

Exploring new physics with pulsar timing arrays.

Lightning talk at the Invisibles workshop 2024, Bologna

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In case you haven't heard the news.

At Last, There's a Cosmic Bass Note
A globe-spanning...
Astronomers detect 'cosmic bass note' of low-frequency gravitational waves
Sound comes from the merging of supermassive black holes across the universe, according to scientists

Scientists 'hear' cosmic hum from gravitational waves
Scientists observed for the first time faint ripples caused by the motion of black holes merging everything in the universe.

Gravitational waves finally 'heard' the chorus of gravitational waves that ripple through the universe
Scientists have observed for the first time the faint ripples caused by the motion of black holes that are gently stretching and squeezing everything in the universe

Colossal gravitational waves—trillions of miles long—found for the first time
Astronomers are now seeking to pinpoint the origins of an exciting new form of gravitational waves that was announced earlier this year

First Evidence of Giant Gravitational Waves Thrills Astronomers
For first time ever, scientists "hear" gravitational waves rippling through the universe
Astronomers tuning in to a never-before-seen type of gravitational waves spawned by pairs of supermassive black holes

Monster gravitational waves spotted for first time
Astronomers discover that universe is a chorus of gravitational waves

Black Holes at the Center of the Milky Way
Gravitational waves reverberating across the cosmos, most likely from supermassive black holes merging in the early universe.

The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find
Radio telescopes around the world picked up a telltale hum reverberating across the cosmos, most likely from supermassive black holes merging in the early universe.

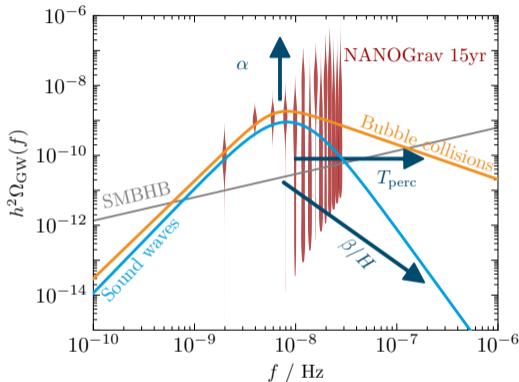
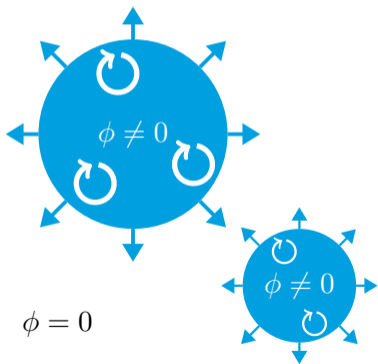
Scientists reveal how black holes come from collisions
The most exciting discovery, scientists say space-time churns like a choppy sea

Gravitational waves produce a background hum across the whole universe
After decades of searching, astronomers have found a distinctive pattern of light, from spinning stars called pulsars, that suggests huge gravitational waves are creating gentle ripples in space-time across the universe

Gravitational waves block our view of the universe
The results are...

Gravitational waves from first-order phase transitions.

Bubbles of the new phase nucleate, collide and perturb the plasma...




... giving rise to a stochastic gravitational wave background which could've been observed already.

Let's put the transition in a dark sector.

Stable dark sector:

The liberated energy leads to an extra Hubble expansion, impacting BBN and the CMB through [Planck '18]

$$\Delta N_{\text{eff}} \gtrsim 6 \times \alpha \quad \text{but:} \quad \Delta N_{\text{eff}} < 0.22$$

A good fit would require super-Hubble bubbles 

Decaying dark sector:

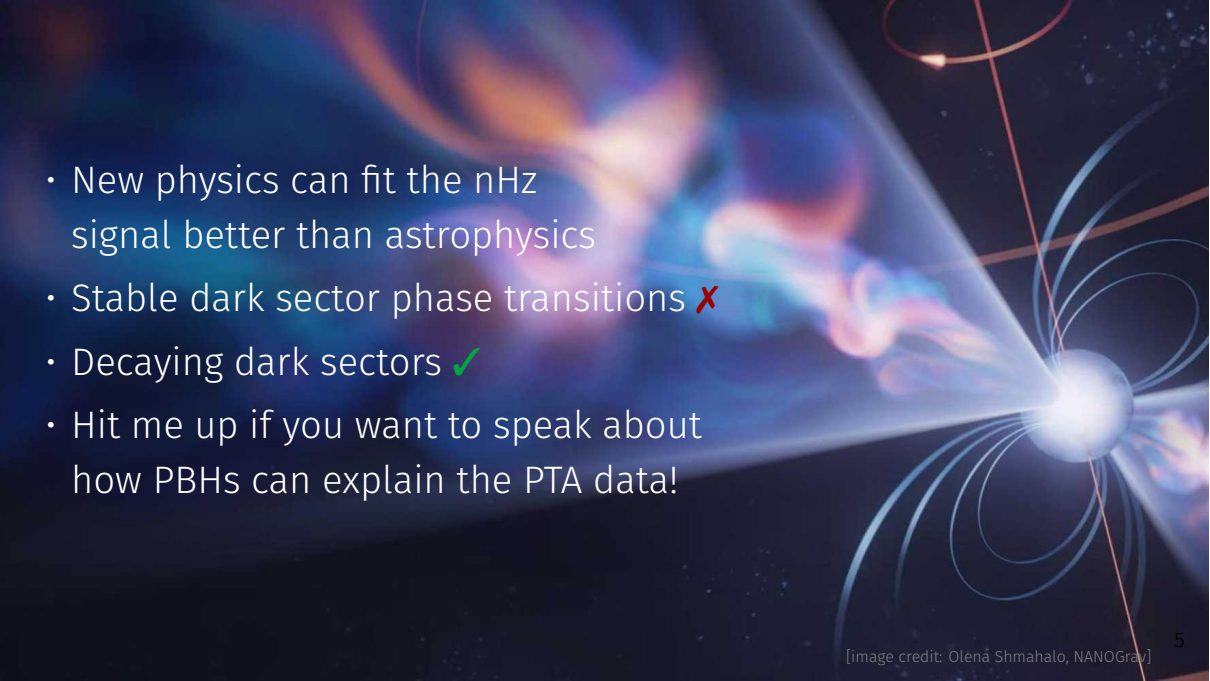
We can circumvent the effect on BBN and the CMB if the dark sector decays quick enough after the phase transition.

We find: [Depta+, 2011.06519]

$$\tau_{\phi} < 0.1 \text{ s}$$



↪ Cries for a global fit!

- 
- New physics can fit the nHz signal better than astrophysics
 - Stable dark sector phase transitions ✗
 - Decaying dark sectors ✓
 - Hit me up if you want to speak about how PBHs can explain the PTA data!

Thanks for your attention!

CLUSTER OF EXCELLENCE
QUANTUM UNIFORMITY

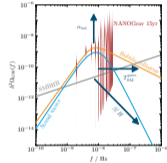
Do pulsar timing arrays observe a dark sector phase transition?

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Fitting the new PTA data with a phase transition

Several pulsar timing arrays observed a gravitational wave background of nano-Hertz frequencies [1, 2], which can be explained by a background of merging supermassive black hole binaries (SMBHs). The predicted SMBH signal amplitude is however too low, motivating alternative explanations, for instance first-order phase transitions in the early Universe [4].



The peak frequency f_{peak} is linked to the signal from the percolation temperature $T_{\text{per}} \sim 30 \text{ MeV}$, being the temperature of the primordial plasma when the phase transition must have happened. This **hints towards a new scalar field** with a corresponding Higgs scale mass. Such a Higgs boson was not yet found at colliders, indicating that the transition instead happened in a dark sector, only feebly coupled to the SM particles.

Cosmological constraints

We differentiate between the following two cases:

- If the dark sector is secluded its energy density is constrained through the primordial element abundances and the cosmic microwave background,

$$\Delta N_{\text{eff}} < 0.22 @ 95\% \text{ CL}$$

A higher value of ΔN_{eff} would indicate a faster expansion of the Universe, changing the production of the early elements and shifting the peaks of the CMB multipole.

- If the dark sector is **not secluded**, decay to SM particles must have happened before the onset of Big Bang Nucleosynthesis. More precisely, the dark sector would need to decay before the neutrinos decoupling at $T \sim 2 \text{ MeV}$ to not interfere with the results of precision cosmology.

Performing a global fit

To make a statistically sound analysis we perform a global fit to show how strong (or how flat) $f(M)$ and when T_{per} the phase transition happens and how good the fit is compared to SMBHs. We construct a global likelihood

$$\mathcal{L}_{\text{global}}(\theta_{\text{PT}}, \theta_{\text{SM}}) = \mathcal{L}_{\text{PT}}(\theta_{\text{PT}} | \theta_{\text{SM}}) \times \mathcal{L}_{\text{SMBH}}(\theta_{\text{SM}} | \theta_{\text{PT}})$$

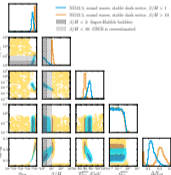
whose global maximum is searched for using Markov Chain Monte Carlo methods. The parameter space we are sampling over is huge, since over 100 pulsar-timing-array parameters θ_{SM} need to be considered next to the few phase transition parameters θ_{PT} .

The secluded dark sector scenario

For arbitrarily slow phase transitions ($f(M) > 1$, ν), a best fit point can be found, which corresponds to a strong phase transition at around 10 MeV temperature and an initially not too dark sector, $\frac{g_{\text{eff}}}{g_{\text{SM}}} = \frac{T_{\text{per}}^4}{T_{\text{dec}}^4} < 6.8$.

The transition can however not be arbitrarily slow. Otherwise, for $f(M) < 1$, bubbles larger than the Hubble sphere would be produced, which is forbidden by causality. Further, only for $f(M) > 10$ the GW signal prediction can be trusted.

We therefore also show contours of the favored parameter space assuming a slightly faster phase transition with $f(M) \sim 10$ (orange), i.e., two distinct realized regions of parameter space maximize $\mathcal{L}_{\text{global}}$. An even stronger phase transition (with correspondingly higher ΔN_{eff}) or no phase transition at all (not shown in plot). In that case the GW signal is absorbed into the pulsar-timing noise.

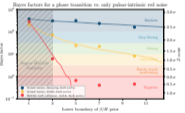


The decaying dark sector scenario

We also construct a global likelihood for the decaying dark sector scenario, assuming that the dark sector thermally decays with the Standard Model particles. We first find that the phase transition can be practically arbitrarily strong, as long as the couplings to the SM particles are large enough to ensure that the **lifetime of the dark Higgs boson does not exceed 0.1 s**. These long dark Higgs lifetimes are still allowed by collider searches.

The evidence for a phase transition explanation

We compare Bayes factors indicating the evidence in favor of a dark sector phase with respect to the alternative hypothesis of only pulsar-timing-array noise explaining the observed GW signal.



We find **decisive evidence for the decaying dark sector scenario**, regardless of the lowest possible $f(M)$ in the prior range (blue curve). For stable dark sectors, the fit is much weaker and decreases fast with an increased exponential speed of the transition. An extra suppression in the GW signal from bubble collisions, a $1/(f(M))$ with respect to second-order models, leads to an even lower likelihood for that scenario, **strongly disfavoring the stable dark sector explanation**.

Note: This analysis was performed using the new outdated NANOGrav 12.5yr data set. We are working on an updated analysis. The central conclusions presented here will hold when using the latest data.

References

- [1] NANOGrav Collaboration, C. Auluck et al., *The NANOGrav 12.5 Year Data Release: An Improved Search for Gravitational Waves*, *Physical Review Letters* **124**, 151101 (2020).
- [2] IPTA, *International Pulsar Timing Array (IPTA) 2019 White Paper*, *International Journal of Pulsar Timing* **1**, 1 (2019).
- [3] S. J. Taylor et al., *Search for Anomalous Gravitational-wave Backgrounds with the International Pulsar Timing Array*, *Astronomy & Astrophysics* **551**, A106 (2013).
- [4] T. Bringmann, P. F. Depts, T. Konstandin, K. Schmidt-Hoberg, and C. Taubold, *Dark Sector Phase Transitions and Gravitational Waves*, *Physical Review D* **102**, 023511 (2020).



<https://fig.uni-hamburg.de>

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I'm looking forward to your questions!

