CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

# GRAVITATIONAL AXIVERSE SPECTROSCOPY

## Seeing The Forest For The Axions

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StringPheno2024

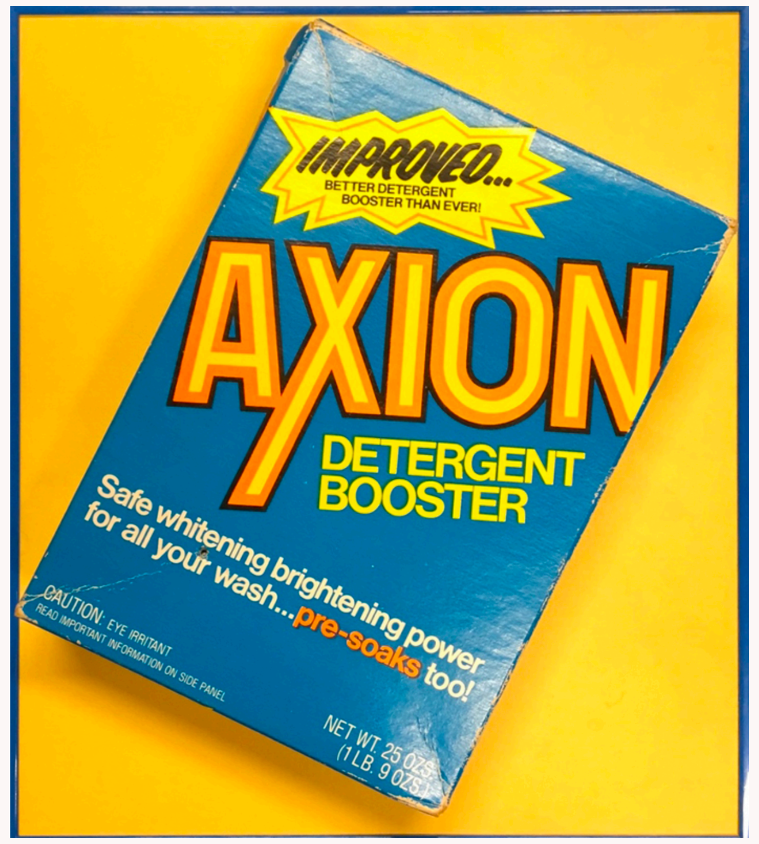
Work with
E. Dimastrogiovani, M. Fasiello,
J. Leedom, A. Westphal

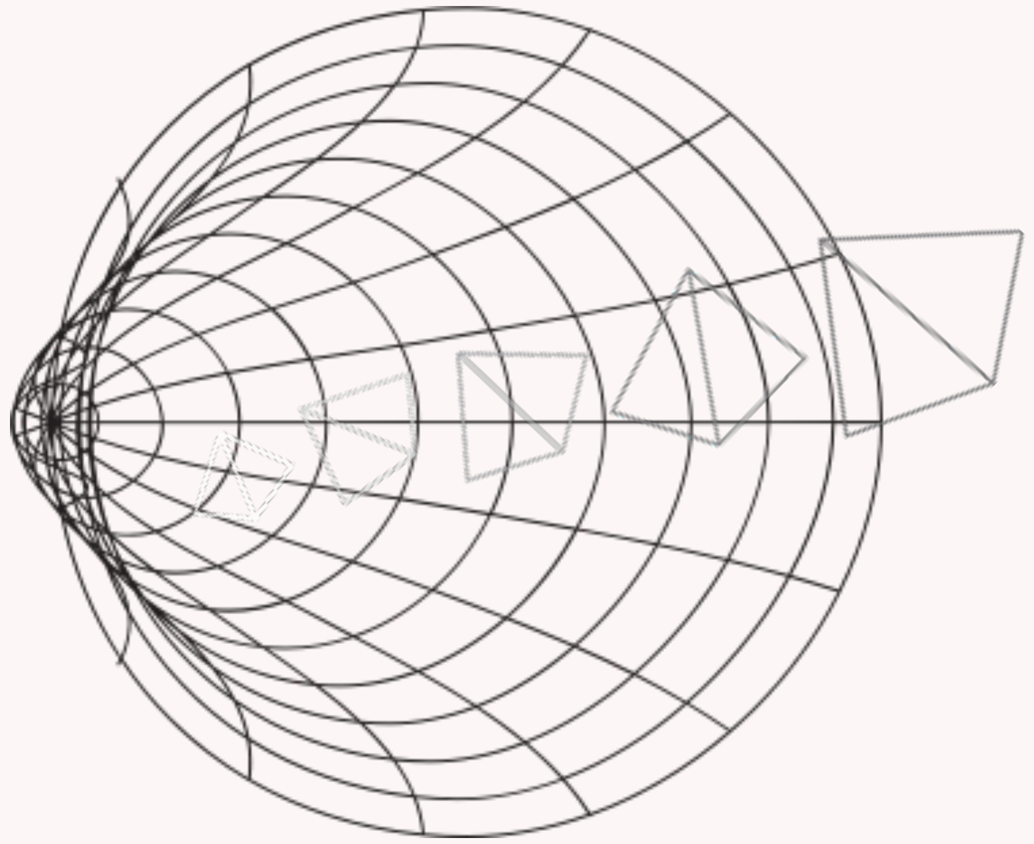
arXiv:2312.13431

# Summary

How can we tie string theory to experiments?

AXIONS



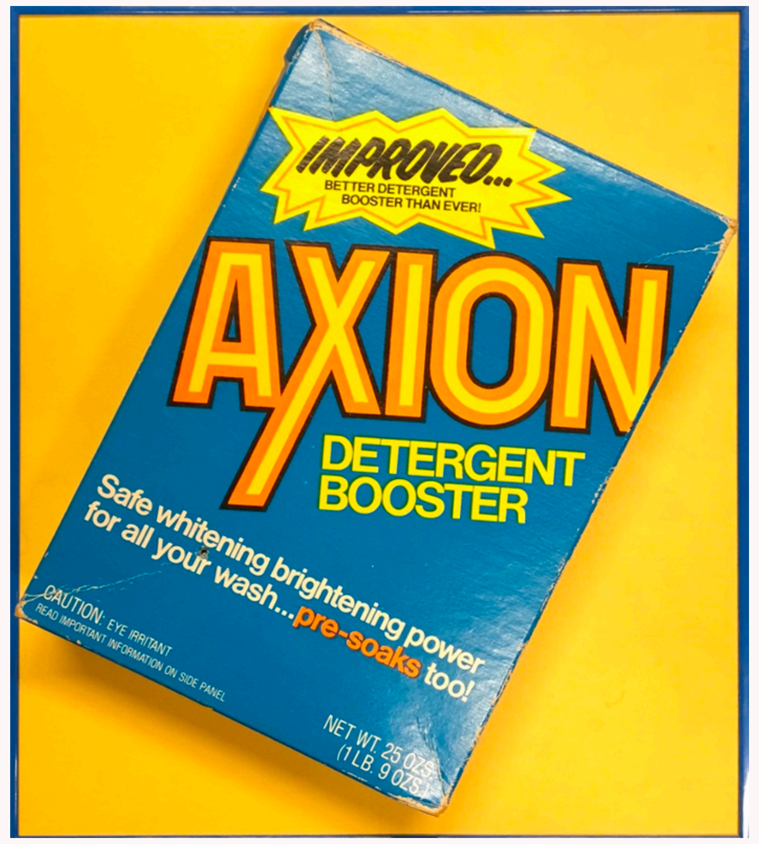



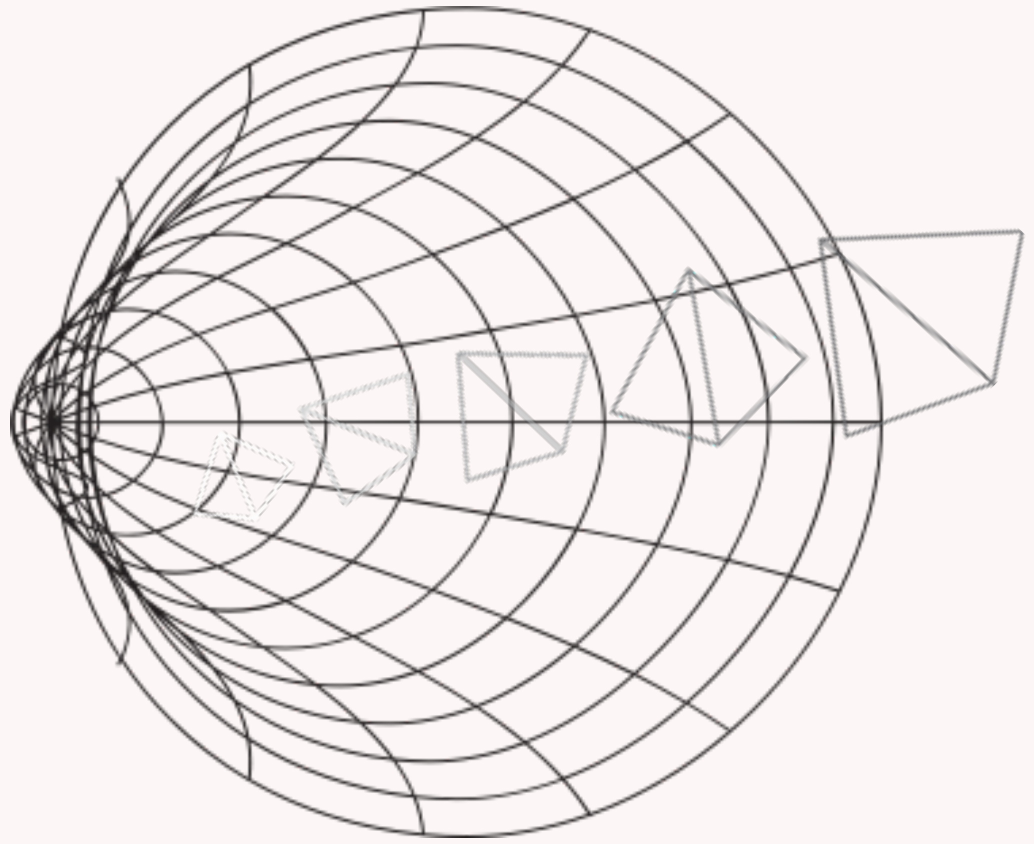
INFLATION

# Summary

How can we tie string theory to experiments?

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

Filippo + Gonzalo

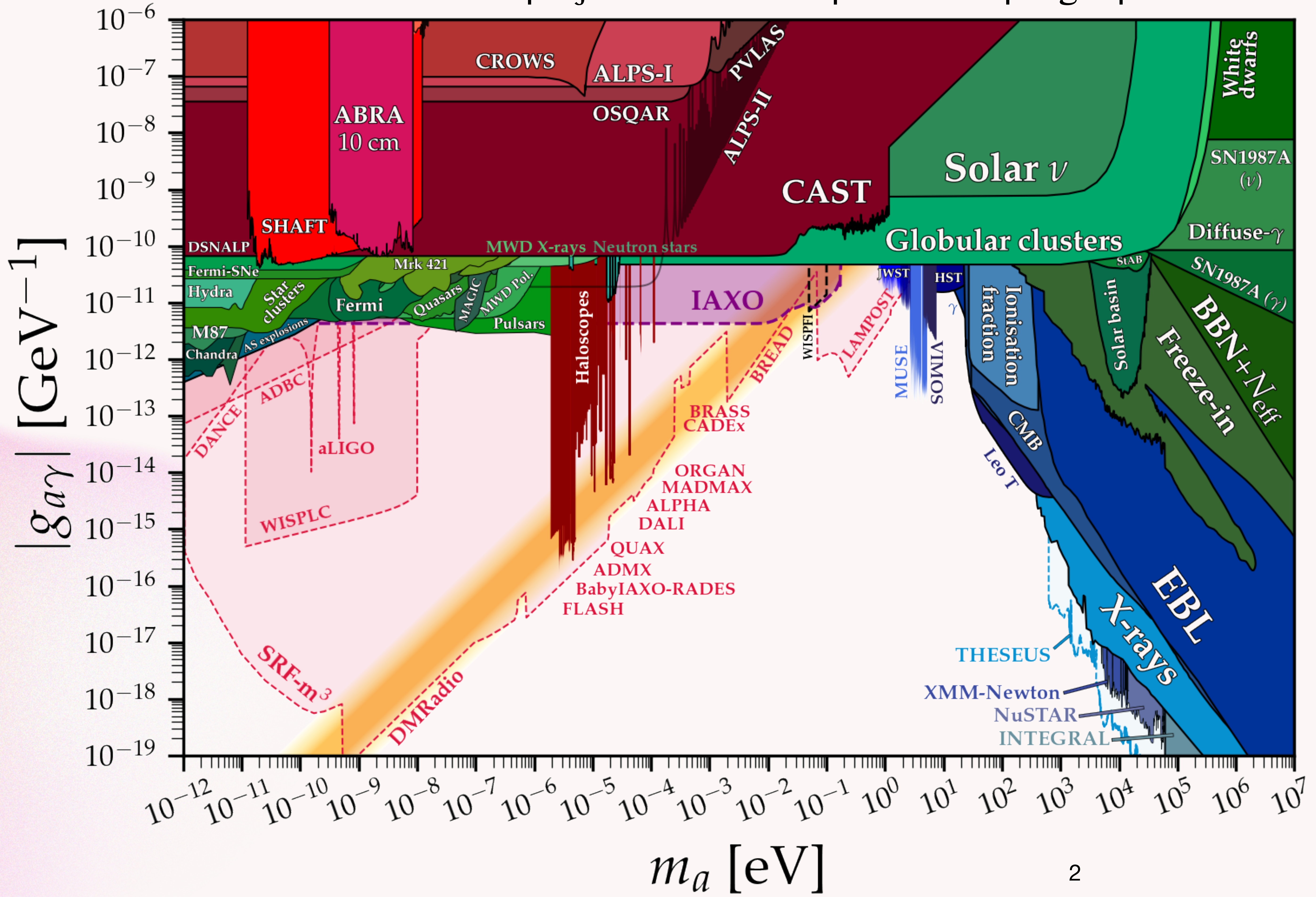
# Detecting the Axiverse

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.




However, string axions may not be

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

What about the rest of the axiverse?

# Spectator Mechanism

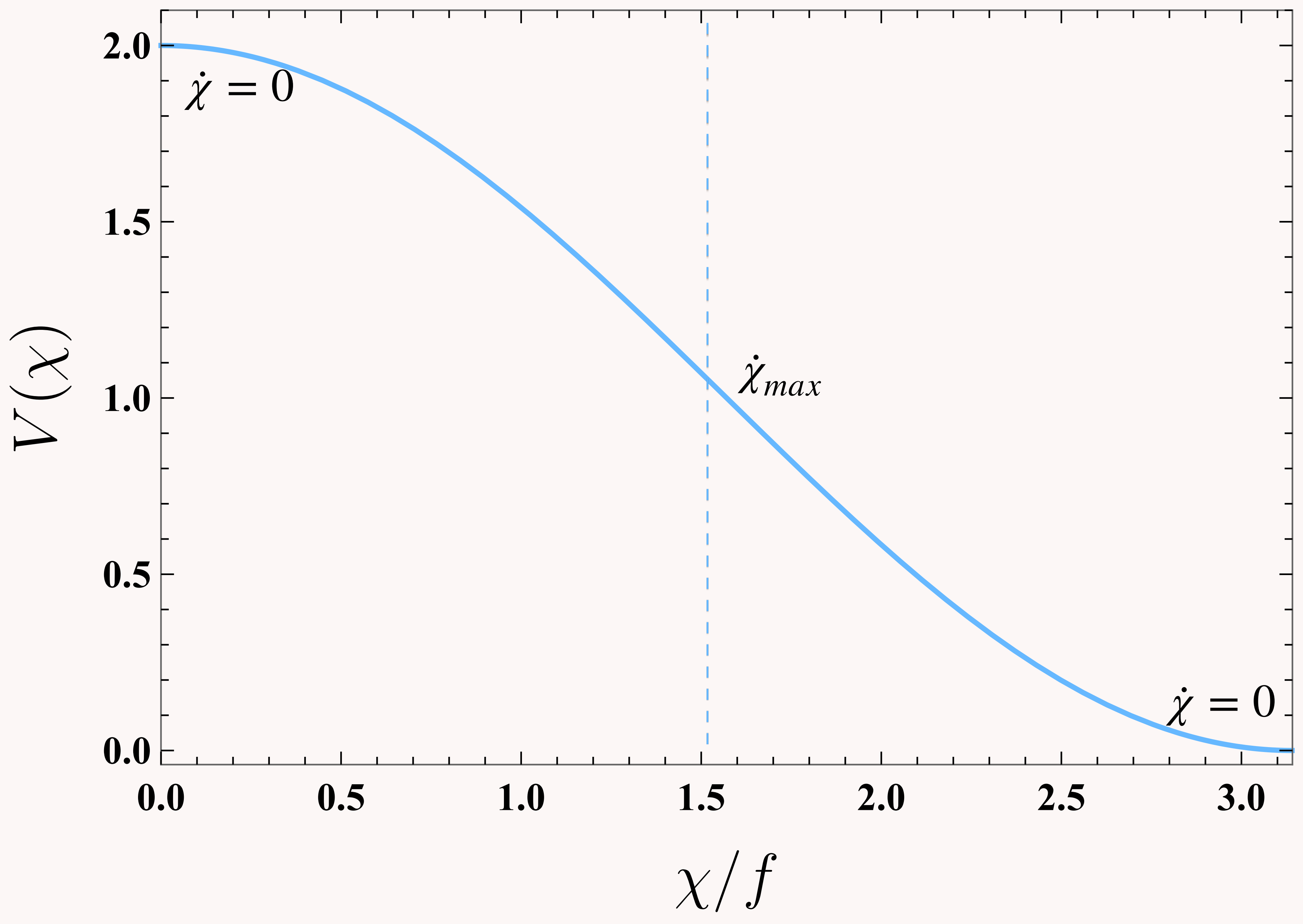
[Peloso et al.]
[Dimastrogiovanni et al.]

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

$$V(\chi) = \Lambda^4\left(\cos\left(\chi/f\right) + 1\right)$$

$\dot{\chi} \neq 0 \longrightarrow \delta A$

$\delta A + \delta A \rightarrow \zeta,\ \delta h_\pm$




Enhancement of primordial perturbations.
For non-Abelian spectators
spectra remains flat.

# Spectator Mechanism

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

$$P_{\zeta,GW} = P^{(vac)}_{\zeta,GW} + P^{(src)}_{\zeta,GW}$$

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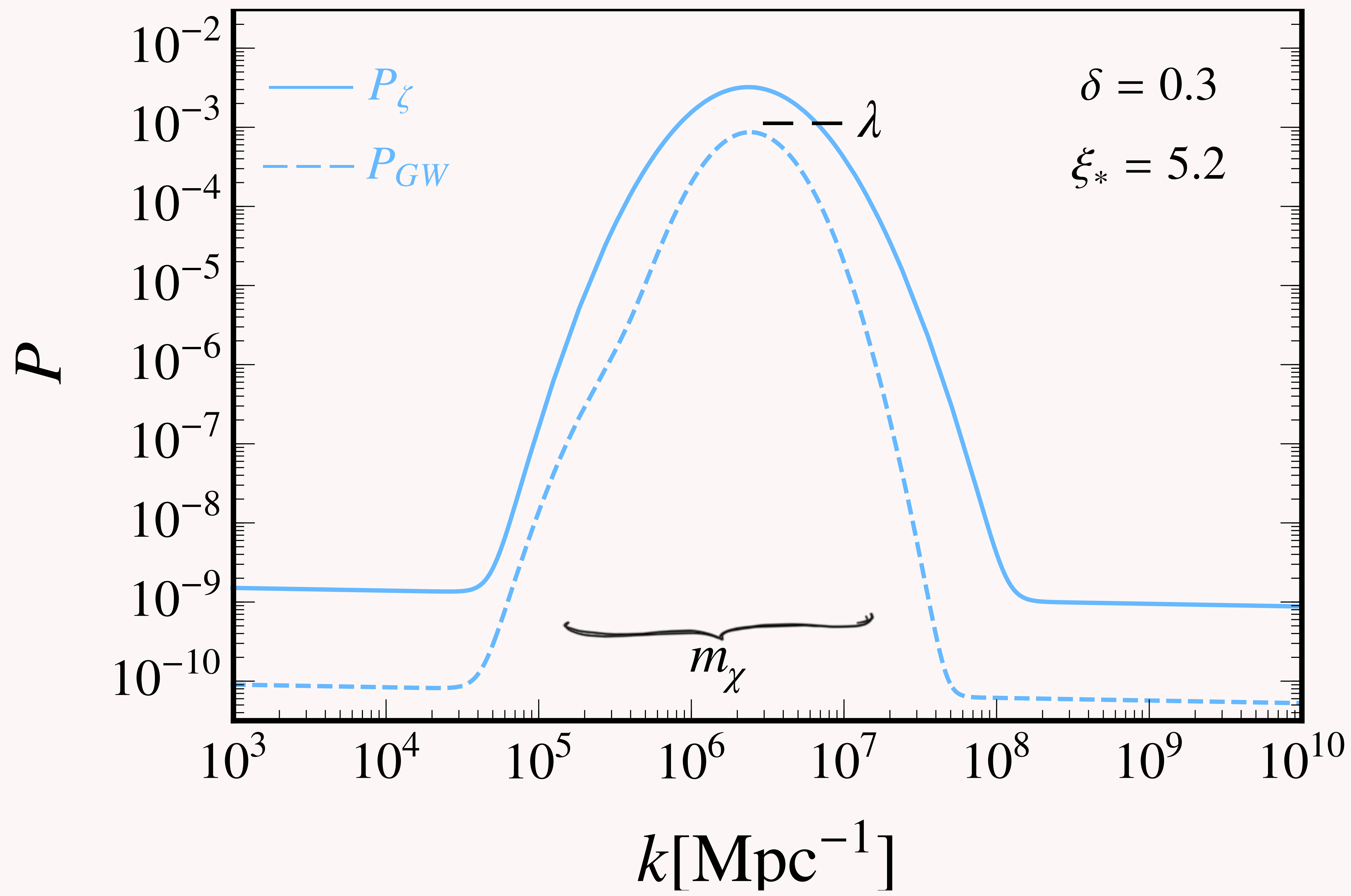
$\delta A + \delta A \rightarrow \zeta,\ \delta h_{\pm}$

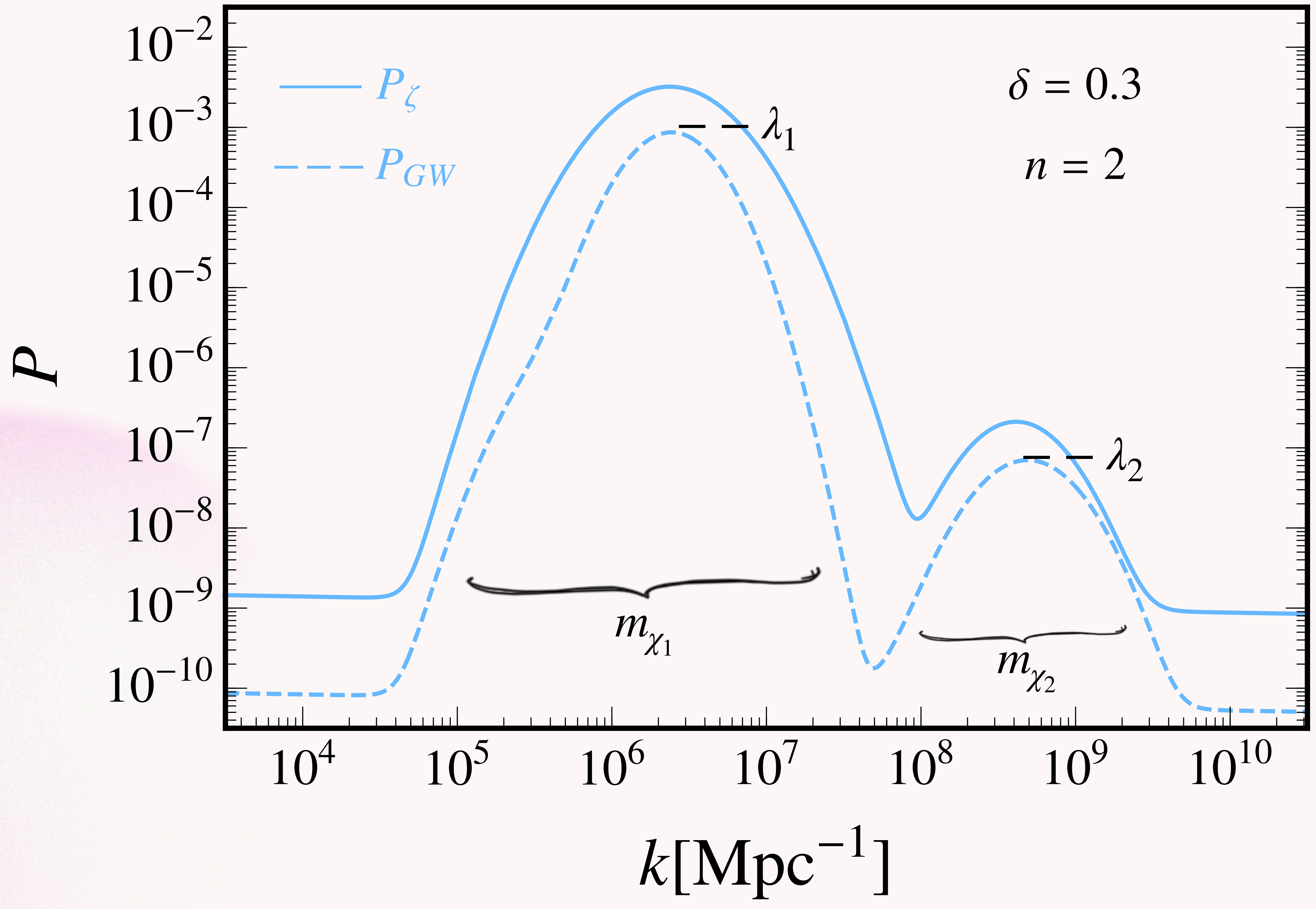



Enhancement of primordial perturbations.
For Abelian spectators signal
present a peak.

# Inflationary Axiverse

A multitude of abelian spectators

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

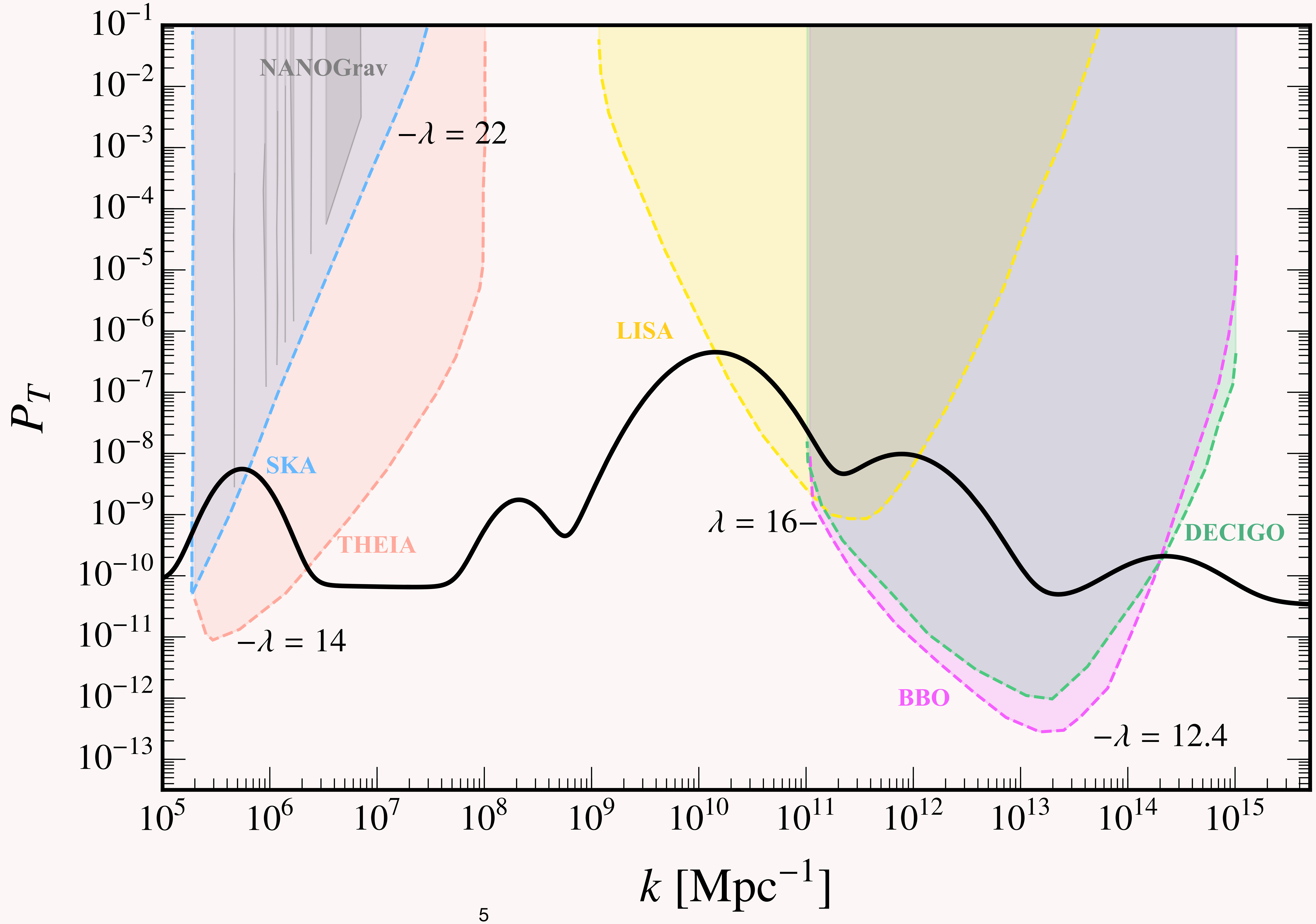



Peak parameters determined by:

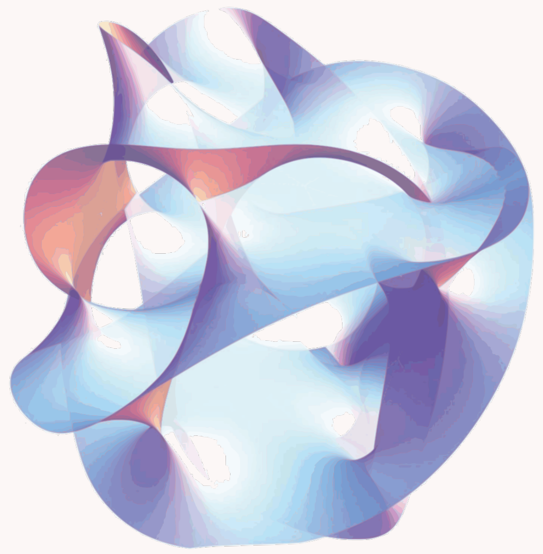
- $\lambda$ CS coupling: height
- $m_\chi$ Axion mass: width
- $\chi_{in}$ Initial condition: position

# Inflationary Axiverse

Axion properties determine GW features: **Gravitational spectroscopy**



# UV Embedding



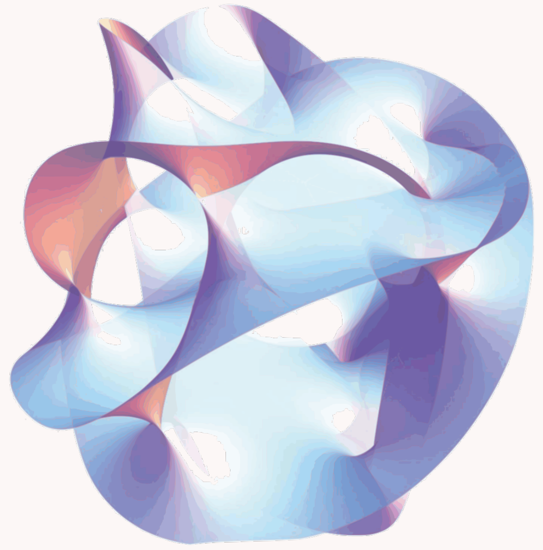
We motivated the GW forest via the existence of the string axiverse

Can we actually embed this in string theory?

↓

- ✦ How generic can the spectator mechanism be?
- ✦ Does the landscape allow observable signals?

# Candidates



Type IIB orientifold compactification

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

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

$X_3$ CY 3-fold

Candidates:

✦ $C_2$ or $C_4$ axions from 10D p-form fields

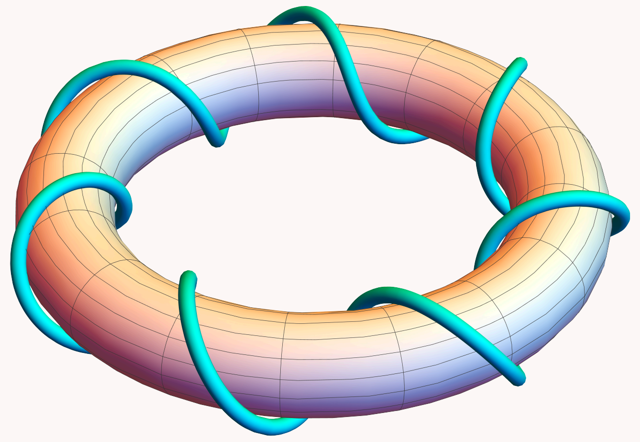
$$S = C_0 + ie^{-\phi}$$
$$G^a = c^a - Sb^a$$
$$T_\alpha = \tau_\alpha - i(\rho_\alpha - \kappa_{\alpha bc}c^b b^c) + \frac{i}{2}S\kappa_{\alpha bc}b^b b^c$$

Volume modulus ($\tau_\alpha$)

$\rho_\alpha$ 4-form even axion

$c^a$ 2-form odd axion

✦ $A_\mu$ gauge fields from D7-brane



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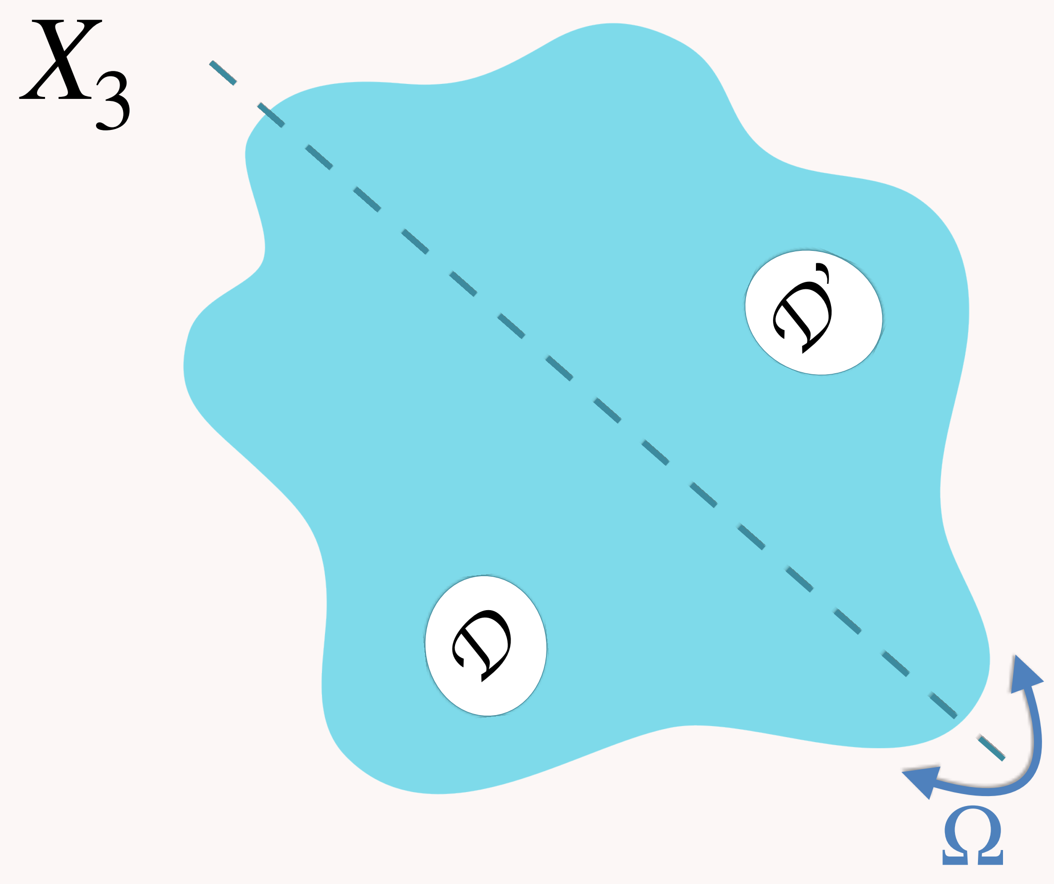
Introduce odd flux: $\frac{1}{2\pi}F_2 = m^a\omega_a$ → coupling with $c^a$

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

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

# Stückelberg




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

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

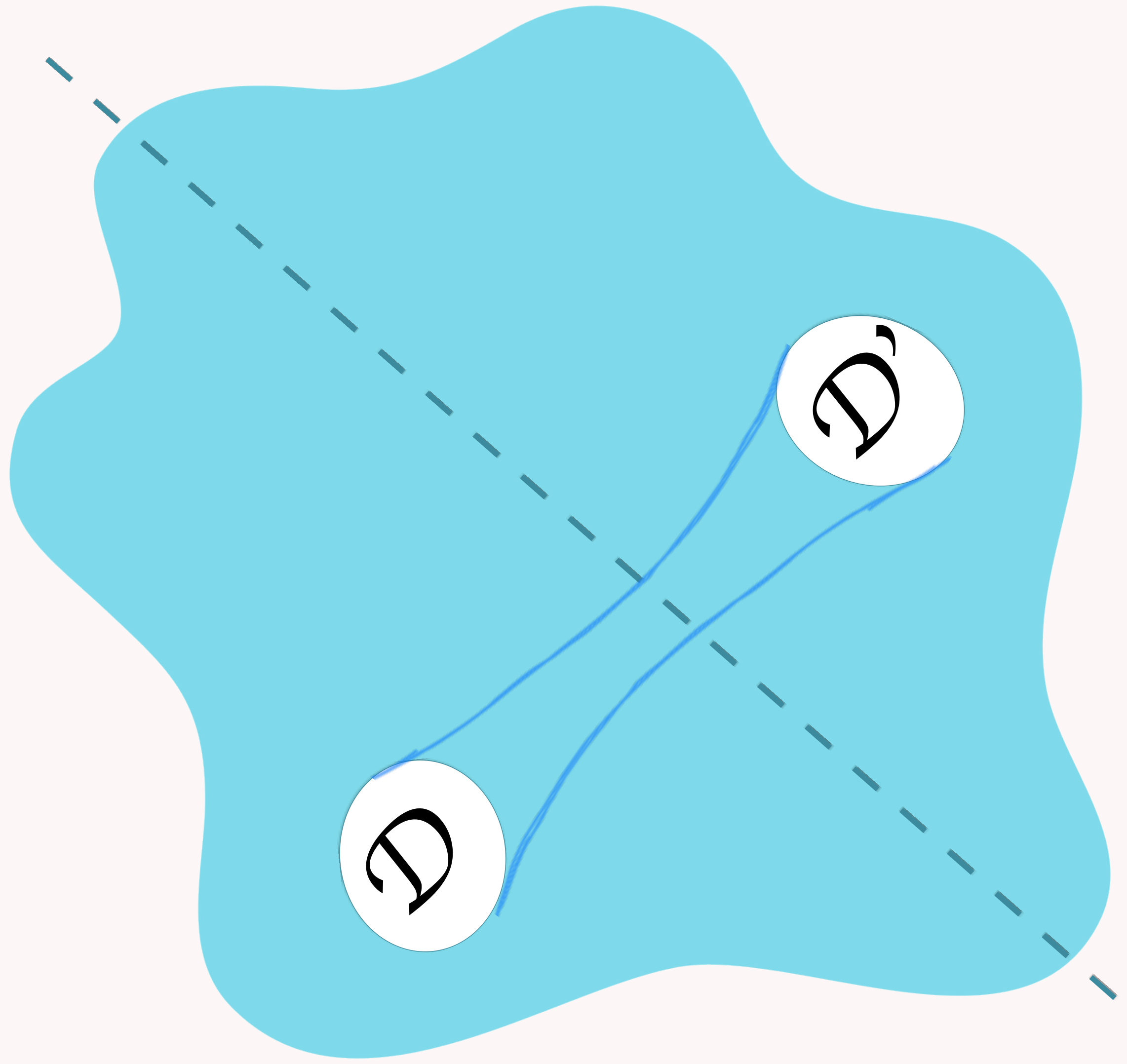
flux-induced $\quad d\rho_\alpha \to \nabla \rho_\alpha = d\rho_\alpha - iq_\alpha A, \qquad q_\alpha \sim \kappa_{\alpha bc} m^b w^c$

Problems → Lose candidate axions

Problems → Spectator mechanism doesn't work with massive gauge fields

# 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 $\rho_\alpha$

# 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 ED1: $2\pi v \gtrsim \mathcal{O}(1) \rightarrow \frac{\pi^2}{\kappa w \alpha} \gtrsim 1$, where $\tau = \frac{1}{2}\kappa v^2$
3. Control of ED3: $2\pi\langle\tau\rangle \gtrsim 2$

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

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

} Signal very low
Not observable

# CS coupling constraints

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3. Control of ED3: $2\pi\langle\tau\rangle \gtrsim 2$
4. Induced D3 Tadpole

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

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

Not for free!

# CS coupling constraints

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

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3. Control of ED3: $2\pi\langle\tau\rangle \gtrsim 2$
4. Induced D3 Tadpole

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

F-theory picture:

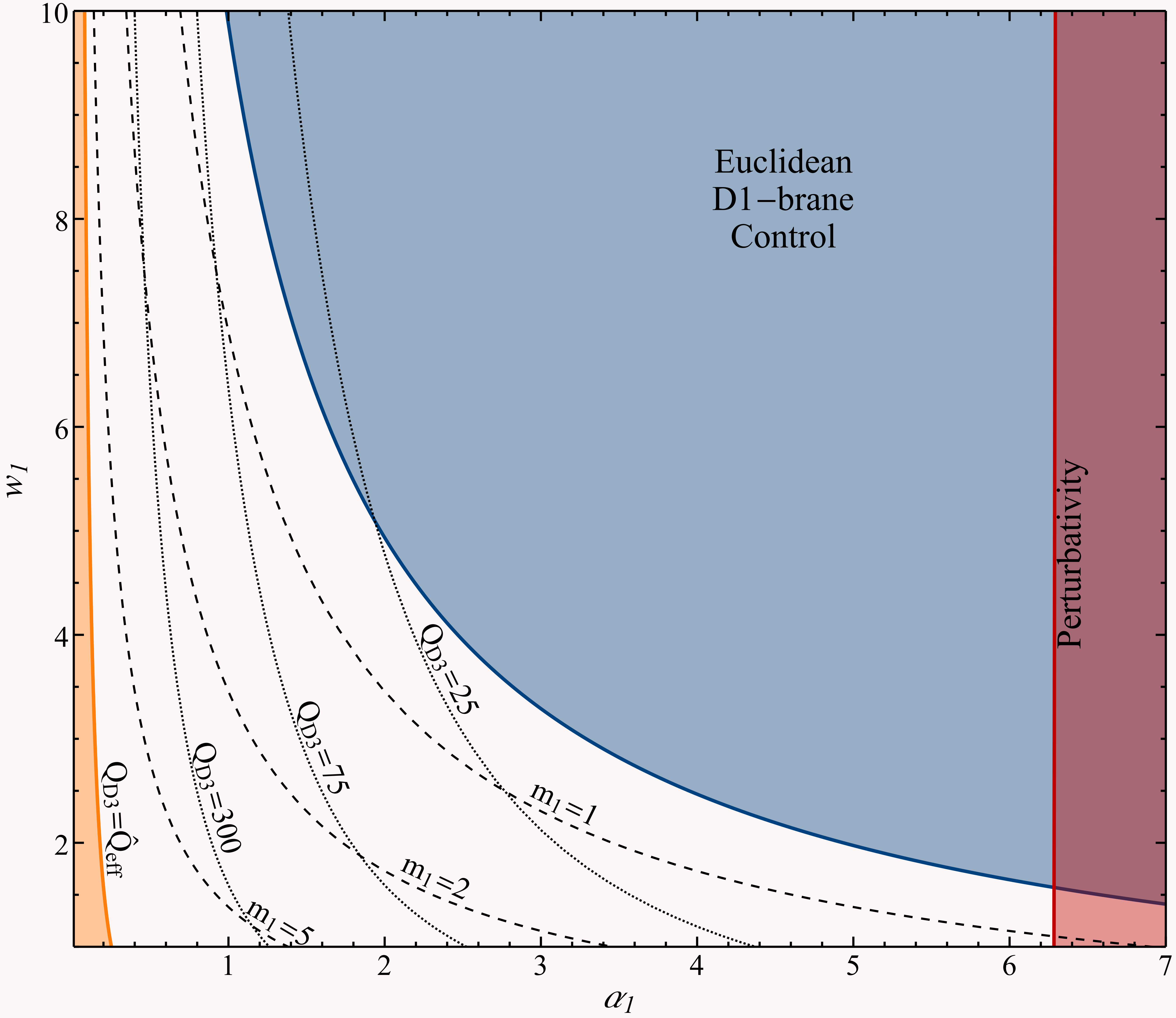
$$N_{D3} + \int_{Y_4} G_4 \wedge G_4 = \frac{\chi(Y_4)}{24}$$

$\rightarrow$ $Q_{D3} \lesssim 0.1\,\frac{\chi(Y_4)}{24}\,(\sim 10^4)$ [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

- ✦ Big tadpole (D3 charge)
- ✦ Large Euler characteristic
- ✦ Big Hodge number
- ✦ Many axions → smaller peaks

# Backup - 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

Holland et al. tried to embed in String Inflation

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

✦Fibre inflation: $\left(N_{D7}, m, w\right) = \left(10^3, 10^2, 1\right) \rightarrow Q_{D3} \sim \mathcal{O}(10^5 - 10^7)$

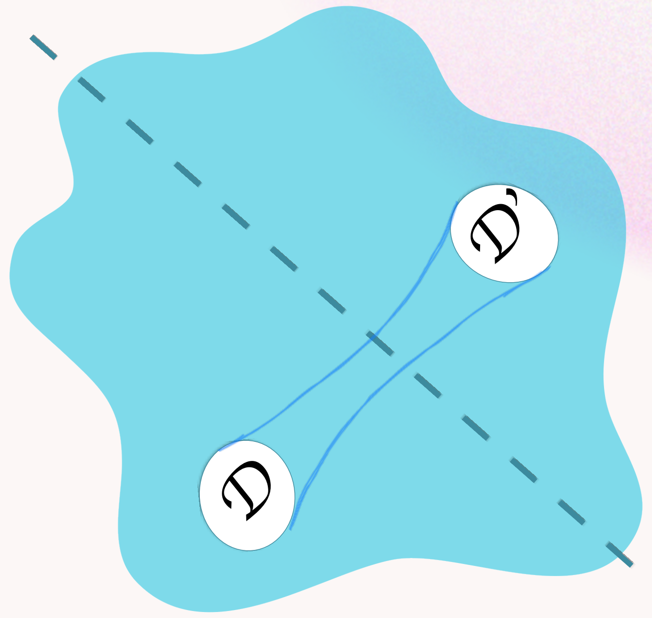
Non - Abelian spectators are swamplandish

# Backup -Avoiding Stückelberg

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

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

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



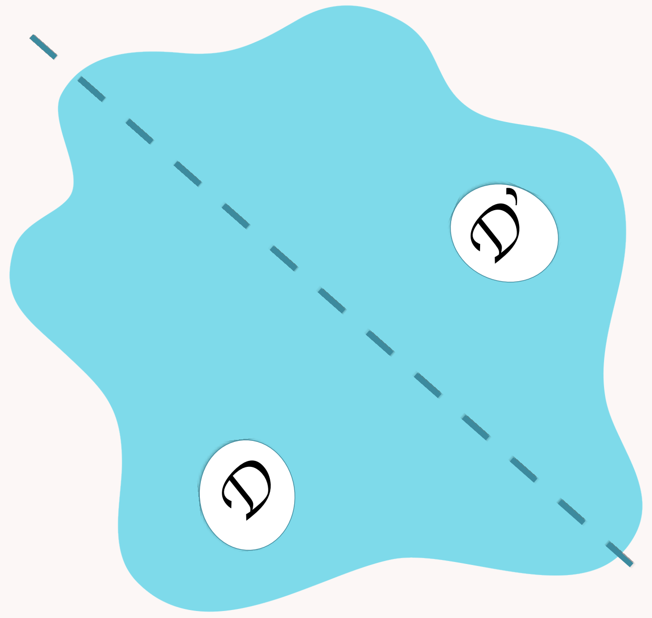

- Class II: $[\mathcal{D}]\neq[\mathcal{D}']$

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

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

  $m^a = 0$ → No flux Stückelberg

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

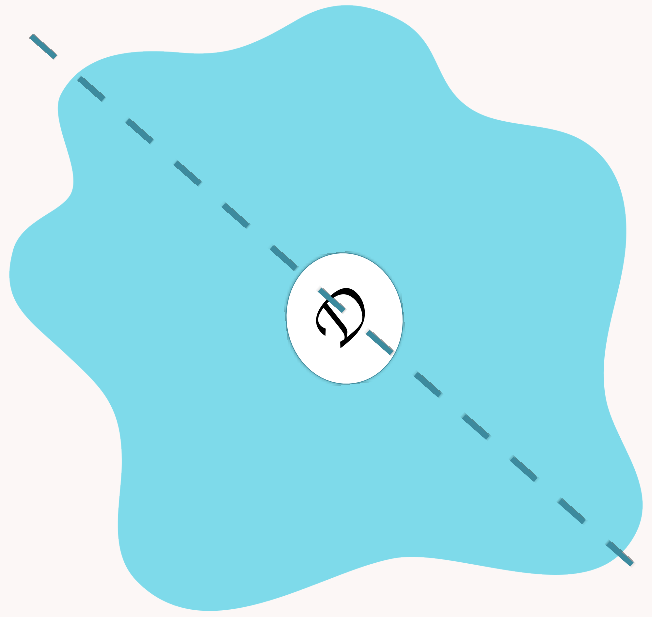



- Class III: $\mathcal{D} = \mathcal{D}'$ pointwise

  $w^a = 0$ → No Stückelberg

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

  break group to get $U(1)$



# Backup - Model parameters

✦ Gauge coupling: Vev of kähler moduli

✦ Axion decay constants: kinetic terms

$$S_{EFT} \supset M_p^2 \int \left( \frac{1}{\mathcal{V}^2} G^{\alpha\beta} d\rho_\alpha \wedge \star\rho_\beta - e^{\phi} G_{ab} dc^a \wedge \star dc^b \right)$$

$$G_{ab} = -\frac{\mathcal{T}_{ab}}{4\mathcal{V}^2} \qquad G_{\alpha\beta} = \frac{1}{4\mathcal{V}^2}\left(\frac{\tau_\alpha \tau_\beta}{\mathcal{V}^2} - \mathcal{T}_{\alpha\beta}\right) \qquad \mathcal{T}_{AB} = \kappa_{AB\gamma} v^\gamma \qquad \mathcal{V} = \frac{1}{6}\kappa_{\alpha\beta\gamma} v^\alpha v^\beta v^\gamma$$

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

$$W_{ED3} \sim Ae^{-2\pi T} \rightarrow \delta V_{ED3} \simeq e^{-2\pi\tau} \cos(\chi_e / f)$$

$$K_{ED1} \sim -3\ln(T + \overline{T} + \dots) \rightarrow \delta V_{ED1} \simeq e^{-2\pi v} \cos(\chi_o / f)$$