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

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- Statistical approach to string vacuum problem

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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?

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General setup:

- Type IIB orientifold flux compactifications
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- RR/NSNS 3-form fluxes to freeze complex structure moduli and dilaton
  $\rightsquigarrow$ we want a finite number of vacua
- Add magnetized D-branes to cancel tadpoles and get chiral fermions
  $\rightsquigarrow$ in the special class of orbifolds we are considering the consistency conditions are well under control

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T-dual picture:
type IIA$/\Omega\overline{\sigma}$ with D6-branes at angles

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- Symplectic basis: (α_I, β_I) of $H_3(M, \mathbb{Z})$, where $\alpha_I \in H_3^+(M)$ and $\beta_I \in H_3^-(M)$
- O6-planes:

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

- D6-branes:

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

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Tadpole cancellation:

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

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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; Cvetic, Liu]

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- Wrapping numbers $(n_I, m_I), I \in \{1, 2, 3\}$
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- Tilted tori: $\tilde{m}_I = m_I + b_I n_I, \quad b_I \in \{1/2, 1\}$
- Define

$$X_0 = n_1\, n_2\, n_3,\ X_1 = -n_1\, m_2\, m_3,\ X_2 = -m_1\, n_2\, m_3,\ X_3 = -m_1\, m_2\, n_3,$$
$$Y_0 = m_1\, m_2\, m_3,\ Y_1 = -m_1\, n_2\, n_3,\ Y_2 = -n_1\, m_2\, n_3,\ Y_3 = -n_1\, n_2\, m_3,$$

satisfying

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

Models

- SUSY: $\sum_{I=0}^{3} Y_I U_I^{-1} = 0, \quad \sum_{I=0}^{3} X_I U_I > 0,$
  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

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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: $X_A = -\left(\sum_i \frac{U_A}{U_i\, X_i}\right)^{-1}$
  $\rightsquigarrow$ for a sufficient number of these branes the complex structures are fixed at rational values

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$$1 \leq X_i \leq \sum_{P=0}^{3} \frac{u_{P,2} u_{Q,1} u_{R,1} u_{S,1} L_P}{u_{i,2} u_{J,1} u_{K,1} u_{L,1}}$$

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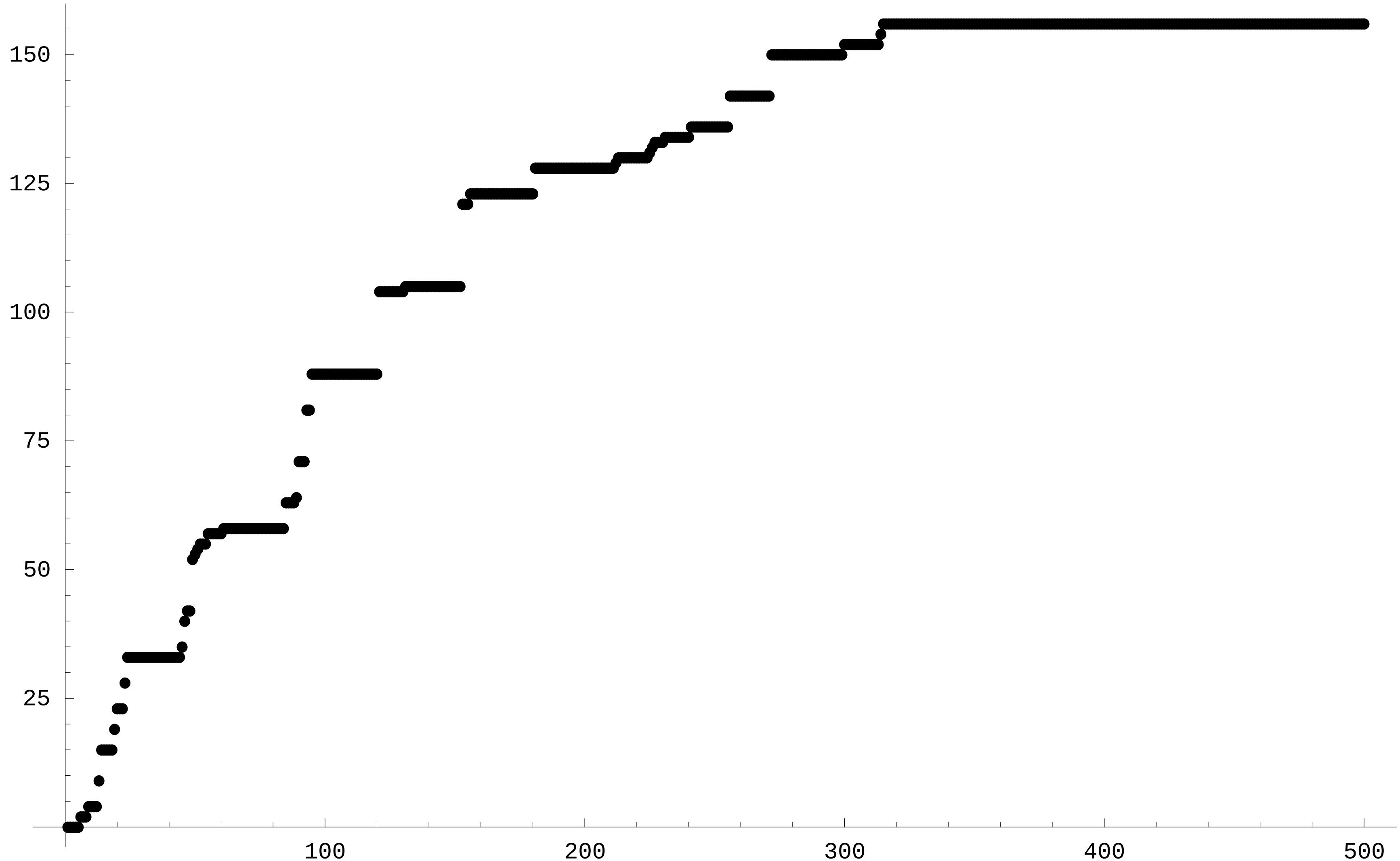
- computer analysis: for fixed L_I also only a finite number of complex structures allow any solution

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

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

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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):

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

Saddle point method

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

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

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- Leading order SAP

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

Next-to-leading order SAP

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

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

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

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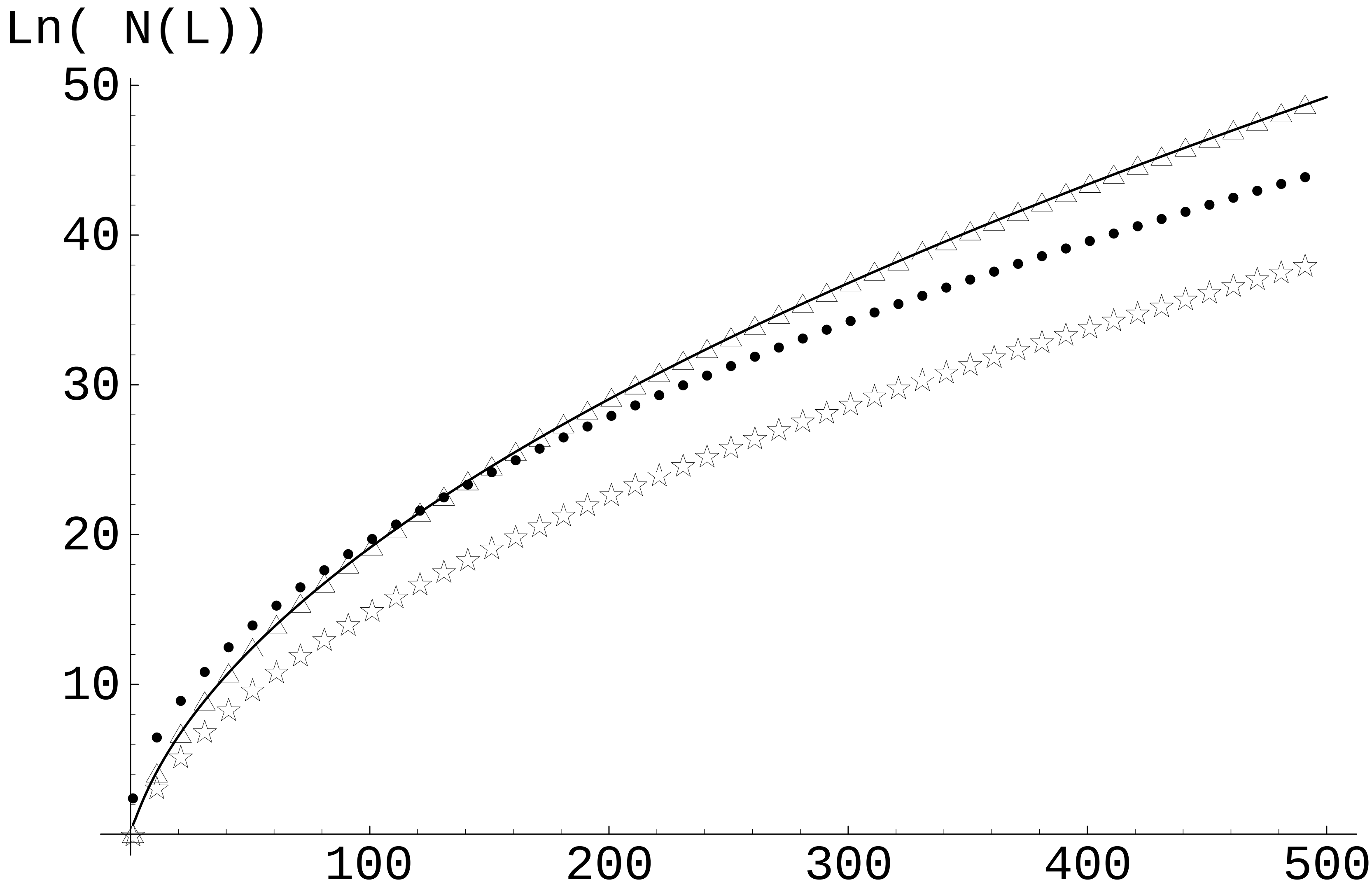
- Is this approximation justified?

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

Methods



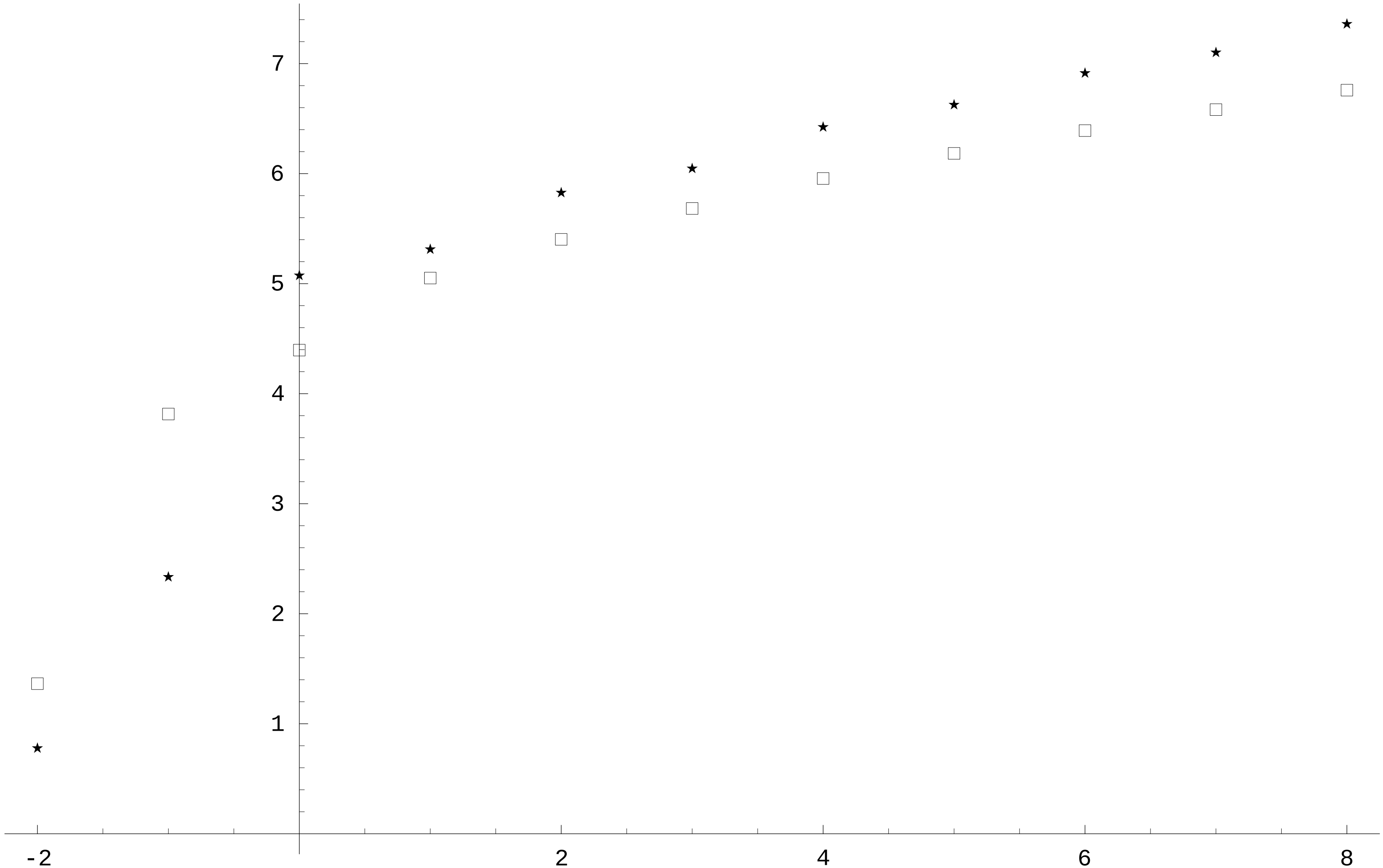
Line: exact result, Dots: leading order SPA, Stars: 2nd order SPA, Triangles: 2nd order with factor 1.28

Results - 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)



$L_i = 8, \quad U_I = 1,$ 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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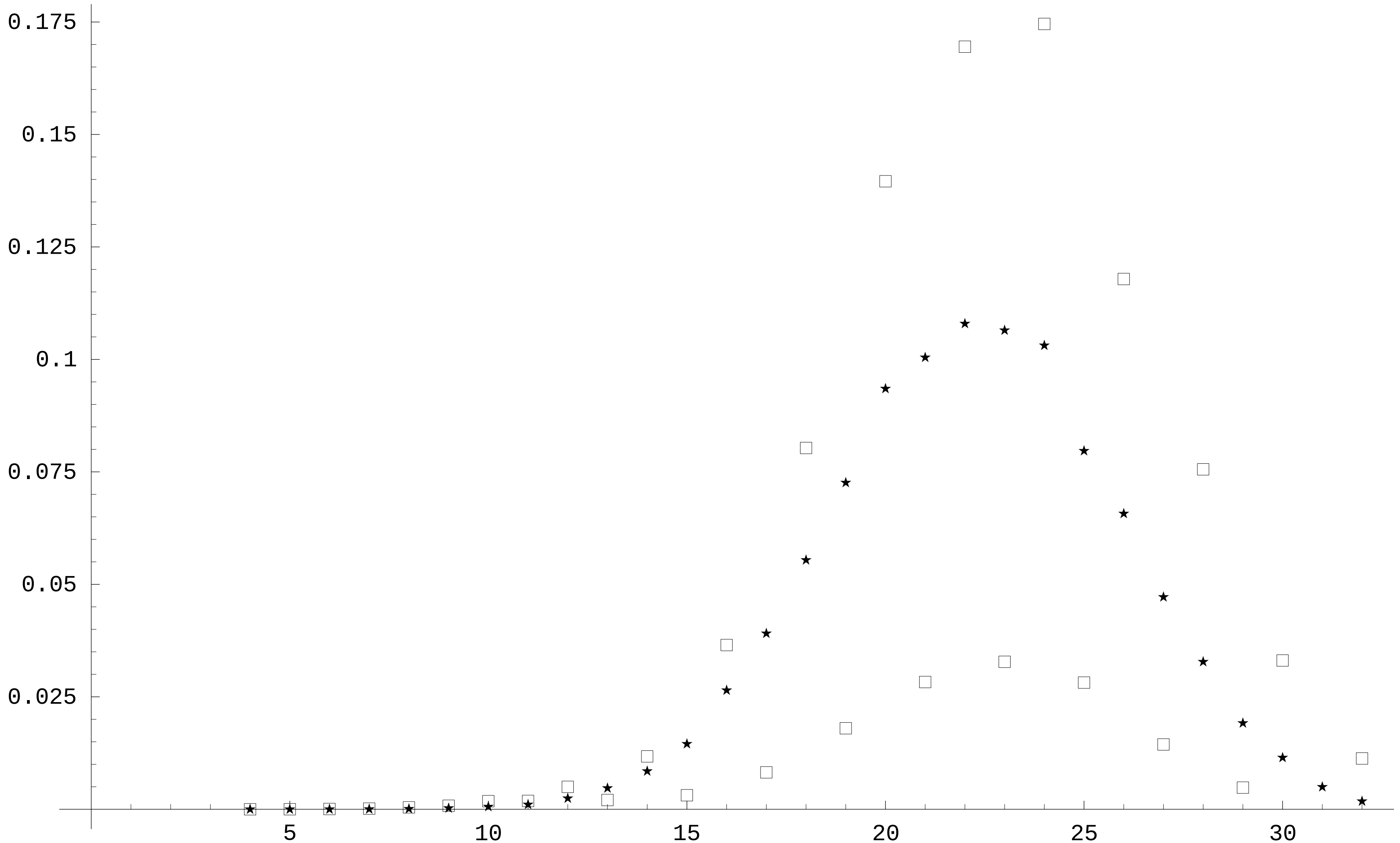
$$\sum_a N_a Y_{0,a} \in 2\mathbb{Z}$$

- 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. $(rk = \sum_a N_a)$

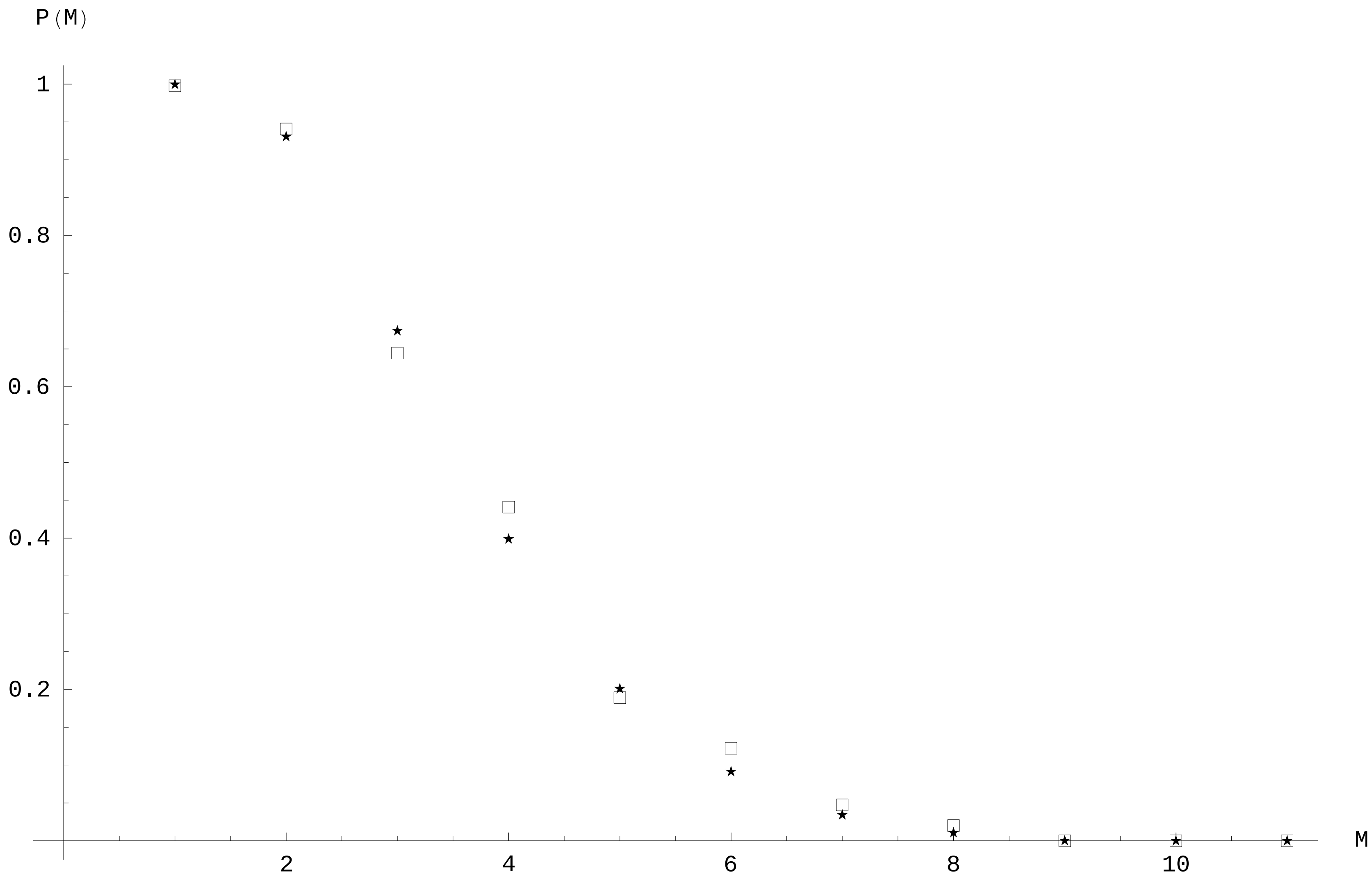
Results - rank distribution



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

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

Results - P(M)



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

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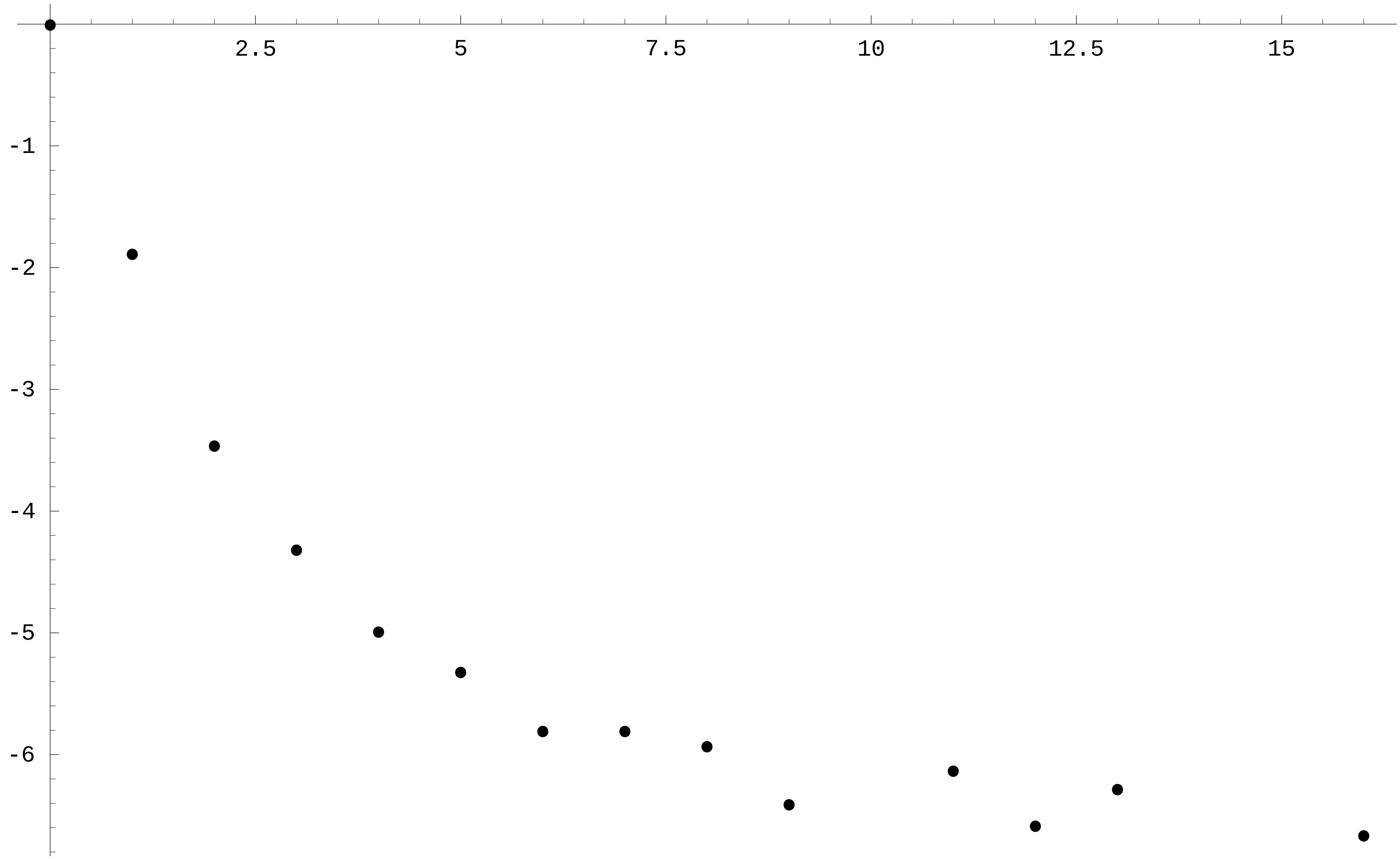
Results - chirality

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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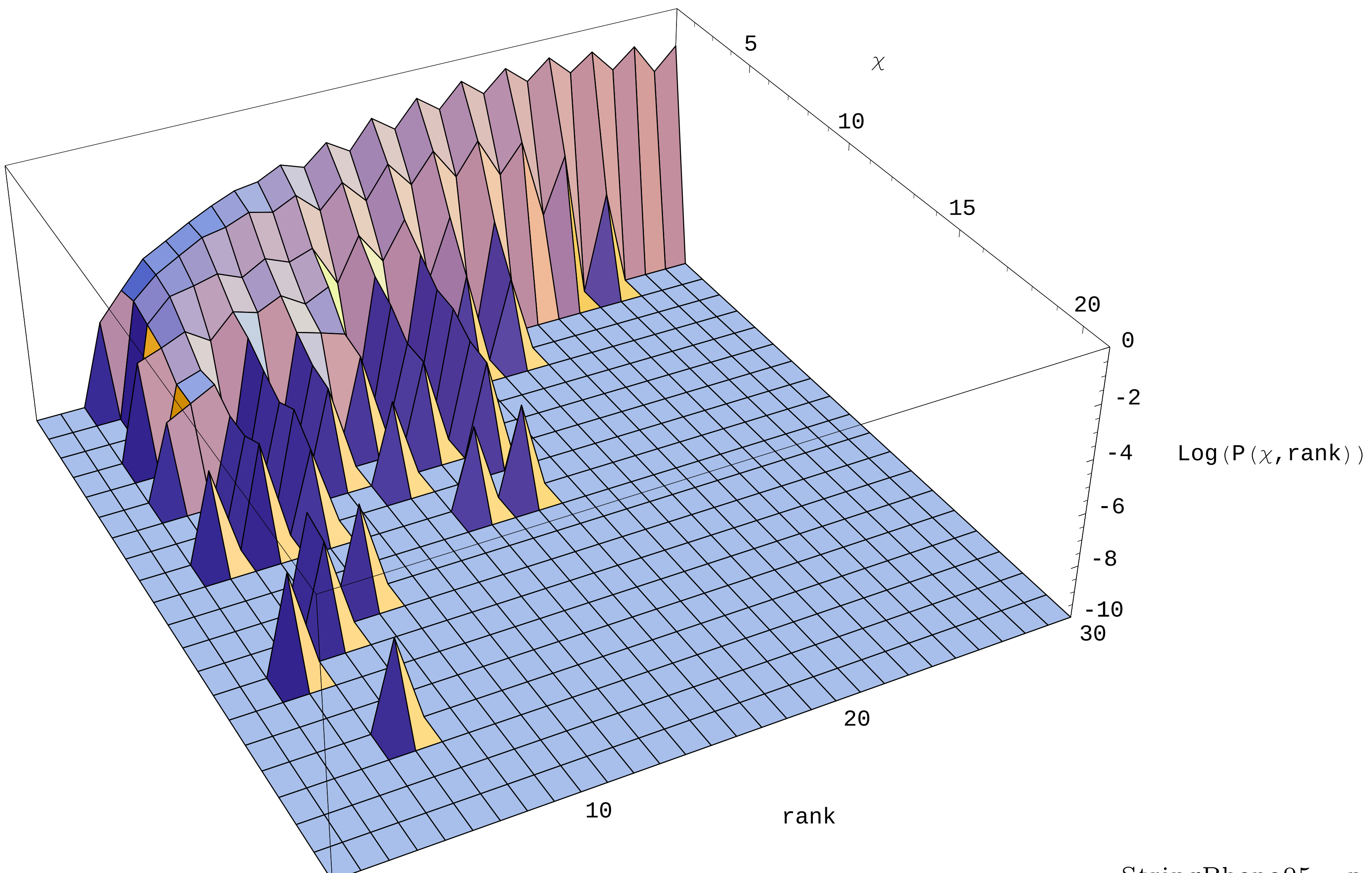
Results - rank-chirality-distribtion



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

[Ashok, Denef, Douglas, Shiffman, Zelditch]

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  [Ashok, Denef, Douglas, Shiffman, Zelditch]

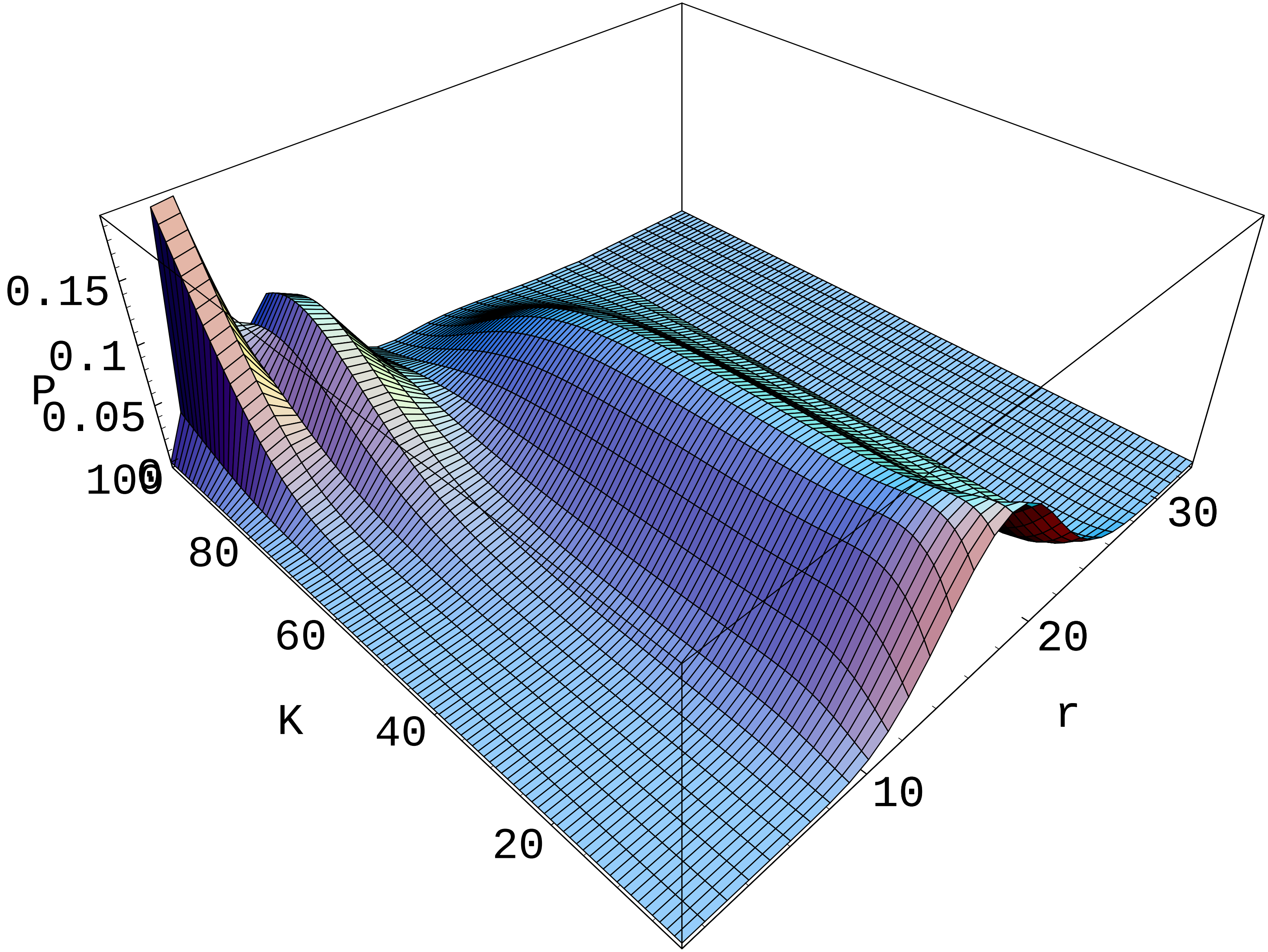
- our case: $L \leq 8$, $K \simeq 10$ if we only allow for bulk fluxes, $K \simeq 100$ if we allow for twisted fluxes
  nevertheless: assume polynomial scaling as above

Results - inclusion of fluxes

Example: rank distribution:

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

Results- inclusion of fluxes



MSSM statistics

Final aim: Systematic investigation of number distribution of MSSM vacua (and modifications thereof) among set of SUSY solutions
$\rightsquigarrow$ MSSM realized on 4 or 3 stacks of branes

- 4 stacks:
  $U(3)_a \times U(2)_b/Sp(2)_b \times U(1)_c \times U(1)_d$
  stack a: QCD: $U(3)_a = SU(3)_{QCD} \times U(1)_a$
  stack b: weak physics: $U(2)_b = SU(2)_w \times U(1)_b$ / $Sp(2) = SU(2)_w$
  $U(1)_Y$: 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

$\rightsquigarrow$ Minimal set of additional constraints on wrapping numbers: MSSM chiral spectrum on intersections of MSSM branes

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

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

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

$\rightsquigarrow$ 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.

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

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

$$L_a = \prod_{i=1}^{3} \sqrt{(n_i^a\, R_i^{(1)})^2 + (\widetilde{m_i^a}\, R_i^{(2)})^2}$$

$$= (\prod_{i=1}^{3} R_i^{(1)})(\sum_{I=0}^{3} X_I^a U_I)$$

MSSM statistics

$\rightsquigarrow$ 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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- Indications that characteristic features of distributions survive after coupling to flux sector
- How model dependent are these results?
  Compare with gauge sector from dual theories (M-theory, heterotic).

Conclusions

- Explicit calculations of parts of the landscape can be done.
- The saddle point approximation leads to a reasonably good estimate of statistics.
- There exist non-trivial statistical correlations between observables.
- Indications that characteristic features of distributions survive after coupling to flux sector
- 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.