**Title:** Adventures in Flat Holography

**Speakers:** Sabrina Pasterski

**Collection/Series:** Colloquium

**Subject:** Other

**Date:** November 27, 2024 - 2:00 PM

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**Abstract:**

Celestial Holography encompasses a decade-long endeavor to understand a flat space realization of the holographic principle starting from symmetries in the infrared. But where does it fit within other attempts at constructing a flat hologram? This colloquium delves into some fun tensions in the literature and hopes for resolving them.


ADVENTURES
IN FLAT HOLOGRAPHY
PERIMETER INSTITUTE COLLOQUIUM
SABRINA PASTERSKI
11-27-24

# Outline

I. Context for Flat Holography

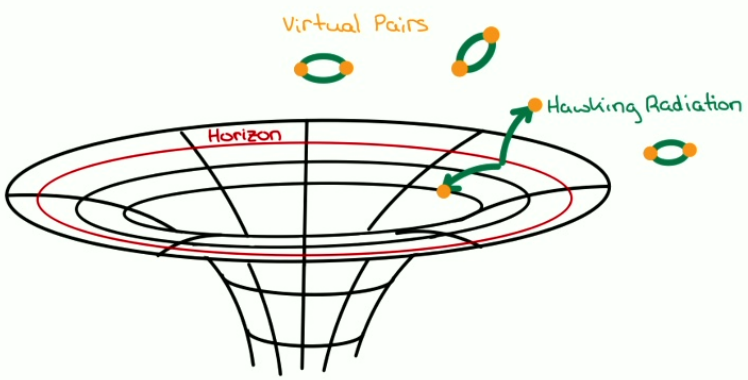
II. The Celestial Holography Program

III. Fun with Swing Surfaces

Celestial Holography encompasses a decade-long endeavor to understand a flat space realization of the holographic principle starting from symmetries in the infrared. But where does it fit within other attempts at constructing a flat hologram? This colloquium delves into some fun tensions in the literature and hopes for resolving them.

The **Holographic Principle** proposes that a quantum theory of gravity has an **equivalent** lower dimensional description **without gravity.**

$$S_{BH} = \frac{c^3 Area_{Horizon}}{4 G_N \hbar}$$



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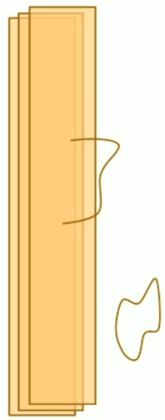

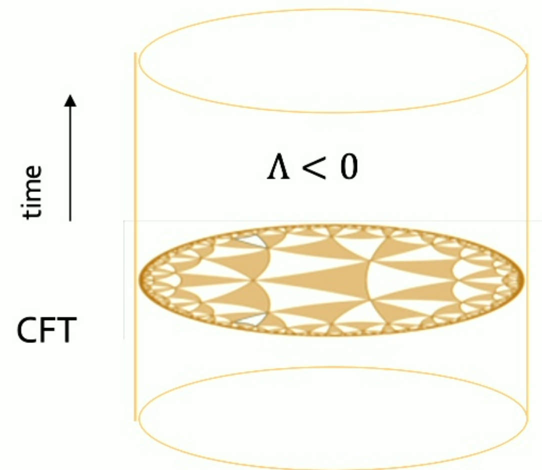

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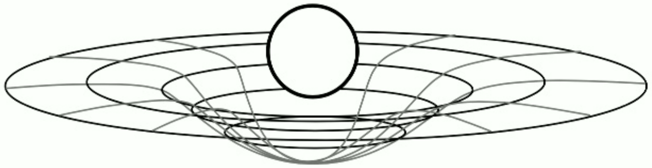
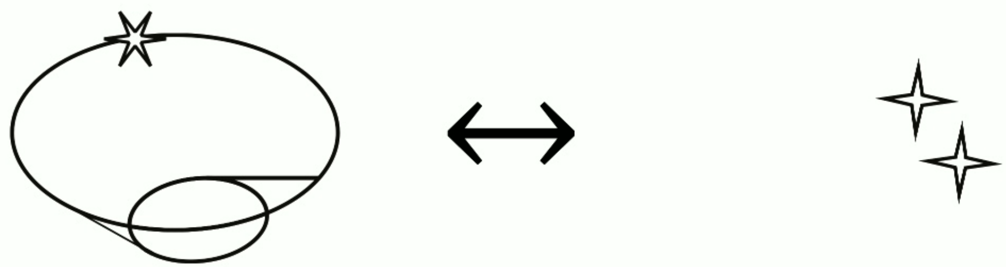
$$i\hbar \frac{\partial}{\partial t}|\psi\rangle = H|\psi\rangle \quad +$$



Asymptotically flat spacetimes, approximate a broad range of physics: from collider experiments to gravitational wave astronomy.



Can we find a dual hologram?

# Approaches

**Bottom Up**

- Matching symmetries

  ASG generators on both sides

- Consistency conditions

  unitary bulk S-matrix

- Reasonable expectations

  should include bulk graviton...

↑

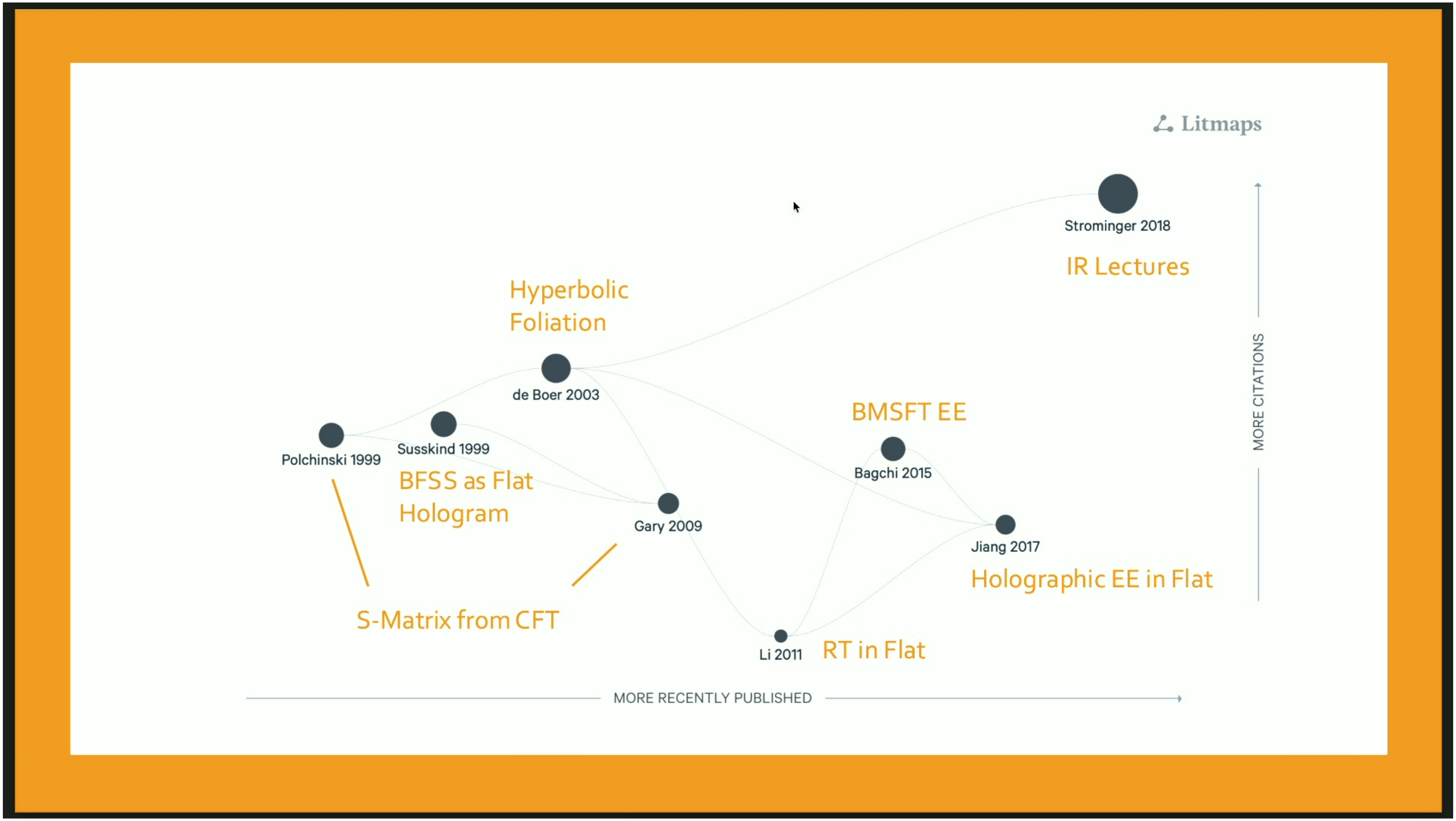
**Top Down**

- Limit of UV complete theory

  stringy constructions of AdS/CFT

↓

Gold Standard


Litmaps
Strominger 2018
IR Lectures
Hyperbolic
Foliation
de Boer 2003
BMSFT EE
Polchinski 1999
Susskind 1999
BFSS as Flat
Hologram
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Gary 2009
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Holographic EE in Flat
S-Matrix from CFT
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RT in Flat
MORE RECENTLY PUBLISHED
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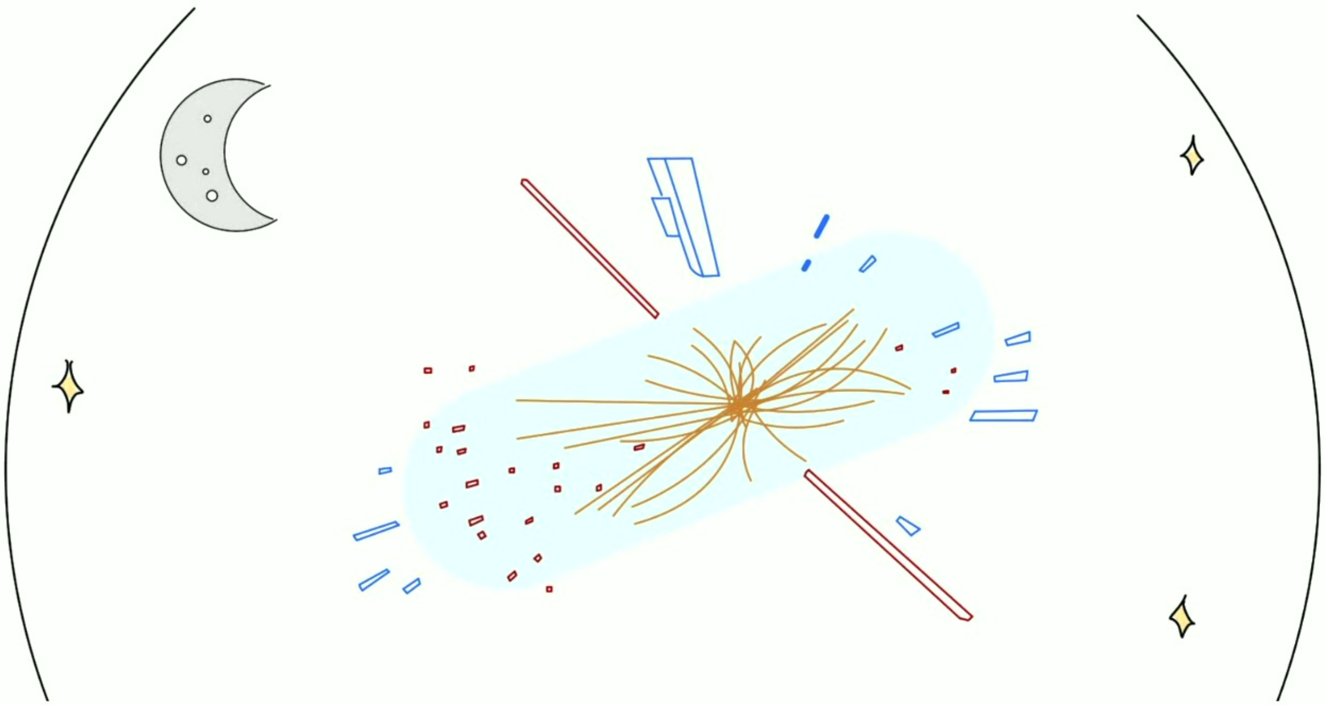
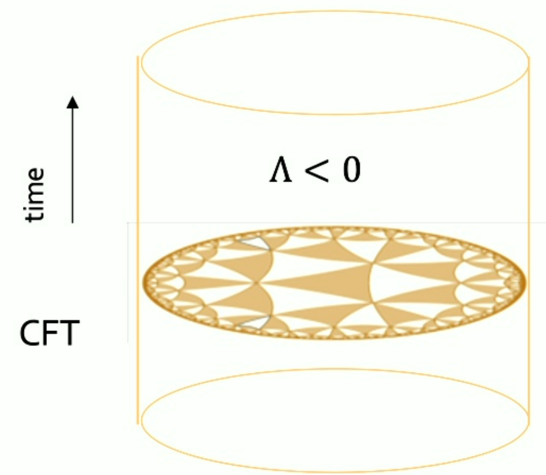
Celestial Holography proposes that scattering in asymptotically flat spacetimes is dual to a CFT living on the celestial sphere.



# What's special about flat?



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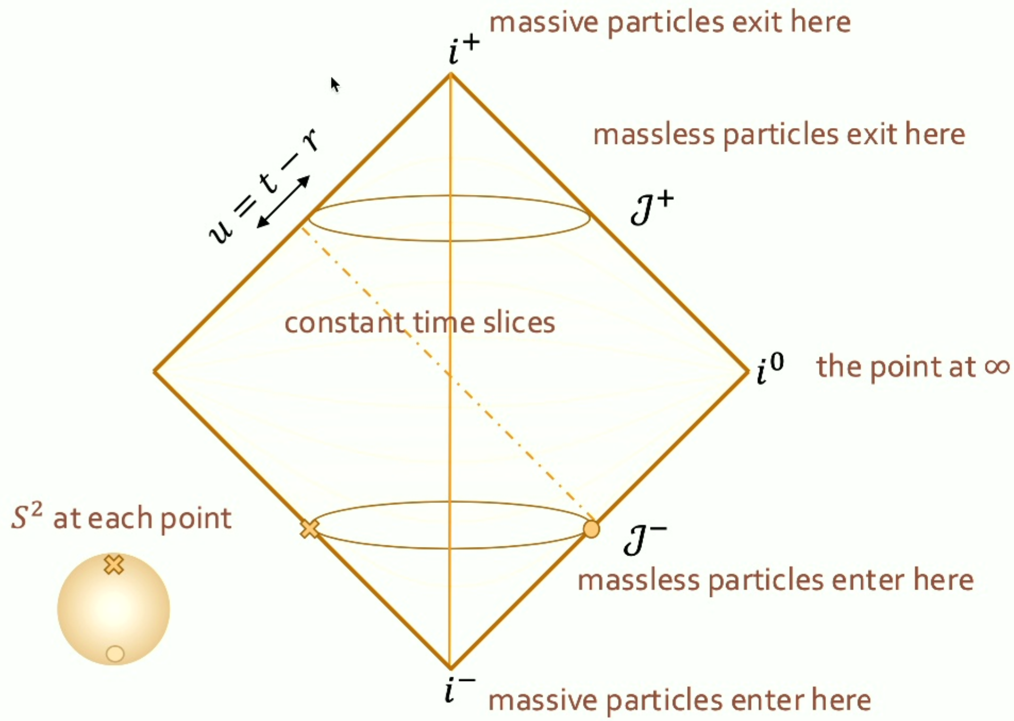
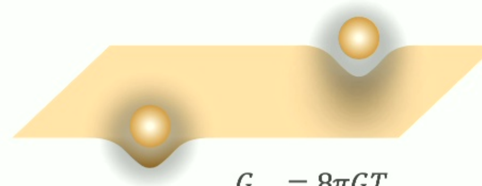


# What’s special about flat?



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



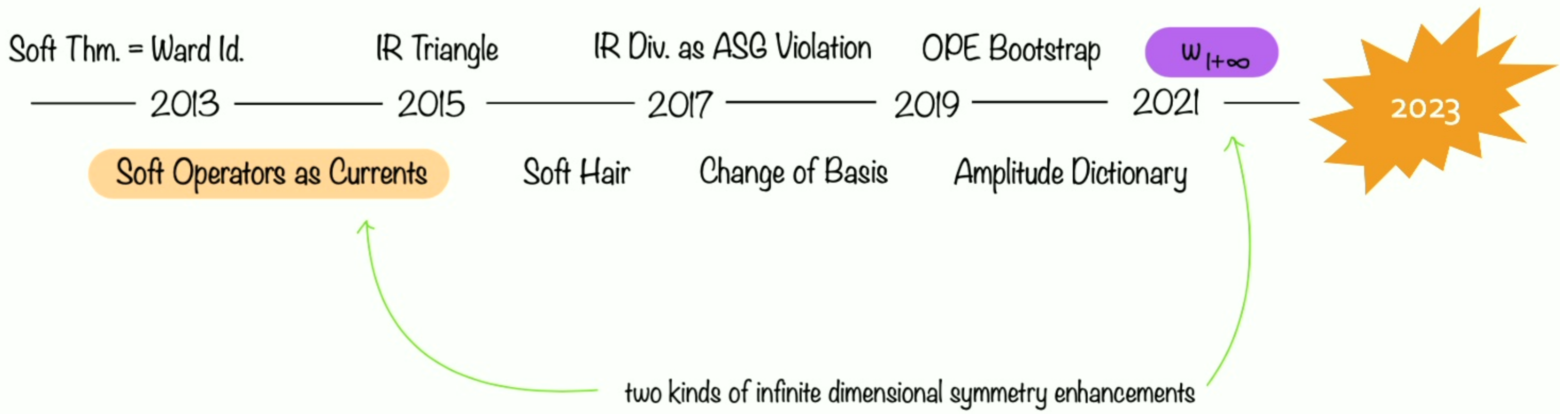
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

How to identify the Asymptotic Symmetry Group:

1. Pick a gauge.
2. Identify physical falloffs.
3. Ask which diffeomorphisms preserve those falloffs.

BMS is an infinite dimensional enhancement of Poincare!

Celestial Holography proposes that scattering in asymptotically flat spacetimes is dual to a CFT living on the celestial sphere.



The program started as a **bottom up** approach, asking how the BMS group constrained scattering.

For a holographic dual living on null infinity the constraints point to a **2D CFT** structure.

Treating the dual as a 2D CFT led to recognizing collinear limits as encoding chiral algebras from twisted holography, providing a **top down** example.

→ Simons Collaboration!

- Along the way we learned fun things about: memory effects, IR divergences, soft hair…

- But perhaps the best takeaway is the lesson that

  *Examining connections between old ideas can lead to new physics.*

- The former is systematic! The latter often seems to need too much luck :(

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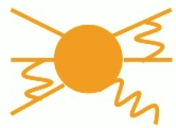
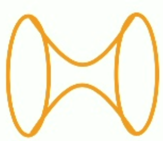


## Amplitudes

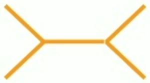
The S-matrix is a boundary observable.

Many subfields of hep-th nominally care about flat holography, even if its less explicit…



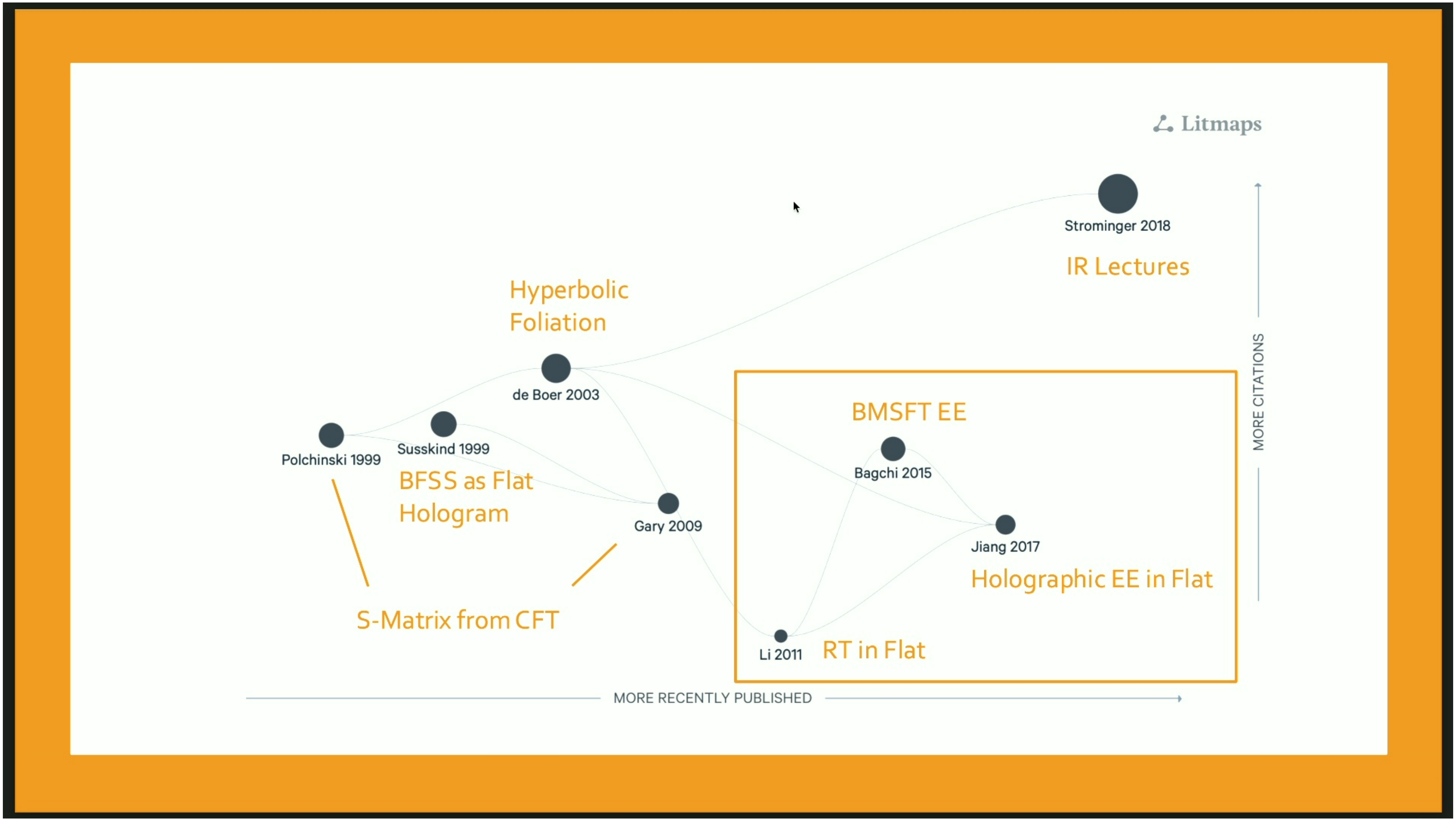
## ItFromQubit

BH entropy has no Λ!



## Bootstrap

S-matrix insights from CFTs.
What CFTs have bulk duals?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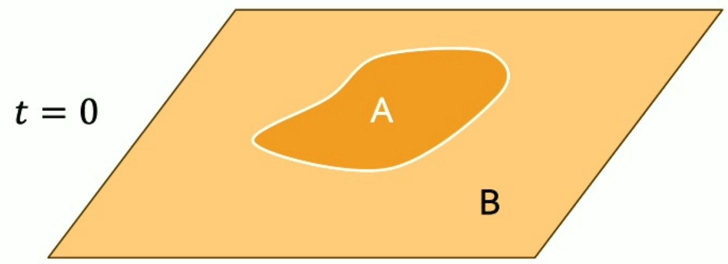
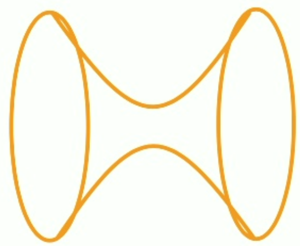
# The RT Proposal

The entanglement entropy is the von Neumann entropy of the reduced density matrix $\rho_A = Tr_B(\rho_{AB})$ and measures entanglement between A and B.




$$\mathcal{S}(\rho_A) = -\,\mathrm{Tr}[\rho_A \log \rho_A]$$

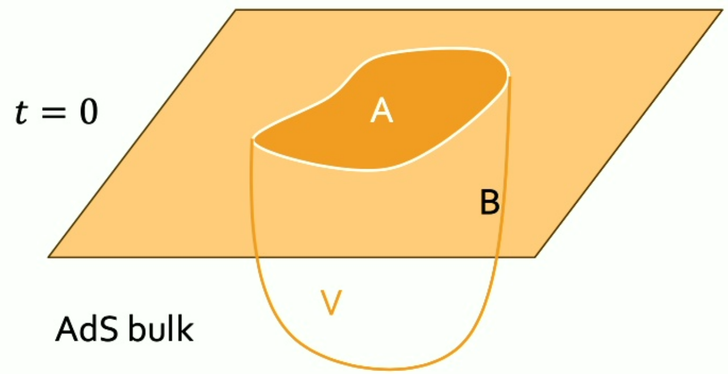


$$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

# Geometry = Entanglement

# The RT Proposal

For holographic CFTs the entanglement entropy is equal to the minimal area surface homologous to the boundary region.



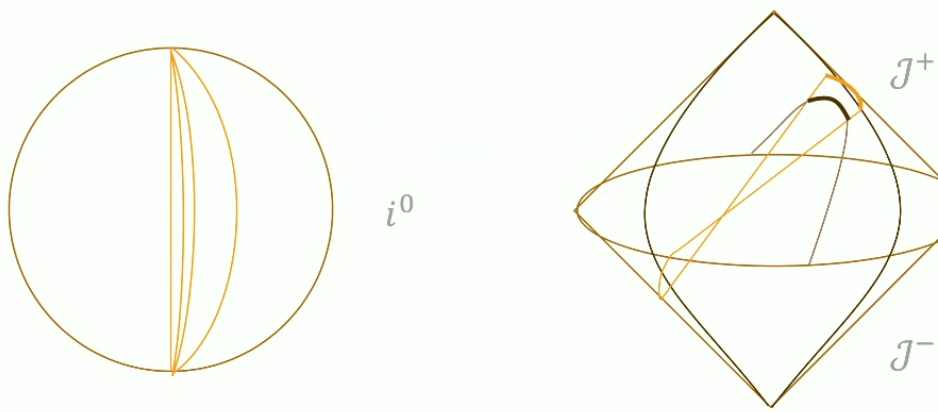

$$S(A) = \underset{V \sim A}{\text{ext}} \frac{A_V}{4G_N}$$

[Ryu, Takayanagi '06]

# What's scary about flat?

Now a few things become strange when try to take the flat limit:

- Minimal surfaces have restricted ends.
  - For equal time slices they end on great circles.
  - Only null geodesics reach null infinity.



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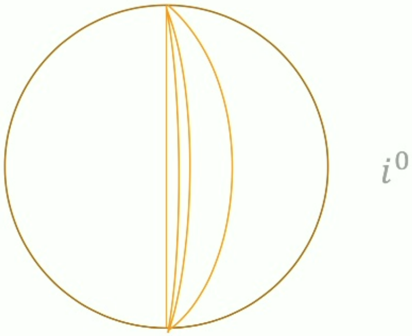


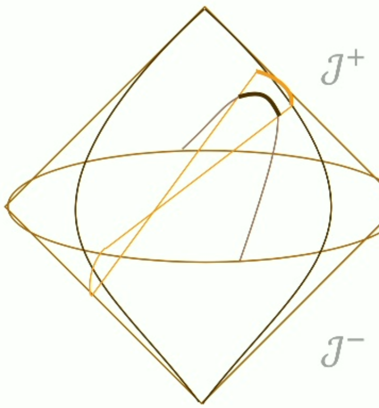

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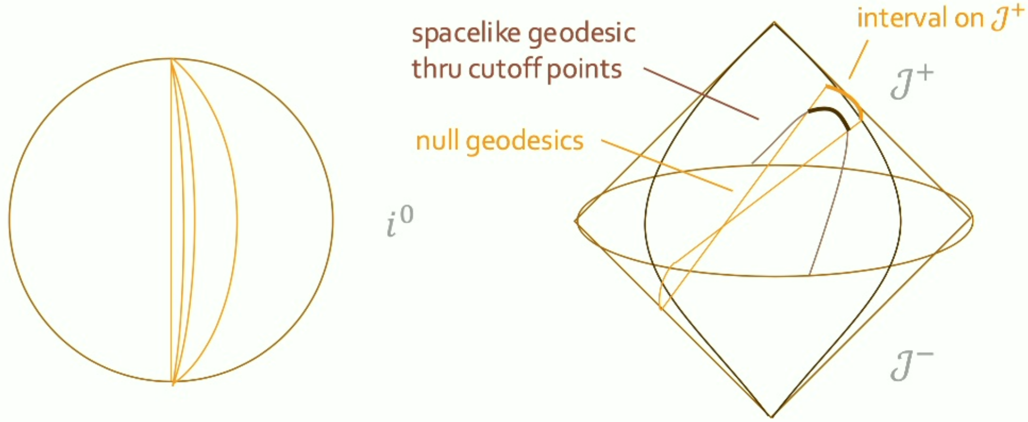

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  - This effects how we regulate the minimal surfaces
  - and leads to problems identifying a finite central charge.

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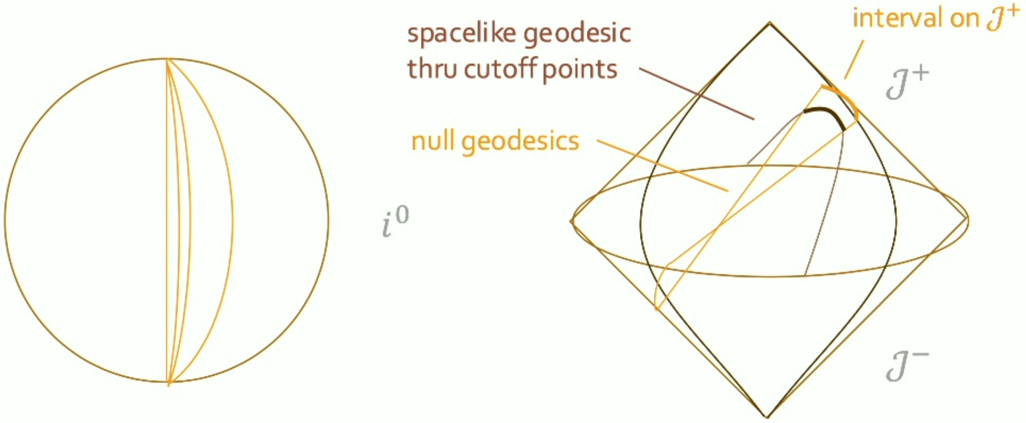

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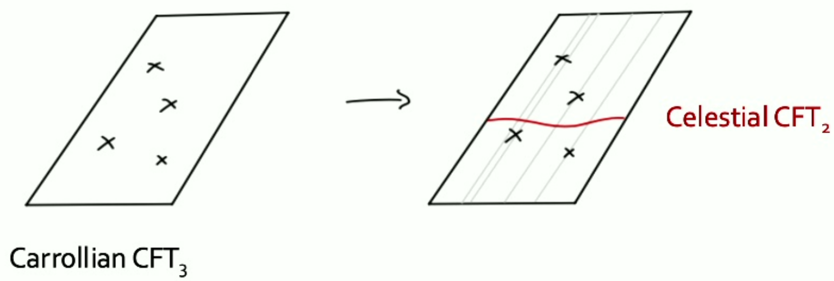
However, there is a holographic EE proposal!

# Rant I:
## Carrollian vs (=) Celestial

There are two natural ways to think about the flat hologram living at null infinity.

- The Carrollian description lives on a codimension 1 null surface
- The Celestial description lives on a codimension 2 spacelike surface that is a cross section of this null cone.



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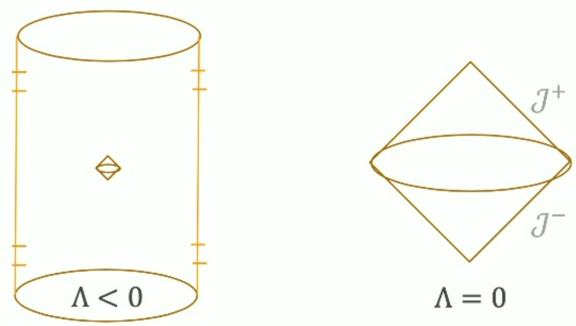


# Rant II:
## 3D vs 4D

Which bulk dimension is your favorite?

# 4D

- You have more interesting soft physics.
- It's the real world!

# 3D

- Everything else is easier.

  BMS3 from Vir x Vir, non-zero c, simpler EE computation, simpler RT surfaces ...

# Rant II:
## 3D vs 4D

Starting from the Virasoro generators in AdS3/CFT2

$$[\mathcal{L}_n^{\pm}, \mathcal{L}_m^{\pm}] = (n-m)\mathcal{L}_{n+m}^{\pm} + \frac{c^{\pm}}{12} n\left(n^2-1\right)\delta_{n+m,0}$$
$$[\mathcal{L}_n^{+}, \mathcal{L}_m^{-}] = 0$$

we can form the linear combinations

$$\mathcal{L}_n = \mathcal{L}_n^{+} - \mathcal{L}_{-n}^{-}, \quad \mathcal{M}_n = \frac{1}{l}\left(\mathcal{L}_n^{+} + \mathcal{L}_{-n}^{-}\right)$$ ← here be dragons
$$c_L = c^{+} - c^{-}, \quad c_M = \frac{1}{l}\left(c^{+} + c^{-}\right)$$

which limit to the BMS3 algebra when we take *l* large.

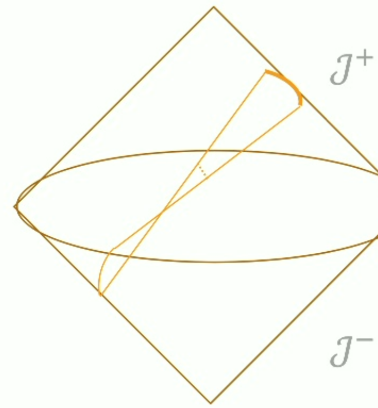
$$[\mathcal{L}_n, \mathcal{L}_m] = (n-m)\mathcal{L}_{n+m} + \frac{c_L}{12} n\left(n^2-1\right)\delta_{n+m,0}$$ ← rotations
$$[\mathcal{L}_n, \mathcal{M}_m] = (n-m)\mathcal{M}_{n+m} + \frac{c_M}{12} n\left(n^2-1\right)\delta_{n+m,0}$$ ← translations
$$[\mathcal{M}_n, \mathcal{M}_m] = 0$$

# RT proposal in flat

- Using some Galilean CFT tricks [Bagchi et al '14] computed the entanglement entropy of an interval in a BMSFT at null infinity.

$$S_{EE}^{BMSFT}(A) = \frac{c_L}{6} \ln\left(2 \sin \frac{l_\phi}{2}\right) + \frac{c_M}{12} l_u \cot \frac{l_\phi}{2}$$

- In [Jiang et al '17] Wei Song and friends then identified a geometric quantity that matches this answer.

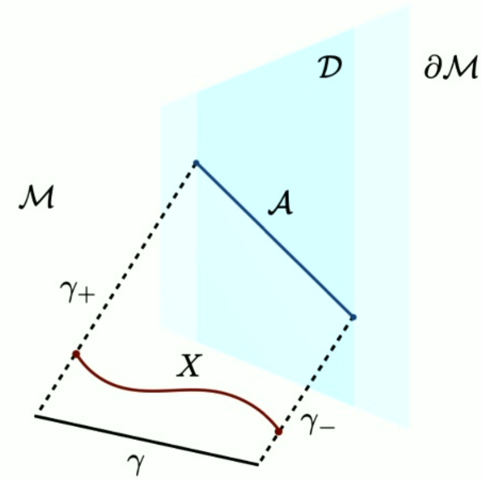


# RT proposal in flat

The Swing Proposal states that the BMSFT EE can be computed from the minimal length spacelike geodesic between radial null geodesics tangent to the approximate modular flow.

$$S_{\mathcal{A}} = \min_{X_{\mathcal{A}} \sim \mathcal{A}} \operatorname{ext} \frac{\text{Area}\,(X_{\mathcal{A}})}{4G},$$
$$X_{\mathcal{A}} = X \cup_{p \in \partial\mathcal{A}} \gamma_{(p)}$$

[Jiang et al '20]

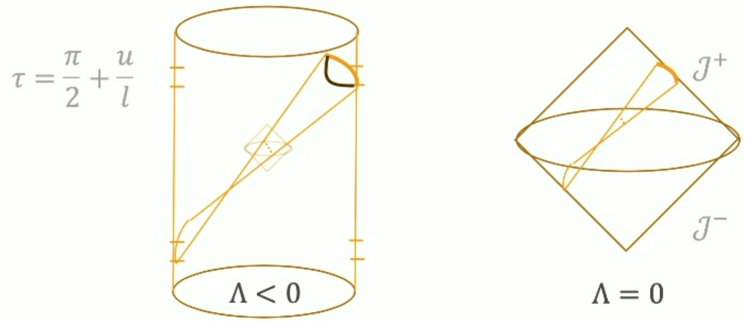



But this sounds very different than RT proposal!

# Lifting to AdS

This prescription would seemingly lift to AdS3.

- Null infinity maps to a small window near $\tau = \frac{\pi}{2}$.
- Can send in radial geodesics and construct the swing.



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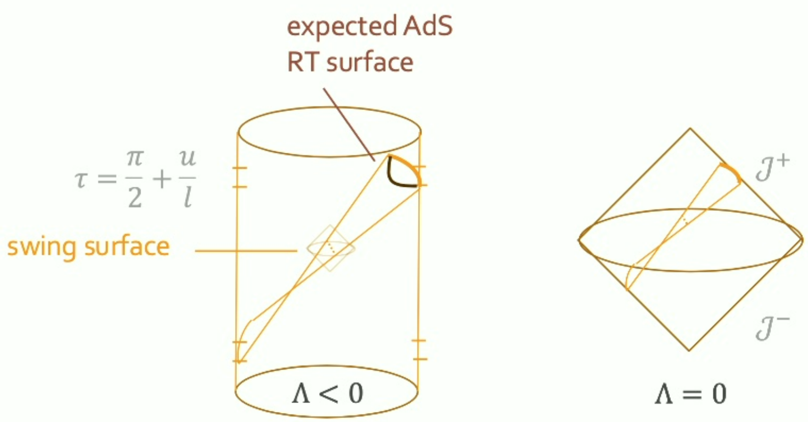


# Lifting to AdS

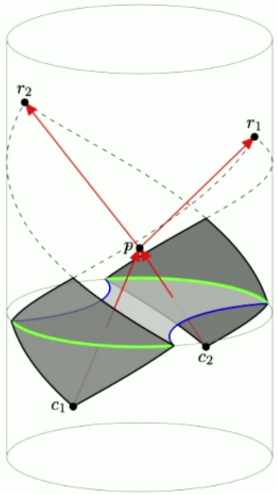
There seem to be various red flags:

- The proposal does not match what we expect in AdS!
- The BMSFT EE is zero for an equal u cut!
- The BMSFT is likely not even positive?
- The radial geodesics should not be so special?!

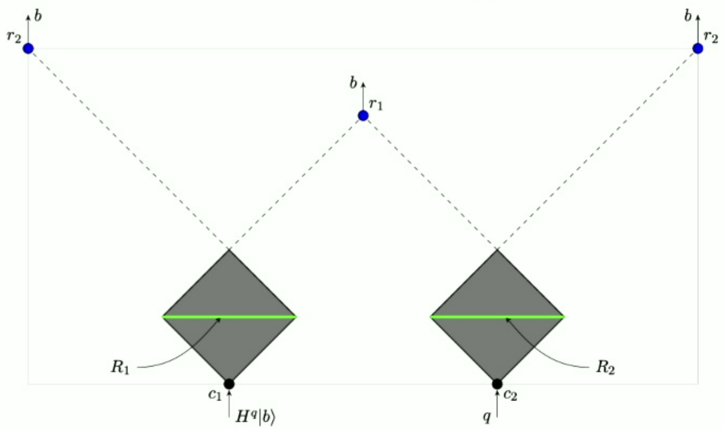
? ? ?

What gives?

Flat space physics naturally lifts to scattering questions in AdS. Thankfully, Alex and friends have given us some relevant information theoretic tools.




Boundary entanglement mediates what would be bulk-only scattering.




[May '19]

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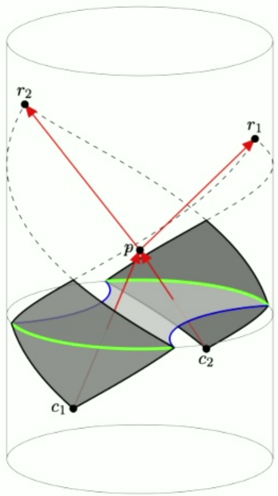


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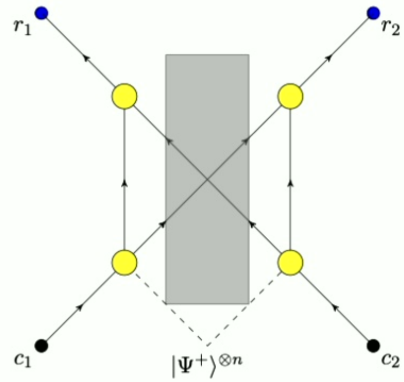
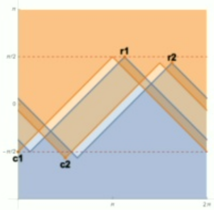



[May '19]

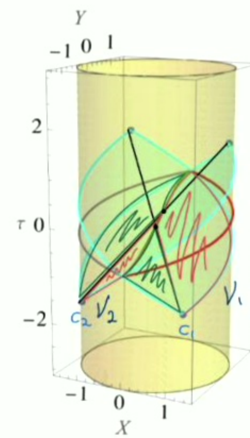
1

In global AdS3 the BMSFT EE is the mutual information of a near-forward scattering configuration.

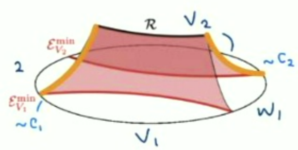
- We can identify the swing as the ridge surface in [May '19]




$$|S_{EE}^{BMSFT}| = \frac{1}{2}\max\{I(V_1 : V_2), I(W_1 : W_2)\}$$



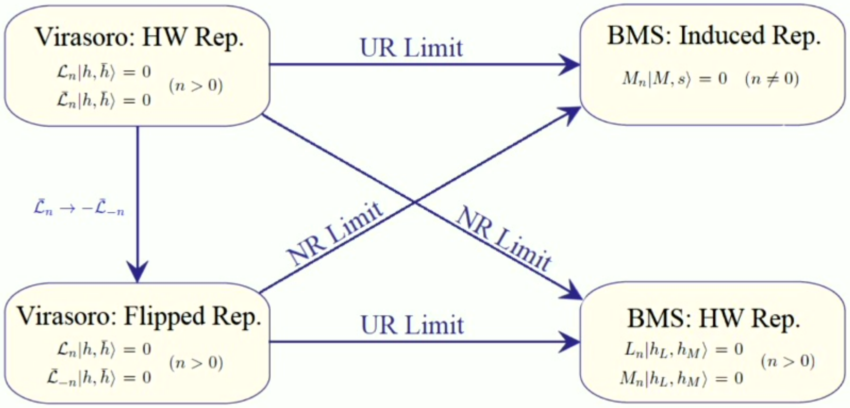

- In Alex's proof this would generally be a lower bound.




$$I\left(V_1 : V_2\right) \geq \frac{\mathrm{area}(\mathscr{R})}{2G_N} + O(1)$$

2

The BMSFT entanglement entropy computation uses some trickery to handle the lowest weight conditions.




[Bagchi '20]

2

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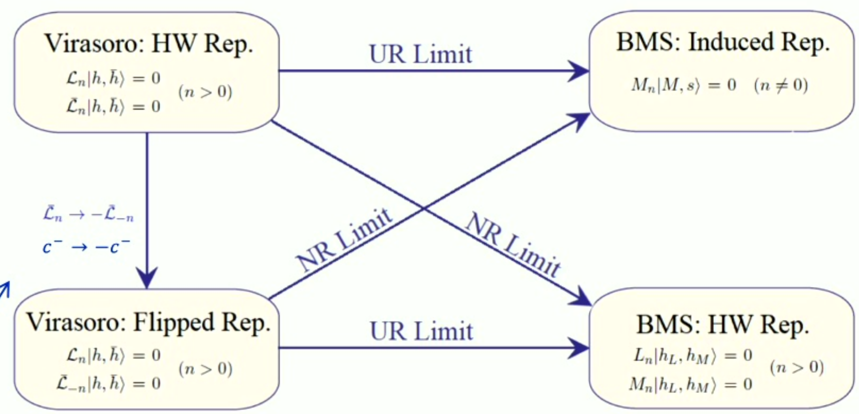


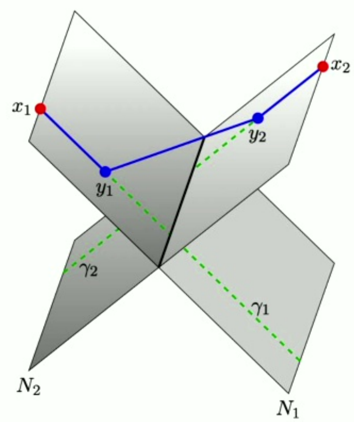

suspicious use of automorphism

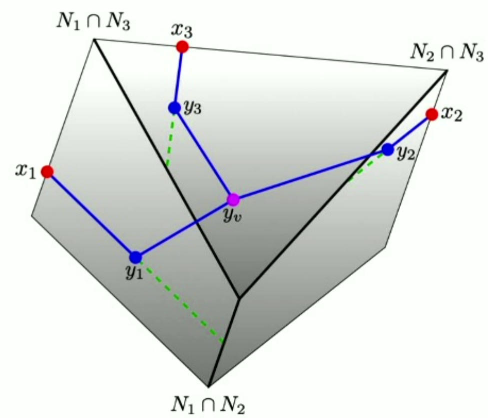
[Bagchi '20]

# Lifting to AdS

While we might be happy to point out mistakes some things work!

- The swing surface is still equal to the |'EE'|.
- [Hijano '17] can reproduce BMSFT correlators from null geodesic networks.



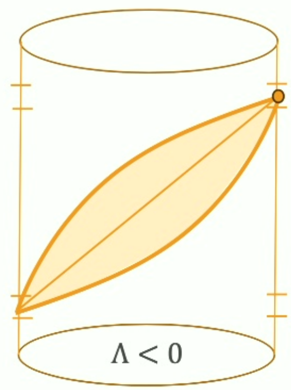

! ! !

What?!

3

We can spoof BMSFT correlators with highly spinning primaries near the bulk point configuration.

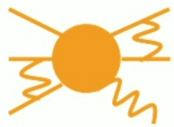
- Light ray operators on the boundary are a natural new candidate for BMSFT primaries.
- Light ray operators through the bulk are linear superpositions.




$$\langle \phi(u_1,\phi_1)\,\phi(u_2,\phi_2)\rangle \propto \left(\frac{\sin\left(\frac{\phi_1-\phi_2}{2}+\frac{u_1-u_2}{2L}\right)}{\sin\left(\frac{\phi_1-\phi_2}{2}-\frac{u_1-u_2}{2L}\right)}\right)^{J}$$

$$\lim_{L\to\infty}\left(\frac{\sin\left(\frac{\phi_1-\phi_2}{2}+\frac{u_1-u_2}{2L}\right)}{\sin\left(\frac{\phi_1-\phi_2}{2}-\frac{u_1-u_2}{2L}\right)}\right)^{-L\xi} = e^{-\xi(u_1-u_2)\cot\left(\frac{\phi_1-\phi_2}{2}\right)}$$

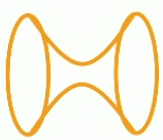
[wip w/ Jackie & Rob '25]



## Amplitudes

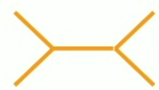
The S-matrix is a boundary observable.

Many subfields of hep-th nominally care about flat holography, even if its less explicit…



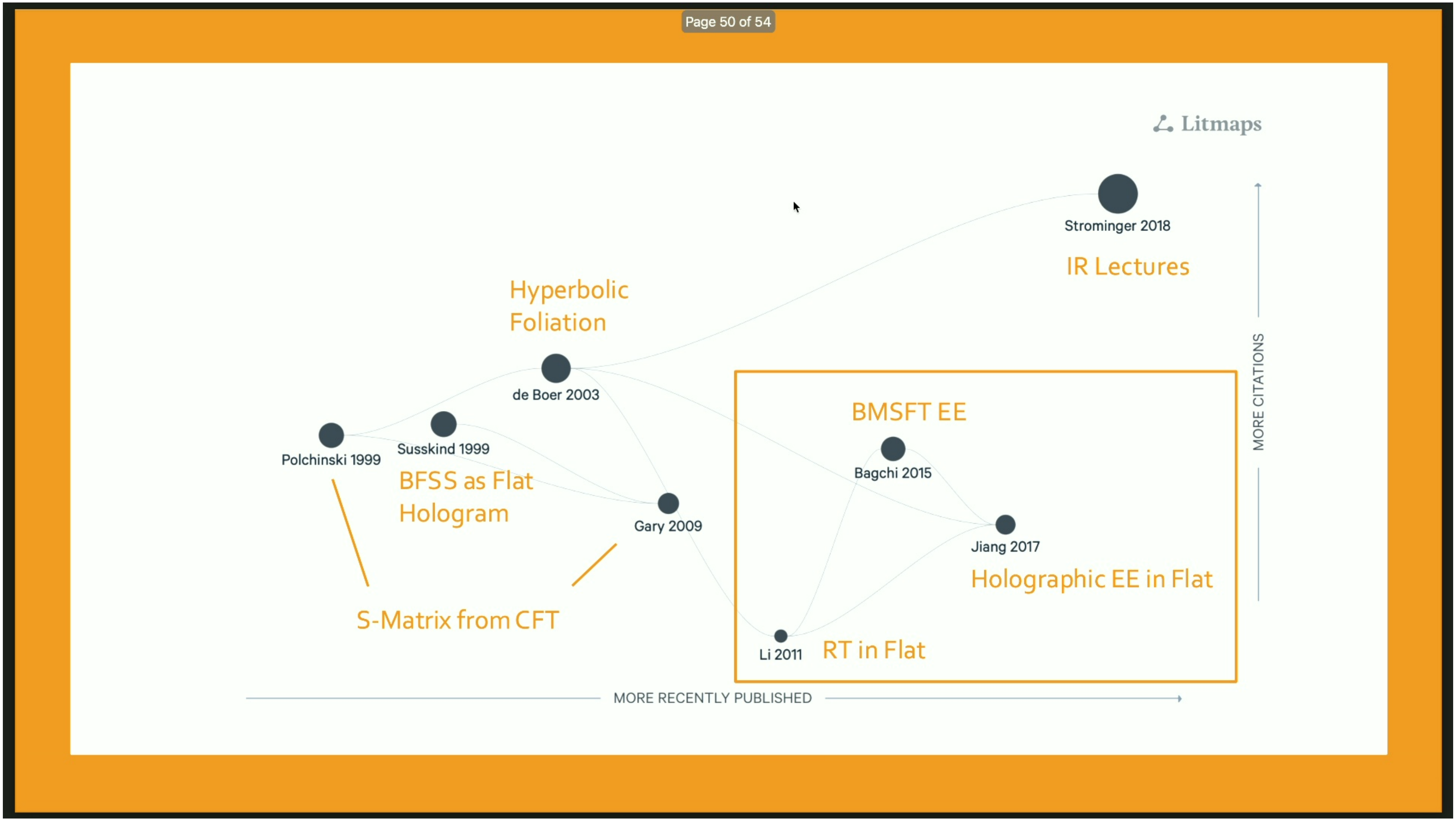
## ItFromQubit

BH entropy has no $\Lambda$!



## Bootstrap

S-matrix insights from CFTs.
What CFTs have bulk duals?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Gary 2009
Jiang 2017
Holographic EE in Flat
S-Matrix from CFT
Li 2011
RT in Flat
MORE RECENTLY PUBLISHED
MORE CITATIONS

• Along the way we learned fun things about: memory effects, IR divergences, soft hair…
• But perhaps the best takeaway is the lesson that
inconsistencies
*Examining ~~connections~~ between old ideas can lead to new physics.*
• The former is systematic! The latter often seems to need too much luck :(
+ is fun!

# Thank You!