Gravitational Axiverse Spectroscopy: Seeing the forest for the axions.

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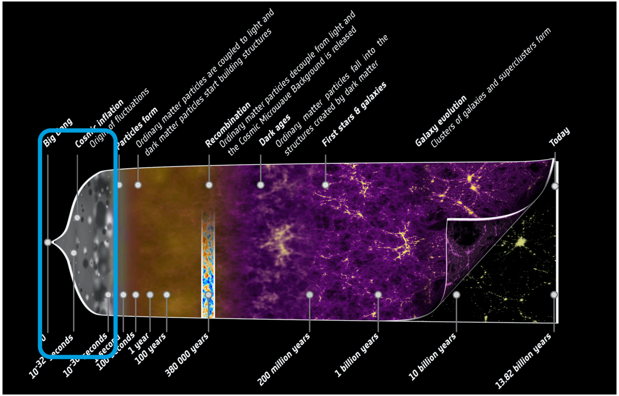
Based on work with E. Dimastrogiovanni, M. Fasiello, J. Leedom and A. Westphal

arXiv: [23XX.XXXXX]

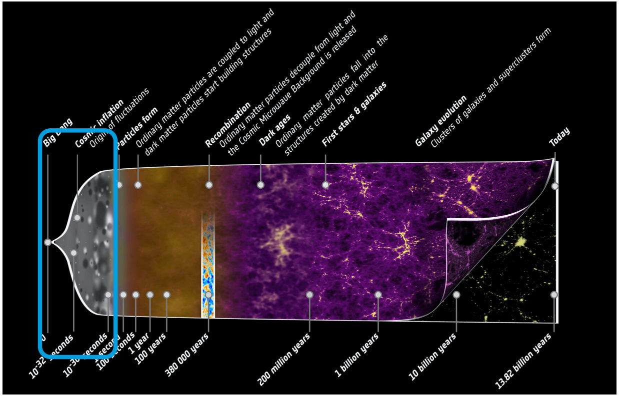
September 28^{th}, 2023



Inflation

- homogeneity, isotropy, ...
- Slow roll $\rightarrow$ UV physics?

Motivation.



Inflation

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String theory inflationary models

- axion monodromy, fibre inflation, ...
- Generic prediction: several axions coupled to gauge fields

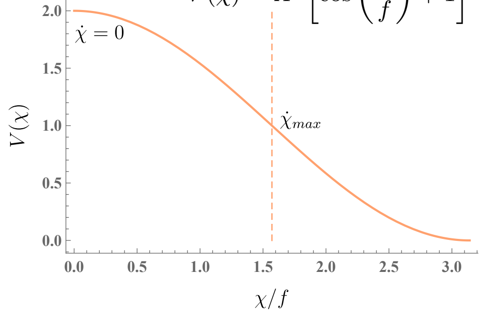
$\longrightarrow$ String Axiverse: how can we observe it?

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell, 2009

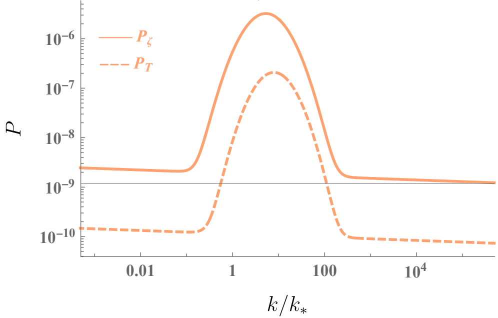
Inflationary models.

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

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



$$P = P^{(0)} + P^{(sourced)}$$



$$\dot\chi \neq 0 \rightsquigarrow \to \delta A$$

$$\delta A + \delta A \to \delta\chi, \delta\phi, \delta h_\pm$$

M. Peloso et al., 2016, arXiv:1509.07521
E. Dimastrogiovanni et al., 2017, arXiv:1608.04216

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Axiverse $f \sim 10^{-2} M_P$

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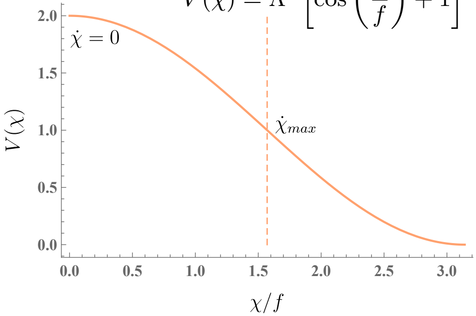

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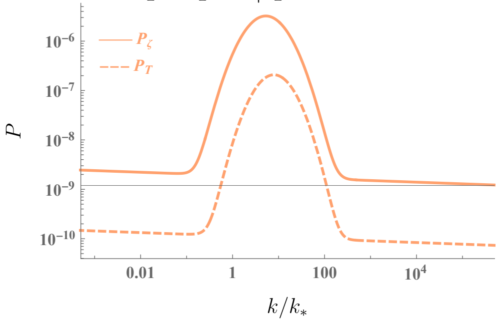

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String axiverse:

- Widely distributed mass spectrum
- Shift symmetry is perturbatively exact $\rightarrow$ ultralight axions?

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1. Consistency
2. PBH bounds
3. Backreaction

$\rightsquigarrow$ χ heavy

If $\Delta N \gg 60$ can $\dot{\chi} \neq 0$?

$$1 < \Delta N < 60$$

$$\Delta N \sim \frac{6H^2}{m_\chi^2} \rightsquigarrow m_\chi \gtrsim \frac{H}{\sqrt{10}}$$

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Multiple (n) abelian spectators:

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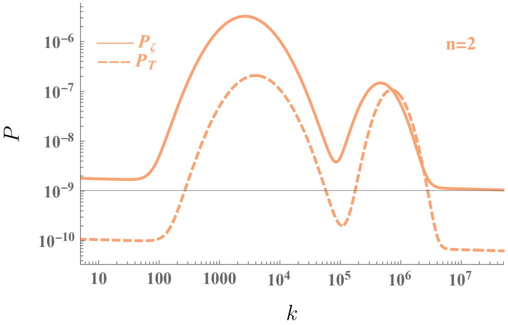

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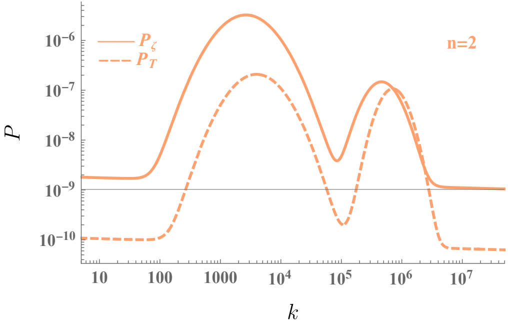

GW forest

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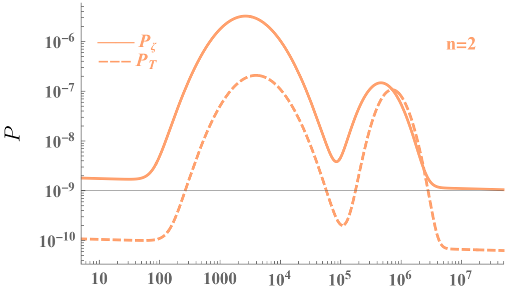
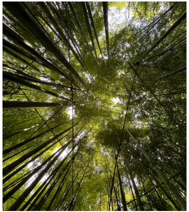


GW forest

Scalar forest



Random draws of parameters:

- $\xi_* = \frac{\lambda\delta}{2} \in [2.5, 5.5]$
- $\delta = \frac{1}{\Delta N} \in [0.2, 0.5]$
- $x_{in} = \frac{\chi_{in}}{f} \in [0, \frac{\pi}{4}]$

Peak around $k_* = k_{in} \tan\left(x_{in}\right)^{-\frac{1}{\delta}}$

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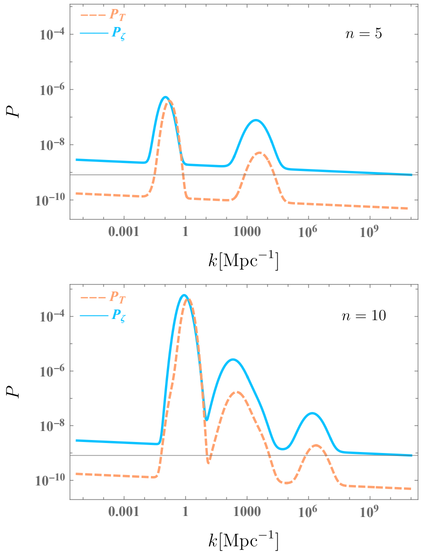

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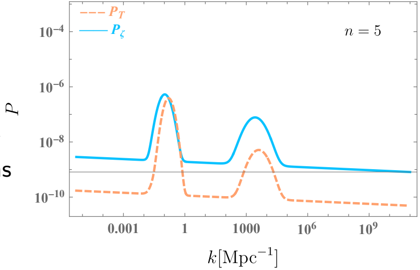
$y \simeq 10^{-9}$

$\mu \simeq 10^{-7}$

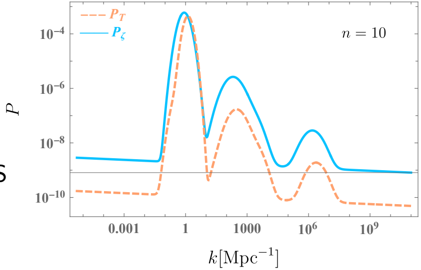
detectable by future missions

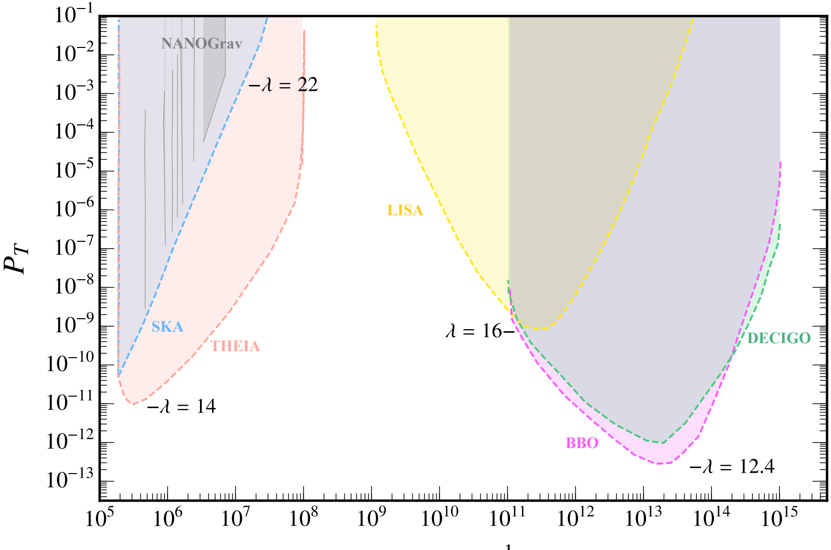


$y \simeq 10^{-4}$

$\mu \simeq 10^{-5}$

ruled out by COBE/FIRAS





- λ CS:
- $\lambda \frac{\chi}{4f} F\tilde{F}$
- $\lambda \propto \log(P_T)$

UV string embedding.

A forest in the landscape.

Goal: embed spectator models in type IIB. Problem: **Required CS coupling too big**.

$$\chi = \chi_{c4}, \chi_{c2}\,, \qquad\qquad S_{CS}^{D7} = \int_{M_4} g^2 \frac{1}{8\pi} \frac{\chi_{c4}}{2\pi f} F\tilde{F}$$

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Solution: flux on a 2-cycle

$$\int_{\Pi_2} (\frac{1}{2\pi} F_2) = m \in \mathbb{Z} \qquad \longrightarrow \quad S_{CS}^{D7} \supset \int_{M_4} \frac{1}{8\pi} g^2\, \kappa\, m\, \frac{\chi_{c2}}{2\pi f} F\tilde{F}$$

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$SU(N)$ ↙ ↘ $U(1)$

Kähler inflation (KI) $m = 10^4,\ N_{D7} = 10^5$
Fibre inflation (FI) $m = 10^2,\ N_{D7} = 10^3$

$N_{D7} = 1,\ m \sim 10^2 - 10^3$

Holland, Zavala, Tasinato, 2020

Tadpole.

$$\text{Further term in action: } S_{CS}^{D7} \supset \frac{1}{4\pi} \int_{\Pi_4} F_2 \wedge F_2 \int_{M_4} C_4$$

- Induced D3-brane charge:

$$Q_{\mathrm{D3},ind.} = \kappa\, m^2\, N_{D7}$$

- Type IIB lift to F-theory, D3 charge completely fixed by topology

$$\rightarrow Q_{D3,tot}(X_4) = \frac{1}{24}\chi(X_4)$$

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Tadpole bound $Q_{D3,ind} = \kappa\, m^2\, N_{D7} < \mathcal{O}(0.1)\frac{1}{24}\chi(X_4) \sim 10^4 = Q_{D3,tot}^{max,known}$

Landscaping.

	m large, $\kappa \sim \mathcal{O}(1)$	κ large, $m \sim \mathcal{O}(1)$	
SU(N):	$Q_{D3} \simeq \begin{cases} (10^4)^2 10^5 \sim 10^{13} \text{ KI} \\ (10^2)^2 10^3 \sim 10^7 \text{ FI} \end{cases}$	$Q_{D3} \simeq \begin{cases} (10^4) 10^5 \sim 10^9 \\ (10^2) 10^3 \sim 10^5 \end{cases}$	Swampland?

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Swampland?

U(1): Choose $\lambda_{\mathrm{D7}} = \lambda_{GW peak}$

$$Q_{\mathrm{D3},ind.} = 16\pi^2 \frac{1}{\kappa} \left(\frac{1}{g^2} \right)^2 \lambda^2_{GW peak}$$

NANOgrav signal with $\delta = 0.5$, $\kappa_0 = 1$, $g_0^2 = 1$, $\lambda_{GW peak} = 22$:

$$Q_{\mathrm{D3},ind.} = 7.6 \cdot 10^5 \times \frac{\kappa_0}{\kappa} \left(\frac{g_0^2}{g^2} \right)^2 \left(\frac{\lambda_{GW peak}}{22} \right)^2$$

Implications and conclusions .

Generic Expectation of String Axiverse

- Presence of multiple axions with CS couplings.
- Spectrum of peaked GW from multiple spectator sectors.
- Be careful of the tadpole.

→ Search for GW/ Scalar forest

Explanation of nanoGRAV Signal

- Need large Euler characteristic → specific corner of the landscape.
- Large Hodge number → many axions.
- Additional axions generate smaller GW peaks.