How loud was the dark Big Bang? Dark sector phase transitions in the light of PTAs and BBN.

Seminar talk at TU Dortmund University

Carlo Tasillo,
Deutsches Elektronen Synchrotron (DESY)

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

arXiv: `[2306.nextweek]`

June 7, 2023

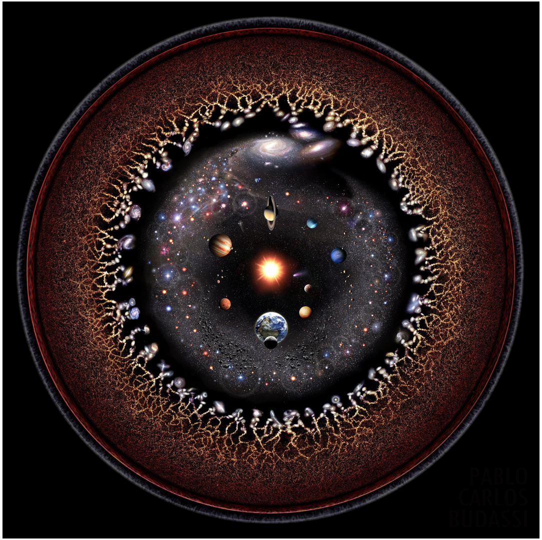
Outline of this talk.

1 The Early Universe
2 Pulsar timing arrays
3 Gravitational waves from dark sector phase transitions
4 The tension between BBN, CMB and NANOGrav
5 Outlook: New data in $\approx$ 2 weeks!

[Camille Flammarion, 1888]

What do we know about the Early Universe?

What we know about our Universe.

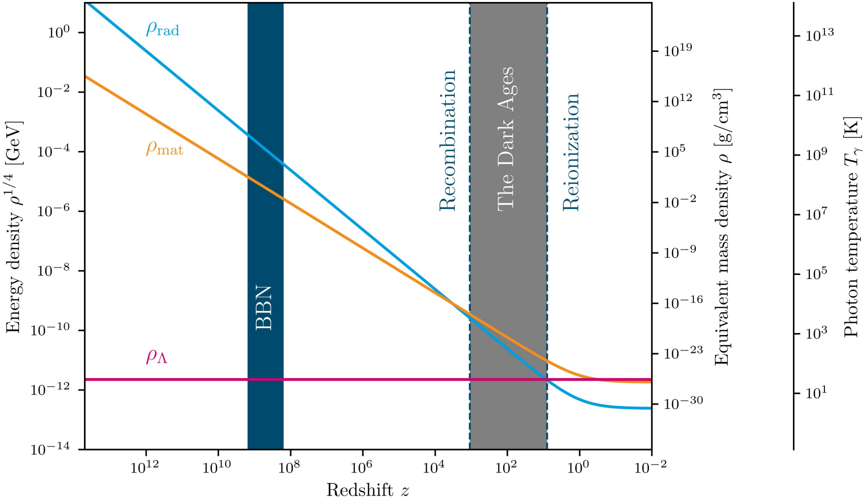


[Pablo Carlos Budassi, 2020]

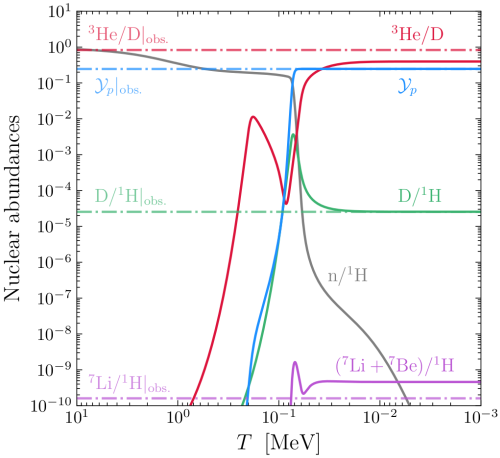
LCDM:

- Isotropic and homogeneous
- Expands since 13.8 billion years
- 95 % is dark!?
- Not probed above $\mathcal{O}$(few) MeV temperatures...

A brief history of time: LCDM.



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]

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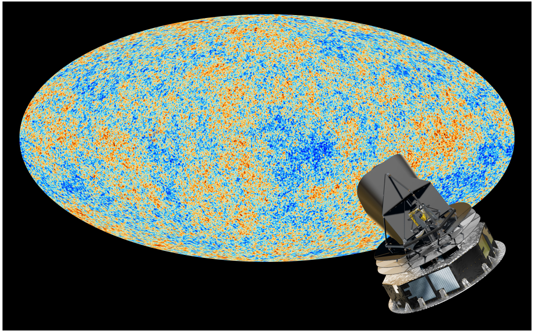

[ESA and the Planck Collaboration, D. Ducros]

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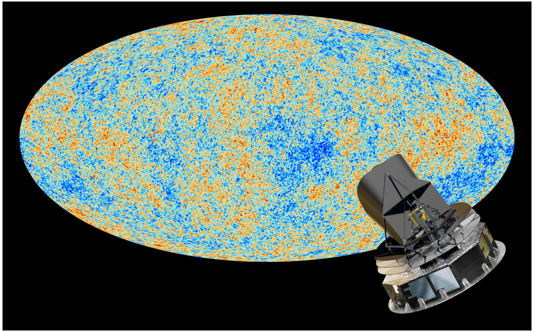
- $N_{\text{eff}}^{\text{BBN}} = 2.898 \pm 0.141$ [Yeh, 2207.13133]
- $N_{\text{eff}}^{\text{CMB}} = 2.99 \pm 0.17$ [Planck, 1807.06209]
- Consistent with $N_{\text{eff}}^{\text{SM}} = 3.044$ from 3 ν generations [Bennet, 2012.02726v3]

The Big Bang Nucleosynthesis and the CMB.



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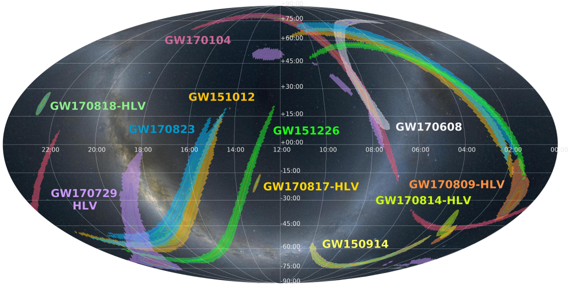
$\rightsquigarrow$ Cosmologies with extra species at $T \lesssim$ MeV are severely constrained. What about earlier times?

Gravitational waves as a “new” messenger.

- LIGO + Virgo observed $\mathcal{O}(100)$ mergers since 2015 [GWTC3]



[LIGO, Virgo & KAGRA Collaboration, 2020]

Gravitational waves as a "new" messenger.

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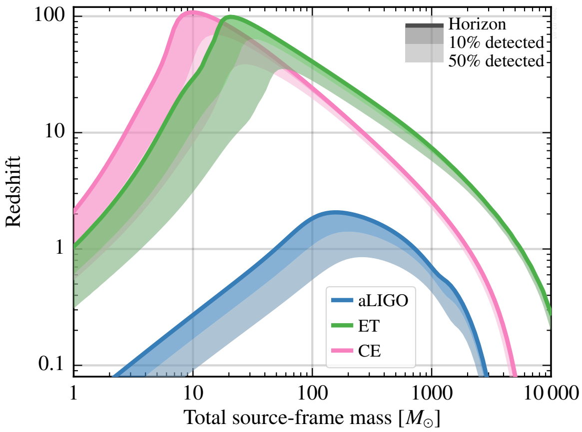

[Maggiore et al., JCAP 03, 050 (2020)]

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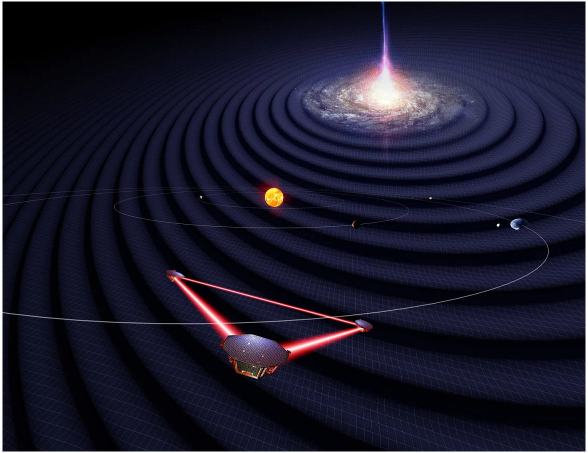

[University of Florida, Simon Barke (CC BY 4.0)]

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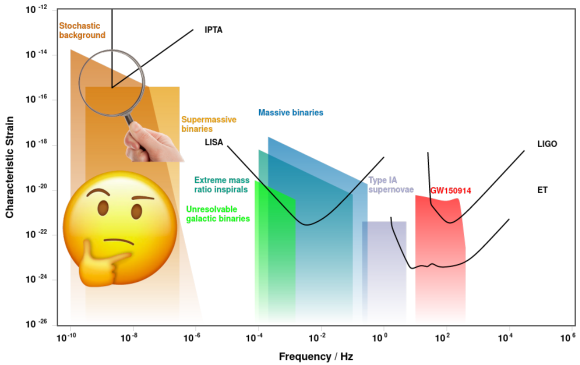
- The Einstein Telescope will be able to probe mergers during the Dark Ages ($\rightsquigarrow$ PBHs?)
- LISA will be able to test electroweak symmetry breaking ($\rightsquigarrow$ Baryogenesis?)
- PTAs already detected something that might be a stochastic GW background!



[adapted from gwplotter.com]

Pulsar timing arrays.

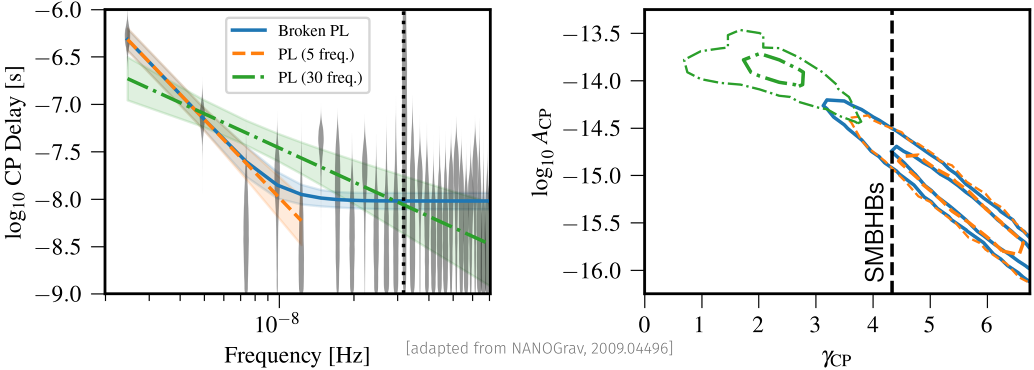
Pulsar timing arrays.

[Tonia Klein, NANOGrav]

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
- Fit pulse data with timing model
- Fourier decomposition of timing residuals shows “common red noise”, which could be due to GWs

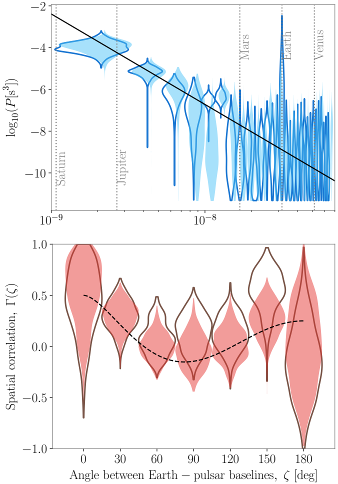
The measured PTA signal.



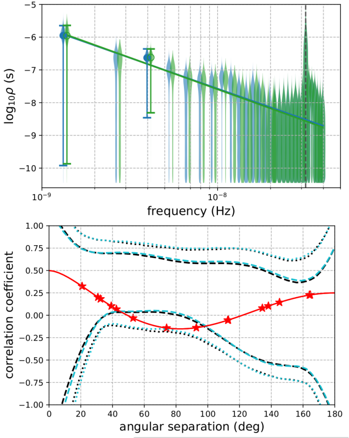
[adapted from NANOGrav, 2009.04496]

The five lowest Fourier modes agree with a power-law "common red signal", described by an amplitude $A_{\rm CP}$ and a spectral index $\gamma_{\rm CP}$.

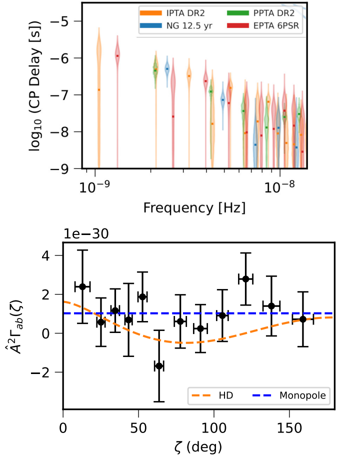
The same signal was also measured by EPTA, PPTA and IPTA.



[PPTA, 2107.12112]

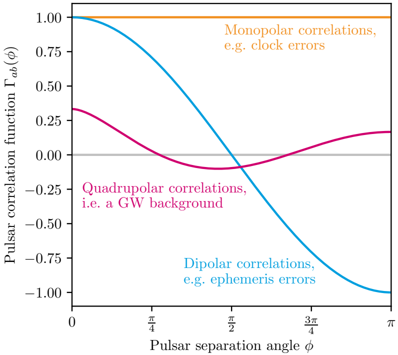


[EPTA, 2110.13184]



[IPTA, 2201.03980]

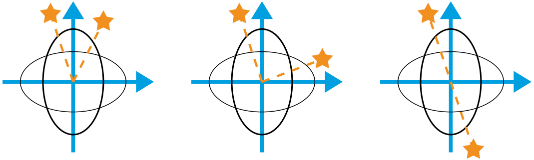
Is it actually a GW background or just noise?



Red noise spectra can have many sources:

- Pulsar mismodelling: no correlation
- Clock errors: monopole, $\mathcal{B} = 10^{-2.3}$ 🥰
- Ephemeris errors: dipole, $\mathcal{B} = 10^{-2.4}$ 🥳
- GWs: Hellings-Downs curve, $\mathcal{B} = 10^{0.64}$ 😐

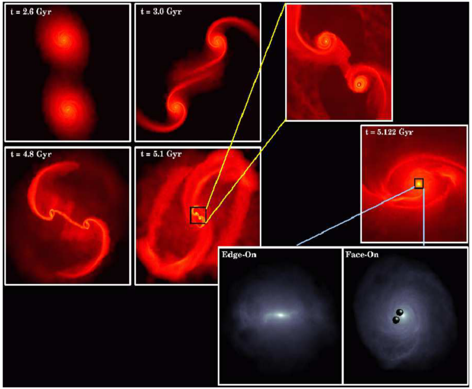
$\rightsquigarrow$ No decisive evidence for GWs... yet.



What are possible GW sources?

The signal is consistent with a single power law at nHz frequencies. Likely explanation:

- Astrophysics: Inspiral of supermassive black hole binaries, $\gamma_{\rm CP} = 4.33$



[Mayer et al., 0706.1562]

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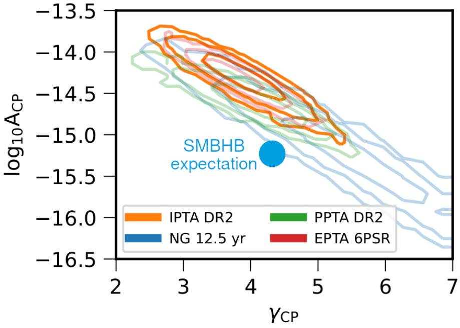

[adapted from IPTA, 2201.03980]

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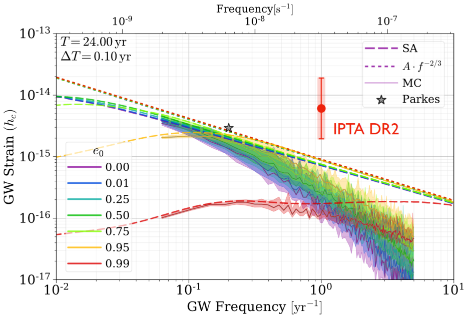
Alternative cosmological sources include

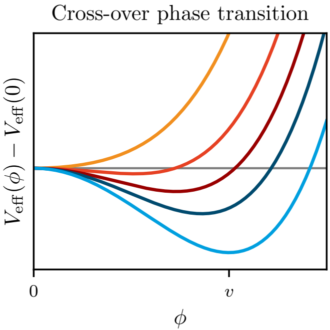
- Primordial black holes
- Cosmic strings
- *First-order phase transitions*

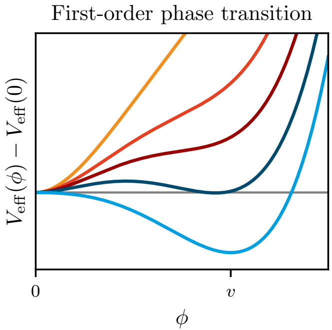


[Kelley et al., 1702.02180; adapted by Andrea Mitridate]

Gravitational waves from dark sector phase transitions.

Cross-over and first-order phase transitions.



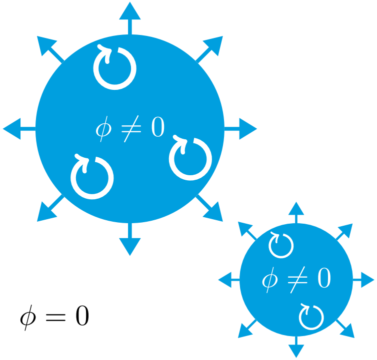


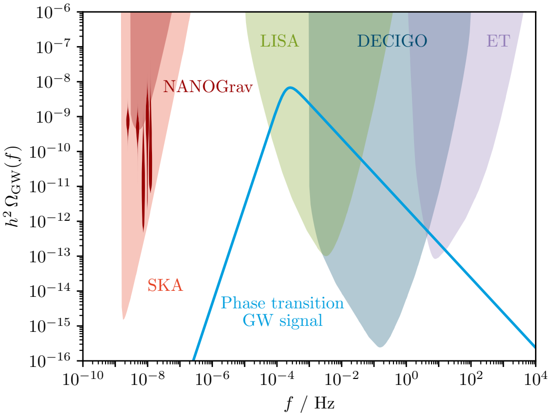
A scalar field "rolls down" from $\phi = 0$ to $\phi = v$, when the bath cools from high temperatures to low temperatures.

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.

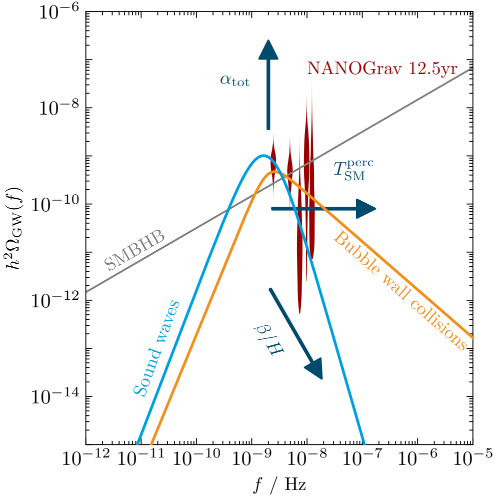
Bubbles of the new phase nucleate, collide and perturb the plasma…





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

Parametrization of the GW signal.



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

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

For signals that fit NANOGrav:

- Strong transitions, high α
- Slow transitions, low β/H
- Percolation around $T \simeq \mathcal{O}(\mathrm{MeV})$?!

Let’s put the transition in a dark sector.

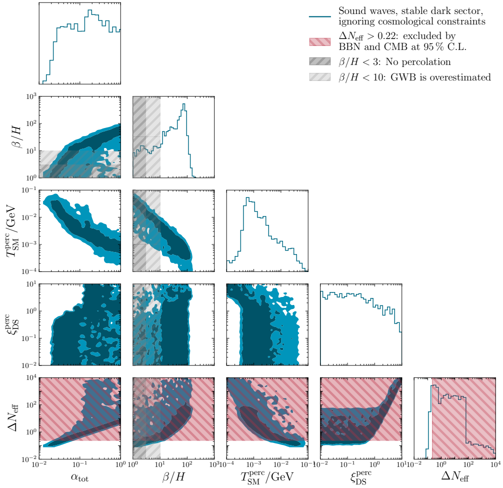
- Dark sector temperature ratio is crucial, $T_{\text{DS}} = \xi_{\text{DS}}\, T_{\text{SM}}$ [Breitbach, 1811.11175]
- Bubble wall dynamics are independent from SM plasma
- Potential dilution of the GW signal due to changed redshift history [CT, 2109.06208]
- **Stable dark sector:** additional DS energy density accelerates expansion and changes early element abundances and CMB anisotropies through

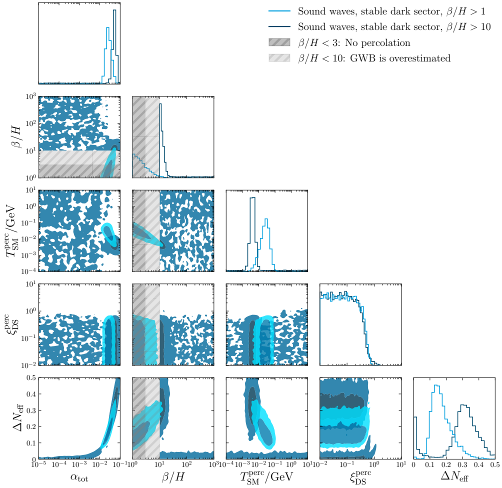
$$\Delta N_{\text{eff}} \approx 6 \times \left(\alpha_{\text{tot}} + \frac{1+\alpha_{\text{tot}}}{10} \left(\xi_{\text{DS}}^{\text{perc}}\right)^4 \right) , \quad \Delta N_{\text{eff}} < 0.22 \text{ @}95\,\% \text{ C.L.}$$

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

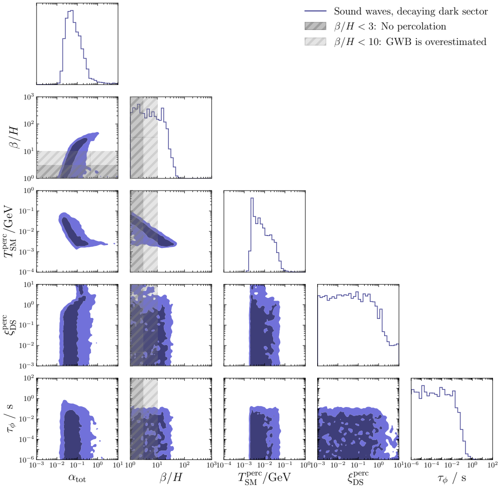
The tension between BBN, CMB and NANOGrav.

You cannot ignore the tension.



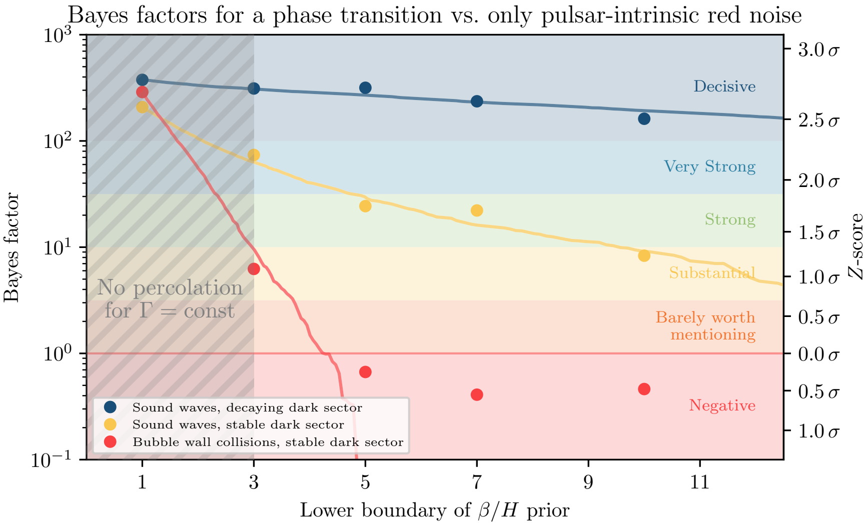


But you can circumvent the tension.



If the dark sector is allowed to decay, the tension with cosmology can be circumvented.
We find that the decays need to happen at $T_{\rm SM} \gtrsim 2$ MeV (just before neutrino decoupling), corresponding to decays happening with $\tau \lesssim 0.1$ s.

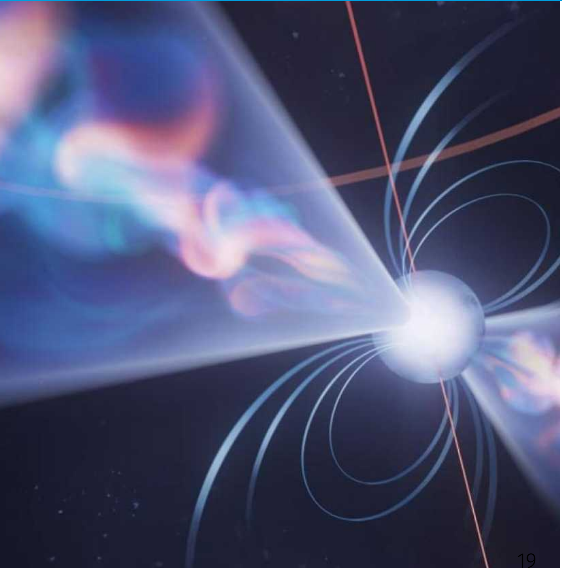
How likely is a dark sector phase transition explanation?



Conclusions.

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 are a viable option and can compete with SMBHBs.
- Look out for coming data releases that could confirm quadrupole correlation of the “common red signal” in $t \sim 2$ weeks!



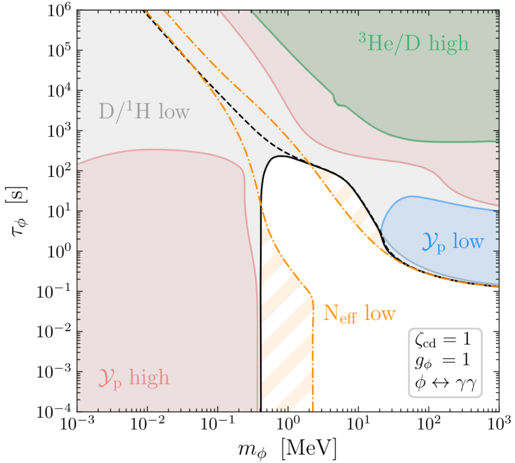
[image credit: Olena Shmahalo, NANOGrav]

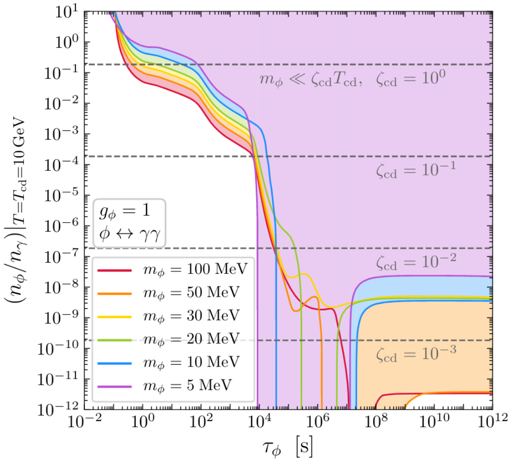
Thank you very much for your attention!

Do you have any questions?

Backup slides.

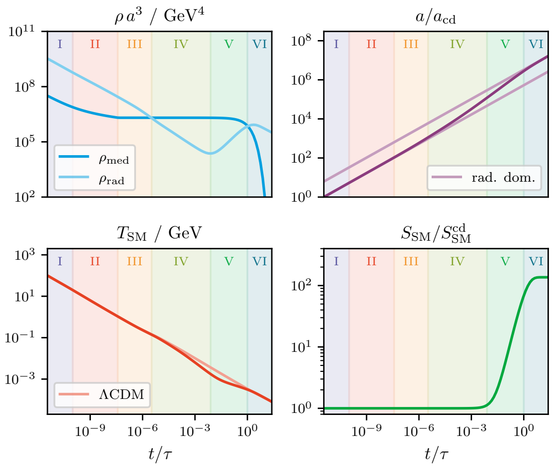
Electromagnetic scalar decays at MeV temperatures.





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

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

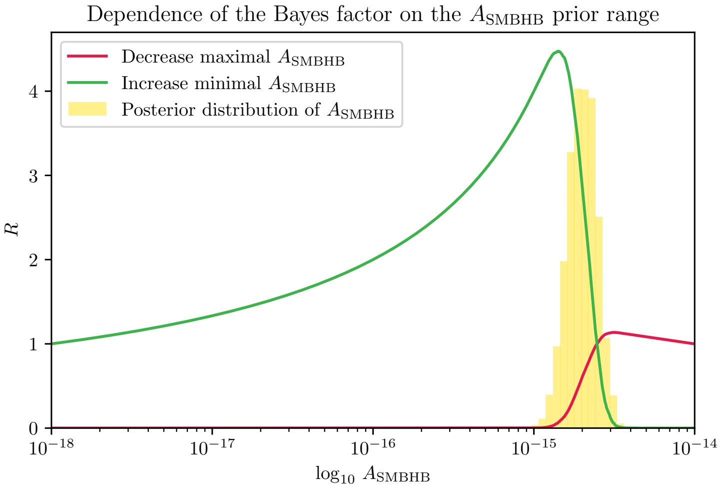


Energy densities $\rho_i(t)$ $\overset{\text{sets}}{\rightsquigarrow}$ Scale factor $a(t)$ $\overset{\text{sets}}{\rightsquigarrow}$ Temperatures $T_{\mathrm{SM/DS}}(t)$ $\overset{\text{set}}{\rightsquigarrow}$ Particle content $\overset{\text{sets}}{\rightsquigarrow}$ $\rho_i(t)$ $\overset{\text{sets}}{\rightsquigarrow}$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

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.