PROBING STRING COSMOLOGY WITH GRAVITATIONAL WAVES

Ivonne Zavala

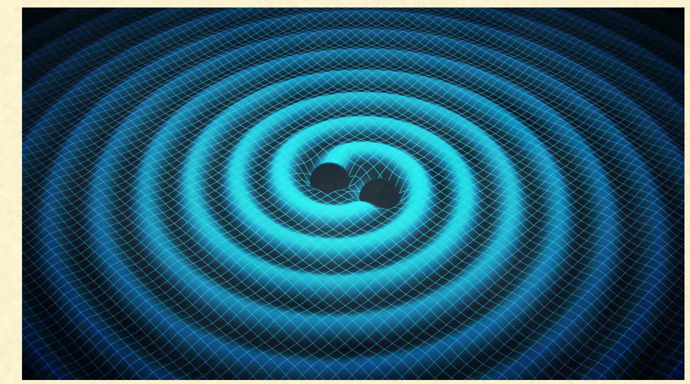
Swansea University

Thanks to my collaborators:
Aragam, Battacharya, Chakraborty, Chowdhury, Chiovoloni, Loaiza-Brito, Niz, Özsoy, Paban, Parameswaran, Rosati, Tasinato

ICTS workshop
January, 2025

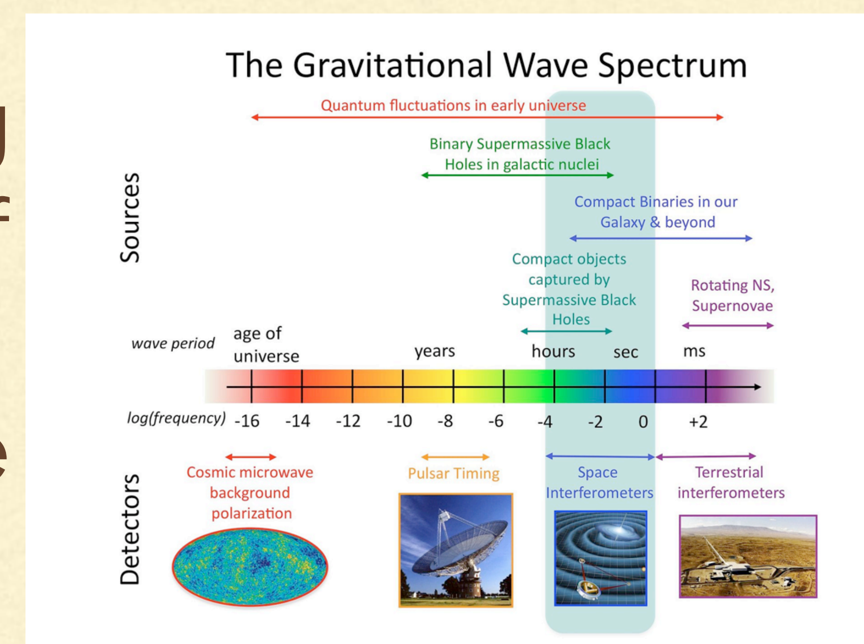
GRAVITATIONAL WAVE COSMOLOGY

The first detection of gravitational waves from black holes and neutron stars mergers has opened up a new way to study our Universe.



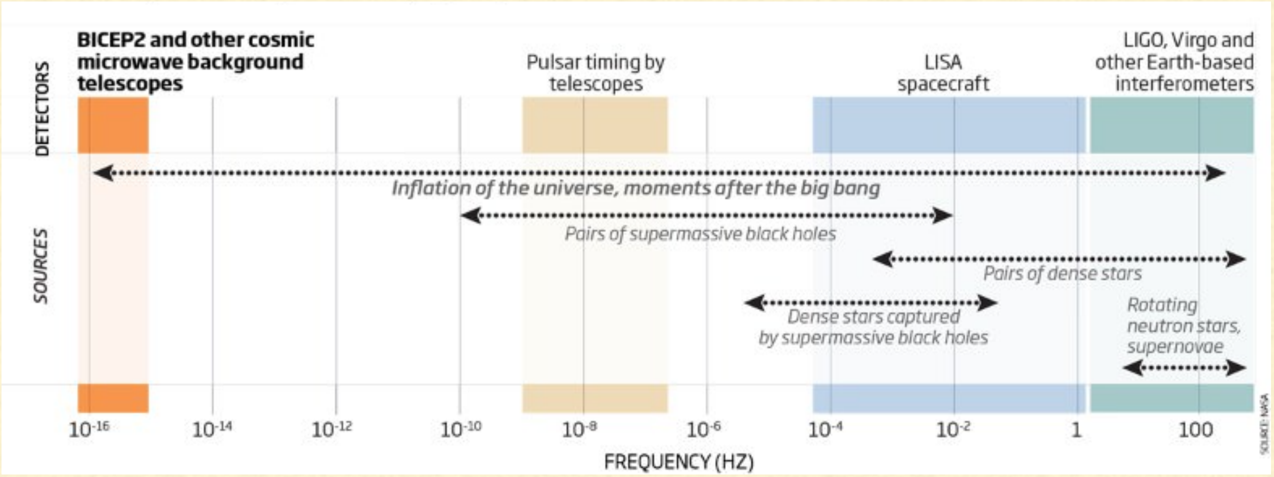
[LIGO collaboration, '15]

One very exciting, though challenging prospect, is the measurement of primordial gravitational waves (PGW) produced in the very early universe during cosmological inflation.



GRAVITATIONAL WAVE COSMOLOGY

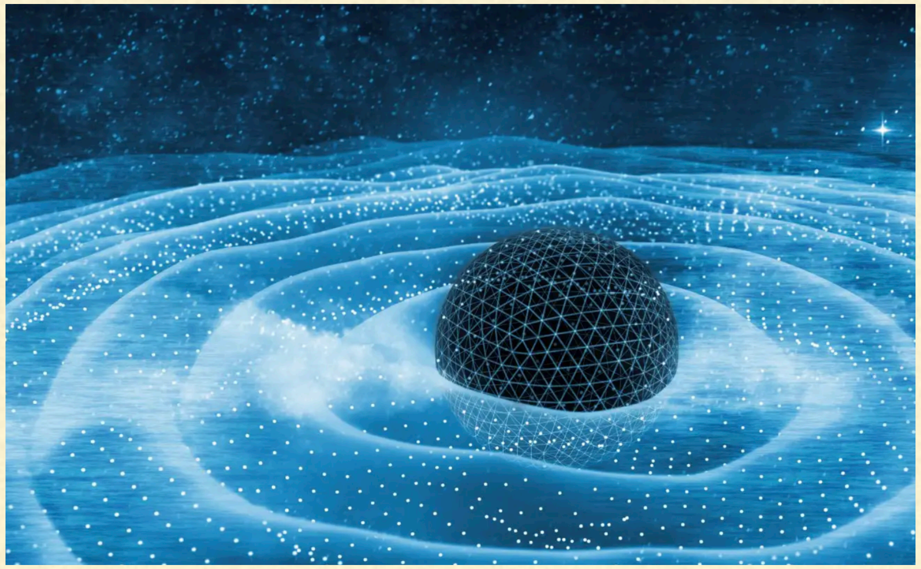
Primordial gravitational waves are a generic prediction of cosmological inflation. Their amplitude is typically too small for being directly detected by gravitational wave (GW) experiments.



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

GRAVITATIONAL WAVE COSMOLOGY & QUANTUM GRAVITY

Gravitational wave cosmology has opened up a new window to test theories of quantum gravity such as string theory.



It is thus important to understand the properties of string (motivated) cosmology models that can enhance the primordial spectra at different scales.

May be able to constraint models and parameters!

[String cosmology review: Cicoli, Conlon, Maharana, Parameswaran, Quevedo, IZ, '23]

PLAN

- Power spectra enhancement in mulfitield axion monodromy inflation
- Post-inflationary non-standard cosmologies and gravitational waves signatures
- Summary

MULTIFIELD INFLATION

Consider the low energy effective action for scalar sector, which arise from some consistent theory of quantum gravity:

$$S = \int d^4x\sqrt{-\mathrm{g}}\left[M_{\rm Pl}^2\frac{R_4}{2} - \frac{g_{ab}}{2}\partial_\mu\phi^a\partial^\mu\phi^b - V(\phi^a)\right]$$

In FRW spacetime, equations of motion are

$$H^2 = \frac{1}{3M_P^2}\left(\frac{\dot{\varphi}^2}{2} + V(\phi^a)\right)$$

$$\ddot{\phi}^a + 3H\dot{\phi}^a + \Gamma^a_{bc}\dot{\phi}^b\dot{\phi}^c + g^{ad}V_d = 0$$

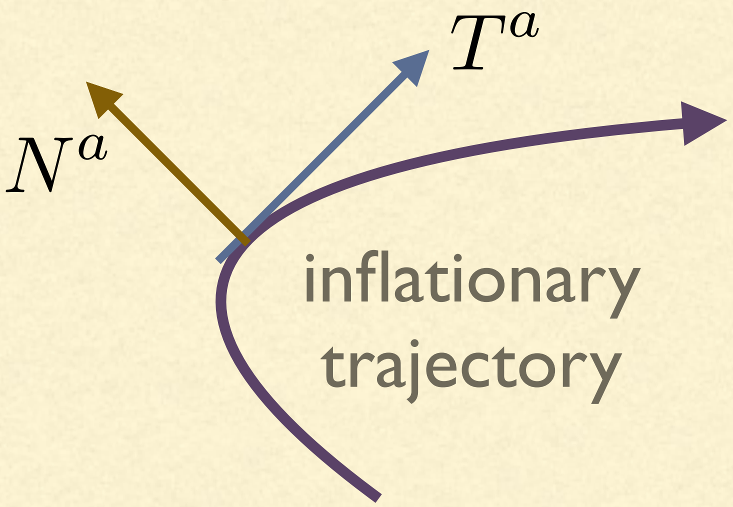
Here

$\dot{\varphi}^2 = g_{ab}\dot{\phi}^a\dot{\phi}^b$ Γ^a_{bc} : Christoffel symbols of field space metric g_{ab}

SLOW-ROLL IN MULTIFIELD INFLATION

Slow-roll conditions can be neatly written in terms of tangent and orthogonal projections of inflationary trajectory:

$$H^2 = \frac{1}{3M_{\rm Pl}^2}\left(\frac{\dot{\varphi}^2}{2} + V(\phi^a)\right)$$



$$\ddot{\varphi} + 3H\dot{\varphi} + V_T = 0\,,$$

$$N_a\dot{T}^a + N_a\Gamma^a_{bc}\,T^b\dot{\phi}^c = -\frac{V_N}{\dot{\varphi}}$$

[Gordon, Wands, Bassett, Maartens, '01; Groot Nibbelink, van Tent, '01]

$$\omega \equiv \frac{V_N}{H\,\dot{\varphi}} \equiv \frac{\Omega}{H} \qquad \textit{turning rate}$$

where $\quad V_T = V_a T^a, \quad V_N = V_a N^a$

SLOW-ROLL IN MULTIFIELD INFLATION

We can now write the projections of the Hessian elements of V along normal and tangent directions as (exact)

$$\frac{V_{TT}}{3H^2} = \frac{\Omega^2}{3H^2} + 2\,\epsilon - \frac{\eta}{2} - \frac{\xi_\varphi}{3}$$

$$\frac{V_{TN}}{3H^2} = \omega\left(1 - \epsilon + \frac{\eta}{3} + \frac{\nu}{3}\right)$$

[Achucarro, et al. '10; Hetz, Palma, '16; Christodoulidis, Roest, Sfakianakis, '18; Chakraborty et al. '19; Aragam et al. '21]

where

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \qquad \eta \equiv \frac{\dot{\epsilon}}{H\epsilon} \qquad \xi_\varphi \equiv \frac{\dddot{\varphi}}{H^2\dot{\varphi}} \quad , \qquad \nu \equiv \frac{\dot{\omega}}{H\omega}$$

SLOW-ROLL IN MULTIFIELD INFLATION

Slow-roll requires

$$\epsilon, \eta, \xi_\varphi \ll 1 \qquad \Rightarrow \qquad 3H^2 \simeq V,$$

Moreover:

$$M_{Pl}^2 \frac{V_{TT}}{V} \simeq \frac{\Omega^2}{3H^2}, \qquad M_{\rm Pl}^2 \frac{V_{TN}}{V} \simeq \frac{\Omega}{H} \qquad \& \qquad \nu \ll 1$$

$$\left(\nu = \frac{\dot{w}}{Hw};\ w = \frac{\Omega}{H}\right)$$

[Chakraborty, Chiovoloni, Loaiza-Brito, Nix, IZ, '19;
Aragam, Paban, Rosati, '20;
Aragam, Chiovoloni, Paban, Rosati, IZ, '21]

MULTIFIELD INFLATION

Focus on two field case with

$$\mathcal{L}_\phi \supset -\frac{f^2(r)}{2}\left[(\partial r)^2 + (\partial\theta)^2\right]$$

Equivalently

$$\mathcal{L}_\phi \supset -\frac{1}{2}\left[(\partial R)^2 + f^2(R)(\partial\theta)^2\right]$$

$$\supset -\frac{f^2(\rho)}{2}\left[(\partial\rho)^2 + \rho^2(\partial\theta)^2\right]$$

Scalar fields equations of motion become

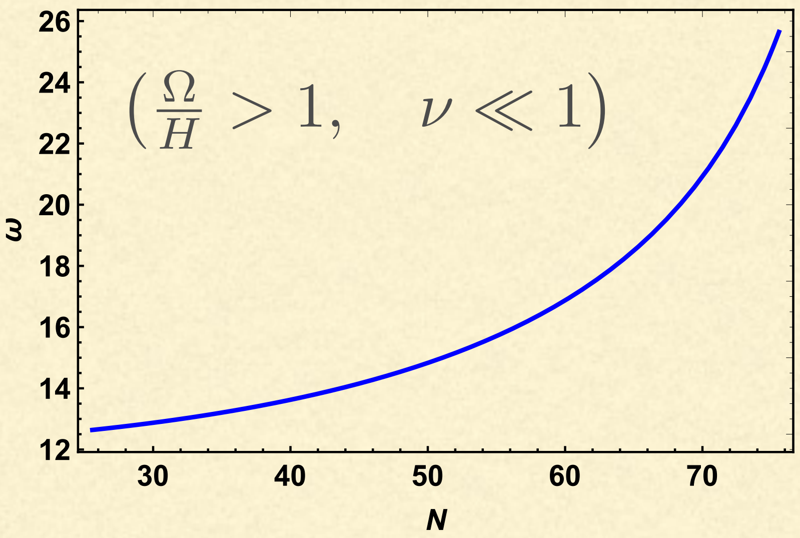
$$r'' + \left(3 - \frac{\varphi'^2}{2M_{\rm Pl}^2}\right) r' - \frac{f_r}{f}\left(\theta'^2 - r'^2\right) + \frac{V_r}{H^2 f^2} = 0\,,$$

$$\theta'' + \left(3 - \frac{\varphi'^2}{2M_{\rm Pl}^2}\right) \theta' + 2\frac{f_r}{f}\theta' r' + \frac{V_\theta}{H^2 f^2} = 0\,,$$

INFLATIONARY TRAJECTORIES

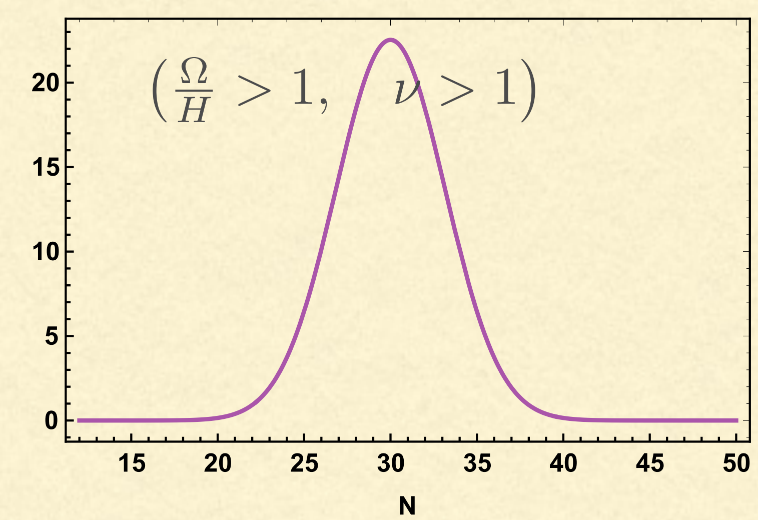
- Large slowly varying turning rate

[Achucaro, Atal, Aragam, Bjorkmo, Brown, Chakraborty, Chen, Chiovoloni, Christodoulidis, Fumagalli, Garcia-Saenz, Marsh, Loaiza-Brito, Niz, Paban, Palma, Renaux-Petel, Riquelme, Ronayne, Rosati, Scheihing, Sfakianakis, Sypsas, Slosar, Welling, Witkowski, Zenteno, IZ,... '18-'24]



- Sharp turning rates (PBHs, SIGWs)

[Addazi, Aldabergenov, Anguelova, Aragam, Bhattacharya, Chen, Barausse, Bhattacharya, Braglia, Domenech, Finelli, Fumagalli, Hazra, Ishikawa, Ketov, Paban, Palma, Renaux-Petel, Riquelme, Ronayne, Rosati, Scheihing, Sypsas, Slosar, Smoot, Sriramkumar, Starobinsky, Witkowski, Zenteno, IZ,... '18-'24]



SHARP TURNS IN SUPERGRAVITY

- A mechanism to generate **transient large turns** arises through **transient violations of slow-roll.** [Bhattacharya, IZ, '22]
- Natural realisation via subleading corrections to (supergravity) 2-field axion monodromy inflation. [Parameswaran, Tasinato, IZ, '16; Cabo-Bizet, Loaiza-Brito, IZ, '16; Özsoy, Parameswaran, Tasinato, IZ, '18]
- Supergravity scalar metric and potential take form:

$$M_{\rm Pl}^{-2}\,K = -\alpha\log[(\Phi+\bar\Phi)/M_{\rm Pl} - \beta S\bar S/M_{\rm Pl}^2] \qquad (S^2=0)$$

$$W = S(M\Phi + i\lambda e^{-b\Phi})\,. \qquad (\mathbb{R}=-4)$$

$$(\Phi = \rho + i\theta)$$

$$V = e^{K/M_{\rm Pl}^2}(K^{i\bar\jmath}D_iW\,D_{\bar\jmath}\bar W - 3|W|^2M_{\rm Pl}^{-2}) \qquad (D_iW = W_i + K_iW)$$

SHARP TURNS IN SUPERGRAVITY

- A mechanism to generate **transient large turns** arises through **transient violations of slow-roll.** [Bhattacharya, IZ, '22]

- Natural realisation via subleading corrections to (supergravity) 2-field axion monodromy inflation.
[Parameswaran, Tasinato, IZ, '16; Cabo-Bizet, Loaiza-Brito, IZ, '16; Özsoy, Parameswaran, Tasinato, IZ, '18]

- Supergravity scalar metric and potential take form:

$$\mathcal{L}_\phi = \frac{f^2(\rho)}{2}\left[(\partial\rho)^2 + (\partial\theta)^2\right], \quad \text{with} \quad f(\rho) = \frac{1}{\sqrt{2}\rho}$$

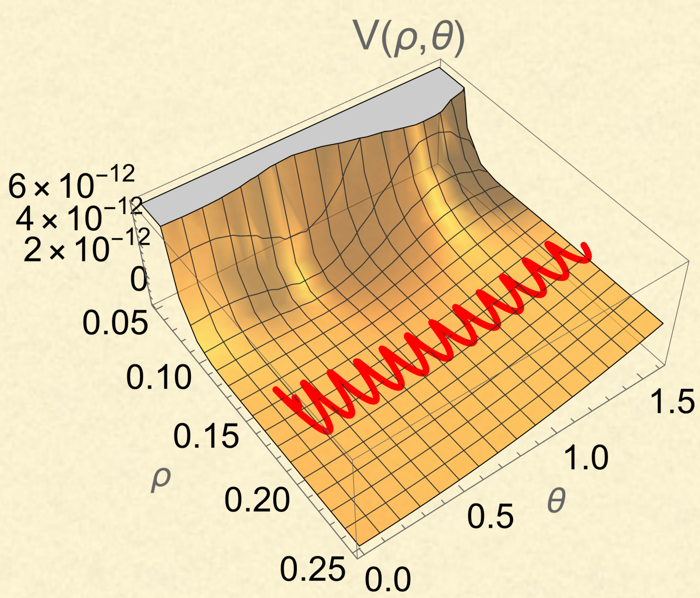
$$V = \frac{M^2}{\beta}\left(\rho^2 + \theta^2 + \frac{2\lambda}{M}\, e^{-b\rho}\left[\theta\,\cos\left(b\,\theta\right) + \rho\,\sin\left(b\,\theta\right) + \frac{\lambda}{2M}\, e^{-b\rho}\right]\right)$$

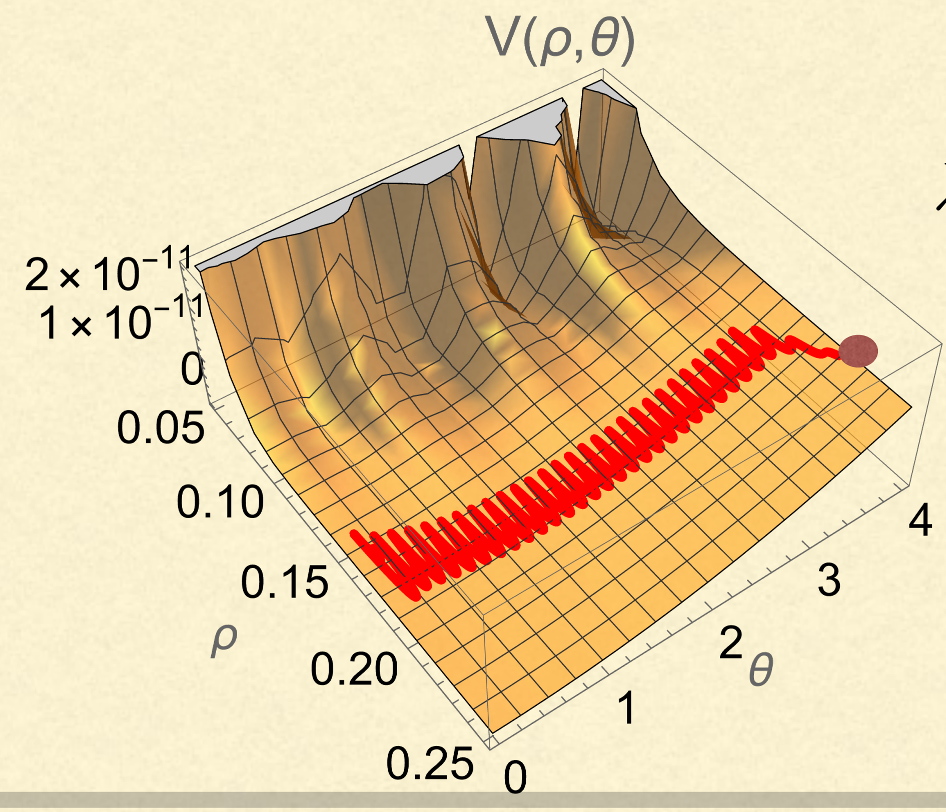
SUGRA (MULTIFIELD) AXION MONODROMY

- A mechanism to generate **transient large turns** arises through **transient violations of slow-roll.** [Bhattacharya, IZ, '22]

$$\mathcal{L}_\phi = \frac{f^2(\rho)}{2}\left[(\partial\rho)^2 + (\partial\theta)^2\right], \quad \text{with} \quad f(\rho) = \frac{1}{\sqrt{2}\rho}$$

$$V = \frac{M^2}{\beta}\left(\rho^2 + \theta^2 + \frac{2\lambda}{M}\, e^{-b\rho}\left[\theta\,\cos\left(b\,\theta\right) + \rho\,\sin\left(b\,\theta\right) + \frac{\lambda}{2M}\, e^{-b\rho}\right]\right)$$





$\lambda/M = 80\,, \quad b = 50$

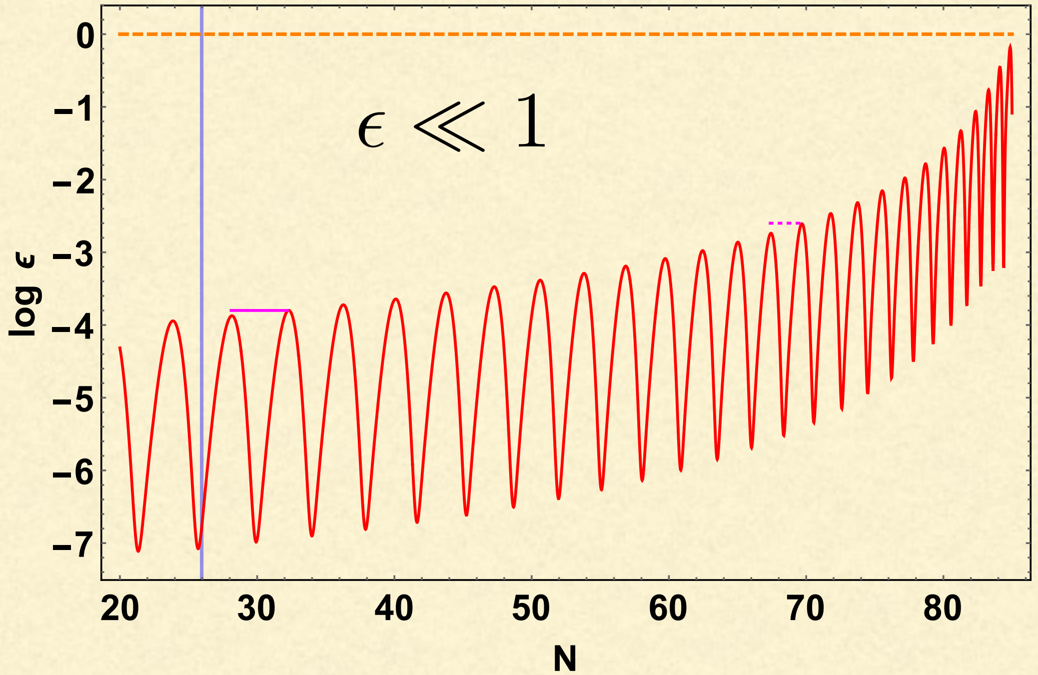
$M \sim \mathcal{O}(10^{-6})$

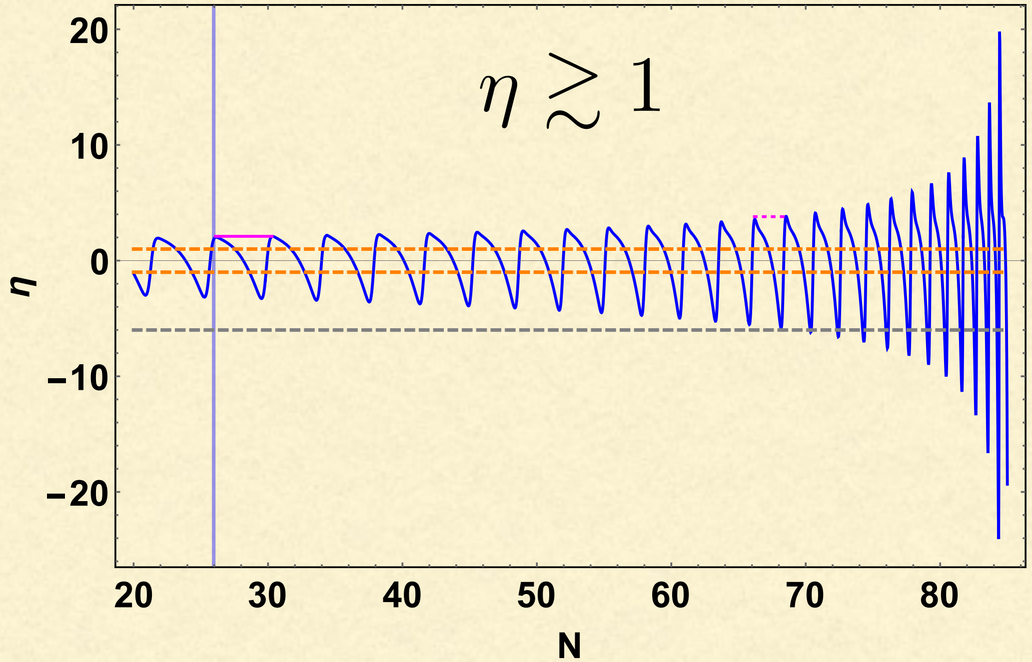
SUGRA (MULTIFIELD) AXION MONODROMY

- A mechanism to generate **transient large turns** arises through **transient violations of slow-roll.** [Bhattacharya, IZ, '22]

$$\mathcal{L}_\phi = \frac{f^2(\rho)}{2}\left[(\partial\rho)^2 + (\partial\theta)^2\right], \quad \text{with} \quad f(\rho) = \frac{1}{\sqrt{2}\rho}$$

$$V = \frac{M^2}{\beta}\left(\rho^2 + \theta^2 + \frac{2\lambda}{M} e^{-b\rho}\left[\theta\cos(b\,\theta) + \rho\sin(b\,\theta) + \frac{\lambda}{2M} e^{-b\rho}\right]\right)$$





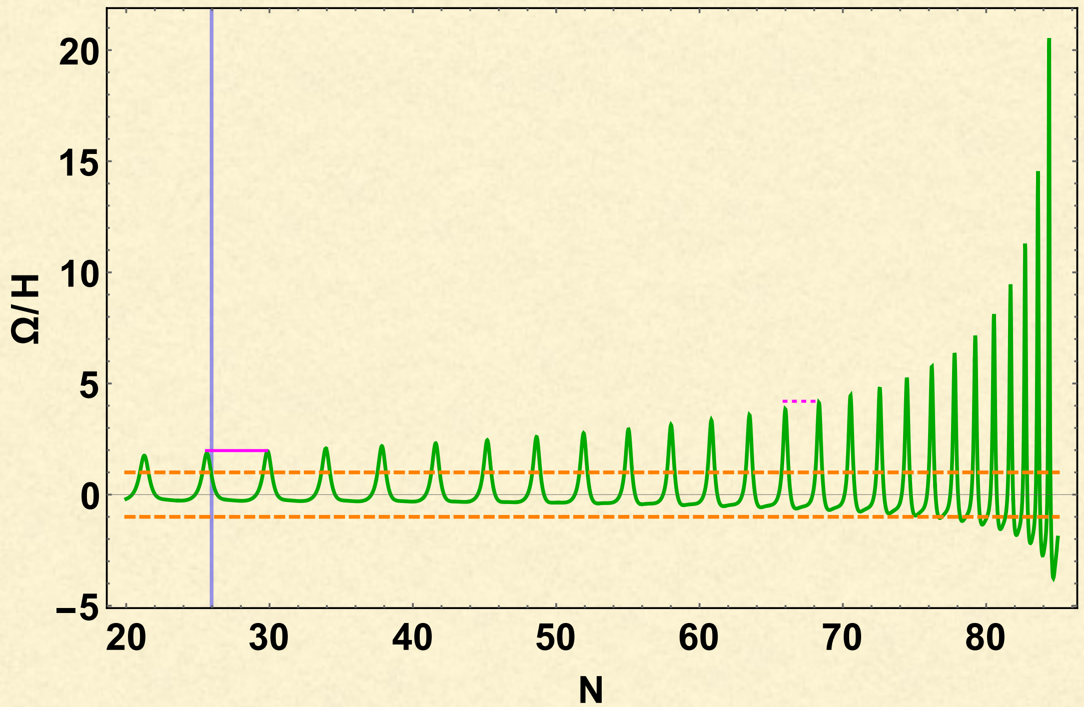
$\lambda/M = 80\,, \quad b = 50 \quad M \sim \mathcal{O}(10^{-6})$

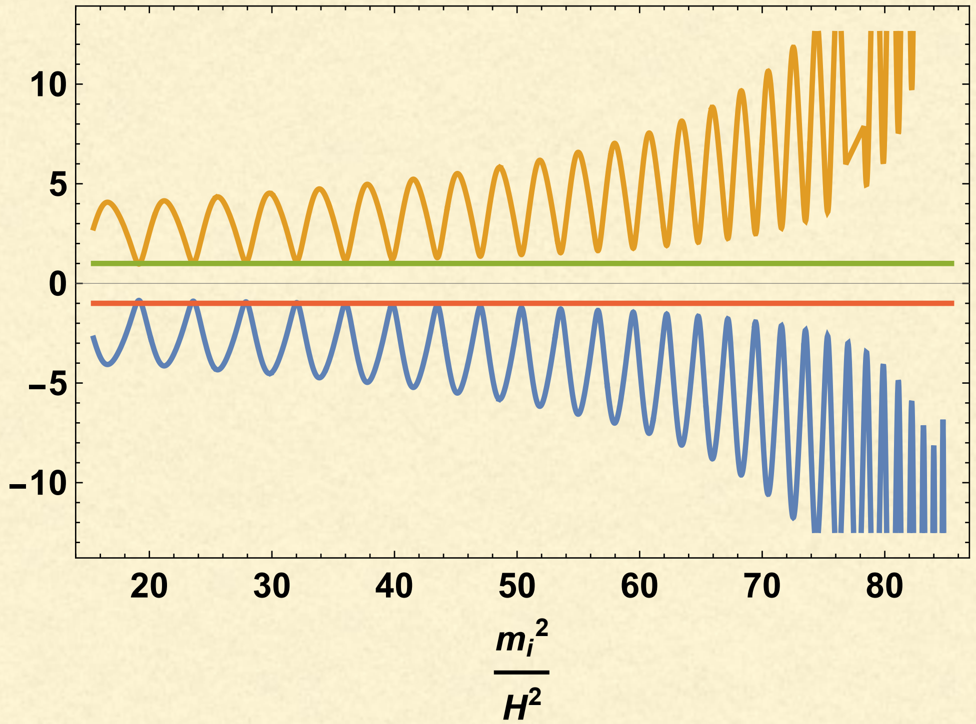
SUGRA (MULTIFIELD) AXION MONODROMY

- A mechanism to generate **transient large turns** arises through **transient violations of slow-roll.** [Bhattacharya, IZ, '22]

$$\mathcal{L}_\phi = \frac{f^2(\rho)}{2}\left[(\partial\rho)^2 + (\partial\theta)^2\right], \quad \text{with} \quad f(\rho) = \frac{1}{\sqrt{2}\rho}$$

$$V = \frac{M^2}{\beta}\left(\rho^2 + \theta^2 + \frac{2\lambda}{M}\, e^{-b\rho}\left[\theta\, \cos\left(b\,\theta\right) + \rho\, \sin\left(b\,\theta\right) + \frac{\lambda}{2M}\, e^{-b\rho}\right]\right)$$





$\lambda/M = 80\,, \quad b = 50 \quad M \sim \mathcal{O}(10^{-6})$

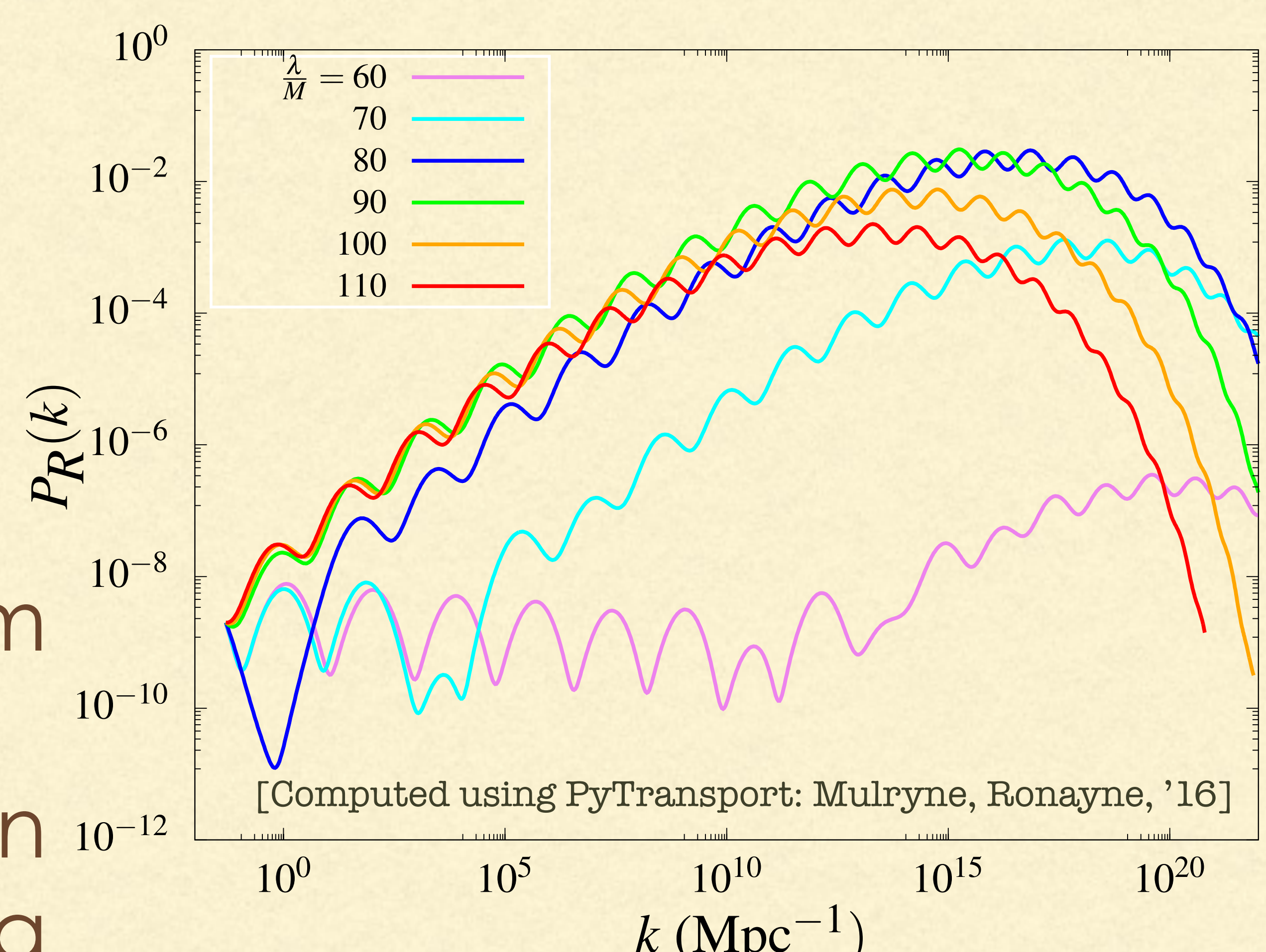
POWER SPECTRUM

[Bhattacharya, IZ, '22]

- Large enhancement of adiabatic spectrum at small scales due to combined oscillatory effects

M	λ/M	b	$\rho_{\rm ini}$	$\theta_{\rm ini}$	$N_{\rm inf}$	r	$V_{\rm inf}^{1/4}$
2.52×10^{-6}	60	50	0.250	4.20	64.77	0.010	0.0029
2.73×10^{-6}	70	50	0.250	4.20	62.32	0.016	0.0030
2.15×10^{-6}	80	50	0.245	4.20	59.48	0.018	0.0027
6.41×10^{-7}	90	50	0.250	4.20	57.49	0.020	0.0015
1.10×10^{-7}	100	50	0.250	4.20	56.07	0.022	0.0006
1.25×10^{-8}	110	50	0.250	4.20	55.06	0.024	0.0002

$n_s = 0.9649 \pm 0.0042$ $(\beta = 1)$

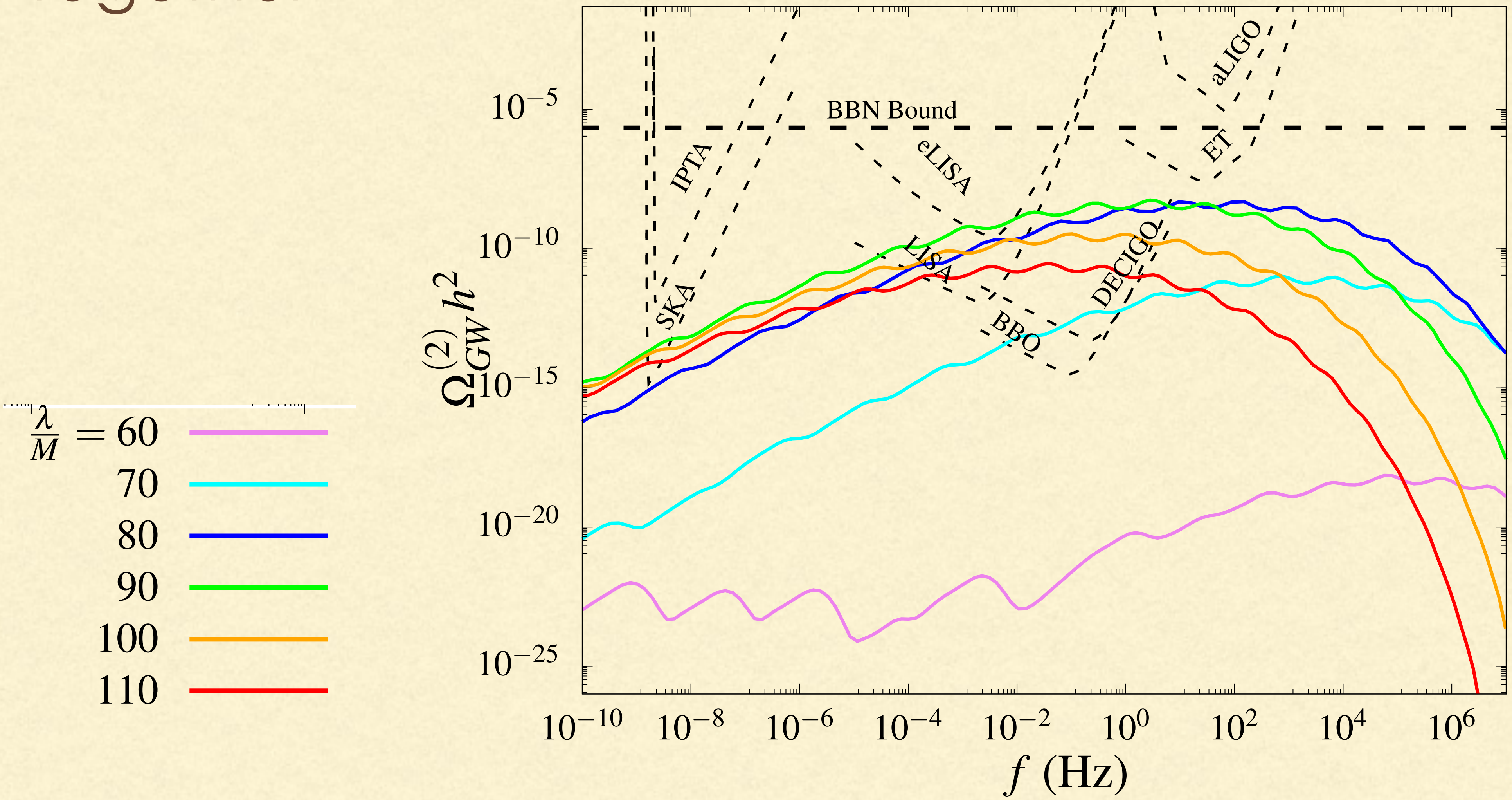


- Non-trivial PBHs mass spectrum with multiple peaks.
- Lead to abundance of PBHs in narrow mass ranges, keeping the total abundance small.

INDUCED GRAVITATIONAL WAVES

[Bhattacharya, IZ, '22]

- Broad and large GW spectrum with characteristic modulated shape. Can be probed by multiple future surveys together



SUMMARY PART I

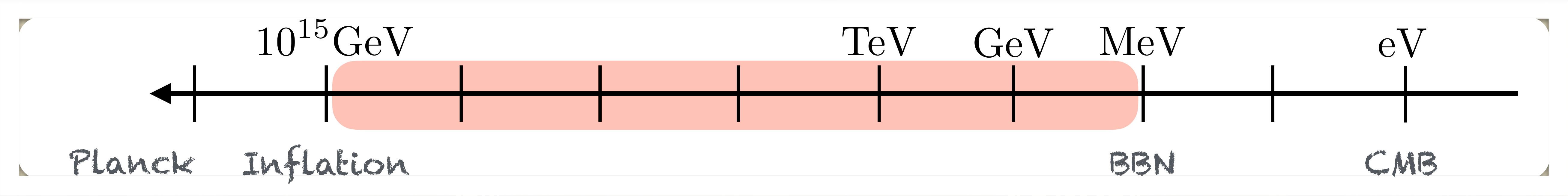
- Transient large turns induced from transient slow-roll violations offers a novel mechanism to generate strong non-geodesic trajectories with rich testable phenomenology: PBHs, SIGWs.
- This mechanism arises naturally in string inflation: multi-field axion monodromy inflation.
- Challenges: CMB constraints; embedding in full string theory.

POST-INFLATION PERIOD

- Post-inflationary non-standard cosmologies and gravitational waves signatures

POST-INFLATIONARY EVOLUTION

- ΛCDM model is relatively well supported by current data. However, 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

CONFORMAL AND DISFORMAL COUPLINGS

- In *scalar tensor theories*, besides a conformal relation between two metrics:

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

- Bekenstein deduced the most general relation compatible with general covariance to be of the form: [Bekenstein, '92]

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

$C(\phi)$ *conformal* transformation (preserves angles)

$D(\phi)$ *disformal* transformation (distorts angles)

where C, D satisfy the *causality constraint*

$$C(\phi) > 0 \text{ and } C(\phi) + 2D(\phi)X > 0, \; (X = \tfrac{1}{2}(\partial\phi)^2)$$

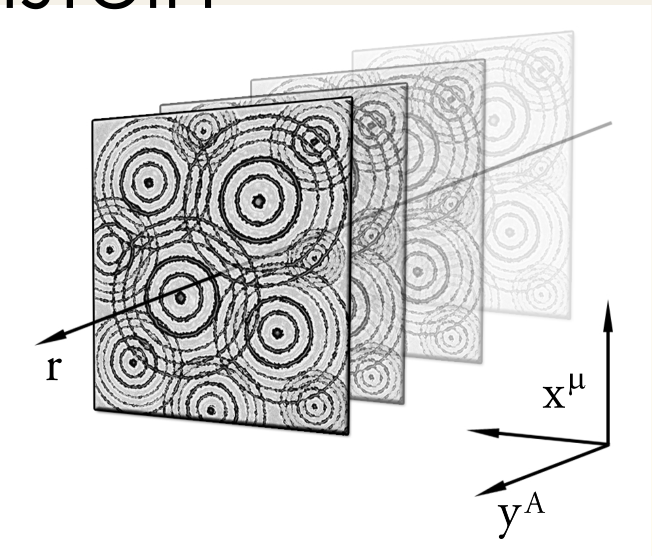
D-BRANE SCALAR-TENSOR THEORIES

- 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]

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



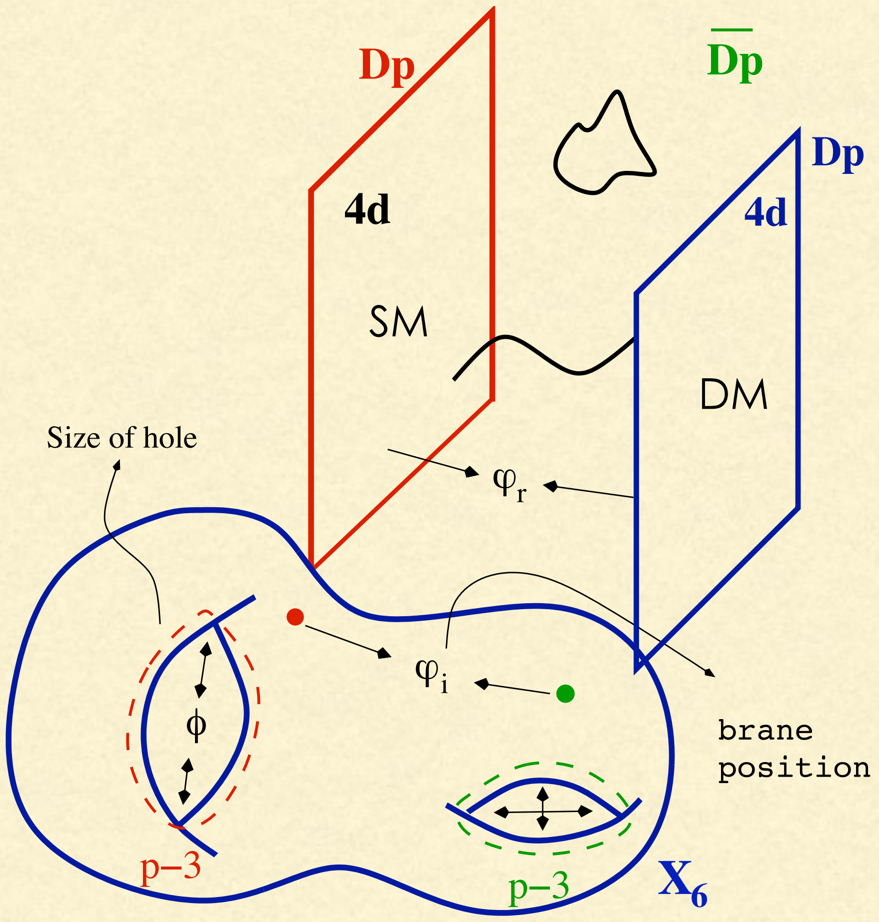
[Dimopoulos, Wills, IZ,'11; Koivisto, Wills, IZ '13]

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

D-BRANE SCALAR-TENSOR EPOCH

- After string inflation & reheating, radiation domination follows.

- Matter lives on a (stack of) D-brane(s): coupled to brane scalar field conformal and disformally via induced metric on brane.



- In what follows I describe a field theory picture of the modification of expansion rate due to such epoch and its implications for the GW spectrum.

SCALAR-TENSOR FROM D-BRANES

[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

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

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

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

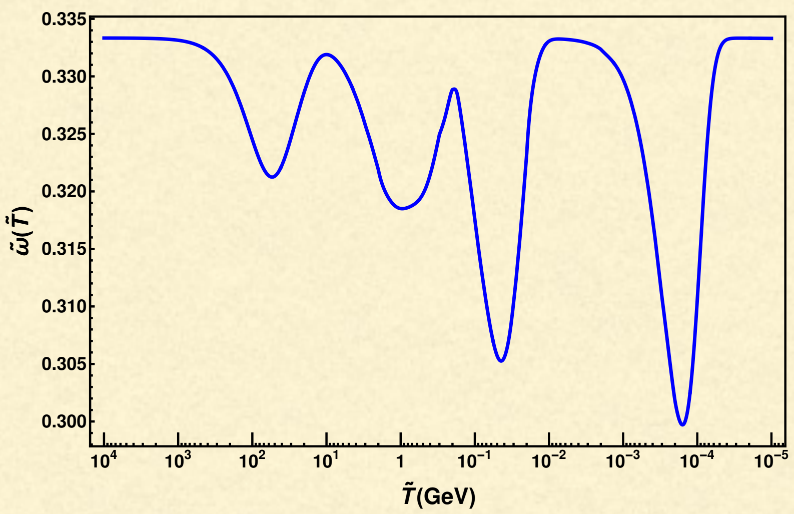
where:

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

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

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)

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)

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.

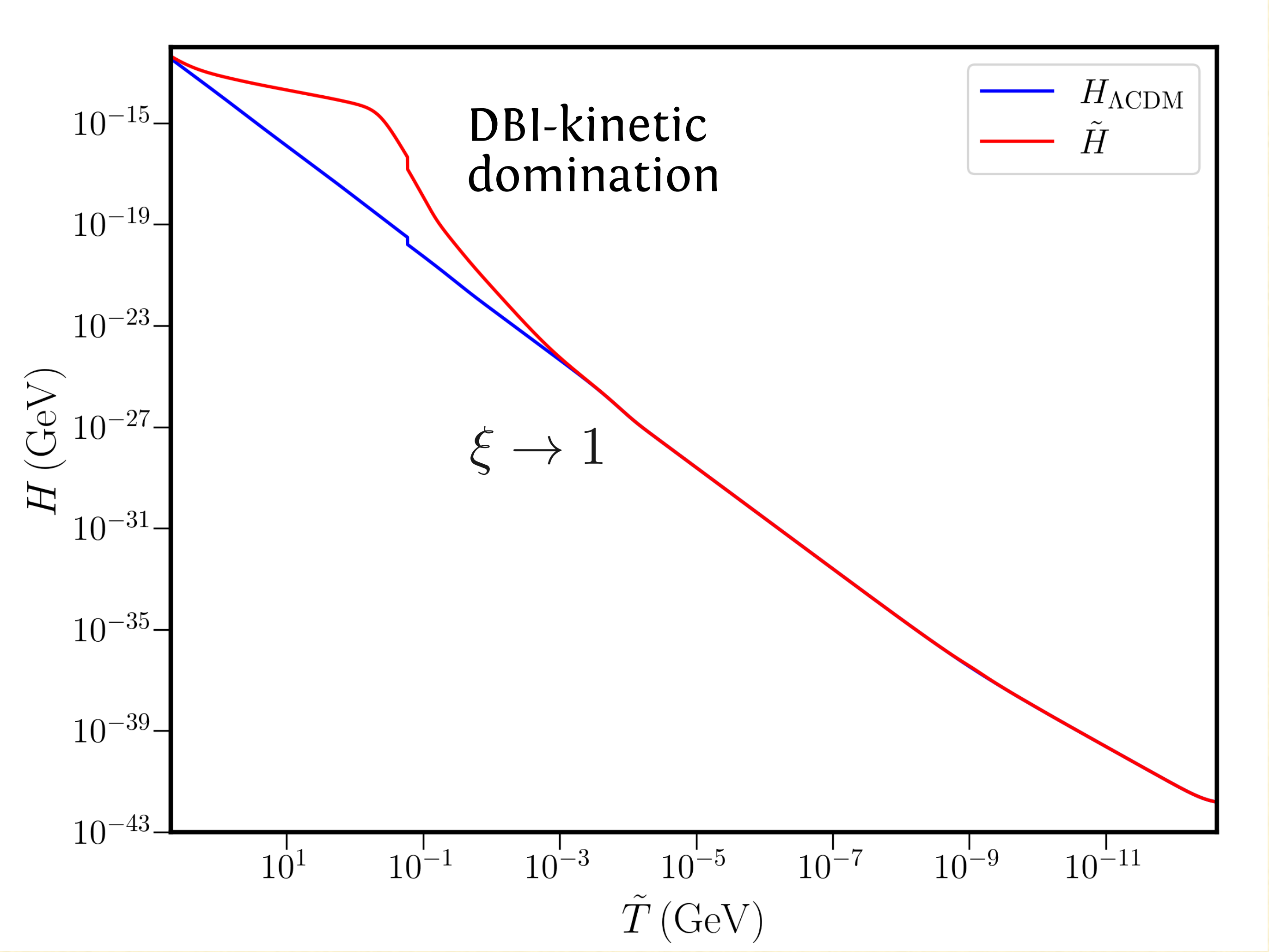
EARLY UNIVERSE EVOLUTION

During the early evolution, the potential term can be ignored, dynamics fully dictated by DBI kinetic (M) $\lambda \sim 0$.

[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 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

$$h^2\Omega^0_{\rm GW} = \left(\frac{\mathcal{P}_T}{24}\right)\left(\frac{a}{a_0}\right)^4 \frac{\gamma^3 H^2_{\rm GR}}{B(H_0/h)^2}$$

Where the primordial spectrum is set by

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

THE RISE OF THE PRIMORDIAL SPECTRUM

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

The initial enhancement of 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

$$h^2\Omega^0_{\rm GW} = \left(\frac{\mathcal{P}_T}{24}\right)\left(\frac{a}{a_0}\right)^4 \frac{\gamma^3 H^2_{\rm GR}}{B(H_0/h)^2}$$

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

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

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

THE RISE OF THE PRIMORDIAL SPECTRUM

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

The initial enhancement of 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

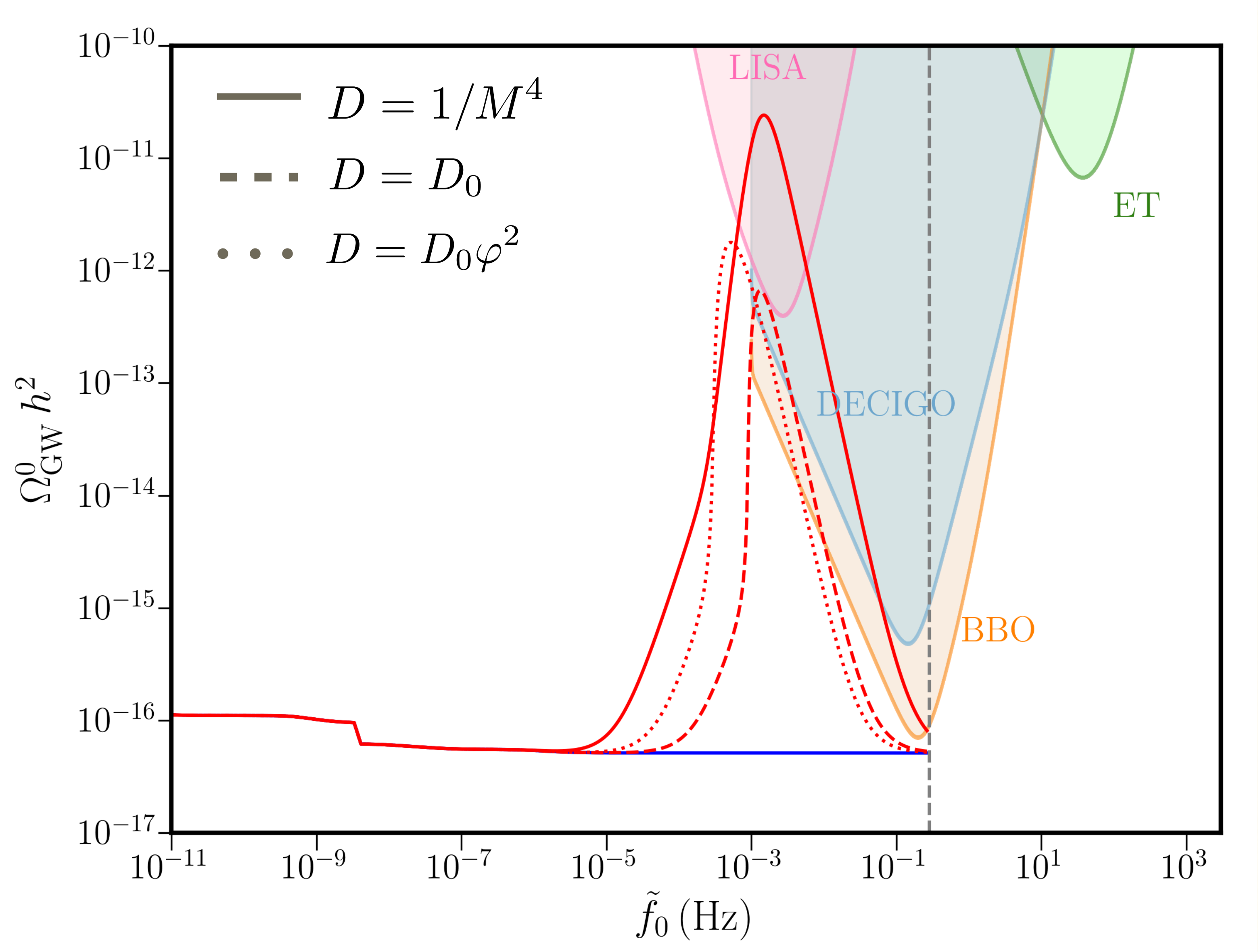
$$h^2\Omega^0_{\rm GW} = \left(\frac{\mathcal{P}_T}{24}\right)\left(\frac{a}{a_0}\right)^4 \frac{\gamma^3 H^2_{\rm GR}}{B(H_0/h)^2}$$

Depending on the initial conditions, the enhancement of the PGWs can happen at frequencies relevant for different GW experiments: PTA, ET, LISA.

DISFORMAL RISE OF THE PGW SPECTRUM

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

During a disformal dominated epoch, the PGW spectrum has a characteristic peak with a distinctive frequency profile, which offers a smoking-gun signature of a disformal early scalar-tensor epoch.



Peak position depends on initial conditions

	$D_0(\text{GeV}^{-4})$	$H_i(\text{GeV})$
Pheno case: $D = D_0$	5.000×10^{-38}	1.413×10^4
Pheno case: $D = D_0\varphi^2$	6.000×10^{-37}	1.408×10^4
D-brane case: $D = 1/M^4$	4.822×10^{-37}	1.516×10^4

$\varphi^i = 0.200,\ \varphi^i_{\tilde{N}} = 2.000 \times 10^{-5}, \tilde{T}_i = 10^7(\text{GeV}).$

DISFORMAL RISE OF THE PGW SPECTRUM

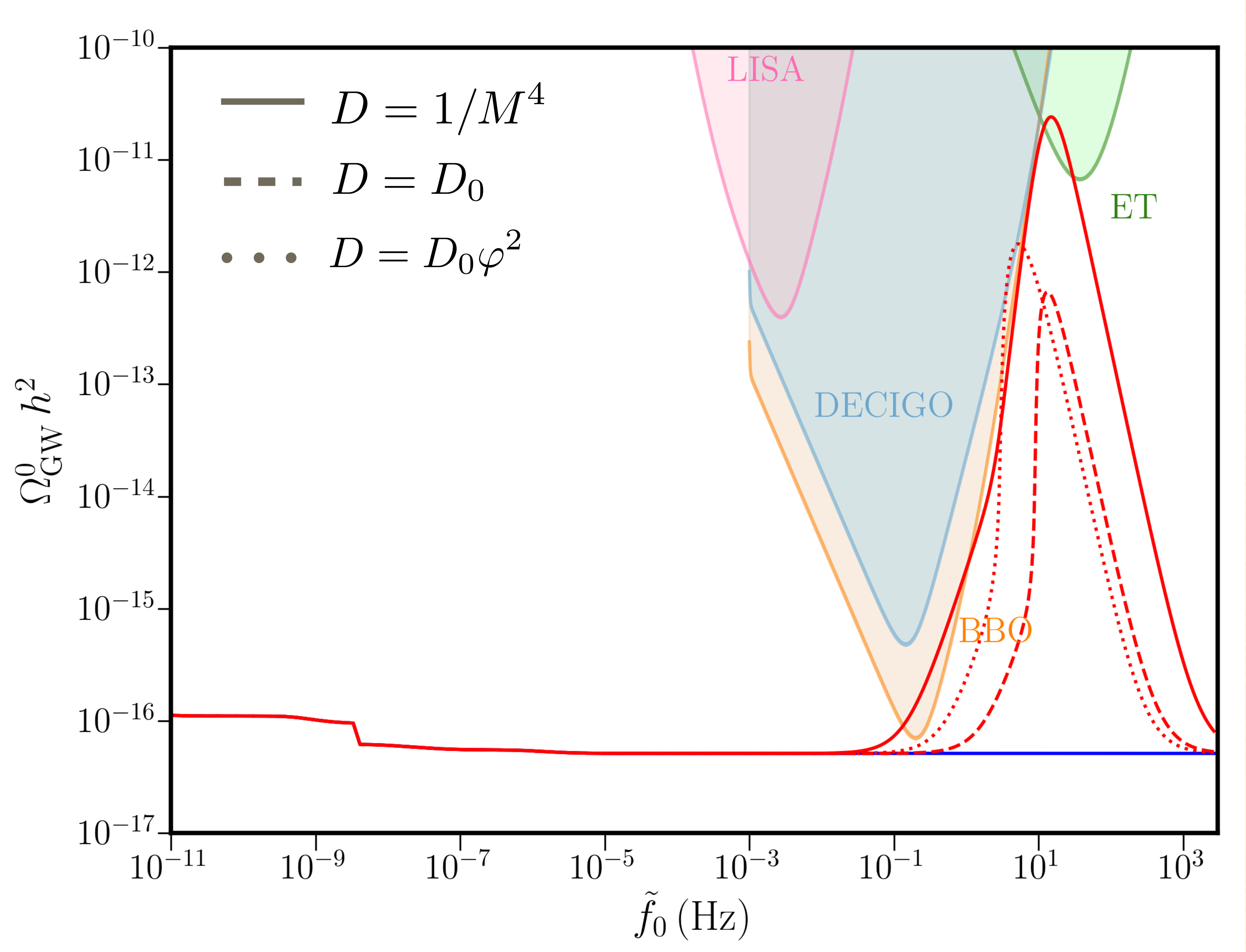
[Chowdhury, Tasinato, IZ, '22,23]

During a disformal dominated epoch, the PGW spectrum has a characteristic peak with a distinctive frequency profile, which offers a smoking-gun signature of a disformal early scalar-tensor epoch.

Peak position depends on initial conditions

	$D_0(\mathrm{GeV}^{-4})$	$H_i(\mathrm{GeV})$
Pheno case: $D = D_0$	5.000×10^{-38}	1.413×10^4
Pheno case: $D = D_0\varphi^2$	6.000×10^{-37}	1.408×10^4
D-brane case: $D = 1/M^4$	4.822×10^{-37}	1.516×10^4

$\varphi^i = 0.200,\ \varphi^i_{\tilde{N}} = 2.000 \times 10^{-5},\ \tilde{T}_i = 10^{11}(\mathrm{GeV})$



THE RISE OF THE PRIMORDIAL SPECTRUM

[Chowdhury, Tasinato, IZ, '23]

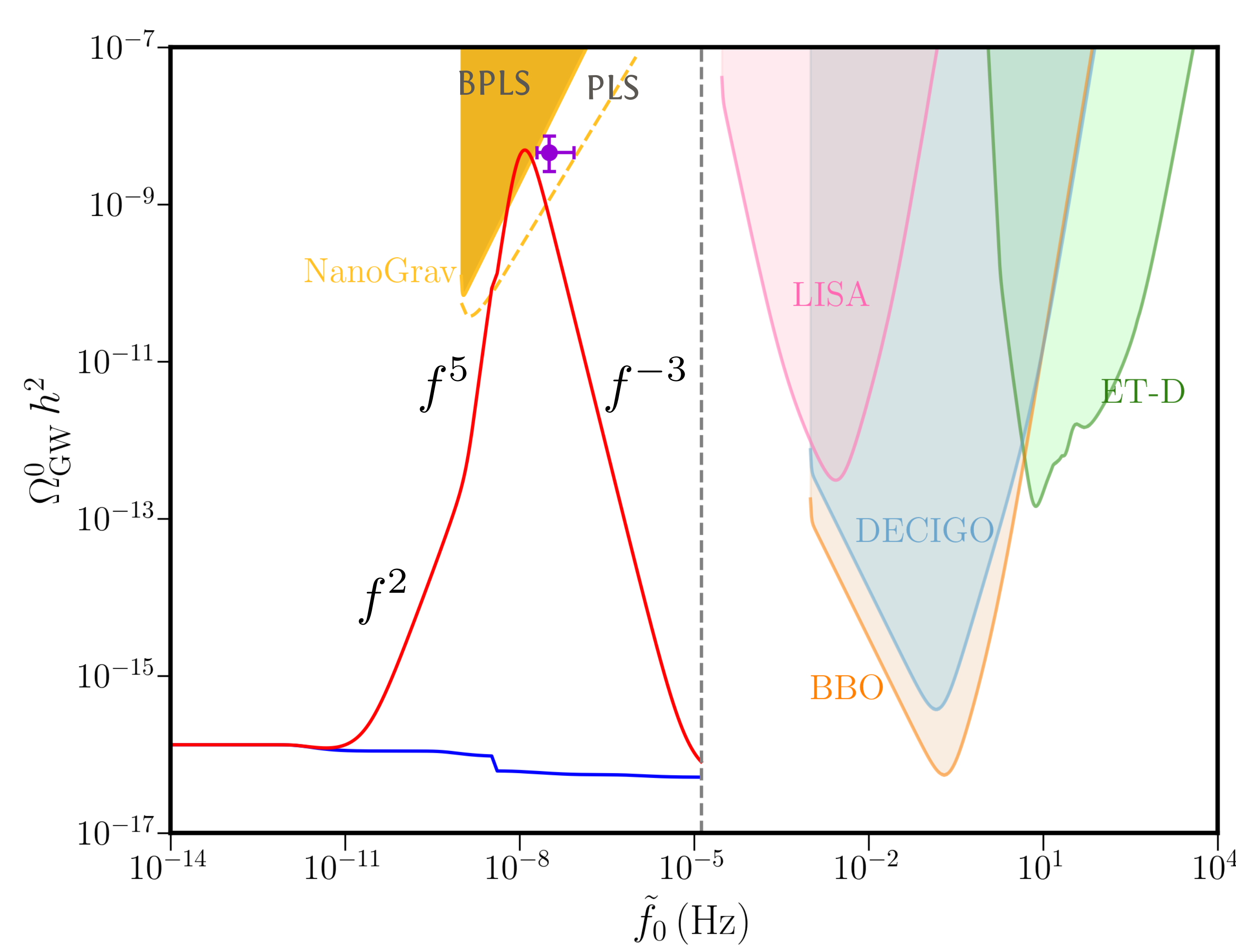
For suitable initial conditions, the SPGW spectrum rises at scales accessible to PTA experiments $f \sim 10^{-9} - 10^{-8}\,\mathrm{Hz}$

[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]



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

POST-DBI EVOLUTION

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

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

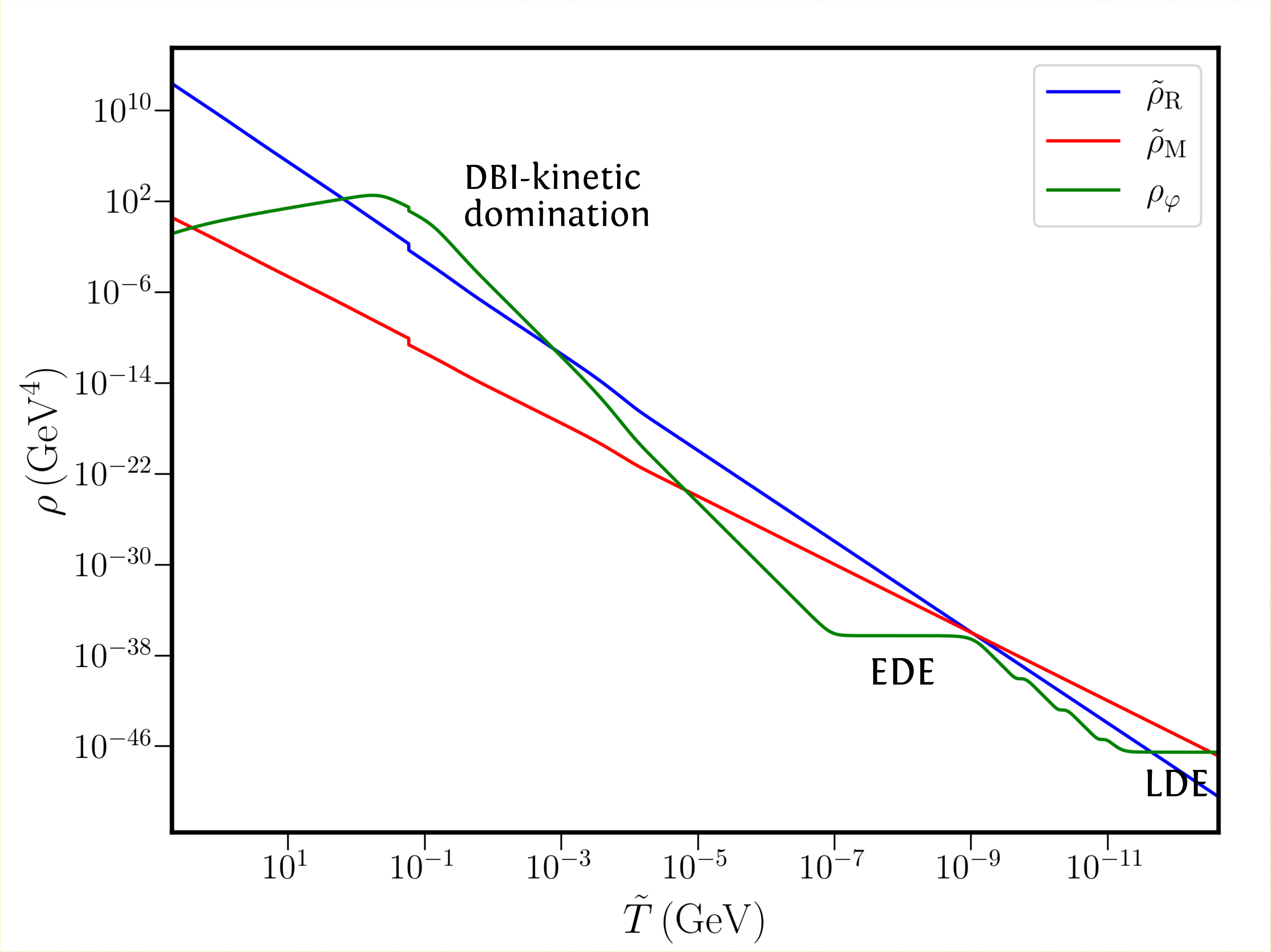
Scalar potential cannot affect cosmological predictions

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

EARLY AND LATER DARK ENERGY

[Chowdhury, Tasinato, IZ, '23]

Energy densities' evolution of radiation, matter, axion



SUMMARY PART II

- *D-brane scalar-tensor* theories, can trigger a period of (coupled) DBI-kinetic domination.

- Such an epoch modifies *the expansion rate*, and enhances the PGW spectrum with *distinctive* broken power law profiles, that can be tested by GW experiments (PTA, ET, LISA)

SUMMARY

- Gravitational wave cosmology offers a great opportunity to test models of cosmology derived from consistent theories of quantum gravity, specifically string theory.
- Several theoretical challenges, but several observational opportunities. We must use them!