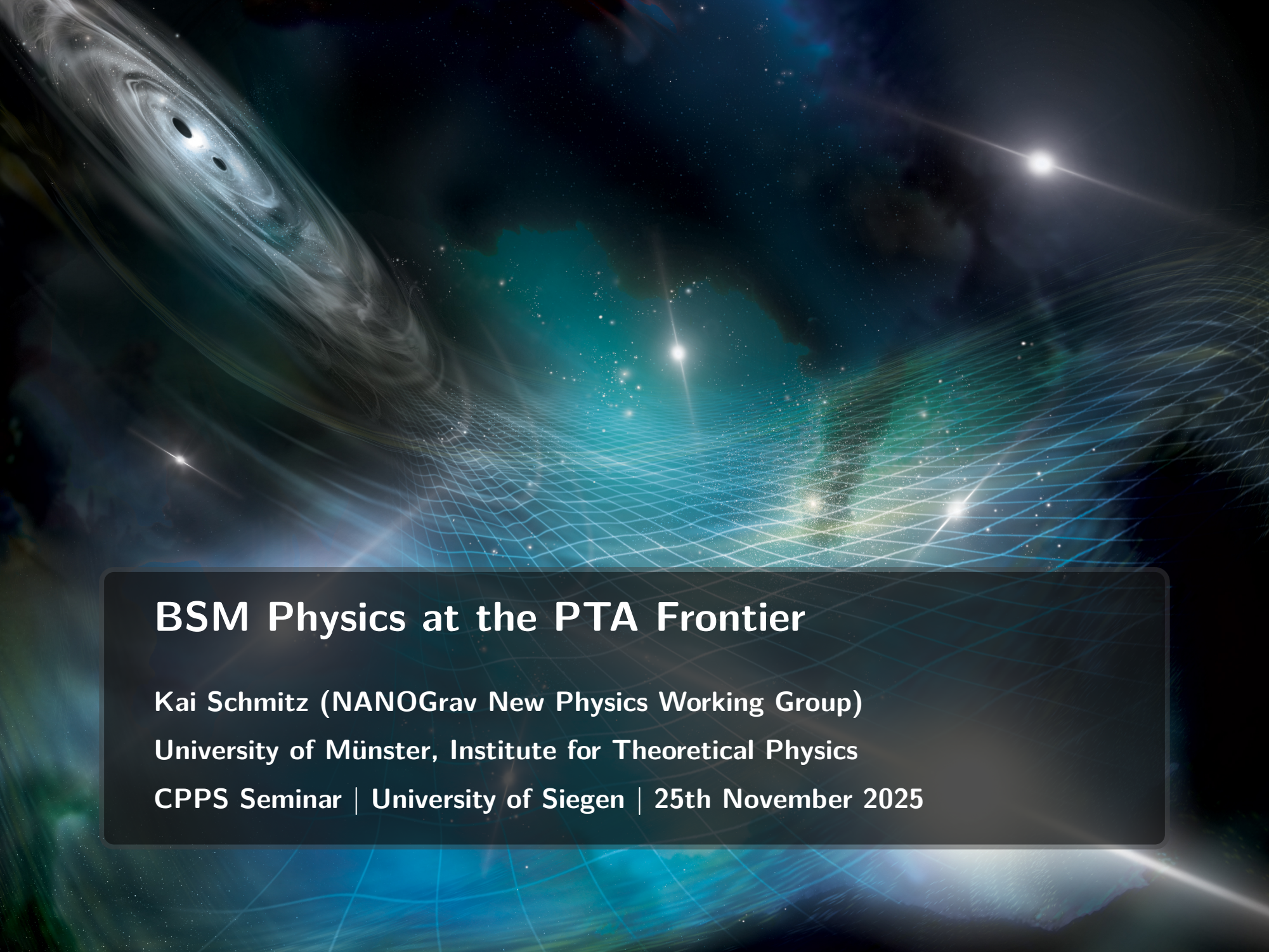


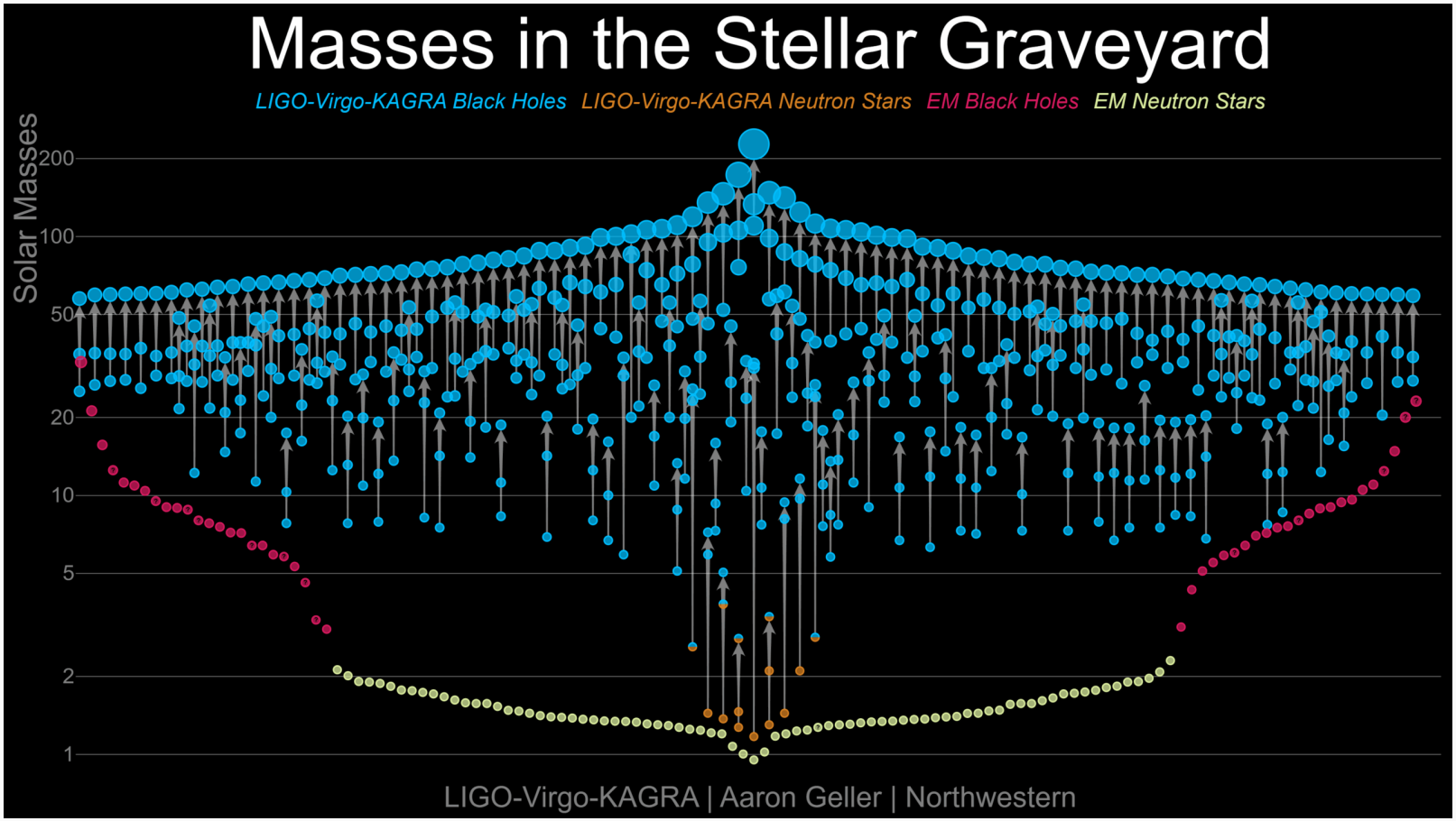
# BSM Physics at the PTA Frontier

Kai Schmitz (NANOGrav New Physics Working Group)

University of Münster, Institute for Theoretical Physics

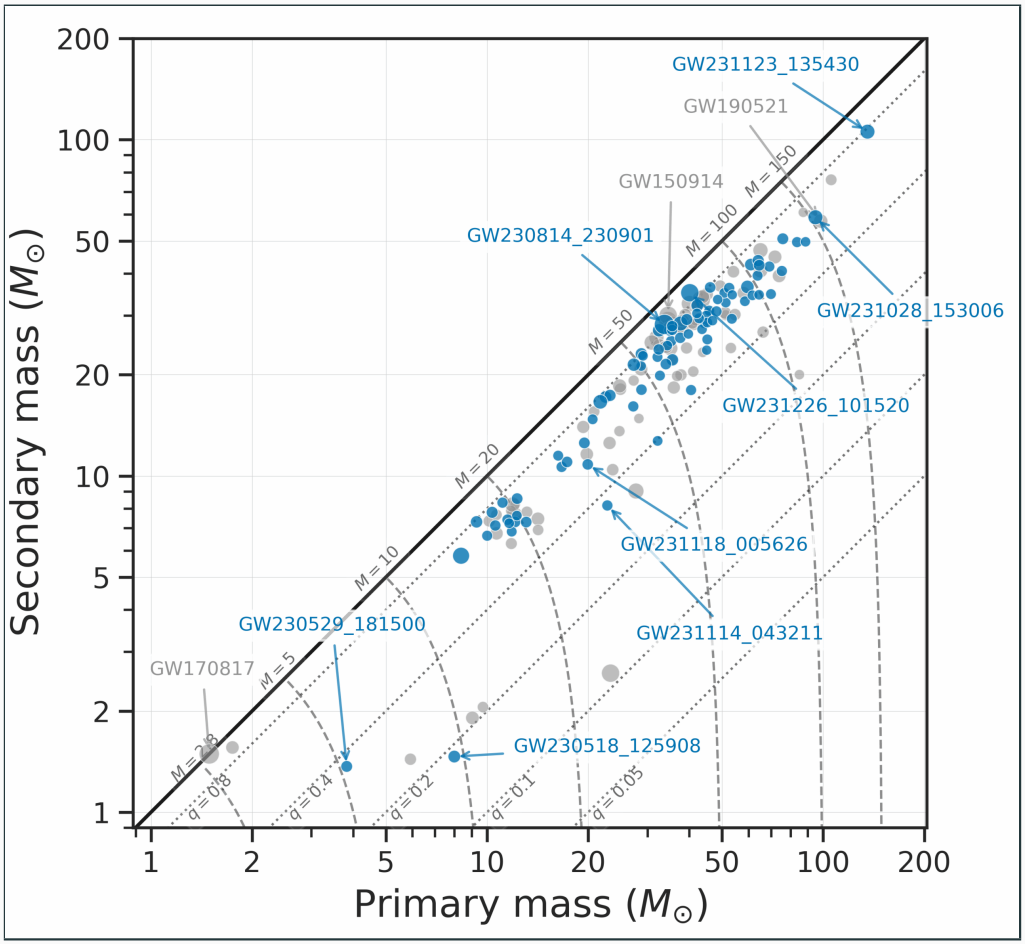
CPPS Seminar | University of Siegen | 25th November 2025

GW Transient Catalog 4.0 by the LVK collaboration




218 compact-binary mergers, data from observing runs O1, O2, O3, O4a

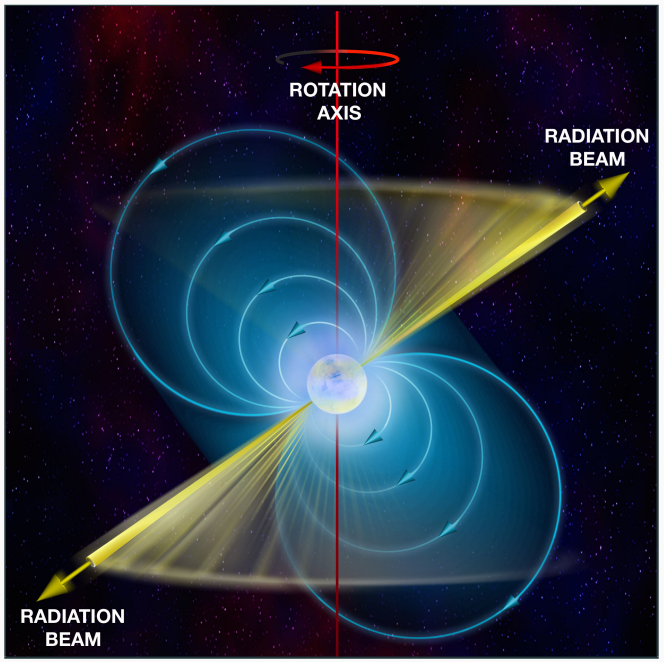
## GW Transient Catalog 4.0 by the LVK collaboration



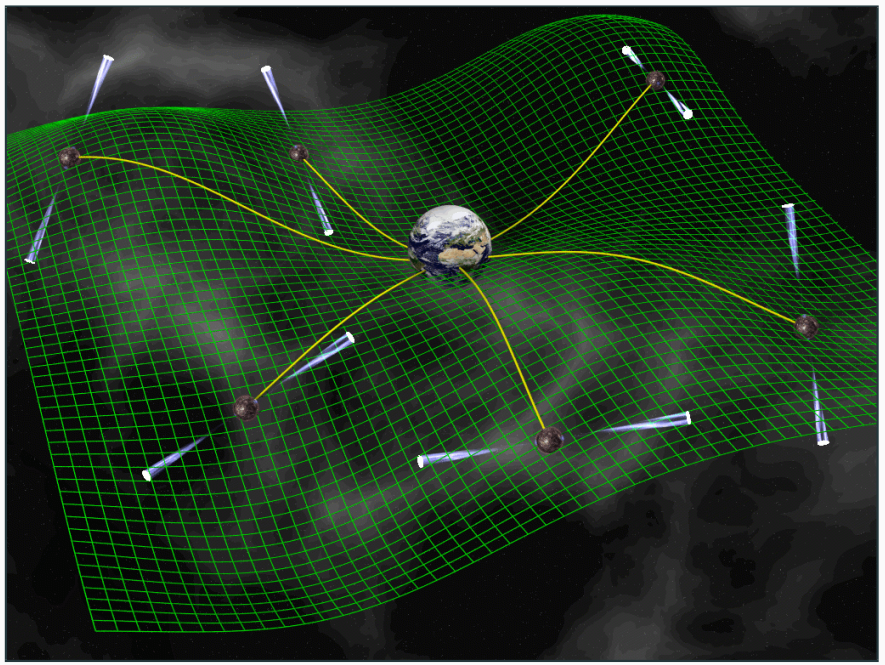

218 compact-binary mergers, data from observing runs O1, O2, O3, O4a

# Pulsar timing arrays (PTAs)

Array of pulsars across our MW spiral arm → GW detector of galactic dimensions!




[nrao.edu]



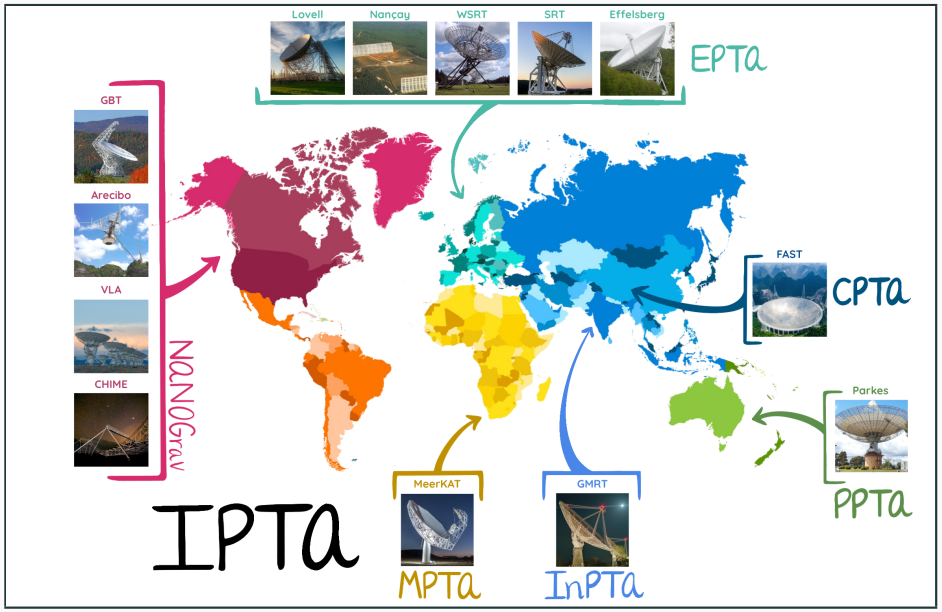
[MPIfR]

Pulsars: **Highly magnetized rotating neutron stars**

- Beamed radio pulses emitted from magnetic N and S poles → cosmic lighthouses
- Stable rotation with periods as short as a few milliseconds → celestial clocks

Look for tiny distortions in pulse times of arrival (TOAs) caused by nanohertz GWs

# 2023 PTA results



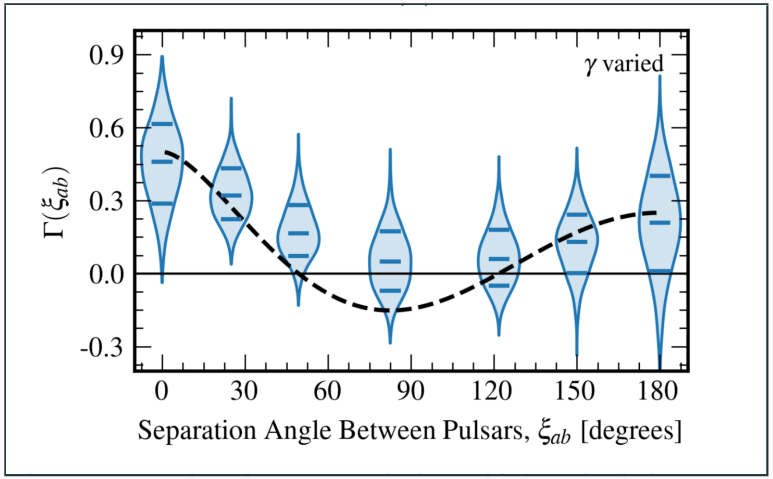

EPTA: European PTA
CPTA: Chinese PTA
PPTA: Parkes PTA
InPTA: Indian PTA
MPTA: MeerKAT PTA
NANOGrav: North American Nanohertz Observatory for Gravitational Waves

18 papers on the arXiv on June 29, 2023

| | | |
|---|---|---|
| [2306.16213] | NANOGrav | GWB |
| [2306.16214] | EPTA | GWB |
| [2306.16215] | PPTA | GWB |
| [2306.16216] | CPTA | GWB |
| [2306.16217] | NANOGrav | Data set |
| [2306.16218] | NANOGrav | Noise model |
| [2306.16219] | NANOGrav | New physics |
| [2306.16220] | NANOGrav | SMBHBs |
| [2306.16221] | NANOGrav | Anisotropies |
| [2306.16222] | NANOGrav | Continuous GW |
| [2306.16223] | NANOGrav | Analysis pipeline |
| [2306.16224] | EPTA | Data set |
| [2306.16225] | EPTA | Noise model |
| [2306.16226] | EPTA | Continuous GW |
| [2306.16227] | EPTA | Implications |
| [2306.16228] | EPTA | ULDM |
| [2306.16229] | PPTA | Noise model |
| [2306.16230] | PPTA | Data set |

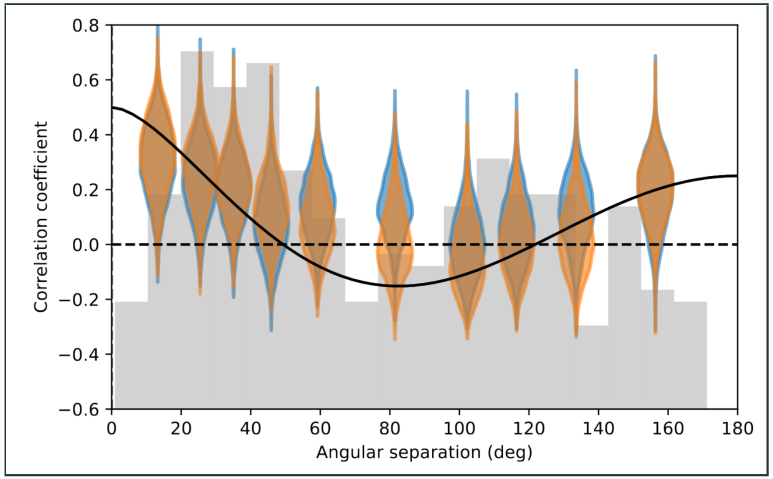
# Evidence for Hellings–Downs (HD) correlations Γ ($\xi_{ab}$)

## 2306.16213: NANOGrav



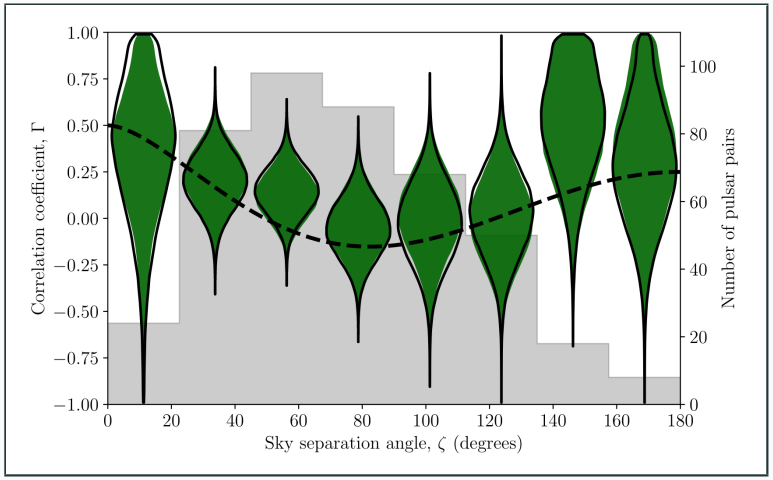

68 pulsars, 16 yr of data, HD at $\sim 3 \cdots 4\,\sigma$

## 2306.16214: EPTA+InPTA



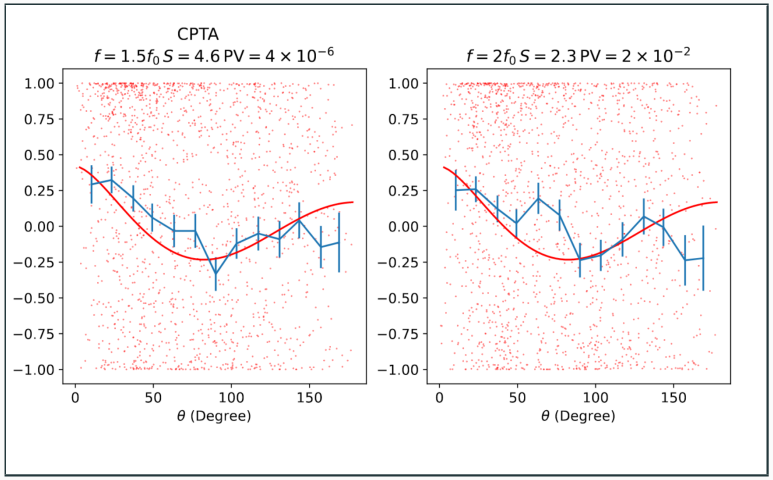

25 pulsars, 25 yr of data, HD at $\sim 3\,\sigma$

## 2306.16215: PPTA




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

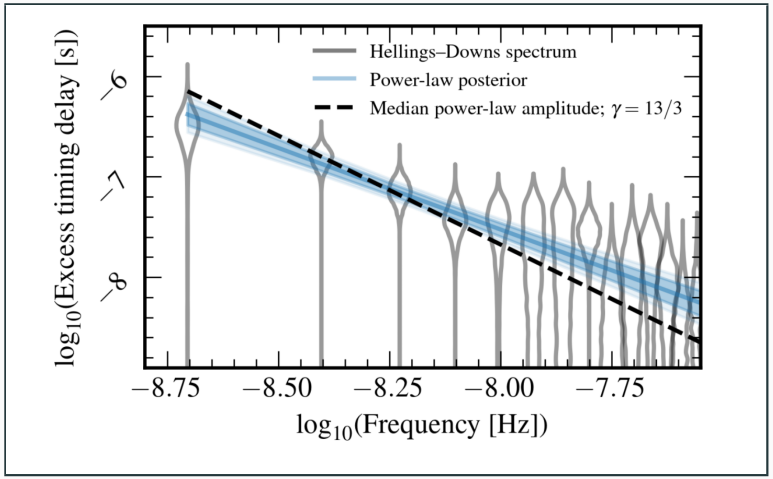
## 2306.16216: CPTA




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

# Common power spectrum $\sqrt{\Delta f\, P_g\,(f)}$

## 2306.16213: NANOGrav

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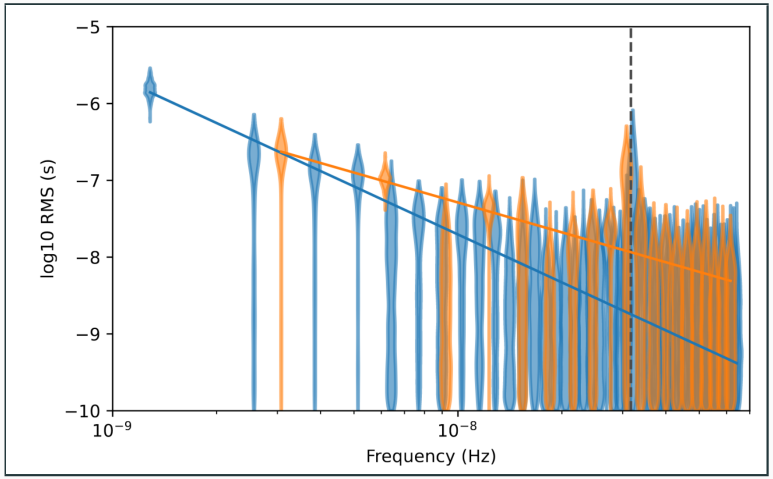


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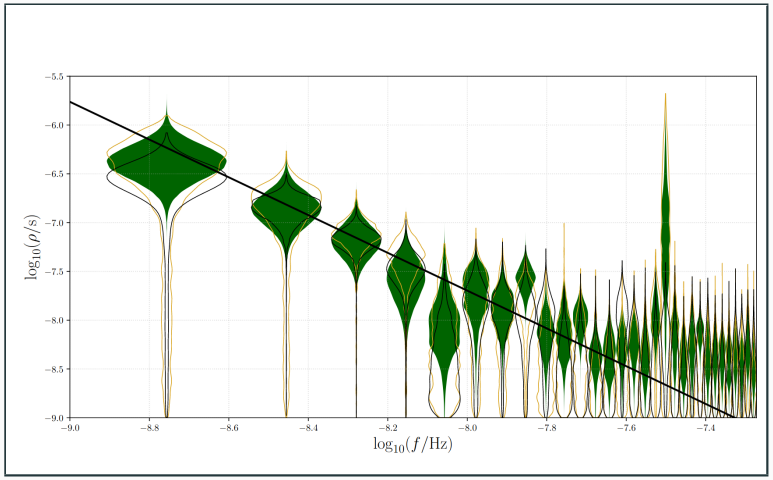


32 pulsars, 18 yr of data, HD at $\sim 2\,\sigma$

## 2306.16216: CPTA

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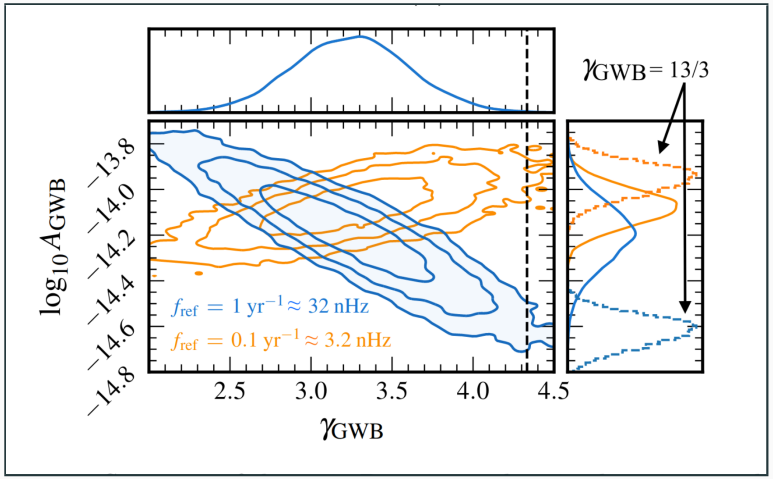
# Power-law parameters $A$ and $\gamma$

## 2306.16213: NANOGrav

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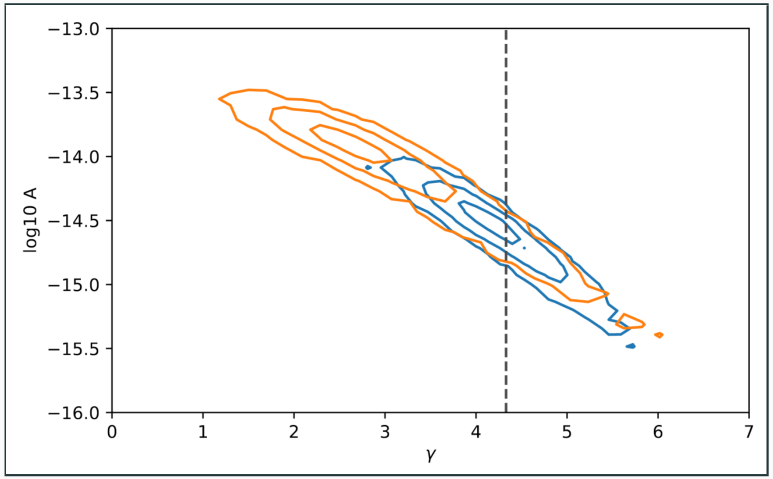


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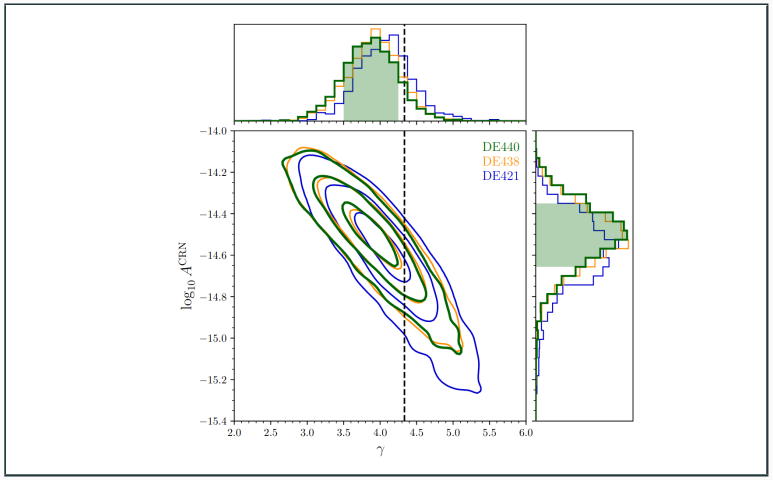


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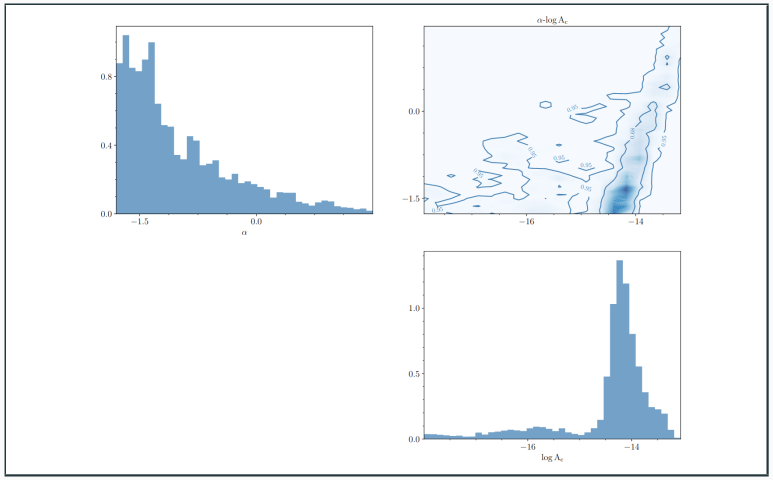
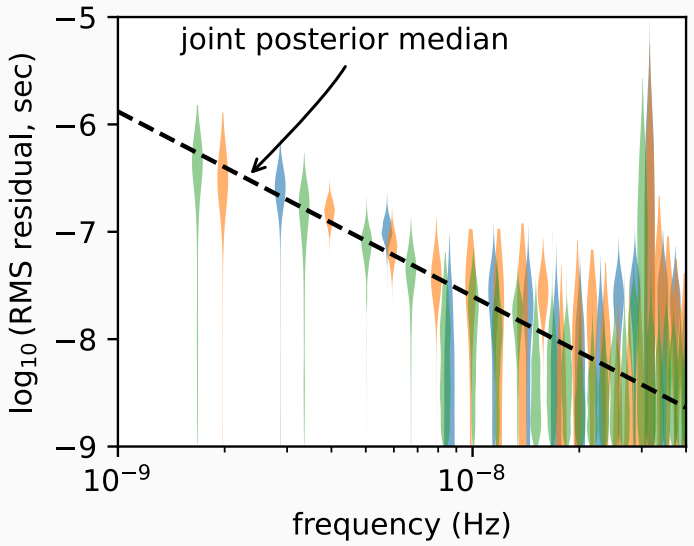
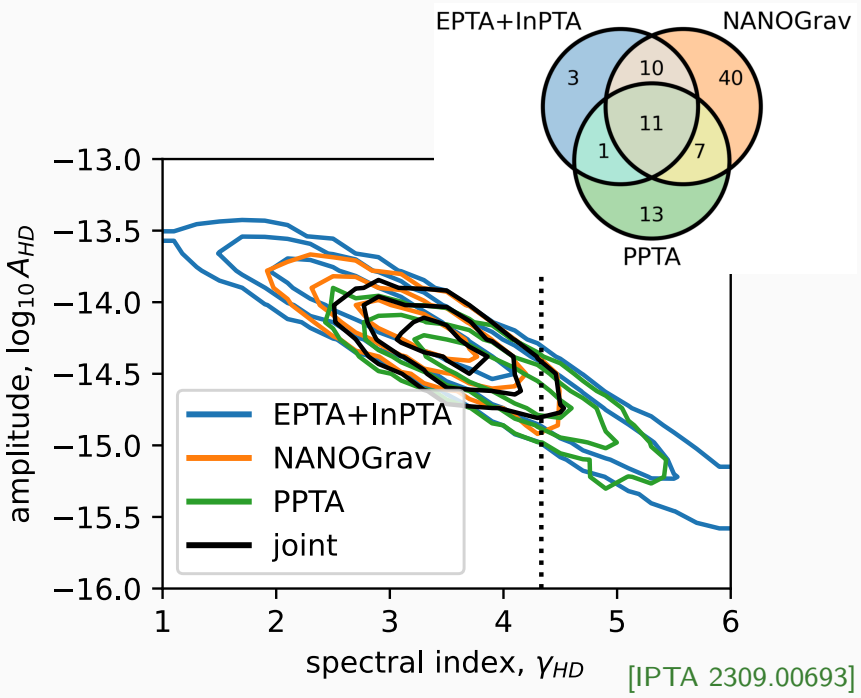


57 pulsars, 3.5 yr of data, HD at $\sim 4.6\,\sigma$

# IPTA comparison

## Current world data on the GWB



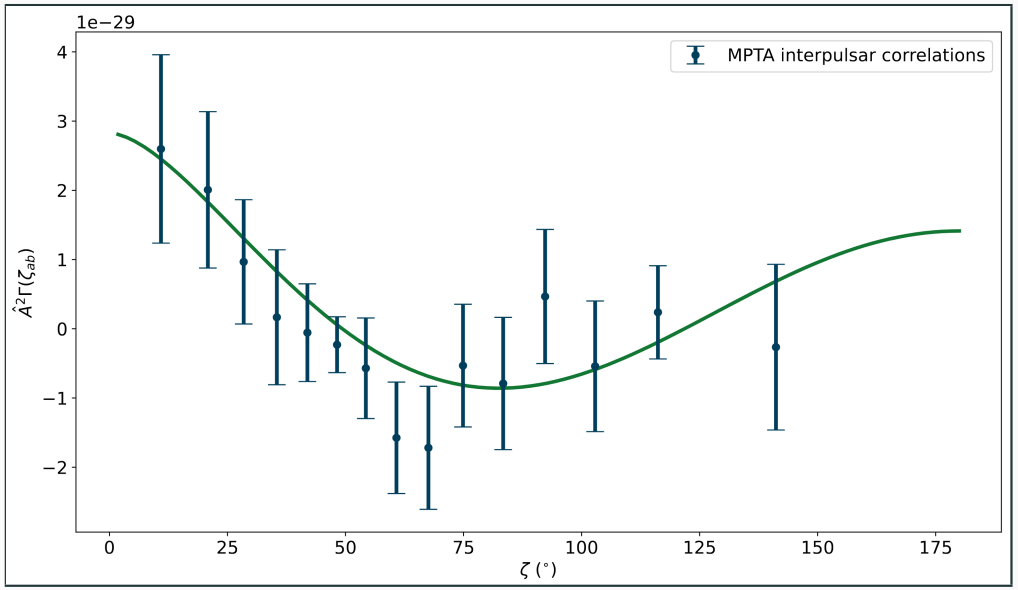



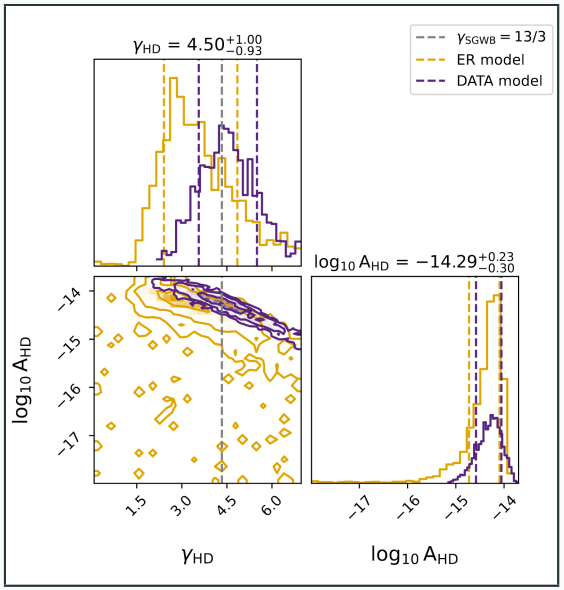

[IPTA 2309.00693]

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

# New kid on the block

MeerKAT Pulsar Timing Array (MPTA): 83 pulsars, 4.5 yr of data [MPTA 2412.01153]

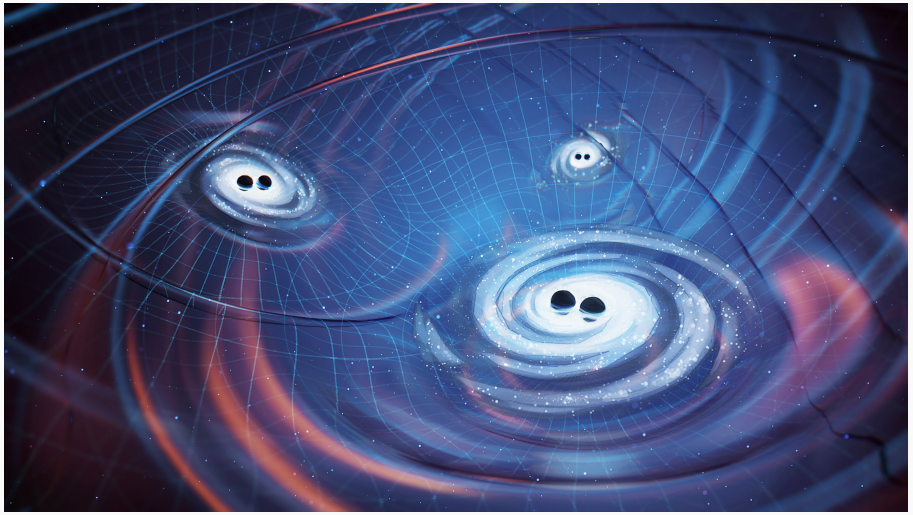


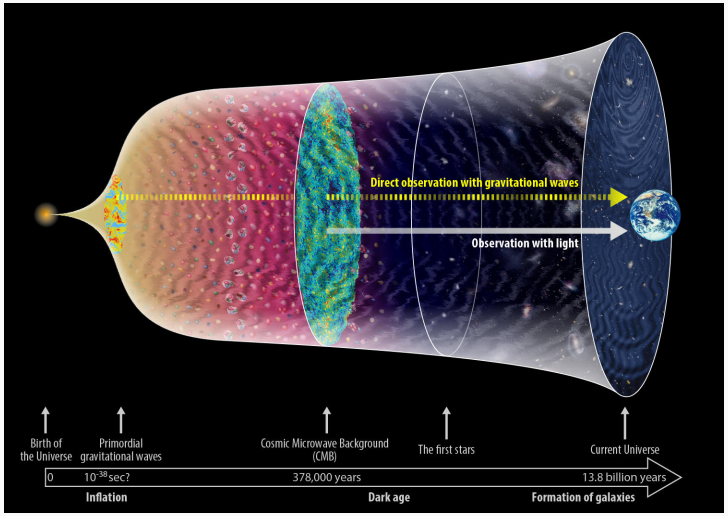

**Abstract:** *[...] Under different assumptions about noise processes we can produce either what appear to be compelling Hellings-Downs correlations of high significance (3–3.3$\sigma$) with a spectrum close to that which is predicted, or surprisingly, under slightly different assumptions, ones that are insignificant. This appears to be related to the fact that many of the highest precision MeerKAT Pulsar Timing Array pulsars are in close proximity and dominate the detection statistics [...]*

# Interpretations

## ❶ Supermassive black-hole binaries



## ❷ GWs from the Big Bang




## ❶ SMBHBs (realistic)

- No SMBHB mergers directly observed as of yet → data-driven field thanks to PTAs
- Viable explanation, several open questions → unexpected corners of parameter space?

## 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

# 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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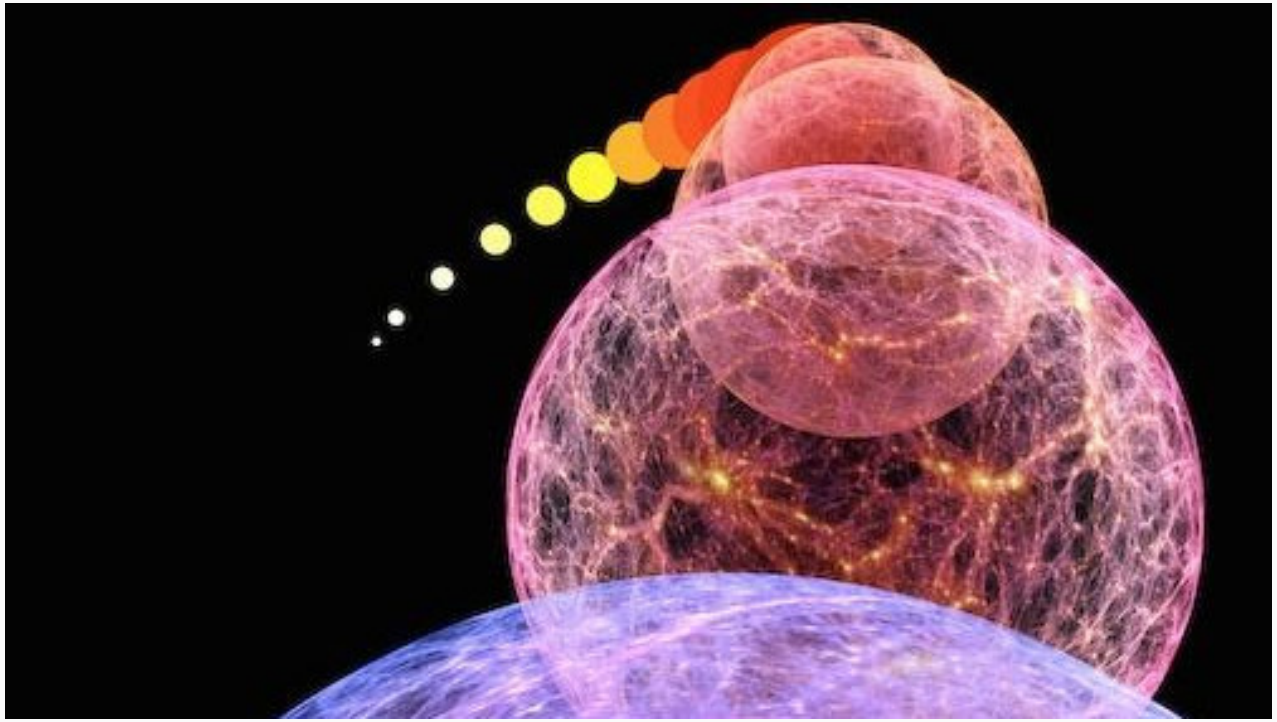


Cosmic inflation: Stage of exponentially fast expansion before the Hot Big Bang

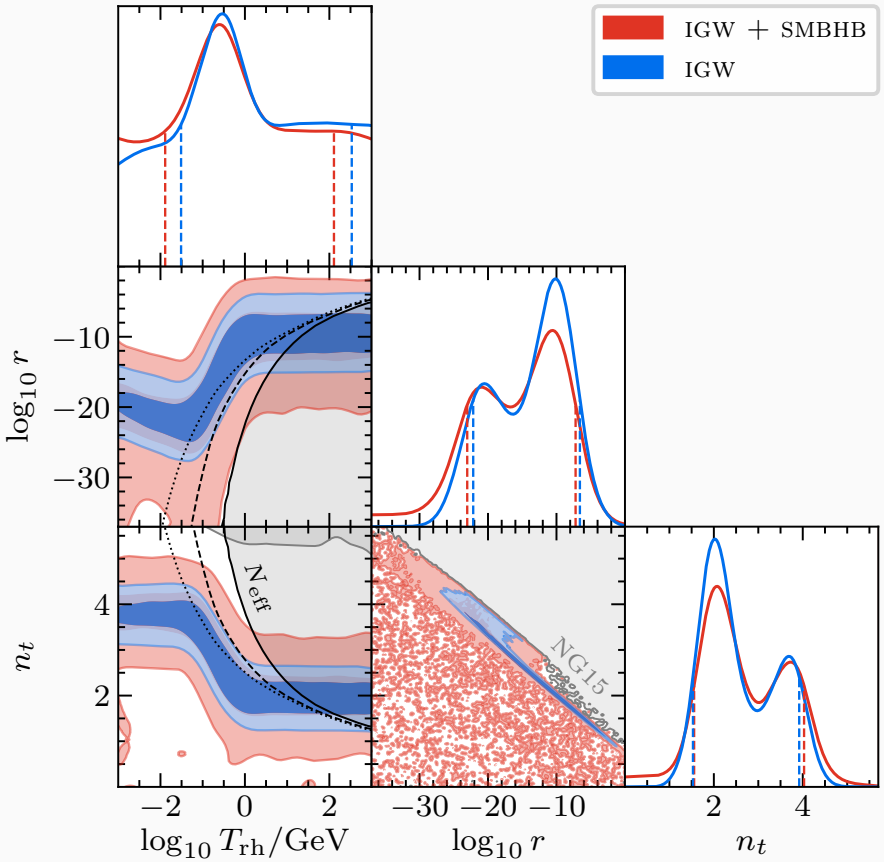
- Requires form of dark energy, e.g., potential energy of a scalar "inflaton" field
- Inflaton and metric fluctuations $\rightarrow$ primordial scalar and tensor perturbations

## 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 |

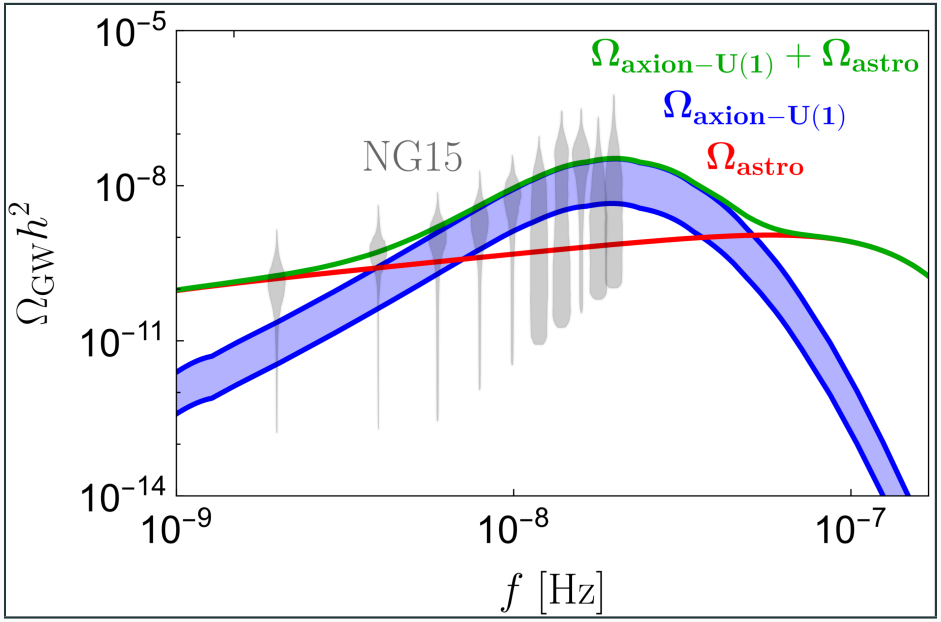



## Lessons

- 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**

# Example: Axion spectator dynamics during inflation

[Obata, Papagerogiou, Ünal 2307.02322]



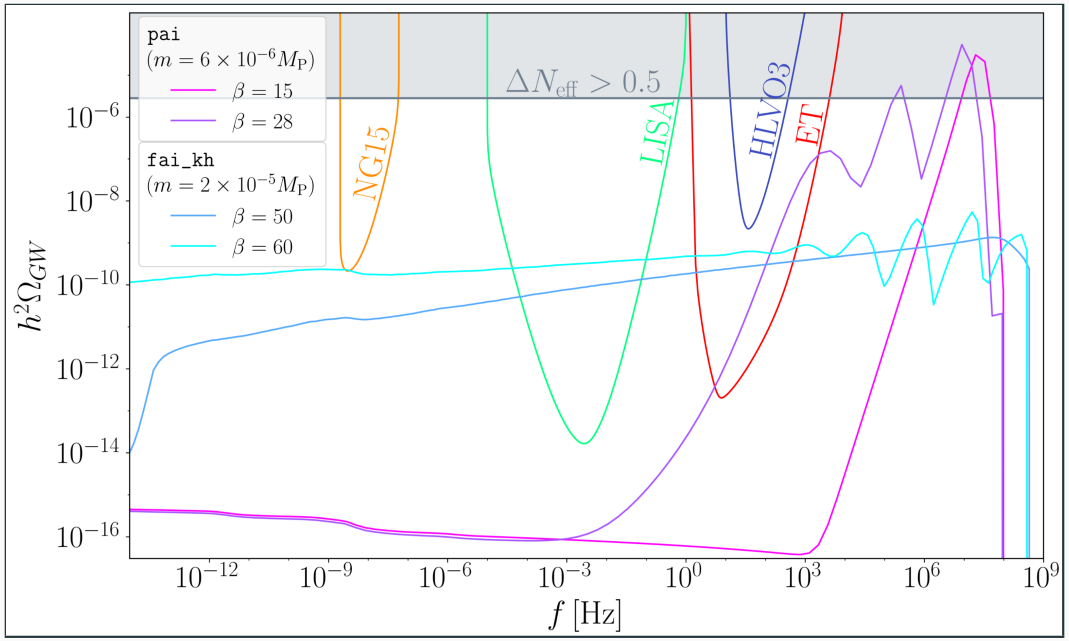

Inflaton $\phi$ + axion spectator $\chi$ + Abelian gauge field $A_\mu$

$$\mathcal{L} = \frac{1}{2}\,\partial_\mu\phi\,\partial^\mu\phi + \frac{1}{2}\,\partial_\mu\chi\,\partial^\mu\chi - \frac{1}{4}\,F_{\mu\nu}F^{\mu\nu} - V(\phi) - V(\chi) - \lambda\frac{\chi}{f}\frac{1}{4}\,F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Axion spectator field rolls down potential $V(\chi) \propto \cos(\chi/f)$ at some point during inflation
- Gauge-field modes with either positive or negative helicity become tachyonically unstable
- GWs from vacuum tensor perturbations + **classical electric and magnetic fields**

# GWs from axion inflation

[von Eckardstein, **KS**, Sobol 2508.00798] [von Eckardstein, **KS**, Sobol 2509.25013] [von Eckardstein 2510.12644]
**New software package:** ***Gradient Expansion Formalism Factory (GEFF)***




Axion inflaton $\chi$ + Abelian gauge field $A_\mu$ (+ charged fermions $\psi_i$)

$$\mathcal{L} = \frac{1}{2}\,\partial_\mu\chi\,\partial^\mu\chi - \frac{1}{4}\,F_{\mu\nu}F^{\mu\nu} - V(\chi) - \lambda\frac{\chi}{f}\frac{1}{4}\,F_{\mu\nu}\tilde{F}^{\mu\nu} - A_\mu J^\mu_\psi$$

- **Pure axion inflation (PAI):** GW production at the end of inflation; too much dark radiation
- **Fermionic axion inflation (FAI):** LISA/CE/ET target; PTA explanation in conflict with CMB

# ❷ BSM scenario: Primordial black holes

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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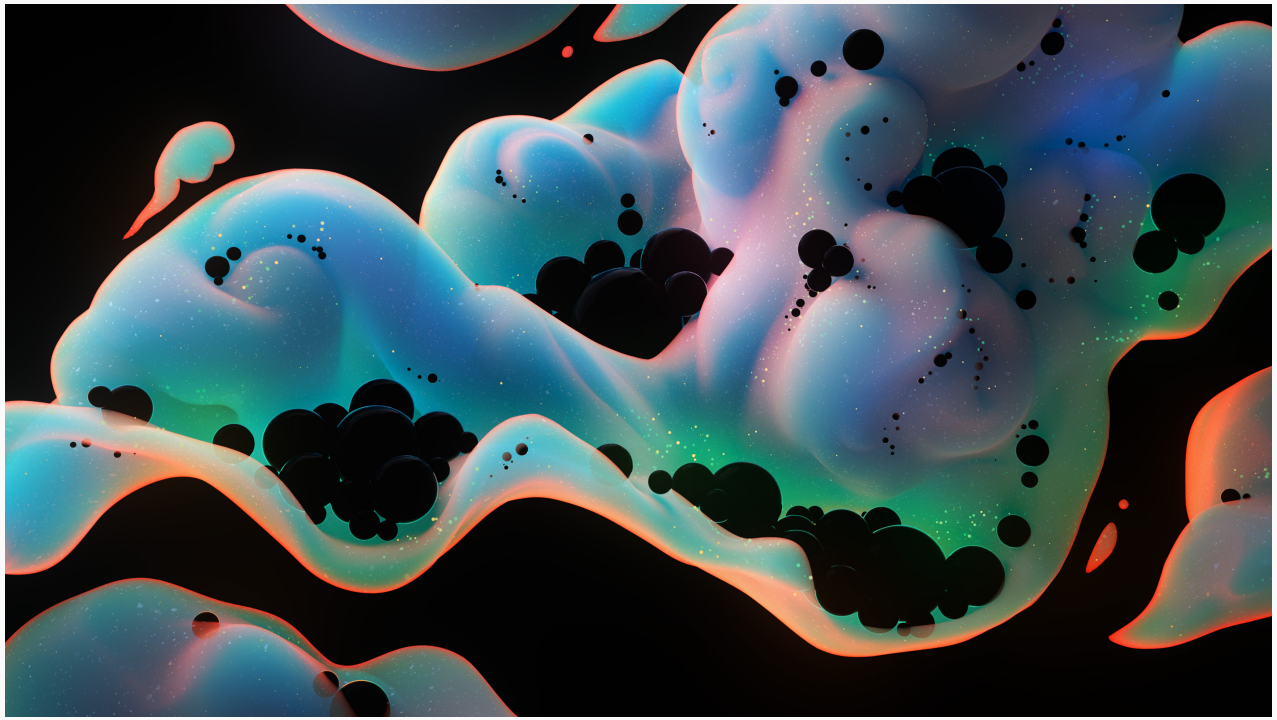


PBHs: Form in the gravitational collapse of large overdensities in the early Universe

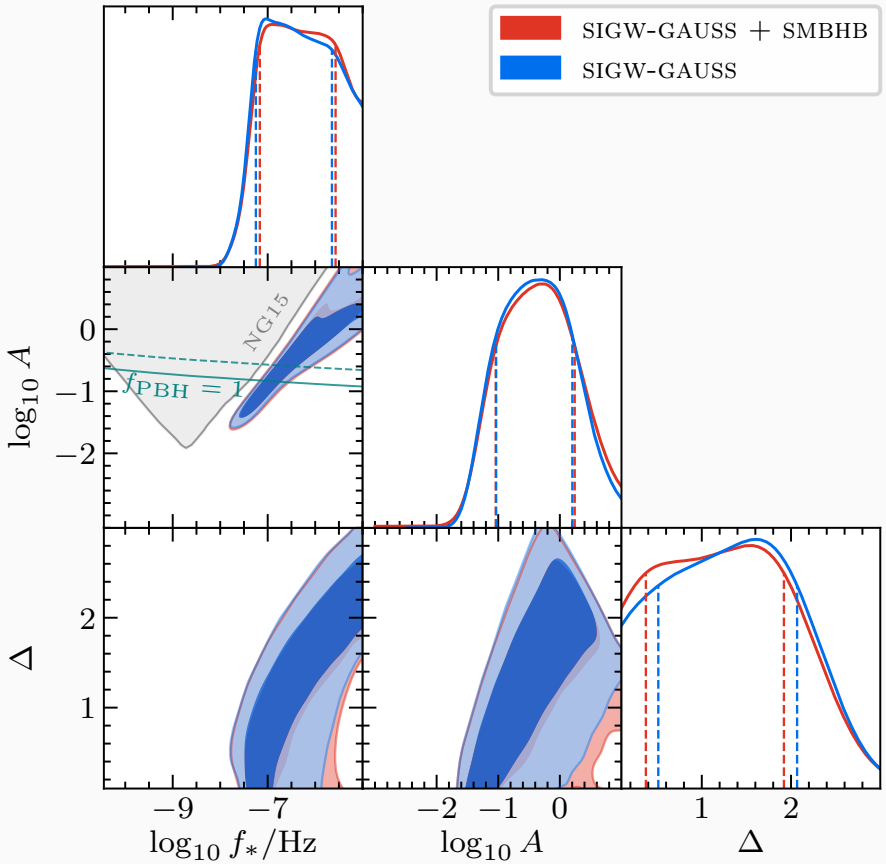
- Typical scenario: Scalar perturbations enhanced during ultra-slow-roll inflation
- Enhanced scalar perturbations $\rightarrow$ GWs at second order in perturbation theory

## 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 |
| $\Delta$ | 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

# ❸ BSM scenario: Phase transition

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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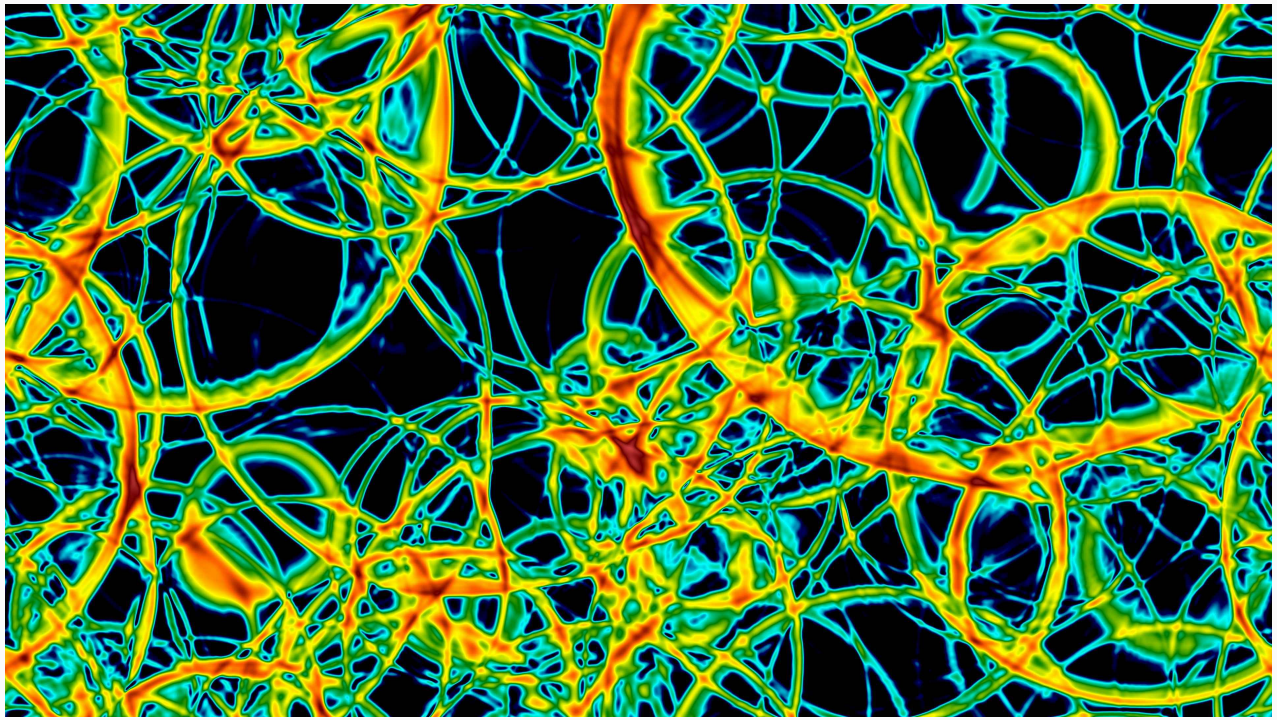


Cosmological phase transitions: Changes in the quantum field theory vacuum structure

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

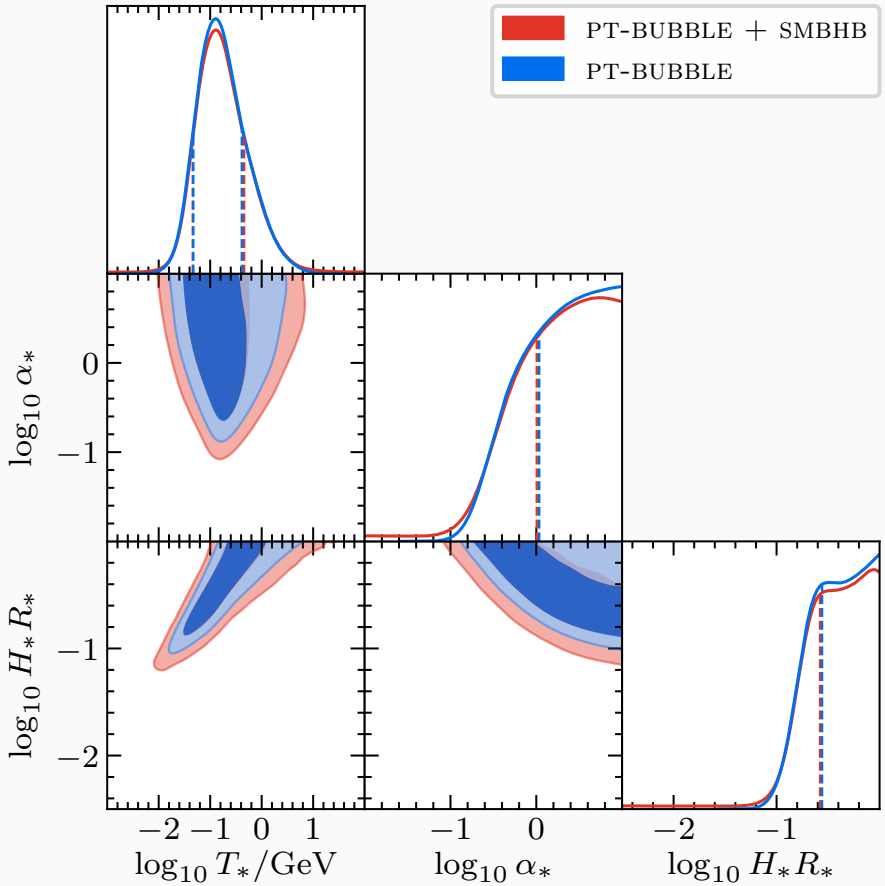
## Peak amplitude and frequency

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

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

## Parameters

| | |
|---|---|
| $T_*$ | Percolation temperature |
| $\alpha_*$ | 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

# ❹ BSM scenario: Cosmic defects

Big questions: How are the tiny SM neutrino masses generated? What is the origin of the matter–antimatter asymmetry? Is the SM embedded in a grand unified theory?

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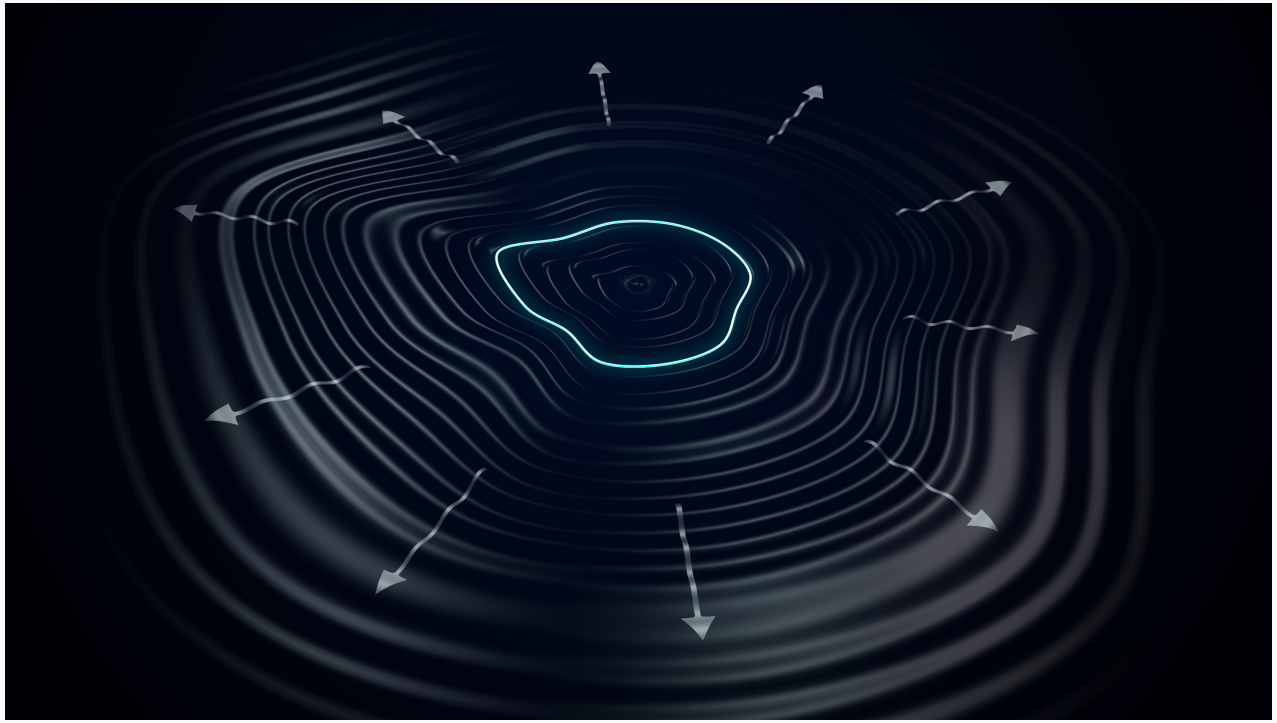


Cosmic strings / domain walls: Defects after spontaneous breaking of GUT symmetries

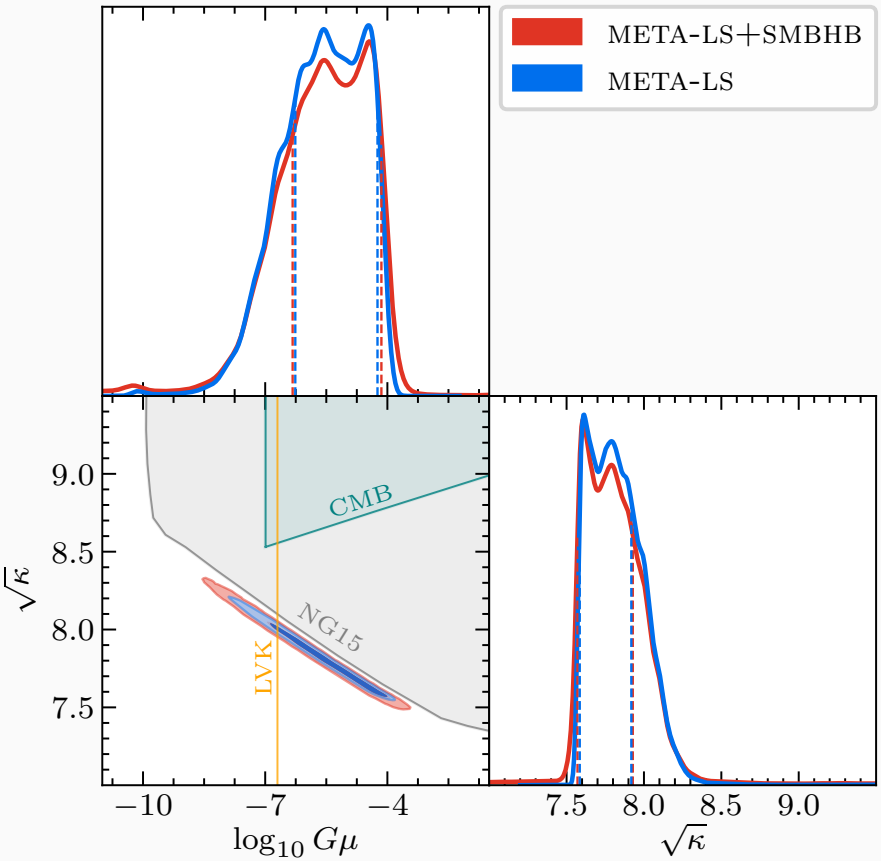
- Typical scenario: $U(1)_{B-L}$ breaking $\rightarrow$ neutrino masses, leptogenesis, and strings
- Dynamics and decay of defect networks yield anisotropic stress and hence GWs

Decay rate per length

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

Parameters

- $\mu$ Tension (energy per length)
- $\kappa$ Decay parameter

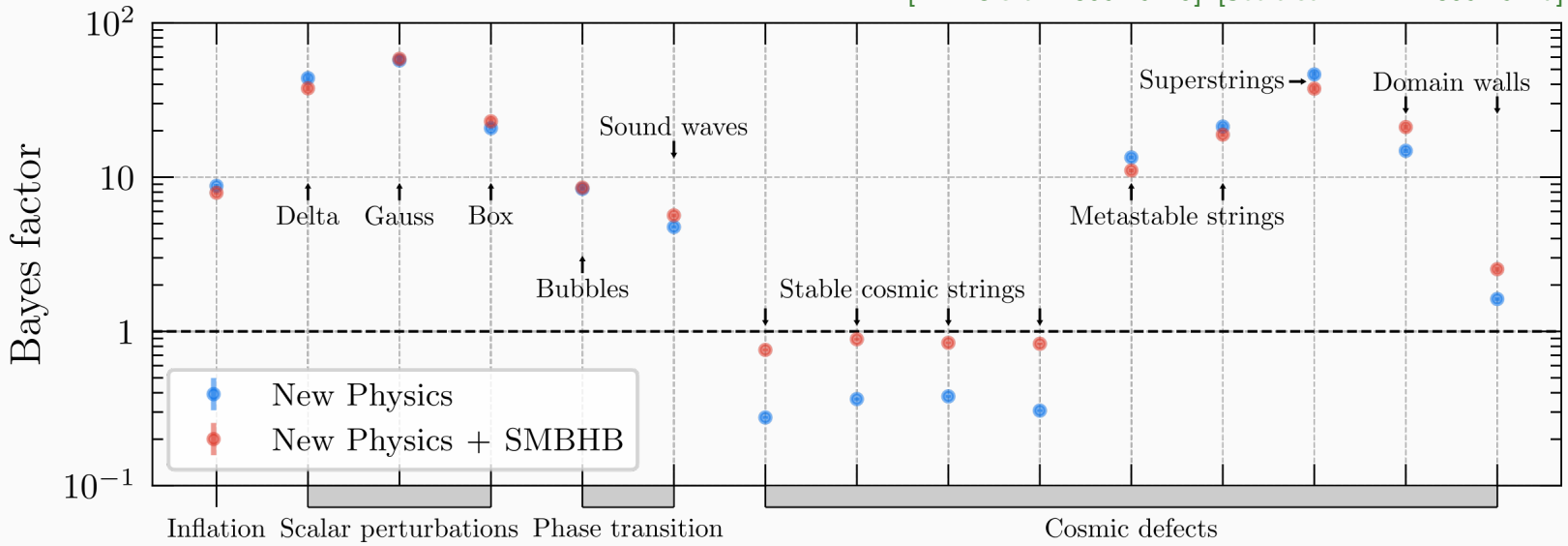



Lessons

- 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 (!)*

# Bayesian model comparison

[NANOGrav 2306.16219] [See also: EPTA 2306.16227]




$$\text{Bayes factor } B = \frac{\text{Evidence for model } M_1,\ P(D|M_1)}{\text{Evidence for model } M_0,\ P(D|M_0)}, \qquad M_0 = \{\text{SMBHBs only}\}$$

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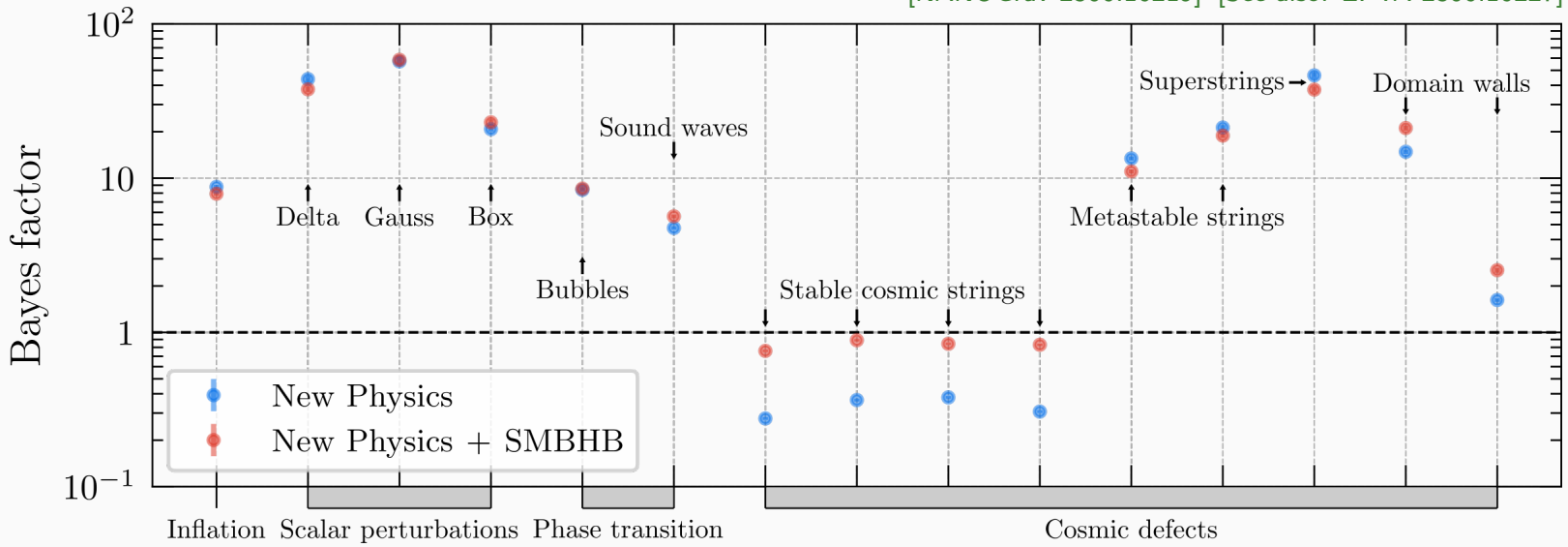
- Many BSM models reach Bayes factors of the order of $10 \cdots 100$
- Interesting but not conclusive; lots of uncertainties in SMBHB and BSM models

# Bayesian model comparison

[NANOGrav 2306.16219] [See also: EPTA 2306.16227]



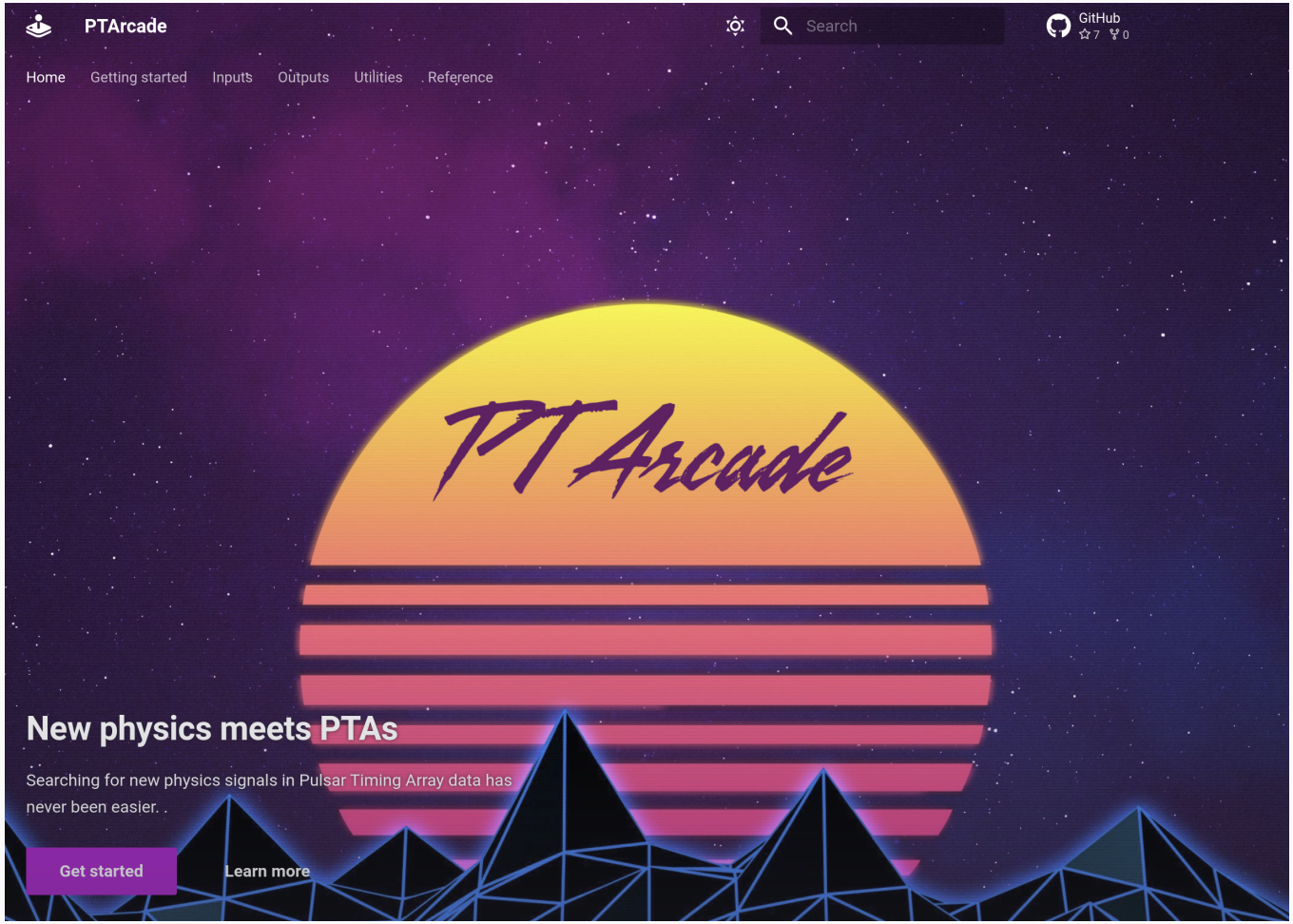

$$\text{Bayes factor } B = \frac{\text{Evidence for model } M_1,\ P(D|M_1)}{\text{Evidence for model } M_0,\ P(D|M_0)}, \qquad M_0 = \{\text{SMBHBs only}\}$$

---

- Many BSM models reach Bayes factors of the order of $10 \cdots 100$
- Interesting but not conclusive; lots of uncertainties in SMBHB and BSM models

**Call to action:** Improve modelling on both the astro and the cosmo side!

# PTArcade

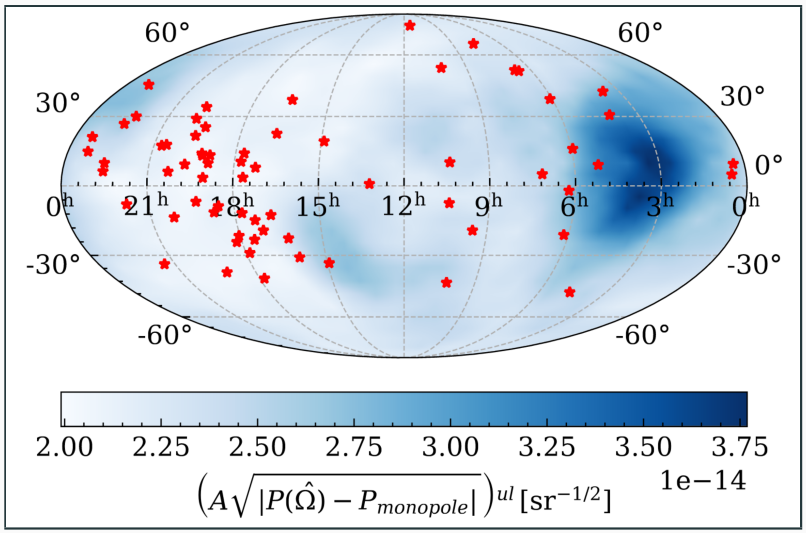


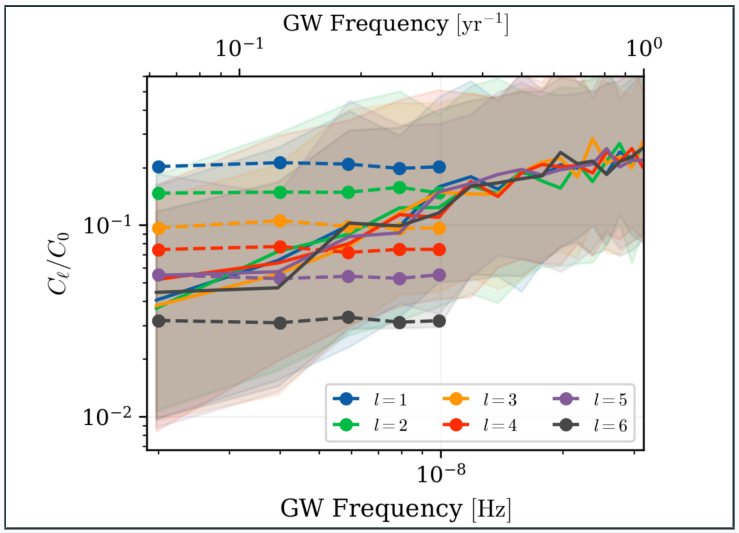

Our code developed for 2306.16219: Fit your favorite BSM model to the NG15 data!

New functionalities, new models, and new data (when available) added on a steady basis

# Complementary observables: Anisotropies

[NANOGrav 2306.16221]



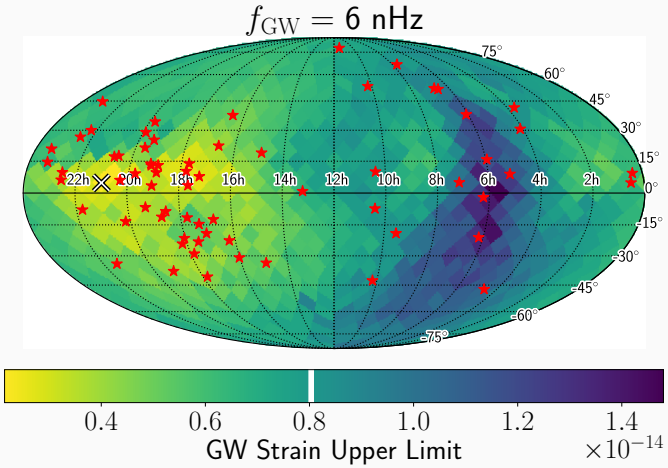

Search for anisotropies in the GWB signal in the sky

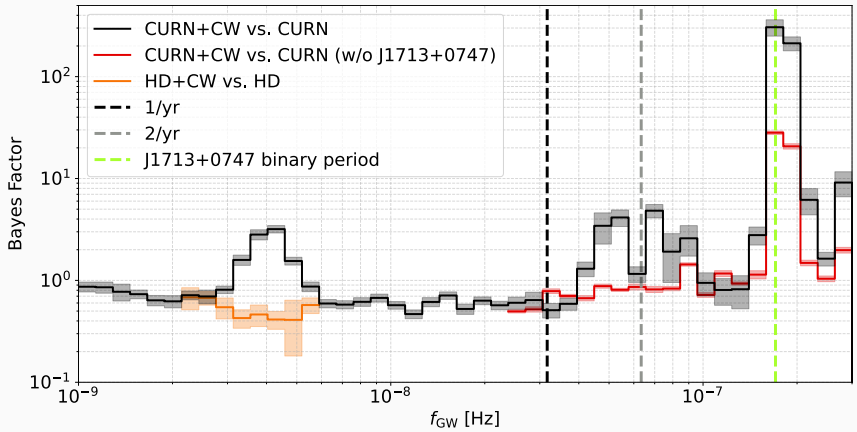
- Current sensitivity already at the level of expected anisotropies from SMBHBs
- No signal detected $\rightarrow$ sky-dependent upper limits on deviation from monopole

No detection of anisotropies with future data sets $\rightarrow$ hint of primordial origin!?

# Complementary observables: Continuous waves

[NANOGrav 2306.16222]

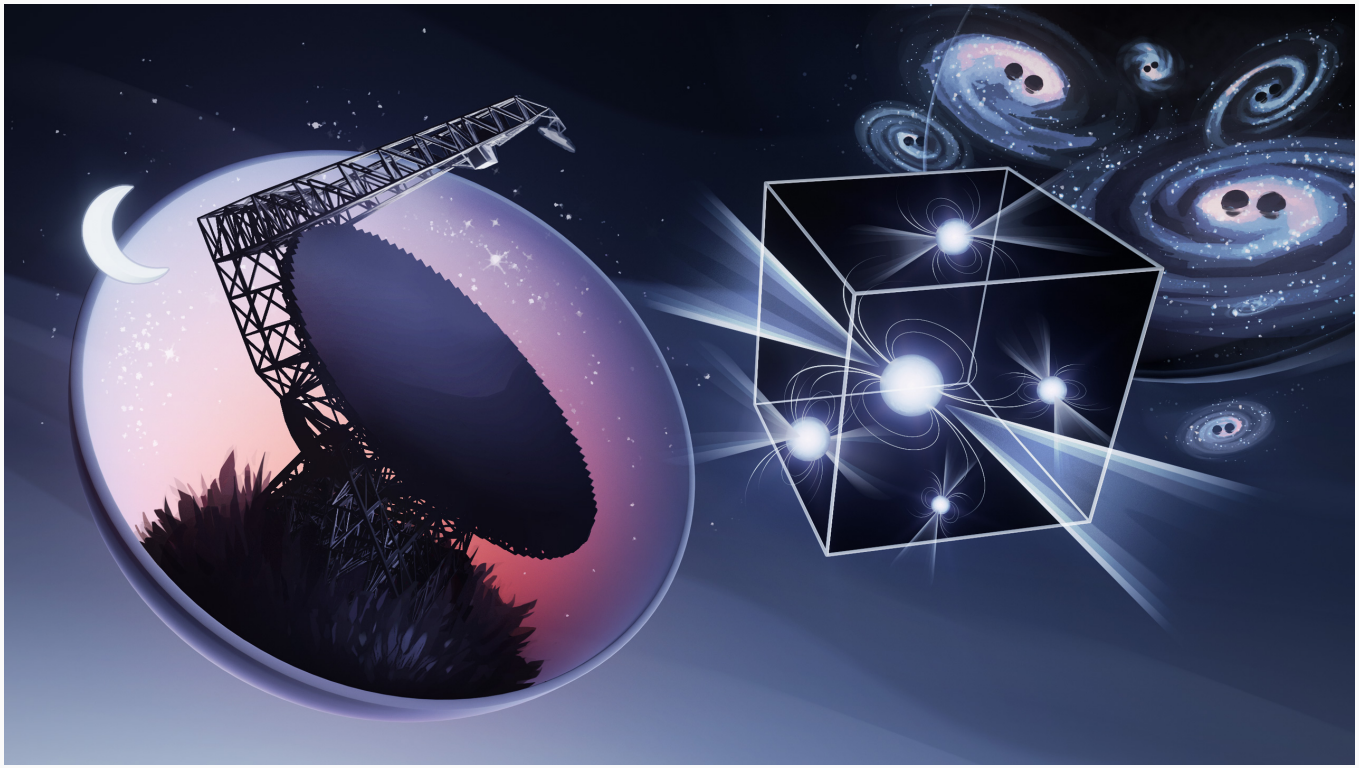



Search for continuous-wave signals from individual nearby SMBHB systems

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

# This is only the beginning!



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 new physics

# Stay tuned!

And thanks a lot for your attention