# Holographic energy correlators from Wightman-Witten diagrams

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EXCELENCIA SEVERO OCHOA

Work in progress with:
**Alex Pomarol** and **Andrea Wulzer**

**Horizons Beyond the Standard Model:**
from Colliders to Dark Matter and Axions

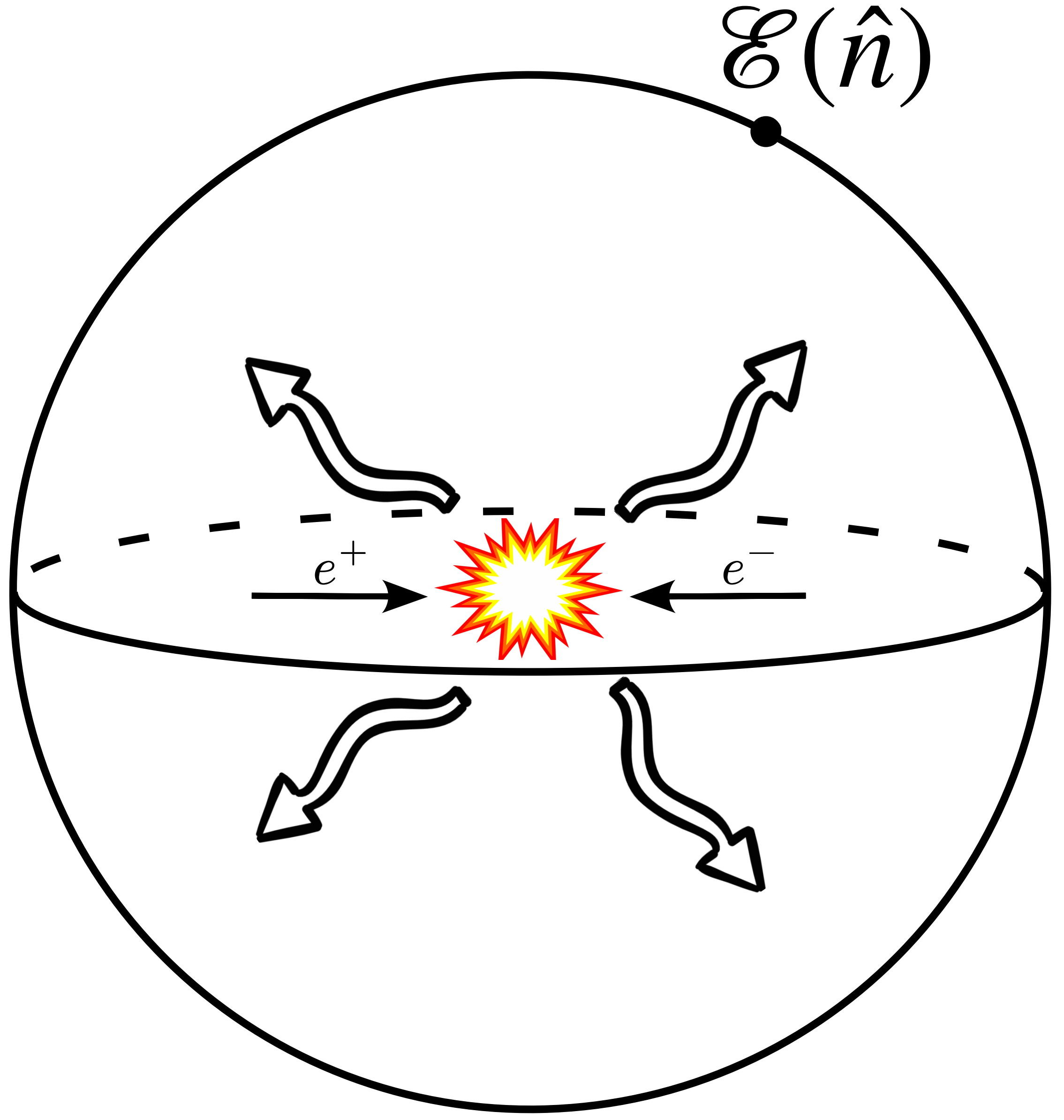
# Energy flow as a collider observable

*The standard energy detector*

$$\mathcal{E}(\hat{n}) = \lim_{r \to +\infty} r^{d-2} \int_{-\infty}^{+\infty} dt \ \hat{n}_i T^{0i}(t, r\hat{n})$$

$\hat{n}$ parametrizes angles on the celestial sphere

Measures the total energy flux in the direction $\hat{n}$ at $r \to \infty$



Basham, Brown, Ellis & Love (1978)

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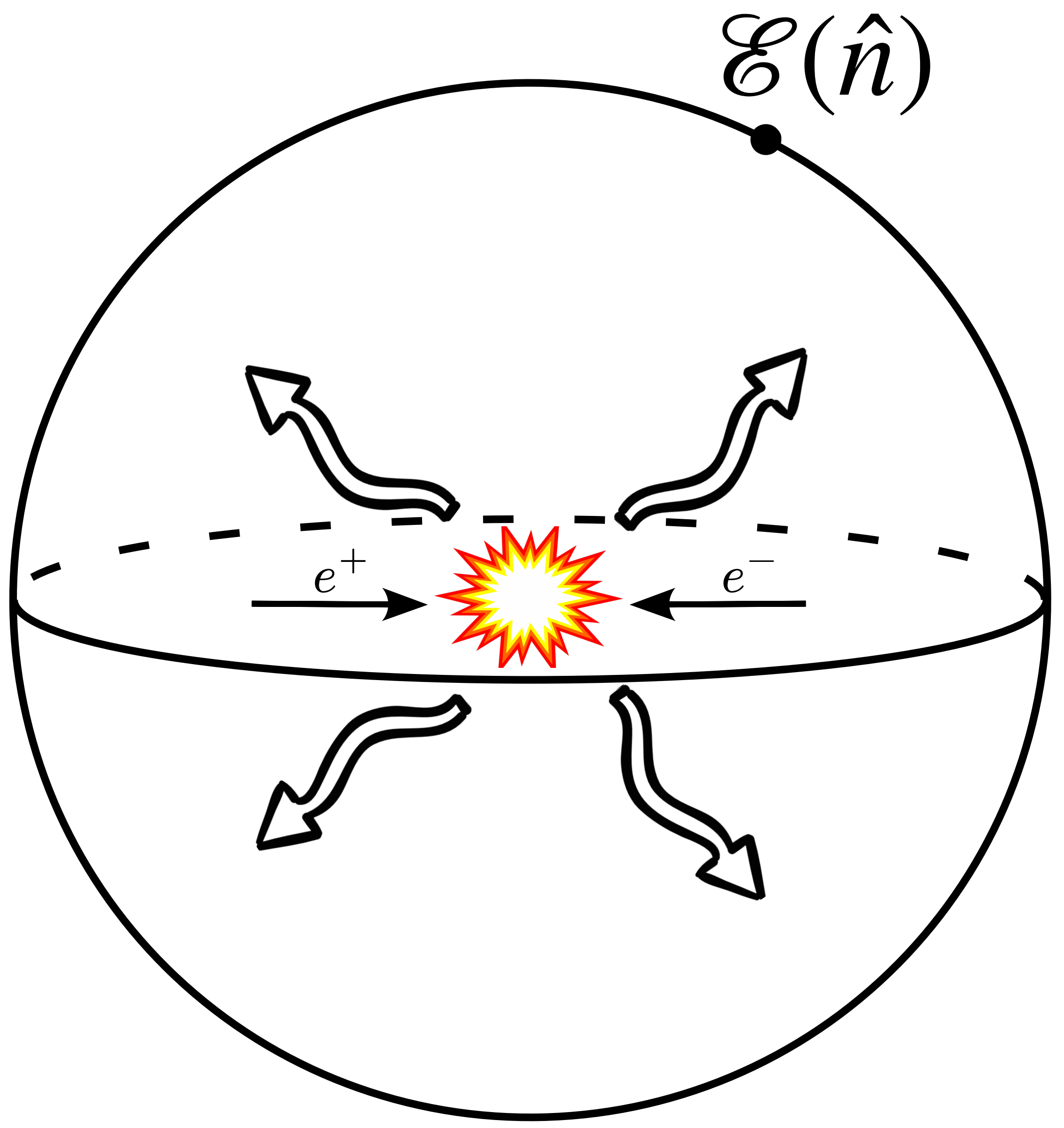



Basham, Brown, Ellis & Love (1978)

**Particle interpretation:**

$$\mathcal{E}(\hat{n})\,|X\rangle = \sum_{a\in X} E_a \delta^{(d-2)}(\hat{n} - \hat{p}_a)\,|X\rangle$$

A weighted angular sum over all final particles

**Energy sum rule:**

$$\int d\Omega_{\hat{n}}\ \mathcal{E}(\hat{n}) = H$$

# Energy flow as a collider observable

*The null calorimeter*

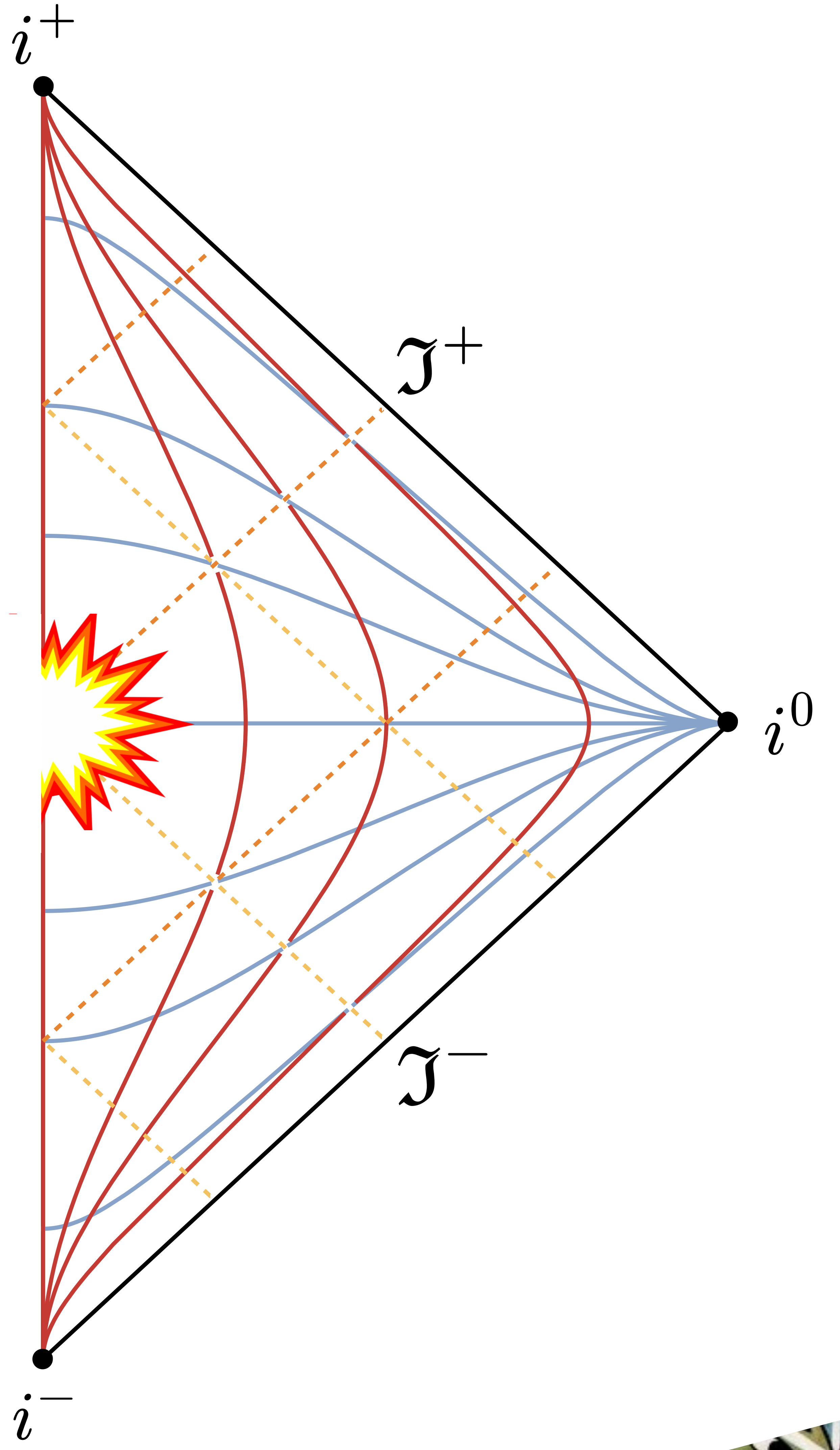
Light-cone coordinates: $x^{\pm} = t \pm r$

**Null detector limit:**

take $x^+ = t + r \to \infty$ at fixed finite $x^- = t - r$

$$\mathscr{E}(\hat{n}) = \int_{-\infty}^{+\infty} dx^- \lim_{x^+ \to +\infty} \frac{(x^+)^2}{4} T_{--}(x^+, x^-, x_\perp = 0)$$

- Detector place at future null infinity $\mathfrak{I}^+$
- Integrate the null energy flux along the light-ray
- Natural form of the calorimeter in a CFT



# Energy flow as a collider observable

*Energy correlators*

$N$-point energy correlator: $$\langle \mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_N)\rangle_{\mathcal{O}_q} = \frac{\langle 0 | \mathcal{O}_q^\dagger \mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_N)\mathcal{O}_q | 0\rangle}{\langle 0 | \mathcal{O}_q^\dagger \mathcal{O}_q | 0\rangle}$$

Hofman & Maldacena (2008)

# Energy flow as a collider observable

## *Energy correlators*

$N$-point energy correlator: $$\langle \mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_N)\rangle_{\mathcal{O}_q} = \frac{\langle 0|\mathcal{O}_q^\dagger \mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_N)\mathcal{O}_q|0\rangle}{\langle 0|\mathcal{O}_q^\dagger \mathcal{O}_q|0\rangle}$$

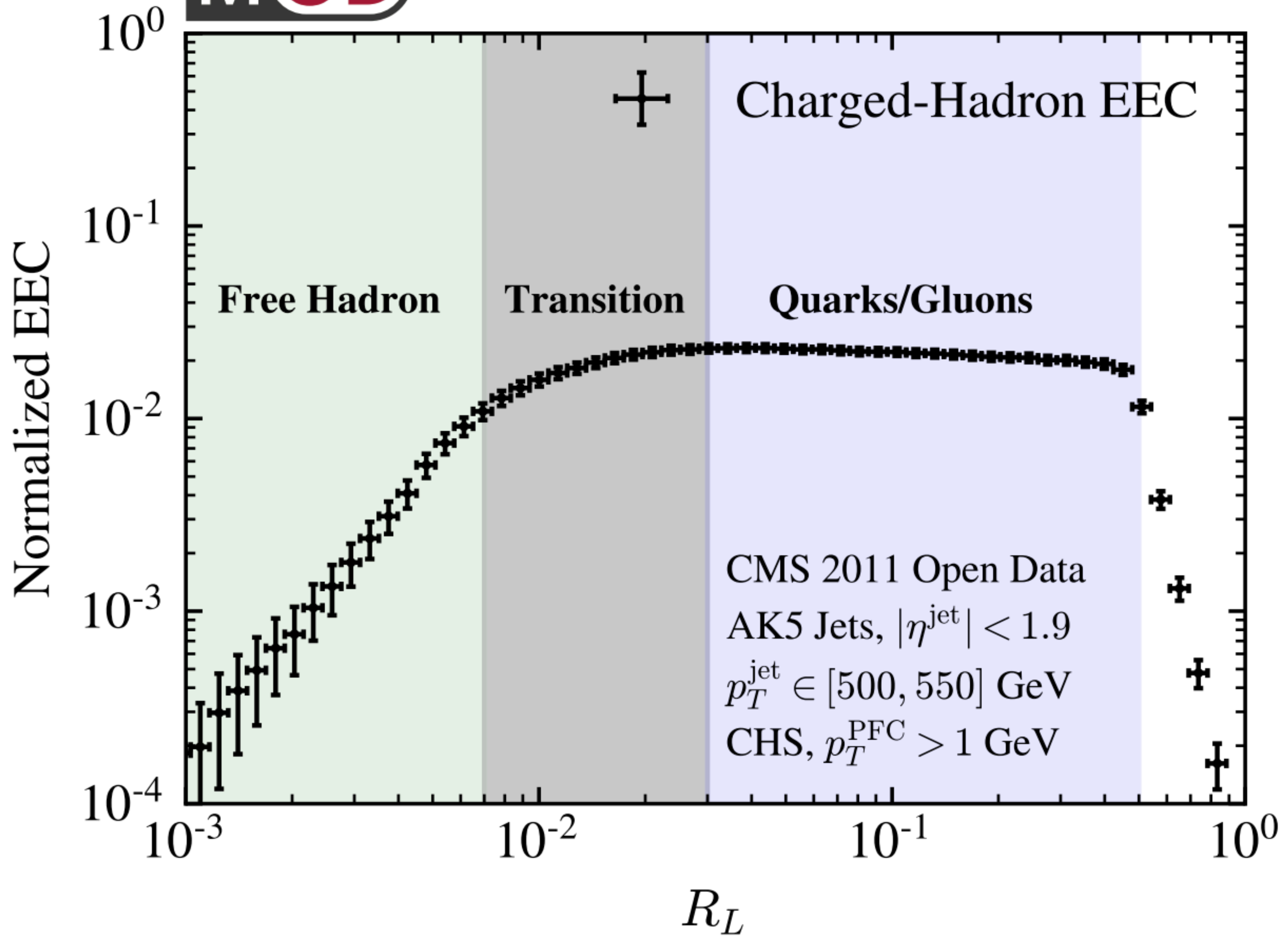
***Prepared wave-packet:*** $$\mathcal{O}_q|0\rangle = \int d^dx\, e^{-iEx^0} e^{-x_E^2/\xi^2}\,\mathcal{O}(x)|0\rangle, \qquad q^\mu = (E,\vec{0}) + O(\xi^{-1})$$

The smearing fixes the total momentum up to wave-packet-width corrections and is essential to have normalized states

Hofman & Maldacena (2008)

# Energy flow as a collider observable

*Angular dependence separates dynamical regimes*




Komiske, Moult, Thaler & Zhu (2022)

- $R_L$: opening angle between the detectors operators
- Varying $R_L$ probes different physical regimes
- **Perturbative region:** asymptotically free quarks and gluons
- **Transition region:** onset of confinement/hadronization
- **Deep-IR region:** free-hadron scaling

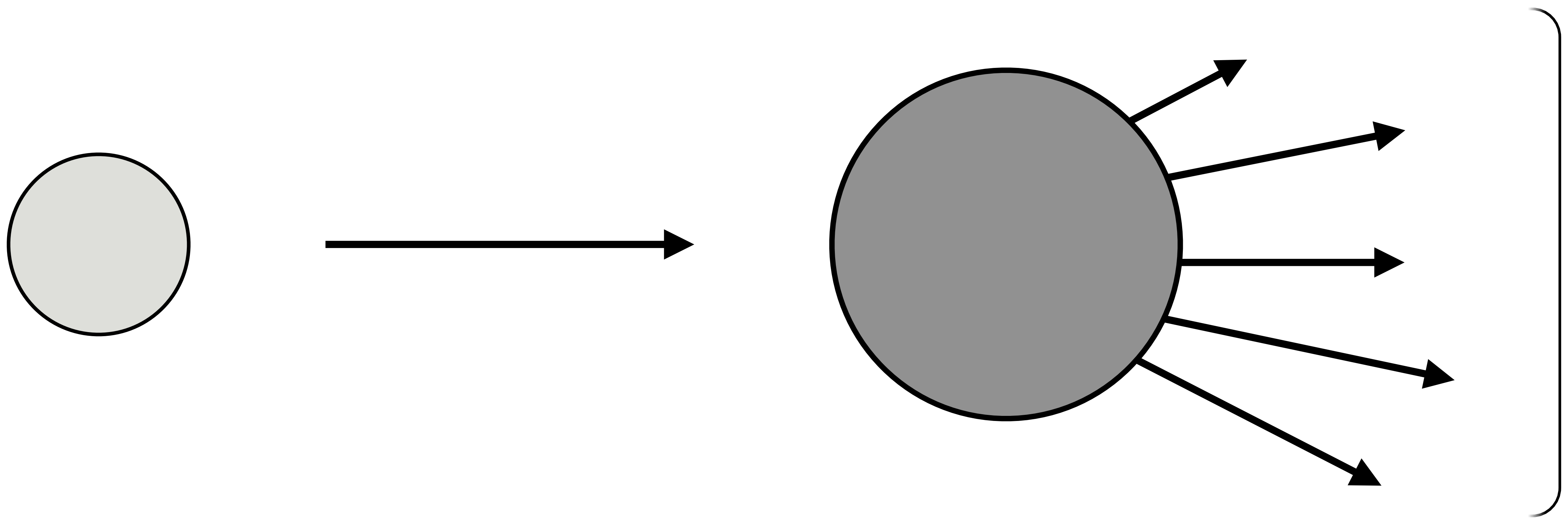
*Takeaway:* the angular dependence reveals the flow from partons to hadrons

# Energy correlators as Wightman In-In observables

### *Exclusive observable: In-Out amplitude*

$$\sigma \sim |\mathscr{M}(\text{In} \to \text{Out})|^2$$

In state
(prepare)



Out state
(specific final state)

- Choose a very specific final state $|\text{Out}\rangle$
- Highly exclusive information
- Natural for scattering amplitudes

# Energy correlators as Wightman In-In observables

## *Inclusive detector observable*

$$\langle \mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_N)\rangle_{\mathcal{O}_q} = \frac{\langle 0|\,\mathcal{O}_q^\dagger \mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_N)\mathcal{O}_q\,|0\rangle}{\langle 0|\,\mathcal{O}_q^\dagger\,\mathcal{O}_q\,|0\rangle} = \sum_X \frac{\langle 0|\,\mathcal{O}_q^\dagger\,|X\rangle\,\langle X|\,\mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_N)\,|X\rangle\,\langle X|\,\mathcal{O}_q\,|0\rangle}{\langle 0|\,\mathcal{O}_q^\dagger\,\mathcal{O}_q\,|0\rangle}$$

***Read the second equality as an inclusive sum over final states***

*Insert a complete set of asymptotic states between the sources and detector operators*

**Prepared state**

- Rightmost operator prepares the wave-packet state
- Outer factors are overlaps with a final state $|X\rangle$
- Zero-overlap states do not contribute

**Detector average**

- Middle matrix element = calorimeter response of $X$
- Sum over all $X$: no exclusive final-state projection
- Operators are Wightman ordered, not time-ordered

# Holographic energy correlators in AdS

*CFTs with gravity duals*

**Hofman & Maldacena (2008)**

Conformal collider physics in a CFT with an AdS dual

Energy detectors at null infinity $\longleftrightarrow$ shockwaves in AdS

Using conformal symmetry, the null calorimeter problem is mapped to
a shockwave computation in AdS

This gives a very efficient description of energy correlators in AdS/CFT settings

# Holographic energy correlators beyond AdS

*Other warped geometries*

**Csáki & Ismail (2024), Csáki, Ferrante & Ismail (2024), Csáki, Ismail & Kiriliuk (2025)**

Extending the AdS/CFT shockwave formalism to confining warped backgrounds:

*hard wall → soft walls → logarithmically running geometries*

**Ricci & Sundrum (2026)**

Canonical quantization to compute In-In correlators in AdS and RS1

*some aspects of the In-In Witten diagram computation can be found for AdS*

# Holographic energy correlators beyond AdS

*Other warped geometries*

Pomarol, PS & Wulzer (in preparation)

**QFT-based techniques for holographic ECs:**

Euclidean Witten diagrams → analytic continuation to Wightman → detector limit

***What this gives:***

*Selection rules, universal building blocks, and controlled deformations beyond exact AdS*

# From Euclidean to Wightman correlators

$$\tau_i = \epsilon_i + it_i$$

$$\epsilon_1 > \cdots > \epsilon_n > 0$$

# From Euclidean to Wightman

*Energy correlators are In-In correlation functions*

For local operators $A_1(x_1), \ldots, A_n(x_n)$, a Wightman correlator is just a vacuum expectation value with a fixed operator order

$$W_{1\cdots n}(x_1, \ldots, x_n) = \langle 0 | A_1(x_1) \cdots A_n(x_n) | 0 \rangle$$

Simmons-Duffin (TASI 2015)

# From Euclidean to Wightman

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$$W_{1\cdots n}(x_1, \ldots, x_n) = \langle 0 | A_1(x_1) \cdots A_n(x_n) | 0 \rangle$$

In Euclidean QFT naturally compute $G_E(\tau_1, \ldots, \tau_n)$ that does not directly know the Lorentzian operator order

The Euclidean correlator analytically continued with

$$\tau_i = it_i + \epsilon_i \,, \qquad \epsilon_1 > \epsilon_2 > \cdots > \epsilon_n > 0$$

produces the Wightman correlator with operator order $1 \to 2 \to \cdots \to n$

**Simmons-Duffin (TASI 2015)**

# From Euclidean to Wightman

*Example: three-point flat space* $\langle \mathcal{O}\mathcal{O}\mathcal{O}\rangle_E$

$$G_E^{(1)}(1,2,3) = -\lambda \int d^{d-1}\vec{z}\, d\tau\ G_E(1,Y)G_E(2,Y)G_E(3,Y)\,, \qquad Y = (\tau, \vec{z})\,, \qquad \tau_1 > \tau_2 > \tau_3$$

$$G_E(\Delta\tau, \Delta\vec{x}) = \int \frac{d^{d-1}\vec{p}}{(2\pi)^{d-1}} \frac{1}{2E_{\vec{p}}}\, e^{i\vec{p}\cdot\Delta\vec{x}} e^{-E_{\vec{p}}|\Delta\tau|} = \begin{cases} G_E^{(+)}(\Delta\tau, \Delta\vec{x})\,, & \Delta\tau > 0 \\ G_E^{(-)}(\Delta\tau, \Delta\vec{x})\,, & \Delta\tau < 0 \end{cases}$$

Integrand non-analytic at $\tau = \tau_1\,, \tau_2\,, \tau_3$: integration region split into four regions

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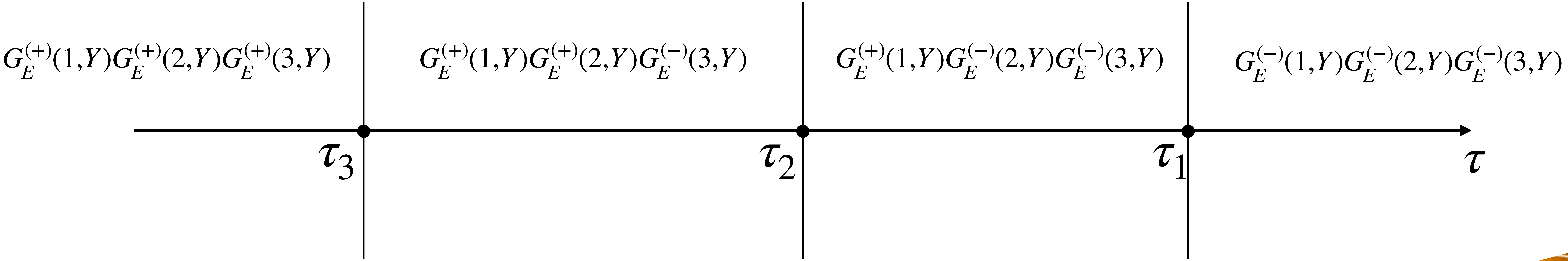
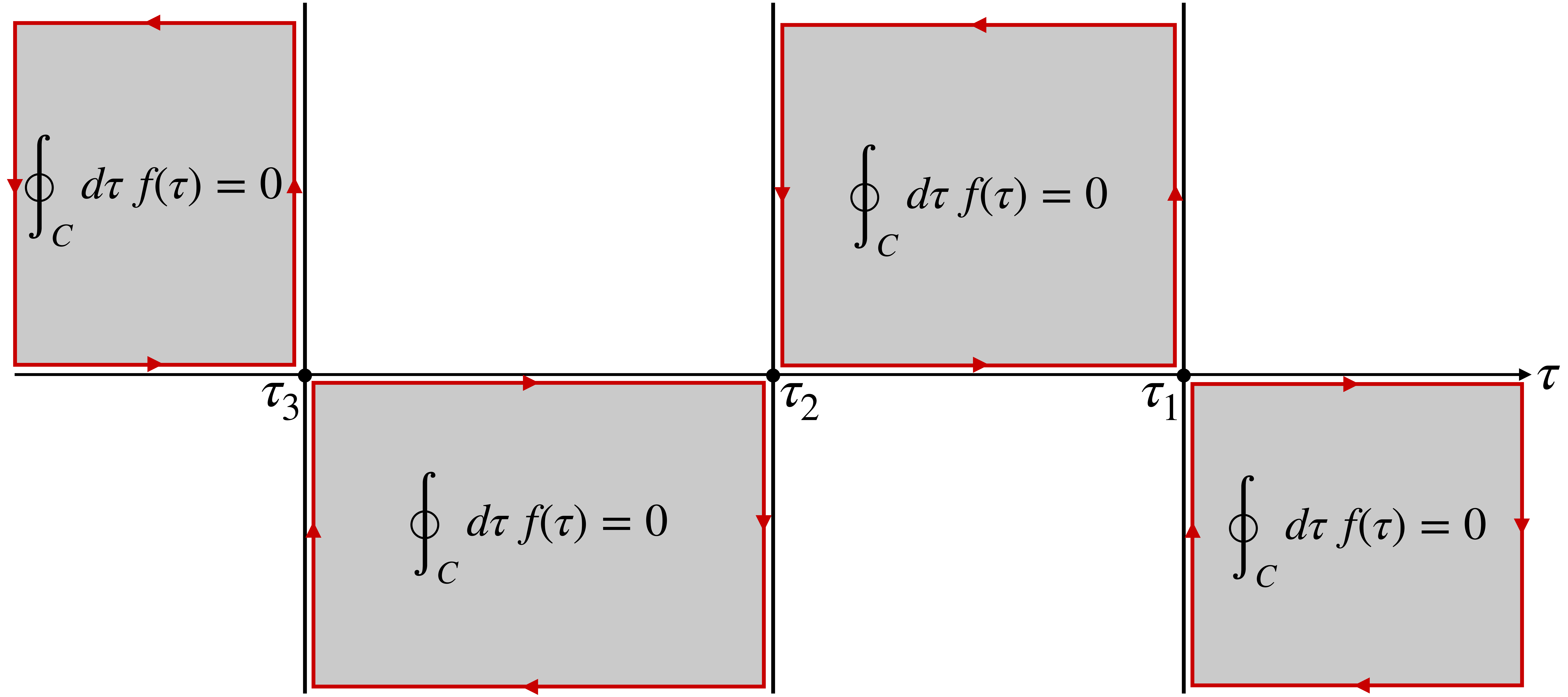
Integrand non-analytic at $\tau = \tau_1\,,\tau_2\,,\tau_3$: integration region split into four regions, the integrand is analytic in each of these regions



# From Euclidean to Wightman



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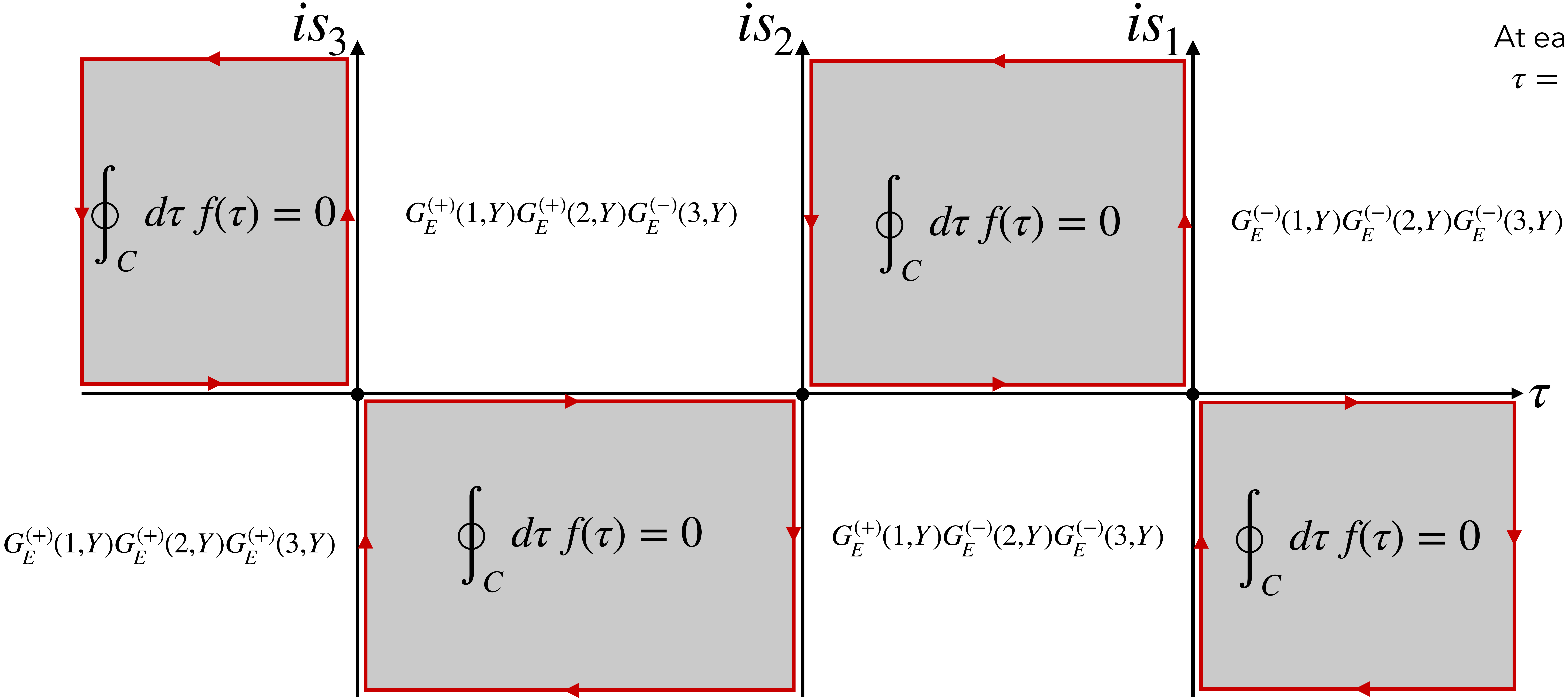
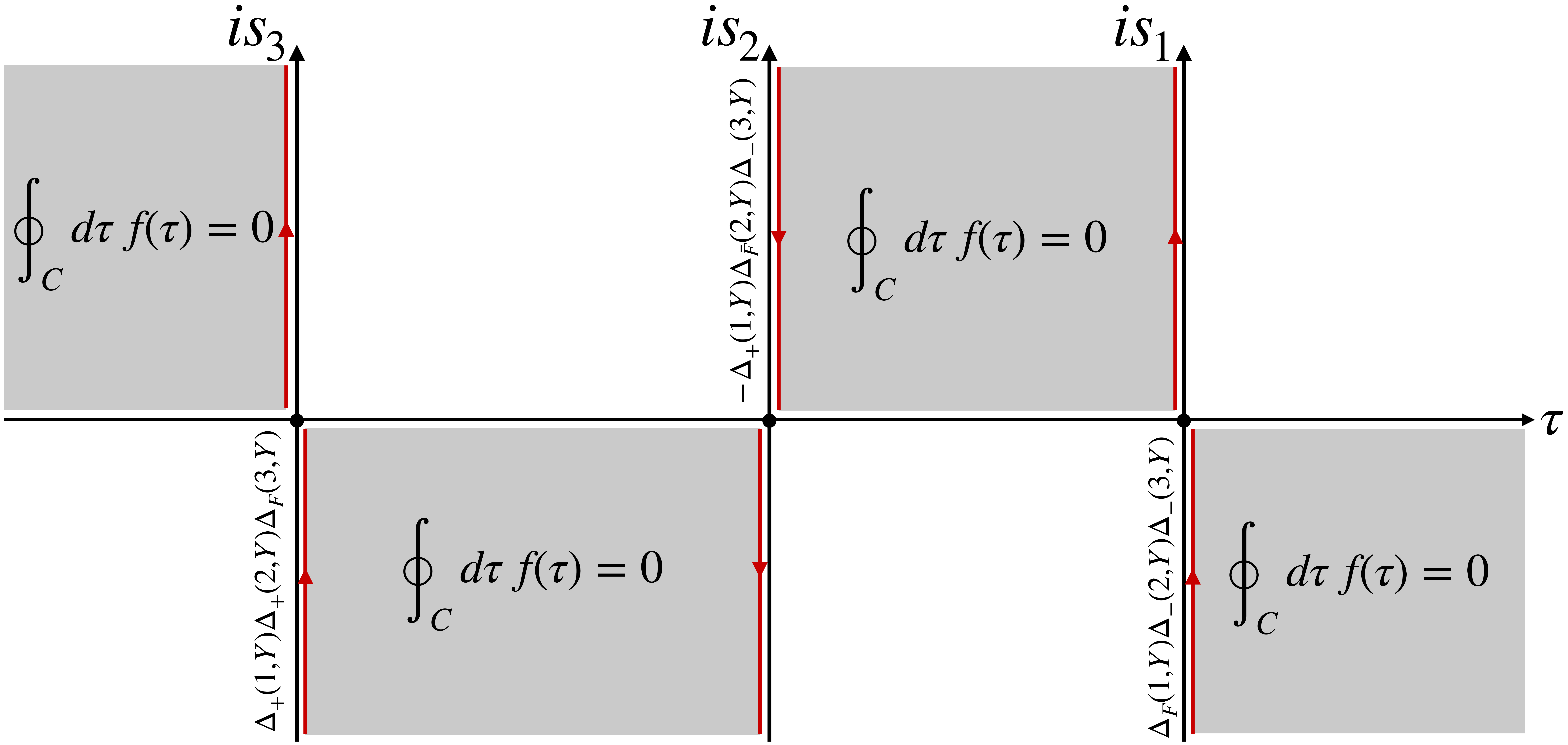



At each wall:
$\tau = \epsilon_i + is_i$

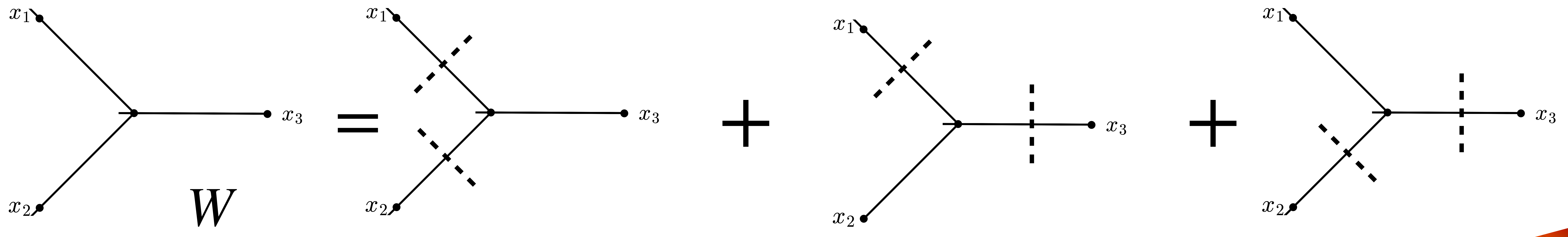
# From Euclidean to Wightman



# From Euclidean to Wightman

*Example: three-point flat space $\langle \mathcal{O}\mathcal{O}\mathcal{O}\rangle_E$*

$$G^{(1)}_{123}(x_1,x_2,x_3) = -\,i\lambda \int d^d z\, \Big[ +\Delta_+(x_1-z)\Delta_+(x_2-z)\Delta_F(x_3-z) \\ -\Delta_+(x_1-z)\Delta_{\bar{F}}(x_2-z)\Delta_-(x_3-z) \\ +\Delta_F(x_1-z)\Delta_-(x_2-z)\Delta_-(x_3-z)\Big]$$



# From Euclidean to Wightman

*Example: 4-point exchange in the **t-channel***

Off-diagonal pieces ($\tau_Y \neq \tau_Z$)

$$+\Delta_{1,F}(Y)\Delta_2^-(Y)D_+(Y,Z)\Delta_3^+(Z)\Delta_{4,F}(Z)$$

$$-\Delta_{1,F}(Y)\Delta_2^-(Y)D_+(Y,Z)\Delta_{3,\bar{F}}(Z)\Delta_4^-(Z)$$

$$-\Delta_1^+(Y)\Delta_{2,\bar{F}}(Y)D_+(Y,Z)\Delta_3^+(Z)\Delta_{4,F}(Z)$$

$$+\Delta_1^+(Y)\Delta_{2,\bar{F}}(Y)D_+(Y,Z)\Delta_{3,\bar{F}}(Z)\Delta_4^-(Z)$$

Diagonal pieces ($\tau_Y = \tau_Z$)

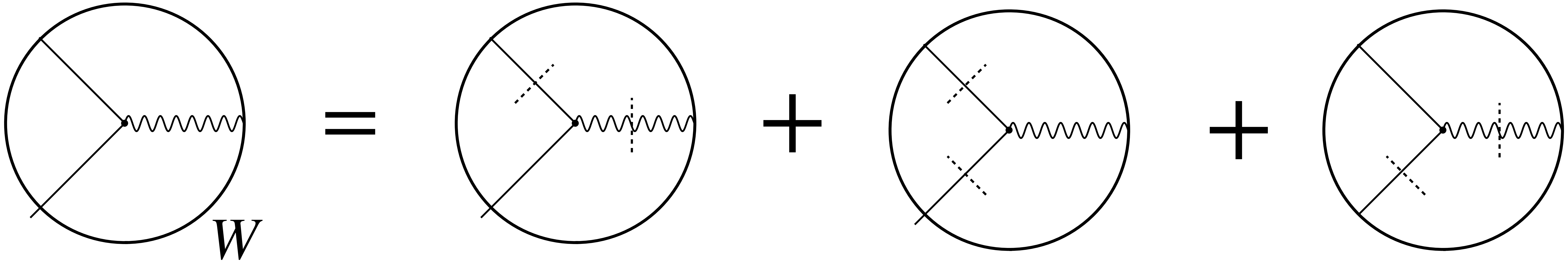
$$-\Delta_{1,\bar{F}}(Y)\Delta_2^-(Y)D_F(Y,Z)\Delta_3^-(Z)\Delta_4^-(Z)$$

$$+\Delta_1^+(Y)\Delta_{2,F}(Y)D_F(Y,Z)\Delta_3^-(Z)\Delta_4^-(Z)$$

$$-\Delta_1^+(Y)\Delta_2^+(Y)D_F(Y,Z)\Delta_{3,\bar{F}}(Z)\Delta_4^-(Z)$$

$$+\Delta_1^+(Y)\Delta_2^+(Y)D_F(Y,Z)\Delta_3^+(Z)\Delta_{4,F}(Z)$$

# Holographic energy correlators from Wightman-Witten diagrams



# One-point EC in AdS

*Energy correlators are detector observables*

In AdS/CFT we take the null definition of the energy detector in the CFT

$$\mathscr{E}(\hat{n}) = \lim_{\hat{x}^+ \to +\infty} \frac{(\hat{x}^+)^2}{4} \int_{-\infty}^{+\infty} d\hat{x}^- \; T_{--}(\hat{x}^+, \hat{x}^-, \hat{x}_\perp = 0)$$

So we need to compute Wightman correlation functions of the form $\langle \mathcal{O} T \mathcal{O} \rangle$:

$$\lim_{\hat{x}^+ \to +\infty} \frac{(\hat{x}^+)^2}{4} \int_{-\infty}^{+\infty} d\hat{x}^- \; \langle 0 | \, \mathcal{O}^\dagger(x_1) T_{--}(\hat{x}^+, \hat{x}^-, \hat{x}_\perp = 0) \mathcal{O}(x_2) \, | 0 \rangle$$

# A holographic dictionary interlude

**Boundary sources are bulk boundary conditions**

The holographic dictionary tells us

$$Z_{\rm CFT}[\phi^{(0)}, h^{(0)}_{\mu\nu}] = Z_{\rm grav}[\Phi \to \phi^{(0)}, h_{MN} \to h^{(0)}_{\mu\nu}] = e^{-S_{\rm grav}[\Phi, h_{MN}]}$$

**CFT: choose sources**

Scalar source: $\int d^d x \; \phi^{(0)}(x)\mathcal{O}(x)$

Metric source: $\int d^d x \; h^{(0)}_{\mu\nu}(x) T^{\mu\nu}(x)$

sources are book-keeping variables for operator insertions

**AdS: bulk fields from boundary sources**

$$\Phi \leftrightarrow \mathcal{O} \qquad h_{MN} \leftrightarrow T_{\mu\nu}$$

$$\Phi(X) = \int d^4 y \; K^{(\phi)}(X; y)\phi^{(0)}(y)$$

$$h_{MN}(X) = \int d^4 y \; K^{(h)}_{MN|\mu\nu}(X; y) h^{(0)}_{\mu\nu}(y)$$

# A holographic dictionary interlude

*CFT correlation functions from bulk dynamics*

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$$\langle \mathcal{O}(x) \rangle = \frac{\delta W_{\mathrm{CFT}}[\phi^{(0)}]}{\delta \phi^{(0)}(x)} = \frac{\delta S_{\mathrm{grav}}\left[\Phi[\phi^{(0)}]\right]}{\delta \phi^{(0)}(x)}, \qquad W_{\mathrm{CFT}} = -\log Z_{\mathrm{CFT}} = S_{\mathrm{grav}}$$

Minimal coupling: $S_{\mathrm{grav}} \supset \dfrac{\kappa}{2} \displaystyle\int d^5X \sqrt{g_{\mathrm{AdS}}}\; h_{MN}(X) T^{MN}_{(\Phi)}(X)$

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*CFT correlation functions from bulk dynamics*

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$$\langle \mathcal{O}(x_1) T_{\mu\nu}(y) \mathcal{O}(x_2) \rangle = \frac{\delta^3 W_{\mathrm{CFT}}[\phi^{(0)}, h^{(0)}_{\mu\nu}]}{\delta\phi^{(0)}(x_1)\delta h^{(0)}_{\mu\nu}(y)\delta\phi^{(0)}(x_2)} = \frac{\delta^3 S_{\mathrm{grav}}\left[\Phi[\phi^{(0)}], h_{MN}[h^{(0)}_{\mu\nu}]\right]}{\delta\phi^{(0)}(x_1)\delta h^{(0)}_{\mu\nu}(y)\delta\phi^{(0)}(x_2)}$$

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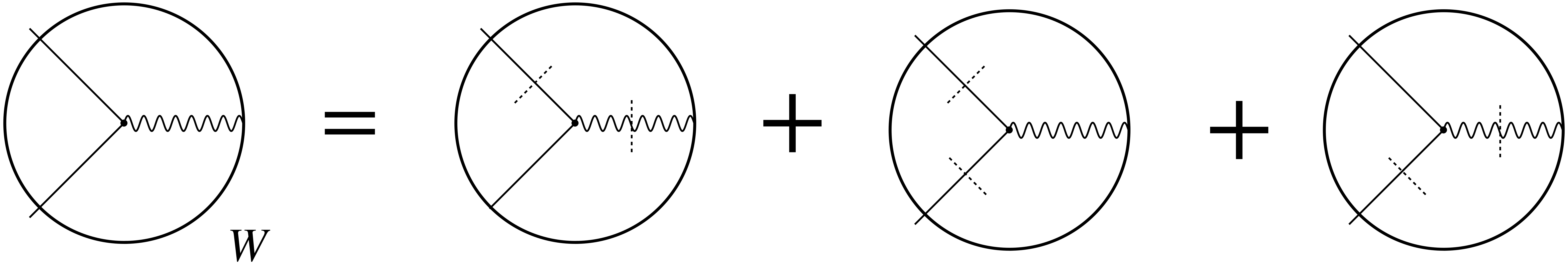
# One-point EC in AdS

*Three-point Wightman-Witten diagram*




***Schematically:***

$$G = -i\kappa \int d^5Z \sqrt{-g_{\mathrm{AdS}}} \Big[ + K_+^{(\Phi)}(X_1 - Z) K_+^{(h)}(X_2 - Z) K_F^{(\Phi)}(X_3 - Z) - K_+^{(\Phi)}(X_1 - Z) K_{\bar{F}}^{(h)}(X_2 - Z) K_-^{(\Phi)}(X_3 - Z) + K_F^{(\Phi)}(X_1 - Z) K_-^{(h)}(X_2 - Z) K_-^{(\Phi)}(X_3 - Z) \Big]$$

# One-point EC in AdS

*The detector limit induces a simplification*

D'Hoker & Freedman (2002)

$$G = -i\kappa \int d^5 Z \sqrt{-g_{\text{AdS}}} \Big[ + K_+^{(\Phi)}(X_1 - Z) K_+^{(h)}(X_2 - Z) K_F^{(\Phi)}(X_3 - Z)$$
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$$K_E(x, z; y) = \mathscr{C}_\Delta \left( \frac{z}{z^2 + (x-y)^2} \right)^\Delta$$

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$$\Big\downarrow \, \partial\,\mathrm{F.T.}$$

$$\tilde{K}_E(p, z) = \frac{2^{1-\nu}}{\Gamma(\nu)} z^{d/2} p^\nu K_\nu(pz)$$

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$$\Big\downarrow \ \text{Feynman}$$

$$\tilde{K}_F(p, z) = A_\nu z^{d/2} (p^2 + i\epsilon)^\nu K_\nu \left( z\sqrt{p^2 + i\epsilon} \right)$$

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**Wightman kernels are on-shell with support $\Theta(+k^2)\Theta(\pm k^0)$**

$$\tilde{K}^{\pm}(k, z) = \Theta(\pm k^0)\text{Disc } \tilde{K}_F(k, z) = B_\nu z^{d/2} \left(\sqrt{-k^2}\right)^\nu J_\nu\left(z\sqrt{-k^2}\right) \Theta(+k^2)\Theta(\pm k^0)$$

$\tilde{K}^+$ selects positive energy, $\tilde{K}^-$ selects negative energy; both require time-like momentum $k^2 > 0$

# One-point EC in AdS

*The detector limit selects the Feynman graviton leg*

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**The null detector projects the graviton momentum**

$$K^{\pm}_{MN|\mu\nu}(X;\hat{x}) = \int \frac{d^4k}{(2\pi)^4}\ e^{-\frac{i}{2}k^-(x^+-\hat{x}^+)}e^{-\frac{i}{2}k^+(x^--\hat{x}^-)}e^{i\vec{k}_\perp\cdot\vec{x}_\perp}\tilde{K}^{\pm}_{MN|\mu\nu}(k,z)$$

$$\int_{-\infty}^{+\infty} d\hat{x}^-\ e^{+\frac{i}{2}k^+\hat{x}^-} = 4\pi\delta(k^+) \quad \Longrightarrow \quad k^+ = 0$$

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$\tilde{K}^+$ selects positive energy, $\tilde{K}^-$ selects negative energy; both require time-like momentum $k^2 > 0$

**The null detector projects the graviton momentum**

$$K^{\pm}_{MN|\mu\nu}(X;\hat{x}) = \int \frac{d^4k}{(2\pi)^4}\ e^{-\frac{i}{2}k^-(x^+-\hat{x}^+)}e^{-\frac{i}{2}k^+(x^--\hat{x}^-)}e^{i\vec{k}_\perp\cdot\vec{x}_\perp}\tilde{K}^{\pm}_{MN|\mu\nu}(k,z)$$

$$\int_{-\infty}^{+\infty} d\hat{x}^-\ e^{+\frac{i}{2}k^+\hat{x}^-} = 4\pi\delta(k^+) \quad \Longrightarrow \quad k^+ = 0$$

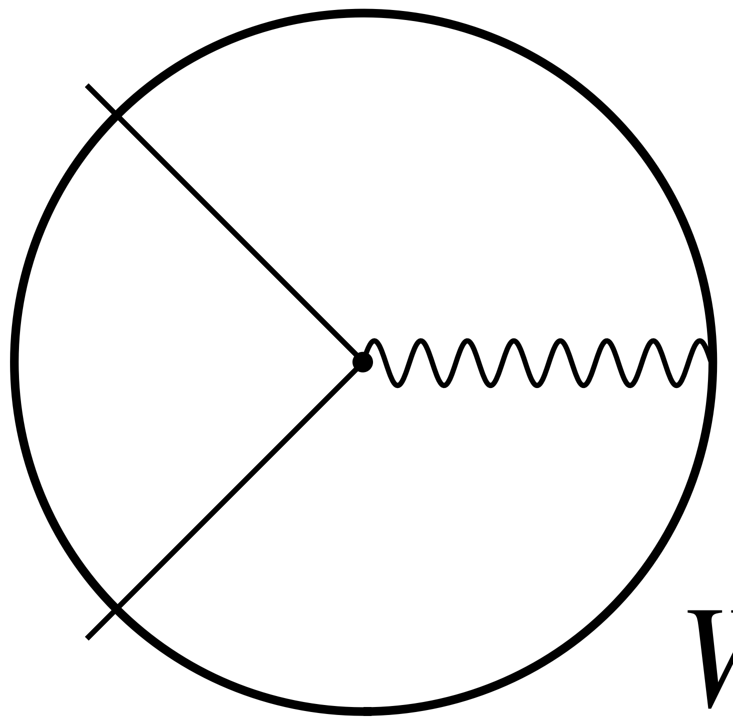
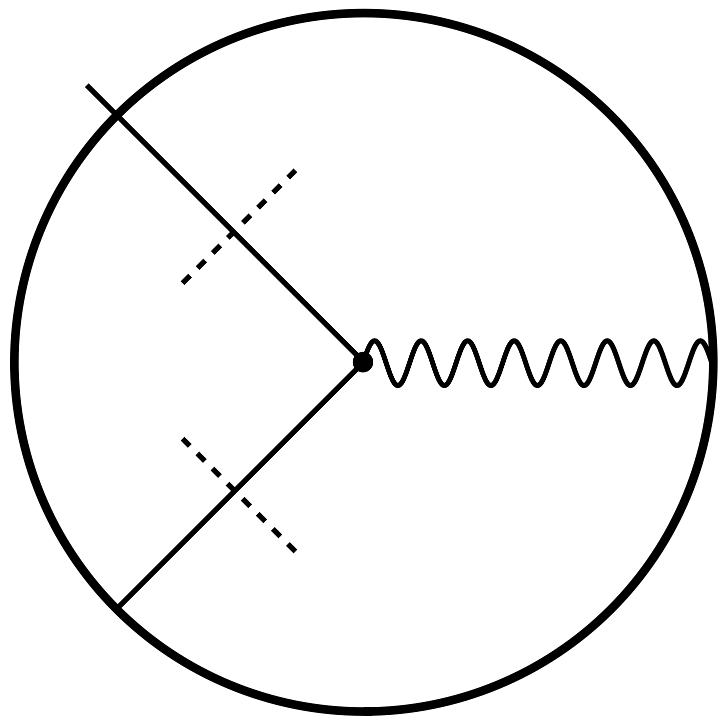
**Support test: only Feynman graviton survives**

$$k^2 = k^+k^- - |\vec{k}_\perp|^2 \ \to -|\vec{k}_\perp|^2: \qquad \Theta(+k^2) \to \Theta(-|\vec{k}_\perp|^2) = 0, \qquad \tilde{K}^{\pm}_{(h)} \to 0$$

# One-point EC in AdS

*The detector limit selects the Feynman graviton leg*

> ***Takeaway:*** the only terms surviving the detector time integral are those with (anti-)Feynman detector gravitons

$\int d\hat{x}^-$  $_W$ $= \int d\hat{x}^-$ 

# One-point EC in AdS

**Compact form for the one-point EC**

$$\langle \mathscr{E}(\hat{n}) \rangle = \mathcal{N} \frac{\kappa}{2} \int_0^\infty \frac{dz}{z^3} \int dx^+ dx^- d^2 x_\perp \mathfrak{D}_{\mu\nu}(X;\hat{n}) \partial^\mu \Phi^*_{\text{out}} \partial^\nu \Phi_{\text{in}}$$

***Detector kernel:***

$$\mathfrak{D}_{\mu\nu}(Z;\hat{n}) = \frac{1}{4} \lim_{\hat{x}^+ \to \infty} (\hat{x}^+)^2 \int_{-\infty}^{+\infty} d\hat{x}^- \; K^{(h)}_{\mu\nu|++,\bar{F}}(Z;\hat{x})$$

# One-point EC in AdS

*Compact form for the one-point EC*

$$\langle \mathcal{E}(\hat{n}) \rangle = \mathcal{N}\frac{\kappa}{2}\int_0^\infty \frac{dz}{z^3}\int dx^+ dx^- d^2x_\perp \mathfrak{D}_{\mu\nu}(X;\hat{n})\partial^\mu \Phi^*_{\text{out}}\partial^\nu \Phi_{\text{in}}$$

*Shockwave profile*
Hofman & Maldacena (2008)
Csáki & Ismail (2024)

***Detector kernel:***

$$\mathfrak{D}_{\mu\nu}(Z;\hat{n}) = \frac{1}{4}\lim_{\hat{x}^+\to\infty}(\hat{x}^+)^2\int_{-\infty}^{+\infty} d\hat{x}^-\; K^{(h)}_{\mu\nu|++,\bar{F}}(Z;\hat{x}) = \frac{1}{\pi}\lim_{\hat{x}^+\to\infty}(\hat{x}^+)^2\delta(x^+-\hat{x}^+)\boxed{\frac{z^4}{(\rho^2+z^2)^3}}\,\eta_{\mu+}\eta_{\nu+}$$

# One-point EC in AdS

**Compact form for the one-point EC**

$$\langle \mathcal{E}(\hat{n}) \rangle = \mathcal{N} \frac{\kappa}{2} \int_0^\infty \frac{dz}{z^3} \int dx^+ dx^- d^2 x_\perp \mathfrak{D}_{\mu\nu}(X; \hat{n}) \partial^\mu \Phi^*_{\text{out}} \partial^\nu \Phi_{\text{in}}$$

**Shockwave profile**

Hofman & Maldacena (2008)

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**Detector kernel:**

$$\mathfrak{D}_{\mu\nu}(Z; \hat{n}) = \frac{1}{4} \lim_{\hat{x}^+ \to \infty} (\hat{x}^+)^2 \int_{-\infty}^{+\infty} d\hat{x}^- \; K^{(h)}_{\mu\nu|++, \bar{F}}(Z; \hat{x}) = \frac{1}{\pi} \lim_{\hat{x}^+ \to \infty} (\hat{x}^+)^2 \delta(x^+ - \hat{x}^+) \boxed{\frac{z^4}{(\rho^2 + z^2)^3}} \eta_{\mu +} \eta_{\nu +}$$

**Outgoing scalar source:** $$\Phi^*_{\text{out}}(z, x) = \int \frac{d^4 p}{(2\pi)^4} \; e^{ip \cdot x} K^+(p, z) \tilde{f}^*(q - p)$$

$$\tilde{f}(q) = \pi^2 \xi^4 \exp\left( -\frac{\xi^2}{4} q_E^2 \right)$$

**Incoming scalar source:** $$\Phi_{\text{in}}(z, x) = \int \frac{d^4 p'}{(2\pi)^4} \; e^{ip' \cdot x} K^-(p', z) \tilde{f}(p' + q)$$

# One-point EC in AdS

*Final result and physical picture*

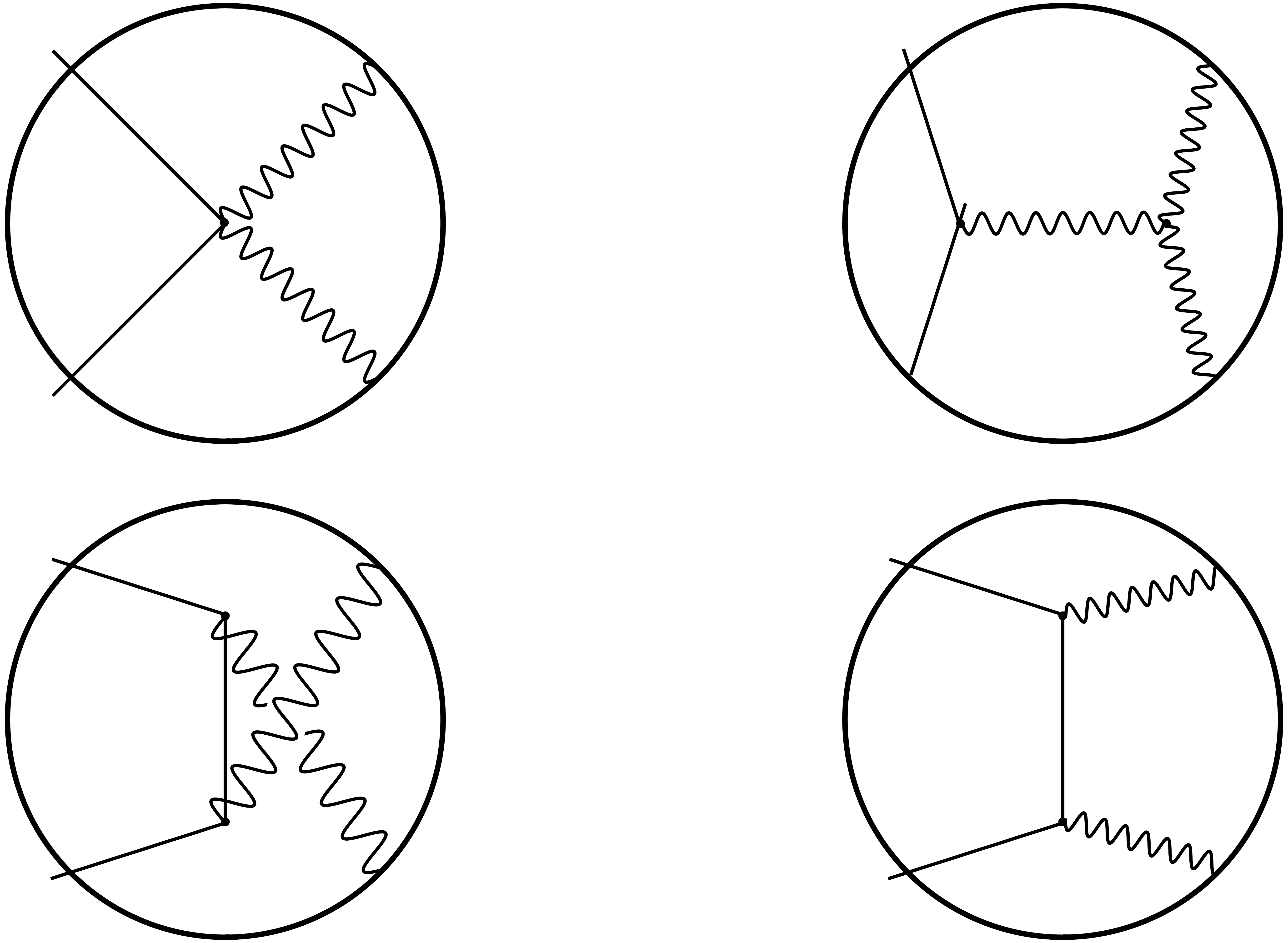
$$\langle \mathscr{E}(\hat{n}) \rangle = \frac{E}{4\pi} + O\left(\frac{1}{\xi}\right)$$

In AdS the detector limit $\hat{x}^+ \to \infty$ makes the detector probe $z \to \infty$

At large $z$ the excitation looks infinitely large, so the one-point EC is isotropic

**Physical picture:** in AdS the detector effectively samples arbitrarily large radial scales, so the state appears infinitely spread ($R \sim z$) and the energy flow is uniform: there is no need to point at the detector

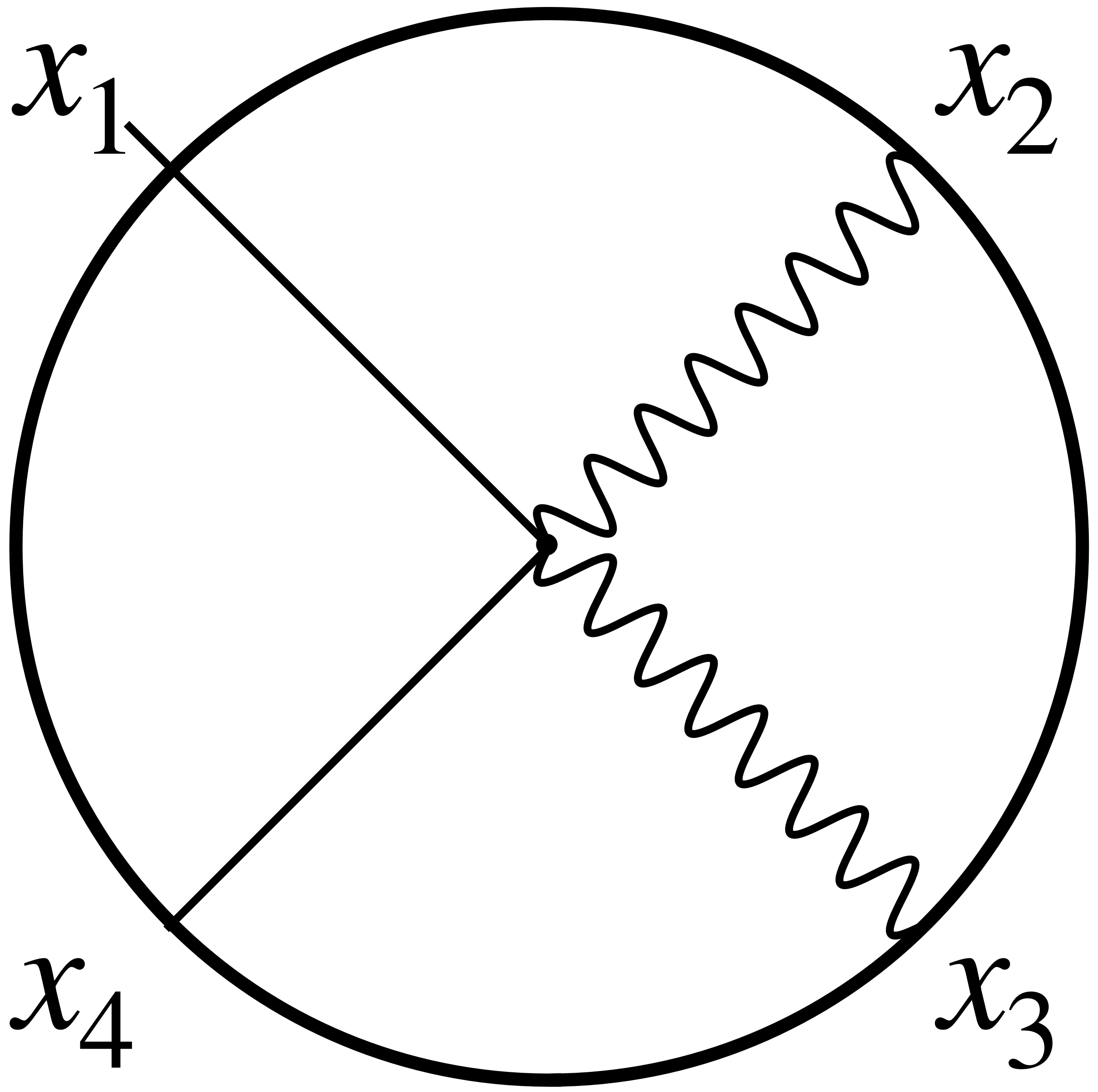
# Two-point EC in AdS



Bulk interactions at our disposal for the 2-point energy correlator:

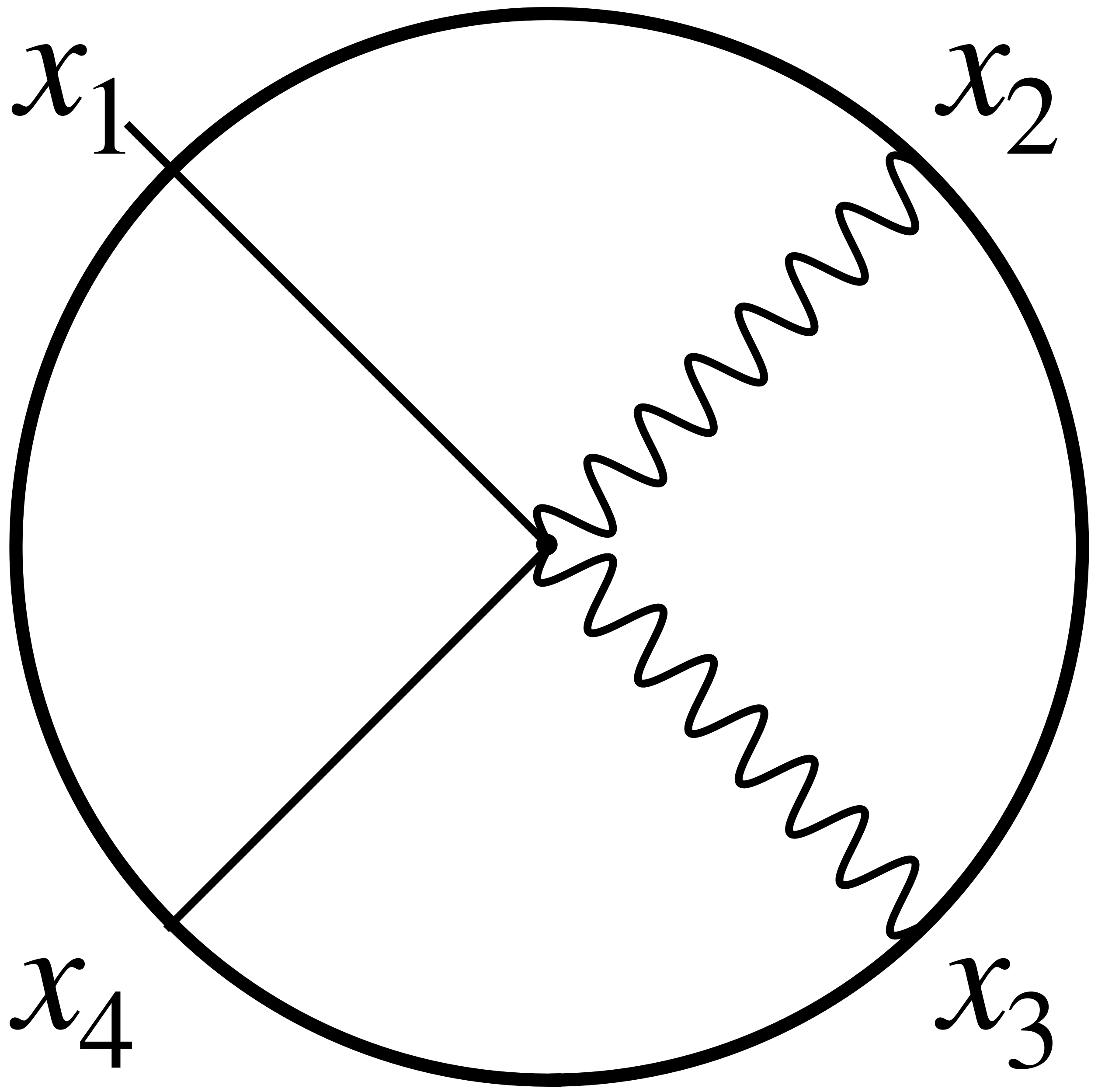
$h\Phi^2$, $h^2\Phi^2$ and $h^3$

# Two-points EC in AdS



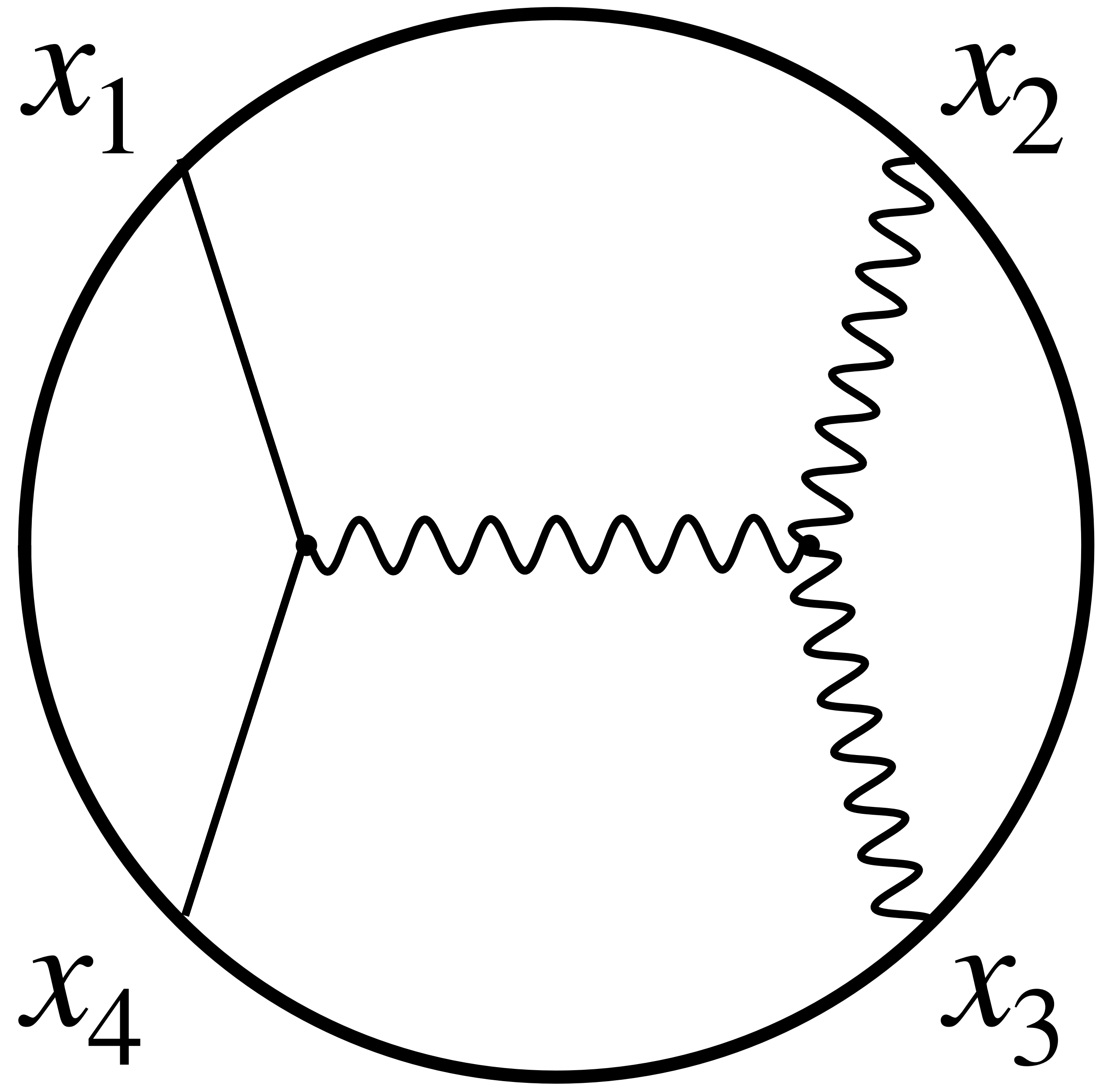

$$
\begin{aligned}
&+\Delta_1^+(Y)\Delta_2^+(Y)\Delta_3^+(Y)\Delta_{4,F}(Y)\\
&-\Delta_1^+(Y)\Delta_2^+(Y)\Delta_{3,\bar{F}}(Y)\Delta_4^-(4Y)\\
&+\Delta_1^+(Y)\Delta_{2,F}(Y)\Delta_3^-(Y)\Delta_4^-(Y)\\
&-\Delta_{1,\bar{F}}(Y)\Delta_2^-(Y)\Delta_3^-(Y)\Delta_4^-(Y)
\end{aligned}
$$

# Two-points EC in AdS




$$\int d\hat{x}_2^- \, d\hat{x}_3^- \begin{array}{l} \cancel{+\Delta_1^+(Y)\Delta_2^+(Y)\Delta_3^+(Y)\Delta_{4,F}(Y)} \to 0 \\ \cancel{-\Delta_1^+(Y)\Delta_2^+(Y)\Delta_{3,\bar{F}}(Y)\Delta_4^-(4Y)} \to 0 \\ \cancel{+\Delta_1^+(Y)\Delta_{2,F}(Y)\Delta_3^-(Y)\Delta_4^-(Y)} \to 0 \\ \cancel{-\Delta_{1,\bar{F}}(Y)\Delta_2^-(Y)\Delta_3^-(Y)\Delta_4^-(Y)} \to 0 \end{array}$$

# Two-points EC in AdS



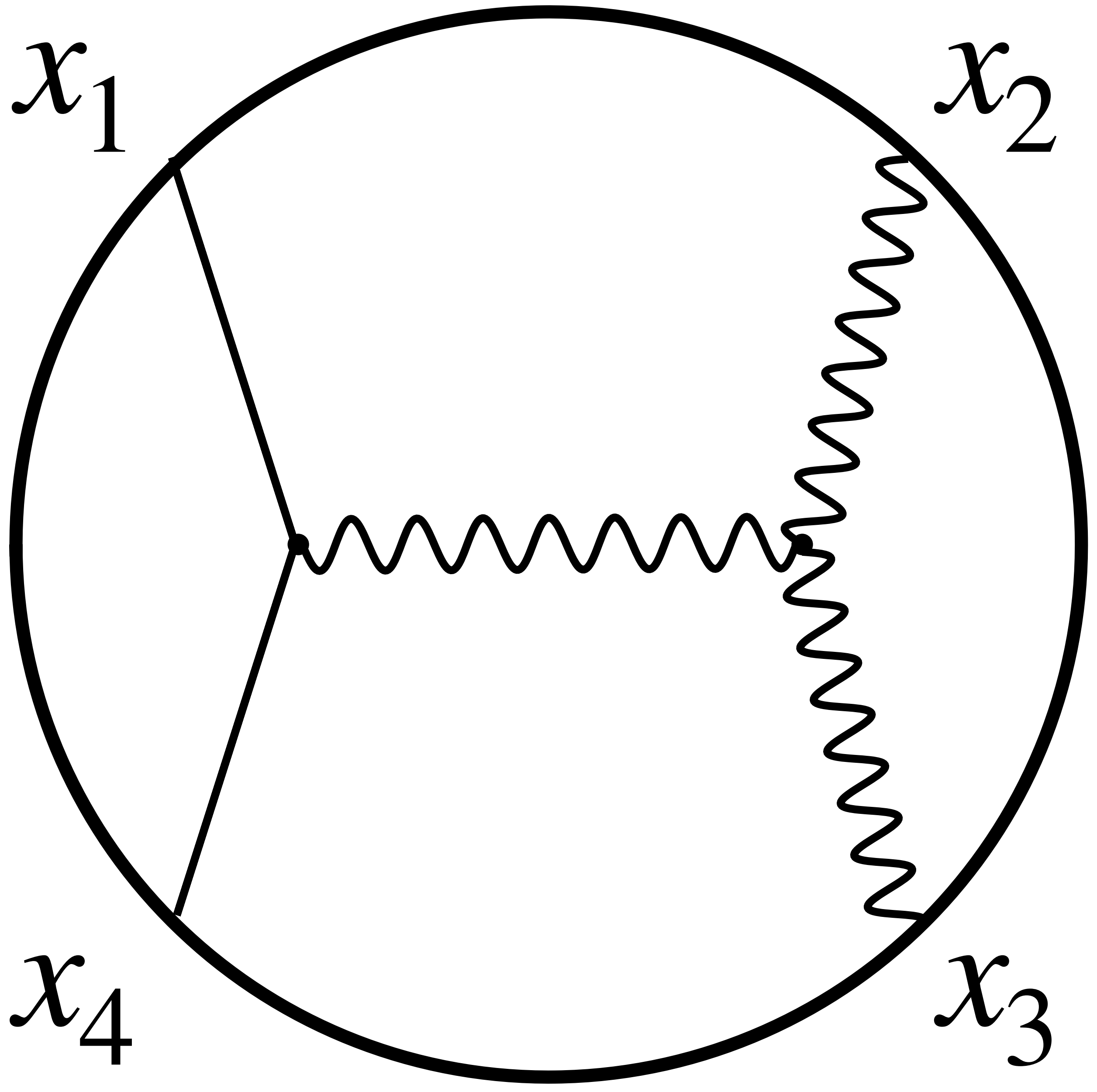

Off-diagonal pieces ($\tau_Y \neq \tau_Z$)

$$
\begin{aligned}
&-\Delta_{1,F}(Y)\Delta_4^-(Y)D_+(Y,Z)\Delta_{2,\bar{F}}(Z)\Delta_3^-(Z)\\
&+\Delta_{1,F}(Y)\Delta_4^-(Y)D_+(Y,Z)\Delta_2^+(Z)\Delta_{3,F}(Z)\\
&+\Delta_1^+(Y)\Delta_{4,F}(Y)D_-(Y,Z)\Delta_{2,F}(Z)\Delta_3^-(Z)\\
&-\Delta_1^+(Y)\Delta_{4,F}(Y)D_-(Y,Z)\Delta_2^+(Z)\Delta_{3,\bar{F}}(Z)
\end{aligned}
$$

Diagonal pieces ($\tau_Y = \tau_Z$)

$$
\begin{aligned}
&-\Delta_{1,\bar{F}}(Y)D_F(Y,Z)\Delta_2^-(Z)\Delta_3^-(Z)\Delta_4^-(Y)\\
&+\Delta_1^+(Y)D_{\bar{F}}(Y,Z)\Delta_{2,\bar{F}}(Z)\Delta_3^-(Z)\Delta_4^-(Y)\\
&-\Delta_1^+(Y)D_{\bar{F}}(Y,Z)\Delta_2^+(Z)\Delta_{3,F}(Z)\Delta_4^-(Y)\\
&+\Delta_1^+(Y)D_F(Y,Z)\Delta_2^+(Z)\Delta_3^+(Z)\Delta_{4,F}(Y)
\end{aligned}
$$

# Two-points EC in AdS



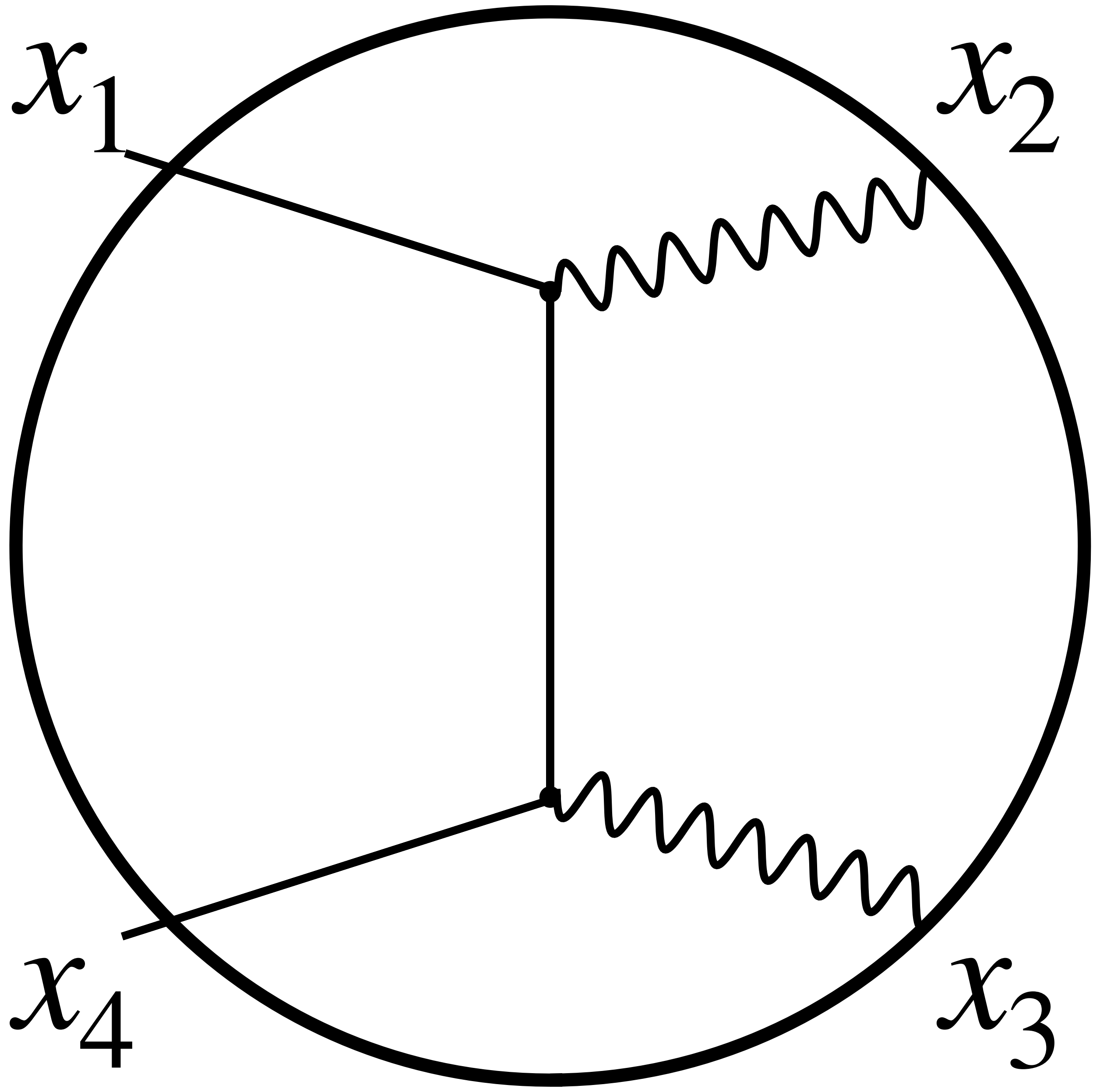

Off-diagonal pieces ($\tau_Y \neq \tau_Z$)

$$\int d\hat{x}_2^- \, d\hat{x}_3^- \quad \begin{aligned} &\cancel{-\Delta_{1,F}(Y)\Delta_4^-(Y)D_+(Y,Z)\Delta_{2,F}(Z)\Delta_3^-(Z)} \to 0 \\ &\cancel{+\Delta_{1,F}(Y)\Delta_4^-(Y)D_+(Y,Z)\Delta_2^+(Z)\Delta_{3,F}(Z)} \to 0 \\ &\cancel{+\Delta_1^+(Y)\Delta_{4,F}(Y)D_-(Y,Z)\Delta_{2,F}(Z)\Delta_3^-(Z)} \to 0 \\ &\cancel{-\Delta_1^+(Y)\Delta_{4,F}(Y)D_-(Y,Z)\Delta_2^+(Z)\Delta_{3,F}(Z)} \to 0 \end{aligned}$$

Diagonal pieces ($\tau_Y = \tau_Z$)

$$\int d\hat{x}_2^- \, d\hat{x}_3^- \quad \begin{aligned} &\cancel{-\Delta_{1,F}(Y)D_F(Y,Z)\Delta_2^-(Z)\Delta_3^-(Z)\Delta_4^-(Y)} \to 0 \\ &\cancel{+\Delta_1^+(Y)D_F(Y,Z)\Delta_{2,F}(Z)\Delta_3^-(Z)\Delta_4^-(Y)} \to 0 \\ &\cancel{-\Delta_1^+(Y)D_F(Y,Z)\Delta_2^+(Z)\Delta_{3,F}(Z)\Delta_4^-(Y)} \to 0 \\ &\cancel{+\Delta_1^+(Y)D_F(Y,Z)\Delta_2^+(Z)\Delta_3^+(Z)\Delta_{4,F}(Y)} \to 0 \end{aligned}$$

# Two-points EC in AdS



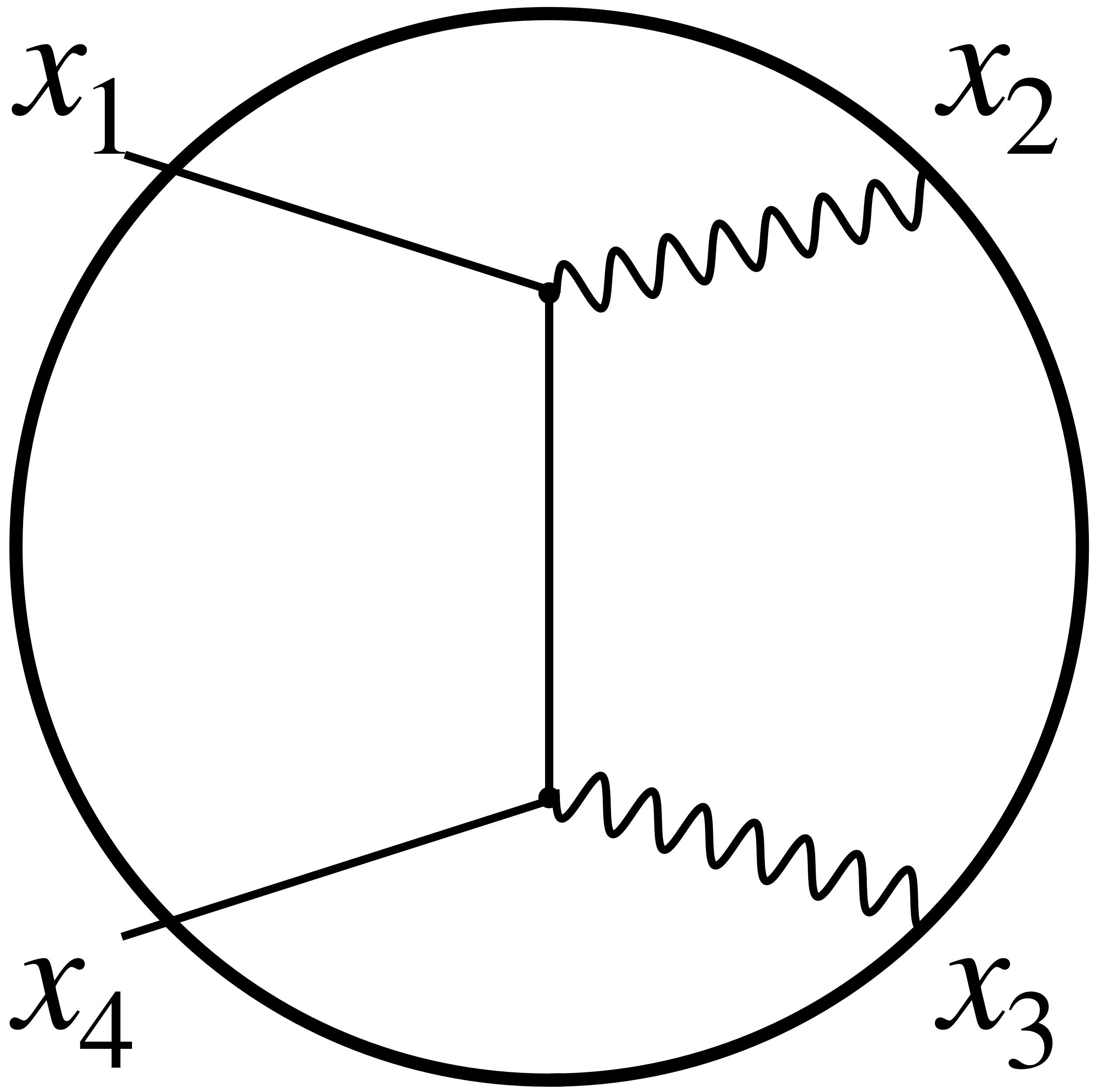

Off-diagonal pieces ($\tau_Y \neq \tau_Z$)

$$
\begin{aligned}
&+\Delta_{1,F}(Y)\Delta_2^-(Y)D_+(Y,Z)\Delta_3^+(Z)\Delta_{4,F}(Z)\\
&-\Delta_{1,F}(Y)\Delta_2^-(Y)D_+(Y,Z)\Delta_{3,\bar{F}}(Z)\Delta_4^-(Z)\\
&-\Delta_1^+(Y)\Delta_{2,\bar{F}}(Y)D_+(Y,Z)\Delta_3^+(Z)\Delta_{4,F}(Z)\\
&+\Delta_1^+(Y)\Delta_{2,\bar{F}}(Y)D_+(Y,Z)\Delta_{3,\bar{F}}(Z)\Delta_4^-(Z)
\end{aligned}
$$

Diagonal pieces ($\tau_Y = \tau_Z$)

$$
\begin{aligned}
&-\Delta_{1,\bar{F}}(Y)\Delta_2^-(Y)D_F(Y,Z)\Delta_3^-(Z)\Delta_4^-(Z)\\
&+\Delta_1^+(Y)\Delta_{2,F}(Y)D_F(Y,Z)\Delta_3^-(Z)\Delta_4^-(Z)\\
&-\Delta_1^+(Y)\Delta_2^+(Y)D_F(Y,Z)\Delta_{3,\bar{F}}(Z)\Delta_4^-(Z)\\
&+\Delta_1^+(Y)\Delta_2^+(Y)D_F(Y,Z)\Delta_3^+(Z)\Delta_{4,F}(Z)
\end{aligned}
$$

# Two-points EC in AdS



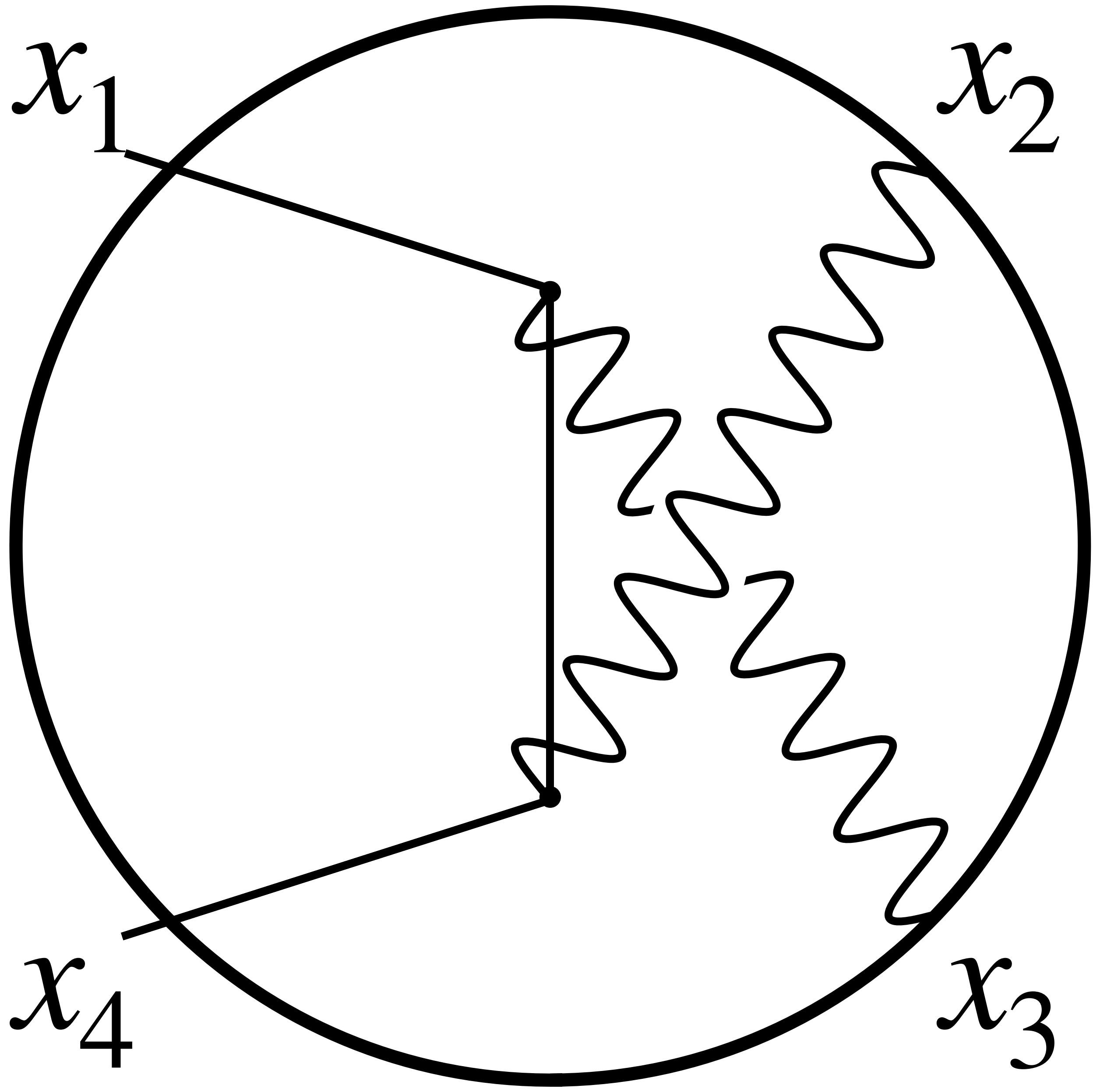

Off-diagonal pieces ($\tau_Y \neq \tau_Z$)

$$\int d\hat{x}_2^- \, d\hat{x}_3^- \quad \begin{aligned} &\cancel{+\Delta_{1,F}(Y)\Delta_2^-(Y)D_+(Y,Z)\Delta_3^+(Z)\Delta_{4,F}(Z)} \to 0 \\ &\cancel{-\Delta_{1,F}(Y)\Delta_2^-(Y)D_+(Y,Z)\Delta_{3,F}(Z)\Delta_4^-(Z)} \to 0 \\ &\cancel{-\Delta_1^+(Y)\Delta_{2,F}(Y)D_+(Y,Z)\Delta_3^+(Z)\Delta_{4,F}(Z)} \to 0 \\ &+\Delta_1^+(Y)\Delta_{2,\bar{F}}(Y)D_+(Y,Z)\Delta_{3,\bar{F}}(Z)\Delta_4^-(Z) \end{aligned}$$

Diagonal pieces ($\tau_Y = \tau_Z$)

$$\int d\hat{x}_2^- \, d\hat{x}_3^- \quad \begin{aligned} &\cancel{-\Delta_{1,F}(Y)\Delta_2^-(Y)D_F(Y,Z)\Delta_3^-(Z)\Delta_4^-(Z)} \to 0 \\ &\cancel{+\Delta_1^+(Y)\Delta_{2,F}(Y)D_F(Y,Z)\Delta_3^-(Z)\Delta_4^-(Z)} \to 0 \\ &\cancel{-\Delta_1^+(Y)\Delta_2^+(Y)D_F(Y,Z)\Delta_{3,\bar{F}}(Z)\Delta_4^-(Z)} \to 0 \\ &\cancel{+\Delta_1^+(Y)\Delta_2^+(Y)D_F(Y,Z)\Delta_3^+(Z)\Delta_{4,F}(Z)} \to 0 \end{aligned}$$

# Two-points EC in AdS



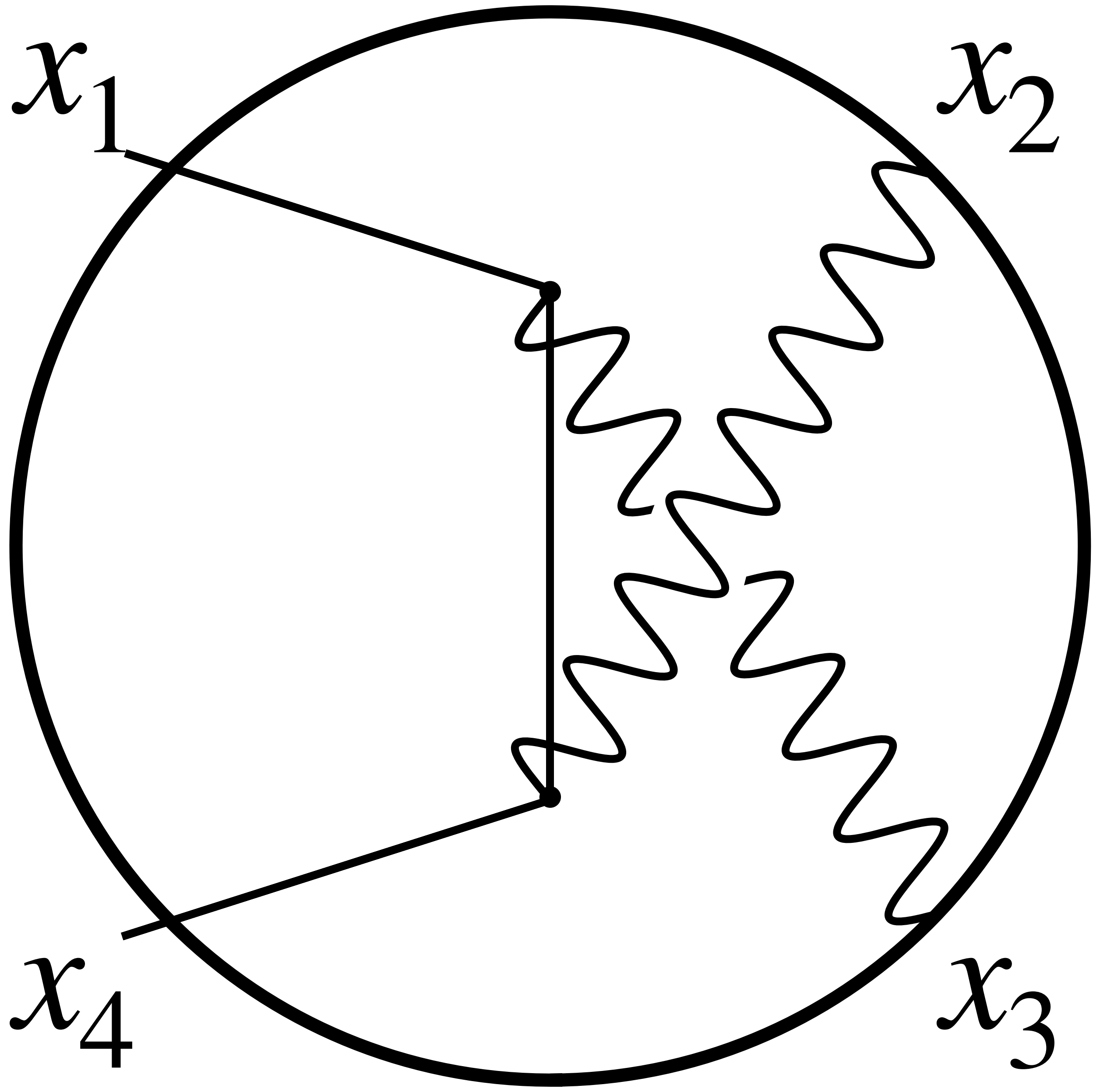

Off-diagonal pieces ($\tau_Y \neq \tau_Z$)

$$
\begin{aligned}
&-\Delta_{1,F}(Y)\Delta_3^-(Y)D_+(Y,Z)\Delta_{2,\bar{F}}(Z)\Delta_4^-(Z)\\
&+\Delta_{1,F}(Y)\Delta_3^-(Y)D_+(Y,Z)\Delta_2^+(Z)\Delta_{4,F}(Z)\\
&-\Delta_1^+(Y)\Delta_{3,\bar{F}}(Y)D_+(Y,Z)\Delta_2^+(Z)\Delta_{4,F}(Z)\\
&+\Delta_1^+(Y)\Delta_{3,F}(Y)D_-(Y,Z)\Delta_{2,F}(Z)\Delta_4^-(Z)
\end{aligned}
$$

Diagonal pieces ($\tau_Y = \tau_Z$)

$$
\begin{aligned}
&-\Delta_{1,\bar{F}}(Y)D_F(Y,Z)\Delta_2^-(Z)\Delta_3^-(Y)\Delta_4^-(Z)\\
&+\Delta_1^+(Y)D_{\bar{F}}(Y,Z)\Delta_{2,\bar{F}}(Z)\Delta_3^-(Y)\Delta_4^-(Z)\\
&-\Delta_1^+(Y)D_{\bar{F}}(Y,Z)\Delta_2^+(Z)\Delta_{3,F}(Y)\Delta_4^-(Z)\\
&+\Delta_1^+(Y)D_F(Y,Z)\Delta_2^+(Z)\Delta_3^+(Y)\Delta_{4,F}(Z)
\end{aligned}
$$

# Two-points EC in AdS




Off-diagonal pieces ($\tau_Y \neq \tau_Z$)

$$\int d\hat{x}_2^- \, d\hat{x}_3^-$$

$$\cancel{-\Delta_{1,F}(Y)\Delta_3^-(Y)D_+(Y,Z)\Delta_{2,F}(Z)\Delta_4^-(Z)} \to 0$$
$$\cancel{+\Delta_{1,F}(Y)\Delta_3^-(Y)D_+(Y,Z)\Delta_2^+(Z)\Delta_{4,F}(Z)} \to 0$$
$$\cancel{-\Delta_1^+(Y)\Delta_{3,F}(Y)D_+(Y,Z)\Delta_2^+(Z)\Delta_{4,F}(Z)} \to 0$$
$$\boxed{+\Delta_1^+(Y)\Delta_{3,F}(Y)D_-(Y,Z)\Delta_{2,F}(Z)\Delta_4^-(Z)}$$

Diagonal pieces ($\tau_Y = \tau_Z$)

$$\int d\hat{x}_2^- \, d\hat{x}_3^-$$

$$\cancel{-\Delta_{1,F}(Y)D_F(Y,Z)\Delta_2^-(Z)\Delta_3^-(Y)\Delta_4^-(Z)} \to 0$$
$$\cancel{+\Delta_1^+(Y)D_F(Y,Z)\Delta_{2,F}(Z)\Delta_3^-(Y)\Delta_4^-(Z)} \to 0$$
$$\cancel{-\Delta_1^+(Y)D_{\bar{F}}(Y,Z)\Delta_2^+(Z)\Delta_{3,F}(Y)\Delta_4^-(Z)} \to 0$$
$$\cancel{+\Delta_1^+(Y)D_F(Y,Z)\Delta_2^+(Z)\Delta_3^+(Y)\Delta_{4,F}(Z)} \to 0$$

# Two-points EC in AdS

*The detector limit induces a huge simplification for the two-point*

**1. Kills entire topologies**

The detector time integrals kill the contact diagram and the $s$-channel, so no need to keep track of the $h^3$ and $h^2\Phi^2$ couplings

**2. Eliminates almost all terms**

The detector time integrals eliminate almost all terms in the Wightman decomposition

**3. Only two terms survive**

Only two terms remain, coming from the $t$- and $u$-channel diagrams

**4. Final selection rule from the detector limit**

The last selection rule comes from the $\hat{x}^+_{2,3} \to \infty$ detector limit, which kills the remaining $u$-channel contribution

***Takeaway:*** We have simplified a computation that was believed to be extremely complicated to realize, all that through a simple organizing principle coming from both the Wightman decomposition and the detector limits

# N-points EC in AdS

*From the rules derived we know the N-point*

To compute the $N$-point energy correlator we need the following couplings

$$h^m, \; m = 3, \ldots, N+1 \qquad\qquad \Phi^2 h^n, \; n = 1, \ldots, N$$

Using the same selection rules we find that a single diagram survives

# What about RS1?

*Use the standard calorimeter*

In RS1 we use the standard calorimeter, sensitive to **both null and time-like radiation**

$$\mathcal{E}(\hat{n}) = \lim_{r\to\infty} r^2 \int_{-\infty}^{+\infty} dt\ \hat{n}_i T^{0i}(t, r\hat{n})$$

From which we construct the detector kernel

$$\mathfrak{D}^{\text{std}}_{\mu\nu}(X, \hat{x}) = \lim_{r\to\infty} r^2 \int_{-\infty}^{+\infty} dt\ \hat{n}^i\, K^{(h)}_{\mu\nu|0i}(X; \hat{x})$$

This is the **RS1 building block** that replaces the null-detector kernel used in AdS

# What about RS1?

*The building blocks (detector kernel, scalar sources…)*

**Feynman graviton bulk-to-boundary propagator**

$$K^{(h),\,\mathrm{RS1}}_{MN|\alpha\beta,\,F}(k;z) = \frac{q^2 z^2}{2}\mathscr{B}_{\mathrm{RS1}}(q,z)\Pi^{\mathrm{TS}}_{MN|\alpha\beta}$$

**RS1 radial profile**

$$\mathscr{B}_{\mathrm{RS1}}(q,z) = K_2(qz) + \frac{K_1(qz_{\mathrm{IR}})}{I_1(qz_{\mathrm{IR}})}I_2(qz)$$

The detector time integral produces $2\pi\,\delta(k^0)$

**Standard detector kernel**

$$\mathfrak{D}^{\mathrm{RS1}}_{MN}(X;\hat{n}) = P_{MN}(\hat{n})\lim_{r\to\infty} r^2 \frac{1}{4\pi^2|\vec{x} - r\hat{n}|}\int_0^\infty dq\; q^3 \sin(q|\vec{x} - r\hat{n}|)\mathscr{B}_{\mathrm{RS1}}(q,z)$$

# What about RS1?

*The building blocks (detector kernel, scalar sources…)*

$$\langle \mathcal{E}(\hat{n})\rangle_{\mathrm{RS1}} = \mathcal{N}\frac{i\kappa}{2}\int_{z_{\mathrm{UV}}}^{z_{\mathrm{IR}}} \frac{dz\, d^4x}{z^3}\, \mathfrak{D}^{\mathrm{RS1}}_{MN}(X;\hat{n}) V^{MN}\left[\Phi^{\mathrm{RS1}\,*}_{\mathrm{out}}(X), \Phi^{\mathrm{RS1}}_{\mathrm{in}}(X)\right]$$

***Detector kernel:***

$$\mathfrak{D}^{\mathrm{RS1}}_{MN}(X;\hat{n}) = P_{MN}(\hat{n}) \lim_{r\to\infty} r^2 \frac{1}{4\pi^2|\vec{x}-r\hat{n}|}\int_0^\infty dq\; q^3 \sin(q|\vec{x}-r\hat{n}|)\left[K_2(qz) + \frac{K_1(qz_{\mathrm{IR}})}{I_1(qz_{\mathrm{IR}})} I_2(qz)\right]$$

***Outgoing scalar source:*** $\Phi^*_{\mathrm{out}}(z,x) = \int \frac{d^4p}{(2\pi)^4}\; e^{ip\cdot x} K^+(p,z)\tilde{f}^*(q-p)$

***~ RS1 shockwave profile***

Csáki & Ismail (2024)

***Incoming scalar source:*** $\Phi_{\mathrm{in}}(z,x) = \int \frac{d^4p'}{(2\pi)^4}\; e^{ip'\cdot x} K^-(p',z)\tilde{f}(p'+q)$

# What about RS1?

*The building blocks (detector kernel, scalar sources…)*

1. Wightman kernels from the discontinuity: $\tilde{K}_\pm(k,z) = \Theta(\pm k^0)\,\mathrm{Disc}\;\tilde{K}_F(k,z)$

2. Feynman kernel: KK pole expansion

$$\tilde{K}_F(p,z) = \sum_a \frac{R_a(z)}{p^2 - m_a^2 + i\epsilon}$$

3. Resulting KK representation of the Wightman kernels

$$\tilde{K}_\pm(p,z) = 2\pi i \sum_a R_a(z)\Theta(\pm p^0)\delta(p^2 + m_a^2) = 2\pi i \sum_a \frac{R_a(z)}{2E_{a,p}}\delta(p^0 \mp E_{a,p})$$

Natural representation for the RS1 scalar sources

# What about RS1?

*The one-point EC in RS1*

$$\langle \mathcal{E}(\hat{n}) \rangle_{\mathrm{RS1}} = \sum_a E_a \delta^{(2)}(\hat{n} - \hat{p}_a)$$

- RS1 has an IR brane/mass gap, so the outgoing object has finite size, $R \sim z_{\mathrm{IR}}$
- Unlike exact AdS, the detector does not probe an infinitely spread object
- The detector registers energy only when the particle momentum points at it: $\hat{n} = \hat{p}_a$

# What about RS1?

*The two-point EC in RS1*

$$\langle \mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)\rangle_{\mathrm{RS1}} = E_p^2 \delta^{(2)}(\hat{n}_1 - \hat{p})\delta^{(2)}(\hat{n}_2 - \hat{p})$$

At leading large $N$, RS1 gives free stable KK calorimetry, not a smooth EEC

# Conclusion

## *What we have achieved*

- Built a **QFT-based Wightman-Witten formalism** for energy correlators
- Start from **Euclidean Witten diagrams**, then analytically continue propagators to Wightman order
- Detector limits become **selection rules**, drastically simplifying the calculation
- The shockwave emerges as the **detector graviton bulk-to-boundary kernel**
- Smearing is incorporated naturally, giving normalizable states and a controllable calculation
- Applied to **AdS and RS1**, including one- and two-point energy correlators
- Flexible framework for deformations beyond exact AdS

# Obrigado :)