D-BRANES, DARK ENERGY AND PULSAR TIMING ARRAYS

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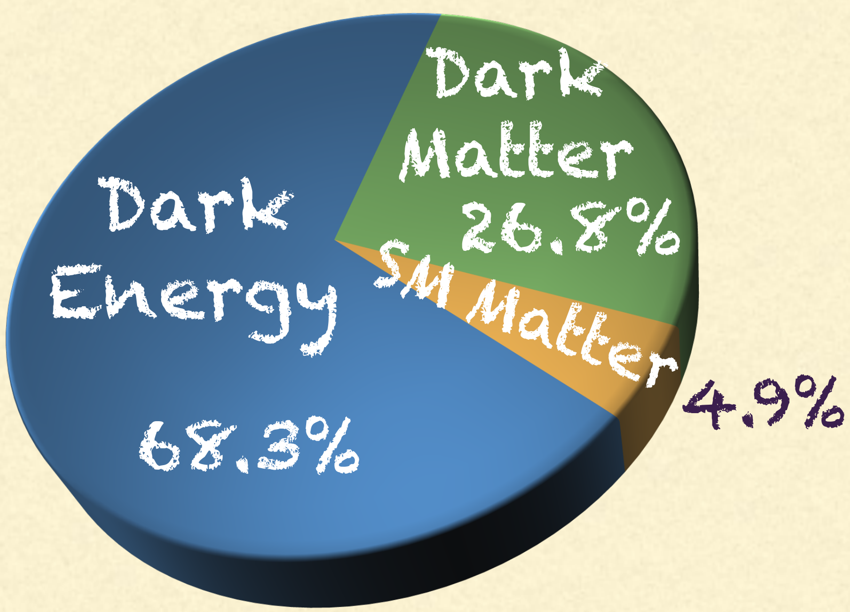
Based on work in collaboration with
Chowdhury, Tasinato

THE ΛCDM MODEL OF COSMOLOGY

The ΛCDM model has emerged as a *phenomenological* model in good agreement to a large span of cosmological data.

The ΛCDM model (Lambda cold dark matter)



cosmic pie

In this model, the universe contains three major components: *dark energy (Λ) cold dark matter* and ordinary matter.

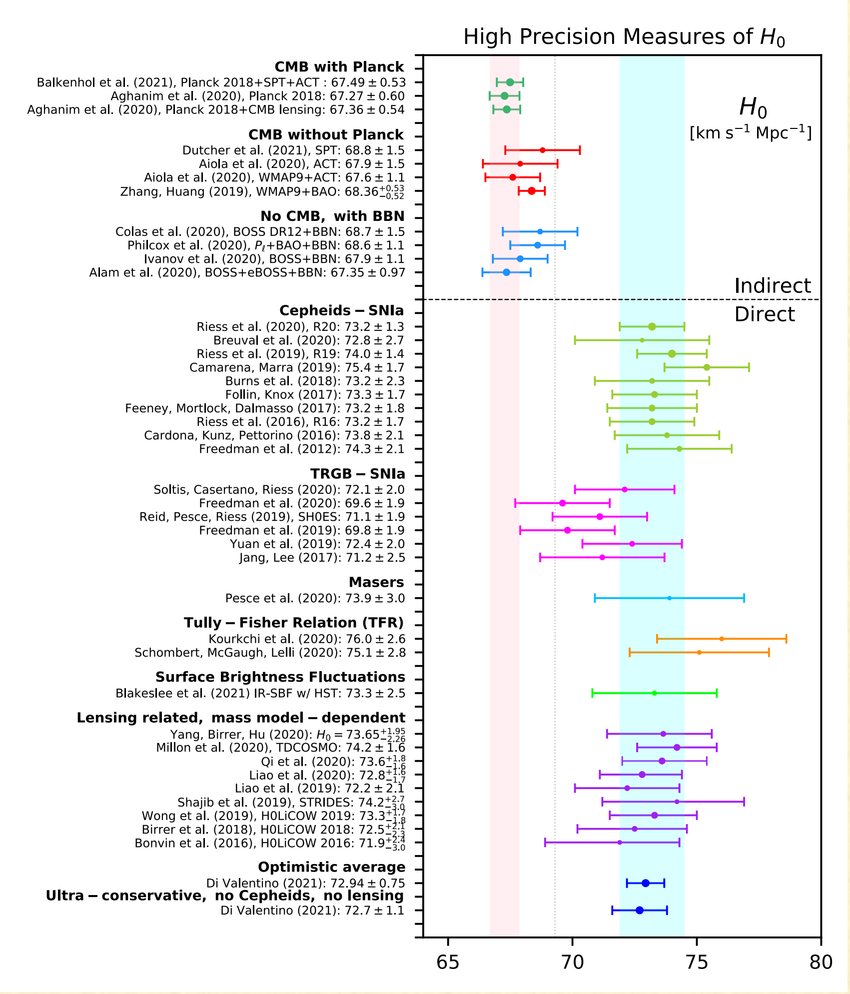
Complemented with the *inflationary scenario to generate primordial fluctuations that seed large scale structures* we observe today

THE ΛCDM MODEL OF COSMOLOGY

With the improvement of the number and the accuracy of observations, discrepancies among key cosmological parameters of the model have emerged.

One of the most statistically significant tension is the **H_0-tension**:

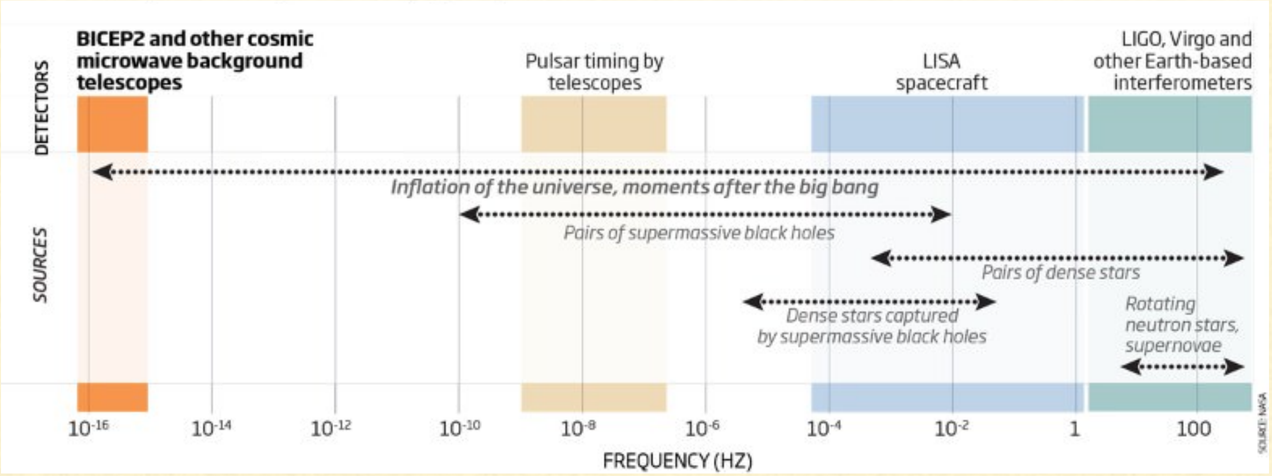
The disagreement between predictions of H_0 from early universe probes assuming the ΛCDM model, and late time, determinations of H_0 from measurements of distances and redshifts.



[Abdalla et al., ‘22]

PRIMORDIAL GRAVITATIONAL WAVES

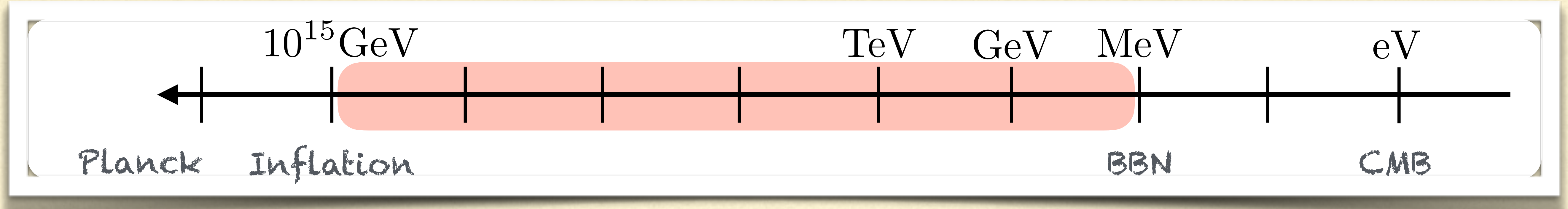
- Primordial gravitational waves are a generic prediction of cosmological inflation. Their amplitude is typically too small for being directly detected by gravitational wave (GW) experiments.



- Cosmological scenarios that can *enhance the tensor primordial spectrum* at different scales might be *tested with gravitational wave experiments* at different scales

POST-INFLATIONARY EVOLUTION

- While ΛCDM model is supported by current data, the physics from reheating to Big-Bang Nucleosynthesis (BBN) remains highly unconstrained.



- During such period, the universe may have gone through a *non-standard* period of expansion due to presence of new dof's driving non-standard epochs

- Interestingly, a scalar-tensor dominated epoch may rise the primordial gravitational wave spectrum to observable levels

PLAN

- D-brane scalar-tensor theories
- DBI-kinetic domination
- Gravitational waves and Pulsar Timing Arrays
- Early and late dark energy
- Summary

D-BRANE SCALAR-TENSOR THEORIES

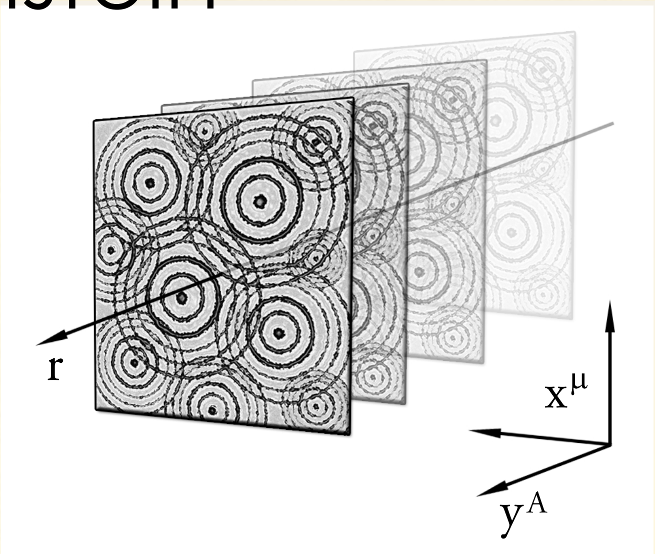
- Scalar-tensor theories arise naturally in string theory models of cosmology
- Particularly interesting are those arising in D-brane models of cosmology and particle physics:

The induced metric on the brane is a particular form of more general metric introduced by Bekenstein

[Bekenstein, '92]

$$\tilde{g}_{\mu\nu} = C(\phi) g_{\mu\nu} + D(\phi) \partial_\mu \phi \partial_\nu \phi$$

Longitudinal (matter) and transverse (scalar) fluctuations are *disformally* coupled via DBI action.



[Dimopoulos, Wills, IZ,'11; Koivisto, Wills, IZ '13]

[Koivisto, Wills, IZ, '14;
Dutta, Jimenez, IZ, '16-'17;
Chowdhury, Tasinato, IZ, '22-23]

- Consider the following action:

$$S_{\rm tot} \;=\; S_\phi + S_{\rm m}\,,$$

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

$$S_{\rm m} = -\int d^4x\,\sqrt{-g}\,\mathcal{L}_{\rm m}(\tilde{g}_{\mu\nu})$$

where matter is coupled to ϕ via

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

($M =$ scale, related to brane tension, warping, wrapping, etc)

COSMOLOGICAL EVOLUTION

In FRW background, evolution equations in Einstein frame (with respect to $g_{\mu\nu}$) become

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

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

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

where:

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

(ω takes into account departures from 1/3 when a species becomes non-relativistic)

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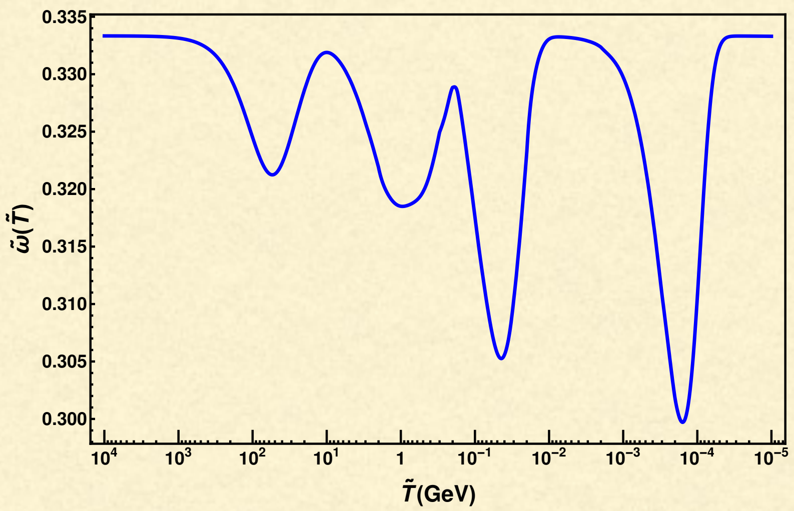

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MODIFIED EXPANSION RATE

Modified expansion rate is given by the *disformal or Jordan frame* Hubble parameter whose deviation from standard evolution is given by

$$\xi = \frac{\tilde{H}}{H_{GR}} = \frac{\gamma^{3/2}(1+\lambda)^{1/2}}{B^{1/2}}$$

$$\left(H_{GR}^2 = \frac{\kappa_{GR}^2}{3}\,\tilde{\rho}\right)$$

BBN imposes a strong constraint on this modification:

$$\xi \to 1$$

at the onset of BBN.

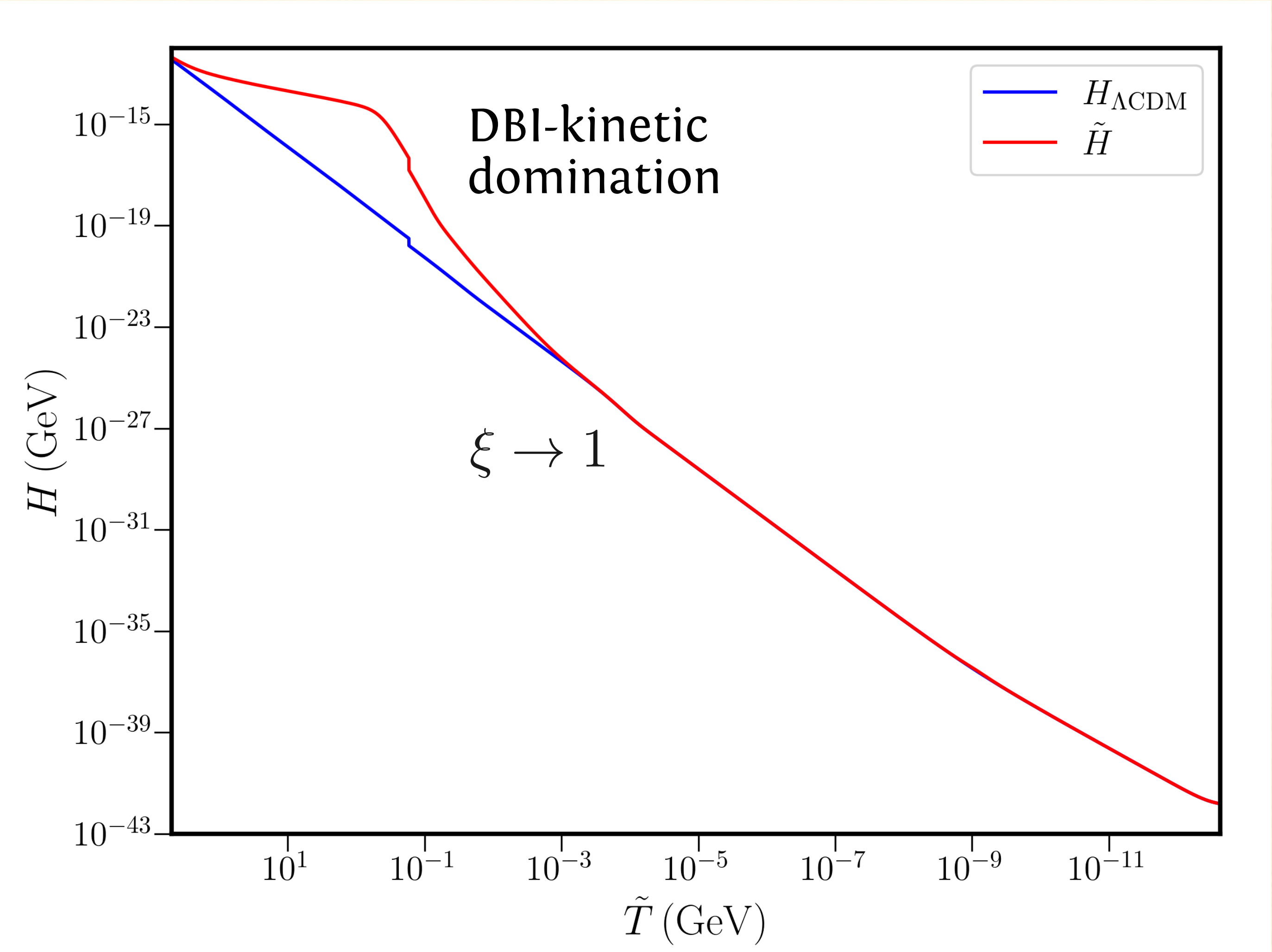
EARLY UNIVERSE EVOLUTION

During the early evolution, the potential term can be ignored, dynamics fully dictated by DBI kinetic term and coupling $\lambda \sim 0$

[Dutta, Jimenex, IZ, '16-17; Chowdhury, Tasinato, IZ, '22-23]

Non-standard evolution of coupled system driven by DBI kinetic term γ

For M around QCD phase transition scale, smallest value consistent with BBN



φ_i	φ_N^i	H_i	T_i	M
0.2	5×10^{-7}	3.66127×10^{-13} GeV	499.8043 GeV	930 MeV

THE RISE OF THE PRIMORDIAL SPECTRUM

[Chowdhury, Tasinato, IZ, '22-23]

The initial enhancement of the Lorentz factor, and the Hubble parameter, leads to an enhancement of the primordial gravitational wave spectrum.

The fractional energy density of primordial gravitational waves measured today can be written as

$$\tilde{\Omega}^0_{\rm GW}(k)\, h^2 \simeq \frac{1}{24}\, \mathcal{P}_{\rm T}(k)\, \left(\frac{\tilde{a}_{\rm hc}}{\tilde{a}_0}\right)^4 \left(\frac{\tilde{H}_{\rm hc}}{H_0/h}\right)^2$$

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Where the primordial spectrum is set by

$$\mathcal{P}_T(k) = \left.\frac{2\,H^2}{\pi^2\,M^2_{\rm Pl}}\right|_{k=aH}$$

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Using entropy conservation we can express it in terms of frequency:

$$f = 2.41473\times 10^{23}\left(\frac{T_0}{T_{\rm hc}}\right)\left(\frac{g_{*s,0}}{g_{*s,{\rm hc}}}\right)^{1/3}\sqrt{\frac{8\pi\rho_{\rm hc}}{3M^2_{\rm Pl}}}\,{\rm Hz}$$

$$\left(\frac{a}{a_0} = \left(\frac{g_{*s,0}}{g_{*s}}\right)^{1/3}\frac{T_0}{T}\right)$$

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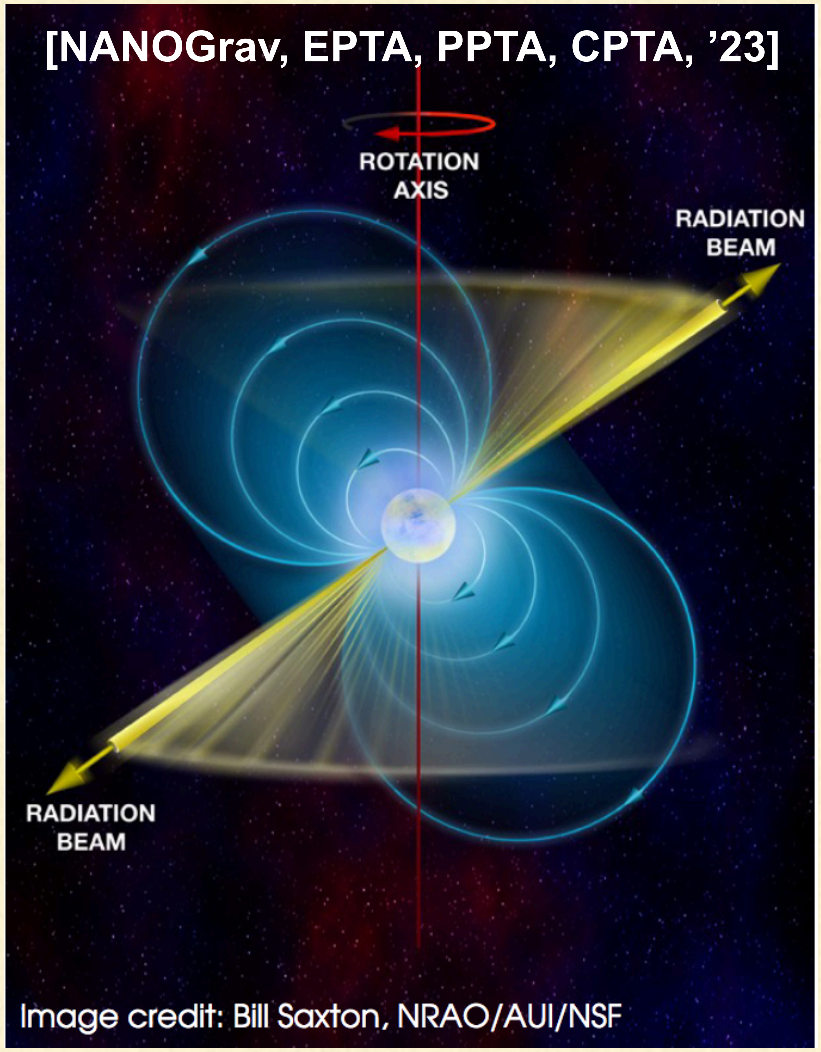
For the initial conditions before, the SPGW spectrum rises at frequencies accessible to **Pulsar Timing Array** experiments

$$f \sim 10^{-9} - 10^{-8}\,{\rm Hz}$$

PULSAR TIMING ARRAYS (PTA)

Pulsars, discovered by J. Bell in 1967: rapidly rotating neutron stars, emitting radio waves at very precise timing.



A gravitational wave passing Earth will cause a small change in the rate at which a pulsar ticks.

PTA's look for this effect in several millisecond pulsars .

NANOGrav, EPTA, PPTA, CPTA have just announced the relatively strong evidence for a signal compatible with **stochastic gravitational wave background** (SGWB) at nano-Hz frequencies.

PULSAR TIMING ARRAYS (PTA)

NANOGrav monitored 67 pulsars for a 15 years period.

They found the characteristic **angular correlation** between signals detected with different pulsars, as predicted by General Relativity.

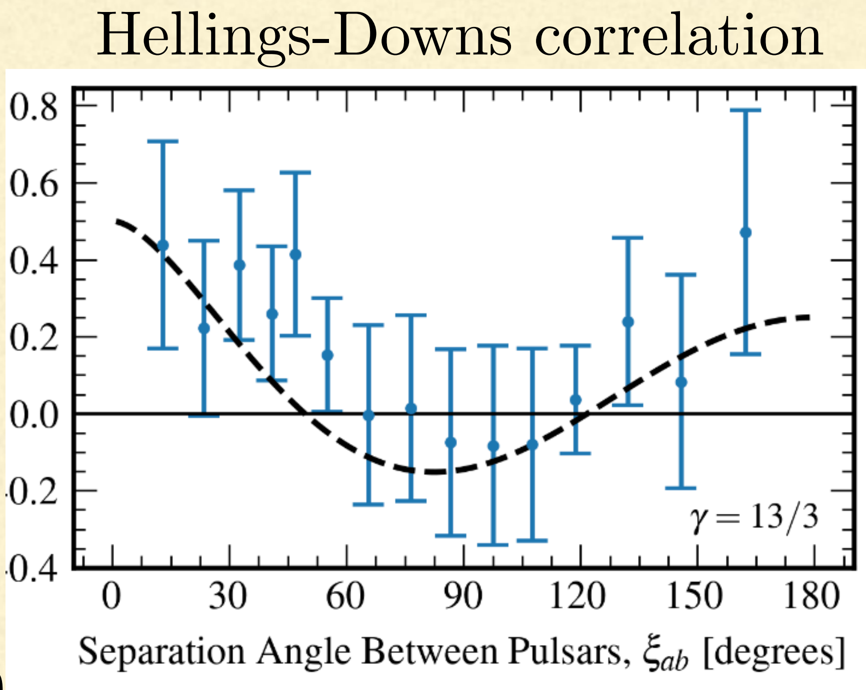
This is called **Hellings-Downs** curve.

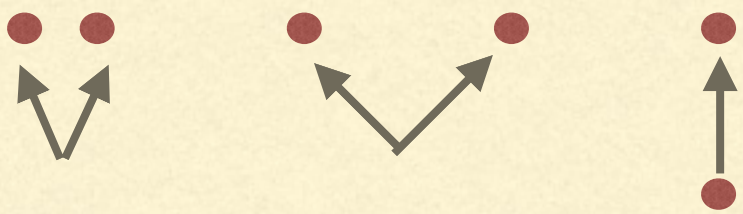
The measured amplitude is

$$\Omega_{\rm GW} \simeq (5 \pm 2) \times 10^{-9}$$

Slope larger than what expected from supermassive black hole binaries

Signal might have a cosmological origin





THE RISE OF THE PRIMORDIAL SPECTRUM

[Chowdhury, Tasinato, IZ, ’23]

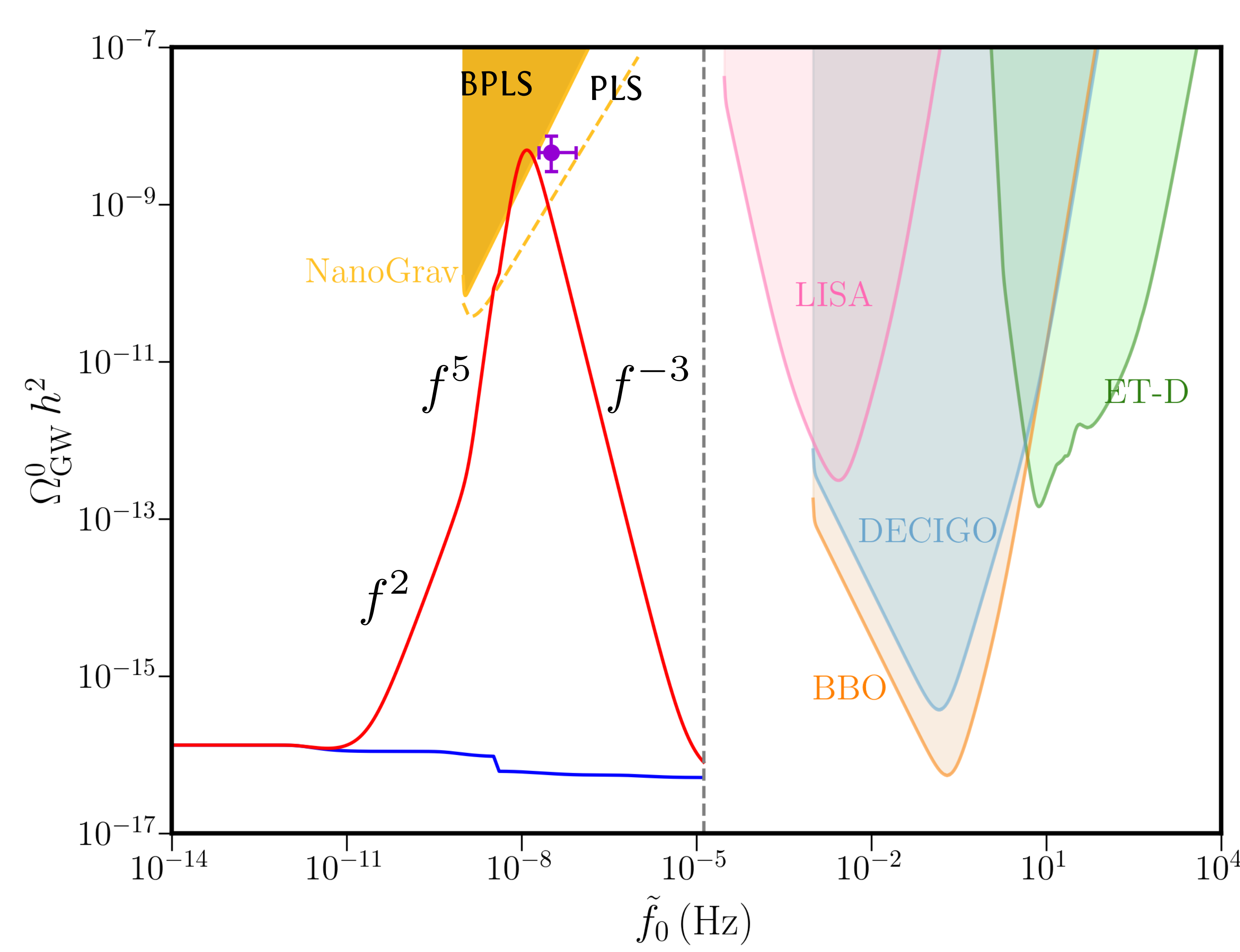
For the initial conditions before, the SPGW spectrum rises at scales accessible to PTA experiments $f \sim 10^{-9} - 10^{-8}\,\mathrm{Hz}$

[NANOGrav, EPTA, PPTA, CPTA, ’23]

The frequency profile of the spectrum acquires a distinctive **broken power-law** shape.

The **peak** amplitude is of the same order of the value detected by the **NANOGrav** collaboration

[NANOGrav , ’23]



POST-DBI EVOLUTION

After the DBI kinetic epoch, $\xi \sim 1$, standard evolution

At some scale after BBN, the scalar potential will become important.

Scalar potential cannot affect cosmological predictions

Considering the potential to become dominant around recombination, the axion field can drive a period of early dark energy.

THE SCALAR POTENTIAL I

Consider a D-brane moving in an angular direction of a *warped* resolved conifold in type IIB string theory compactification.

[Pando Zayas, Tseytlin, 00; Klebanov, Murugan, '07]

Scalar potential of the form

[Bauman et al. '07-10; Kenton-Thomas, '14]

$$V(\theta) = \bar{V}(\rho_0) + \delta\left(\overline{\Phi}_-(\rho_0) + \Phi_h(\rho_0, \theta)\right)$$

where

$$\Phi_h = A_1(\rho_0) + A_2(\rho_0)\,\cos\theta + A_3(\rho_0)\,\cos^2\theta + A_4(\rho_0)\,\cos^3\theta$$

for suitable values of parameters, this could take form

$$V_1(\phi) = V_{0_{\rm ede}}\left(1 - \cos[\kappa\,\phi/f_1]\right)^3$$

EARLY DARK ENERGY AND THE H0-TENSION

A proposal to resolve the Hubble tension via a modification of the early time physics is to have a period of early dark energy *injection* $(z \gtrsim 1100)$

[Kamionkowski, Riess, '22; Poulin, Smith, Karwal, '23]

$$f_{\rm EDE} \equiv \frac{\rho_{\rm EDE}}{\rho_T} \sim 10 - 12\%$$

A frozen scalar field at a critical redshift $z_c \sim 3500$ diluting faster than matter afterwards $\omega \gtrsim 1/3$

This can increase the Hubble parameter for a limited amount of time leading to a decrease in the sound horizon

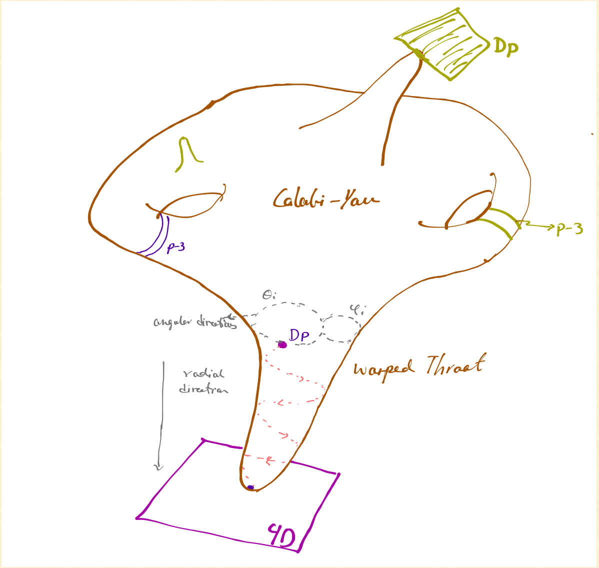
Prototype example: axion with potential

$$V = V_0 \left(1 - \cos[\theta/f]\right)^n$$

$$(V_0 \sim {\rm eV}, \quad n = 3\,, \quad f \sim 0.2\, M_P)$$

THE SCALAR POTENTIAL II

Assuming further bulk non-perturbative effects, generate another term of the form



$$V_2(\phi) = V_{0_{\rm de}}(1 - \cos[\kappa\phi/f_2])$$

The total potential we consider is

$$V(\varphi) = V_{0_1}\,(1 - \cos[\varphi/f_1])^3 + V_{0_2}\,(1 - \cos[\varphi/f_2])$$

with

$$V_{0_1}^{1/4} \sim 10^2 V_{0_2}^{1/4} \sim \mathrm{eV}$$

EARLY AND LATER DARK ENERGY

First term becomes relevant around recombination driving a period of EDE followed by *late dark energy* driven by the axion

EDE behaves like a cosmological constant before matter-radiation equality decaying away faster than radiation afterwards.

[Pettorino, Amendola, Wetterich, '13;
Karwal, Kamionkowski, '16;
Poulin et al. '19]

EDE should increase the value of H(z) without affecting late time CMB data. Proposed to help relax H0-tension

Dynamical late dark energy driven by the axion, with CC=0

[Kim-Nilles, '02]

EARLY AND LATER DARK ENERGY

[Chowdhury, Tasinato, IZ, '23]

The ELDE potential

$$V(\varphi) = V_{0_1}\left(1 - \cos[\varphi/f_1]\right)^3 + V_{0_2}\left(1 - \cos[\varphi/f_2]\right)$$

with

$$f_1 \sim 0.4 M_P\,, \quad f_2 \sim \frac{2r}{2m+1} f_1$$

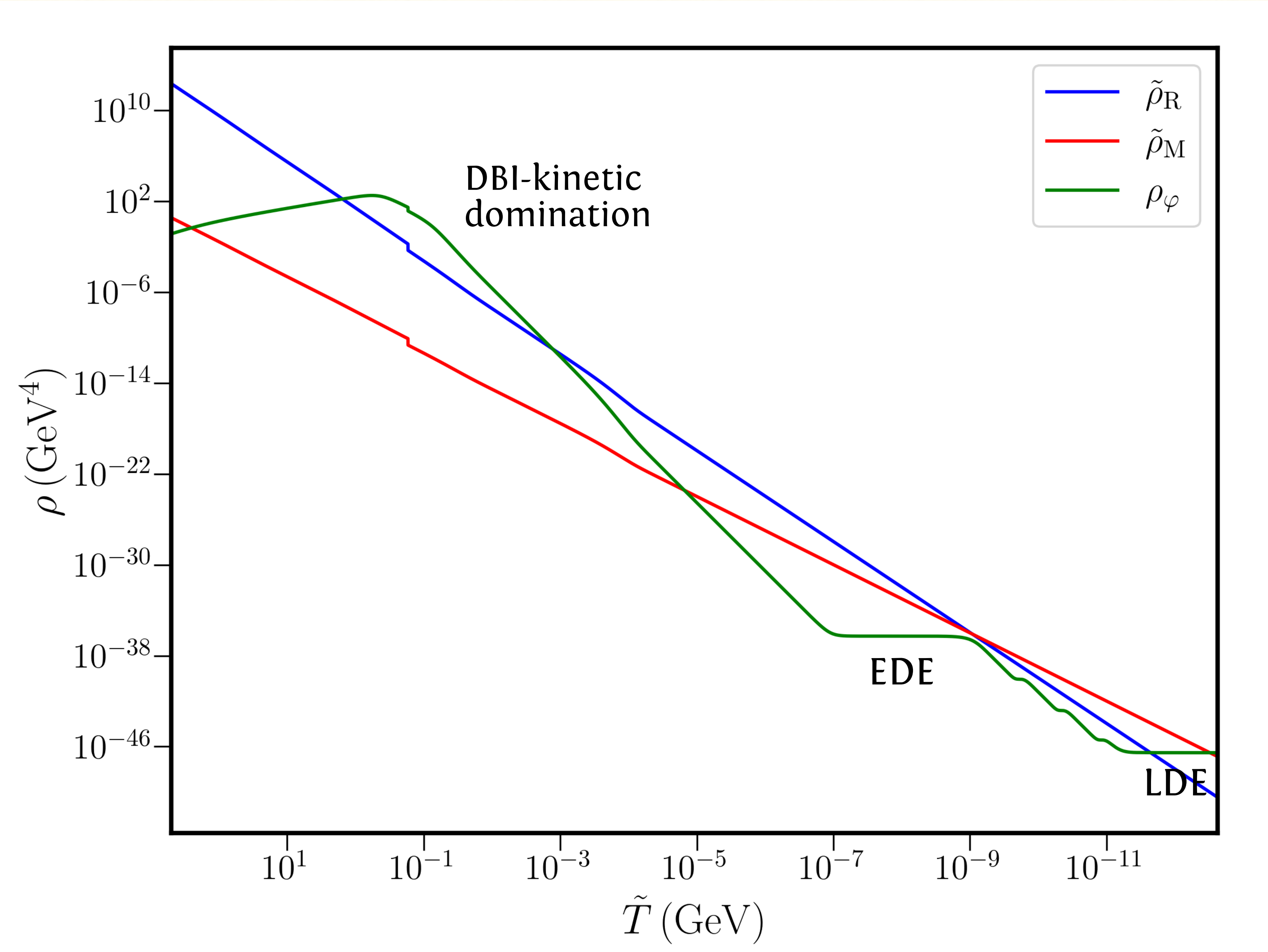
r, m integers. r fixed by initial conditions in early universe, m in principle anything

$V_{0_{\rm ede}}$	$V_{0_{\rm de}}$	f_1	f_2
$(6.68 \times 10^{-10}\,\mathrm{GeV})^4$	$1.44925 \times 10^{-47}\,\mathrm{GeV}^4$	0.38868	0.0948

EARLY AND LATER DARK ENERGY

[Chowdhury, Tasinato, IZ, '23]

Energy densities' evolution of radiation, matter, axion



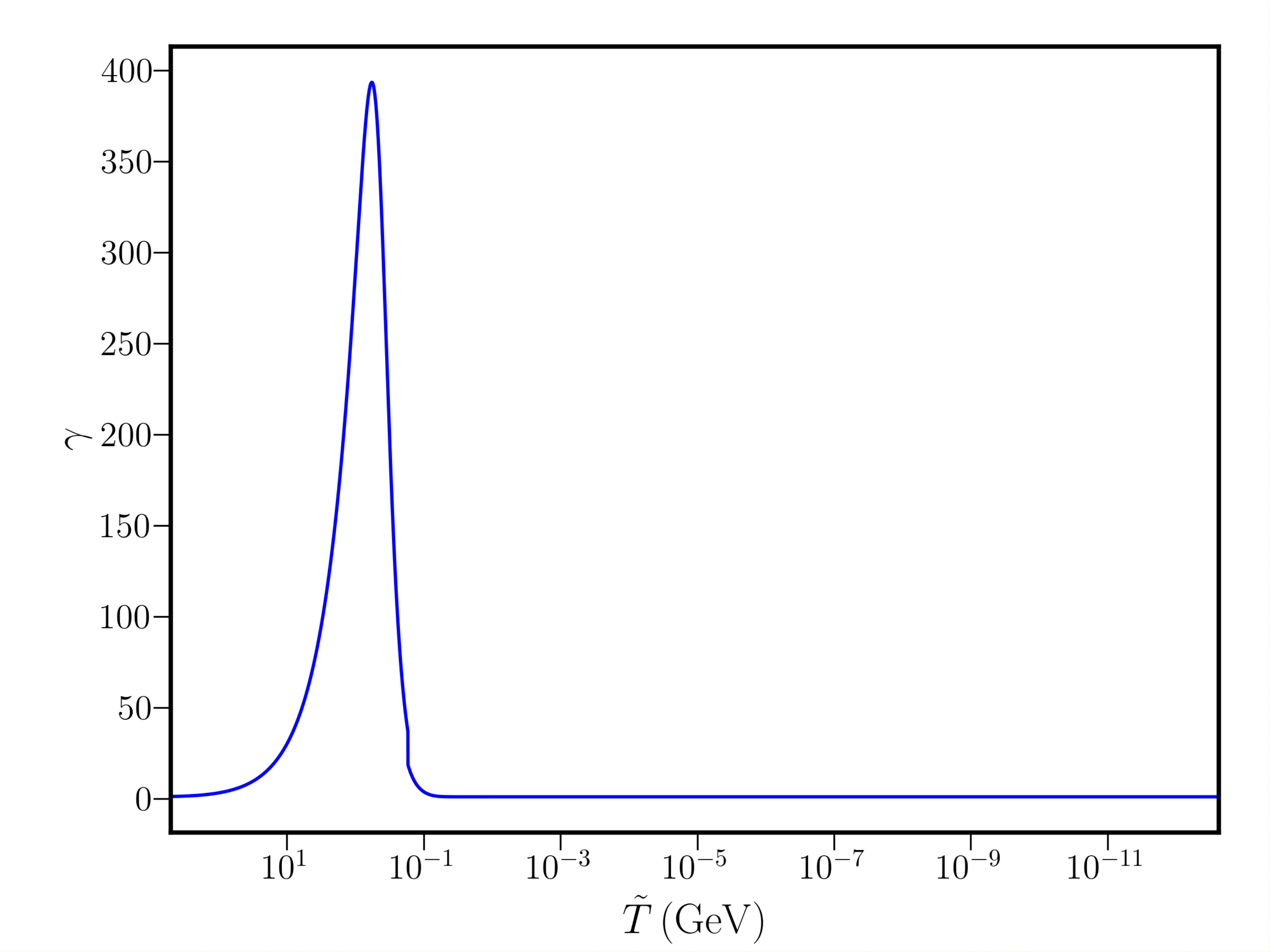
SUMMARY

- *D-brane scalar-tensor* theories, can trigger a period of (coupled) DBI-kinetic domination.
- Such an epoch modifies *the expansion rate*, and enhances the SPGW spectrum with *distinctive* broken power law profiles, that can contribute to observed SGWB by PTAs
- Scalar field driving such a DBI-kinetic period may act as EDE and LDE, relaxing H_0-tension
- Full analysis of CMB (e.g. `CLASS`) needed for full check of set up. Theoretical construction …

EARLY AND LATER DARK ENERGY

[Chowdhury, Tasinato, IZ, '23]

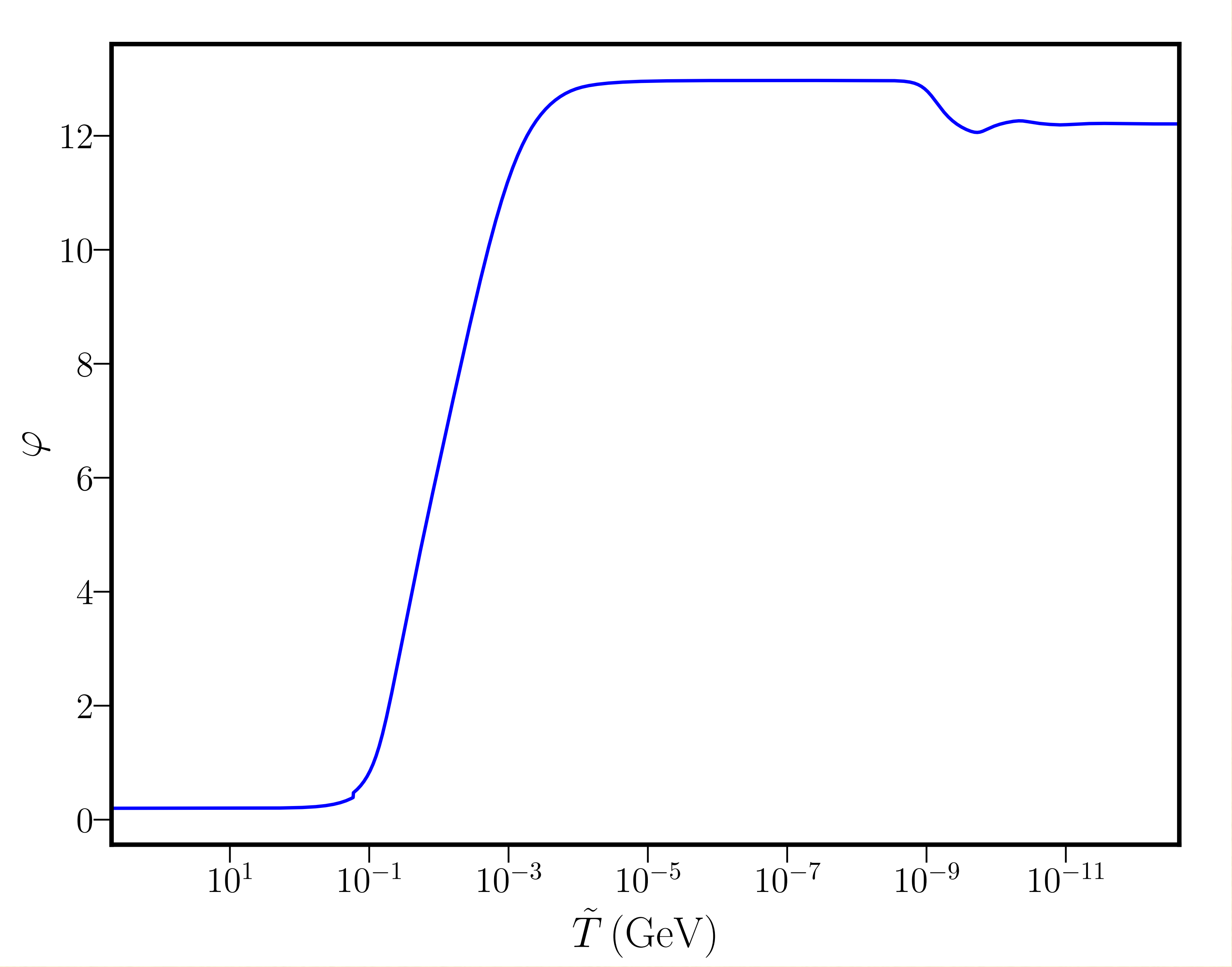
Lorentz factor evolution



EARLY AND LATER DARK ENERGY

[Chowdhury, Tasinato, IZ, '23]

Axion field evolution: initial conditions set at early universe



EARLY AND LATER DARK ENERGY

[Chowdhury, Tasinato, IZ, '23]

Fractional contribution of EDE to the total energy density