CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Spotting String Axions

Spectators, GWs and Preheating

Margherita Putti

Dark World to The Swampland

Based on
arXiv:2312.13431
arXiv:2411.xxxx,

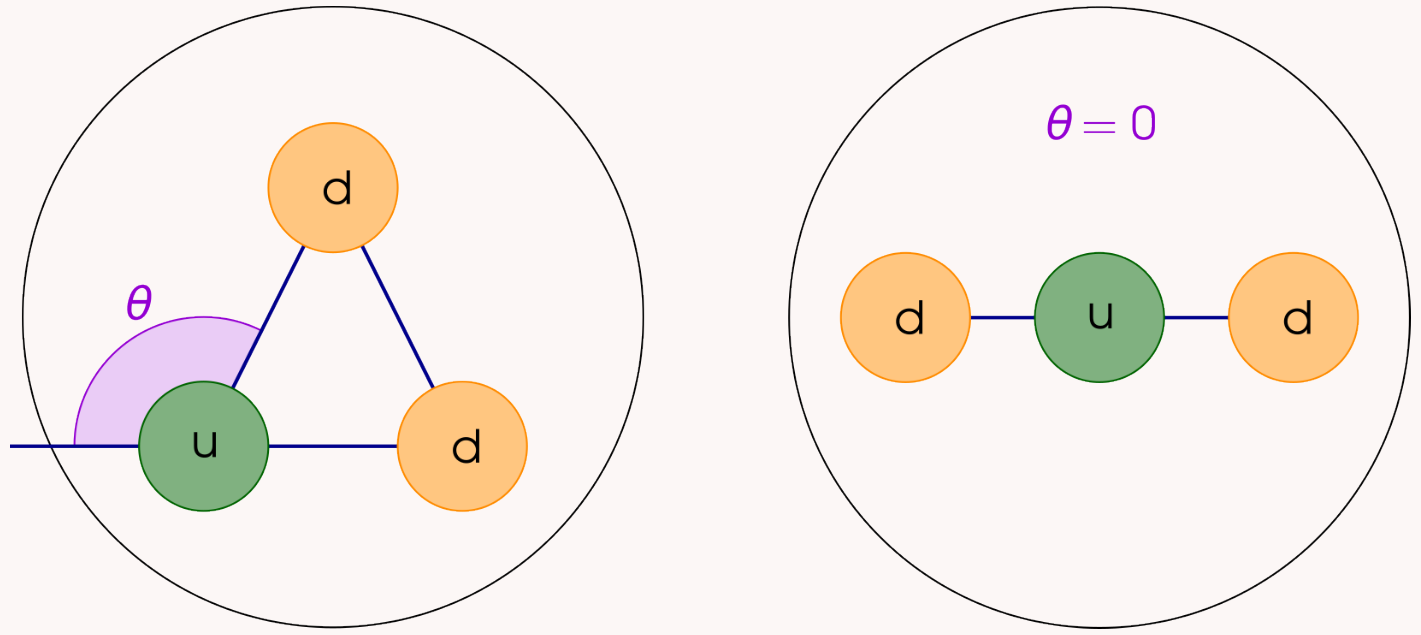
Axions

- Potential solution to the Strong CP problem

$$\mathscr{L}_{SM} \supset \frac{1}{32\pi^2}\theta F^A_{\mu\nu}\tilde{F}^{A\mu\nu}$$

$$|d_n| \simeq 10^{-16}\,\theta\, e\ \text{cm}$$

$$\theta \lesssim 10^{-10}$$



$$\theta \to \frac{\chi}{f} \implies \theta = 0$$

Axions

- Pseudo-scalar particles with perturbative continuous shift symmetry

$$\chi \to \chi + c \qquad c \in \mathbb{R}$$

Broken by non-perturbative effects

$$V(\chi) \sim \Lambda^4(1 - \cos(\chi/f_\chi))$$

To discrete shift symmetry

$$\chi \to \chi + 2\pi n f_\chi \quad n \in \mathbb{Z}$$

- QFT axions arise as massless modes after SSB

Stringy Axions

Unified QG theories have p-form gauge potentials

10D Type IIB

$$C_4,\ C_2,\ B_2,\ C_0$$

Compactification: $M_{10} \rightarrow M_4 \times X_6$

Gives rise to axions $C_4 = \rho_\alpha \omega^\alpha + ..$ $\alpha \in \{1,2,...h^{1,1}\}$

Axions

Few - $\mathcal{O}(10^2)$ → axiverse

- ✦ Gauge symmetry protects shift symmetry
- ✦ Inflation models / quintessence
- ✦ …

Axiverse is the best prospect to tie string theory to experiments

Arvanitaki, Dimopolous, Dubovsky, Kaloper, March-Russel arXiv:0905.4720
Cicoli, Goodsell, Ringwald arXiv:1206.0819
Acharya, Bobkov, Kumar arXiv:1004.5138
…

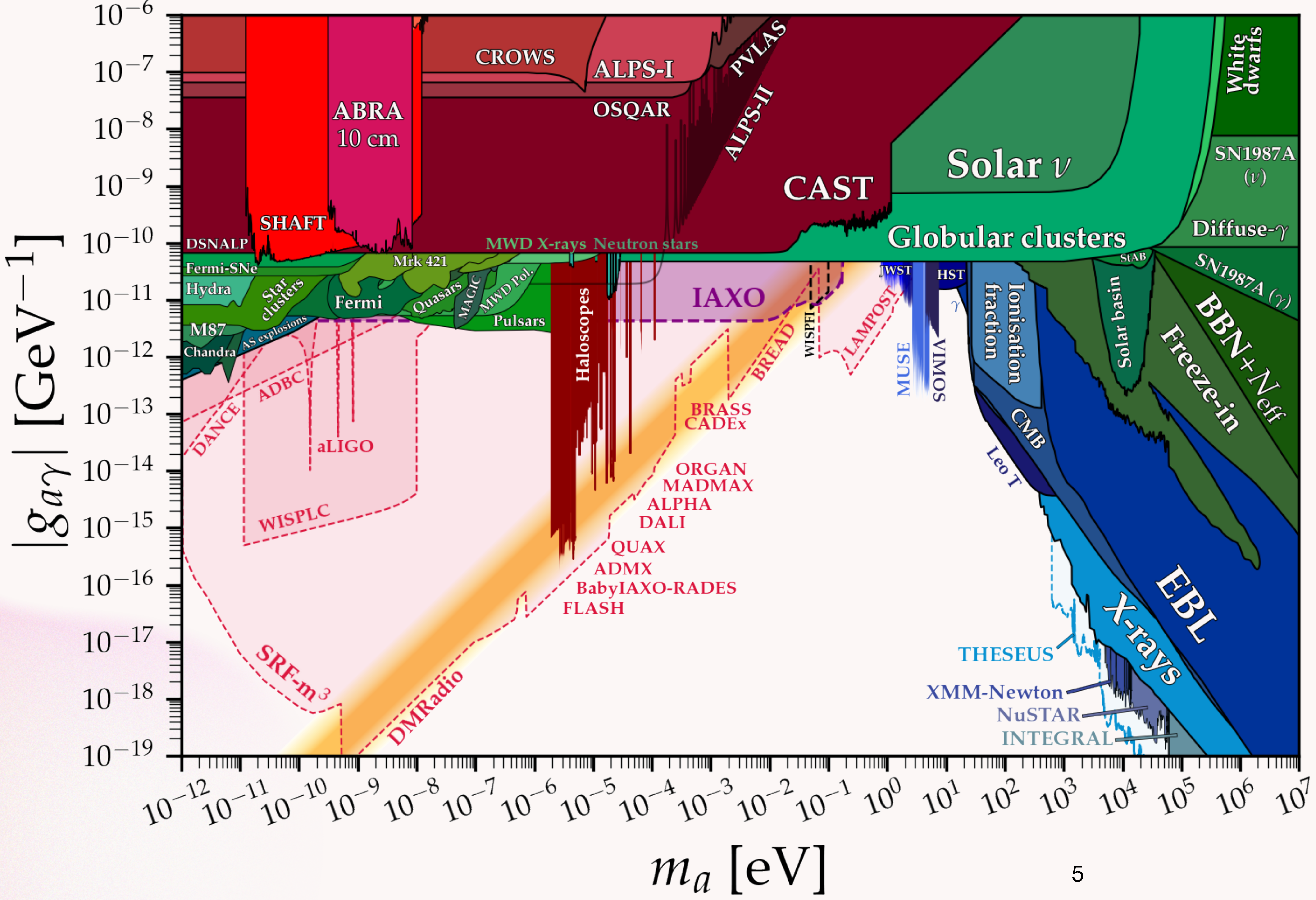
Detecting the Axiverse

If axions couple to SM →

- ✦ Axion - photon coupling $g_{a\gamma}$
- ✦ Axion - nucleon coupling g_N

O'Hare Github

Constraints and future projections of axion-photon coupling experiments.



Assumptions:
axion is very light,
makes up DM.

Detecting the Axiverse

If axions couple to SM →

- ✦ Axion - photon coupling $g_{a\gamma}$
- ✦ Axion - nucleon coupling g_N

However, string axions may not be:

- ✦ Light enough
- ✦ DM
- ✦ Coupled to SM

Naively:

- ✦ One QCD axion
- ✦ One for inflation
- ✦ One for quintessence

What about the rest of the axiverse?

How can we detect string axions that don't necessarily couple to the Standard model

Goal

How can we detect string axions that don’t couple to the Standard model

Gravitational Waves

Dimastrogiovanni, Fasiello, Leedom, MP, Westphal

arXiv:2312.13431

Dark Radiation

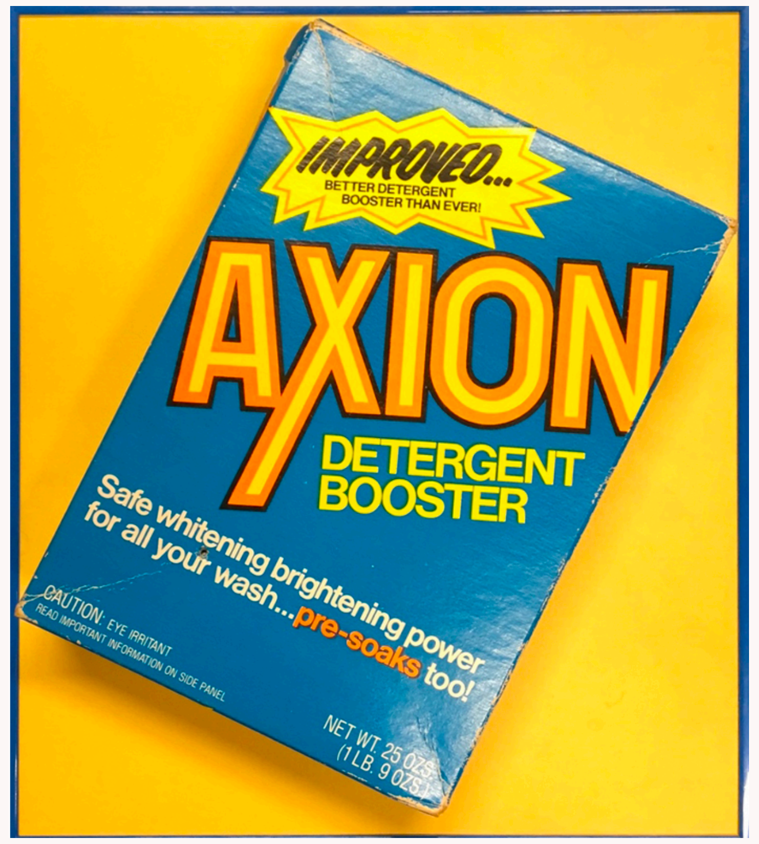
Leedom, MP, Righi, Westphal

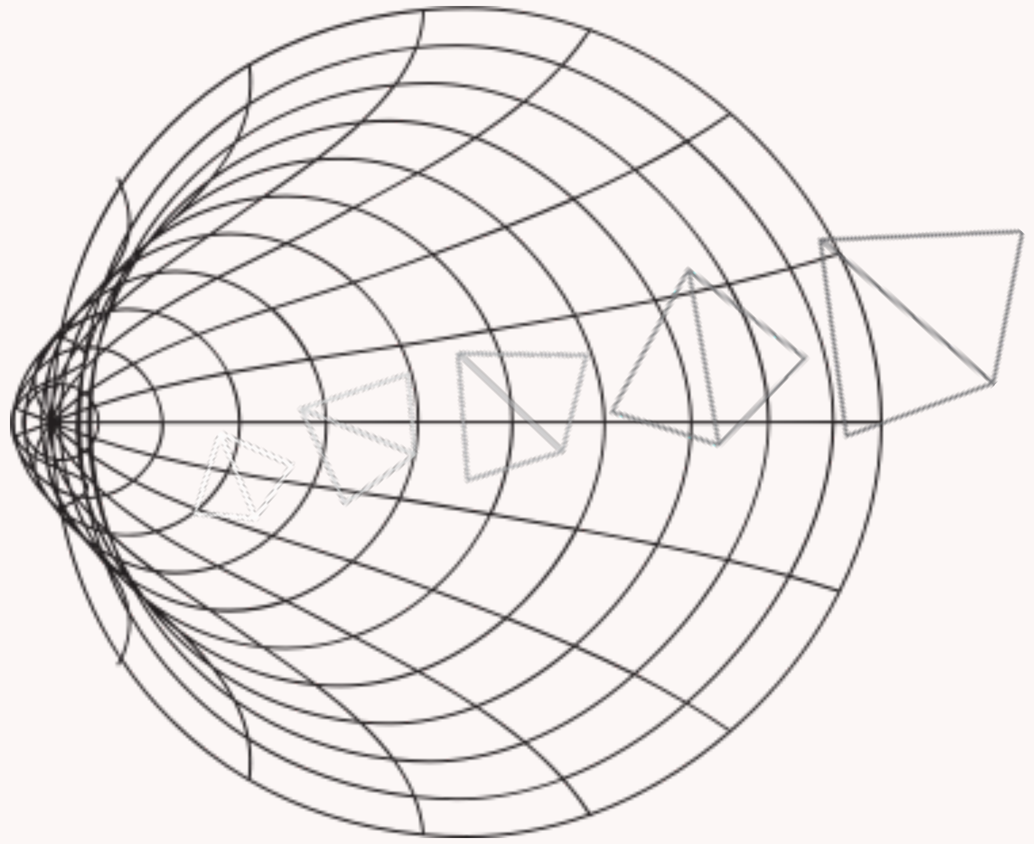
arXiv:2411.xxxx,

…

Ingredients

AXIONS





INFLATION

Axions are spectators during inflation

- ✦ Axions coupled to hidden gauge fields

GWs from the AXIVERSE

- ✦ Axionic preheating

ΔN_{eff} from the AXIVERSE

Axion spectators in type IIB

- ✦ Type IIB compactified on 6d CY → $\{h^{1,1}, h^{2,1}\}$ Hodge numbers
- ✦ $\mathcal{N} = 1 \iff \widetilde{X}_6 \equiv X_6/\Omega$ → $h^{1,1} = h^{1,1}_+ + h^{1,1}_-$, $h^{2,1} = h^{2,1}_+ + h^{2,1}_-$
- ✦ Graviton, axiodilaton, $h^{2,1}$ CS, $h^{1,1}$ Kähler moduli + susy partners

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stabilized by fluxes

saxion

axion

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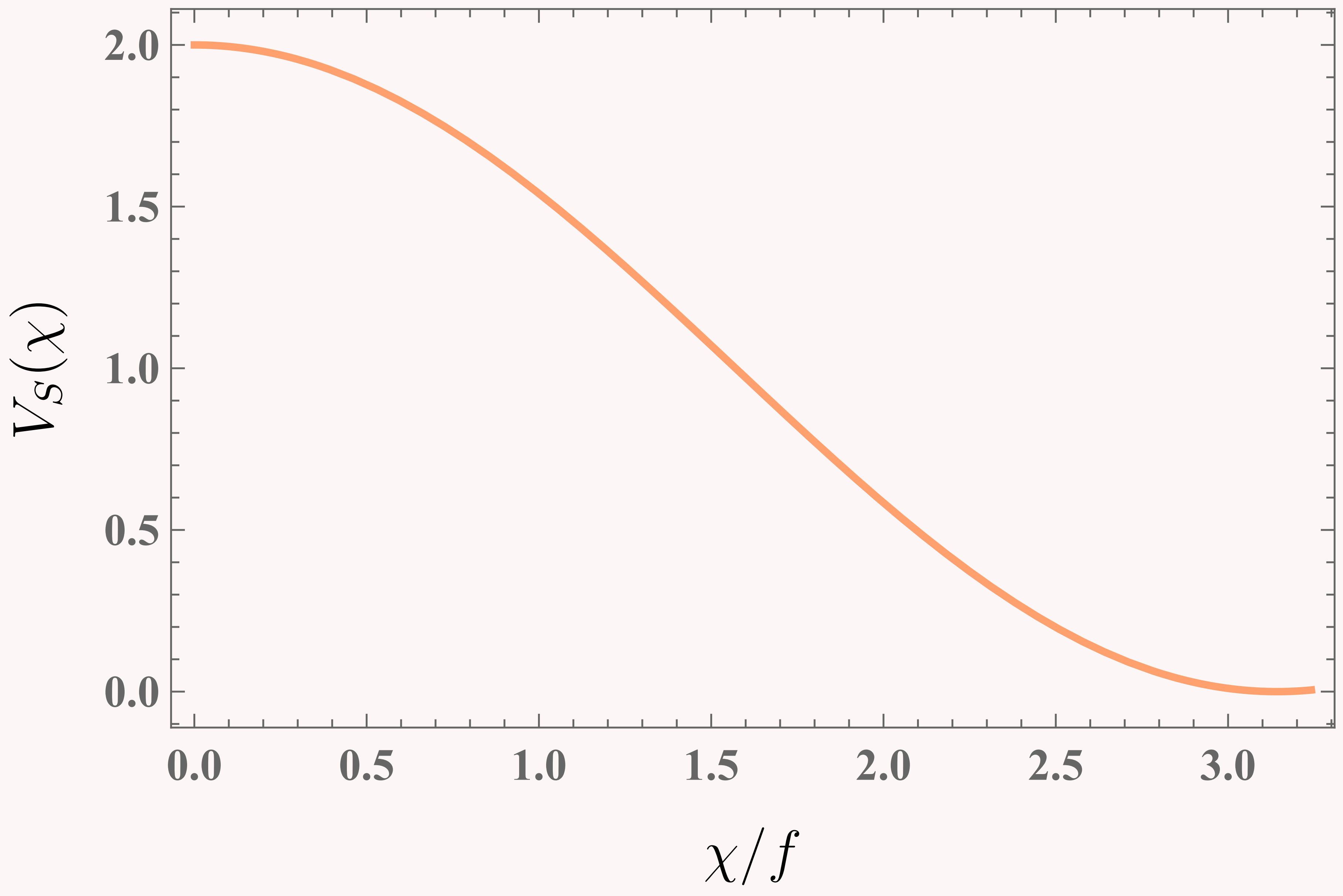
- $T^j = \tau^j + i\theta^j$,
- → $\mathscr{L} \supset K_{i\bar{j}} \partial T^i \partial T^{\bar{j}} - V(T^i, \overline{T}^{\bar{i}})$, with $K_{i\bar{j}} = \partial_{T^i} \partial_{T^{\bar{j}}} K$
- $V = e^K \left(K^{i\bar{j}} D_i W D_{\bar{j}} \overline{W} - 3\,|W|^2 \right)$, with $W = W_0 + A_i e^{-a_i T_i}$

Axion spectators during inflation

✦ Type IIB compactified on 6d orientifold $\rightarrow h^{1,1} = h^{1,1}_{+} + h^{1,1}_{-}$ axions

✦ Canonical renormalization: $\vartheta_i = a_i f_i \theta_i$

$$V \supset \Lambda_i^4 e^{-a_i \tau_i} \cos(\vartheta_i / f_i) \quad \rightarrow m^2_{\vartheta,\mathrm{eff}} = \frac{\Lambda_i^4 e^{-a_i \tau_i}}{f_i^2}$$



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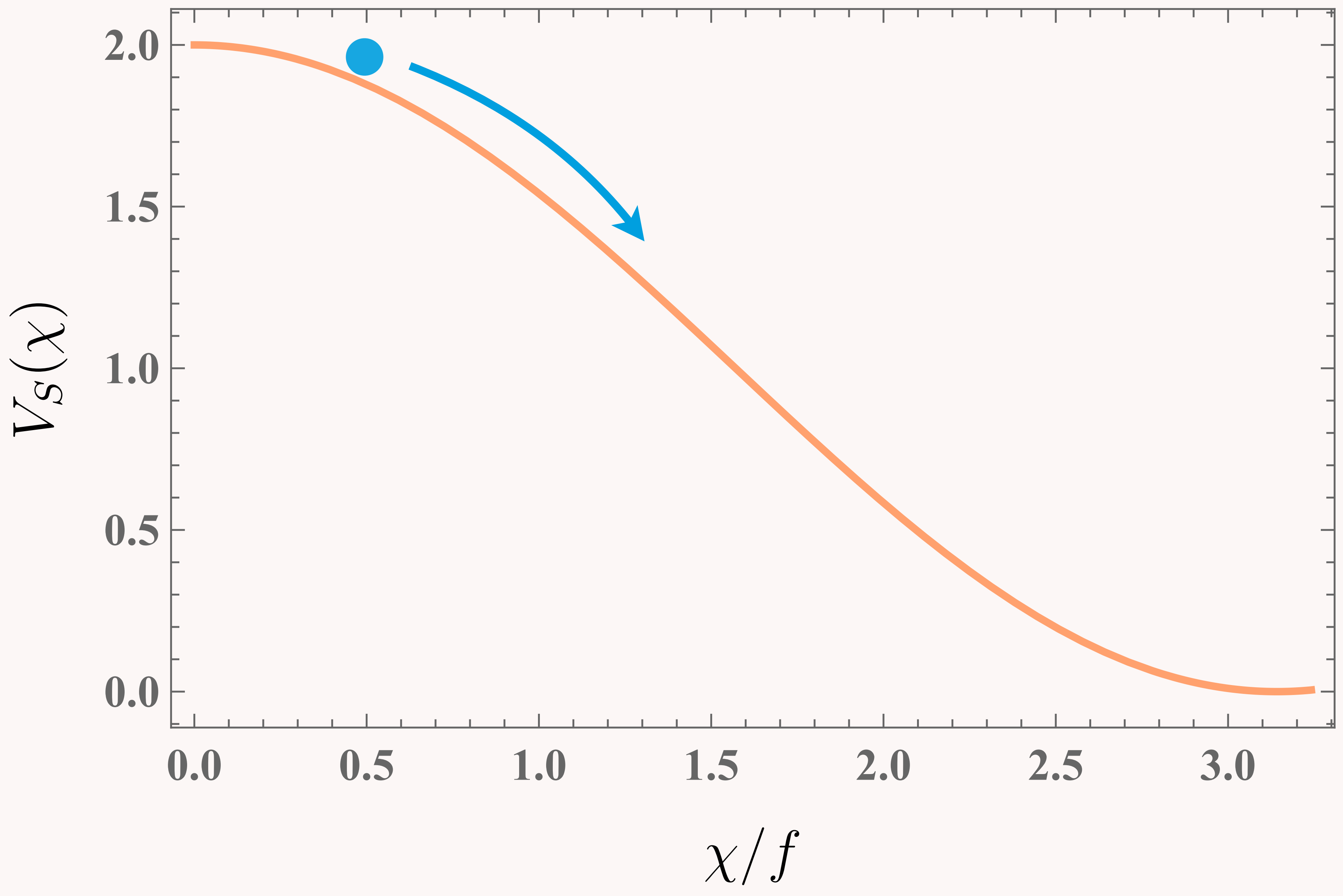


✦ During inflation $m_{\vartheta,\text{eff}} \ll H$: no contribution to V_{inf}

✦ If $m_\vartheta \lesssim H$ $\rightarrow$ axion rolls down its potential during inflation

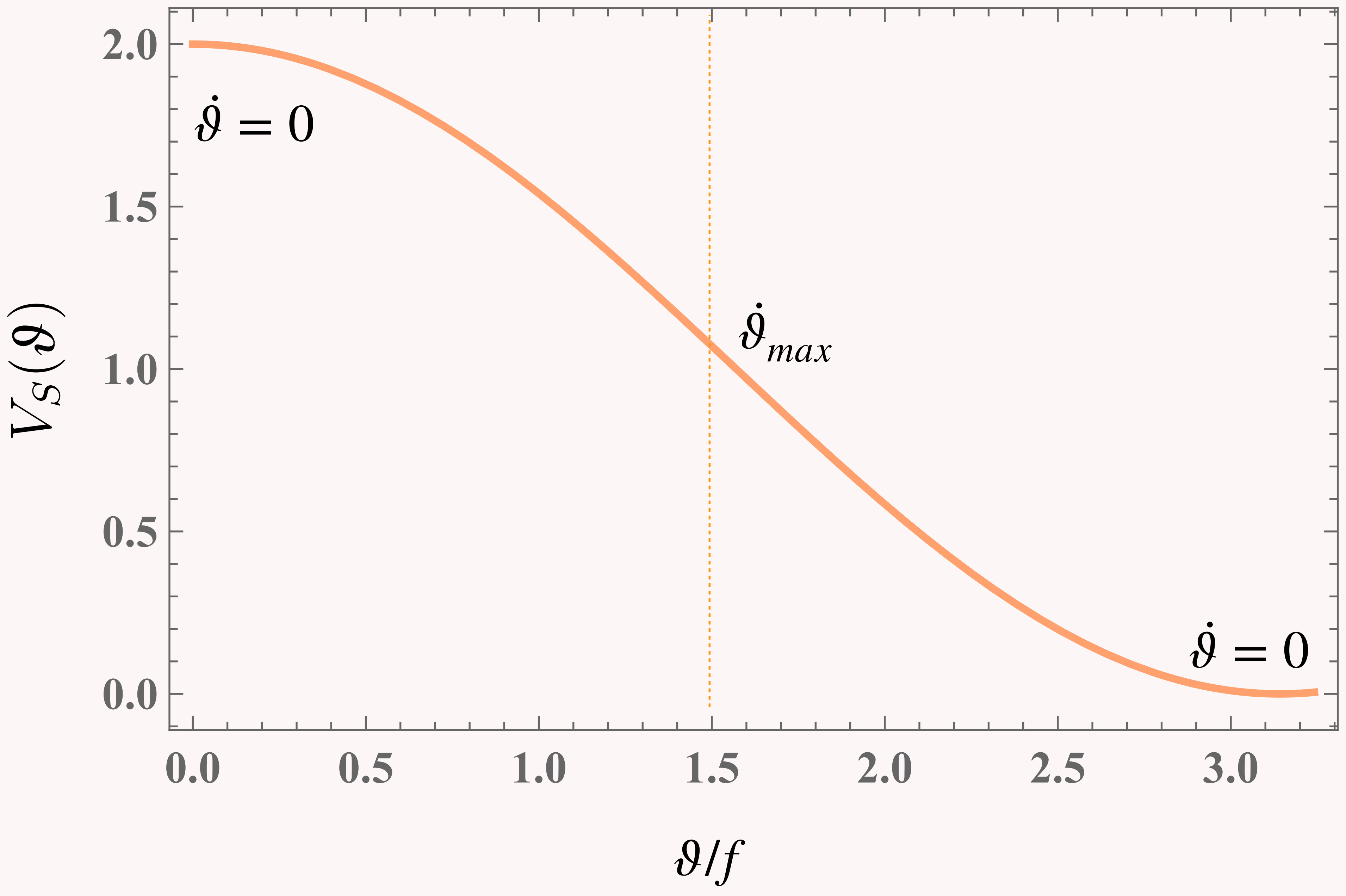
GW from spectators

Spectator Mechanism

$$\mathscr{L} = \underbrace{-\frac{1}{2}(\partial\varphi)^2 - V(\varphi)}_{\mathscr{L}_{inf}} \underbrace{-\frac{1}{2}(\partial\vartheta)^2 - V(\vartheta) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \lambda\frac{\vartheta}{4f}F_{\mu\nu}\tilde{F}^{\mu\nu}}_{\mathscr{L}_{spectator}}$$

$$\dot{\vartheta} \neq 0 \longrightarrow P_{\zeta,GW} = P^{(vac)}_{\zeta,GW} + P^{(src)}_{\zeta,GW}$$

$$V(\vartheta) = \Lambda^4\left(1 - \cos\frac{\vartheta}{f}\right) \longrightarrow$$



Enhancement of primordial perturbations.

Signal present a peak.

Spectator Mechanism

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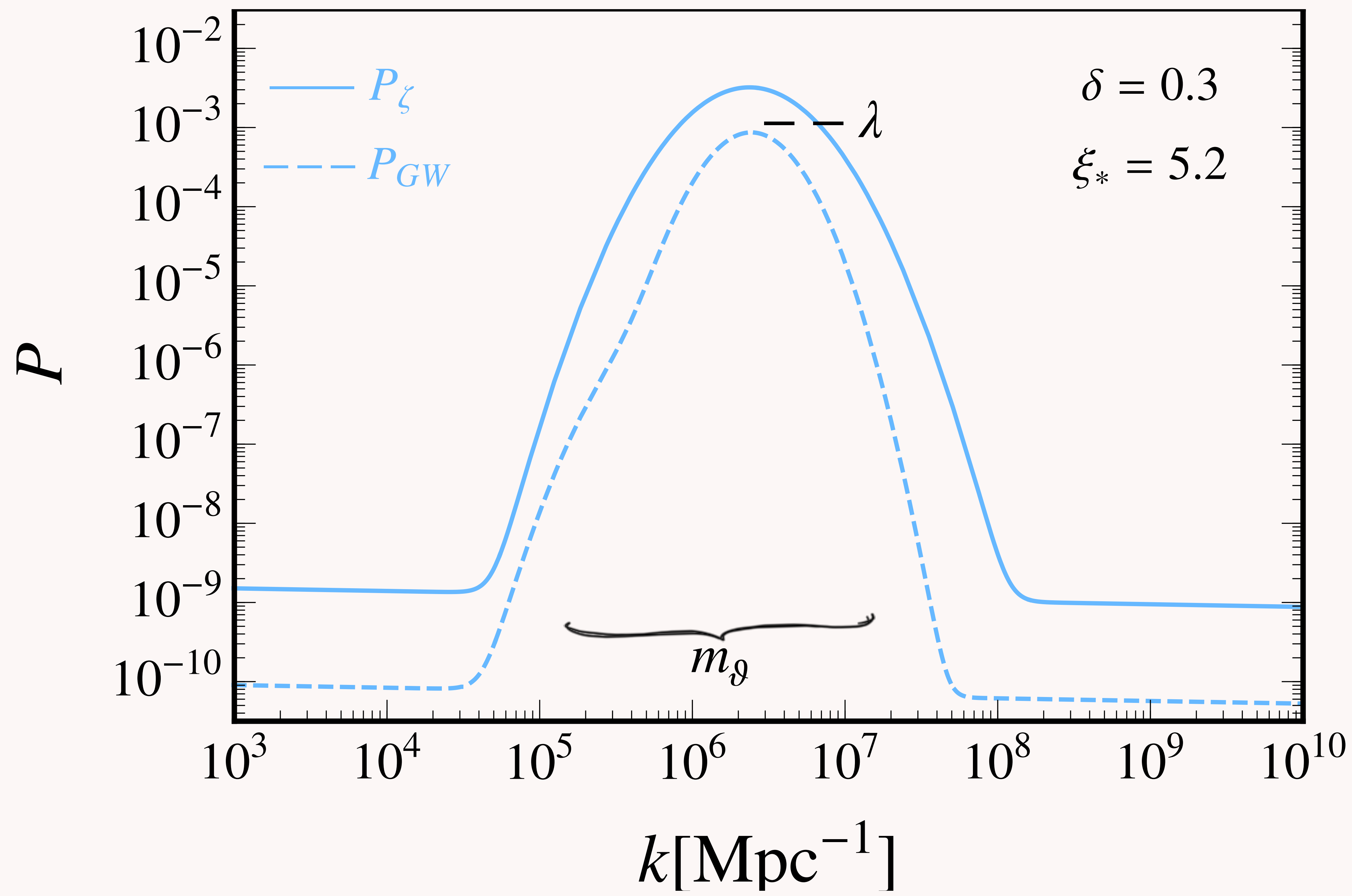


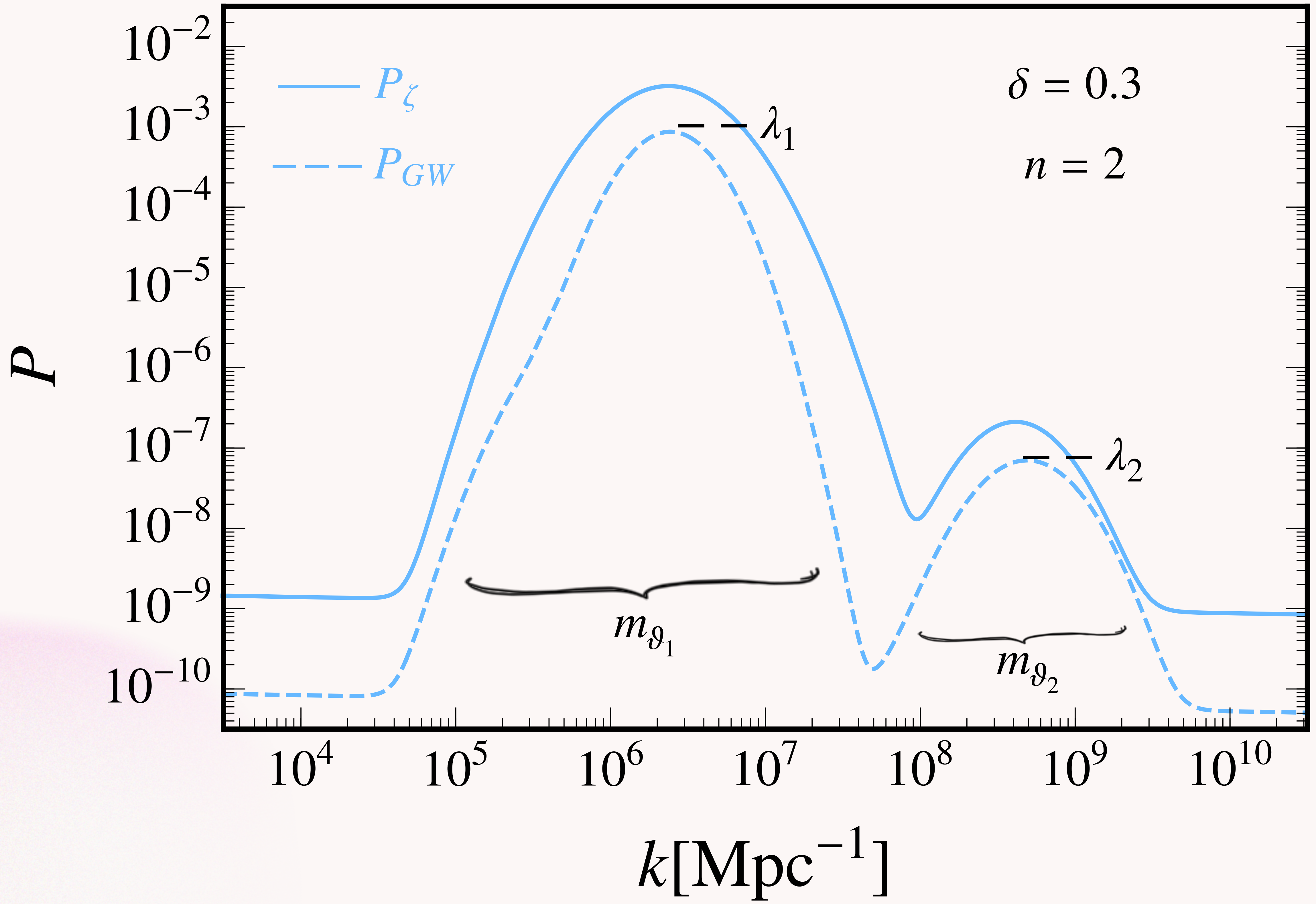
Enhancement of primordial perturbations.

Signal present a peak.

Inflationary Axiverse

A multitude of abelian spectators

$$\mathscr{L} = \mathscr{L}_{inf} + \sum_{i=1}^{n} \mathscr{L}_{spect} \longrightarrow P_{\zeta,GW} = P^{(vac)}_{\zeta,GW} + \sum_{i=1}^{n} P^{(src)i}_{\zeta,GW}$$



Peak parameters determined by:

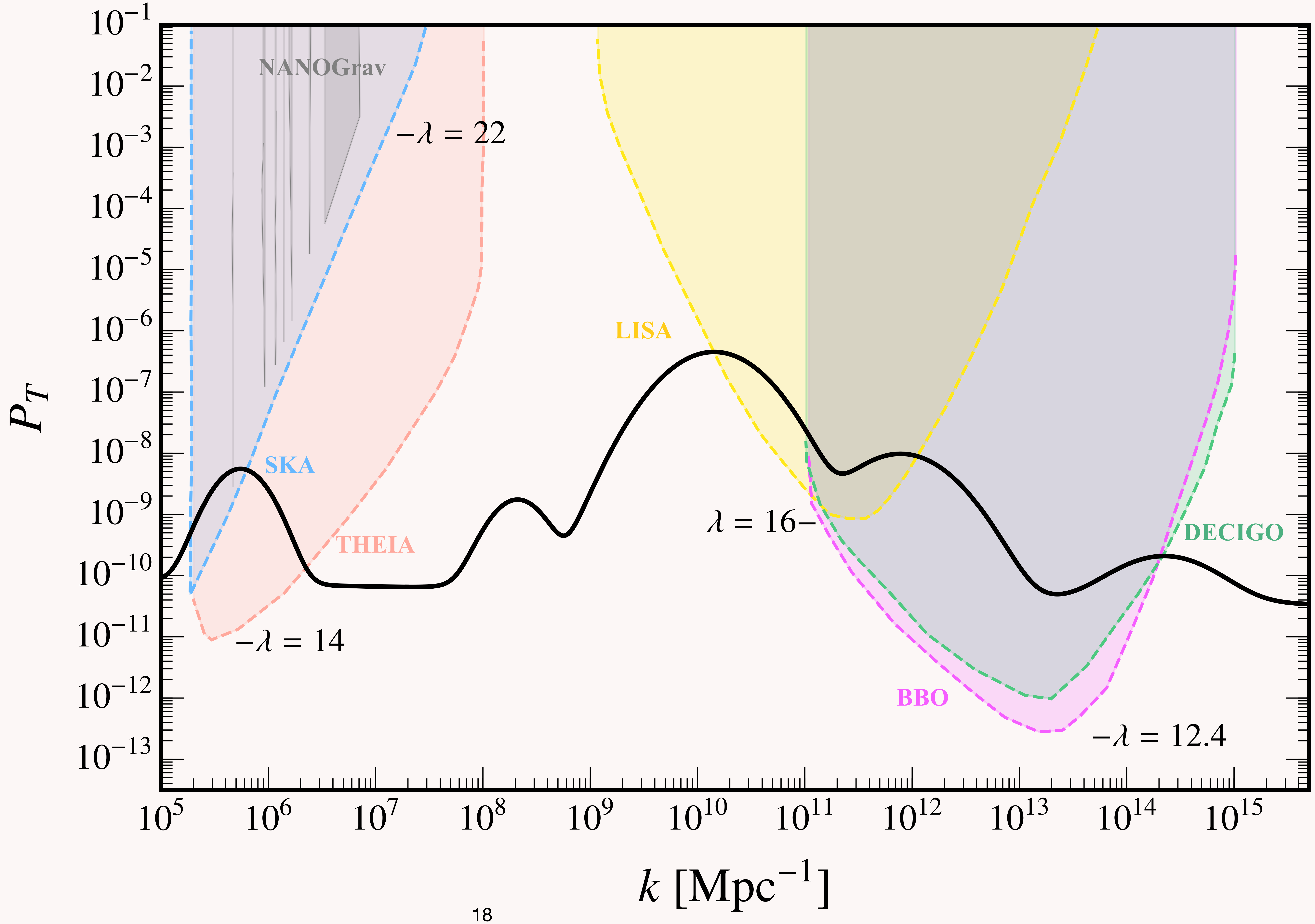
λ CS coupling: height $\quad \xi_* = \lambda \dfrac{\delta}{2}$

m_ϑ Axion mass: width $\quad \delta = \dfrac{m_\vartheta^2}{6H^2}$

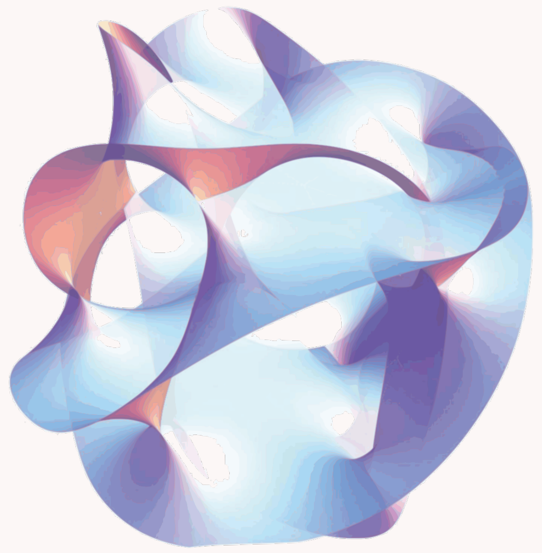
ϑ_{in} Initial condition: position

Inflationary Axiverse: GW

Axion properties determine GW features: Gravitational spectroscopy



UV Embedding



We motivated the GW forest via the existence of the string axiverse

Can we actually embed this in string theory?

↓

✦ How generic can the spectator mechanism be?

✦ Does the landscape allow observable signals?

$$\lambda \gtrsim 10$$

Axion candidates

Type IIB on 6d
Orientifold

$M_{10} \to M_4 \times \tilde{X}_3$

P-forms $C_4,\ C_2$

X_3 CY 3-fold

$\tilde{X}_3 = X_3/\Omega$

ρ_α 4-form
even axion

Axion candidates

c^a 2-form
odd axion

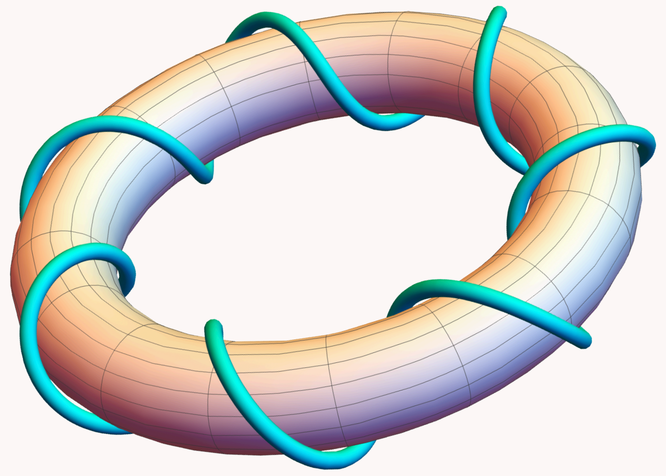
Gauge theory from D7 branes

$$S_{D7} \supset \underbrace{\int_{\Sigma_4} C_4}_{\rho_\alpha} \int_{4D} F_2 \wedge F_2$$

$$\lambda \sim \langle \tau \rangle^{-1} < \mathcal{O}(1)$$

$$S_{D7} \supset \underbrace{\int_{\Sigma_2} F_2}_{\text{gauge flux } m} \underbrace{\int_{\Sigma_2} C_2}_{c^a} \int_{4D} F_2 \wedge F_2$$

$$\lambda \sim w\,\kappa\,m$$

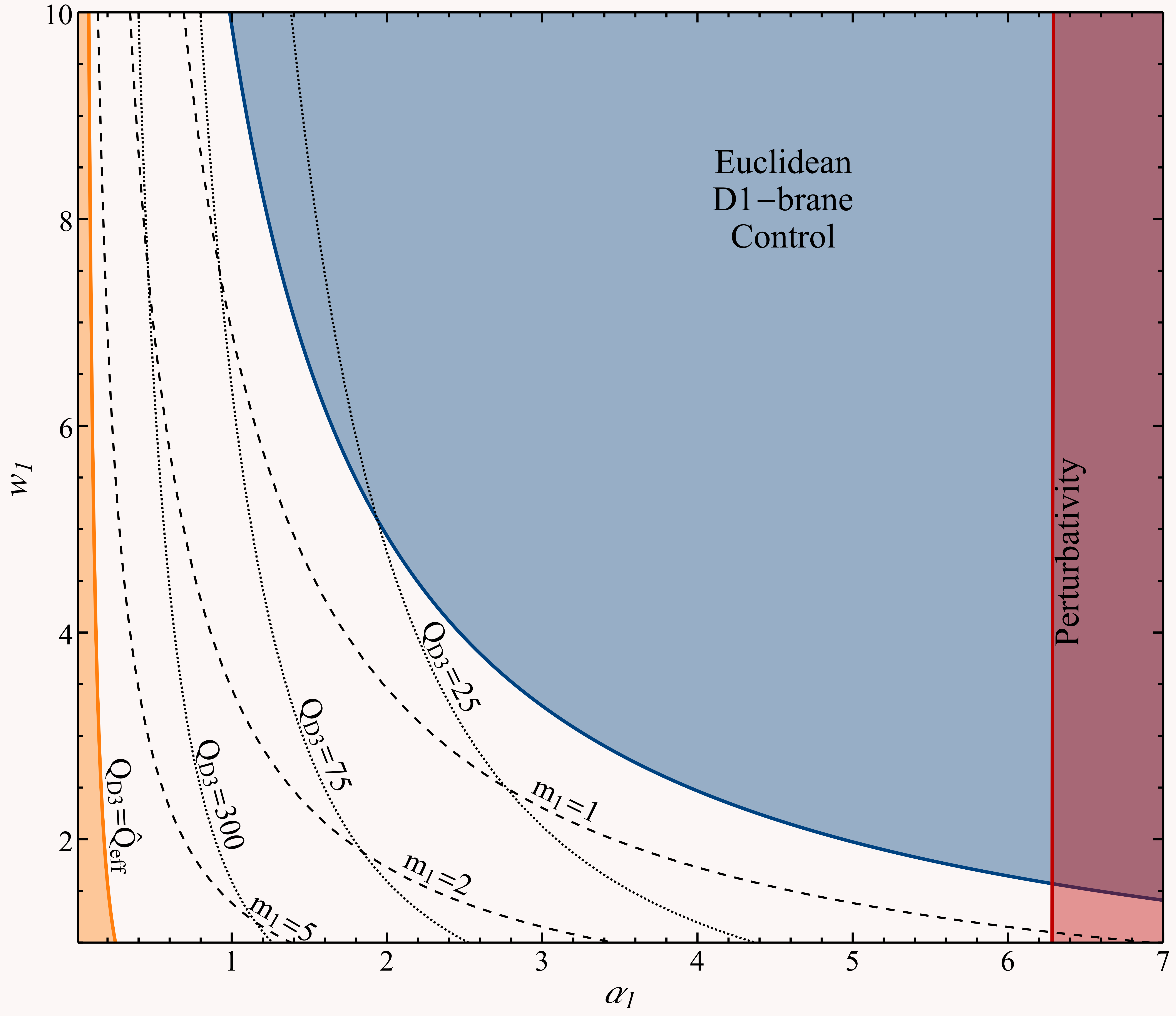


CS coupling constraints

Parameter space for c^a with magnetized D7 brane to reach PTA amplitudes in GW signal

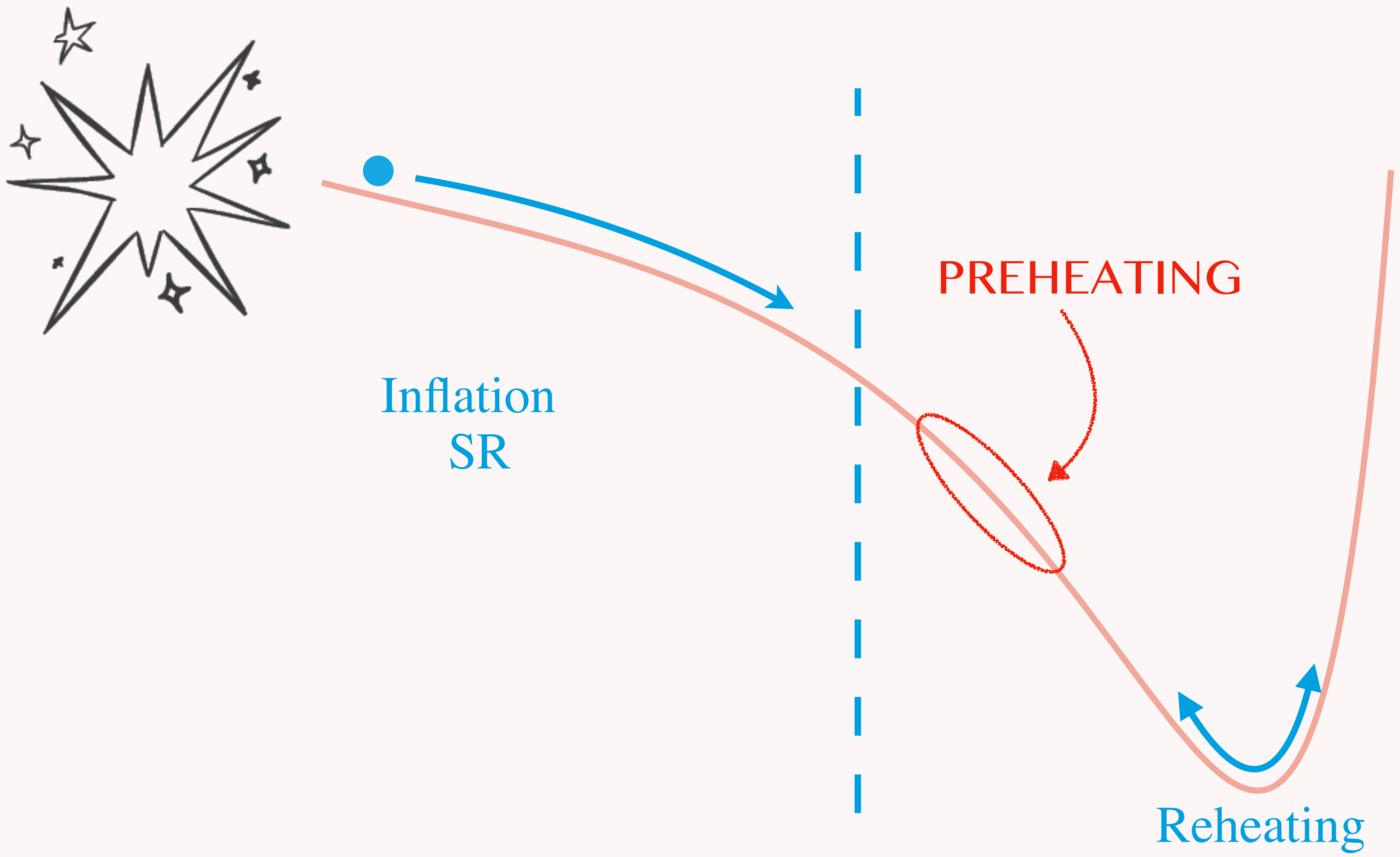
- ✦ Perturbativity control for U(1) theory
- ✦ ED1 control (axion potential)
- ✦ Induced D3 Tapole

- ✦ Specific topology to avoid Stückelberg couplings (no massive U(1))



Preheating spectators

Preheating



Parametric resonance

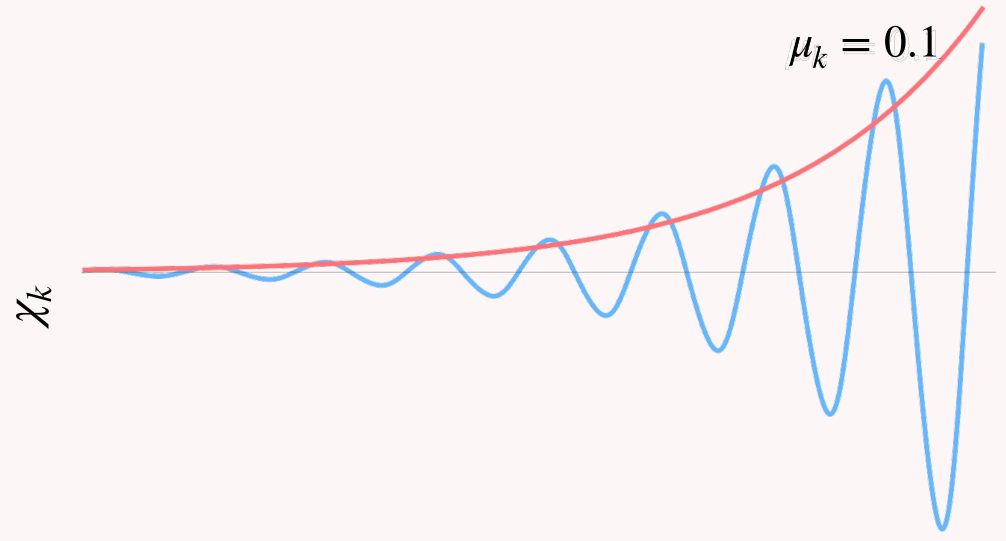
$$\phi \simeq \langle \phi \rangle + \Delta\phi \cos(mt)$$

$$\vartheta(t, \overrightarrow{x}) = \langle \vartheta \rangle + \delta\vartheta_k(t, \overrightarrow{x})$$

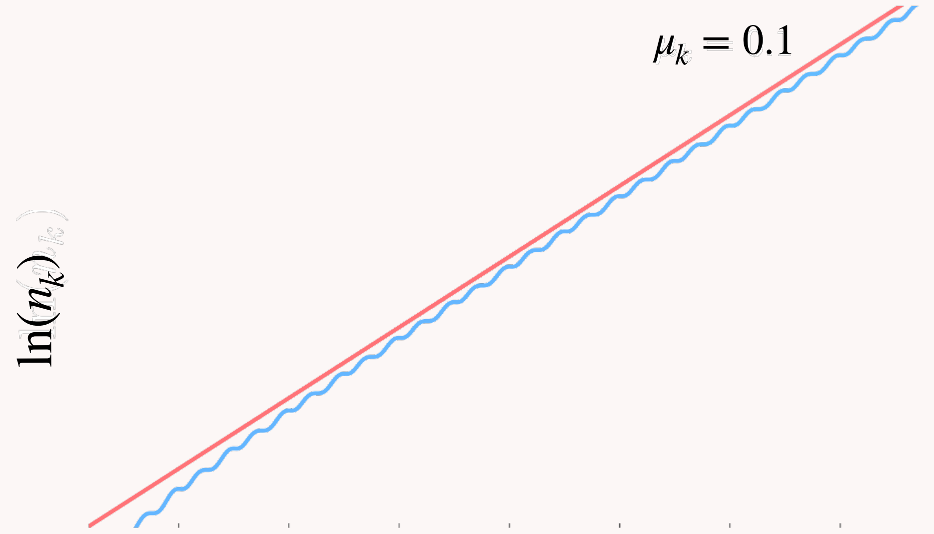
$$\Theta_k'' + \Bigg(\underbrace{\frac{k^2}{a^2} + \frac{\partial^2 V(\vartheta, \varphi)}{\partial \vartheta^2}}_{\omega_k^2(t)} \Bigg) \Theta_k = 0$$

$$\Big\downarrow$$

$$\vartheta_k(t, \overrightarrow{x}) \propto e^{\mu_k t}$$



$$n_k(t, \overrightarrow{x}) \propto e^{2\mu_k t}$$



Particle production

$$n_k = \frac{\omega_k}{2} \left(\frac{|\dot{\Theta}_k|^2}{\omega_k} + |\Theta_k|^2 \right) - \frac{1}{2}$$

$$\rho_\vartheta = \frac{1}{(2\pi a)^4} \int d^3k n_k \omega(t, k) \qquad n_\vartheta = \frac{1}{(2\pi a)^3} \int d^3k n_k$$

Axion - saxion

- $\mathcal{N} = 1$ type IIB compactification on CY_3
- At least 1 Kähler modulus τ + axion θ

  → complexified field $T = \tau + i\theta$

saxion

axion

kinetic mixing
$\beta \propto \tau^{-1}$

$$\left\{ \begin{aligned} \mathcal{L}_{kin} &\supset K_{i\bar{j}}\, \partial\tau^i \partial\tau^{\bar{j}} + K_{i\bar{j}}\, \partial\theta^i \partial\theta^{\bar{j}} \\ V &= V_{inf} + V_{axion} \\ V_{axion} &= \Lambda^4 e^{-a_\tau \tau} \cos(a_\tau \theta) \end{aligned} \right.$$

String Inflation

saxion ↔ inflaton

$\tau \propto e^{\phi}$,
$\vartheta \propto \theta a_\tau f$

$\Rightarrow$ Very simple, but generic!

LVS, Fibre inflation, Kähler inflation, …

2023: Cicoli, Conlon, Maharana, Parameswaran, Quevedo, Zavala

String Axion Preheating

$$\ddot{\Theta}_k + \beta\frac{\dot{\tau}}{\tau}\dot{\Theta}_k + \omega(k,t)^2\,\Theta_k = 0$$

$$\omega(k,t)^2 = \frac{k^2}{a^2} - \beta\frac{\dot{\tau}}{2\tau}H + \frac{\Lambda^4}{f^2}e^{-a_\tau\tau} \qquad \tau \simeq \langle\tau\rangle + \Delta\tau\cos(m_\tau t)$$

No expansion: Whittaker Hill equation

$$\vartheta_k'' - 2\beta\frac{\Delta\tau}{\langle\tau\rangle}\vartheta_k'\sin(m_\tau t) + \left(4\frac{k^2}{m_\tau^2} + \underbrace{4\frac{\Lambda^4}{m_\tau^2 f^2}e^{-a_\tau\langle\tau\rangle}}e^{-a_\tau\Delta\tau\cos(2s)}\right)\vartheta_k = 0 \qquad ' = \frac{d}{ds} = \frac{2}{m}\frac{d}{dt}$$

resonance parameter q $= 4a_\tau\frac{m_\vartheta^2}{m_\tau^2}$

Non-perturbative production of axions

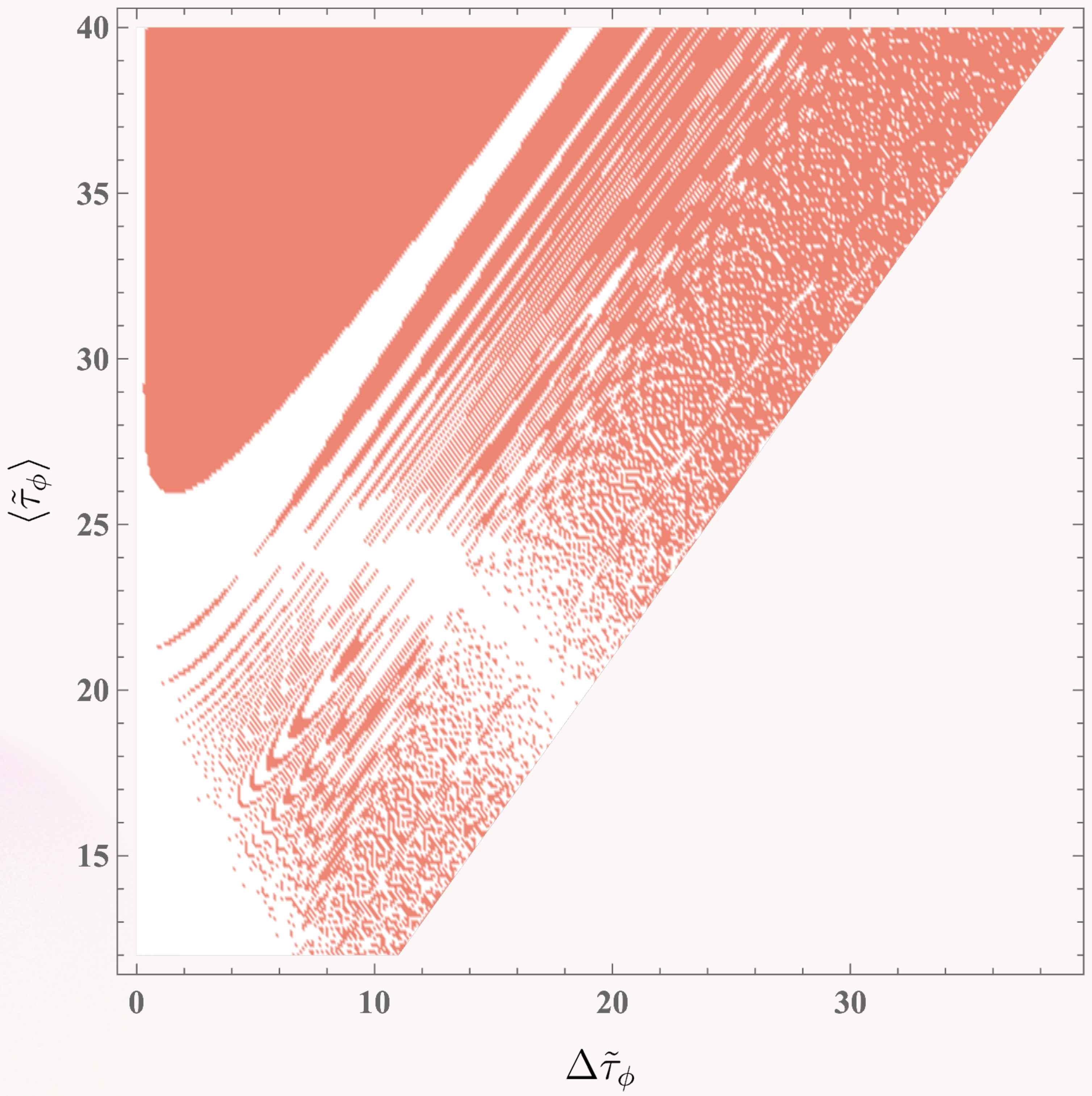
- ✦ Dark radiation: $m_\vartheta \leq 10^{-31}M_{pl} \rightarrow$ contribute to ΔN_{eff} $\longrightarrow$ $q \lesssim 10^{-43}$ Very narrow resonance
- ✦ Dark matter: $\Omega_\vartheta^0 = \frac{m_\vartheta n_\vartheta(a_0)}{\rho_c^0}$ $q \gtrsim 1$ Broad resonance

Stability charts

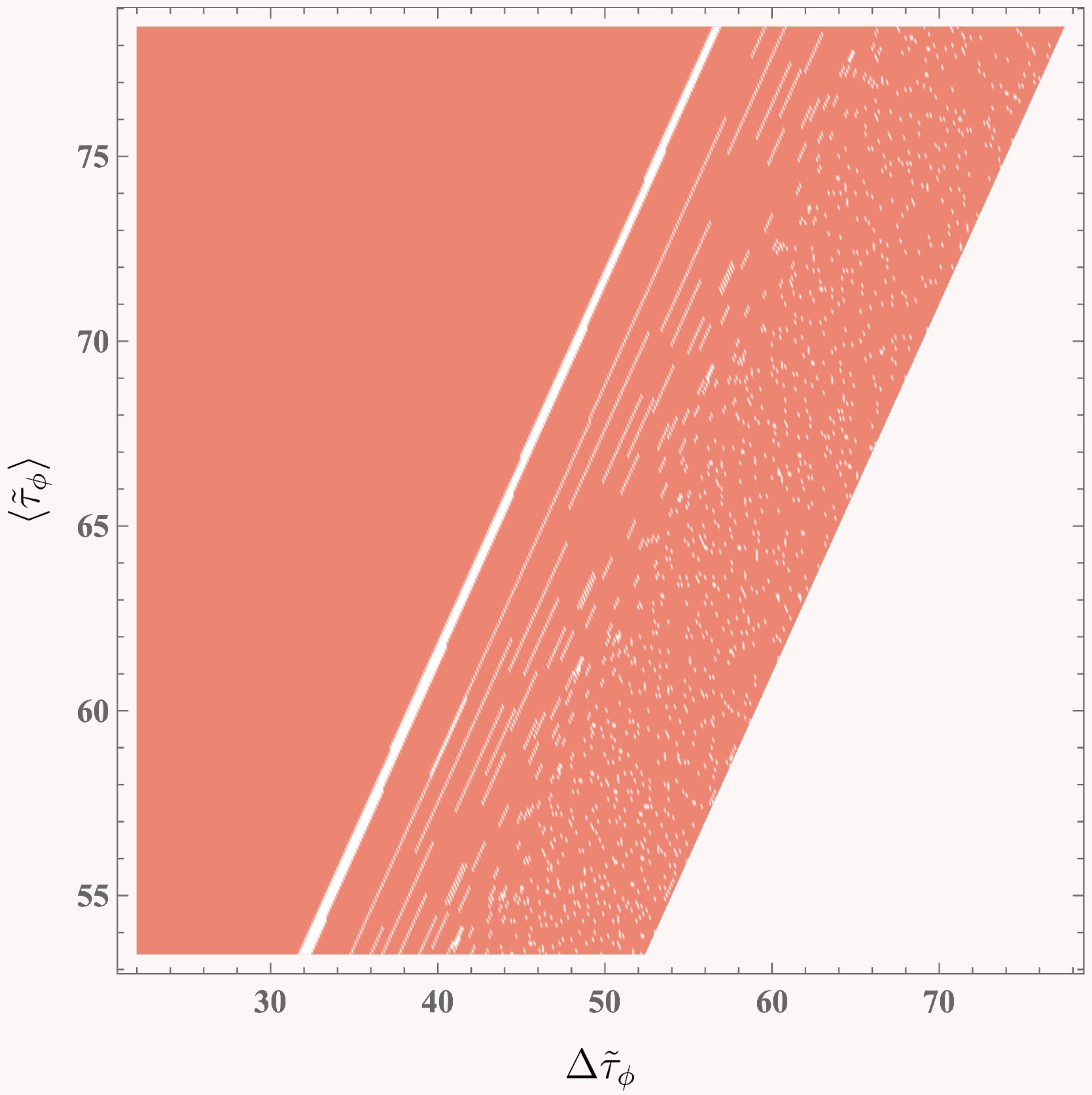
$$q = 4\frac{m_\vartheta^2}{m_\tau^2}a_\tau$$

- ✦ Dark radiation: $m_\vartheta \leq 10^{-31}M_{pl} \rightarrow$ contribute to ΔN_{eff}
- ✦ Dark matter: $\Omega_\vartheta^0 = \dfrac{m_\vartheta n_\vartheta(a_0)}{\rho_c^0}$

$10^{-38}M_P \leq m_\vartheta \leq 10^{-31}M_P$



$10^{-11}M_P \leq m_\vartheta \leq 10^{-5}M_P$

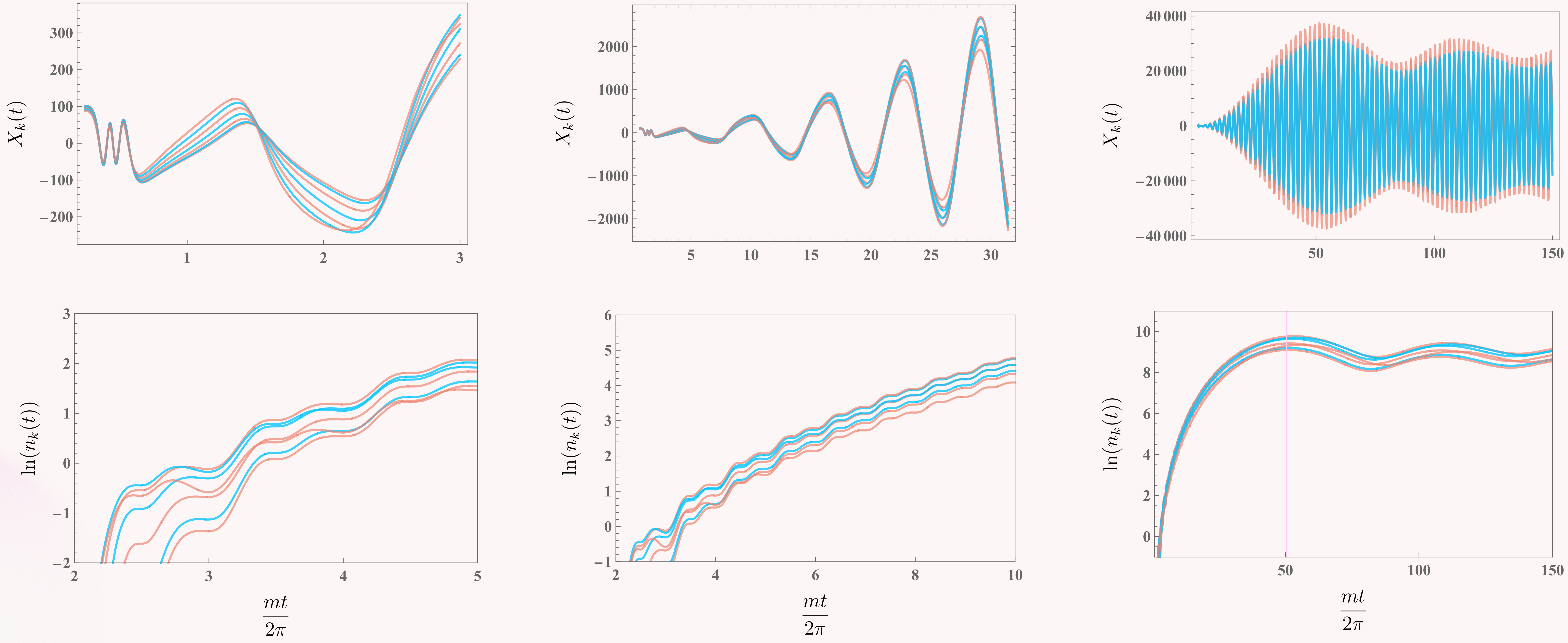


String Preheating - II

$$\ddot{\Theta}_k + \beta\frac{\dot{\tau}}{\tau}\dot{\Theta}_k + \omega(k,t)^2\,\Theta_k = 0$$

$$\omega(k,t)^2 = \frac{k^2}{a^2} - \beta\frac{\dot{\tau}}{2\tau}H + \frac{\Lambda^4}{f^2}e^{-a_\tau \tau} \qquad \tau \simeq \langle\tau\rangle + \Delta\tau\cos(m_\tau t)$$

Expanding background



Cosmological consequences

Fate of the produced axion depends on details of the compactification.

SM on D7-branes

- Inflation on 4-cycle Π_4
- SM lives on D7-branes wrapped around Π_4
- SM talks to inflaton and hidden sector
- $m_\theta \to 0 \Rightarrow q \to 0$: PR only via kinetic mixing.

  $\Delta N_{eff} \lesssim 10^{-6}$
- If axion is heavy ⇒ decay into SM ⇒reheating

Sequestered SM

- SM lives on D3-branes at signularities.
- $m_\theta \to 0 \Rightarrow q \to 0$: PR only via kinetic mixing.

  $\Delta N_{eff} \lesssim 10^{-6}$
- If axion is heavy ⇒ decay into:

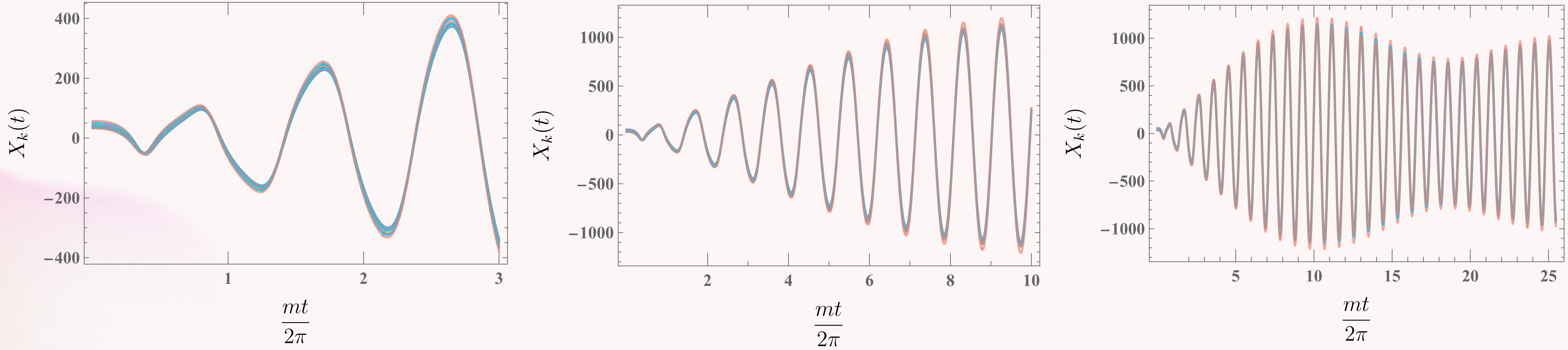
  1. Massless gauge bosons
  2. Gravitons
  3. SM
  4. Light axions
  5. Condensing gauge group

Application: Fibre inflation

2008: Cicoli, Burgess, Quevedo

$$V_{inf} = W_0^2\left(g_s^2\frac{A}{\tau_f^2} - \frac{B}{\mathscr{V}\sqrt{\tau_f}} + g_s^2\frac{C\tau_f}{\mathscr{V}^2}\right)\frac{W_0^2}{\mathscr{V}^2} \qquad \varphi = \frac{\sqrt{3}}{2}\ln\tau_f \qquad V_{ax} \supset g_s^2\frac{a_f|A_fW_0|}{\mathscr{V}^2}\tau_f e^{-a_f\tau_f}\cos(a_f\theta_f)$$

$$\begin{cases} \varphi'' + 3\frac{2}{m_\varphi}H\varphi' + \frac{4}{m_\varphi^2}\left(\frac{\partial V_{inf}}{\partial\varphi}\right) = 0 \\ \Theta_k'' + 2\varphi'\Theta_k' + \left(\frac{4}{m_\chi^2}k^2 - \frac{\varphi'}{a^{3/2}} + 64\frac{|A_fW_0|}{m_\varphi^2\mathscr{V}^2}\langle\tilde{\tau}_f\rangle^2(\langle\tilde{\tau}_f\rangle e^{\frac{2}{\sqrt{3}}\varphi})e^{-\langle\tilde{\tau}_f\rangle e^{\frac{2}{\sqrt{3}}\varphi}}\right)\Theta_k = 0 \end{cases}$$



Application: Fibre inflation

SM on D3-branes

✦ SM lives on D3-branes at signularities.

✦ SM sequestered from inflation

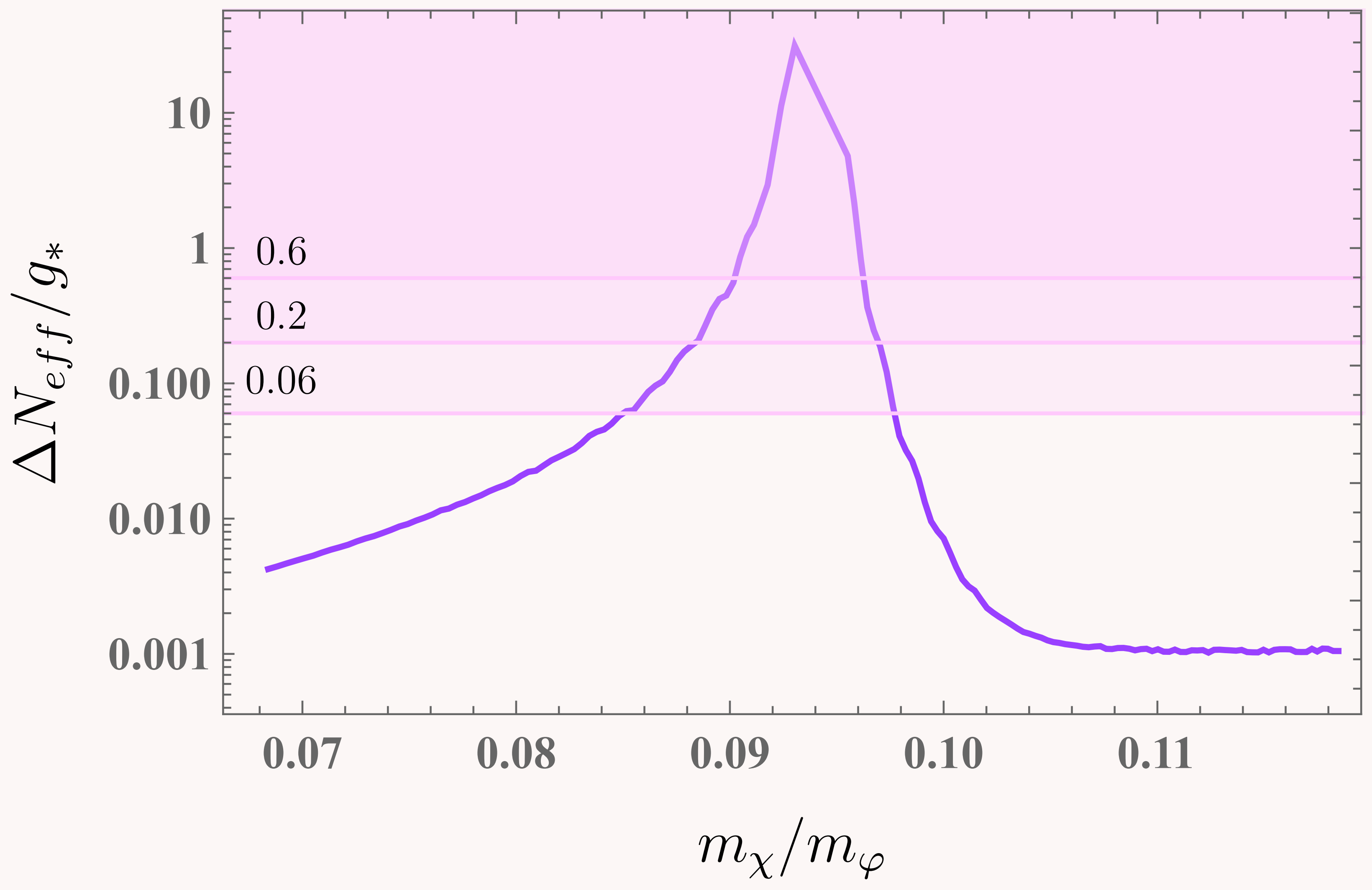
✦If axion is heavy ($m_{\chi_f} \simeq 8 \times 10^{-5} M_{Pl}$), decays:

1. **Massless gauge bosons**
2. Gravitons
3. SM
4. Light axions
5. Condensing gauge group

$$\mathscr{L} \supset - g_{a\tilde{\gamma}\tilde{\gamma}} \frac{\chi_f}{f_f} F\tilde{F}$$

$$\Gamma_{\chi \to \tilde{\gamma}\tilde{\gamma}} \simeq \frac{1}{64\pi} \frac{m_\chi^3}{f_{\chi_f}^2} \qquad T_{dec} \sim \Gamma^{1/2} M_{Pl}^{1/2}$$

$$\Delta N_{eff} = \frac{8}{7} \left(\frac{T}{T_\nu} \right)^4 \frac{\rho_{\tilde{\gamma}}}{\rho_\gamma} = \frac{120}{7\pi^2} \left(\frac{11}{4} \right)^{4/3} \frac{\rho_{\tilde{\gamma}}^{dec}}{T_{reh}^4} \left(\frac{a_{dec}}{a_{reh}} \right)^4$$



Conclusions

- String theory axiverse of p-forms can be used to probe string theory
- Most of these axions are dark → probe them through gravity
- Axions as spectators during inflation produce various signals:

- Axion-gauge field spectator sectors

  → GW forest

- Axions spectators of string inflation

  get produced via parametric resonance

  → decay to dark sector ΔN_{eff}

More?

Thank you!

Back-up: Fibre inflation

2008: Cicoli, Burgess, Quevedo

$$T_f = \tau_f + i\theta_f\,,\quad T_b = \tau_b + i\theta_b\,,\quad T_s = \tau_s + i\theta_s$$

$$\mathcal{V} = \sqrt{\tau_f}\tau_b - \tau_s^{3/2} \simeq \sqrt{\tau_f}\tau_b$$

$$K = 2\ln\left(\mathcal{V} + \frac{\xi}{g_s^{3/2}}\right)$$

$$W = W_0 + A_f\, e^{-a_f T_f} + A_b\, e^{-a_b T_b} + A_s\, e^{-a_s T_s}$$

$$\longrightarrow$$

$$V_{ax} \supset g_s^2 \frac{a_f |A_f W_0|}{\mathcal{V}^2} \tau_f e^{-a_f \tau_f} \cos(a_f \theta_f)$$

$$g_{ij} = 2\frac{\partial^2 K}{\partial T^i \partial T^j} \qquad f_{\chi_f} = \frac{1}{\sqrt{2} a_f \tau_f}\,, \quad f_{\chi_b} = \frac{1}{a_b \tau_b}$$

$$m^2_{\chi f,b} = g_s^2 a_{f,b} \frac{|A_f W_0|}{\mathcal{V}^2 f^2_{f,b}} \langle \tau_{f,b} \rangle e^{-a_{f,b}\langle \tau_{f,b}\rangle}$$

$$\downarrow$$

String loops corrections give:

$$V_{inf} = W_0^2 \left(g_s^2 \frac{A}{\tau_f^2} - \frac{B}{\mathcal{V}\sqrt{\tau_f}} + g_s^2 \frac{C\tau_f}{\mathcal{V}^2} \right) \frac{W_0^2}{\mathcal{V}^2}$$

$$\varphi = \frac{\sqrt{3}}{2} \ln \tau_f \qquad m_\varphi \simeq \sqrt{\frac{W_0^2}{\mathcal{V}^{10/3}}} \simeq 10^{-4} M_{Pl}$$

Ex. set:

$$\langle \tau_f \rangle \simeq 7.5,\ a_f = \frac{2\pi}{4},\ f_{\chi_f} \simeq 0.06 M_{Pl} \quad \rightarrow \ m_{\chi_f} \simeq 8 \times 10^{-5} M_{Pl}$$

$$\mathcal{V} \simeq 935.5\,,\ \langle \tau_b \rangle = \frac{\mathcal{V}}{\sqrt{\langle \tau_f \rangle}} \simeq 341.2 \quad \rightarrow \quad m_{\chi_b} \simeq 0$$