

Exploring new physics with pulsar timing arrays.

GAPS seminar talk at University of Illinois, Chicago

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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 19, 2023



Outline of this talk.

1. The PTA signal
2. The null hypothesis: black hole mergers
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 are produced from pairs of merging 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

SCIENCE
Colossal gravitational waves—trillions of miles long—found for the first time
by studying rapidly spinning dead stars that create giant ripples of spacetime likely from merging supermassive black holes—

In a major discovery, scientists say space-time churns like a choppy sea
The mind-bending finding suggests that everything around us is constantly being stretched and squeezed by gravitational waves

For first time ever, scientists "hear" gravitational waves rippling through the universe
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 merging in the early universe

Monster gravitational waves spotted for first time
Scientists discover that universe is a cacophony of gravitational waves

Gravitational waves produce a background hum across the whole universe
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 a hum of gravitational waves, a hum of the universe

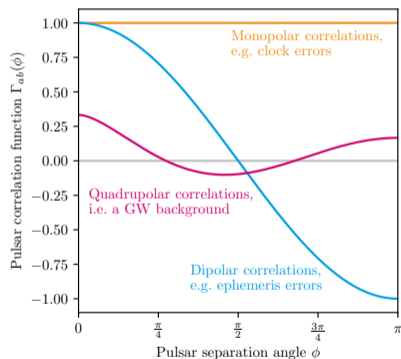
Pulsar timing arrays.



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?

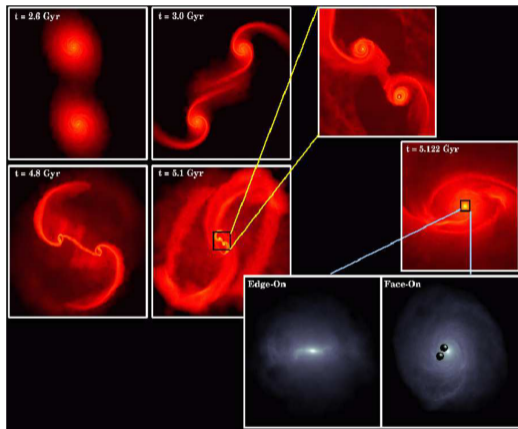


Red noise spectra can have many sources:

- 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.



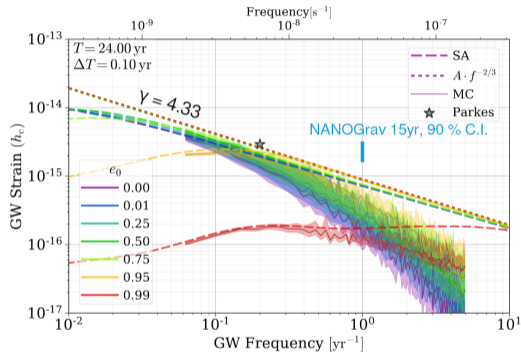
[Mayer et al., 0706.1562; NASA/CXC/A. Hobart]

- 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 γ :

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

GW background from supermassive black hole binaries.

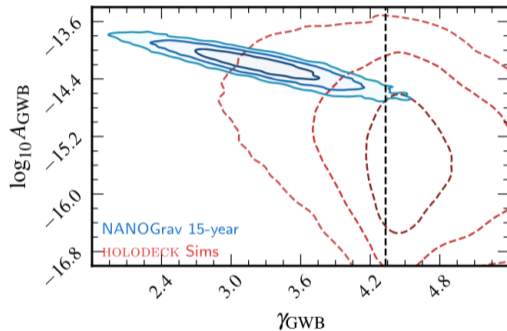
- ↪ If the only energy loss shrinking binary orbit is through GWs: $\gamma = 4.33$
- ↪ **Astrophysical simulations** for realistic BH populations: deviations from $\gamma = 4.33$, $A \simeq 10^{-16} \dots -15$



[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 γ and larger A !?



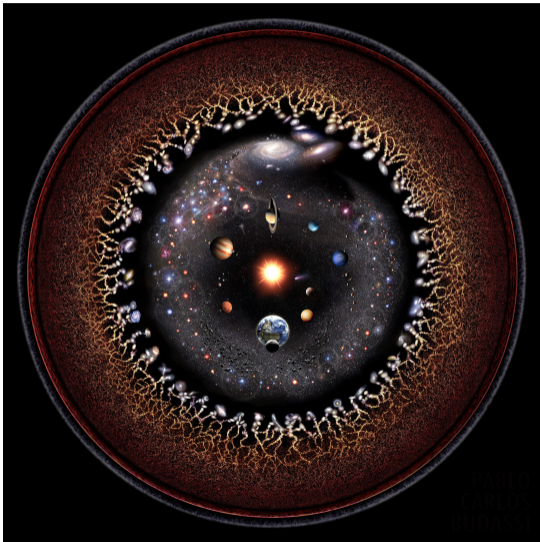
[NANOGrav collaboration, 2023]

What other signal sources
are thinkable?

A medieval manuscript illustration. In the foreground, a scholar in a red robe is shown from the side, looking up at a vast, starry sky. The sky is filled with numerous yellow stars of varying sizes. A large, green tree stands in the middle ground. In the background, a landscape with rolling hills and a small village is visible. A large, radiant sun with a human face is on the right side of the image. 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.

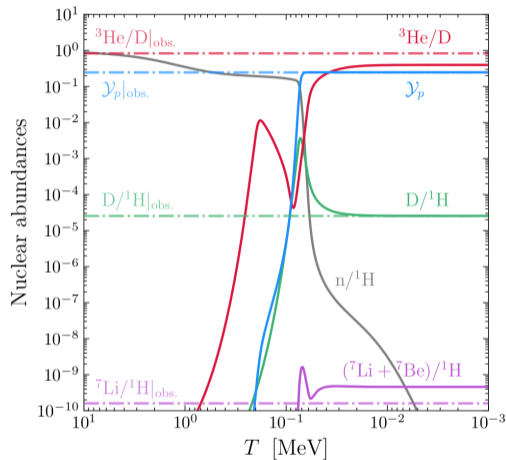


[Pablo Carlos Budassi, 2020]

LCDM:

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

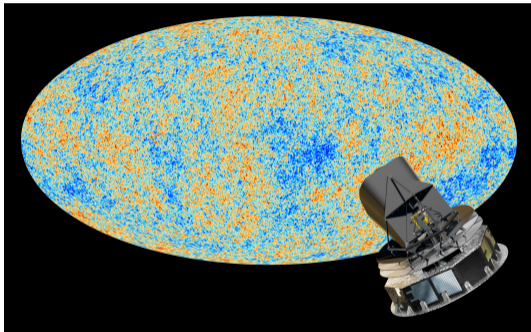
The Big Bang Nucleosynthesis and the CMB.



[Paul Frederik Depta, 2021]


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

The Big Bang Nucleosynthesis and the CMB.



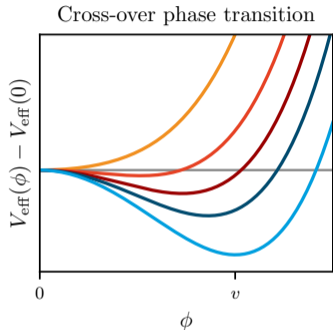
[ESA and the Planck Collaboration, D. Ducros]

- 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 ν generations [Bennet, 2012.02726v3]
- ⇒ Thermalized BSM species after BBN are ruled out. But we have no constraints before that.

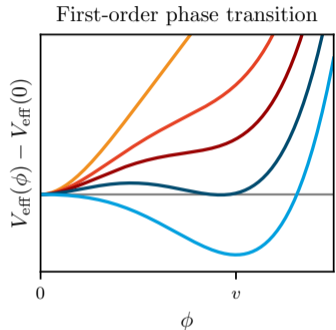
The background of the slide is a vibrant, abstract representation of the universe. It features a complex network of glowing filaments in shades of blue, cyan, and purple, which resemble the cosmic web. Interspersed among these filaments are numerous spherical structures of varying sizes, some appearing as bright, fiery orange and yellow cores, while others are more diffuse, glowing with a reddish-pink hue. The overall effect is one of dynamic energy and cosmic scale.

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

Cross-over and first-order phase transitions.



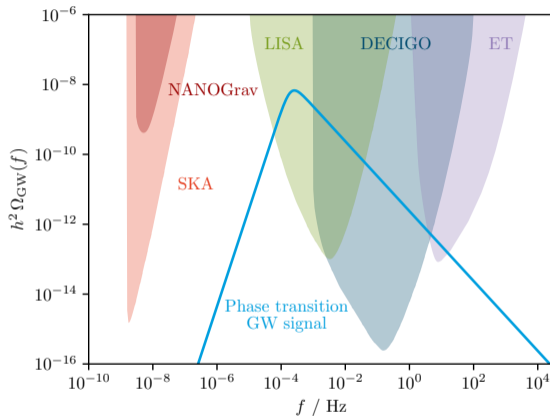
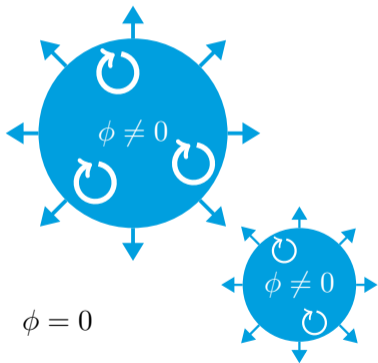
A scalar field “rolls down” from $\phi = 0$ to $\phi = v$, when the bath cools from **high temperatures** to **low temperatures**.



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

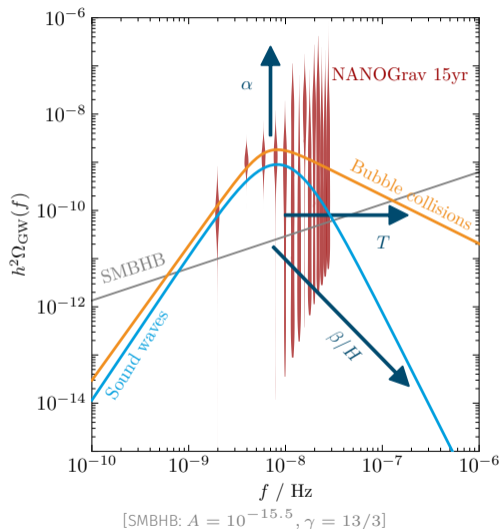
Gravitational waves from first-order phase transitions.

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.



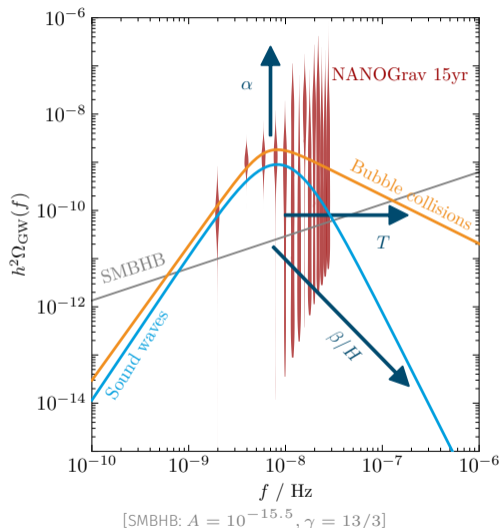
$$h^2 \Omega_{\text{GW}}^{\text{sw}, \text{bw}}(f) \simeq 10^{-6} \left(\frac{\alpha}{\alpha + 1} \right)^2 \left(\frac{H}{\beta} \right)^{1,2} \mathcal{S} \left(\frac{f}{f_{\text{peak}}} \right)$$

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

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?!

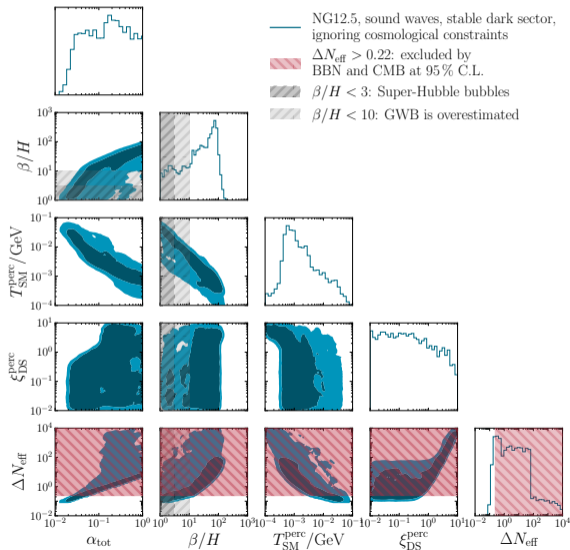
Let's put the transition in a dark sector.

- 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.

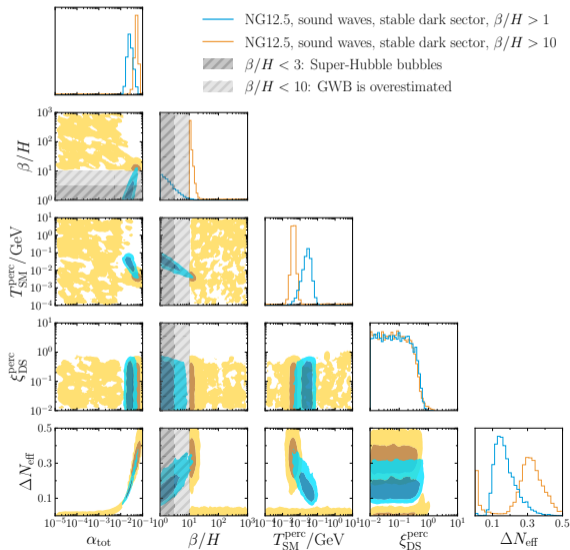


- Performed fit of the pulsar data with NANOGrav's own code **enterprise**

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

→ The tension cries for a global fit

Global fits kill stable dark sectors.



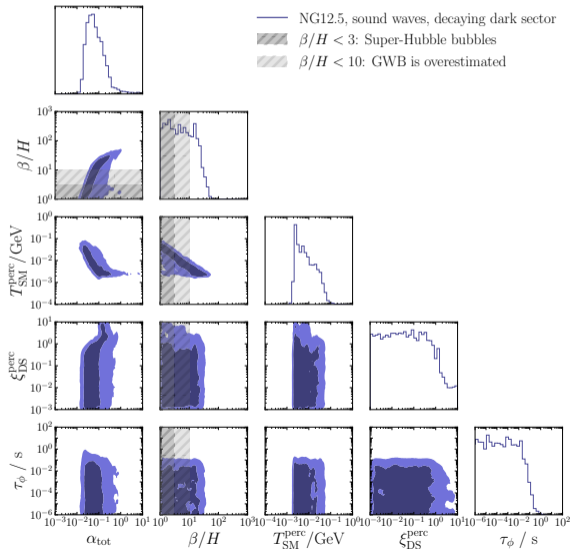
Global fit = compute global maximum of

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

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!

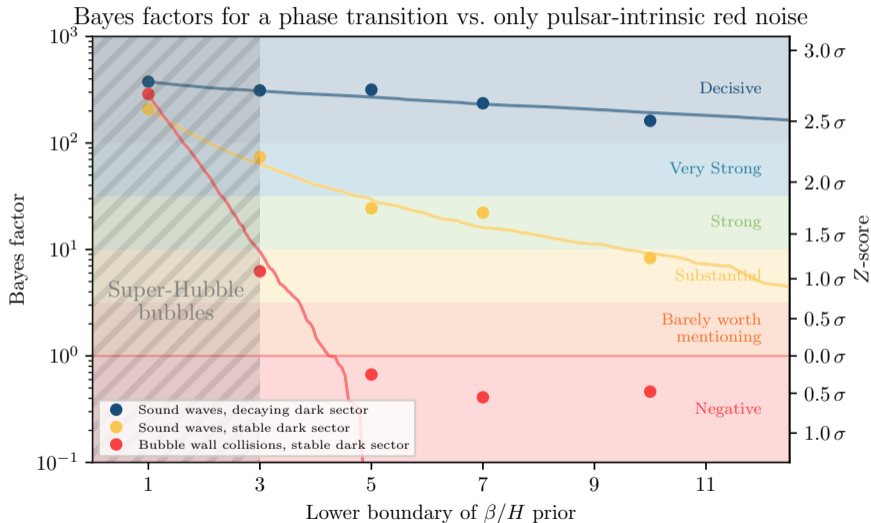
Decays to the rescue.



Decays save the fit!

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

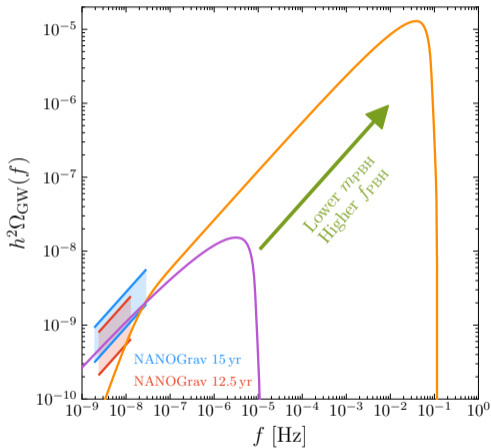
The evidence for a dark sector phase transition.





Merging primordial black holes.

Gravitational waves from primordial black hole mergers.

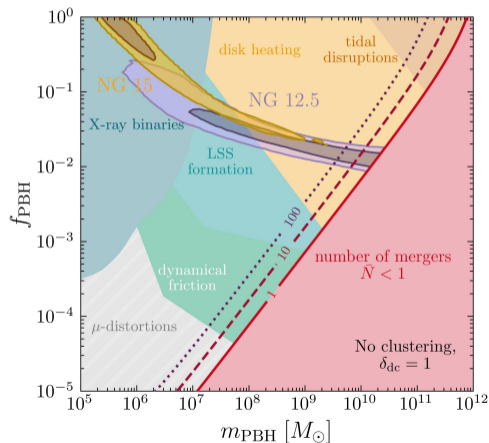


- Inflation leaves large super-Hubble density perturbations
- Black holes form when these come into causal contact again, long before the death of the first stars



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

PBHs without clustering cannot explain the PTA data.



[CT et al., 2023]

- Scan over m_{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?

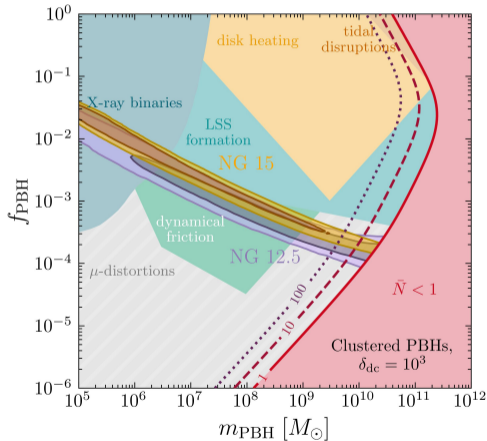
$\delta_{\text{dc}} = 1$: Poisson-distributed PBHs



$\delta_{\text{dc}} = 1 + \frac{\delta n_{\text{PBH}}^{\text{loc}}}{\bar{n}_{\text{PBH}}} \gg 1$: 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_{PBH}
- Astrophysical bounds are dubious
- Colleagues from UChicago say that μ -distortions can be circumvented

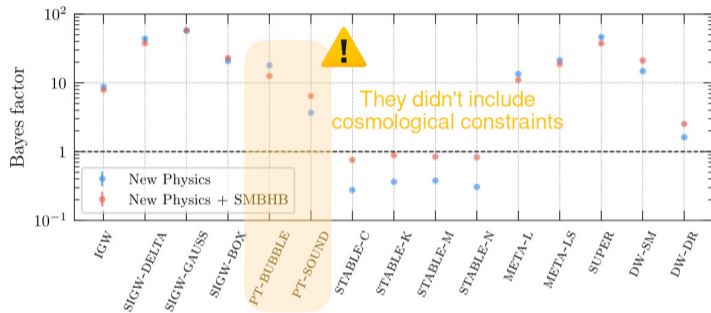
[2308.00756]

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.

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.
- Merging primordial black holes need to be clustered: Stay tuned!

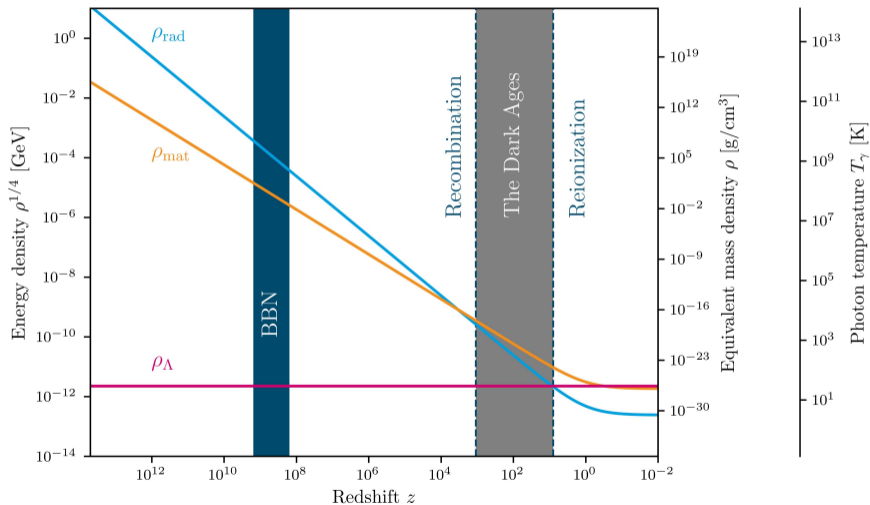
**Thank you very
much for your
attention!**

Do you have any
questions?

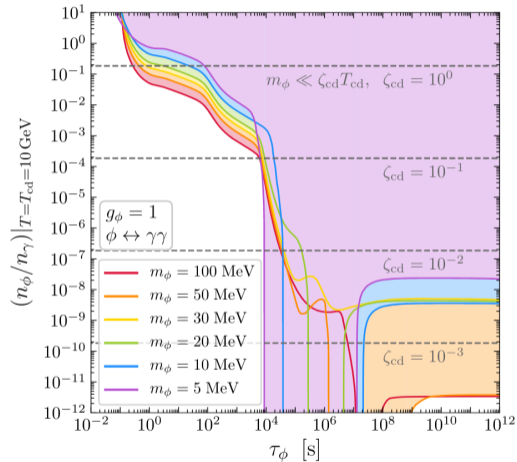
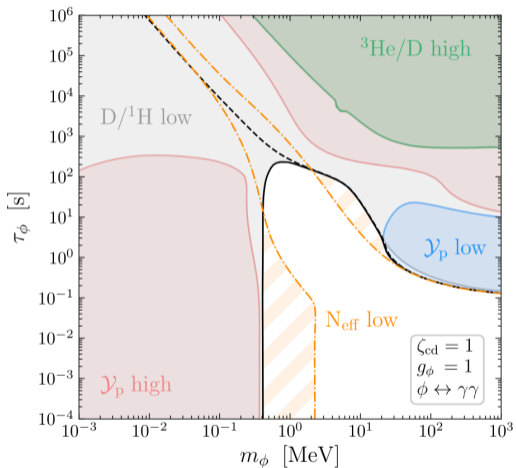


Backup slides.

A brief history of time: LCDM.

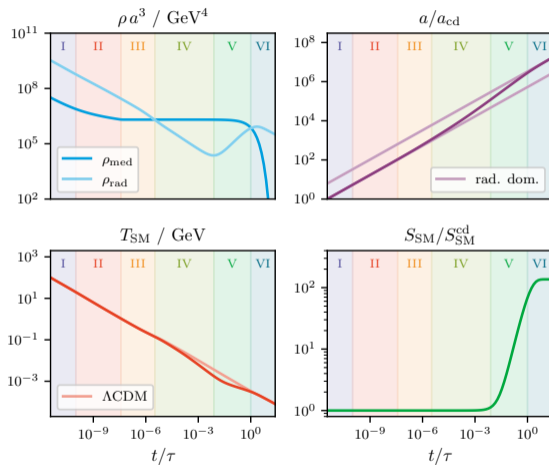


Electromagnetic scalar decays at MeV temperatures.



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

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

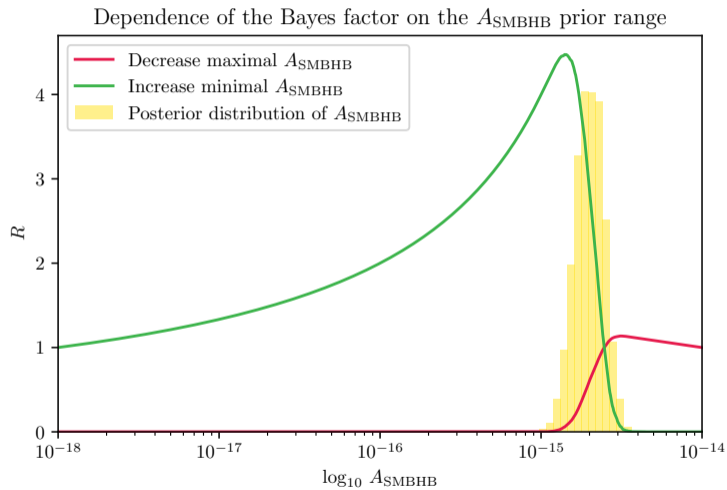


Energy densities $\rho_i(t)$ \rightsquigarrow Scale factor $a(t)$ \rightsquigarrow Temperatures $T_{\text{SM/DS}}(t)$ \rightsquigarrow Particle content $\rightsquigarrow \rho_i(t)$ \rightsquigarrow ...

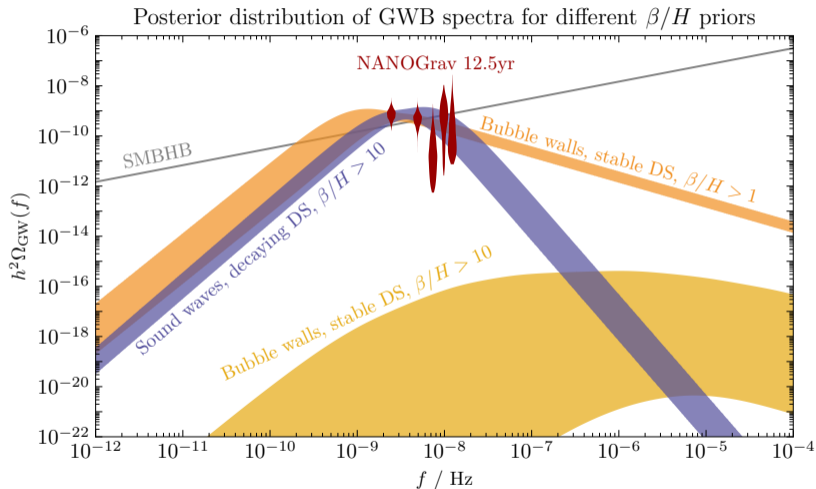
Six phases:

- 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