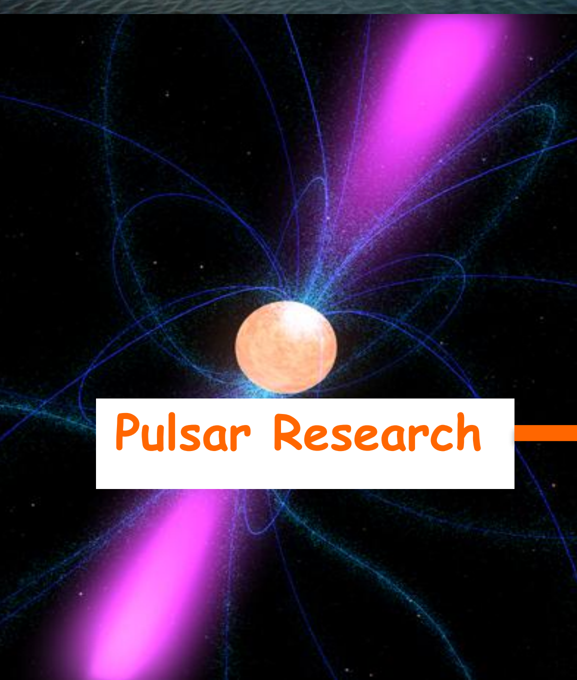
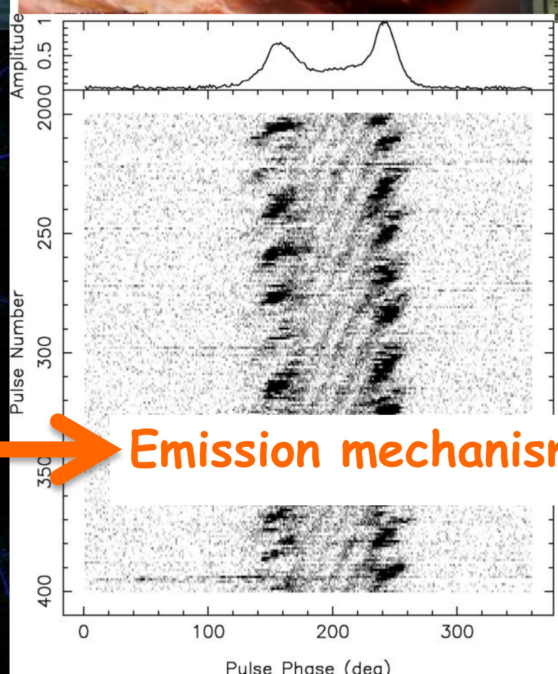
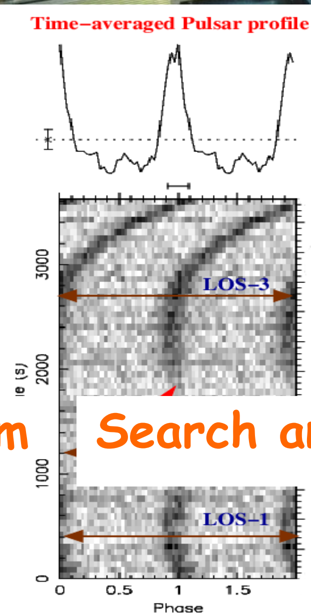
Pulsars

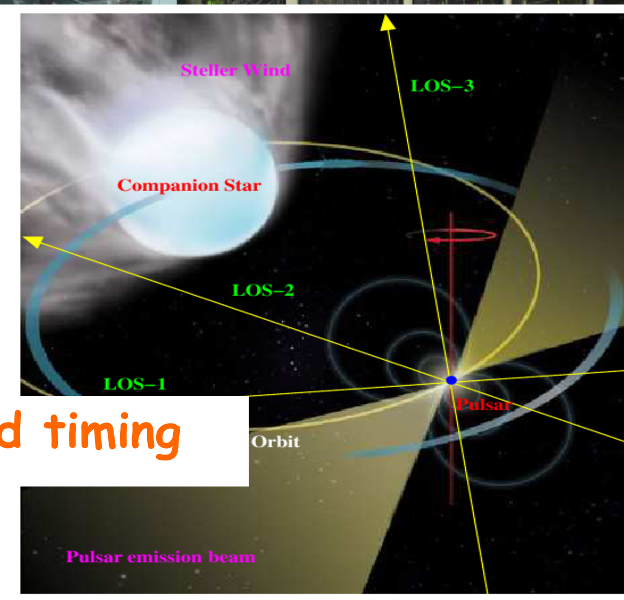
Radio Astronomy School Talk
26th August, 2013

Bhaswati Bhattacharyya









Note : LOS stands for Line−of−sight

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

Plan of Talk

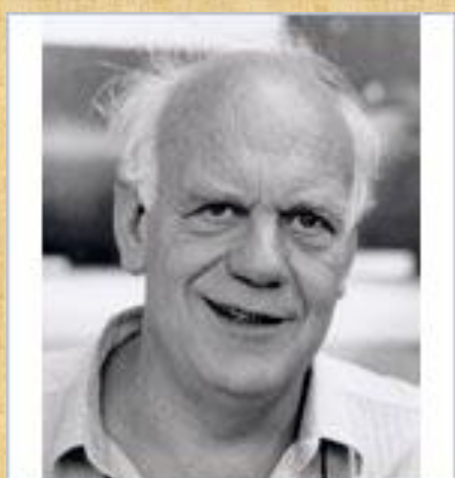
- ✓ Neutron stars and pulsars – Early History
- ✓ Introduction
  - Radio pulsars
  - Interstellar dispersion effect; Polarization
  - Pulsar classification: normal pulsars and MSPs
  - Pulsars as astrophysical tools
- ✓ Search of pulsars
  - Blind Radio surveys
  - Fermi Directed pulsar search
  - GMRT effort of Fermi Directed search & Discovery
- ✓ Timing of pulsars
- ✓ Imaging study of pulsars
- ✓ Investigation of emission mechanism of pulses

Neutron Stars and Pulsars – Early History

Neutron Stars and Pulsars – Early History

Walter Baade & Fritz Zwicky
1934

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

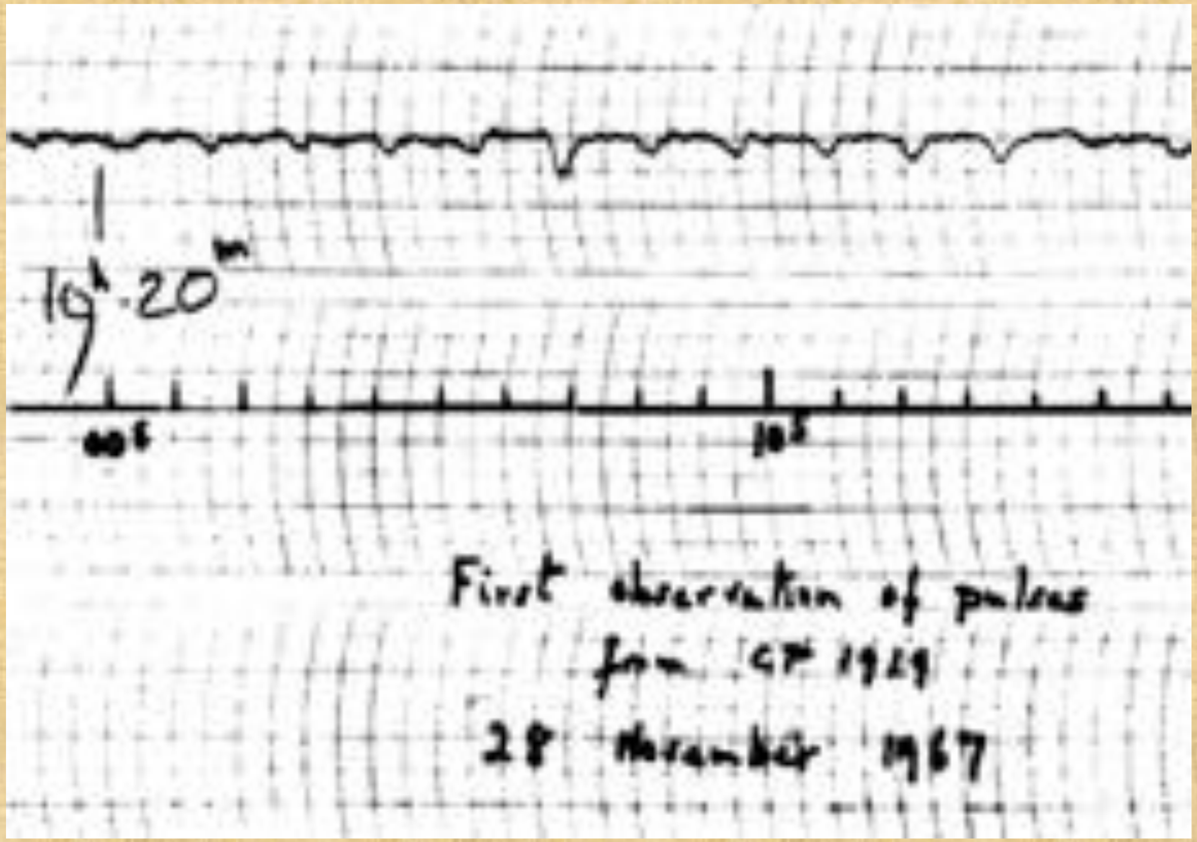


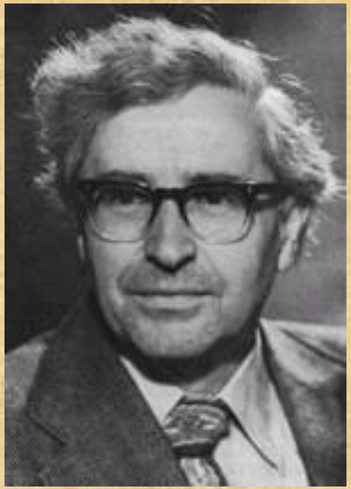
Franco Pacini 1967

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



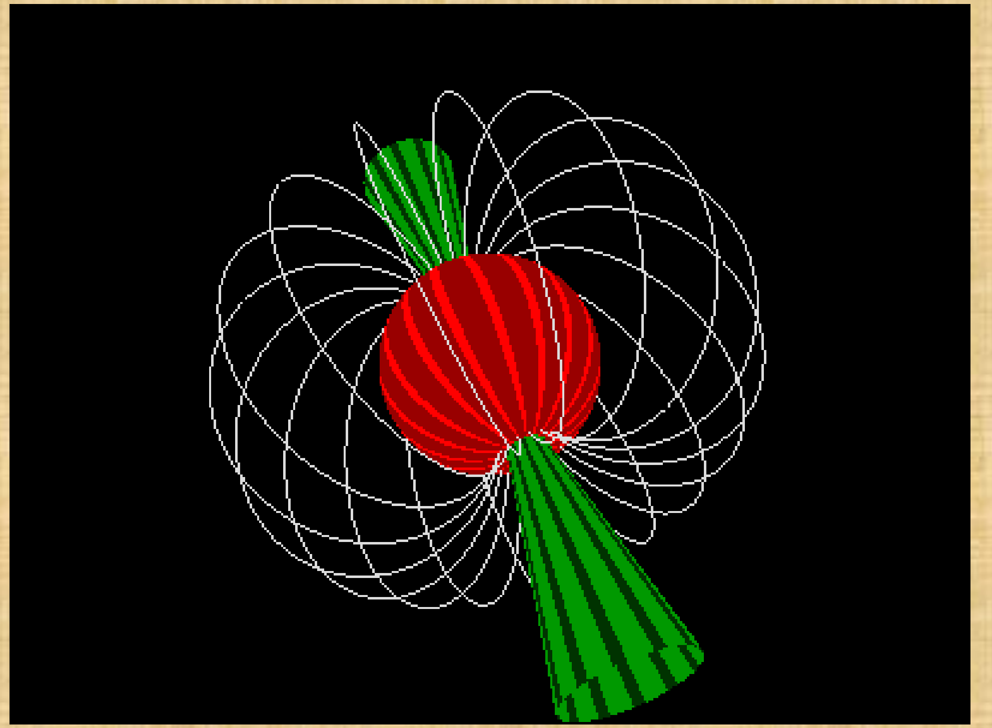


Discovery of radio pulsars → Nobel Prize in 1974

Neutron Stars and Pulsars – Early History

Franco Pacini 1968

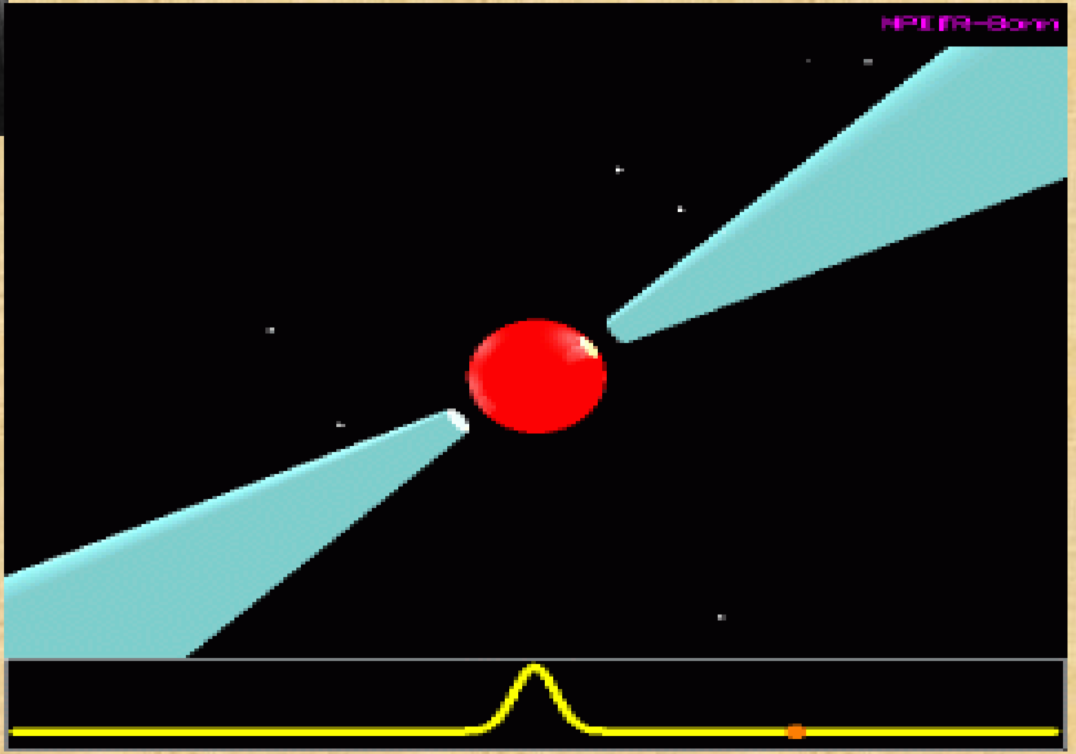
- ✓ "Pulsars" are formed after supernovae explosion !



Neutron Stars and Pulsars – Early History

Tommy Gold 1968
: Pulsars are rotating neutron stars

Lighthouse model of pulsations



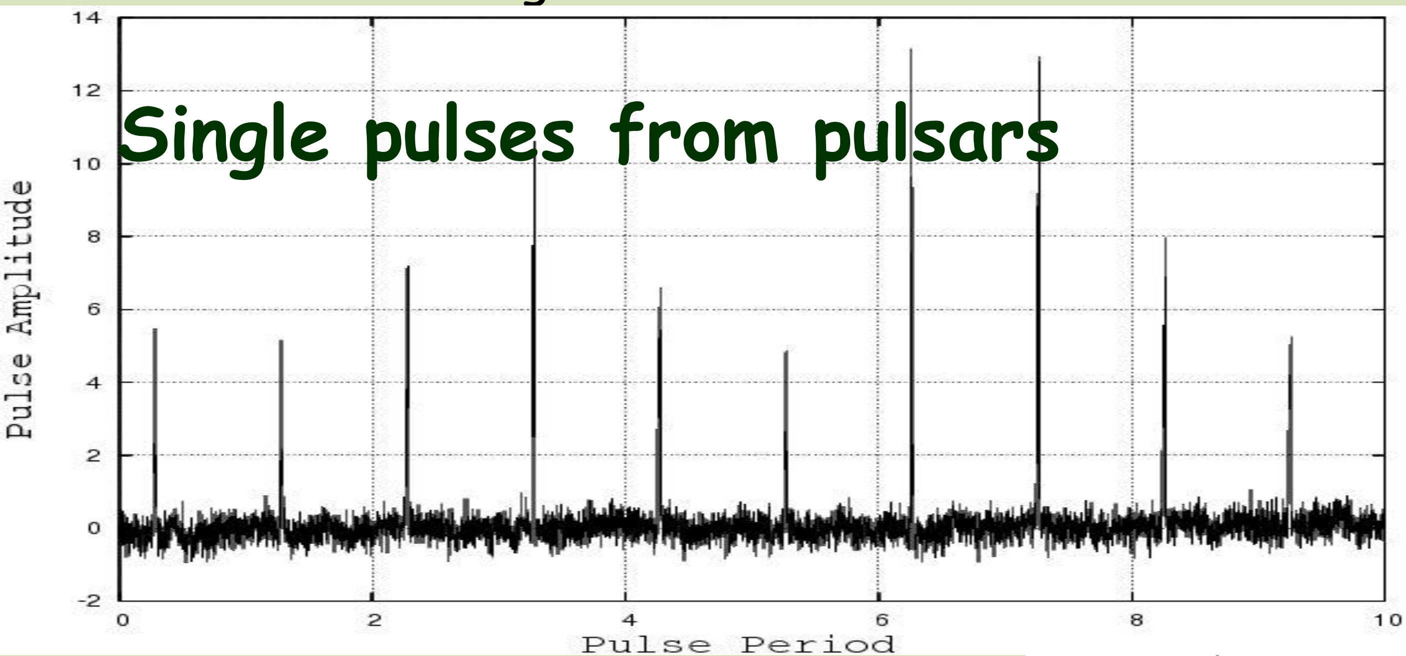

Light house in the sea

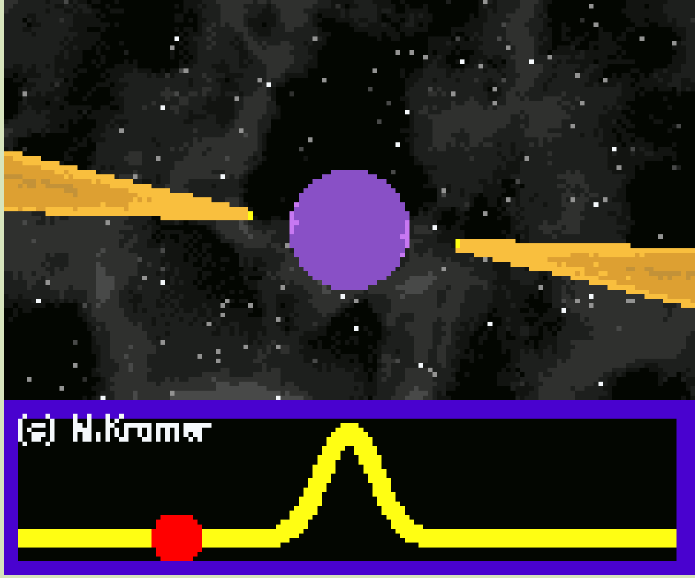
Radio pulsars

Pulsars

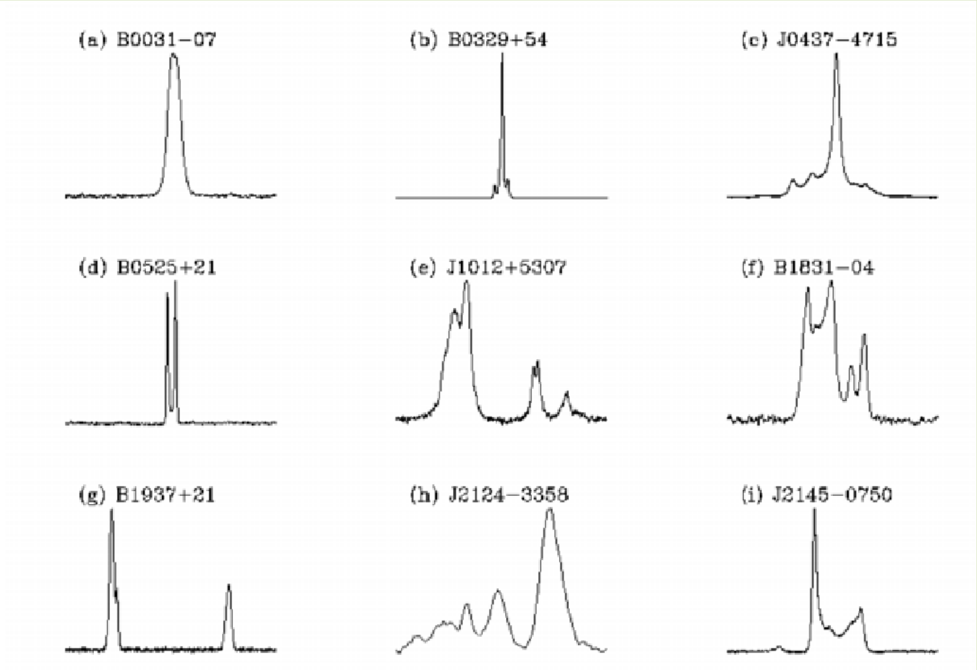
Rapidly rotating strongly magnetized neutron stars

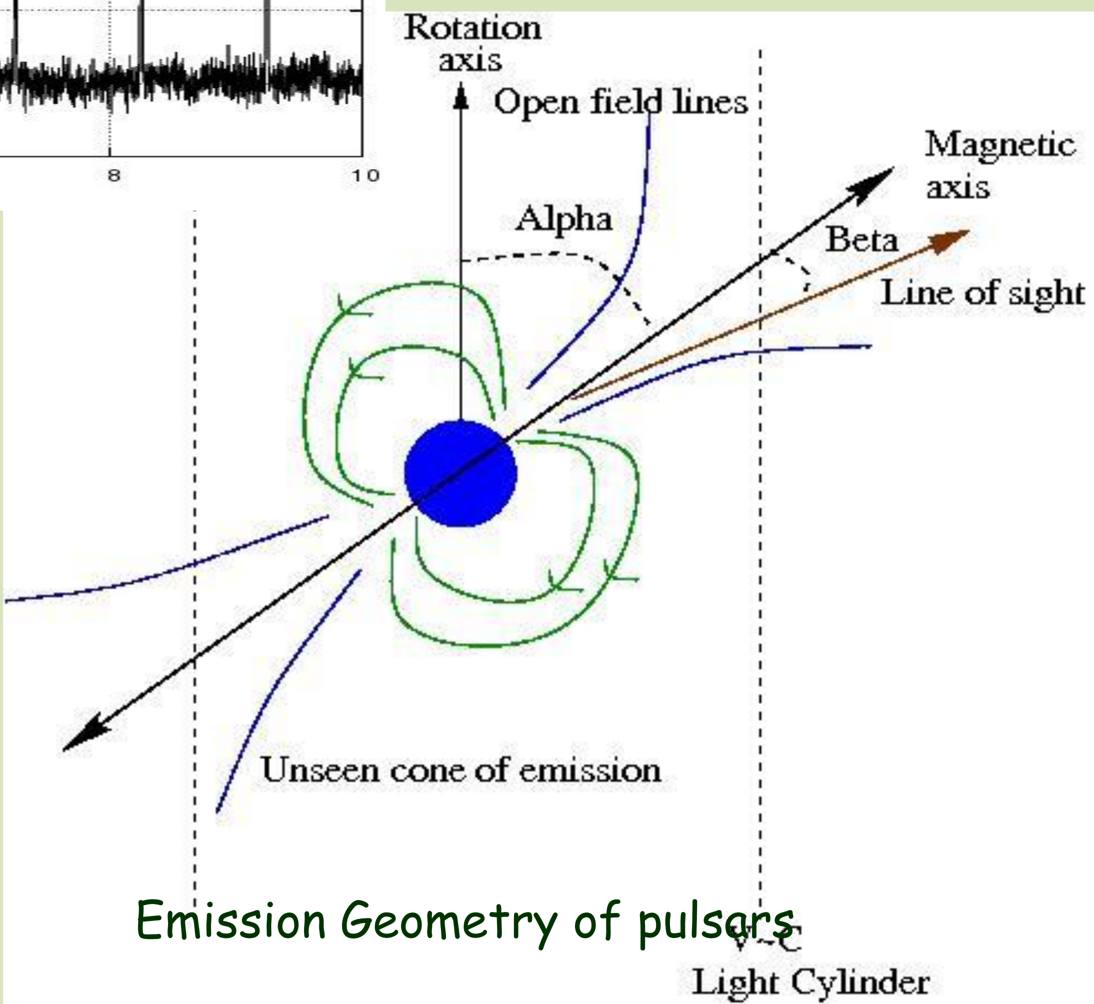
Single pulses from pulsars





Average pulse profile of pulsars

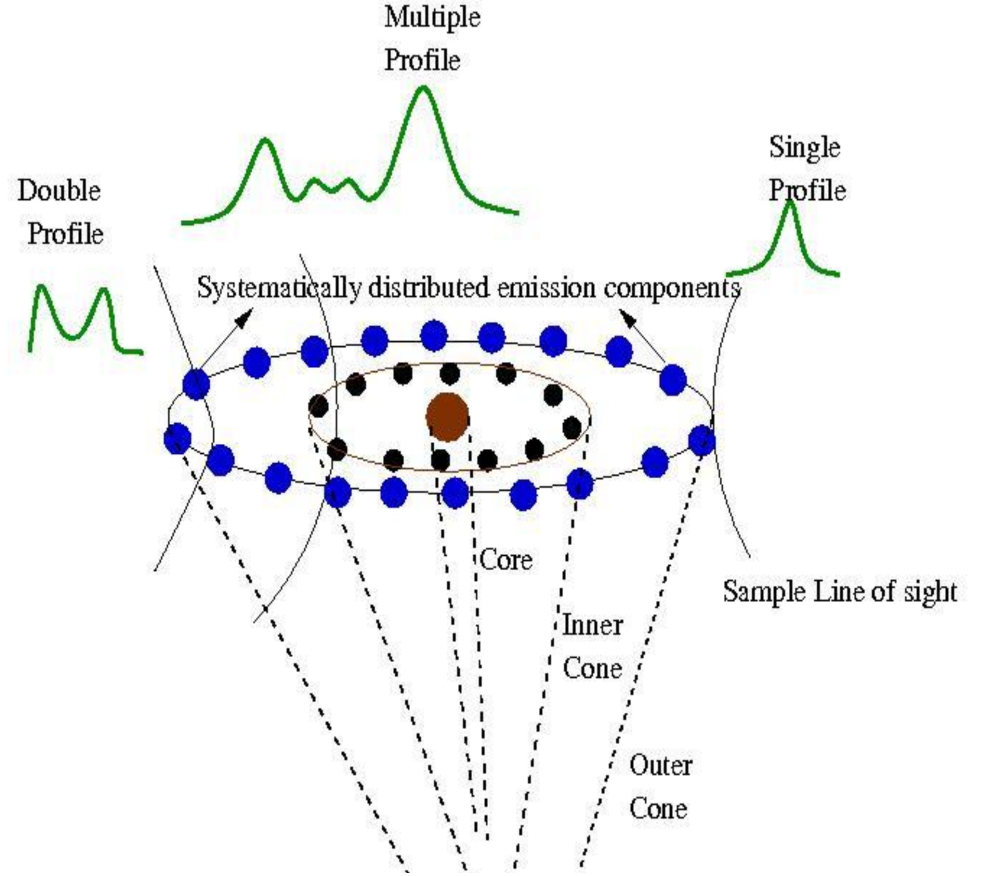




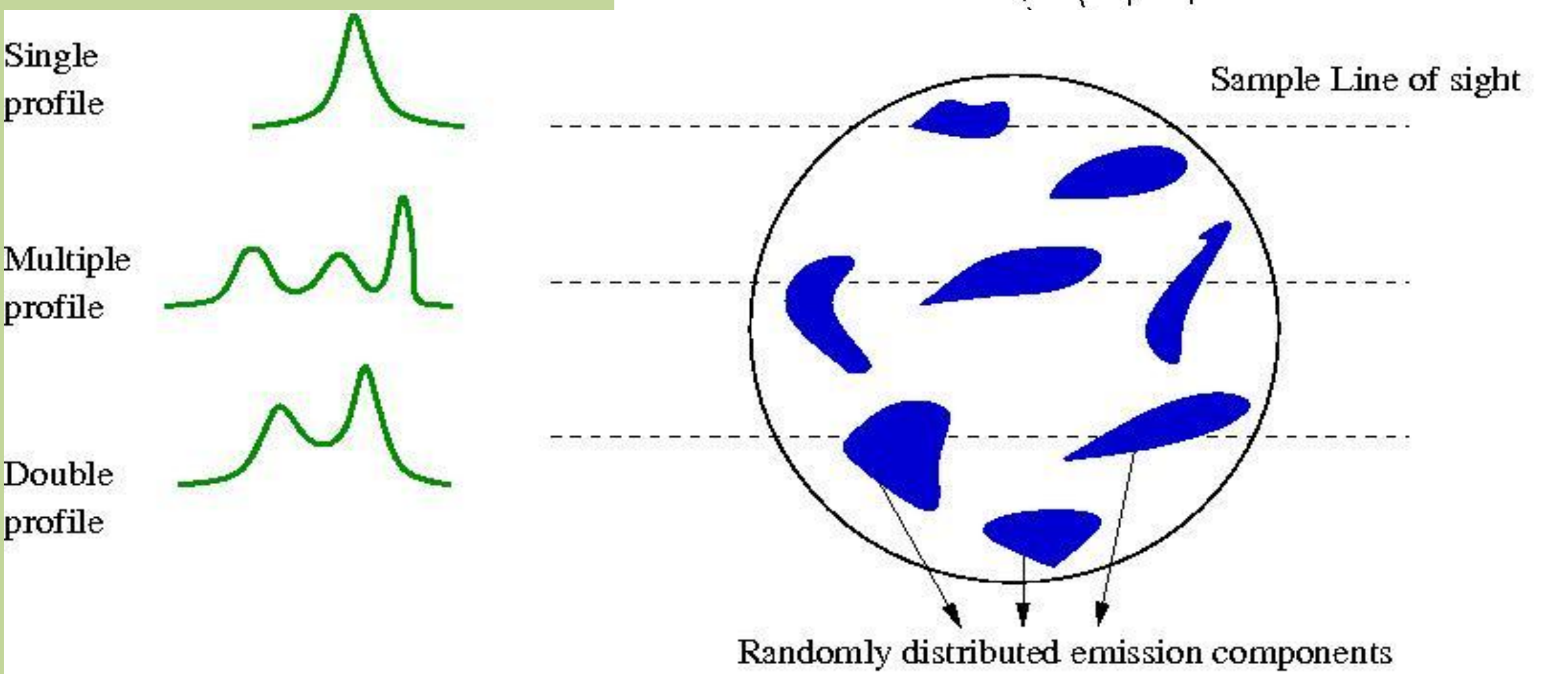
Emission Geometry of pulsars

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

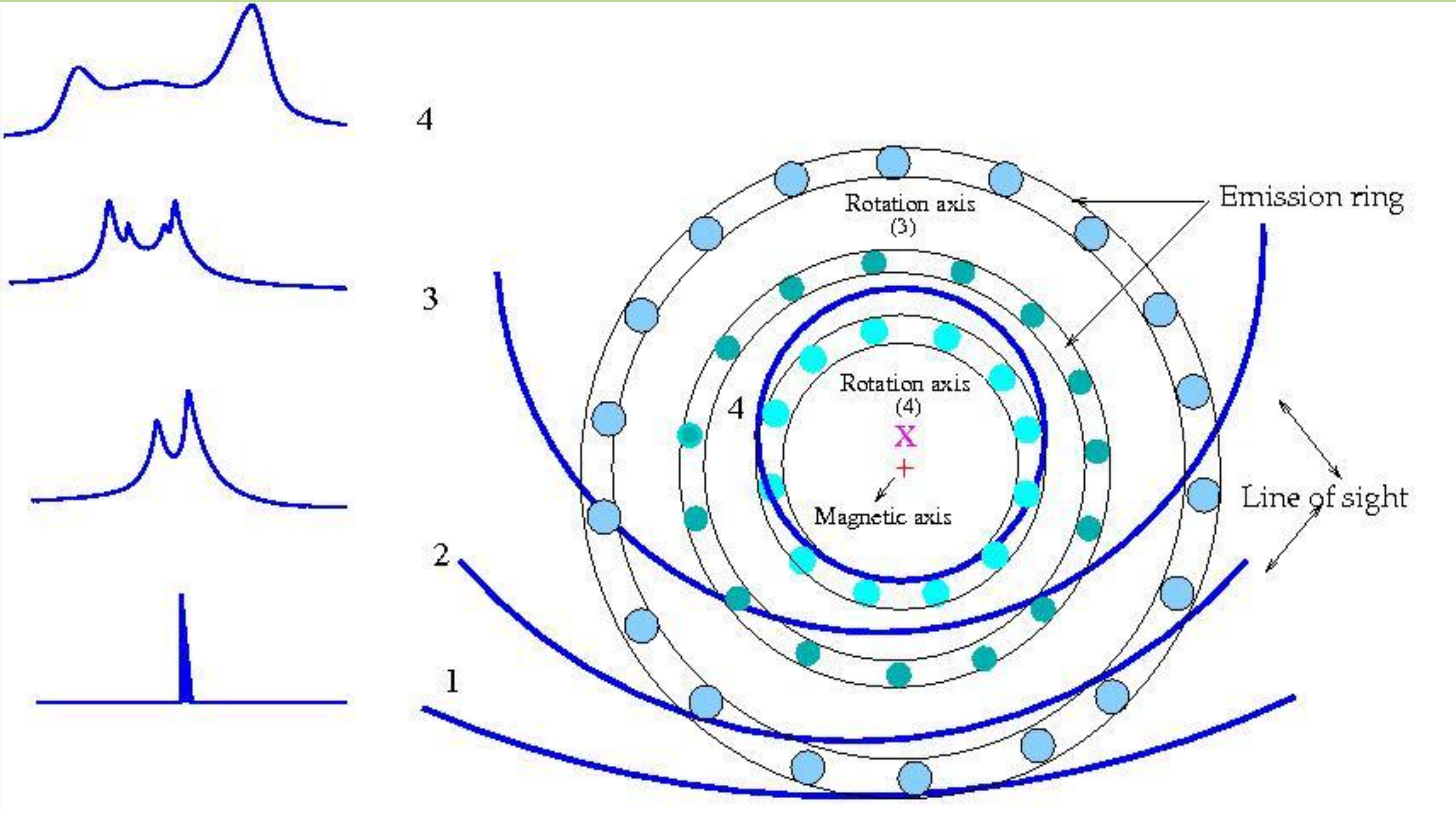
(1) Core – Conal Model
(Rankin 1993)



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

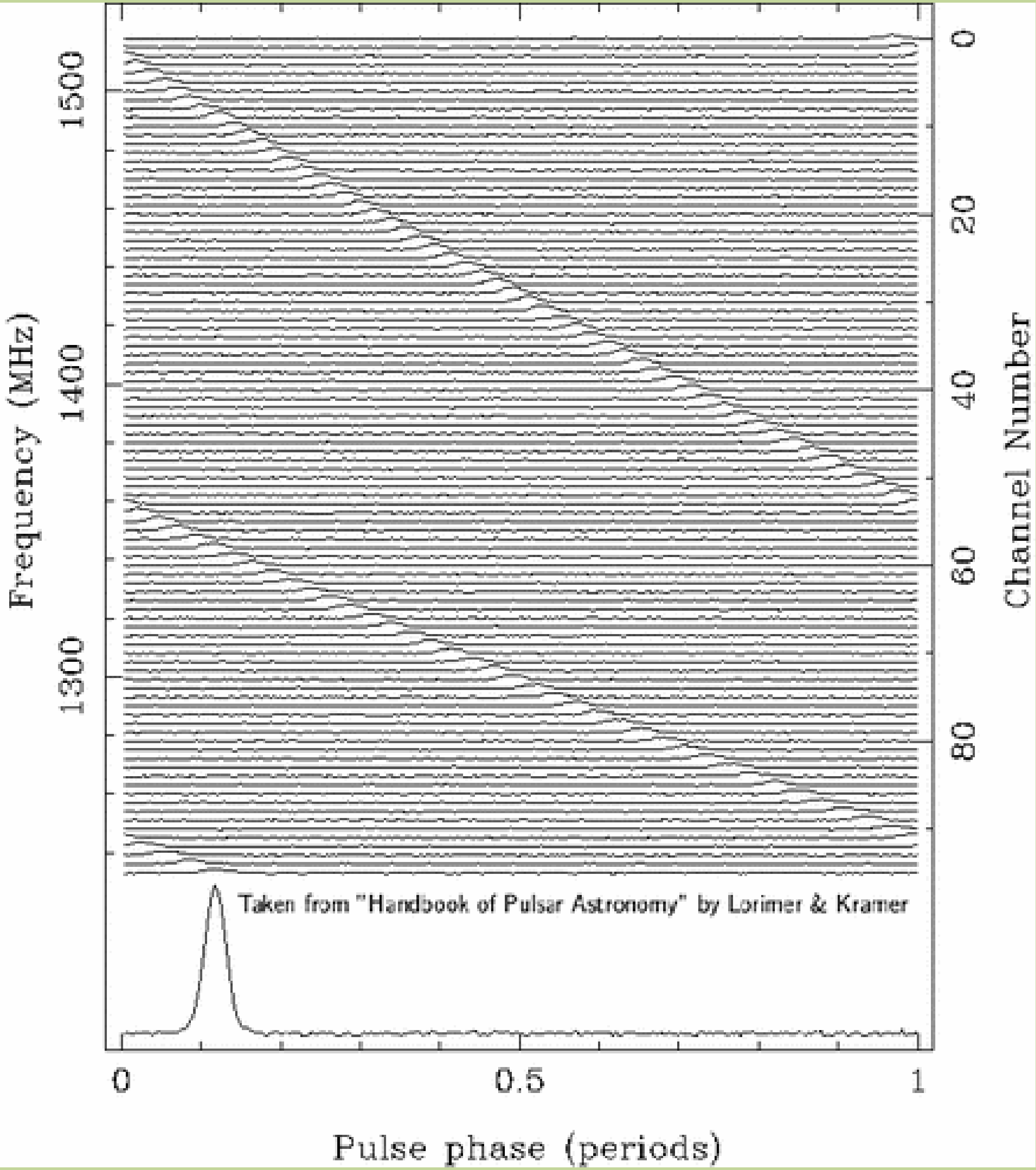


Pulse profiles : Looking down on the polar cap



LOS cuts with corresponding pulse profiles

Interstellar disspersion effect:

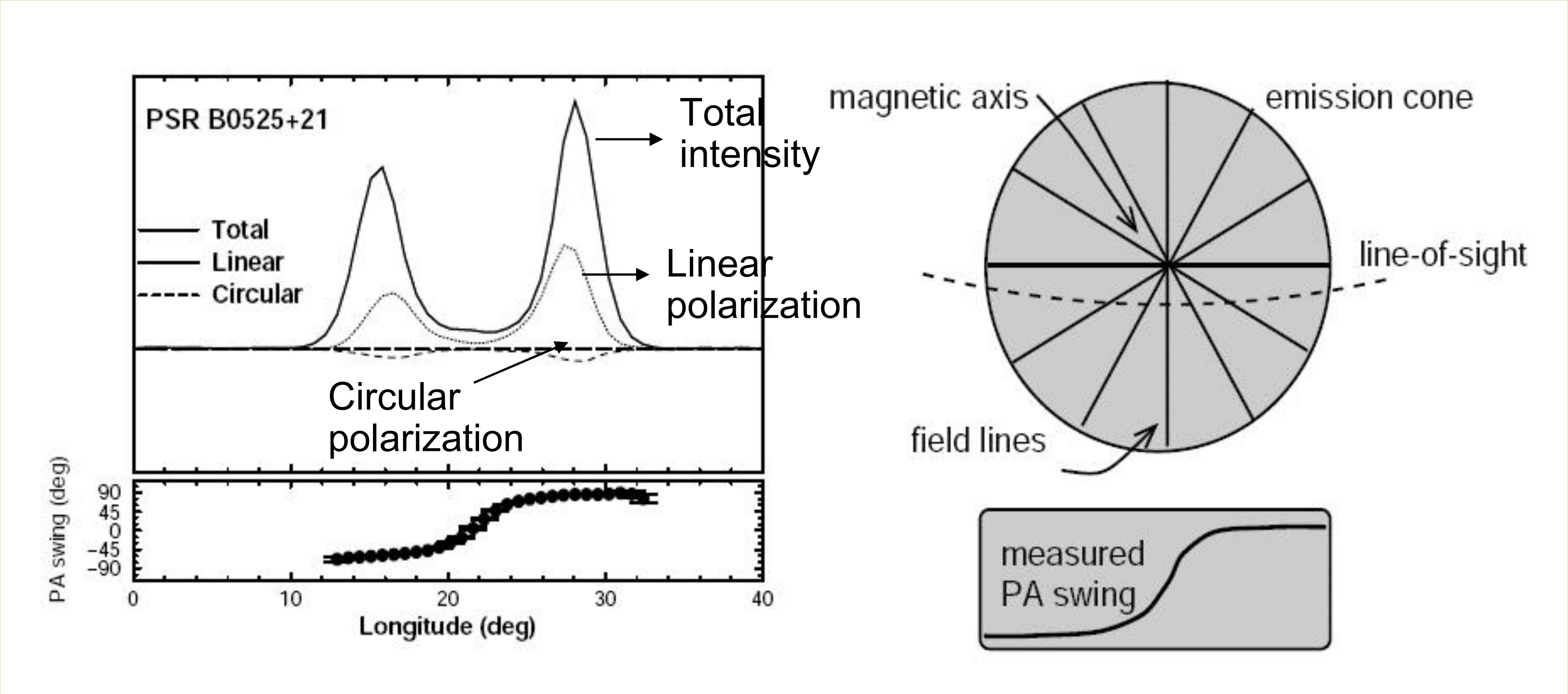


Interstellar medium (in fact the free electrons in it) is a dispersive medium for radio waves.

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

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

Pulsar Polarization



Polarization study can be used for

Understanding the emission geometry
Determining α, β

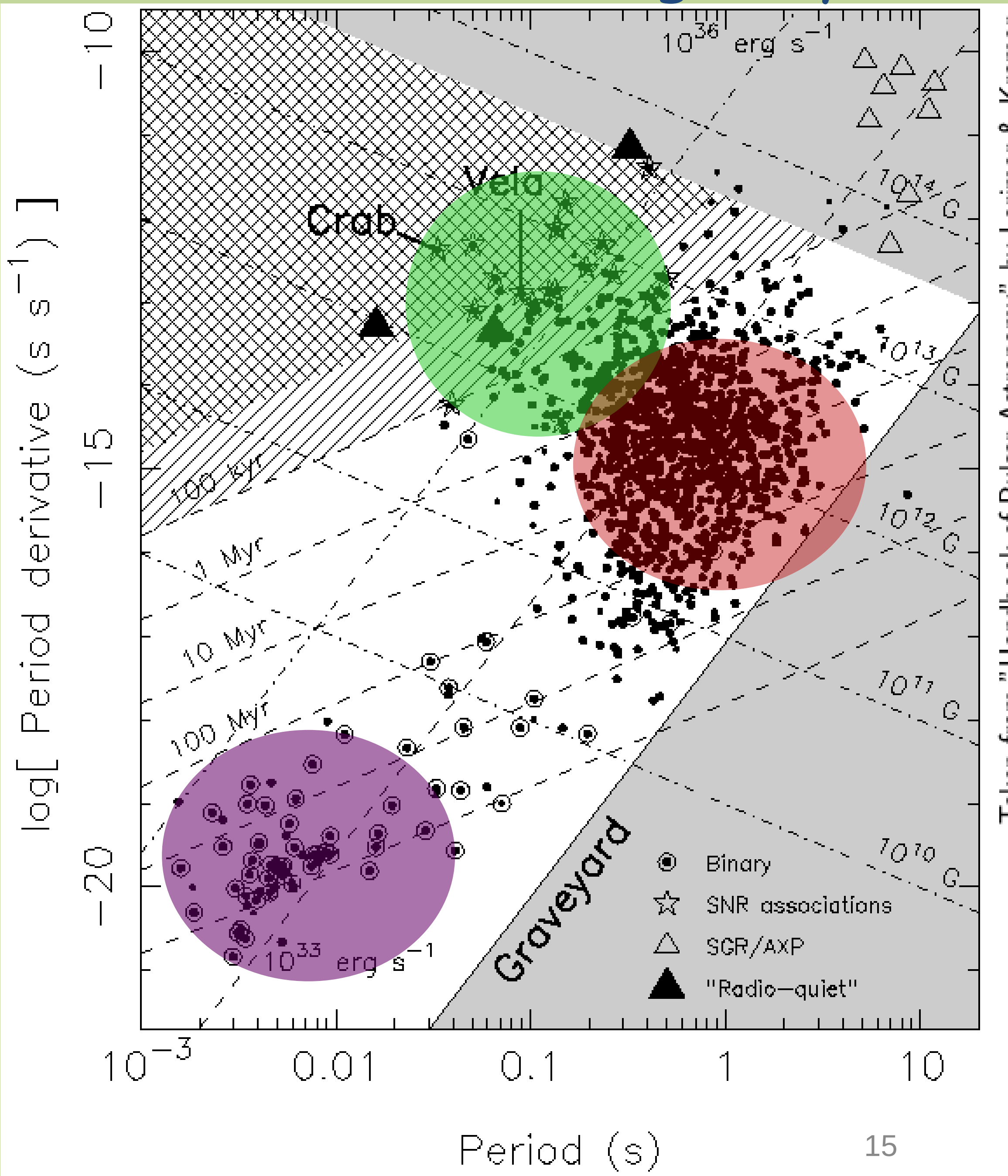
Pulsar classification

2000 known radio Pulsars in our galaxy

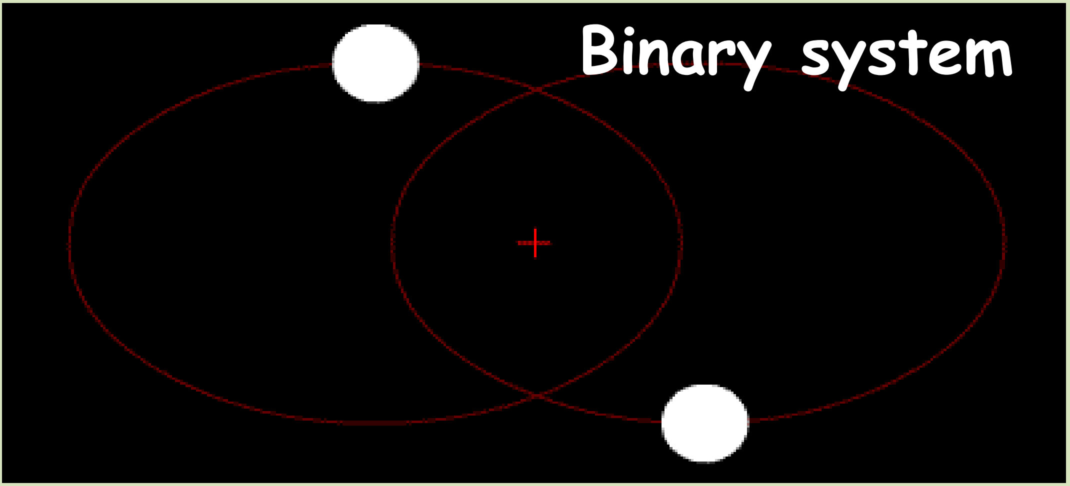
Young (~20)
- Energetic, with significant spin-down noise and glitches.

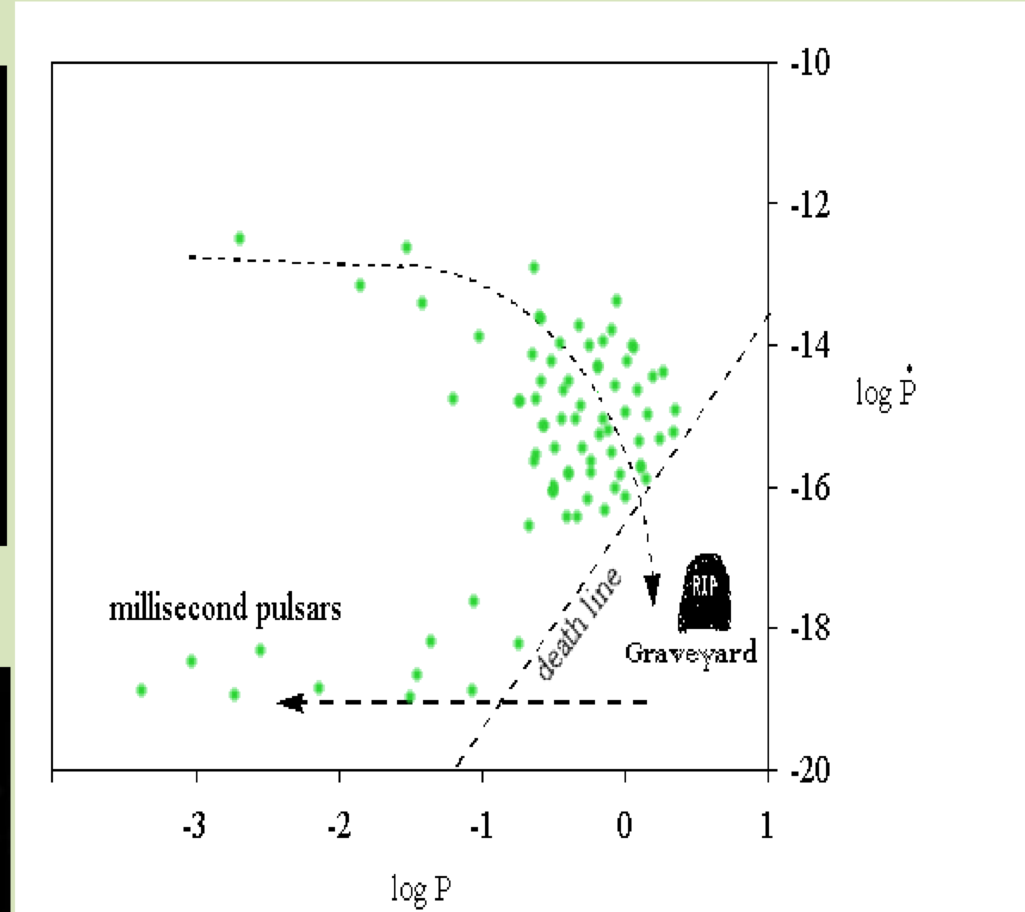
Normal (~1800)
- Slower, More stable, Mostly isolated

Recycled pulsars (~200)
- Faster, Most in binaries, **extremely** stable rotators
->**MILLISECOND PULSARS**



Millisecond pulsars

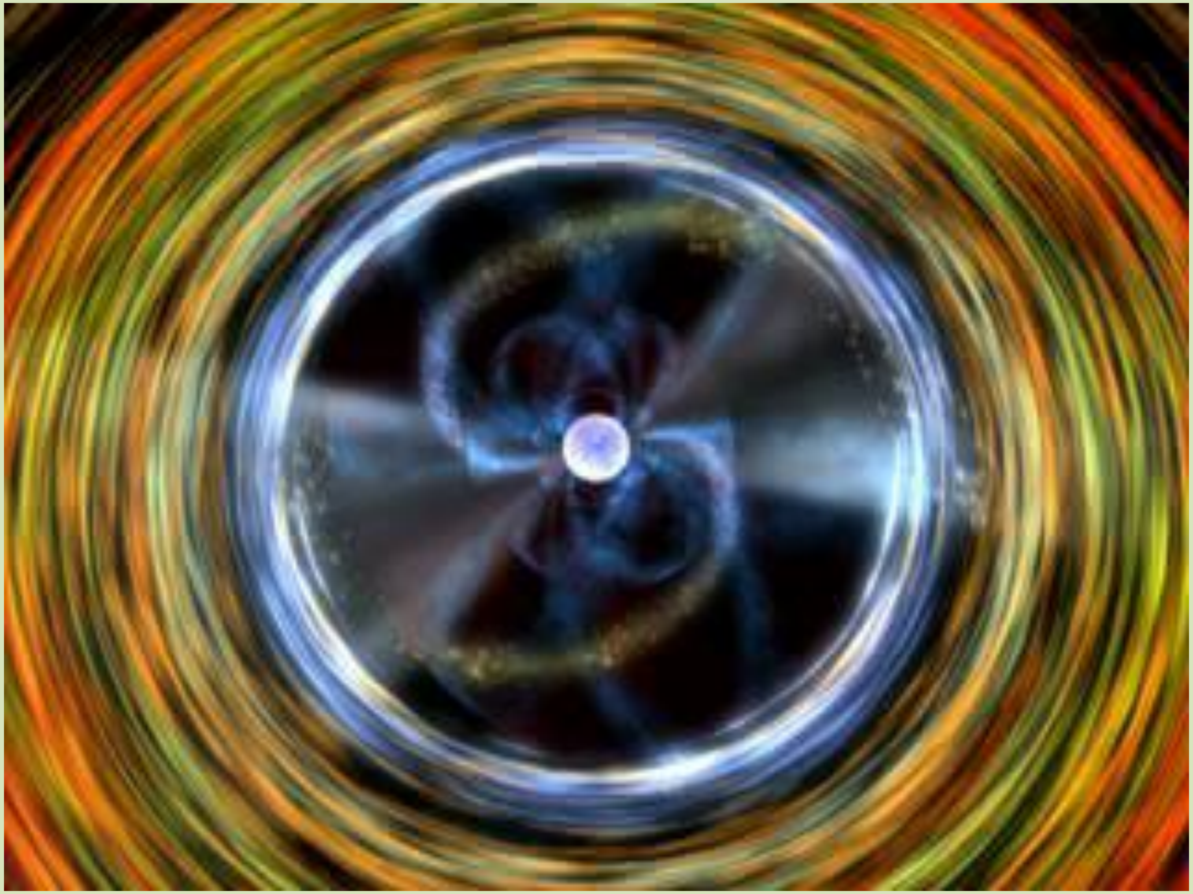




pulsar but are spun up or recycled through accretion
thus millisecond pulsars are often called recycled pulsars.

MSPs can be considered as Celestial GPS

Millisecond pulsars : Top view



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 astrophysics "tools"

- Due to their physical properities pulsars are (in most cases) VERY stable rotators – one needs an unimaginable force to unhinge it.

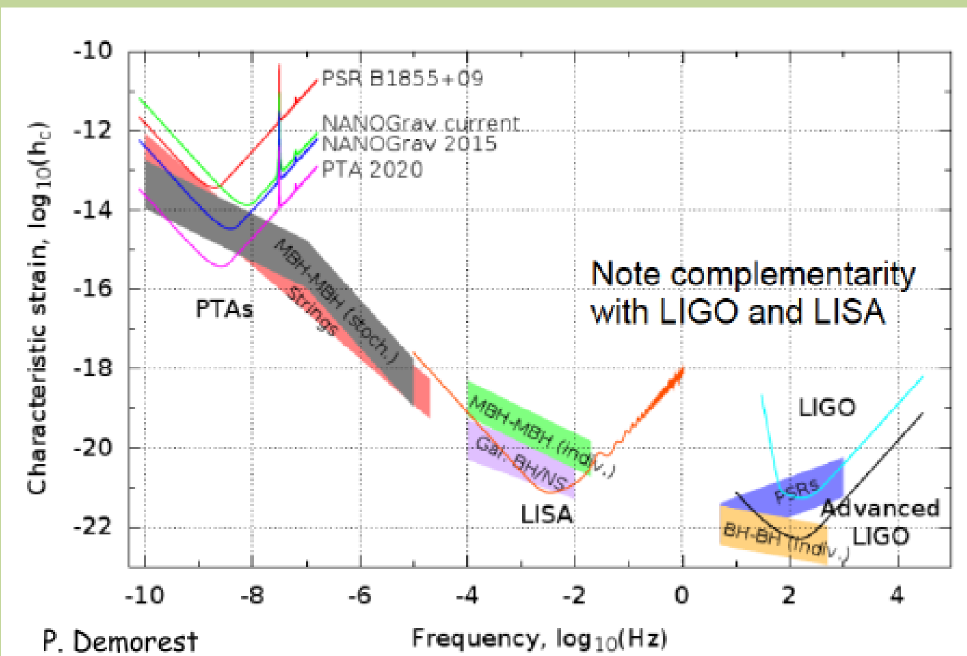
  The incomming pulses of radiation may be therefore treated as "ticking" of cosmic clocks.

- We can treat pulsars as naturally created probes of specific conditions in which they exist – i.e. strong gravitational fields.

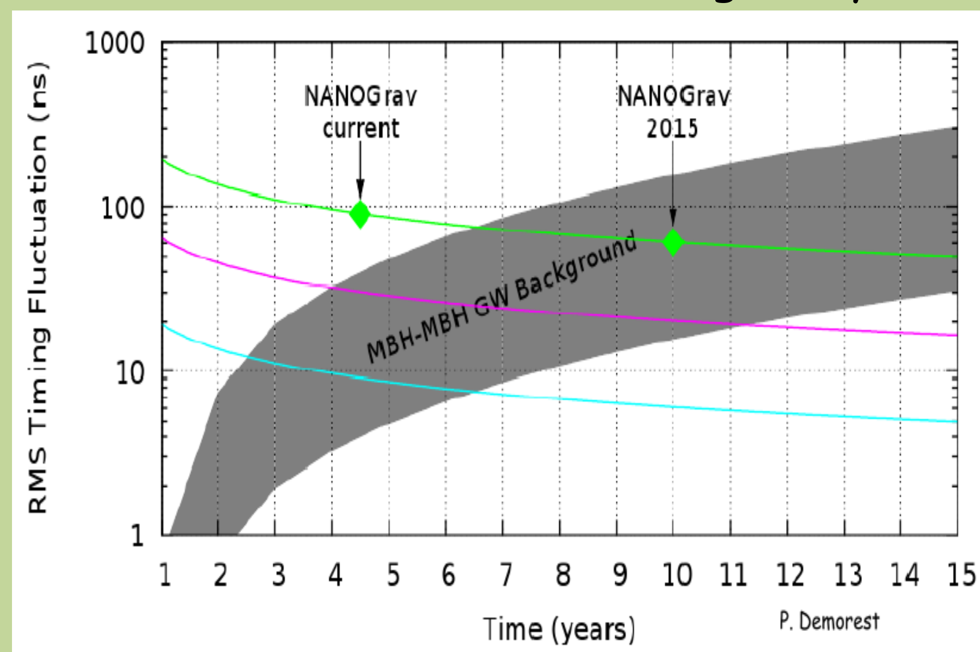
- Pulsars allows to investigate their dynamics – especially the movement caused by external forces. This includes binary systems, and globular clusters dynamics.

MSP as a Probe to fundamental physics

- Equation of state at nuclear density
- Gravitational wave detection
- Interstellar medium
- Binary evolution
- Plasma physics (eclipse and magnetosphere)



20 MSP NanoGrav Pulsar timing array



h ~ σ_{rms}/T ~ 100ns/5 yr ~ 10^{-15}

$$h = \frac{\sigma_{rms}}{T\sqrt{N_{TOAs} N_{PSR}}}$$

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 !!*

In last four years population of Galactic Field millisecond pulsars (MSPs) increased by about 61 %

Discoveries are contributed by surveys from major radio telescopes around the world : GBT, Parkes, Arecibo..

Some Important surveys

1) Parkes Multi beam: 1000 PSR
2) PALFA Arecibo: 116 PSR, 16 MSP
3) HTRU at Parkes and Effelsberg:140 PSR, 27 MSP
4) GBNCC at GBT: 62 PSR, 9 MSP
5) GBT drift scan: 26 PSR, 7MSP

Fermi-directed pulsar surveys (last 3 years)> 52 MSPs

GMRT

GBT

PARKES

Fermi γ-ray Space Telescope

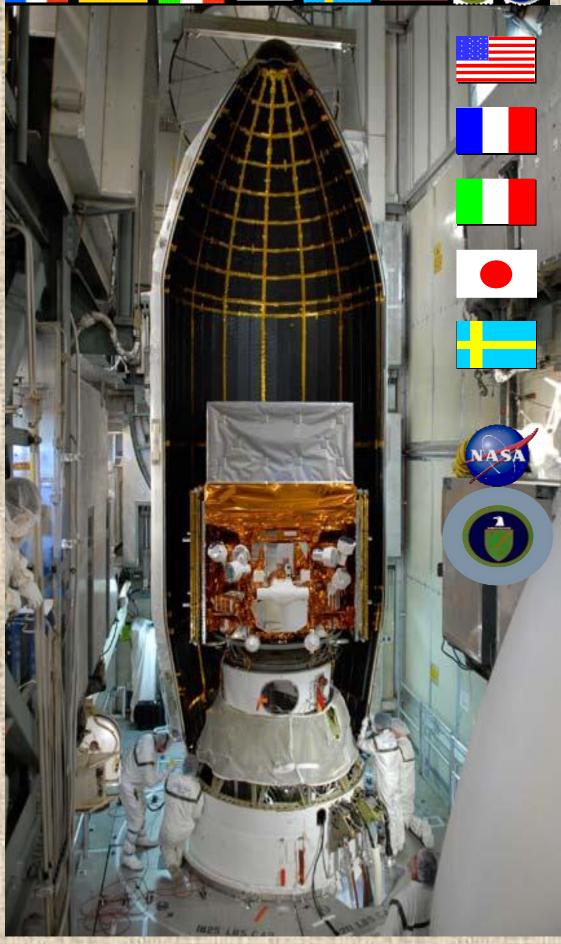
Large AreaTelescope (LAT)
20 MeV - >300 GeV

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)

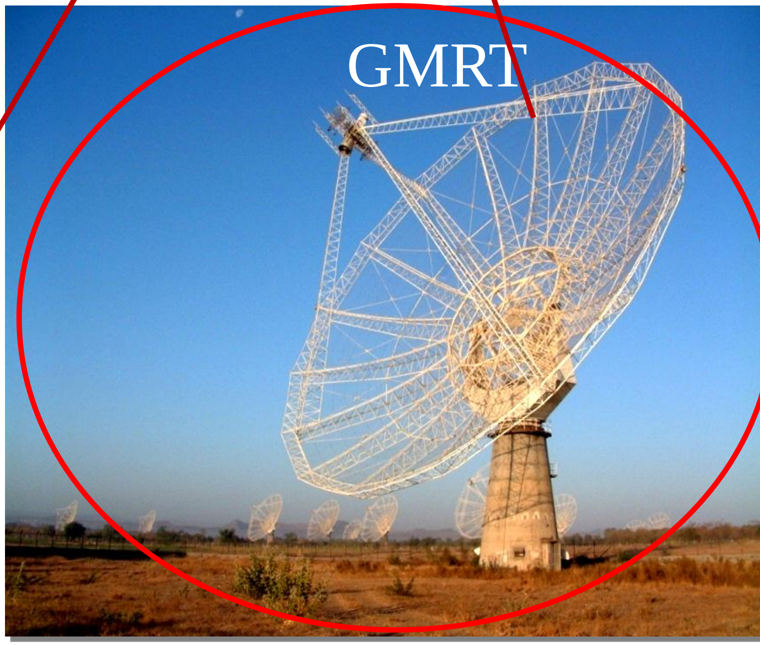
Low frequency facility

Jodrell Bank (UK)

Nançay (France)

Parkes (Australia)

Green Bank (USA)



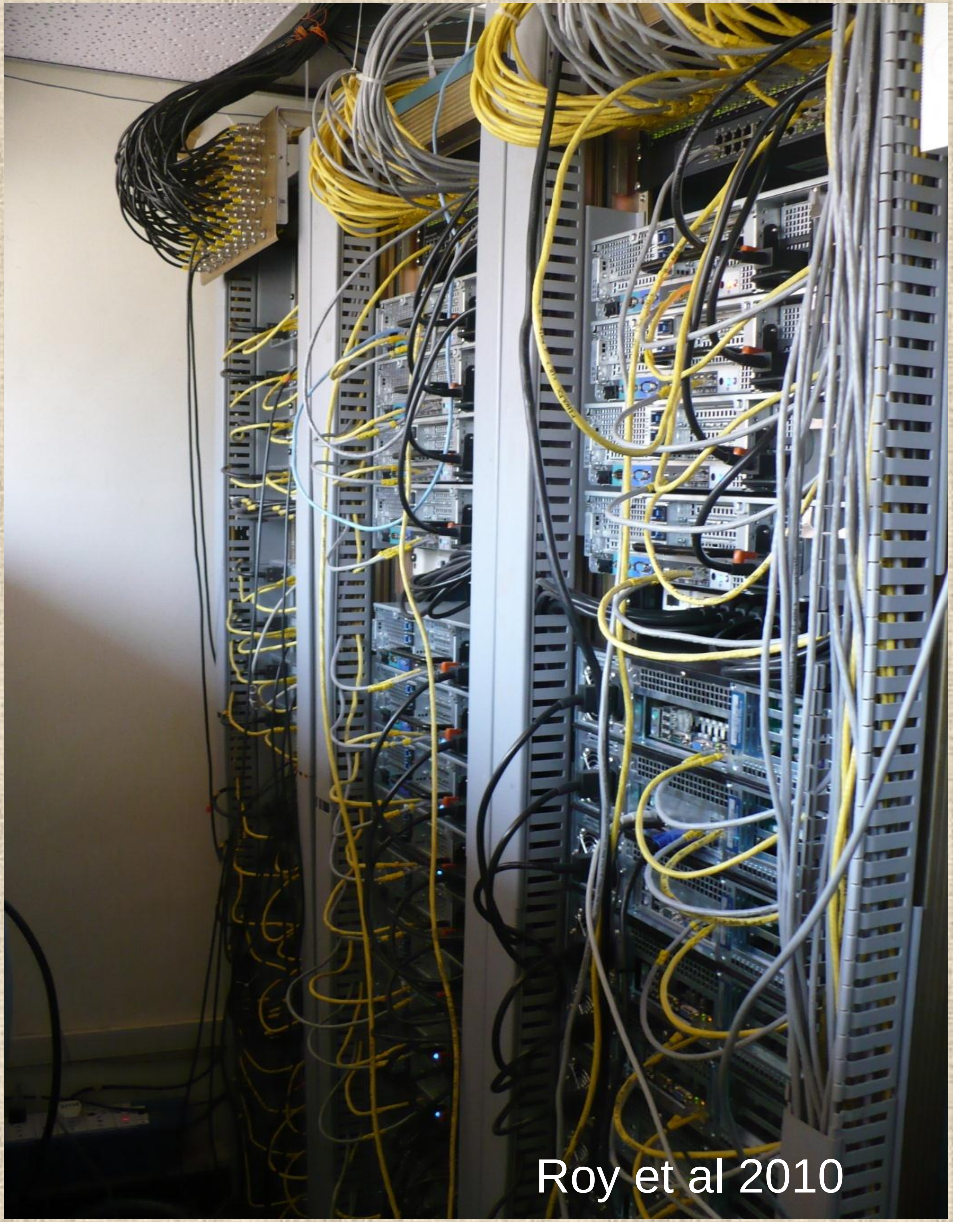
GMRT as a PSC telescope

- ❑ Pulsar search is benefitted by low radio frequency because of steep spectral nature
→ GMRT have sensitive low frequency coverage for larger declination range

- ❑ Large field of view of the GMRT
→ easily covers the positional error boxes of the Fermi sources; this also increases chances for serendipitous discoveries.

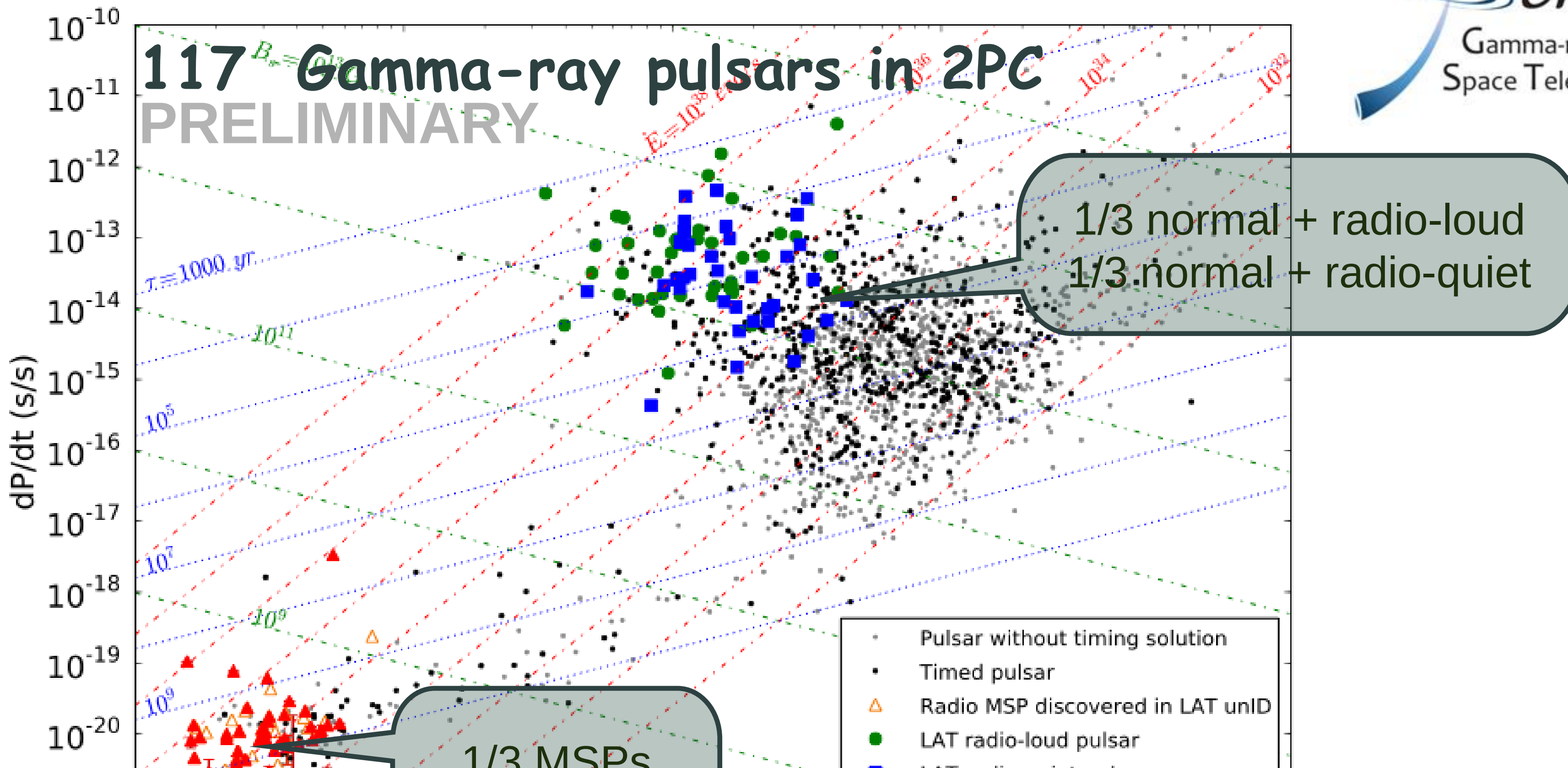
- ❑ New techniques of multi-beaming and pulsar gating (Roy et al. 2012, 2013)
→ enables precision Astrometry and helps in timing

New HPC back-end at the GMRT : an efficient/flexible receiver to look for nearby fast pulsars



Second LAT Pulsar Catalog (2PC)

Fermi Gamma-ray Space Telescope



Submitted to ApJ Suppl

Revision: 9559: Last update: 2013-05-19 19:48:00 +0200

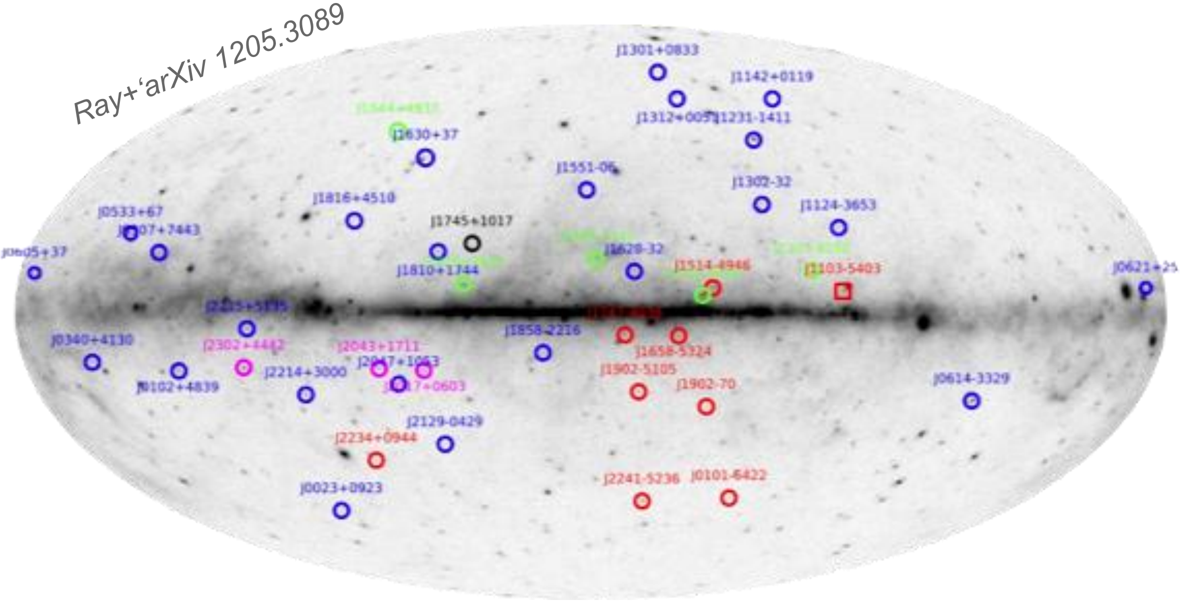
The Second *Fermi* Large Area Telescope Catalog of Gamma-ray Pulsars

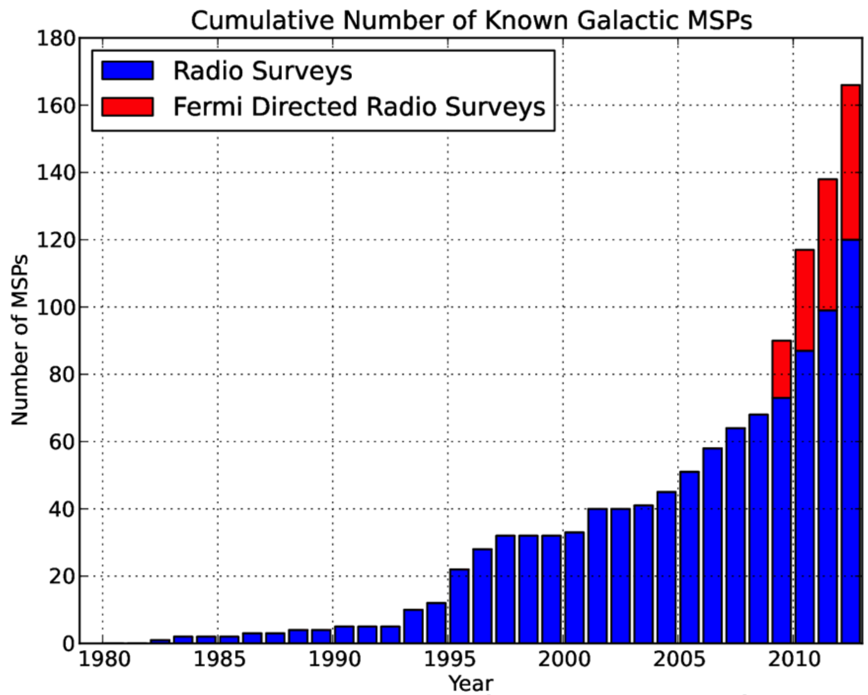
arXiv:1305.4385

A. A. Abdo[1], M. Ajello[2], A. Allafort[3], L. Baldini[4], J. Ballet[5], G. Barbiellini[6,7], M. G. Baring[8], D. Bastieri[9,10], A. Belfiore[11,12,13], R. Bellazzini[14], B. Bhattacharyya[15],

Fermi-directed radio searches : 48 MSPs discovered

Ray+'arXiv 1205.3089



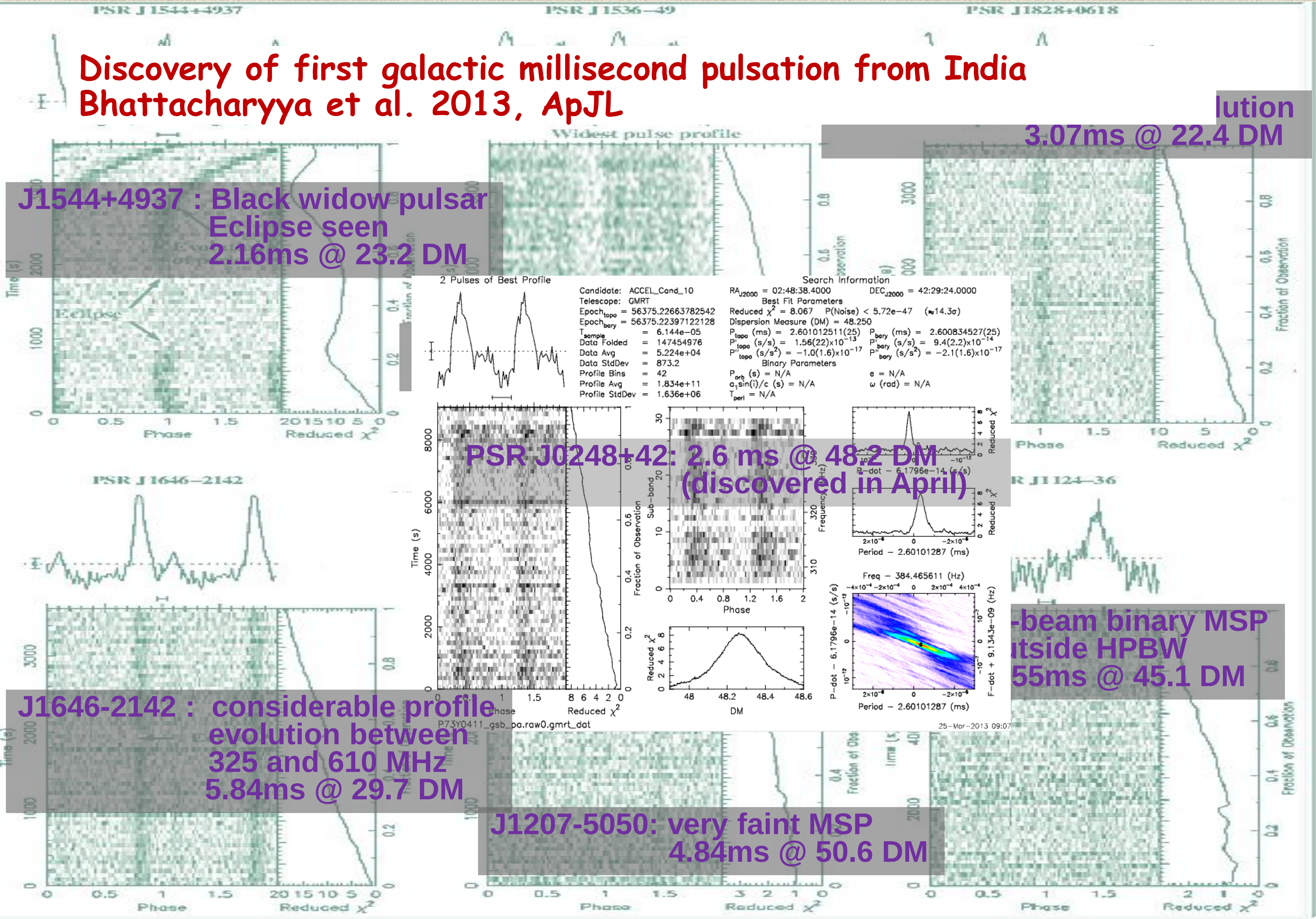


Courtesy P. S. Ray

Nançay (France) GMRT (India) GreenBank (USA) Parkes (Asutralia) Effelsberg(Germany)

Seven MSPs discovered at GMRT from 2011-2013

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



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

Timing of pulsars

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

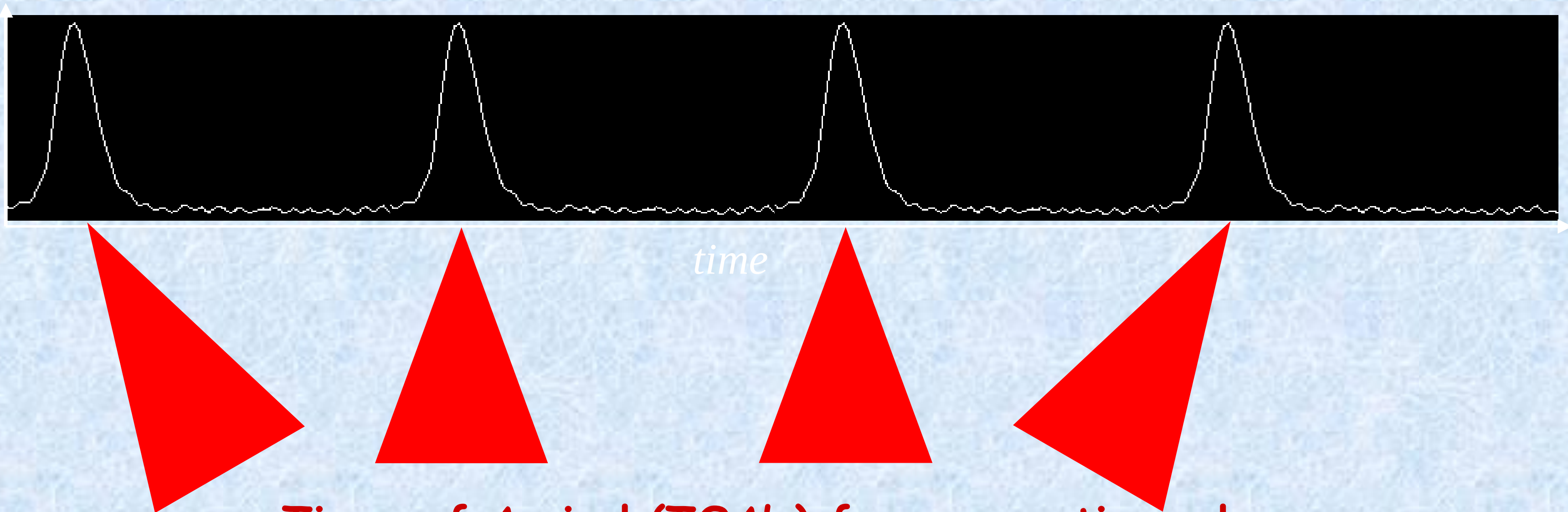
Pulsar Timing – a cryptic name for a very simple procedure

So, how to measure pulsar period?

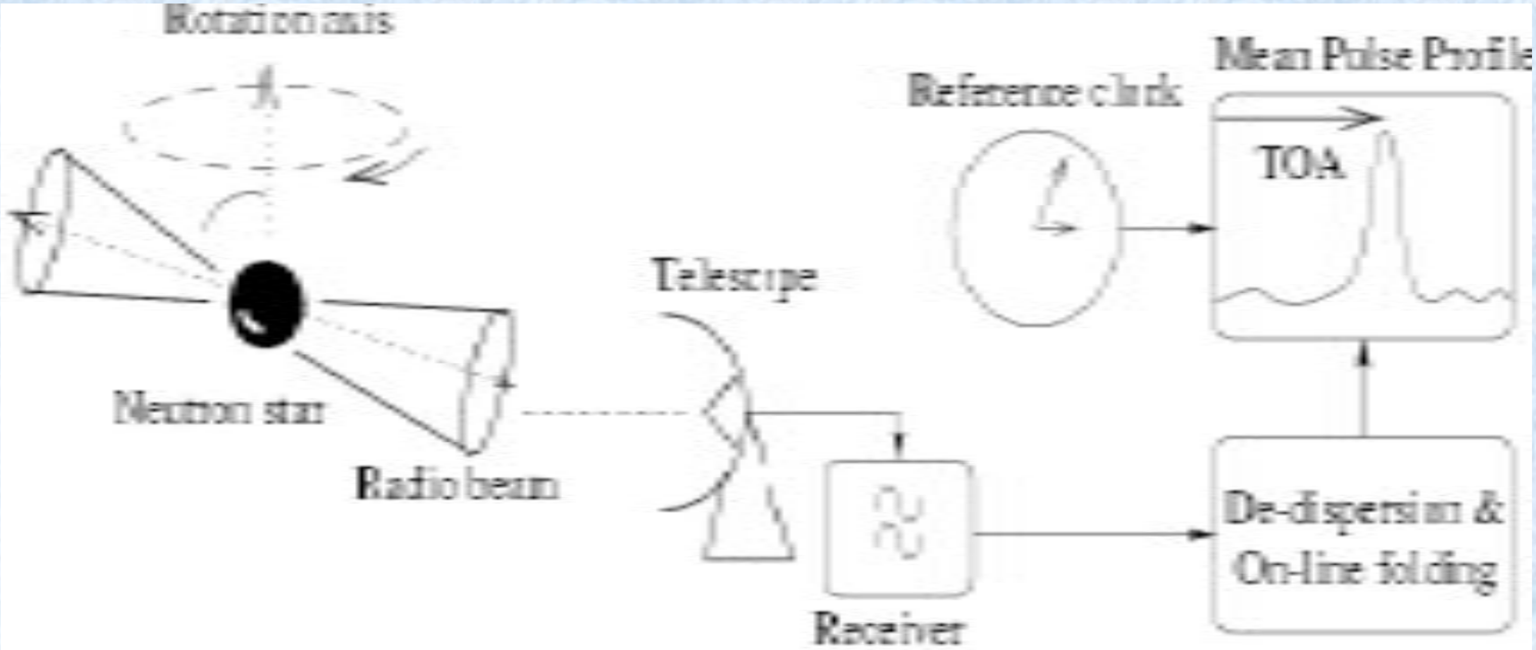
- ✓ How to measure how long is a second on your pulsar watch?
- ✓ Prediction and observation of pulse arrival time (TOA)
- ✓ Pulsar timing model – a collection of the important physical parameters, describing its rotation, movement etc.

How the timing actually works?

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

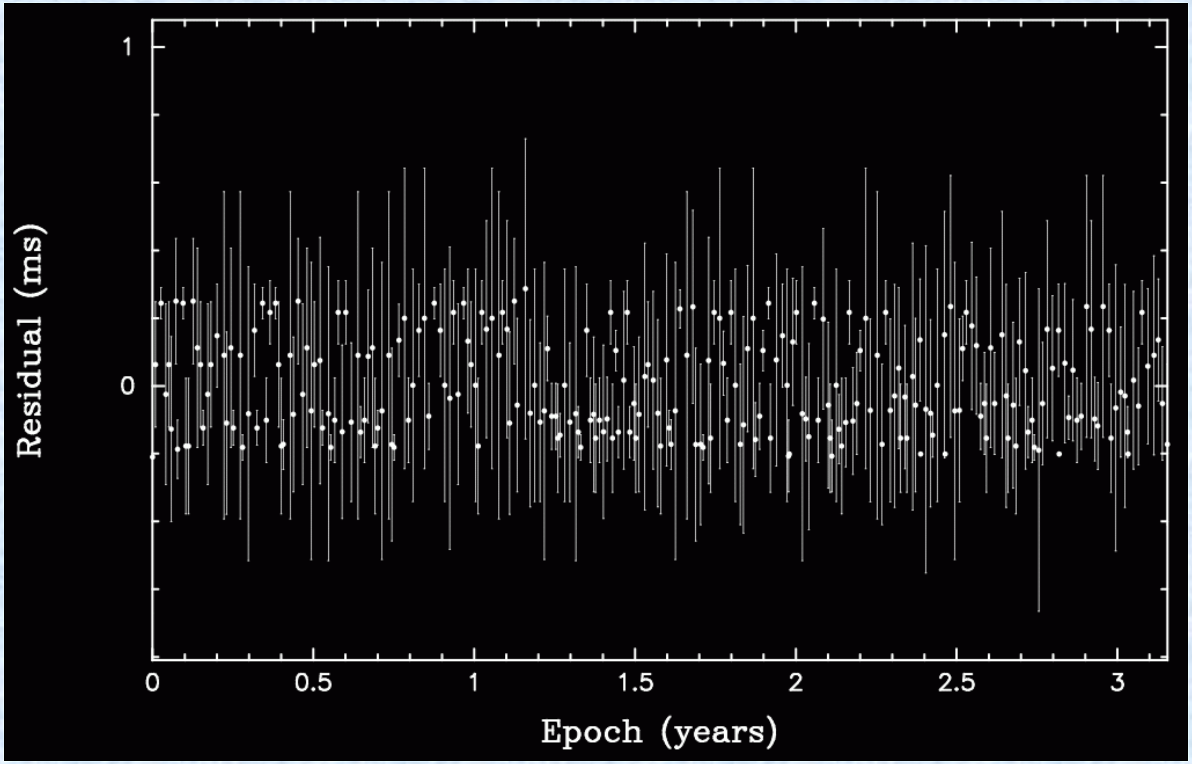


Times of Arrival (TOA's) for consecutive pulses



Now it is necessary to apply corrections to your TOA's (basically subtract your observatory position and movement). This is done by recalculating the TOAs to the solar system barycenter:

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).

How preciselly one can measure pulsar period?

Pulsar PSR J0613-0200:

- ✓ Rotation period: 0.00306184403674401 +/- 0.000000000000000005 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!

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
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.

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..

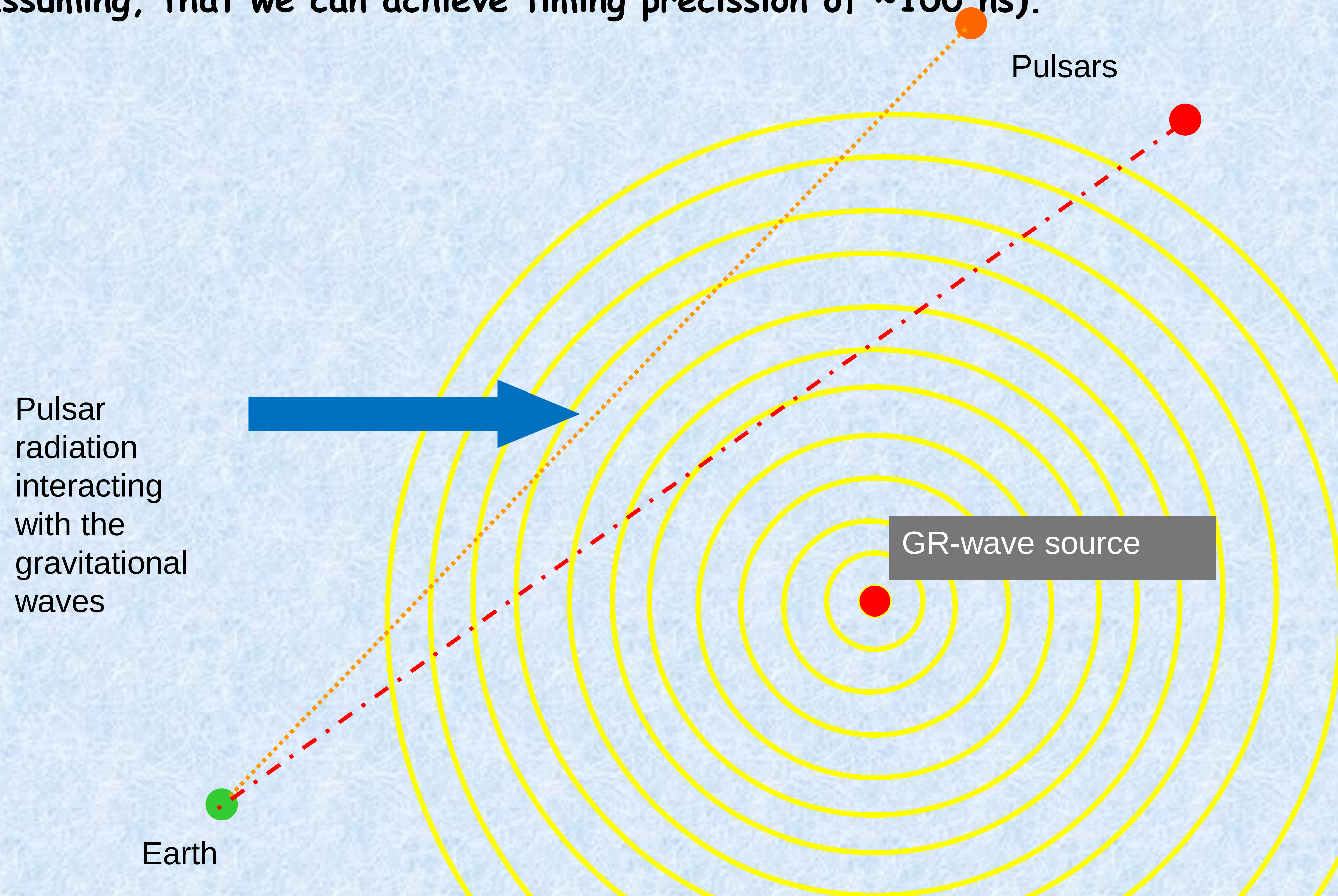
But that is only a beginning. It gets more interesting with the binary pulsars...

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

And lots more depending on the particular system

Pulsar timing array for detecting Gravitational wave

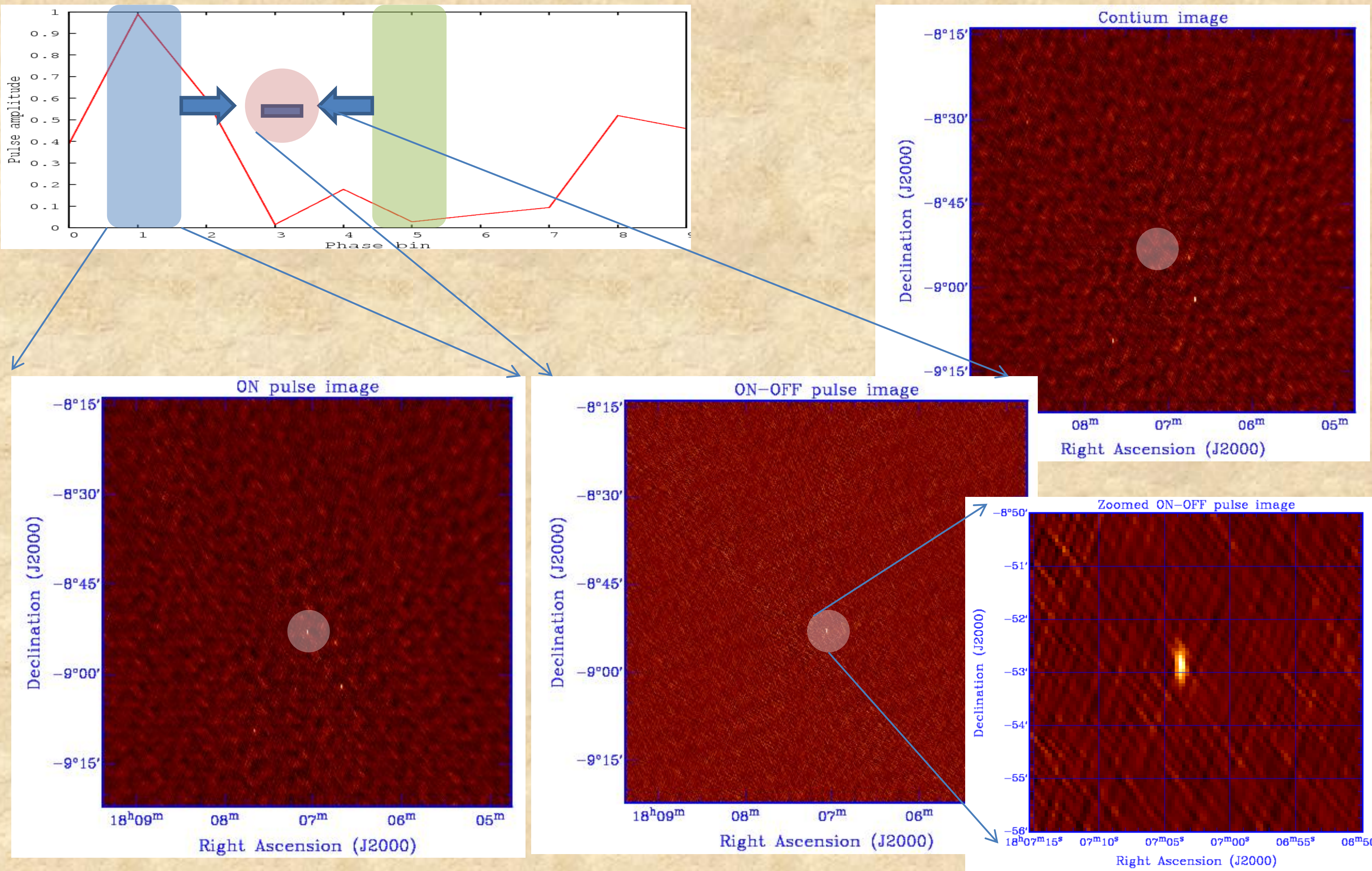
Measuring the Gravitational waves:
(assuming, that we can achieve timing precission of ~100 ns).



Imaging of pulsars

Pulsar gating

Roy & Bhattacharyya 2013, ApJL

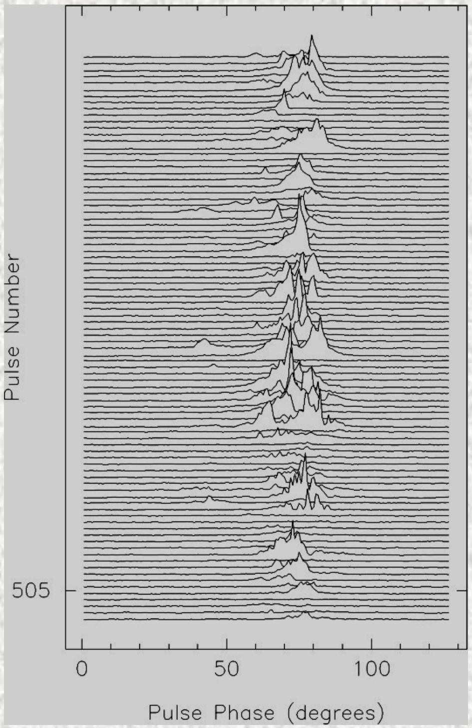


Investigation of pulse emission mechanism (existing for isolated slow pulsars)

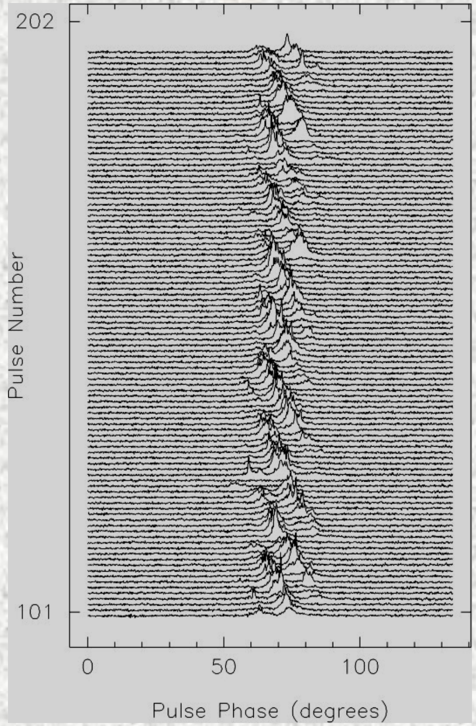
Drifting & Nulling

Sequence of pulses

PSR B0950+08



PSR B0809+74



Subpulse : Individual pulses are composed of narrower emission features

➢ Drifting:

Subpulses appear in progressively changing longitude & follow pulsar specific patterns

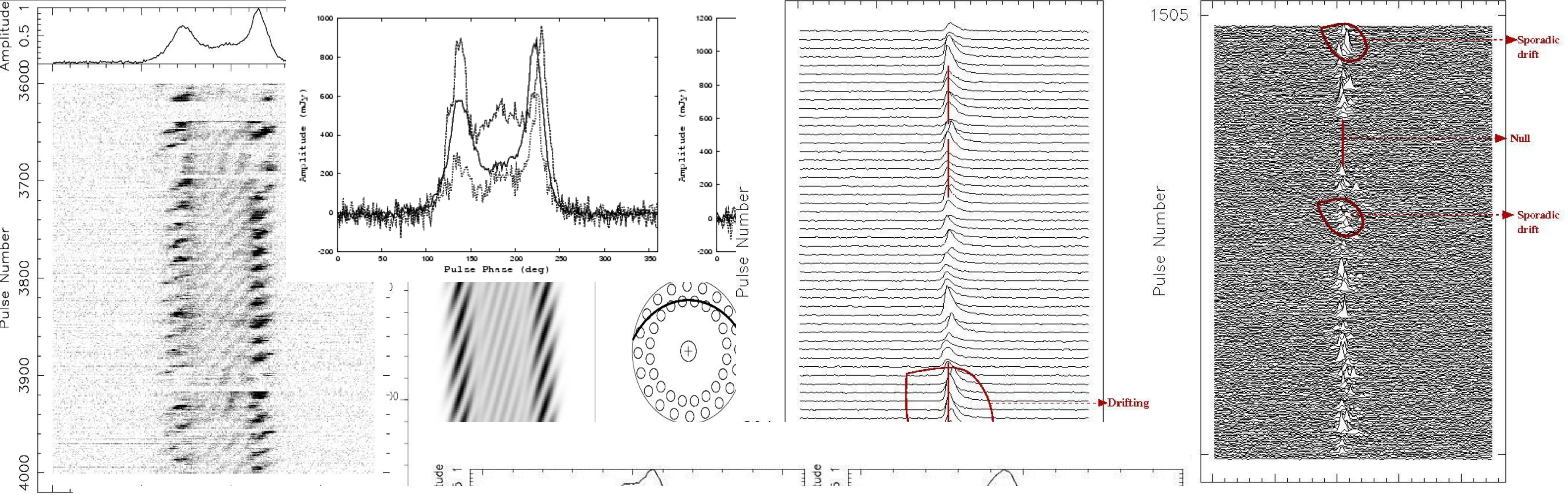
Weltevrede et al. (2006) , (2007) : some kind of drifting behaviour is seen in a large number of pulsars

Drifting is intrinsic property of the emission mechanism

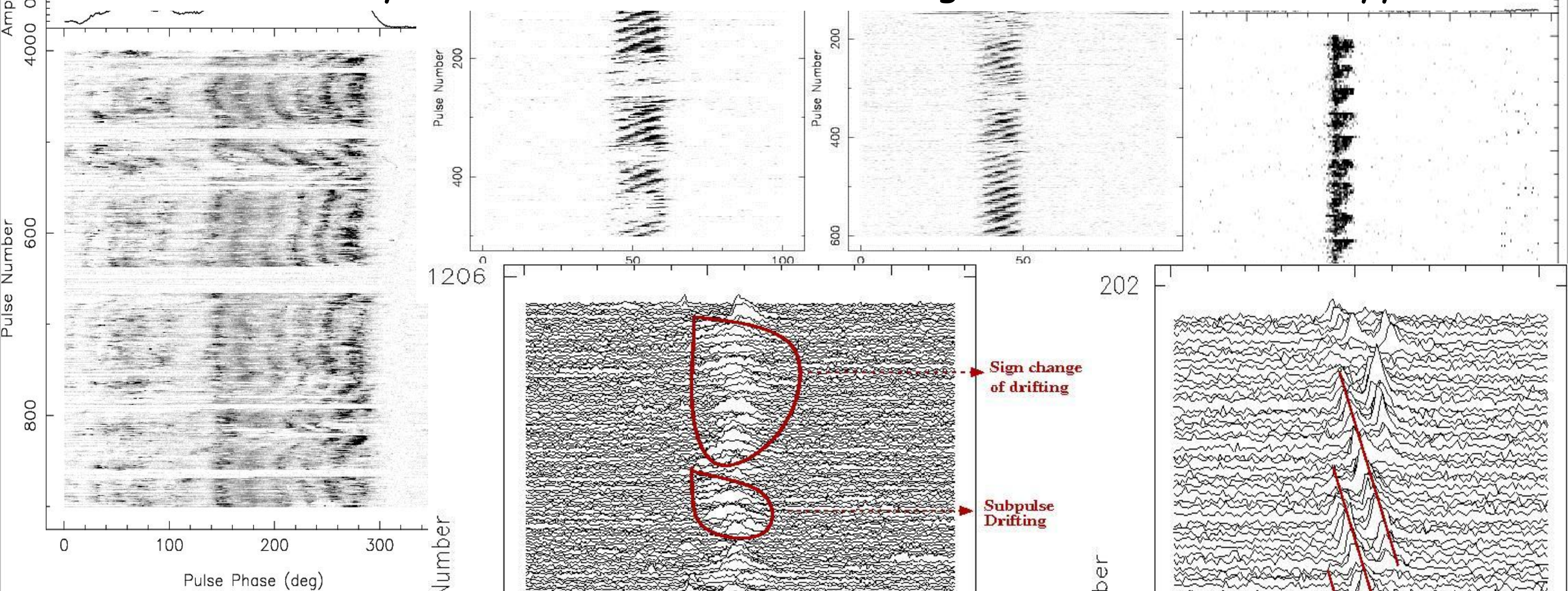
➢ Nulling: pulse intensity suddenly drops abruptly returns

Reason for such switching off is not known…and is subject to investigation

Mechanism of nulling is expected to be very closely tied with pulse emission mechanism

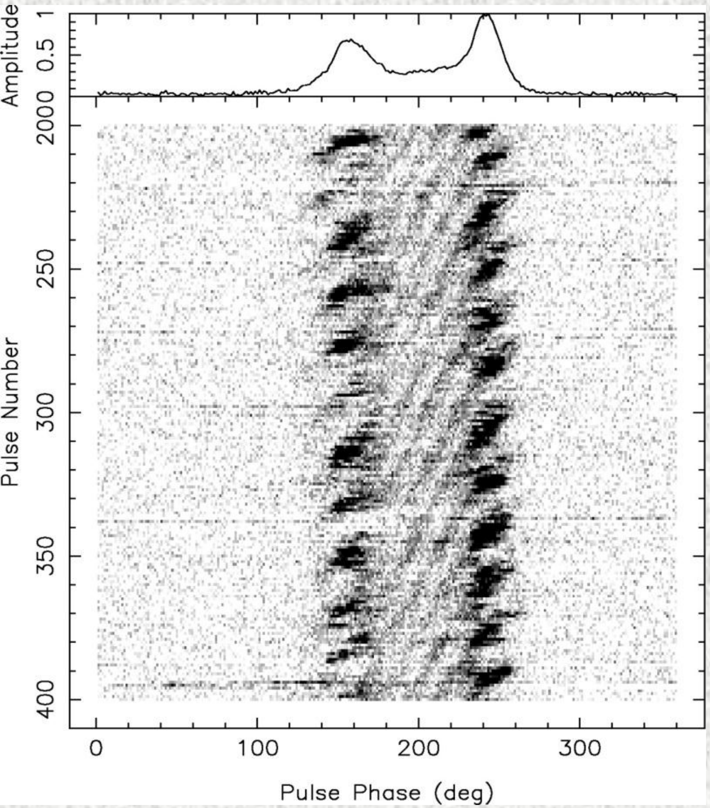


More on emission mechanism?
Refer to work by Rankin, Gil, Weltevrede, Wright, Mitra, Bhattacharyya …



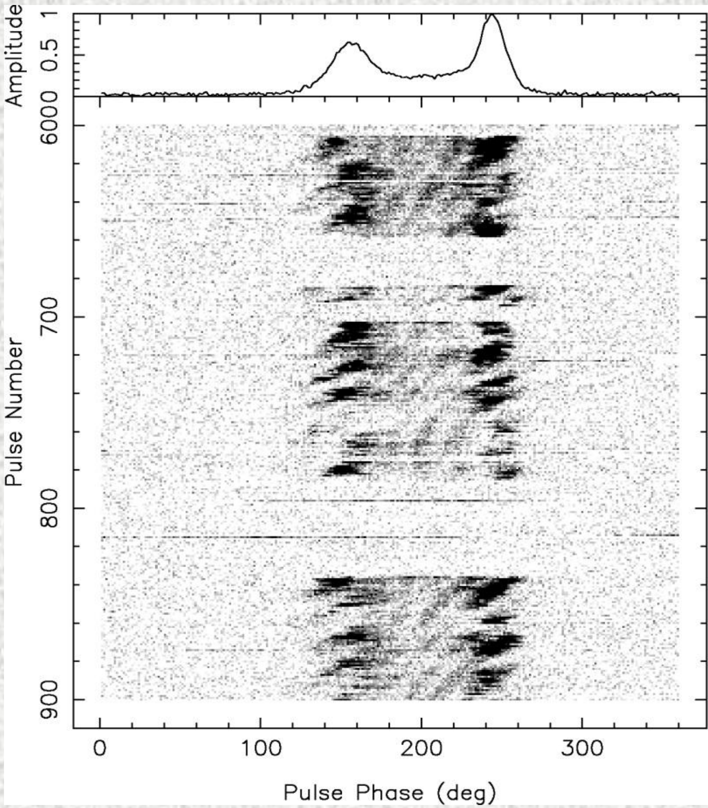
Remarkable drift pattern of PSR B0818-41

Single pulses at 325 MHz (regular drifting)



- Three drift regions
  - Inner region: Multiple drift bands
  - Outer region: Single drift band
- **"Phase locked" drift regions**
- Frequent Nulls

Single pulses at 325 MHz (irregular drifting)



Synchronised drifting of subpulses from multiple rings of emission from pulsar magnetosphere (e.g. B0818-41, B0826-34) : constrains to pulsar emission models

Electromagnetic conditions in magnetosphere responsible for radio emissions emission reach a well defined state during or towards end of each nulls:
Reset of pulsar's radio emission engine takes place

Bhattachraryya et al. 2007, 2008, 2009, 2010 MNRAS

Pulsar Research 1967-2013

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

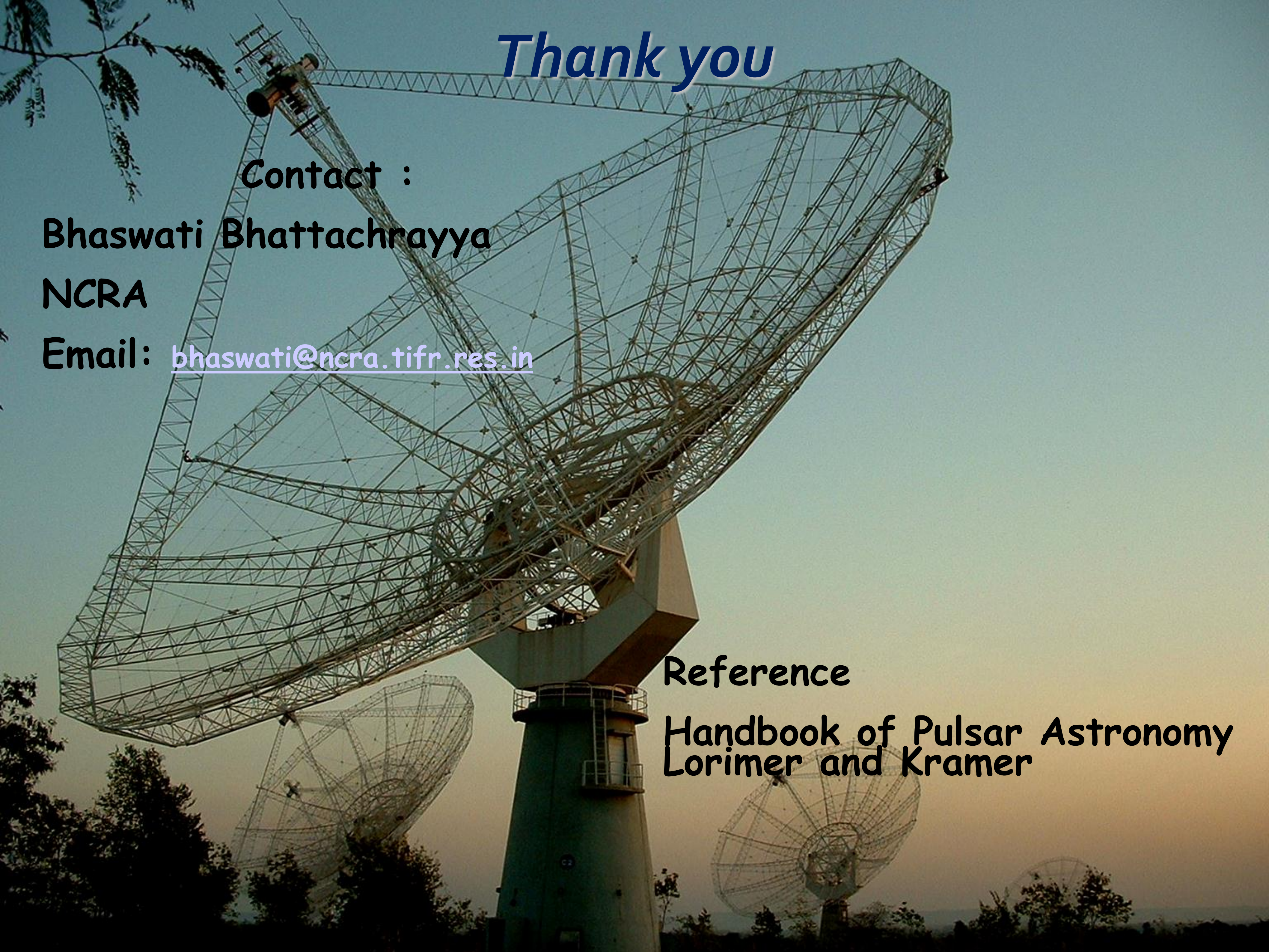
Discovery of the 1st Millisecond pulsar:
Becker , Kulkarni et al., 1982, Nature, 300, 615

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

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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Reference

Handbook of Pulsar Astronomy
Lorimer and Kramer