Probing New Physics with Pulsar Timing Arrays

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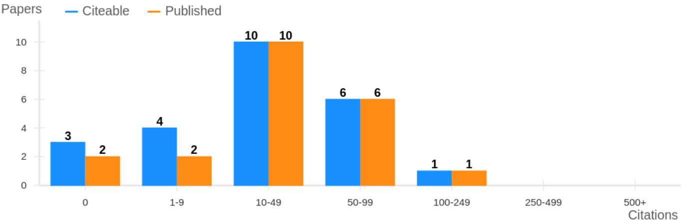
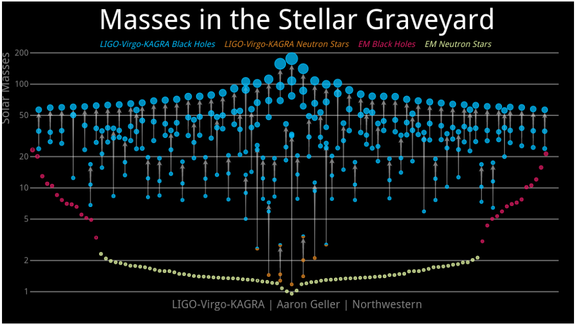
个人简介

- 2021 年博士毕业于中科院理论物理研究所，目前在北师大做博后；
- PPTA 和 IPTA 成员，前 LIGO 成员，即将加入 KAGRA；
- 获 2021 年和 2022 年英国皇家物理学会（IOP）“中国高被引论文奖”；
- 获 2021 年中科院院长特别奖、2022 年中科院优秀博士学位论文；
- 获国自科理论物理专项和博后面上资助；
- 在 PRL、PRD、ApJ 等杂志发表 20 余篇文章。

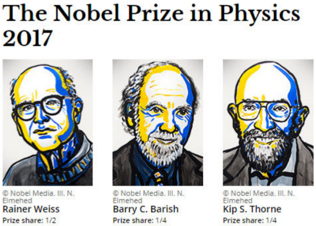
	Citeable	Published
Papers	**24**	**21**
Citations	**672**	**667**
h-index	**13**	**13**
Citations/paper (avg)	**28**	**31.8**



Outline



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



The Nobel Prize in Physics 2017

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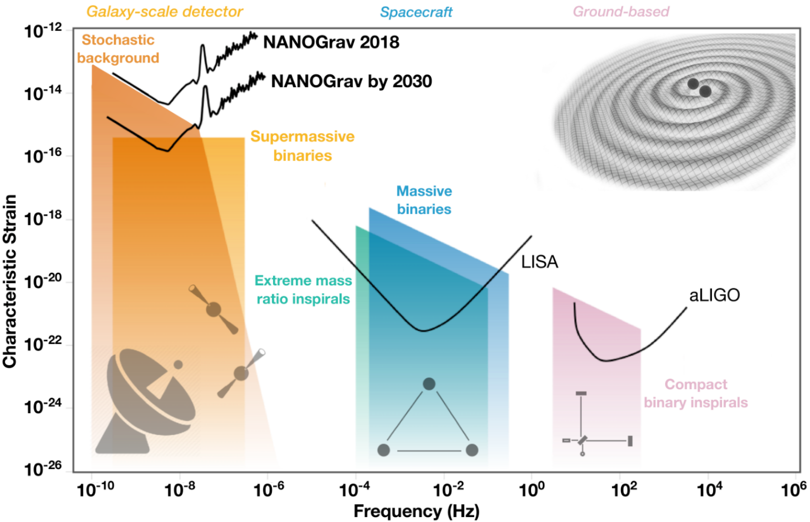
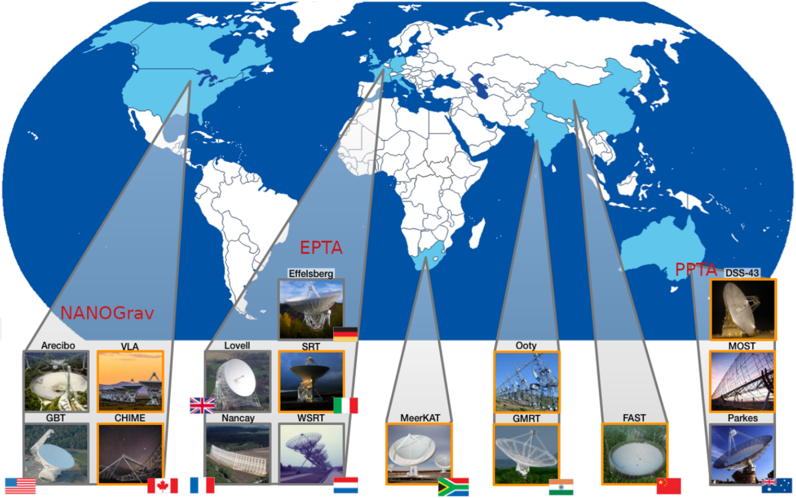
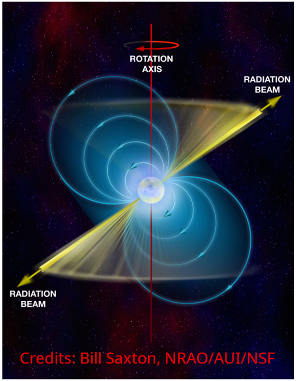
- New era of GW astronomy
- Multi-messenger astronomy


Galaxy-scale detector
Spacecraft
Ground-based
Stochastic background
NANOGrav 2018
NANOGrav by 2030
Supermassive binaries
Massive binaries
Extreme mass ratio inspirals
LISA
aLIGO
Compact binary inspirals
Characteristic Strain
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Frequency (Hz)

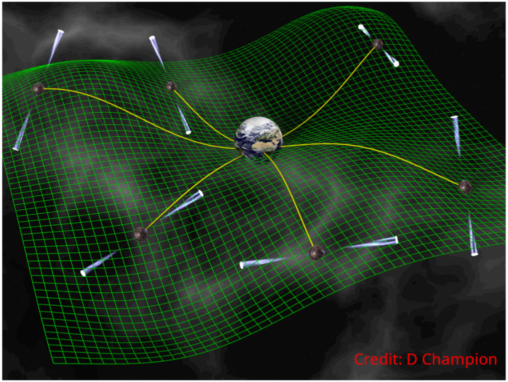
IPTA


EPTA
Effelsberg
NANOGrav
PPTA
DSS-43
Arecibo
VLA
Lovell
SRT
Ooty
MOST
GBT
CHIME
Nancay
WSRT
MeerKAT
GMRT
FAST
Parkes

Pulsar and PTA



Credits: Bill Saxton, NRAO/AUI/NSF



Credit: D Champion

A pulsar timing array (PTA) pursues to detect nHz GWs by regularly monitoring time of arrivals from an array of the ultra rotational stable millisecond pulsars.

Time of Arrivals (TOAs)

$$\tau = \tau^{\mathrm{TM}} + n = \tau^{\mathrm{TM}} + \tau^{\mathrm{RN}} + \tau^{\mathrm{DM}} + \tau^{\mathrm{WN}} + \tau^{\mathrm{GW}}$$

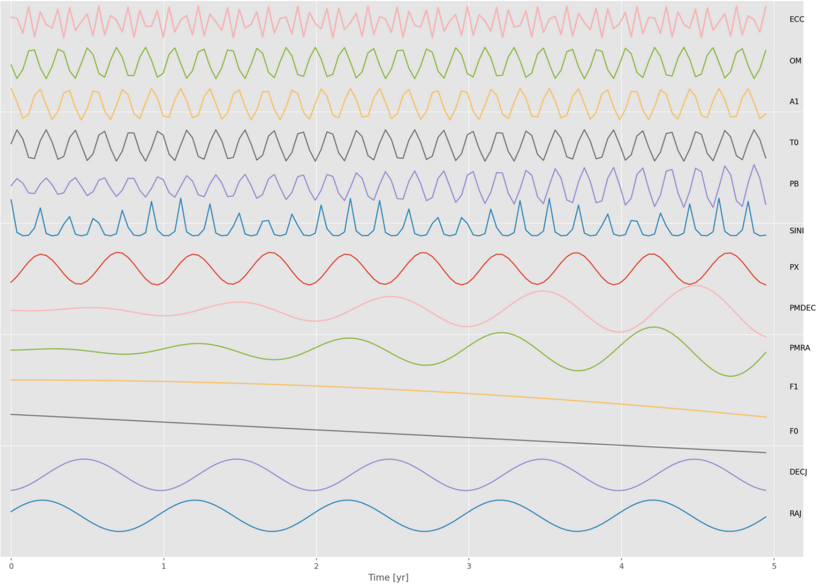
- τ^{TM} – timing model: physical model for TOAs taking in to account spin period, proper motion, binary orbital dynamics, etc.
- τ^{RN} – red noise (i.e. low-frequency correlated noise). Correlation timscales on the order of weeks - years.
- τ^{DM}: Model for time-varying dispersion measure variations (i.e. has $1/\nu^2$ dependence, where ν is the radio frequency).
- τ^{WN} – white noise: it is more than just a variance since we have data taken from different observing systems and different telescopses.
- τ^{GW} – GW signal.

Timing Residuals

$$\begin{aligned}
\delta\tau &= \tau^{\rm obs} - \tau^{\rm det}(\xi_{\rm est}) \\
&= \tau^{\rm det}(\xi_{\rm true}) - \tau^{\rm det}(\xi_{\rm est}) + n \\
&= \tau^{\rm det}(\xi_{\rm est}+\epsilon) - \tau^{\rm det}(\xi_{\rm est}) + n \\
&= \tau^{\rm det}(\xi_{\rm est}) + \left.\frac{\partial\tau^{\rm det}(\xi_{\rm est}+\epsilon)}{\partial\xi}\right|_{\epsilon=0}\epsilon - \tau^{\rm det}(\xi_{\rm est}) + n + \mathcal{O}(\epsilon^2) \qquad (1) \\
&\approx \left.\frac{\partial\tau^{\rm det}(\xi_{\rm est}+\epsilon)}{\partial\xi}\right|_{\epsilon=0}\epsilon + n \\
&= M\epsilon + n,
\end{aligned}$$

- M is the design matrix and ϵ is an offset parameter.
- $\tau^{\rm TM} \sim$ milliseconds
- $n \sim$ nano- or microseconds

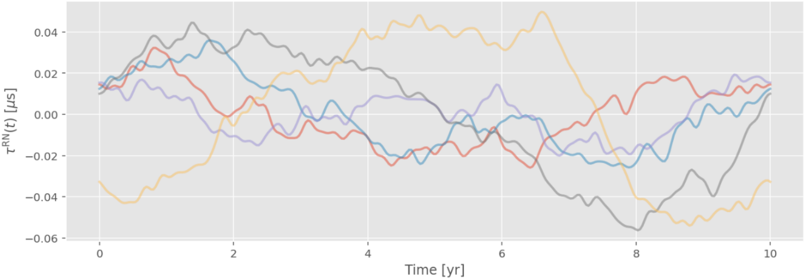
Timing Model



Red Noise

$$\tau_{\mathrm{RN}} = \sum_{j=1}^{N_{\mathrm{mode}}} \left[a_j \sin\left(\frac{2\pi j t}{T}\right) + b_j \cos\left(\frac{2\pi j t}{T}\right) \right] = F_{\mathrm{red}} a_{\mathrm{red}},$$

- a_{red} is a vector of the alternating sine and cosine amplitudes
- T is the total time span of the data
- F_{red} is a $N_{\mathrm{TOA}} \times 2N_{\mathrm{mode}}$ matrix with alternating sine and cosine terms
- N_{mode} the number of frequencies used. Typically we use 50 Fourier modes.



Red Noise

- Covariance matrix

$$\begin{aligned} K_{\mathrm{red}} &= \langle \tau^{\mathrm{RN}} (\tau^{\mathrm{RN}})^T \rangle \\ &= F_{\mathrm{red}} \langle a_{\mathrm{red}} a_{\mathrm{red}}^T \rangle F_{\mathrm{red}}^T \\ &= F_{\mathrm{red}} \varphi F_{\mathrm{red}}^T \end{aligned}$$

- $\varphi = \langle a_{\mathrm{red}} a_{\mathrm{red}}^T \rangle$ is a matrix with zero off-diagonal elements

$$\varphi_{i,i} = P(f_i)$$

- Power spectrum
  - power-law

$$P_{\mathrm{PL}}(f; A, \gamma) = \frac{A^2}{12\pi^2} \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{-\gamma} \mathrm{yr}^3$$

  - broken power-law

$$P_{\mathrm{BPL}}\left(f; A, \gamma, \delta, f_b, \kappa\right) = \frac{A^2}{12\pi^2} \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{-\gamma} \left(1 + \left(\frac{f}{f_b} \right)^{1/\kappa} \right)^{\kappa(\gamma-\delta)} \mathrm{yr}^3$$

  - free spectrum

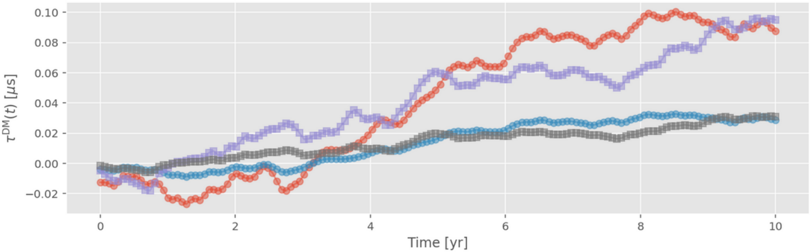
$$P_{\mathrm{FS}}\left(f_i; \rho_i\right) = \rho_i^2 T,$$

ρ_i is the spectral amplitude at frequency $f_i = i/T$.

Dispersion Measure Variations

Dispersion measure is due to the propagation of radio waves through the charged plasma of the interstellar medium (ISM),

$$\mathrm{DM}(t) = \int_0^{L(t)} n_e(\mathbf{x}) d\ell.$$



Dispersion Measure Variations

- Timing residual

$$\tau^{\mathrm{DM}} = F_{\mathrm{DM}} a_{\mathrm{DM}}$$

- Covariance matrix

$$\begin{aligned} K_{\mathrm{DM}} &= F_{\mathrm{DM}} \langle a_{\mathrm{DM}} a_{\mathrm{DM}}^T \rangle F_{\mathrm{DM}}^T \\ &= F_{\mathrm{DM}} \varphi_{\mathrm{DM}} F_{\mathrm{DM}}^T \end{aligned}$$

- $\varphi_{\mathrm{DM}} = \langle a_{\mathrm{DM}} a_{\mathrm{DM}}^T \rangle$ is a matrix with zero off-diagonal elements

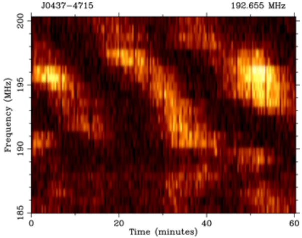
$$\varphi_{i,i} = P(f_i)$$

- Radio frequency dependent power spectrum

$$P_{DM}(f; A_{DM}, \gamma_{DM}) = \frac{A_{DM}^2}{12\pi^2} f_{yr}^{-3} \left(\frac{f}{f_{yr}} \right)^{-\gamma_{DM}} \left(\frac{1400 MHz}{\nu} \right)^2$$

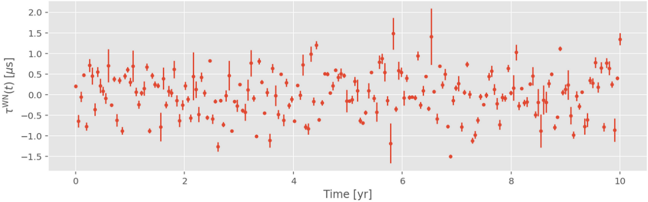
White Noise

- Measurement error is the biggest contributor.
- A function of radio frequencies and observation times.



- Covariance matrix

$$N_{ij} = \delta_{ij} \left(\sigma^2_{\mathrm{meas,ij}} + \sigma^2_{\mathrm{equad,ij}} \right),$$



GWB

$$\tau_{\mathrm{GWB}} = \sum_{j=1}^{N_{\mathrm{mode}}} \left[a_j \sin\left(\frac{2\pi j t}{T}\right) + b_j \cos\left(\frac{2\pi j t}{T}\right) \right] = F_{\mathrm{GWB}} a_{\mathrm{GWB}},$$

- Covariance matrix

$$\begin{aligned} K_{\mathrm{GWB}} &= \langle \tau^{\mathrm{GWB}} (\tau^{\mathrm{GWB}})^T \rangle \\ &= F_{\mathrm{GWB}} \langle a_{\mathrm{GWB}} a_{\mathrm{GWB}}^T \rangle F_{\mathrm{GWB}}^T \\ &= F_{\mathrm{GWB}} \varphi F_{\mathrm{GWB}}^T \end{aligned}$$

- Correlations

$$\varphi_{IJ;i,i} = \Gamma_{IJ} P(f_i)$$

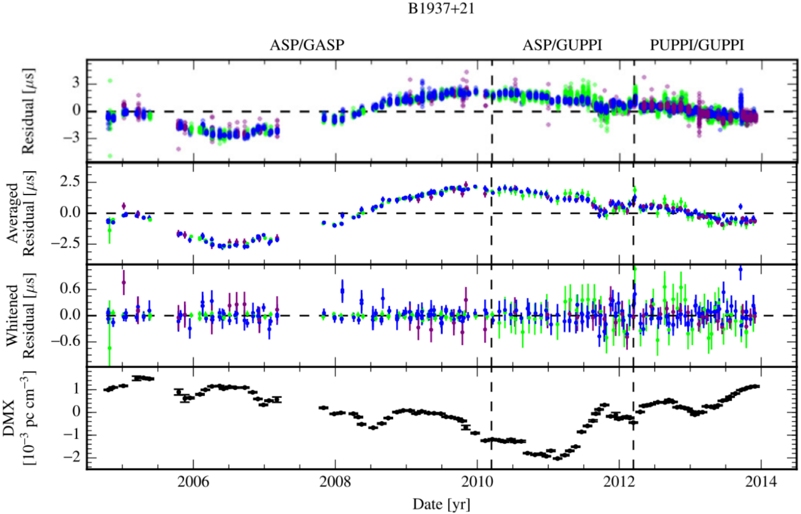
- Hellings & Downs correlations

$$\boxed{\Gamma_{IJ}^T = \frac{3}{2}\left(\frac{1-\cos\xi}{2}\right)\ln\frac{1-\cos\xi}{2} - \frac{1-\cos\xi}{8} + \frac{1}{2}}$$

- Power spectrum from SMBHBs

$$P(f; A, \gamma) = \frac{A^2}{12\pi^2}\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-\gamma} \mathrm{yr}^3$$

Putting them all together



- Timing residuals

$$\begin{aligned}\delta\tau &= M\epsilon + F_{\rm red}a_{\rm red} + F_{\rm DM}a_{\rm DM} + n \\ &= Tb + n\end{aligned}$$

- Definitions

$$T = [M \;\; F_{\rm red} \;\; F_{\rm DM}]; \qquad b = \begin{bmatrix} \epsilon \\ a_{\rm red} \\ a_{\rm DM} \end{bmatrix} \qquad B = \begin{bmatrix} \infty & & \\ & \varphi & \\ & & \varphi_{\rm DM} \end{bmatrix}$$

- Covariance matrix

$$C = N + K = N + TBT^T$$

where $N = \langle nn^T \rangle$ is covariance matrix for white noise.

Likelihood

- Basis Picture:

$$p(\delta\tau|b,\phi) = \frac{\exp\left[-\frac{1}{2}(\delta\tau - Tb)^T N^{-1}(\delta\tau - Tb)\right]}{\sqrt{\det 2\pi N}} \frac{\exp\left[-\frac{1}{2}b^T B^{-1} b\right]}{\sqrt{\det 2\pi B}}$$

- Kernel Picture

$$p(\delta\tau|\phi) = \frac{\exp\left[-\frac{1}{2}\delta\tau^T C^{-1}\delta\tau\right]}{\sqrt{\det 2\pi C}}$$

- Woodbury Lemma

$$C^{-1} = (N + TBT^T)^{-1} = N^{-1} - N^{-1}T\left(B^{-1} + T^T N^{-1} T\right)^{-1} T^T N^{-1}$$

$$\det C = \det\left(N + TBT^T\right) = \det\left(N\right)\det\left(B\right)\det\left(B^{-1} + T^T N^{-1} T\right)$$

$B \sim 1000 \times 1000$ and $C \sim 30000 \times 30000$ means speedup of ~ 1000

Bayes' theorem

$$\underbrace{p(H|D)}_{\text{posterior}} = \frac{\overbrace{p(D|H)}^{\text{likelihood}}\overbrace{p(H)}^{\text{prior}}}{\underbrace{p(D)}_{\text{normalization factor}}}$$

- Bayes factor

$$\mathrm{BF} = \frac{\Pr\left(\mathcal{D} \mid \mathcal{H}_1\right)}{\Pr\left(\mathcal{D} \mid \mathcal{H}_0\right)}$$

Table 2. An interpretation of the Bayes factor in determining which model is favored, as given by Kass & Raftery (1995).

$\mathcal{BF}$	$\ln \mathcal{BF}$	Strength of evidence
< 1	< 0	Negative
$1 - 3$	$0 - 1$	Not worth more than a bare mention
$3 - 20$	$1 - 3$	Positive
$20 - 150$	$3 - 5$	Strong
> 150	> 5	Very strong

Scalar-Induced Gravitational Waves (SIGWs)

- Primordial perturbations can be generated by quantum fluctuations during inflation.
- Metric

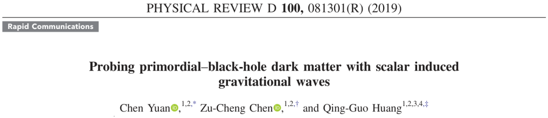
$$\mathrm{d}s^2 = a^2 \left\{ -(1+2\phi)\mathrm{d}\eta^2 + \left[(1-2\phi)\delta_{ij} + \frac{h_{ij}}{2} \right] \mathrm{d}x^i \mathrm{d}x^j \right\}, \tag{2}$$

  where $\phi \equiv \phi^{(1)}$ and $h_{ij} \equiv h_{ij}^{(2)}$ are the scalar and tensor perturbations, respectively.

- Primordial scalar perturbation can be the source of SIGWs, as well as primordial black holes (PBHs).
- EoM

$$h_{ij}'' + 2\mathcal{H}h_{ij}' - \nabla^2 h_{ij} = -4\mathcal{T}_{ij}^{\ell m} S_{\ell m}. \tag{3}$$

SIGW up to 3rd order



PHYSICAL REVIEW D **100,** 081301(R) (2019)

Rapid Communications

Probing primordial–black-hole dark matter with scalar induced gravitational waves

Chen Yuan,[1,2,*] Zu-Cheng Chen,[1,2,†] and Qing-Guo Huang[1,2,3,4,‡]

$$\Omega_{\mathrm{GW}}(\eta,k)=\frac{1}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{d\ln f}\propto\left\langle S^{(2)}S^{(2)}\right\rangle+\left\langle S^{(3)}S^{(3)}\right\rangle+\left\langle S^{(2)}S^{(4)}\right\rangle$$

$$S_{ij}^{(2)}=4\phi\partial_i\partial_j\phi+2\partial_i\phi\partial_j\phi-\partial_i\left(\phi+\frac{\phi'}{\mathscr{H}}\right)\partial_j\left(\phi+\frac{\phi'}{\mathscr{H}}\right)$$

$$\begin{aligned}S_{ij}^{(3)}=&\frac{1}{\mathscr{H}}\left(12\mathscr{H}\phi-\phi'\right)\partial_i\phi\partial_j\phi-\frac{1}{\mathscr{H}^3}\left(4\mathscr{H}\phi-\phi'\right)\partial_i\phi'\partial_j\phi'\\&+\frac{1}{3\mathscr{H}^4}\left(2\partial^2\phi-9\mathscr{H}\phi'\right)\partial_i\left(\mathscr{H}\phi+\phi'\right)\partial_j\left(\mathscr{H}\phi+\phi'\right)\end{aligned}$$

$$\begin{aligned}S_{ij}^{(4)}=&16\phi^3\partial_i\partial_j\phi+\frac{1}{3\mathscr{H}^3}\Big[2\phi'\partial^2\phi-9\mathscr{H}\phi'^2-8\mathscr{H}\phi\partial^2\phi+18\mathscr{H}^2\phi\phi'+96\mathscr{H}^3\phi^2\Big]\partial_i\phi\partial_j\phi\\&+\frac{2}{3\mathscr{H}^5}\Big[-\phi'\partial^2\phi+3\mathscr{H}\phi'^2+4\mathscr{H}\phi\partial^2\phi+3\mathscr{H}^2\phi\phi'-12\mathscr{H}^3\phi^2\Big]\partial_i\phi'\partial_j\phi'\\&+\frac{1}{36\mathscr{H}^6}\Big[-16(\partial^2\phi)^2-3\partial_k\phi'\partial^k\phi'+120\mathscr{H}\phi'\partial^2\phi-6\mathscr{H}\partial_k\phi\partial^k\phi'\\&\quad+144\mathscr{H}^2\phi\partial^2\phi-180\mathscr{H}^2\phi'^2+33\mathscr{H}^2\partial_k\phi\partial^k\phi-504\mathscr{H}^3\phi\phi'-144\mathscr{H}^4\phi^2\Big]\\&\quad\times\partial_i\left(\mathscr{H}\phi+\phi'\right)\partial_j\left(\mathscr{H}\phi+\phi'\right)\end{aligned}$$

PHYSICAL REVIEW D **100,** 081301(R) (2019)

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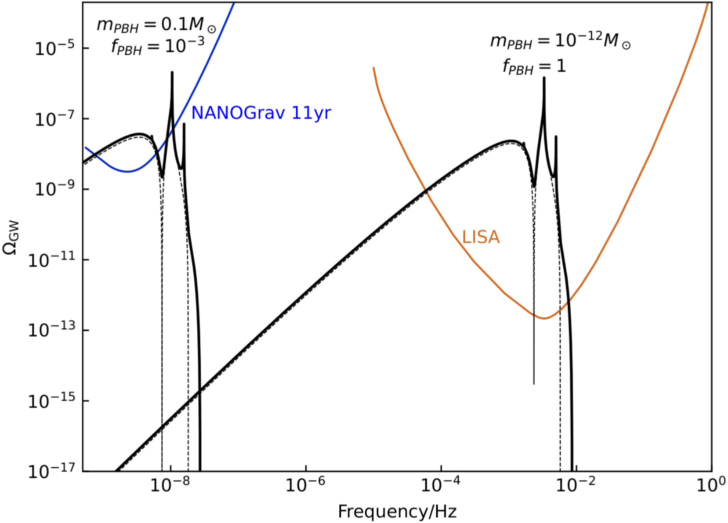
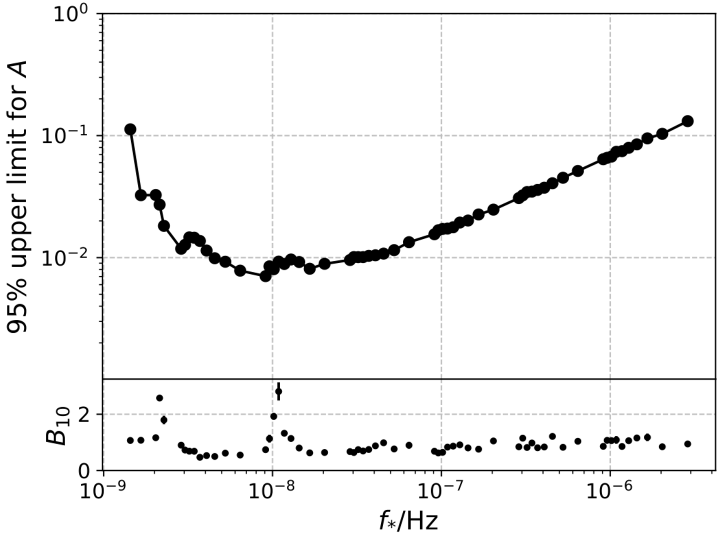


PHYSICAL REVIEW LETTERS **124,** 251101 (2020)

Pulsar Timing Array Constraints on Primordial Black Holes with NANOGrav 11-Year Dataset

Zu-Cheng Chen,[1,2,3,*] Chen Yuan,[1,2,†] and Qing-Guo Huang[1,2,4,5,6,‡]



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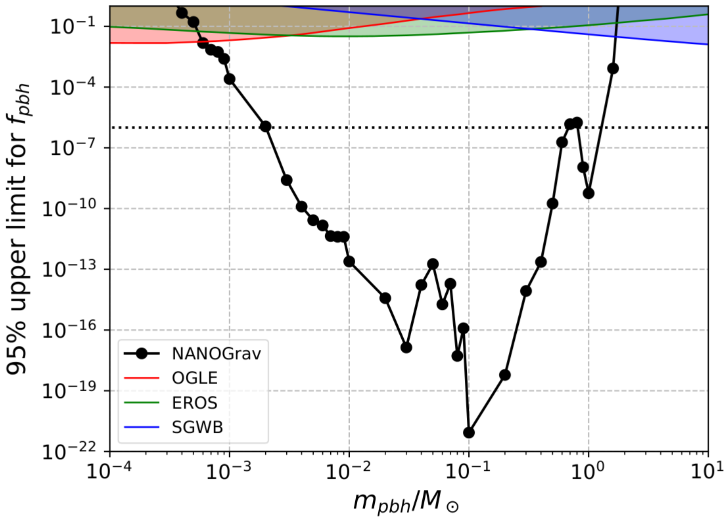
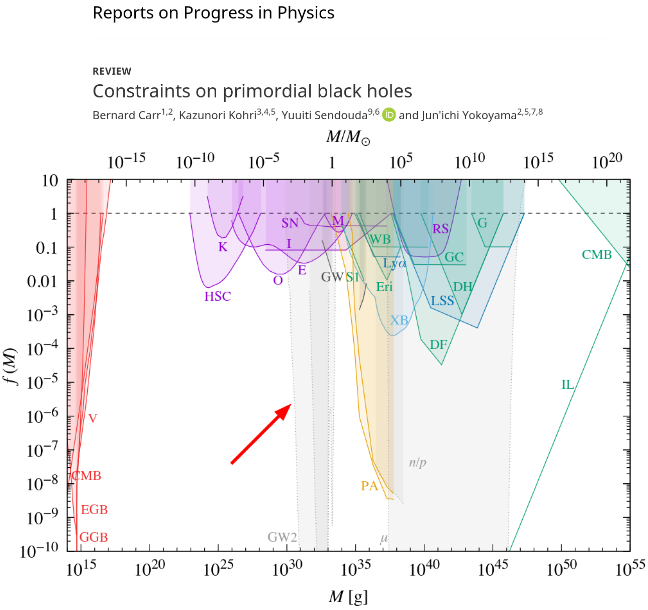


Our results have been cited by 12 review articles.



Reports on Progress in Physics

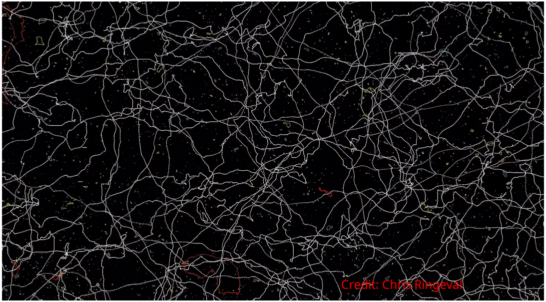
REVIEW

Constraints on primordial black holes

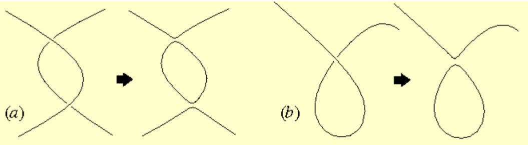
Bernard Carr[1,2], Kazunori Kohri[3,4,5], Yuuiti Sendouda[9,6] and Jun'ichi Yokoyama[2,5,7,8]

Cosmic String

- Cosmic strings are linear topological defects that can form in the early Universe from symmetry-breaking phase transitions.

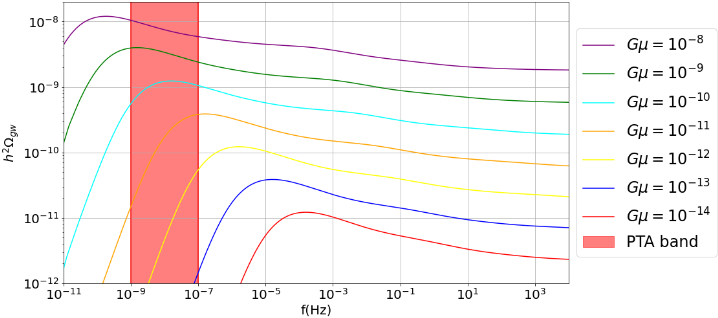


- The intersection between cosmic strings can lead to reconnections and form loops, which will then decay due to relativistic oscillation and emit gravitational waves.

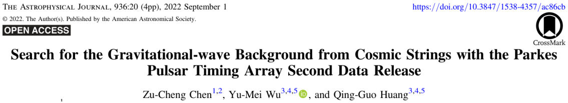


Cosmic string loop formation. A loop forms (a) when two strings interacts in 2 separate points or (b) when a string crosses itself.
© Cambridge cosmology group

GW energy density spectrum of cosmic strings



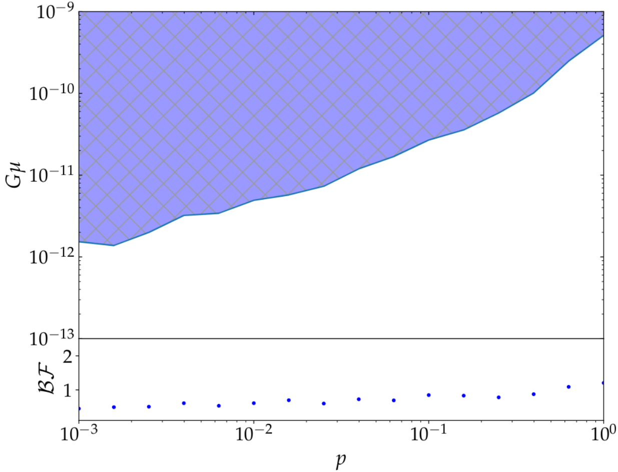
- Here, $p = 1$ is the reconnection probability.
- $G\mu$ is string tension – the energy stored per unit length.



The Astrophysical Journal, 936:20 (4pp), 2022 September 1 https://doi.org/10.3847/1538-4357/ac86cb

Search for the Gravitational-wave Background from Cosmic Strings with the Parkes Pulsar Timing Array Second Data Release

Zu-Cheng Chen[1,2], Yu-Mei Wu[3,4,5], and Qing-Guo Huang[3,4,5]



Ultralight Vector Dark Matter (UVDM)

- Ultralight vector field with mass $\sim 10^{-22}$eV can be DM candidate.
- The vector field oscillating coherently on galactic scales induces oscillations of the spacetime metric with a frequency around nHz, which is detectable by PTAs.
- Action for a free massive vector filed

$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} m^2 A_\mu A^\mu \right), \tag{4}$$

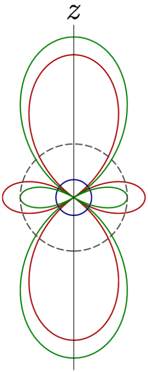
where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$.

- Only longitudinal mode survives during inflation

$$A_{\hat{k}}(t, \mathbf{x}) = A(\mathbf{x}) \cos(mt + \alpha(\mathbf{x})). \tag{5}$$

where $\hat{k} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$ is the oscillating direction.

Redshift induced by UVDM



$$ds^2 = \eta_{\mu\nu}dx^\mu dx^\nu - 2\Phi(t,\mathbf{x})dt^2 + 2\Psi(t,\mathbf{x})\delta_{ij}dx^i dx^j + h_{ij}(t,\mathbf{x})dx^i dx^j$$

$$\Psi(t,\mathbf{x}) = \Psi_0(\mathbf{x}) + \Psi_{\rm osc}(\mathbf{x})\cos(2mt + 2\alpha(\mathbf{x}))$$

$$z_\Psi(t) = \Psi_{\rm osc}(\mathbf{x}_e)\cos(2mt + 2\alpha(\mathbf{x}_e)) - \Psi_{\rm osc}(\mathbf{x}_p)\cos[2m(t - |\mathbf{x}_p|) + 2\alpha(\mathbf{x}_p)]$$

$$h_{ij}(t,\mathbf{x}) = h_{\rm osc}(\mathbf{x})\cos(2mt + 2\alpha(\mathbf{x}))(\hat{l}\otimes\hat{l} + \hat{n}\otimes\hat{n} - 2\hat{k}\otimes\hat{k}),$$

$$z_h(t) = \frac{1}{2}\hat{p}^i\hat{p}^j[h_{ij}(t,\mathbf{x}_e) - h_{ij}(t - |\mathbf{x}_p|,\mathbf{x}_p)],$$

The redshift is angular dependent due to the oscillation of UVDM. The blue line and red line represent the contribution of the trace part $z_\Psi(t)$ and the traceless part $z_h(t)$, respectively. Actually, we only observe the summation of z_Ψ and z_h, which is depected by the green line. The angle is measured from the direction of the oscillation chosen as the z-axis. A gray dashed line shows the magnitude of the redshift when the DM is a scalar field.

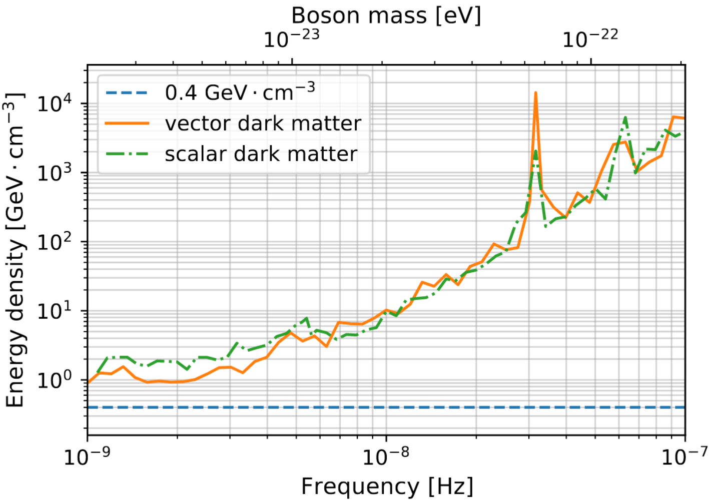
PHYSICAL REVIEW D **106,** L081101 (2022)

Letter

Constraining ultralight vector dark matter with the Parkes Pulsar Timing Array second data release

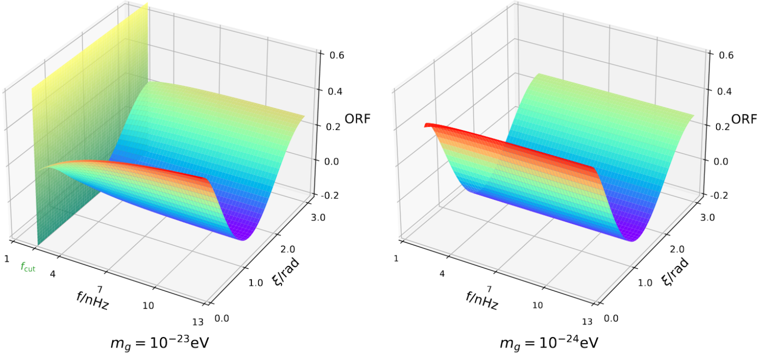
Yu-Mei Wu,[1,2,3,*] Zu-Cheng Chen,[4,5,†] Qing-Guo Huang,[1,3,2,‡] Xingjiang Zhu,[5,§] N. D. Ramesh Bhat,[6] Yi Feng,[7]
George Hobbs,[8] Richard N. Manchester,[8] Christopher J. Russell,[9] and R. M. Shannon[10,11]

(PPTA Collaboration)



Massive Gravity

- Massive gravity is a theory of gravity endowing the graviton with a nonzero mass.
- The geodesics of light will be altered in massive gravity leaving an imprint on pulsar's timing residuals.
- Overlap reduction function

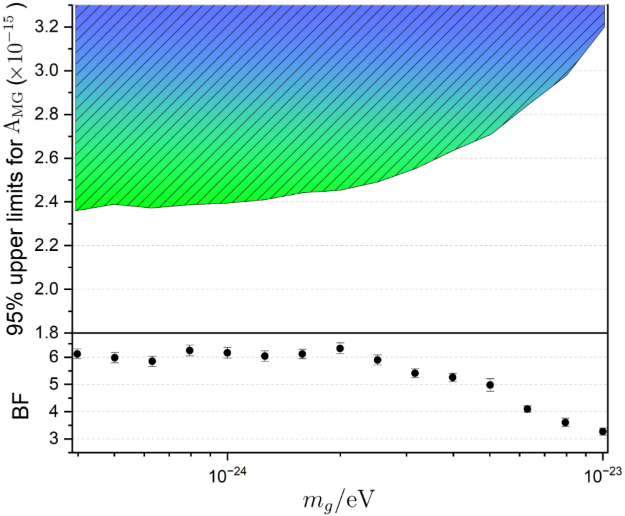


Qiuyue Liang, Mark Trodden, PRD (2021); Yu-Mei Wu, Zu-Cheng Chen, Qing-Guo Huang, PRD (2023)

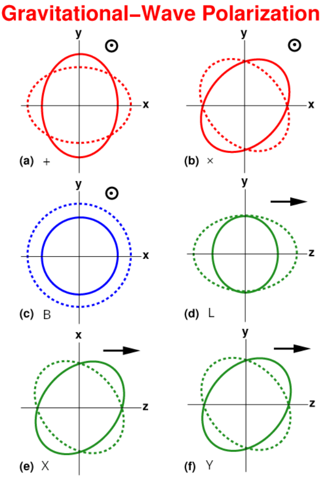
PHYSICAL REVIEW D **107,** 042003 (2023)

Search for stochastic gravitational-wave background from massive gravity in the NANOGrav 12.5-year dataset

Yu-Mei Wu,[1,2,3,*] Zu-Cheng Chen,[4,5,†] and Qing-Guo Huang[1,2,3,‡]



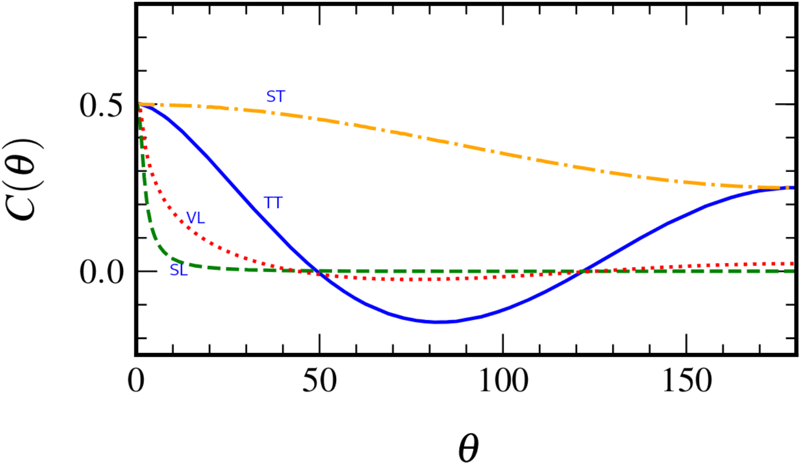
Alternative Polarizations



- polarization tensors

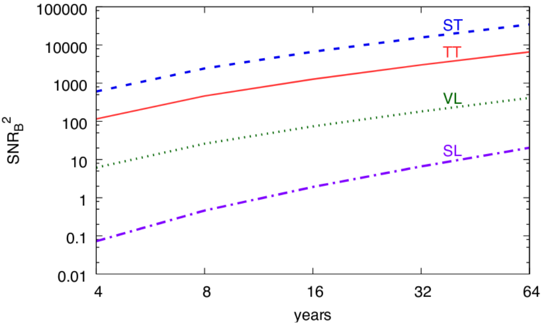
$$\begin{aligned}
\epsilon_{ij}^{+} &= \hat{m}\otimes\hat{m}-\hat{n}\otimes\hat{n},\\
\epsilon_{ij}^{\times} &= \hat{m}\otimes\hat{n}+\hat{n}\otimes\hat{m},\\
\epsilon_{ij}^{B} &= \hat{m}\otimes\hat{m}+\hat{n}\otimes\hat{n},\\
\epsilon_{ij}^{L} &= \hat{\Omega}\otimes\hat{\Omega},\\
\epsilon_{ij}^{X} &= \hat{m}\otimes\hat{\Omega}+\hat{\Omega}\otimes\hat{m},\\
\epsilon_{ij}^{Y} &= \hat{n}\otimes\hat{\Omega}+\hat{\Omega}\otimes\hat{n}
\end{aligned}$$

ORF



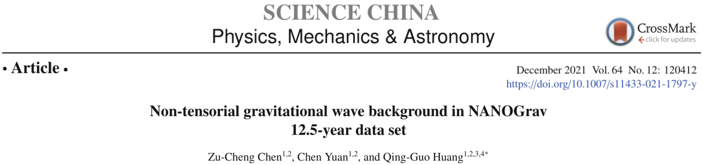
Signal-to-noise-ratio

$$\mathrm{SNR}_B^2 = 2\sum_f \sum_a^{N_p} \sum_{b>a}^{N_p} \frac{\Gamma_{ab}^{I^2(f)}}{\Gamma_{aa}^I(f)\Gamma_{bb}^I(f) + \Gamma_{ab}^I(f)}.$$



Neil J. Cornish, Logan O'Beirne, Stephen R. Taylor, Nicolás Yunes, PRL 120 (2018)

Evidence for the ST correlations in NANOGrav 12.5-yr



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• Article •

December 2021 Vol. 64 No. 12: 120412
https://doi.org/10.1007/s11433-021-1797-y

Non-tensorial gravitational wave background in NANOGrav 12.5-year data set

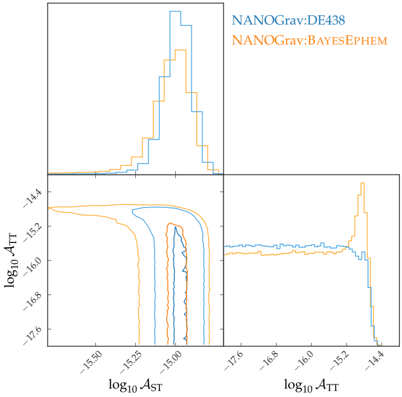
Zu-Cheng Chen[1,2], Chen Yuan[1,2], and Qing-Guo Huang[1,2,3,4*]

$\mathcal{BF}$ compared to the UCP model with $\gamma_{\rm UCP} = 13/3$.

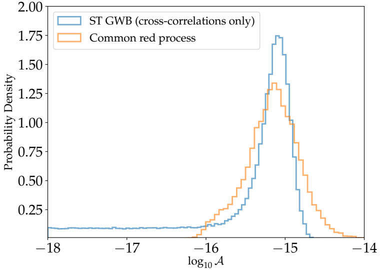
ephemeris	TT	ST	VL	SL	ST+TT
DE438	4.96(9)	107(7)	1.94(3)	0.373(5)	96(3)
BayesEphem	2.35(3)	18.4(7)	1.31(2)	0.555(7)	16.7(3)

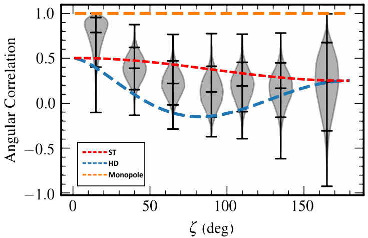
- No significant evidence for TT/VL/SL modes
- Strong Bayesian evidence for ST correlations;
- No TT correlations in addition to the ST mode;

Evidence for the ST correlations in NANOGrav 12.5-yr



ST+TT model



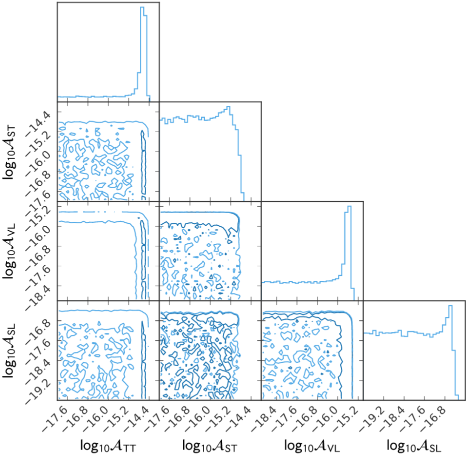


Constrain GW Polarization with PPTA DR2

The Astrophysical Journal, 925:37 (6pp), 2022 January 20 https://doi.org/10.3847/1538-4357/ac35cc

Constraining the Polarization of Gravitational Waves with the Parkes Pulsar Timing Array Second Data Release

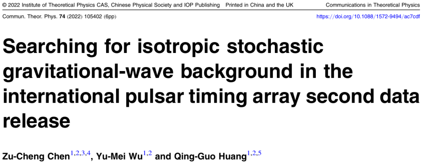
Yu-Mei Wu[1,2], Zu-Cheng Chen[1,2], and Qing-Guo Huang[1,2,3,4]



Model	TT	ST	VL	SL
BF	2.15(4)	0.183(3)	1.06(2)	0.362(6)

No significant evidence for TT/ST/VL/SL correlations.

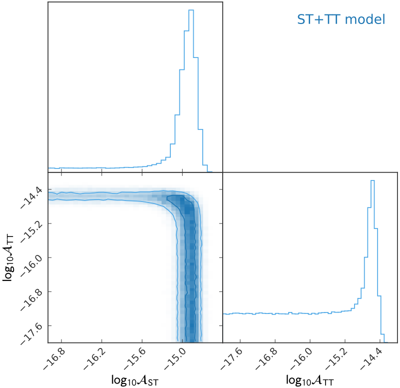
Evidence for the ST correlations in IPTA DR2



Communications in Theoretical Physics
Commun. Theor. Phys. **74** (2022) 105402 (6pp)
https://doi.org/10.1088/1572-9494/ac7cdf

Searching for isotropic stochastic gravitational-wave background in the international pulsar timing array second data release

Zu-Cheng Chen[1,2,3,4], **Yu-Mei Wu**[1,2] **and Qing-Guo Huang**[1,2,5]



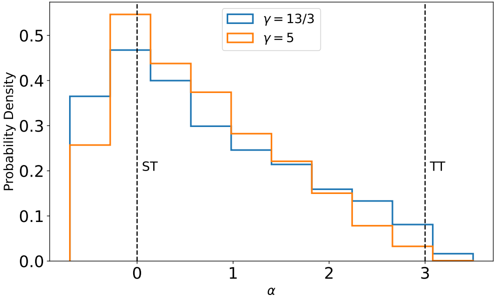
Model	TT	ST	ST+TT
$\ln \mathcal{BF}$	2.53(3)	3.39(4)	3.63(4)

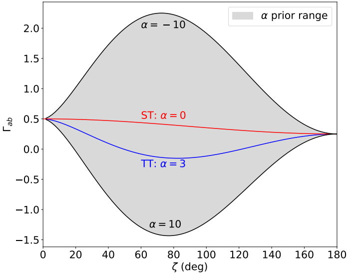
- Strong evidence for a common-spectrum process.
- Strong evidence for ST correlations.
- No significant evidence for an additional TT correlations.

We also consider a parameterized transverse ORF as

$$\Gamma_{ab}(f) = \frac{1}{8}\left(3 + 4\delta_{ab} + \cos\xi_{ab}\right) + \frac{\alpha}{2} k_{ab} \ln k_{ab}. \tag{6}$$

ST: $\alpha = 0$ TT: $\alpha = 3$ prior of α: Uniform(-10, 10)





- ST mode is favored by IPTA DR2.
- TT mode is ruled out at 90% credible interval.

Summary for the results of alternative polarizations

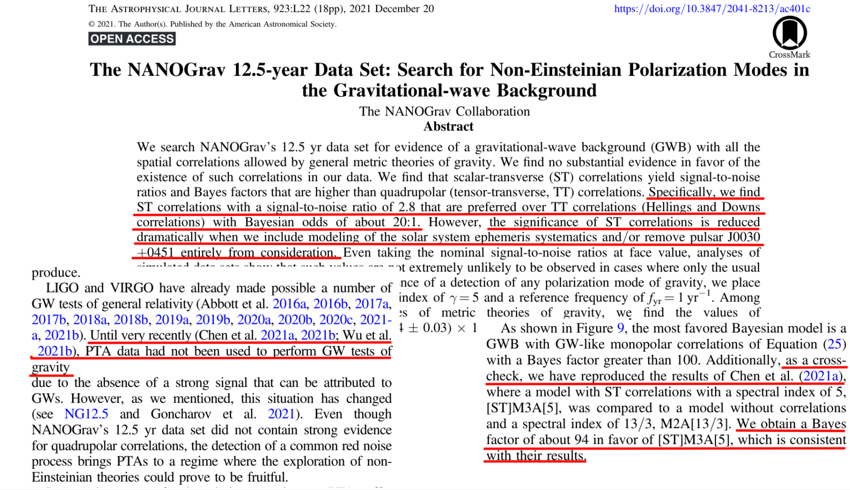
PTA	UCP	TT	ST	VL	SL	Monopole	Dipole
NANOGrav 12.5-yr	✓	✗	✓	✗	✗	✗	✗
PPTA DR2	✓	✗	✗	✗	✗	✗	✗
IPTA DR2	✓	✗	✓	N/A	N/A	✗	✗

- All three PTAs support the evidence for a common process, but the evidence for TT correlations is insignificant.

- NANOGrav 12.5-yr and IPTA DR2 indicate the common process has ST correlations, and the obtained $\mathcal{A}_{\rm ST}$ is consistent with the upper limit from PPTA DR2.

	NANOGrav 12.5-yr	PPTA DR2	IPTA DR2
$\mathcal{A}_{\rm ST}$	$1.06^{+0.35}_{-0.28} \times 10^{-15}$	$\lesssim 1.8 \times 10^{-15}$	$1.29^{+0.51}_{-0.44} \times 10^{-15}$

Response from NANOGrav Collaboration



The Astrophysical Journal Letters, 923:L22 (18pp), 2021 December 20 https://doi.org/10.3847/2041-8213/ac401c

The NANOGrav 12.5-year Data Set: Search for Non-Einsteinian Polarization Modes in the Gravitational-wave Background

The NANOGrav Collaboration

Abstract

We search NANOGrav's 12.5 yr data set for evidence of a gravitational-wave background (GWB) with all the spatial correlations allowed by general metric theories of gravity. We find no substantial evidence in favor of the existence of such correlations in our data. We find that scalar-transverse (ST) correlations yield signal-to-noise ratios and Bayes factors that are higher than quadrupolar (tensor-transverse, TT) correlations. Specifically, we find ST correlations with a signal-to-noise ratio of 2.8 that are preferred over TT correlations (Hellings and Downs correlations) with Bayesian odds of about 20:1. However, the significance of ST correlations is reduced dramatically when we include modeling of the solar system ephemeris systematics and/or remove pulsar J0030 +0451 entirely from consideration. Even taking the nominal signal-to-noise ratios at face value, analyses of

t extremely unlikely to be observed in cases where only the usual

nce of a detection of any polarization mode of gravity, we place

index of $\gamma = 5$ and a reference frequency of $f_{\rm yr} = 1\ {\rm yr}^{-1}$. Among

s of metric theories of gravity, we find the values of

$4 \pm 0.03) \times 1$

produce.

LIGO and VIRGO have already made possible a number of GW tests of general relativity (Abbott et al. 2016a, 2016b, 2017a, 2017b, 2018a, 2018b, 2019a, 2019b, 2020a, 2020b, 2020c, 2021a, 2021b). Until very recently (Chen et al. 2021a, 2021b; Wu et al. 2021b), PTA data had not been used to perform GW tests of gravity

due to the absence of a strong signal that can be attributed to GWs. However, as we mentioned, this situation has changed (see NG12.5 and Goncharov et al. 2021). Even though NANOGrav's 12.5 yr data set did not contain strong evidence for quadrupolar correlations, the detection of a common red noise process brings PTAs to a regime where the exploration of non-Einsteinian theories could prove to be fruitful.

As shown in Figure 9, the most favored Bayesian model is a GWB with GW-like monopolar correlations of Equation (25) with a Bayes factor greater than 100. Additionally, as a cross-check, we have reproduced the results of Chen et al. (2021a), where a model with ST correlations with a spectral index of 5, [ST]M3A[5], was compared to a model without correlations and a spectral index of 13/3, M2A[13/3]. We obtain a Bayes factor of about 94 in favor of [ST]M3A[5], which is consistent with their results.

Works in Progress for PPTA

- Searching for GWB predicted by GR in PPTA DR3
- Searching for alternative polarizations in PPTA DR3
- Searching for the continuous waves from SMBBHs in PPTA DR2/DR3
- Searching for GWB from domain walls in PPTA DR2
- Searching for SIGW in PPTA DR2/DR3
- Searching for ultralight scalar/vector/tensor DM in PPTA DR3
- Searching for memory effect in PPTA DR2/DR3
- $\cdots$