Do pulsar timing arrays observe a dark sector phase transition?

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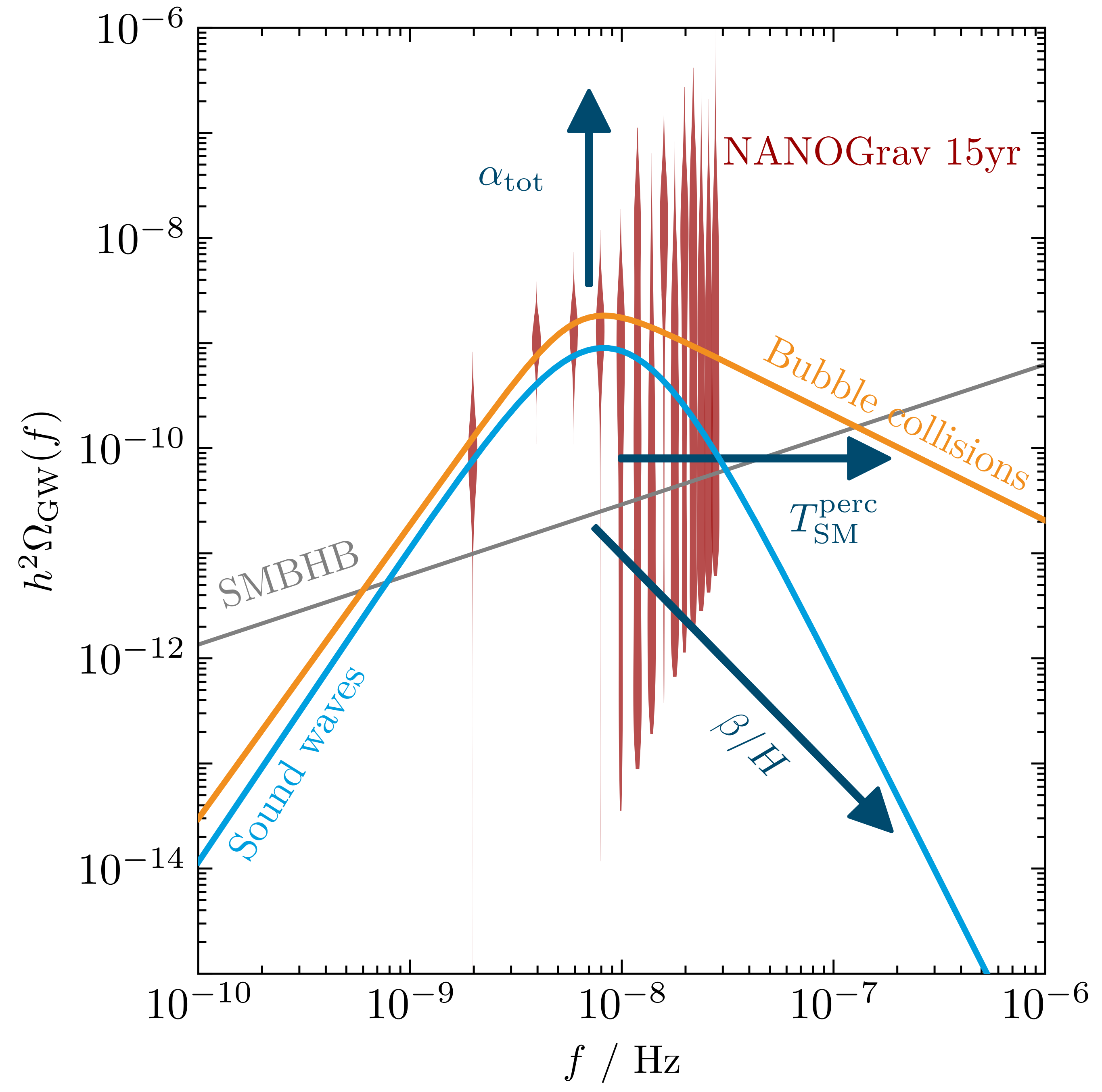
Fitting the new PTA data with a phase transition.

Several pulsar timing arrays observed a gravitational wave background at nano-Hertz frequencies [1-3], which can be explained by a background of merging supermassive black hole binaries (SMBHBs). The predicted SMBHB signal amplitude is however too low, motivating alternative explanations, for instance first-order phase transitions in the early Universe [4].



The peak frequency $f \simeq 10\,\mathrm{nHz}$ of the signal fixes the percolation temperature $T_{\mathrm{perc}} \simeq 10\,\mathrm{MeV}$, fixing the temperature of the primordial plasma when the phase transition must have happened. This **hints towards a new scalar field** with a corresponding MeV-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,

  $$\Delta N_{\mathrm{eff}} < 0.22 \quad \text{at 95\% C.L.}$$

  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 multipoles.
- If the dark sector is instead unstable, decays to SM particles must have happened before the onset of Big Bang Nucleosynthesis. More precisely, the dark sector would need to decay before the neutrino decoupling at $T \simeq 2\,\mathrm{MeV}$ 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 (α), how fast (β/H) and when (T_{perc}) the phase transition happened and how good the fit is compared to SMBHBs. We construct a global likelihood,

$$\mathcal{L}_{\mathrm{glob}}(\vec{\theta}_{\mathrm{PSR}}, \vec{\theta}_{\mathrm{PT}}) = \mathcal{L}_{\mathrm{PTA}}(\vec{\theta}_{\mathrm{PSR}}, \vec{\theta}_{\mathrm{PT}}) \times \mathcal{L}_{\mathrm{cosmo}}(\Delta N_{\mathrm{eff}}(\vec{\theta}_{\mathrm{PT}}))$$

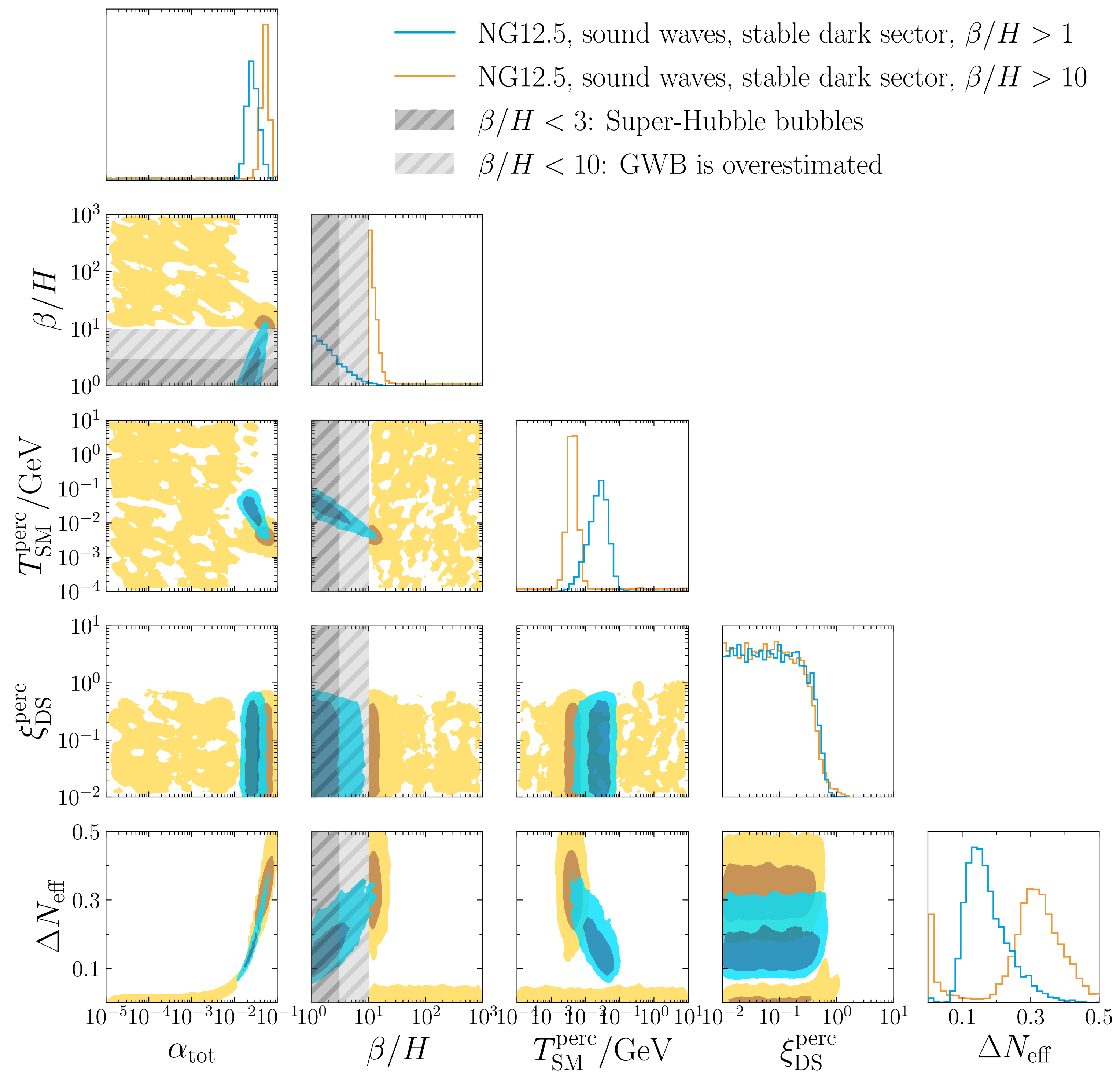
whose global maximum is searched for using Markov chain Monte Carlo methods. The parameter space we are sampling over is huge, since over 100 pulsar-intrinsic noise parameters $\vec{\theta}_{\mathrm{PSR}}$ need to be considered next to the few phase transition parameters $\vec{\theta}_{\mathrm{PT}}$.

The secluded datk sector scenario.

For arbitrarily slow phase transitions ($\beta/H > 1$, cyan), a best-fit point can be found, which corresponds to a strong phase transition at around 10 MeV temperatures and an initially not too hot dark sector, $\xi_{\mathrm{DS}}^{\mathrm{perc}} \equiv T_{\mathrm{DS}}^{\mathrm{perc}}/T_{\mathrm{SM}}^{\mathrm{perc}} < 0.8$.

The transition can however not be arbitrarily slow. Otherwise, for $\beta/H < 3$, bubbles larger than the Hubble sphere would be produced, which is forbidden by causality. Further, only for $\beta/H > 10$ the GW signal prediction can be trusted.

We therefore also show contours of the favored parameter spaces assuming a slightly faster phase transition with $\beta/H > 10$ (orange). Here, two distinct maximal regions of parameter space maximise $\mathcal{L}_{\mathrm{glob}}$: An even stronger phase transition (with correspondingly higher ΔN_{eff}), or no phase transition at all (shot noise in plot). In that case the GW signal is absorbed into the pulsar-intrinsinc noise.

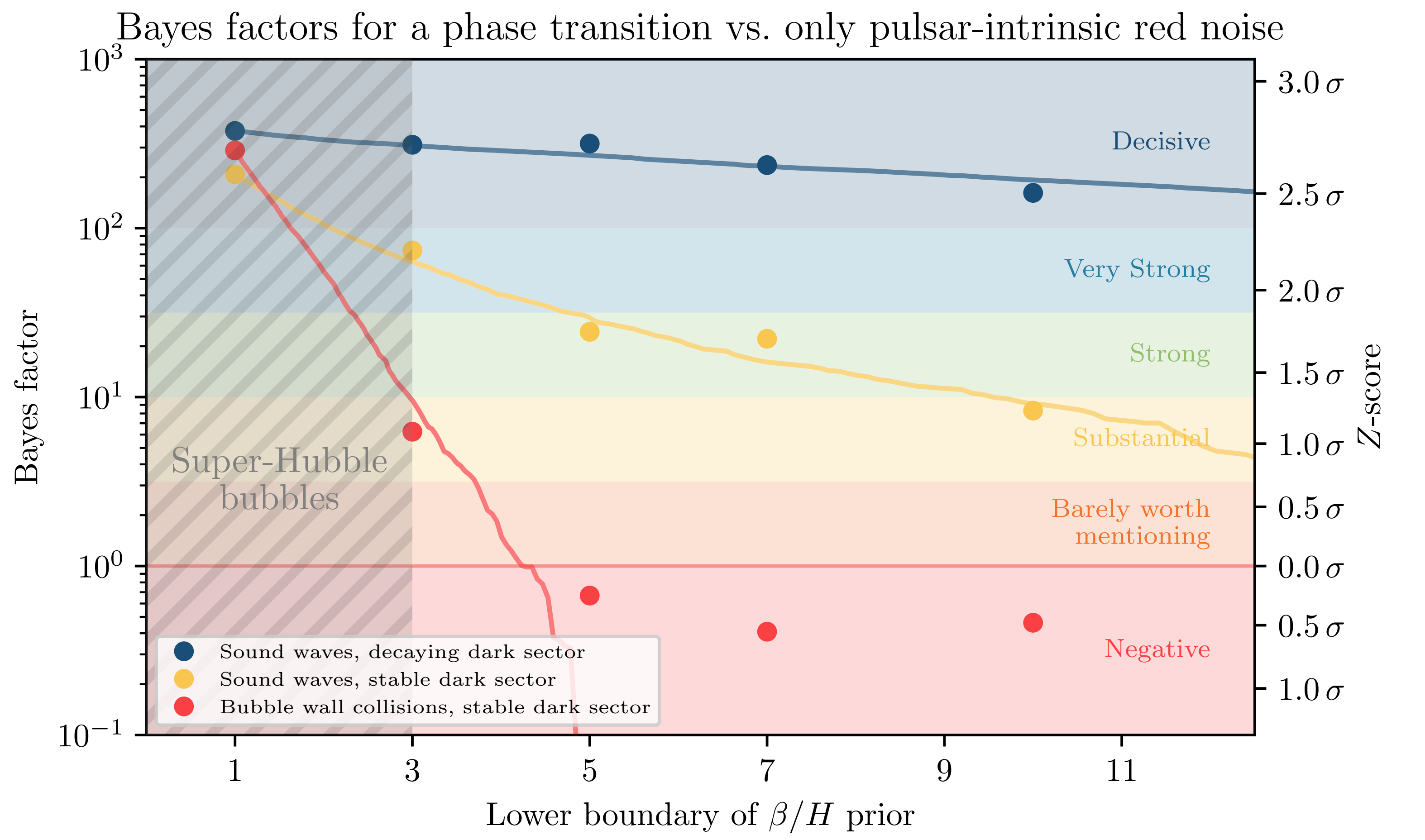


The decaying dark sector scenario.

We also construct a global likelihood for the decaying dark sector scenario, assuming that the dark scalar thermalizes with the Standard Model particles. We 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 compute Bayes factors indicating the evidence in favor of a dark sector phase with respect to the alternative hypothesis of only pulsar-intrinsic noise explaining the observed GW signal.



We find decisive evidence for the decaying dark sector scenario, regardless of the lowest possible β/H in the prior range (blue curve). For stable dark sectors, the fit is much worse and decreases fast with an increased imposed minimal speed of the transition. An extra suppression in the GW signal from bubble collisions $\propto 1/(\beta/H)$ with respect to sound waves leads to an even lower likelihood for that scenario, strongly disfavoring the stable dark sector explanation.

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

References.

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[3] D. J. Reardon et al., *Search for an Isotropic Gravitational-wave Background with the Parkes Pulsar Timing Array*, *Astrophys. J. Lett.* **951** (2023), no. 1 L6, [`2306.16215`].

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