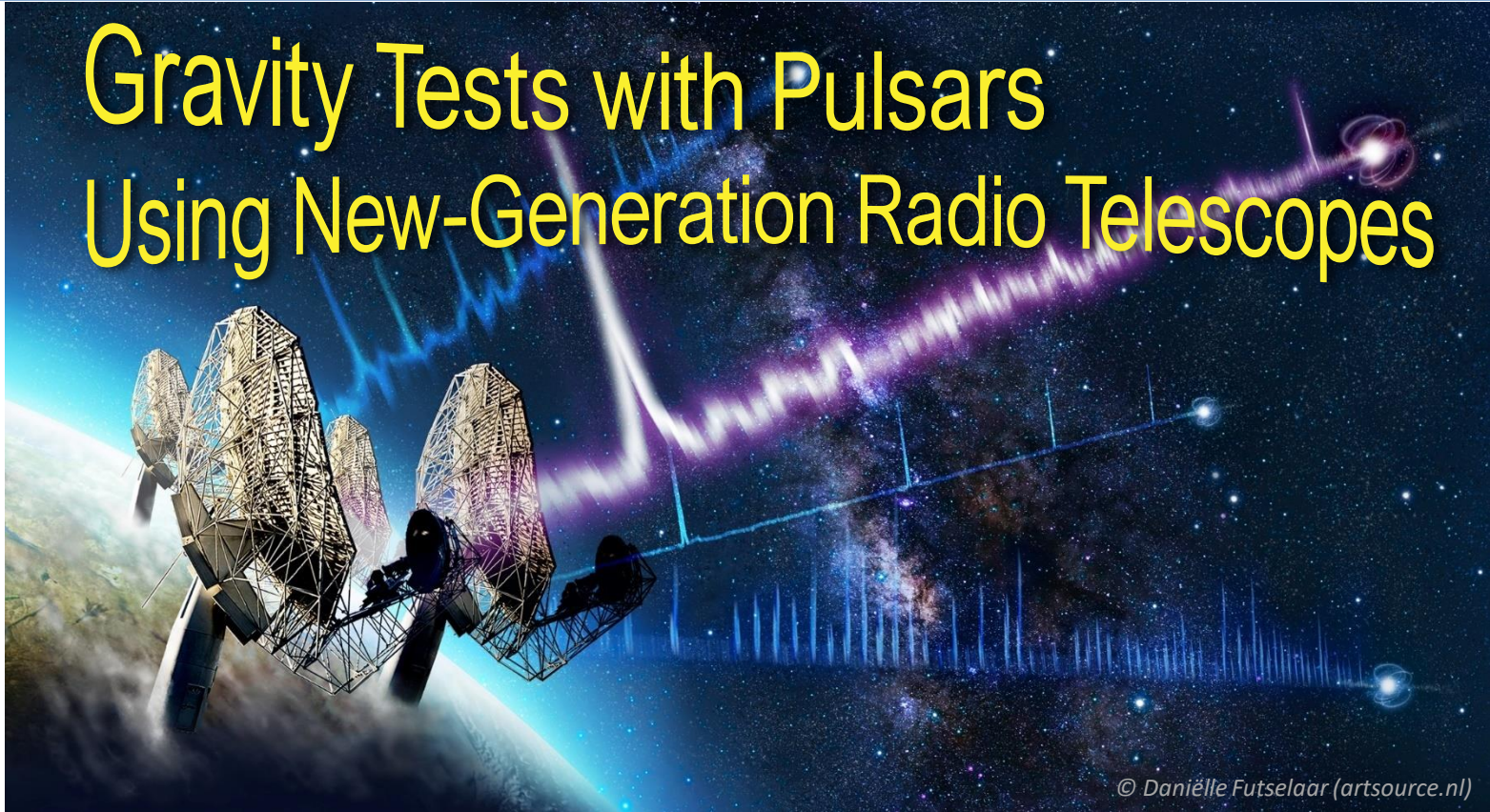


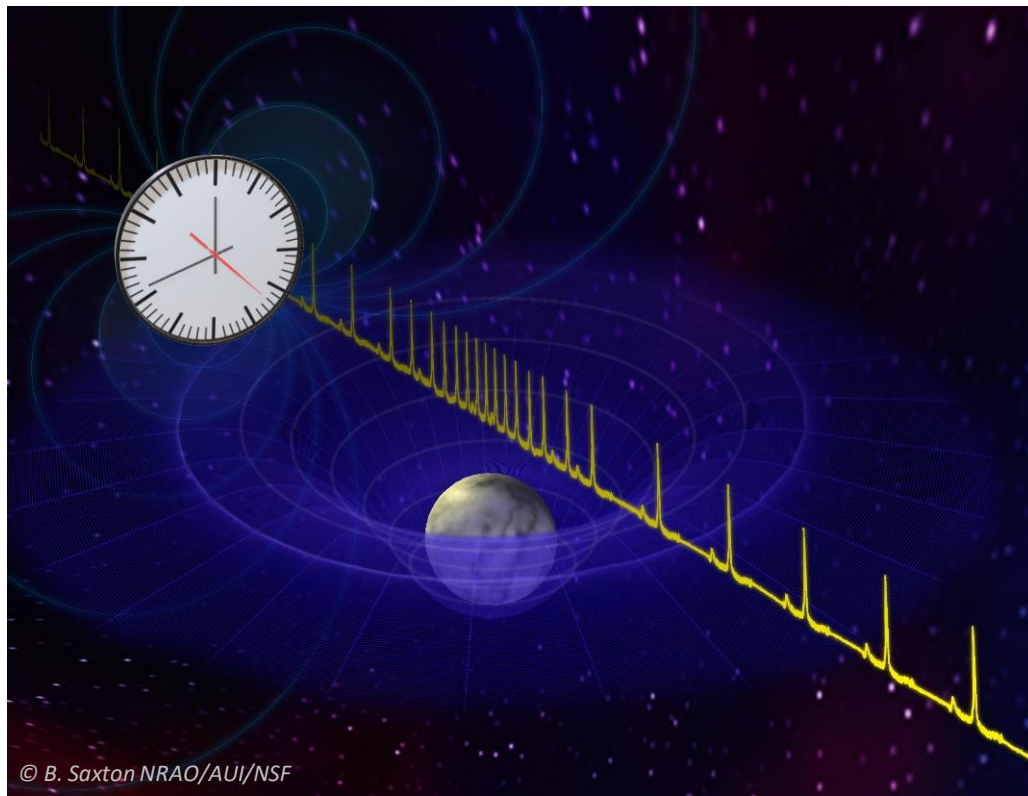
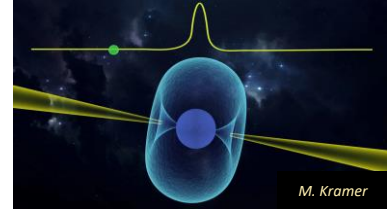
# Gravity Tests with Pulsars Using New-Generation Radio Telescopes



© Daniëlle Futselaar (artsource.nl)



# Cosmic clocks → Pulsars



Magnetised rotating neutron stars

$M \sim 1.4 M_{\odot}$ ,  $R \sim 10 \text{ km}$

$P \sim 10^{-3} - 10^1 \text{ s}$ ,  $\dot{P} \sim 10^{-20} \text{ s/s}$

PSR J1713+0747:

$P = 4.570\,136\,598\,154\,467 \text{ ms}$   
 $\pm 0.000\,000\,000\,000\,004$

Attosecond precision!

Ideal probes for gravity and matter  
under extreme conditions



# Scientific questions addressed in my thesis



## **Is general relativity (GR) is a complete description of macroscopic gravity?**

- Higher-order GR effect: gravitational signal propagation effects in the Double Pulsar
- Pulsar timing arrays: hunting for nanohertz gravitational waves
- Testing scalar-tensor gravity with pulsar - white dwarf / black hole systems

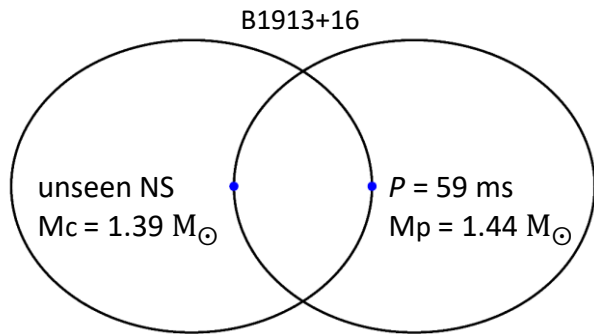
## **How matter behaves at extreme densities?**

- Measuring neutron star moment of inertia with radio pulsars



# Φ 50<sup>th</sup> anniversary of PSR B1913+16

- First binary pulsar discovered by Russell Hulse and Joseph Taylor in 1974
- First precision GR tests beyond Solar System
- First evidence of gravitational waves (GWs)
- 1993 Nobel Prize in Physics “for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation.”

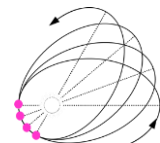


$$P_b = 7.8\text{h}, e = 0.617$$

## PK parameters in GR (leading order)

*Orbital precession*

$$\dot{\omega}^{\text{1PN}} = 3T_{\odot}^{2/3} \left( \frac{2\pi}{P_b} \right)^{5/3} \frac{1}{1 - e_T^2} (m_A + m_B)^{2/3}$$



*Orbital period decay*

$$\dot{P}_b^{2.5\text{PN}} = -\frac{192\pi}{5} T_{\odot}^{5/3} \left( \frac{2\pi}{P_b} \right)^{5/3} \frac{1 + \frac{73}{24} e_T^2 + \frac{37}{96} e_T^4}{(1 - e_T^2)^{7/2}} \frac{m_A m_B}{(m_A + m_B)^{1/3}}$$



*Einstein delay*

$$\gamma_E = T_{\odot}^{2/3} \left( \frac{2\pi}{P_b} \right)^{-1/3} e_T \frac{m_B(m_A + 2m_B)}{(m_A + m_B)^{4/3}}$$



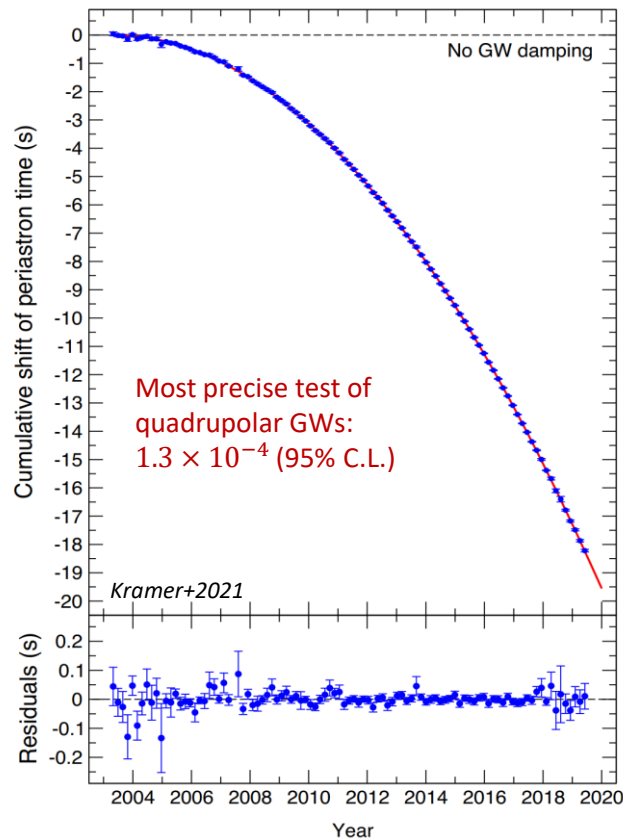
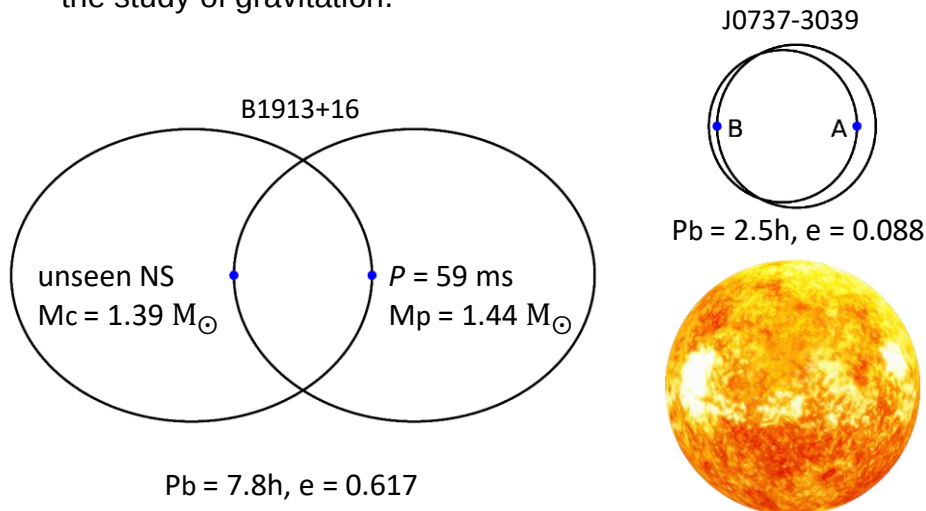
*Shapiro delay*

$$r = T_{\odot} m_B \quad s = T_{\odot}^{-1/3} \left( \frac{2\pi}{P_b} \right)^{2/3} x \frac{(m_A + m_B)^{2/3}}{m_B}$$



# $\Phi$ 50<sup>th</sup> anniversary of PSR B1913+16

- First binary pulsar discovered by Russell Hulse and Joseph Taylor in 1974
- First precision GR tests beyond Solar System
- First evidence of gravitational waves (GWs)
- 1993 Nobel Prize in Physics “for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation.”

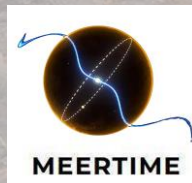




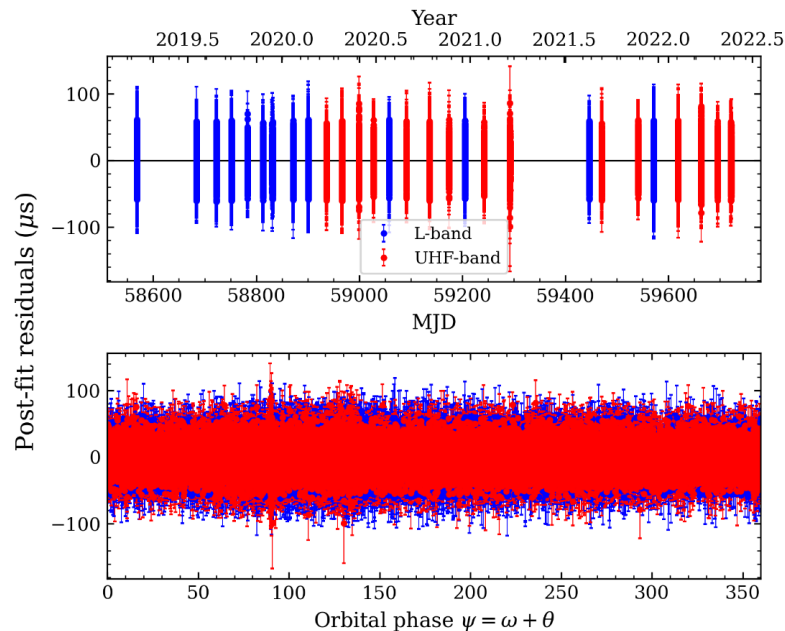
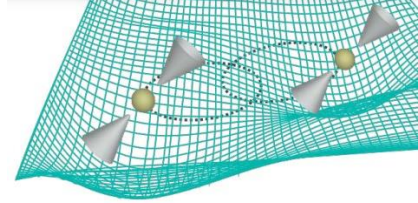
# MeerKAT observations



- MeerKAT: 64 dishes, precursor of the Square Kilometre Array (SKA) at mid frequency in South Africa
- MeerTime's (Bailes+2020) "RelBin" programme (Kramer+2021b)
- Monthly observations started in 2019:  
29 observations in ~ 3 years, 87 hr in total
- ~3x better than the GBT, 7x better than Parkes



# $\Phi$ Timing results



221,381 TOAs  
4,388,187,911 rotations  
reduced  $\chi^2 = 0.99$

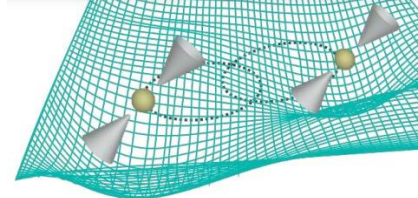
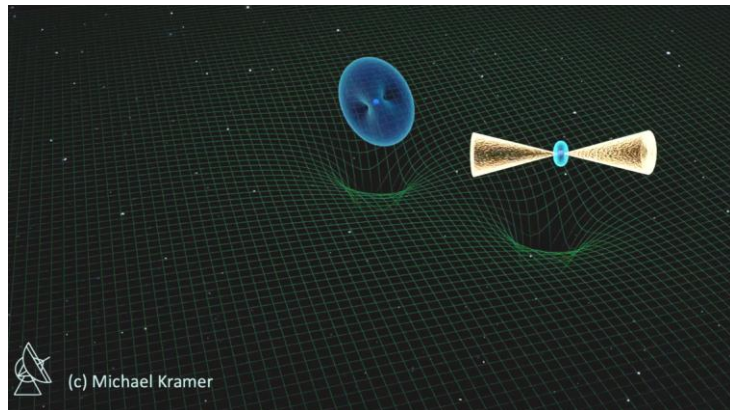
## Binary parameters

|                                                       |                         |
|-------------------------------------------------------|-------------------------|
| Orbital period, $P_b$ (days)                          | 0.102 251 559 297 2(29) |
| Projected semi-major axis, $x$ (s)                    | 1.415 028 299(88)       |
| Eccentricity, $e_T$                                   | 0.087 777 036(48)       |
| Epoch of periastron, $T_0$ (MJD)                      | 55700.233 017 54(10)    |
| Longitude of periastron, $\omega$ (deg)               | 204.753 72(36)          |
| Periastron advance, $\dot{\omega}$ (deg yr $^{-1}$ )  | 16.899 321(37)          |
| Orbital period derivative ( $10^{-12}$ ), $\dot{P}_b$ | -1.247 920(78) (*)      |
| Einstein delay amplitude, $\gamma_E$ (ms)             | 0.384 045(94) (*)       |
| Logarithmic Shapiro shape, $z_s$                      | 9.669(77)               |
| Range of Shapiro delay, $r$ ( $\mu$ s)                | 6.163(16)               |
| NLO factor for signal prop., $q_{\text{NLO}}$         | 0.999(79)               |

## Derived parameters

|                                       |                      |
|---------------------------------------|----------------------|
| $s \equiv \sin i = 1 - e^{-z_s}$      | 0.999 936 9(+46/-51) |
| Orbital inclination, $i$ (deg)        | 89.36(3) or 90.64(3) |
| Mass of pulsar A, $m_A$ ( $M_\odot$ ) | 1.338 186(10)        |
| Mass of pulsar B, $m_B$ ( $M_\odot$ ) | 1.248 866(7)         |
| Total mass, $M$ ( $M_\odot$ )         | 2.587 052(11)        |

# Φ Shapiro delay



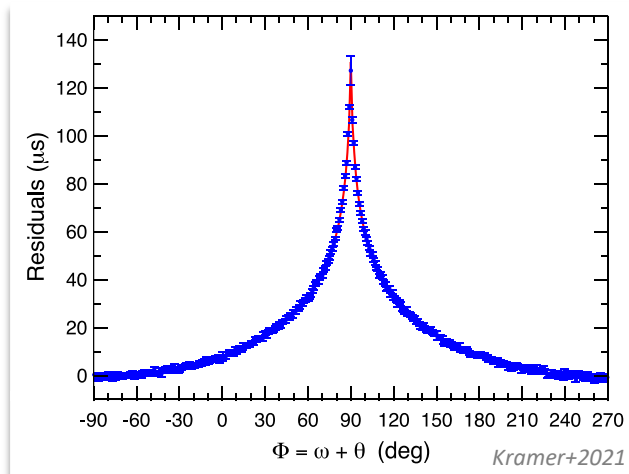
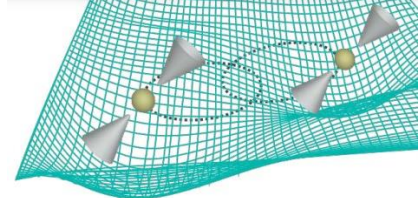
## Binary parameters

|                                                       |                         |
|-------------------------------------------------------|-------------------------|
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| Total mass, $M$ ( $M_\odot$ )         | 2.587 052(11)        |

# Φ Shapiro delay



“Shape” improves by 2 times

“Range”: Obs./Exp. = 1.0019(26),  
validating GR at  $5.3 \times 10^{-3}$  (95% C.L.)

Most precise NS mass measurements!

## Binary parameters

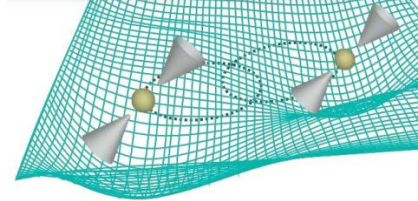
|                                                       |                         |
|-------------------------------------------------------|-------------------------|
| Orbital period, $P_b$ (days)                          | 0.102 251 559 297 2(29) |
| Projected semi-major axis, $x$ (s)                    | 1.415 028 299(88)       |
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| NLO factor for signal prop., $q_{\text{NLO}}$         | 0.999(79)               |

## Derived parameters

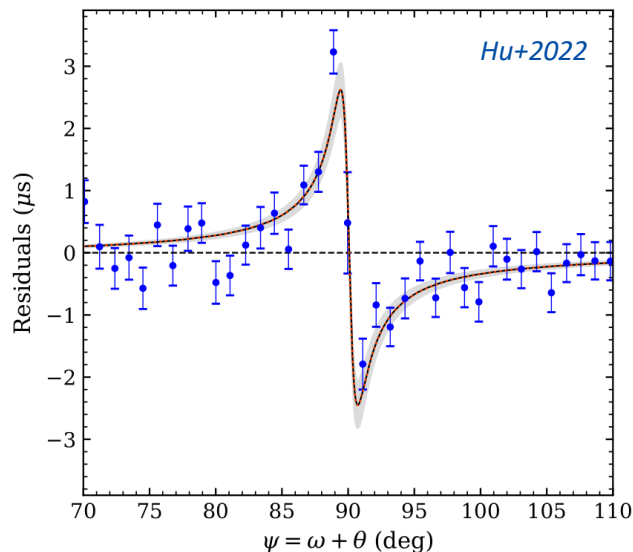
|                                       |                      |
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| Total mass, $M$ ( $M_\odot$ )         | 2.587 052(11)        |



# NLO light propagation effects

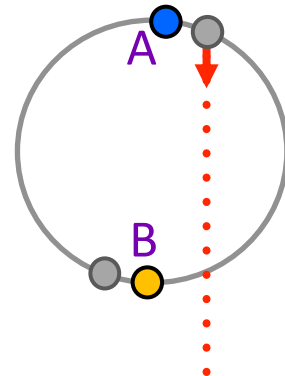
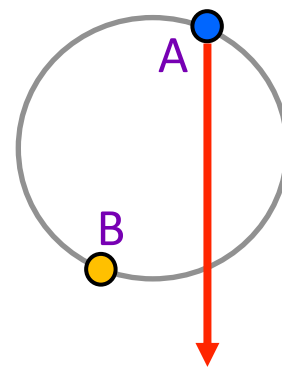


3-yr MeerKAT data

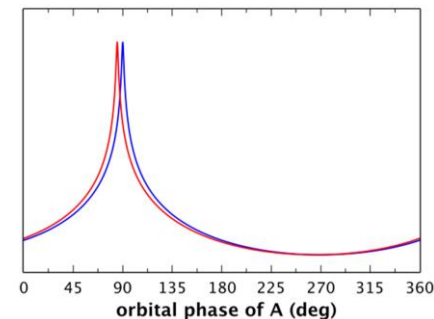
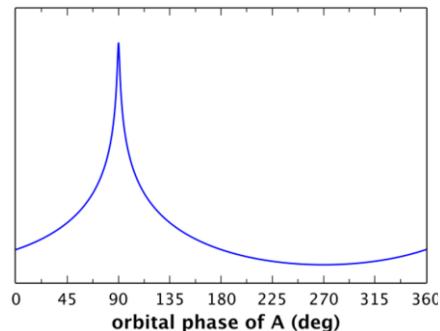


## Retardation effect

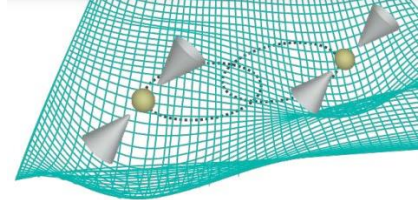
(Kopeikin & Schäfer 1999,  
Rafikov & Lai 2006a)



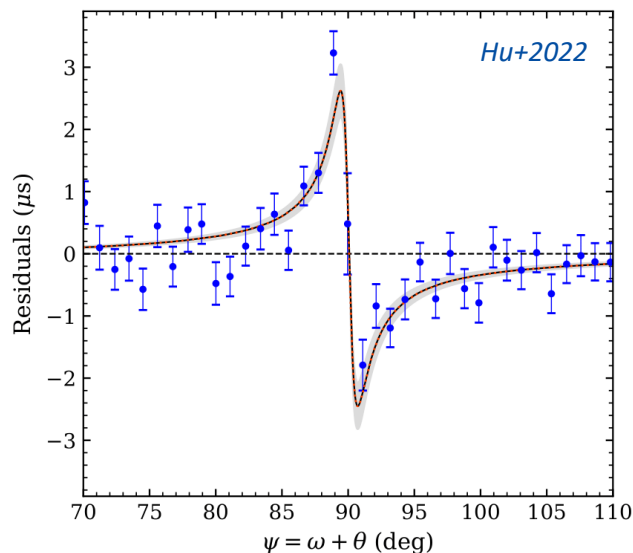
© N. Wex



# $\Phi$ NLO light propagation effects



3-yr MeerKAT data

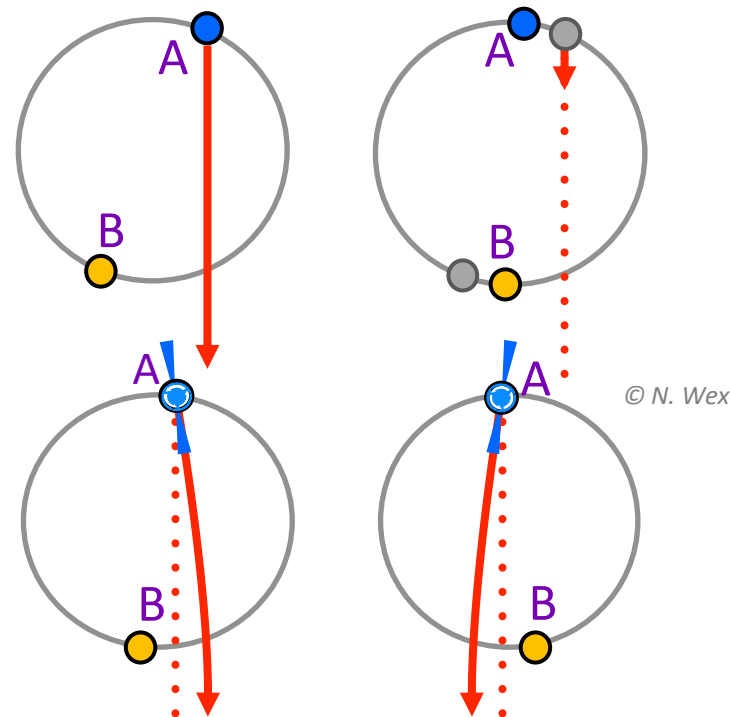


## Retardation effect

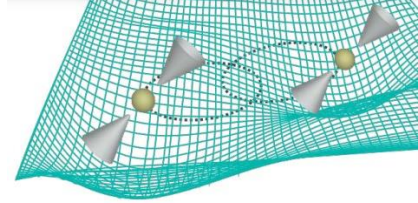
(Kopeikin & Schäfer 1999,  
Rafikov & Lai 2006a)

## Rotational deflection delay

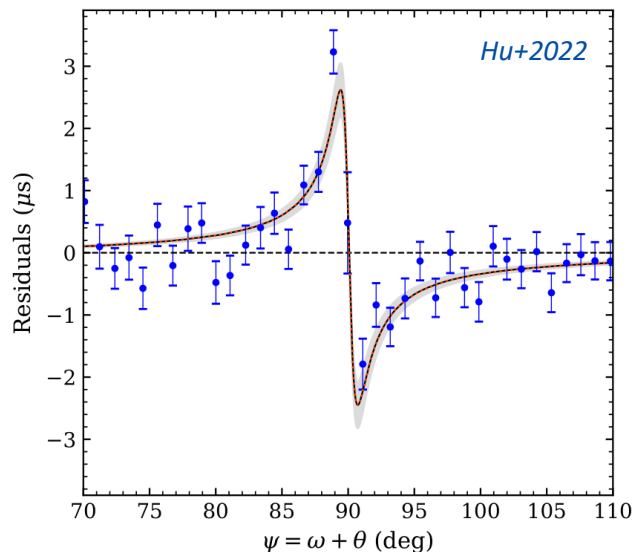
(Doroshenko & Kopeikin 1995,  
Rafikov & Lai 2006b)



# $\Phi$ NLO light propagation effects

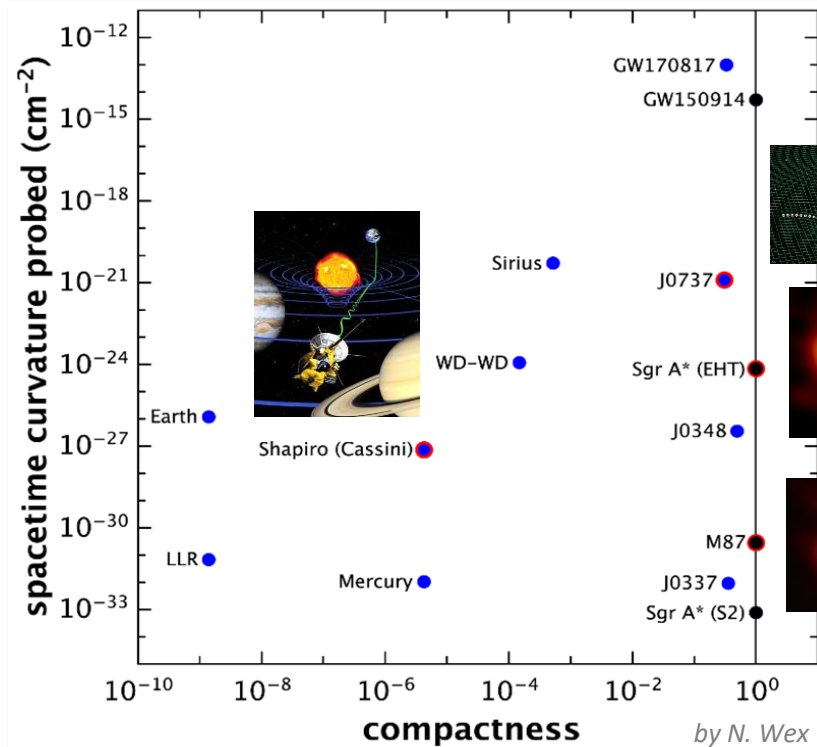


3-yr MeerKAT data



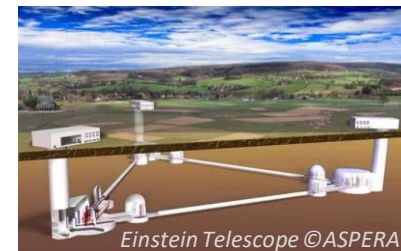
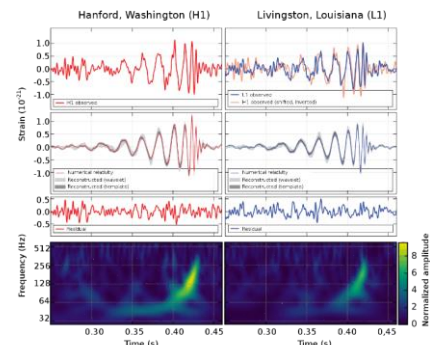
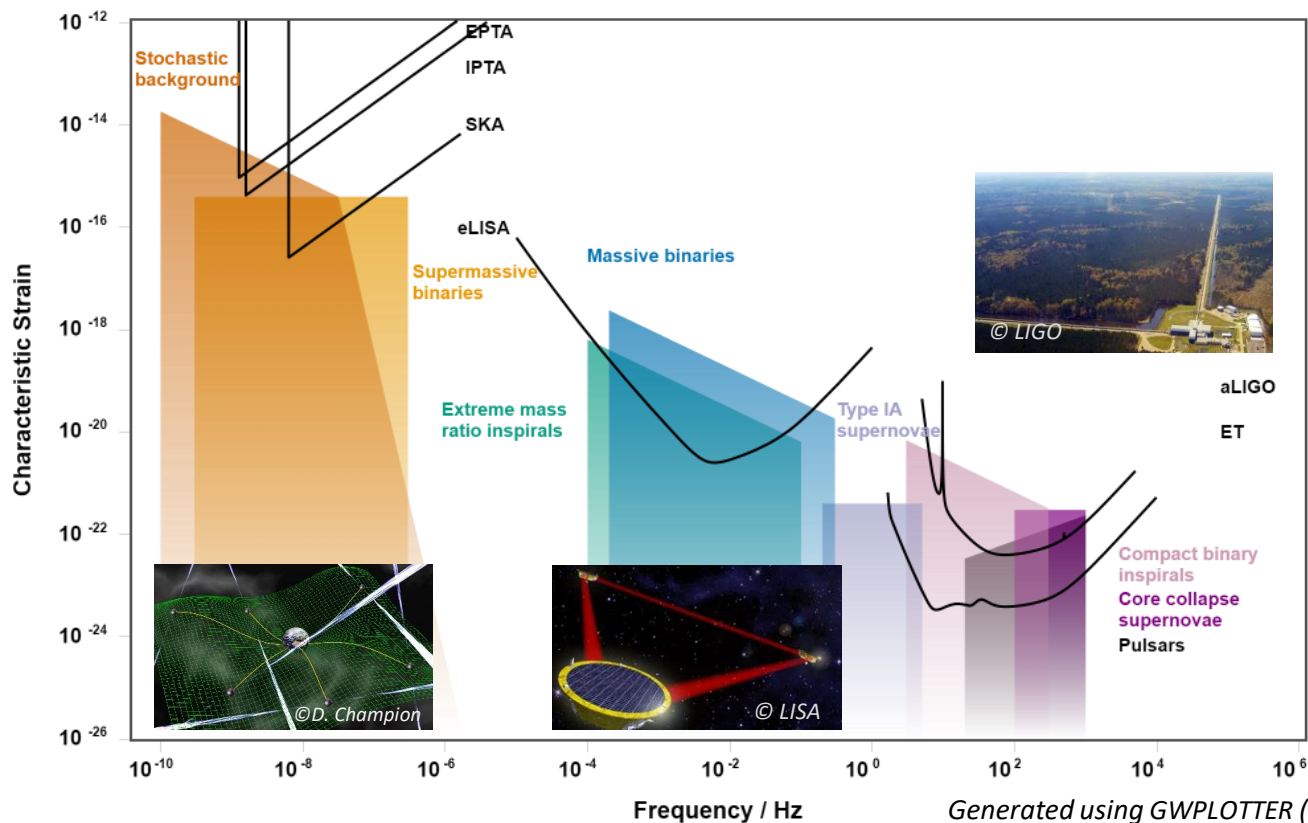
Obs./Exp: 0.999(79)

Best & unique test of NLO light propagation effects



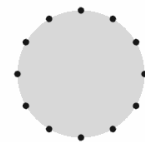


# GW spectrum and detectors

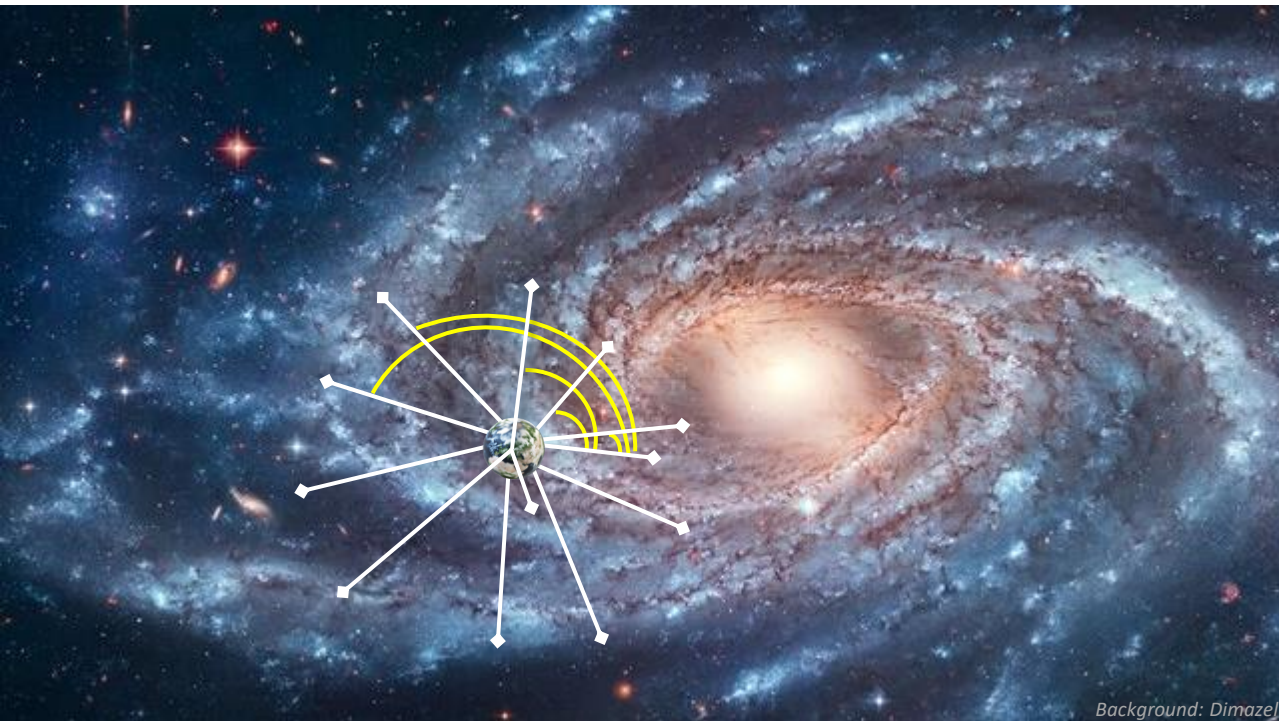


## II: Pulsar timing arrays: listening to the cosmic symphony from nanohertz GW sources





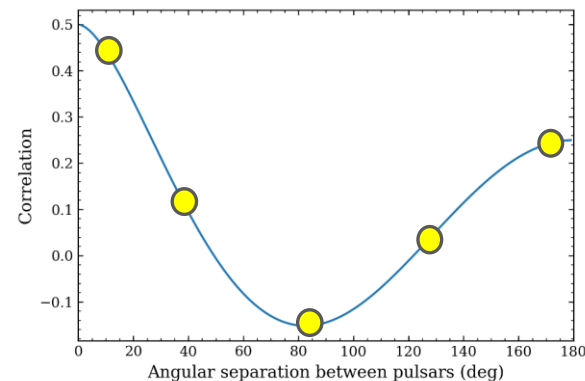
# A Galactic-Size GW detector



Background: DimazeJ

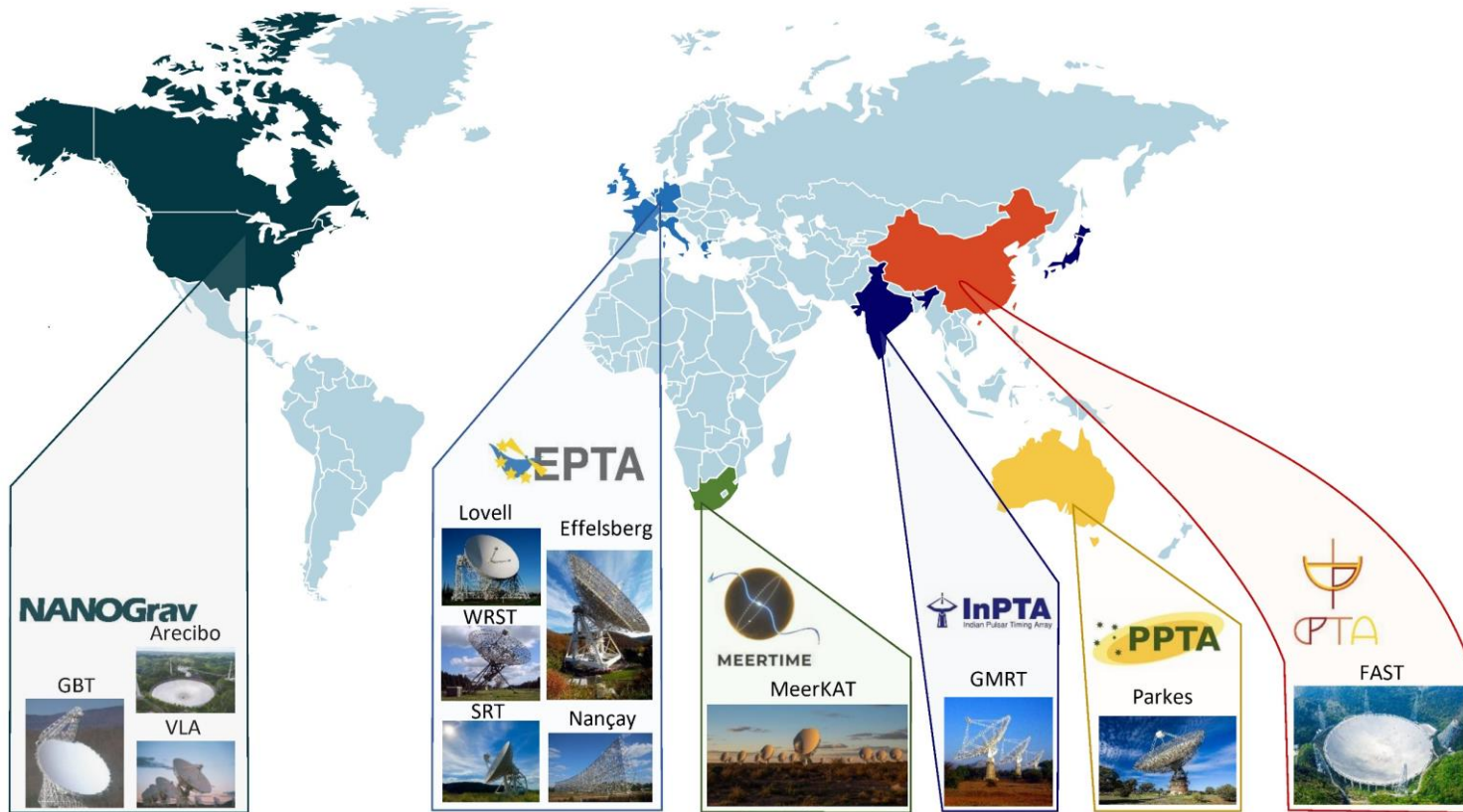
GWB induces a spacial correlation in pulsar pairs (Hellings & Downs 1983)

$$r(\theta) = \frac{1}{2} - \frac{1}{4} \left( \frac{1 - \cos \theta}{2} \right) + \frac{3}{2} \left( \frac{1 - \cos \theta}{2} \right) \ln \left( \frac{1 - \cos \theta}{2} \right)$$





# The International Pulsar Timing Array





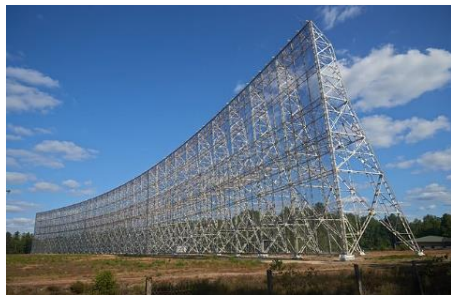
# European Pulsar Timing Array



Lovell (LT), 76 m, U.K.



Westerbork (WRST), 94 m, Netherlands



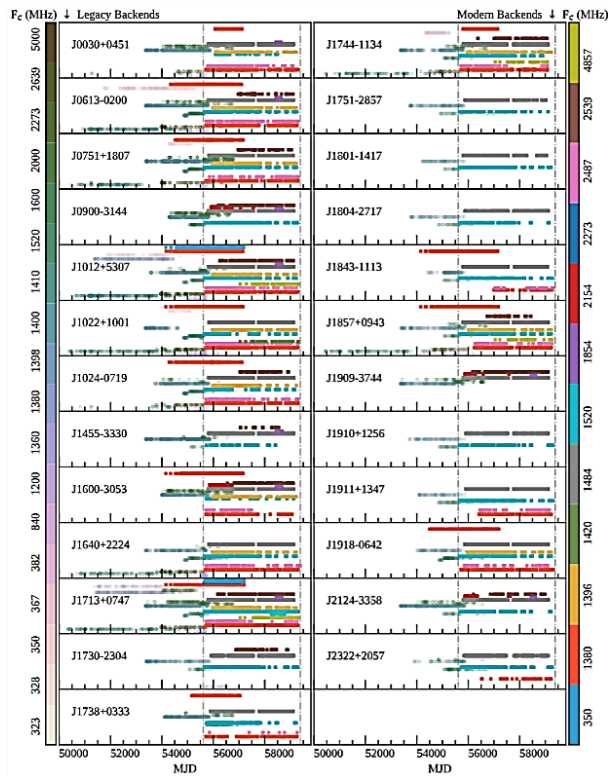
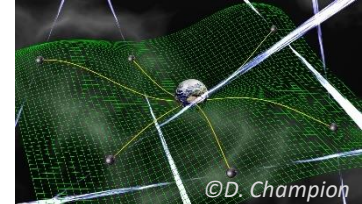
Nançay (NRT), 94 m, France



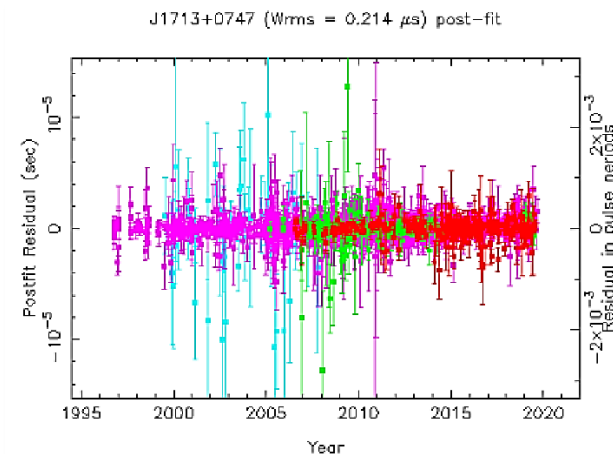
Sardinia (SRT), 64 m, Italy



# EPTA data release 2



EPTA DR2 25-yr data on 25 PSRs, longest data set!



$$P = 4.570\,136\,598\,154\,467\,\text{ms} \\ \pm 0.000\,000\,000\,000\,004$$

## PTA publications released on 29 June 2023

[illegible][illegible][illegible]

<https://doi.org/10.1093/ptc/ptaa001>

[illegible][illegible]

The narrowest gravitational wave background (GWB) is expected to be an aggregation of an ensemble of gravitational waves emitted predominantly by a large population of coalescing supermassive black hole binaries in the centers of merging galaxies. Pulsar timing arrays, ensembles of extremely stable pulsars, are the most precise experiments capable of detecting this background. However, the subtle metrics that the GWB induces on pulsar timing data are obscured by many sources of noise. These must be carefully characterized to increase the sensitivity to the GWB. In this paper, we present a new pipeline to estimate the optimal number of frequency calibrators for modelling the stochastic GWB. We compare our results against previous work, showing that the minimum number of calibrators required to detect the GWB can be reduced by up to a factor of two. We also perform a detailed analysis of the noise processes from 27 millisecond pulsars (MSPs) that form the second data release (SR2) of the IPTA and investigate the effects of incorporating low-frequency data from the Indian ITCA project. We compare our temporal parameters to compare noise models with those reported with the IPTA (SR1), find that, which is as expected, the SR2 model fits the data better than the SR1 model. Finally, we compare the results of our analysis with the current state-of-the-art GWB estimates from the IPTA (SR1–SR2). Using our simulations, we identify errors arising from our current analysis techniques and discuss their effect on GWB searches. The results presented here directly impact the GWB and are thus always being used as part of future FTA efforts.

<https://doi.org/10.1016/j.sbspro.2012.07.008>

We present the results of a search for continuous gravitational-wave signals (CWGs) at various window sizes during O3 by the LIGO-Virgo-KAGRA collaboration. The most significant candidate event from this search has a gravitational-wave frequency of  $\sim 1$ - $10$  Hz, which signal could be generated by a supermassive black hole binary (SMBHB) in the local Universe. We present the results of a follow-up analysis of this event using both Bayesian and frequentist methods. The Bayesian analysis gives a Bayes factor of  $\sim 10^6$  in favor of the presence of the CWG over a common uncorrelated noise process, while a signal model estimates the  $p$ -value of the fit as  $1\%$ , although it does not account for the uncertainty associated with the choice of the waveform template. In contrast, the frequentist analysis shows that the power spectrum of the observed feature, had we no access to real or a CWG source. We present results of simulations that demonstrate that data containing a weak gravitational-wave background can be misinterpreted as data including a CWG and vice versa, providing no conclusive explanation of the O3 data. Further investigations combining data from all GW collaborations will be needed to reach the true origin of this feature.

[illegible]

The European Pulsar Timing Array (EPTA) and Indian Pulsar Timing Array (IPTA) campaigns have measured a low-frequency common signal in the combination of their second and first data release respectively, with the correlation properties of a quasi-stochastic wave background (CWB). Such signal may have its origin in a number of physical processes including a remote population of inspiralling supermassive black hole binaries (SMBHBs), isotropic cosmic strings or tensor mode gravity by the non-linear evolution of scalar perturbations in the early universe, oscillations of the Galactic potential in the presence of ultra-light dark matter particles (ULDM). As the current generation of pulsar timing arrays are sensitive to frequencies below 100 nHz, it is difficult to distinguish between these different models. However, if the ULDM model is correct, the CWB will exhibit a characteristic frequency dependence where the relative high amplitude can be used to place constraints on dark energy timescales and on the SMBH-log galaxy scaling relations. If the signal is confirmed, this is the first direct evidence that SMBHs grow in nature, adding an important observational piece in the puzzle of structure formation and galaxy evolution. As for early universe processes, the ULDM model predicts a specific frequency dependence of the CWB which can be tested by future observations. The present work requires more standard scenarios, such as a lower inflationary reheating rate or an excess of production of solar polarizations at large wavelengths. Finally, a ULDM origin of the detected signal is discussed, along with binary drag constraints on the abundance of ULDM in our Galaxy.

[illegible]

150 <https://doi.org/10.1093/mnras/stz298>

510 [doi:10.1371/journal.pone.0142439.g001](#) [http://dx.doi.org/10.1371/journal.pone.0142439.g001](#)

**Figure 9: High Energy Astrophysical Phenomena (HEAP) and Solar and Stellar Anomalous (SSA) General Model and Quantum Correlation (qq).** The figure shows the results of the model fit to the SSA and HEAP data. The top panel displays the SSA data (red circles) and the model fit (blue line). The bottom panel displays the HEAP data (red circles) and the model fit (blue line). The x-axis represents the energy in GeV, and the y-axis represents the flux in  $\text{cm}^{-2} \text{s}^{-1} \text{GeV}^{-1}$ . The model fit is shown as a solid blue line, and the data points are shown as red circles with error bars. The top panel also includes a legend for the SSA data and the model fit. The bottom panel includes a legend for the HEAP data and the model fit. The figure is titled "Figure 9: High Energy Astrophysical Phenomena (HEAP) and Solar and Stellar Anomalous (SSA) General Model and Quantum Correlation (qq)".

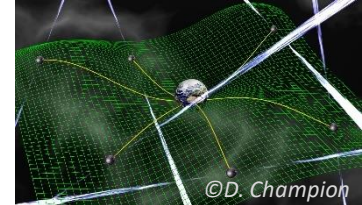
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[www.elsevier.com/locate/chaos](http://www.elsevier.com/locate/chaos)   
 CHAOS, SOLITONS & FRACTALS

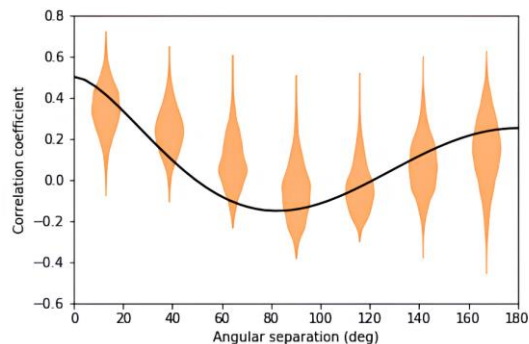
19



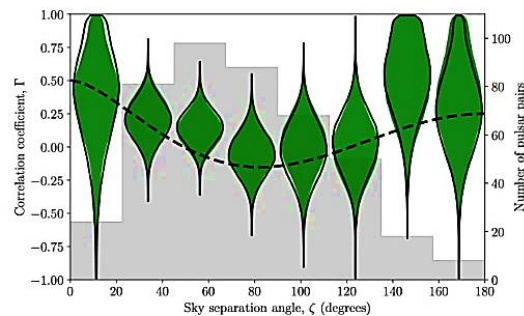
# Evidence of HD correlation



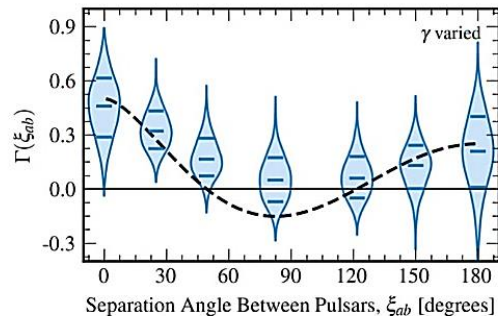
*EPTA*



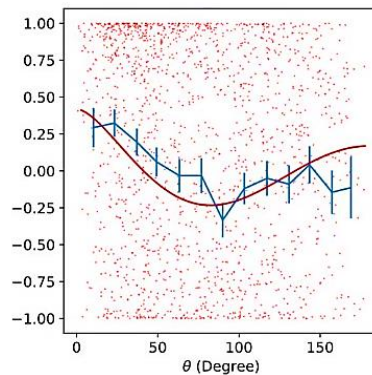
*PPTA*



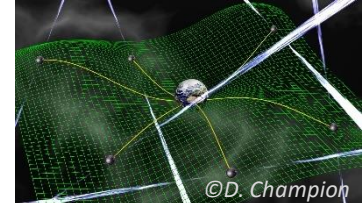
*NANOGrav*



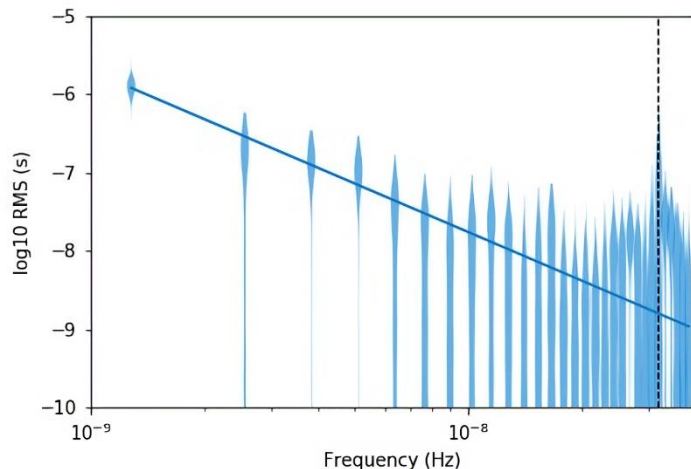
*CPTA*



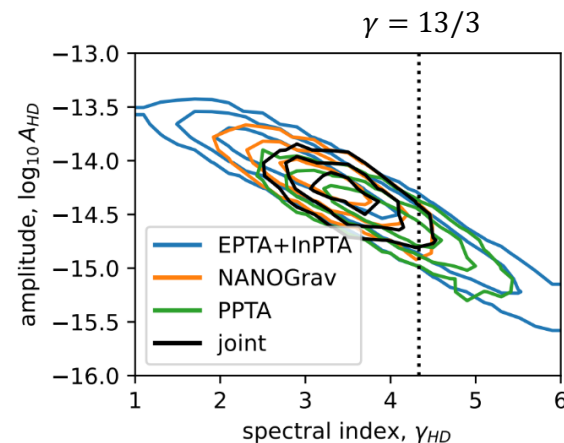
# Φ GWB spectrum



- The stochastic GWB is characterized by a strain spectrum:  $h_c(f) = A \left(\frac{f}{f_c}\right)^\alpha$
- Power spectral density of the GWB induced residuals:  $S_{\text{GWB}} = \frac{A^2}{12\pi^2} \left(\frac{f}{f_c}\right)^{-\gamma} f_c^{-3}$ , where  $\gamma = 3 - 2\alpha$
- For a population of circular SMBHBs,  $\gamma = 13/3$

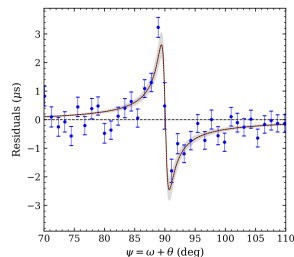


EPTA paper III (2023)



IPTA 3P+ (under review, arXiv:2309.00693)

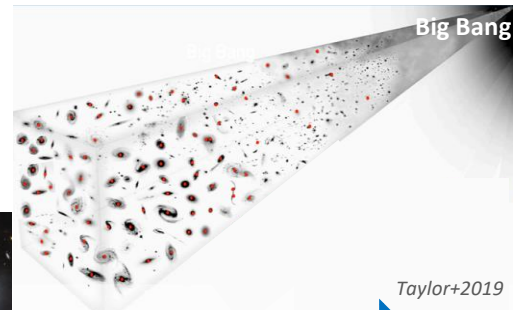
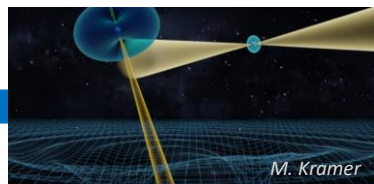
# $\Phi$ Summary



## Best test of gravitational signal propagation effects

in pulsars using MeerKAT telescope [Hu+2022, A&A, 667, A149](#)

- Data processing challenge with MeerKAT/SKA (Hu+ in prep.)
- Data combination challenge (Hu+ in prep.)



## Matter

A novel method to measure neutron star moment of inertia

[Hu+2020, MNRAS, 497, 3118](#)

Invited review on this method (Hu & Freire, submitted)

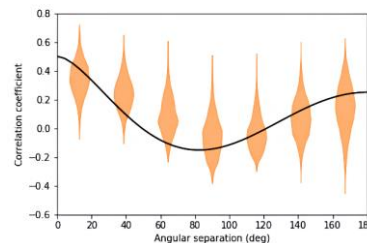
New **gravity** tests with MeerKAT & SKA:

Lense-Thirring effect and NLO GW damping [Hu+2020, MNRAS, 497, 3118](#)

Testing scalar-tensor gravity with PSR-BH systems [Batraikov, Hu+2023, A&A](#)

## First evidence of nanohertz **GWB** with EPTA

[EPTA I-VI 2023, IPTA 2024&2023&2022, EPTA 2021 etc.](#)



More to come with MeerTime PTA, IPTA DR3, and SKA...

# Thank you



First SKA-mid dish,  
Feb 2024



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First SKA-low dish,  
Mar 2024



© SKAO