

Exploring new physics with pulsar timing arrays.

Colloquium at Karlsruhe Institute of Technology

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JCAP 11 (2023) 053 and [2306.17836]

June 26, 2024



Outline of this talk.

1. The PTA signal
2. Phase transitions vs. precision cosmology
3. Clustered PBHs
4. 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
Scientists have 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

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 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
Scientists have detected a never-before-seen type of gravitational wave produced 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

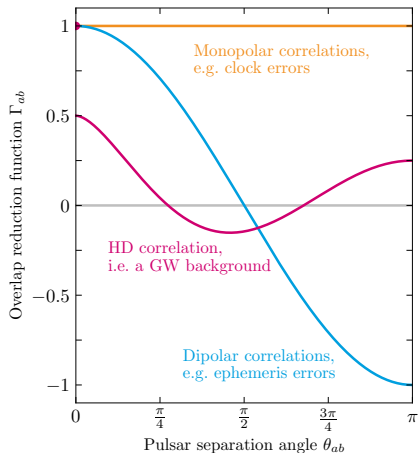
Pulsar timing arrays.



Millisecond pulsars emit radio pulses with an extremely stable frequency

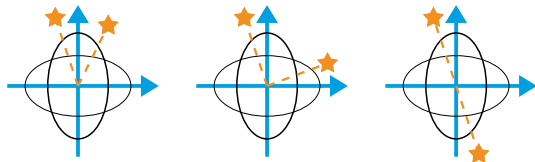
- GWs affect propagation time \rightsquigarrow modulate observed pulse frequency
- PTAs monitor pulse frequency using radio telescopes on Earth
- Fit pulse data with timing model
- Fourier decomposition of timing residuals shows **common spectrum**, which is **due to GWs**

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

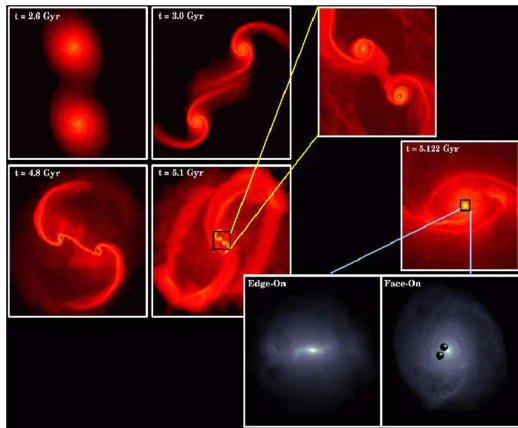


Noise spectra can have many sources:

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



Merging supermassive black hole binaries.



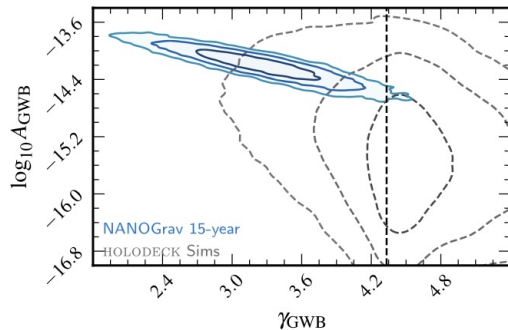
[Mayer et al., 0706.1562; NASA/CXC/A. Hobart]

- Expect **supermassive black hole mergers** after galaxy mergers
- Predictions are hard to obtain (distance hierarchies, extreme environments, final pc problem, ...)
- GW predictions span several orders of magnitude, but approximately follow a power-law with $\gamma = 4.\bar{3}$

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

GW background from supermassive black hole binaries.

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

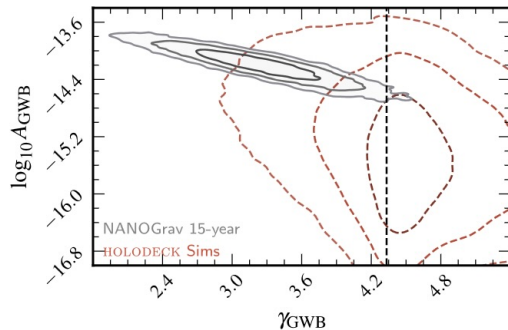


[NANOGrav collaboration, 2023]

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

The standard explanation is off! Other signal sources?

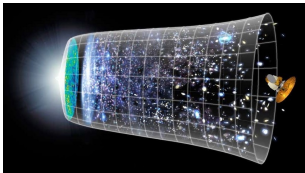


[NANOGrav collaboration, 2023]

Possible cosmological sources of the nHz background.

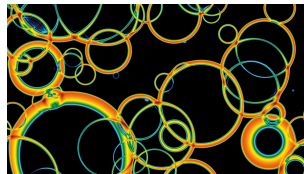
Inflation

Reentering of tensor fluctuations



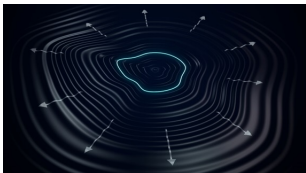
Phase transitions

Connection to dark matter?



Topological defects

Cosmic strings and domain walls



Primordial black holes

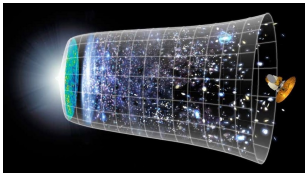
But only if they are clustered...



Possible cosmological sources of the nHz background.

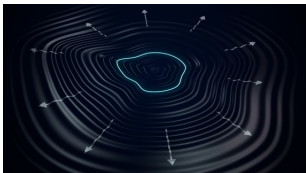
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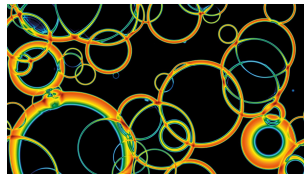
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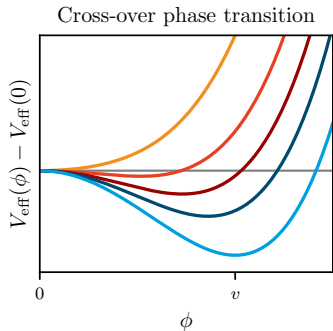
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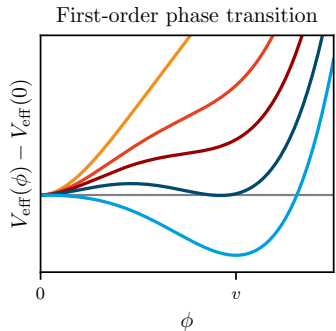
The background of the slide is a vibrant, abstract representation of the universe. It features a complex network of glowing filaments and numerous spherical structures that resemble bubbles or galaxies. The color palette is dominated by deep blues, purples, and magentas, with bright, fiery orange and yellow highlights that suggest intense energy or star formation. The overall effect is one of dynamic movement and cosmic scale.

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

Cosmological phase transitions.



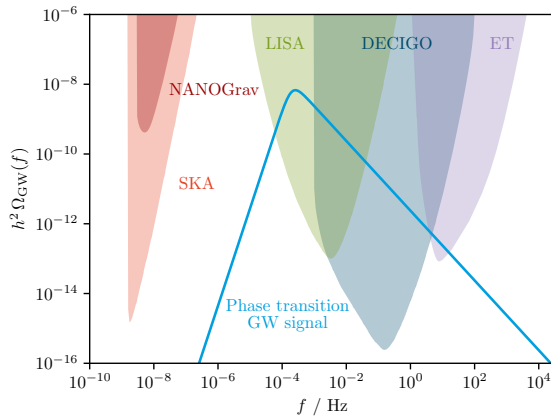
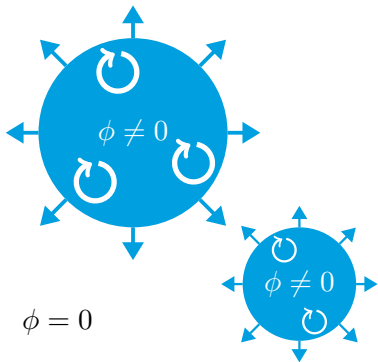
A scalar field “rolls down” from $\phi = 0$ to $\phi = v$, when the bath cools from **high temperatures** to **low temperatures**.



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

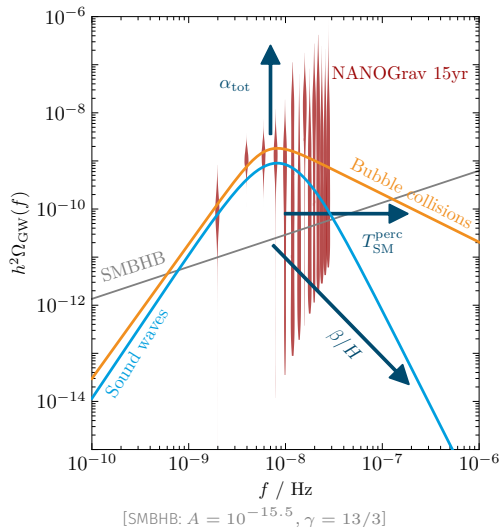
Gravitational waves from first-order phase transitions.

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.



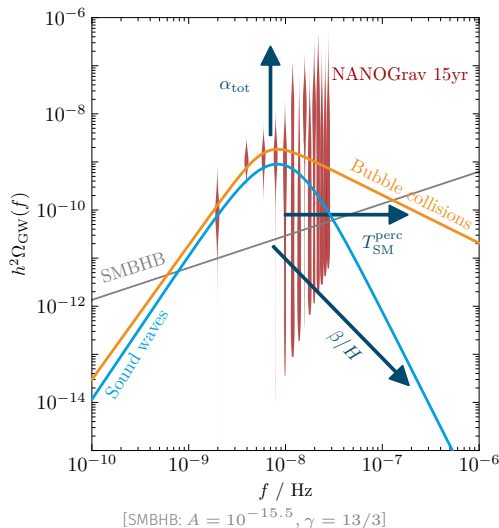
$$h^2 \Omega_{\text{GW}}^{\text{sw,bw}}(f) \simeq 10^{-6} \left(\frac{\alpha}{\alpha + 1} \right)^2 \left(\frac{H}{\beta} \right)^{1,2} \mathcal{S} \left(\frac{f}{f_{\text{peak}}} \right)$$

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

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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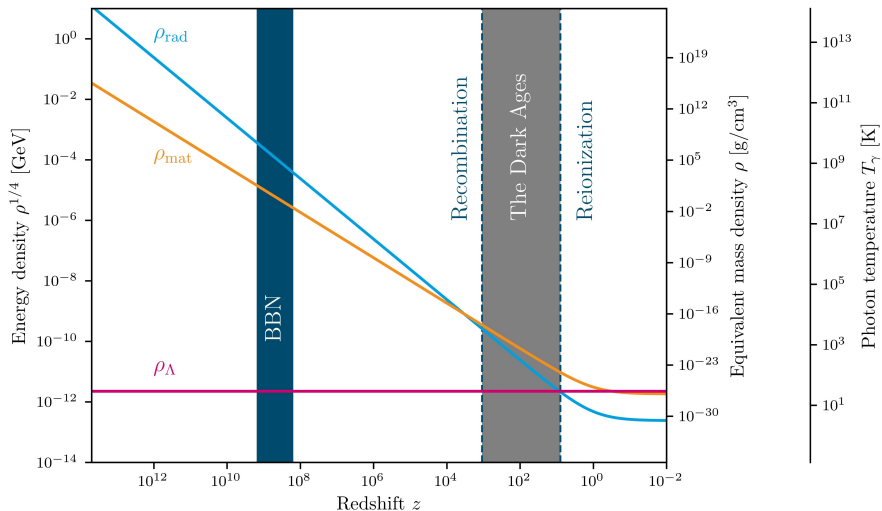
- Strong transitions, $\alpha \simeq \frac{\Delta V}{\rho_{\text{tot}}} \approx 1$
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But there's no SM phase transition at 10 MeV?!

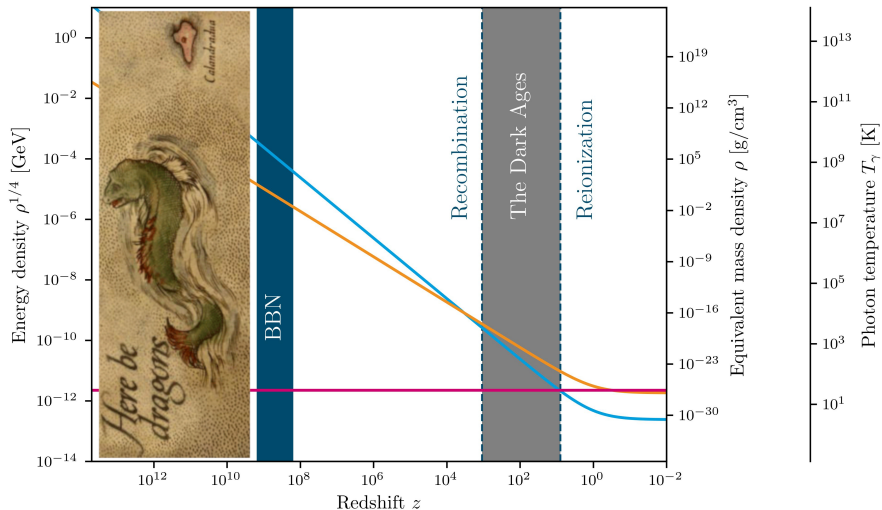
A medieval manuscript illustration. In the foreground, a scholar in a red robe and cap is shown from the side, looking up at a vast, blue sky filled with numerous yellow stars. The sky is divided by a diagonal line. To the right, a large, bright sun with a human face and long rays shines over a landscape.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

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

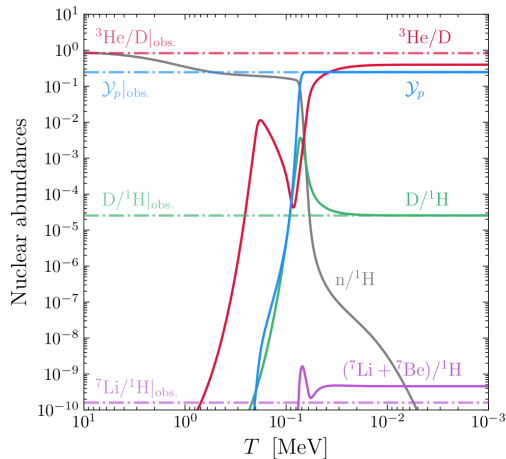
A brief history of time.



A brief history of time.



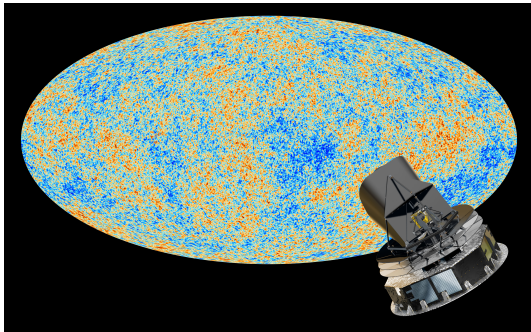
The Big Bang Nucleosynthesis and the CMB.



[Paul Frederik Depta, 2021]

- Observations of primordial light element abundances in excellent 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 excellent 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+, 2012.02726]
- ⇒ 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.

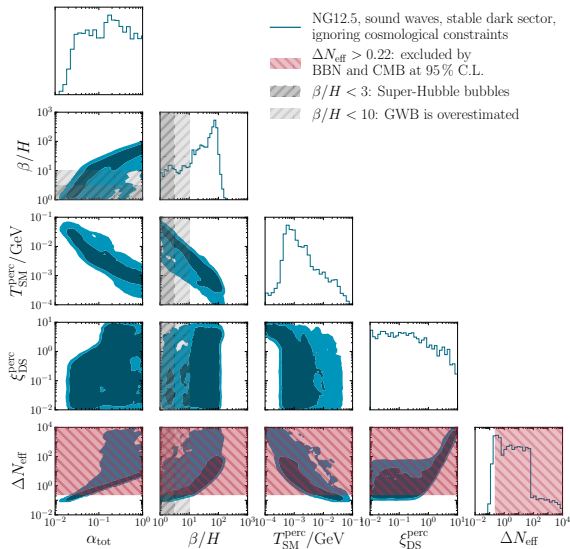
- SM has no MeV phase transition \rightsquigarrow Assume a weakly coupled $\mathcal{O}(\text{MeV})$ scalar!
- Dark sector temperature is crucial for GW prediction, $T_{\text{DS}} = \xi_{\text{DS}} T_{\text{SM}}$ [CT+, 2109.06208]
- **Stable dark sector:** additional DS energy density contributes to Hubble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

$$\Delta N_{\text{eff}} \gtrsim 6 \times \alpha \quad \textbf{but:} \quad \Delta N_{\text{eff}} < 0.22 \text{ @95 \% C.L.}$$

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

$$\tau \lesssim 0.1 \text{ s}$$

The tension between PTAs, CMB and BBN.

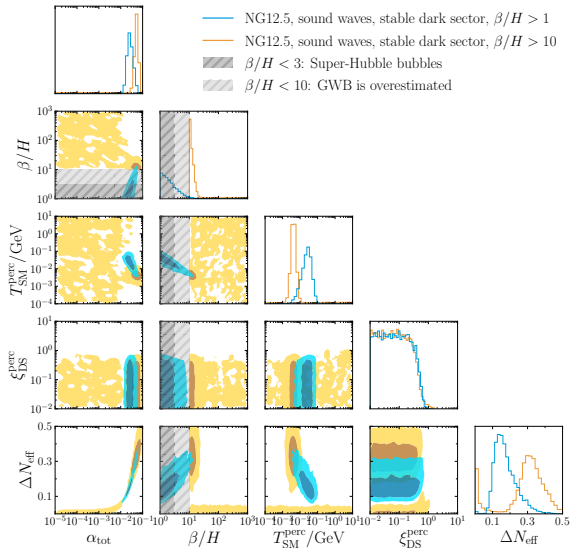


- Performed fit of the pulsar data with NANOGrav's own code **enterprise**

⚡ 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

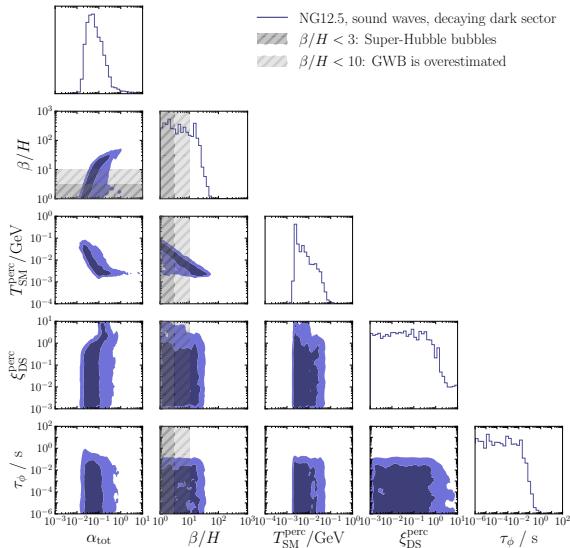


Global fit = compute global maximum of

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

- $\beta/H > 1$: 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.



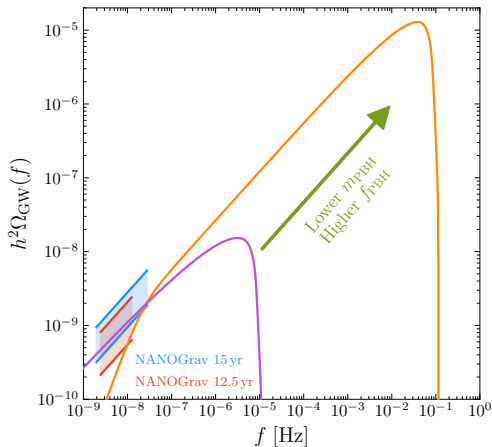
Decays save the fit!

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



Merging primordial black holes.

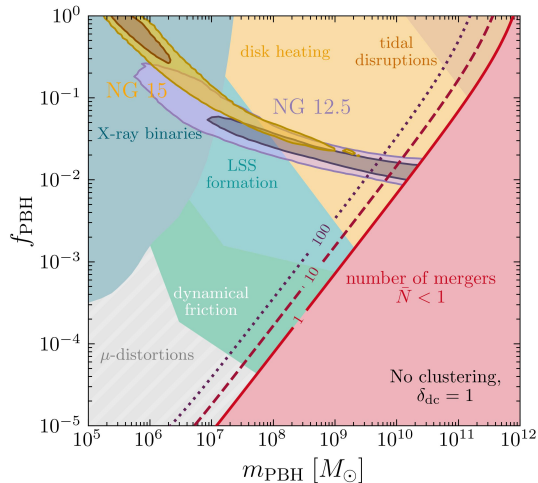
Gravitational waves from primordial black hole mergers.



- 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
- Described by (monochromatic) mass m_{PBH} and DM fraction f_{PBH}



PBHs without clustering cannot explain the PTA data.



[CT+, 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])

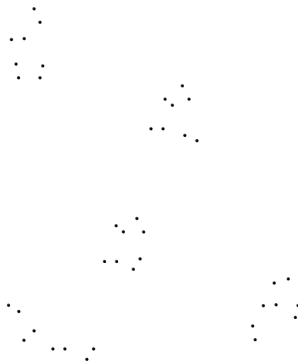
Homogeneously distributed PBHs cannot explain the PTA data!

What is clustering?

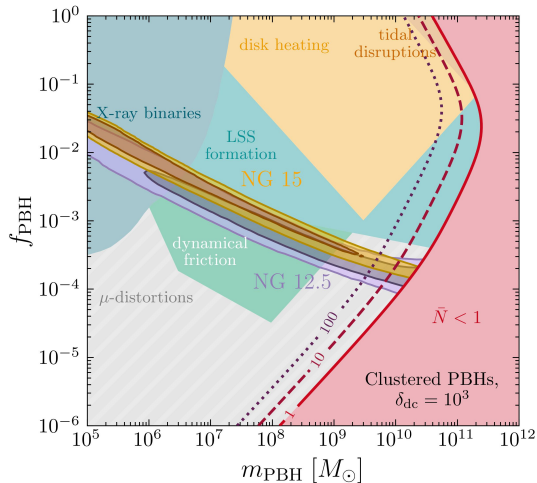
$\delta_{\text{dc}} = 1$: Poisson-distributed PBHs



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



Clustered PBHs can explain the PTA data.

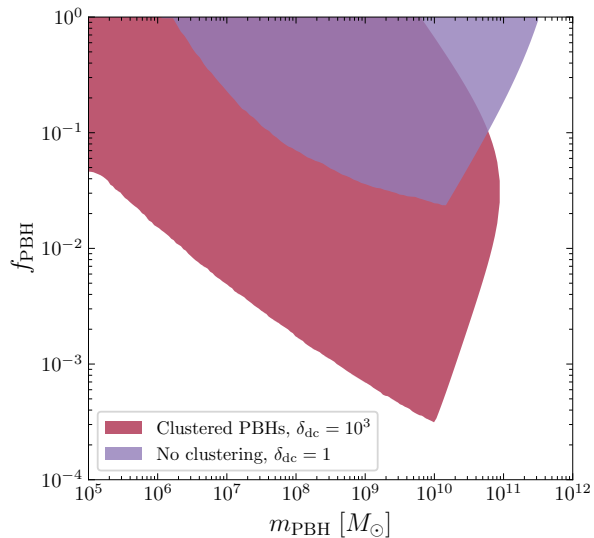


[CT+, 2023]

- Clustering increases the merger rates, requiring less PBHs to explain the signal: shift to smaller f_{PBH}
- Astrophysical bounds are dubious for clustering
- Fermilab group showed that μ -distortion bounds can be circumvented [Hooper+, 2308.00756]

Clustered PBHs *can* explain the PTA data!

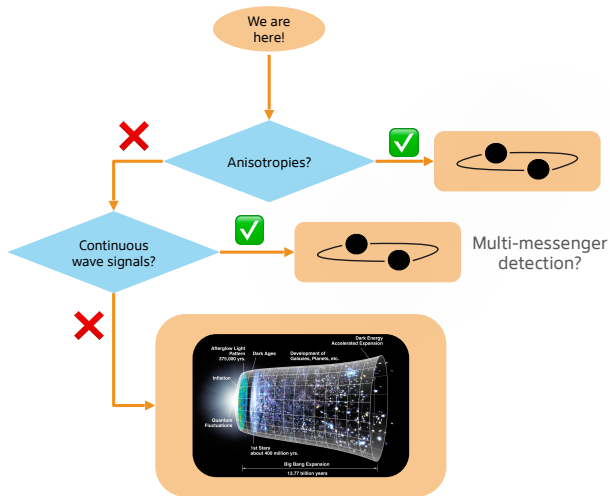
Novel PBH constraints!





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

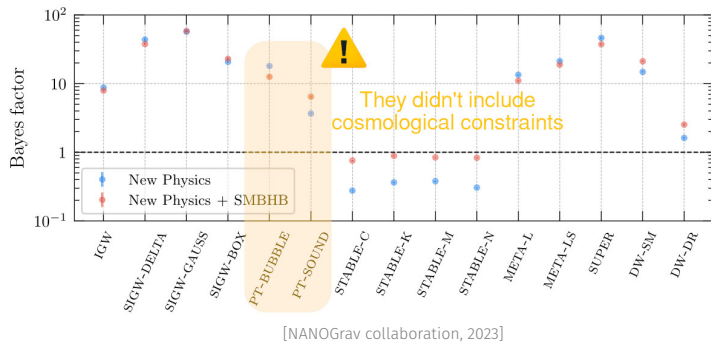
Quo vadis pulsar timing?



- HD correlation found!
- So far no evidence for anisotropies and continuous waves in data
- Spectral shape and amplitude in slight tension with SMBHBs

⇒ **More data needed** to distinguish SMBHBs from cosmic background!

The evidence for new physics.



- New physics matches spectra better than standard SMBHBs
- 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, all¹ cosmological explanations will be dead.

¹except for our scenario with an anisotropic distribution of supermassive merging PBHs... 🤔

Take-home messages.

- We are at the dawn of GW cosmology!
- New physics can explain the nHz signal better than astrophysics
- Stable dark sector phase transitions ✗
- Decaying dark sectors ✓
- Primordial black hole mergers can only explain the signal if they are clustered

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

Do you have any
questions?



Backup slides.

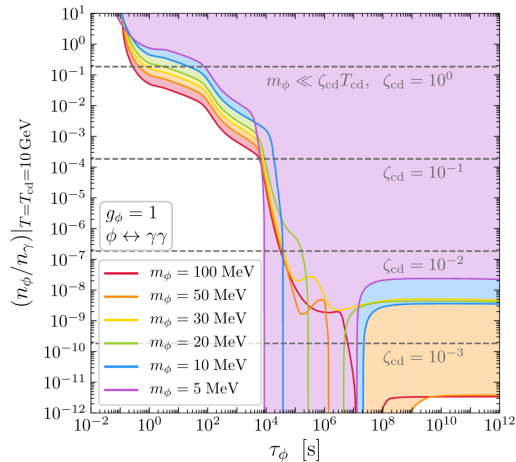
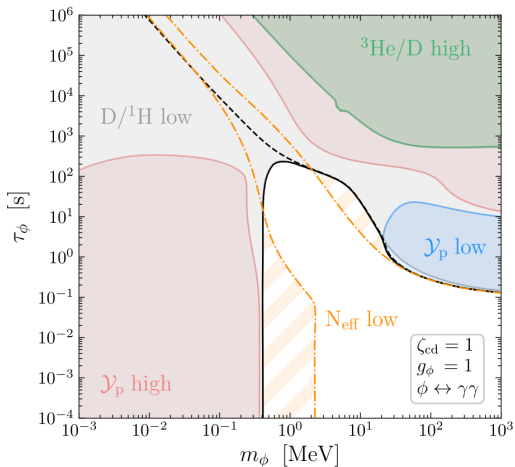
How the density contrast increases the merger rate

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

With:

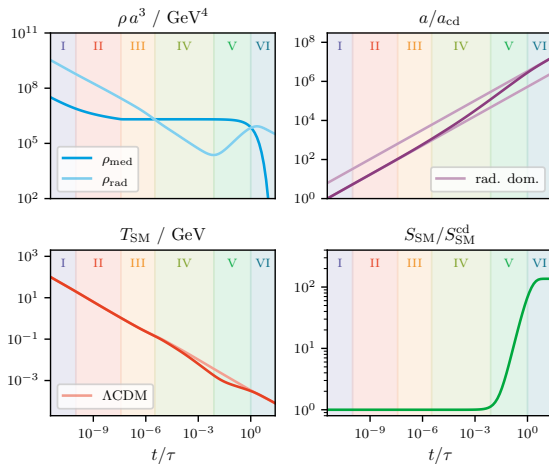
- $\delta_{\text{dc}} \simeq \frac{n_{\text{PBH}}^{\text{loc}}}{\bar{n}_{\text{PBH}}^{\text{loc}}}$: Density contrast
- $x, (y)$: comoving distance of (next-to-) nearest neighbor PBH
- \tilde{x} : farthest comoving distance two PBHs can have
- $\tilde{\tau}$: Merger timescale

Electromagnetic scalar decays at MeV temperatures.



[Depta+, JCAP 04 (2021) 011]

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

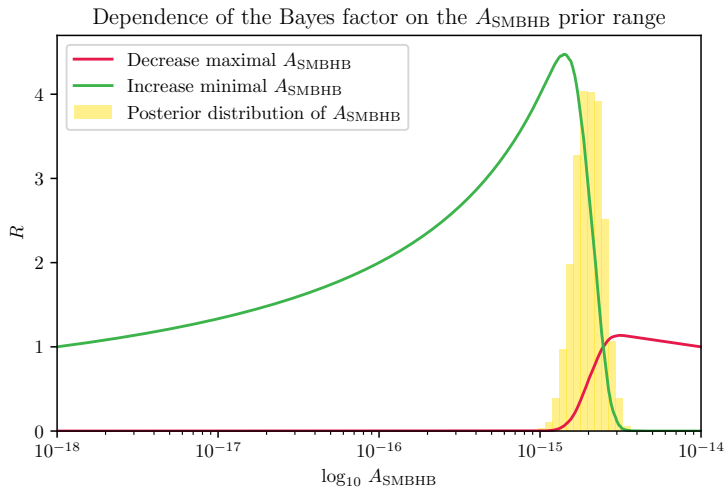


Energy densities $\rho_i(t)$ \rightsquigarrow Scale factor $a(t)$ \rightsquigarrow Temperatures $T_{\text{SM/DS}}(t)$ \rightsquigarrow Particle content $\rightsquigarrow \rho_i(t)$ \rightsquigarrow ...

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.

