Exploring new physics with pulsar timing arrays.

Colloquium at Karlsruhe Institute of Technology

Carlo Tasillo,
Deutsches Elektronen Synchrotron (DESY)

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

JCAP 11 (2023) 053 and [2306.17836]

June 26, 2024

Outline of this talk.

1. The PTA signal
2. Phase transitions vs. precision cosmology
3. Clustered PBHs
4. BSM or boring?

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

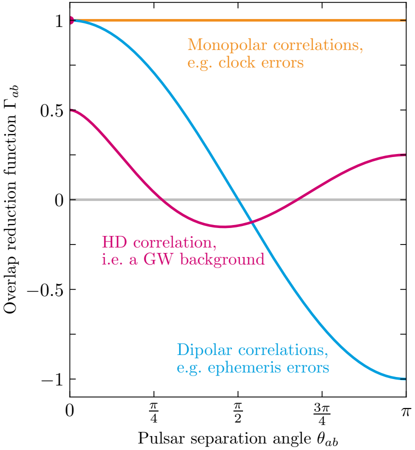
In case you haven't heard the news.

Pulsar timing arrays.

Millisecond pulsars emit radio pulses with an extremely stable frequency

- GWs affect propagation time ⇝ modulate observed pulse frequency
- PTAs monitor pulse frequency using radio telescopes on Earth
- Fit pulse data with timing model
- Fourier decomposition of timing residuals shows **common spectrum**, which is **due to GWs**

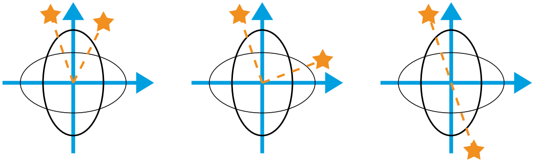
How can we be sure it's actually gravitational waves?



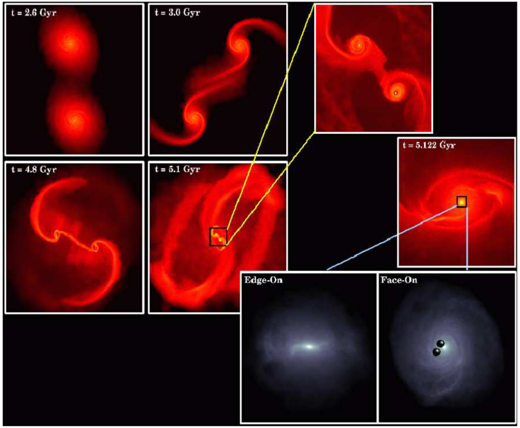
Noise spectra can have many sources:

- Pulsars: no common 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.



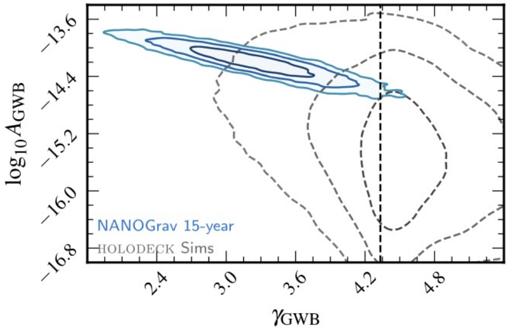
[Mayer et al., 0706.1562; NASA/CXC/A. Hobart]

- Expect **supermassive black hole mergers** after galaxy mergers
- Predictions are hard to obtain (distance hierarchies, extreme environments, final pc problem, ...)
- GW predictions span several orders of magnitude, but approximately follow a power-law with $\gamma = 4.\overline{3}$

$$h_c(f) \propto A\, f^{\frac{3-\gamma}{2}} \Leftrightarrow \Omega_{\mathrm{GW}}(f) \propto A^2 f^{5-\gamma}$$

GW background from supermassive black hole binaries.

- The observed GW spectrum is consistent with a power-law of amplitude A and slope γ

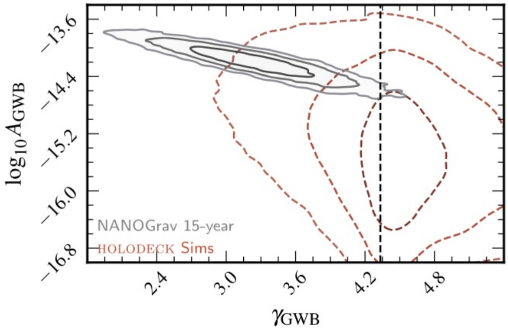


[NANOGrav collaboration, 2023]

GW background from supermassive black hole binaries.

- The observed GW spectrum is consistent with a power-law of amplitude A and slope γ
- But: Astrophysical simulations based on realistic BH populations predict much weaker signals with higher γ

The standard explanation is off! Other signal sources?

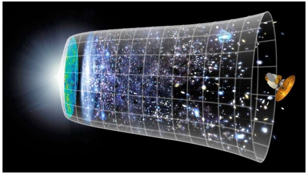


[NANOGrav collaboration, 2023]

Possible cosmological sources of the nHz background.

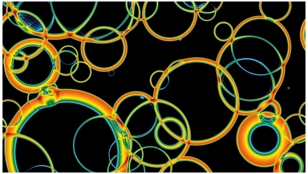
Inflation

Reentering of tensor fluctuations



Phase transitions

Connection to dark matter?

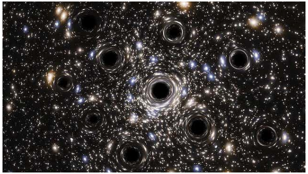


Topological defects

Cosmic strings and domain walls

Primordial black holes

But only if they are clustered…



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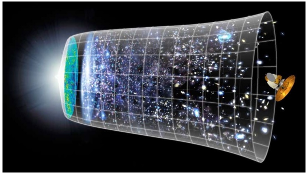

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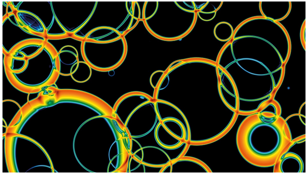

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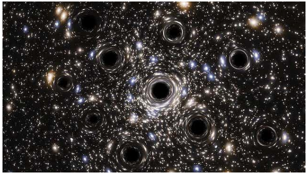
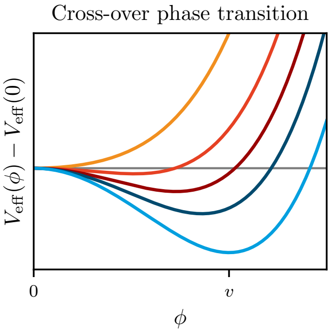
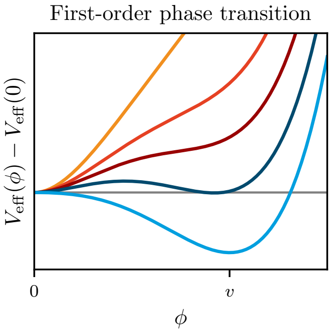


Gravitational waves from dark sector phase transitions.

Cosmological phase transitions.



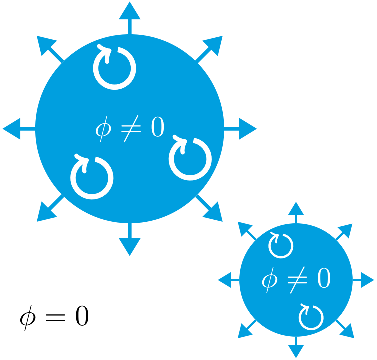


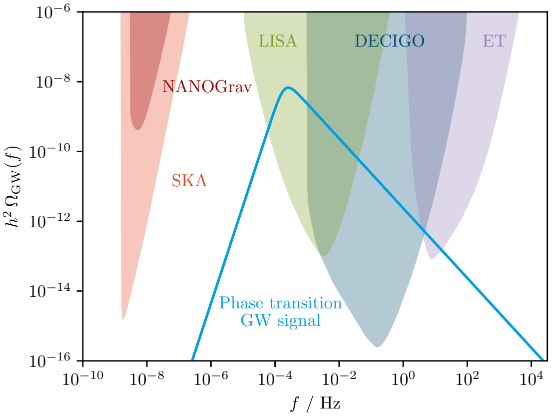
A scalar field “rolls down” from $\phi = 0$ to $\phi = v$, when the bath cools from high temperatures to low temperatures.

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.

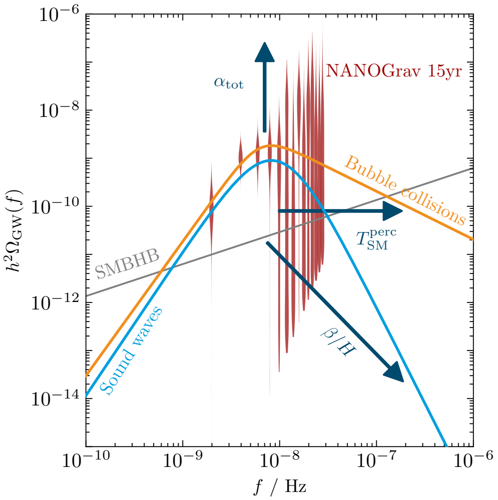
Bubbles of the new phase nucleate, collide and perturb the plasma...





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

Parametrization of the GW signal.



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

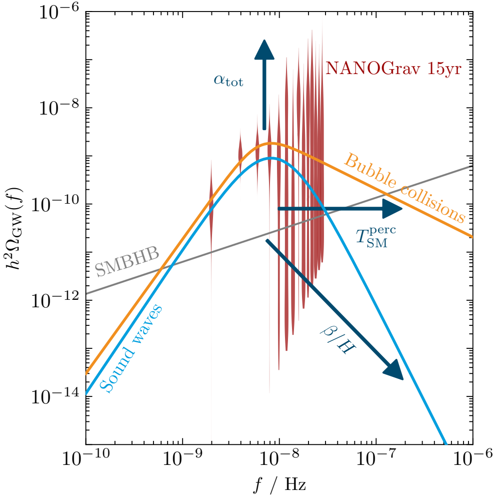
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

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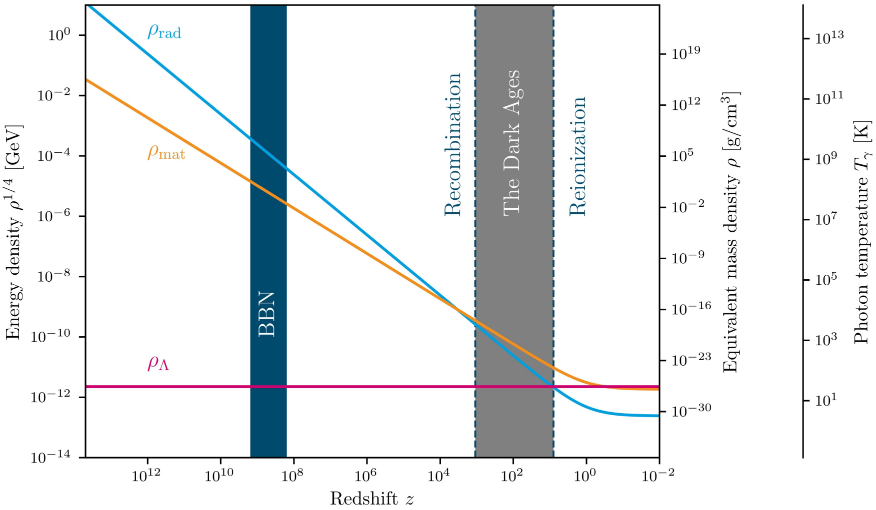
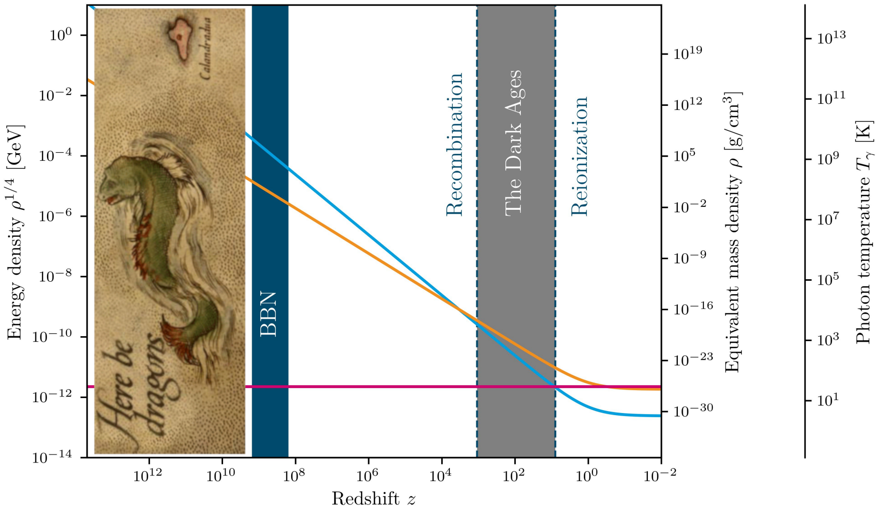
But there's no SM phase transition at 10 MeV?!

What do we know about the early Universe?

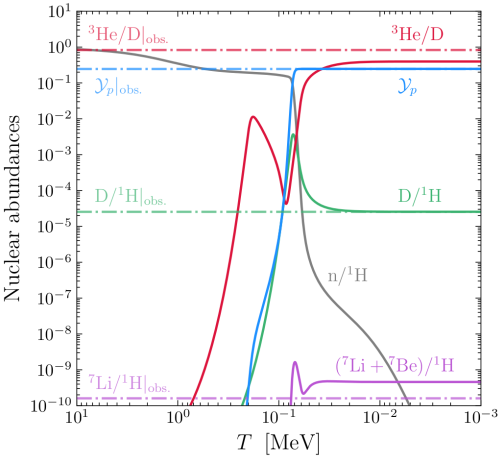
A brief history of time.



A brief history of time.



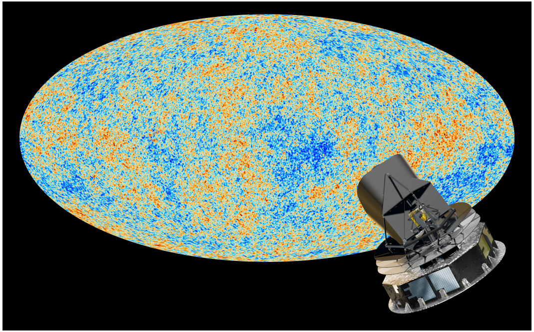
The Big Bang Nucleosynthesis and the CMB.



[Paul Frederik Depta, 2021]

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

The Big Bang Nucleosynthesis and the CMB.



[ESA and the Planck Collaboration, D. Ducros]

- Observations of primordial light element abundances in excellent 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+, 2012.02726]

⇝ Thermalized BSM species at $T \lesssim 1\,\text{MeV}$ are ruled out. Before that: no constraints.

Let's put the transition in a dark sector.

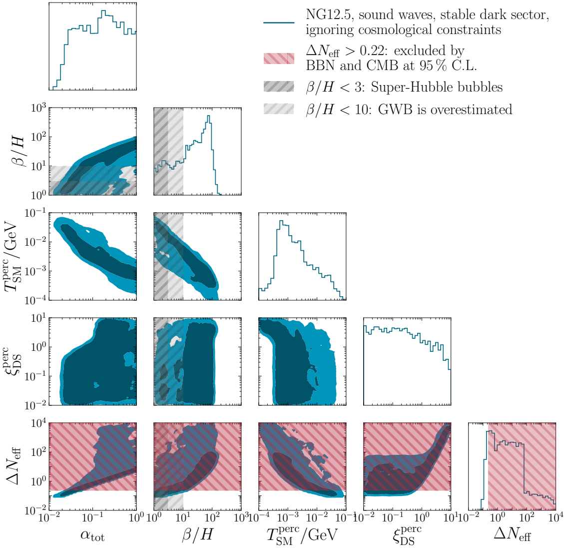
- SM has no MeV phase transition $\rightsquigarrow$ Assume a weakly coupled $\mathcal{O}(\mathrm{MeV})$ scalar!
- Dark sector temperature is crucial for GW prediction, $T_{\mathrm{DS}} = \xi_{\mathrm{DS}}\, T_{\mathrm{SM}}$ [CT+, 2109.06208]
- **Stable dark sector:** additional DS energy density contributes to Hubble expansion, changing BBN abundances and CMB anisotropies through

$$\Delta N_{\mathrm{eff}} \gtrsim 6 \times \alpha \qquad \textbf{but:} \qquad \Delta N_{\mathrm{eff}} < 0.22 \text{ @95\,\% C.L.}$$

- **Decaying dark sector:** Energy transfer to the SM plasma, changing element abundances and CMB anisotropies. Constraints require [Depta+, 2011.06519]

$$\tau \lesssim 0.1\,\mathrm{s}$$

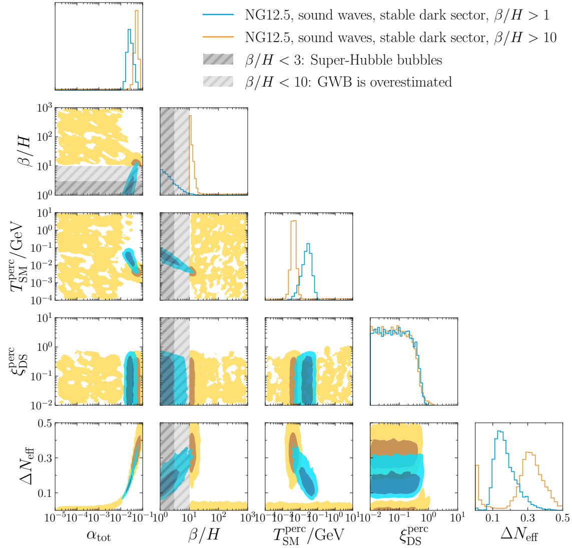
The tension between PTAs, CMB and BBN.



- 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.

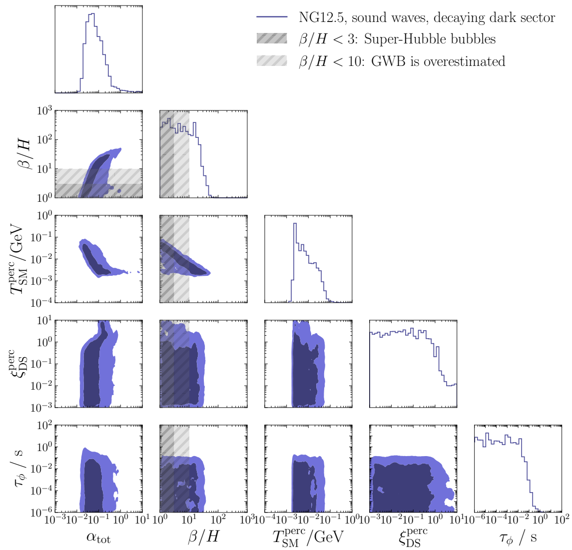


Global fit = compute global maximum of

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

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

Decays to the rescue.

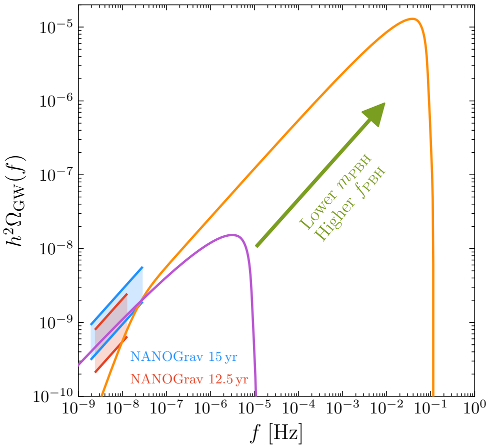


Decays save the fit!

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

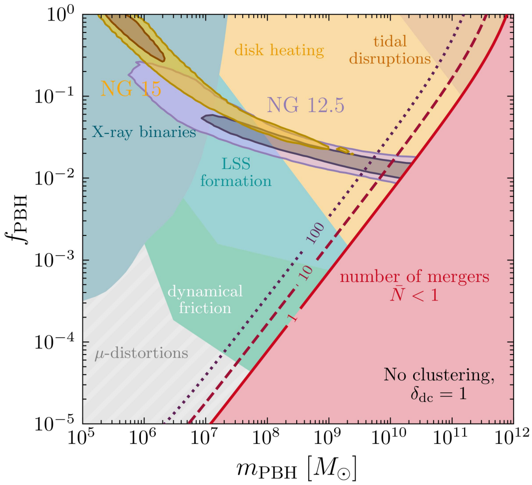
Merging primordial black holes.

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
- Described by (monochromatic) mass m_{PBH} and DM fraction f_{PBH}

PBHs without clustering cannot explain the PTA data.



[CT+, 2023]

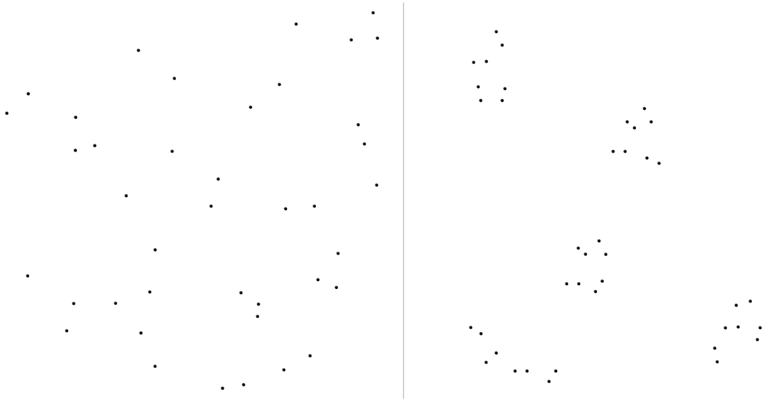
- Scan over m_{PBH} and f_{PBH}
- Region favored by PTAs is excluded by astrophysical bounds
- Crucial: exclude regions with small merger numbers. (Atal et al. came to the wrong conclusion [2012.14721])

Homogeneously distributed PBHs cannot explain the PTA data!

What is clustering?

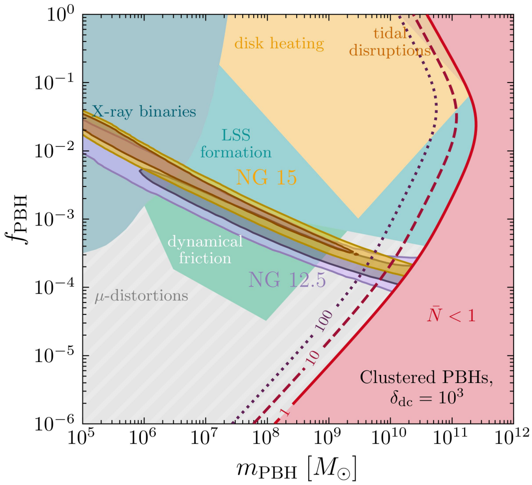
$\delta_{\mathrm{dc}} = 1$: Poisson-distributed PBHs

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



[Paul Frederik Depta, 2023]

Clustered PBHs can explain the PTA data.

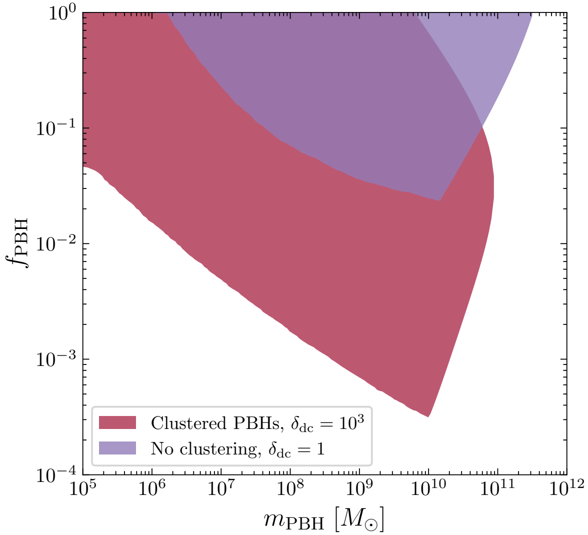


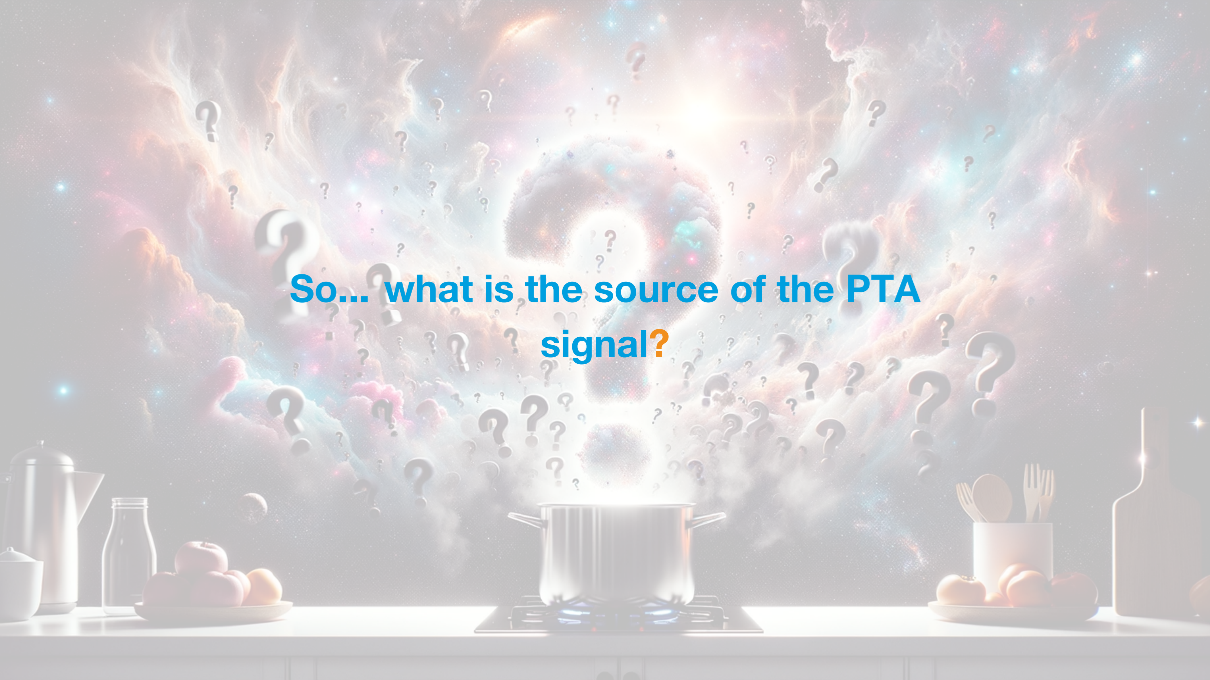
[CT+, 2023]

- Clustering increases the merger rates, requiring less PBHs to explain the signal: shift to smaller $f_{\rm PBH}$
- Astrophysical bounds are dubious for clustering
- Fermilab group showed that μ-distortion bounds can be circumvented [Hooper+, 2308.00756]

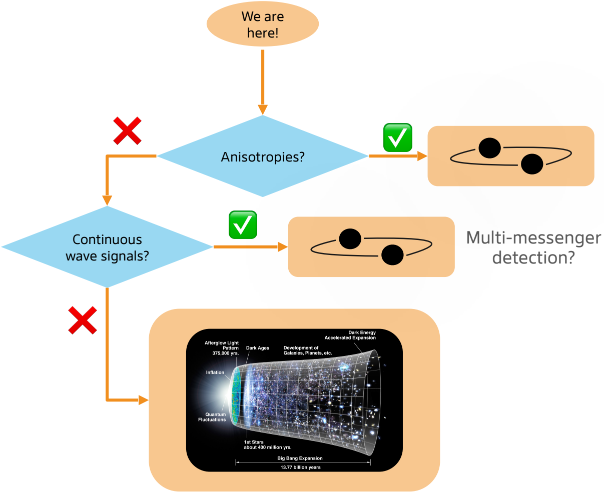
Clustered PBHs *can* explain the PTA data!

Novel PBH constraints!




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

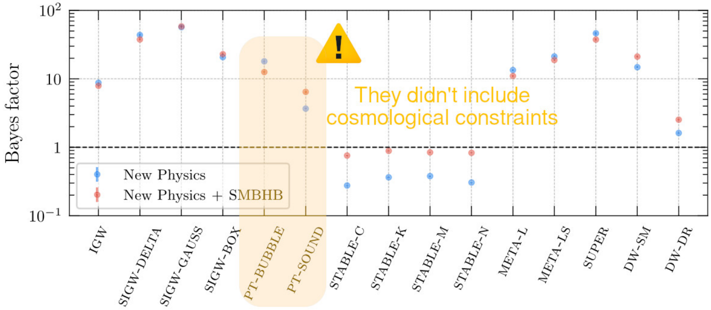
Quo vadis pulsar timing?



- HD correlation found!
- So far no evidence for anisotropies and continuous waves in data
- Spectral shape and amplitude in slight tension with SMBHBs

⇝ **More data needed** to distinguish SMBHBs from cosmic background!

The evidence for new physics.



[NANOGrav collaboration, 2023]

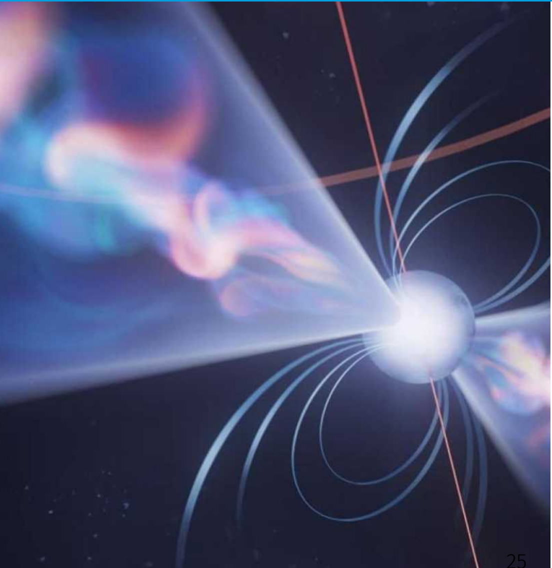
- New physics matches spectra better than standard SMBHBs
- We should perform global fits, including additional constraints & astrophysical parameters

Still: As soon as a single merger or strong anisotropy is found in the data, all[1] cosmological explanations will be dead.

[1] except for our scenario with an anisotropic distribution of supermassive merging PBHs... 😉

Take-home messages.

- We are at the dawn of GW cosmology!
- New physics can explain the nHz signal better than astrophysics
- Stable dark sector phase transitions ✗
- Decaying dark sectors ✓
- Primordial black hole mergers can only explain the signal if they are clustered



[image credit: Olena Shmahalo, NANOGrav]

Thank you very much for your attention!

Do you have any questions?

Backup slides.

How the density contrast increases the merger rate

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

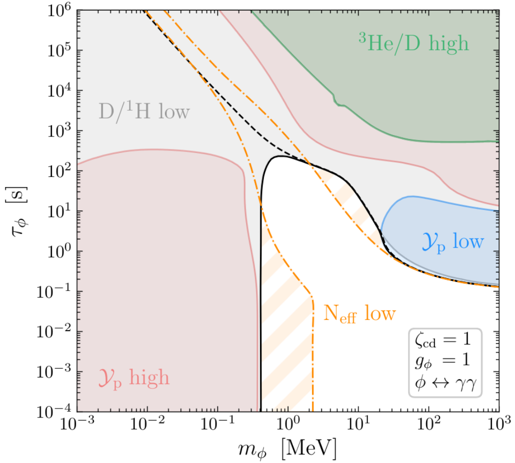
$$R(t) = \int_0^{\tilde{x}} \mathrm{d}x \int_x^{\infty} \mathrm{d}y \frac{\partial^2 n_3}{\partial x \, \partial y} \delta(t - \tau(x,y))$$

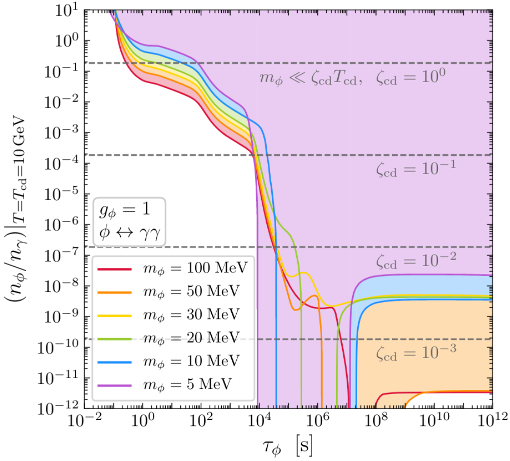
$$\propto \frac{\delta_{\mathrm{dc}}{}^{16/37}}{\tilde{x}^3 \tilde{\tau}} \left(\frac{t}{\tilde{\tau}}\right)^{-34/37} \left(\Gamma\left[\frac{58}{37}, \frac{4\pi}{3} \tilde{x}^3 \delta_{\mathrm{dc}} n_{\mathrm{PBH}} \left(\frac{t}{\tilde{\tau}}\right)^{3/16}\right] - \Gamma\left[\frac{58}{37}, \frac{4\pi}{3}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

With:

- $\delta_{\mathrm{dc}} \simeq \frac{n_{\mathsf{PBH}}^{\mathsf{loc}}}{\bar{n}_{\mathsf{PBH}}^{\mathsf{loc}}}$: 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

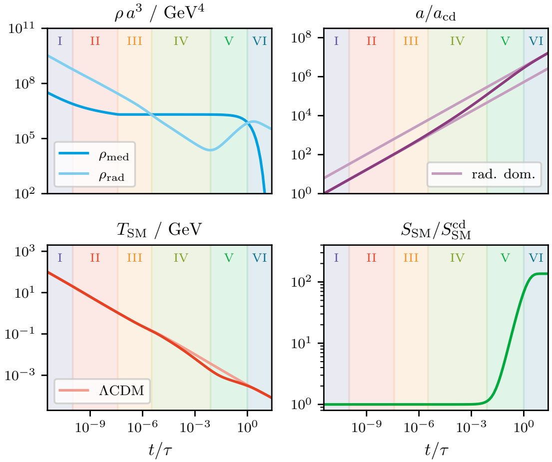
Electromagnetic scalar decays at MeV temperatures.





[Depta+, JCAP 04 (2021) 011]

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

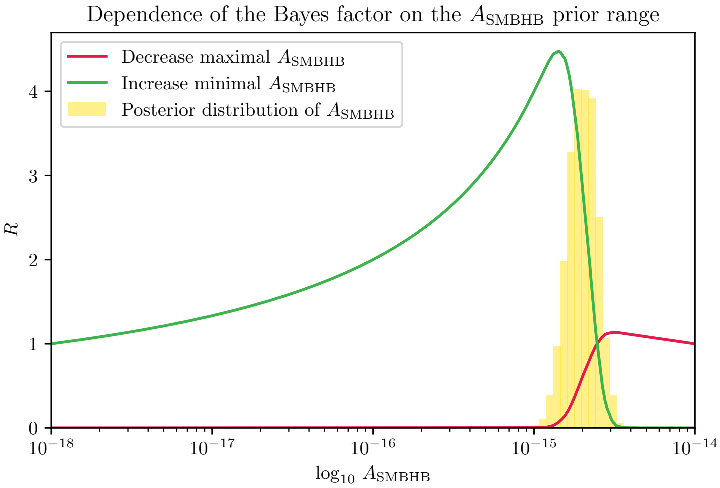


Energy densities $\rho_i(t) \overset{\text{sets}}{\rightsquigarrow}$ Scale factor $a(t) \overset{\text{sets}}{\rightsquigarrow}$ Temperatures $T_{\mathsf{SM/DS}}(t) \overset{\text{set}}{\rightsquigarrow}$ Particle content $\overset{\text{sets}}{\rightsquigarrow} \rho_i(t) \overset{\text{sets}}{\rightsquigarrow}$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

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.