

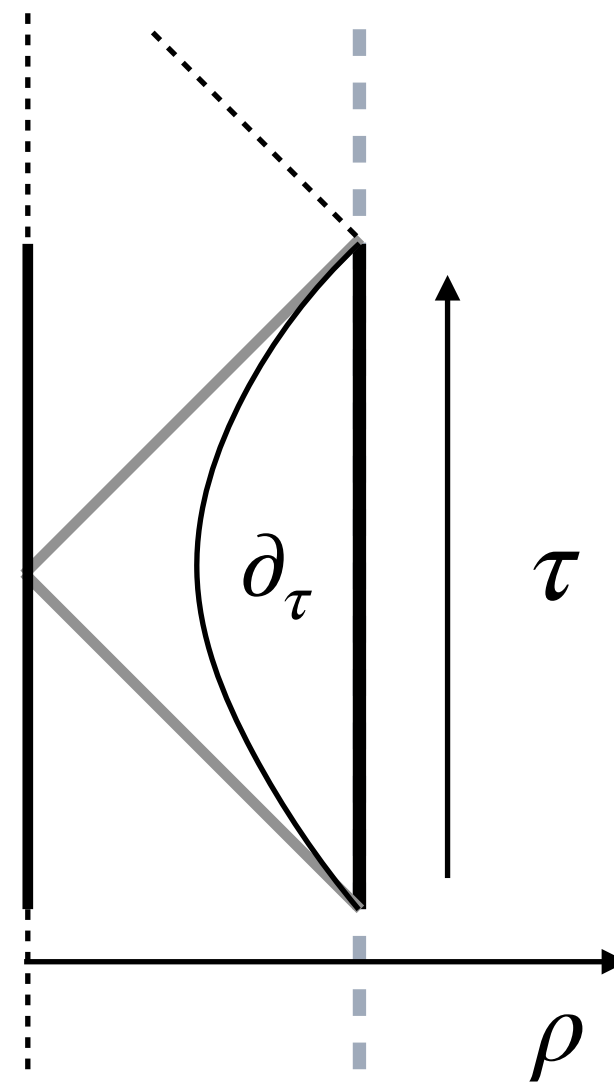
Flat space holography from AdS/CFT

Ana-Maria Raclariu, KCL

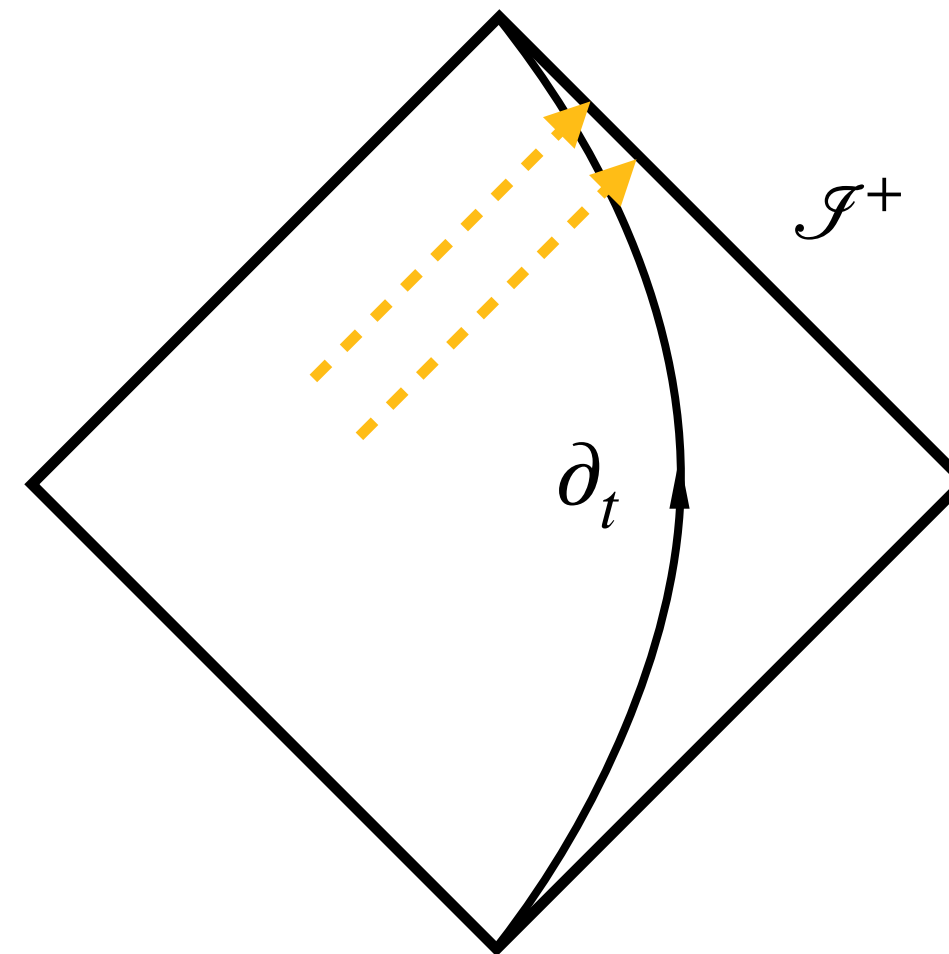
Puzzles in the QG landscape, Graz 2026

Motivation

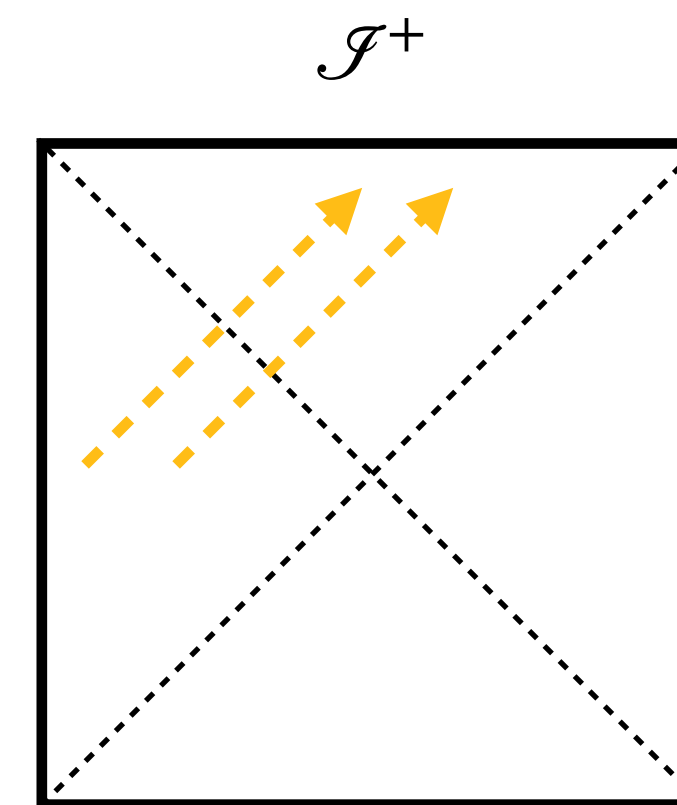
Is (quantum) gravity **holographic**?



AdS: $\Lambda < 0$



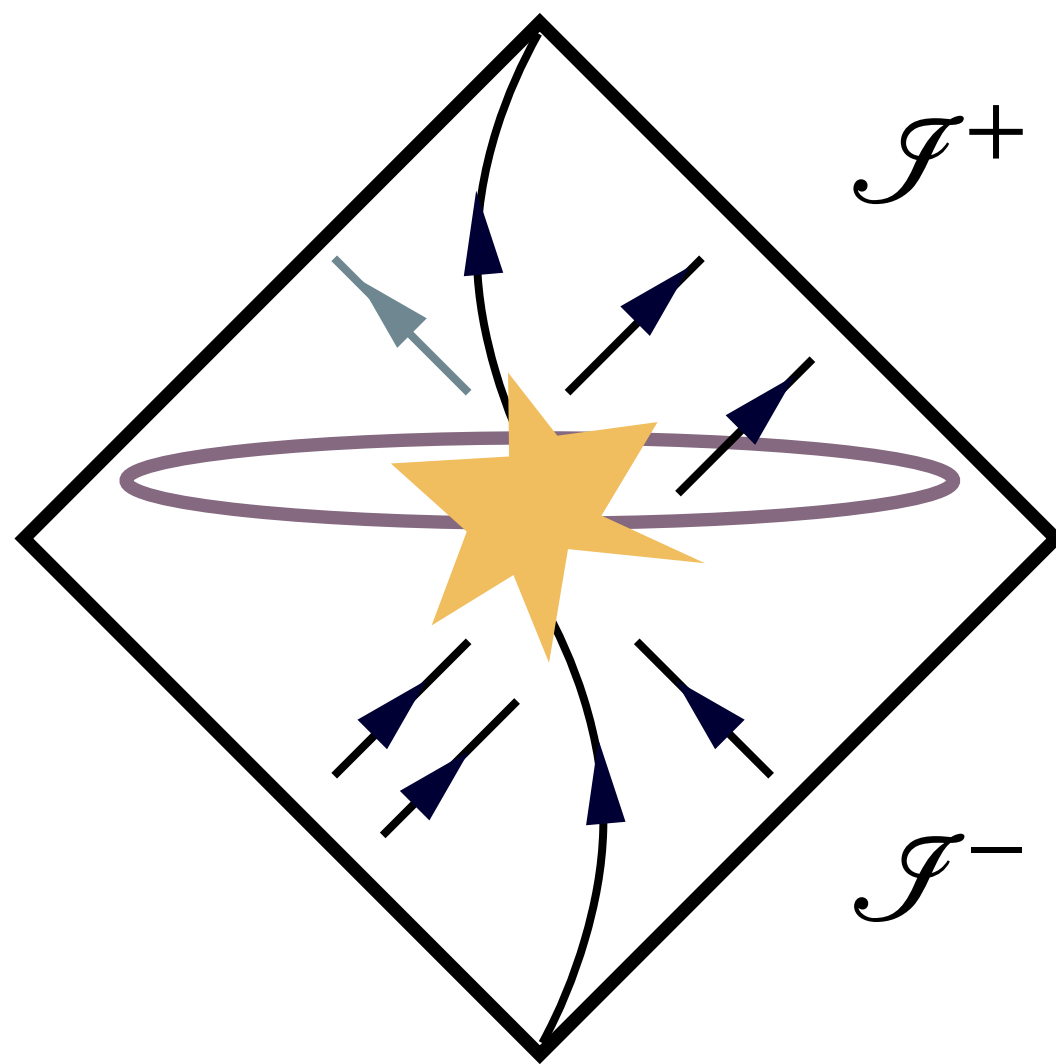
AFS: $\Lambda = 0$



dS: $\Lambda > 0$

Motivation

Why it matters? Compute 4d gravitational scattering amplitudes (observables) using QFT tools:



Long-wavelength regime $\sim$ CFT

Black holes, UV-IR relation?

- IR/collinear divergences
 - Detector observables
 - Quantum perturbative effects
-
- Non-trivial backgrounds
 - Analyticity, unitarity, dispersion relations
 - Non-perturbative effects

Approaches in asymptotically flat spacetimes

Carrollian: $(d + 1)$ -dim. bulk/ d -dim. null boundary

- $\text{Poincare}_{d+1} = \text{Conformal Carroll}_d$



conformal symmetries of
 d -dim. null surfaces

[Laurent's talk]

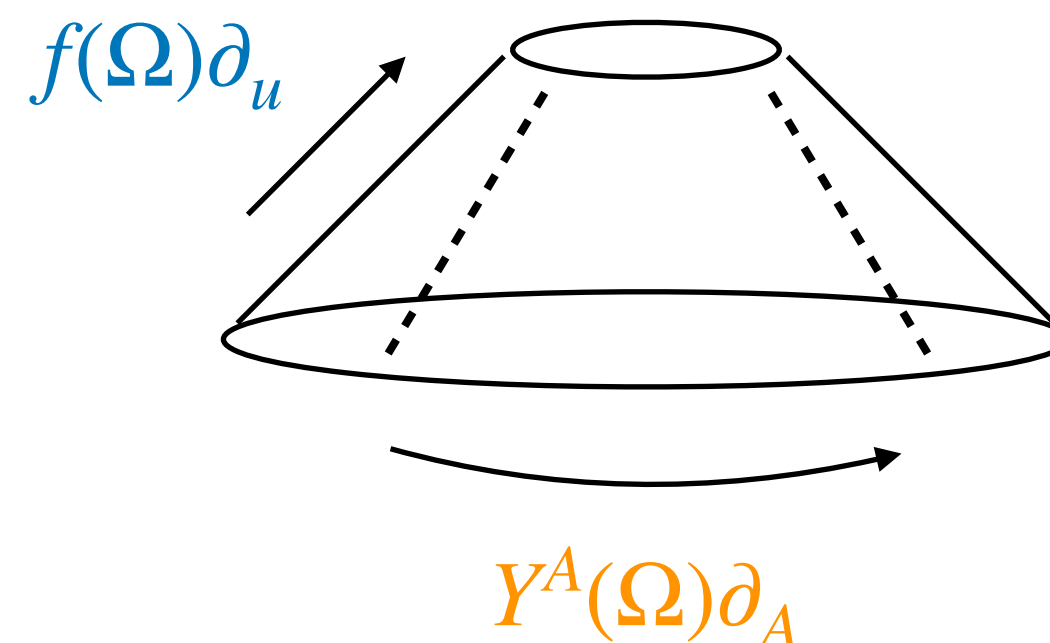
Celestial: $(d + 1)$ -dim. bulk/ $(d - 1)$ -dim. boundary

- $\text{Poincare}_{d+1} = \bigoplus_{\lambda} \text{Lorentz}_{d+1}(\lambda)$



conformal symmetries of
 $(d-1)$ -dim. surfaces

Local (infinite-dimensional) enhancement for $d = 3$: $\text{Poincare}_4 \rightarrow \text{BMS}_4 + \text{superrotations}$



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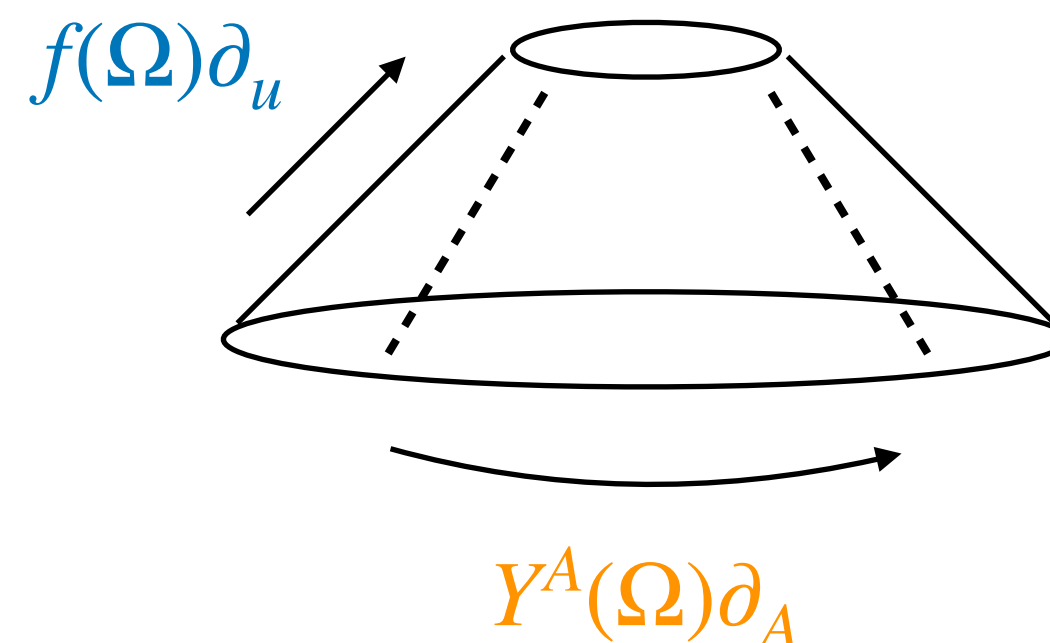
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+ tower of "higher-spin" symmetries

[Guevara, Himwich, Pate, Strominger '21]

Hopes for (flat) holography

What are the defining properties of quantum gravity?

- Interplay between canonical methods, holography and top-down approaches



bulk-boundary dictionary: geometry $\leftrightarrow$ rep. theory + dynamics

Do CCFTs lie in the space of consistent quantum field theories?

- Defining properties of holographic CFT?

admits large c /large N limit; sparse low-lying spectrum and large gap

stress tensor; crossing, unitarity, causality

special high-energy/finite-temperature limit

special entanglement pattern

Roadmap

1. Foundations: Geometry of null hypersurfaces $\longleftrightarrow$ Symmetries (kinematics) of 3d/2d CCFT)

Matching/conservation of asymptotic charges = Ward identities (BMS, Virasoro, w-infinity)

Ashtekar, Bagchi, Barnich, Basu, Beig, Bonga, Bondi, Bramson, Bunster, Campiglia, Campoleoni, Chandrasekaran, Chrusciel, Ciambelli, Compère, Dehouck, Detournay, Donnay, Fiorucci, Flanagan, Francia, Freidel, Fuentealba, Geroch, Geiller, Godazgar, Gomberoff, González, Grumiller, Hansen, Hawking, He, Henneaux, Herfray, Himwich, Hollands, Ishibashi, Kapec, Laddha, Leigh, Long, Lysov, Mao, Marteau, Metzner, Mitra, Newman, Nichols, Oblak, Oliveri, Pasterski, Penrose, Perry, Prabhu, Pranzetti, A.R., Regge, Riegler, Ruzziconi, Sachs, Satishchandran, Speziale, Streubel, Strominger, Teitelboim, Tempo, Troncoso, Troessaert, Unti, van der Burg, Wald, Winicour, Zhiboedov, Zwickel. [Laurent's talk]

2. Observables: 4d scattering amplitudes $\longleftrightarrow$ 3d (2d) Carrollian (celestial) correlators

IR/UV properties = Analytic structure in retarded time/boost weight

Arkani-Hamed, Atanasov, Ball, Banerjee, Bu, Casali, Cheung, Choi, Costello, Cresto, Donnay, Fiorucci, Freidel, Guevara, He, Himwich, Hu, Jorstad, Kadhe, Kapec, Kmec, Kulp, Laddha, Law, Lipstein, Mason, McLoughlin, Melton, Mitra, Miller, Moulton, Moynihan, Narayanan, Pasterski, Pate, Puhm, A.R., Ren, Ruzziconi, Sharma, Shao, Skinner, Spradlin, Stieberger, Strominger, Taylor, Trevisani, Tropper, Volovich, Zhu, Zlotnikov.

3. Top-down: Flat space holography from twistor space and AdS/CFT

Flat space holography = limit of AdS/CFT

Adamo, Alday, Bekaert, Bittleston, Bogna, Boulanger, Campoleoni, Costello, de Gioia, Francia, Garner, Heuveline, Heslop, Kmec, Lipstein, Mason, Miller, Nocchi, Ogawa, Paquette, Pekar, A.R., Ruzziconi, Sharma, Skinner, Sleight, Srikant, Skvortsov, Strominger, Takayanagi, Taronna, Taylor, Tropper, Wang

1. Charge algebras

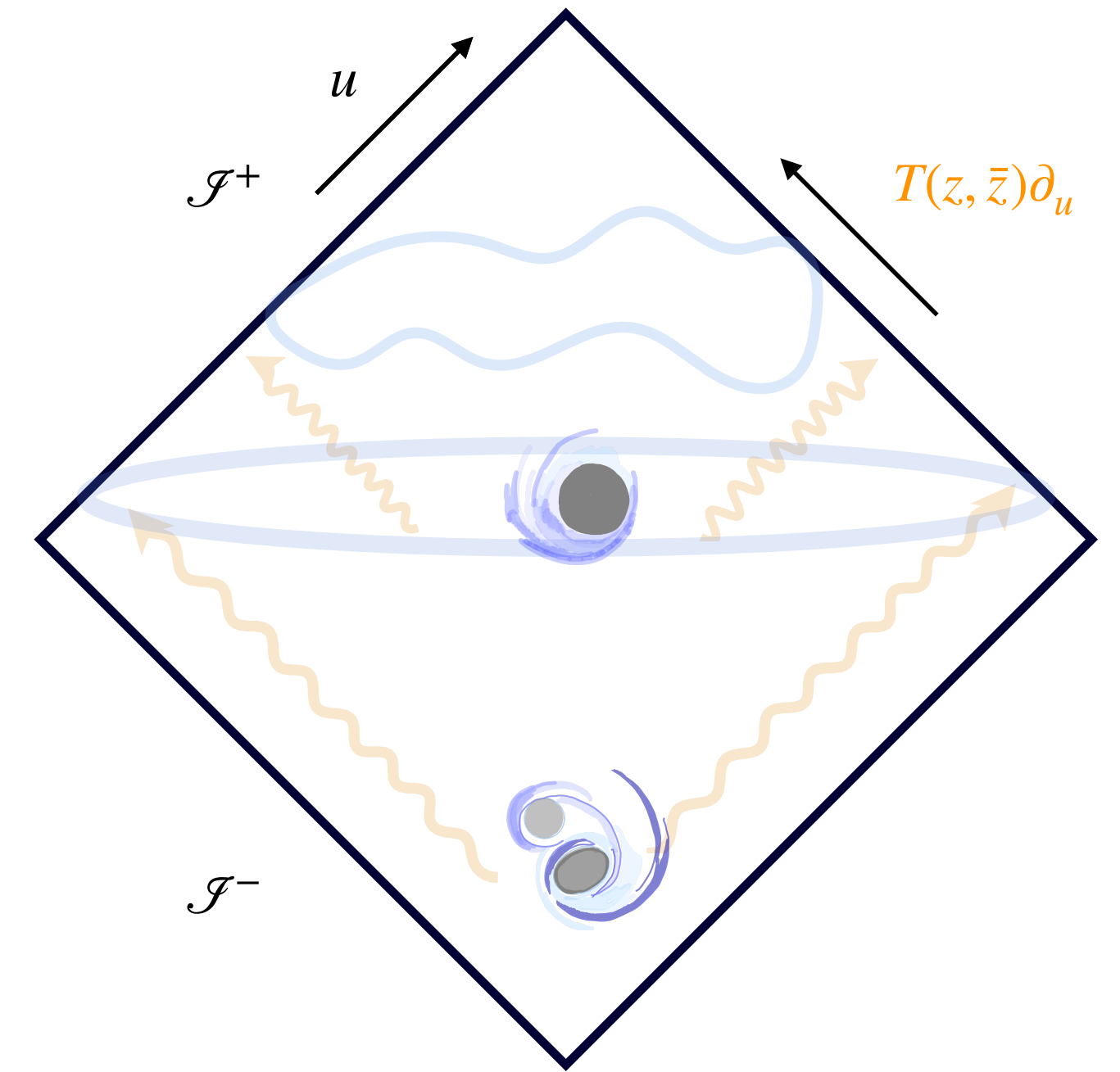
Asymptotic symmetries

Diffeomorphisms that act non-trivially at the boundary:

- Translations $\longrightarrow$ Supertranslations $\xi_F \equiv T(z, \bar{z})\partial_u + \dots$ [BBMS '62]
 - Rotations $\left\{ \begin{array}{l} \longrightarrow \\ \longrightarrow \end{array} \right.$ Superrotations $\xi_Y \equiv Y^A(z, \bar{z})\partial_A + \dots$ [Barnich, Troessaert '11]
 - Boosts
- $$\partial_z Y^{\bar{z}} = \partial_{\bar{z}} Y^z = 0$$

$$\xi_{(T,Y)} = T(z, \bar{z})\partial_u + Y^A\partial_A + \frac{1}{2}D \cdot Y(u\partial_u - r\partial_r) + \dots$$

satisfies **ebms**₄ algebra: $[\xi_{T_1}, \xi_{T_2}] = 0, \quad [\xi_{Y_1}, \xi_{Y_2}] = i\xi_{[Y_1, Y_2]}, \quad [\xi_T, \xi_Y] = i\xi_{T'=\frac{1}{2}(D \cdot Y)T - Y(T)}$



Asymptotic charges

Asymptotic expansion of Einstein constraints + Bianchi id.: $\partial_u Q_s = DQ_{s-1} + \frac{s+1}{2} CQ_{s-2}, \quad s = 0, 1, 2$

transverse covariant derivative
shear/radiation

Q_0, Q_1 : supertranslation and superrotation charges (Bondi mass and angular momentum)

$Q_s, s \geq 2$: higher multipole moments of gravitational field (higher-spin charges)

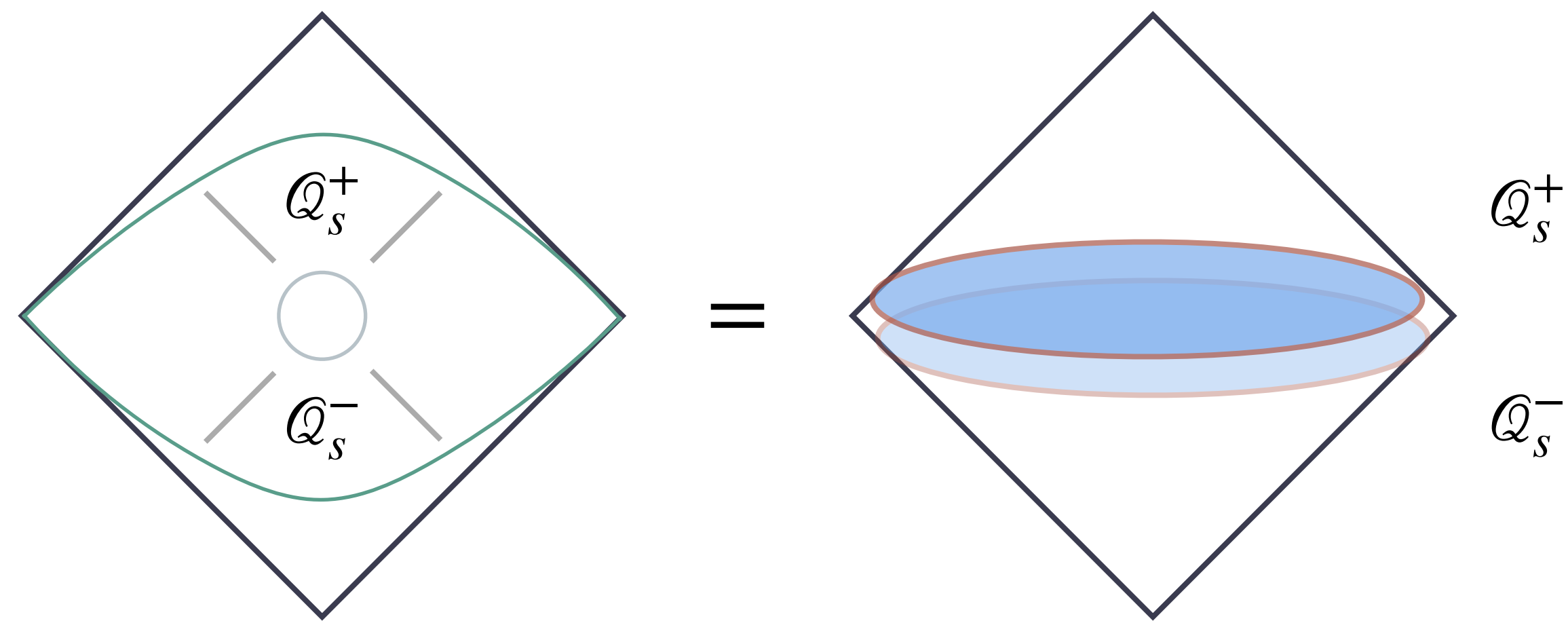
$s > 3$: truncation of $G_{AB} = 0 @ \mathcal{O}(r^{-s+1})$ $\partial_u Q_s = DQ_{s-1} + \frac{s+1}{2} CQ_{s-2}, \quad s \in \mathbb{N}$

Higher-spin charge algebra

$$\partial_u Q_s = DQ_{s-1} + \frac{s+1}{2} CQ_{s-2}, \quad s \in \mathbb{N}$$

$\lim_{u \rightarrow -\infty} Q_s(u, z, \bar{z})$ diverges; **regularize** by imposing no-flux condition at cut of $\mathcal{I}$

[Freidel, Pranzetti, A.R. '21; Cresto, Freidel '24-'25]



Antipodal matching $\iff$ symmetry of scattering

[Strominger '13 + friends]

Conservation law/matching $\implies$ tower of soft theorems

Matching condition $\iff$ charge conservation: $\langle \text{out} | \mathcal{Q}_s^+ \mathcal{S} - \mathcal{S} \mathcal{Q}_s^- | \text{in} \rangle = 0$

Matching of $\mathcal{Q}_s = \mathcal{Q}_s^{(1)} + \mathcal{Q}_s^{(2)}$ leads to **tower of** subleading soft theorems:

$$\langle \text{out} | [Q_{\text{soft}}, \mathcal{S}] | \text{in} \rangle = - \langle \text{out} | [Q_{\text{hard}}, \mathcal{S}] | \text{in} \rangle$$

Linear in phase space variables

Quadratic in phase space variables

$$\begin{aligned}
 & \begin{matrix} Q_s^+ \\ \parallel \\ Q_s^- \end{matrix} \implies \lim_{q \rightarrow 0} \text{diagram} = \sum_{n=0}^{\infty} \omega^{-1+n} \mathbf{S}^{(0)} \times \text{diagram} + \dots
 \end{aligned}$$

Charges obey 2d higher-spin algebra

$Q_s^{(i)}$ are (non-linear) functionals of $\mathcal{N}, \mathcal{C}$ (canonically conjugate variables on gravity phase space)

- algebra computed from canonical bracket $\{\mathcal{N}(u, z), \mathcal{C}(u', z')\} \propto \delta(u - u')\delta^{(2)}(z, z')$

$$\{q_s(z), q_{s'}(z')\}^1 = \frac{\kappa^2}{8} \left[-(s' + 1) q_{s'+s-1}^1(z') D_z \delta(z, z') + (s + 1) q_{s'+s-1}^1(z) D_{z'} \delta(z, z') \right] \quad [\text{Freidel, Pranzetti, A.R. '21-'23}]$$

= $w_{1+\infty}$ algebra on the gravitational phase space

- Same algebra from OPE of gravitons in 2d CCFT & Poisson structure in (6d) twistor space [Guevara, Himwich, Pate, Strominger '21]

[Adamo, Mason, Sharma '21]

- Phase space construction extends in the presence of a cosmological constant: Λ -deformation of $w_{1+\infty}$!

[Di Giacomo, Micol, Pranzetti, A.R. '26]

2. Observables

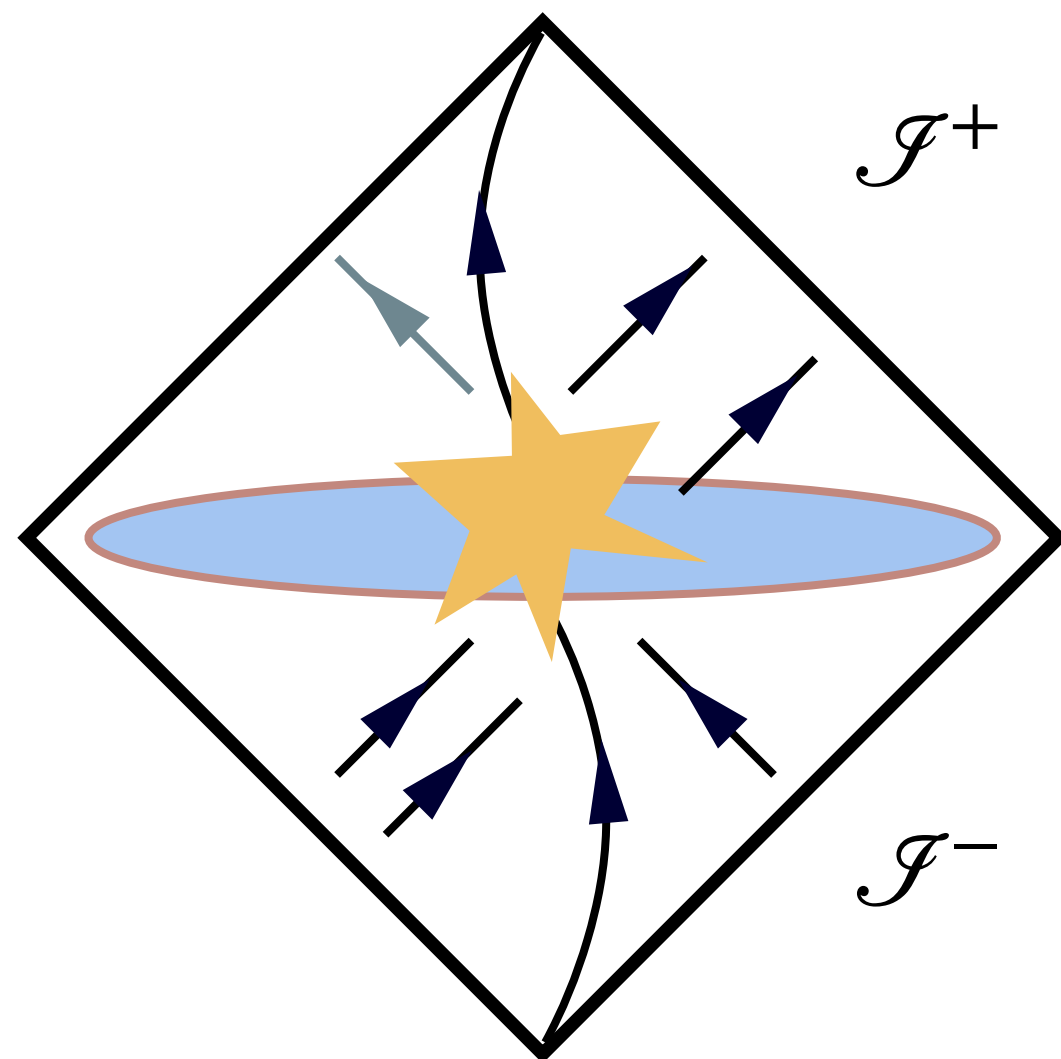
Carrollian/conformal primary wavefunctions

- Relation between asymptotic expansion of Einstein constraints and soft theorems was rather indirect

spacetime picture

momentum space amplitudes

Is there a class of observables on which symmetries act more naturally?



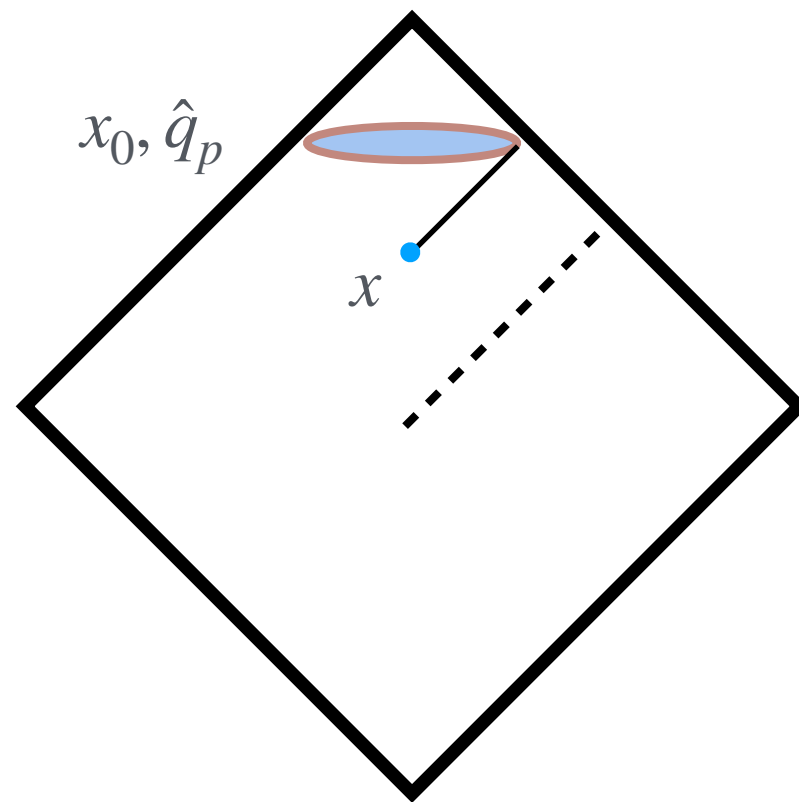
- Massless: correlation functions at null infinity
- Massive: correlation functions at timelike infinity
- AdS/CFT: correlation functions at spacelike infinity?

Carrollian/conformal primary wavefunctions

Standard quantization of free field: $\Phi(x) = \int \frac{d^3\vec{p}}{2\omega(2\pi)^d} (e^{-ip \cdot x} a^\dagger(\vec{p}) + e^{ip \cdot x} a(\vec{p}))$

Alternative quantizations: $\Phi(x) = \int d^2\hat{q}_p \int dt_p \left(\frac{1}{t - t_p - r\hat{q} \cdot \hat{q}_p} \mathcal{O}^\dagger(t_p, \hat{q}_p) + h.c. \right)$ Carrollian

$$= \int d^2\hat{q}_p \int d\Delta \left(\frac{1}{(t - r\hat{q} \cdot \hat{q}_p + i\epsilon)^\Delta} \widetilde{\mathcal{O}}_\Delta^\dagger(\hat{q}_p) + h.c. \right) \quad \text{Celestial}$$



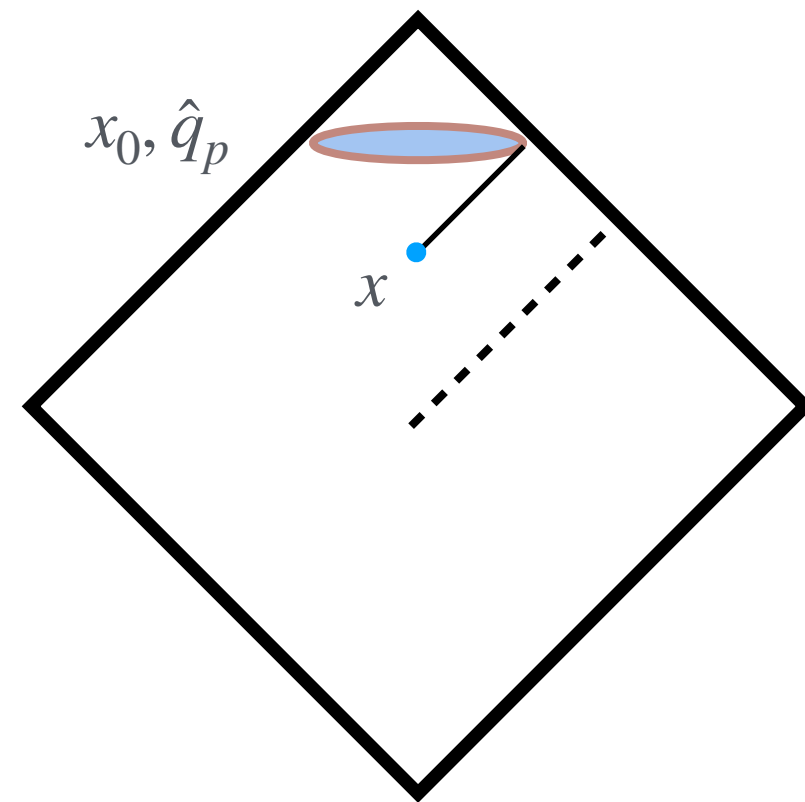
- $\Delta = 1, x_0$ arbitrary time: Carrollian wavefunctions [Poincare irreps]
- $x_0 = 0, \Delta$ arbitrary: conformal primary wavefunctions [Lorentz irreps]

[Pasterski, Shao, Strominger '16; Bagchi et. al.; reviews by AR, Donnay, Pasterski, Bagchi, Ruzziconi, etc.]

Carrollian/conformal primary wavefunctions

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$= \int d^2\hat{q}_p \int d\Delta \left(\frac{1}{(t - r\hat{q} \cdot \hat{q}_p + i\epsilon)^\Delta} \widetilde{\mathcal{O}}_\Delta^\dagger(\hat{q}_p) + h.c. \right)$ Celestial

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Carrollian amplitude: $\langle \mathcal{O}(t_1, \hat{q}_1) \cdots \rangle = \int_0^\infty d\omega e^{i\omega t_1} \mathcal{A}(\omega \hat{q}_1, \cdots)$

Celestial amplitude: $\langle \widetilde{\mathcal{O}}_{\Delta_1}(\hat{q}_1) \cdots \rangle = \int_0^\infty d\omega \omega^{\Delta-1} \mathcal{A}(\omega \hat{q}_1, \cdots)$

$\int_{-\infty}^\infty dt_1 t_1^{-\Delta}$ "light transform"

massless scattering amplitude

IR aspects of CCFT

Celestial amplitude

$$\langle \widetilde{\mathcal{O}}_{\Delta_1}(\hat{q}_1) \cdots \rangle = \int_0^\infty d\omega \omega^{\Delta_1-1} \mathcal{A}(\omega \hat{q}_1, \cdots) = \int_{-\infty}^\infty dt_1 t_1^{-\Delta_1} \langle \mathcal{O}(t_1, \hat{q}_1) \cdots \rangle$$

Carrollian amplitude

Bulk soft modes fall into integer $\Delta \leq 1$ representations of $sl(2, \mathbb{R}) \times sl(2, \mathbb{R})$:

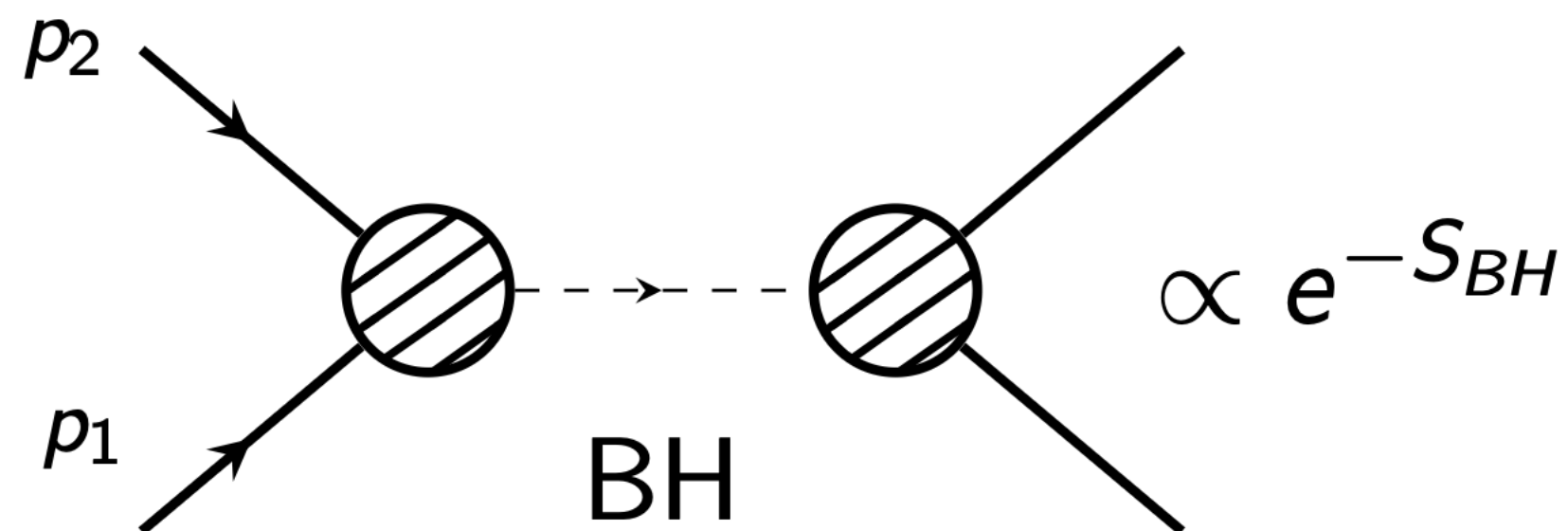
- leading soft mode: $\lim_{\omega \rightarrow 0} \omega \mathcal{O}(\omega, z, \bar{z}) = \lim_{\Delta \rightarrow 1} (\Delta - 1) \underbrace{\int_0^\infty d\omega \omega^{\Delta-1} \mathcal{O}(\omega, z, \bar{z})}_{\widetilde{\mathcal{O}}_\Delta(z, \bar{z})}$
- (sub)^k-leading soft modes: $\lim_{\Delta \rightarrow 1-k} (\Delta - 1 + k) \widetilde{\mathcal{O}}_\Delta(z, \bar{z})$ [= coeff. in late time expansion of Carrollian amplitude]
[= CCFT dual operators to higher-spin bulk charges]

IR expansion of 4d amplitude $\implies$ Celestial amplitudes have poles at negative integer Δ

Carrollian amplitudes have power-law decay at late time

UV properties of CCFT

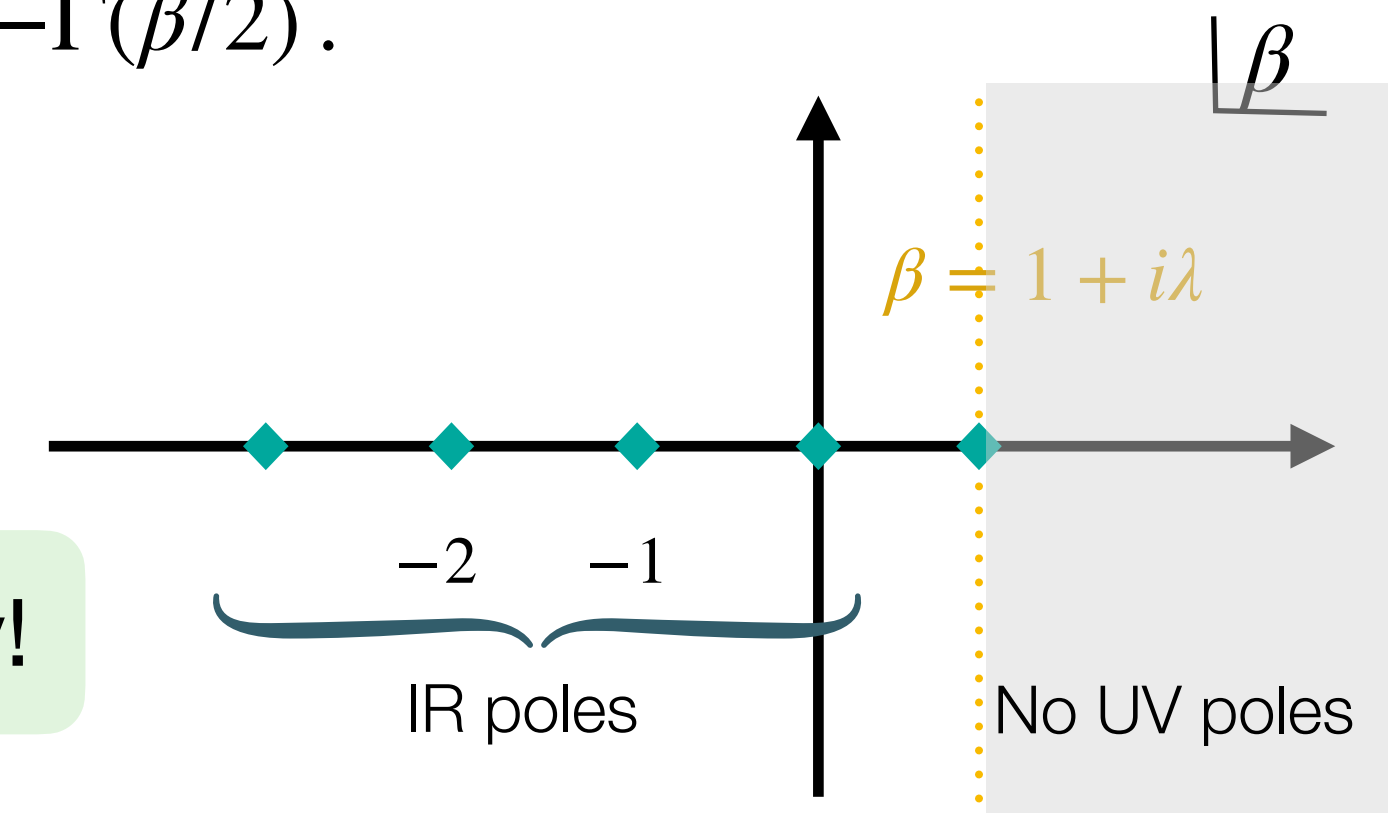
- Poles in the RH complex dimension plane related to high-energy expansion of 4d amplitude
- Black holes expected to lead to exponential suppression at high energy:



$$S_{BH} \sim \omega^2/M_{Pl}^2 \implies \mathcal{A} \rightarrow e^{-\omega^2/M_{Pl}^2}, \quad \omega \rightarrow \infty$$

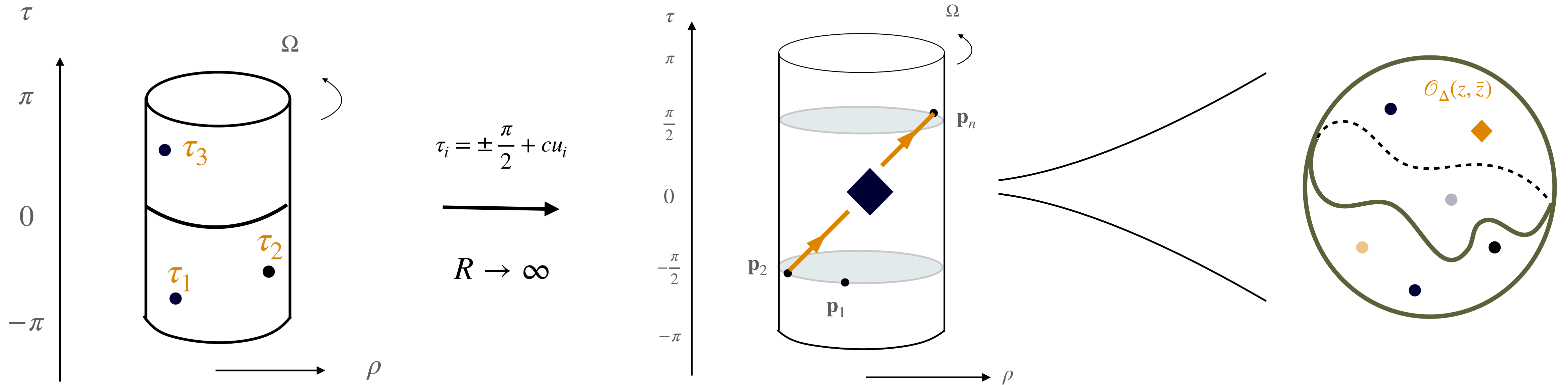
$$\widetilde{\mathcal{A}} \rightarrow \int_0^\infty d\omega \omega^{\beta-1} e^{-\omega^2/M^2} = \frac{M^\beta}{2} \Gamma(\beta/2).$$

Exponentially soft behavior at high energies erases the UV poles in quantum gravity!



3. Flat from (A)dS

Carrollian limits of 3d CFT



@large R, AdS_{d+1} bulk-to-boundary propagator $K_\Delta(P; X) \Big|_{\tau_p = \pm \frac{\pi}{2} + cu} \rightarrow \frac{C_\Delta^{d=3} c^{1-\Delta}}{i^\Delta \Gamma(\Delta)} \varphi_\Delta^\pm(x - \boxed{x_0}; \hat{q})$ $x_0 = (u, 0, 0, 0)$

$\int_{-\infty}^{\infty} du u^{-\lambda} \Rightarrow \text{CCFT}_2 \text{ wavefunction with } \Delta_{\text{CCFT}} = \Delta + \lambda - 1$

From AdS to flat space wavefunctions

All (kinematic) flat space results follow from limits of AdS

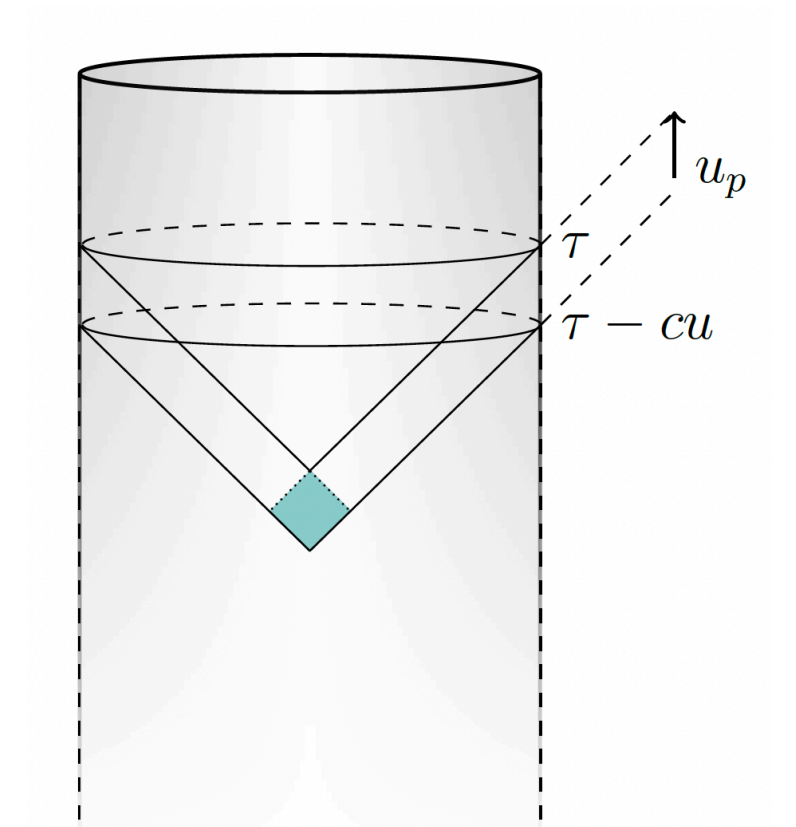
4d Poincare = Inonu-Wigner contraction of 4d (A)dS isometry algebra

Bulk: IW contraction = flat space limit

- $so(3,2)$ covariant “bulk reconstruction” in AdS admits equivalent representations

$$\Phi(X) = \int_B d^3P G_{\Delta}^{\text{T.O.}}(P; X) \widetilde{\mathcal{O}}_{3-\Delta}^{-}(P) + \int_B d^3P G_{\Delta}^{\text{A.T.O.}}(P; X) \widetilde{\mathcal{O}}_{3-\Delta}^{+}(P)$$

- Flat space limit identifies 3d Carrollian operators with 3d CFT shadows!



[Navarro, A.R. '25, '26]

Infinite towers of 2d symmetry algebras from 3d CFT

Boundary: IW contraction = Carrollian limit

AdS/CFT $\implies$ gluons dual to conserved currents, gravitons dual to the stress tensor $\implies$

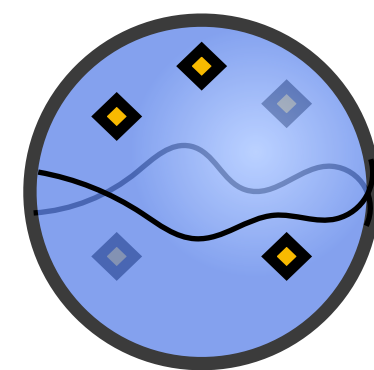
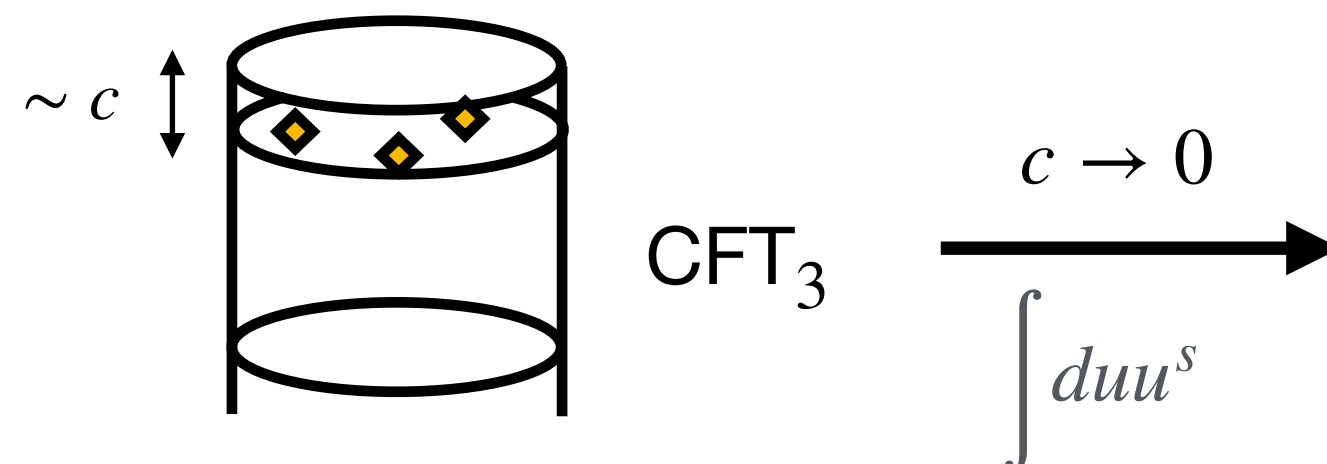
- OPE blocks of (eg.) the stress tensor in CFT_3 encodes 3d Carrollian/2d celestial tower of higher-spin operators:

$$T^+ \equiv Z_+^{\mu\nu} T_{\mu\nu} \leftrightarrow \text{positive helicity graviton}$$

$$\lim_{c \rightarrow 0} T^+(cu, z, \bar{z}) \sim \mathcal{T}^+(u, z, \bar{z}) = \sum_n u^n \mathcal{G}_{3+n}^+(z, \bar{z})$$

$$P = P(x) = P(t, z, \bar{z})$$

$$\oint du_1 u_1^{s_1} \oint du_2 u_2^{s_2} \lim_{c \rightarrow 0} T^+(cu_1, \vec{z}_1) T^+(cu_2, \vec{z}_2) \sim \underbrace{\mathcal{G}_{2-s_1}^+(\vec{z}_1) \mathcal{G}_{2-s_2}^+(\vec{z}_2)}$$



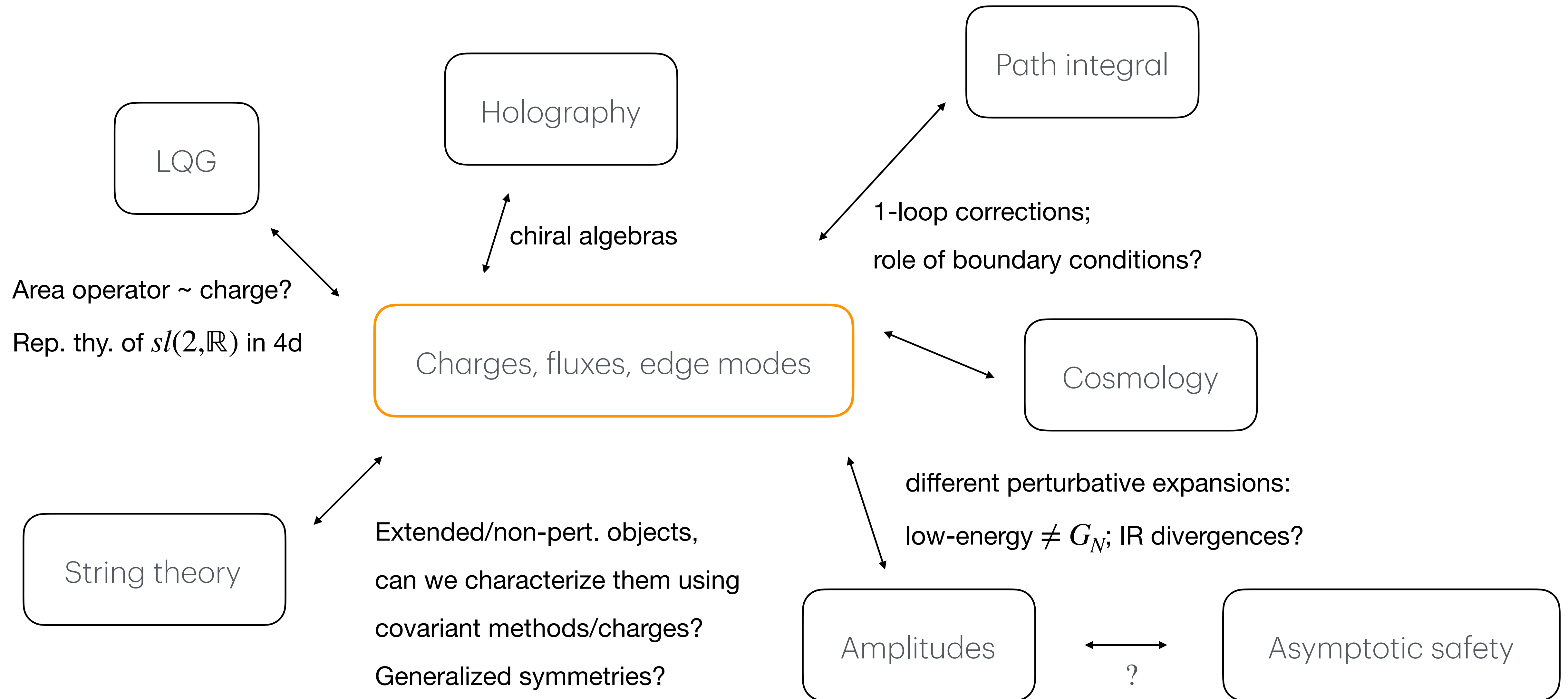
CCFT_2

2d OPE block of conformal primary gravitons

It works!

[de Gioia, AR '25]

Connections across QG



Summary & Outlook

- Tower-of higher spin charges in 4d AFS = operators obeying the $w_{1+\infty}$ algebra in 2d CFT
- IR and UV properties of 4d scattering amplitudes = analytic structure of 3d/2d CCFT correlators
- Analog statements in 4d (A)dS all of which reduce to flat space results in appropriate limits

- unified picture of light-ray operators and other defects in gravity?
- implications for gravitational observables?

Thank you!

Backup

IR properties (collinear limits)

$$G_{\Delta_1}^{++}(z_1)G_{\Delta_2}^{\pm\pm}(z_2) \sim -\frac{\kappa}{2}\frac{1}{z_{12}}\sum_{n=0}^{\infty}B(2\bar{h}_1+1+n,2\bar{h}_{2\pm}+1)\frac{\bar{z}_{12}^{n+1}}{n!}\bar{\partial}^n G_{\Delta_1+\Delta_2}^{\pm\pm}(z_2)+\mathcal{O}(z_{12}^0)$$

[Taylor, Zhu '23]

$$+\frac{\kappa\Lambda}{2}\frac{c(\Delta_1,\Delta_2)}{z_{12}^2}\sum_{n=0}^{\infty}B(\Delta_1-2+n,\Delta_2-2)\frac{\bar{z}_{12}^n}{n!}\bar{\partial}^n G_{\Delta_1+\Delta_2-2}^+(z_2)+\frac{\kappa\Lambda}{2}\frac{d(\Delta_1,\Delta_2)}{z_{12}}\sum_{n=0}^{\infty}B(\Delta_1-2+n,\Delta_2-2)\frac{\bar{z}_{12}^n}{n!}\partial\bar{\partial}^n G_{\Delta_1+\Delta_2-2}^+$$

- Gives rise to the Λ -deformed algebra:

$$[w_{a,m}^p, w_{b,n}^q] = (m(q-1) - n(p-1)) w_{a+b,m+n}^{p+q-2} - \Lambda [a(q-2) - b(p-2)] w_{a+b,m+n}^{p+q-1}$$

- SO(3,2) subalgebra generated by $w_{a,0}^1, w_{0,m}^2$ ($a, m = -1, 0, 1$), and $w_{\pm\frac{1}{2}, \pm\frac{1}{2}}^{\frac{3}{2}}$, contracts to Poincare as $\Lambda \rightarrow 0$