Gravitational waves and dark energy in modified cosmological scenarios

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This talk is based on: D. Chowdhury, G. Tasinato, and I. Zavala, arXiv:2307.01188 [hep-th].

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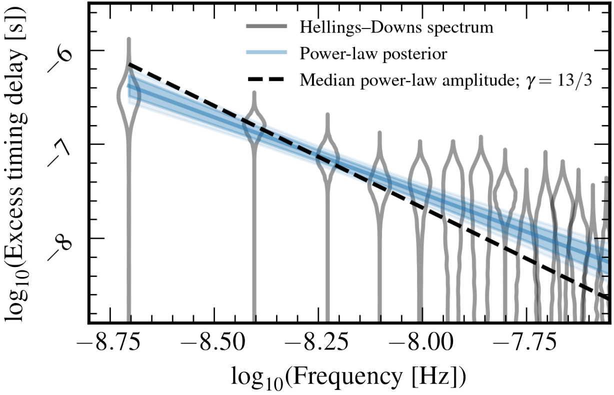
Outline of the talk

The NANOGrav Pulsar Timing Array[1]

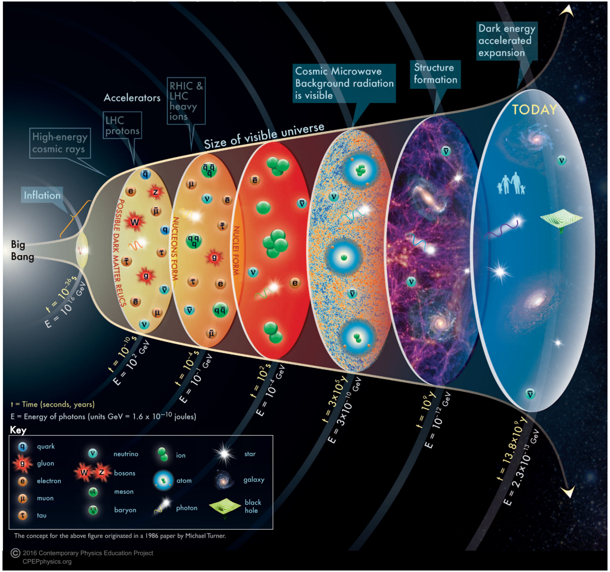
[1] Illustration Credit: Tonia Klein / NANOGrav (https://nanograv.org).

The stochastic gravitational wave background[2]



[2] Figure from: NANOGrav Collaboration, Astrophys. J. Lett. **951**, L8 (2023).

The unconstrained window of time[3]



[3] Image from: https://www.cpepphysics.org/images/expansion.jpg.

PGW spectrum in standard cosmology I

Equation of motion for primordial tensor fluctuations[4]:

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{\nabla^2}{a^2}h_{ij} = 0.$$

To solve the tensor perturbation equations, one can write it in Fourier space as

$$h_{ij}(t,\vec{x}) = \sum_{\lambda}\int \frac{d^3k}{(2\pi)^3} h^{\lambda}(t,\vec{k})\epsilon^{\lambda}_{ij}(\vec{k})e^{i\vec{k}\cdot\vec{x}}.$$

Energy density of the relic GW:

$$\rho_{\rm GW}(t) = \frac{1}{16\pi G}\sum_{\lambda}\int \frac{d^3k}{(2\pi)^3}|\dot{h}^{\lambda}(t,\vec{k})|^2 .$$

Relic density of the PGWs:

$$\Omega_{\rm GW}(t,k) = \frac{1}{\rho_c(t)}\frac{d\rho_{\rm GW}(t,k)}{d\ln k}.$$

[4] Y. Watanabe and E. Komatsu, Phys. Rev. D **73**, 123515 (2006); K. Saikawa and S. Shirai, JCAP **05**, 035 (2018); N. Bernal and F. Hajkarim, Phys. Rev. D **100**, 063502 (2019); N. Bernal, *et al.*, JCAP **11**, 015 (2020).

PGW spectrum in standard cosmology II

Fractional energy density in primordial gravitational waves, observed today:

$$\Omega^0_{\rm GW}(k)\, h^2 \simeq \frac{1}{24}\, \mathcal{P}_{\rm T}(k) \left(\frac{g_{*s,0}}{g_{*s,\rm hc}}\right)^{4/3} \left(\frac{T_0}{T_{\rm hc}}\right)^4 \left(\frac{H_{\rm hc}}{H_0/h}\right)^2,$$

where $\mathcal{P}_{\rm T} = r\, \mathcal{A}_{\rm S}$.

Frequency of GWs observed today:

$$f_0 = 2.6461 \times 10^{-8} \left(\frac{T_{\rm hc}}{1{\rm GeV}}\right) \left(\frac{g_{*s,\rm hc}}{106.75}\right)^{-1/3} \left(\frac{g_{*,\rm hc}}{106.75}\right)^{1/2} \ {\rm Hz}.$$

Scalar-tensor theories

Action[5]:

$$S = S_\phi + S_m,$$

where

$$S_\phi = \int \mathrm{d}^4x \sqrt{-g} \left[\frac{R}{2\,\kappa^2} - M^4 \sqrt{1 + \frac{(\partial\phi)^2}{M^4}} - V(\phi) \right],$$

$$S_m = - \int \mathrm{d}^4x \sqrt{-\tilde{g}}\, \mathcal{L}_M(\tilde{g}_{\mu\nu}),$$

with $\kappa^2 = M_{\rm Pl}^{-2} = 8\,\pi\,G$.

The disformally coupled metric is given by

$$\tilde{g}_{\mu\nu} = g_{\mu\nu} + \frac{\partial_\mu\phi\,\partial_\nu\phi}{M^4}.$$

[5] B. Dutta, E. Jimenez, and I. Zavala, JCAP **06**, 032 (2017); B. Dutta, E. Jimenez, and I. Zavala, Phys. Rev. D **96**, 103506 (2017), D. Chowdhury, G. Tasinato, and I. Zavala, arXiv:2307.01188 [hep-th].

Equations of motion

$$H^2 = \frac{\kappa^2}{3}\frac{(1+\lambda)}{B}\rho\,,$$

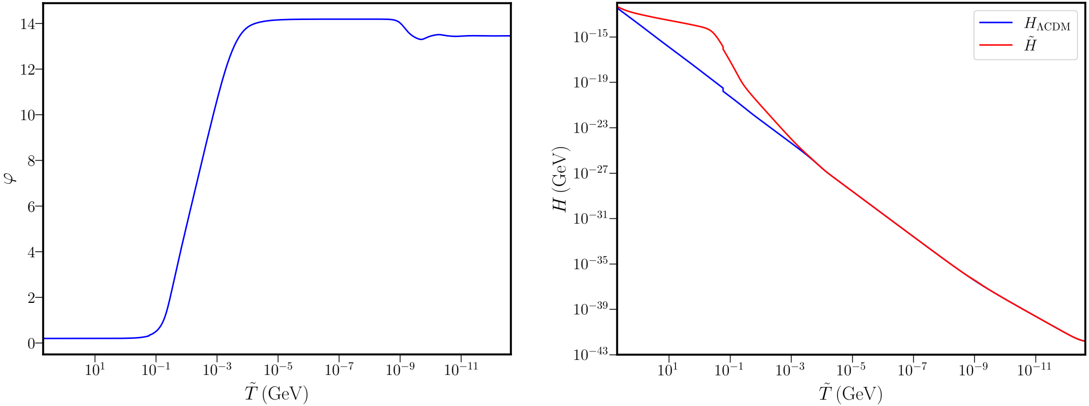
$$H_N = -H\left[\frac{3\,B}{2(1+\lambda)}(1+w) + \frac{\varphi_N^2}{2}\gamma\right],$$

$$\varphi_{NN}\left[1+\frac{\gamma^{-1}}{M^4}\frac{3\,B\,H^2}{\kappa^2(1+\lambda)}\right] + 3\,\varphi_N\left[\gamma^{-2} - \frac{w}{M^4\,\gamma}\frac{3\,B\,H^2}{\kappa^2(1+\lambda)}\right]$$
$$+\frac{H_N}{H}\varphi_N\left[1+\frac{\gamma^{-1}}{M^4}\frac{3\,B\,H^2}{\kappa^2(1+\lambda)}\right] + \frac{3\,B\,\lambda}{\gamma^3\,(1+\lambda)}\frac{V_{,\varphi}}{V} = 0,$$

where

$$\gamma^{-2} = 1 - \frac{H^2\,\varphi_N^2}{M^4\kappa^2},$$
$$B = 1 - \frac{\gamma^2\,\varphi_N^2}{3\,(\gamma+1)},$$
$$\lambda = \frac{V}{\rho}.$$

Field evolution and the expansion rate



The evolution of the field and the Hubble parameter with $\varphi^i = 0.2$, $\varphi^i_{\tilde{N}} = 3.9 \times 10^{-7}$, $M = 765\,\mathrm{MeV}$, and $\tilde{T}_i \sim 500\,\mathrm{GeV}$.

Power-law integrated sensitivity (PLS) curves

GW spectra of a power-law form are assumed:

$$\Omega_{\rm GW}(f) = \Omega_\beta \left(\frac{f}{f_*}\right)^\beta .$$

For a set of β and some choice of f_*, the following amplitude is evaluated:

$$\Omega_\beta = \frac{\rho}{\sqrt{2T}} \left[\int_{f_{\rm min}}^{f_{\rm max}} {\rm d}f \, \frac{(f/f_*)^{2\beta}}{\Omega^2_{\rm eff}(f)}\right]^{-1/2} .$$

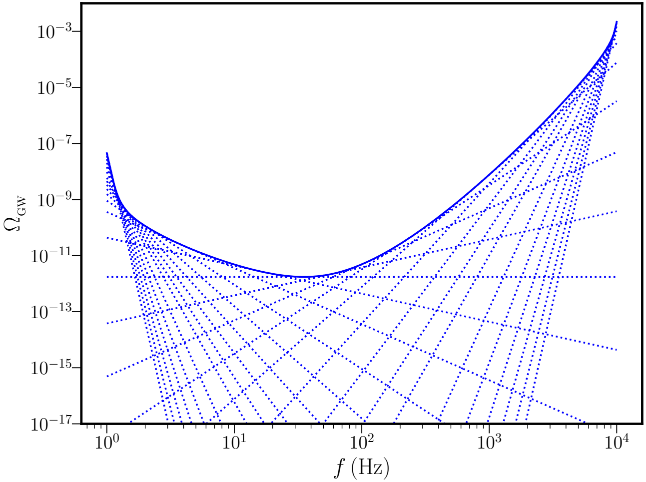
For each pair (β, Ω_β), $\Omega_{\rm GW}(f)$ is plotted against f.

The resulting envelope of the family of such curves is the PLS curve[6]:

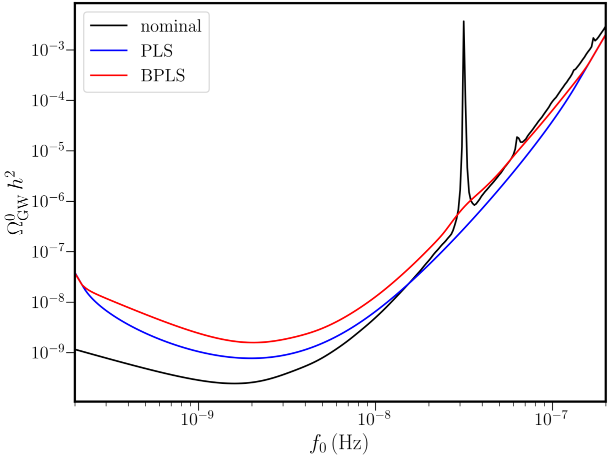
$$\Omega^{\rm PLS}_{\rm GW}(f) = \max_\beta \left[\Omega_\beta \left(\frac{f}{f_*}\right)^\beta\right] .$$

[6] E. Thrane and J. D. Romano, Phys. Rev. D **88**, 124032 (2013).

Plotting the envelope



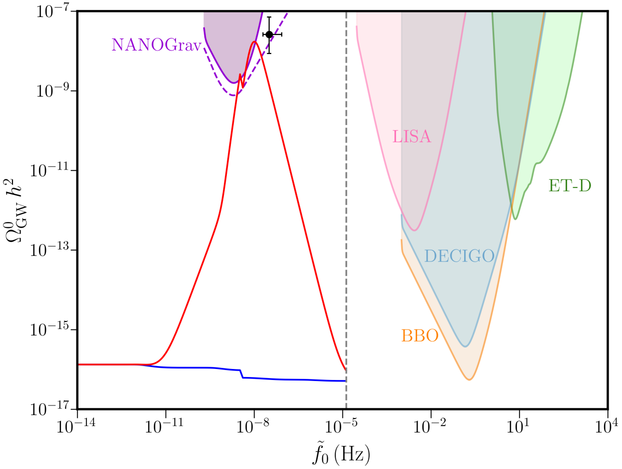
Broken power-law integrated sensitivity (BPLS) curves



Nominal (black solid line), BPLS[7] (red solid line), and PLS (blue solid line) curves for the NANOGrav 15-year data, using the corresponding noise spectra for the stochastic gravitational wave background[8].

[7] D. Chowdhury, G. Tasinato, and I. Zavala, JCAP **08**, 010 (2022), D. Chowdhury, G. Tasinato, and I. Zavala, arXiv:2307.01188 [hep-th].
[8] NANOGrav Collaboration, Astrophys. J. Lett. **951**, L10 (2023), NANOGrav Collaboration, `https://doi.org/10.5281/zenodo.8092346`.

PGW spectrum



The PGW spectrum for the D-brane disformal scenario has been plotted (in red) against the PGW spectrum in the GR case (in blue) for comparison[9]. The peak of the GW spectrum reaches a maximum value of $\sim 1.7\times 10^{-8}$, in agreement with the NANOGrav bound[10].

[9] D. Chowdhury, G. Tasinato, and I. Zavala, arXiv:2307.01188 [hep-th].

[10] NANOGrav Collaboration, Astrophys. J. Lett. **951**, L8 (2023).

Fitting the broken power-law spectrum

We fit the peak of our spectrum with[11]:

$$\tilde{\Omega}^0_{\rm GW}\, h^2 = A_{\rm b}^2\, f^2 \left(\frac{f}{f_{\rm yr}}\right)^{\sigma-3} \left[1 + \left(\frac{f}{f_{\rm b}}\right)^{1/\varepsilon}\right]^{\varepsilon(\mu-\sigma)},$$

where $f_{\rm yr} = 1/{\rm year}$ in Hz.

We find: $\log_{10}(A_{\rm b}/{\rm s}) = 5.279$, $\log_{10}(f_{\rm b}/{\rm Hz}) = -8.048$, $\sigma = 6.0$, $\varepsilon = 0.25$, and $\mu = -2.0$.

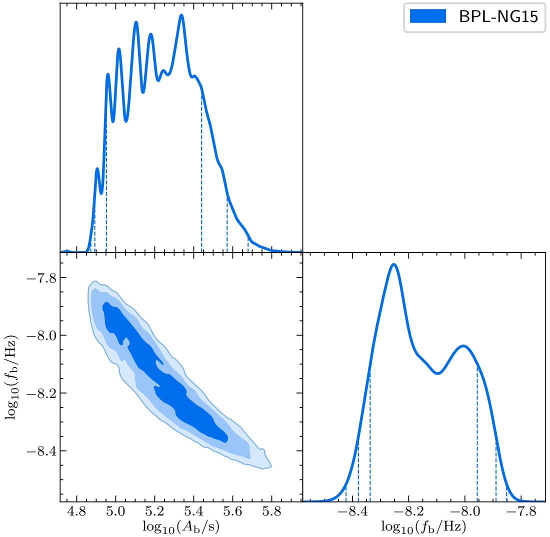
We vary $\log_{10}(A_{\rm b}/{\rm s})$ and $\log_{10}(f_{\rm b}/{\rm Hz})$ using PTArcade[12], and find the following best-fit values:

$$\log_{10}(A_{\rm b}/{\rm s}) = 5.242 \pm 0.191,$$
$$\log_{10}(f_{\rm b}/{\rm Hz}) = -8.149 \pm 0.144.$$

[11] D. Chowdhury, G. Tasinato, and I. Zavala, arXiv:2307.01188 [hep-th], NANOGrav Collaboration, Astrophys. J. Lett. **905**, L34 (2020), NANOGrav Collaboration, Astrophys. J. Lett. **951**, L8 (2023).

[12] A. Mitridate and D. Wright, **PTArcade** (`https://doi.org/10.5281/zenodo.8106173`) (2023), A. Mitridate *et al.*, arXiv:2306.16377 [hep-ph], W. G. Lamb, S. R. Taylor, and R. van Haasteren, arXiv:2303.15442 [astro-ph.HE].

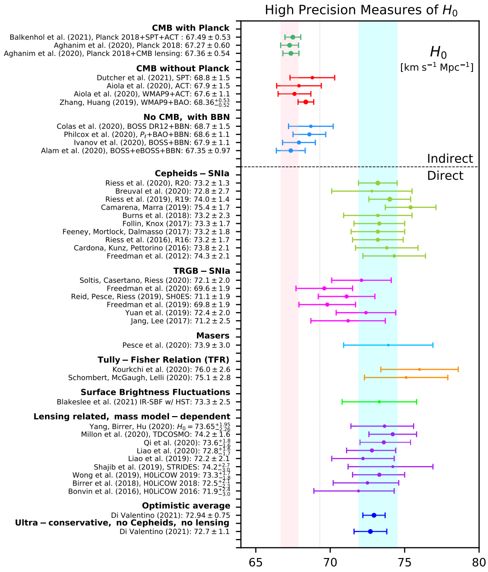
Parameter estimation



Posterior distributions for the parameters of the broken power-law fitting function indicating the 68%, 95%, and 99% credible intervals.

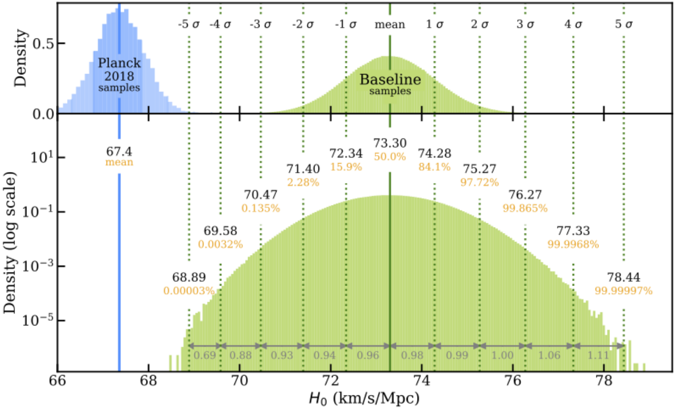
Dark energy

Hubble tension I[13]



[13] Figure from: Di Valentino *et al.*, Class. Quant. Grav. **38**, 153001 (2021).

Hubble tension II[14]



[14]Figure from: M. Kamionkowski and A. G. Riess, arXiv:2211.04492 [astro-ph.CO].

Early Dark Energy (EDE)

An early period of dark energy domination has been considered as a possible means of relaxing the H_0 tension[15].

Hubble constant[16]:

$$H_0 = \sqrt{3}\, H_{\rm ls}\, \theta_{\rm s} \frac{\int_0^{z_{\rm ls}} {\rm d}z\, [\rho(z)/\rho_0]^{-1/2}}{\int_{z_{\rm ls}}^{\infty} {\rm d}z\, [\rho(z)/\rho(z_{\rm ls})]^{-1/2}\, (1+R)^{-1/2}},$$

where $\theta_{\rm s} = (1.04109 \pm 0.00030) \times 10^{-2}$.

Requirements:

- Contributes $\sim 10\%$ of total energy density briefly before recombination.
- Must decay faster than radiation, to leave later evolution unchanged.

This can be driven by a scalar field.

[15] V. Poulin *et al.*, Phys. Rev. D **98**, 083525 (2018), V. Poulin *et al.*, Phys. Rev. Lett. **122**, 221301 (2019), J. C. Hall *et al.*, Phys. Rev. D **102**, 043507 (2020).

[16] M. Kamionkowski and A. G. Riess, arXiv:2211.04492 [astro-ph.CO].

EDE energy density

A potential of the following form is chosen[17]:

$$V(\varphi) = V_0 \left(1 - \cos\frac{\varphi}{f}\right)^n .$$

Field oscillates with an equation of state[18]:

$$w_n = \frac{n-1}{n+1} .$$

Energy density decays as:

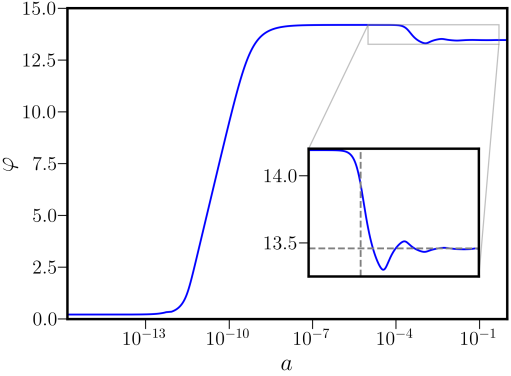
$$\rho_n \propto a^{-6n/(n+1)} .$$

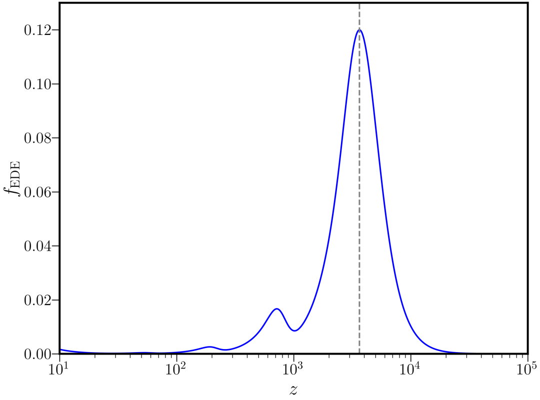
We must have $n \geq 3$.

[17] V. Poulin *et al.*, Phys. Rev. D **98**, 083525 (2018), V. Poulin *et al.*, Phys. Rev. Lett. **122**, 221301 (2019), J. C. Hall *et al.*, Phys. Rev. D **102**, 043507 (2020).

[18] M. S. Turner, Phys. Rev. D **28**, 1243 (1983).

Evolution of the field and energy density



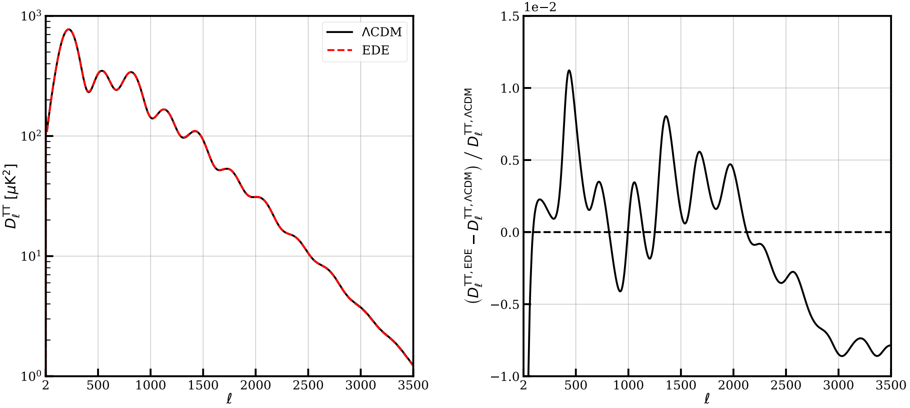


Left: The evolution of the scalar field as a function of the scale factor.

Right: The fractional contribution of the EDE to the total energy density as a function of redshift.

Resolving the Hubble tension

Value of H_0 is 72.19 km/s/Mpc.



CMB temperature anisotropy power spectra (left panel) and residuals (right panel) for ΛCDM and EDE models[19].

[19] Figure from: J. C. Hill *et al.*, Phys. Rev. D **102**, 043507 (2020).

Late Dark Energy (LDE)

A scalar field potential can also drive a period of Late Dark Energy (LDE) domination.

This can lead to the current phase of accelerated expansion, without requiring a cosmological constant.

The total potential is given by[20]:

$$V(\varphi) = V_{0_{\rm ede}} \left(1 - \cos\frac{\varphi}{f_1}\right)^3 + V_{0_{\rm de}} \left(1 - \cos\frac{\varphi}{f_2}\right).$$

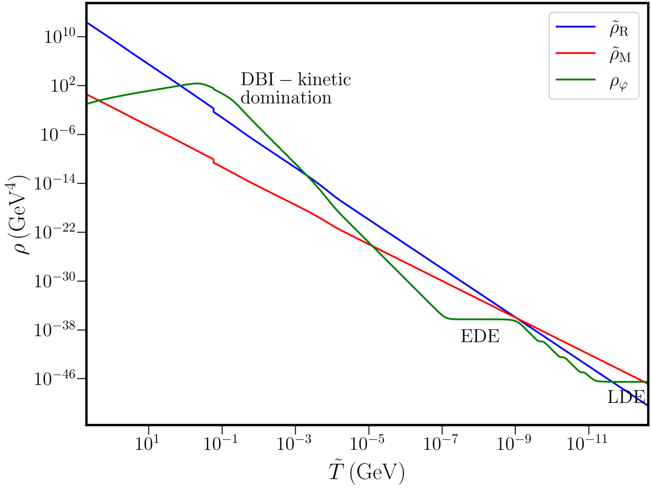
We choose:

$$V_{0_{\rm ede}} \sim {\rm eV}^4, \qquad V_{0_{\rm de}} \sim (0.002\,{\rm eV})^4,$$

$$f_1 \sim 0.4, \qquad f_2 \sim 0.1.$$

[20] D. Chowdhury, G. Tasinato, and I. Zavala, arXiv:2307.01188 [hep-th].

Evolution of the energy density



Plot of the different contributions to the energy density of the universe as a function of the universe temperature.

Summary

- Modifications to the expansion rate of the early universe can leave imprints on the gravitational wave spectrum.
- We have studied the effects of such modifications in the presence of a disformal coupling.
- The resulting GW energy density has a broken power-law frequency profile, entering the PTA band with a peak amplitude consistent with the recent GW detection.
- Our model provides a realization of an early dark energy scenario aimed at relaxing the H_0 tension, and a late dark energy model which explains the current cosmological acceleration with no need of a cosmological constant.

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- Our model provides a realization of an early dark energy scenario aimed at relaxing the H_0 tension, and a late dark energy model which explains the current cosmological acceleration with no need of a cosmological constant.

Thank you!