

Exploring new physics with pulsar timing arrays.

Workshop of the JENAS Initiative “Gravitational Wave Probes of Fundamental Physics”, GWs and Cosmology session

Carlo Tasillo,
Deutsches Elektronen Synchrotron (DESY)

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

[2306.09411], JCAP 11 (2023) 053

February 14, 2024



Outline of this talk.

1. The PTA signal
2. Phase transitions vs. precision cosmology
3. 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 team of astronomers has detected the first evidence of gravitational waves 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.

Black Hole Galaxy Space
Gravitational waves at the center of the Milky Way.

Scientists report first detection of gravitational waves from merging supermassive black holes

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
Astronomers are now seeking to pinpoint the origins of an exciting new form of gravitational waves that was announced earlier this year.

A Background 'Hum' Pervades the Universe. Scientists Are Racing to Find Its Source

Colossal gravitational waves—trillions of miles long—found for the first time
by studying rapidly spinning dead stars called pulsars, that suggests huge gravitational waves are creating gentle ripples in space-time across the universe.

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

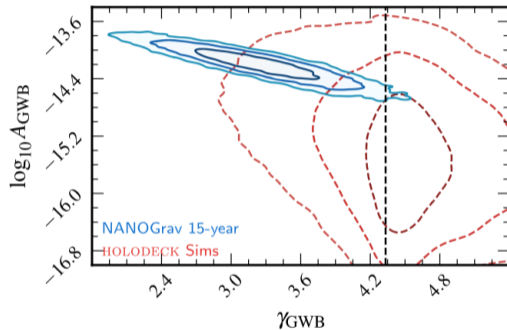
First Evidence of Giant Gravitational Waves Thrills Astronomers
For first time ever, scientists "hear" gravitational waves rippling through the universe.

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 spinning stars called pulsars, that suggests huge gravitational waves are creating gentle ripples in space-time across the universe.

GW background from supermassive black hole binaries.

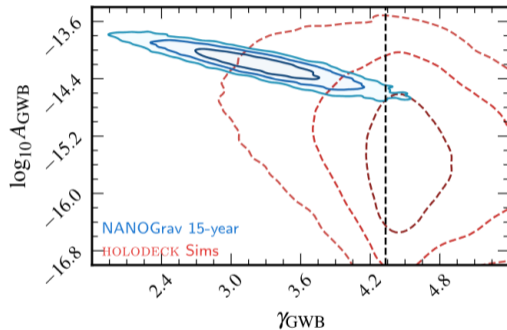
- The observed GW spectrum is consistent with a power-law shape of amplitude A and slope γ



[NANOGrav collaboration, 2023]

GW background from supermassive black hole binaries.

- ↪ The **observed GW spectrum** is consistent with a power-law shape of amplitude A and slope γ
- ↪ But: **Astrophysical simulations** based on realistic BH populations predict much weaker signals with higher γ
- ↪ Additional contribution from merging primordial black holes? [CT+, 2306.17836]



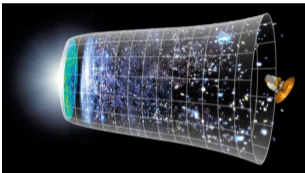
[NANOGrav collaboration, 2023]

What other signal sources
are thinkable?

Possible cosmological sources of the nHz background.

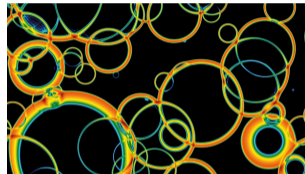
Inflation

Reentering of tensor fluctuations



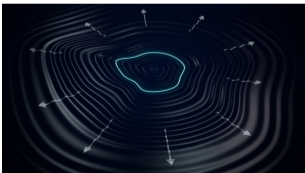
Phase transitions

Connection to dark matter?



Topological defects

Cosmic strings and domain walls



Scalar perturbations

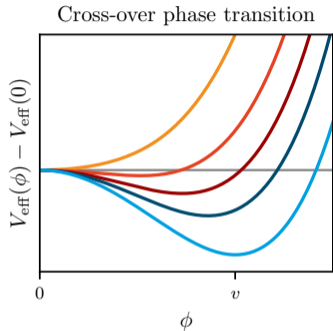
Incl. primordial black hole formation



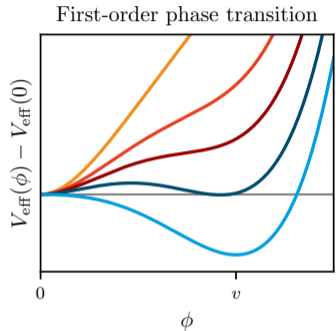


**Gravitational waves from dark
sector phase transitions.**

Cosmological phase transitions.



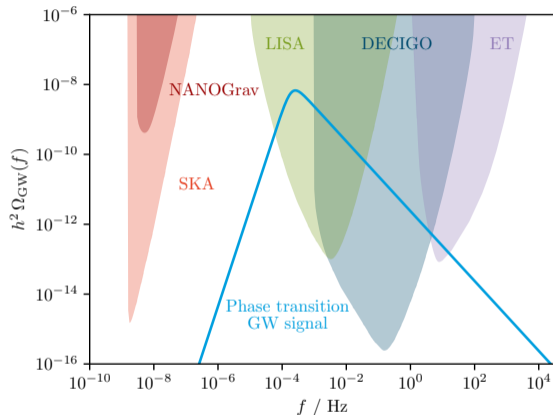
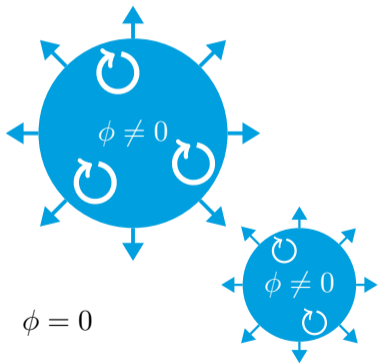
A scalar field “rolls down” from $\phi = 0$ to $\phi = v$, when the bath cools from **high temperatures** to **low temperatures**.



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

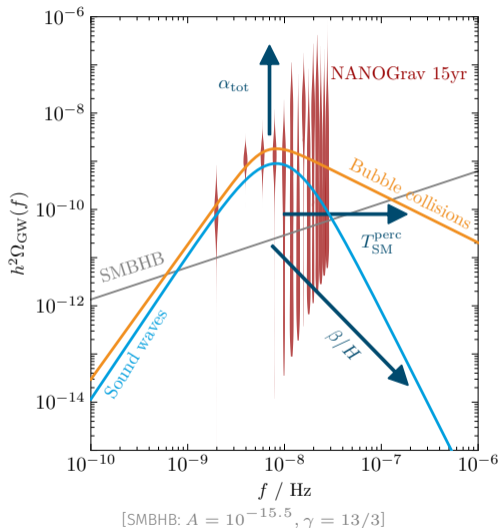
Gravitational waves from first-order phase transitions.

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.



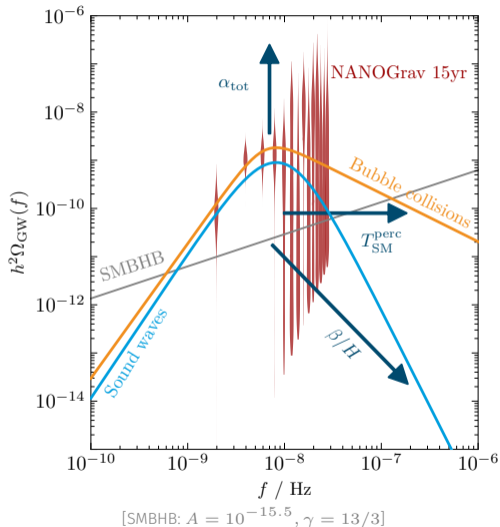
$$h^2 \Omega_{\text{GW}}^{\text{sw,bw}}(f) \simeq 10^{-6} \left(\frac{\alpha}{\alpha + 1} \right)^2 \left(\frac{H}{\beta} \right)^{1,2} \mathcal{S} \left(\frac{f}{f_{\text{peak}}} \right)$$

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

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 $T \approx 10 \text{ MeV}$

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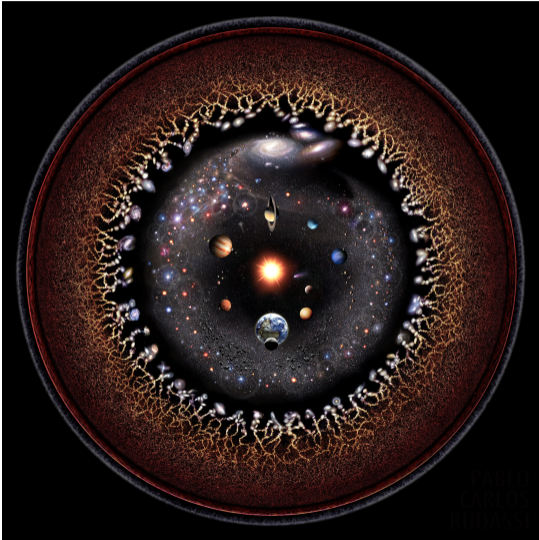
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But there's no SM phase transition at 10 MeV?!

A medieval manuscript illustration. The scene is divided into two main parts by a diagonal line. The upper part shows a dark blue sky filled with numerous yellow stars of various sizes and shapes. A crescent moon is visible in the top right. The lower part shows a landscape with rolling green hills, a large green tree, and a village with several buildings and a church spire. A bright sun with a human-like face and radiating lines is on the right. On the left, a figure in a red robe is shown from the back, looking up at the sky. The entire scene is framed by a decorative border with Gothic-style patterns.

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

What we know about our Universe.

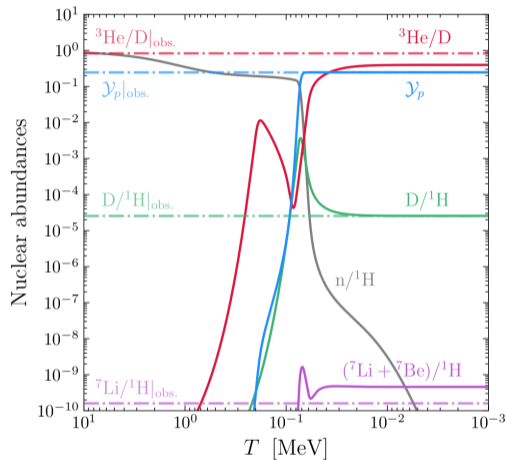


[Pablo Carlos Budassi, 2020]

LCDM:

- Allows for precision cosmology
- Not probed above MeV (= billion Kelvin) temperatures...

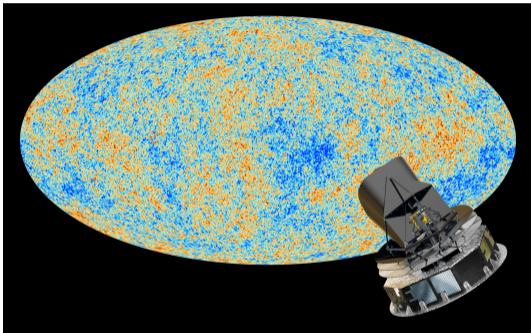
The Big Bang Nucleosynthesis and the CMB.



[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 at $T \lesssim 1 \text{ MeV}$ are ruled out. Before that: no constraints.

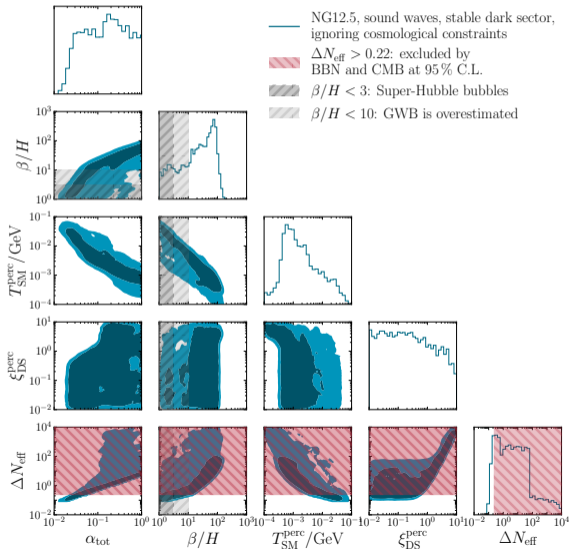
Let's put the transition in a dark sector.

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

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

- **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.



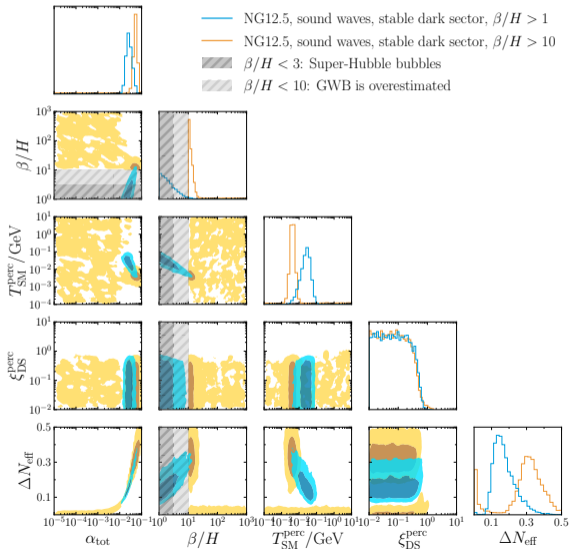
- Performed fit of the pulsar data with NANOGrav's own code **enterprise**

⚡ 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.

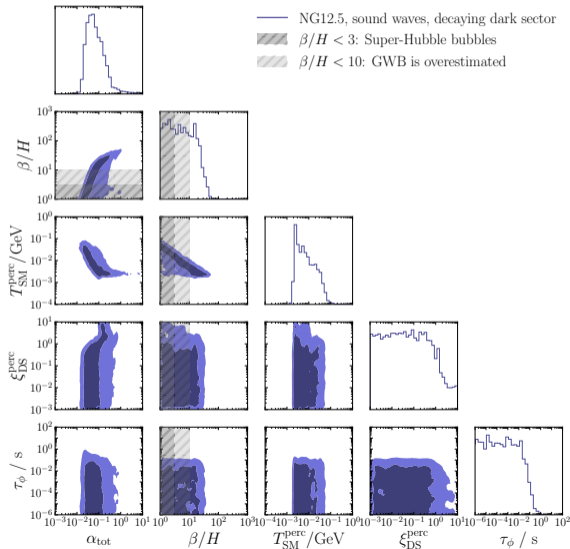


Global fit = compute global maximum of

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

- $\beta/H > 1$: 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!

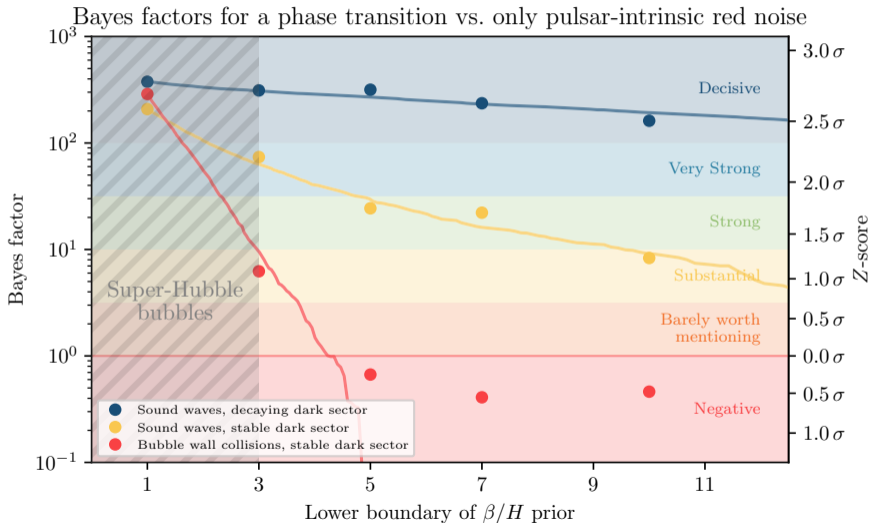
Decays to the rescue.



Decays save the fit!

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

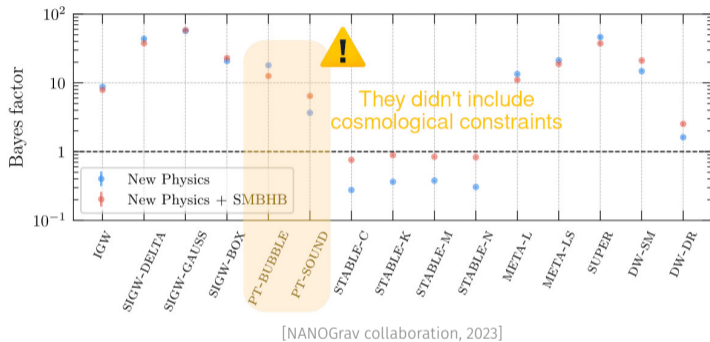
The evidence for a dark sector phase transition.



A kitchen scene is shown in the foreground, featuring a stainless steel pot on a gas stove with a blue flame. To the left of the stove is a white teapot, a glass bottle, and a plate of fruit. To the right is a white container with a fork and spoon, and another plate of fruit. The background is a vibrant, colorful cosmic scene with galaxies, nebulae, and a large question mark in the center. Numerous smaller question marks are scattered throughout the background.

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

The evidence for new physics.



- New physics matches spectra better than (only) astrophysics
- 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 cosmological explanations will be practically dead.

Take-home messages.

- We are for the first time able to probe the early Universe before BBN!
- New physics can explain the signal better than astrophysics.
- 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.
- Ongoing: include constraints in other PTA model comparisons.

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

Do you have any
questions?

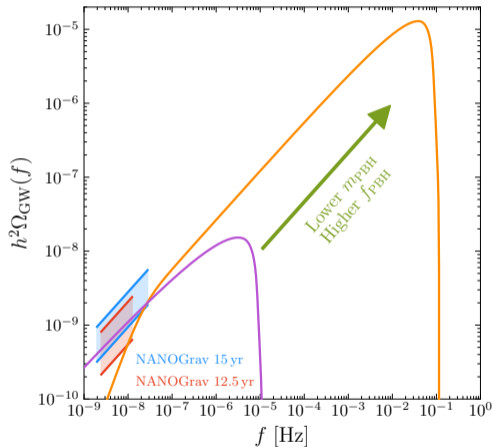


Backup slides.



Merging primordial black holes.

Gravitational waves from primordial black hole mergers.

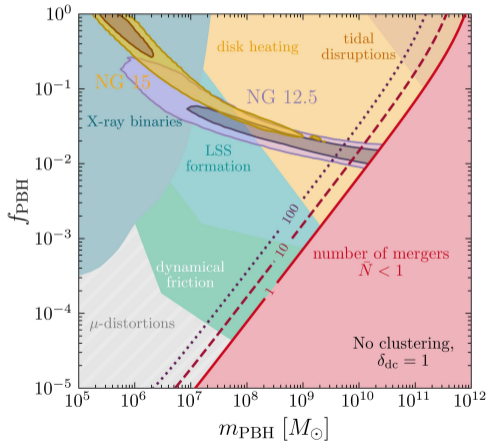


- Inflation leaves large super-Hubble density perturbations
- Black holes form when these come into causal contact again, long before the death of the first stars



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

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?

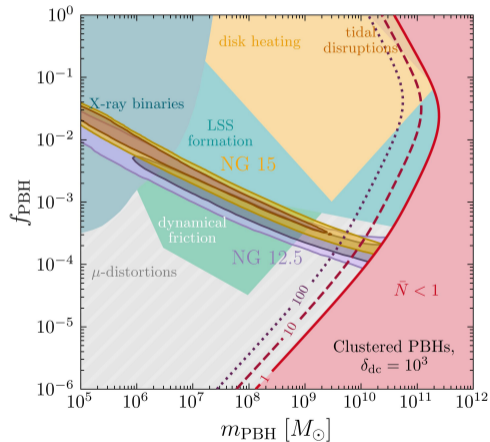
$\delta_{\text{dc}} = 1$: Poisson-distributed PBHs



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



Clustered PBHs can explain the PTA data.

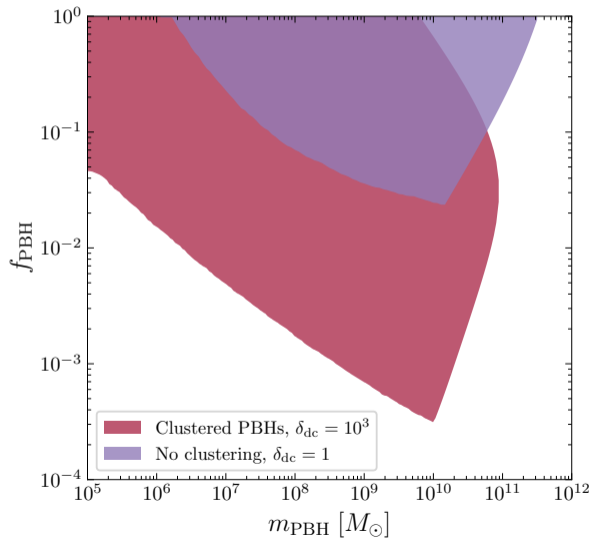


[CT et al., 2023]

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

Clustered PBHs can explain the PTA data!

In any case: we can derive cool new bounds.



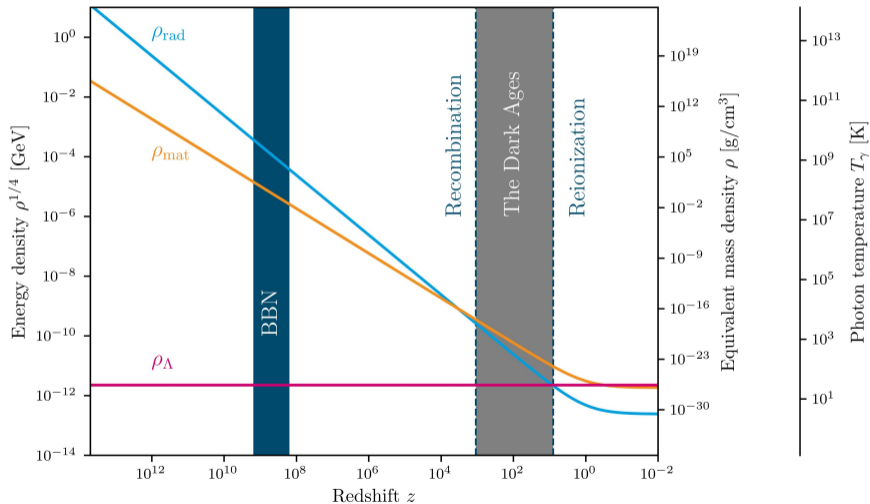
How the density contrast increases the merger rate

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

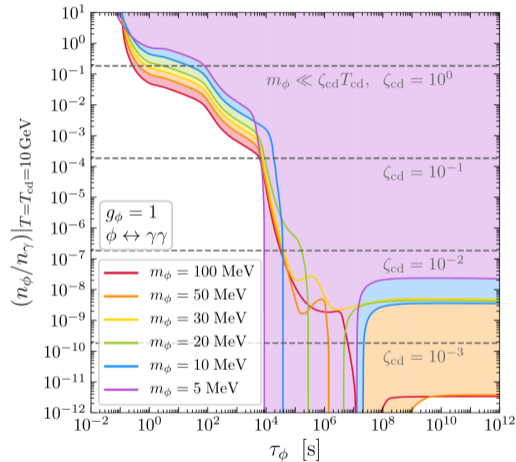
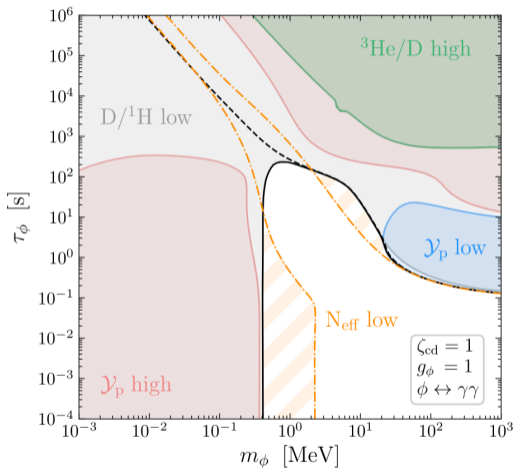
With:

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

A brief history of time: LCDM.

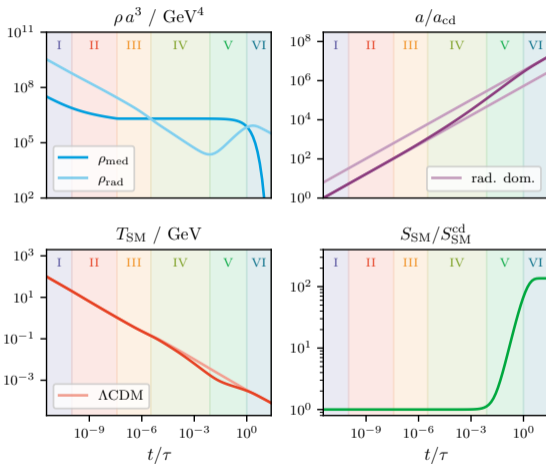


Electromagnetic scalar decays at MeV temperatures.



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

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

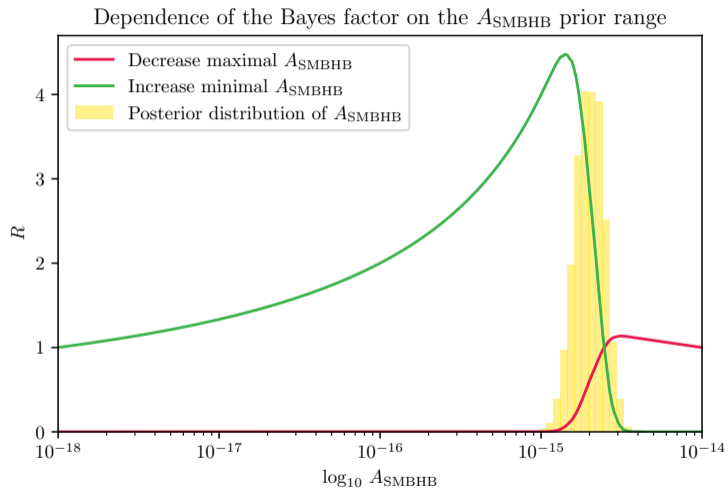


Energy densities $\rho_i(t)$ \rightsquigarrow Scale factor $a(t)$ \rightsquigarrow Temperatures $T_{\text{SM}/\text{DS}}(t)$ \rightsquigarrow Particle content $\rightsquigarrow \rho_i(t)$ \rightsquigarrow ...

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.

