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Looking for Gravitational Waves with a radio pulsar observatory

Indian Pulsar Timing Array experiment
and
TATA Pulsar Timing Array

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+ …..

OUTLINE

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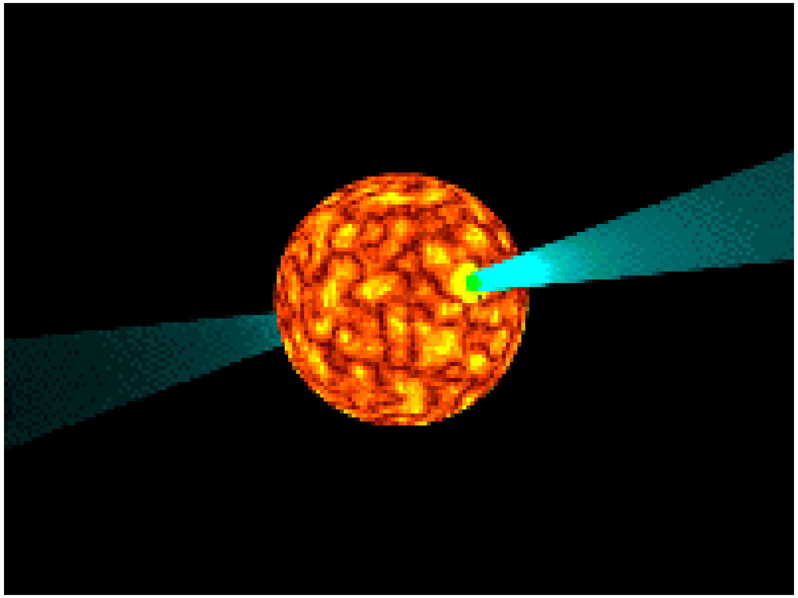
- Introduction to Radio pulsars and pulsar timing
- Gravitational Wave sources and spectrum
- Historical perspective of Pulsar Timing Arrays
- Pulsar Timing Array - understanding the instrument
- Pulsar Timing Array experiments in operation and current state-of-art
- Indian Pulsar Timing Array (InPTA) initiative
- Results from InPTA so far and road ahead
- Future prospects - TATA Pulsar Timing Array (TAPTA)

Radio Pulsars

- **Radio pulsars are highly magnetized rotating stars.**
- **Pulsed radio emission is due to a narrow beam anchored on the magnetic poles of rotating NS, with its magnetic axis offset from its rotational axis**
- **They are almost entirely made up of neutron stars, which makes them massive and compact**
  - Mass ~ 1.4 M_0
  - Radius ~ 10 km
  - $I \sim 10^{45}$ g-cm^2

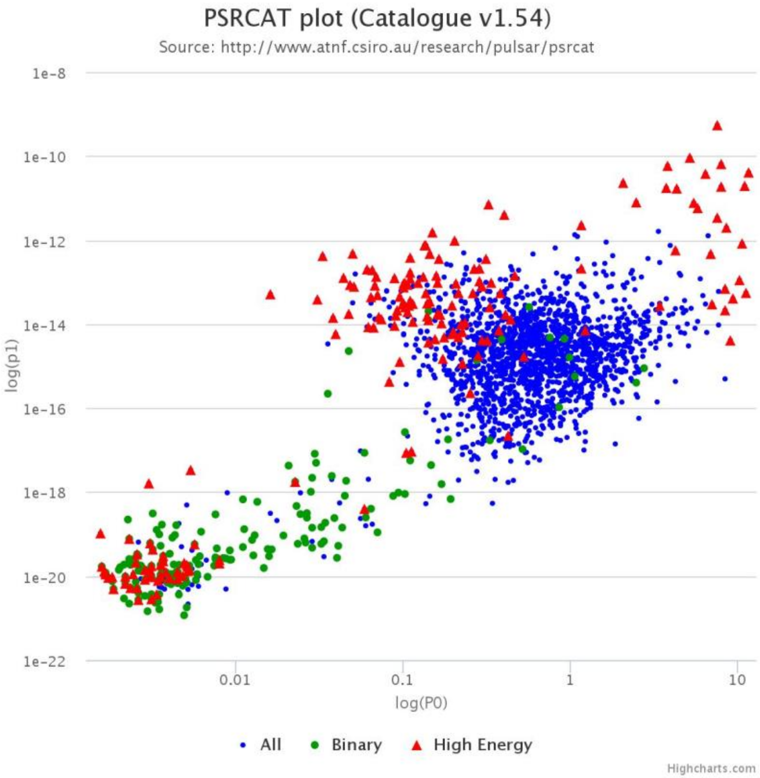


Pulsar as a clock

- **Their massive compact nature implies a very precise rotation**
- **Pulses show a remarkable clock like stability**
- **Stability of period ~ 1 part in 100 quintillion**
- **Some pulsars rival the best atomic clocks**
- **This plays important role in their usefulness for detection of Gravitational Waves (GWs)**

Pulsar population & GW detection

- Known radio pulsars ~ 2500
- Three main classes of radio pulsars
  - Normal pulsars
    - P ~ 1 s
    - B ~ 10^{12} G
  - Magnetars
    - P ~ 2 to 11 s
    - B ~ 10^{14} G
  - Millisecond pulsars (MSPs)
    - P ~ 10 ms
    - B ~ 10^{9} G
    - Lower magnetic field implies a more stable rotation - excellent clocks
    - Exception – MSP in relativistic binaries
    - Exception – distant MSPs as pulsed signal is affected by propagation effects in the inter-stellar medium
  - Nearby MSPs (non-relativistic if in a binary system) are preferred for GW detection

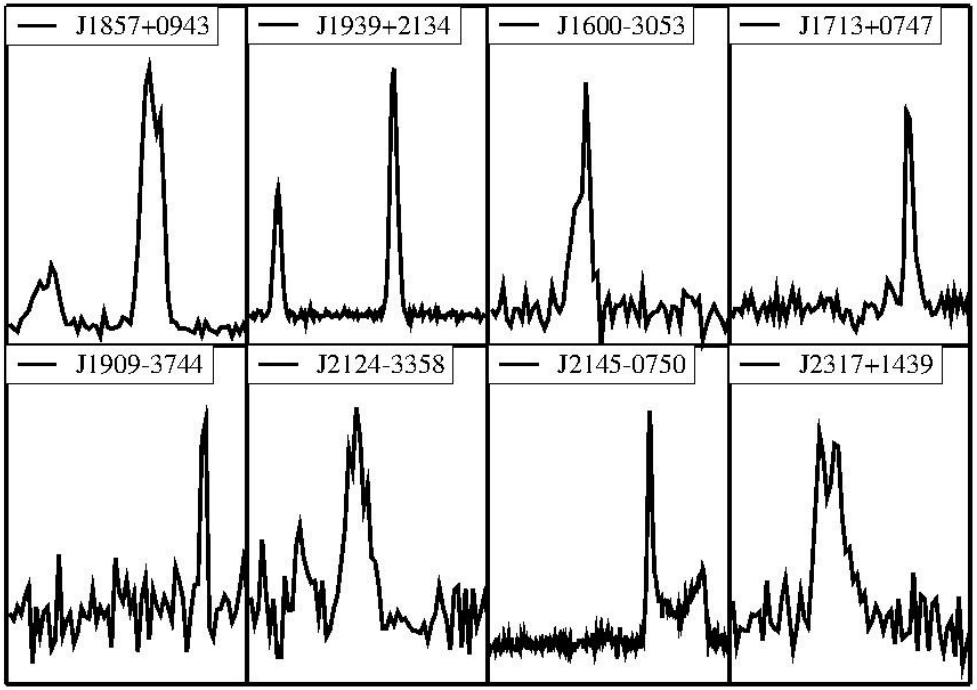


Introduction to pulsar timing

- **GW detection involves precision measurements of rotational parameters**
- **Keeping track of the rotation cycles of the pulsar enables improving the precision of measurement as a function of time – pulsar timing**
- $\delta\nu = \delta\phi / T$
- **T ~ 1 year = 3 x 10^7 s → 1 part 1000 measurement of phase error gives 1 part in 10^{12} precision in measurement of rotational frequency (picoseconds)**
- **Thus, pulsar timing compares prediction of pulse time-of-arrival (TOA) from a rotational model of star with that of observed TOA to refine the model**

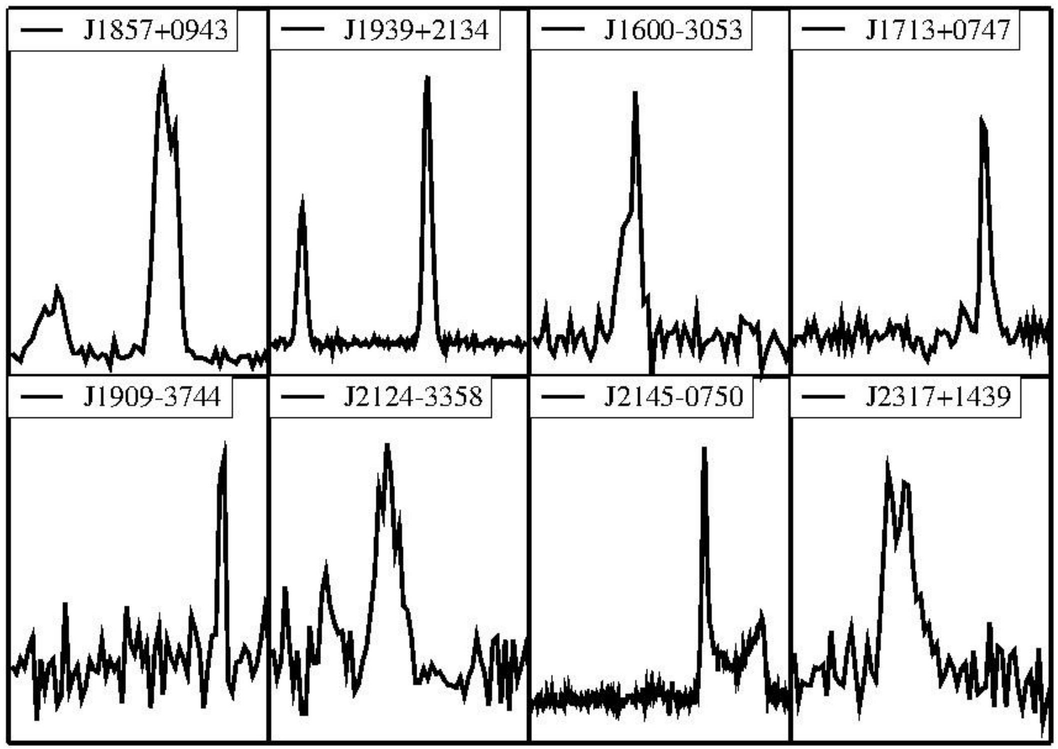
Pulsar timing - II

- **Pulsar Profiles and pulse time of arrival**
  - **Pulsars are weak radio sources - typical flux density 10 mJy (10^{-28} W/m^2/Hz)**
  - **With 5 to 6 order of magnitude larger background noise, single pulses are detectable for a handful of pulsars only**
  - **Pulsed emission is averaged, modulo pulse period, over several thousand pulses to obtain a stable integrated pulse profile**



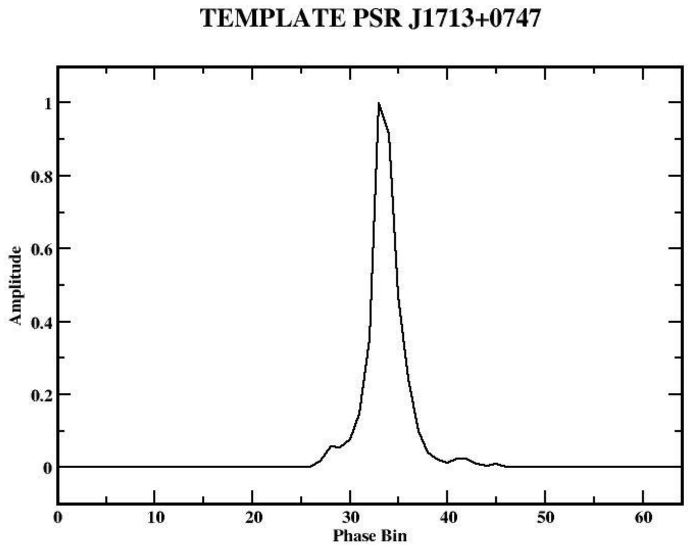
Pulsar timing - III

- **Time-of-Arrival (TOA) of pulse is determined at a fiducial point**
- **TOA referenced against Hydrogen Maser upto a few ns precision**



Pulsar timing - template matching

- **TOAs are obtained by cross-correlating a Noise Free template, s(t), to average profile, p(t), where**
  - **$p(t) = a * s(t - t_{\phi}) + n$**
- **Cross correlation is done in Fourier Domain to determine t_{ϕ} independent of bin size in time** (Taylor, 1992. Phil. Trans. Roy. Soc., 341,117)
- **Time at the middle of observations, as determined from the local observatory atomic clock, is adjusted by t_{ϕ} to get TOA**



Pulsar Timing Recipe

- **Assign Time of Arrival (TOA) to a fiducial point on integrated profile**
  - **Observable at a radio telescope like Ooty Radio Telescope or GMRT**
- **Correct TOAs to SSB - perturbations on rotation frequency from solar system, inter-stellar medium, gravitational potential (galaxy or cluster) and a companion in case of a binary**

$$t_{SSB} = t_{topo} + t_{clock} - D/f^2 + \Delta_R + \Delta_S + \Delta_E$$

- **Assume a model of pulsar rotation ($t = t_{SSB}$)**

$$\nu(t) = \nu_0 + \nu_{dot}(t-t_0) + ½\, \nu_{ddot}(t - t_0)^2$$

- **Calculate pulse number from the above two relations**

$$N = \nu * (t - t_1)$$

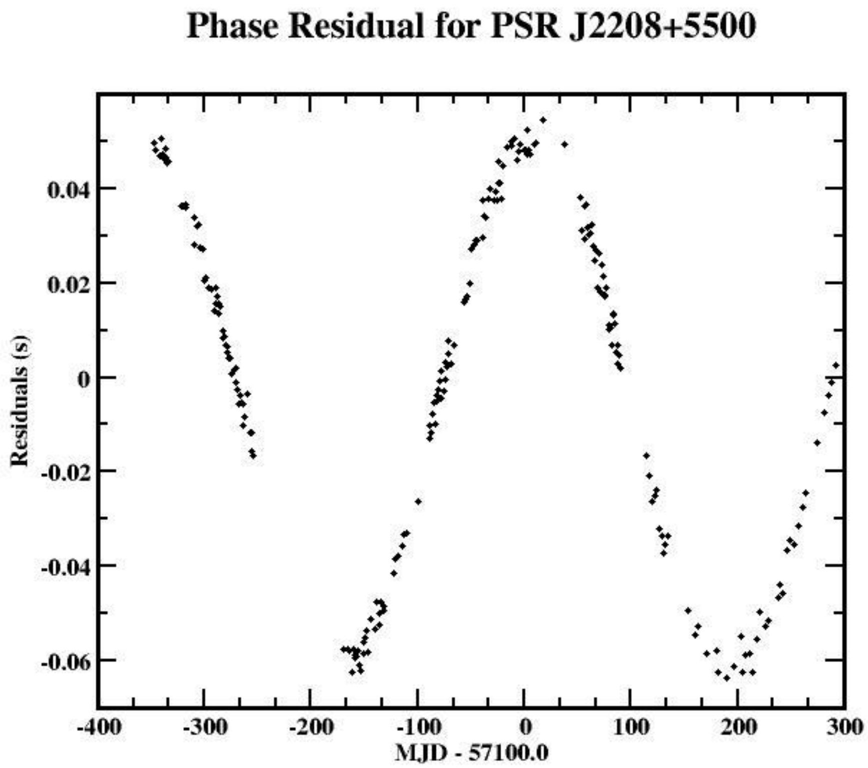
- **The integral part is a prediction of period number of the pulse from t_1**
- **The fractional part should be zero for a prediction matching the data**
- **The timing residual = fractional part = difference between the observed and predicted TOAs**
- **Minimize the timing residual in a least square sense counting each pulse**

Model Parameters

- **Pulsar Timing technique allows high precision determination of**
  - **Pulsar spin period and its higher order derivatives**
  - **Position and proper motion**
  - **Parallax**
  - **Dispersion delay**
  - **Binary Keplerian parameters**
    - **Orbital period**
    - **Orbital separation**
    - **Component masses**
  - **Binary post Keplerian parameters**
    - **Advance of periastron**
    - **Orbital period decay**
    - **Gravitational redshift**
    - **Range and shape of Shapiro delay**
  - **Miscellaneous**
    - **Solar wind, ephemeris for solar system bodies, tie with absolute ICRF system**
  - **Discovery of new effects**
    - **A good model implies “white noise” like timing residuals**
    - **Systematics in timing noise indicate un-modeled parameters – timing noise, GW**
  - **GW appears as a systemic effect in timing residuals**

Pulsar Timing in action – position

- Determining position of GMRT discovery pulsar – PSR J2208+5500



(Joshi et al. 2009, MNRAS, 398, 943; Surnis, Joshi et al. 2017 submitted)

Pulsar Timing - quest for precision

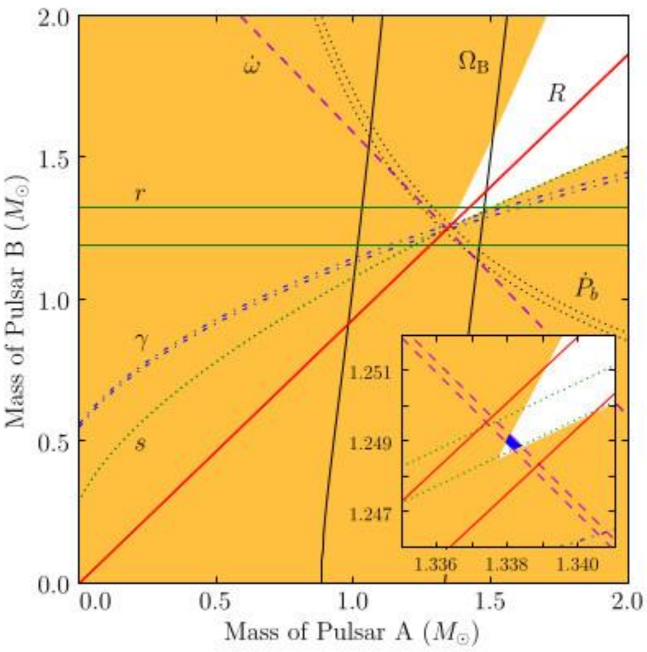
- Double pulsar (PSR J0737-3039A & B)
  (Burgay …Joshi.. et al. 2003,Nature,426,531;
  Lyne..Joshi… et al. 2004, Science, 303,1153)

  - Only system with both NS observed as radio pulsars
  - Tight (2.5 hr) edge on orbit
  - Both NS were seen as pulsars
  - Two clocks going round each other

- Two pulsars come closer to each other every day by 7.152 (0.008) mm !!

- > 0.05 % tests of GTR possible
  (Kramer et al. 2006; Kramer et al. in prep)

- Pulsar timing is very handy for detection of GWs



Kramer et al. 2006

Gravitational Waves

- Gravitational Waves were unique distinguishing feature of General theory of Relativity, when it was proposed by Einstein

(Einstein, “About Gravitational Waves”, RPAS, 1918, 154)

- Gravitational waves (GW) are tiny propagating fluctuations in space-time
- Radiated by changing quadrupole moment by sources, such as two orbiting super-massive black holes (SMBHB)

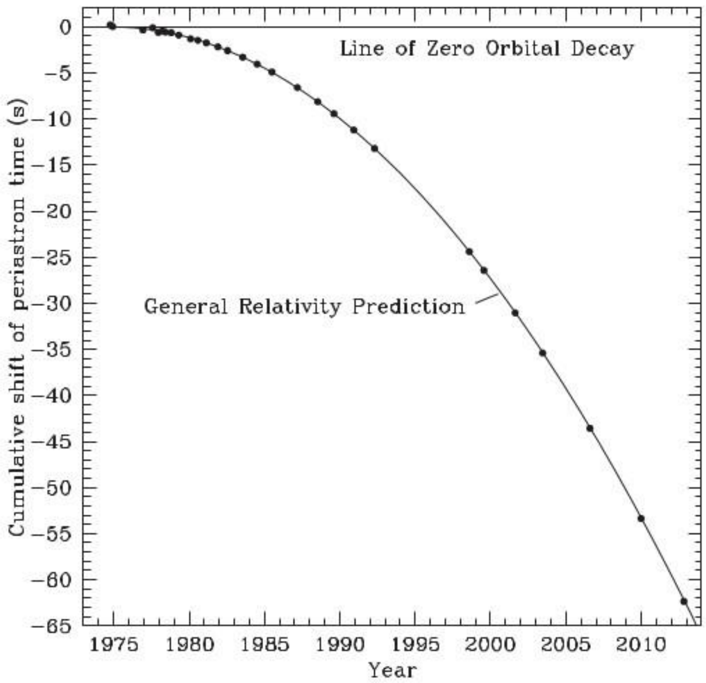
- Amplitude is given by characteristic strain, h
  - $h = \delta L / L$
- Measurement of h requires high precision experiments

Indirect detection of GWs

- **Indirect detection of Gravitational Waves (GW) was first reported by Hulse & Taylor in double neutron star binary (DNS) - PSR B1913+16**

- **Rate of loss of energy from the binary system is exactly matched with the expected loss due to GW radiation from this system over more than 40 years**

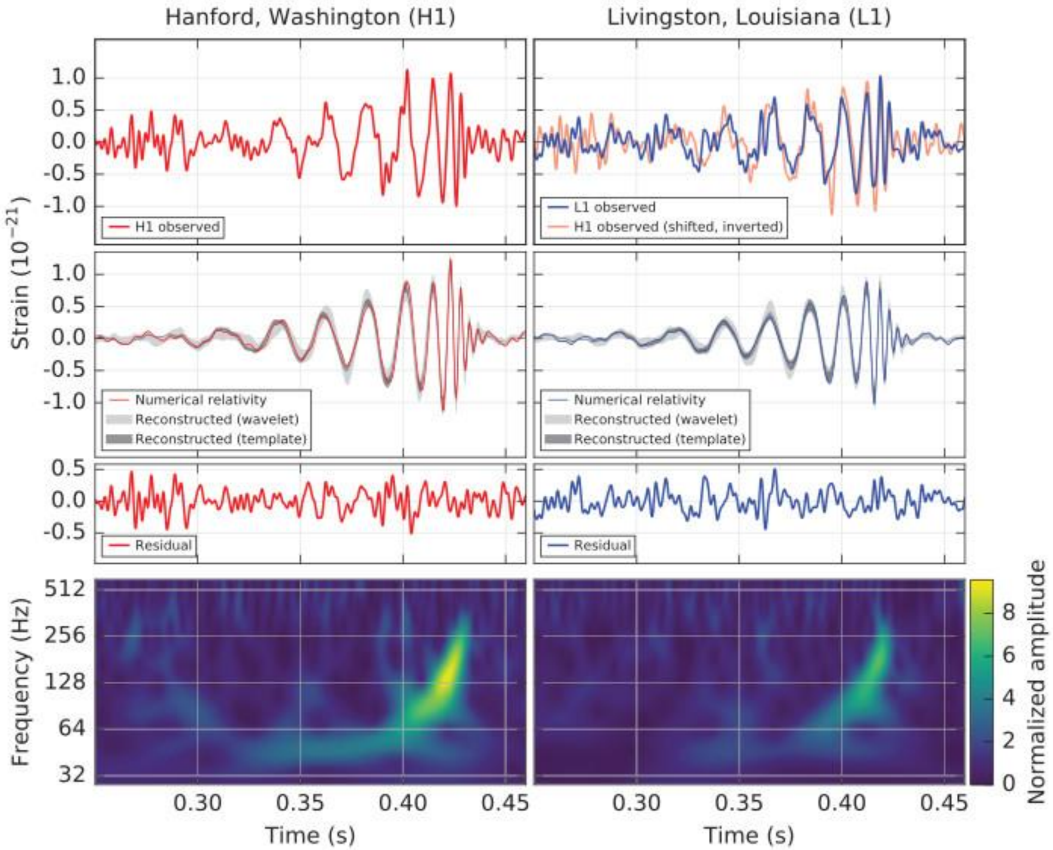
- **Since then this effect is reported in 9 DNS systems**



Weisberg & Huang 2016

Direct detection of GWs

30 and 35 M_o



Abbott et al. 2016, PRL, 116, 0611002

Sources of GWs - I

- **A system with changing quadrupole moment**

- **Most natural choice for a continuous persistent GW is a binary system with unequal masses**

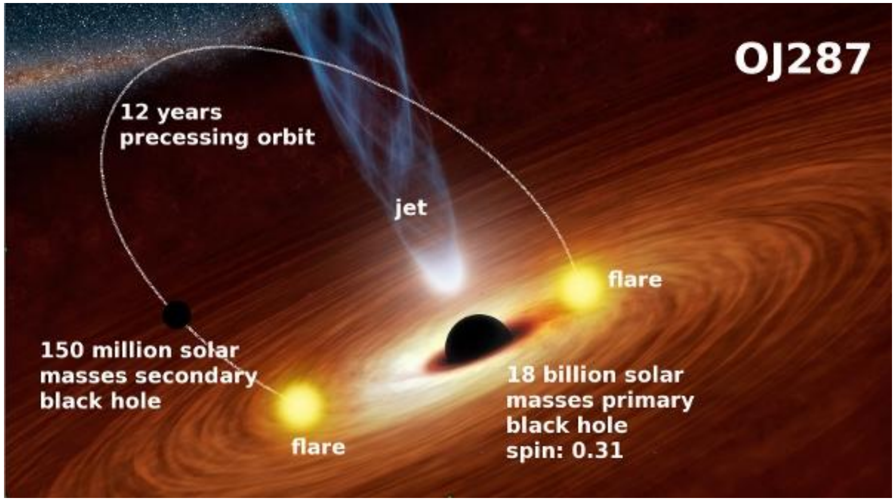
- **Transient high amplitude GW sources occur during merger of binary systems with compact objects**

- **Typical candidate sources**
  - **White Dwarf – White Dwarf binaries**
  - **Neutron Star – White Dwarf binaries**
  - **Neutron Star – Neutron Star**
  - **Neutron Star – Black hole** - **Not Yet Discovered !!!!**
  - **Black hole – Black hole**

- **GW in different frequency ranges**

Sources of GWs - II

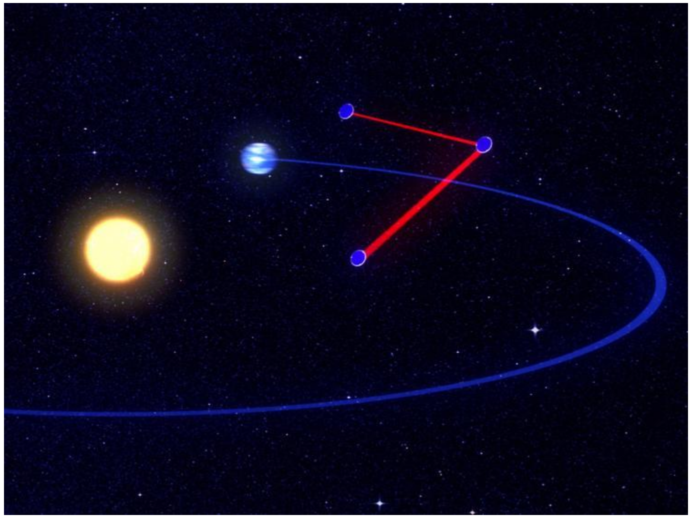
- Ultra-low frequency persistent GW in the frequency range of nano-Hertz are produced by a binary with two supermassive black hole (SMBHB – 100 million to 1 billion M_o)
- Such binaries can exist in the center of a galaxy formed by merger of two galaxies, e.g., OJ 287 (See recent papers by Mauri, Gopakumar 2010,2011, 2016)



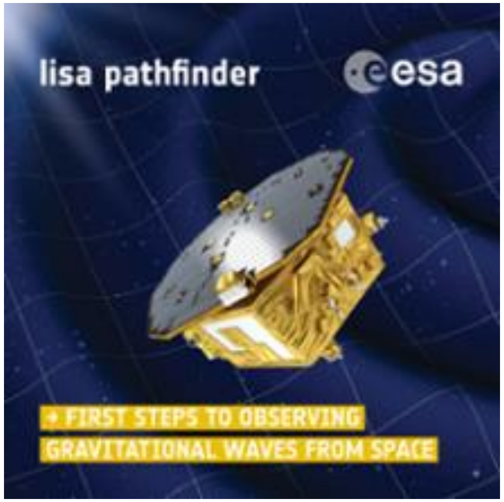
- Typical orbital periods of many years implying frequency of nano-Hertz and wavelength of few parsecs (10^{17} m)
- Superposition of GW from many such sources forms a stochastic Gravitational Wave background (SGWB)

Experiments for detection of GW

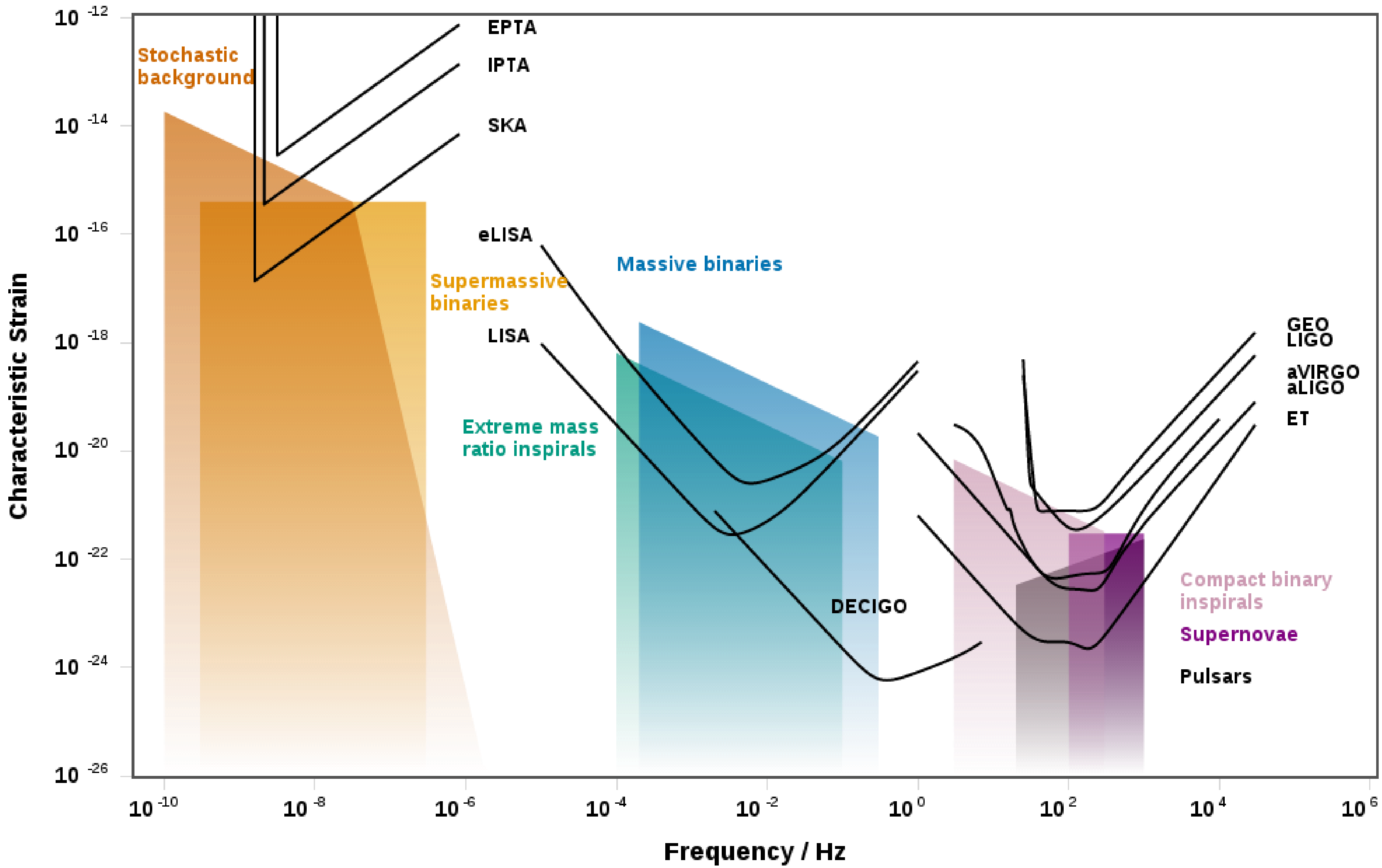
- Initial experiments by Joseph Weber in 1960s (Weber 1969)
- Advanced Laser Interferometer GW Observatory (ALIGO)
- Two detectors at Hanford and Livingston, USA (India?)



- evolved Laser Interferometer Space Antenna (eLISA)
- LISA path finder launched on Dec 2, 2015 and working well
- Pulsar Timing Array



GW spectrum and instruments



Even bigger GW Detector - PTA

- Frequency of GW radiated by super-massive black hole binary systems (SMBH) fall in the frequency range of nano-hertz
- Detector sensitive to such frequency has to have arm – lengths of the order of parsecs (Joshi 2013, IJMPD, 22, 1341008)
- Pulsar Timing Array (PTA) provide such a detector with passive observations of an ensemble of pulsars
- Experiments, using radio pulsars as gravitational wave detectors, are called Pulsar Timing Arrays
- PTAs complement other experiments (ALIGO, LISA, Cosmological)
  - Frequency range
  - Spectrum

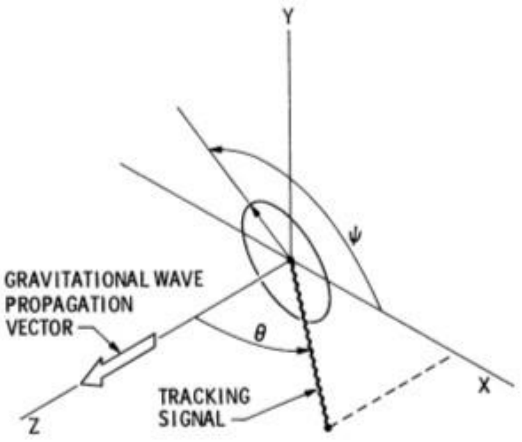
Pulsar Timing Arrays

- **Apparent frequency of pulsar clock varies due to perturbtion in metric by a passing GW – imprinted on timing residuals and correlated across an ensemble of pulsars**

- **Historical perspective**
  - Detection of stochastic gravitational wave background (SGWB) first proposed considering 5-year timing residuals of long period PSRs B1919+21, B1933+16 & B2016+28 (Sazhin 1978; Detweiler 1979)
  - Limits from slow pulsars ~ 0.01 % of closure/critical density
    - 4 pulsars - DSN antennas (Hellings & Downs 1983)
    - PSR B1237+25 (Romani & Taylor 1983)
  - Discovery of millisecond pulsars(MSP) - short P, low B (Backer et al. 1982)
  - Better clocks, higher precision time of arrivals (TOAs)
  - Interesting limits from MSP (Foster & Backer 1990; Kaspi et al. 1994)
  - Challenges - errors due to ephmeris, DM variations, red noise
  - Use of a pair or ensemble for better sensitivity to SGWB, also individual sources (Detweiler 1978; Hellings & Downs 1983, Foster & Backer 1990)
  - Parkes PTA (PPTA), North American Nano-hertz Observatory for Gravitational Waves (nanograv), European PTA (EPTA) - IPTA

Pulsars as GW telescope

- **GW signature in residuals**
  - GWs are solutions of weak-field linearized Einstein's field equations
  - Perturbations in flat space time
  - Retard/advance travel time of EM radiation from pulsars
  - Changes in travel time with time contributes to residuals
  - Fractional frequency change

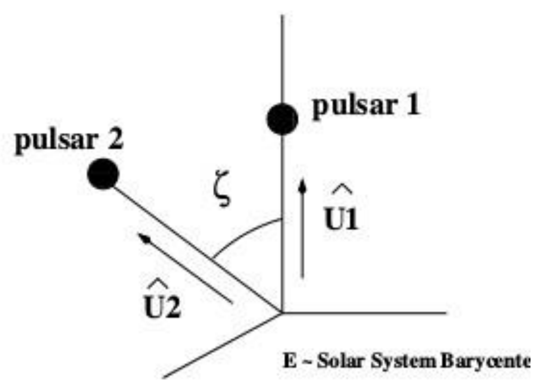


$$\delta\nu/\nu = 0.5 \cos 2\psi\, (1 - \cos\theta)\ [h(t) - h(t - d/c - d\cos\theta/c)]$$

  - Information about amplitude at two time and space coordinates - reception (earth) & emission (pulsar)

Response of PTA

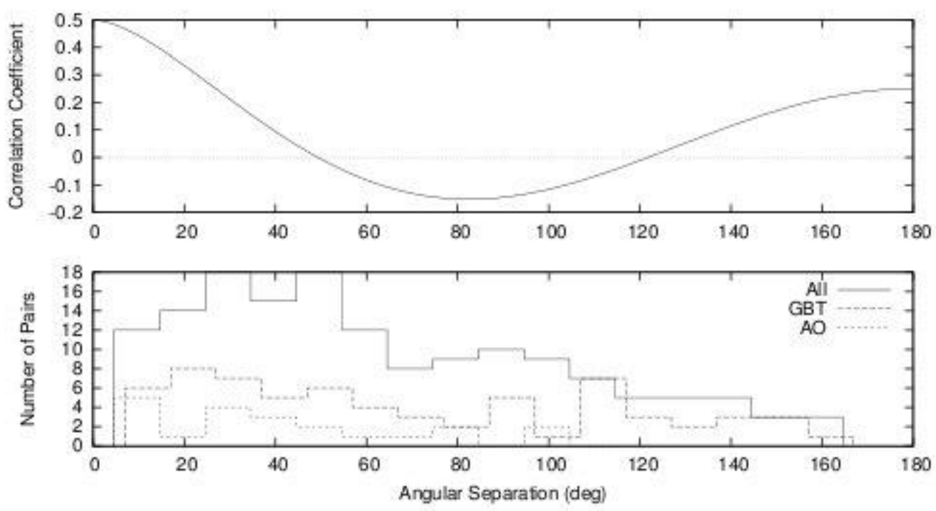
- **Principle of detection of SGWB**
  - PTA is formed by measuring $\delta\nu/\nu$ over an ensemble of pulsars
  - **Emission (pulsar)** term will be uncorrelated over the ensemble
  - **Reception (earth)** term will be correlated

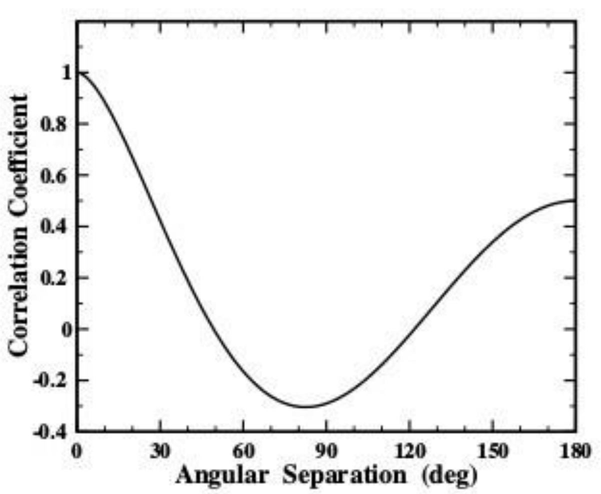


$$\rho(\zeta) = (1-\cos(\zeta))/2 * \ln[(1-\cos(\zeta)/2] - 1/6 * (1-\cos(\zeta))/2 + 1/3$$

"Antenna pattern" of PTA

- PTA attempts to measure correlations in the fractional frequency change across pairs of pulsars in the ensemble of pulsars
- Response or "antenna pattern" of PTA
- SGWB excites the full "antenna pattern"





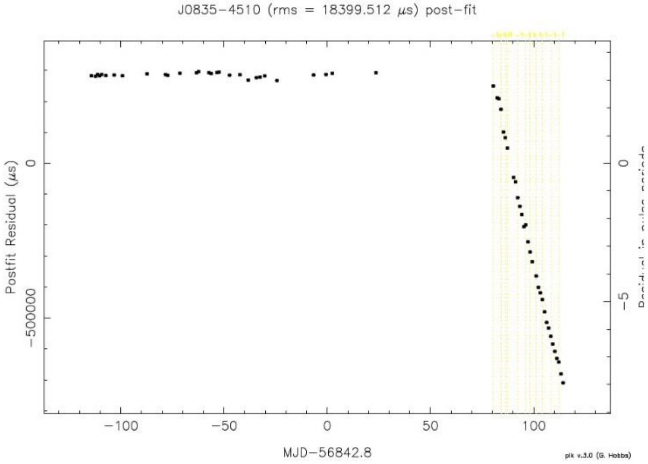
(Hellings & Downs 1983; Backer & Demorest 2008; Joshi 2013)

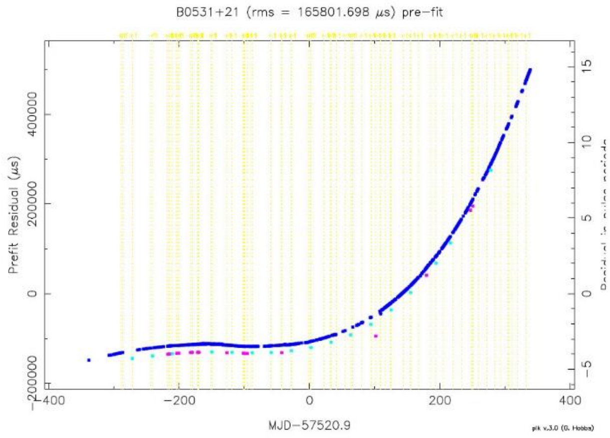
Design of PTA

- **The aim of PTAs is to detect Hellings-Down correlation**
-
- **Accordingly, a good PTA requires**
  - Pulsars with exceptionally high rotational stability
  - A reasonable distribution of pulsars mimicking the pair-wise angular separation
  - Pulsars with high signal to noise ratio pulsed emission
  - Pulsars with stable light curves
  - Pulsars on line of sites without unusual ISM structures
- **Absence complicates timing precision and efficacy of PTA**
- **Sample for PTA is small even though 2500 pulsars are known todate**

Challenges - rotational irregularities

- **Two types of rotational irregularities**
  - **Pulsar glitches**
  - **Timing noise**
- **Covariant with GW signature**





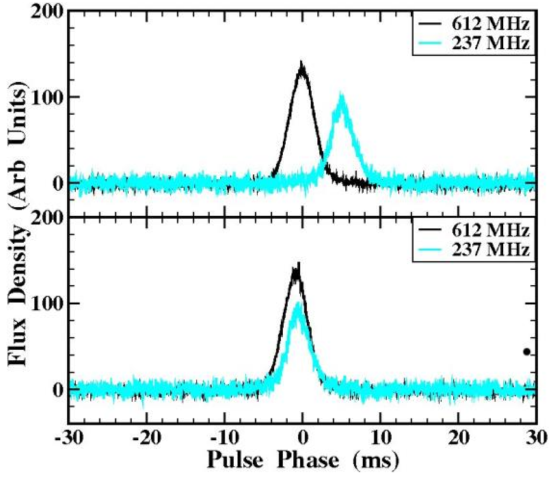
Vela glitch(ORT) Dec 12, 2016 **3 Years of Crab monitoring at ORT**

- **MSPs not prone to glitches, but have timing noise - “red noise”**
- **Use pulsars with “white” residuals**

Challenges - propogation effects

- Dispersion, Interstellar scintillation and Interstellar scatter-broadening
- Dispersive delays
- 6 ms delay for a DM error of 0.08 pc cm^{-3} 613-237 MHz pair for coherently dedispersed data

(Joshi & Ramakrishna 2006)



- Variation of 0.0001 pc/cm^3 leads to a variation of TOA by 212 ns at 1400 MHz and more at lower frequencies (Joshi 2013)
- PTAs use higher frequency (> 1 GHz), but this a trade off between SNR and propogation effects

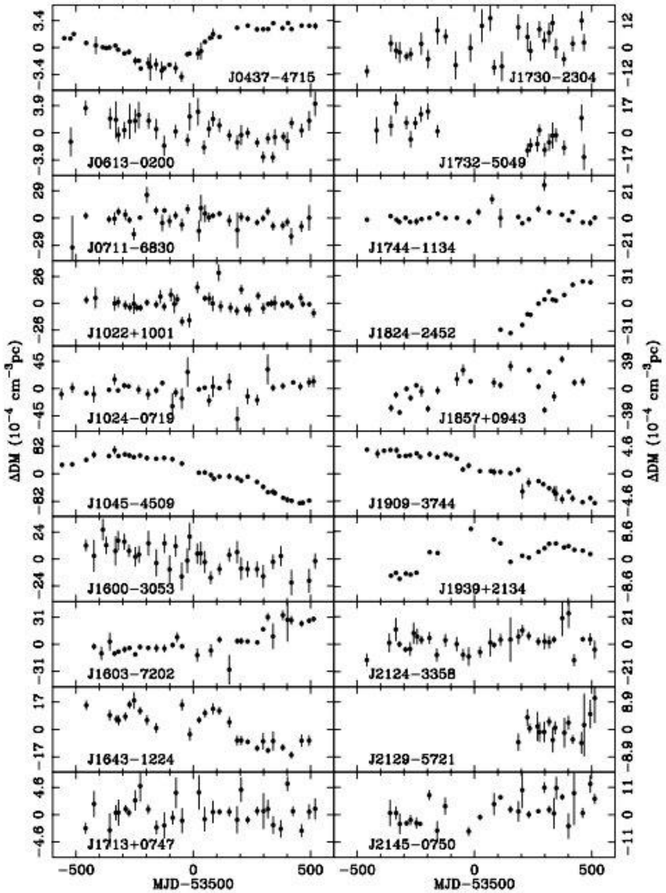
Dispersion measure variations

- **Measuring DM variation is very important for PTAs**

- **DM variations have been measured for the first time in last decade as a side-product of PTA experiments .** **(You et al. 2007)**

- **This requires frequent two frequency near simultaneous observations**
  - **GMRT at 1400 MHz**
  - **ORT at 326.5 MHz**

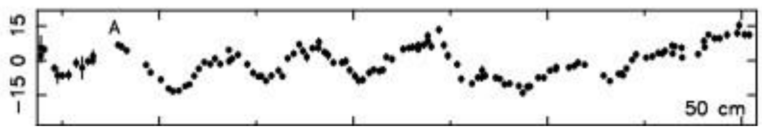
- **TIFR's facilities can play a major role**



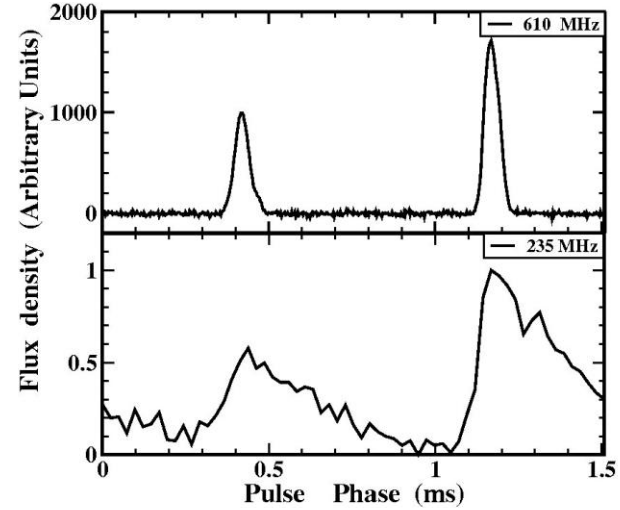
Challenges - propogation effects

- **Interstellar scatter-broadening**
  - **Broadens the pulse**
  - **Systematic delay in TOA**

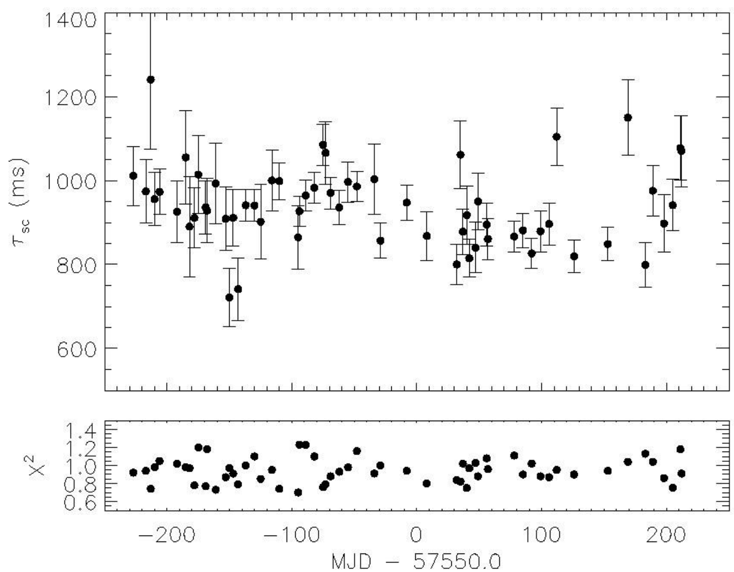
Shannon et al. 2016

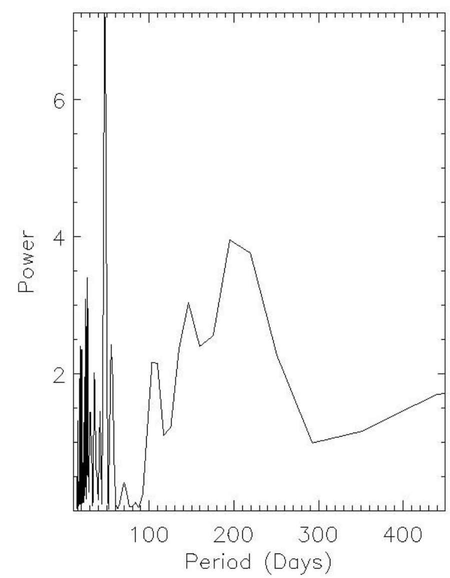


Joshi & Ramakrishna 2006



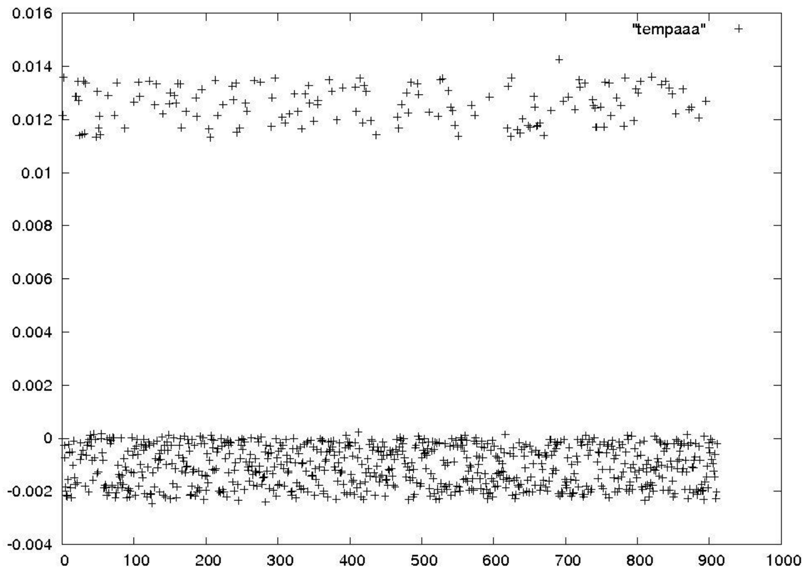
PSR J1642-1224
Variations in
pulse broadening
seen at ORT





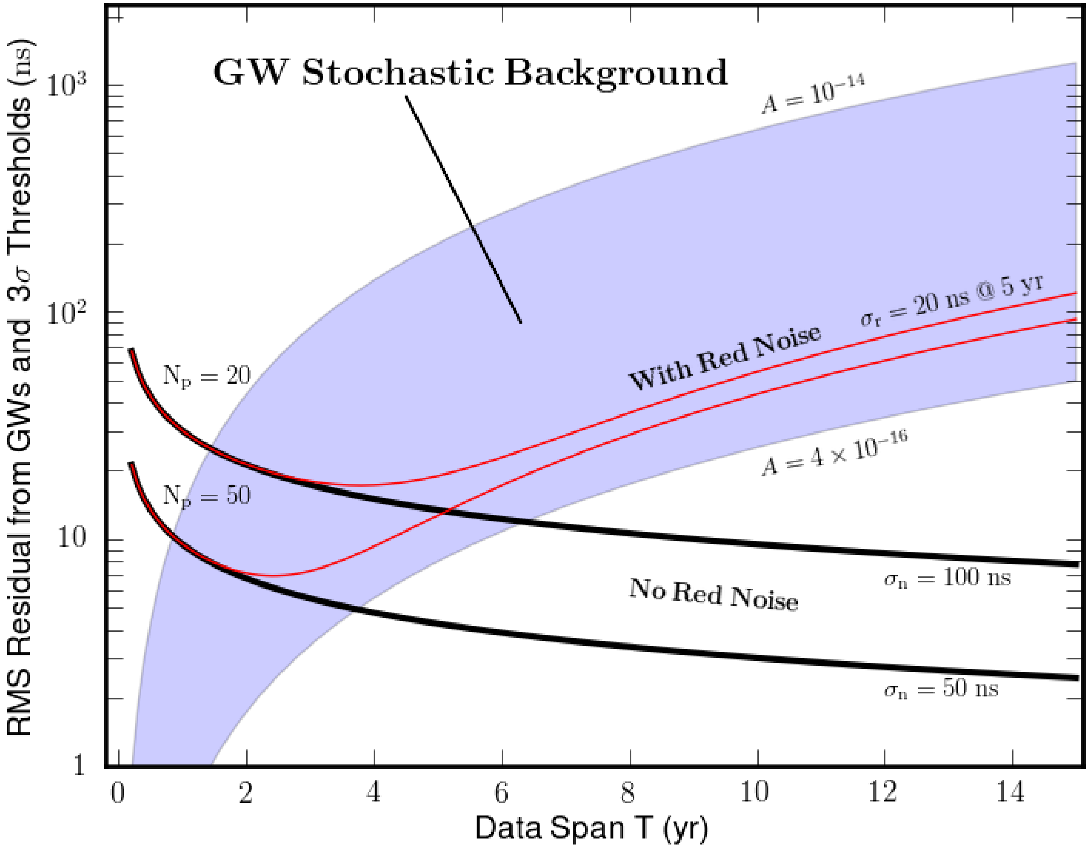
Challenges - SNR & pulse jitter

- **TOA precision depends on SNR - strong MSP only** (Cordes & Shannon 2010)
- **Phase and Amplitude Jitter**
  - Frequency dependent emission region => shape, width, phase evolution
  - Movement of emission region
- **10 μs jitter in Crab pulsar**



- **Use pulsars with little jitter**

Noise Budgets



Courtsey Cordes & McLaughlin

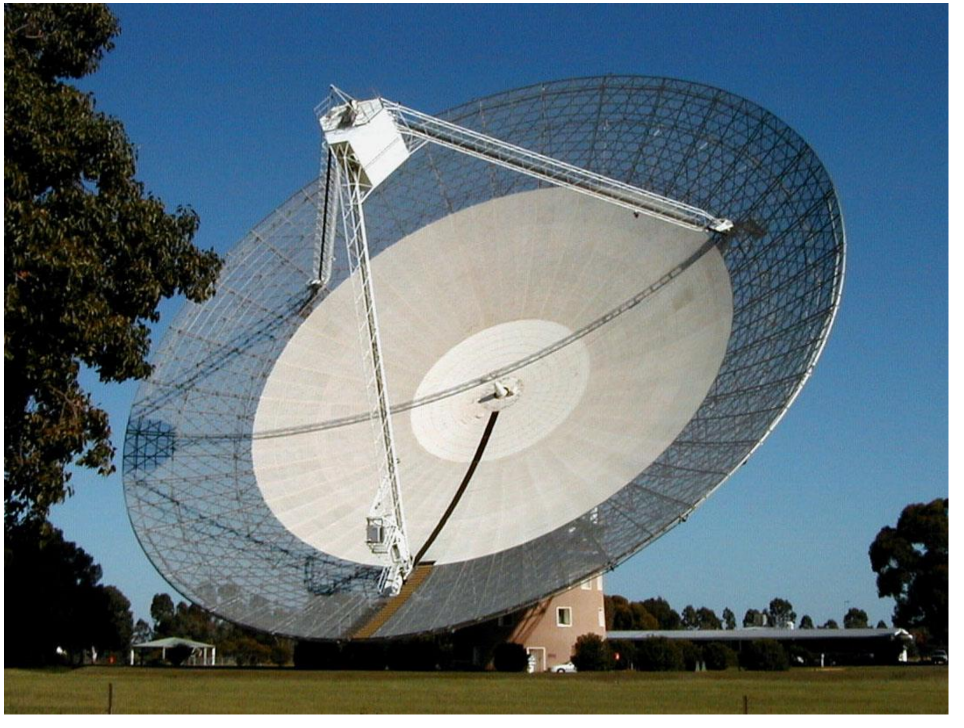
Design of PTA

- **PTA - pulsar sample selection criteria**
  - Reasonably strong
  - Good rotators - GC pulsars excluded - evolving sample
  - Tight binaries excluded - to avoid relativistic effects
  - Short period and narrow pulses field or wide binary pulsars prefered
  - Nearby pulsars - reduces dispersive and scatter-broadening effect
  - Pulsars with profile jumps avoided (Lyne et al. 2010)
  - Low frequency monitoring of MSPs needed to characterize / model phase jitter
  - 20 preferably 50 "white" pulsars required (Cordes & Shannon 2010)
- **Observing Requirements**
  - Two frequency simultaneous or close observations needed
  - Preferably one of the pair < 400 MHz $t \propto \nu^{-3}$
  - > 1 GHz observing frequency as a trade-off
  - Wide bandwidth receiver for large SNR
  - Full polar calibrated observations - pulsars are polarized sources
  - Calibration of fixed delay between different backends and different telescopes
  - Large number of high sensitivity large collecting area telescope required for more frequent monitoring
  - Preferably coherent dedispersed data - particularly for DM estimation

Parkes Pulsar Timing Array (PPTA)

- **PPTA uses the Parkes 64-m**
- **20 MSPs are timed every 2-3 weeks**

Australia Telescope National Facility, CSIRO, Sydney



North American Nanohertz Observatory for Gravitational Waves (NANOGrav)

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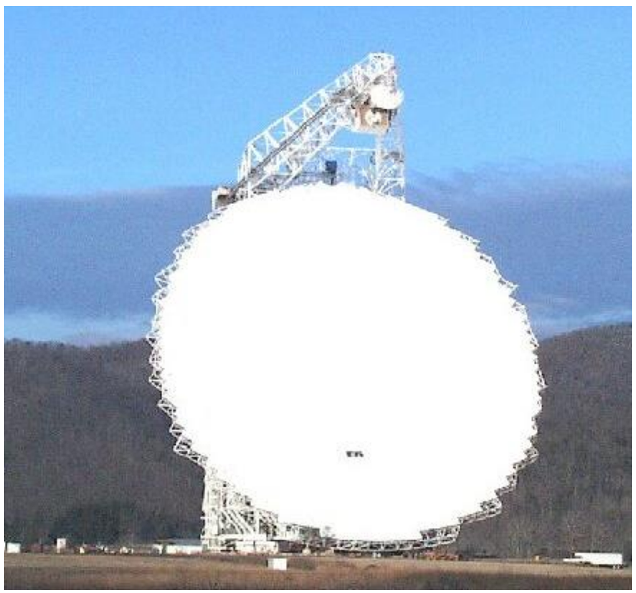
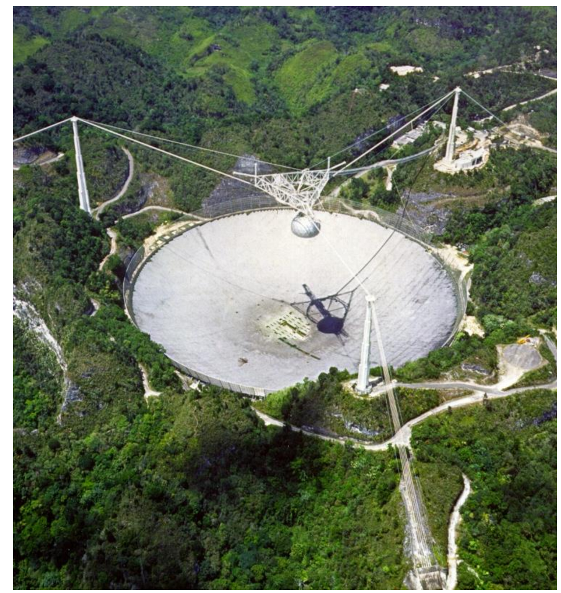
- NANOGrav uses Arecibo and Green Bank Telescope
- 35 pulsar are timed every 20 days
- West Virginia University





The European Pulsar Timing Array (EPTA)

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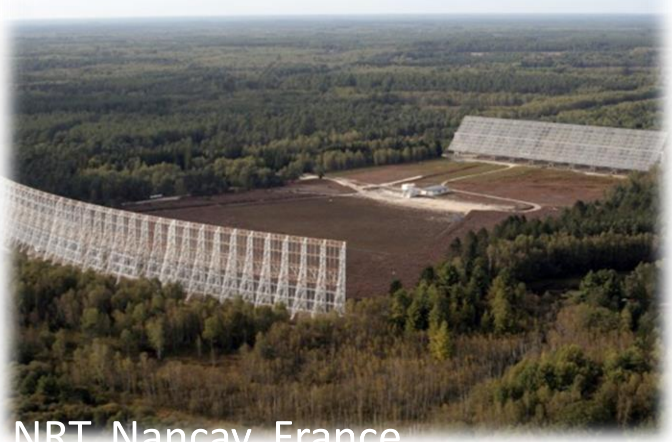
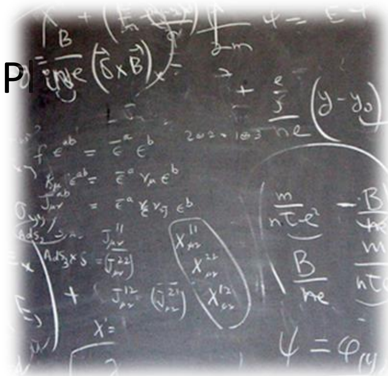
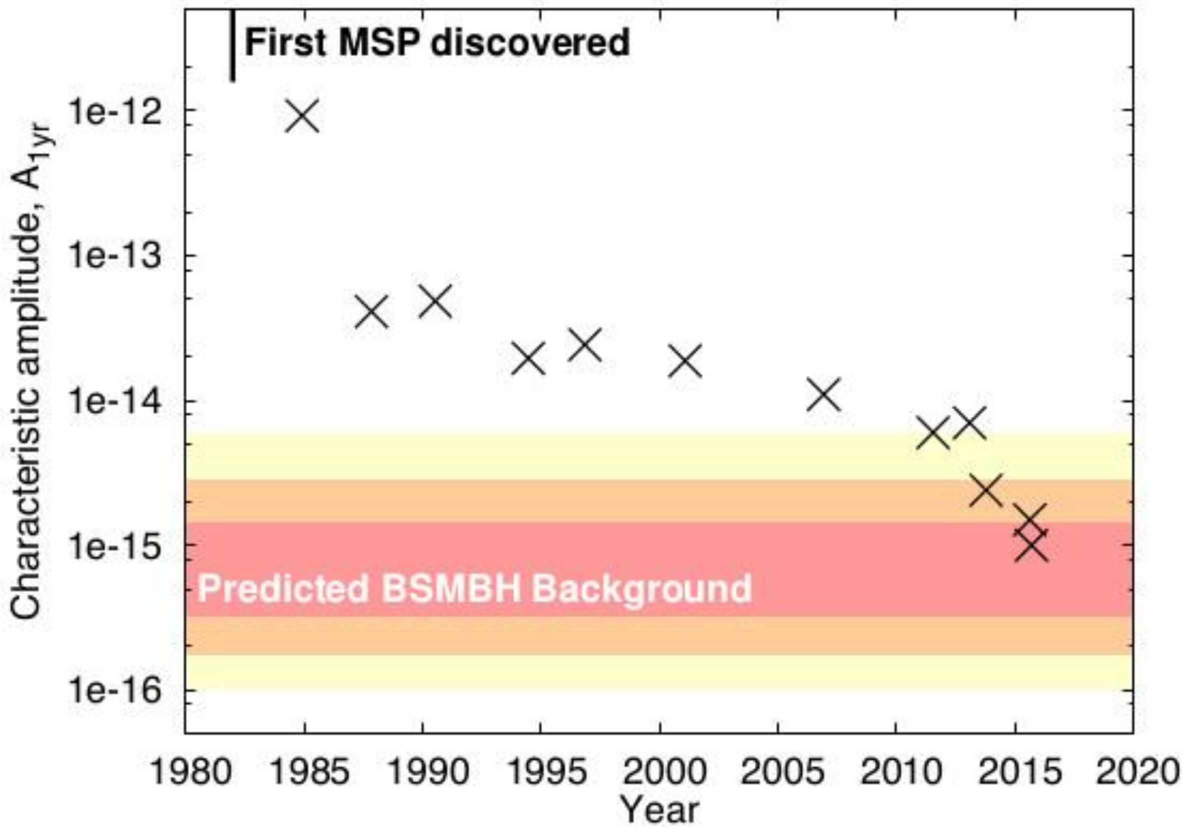




Current status of IPTA



Burke-Spoloar 2015, arXiv:1511.07869

Current status of IPTA

- Verbiest et al. 2016, MNRAS, 458, 126

Table 1: A brief description and characteristics of the three leading Pulsar Timing Arrays and the proposed TAPTA. The sixth column provides the upper limits on the power-law GW background, namely $A_{1\mathrm{yr}}$, with $\alpha = -2/3$. For completion, we also list certain important characteristics of the International Pulsar Timing Array (IPTA).

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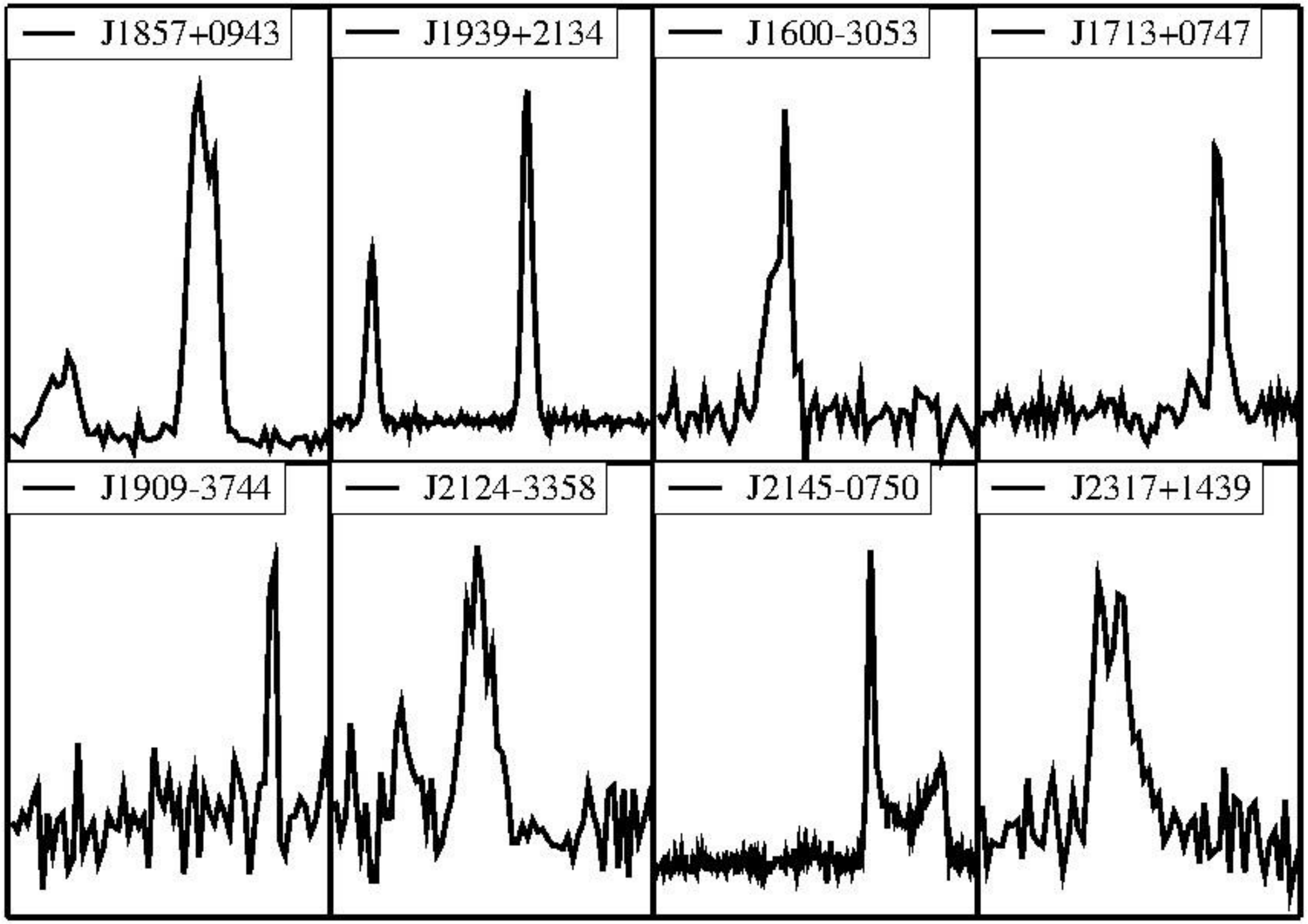
IPTA		49			1.7	Verbiest et al. (2016)
TAPTA (Proposed)	Arvi	21	2.5	Daily	$\sim$1.0	In about five years

Indian PTA

- **Recently, we initiated an experiment with two major Indian facilities**
- **The Ooty Radio Telescope and the Giant Meterwave Radio Telescopes are being used simultaneously since last two years for this experiment**
- **A sample of 9 MSPs is being monitored once every 20 days using the Giant Meterwave Radio Telescopes (GMRT) at 1300 MHz**

- **Apart from simultaneous observations, the same 9 pulsars are also being monitored every 3 days at the Ooty Radio Telescope (ORT) at 334 MHz**
- **ORT high cadence data allows good phase connection**
- **Simultaneous low cadence ORT-GMRT data allows determination of DM variations to fourth decimal place**

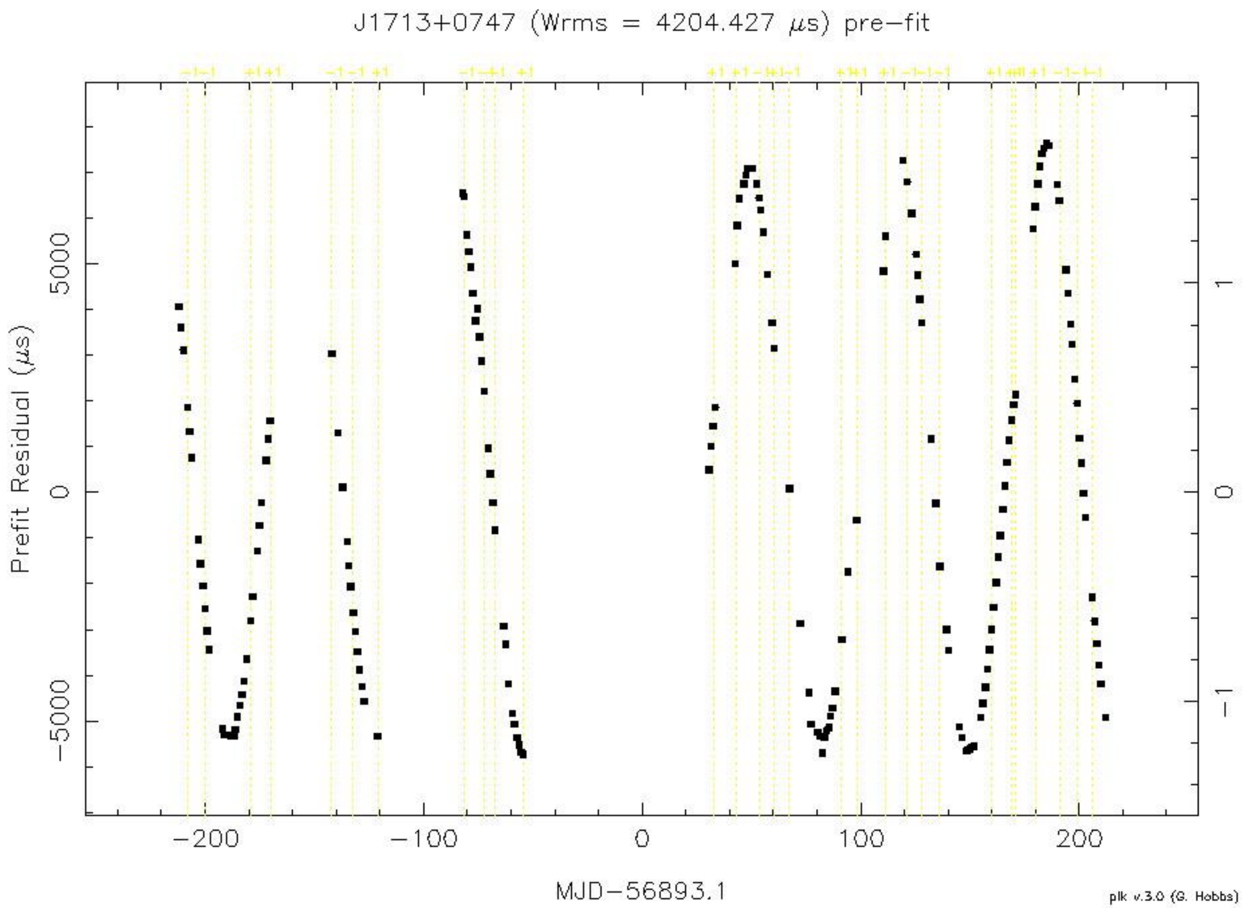
Pulsar sample



Sample of Pulsars

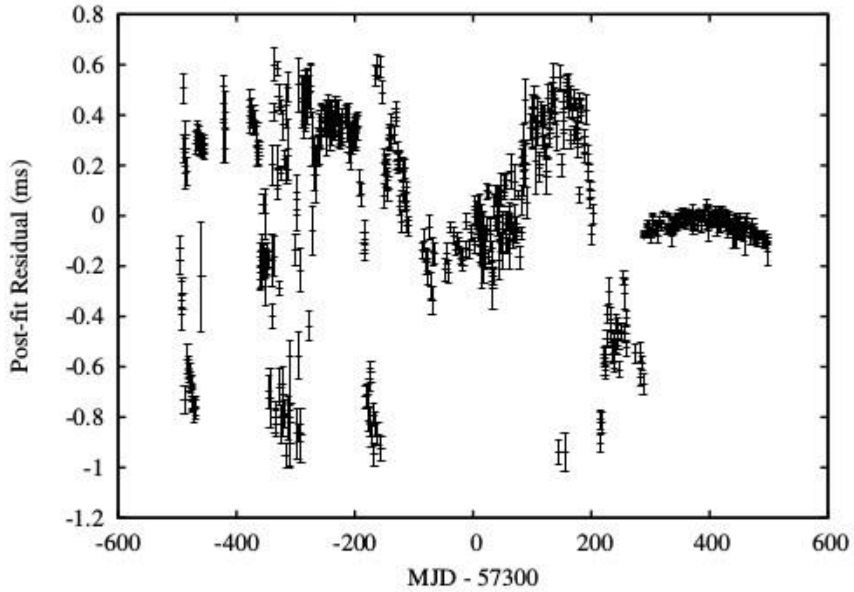
Timing J1713+0747

- **Sub-μs precision requires accurate timing solutions of pulsars**
- **Sub-μs precision requires characterization of observatory clocks and instruments and coherent dedispersion capability**



Towards sub-μs residuals

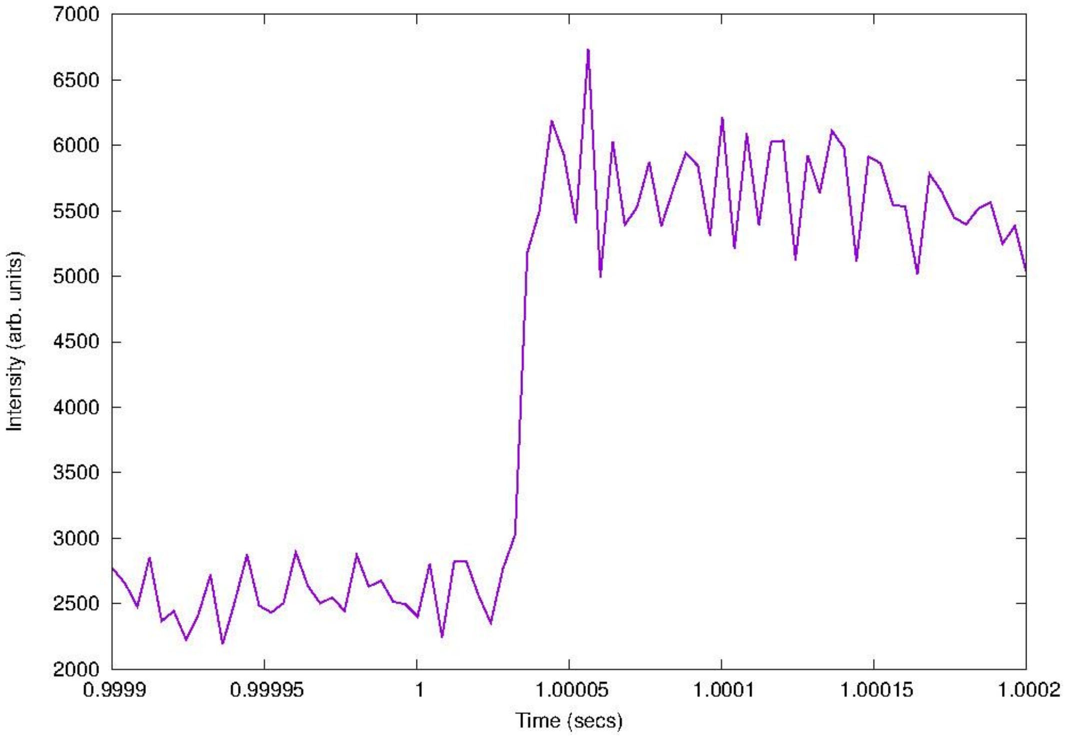
- **Important to characterize the stability of observatory clock**



- **High Jitter was noticed in the observatory clock**
- **A new Rb clock is now installed at ORT**
- **H – Masers to be commissioned next year at GMRT and ORT**

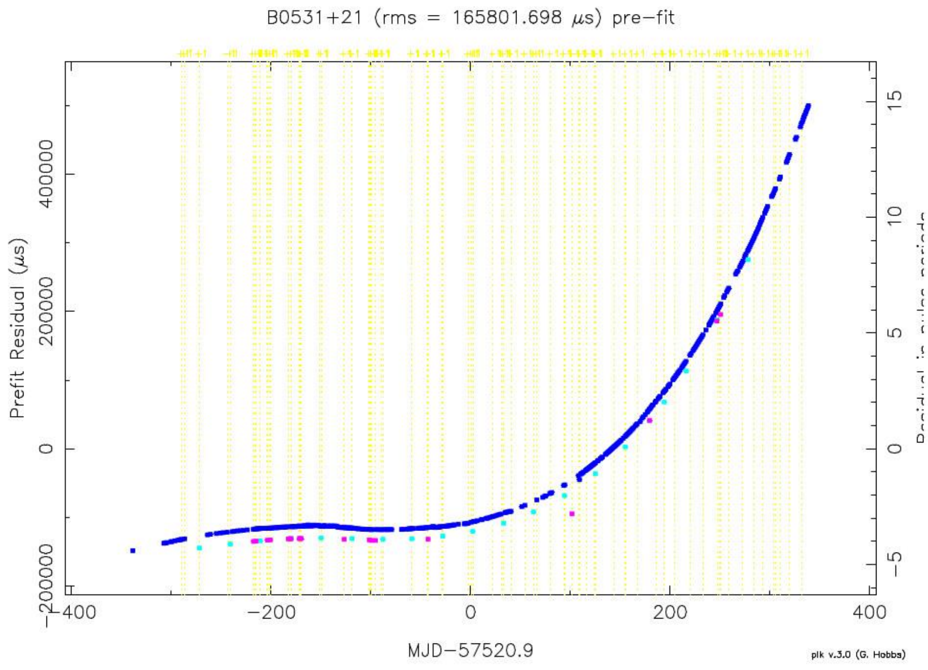
Towards sub-μs residuals

- **Calibration of absolute offsets between observatories is important**
- **Radiation of artificial pulsar synchronized to GPS minute pulse**

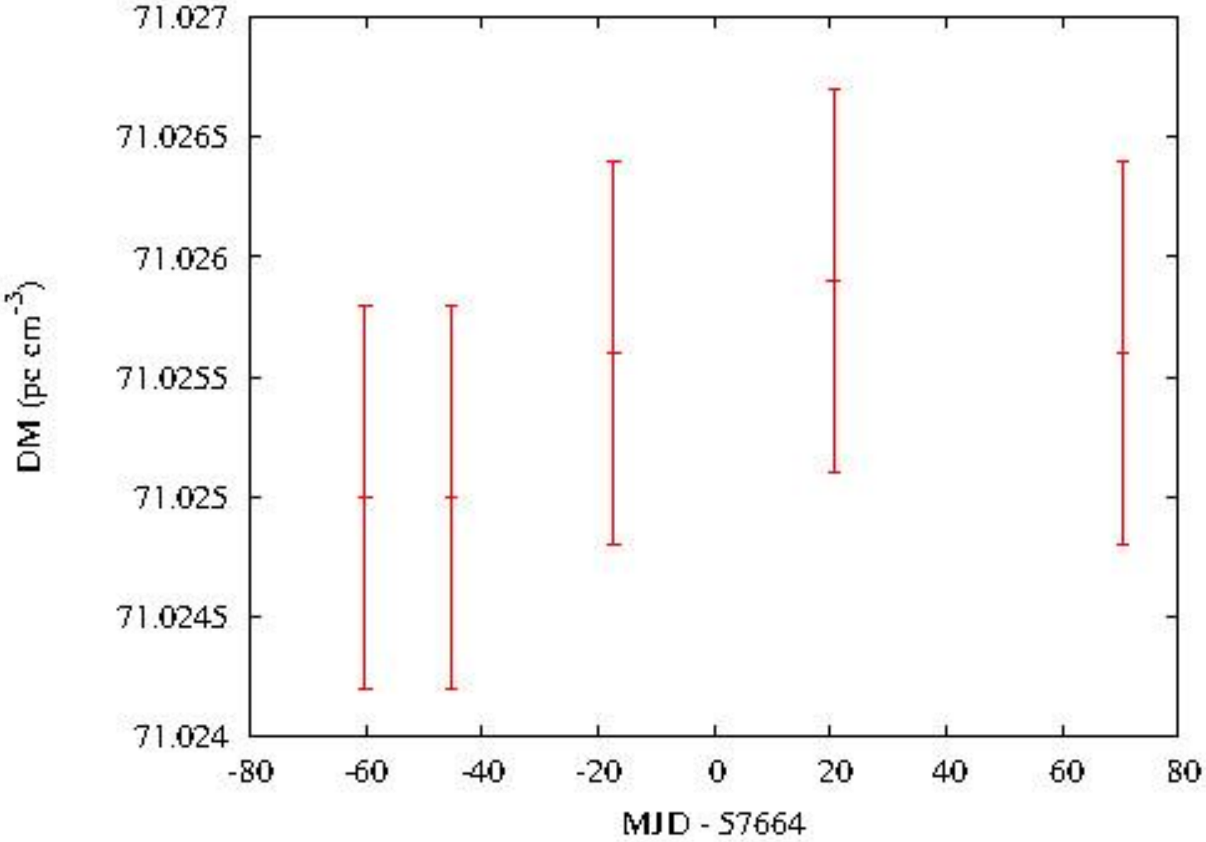


Towards sub-μs residuals

- **Observatory offsets between ORT, GMRT, Jodrell Bank, ASTROSAT were also measured by continuous and simultaneous monitoring of Crab and 3 other pulsars**

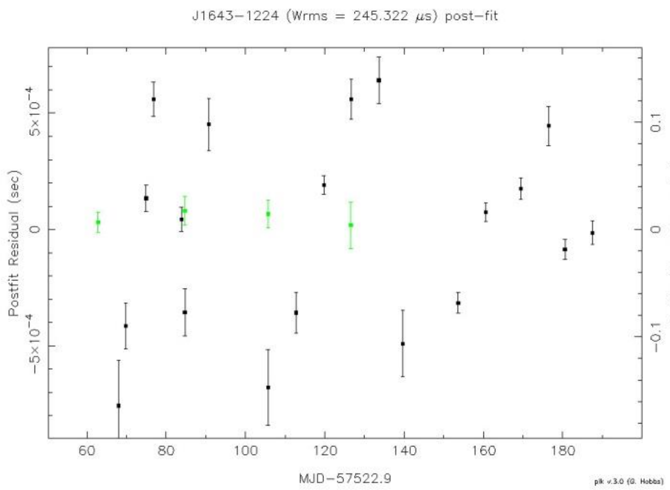


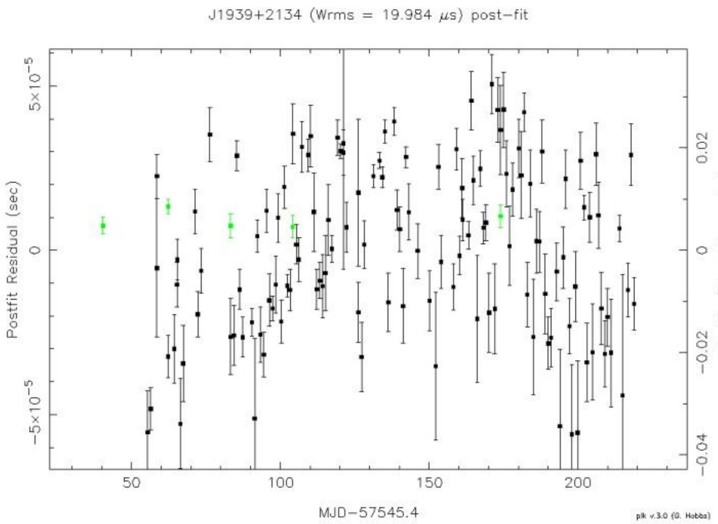
Variation in DM

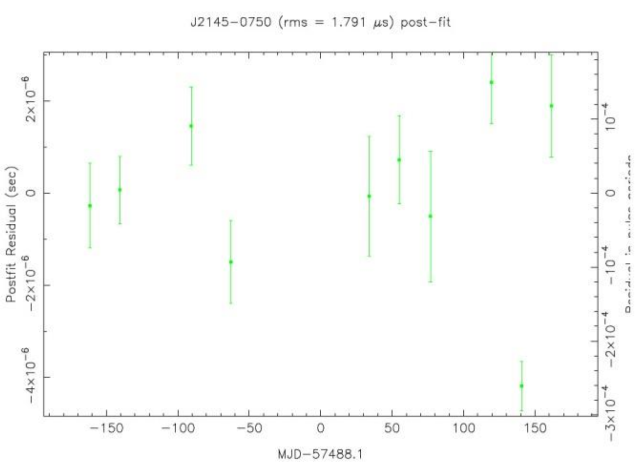


DM variations in PSR B2937+21

Timing solutions and precision







Timing solutions for three pulsars in our monitoring program

InPTA pulsars preliminary status table

Name of Pulsar	Epochs detected	typical TOA error(μs)	Typical post fit (μs)
J1600-3053	17	11	70
J1643-1224	18	33	245
J1713+0747	16	4	3
J1857+0943	16	5	23
J1909-3744	13	34	55
J1939+2134	18	2	20
J2124-3358	12	87	453
J2145-0750	18	5	2
J2317+1439	8	91	507

Tata Pulsar Timing Array:

A dedicated nano-Hz GW observatory

B C Joshi, A Gopakumar, S Roy

TAPTA ?

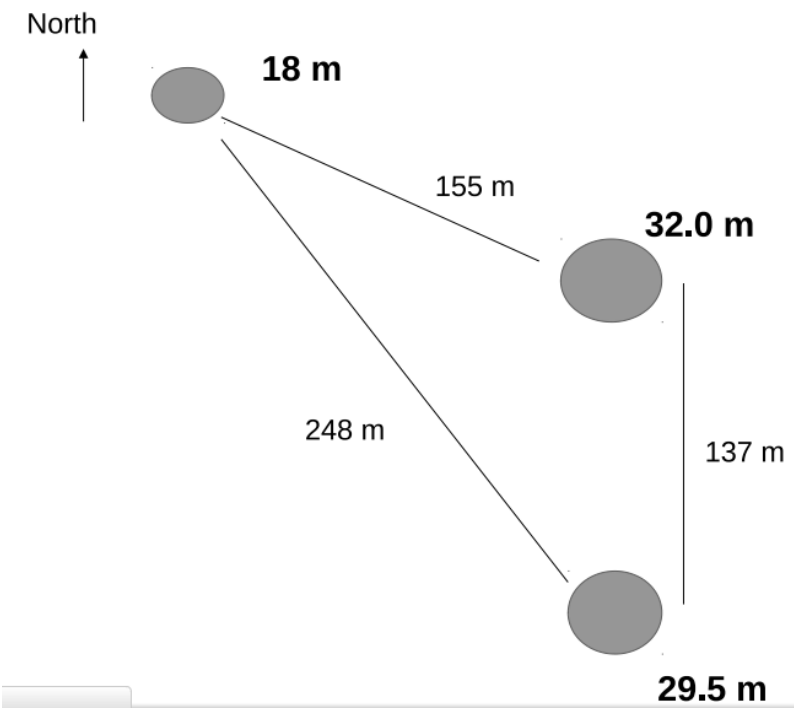
NCRA • TIFR

- The idea is to use the available three Arvi dishes to create an equivalent 50-meter dish, which will be used to monitor IPTA millisecond pulsars on a daily basis.

- This will be the only facility in the world that would make such daily observations of IPTA pulsars for directly detecting nano-Hz gravitational waves

- This would allow the TATA Pulsar Timing Array (TAPTA) to reach the sensitivities of existing Pulsar Timing Arrays like PPTA, EPTA and NANOGrav rapidly and complement the international effort of International pulsar timing arrays (IPTA) towards the goal of detecting and studying nano-Hertz GWs

TAPTA: II


North
18 m
155 m
32.0 m
248 m
137 m
29.5 m


http://lifestyleproblog.me

Current status of IPTA

- Verbiest et al. 2016, MNRAS, 458, 126

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Summary

- Clocklike stability of radio pulsars make them useful astronomy tools in experiments to test gravity theories and detecting GW
- Pulsar timing technique, where a comparison of observed TOA with that predicted by a rotational models allows high precision measurements is used for this purpose
- GW passing near earth imprints low frequency systematic variations in TOA residuals
- Correlation in TOA residuals over several pairs of pulsars is used to put limits on SGWB in nano-Hertz frequency range, produced by superposition of an ensemble of SMBHB
- Three experiments – PPTA, nanoGRAV and EPTA are operational sharing their data in an international collaboration called International Pulsar Timing Array (IPTA) and have reached upper limits on h of 10^{-15} although no detection has been made
- TIFR's facilities – ORT and GMRT can make and are making contributions to this effort

Summary

- **Indian Pulsar Timing Array (INPTA)**
  - **ORT and GMRT timing of pulsars is capable of giving post-fit residuals of the order of 1 – 10 μs**
  - **This translates to a limit on GW amplitude of 10^{-13}**
  - **Systematics need to be reduced in timing solutions of pulsars**
  - **Regular clock monitoring is continuing to remove clock associated systematics**
  - **ORT – GMRT data combination being used to determine epoch dependent DM**

- **We hope to achieve post-fit residuals of the order at sub-μs in the next 6 months comparable to International Pulsar Timing Array experiments**

- **A new dedicated high cadence PTA facility called TAPTA is proposed**

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Thank you

IPTA

- O