Title: Piecing Together a Flat Hologram

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Collection: Puzzles in the Quantum Gravity Landscape: viewpoints from different approaches

Date: October 23, 2023 - 12:05 PM

URL: https://pirsa.org/23100061

Abstract: The Celestial Holography program encompasses recent efforts to understand the flat space hologram in terms of a CFT living on the celestial sphere. A key development instigating these efforts came from understanding how soft limits of scattering encode infinite dimensional symmetry enhancements corresponding to the asymptotic symmetry group of the bulk spacetime. Historically, the construction of the bulk-boundary dual pair has followed bottom up approach matching symmetries on both sides. Recently, however, there has been exciting progress in formulating top down descriptions using insights from twisted holography. We review salient aspects of the celestial construction, the status of the dictionary, and active research directions.


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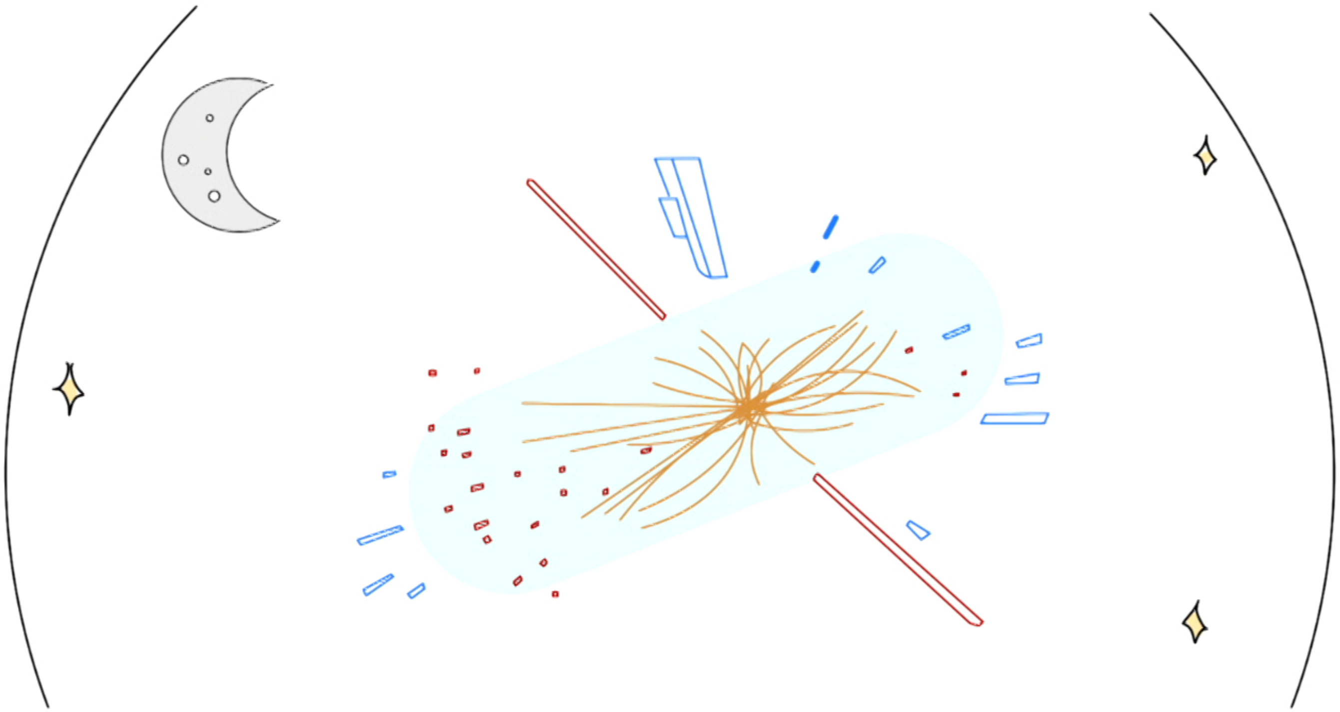
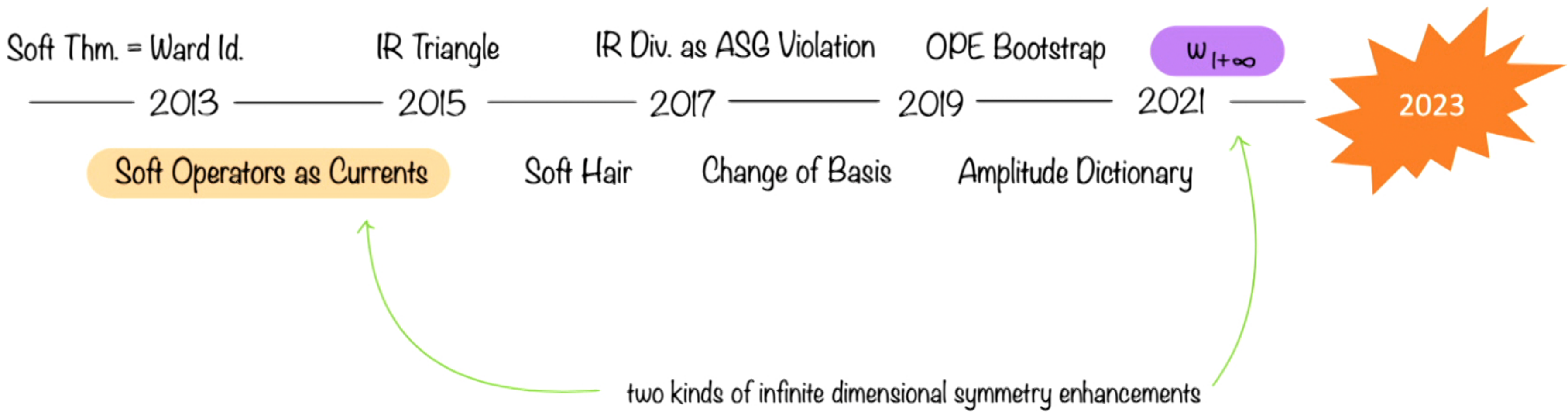
Piecing Together a Flat Hologram
Sabrina Pasterski

The Celestial Conjecture:

scattering in asymptotically flat spacetimes is dual to a CFT living on the celestial sphere

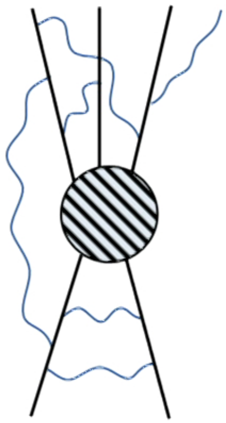


This program evolved from a **bottom-up** approach to flat holography…



… recognizing **soft theorems as Ward Identities** for asymptotic symmetries and recasting the **soft operators as currents** in a codimension 2 CFT.

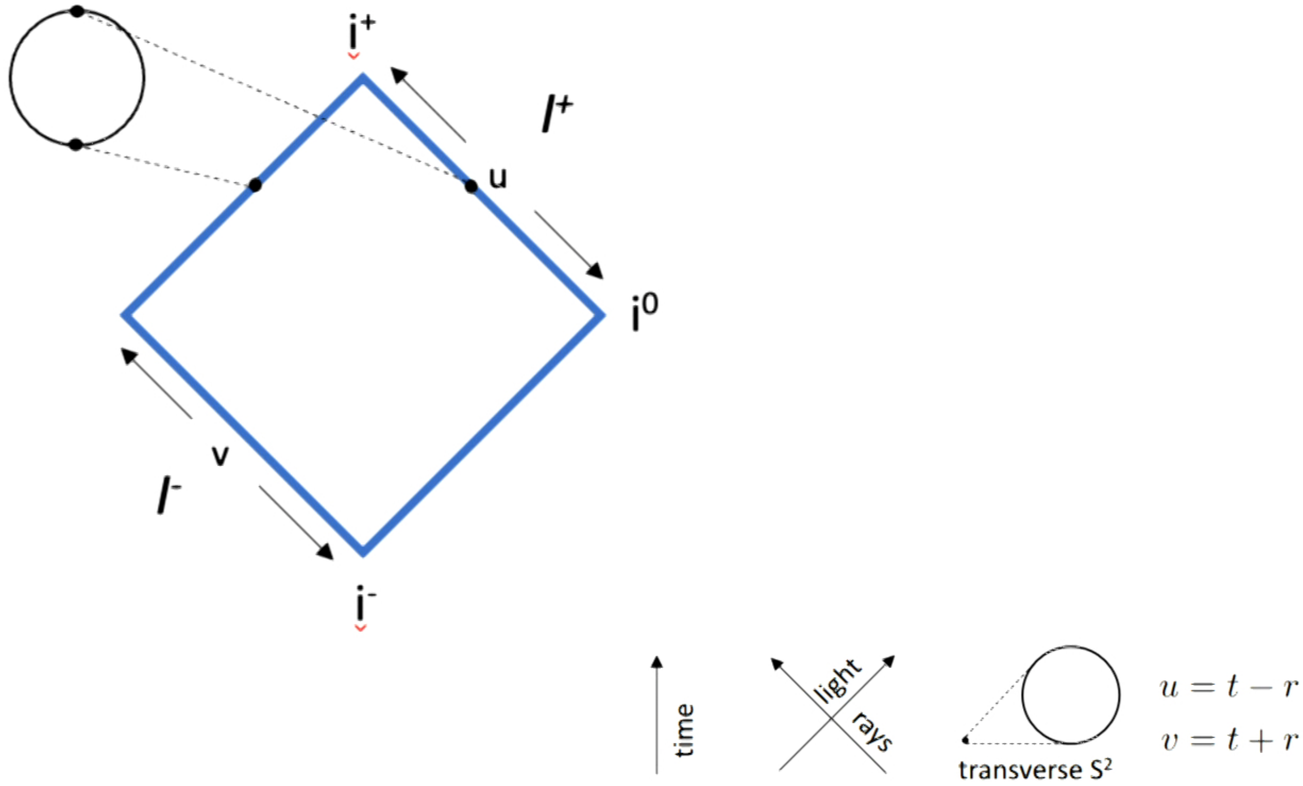
Soft Thm = Ward Id



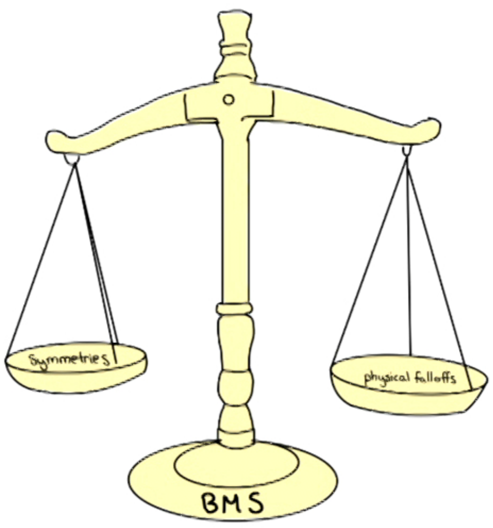
$$\Leftrightarrow \qquad \langle out|Q^+[Y]\mathcal{S} - \mathcal{S}Q^-[Y]|in\rangle = 0$$

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2$$

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$



i+
I+
u
i0
v
I-
i-
time
light
rays
transverse S2
$u = t - r$
$v = t + r$



$$\text{ASG} = \frac{\text{allowed gauge symmetries}}{\text{trivial gauge symmetries}}$$

In Bondi gauge the metric near future null infinity takes the form

$$\begin{aligned} ds^2 &= -du^2 - 2dudr + 2r^2\gamma_{z\bar{z}}dzd\bar{z} + 2\frac{m_B}{r}du^2 \\ &+\left(rC_{zz}dz^2 + D^zC_{zz}dudz + \frac{1}{r}\left(\frac{4}{3}N_z - \frac{1}{4}\partial_z(C_{zz}C^{zz})\right)dudz + c.c.\right) + \ldots \end{aligned}$$

Radiative Data

which is preserved by the residual diffeomorphisms

$$\begin{aligned} \xi^+ =& \left(1+\frac{u}{2r}\right)Y^{+z}\partial_z - \frac{u}{2r}D^{\bar{z}}D_zY^{+z}\partial_{\bar{z}} - \frac{1}{2}(u+r)D_zY^{+z}\partial_r + \frac{u}{2}D_zY^{+z}\partial_u + c.c \\ &+ f^+\partial_u - \frac{1}{r}\left(D^zf^+\partial_z + D^{\bar{z}}f^+\partial_{\bar{z}}\right) + D^zD_zf^+\partial_r \end{aligned}$$

Superrotations

Supertranslations

$$8\pi G Q^+[Y] = \int_{\mathcal{I}^+} \sqrt{\gamma} d^2z du \, \left[-\frac{1}{2} D_z^3 Y^z u \partial_u C^{zz} + Y^z T_{uz} + u D_z Y^z T_{uu} + h.c. \right]$$

$$Q^+[Y] = Q_S^+[Y] + Q_H^+[Y]$$

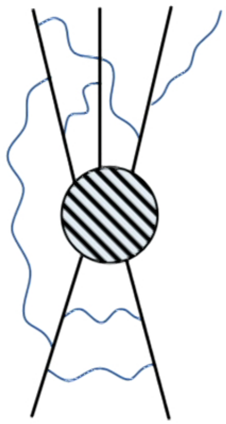
$$h_{\mu\nu}(x) = \sum_{\alpha=\pm} \int \frac{d^3q}{(2\pi)^3} \frac{1}{2\omega_q} \left[\epsilon^{\alpha *}_{\mu\nu}(\vec{q}) a_\alpha(\vec{q}) e^{iq\cdot x} + \epsilon^{\alpha}_{\mu\nu}(\vec{q}) a_\alpha(\vec{q})^\dagger e^{-iq\cdot x}\right]$$

radiative mode

$$C_{\bar{z}\bar{z}} = 2 \lim_{r\to\infty} \frac{1}{r} \partial_{\bar{z}} x^\mu \partial_{\bar{z}} x^\nu \sum_{\alpha=\pm} \int \frac{d^3q}{(2\pi)^3} \frac{1}{2\omega_q} \left[\epsilon^{\alpha *}_{\mu\nu}(\vec{q}) a_\alpha(\vec{q}) e^{-i\omega_q u - i\omega_q r(1-\cos\theta)} + h.c.\right]$$

saddle

$$C_{\bar{z}\bar{z}} = -\frac{i}{4\pi^2} \hat{\epsilon}^{+}_{\bar{z}\bar{z}} \int_0^\infty d\omega_q [a_-(\omega_q \hat{x}) e^{-i\omega_q u} - a_+(\omega_q \hat{x})^\dagger e^{i\omega_q u}]$$



$$\langle out|a_-(q)\mathcal{S}|in\rangle = \left(S^{(0)-} + S^{(1)-}\right)\langle out|\mathcal{S}|in\rangle + \mathcal{O}(\omega)$$

$$S^{(0)-} = \sum_k \frac{(p_k \cdot \epsilon^-)^2}{p_k \cdot q} \qquad S^{(1)-} = -i\sum_k \frac{p_{k\mu}\epsilon^{-\mu\nu}q^\lambda J_{k\lambda\nu}}{p_k \cdot q}$$

Soft Thm = Ward Id

$$< out|Q^+[Y]\mathcal{S} - \mathcal{S}Q^-[Y]|in >= 0$$

$$Q^+[Y] = Q^+_S[Y] + Q^+_H[Y]$$

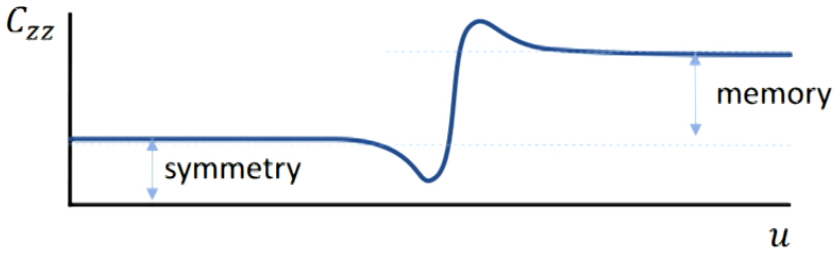
$$Q^+_S[Y] = \frac{1}{2}\int_{\mathcal{I}^+} du d^2z D_z^3 Y^z u \partial_u C^z_{\bar{z}}$$

$$Q^+_H[Y] = \lim_{\Sigma \to \mathcal{I}^+} \int_\Sigma d\Sigma \, \xi^\mu n^\nu_\Sigma T^M_{\mu\nu}$$

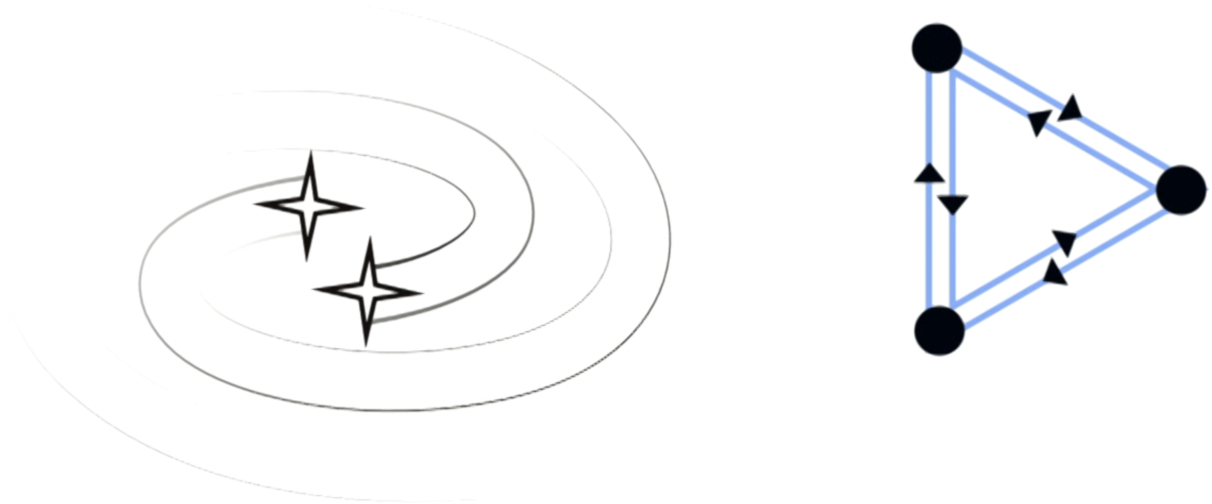
$$\langle out|a_-(q)\mathcal{S}|in\rangle = \left(S^{(0)-} + S^{(1)-}\right)\langle out|\mathcal{S}|in\rangle + \mathcal{O}(\omega)$$

$$S^{(1)-} = -i\sum_k \frac{p_{k\mu}\epsilon^{-\mu\nu}q^\lambda J_{k\lambda\nu}}{p_k \cdot q}$$

Soft Thm = Memory



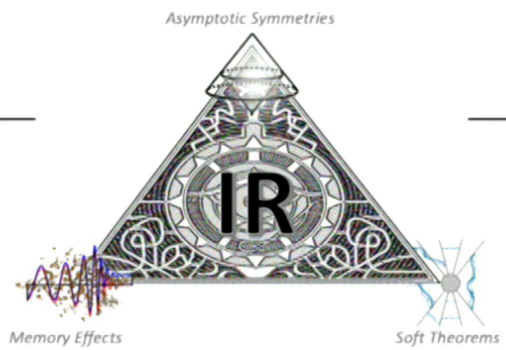
Soft Thm = Memory



IR Triangle

Our story starts with Strominger's suggestion that...

The relativists were systematizing what happens at long distances...



The quantum field theorists were worried about what was going on at low energies...

And, a little later, someone remembered there was a physical observable attached to each of these things....

IR Triangle

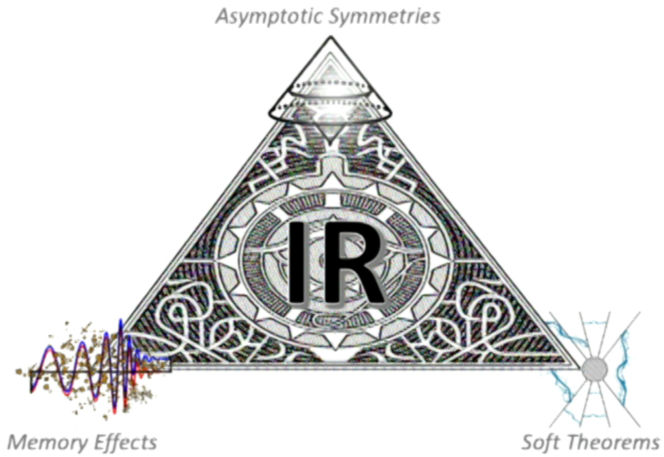
Boost Basis

2D Stress Tensor

Superrotation
Symmetry

New Subleading
Soft Graviton Thm.

Spin Memory



4D Soft Mode = 2D Current

For a particular choice of Y

$$T_{zz} = 2iQ_S^+(Y^w = \frac{1}{z-w}, Y^{\bar{w}} = 0)$$

the superrotation Ward Id takes the form of a 2D stress tensor Ward Id.

$$\langle T_{zz}\mathcal{O}_1 \cdots \mathcal{O}_n \rangle = \sum_{k=1}^{n} \left[\frac{h_k}{(z-z_k)^2} + \frac{\Gamma^{z_k}_{z_k z_k}}{z-z_k} h_k + \frac{1}{z-z_k} \left(\partial_{z_k} - |s_k| \Omega_{z_k} \right) \right] \langle \mathcal{O}_1 \cdots \mathcal{O}_n \rangle$$

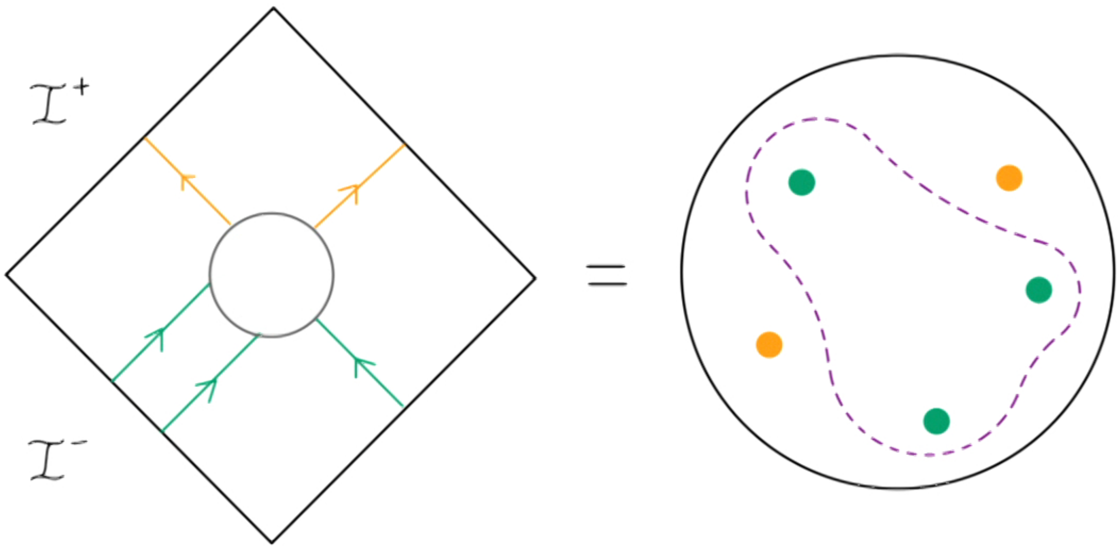
subleading soft graviton theorem = Ward identity for 4D superrotations = Ward identity for 2D stress tensor

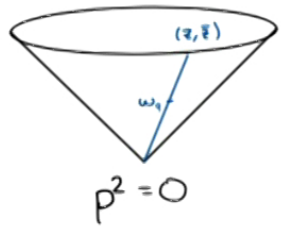
the asymptotic symmetry is physical

subleading soft graviton theorem = Ward identity for 4D superrotations = Ward identity for 2D stress tensor

we should look for a 2D dual CFT

4D Soft Mode = 2D Current



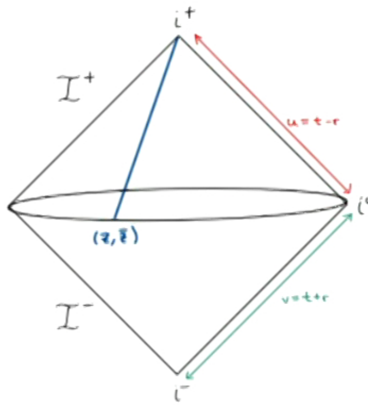


4D Amplitude = 4D Correlator

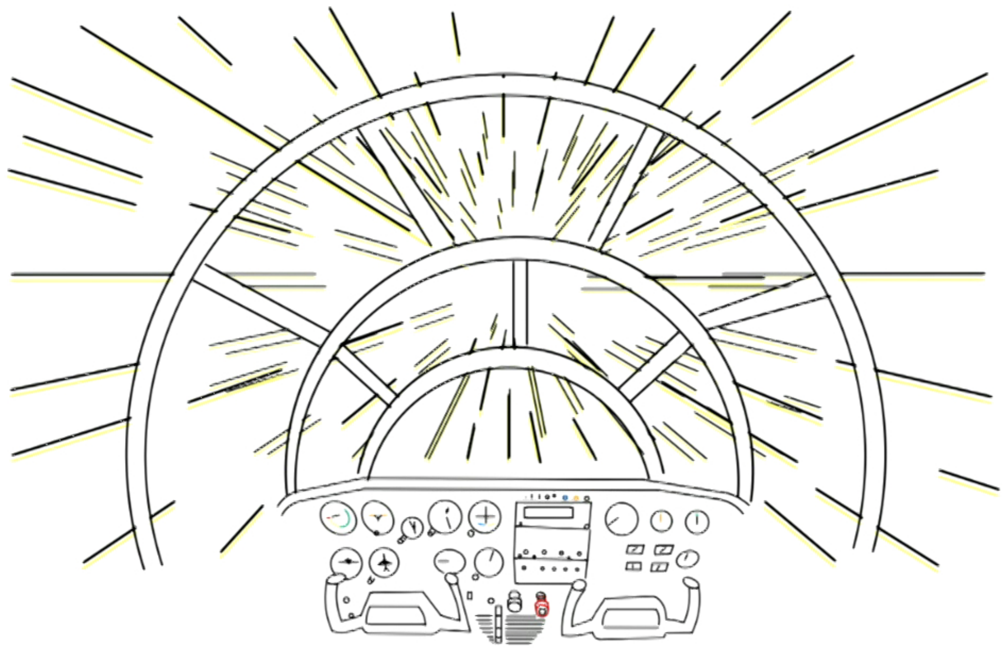
LSZ ⇔ Extrapolate Dict.

$$\langle out|S|in\rangle_{boost} = \prod_i \lim_{r\to\infty}\int_{-\infty}^{\infty} \mathrm{d}\nu_i\, \nu_i^{-\Delta_i}\, \langle r\Phi(\nu_1,r,z_1,\bar{z}_1)...r\Phi(\nu_n,r,z_n,\bar{z}_n)\rangle$$

$$\nu = \{u, v\}$$



4D Amplitude = 2D Correlator

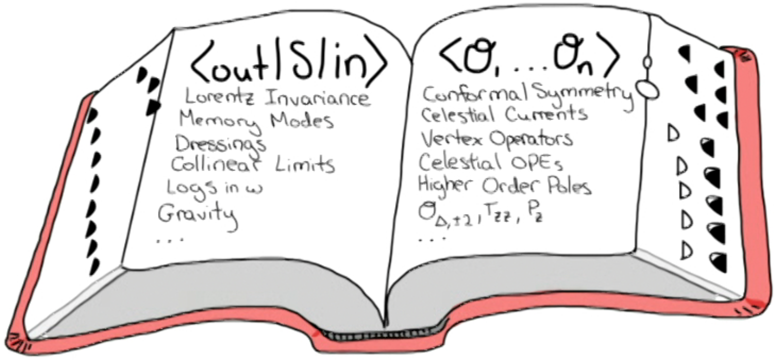


4D Amplitude = 2D Correlator

4D Lorentz invariance = 2D global conformal symmetry

$$\langle \mathcal{O}^{\pm}_{\Delta_1}(z_1,\bar{z}_1)...\mathcal{O}^{\pm}_{\Delta_n}(z_n,\bar{z}_n)\rangle = \prod_{i=1}^{n}\int_0^{\infty} d\omega_i \omega_i^{\Delta_i-1}\langle out|\mathcal{S}|in\rangle$$

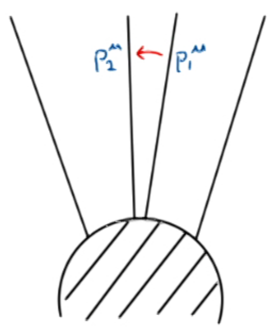
If we go to a boost basis, amplitudes transform as CFT correlators under the Lorentz group.

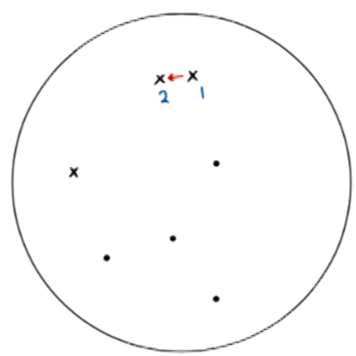


Collinear Limit = OPE

$$\mathcal{O}_{\Delta_1,+2}(z_1,\bar z_1)\mathcal{O}_{\Delta_2,+2}(z_2,\bar z_2) \sim -\frac{\kappa}{2}\frac{\bar z_{12}}{z_{12}}B(\Delta_1-1,\Delta_2-1)\mathcal{O}_{\Delta_1+\Delta_2,+2}(z_2,\bar z_2)+\ldots\ ,$$

$$\begin{aligned}\mathcal{O}_{\Delta_1,+2}(z_1,\bar z_1)\mathcal{O}_{\Delta_2,-2}(z_2,\bar z_2) \sim &-\frac{\kappa}{2}\frac{\bar z_{12}}{z_{12}}B(\Delta_1-1,\Delta_2+3)\mathcal{O}_{\Delta_1+\Delta_2,-2}(z_2,\bar z_2)\\ &-\ \frac{\kappa}{2}\frac{z_{12}}{\bar z_{12}}B(\Delta_1+3,\Delta_2-1)\mathcal{O}_{\Delta_1+\Delta_2,+2}(z_2,\bar z_2)+\ldots\ ,\end{aligned}$$





2D Radial Quantization → More Symmetries

For special weights, the SL(2,C) multiplets have primary descendants.

$$H^k(z,\bar{z}) \;:=\; \lim_{\epsilon\to 0} \epsilon\, \mathcal{O}_{k+\epsilon,2}(z,\bar{z}), \quad \Delta = k \;=\; 2,1,0,-1,\ldots$$

Assuming these multiplets shorten, we have

$$H^k(z,\bar{z}) \;=\; \sum_{m=\frac{k-2}{2}}^{\frac{2-k}{2}} \bar{z}^{-\frac{k-2}{2}-m} H^k_m(z)\;, \qquad w^p_n \;=\; \frac{1}{\kappa}\,(p-n-1)!(p+n-1)!\, H_n^{-2p+4}$$

2D Radial Quantization → More Symmetries

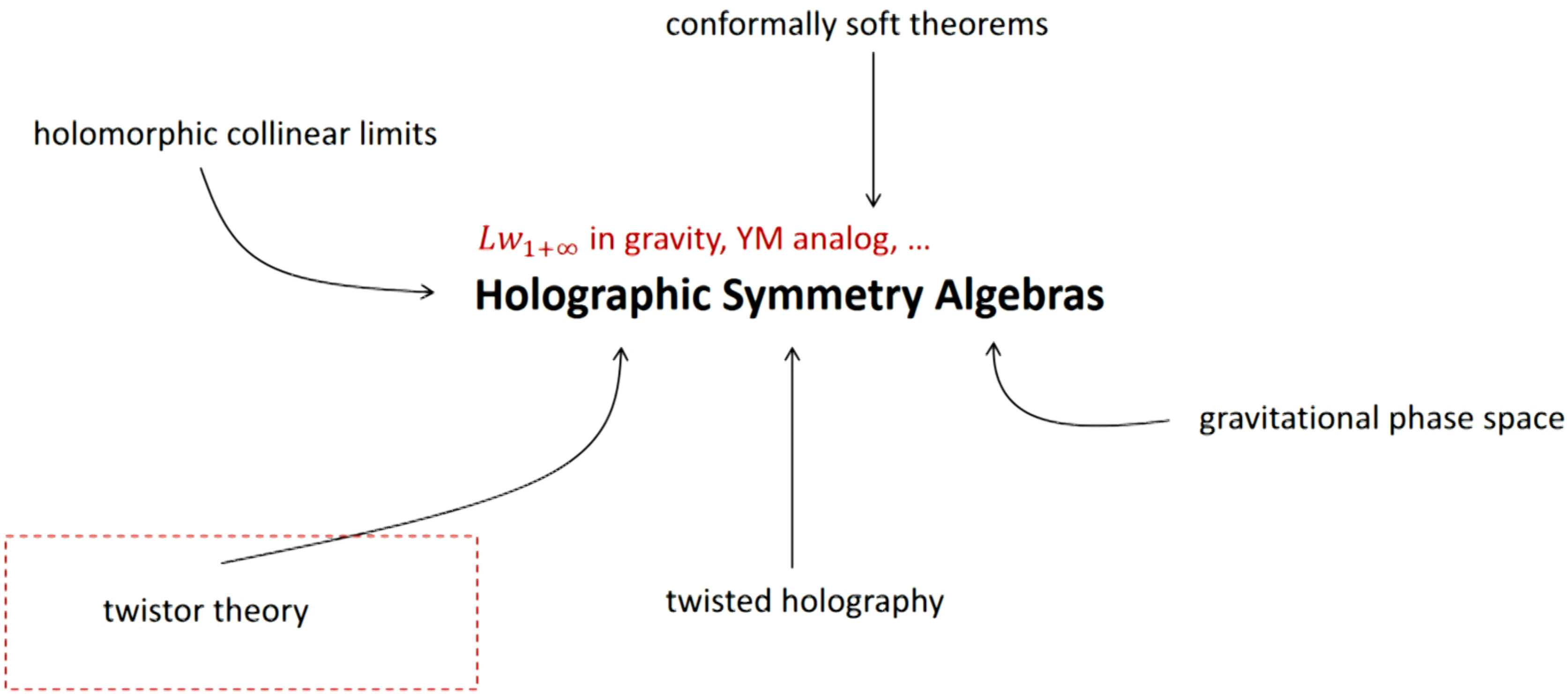
Complexifying the celestial sphere variables and defining a holomorphic commutator

$$[A, B](z) \;=\; \frac{1}{2\pi i}\oint_z dw\, A(w)B(z)$$

gives a $Lw_{1+\infty}$ symmetry algebra for appropriately rescaled modes

$$\Big[w^p_n, w^q_m\Big](z) \;=\; \Big[n(q-1) - m(p-1)\Big]\, w^{p+q-2}_{m+n}(z)$$

Celestial Algebra = Sym of SDG

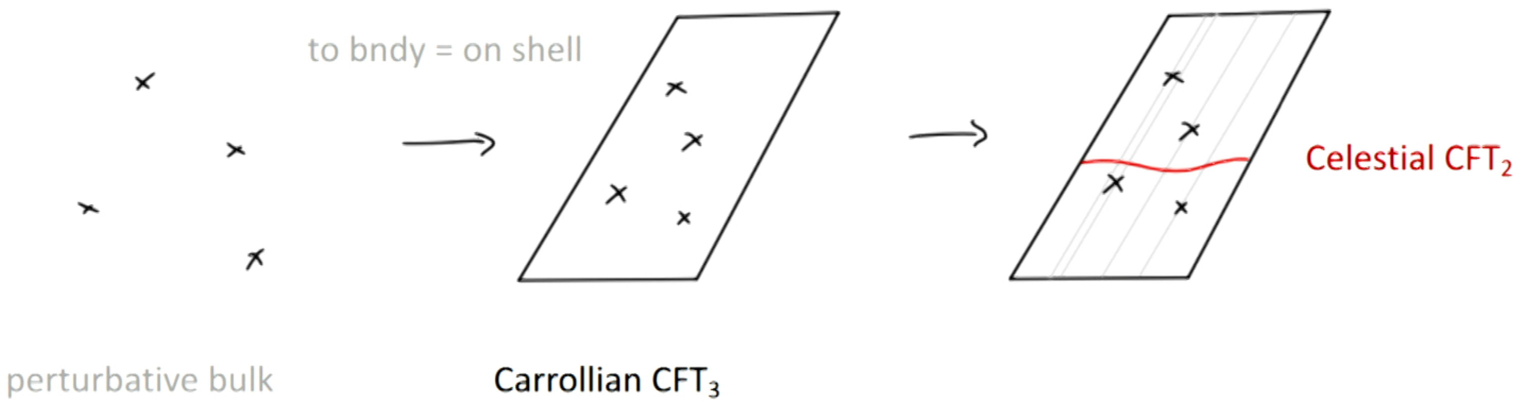


Do these symmetries beyond tree level, or the self-dual sector?

Can we realize them in the matter sector?

Can we really complexify the celestial sphere to define these currents?

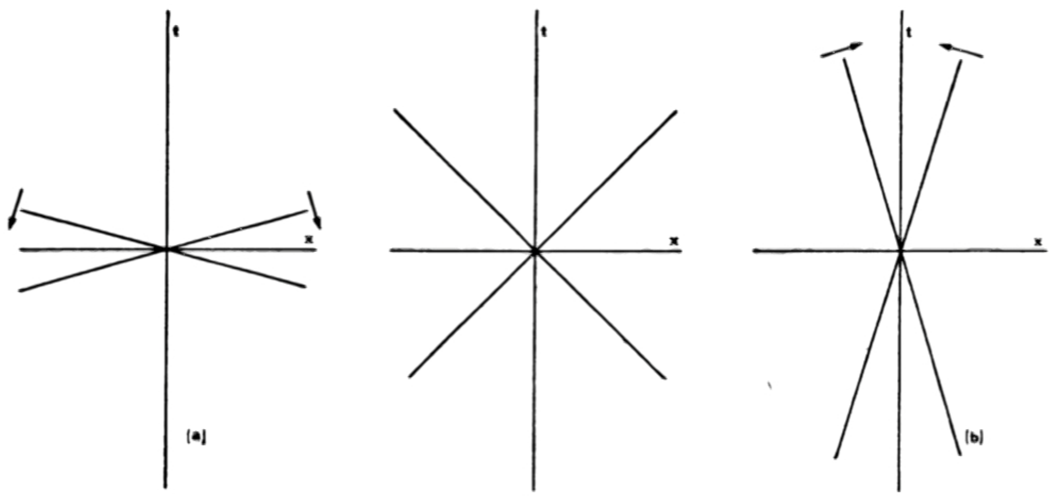
Celestial = Carrollian



Celestial = Carrollian

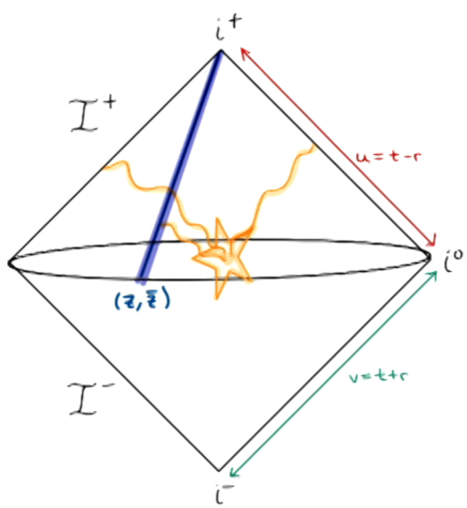
$$ds^2 = -c^2 dt^2 + d\vec{x}^2$$

$c \to \infty$	$c = 1$	$c \to 0$
Galilean	Lorentzian	Carrollian



Hard Charges = Light Ray Operators

$$Q^{\mathcal{I}^+}_{H,matter} \quad \Leftrightarrow \quad \mathcal{E}(z,\bar{z}) = \lim_{r\to\infty} r^2 \int du\, T_{uu}(u,r,z,\bar{z})$$



Hard Charges = Light Ray Operators

CCFT

$$\langle \mathcal{O}^{\pm}_{\Delta_1}(z_1, \bar{z}_1)...\mathcal{O}^{\pm}_{\Delta_n}(z_n, \bar{z}_n)\rangle$$

Single Particle

Exclusive

vs

Conformal Colliders

$$\frac{\langle 0|\mathcal{O}^{\dagger}\mathcal{E}(\theta_1)\cdots\mathcal{E}(\theta_n)\mathcal{O}|0\rangle}{\langle 0|\mathcal{O}^{\dagger}\mathcal{O}|0\rangle}$$

2-Particle

Inclusive

Hard Charges = Light Ray Operators

CCFT

$$\langle \mathcal{O}^{\pm}_{\Delta_1}(z_1, \bar{z}_1)...\mathcal{O}^{\pm}_{\Delta_n}(z_n, \bar{z}_n) \rangle$$

Single Particle

Exclusive

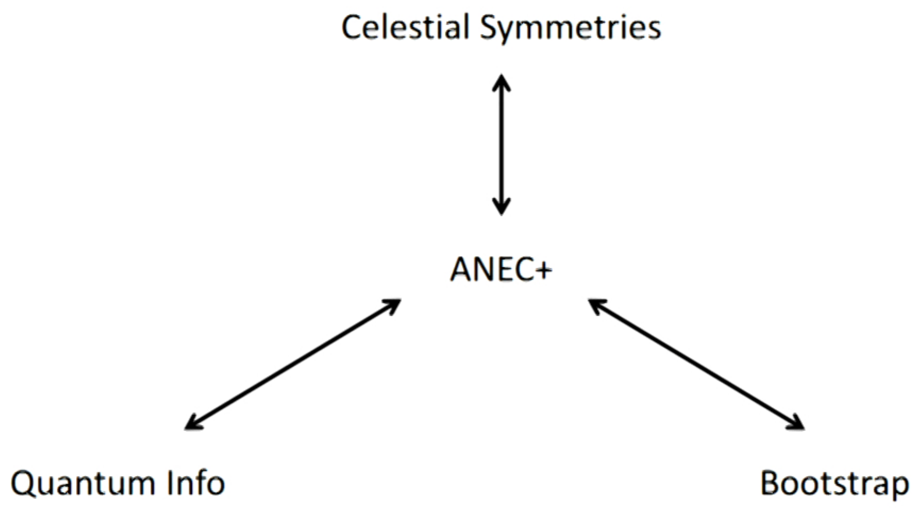
vs

Conformal Colliders

$$\frac{\langle 0|\mathcal{O}^\dagger \mathcal{E}(\theta_1)\cdots\mathcal{E}(\theta_n)\mathcal{O}|0\rangle}{\langle 0|\mathcal{O}^\dagger\mathcal{O}|0\rangle}$$

2-Particle

Inclusive


Celestial Symmetries
ANEC+
Quantum Info
Bootstrap

Amplitudes

soft and collinear factorization

IR finite S-matrix

It From Qubit

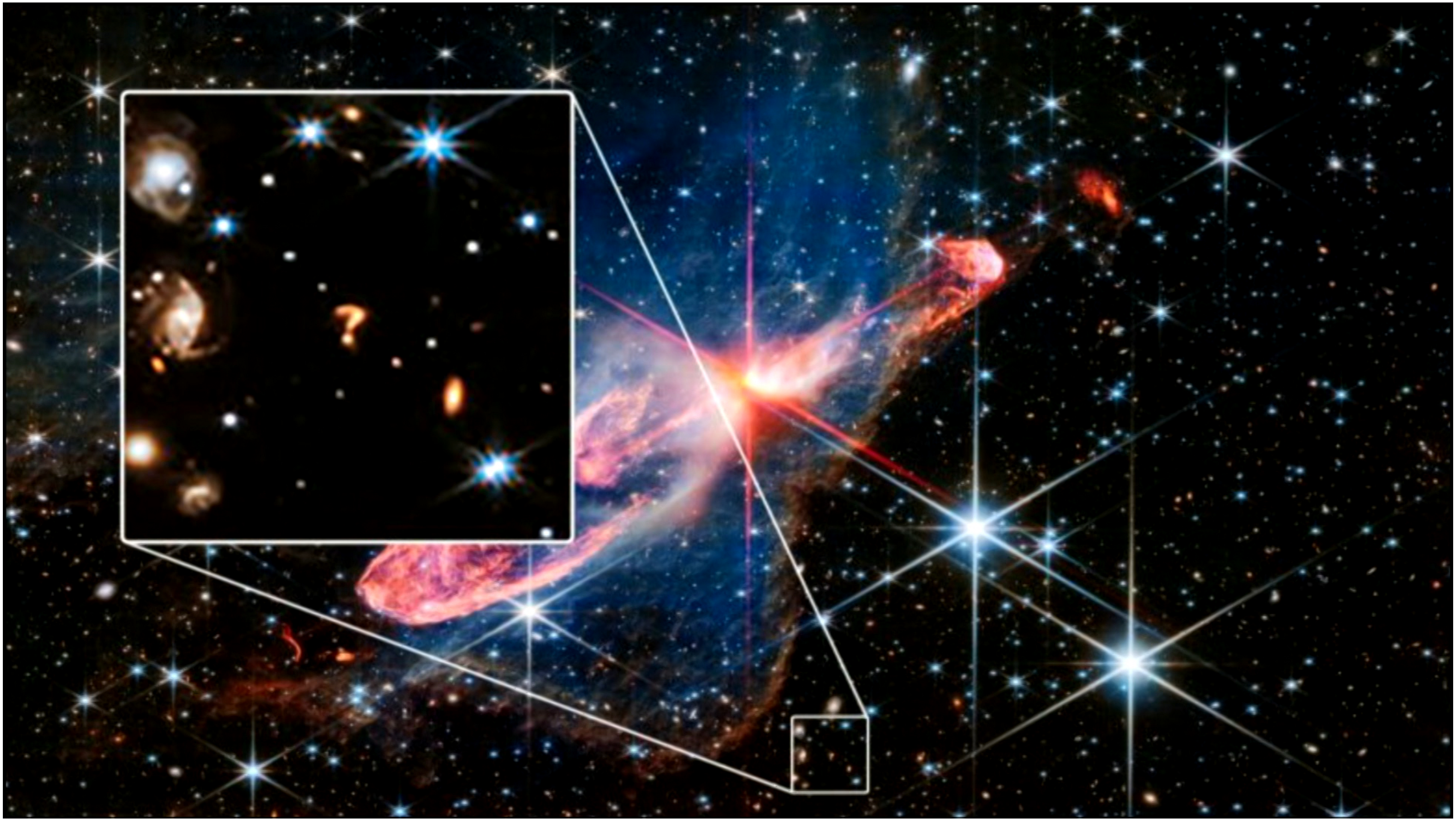
conformal colliders

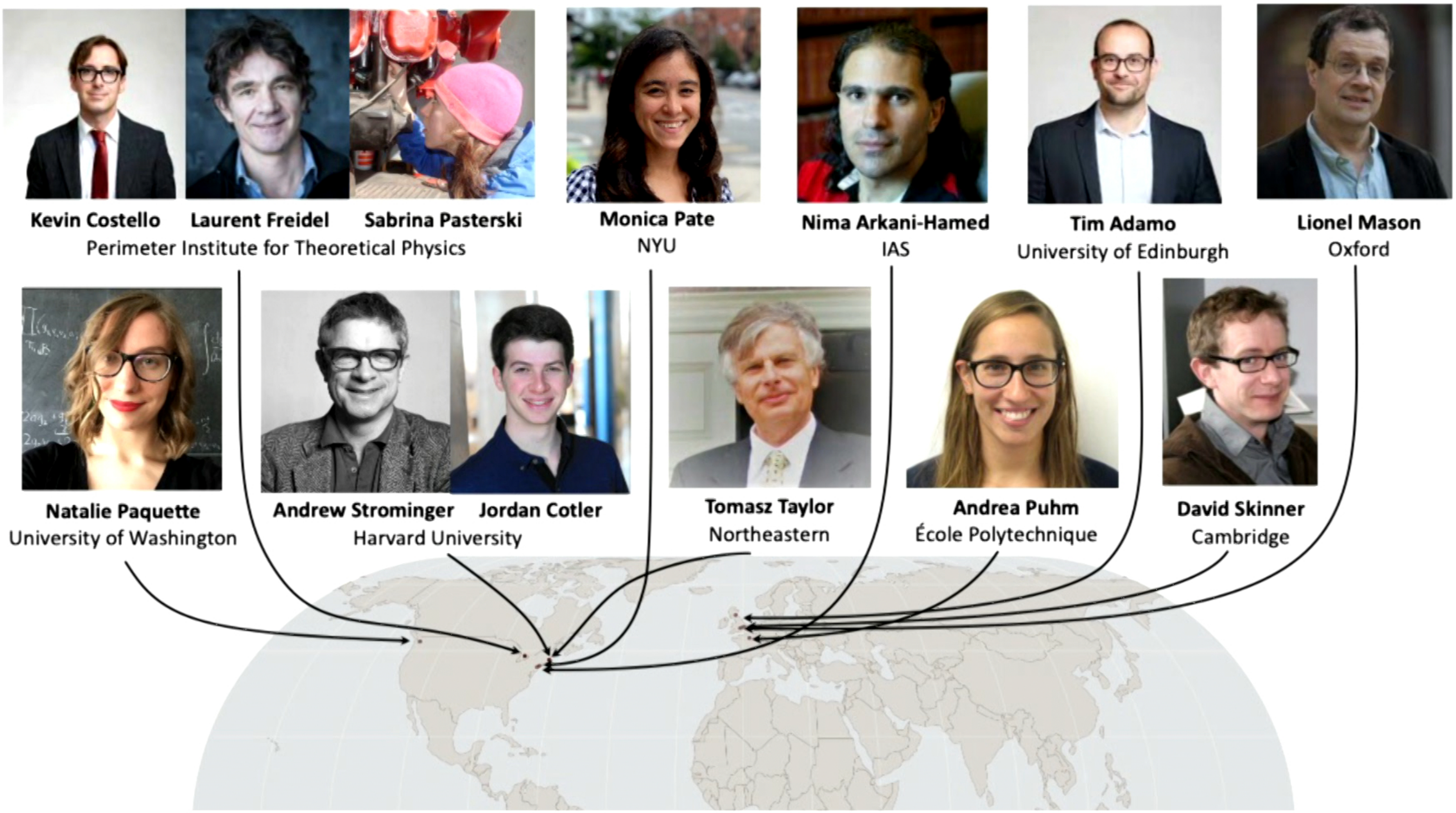
detector operators

light ray operators

complex spin

Bootstrap

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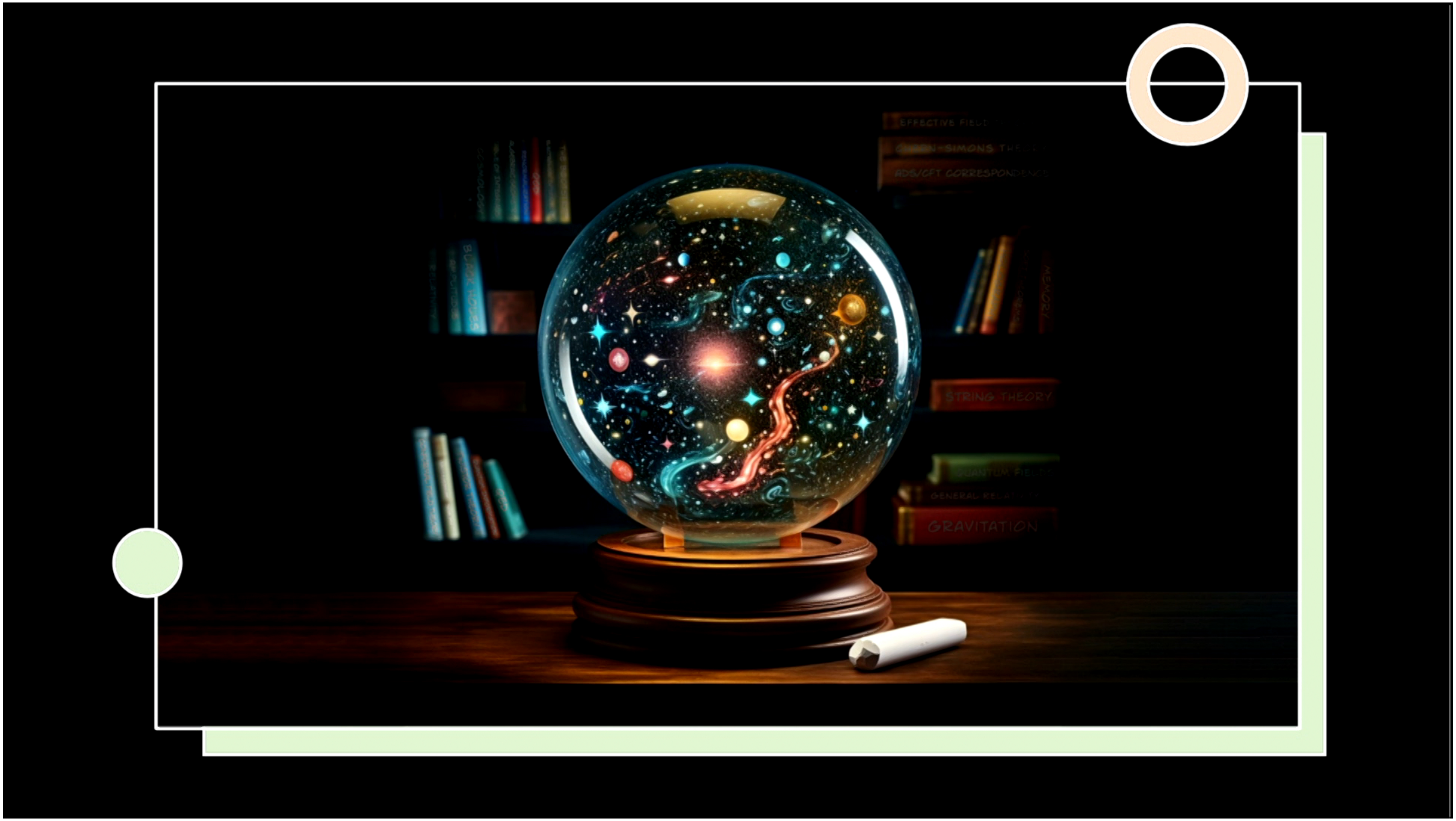
STRING THEORY
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