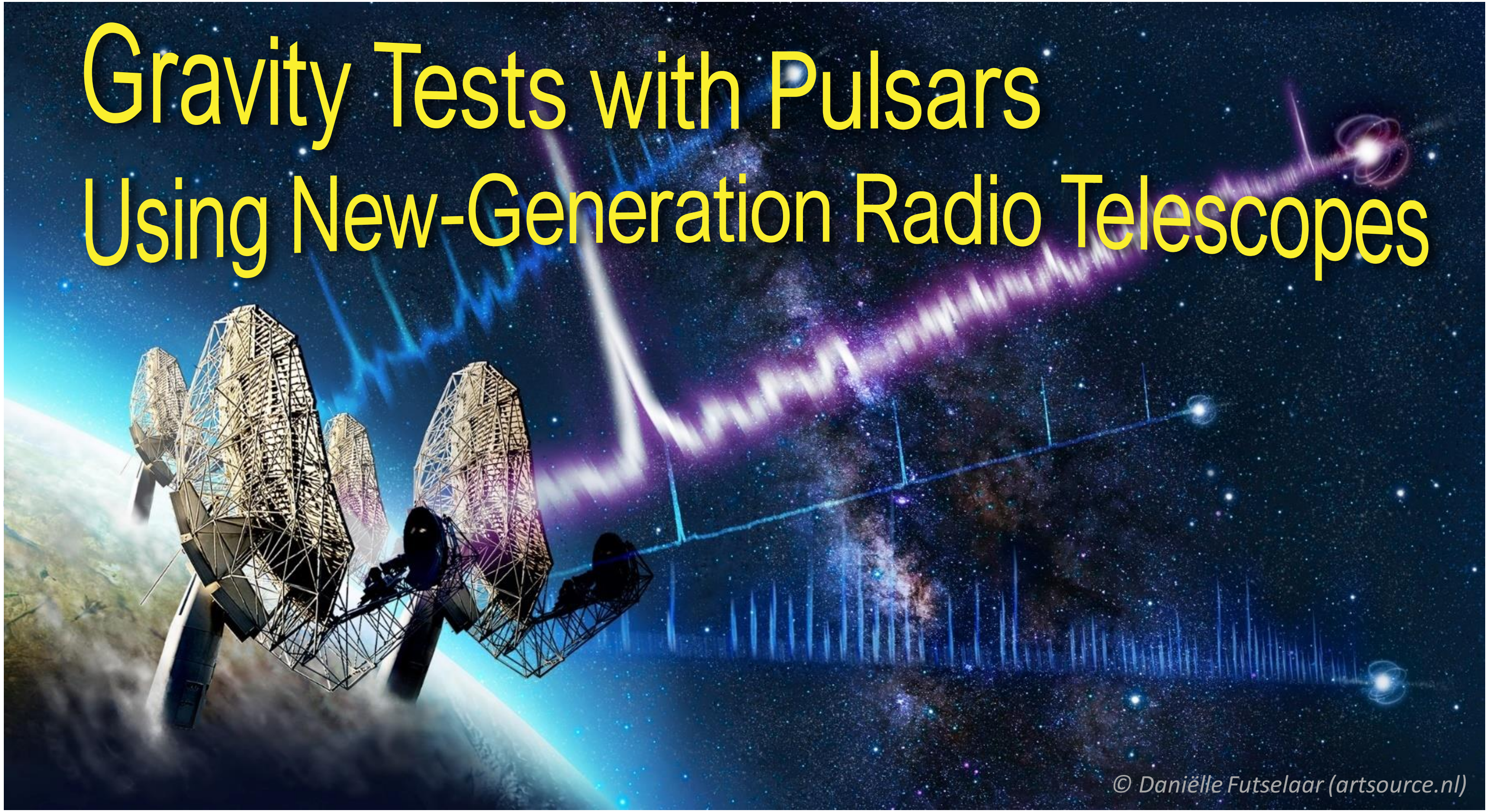
Gravity Tests with Pulsars Using New-Generation Radio Telescopes

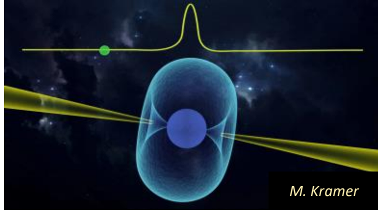


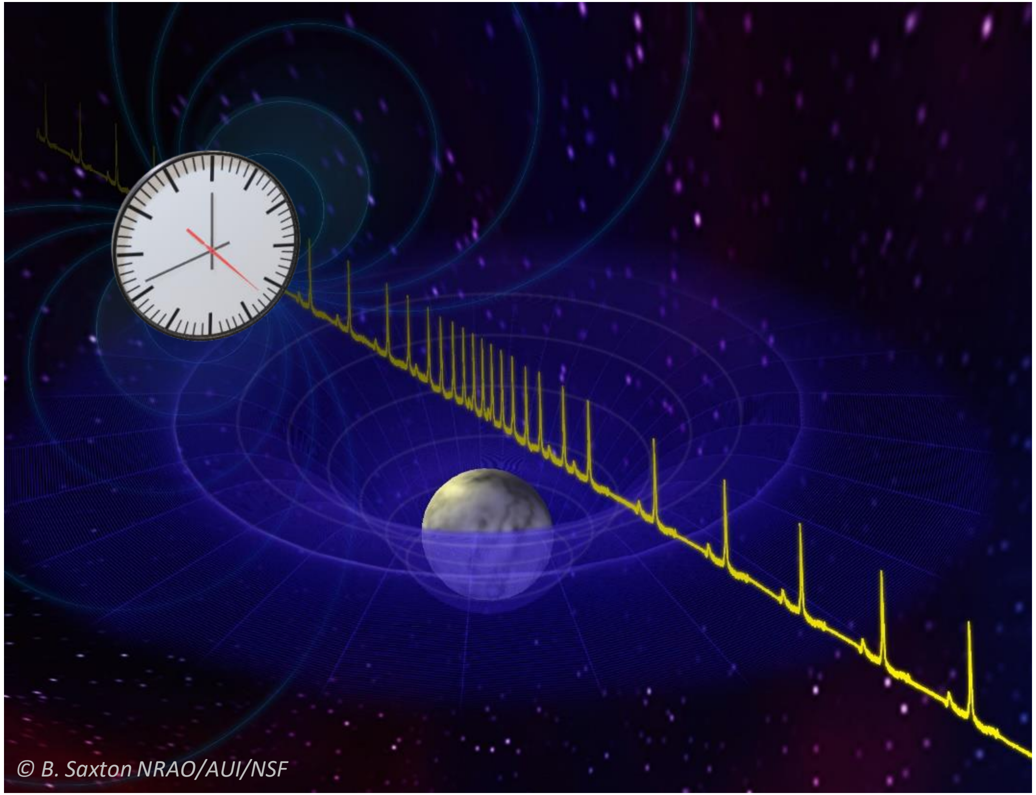
Huanchen Hu

DPG SMuK Dissertation Symposium, Gießen

11.3.2024

Cosmic clocks → Pulsars





Magnetised rotating neutron stars

$\mathrm{M} \sim 1.4\ \mathrm{M}_{\odot},\ R \sim 10\ \mathrm{km}$

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

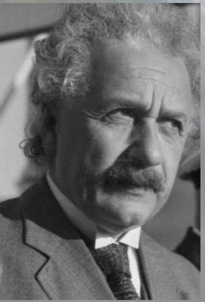
PSR J1713+0747:

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

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

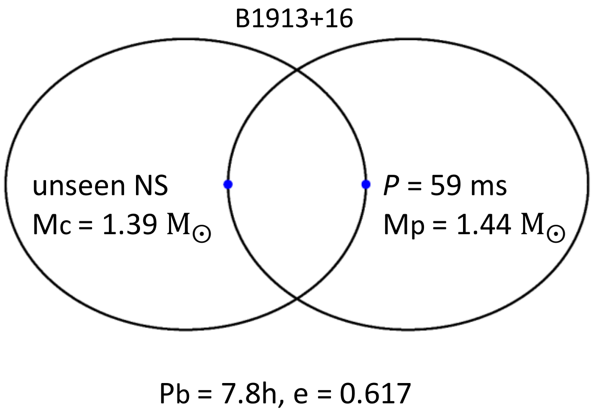
How matter behaves at extreme densities?

- Measuring neutron star moment of inertia with radio pulsars

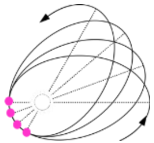
Einstein photo by Bettmann Archive
Background image: Aurore Simonnet

50th 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."



PK parameters in GR (leading order)



Orbital precession

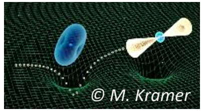
$$\dot{\omega}^{1\mathrm{PN}} = 3T_\odot^{2/3}\left(\frac{2\pi}{P_\mathrm{b}}\right)^{5/3}\frac{1}{1-e_\mathrm{T}^2}(m_\mathrm{A}+m_\mathrm{B})^{2/3}$$

Orbital period decay

$$\dot{P}_\mathrm{b}^{2.5\mathrm{PN}} = -\frac{192\pi}{5}T_\odot^{5/3}\left(\frac{2\pi}{P_\mathrm{b}}\right)^{5/3}\frac{1+\frac{73}{24}e_\mathrm{T}^2+\frac{37}{96}e_\mathrm{T}^4}{(1-e_\mathrm{T}^2)^{7/2}}\frac{m_\mathrm{A}m_\mathrm{B}}{(m_\mathrm{A}+m_\mathrm{B})^{1/3}}$$

Einstein delay

$$\gamma_\mathrm{E} = T_\odot^{2/3}\left(\frac{2\pi}{P_\mathrm{b}}\right)^{-1/3} e_\mathrm{T}\frac{m_\mathrm{B}(m_\mathrm{A}+2m_\mathrm{B})}{(m_\mathrm{A}+m_\mathrm{B})^{4/3}}$$



Shapiro delay

$$r = T_\odot m_\mathrm{B} \qquad s = T_\odot^{-1/3}\left(\frac{2\pi}{P_\mathrm{b}}\right)^{2/3} x\,\frac{(m_\mathrm{A}+m_\mathrm{B})^{2/3}}{m_\mathrm{B}}$$

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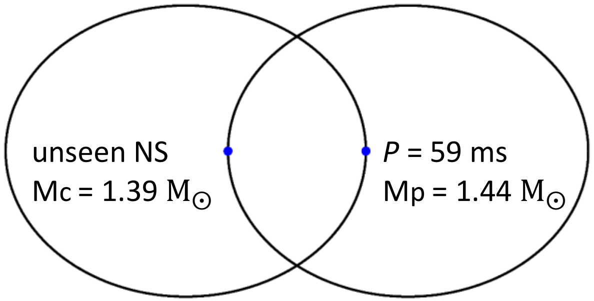
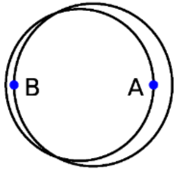
B1913+16

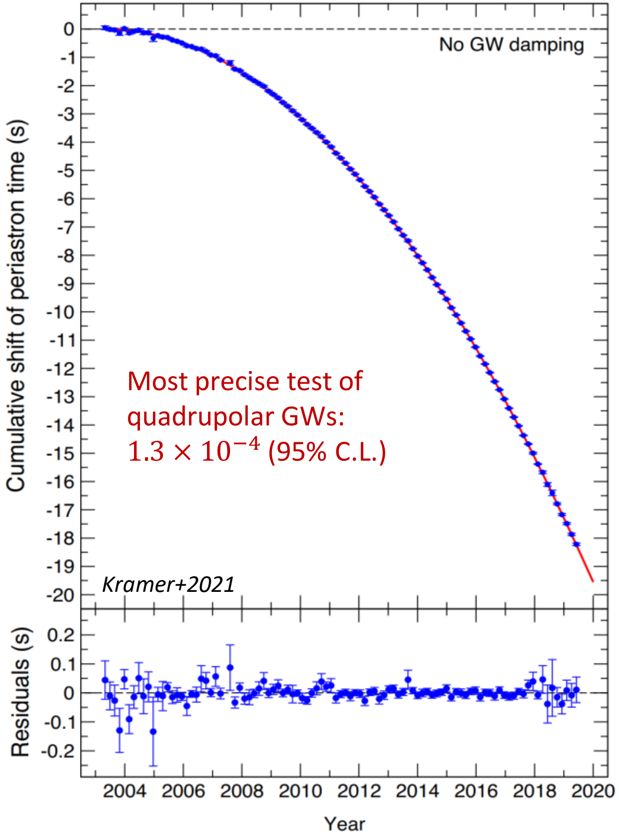


Pb = 7.8h, e = 0.617

J0737-3039



Pb = 2.5h, e = 0.088



Φ 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

MEERTIME

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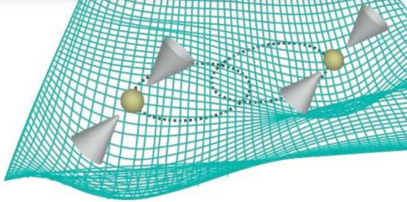
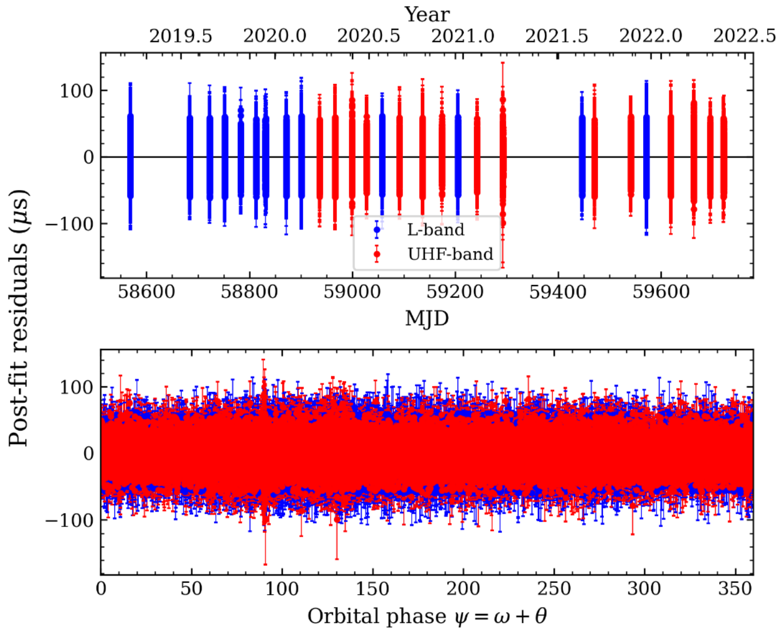


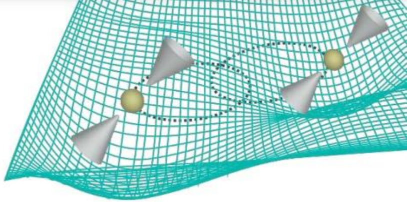
Timing results



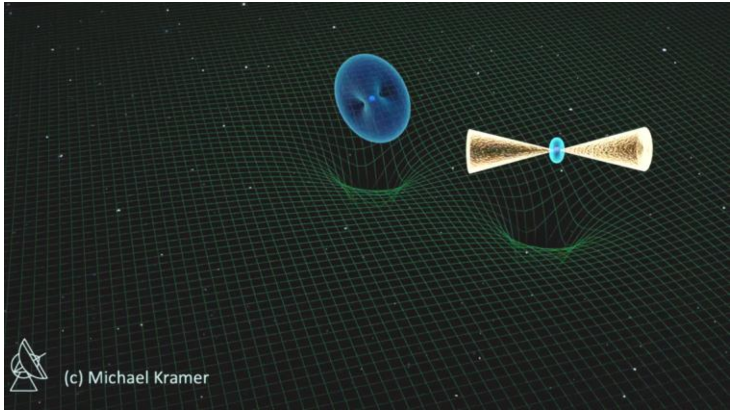
221,381 TOAs
4,388,187,911 rotations
reduced χ^2 = 0.99

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, ω (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, γ_E (ms)	0.384 045(94) (*)
Logarithmic Shapiro shape, z_s	9.669(77)
Range of Shapiro delay, r (μs)	6.163(16)
NLO factor for signal prop., q_{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)

Hu et al. 2022



Shapiro delay



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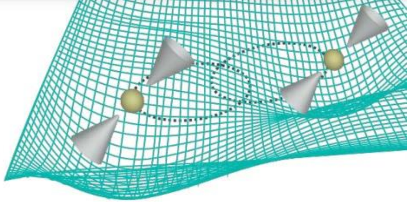
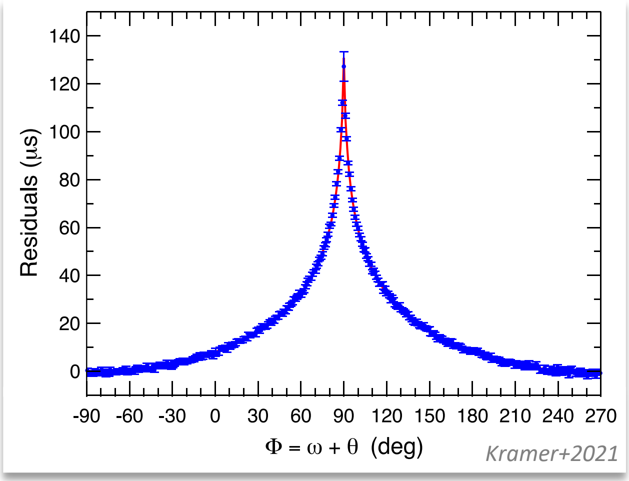


Φ Shapiro delay



Kramer+2021

"Shape" improves by 2 times

"Range": Obs./Exp. = 1.0019(26), validating GR at 5.3 × 10^{-3} (95% C.L.)

Most precise NS mass measurements!

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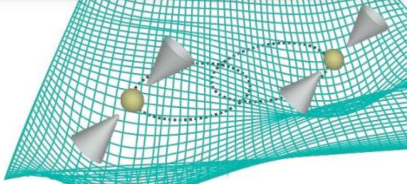
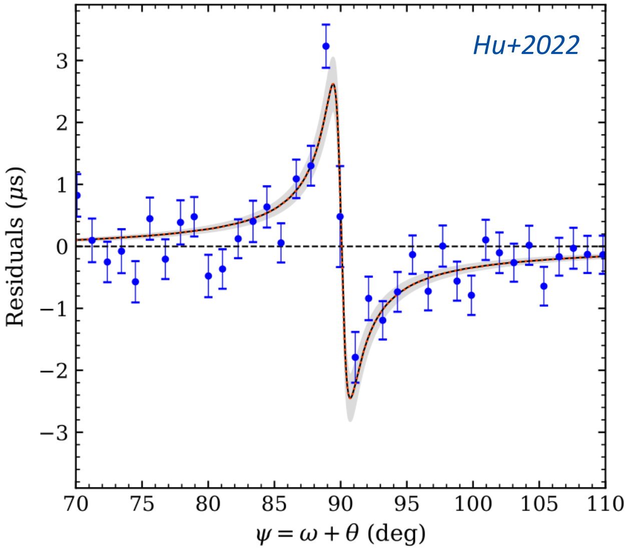


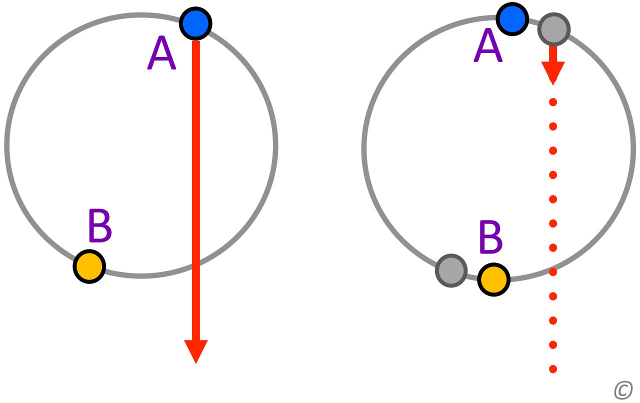
Φ NLO light propagation effects

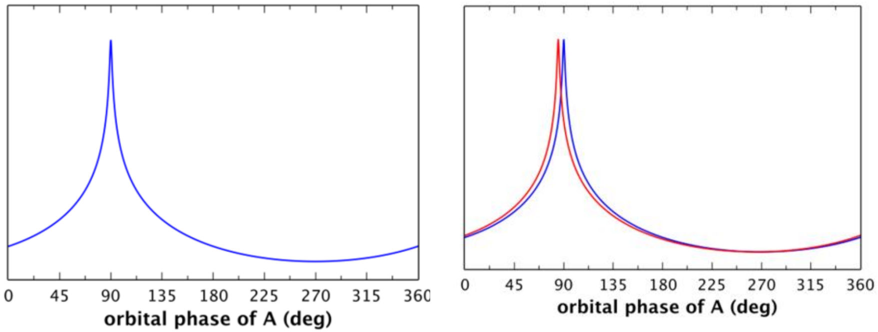
3-yr MeerKAT data



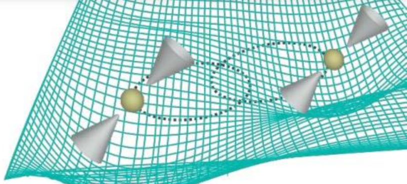
Retardation effect

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





Hu et al. 2022



NLO light propagation effects

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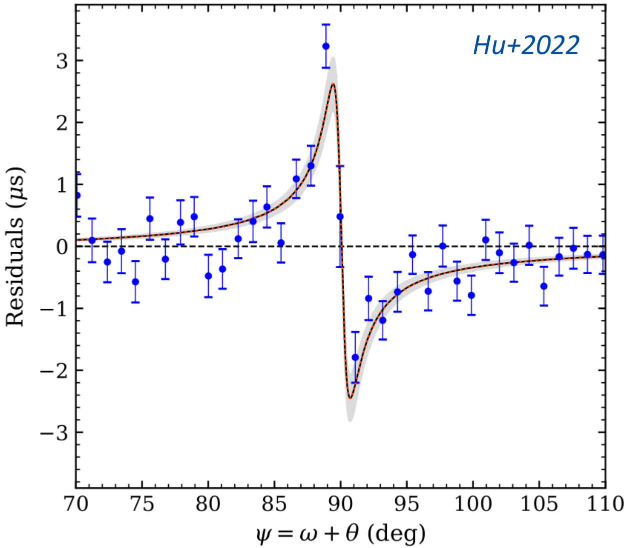
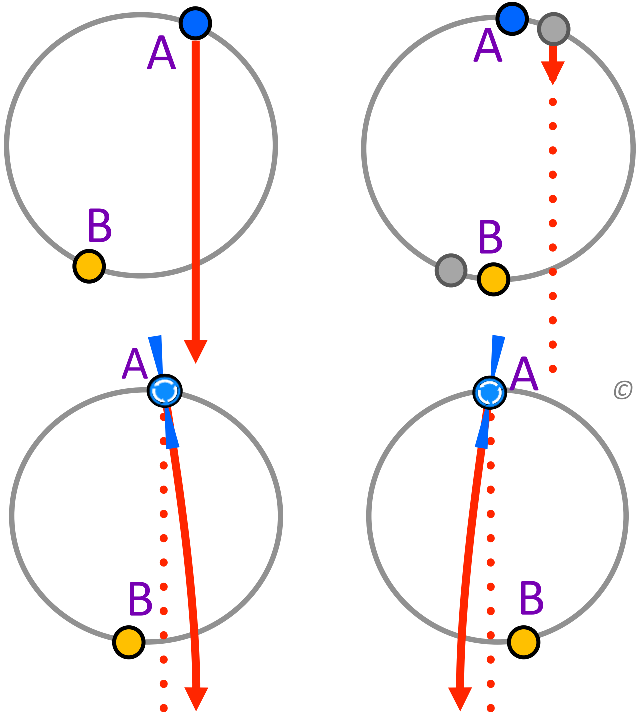


Retardation effect

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

Rotational deflection delay

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



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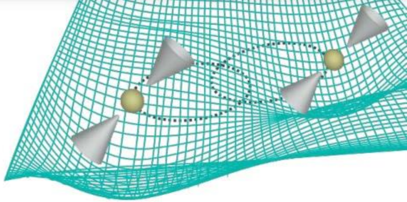

NLO light propagation effects

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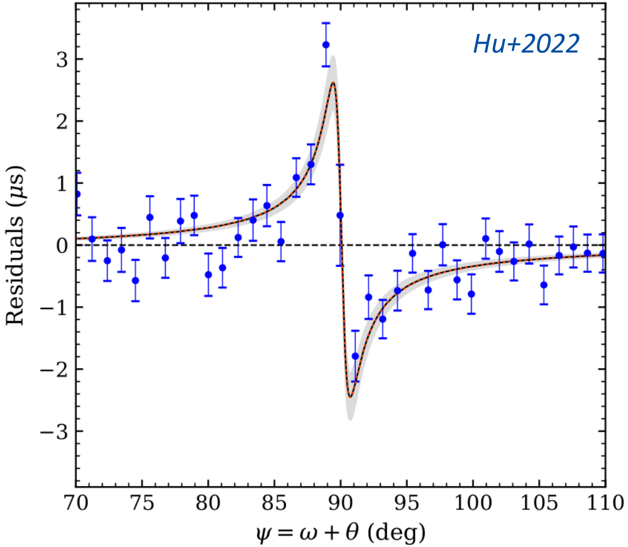
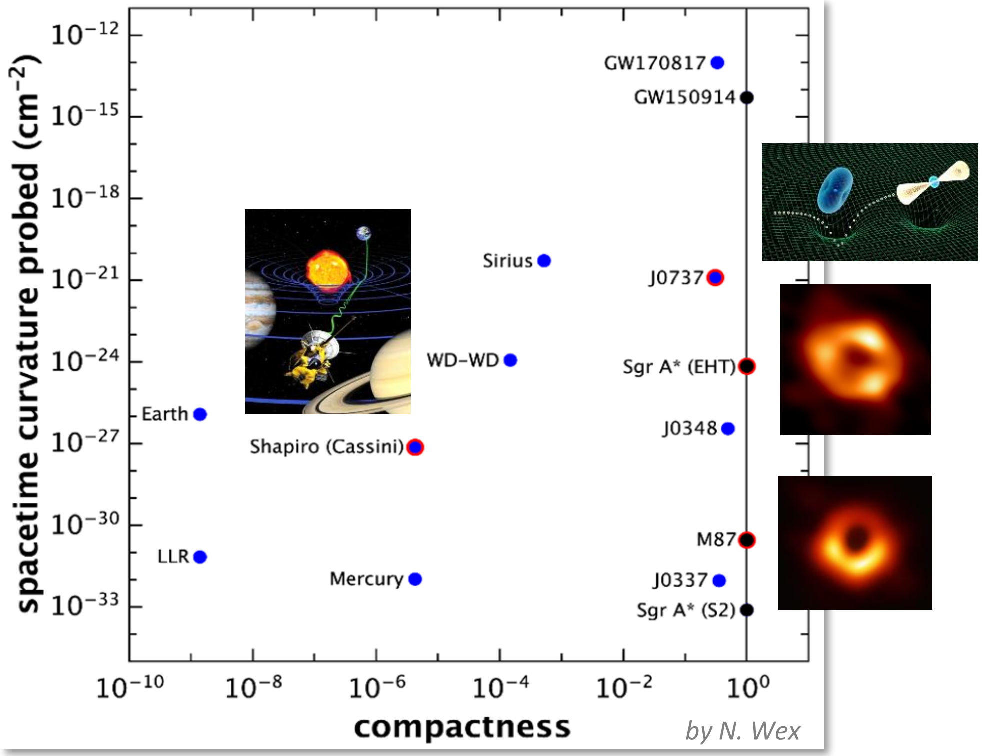


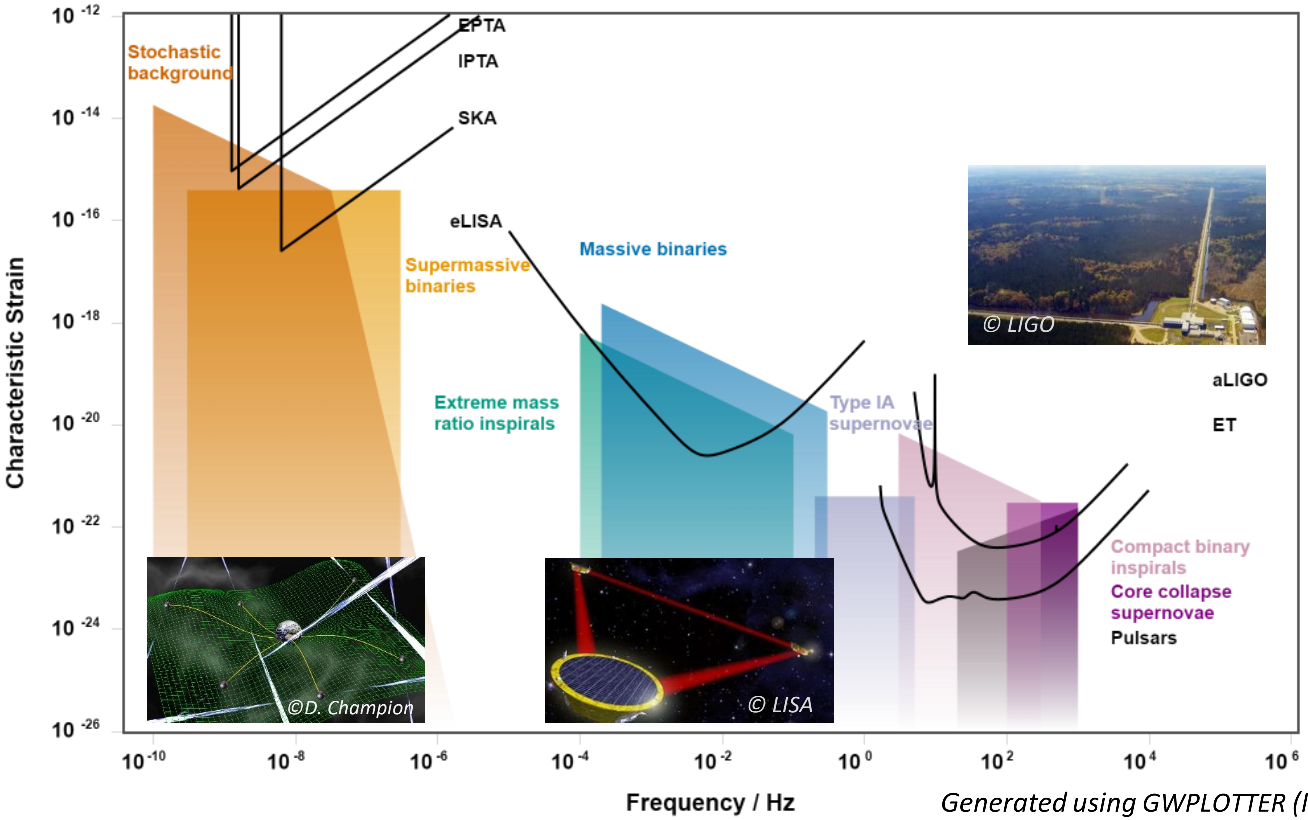


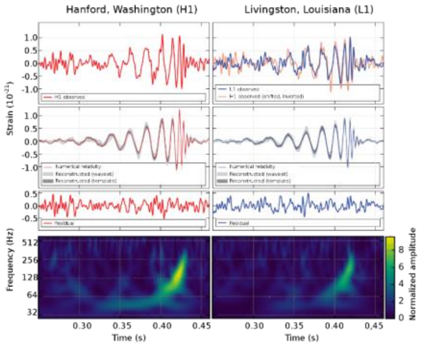
Obs./Exp: 0.999(79)

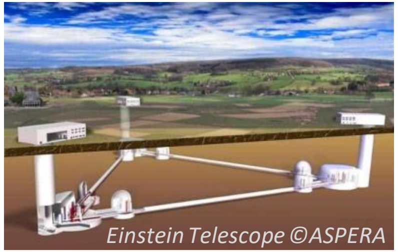
Best & unique test of NLO light propagation effects

Hu et al. 2022

GW spectrum and detectors





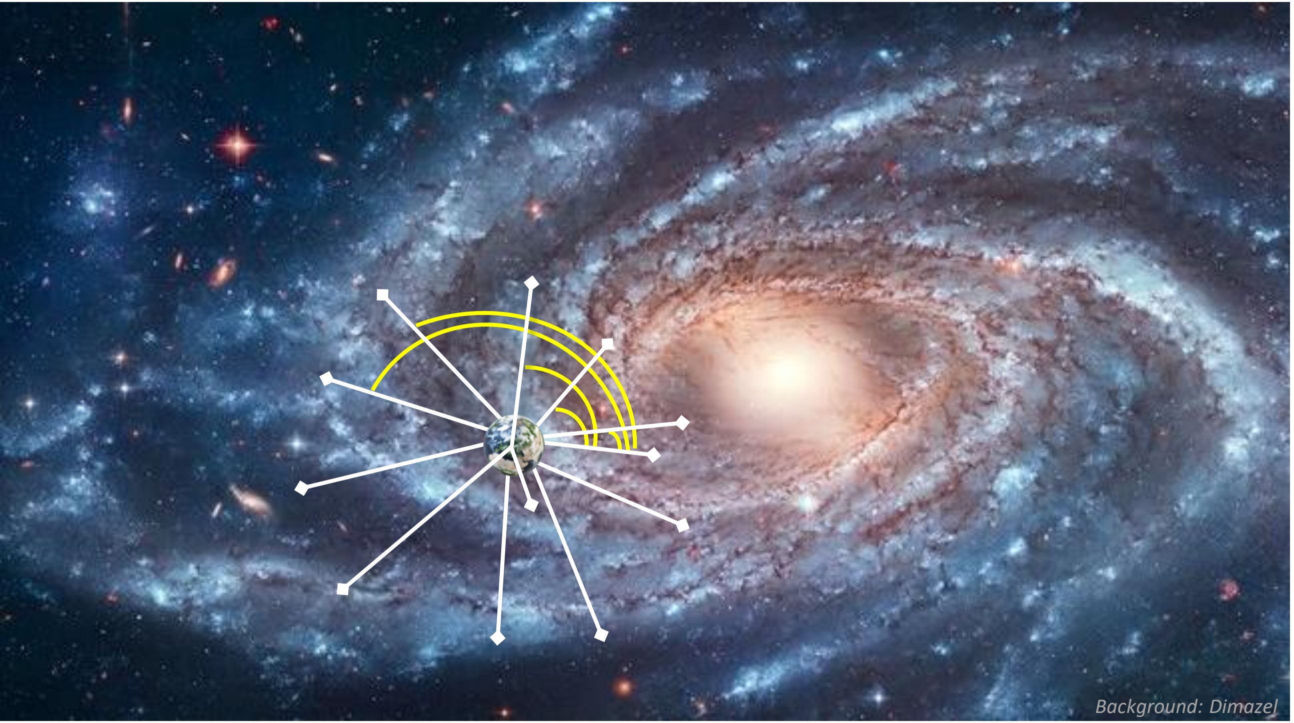


Generated using GWPLOTTER (Moore+2015)

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

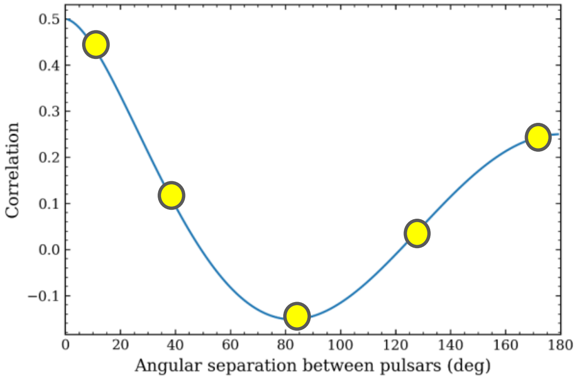
© Daniëlle Futselaar / MPIfR

A Galactic-Size GW detector

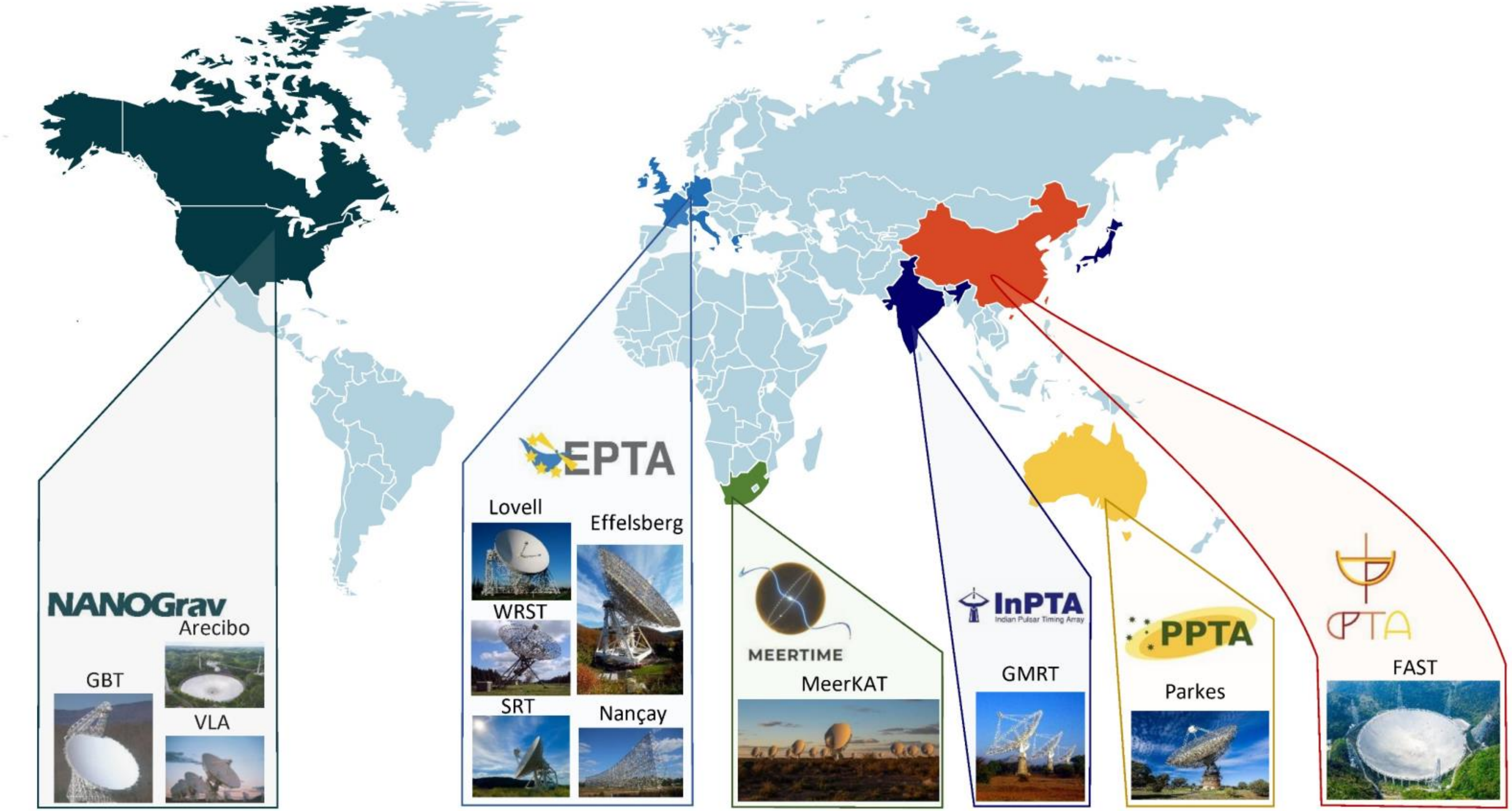


GWB induces a spacial correlation in pulsar pairs (Hellings & Downs 1983)

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



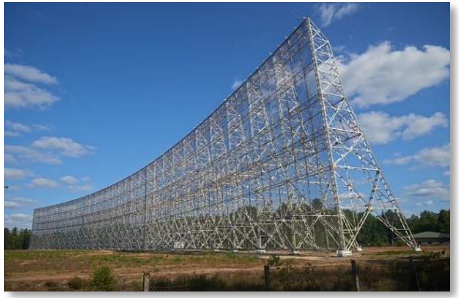
The International Pulsar Timing Array



European Pulsar Timing Array

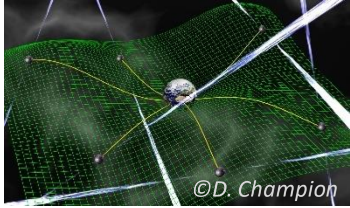
Lovell (LT), 76 m, U.K.

Westerbork (WRST), 94 m, Netherlands

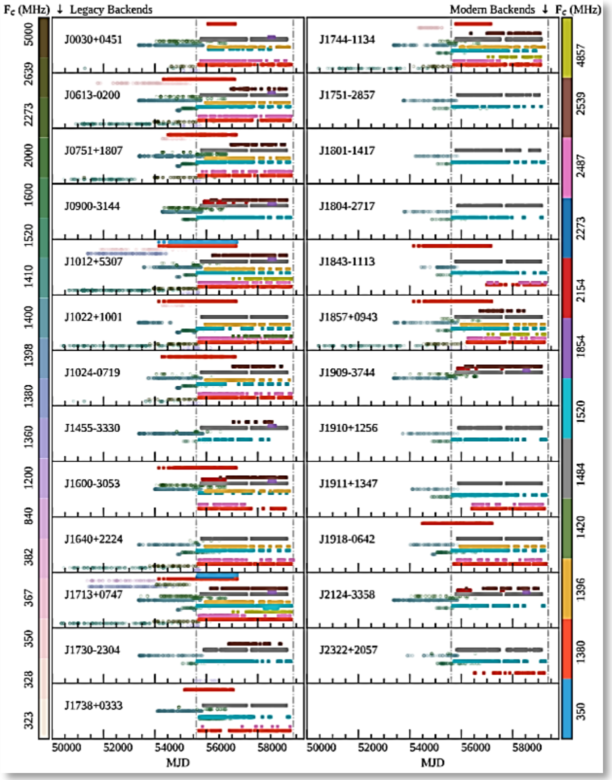


Nançay (NRT), 94 m, France

Sardinia (SRT), 64 m, Italy

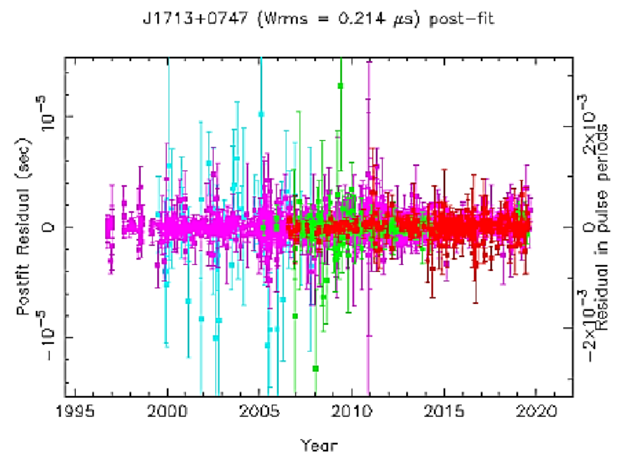


EPTA data release 2



EPTA paper I (2023)

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



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

18 PTA publications released on 29 June 2023

arXiv:2306.16213 - 2306.16230

37) arXiv:2306.16213 [pdf, other] The NANOGrav 15-year Data Set: Evidence for a Gravitational-Wave Background

38) arXiv:2306.16214 [pdf, other] The second data release from the European Pulsar Timing Array III. Search for gravitational wave signals

39) arXiv:2306.16215 [pdf, other] Search for an isotropic gravitational-wave background with the Parkes Pulsar Timing Array

40) arXiv:2306.16216 [pdf, other] Searching for the nano-Hertz stochastic gravitational wave background with the Chinese Pulsar Timing Array Data Release I

41) arXiv:2306.16217 [pdf, other] The NANOGrav 15-year Data Set: Observations and Timing of 68 Millisecond Pulsars

42) arXiv:2306.16218 [pdf, other] The NANOGrav 15-Year Data Set: Detector Characterization and Noise Budget

43) arXiv:2306.16219 [pdf, other] The NANOGrav 15-year Data Set: Search for Signals from New Physics

44) arXiv:2306.16220 [pdf, other] The NANOGrav 15-year Data Set: Constraints on Supermassive Black Hole Binaries from the Gravitational Wave Background

45) arXiv:2306.16221 [pdf, other] The NANOGrav 15-year Data Set: Search for Anisotropy in the Gravitational-Wave Background

46) arXiv:2306.16222 [pdf, other] The NANOGrav 15-year Data Set: Bayesian Limits on Gravitational Waves from Individual Supermassive Black Hole Binaries

47) arXiv:2306.16223 [pdf, other] The NANOGrav 15-year Gravitational-Wave Background Analysis Pipeline

48) arXiv:2306.16224 [pdf, other] The second data release from the European Pulsar Timing Array I. The dataset and timing analysis

49) arXiv:2306.16225 [pdf, other] The second data release from the European Pulsar Timing Array II. Customised pulsar noise models for spatially correlated gravitational waves

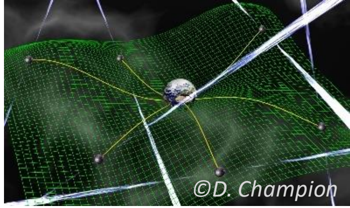
50) arXiv:2306.16226 [pdf, other] The second data release from the European Pulsar Timing Array IV. Search for continuous gravitational wave signals

51) arXiv:2306.16227 [pdf, other] The second data release from the European Pulsar Timing Array: V. Implications for massive black holes, dark matter and the early Universe

52) arXiv:2306.16228 [pdf, other] The second data release from the European Pulsar Timing Array: VI. Challenging the ultralight dark matter paradigm

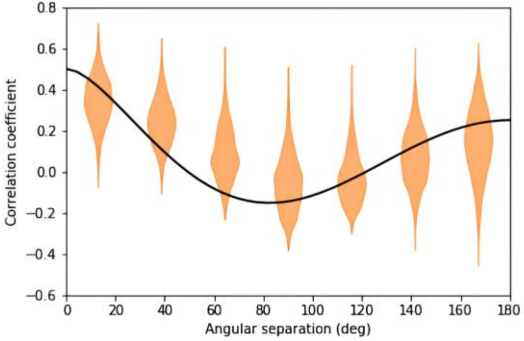
53) arXiv:2306.16229 [pdf, other] The gravitational-wave background null hypothesis: Characterizing noise in millisecond pulsar arrival times with the Parkes Pulsar Timing Array

54) arXiv:2306.16230 [pdf, other] The Parkes Pulsar Timing Array Third Data Release

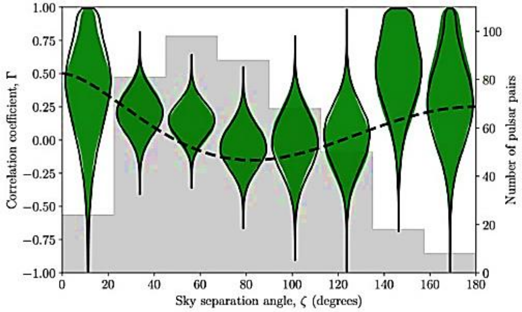


Evidence of HD correlation

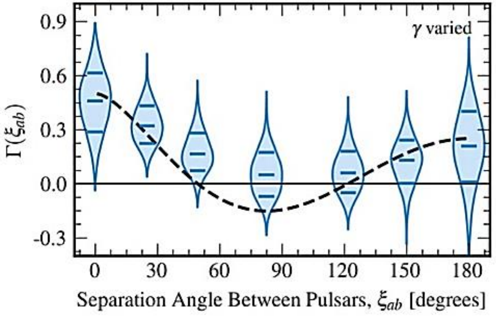
EPTA



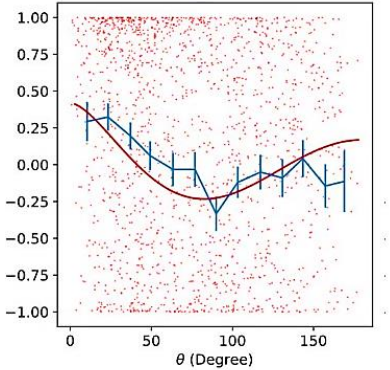
PPTA

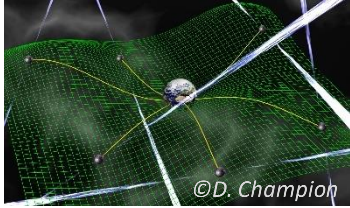


NANOGrav



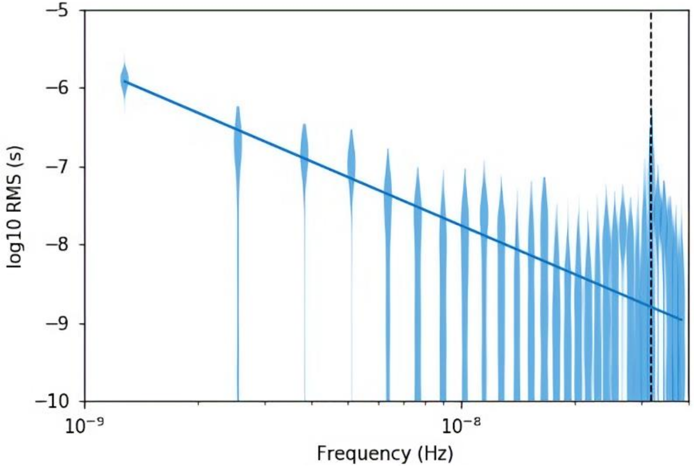
CPTA



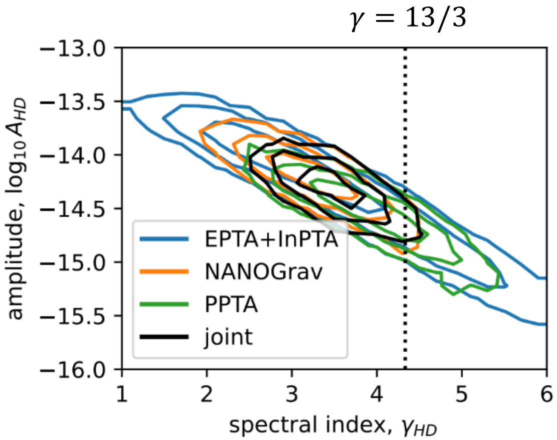


GWB spectrum

- 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: $S_{\mathrm{GWB}} = \frac{A^2}{12\pi^2}\left(\frac{f}{f_c}\right)^{-\gamma} f_c^{-3}$, where $\gamma = 3 - 2\alpha$
- For a population of circular SMBHBs, $\gamma = 13/3$

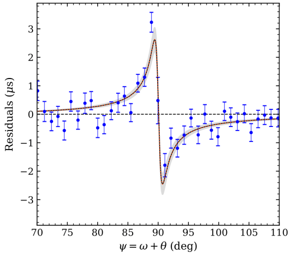


EPTA paper III (2023)



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

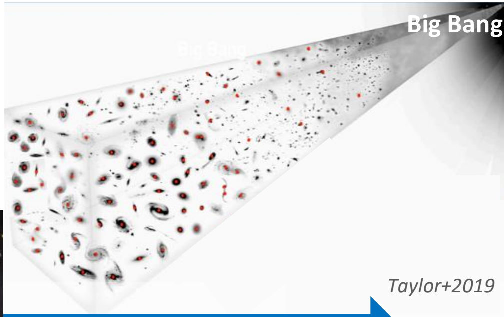
Summary

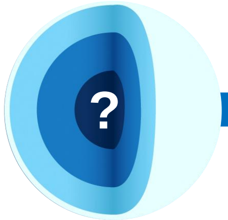


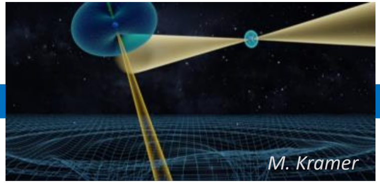
Best test of gravitational signal propagation effects

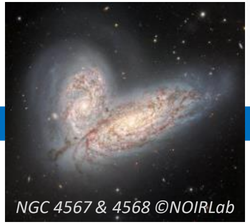
in pulsars using MeerKAT telescope Hu+2022, A&A, 667, A149

- 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)

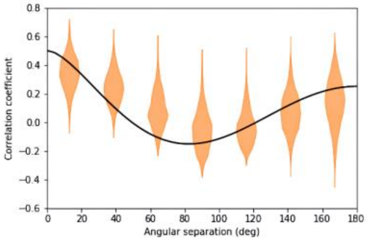
New **gravity** tests with MeerKAT & SKA:

Lense-Thirring effect and NLO GW damping Hu+2020, MNRAS, 497, 3118

Testing scalar-tensor gravity with PSR-BH systems Batrakov, 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

First SKA-low dish, Mar 2024