

# 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.

**At Last, There's a 'cosmic bass note'**  
A globe-spanning...  
**Astronomers detect 'cosmic bass note' of 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 that are gently stretching and squeezing everything in the universe  
**Gravitational waves finally 'heard' the chorus of gravitational waves that ripple through the universe**

**Black Holes in Space**  
Gravitational wave... at the center of the Milky Way

**Scientists reveal how black holes come from cosmic collisions**

**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.

**of Low-Frequency Gravitational Waves**  
the waves, which... from pairs of supermassive black holes

**Scientists 'hear' cosmic hum from gravitational waves**  
Scientists observed for the first time faint ripples caused by the motion of black holes that are gently stretching and squeezing everything in the universe.  
**A Background 'Hum' Pervades the Universe. Scientists Are Racing to Find Its Source**  
Astronomers are now seeking to pinpoint the origins of an exciting new form of gravitational waves that was announced earlier this year

**Colossal gravitational waves—trillions of miles long—found for the first time**  
by studying rapidly spinning dead stars... giant ripples of spacetime likely from merging supermassive black holes—  
**In a major discovery, scientists say spacetime churns like a choppy sea**  
The mind-bending finding suggests that everything around us is constantly being stretched and squeezed by gravitational waves

**First Evidence of Giant Gravitational Waves Thrills Astronomers**  
Astronomers are 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**

**Scientists discover that universe is a giant gravitational wave**  
After decades of searching, astronomers have found a distinctive pattern of light, from scattering stars called pulsars, that suggests huge gravitational waves are creating gentle ripples in space-time across the universe  
**Gravitational waves produce a background hum across the whole universe**  
The results are... background, a hum of gravitational waves

**For first time ever, scientists "hear" gravitational waves rippling through the universe**

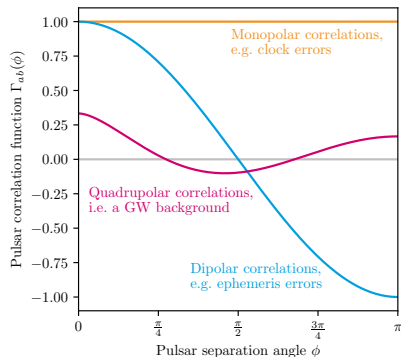
# Pulsar timing arrays.



Millisecond pulsars emit radio pulses with an extremely stable frequency

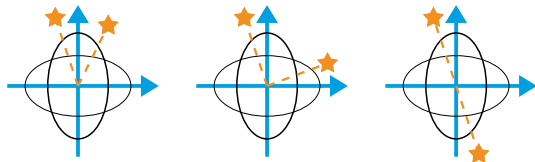
- GWs affect propagation time  $\rightsquigarrow$  change observed pulse frequency
- PTAs monitor pulse frequency using radio telescopes on Earth
- Fit pulse data with timing model
- Fourier decomposition of timing residuals shows “**red noise**”, which **can be due to GWs**

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

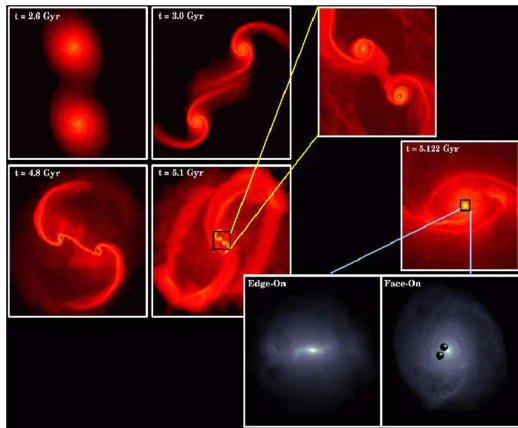


Red noise spectra can have many sources:

- 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**,  $\mathcal{B} = 200 - 1000$   
~> **Decisive evidence for GWs!** 🥳



# Merging supermassive black hole binaries.



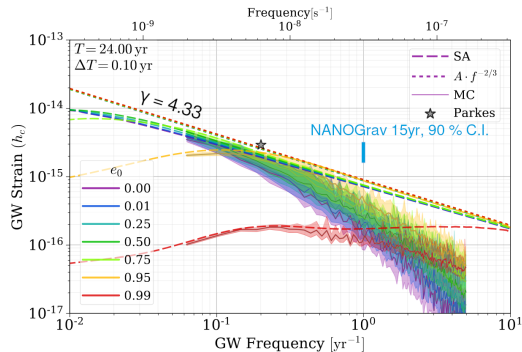
[Mayer et al., 0706.1562; NASA/CXC/A. Hobart]

- 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  $\gamma$ :

$$h_c(f) \propto A f^{\frac{3-\gamma}{2}}$$
$$\rightsquigarrow \Omega_{\text{GW}}(f) \propto A^2 f^{5-\gamma}$$

# GW background from supermassive black hole binaries.

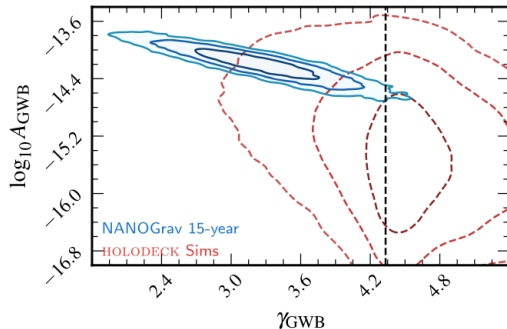
- ↪ If the only energy loss shrinking binary orbit is through GWs:  $\gamma = 4.33$
- ↪ **Astrophysical simulations** for realistic BH populations: deviations from  $\gamma = 4.33$ ,  $A \simeq 10^{-16} \dots -15$



[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  $\gamma = 4.33$ ,  $A \simeq 10^{-16} \dots -15$
- ↪ But: **observed GW spectrum** indicates lower  $\gamma$  and larger  $A$ !?



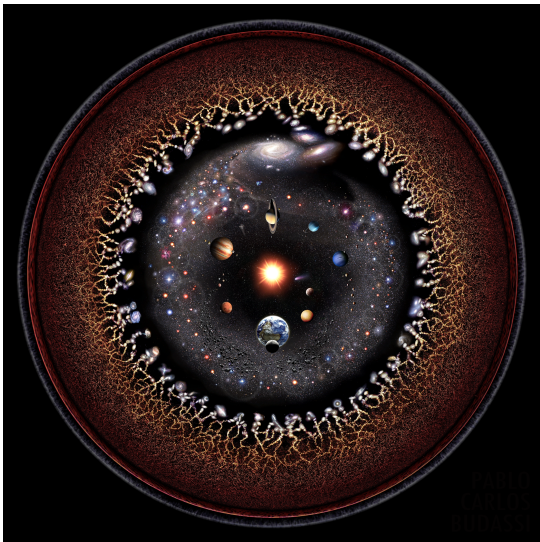
[NANOGrav collaboration, 2023]

What other signal sources  
are thinkable?

A medieval manuscript illustration. In the foreground, a scholar in a red robe and cap is shown from the side, looking up at a vast, dark blue sky filled with numerous yellow stars. The sky is divided by a diagonal line. To the right, a large, bright sun with a human face and long rays shines over a landscape. The landscape features rolling green hills, a small village with a church, and a large green tree. On the left, a rainbow arches over a body of water with a large wheel visible in the background. The entire scene is framed by a decorative border with Gothic architectural elements.

**What do we know about the early  
Universe?**

# What we know about our Universe.



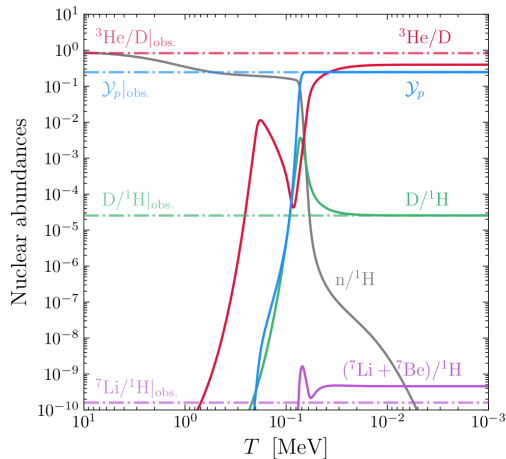
[Pablo Carlos Budassi, 2020]

## **LCDM:**

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



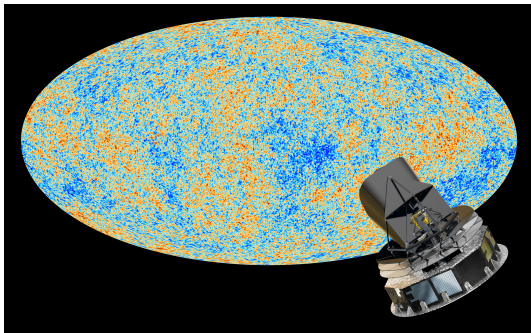
# The Big Bang Nucleosynthesis and the CMB.



[Paul Frederik Depta, 2021]


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

# The Big Bang Nucleosynthesis and the CMB.



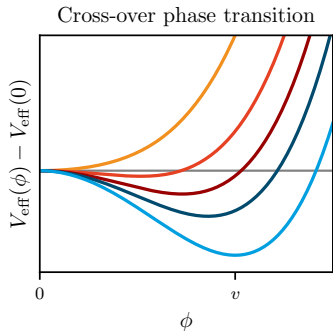
[ESA and the Planck Collaboration, D. Ducros]

- Observations of primordial light element abundances in 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  $\nu$  generations [Bennet, 2012.02726v3]
- ⇒ Thermalized BSM species after BBN are ruled out. But we have no constraints before that.

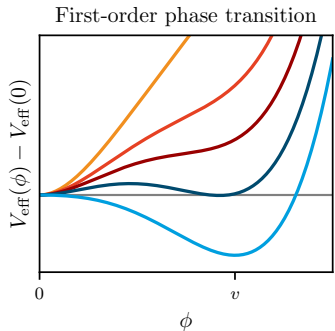
The background of the slide is a vibrant, abstract representation of the universe. It features a complex network of glowing filaments and numerous spherical bubbles of varying sizes. The color palette is dominated by cool blues and purples, with warm oranges and yellows highlighting specific regions, possibly representing star formation or high-energy events. The overall effect is one of dynamic, swirling energy.

**Gravitational waves from dark  
sector phase transitions.**

# Cross-over and first-order phase transitions.



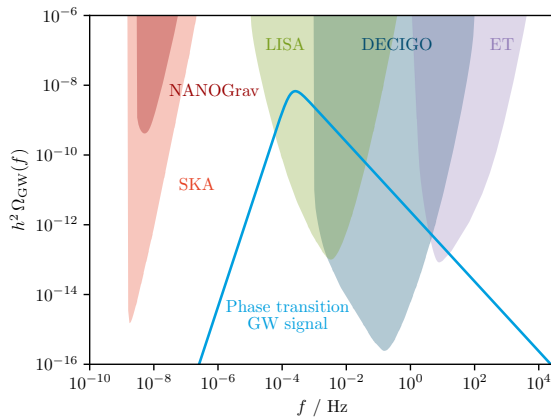
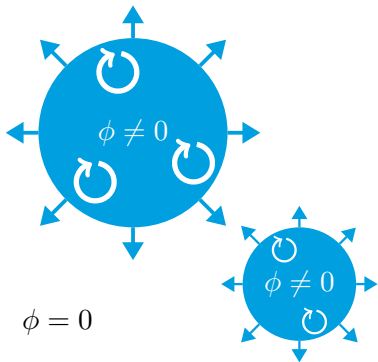
A scalar field “rolls down” from  $\phi = 0$  to  $\phi = v$ , when the bath cools from **high temperatures** to **low temperatures**.



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

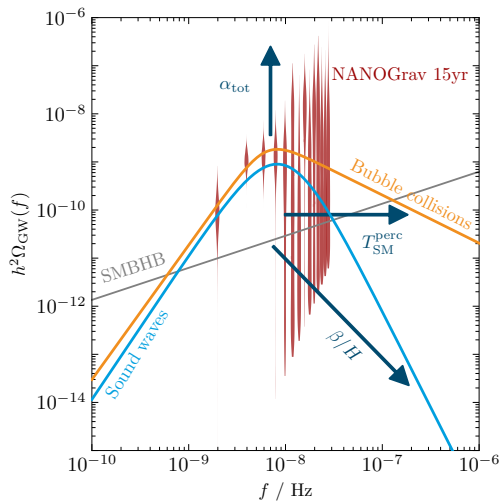
# Gravitational waves from first-order phase transitions.

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

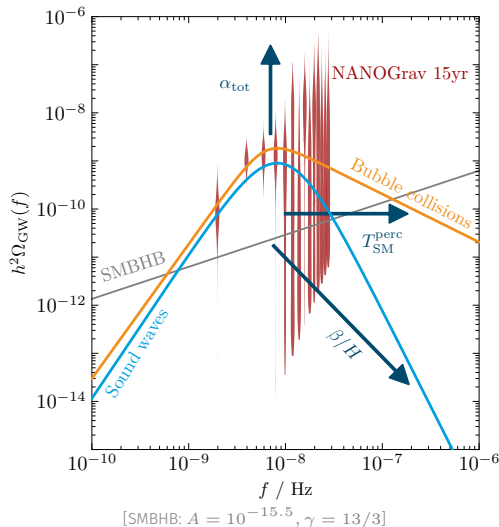
$$h^2 \Omega_{\text{GW}}^{\text{sw,bw}}(f) \simeq 10^{-6} \left( \frac{\alpha}{\alpha + 1} \right)^2 \left( \frac{H}{\beta} \right)^{1,2} \mathcal{S} \left( \frac{f}{f_{\text{peak}}} \right)$$

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

To fit the **new pulsar timing data**:

- Strong transitions,  $\alpha \simeq \frac{\Delta V}{\rho_{\text{tot}}} \approx 1$
- 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.

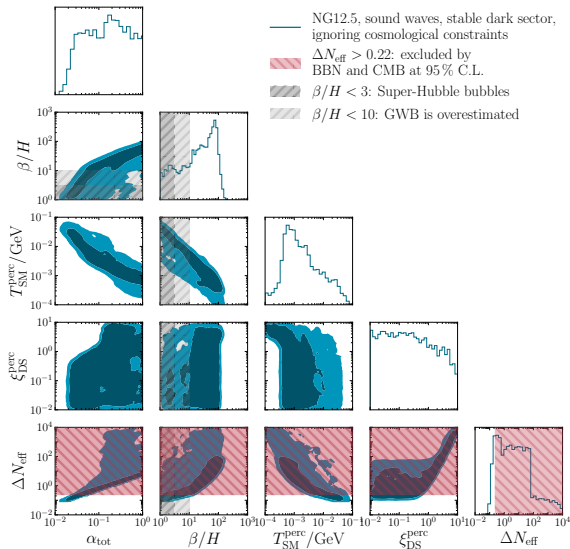
- Dark sector temperature ratio is crucial,  $T_{\text{DS}} = \xi_{\text{DS}} T_{\text{SM}}$  [Breitbach, 1811.11175]
- Potential dilution of the GW signal due to changed redshift history [CT, 2109.06208]
- **Stable dark sector:** additional DS energy density accelerates expansion and changes early element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

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

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



# The tension between PTAs, CMB and BBN.

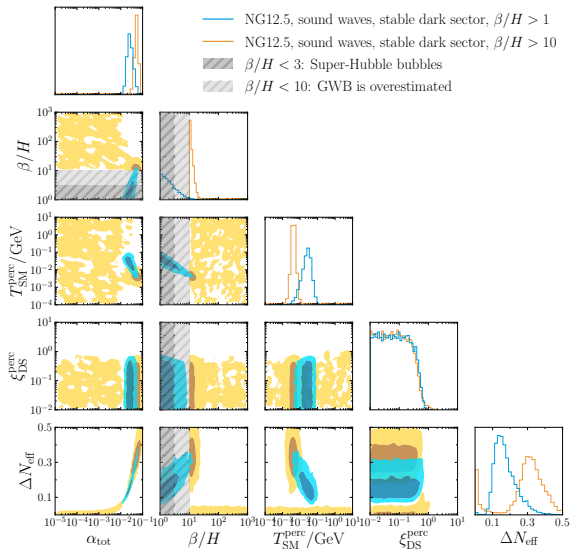


- Performed fit of the pulsar data with NANOGrav's own code **enterprise**

- ⚡ A good fit requires an enormous reheating of the dark sector:  $\Delta N_{\text{eff}}$  can grow arbitrarily large
- ⚡ Bubble sizes would need to be super-Hubble to be okay with  $\Delta N_{\text{eff}}$   
Causality ⚡ GW prediction ⚡

→ The tension cries for a global fit

# Global fits kill stable dark sectors.



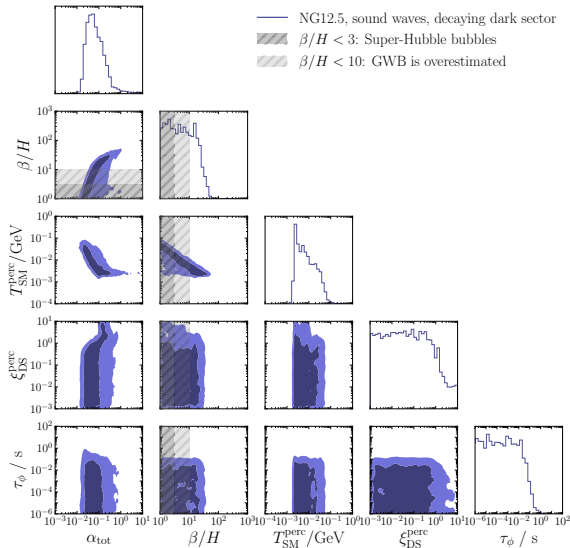
Global fit = compute global maximum of

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

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!

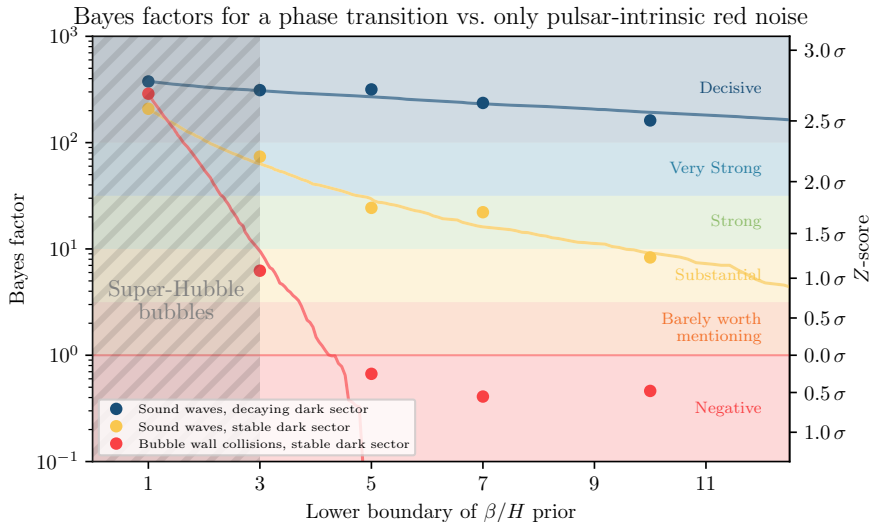
# Decays to the rescue.



Decays save the fit!

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

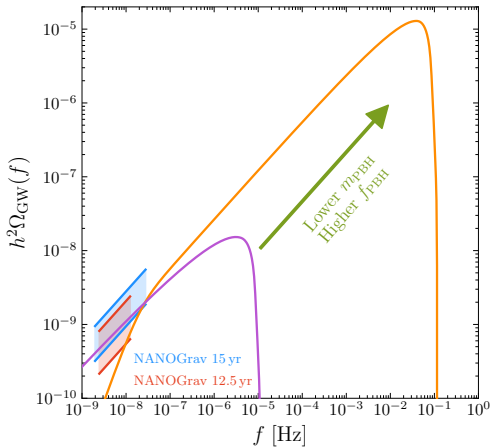
# The evidence for a dark sector phase transition.





**Merging primordial black holes.**

# Gravitational waves from primordial black hole mergers.

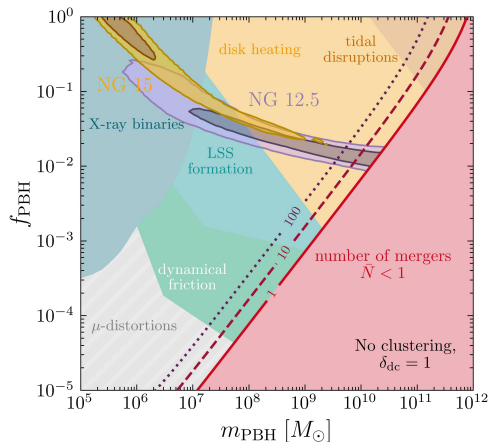


- Inflation leaves large super-Hubble density perturbations
- Black holes form when these come into causal contact again, long before the death of the first stars



$$\Omega_{\text{GW}}(f) = \frac{f}{\rho_{\text{crit}}} \int_0^{t_0} dt \left[ R(t) \frac{dE_{\text{GW}}}{df_r} \right] \Big|_{f_r=(1+z)f}$$

# PBHs without clustering cannot explain the PTA data.



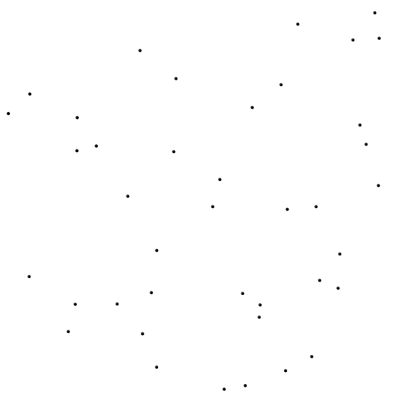
[CT et al., 2023]

- Scan over  $m_{\text{PBH}}$  and  $f_{\text{PBH}}$
- 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?

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

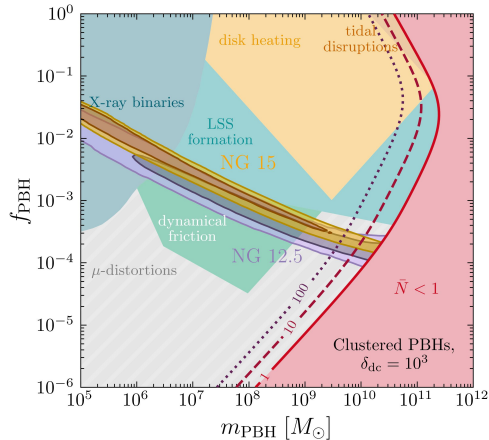


$\delta_{\text{dc}} = 1 + \frac{\delta n_{\text{PBH}}^{\text{loc}}}{\bar{n}_{\text{PBH}}} \gg 1$ : Clustering





# Clustered PBHs can explain the PTA data.



[CT et al., 2023]

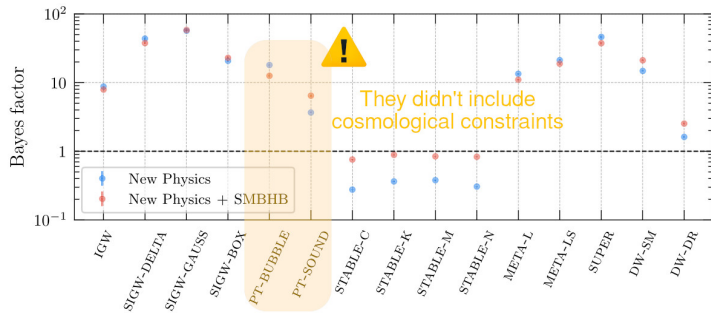
- Clustering increases the merger rates, requiring less PBHs to explain the signal: smaller  $f_{\text{PBH}}$
- Astrophysical bounds are dubious
- Aurora, Albert, Dan and Gordan say that  $\mu$ -distortions can be circumvented [2308.00756]

*Clustered* PBHs can explain the PTA data!



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

# The evidence for new physics.

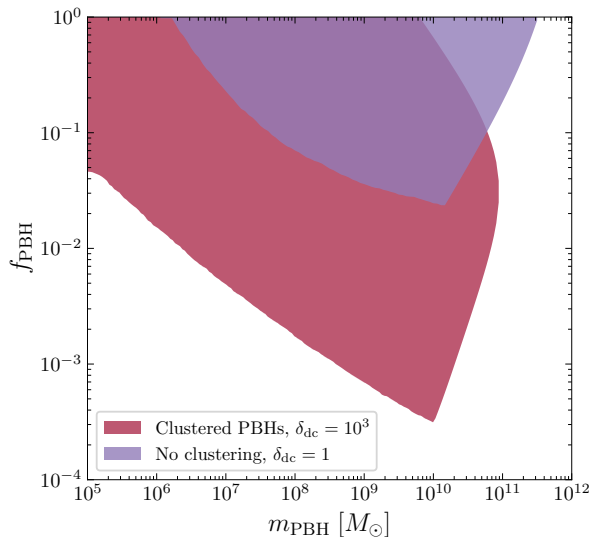


[NANOGrav collaboration, 2023]

- 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!

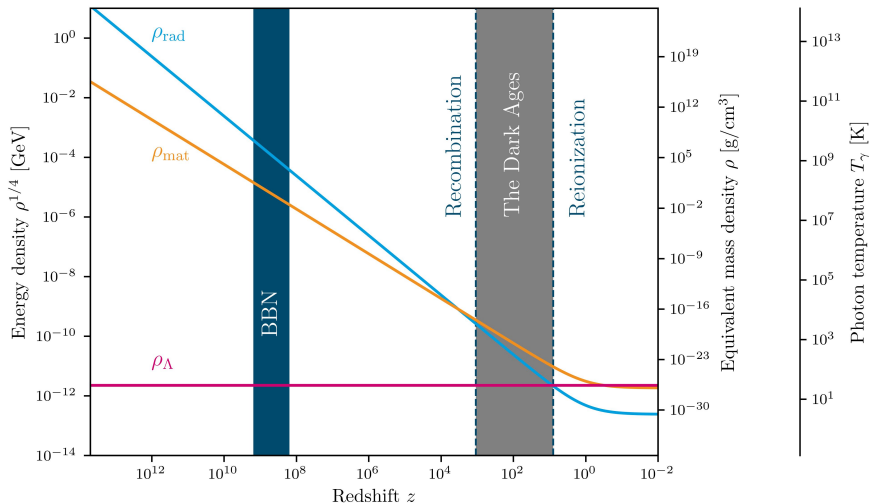
**Thank you very  
much for your  
attention!**

Do you have any  
questions?



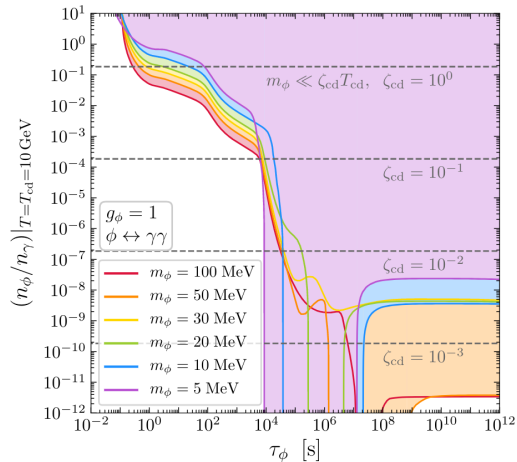
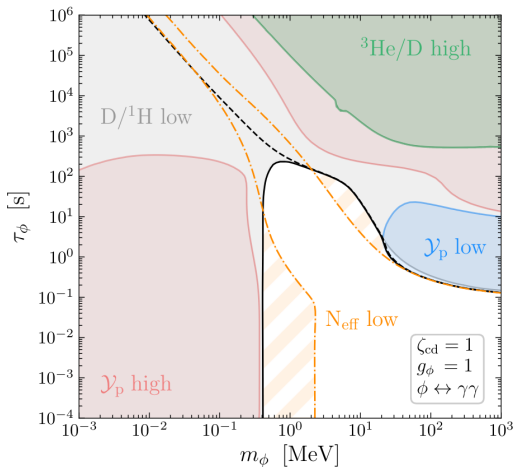
**Backup slides.**

# A brief history of time: LCDM.



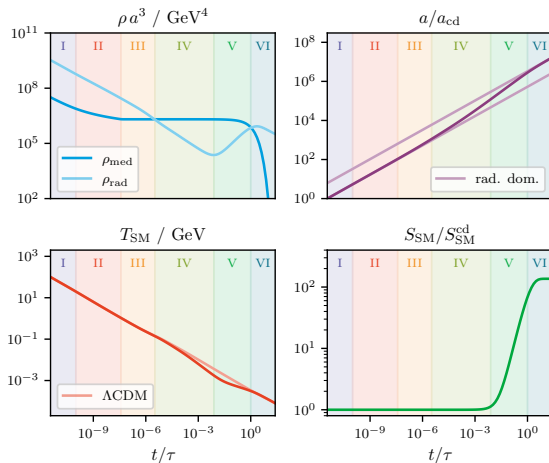


# Electromagnetic scalar decays at MeV temperatures.



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

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

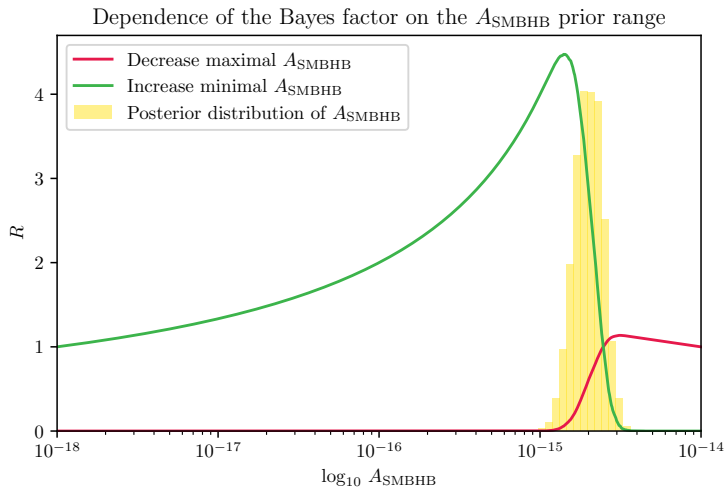


Energy densities  $\rho_i(t)$   $\rightsquigarrow$  Scale factor  $a(t)$   $\rightsquigarrow$  Temperatures  $T_{\text{SM/DS}}(t)$   $\rightsquigarrow$  Particle content  $\rightsquigarrow \rho_i(t)$   $\rightsquigarrow$  ...

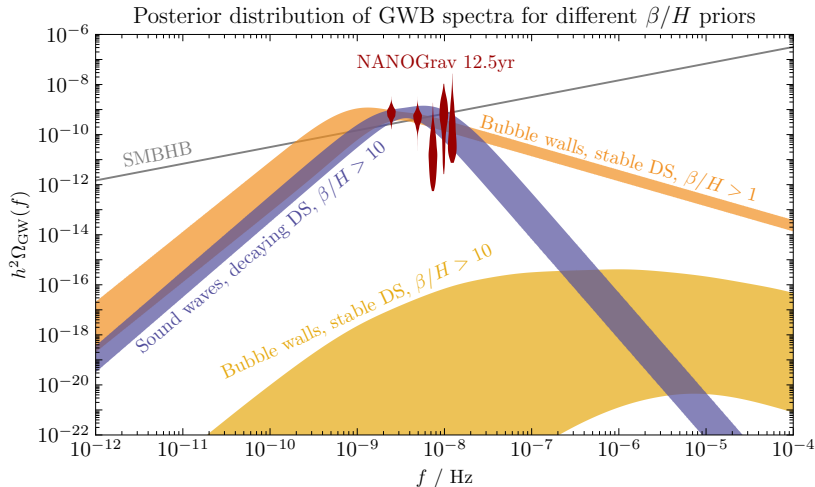
## Six phases:

- 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

$$\begin{aligned}\Omega_{\text{GW}}(f) &= \frac{f}{\rho_{\text{crit}}} \int_0^{t_0} dt \left[ R(t) \frac{dE_{\text{GW}}}{df_r} \right] \Big|_{f_r=(1+z)f} \\ R(t) &= \int_0^{\tilde{x}} dx \int_x^\infty dy \frac{\partial^2 n_3}{\partial x \partial y} \delta(t - \tau(x, y)) \\ &\propto \frac{\delta_{\text{dc}}^{16/37}}{\tilde{x}^3 \tilde{\tau}} \left( \frac{t}{\tilde{\tau}} \right)^{-34/37} \left( \Gamma \left[ \frac{58}{37}, \frac{4\pi}{3} \tilde{x}^3 \delta_{\text{dc}} n_{\text{PBH}} \left( \frac{t}{\tilde{\tau}} \right)^{3/16} \right] - \right. \\ &\quad \left. \Gamma \left[ \frac{58}{37}, \frac{4\pi}{3} \tilde{x}^3 \delta_{\text{dc}} n_{\text{PBH}} \left( \frac{t}{\tilde{\tau}} \right)^{-1/7} \right] \right)\end{aligned}$$

With:

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