Bootstrapping $\mathcal{N} = 2$ SCFTs

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Iberian Strings
Lisbon, Jan. 18 2017

Based on:
1312.5344 w/ C. Beem, P. Liendo, W. Peelaers, L. Rastelli and B. van Rees
1511.07449 w/ P. Liendo
1612.01536 w/ P. Liendo, C. Meneghelli and V. Mitev

1702.xxxxx w/ M. Cornagliotto and V. Schomerus

Outline

1. The (Super)conformal Bootstrap Program
2. A solvable subsector
3. Constraining the space of $\mathcal{N} = 2$ SCFTs
4. $4d$ $\mathcal{N} = 3$ SCFTs
5. Summary and Outlook

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The (Super)conformal Bootstrap Program

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Can we bootstrap specific theories?

- → Particularly helpful if theory is uniquely fixed by a set of discrete data
- → Only tool available for finite N non-Lagrangian theories

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- Step 2: Full blown numerics for the rest

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Chiral algebra

Organize operators in representations of superconformal algebra

$\{\mathcal{O}_{\Delta,(j_1,j_2),} \qquad\qquad \}$

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$$\{\mathcal{O}_{\Delta,(j_1,j_2),\underbrace{R}_{SU(2)_R},\underbrace{r}_{U(1)_r}}\}$$

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→ Meromorphic!

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Example: free hypermultiplet

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$$\rightarrow \; q(z,\bar{z})\tilde{q}(0) \sim \bar{z}\tilde{Q}^\star(z,\bar{z})\tilde{Q}(0) \sim \frac{\bar{z}}{z\bar{z}} = \frac{1}{z}$$

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Which operators are in the cohomology?

$\rightarrow$ Stress tensor $T_{\mu\nu}$

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↪ $\boxed{c_{2d} = -12c_{4d}}$

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$\rightarrow$ ...

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$4d$ $\mathcal{N}=2$ SCFTs with a flavor symmetry

$\langle TTTT \rangle\,, \quad \langle J^a J^b J^c J^d \rangle\,, \quad \langle TTJ^a J^b \rangle$

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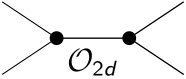
- Block decomposition:

$\sum_{\mathcal{O}_{2d}} \lambda^2_{\mathcal{O}_{2d}}$ 

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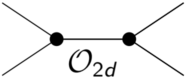
$\sum_{\mathcal{O}_{2d}} \lambda^2_{\mathcal{O}_{2d}}$ 

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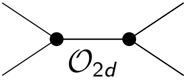
$\sum_{\mathcal{O}_{2d}} \lambda^2_{\mathcal{O}_{2d}}$ 

$\rightarrow$ $\lambda^2_{\mathcal{O}_{2d}} \rightsquigarrow \lambda^2_{\mathcal{O}_{4d}}$

assumptions: interacting theory, unique stress tensor

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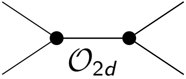
$\sum_{\mathcal{O}_{2d}} \lambda^2_{\mathcal{O}_{2d}}$ 

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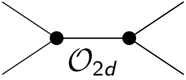
$\sum_{\mathcal{O}_{2d}} \lambda^2_{\mathcal{O}_{2d}}$ 

$$\rightarrow\ \lambda^2_{\mathcal{O}_{2d}} \rightsquigarrow \lambda^2_{\mathcal{O}_{4d}} \underbrace{\geqslant}_{4d \text{ unitarity}} 0 \ \Rightarrow \text{New unitarity bounds}$$

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$4d\ \mathcal{N}=2$ SCFTs with E_6 flavor symmetry

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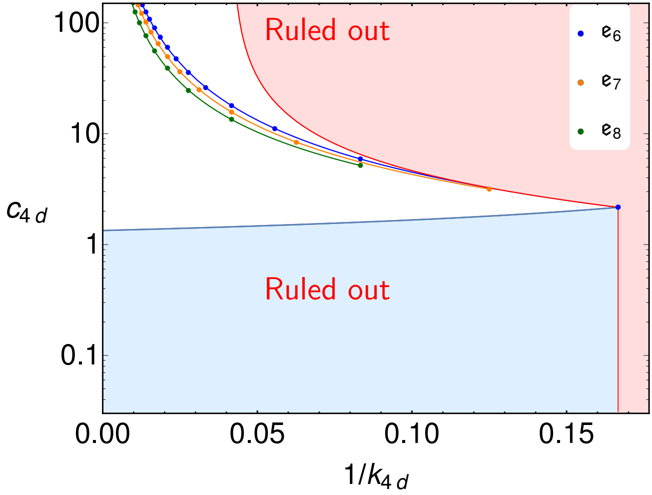

[Beem, ML, Liendo, Peelaers, Rastelli, van Rees] [ML, Liendo]

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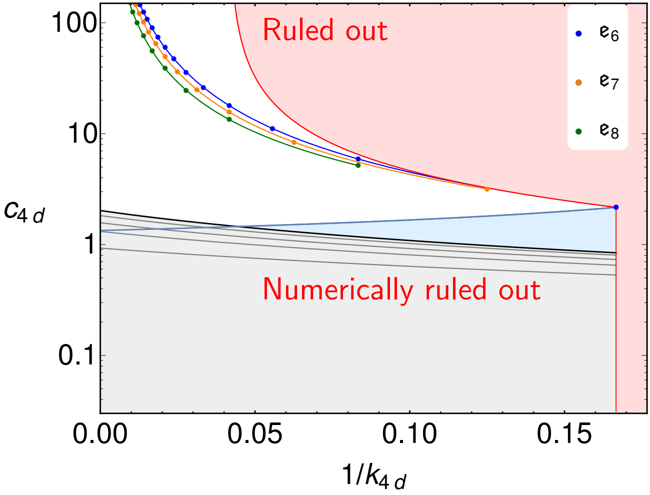

[Beem, ML, Liendo, Rastelli, van Rees]

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$4d$ $\mathcal{N} = 3$ SCFTs

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[García-Etxebarria, Regalado] [Aharony, Tachikawa]

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$\hookrightarrow$ Not saturated by any known SCFT

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$\hookrightarrow$ Not saturated by any known SCFT

smallest interacting $c_{4d} = \frac{15}{12}$

Chiral algebra

- $4d$ $\mathcal{N} \geqslant 3$: some of the extra supercharges commute with $\mathbb{Q}$
  - $\hookrightarrow$ $4d$ $\mathcal{N} = 4 \Rightarrow 2d$ "small" $\mathcal{N} = 4$ chiral algebra
  - $\hookrightarrow$ $4d$ $\mathcal{N} = 3 \Rightarrow 2d$ $\mathcal{N} = 2$ chiral algebra [Nishinaka, Tachikawa]

$2d$ $\mathcal{N} = 2$ Stress tensor $\langle \mathcal{J}\mathcal{J}\mathcal{J}\mathcal{J} \rangle$

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$\hookrightarrow$ Similar bounds in $\mathcal{N} = 4$ and $\mathcal{N} = 2$ saturated by known SCFTs [Beem, Rastelli, van Rees] [Liendo, Ramirez, Seo]

Outline

Summary and Outlook

$\rightarrow$ New constraints on the space of allowed $\mathcal{N} \geqslant 2$ SCFTs

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[ML, Liendo, Meneghelli, Mitev]

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  [ML, Liendo, Meneghelli, Mitev]

Other analytic approaches?

Summary and Outlook

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  [ML, Liendo, Meneghelli, Mitev]

Other analytic approaches?

- $\rightarrow$ Is c bounded by k for large k?

Thank you!

Backup slides

Outline

Conformal bootstrap
Constraining the space of $\mathcal{N} = 2$ SCFTs
Bootstrapping $\mathcal{N} = 3$ SCFTs

Conformal Bootstrap

Conformal field theory defined by

Set of local operators and their correlation functions

Conformal Bootstrap

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Set of local operators and their correlation functions

CFT data

$\{\mathcal{O}_{\Delta,\ell,\ldots}(x)\}$ and

Conformal Bootstrap

Conformal field theory defined by

Set of local operators and their correlation functions

CFT data

$\{\mathcal{O}_{\Delta,\ell,\dots}(x)\}$ and

Operator Product Expansion

$\mathcal{O}_1(x)\mathcal{O}_2(0) = \sum_k \quad \lambda_{\mathcal{O}_1\mathcal{O}_2\mathcal{O}_k} \qquad \mathcal{O}_k(0)$

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$\mathcal{O}_1(x)\mathcal{O}_2(0) = \sum_{k\text{prim.}} \lambda_{\mathcal{O}_1\mathcal{O}_2\mathcal{O}_k} c(x,\partial_x)\mathcal{O}_k(0)$

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$\rightarrow$ Finite radius of convergence

$\rightarrow$ $n-$point function by recursive use of the OPE until $\langle \mathbb{1} \rangle = 1$

CFT data strongly constrained

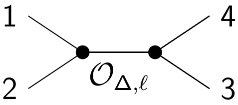
- Unitarity
- Associativity of the operator product algebra

Conformal Bootstrap

Crossing Symmetry

$\langle (\mathcal{O}_1(x_1)\ \mathcal{O}_2(x_2))\mathcal{O}_3(x_3)\ \mathcal{O}_4(x_4)\rangle =$

$$\sum_{\mathcal{O}_{\Delta,\ell}}$$

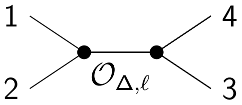


Conformal Bootstrap

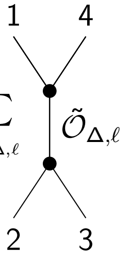
Crossing Symmetry

$\langle\, \mathcal{O}_1(x_1)(\mathcal{O}_2(x_2)\; \mathcal{O}_3(x_3))\mathcal{O}_4(x_4)\rangle =$

$\sum_{\mathcal{O}_{\Delta,\ell}}$



$= \sum_{\tilde{\mathcal{O}}_{\Delta,\ell}}$



Conformal Bootstrap

Crossing Symmetry

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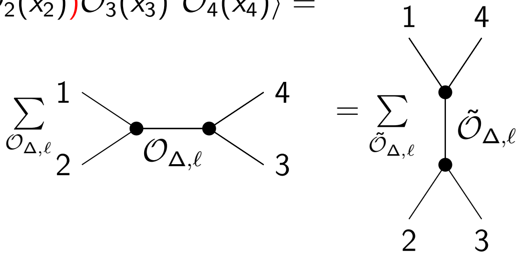


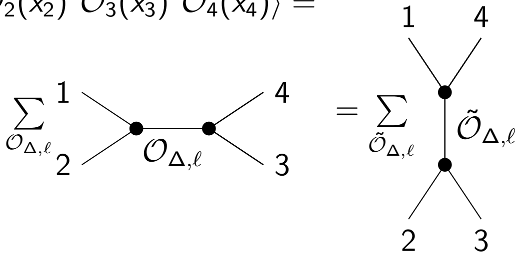
$$\frac{1}{x_{12}^{2\Delta_{\mathcal{O}}} x_{34}^{2\Delta_{\mathcal{O}}}} \sum_{\mathcal{O}_{\Delta,\ell}} \lambda_{\mathcal{O}_1\mathcal{O}_2\mathcal{O}_{\Delta,\ell}} \lambda_{\mathcal{O}_3\mathcal{O}_4\mathcal{O}_{\Delta,\ell}} g_{\Delta,\ell}(u,v) =$$

where $\Delta_{\mathcal{O}_i} = \Delta_{\mathcal{O}}$, $u = \frac{x_{12}^2 x_{34}^2}{x_{13}^2 x_{24}^2} = z\bar{z}$, $v = \frac{x_{23}^2 x_{14}^2}{x_{13}^2 x_{24}^2} = (1-z)(1-\bar{z})$

Conformal Bootstrap

Crossing Symmetry

$\langle\, \mathcal{O}_1(x_1)\ \mathcal{O}_2(x_2)\ \mathcal{O}_3(x_3)\ \mathcal{O}_4(x_4)\rangle =$



$$\frac{1}{x_{12}^{2\Delta_{\mathcal{O}}} x_{34}^{2\Delta_{\mathcal{O}}}} \sum_{\mathcal{O}_{\Delta,\ell}} \lambda_{\mathcal{O}_1\mathcal{O}_2\mathcal{O}_{\Delta,\ell}} \lambda_{\mathcal{O}_3\mathcal{O}_4\mathcal{O}_{\Delta,\ell}} g_{\Delta,\ell}(u,v) =$$
$$\frac{1}{x_{14}^{2\Delta_{\mathcal{O}}} x_{23}^{2\Delta_{\mathcal{O}}}} \sum_{\tilde{\mathcal{O}}_{\Delta,\ell}} \lambda_{\mathcal{O}_1\mathcal{O}_4\tilde{\mathcal{O}}_{\Delta,\ell}} \lambda_{\mathcal{O}_2\mathcal{O}_3\tilde{\mathcal{O}}_{\Delta,\ell}} g_{\Delta,\ell}(v,u)$$

where $\Delta_{\mathcal{O}_i} = \Delta_{\mathcal{O}}$, $u = \frac{x_{12}^2 x_{34}^2}{x_{13}^2 x_{24}^2} = z\bar{z}$, $v = \frac{x_{23}^2 x_{14}^2}{x_{13}^2 x_{24}^2} = (1-z)(1-\bar{z})$

Conformal Bootstrap

$\rightarrow$ Solve crossing equations for *all* four-point functions

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[Rattazzi, Rychkov, Tonni, Vichi]

- Solving $\Rightarrow$ constraining

Conformal Bootstrap

$\rightarrow$ Solve crossing equations for *all* four-point functions

[Rattazzi, Rychkov, Tonni, Vichi]

- Solving $\Rightarrow$ constraining
  - $\rightarrow$ Guess for the spectrum

Conformal Bootstrap

$\to$ Solve crossing equations for *all* four-point functions

[Rattazzi, Rychkov, Tonni, Vichi]

- Solving $\Rightarrow$ constraining
  - $\to$ Guess for the spectrum
    - $\hookrightarrow$ there's a large gap in the spectrum

Conformal Bootstrap

$\rightarrow$ Solve crossing equations for *all* four-point functions

[Rattazzi, Rychkov, Tonni, Vichi]

- Solving $\Rightarrow$ constraining
  - $\rightarrow$ Guess for the spectrum
    - $\hookrightarrow$ there's a large gap in the spectrum
  - $\rightarrow$ Can it ever define a consistent CFT?

Conformal Bootstrap

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[Rattazzi, Rychkov, Tonni, Vichi]

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Sum rule: identical scalars ϕ

Conformal Bootstrap

→ Solve crossing equations for *all* four-point functions

[Rattazzi, Rychkov, Tonni, Vichi]

- Solving ⇒ constraining
  - → Guess for the spectrum
    - ↪ there's a large gap in the spectrum
  - → Can it ever define a consistent CFT?

Sum rule: identical scalars ϕ

→ Identity operator $\lambda_{\mathcal{O}\mathcal{O}\mathbb{1}} = 1$

$$1 = \sum_{\substack{\mathcal{O}_{\Delta_\ell} \neq \mathbb{1} \\ \mathcal{O} \in \phi\phi}} \lambda^2_{\phi\phi\mathcal{O}} \underbrace{\frac{u^{\Delta_\phi} g_{\Delta,\ell}(v,u) - v^{\Delta_\phi} g_{\Delta,\ell}(u,v)}{v^{\Delta_\phi} - u^{\Delta_\phi}}}_{F_{\Delta,\ell}}$$

Conformal Bootstrap

Sum rule

$$1 = \sum_{\substack{\mathcal{O}_{\Delta_\ell} \neq \mathbb{1} \\ \mathcal{O} \in \phi\phi}} \lambda^2_{\phi\phi\mathcal{O}} F_{\Delta,\ell}$$

Conformal Bootstrap

Sum rule

$$1 = \sum_{\substack{\mathcal{O}_{\Delta_\ell} \neq \mathbb{1} \\ \mathcal{O} \in \phi\phi}} \lambda^2_{\phi\phi\mathcal{O}} F_{\Delta,\ell}$$

- Find Functional Ψ such that
  - $\hookrightarrow \psi \cdot 1 < 0 \ (\mathbb{1})$
  - $\hookrightarrow \psi \cdot F_{\Delta,\ell}(u,v) \geq 0$ for all $\{\Delta, \ell\}$ in spectrum

Conformal Bootstrap

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$\rightarrow$ Spectrum is inconsistent $\Rightarrow$ rule out CFT

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- Truncate

$$\psi = \sum_{m,n}^{m,n \leqslant \Lambda} a_{mn} \partial_z^m \partial_{\bar{z}}^n |_{z=\bar{z}=\frac{1}{2}}$$

Conformal Bootstrap

Sum rule

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$\rightarrow$ Increase Λ $\Rightarrow$ bounds get stronger

Conformal Bootstrap

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$$1 = \sum_{\substack{\mathcal{O}_{\Delta_\ell} \neq \mathbb{1} \\ \mathcal{O} \in \phi\phi}} \lambda^2_{\phi\phi\mathcal{O}} F_{\Delta,\ell}$$

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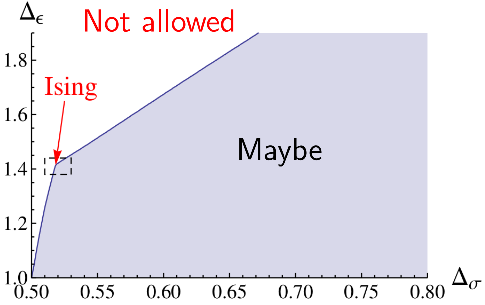
$\rightarrow$ Increase $\Lambda \Rightarrow$ bounds get stronger

$\rightarrow$ Always true bounds

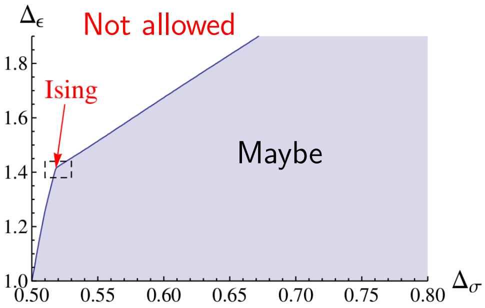
3*d* Ising Model

[El-Showk, Paulos, Poland, Rychkov, Simmons-Duffin, Vichi, PRD 86 025022]



$3d$ Ising Model

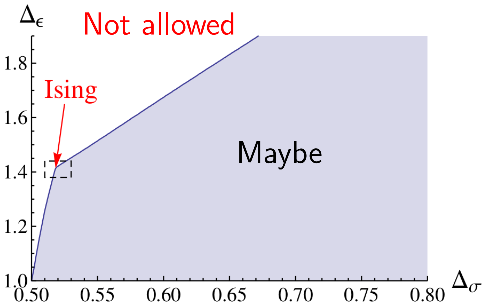
[El-Showk, Paulos, Poland, Rychkov, Simmons-Duffin, Vichi, PRD 86 025022]



$\rightarrow$ Saturated by $3d$ Ising model

3d Ising Model

[El-Showk, Paulos, Poland, Rychkov, Simmons-Duffin, Vichi, PRD 86 025022]



$\longrightarrow$ Saturated by 3d Ising model

$\longrightarrow$ 3d Ising lives at "kink"

Outline

Conformal bootstrap

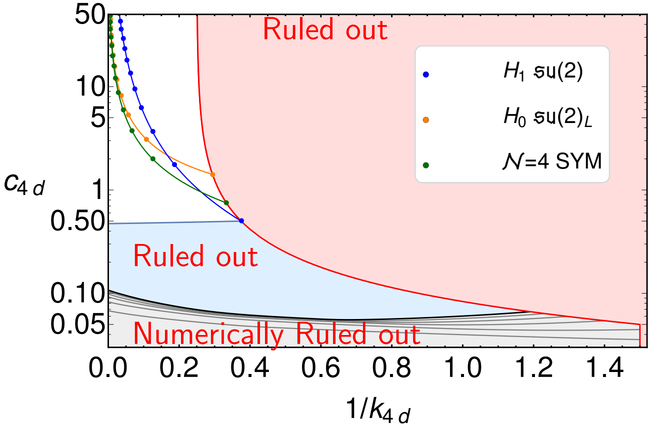
Constraining the space of $\mathcal{N} = 2$ SCFTs

Bootstrapping $\mathcal{N} = 3$ SCFTs

What is the space of consistent SCFTs?

$4d$ $\mathcal{N} = 2$ SCFTs with $SU(2)$ flavor symmetry

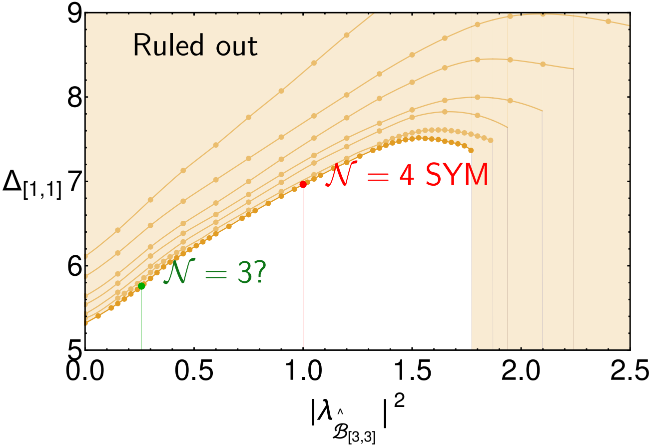
$\langle TTTT \rangle\,,\ \ \langle J^a J^b J^c J^d \rangle\,,\ \ \langle TTJ^a J^b \rangle$



Outline

Conformal bootstrap
Constraining the space of $\mathcal{N} = 2$ SCFTs
Bootstrapping $\mathcal{N} = 3$ SCFTs

$4d$ $\mathcal{N} = 3$ SCFTs with $c = \frac{15}{12}$



[ML, Liendo, Meneghelli, Mitev]