Exploring new physics with pulsar timing arrays.

"Quarkonia meet Dark Matter" workshop, TUM

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

JCAP 11 (2023) 053 and [2306.17836]

March 21, 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.

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 have finally 'heard' the chorus of gravitational waves that ripple through the universe

Scientists have observed for the first time the 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

First Evidence of Giant Gravitational Waves Thrills Astronomers

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

Monster gravitational …

The New York Times

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.

SCIENCE

Colossal gravitational waves—trillions of miles long—found for the first time

… by studying rapidly spinning dead … giant ripples of spacetime likely … from merging supermassive black holes—

The Washington Post

In a major discovery, scientists say space-time churns like a choppy sea

… gravitational waves

Physics

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

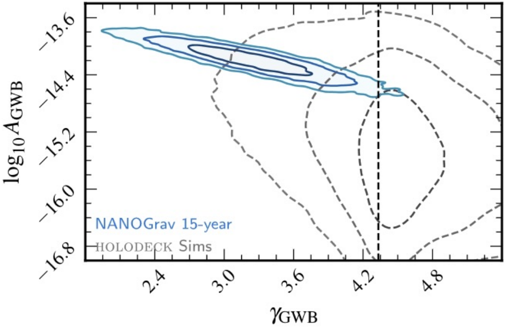
Pulsar timing arrays.

Millisecond pulsars emit radio pulses with an extremely stable frequency

- GWs affect propagation time ⇝ 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**

GW background from supermassive black hole binaries.

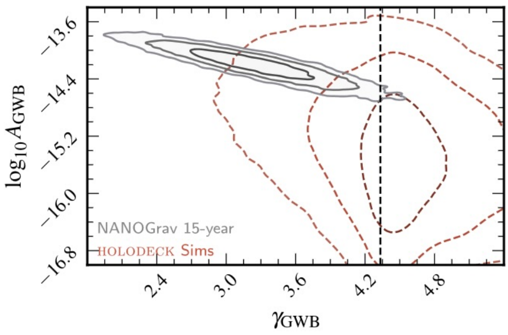
- The observed GW spectrum is consistent with a power-law of amplitude A and slope γ



[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



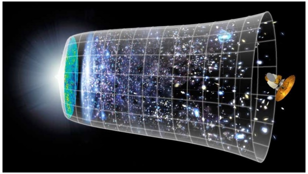
[NANOGrav collaboration, 2023]

The standard explanation is off! Other signal sources?

Possible non-standard sources of the nHz background.

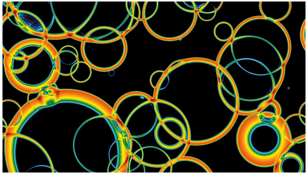
Inflation

Reentering of tensor fluctuations



Phase transitions

Connection to dark matter?

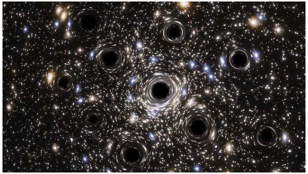


Topological defects

Cosmic strings and domain walls

Primordial black holes

But only if they are clustered…



Possible non-standard sources of the nHz background.

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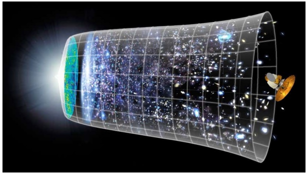
Reentering of tensor fluctuations



Topological defects

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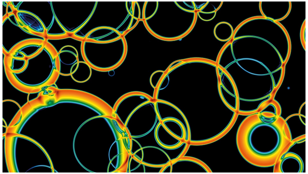

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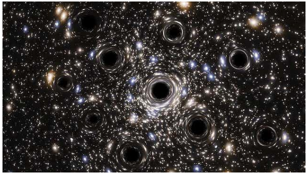
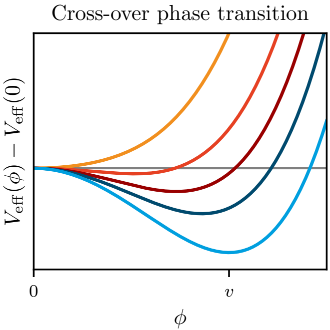
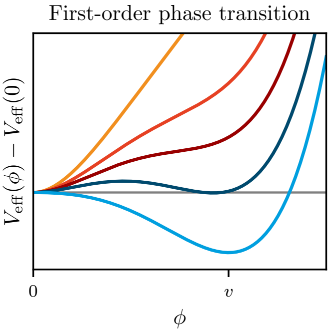


Gravitational waves from dark sector phase transitions.

Cosmological phase transitions.



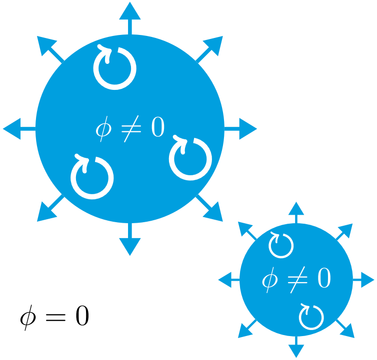


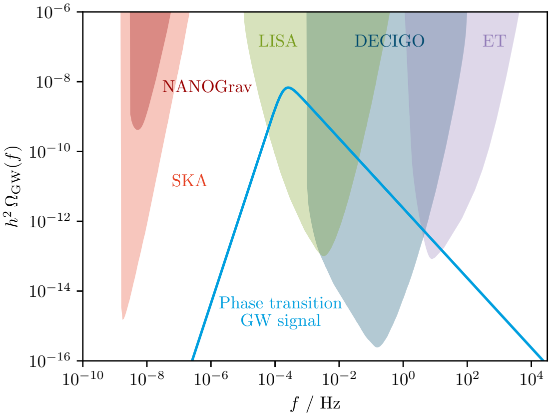
A scalar field "rolls down" from $\phi = 0$ to $\phi = v$, when the bath cools from high temperatures to low temperatures.

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.

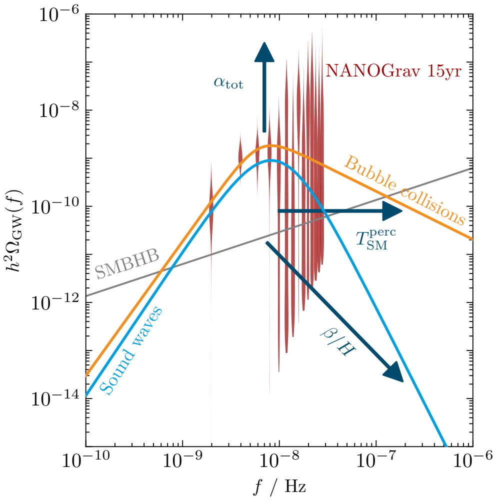
Bubbles of the new phase nucleate, collide and perturb the plasma…





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

Parametrization of the GW signal.



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

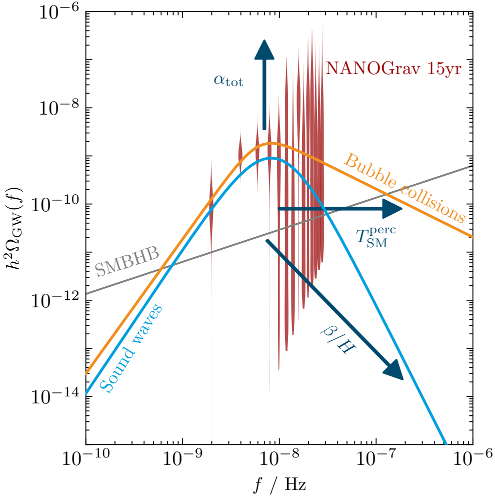
$$h^2\Omega_{\mathrm{GW}}^{\mathrm{sw,bw}}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\mathrm{peak}}}\right)$$

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

To fit the new pulsar timing data:

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

Parametrization of the GW signal.



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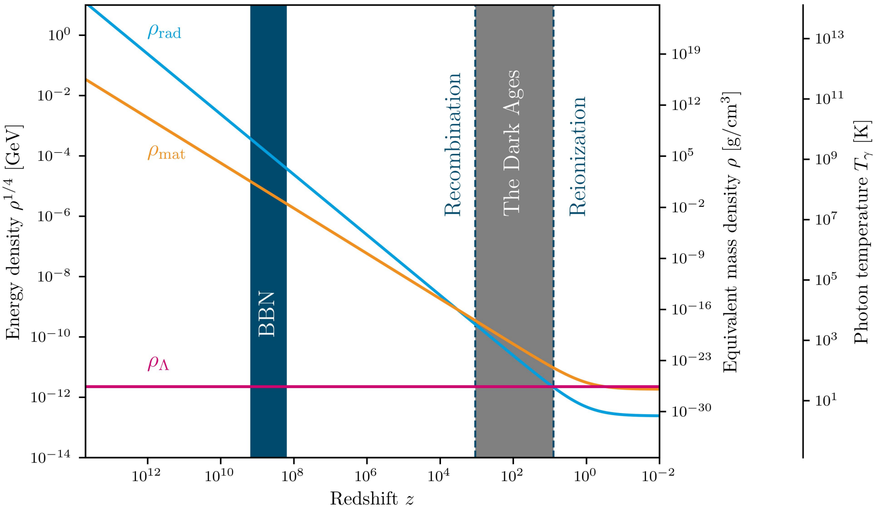
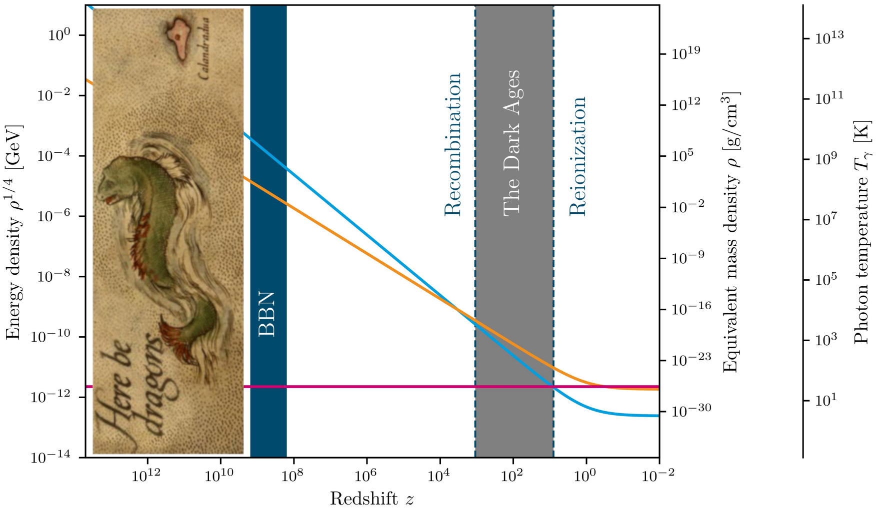
But there’s no SM phase transition at 10 MeV?!

What do we know about the early Universe?

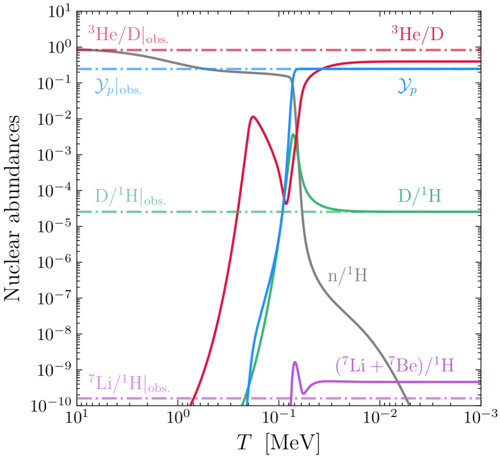
A brief history of time.



A brief history of time.



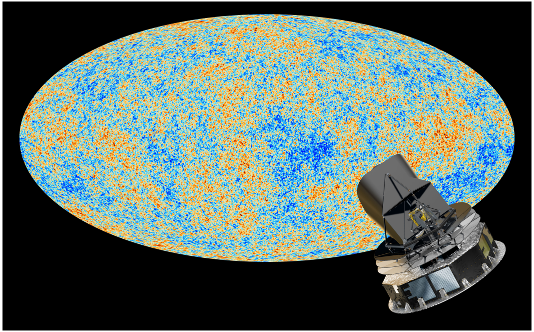
The Big Bang Nucleosynthesis and the CMB.



[Paul Frederik Depta, 2021]

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

⇝ Thermalized BSM species at $T \lesssim 1\,\text{MeV}$ are ruled out. Before that: no constraints.

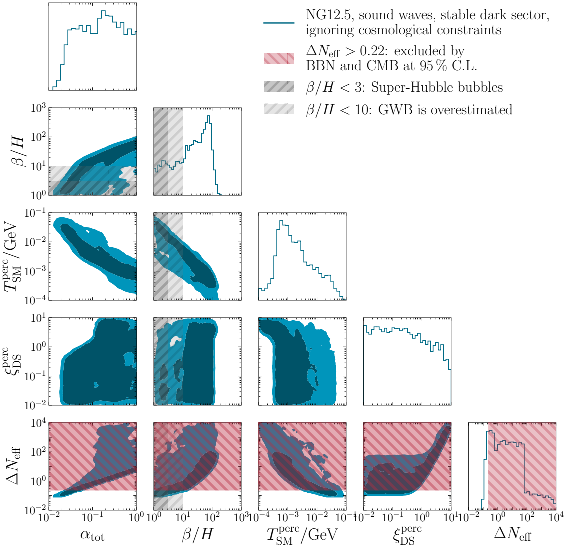
Let's put the transition in a dark sector.

- 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 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 $\tau < 0.1\,\text{s}$. [Depta+, 2011.06519]

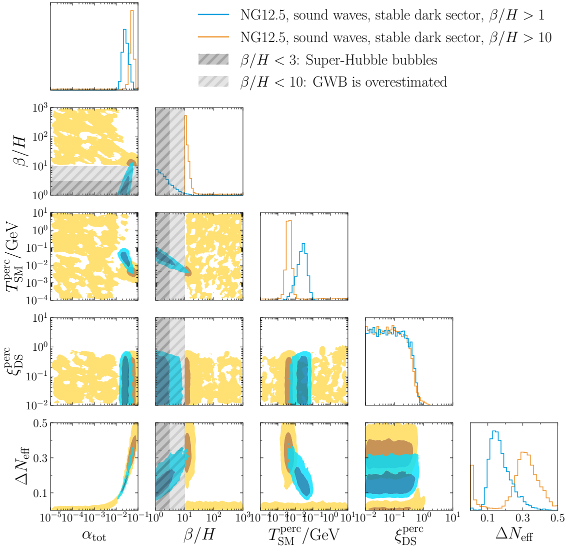
The tension between PTAs, CMB and BBN.



- Performed fit of the pulsar data with NANOGrav's own code `enterprise`
- A good fit requires an enormous reheating of the dark sector: $\Delta N_{\rm eff}$ 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.

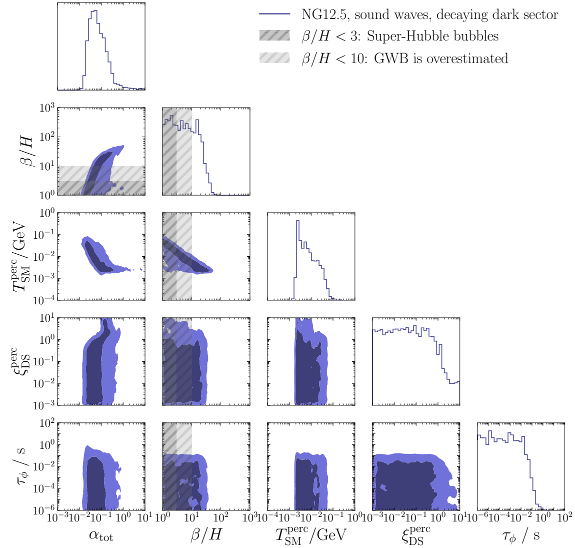


Global fit = compute global maximum of

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

- $\beta/H > 1$: 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.

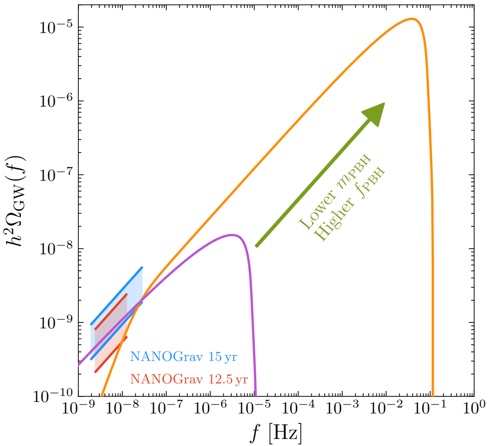


Decays save the fit!

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

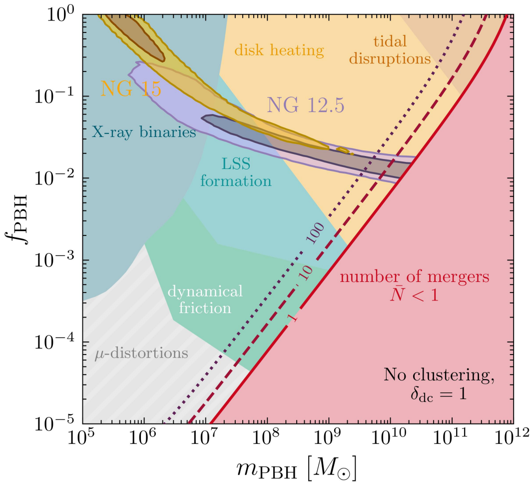
Merging primordial black holes.

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 $m_{\rm PBH}$ and DM fraction $f_{\rm PBH}$

PBHs without clustering cannot explain the PTA data.



[CT+, 2023]

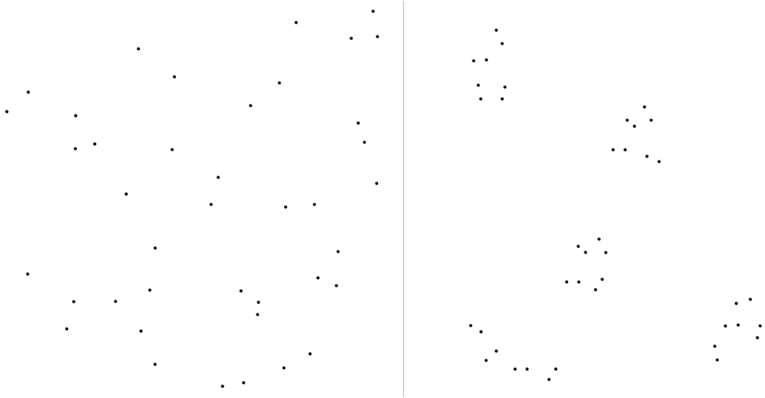
- Scan over m_{PBH} and f_{PBH}
- Region favored by PTAs is excluded by astrophysical bounds
- Crucial: exclude regions with small merger numbers. (Atal et al. came to the wrong conclusion [2012.14721])

Homogeneously distributed PBHs cannot explain the PTA data!

What is clustering?

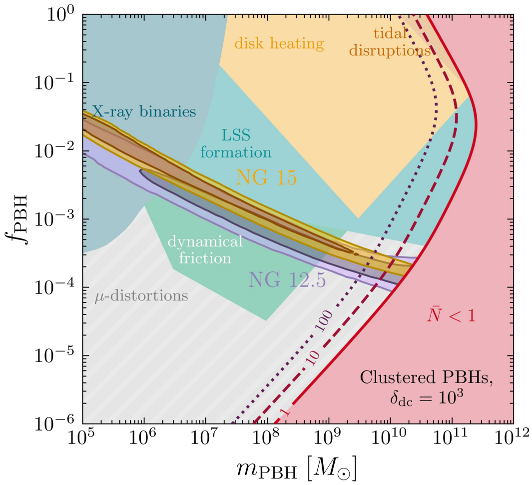
$\delta_{\mathrm{dc}} = 1$: Poisson-distributed PBHs

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



[Paul Frederik Depta, 2023]

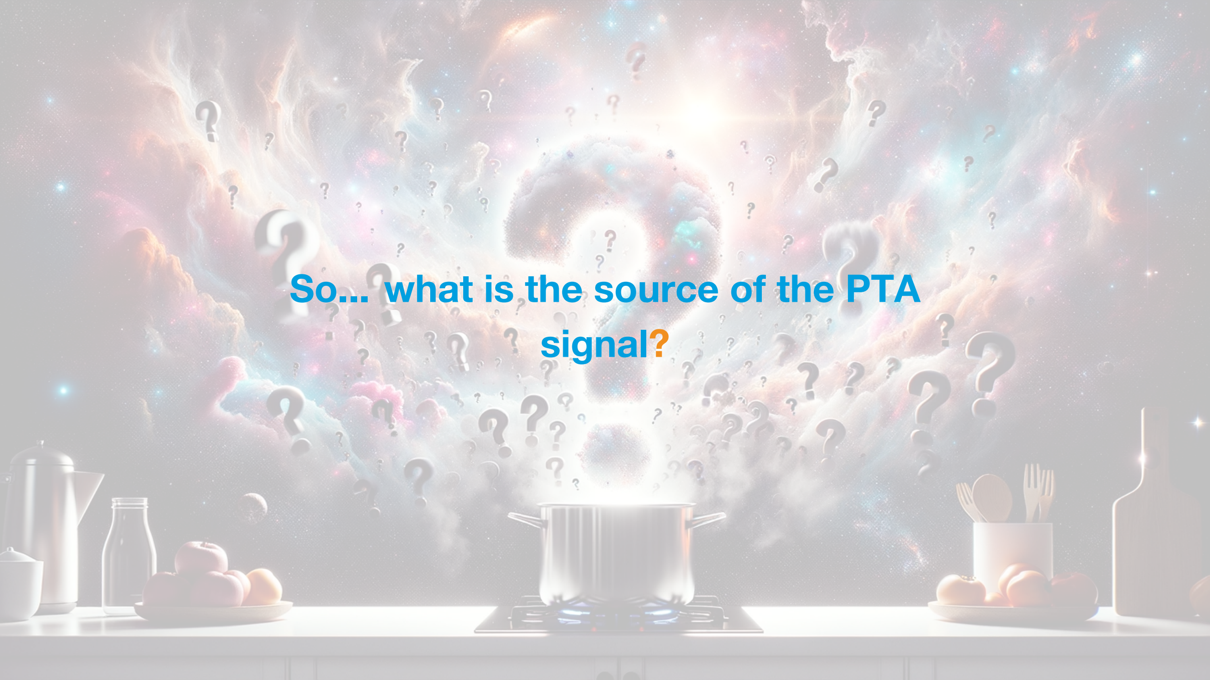
Clustered PBHs can explain the PTA data.



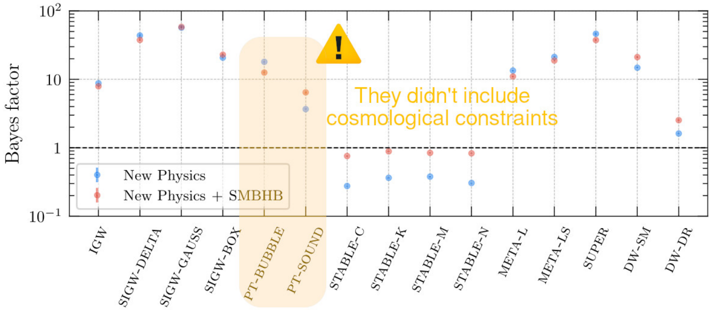
[CT+, 2023]

- Clustering increases the merger rates, requiring less PBHs to explain the signal: shift to smaller $f_{\rm PBH}$
- Astrophysical bounds are dubious for clustering
- Fermilab group pointed out that μ-distortion bounds are model dependent [Hooper+, 2308.00756]

Clustered PBHs can explain the PTA data!


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

The evidence for new physics.



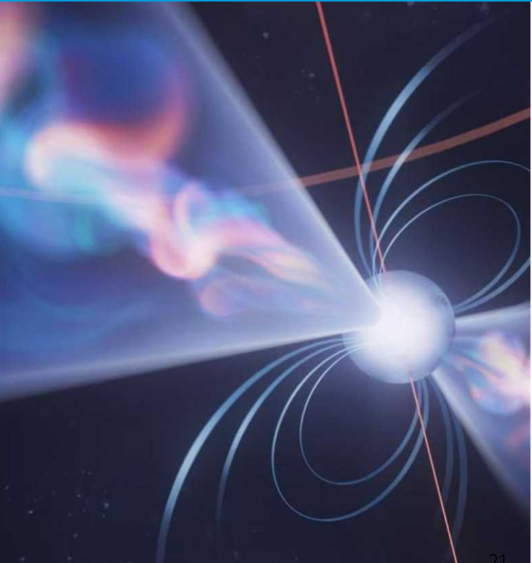
[NANOGrav collaboration, 2023]

- New physics matches spectra better 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, all cosmological explanations will be practically dead.

Take-home messages.

- 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 with $\tau < 0.1\,\mathrm{s}$ are a viable option, can compete with SMBHBs
- Primordial black hole mergers can only explain the signal if they are clustered



[image credit: Olena Shmahalo, NANOGrav]

Thank you very much for your attention!

Do you have any questions?

Backup slides.

How the density contrast increases the merger rate

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

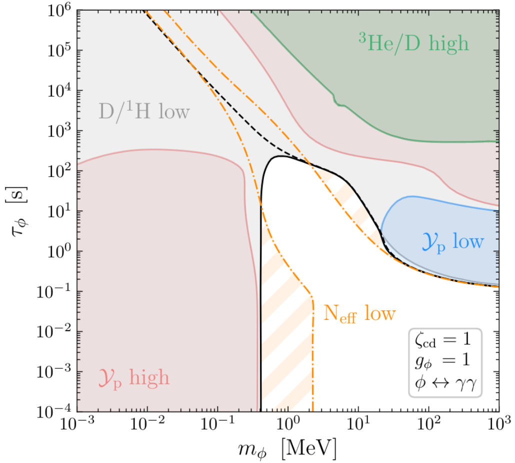
$$R(t) = \int_0^{\tilde{x}} \mathrm{d}x \int_x^{\infty} \mathrm{d}y \frac{\partial^2 n_3}{\partial x \, \partial y} \delta(t - \tau(x,y))$$

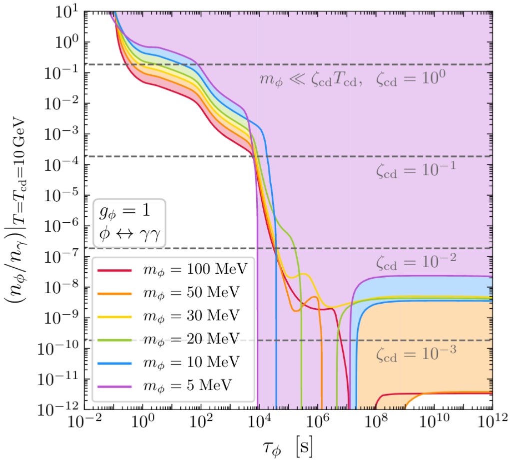
$$\propto \frac{{\delta_{\mathrm{dc}}}^{16/37}}{\tilde{x}^3 \tilde{\tau}} \left(\frac{t}{\tilde{\tau}}\right)^{-34/37} \left(\Gamma\left[\frac{58}{37}, \frac{4\pi}{3}\tilde{x}^3 \delta_{\mathrm{dc}} n_{\mathrm{PBH}} \left(\frac{t}{\tilde{\tau}}\right)^{3/16}\right] - \Gamma\left[\frac{58}{37}, \frac{4\pi}{3}\tilde{x}^3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

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

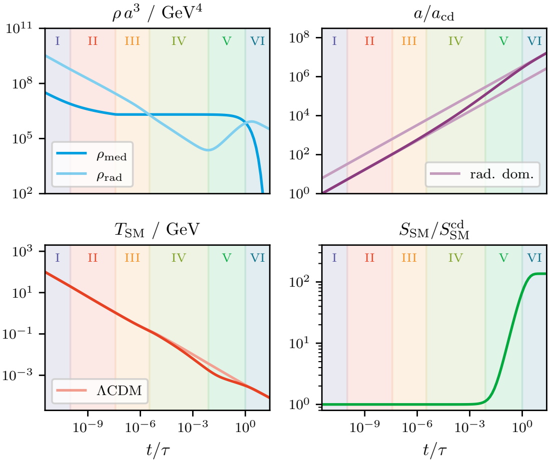
Electromagnetic scalar decays at MeV temperatures.





[Depta+, JCAP 04 (2021) 011]

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

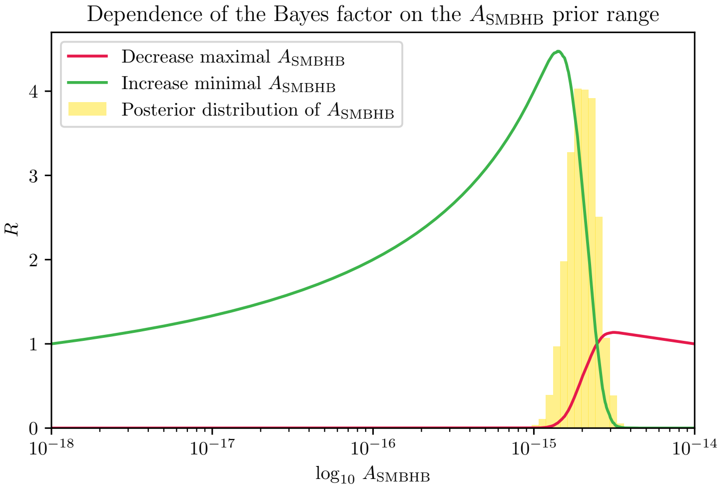


Energy densities $\rho_i(t)$ $\overset{\text{sets}}{\rightsquigarrow}$ Scale factor $a(t)$ $\overset{\text{sets}}{\rightsquigarrow}$ Temperatures $T_{\mathrm{SM/DS}}(t)$ $\overset{\text{set}}{\rightsquigarrow}$ Particle content $\overset{\text{sets}}{\rightsquigarrow}$ $\rho_i(t)$ $\overset{\text{sets}}{\rightsquigarrow}$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

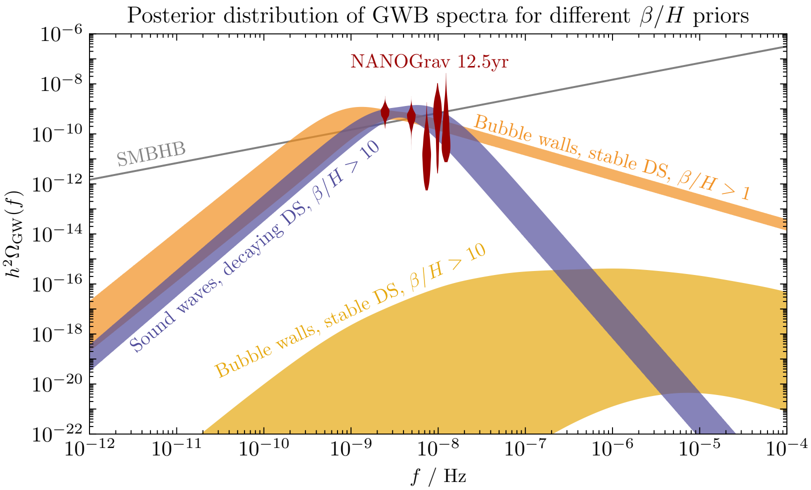
Six phases:

- 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.



We can derive new bounds on clustered PBHs.