# Lightrays, Shocks, Strings, and Conformal Colliders

Alexander Zhiboedov, CERN

Strings 2019, Brussels

based on the joint work with M. Kologlu, P. Kravchuk, D. Simmons-Duffin

(related work with: A. Belitsky, X. Camanho, J. Edelstein, J. Henn, S. Hohenegger, Z. Komargodski, G. Korchemsky, M.Kulaxizi, J. Maldacena, A. Parnachev, E. Sokatchev, K. Yan)

# Introduction

Consider a unitary QFT in d>2. Assume a stress tensor

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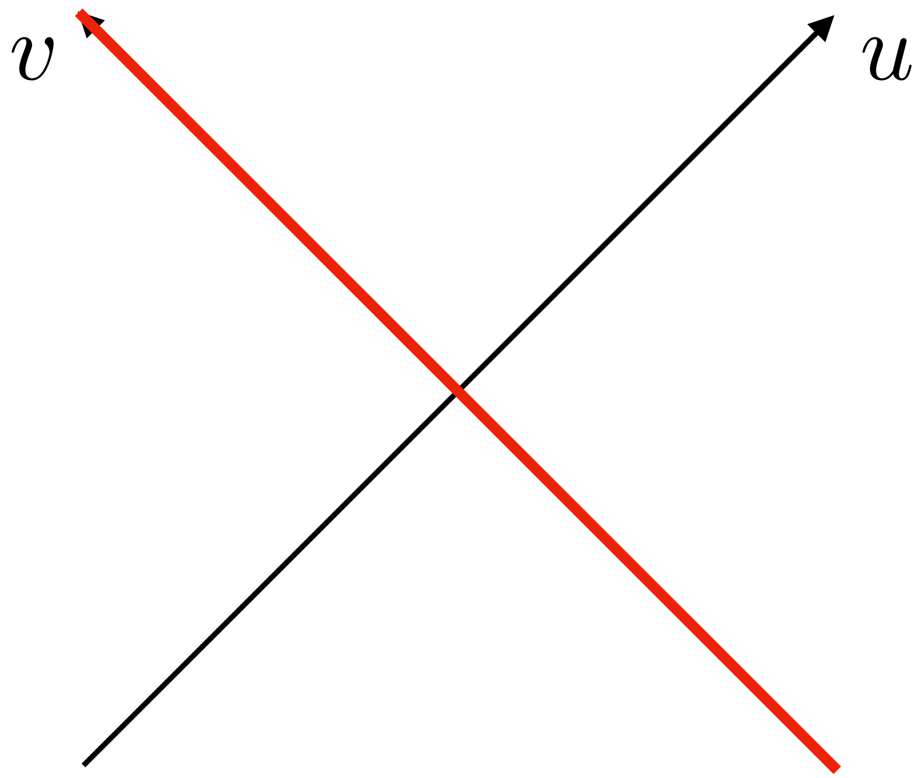
$$ds^2 = -du dv + d\vec{y}^2 \qquad \vec{y} \in \mathbb{R}^{d-2}$$




The ANEC operator (energy density):

$$\mathcal{E}(\vec{y}) = \int_{-\infty}^{\infty} dv T_{vv}(0, v, \vec{y}) \geq 0$$

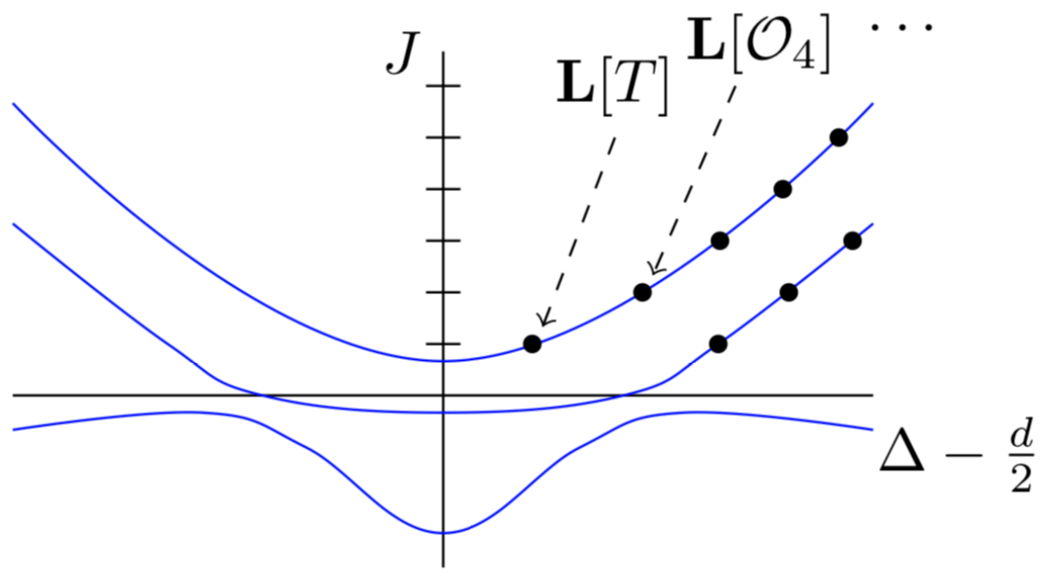
[Faulkner, Leigh, Parrikar, Wang 16']
[Hartman, Kundu, Tajdini 16']

# ANECology

[Review talk by T. Hartman, Strings 2018]
[Review talk by D. Simmons-Duffin, Strings 2018]

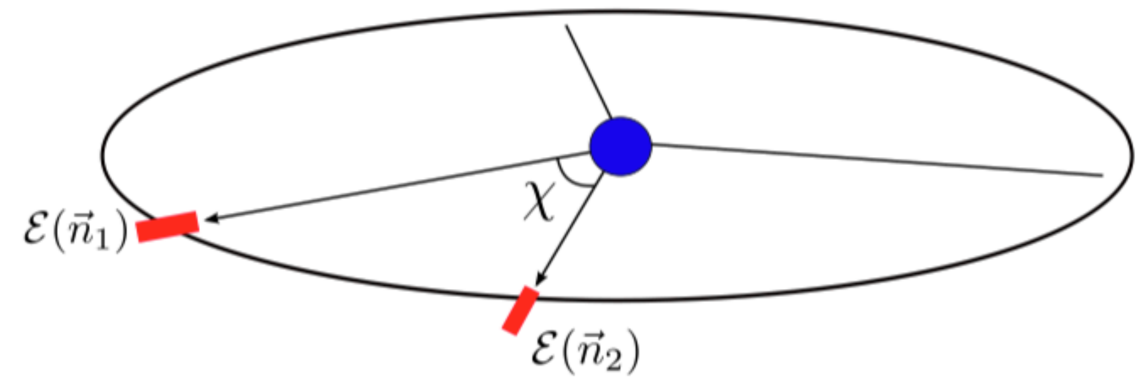
The ANEC operator has many appearances and applications.

**light-ray operators (lightrays)**



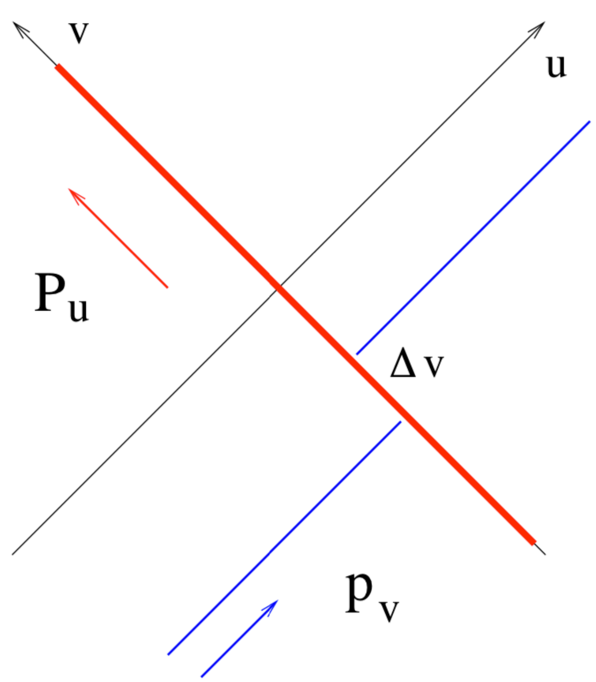

[Kravchuk, Simmons-Duffin '18]

**event shapes**



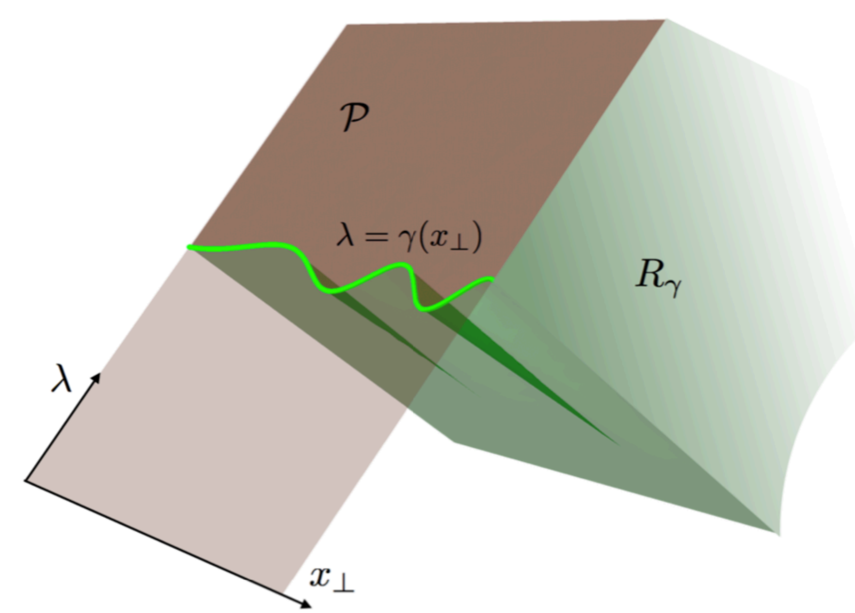

[Hofman, Maldacena '08]

**gravitational shocks**




[Afkhami-Jeddi, Hartman, Kundu, Tajdini '17]

**QIT**




[Casini, Testé, Torroba '18]

# ANECology

Many of the studies up to date focused on

**1-point:** $\langle\Psi'|\mathcal{E}(\vec{y})|\Psi\rangle$

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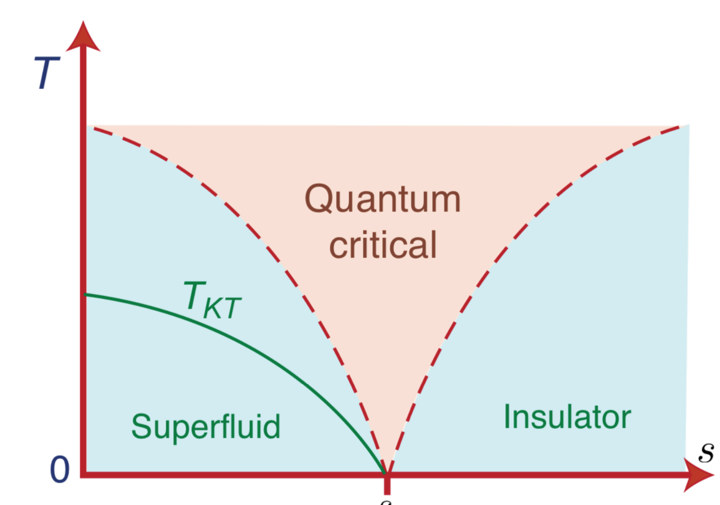
*
This is just a particular example of a generic class of observables that involve light-ray operators in Lorentzian CFTs.




[Hartnoll, Lucas, Sachdev '18]

**Part I:** new lightray technology

- convergence and commutativity
- local $\times$ lightray OPE
- lightray $\times$ lightray OPE

**Part II:** applications

- Deriving AdS gravity from CFT
- Conformal collider physics

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# Commutativity of ANECs

**Q:** Do ANEC operators commute?

$$[\mathcal{E}(\vec{y}_1), \mathcal{E}(\vec{y}_2)] \stackrel{?}{=} 0 \qquad \mathcal{E}(\vec{y}) = \int_{-\infty}^{\infty} dv T_{vv}(0, v, \vec{y})$$

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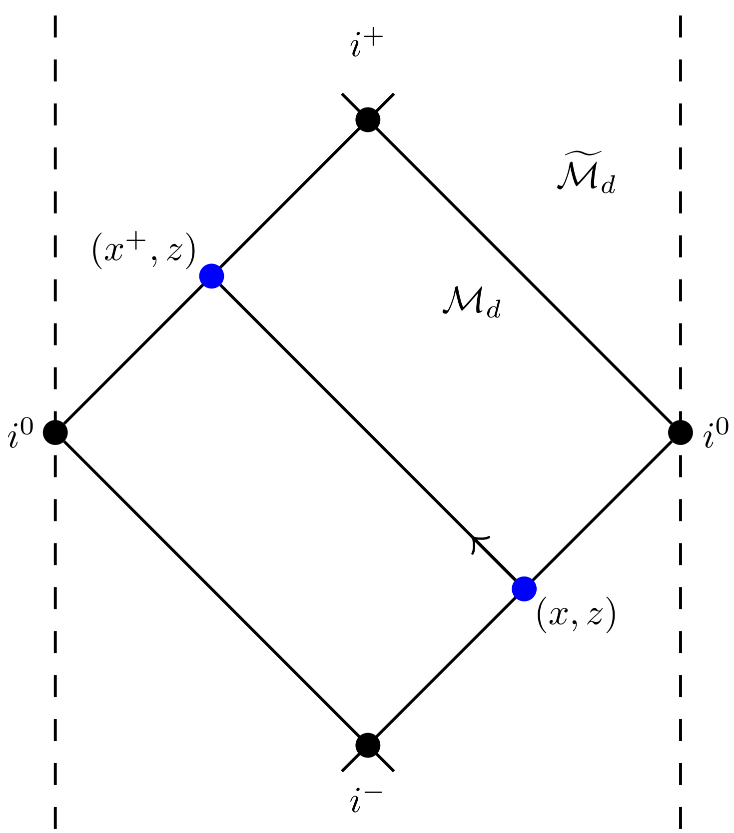
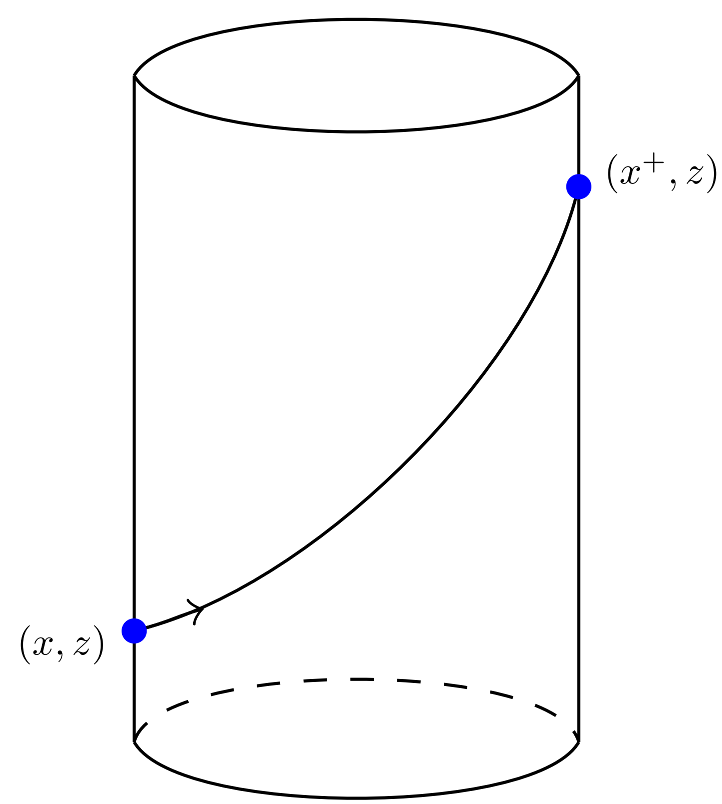
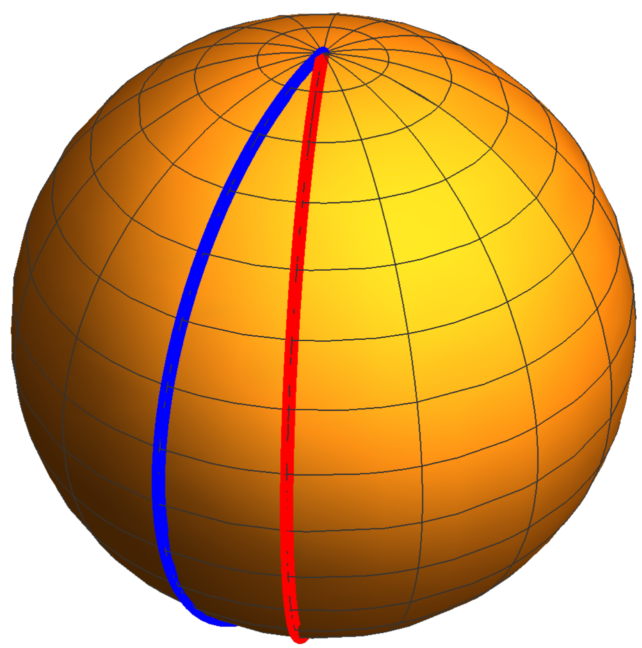
**They are not space-like separated at the endpoints.**



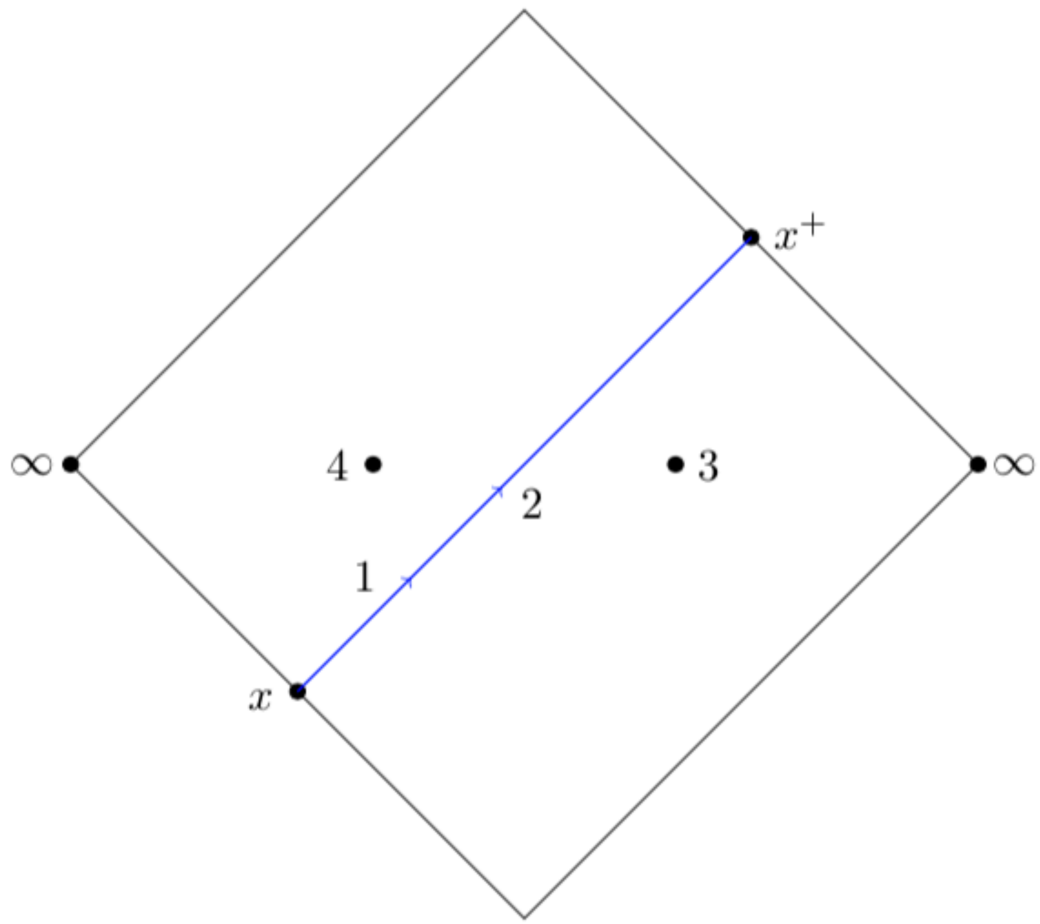



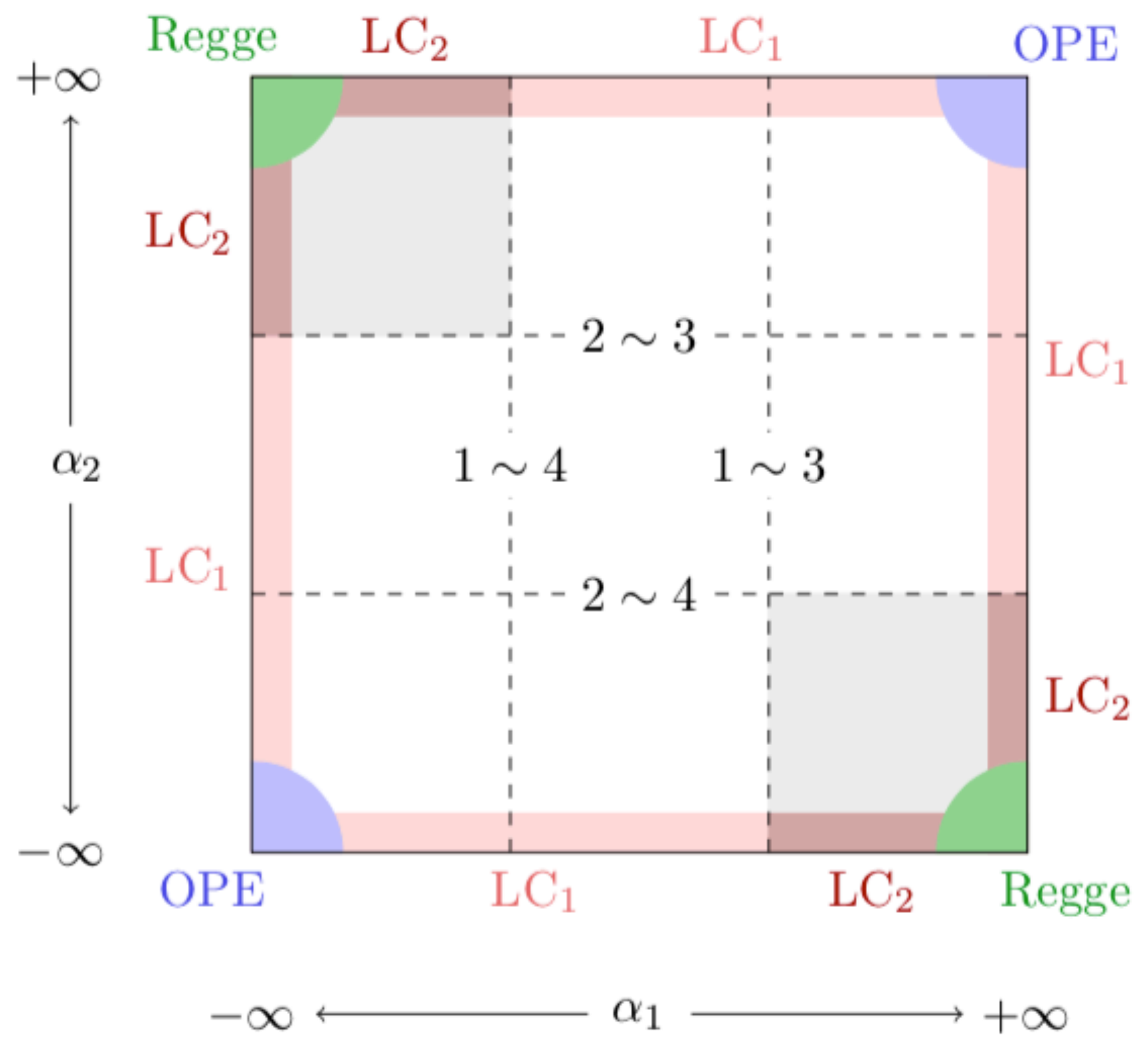



$$\mathbf{L}[T](x, z_1)\mathbf{L}[T](x, z_2)$$

**light transform**

# Commutativity of light-ray operators



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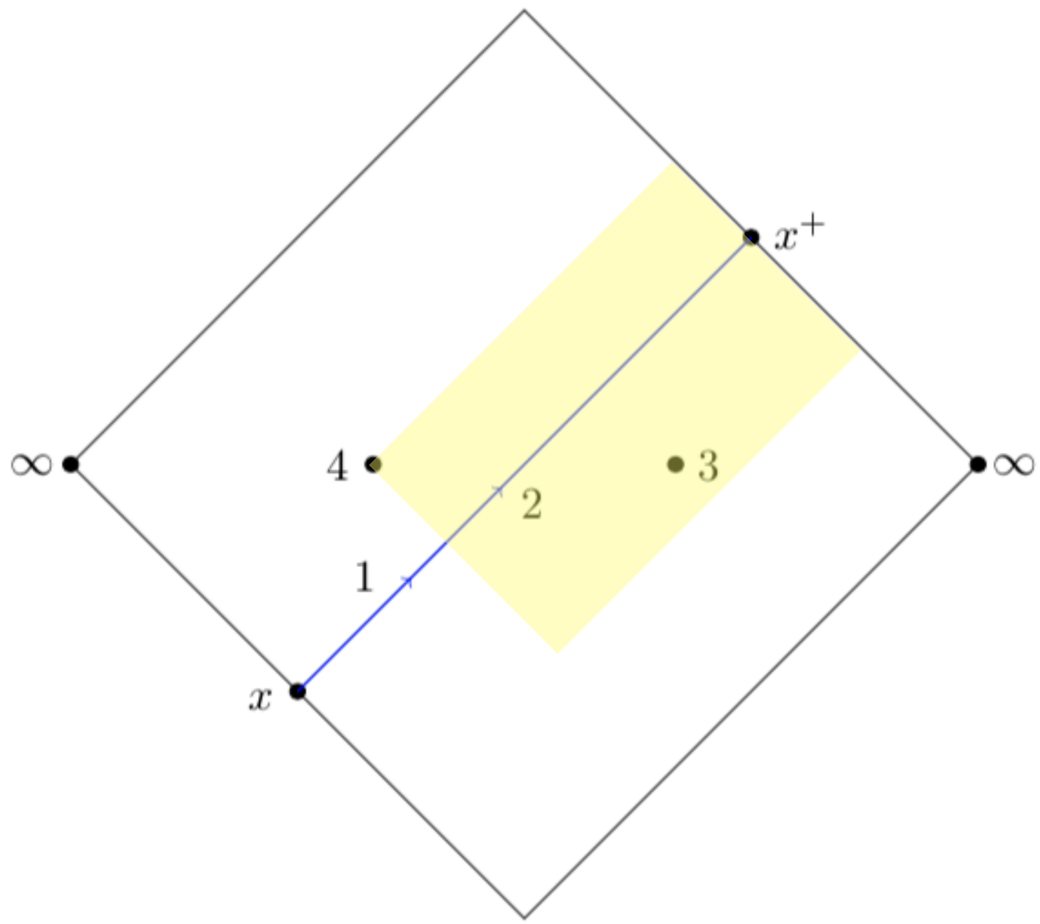


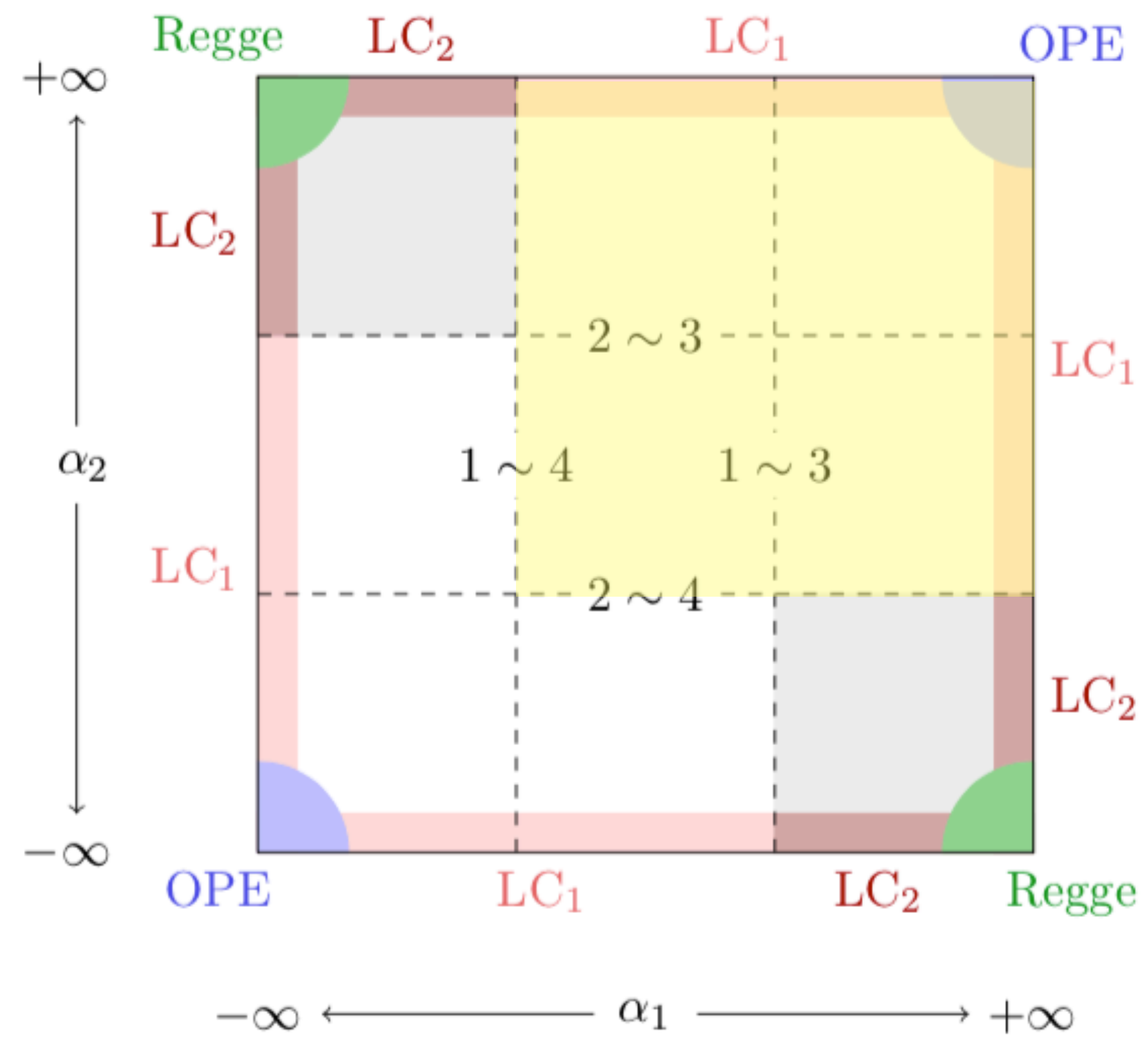

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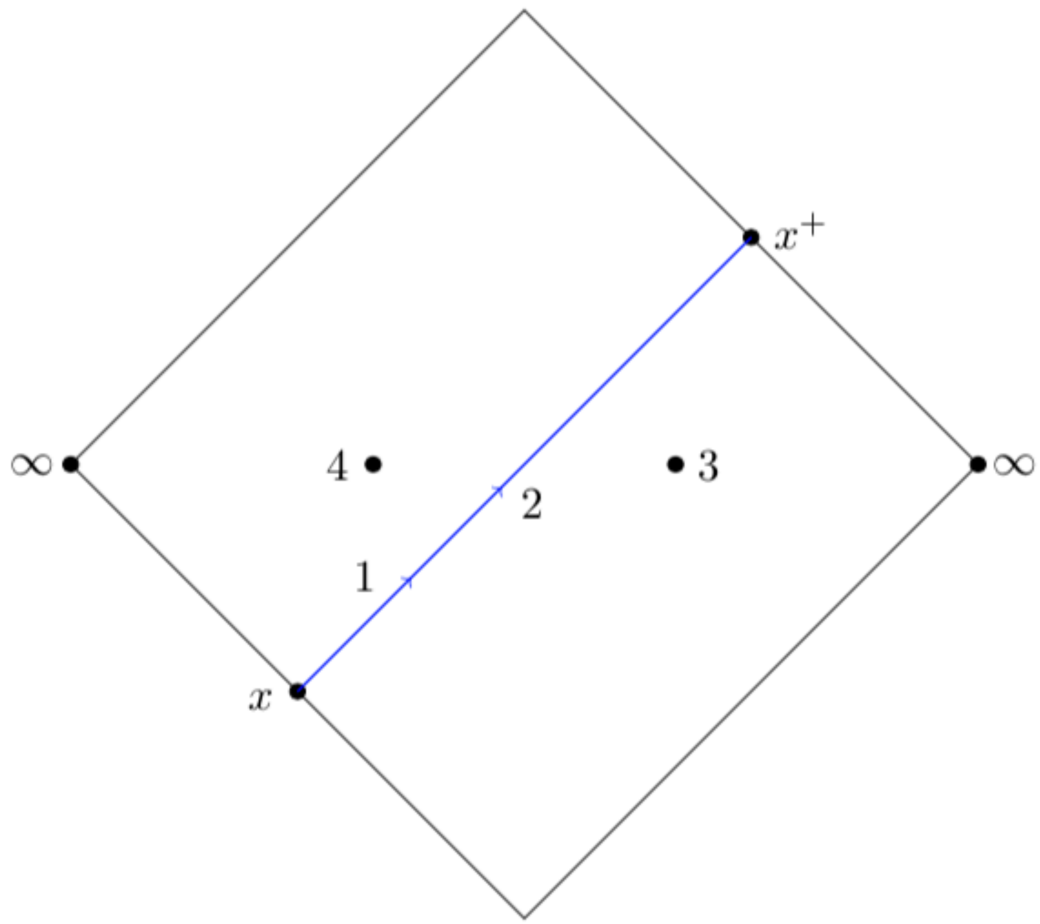


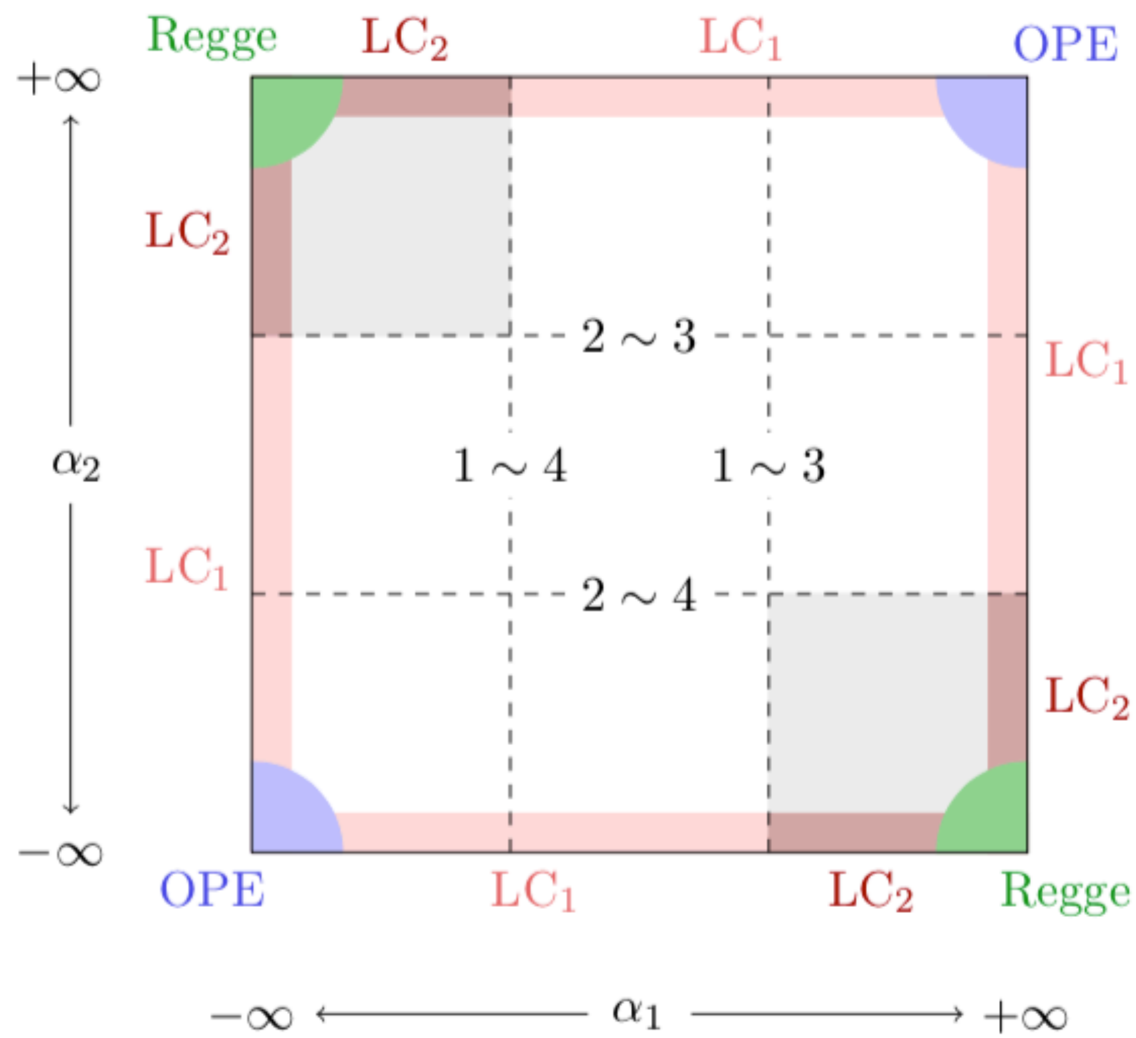

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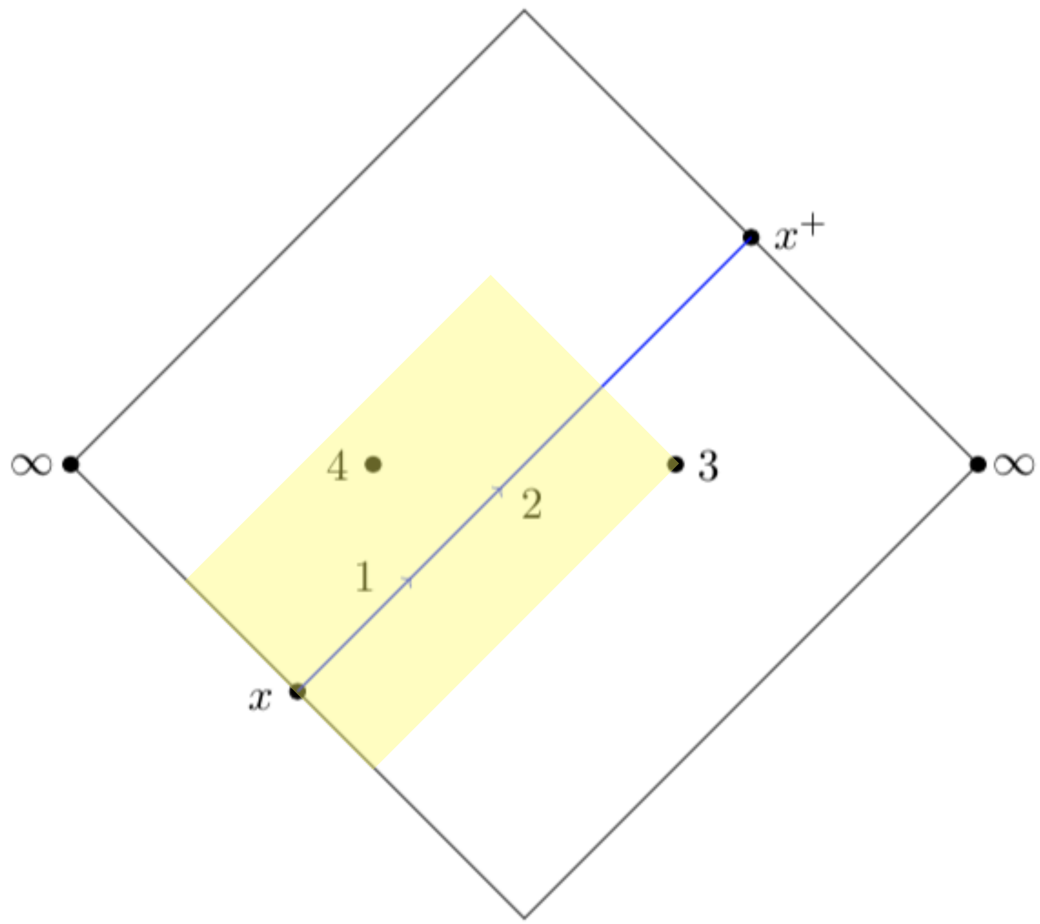


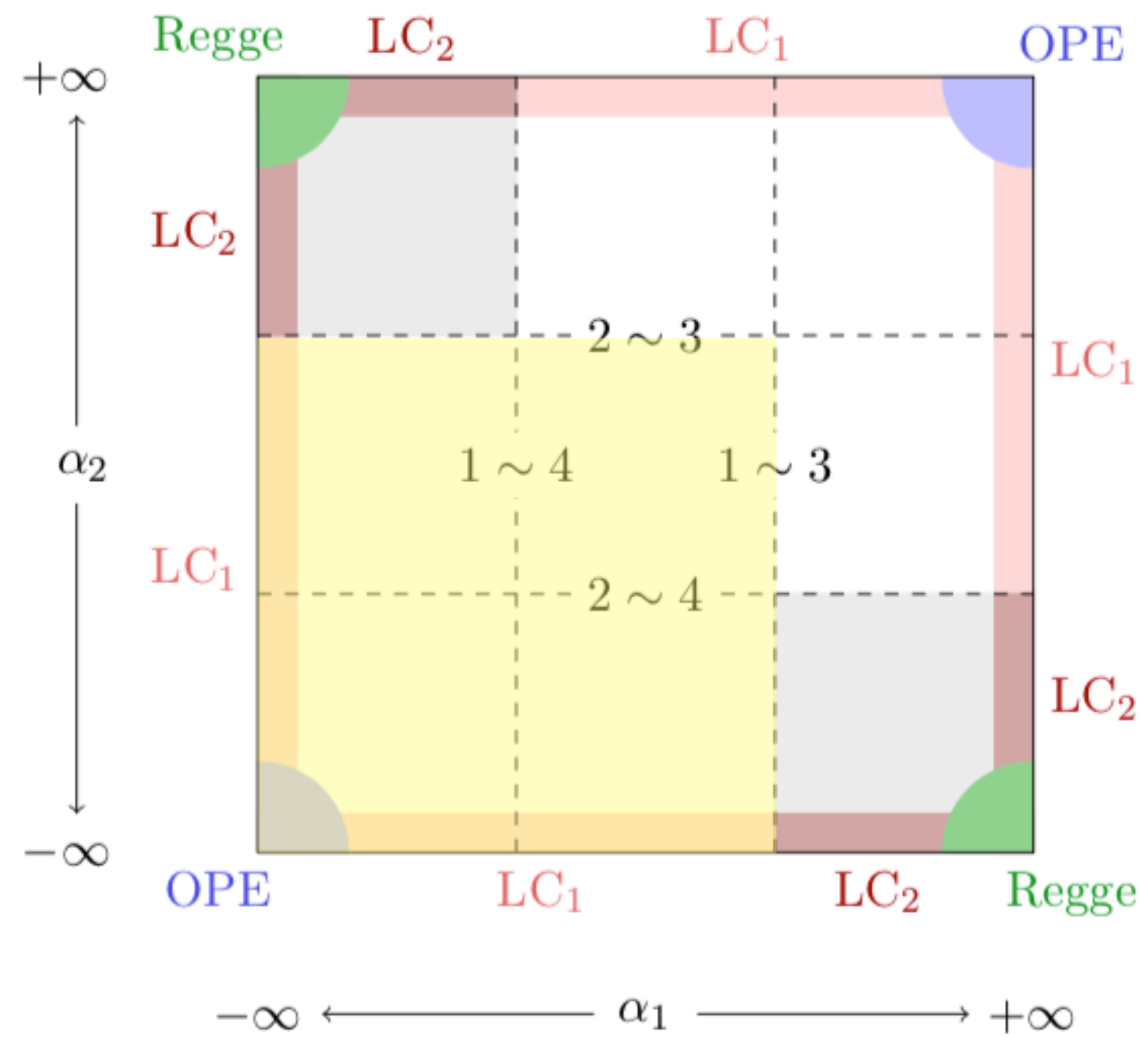

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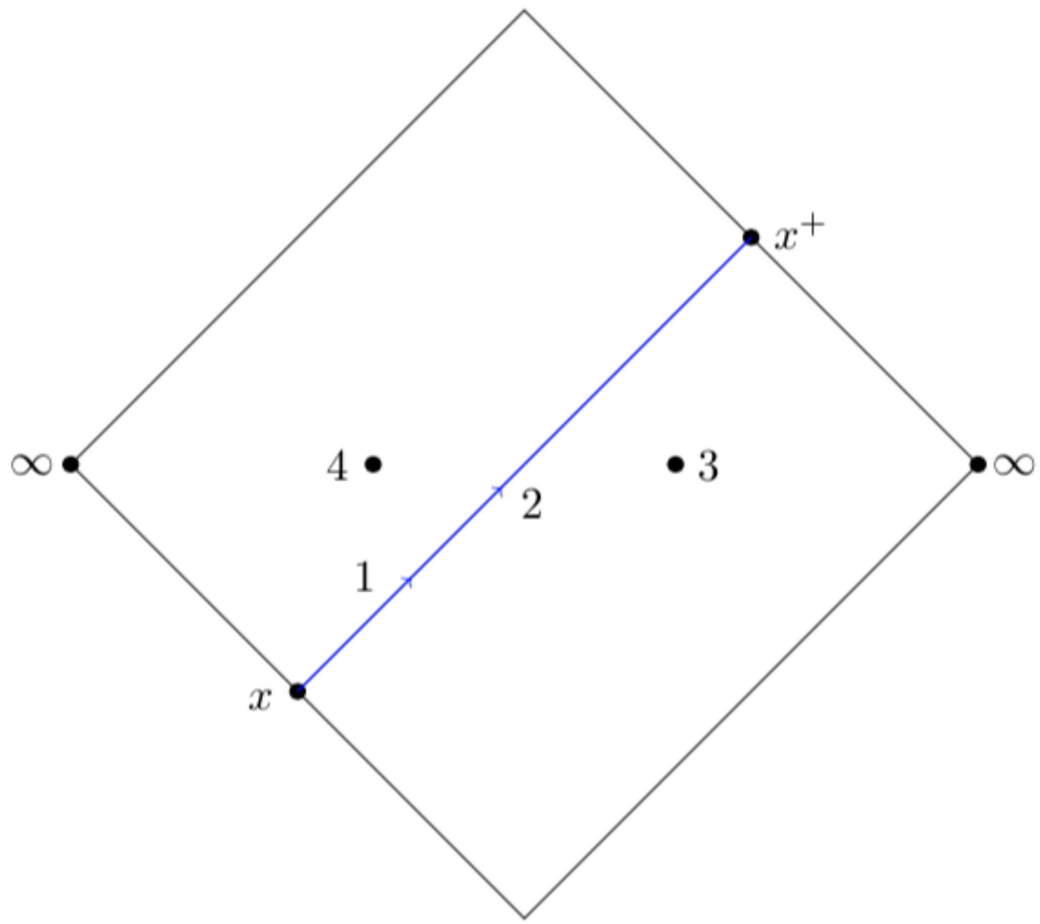


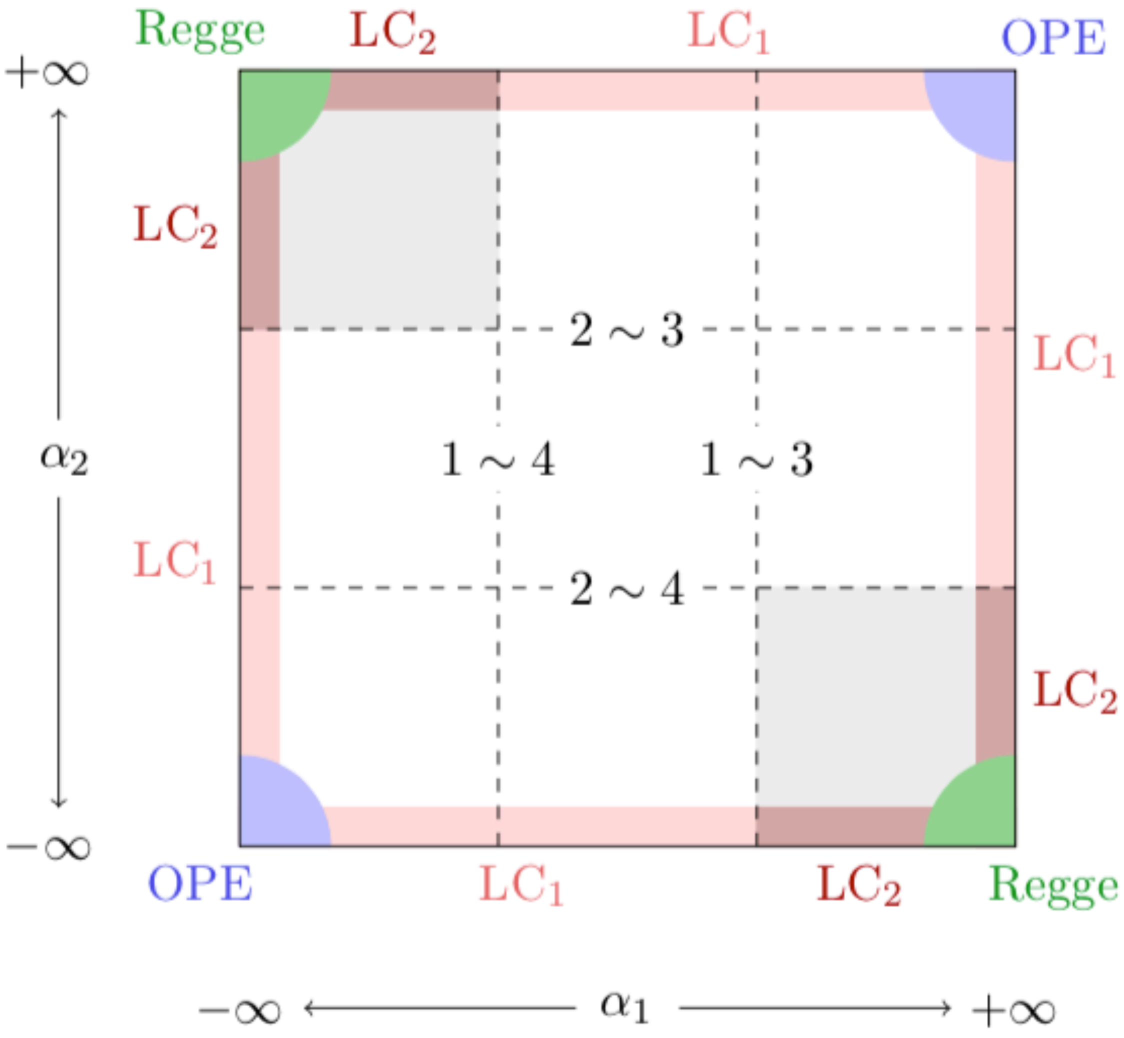

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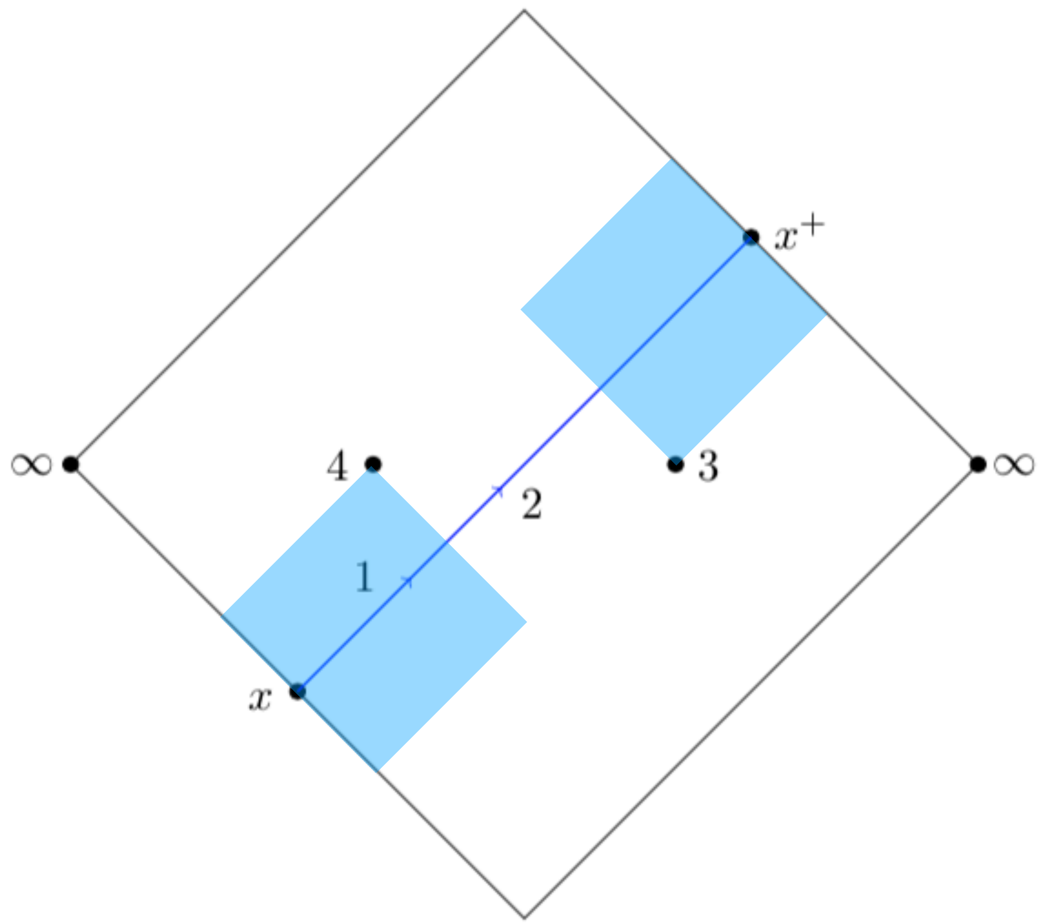
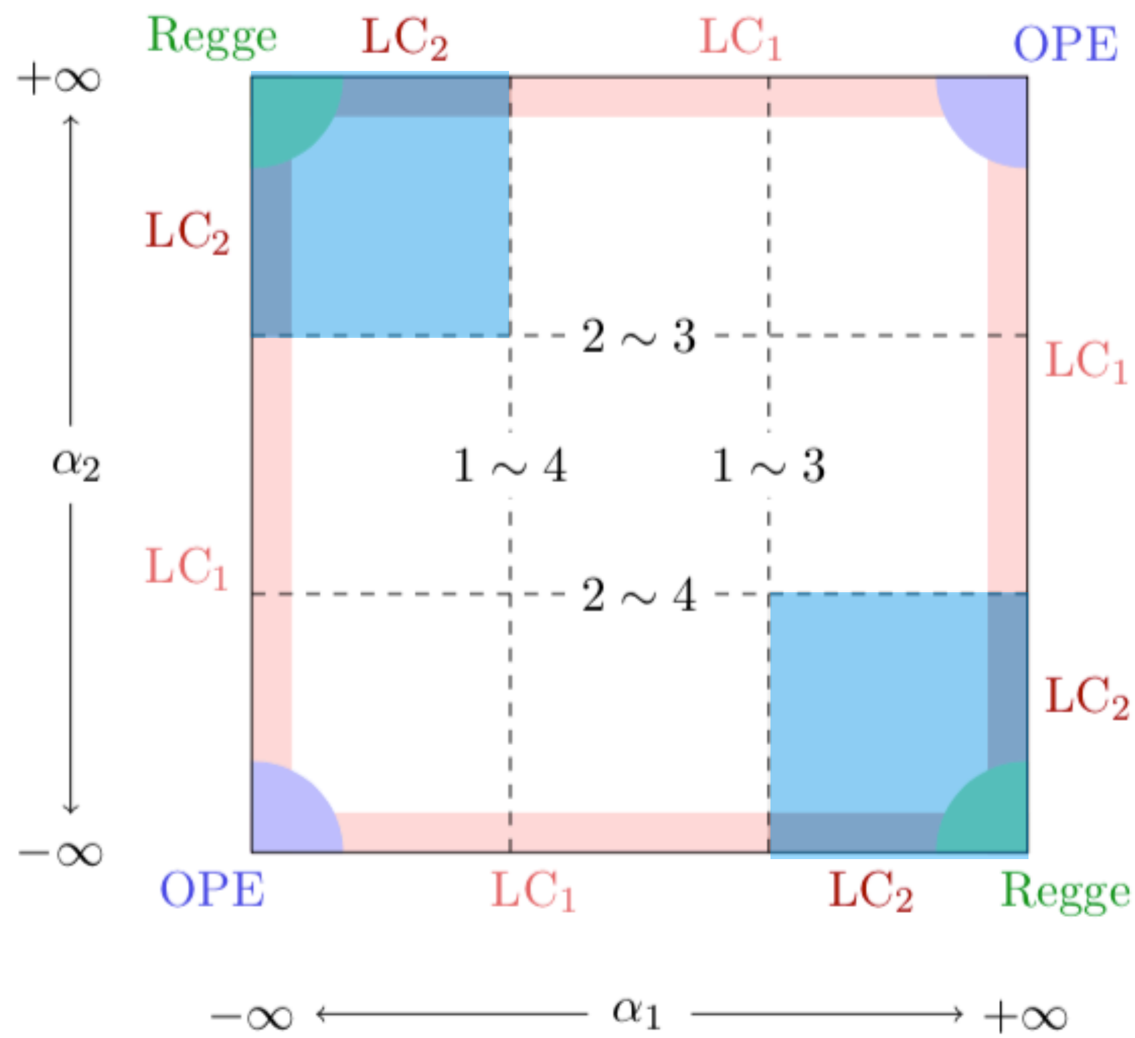



**Rindler positivity**
**+asymptotic light-cone expansion**

# Commutativity of light-ray operators

More generally, a necessary condition for a product to be well-defined and commutative

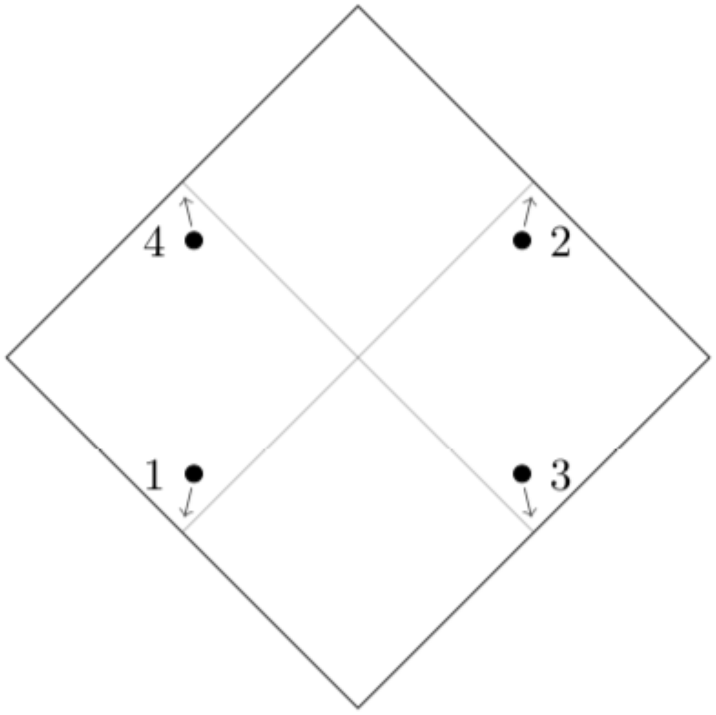
$$\langle\Omega|\mathcal{O}_4\mathbf{L}[\mathcal{O}_{J_1}](x,z_1)\mathbf{L}[\mathcal{O}_{J_2}](x,z_2)\mathcal{O}_3|\Omega\rangle$$

$$J_1 + J_2 > 1 + J_0$$

Here $J_0$ is the Regge intercept

$$\frac{\langle ABAB\rangle}{\langle AA\rangle\langle BB\rangle} = 1 - f_{AA\mathcal{O}}(J_0)f_{BB\mathcal{O}}(J_0)e^{t(J_0-1)}$$

$$\mathcal{A}(s,t) \sim s^{J_0}$$



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**Claim**: In any unitary CFT ANEC operators commute

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**Reason:** $J_0 < 3$

$J_1 + J_2 > 1 + J_0$

**Nonperturbatively:** $J_0 \leq 1$ [Caron-Huot 17′]

**Planar:** $J_0^{\text{planar}} \leq 2$ [Maldacena, Shenker, Stanford 15′]

Conversely, a non-vanishing commutator leads to a Regge pole at

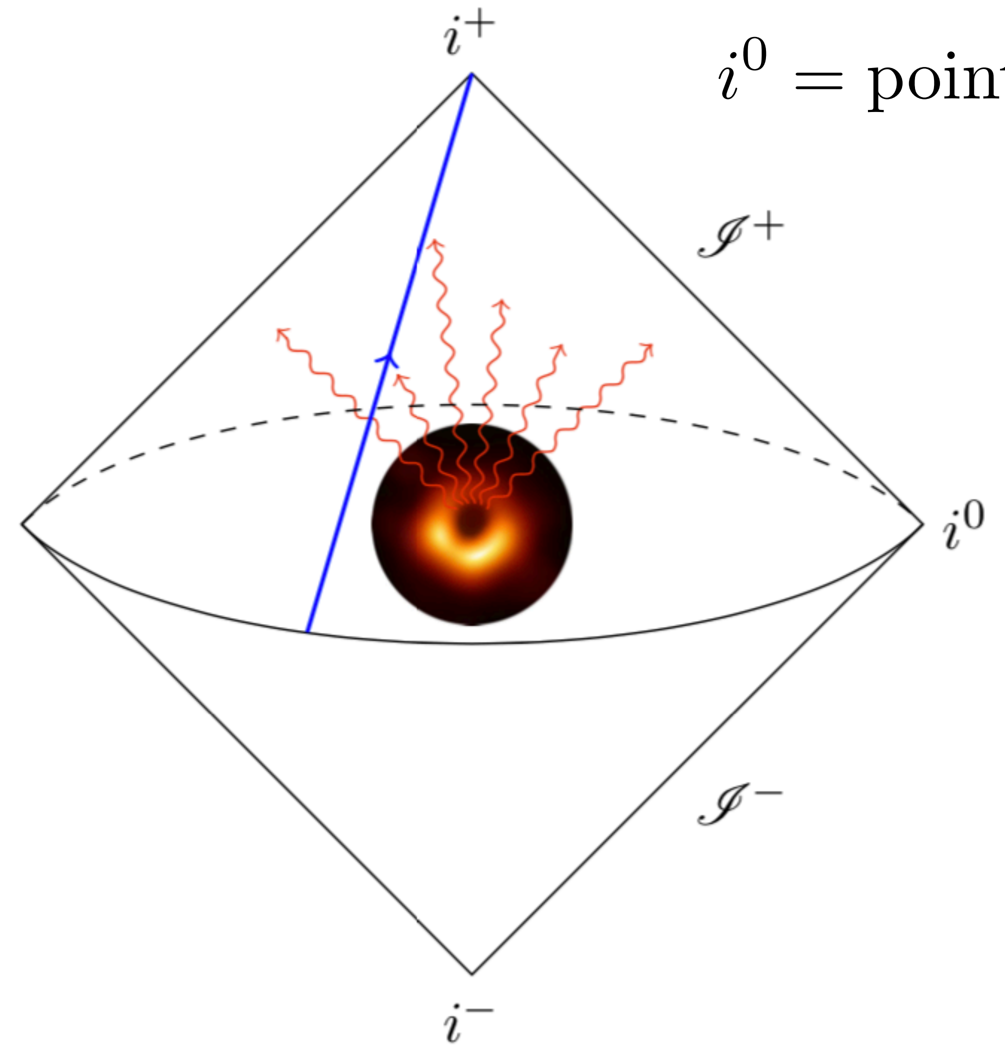
$$J_0 = 3$$

# Event Shapes

A convenient frame:

$$[P^\mu, \mathbf{L}[\mathcal{O}](\infty, z)] = 0$$

$$|\phi(p)\rangle = \int d^d x\, e^{ip\cdot x} \phi(x)|\Omega\rangle$$

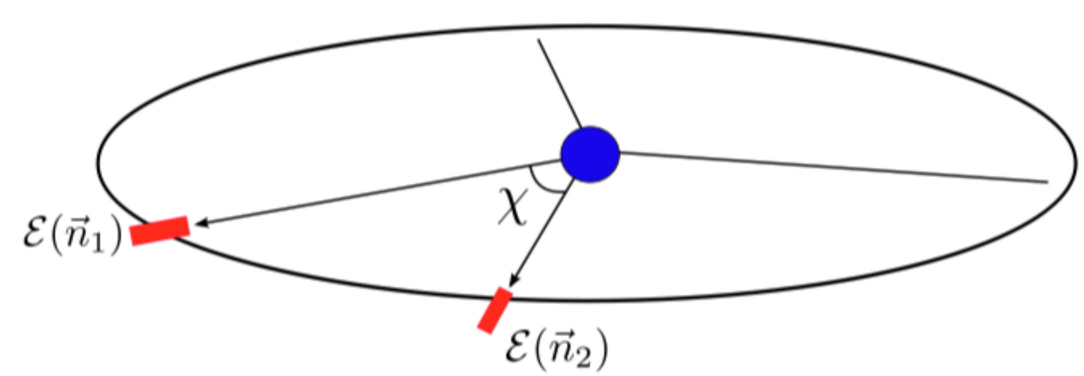



Event shapes:

$$\langle \phi_1(p)|\mathbf{L}[\mathcal{O}_1](\infty, z_1)\cdots \mathbf{L}[\mathcal{O}_n](\infty, z_n)|\phi_2(p)\rangle$$

**(integrated Wightman functions)**

$$z = (1, \vec{n})$$
$$z_1 \cdot z_2 = -1 + \cos\chi$$




**lightray = detector**

# Two-point event shapes

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For the two-point event shape

$$\langle \mathcal{O}_4(p)|\mathbf{L}[\mathcal{O}_1](\infty, z_1)\mathbf{L}[\mathcal{O}_2](\infty, z_2)|\mathcal{O}_3(p)\rangle$$

we can consider two types of OPE:

**t-channel:** $\text{lightray} - \text{local} \to \text{lightray} - \text{local}$

**s-channel:** $\text{lightray} - \text{lightray} \to \text{local} - \text{local}$

# Local-Lightray OPE

[Belin, Hofman, Mathys '19]
[Kologlu, Kravchuk, Simmons-Duffin, AZ '19]

$$\langle \mathcal{O}_4(p)|\mathbf{L}[\mathcal{O}_1](\infty, z_1)\mathbf{L}[\mathcal{O}_2](\infty, z_2)|\mathcal{O}_3(p)\rangle$$

$$= \sum_{\mathcal{O}} \sum_{\Psi_{\mathcal{O}}} \langle \mathcal{O}_4(p)|\mathbf{L}[\mathcal{O}_1](\infty, z_1)|\Psi_{\mathcal{O}}\rangle\langle\Psi_{\mathcal{O}}|\mathbf{L}[\mathcal{O}_2](\infty, z_2)|\mathcal{O}_3(p)\rangle$$

$$\sum_{\Psi_{\mathcal{O}}} |\Psi_{\mathcal{O}}\rangle\langle\Psi_{\mathcal{O}}| = \mathcal{A}(\Delta)^{-1}\int_{p>0} \frac{d^d p}{(2\pi)^d}(-p^2)^{\frac{d}{2}-\Delta}|\mathcal{O}(p)\rangle\langle\mathcal{O}(p)|$$

$$= \sum_{\mathcal{O},a,b} \lambda_{14\mathcal{O},a}\lambda_{23\mathcal{O},b}G^{t,ab}_{\Delta_{\mathcal{O}},\rho_{\mathcal{O}}}(p, z_1, z_2)$$

These are the t-channel blocks

**Example**: For four scalars

$$G^t_{\Delta_{\mathcal{O}},J_{\mathcal{O}}}(z_1, z_2, p) = \sum_{s=0}^{J} G^t_{\Delta_{\mathcal{O}},J_{\mathcal{O}}}(s)C_s^{(\frac{d-3}{2})}(\cos\chi)$$

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[Kologlu, Kravchuk, Simmons-Duffin, AZ '19]

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**Example:** For four scalars

involve ${}_4F_3(...;1)$

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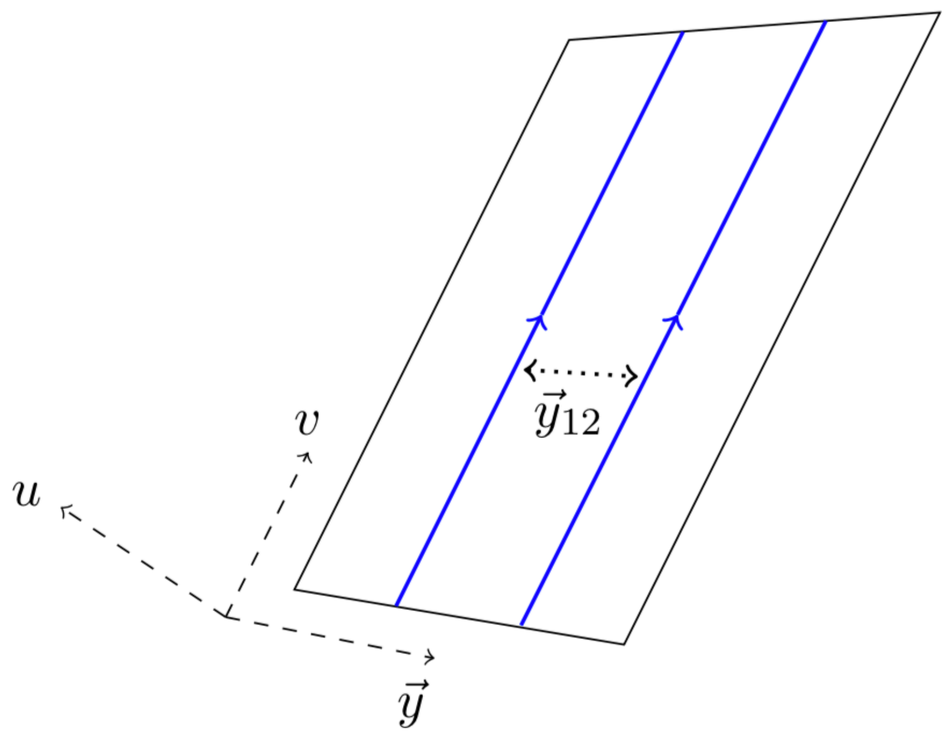
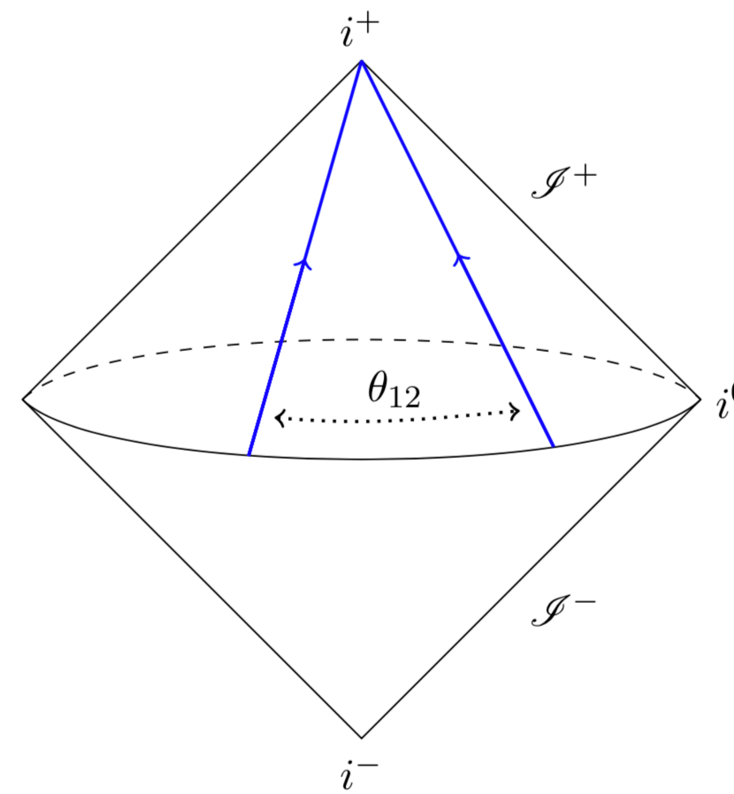
# Lightray-Lightray OPE

A light-ray operator is point-like in the transverse plane.
It is natural to expand in small transverse separations.




$$\int_{-\infty}^{\infty} dv_1\, \mathcal{O}_{1;v\cdots v}(u=0, v_1, \vec{y}_1) \times \int_{-\infty}^{\infty} dv_2\, \mathcal{O}_{2;v\cdots v}(u=0, v_2, \vec{y}_2)$$

$$\stackrel{?}{=} \sum_i |\vec{y}_{12}|^{\delta_i-(\Delta_1-1)-(\Delta_2-1)} \mathbb{O}_i$$

# Lightray-Lightray OPE

Small angle:

- QCD [Konishi, Ukawa, Veneziano ’79]
- planar $\mathcal{N} = 4$ [Hofman, Maldacena, ’08]

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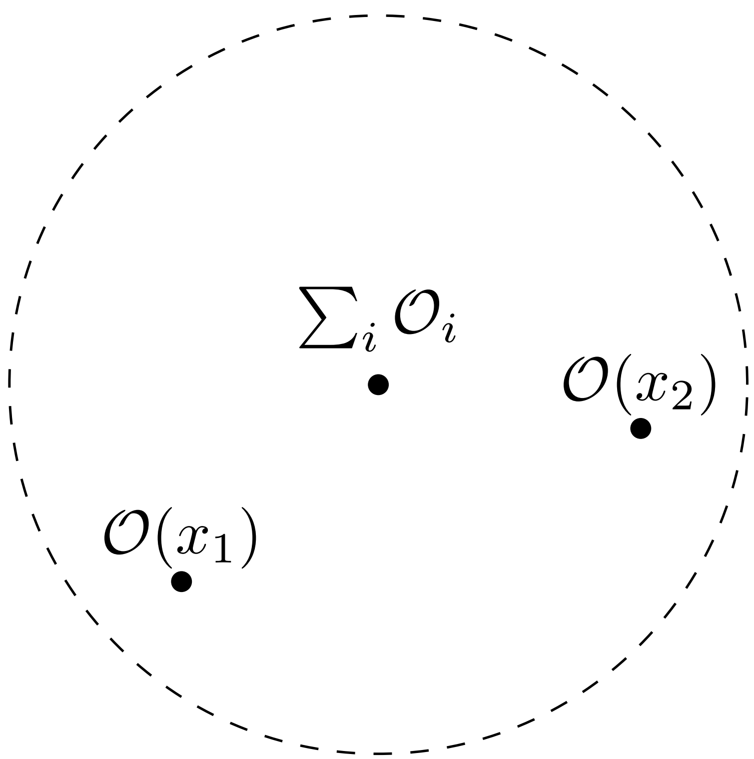
Can we develop a systematic expansion in a general CFT?

The usual argument does not apply

$$\mathcal{O}_1 \mathcal{O}_2 |\Omega\rangle = |\Psi\rangle = \sum_i |\mathcal{O}_i\rangle$$

$$|\mathcal{O}_i\rangle = \mathcal{O}_i |\Omega\rangle$$

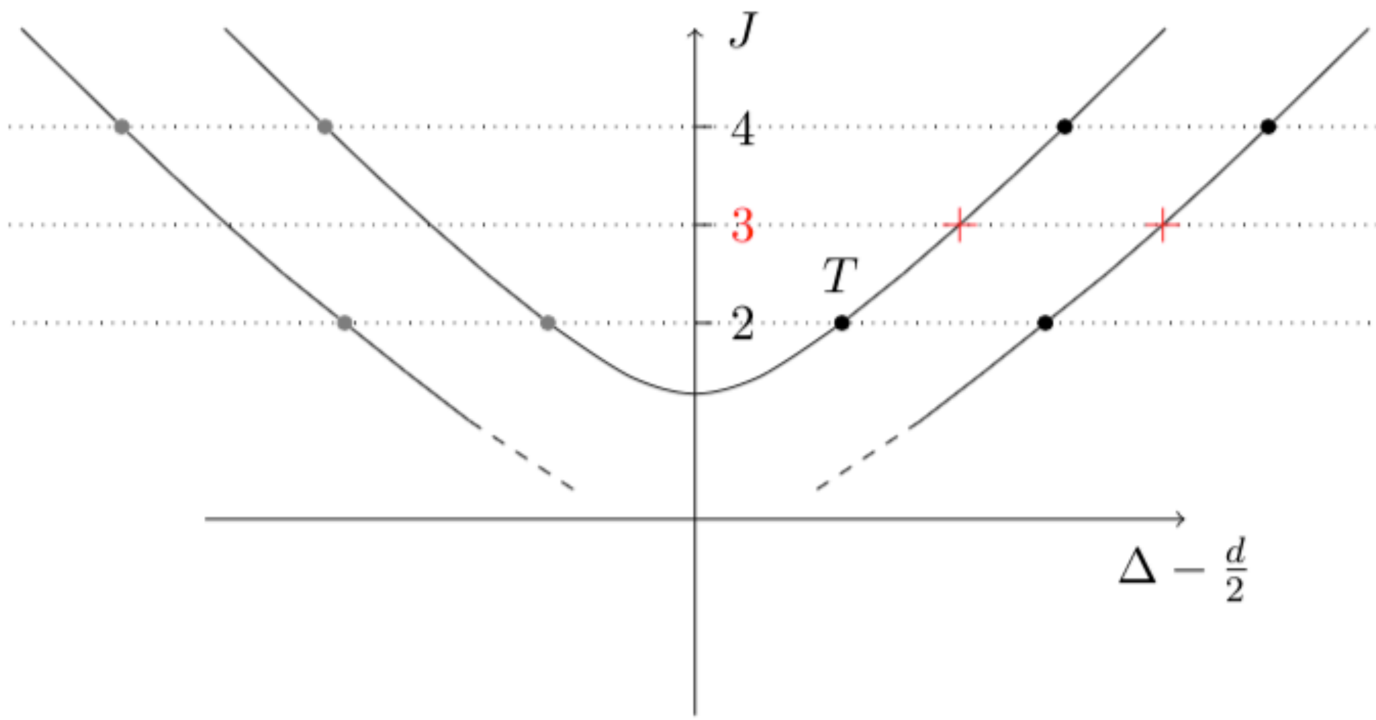



No such argument for light-ray operators.

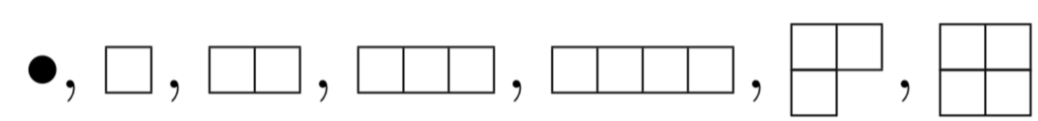
# ANEC OPE

**Claim:** The ANEC x ANEC OPE in a unitary CFT is given by

$$\int dv_1 T_{vv}(0, v_1, \vec{y}_1) \times \int dv_2 T_{vv}(0, v_2, \vec{y}_2)$$
$$= \pi i \sum_{\lambda, a} \sum_i \mathcal{D}^{(a),+}_{\Delta_i - 1, \lambda}(\vec{y}_{12}, \partial_{\vec{y}_2}) \mathbb{O}^+_{i, J=3, \lambda, (a)}(\vec{y}_2)$$




$\lambda$ is the transverse spin SO(d-2) representation:



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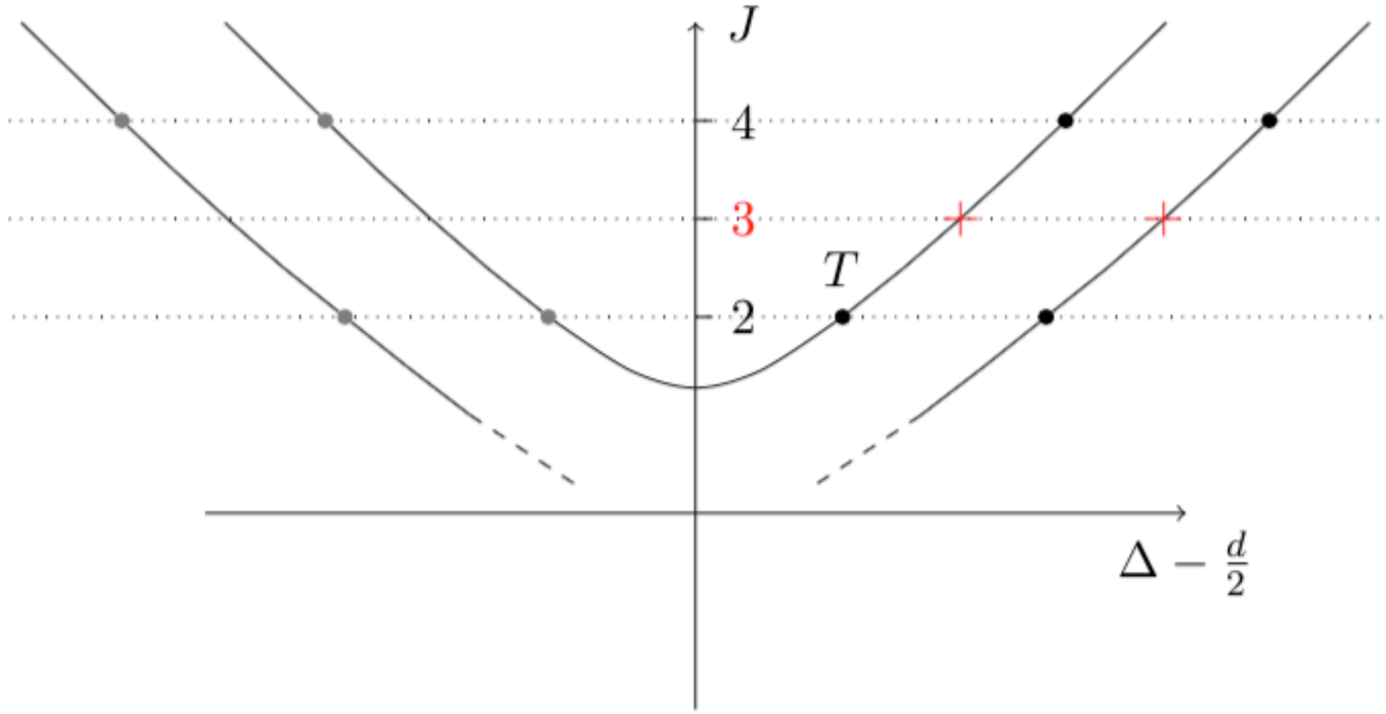
spin selection rule:

$$J = J_1 + J_2 - 1$$

[Hofman, Maldacena 08']

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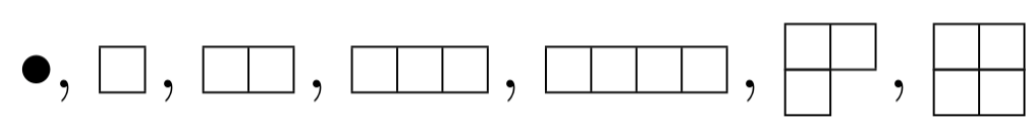
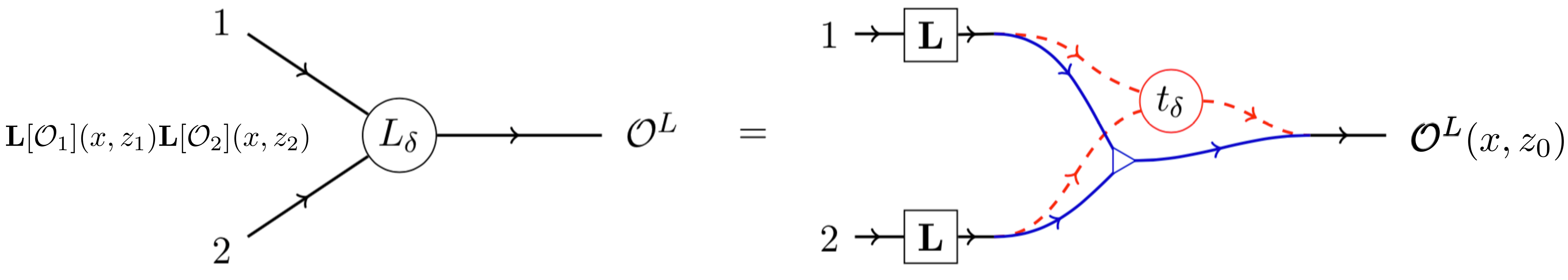


# Lightray-Lightray OPE

Different strategy:

1. Decompose the product of light-ray operators into conformal irreps (harmonic analysis for the transverse conformal group $SO(d-1,1)$ )



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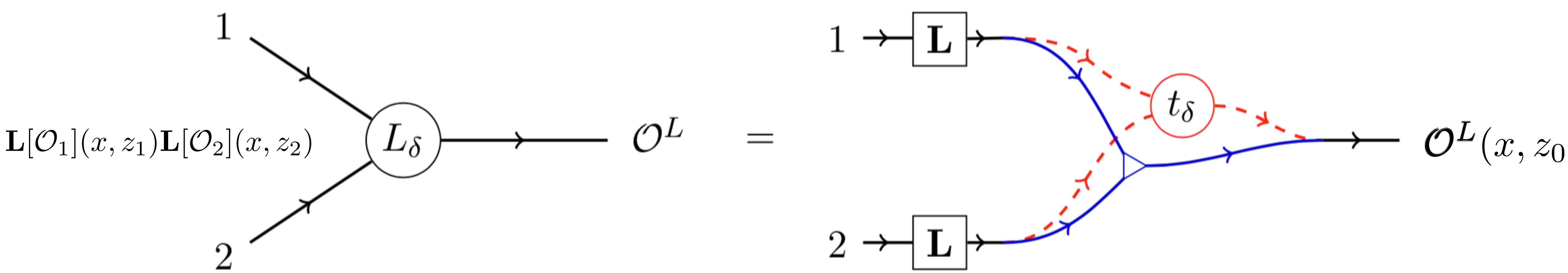
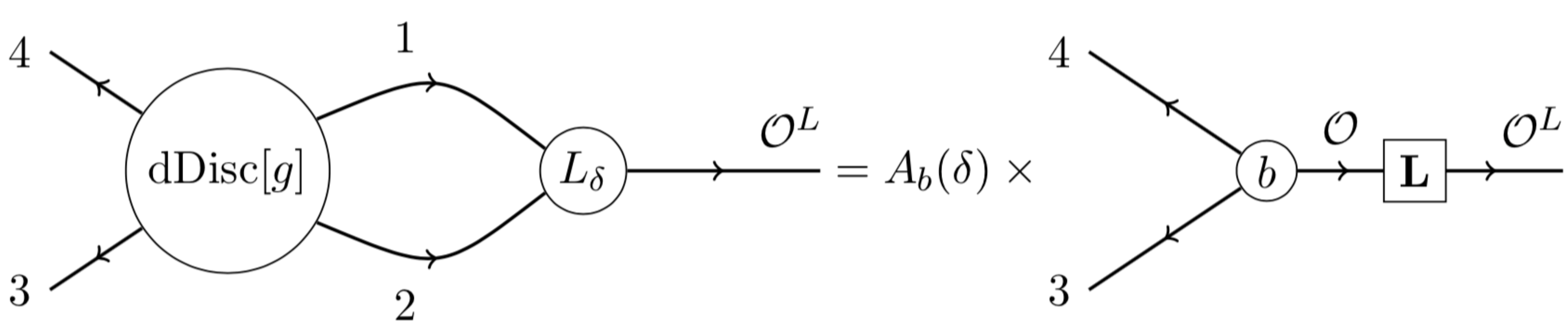



2. Compute a matrix element of a single irrep
   (in terms of an integral of a double commutator)

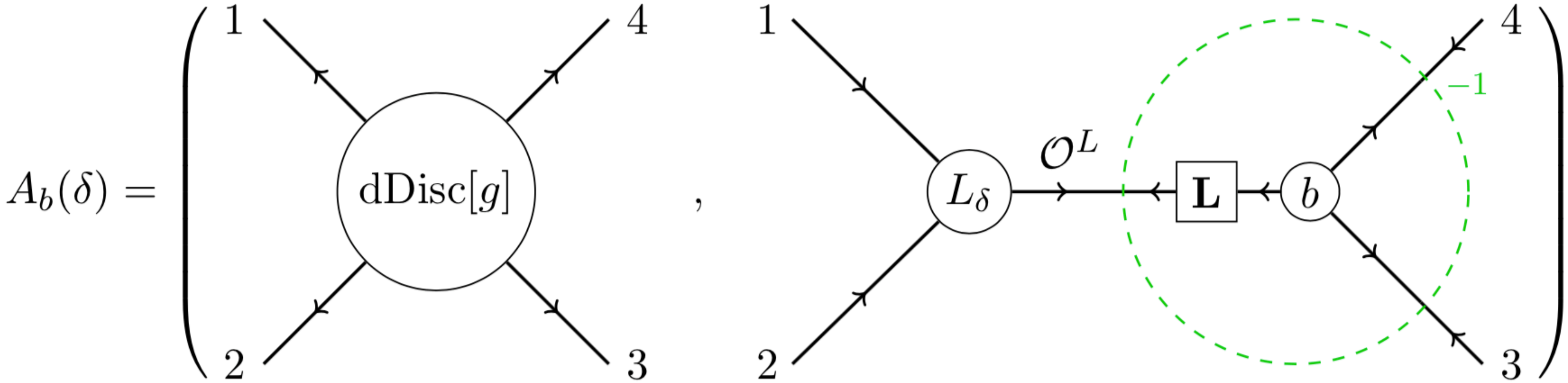


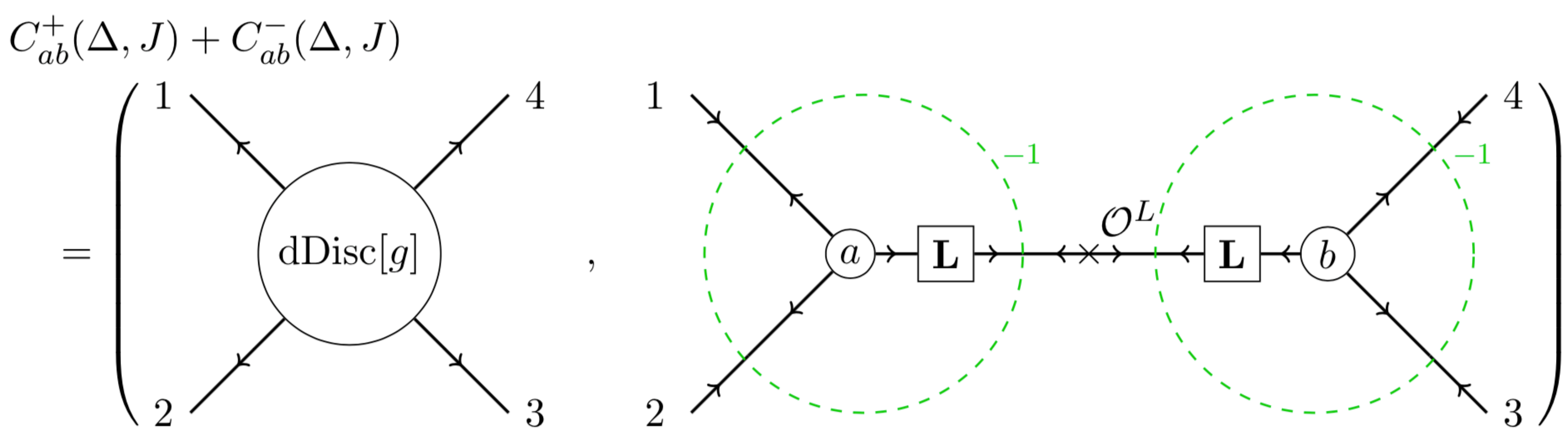

$\mathbf{L}[\mathcal{O}]|\Omega\rangle = 0$

$$\langle \mathcal{O}_1 \mathbf{L}[\mathcal{O}_2]\mathbf{L}[\mathcal{O}_3]\mathcal{O}_4\rangle = \langle [\mathcal{O}_1, \mathbf{L}[\mathcal{O}_2]][\mathbf{L}[\mathcal{O}_3], \mathcal{O}_4]\rangle$$

# Lightray-Lightray OPE

3. Relate to the Lorentzian inversion formula




$$A_b(\delta) \equiv \gamma^a \left( C^+_{ab} + C^-_{ab} \right)$$

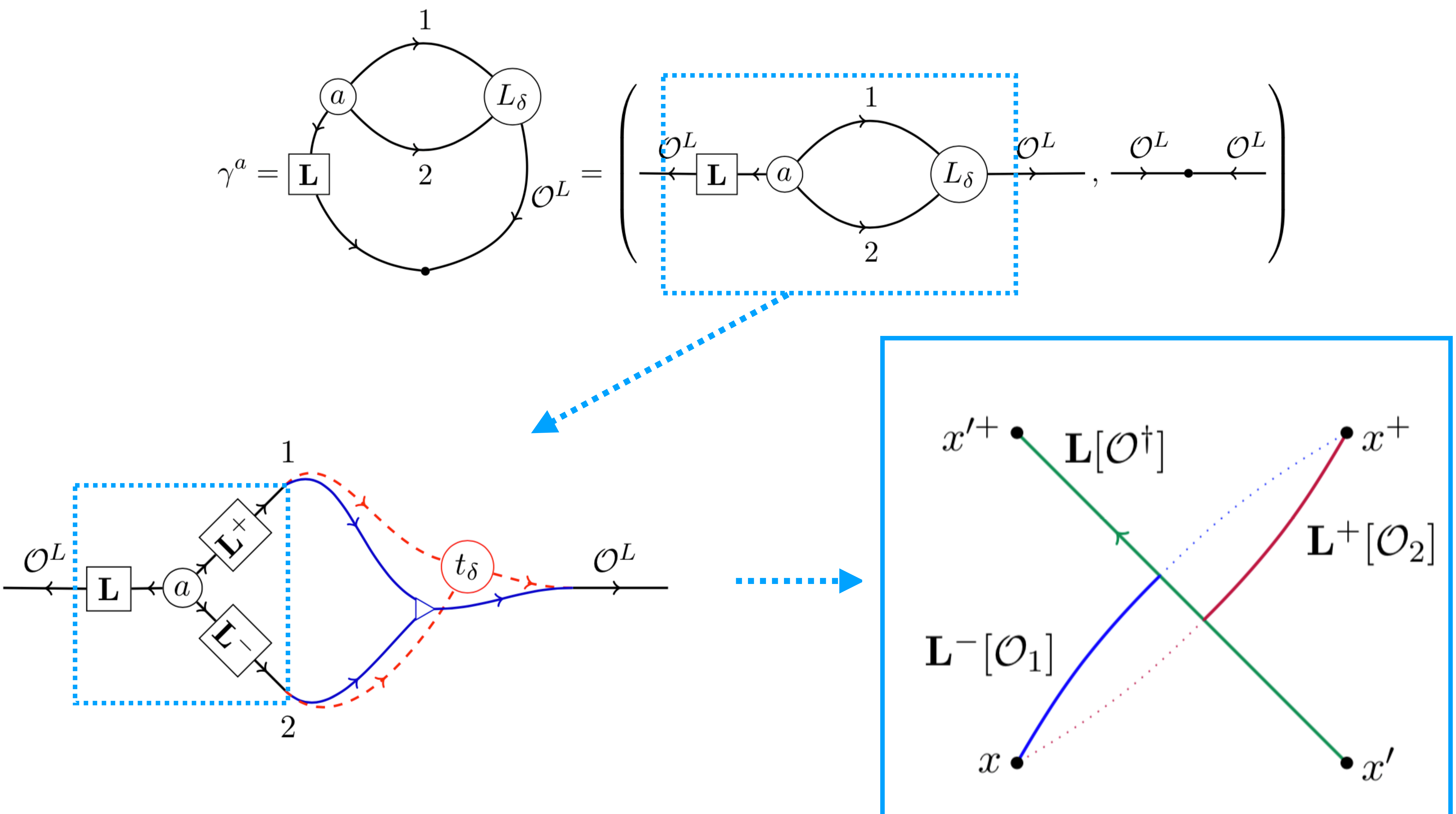
[Caron-Huot 17']

[Simmons-Duffin, Stanford, Witten 17']

[Kravchuk, Simmons-Duffin 18']

# Lightray-Lightray OPE

The relation is given by a bubble integral



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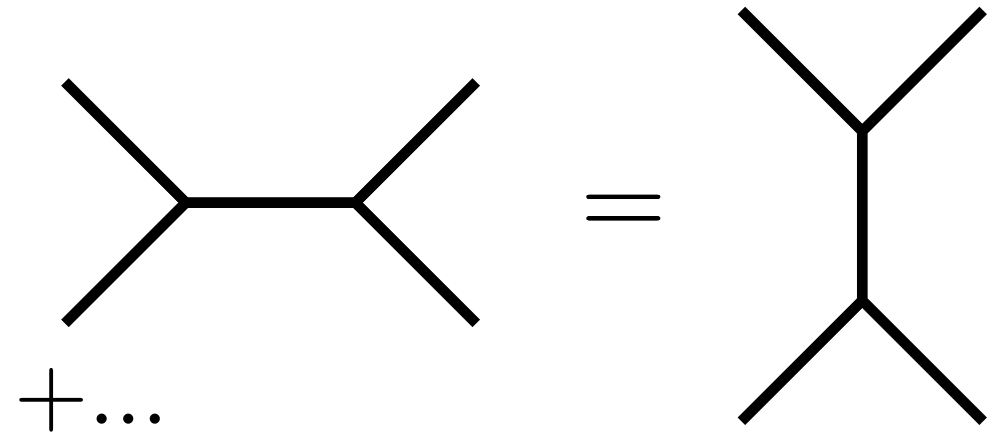
# Holographic CFTs

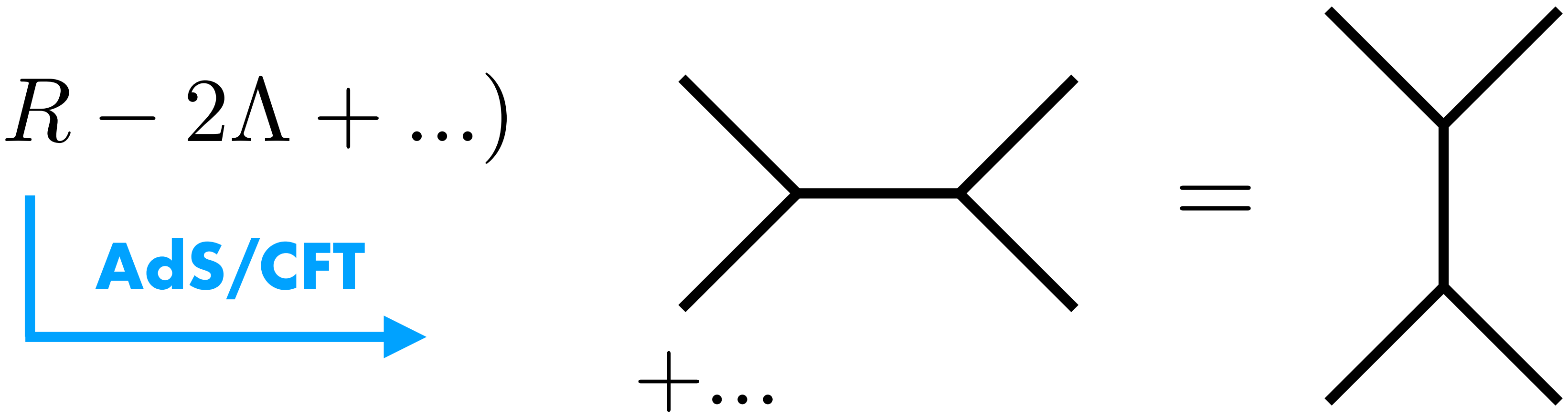
$$\frac{1}{l_{Pl}^{D-2}} \int d^D x \sqrt{-g} \left( R - 2\Lambda + \ldots \right)$$

AdS/CFT

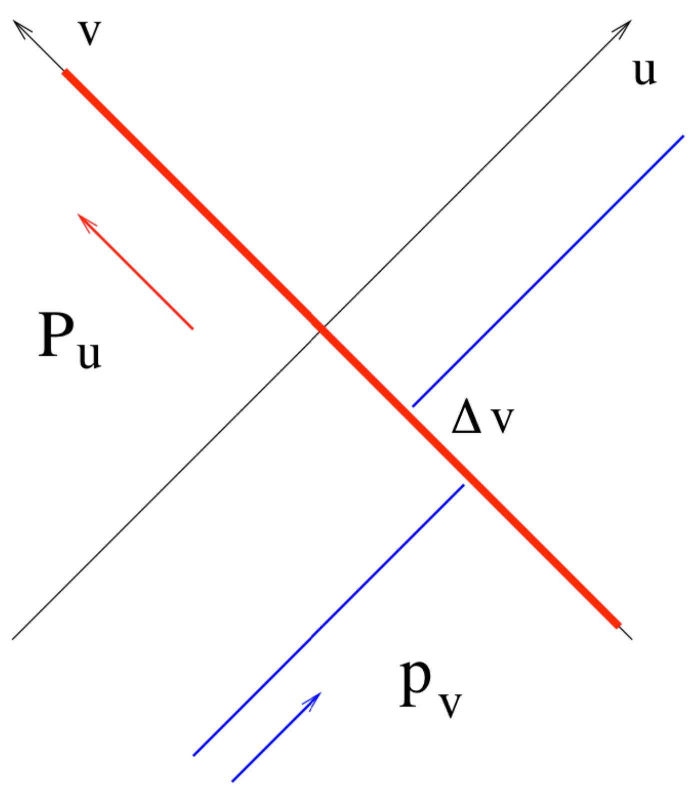


# Holographic CFTs

$$\frac{1}{l_{Pl}^{D-2}} \int d^D x \sqrt{-g}\,(R - 2\Lambda + \ldots)$$

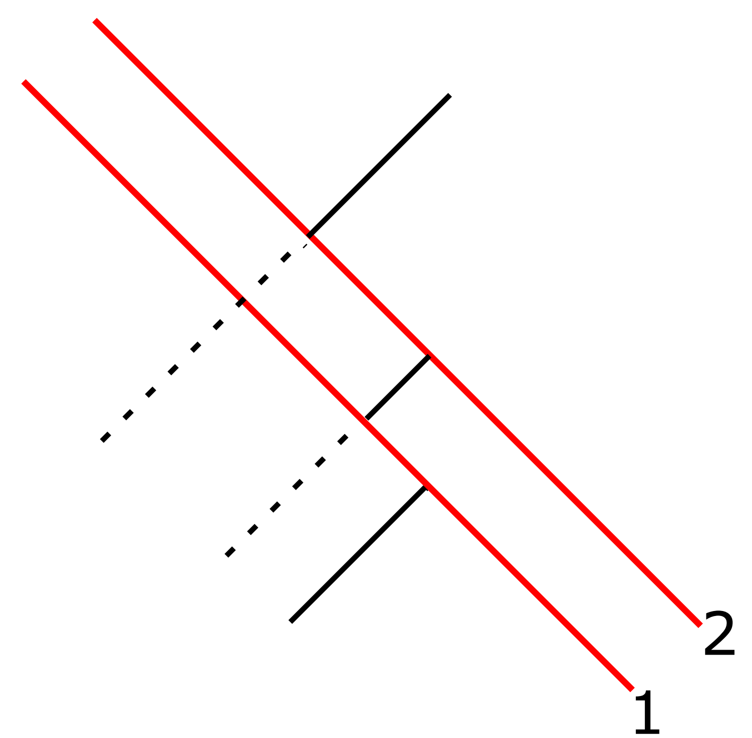



**ANEC:**



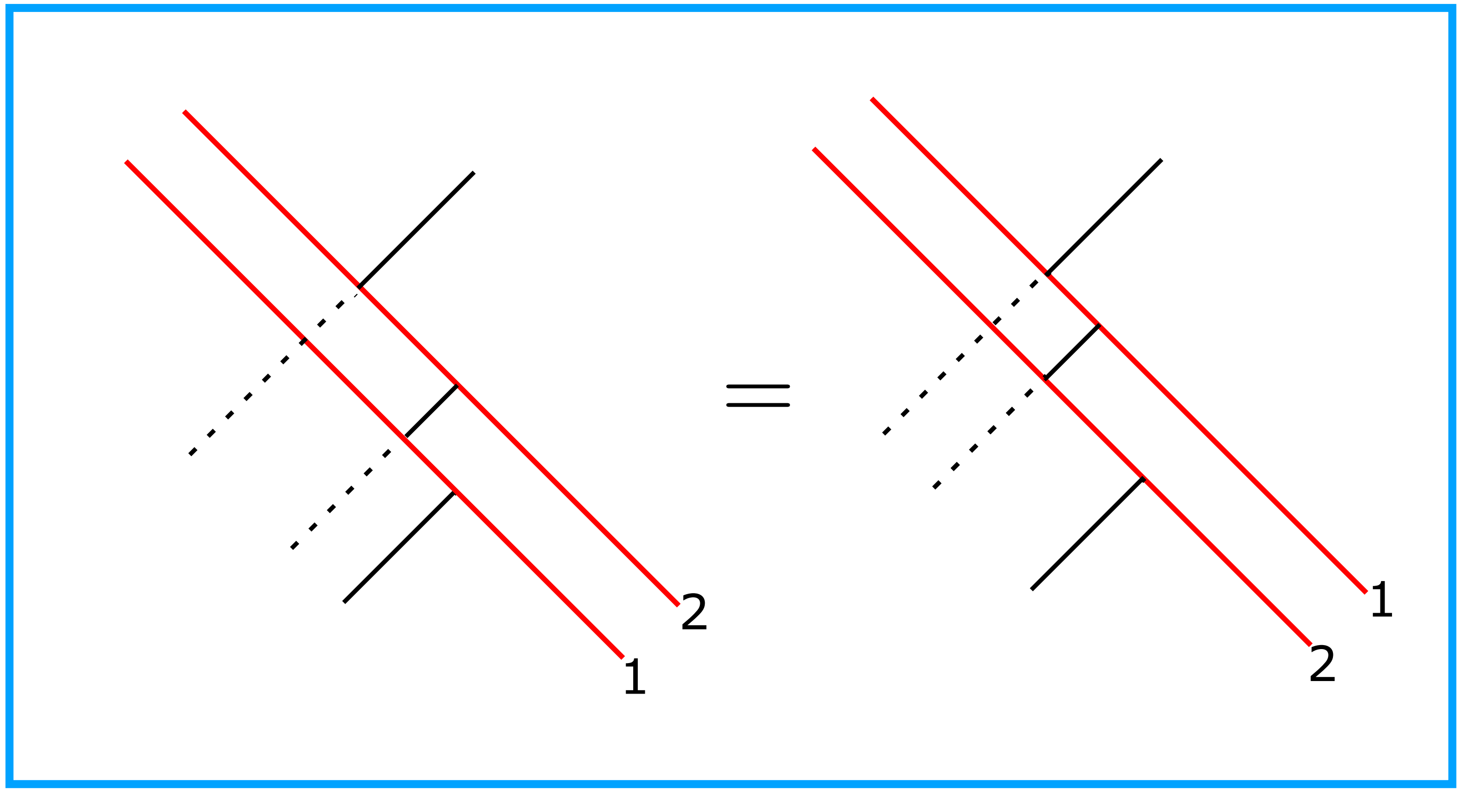

[Hofman, Maldacena, '08]

**two-point event shape:**



# AdS EFT: ANEC commutativity

## ANEC commutativity



# AdS EFT: ANEC commutativity

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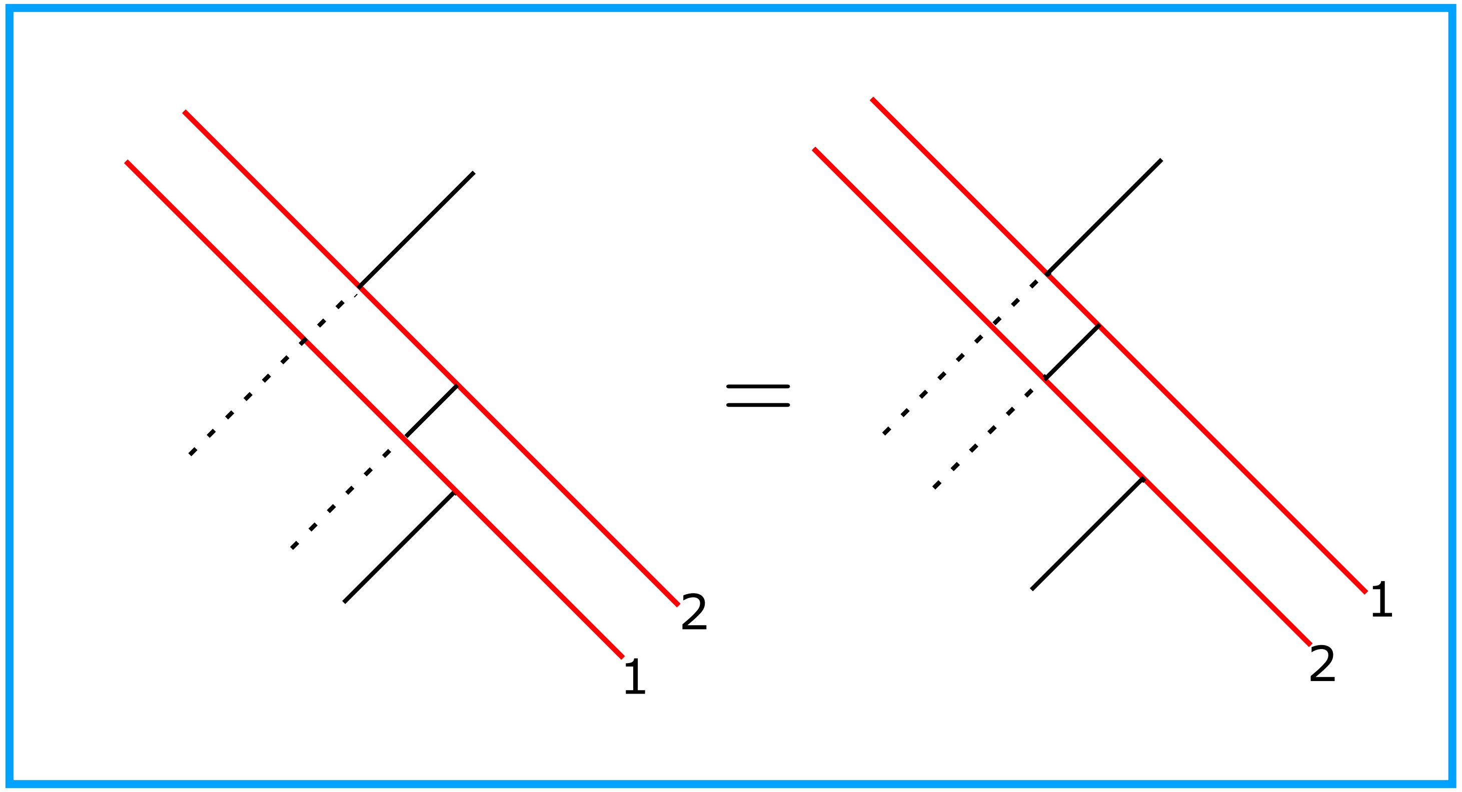


**Claim:** Any non-minimal graviton 3pt coupling violates ANEC commutativity

[Belin, Hofman, Mathys '19]
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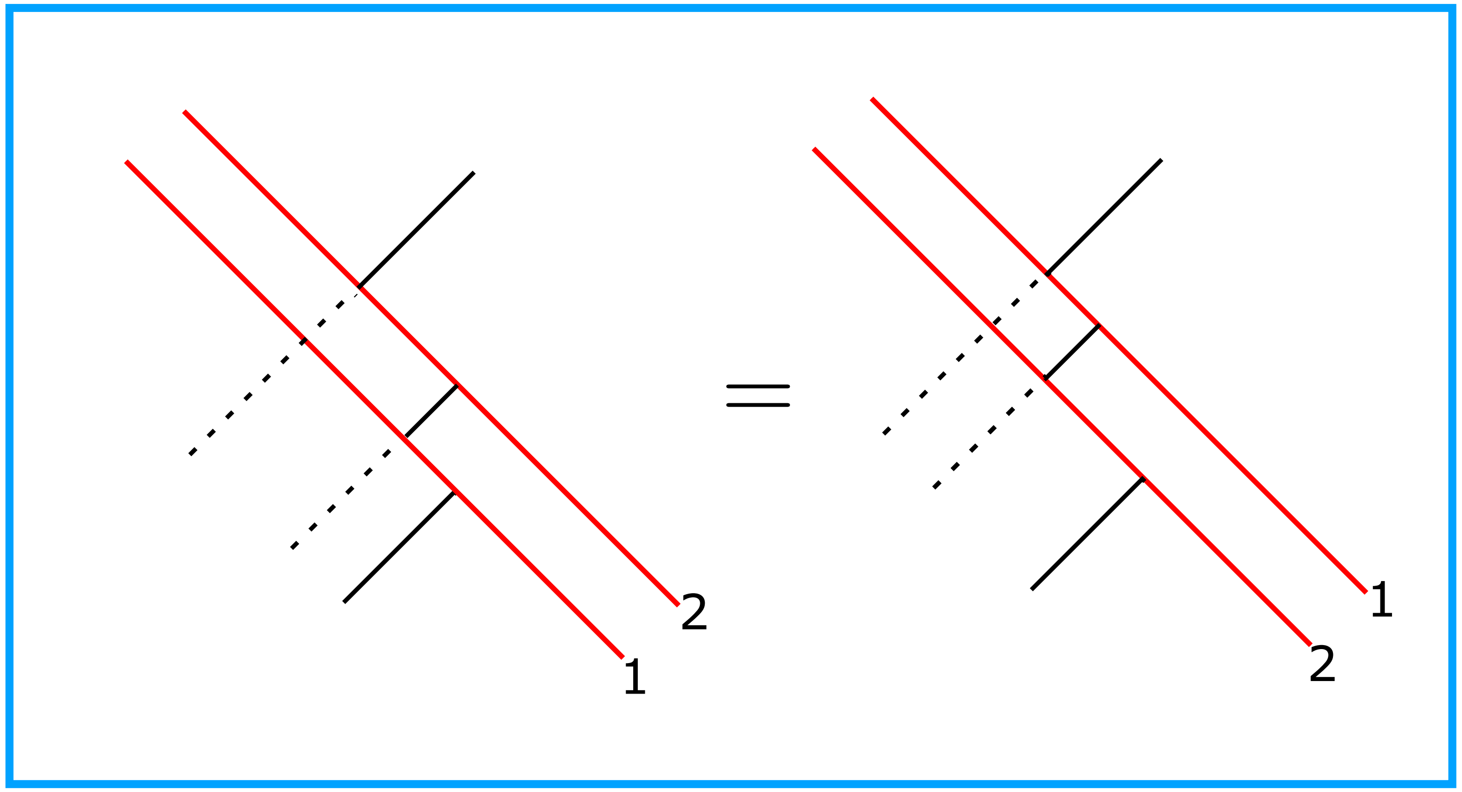


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Stringy Equivalence Principle: In every UV complete theory of quantum gravity AdS/flat/dS gravitational (and higher spin) shocks commute.
(should be applicable to our Universe as well)

# AdS EFT: ANEC commutativity

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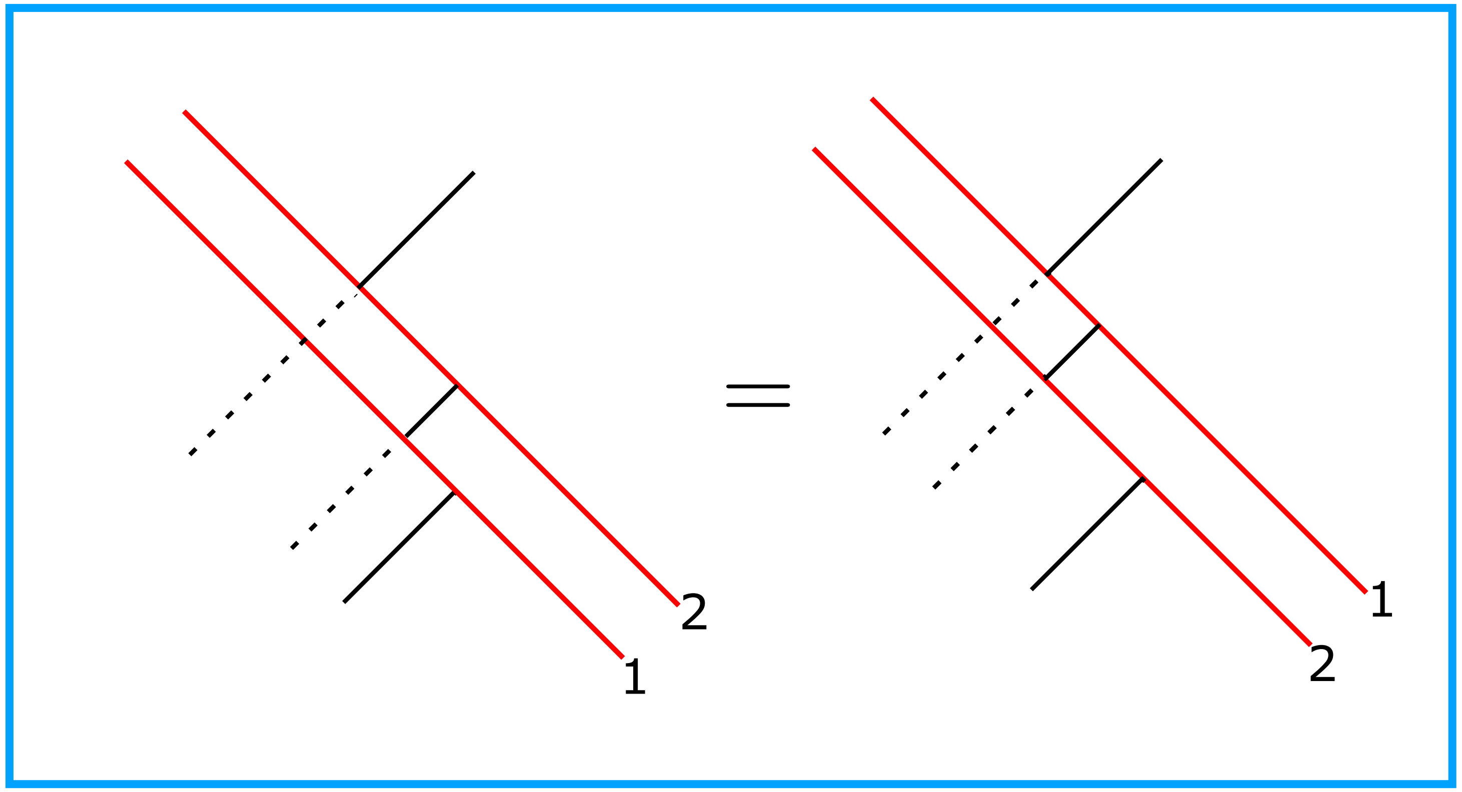


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**Stringy Equivalence Principle**: In every UV complete theory of quantum gravity AdS/flat/dS gravitational (and higher spin) shocks commute.
(should be applicable to our Universe as well)

$$\int dt \mathrm{Disc}_t A(s,t) = 0$$

**superconvergence**

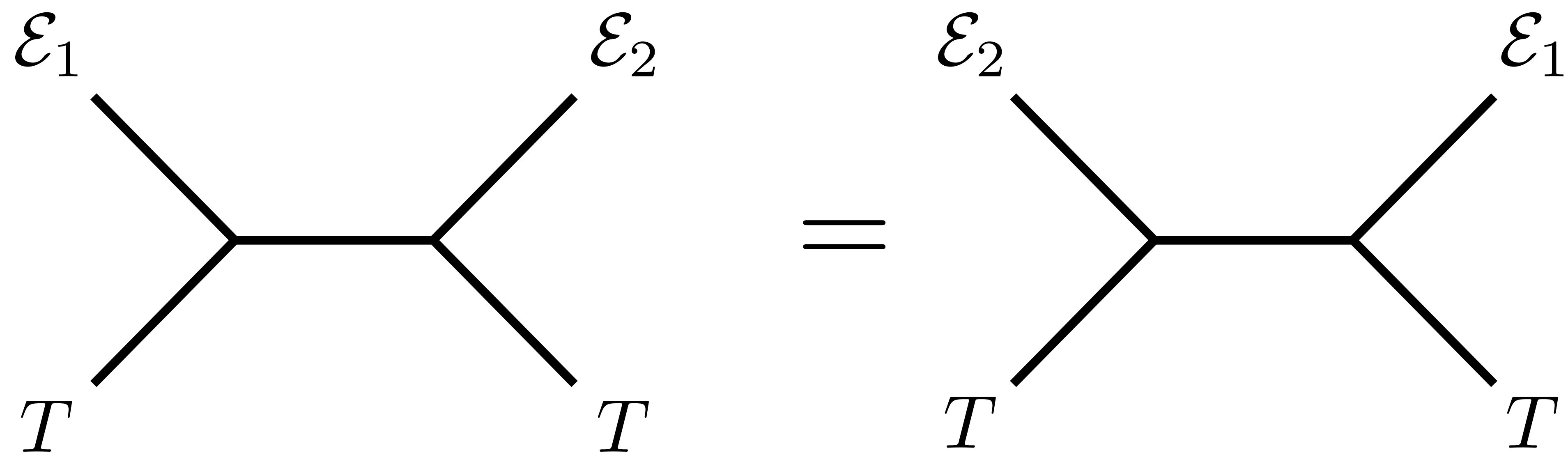
[Alfaro, Fubini, Rossetti, Furlan 66']

# AdS EFT: ANEC commutativity

$$[\mathbf{L}[T](x,z_1), \mathbf{L}[T](x,z_2)] = 0$$

Using the **t-channel OPE**:

$$\langle TTT\rangle = \langle TTT\rangle_R + t_2\langle TTT\rangle_{R^2} + t_4\langle TTT\rangle_{R^3}$$




$$(t_4+2t_2)^2 = \sum_\phi |\lambda_{TT\phi}|^2 \frac{15\cdot 2^4\pi^4\Gamma(\Delta_\phi-1)\Gamma(\Delta_\phi)}{C_T\Gamma(4-\frac{\Delta_\phi}{2})^2\Gamma(2+\frac{\Delta_\phi}{2})^6} + \text{non-scalar},$$

$$(t_4+2t_2)^2 = -\sum_\phi |\lambda_{TT\phi}|^2 \frac{360^2\pi^4\Gamma(\Delta_\phi-1)\Gamma(\Delta_\phi)}{7C_T\Gamma(4-\frac{\Delta_\phi}{2})^2\Gamma(2+\frac{\Delta_\phi}{2})^6} + \text{non-scalar}$$

**Sum over single trace operators only! (at large N)**

[Camanho, Edelstein, Maldacena, AZ '14]

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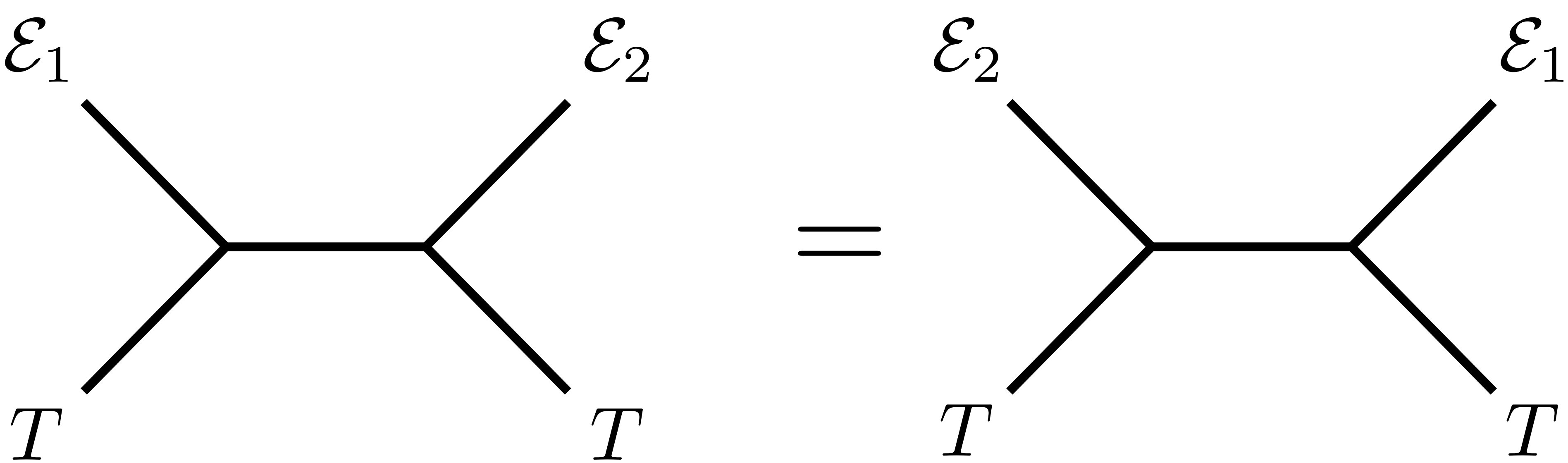


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**Sum over single trace operators only! (at large N)**

**How do we bound these infinite sums?**

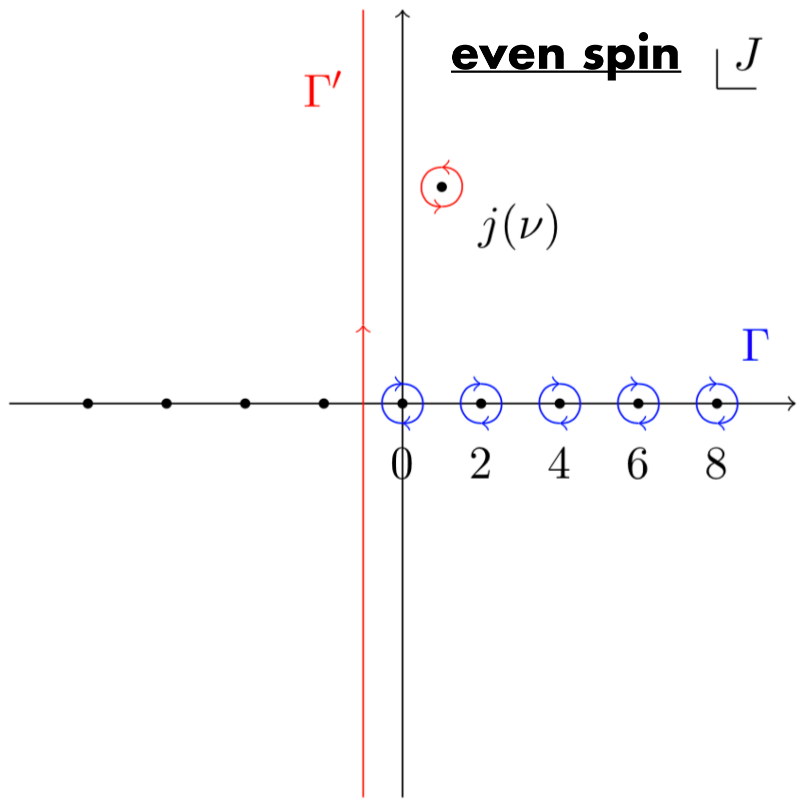
[Camanho, Edelstein, Maldacena, AZ '14]

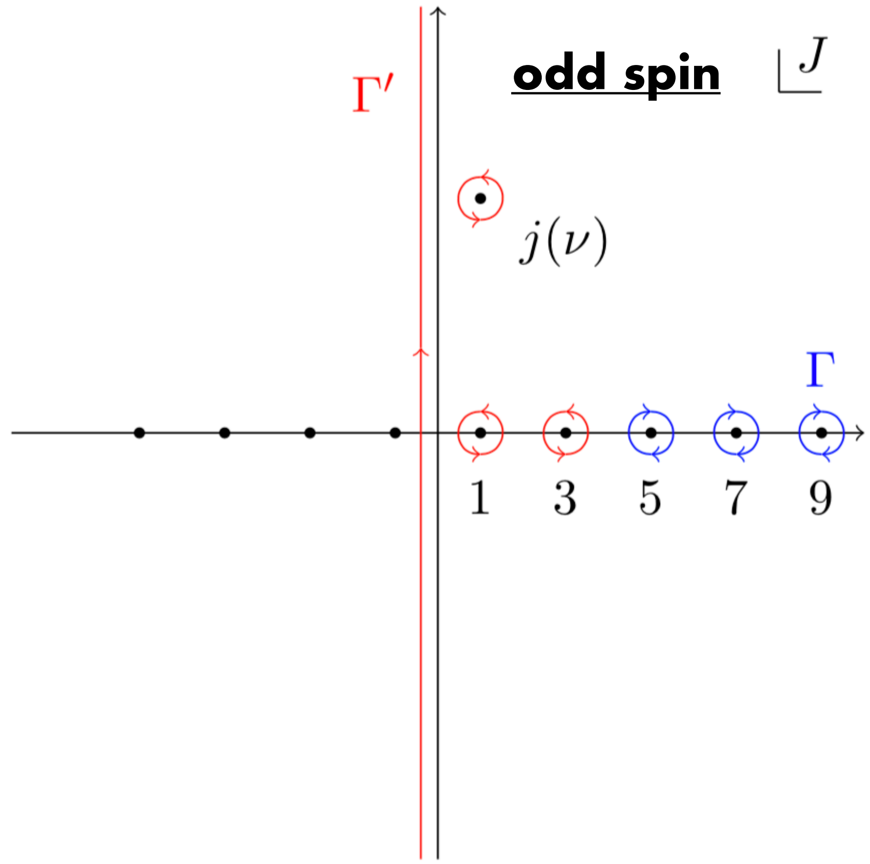
# AdS EFT: ANEC commutativity

[Kologlu, Kravchuk, Simmons-Duffin, AZ, work in progress]

Using the **s-channel OPE (lightray-lightray)** and conformal Regge theory:

**ANEC commutativity** **=** **absence of the J=3 Regge pole**




**Euclidean OPE** **vs** **analyticity in spin**

$$[\mathbf{L}[T](x,z_1),\mathbf{L}[T](x,z_2)] = 0$$

$\Leftrightarrow$

$$C^{-}_{ab}(\Delta, J=3) = 0$$

# Toy Model

[Caron-Huot '17]

We next use the Froissart-Gribov formula:

**correlator** $\mathcal{A}(s,t) = \sum_J a_J(s)\nu^J, \quad \nu = \frac{t-u}{2}$

**unitarity:** $\mathrm{Disc}\mathcal{A} \geq 0$

**CPW** $a_J^{\pm}(s) = \int_0^\infty \frac{d\nu}{\nu}\, \nu^{-J}\mathrm{Disc}_t\mathcal{A}(s,\nu) \pm \int_{-\infty}^{0} \frac{d\nu}{-\nu}(-\nu)^{-J}\mathrm{Disc}_u\mathcal{A}(s,\nu)$

$$a^-_{J=3}(s) = \alpha^2_{\mathrm{GB}}(s) + \int_{\Delta^2_{\mathrm{gap}}}^{\infty} \frac{d\nu}{\nu}\, \nu^{-3}\mathrm{Disc}_t\mathcal{A}(s,\nu) - \int_{-\infty}^{-\Delta^2_{\mathrm{gap}}} \frac{d\nu}{-\nu}(-\nu)^{-3}\mathrm{Disc}_u\mathcal{A}(s,\nu) = 0$$

$$|\alpha^2_{\mathrm{GB}}(s)| = \left| \int_{\Delta^2_{\mathrm{gap}}}^{\infty} \frac{d\nu}{\nu}\, \nu^{-3}\mathrm{Disc}_t\mathcal{A}(s,\nu) - \int_{-\infty}^{-\Delta^2_{\mathrm{gap}}} \frac{d\nu}{-\nu}(-\nu)^{-3}\mathrm{Disc}_u\mathcal{A}(s,\nu) \right| \leq a^+_{J=3}(s)$$

$$|\alpha_{GB}(s)|^2 \leq a^+_{J=3}(s)$$

# Toy Model

[Caron-Huot '17]

Reproducing the graviton pole requires:

$$a^{+}_{J=2}(s): \ \lim_{s\to 0} \frac{C^2_{\phi\phi P}(s)}{2-J(s)} = -\frac{1}{c_T}\frac{1}{s}$$

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**Pomeron pole:** $a^{+}_{J}(s) \sim \dfrac{C^2_{\phi\phi P}(s)}{J - J(s)}$ $\quad \mathrm{Disc}_t \mathcal{A}(s,\nu) \sim C^2_{\phi\phi P}(s)\nu^{J(s)}$

**"No outliers":** $\boxed{\mathrm{Disc}_t \mathcal{A}(s,\nu) < c_0 C^2_{\phi\phi P}(s)\nu^{J(s)}}$

$\nu > m^2_{gap}$

$c_0 = O(1)$

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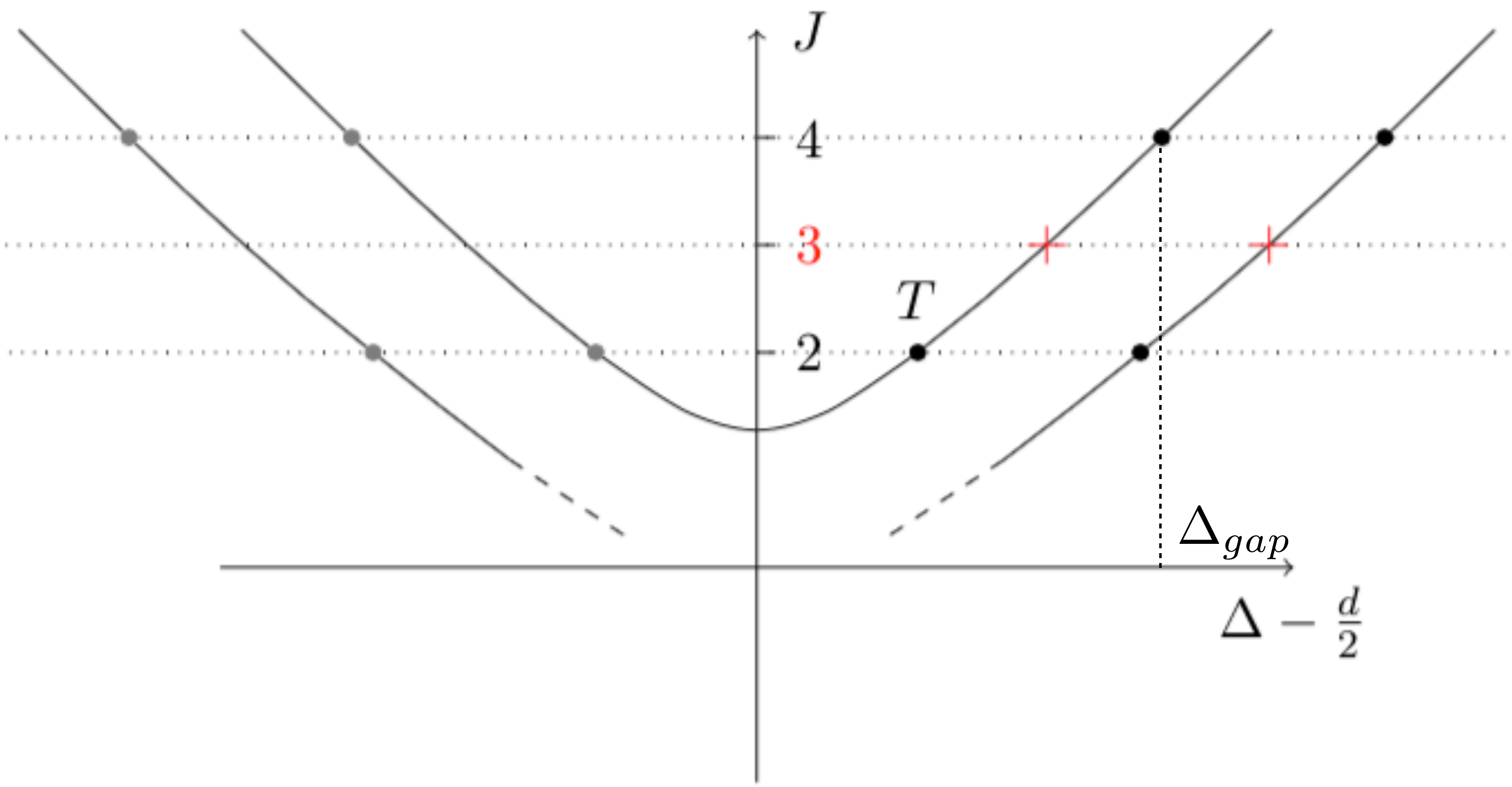
Assuming **no outliers** we get:

$$|\alpha_{GB}(s)|^2 \leq \frac{2c_0}{3 - J(s)} \frac{C^2_{\phi\phi P}(s)}{(\Delta^2_{gap})^{3-J(s)}}$$

# Toy Model

[Hartman, Keller, Stoica '14]
[Caron-Huot '17]

$$|\alpha_{GB}(0)|^2 \leq \frac{2c_0}{\Delta_{gap}^2 J'(0)}$$



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[Caron-Huot '17]

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**(HKS-type bound)**

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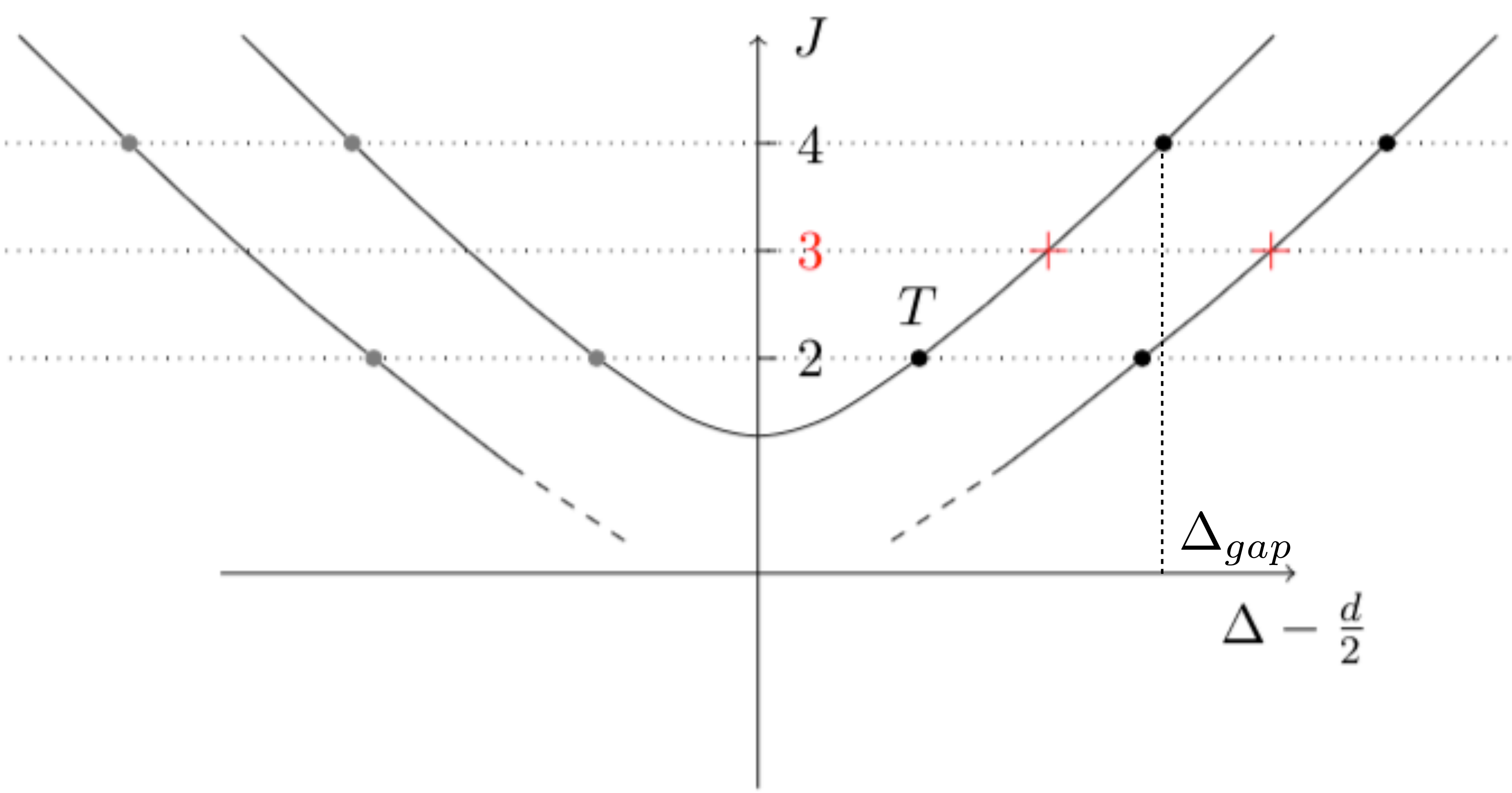

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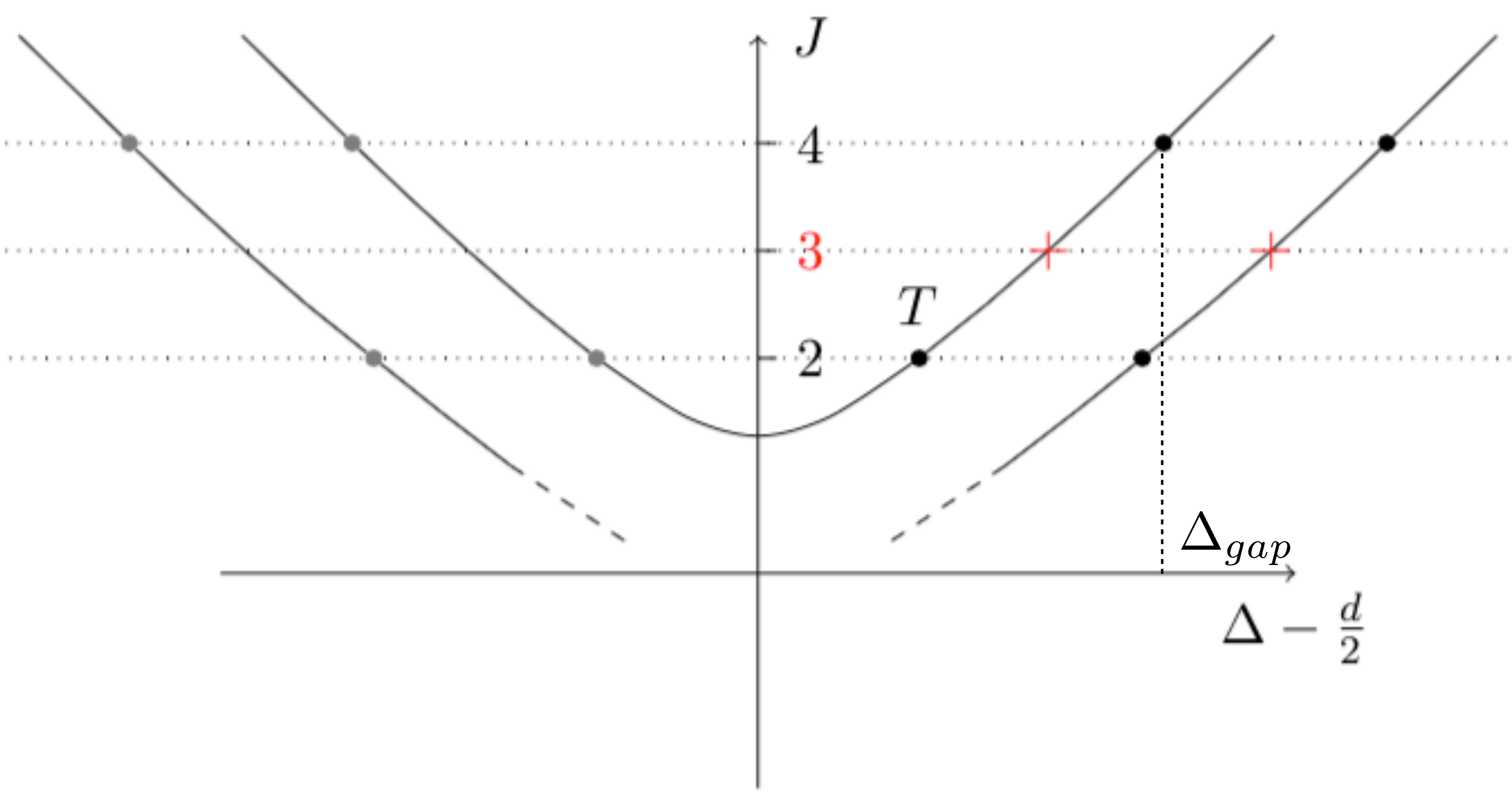

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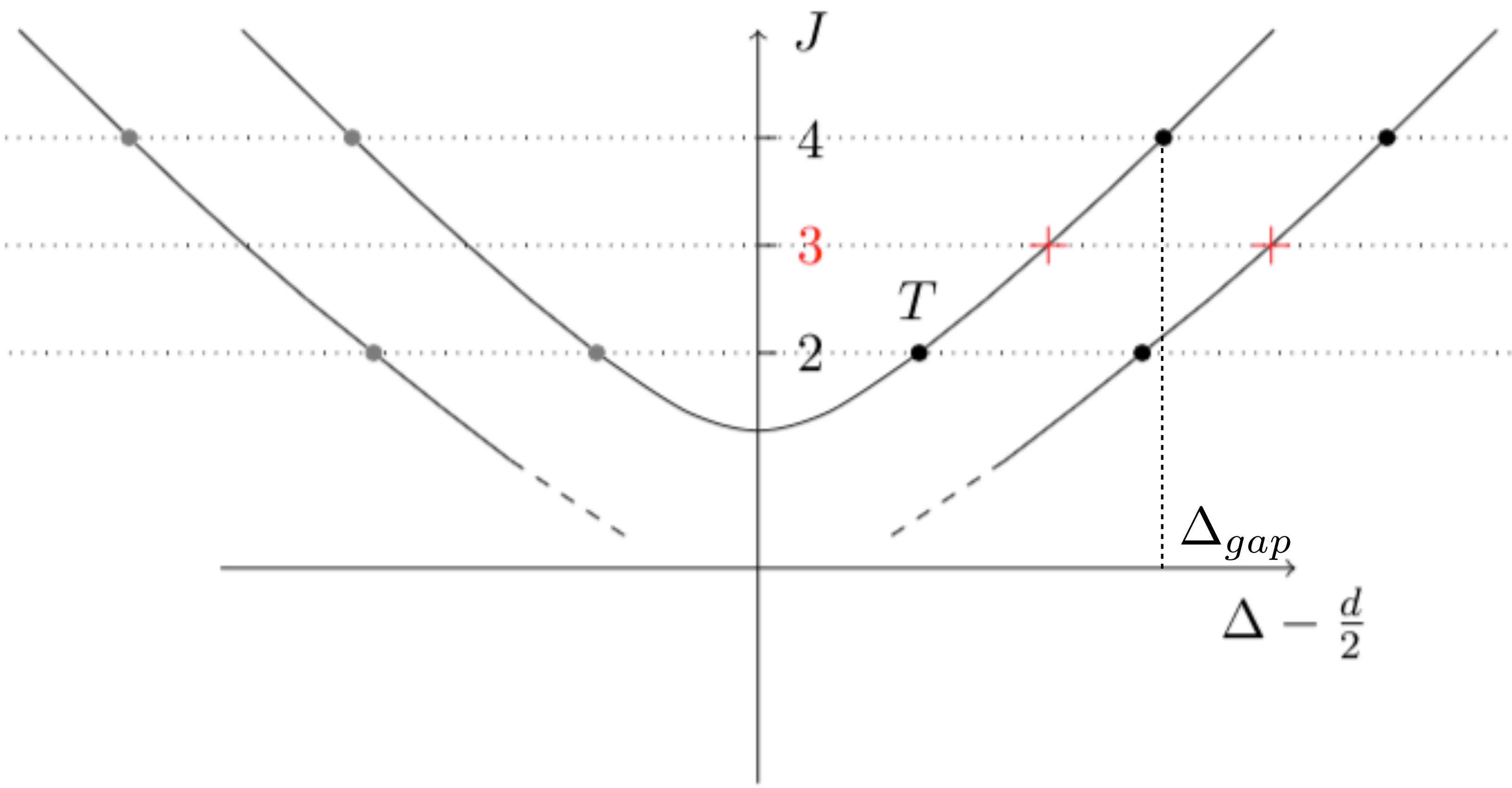
**Regge intercept**
**("Lyapunov exponent")**




$$J'(0) \sim \frac{1}{\Delta_{gap}^2}$$

[Camanho, Edelstein, Maldacena, AZ '14]
[Costa, Hansen, Penedones '17]
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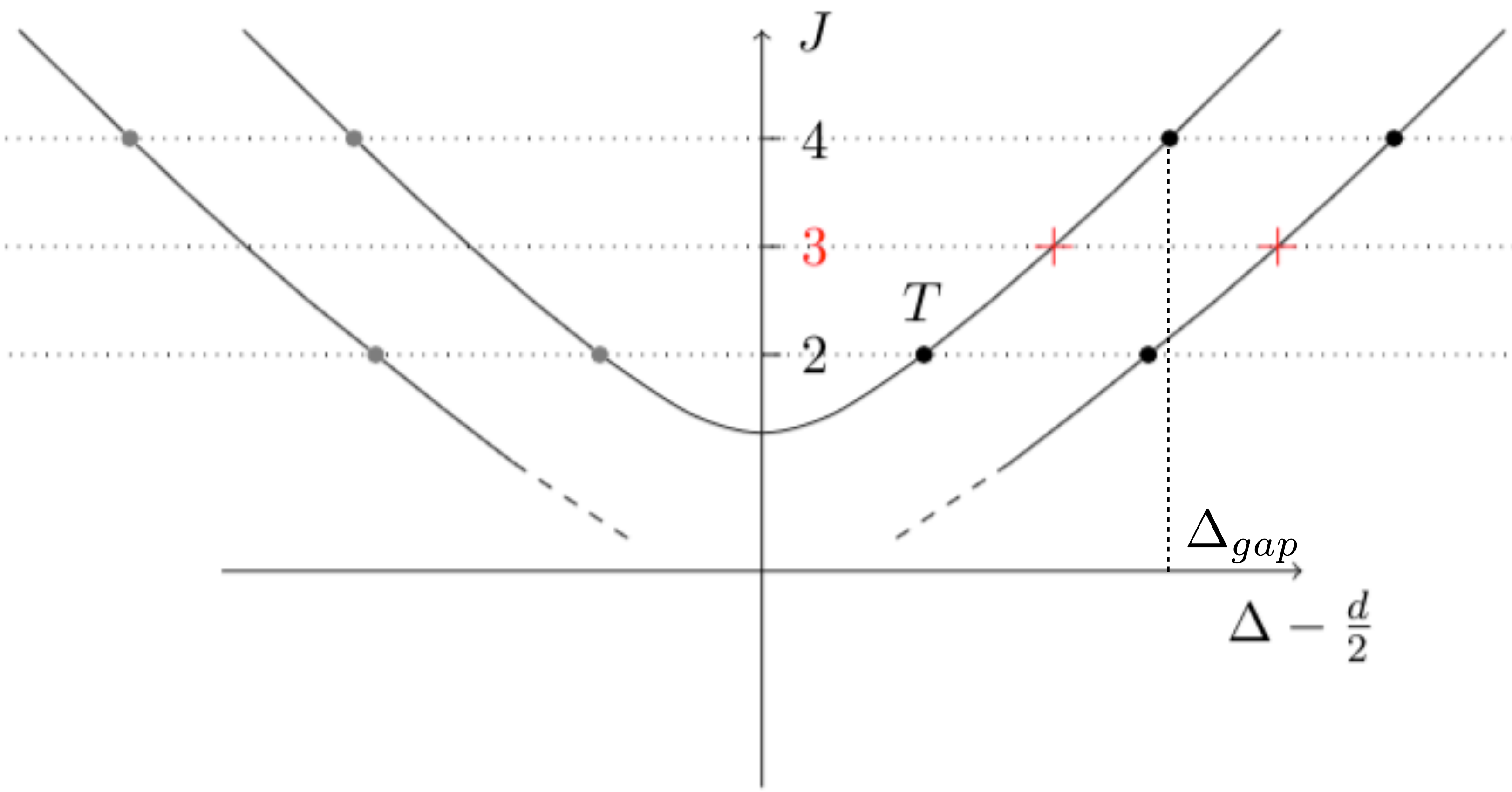


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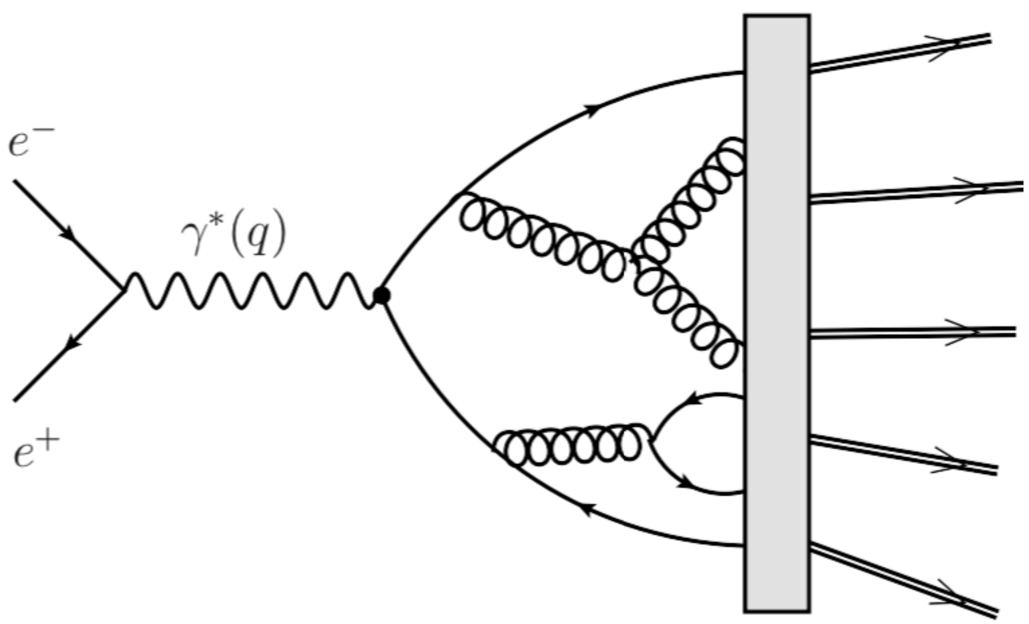
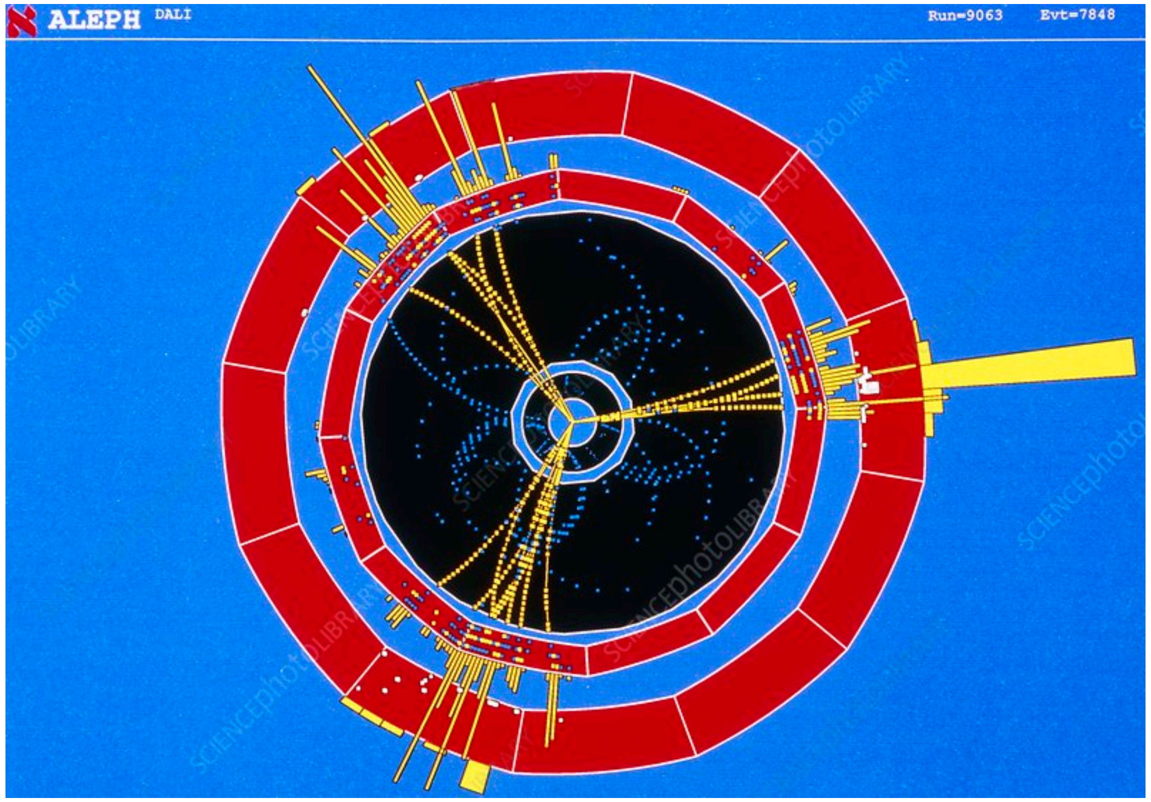
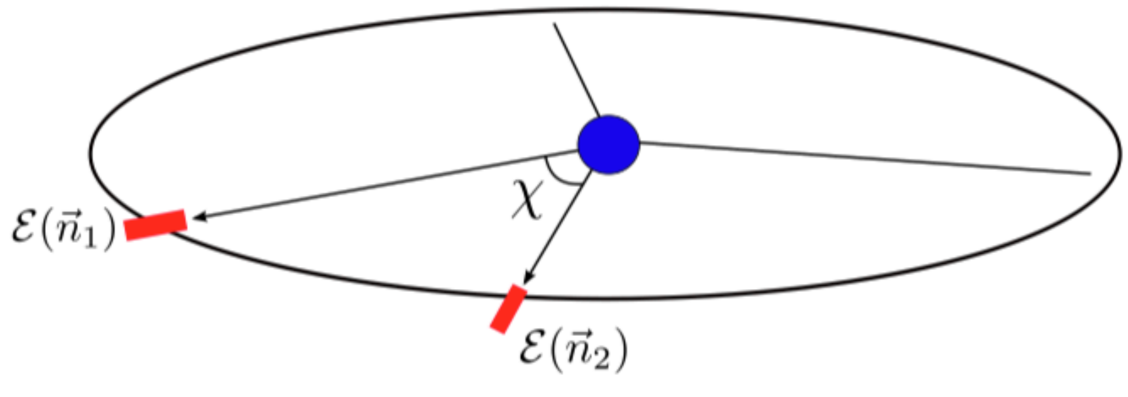
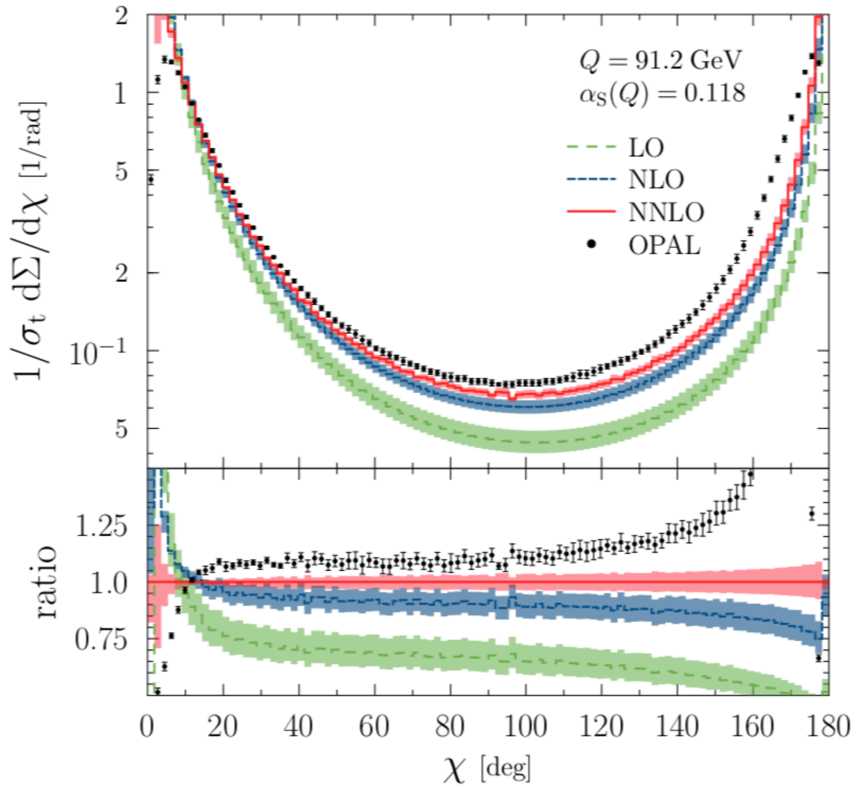
# Conformal Collider Physics




**very precise experimental data**




[Tulipánt, Kardos, Somogyi '17]

# Conformal Collider Physics

**QCD:** $$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle_p = \alpha_s(p)A(\chi) + \alpha_s^2(p)B(\chi) + O(\alpha_s^3)$$

**LO** $\alpha_s(p)$ : [Basham, Brown, Ellis, Love '78]

**NLO** $\alpha_s^2(p)$ : [Dixon, Luo, Shtabovenko, Yang, Zhu '18]

**40 years!**

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$$\boxed{\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle^{\mathrm{QCD}} = \langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle^{\mathcal{N}=4\ \mathrm{SYM}} + \text{“simpler”}}$$

[Belitsky, Hohenneger, Korchemsky, Sokatchev, AZ '13]

[Dixon, Moult, Zhu '19] [Korchemsky '19]

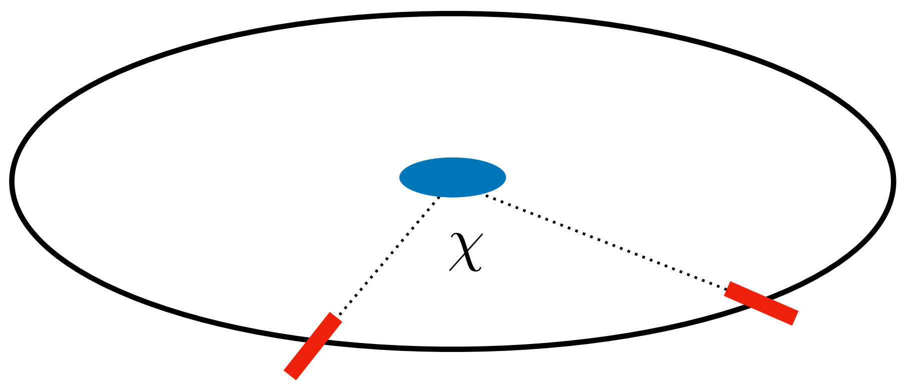
**LO+NLO: polylogs**

**NNLO: elliptic integrals!** [Henn, Sokatchev, Yan, AZ '19]

# Conformal Collider Physics

[Sveshnikov, Tkachov 95′]
[Korchemsky, Oderda, Sterman 97′]
[Hofman, Maldacena 08′]

Use correlators instead of amplitudes!

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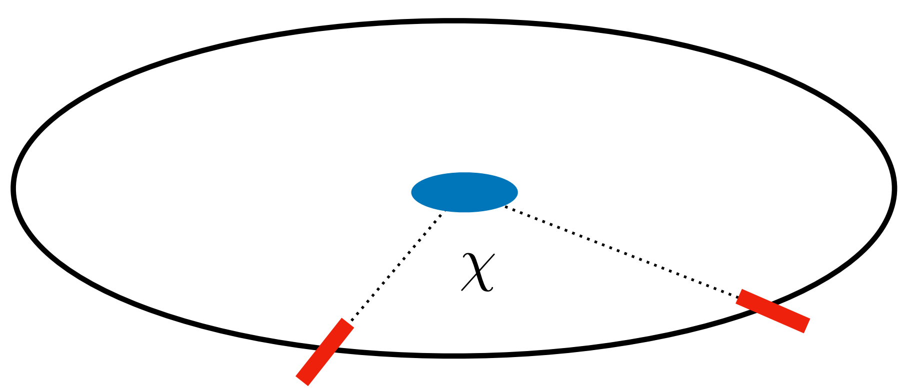


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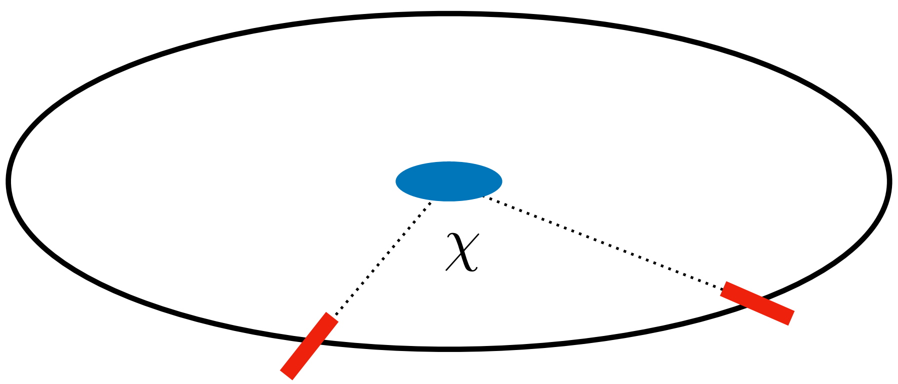


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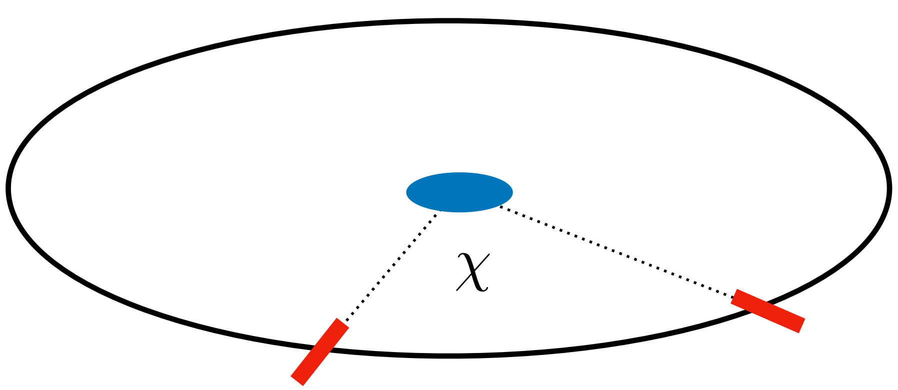


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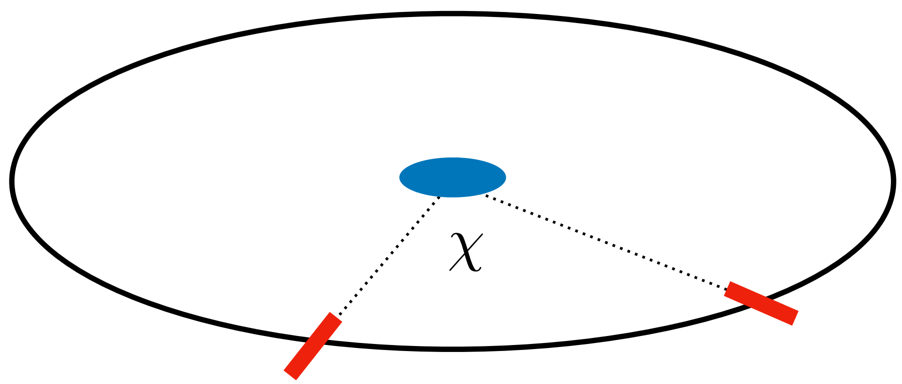


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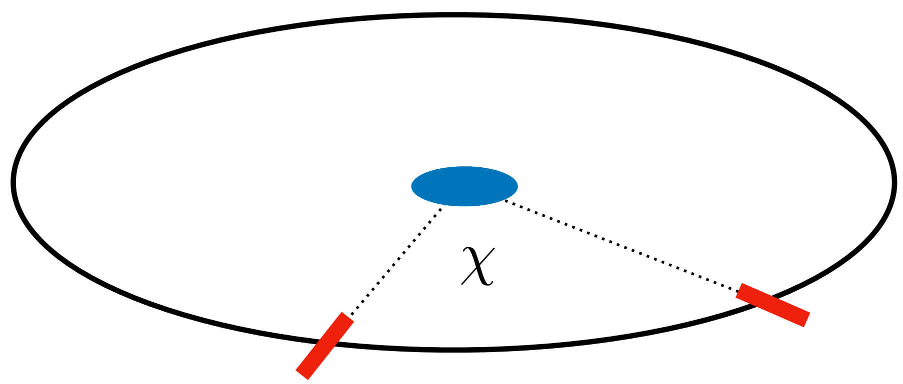


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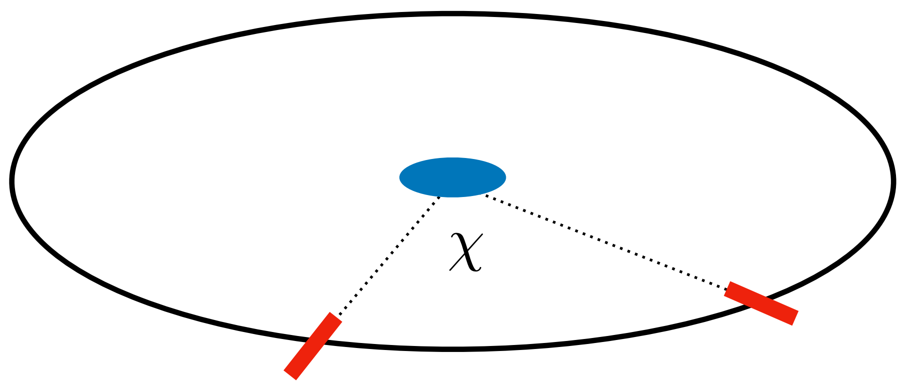


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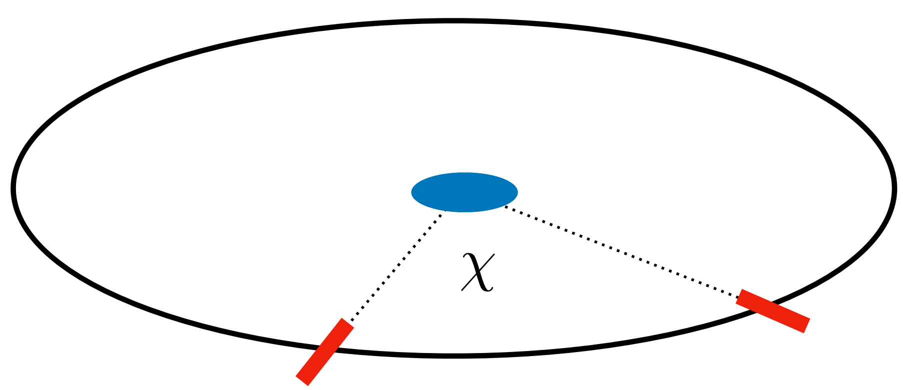


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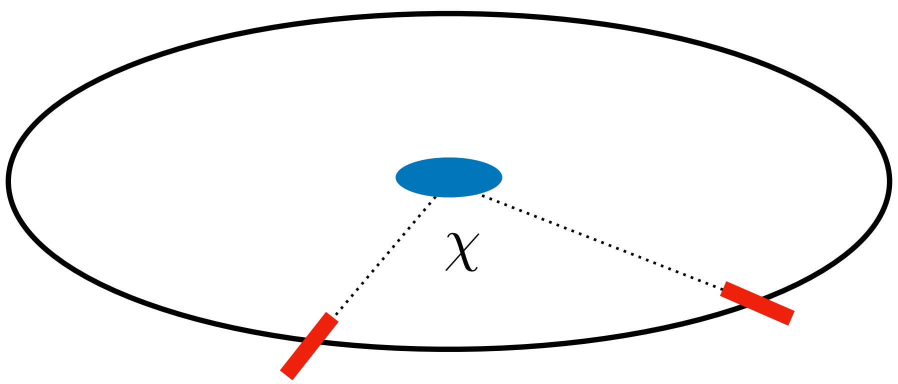


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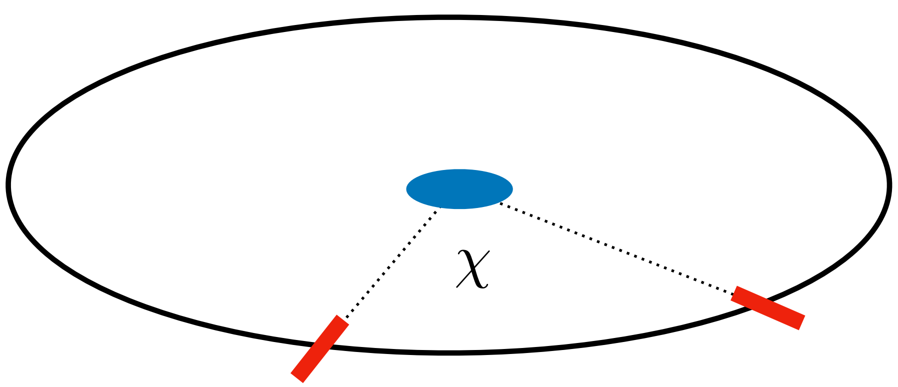


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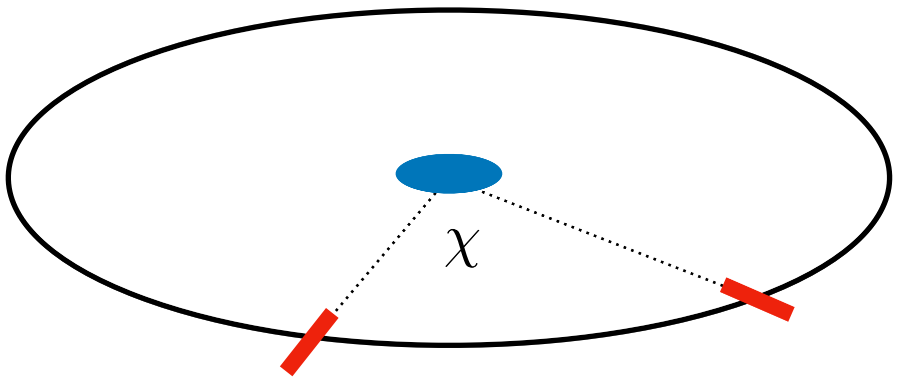


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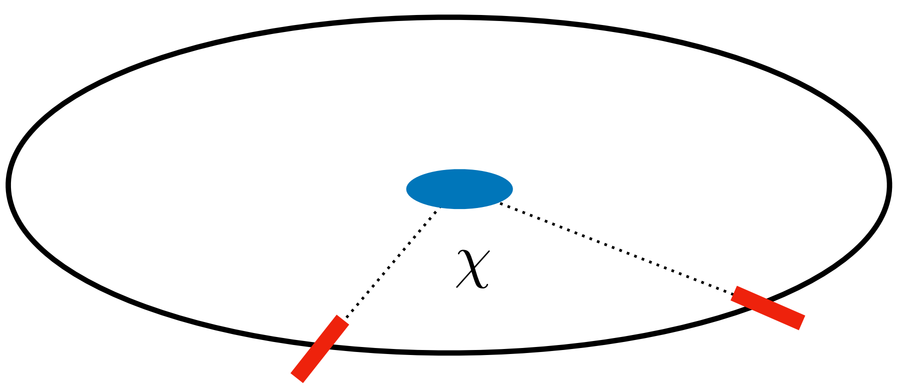



$$\langle \mathcal{E}(\vec{n}) \rangle = \frac{q^0}{\mathrm{vol} S^{d-2}}$$

$$\langle \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \rangle = \left( \frac{q^0}{\mathrm{vol} S^{d-2}} \right)^2$$

[Hofman, Maldacena 08′]

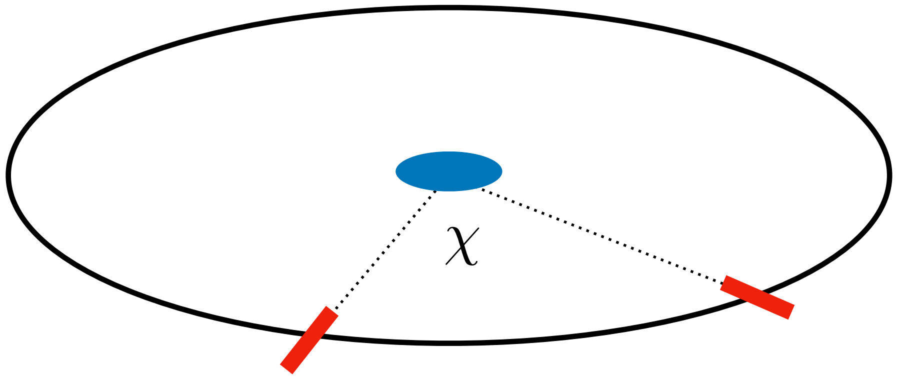
How do we interpolate between the two pictures?

# Conformal Collider Physics

[Sveshnikov, Tkachov 95′]
[Korchemsky, Oderda, Sterman 97′]
[Hofman, Maldacena 08′]

Use correlators instead of amplitudes!

**Weak coupling (jets):**

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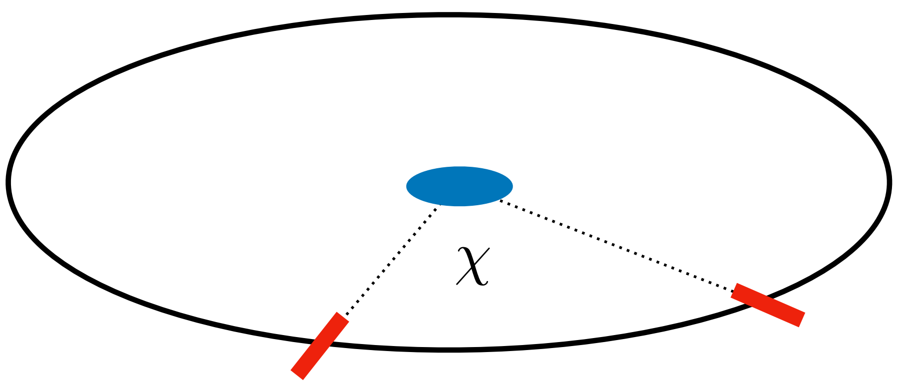


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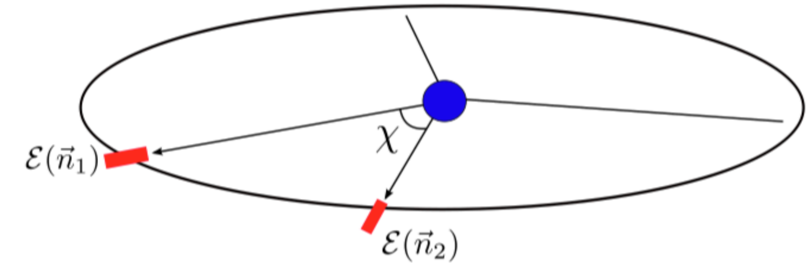
[Hofman, Maldacena 08′]

# Energy Correlators in N=4 SYM




**SUSY:** $\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle \sim \langle \mathcal{O}(\vec{n}_1)\mathcal{O}(\vec{n}_2)\rangle$

[Belitsky, Hohenneger, Korchemsky, Sokatchev, AZ '13]

**The lightray-lightray OPE (finite coupling):**

$$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle = \frac{(p^0)^2}{8\pi^2}\left[\sum_i p_{\Delta_i}\frac{4\pi^4\Gamma(\Delta_i-2)}{\Gamma(\frac{\Delta_i-1}{2})^3\Gamma(\frac{3-\Delta_i}{2})}f^{4,4}_{\Delta_i}(\zeta)+\frac{1}{4}(2\delta(\zeta)-\delta'(\zeta))\right]$$

$$f^{\Delta_1,\Delta_2}_{\Delta}(\zeta)=\zeta^{\frac{\Delta-\Delta_1-\Delta_2+1}{2}}\,{}_2F_1\left(\frac{\Delta-1+\Delta_1-\Delta_2}{2},\frac{\Delta-1-\Delta_1+\Delta_2}{2},\Delta+1-\frac{d}{2},\zeta\right)$$

- Sum is over Regge trajectories
- OPE data is evaluated at **J=-1** $(p_{\Delta_i})$
- Correctly captures contact terms (cf. QNEC saturation)
- Passes many perturbative tests and leads to new predictions

$$\zeta = \frac{1-\cos\chi}{2}$$

**conformal WI:**

$$\int_0^1 d\zeta\ \langle \mathcal{E}\mathcal{E}\rangle = 1$$

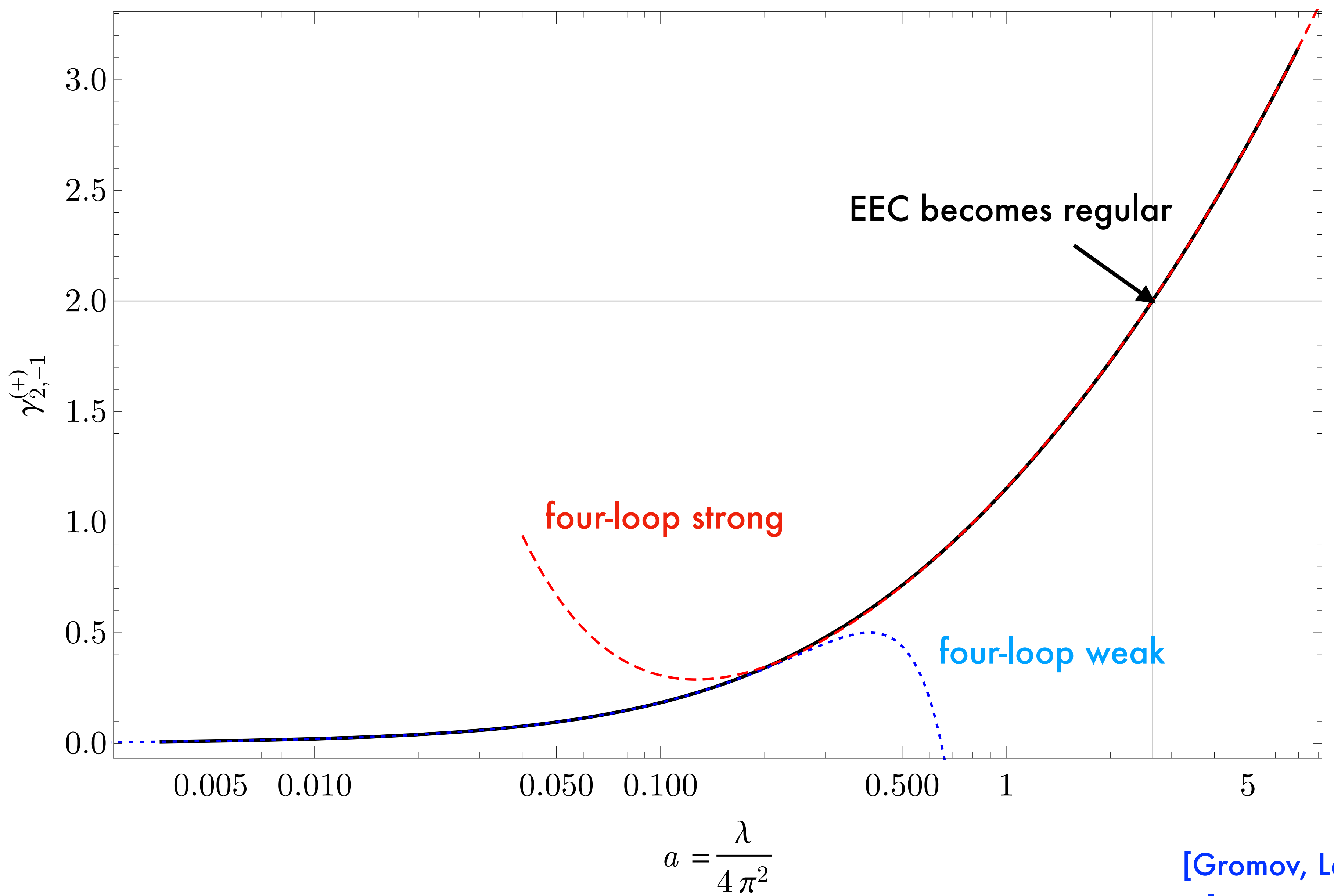
$$\int_0^1 d\zeta\ (2\zeta-1)\langle \mathcal{E}\mathcal{E}\rangle = 0$$

# Jets at Finite Coupling in N=4 SYM

$$\langle \mathcal{E}(\theta)\mathcal{E}(0)\rangle \sim \frac{1}{\theta^{2(1-\frac{\gamma^{+}_{2,-1}}{2})}}$$

[Hofman, Maldacena 08']
[Korchemsky 19']
[Dixon, Moult, Zhu 19']

**integrability:**




[plot by N.Gromov]
[Gromov, Levkovich-Maslyuk, Sizov 15']
[Gromov, Kazakov, Leurent, Volin 13']

# Further Directions

Lorentzian methods/observables:

- superconvergence (dS/flat/AdS, quantum)

$$[\mathcal{E}(\vec{n}_1), \mathcal{E}(\vec{n}_2)] = 0$$

- positivity of the ANEC two-point function constraint

$$\langle \mathcal{O} | \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) | \mathcal{O} \rangle \geq 0$$

- multi-point event shapes, celestial bootstrap, more general lightrays

$$\langle \Psi | \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \mathcal{E}(\vec{n}_3) \mathcal{E}(\vec{n}_4) | \Psi \rangle$$

- event shapes in QFTs (numerics, effects of beta-function)

[Dixon, Moult, Zhu '19]

- shockwave amplitudes (OPE for amplitudes, CFT S-matrix, soft limits)

# Open Questions

How to efficiently combine Lorentzian methods with numerics?

Is it possible to measure event shapes in a lab?

**coarse-grained holography bootstrap challenge**:

With more efforts we can hopefully derive the rules of AdS EFT.
(flat space mini-challenge: UV complete R^3)

**fine-grained holography bootstrap challenge**:

How hard it is to UV complete a given AdS EFT?
Can we exclude some theories which look like perfect AdS EFTs?

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**Thank you!**

# Four-loop Prediction in N=4 SYM

[Korchemsky '19]
[Kologlu, Kravchuk, Simmons-Duffin, AZ '19]

To be concrete:

$$\begin{aligned}
\mathcal{F}_{\mathcal{E}}^{(4),\text{pl}}(\zeta) &= c_0^{(4)}\delta(\zeta) + \frac{1}{24}\left[\frac{\log^3\zeta}{\zeta}\right]_0 + \left(-\frac{7}{8}+\frac{1}{16}\pi^2-\frac{3}{16}\zeta_3\right)\left[\frac{\log^2\zeta}{\zeta}\right]_0 \\
&+ \frac{1}{4}\left(31-\frac{17}{6}\pi^2+\frac{1}{15}\pi^4-\frac{1}{6}\pi^2\zeta_3+\frac{1}{4}\zeta_3^2+3\zeta_5\right)\left[\frac{\log\zeta}{\zeta}\right]_0 \\
&+ \frac{1}{4}\left(-111+\frac{65}{6}\pi^2-\frac{3}{16}\pi^4-\frac{389}{30240}\pi^6+10\zeta_3-2\pi^2\zeta_3-\frac{3}{160}\pi^4\zeta_3+3\zeta_3^2+20\zeta_5+\frac{1}{12}\pi^2\zeta_5-\frac{69}{16}\zeta_7\right)\left[\frac{1}{\zeta}\right]_0 \\
&+ c_1^{(4)}\delta(y) + \frac{1}{192}\left[\frac{\log^7 y}{y}\right]_1 + \frac{5}{384}\pi^2\left[\frac{\log^5 y}{y}\right]_1 + \frac{95}{192}\zeta_3\left[\frac{\log^4 y}{y}\right]_1 + \frac{29}{1920}\pi^4\left[\frac{\log^3 y}{y}\right]_1 \\
&+ \left(\frac{67}{192}\pi^2\zeta_3+\frac{69}{16}\zeta_5\right)\left[\frac{\log^2 y}{y}\right]_1 + \left(\frac{367}{48384}\pi^4+\frac{97}{32}\zeta_3^2\right)\left[\frac{\log y}{y}\right]_1 \\
&+ \left(\frac{187}{5760}\pi^4\zeta_3+\frac{95}{192}\pi^2\zeta_5+\frac{785}{128}\zeta_7\right)\left[\frac{1}{y}\right]_1 + \mathcal{F}_{\mathcal{E}}^{(4),\text{reg}}(\zeta)
\end{aligned}$$

$$\boxed{y = 1-\zeta}$$

## Commutativity of light-ray operators

The product of the light-ray operators $\mathbf{L}[\mathcal{O}_{J_1}](x, z_1)\mathbf{L}[\mathcal{O}_{J_2}](x, z_2)$ is well-defined and commutative **if and only if ***

$$J_1 + J_2 > \max\left(2 - \Delta_0', 1 + J_0\right)$$

$$J_1 + J_2 > 2 - \tau_0' + |\Delta_1 - \Delta_2|$$

where

$$\Delta_0', \tau_0' \geq \frac{d-2}{2}$$

are smallest non-zero twist and dimension in the OPE of

$$\mathcal{O}_{J_1} \times \mathcal{O}_{J_2}$$

***** assuming the asymptotic light-cone expansion

# CFT Light-Ray Operators

Start with a bi-local object

$$\mathbb{O}^{\pm}_{\Delta,J}(x,z) = \int d^d x_1 d^d x_2 K^{\pm}_{\Delta,J}(x_1,x_2,x,z)\phi_1(x_1)\phi_2(x_2).$$

The kernel is obtained by Wick-rotating and light-transforming the partial wave expansion.

The **residues** are light-ray operators:

$$\mathbb{O}^{\pm}_{\Delta,J}(x,z) \sim \frac{1}{\Delta - \Delta^{\pm}_i(J)}\mathbb{O}^{\pm}_{i,J}(x,z)$$

[Kravchuk, Simmons-Duffin '18]

# Spin Selection Rule

Consider the small separation limit between two light-ray operators

$$\lim_{z_1\cdot z_2\to 0}\mathbf{L}[\mathcal{O}_1](x,z_1)\mathbf{L}[\mathcal{O}_2](x,z_2)=\sum_i (z_1\cdot z_2)^{\delta_i}\mathbb{O}_{\delta_i,J}(x,z_2)$$

Analogy

$$\mathcal{O}_{\Delta_1}(x)\mathcal{O}_{\Delta_2}(x)=\sum_i \mathcal{O}^i_{\Delta_1+\Delta_2}(x)$$

This leads to the spin selection rule [Hofman, Maldacena 08']

$$(J-1)=(J_1-1)+(J_2-1)\Rightarrow J=J_1+J_2-1$$

$$\int_{-\infty}^{\infty}dx_1^- T_{--}(x_1^-,x_1^+,\vec{x}_1)\int_{-\infty}^{\infty}dx_2^- T_{--}(x_2^-,x_2^+,\vec{x}_2)\ =\sum_i\int dx^-\mathcal{O}_{---}$$

# Signature of Light-ray Operators

Analytic continuation in spin is performed separately from even spins (signature +) and from odd spins (signature -).

One way to state this is to consider CRT transformation

$$\mathsf{CRT} : (u, v, \vec{y}) \;\to\; (-u, -v, \vec{y})$$

$$\left((\mathsf{CRT}) \int_{-\infty}^{\infty} dv\, \mathcal{O}_{i;v\cdots v}(0, v, \vec{y})(\mathsf{CRT})^{-1}\right)^{\dagger} = (-1)^{J_i} \int_{-\infty}^{\infty} dv\, \mathcal{O}_{i;v\cdots v}(0, v, \vec{y})$$

The same continues for the non-local operators

$$\left((\mathsf{CRT})\mathbb{O}^{\pm}_{\Delta,J}(x, z)(\mathsf{CRT})^{-1}\right)^{\dagger} = \pm\mathbb{O}^{\pm}_{\Delta,J}(x, z)$$

# Transverse Representations

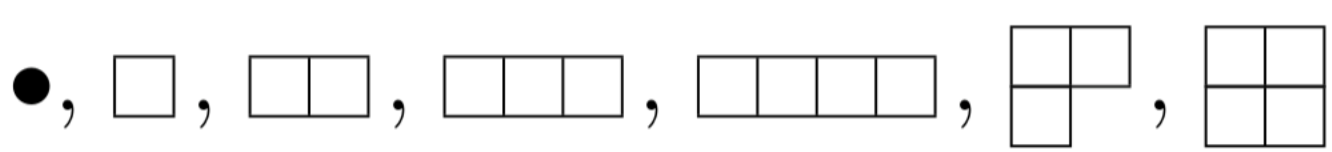
Naively, one would think that light-ray operators transforming in the arbitrary representations of the transverse SO(d-2) can appear in the OPE.

**Rule:** For the OPE $\int dv_1 \mathcal{O}_1 \times \int dv_2 \mathcal{O}_2$

1. List all SO(d-1,1) representations in the OPE $\mathcal{O}_1 \times \mathcal{O}_2$

2. Remove first row in the corresponding Young diagram

ANEC x ANEC

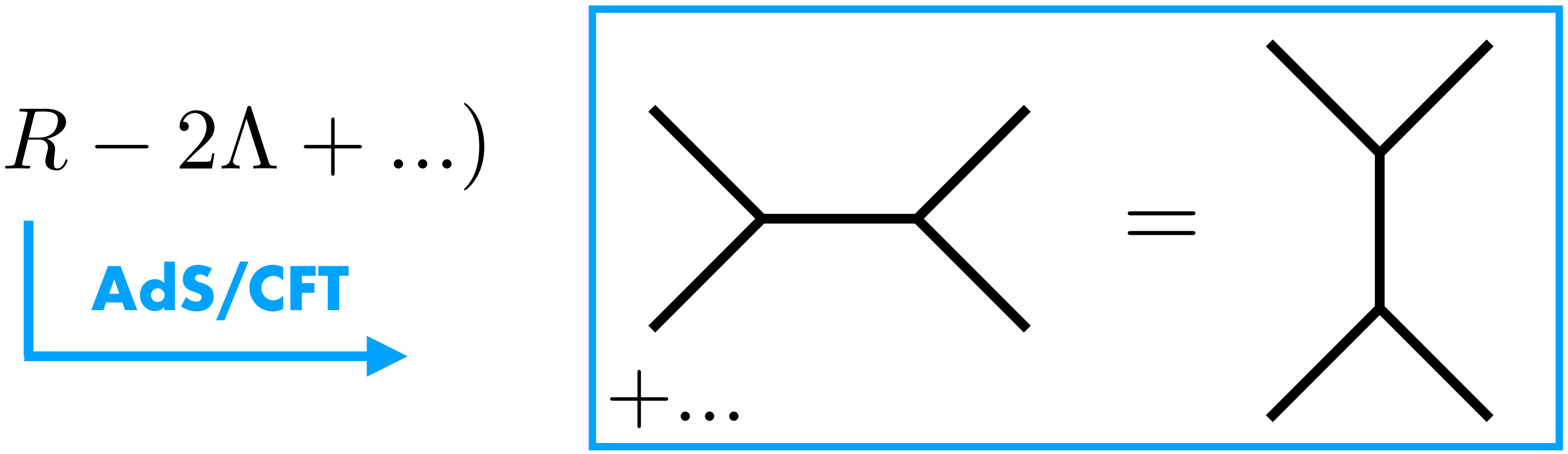


# Flat Space and AdS/dS Bulk

| CFT | S-matrix (AdS/dS) |
|---|---|
| light-ray operator | shockwave state<br>(on-shell state in the mixed signature)<br>$p^{\mu} = (0, p^{v}, \vec{q}), \qquad \vec{q}^{2} = 0$ |
| ANEC operator | gravitational shock |
| event shapes | scattering amplitudes<br>(in mixed signature) |
| bound on Regge | bound on Regge<br>(causality)<br>$\lim_{s\to\infty} \mathcal{A}(s,t) < s^2, \quad t < 0$ |
| commutativity of ANECs | superconvergence<br>$\int dt \mathrm{Disc}_t A(s,t) = 0$<br>[Alfaro, Fubini, Rossetti, Furlan 66'] |
| light-ray OPE | amplitude OPE?<br>(worldsheet OPE in string theory) |

# Holographic CFTs

$$\frac{1}{l_{Pl}^{D-2}} \int d^D x \sqrt{-g} \left( R - 2\Lambda + \dots \right)$$



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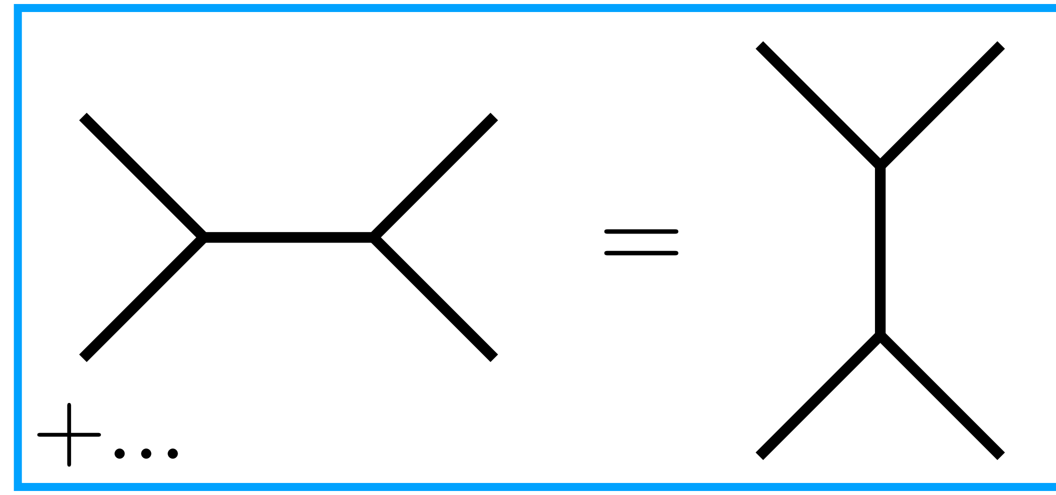
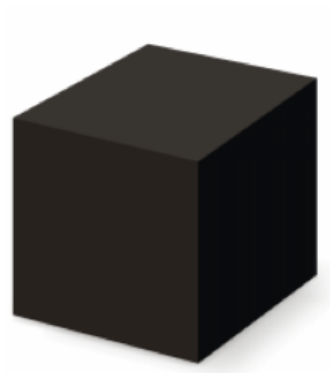
AdS/CFT

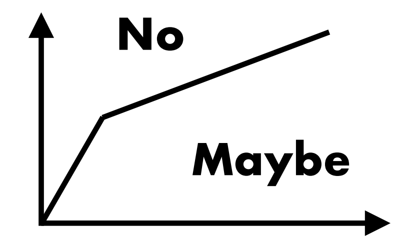



Tentative CFT data



NO

MAYBE




[Rattazzi, Rychkov, Tonni, Vichi '08]

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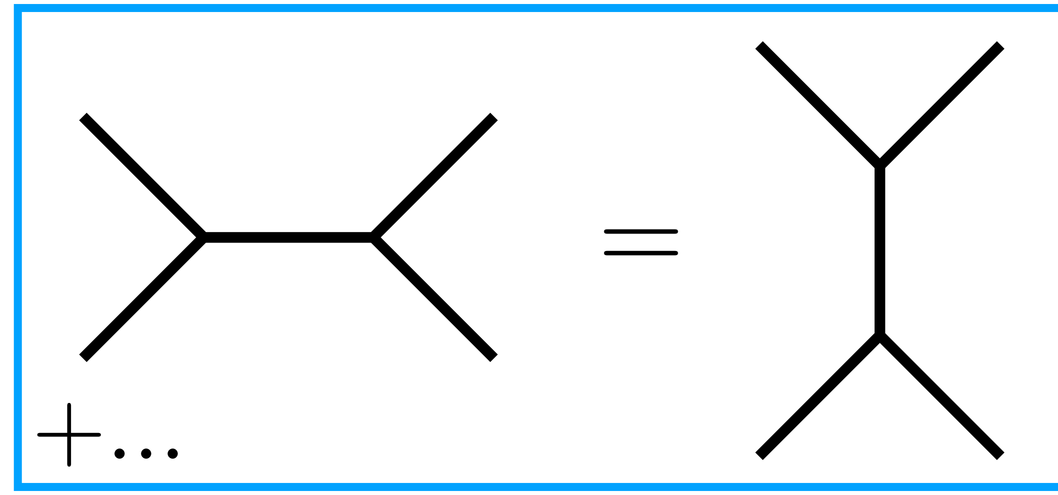


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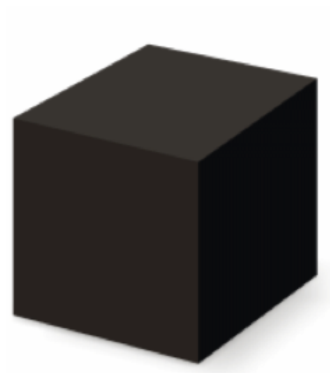
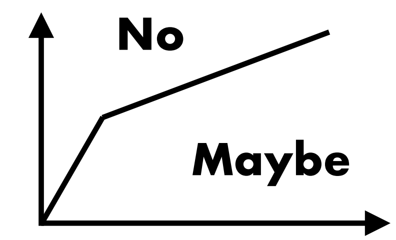


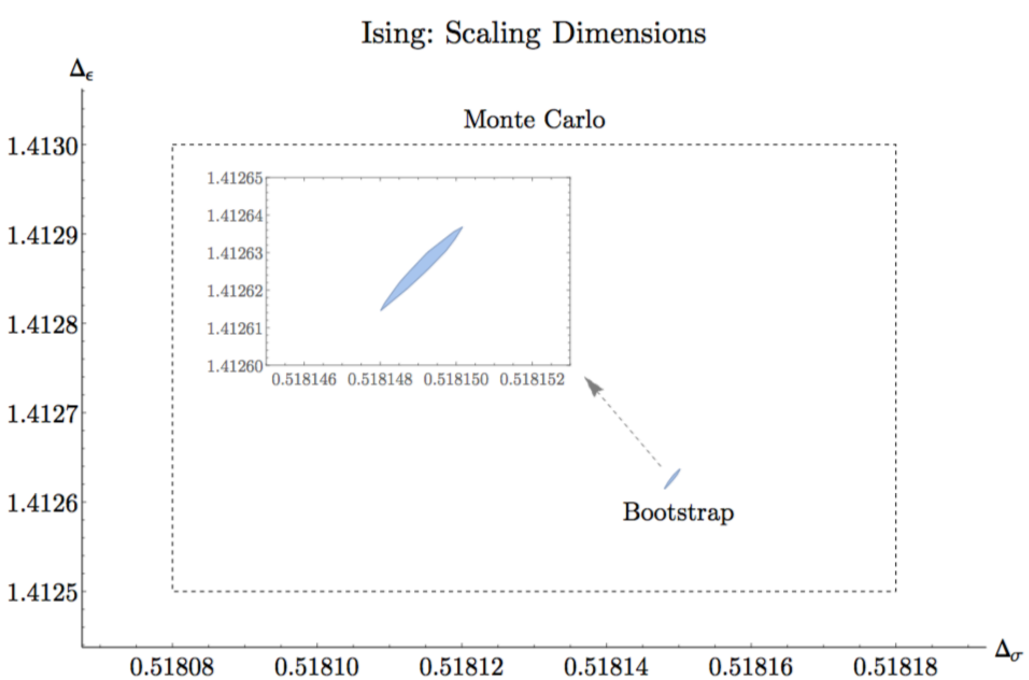
NO

MAYBE

"YES"!




[Rattazzi, Rychkov, Tonni, Vichi '08]




[Kos, Poland, Simmons-Duffin, Vichi '16]

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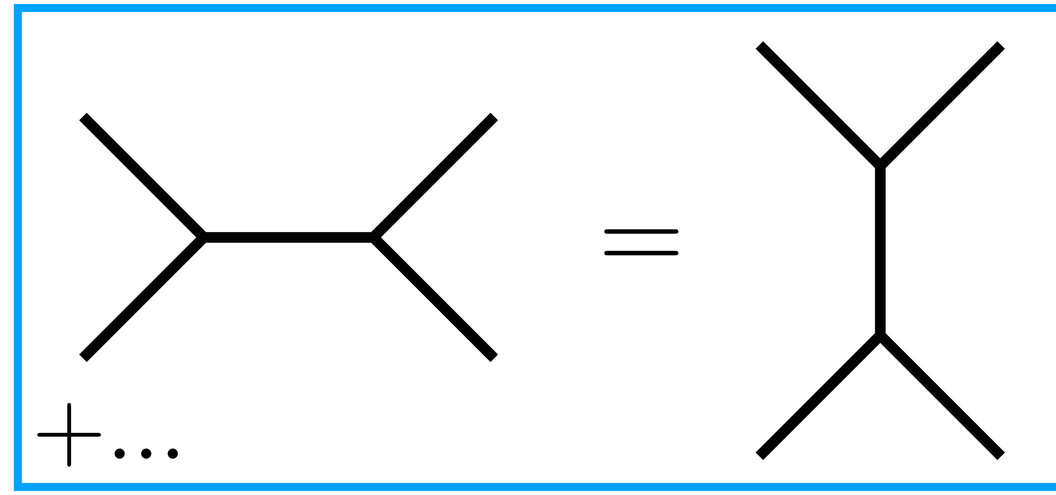


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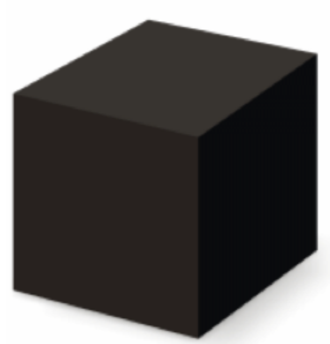

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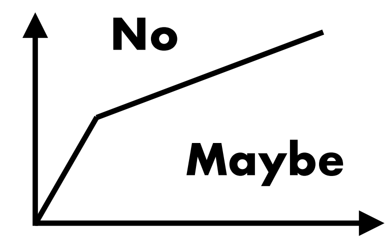
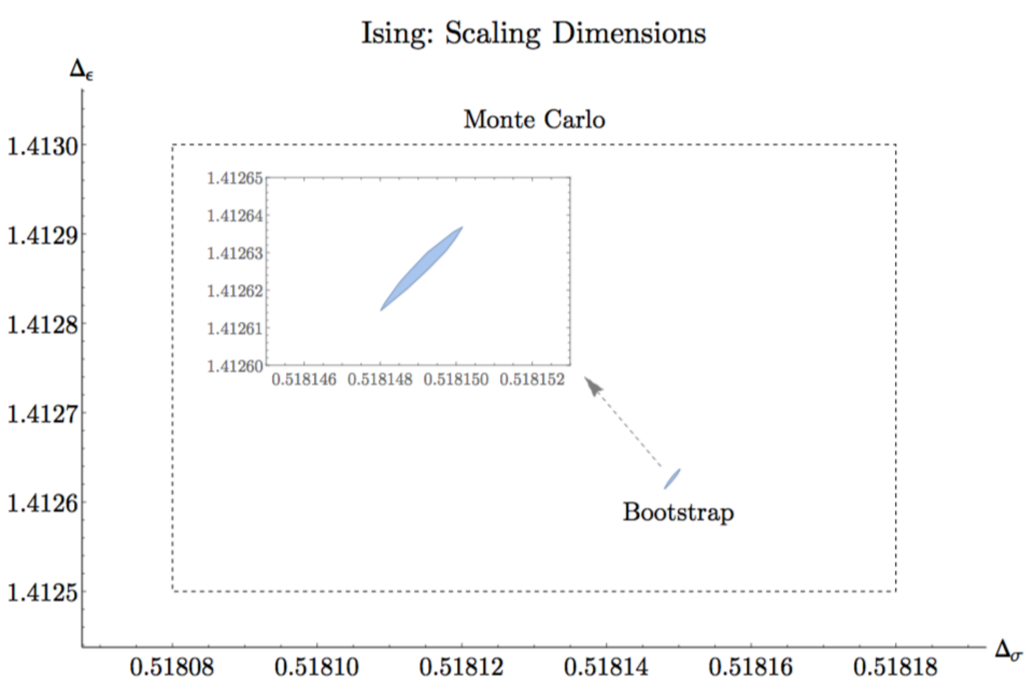



[Rattazzi, Rychkov, Tonni, Vichi '08]




[Kos, Poland, Simmons-Duffin, Vichi '16]

AdS/CFT

HPPS: any consistent EFT in AdS looks OK!

[Heemskerk, Penedones, Polchinski, Sully '09]

**fine-grained holography**: landscape vs. swampland

(hard)

**coarse-grained holography**: assume landscape derive the rules of consistent AdS EFTs

("easy")

# AdS EFT ("easy")

$$\frac{1}{l_{Pl}^{D-2}} \int d^D x \sqrt{-g} \left( R - 2\Lambda + \frac{c_2}{M^2} R^2 + ... \right)$$

**HPPS conjecture:** large N + large gap $\Rightarrow$

$M$ - string scale

$c_2 = O(1)$

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**Causality:**
- non-minimal couplings cannot be primordial
- non-minimal couplings should timely Reggeize (extra HS DoF are needed)

[Camanho, Edelstein, Maldacena, AZ '14]

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(squiggly line curse)

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**(squiggly line curse)**

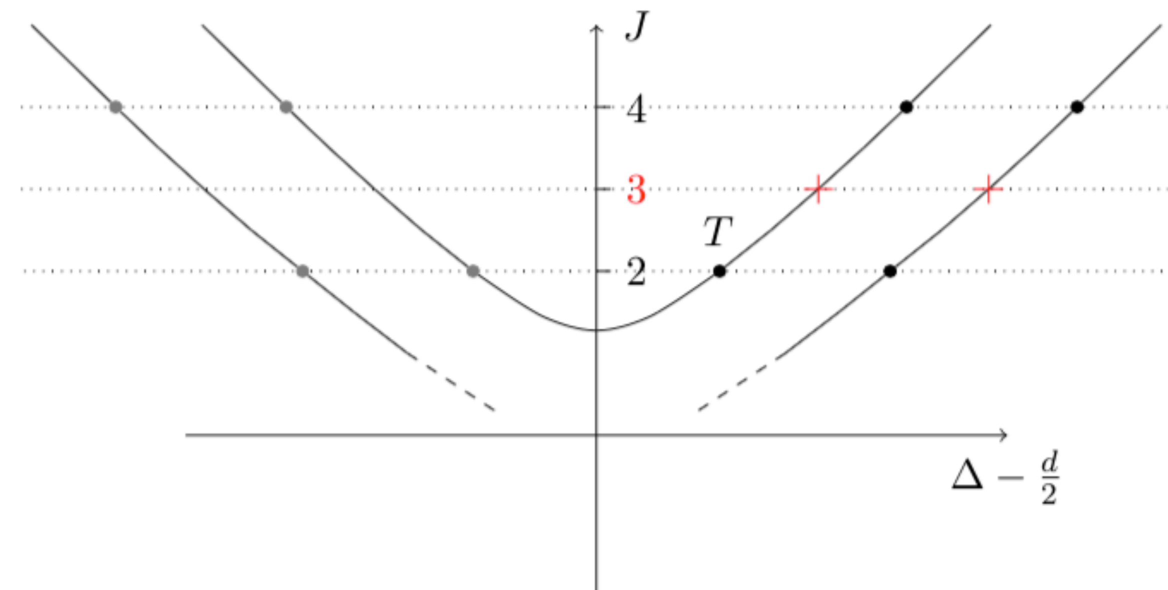
**Bound on Pomeron couplings:**

$$C^{R^2}_{TTJ(\nu)} = O(\nu^2)$$
$$C^{R^3}_{TTJ(\nu)} = O(\nu^4)$$

(non-minimal TT-pomeron coupling)

**from unitarity**

[Costa, Hansen, Penedones '17]
[Kulaxizi, Parnachev, AZ '17]




$T: \quad \nu = i\ d/2$