Exploring phase transitions with pulsar timing arrays.

QU Day 4/2023 – DM parallel session

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

arXiv: [2306.09411], JCAP 11 (2023) 053

November 21, 2023

Outline of this talk.

1. The PTA signal
2. The null hypothesis: astrophysics
3. Phase transitions vs. precision cosmology
4. BSM or boring?

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

In case you haven't heard the news.

Pulsar timing arrays.

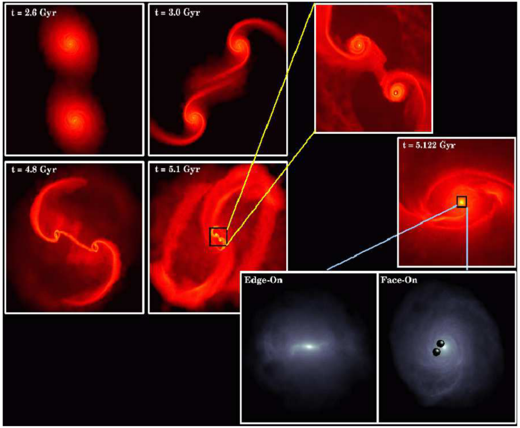
Millisecond pulsars emit radio pulses with an extremely stable frequency

- GWs affect propagation time ⇝ change observed pulse frequency
- PTAs monitor pulse frequency using radio telescopes on Earth
- Fourier decomposition of arrival times shows that pulse frequency modulations is due to GWs!

Merging supermassive black hole binaries.

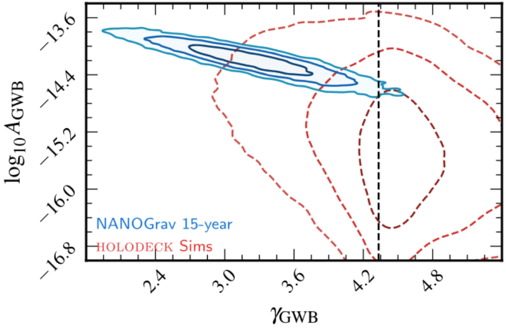
- Expect **supermassive black hole mergers** after galaxy mergers
- The resulting GW predictions can be well described by a power-law with amplitude A and slope γ:

$$\Omega_{\mathrm{GW}}(f) \propto A^2 f^{5-\gamma}$$



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

GW background from supermassive black hole binaries.



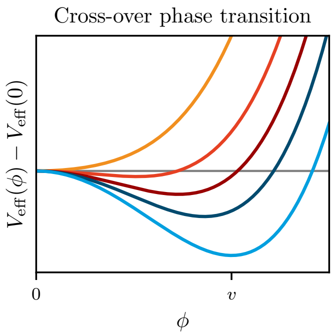
[NANOGrav collaboration, 2023]

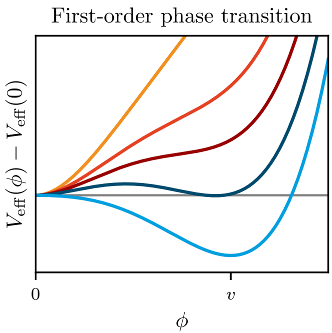
⇝ Astrophysical simulations with realistic BH populations generate GW spectra that are in tension with the observed GW spectrum!

What other signal sources are thinkable?

Gravitational waves from dark sector phase transitions.

Cross-over and first-order phase transitions.



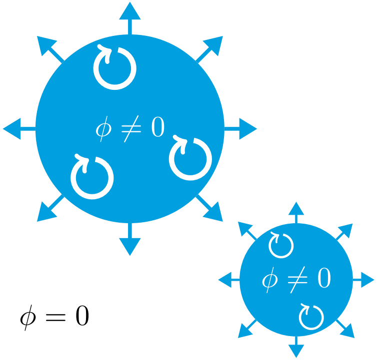


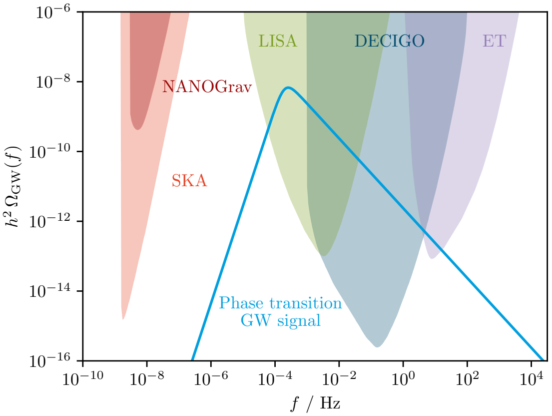
A scalar field "rolls down" from $\phi = 0$ to $\phi = v$, when the bath cools from high temperatures to low temperatures.

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.

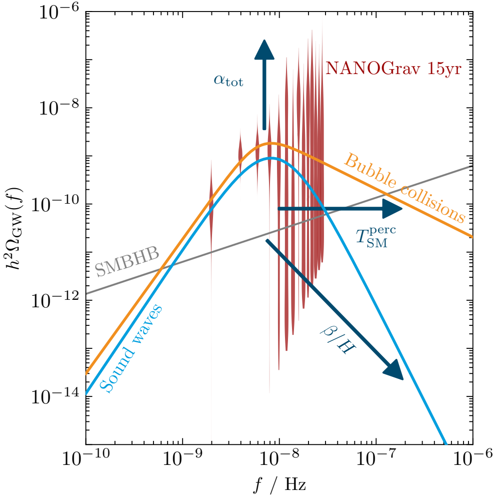
Bubbles of the new phase nucleate, collide and perturb the plasma…





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

To fit the pulsar timing data:

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

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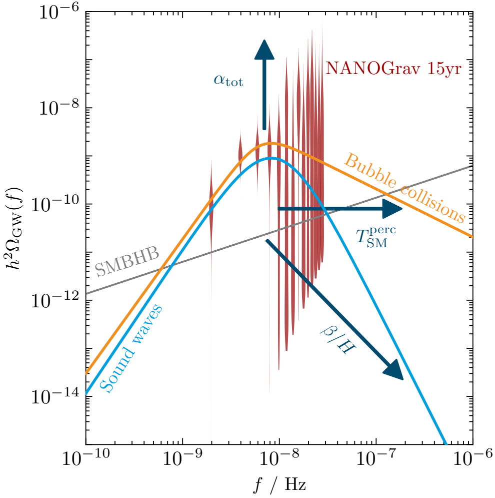

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But there's no SM phase transition at 10 MeV?!

Let's put the transition in a dark sector.

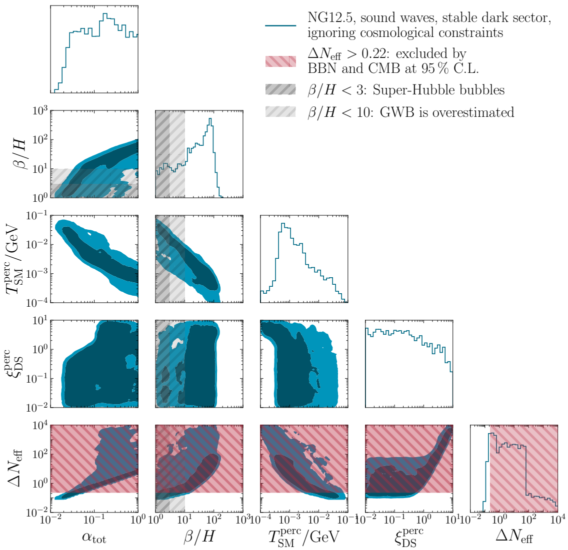
- **Stable dark sector:** additional DS energy density leads to larger Hubble rate, changing early element abundances and shifting CMB anisotropies through

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

with the temperature ratio $\xi = T_{\text{DS}}/T_{\text{SM}}$ before the transition.

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

Stable dark sectors = strong tension between PTAs, CMB and BBN.

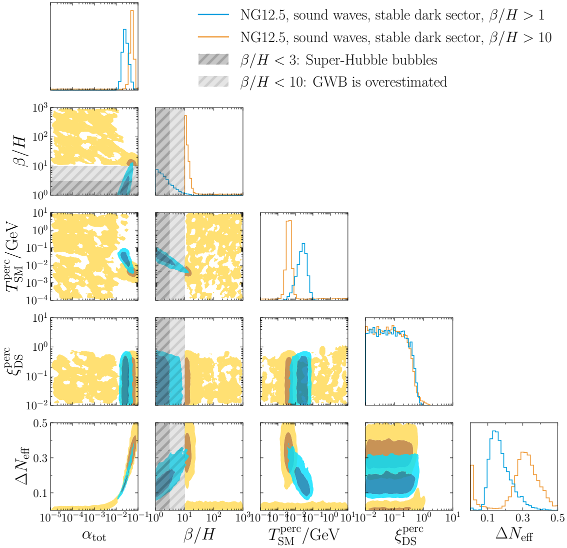


- Performed fit of the pulsar data with NANOGrav's own code `enterprise`
- A good fit requires an enormous reheating of the dark sector: $\Delta N_{\rm eff}$ can grow arbitrarily large
- Bubble sizes would need to be super-Hubble to be okay with $\Delta N_{\rm eff}$

  Causality   GW prediction

⇝ The tension cries for a global fit

Global fits.



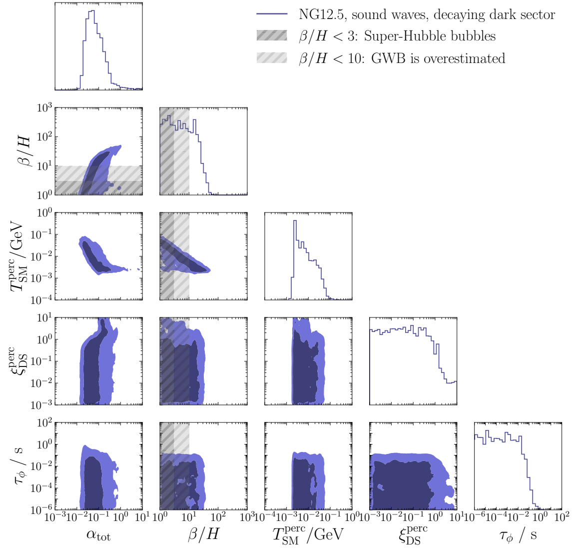
Global fit = compute global maximum of

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

Find:

- $\beta/H > 1$: would be a good fit, if the GW spectrum were reliable
- $\beta/H > 10$: $\mathcal{L}_{\text{glob}}$ starts preferring to not have a phase transition over violating BBN and CMB bounds!

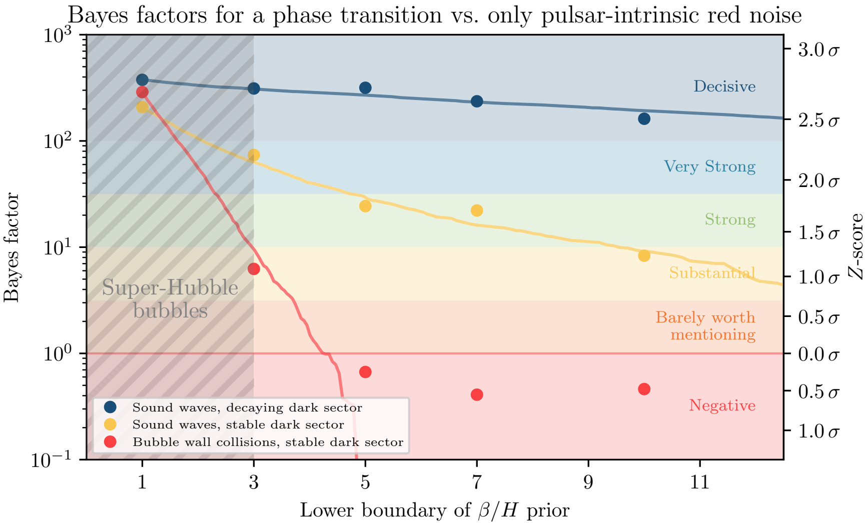
Decays to the rescue.

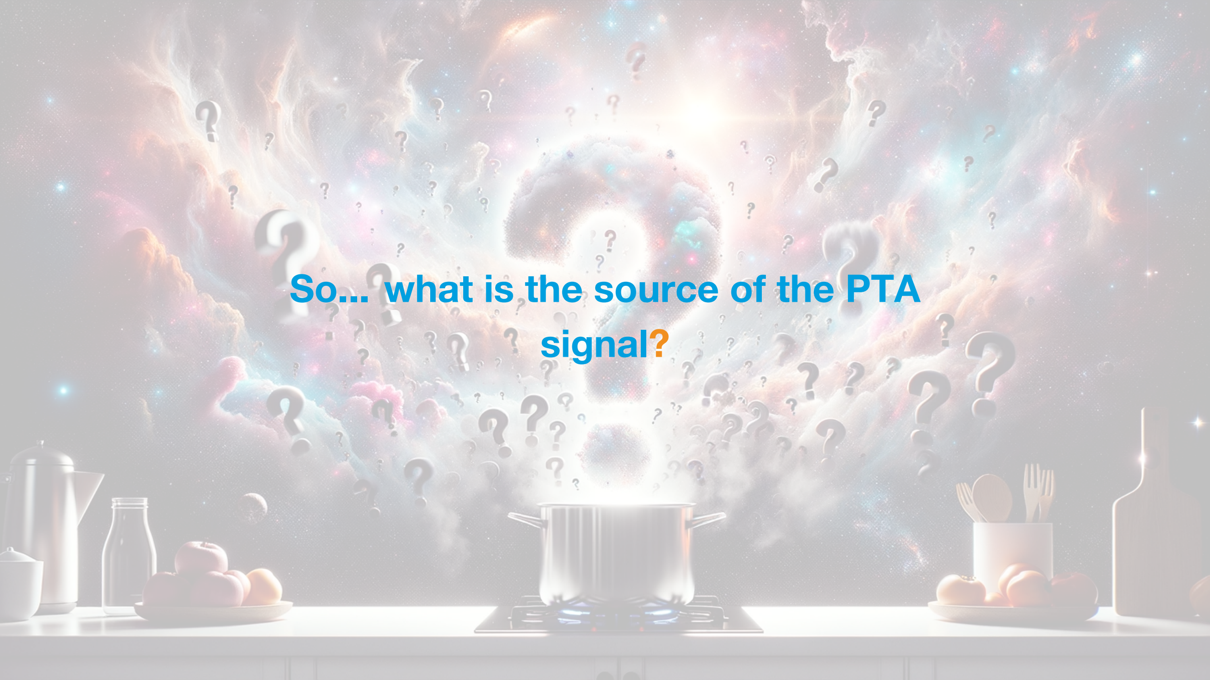


Decays save the fit...

... since more energy can be used to reheat the DS and emit GWs. They only need to happen before neutrino decoupling, $T_{SM} \gtrsim 2\,\text{MeV}$, corresponding to fast decays, $\tau \lesssim 0.1\,\text{s}$.

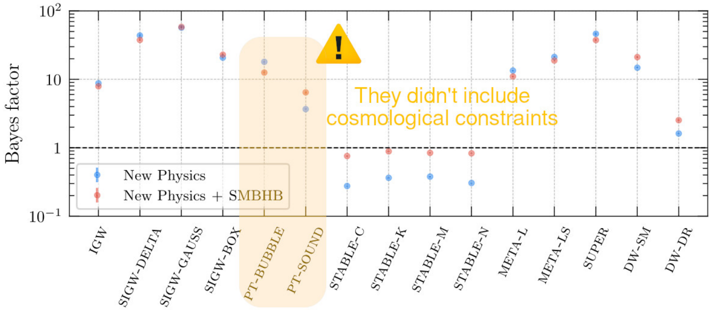
The evidence for a dark sector phase transition.





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

The evidence for new physics.



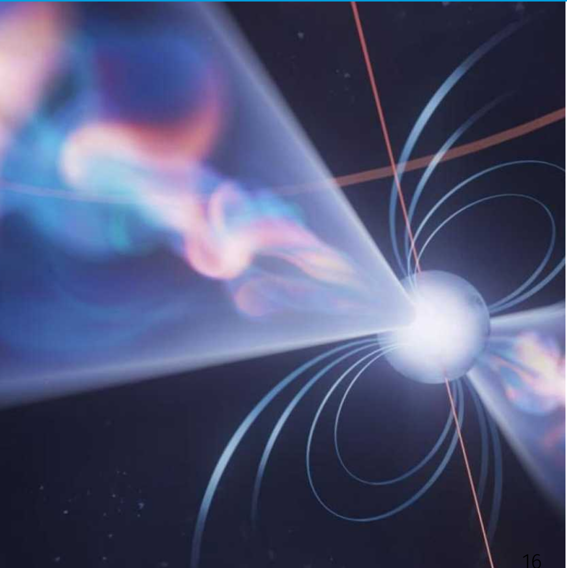
[NANOGrav collaboration, 2023]

- New physics matches spectra better
- BSM + SMBHB has highest Bayes factors
- We should perform global fits, including constraints & open astrophysical parameters

Still: As soon as a single merger or strong anisotropy is found in the data, all cosmological explanations will be dead.

Take-home messages.

- We are for the first time able to probe the early Universe before BBN!
- *Stable* dark sector phase transition explanations for PTA data are in tension with precision cosmology.
- *Decaying* dark sectors can compete with the SMBHB explanation and can even fit the data better
- Stay tuned for a follow-up incl. the latest PTA data



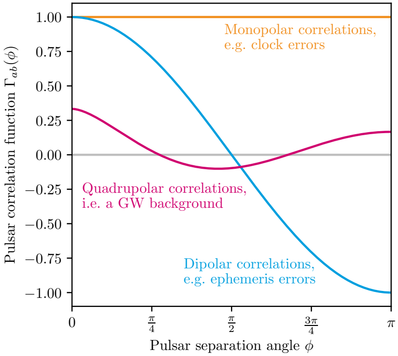
[image credit: Olena Shmahalo, NANOGrav]

Thank you very much for your attention!

Do you have any questions?

Backup slides.

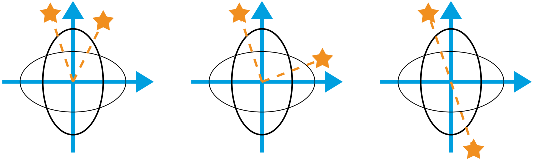
How can we be sure it's actually gravitational waves?



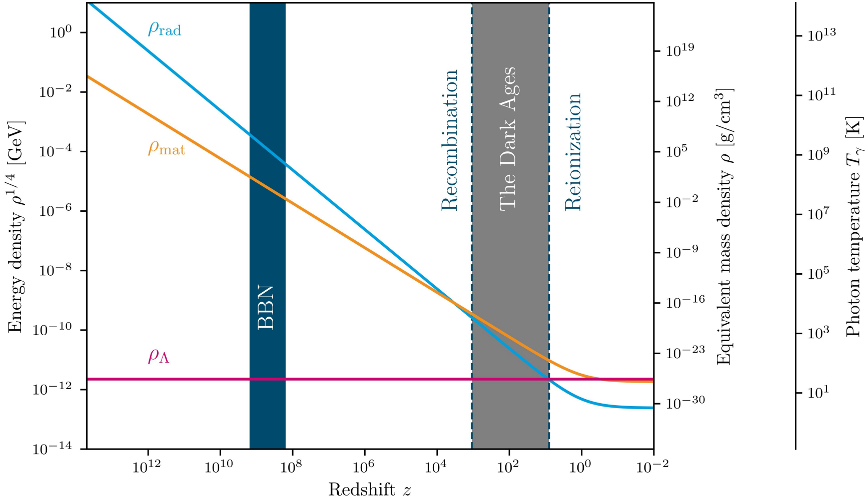
Red noise spectra can have many sources:

- Pulsars: no common red noise, $\mathcal{B} < 10^{-12}$
- Clock errors: monopole, $\mathcal{B} < 10^{-8}$
- Ephemeris errors: dipole, $\mathcal{B} < 10^{-7}$
- GWs: Hellings-Downs curve, $\mathcal{B} = 200 - 1000$

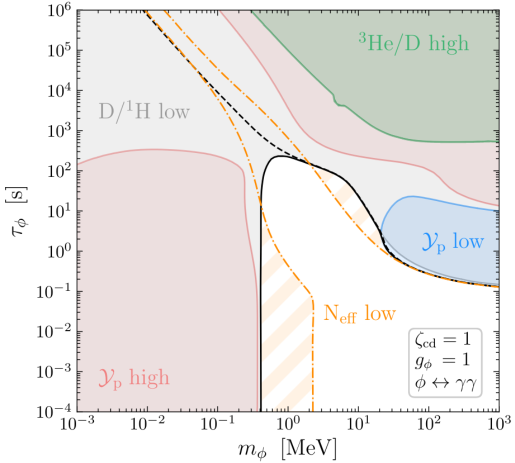
$\rightsquigarrow$ **Decisive evidence for GWs!** 🥳

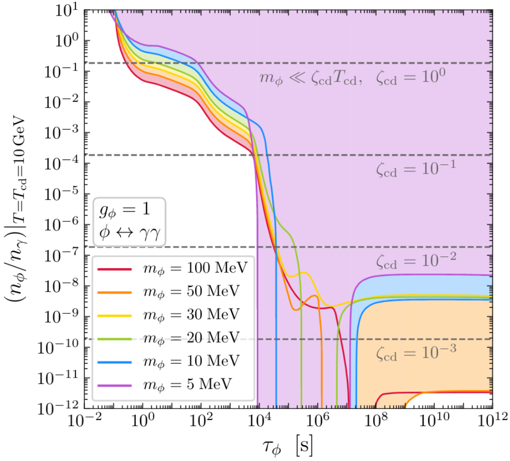


A brief history of time: LCDM.



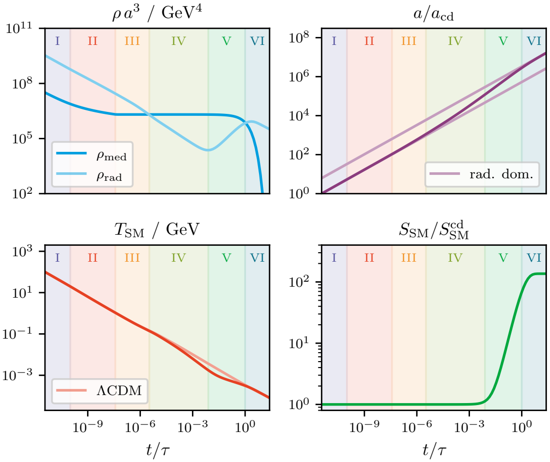
Electromagnetic scalar decays at MeV temperatures.





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

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

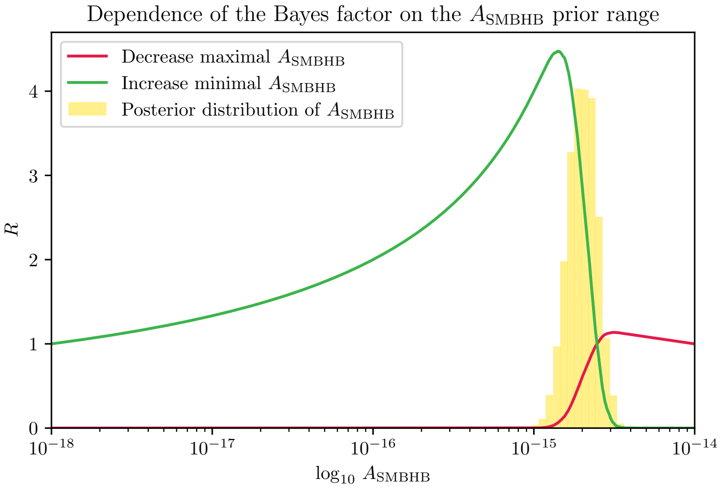


Energy densities $\rho_i(t)$ $\overset{\text{sets}}{\rightsquigarrow}$ Scale factor $a(t)$ $\overset{\text{sets}}{\rightsquigarrow}$ Temperatures $T_{\mathsf{SM/DS}}(t)$ $\overset{\text{set}}{\rightsquigarrow}$ Particle content $\overset{\text{sets}}{\rightsquigarrow}$ $\rho_i(t)$ $\overset{\text{sets}}{\rightsquigarrow}$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

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.