Exploring cosmological phase transitions with pulsar timing arrays.

Theory seminar at Oslo University

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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

March 13, 2024

Outline of this talk.

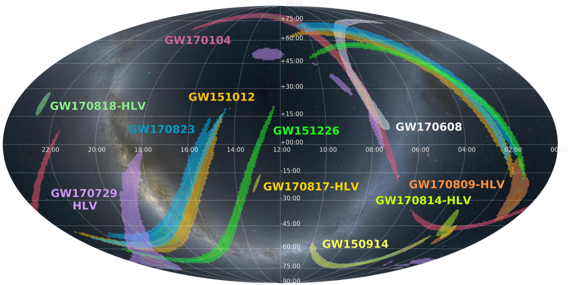
1. The PTA signal
2. Phase transitions vs. precision cosmology
3. BSM or boring?

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

In case you haven’t heard the news.

Gravitational waves observations.

- LIGO + Virgo + KAGRA observed $\simeq 100$ mergers since 2015 [GWTC3]



[LVK, 2020]

Gravitational waves observations.

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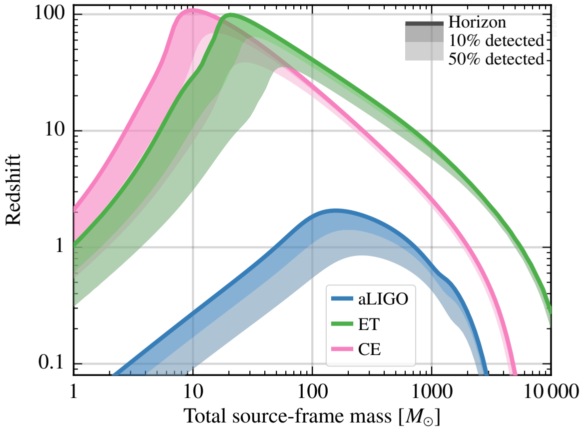
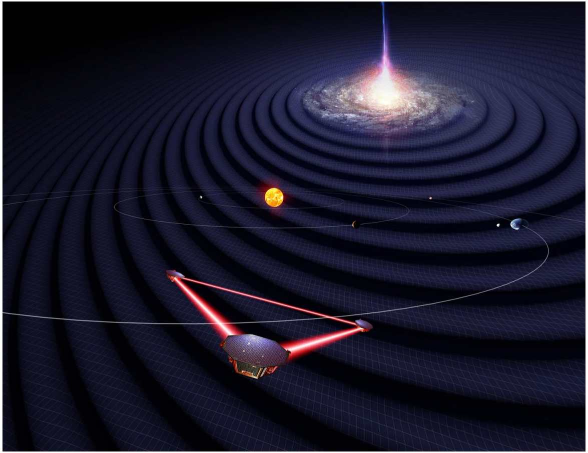
- The Einstein Telescope will probe mergers happening even before star formation times



[Maggiore et al., JCAP 03, 050 (2020)]

Gravitational waves observations.

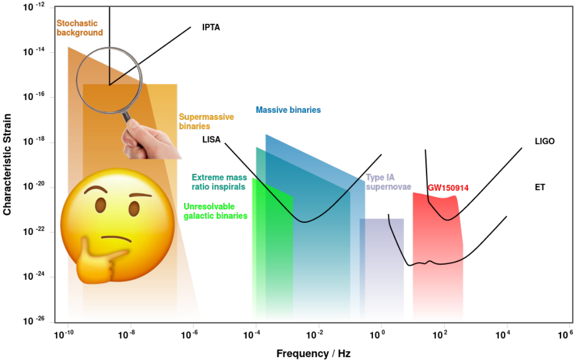
- LIGO + Virgo + KAGRA observed $\simeq 100$ mergers since 2015 [GWTC3]
- The Einstein Telescope will probe mergers happening even before star formation times
- LISA's funding is now confirmed



[University of Florida, Simon Barke (CC BY 4.0)]

Gravitational waves observations.

- LIGO + Virgo + KAGRA observed $\simeq 100$ mergers since 2015 [GWTC3]
- The Einstein Telescope will probe mergers happening even before star formation times
- LISA's funding is now confirmed
- PTAs detected a stochastic GW background at low frequencies!



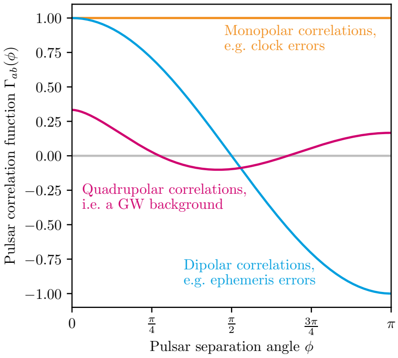
[adapted from gwplotter.com]

Pulsar timing arrays.

Millisecond pulsars emit radio pulses with an extremely stable frequency

- GWs affect propagation time ⇝ observe modulated periodicities
- 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**

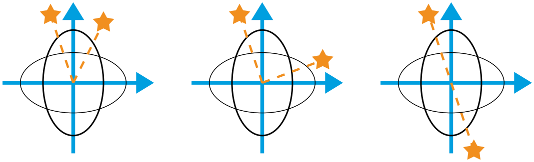
How can we be sure it's actually gravitational waves?



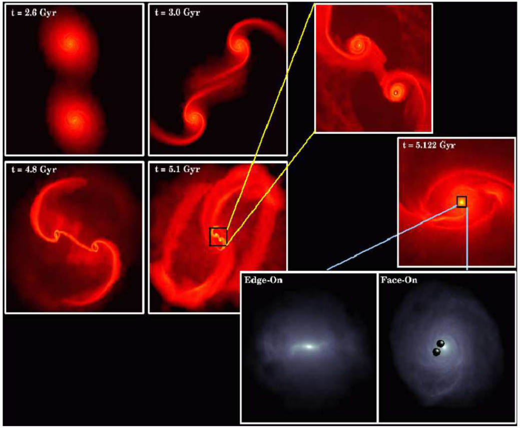
Noise spectra can have many sources:

- 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.



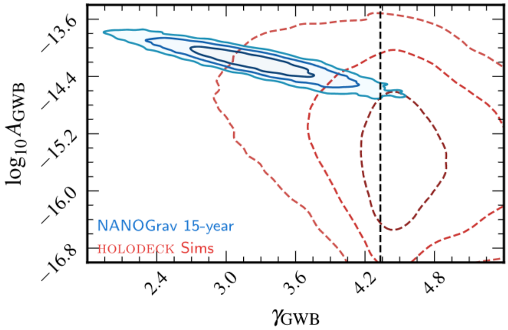
[Mayer et al., 0706.1562; NASA/CXC/A. Hobart]

- Expect **supermassive black hole mergers** after galaxy mergers
- Predictions are hard to obtain (distance hierarchies, extreme environments, unknown astrophysics, ...)
- GW predictions span several orders of magnitude, but approximately follow a power-law:

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

GW background from supermassive black hole binaries.

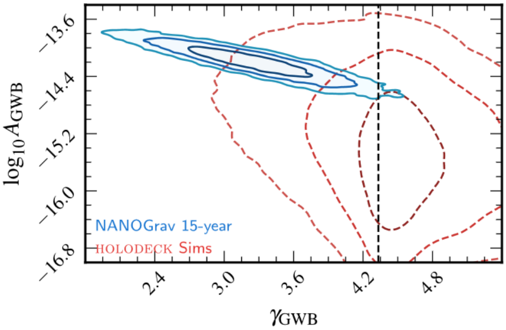
- The observed GW spectrum is consistent with a power-law of amplitude A and slope γ



[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
- Additional contribution from merging primordial black holes? [CT+, 2306.17836]



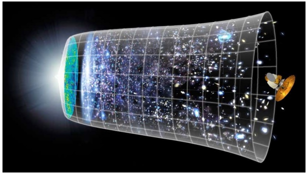
[NANOGrav collaboration, 2023]

What other signal sources are thinkable?

Possible cosmological sources of the nHz background.

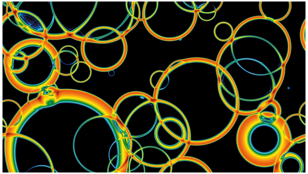
Inflation

Reentering of tensor fluctuations



Phase transitions

Connection to dark matter?

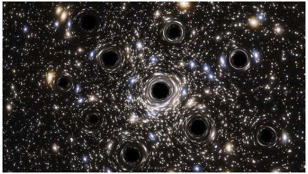


Topological defects

Cosmic strings and domain walls

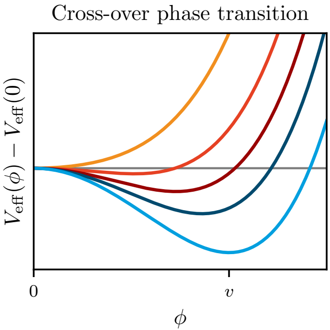
Scalar perturbations

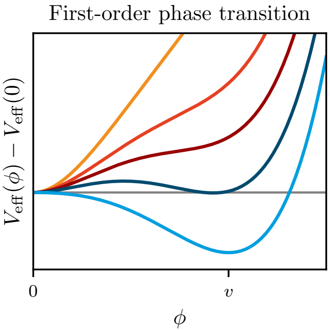
Incl. primordial black hole formation



Gravitational waves from dark sector phase transitions.

Cosmological phase transitions.



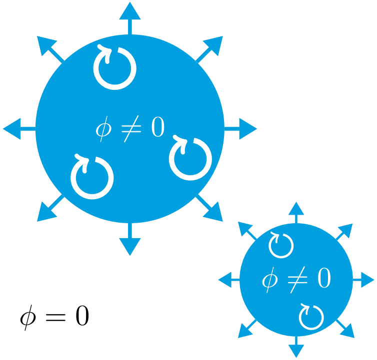


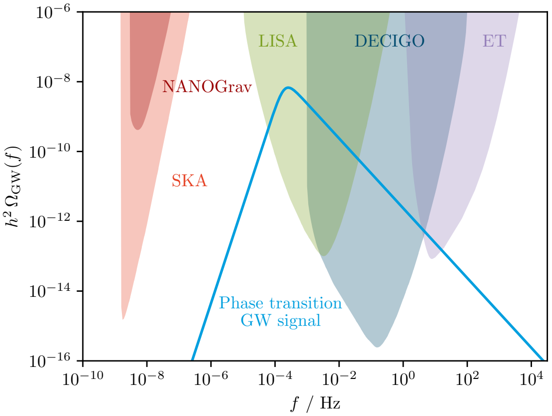
A scalar field "rolls down" from $\phi = 0$ to $\phi = v$, when the bath cools from high temperatures to low temperatures.

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.

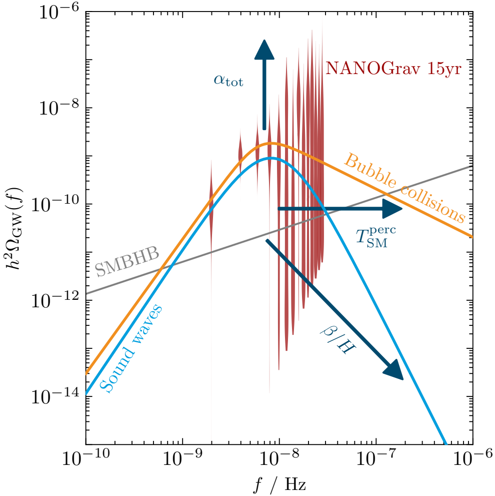
Bubbles of the new phase nucleate, collide and perturb the plasma...





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

Parametrization of the GW signal.



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

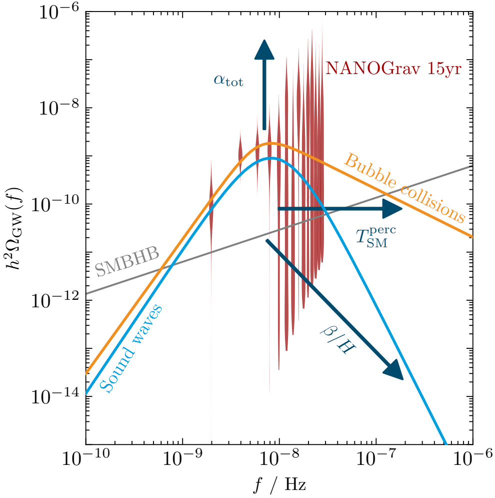
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

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

To fit the new pulsar timing data:

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

Parametrization of the GW signal.



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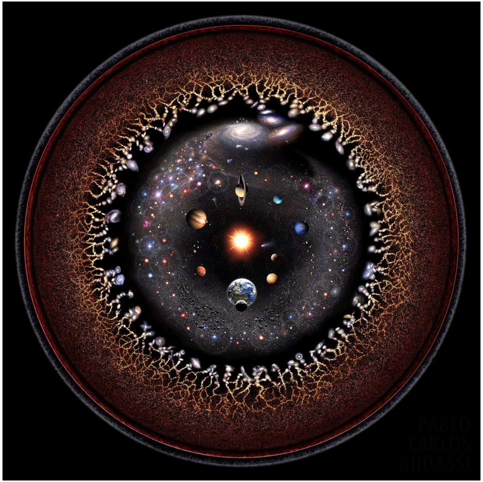
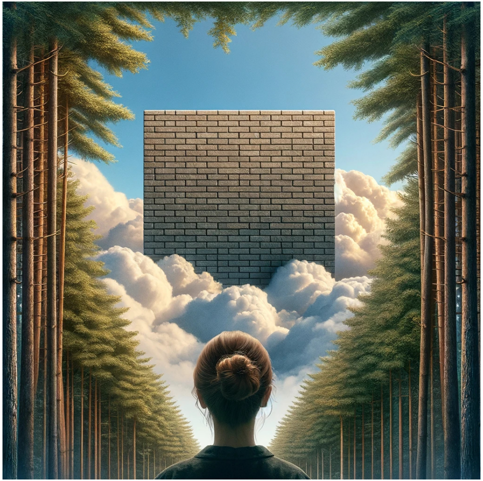
But there's no SM phase transition at 10 MeV?!

What do we know about the early Universe?

What we know about our Universe.

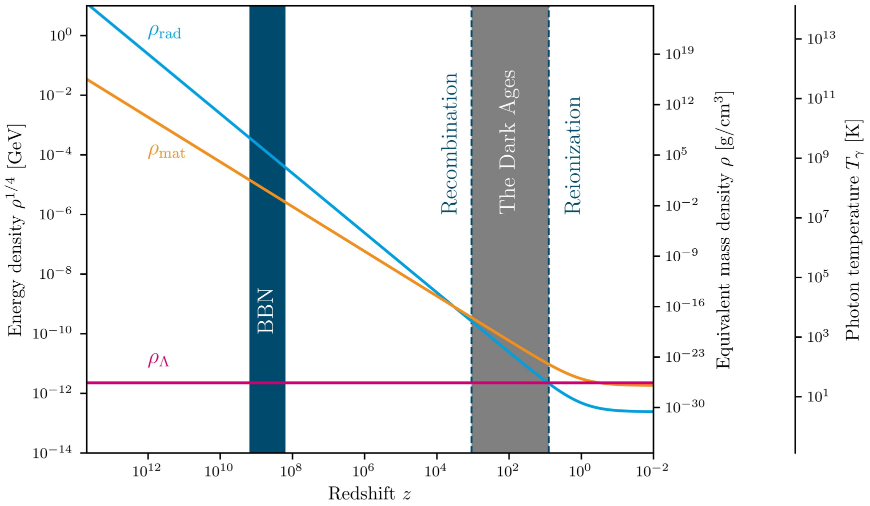


[Pablo Carlos Budassi, 2020]

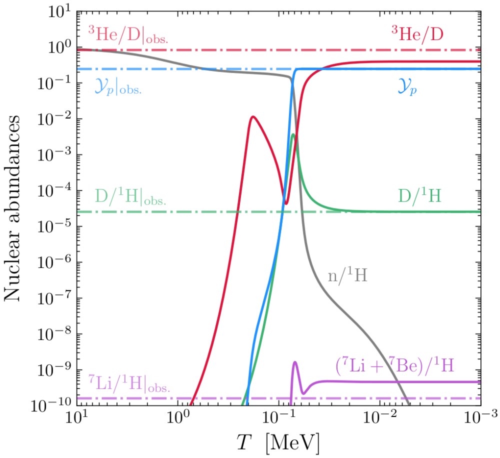


[ChatGPT when asked to depict CT's intuition for the CMB]

A brief history of time.



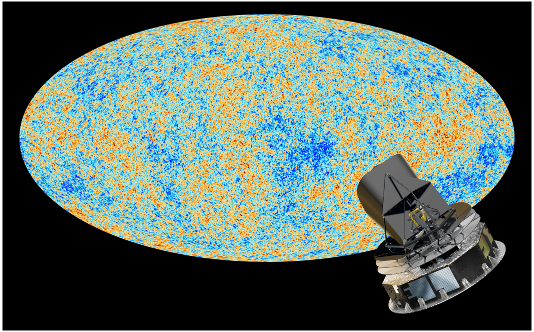
The Big Bang Nucleosynthesis and the CMB.



[Paul Frederik Depta, 2021]

- Observations of primordial light element abundances in good agreement with standard BBN
- $N_{\rm eff}^{\rm BBN} = 2.898 \pm 0.141$ [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 are ruled out after $t \gtrsim 1\,\text{s}$, i.e. $T \lesssim 1\,\text{MeV}$.

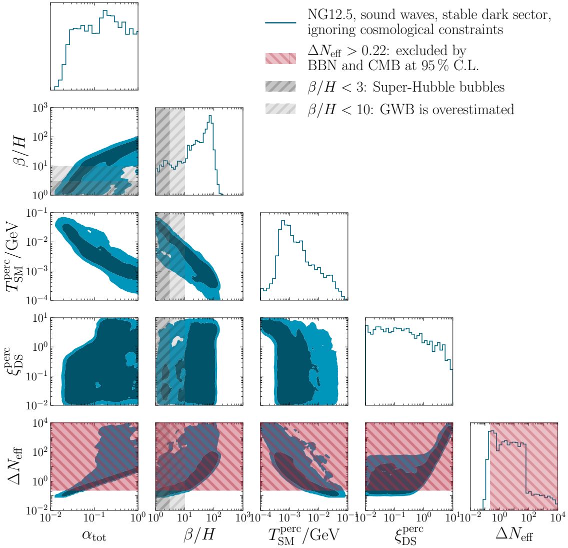
Let's put the transition in a dark sector.

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

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

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

The tension between PTAs, CMB and BBN.

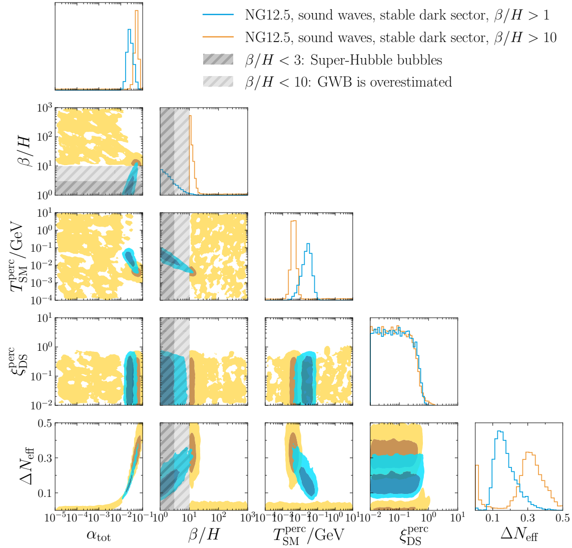


- Performed fit of the pulsar data with NANOGrav's own code `enterprise`
- A good fit requires an enormous reheating of the dark sector: $\Delta N_{\rm eff}$ can grow arbitrarily large
- Bubble sizes would need to be super-Hubble to be okay with $\Delta N_{\rm eff}$

  Causality ϟ GW prediction ϟ

⇝ The tension cries for a global fit

Global fits.

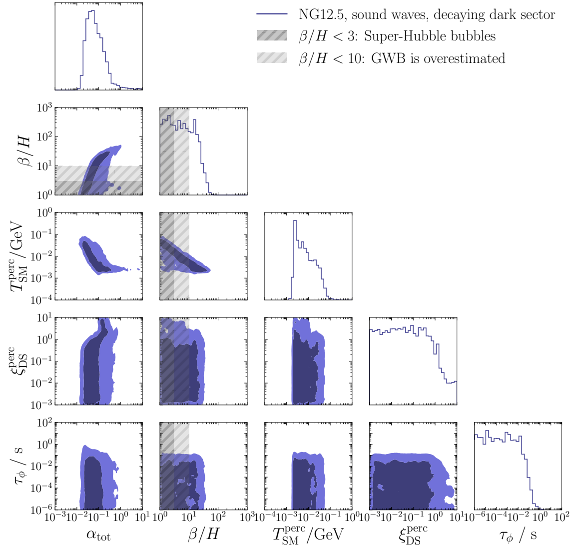


Global fit = compute global maximum of

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

- $\beta/H > 1$: would be a good fit, if the GW spectrum were reliable…
- $\beta/H > 10$: spectra reliable, but GWs from phase transition still come with high penalty $\rightsquigarrow$ “Shot” noise.

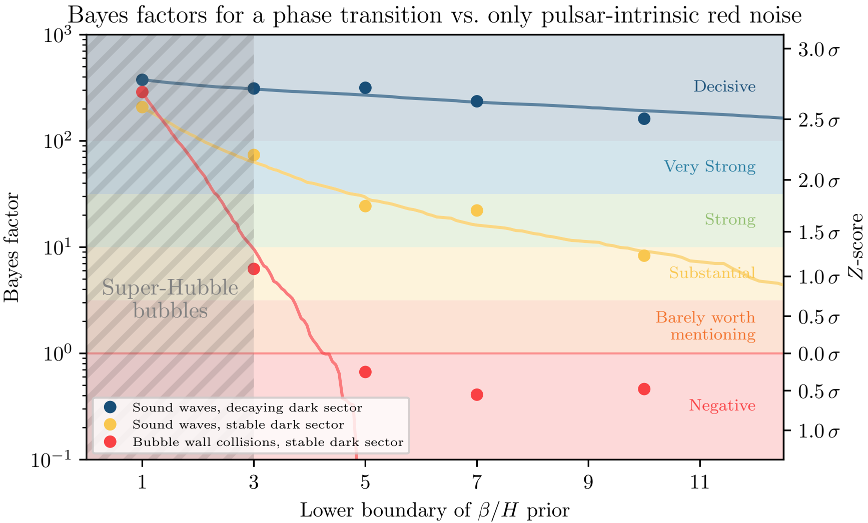
Decays to the rescue.

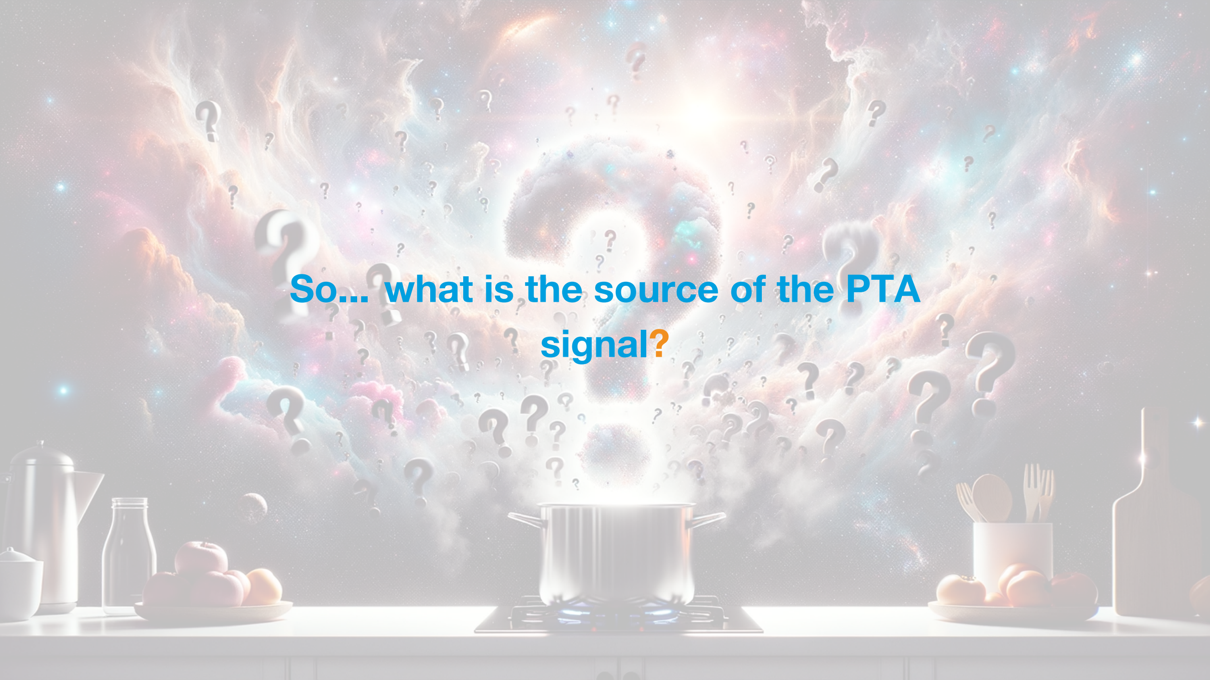


Decays save the phase transition interpretation!

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

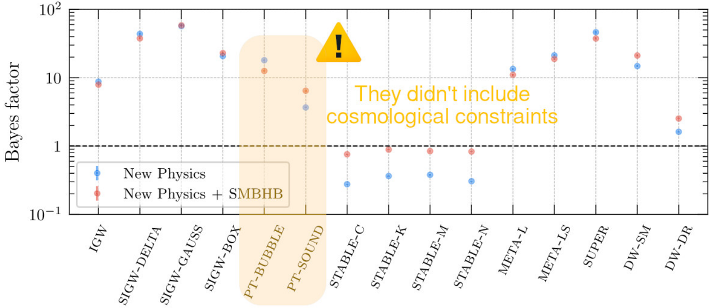
The evidence for a dark sector phase transition.





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

The evidence for new physics.



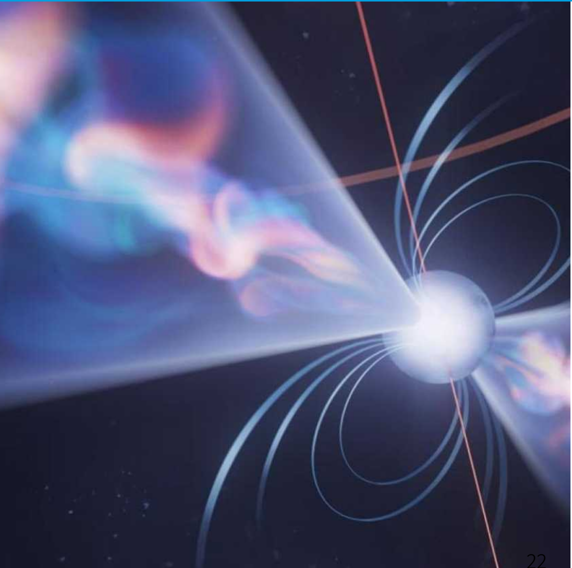
[NANOGrav collaboration, 2023]

- 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 work with Torsten: Study viability of specific dark sector models.



[image credit: Olena Shmahalo, NANOGrav]

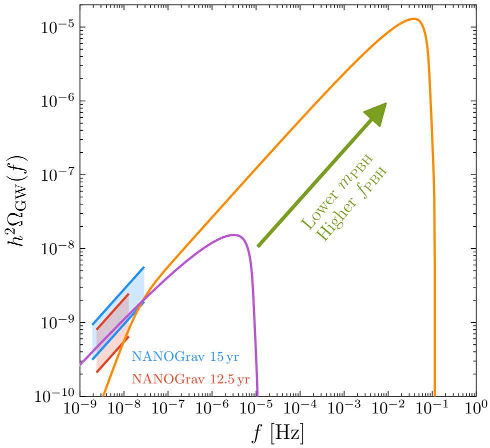
Thank you very much for your attention!

Do you have any questions?

Backup slides.

Merging primordial black holes.

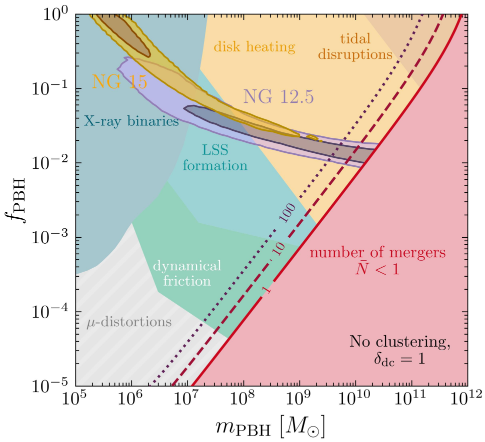
Gravitational waves from primordial black hole mergers.



- 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

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

PBHs without clustering cannot explain the PTA data.



[CT et al., 2023]

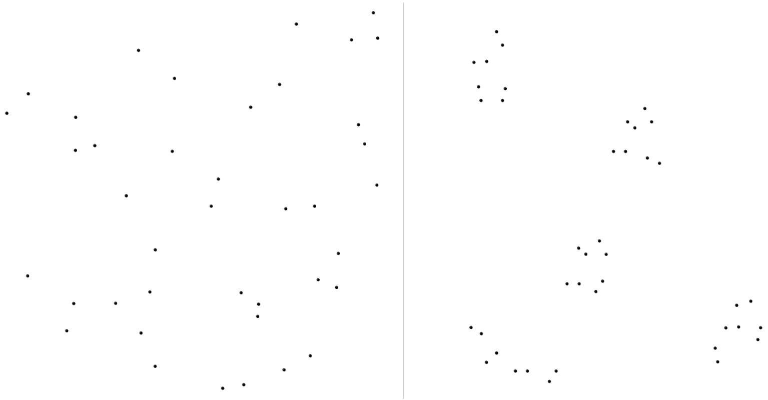
- Scan over $m_{\rm PBH}$ and $f_{\rm PBH}$
- Region favored by PTAs is excluded by astrophysical bounds
- Crucial: exclude regions with small merger numbers. (Atal et al. came to the wrong conclusion [2012.14721].)

Homogeneously distributed PBHs cannot explain the PTA data!

What is clustering?

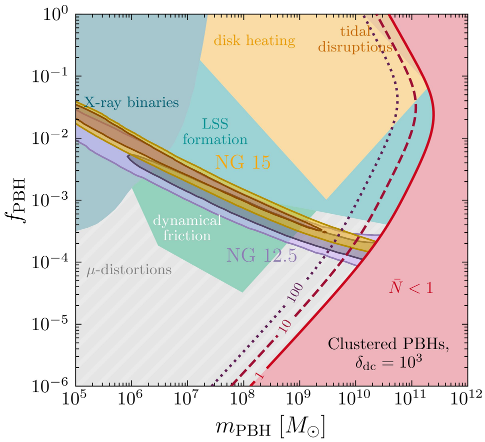
$\delta_{\rm dc} = 1$: Poisson-distributed PBHs

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



[Paul Frederik Depta, 2023]

Clustered PBHs can explain the PTA data.

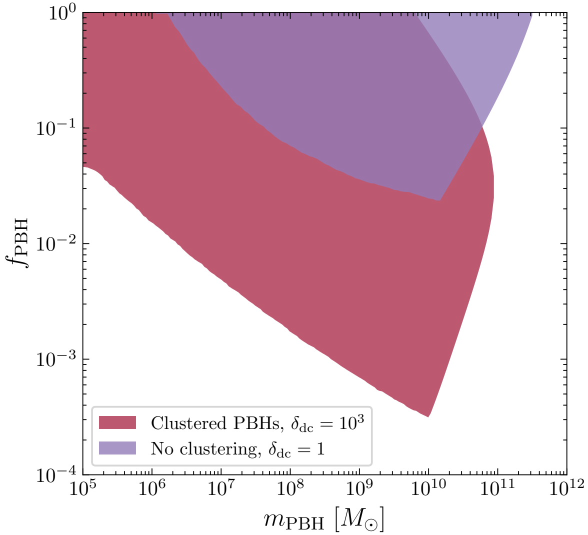


[CT et al., 2023]

- 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

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

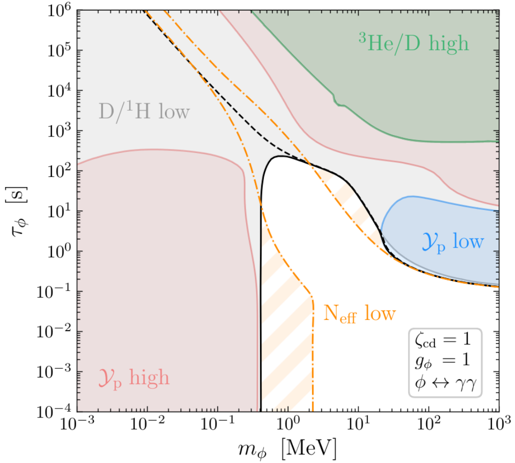
$$R(t) = \int_0^{\tilde{x}} \mathrm{d}x \int_x^{\infty} \mathrm{d}y \frac{\partial^2 n_3}{\partial x \, \partial y} \delta(t - \tau(x, y))$$

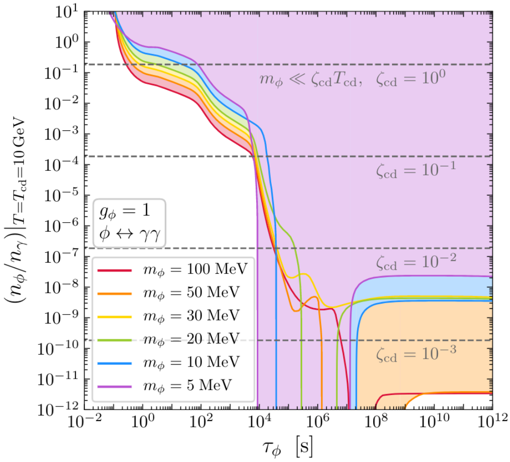
$$\propto \frac{\delta_{\mathrm{dc}}{}^{16/37}}{\tilde{x}^3 \tilde{\tau}} \left(\frac{t}{\tilde{\tau}} \right)^{-34/37} \left(\Gamma \left[\frac{58}{37}, \frac{4\pi}{3} \tilde{x}^3 \delta_{\mathrm{dc}} n_{\mathrm{PBH}} \left(\frac{t}{\tilde{\tau}} \right)^{3/16} \right] - \Gamma \left[\frac{58}{37},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

With:

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

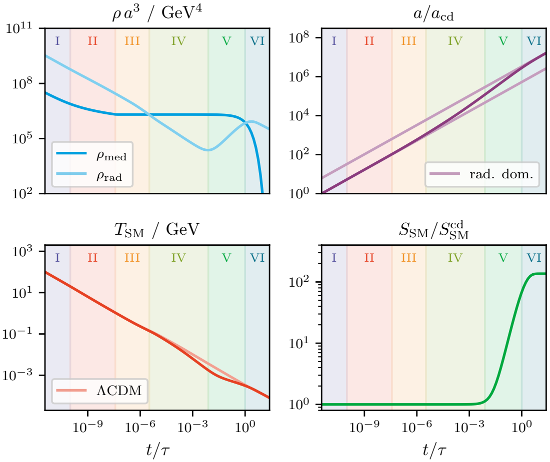
Electromagnetic scalar decays at MeV temperatures.





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

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

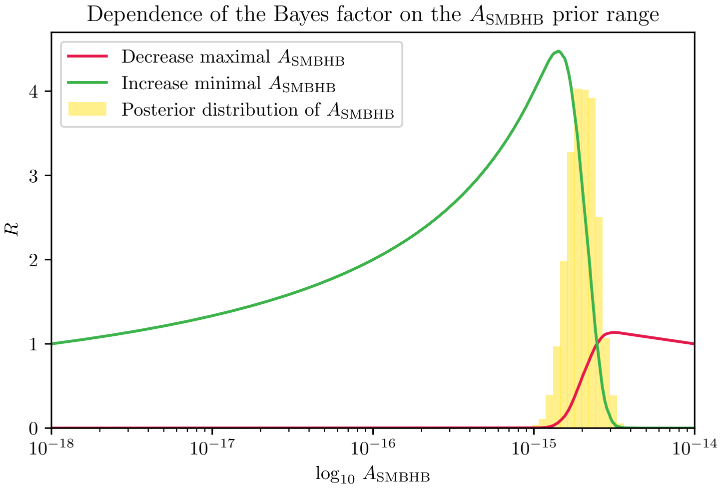


Energy densities $\rho_i(t)$ $\overset{\text{sets}}{\rightsquigarrow}$ Scale factor $a(t)$ $\overset{\text{sets}}{\rightsquigarrow}$ Temperatures $T_{\mathrm{SM/DS}}(t)$ $\overset{\text{set}}{\rightsquigarrow}$ Particle content $\overset{\text{sets}}{\rightsquigarrow}$ $\rho_i(t)$ $\overset{\text{sets}}{\rightsquigarrow}$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

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.