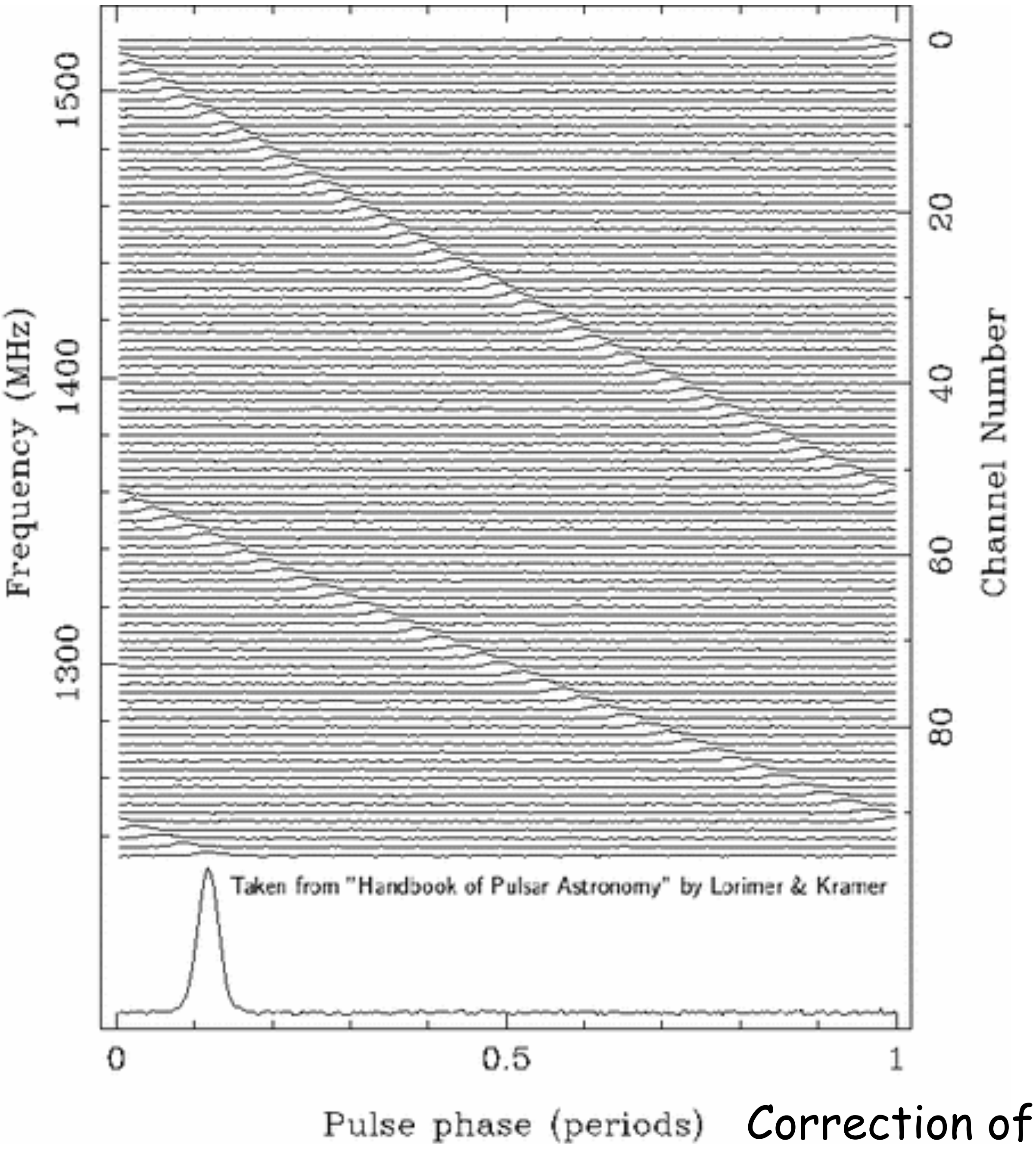
↓

Dispersive medium for radio waves

Different radio frequencies travel at differnet speeds


Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Interstellar dispersion effect:



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Interstellar medium (in fact the free electrons in it) is a dispersive medium for radio waves.

Radio waves of different frequencies have different speeds, while traveling through such medium

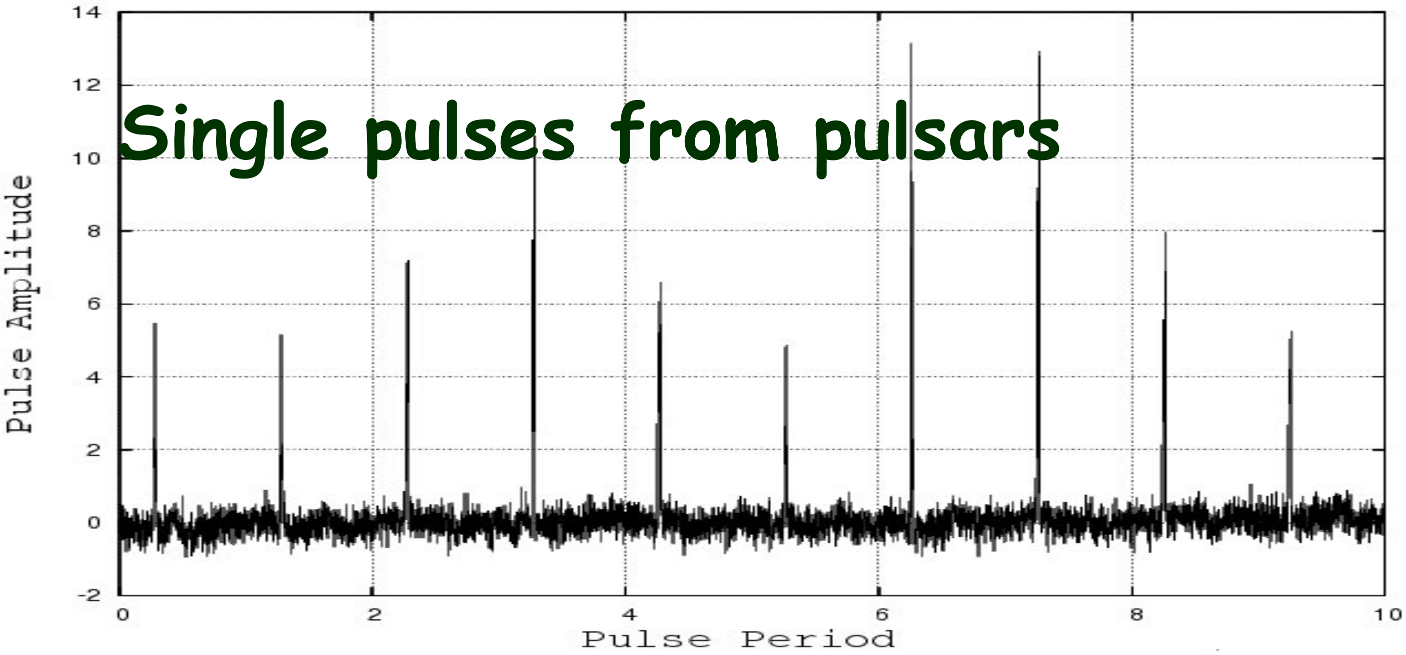
The effect is such, that the pulse comes at higher frequencies first (the speed of its travel is higher), at lower frequencies later.

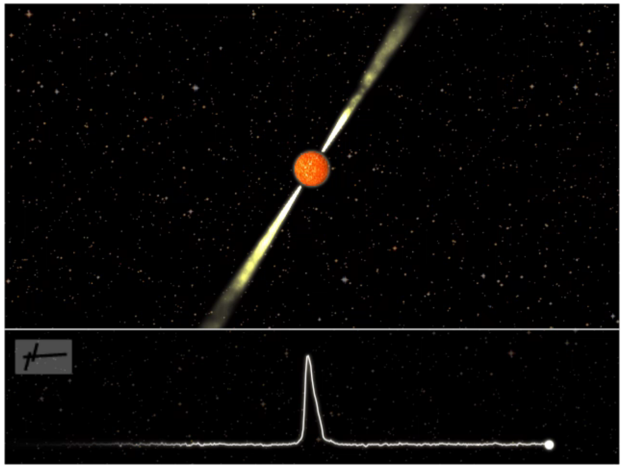
Correction of this effect is called **de-dispersion**

Pulsars

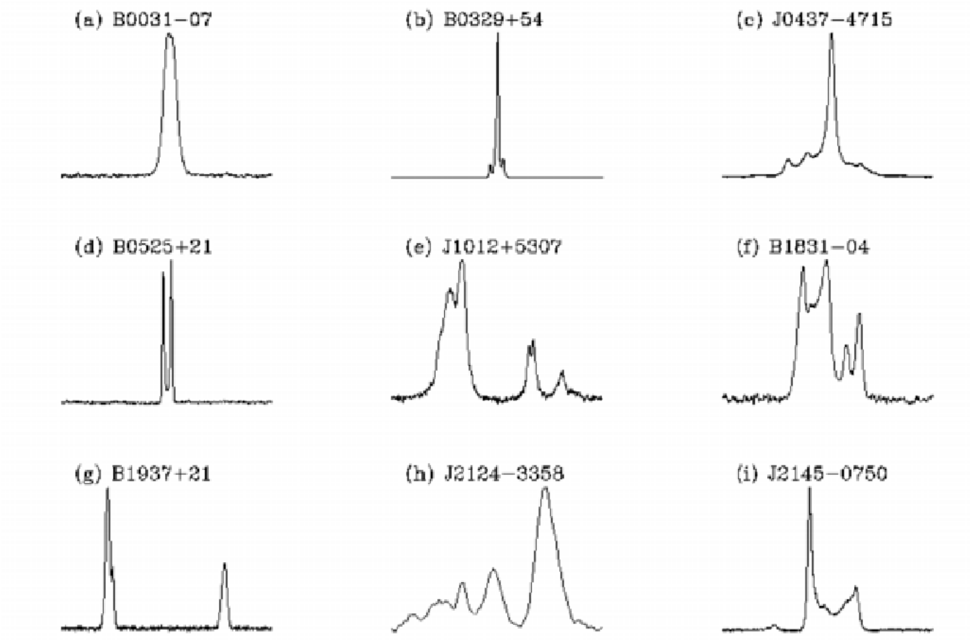
Rapidly rotating strongly magnetized neutron stars

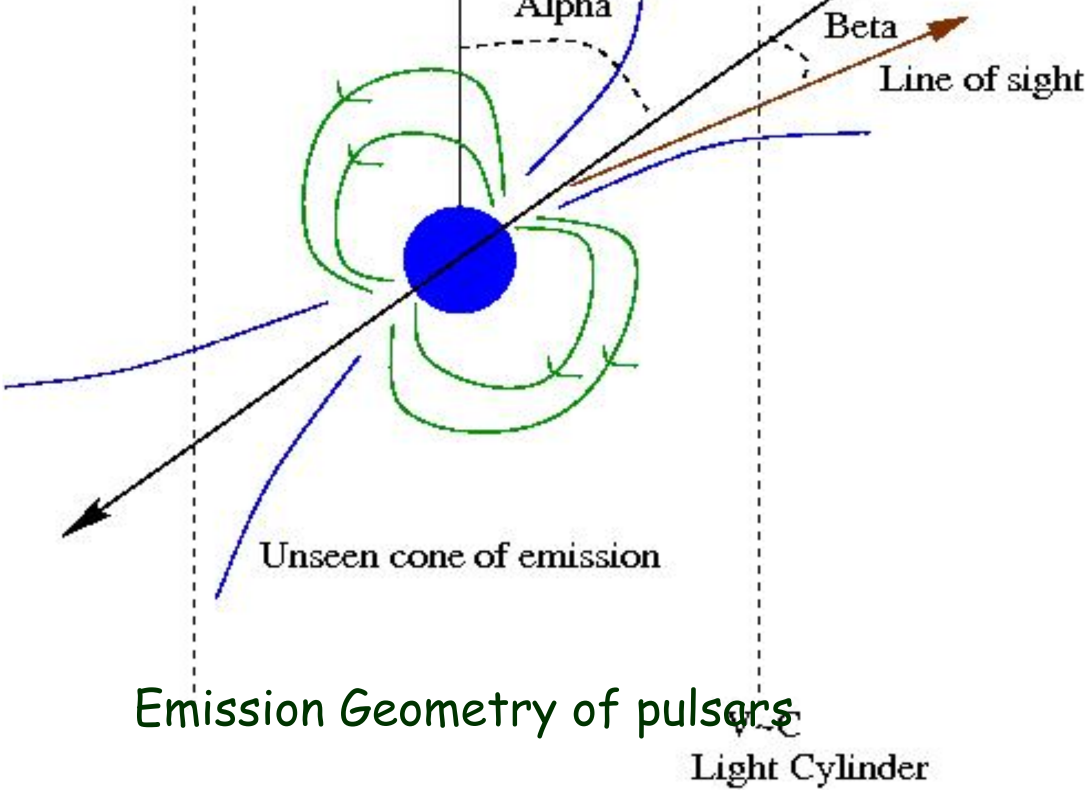
Single pulses from pulsars





Average pulse profile of pulsars





Emission Geometry of pulsars

Dispersion measure (DM)

DM is defined as the integrated line of sight electron column density.
Each pulsar has its own DM value.

$$\boxed{\mathrm{DM} = \int_0^d n_e \, \mathrm{d}l}$$

✓ Dispersion measure tells us about the space between Earth and the pulsar. Electrons in the ISM disperse the pulsar's signal (hence the name "dispersion measure"), causing lower observing frequencies to arrive later than higher observing frequencies.

✓ The dispersion measure is a way of telling us how many electrons the signal encountered on it's way to Earth. The larger the dispersion measure, the more electrons the signal encountered.

⬇

This could happen for two reasons – either the pulsar is very far away,
or the density of electrons in the space between Earth and the pulsar is relatively high.

Correction of this dispersion effect is called **de-dispersion**

De-dispersion

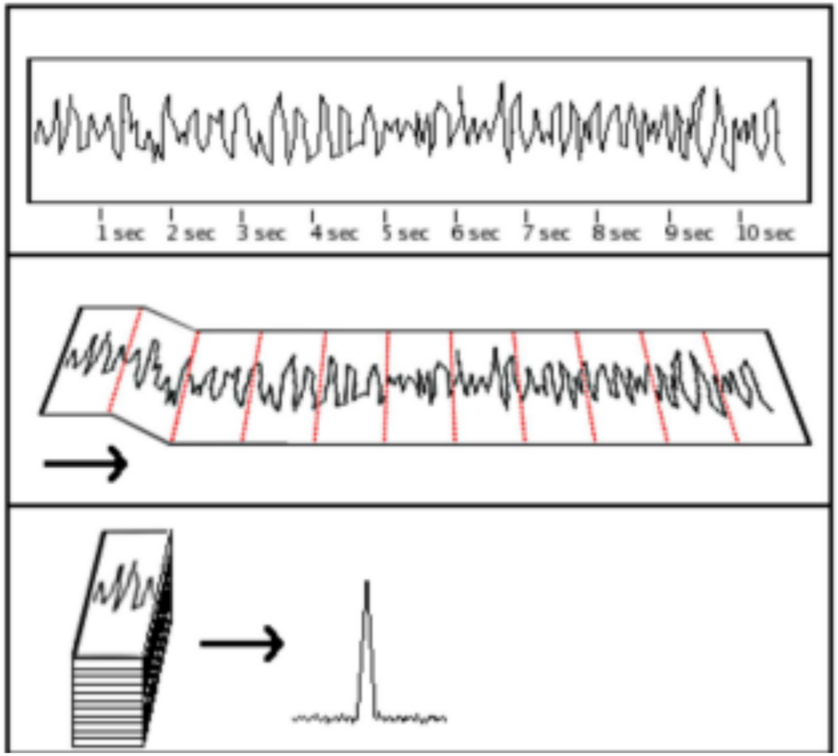
Correction of dispersion effect

$$\Delta t = \frac{\mathrm{DM}}{2.41 \times 10^{-4}} \left(\frac{1}{\nu_{\mathrm{low}}^2} - \frac{1}{\nu_{\mathrm{high}}^2} \right)$$

Input: raw data
Output: de-dispersed time series

Folding

Combine many pulses together to build up detectable signals

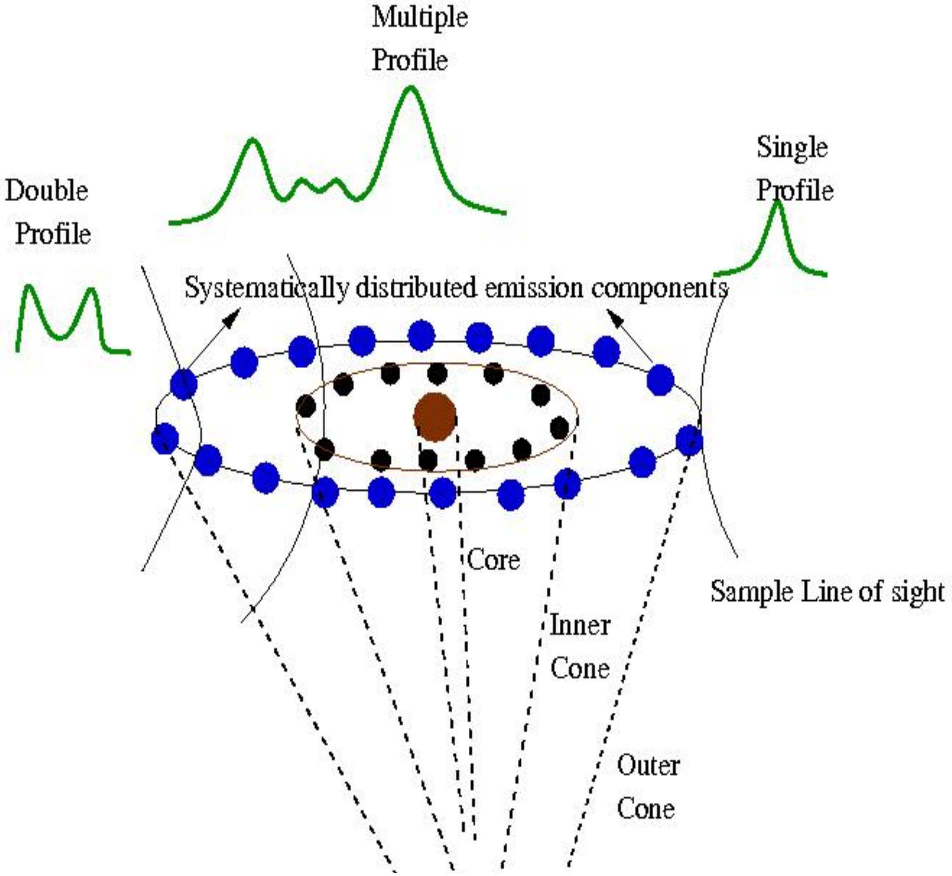


Input: de-dispersed time series
Output: average profile

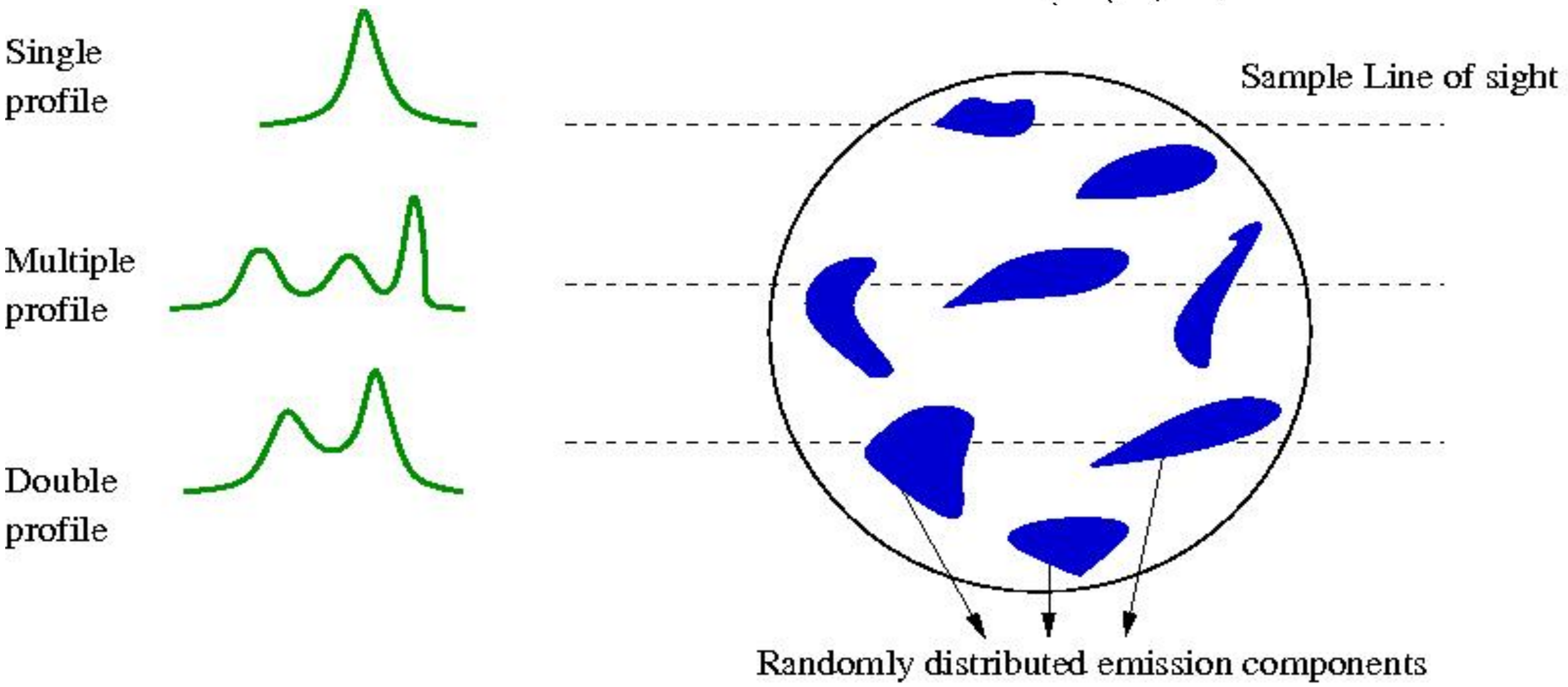
Credit : http://pulsarsearchcollaboratory.com/wp-content/uploads/2016/01 PSC_search_guide.pdf

Phenomenological models of pulse shapes produced by different LOS cuts across the beam

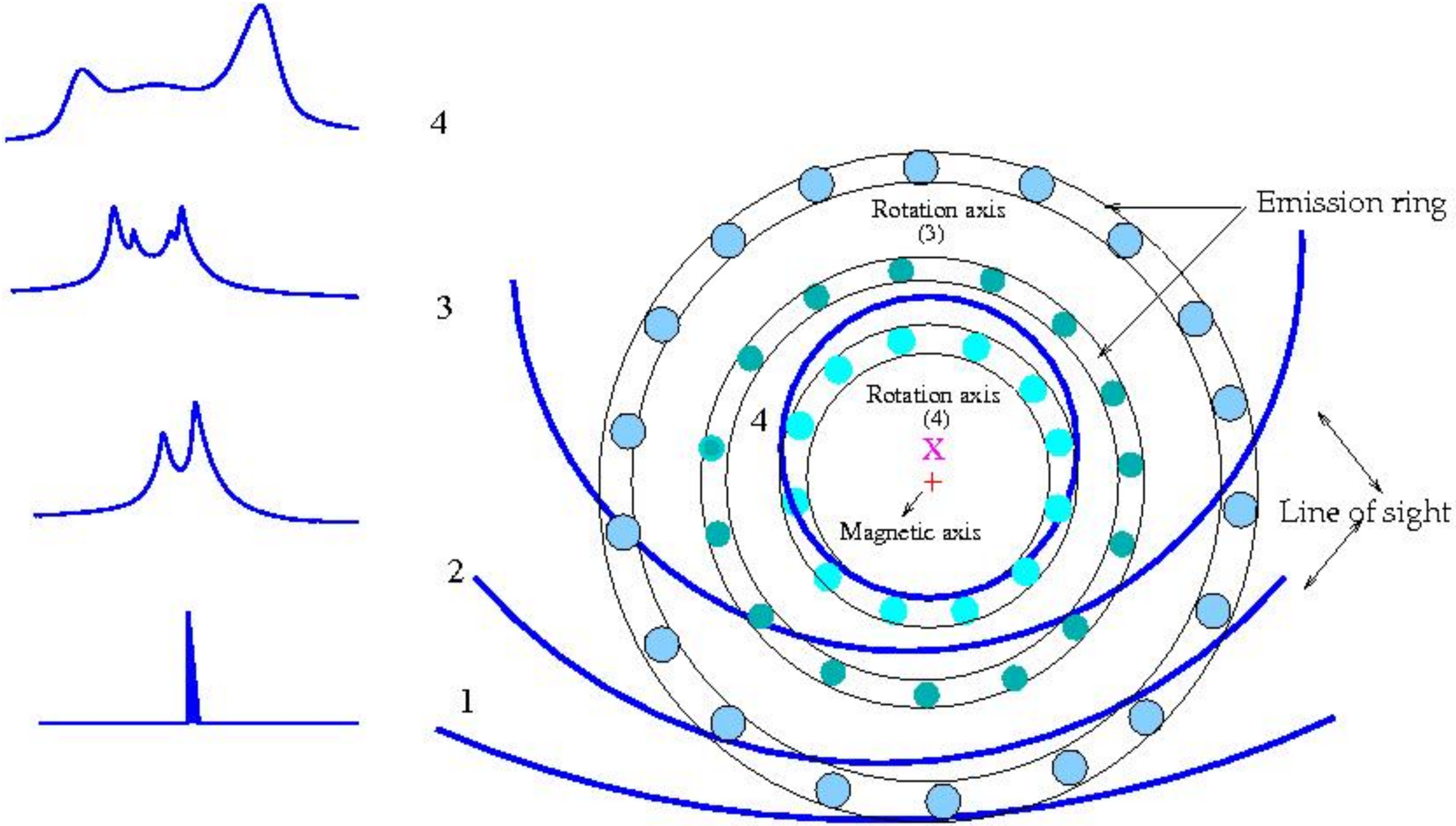
(1) Core – Conal Model
(Rankin 1993)



(2) Patchy beam Model
(Lyne & Manchester 1988)

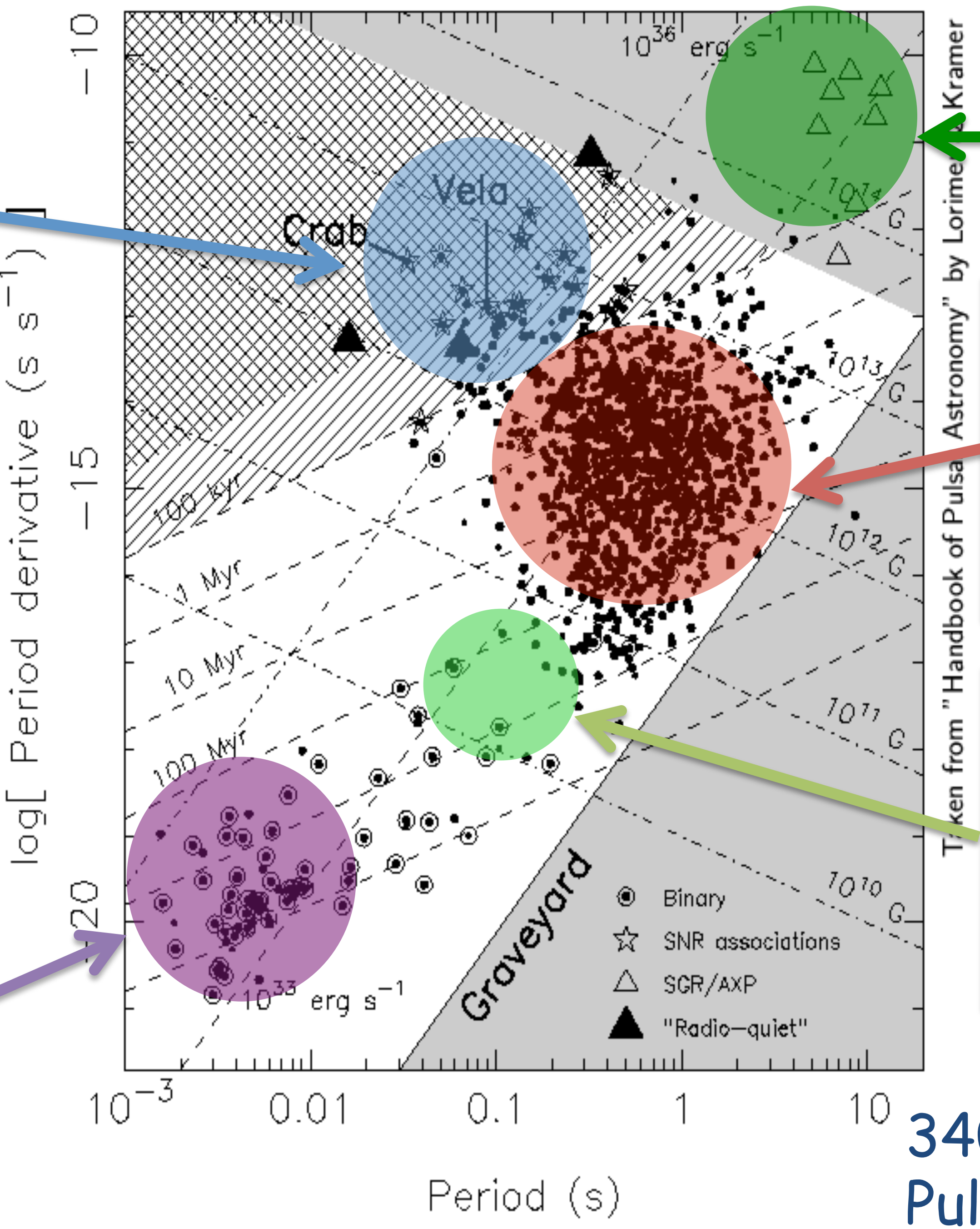


Pulse profiles : Looking down on the polar cap



LOS cuts with corresponding pulse profiles

P-Pdot diagram of Neutron stars



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Young Pulsars
– Energetic, with significant spin-down noise, glitches, SNRs associations

Millisecond Pulsars
– Faster, Most in binaries, stable rotators

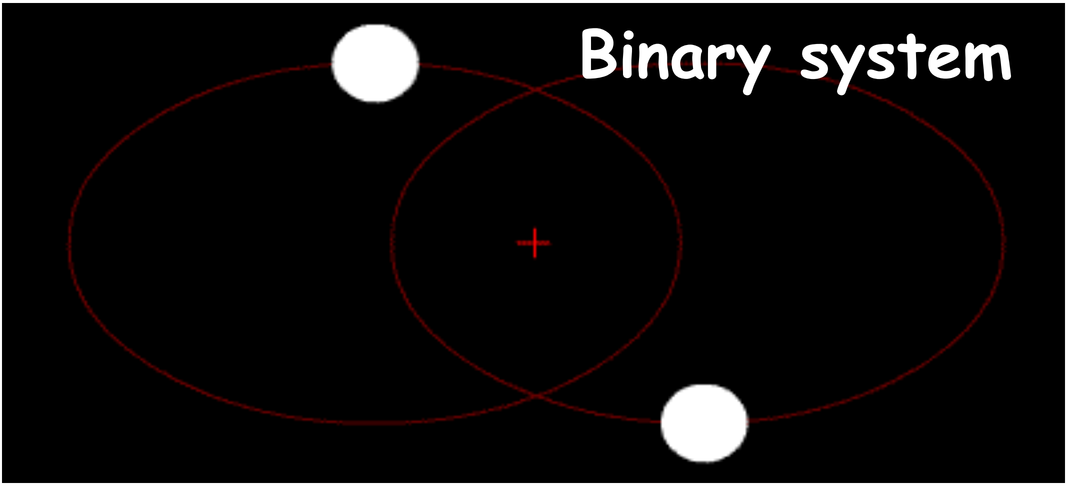
Magnetars
– High B, few in radio

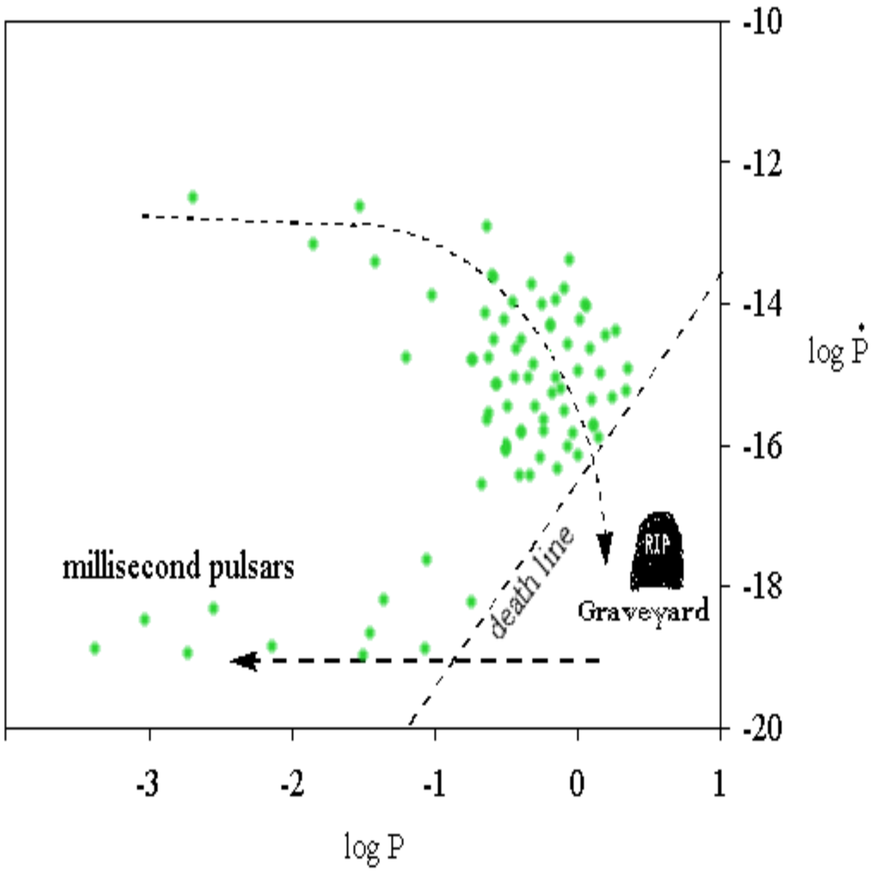
Normal Pulsars
– slower, mostly isolated, bulk of them, good for PSR studies

Double Neutron stars
– spin fast, double pulsars, good for GR tests

3400 known radio Pulsars in our galaxy

Millisecond pulsars :back from Dead





✓ Millisecond pulsars are a small population compared to the normal pulsars with period ~ millisecond, magnetic Field ~10^9G

✓ Majority of MSPs are in binary MSPs are detected in the radio, x-ray and gamma-rays

✓ Origin of millisecond pulsars is yet not pinned down.

Leading theory :

MSPs begin their life as longer period pulsar but are spun up or recycled through accretion thus millisecond pulsars are often called recycled pulsars.

MSPs considered as Celestial GPS

Binary and isolated MSPs

- ✓ Majority of MSPs are naturally expected to be in binaries
  about 81% of MSPs are in binaries

What about Isolated MSPs?

- ✓ Isolated MSPs are conceived to be formed in binary systems where the pulsar radiation can ablate the companion

"Black widow systems" – Missing link between
Binary and isolated MSPs

Pulsars as astrophysical "tools"

- ✓ **Time keeper in Sky**: Due to their physical properities pulsars are (in most cases) VERY stable rotator

  pulses → ticking of cosmic clocks precise up to 1 s in about 31 million years
  Examples of Pulsar Clocks in Earth

- ✓ **Sensitive GW detector**: Combined observations of many pulsars to detect Gravitational wave

- ✓ **Probs of matter in extreme state**: can treat pulsars as naturally created probes of specific conditions in which they exist – i.e. strong gravitational fields.

- ✓ **Investigation of dynamics** – especially the movement caused by external forces. This includes binary systems, and globular clusters dynamics.

- ✓ **Probes of space-time**

- ✓ **Probes of interstaller medium**

Pulsars – Marvellous Probes

TOP 10 !

B1919+21 : First pulsar discovered in 1967

B1913+16 : The first binary pulsar (Hulse-Taylor binary pulsar)
Orbit is decaying at the exact rate predicted due to emission of gravitational radiation by general relativity

B1937+21 : The first millisecond pulsar

J0437-4715 : The brightest millisecond pulsar, with very stable period

B1257+12 : First millisecond pulsar with planets

J0737-3039 : Double pulsar system

B1748-2446 : Pulsar with shortest period, 716 Hz

J1311-3430 : First MSP discovered via gamma-ray pulsations, part of binary system with shortest period

J1023+0038 : Transition between the LMXB and MSP state

Search for Pulsars

Reference: Chapter 6; Handbook of Pulsar Astronomy
Lorimer and Kramer

Pre-requisites for searching of millisecond pulsars

- 3-D search :
  - search in dispersion delay in order to compensate ISM effect
  - searching for periodicity in time-series data using spectral domain search algorithm
  - search in acceleration (required in case of binary objects)

1. **High time resolution data recording facility (~micro secs)**
2. **Managing Large data volume** ~ 1TB per epoch of observation
3. **Compute intensive search analysis**

3-D search is very expensive ~ **3.5 Tflops** over the same range of DM grid (1200 values)

On a single Desktop 1hr of data (~ 60 GB) takes ~ 1280 hours

On typical High Performance compute cluster 1 hr of data takes ~ 10 hrs

✓ *217600 CPU hrs of GMRT search data analysis ~ 25 years on single CPU !!*

Pulsar Search Problem

Two popular ways to search for pulsars

- ✓ Targeted search : With apriori knowledge of position

- ✓ Blind search : With out apriori knowledge of position

Pulsar Search with GMRT

Pulsars are faint – surveys are sensitivity limited → array of telescopes

GMRT being the largest array telescope
→ have potential to undertake sensitive pulsar searches

Explored in past resulting in discovery of 5 pulsars (2002-2009)–
a pulsar in Globular cluster (Freire et al. 2004)
a pulsar in supernovae remnant (Gupta et al. 2005)
3 pulsars in 610 MHz blind search (Joshi et al. 2009)

Pulsar Search with GMRT

✓ Targeted search : With apriori knowledge of position

Fermi directed targeted searches

✓ Blind search : With out apriori knowledge of position

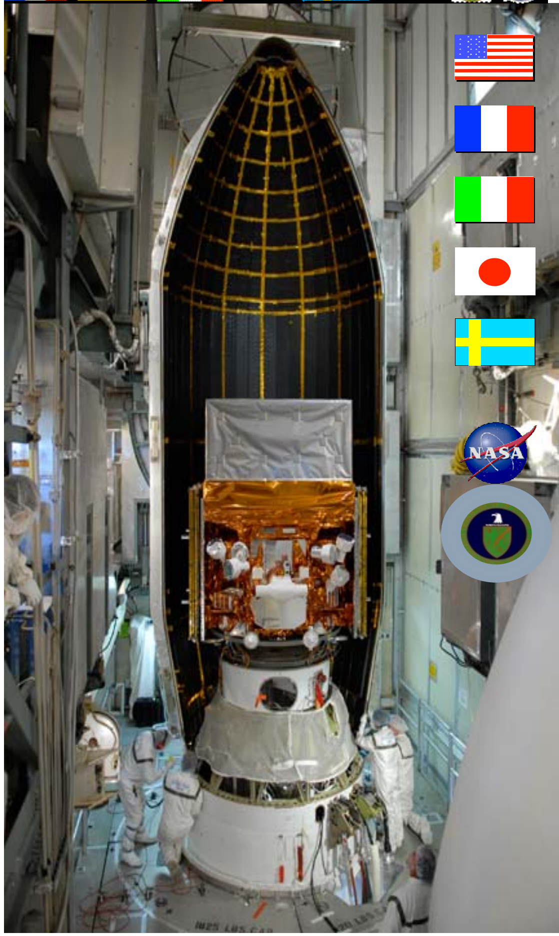
GHRSS survey :
GMRT High Resolution Southern Sky survey for pulsars and transients

Fermi γ-ray Space Telescope

Large AreaTelescope (LAT)
20 MeV - >300 GeV

Established pulsars as dominant γ-ray sources in Milyway

(Atwood et al. 2009, ApJ, 697, 1071)



Fermi-directed pulsar searches

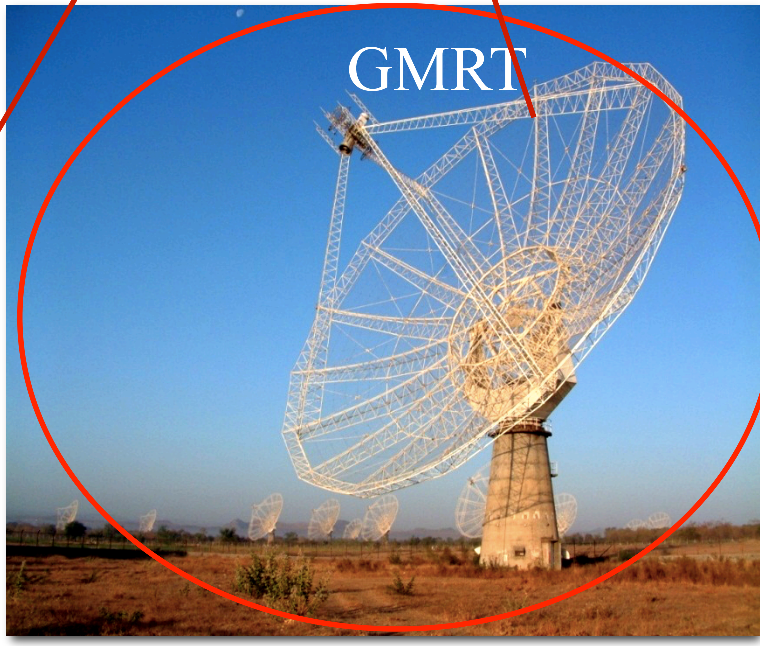
1) Catalogs of unassociated γ-ray point sources
2) These sources are rank ordered according to their likeliness of being pulsars
3) Radio telescopes all over the World searches for pulsations from these sources as part of Fermi Pulsar Search Consortium (PSC)

Fermi pulsar search consortium (PSC)

Jodrell Bank (UK)

Nançay (France)

Low frequency facility



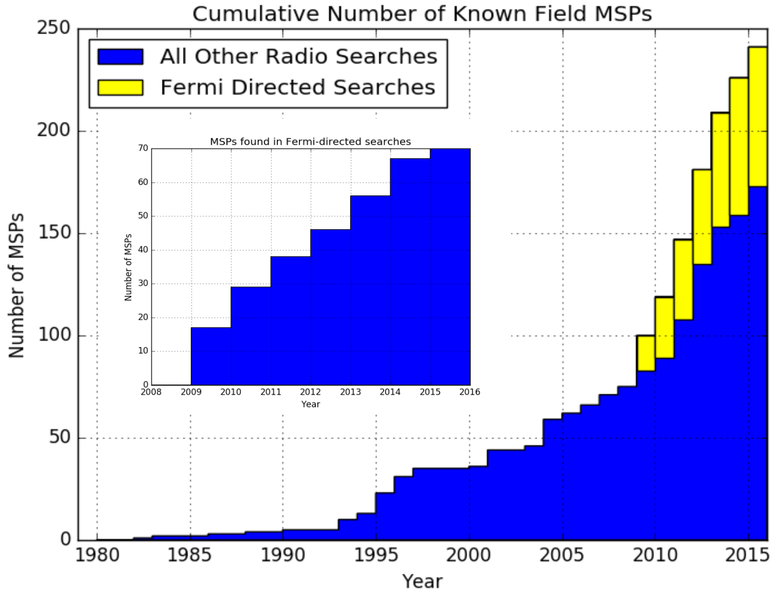
Parkes (Australia)

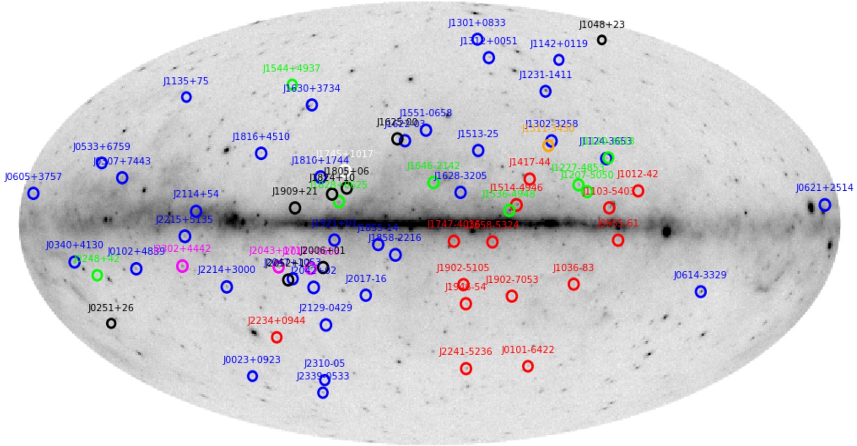
Green Bank (USA)

Fermi pulsar search consortium (PSC)

Fermi Pulsar Search Consortium efforts ➡ >100 new MSPs

GMRT discovery (2012 to 2014) ➡ 7+1 MSPs





Nançay (France)

GMRT (India)

GreenBank (USA)

Parkes (Asutralia)

Effelsberg(Germany)

Fermi directed radio searches

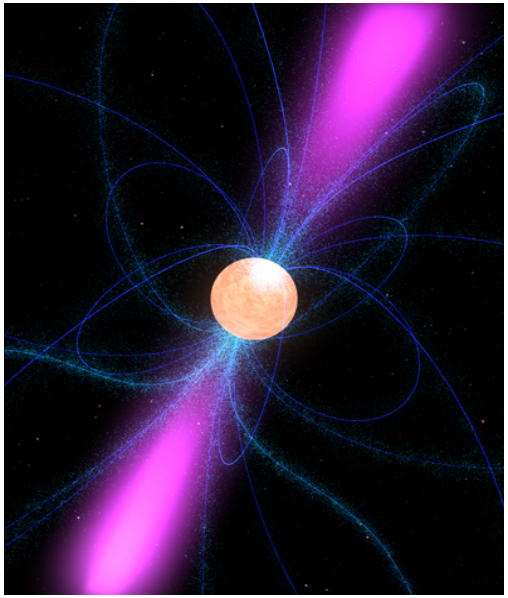
Team GMRT: Bhattacharyya, Roy, Ray, Gupta, Bhattacharya, Ferrara +PSC

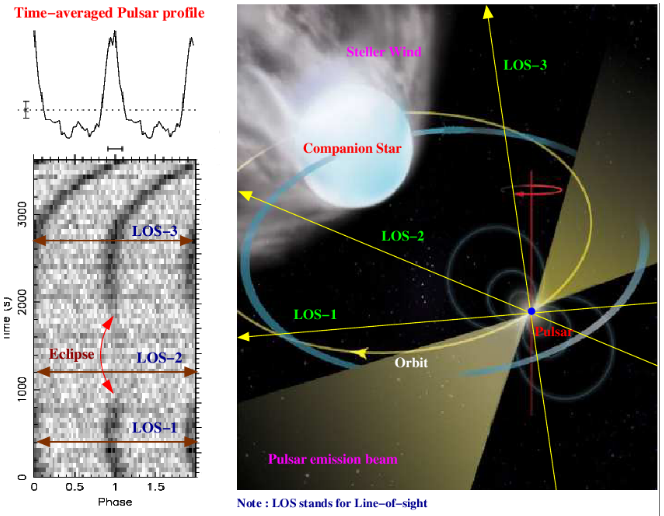
Source selection :
Fermi

Observations:
GMRT

Analysis:
HPC

Result:
Pulsar discovery





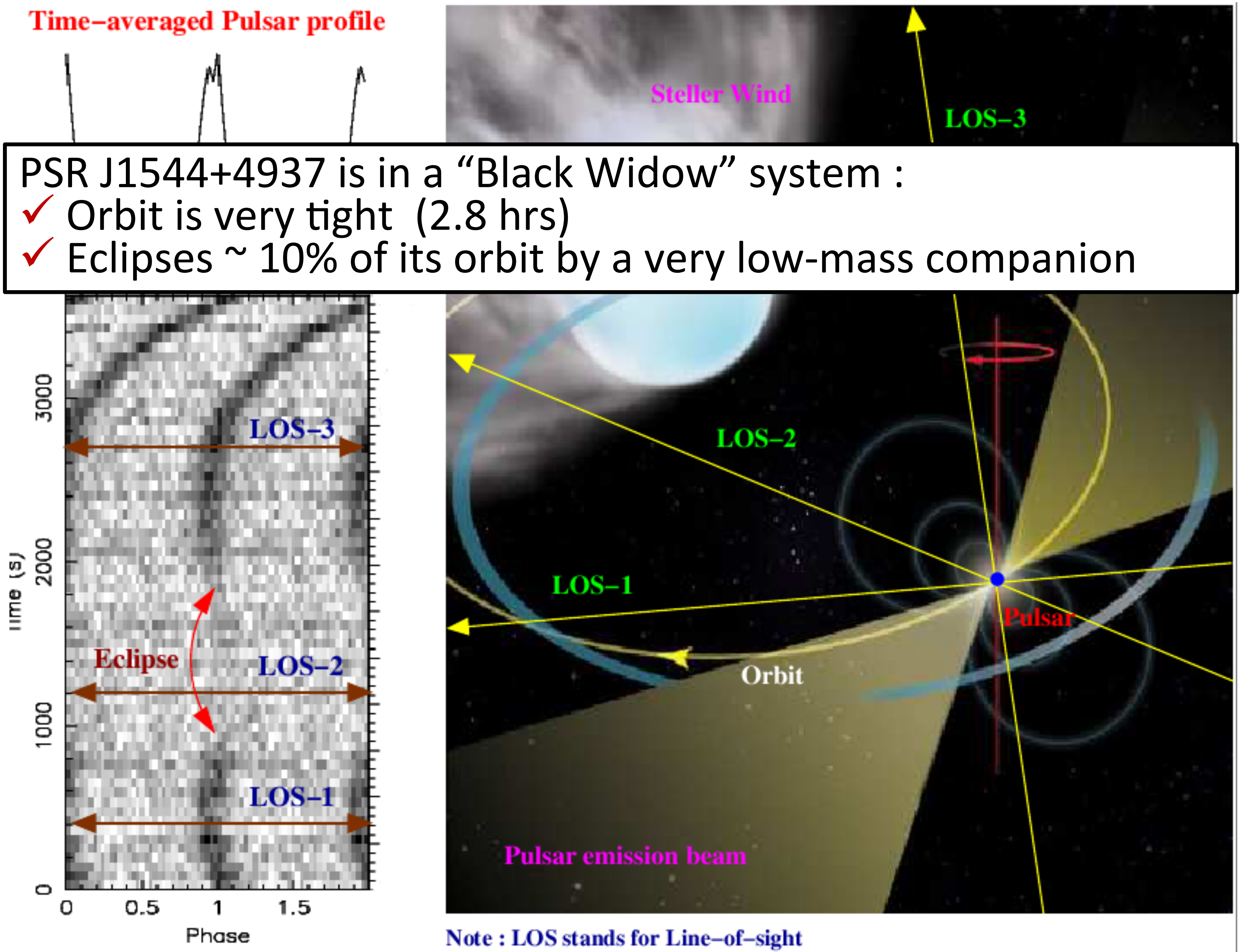
Note : LOS stands for Line–of–sight

Artistic impression of a Black Widow system with real data of the discovered MSP

Eclipsing Black-widow pulsar
Provides clue on isolated MSP formation
GMRT discovery
Bhattacharyya et al. 2013

J1544+4937 : Third eclipsing black widow !

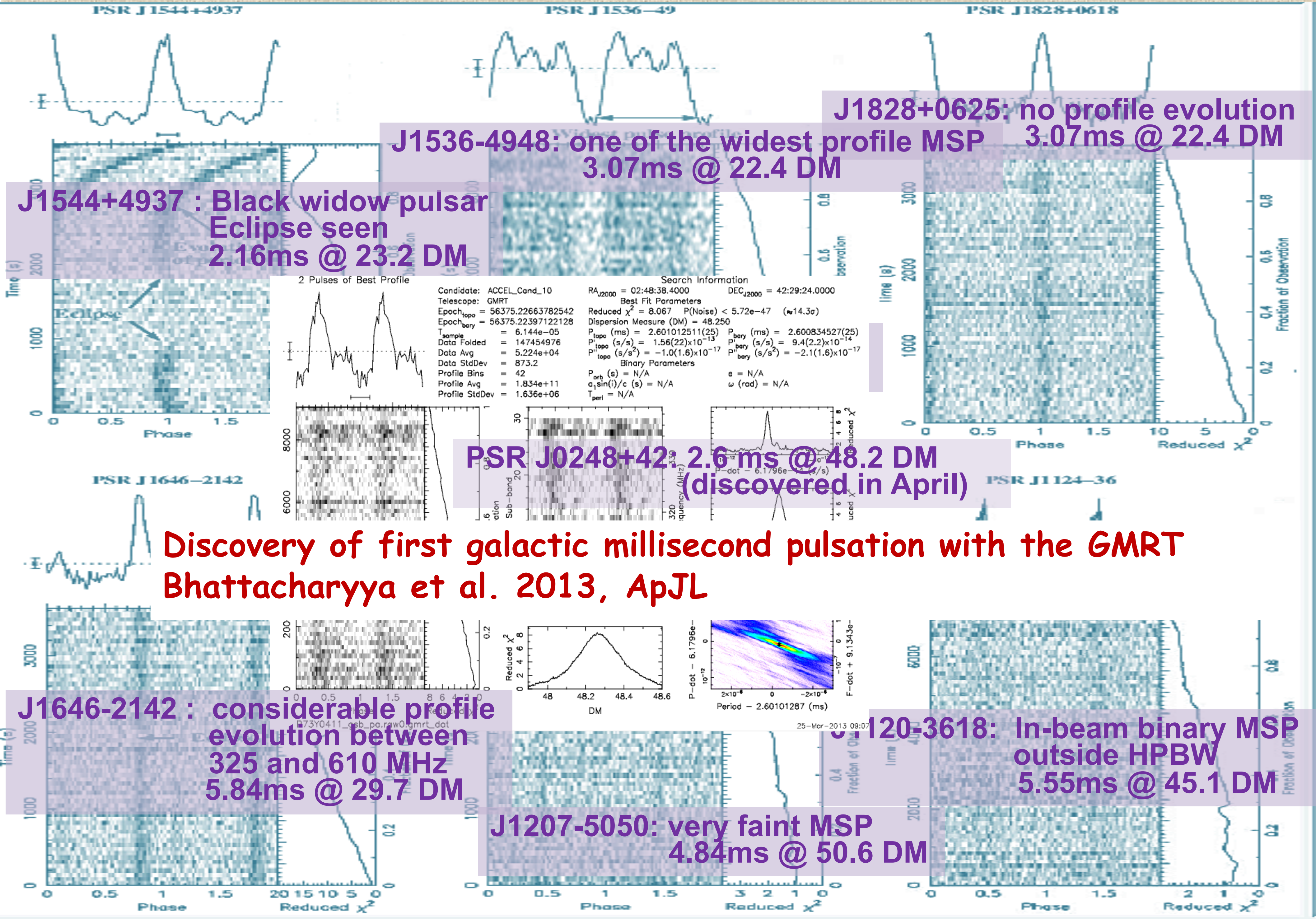
PSR J1544+4937 is in a “Black Widow” system :
- ✓ Orbit is very tight (2.8 hrs)
- ✓ Eclipses ~ 10% of its orbit by a very low-mass companion



Note : LOS stands for Line–of–sight

Artistic impression of a Black Widow system with real data of the discovered MSP

Seven MSPs discovered at GMRT from 2011-2013



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

J1536-4948: one of the widest profile MSP
3.07ms @ 22.4 DM

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

Search Information

Candidate: ACCEL_Cand_10
Telescope: GMRT
$\mathrm{Epoch_{topo}}$ = 56375.22663782542
$\mathrm{Epoch_{bary}}$ = 56375.22397122128
$\mathrm{T_{sample}}$ = 6.144e−05
Data Folded = 147454976
Data Avg = 5.224e+04
Data StdDev = 873.2
Profile Bins = 42
Profile Avg = 1.834e+11
Profile StdDev = 1.636e+06

$\mathrm{RA_{J2000}}$ = 02:48:38.4000 $\mathrm{DEC_{J2000}}$ = 42:29:24.0000

Best Fit Parameters

Reduced χ^2 = 8.067 P(Noise) < 5.72e−47 (≈14.3σ)
Dispersion Measure (DM) = 48.250
P_{topo} (ms) = 2.601012511(25) P_{bary} (ms) = 2.600834527(25)
P'_{topo} (s/s) = $1.56(22)\times10^{-13}$ P'_{bary} (s/s) = $9.4(2.2)\times10^{-14}$
P''_{topo} (s/s^2) = $-1.0(1.6)\times10^{-17}$ P''_{bary} (s/s^2) = $-2.1(1.6)\times10^{-17}$

Binary Parameters

P_{orb} (s) = N/A e = N/A
$a_1\sin(i)/c$ (s) = N/A ω (rad) = N/A
T_{peri} = N/A

PSR J0248+42: 2.6 ms @ 48.2 DM
(discovered in April)

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

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

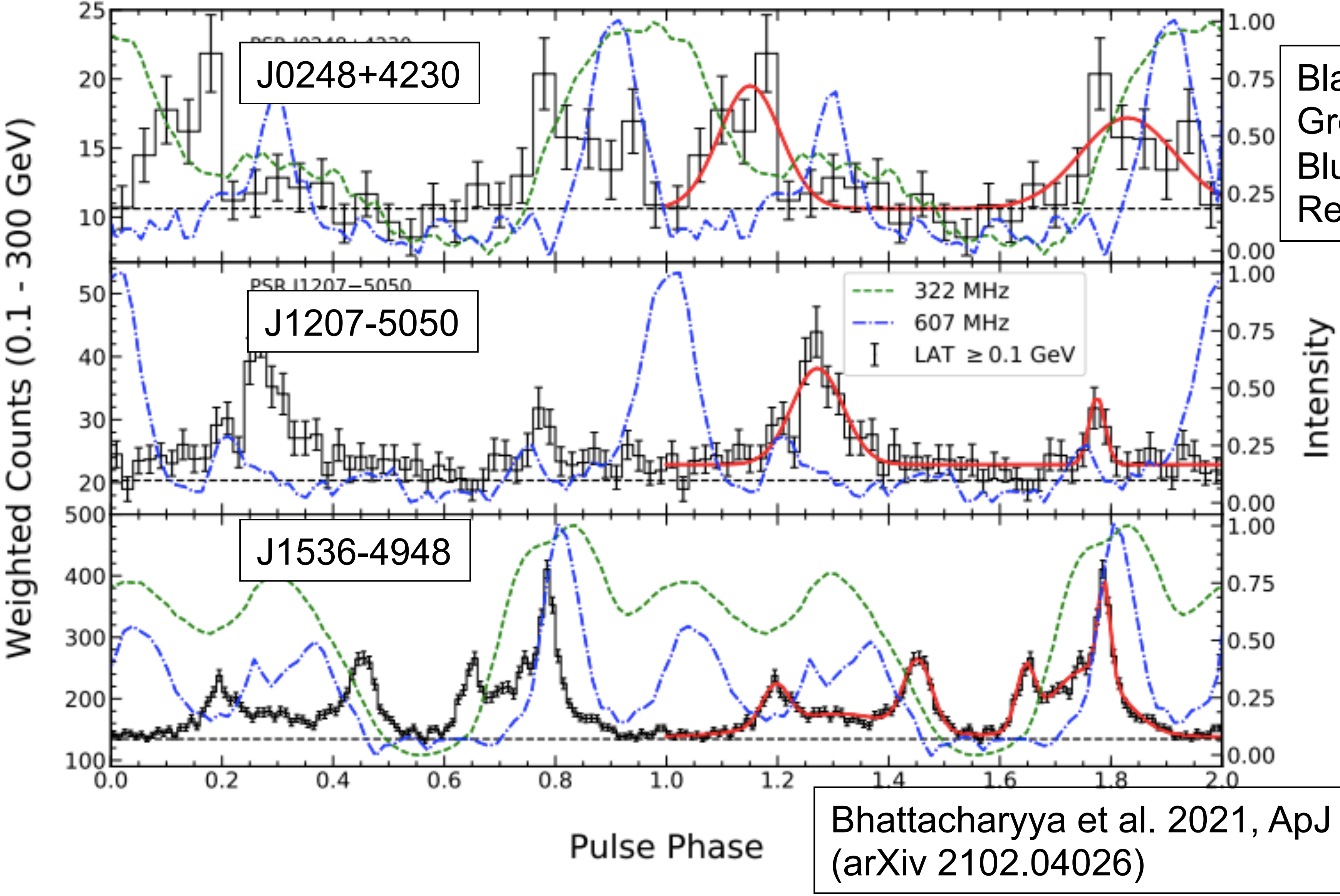
J1120-3618: In-beam binary MSP outside HPBW
5.55ms @ 45.1 DM

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

Targeted search: Fermi directed searches with GMRT

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

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

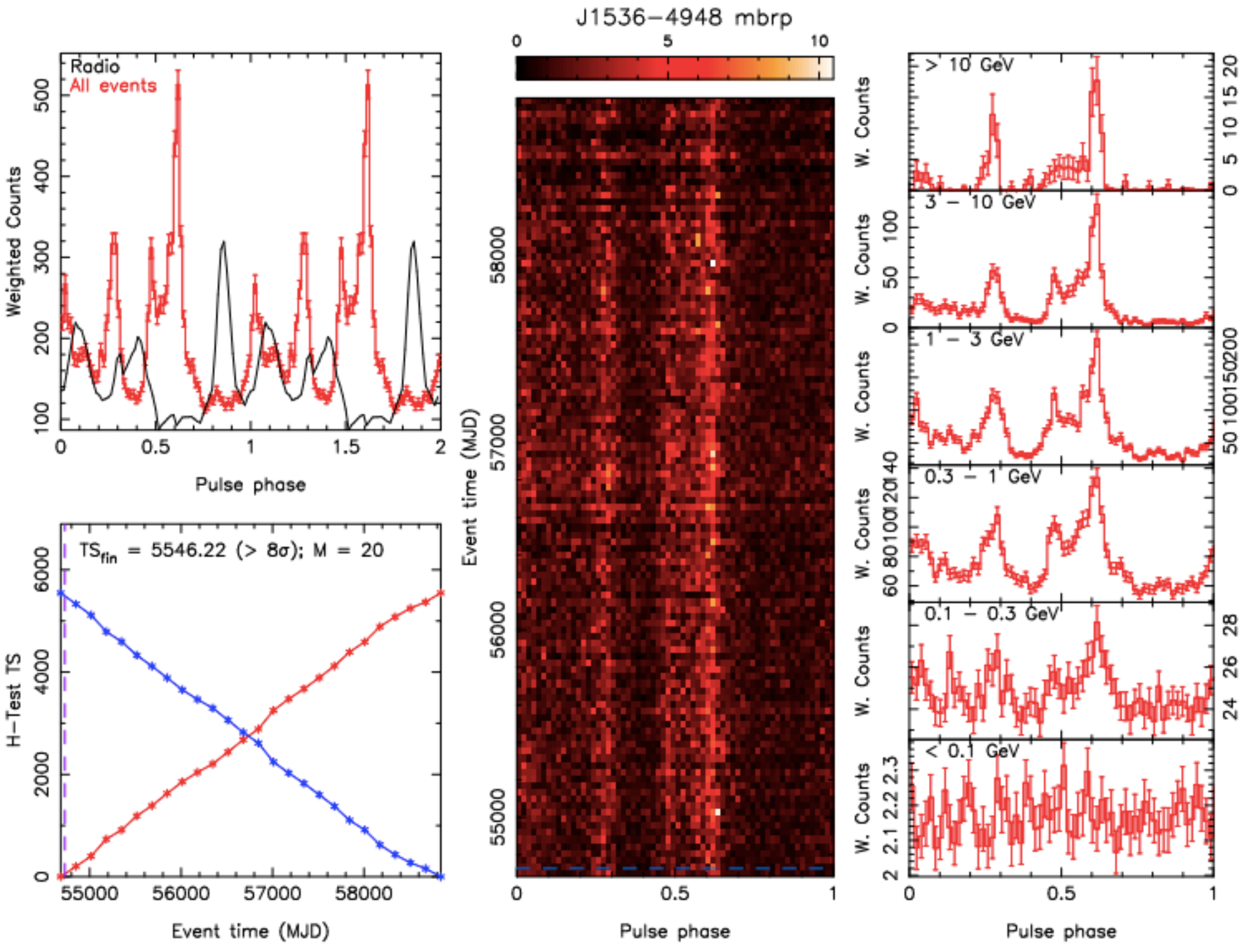


Black: Fermi LAT
Green: 322 MHz
Blue: 607 MHz
Red: Fitting

Bhattacharyya et al. 2021, ApJ
(arXiv 2102.04026)

Targeted search: Fermi directed searches with GMRT

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



Detected photon at 60 GeV !

Interesting for study of emission

Only 3 MSPs has higher gamma-ray luminosity

Bhattacharyya et al. 2021, ApJ (arXiv 2102.04026)

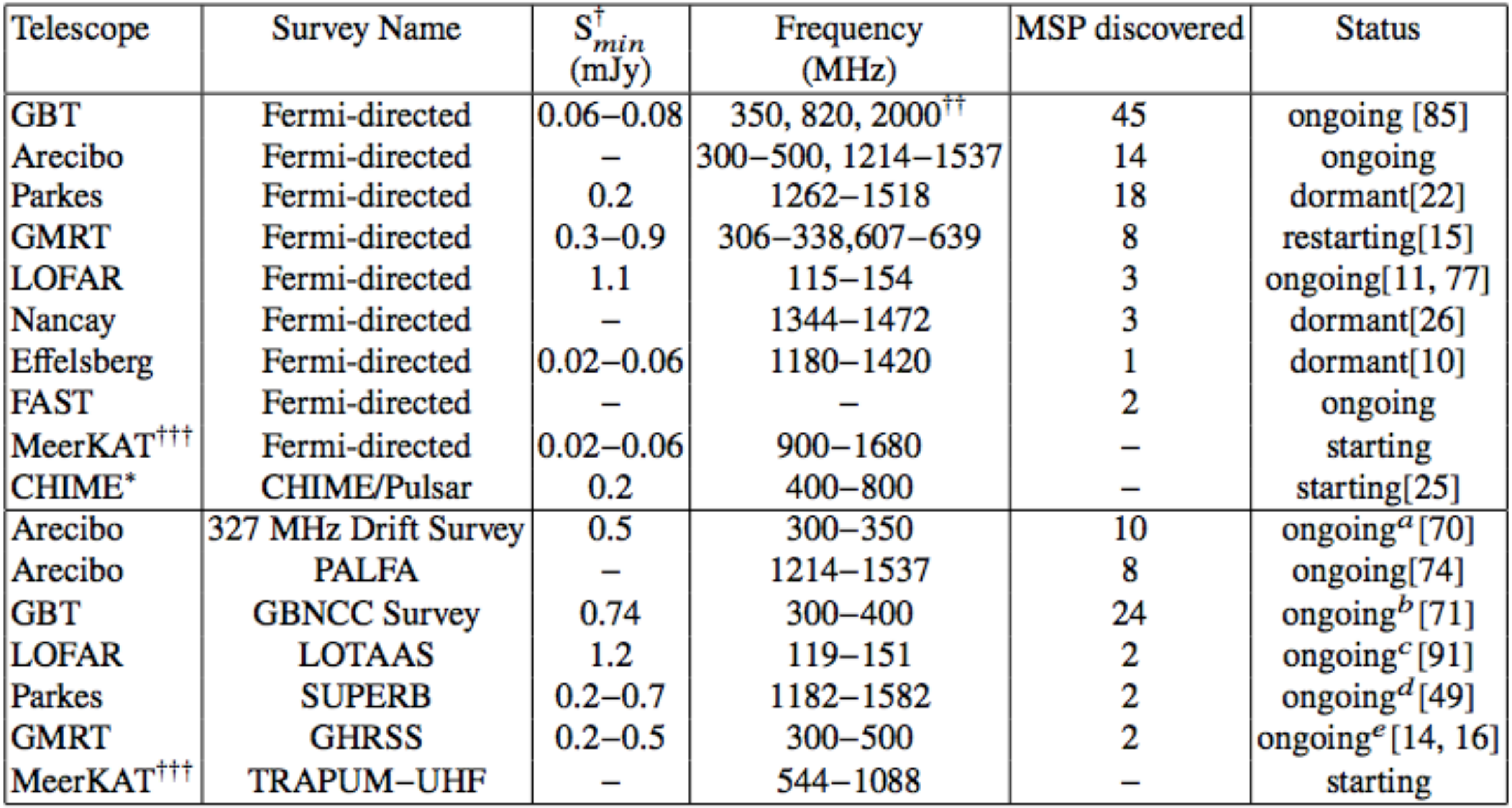
Significance of MSP discovery

- Enhance the population of MSPs that can contribute to International Pulsar Timing Array designed to study the gravitational wave background

- With the increased population of MSPs the number of MSPs in special Evolutionary phases would increase and hence will allow a more detailed study of evolutionary processes leading to MSP formation.
e.g. the black widow system discovered by us will aid to track evolutionary history of isolated MSPs

- Simultaneous study of gamma-ray and radio light curve Lag, lead or alignment of gamma-ray and radio profile can lead to the question of offset or co-location of the emission radio and gamma-ray regions

Major ongoing low-frequency survey

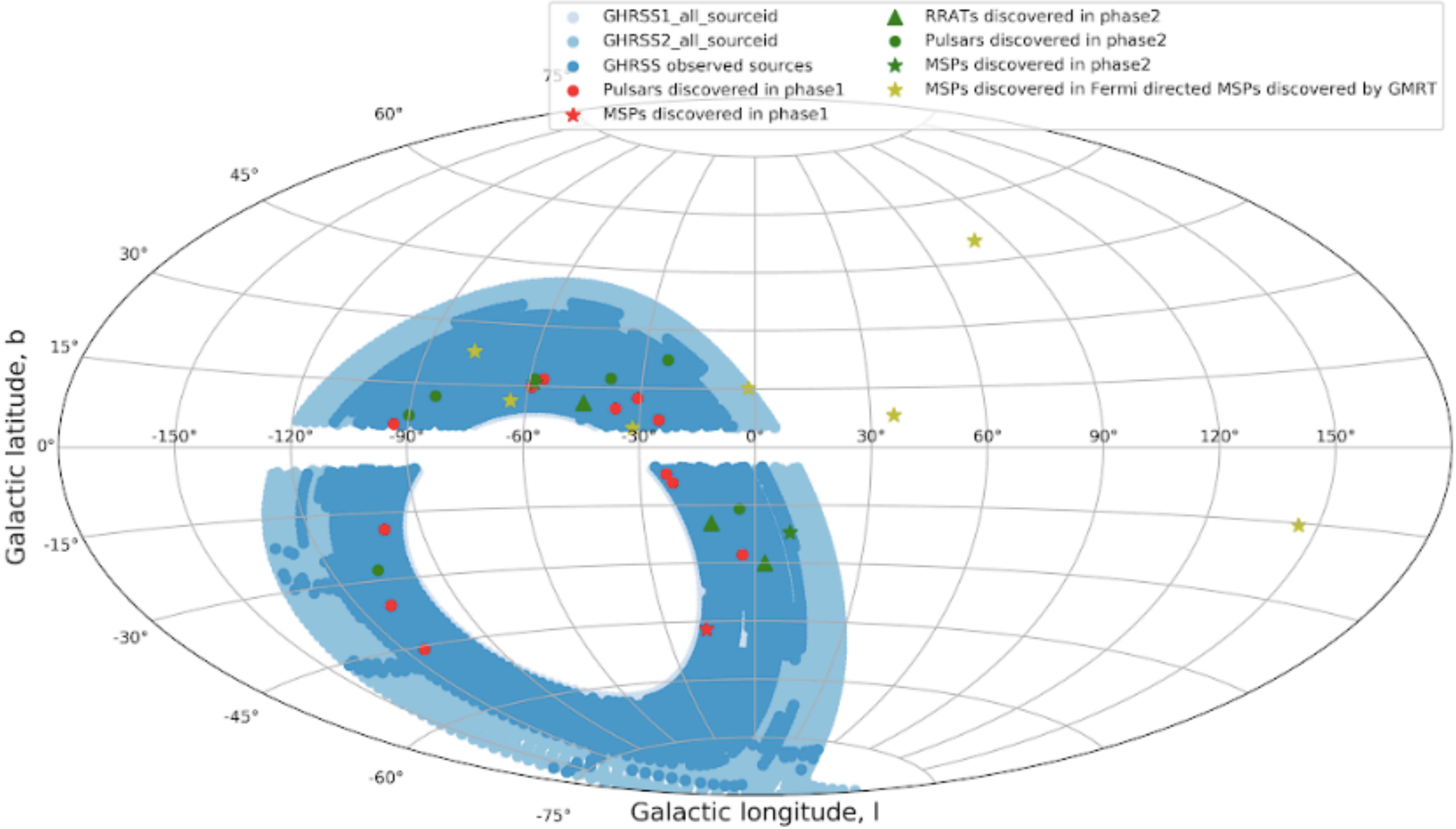


Telescope	Survey Name	$S^{\dagger}_{min}$ (mJy)	Frequency (MHz)	MSP discovered	Status
GBT	Fermi-directed	0.06–0.08	350, 820, 2000[††]	45	ongoing [85]
Arecibo	Fermi-directed	–	300–500, 1214–1537	14	ongoing
Parkes	Fermi-directed	0.2	1262–1518	18	dormant[22]
GMRT	Fermi-directed	0.3–0.9	306–338,607–639	8	restarting[15]
LOFAR	Fermi-directed	1.1	115–154	3	ongoing[11, 77]
Nancay	Fermi-directed	–	1344–1472	3	dormant[26]
Effelsberg	Fermi-directed	0.02–0.06	1180–1420	1	dormant[10]
FAST	Fermi-directed	–	–	2	ongoing
MeerKAT[†††]	Fermi-directed	0.02–0.06	900–1680	–	starting
CHIME[*]	CHIME/Pulsar	0.2	400–800	–	starting[25]
Arecibo	327 MHz Drift Survey	0.5	300–350	10	ongoing[a] [70]
Arecibo	PALFA	–	1214–1537	8	ongoing[74]
GBT	GBNCC Survey	0.74	300–400	24	ongoing[b] [71]
LOFAR	LOTAAS	1.2	119–151	2	ongoing[c] [91]
Parkes	SUPERB	0.2–0.7	1182–1582	2	ongoing[d] [49]
GMRT	GHRSS	0.2–0.5	300–500	2	ongoing[e] [14, 16]
MeerKAT[†††]	TRAPUM–UHF	–	544–1088	–	starting

Bhattacharyya & Roy 2021
https://arxiv.org/pdf/2104.02294.pdf

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

Team: Bhattacharyya, Roy, Stappers, Keith, McLaughlin, Ray, Ransom, Chengalur,



1st MSP from uGMRT

1st RRAT from GMRT

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

Bhattacharyya et al. 2019,
(Astrophysical Journal, minor revision)

Webpage :

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

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
31 pulsars
3 MSPs
2 mildly recycled pulsars
1 with γ-ray emission

11 discoveries with uGMRT

1st MSP from uGMRT
1st RRAT from GMRT

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

Bhattacharyya et al. 2019,
(Astrophysical Journal, minor revision)

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

Discoveries from GHRSS survey (one of the highest discovery rate)

Probing a different luminosity distribution?

γ-ray pulsation

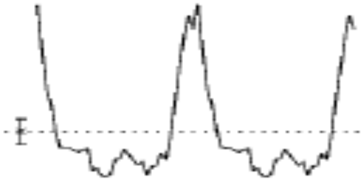
MSP

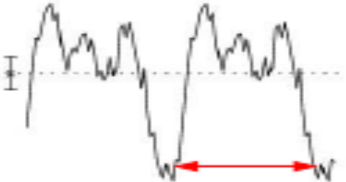
Mildly recycled

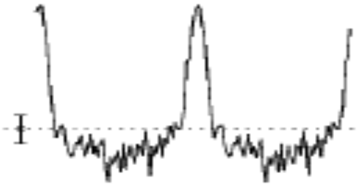
Mildly recycled

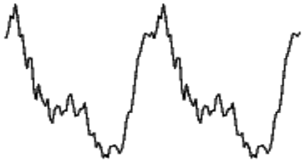
MSP

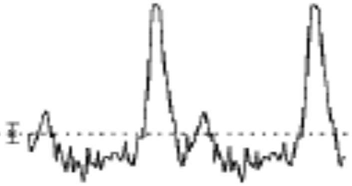
Pulsar name	Period (ms)	Dispersion measure (pc cm^{-3})	Detection significance (σ)	Flux density† (mJy)
PSR J0418−4154	757.11	24.5	50	10.3
PSR J0514−4407	320.7	15.4	42	9.7
PSR J0600−46	798.8	50.36	45	10
PSR J0702−4956	666.66	98.7	30	15.7
PSR J0919−42	812.6	57	19	6.4
PSR J0941−43	447.7	105.5	53	2.3
PSR J1023−43	454.3	62.7	38	1.6
PSR J1239−48	653.89	107.6	21	0.4
PSR J1242−46	1411.3	76.5	68	12
PSR J1243−47	5.31	78.6	18	0.9
PSR J1255−46	52.0	42.9	12	0.8
RRAT J1406−50	–	40	80	–
PSR J1428−42	234.7	66.0	41	1.8
PSR J1456−48	536.81	133.0	15	1.2
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 J1845−40‡	373.48	47.8	112	–
PSR J1726−52	631.84	119.7	8	0.7
RRAT J1850−48		23	–	–
PSR J1947−43	180.94	29.9	17	4.7
RRAT J2004-38		23	–	–
PSR J2144−5237	5.04	19.0	9	1.6


J1544+4937
2.16ms @ 23.2 DM


J1536-4948
3.16ms @ 38.0 DM

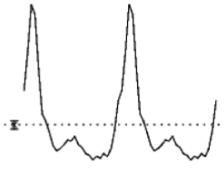

J1828+0625
3.07ms @ 22.4 DM

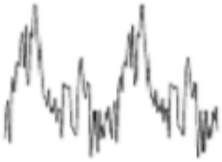

J0248+4230
2.60ms @ 48.2 DM

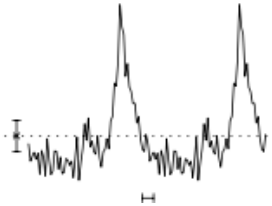

J1646-2142
5.84ms @ 29.7 DM

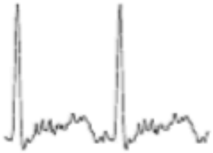

J1207-5050
4.84ms @ 50.6 DM

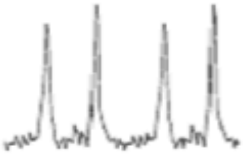

J1120-3618
5.55ms @ 45.1 DM

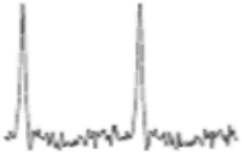

J1227-4853
1.69ms @ 43.2 DM

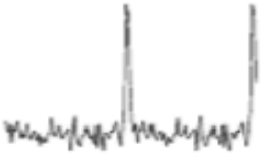

J2144-5237
5.04ms @ 19.0 DM

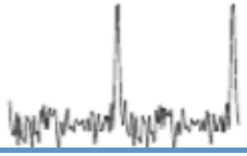

J1243-47
5.31ms @ 78.6 DM

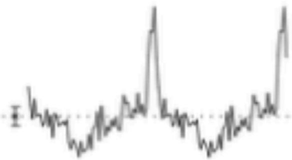

J0418-4154
757ms @ 24 DM

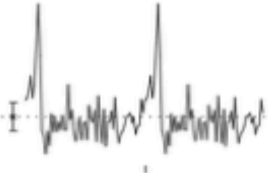

J0514-4408
320ms @ 15 DM

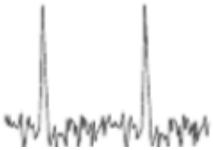

J0702-4906
666ms @ 98 DM

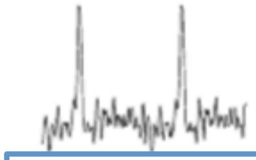

J0919-42
812ms @ 57 DM

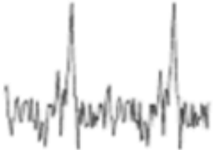

J1255-46
52.0ms @ 42 DM

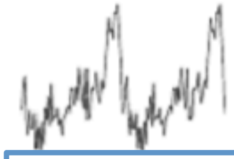

J1239-48
653ms @ 107

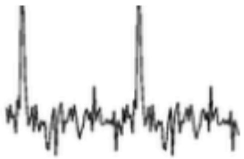

J1726-52
631ms @ 119

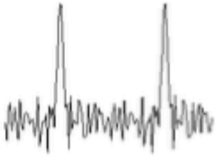

J1456-48
536ms @ 133

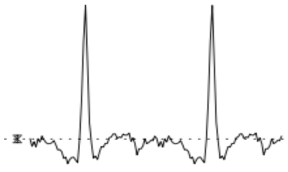

J1559-44
1169ms @ 122

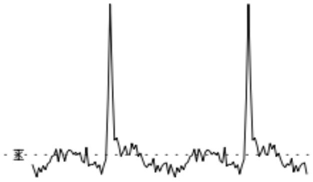

J1708-52
449ms @ 102

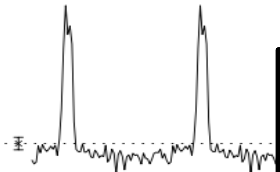

J1947-43
180ms @ 29


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: 26

GHRSS survey for last 5 years

GHRSS1 (0.5 mJy)
10% SKA1

GHRSS2 (0.3 mJy)
1/5th SKA1

SKA1 (0.05 mJy)

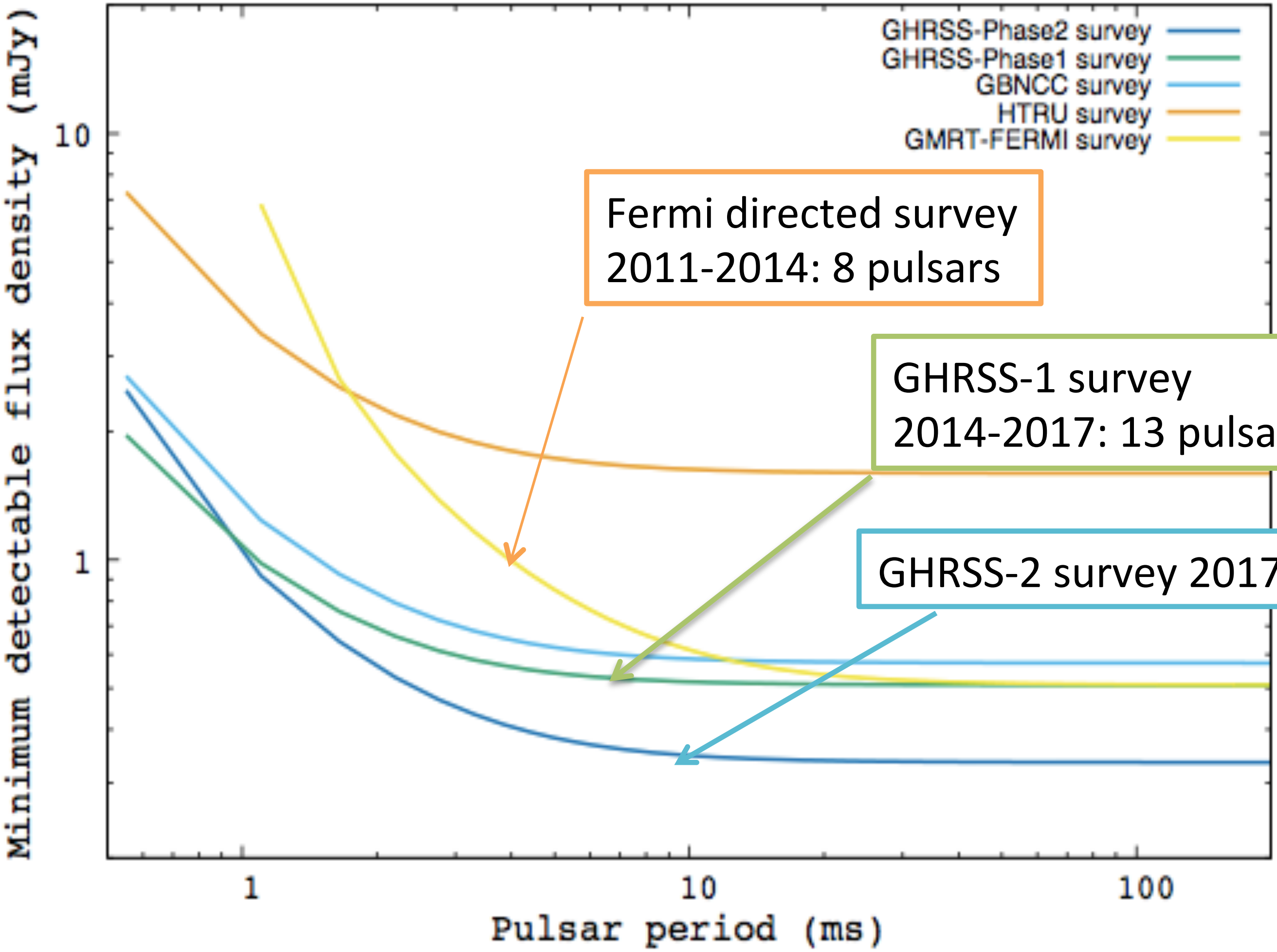
13 pulsars discovered
→ 1 pulsar per 20 hrs

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

Timing of pulsars

Reference: Chapter 8; Handbook of Pulsar Astronomy
Lorimer and Kramer

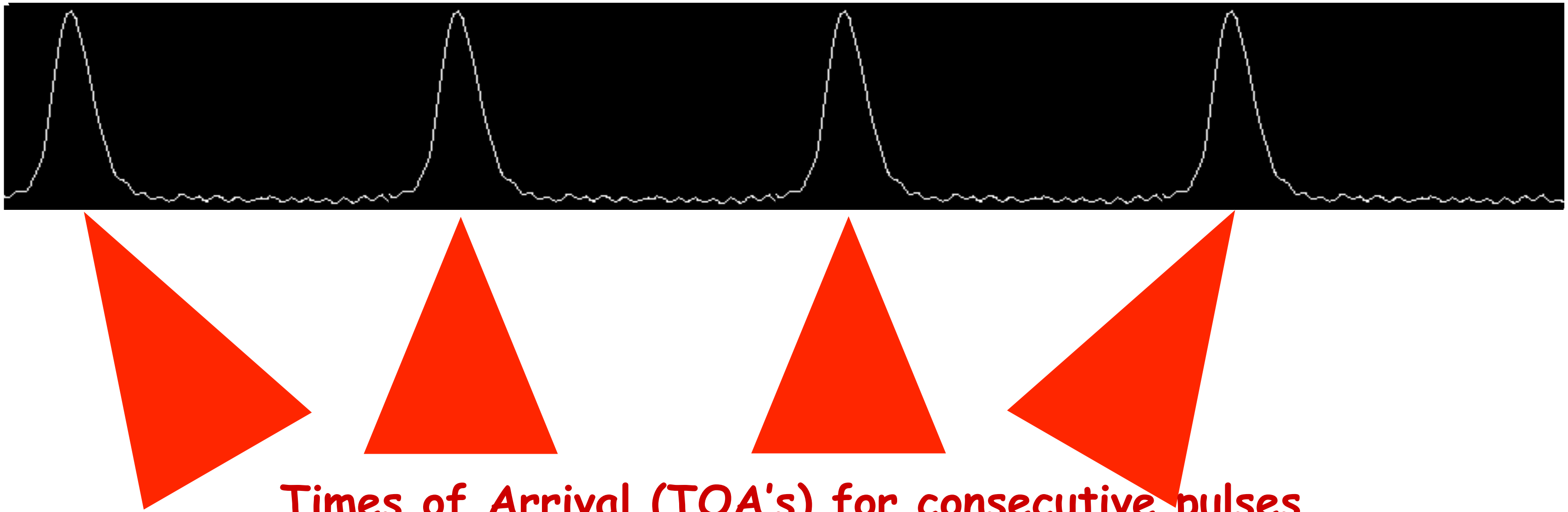
Pulsar Timing – a cryptic name for a very simple procedure

So, how to measure pulsar period?

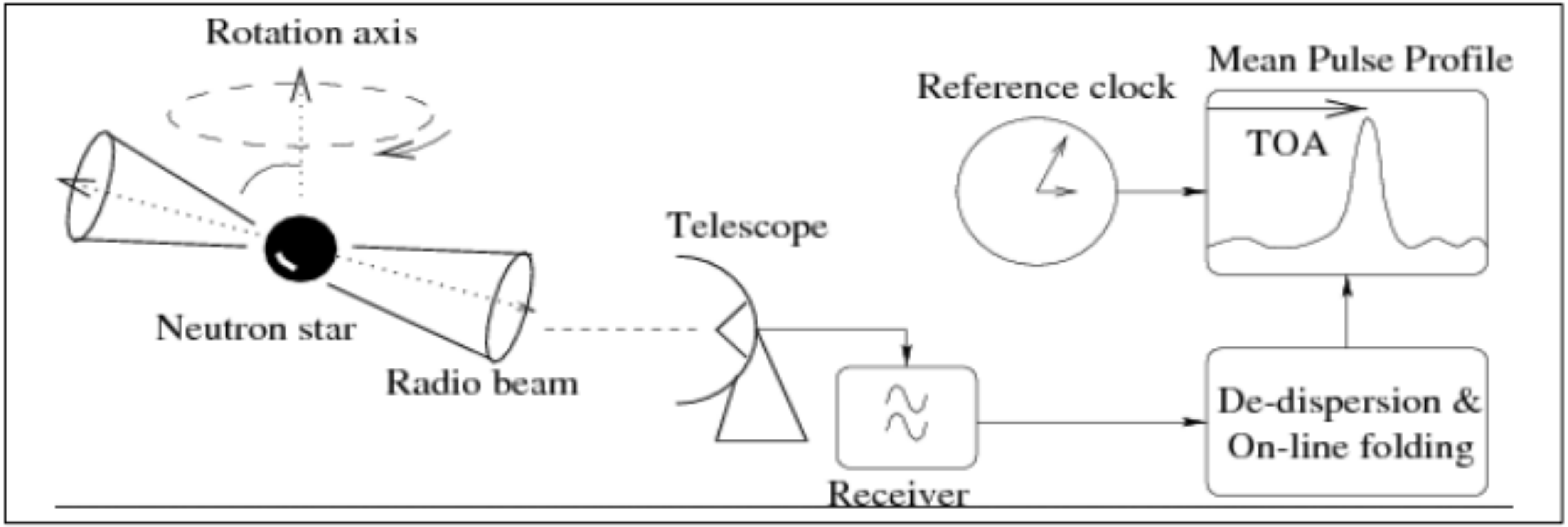
- ✓ How to measure how long is a second on your pulsar watch?
- ✓ Prediction and observation of pulse arrival time (TOA)
- ✓ Pulsar timing model – a collection of the important physical parameters, describing its rotation, movement etc.

How the timing work?

Time of Arrival (TOA) is the moment in time, when the pulsar reaches some arbitrary decided phase (usually close to the pulse maximum).

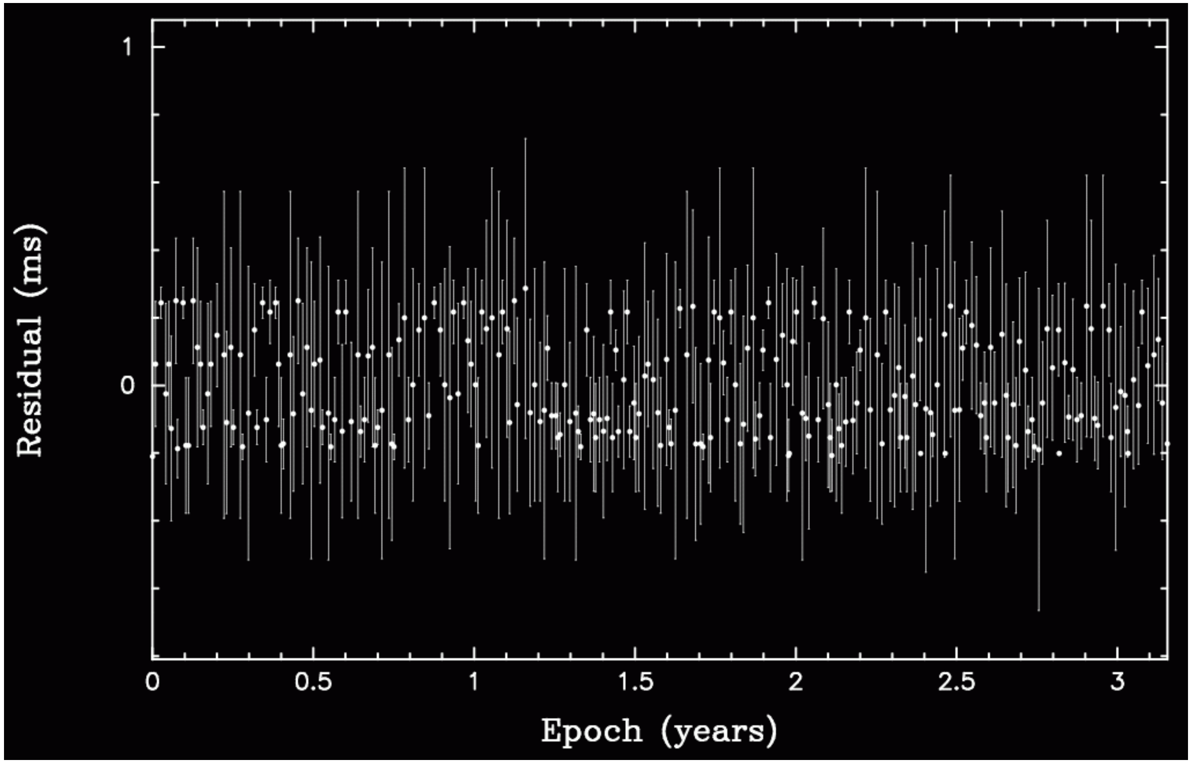


Times of Arrival (TOA's) for consecutive pulses



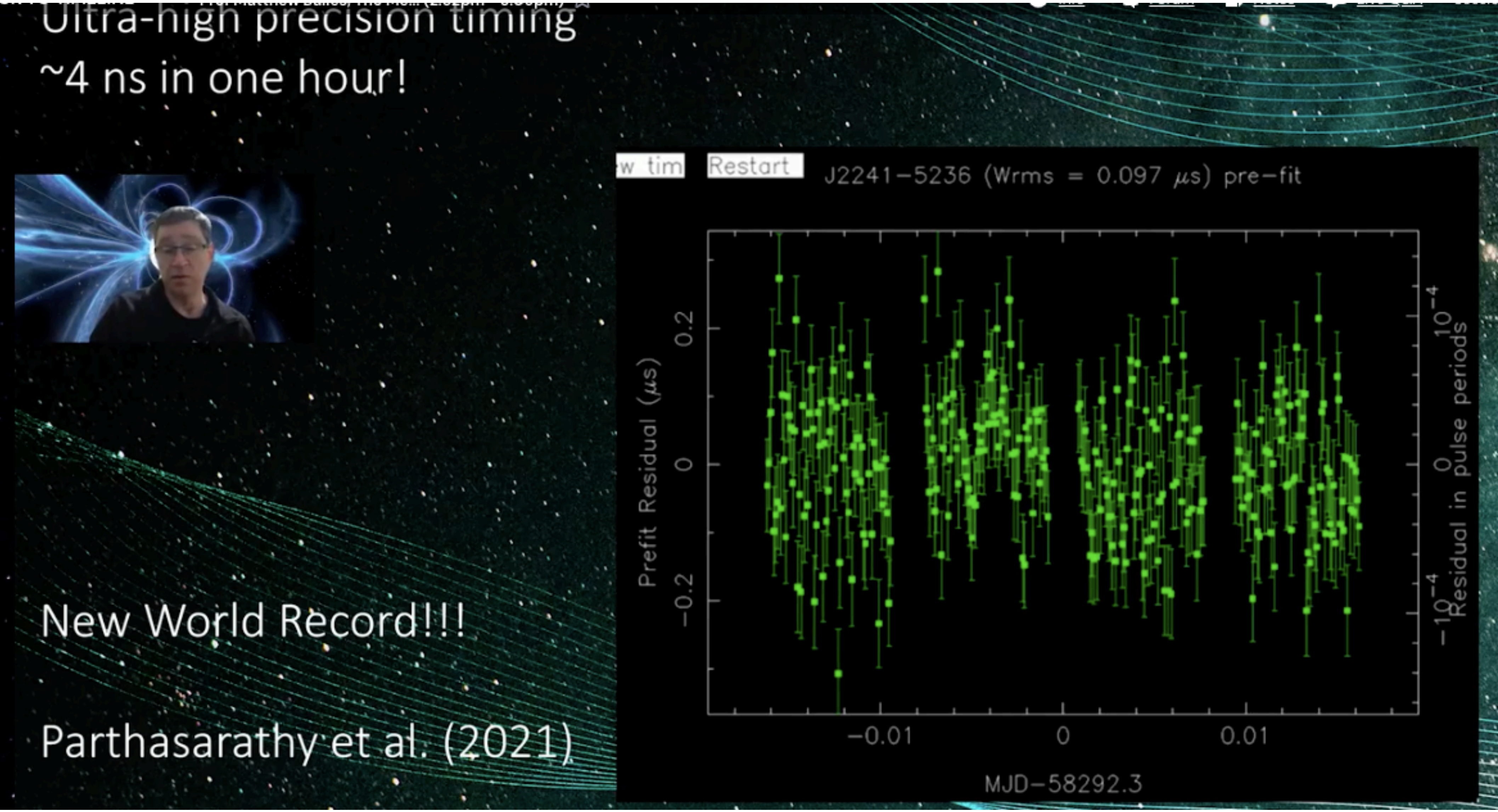
Now it is necessary to apply corrections to your TOA's (basically subtract your observatory position and movement).

Finally, with a proper timing fit, this is what you would like to see - nothing but white noise, which is due to the TOA measurement uncertainties comming mainly from the receiver noises (and the pulsar itself) .



If the residuals show only the white noise - this means, that we know everything there is to know about the pulsar (at least from the timing point of view).

Precision timing



Ultra-high precision timing

~4 ns in one hour!

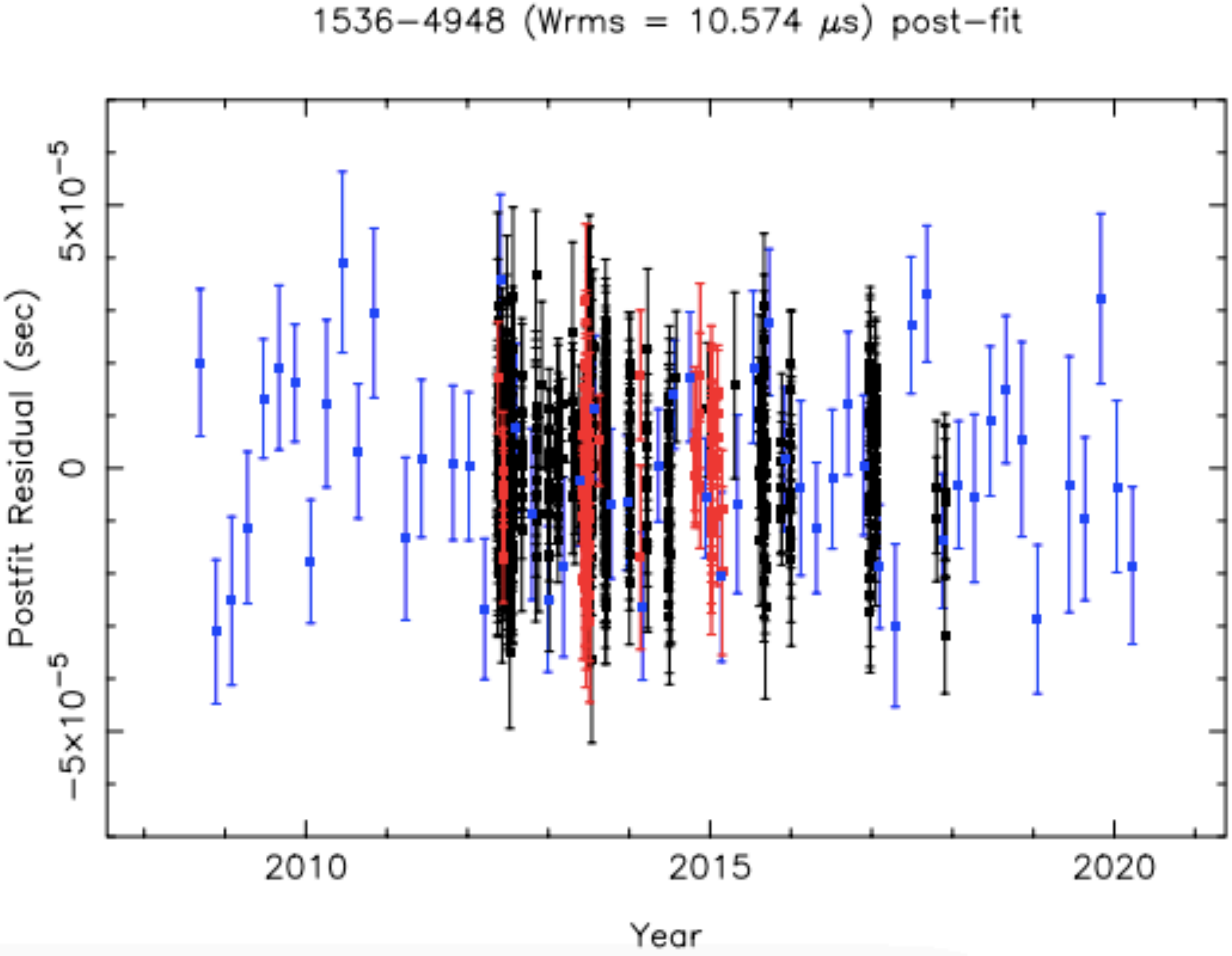
New World Record!!!

Parthasarathy et al. (2021)

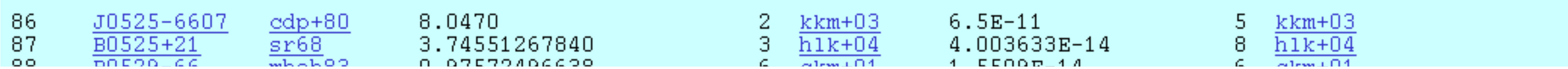
Matthew Balies in SKA 2021 conference on timing with MeerKAT

Precision timing with GMRT

For a newly discovered pulsar



How precisely one can measure pulsar period?



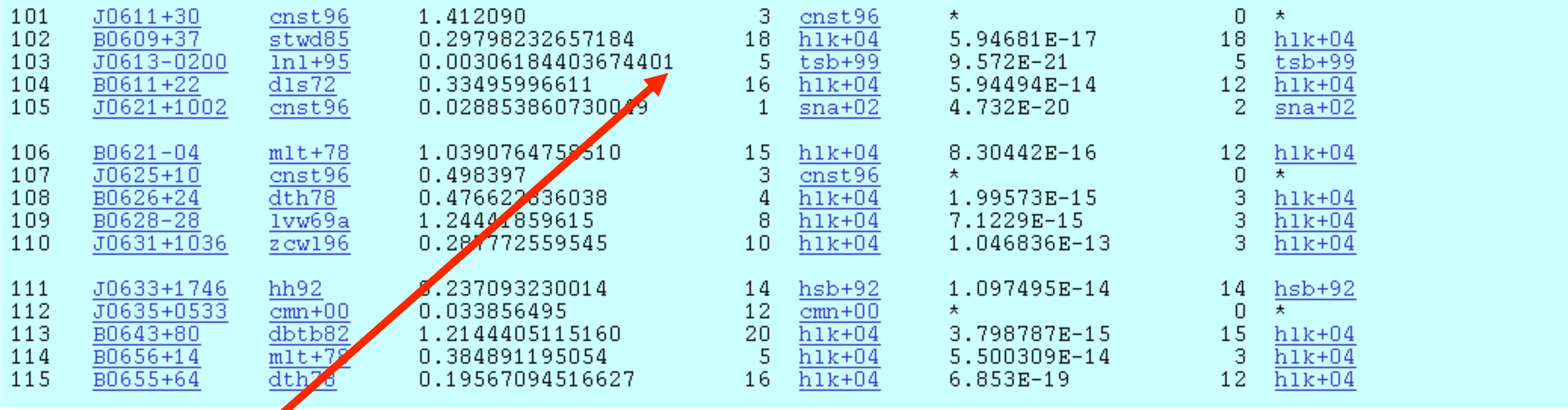
86	J0525-6607	cdp+80	8.0470	2	kkm+03	6.5E-11	5	kkm+03
87	B0525+21	sr68	3.74551267840	3	hlk+04	4.003633E-14	8	hlk+04

Pulsar PSR J0613-0200:

✓Rotation period: 0.0030618440367440 +/- 0.0000000000000005 sec

✓The precission we know it's period allows us to predict the arrival times of all incoming pulses for long (the next 10 million years)!

✓It is the order of magnitude simillar to the best atomic clocks used on Earth!



101	J0611+30	cnst96	1.412090	3	cnst96	*	0	*
102	B0609+37	stwd85	0.29798232657184	18	hlk+04	5.94681E-17	18	hlk+04
103	J0613-0200	lnl+95	0.0030618440367440	5	tsb+99	9.572E-21	5	tsb+99
104	B0611+22	dls72	0.33495996611	16	hlk+04	5.94494E-14	12	hlk+04
105	J0621+1002	cnst96	0.028853860730049	1	sna+02	4.732E-20	2	sna+02
106	B0621-04	mlt+78	1.0390764758510	15	hlk+04	8.30442E-16	12	hlk+04
107	J0625+10	cnst96	0.498397	3	cnst96	*	0	*
108	B0626+24	dth78	0.476622836038	4	hlk+04	1.99573E-15	3	hlk+04
109	B0628-28	lvw69a	1.24441859615	8	hlk+04	7.1229E-15	3	hlk+04
110	J0631+1036	zcwl96	0.287772559545	10	hlk+04	1.046836E-13	3	hlk+04
111	J0633+1746	hh92	0.237093230014	14	hsb+92	1.097495E-14	14	hsb+92
112	J0635+0533	cmn+00	0.033856495	12	cmn+00	*	0	*
113	B0643+80	dbtb82	1.2144405115160	20	hlk+04	3.798787E-15	15	hlk+04
114	B0656+14	mlt+78	0.384891195054	5	hlk+04	5.500309E-14	3	hlk+04
115	B0655+64	dth78	0.19567094516627	16	hlk+04	6.853E-19	12	hlk+04

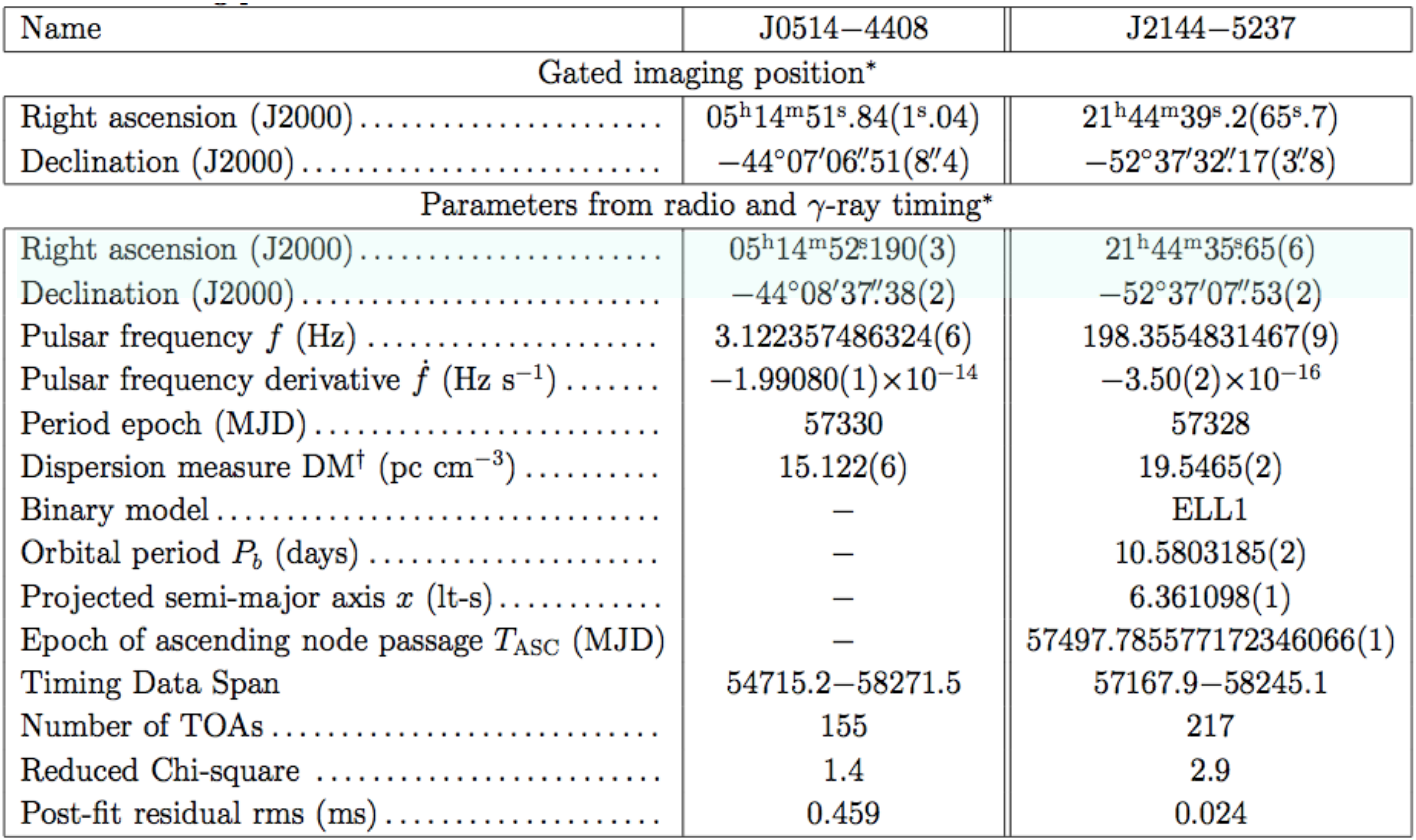
From ATNF pulsar catalogue: http://atnf.csiro.au/research/pulsar/psrcat/

Seventeenth significant digit!!!

The fastest pulsar is PSR J1748-2446ad, which is rotating 713 times per second.

Timing parameters of two pulsars discovered with the GMRT

Bhattacharyya et al. 2019



Name	J0514−4408	J2144−5237
Gated imaging position*		
Right ascension (J2000)	$05^{\rm h}14^{\rm m}51^{\rm s}.84(1^{\rm s}.04)$	$21^{\rm h}44^{\rm m}39^{\rm s}.2(65^{\rm s}.7)$
Declination (J2000)	$-44^\circ07'06''.51(8''.4)$	$-52^\circ37'32''.17(3''.8)$
Parameters from radio and γ-ray timing*		
Right ascension (J2000)	$05^{\rm h}14^{\rm m}52^{\rm s}.190(3)$	$21^{\rm h}44^{\rm m}35^{\rm s}.65(6)$
Declination (J2000)	$-44^\circ08'37''.38(2)$	$-52^\circ37'07''.53(2)$
Pulsar frequency f (Hz)	3.122357486324(6)	198.3554831467(9)
Pulsar frequency derivative $\dot{f}$ (Hz s^{-1})	$-1.99080(1)\times10^{-14}$	$-3.50(2)\times10^{-16}$
Period epoch (MJD)	57330	57328
Dispersion measure DM† (pc cm^{-3})	15.122(6)	19.5465(2)
Binary model	–	ELL1
Orbital period P_b (days)	–	10.5803185(2)
Projected semi-major axis x (lt-s)	–	6.361098(1)
Epoch of ascending node passage $T_{\rm ASC}$ (MJD)	–	57497.785577172346066(1)
Timing Data Span	54715.2−58271.5	57167.9−58245.1
Number of TOAs	155	217
Reduced Chi-square	1.4	2.9
Post-fit residual rms (ms)	0.459	0.024

Timing parameters of two pulsars discovered with the GMRT

Bhattacharyya et al. 2019

How to measure magnetic field of a bar magnet ?

How to measure magnetic field of pulsar ?

Pulsar Timing

Derived parameters

Period (ms)	320.270822408985(6)	5.04145377851813(2)
Period Derivative (s/s)	$2.04203(2)\times10^{-15}$	$8.89(7)\times10^{-21}$
Total time span (yr)	9.7	2.9
Spin down energy loss rate $\dot{E}$ (erg/s)	2.4×10^{33}	2.7×10^{33}
Characteristic age (yr)	2.5×10^{6}	8.9×10^{9}
Surface magnetic flux density (Gauss)	8.2×10^{11}	2.1×10^{8}
Rotation measure (rad m^{-2})	17.3	25.1
DM distance (kpc)[‡]	0.8	0.8
DM distance (kpc)[‡†]	0.9	1.6

What do we learn from pulsar timing?

We can learn a lot by just timing the solitary pulsars:

- their sky coordinates
- their movements
- their age
- their evolutional stage (and of course the overal evolution of a pulsar)
- their magnetic fields
- details of their births (natal kicks)
- their associations with supernova remnants
- their galactic distribution
- the galactic distribution of free electrons (from the dispersion measure)
- also about neutron star interiors..

But that is only a beginning. It gets more interesting with the binary pulsars...

- Eccentricity of the orbit
- Semi major axis
- Orbital period
- Planets around pulsar

And lots more depending on the particular system

Pulsar Research last 50 years

Discovery of pulsars :
Hewish, Bell et al. 1968, Nature, 217, 709

Vacuum Gap model pulsar radio radiation:
Ruderman & Sutherland 1975, ApJ, 196,51

Discovery of pulsar in a binary system:
Hulse & Taylor, 1975, ApJ, L51

Discovery of the 1st Millisecond pulsar:
Becker, Kulkarni et al., 1982, Nature, 300, 615

Discovery of the 1st extrasolar planet around PSR J1257+12:
Wolszczan, Frail, 1992, Nature, 355, 145

Discovery of the double pulsar system:
Burgay et al. 2004, Science, 303, 1153

Synchronous X-ray and radio mode switches of pulsar magnetosphere of PSR B0943+10 :
Hermsen et al. 2013

+ Fast Radio Bursts
+ Rotating radio Transients
+ MSP-LMXB transitioning systems

Pulsar research in different directions :
2 Nobel prizes : 1 on discovery of pulsars(1974), 1 on discovery of Hulse-Taylor binary (1993)
More than 50 Nature papers

Thank you

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Pulsar sounds:

http://www.jb.man.ac.uk/~pulsar/Education/Sounds/

http://www.atnf.csiro.au/people/pulsar/psrcat/

http://www.astron.nl/pulsars/animations/