CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

# GRAVITATIONAL AXIVERSE SPECTROSCOPY

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WISPs in String Cosmology,
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Work with
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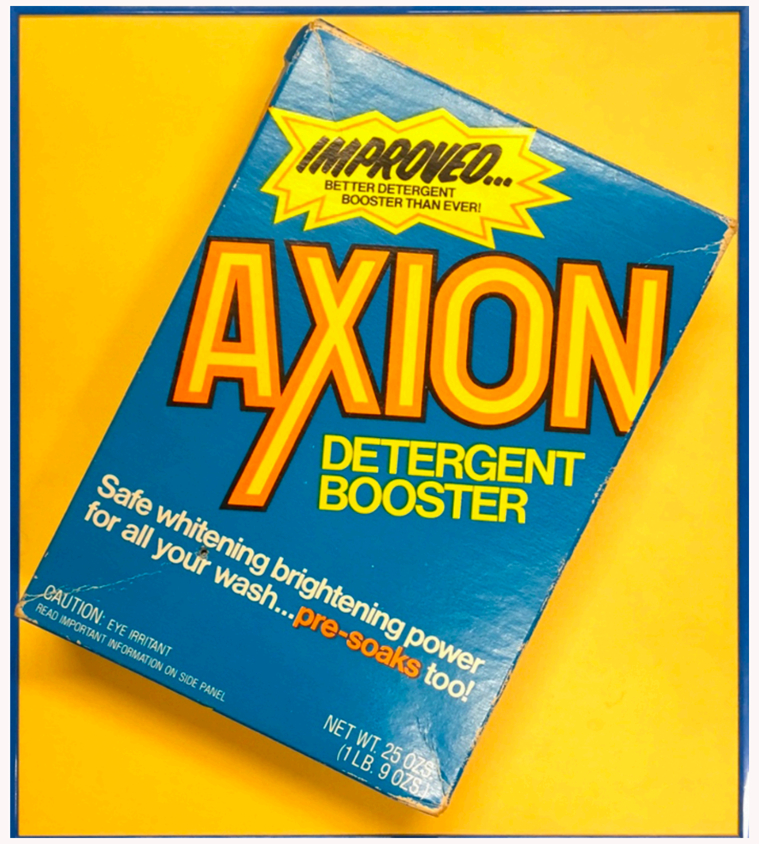
arXiv:2312.13431

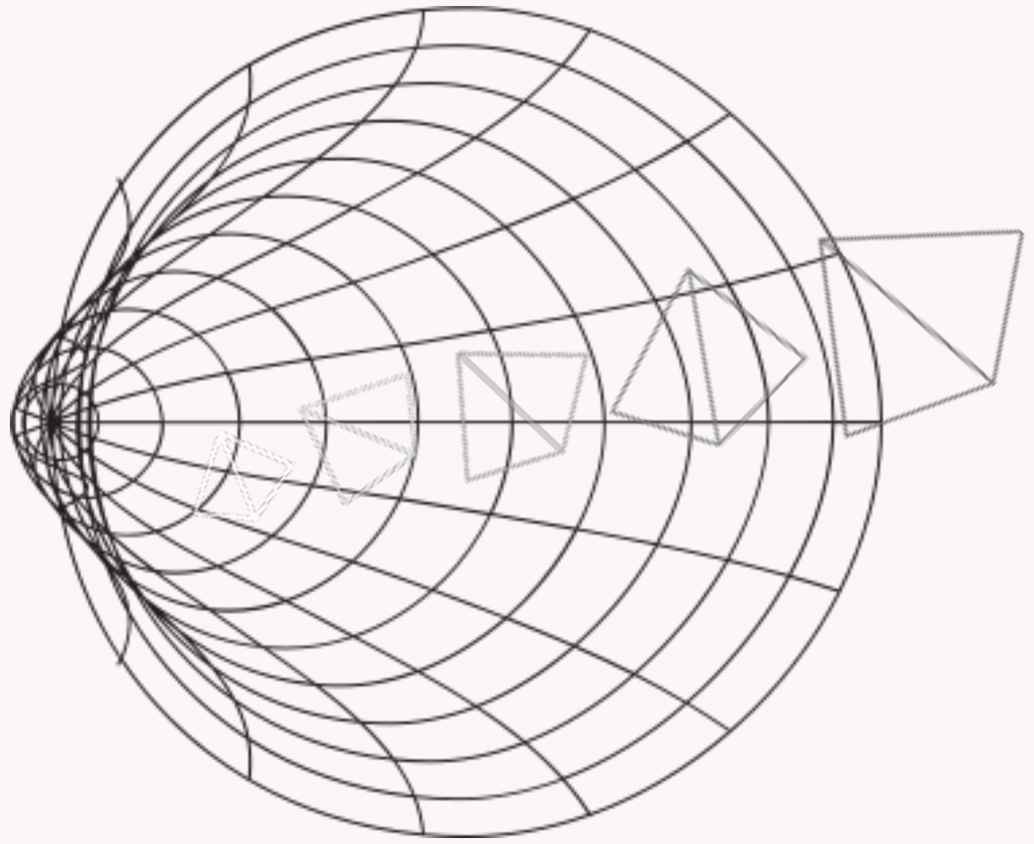
# Ingredients

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
…

AXIONS



INFLATION

- ✦ String axiverse does not need to couple to SM
- ✦ Can be coupled to hidden gauge fields

- ✦ Spectator axions coupled to gauge fields during inflation produce $\zeta$ and GW

GWs from the AXIVERSE

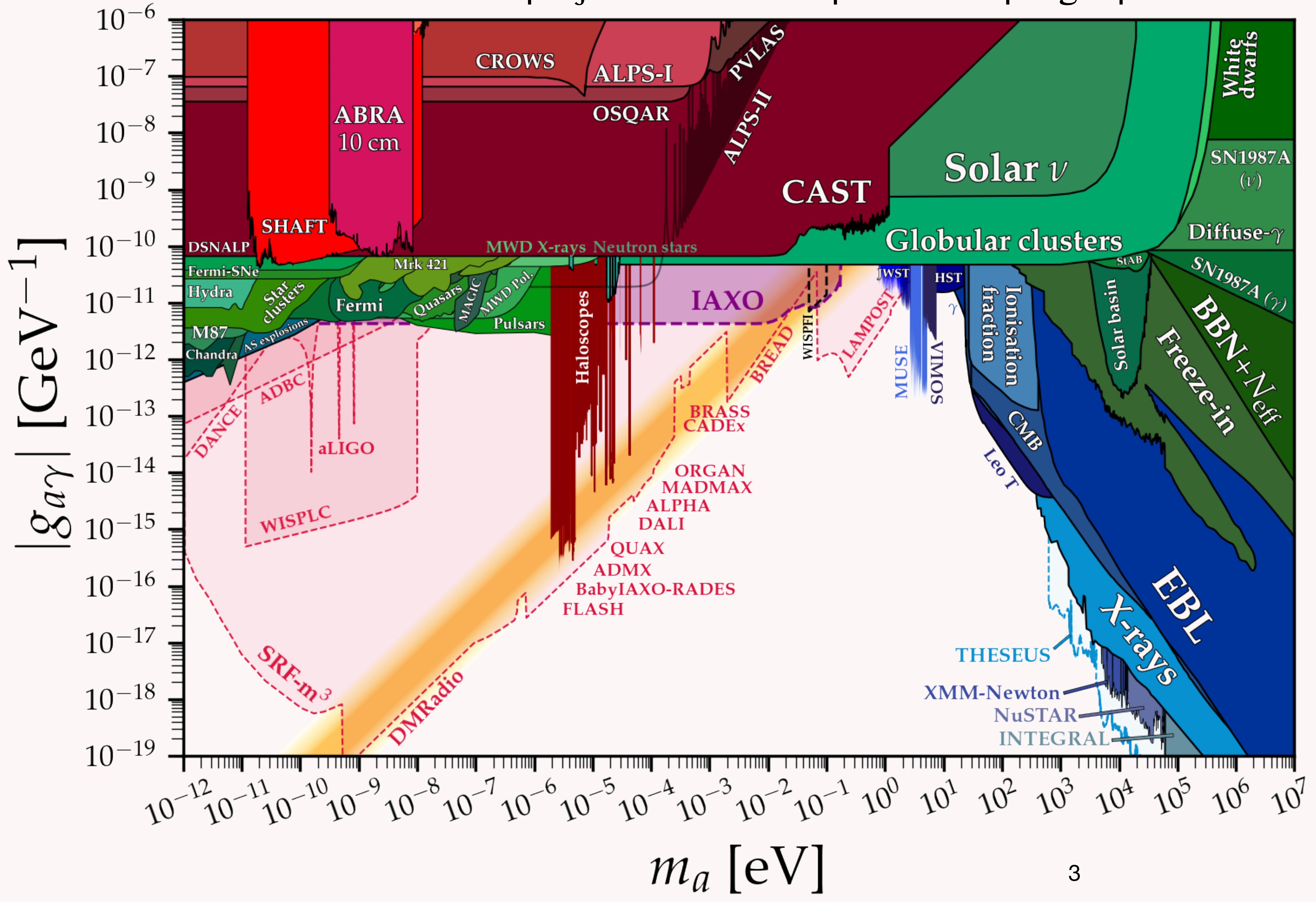
# Detecting the Axiverse

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

# 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?

Can we detect the part of the axiverse that does not talk to the SM?

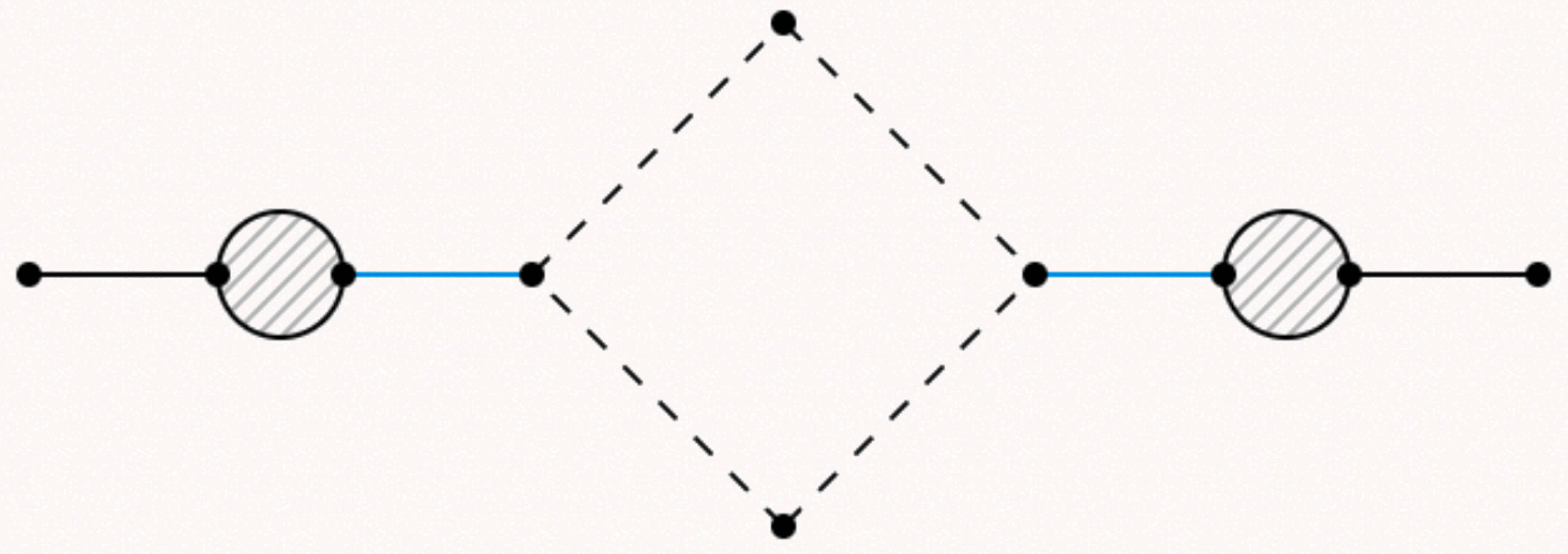
# Spectator Mechanism

[Peloso et al.]
[Dimastrogiovanni et al.]

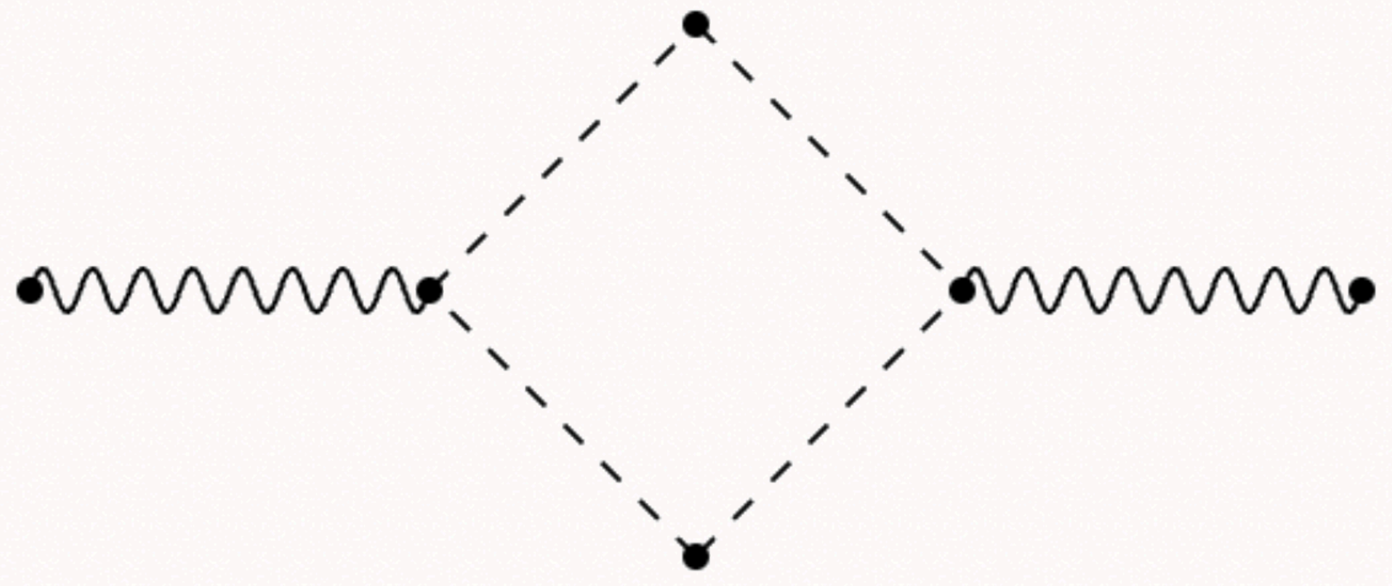
$$\mathscr{L} = \underbrace{-\frac{1}{2}(\partial\varphi)^2 - V(\varphi)}_{\mathscr{L}_{inf}} \underbrace{-\frac{1}{2}(\partial\chi)^2 - V(\chi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \lambda\frac{\chi}{4f}F_{\mu\nu}\tilde{F}^{\mu\nu}}_{\mathscr{L}_{spectator}}$$

$\dot{\chi} \neq 0 \longrightarrow \delta A$ $\qquad$ $\delta A + \delta A \to \delta\varphi$ (via $\delta\chi$), $\delta h_{\pm}$

$$P_\zeta(k)\delta^{(3)}(\bar{k}+\bar{k}') \equiv \frac{k^3}{2\pi^2}\langle\delta\varphi(\bar{k})\delta\varphi(\bar{k}')\rangle \qquad P_{h_\lambda}(k)\delta^{(3)}(\bar{k}+\bar{k}') \equiv \frac{k^3}{2\pi^2}\langle h_\lambda(\bar{k})h_\lambda(\bar{k}')\rangle$$



Sourced curvature power spectrum



Sourced tensor power spectrum

# Spectator Mechanism

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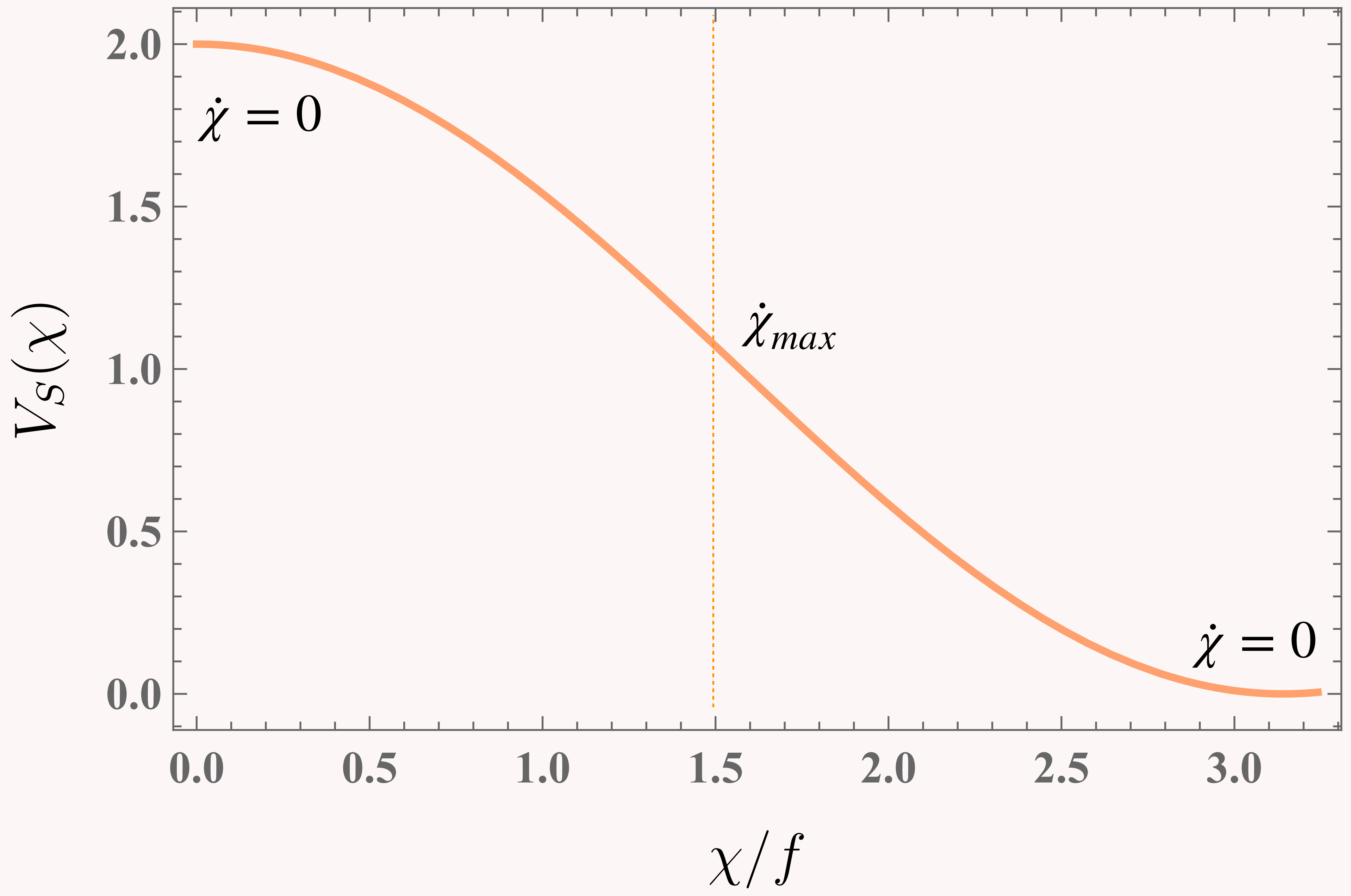
$$\dot{\chi} \neq 0 \longrightarrow P_{\zeta,GW} = P^{(vac)}_{\zeta,GW} + P^{(src)}_{\zeta,GW}$$

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




Enhancement of primordial perturbations.

Signal present a peak.

# Spectator Mechanism

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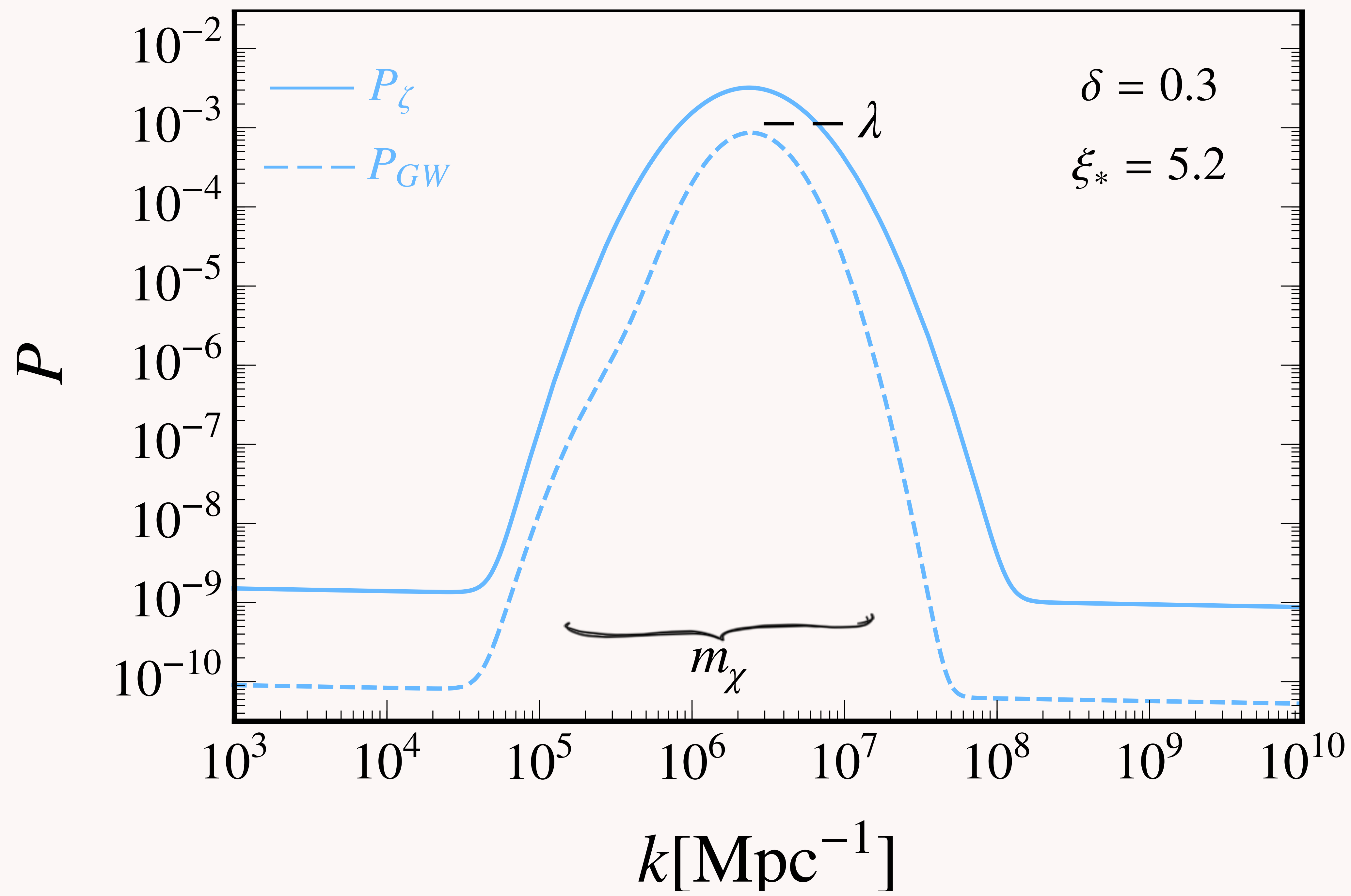


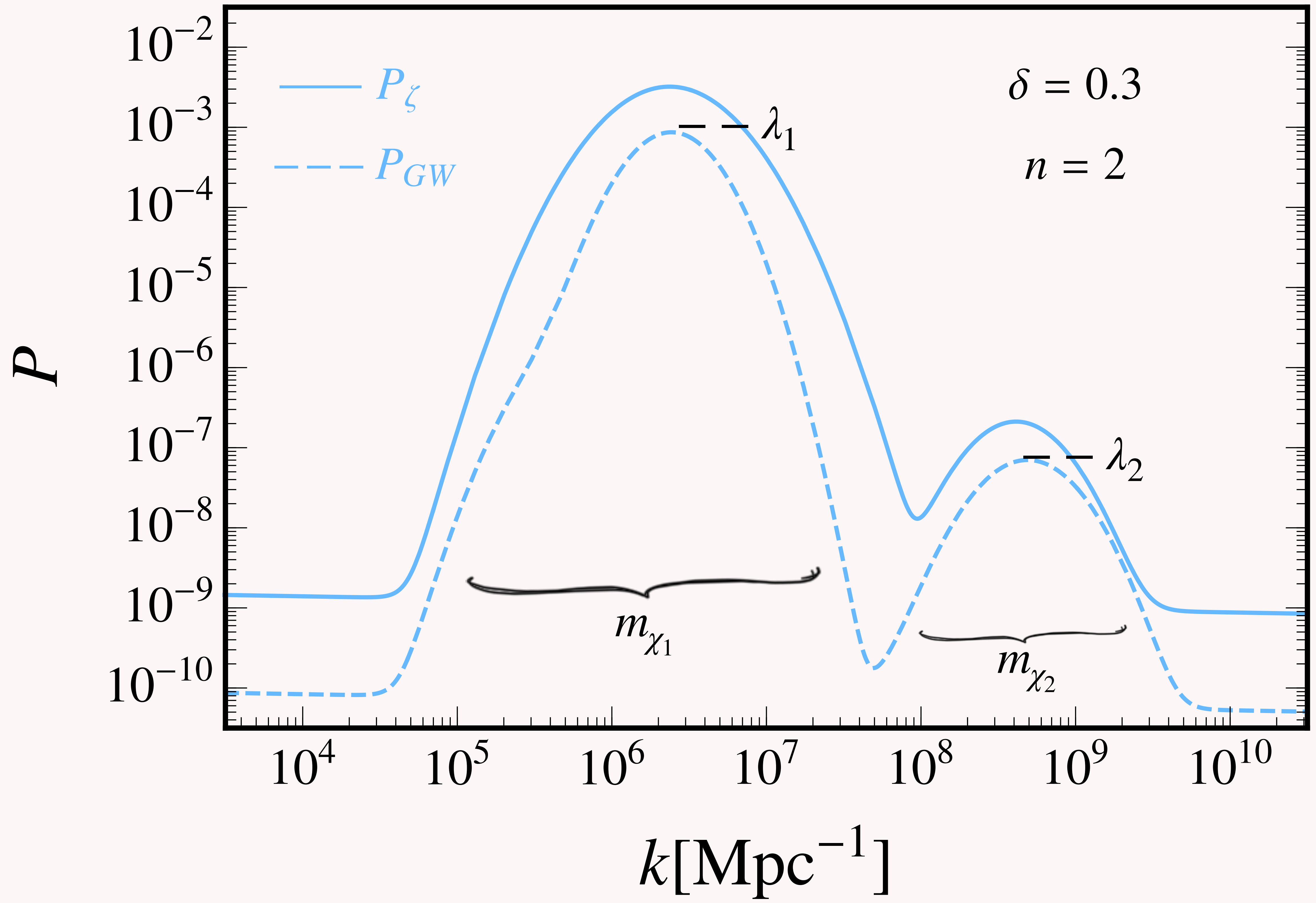

Enhancement of primordial perturbations.

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:

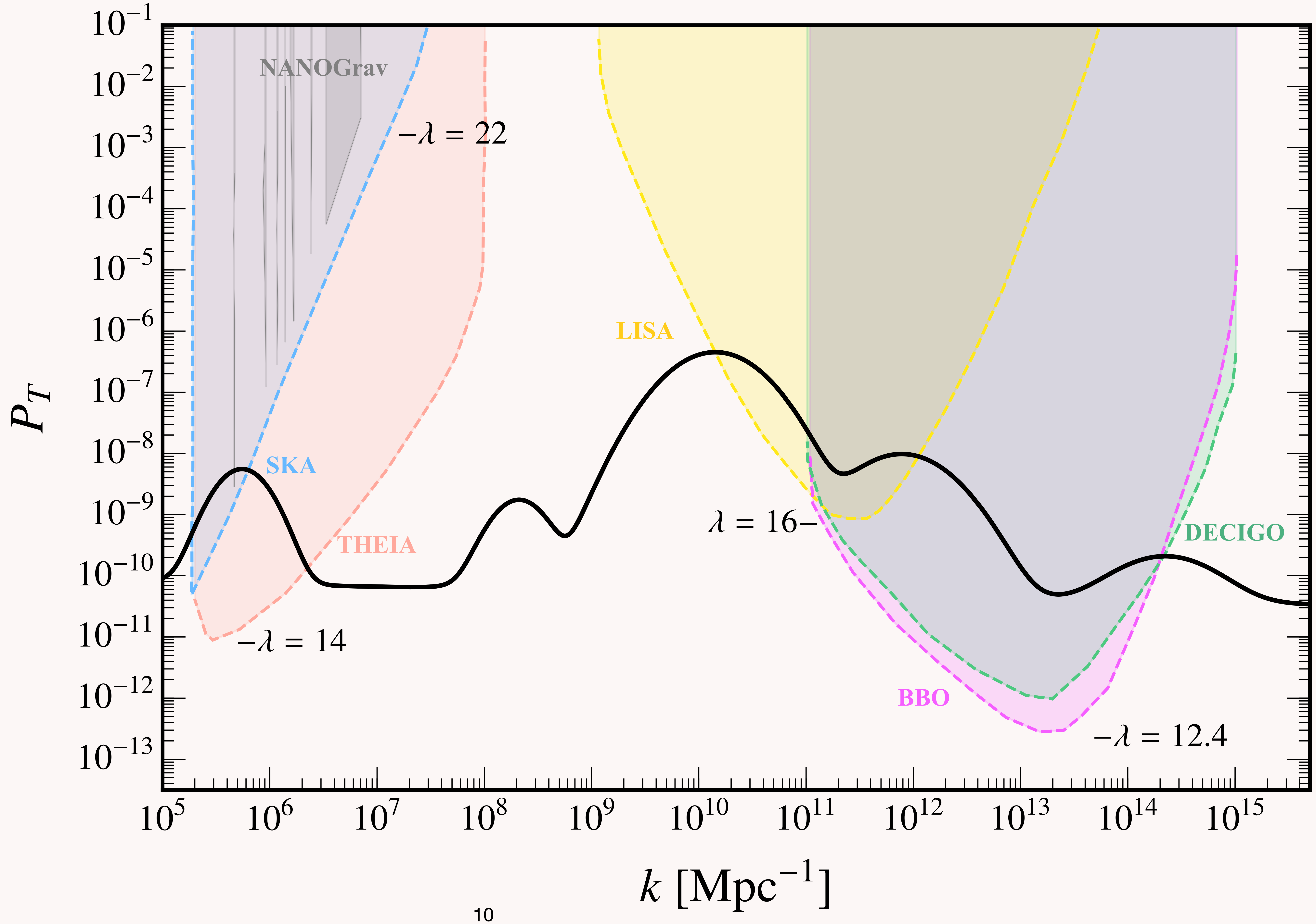
$\lambda$ CS coupling: height $\quad \xi_* = \lambda \frac{\delta}{2}$

$m_\chi$ Axion mass: width $\quad \delta = \frac{m_\chi^2}{6H^2}$

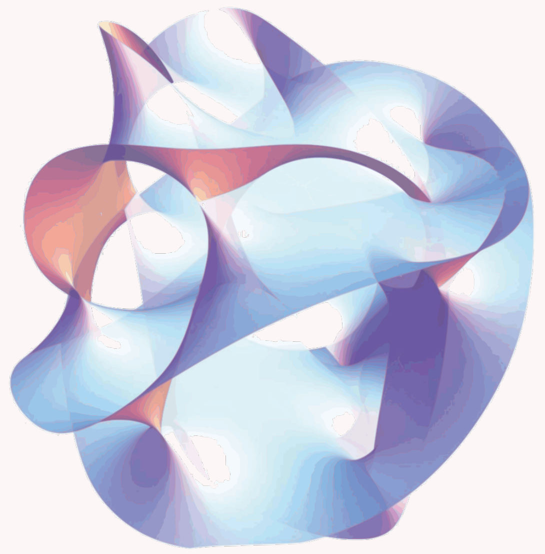
$\chi_{in}$ Initial condition: position

# 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?

# Axion candidates

Type IIB on 6d Orientifold

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

$X_3$ CY 3-fold
$\tilde{X}_3 = X_3/\Omega$

- $H^{(1,1)} = H^{(1,1)}_{-} \oplus H^{(1,1)}_{+}$  $\omega_a$  $a = 1,\ldots,h^{(1,1)}_{-}$  $\omega_\alpha$  $\alpha = 1,\ldots,h^{(1,1)}_{+}$

p-form axions  $C_4,\ C_2,\ B_2,\ C_0 \ \to\ \rho_\alpha,\ c^a,\ b^a,\ C_0$

- 4d $\mathcal{N} = 1$ theory

$$S = C_0 + ie^{-\phi}$$

$$G^a = c^a - Sb^a$$

$$T_\alpha = \tau_\alpha - i(\rho_\alpha - \kappa_{\alpha bc}c^b b^c) + \frac{i}{2}S\kappa_{\alpha bc}b^b b^c$$

$c^a$ 2-form odd axion

$\rho_\alpha$ 4-form even axion

Axion candidates

# Axion parameters

✦ Axion decay constants: kinetic terms

✦ Axion masses: ED3, ED1, ED1s dissolved in an ED3 or Gaugino condensation

ED3 brane wrapping 4-cycle of $\tilde{X}_3$

$$W_{ED3} \sim Ae^{-2\pi T}$$

$$\rightarrow \delta V_{ED3} \simeq e^{-2\pi\tau} \cos(2\pi\rho)$$

$$= e^{-2\pi\tau} \cos \frac{\chi_e}{f_e}$$

ED1 brane wrapping 2-cycle of $\tilde{X}_3$

$$K_{ED1} \sim -3\ln(T + \overline{T} + \dots)$$

$$\rightarrow \delta V_{ED1} \simeq e^{-2\pi v - 2\pi i c}$$

$$= e^{-2\pi v} \cos \frac{\chi_e}{f_e}$$

# Gauge theory

D7-brane wrapping divisor $\tilde{\mathcal{D}}$ of $\tilde{X}_3$ → Worlvolume theory: $\mathcal{N} = 1$ gauge theory

Automatically coupled to $\rho_\alpha$

$$\mathcal{L}_{gauge} \supset -\frac{1}{4}Re[f_{\tilde{D}}]F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}Im[f_{\tilde{D}}]F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$f_{\tilde{D}} = \frac{w^\alpha}{2\pi}(\tau_\alpha + i\rho_\alpha + \dots) \qquad w^\alpha = \int_{D^+} \tilde{\omega}^\alpha$$

$g^{-2} = \langle Re[f_{\tilde{D}}] \rangle$ → $A_\mu \to g\, A_\mu$ canonical normalization: $\lambda_\rho \sim \frac{1}{\langle \tau \rangle}$

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Introduce odd flux: $\frac{1}{2\pi}F_2 = m^a\omega_a$ → coupling with $c^a$

$$f_{\tilde{D}} = \frac{w^\alpha}{2\pi}\left[(\tau_\alpha + \dots) + i(\rho_\alpha + \kappa_{abc}c^b m^c + ..)\right]$$

$$\lambda_c \propto w g^2 \kappa\, m$$

# Stückelberg

$$\mathscr{L}_{St} = \frac{1}{2}\left(\partial_\mu \chi - qA_\mu\right)^2 - \frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu}$$

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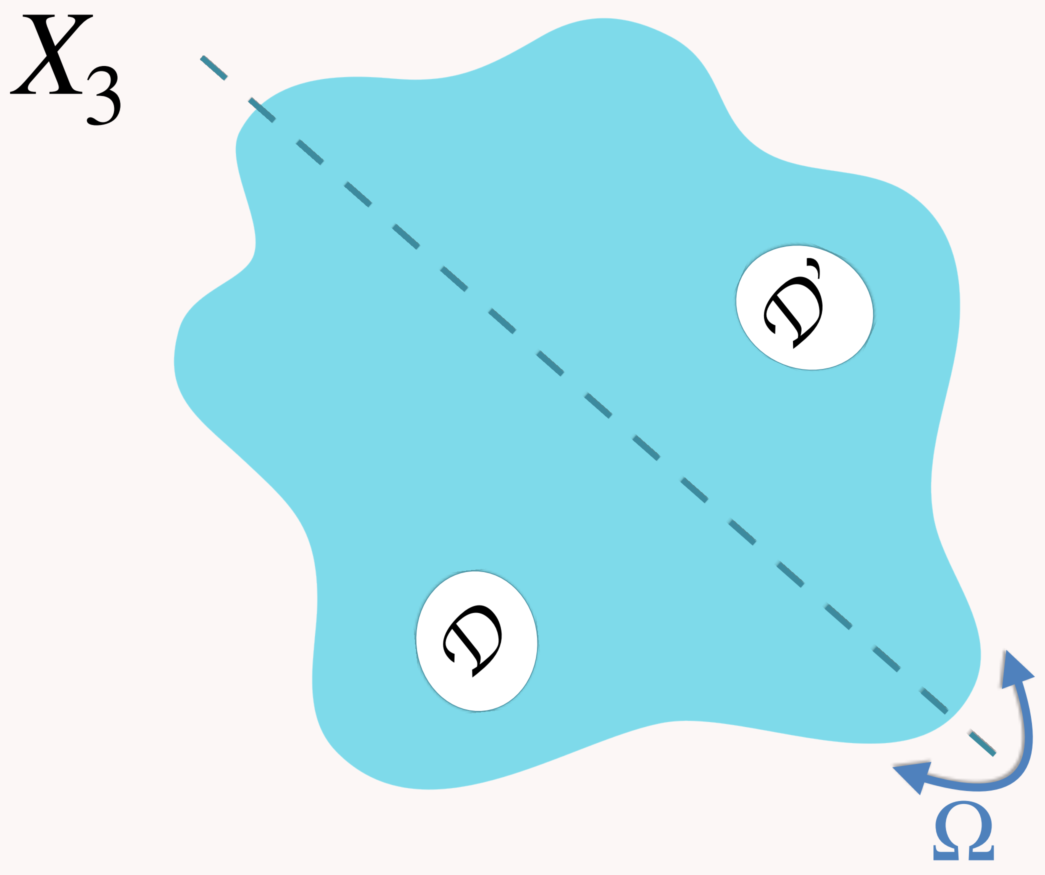


✦ $\mathcal{D}$ and $\mathcal{D}'$ divisors that map into each other under $\Omega$

✦ If D7 branes wrap both $\mathcal{D}$ and $\mathcal{D}'$ axion symmetries can be gauged

✦ Stückelberg terms, gauge field becomes massive

$\mathcal{D}^+ := \mathcal{D} \cup \mathcal{D}'$

$\mathcal{D}^- := \mathcal{D} \cup (-\mathcal{D}')$

$$w^a = \int_{\mathcal{D}^-} \tilde{\omega}^a$$

geometric $\quad dc^a \rightarrow \nabla c^a = dc^a - q^a A, \qquad q^a \sim w^a$

flux-induced $\quad d\rho_\alpha \rightarrow \nabla \rho_\alpha = d\rho_\alpha - iq_\alpha A, \qquad q_\alpha \sim \kappa_{\alpha bc} m^b w^c$

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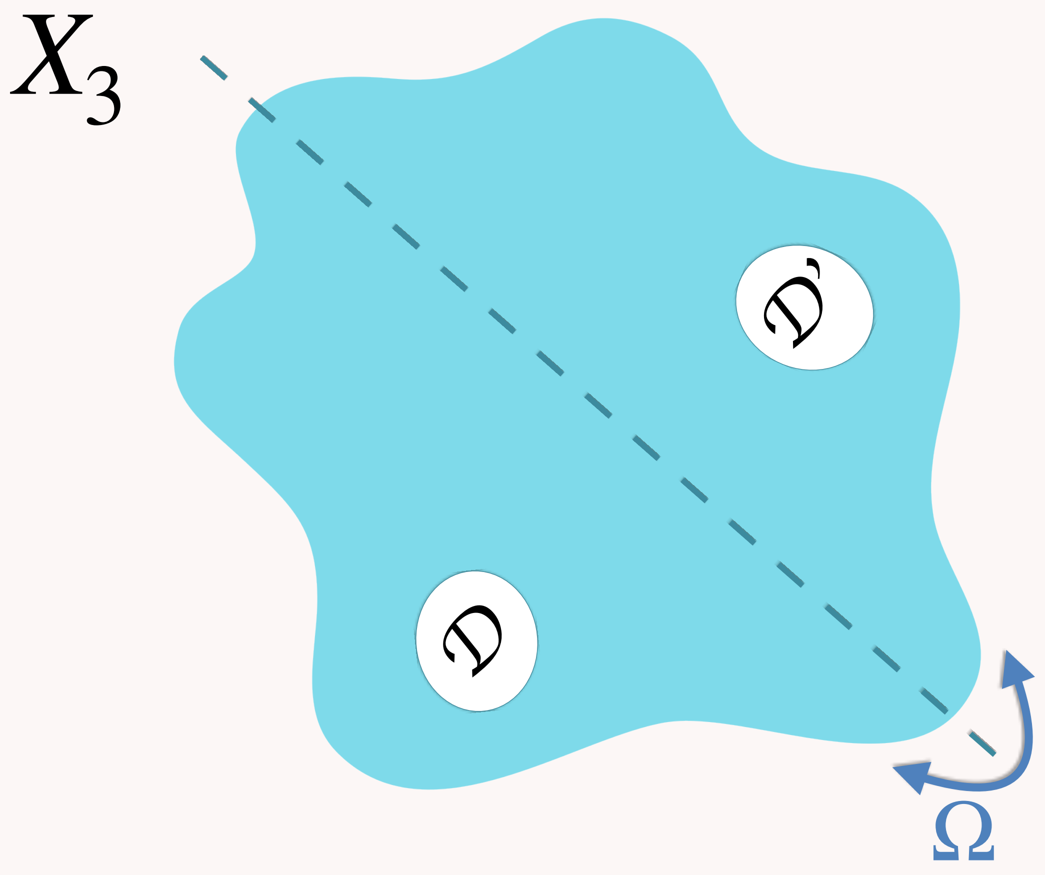


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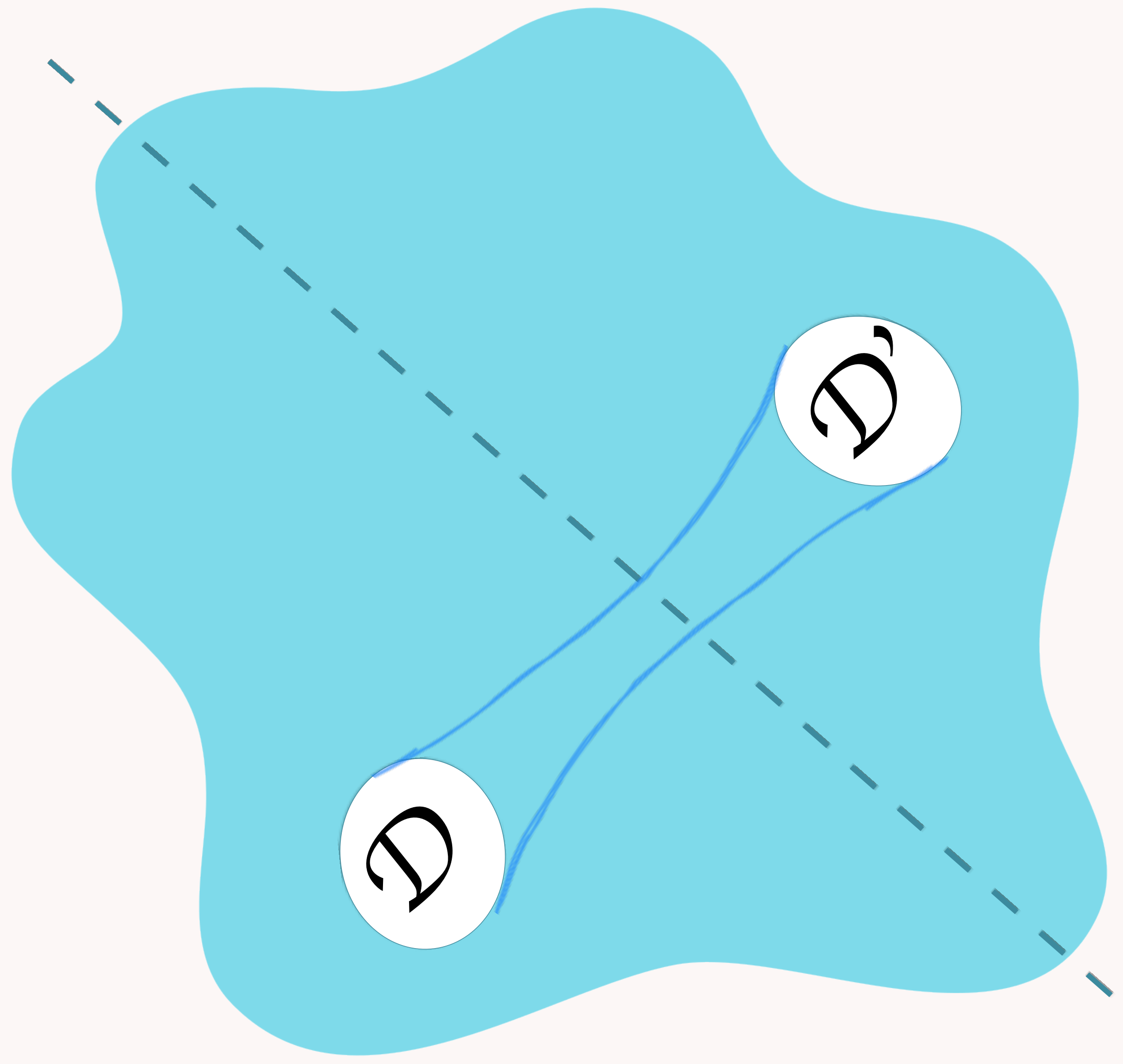
Problems
→ Lose candidate axions
→ Spectator mechanism doesn't work

# Avoiding Stückelberg

- Class I: $[\mathcal{D}]=[\mathcal{D}']$

  Same homology class

$U(1)$ from D7 brane wrapping $\tilde{D}$ of $\tilde{X}_3$




$w^a = 0$ → No Stückelberg: $\nabla c^a = dc^a$ and $\nabla \rho_\alpha = d\rho_\alpha$

Candidate axions: $c^a$ and $\rho_\alpha$

# Avoiding Stückelberg

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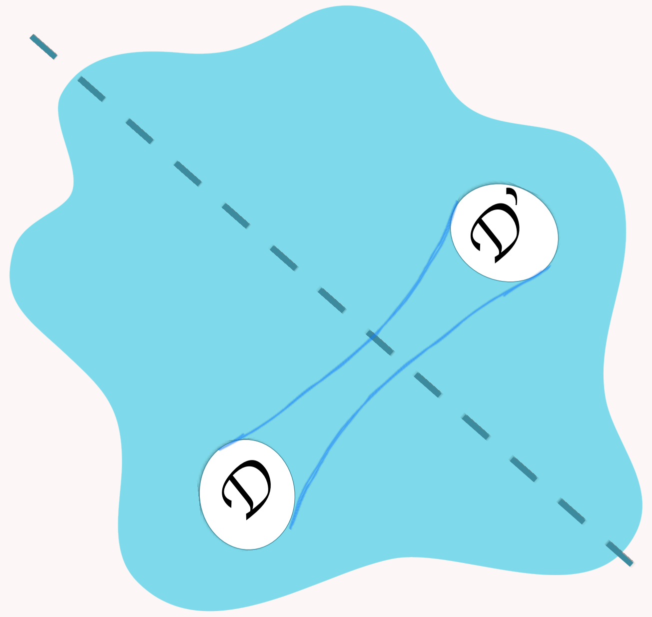
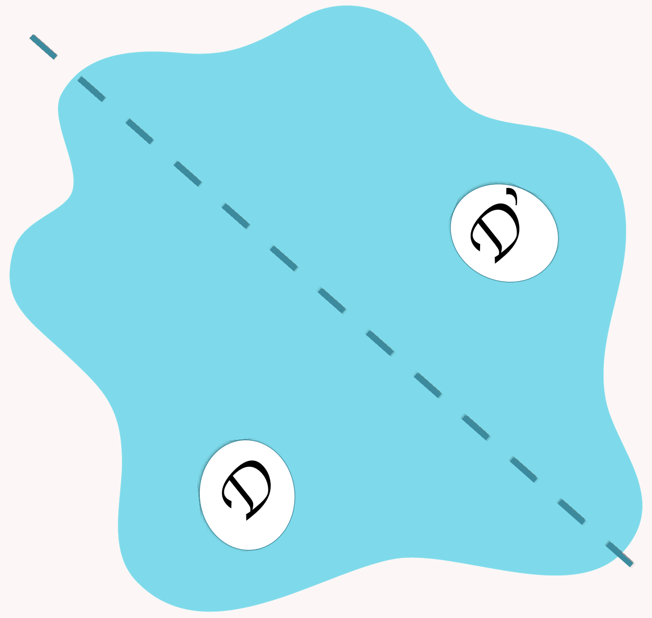



$w^a = 0$ → No Stückelberg ($q^a$ and $q_\alpha \propto w^a$)

Candidate axions: $c^a$ and $\rho_\alpha$

- Class II: $[\mathcal{D}]\neq[\mathcal{D}']$



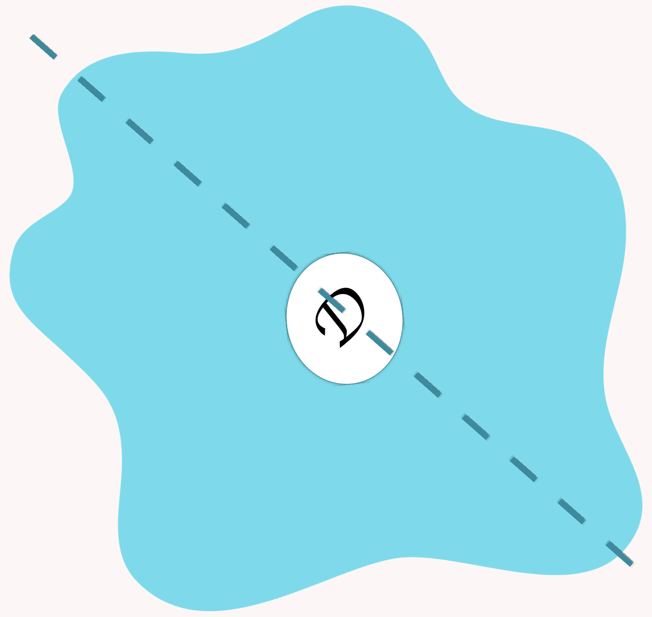

$$U(N) = SU(N) \times U(1)$$

$w^a \neq 0$ → Geometric Stückelberg: $A$ eats $c^a$

$m^a = 0$ → No flux Stückelberg

$\rho_\alpha$ axion, break $SU(N)$ to get $U(1)$

- Class III: $\mathcal{D} = \mathcal{D}'$ pointwise




$w^a = 0$ → No Stückelberg

$Sp(N)$ or $SO(N)$ gauge theory

break group to get $U(1)$

# CS coupling constraints

$$\mathscr{L}_{EFT} \supset -\frac{\lambda}{4f_\chi}\chi F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \lambda \sim \mathcal{O}(10)$$

1. Perturbative control $\frac{\alpha}{2\pi} \lesssim 1$, where $\alpha = \frac{1}{2w\langle\tau\rangle}$

2. Control of ED3: $2\pi\langle\tau\rangle \gtrsim \mathcal{O}(1)$

$$\lambda_\rho \sim \frac{1}{\langle\tau\rangle}$$

For 3. $\lambda_\rho \lesssim \mathcal{O}(1)$

Signal very low

Not observable

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2. Control of ED1: $2\pi v \gtrsim \mathcal{O}(1) \rightarrow \frac{\pi^2}{\kappa_{+++}w\alpha} \gtrsim 1$, where $\tau = \frac{1}{2}\kappa v^2$

$$\lambda_c \sim w^\alpha \kappa_{\alpha b d} m^b$$

Can be boosted by $w, \kappa, m$

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3. Induced D3 Tadpole

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Can be boosted by $w, \kappa, m$

Not for free!

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3. Induced D3 Tadpole

$$Q_{D3} \simeq w\kappa m^2 N_{D7}$$

F-theory picture:

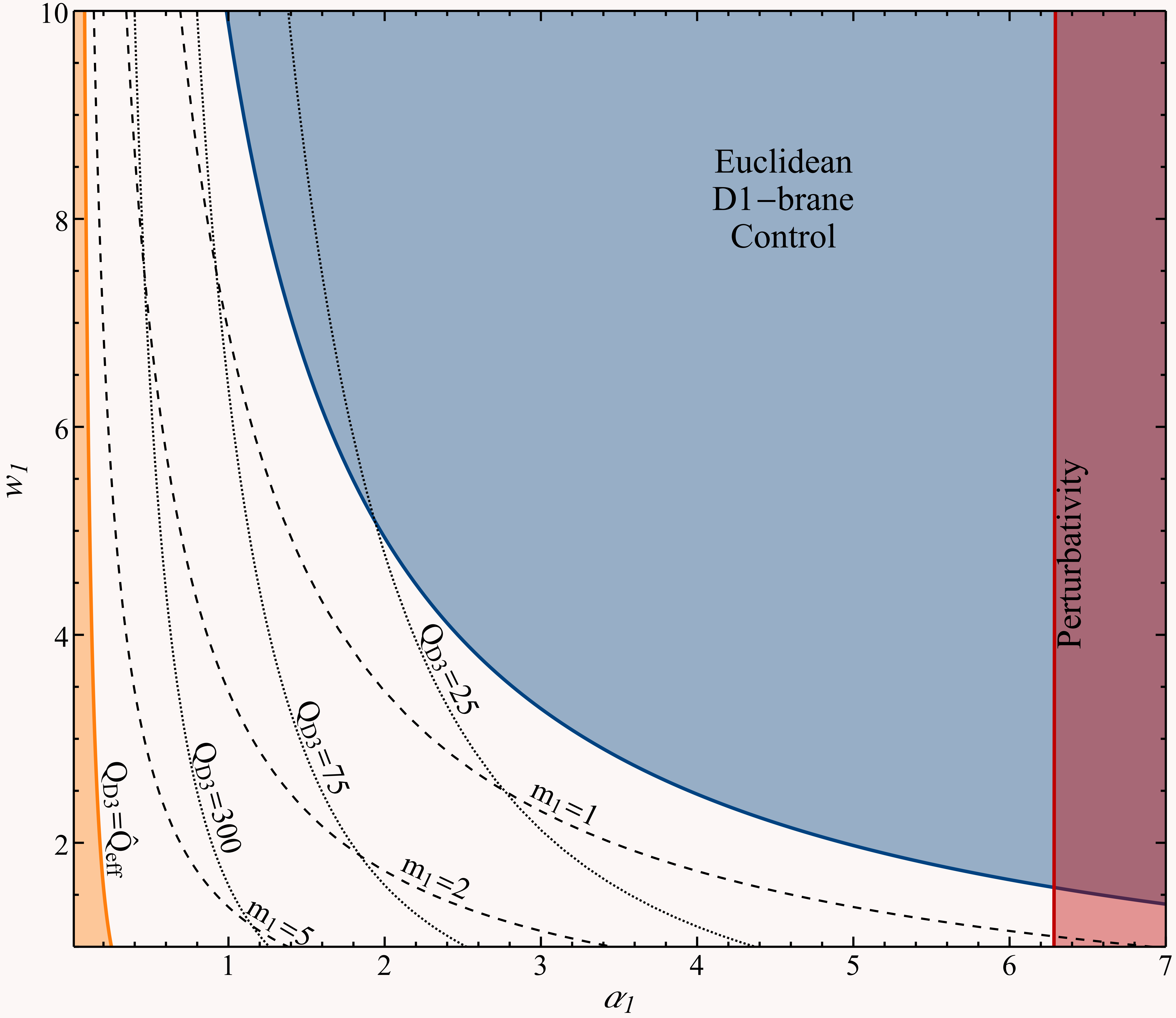
$$N_{D3} + \int_{Y_4} G_4 \wedge G_4 = \frac{\chi(Y_4)}{24}$$

→ $Q_{D3} \lesssim 0.1\,\frac{\chi(Y_4)}{24}\ (\sim 10^4)$ [Candelas et al..]

Non Abelian spectators need huge tadpole

# CS coupling constraints

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



# Conclusions

## String Theory Axiverse

- ✦ Connect string theory to experiments
- ✦ Spectator mechanism → GW
- ✦ Different axions → different peaks
- ✦ CS coupling very constrained

## Observation of GW

- ✦ $C_2$ axions are the best candidate
- ✦ Probe odd axiverse
- ✦ Big tadpole
- ✦ Many axions → smaller peaks

## Future Directions

- ✦ Massive gauge fields GW
- ✦ Specific construction

# Inflationary Axiverse

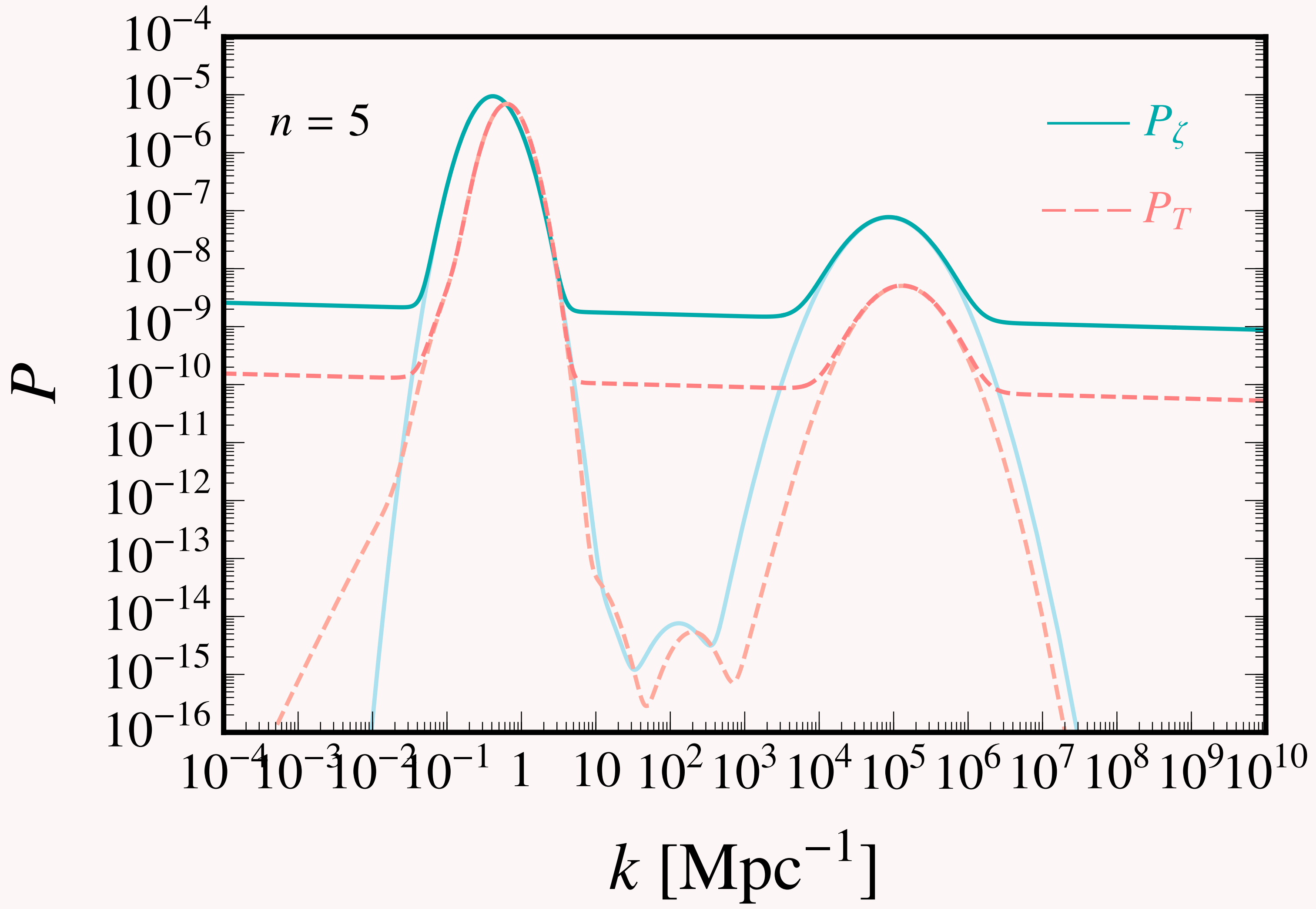
A multitude of abelian spectators

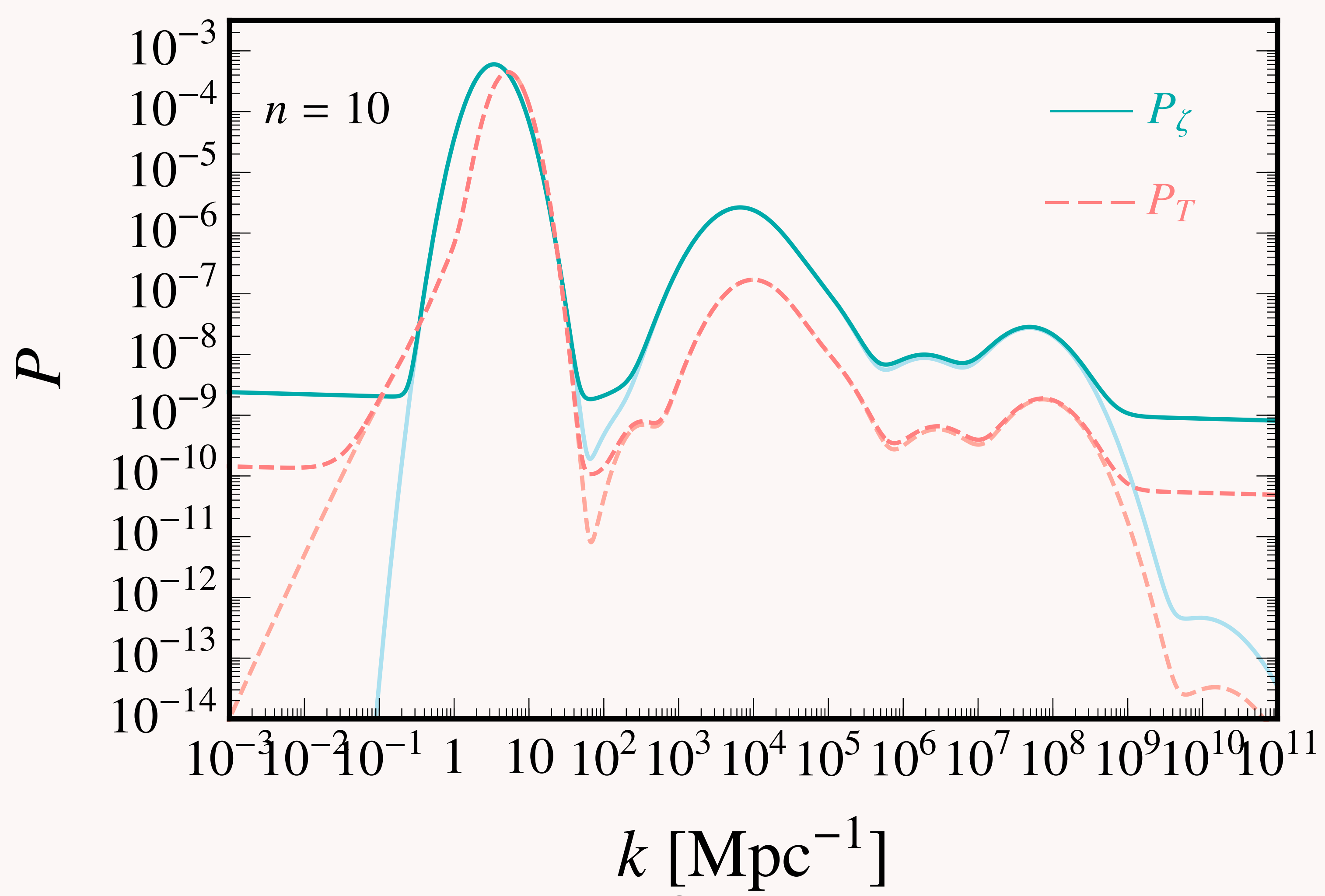
$$\mathscr{L} = \mathscr{L}_{inf} + \sum_{i=1}^{n} \mathscr{L}_{spect} \longrightarrow P_{\zeta,GW} = P^{(vac)}_{\zeta,GW} + \sum_{i=1}^{n} P^{(src)i}_{\zeta,GW}$$

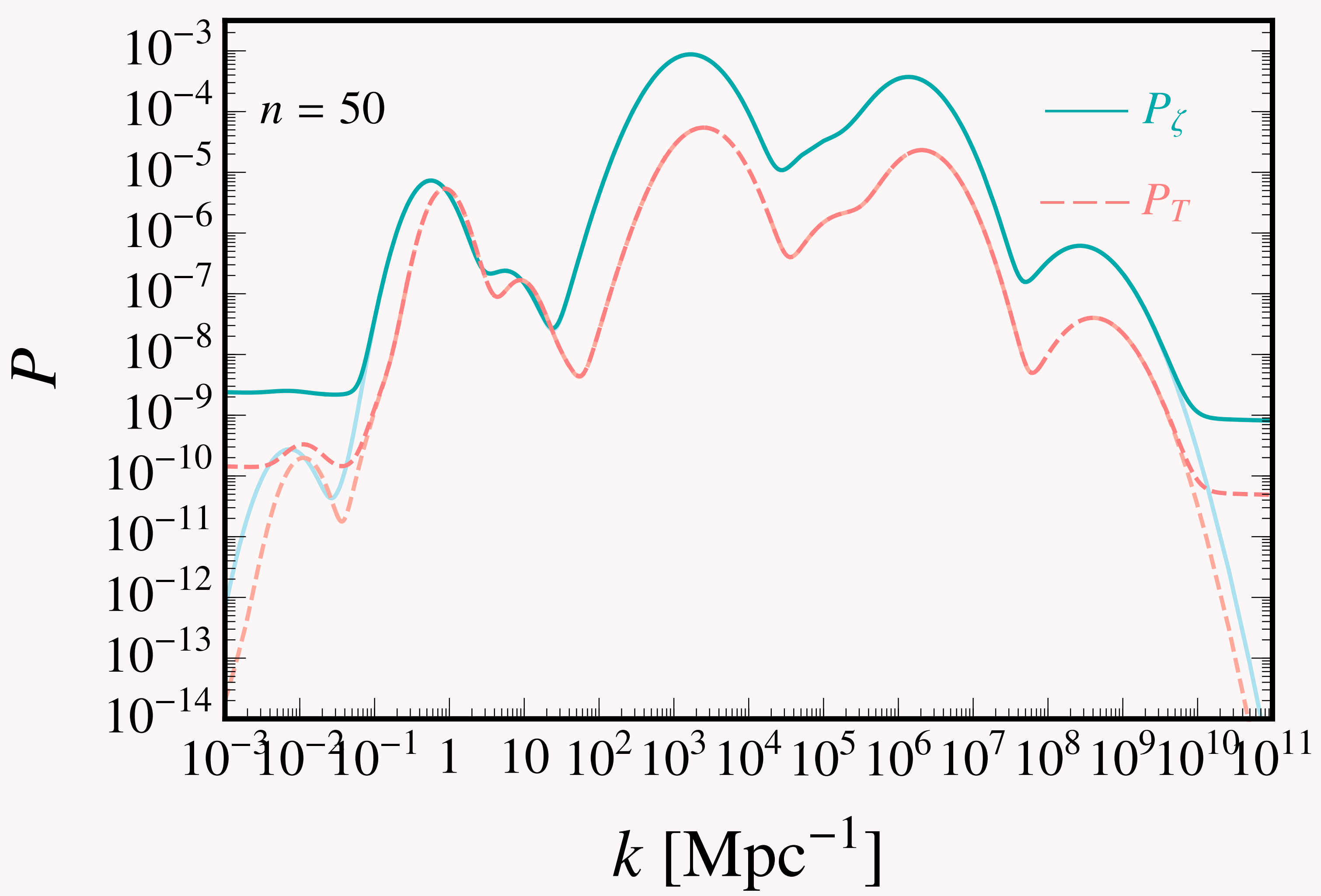
Random draws:

$\chi_{in} \rightarrow$ signals at different $k^i_*$

$\lambda$ Chern Simons coupling , $\quad \delta = \dfrac{1}{\Delta N} \sim \dfrac{m_\chi^2}{H^2}$



# Inflationary Axiverse: Curvature

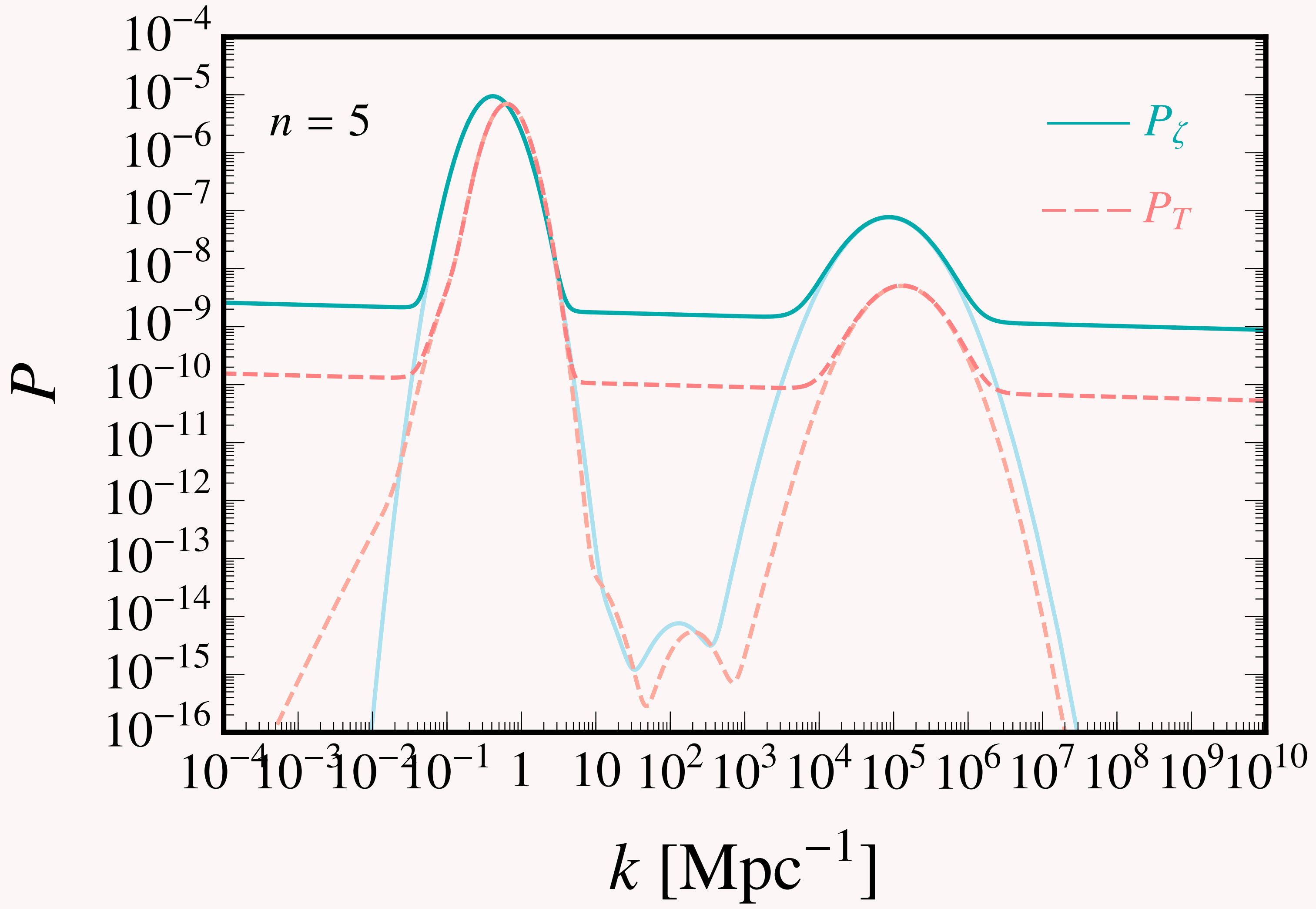
## Spectral Distortions

$$\mu_\zeta = \int_{k_{\min}}^{\infty} d\ln k\, P_\zeta(k)\ W_\zeta^\mu(k)\ ,\quad y_\zeta = \int_{k_{\min}}^{\infty} d\ln k\, P_\zeta(k)\ W_\zeta^y(k)$$

COBE/FIRAS $\quad y \lesssim 1.5\times10^{-5} \quad \mu \lesssim 9\times10^{-5}$

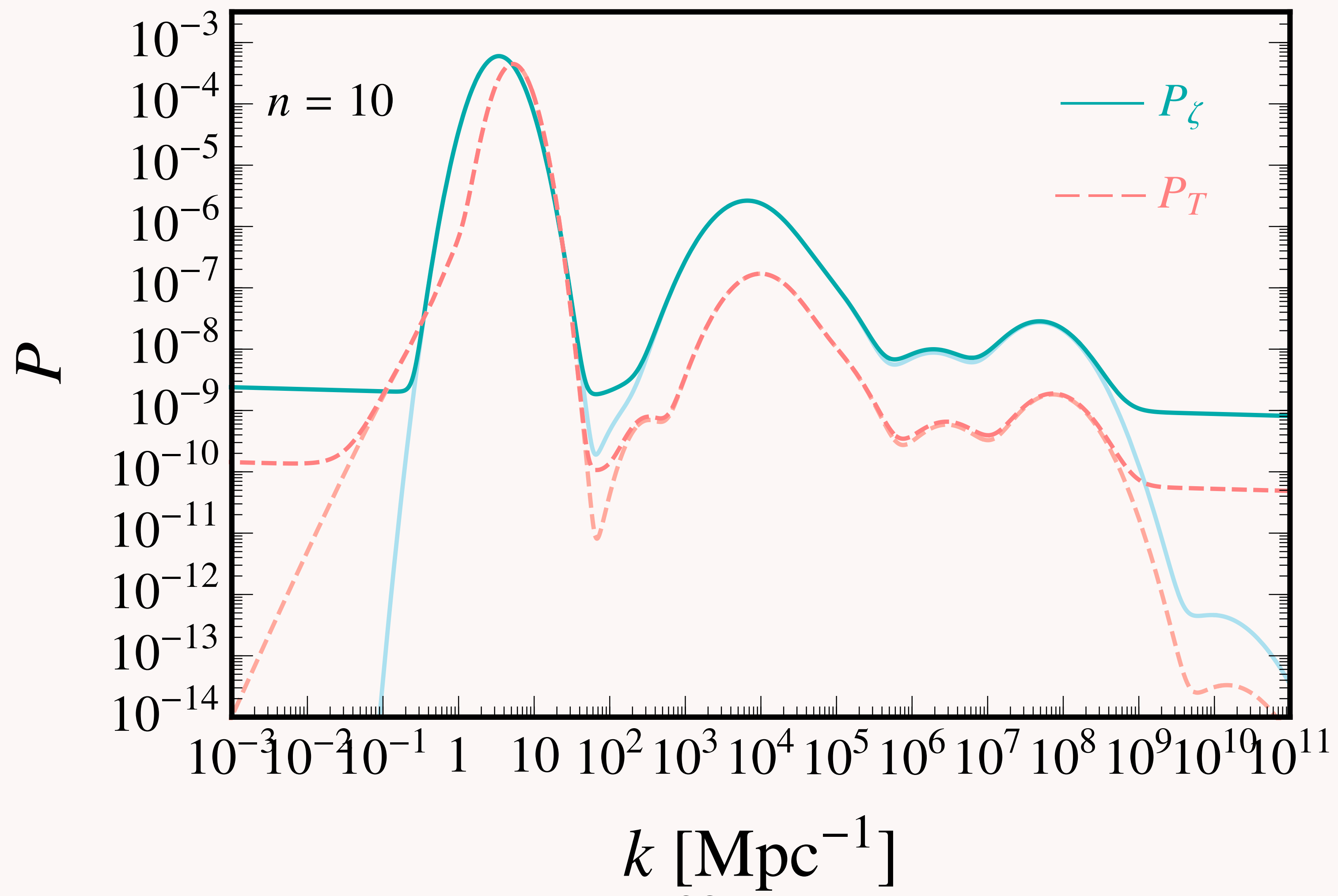
$y \simeq 2.3\times10^{-9} \quad \mu \simeq 2.7\times10^{-7}$

Detectable by future missions



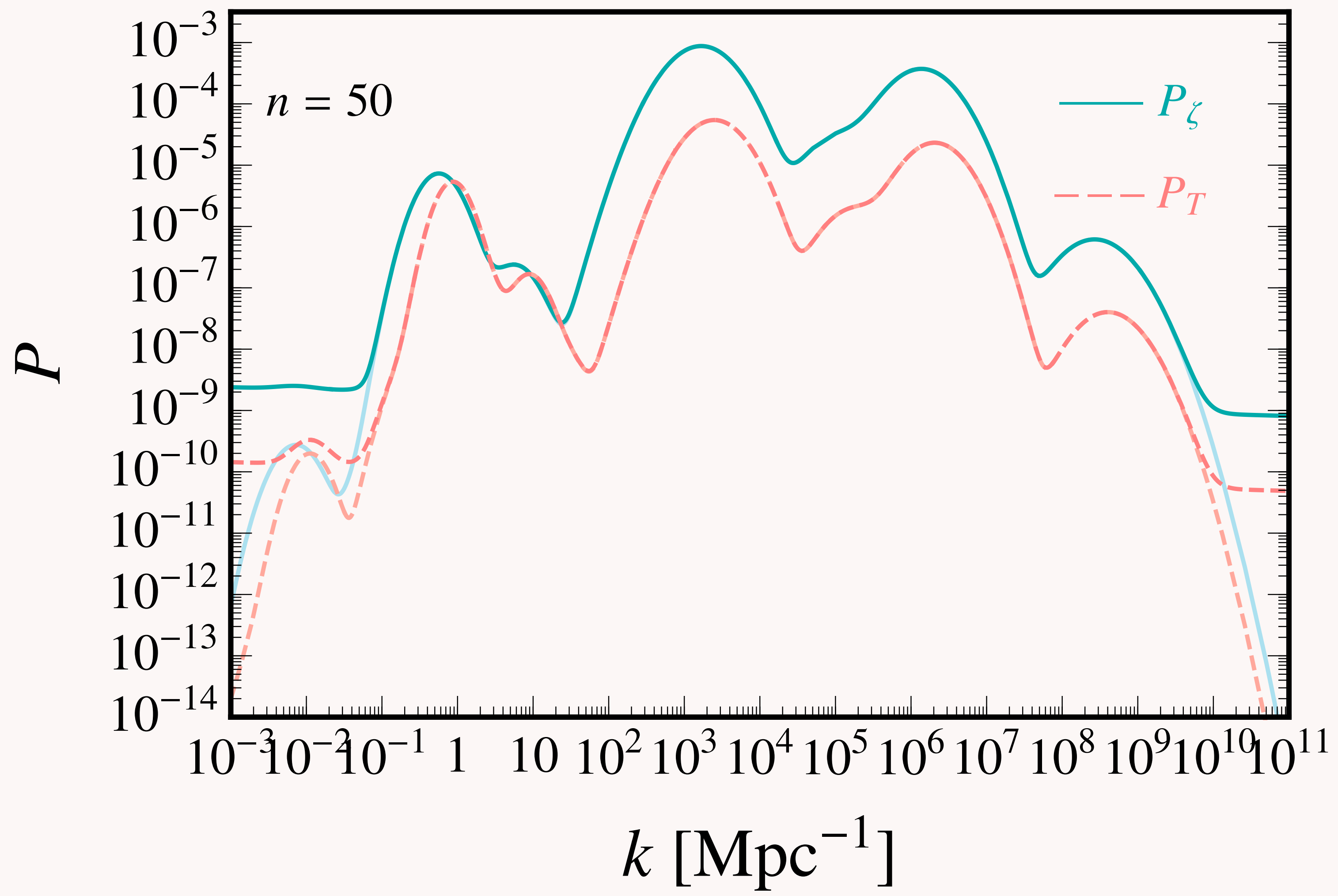

$y \simeq 1.2\times10^{-4} \quad \mu \simeq 1.5\times10^{-5}$

Ruled out by COBE/FIRAS




$y \simeq 3.2\times10^{-9} \quad \mu \simeq 1.2\times10^{-3}$

Ruled out by COBE/FIRAS



# Non Abelian

✦ Flat signal: very very large peak

✦If the gauge field dies huge instability

✦ Non-Abelian case needs very large CS coupling ($\lambda \sim \mathcal{O}(10^2)$) → huge tadpole

Compare with Holland et al.

✦Kähler inflation: $\left(N_{D7}, m, w\right) = \left(10^5, 10^4, 25\right) \to Q_{D3} \sim \mathcal{O}(10^{10} - 10^{14}) \gg 10^5$

✦Fibre inflation: $\left(N_{D7}, m, w\right) = \left(10^3, 10^2, 1\right) \to Q_{D3} \sim \mathcal{O}(10^5 - 10^7)$ [Holland et al. 2020]

Non - Abelian spectators are swamplandish