Title: Nano-Hz Gravitational Wave Astronomy: Its implications and promises

Speakers: Achamveedu Gopakumar

Collection/Series: Strong Gravity

Subject: Strong Gravity

Date: October 24, 2024 - 1:00 PM

URL: https://pirsa.org/24100134

Abstract:

Maturing Pulsar Timing Arrays are expected to inaugurate the era of nano-hertz GW astronomy in the coming days under the auspices of the International Pulsar Timing Array. Implications of ongoing IPTA efforts for astrophysics and cosmology will be discussed while focussing on PTA contributions. Ongoing IPTA efforts should lead to persistent multi-messenger GW astronomy with massive BH binaries especially during the Square Kilometre Array era, and its implications will be discussed.

Pulsar Timing Array Efforts and Their Implications

A. Gopakumar

Perimeter Institute, 10/24/2024

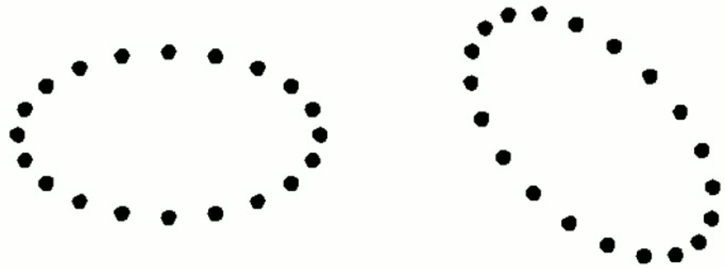
Outline

- Era of Multi-Frequency Band (transient/persistent) GW Astronomy (?): Why this should be exciting from astrophysical, cosmological & theoretical physics perspectives?

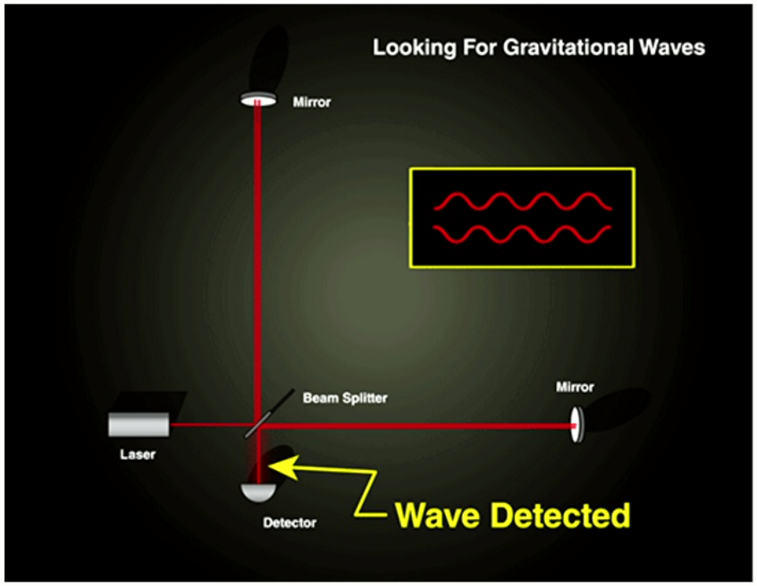
- International Pulsar Timing Array Efforts
  Its implications

  - Promise of Persistent Multi-Messenger nHz GW Astronomy with sources at cosmological distances during the Square Kilometre Array Era!!!

Gravitational Waves: Dark Messengers!

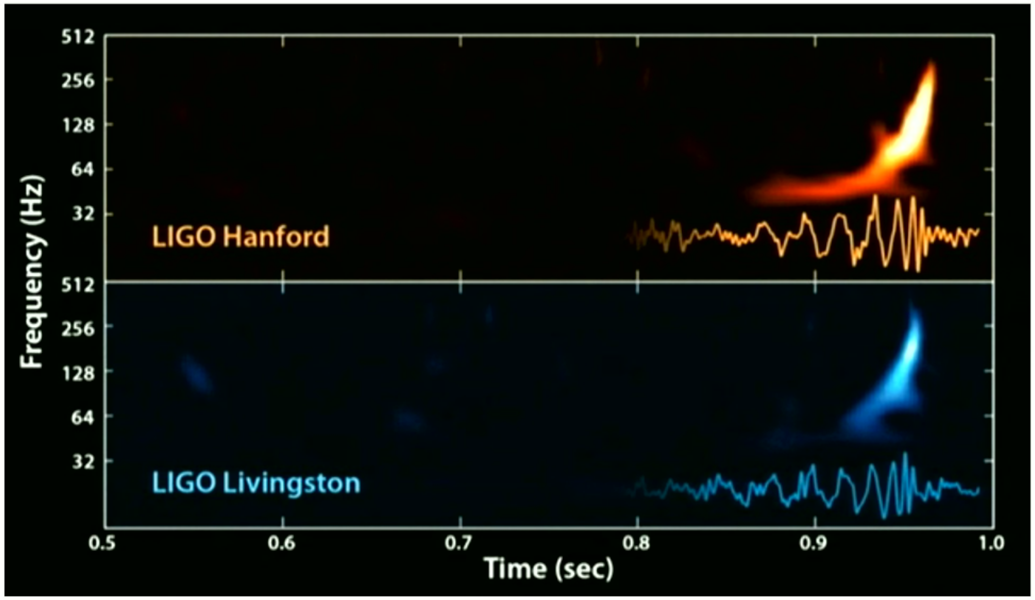


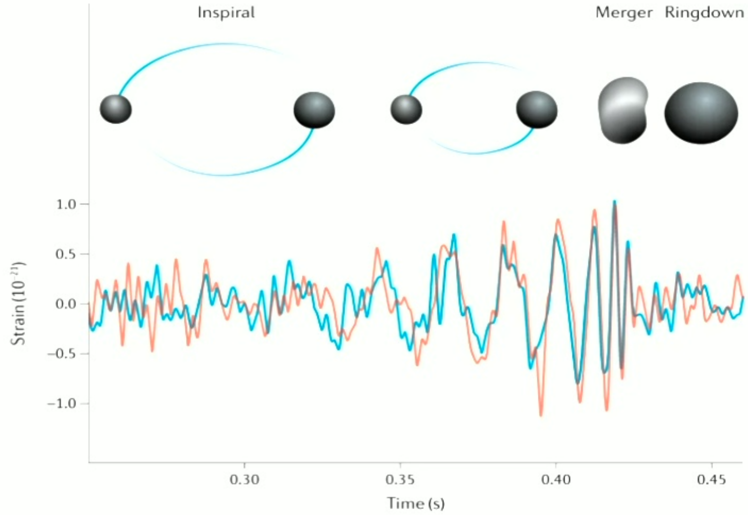
- *GWs are tidal interactions that propagate with the speed of light*



- *GWs cause changes in the travel time of light between two free particles*

Era of hecto-hertz GW Astronomy: LVK's GW150914 (arXiv:1602.03838)





$$h_{\rm eff} \simeq 10^{-21}\left(\frac{\nu}{0.25}\right)\left(\frac{M}{20M_\odot}\right)\left(\frac{r}{200\ {\rm Mpc}}\right)^{-1}.$$

$$\dot{f} = \frac{96}{5}\pi^{5/8}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}$$

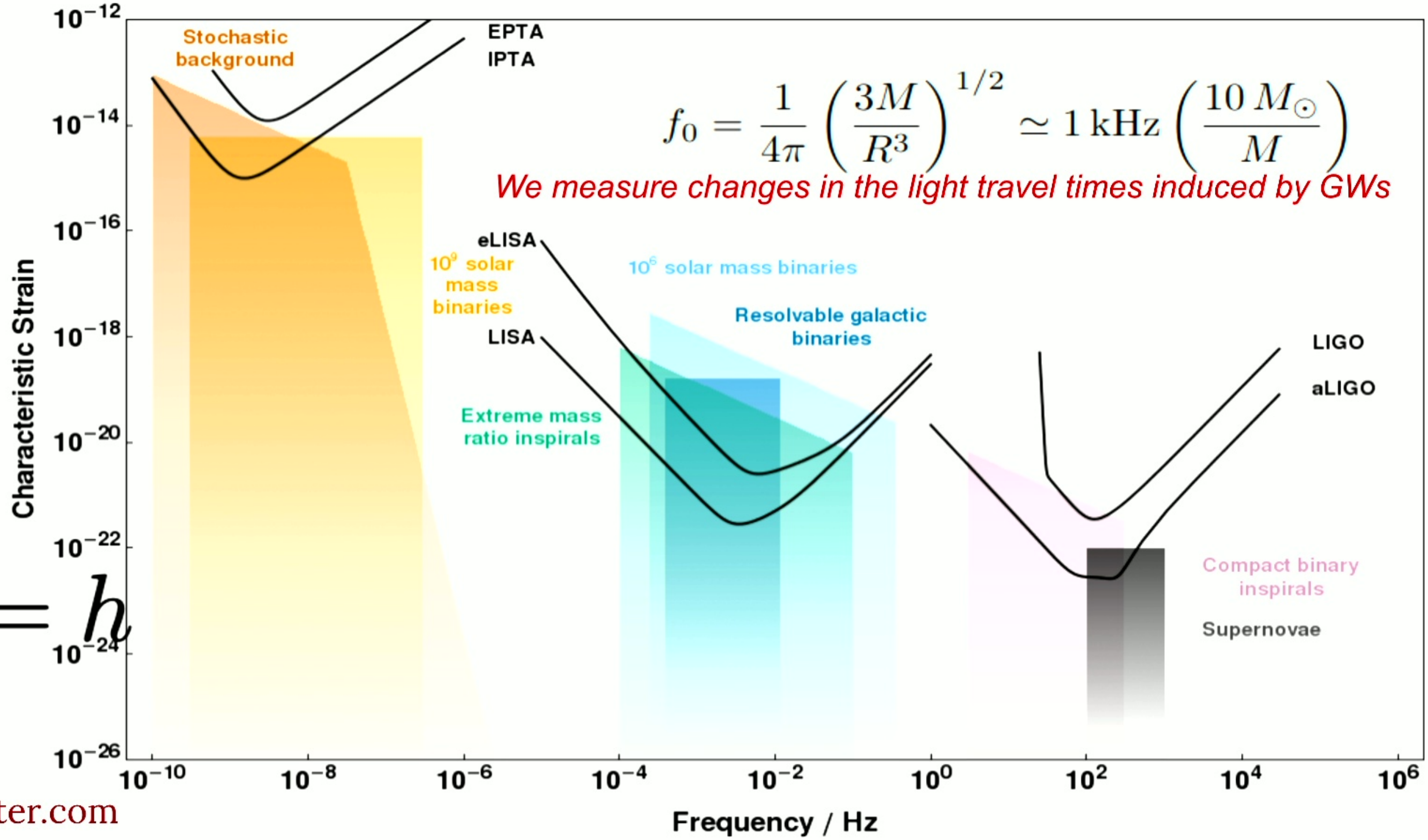
- Merger of ~30 & 35 Solar Mass BHs at ~ 400 Mpc

→ A new branch of Astronomy

Nano to hecto-Hz GW Astronomy by 2050!!!

h = ΔL/L
GW strain

$$\delta T/T = h$$



http://gwplotter.com

A Lunar GW Observatory may not be a pipedream

Lunar-GW in Senate & House Appropriations Bills

Inbox ×

Jani, Karan <karan.jani@vanderbilt.edu>
to Lunar

Sat, Jul 27, 7:30 AM

Dear LILA Community and GW colleagues,

I am delighted to share the news that our lunar-GW project, the Laser Interferometer Lunar Antenna (LILA), has been recommended for a feasibility study in both the Senate and House Appropriations Bills for FY2025. Below is the exact text from the bills:

Senate report:
"Lunar-based Astronomy.—The Committee encourages NASA to assess of the feasibility of a U.S. led lunar-based gravitational wave observatory. The assessment should investigate laser interferometry on the Moon to broaden the spectrum of gravitational waves, which could open a new frontier of multi-band, multi-messenger astronomy."

House report:
"Lunar-Based Gravitational Wave Astronomy.—Within the amount for Astrophysics, the recommendation includes $1,000,000 for a study on the feasibility of a U.S.-led lunar-based gravitational wave observatory, focused on investigating laser interferometry on the Moon to broaden the spectrum of gravitational waves. The Committee acknowledges

A Lunar GW Observatory may not be a pipedream

Lunar-GW in Senate & House Appropriations Bills Inbox ×

Jani, Karan <karan.jani@vanderbilt.edu> Sat, Jul 27, 7:30 AM

to Lunar

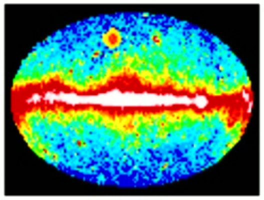
Gravitational-Wave Lunar Observatory for Cosmology

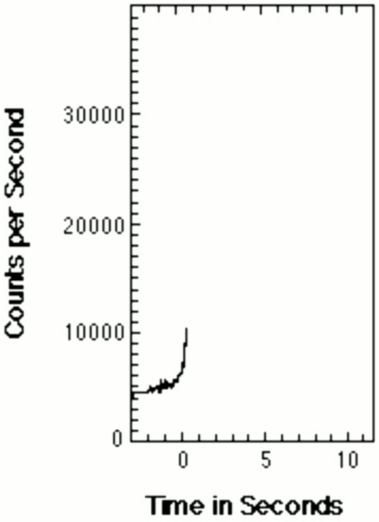
Karan Jani, Abraham Loeb

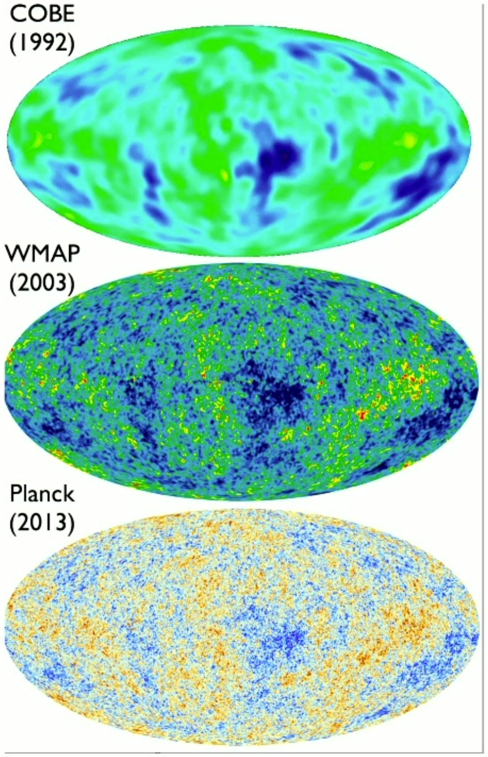
Several large-scale experimental facilities and space-missions are being suggested to probe the universe across the gravitational-wave (GW) spectrum. Here we propose Gravitational-wave Lunar Observatory for Cosmology (GLOC) - the first concept design in the NASA Artemis era for a GW observatory on the Moon. Using feasible interferometer technologies, we find that a lunar-based observatory is ideal for probing GW frequencies in the range between deci-Hz to 5 Hz, an astrophysically rich regime that is very challenging for both Earth- and space-based detectors. GLOC can survey binaries with neutron stars, stellar and intermediate-mass black holes to $\gtrsim 70\%$ of the observable volume of our universe without significant background contamination. The sensitivity at □(1 Hz) allows a unique window into calibrating Type Ia supernovae. At its ultimate sensitivity limits, GLOC would trace the Hubble expansion rate up to redshift $z \sim 3$ and test General Relativity and ΛCDM cosmology up to $z \sim 350$.

Remarkable developments

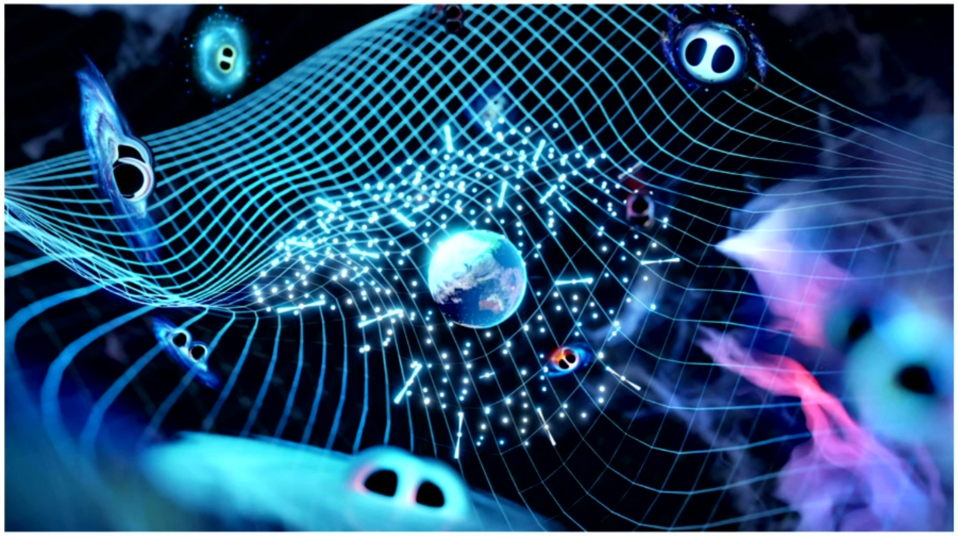
Transient & persistent GW Astronomy !!







Maturing Pulsar Timing Array Efforts are key to such a scenario



Pulsar Timing Array (PTA): How does it work?

- Observe a bunch of MSPs at different locations in the sky using the ***best radio telescopes*** of our times

- Residuals due to GWs are **correlated** with **quadrupolar** nature
  PTR -> *differences between the predicted and the measured TOAs*

- Search for the correlated timing residual for detecting nHz GWs

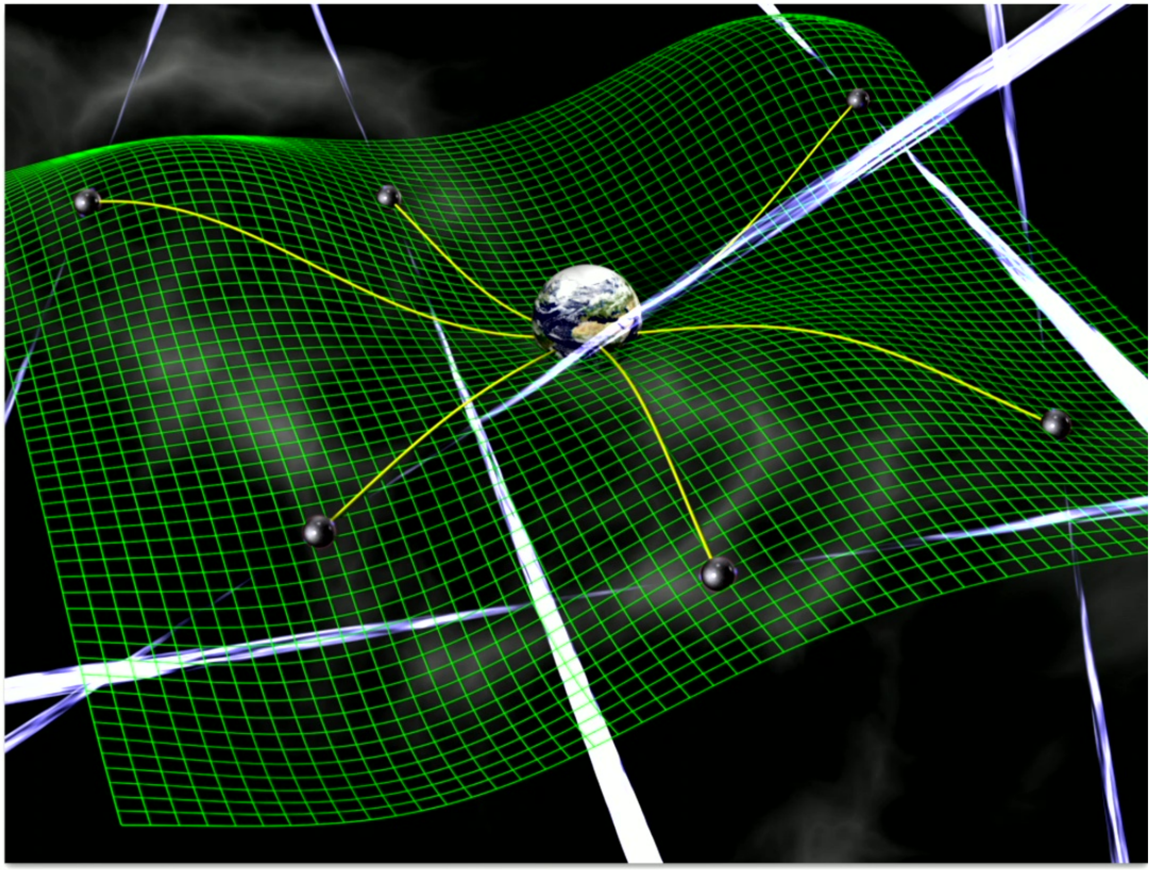
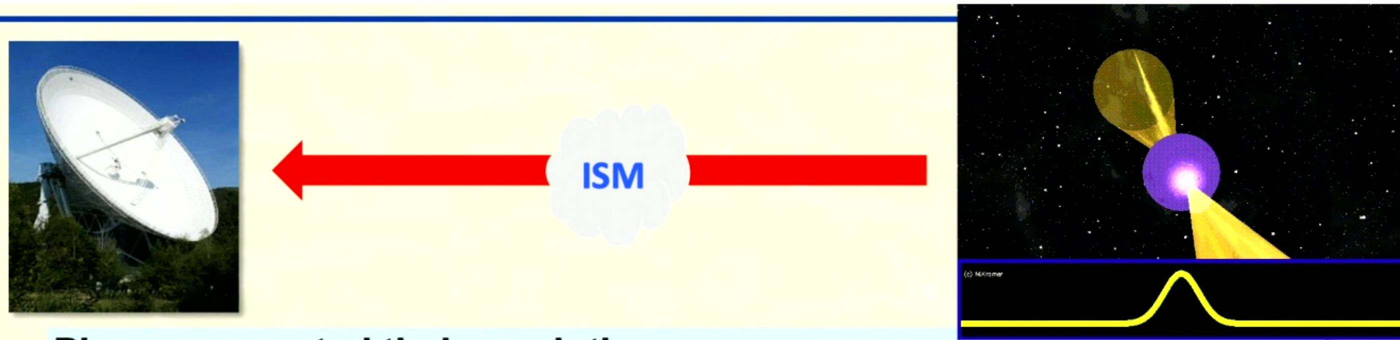
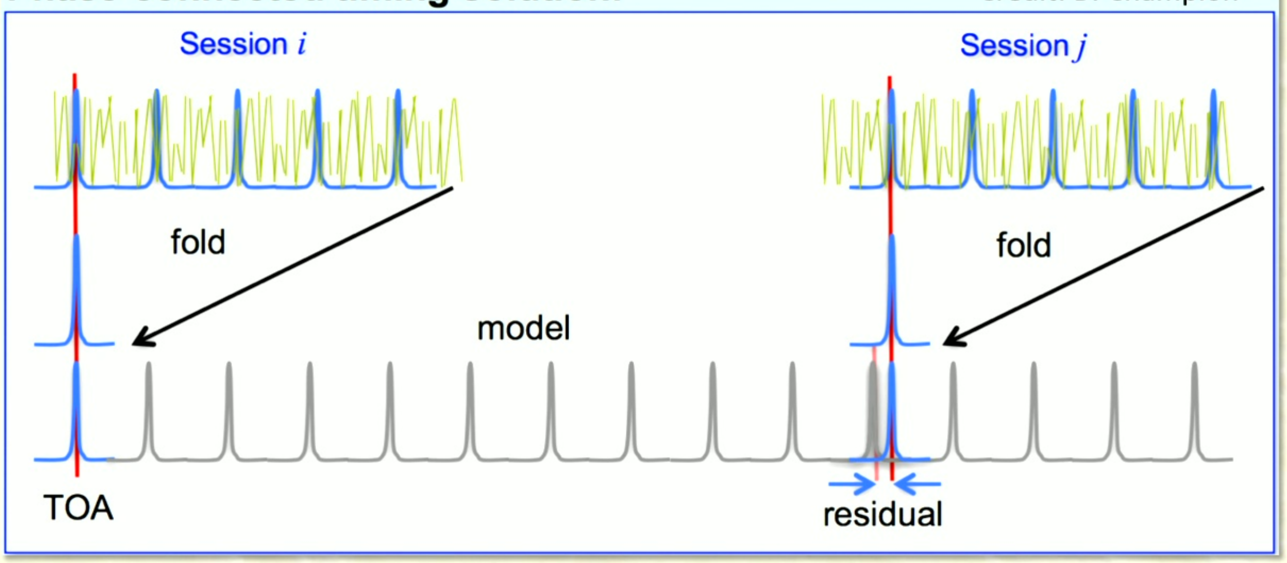


Image Source: Internet



Phase-connected timing solution:

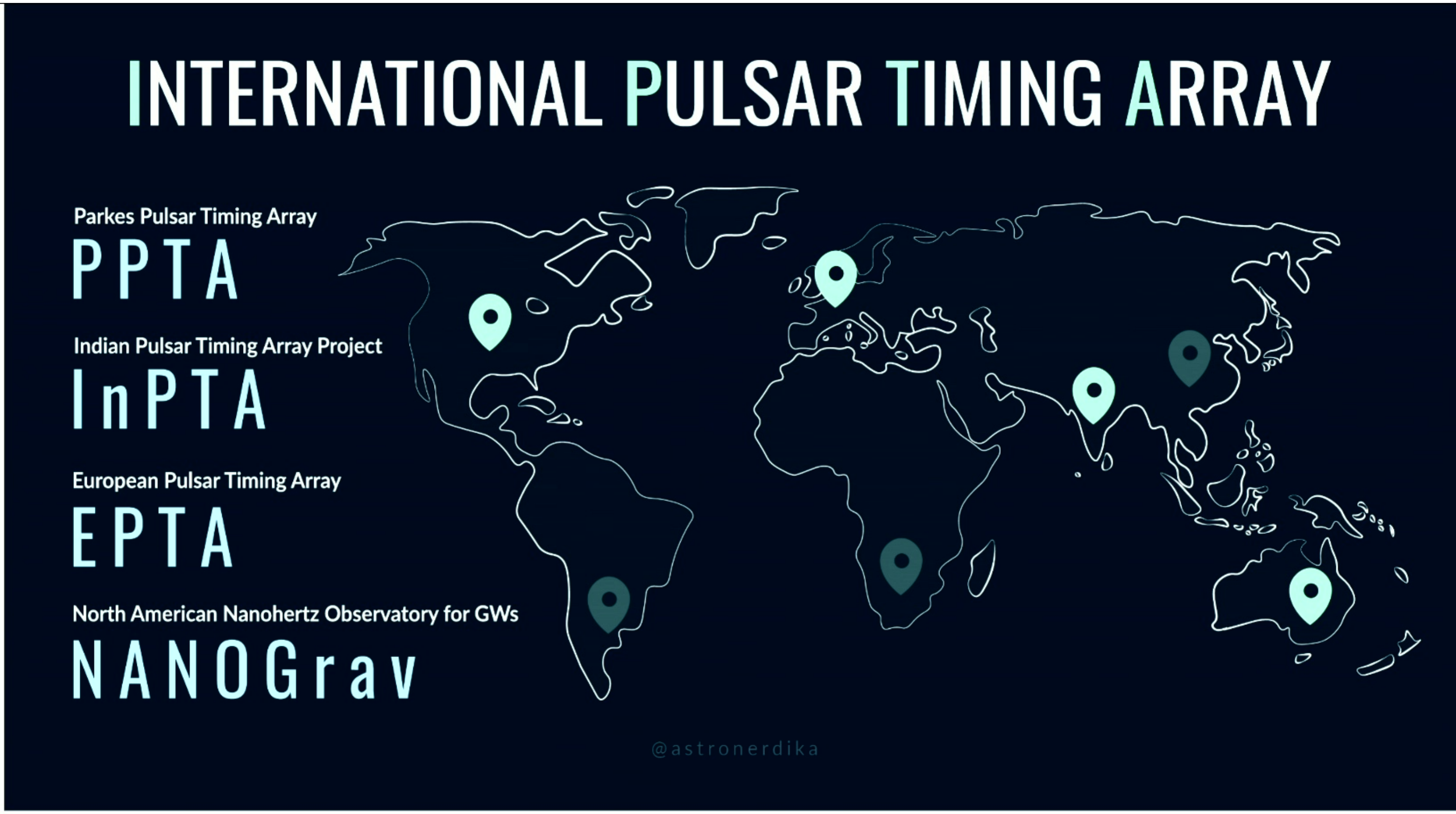
Credit: D. Champion



PSR J1012+5307: P= 0.0052557490101970103(19) **s** (Desvignes et al. 2016);

<- By counting all pulses (3×10^{13} rotations!!) in **20 years**!!

Pulsar Timing Residuals are PTA observables!!



Our astrophysical nano-Hz GW sources are SMBH binaries & we create a Galaxy-based GW observatory

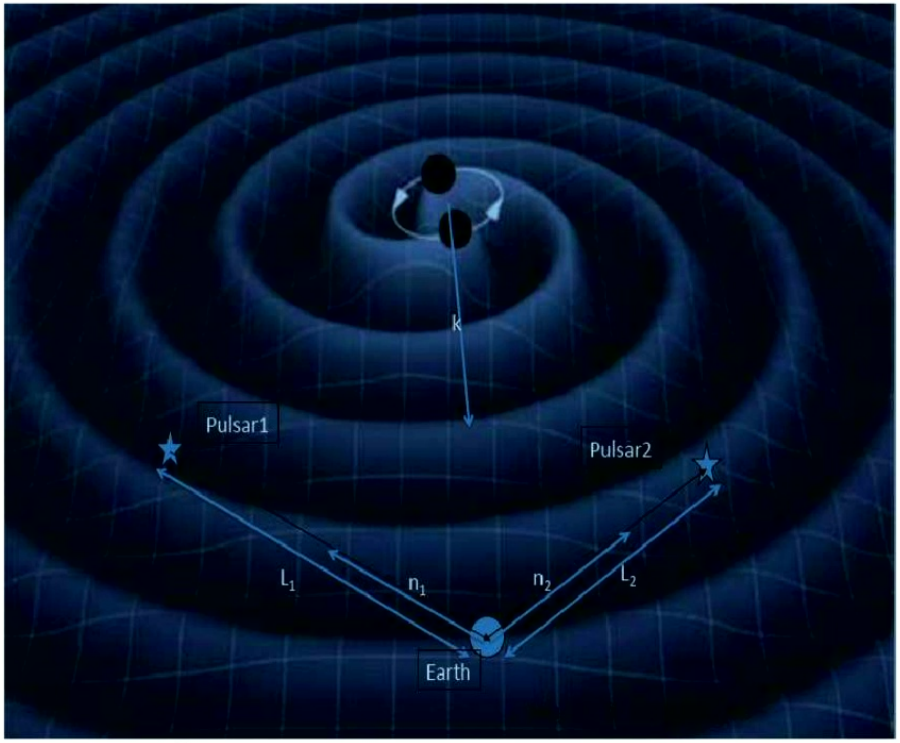
Pulsar Timing Arrays for nano-hertz GW Astronomy

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

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

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

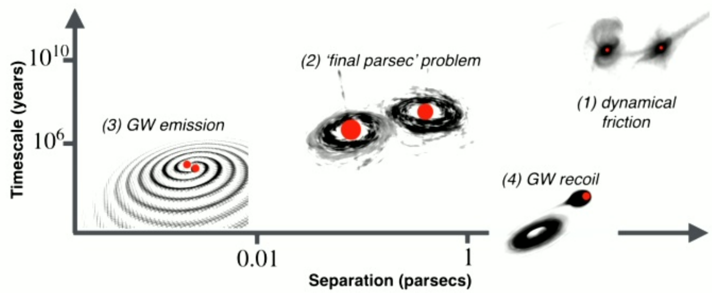
Detweiler, S. (1979)

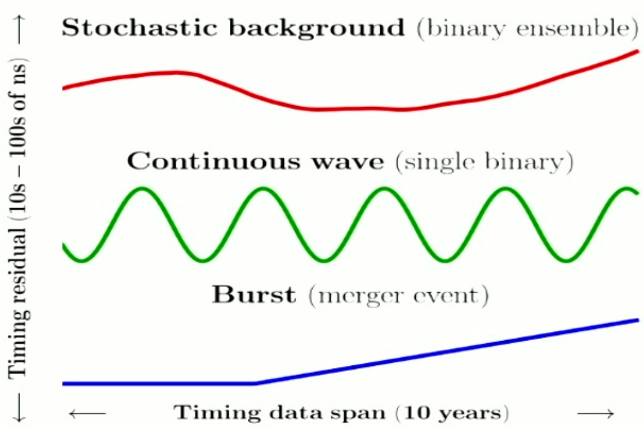


$$\delta T / T = h$$

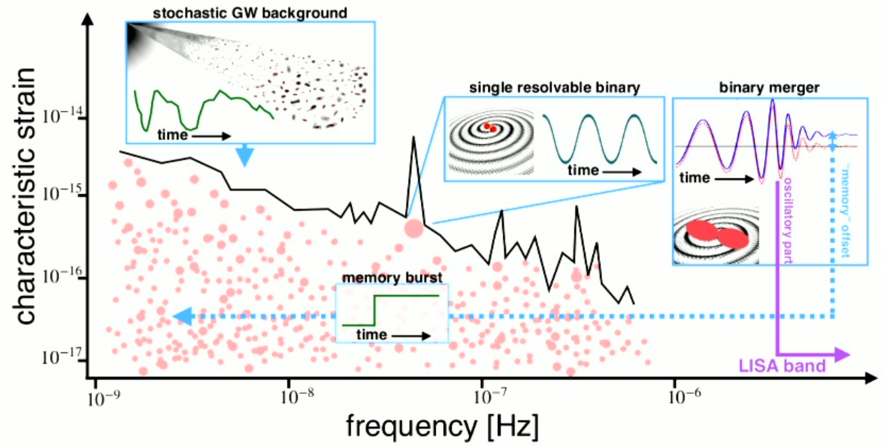
Courtesy: Web

Maturing IPTA efforts should lead many persistent nHz events at cosmological distances





[arXiv:1903.08183;](https://arxiv.org/abs/1903.08183)
Taylor+



Stochastic GWB from massive BH binaries ?: I

Cosmological population of MBH binaries is expected to provide a diffusive GW background for PTAs !!
We need to compute # of sources in a frequency interval $\Delta f = 1/T_{\rm obs}$

- $$\Delta N = \left(\frac{dN}{df}\right)\Delta f \;\; = \frac{dN}{dt}\left(\frac{df}{dt}\right)^{-1}\Delta f \qquad (1)$$
- $$\Delta N \propto \frac{dN}{dt}\left(\mathcal{M}_c{}^{-5/3}\, f_{\rm GW}^{-11/3}\right)\Delta f \qquad (2)$$
- There are some 10^{11} galaxies in our Universe and each galaxy is likely to experience one merger with another galaxy in Hubble time (10^{10} year)
- $\rightarrow \frac{dN}{dt} \sim 10$ mergers/year

Galaxy mergers can lead to merger of their constituent BHs

(White & Rees, 78, Begelman,Blandford & Rees, 80)

- $\rightarrow$ a rough estimate for the number of binary BH sources in a frequency interval $\Delta f = 1/T_{\rm obs}$

- $$\Delta N \sim 3 \times 10^{12} \left(\frac{\mathcal{M}}{10^9\, M_\odot}\right)^{-5/3} \left(\frac{f_{\rm GW}}{10^{-8}\, Hz}\right)^{-11/3} \left(\frac{T_{\rm obs}}{10\, yr}\right)^{-1} \times \left(\frac{dN/dt}{10 {\rm merger/yr}}\right)$$

- This is clearly $>> 1$

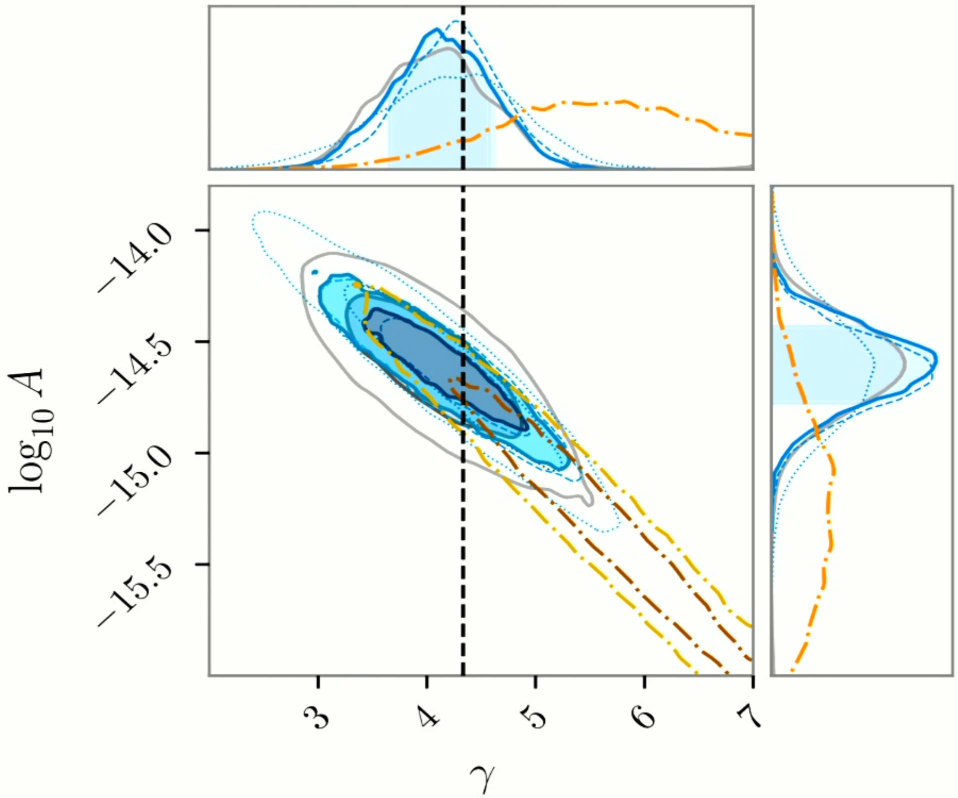
  This ensures a diffuse GW background in the PTA GW frequency window from merging massive BHs in the universe

Till recently, PTAs were inferring evidences for a common-red process in their R(t)

- This SGWB manifests as a slow drift in the pulse TOAs from their MSPs
- One underlying distribution for delays and advances across pulsars
- Stochastic GWB due to SMBH binaries is expected to produce a similar observational feature

$$P(f|A,\gamma) = \Gamma(\zeta_{ab})\frac{A^2}{12\pi^2}\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-\gamma};$$

$$\gamma = 3 - 2\alpha \Rightarrow \gamma = 13/3$$



[Goncharov, et al. (2021)]
(From PPTA DR2) ; IPTA DR2 17

Convert CRN → SGWB with GR Inputs

- The cross-correlation of GW induced rotaional frequency variations between 2 Pulsars leads to

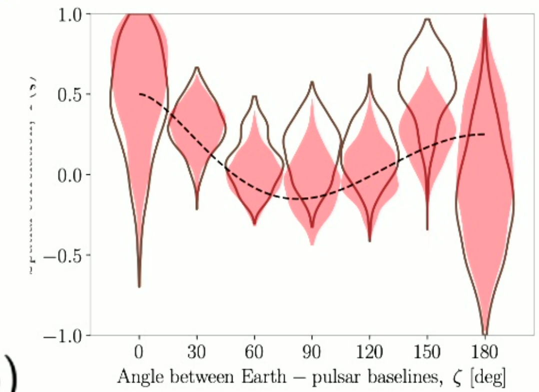
$$c_{ij}(\tau) = \alpha_{ij} < h^2 > + \delta c_{ij} \,, \qquad (4)$$

⇦ Cross correlation enhances the signal strength

where δc_{ij} is an estimation error due to 'finite' T and due to 'finite' # of SMBH binaries in SGWB!!

- The average of the angular factors

$$\alpha_{ij} = \frac{1-\cos\theta_{ij}}{2}\ln\left(\frac{1-\cos\theta_{ij}}{2}\right) - \frac{1}{6}\,\frac{1-\cos\theta_{ij}}{2} + \frac{1}{3} \qquad (5)$$



⇦ Helling-Downs Correlation

where θ_{ij} gives the angle between two pulsars.

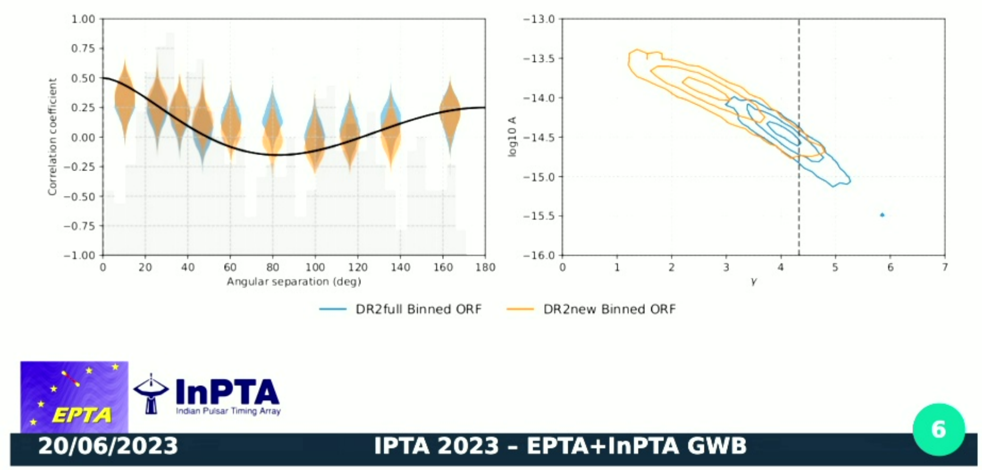
Earlier PTA results didn't find any evidence for such a correlation

We (InPTA) combined our resources with EPTA for the 3P+ efforts

To clarify the nature of the observed CRN

(NANOGrav, EPTA+InPTA, PPTA) + *CPTA*

Fixed SSE DE440



arXiv:2306.16214 (A&A 2023)

Bayes factor of 60 & a false alarm probability of ~ 0.1%

DR2full and DR2Bew find a variation in DM consistent with Kolmogorov, though preferring a flatter γ_{DM}.

PSR J2322+2057 – Does not show evidence of time-correlated noise in any EPTA dataset.

4.2. Changes in noise models after the inclusion of the InPTA data

Here we study the impact of including low radio frequency observations from the InPTA on the estimated noise models. The InPTA dataset complements the EPTA data with simultaneous observations at 300-500 MHz and at 1260-1460 MHz between MJDs 58235 and 59496 observed with the upgraded Giant Metrewave Radio Telescope (uGMRT). The frequency coverage at 300-500 MHz is particularly important since EPTA has a limited number of observations at this frequency band. Therefore, the inclusion of the InPTA data is of particular interest in constraining noise due to the IISM such as DM and scattering variations. To allow a quantitative comparison of the posterior noise models before and after the inclusion of InPTA data, we adapt and

which incorporates the posterior mass above the iso-contour of no shift. We then convert the above Δ into an effective number of σ using the standard normal distribution. Detailed comparisons that arise from the posteriors of DR2full and DR2full+ are available in the following URL[7]. In Table 6, we report the estimated tension (in σ) for the red and DM noise models while dealing with DR2full and DR2full+ datasets. It shows that the 2D posterior distributions of the RN and DM parameters are consistent ($\Delta < 1\sigma$) for all parameters, except for the power law DM variations of the PSRs J0613−0200, J1600−3053, J1744−1134 and J1909−3744. In the following, we discuss possible explanations for these pulsars.

4.2.1. PSR J0613−0200

For this pulsar, combining InPTA with the EPTA data yields a lower spectral index and higher amplitude at f_{yr} for the chromatic noise. We observe an interesting sharp jump in the last

[6] https://github.com/mraveri/tensiometer

[7] https://github.com/subhajitphy/Posterior_comparisons

https://arxiv.org/abs/2306.16225

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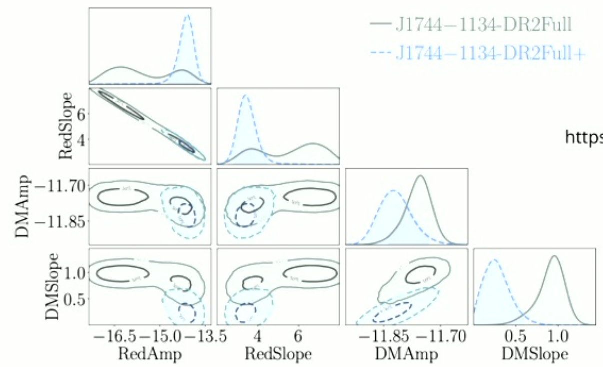
tions for these pulsars.



https://arxiv.org/abs/2306.16225

Fig. 5. Red and DM noise models for PSR J1744−1134 using DR2full and DR2full+ datasets. The inclusion of InPTA data allows a better constraint on the achromatic noise.

4.2.1. PSR J0613−0200

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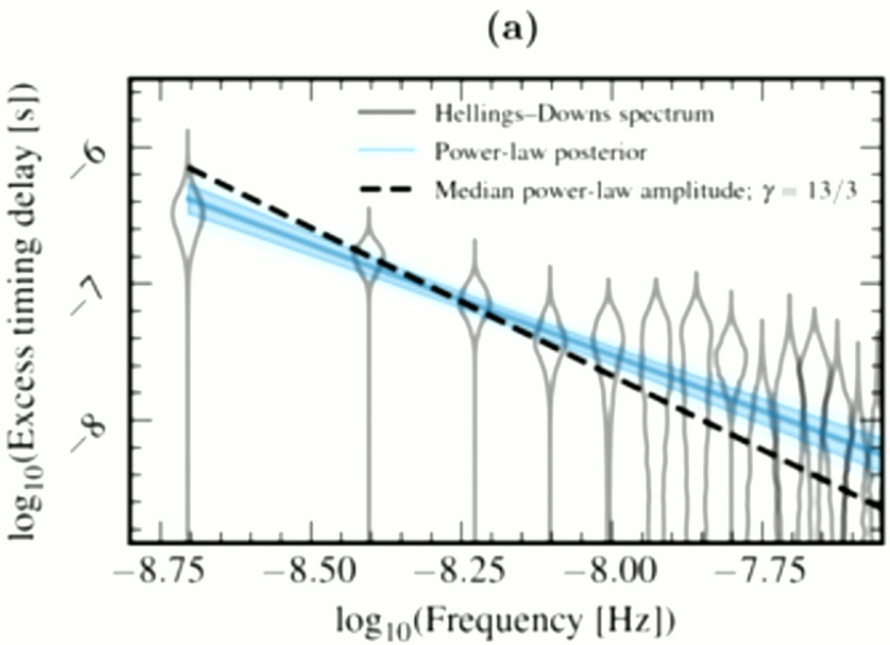

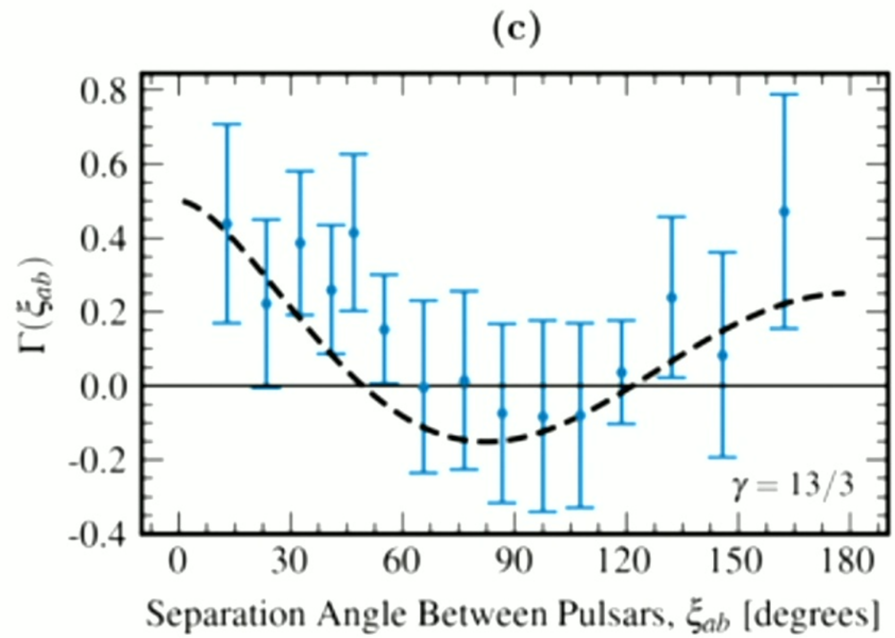

(b)

$$\delta T/T = h$$

OPEN ACCESS

The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background

Gabriella Agazie[1], Akash Anumarlapudi[1], Anne M. Archibald[2], Zaven Arzoumanian[3], Paul T. Baker[4], Bence Bécsy[5], Laura Blecha[6], Adam Brazier[7,8], Paul R. Brook[9], Sarah Burke-Spolaor[10,11] + Show full author list

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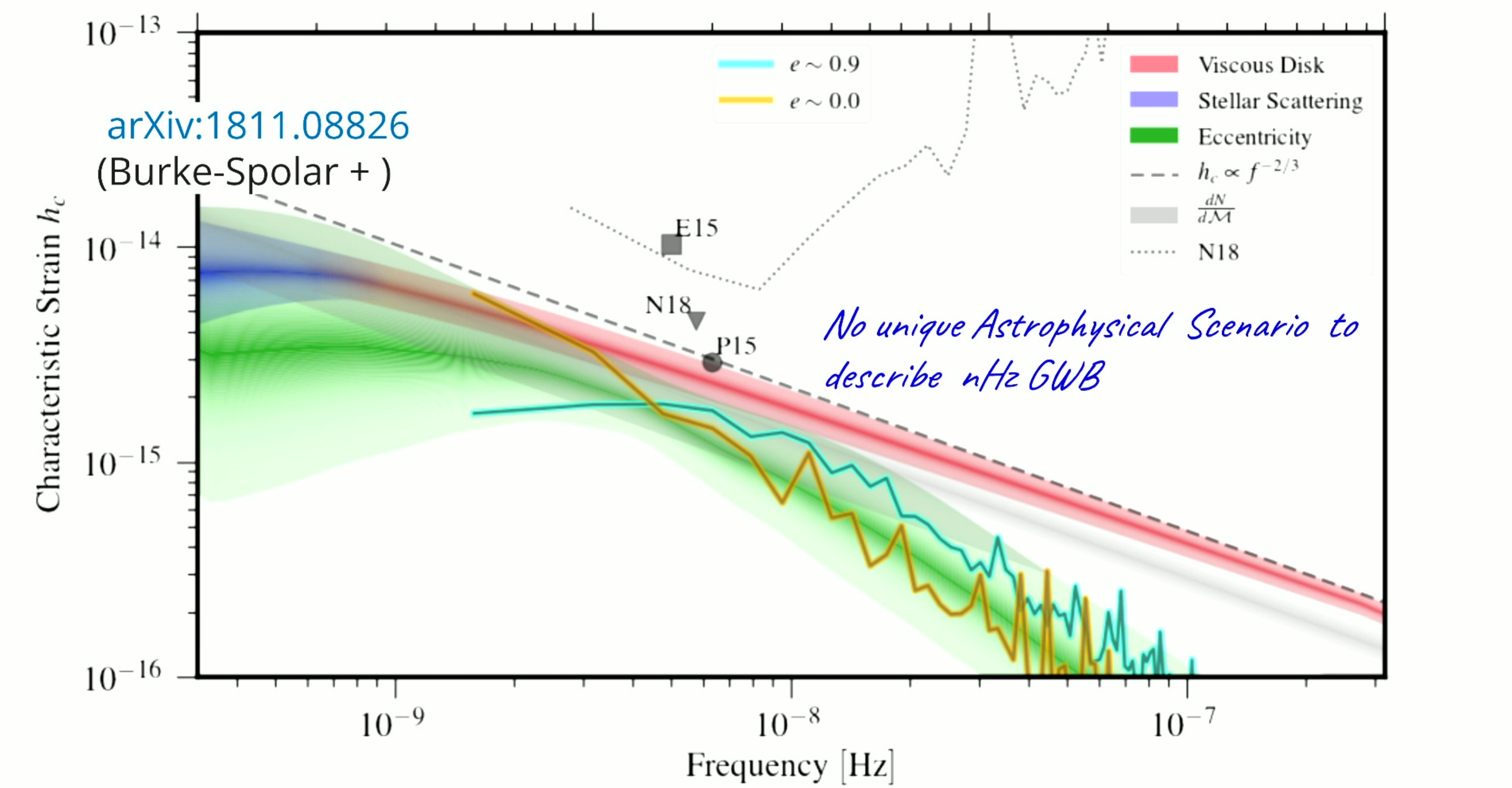
The Astrophysical Journal Letters, Volume 951, Number 1
Focus on NANOGrav's 15 yr Data Set and the Gravitational Wave Background
Citation Gabriella Agazie *et al* 2023 *ApJL* **951** L8
DOI 10.3847/2041-8213/acdac6

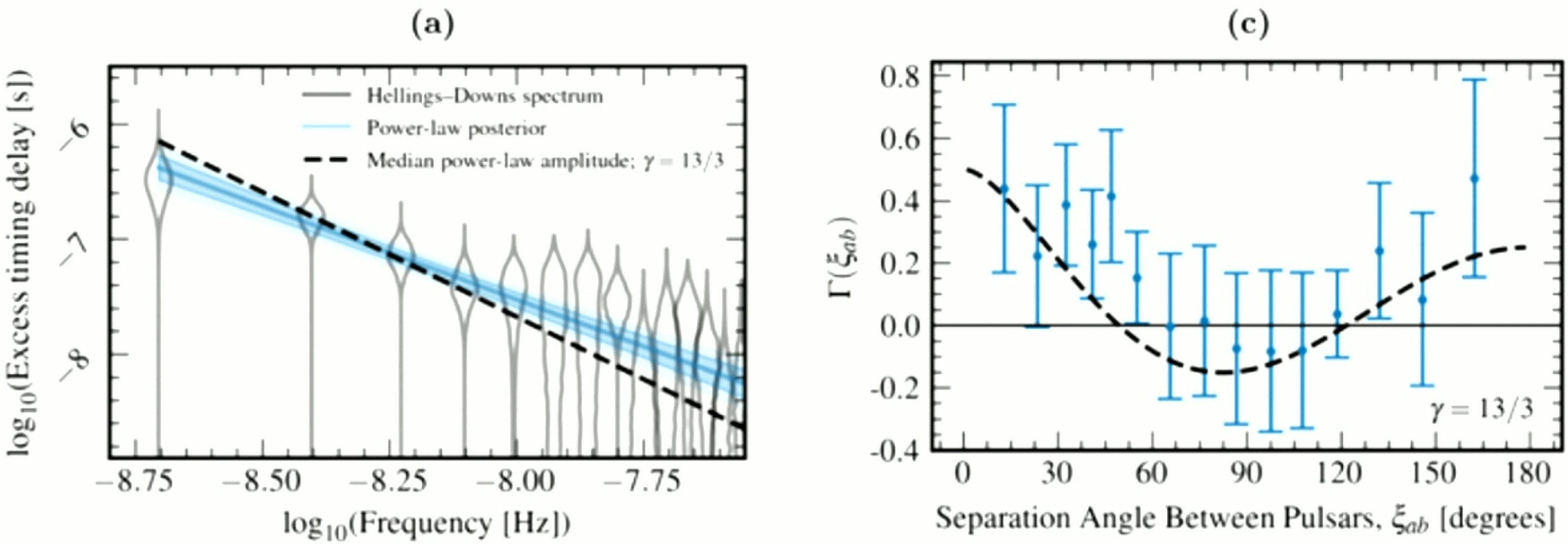
$h_c(f)$ derivation : II

- $\mathcal{E}_{gw} = \int_0^\infty \int_0^\infty N(z) \frac{1}{1+z} f_r \frac{dE_{gw}}{df_r} \, dz \, \frac{df}{f}$
- We have already argued that
  $\mathcal{E}_{gw} \equiv \int_0^\infty \rho_c c^2 \Omega_{gw}(f) \, df / f$........(1)
- Equating the above two equations $\rightarrow$

$$\rho_c c^2 \Omega_{gw}(f) = \int_0^\infty N(z) \frac{1}{1+z} \left(f_r \frac{dE_{gw}}{df_r} \right) \Bigg|_{f_r = f(1+z)} dz \, .$$

- The energy density in GWs per log frequency interval is equal to the comoving number density of event remnants, times the (redshifted) energy each event produced per log frequency interval.


arXiv:1811.08826
(Burke-Spolar +)
No unique Astrophysical Scenario to describe nHz GWB
Characteristic Strain h_c
Frequency [Hz]
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-9}
10^{-8}
10^{-7}
$e \sim 0.9$
$e \sim 0.0$
Viscous Disk
Stellar Scattering
Eccentricity
$h_c \propto f^{-2/3}$
$\frac{dN}{d\mathcal{M}}$
N18
E15
N18
P15



$$\delta T/T = h$$

How do we compute the effective strain for PTAs?

OPEN ACCESS

The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background

Gabriella Agazie[1], Akash Anumarlapudi[1], Anne M. Archibald[2], Zaven Arzoumanian[3], Paul T. Baker[4], Bence Bécsy[5], Laura Blecha[6], Adam Brazier[7,8], Paul R. Brook[9], Sarah Burke-Spolaor[10,11] + Show full author list

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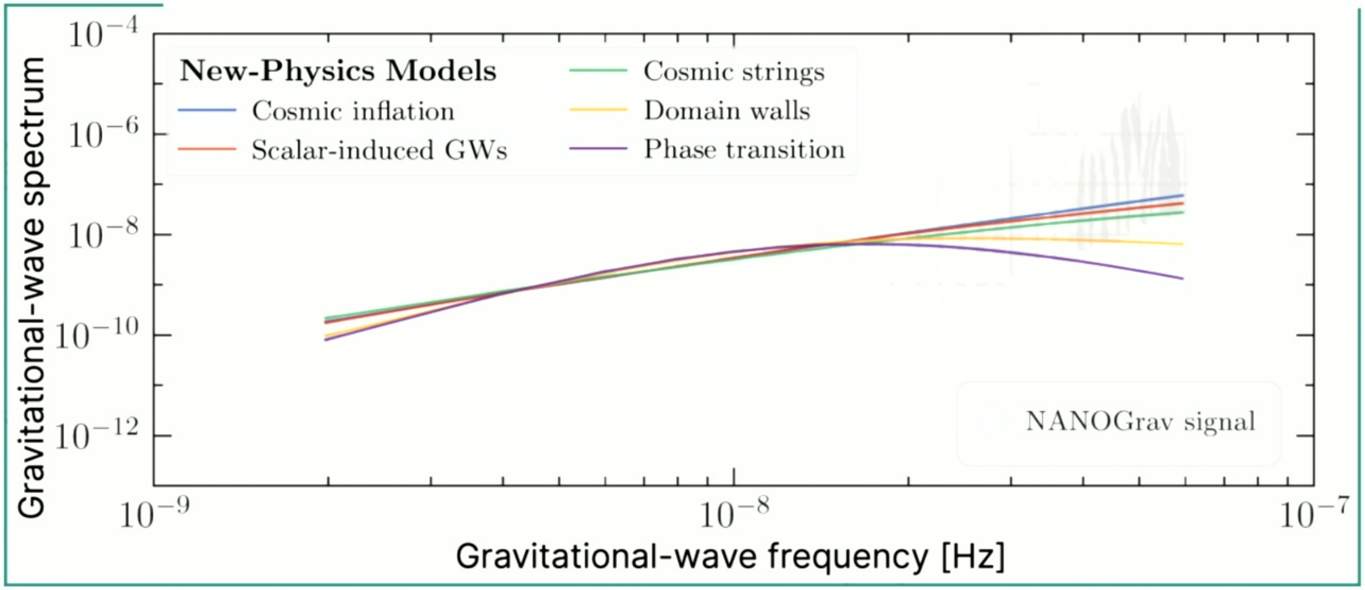
Citation Gabriella Agazie et al 2023 ApJL 951 L8
DOI 10.3847/2041-8213/acdac6

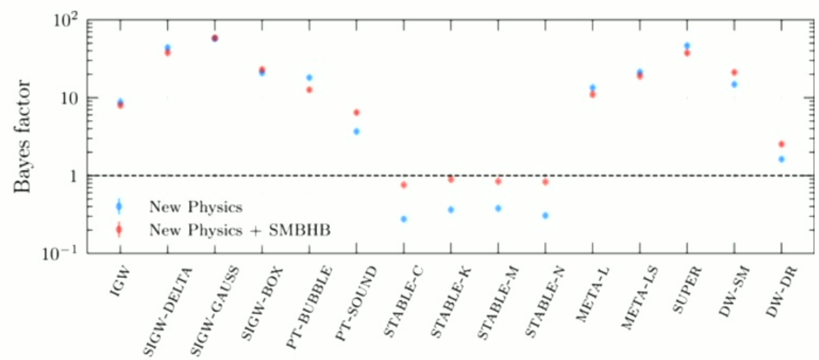
No unique interpretation for the observed nHz GWB



The NANOGrav 15 yr Data Set: Search for Signals from New Physics, ApJL (23)

Large uncertainties still exist in modeling of GWB due to SMBH Binaries

Single GW source searches show hints of a possible source at 4.2 nHz with $\mathcal{A}\sim 10^{-14}$



An exciting Astrophysical scenario to explain observed GWB

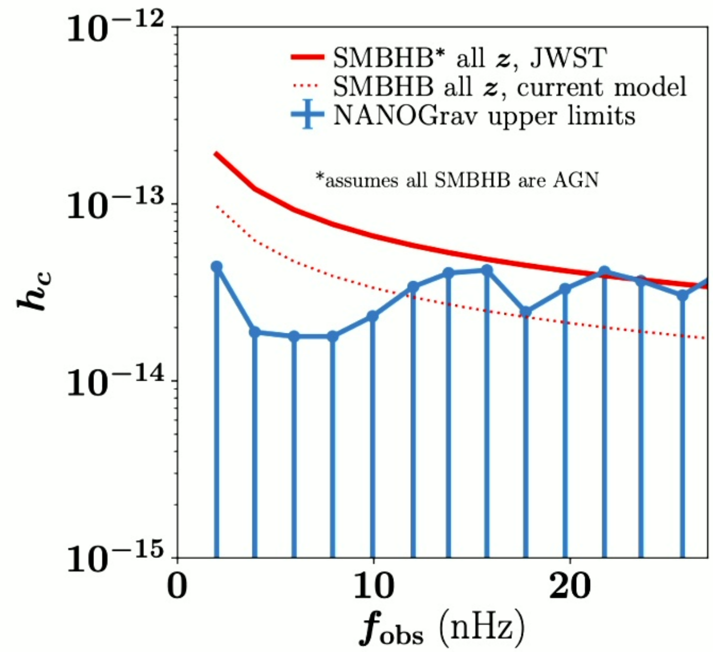
Constraints on supermassive black hole binaries from JWST and NANOGrav

IPTA DR3 GWB, LSST,+++

A&A (24)

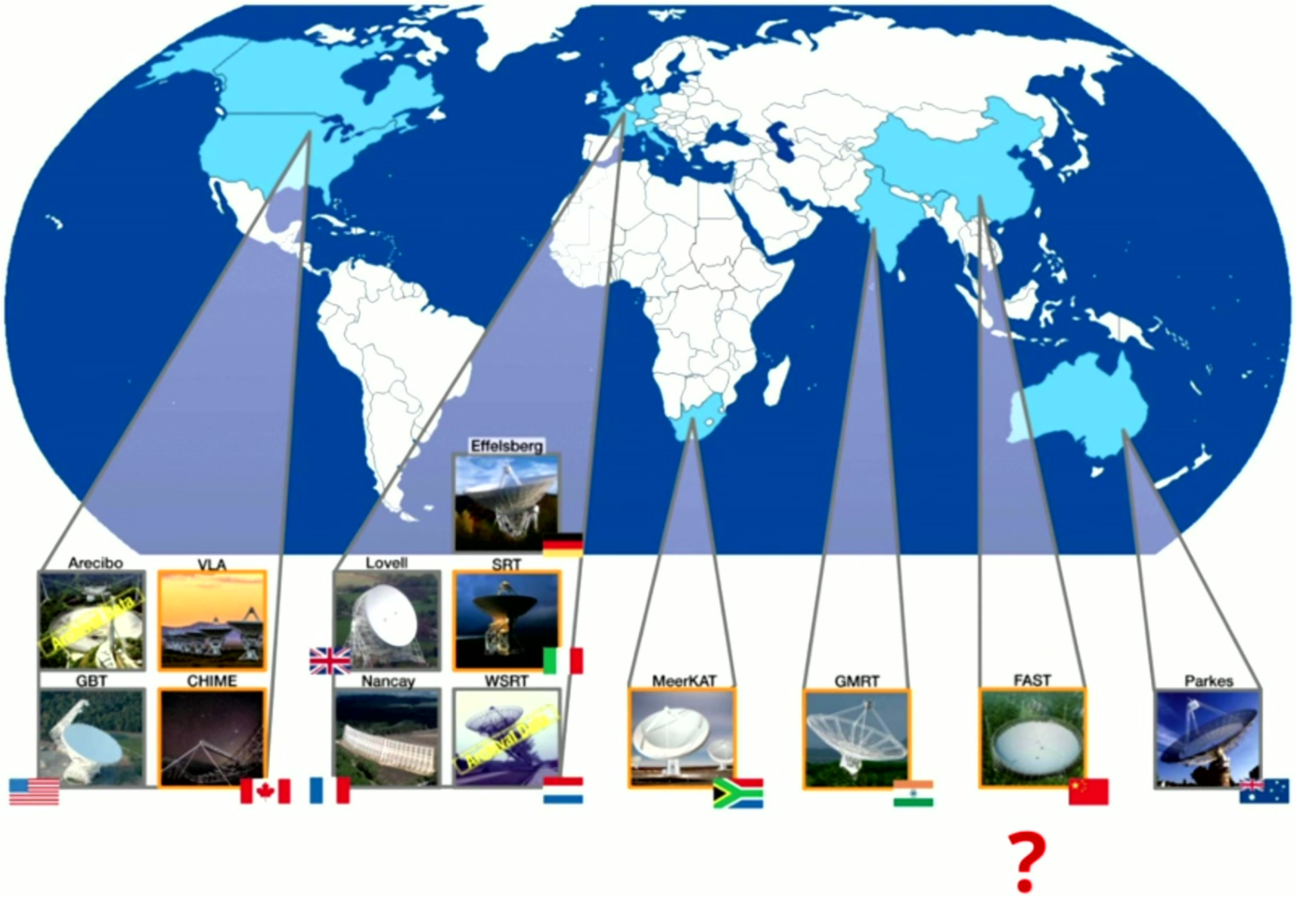
Hamsa Padmanabhan[1] and Abraham Loeb[2]

- It factors in recent *many high z dual AGN observations by JWST*
- Model computes GWB strain by invoking i) merger rate of DM halos, halo-SMBH mass relation & GW driven binary BH evolution



Critical to develop it further & look for other observational implications!

IPTA Data Release 3 should lead to discoveries



We expect 5 σ detection of SGWB in the coming years

We will be hunt for isolated SMBH Binaries using sophisticated R(t) models

i) Aman Srivastava
ii) Subhajit Dandapat
iii) Abhimanyu S
iv) Lankeswar Dey

Co-leads of DR3 GWA efforts

SKA: Construction to begin on world's biggest telescope

December 5, 2022 in News

AA

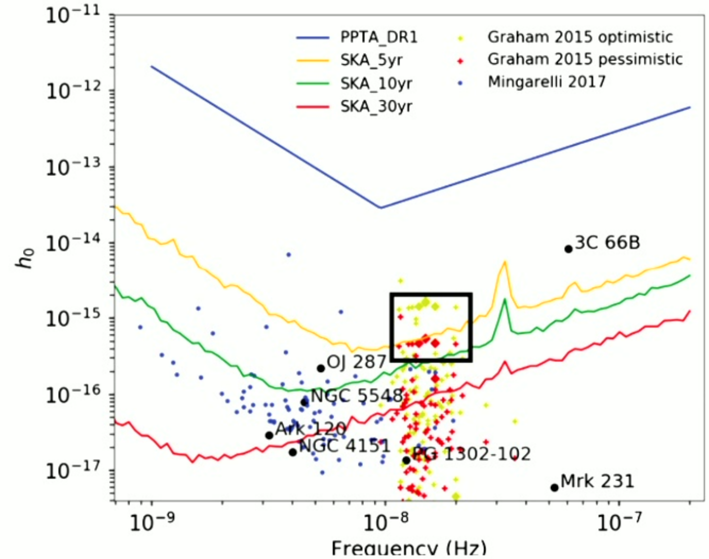
One of the grand scientific projects of the 21st Century begins its construction phase on Monday.

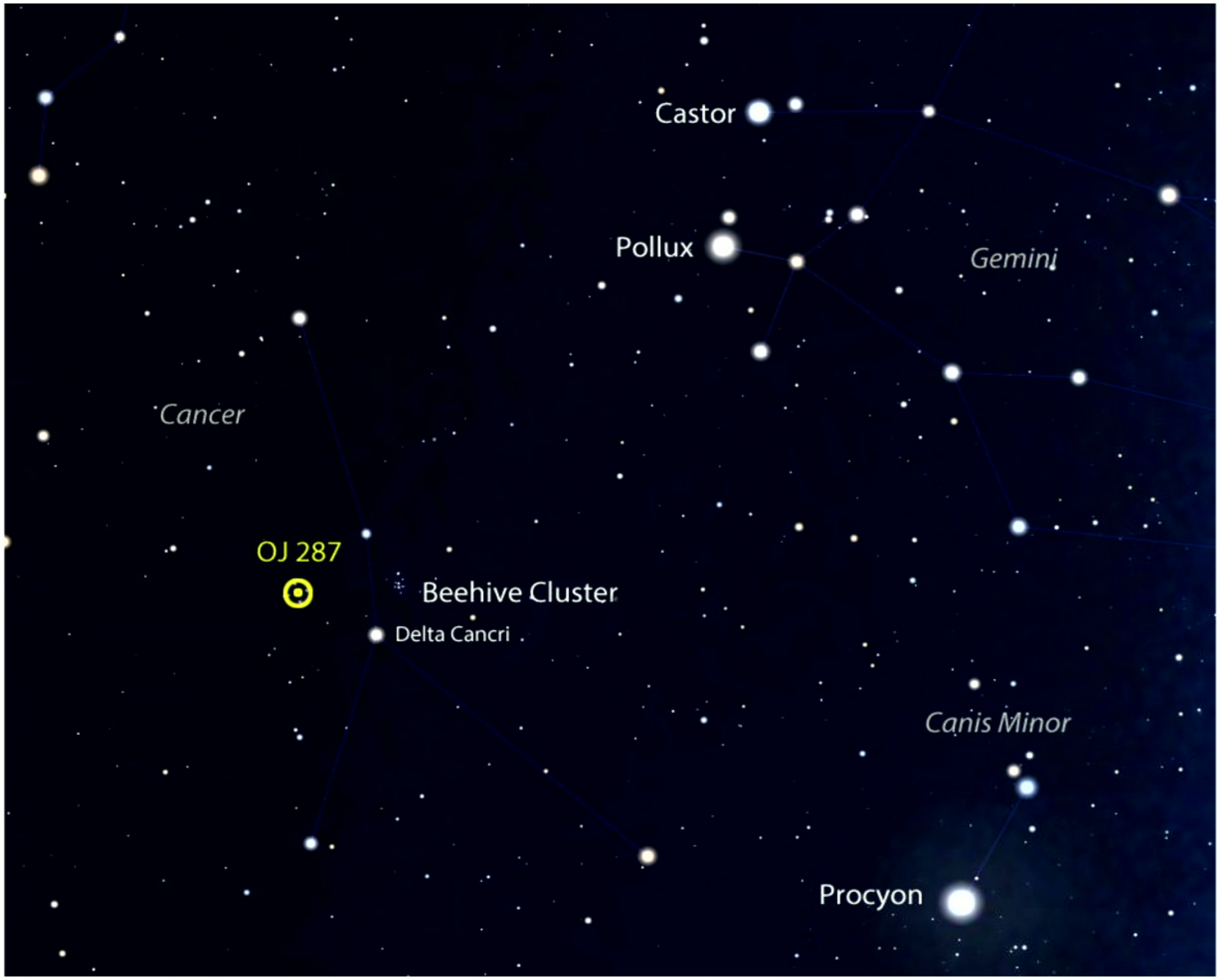
The Square Kilometre Array (SKA) will be the largest telescope in the world when completed in 2028.

Split across South Africa and Australia, with a headquarters in the UK, the facility will address the biggest questions in astrophysics.

It will perform the most precise tests of Einstein's theories, and even search for extra-terrestrials.

Feng,Li + (20)





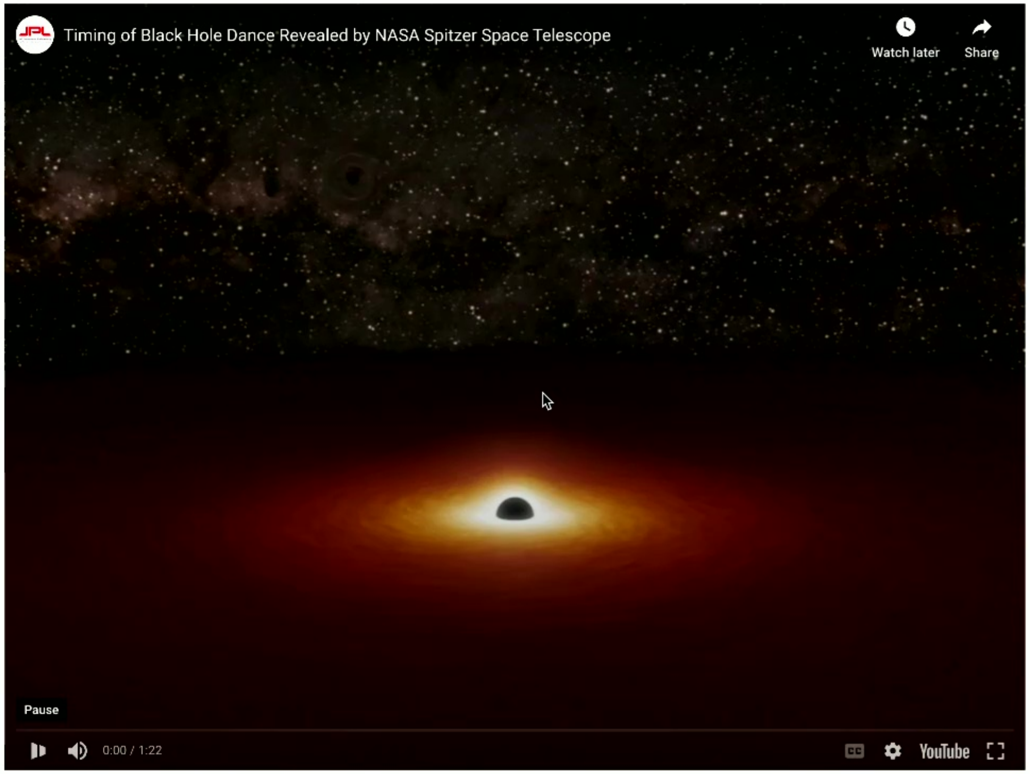
Credit: *Bob King*

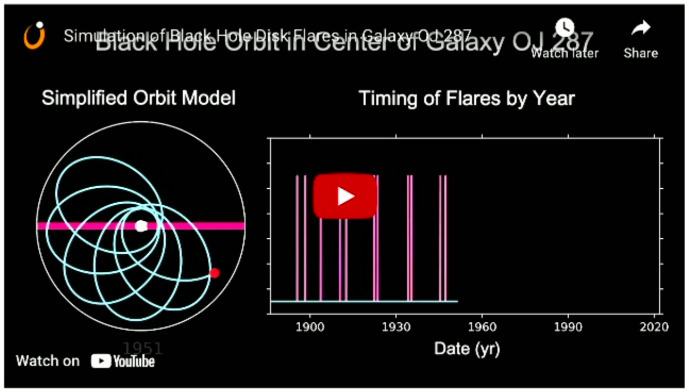
Blazar OJ 287 is a strong candidate to host a nHz GW emitting SMBH binary!!

Thanks to multi-band EM observational campaigns prompted by detailed theoretical investigations

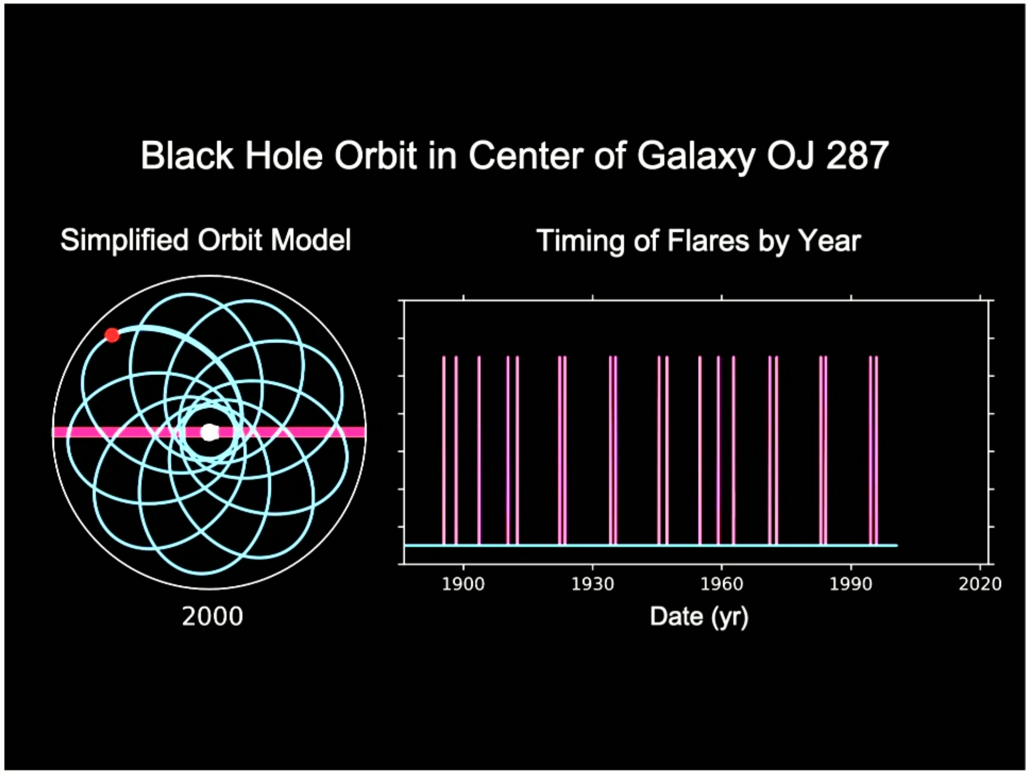
Valtonen, Dey+ 23

Credit: NASA/JPL & Abhimanyu S (TIFR)





Credit: NASA/JPL & Abhimanyu S (TIFR)



THE ASTROPHYSICAL JOURNAL LETTERS

Spitzer Observations of the Predicted Eddington Flare from Blazar OJ 287

Seppo Laine[1], Lankeswar Dey[2], Mauri Valtonen[3], A. Gopakumar[2], Stanislaw Zola[4,5], S. Komossa[6], Mark Kidger[7], Pauli Pihajoki[8], José L. Gómez[9], Daniel Caton[10]

+ Show full author list

Published 2020 April 28 •

The Astrophysical Journal Letters, Volume 894, Number 1

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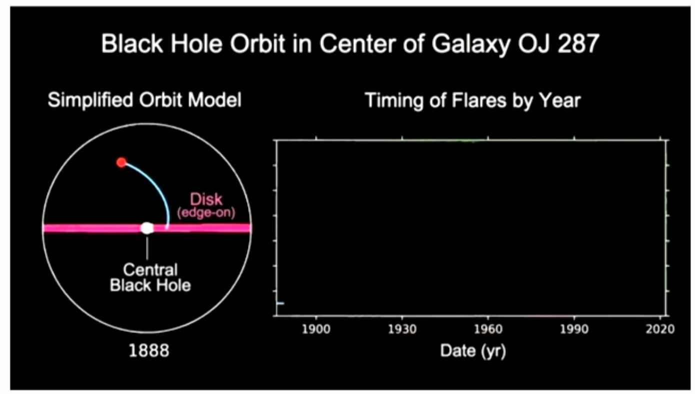
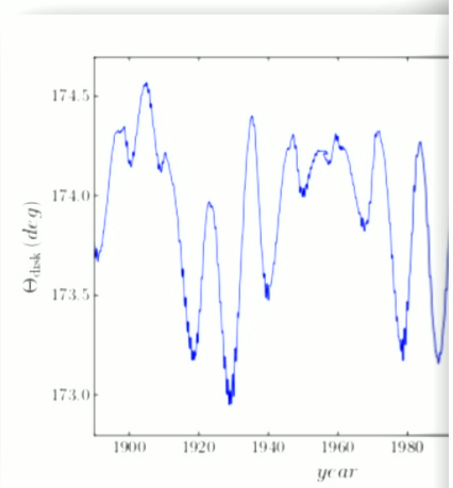
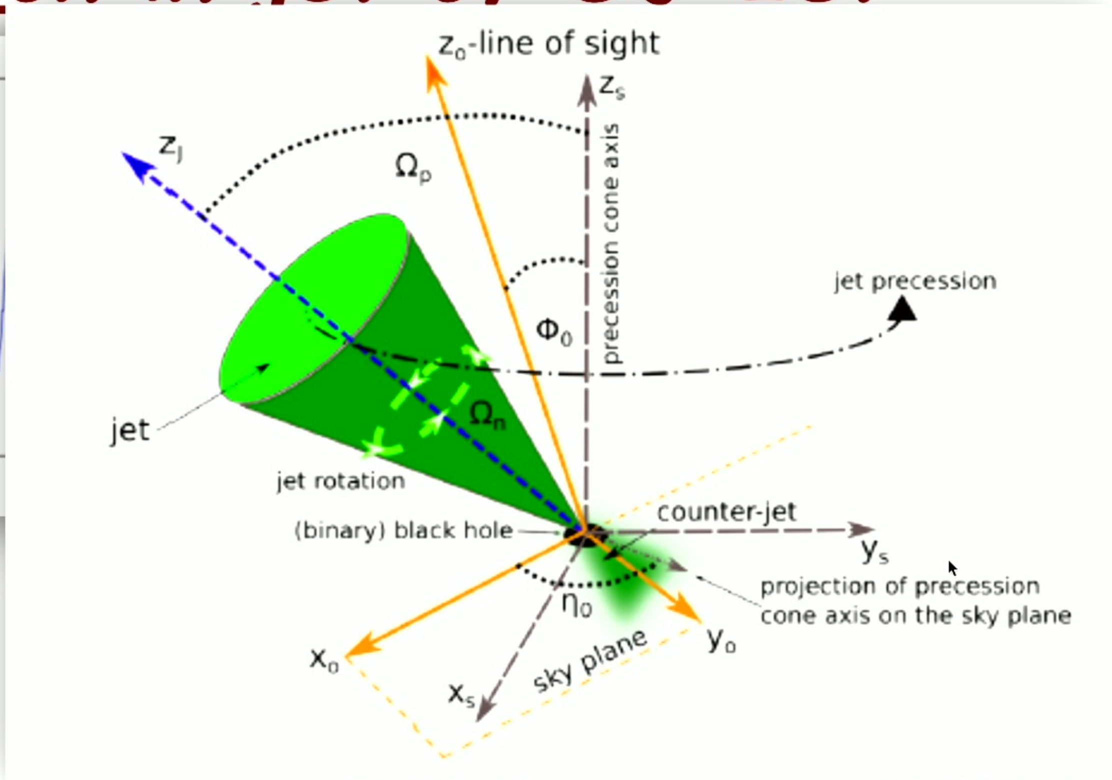


Spitzer Space Telescope 'performed' a test of General Relativity

< 34 >

PA variation in jet of OJ 287





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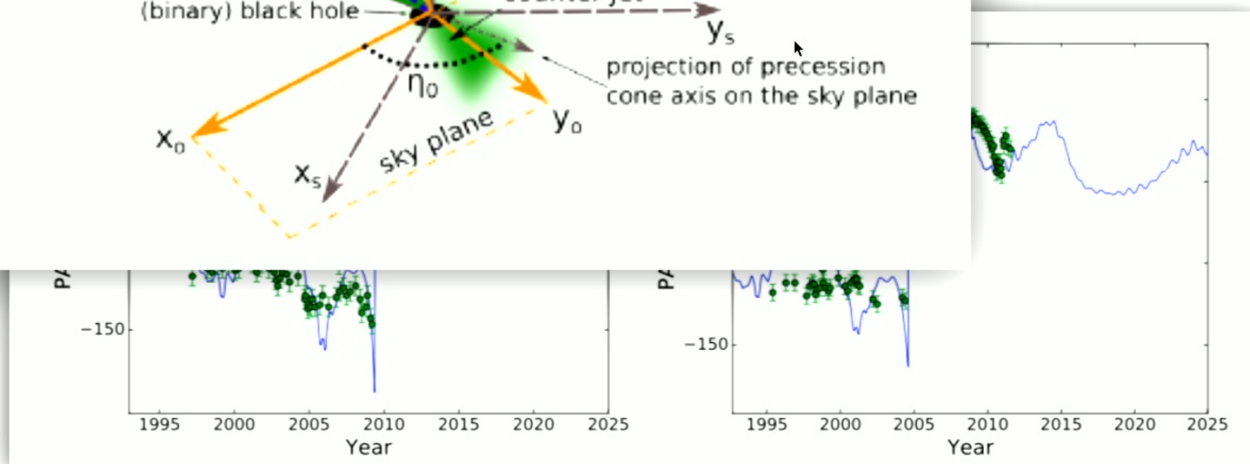
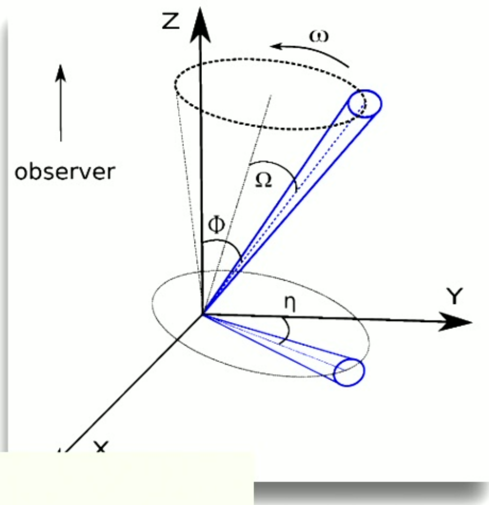


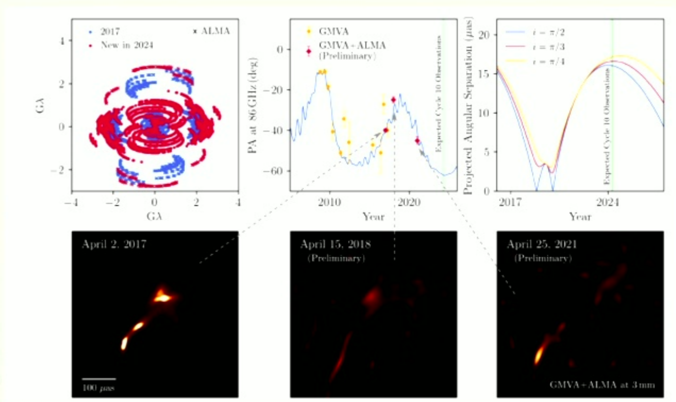
Variation in position angle in of the jet in OJ 287

(Dey + 21, arXiv:2103.05274)



Explaining temporal variations in the jet PA of the blazar OJ 287 using its BBH central engine model

Lankeswar Dey, Mauri J Valtonen, A Gopakumar, Rocco Lico, José L Gómez, Abhimanyu Susobhanan, S Komossa, Pauli Pihajoki



Guang-Yao ZHAO+, GMVA+ALMA (Cycle 10 proposal)

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Unravelling the Innermost Jet Structure of OJ 287 with the First GMVA+ALMA Observations

Guang-Yao Zhao, Jose L. Gomez, Antonio Fuentes, Thomas P. Krichbaum, E. Traianou, Rocco Lico, Ilje Cho, Eduardo Ros, S. Komossa, Kazunori Akiyama, Keiichi Asada, Lindy Blackburn, Silke Britzen, Gabriele Bruni, Geoffrey Crew, Rohan Dahale, Lankeswar Dey, Roman Gold, Achamveedu Gopakumar, Sara Issaoun, Michael Janssen, Svetlana G. Jorstad, Jae-Young Kim, Jun Yi Koay, Yuri Y. Kovalev, Shoko Koyama, Andrei Lobanov, Laurent Loinard, Rusen Lu, Sera Markoff, Alan P. Marscher, Ivan Marti-Vidal, Yosuke Mizuno, Jongho Park, Tuomas Savolainen, Teresa Toscano

IPTA's efforts during SKA & DSA 2000 era should be very critical to probe *our SMBH Binary central engine description for OJ 287*

Chances of observing such SMBH Binaries are miniscule!!

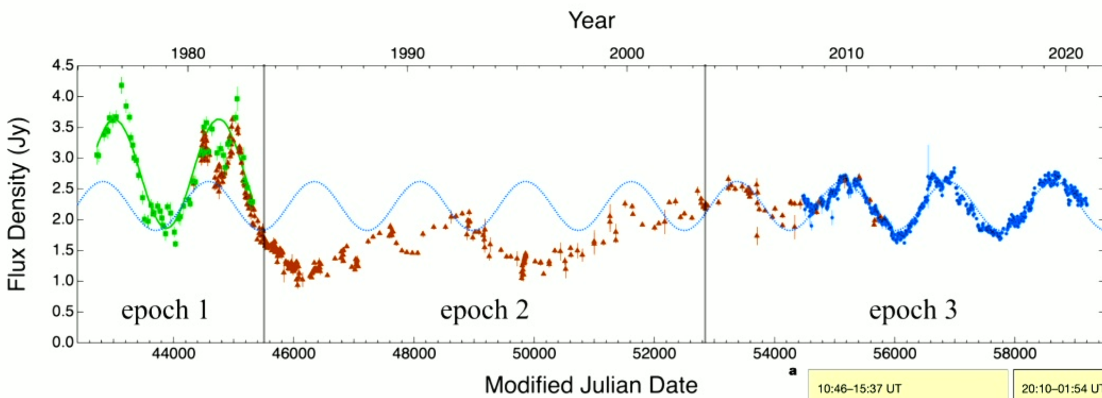

Figure 1. The 14.5 GHz - 15.5 GHz light curve of PKS 2131−021. The Haystack data are sh
brown triangles and the OVRO data by the blue dots. Note the excellent agreement between
OVRO in the regions of overlap. The light curve shows three distinct epochs of activity: In
signal, $P_1 = 1729.1 \pm 32.4$ days; in epoch 2 (45500<MJD<52850) this periodic signal
signal of epoch 1 returns, with $P_3 = 1760.4 \pm 5.3$ days, in phase but with lower amplitude tl
least-squares sine wave fit to the Haystack data, and the dotted blue line shows the least-squ
backwards to provide a comparison with the Haystack data. The periods of the Haystack an
of the OVRO periodic signal extrapolated back to epoch 1 matches to $\sim 10\%$ of the period.

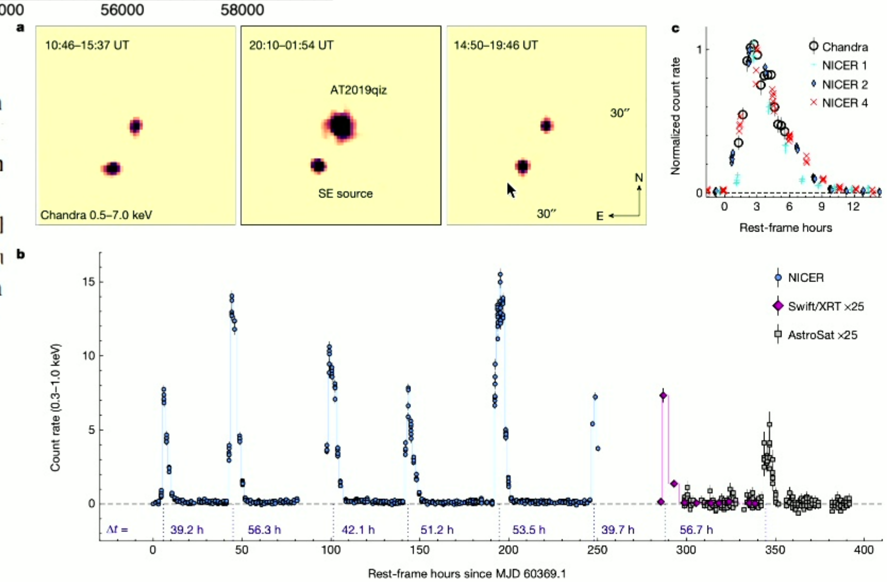

Fig. 1 | Detection of QPEs from the nearby TDE AT2019qiz. a, Chandra images   Without stacking, the count rate between the eruptions is consistent with zero.

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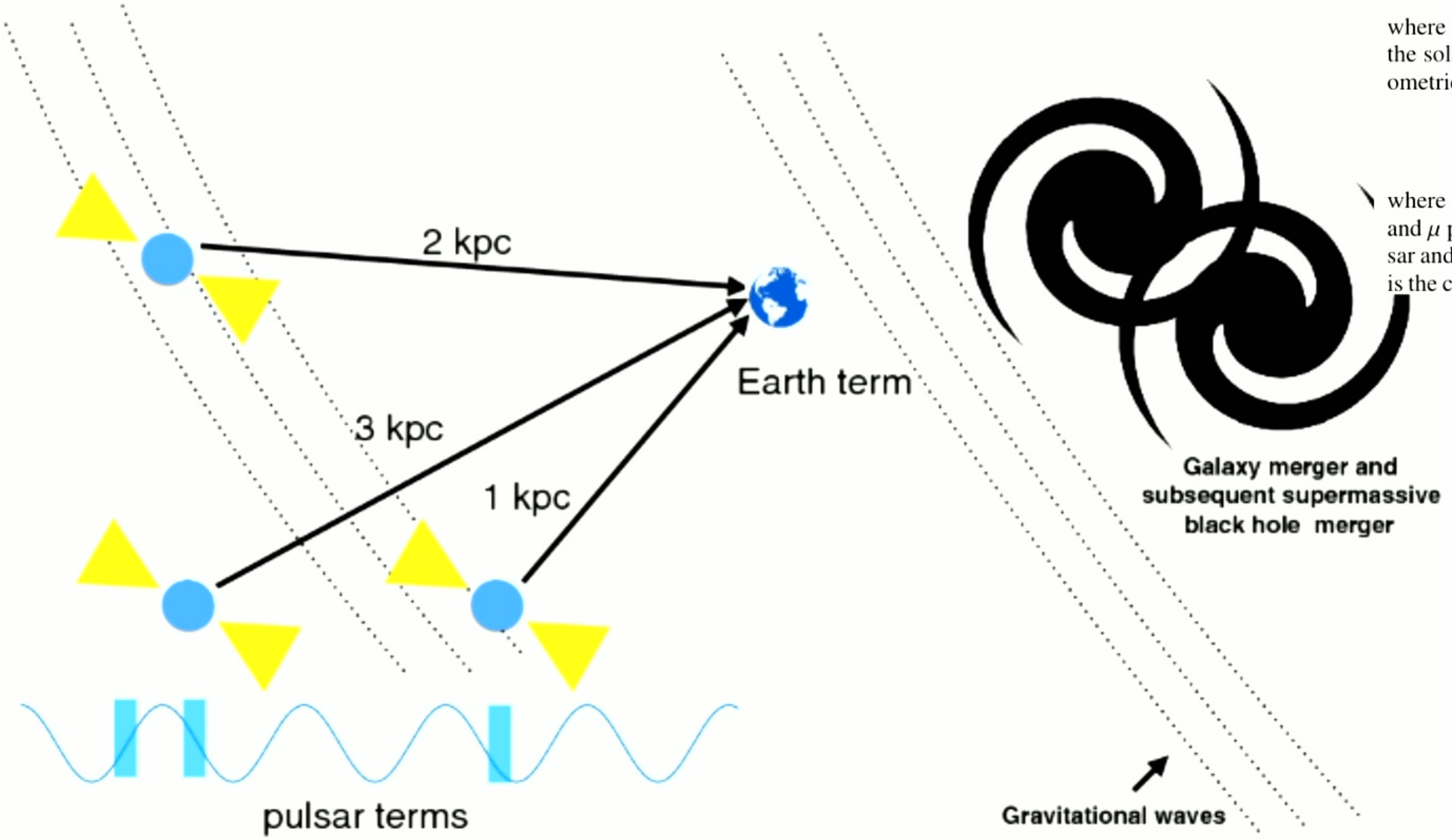

$$R(t) = \int_0^t \left[h(t' - \tau_P) - h(t')\right] \, dt' \, , \qquad (1)$$

where the coordinate time variables t and t' are measured at the solar system barycenter (SSB) frame. Further, τ_P is a geometric time delay given by

$$\tau_P = \frac{D_P}{c}(1 - \cos\mu) \, , \qquad (2)$$

where D_P represents the distance to the pulsar from the SSB, and μ provides the angle between the lines of sight to the pulsar and the GW source. In GR, the gravitational waveform $h(t)$ is the combination of two polarization states ($h_{+,\times}(t)$) such that

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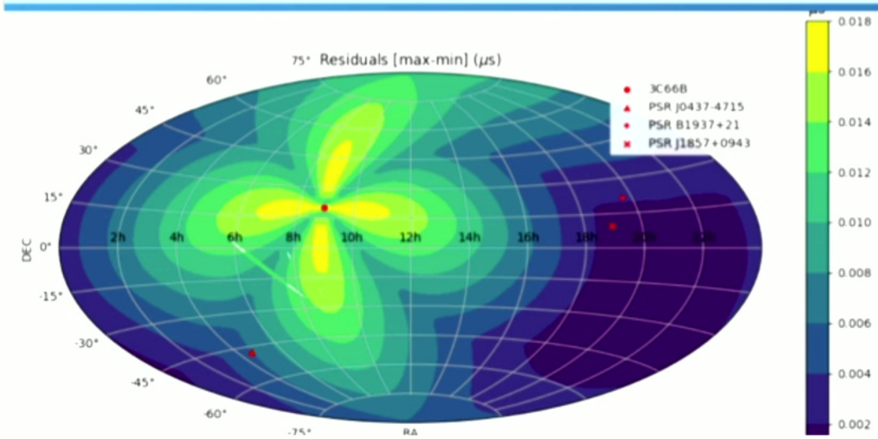
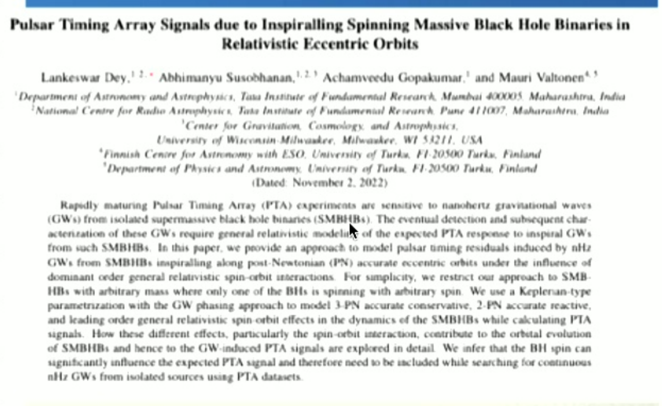
Efficient Computation of Timing Residuals Induced by Eccentric Black Hole Binaries

Abhimanyu Susobhanan

Tata Institute of Fundamental Research, Mumbai, India

Collaborators: A. Gopakumar, G. Hobbs, S.R. Taylor





Pulsar Timing Array Signals due to Inspiralling Spinning Massive Black Hole Binaries in Relativistic Eccentric Orbits

Lankeswar Dey,[1,2,*] Abhimanyu Susobhanan,[1,2,3] Achamveedu Gopakumar,[1] and Mauri Valtonen[4,5]

[1]*Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Mumbai 400005, Maharashtra, India*
[2]*National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune 411007, Maharashtra, India*
[3]*Center for Gravitation, Cosmology, and Astrophysics, University of Wisconsin-Milwaukee, Milwaukee, WI 53211, USA*
[4]*Finnish Centre for Astronomy with ESO, University of Turku, FI-20500 Turku, Finland*
[5]*Department of Physics and Astronomy, University of Turku, FI-20500 Turku, Finland*

(Dated: November 2, 2022)

Rapidly maturing Pulsar Timing Array (PTA) experiments are sensitive to nanohertz gravitational waves (GWs) from isolated supermassive black hole binaries (SMBHBs). The eventual detection and subsequent characterization of these GWs require general relativistic modeling of the expected PTA response to inspiral GWs from such SMBHBs. In this paper, we provide an approach to model pulsar timing residuals induced by nHz GWs from SMBHBs inspiralling along post-Newtonian (PN) accurate eccentric orbits under the influence of dominant order general relativistic spin-orbit interactions. For simplicity, we restrict our approach to SMBHBs with arbitrary mass where only one of the BHs is spinning with arbitrary spin. We use a Keplerian-type parametrization with the GW phasing approach to model 3-PN accurate conservative, 2-PN accurate reactive, and leading order general relativistic spin-orbit effects in the dynamics of the SMBHBs while calculating PTA signals. How these different effects, particularly the spin-orbit interaction, contribute to the orbital evolution of SMBHBs and hence to the GW-induced PTA signals are explored in detail. We infer that the BH spin can significantly influence the expected PTA signal and therefore need to be included while searching for continuous nHz GWs from isolated sources using PTA datasets.

The NANOGrav 12.5-year data set: Multi-messenger targeted search for gravitational waves from an eccentric supermassive binary in 3C 66B

(arXiv:2210.11454)

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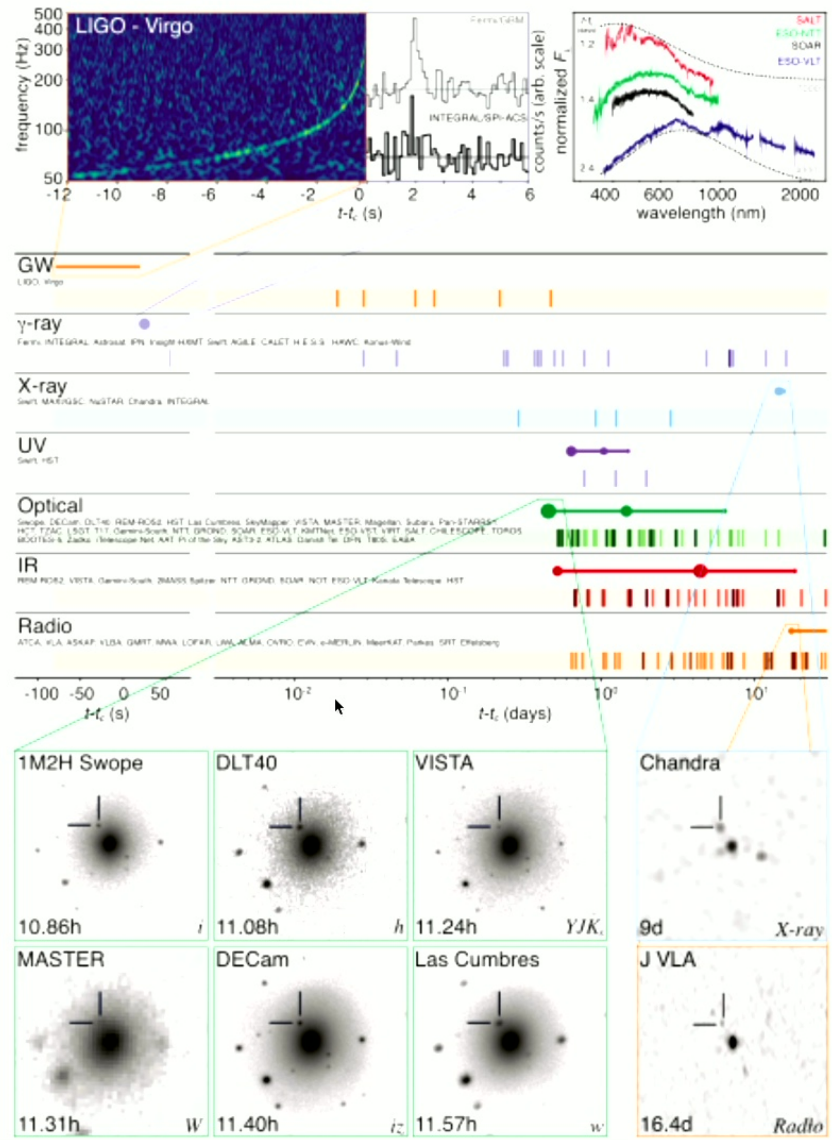
Slowly Inspiralling Massive Black Hole Binaries are of definite interest to both SKA era IPTA, ngEHT, IceCube-Gen2 & Great Observatories++

Such systems will be critical to pursue persistent multi-messenger GW Astronomy

‹ 43 › ⋮

GW170817 induced MM GW Astronomy is having fundamental Implications for Physics, Astrophysics & Cosmology (arXiv:1710.05832) !!

- *This is despise the fact that the observed GWs lasted around 100 seconds & the source was at ~40 Mpc!!*



nHz GWs from individual SMBH Binaries should lead to

- ★ Accurate measurements of Hubble constant
  (*with or without an EM counterpart*)
- ★ Test GR at epochs separated by 1000s of years
- ★ Probing linear/ non-linear memory in GR ; recoil SMBHs
- ★ GW Lensing events
- ★ *Constraints of ULDM candidates*
- ★ Amazing constraints of BSM physics
  & many more GWB related explorations
  (*Watch out for papers from R. Bernardo+*)

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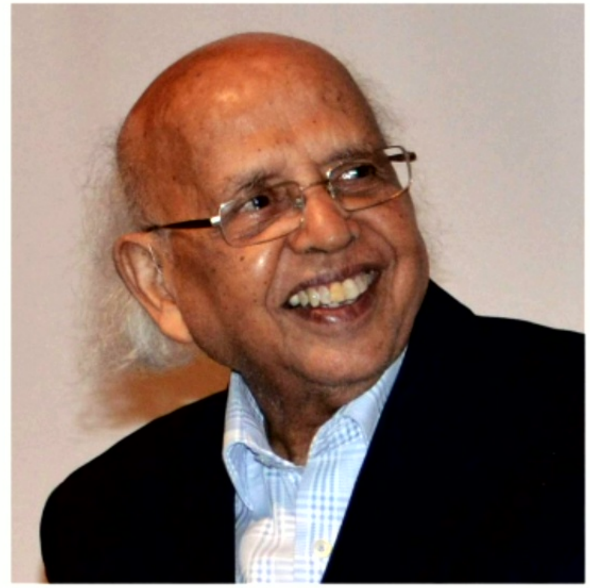
The Giant Metre-wave Radio Telescope

G. Swarup, S. Ananthakrishnan, V. K. Kapahi, A. P. Rao, C. R. Subrahmanya and V. K. Kulkarni

The Giant Metre-wave Radio Telescope, an aperture-synthesis array consisting of 30 fully steerable parabolic dishes of 45-m diameter each, is being set up about 80 km north of Pune as a national facility for frontline research in radio astronomy in the frequency range 38 MHz to 1420 MHz. The new and novel design of a low-solidity dish for metre-wave operation, in which a thin wire mesh (varying in size from 10 mm × 10 mm to 20 mm × 20 mm and made of 0.55 mm diameter stainless-steel wire), which constitutes the reflecting surface, is stretched over a parabolic surface formed by rope trusses, has made it possible to build a large collecting area (total effective area of about 30,000 m^2, over three times that of the Very Large Array in the USA) at modest cost. It will be a major new instrument designed to fill the existing world-wide gap in powerful radio telescopes operating at metre wavelengths, where there are many exciting and challenging astrophysical problems and phenomena to be investigated. Two of the primary scientific objectives of the telescope are to detect the highly redshifted '21-cm' line of neutral hydrogen from protoclusters or protogalaxies in the early epochs of the Universe before galaxy formation and to detect and study a large number of millisecond pulsars in an attempt to detect the primordial background of gravitational radiation.

G. Swarup et al. 1991, Current Science, Vol. 60, pp. 95-105



Govind Swarup (1929-2020). Credit: NCRA

Prof Bhal Chandra Joshi founded the collaboration with few of us

Unique strength of uGMRT:

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

- *Simultaneous multi-band MSP observations*
- Band 3 (300-500 MHz) + Band 5 (1260-1460 MHz)
- Presently observing 22+ IPTA pulsars (Cadence: 10-14 days)

Indian Pulsar Timing Array (InPTA) for nHz GW Astronomy
(https://inpta.iitr.ac.in/)

- **InPTA** is a *frugal (& indigenous) consortium* that employs niche abilities of *TIFR's upgraded GMRT* to inaugurate the era nano-hertz Gravitational Wave Astronomy in the very near future

- **InPTA** is contributing the world-wide effort to *detect and characterise a diffuse GW background* due to merging Super Massive Black Hobe binaries with the help of *indigenous data, analysis algorithms & theoretical constructs*

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Join us in this amazing adventure

Thank you for the privilege of your time

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