International Pulsar Timing Array Consortium for Nano-Hertz GW Astronomy

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tifr

InPTA
Indian Pulsar Timing Array

Outline

- We (*Team Eccentric*) work on various aspects of hecto & nano-Hz GW Astronomy
- A brief update on our LIGO relevant efforts
- Ongoing effort to establish the presence of a SMBH binary in a unique Blazar OJ 287
- General Introduction to nano-Hz GW astronomy
- Persistent MM GW Astronomy during SKA-ngEHT era

We employ Post-Newtonian approximation to GR to describe compact binaries

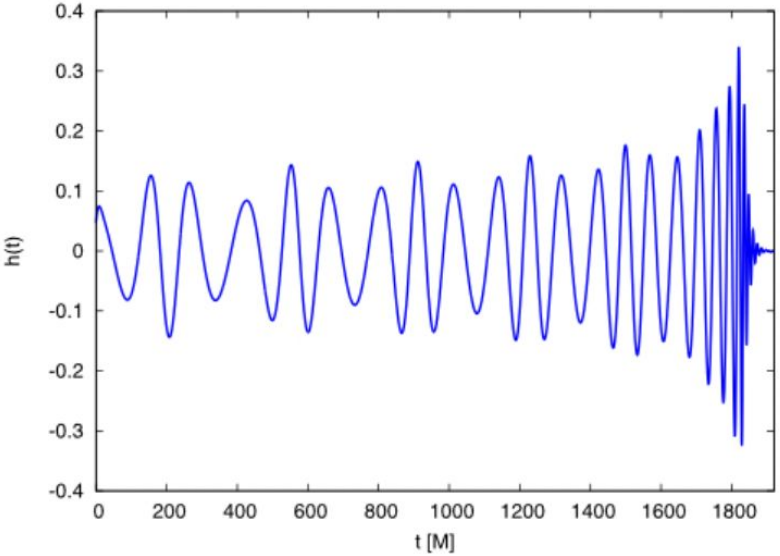
- In the case of non-spinning compact binaries, for LIGO/VIRGO applications, one needs to tackle two problems (usually analyzed separately)
- Problem of finding equations of motion $\ddot{\boldsymbol{X}}$
- Problem of computing gravitational-wave luminosity $\mathcal{L}$, $h_{\times,+}$

$\ddot{\boldsymbol{X}}$	N	1PN	2PN	2.5PN	3PN	3.5PN	4PN	4.5PN	5PN	5.5PN	6PN
$\mathcal{L}$	—	—	—	N	—	1PN	1.5PN	2PN	2.5PN	3PN	3.5PN
$h_{\times,+}$	—	—	N	0.5N	1PN	1.5PN	2PN	2.5PN	3PN		

LIGO Relevant Efforts

We provide time and frequency domain inspiral templates for compact binaries
In non-circular orbits

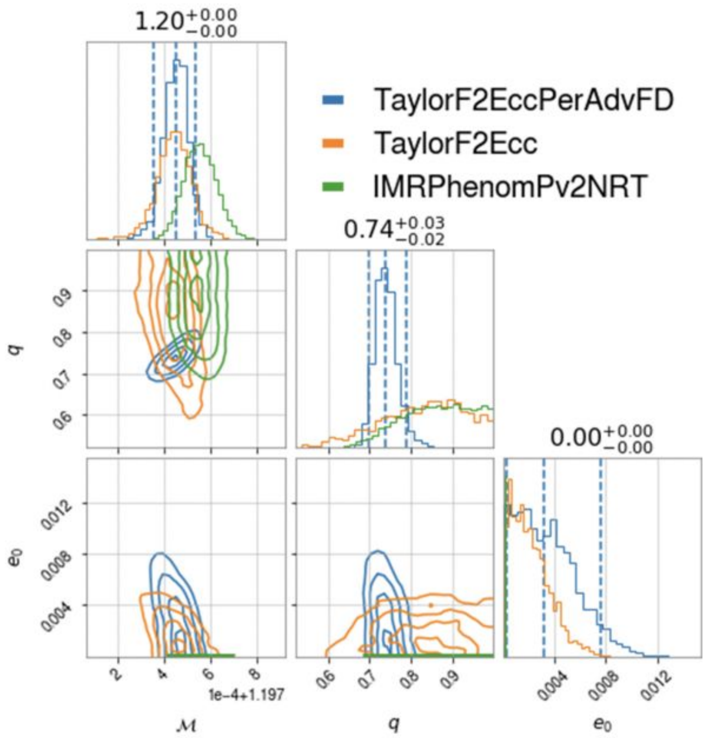
Our inspiral template is a crucial input to construct phenomenological **Frequency-domain** Inspiral-Merger-Ringdown (IMR) GW waveform for moderately eccentric binaries ($e \sim 0.4$).

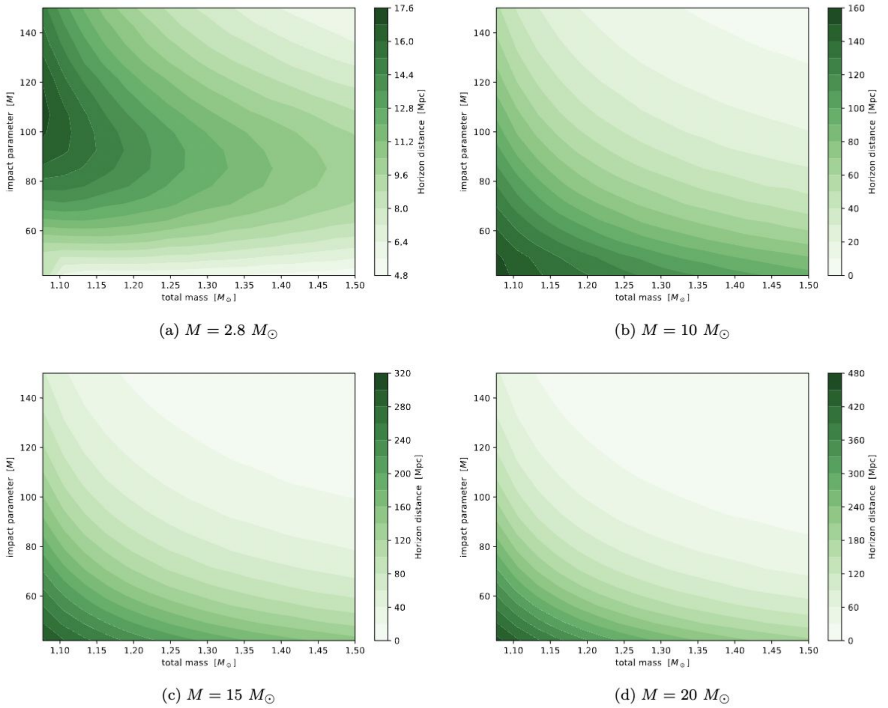


These efforts are driven by
Prof. Maria Haney (Nikhef, Amsterdam)
Prof. Hyung Mok Lee
Dr Srishti Tiwari (IUCAA)
Dr Gihyuk Cho (SNU, Seoul)
Dr Sashwat Tanay (Olemss)
Dr. Prerna Rana (TIFR)
Dr. Shubhanshu Tiwari
Mr Hemantakumar P (CUHK)
Mr Subhajit Dandapt (TIFR)
Mr Yumeng Xu (Zurich)

We provide the *LVK collaboration* with *GW templates for BH-BH, BH-NS & NS-NS binaries in non-circular orbits*

Dr Bae's efforts will be crucial for us





BWM events reach for LVK (hyperbolic passages)
Subhajit Dandapat, M. Ebersold +

Eccentric h(f) with `k` effects; PE runs for GW170817 (Hemantakumar+)
Rapid PE efforts will be required!!

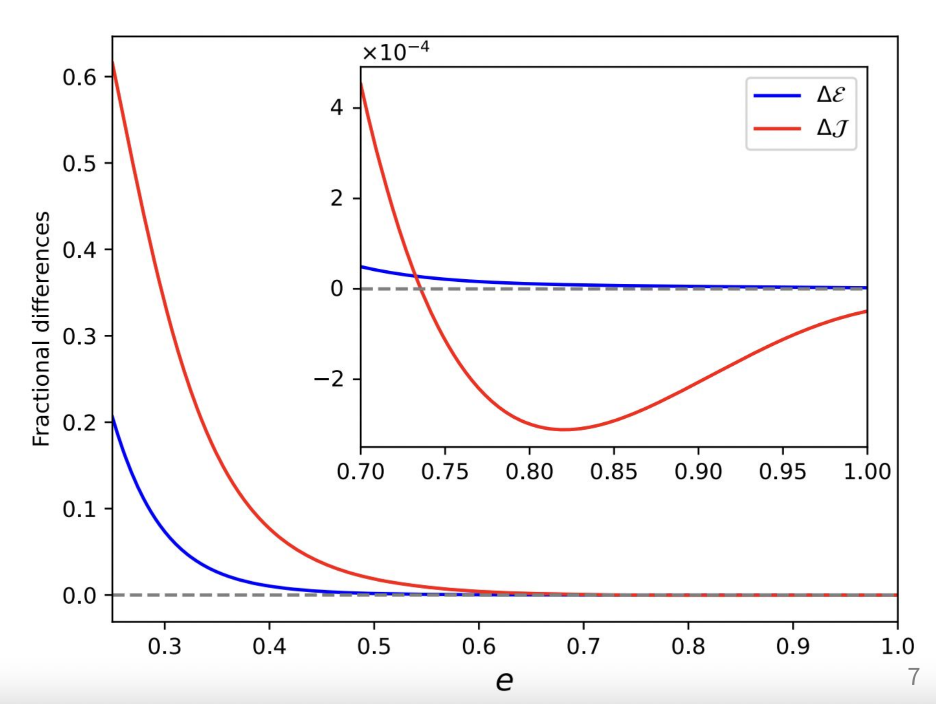
[Cho, Dandapat & Gopakumar (DOI: 10.1103/PhysRevD.105.084018)]

- We derived explicit expressions for the 3PN accurate instantaneous contributions to the radiated energy and angular momentum during hyperbolic encounters.
- This effort allow us to develop a prescription for describing GW emission aspects of highly eccentric compact binaries.

$$\frac{\Delta\mathcal{Q}_{\rm hyp}-\Delta\mathcal{Q}_{\rm ecc}}{\Delta\mathcal{Q}_{\rm hyp}}, \text{ where } \mathcal{Q}=\mathcal{E},\mathcal{J}$$

- Hyperbolic fluxes are expanded in the post-bremsstrahlung limit i.e in $(e\to\infty)$
- $e(\mathcal{E}_{\rm 3PN},\mathcal{J}_{3PN})$ is the newtonian eccentricity

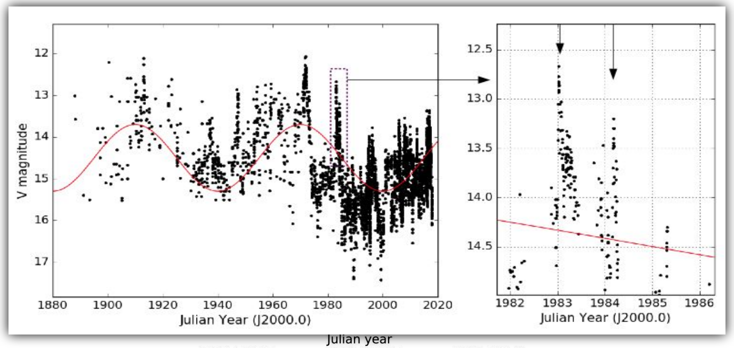
$$\Delta\mathcal{E}\Rightarrow\mathcal{O}\left(\frac{1}{e^5}\right) \text{ and } \Delta\mathcal{J}\Rightarrow\mathcal{O}\left(\frac{1}{e^7}\right)$$

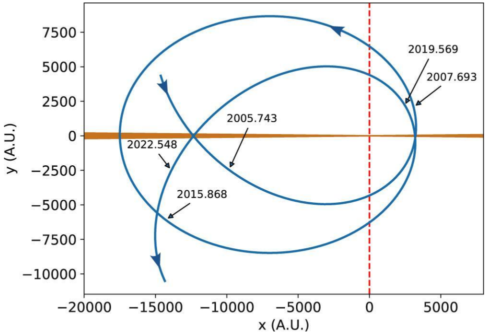


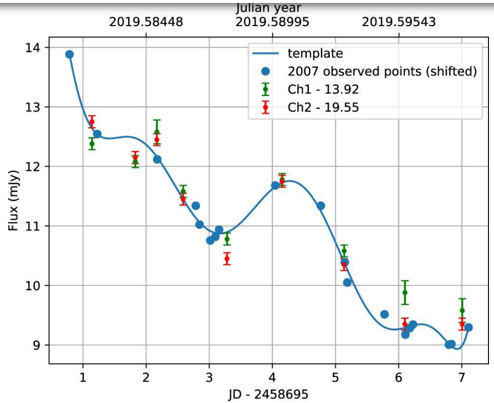
Authenticating SMBH Binary Presence in OJ 287

With L. Dey, Mauri Valtonen +

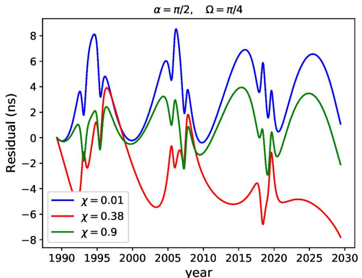
A unique blazar may be hosting a SMBH binary that emits nano-hz GWs



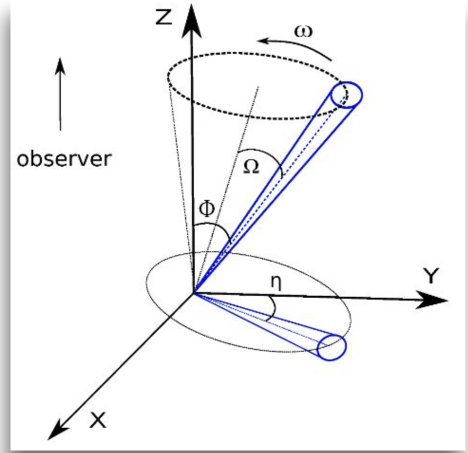


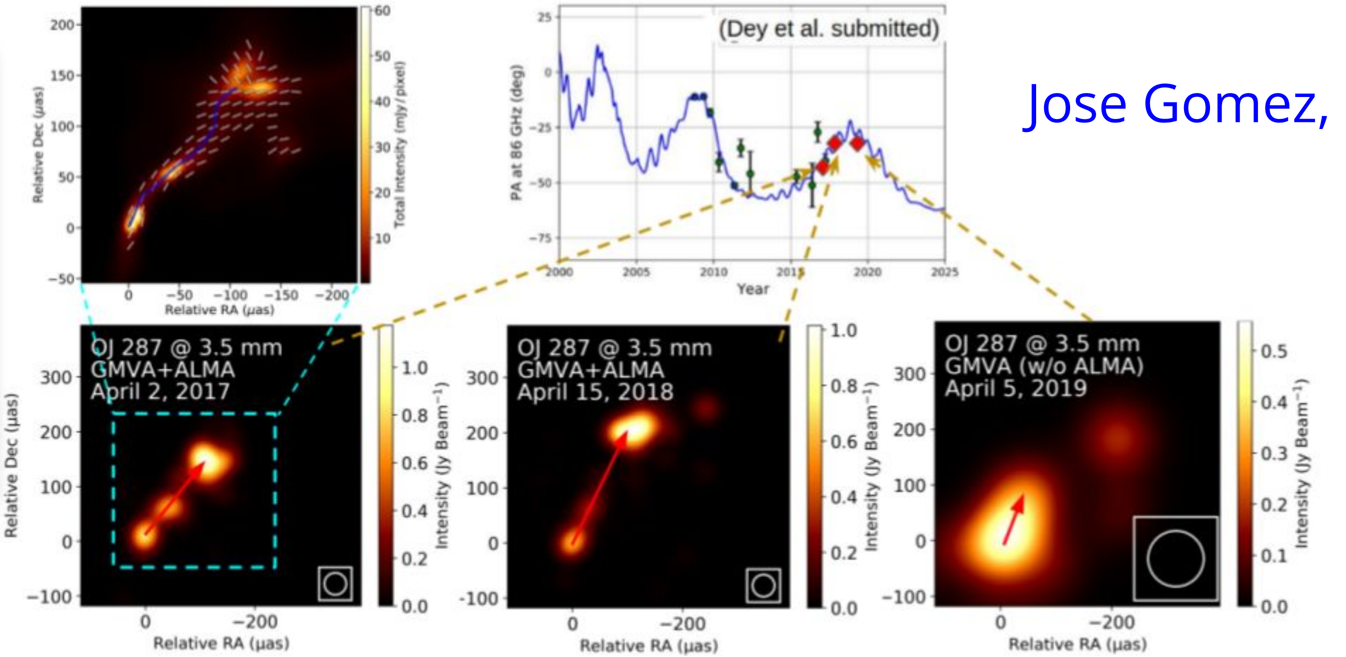


Observations of predicted flares of 2007,2015 and 2019 impact flares are consistent with the presence of nano-Hz GW emitting SMBH binary in Blazar OJ 287 (Laine ,Dey + 2020, Dey +,2018; Valtonen et al. 2016, 2010,2008,2006)



The expected IPTA signals from SMBH binaries like OJ 287 (Dey, Abhimanyu + 2022)





Jose Gomez, +

KVN is planning to pursue `astrometry` with OJ 287 using KVN-style"multi-frequency system" for GMVA

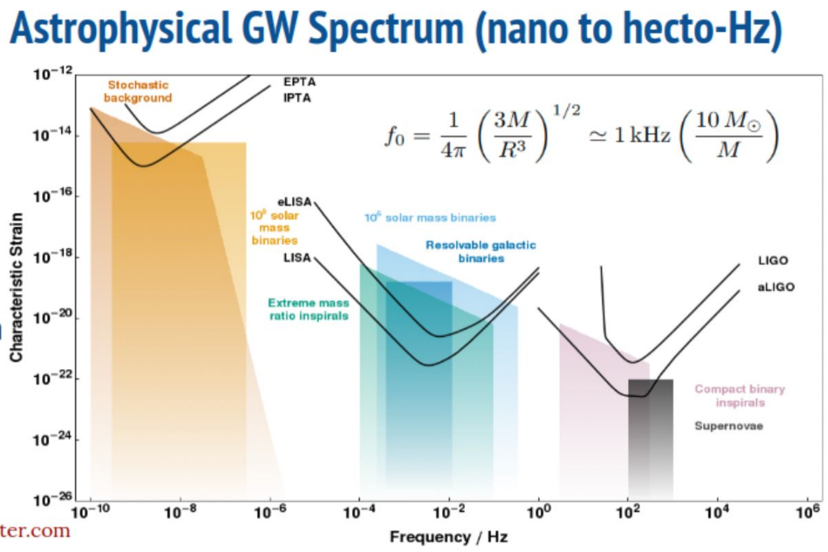
Figure 2: [*Top left*] 3 mm total intensity and polarization map of OJ 287 in 2017. The super-resolution image was reconstructed with the *eht-imaging* library. Blue curve indicates the twisted jet ridge line, and bars the EVPAs. [*Top right*] Time evolution of the jet position angle at 86 GHz (green data points), predictions by binary BH orbital modeling (blue curve from Dey et al., submitted.), and the preliminary estimates from our GMVA+ALMA observations in 2017-2019 (red diamonds). The green dots are from previous GMVA-only observations during 2008-2017. [*Bottom, from left to right*] 3 mm total intensity maps of OJ 287 obtained with GMVA+ALMA on April 2, 2017, GMVA+ALMA on April 15, 2018, and GMVA (without ALMA) on April 5, 2019, respectively. Each map is convolved with a circular beam that matches the major axis of the nominal beam. The red arrow on each panel indicates the inner jet direction.

Ongoing efforts related to International Pulsar Timing Array

Multi-Band GW Astronomy

Is it possible to do Persient Multi-Messenger GW Astronomy in the coming years?

h = ΔL/L
GW strain



http://gwplotter.com

$$\delta T/T = h$$

Pulsar Timing

- **Pulsar timing** = Tracking of pulsar rotation by very accurately measuring pulse arrival times (TOAs)

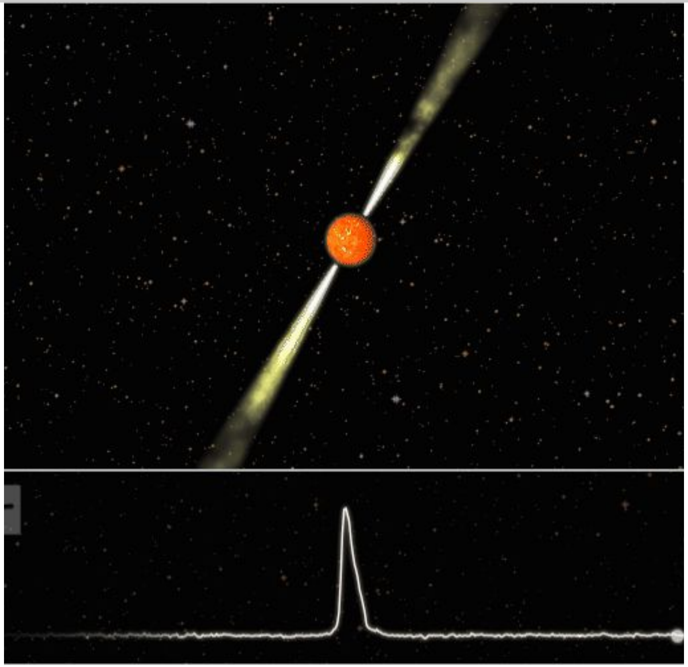
- Passing GWs induces a shift in Pulsar's intrinsic spin frequency ν_0 ⇨ ν(t).

- Observable timing residuals, induced by GWs, are given by the time integral of $\Delta\nu_0/\nu_0$.

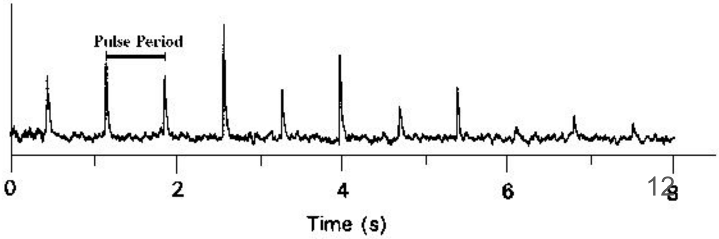
- **Timing Residual R(t)**:

$$R(t) = \int_0^t \frac{\nu_0 - \nu(t')}{\nu_0}\, dt'$$

[Hobbs, & Dai 2017 (arXiv:1707.01615) (We model the expected R(t) from SMBH Binaries using GR approaches)



Source : astron.nl



Pulsar Timing Arrays for nano-hertz GW Astronomy

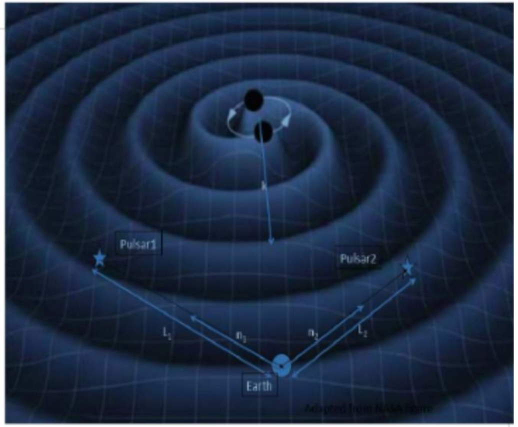
- SMBH binaries can provide nano hertz GWs with amplitudes ~10^{-15}

$$\omega = 2 \times 10^{-8}\, \mathrm{s}^{-1} \left(\frac{200M}{R_0}\right)^{3/2} \left(\frac{10^{10}\, M_\odot}{M}\right)$$

$$A \sim 5 \times 10^{-14} \left(\frac{200M}{R_0}\right) \left(\frac{M}{10^{10}\, M_\odot}\right) \left(\frac{10^{10}\ \text{lt-yr}}{r}\right) .$$

Detweiler, S. (1979)

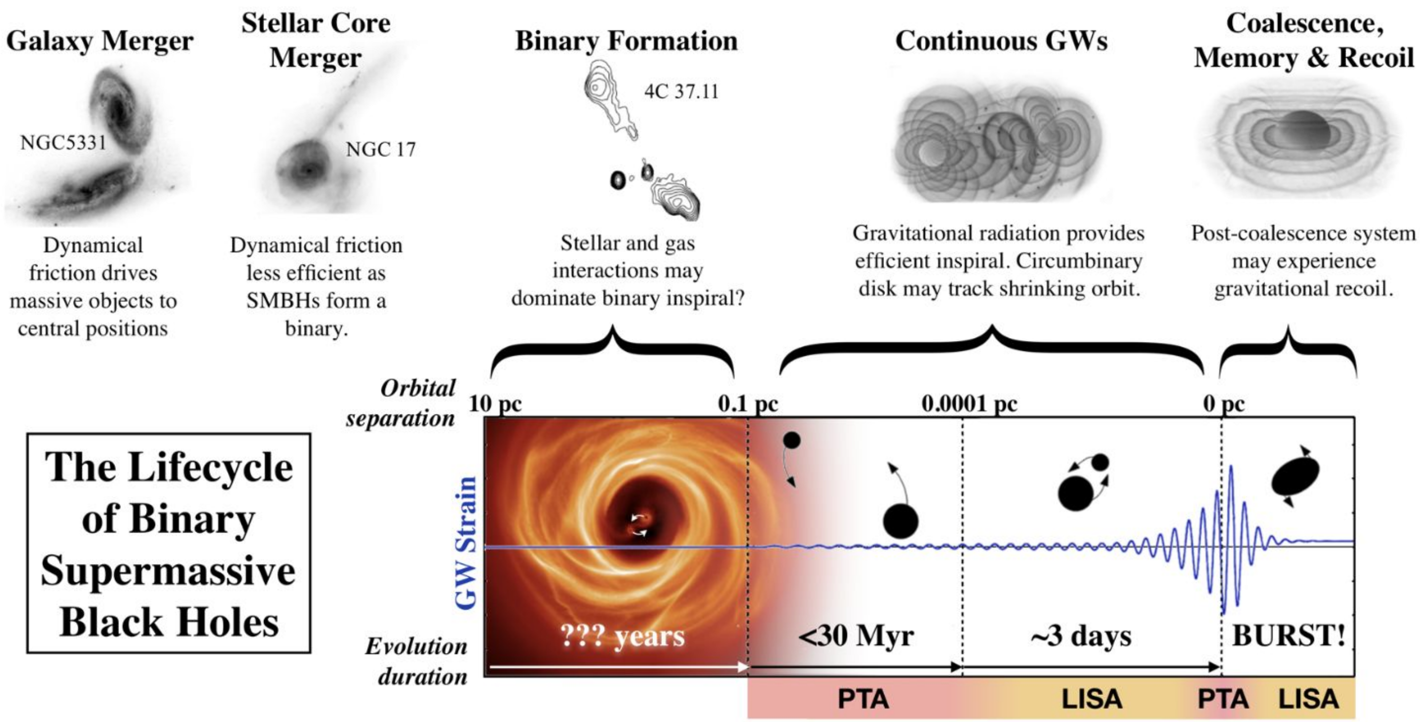
- We need highly accurate and stable celestial clocks
Employ MSPs!!



Courtesy: Web

$$\delta T/T = h$$

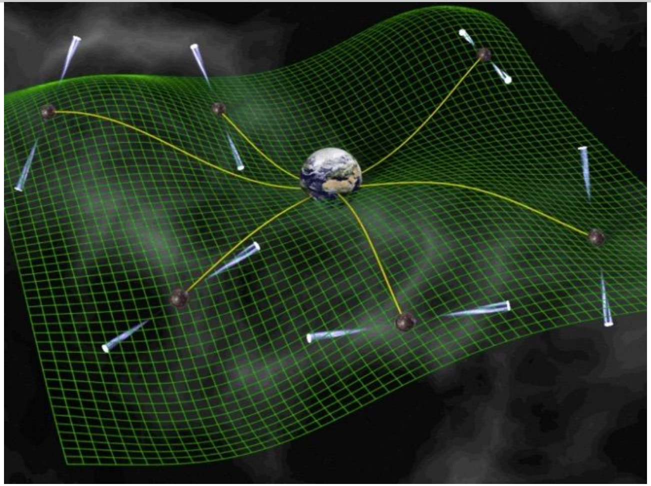
SMBH Binary Coalescence for Multi-Messenger GW Astronomy



$$\Delta h_{+,\times} = \lim_{t \longrightarrow +\infty} h_{+,\times} - \lim_{t \longrightarrow -\infty} h_{+,\times}$$

Burke-Spolaor, Sarah, et al (2019)

IPTA consortia includes NANOGrav, EPTA, InPTA and PPTA



We monitor a bunch of milli-second pulsars using the best radio telescopes *to detect nano-Hz GWs*

NANOGrav EPTA InPTA Indian Pulsar Timing Array PPTA

2019 IPTA Conference @ Tata Institute of Fundamental Research in Pune, India – *Photo credit: B.C. Joshi*

Press Release: IPTA strengthens evidence of signal that may hint at gravitational waves

We are pleased to share

A Global, Galactic-Scale Gravitational Wave Detector

The International Pulsar Timing Array (IPTA) is a consortium of consortia[1] , comprised of the European Pulsar Timing Array (EPTA), the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), the Indian Pulsar Timing Array Project (InPTA, and the Parkes Pulsar Timing Array (PPTA). The goal of the IPTA is to detect and characterize the low-frequency gravitational wave universe through timing a global array of approximately 100 millisecond pulsars using the largest radio telescopes in the world. Through sharing

Check out -> http://ipta4gw.org/

Rapidly maturing PTAs are expected to inaugurate the era of nano-Hz GW Astronomy very soon!!

The NANOGrav 12.5 yr Data Set: Search for an Isotropic Stochastic Gravitational-wave Background

Show affiliations Show all authors

Arzoumanian, Zaven ; Baker, Paul T. ; Blumer, Harsha ; Bécsy, Bence ; Brazier, Adam ; Brook, Paul R. ; Burke-Spolaor, Sarah ; Chatterjee, Shami ; Chen, Siyuan ; Cordes, James M. ; Cornish, Neil J. ; Crawford, Fronefield ; Cromartie, H. Thankful ; Decesar, Megan E. ; Demorest, Paul B. ; Dolch, Timothy ; Ellis, Justin A. ; Ferrara, Elizabeth C. ; Fiore, William ; Fonseca, Emmanuel ; ...

We search for an isotropic stochastic gravitational-wave background (GWB) in the 12.5 yr pulsar-timing data set collected by the North American Nanohertz Observatory for Gravitational Waves. Our analysis finds strong evidence of a stochastic process, modeled as a power law, with common amplitude and spectral slope across pulsars. Under our fiducial model, the Bayesian posterior of the amplitude for an

[Submitted on 26 Jul 2021 (v1), last revised 11 Aug 2021 (this version, v2)]

On the evidence for a common-spectrum process in the search for the nanohertz gravitational-wave background with the Parkes Pulsar Timing Array

Boris Goncharov, R. M. Shannon, D. J. Reardon, G. Hobbs, A. Zic, M. Bailes, M. Curylo, S. Dai, M. Kerr, M. E. Lower, R. N. Manchester, R. Mandow, H. Middleton, M. T. Miles, A. Parthasarathy, E. Thrane, N. Thyagarajan, X. Xue, X. J. Zhu, A. D. Cameron, Y. Feng, R. Luo, C. J. Russell, J. Sarkissian, R. Spiewak, S. Wang, J. B. Wang, L. Zhang, S. Zhang

A nanohertz-frequency stochastic gravitational-wave background can potentially be detected through the precise timing of an array of millisecond pulsars. This background produces low-frequency noise in the pulse arrival times that would have a characteristic spectrum common to all pulsars and a well-defined spatial correlation. Recently the North American Nanohertz Observatory for Gravitational Waves collaboration (NANOGrav) found evidence for the common-spectrum component in their 12.5-year data set. Here we report on a search for the background using the second data release of the Parkes Pulsar Timing Array. If we are forced to choose between the two NANOGrav models — one with a common-spectrum process and one without — we find strong support for the common-spectrum process. However, in this paper, we consider the possibility that the analysis suffers from model misspecification. In particular, we present simulated data sets that contain noise with distinctive spectra but show strong evidence for a common-spectrum process under the standard assumptions. The Parkes data show no significant evidence for, or against, the spatially correlated Hellings-Downs signature of the gravitational-wave background. Assuming we did observe the process underlying the spatially uncorrelated component of the background, we infer its amplitude to be $A = 2.2^{+0.4}_{-0.3} \times 10^{-15}$ in units of gravitational-wave strain at a frequency of $1\ \mathrm{yr}^{-1}$. Extensions and combinations of

EPTA & InPTA are pooling resources for ***the NEXT STEP***

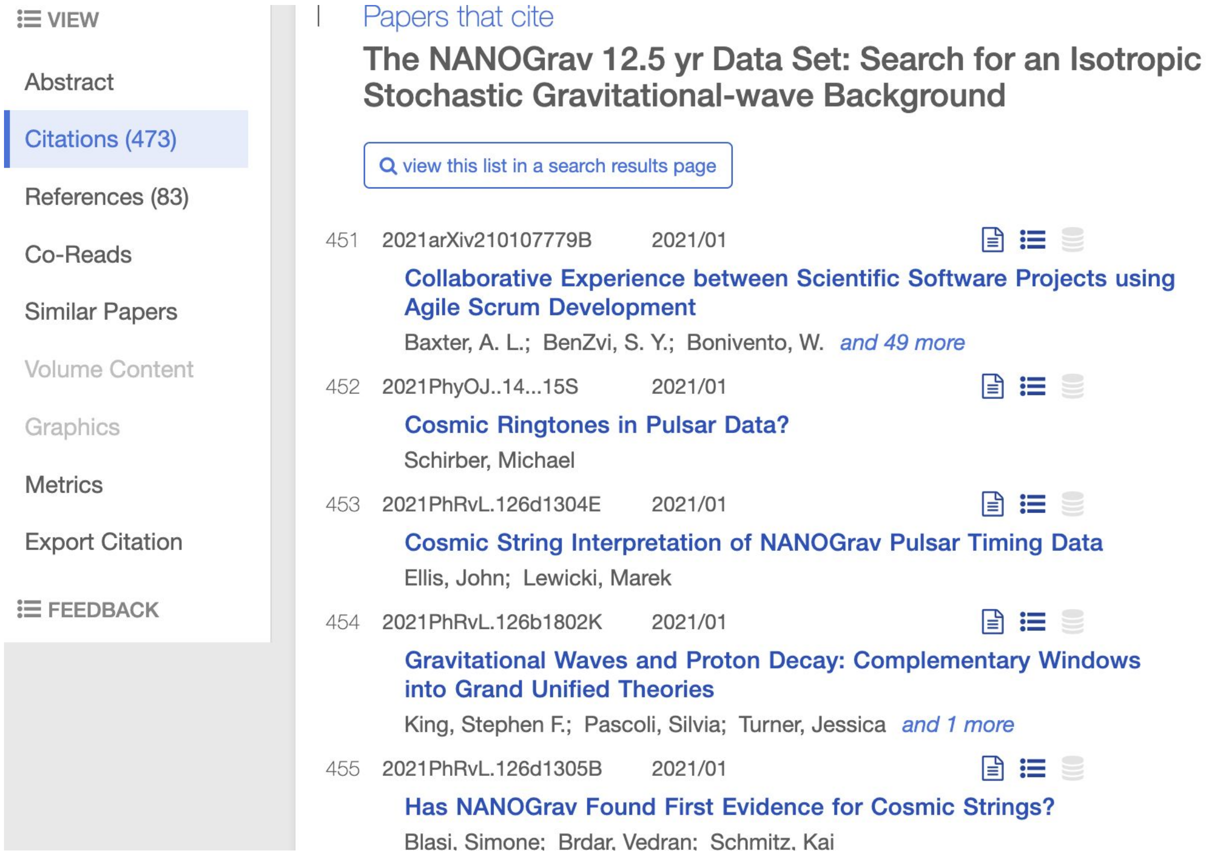
Common-red-signal analysis with 24-yr high-precision timing of the European Pulsar Timing Array: Inferences in the stochastic gravitational-wave background search

S. Chen, R. N. Caballero, Y. J. Guo, A. Chalumeau, K.Liu, G. Shaifullah, K. J. Lee, S. Babak, G. Desvignes, A. Parthasarathy, H. Hu, E. van der Wateren, J. Antoniadis, A.-S. Bak Nielsen, C. G. Bassa, A. Berthereau, M. Burgay, D. J. Champion, I. Cognard, M. Falxa, R. D. Ferdman, P. C. C. Freire, J. R. Gair, E. Graikou, L. Guillemot, J. Jang, G. H. Janssen, R. Karuppusamy, M. J. Keith, M. Kramer, X. J. Liu, A. G. Lyne, R. A. Main, J. W. McKee, M. B. Mickaliger, B. B. P. Perera, D. Perrodin, A. Petiteau, N. K. Porayko, A. Possenti, A. Samajdar, S. A. Sanidas, A. Sesana, L. Speri, B. W. Stappers, G. Theureau, C. Tiburzi, A. Vecchio, J. P. W. Verbiest, J. Wang, L. Wang, H. Xu

We present results from the search for a stochastic gravitational-wave background (GWB) as predicted by the theory of General Relativity using six radio millisecond pulsars from the Data Release 2 (DR2) of the European Pulsar Timing Array (EPTA) covering a timespan up to 24 years. A GWB manifests itself as a long-term low-frequency stochastic signal common to all pulsars, a common red signal (CRS), with the characteristic Hellings-Downs (HD) spatial correlation. Our analysis is performed with two independent pipelines, \eprise{} and \tn{}+\ftwo{}, which produce

PTAs are expected to detect a diffuse (& persistent) GW background from merging SMBH binaries in our Universe very soon!!!

Upcoming IPTA results will have important implications for Theoretical Physics & Astrophysics



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Schirber, Michael

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Ellis, John; Lewicki, Marek

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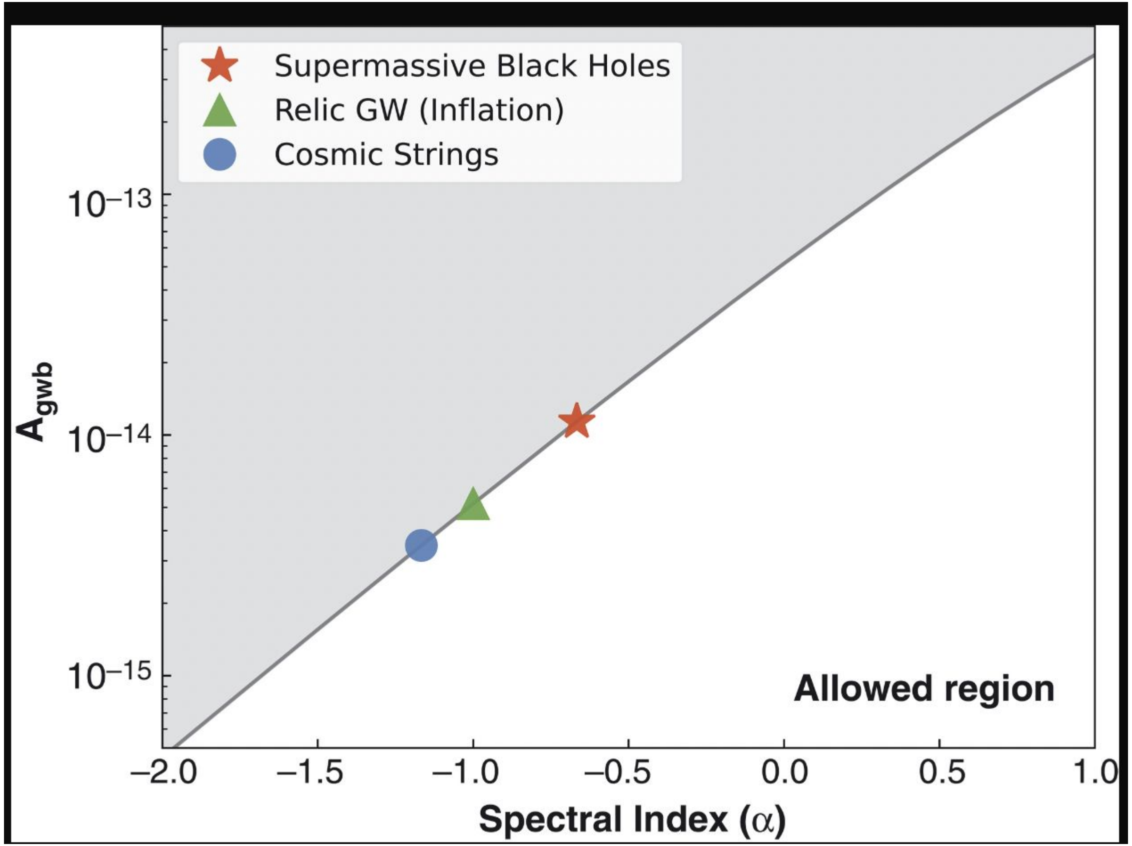
Gravitational Waves and Proton Decay: Complementary Windows into Grand Unified Theories
King, Stephen F.; Pascoli, Silvia; Turner, Jessica *and 1 more*

455 2021PhRvL.126d1305B 2021/01
Has NANOGrav Found First Evidence for Cosmic Strings?
Blasi, Simone; Brdar, Vedran; Schmitz, Kai

SKA era PTA can make fundamental contributions



Fermi-LAT; Science, Vol 376, Issue 6592 (2022)

A brief introduction to PTAs

InPTA
Indian Pulsar Timing Array

Unique strength of uGMRT:

- High sensitivity at low frequencies.
- Ideal for studying frequency dependent effects dominant at low frequencies.

- The InPTA experiment started in 2015.
- Presently observing 17 IPTA pulsars.
- Cadence: 10-14 days
- Plans to extension to more pulsars in future.

InPTA first data release: InPTA DR1

- J0613-0200
- J1012+5307
- J1600-3053
- J1713+0747
- J1857+0943
- J1939+2134
- J2145-0750
- J0437-4715
- J0751+1807
- J1022+1001
- J1643-1224
- J1744-1134
- J1909-3744
- J2124-3358

Band 3 (300-500 MHz) +
Band 5 (1260-1460 MHz)
Bandwidth = 200MHz

InPTA DR1 team:
- **22 members**
- **Various working sub-groups**

Two traditional techniques:
- **Narrowband**
- **Wideband**

- **AIM:**
  - Dispersion measure (DM)
  - Time Of Arrival (TOA) of pulse
  - Timing residual=(observed TOA - expected TOA)

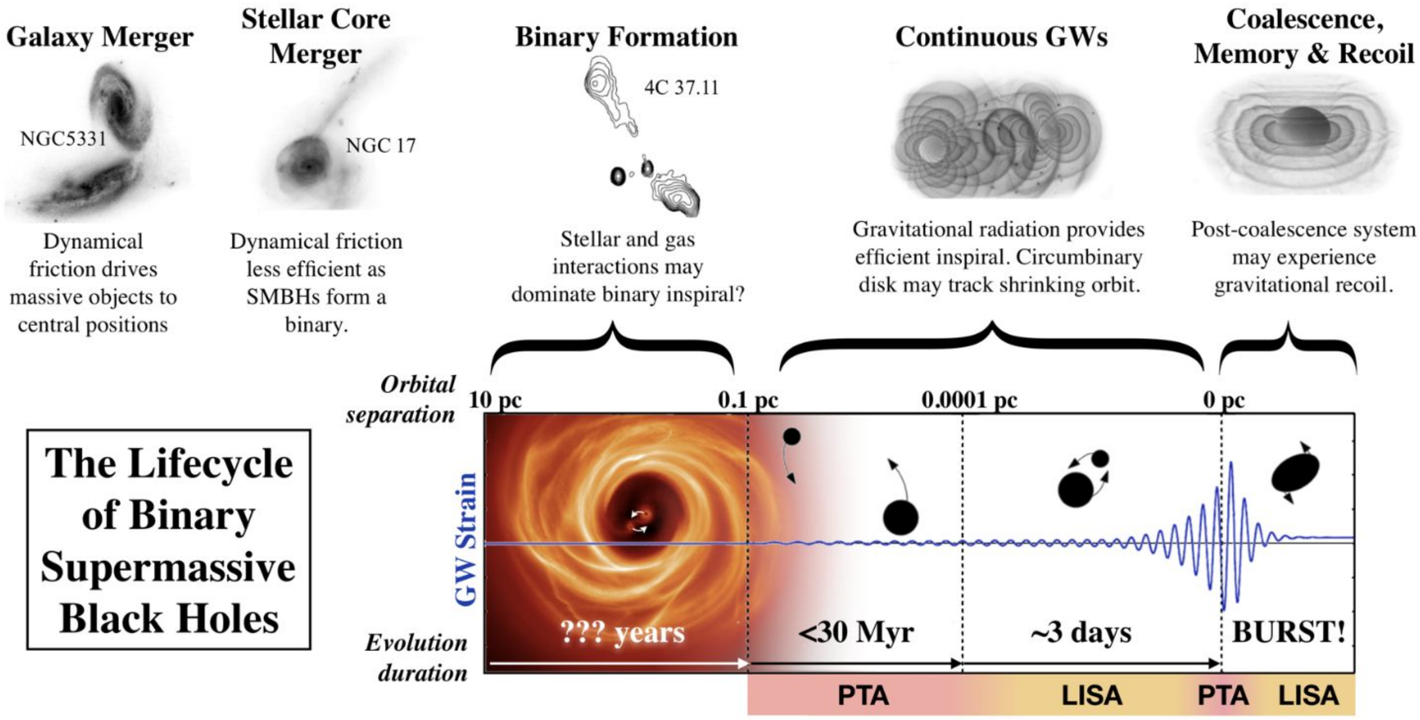
Tarafdar, Nobelson, Rana+,
(arXiv:2206.0928)

InPTA DR1 - Summary

- InPTA 3.5+ years data from uGMRT of 14 pulsars is being shared to assemble for IPTA DR3
- Ongoing: Narrowband and Wideband DM and residuals comparison.
- Ongoing: We are working on checking the radio frequency dependence of DMs.
- DMs are estimated with precision of 10^{-4} to 10^{-6} pc-cm^{-3}
- TOAs are obtained with sub-μs precision.

Tarafdar, Nobelson, Rana+,
(arXiv:2206.0928)

PTA + ngEHT/KVN + SMBH Binary -> Persistent MM GW Astronomy



I hope IBS colleagues will join IPTA DR3 efforts (via InPTA) (Chan +)

Burke-Spolaor, Sarah, et al (2019)

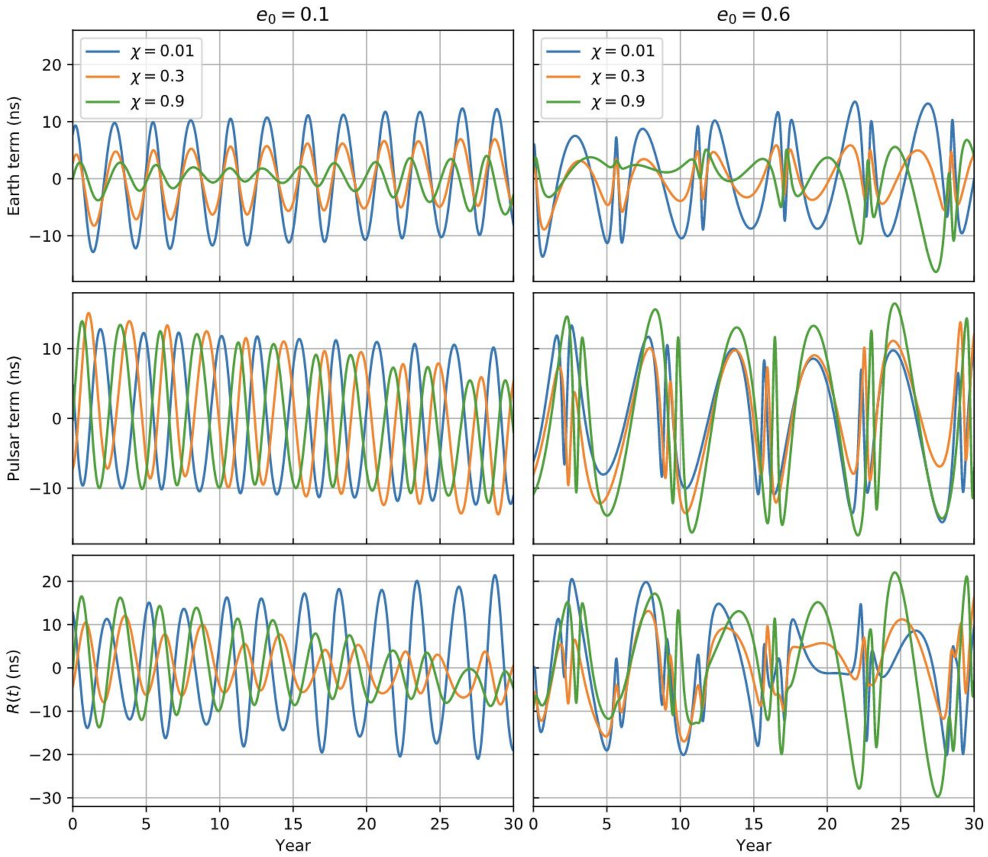
Expected PTA observables from sources like OJ 287

We are modeling the expected PTA response from spinning MBH binaries inspiraling along relativistic eccentric orbits

i) A.Susobhanan+
arXiv:2002.03285

ii) L.Dey, A. Susobhanan, + (2023)

Crucial Post-Newtonian accurate BH binary dynamics constructs should be useful for KVN observations



Team Eccentric

Hopes to contribute towards persistent multi-messenger nano-Hertz GW Astronomy during the SKA-era PTA

Hopes to help to observe GWs from compact binaries in non-circular orbits

Thank you very much for the privilege of your time

tifr

InPTA
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