GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Unterstützt von / Supported by
Alexander von Humboldt Stiftung/Foundation

VACUA IN THE STRING AXIVERSE

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2209.XXXX

STRING PHENO 2022

LIVERPOOL

KREUZER-SKARKE AXIVERSE

PHYSICAL QUANTITIES

$$\mathcal{L} = -\frac{1}{8\pi^2} M_{\rm pl}^2 K_{ij} g^{\mu\nu} \partial_\mu \theta^i \partial_\nu \theta^j$$

$$+ \sum_{a=1}^{\infty} \Lambda_a^4 \left\{ 1 - \cos\left(\sum_i \mathcal{Q}_i^a \theta^i + \delta^a \right) \right\}$$

PHYSICAL QUANTITIES

$$\mathcal{L} = -\frac{1}{8\pi^2} M_{\rm pl}^2 K_{ij} g^{\mu\nu} \partial_\mu \theta^i \partial_\nu \theta^j + \sum_{a=1}^{\infty} \Lambda_a^4 \left\{ 1 - \cos\left(\sum_i Q_i^a \theta^i + \delta^a \right) \right\}$$

geometry

0

CYTOOLS

DEMIRTAS+ 2018, 2020

- Cornell group modified and automated an algorithm to compute various geometric quantities including
  - basis of divisors and their volumes, τ_i
  - volume of the CY_3, $\mathcal{V}$
  - Kähler metric, K
  - … and many
  - … many more!

GEOMETRIC QUANTITIES → PHYSICS

$$V = -\frac{8\pi}{\mathcal{V}^2}\Bigg[\sum_\alpha q_\alpha{}^i \tau_i e^{-2\pi q_\alpha{}^i \tau_i}\cos\left(2\pi q_\alpha{}^i \theta_i\right)$$

$$+ \sum_{\alpha>\alpha'}\left(\pi (K^{-1})_{ij} q_\alpha{}^i q_{\alpha'}{}^j + (q_\alpha{}^i + q_{\alpha'}{}^i)\tau_i\right)$$

$$\times\ e^{-2\pi\tau_i (q_\alpha{}^i + q_{\alpha'}{}^i)}\cos\left(2\pi\theta_i (q_\alpha{}^i - q_{\alpha'}{}^i)\right)\Bigg]$$

subleading cross-terms
i.e. positive integer linear
combinations of volumes

GEOMETRIC QUANTITIES → PHYSICS

instanton charge matrix –
$\mathbb{I}_{h^{1,1}}$ + 4 rows of integers
inherited from polytope

$$V = -\frac{8\pi}{\mathcal{V}^2}\left[\sum_\alpha q_\alpha{}^i \tau_i e^{-2\pi q_\alpha{}^i \tau_i} \cos\left(2\pi q_\alpha{}^i \theta_i\right)\right]$$

instanton scales –
extremely hierarchical!

axions –
string lattice basis

MINIMA IN THE AXIVERSE

SYSTEMS WITH HOMOGENEOUS Λ

KLEBAN+ 2017, 2018,...

- For $P = N + 1$ and $N \gg 1$, number of vacua scales like

RM size of Q ←

$$\sigma_Q^N \sqrt{N!}$$

- What about multiaxion systems derived from string geometries? i.e. with large hierarchies

SYSTEMS WITH HIERARCHIES

- In a single axion, 2 instanton example

$$V(\theta) = \Lambda_1^4 \left[1 - \cos(q_1 \theta)\right] + \Lambda_2^4 \left[1 - \cos(q_2 \theta)\right]$$

- Hierarchy is defined as

$$\frac{|\Lambda_2^4|}{|\Lambda_1^4|} \frac{q_2}{q_1} \left(1 + \frac{q_2}{q_1}\right) < \frac{2}{\pi}$$

SYSTEMS WITH HIERARCHIES

- using an irreducible form

$$\frac{q_1}{q_2} = \frac{a}{b} \in \mathbb{Q}^+$$

- the fundamental domain

$$\theta \in \left[0, \frac{2\pi\, a}{q_1}\right)$$

- number of vacua

$$\mathcal{N}_{\text{vacua}} = a$$

SYSTEMS WITH HIERARCHIES

- with multiple axions, fundamental domain (leading)

$$\mathcal{F}_{\text{leading}} = \left\{ \sum_{i=1}^{N} p_i \tilde{\boldsymbol{\theta}}_{(i)} \,\middle|\, p_i \in [0,1) \right\}$$

- single vacuum

$$\boldsymbol{\theta} = 0$$

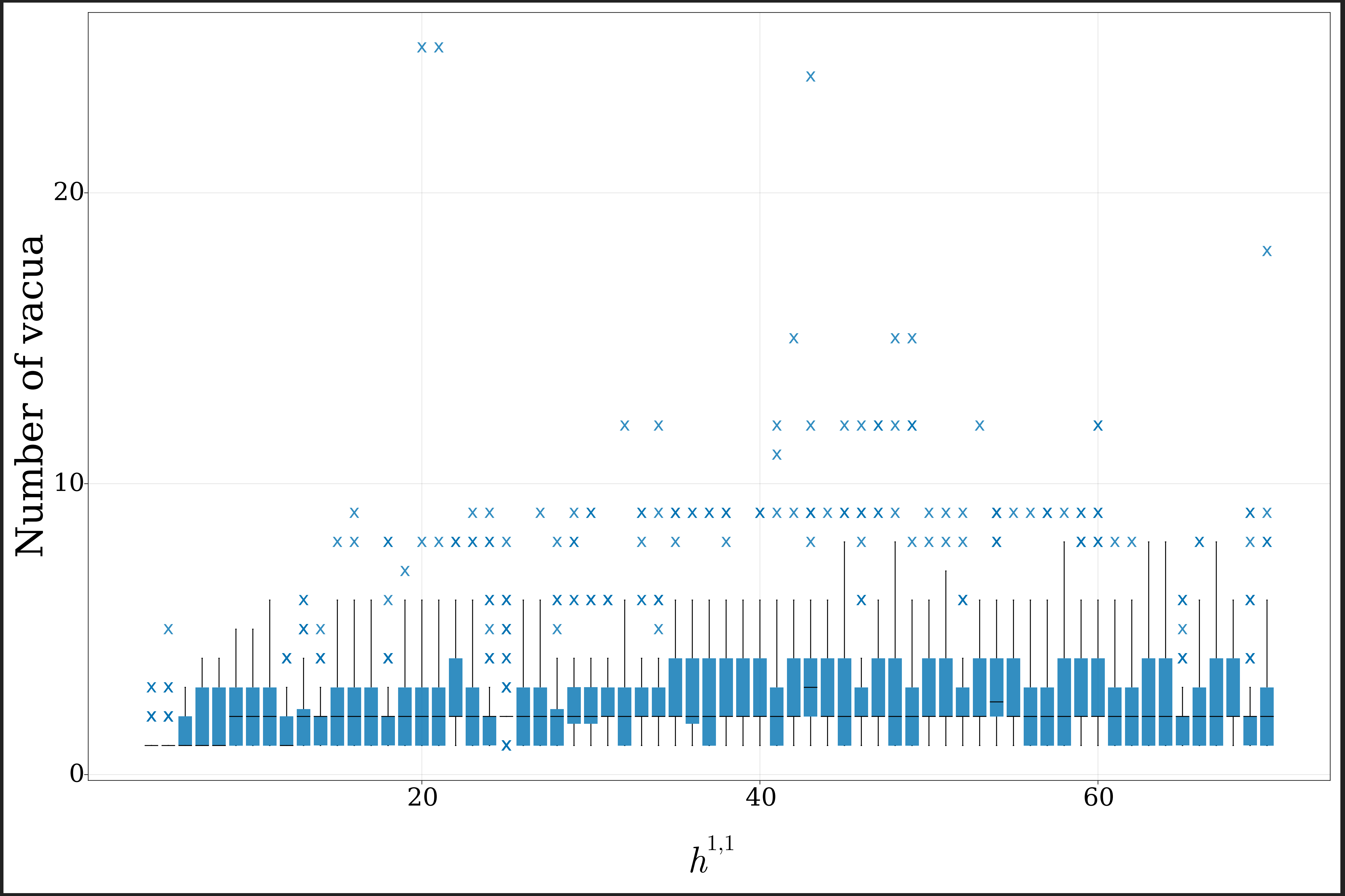
- other vacua at edges (outside leading FD)

SYSTEMS WITH HIERARCHIES

- extending to multiple axions, number of vacua is given by number of `replica` leading FDs in fully potential

$$\mathcal{N}_{\text{vacua}} = \frac{\text{vol}\left(\mathcal{F}_{\text{full}}\right)}{\text{vol}\left(\mathcal{F}_{\text{leading}}\right)}$$

AXIVERSE STATISTICS



COMPUTING AXIVERSE STATISTICS

- Using **ju**(lia)**CY**(Tools)**Axiverse**(calculator) full spectrum statistics derived from KS database
- Outputs include vacua (locations and number as discussed), masses, decay constants, quartic self-couplings(?)
- Fully parallelised code – ideal for HPC

The juCYAxiverse is coming to a cluster near you soon!

THANKS!