






Probing New Physics at the Pulsar Timing Array Frontier

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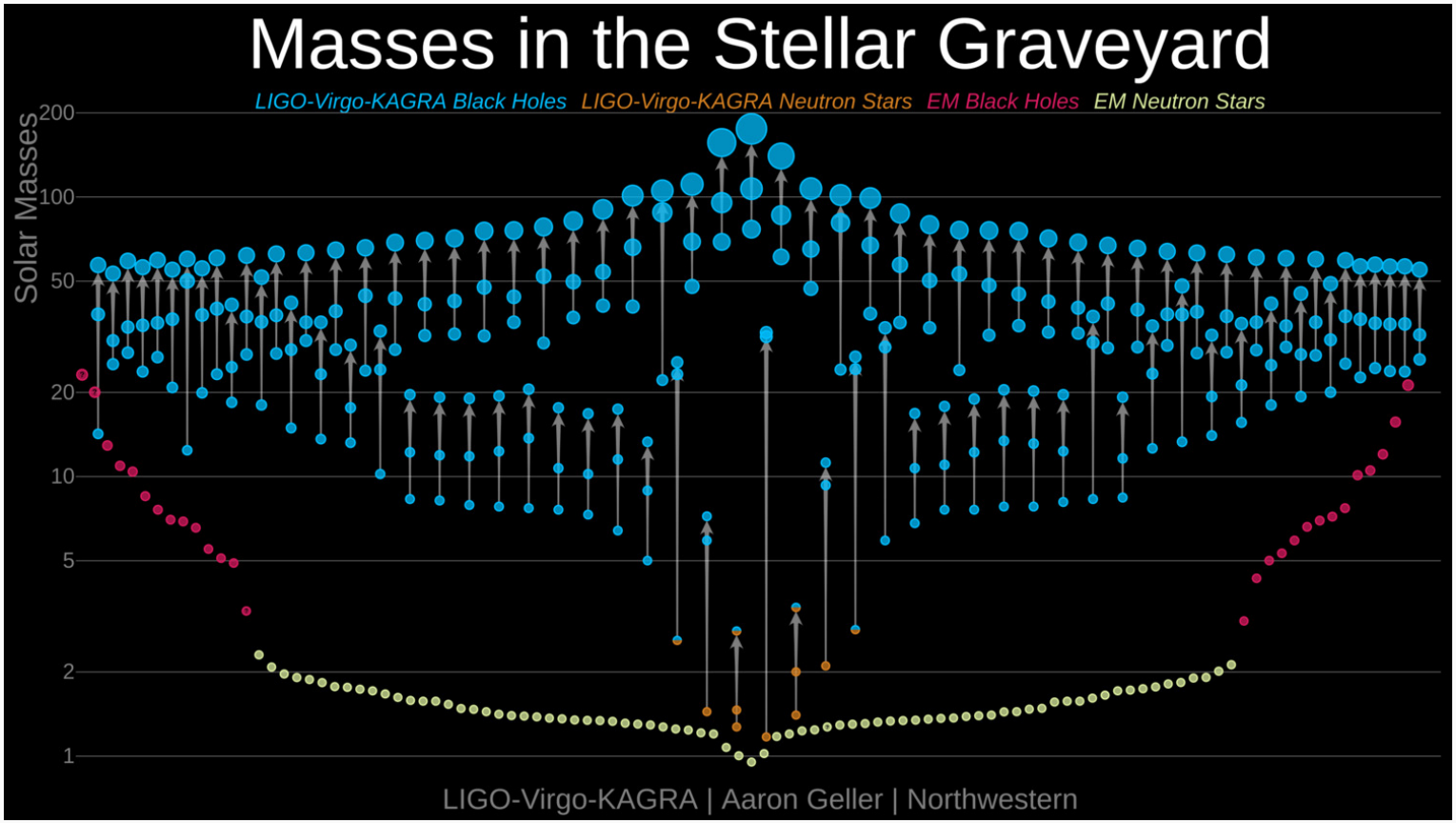
Copernicus Webinar
October 10, 2023

Next milestone in gravitational-wave (GW) astronomy

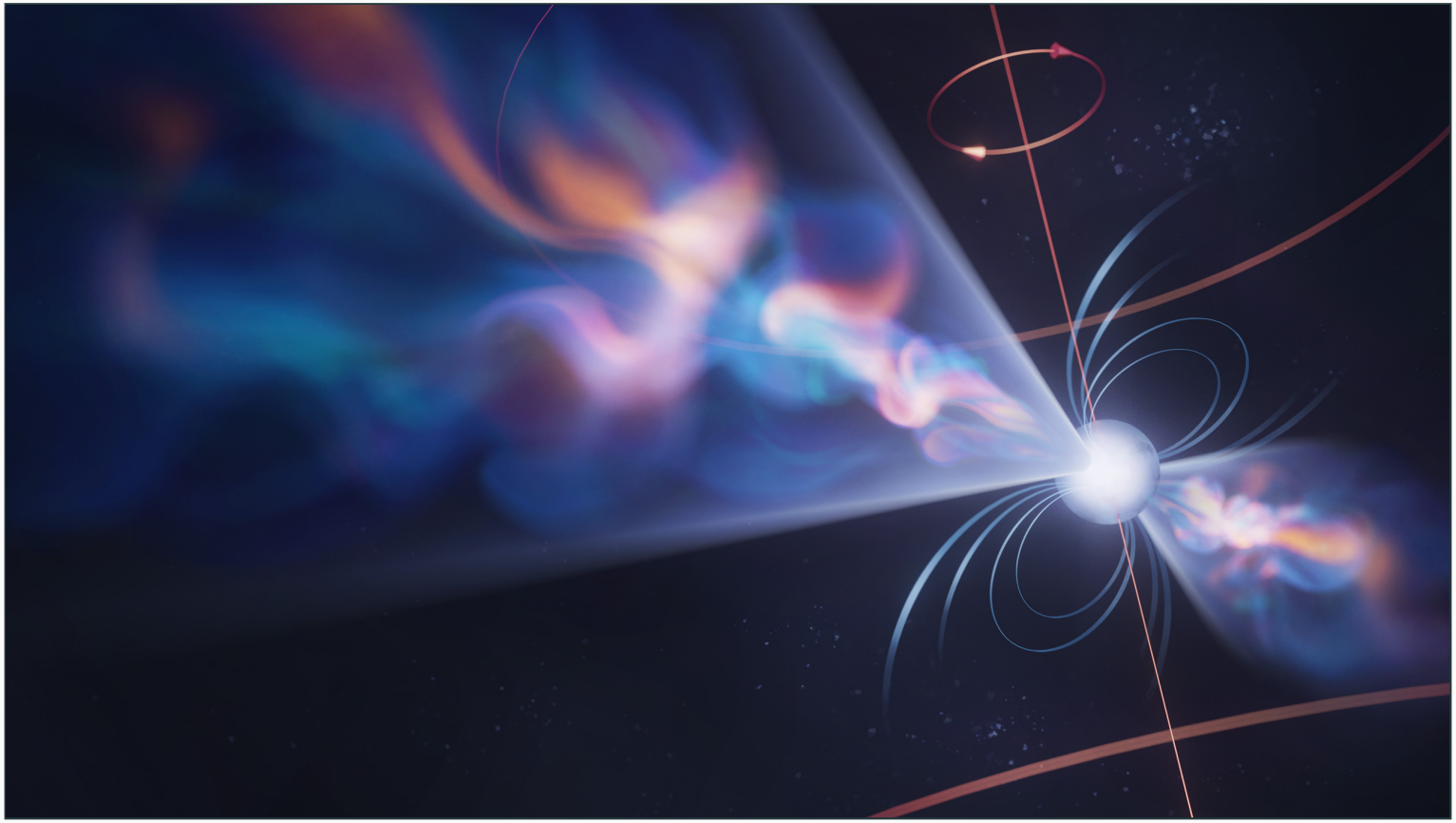


- Status: LVK now routinely observe transient GW signals of astrophysical origin
- Next milestone: Detection of a stochastic GW background (GWB)
- Big news on June 29: **Compelling evidence** for a GWB reported by several teams!

Pulsar timing arrays

Global effort under the umbrella of the International Pulsar Timing Array (IPTA)

Pulsars: cosmic clocks scattered across the Milky Way

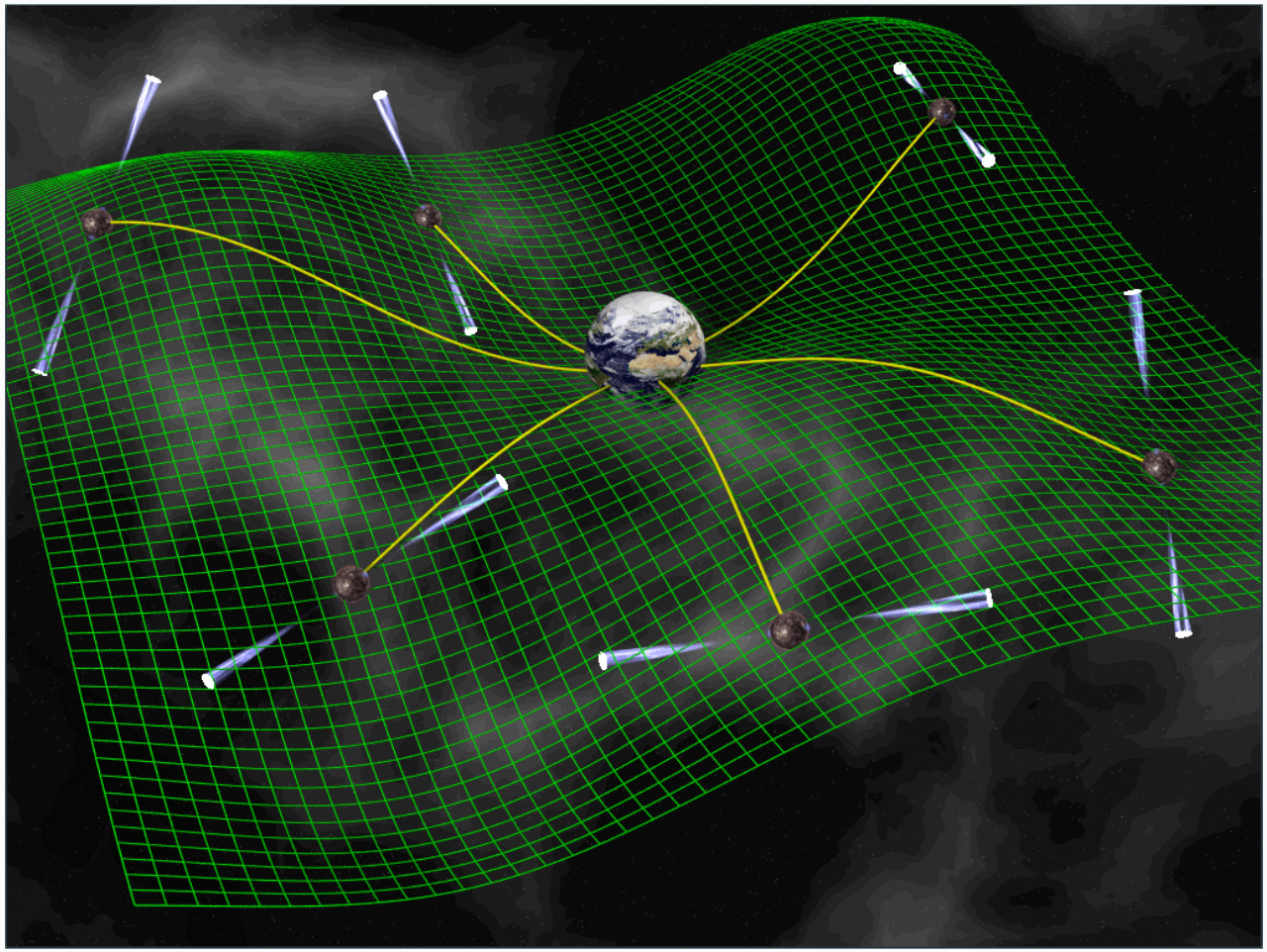


Highly magnetized rotating neutron stars, ultra-precise stellar clocks

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

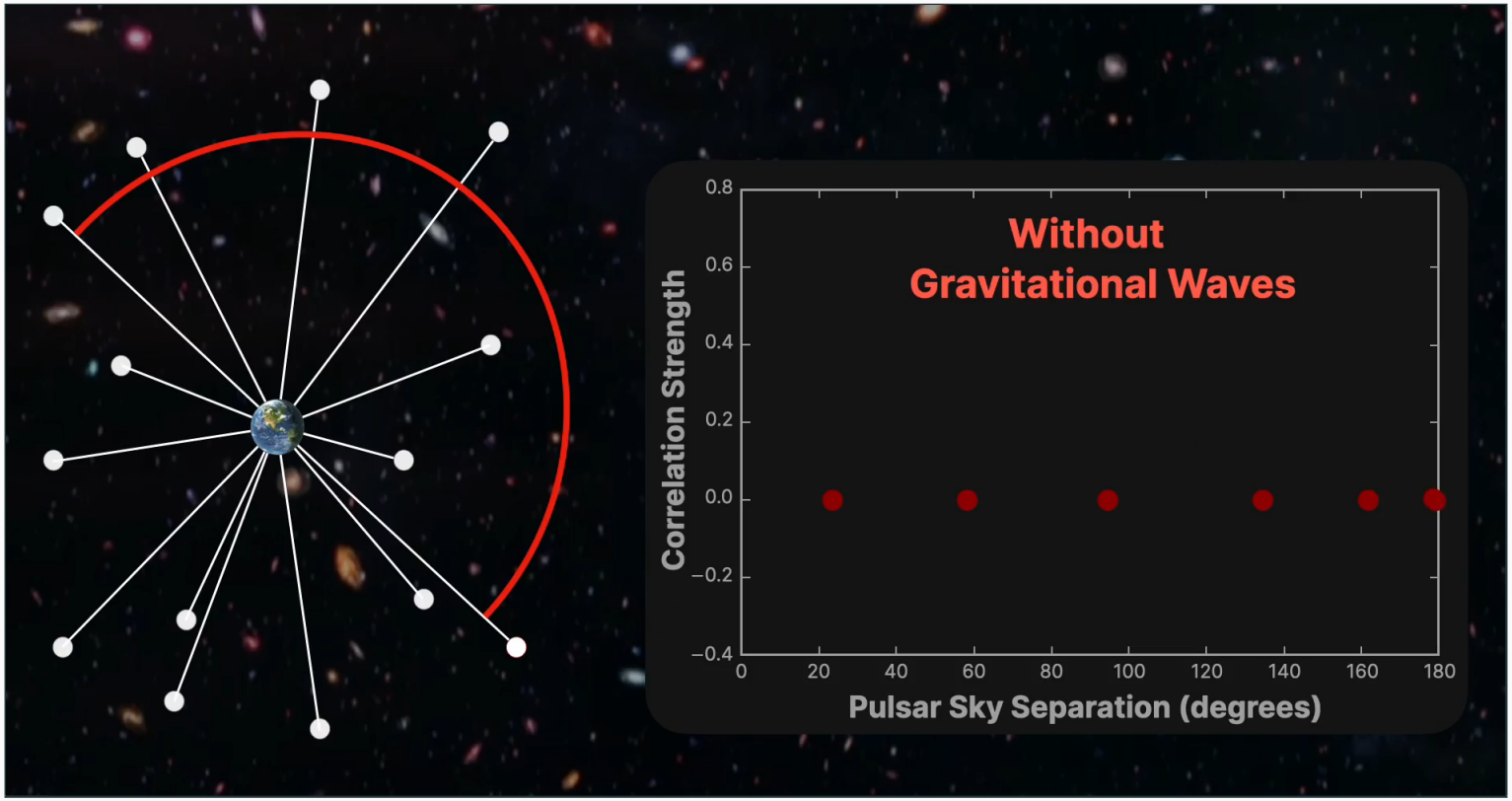
Galaxy-sized gravitational-wave detectors

[David Champion / MPIfR]



- Look for tiny distortions in pulse travel times caused by nHz gravitational waves
- Cross-correlate timing residuals of pairs of pulsars $\rightarrow$ identify characteristic pattern

Hallmark signature



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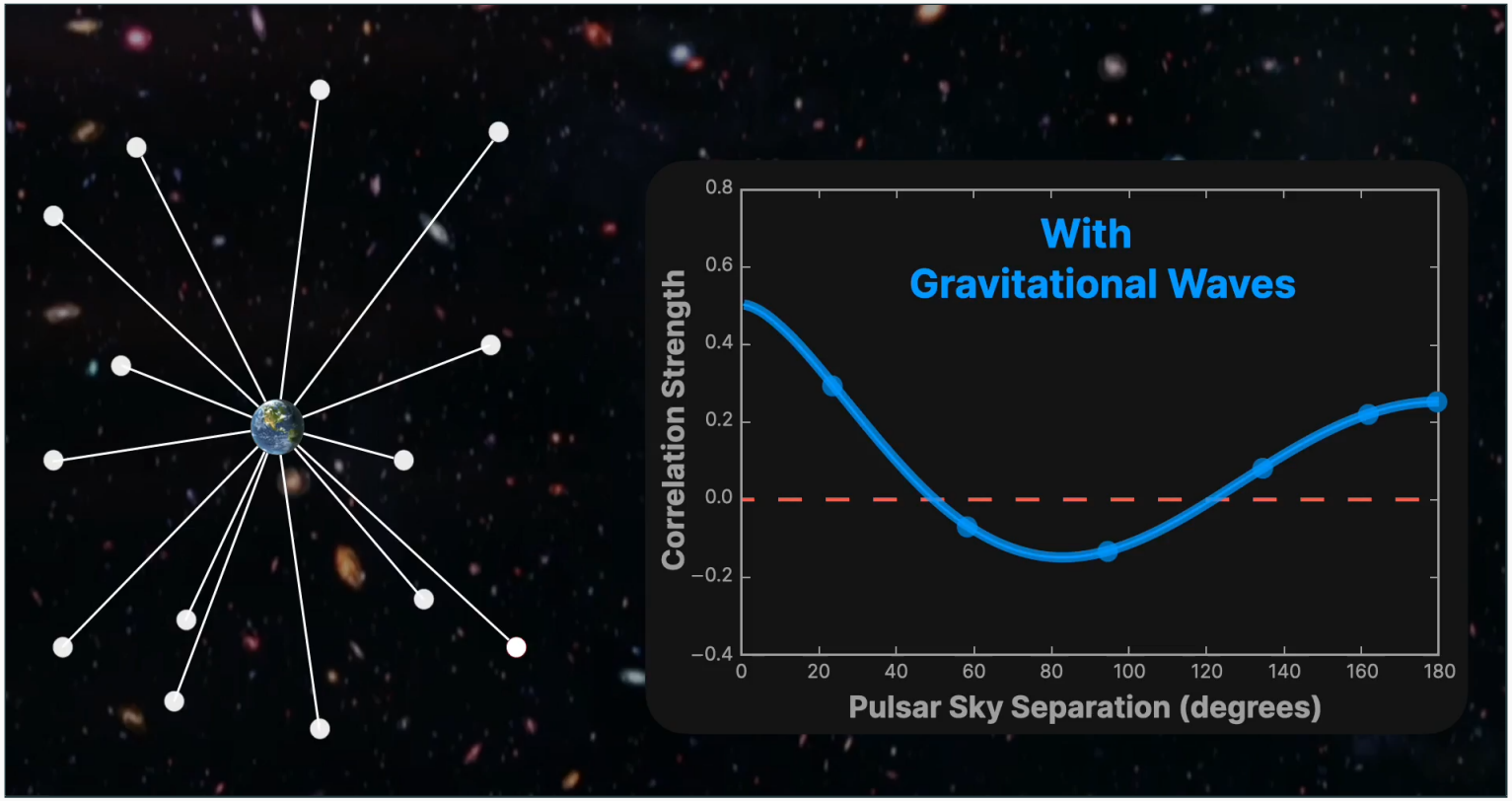
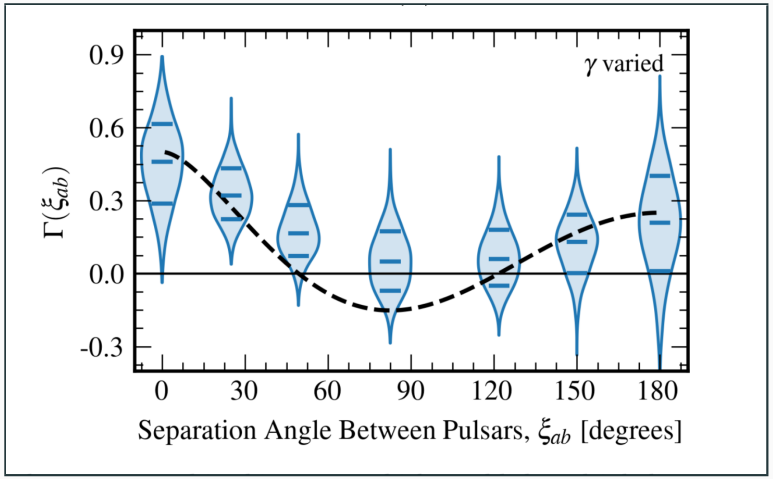


Quadrupolar correlations described by Hellings–Downs (HD) curve

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

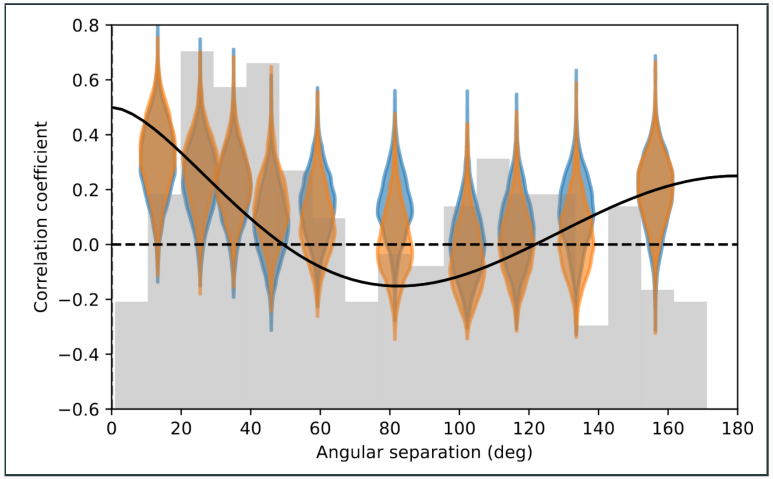
Compelling evidence for HD correlations

2306.16213: NANOGrav



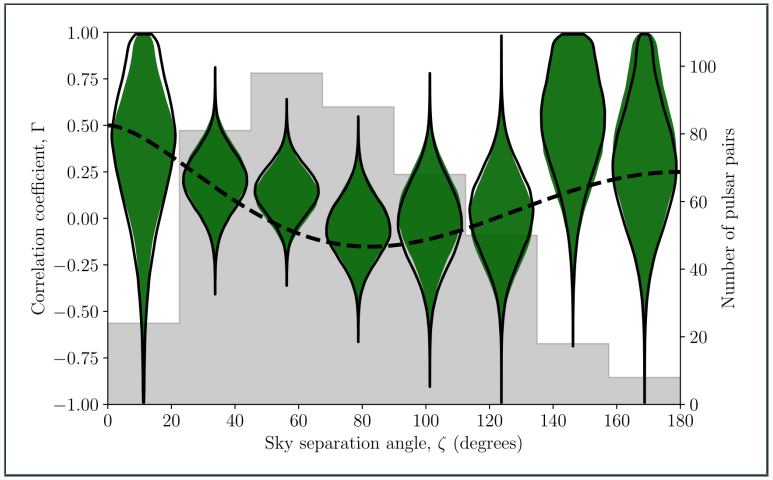
68 pulsars, 16 yr of data, HD at $\sim 3 \cdots 4\,\sigma$

2306.16214: EPTA+InPTA



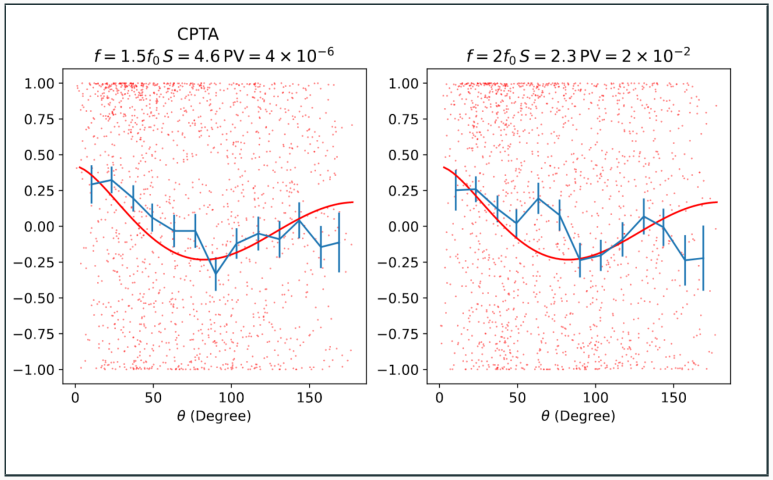
25 pulsars, 25 yr of data, HD at $\sim 3\,\sigma$

2306.16215: PPTA



32 pulsars, 18 yr of data, HD at $\sim 2\,\sigma$

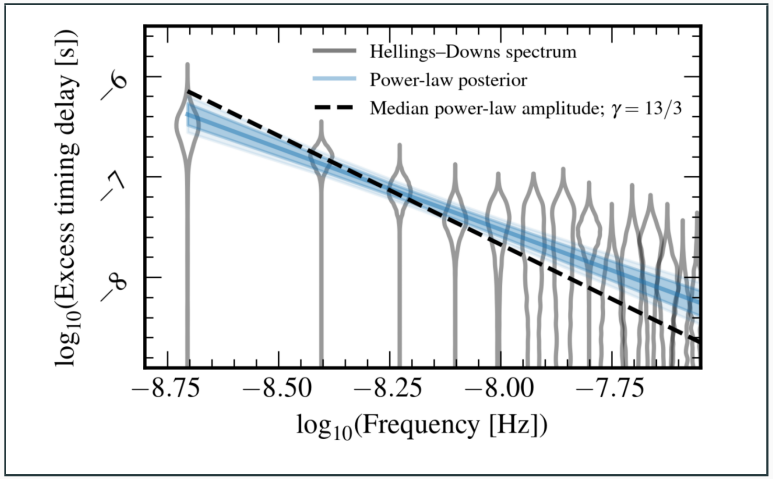
2306.16216: CPTA



57 pulsars, 3.5 yr of data, HD at $\sim 4.6\,\sigma$

Spectral characterization

2306.16213: NANOGrav



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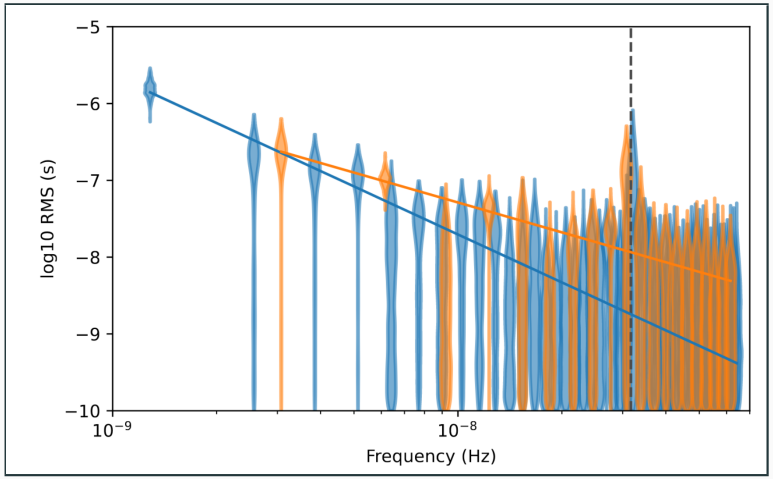

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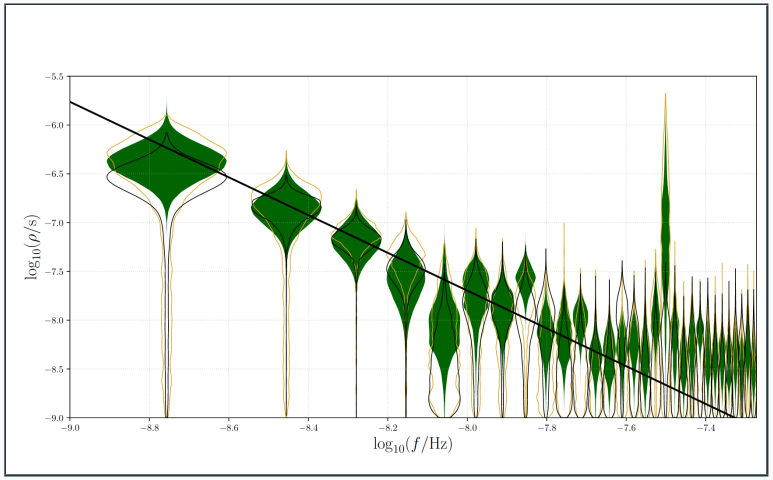

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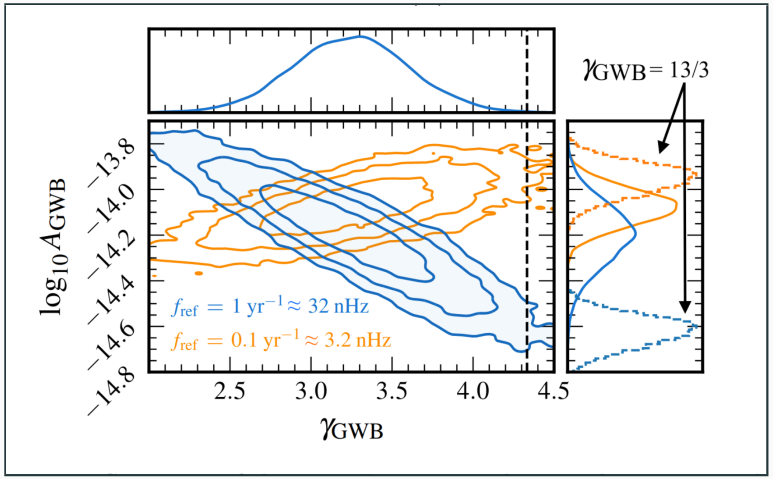
Parameter inference

2306.16213: NANOGrav



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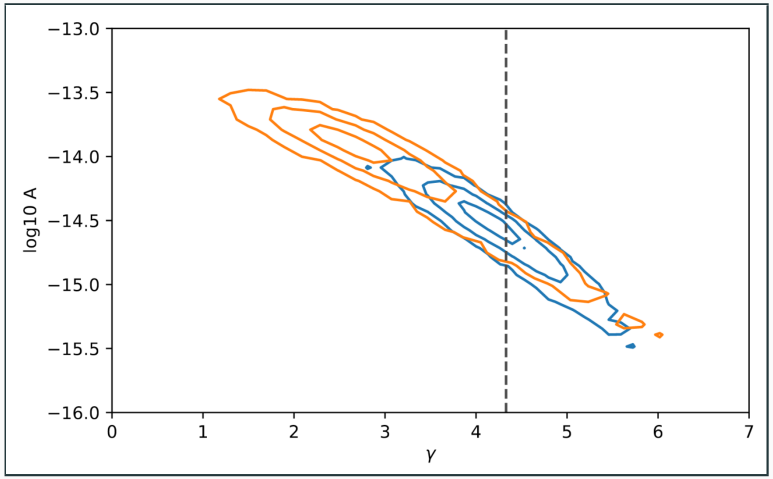

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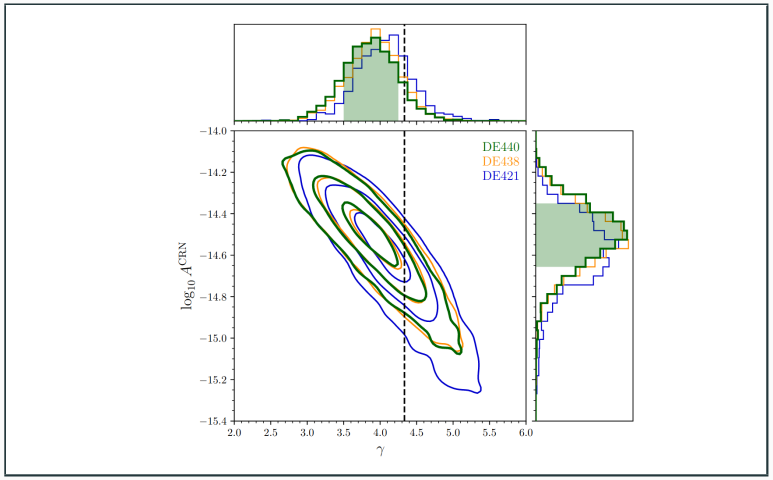

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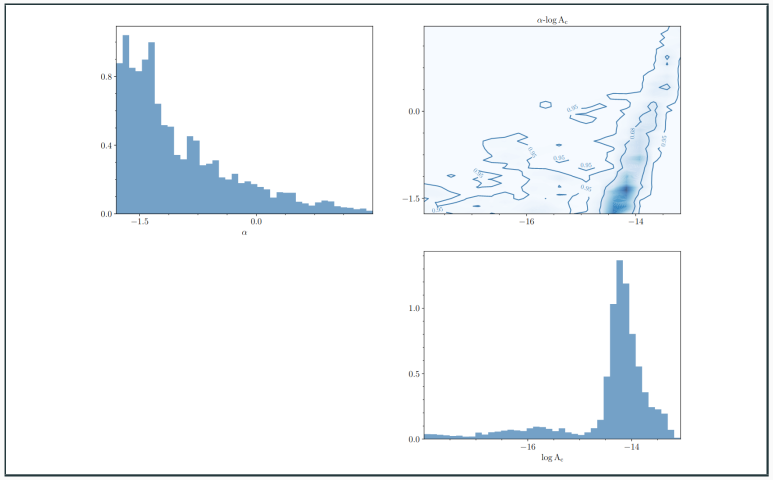

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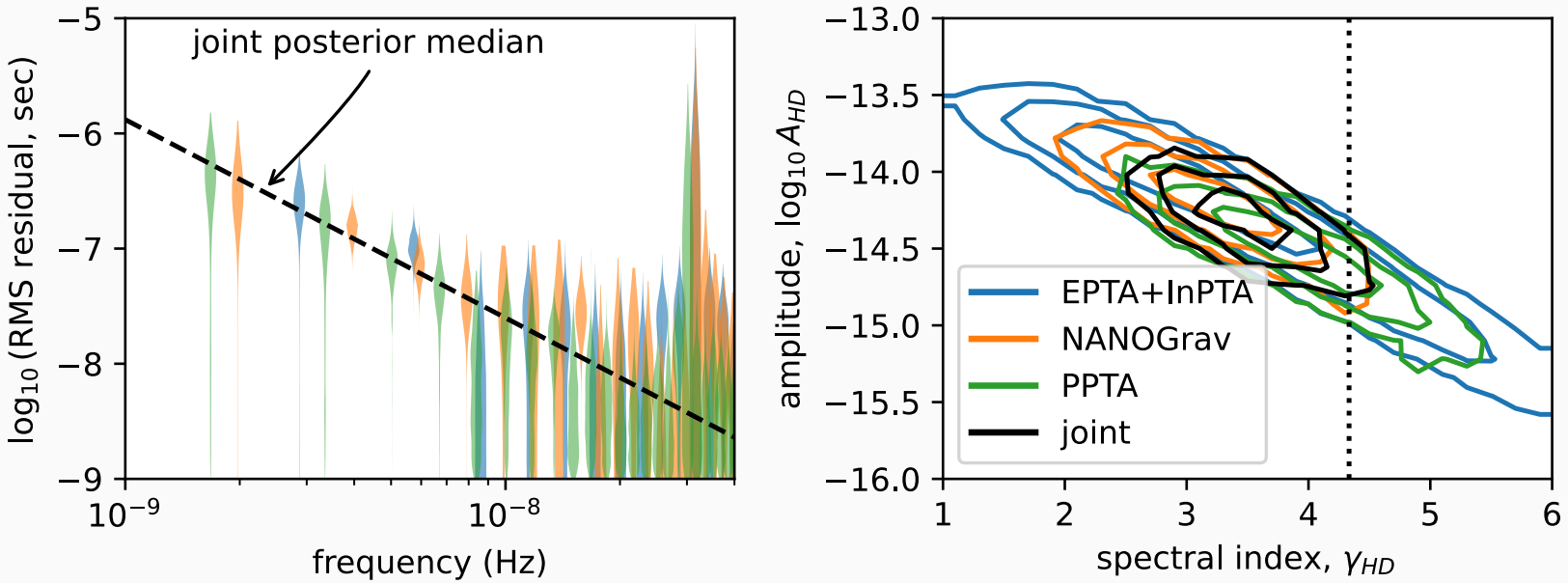
IPTA comparison

[IPTA 2309.00693]

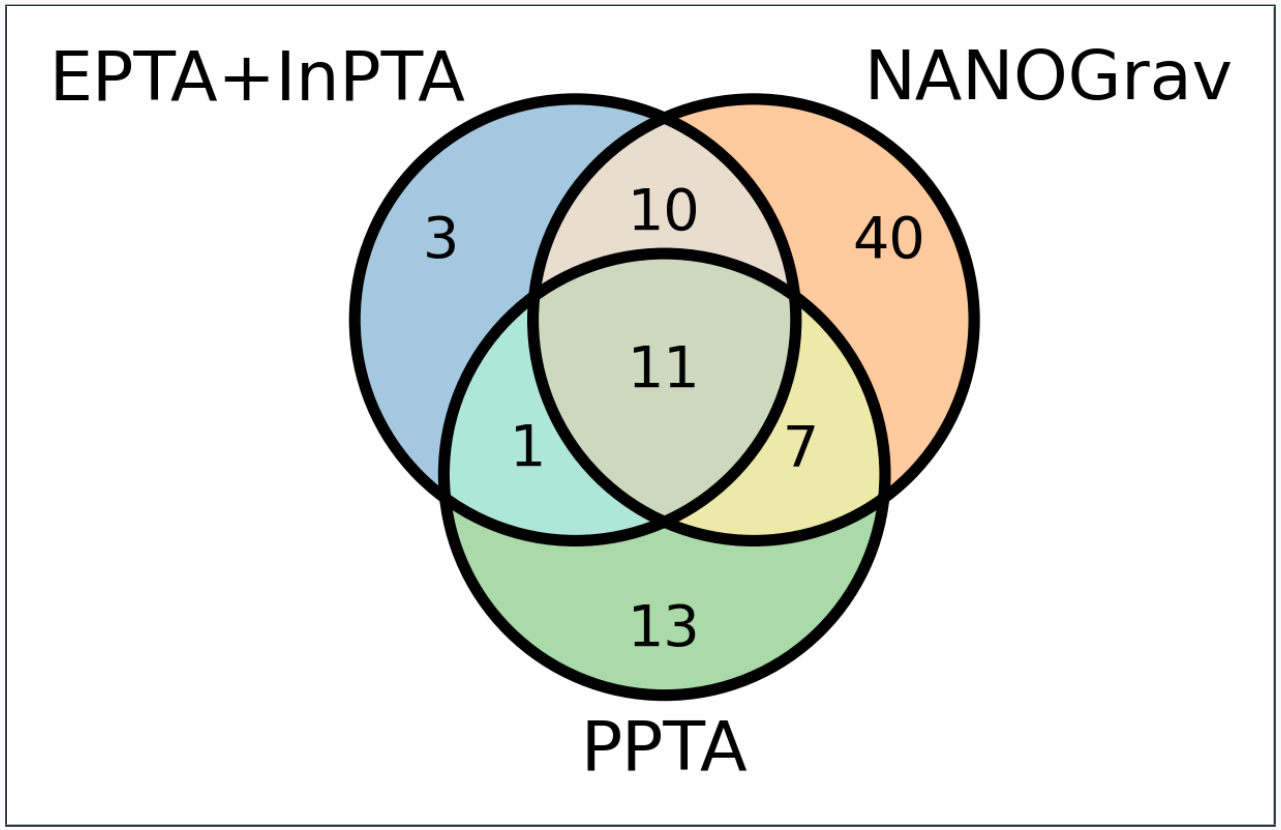
Current world data on the HD-correlated common-spectrum process



- Results from regional PTAs are consistent with each other (1σ posteriors overlap)
- Joint posterior = naive product (properly normalized) of individual posteriors
- Proper data combination and combined data analysis → IPTA DR3

Radio pulsars Venn diagram

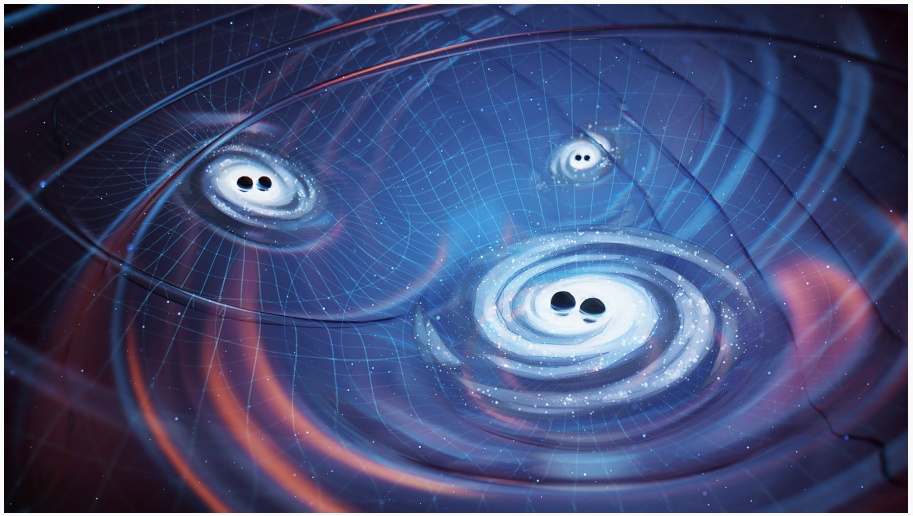
[IPTA 2309.00693]



- 85 pulsars contained in latest PTA data sets
- IPTA DR3: 115 pulsars (CHIME, EPTA, InPTA, MeerKAT, NANOGrav, PPTA)

Interpretations

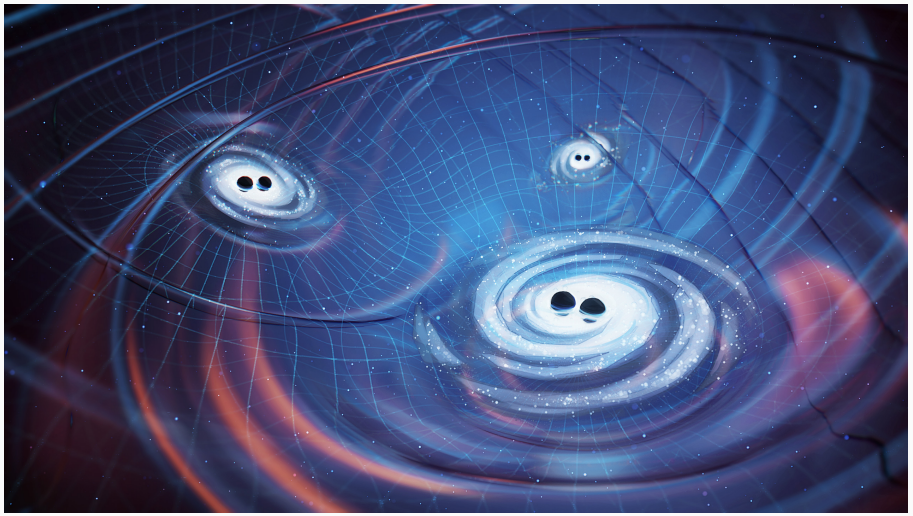
1. Supermassive black-hole binaries



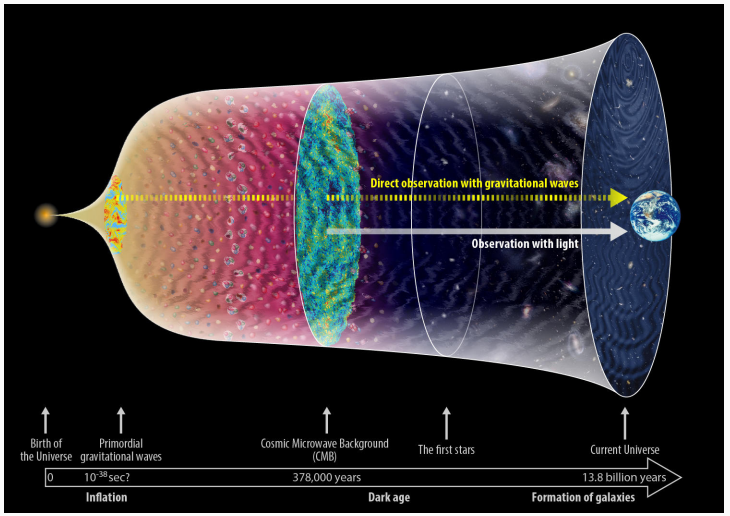
1. SMBHBs (realistic)
   - No SMBHB mergers directly observed as of yet $\rightarrow$ data-driven field thanks to PTAs
   - Viable explanation, several open questions $\rightarrow$ exciting topic, but a different talk

Interpretations

❶ Supermassive black-hole binaries



❷ GWs from the Big Bang



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❷ New physics (speculative)

- Logical possibility: PTA signal is not of SMBHB origin or receives several contributions
- **Probe** and **constrain** cosmology at early times as well as particle physics at high energies

Interpretations

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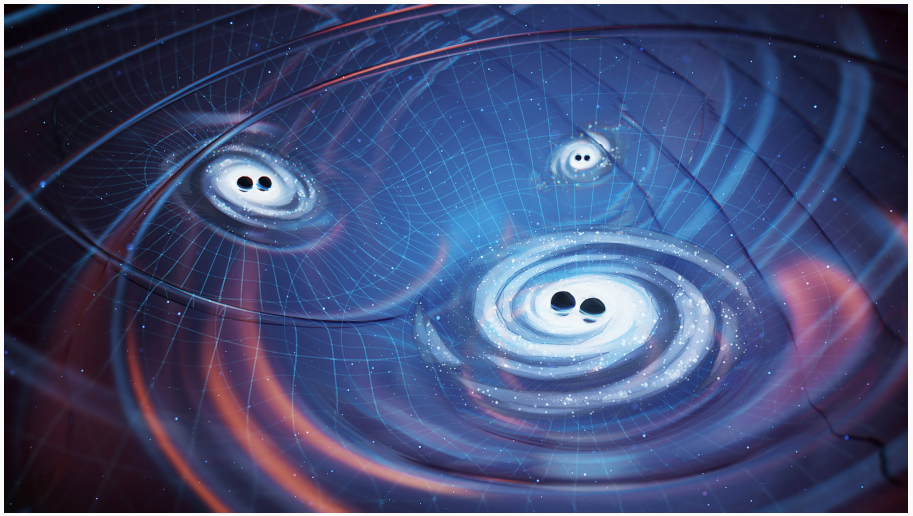

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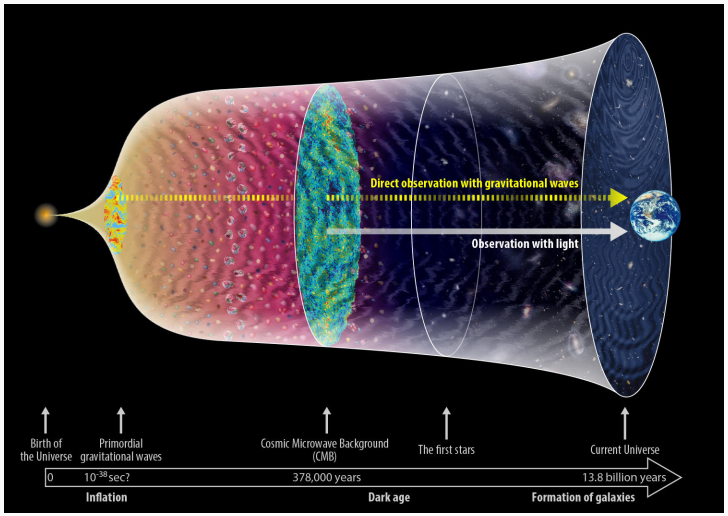

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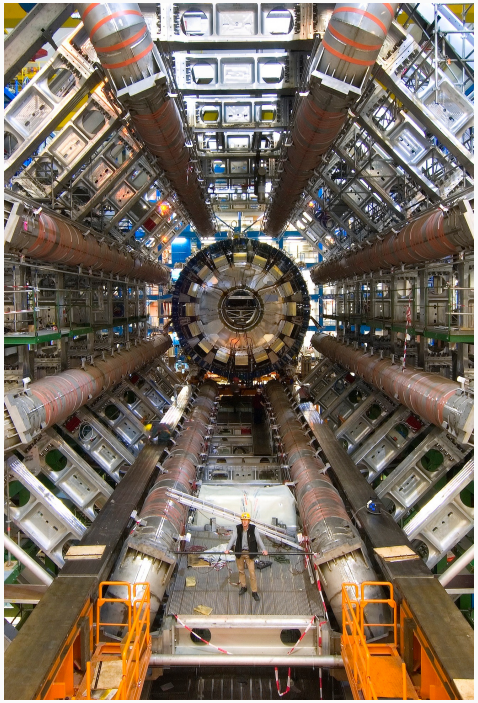
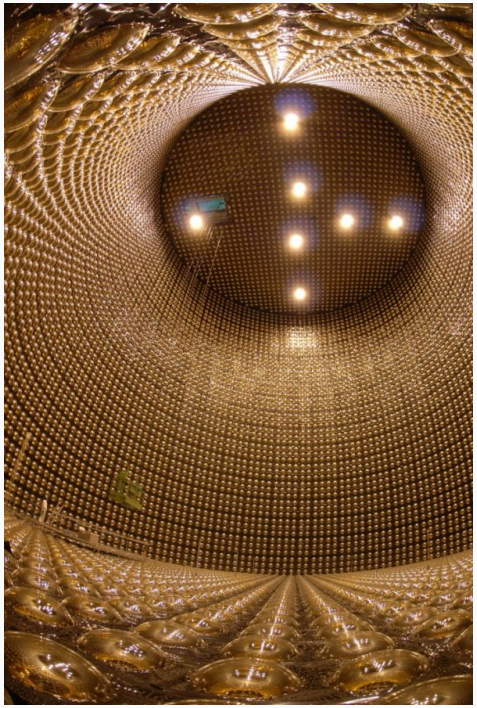
For the rest of the talk, let's focus on probing new physics at the PTA frontier!

PTA frontier of particle physics

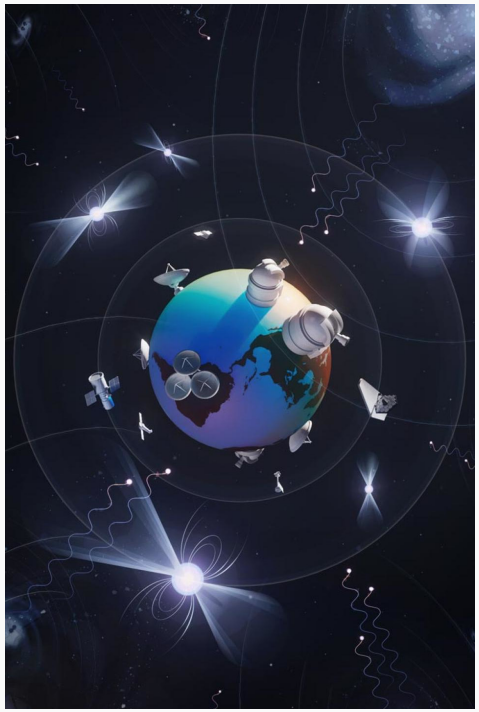
Energy frontier



Intensity frontier



PTA frontier

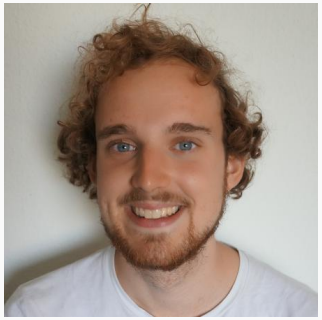


New physics at the PTA frontier

- Probe BSM models in regions of parameter space inaccessible by other methods
- Derive new constraints, irrespective of the origin of the PTA signal
- Complementary to laboratory searches at the energy and intensity frontiers

Our team

R. v. Eckardstein*

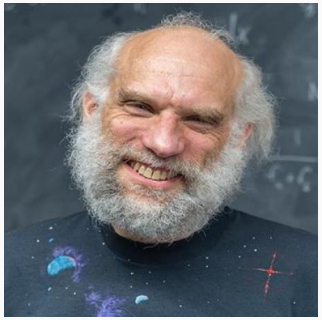


R. Lino d. Santos*

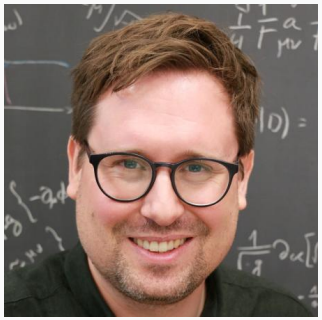
Andrea Mitridate

Jonathan Nay

Ken Olum



Kai Schmitz*



Tobias Schröder*

Tanner Trickle

David Wright

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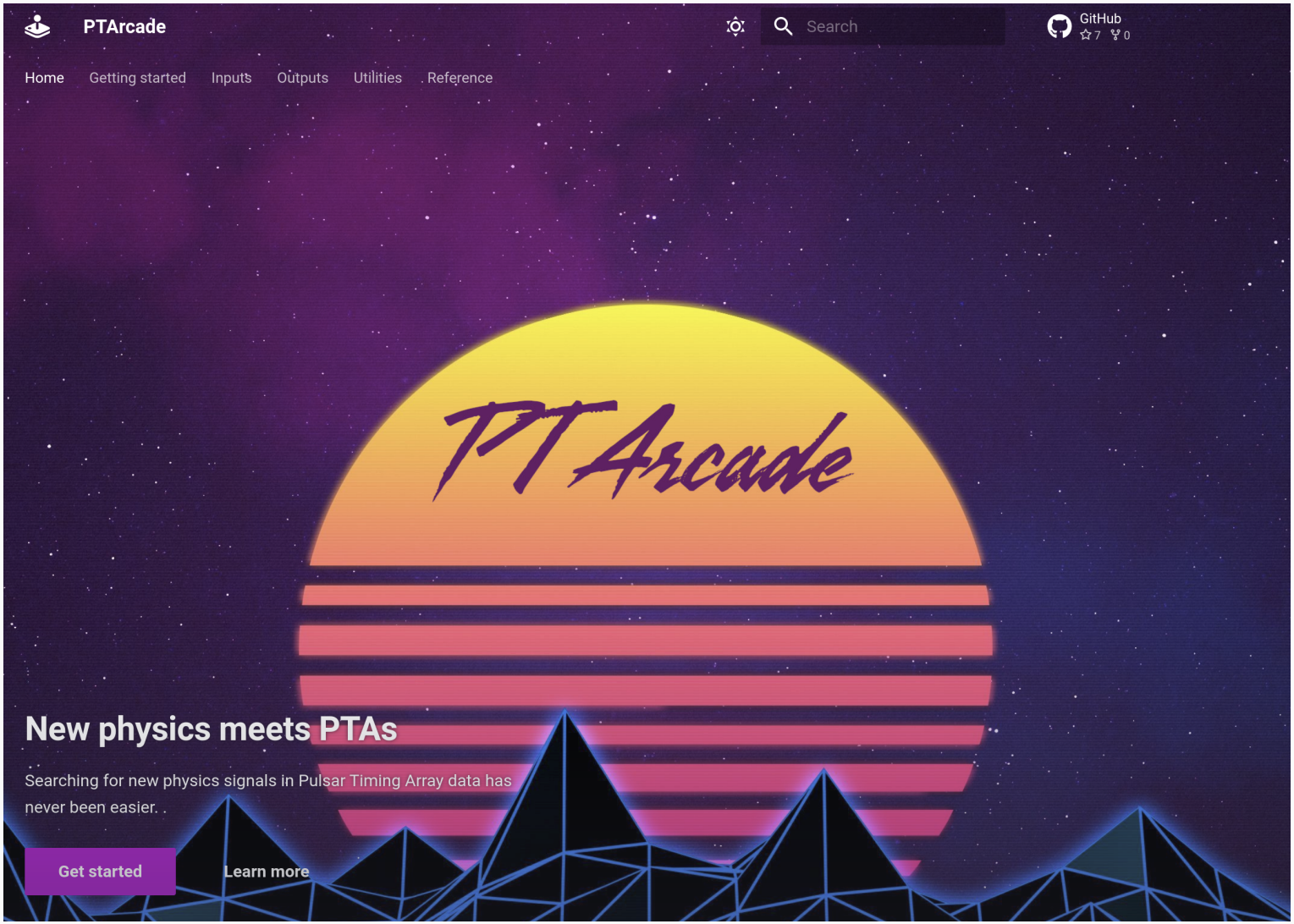
1. Searches for signals from new physics in NANOGrav data → 2306.16219
2. New software tools for fitting BSM models to PTA data → `PTArcade`

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

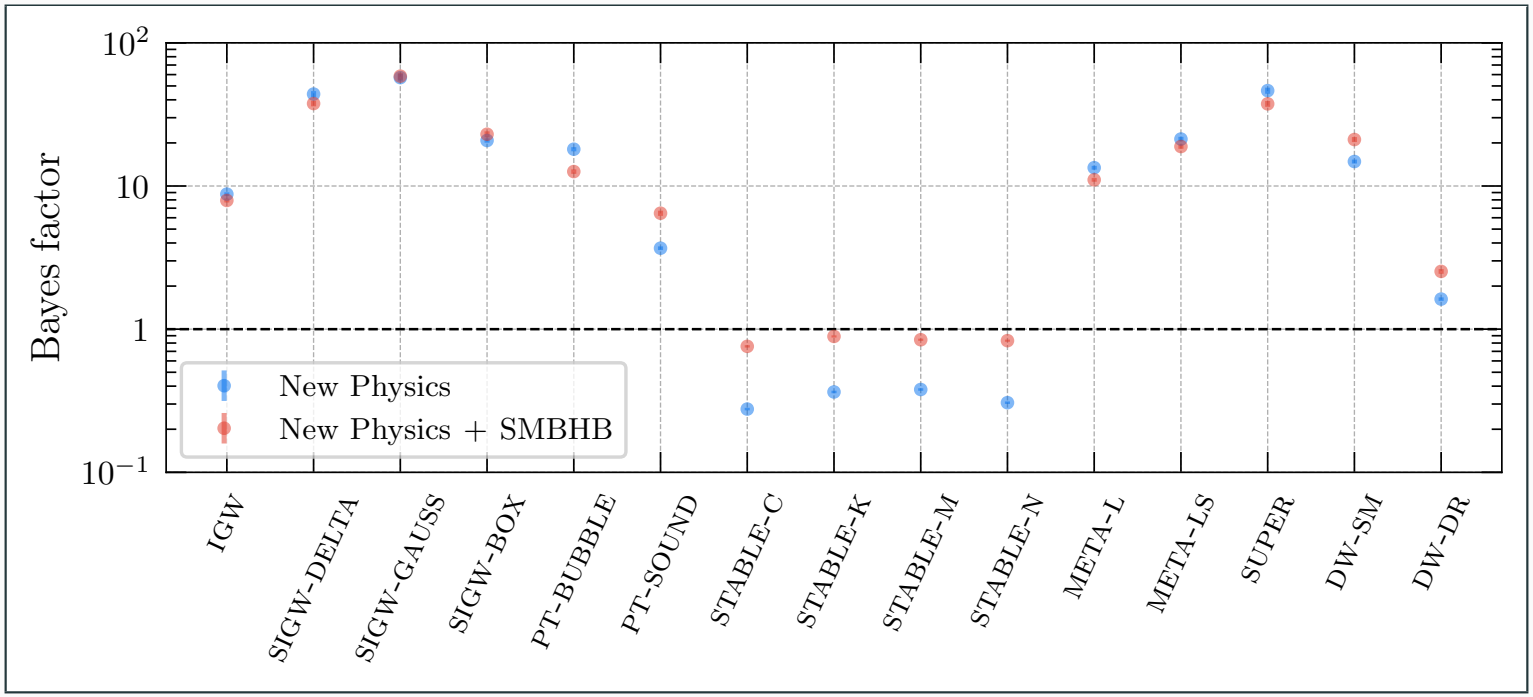
PTArcade



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

New physics: many models can fit the data, but situation inconclusive

[NANOGrav 2306.16219] [See also: EPTA 2306.16227]

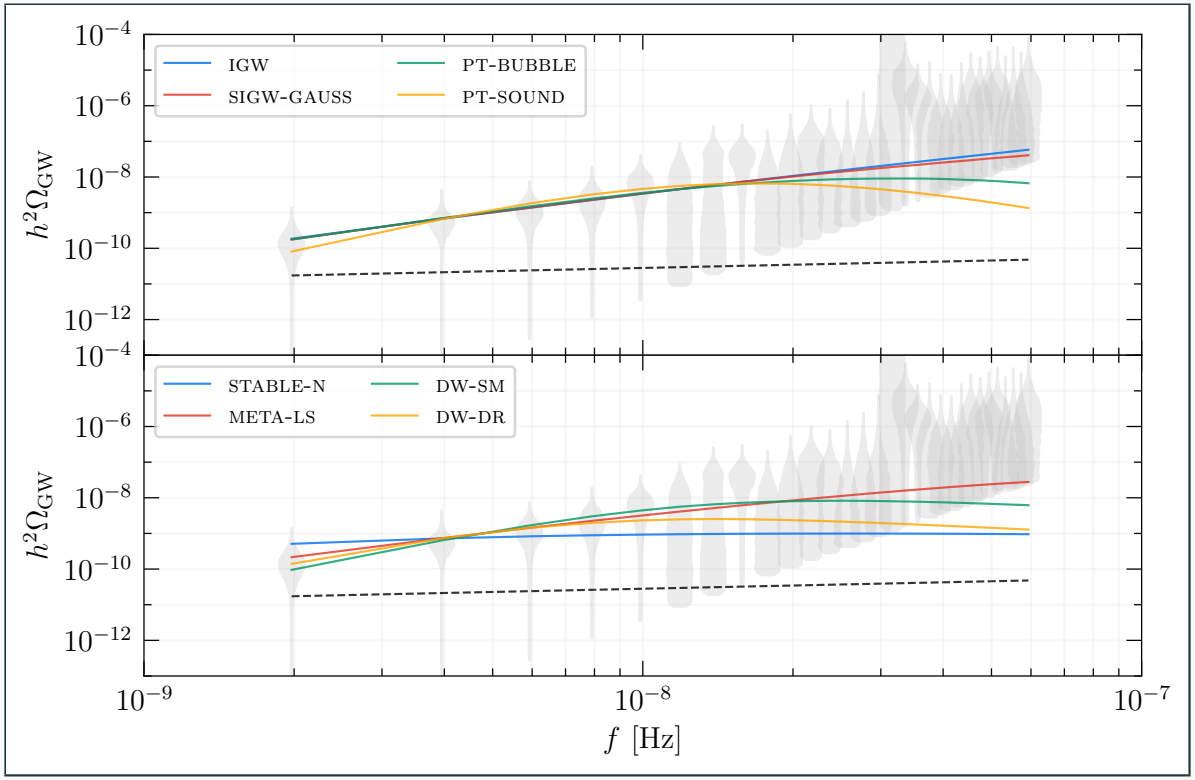


Bayesian model comparison

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 $\mathcal{H}_0$.

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

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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?

❶ BSM scenario: Cosmic inflation

Big questions: What set the initial conditions of the Hot Big Bang: homogeneity, isotropy, spatial flatness? What seeded the temperature fluctuations in the CMB?

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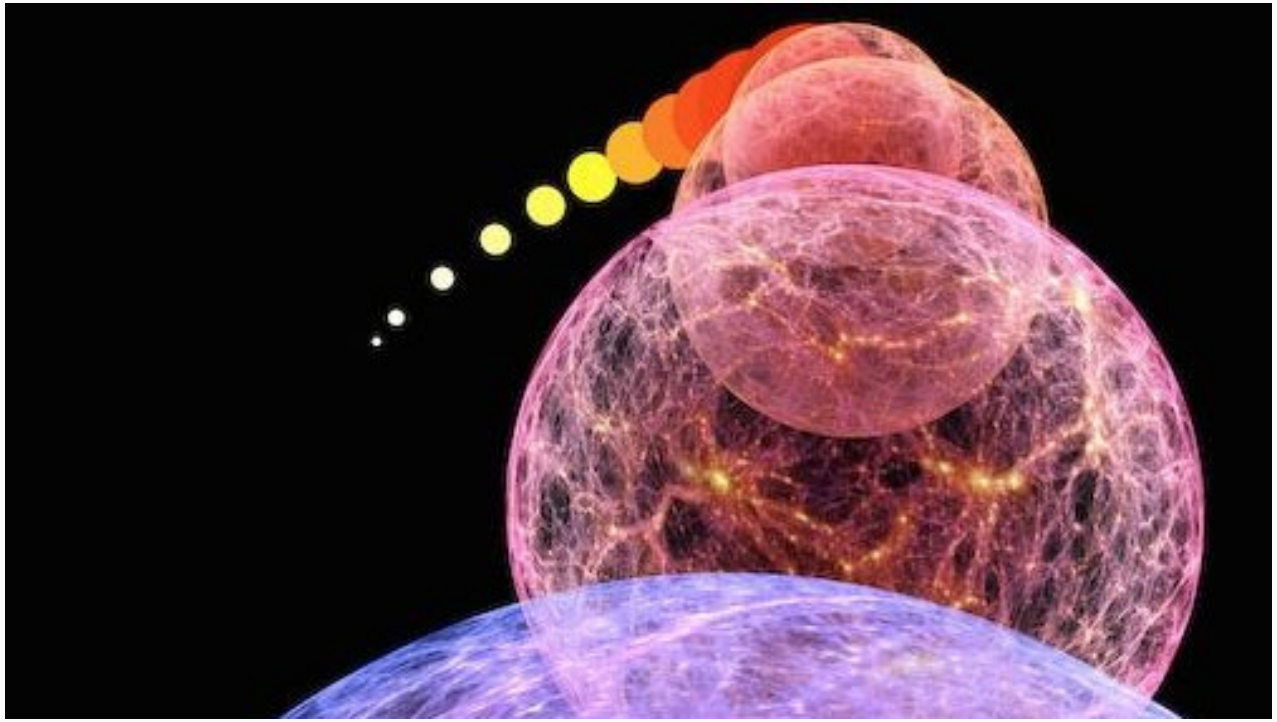


Cosmic inflation: Stage of exponentially fast expansion before the Hot Big Bang

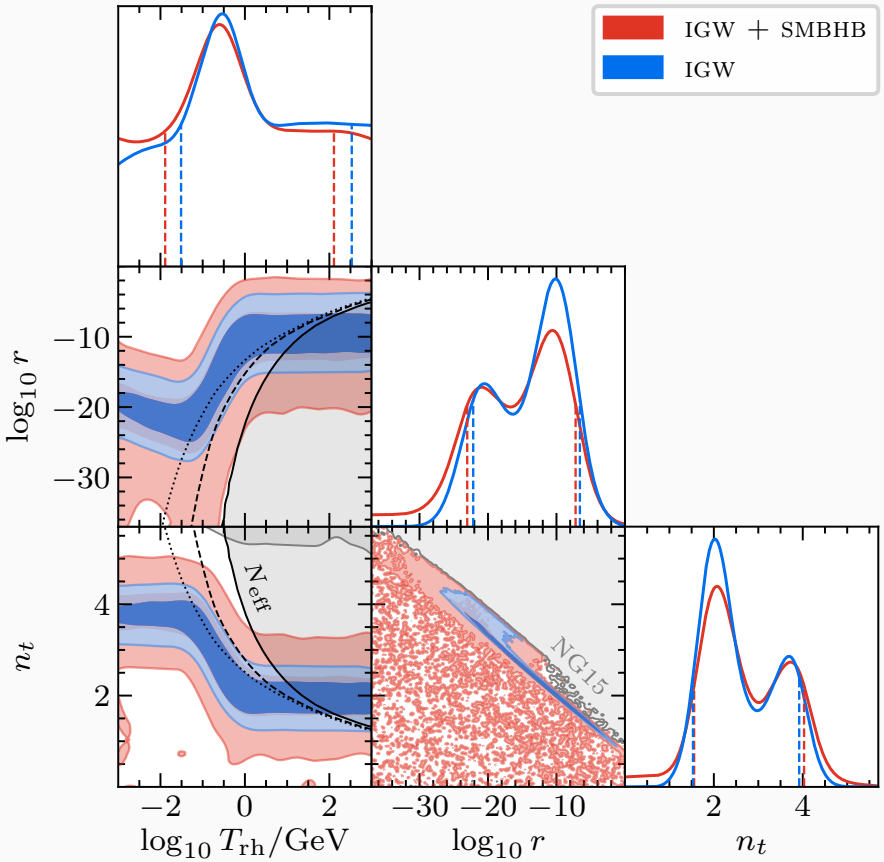
- Requires form of dark energy, e.g., potential energy of a scalar "inflaton" field
- Inflaton and metric fluctuations $\rightarrow$ primordial scalar and tensor perturbations

Primordial tensor spectrum

$$\mathcal{P}_t = r\, A_s \left(\frac{f}{f_{\rm cmb}}\right)^{n_t}$$

Parameters

$T_{\rm rh}$	Reheating temperature
r	Tensor-to-scalar ratio
n_t	Tensor spectral index



Lessons

- Strongly blue-tilted spectrum, $n_t \sim 2 \cdots 4 \rightarrow$ probe **nonminimal inflation models**
- Transition from **reheating** to the Hot Big Bang in the PTA band for $T_{\rm rh} \sim 1\,{\rm GeV}$
- If GWB extrapolated to higher frequencies $\rightarrow$ large contribution to **dark radiation**

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Big questions: Are some of the black holes seen by LVK of primordial origin? To what extent do PBHs contribute to dark matter? How do galactic SMBHs form?

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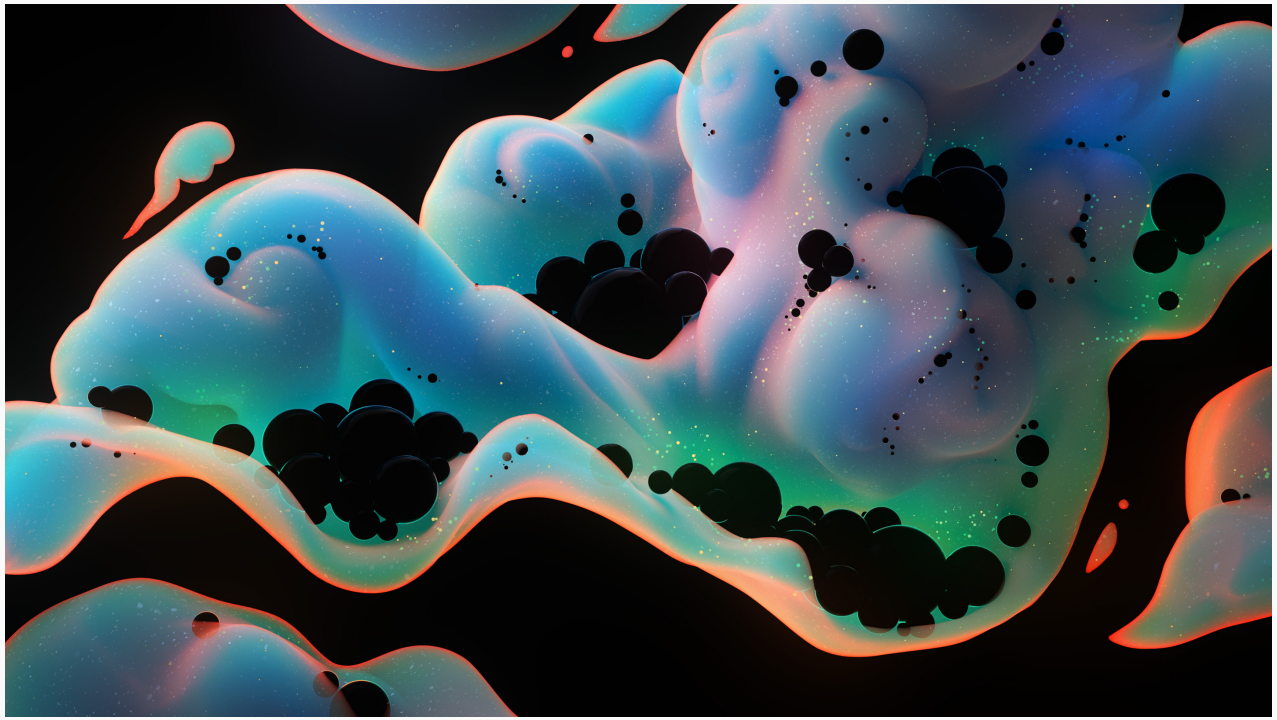


PBHs: Form in the gravitational collapse of large overdensities in the early Universe

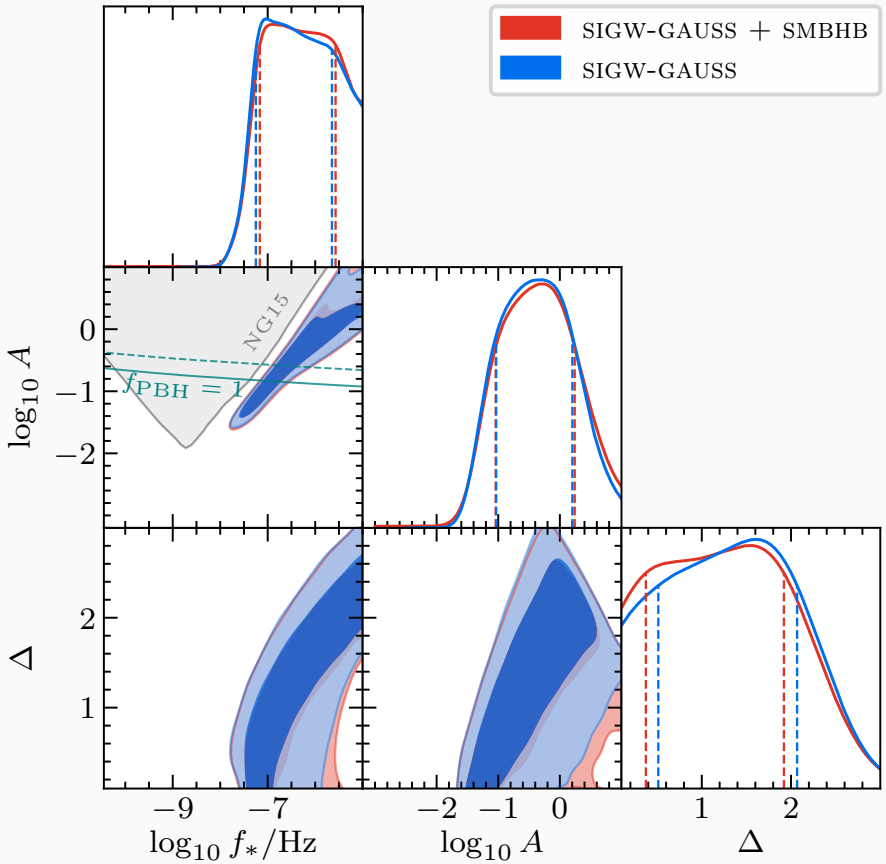
- Typical scenario: Scalar perturbations enhanced during ultra-slow-roll inflation
- Enhanced scalar perturbations $\rightarrow$ GWs at second order in perturbation theory

Primordial scalar spectrum

$$\mathcal{P}_s = \frac{A}{\sqrt{2\pi}\,\Delta}\,\exp\left[-\frac{(\ln(f/f_*))^2}{2\,\Delta^2}\right]$$

Parameters

f_*	Peak frequency
A	Peak amplitude
Δ	Width



Lessons

- Require large-amplitude peak in $\mathcal{P}_s \rightarrow$ input for building models of **inflation**
- **PBH dark matter** might be possible; but some tension with PBH overproduction
- On-going debate on impact of **non-Gaussianities** on efficiency of PBH production

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Big questions: How are the Higgs mechanism and the quark–hadron transition realized in the early Universe? Are there other fundamental forces beyond the Standard Model?

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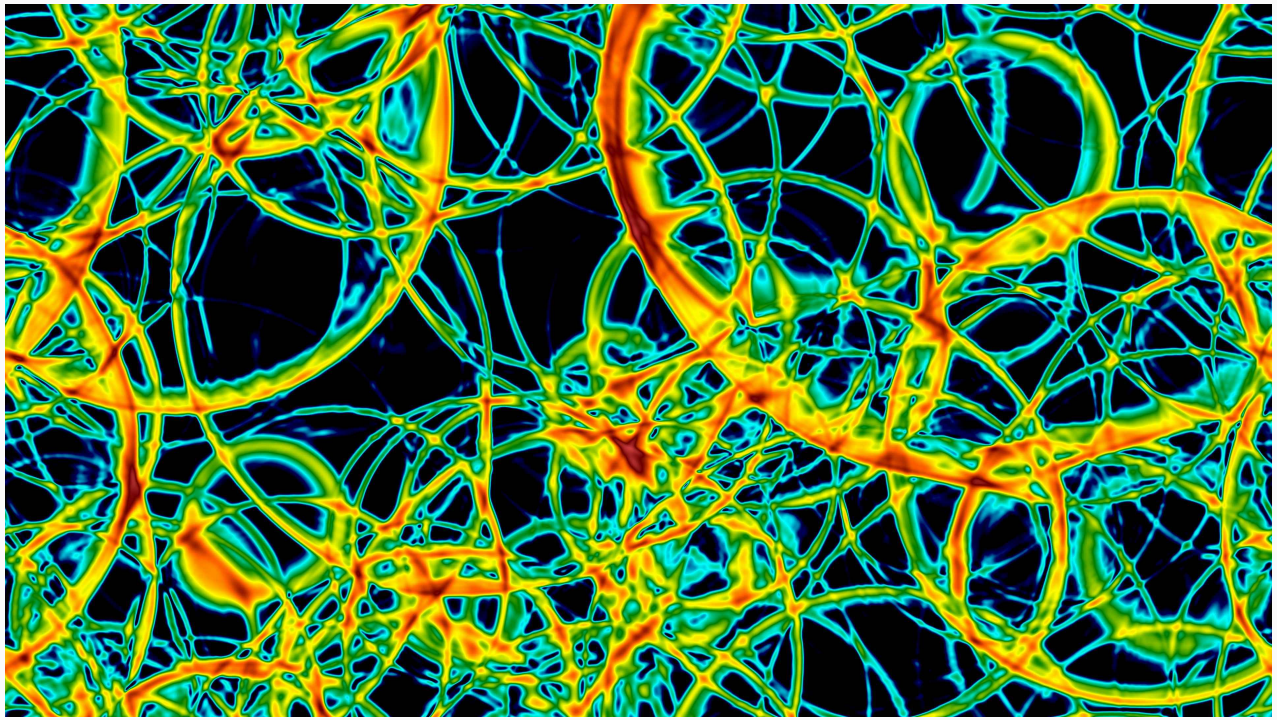


Cosmological phase transitions: Changes in the quantum field theory vacuum structure

- SM predicts smooth crossovers; strong first-order phase transitions require BSM
- GWs from bubble collisions, sound waves, and magnetohydrodynamic turbulence

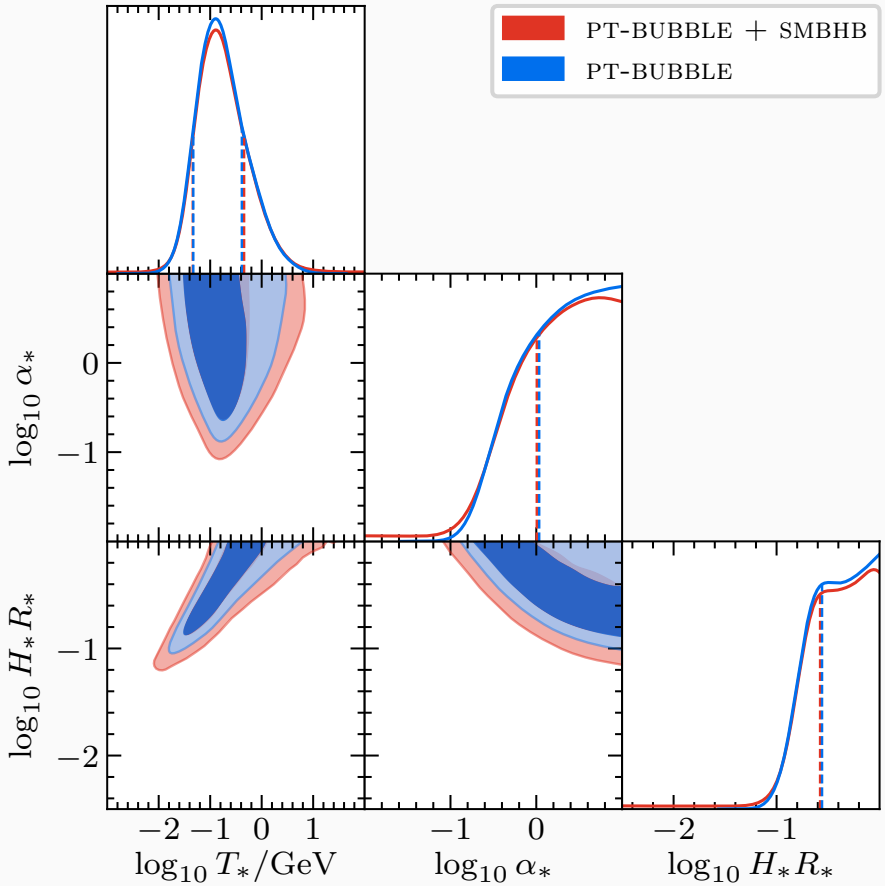
Peak amplitude and frequency

$$\Omega_{\mathrm{GW}}^{\mathrm{peak}} \propto (H_* R_*)^2 \left(\frac{\alpha_*}{1+\alpha_*}\right)^2$$

$$f_{\mathrm{peak}} \propto \frac{T_*}{H_* R_*}$$

Parameters

T_*	Percolation temperature
α_*	Transition strength
$H_* R_*$	Bubble separation



Lessons

- Strong ($\alpha_* \sim 1$) and slow ($H_* R_* \sim 1$) transition at a temperature $T_* \sim 100\,\mathrm{MeV}$
- Just the right ballpark for BSM modifications of the **QCD phase transition**
- Alternatively, phase transition in a **dark sector** $\rightarrow$ complementary to lab searches

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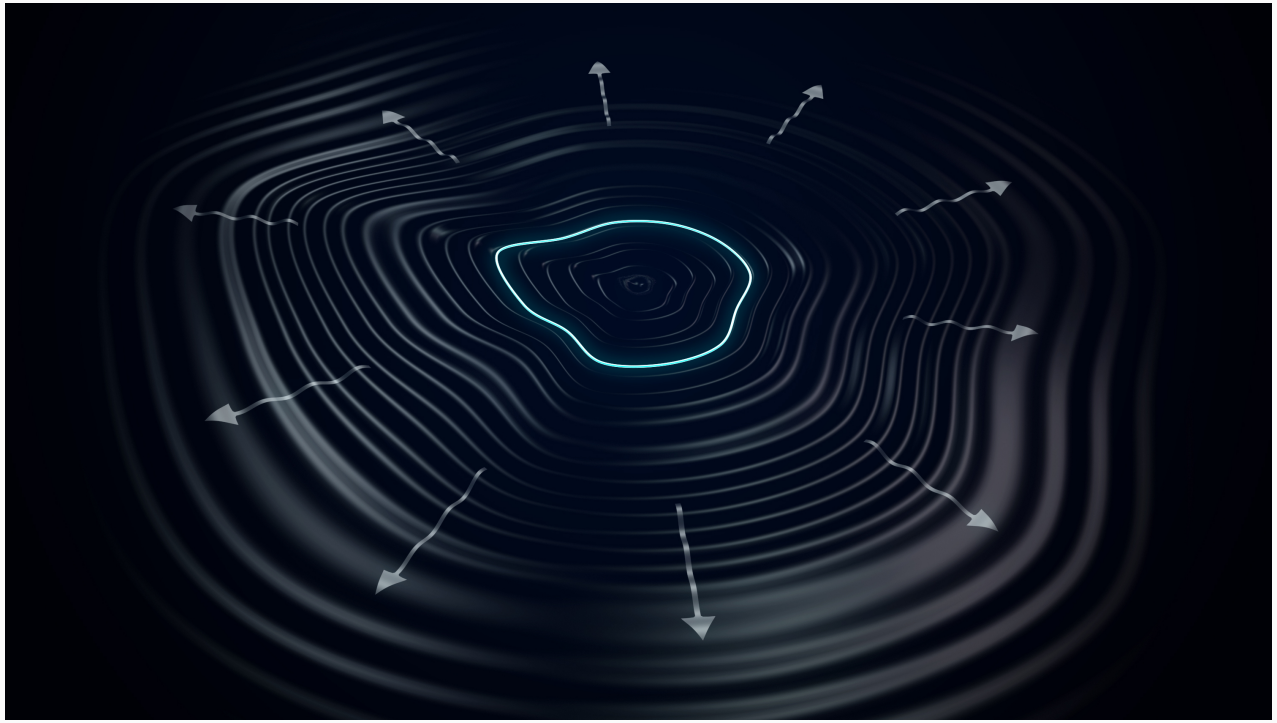


Cosmic strings / domain walls: Defects after spontaneous breaking of GUT symmetries

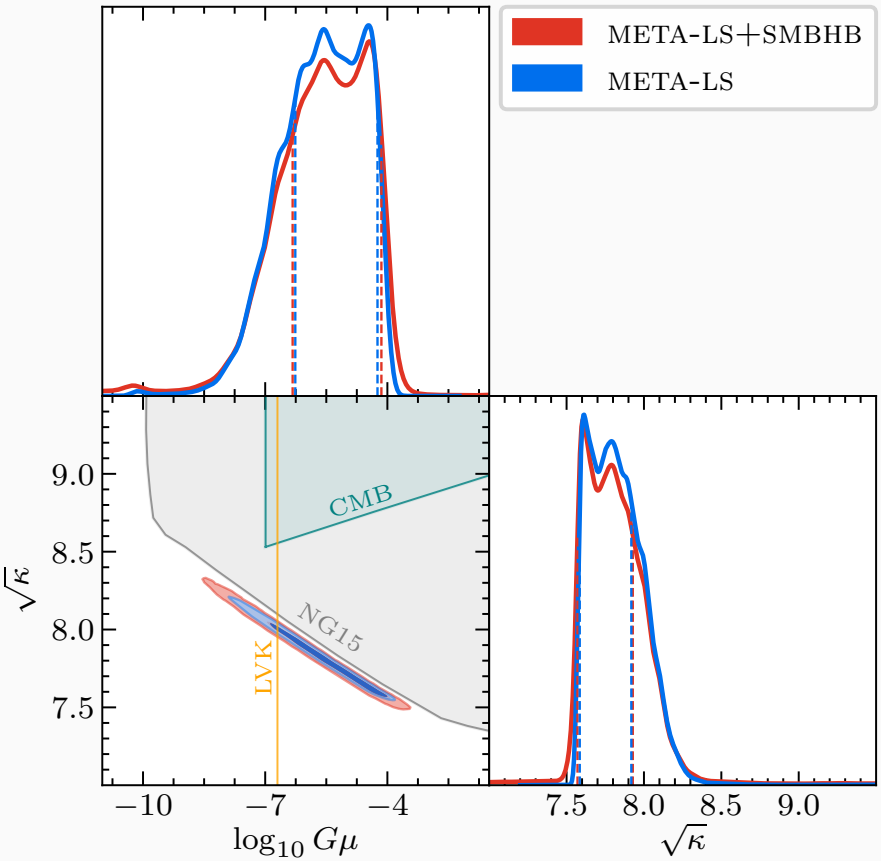
- Typical scenario: $U(1)_{B-L}$ breaking $\rightarrow$ neutrino masses, leptogenesis, and strings
- Dynamics and decay of defect networks yield anisotropic stress and hence GWs

Decay rate per length

$$\Gamma_d = \frac{\mu}{2\pi} e^{-\pi\kappa}$$

Parameters

- μ Tension (energy per length)
- κ Decay parameter



Lessons

- Prefered parameter values → input for **GUT model building** at $E \lesssim 10^{16}\,\mathrm{GeV}$
- Metastable strings yield a good fit; can be probed / excluded by **LVK observations**
- PTA bounds outperform **CMB bounds**, *irrespective of the origin of the signal (!)*

Deterministic signals

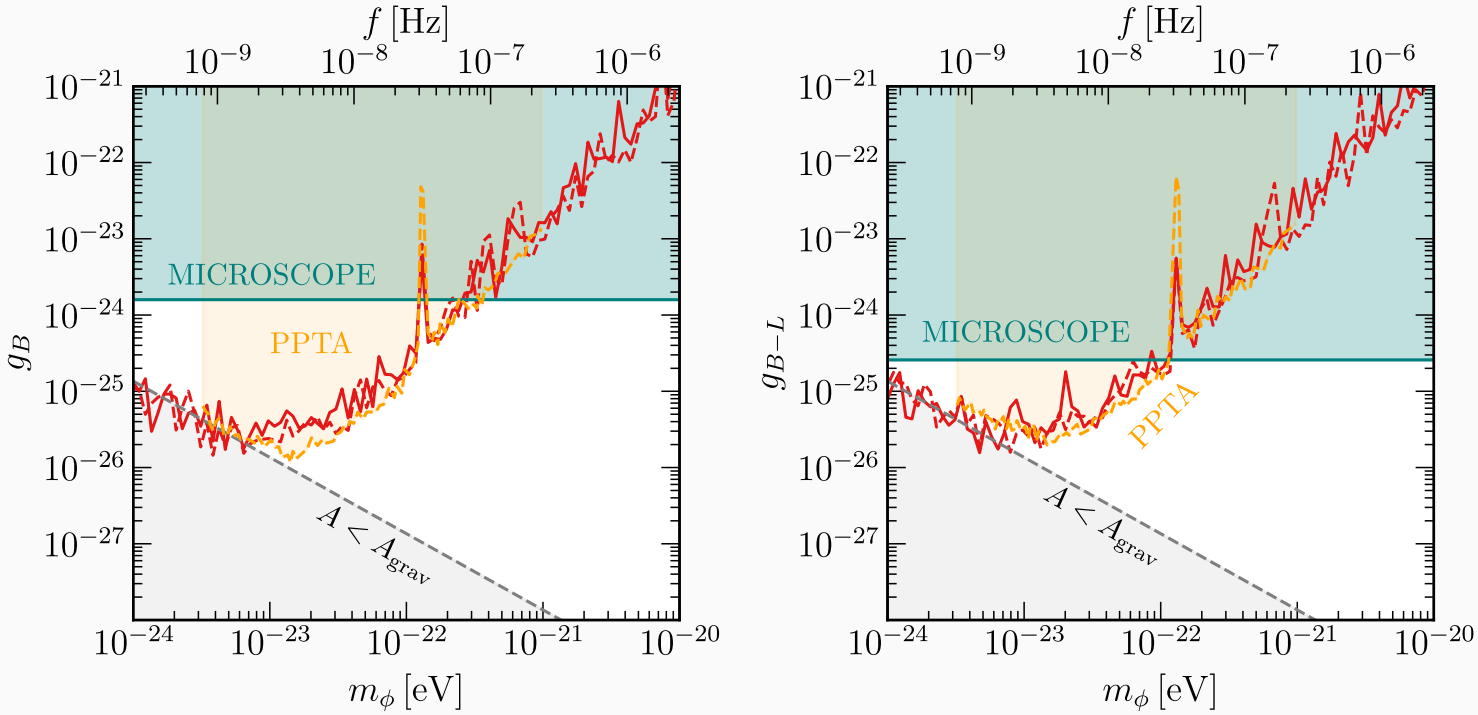
New physics in the early Universe $\rightarrow$ new physics in our Milky Way today

Additional, deterministic contributions to timing residuals on top of the GWB

Deterministic signals

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

Additional, deterministic contributions to timing residuals on top of the GWB



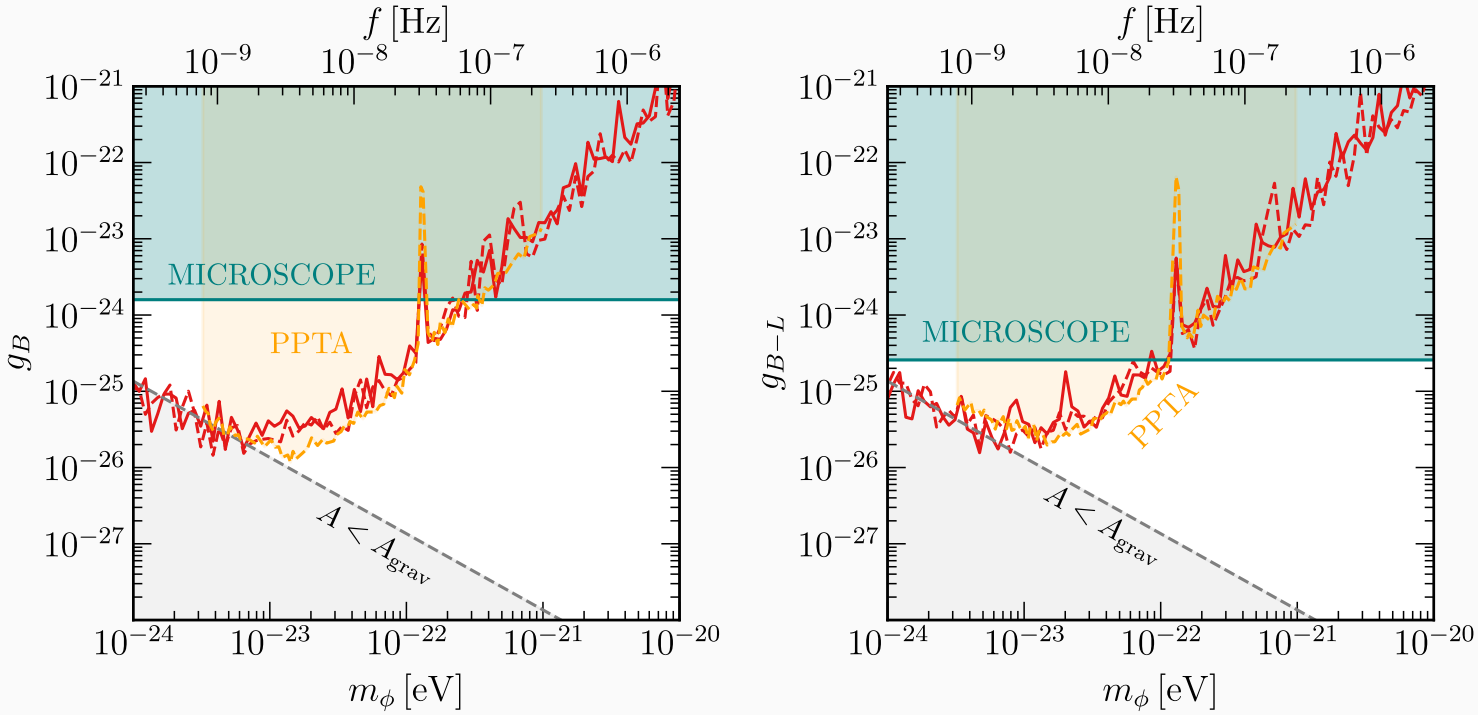
Search for signals from ultralight dark matter and dark-matter substructures

- 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

Additional, deterministic contributions to timing residuals on top of the GWB



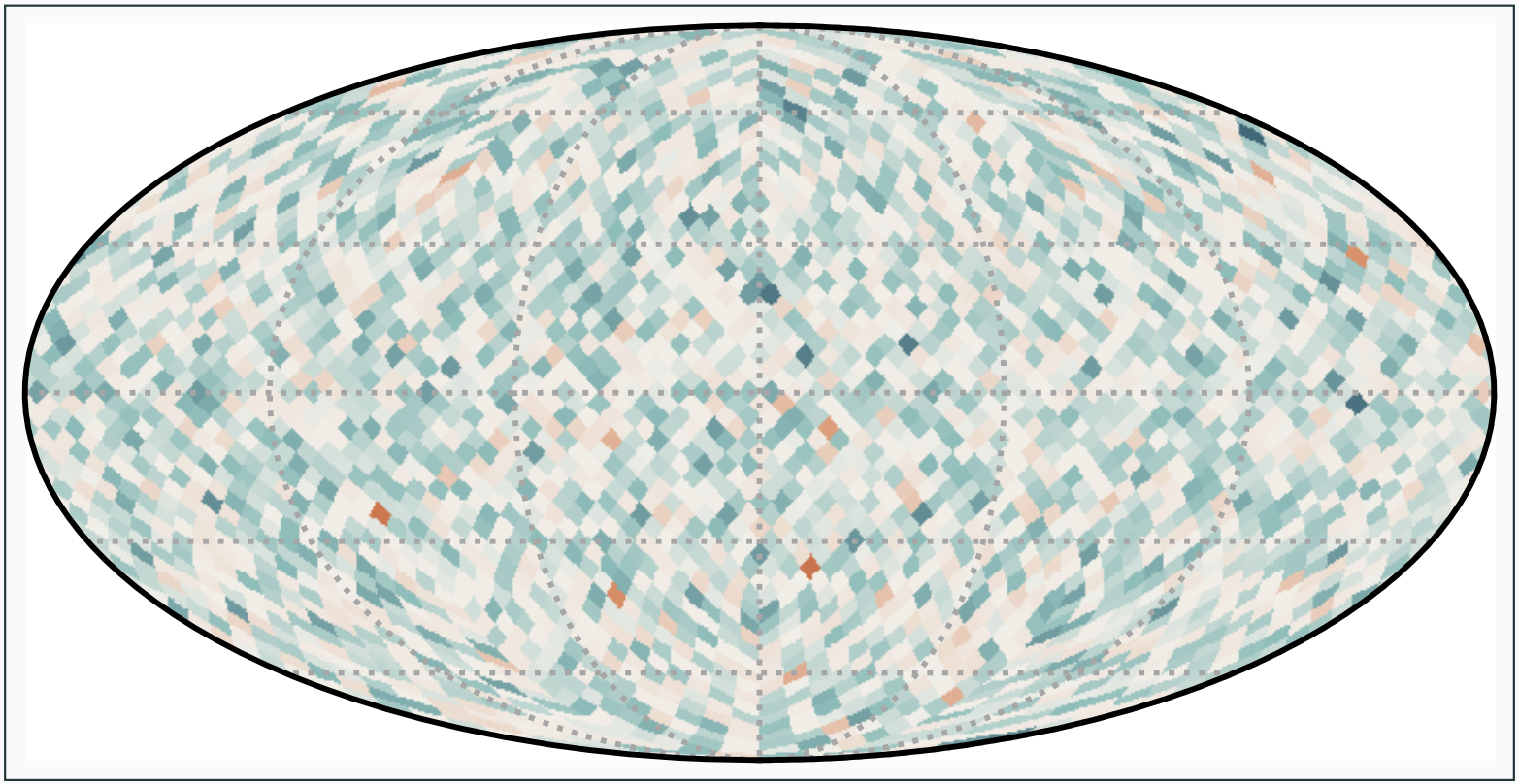
Search for signals from ultralight dark matter and dark-matter substructures

- 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)

Complementary observables: Anisotropies

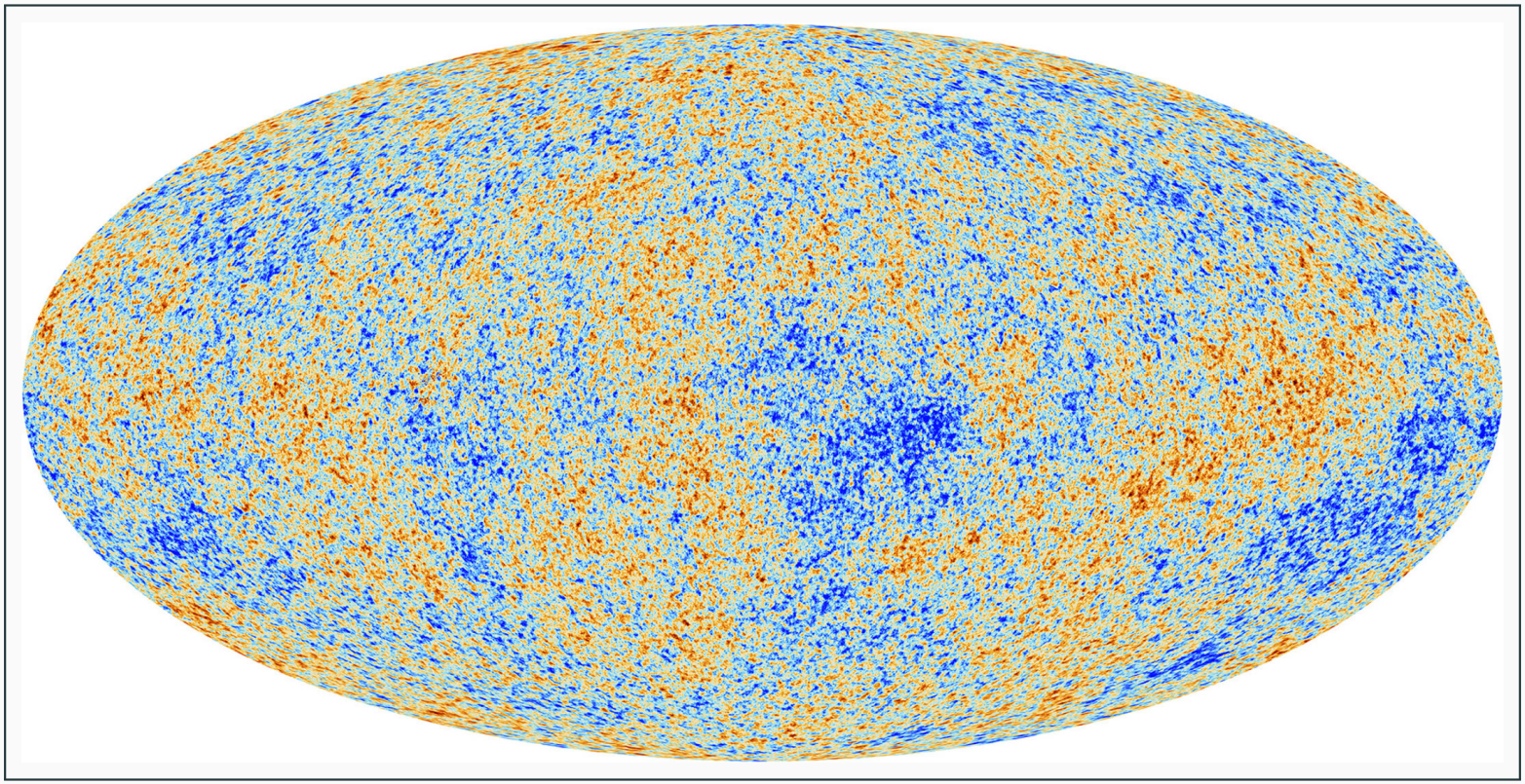
[Sato-Polito, Kamionkowski: 2305.05690]



Simulated anisotropies for an astrophysical GWB (due to discrete source population)

Complementary observables: Anisotropies

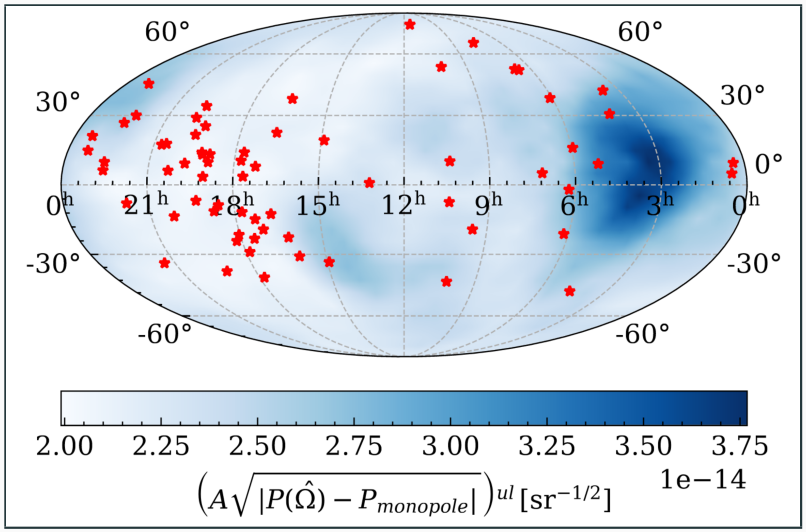
[PLANCK Collaboration]

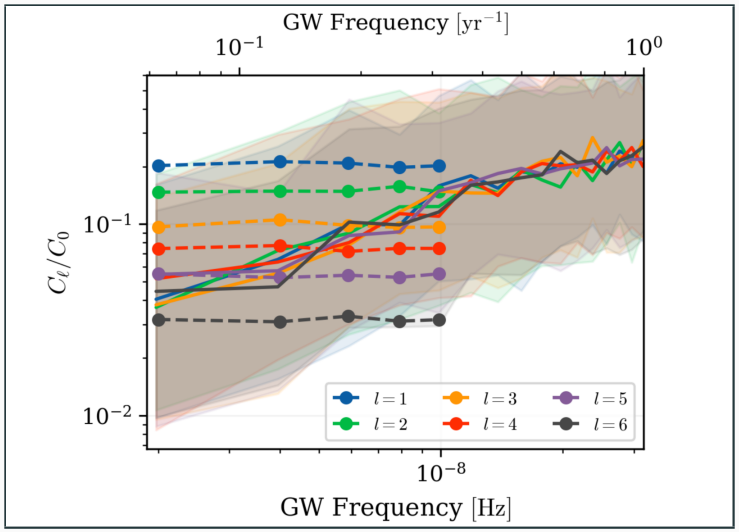


Think of GWB as 21st-century equivalent of the 20th-century discovery of the CMB

Complementary observables: Anisotropies

[NANOGrav 2306.16221]



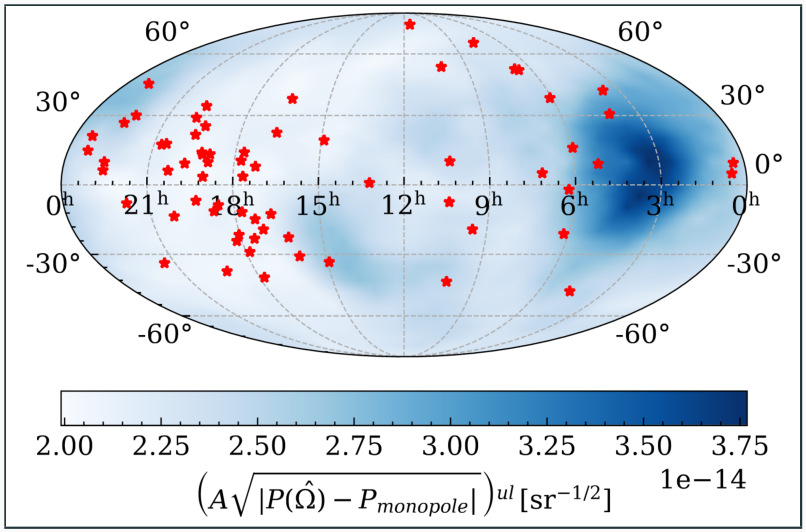


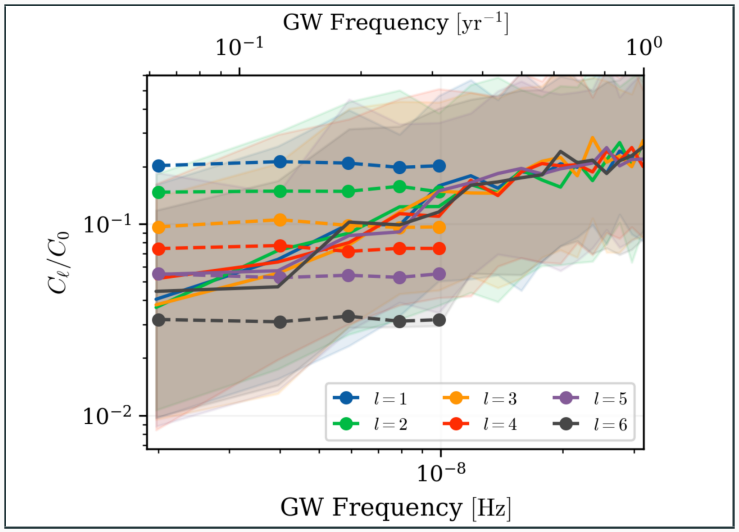
Search for anisotropies in the GWB signal in the sky

- Current sensitivity already at the level of expected anisotropies from SMBHBs
- No signal detected $\rightarrow$ sky-dependent upper limits on deviation from monopole

Complementary observables: Anisotropies

[NANOGrav 2306.16221]





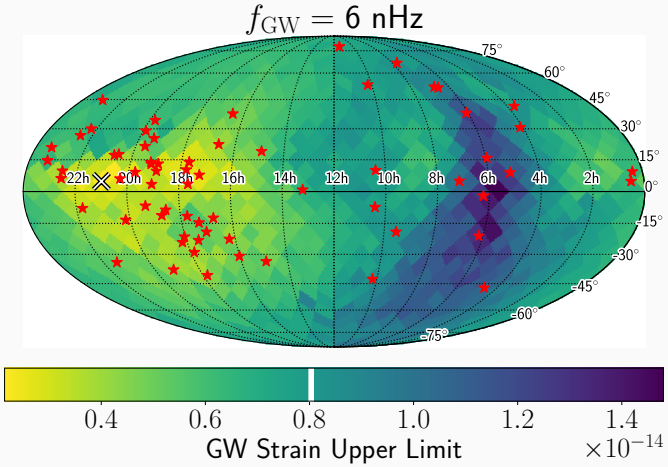
Search for anisotropies in the GWB signal in the sky

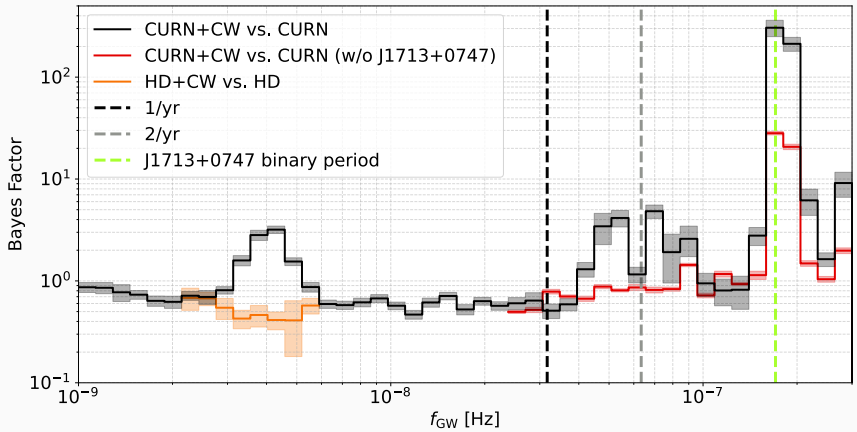
- Current sensitivity already at the level of expected anisotropies from SMBHBs
- No signal detected → sky-dependent upper limits on deviation from monopole

No detection of anisotropies with future data sets → hint of primordial origin?

Complementary observables: Continuous-wave signals

[NANOGrav 2306.16222]



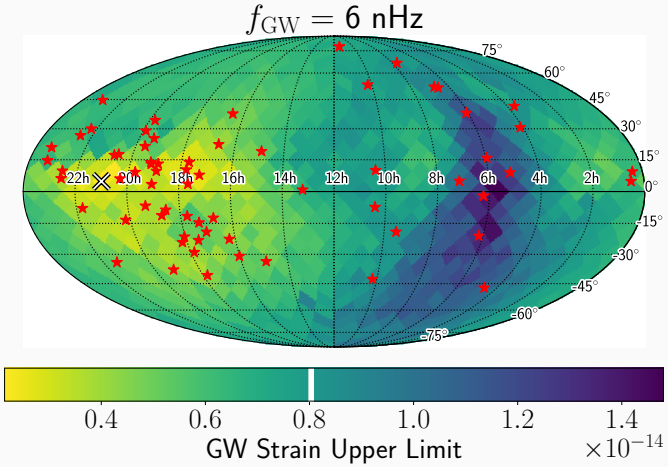


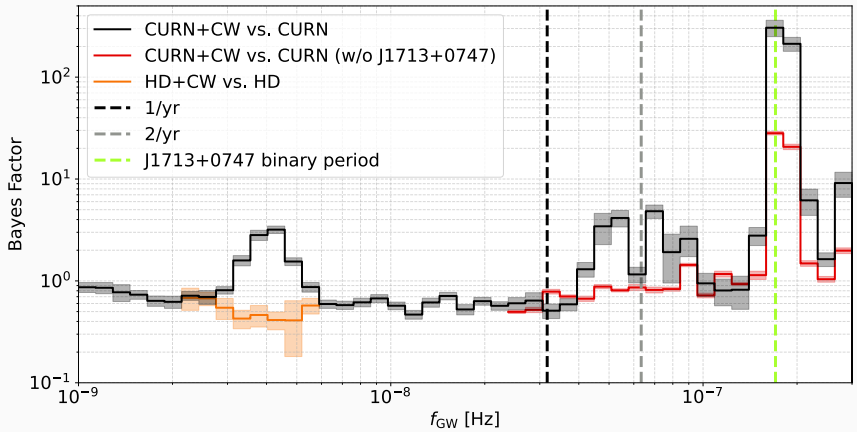
Search for continuous-wave signals from individual nearby SMBHB systems

- Interesting hints in the data, which, however, do not withstand further scrutiny
- Overall, no signal detected $\rightarrow$ sky-dependent upper limits on GW amplitude

Complementary observables: Continuous-wave signals

[NANOGrav 2306.16222]





Search for continuous-wave signals from individual nearby SMBHB systems

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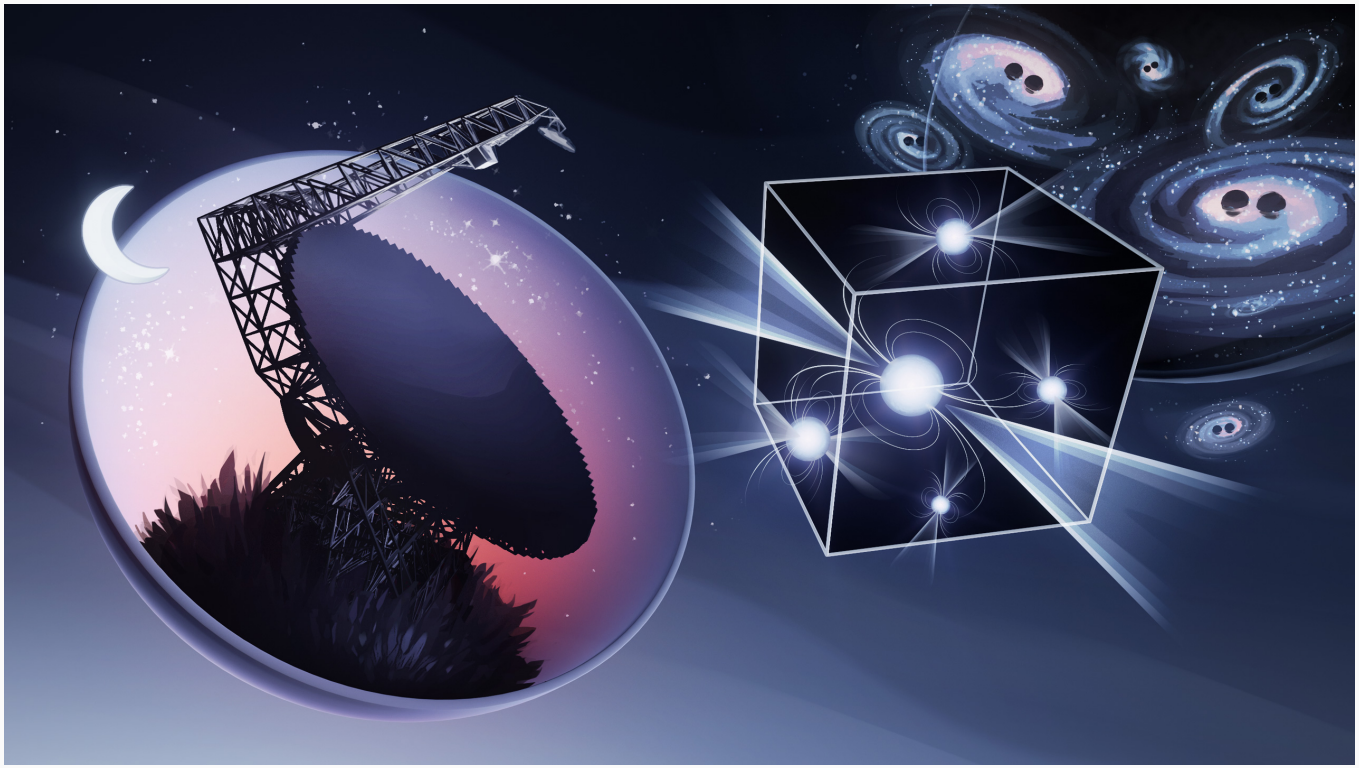
Prospect: Combined information on GWB spectrum, anisotropies, continuous-wave signals (plus other GW searches, CMB observations, etc.) $\rightarrow$ origin of the PTA signal

This is only the beginning!



New Physics at the PTA Frontier

- Rich and exciting research program for many years and decades to come
- Build new models, improve theoretical modeling, develop better tools
- Streamline analysis pipelines for IPTA eDR3, IPTA DR3, and beyond

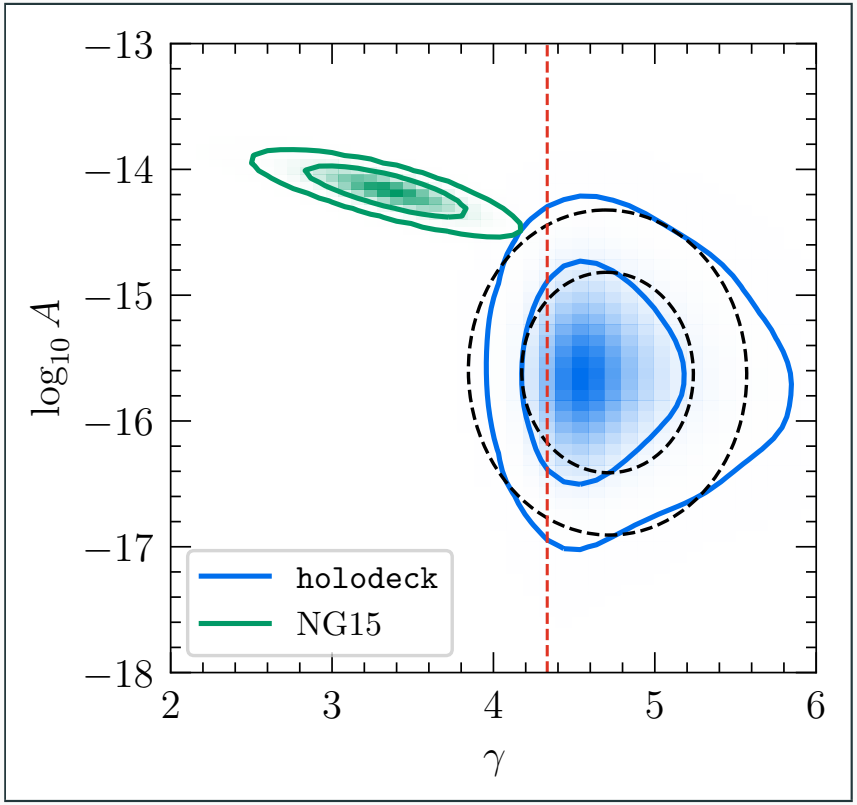
Stay tuned!

And thanks a lot for your attention

Supplementary material

SMBHBs: simplest models of binary evolution struggle to explain the data

[NANOGrav 2306.16219]

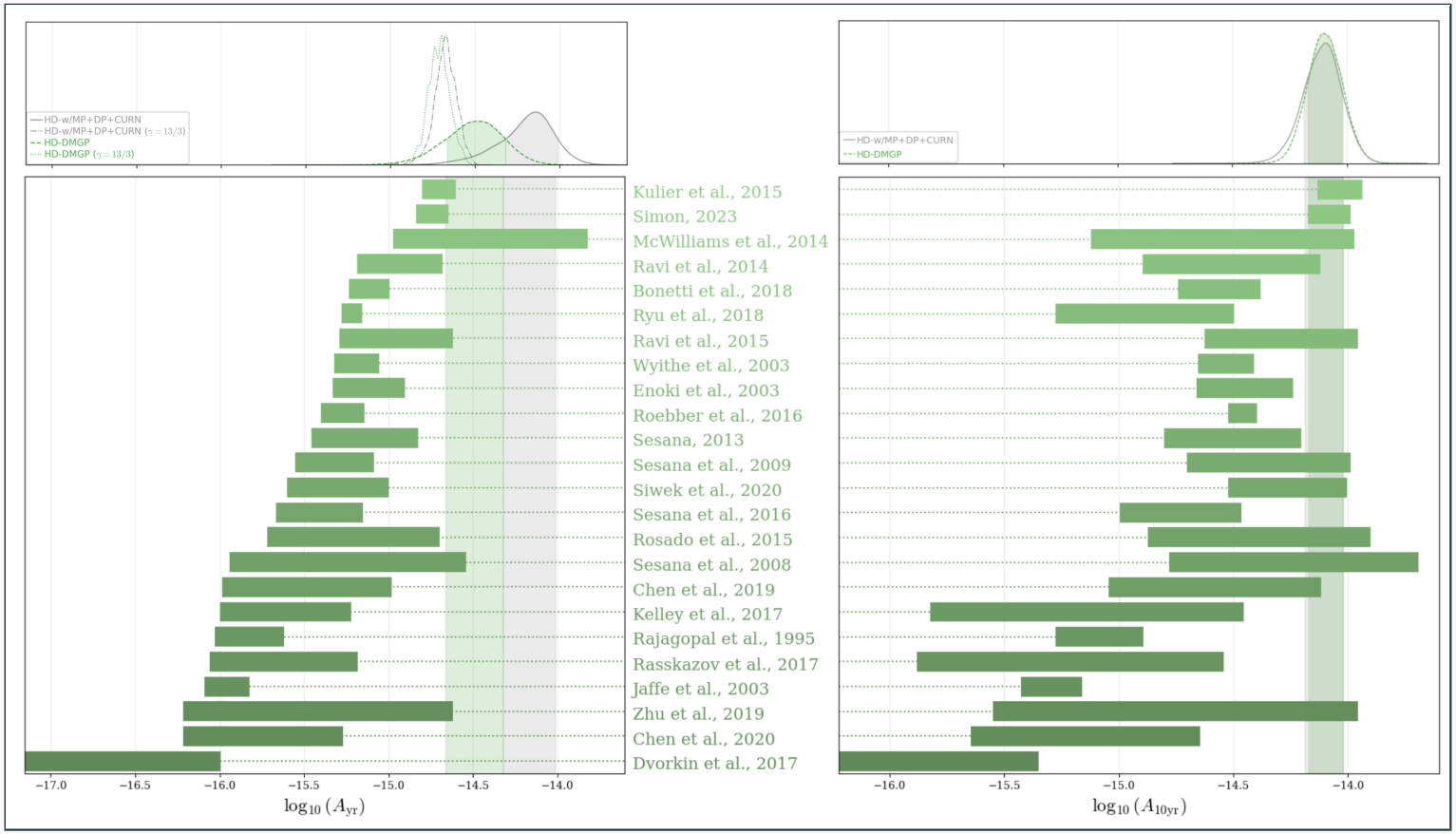


Compare observed spectrum (NG15) to theoretical expectation (`holodeck`)

- Assume SMBHBs on circular orbits and purely GW-driven orbital evolution
- 95 % regions barely touch $\rightarrow 2\sigma$ tension between observations and theory
- GW-only evolution unable to bring binaries to the PTA band within a Hubble time

SMBHBs: viable explanation, but unexpected corners of parameter space

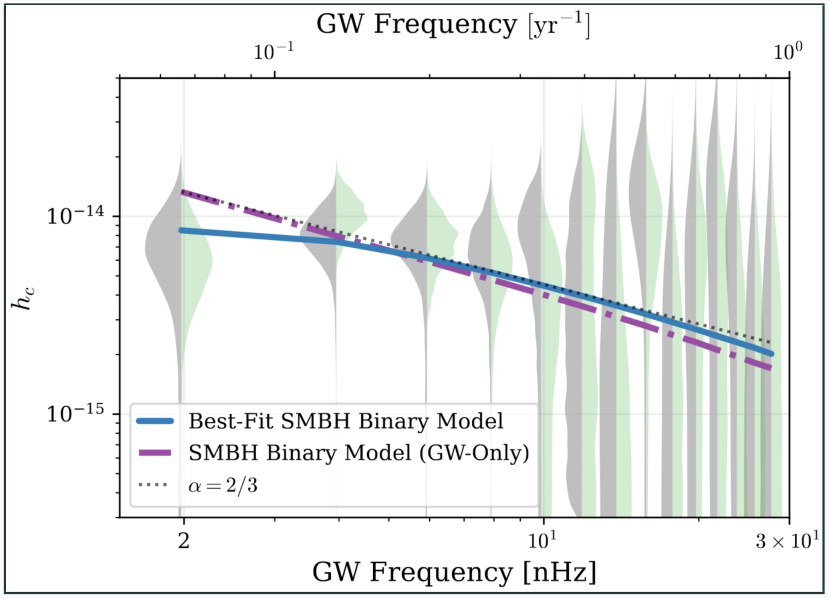
[NANOGrav 2306.16220]

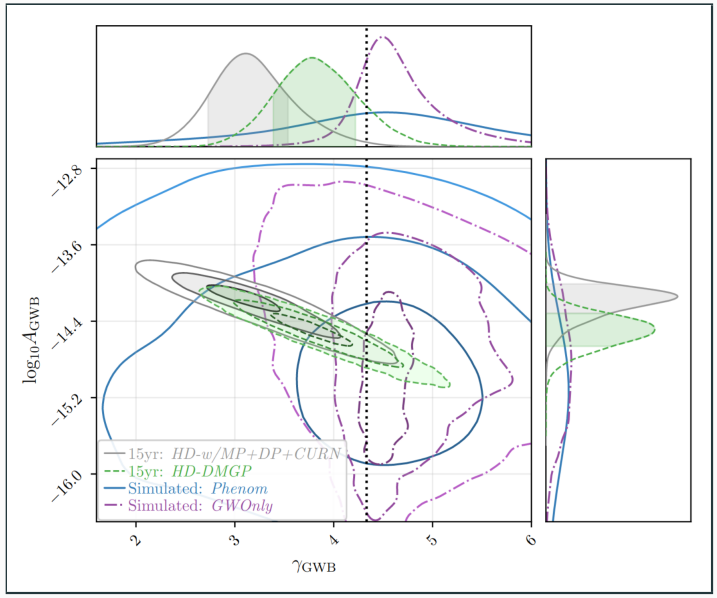


- Parameter shifts towards larger GWB amplitudes than previously expected
- Self-consistent phenomenological description of environmental interactions
- Generally higher binary masses or densities, or highly efficient binary mergers

Phenomenological models

Self-consistent phenomenological models accounting for environmental interactions



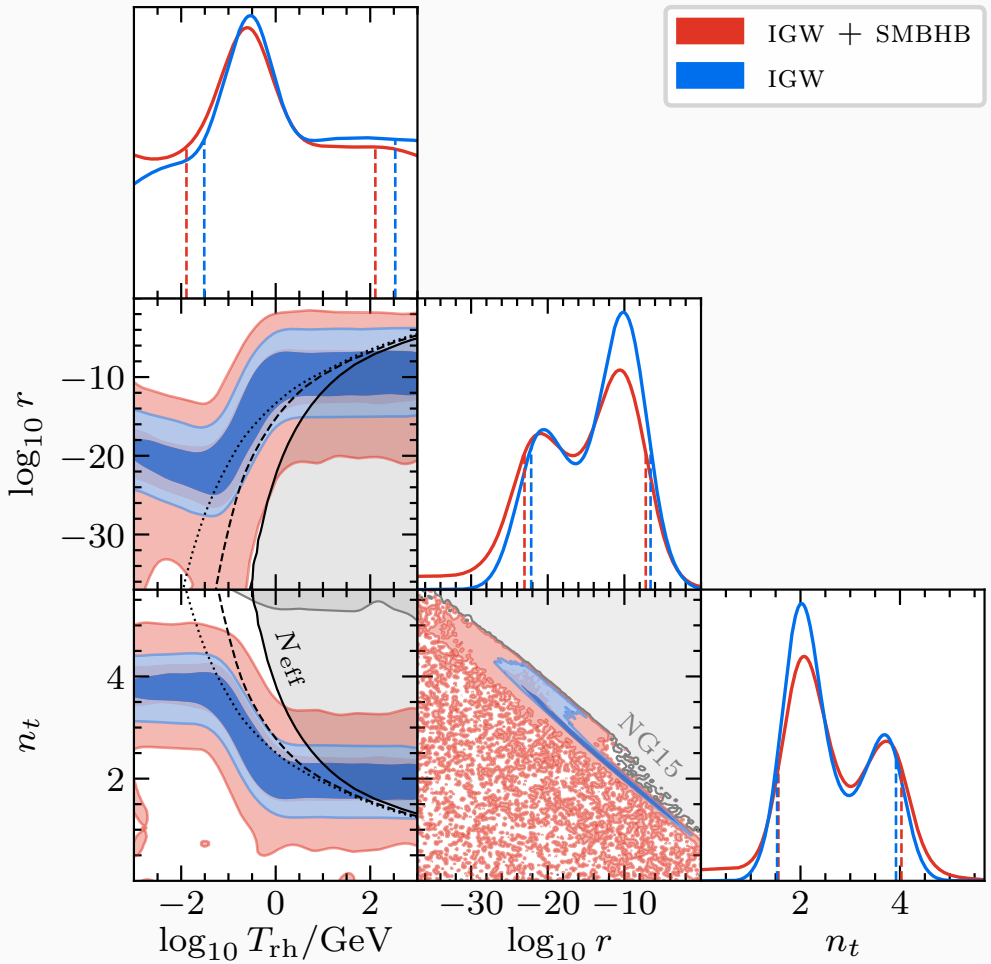


SMBHB interpretation: **Need to go to unexpected corners of parameter space!**

- Parameter shifts towards larger GWB amplitudes than previously expected
- Generally higher binary masses or densities, or highly efficient binary mergers

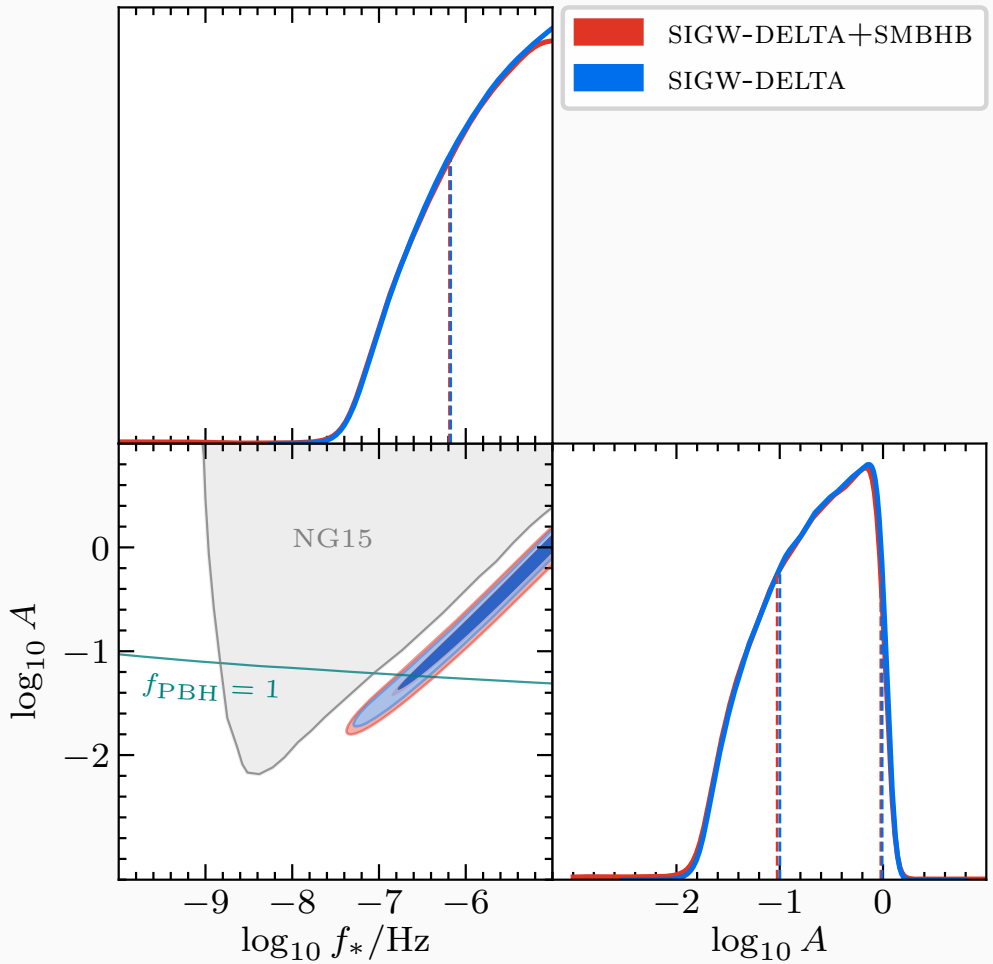
Bayesian inference: posteriors, point values, credible intervals, etc.

Inflationary gravitational waves (IGW)



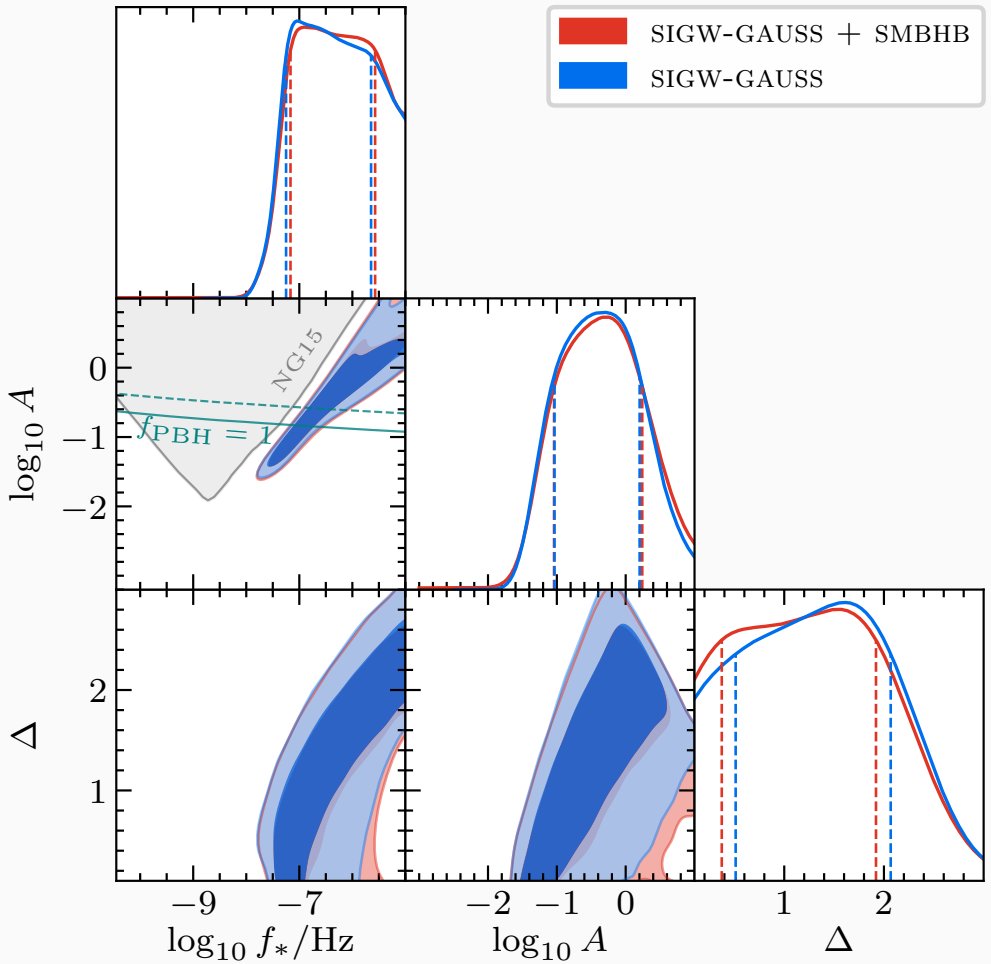
Bayesian inference: posteriors, point values, credible intervals, etc.

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



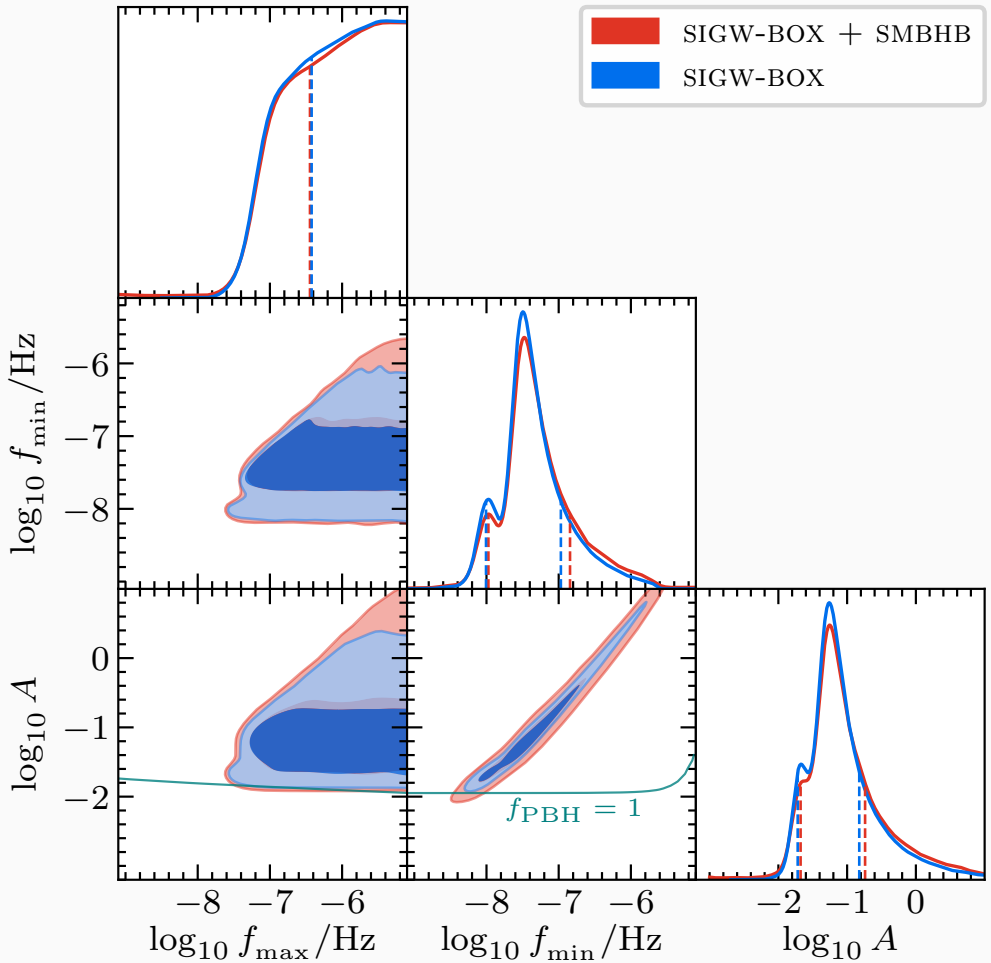
Bayesian inference: posteriors, point values, credible intervals, etc.

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



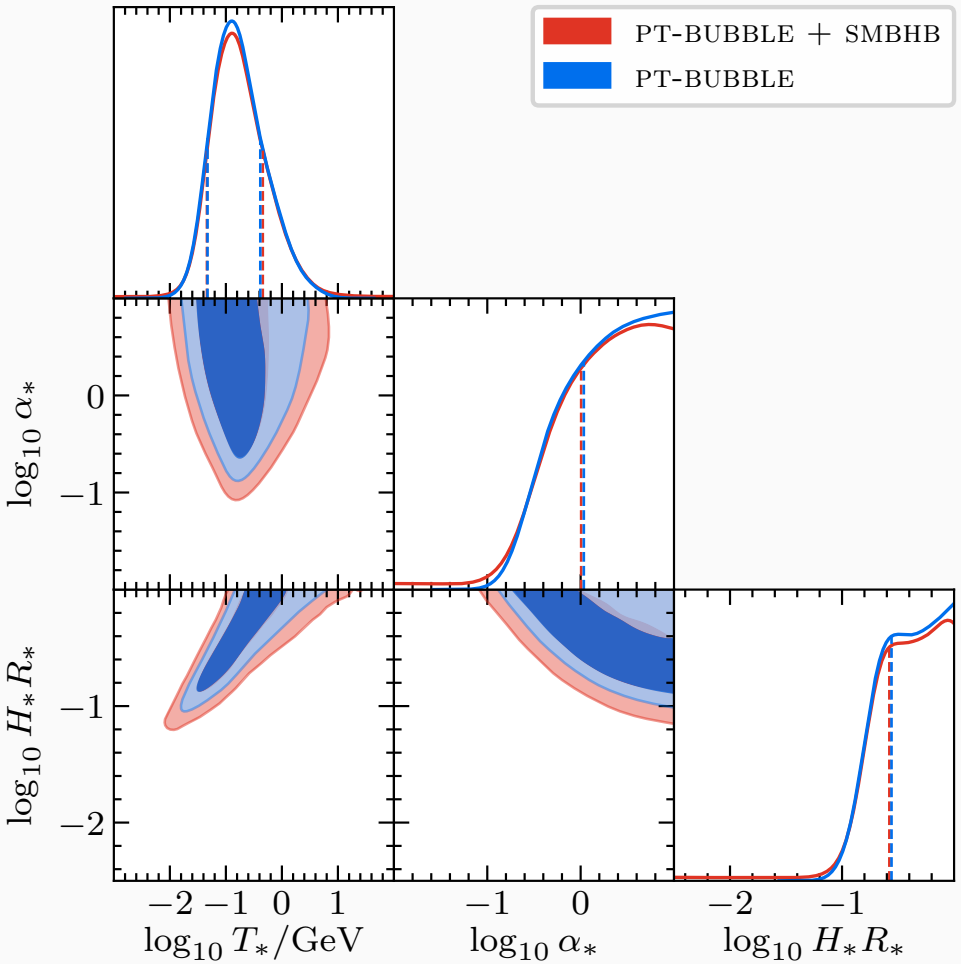
Bayesian inference: posteriors, point values, credible intervals, etc.

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



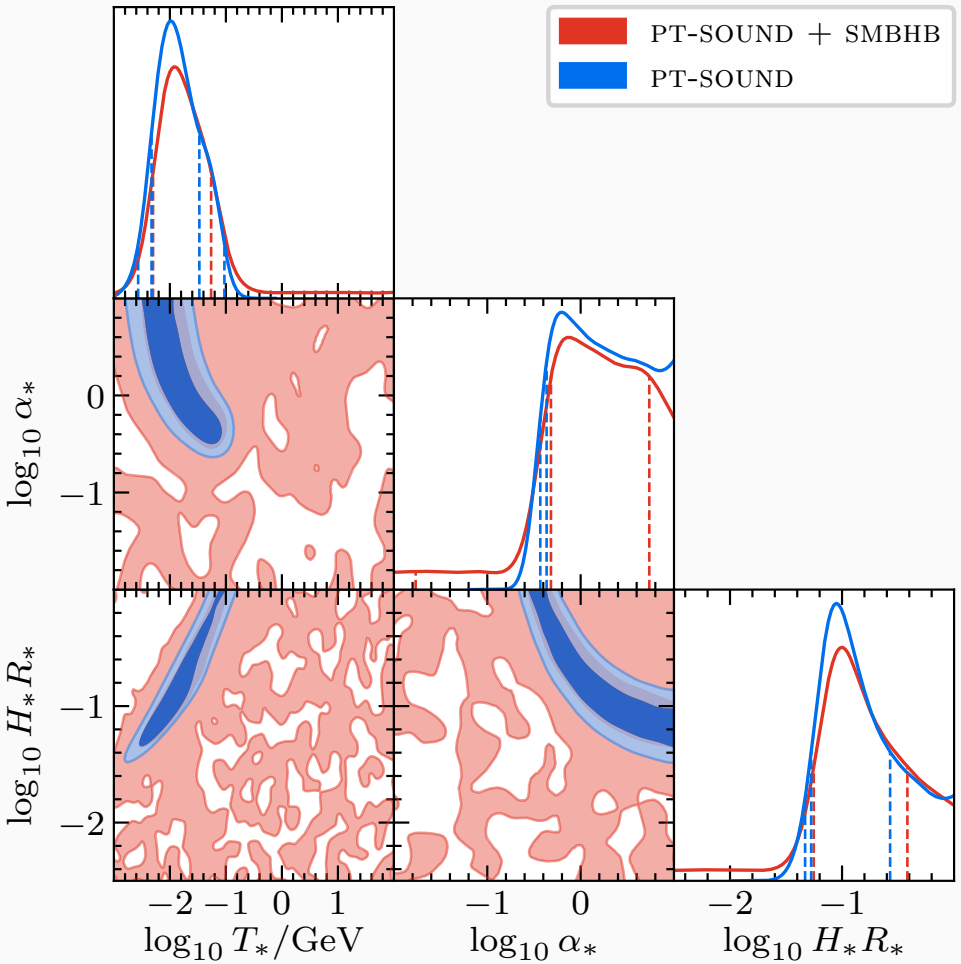
Bayesian inference: posteriors, point values, credible intervals, etc.

Phase transition, bubble collisions (PT-BUBBLE)

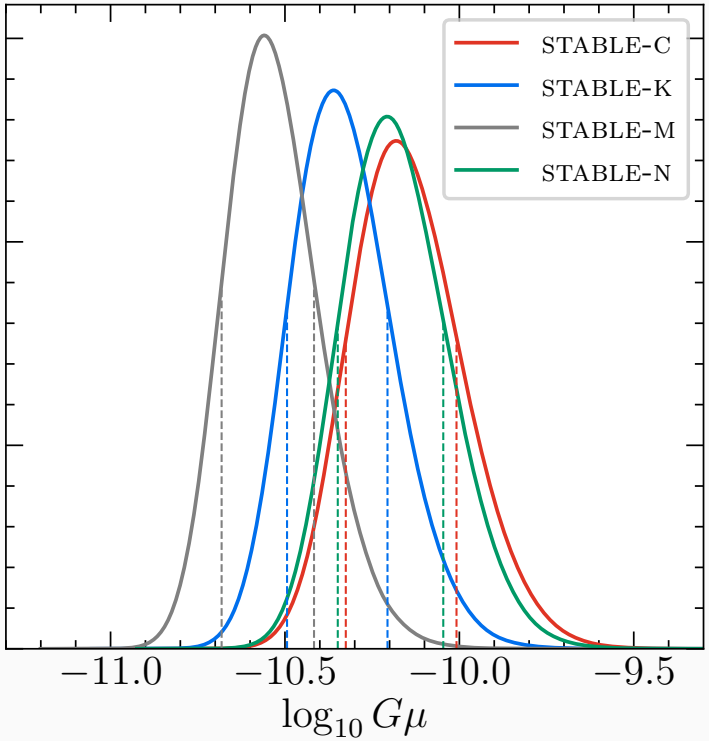


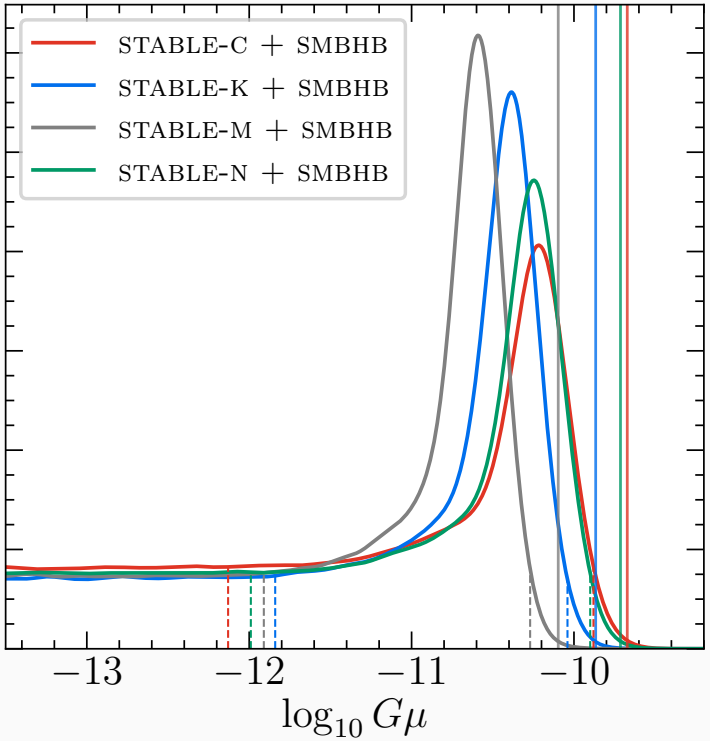
Bayesian inference: posteriors, point values, credible intervals, etc.

Phase transition, sound waves (PT-SOUND)

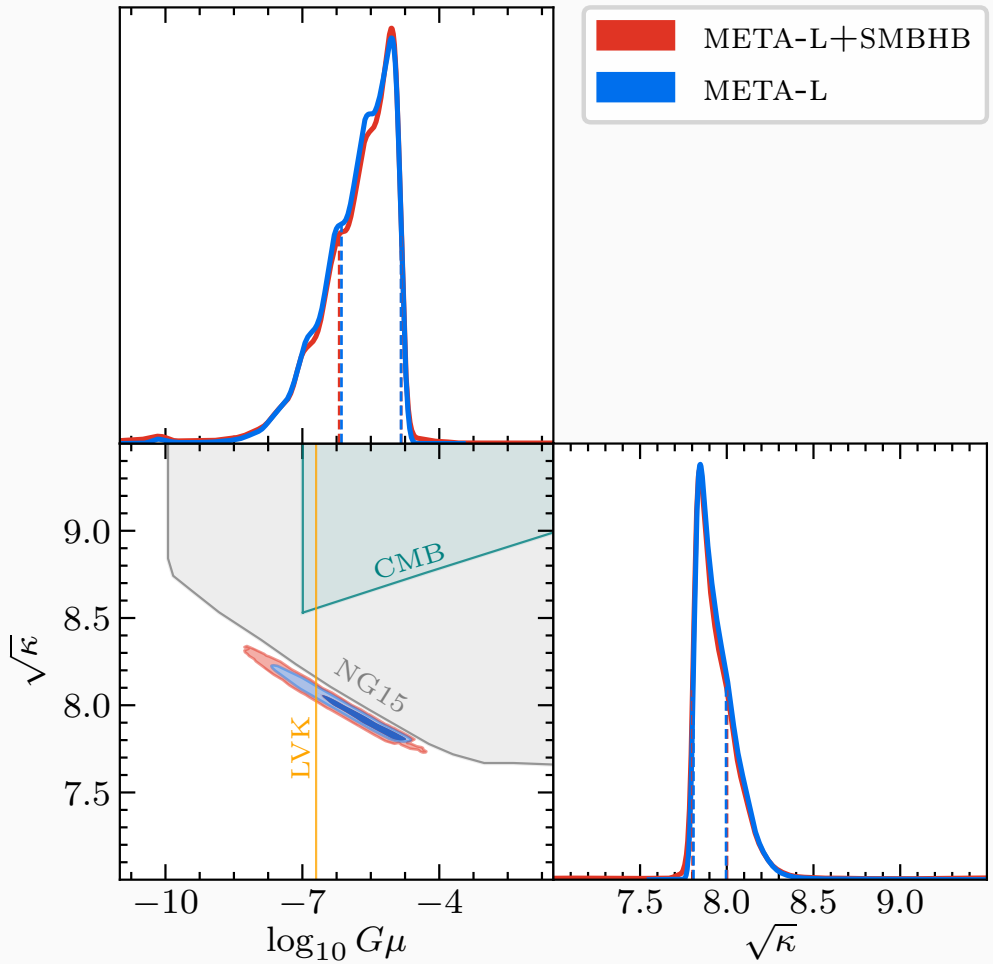


Stable cosmic strings (STABLE)



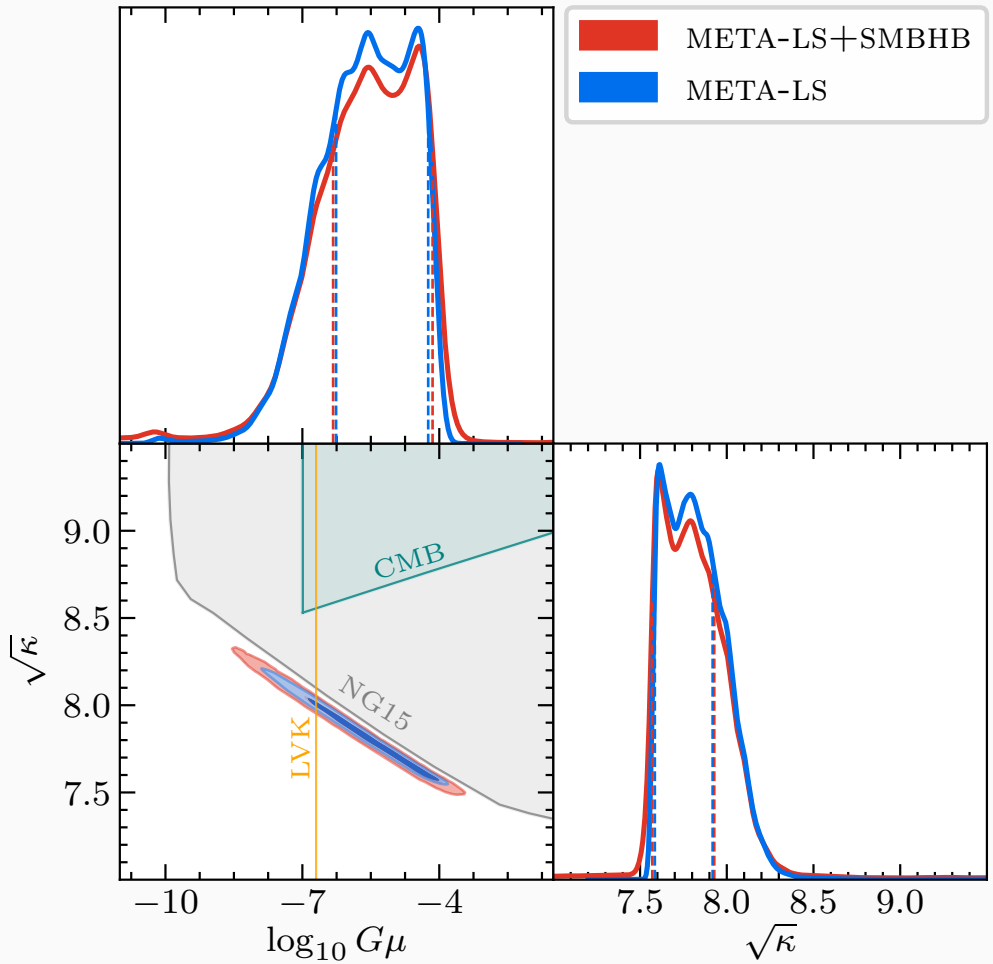


Metastable cosmic strings, loops (META-L)

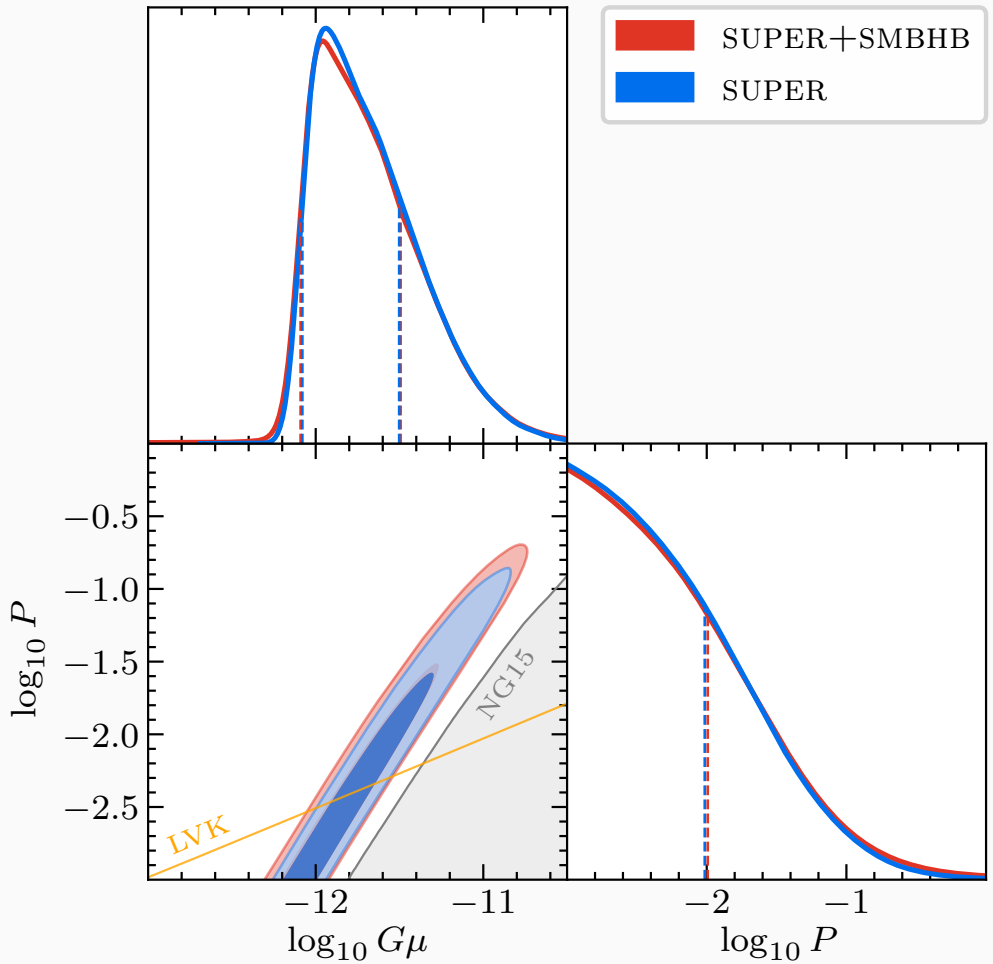


Bayesian inference: posteriors, point values, credible intervals, etc.

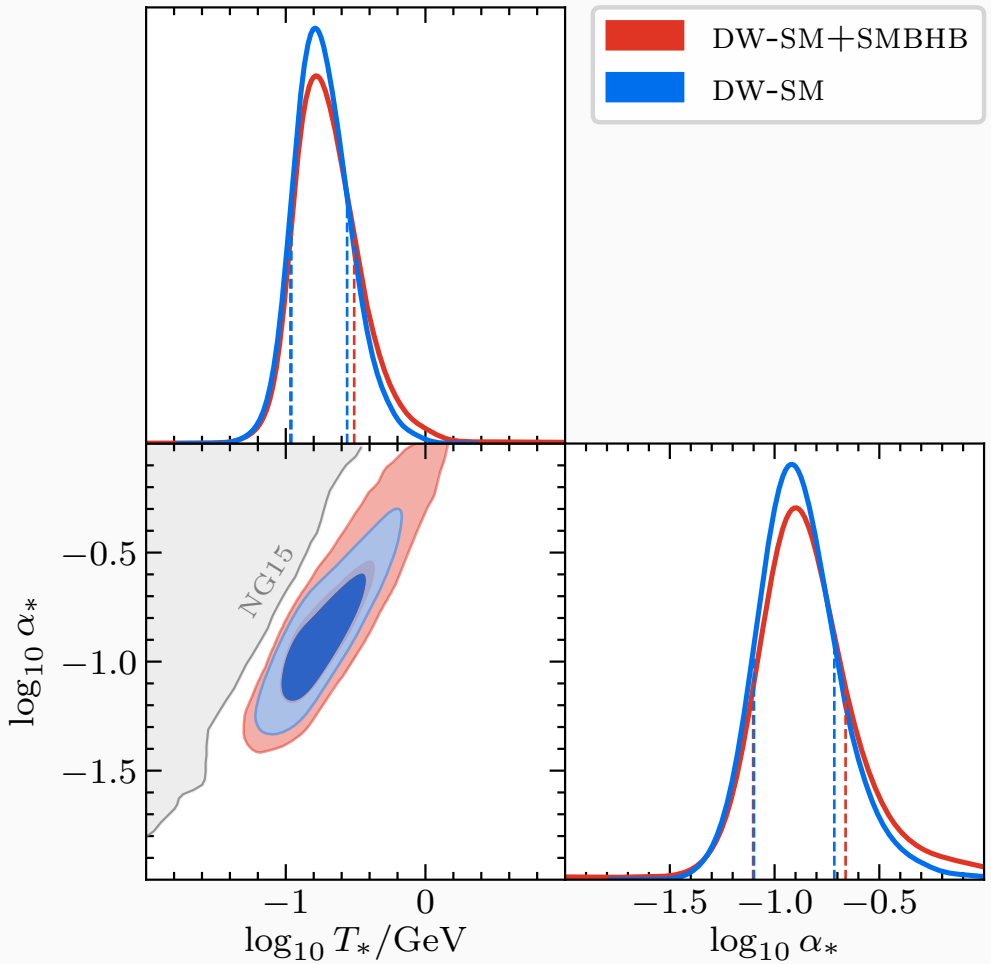
Metastable cosmic strings, loops and segments (META-LS)



Cosmic superstrings (SUPER)



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



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