

Multi-trace operators in $\mathcal{N}=4$ Super Yang-Mills

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Based on WIP with Fitzpatrick, Li, Mei, Novikova
and 2508.20158, 2508.20160, 2403.07079 with Fitzpatrick, Li

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Overview and motivations

$\mathcal{N} = 4$ SYM with $SU(N)$ gauge group at **large N** and $\lambda \rightarrow \infty$ $\longleftrightarrow$ Type IIB SUGRA on $AdS_5 \times S^5$

$$\mathcal{O}_p \sim \text{tr}(\phi^p)$$
$$\mathcal{O}_p \cdots \mathcal{O}_p \sim \text{tr}(\cdots)^Q$$

single particle state
Q-particle state

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Why multi-trace operators? They belong to the lowest-energy part of the spectrum, fundamental for charting the phase space of theories, emerge in kinematic limits of higher-point correlators. [\[GF, Fitzpatrick, Li '24,'25; Kravchuk, Mann '24\]](#)

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Why $\mathcal{N} = 4$ SYM?

- Great playground!
- Evidence of **triple-trace** operators $\mathcal{T}$ in correlators

[Bissi, GF, Georgoudis '20; Drummond, Paul '22; Bissi, GF, Manenti '24; Aprile, Giusto, Russo '24,'25 + Vilas Boas '26]

$$\langle \mathcal{O}_2 \mathcal{O}_2 \mathcal{O}_2 \mathcal{O}_2 \rangle$$

@ 1,2-loops

$$\langle \mathcal{O}_2 \mathcal{O}_2 \mathcal{T} \rangle \sim N^{-2}$$

$$\langle \mathcal{O}_2^n \mathcal{O}_2 \mathcal{O}_2 \mathcal{O}_2^n \rangle$$

$$\langle \mathcal{O}_2 \mathcal{O}_2 \mathcal{O}_2 \mathcal{O}_2 \mathcal{O}_2 \mathcal{O}_2 \rangle$$

very hard!

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Main challenge of correlator-based method is the **high-degeneracy** of operators at fixed spin ℓ . For ex. $\#$ leading-twist 3-particle primaries $\xrightarrow{\ell \rightarrow \infty} \ell/6$

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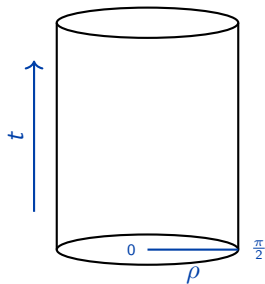
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We will take an alternative approach to determine the spectrum of multi-particle operators $\Rightarrow$ construct a **Hamiltonian** in **AdS**

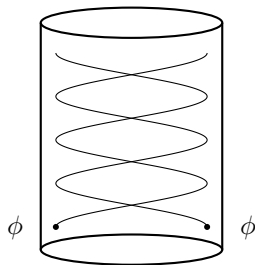


AdS in global coordinates

AdS time translation $\leftrightarrow$ CFT dilatation

$E_{\text{AdS}} \leftrightarrow \Delta_{\text{CFT}}$

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$$E_{\text{AdS}} \leftrightarrow \Delta_{\text{CFT}}$$

Free scalar $\phi(x) = \sum \phi_{nlL} a_{nlL} + \phi_{nlL}^* b_{nlL}^\dagger$

$$|\ell_1 \ell_2\rangle = b_{\ell_1}^\dagger b_{\ell_2}^\dagger |\text{vac}\rangle$$

Anomalous dimensions

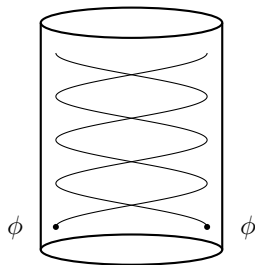
$H \sim V_{ijkl} b_i^\dagger b_j^\dagger a_k a_l$

Only 2-body interactions @ $1/N^2$

Eig $\begin{pmatrix} 1 & 1 \\ 2 & 2 \\ 3 & 3 \\ \vdots & \vdots \\ Q & Q \end{pmatrix} = \gamma_{n,\ell} \quad \Delta = Q\Delta_\phi + \gamma_{n,\ell}$

$H = H_{\text{GFF}} + H_2$

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Two ingredients to build H

- A good basis of states
- 2-body interactions

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Basis of states in $\mathcal{N} = 4$ SYM

Supergraviton $\mathcal{O}_2$

$$\Delta = 2 \quad [0, 2, 0]_R$$

Basis of states in $\mathcal{N} = 4$ SYM

Supergraviton $\mathcal{O}_2$

$$\Delta = \textcolor{red}{p} [0, \textcolor{red}{p}, 0]_R$$

KK modes $\mathcal{O}_{\textcolor{red}{p}}$

Basis of states in $\mathcal{N} = 4$ SYM

$$\text{Supergraviton } \mathcal{O}_2 \xrightarrow{Q} \dots \xrightarrow{Q} \dots \xrightarrow{Q} \dots \xrightarrow{Q} \mathcal{L}_2$$
$$\Delta = p \quad [0, p, 0]_R$$

$$\text{KK modes } \mathcal{O}_p \xrightarrow{Q} \dots \xrightarrow{Q} \dots \xrightarrow{Q} \dots \xrightarrow{Q} \mathcal{L}_p$$

$$\Delta = p + 2$$
$$[0, p - 2, 0]_R$$
$$U(1)_Y \text{ charge } +4$$

[Intriligator '98; Intriligator, Skiba '99]

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$$\Delta = p + 2$$
$$[0, p - 2, 0]_R$$
$$\text{U}(1)_Y \text{ charge } +4$$

We want to build multi-particle states out of $\mathcal{L}$ s, in the **singlet** of $\text{SU}(4)_R$

$$O = [\mathcal{L}_p \cdots \mathcal{L}_p]_{n,\ell} = \sum P_{\mu_1} \cdots P_{\mu_{k_1}} \mathcal{L}_p (P^2)^i \mathcal{L}_p \cdots (P^2)^j P_{\mu_{k_2}} \cdots P_{\mu_\ell} \mathcal{L}_p$$

- We only need to impose that O is a primary $[K^\mu, O] = 0$
- Bonus $\text{U}(1)_Y$ symmetry $\iff$ No mixing between states with different number of particles
- In this basis, “hidden $10d$ symmetry” is manifest

Extracting 2-body interactions from correlators

Hamiltonian matrix elements can be obtained by the SUGRA action, but much more convenient to start from **correlators**

$$\langle \mathcal{L}_p \mathcal{L}_p \bar{\mathcal{L}}_q \bar{\mathcal{L}}_q \rangle = \Delta^{(8)} \langle \mathcal{O}_p \mathcal{O}_p \mathcal{O}_q \mathcal{O}_q \rangle$$

[Drummond, Gallot, Sokatchev '06; Goncalves '14; Korchemsky, Sokatchev '15; Aprile, Drummond, Heslop, Paul '18]

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 \text{Mellin tfm} \downarrow & & \downarrow \text{difference operator} \quad \downarrow \text{Reduced Mellin ampl [Rastelli, Zhou '17]} \\
 \mathcal{M}_{ppqq}^{\mathcal{L}}(s, t) & = & \mathbb{D}(s, t) \quad \widetilde{\mathcal{M}}_{ppqq} = \sum \frac{a_{ijk} \sigma^i \tau^j}{(s-s_k)(t-t_j)(\tilde{u}-\tilde{u}_i)}
 \end{array}$$

$\Delta^{(8)} \sim Q^8 \bar{Q}^8$ kills all protected contributions and isolates the interactions producing the anomalous dimensions

$$\begin{aligned}
 \mathcal{M}_{2222}^{\mathcal{L}} &= \frac{24}{c} \left(\frac{2(3s^2 - 42s + 148)}{t-2} + \frac{8(s-6)^2}{t-4} + \frac{(s-4)(s-6)}{t-6} + t \leftrightarrow u \right) \\
 &= \text{[Diagram 1]} + \text{[Diagram 2]}
 \end{aligned}$$

The first diagram is a circle with four external lines (two on the left, two on the right). A wavy red line labeled $T_{\mu\nu}$ connects the two left vertices. The second diagram is a circle with four external lines and two internal diagonal lines forming an 'X' shape.

Extracting 2-body interactions from correlators

Hamiltonian matrix elements can be obtained by the SUGRA action, but much more convenient to start from **correlators**

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1. Use $\mathcal{M}^{\mathcal{L}}$ to classify interactions and extract the couplings
2. Transform back to position space and use

$$\text{Correlator} \quad \left\langle \mathcal{L}_p(x_1) \mathcal{L}_p(x_2) \bar{\mathcal{L}}_q(x_3) \bar{\mathcal{L}}_q(x_4) \int dt d\rho d\Omega \frac{\sin^{d-1} \rho}{\cos^{d+1} \rho} V_{\text{int}}(x) \right\rangle$$

$$H - \text{matrix} \quad \langle [\mathcal{L}_p, \mathcal{L}_p] | \int d\rho d\Omega \frac{\sin^{d-1} \rho}{\cos^{d+1} \rho} V_{\text{int}}(\rho, \Omega) | [\bar{\mathcal{L}}_q, \bar{\mathcal{L}}_q] \rangle$$

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$$\gamma_{0,\ell} = -\frac{24}{c(\ell+1)(\ell+6)}$$

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- **SubLeading twist** $\tau = 10$:

$$\begin{array}{cc} [\mathcal{L}_2 \mathcal{L}_2]_{1,\ell} & [\mathcal{L}_3 \mathcal{L}_3]_{0,\ell} \\ [\bar{\mathcal{L}}_2 \bar{\mathcal{L}}_2]_{1,\ell} & \left(\begin{array}{cc} -\frac{120}{c(\ell+1)(\ell+8)} & -\frac{720}{c(\ell+1)\sqrt{(\ell+2)(\ell+7)(\ell+8)}} \\ -\frac{720}{c(\ell+1)\sqrt{(\ell+2)(\ell+7)(\ell+8)}} & -\frac{120(\ell^2+9\ell+44)}{c(\ell+1)(\ell+2)(\ell+7)(\ell+8)} \end{array} \right) \\ [\bar{\mathcal{L}}_3 \bar{\mathcal{L}}_3]_{0,\ell} & \end{array}$$

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$$\begin{array}{l} [\mathcal{L}_2\mathcal{L}_2]_{2,\ell} \quad [\mathcal{L}_3\mathcal{L}_3]_{1,\ell} \quad [\mathcal{L}_4\mathcal{L}_4]_{0,\ell} \\ \begin{pmatrix} [\tilde{\mathcal{L}}_2\tilde{\mathcal{L}}_2]_{2,\ell} \\ [\tilde{\mathcal{L}}_3\tilde{\mathcal{L}}_3]_{1,\ell} \\ [\tilde{\mathcal{L}}_4\tilde{\mathcal{L}}_4]_{0,\ell} \end{pmatrix} \begin{pmatrix} -\frac{360}{c(\ell+1)(\ell+10)} & -\frac{720\sqrt{21}}{c(\ell+1)\sqrt{\ell+3}\sqrt{\ell+8}(\ell+10)} & -\frac{2880\sqrt{35}}{c(\ell+1)\sqrt{\ell+2}\sqrt{\ell+3}\sqrt{\ell+8}\sqrt{\ell+9}(\ell+10)} \\ * & -\frac{360(\ell^2+11\ell+94)}{c(\ell+1)(\ell+3)(\ell+8)(\ell+10)} & -\frac{720\sqrt{15}(\ell^2+11\ell+66)}{c(\ell+1)\sqrt{\ell+2}(\ell+3)(\ell+8)\sqrt{\ell+9}(\ell+10)} \\ * & * & -\frac{360(\ell^4+22\ell^3+219\ell^2+1078\ell+3120)}{c(\ell+1)(\ell+2)(\ell+3)(\ell+8)(\ell+9)(\ell+10)} \end{pmatrix} \end{array}$$

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$$\gamma_{2,\ell} = \left\{ -\frac{360(\ell+7)}{c(\ell+1)(\ell+2)(\ell+3)}, -\frac{360}{c(\ell+3)(\ell+8)}, -\frac{360(\ell+4)}{c(\ell+8)(\ell+9)(\ell+10)} \right\}$$

10d Hidden symmetry

[Caron-Huot, Trinh '18; Aprile, Drummond, Paul, Santagata '20; Abl, Heslop, Lipstein '20]

$[\mathcal{L}_p \mathcal{L}_p]_{n-p+2, \ell}$ degenerate under $SO(4,2) \times SO(6)$ at $N \rightarrow \infty$

$$SO(10,2) \rightarrow SO(4,2) \times SO(6)$$

$$X^a = (P^A, y^m)$$

One 10d free massless scalar $\Delta = 4$

$$\Phi(X) = \sum y_{m_1} \cdots y_{m_{p-2}} \mathcal{L}_p^{m_1 \cdots m_{p-2}}(P)$$

H-eigenvectors **diagonalize** the 10d quadratic Casimir

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$$[\Phi\Phi]_L \sim \Phi \partial_{a_1} \cdots \partial_{a_L} \Phi, \quad \Delta^{(10d)} = L + 8 \text{ and } \ell \leq L \leq 2n + \ell,$$
$$\mathcal{C}^{(10,2)}[\Phi\Phi]_L = 2(L-1)(L+8)[\Phi\Phi]_L$$

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When restricted to $SO(4,2) \times SO(6)$, acting on $[\mathcal{L}_p \mathcal{L}_p]_{n-p+2,\ell}$

$$\mathcal{C}^{(10,2)} = \begin{pmatrix} \overset{[\mathcal{L}_2 \mathcal{L}_2]_n [\mathcal{L}_3 \mathcal{L}_3]_{n-1}}{c_{2,2}} & c_{2,3} & 0 & \cdots & \overset{[\mathcal{L}_{n+2} \mathcal{L}_{n+2}]_0}{0} \\ c_{2,3} & c_{3,3} & c_{3,4} & \cdots & 0 \\ \vdots & & \ddots & & \vdots \\ 0 & & & c_{n+1,n+2} & c_{n+2,n+2} \end{pmatrix}$$

$$\text{Eig}(\mathcal{C}^{(10,2)}) = \text{Eig}(H_2)$$

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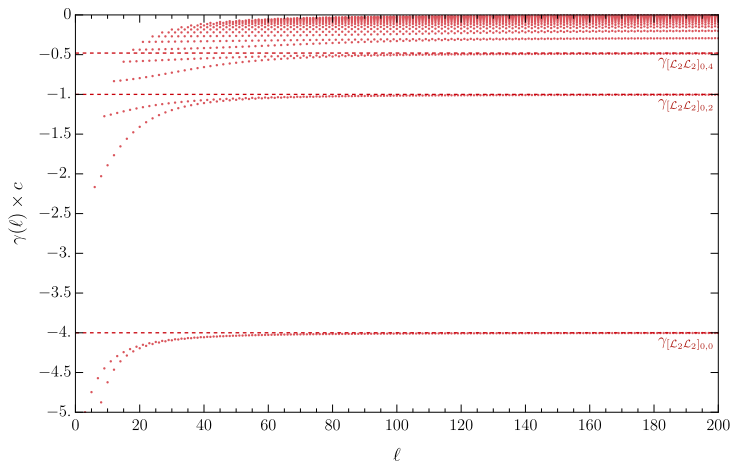
$$\mathcal{C}^{(10,2)} = \begin{pmatrix} \overset{[\mathcal{L}_2 \mathcal{L}_2]_n [\mathcal{L}_3 \mathcal{L}_3]_{n-1}}{c_{2,2}} & c_{2,3} & 0 & \cdots & \overset{[\mathcal{L}_{n+2} \mathcal{L}_{n+2}]_0}{0} \\ c_{2,3} & c_{3,3} & c_{3,4} & \cdots & 0 \\ \vdots & & \ddots & & \vdots \\ 0 & & & c_{n+1,n+2} & c_{n+2,n+2} \end{pmatrix}$$

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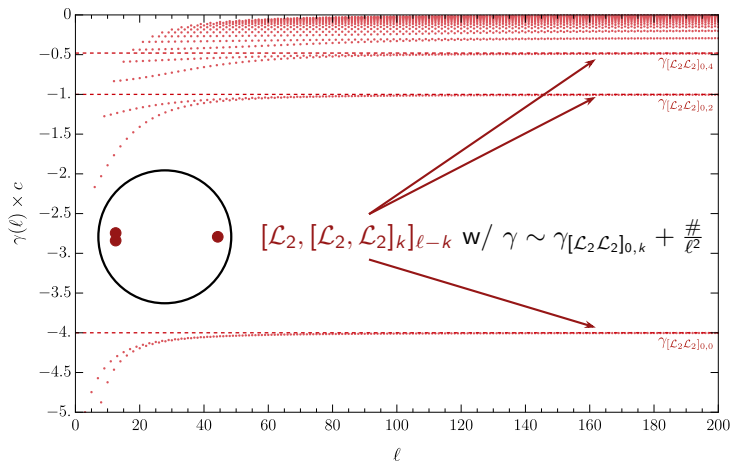
$$R_\ell : [\mathcal{L}_3 \mathcal{L}_3]_{0,\ell} - \sqrt{\frac{\ell+2}{\ell+7}} [\mathcal{L}_2 \mathcal{L}_2]_{1,\ell}$$

$$R_{\ell+2} : [\mathcal{L}_3 \mathcal{L}_3]_{0,\ell} + \sqrt{\frac{\ell+7}{\ell+2}} [\mathcal{L}_2 \mathcal{L}_2]_{1,\ell}$$

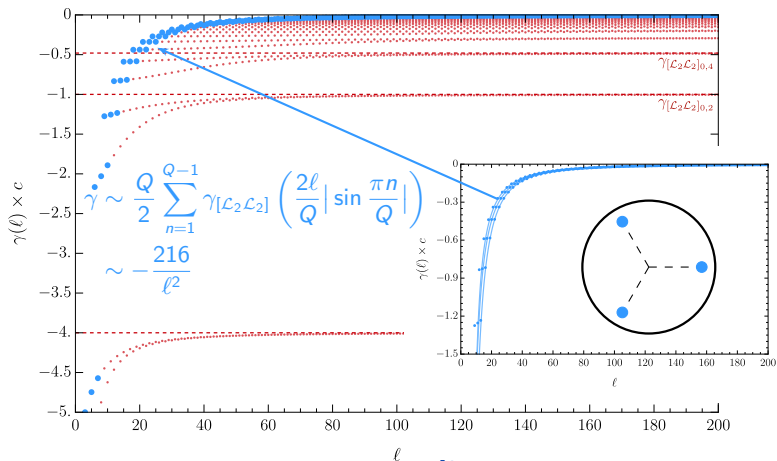
Leading triple-trace operators $[\mathcal{L}_2\mathcal{L}_2\mathcal{L}_2]_{0,\ell}$



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[See also Kravchuk, Mann '24 for an alternative interpretation]

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At fixed spin ℓ

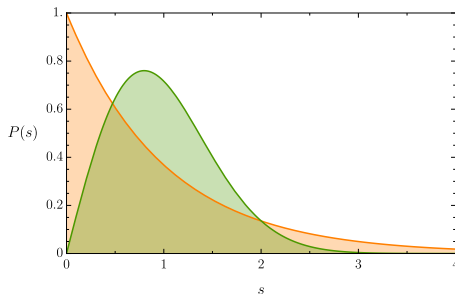
$$s_n = E_{n+1} - E_n, \quad \tilde{s}_n = \frac{s_n}{\langle s_n \rangle}, \quad n = 1, \dots, N_\ell - 1$$

Integrable: levels are **uncorrelated** and spacing distribution

$$P(s) = e^{-s} \quad \text{Poisson}$$

Chaotic: levels **repel** like eigenvalues of a random matrix

$$P(s) = \frac{1}{2} \pi e^{-\frac{\pi s^2}{4}} s \quad \text{GOE}$$



$\mathcal{N} = 4$ is not analytically solvable at N^{-2}

WIP w/ Fitzpatrick, Novikova

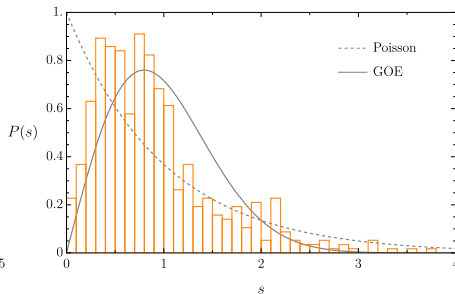
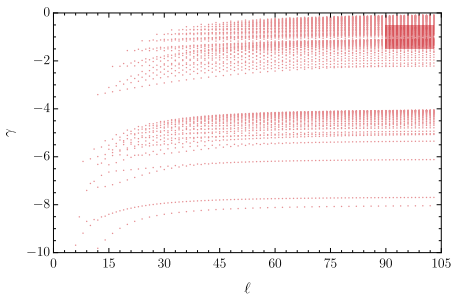
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$Q = 4$



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Q = 5

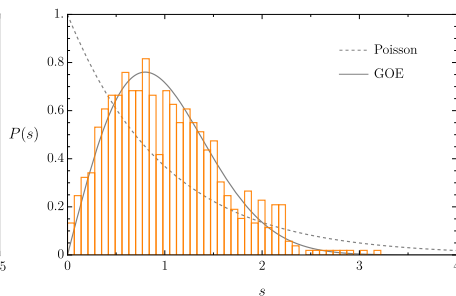
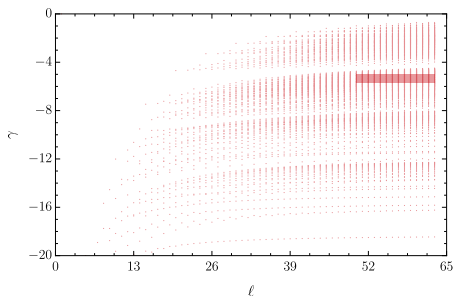


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- Initiated the study of the spectrum of Q -trace operators in the $SU(4)_R$ singlet of $\mathcal{N} = 4$ SYM via an AdS Hamiltonian: first results for the leading triple-trace spectrum.

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- At $Q = 2$, we showed how the eigenvectors organize themselves under a hidden $10d$ conformal symmetry.
- Signs of quantum chaos in the anomalous dimensions of $Q \geq 5$ -particle states at order $1/N^2$: level repulsion and GOE-like spacing statistics.
- Uncharged triple-trace operators $[\mathcal{O}_2\mathcal{O}_2\mathcal{O}_2]_\ell$?
- Extend the method to OPE coefficients.
- Sharpen the chaos diagnostics: larger sectors and more spins, eigenvector statistics.

Thank you!

