Holographic Correlators for all Λs

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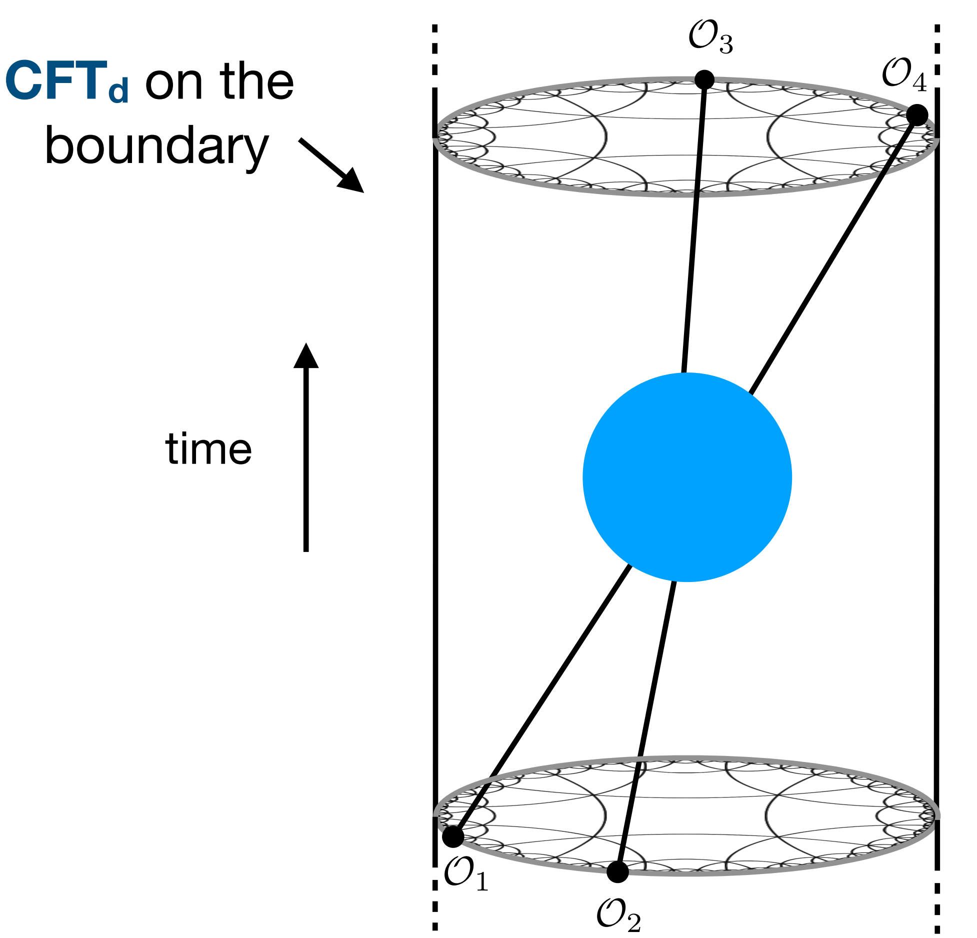
AdS-CFT

Quantum Gravity in AdS_{d+1}	=	(non-gravitational) CFT in $\mathbb{M}^d$

Observables ?! ⟷ **Correlation functions**



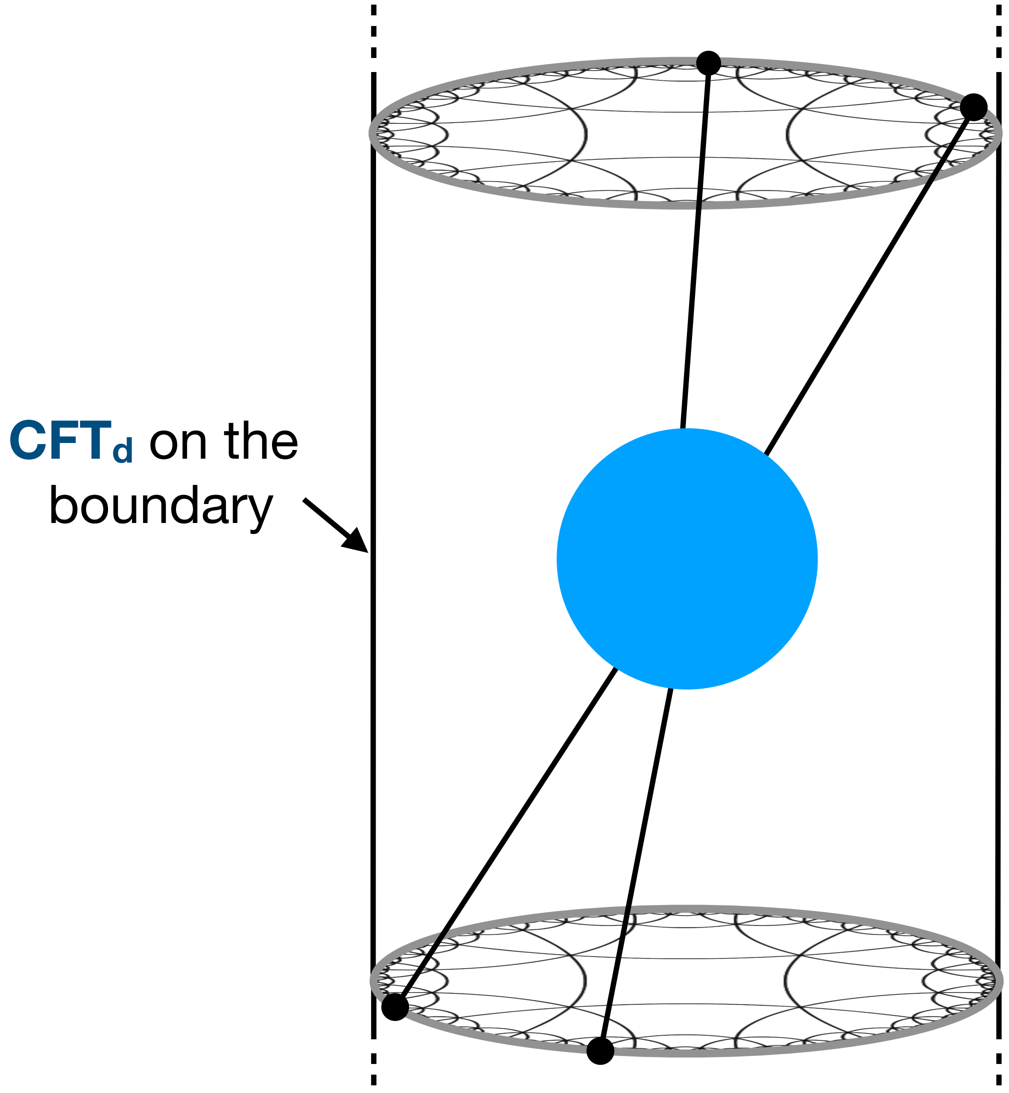
Constrained non-perturbatively by the Conformal Bootstrap:

- Conformal symmetry
- Unitarity
- Associative OPE

$$(\mathcal{O}_1\mathcal{O}_2)\,\mathcal{O}_3 = \mathcal{O}_1\,(\mathcal{O}_2\mathcal{O}_3)$$

[Belavin, Polyakov, Zamolodchikov 1984; Rattazzi, Rychkov, Tonni, Vichi 2008]

AdS-CFT



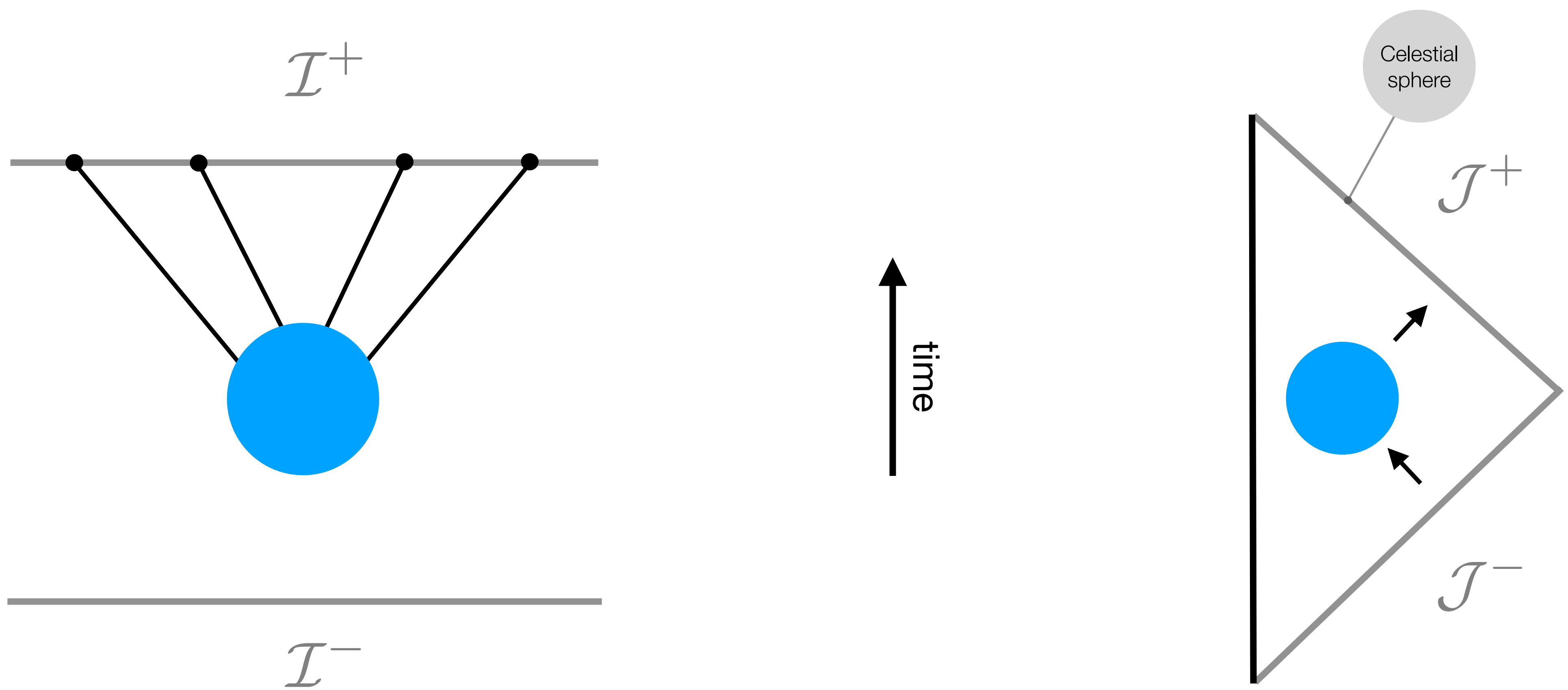
Can we extend this understanding to our own universe?

Holography for all Λs?

The maximally symmetric cousins of AdS

$\Lambda > 0$ de Sitter

$\Lambda = 0$ Minkowski



- Cosmological scales
- Primordial inflation

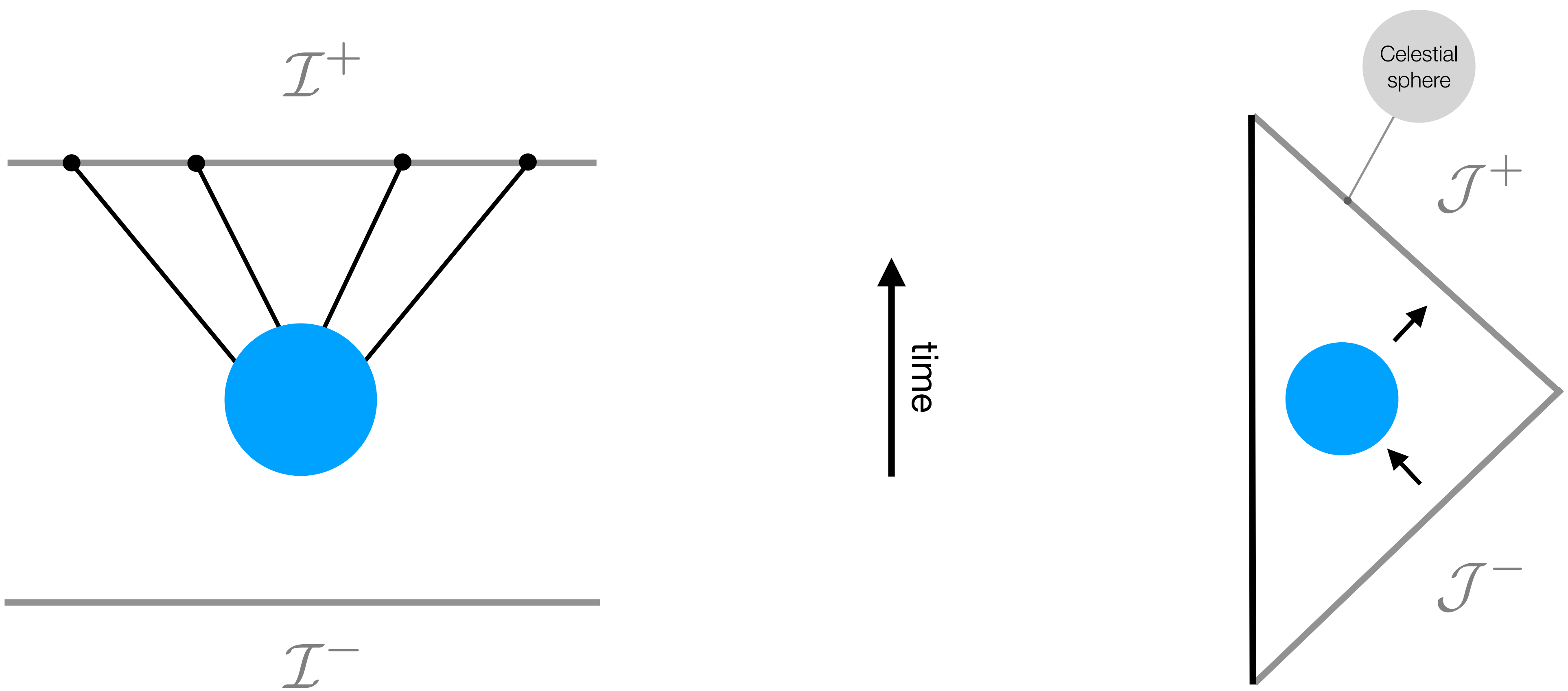
- intermediate scales

Holography for all Λs?

The maximally symmetric cousins of AdS

$\Lambda > 0$ de Sitter

$\Lambda = 0$ Minkowski



Cosmological Bootstrap

[Arkani-Hamed and Maldacena ’15]

[Arkani-Hamed and Benincasa ’17]

[Arkani-Hamed, Baumann, Lee and Pimentel ’18]

[Sleight and Taronna ’19] [Pajer et al ’20] […]

Celestial holography

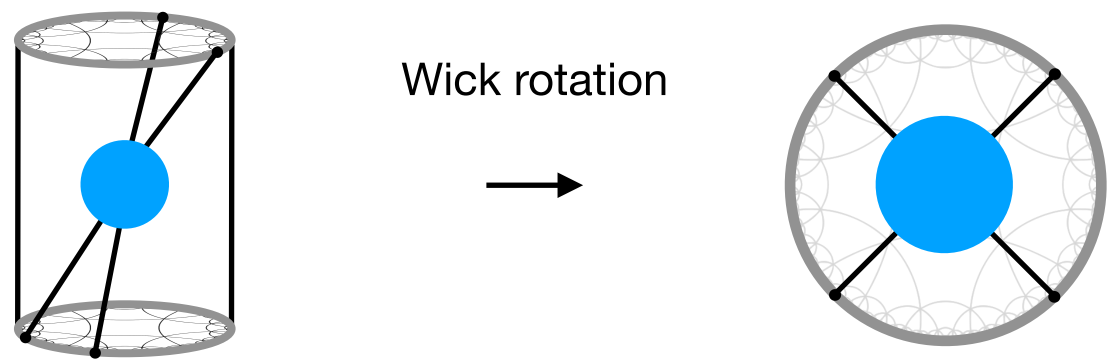
[de Boer and Solodukhin '03]

[Strominger ’17] [Pasterski, Shao, Strominger ’17]

[Pasterski, Shao ’17] […]

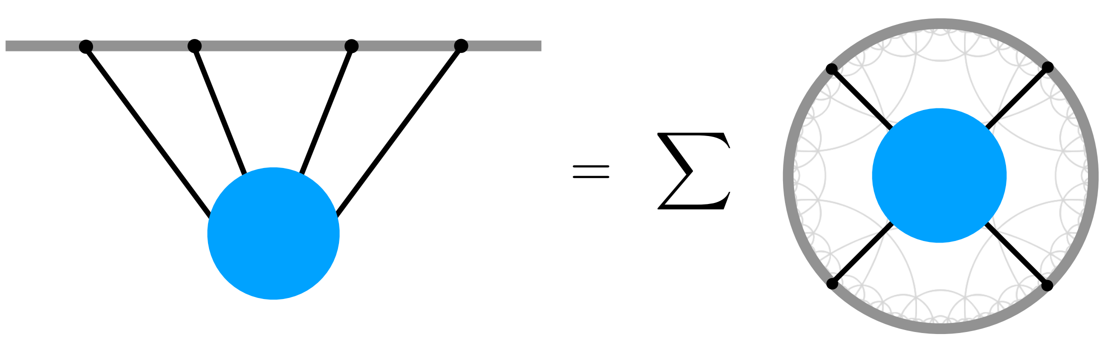
Holography for all Λs?

Boundary correlators in AdS, dS and on the celestial sphere can be reformulated as boundary correlators in Euclidean AdS:



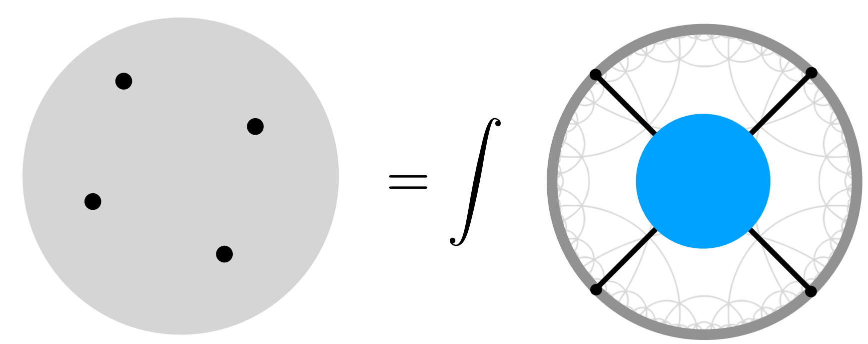
$\Lambda < 0$

Perturbatively:



$\Lambda > 0$

[C.S. & Taronna '19, '20, '21]



$\Lambda = 0$

[Iacobacci, C.S. & Taronna '22]
[C.S. & Taronna '23]

dS and Celestial correlators therefore have a similar analytic structure to their EAdS counterparts!
On a practical level, can use such identities to import techniques and understanding from AdS.

Outline

I. $\Lambda > 0$

II. $\Lambda = 0$

III. Some Applications.

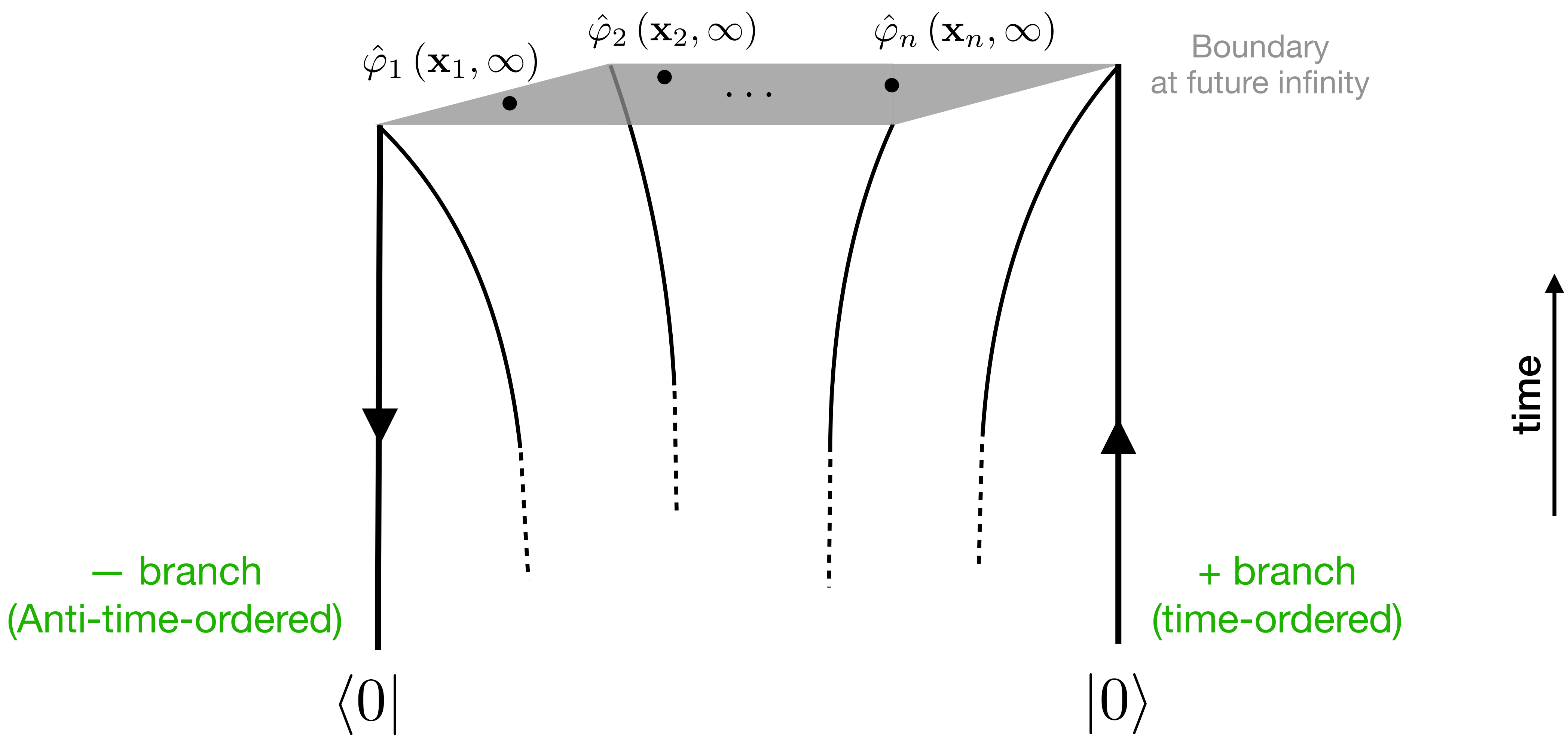
$$\Lambda > 0$$

dS Boundary Correlators

in-in formalism

[Maldacena '02, Weinberg '05]

$$\lim_{\tau \to \infty} \langle 0 | \hat{\varphi}_1 (\mathbf{x}_1, \tau) \ldots \hat{\varphi}_n (\mathbf{x}_n, \tau) | 0 \rangle$$



Take $|0\rangle$ to be the de Sitter vacuum which reduces to the Minkowski vacuum at early times.

(Bunch Davies vacuum)

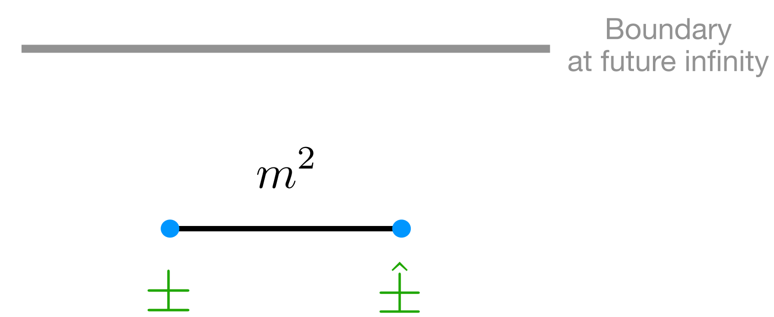
dS Boundary Correlators

in-in formalism [Maldacena '02, Weinberg '05]

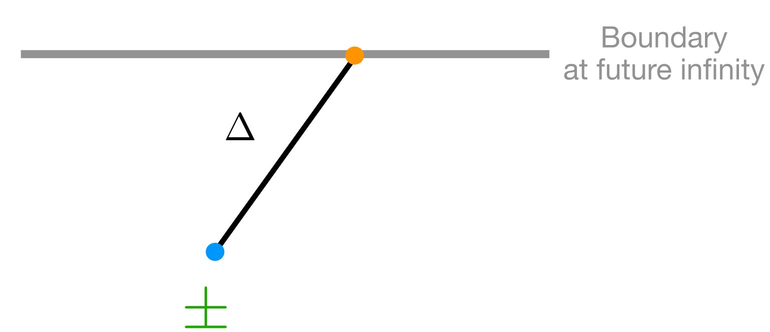
$$\lim_{\tau\to\infty} \langle 0 | \hat{\varphi}_1 (\mathbf{x}_1, \tau) \ldots \hat{\varphi}_n (\mathbf{x}_n, \tau) | 0 \rangle$$

Feynman rules:

$\pm$ bulk-to- $\hat{\pm}$ bulk propagator:



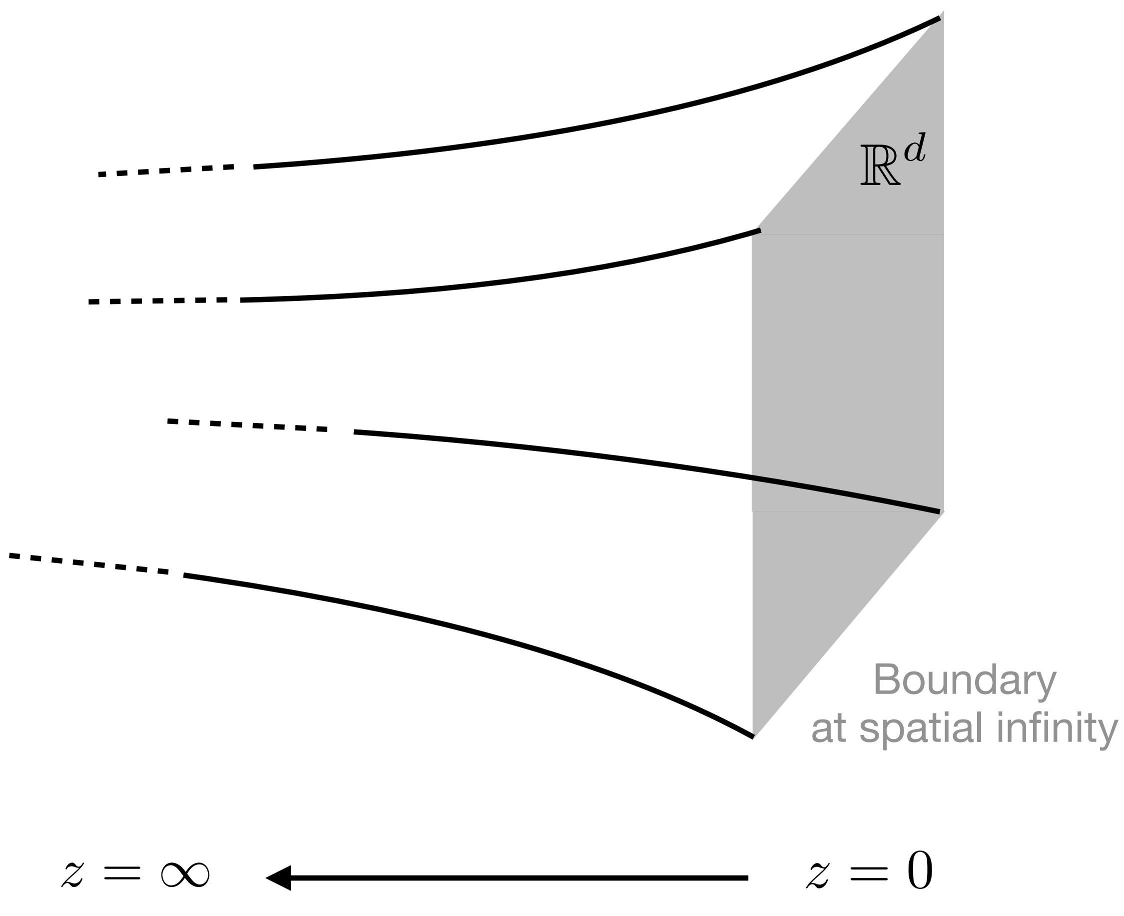
$\pm$ bulk-to-boundary propagator:



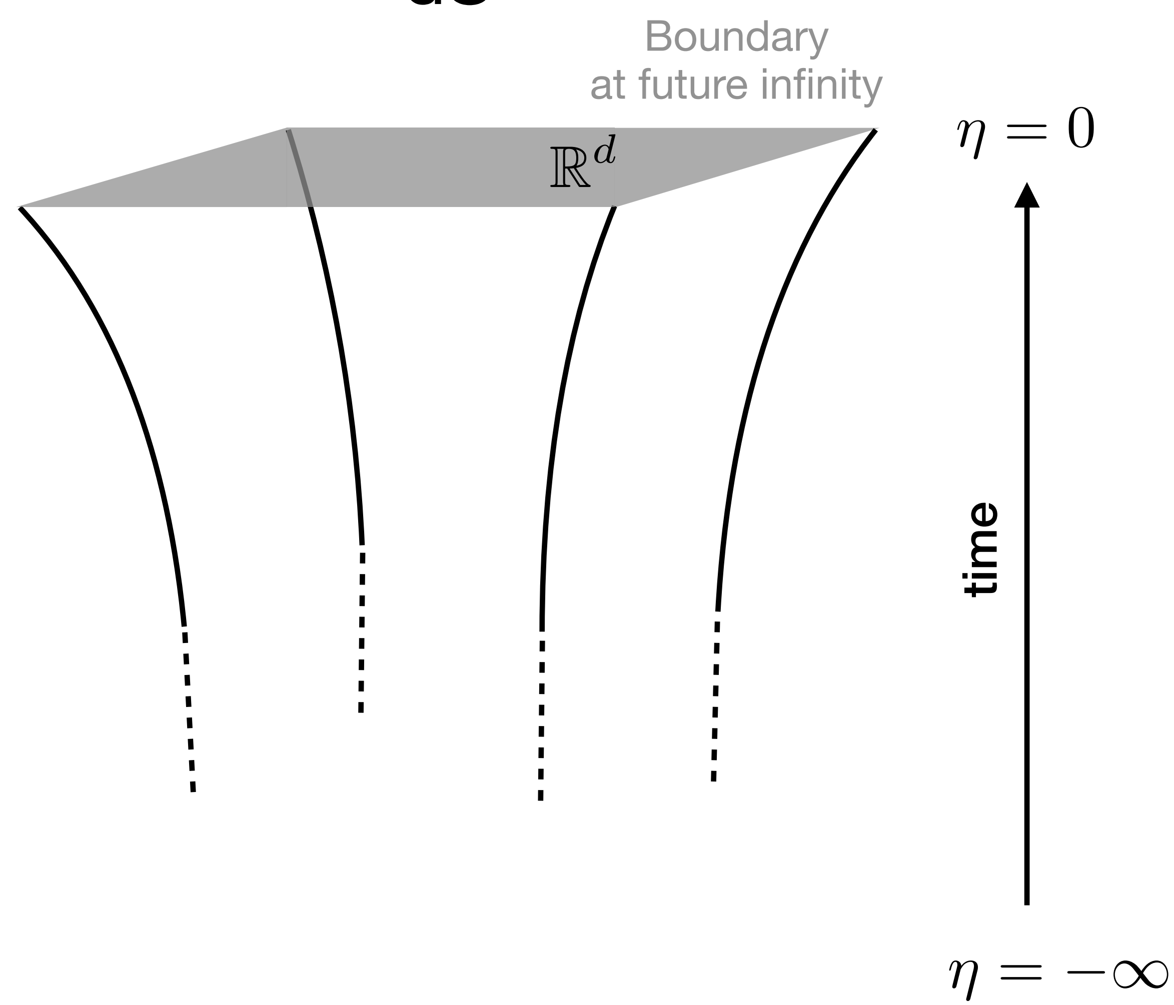
Sum contributions from each branch (±) of the time (in-in) contour!

From dS to Euclidean AdS

Euclidean AdS



dS



$$ds^2 = R_{\mathrm{AdS}}^2 \frac{dz^2 + d\mathbf{x}^2}{z^2} \quad \longleftrightarrow \quad ds^2 = R_{\mathrm{dS}}^2 \frac{-d\eta^2 + d\mathbf{x}^2}{\eta^2}$$

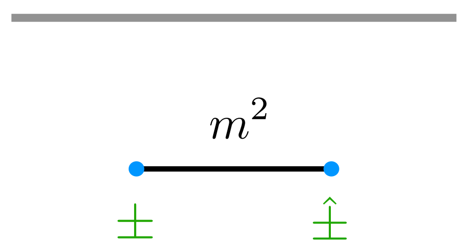
EAdS and dS are identified under:

$$R_{\mathrm{AdS}} = \pm i R_{\mathrm{dS}} \qquad z = \pm i\,(-\eta)$$

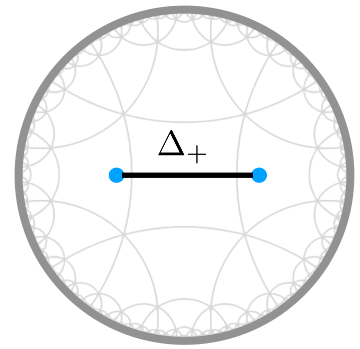
From dS to Euclidean AdS

$\pm$ bulk-to-$\hat{\pm}$ bulk propagator:

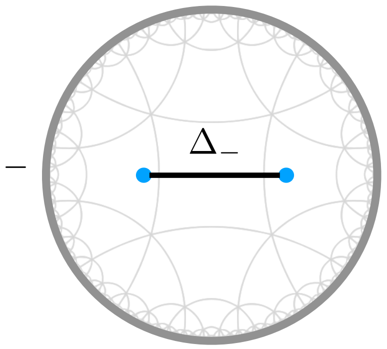
[C.S. and M. Taronna ’19, ’20, ’21]



$= e^{\mp\frac{i\pi}{2}\Delta_+} e^{\hat{\mp}\frac{i\pi}{2}\Delta_+}$



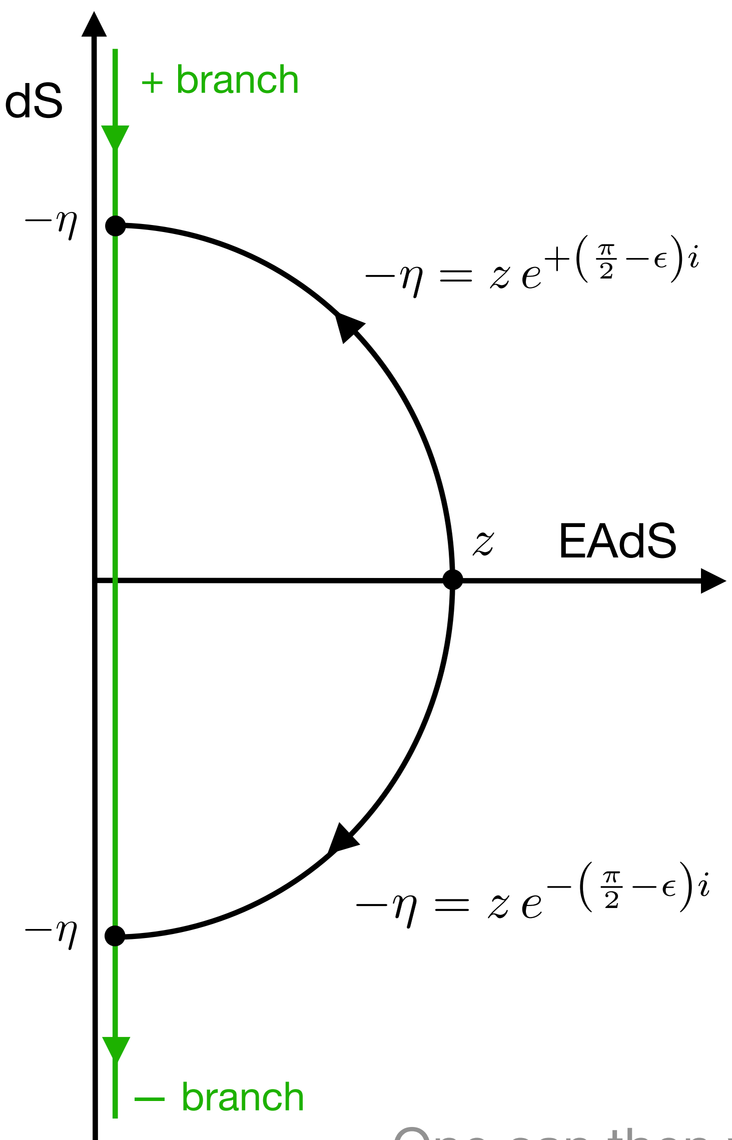
$+\, e^{\mp\frac{i\pi}{2}\Delta_-} e^{\hat{\mp}\frac{i\pi}{2}\Delta_-}$



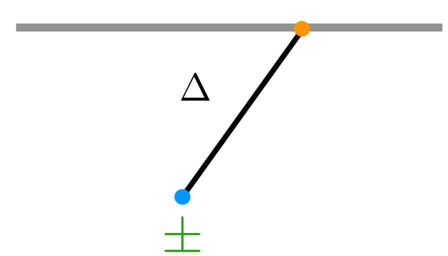
Dirichlet boundary condition

Neumann boundary condition

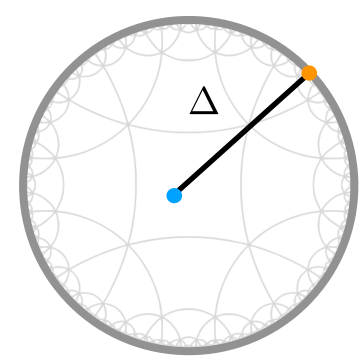
$m^2 R_{\rm dS}^2 = \Delta_+\Delta_-$



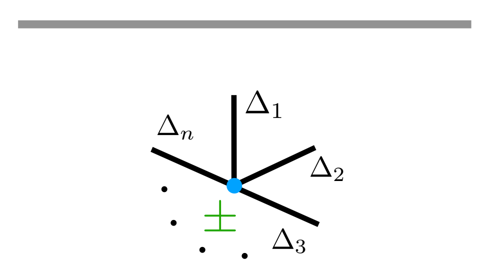
$\pm$ bulk-to-boundary propagator:



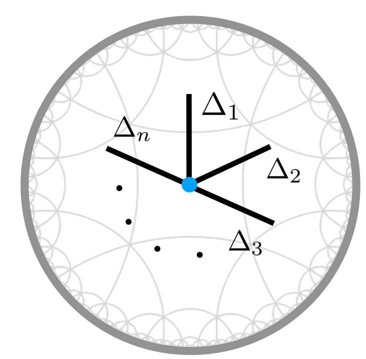
$= e^{\mp\frac{i\pi}{2}\Delta}$



$\pm$ bulk integrals:



$= e^{\pm(d-1)\frac{\pi i}{2}}$



One can then write an EAdS Lagrangian for dS correlators [Gorbenko, Komatsu, di Pietro ’21]

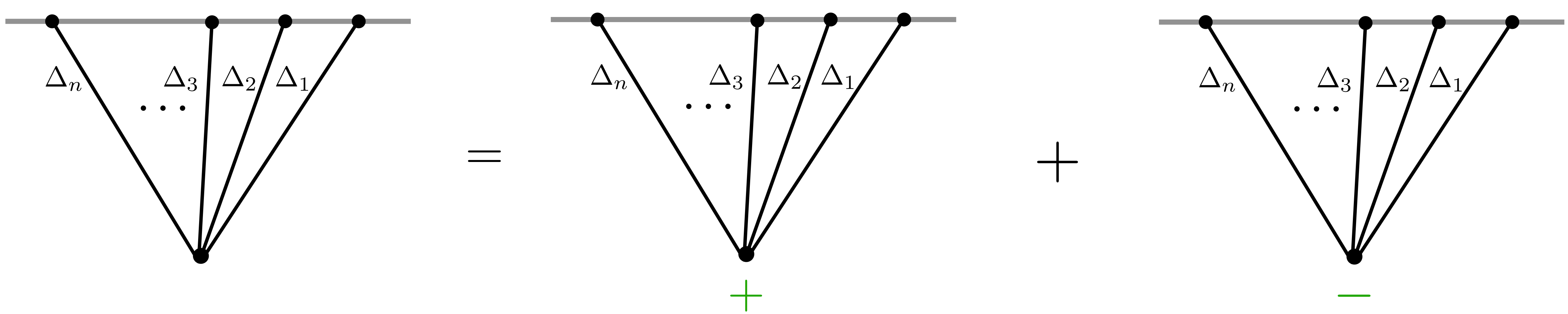
From dS to Euclidean AdS

Examples.

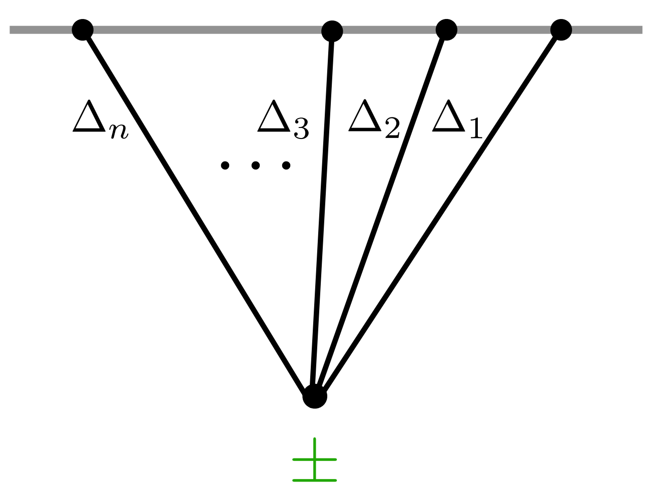
[C.S. and M. Taronna '19]

Non-derivative vertex of scalars fields $\mathcal{V}(X) = g\phi_1(X)\ldots\phi_n(X)$

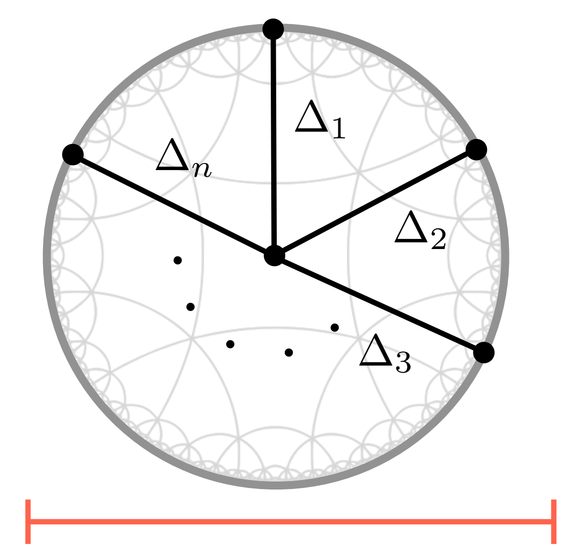
Contact diagram:



Where



$$= e^{\pm\frac{i\pi}{2}(d-1)}\prod_{j=1}^{n} e^{\mp\frac{i\pi}{2}\Delta_j}$$



Same contact diagram in EAdS

From dS to Euclidean AdS

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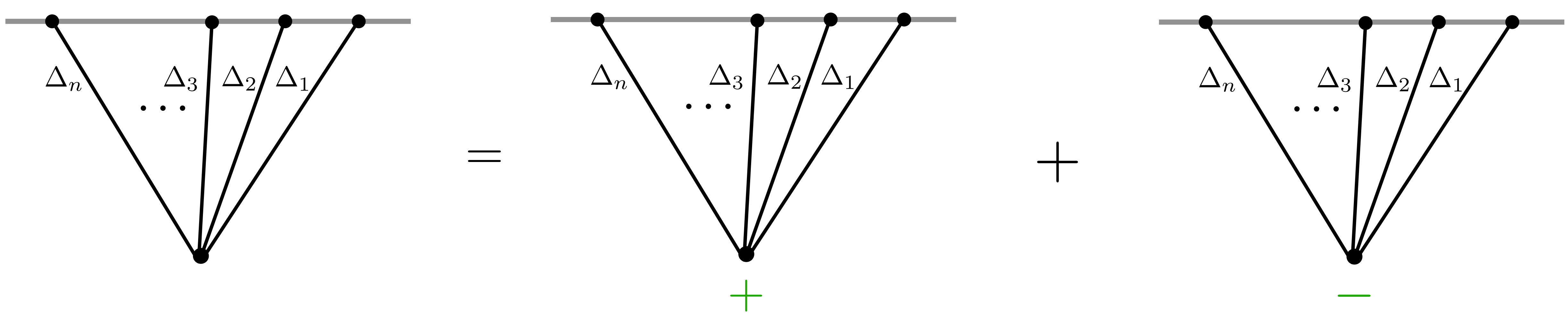
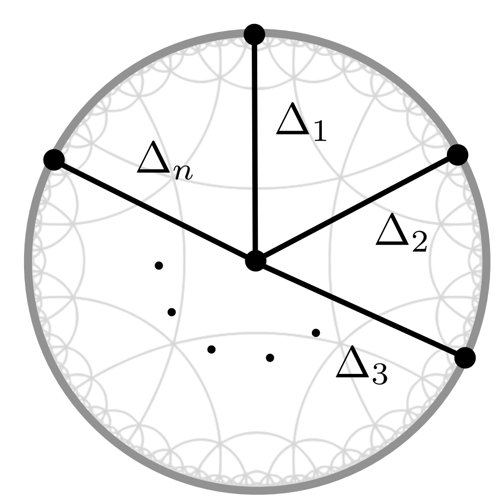


Same contact diagram in EAdS

$$= \sin\left(-\frac{d}{2} + \frac{1}{2}\sum_{i=1}^{n}\Delta_i\right)\pi$$



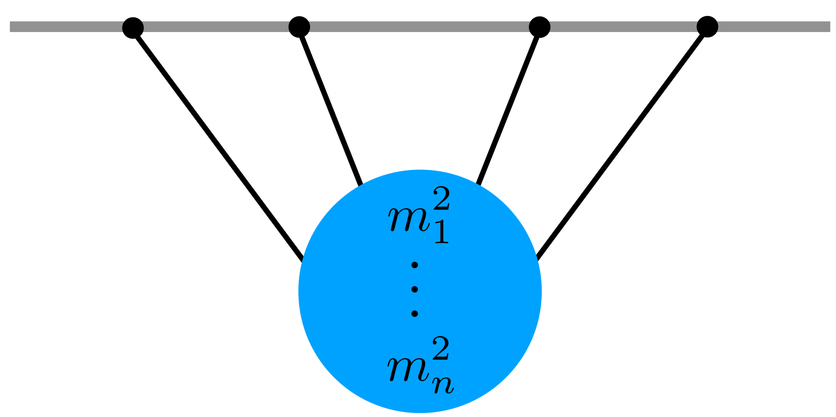
Encodes unitary time evolution

c.f. *"Cosmological Optical Theorem"* [Goodhew et al, 2020]

From dS to EAdS, and back

dS boundry correlators are perturbatively recast as Witten diagrams in EAdS:

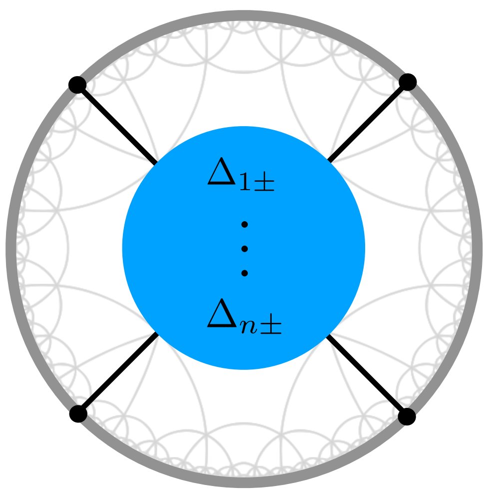
e.g. four-points



Process with M vertices

Combines contributions from each branch of the in-in contour

$$= \underbrace{\sum_{\Delta_{1\pm}\dots\Delta_{n\pm}}}_{\text{Sum over boundary conditions for exchanged particles}} \underbrace{C_{\Delta_{1\pm}\dots\Delta_{n\pm}}}_{\text{factorises into: } C_1^{\text{contact}} \times \dots \times C_M^{\text{contact}}}$$



Notes:

- Contributions from both $\Delta_{\pm}$ modes, which is not always possible in AdS
- $\Delta_{i\,\pm}$ $\in$ Unitary Irreducible Representation of **dS** isometry

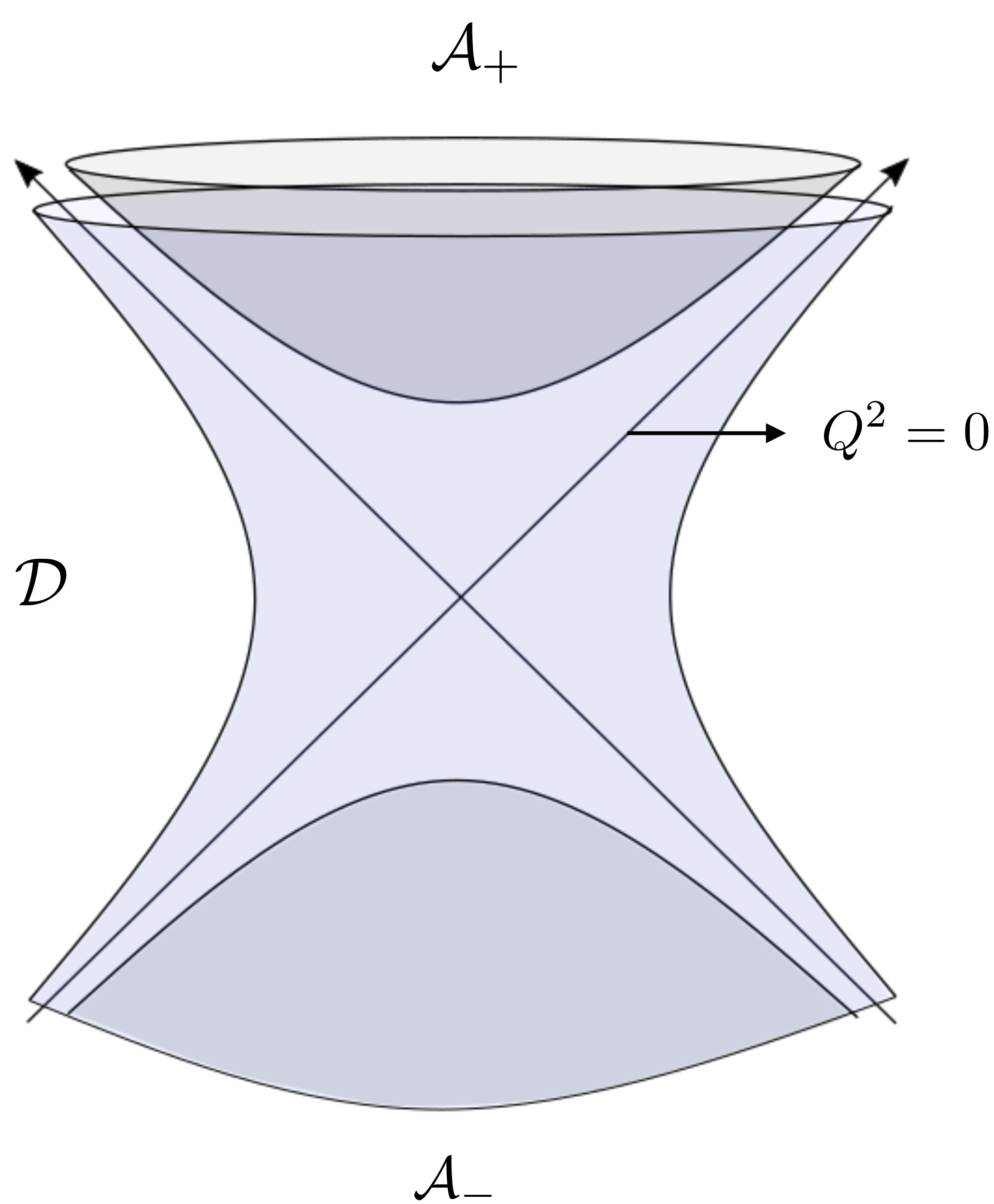
Can use to import techniques and results from AdS to dS!

$$\Lambda = 0$$

Hyperbolic slicing of Minkowski space

[de Boer and Solodukhin '03]

(d+2)-dimensional Minkowski space $\mathbb{M}^{d+2}$, coordinates $X^A, \quad A = 0, \dots d+1$



$\mathcal{A}_\pm : \quad X^2 = -t^2$ (EAdS$_{d+1}$, radius t)

$\mathcal{D} : \quad X^2 = R^2$ (dS$_{d+1}$, radius R)

Conformal boundary:

$$Q^2 = 0, \quad Q \equiv \lambda Q, \quad \lambda \in \mathbb{R}^+$$

Introduce projective coordinates:

$$\xi_i = Q^i/Q^0, \quad i = 1, \dots, d+1$$

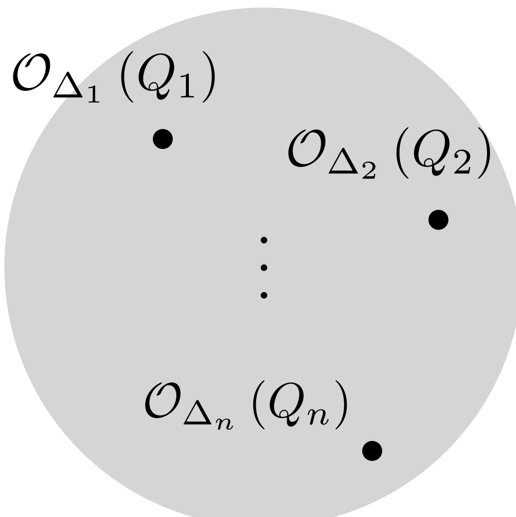
$$\xi_1^2 + \dots + \xi_{d+1}^2 = 1$$

d-dimensional unit sphere

Minkowski boundary correlators

[C.S. and M. Taronna ’23]

Radial Mellin transform of Minkowski correlators implements a radial reduction onto the hyperbolic slicing:



Hyperbolic coordinate

$$= \prod_i \lim_{\hat{X}_i \to Q_i} \int_0^\infty \frac{dt_i}{t_i}\, t_i^{\Delta_i} \left\langle \phi_1(t_1 \hat{X}_1) \dots \phi_n(t_n \hat{X}_n) \right\rangle$$

radial coordinate

Celestial correlators then arise in the boundary limit $\hat{X}_i \to Q_i$!

Mellin transform

$$\int_0^\infty \frac{dt}{t} t^{\Delta} (\dots)$$

Inverse Mellin transform

$$\int_{\frac{d}{2}-i\infty}^{\frac{d}{2}+i\infty} \frac{d\Delta}{2\pi i}\, t^{-\Delta} (\dots)$$

Unitary Principal Series representations of SO(d+1,1)

Minkowski boundary correlators

[C.S. and M. Taronna '23]

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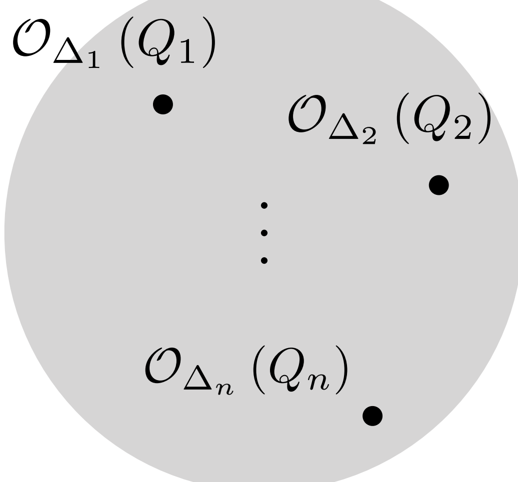

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radial coordinate

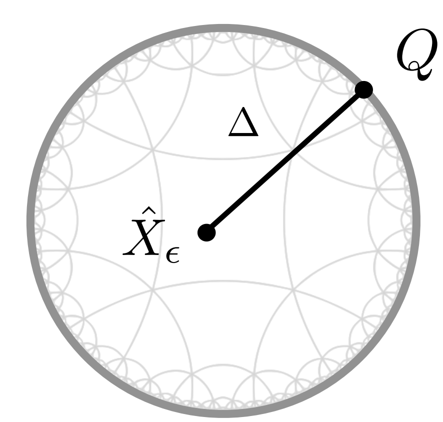
Celestial correlators then arise in the boundary limit $\hat{X}_i \to Q_i$!

"Celestial" bulk-to-boundary propagator:

Kernel of the radial reduction (Bessel-K function)

bulk-to-boundary propagator in EAdS

$$G_\Delta^{\text{flat}}(X,Q) = \lim_{\hat{Y}\to Q} \int_0^\infty \frac{dt}{t} t^\Delta G_F\left(X, t\hat{Y}\right) = \overbrace{\mathcal{K}^{(m)}_{i\left(\frac{d}{2}-\Delta\right)}\left(\sqrt{X^2+i\epsilon}\right)} \times$$



From the Celestial Sphere to EAdS

[C.S. and M. Taronna '23]

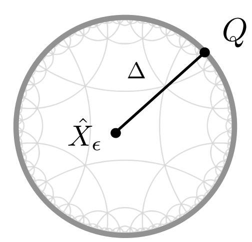
Examples.

Non-derivative vertex of scalars fields $\mathcal{V}\left(X\right)=g\phi_{1}\left(X\right)\ldots\phi_{n}\left(X\right)$

Contact diagram:

$$\langle\mathcal{O}_{\Delta_1}(Q_1)\ldots\mathcal{O}_{\Delta_n}(Q_n)\rangle=-ig\int d^{d+2}X\,G^{\text{flat}}_{\Delta_1}(X,Q_1)\cdots G^{\text{flat}}_{\Delta_n}(X,Q_n)\,.$$

$$G^{\text{flat}}_{\Delta}\left(X,Q\right)\quad=\quad\mathcal{K}^{(m)}_{i\left(\frac{d}{2}-\Delta\right)}\left(\sqrt{X^2+i\epsilon}\right)\;\times$$

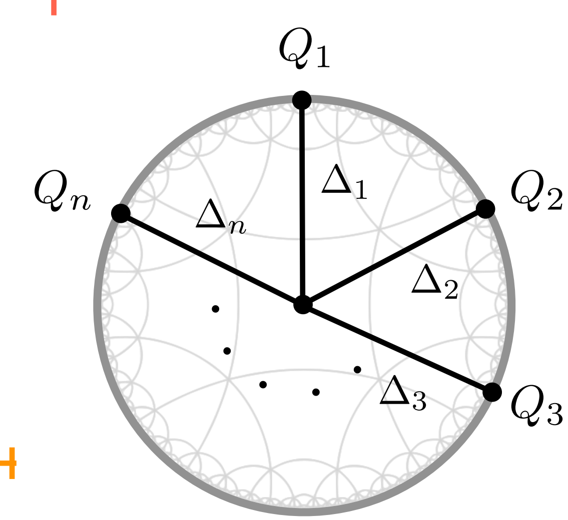


$$=\quad R_{\Delta_1\ldots\Delta_n}\left(m_1,\ldots,m_n\right)\;\times\;\sin\left(-\frac{d}{2}+\frac{1}{2}\sum_{i=1}^{n}\Delta_i\right)\pi$$

Contribution from radial integral.
Encodes all mass dependence.
(Generalised hypergeometric)

Same factor as for dS contact diagrams.
Comes from combining contributions
from regions inside and outside lightcone

(Analytically continued)
EAdS contact diagram

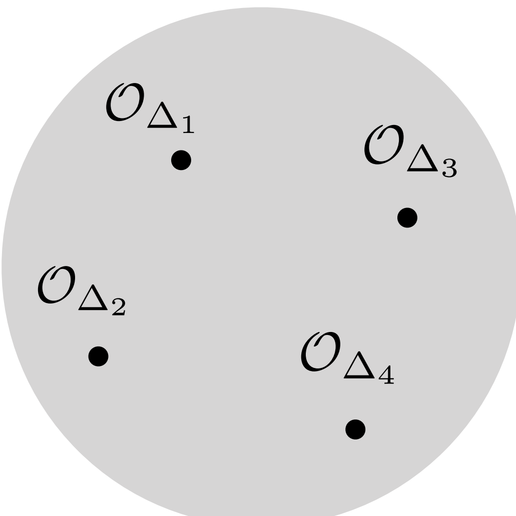


Like in dS, Celestial contact diagrams are proportional to their EAdS counterparts

From the Celestial Sphere to EAdS

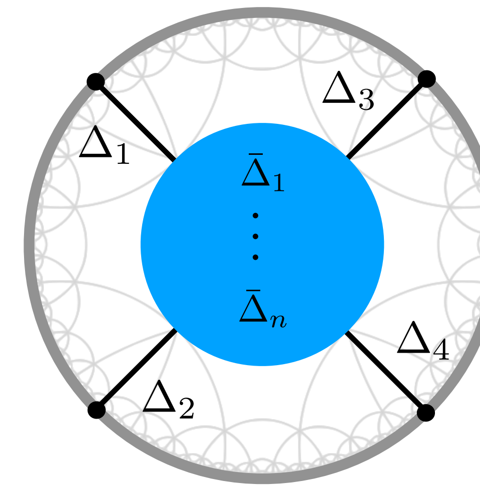
[C.S. and M. Taronna '23]

In general, for exchanges of particles of mass $m_i, \quad i = 1, \dots, n$



Unitary Principal Series representations of SO(d+1,1)

$$= \int_{\frac{d}{2}-i\infty}^{\frac{d}{2}+i\infty} \frac{d\bar{\Delta}_1}{2\pi i} \dots \frac{d\bar{\Delta}_n}{2\pi i} \, C_{\bar{\Delta}_1 \dots \bar{\Delta}_n}(m_1, \dots, m_n)$$



Minkowski exchanges are a *continuum* of EAdS exchanges

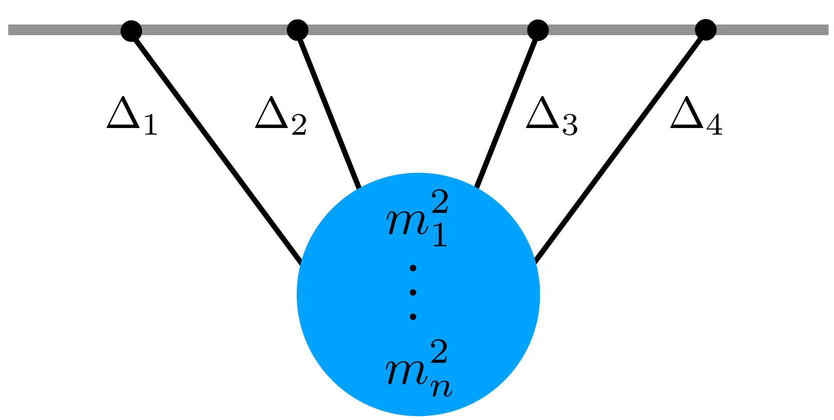
Process with M vertices

factorises into:

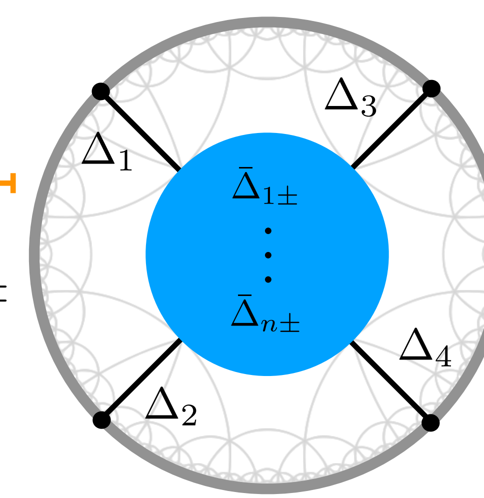
$$C_1^{\text{contact}} \times \dots \times C_M^{\text{contact}}$$

Makes manifest conformal symmetry

Compare with de Sitter:



$$= \sum_{\bar{\Delta}_{1\pm} \dots \bar{\Delta}_{n\pm}} C_{\bar{\Delta}_{1\pm} \dots \bar{\Delta}_{n\pm}}$$



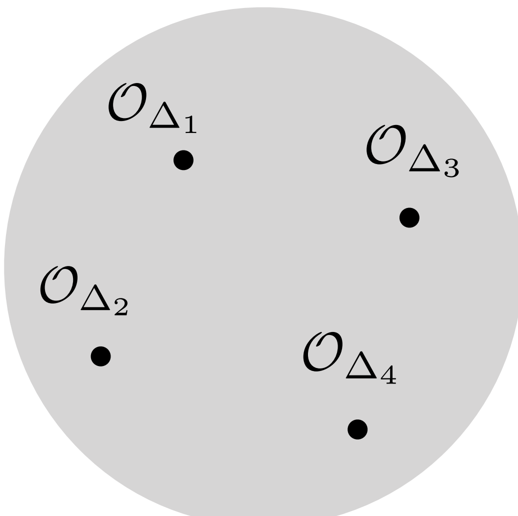
Process with M vertices

dS exchanges are a *discrete sum* of EAdS exchanges

From the Celestial Sphere to EAdS

[C.S. and M. Taronna '23]

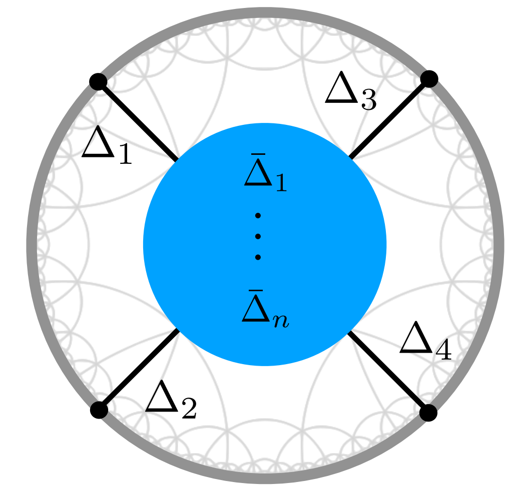
In general, for exchanges of particles of mass $m_i, \quad i = 1, \ldots, n$



Process with M vertices

Unitary Principal Series representations of SO(d+1,1)

$$= \int_{\frac{d}{2}-i\infty}^{\frac{d}{2}+i\infty} \frac{d\bar{\Delta}_1}{2\pi i} \ldots \frac{d\bar{\Delta}_n}{2\pi i} \, C_{\bar{\Delta}_1 \ldots \bar{\Delta}_n}(m_1, \ldots, m_n)$$



Minkowski exchanges are a *continuum* of EAdS exchanges

factorises into:

$$C_1^{\text{contact}} \times \ldots \times C_M^{\text{contact}}$$

Makes manifest conformal symmetry

Comments:

- Relation to definition [Pasterski, Shao, Strominger '17] of celestial correlators as scattering amplitudes in a conformal basis?

  [Pasterski, Shao, Strominger '17] = LSZ ([Sleight, Taronna '23]) ?

- Celestial correlators defined as an extrapolation of bulk Minkowski correlators give a definition of celestial correlators for theories without an S-matrix.

  What lessons can we draw from Minkowski CFT?

Some applications.

Perturbative OPE data

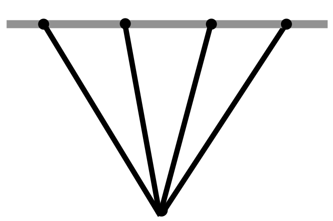
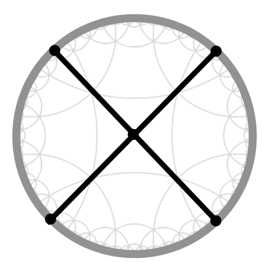
Perturbative OPE data on the boundary of dS and Minkowski space from EAdS

E.g. Composite operators on the boundary [C.S. and M. Taronna '20]

$$[\mathcal{O}\mathcal{O}]_{n,\ell} \sim \mathcal{O}\left(\partial^2\right)^n \partial_{i_1}\dots\partial_{i_\ell}\mathcal{O} + \dots$$

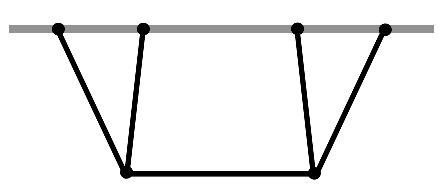
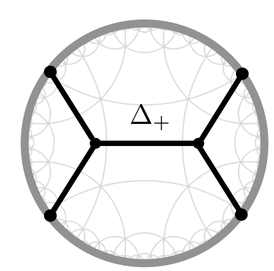
scaling dimension: $\Delta_{n,\ell} = \underbrace{2\Delta + 2n + \ell}_{\text{Free theory}} + \underbrace{\gamma_{n,\ell}}_{\text{anomalous dimension}}$

- $\gamma_{n,\ell}$ induced by bulk ϕ^4 contact diagram in dS:


$= \sin\left(-\frac{d}{2}+2\Delta\right)\pi$


$$\longrightarrow \quad \gamma^{\phi^4}_{n,\ell} = \sin\left(-\frac{d}{2}+2\Delta\right)\pi \times {}^{(\mathrm{EAdS})}\gamma^{\phi^4}_{n,\ell}$$

- $\gamma_{n,\ell}$ induced by an exchange diagram in dS:


$= \sin\left(\frac{-d+2\Delta+\Delta_+}{2}\right)\pi \sin\left(\frac{-d+2\Delta+\Delta_+}{2}\right)\pi$


$+ \quad (\Delta_+ \to \Delta_-)$

$$\longrightarrow \quad \gamma^{\phi^3\,\mathrm{exch}}_{n,\ell} = \sin\left(\frac{-d+2\Delta+\Delta_+}{2}\right)\pi \sin\left(\frac{-d+2\Delta+\Delta_+}{2}\right)\pi \times {}^{(\mathrm{EAdS})}\gamma^{\phi^3\,\mathrm{exch}\,\Delta_+}_{n,\ell} + (\Delta_+ \to \Delta_-)$$

Perturbative OPE data

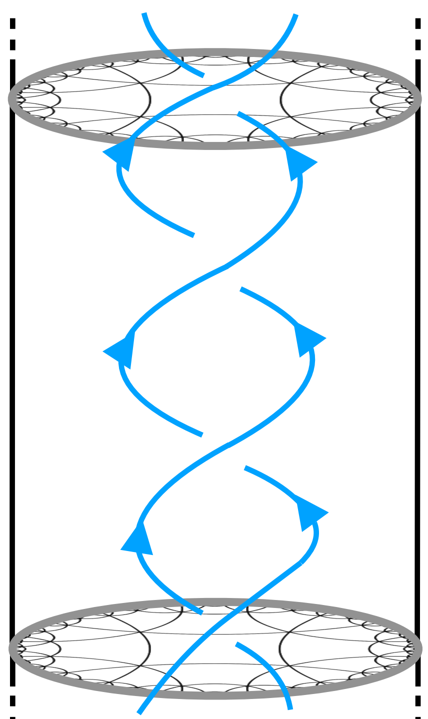
Perturbative OPE data on the boundary of dS and Minkowski space from EAdS

E.g. Composite operators on the boundary

$$[\mathcal{O}\mathcal{O}]_{n,\ell} \sim \mathcal{O}\left(\partial^2\right)^n \partial_{i_1}\ldots\partial_{i_\ell}\mathcal{O} + \ldots$$

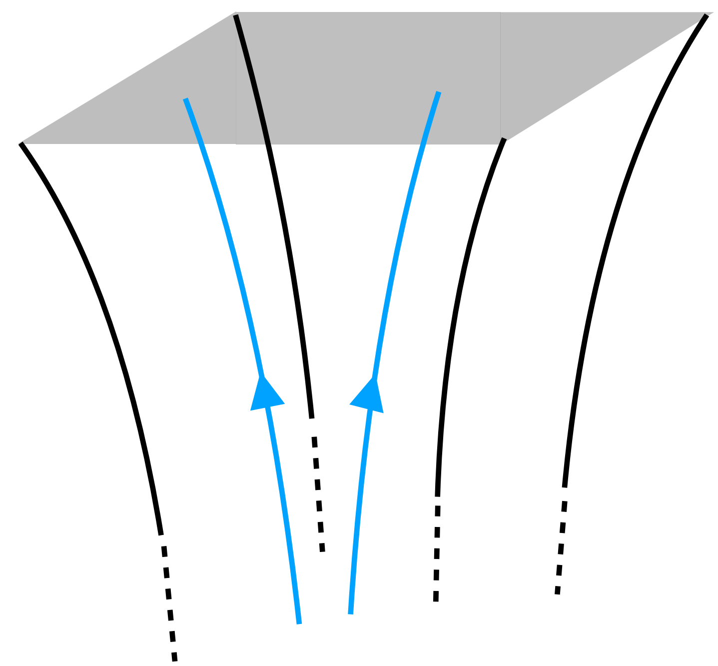
scaling dimension: $\Delta_{n,\ell} = \underbrace{2\Delta + 2n + \ell}_{\text{Free theory}} + \underbrace{\gamma_{n,\ell}}_{\text{anomalous dimension}}$

AdS



vs.

dS



$\Delta_{n,\ell}$ is unitary

$\longrightarrow$ stable particle (bound state)

$\Delta_{n,\ell}$ is (generally) non-unitary

$\longrightarrow$ resonance

[Bros et al ’06-’09, Marolf and Morrison ’10, Krotov and Polyakov ’10, Arkani-Hamed and Maldacena ’15]

Conformal Partial Wave Expansion

[Sleight, Taronna ’20] [Hogervorst, Penedones, Vaziri ’21] [di Pietro, Komatsu, Gorbenko '21]

Perturbative dS and celestial correlators have a similar analytic structure to those in AdS.

$\longrightarrow$ Like in AdS they admit a conformal partial wave expansion

Spectral density, meromorphic in Δ

$$\langle\mathcal{O}(\mathbf{x}_1)\,\mathcal{O}(\mathbf{x}_2)\,\mathcal{O}(\mathbf{x}_3)\,\mathcal{O}(\mathbf{x}_4)\rangle = \sum_{J=0}^{\infty}\int_{\frac{d}{2}-i\infty}^{\frac{d}{2}+i\infty}\frac{d\Delta}{2\pi i}\,\rho_J(\Delta)\,\underbrace{\mathcal{F}_{\Delta,J}(\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_3,\mathbf{x}_4)}_{\text{Conformal Partial Wave}}$$

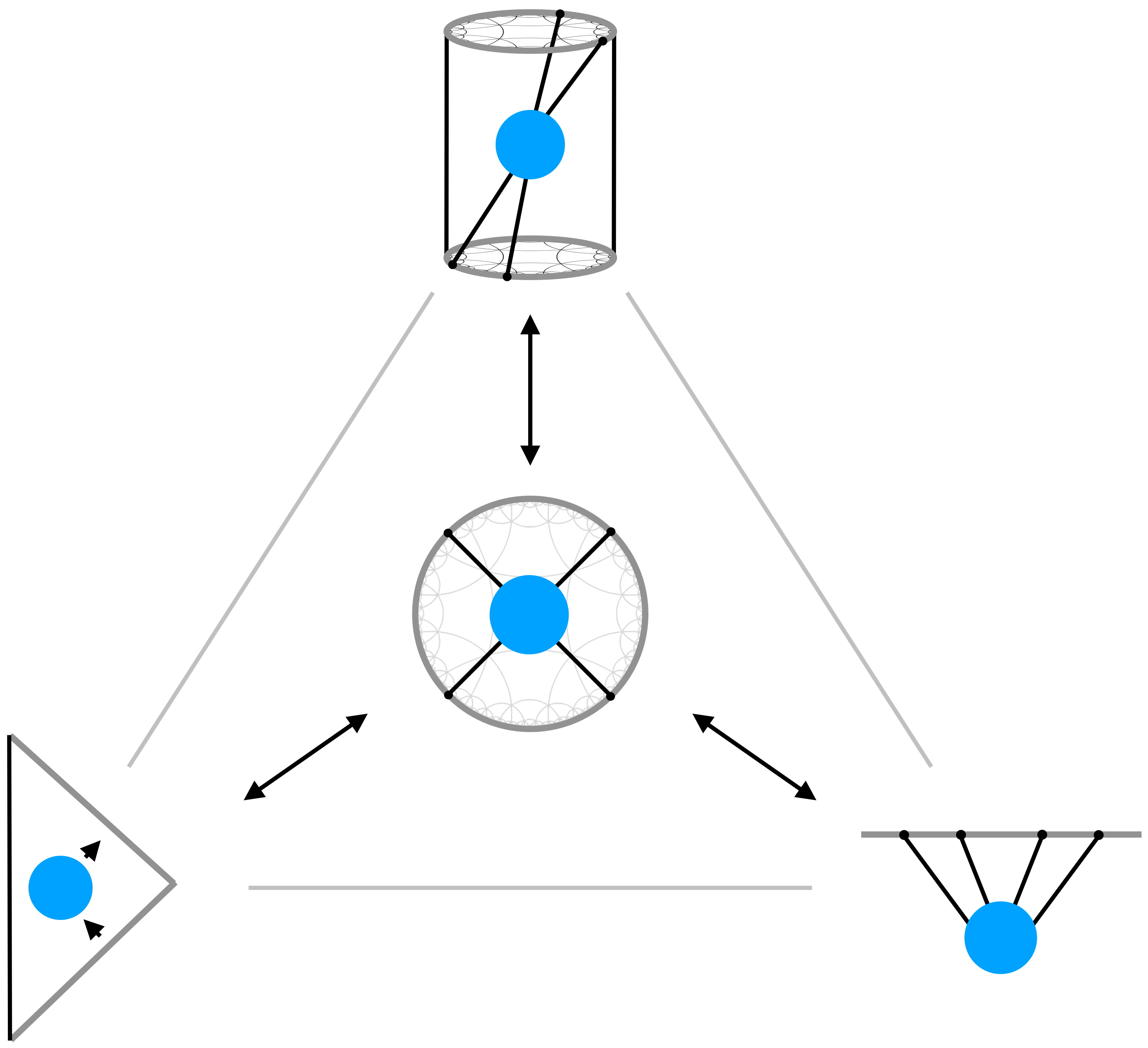
This has been argued to hold non-perturbatively as well [Hogervorst, Penedones, Vaziri ’21, di Pietro, Komatsu, Gorbenko '21]

Unitarity: $\rho_J(\Delta)\geq 0$ + crossing $\longrightarrow$ Bootstrap for Euclidean CFTs?

Cf. Lorentzian CFT:

$$\langle\mathcal{O}(\mathbf{x}_1)\,\mathcal{O}(\mathbf{x}_2)\,\mathcal{O}(\mathbf{x}_3)\,\mathcal{O}(\mathbf{x}_4)\rangle = \sum_{\Delta,J}^{\infty} C^2_{\Delta,J}\,\underbrace{G_{\Delta,J}(\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_3,\mathbf{x}_4)}_{\text{Conformal Block}}$$

Unitarity: $C^2_{\Delta,J}\geq 0$ + crossing $\longrightarrow$ Conformal Bootstrap



Thank you.