

Statistical aspects of type II orientifolds

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Plan

- Motivation

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- Orientifold models

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- Methods of statistical analysis

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- Results

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- Methods of statistical analysis
- Results
- Conclusions and Outlook

Motivation

- **Statistical approach** to string vacuum problem

[Ashok, Denef, Douglas, Shiffman, Zelditch; De Wolfe, Giryavets, Kachru, Taylor, Tripathi; Misra, Nanda; Conlon, Quevedo; Kumar, Wells; Dine, Gorbатов, Thomas, O'Neil, Sun; Dienes, Dudas, Gherghetta; Acharya, Denef, Valandro]

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- Analysis of the gauge sector in a specific setup
- Compare results of an alternative approach to brute force calculation
- Correlations between observables?
- How does the **coupling to fluxes** affect the statistics?

Models

General setup:

- Type IIB orientifold flux compactifications
- Analysis of the ($\mathcal{N} = 1$) gauge sector

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General setup:

- Type IIB orientifold flux compactifications
- Analysis of the ($\mathcal{N} = 1$) gauge sector
- RR/NSNS 3-form fluxes to freeze complex structure moduli and dilaton
 - ↪ we want a finite number of vacua
- Add magnetized D-branes to cancel tadpoles and get chiral fermions
 - ↪ in the special class of orbifolds we are considering the consistency conditions are well under control

Models

T-dual picture:

type IIA/ $\Omega\bar{\sigma}$ with D6-branes at angles

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- **O6-planes:**

$$\pi_{\text{O6}} = \frac{1}{2} \sum_{I=1}^{b_3/2} L_I \alpha_I$$

- **D6-branes:**

$$\pi_a = \sum_{I=1}^{b_3/2} (X_{a,I} \alpha_I + Y_{a,I} \beta_I),$$

$$\pi'_a = \sum_{I=1}^{b_3/2} (X_{a,I} \alpha_I - Y_{a,I} \beta_I)$$

Models

Tadpole cancellation:

$b_3/2 = 1 + h_{21}$ conditions **TAD**:

$$\sum_{a=1}^k N_a X_{a,I} = L_I - L_{I,flux}$$

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Supersymmetry conditions **SUSY**:

- sLag condition: $\Im(\Omega_3)|_{\pi_a} = \sum_{I=1}^{b_3/2} Y_{a,I} F_I(U) = 0$, where

$$F_I = \int_{\beta_I} \Omega_3$$

- anti-branes: $\Re(\Omega_3)|_{\pi_a} = \sum_{I=1}^{b_3/2} X_{a,I} U_I > 0$

Models

Chiral matter:

At the **intersection** of D-branes

$$I_{ab} = \sum_I X_{a,I} Y_{b,I} - Y_{a,I} X_{b,I}$$

\rightsquigarrow I_{ab} chiral multiplets in a bifundamental $U(N_a) \times U(N_b)$ representation.

Models

$$M = T^2 \times T^2 \times T^2 / \mathbb{Z}_2 \times \mathbb{Z}_2, (h_{1,1}, h_{2,1}) = (51, 3)$$

see e.g. [Blumenhagen, Lüst, Taylor; Cascales, Uranga; Marchesano, Shiu; Cvetič, Liu]

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- Wrapping numbers $(n_I, m_I), I \in \{1, 2, 3\}$
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- Define

$$X_0 = n_1 n_2 n_3, \quad X_1 = -n_1 m_2 m_3, \quad X_2 = -m_1 n_2 m_3, \quad X_3 = -m_1 m_2 n_3,$$

$$Y_0 = m_1 m_2 m_3, \quad Y_1 = -m_1 n_2 n_3, \quad Y_2 = -n_1 m_2 n_3, \quad Y_3 = -n_1 n_2 m_3,$$

satisfying

$$X_I Y_I = X_J Y_J \quad \forall I, J, \quad X_I X_J = -Y_K Y_L,$$

$$X_L (Y_L)^2 = -X_I X_J X_K, \quad Y_L (X_L)^2 = -Y_I Y_J Y_K \quad \forall I \neq J \neq K \neq L \neq I$$

Models

- **SUSY**: $\sum_{I=0}^3 Y_I U_I^{-1} = 0$, $\sum_{I=0}^3 X_I U_I > 0$,
where $U_i = \tilde{U}_j \tilde{U}_k = \frac{R_{j2} R_{k2}}{R_{j1} R_{k1}}$
- **TAD**: $\sum_a N_a X_{a,I} = L_I$, with $I \in \{0, 1, 2, 3\}$

Physically: $L_0 = 8 - N_{flux}$, $L_i = 8$ with $i \in \{1, 2, 3\}$

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SUSY restricts amount of admissible 3-form flux

- only stacks with 1, 2, or 4 non-vanishing X_I are possible

Models

- in the latter case: $X_A = - \left(\sum_i \frac{U_A}{U_i X_i} \right)^{-1}$
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$$1 \leq X_i \leq \sum_{P=0}^3 \frac{u_{P,2} u_{Q,1} u_{R,1} u_{S,1} L_P}{u_{i,2} u_{J,1} u_{K,1} u_{L,1}}$$

\rightsquigarrow for fixed complex structures only a finite number of branes are admissible

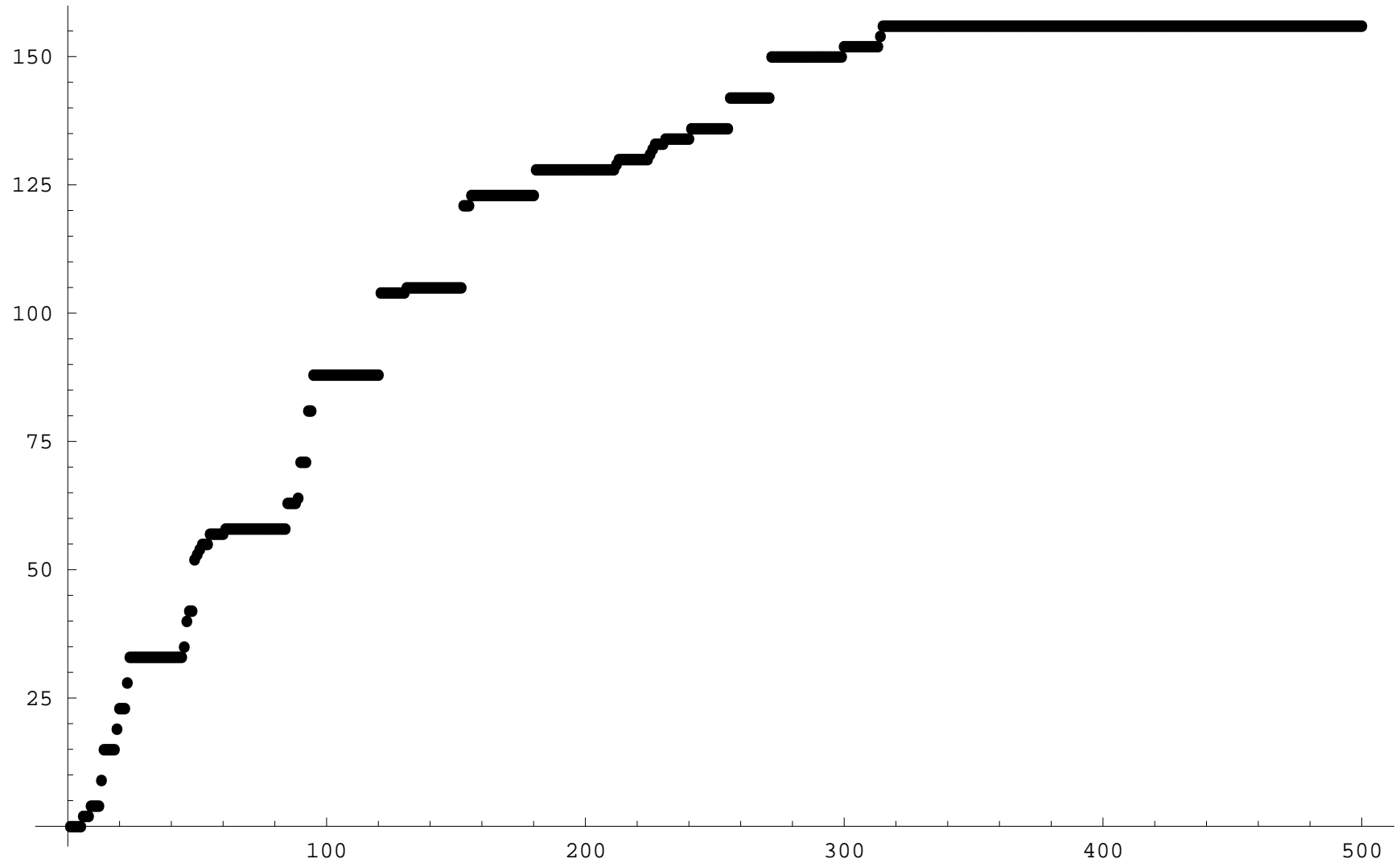
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- \rightsquigarrow for fixed complex structures only a finite number of branes are admissible
- computer analysis: for fixed L_I also only a finite number of complex structures allow any solution

Number of solutions



Numerical analysis of the growth of solutions, $L_I = 2$

Methods

Aim: Estimate number of unordered solutions of diophantine equations of the form

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Two possible methods:

- Brute force computer analysis
- Saddle point approximation

Computer search

Based on fast algorithm to calculate partitions and factorisations of natural numbers.

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Def. $\hat{U}_I = U_I R_{11} R_{21} R_{31} \in \mathbb{N}$, $\sigma_a = \sum_I \hat{U}_I X_{a,I}$.

$$\rightsquigarrow \sum_a N_a \sigma_a = \sum_I L_I \hat{U}_I$$

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- With the help of a computer cluster all possible solutions (for a given set of U_I) can be found.
- This has been done and an almost complete classification of models on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ has been achieved.

Saddle point method

- **Problem:** Find an analytic method to get an approximate solution to the number of partitions.

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- **Solution** (ordered, k terms):

$$\begin{aligned}\tilde{\mathcal{N}}_k(L) &= \sum_{all} \delta_{\sum S_a} S_a - L, 0 \\ &\simeq \frac{1}{2\pi i} \oint dq \frac{1}{q^{L+1}} \sum_{S_1=1}^{\infty} \cdots \sum_{S_k=1}^{\infty} q^{\sum_a S_a} \\ &= \frac{1}{2\pi i} \oint dq \frac{1}{q^{L+1}}\end{aligned}$$

Saddle point method

- **saddle point approximation:** Set $q = \rho \exp(i\varphi)$ and Taylor expand $f(q)$ around the saddle point q_0

$$f(\rho_0, \varphi) = f(q_0) + \frac{1}{2} \frac{\partial^2 f}{\partial \varphi^2} \Big|_{q_0} \varphi^2 + \dots$$

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- Leading order SAP

$$\mathcal{N}^{(0)}(L) = e^{f(q_0)}$$

Next-to-leading order SAP

$$\mathcal{N}^{(2)}(L) = \frac{1}{\sqrt{2\pi}} \frac{e^{f(q_0)}}{\sqrt{\frac{\partial^2 f}{\partial q^2} \Big|_{q_0}}}$$

Saddle point method

Further approximation to arrive at tractable generating functions:

divide number of ordered solutions with k summands by $k!$ and sum over all k

$$\begin{aligned}\tilde{\mathcal{N}}(L) &\simeq \frac{1}{2\pi i} \oint dq \frac{1}{q^{L+1}} \sum_{k=1}^{\infty} \frac{1}{k!} \sum_{S_1=1}^{\infty} \cdots \sum_{S_k=1}^{\infty} q^{\sum_a S_a} S_a \\ &= \frac{1}{2\pi i} \oint dq \frac{1}{q^{L+1}} \sum_{k=1}^{\infty} \frac{1}{k!} \left(\frac{q}{1-q} \right)^k \\ &\simeq \frac{1}{2\pi i} \oint dq \frac{1}{q^{L+1}} \exp \left(\frac{q}{1-q} \right)\end{aligned}$$

Saddle point method

- Leading order SPA:

$$\tilde{\mathcal{N}}(L) \simeq e^{2\sqrt{L}}$$

Saddle point method

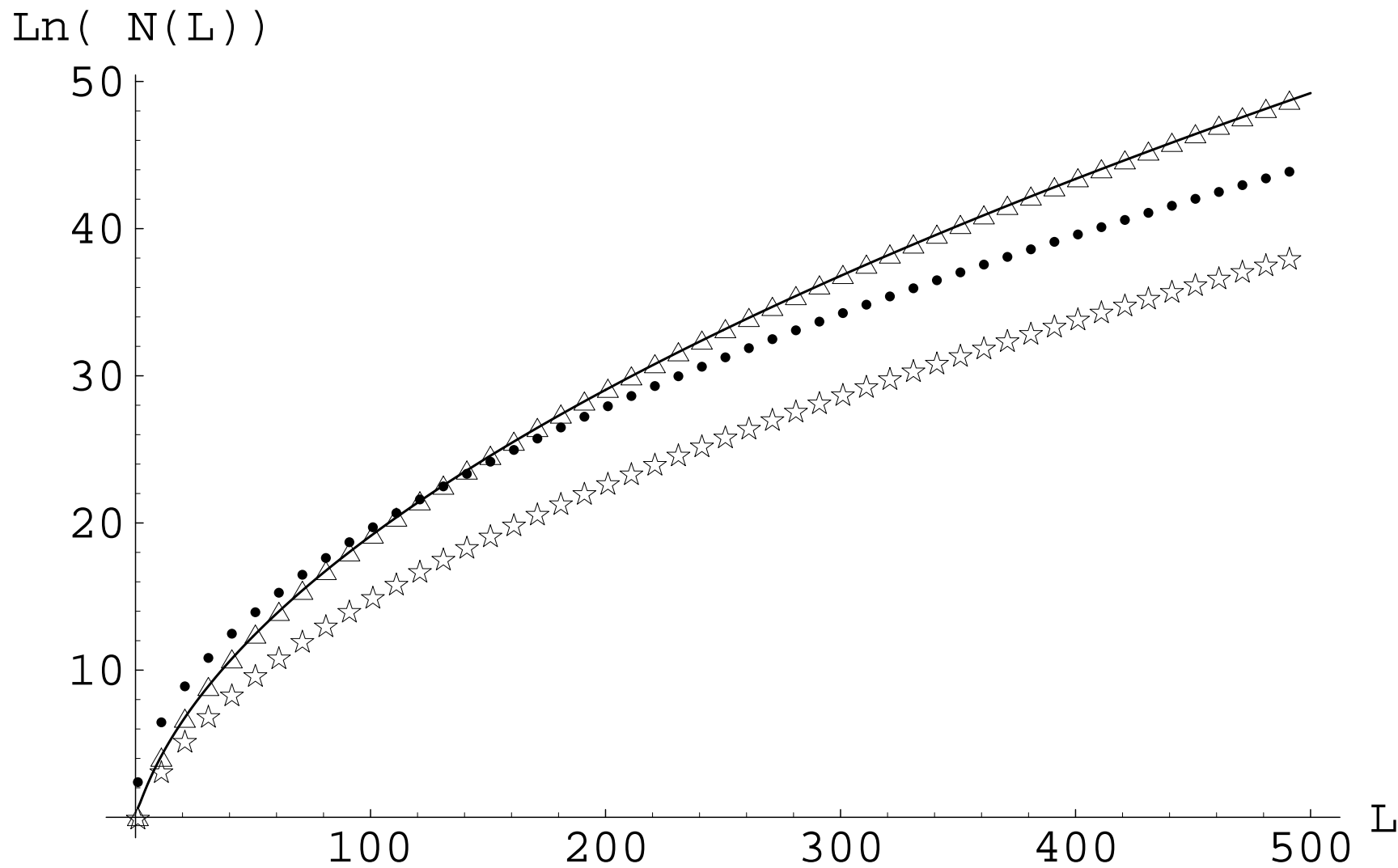
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- Is this approximation justified?

$$\frac{\log \mathcal{N}}{\log \tilde{\mathcal{N}}} = \frac{\pi}{\sqrt{6}} \simeq 1.28$$

Methods



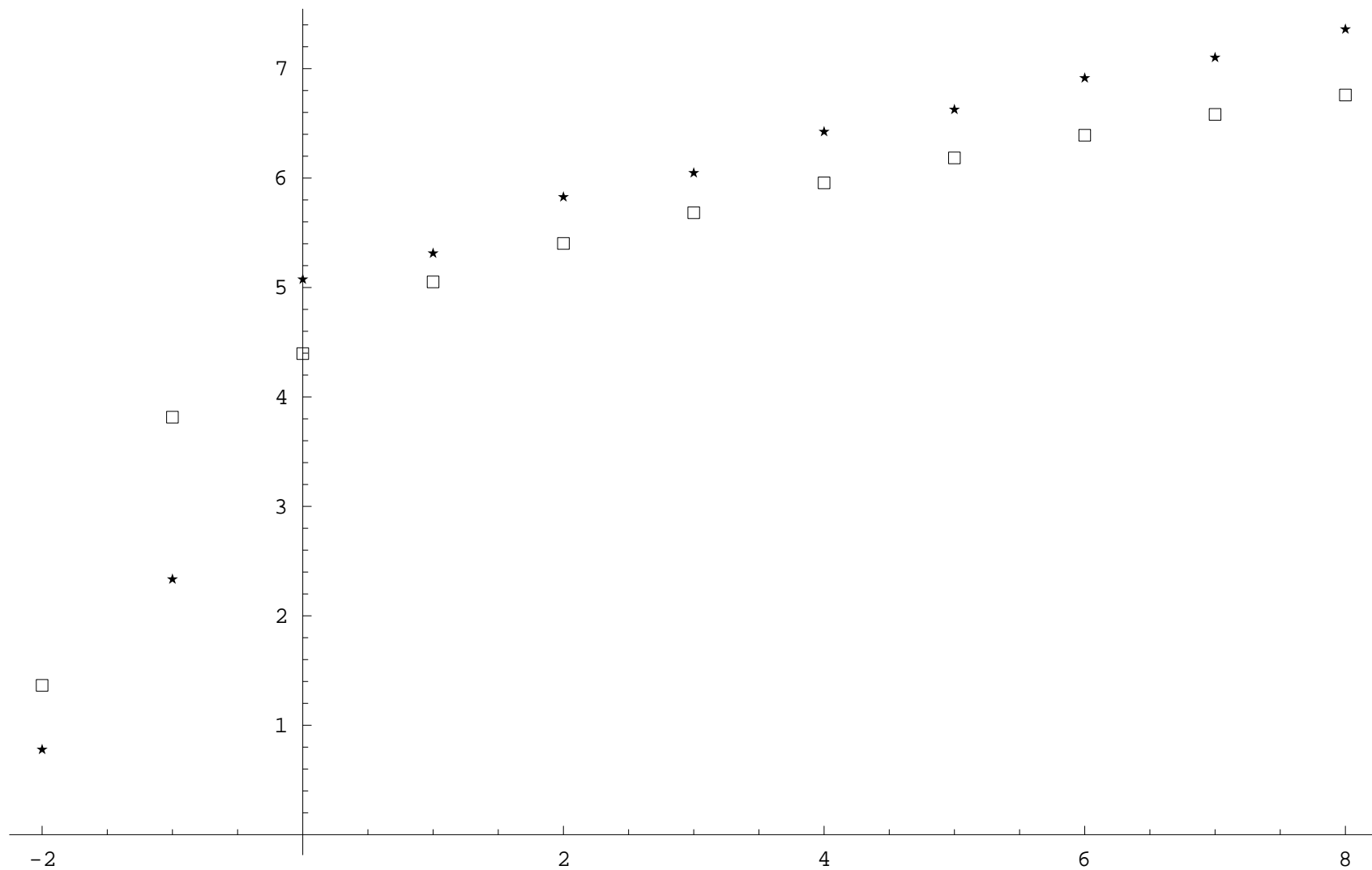
Line: exact result, Dots: leading order SPA, Stars: 2nd order SPA,
Triangles: 2nd order with factor 1.28

Results - $\mathcal{N}(L)$

Total number of models:

$$\mathcal{N}(L_I) \simeq \frac{1}{(2\pi i)^4} \oint dq_0 dq_1 dq_2 dq_3 \exp \left(\sum_{X_I} \frac{\prod_I q_I^{X_I}}{1 - \prod_I q_I^{X_I}} - \sum_I (L_I + 1) \log q_I \right)$$

Results - $N(L)$



$L_i = 8, \quad U_I = 1, \quad \text{Stars: Exact, Boxes: Saddle point approx.}$

K-Theory constraints

In addition to the susy and tadpole equations we get an additional constraint from K-Theory: [Uranga; Marchesano, Shiu]

$$\sum_a N_a Y_{0,a} \in 2\mathbb{Z}$$

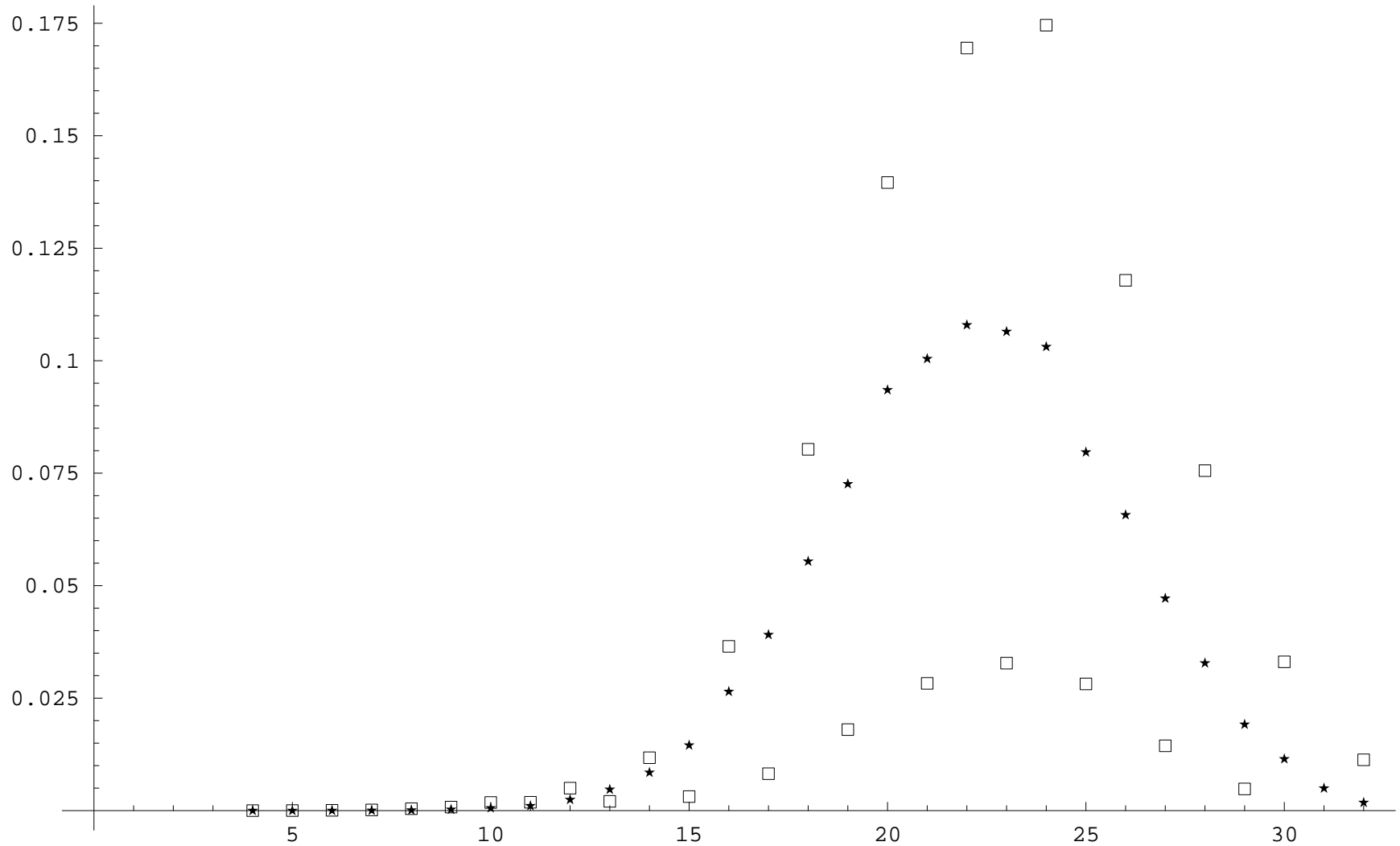
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- Number of solutions changes by a factor of 6
- Models which have an odd rank of the gauge group are suppressed
 \rightsquigarrow rank-distribution changes. ($rk = \sum_a N_a$)

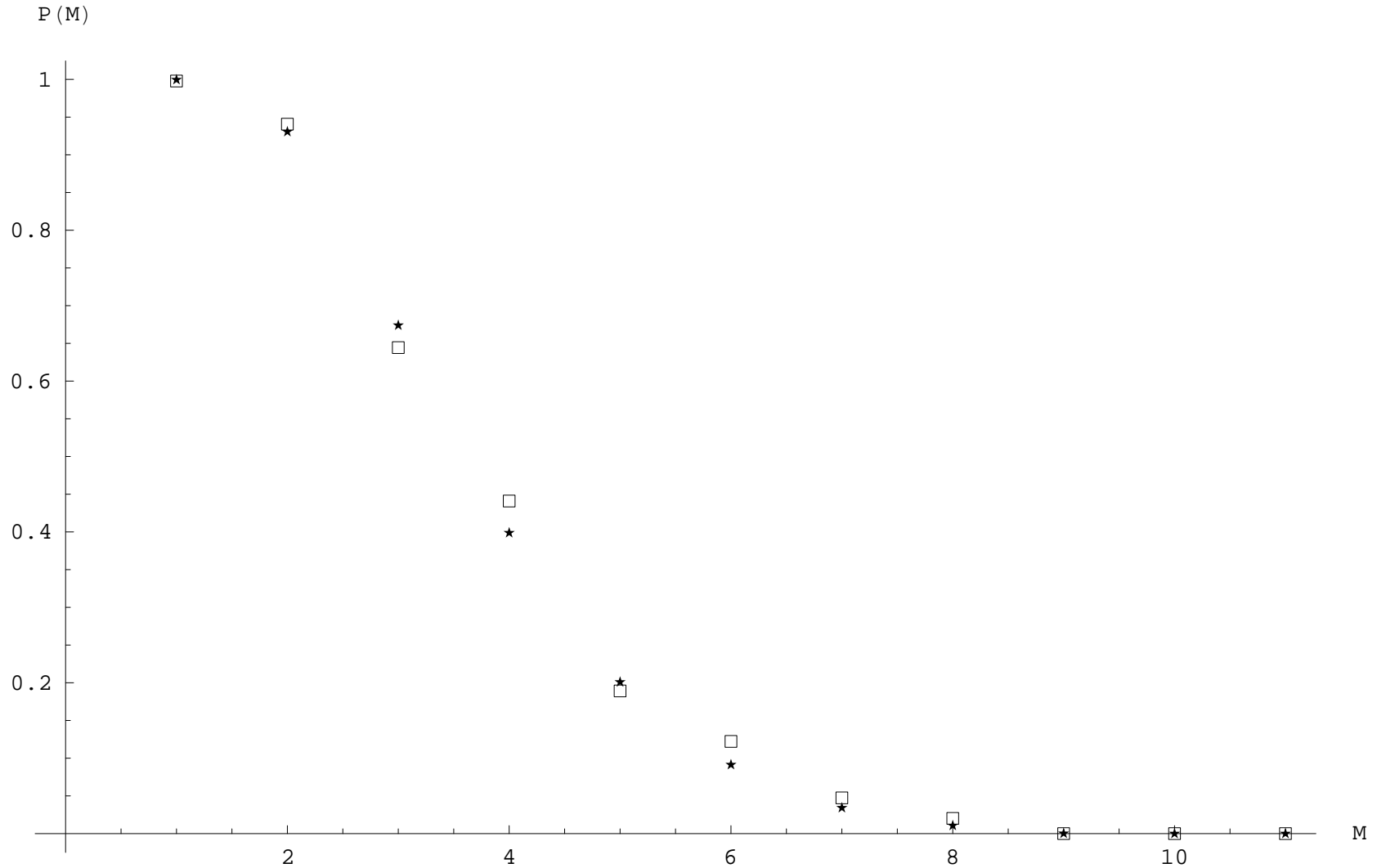
Results - rank distribution



$L_0 = L_1 = L_2 = L_3 = 8, \quad U_I = 1, \quad \text{exact results,}$

Stars: without K-Theory constraints, Boxes: with K-Theory constraints

Results - P(M)



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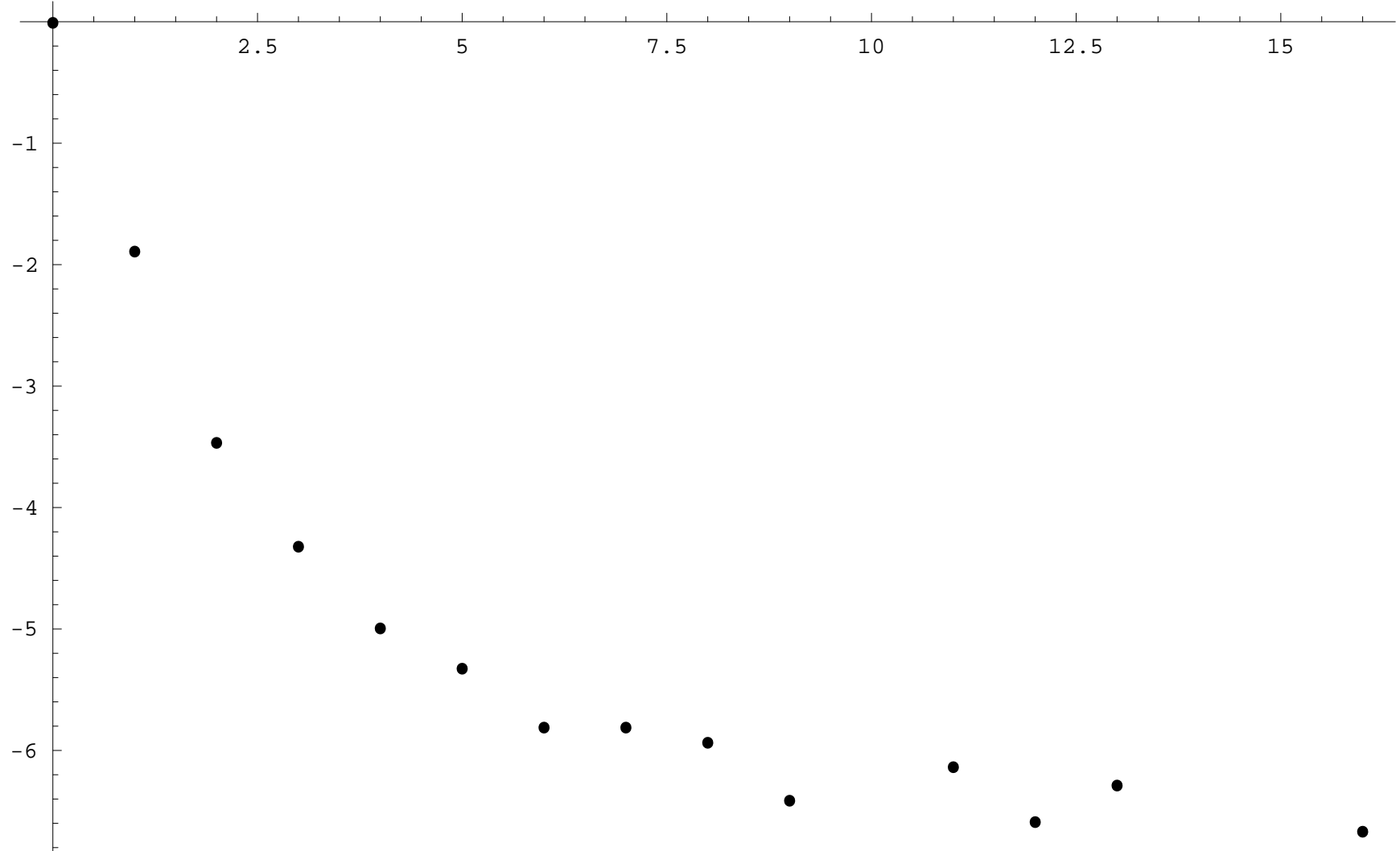
Results - chirality

Consider as measure for **chirality** the quantity

$$\chi = I_{a',b} - I_{a,b} = 2 \vec{Y}_a \vec{X}_b$$

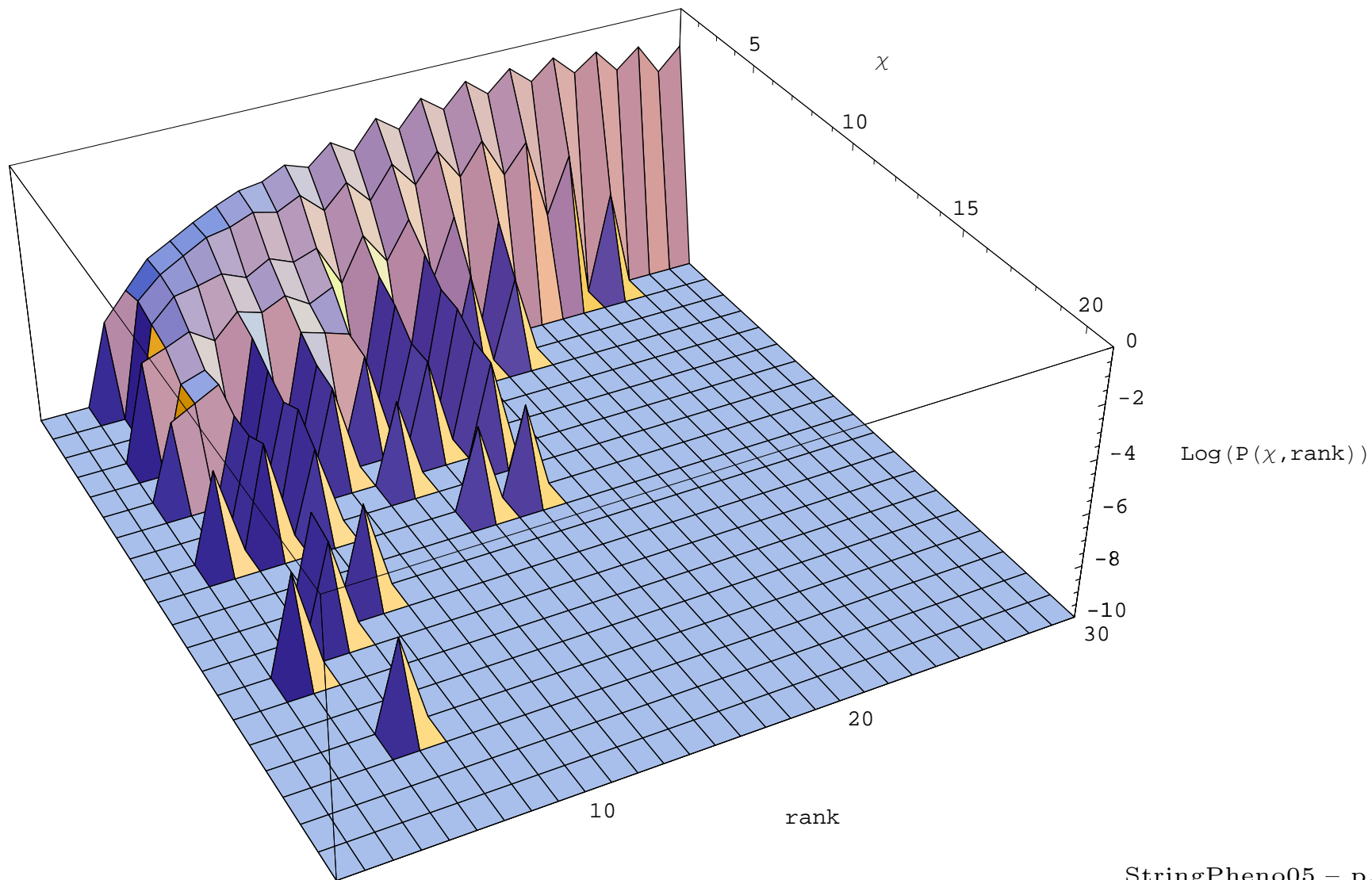
odd χ possible from **tilted tori**

Results - chirality



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Results - rank-chirality-distribution



Results - inclusion of fluxes

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- # of flux vacua for given $N_{flux} \leq L^*$ scales like

$$\mathcal{N} \simeq (L^*)^K$$

where K : number of three-cycles,
above scaling valid if $L^* \gg K$

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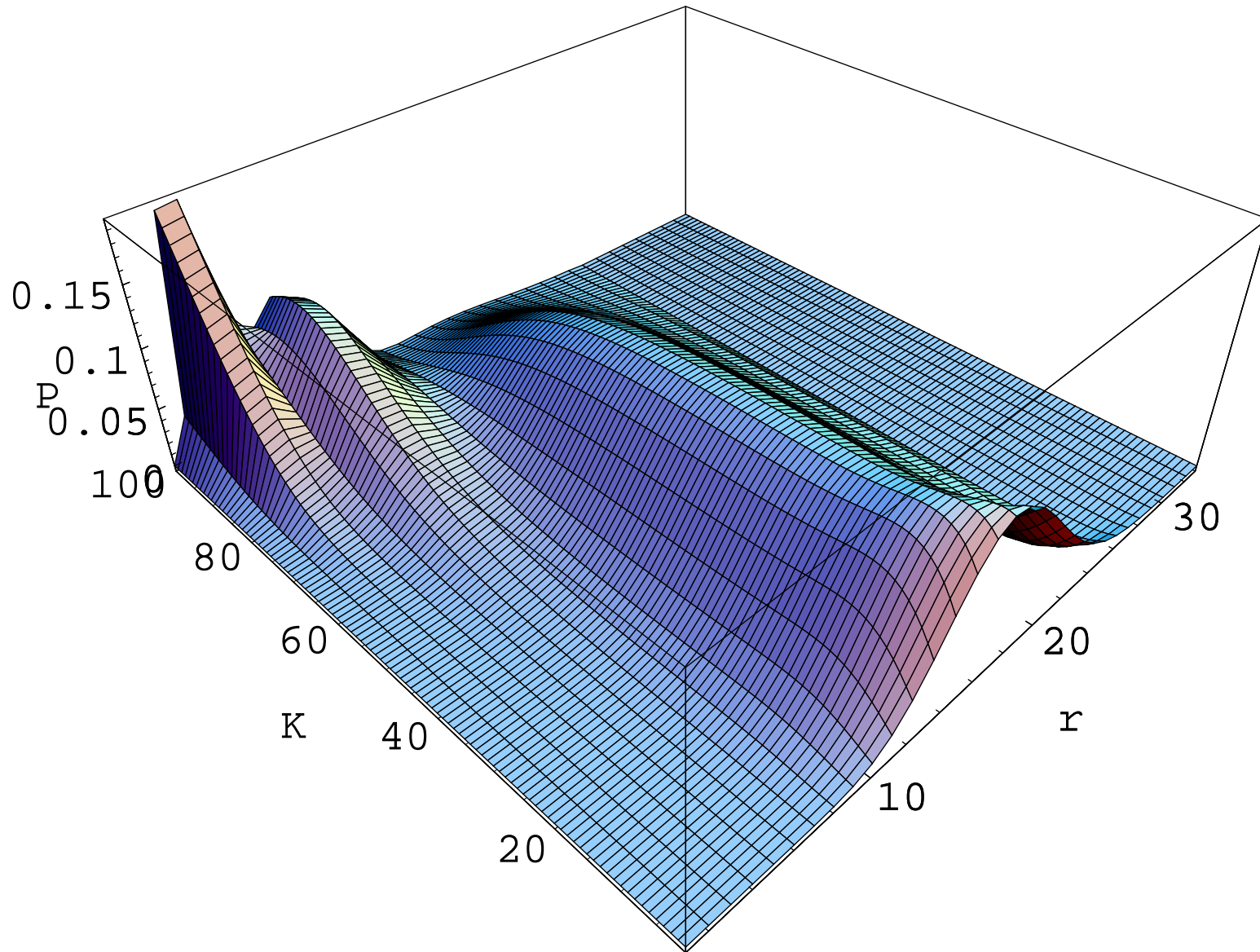
- our case: $L \leq 8$, $K \simeq 10$ if we only allow for bulk fluxes,
 $K \simeq 100$ if we allow for twisted fluxes
nevertheless: assume polynomial scaling as above

Results - inclusion of fluxes

Example: rank distribution:

$$\bar{P}(r) = \frac{1}{N_{norm}} \sum_{N_{flux}=0}^{N_{flux}^{max}} (N_{flux} + 1)^K \mathcal{N}(r; L_0 - N_{flux}, L_1, L_2, L_3)$$

Results- inclusion of fluxes



MSSM statistics

Final aim: Systematic investigation of number distribution of MSSM vacua (and modifications thereof) among set of SUSY solutions

↪ MSSM realized on 4 or 3 stacks of branes

- 4 stacks:

$$U(3)_a \times U(2)_b / Sp(2)_b \times U(1)_c \times U(1)_d$$

$$\text{stack a: QCD: } U(3)_a = SU(3)_{QCD} \times U(1)_a$$

$$\text{stack b: weak physics: } U(2)_b = SU(2)_w \times U(1)_b / \\ Sp(2) = SU(2)_w$$

$$U(1)_Y: \text{ appropriate massless combination } Q_Y = \sum x_i Q_i$$

- 3 stacks:

possible if $x_c = x_d$ by dropping stack d in 4 stack solution

MSSM statistics

⇒ Minimal set of additional constraints on wrapping numbers: **MSSM chiral spectrum** on intersections of MSSM branes

$$\#(N_a, \overline{N}_b) = \pi_a \circ \pi_b = \sum_{I=0}^3 (X_I^a Y_I^b - X_I^b Y_I^a)$$

$$\#\text{Anti}_a = \frac{1}{2}(\pi_a \circ \pi_{a'} + \pi_a \circ \pi_{O6}) = \sum_{I=0}^3 (-X_I^a Y_I^a + \frac{1}{4}L_I Y_I^a)$$

$$\#\text{Sym}_a = \frac{1}{2}(\pi_a \circ \pi_{a'} - \pi_a \circ \pi_{O6}) = \sum_{I=0}^3 (-X_I^a Y_I^a - \frac{1}{4}L_I Y_I^a)$$

⇒ systematic realization of MSSM quantum numbers

MSSM statistics

- Anomaly considerations
 - Freedom of non-abelian anomalies guaranteed by RR- tadpole cancellation and anomalous coupling of RR/NSNS-flux to D-branes
 - $U(1)_a - SU(N_b)^2$ mixed anomalies cancelled by GS mechanism

But have to ensure that specific realization of $U(1)_Y = \sum x_i U(1)_i$ is anomaly free in first place and does not receive mass by GS-coupling, i.e.

$$\sum_a x_a N_a Y_I^a = 0, \quad I = 0, \dots, 3$$

MSSM statistics

- Distribution of models with **gauge unification** at string scale among MSSM vacua:

Gauge coupling on stack a given by

$$\frac{4\pi^2}{(g_{YM})_a^2} = \frac{M_S}{g_S} L_a,$$

where length L_a of SUSY brane a is given by

$$\begin{aligned} L_a &= \prod_{i=1}^3 \sqrt{(n_i^a R_i^{(1)})^2 + (\widetilde{m}_i^a R_i^{(2)})^2} \\ &= \left(\prod_{i=1}^3 R_i^{(1)} \right) \left(\sum_{I=0}^3 X_I^a U_I \right) \end{aligned}$$

MSSM statistics

↪ For gauge unification at M_S :

$$L_a = L_b = \sum x_i L_i$$

Work in progress:

Systematic analysis of computational data for MSSM properties.

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Compare with gauge sector from dual theories (M-theory, heterotic).

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- How model dependent are these results?
Compare with gauge sector from dual theories (M-theory, heterotic).
- Explicit evaluation for MSSM-like configurations needs to be done.