Searching for New Physics with the NANOGrav Pulsar Timing Array

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University of Münster, Germany

Particle and Astroparticle Theory Seminar
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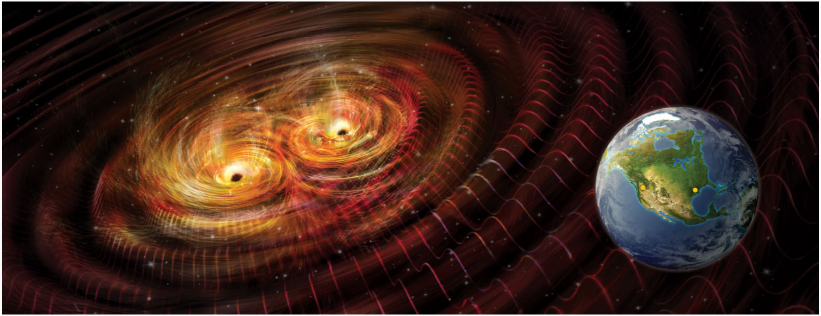
Gravitational waves: A new window onto the Universe



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

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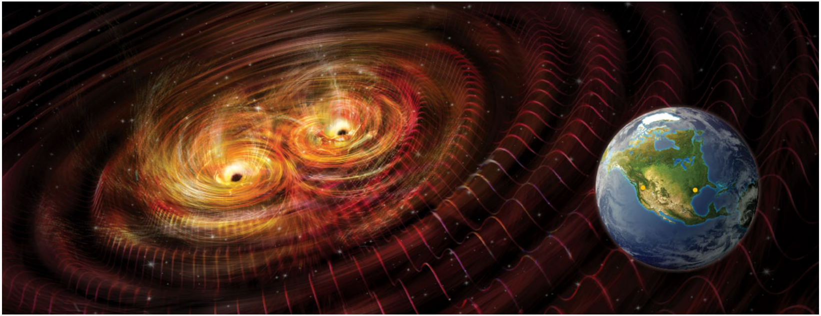

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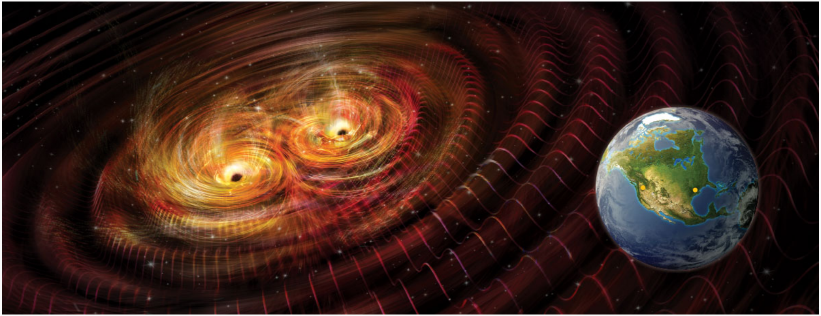

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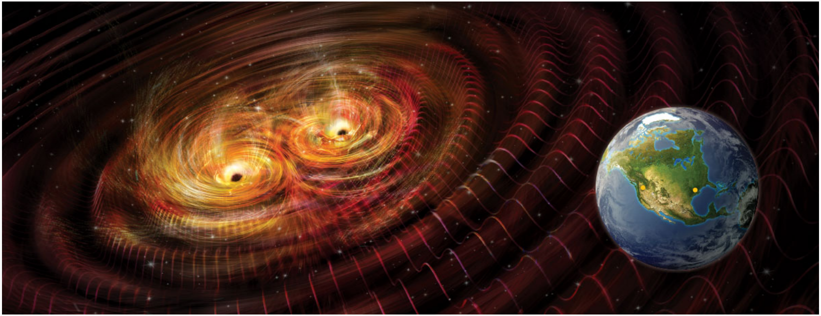

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202x Next milestone: Detection of a stochastic GW background (GWB).

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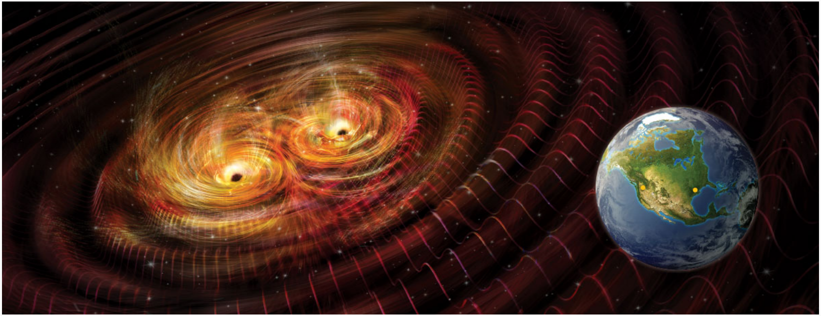

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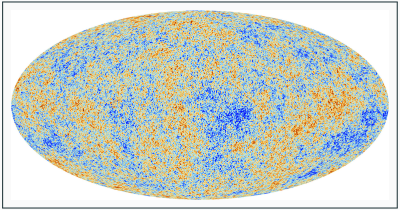
Big news on 29th June: **Compelling evidence** for a GWB reported by several teams!

CMB of the 21st century

20th century

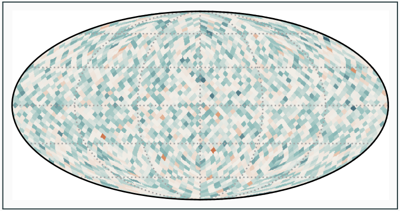
[PLANCK Collaboration]



CMB: Cosmic microwave background

21th century

[Sato-Polito, Kamionkowski: 2305.05690]



GWB: Gravitational-wave background

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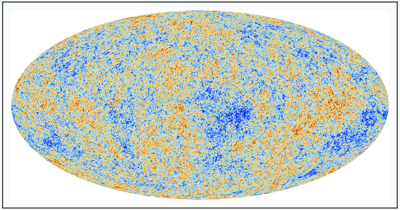

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Relic photons
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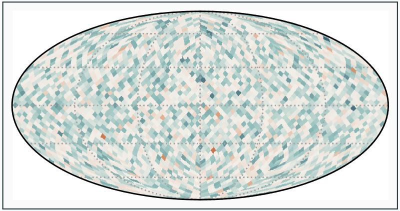
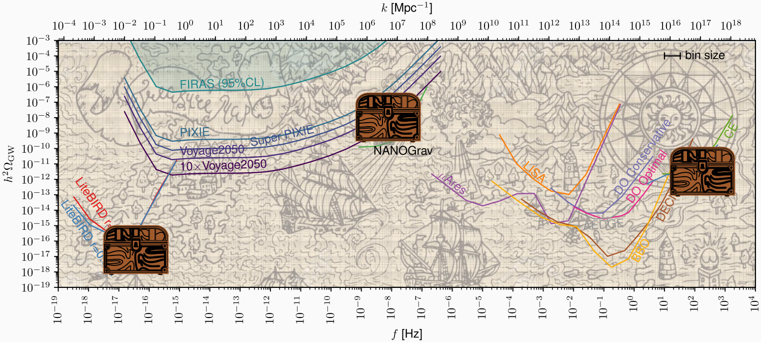


GWB: Gravitational-wave background

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

GWB treasure map



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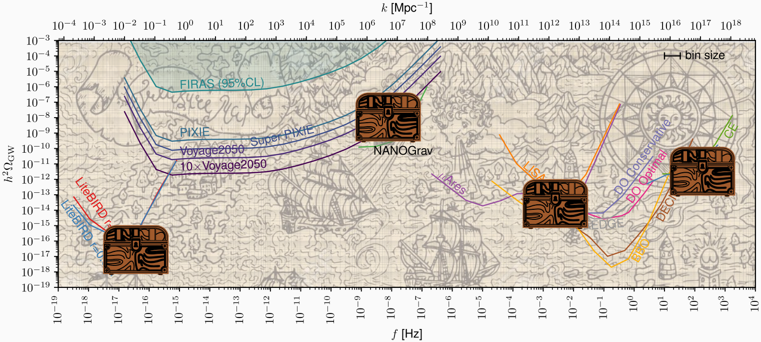

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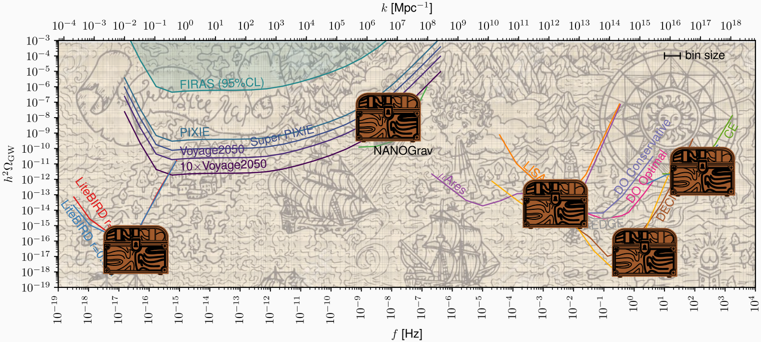

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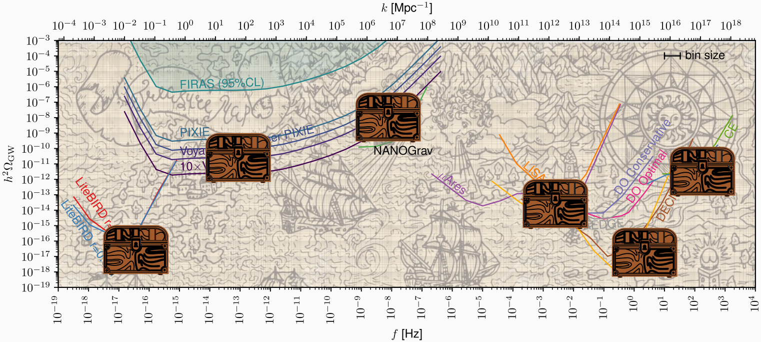

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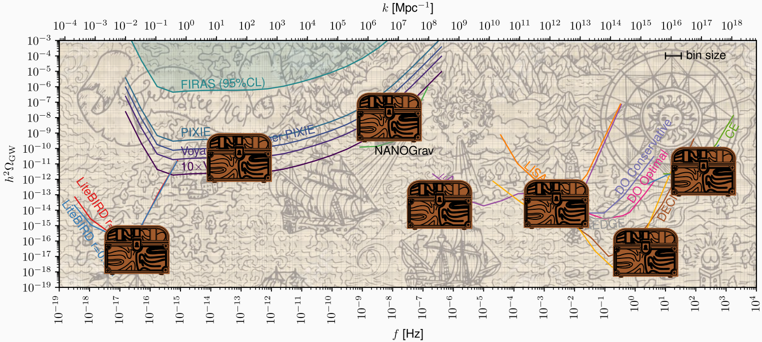


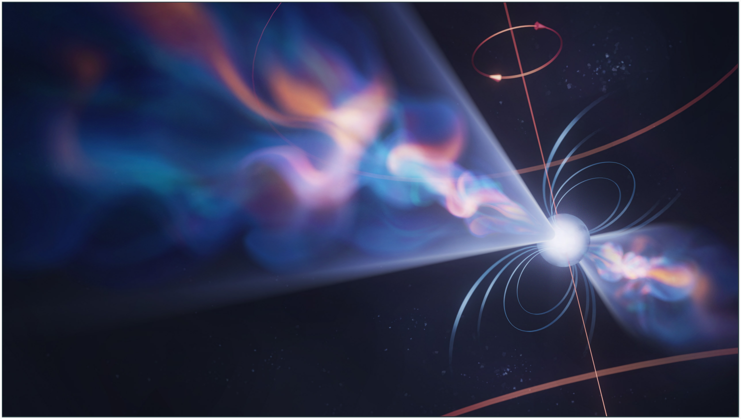
Possible GWB signals across vast frequency range

Galactic and extragalactic astrophysics + **particle physics in the early Universe**

Large arsenal of GW observations and experiments

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

Pulsars



Highly magnetized rotating neutron stars, ultra-precise stellar clocks

- Periods of $10^{-3\cdots1}$ s. Accretion in close-binary systems → **millisecond pulsars**
- Beamed radio pulses emitted from magnetic poles → **cosmic lighthouses**

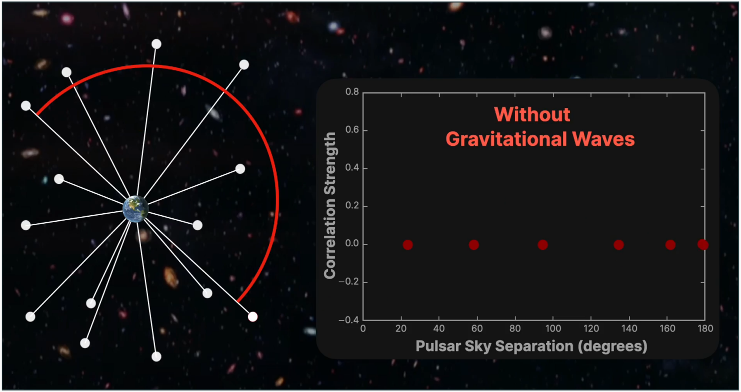
Pulsar timing arrays (PTAs)

YouTube

Array of pulsars across the Milky Way → 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 → GW signature in cross-correlations.

Cross correlations among timing residuals



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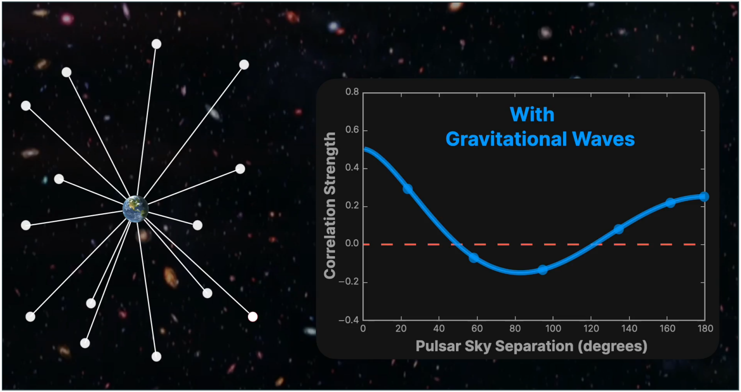
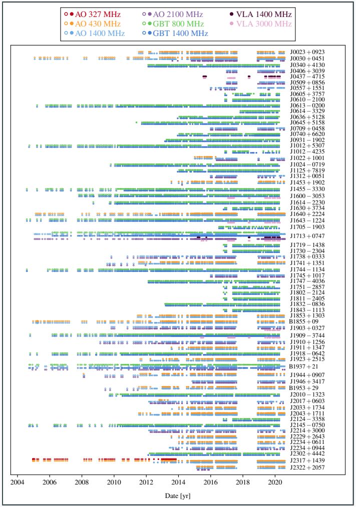


Hallmark signature of a stochastic gravitational-wave background signal:

Quadrupolar correlations described by Hellings–Downs (HD) curve $\Gamma_{ij}(\psi)$

[Hellings, Downs: Astrophys. J. 265 (1983) L39]

NANOGrav 15-year data set



Telescopes

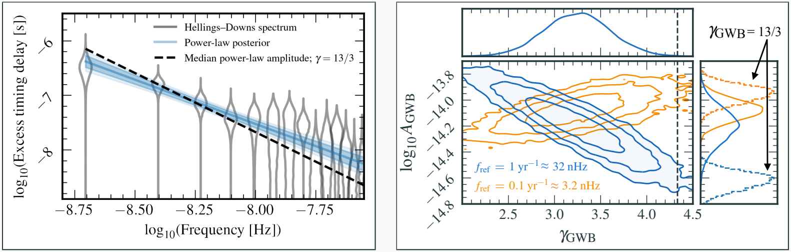
- AO: Arecibo Observatory
- GBT: Green Bank Telescope
- VLA: Very Large Array

Observations

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

Compelling evidence for a GWB

YouTube



Bayesian model comparison in terms of Bayes factors

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

$$\frac{P\,(D|\mathbf{CURN})}{P\,(D|\mathbf{IRN})} = 10^{12.1\pm0.1}\,, \qquad \frac{P\,(D|\mathbf{HD})}{P\,(D|\mathbf{CURN})} \sim 200 \cdots 1000 \tag{1}$$

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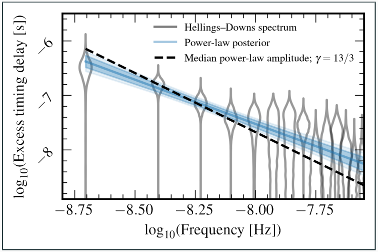

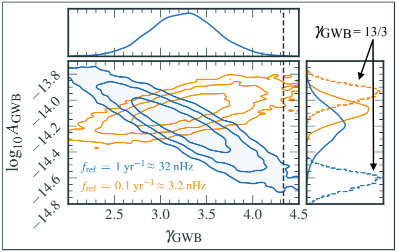

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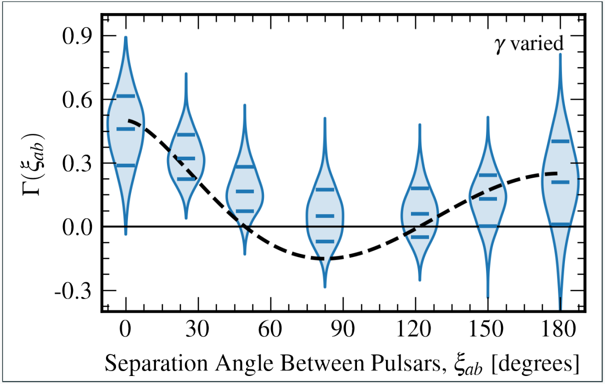
Decisive evidence for a new common-spectrum process; compelling evidence for HD

(Range corresponds to spectral modelling choices, e.g., the number of frequency bins)

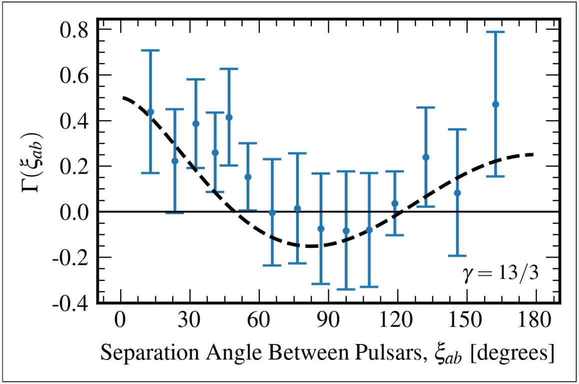
Hellings–Downs curve

Bayesian analysis: Model correlations with cubic splines across seven nodes



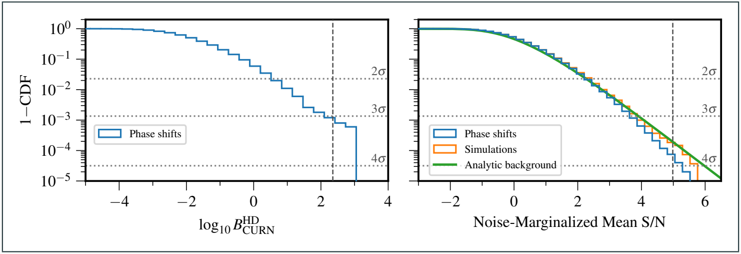
Hellings–Downs curve

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



Statistical significance

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

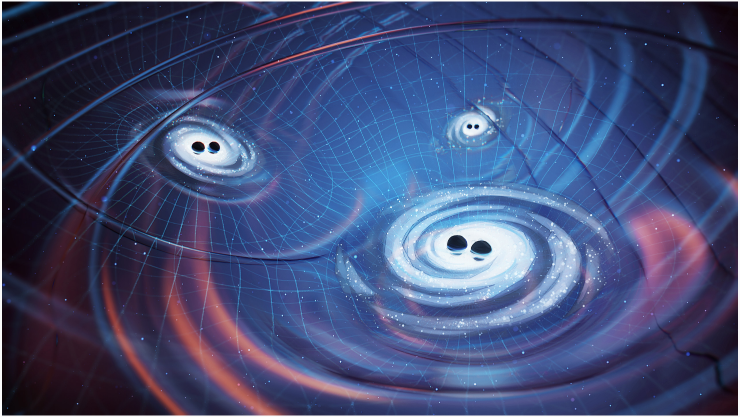


p-value test for two test statistics

- (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

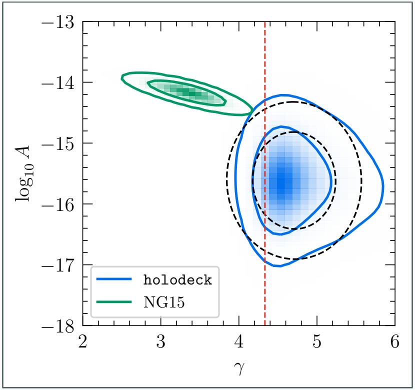
Astrophysical interpretation



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 → 2σ tension between observations and theory
- Tension can be reduced in more "phenomenological" SMBHB models

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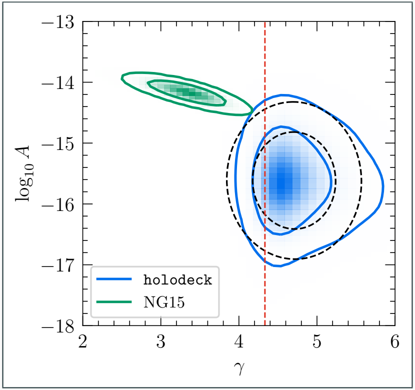

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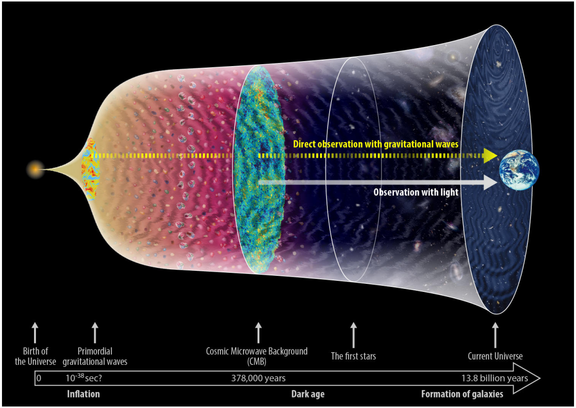
SMBHB interpretation: Need to go to unexpected corners of parameter space

Gravitational waves from the Big Bang

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

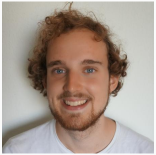


Viable possibility: Signal receives contributions from SMBHBs + X (or X only?)

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

NANOGrav team

R. v. Eckardstein*

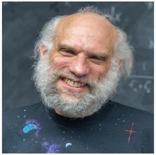


R. Lino d. Santos*

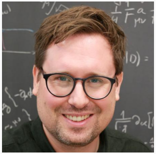
Andrea Mitridate

Jonathan Nay

Ken Olum



Kai Schmitz*



Tobias Schröder*

Tanner Trickle

David Wright

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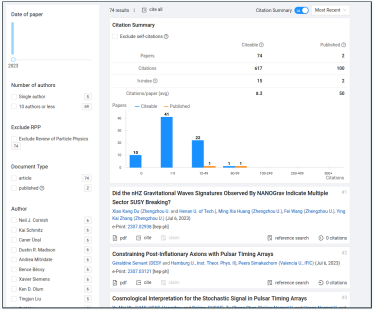
1. Searches for signals from new physics in NANOGrav data → 2306.16219
2. New software tools for fitting BSM models to PTA data → `PTArcade`

* Current or former members of my research group, *Particle Cosmology Münster*

2306.16219: Our contribution to the analysis of the NG15 data



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

Andrea Mitridate

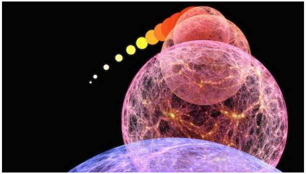
- Initially proposed the project to the Collaboration
- Worked on all aspects of the analysis
- Main developer of `PTArcade`
- Together, Andrea and I wrote almost the entire 74 pages of the paper

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

BSM options

Inflation

- Nonminimal blue-tilted models
- Interplay with CMB observables



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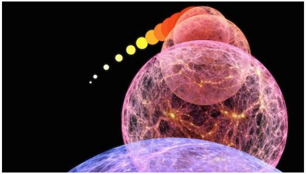
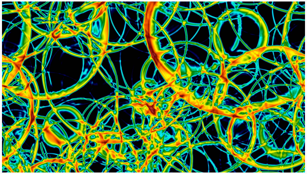


Phase transition

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



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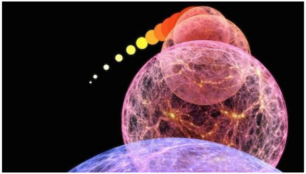

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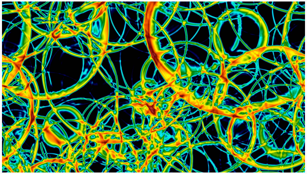
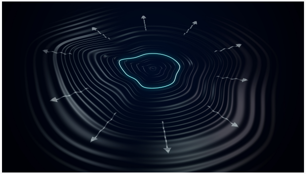


Cosmic defects

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



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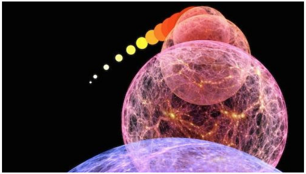

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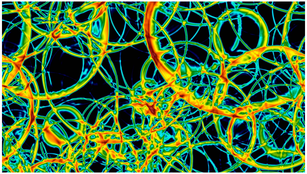

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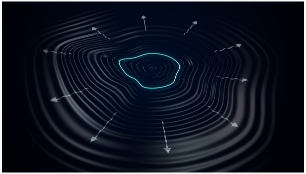
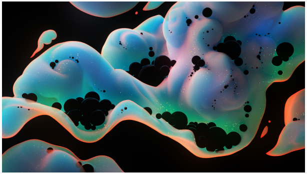
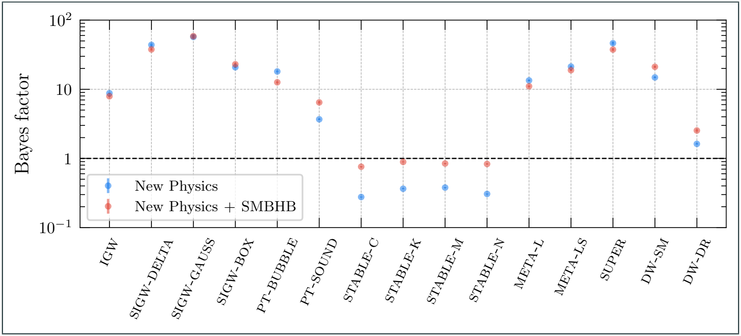


Scalar perturbations

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



Bayes factors



Bayesian model comparison

Reference model: $\mathcal{H}_0 = \{\text{SMBHBs only}\}$

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

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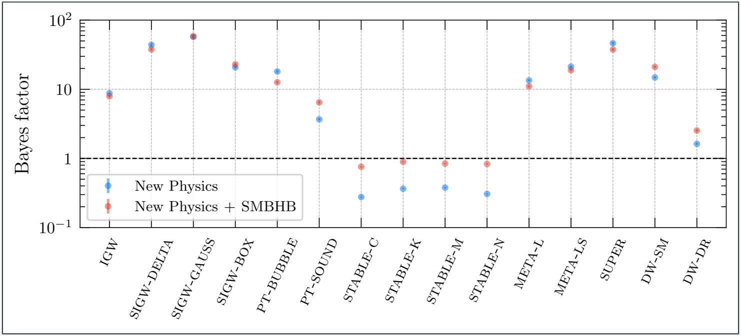

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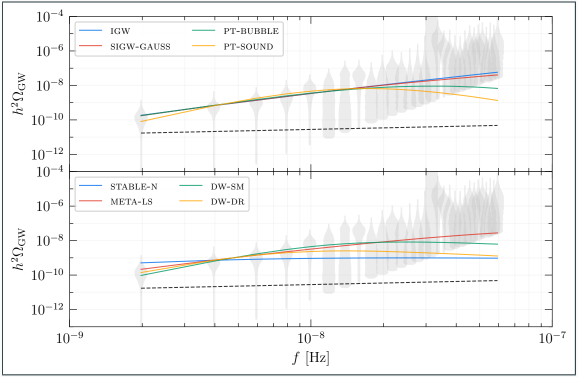
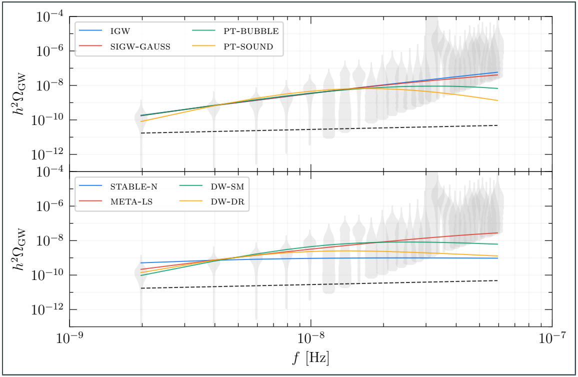
Bottom line: Stable strings don't look good; all other BSM models can fit the data.

Median GW spectra



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

Median GW spectra



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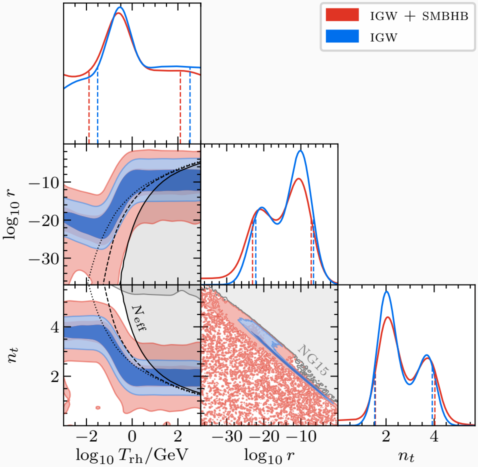
Of course, GW spectra resulting in a good fit all look similar by construction.
→ Relevant question: Which parameter values predict GW spectrum of the right form?

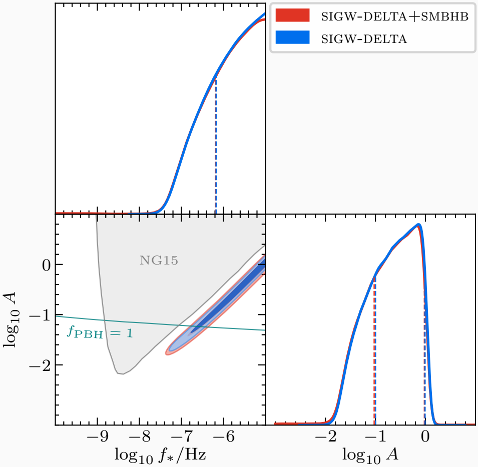
Parameter inference

Inflationary gravitational waves (IGW)



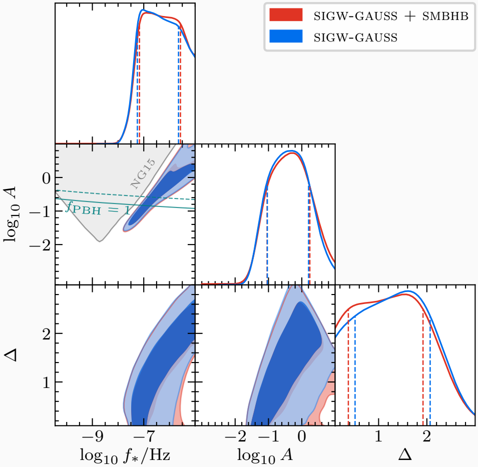
Parameter inference

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

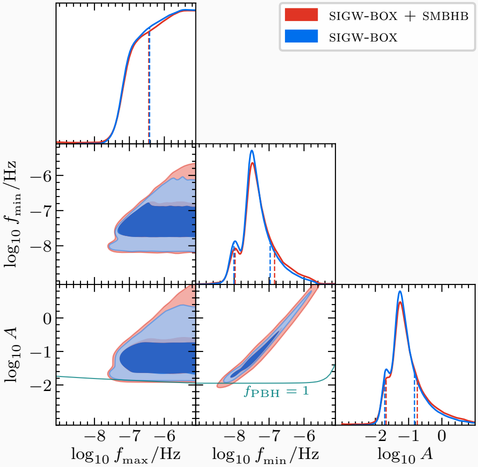


Parameter inference

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

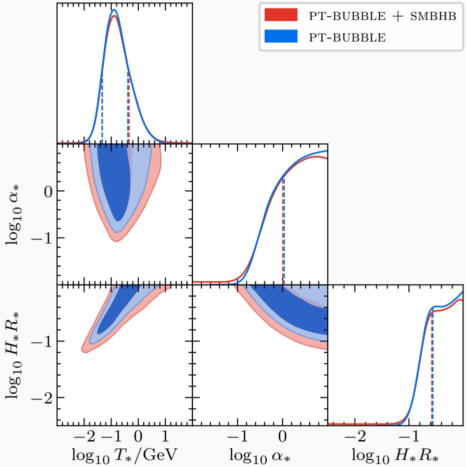


Scalar-induced gravitational waves, box-shaped $\mathcal{P}_\mathcal{R}$ (SIGW-BOX)



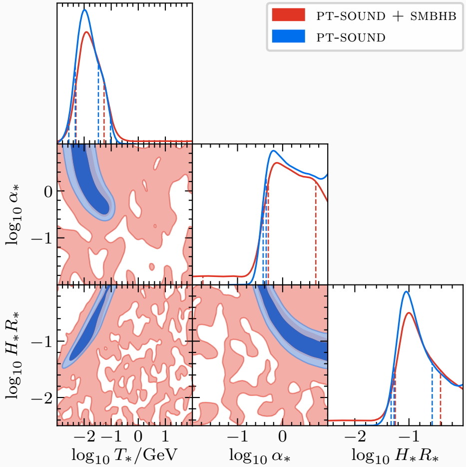
Parameter inference

Phase transition, bubble collisions (PT-BUBBLE)

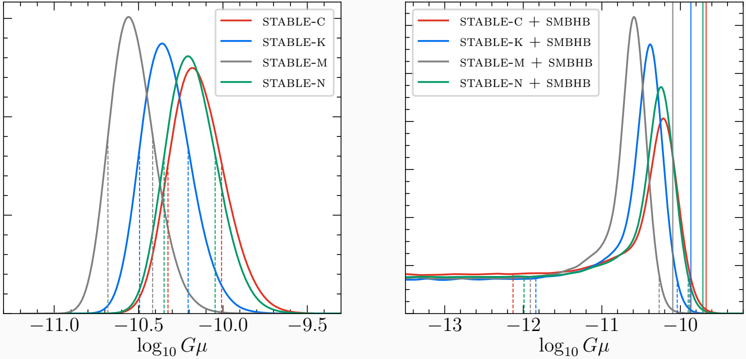


Parameter inference

Phase transition, sound waves (PT-SOUND)

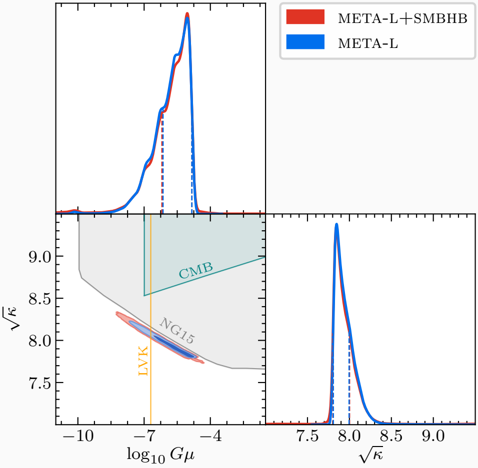


Stable cosmic strings (STABLE)



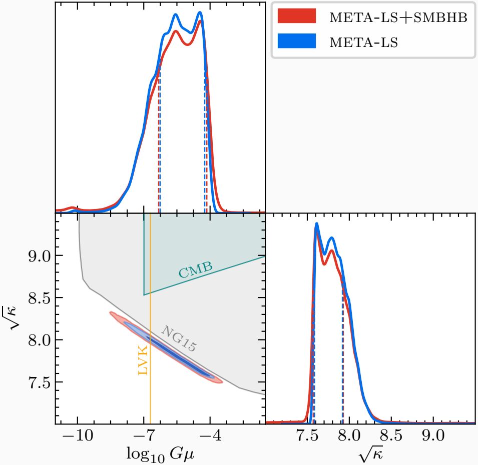
Parameter inference

Metastable cosmic strings, loops (META-L)

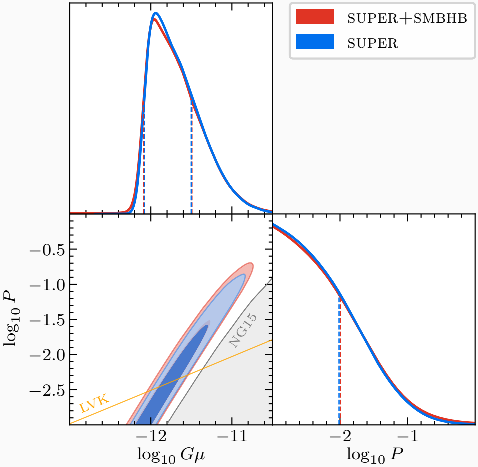


Parameter inference

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

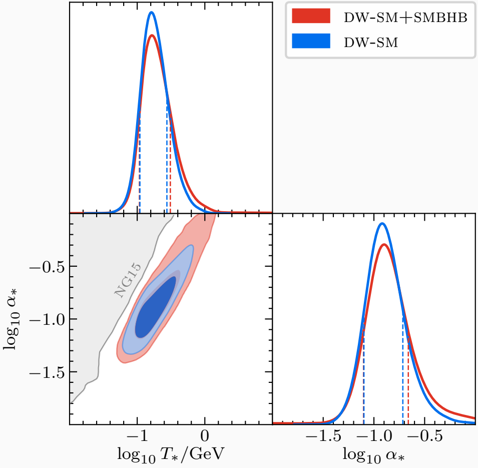


Cosmic superstrings (SUPER)

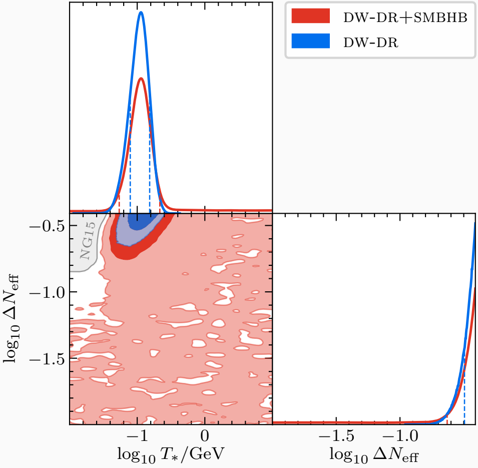


Parameter inference

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



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



Point values and uncertainty estimates

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	
Inflationary Gravitational Waves (IGW)							
$\log_{10} T_{\rm rh}/\mathrm{GeV}$	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	...	$[-16.20, -15.14]$	...
$\gamma_{\rm BHB}$	...	4.61 ± 0.37	...	4.64	...	$[4.26, 5.00]$	...
Scalar-induced Gravitational Waves (SIGW-DELTA)							
$\log_{10} A$	-0.69 ± 0.47	-0.71 ± 0.49	-0.14	-0.17	$[-1.00, -0.01]$	$[-1.03, -0.02]$	...
$\log_{10} f_*/\mathrm{Hz}$	-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	...	$[-16.18, -15.29]$	...
$\gamma_{\rm BHB}$	...	4.65 ± 0.35	...	4.65	...	$[4.31, 4.99]$	...
Scalar-induced Gravitational Waves (SIGW-GAUSS)							
$\log_{10} A$	-0.38 ± 0.58	-0.36 ± 0.61	-0.34	-0.29	$[-1.03, 0.20]$	$[-1.04, 0.24]$	...
$\log_{10} f_*/\mathrm{Hz}$	-6.32 ± 0.71	-6.30 ± 0.73	-7.03	-6.85	$[-7.25, -5.65]$	$[-7.17, -5.57]$	...
Δ	1.35 ± 0.70	1.30 ± 0.70	1.60	1.54	$[0.51, 2.07]$	$[0.37, 1.92]$	...
$\log_{10} A_{\rm BHB}$	...	-15.72 ± 0.46	...	-15.65	...	$[-16.14, -15.22]$	...
$\gamma_{\rm BHB}$	...	4.65 ± 0.34	...	4.65	...	$[4.32, 5.00]$	...

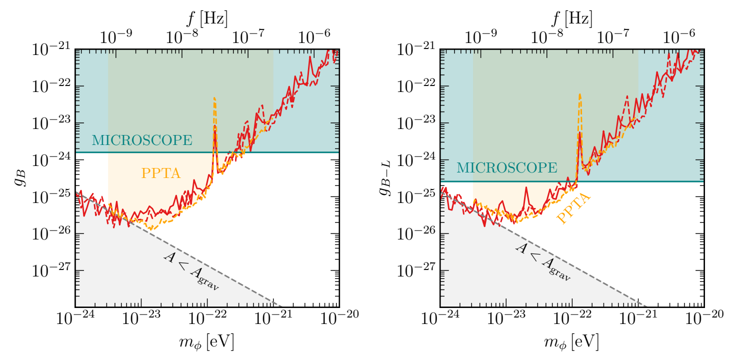
Best-fit values and constraints for the parameters of all BSM models

Deterministic signals

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

Deterministic signals

New physics in the early Universe → new physics in our Milky Way today

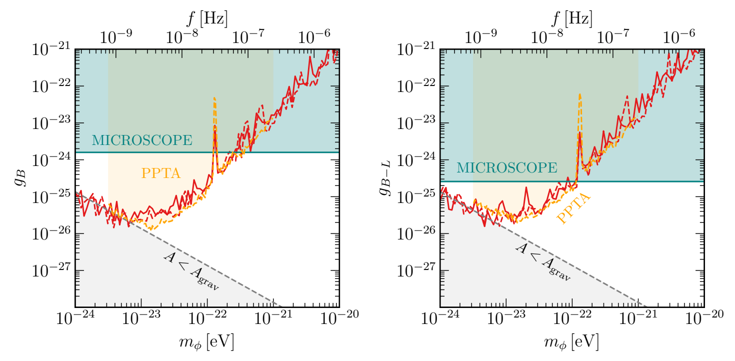


Search for signals from ultralight dark matter and dark-matter substructures

- 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 → 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

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

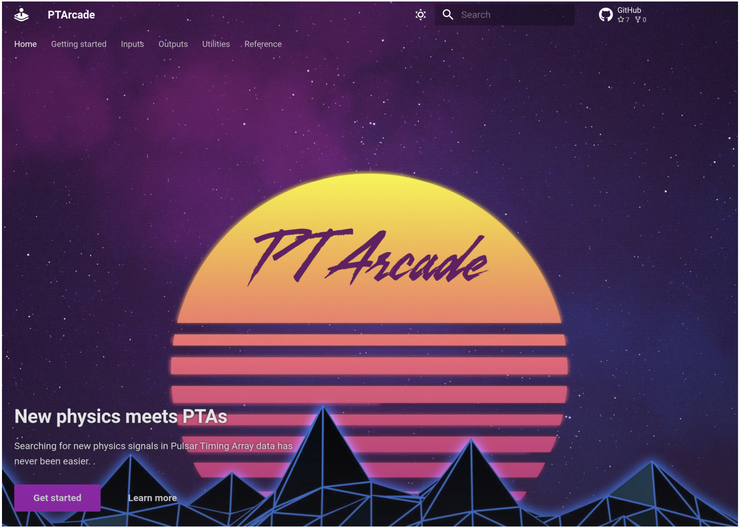
New physics at the PTA frontier

[Image: Olena Shmahalo]

A new frontier of fundamental physics

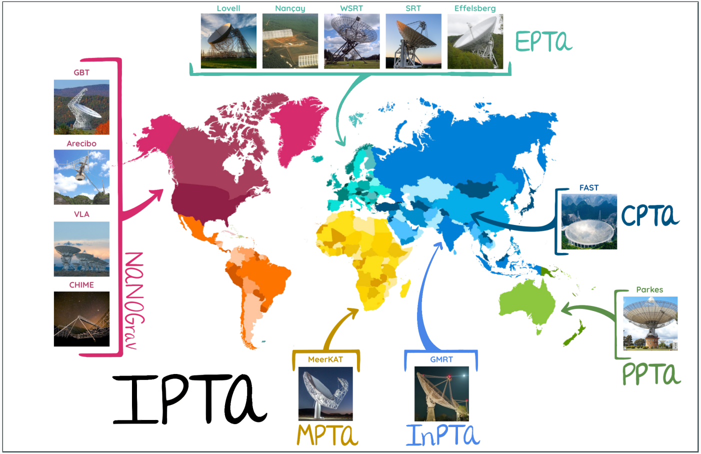
- Probe BSM models in regions of parameter space inaccessible by other methods
- Test particle physics at extremely high energies (GUTs, string theory, etc.)
- Derive new constraints, irrespective of the origin of the NANOGrav signal
- Complementary to laboratory searches for new physics

PTArcade



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

A bright future for GW science with PTAs

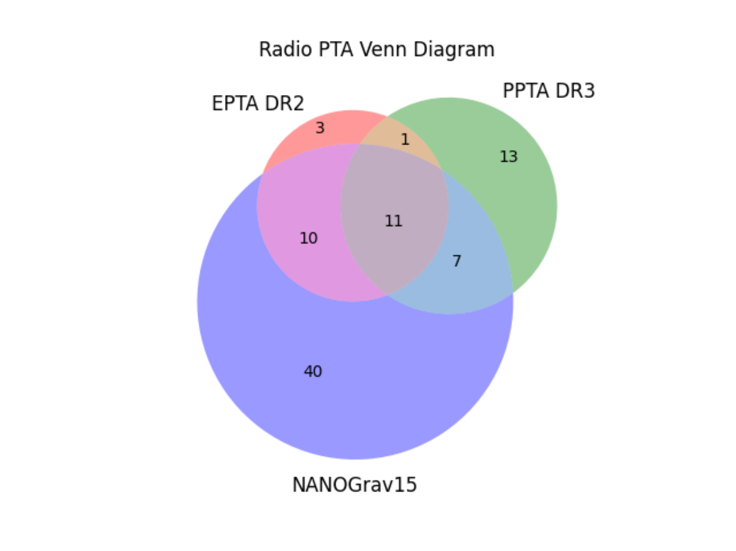


- Status: Common-spectrum process; $3 \cdots 4\,\sigma$ evidence for HD correlations
- Next: HD correlations at $5\,\sigma$, spectral shape, anisotropies across the sky, ...
- Promise: Deep insights into galaxy and BH evolution and/or BSM physics

Stay tuned!

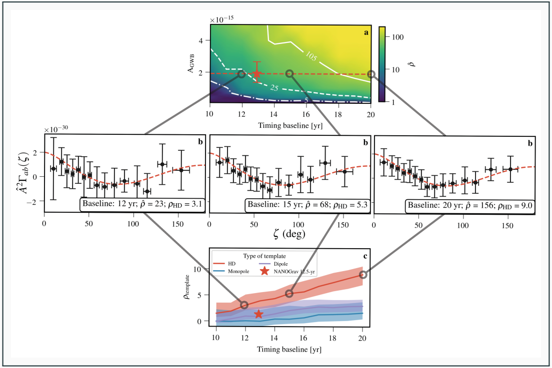
And thanks a lot for your attention

Radio pulsars Venn diagram



Outlook: Projection based on emulated data

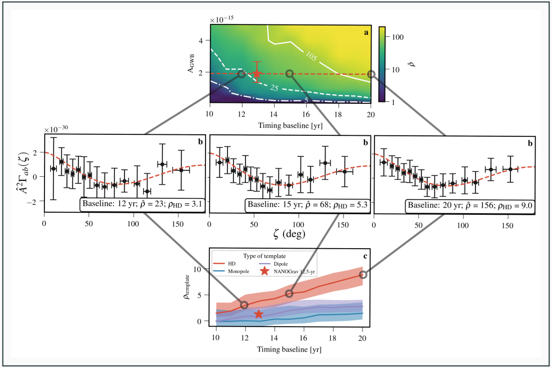
[NANOGrav Collaboration: 2010.11950]



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

Outlook: Projection based on emulated data

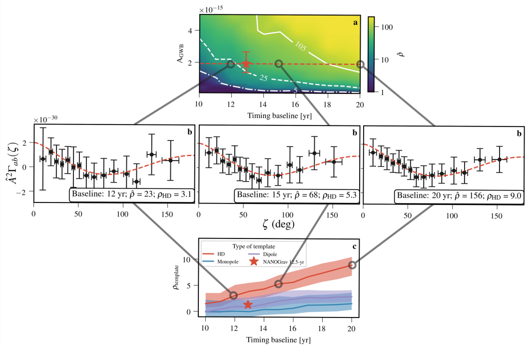
[NANOGrav Collaboration: 2010.11950]



- 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, ...)