

Searching for New Physics with the NANOGrav Pulsar Timing Array

Kai Schmitz University of Münster, Germany Particle and Astroparticle Theory Seminar Max-Planck-Institut für Kernphysik | Heidelberg, Germany | July 10, 2023



A brief history of GW physics: Past, present, future



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202x Next milestone: Detection of a stochastic GW background (GWB).

Big news on 29th June: Compelling evidence for a GWB reported by several teams!

CMB of the 21st century

20th century



CMB: Cosmic microwave background

21th century

[Sato-Polito, Kamionkowski: 2305.05690]



GWB: Gravitational-wave background

20th century



CMB: Cosmic microwave background

Relic photons

from the early Universe

21th century

[Sato-Polito, Kamionkowski: 2305.05690]



GWB: Gravitational-wave background

Relic gravitons from the early Universe \sim or \sim astrophysical signal











Possible GWB signals across vast frequency range

Galactic and extragalactic astrophysics + particle physics in the early Universe

Large arsenal of GW observations and experiments

Cosmic microwave background + pulsar timing arrays + interferometers + ...



Highly magnetized rotating neutron stars, ultra-precise stellar clocks

- Periods of $10^{-3\cdots 1}$ s. Accretion in close-binary systems ightarrow millisecond pulsars
- Beamed radio pulses emitted from magnetic poles \rightarrow cosmic lighthouses

Pulsar timing arrays (PTAs)



Array of pulsars across the Milky Way \rightarrow GW detector of galactic dimensions!

- Look for tiny distortions in pulse travel times caused by nanohertz GWs.
- Measure times of arrival and compare to predictions from a timing model.
- Timing residuals for each individual pulsar \rightarrow GW signature in cross-correlations.





Hallmark signature of a stochastic gravitational-wave background signal: Quadrupolar correlations described by Hellings–Downs (HD) curve $\Gamma_{ij}(\psi)$ [Hellings, Downs: Astrophys. J. 265 (1983) L39]

NANOGrav 15-year data set

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Telescopes

- AO: Arecibo Observatory
- GBT: Green Bank Telescope
- VLA: Very Large Array

Observations

- 68 millisecond pulsars (MSPs)
- 67 MSPs observed for $> 3\,{
 m yr}$
- 21 MSPs more than NG12.5
- 3 more years of observations
- Average cadence of one month



Bayesian model comparison in terms of Bayes factors

- IRN: Intrinsic pulsar noise only
- CURN: Common-spectrum spatially-uncorrelated red noise
- HD: Hellings–Downs correlations

$$\frac{P(D|\mathbf{CURN})}{P(D|\mathbf{IRN})} = 10^{12.1\pm0.1}, \qquad \frac{P(D|\mathbf{HD})}{P(D|\mathbf{CURN})} \sim 200\cdots1000$$
(1)

YouTube



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(1)

Decisive evidence for a new common-spectrum process; compelling evidence for HD (Range corresponds to spectral modelling choices, e.g., the number of frequency bins)

YouTube

Bayesian analysis: Model correlations with cubic splines across seven nodes



Frequentist analysis: Measure correlations based on "optimal statistic" (matched filter)



Statistical significance

Our frequentist friends want to know: "How many sigma?"



p-value test for two test statistics

- (1) HD-vs.-CURN Bayes factor, (2) signal-to-noise ratio for the optimal statistic
- Construct distributions under the null hypothesis $\mathcal{H}_0 = \{\text{no HD correlations}\}$
- Two techniques: (1) phase shifts, (2) sky scrambles
- Convert *p*-values to *z* scores: null hypothesis \mathcal{H}_0 rejected at the $3 \cdots 4\sigma$ level

Evidence for HD correlations on top of HUGE evidence for common-spectrum process

Astrophysical interpretation



Inspiraling supermassive black-hole binaries (SMBHBs)

- Most galaxies host a SMBHB at their center; binaries form after galaxy mergers
- A few binaries are known; no SMBHB merger has been observed so far
- Hope is that PTA observations will shed more light on SMBHB evolution

Expected signal from inspiraling SMBHBs



Compare observed spectrum (NG15) to theoretical expectation (holodeck)

- Assume SMBHBs on circular orbits and purely GW-driven orbital evolution
- = 95 % regions barely touch $\rightarrow 2\sigma$ tension between observations and theory
- Tension can be reduced in more "phenomenological" SMBHB models

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Compare observed spectrum (NG15) to theoretical expectation (holodeck)

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SMBHB interpretation: Need to go to unexpected corners of parameter space

Gravitational waves from the Big Bang



[National Astronomical Observatory of Japan, gwpo.nao.ac.jp]

Viable possibility: Signal receives contributions from SMBHBs + X (or X only?)

- Probe cosmology of the primordial Universe at very early times
- Probe particle physics at extremely high energies → New physics!?

NANOGrav team







R. v. Eckardstein* R. Lino d. Santos* Andrea Mitridate



Tanner Trickle

Jonathan Nay



Ken Olum



Kai Schmitz*









David Wright

0 Searches for signals from new physics in NANOGrav data \rightarrow 2306.16219

- **2** New software tools for fitting BSM models to PTA data \rightarrow PTArcade
- * Current or former members of my research group, Particle Cosmology Münster

2306.16219: Our contribution to the analysis of the NG15 data

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The N	N 2040-2223 IANOGrav 15-year Data Set: Search for Signals from New Physics
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Project leads: Andrea Mitridate, Kai Schmitz*

Richard von Eckardstein*	Cosmological phase transitions
Rafael Robson Lino dos Santos*	Inflation, scalar-induced gravitational waves
Jonathan Nay	Ultralight dark matter
Ken Olum	Cosmic strings, statistical tools
Tobias Schröder*	Cosmic strings
Tanner Trickle	Ultralight dark matter, dark-matter substructure
David Wright	Inflation, scalar-induced gravitational waves
Jonathan Nay Ken Olum Tobias Schröder [*] Tanner Trickle David Wright	Ultralight dark matter Cosmic strings, statistical tools Cosmic strings Ultralight dark matter, dark-matter substructur Inflation, scalar-induced gravitational waves

Andrea Mitridate



- Initially proposed the project to the Collaboration
- Worked on all aspects of the analysis
- Main developer of PTArcade
- Together, Andrea and I wrote almost the entire 74 pages of the paper

If you are currently looking to hire a junior faculty ... He is the best!

Inflation

- Nonminimal blue-tilted models
- Interplay with CMB observables



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- Interplay with CMB observables



Phase transition

- Modified QCD transition, dark sector
- Complementary to laboratory searches



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Cosmic defects

- · Cosmic strings, domain walls
- Access to grand unified theories



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Scalar perturbations

- Associated with primordial black holes
- PBH dark matter, supermassive BHs



Bayes factors



Bayesian model comparison



- Many BSM models reach Bayes of order 10 · · · 100.
- Interesting but not conclusive. Lots of uncertainties in SMBHB and BSM models.
- Bayes factors are sensitive to prior choices. No unique null distribution for \mathcal{H}_0 .

Bayes factors



Bayesian model comparison



- Many BSM models reach Bayes of order 10 · · · 100.
- Interesting but not conclusive. Lots of uncertainties in SMBHB and BSM models.
- Bayes factors are sensitive to prior choices. No unique null distribution for \mathcal{H}_0 .

Bottom line: Stable strings don't look good; all other BSM models can fit the data.



Solid lines: Median GW spectra for BSM models based on parameter posteriors Dashed line: SMBHB prediction based on central values of our 2D parameter prior



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Of course, GW spectra resulting in a good fit all look similar by construction.

 \rightarrow Relevant question: Which parameter values predict GW spectrum of the right form?

Inflationary gravitational waves (IGW)



Scalar-induced gravitational waves, δ -function-shaped $\mathcal{P}_{\mathcal{R}}$ (SIGW-DELTA)



Scalar-induced gravitational waves, bell-curve-shaped $\mathcal{P}_{\mathcal{R}}$ (SIGW-GAUSS)



Scalar-induced gravitational waves, box-shaped $\mathcal{P}_{\mathcal{R}}$ (SIGW-BOX)



Phase transition, bubble collisions (PT-BUBBLE)



Phase transition, sound waves (PT-SOUND)



Stable cosmic strings (STABLE)



Metastable cosmic strings, loops (META-L)



Metastable cosmic strings, loops and segments (META-LS)



Cosmic superstrings (SUPER)



Domain walls, decay into Standard Model particles (DW-SM)



Domain walls, decay into dark radiation (DW-DR)



NANOGRAV 15-YEAR NEW-PHYSICS SIGNALS

Table 4. Bayesian Estimators, Maximum Posterior Values, and 68% Credible Intervals for the Parameters of the New-physics Models. Values annotated with * are at the boundary of the prior range used in the analysis.

Parameter	Bayes Estimator		Maximum Posterior		68% Credible Interval		K Bound
	NP	NP+SMBHB	NP	NP+SMBHB	NP	NP+SMBHB	
		Inflation	ary Gravi	tational Wa	ves (IGW)		
$\log_{10}T_{\rm rh}/{\rm GeV}$	0.02 ± 1.60	-0.07 ± 1.61	-0.53	-0.60	[-1.51, 2.53]	[-1.89, 2.11]	
$\log_{10} r$	-14.06 ± 5.82	-15.97 ± 7.27	-10.14	-10.59	[-22.16, -6.58]	[-23.03, -7.21]	
n_t	2.61 ± 0.85	2.68 ± 0.97	2.02	2.08	[1.53, 3.92]	[1.56, 4.03]	5.72
$\log_{10} A_{\rm BHB}$		-15.60 ± 0.56		-15.64		$\left[-16.20, -15.14 ight]$	
$\gamma_{\rm BHB}$		4.61 ± 0.37		4.64		[4.26, 5.00]	
		Scalar-induce	ed Gravita	tional Wave	s (SIGW-DELTA)		
$\log_{10} A$	-0.69 ± 0.47	-0.71 ± 0.49	-0.14	-0.17	[-1.00, -0.01]	[-1.03, -0.02]	
$\log_{10} f_*/{\rm Hz}$	-5.90 ± 0.60	-5.93 ± 0.67	-5^{*}	-5^{*}	$[-6.17, -5^*]$	$[-6.19, -5^*]$	
$\log_{10} A_{\rm BHB}$		-15.77 ± 0.46		-15.71		$\left[-16.18, -15.29 ight]$	
γвнв		4.65 ± 0.35		4.65		[4.31, 4.99]	
		Scalar-induce	ed Gravita	tional Wave	s (SIGW-GAUSS)		
$\log_{10} A$	-0.38 ± 0.58	-0.36 ± 0.61	-0.34	-0.29	[-1.03, 0.20]	[-1.04, 0.24]	
$\log_{10} f_*/{\rm Hz}$	-6.32 ± 0.71	-6.30 ± 0.73	-7.03	-6.85	[-7.25, -5.65]	$\left[-7.17, -5.57 ight]$	
Δ	1.35 ± 0.70	1.30 ± 0.70	1.60	1.54	[0.51, 2.07]	[0.37, 1.92]	
$\log_{10} A_{BHB}$		-15.72 ± 0.46		-15.65		$\left[-16.14, -15.22 ight]$	
$\gamma_{\rm BHB}$		4.65 ± 0.34		4.65		[4.32, 5.00]	

Best-fit values and constraints for the parameters of all BSM models

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New physics in the early Universe \rightarrow new physics in our Milky Way today

Deterministic signals

New physics in the early Universe \rightarrow new physics in our Milky Way today



Search for signals from ultralight dark matter and dark-matter substructures

- Metric fluctuations, Doppler U(1) forces, pulsar spin fluctuations, clock shifts
- Doppler and Shapiro signals because of passing primordial black holes

Deterministic signals

New physics in the early Universe \rightarrow new physics in our Milky Way today



Search for signals from ultralight dark matter and dark-matter substructures

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We find no signals \rightarrow new bounds on parameter space (partially world-leading)

New physics at the PTA frontier

[Image: Olena Shmahalo]



A new frontier of fundamental physics

- Probe BSM models in regions of parameter space inaccessible by other methods
- Test particle physics at extremely high energies (GUTs, string theory, etc.)
- Derive new constraints, irrespective of the origin of the NANOGrav signal
- Complementary to laboratory searches for new physics

PTArcade



Our code developed for 2306.16219: Fit your favorite BSM model to the NG15 data!

A bright future for GW science with PTAs



- Status: Common-spectrum process; $3 \cdots 4 \sigma$ evidence for HD correlations
- Next: HD correlations at 5σ , spectral shape, anisotropies across the sky, ...
- Promise: Deep insights into galaxy and BH evolution and/or BSM physics

Stay tuned!

And thanks a lot for your attention

Radio pulsars Venn diagram



Outlook: Projection based on emulated data



[NANOGrav Collaboration: 2010.11950]

15 to 20 years of data: Robust evidence for HD correlations

Outlook: Projection based on emulated data



[NANOGrav Collaboration: 2010.11950]

- 15 to 20 years of data: Robust evidence for HD correlations
- 20 years of data: Detect deviation from a simple power law

Outlook: Projection based on emulated data



[NANOGrav Collaboration: 2010.11950]

- 15 to 20 years of data: Robust evidence for HD correlations
- 20 years of data: Detect deviation from a simple power law
- Faster progress for combined data sets, more pulsars (IPTA DR3, ...)