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

Seminar talk at Universidade Federal de Minas Gerais, Belo Horizonte

Carlo Tasillo,
Deutsches Elektronen Synchrotron (DESY)

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

arXiv: `[230x.soon]`

March 21, 2023

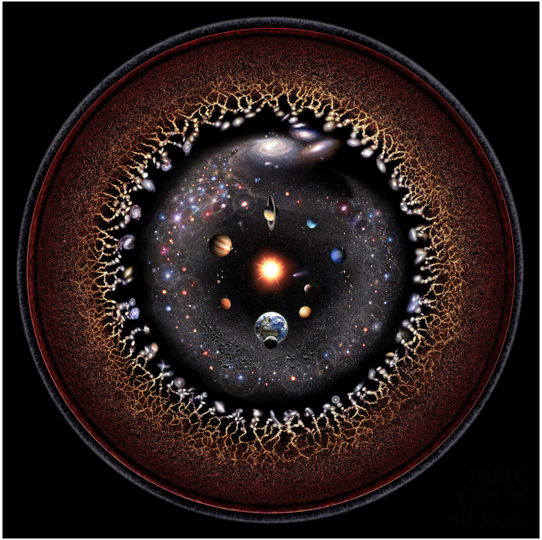
Outline of this talk.

1. What do we know about the Early Universe?
2. Pulsar timing arrays
3. Gravitational waves from dark sector phase transitions
4. The tension between BBN and NANOGrav
5. Outlook

[Camille Flammarion, 1888]

What do we know about the Early Universe?

What we know about our Universe.

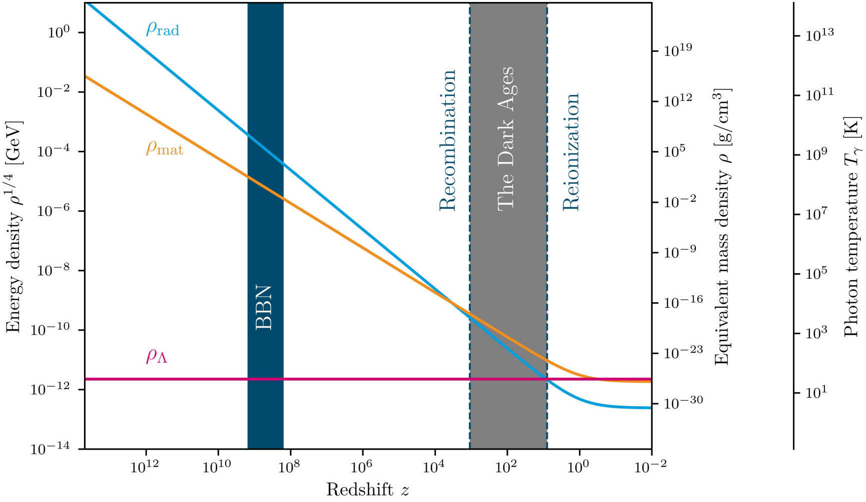


[Pablo Carlos Budassi, 2020]

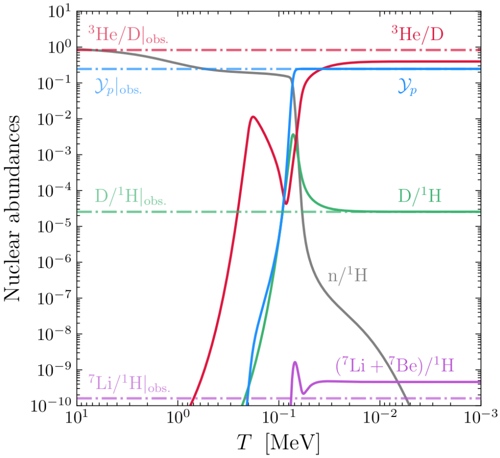
LCDM:

- Isotropic and homogeneous
- Expands since 13.8 billion years
- 95 % is dark!?
- Not probed above MeV temperatures...

A brief history of time: LCDM.



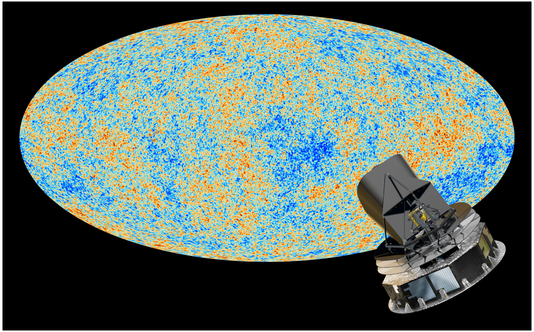
The Big Bang Nucleosynthesis and the CMB.



[Paul Frederik Depta, 2021]

- Observations of primordial light element abundances in good agreement with standard BBN
- $N_{\text{eff}}^{\text{BBN}} = 2.898 \pm 0.141$ [Yeh, 2207.13133]

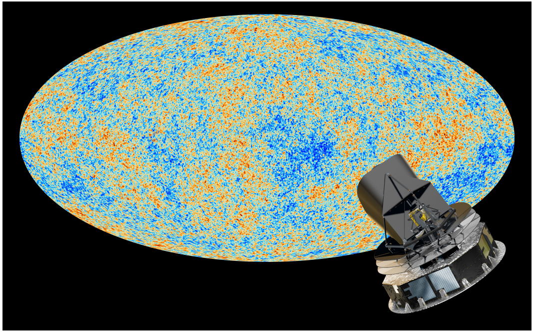
The Big Bang Nucleosynthesis and the CMB.



[ESA and the Planck Collaboration, D. Ducros]

- Observations of primordial light element abundances in 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 species [Bennet, 2012.02726v3]

The Big Bang Nucleosynthesis and the CMB.



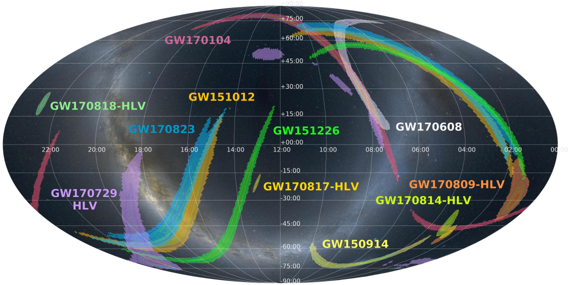
[ESA and the Planck Collaboration, D. Ducros]

- 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 species [Bennet, 2012.02726v3]

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

Gravitational waves as a “new” messenger.

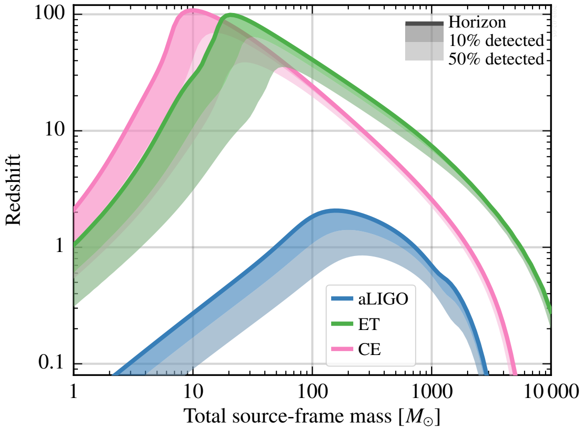
- LIGO + Virgo observed 90 mergers since 2015 [GWTC3]



[LIGO, Virgo & KAGRA Collaboration, 2020]

Gravitational waves as a “new” messenger.

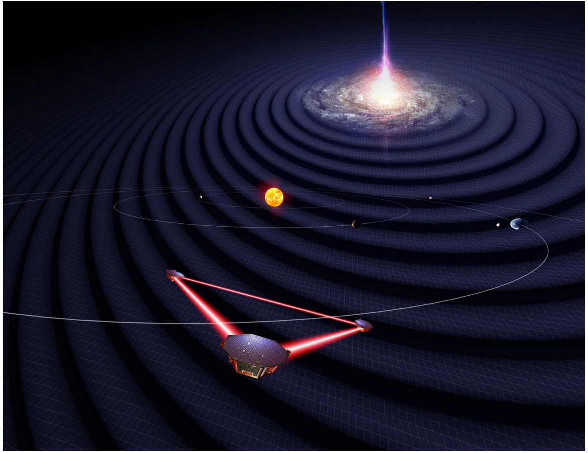
- LIGO + Virgo observed 90 mergers since 2015 [GWTC3]
- Einstein Telescope to be built soon: will be able to probe mergers during the Dark Ages (!)



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

Gravitational waves as a “new” messenger.

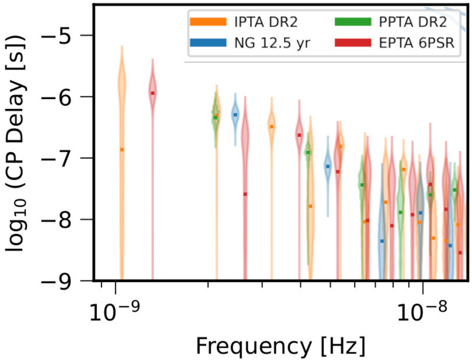
- LIGO + Virgo observed 90 mergers since 2015 [GWTC3]
- Einstein Telescope to be built soon: will be able to probe mergers during the Dark Ages (!)
- LISA will be able to test EWSB



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

Gravitational waves as a “new” messenger.

- LIGO + Virgo observed 90 mergers since 2015 [GWTC3]
- Einstein Telescope to be built soon: will be able to probe mergers during the Dark Ages (!)
- LISA will be able to test EWSB
- PTAs already detected something that might be a stochastic GW background!



[IPTA, 2201.03980]

Pulsar timing arrays.

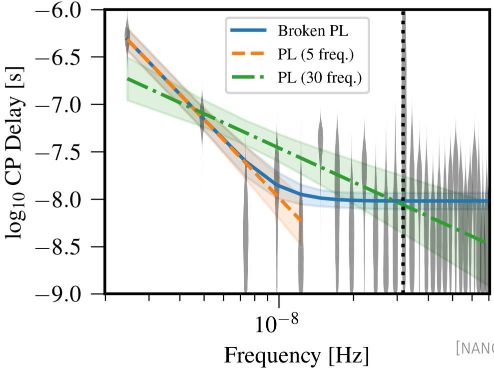
Pulsar timing arrays.

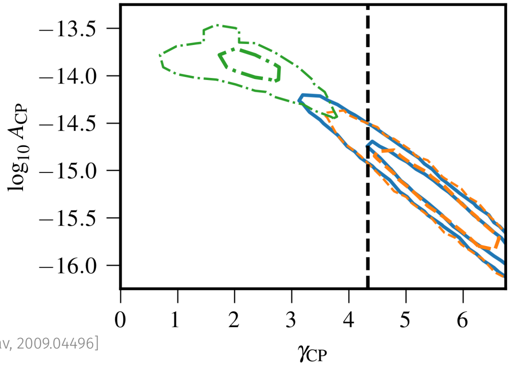
[Tonia Klein, NANOGrav]

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.



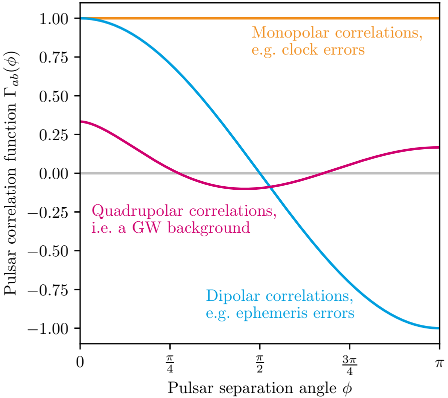


[NANOGrav, 2009.04496]

$$\log_{10} \text{CP delay}\,[s] = \log_{10} \sqrt{\frac{H_{100}^2}{8\pi^4}\,\frac{h^2\Omega_{\mathrm{gw}}(f)}{f^5\, t_{\mathrm{obs}}\, s^2}}$$

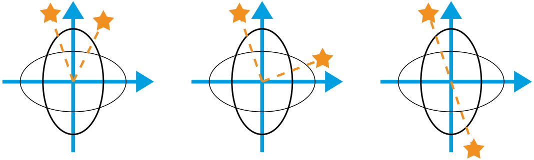
The five lowest Fourier modes agree with a “red” power-law GW background $h^2\Omega_{\mathrm{gw}}(f) \propto A_{\mathrm{CP}}^2\, f^{-\gamma_{\mathrm{CP}}/2}$

Was it actually a GW background or just noise?

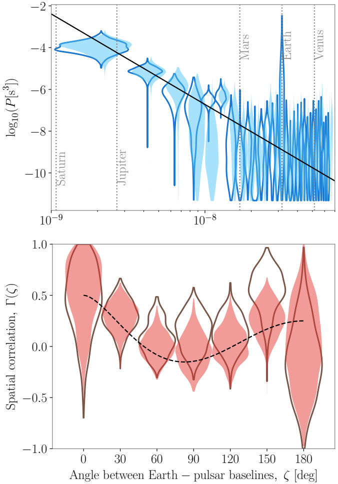


Red noise spectra can have many sources:

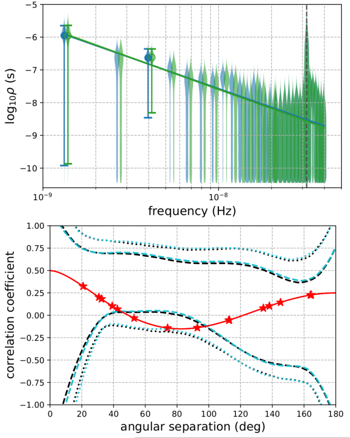
- Pulsar mismodelling: no correlation
- Clock errors: monopole
- Solar system ephemeris errors: dipole
- GWs: Hellings-Downs curve



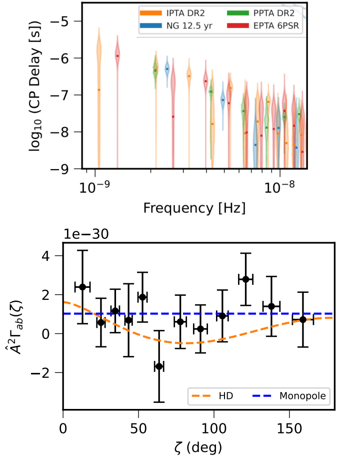
The same signal was also measured by EPTA, PPTA and IPTA.



[PPTA, 2107.12112]

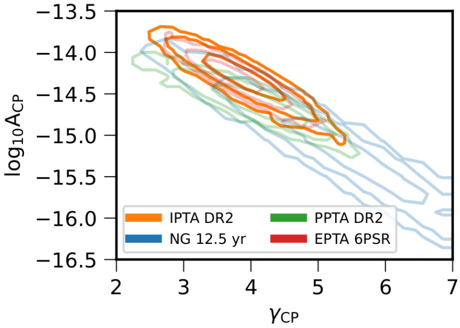


[EPTA, 2110.13184]



[IPTA, 2201.03980]

What are possible GW sources?



[IPTA, 2201.03980]

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

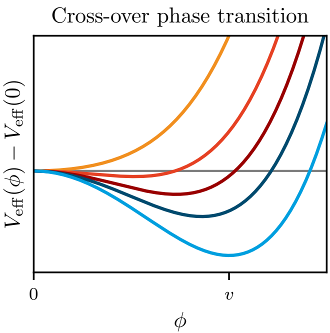
- ⇝ Astrophysics: Supermassive black hole binaries inspiraling, $\gamma_{\rm CP} = 4.33$

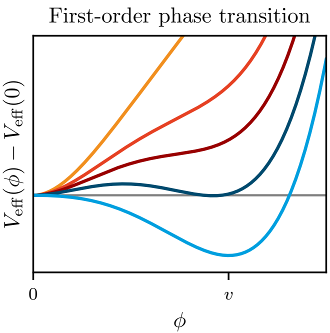
Possible cosmological sources include

- Primordial black holes
- Cosmic strings
- A first-order phase transition

Gravitational waves from dark sector phase transitions.

Cross-over and first-order phase transitions.



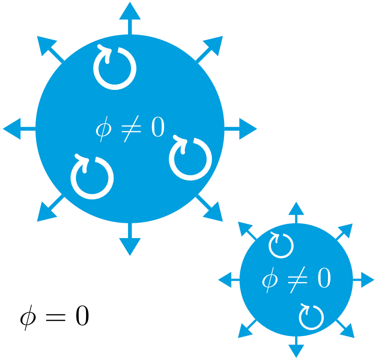


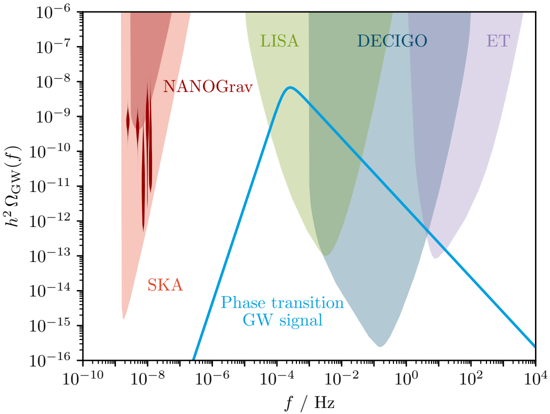
The scalar field "rolls down" from $\phi = 0$ to $\phi = v$, when the bath cools from high temperatures to low temperatures.

The 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.

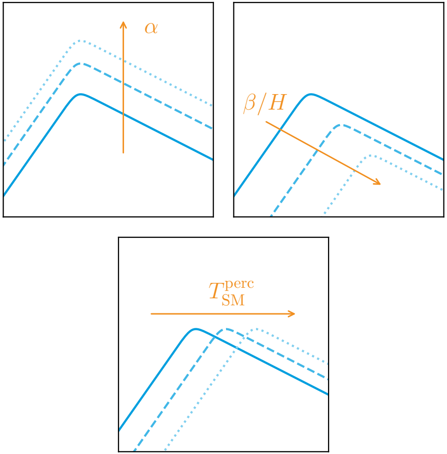
Bubbles of the new phase nucleate, collide and perturb the plasma…





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

Parametrization of the GW signal.



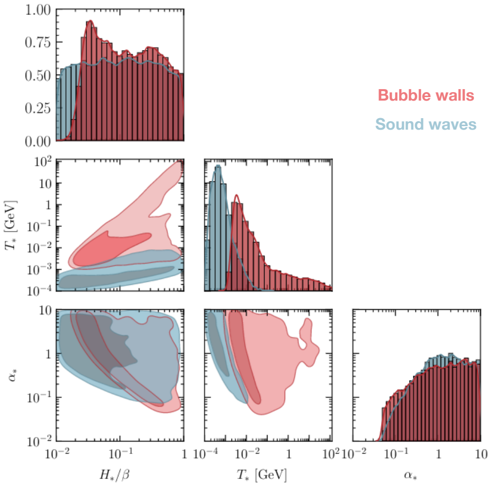
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

with $\quad f_{\rm peak} \simeq 0.1\,\text{Hz}\,\dfrac{\beta}{H}\,\dfrac{T_{\rm SM}^{\rm perc}}{\text{MeV}}$

For signals that fit NANOGrav:

- Strong transitions, high α
- Slow transitions, low β/H
- Percolation around $T_{\rm SM}^{\rm perc} \simeq \mathcal{O}(\text{MeV})$: very low for visible sector transition

Parametrization of the GW signal.



[Adapted from NANOGrav, 2104.13930]

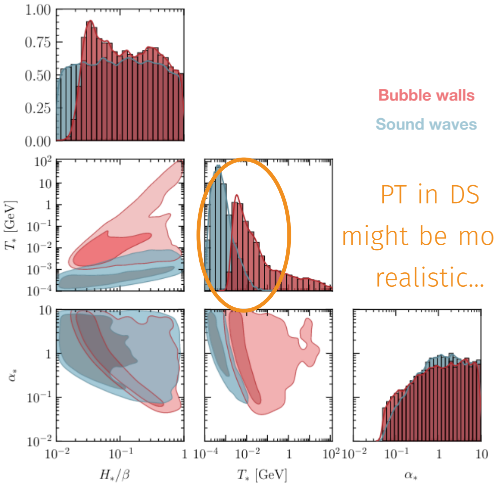
$$h^2\Omega_{\mathrm{GW}}^{\mathrm{sw},\mathrm{bw}}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\mathrm{peak}}}\right)$$

with $\quad f_{\mathrm{peak}} \simeq 0.1\,\mathrm{Hz}\,\dfrac{\beta}{H}\,\dfrac{T_{\mathrm{SM}}^{\mathrm{perc}}}{\mathrm{MeV}}$

For signals that fit NANOGrav:

- Strong transitions, high α
- Slow transitions, low β/H
- Percolation around $T_{\mathrm{SM}}^{\mathrm{perc}} \simeq \mathcal{O}(\mathrm{MeV})$: very low for visible sector transition

Parametrization of the GW signal.



PT in DS might be more realistic...

[Adapted from NANOGrav, 2104.13930]

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

with $\quad f_{\rm peak} \simeq 0.1\,\mathrm{Hz}\,\frac{\beta}{H}\,\frac{T_{\rm SM}^{\rm perc}}{\mathrm{MeV}}$

For signals that fit NANOGrav:

- Strong transitions, high α
- Slow transitions, low β/H
- Percolation around $T_{\rm SM}^{\rm perc} \simeq \mathcal{O}(\mathrm{MeV})$: very low for visible sector transition

What changes for transitions in a dark sector?

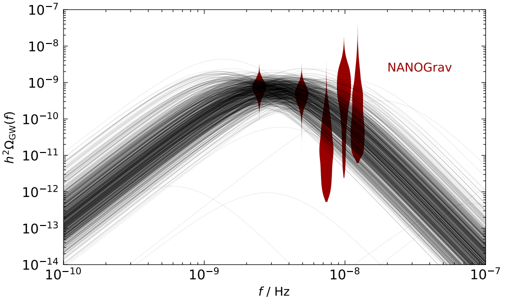
- Transition can happen in sector with distinct temperature $T_{\text{DS}} = \xi_{\text{DS}}\, T_{\text{SM}}$
- Bubble wall dynamics depend on $\alpha_{\text{DS}} = \Delta\theta/\rho_{\text{DS}} \simeq \alpha_{\text{tot}}/\xi_{\text{DS}}^4$ and not on α_{tot}
- Potential dilution of the GW signal due to matter domination [CT, 2109.06208]
- **Stable dark sector:** additional DS energy density contributes to N_{eff} as

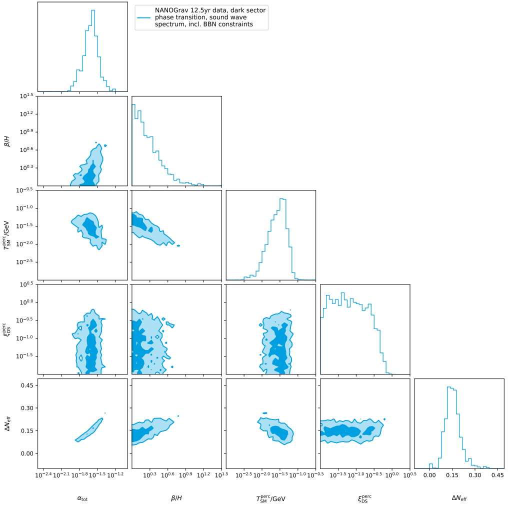
$$\Delta N_{\text{eff}} \simeq 6 \left(\alpha_{\text{tot}} + \frac{g_{\text{DS}}^{\text{perc}}}{g_{\text{SM}}^{\text{perc}}} \left(\alpha_{\text{tot}} + 1\right) \left(\xi_{\text{DS}}^{\text{perc}}\right)^4 \right) , \quad \Delta N_{\text{eff}} < 0.14 \text{ @95 \% C.L.}$$

- **Decaying dark sector:** Energy transfer to the SM plasma, potentially during BBN. We assume: Decays of a 5 MeV dark Higgs.

The tension between BBN and NANOGrav.

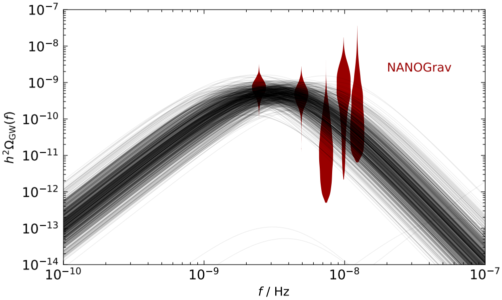
Stable dark sector, transition time scale prior: $\beta/H > 1$

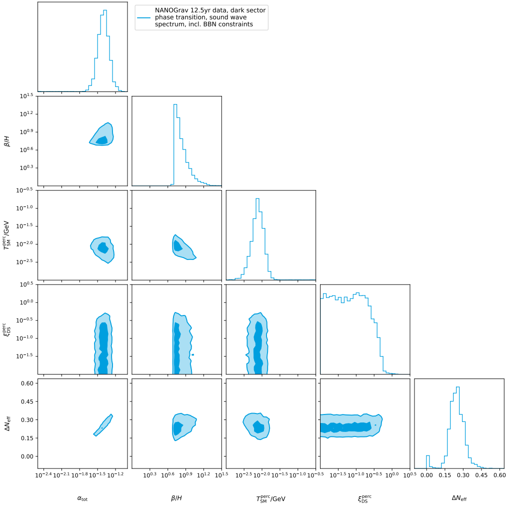




α_{tot}	β/H	T_{SM}^{perc}	ξ_{DS}^{perc}	ΔN_{eff}
$\simeq 0.03$	$1-3$	$\simeq 30$ MeV	$\lesssim 0.3$	$\simeq 0.15$

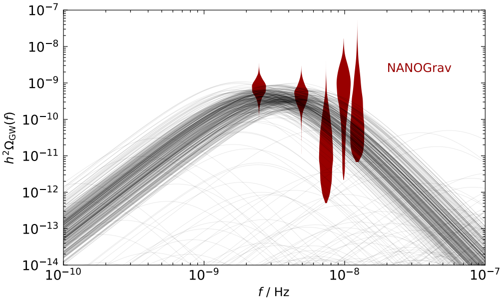
Stable dark sector, transition time scale prior: $\beta/H > 5$

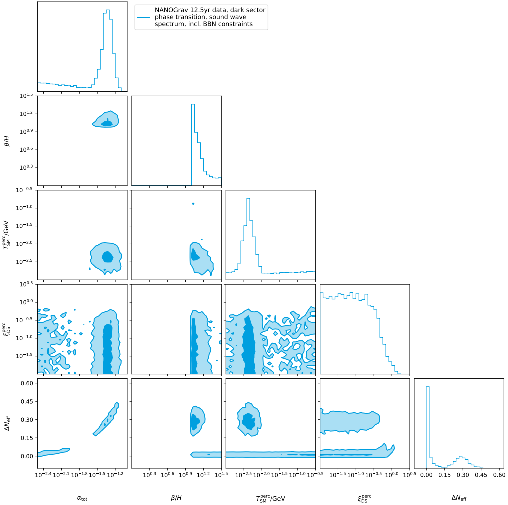




α_{tot}	β/H	T_{SM}^{perc}	ξ_{DS}^{perc}	ΔN_{eff}
$\simeq 0.05$	$5-10$	$\simeq 8$ MeV	$\lesssim 0.3$	$\simeq 0.25$

Stable dark sector, transition time scale prior: $\beta/H > 10$

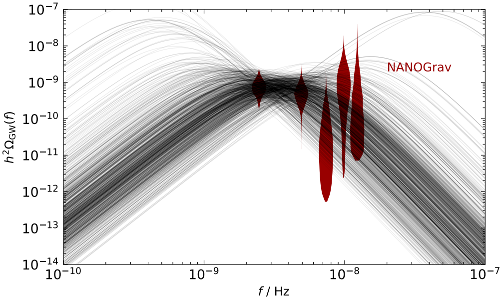




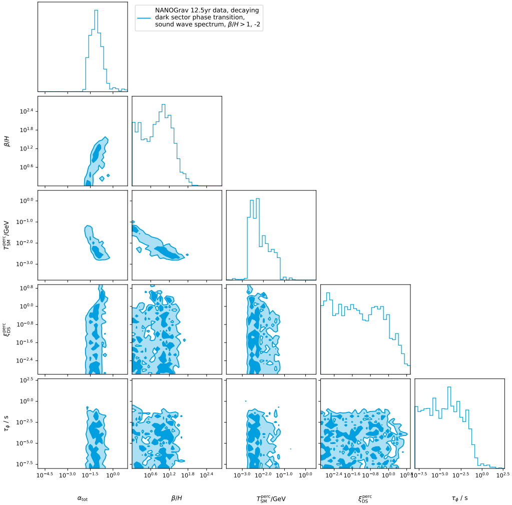
α_{tot} and ΔN_{eff} need to get even higher $\rightsquigarrow$ tension with BBN and CMB!

Global fit prefers $\alpha_{\mathrm{tot}} \to 0$: The signal is then explained by PSR-intrinsic red noise only. ☹

Decaying dark sector

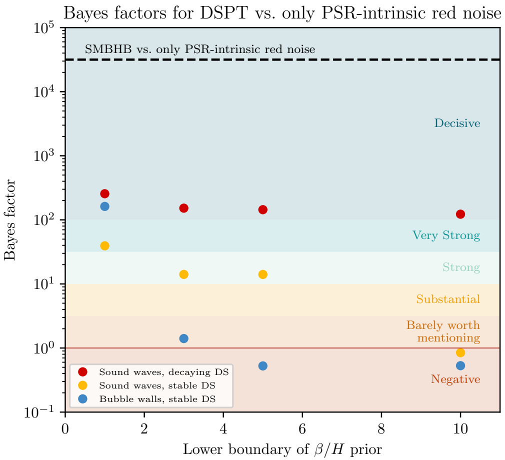


- No strong preference for tiny β/H
- α_{tot} up to $\mathcal{O}(1)$ possible, as long as DS decays before BBN, $\tau_\phi < 0.1\,\text{s}$
- $T_{\text{SM}}^{\text{perc}} \gtrsim 2\,\text{MeV}$ [Bai and Korwar, 2109.14765]



Summary.

- Stable DSPT explanations for NANOGrav are in tension with BBN
- The tension is larger for quicker PTs, as α_{tot} would need to be larger
- GWBs from sound waves are more plausible then from bubble walls
- If the transitioning DS can dump its energy into the SM, the tension decreases



Conclusions.

Conclusions and outlook.

[Camille Flammarion, 1888]

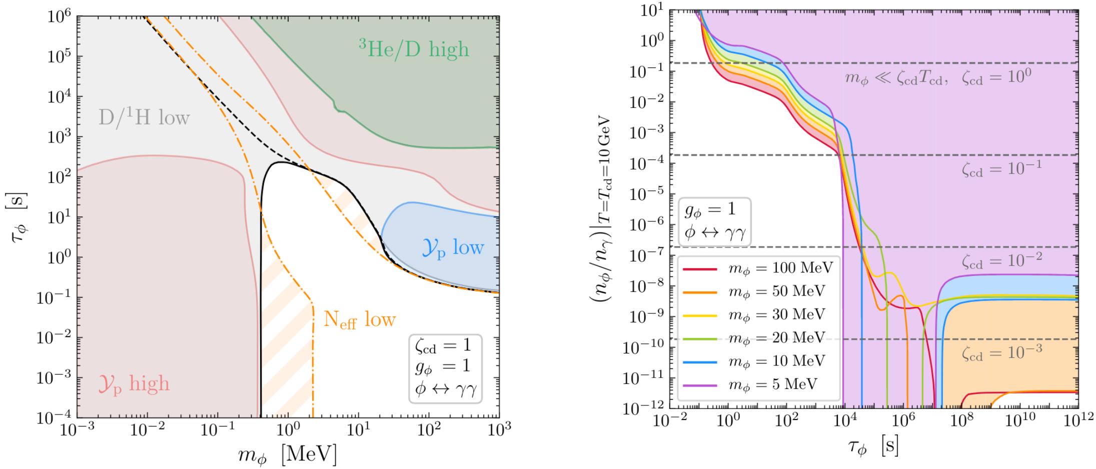
- **BBN and CMB** put strong constraints on beyond-LCDM cosmology, including phase transitions in dark sectors
- **Early Universe can be tested** at times before BBN using GWs
- **PTAs** found a "common red signal", which would require $T_{\mathrm{perc}} < 10\,\mathrm{MeV}$ if from visible sector phase transition
- **Dark sector phase tansitions** can explain NANOGrav, if β/H is (suspiciously) low or the dark sector decays fast enough after the transition!

Muito obrigado pela atenção!

Você tem alguma pergunta?

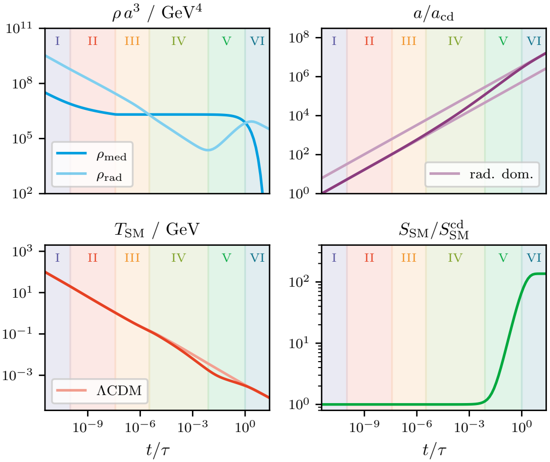
Backup slides.

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 $T_{\mathsf{SM/DS}}(t) \overset{\text{set}}{\rightsquigarrow}$ 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