Title: Vision Talk

Speakers:

Collection: Celestial Holography Summer School 2024

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# Taking Λ out of It:
## Quantum Information & Celestial Holography

Robert Myers,
Simons Celestial Holography
Summer School 2024

# "It from Qubit": New Collision of Ideas

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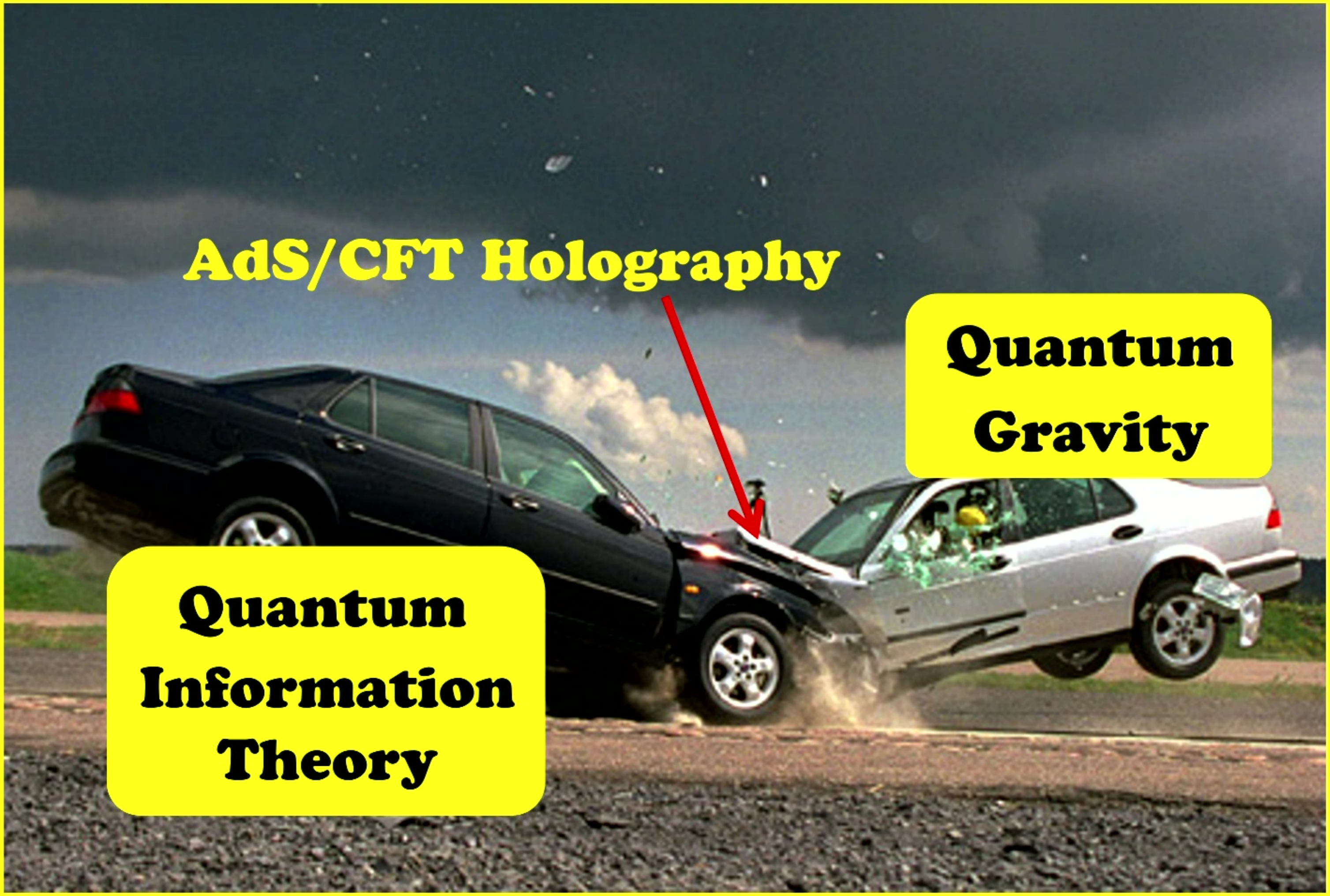
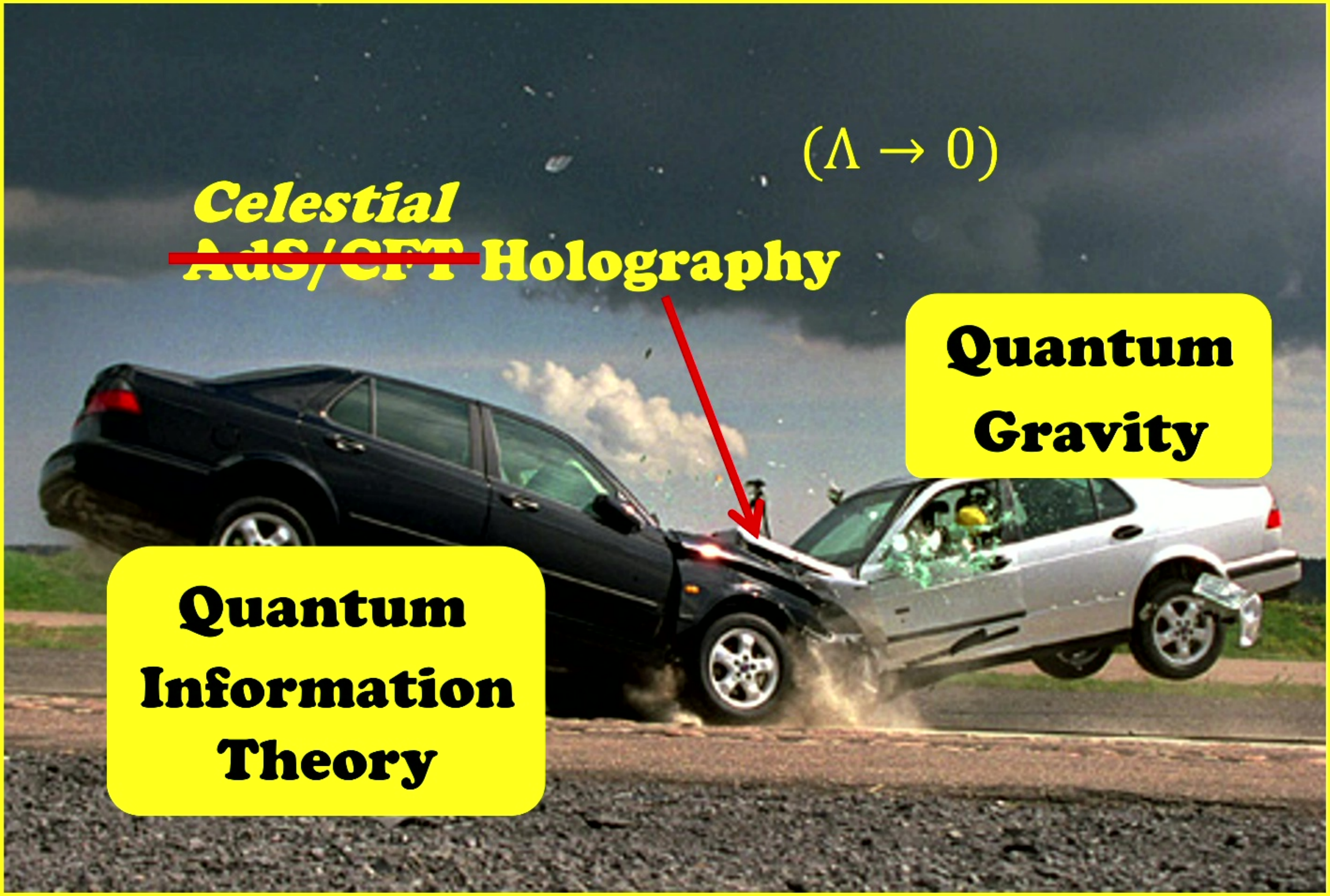


# "It from Qubit": New Collision of Ideas



# Overview:

a) Preliminaries

b) Holographic EE – Take 1

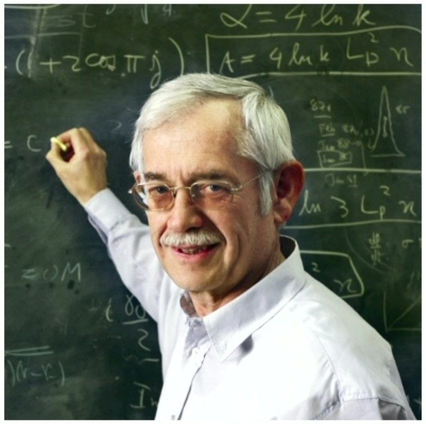
c) Holographic EE – Take 2

d) Outlook

# Black Holes:

- Bekenstein: "black holes have entropy!"

$$S_{BH} = \eta \frac{k_B\, c^3}{\hbar} \frac{\mathcal{A}_{horizon}}{G}$$



"we discuss black-hole physics from the point of view of information theory"

"Black Holes and Entropy", PRD, April 1973

## Black Holes:

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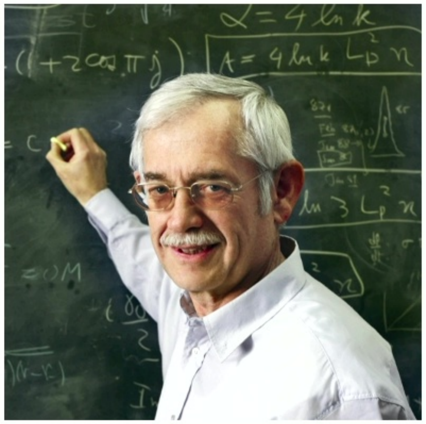



- Hawking radiation: quantum fluctuations allow black holes to emit (almost pure) blackbody radiation with

$$T_H = \frac{\hbar}{k_B\, c} \frac{\kappa}{2\pi}$$

**No $\Lambda$ here!!**

# Black Hole Entropy:

- Bekenstein and Hawking: “black holes have entropy!”

microstates → $S_{BH}$ ; geometry → $\mathcal{A}_{horizon}$

$$S_{BH} = 2\pi \, \frac{\mathcal{A}_{horizon}}{\ell_P^{d-2}}$$

- area measured in terms of Planck scale: $\ell_P^{d-2} = 8\pi \, G \, \hbar / c^3$

- entropy is not extensive; grows with **area** rather than volume

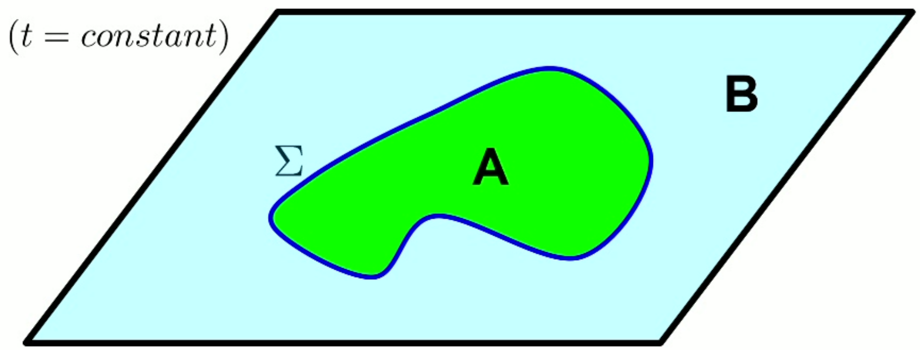
⟶ Sorkin ‘84: black hole entropy ≈ **“entanglement entropy”**

(Sorkin (1402.3589); Bombelli, Koul, Lee & Sorkin; Srednicki; Frolov & Novikov; . . .)

## Entanglement Entropy in Quantum Field Theory:

- EE is a quantitative measure of entanglement using entropy to detect correlations between two subsystems
- in QFT, typically introduce a (smooth) boundary or entangling surface $\Sigma$ which divides the space into two separate regions
- integrate out degrees of freedom in "outside" region
- remaining dof are described by a density matrix $\rho_A$

⟶ calculate von Neumann entropy: $S_{EE} = -Tr\left[\rho_A \, \log \rho_A\right]$



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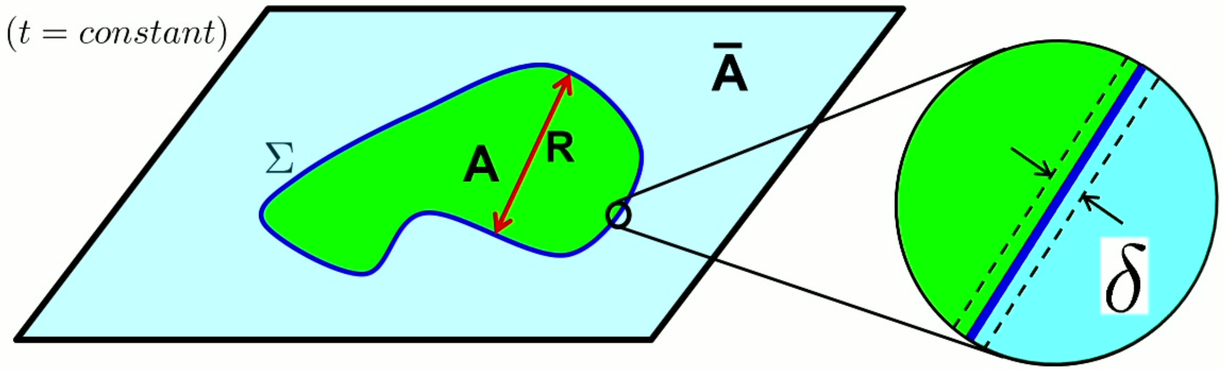


- result is UV divergent! dominated by short-distance correlations
- must regulate calculation: $\delta$ = short-distance cut-off

$$S = c_0 \frac{R^{d-2}}{\delta^{d-2}} + c_2 \frac{R^{d-4}}{\delta^{d-4}} + \cdots$$ $d$ = spacetime dimension

⟶ geometric structure, eg, $S = \tilde{c}_0 \frac{\mathcal{A}_\Sigma}{\delta^{d-2}} + \tilde{c}_2 \frac{\oint_\Sigma \text{“}curvature\text{”}}{\delta^{d-4}} + \cdots$

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$$S_{EE} = \tilde{c}_0 \, \frac{\mathcal{A}_\Sigma}{\delta^{d-2}} + \cdots$$ ⟶ “area law” suggestive of BH formula if $\delta^{d-2} \simeq \ell_P^{d-2}$

(Sorkin (1402.3589); Bombelli, Koul, Lee & Sorkin; Srednicki; Frolov & Novikov; . . .)

## Black Hole Entropy:

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• entanglement entropy of QF’s contributes to gravitational entropy

(Susskind & Uglum; ... Faulkner, Lewkowycz & Maldacena; …)

• entanglement of microscopic gravitational dof also important

# Holography: AdS/CFT correspondence

Bulk: quantum gravity
with negative Λ
in **d+1** dimensions

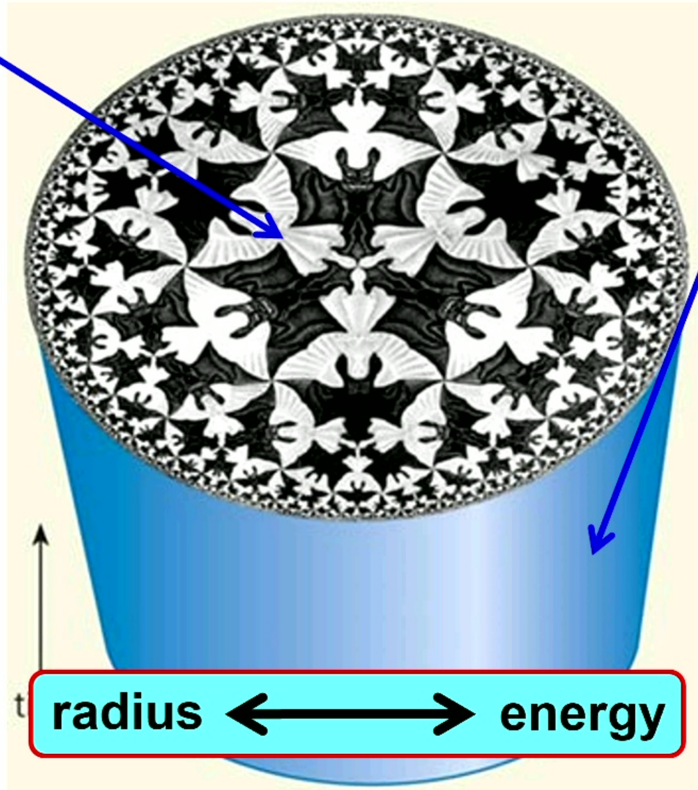
Boundary: quantum field theory
without intrinsic scales
in **d** dimensions

"holography"

anti-de Sitter
space

conformal
field theory

$$\Lambda = -\frac{d(d-1)}{2L^2}$$



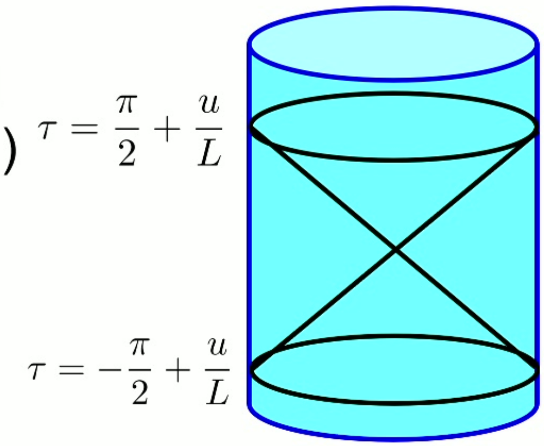

**radius ⟷ energy**

# Flat space limit of AdS/CFT:

- extracting flat space S-matrix from AdS/CFT correlators has a long history
  (Susskind, Polchinski, Giddings, Penedones, Fitzpatrick, Kaplan, Hijano, ….)

- celestial amplitudes arise from AdS Witten diagrams with particular kinematics

- celestial operators on $\mathcal{I}^{\pm}$ mapped to CFT operators on narrow ($\sim 1/L$) band around $\tau = \pm\frac{\pi}{2} + \frac{u}{L}$




- celestial $\mathrm{CCFT}_{d-1}$ amplitudes can be obtained directly from correlation functions in a unitary Lorentzian $\mathrm{CFT}_d$ on $R \times S^{d-1}$
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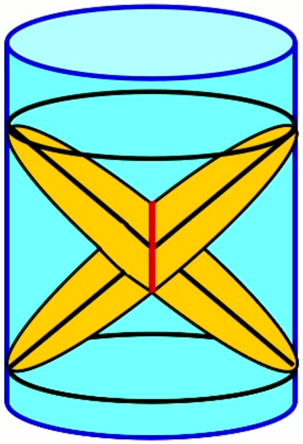


- note Rindler horizons (or RT surfaces) near bulk point given by spacelike extremal surfaces anchored in intermediate zone

- celestial $\mathrm{CCFT}_{d-1}$ amplitudes can be obtained directly from correlation functions in a unitary Lorentzian $\mathrm{CFT}_d$ on $R \times S^{d-1}$

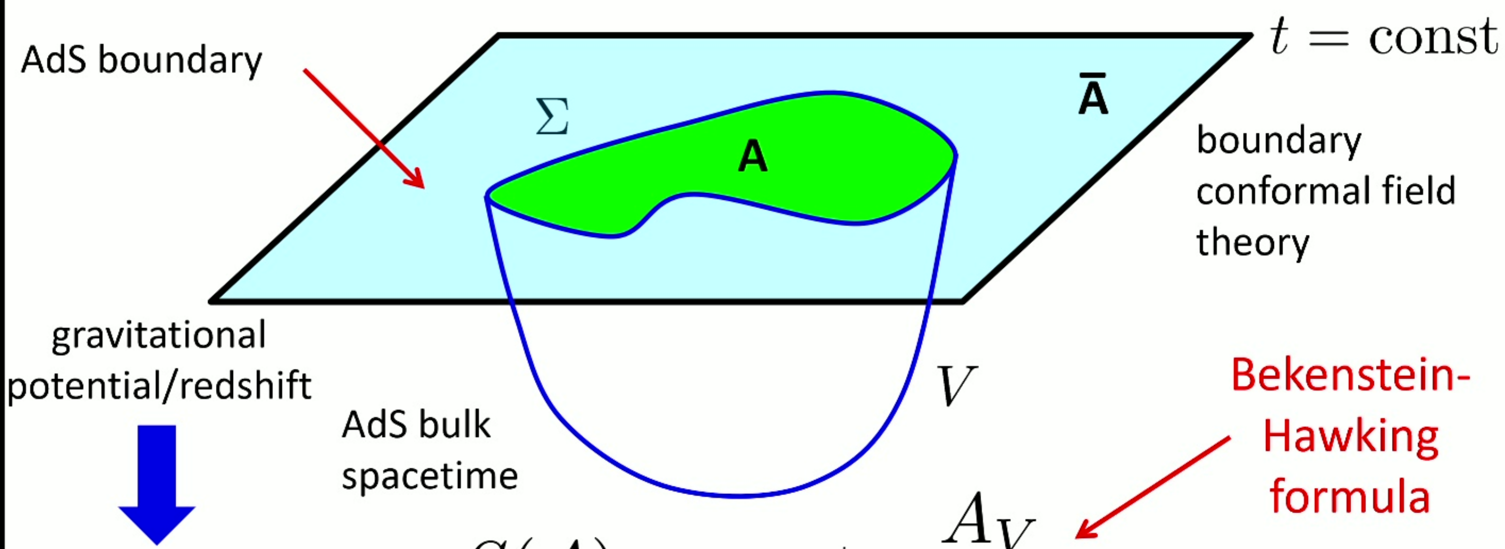
(de Gioia & Raclariu)

(Ryu & Takayanagi `06)

## Holographic Entanglement Entropy:

- CFT dof within **A** described by density matrix $\rho_A = Tr_{\bar{A}}(|\psi\rangle\langle\psi|)$

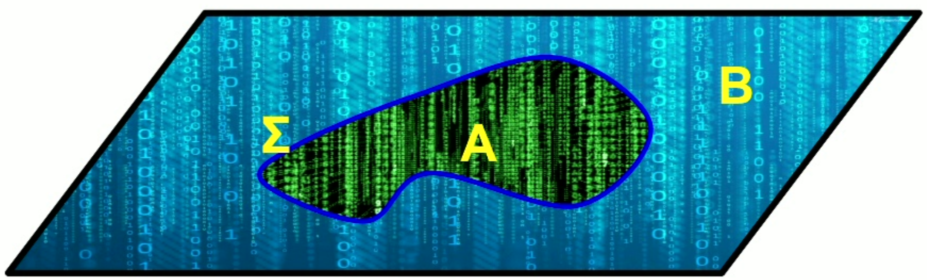
→ calculate von Neumann entropy: $S(A) = -Tr\left[\rho_A \log \rho_A\right]$




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

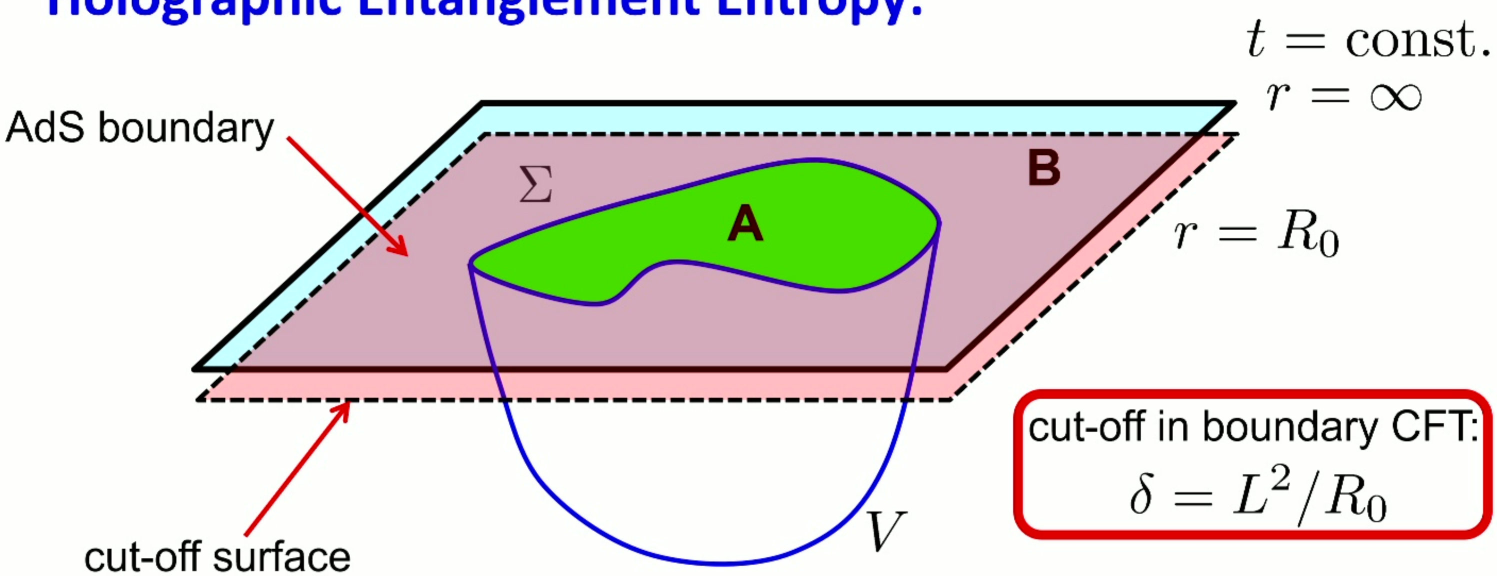
# Spacetime Geometry = Entanglement

- → connectivity of spacetime requires entanglement (van Raamsdonk)
- → AdS spacetime as a tensor network (MERA) (Swingle, Vidal, ….)
- → "ER = EPR" conjecture (Maldacena & Susskind)
- → Einstein's equations from entanglement (van Raamsdonk et al, ……)
- → Spacetime as quantum error correcting code (Almeirhi, Dong & Harlow, ….)
- → Entanglement wedge reconstruction (Dong, Harlow & Wall, ….)
- → Evaluation of Page Curve (Penington; Almeirhi et al, ….)



## Holographic Entanglement Entropy:

(Ryu & Takayanagi `06)




cut-off in boundary CFT:
$\delta = L^2/R_0$

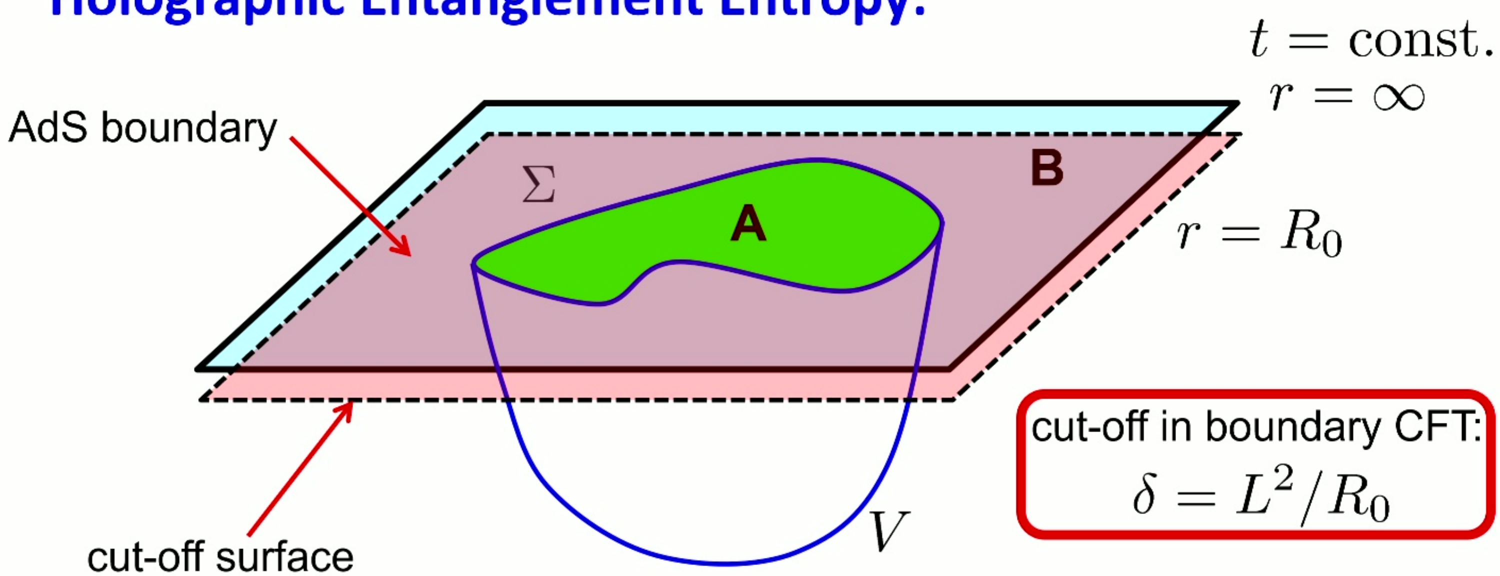
$$S(A) = \underset{V \sim A}{\text{ext}} \frac{A_V}{4G_N} \simeq \frac{L^{d-1}}{G_N} \frac{\mathcal{A}_\Sigma}{\delta^{d-2}} + \cdots$$

- "UV divergence" because area integral extends to $r = \infty$
- finite result by stopping radial integral at large radius: $r = R_0$

  $\longrightarrow$ short-distance cut-off in boundary theory: $\delta = L^2/R_0$

# Holographic Entanglement Entropy:

(Ryu & Takayanagi `06)

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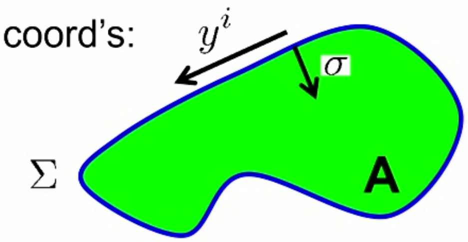
central charge
(counts dof) $(L/\ell_{Planck})^{d-1}$

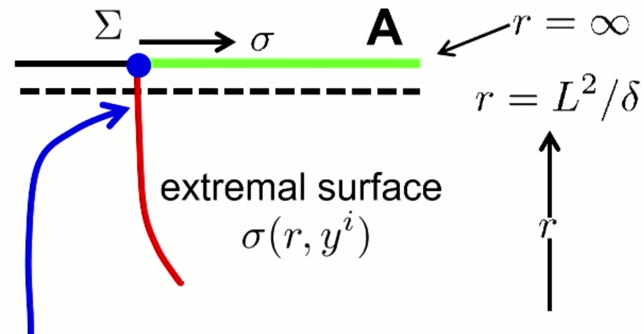
"Area Law"

## Area law contribution:

recall AdS metric: $ds^2 = \frac{r^2}{L^2}\left(-dt^2 + d\vec{x}^2\right) + \frac{L^2}{r^2}dr^2$

bdry coord's:




to leading order, surface falls straight down, ie, $\sigma \simeq 0$

$$S(A) \;=\; \frac{A_V}{4G_N} = \frac{1}{4G_N}\int d^{d-1}\sigma\sqrt{h}$$

$$= \frac{1}{4G_N}\int d^{d-2}y\sqrt{h_y}\;\left(\frac{r}{L}\right)^{d-2} \times \int^{R_0} dr \times \frac{L}{r}$$

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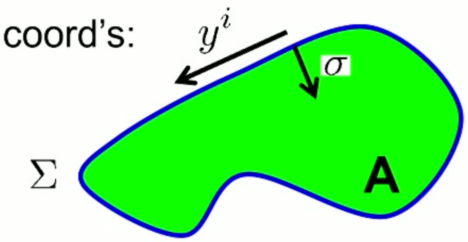


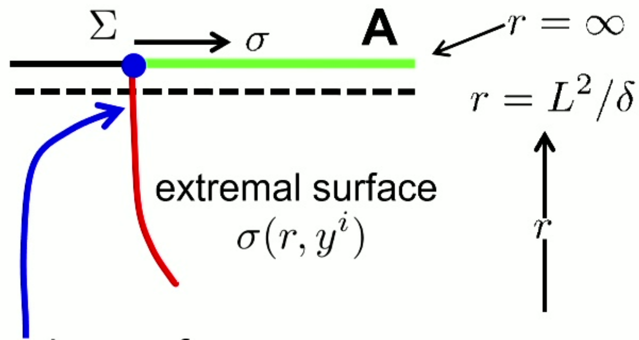


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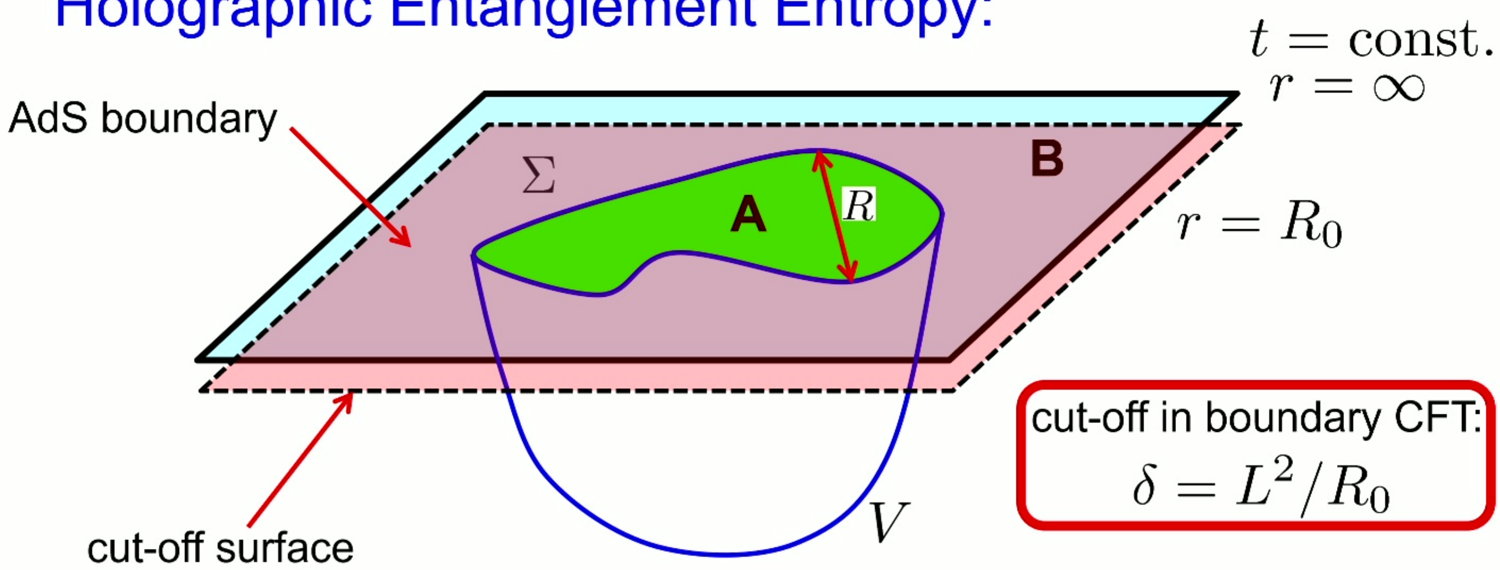
$$S(A) = \frac{A_V}{4G_N} = \frac{1}{4G_N}\int d^{d-1}\sigma\sqrt{h}$$

$$= \frac{1}{4G_N}\mathcal{A}_\Sigma \int^{L^2/\delta} dr \left(\frac{r}{L}\right)^{d-3}$$

(Ryu & Takayanagi `06)

# Holographic Entanglement Entropy:




cut-off in boundary CFT:
$\delta = L^2/R_0$

general expression (as desired):

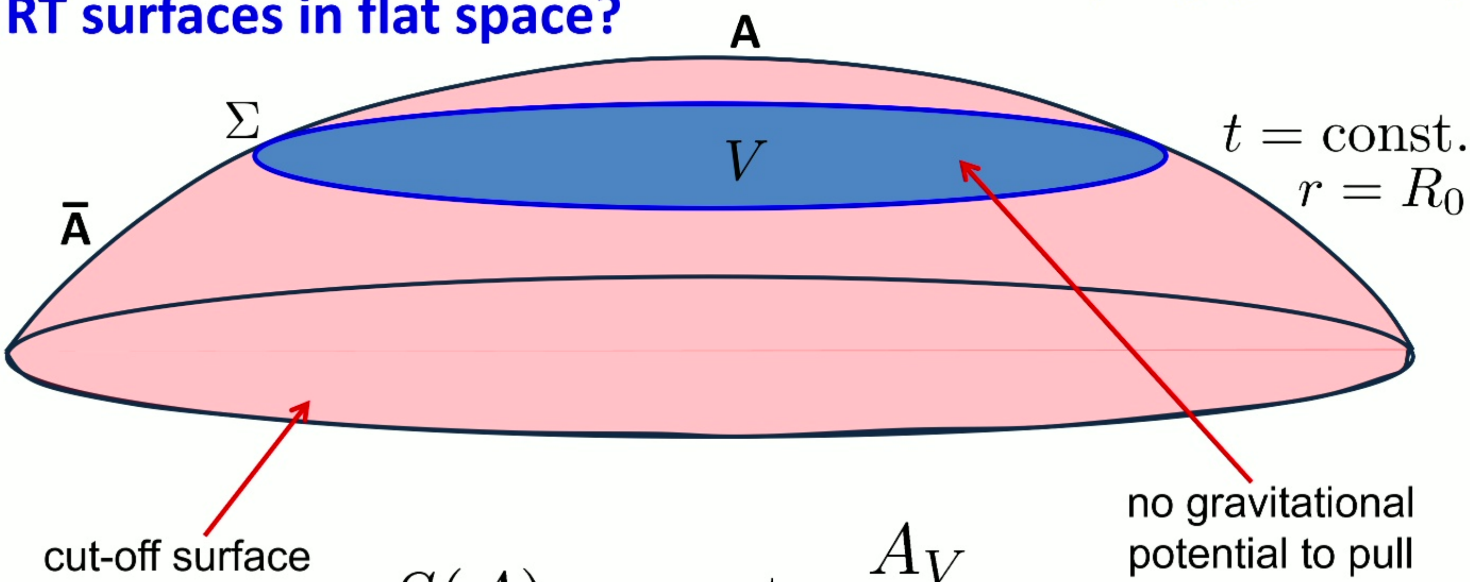
$$S(A) \simeq c_0(R/\delta)^{d-2} + c_1(R/\delta)^{d-4} + \cdots$$

$$\begin{cases} +c_{d-2}\log(R/\delta) + \cdots & \text{(d even)} \\ +\underbrace{c_{d-2}}\ + \cdots & \text{(d odd)} \end{cases}$$

universal contributions

Li & Takayanagi (1010.3700)

## RT surfaces in flat space?




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

- let's try attaching extremal surfaces to boundary of flat space

$$ds^2 = -dt^2 + dr^2 + r^2\, d\Omega_{d-1}^2$$

- regulate radial integral with cut-off surface at large radius: $r = R_0$

## No area law contribution!!

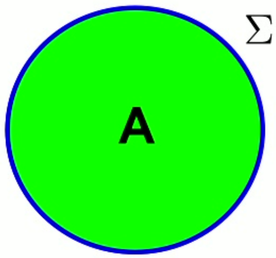
$$d\theta^2 + \sin^2\theta\, d\Omega_{d-1}^2$$

flat space metric: $ds^2 = -dt^2 + dr^2 + r^2\, d\Omega_{d-1}^2$

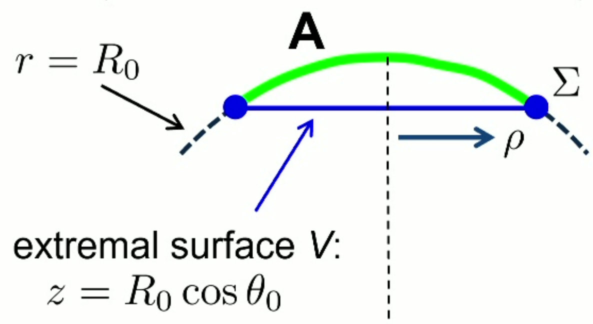
$$= -dt^2 + dz^2 + d\rho^2 + \rho^2\, d\Omega_{d-2}^2$$

$(z = r\,\cos\theta\,, \quad \rho = r\,\sin\theta)$

Consider spherical cap:




$\Sigma : \theta = \theta_0$




$$S(A) = \frac{A_V}{4G_N} = \frac{1}{4G_N}\int d^{d-1}\sigma\sqrt{h}$$

$$= \frac{1}{4G_N}\int d^{d-2}\Omega \;\; \rho^{d-2} \times \int_0^{R_0 \sin\theta_0} d\rho \times 1$$

## No area law contribution!!

$$d\theta^2 + \sin^2\theta \, d\Omega^2_{d-1}$$

flat space metric: $ds^2 = -dt^2 + dr^2 + r^2 \, d\Omega^2_{d-1}$

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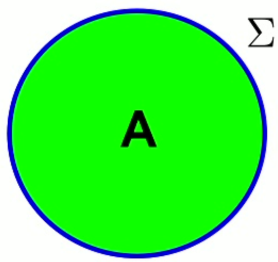
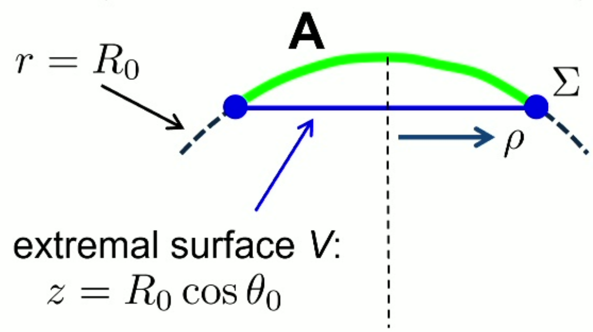



$$S(A) = \frac{A_V}{4G_N} = \frac{1}{4G_N}\int d^{d-1}\sigma\sqrt{h}$$

$$= \frac{\Omega_{d-2}}{4(d-1)G_N}\,(R_0\sin\theta_0)^{d-1}$$

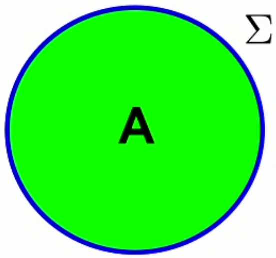
## No area law contribution!!

flat space metric: $ds^2 = -dt^2 + dr^2 + r^2\, d\Omega_{d-1}^2 \rightarrow d\theta^2 + \sin^2\theta\, d\Omega_{d-1}^2$

$$= -dt^2 + \underline{dz^2 + d\rho^2} + \rho^2\, d\Omega_{d-2}^2$$

$(z = r\,\cos\theta\,,\quad \rho = r\,\sin\theta)$

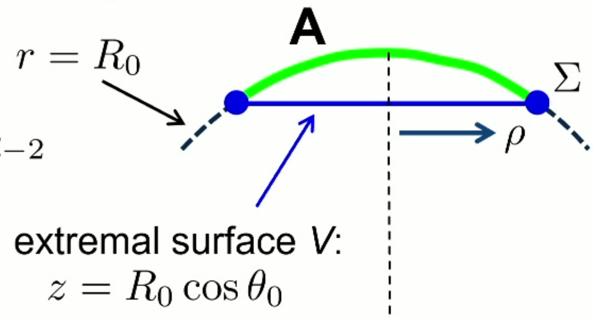
Consider spherical cap:




$\Sigma\,:\,\theta=\theta_0$

$\mathcal{A}_\Sigma = \Omega_{d-2}(R_0\,\sin\theta_0)^{d-2}$

$Vol_A = R_0^{d-1} f(\theta_0)$

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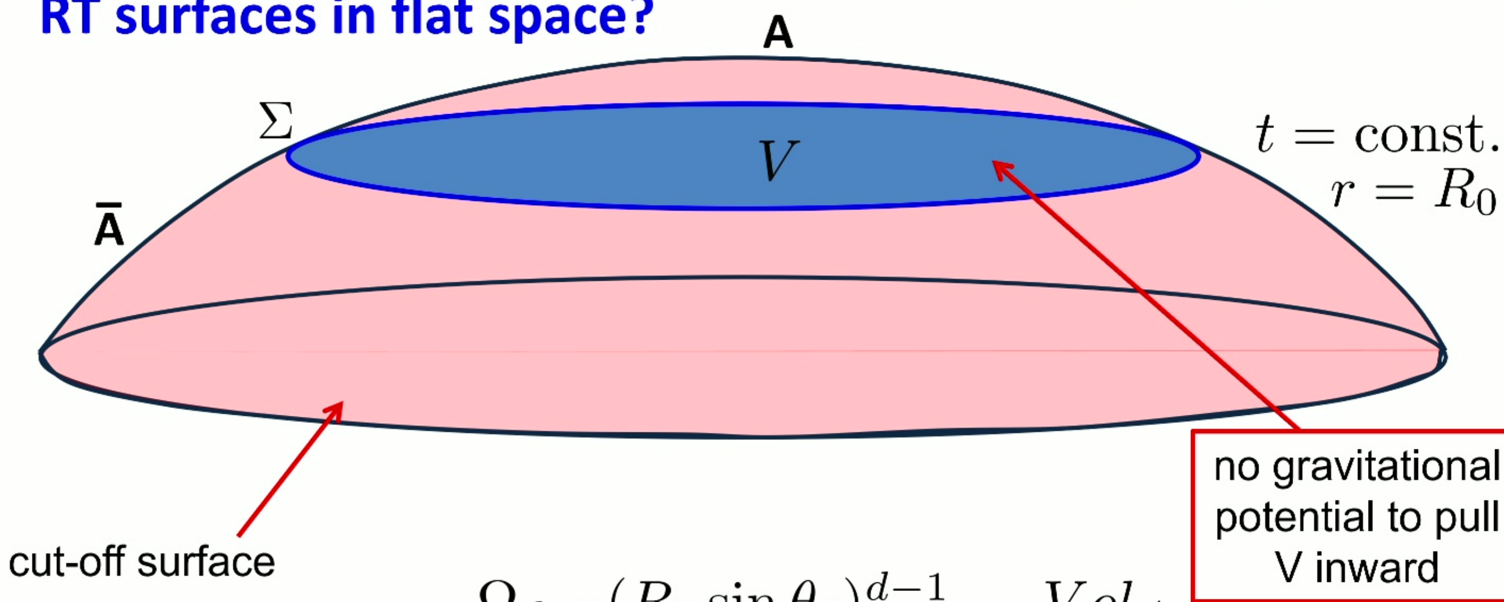
# RT surfaces in flat space?

Li & Takayanagi (1010.3700)




$$S(A) = \frac{\Omega_{d-2}(R_0 \sin\theta_0)^{d-1}}{4(d-1)G_N} \simeq \frac{Vol_A}{G_N}$$

- leading contribution is a volume law, ie, "holo EE" is extensive

→ conjecture: holographic dual is nonlocal field theory (Li & Takayanagi)

→ perhaps holographic dual of flat space vacuum is highly excited state

Li & Takayanagi (1010.3700)

# RT surfaces in flat space?

$$S(A) = \frac{\Omega_{d-2}(R_0 \sin\theta_0)^{d-1}}{4(d-1)G_N} \simeq \frac{Vol_A}{G_N}$$

- what about a boundary cut-off? $R_0 = \frac{\ell^2}{\delta}$ ($\ell^2$ ← macroscopic distance; $\delta$ ← short distance cut-off)

$$S(A) \simeq \frac{\ell^{d-1}}{G_N}\frac{Vol'_A}{\delta^{d-1}}$$

$Vol'_A = \ell^{d-1} f(\theta_0)$

$\frac{\ell^{d-1}}{G_N}$: "central charge"? (depends on macroscopic scale)

- corrections to volume law? (consider $\theta_0 \ll 1$)

$$S(A) \simeq \frac{\ell^{d-1}}{G_N}\frac{Vol'_A}{\delta^{d-1}}\left(1 - \#\,\theta_0^2 + \cdots\right)$$

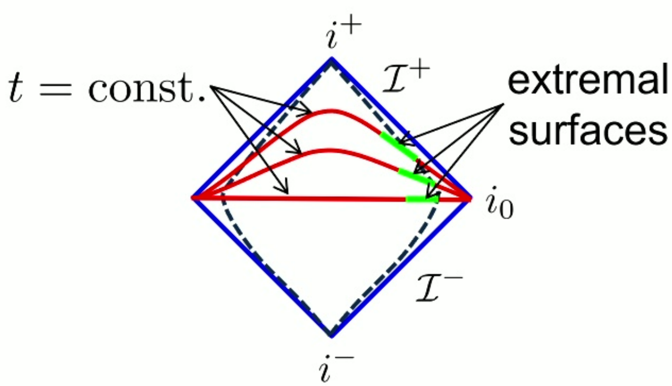
?? $\theta_0 \simeq (Vol'_A)^{1/d-1}/\ell$

Li & Takayanagi (1010.3700)

## RT surfaces in flat space?

$$S(A) = \frac{\Omega_{d-2}(R_0 \sin\theta_0)^{d-1}}{4(d-1)G_N} \simeq \frac{Vol_A}{G_N}$$

- implicitly surfaces are anchored at $i_0$. What about $\mathcal{I}^{\pm}$?




- straightforward to push cut-off surface out holding boundary region A at fixed $u = t - r$
- extremal surfaces are pushed towards cut-off surface/$\mathcal{I}^+$??
- similarly for $\mathcal{I}^-$ ??

Li & Takayanagi (1010.3700)

## RT surfaces in flat space?

$$S(A) = \frac{\Omega_{d-2}(R_0 \sin\theta_0)^{d-1}}{4(d-1)G_N} \simeq \frac{Vol_A}{G_N}$$

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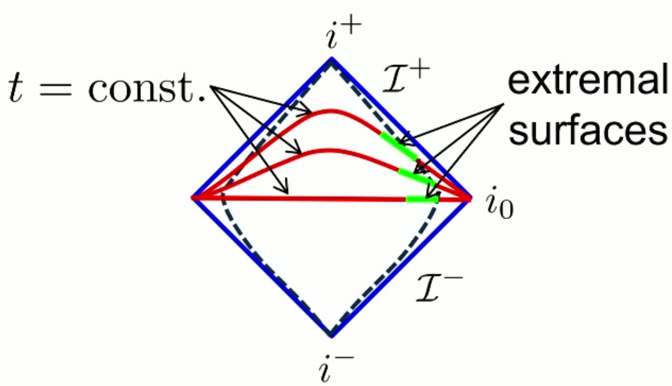


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- strong sub-additivity: $S(A) + S(B) \geq S(A \cup B) + S(A \cap B)$

⟶ proof by pictures (Headrick & Takayanagi) still applies in flat space

⟶ extended to dyanamical settings (Wall) but subtleties arise for present flat space prescription (Grado-White, Marolf & Weinberg)

## Overview:

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## Holographic EE with ropes and swings?

- in three-dimensional AFS, the BMS group has following centrally extended Lie algebra:

super-rotations

$$
\begin{aligned}
[\mathcal{L}_n, \mathcal{L}_m] &= (n-m)\mathcal{L}_{n+m} + \frac{c_L}{12} n(n^2-1)\delta_{n+m,0} \\
[\mathcal{L}_n, \mathcal{M}_m] &= (n-m)\mathcal{M}_{n+m} + \frac{c_M}{12} n(n^2-1)\delta_{n+m,0} \\
[\mathcal{M}_n, \mathcal{M}_m] &= 0
\end{aligned}
$$

super-translations

- with Einstein gravity in bulk: $c_M = \frac{3}{G_N} \quad c_L = 0$ (Barnich & Compere)
- Wigner-Inoünü contraction of bdy Vir X Vir in $AdS_3/CFT_2$:

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

$$
\left[\mathcal{L}_n^{+}, \mathcal{L}_m^{-}\right] = 0
$$

Einstein gravity: $c^{\pm} = \frac{3L}{2G_N}$

$$
L \to \infty \quad \begin{cases} \mathcal{L}_n = \mathcal{L}_n^{+} - \mathcal{L}_{-n}^{-}, & \mathcal{M}_n = \frac{1}{L}(\mathcal{L}_n^{+} + \mathcal{L}_{-n}^{-}) \\ c_M = \frac{1}{L}(c^{+} + c^{-}), & c_L = c^{+} - c^{-} \end{cases}
$$

## Holographic EE with ropes and swings?

- entanglement entropy for two-dimensional BMS field theory?

(Bagchi, Basu Grumiller & Riegler)

- consider EE in 2D CFT and take ultra-relativistic limit $c \to \infty$ *:

$$S(A) = -\lim_{n\to 1} \frac{\partial}{\partial n} \mathrm{Tr}\,\rho_A^n \quad \text{where} \quad \mathrm{Tr}\,\rho_A^n \propto \langle \Phi_{h_L,h_m}(x_1,y_1)\,\Phi_{h_L,h_M}(x_2,y_2)\rangle$$

- for interval with $(\Delta u, \Delta x)$ on a circle of circumference $C$:

$$S(A) = \frac{c_L}{6} \log\left(\frac{C}{\pi\varepsilon_x} \sin\frac{\pi\,\Delta x}{C}\right) + \frac{c_M}{6}\,\frac{C\,\Delta u}{\pi} \cot\frac{\pi\,\Delta x}{C}$$

- planar limit ($C \to \infty$): $S(A) = \frac{c_L}{6}\log\left(\frac{\Delta x}{\varepsilon_x}\right) + \frac{c_M}{6}\,\frac{\Delta u}{\Delta x}$
- similarly for thermal state on infinite line ($C \to i\beta$)
- Renyi entropies: $S_n(A) = \frac{1}{1-n}\log\,\mathrm{Tr}\,\rho_A^n = \frac{1}{2}\left(1+\frac{1}{n}\right)S(A)$

(* actually take non-relativistic limit $c \to 0$ and interchange $t \leftrightarrow x$)

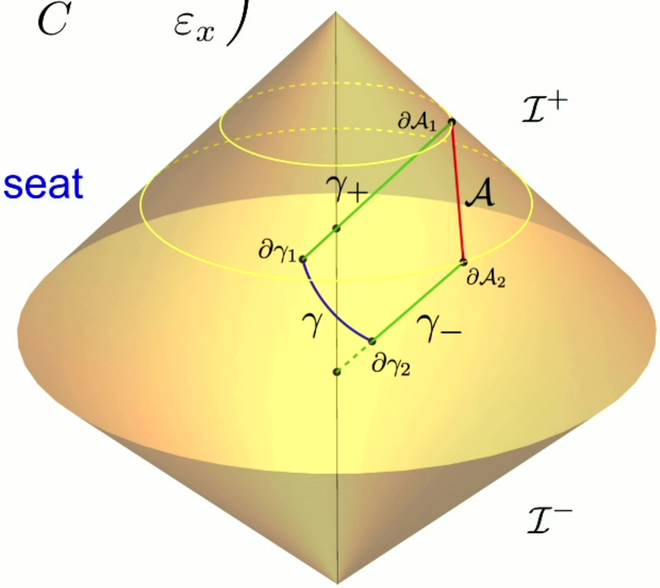
## Holographic EE with ropes and swings?

- swing prescription:
  1) inscribe $\mathcal{A}$ interval of interest on $\mathcal{I}^+$
  2) draw null geodesics $\gamma_\pm$ from $\partial\mathcal{A}$ crossing origin (with $J=0$)
  3) find minimal spacelike geodesic $\gamma$ between $\gamma_\pm$
  4) evaluate BH formula on $\gamma$

$$S(A) = \frac{A_\gamma}{4G_N} = \frac{c_M}{6}\left(\frac{C\,\Delta u}{\pi}\cot\frac{\pi\,\Delta x}{C} - \frac{\varepsilon_u}{\varepsilon_x}\right)$$

$\gamma$ : swing seat

$\gamma_\pm$ : ropes



# Holographic EE with ropes and swings?

- turn on $c_L$ by considering topologically massive gravity

$$\mathcal{S}_{\text{TMG}} = \frac{1}{16\pi G_N}\int d^3x\,\sqrt{-g}\left[R + \frac{2}{L^2} + \underline{\frac{1}{2\mu}\varepsilon^{\alpha\beta\gamma}\left(\Gamma^{\rho}{}_{\alpha\sigma}\partial_\beta\Gamma^{\sigma}{}_{\gamma\rho} + \frac{2}{3}\Gamma^{\rho}{}_{\alpha\sigma}\Gamma^{\sigma}{}_{\beta\eta}\Gamma^{\eta}{}_{\gamma\rho}\right)}\right]$$

$$c^{\pm} = \frac{3L}{2G_N}\left(1 \pm \frac{1}{\mu L}\right) \xrightarrow[L\to\infty]{} c_L = \frac{3}{\mu G_N}\,,\; c_M = \frac{3}{G_N}$$

$$S(A) = \frac{c_L}{6}\log\left(\frac{C}{\pi\varepsilon_x}\sin\frac{\pi\,\Delta x}{C}\right) + \frac{c_M}{6}\left(\frac{C\,\Delta u}{\pi}\cot\frac{\pi\,\Delta x}{C} - \frac{\varepsilon_u}{\varepsilon_x}\right)$$

(see also: Castro, Detournay, Iqbal & Perlmutter)

## Holographic EE with ropes and swings?

### Comments/Personal confusions:

- derivation:

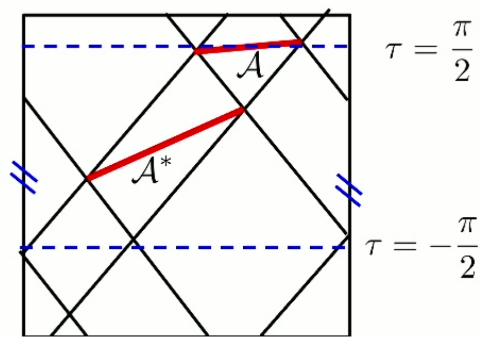
  ⟶ map entanglement entropy to thermal entropy (like CHM) but also add orbifold identifications(?)

- approach not covariant:
  - infinite family of timelike geodesics could define "origin"
  - correspond to changes in frame, absorbed by change of cutoffs

  (Grumiller, Parekh & Riegler)

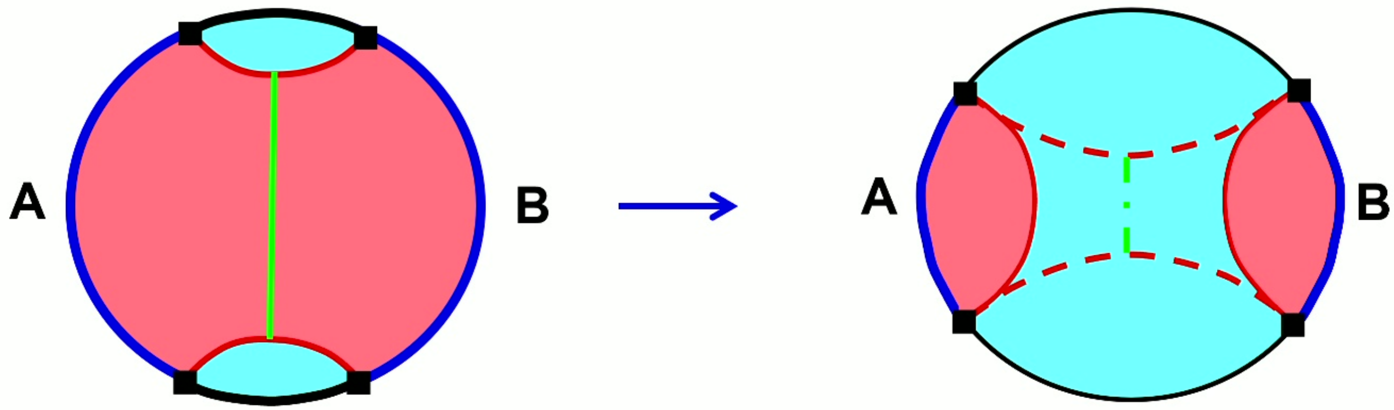
- looking at finite portion of spacelike geodsic; why cutoffs?

- in lifting to $AdS_3$, geodesic $\gamma$ is not RT surface for $\mathcal{A}$ but instead alternate $\mathcal{A}^*$ (?)



## Holographic EE with ropes and swings?

- could holographic BMS EE descend from alternative quantum information observable in $AdS_3/CFT_2$?
- consider reflected entropy: minimal cross-section of connected entanglement wedge, ie, minimal length of spacelike geodesic connecting to **spacelike** geodesics (in $AdS_3$)




- for cross-section to probe "bulk point" must shrink A and B
  → but then enter disconnected phase when $\ell_\gamma \sim L$ !?

# Other Ideas & Directions:

- Celestial Holography from qudits — Guevara & Hu (2312.16298)
- Entanglement on the celestial sphere (& soft modes)
  Chen, Myers & Raclariu (2308.12341; 2403.13913)
- Black hole entropy using soft hair
  Hawking, Perry & Strominger (1601.00921; 1611.09175)
  Haco, Hawking, Perry & Strominger (1810.01847)
- Holographic entanglement entropy of general spacetimes
  Sanches & Weinberg (1603.05250)
  Nomura, Salzetta, Sanches & Weinberg (1611.02702)
  Grado-White, Marolf & Weinberg (2008.07022)
- Flat space with wedge holography
  Ogawa, Takayanagi, Tsuda & Waki (2207.06735)
- And more ……..

# Outlook/Questions:

- intersection of quantum information and quantum gravity led to significant advances in our understanding of holography and QG
  $\longrightarrow$ holographic EE, role of QEC, holographic complexity, …
- focus there was on AdS/CFT but **negative Λ was not essential**, eg, generalized gravitational entropy (Lewkowycz & Maldacena)
- QI in QG has great potential to provide important new insights for holography in flat space
- initial explorations point to unusual properties of dual bdy theory and/or holographic dictionary
- Many open questions:
  - $\longrightarrow$ role of the soft modes?
  - $\longrightarrow$ entanglement entropy in Carrollian theories?
  - $\longrightarrow$ role of Rindler horizons? black holes?

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**Lots to explore!**

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