Exploring new physics with pulsar timing arrays: dark sector phase transitions and clustered primordial black holes.

Seminar talk at Fermilab

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Based on work with Torsten Bringmann, Paul Frederik Depta, Thomas Konstandin, Kai Schmidt-Hoberg and Pedro Schwaller

arXiv: [2306.09411], [2306.17836]

October 12, 2023

Outline of this talk.

1. The PTA signal
2. The null hypothesis: astrophysics
3. Phase transitions vs. precision cosmology
4. Primordial black holes
5. BSM or boring?

[DALL-E's interpretation of this talk's buzzwords]

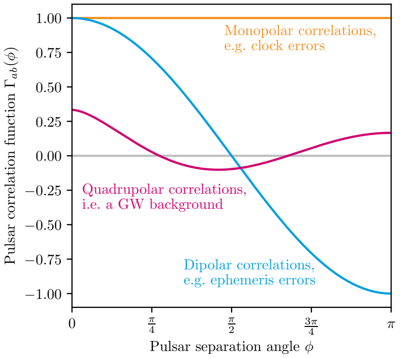
In case you haven’t heard the news.

Pulsar timing arrays.

Millisecond pulsars emit radio pulses with an extremely stable frequency

- GWs affect propagation time ⇝ change observed pulse frequency
- PTAs monitor pulse frequency using radio telescopes on Earth
- Fit pulse data with timing model
- Fourier decomposition of timing residuals shows “**red noise**”, which **can be due to GWs**

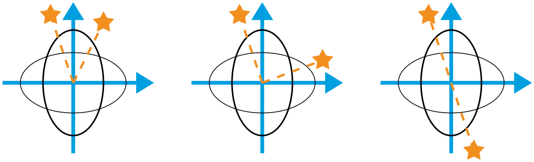
How can we be sure it's actually gravitational waves?



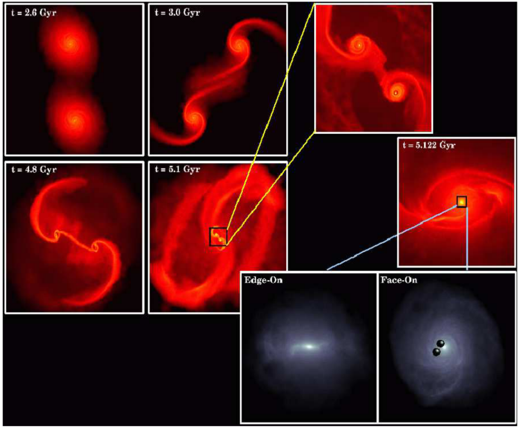
Red noise spectra can have many sources:

- Pulsars: no common red noise, $\mathcal{B} < 10^{-12}$
- Clock errors: monopole, $\mathcal{B} < 10^{-8}$
- Ephemeris errors: dipole, $\mathcal{B} < 10^{-7}$
- GWs: Hellings-Downs curve, $\mathcal{B} = 200 - 1000$

$\rightsquigarrow$ **Decisive evidence for GWs!** 🥳



Merging supermassive black hole binaries.



[Mayer et al., 0706.1562; NASA/CXC/A. Hobart]

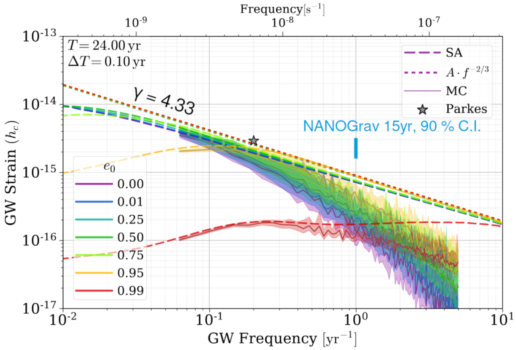
- Expect **supermassive black hole mergers** after galaxy mergers
- Galaxy mergers are messy
- The resulting GW predictions span several orders of magnitude, but can be well described by a power law with amplitude A and slope γ:

$$h_c(f) \propto A\, f^{\frac{3-\gamma}{2}}$$

$$\rightsquigarrow \quad \Omega_{GW}(f) \propto A^2\, f^{5-\gamma}$$

GW background from supermassive black hole binaries.

- If the only energy loss shrinking binary orbit is through GWs: $\gamma = 4.33$
- Astrophysical simulations for realistic BH populations: deviations from $\gamma = 4.33$, $A \simeq 10^{-16\,\ldots\,-15}$

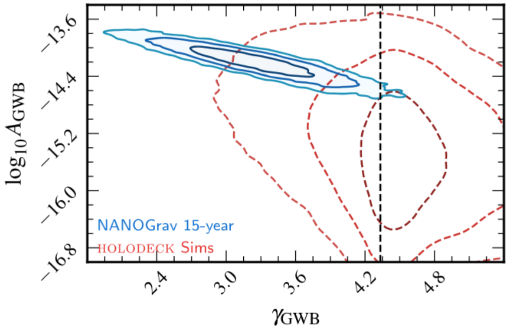


[Kelley et al., 1702.02180]

GW background from supermassive black hole binaries.

- If the only energy loss shrinking binary orbit is through GWs: $\gamma = 4.33$
- Astrophysical simulations for realistic BH populations: deviations from $\gamma = 4.33,\ A \simeq 10^{-16\,\ldots\,-15}$
- But: observed GW spectrum indicates lower γ and larger A?!

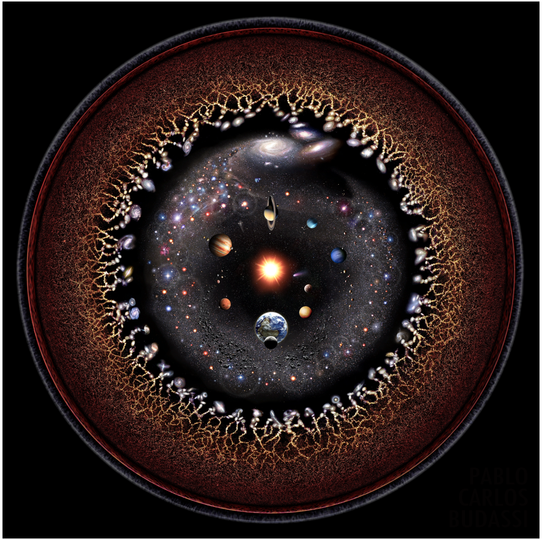
What other signal sources are thinkable?



[NANOGrav collaboration, 2023]

What do we know about the early Universe?

What we know about our Universe.

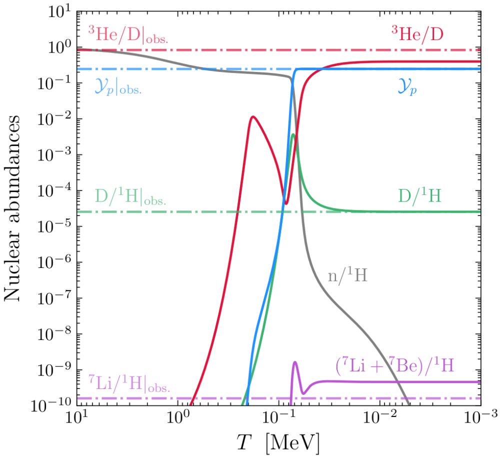


[Pablo Carlos Budassi, 2020]

LCDM:

- 95 % of ρ_{tot} is dark!?
- Not probed above MeV (= billion Kelvin) temperatures...

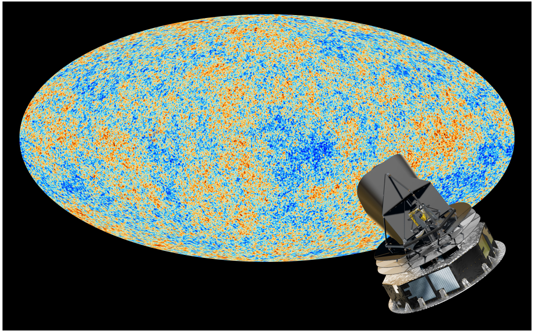
The Big Bang Nucleosynthesis and the CMB.



[Paul Frederik Depta, 2021]

- Observations of primordial light element abundances in good agreement with standard BBN
- $N_{\rm eff}^{\rm BBN} = 2.898 \pm 0.141$ [Yeh, 2207.13133]

The Big Bang Nucleosynthesis and the CMB.



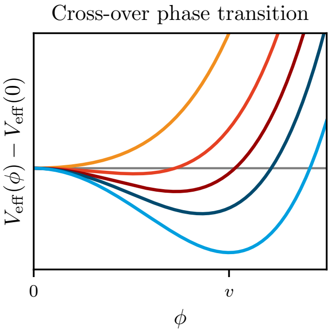
[ESA and the Planck Collaboration, D. Ducros]

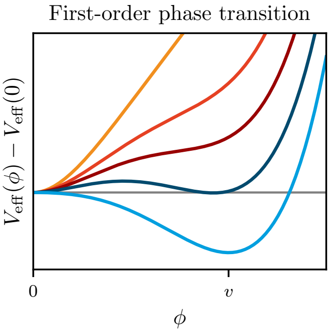
- Observations of primordial light element abundances in good agreement with standard BBN
- $N_{\text{eff}}^{\text{BBN}} = 2.898 \pm 0.141$ [Yeh, 2207.13133]
- $N_{\text{eff}}^{\text{CMB}} = 2.99 \pm 0.17$ [Planck, 1807.06209]
- Consistent with $N_{\text{eff}}^{\text{SM}} = 3.044$ from 3 ν generations [Bennet, 2012.02726v3]

⇝ Thermalized BSM species after BBN are ruled out. But we have no constraints before that.

Gravitational waves from dark sector phase transitions.

Cross-over and first-order phase transitions.



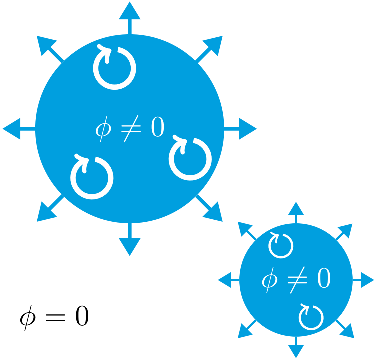


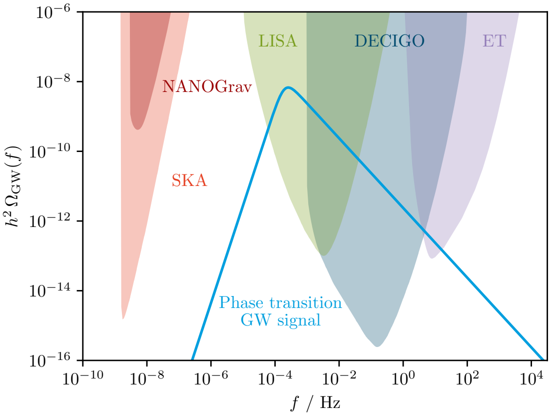
A scalar field "rolls down" from $\phi = 0$ to $\phi = v$, when the bath cools from high temperatures to low temperatures.

A scalar field tunnels to the true potential minimum ($\phi \neq 0$) to minimize its action ($\sim$ free energy).

Gravitational waves from first-order phase transitions.

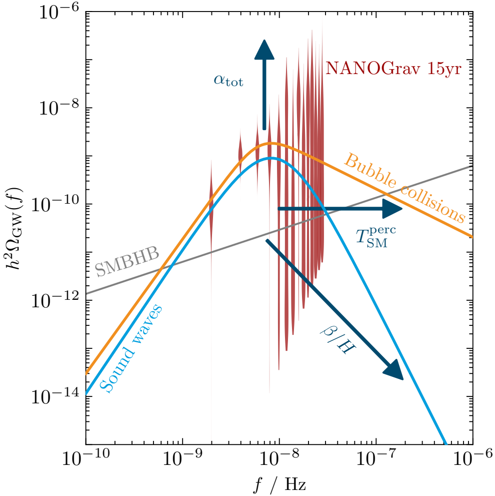
Bubbles of the new phase nucleate, collide and perturb the plasma...





... giving rise to a stochastic gravitational wave background which can be observed.

Parametrization of the GW signal.



[SMBHB: $A = 10^{-15.5}$, $\gamma = 13/3$]

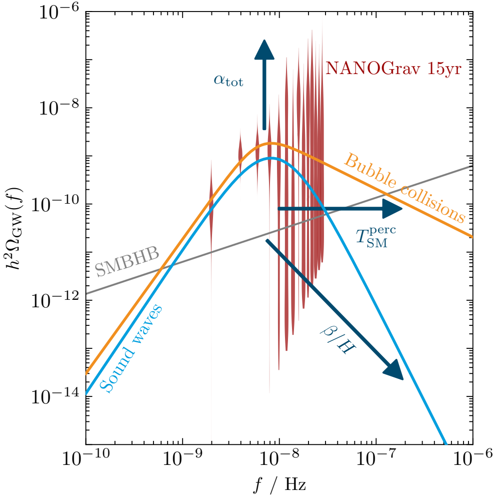
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

with $f_{\rm peak} \simeq 0.1\,\text{nHz} \times \frac{\beta}{H} \times \frac{T}{\text{MeV}}$

To fit the new pulsar timing data:

- Strong transitions, $\alpha \simeq \frac{\Delta V}{\rho_{\rm tot}} \approx 1$
- Slow transitions, $\beta/H \approx 10$
- Percolation around $T \approx 10\,\text{MeV}$

Parametrization of the GW signal.



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But there's no SM phase transition at 10 MeV?!

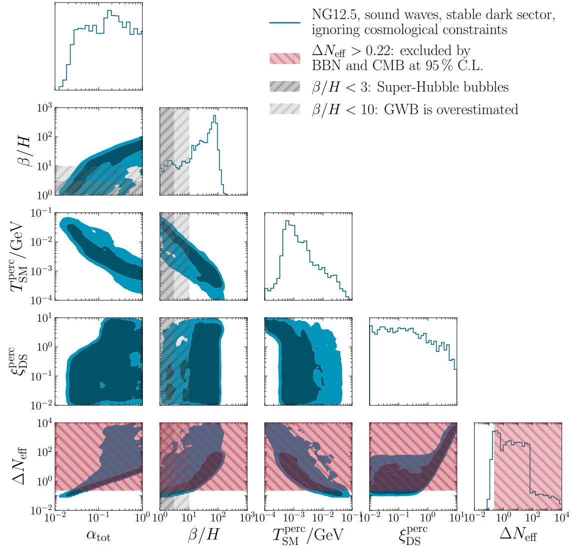
Let's put the transition in a dark sector.

- Dark sector temperature ratio is crucial, $T_{\text{DS}} = \xi_{\text{DS}}\, T_{\text{SM}}$ [Breitbach, 1811.11175]
- Potential dilution of the GW signal due to changed redshift history [CT, 2109.06208]
- **Stable dark sector:** additional DS energy density accelerates expansion and changes early element abundances and CMB anisotropies through

$$\Delta N_{\text{eff}} \approx 6 \times \left(\alpha_{\text{tot}} + \frac{1+\alpha_{\text{tot}}}{10}\left(\xi_{\text{DS}}^{\text{perc}}\right)^4\right), \quad \Delta N_{\text{eff}} < 0.22 \text{ @}95\,\% \text{ C.L.}$$

- **Decaying dark sector:** Energy transfer to the SM plasma, changing element abundances and CMB anisotropies. Constraints require $\tau < 0.1$ s. [Depta, 2011.06519]

The tension between PTAs, CMB and BBN.

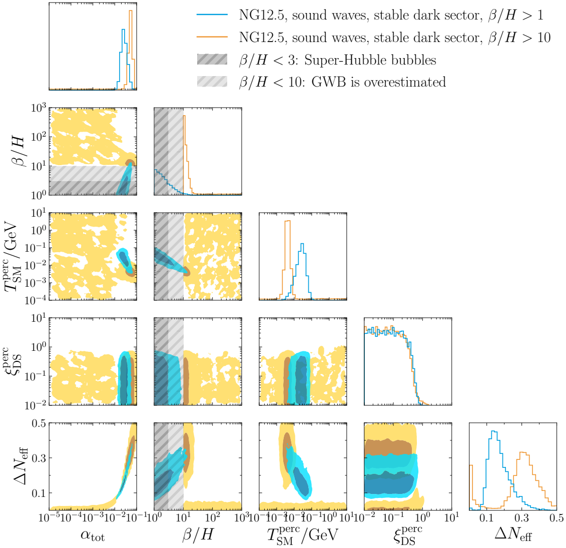


- Performed fit of the pulsar data with NANOGrav's own code `enterprise`
- A good fit requires an enormous reheating of the dark sector: $\Delta N_{\rm eff}$ can grow arbitrarily large
- Bubble sizes would need to be super-Hubble to be okay with $\Delta N_{\rm eff}$

  Causality   GW prediction

⇝ The tension cries for a global fit

Global fits kill stable dark sectors.



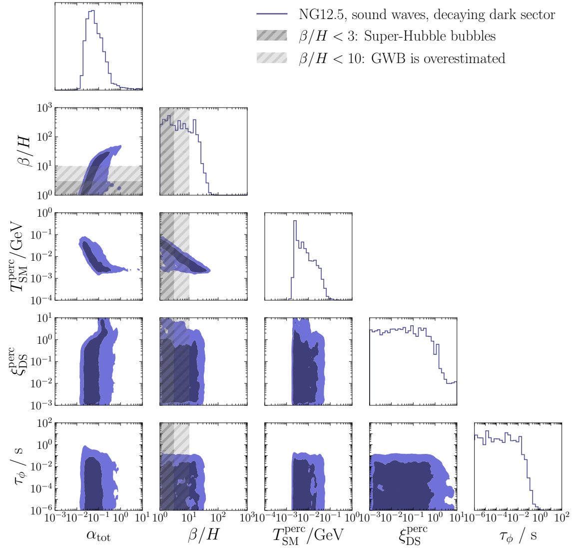
Global fit = compute global maximum of

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

Find:

- $\beta/H > 1$: would be a good fit, if the GW spectrum were reliable
- $\beta/H > 10$: not having a phase transition is better than violating BBN and CMB bounds!

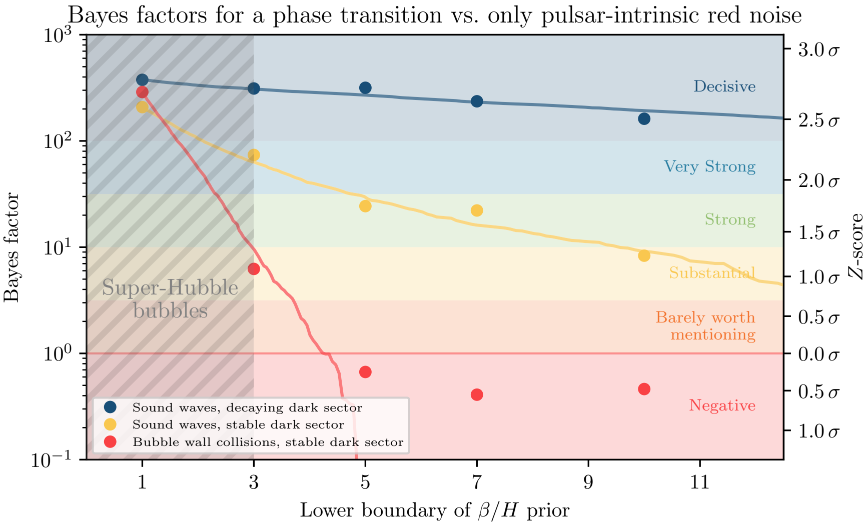
Decays to the rescue.



Decays save the fit!

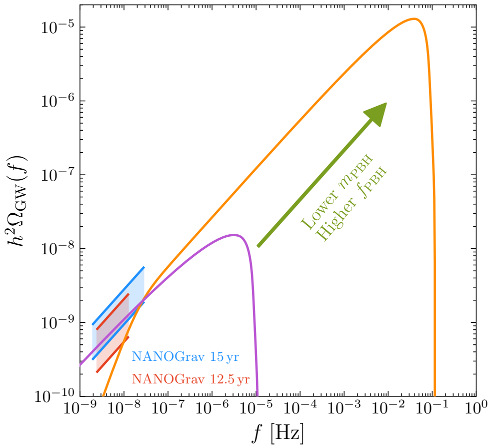
They only need to happen before neutrino decoupling, $T_{\mathsf{SM}} \gtrsim 2\,\mathsf{MeV}$, corresponding to fast decays, $\tau \lesssim 0.1\,\mathsf{s}$.

The evidence for a dark sector phase transition.



Merging primordial black holes.

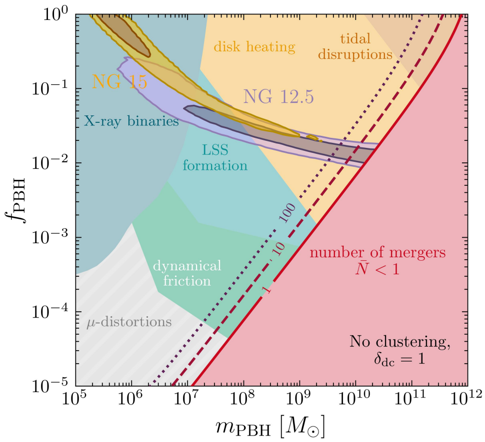
Gravitational waves from primordial black hole mergers.



- Inflation leaves large super-Hubble density perturbations
- Black holes form when these come into causal contact again, long before the death of the first stars

$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_{\mathrm{crit}}} \int_0^{t_0} \mathrm{d}t \left[R(t) \frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}f_{\mathrm{r}}} \right] \Bigg|_{f_r=(1+z)f}$$

PBHs without clustering cannot explain the PTA data.



[CT et al., 2023]

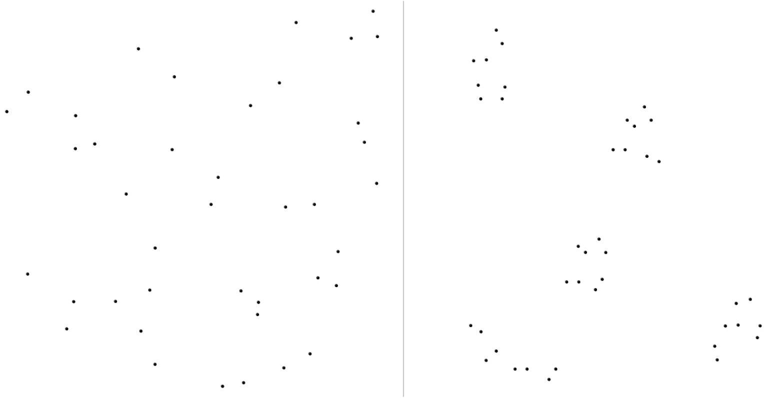
- Scan over $m_{\rm PBH}$ and $f_{\rm PBH}$
- Region favored by PTAs is excluded by astrophysical bounds
- Crucial: exclude regions with small merger numbers. (Atal et al. came to the wrong conclusion [2012.14721].)

Homogeneously distributed PBHs cannot explain the PTA data!

What is clustering?

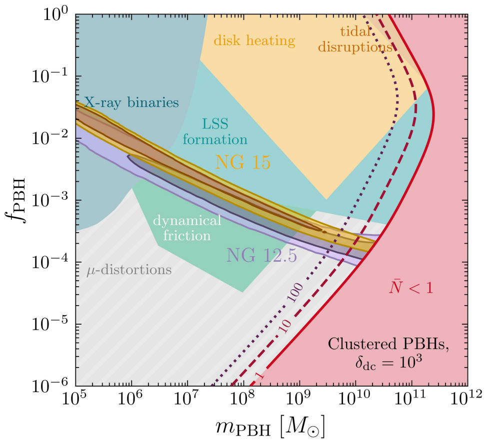
$\delta_{\mathrm{dc}} = 1$: Poisson-distributed PBHs

$\delta_{\mathrm{dc}} = 1 + \frac{\delta n^{\mathrm{loc}}_{\mathrm{PBH}}}{\bar{n}_{\mathrm{PBH}}} \gg 1$: Clustering



[Paul Frederik Depta, 2023]

Clustered PBHs can explain the PTA data.

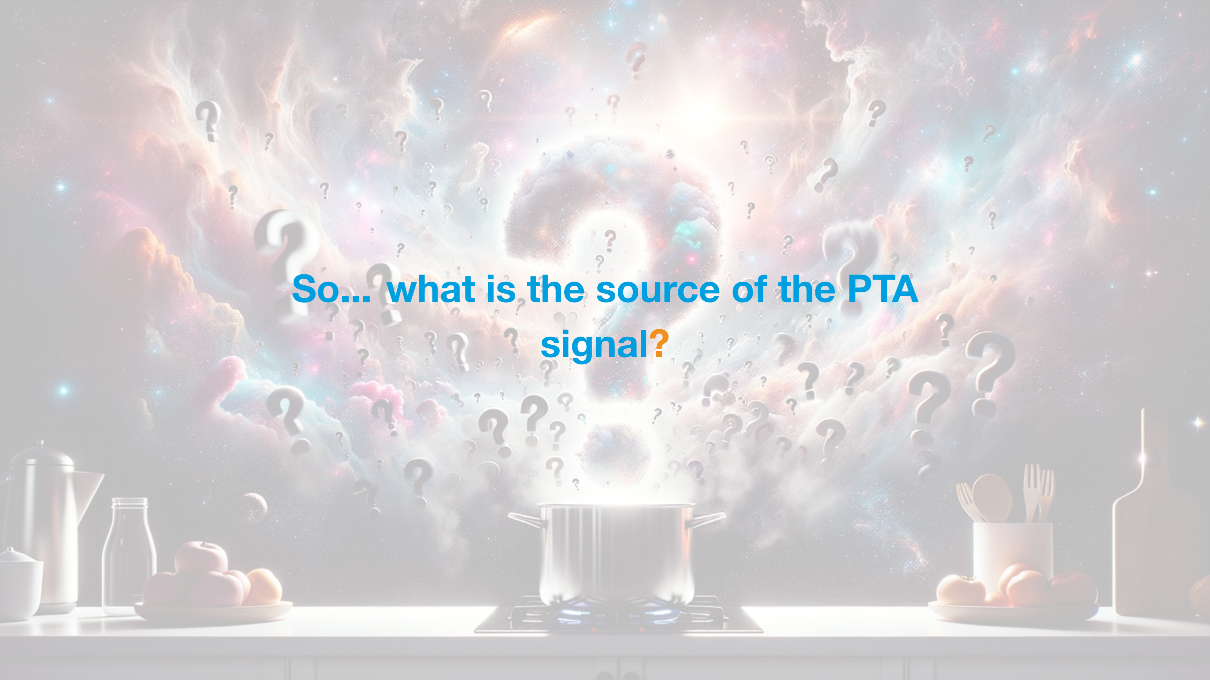


[CT et al., 2023]

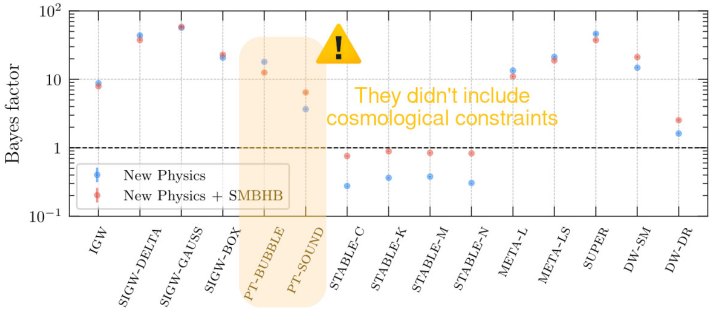
- Clustering increases the merger rates, requiring less PBHs to explain the signal: smaller $f_{\rm PBH}$
- Astrophysical bounds are dubious
- Aurora, Albert, Dan and Gordan say that μ-distortions can be circumvented [2308.00756]

Clustered PBHs can explain the PTA data!

So... what is the source of the PTA signal?



The evidence for new physics.

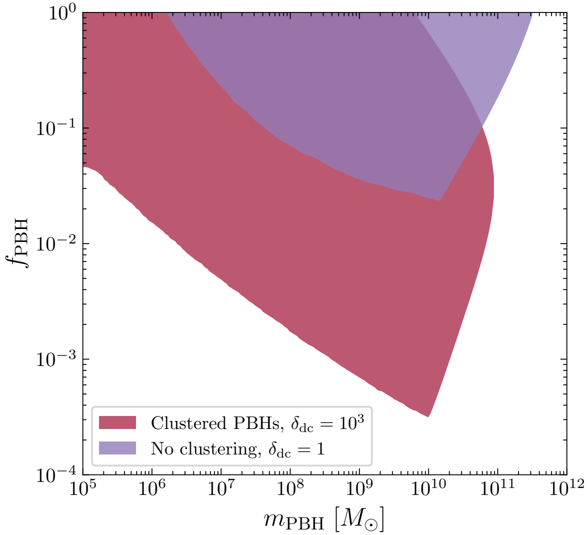


[NANOGrav collaboration, 2023]

- New physics matches spectra better
- BSM + SMBHB has highest Bayes factors
- We should perform global fits, including constraints & open astrophysical parameters

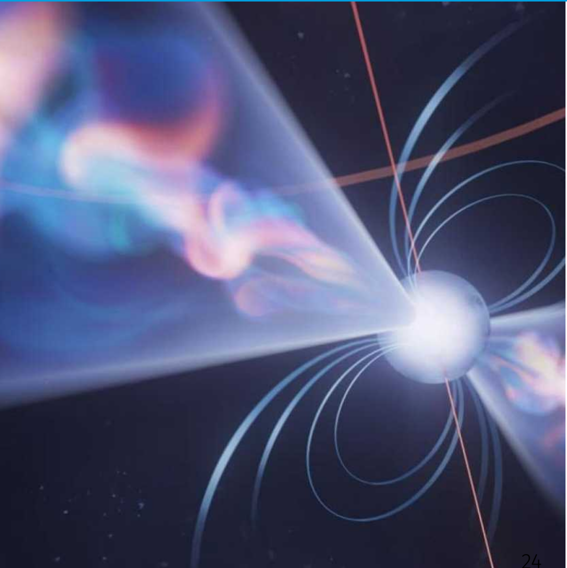
Still: As soon as a single merger or strong anisotropy is found in the data, all cosmological explanations will be dead.

In any case: we can derive cool new bounds.



Take-home messages.

- We are for the first time able to probe the early Universe before BBN!
- Stable dark sector phase transition explanations for PTA data are in tension with precision cosmology.
- Decaying dark sectors are a viable option and can compete with SMBHBs.
- New constraints on PBHs
- Merging primordial black holes need to be clustered: Stay tuned!



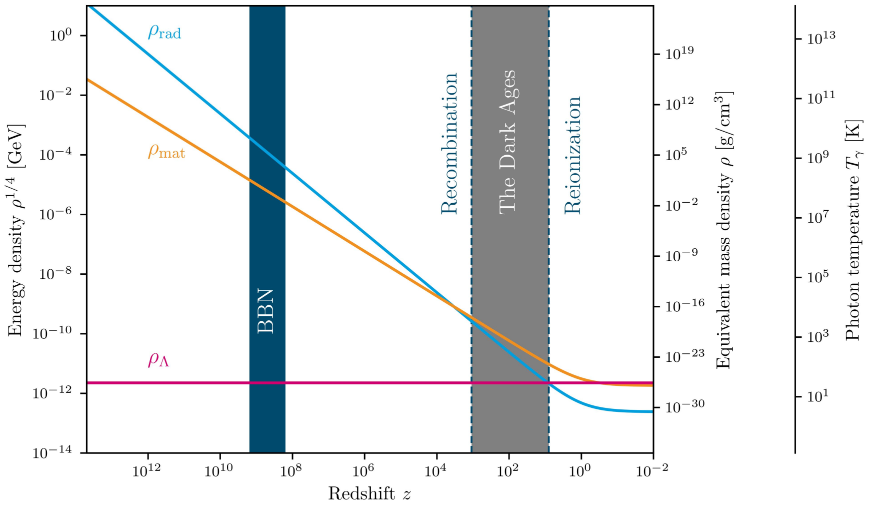
[image credit: Olena Shmahalo, NANOGrav]

Thank you very much for your attention!

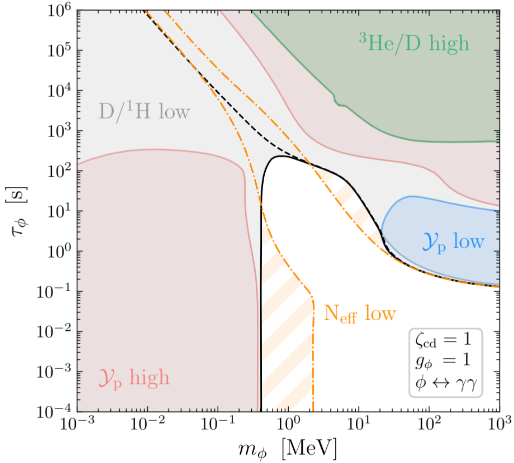
Do you have any questions?

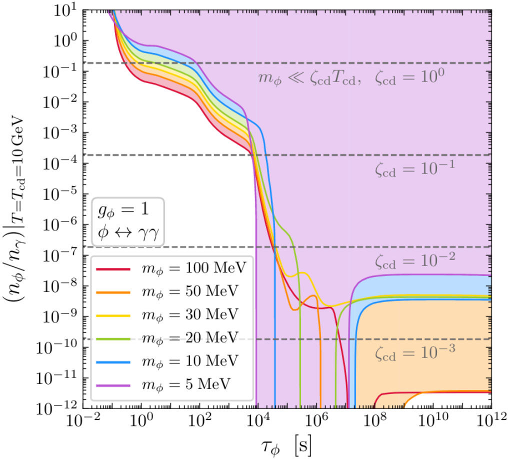
Backup slides.

A brief history of time: LCDM.



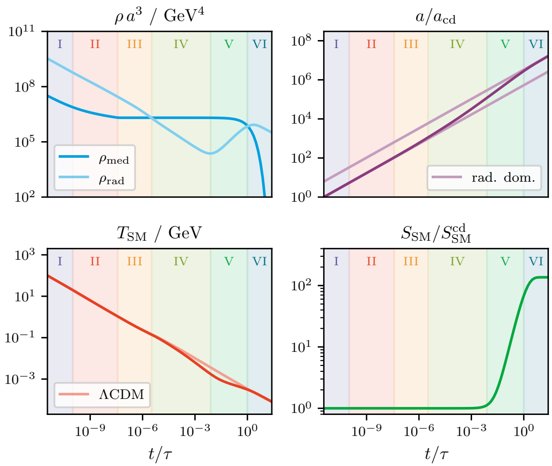
Electromagnetic scalar decays at MeV temperatures.





[Depta et al., JCAP 04 (2021) 011]

The out-of-equilibrium decay of a dark mediator.



Energy densities $\rho_i(t)$ $\overset{\text{sets}}{\rightsquigarrow}$ Scale factor $a(t)$ $\overset{\text{sets}}{\rightsquigarrow}$ Temperatures $T_{\mathsf{SM/DS}}(t)$ $\overset{\text{set}}{\rightsquigarrow}$ Particle content $\overset{\text{sets}}{\rightsquigarrow}$ $\rho_i(t)$ $\overset{\text{sets}}{\rightsquigarrow}$ ...

Six phases:

I Relativistic mediator

II Cannibalistic mediator

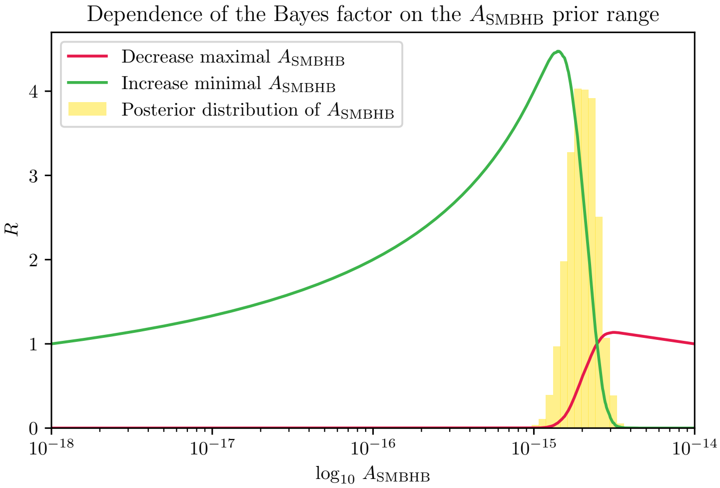
III Non-relativistic mediator

IV Early matter domination

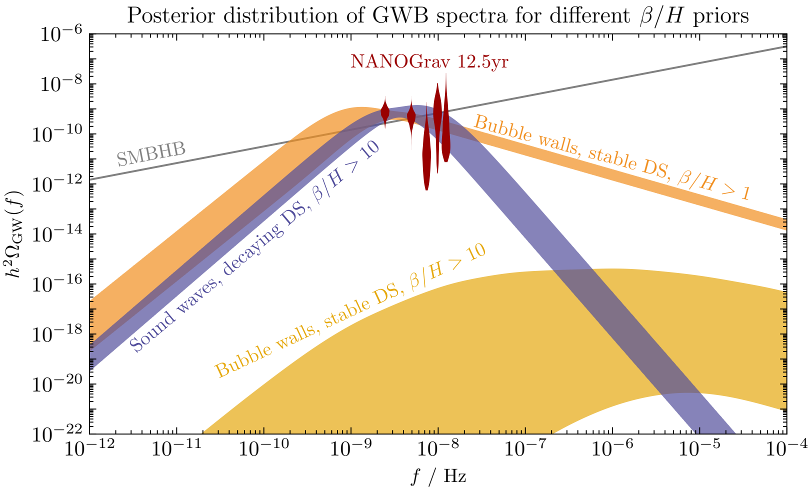
V Entropy injection

VI Mediator decay

How the choice of priors changes a Bayes factor.



Why violins shouldn't be used for fits including cosmological constraints.



How the density contrast increases the merger rate

$$\Omega_{\mathsf{GW}}(f) = \frac{f}{\rho_{\mathsf{crit}}} \int_0^{t_0} \mathrm{d}t \left[R(t) \, \frac{\mathrm{d}E_{\mathsf{GW}}}{\mathrm{d}f_{\mathsf{r}}} \right] \Bigg|_{f_r=(1+z)f}$$

$$R(t) = \int_0^{\tilde{x}} \mathrm{d}x \int_x^{\infty} \mathrm{d}y \frac{\partial^2 n_3}{\partial x \, \partial y} \delta(t - \tau(x,y))$$

$$\propto \frac{\delta_{\mathrm{dc}}{}^{16/37}}{\tilde{x}^3 \tilde{\tau}} \left(\frac{t}{\tilde{\tau}}\right)^{-34/37} \left(\Gamma\left[\frac{58}{37}, \frac{4\pi}{3}\tilde{x}^3 \delta_{\mathrm{dc}} n_{\mathrm{PBH}} \left(\frac{t}{\tilde{\tau}}\right)^{3/16}\right] - \Gamma\left[\frac{58}{37}, \frac{4\pi}{3}\tilde{x}^3 \delta_{\mathrm{dc}} n_{\mathrm{PBH}} \left(\frac{t}{\tilde{\tau}}\right)^{-1/7}\right] \right)$$

With:

- $\delta_{\mathrm{dc}} \simeq \frac{n^{\mathsf{loc}}_{\mathsf{PBH}}}{\bar{n}^{\mathsf{loc}}_{\mathsf{PBH}}}$: Density contrast
- x, (y): comoving distance of (next-to-) nearest neighbor PBH
- $\tilde{x}$: farthest comoving distance two PBHs can have
- $\tilde{\tau}$: Merger timescale