Exploring new physics with pulsar timing arrays.

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

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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.

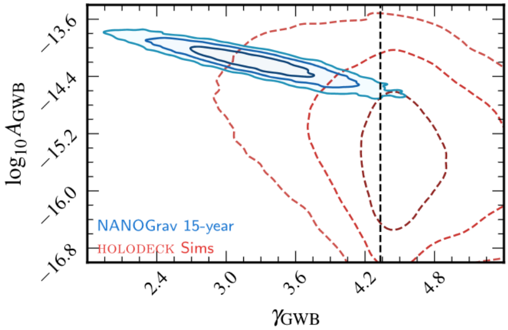
1. The PTA signal
2. Phase transitions vs. precision cosmology
3. BSM or boring?

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

In case you haven't heard the news.

GW background from supermassive black hole binaries.

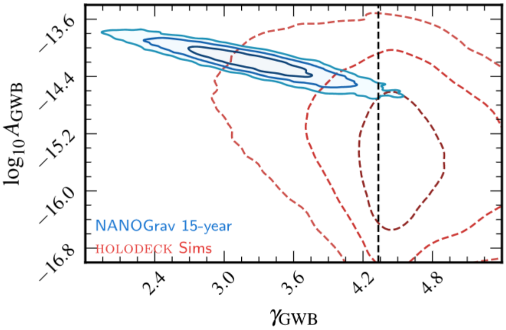
- The observed GW spectrum is consistent with a power-law shape of amplitude A and slope γ



[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]



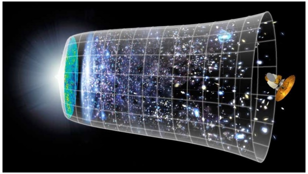
[NANOGrav collaboration, 2023]

What other signal sources are thinkable?

Possible cosmological sources of the nHz background.

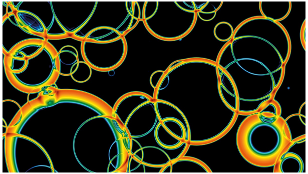
Inflation

Reentering of tensor fluctuations



Phase transitions

Connection to dark matter?

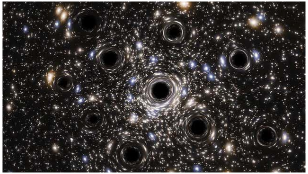


Topological defects

Cosmic strings and domain walls

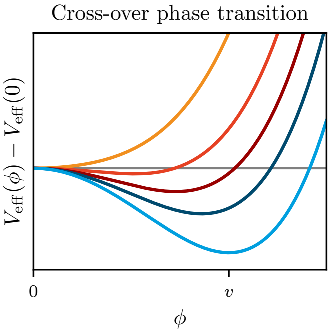
Scalar perturbations

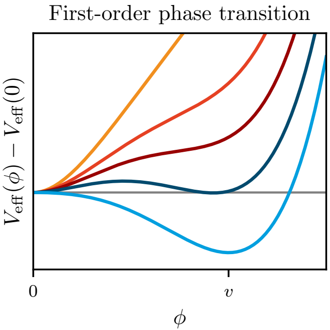
Incl. primordial black hole formation



Gravitational waves from dark sector phase transitions.

Cosmological phase transitions.



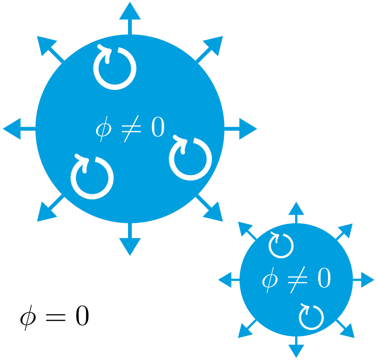


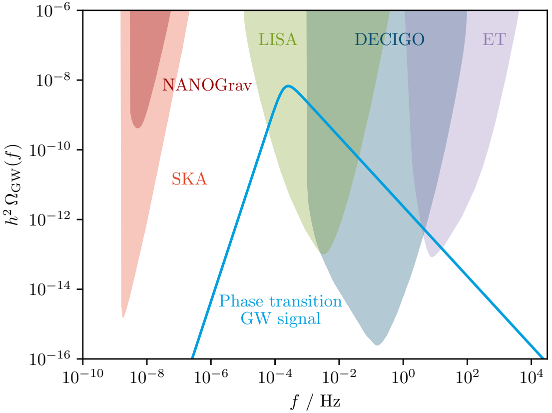
A scalar field "rolls down" from $\phi = 0$ to $\phi = v$, when the bath cools from high temperatures to low temperatures.

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.

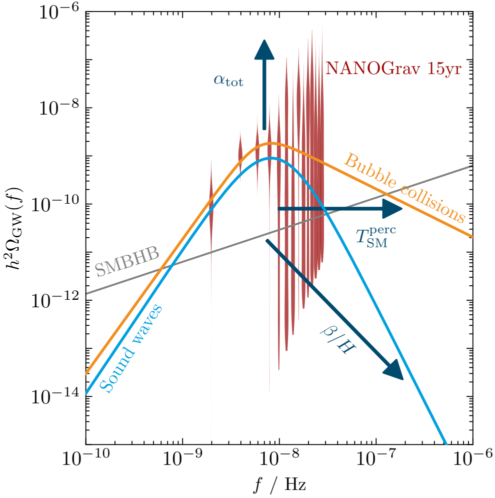
Bubbles of the new phase nucleate, collide and perturb the plasma...





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

Parametrization of the GW signal.



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

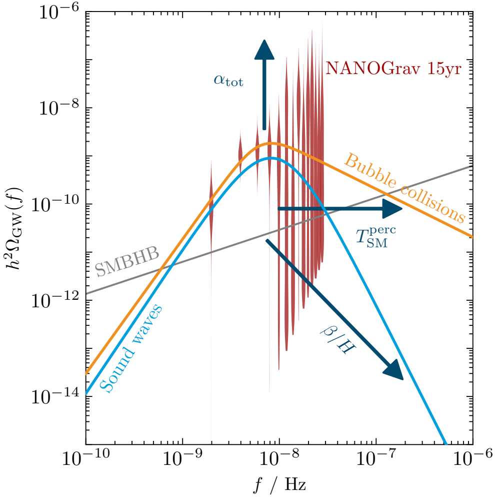
$$h^2\Omega_{GW}^{sw,bw}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{peak}}\right)$$

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

To fit the new pulsar timing data:

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

Parametrization of the GW signal.



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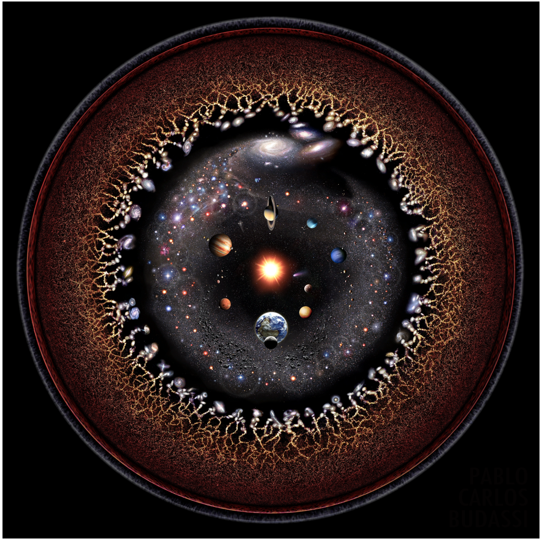
But there's no SM phase transition at 10 MeV?!

What do we know about the early Universe?

What we know about our Universe.

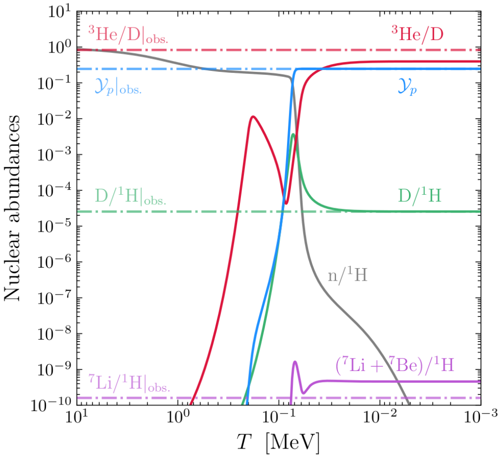


[Pablo Carlos Budassi, 2020]

LCDM:

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

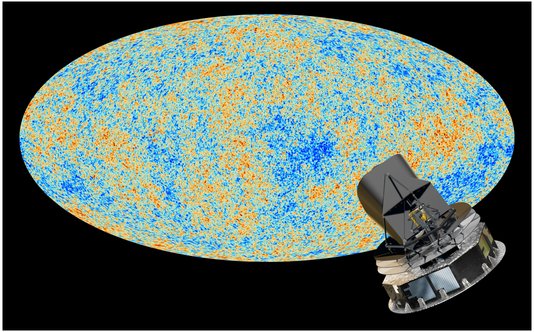
The Big Bang Nucleosynthesis and the CMB.



[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.

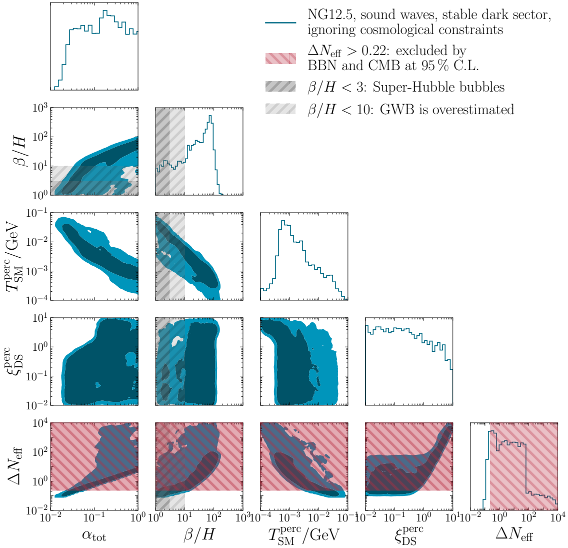
Let's put the transition in a dark sector.

- SM has no MeV phase transition $\rightsquigarrow$ Assume a weakly coupled $\mathcal{O}$(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

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

- **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.

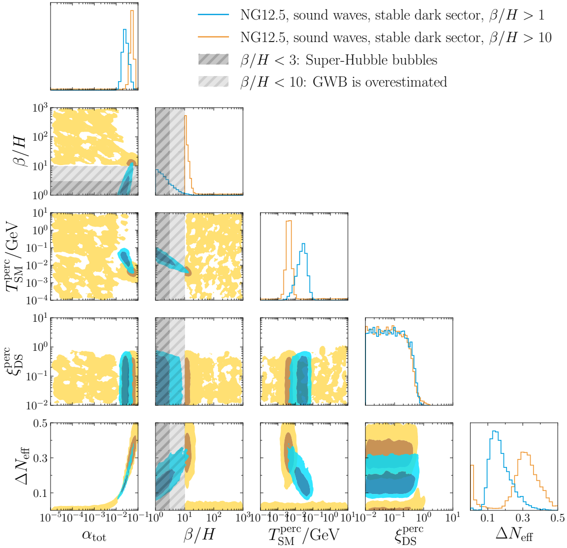


- Performed fit of the pulsar data with NANOGrav's own code `enterprise`
- A good fit requires an enormous reheating of the dark sector: ΔN_{eff} can grow arbitrarily large
- Bubble sizes would need to be super-Hubble to be okay with ΔN_{eff}

  Causality ϟ GW prediction ϟ

⇝ The tension cries for a global fit

Global fits kill stable dark sectors.

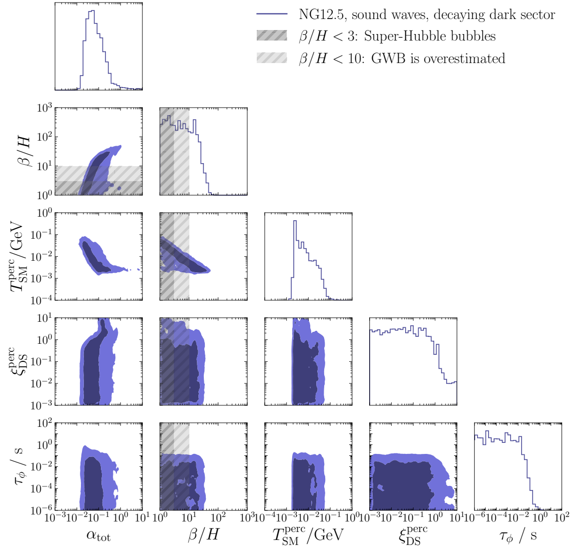


Global fit = compute global maximum of

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

- $\beta/H > 1$: 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!

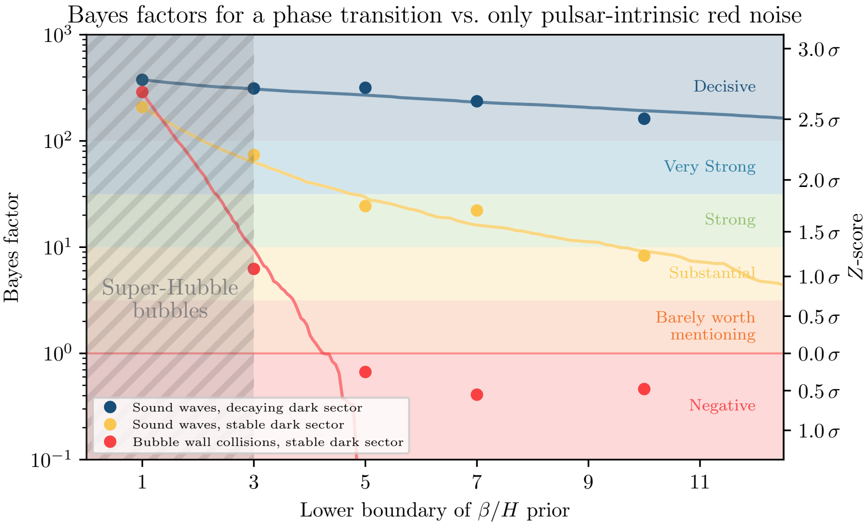
Decays to the rescue.

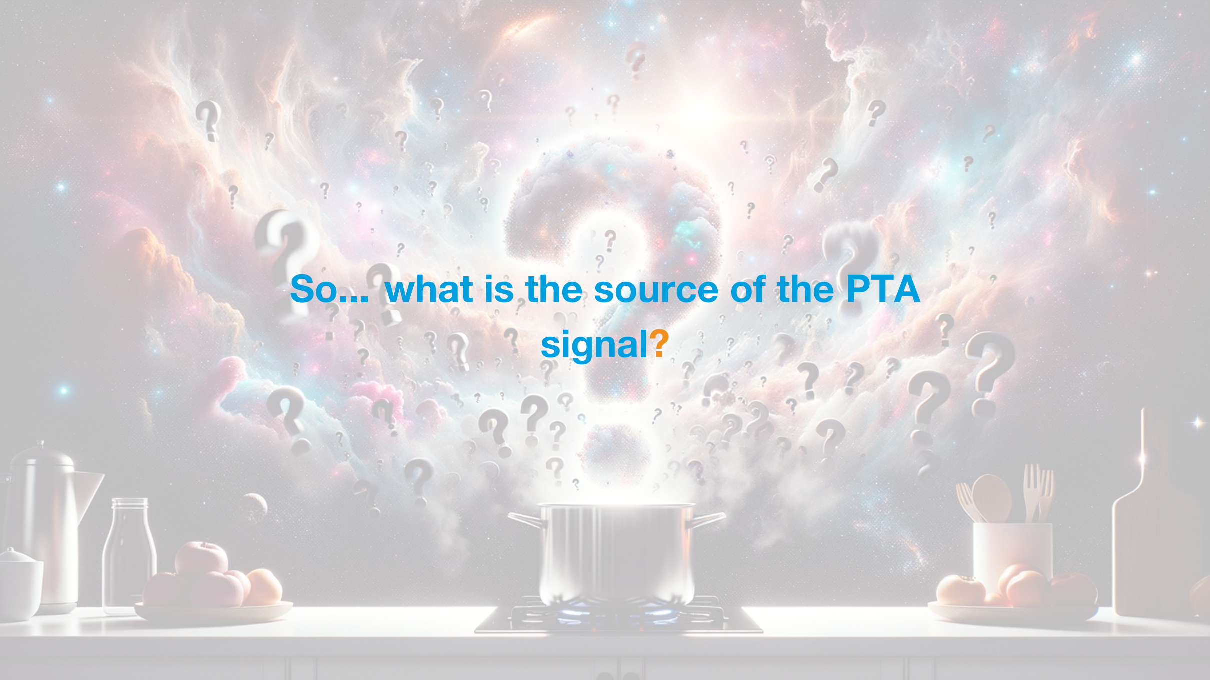


Decays save the fit!

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

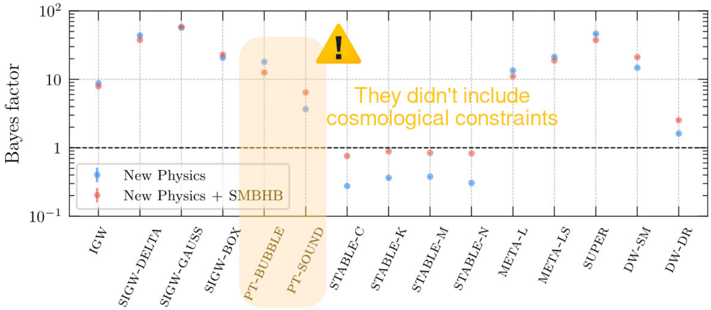
The evidence for a dark sector phase transition.





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

The evidence for new physics.



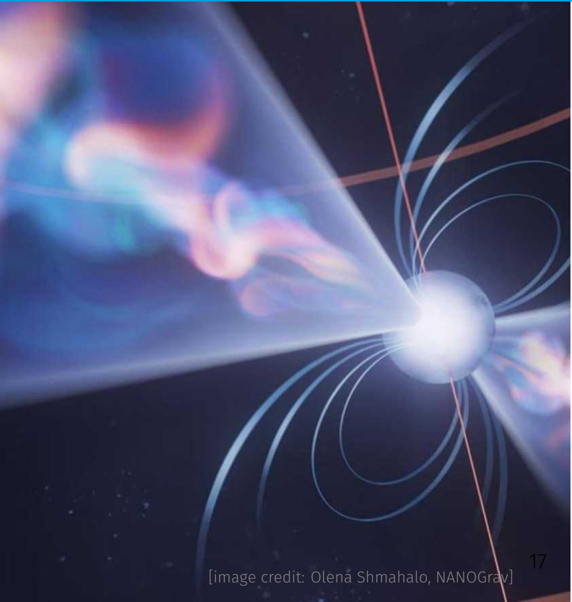
[NANOGrav collaboration, 2023]

- 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.



[image credit: Olena Shmahalo, NANOGrav]

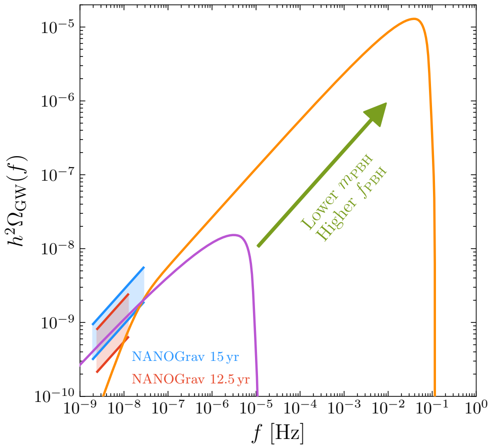
Thank you very much for your attention!

Do you have any questions?

Backup slides.

Merging primordial black holes.

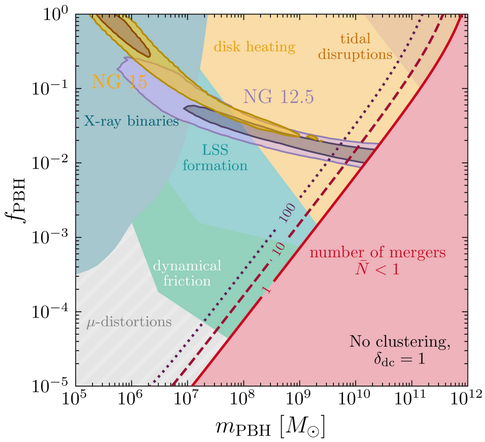
Gravitational waves from primordial black hole mergers.



- 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

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

PBHs without clustering cannot explain the PTA data.



[CT et al., 2023]

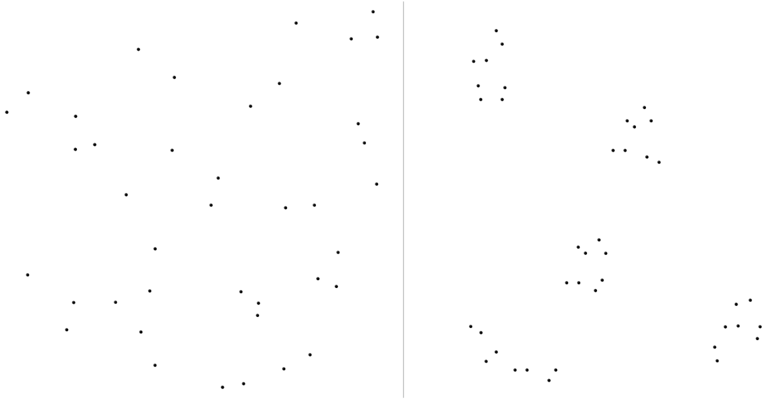
- Scan over $m_{\rm PBH}$ and $f_{\rm PBH}$
- Region favored by PTAs is excluded by astrophysical bounds
- Crucial: exclude regions with small merger numbers. (Atal et al. came to the wrong conclusion [2012.14721].)

Homogeneously distributed PBHs cannot explain the PTA data!

What is clustering?

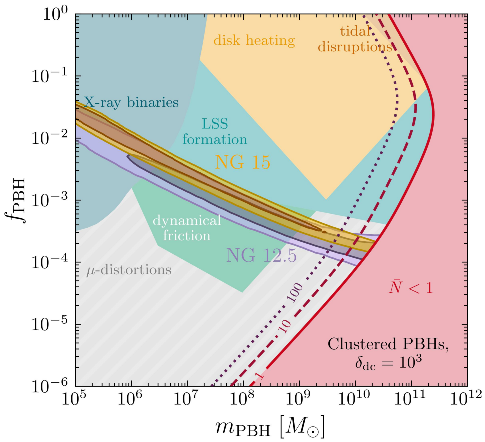
$\delta_{\mathrm{dc}} = 1$: Poisson-distributed PBHs

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



[Paul Frederik Depta, 2023]

Clustered PBHs can explain the PTA data.

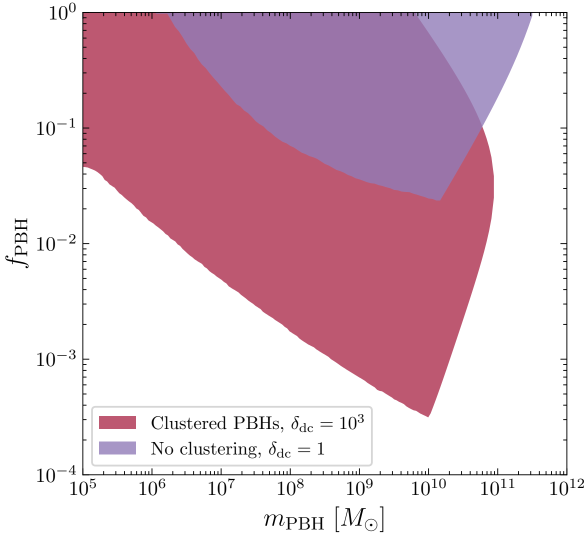


[CT et al., 2023]

- 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!

In any case: we can derive cool new bounds.



How the density contrast increases the merger rate

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

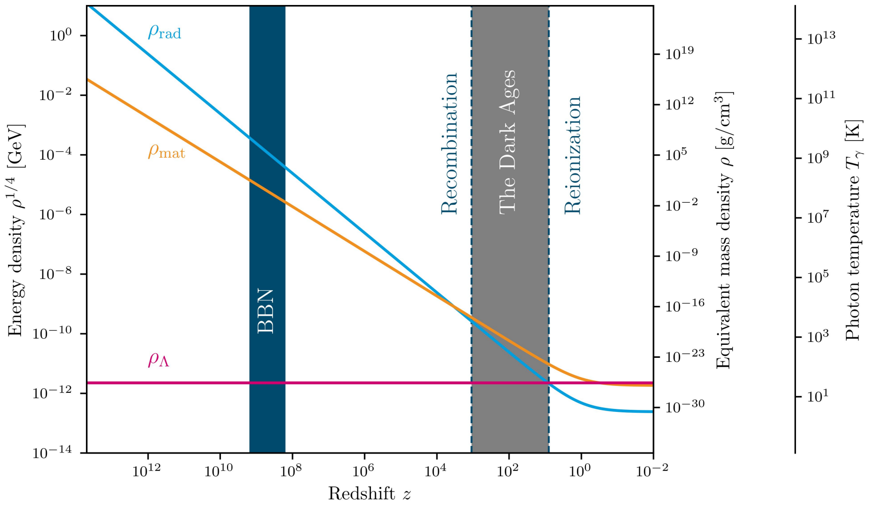
$$R(t) = \int_0^{\tilde{x}} \mathrm{d}x \int_x^{\infty} \mathrm{d}y \frac{\partial^2 n_3}{\partial x \, \partial y} \delta(t - \tau(x,y))$$

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

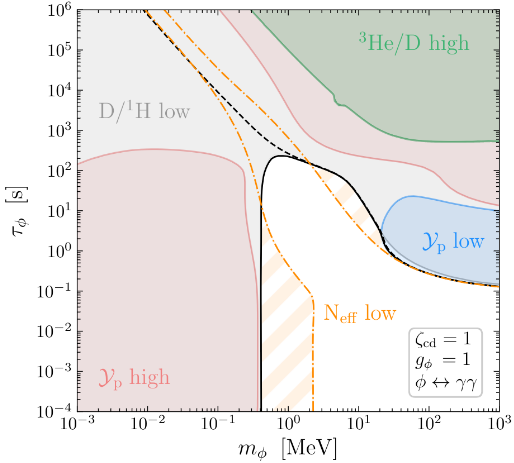
With:

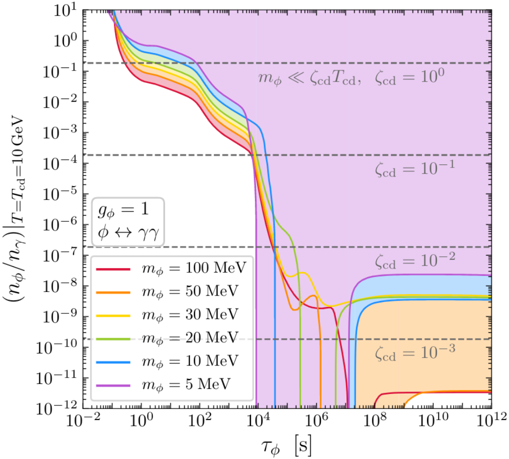
- $\delta_{\mathrm{dc}} \simeq \frac{n^{\mathsf{loc}}_{\mathsf{PBH}}}{\bar{n}^{\mathsf{loc}}_{\mathsf{PBH}}}$: Density contrast
- $x, (y)$: comoving distance of (next-to-) nearest neighbor PBH
- $\tilde{x}$: farthest comoving distance two PBHs can have
- $\tilde{\tau}$: Merger timescale

A brief history of time: LCDM.



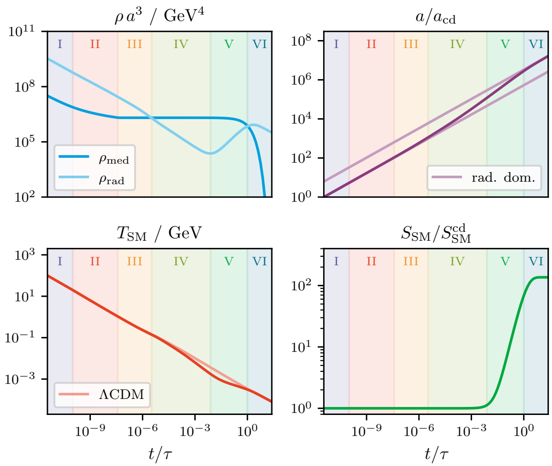
Electromagnetic scalar decays at MeV temperatures.





[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

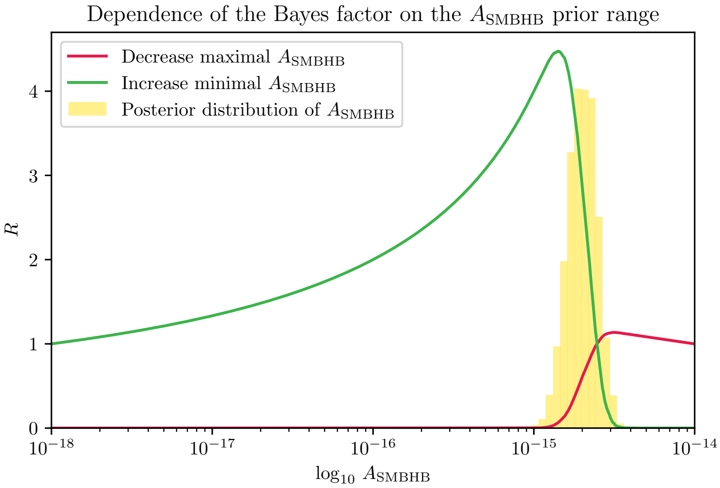
III Non-relativistic mediator

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.