Title: TBA

Date: Aug 17, 2015 04:00 PM

URL: http://pirsa.org/15080062

Abstract: TBA

GEOMETRIC CONSTRUCTS in AdS/CFT

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QIQG 2 workshop
Aug.17, 2015

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

Based (mainly) on 1406.4611

OUTLINE

- Motivation & background: covariant constructions
  - Causal wedge
  - Entanglement wedge
- Hole-ography
  - Review
  - Limitations
- Covariant residual entropy
  - Rim wedge
  - Strip wedge

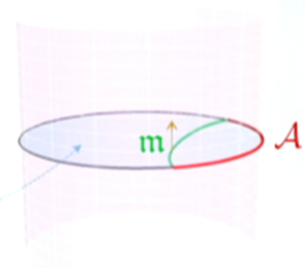
Motivation

- AdS/CFT correspondence:
  - Can provide invaluable insight into strongly coupled QFT & QG
  - To realize its full potential, need to further develop the dictionary…
- Natural expectation:
  - Physically important / natural constructs one side will have correspondingly important / natural duals on the other side…
- Recent progress in QI vs. QG
  - Fundamental quantum information constructs (e.g. entanglement) seem to be intimately related to geometry!
- Hence study natural geometrical / causal constructs in bulk.
- Useful tool in defining new quantities: general covariance…

Ex. 1: Covariant Holographic EE

The RT prescription for holographic EE is not well-defined outside the context of static configurations:

- In Lorentzian geometry, we can decrease the area arbitrarily by timelike deformations
- In time-dependent context, no natural notion of "const. t" slice…



In *time-dependent* situations, RT prescription must be covariantized:

Ex.2: Causal Wedge

Bulk causal region corresponding to $D[\mathcal{A}]$:

- Bulk causal wedge $\blacklozenge_{\mathcal{A}}$

  $$\blacklozenge_{\mathcal{A}} \equiv J^-[D[\mathcal{A}]] \cap J^+[D[\mathcal{A}]]$$

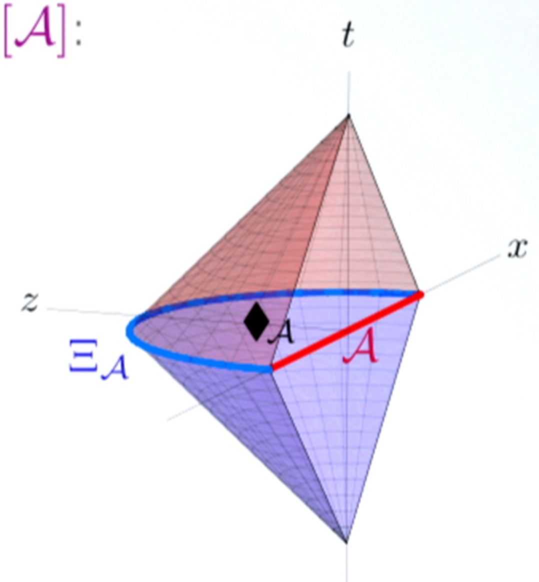
  = { bulk causal curves which begin and end on $D[\mathcal{A}]$ }

- Causal information surface $\Xi_{\mathcal{A}}$

  $$\Xi_{\mathcal{A}} \equiv \partial J^-[D[\mathcal{A}]] \cap \partial J^+[D[\mathcal{A}]]$$

- Causal holographic information $\chi_{\mathcal{A}}$

  $$\chi_{\mathcal{A}} \equiv \frac{\text{Area}(\Xi_{\mathcal{A}})}{4\,G_N}$$



[VH&Rangamani '12]

Power of covariant constructs

- 'Natural' geometrical constructs (defined for general bulk spacetimes, independent of coordinates) provide useful candidates for dual of 'natural' quantities in CFT
- e.g. dual of $\rho_{\mathcal{A}}$? [Bousso, Leichenauer, Rosenhaus; Czech, Karczmarek, Nogueira, Van Raamsdonk;…]

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- In generic Lorentzian spacetime, null congruences which define a causal set provide useful characterization of 'natural' bulk regions.

2 options:

...starting from bdy:

$D[\mathcal{A}] \rightsquigarrow$ Causal Wedge: $\blacklozenge_{\mathcal{A}}$

= future and past causally-separated from bdy region determined by $\rho_{\mathcal{A}}$

[VH & Rangamani]

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[VH & Rangamani]

...starting from bulk:

$\mathfrak{E} \rightsquigarrow$ Entanglement Wedge: $\mathcal{W}_E[\mathcal{A}]$

= spacelike-separated (toward $\mathcal{A}$) from $\mathfrak{E}$

[Headrick, VH, Lawrence, Rangamani]

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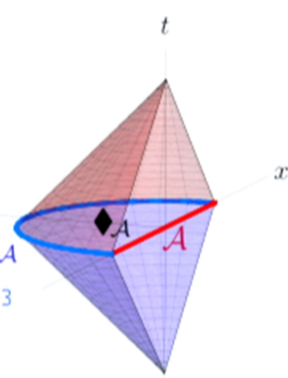
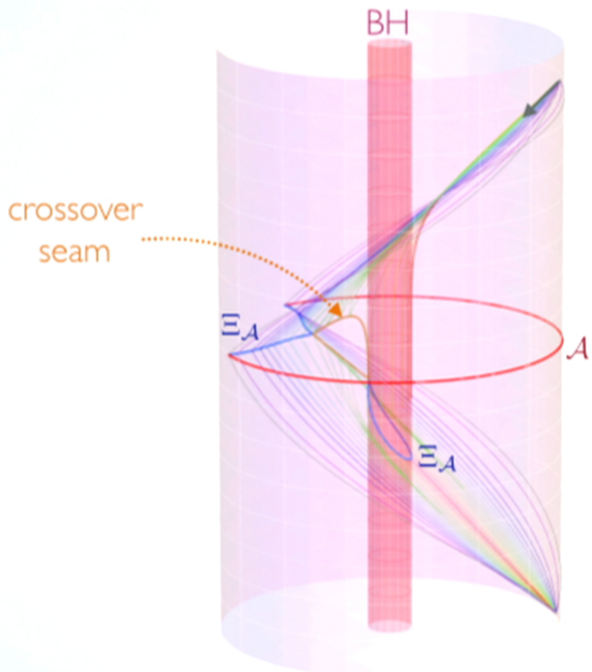


$\mathfrak{E} = \Xi_{\mathcal{A}}$ in AdS_3

NB: in pure AdS, & for spherical $\mathcal{A}$, these coincide: $\blacklozenge_{\mathcal{A}} = \mathcal{W}_E[\mathcal{A}]$ (but not in general)

Causal wedge vs. Entanglement wedge

$D[\mathcal{A}] \rightsquigarrow$ Causal Wedge: $\blacklozenge_{\mathcal{A}}$



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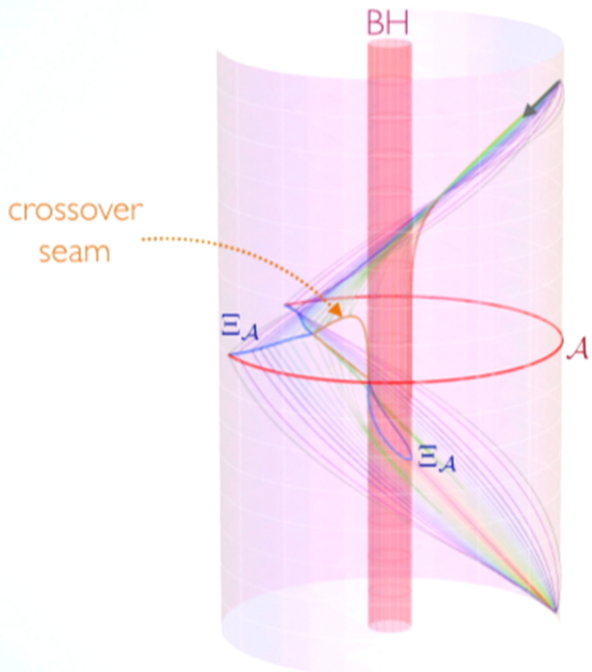

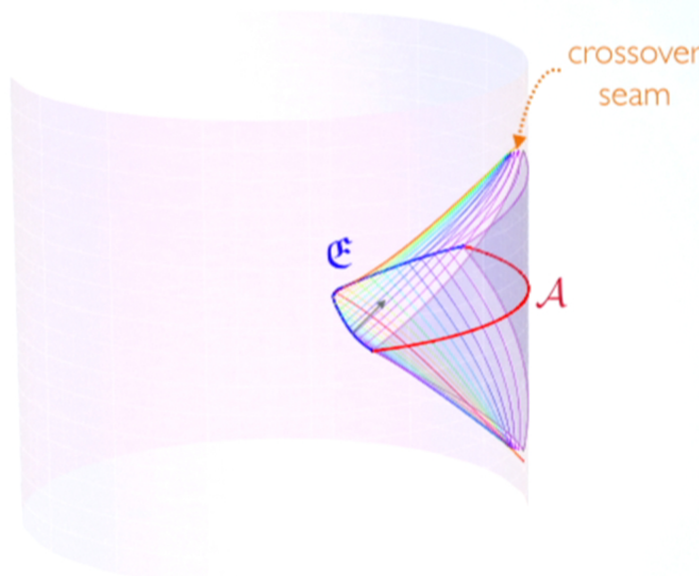

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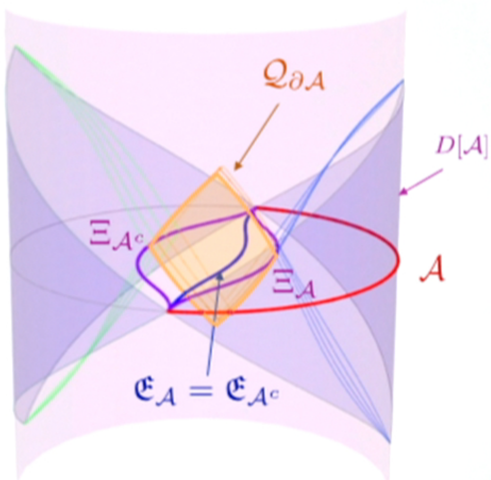
...continued past Ξ: $\rightsquigarrow$ Causal Shadow $\mathcal{Q}_{\partial\mathcal{A}}$

- We can prove the inclusion property [Headrick, VH, Lawrence, Rangamani; Wall]

$\blacklozenge_{\mathcal{A}} \subset \mathcal{W}_E[\mathcal{A}]$

or equivalently, $\mathfrak{E} \subset \mathcal{Q}_{\partial\mathcal{A}}$



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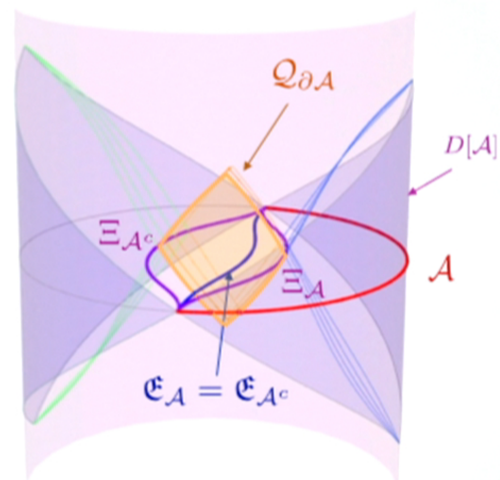


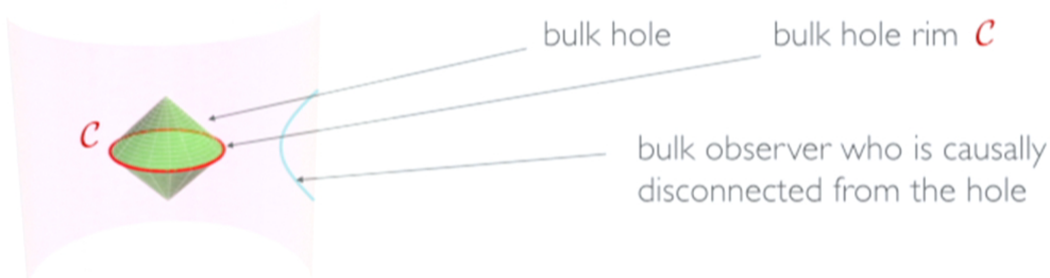
Hole-ography

[Balasubramanian, Chowdhury, Czech, de Boer, & Heller, `13]

- Characterize 'collective ignorance' of a family of observers:

Bulk observers:

restrict to exterior of a hole (w/ rim $\mathcal{C}$)



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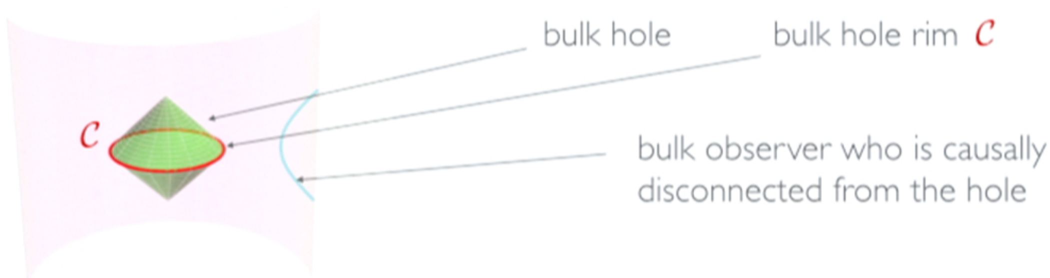

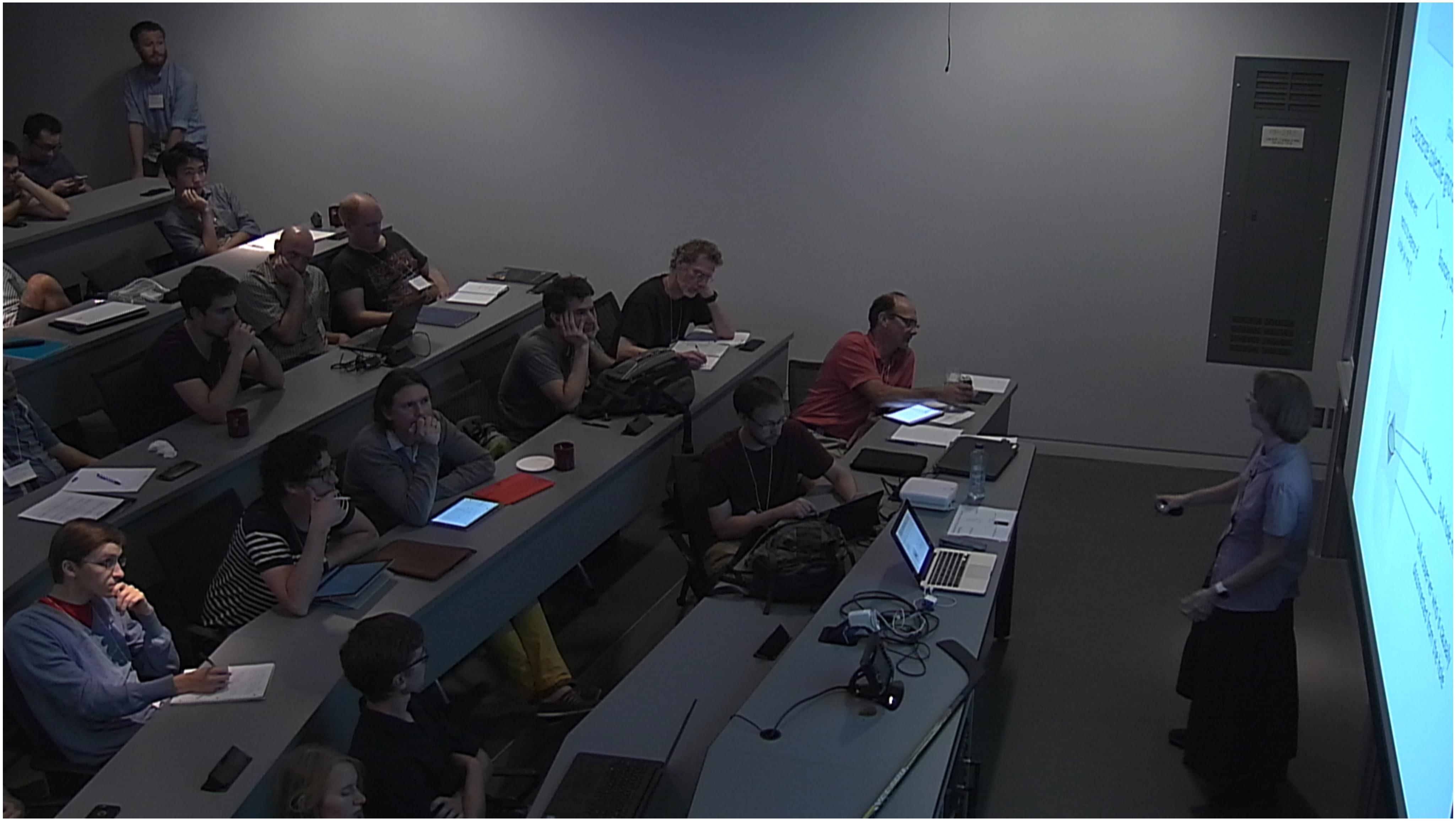

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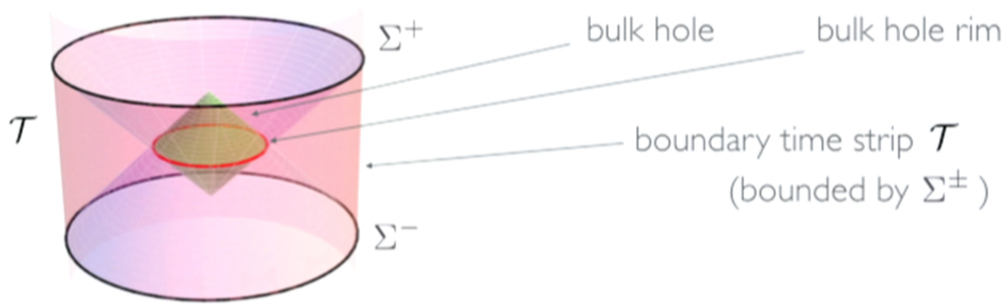

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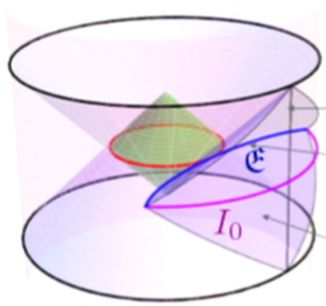

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- [BCCdBH] conflate the two notions; but in general they are distinct, the construction is not reversible…
- Initially called this "residual entropy" (=E), later renamed to "differential entropy" [cf. Myers, Rao, & Sugishita, `14]
- [BCCdBH] present a formula for E:

$$E = \sum_k [S(I_k) - S(I_k \cap I_{k+1})] \quad \rightarrow \frac{1}{2} \int_0^{2\pi} d\varphi \, \frac{dS(\alpha)}{d\alpha} \quad = \frac{\text{Area}(\mathcal{C})}{4\,G_N}$$

Hole-ography: limitations

- However, the [BCCdBH] construction has severe limitations:
  - valid only in 2+1 bulk dimensions
    - Natural ordering for intervals,
      - but not higher dimensional regions
      - & no natural direction for derivative in differential entropy
    - ∃ a unique tangent geodesic to a given smooth curve,
      - but ∄ a unique tangent higher dim. extremal surface
    - Circumvented by considering special symmetry [Myers, Rao, Sugishita; Czech, Dong, Sully]
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      - but not in general (need not even hold for AdS_3 quotients)
      - & when distinct, no residual entropy interpretation…
    - In AdS, extremal surfaces are anchored on bdy
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    - Although diff.ent. generalized to other spacetimes [Myers, Rao, Sugishita],
      - bulk extremal surfaces need not give entanglement entropy
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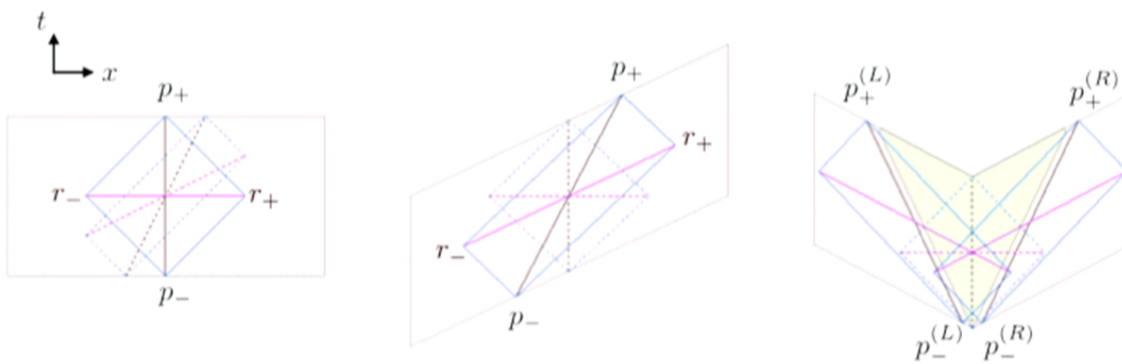

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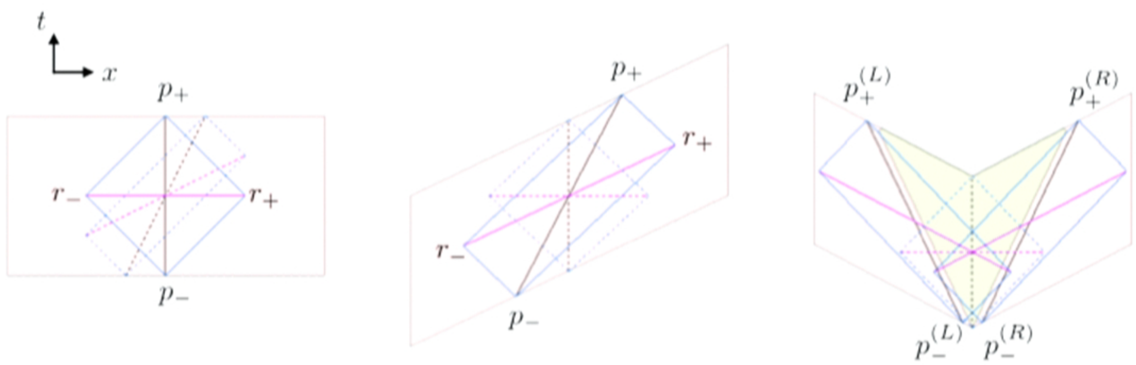

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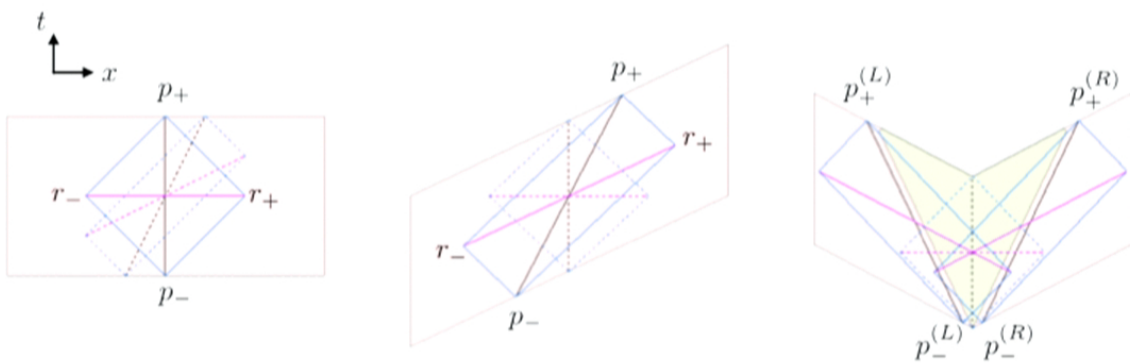

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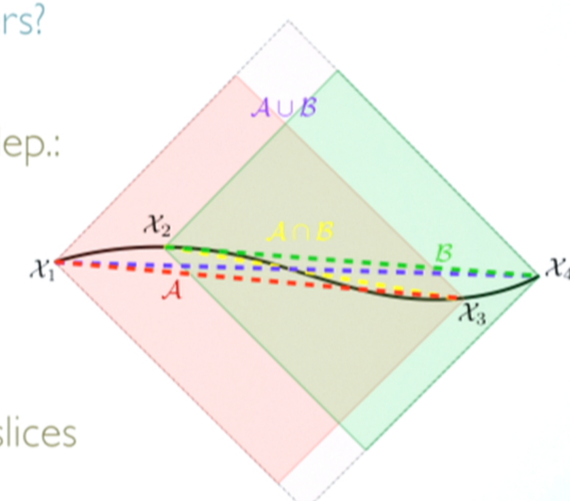
    - Which family of boundary observers?
    - EEs not at equal time…
    - Though can define via domain of dep.:



    - cf. [Headrick, Myers, Wien]
    - still need two (L and R) endpoint slices
    - operational meaning in CFT?

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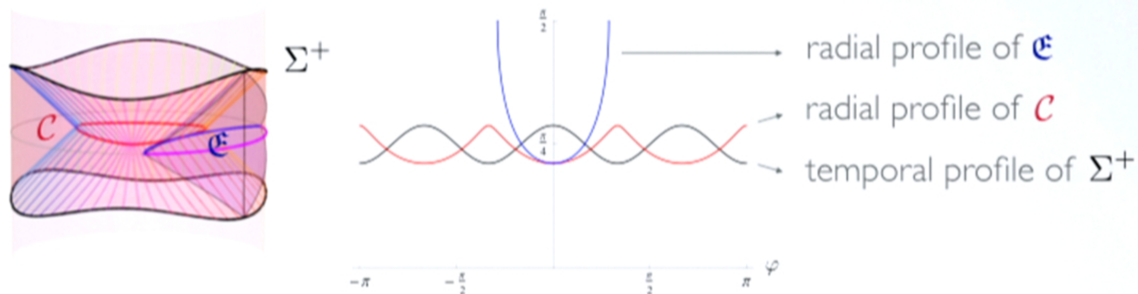
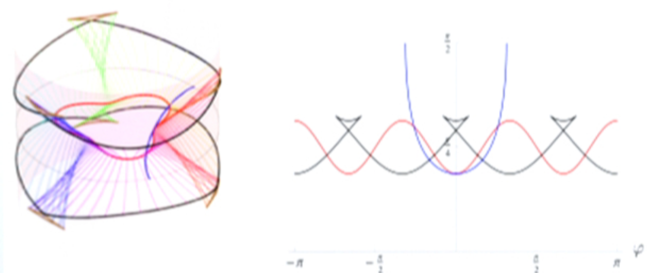
Hole-ography: limitations

"tame" setup: Smooth bulk curve ⇝ smooth time strip

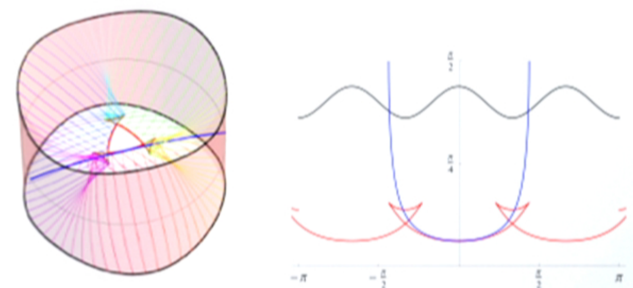


generic case:

Smooth bulk curve ⇝ kinky time strip

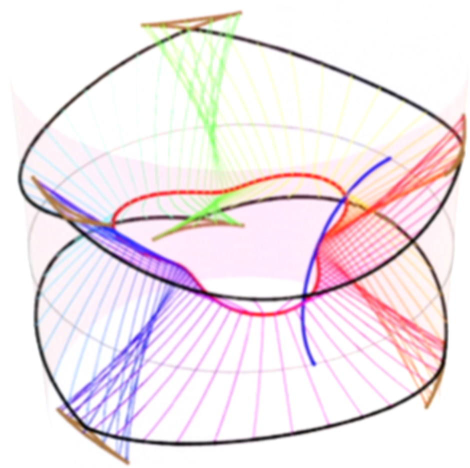


Smooth time strip ⇝ kinky bulk curve



Null generators can cross

Smooth bulk curve
⤳ kinky time strip



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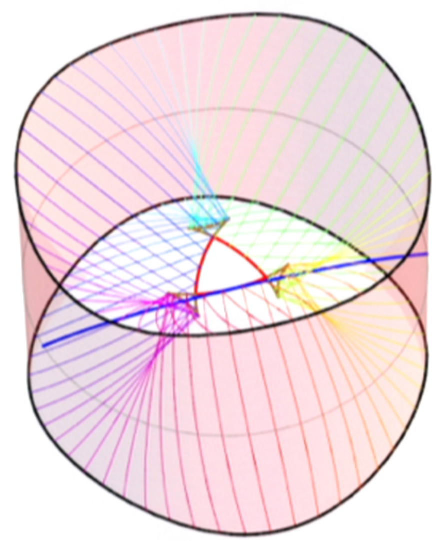

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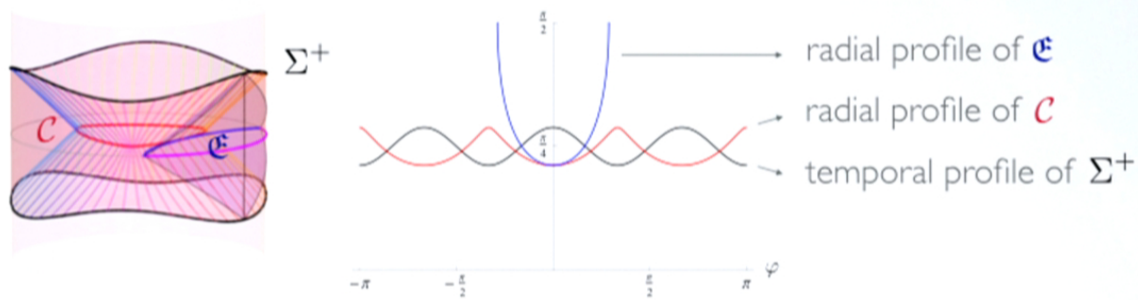

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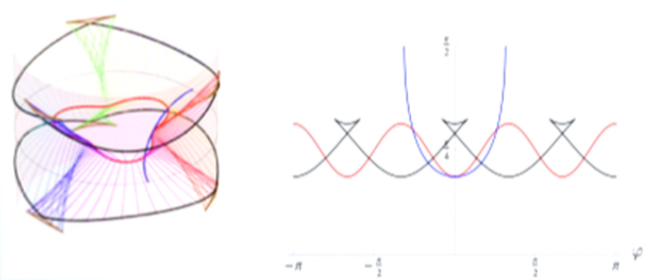

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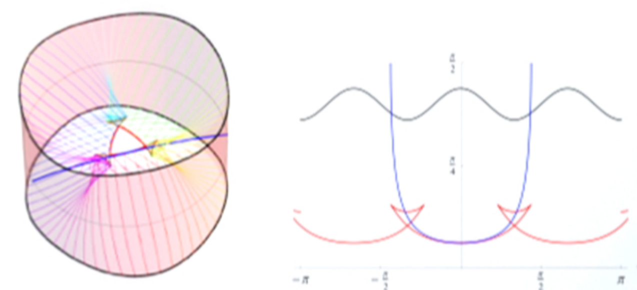

Differential vs. Residual Entropy

- Recall: the [BCCdBH] construction has severe limitations:
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- Upshot: differential entropy given by $E \sim \int d\varphi \, \frac{dS(\alpha)}{d\alpha} |_{\alpha(\varphi)}$ does NOT capture residual entropy.
- ?: is there a more robust notion of residual entropy, applicable for any asymp.AdS geometry in any dimension, & for any region specification?

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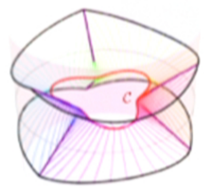
Yes! [VH,'14]

Covariant Residual Entropy

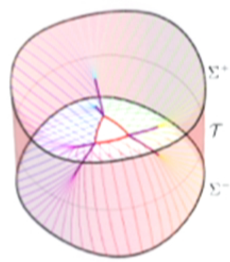
- Two covariant proposals (for bulk vs. bdy starting point)
  - bulk $\mathcal{C}$ defining bulk hole $\rightsquigarrow$ Rim Wedge:



$$\mathcal{W}_{\mathcal{C}} = \left[I^+[\mathcal{C}] \cup I^-[\mathcal{C}]\right]^c \setminus \text{hole}$$

= (closure of) spacelike-separated points from the bulk hole

  - boundary $\Sigma^{\pm}$ defining the time strip $\rightsquigarrow$ Strip Wedge:



$$\mathcal{W}_{\Sigma} = J^+[\Sigma^-] \cap J^-[\Sigma^+]$$

= causally-connected (both in future and past direction) points to the boundary time strip

These are fully robust & well-defined.

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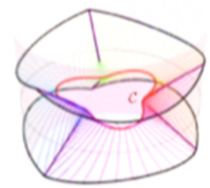
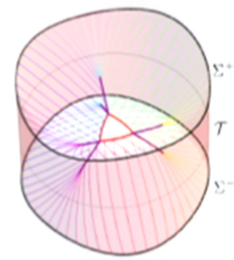


  - boundary $\Sigma^{\pm}$ defining the time strip $\rightsquigarrow$ Strip Wedge:

$$\mathcal{W}_{\Sigma} = J^+[\Sigma^-] \cap J^-[\Sigma^+]$$

= causally-connected (both in future and past direction) points to the boundary time strip



These are fully robust & well-defined.

Covariant Residual Entropy

- Two covariant proposals (for bulk vs. bdy starting point)

  - bulk $\mathcal{C}$ defining bulk hole $\rightsquigarrow$ Rim Wedge:

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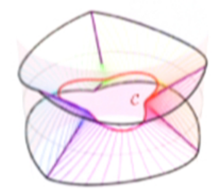

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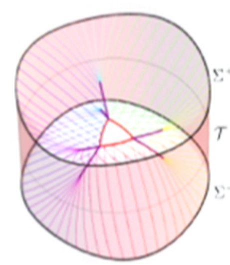

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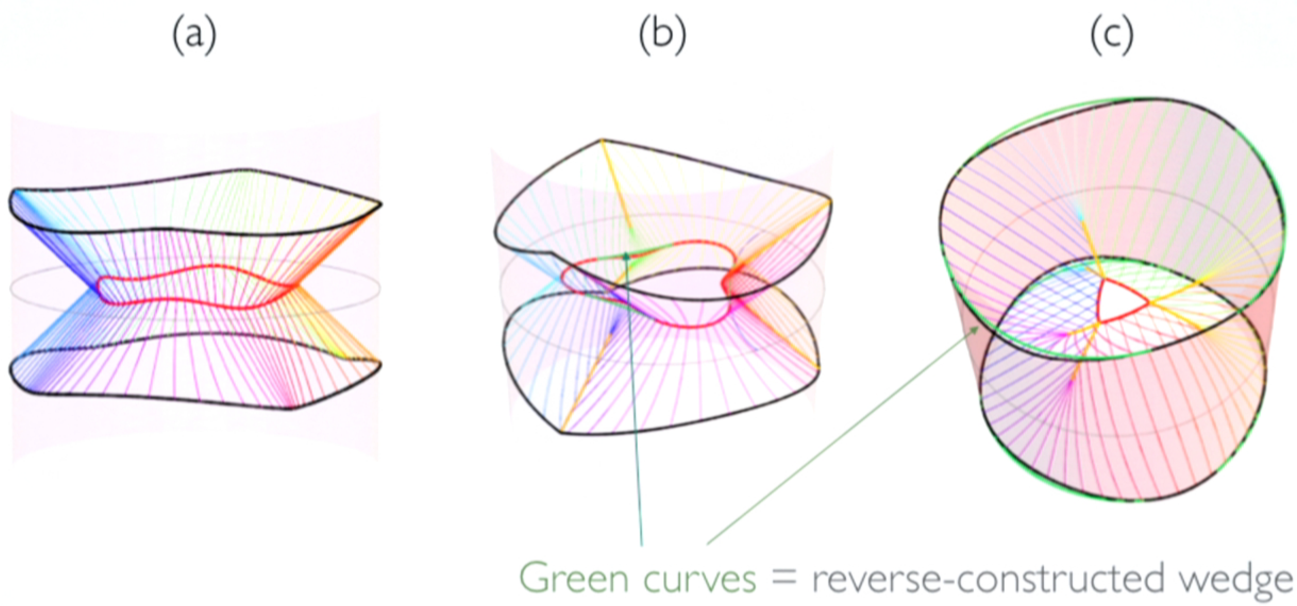
Covariant Residual Entropy

- These coincide only if the generators don't cross — cf. (a)
- Generally neither procedure is reversible — cf. (b) & (c)



- However, it is always true that $\mathcal{W}_\Sigma \subset \mathcal{W}_\mathcal{C}$ (cf. $\blacklozenge_\mathcal{A} \subset \mathcal{W}_E[\mathcal{A}]$)

Covariant Residual Entropy - a puzzle:

- Natural expectations for residual entropy (RE):
  - Bdy RE = area of strip wedge rim

    — cf. expectation of [BCCdBH] and CHI hints [VH&Rangamani, Kelly&Wall]
  - Bulk RE = area of bulk hole rim

    — cf. bulk entanglement entropy [Bianchi&Myers, '12]
- BUT: irreversibility has important implications:
  - Distinct boundary time strips → same hole rim (i.e. same bdy RE)
  - Distinct bulk hole rims (i.e. different bulk RE) → same boundary time strip.
- Hence collective ignorance more global than composite of individual observers' ignorance…
- Apparently, local boundary observers can't recover bulk RE.

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Summary

- Lesson 1: important to distinguish different regimes of validity.
  - dimensionality:
    - only 2+1 dimensional bulk
      - vs. arbitrary dimensions
  - bulk geometry:
    - only pure AdS
    - pure AdS and quotients of AdS
    - only static asymptotically AdS spacetimes
      - vs. arbitrary (physically well-behaved) asymptotically AdS spacetime
  - specification of collective ignorance:
    - rim $\mathcal{C}$ at constant time $\longleftrightarrow$ time-flip symmetric strip $\mathcal{T}$
    - only sufficiently "tame" rim $\mathcal{C}$
    - only sufficiently "tame" or short-duration strip $\mathcal{T}$
      - vs. arbitrary (non-degenerate) $\mathcal{C}$ or $\mathcal{T}$

Summary

- Lesson 2: general covariance is a powerful guiding principle for constructing physically interesting quantities.
- We have seen several distinct causal sets:
  - starting from bdy: Causal wedge $\blacklozenge_{\mathcal{A}}$, Strip wedge $\mathcal{W}_{\mathcal{T}}$
  - starting from bulk: Entanglement wedge $\mathcal{W}_E[\mathfrak{E}_{\mathcal{A}}]$, Rim wedge $\mathcal{W}_{\mathcal{C}}$
- Typically, their boundaries (generated by null geodesics) admit crossover seams, which has important implications.
  - Inclusion properties, e.g. rim wedge contains corresp. strip wedge
  - Local boundary observers may not capture bulk residual entropy, there is a more nonlocal aspect to collective ignorance than {obs}…
- ?: should we expect the notion of Residual Entropy to make sense?

Space Ref (Harvard-Smithsonian CfA)

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