Conformal Collider Bounds for Interacting CFTs

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Work in Progress with Clay Córdova

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Averaged null energy operator

- Averaged null energy (ANEC) operator:

$$\mathcal{E} \sim \int dx^+ T_{++} \qquad\qquad ds^2 = -dx^+ dx^- + d\vec{x}_\perp^2$$

- Measures energy distribution at infinity in a "conformal collider"

- ANEC: $$\mathcal{E} \geq 0$$ [Hartman, Kundu, Tajdini '16] [Faulkner, Leigh, Parrikar, Wang '16]

  - OPE coefficients bounds (λ_{TTT} [Hofman, Maldacena '08], $\lambda_{TT\phi}$ [Córdova, Maldacena, Turiaci '17])

  - Scaling dimension bounds [Córdova, Diab '17; Manenti, Stergiou, Vichi '19]

  - Constraining RG flow (light-ray sum rule $\Rightarrow$ a-theorem/c-theorem) [Hartman, Mathys '23, '24]

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- ANEC: $\mathcal{E} \geq 0$

This talk: generalization of this

- OPE coefficients bounds (λ_{TTT} [Hofman, Maldacena '08], $\lambda_{TT\phi}$ [Córdova, Maldacena, Turiaci '17])
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Conformal collider bound in 3d

- 3d CFT:

$$\langle TTT \rangle = n_B \langle TTT \rangle_B + n_F \langle TTT \rangle_F + n_{\mathrm{odd}} \langle TTT \rangle_{\mathrm{odd}}$$

Ward identity: $n_B + n_F = c_T / c_B$

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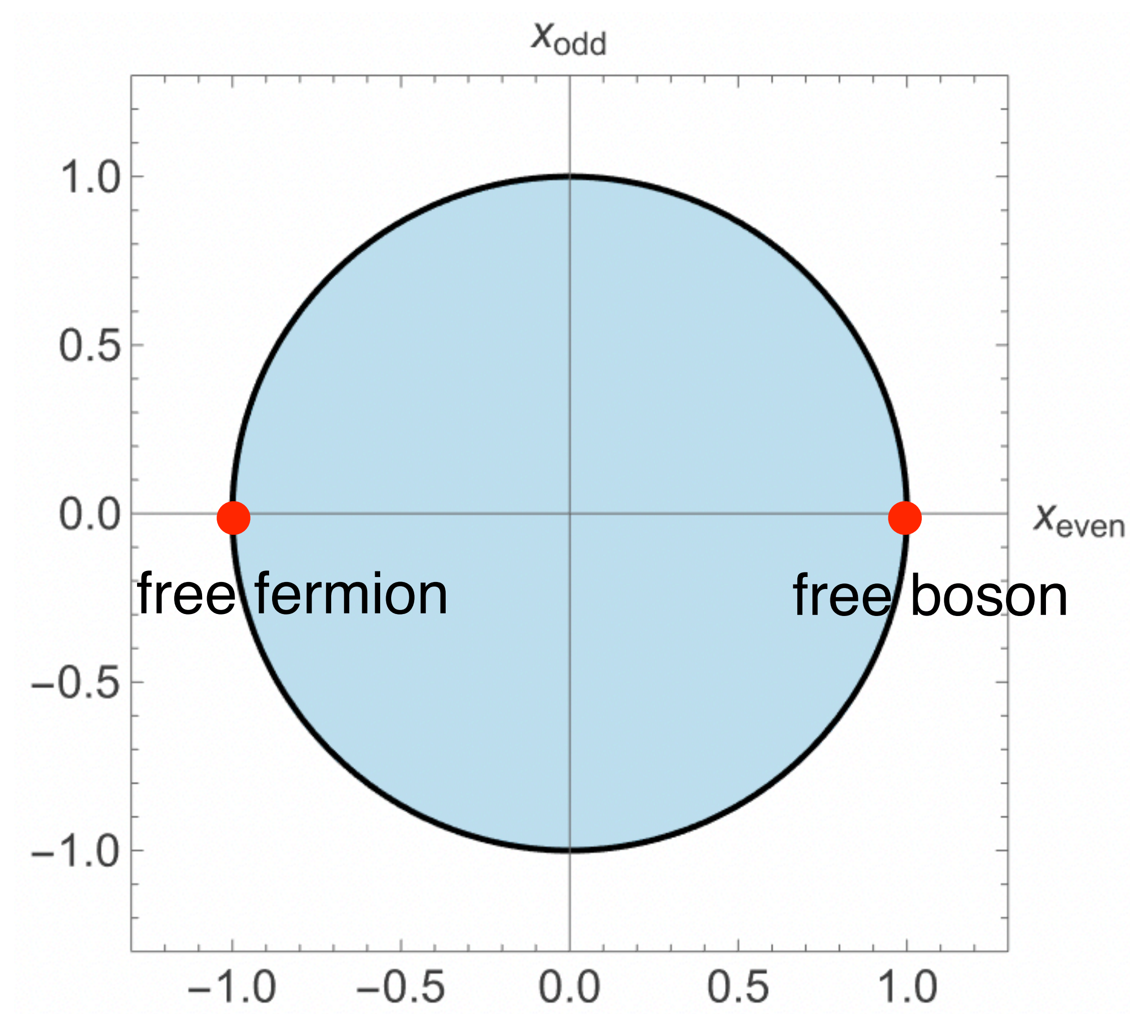
Ward identity: $n_B + n_F = c_T/c_B$

$$\langle T|\mathcal{E}|T\rangle \geq 0$$

$$\begin{pmatrix} n_B & n_{\rm odd} \\ n_{\rm odd} & n_F \end{pmatrix} \succeq 0$$

$$x_{\rm even} \equiv \frac{n_B - n_F}{c_T/c_B} \qquad x_{\rm odd} \equiv \frac{2n_{\rm odd}}{c_T/c_B}$$

$$x_{\rm even}^2 + x_{\rm odd}^2 \leq 1$$



Conformal collider bound in 4d

- 4d CFT:

$$\langle TTT\rangle = n_B\langle TTT\rangle_B + n_F\langle TTT\rangle_F + n_V\langle TTT\rangle_V$$

Ward identity: $$\frac{n_B + 6n_F + 12n_V}{120} = c \propto c_T$$

$$\langle T|\mathcal{E}|T\rangle \geq 0 \quad \Rightarrow \quad n_B \geq 0,\ n_F \geq 0,\ n_V \geq 0$$

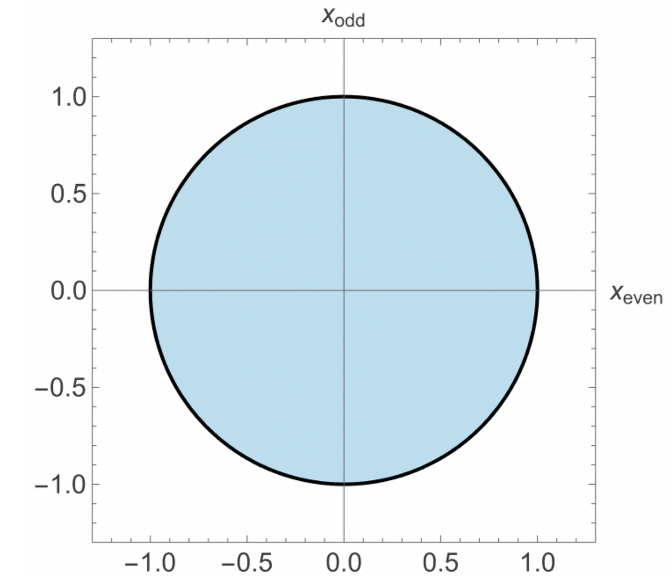
$$\Rightarrow \quad \frac{1}{3} \leq \frac{a}{c} \leq \frac{31}{18}$$

Saturation of conformal collider bounds

- These bounds are all saturated by free theories:

$d = 3:$ [Maldacena, Zhiboedov '12] [Chowdhury, David, Prakash '17]

$$n_B \sim \frac{\tilde{\lambda}^2}{1+\tilde{\lambda}^2} \qquad n_F \sim \frac{1}{1+\tilde{\lambda}^2} \qquad n_{\text{odd}} \sim \frac{\tilde{\lambda}}{1+\tilde{\lambda}^2}$$



(can be realized as large N Chern-Simons matter theories)

$\tilde{\lambda} \to \infty$: free boson $\qquad$ $\tilde{\lambda} \to 0$: free fermion

$d = 4:$ [Zhiboedov '13]

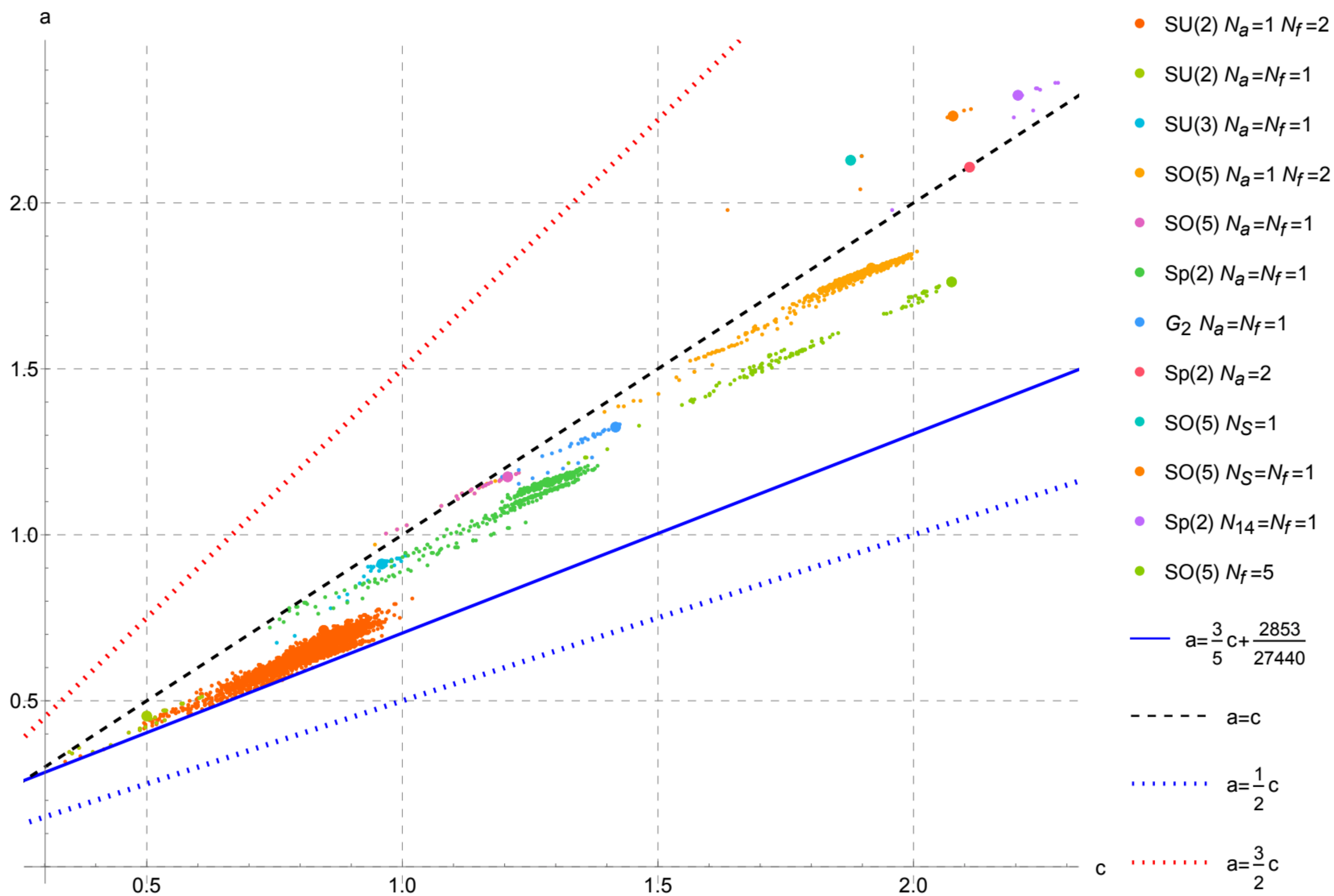
$$\frac{1}{3} \leq \frac{a}{c} \leq \frac{31}{18}$$

free scalar $\qquad$ free vector

- Can one get stronger bounds for interacting CFTs?

a/c for 4d N=1 SCFTs

- Values of a and c for a large set of 4d N=1 SCFTs: [Cho, Maruyoshi, Nardoni, Song '24]



$$0.72 \lesssim \frac{a}{c} \lesssim 1.21$$

$$\mathcal{N}=1 \text{ bound: } \frac{1}{2} \leq \frac{a}{c} \leq \frac{3}{2}$$

Higher-spin ANEC

- Consider the leading spin-4 operator O_4. We will try using its twist τ_4 as a proxy for the interaction:

[Komargodski, Zhiboedov '12]

[Fitzpatrick, Kaplan, Poland, Simmons-Duffin '12]

$$d - 2 \leq \tau_4 \leq 2(d-2)$$

$[TT]$ double-twist

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- Spin-4 ANEC:

$$\mathcal{E}_4 \sim \int dx^+ \mathcal{O}_{4++++} \geq 0$$

[Hartman, Kundu, Tajdini '16]
[Kravchuk, Simmons-Duffin '18]

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[Kravchuk, Simmons-Duffin '18]

- Can we replace e.g., the upper and lower bounds of a/c with functions of τ_4?

$$\frac{1}{3} \leq \frac{a}{c} \leq \frac{31}{18} \quad \Rightarrow \quad f_-(\tau_4) \overset{?}{\leq} \frac{a}{c} \overset{?}{\leq} f_+(\tau_4)$$

Setup

- Idea: impose ANEC and spin-4 ANEC in a mixed system of T and O_4.

$$\begin{pmatrix} \langle T|\mathcal{E}|T\rangle & \langle T|\mathcal{E}|\mathcal{O}_4\rangle \\ \langle\mathcal{O}_4|\mathcal{E}|T\rangle & \langle\mathcal{O}_4|\mathcal{E}|\mathcal{O}_4\rangle \end{pmatrix} \succeq 0$$

$$\begin{pmatrix} \langle T|\mathcal{E}_4|T\rangle & \langle T|\mathcal{E}_4|\mathcal{O}_4\rangle \\ \langle\mathcal{O}_4|\mathcal{E}_4|T\rangle & \langle\mathcal{O}_4|\mathcal{E}_4|\mathcal{O}_4\rangle \end{pmatrix} \succeq 0$$

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$\lambda_{TT\mathcal{O}_4}$

$\lambda_{\mathcal{O}_4T\mathcal{O}_4}$

$$\begin{pmatrix} \boxed{\langle T|\mathcal{E}_4|T\rangle} & \boxed{\langle T|\mathcal{E}_4|\mathcal{O}_4\rangle} \\ \boxed{\langle \mathcal{O}_4|\mathcal{E}_4|T\rangle} & \langle \mathcal{O}_4|\mathcal{E}_4|\mathcal{O}_4\rangle \end{pmatrix} \succeq 0$$

Ward identity:

$$\sum_i c_i \lambda^{(i)}_{\mathcal{O}_4 T \mathcal{O}_4} \sim \Delta_4$$

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$$\langle T|\mathcal{E}_4|T\rangle = x_{4B}\langle T|\mathcal{E}_4|T\rangle_B + x_{4F}\langle T|\mathcal{E}_4|T\rangle_F + x_{4V}\langle T|\mathcal{E}_4|T\rangle_V$$

$$(d=4)$$

$$x_{4B} \geq 0,\ x_{4F} \geq 0,\ x_{4V} \geq 0$$

Setup

$$\begin{pmatrix} \langle T|\mathcal{E}|T\rangle & \langle T|\mathcal{E}|\mathcal{O}_4\rangle \\ \langle \mathcal{O}_4|\mathcal{E}|T\rangle & \langle \mathcal{O}_4|\mathcal{E}|\mathcal{O}_4\rangle \end{pmatrix} \quad \begin{pmatrix} \langle T|\mathcal{E}_4|T\rangle & \langle T|\mathcal{E}_4|\mathcal{O}_4\rangle \\ \langle \mathcal{O}_4|\mathcal{E}_4|T\rangle & \langle \mathcal{O}_4|\mathcal{E}_4|\mathcal{O}_4\rangle \end{pmatrix}$$

[Meltzer '18]

$$x_{4B} = 0 \ \& \ \tau_4 = d-2$$

$$n_B = 0 \Rightarrow$$

or

$$x_{4B} = x_{4F} = x_{4V} = 0$$

- Can't get stronger bound without extra conditions on λ_{TTO_4}.

Setup

$$\begin{pmatrix} \langle T|\mathcal{E}|T\rangle & \langle T|\mathcal{E}|\mathcal{O}_4\rangle \\ \langle \mathcal{O}_4|\mathcal{E}|T\rangle & \langle \mathcal{O}_4|\mathcal{E}|\mathcal{O}_4\rangle \end{pmatrix} \quad \begin{pmatrix} \langle T|\mathcal{E}_4|T\rangle & \langle T|\mathcal{E}_4|\mathcal{O}_4\rangle \\ \langle \mathcal{O}_4|\mathcal{E}_4|T\rangle & \langle \mathcal{O}_4|\mathcal{E}_4|\mathcal{O}_4\rangle \end{pmatrix}$$

[Meltzer '18]

$$n_B = 0 \Rightarrow \begin{array}{c} x_{4B} = 0 \;\&\; \tau_4 = d-2 \\ \text{or} \\ x_{4B} = x_{4F} = x_{4V} = 0 \end{array}$$

- Can't get stronger bound without extra conditions on λ_{TTO_4}.
- Our result:

$$\cancel{f_-(\tau_4) \overset{?}{\leq} \frac{a}{c} \overset{?}{\leq} f_+(\tau_4)} \qquad f_-(\tau_4, \lambda_{TT\mathcal{O}_4}) \leq \frac{a}{c} \leq f_+(\tau_4, \lambda_{TT\mathcal{O}_4})$$

Computing positive matrices

- The positive matrices can be computed by starting with e.g., $\langle O(x_1)T(x_2)O(x_3)\rangle$, and then perform
  - Null integral (light transform) $\int dx^+$

    [Kologlu, Kravchuk, Simmons-Duffin, Zhiboedov '19]
    [Mecaj, Moult, Walters, Xin '25]

  - Fourier transform $\int d^d x\, e^{ip\cdot x}$ $\quad \Rightarrow \quad \langle \mathcal{O}(p)\mathcal{E}(\infty, z)\mathcal{O}(p)\rangle$

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Stabilized by SO(2)!

  - Gelfand-Tsetlin basis: each basis vector is associated with an SO(2) irrep

[Gelfand, Tsetlin '50] [Kravchuk '17]

$$\mathcal{O} = \mathcal{O}_4 : \quad \mathrm{Res}^{SO(3,1)}_{SO(2)} \boxed{}\boxed{}\boxed{}\boxed{} = \bigoplus_{m=-4}^{4} (5-|m|)\mathbf{1}_m \quad \Rightarrow \quad M_m \qquad m = 0, \ldots, 4$$

$$(5-m)\times(5-m)$$

ANEC as an SDP

- Formulate the problem as an SDP:

$$d = 4: \qquad M_m^{(\mathcal{E})} \succeq 0 \qquad M_m^{(\mathcal{E}_4)} \succeq 0 \qquad m = 0, 1, 2, 3, 4$$

$$\left(M_m^{(\mathcal{E})}\right)_{ij} = c_{ij} + \vec{v}_{ij} \cdot \vec{\lambda},$$

$$\vec{\lambda} = \left(\frac{n_B}{c_T}, \frac{n_F}{c_T}, \frac{x_{4B}}{\sqrt{c_T}}, \frac{x_{4F}}{\sqrt{c_T}}, \frac{x_{4V}}{\sqrt{c_T}}, \vec{\lambda}_{\mathcal{O}_4 T \mathcal{O}_4}, \vec{\lambda}_{\mathcal{O}_4 \mathcal{O}_4 \mathcal{O}_4}\right)$$

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  - optimize a/c with some additional conditions on $\lambda_{TT\mathcal{O}_4}$:

e.g., $(x_{4B}, x_{4F}, x_{4V}) = (x^*_{4B}, x^*_{4F}, x^*_{4V})$

$$x_{4B}+x_{4F}+x_{4V} \geq x^*_4$$

- Our bounds are not sensitive to C_T:

$$M^{(\mathcal{E})}_{c_T,\lambda_{TTT},\lambda_{TT\mathcal{O}_4}} = U_{c_T}^T M^{(\mathcal{E})}_{1,\frac{\lambda_{TTT}}{c_T},\frac{\lambda_{TT\mathcal{O}_4}}{\sqrt{c_T}}} U_{c_T}$$

CFT with slightly broken higher-spin symmetry

- With some choice of the polarization, sometimes one can get analytic bounds:

$$\begin{pmatrix} \langle T|\mathcal{E}|T\rangle & \langle T|\mathcal{E}|\mathcal{O}_4\rangle \\ \langle \mathcal{O}_4|\mathcal{E}|T\rangle & \boxed{\langle \mathcal{O}_4|\mathcal{E}|\mathcal{O}_4\rangle} \end{pmatrix} \longrightarrow$$

choose polarization such that all $\lambda_{O_4TO_4}$ vanish

$$\rightarrow \quad \begin{pmatrix} \frac{1+x_{\text{even}}}{2} & \frac{ix_{\text{odd}}}{2} & f_1(\tau_4)\tilde{x}_{4B}+f_2(\tau_4)\tilde{x}_{4F}+\frac{i\tilde{x}_{4\text{odd}}}{2} \\ -\frac{ix_{\text{odd}}}{2} & \frac{1-x_{\text{even}}}{2} & f_2(\tau_4)\tilde{x}_{4B}+f_1(\tau_4)\tilde{x}_{4F}-\frac{i\tilde{x}_{4\text{odd}}}{2} \\ f_1(\tau_4)\tilde{x}_{4B}+f_2(\tau_4)\tilde{x}_{4F}-\frac{i\tilde{x}_{4\text{odd}}}{2} & f_2(\tau_4)\tilde{x}_{4B}+f_1(\tau_4)\tilde{x}_{4F}+\frac{i\tilde{x}_{4\text{odd}}}{2} & \frac{\Gamma(7+\tau_4)^2}{630(7+\tau_4)\Gamma(6+2\tau_4)} \end{pmatrix} \succeq 0$$

(similar bound in 4d)

CFT with slightly broken higher-spin symmetry

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choose polarization such that all $\lambda_{O_4 T O_4}$ vanish

$$\to \begin{pmatrix} \frac{1+x_{\text{even}}}{2} & \frac{i x_{\text{odd}}}{2} & f_1(\tau_4)\tilde{x}_{4B} + f_2(\tau_4)\tilde{x}_{4F} + \frac{i\tilde{x}_{4\text{odd}}}{2} \\ -\frac{i x_{\text{odd}}}{2} & \frac{1-x_{\text{even}}}{2} & f_2(\tau_4)\tilde{x}_{4B} + f_1(\tau_4)\tilde{x}_{4F} - \frac{i\tilde{x}_{4\text{odd}}}{2} \\ f_1(\tau_4)\tilde{x}_{4B} + f_2(\tau_4)\tilde{x}_{4F} - \frac{i\tilde{x}_{4\text{odd}}}{2} & f_2(\tau_4)\tilde{x}_{4B} + f_1(\tau_4)\tilde{x}_{4F} + \frac{i\tilde{x}_{4\text{odd}}}{2} & \frac{\Gamma(7+\tau_4)^2}{630(7+\tau_4)\Gamma(6+2\tau_4)} \end{pmatrix} \succeq 0$$

(similar bound in 4d)

- Application: constraining 1/N corrections for CFTs with slightly broken higher spin symmetry

[Maldacena, Zhiboedov '12]

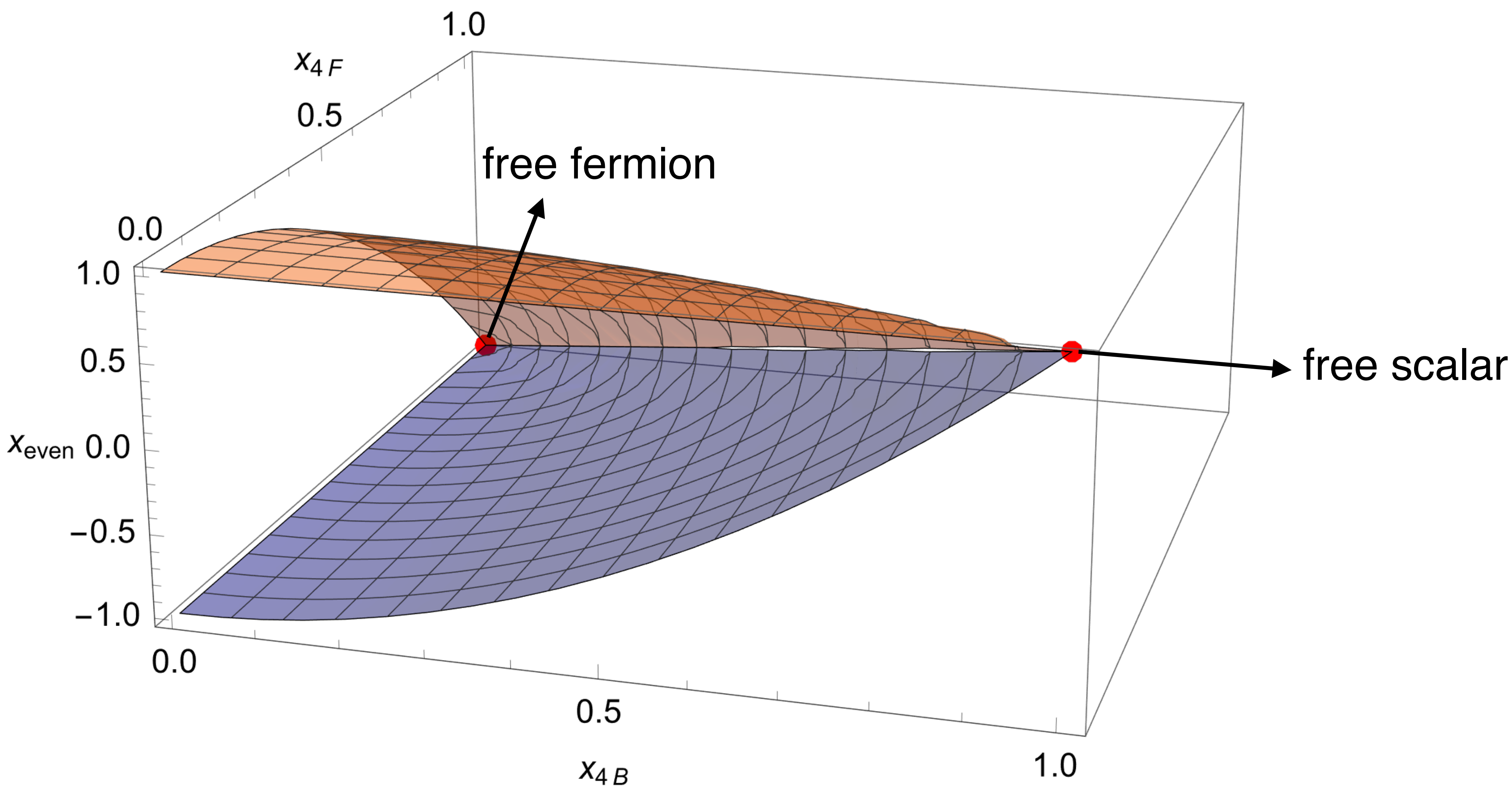
$$x_{\text{even}} = \frac{\tilde{\lambda}^2 - 1}{1+\tilde{\lambda}^2}, \quad x_{\text{odd}} = \frac{2\tilde{\lambda}}{1+\tilde{\lambda}^2} + \alpha_{\text{odd}}\gamma_4, \qquad \tau_4 - 1 = \gamma_4 \ll 1$$

$$\tilde{x}_{4B} = \frac{\tilde{\lambda}^2}{1+\tilde{\lambda}^2} + \alpha_{4B}\gamma_4, \quad \tilde{x}_{4F} = \frac{1}{1+\tilde{\lambda}^2} + \alpha_{4F}\gamma_4, \quad \tilde{x}_{4\text{odd}} = \frac{2\tilde{\lambda}}{1+\tilde{\lambda}^2} + \alpha_{4\text{odd}}\gamma_4.$$

$$\alpha_{4\text{odd}}\tilde{\lambda} \leq -\frac{6}{7}\frac{\tilde{\lambda}^2}{1+\tilde{\lambda}^2} \qquad \alpha_{\text{odd}}\tilde{\lambda} \leq 0, \quad \alpha_{4B} \leq -\frac{\alpha_{4\text{odd}}}{2\tilde{\lambda}} - \frac{3}{7}, \quad \alpha_{4F} \leq -\frac{\alpha_{4\text{odd}}\tilde{\lambda}}{2} - \frac{3}{7},$$

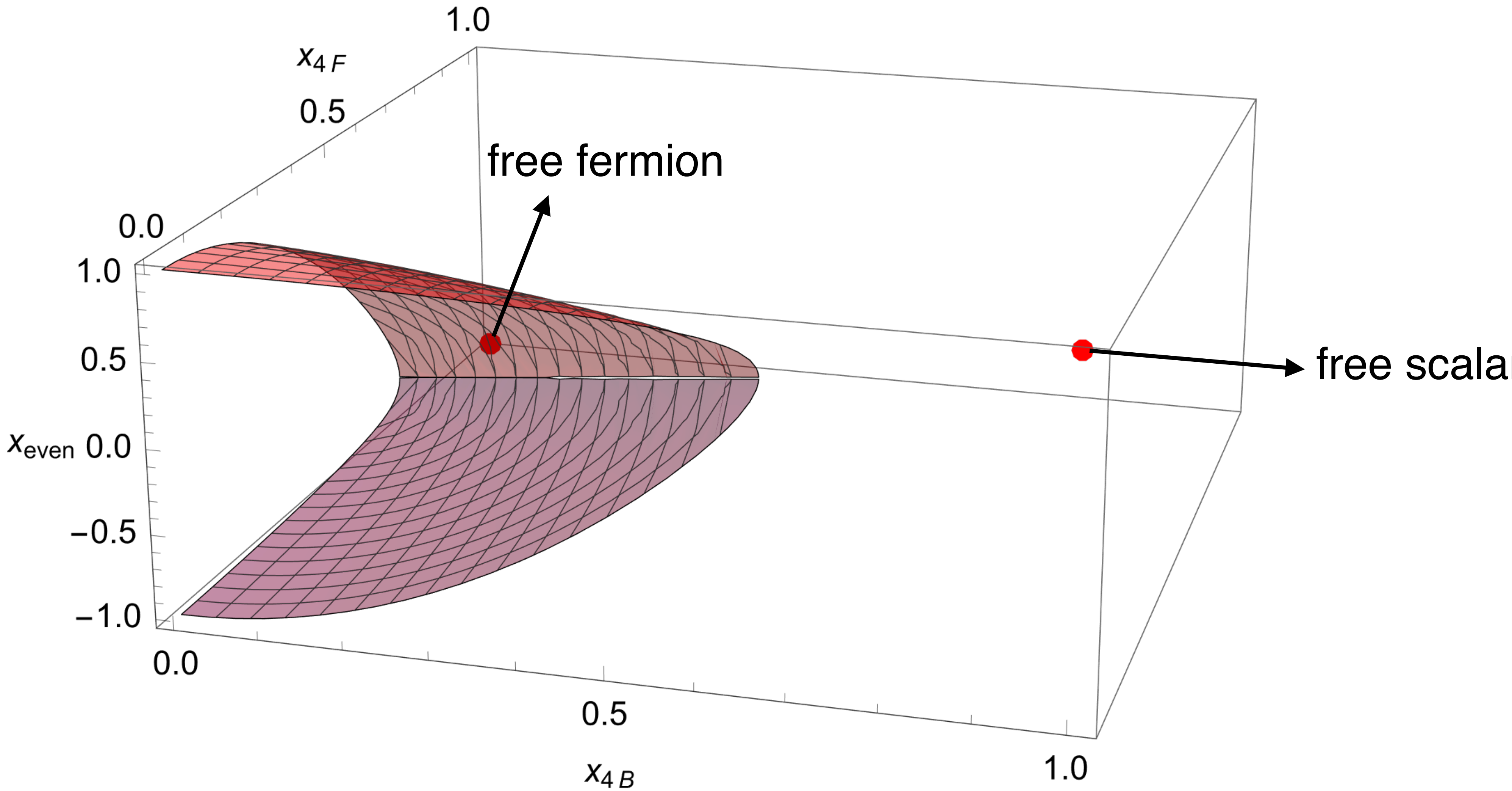
Bounds for parity-preserving 3d CFTs

$$\tau_4 = 1$$



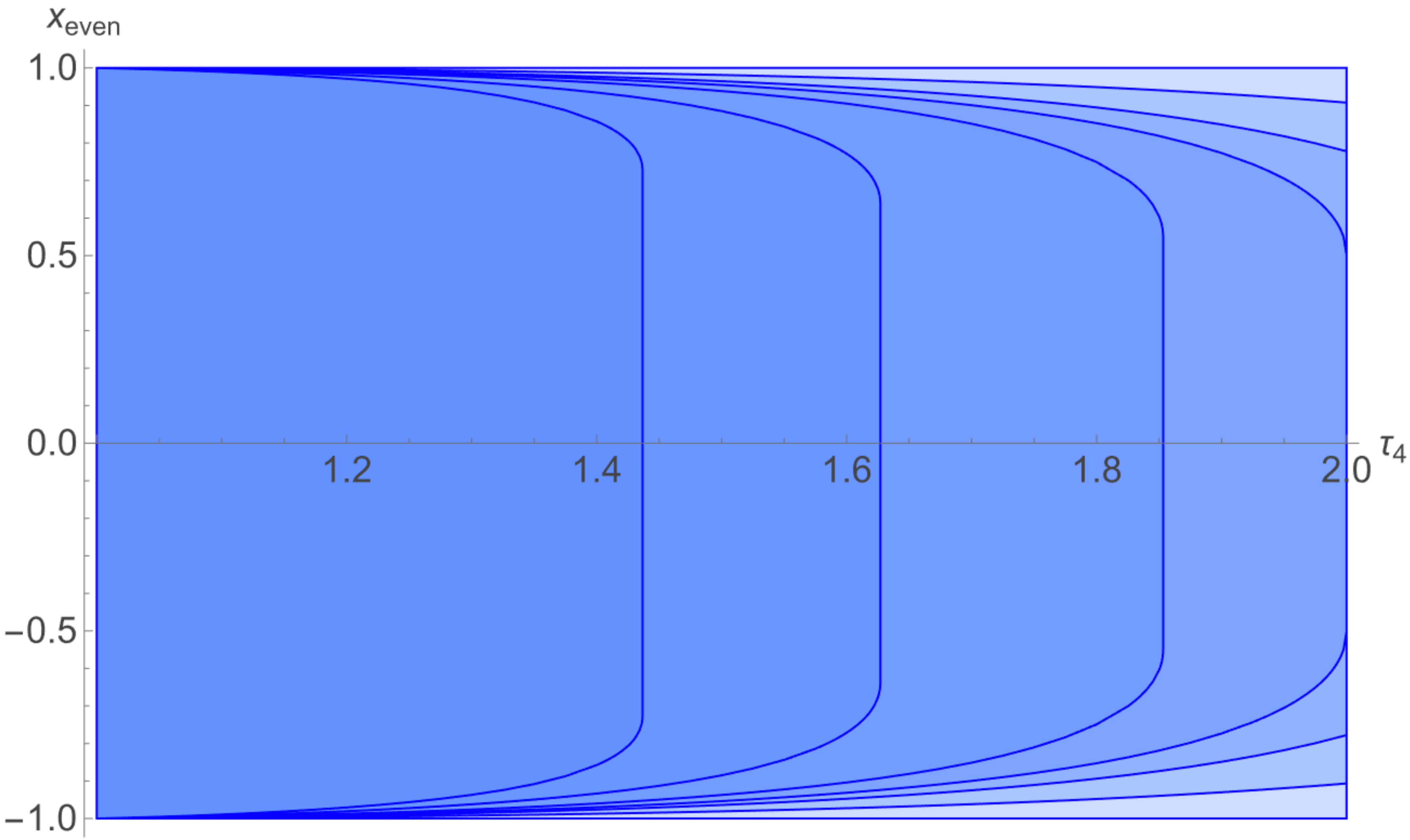
Bounds for parity-preserving 3d CFTs

$$\tau_4 = 1.5$$



Bounds for parity-preserving 3d CFTs

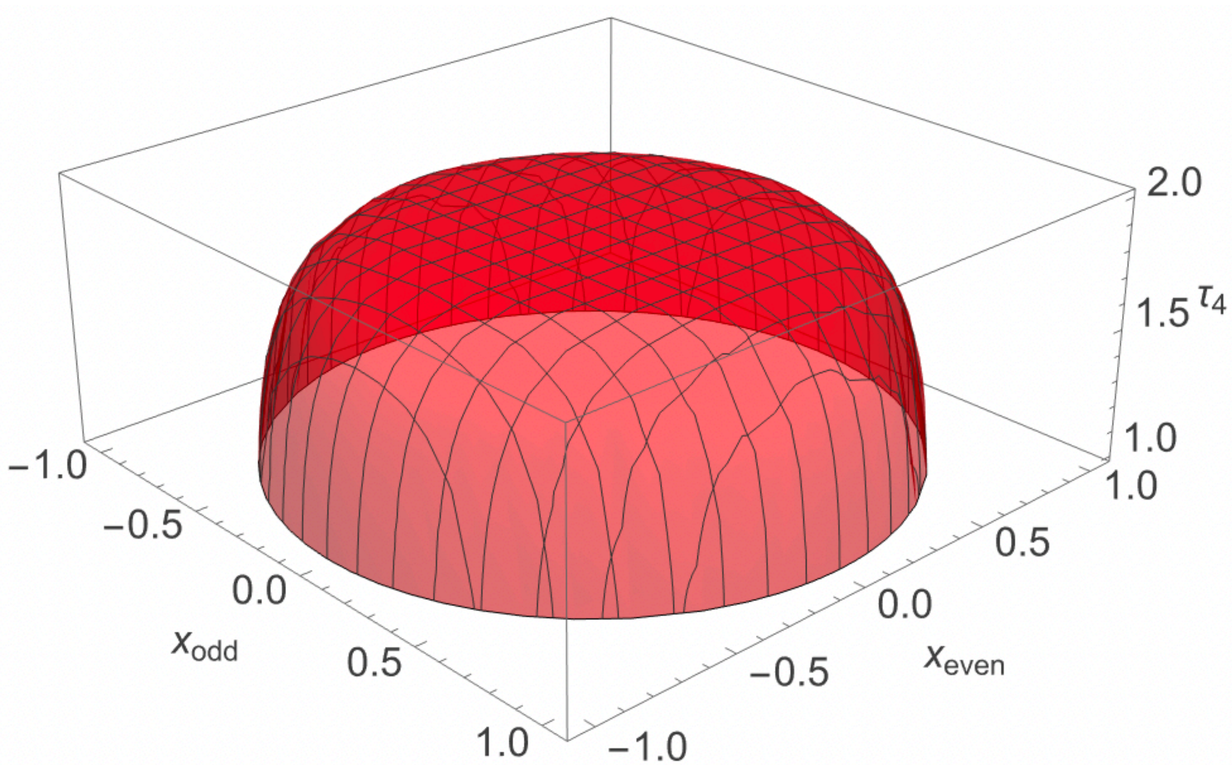
$$x_{4B} + x_{4F} \geq x_{4\text{gap}}$$



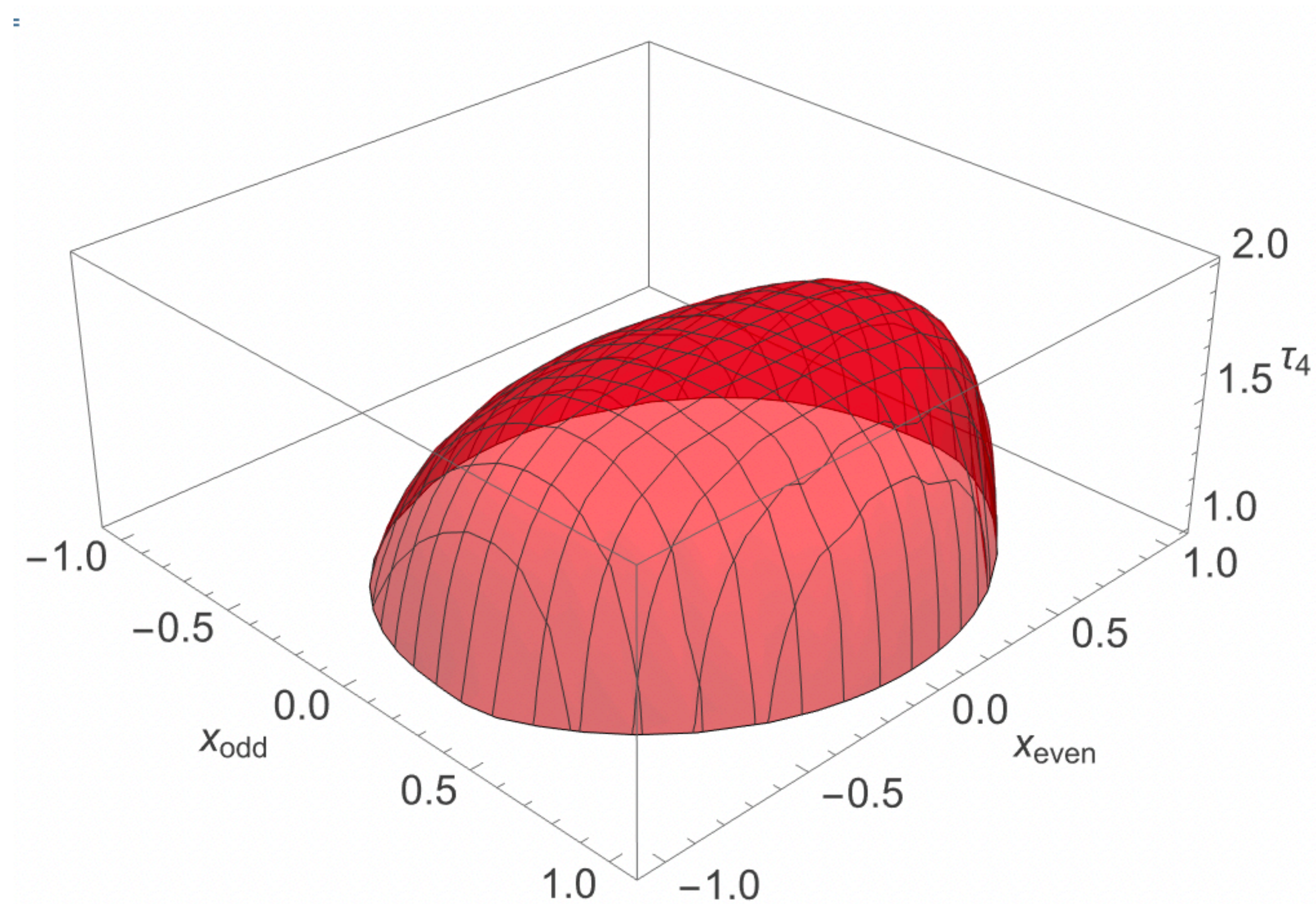
$x_{4\text{gap}} = 0, 0.3, 0.4, 0.44, 0.5, 0.6, 0.7$

Bounds for 3d CFTs

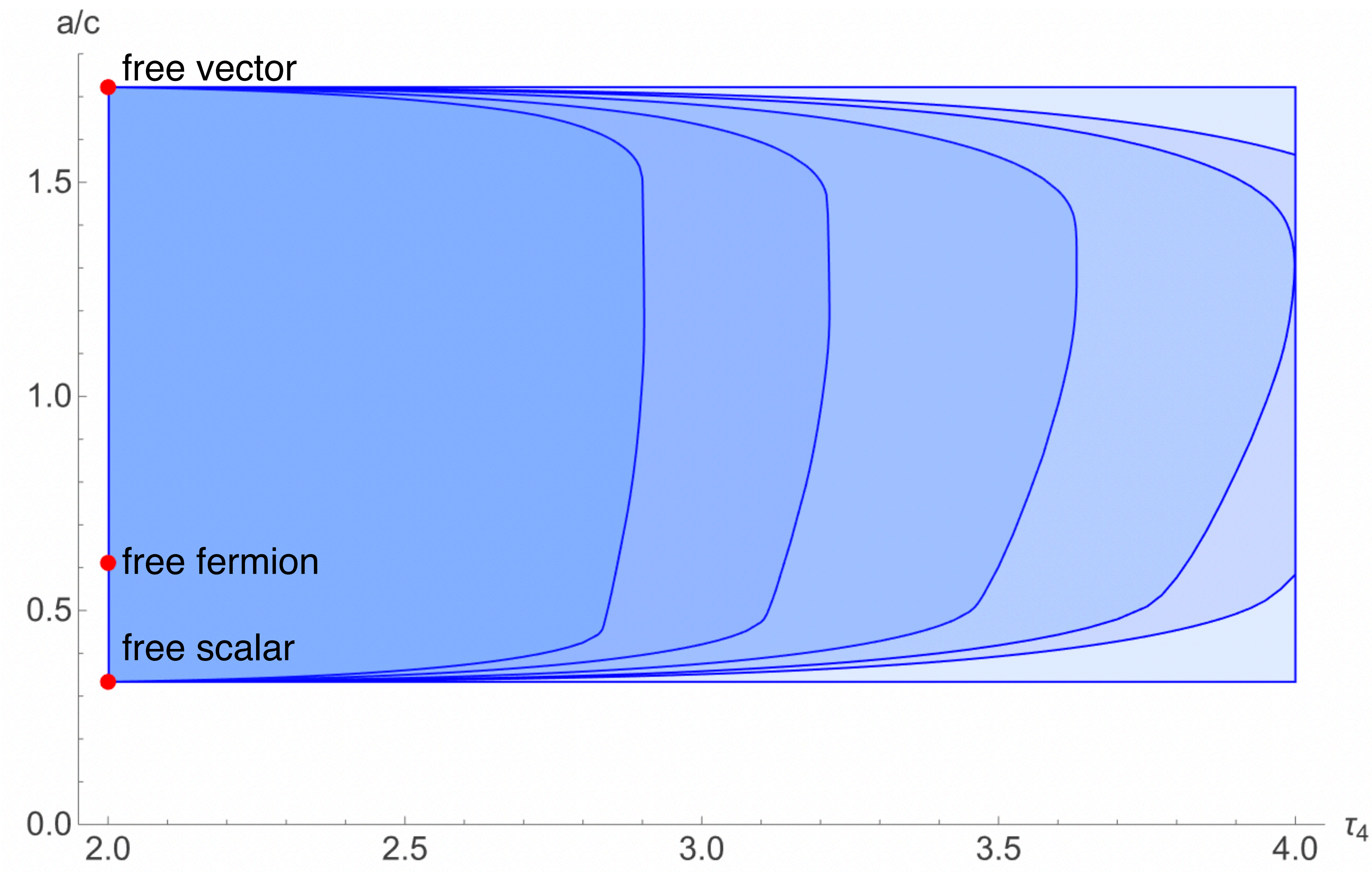
$$x_{4B} + x_{4F} \geq 0.5$$



$$x_{4B} + x_{4F} \geq 0.5,\ x_{4\mathrm{odd}} \geq 0.35$$



Bounds for 4d CFTs



$$x_{4\text{gap}} = 0, 0.2, 0.234, 0.3, 0.4, 0.5$$

Summary and outlook

Summary:

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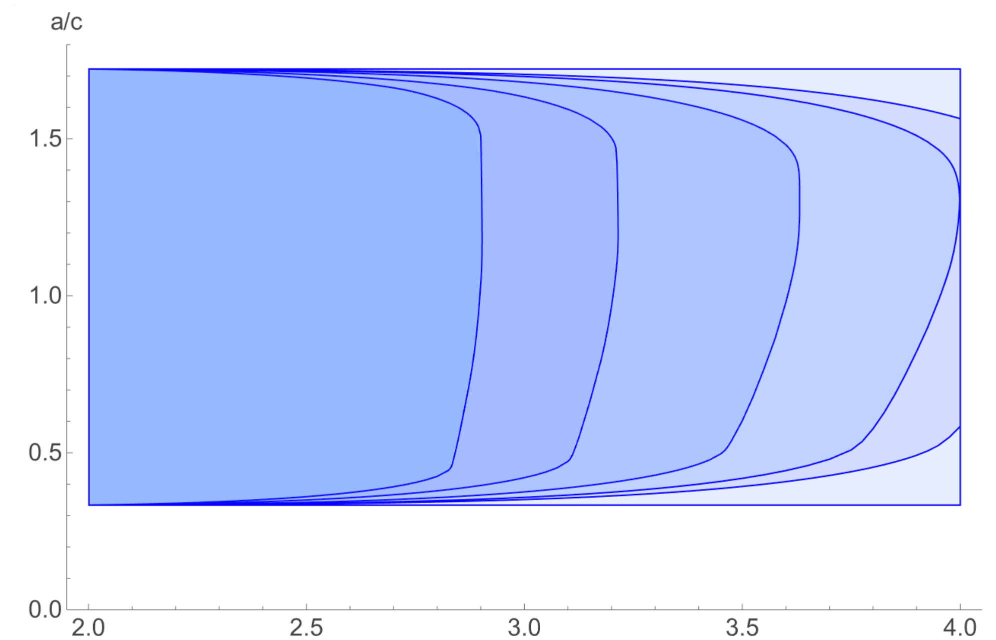
- Stronger bounds on λ_{TTT} as functions of τ_4 and λ_{TTO_4}



Outlook:

- Compare with 4-pt stress tensor bootstrap in 3d (replace x_{4gap} with Δ_4'?); Also in 4d?
- Constraints from higher-point functions of ANEC and higher-spin ANEC in stress tensor state (c_T dependence)
- Continuous-spin ANEC?

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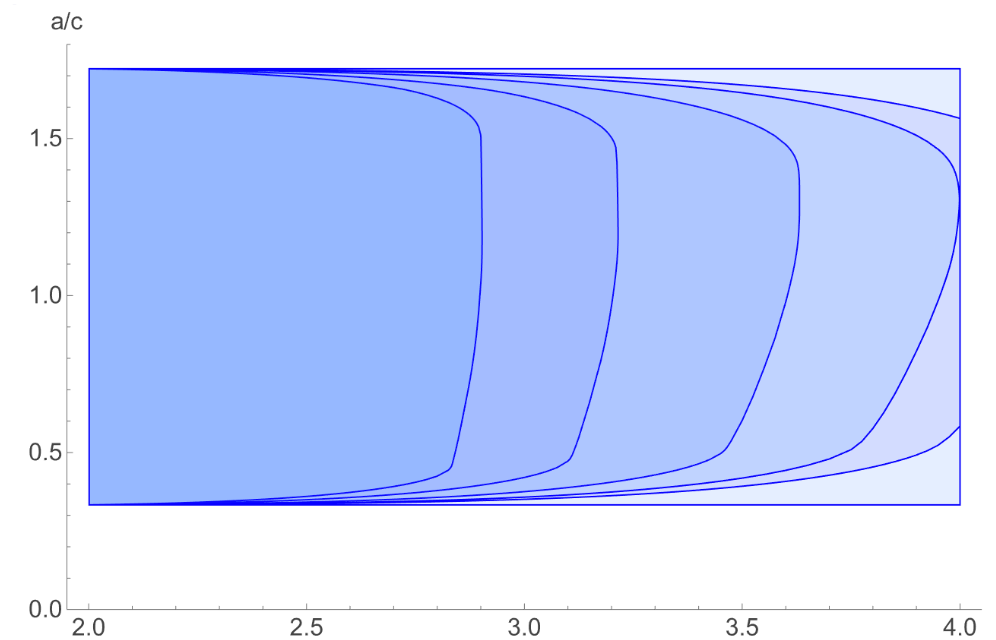

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