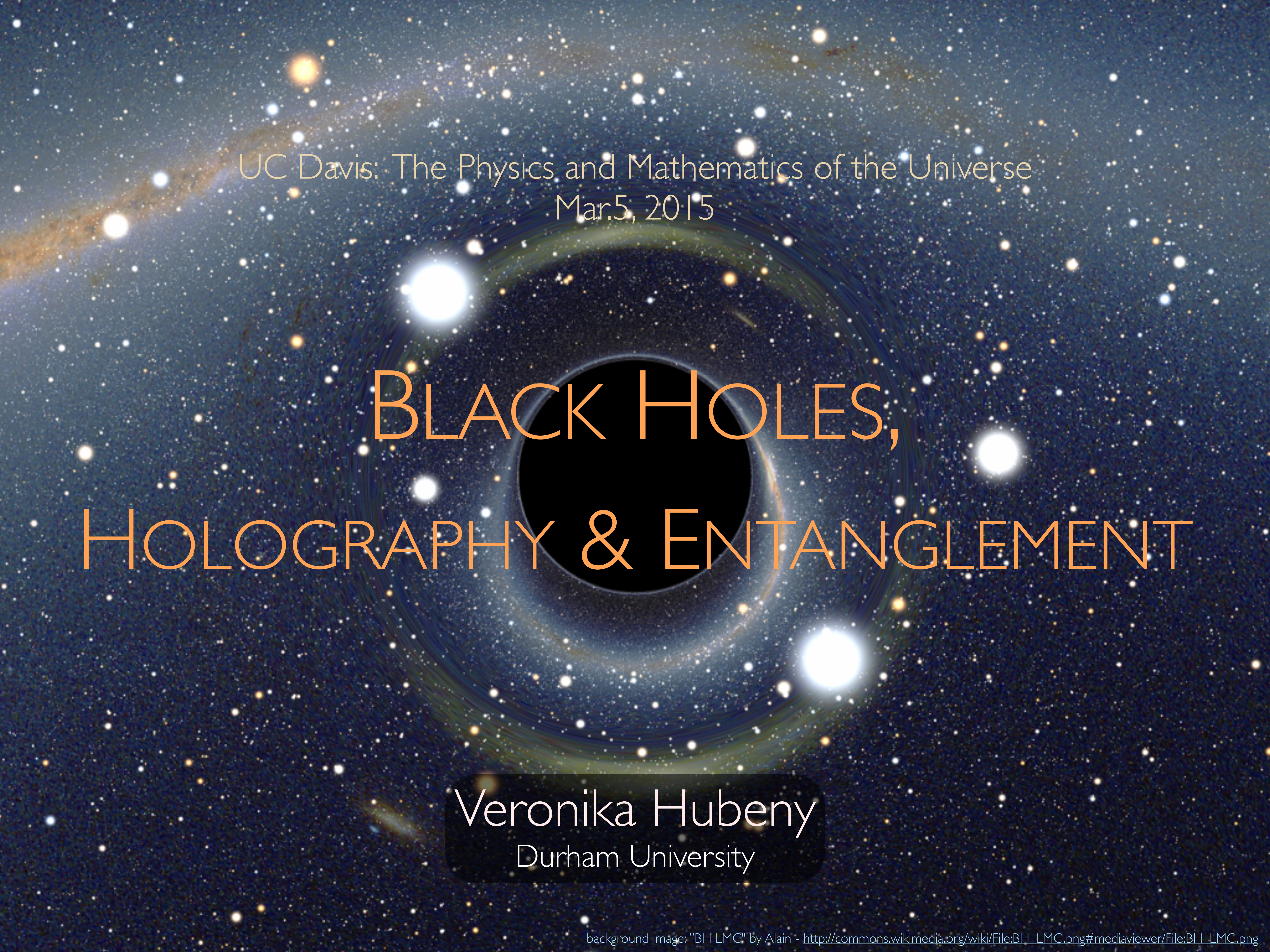

UC Davis: The Physics and Mathematics of the Universe

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Black Holes, Holography & Entanglement

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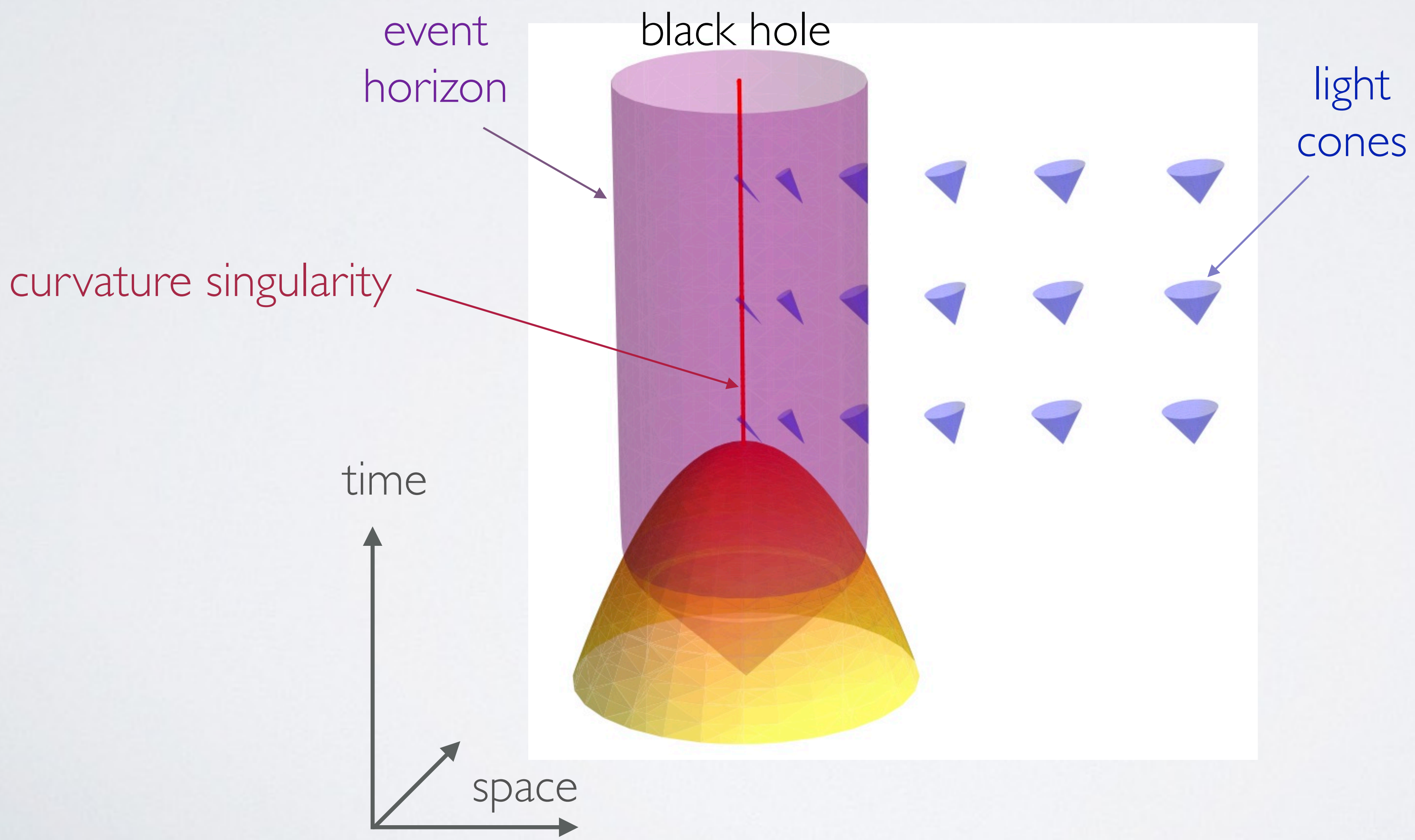
background image: "BH LMC" by Alain - http://commons.wikimedia.org/wiki/File:BH_LMC.png#mediaviewer/File:BH_LMC.png

OUTLINE

- Black holes in many guises
    - AdS/CFT correspondence
        - Holographic entanglement entropy
            - Emergent spacetime

Black holes

- Black hole = region of spacetime which cannot communicate with the external Universe
- In Nature, results as endpoint of gravitational collapse



Many guises of black holes

- Astronomical objects, powering some of the most energetic processes in the Universe
- Mathematically beautiful: *"the most perfect macroscopic objects there are"* [Chandrasekhar]
- Lie at heart of profound dualities (e.g. AdS/CFT)
- Remarkably related to 'ordinary' systems (e.g. fluids)
- May hold a key to quantum gravity...

Black hole thermodynamics

- Stationary black hole characterized by 3 parameters:
  - mass M, angular momentum J, and charge Q
- Important properties: horizon area A and surface gravity κ

Laws of BH mechanics mimic laws of thermodynamics:

BH mechanics	Thermodynamics
0. κ is constant over horizon for stationary BH	0. T is constant over system in thermal equilibrium
1. $dM = (1/8\pi G)\,\kappa\, dA + \Omega_H\, dJ$	1. $dE = T\, dS +$ work terms
2. $\delta A \geq 0$ in any process	2. $\delta S \geq 0$ in any process
3. Impossible to achieve $\kappa = 0$ by a physical process	3. Impossible to achieve $T = 0$ by a physical process

Hence natural to identify $M \sim E$, $\kappa \sim T$, and $A \sim S$

Black holes as thermodynamic objects

- S motivated by gedanken-experiments of matter falling into BH [Bekenstein]
- T substantiated by semi-classical calculations [Hawking]: black holes radiate
- Specifically identify $S_{BH} = \dfrac{k_B\, c^3}{G\, \hbar} \dfrac{A}{4}$ and $T_{BH} = \dfrac{\hbar\, c}{k_B} \dfrac{\kappa}{2\, \pi}$
- Natural question: statistical mechanics origin of BH entropy?

- Generalized Second Law: combined matter+BH entropy increases

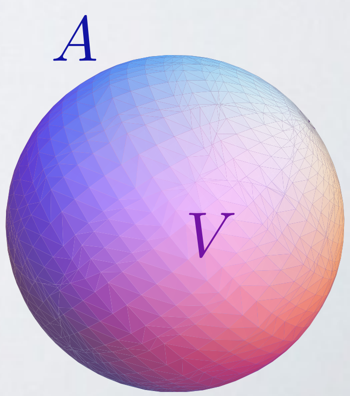
  ⇒ Bekenstein bound (weakly gravitating systems): $S_{\rm matter} \leq 2\pi\, E\, R$

  ⇒ Spherical entropy bound (slowly evolving systems): ['t Hooft, Susskind]

$$S_{\rm matter} \leq \frac{A}{4}$$

$\Longrightarrow$ entropy S is not extensive:

$$S \not\propto V$$

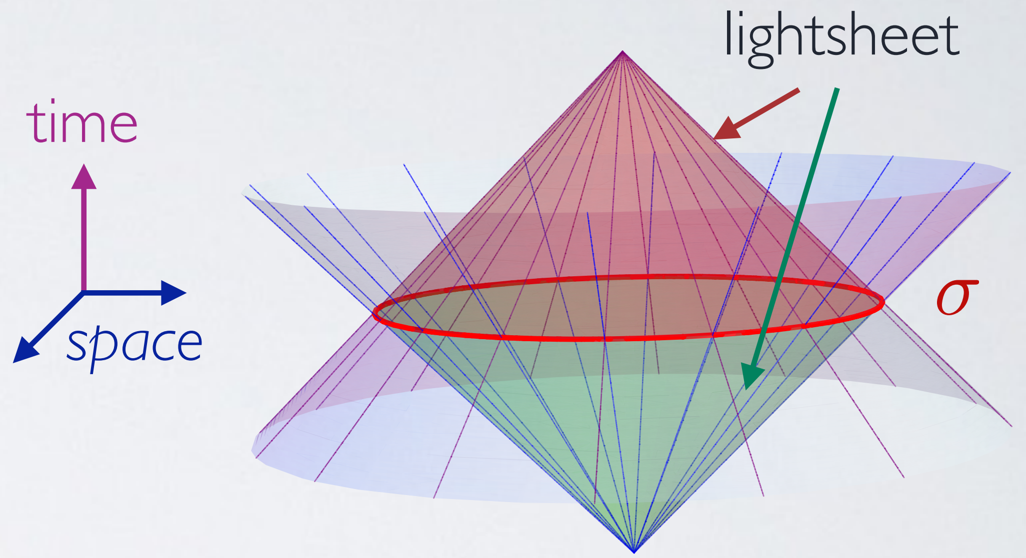


Holographic Principle

- Covariant entropy bound: full spacetime construct [Bousso]

  Entropy on any lightsheet L of a surface σ cannot exceed the area of σ:

$$S(L) \leq \frac{A(\sigma)}{4}$$



- Holographic Principle: in a theory of gravity, the number of degrees of freedom describing the physics on lightsheet $L(\sigma)$ cannot exceed $A(\sigma)/4$

⇒ physical equivalence between 2 theories living in different # of dimensions!

- Concrete realization: AdS/CFT correspondence

AdS/CFT correspondence

String theory ($\ni$ gravity) $\Longleftrightarrow$ gauge theory (CFT)

"in bulk" asymp. AdS × S

"on boundary"

[Maldacena, '97]

'soup can' diagram of AdS:

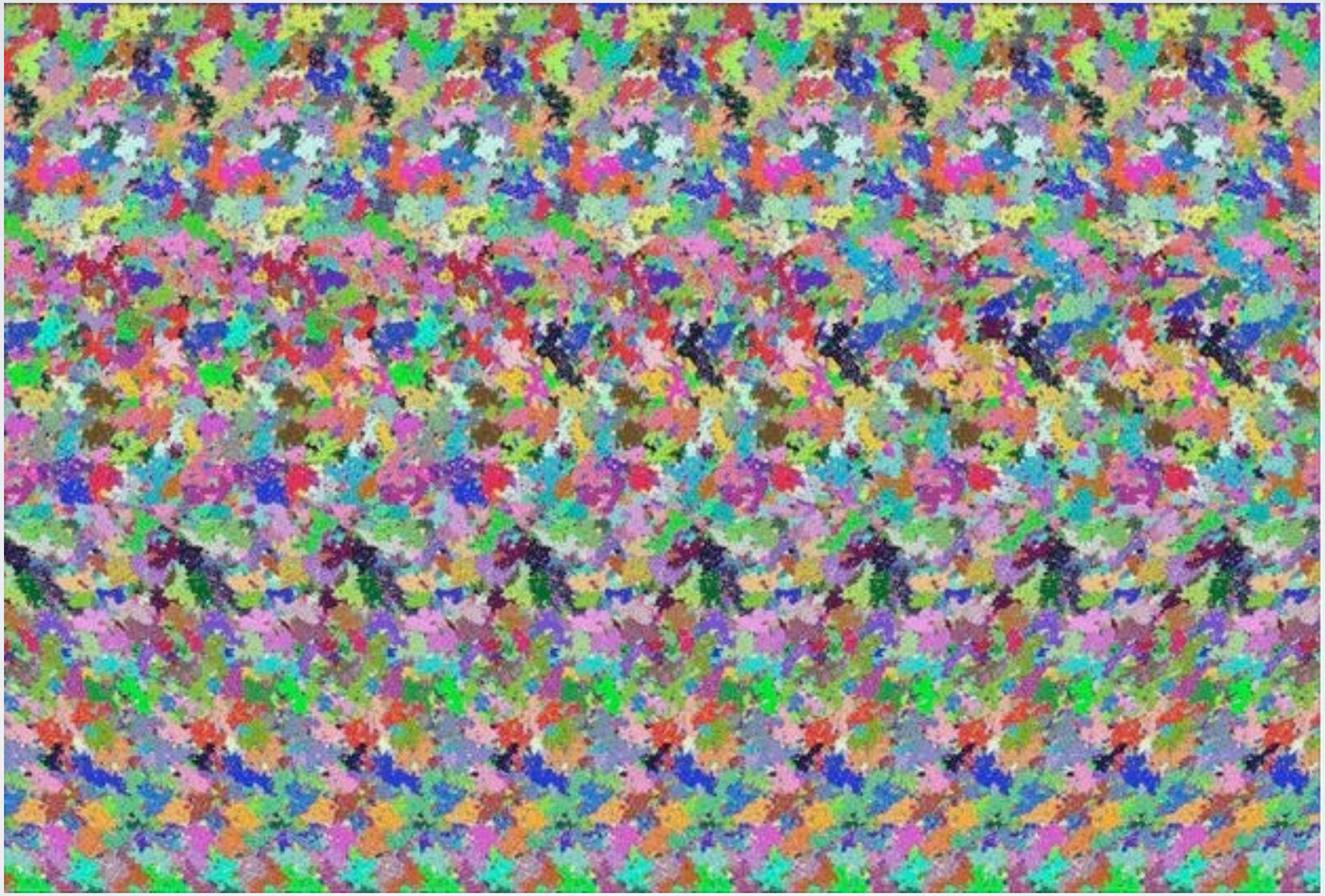
here label is everything...

Key aspects:

- Gravitational theory maps to non-gravitational one!
- *Holographic*: gauge theory lives in fewer dimensions.

AdS/CFT correspondence

* better analogy: stereogram...



...but infinitely more complicated

AdS/CFT correspondence

String theory ($\ni$ gravity) $\Longleftrightarrow$ gauge theory (CFT)

"in bulk" asymp. AdS × K *"on boundary"*

Key aspects:

- ⁎ Gravitational theory maps to non-gravitational one!
- ⁎ *Holographic*: gauge theory lives in fewer dimensions.
- ⁎ Strong/weak coupling duality.

Invaluable tool to:

~ Use gravity on AdS to learn about strongly coupled field theory
(as successfully implemented in e.g. AdS/QCD & AdS/CMT programs)

~ Use the gauge theory to define & study quantum gravity in AdS

Pre-requisite: Understand the AdS/CFT 'dictionary'...

Scale/radius duality

What CFT quantity encodes the extra bulk direction?

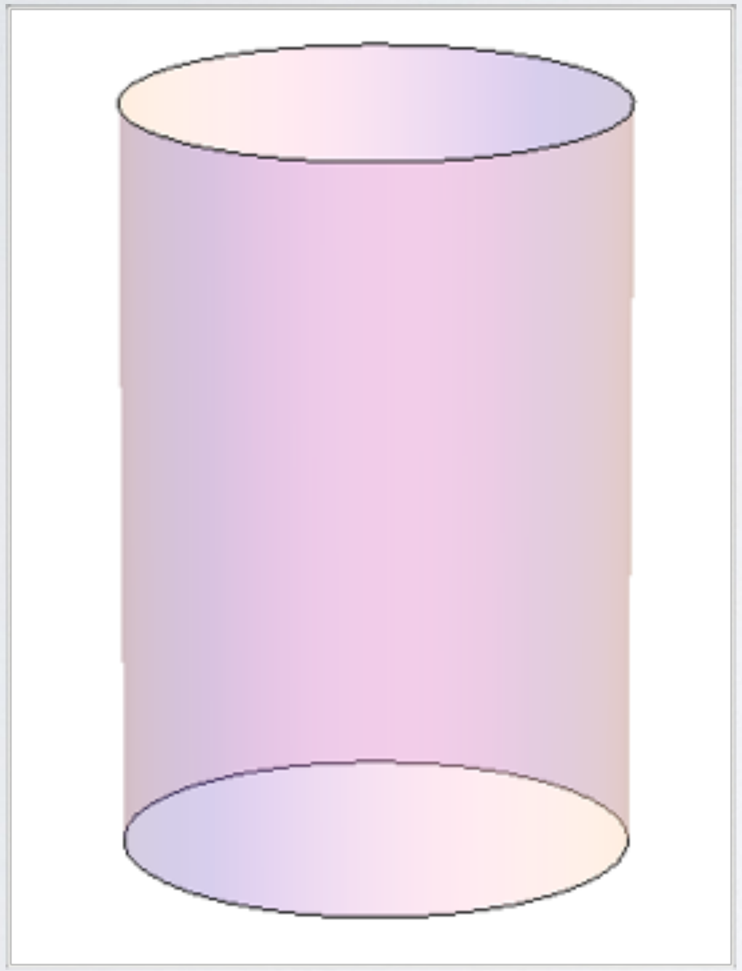
- Scale/radius (or UV/IR) duality:
  - UV (small scale) in CFT ⇜⇝ IR (large radius) in AdS
  - Local bulk excitation at radial position *z* in AdS is manifested by CFT excitation at scale *L~z*. [Susskind & Witten]
  - Follows from AdS geometry…
  - Provides useful intuition: e.g. object falling into a black hole ⇜⇝ CFT excitation spreads & thermalizes [Banks, Douglas, Horowitz, Martinec]

- Asymptotic fall-off of bulk fields ⇜⇝ Expectation values of local gauge-invariant operators in CFT

Bulk geometries and CFT states

different bulk geometries $\longleftrightarrow$ different states in CFT

(asymptotically AdS)

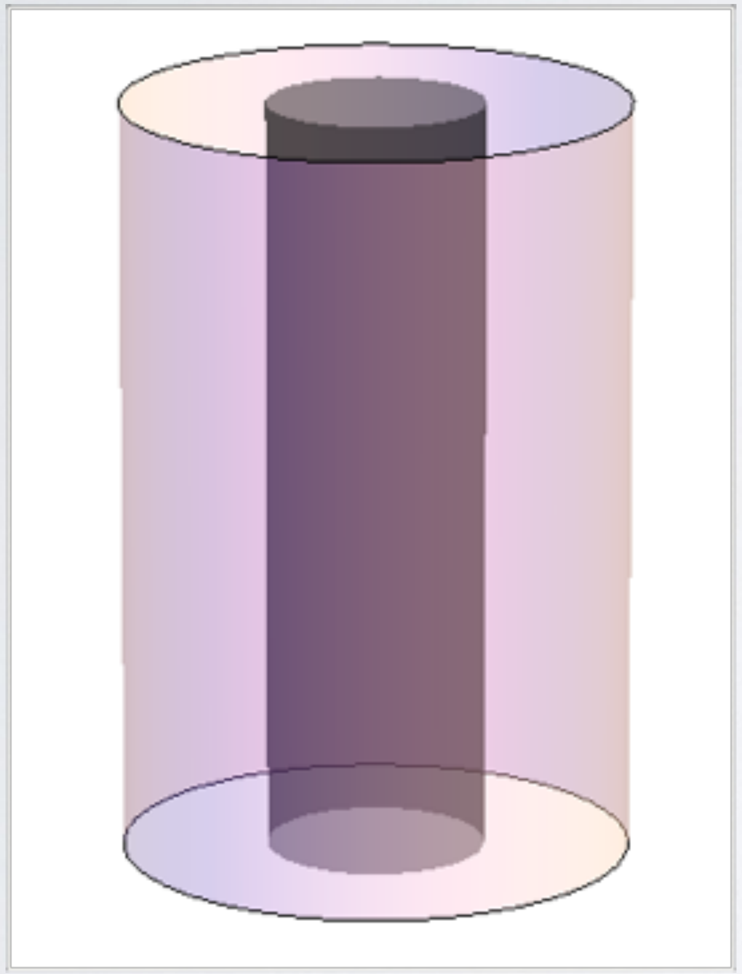


- Pure AdS $\longleftrightarrow$ vacuum state in CFT

  Finite-mass deformations of the bulk geometry result in non-zero boundary stress-energy-momentum tensor

Black holes in equilibrium

different bulk geometries $\longleftrightarrow$ different states in CFT



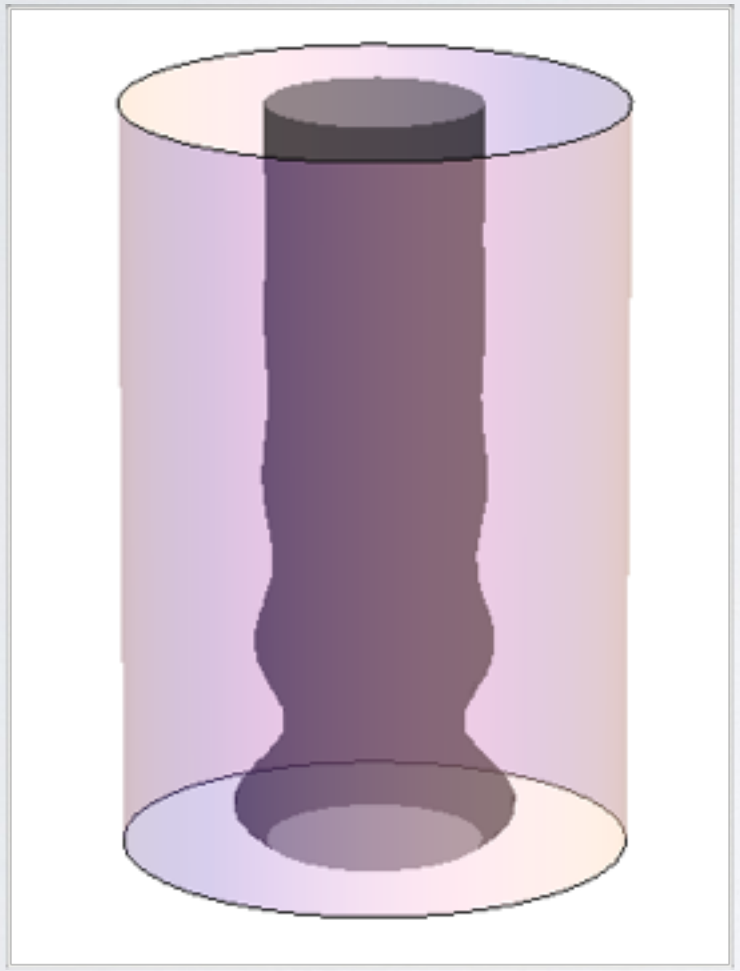
- Pure AdS $\longleftrightarrow$ vacuum state in CFT
- Black hole $\longleftrightarrow$ thermal state in CFT

  But need more refined understanding:
  - (How) Does the CFT describe physics behind an event horizon?
  - What is the nature of the BH singularity?
  - What is the CFT description of causal structure?

- What about time-evolving geometries?

Small deviations from equilibrium

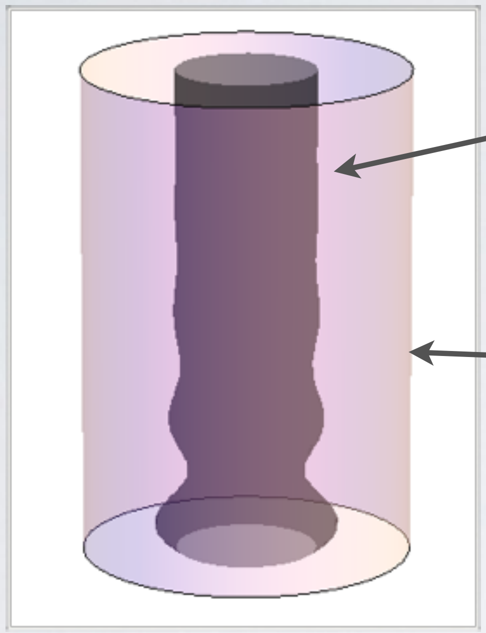
evolving bulk geometries $\longleftrightarrow$ corresponding dynamics



- Pure AdS $\longleftrightarrow$ vacuum state in CFT
- Black hole $\longleftrightarrow$ thermal state in CFT
- Quasinormal modes of perturbed black hole $\longleftrightarrow$ approach to thermal equilibrium [Horowitz & Hubeny]

✶ Horizon response properties $\longleftrightarrow$ transport coefficients in CFT
[Kovtun, Son, Starinets]

Description of dynamics



bulk geometry specified by $g_{ab}(r, x^\mu)$

(asymptotic falloff of g_{ab} induces $T_{\mu\nu}$)

boundary state characterized by $T_{\mu\nu}(x^\mu)$

(for slow variations, describes a fluid)

* Bulk dynamics is specified by Einstein's equations.

$$E_{ab} \equiv R_{ab} - \frac{1}{2} R\, g_{ab} + \Lambda\, g_{ab} = 0$$

* Boundary dynamics satisfies stress tensor conservation.

$$\nabla_\mu T^{\mu\nu} = 0$$

Fluid/Gravity correspondence

[Bhattacharyya, Hubeny, Minwalla, Rangamani, 2008]

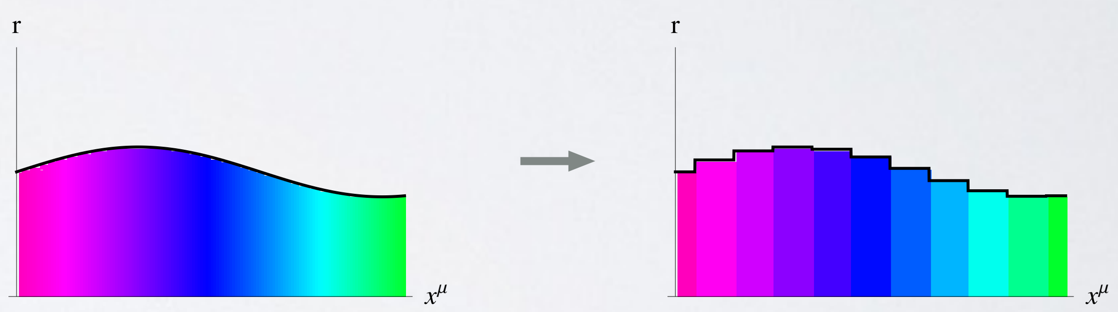
- Dynamics of bulk black hole ⇔ fluid dynamics on boundary

  5-d Einstein's equations ⊃ 4-d Navier-Stokes equations

  w/ negative cosmological const. (describing relativistic, conformal fluid)

- For any given fluid flow, we iteratively construct a solution of a dynamical black hole in AdS whose horizon mimics the fluid.

  - Technically: expand in boundary derivatives and solve order by order
  - The radial equation is fully nonlinear, and gives patched 'tubes' of different black holes



- We calculate 2nd order transport coefficients for the conformal fluid.

- The pull-back of the horizon area form gives a natural entropy current on the boundary, with automatically non-negative divergence.

[Bhattacharyya, Hubeny, Loganayagam, Mandal, Minwalla, Morita, Rangamani, Reall]

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- For any given fluid flow, we iteratively construct a solution of a dynamical black hole in AdS whose horizon mimics the fluid.

- Generalizations:
  - charged fluids,
  - superfluids,
  - non-conformal fluids,
  - non-relativistic fluids,
  - fluids with boundary,
  - forced fluids,
  - other dimensions, ...

- Applications:
  - black hole physics,
  - fluid dynamics,
  - nuclear physics,
  - condensed matter physics,
  - solid state physics, ...

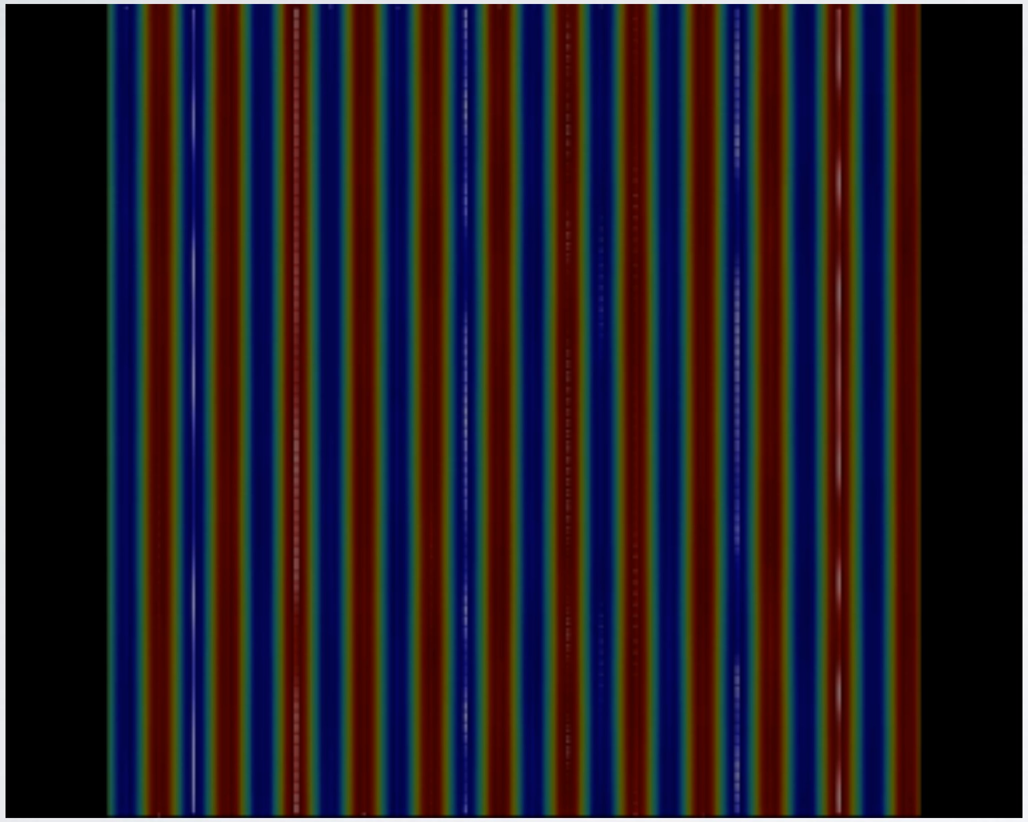
- But not yet everyday liquids, e.g. non-Newtonian fluids.

Holographic Turbulence

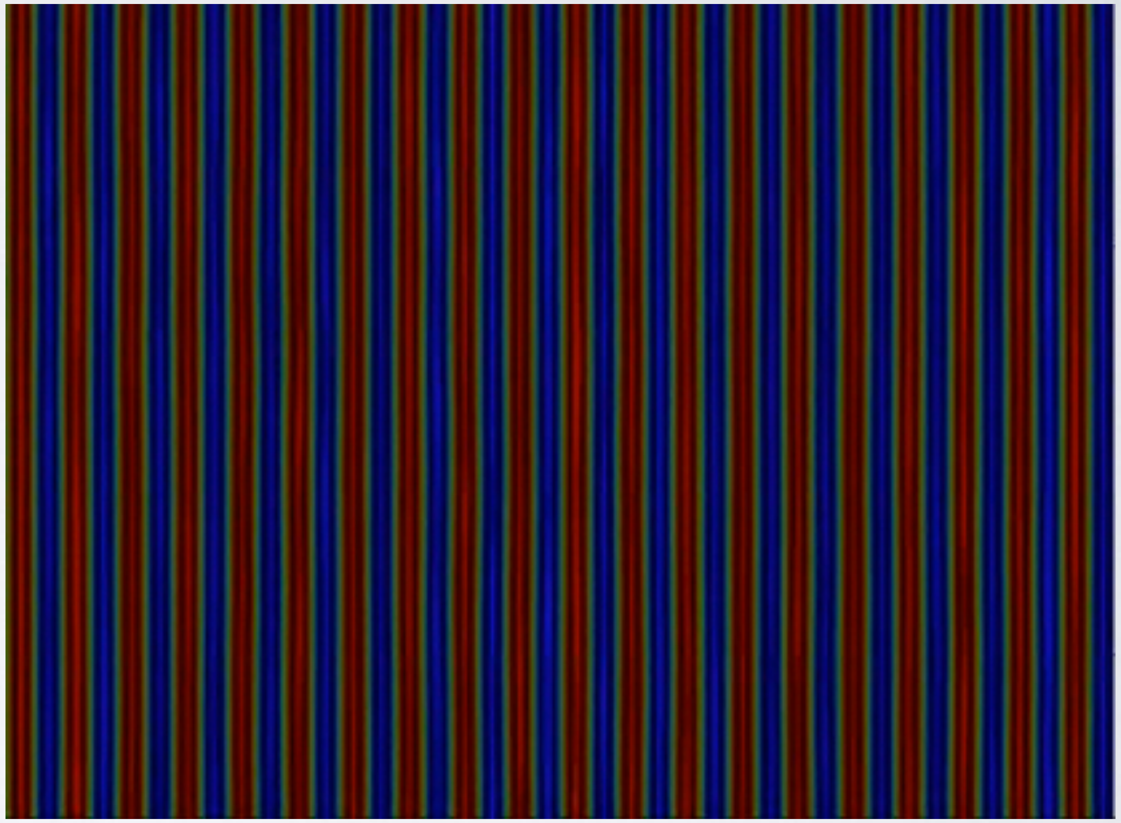
Beyond fluid/gravity:

- Recently, [Adams, Chesler, Liu] constructed turbulent black holes in asymptotically AdS_4 spacetime by numerically solving Einstein equations
- Resulting bulk solution is well-approximated by the metric derived from fluid/gravity expansion
- Both dual holographic fluid and bulk geometry display signatures of an inverse cascade (see hints of Kolmogorov scaling for driven steady-state turbulence: the power spectrum P of the fluid velocity ~ $k^{-5/3}$)
- Surprise for GR: statistically steady-state black holes dual to d dimensional turbulent flows have horizons which are approximately fractal with fractal dimension D = d + 4/3

Holographic Turbulence



http://turbulent.lns.mit.edu/Turbulence/1307.7267/1307.7267.html



http://turbulent.lns.mit.edu/Turbulence/1307.7267/1307.7267.html

The vorticity field of the quantum liquid holographically derived from the turbulent numerical metric: instability of initial perturbation drives ordered state into turbulent evolution with inverse cascade (small vortices merge into larger ones)

Onward from AdS/CFT

String theory ($\ni$ gravity) $\Longleftrightarrow$ gauge theory (CFT)

"in bulk" asymp. AdS $\times$ K *"on boundary"*

Applied AdS/CFT:

- study specific system via its dual
- e.g. AdS/QCD, AdS/CMT, …

Fundamentals of AdS/CFT:

- why/how does the duality work
- map between the 2 sides

Holographic Entanglement Entropy

Quantum Gravity

Entanglement

- Most non-classical manifestation of quantum mechanics
  - "Best possible knowledge of a whole does not include best possible knowledge of its parts — and this is what keeps coming back to haunt us" [Schrodinger '35]
- New quantum resource for tasks which cannot be performed using classical resources [Bennet '98]
- Plays a central role in wide-ranging fields
  - quantum information (e.g. cryptography, teleportation, …)
  - quantum many body systems
  - quantum field theory
- Hints at profound connections to geometry…

Entanglement in 2 qubit system

Consider a system of 2 spins, labeled A and B

- Simple product state: $|\,\psi\,\rangle = |\uparrow\rangle_A \otimes |\downarrow\rangle_B \equiv |\uparrow\downarrow\rangle$
- More complicated product state:

$$|\,\psi\,\rangle = \frac{|\downarrow\rangle_A + |\uparrow\rangle_A}{\sqrt{2}} \otimes \frac{|\downarrow\rangle_B + |\uparrow\rangle_B}{\sqrt{2}} = \frac{1}{2}\left(|\downarrow\downarrow\rangle + |\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle + |\uparrow\uparrow\rangle\right)$$

- Generic state (with arbitrary c_{ij} s.t. $\sum c_{ij}^2 = 1$)

$$|\,\psi\,\rangle = c_{00}\,|\downarrow\downarrow\rangle + c_{01}\,|\downarrow\uparrow\rangle + c_{10}\,|\uparrow\downarrow\rangle + c_{11}\,|\uparrow\uparrow\rangle$$

  is entangled when it is not a product state.
- A Bell (EPR) pair, such as $|\,\psi\,\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle\right)$

  is maximally entangled.

Entanglement Entropy (EE)

The amount of entanglement is characterized by Entanglement Entropy S_A. Since we can only measure A, integrate out B:

- reduced density matrix $\rho_A = \mathrm{Tr}_B \, |\psi\rangle\langle\psi|$

  (more generally, for a mixed total state, $\rho_A = \mathrm{Tr}_B \rho$)

- EE = von Neumann entropy $S_A = -\mathrm{Tr}\, \rho_A \log \rho_A$

- For the maximally entangled state $|\,\psi\,\rangle = \frac{1}{\sqrt{2}}(\,|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle)$

$$\rho_A = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad \Rightarrow \qquad S_A = \log 2$$

- For the non-entangled state $|\,\psi\,\rangle = \frac{1}{2}(\,|\downarrow\downarrow\rangle + |\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle + |\uparrow\uparrow\rangle)$

$$\rho_A = \frac{1}{2}\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \qquad \Rightarrow \qquad S_A = 0$$

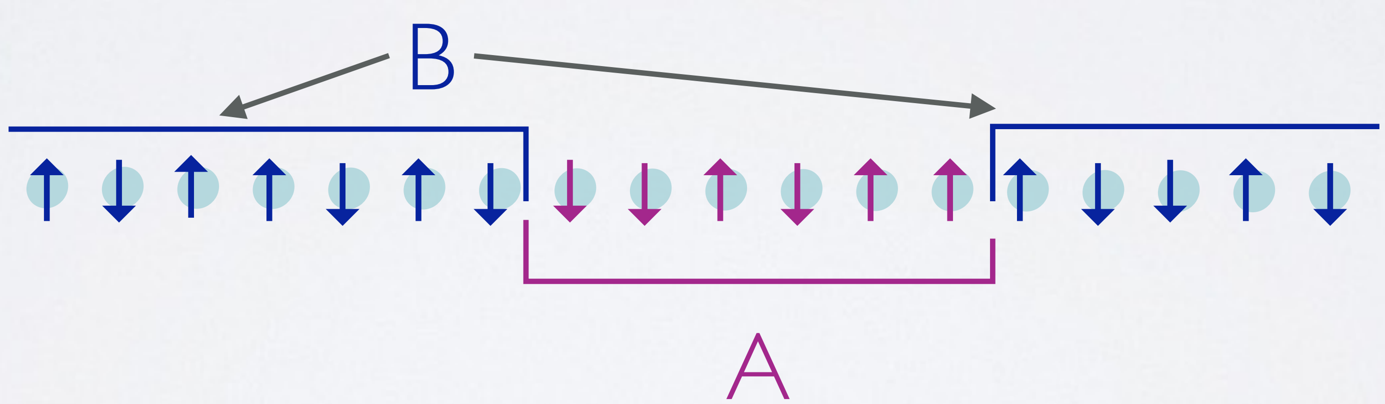
EE more generally

More generally: divide a quantum system into a subsystem A and its complement B, such that the Hilbert space decomposes:

$$\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$$

e.g.:

- spin chain



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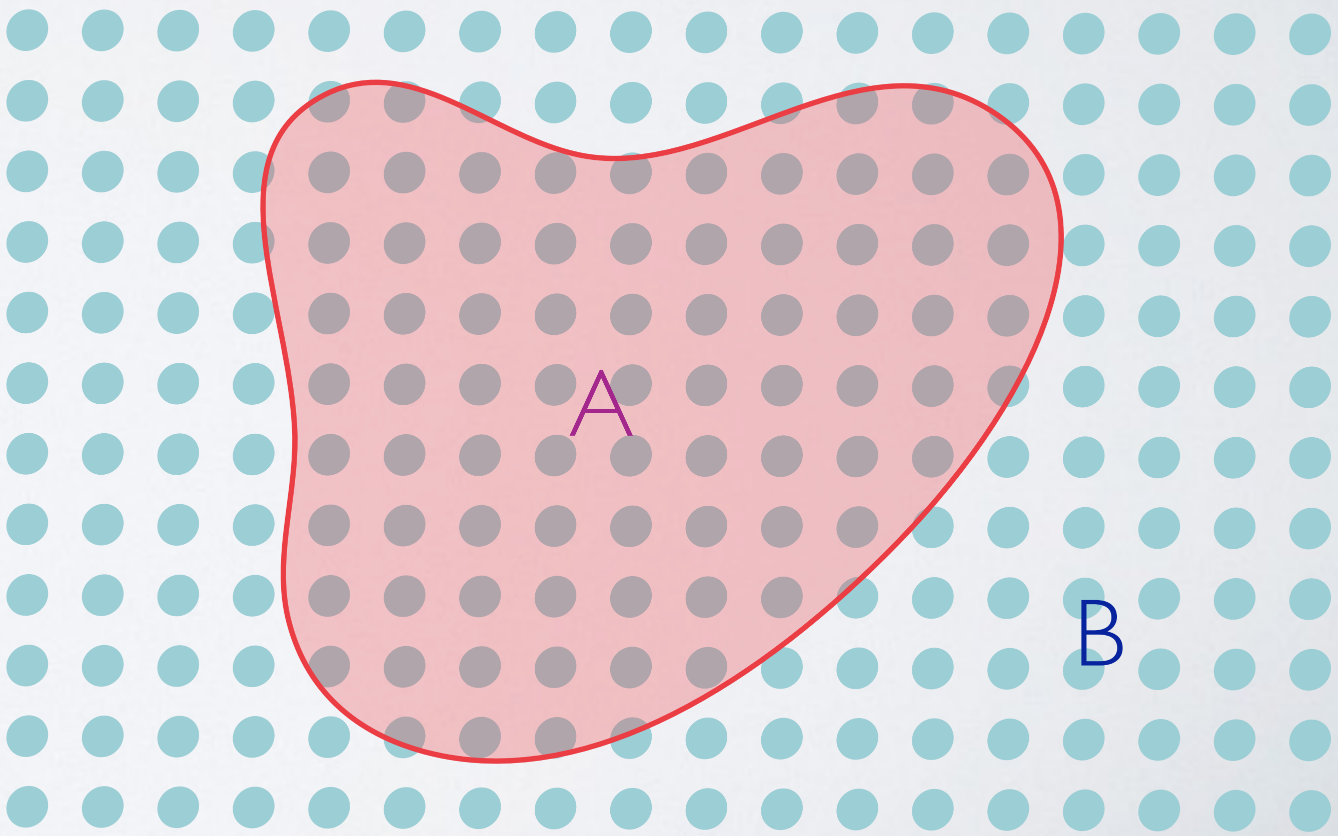
- many-body quantum system, e.g. on a lattice



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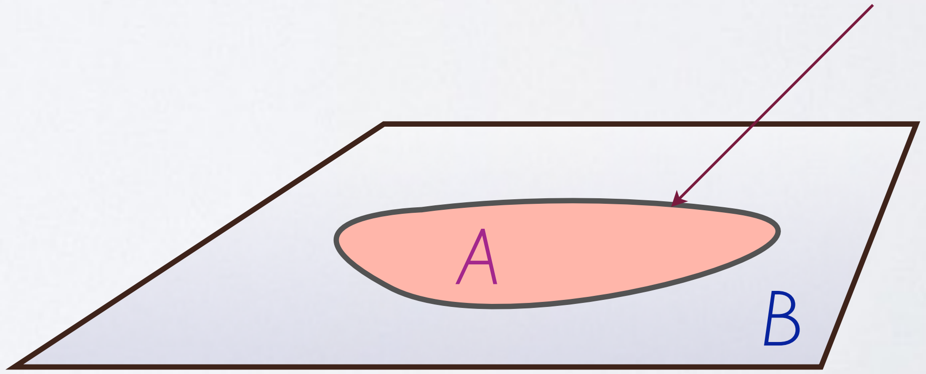
- QFT: A and B can be spatial regions, separated by a smooth entangling surface



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e.g.:

- spin chain
- many-body quantum system, e.g. on a lattice
- QFT: A and B can be spatial regions, separated by a smooth entangling surface

In all cases, $S_A = -\mathrm{Tr}\, \rho_A \log \rho_A$, where $\rho_A = \mathrm{Tr}_B \rho$.

Applications of EE

- Quantum Information theory: new quantum resource [Bennett '98 & Masanes '05]
  - quantum cryptography [Ekert, '91]
  - quantum dense coding [Bennett and Wiesner, '92]
  - quantum teleportation [Bennett et al., '93]
- Condensed Matter theory: diagnostic
  - quantum critical points
  - topological phases
  - computational difficulty, e.g. MERA [Vidal '09]
- Quantum Gravity:
  - suggested as origin of black hole entropy [Bombelli,Koul,Lee&Sorkin, '86 Srednicki, Frolov&Novikov, Callan&Wilczek, Susskind ...]
  - origin of macroscopic spacetime [Van Raamsdonk et.al., Maldecena&Susskind]

The good news & the bad news

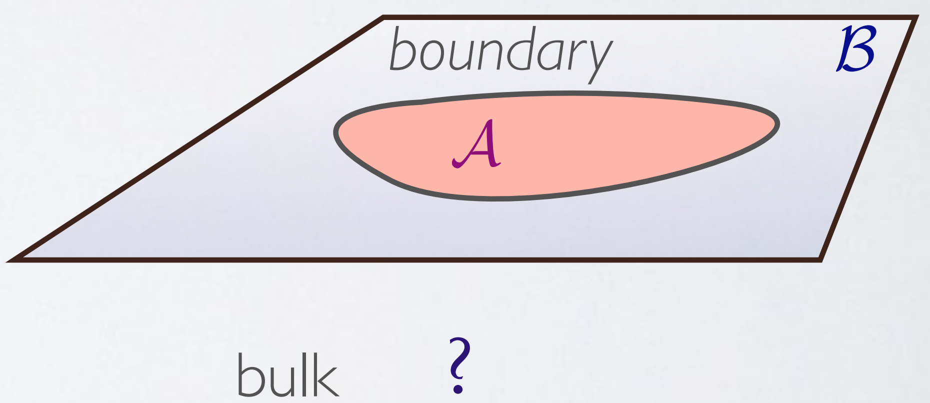
- But EE is hard to deal with…
  - non-local quantity, intricate & sensitive to environment
  - difficult to measure
  - difficult to calculate

… especially in strongly-coupled quantum systems

- AdS/CFT to the rescue?

~ Is there a natural bulk dual of EE?

(= "Holographic EE")

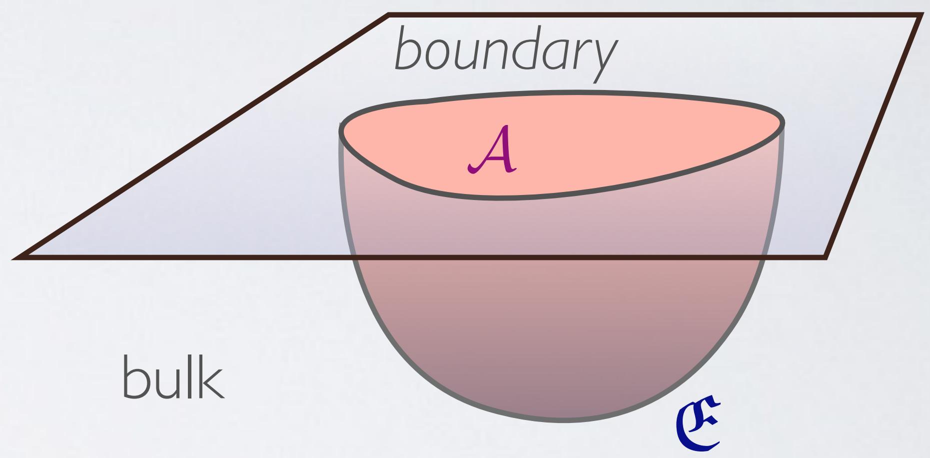


Yes! - described geometrically…

Holographic Entanglement Entropy

Proposal [Ryu & Takayanagi, '06] for *static* configurations:

In the bulk, EE $S_{\mathcal{A}}$ is captured by the area of minimal co-dimension 2 bulk surface $\mathfrak{E}$ *(at constant t)* anchored on $\partial\mathcal{A}$.



$$S_{\mathcal{A}} = \min_{\partial\mathfrak{E}=\partial\mathcal{A}} \frac{\text{Area}(\mathfrak{E})}{4\,G_N}$$

Remarks:

- cf. black hole entropy…
- Minimal surface "hangs" into the bulk due to large distances near bdy.
- Note that both LHS and RHS are in fact infinite…

Evidence for HEE

- ✓ Leading contribution correctly reproduces the area law
- ✓ Recover known results of EE for intervals in 2-d CFT [Calabrese&Cardy] both in vacuum and in thermal state
- ✓ Derivation of holographic EE for spherical entangling surfaces [Cassini,Huerta,&Myers]
- ✓ Attempted proof by [Fursaev] elaborated & refined by [Headrick, Faulkner, Hartman, Maldacena&Lewkowycz]

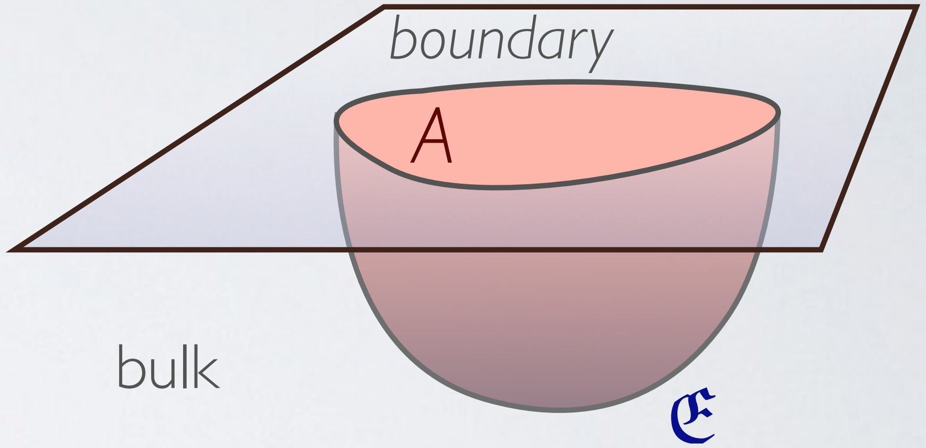
Further suggestive evidence:

- ✓ Automatically satisfies $S_{\mathcal{A}} = S_{\mathcal{A}^c}$ for pure states
- ✓ Automatically satisfies (strong) subadditivity [Lieb&Ruskai] & Araki-Lieb inequality -- easy to prove on the gravity side, far harder within field theory

Covariant Holographic EE

But the RT prescription is not well-defined outside the context of static configurations:

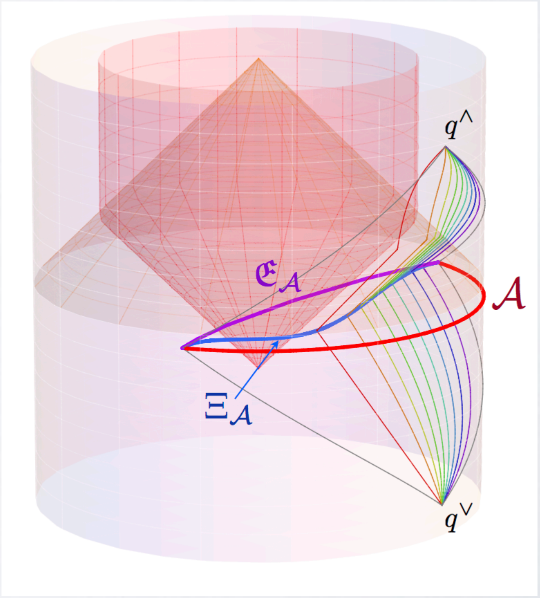
- In Lorentzian geometry, we can decrease the area arbitrarily by timelike deformations
- In time-dependent context, no natural notion of "const. t" slice…



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

4 natural candidates: [Hubeny, Rangamani, Takayanagi '07]

- $\mathfrak{E}$ = Extremal surface
- Ψ = Minimal-area surface on maximal-volume slice
- Φ = Surface with zero null expansions
- Ξ = Causal wedge rim



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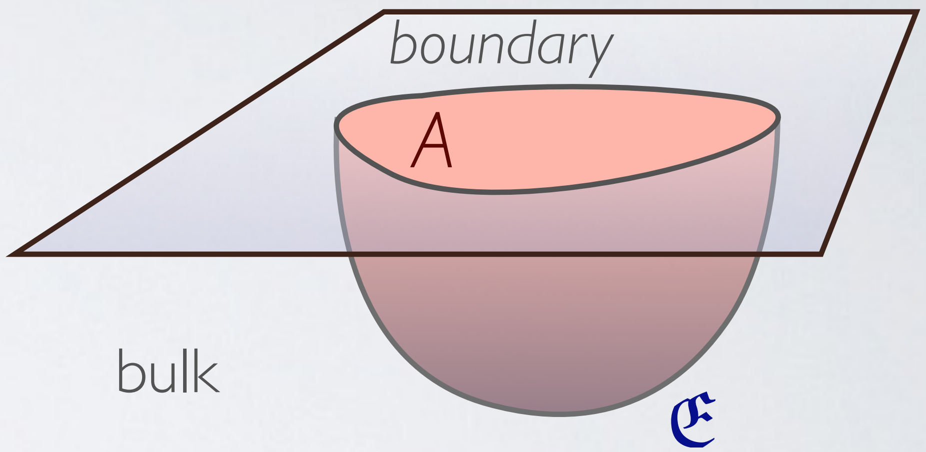

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- $\mathfrak{E}$ = Extremal surface
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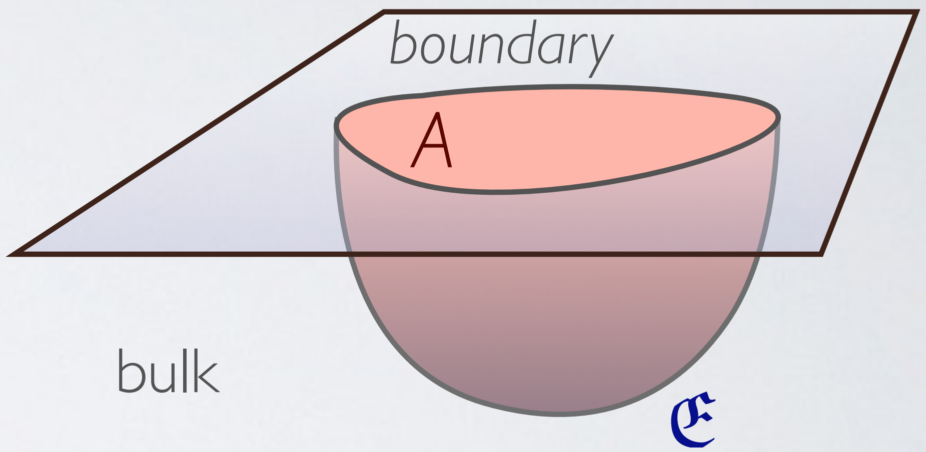
$\mathfrak{E} = \Phi$ is correct = 'HRT prescription'

Later known as Causal Information Surface; w/ area = causal holographic information χ [Hubeny, Rangamani '12]

Covariant Holographic EE

HRT Prescription: [Hubeny, Rangamani, Takayanagi '07]

In the bulk EE $S_{\mathcal{A}}$ is captured by the area of extremal co-dimension 2 bulk surface $\mathfrak{E}$ anchored on $\partial\mathcal{A}$ & homologous to $\mathcal{A}$



$$S_{\mathcal{A}} = \min_{\partial\mathfrak{E}=\partial\mathcal{A}} \frac{\text{Area}(\mathfrak{E})}{4\,G_N}$$

This gives a well-defined quantity in any (arbitrarily time-dependent asymptotically AdS) spacetime ⇒ equally robust as in CFT

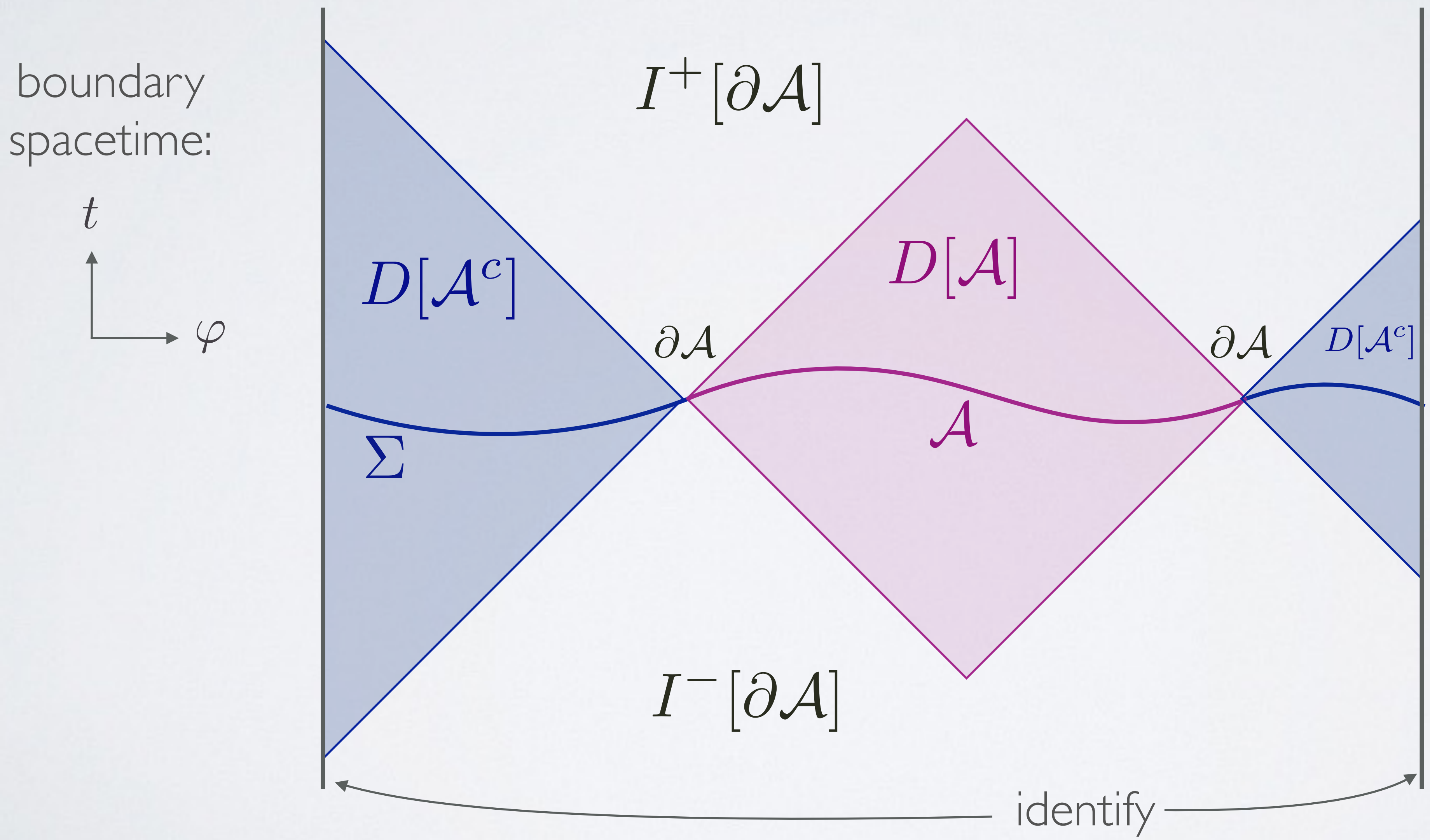
But we can't use Euclidean techniques for proof…

?: Is HRT prescription consistent with CFT constraints, e.g. causality?

CFT causal restriction

- Entanglement entropy $S_{\mathcal{A}}$ only depends on $D[\mathcal{A}]$ and not on Σ.
- Natural separation of boundary spacetime into 4 regions:

$$\partial\mathcal{M} = D[\mathcal{A}] \cup D[\mathcal{A}^c] \cup I^-[\partial\mathcal{A}] \cup I^+[\partial\mathcal{A}]$$



- EE should not be influenced by any change to state within $D[\mathcal{A}]$ or $D[\mathcal{A}^c]$.

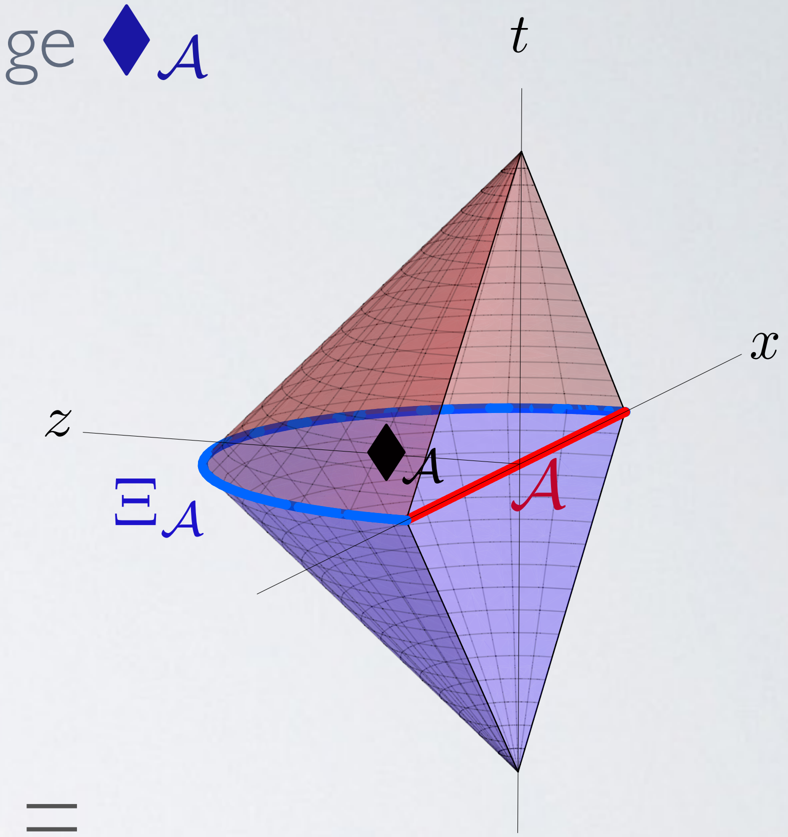
CFT causal requirement on bulk

- Extremal surface cannot lie within the bulk causal wedge $\blacklozenge_{\mathcal{A}}$

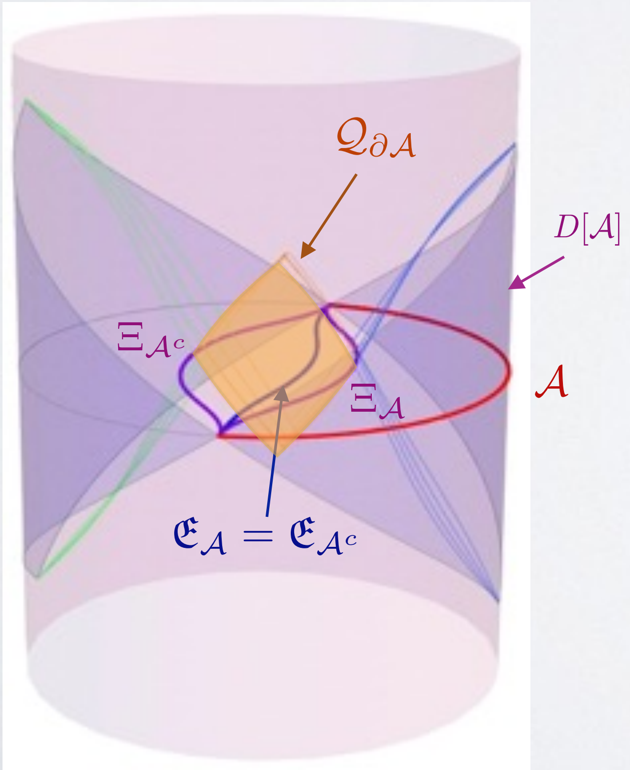
$$\blacklozenge_{\mathcal{A}} \equiv J^{-}[D[\mathcal{A}]] \cap J^{+}[D[\mathcal{A}]]$$

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

shown in [Hubeny, Rangamani '12]



- In fact it must lie in the causal shadow $\mathcal{Q}_{\partial\mathcal{A}}$



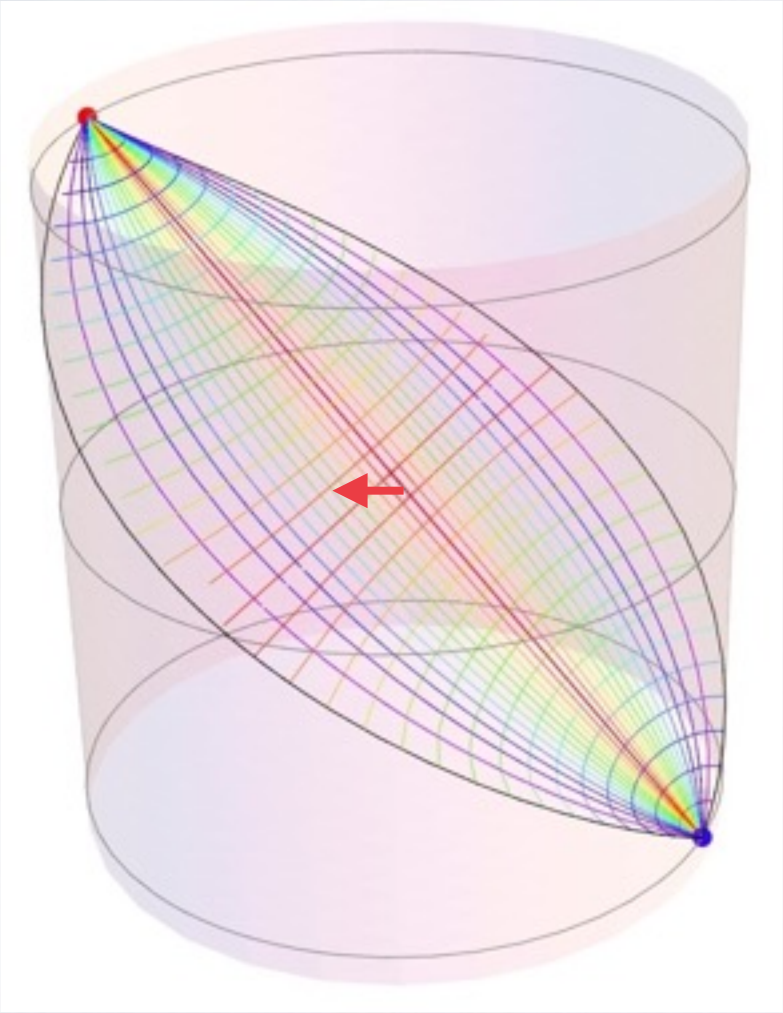
$\mathcal{Q}_{\partial\mathcal{A}}$ = causal shadow = bulk region which is causally disconnected from both $\mathcal{A}$ and $\mathcal{A}^c$

- Shown in [Headrick, Hubeny, Lawrence, Rangamani '14]
- Non-trivial condition on holographic EE

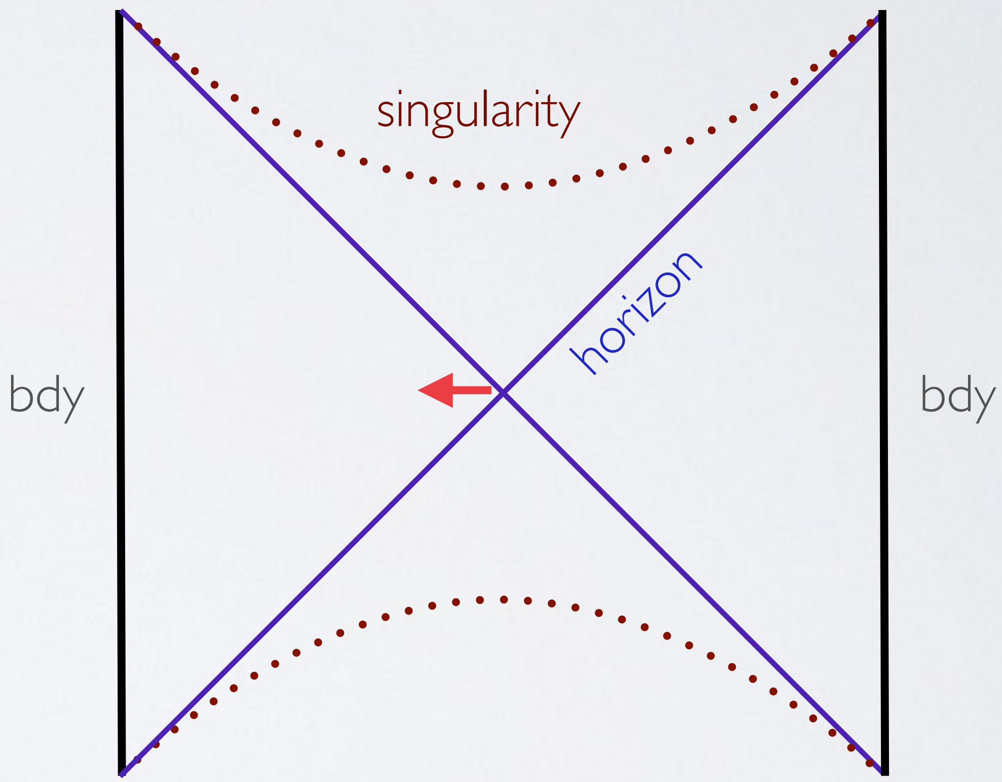
Marginal for static case…

- In static situations where RT applies, causality is upheld just marginally

pure AdS:



Schwarzschild-AdS black hole



- Danger: arb. small deformation of extremal surface could violate causality!

Entanglement wedge

- Boundary spacetime separation:

$$\partial\mathcal{M} = D[\mathcal{A}] \cup D[\mathcal{A}^c] \cup I^-[\partial\mathcal{A}] \cup I^+[\partial\mathcal{A}]$$

- This naturally induces a corresponding separation into 4 bulk regions:

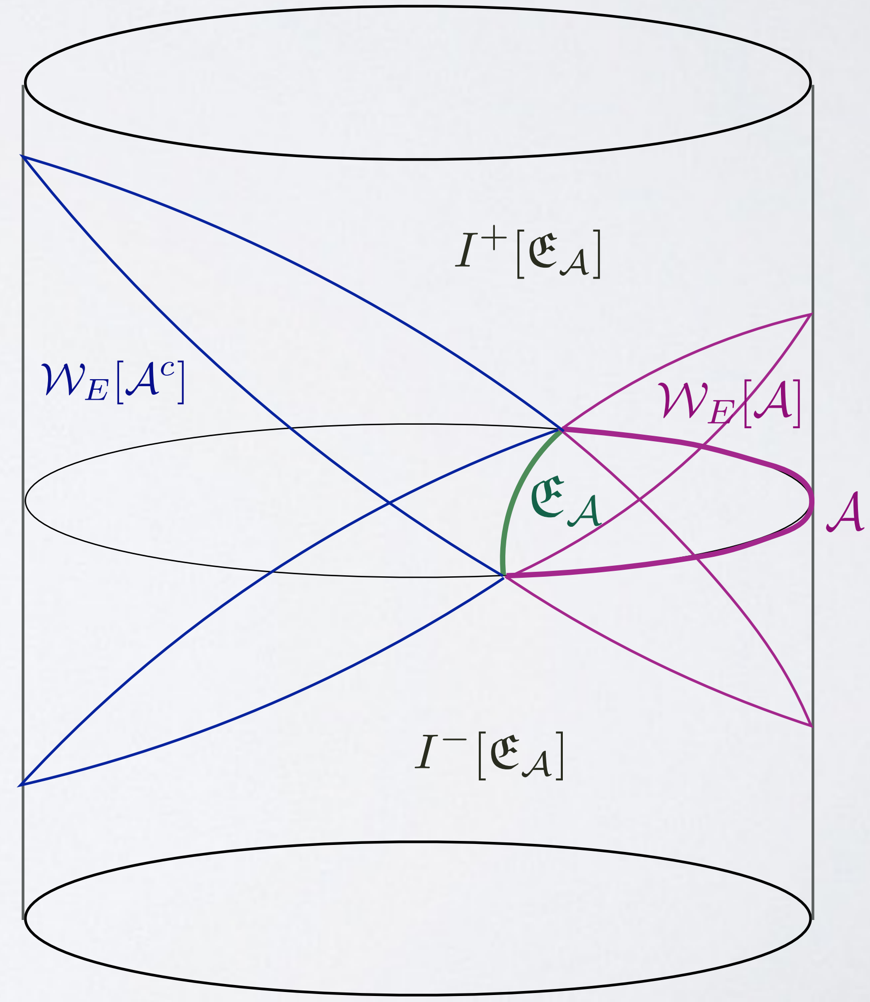
$$\mathcal{M} = \mathcal{W}_E[\mathcal{A}] \cup \mathcal{W}_E[\mathcal{A}^c] \cup I^-[\mathfrak{E}_\mathcal{A}] \cup I^+[\mathfrak{E}_\mathcal{A}]$$

(for pure state)

entanglement wedge of $\mathcal{A}$

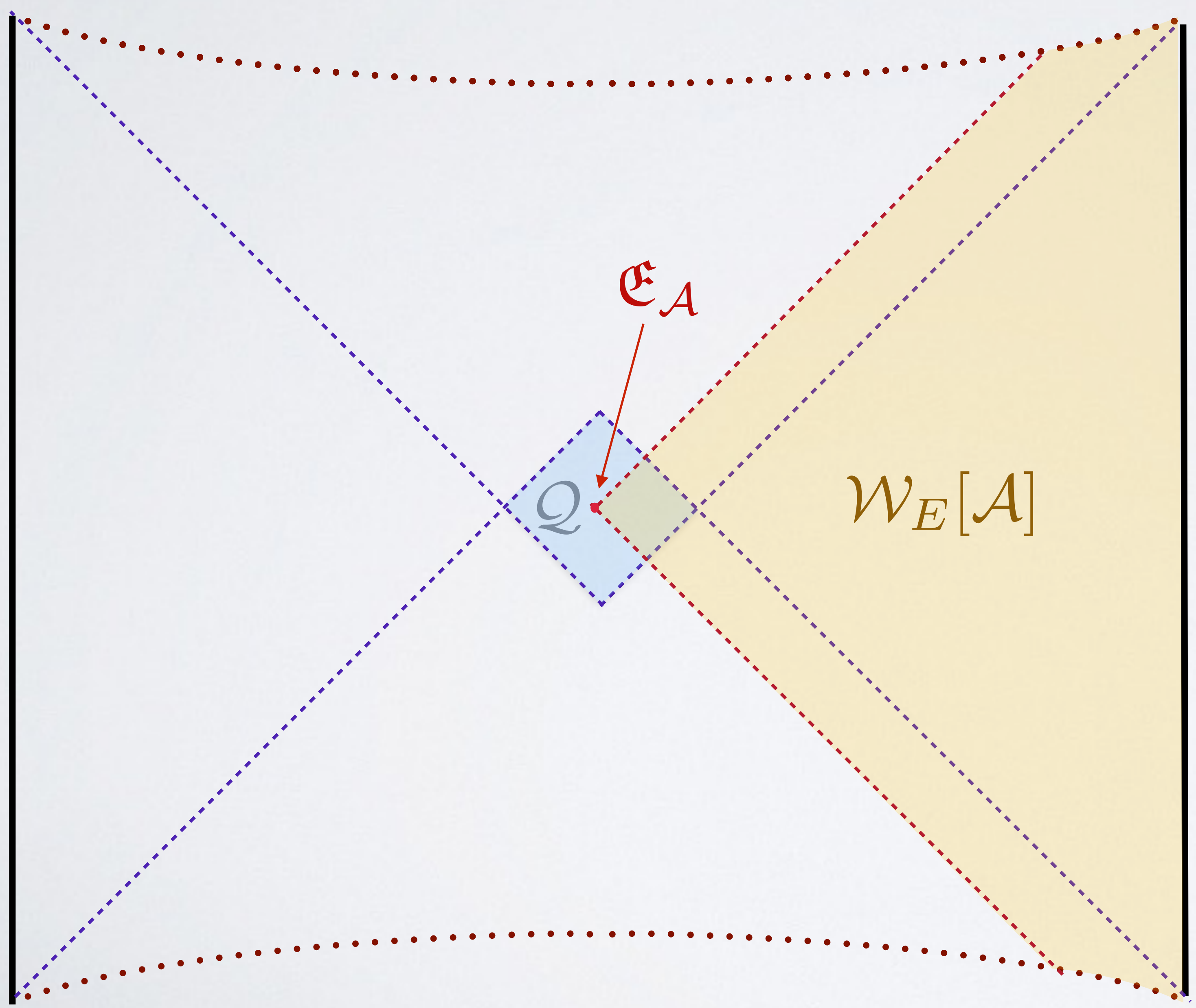
- $\mathcal{W}_E[\mathcal{A}]$ ends on $D[\mathcal{A}]$
- contains the causal wedge $\blacklozenge_\mathcal{A}$
- generated by null geodesics normal to $\mathfrak{E}_\mathcal{A}$

$\Rightarrow$ natural 'dual' of $\rho_\mathcal{A}$



Entanglement wedge in deformed SAdS

In deformed eternal Schw-AdS, (compact) extremal surface corresponding to $\mathcal{A} = \Sigma_L$ or $\mathcal{A} = \Sigma_R$ must lie in the 'shadow region' $\mathcal{Q}$



i.e. causally disconnected from both boundaries…

(for static Schw-AdS, shadow region = bifurcation surface)

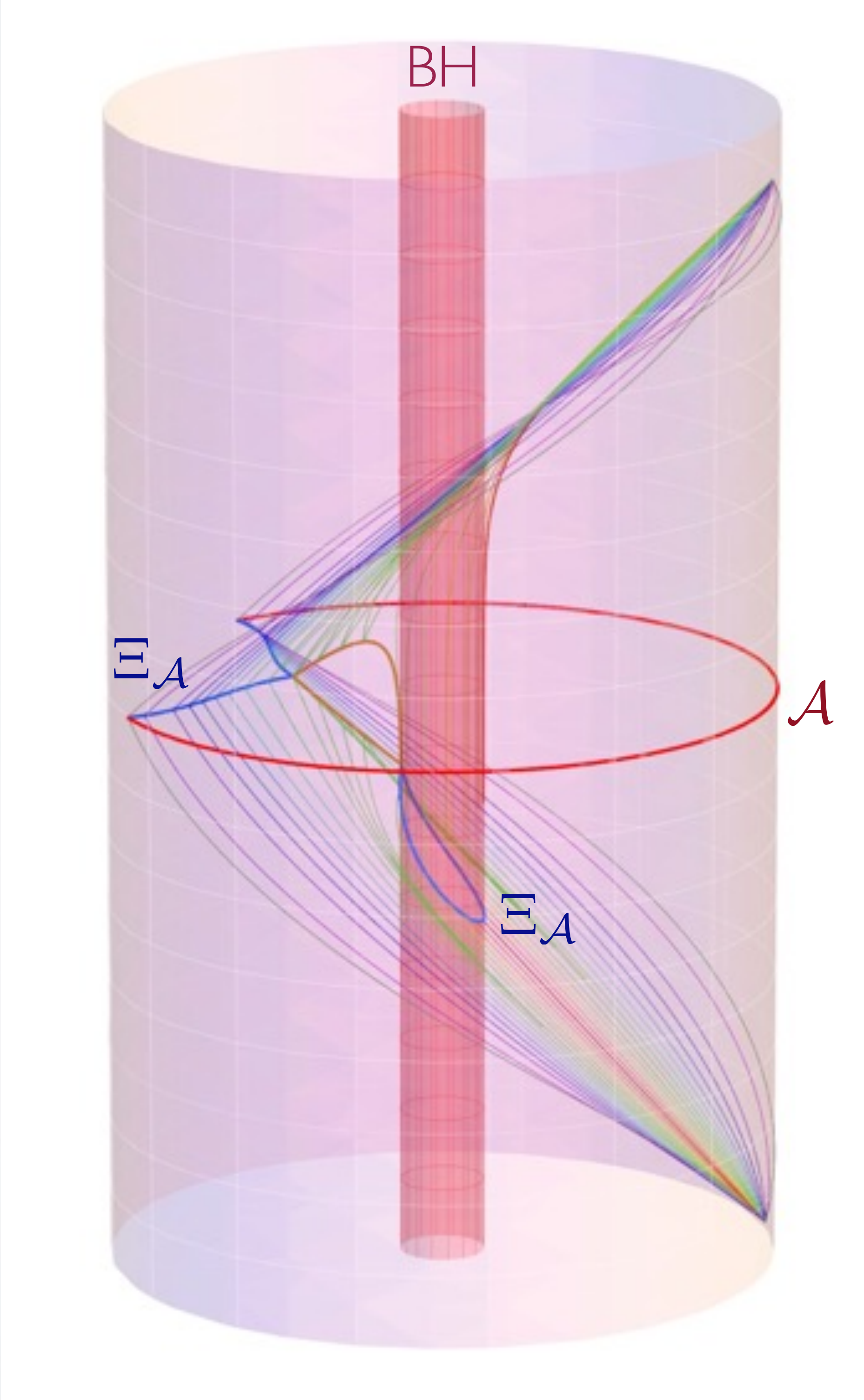
⇒ Entanglement wedge extends past event horizon

Curious properties of EE:

- EE satisfies very nontrivial causality constraints
- Entanglement plateaux ($\delta S_{\mathcal{A}}$ saturates to S_{ρ_Σ} for large enough $\mathcal{A}$)
- EE has two separate components
- EE is a 'fine-grained' observable

These are all easy to see from the holographic dual!

Aside: one use of causal wedge



- Causal wedge can have holes…
- Important implication for entanglement:
  - whenever $\mathcal{A}$ is large enough for $\Xi_{\mathcal{A}}$ to have two disconnected pieces, there cannot exist a single connected extremal (minimal) surface $\mathfrak{E}_{\mathcal{A}}$ homologous to $\mathcal{A}$!
  - in such cases, $\Rightarrow \; S_{\mathcal{A}} = S_{\mathcal{A}^c} + S_{\text{BH}}$

    (saturates Araki-Lieb inequality)

    → *entanglement plateau*

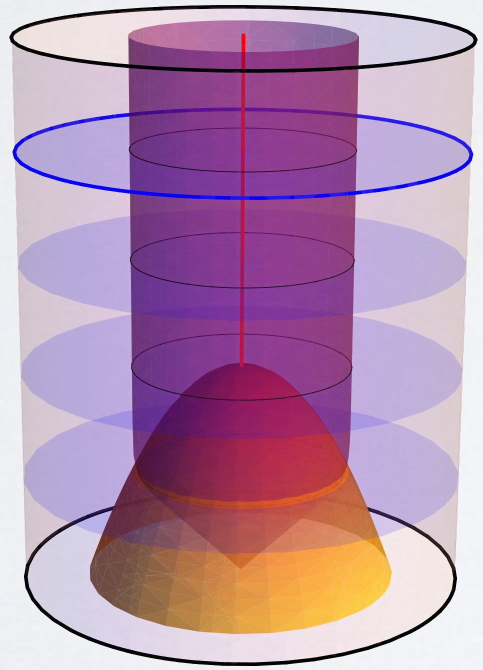
    [VH, Maxfield, Rangamani, Tonni, '13]

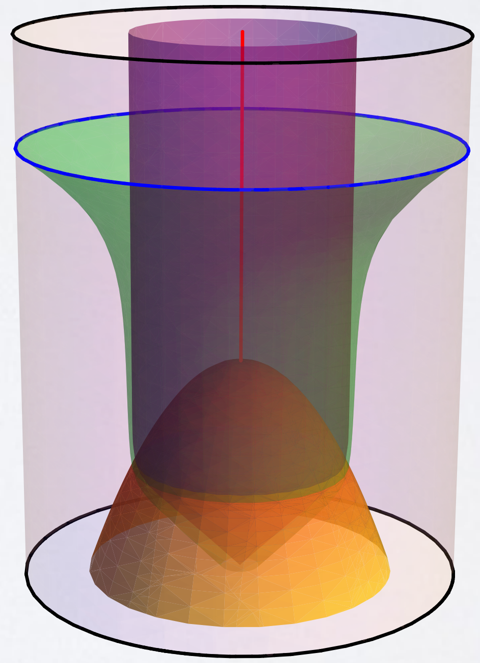
    → two components to entanglement
  - Causal wedge argument guarantees this even for generic time-dependent BHs.

EE is fine-grained observable!

Example: black hole formed from a collapse

- In contrast to the static (i.e. eternal) black hole, for a collapsed black hole, there is no non-trivial homology constraint on extremal surfaces. [cf. Takayanagi & Ugajin]





- Hence we always have $S_{\mathcal{A}} = S_{\mathcal{A}^c}$ as for a pure state.

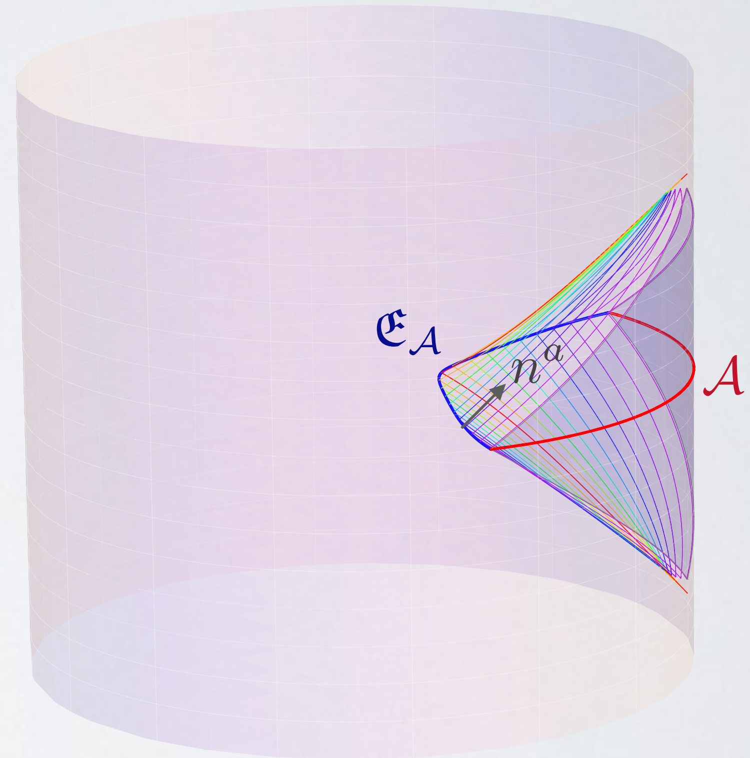
Bulk dynamics from EE?

- We can in principle decode the bulk geometry from $\{S_{\mathcal{A}}\}$ for a suitable set of $\mathcal{A}$'s.
- But can we extract bulk dynamics more directly?
  - Use the strong subadditivity property of EE:

$$\delta^2_{\mathcal{A}} S_{\mathcal{A}} \sim \int_{\mathfrak{E}_{\mathcal{A}}} E_{ab}\, n^a\, n^b \geq 0$$

cf. Null Energy Condition

specific 2nd order variation of region



  - proved at linearized level in 3-d, but conjectured to hold more generally…

[Bhattacharya, Hubeny, Rangamani, Takayanagi, '14]
cf. [Lashkari, Rabideau, Sabella-Garnier, Van Raamsdonk]

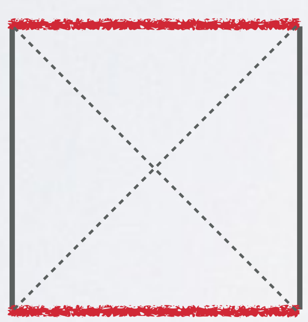
Spacetime from entanglement?

How does bulk spacetime emerge in the first place?

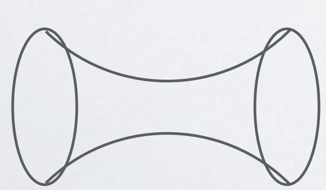
- Some connected spacetimes emerge as superpositions of disconnected spacetimes [Van Raamsdonk; Swingle]

eg. eternal AdS black hole as thermofield double:

$$|\psi\rangle = \sum_i e^{-\frac{\beta E_i}{2}} |E_i\rangle \otimes |E_i\rangle$$



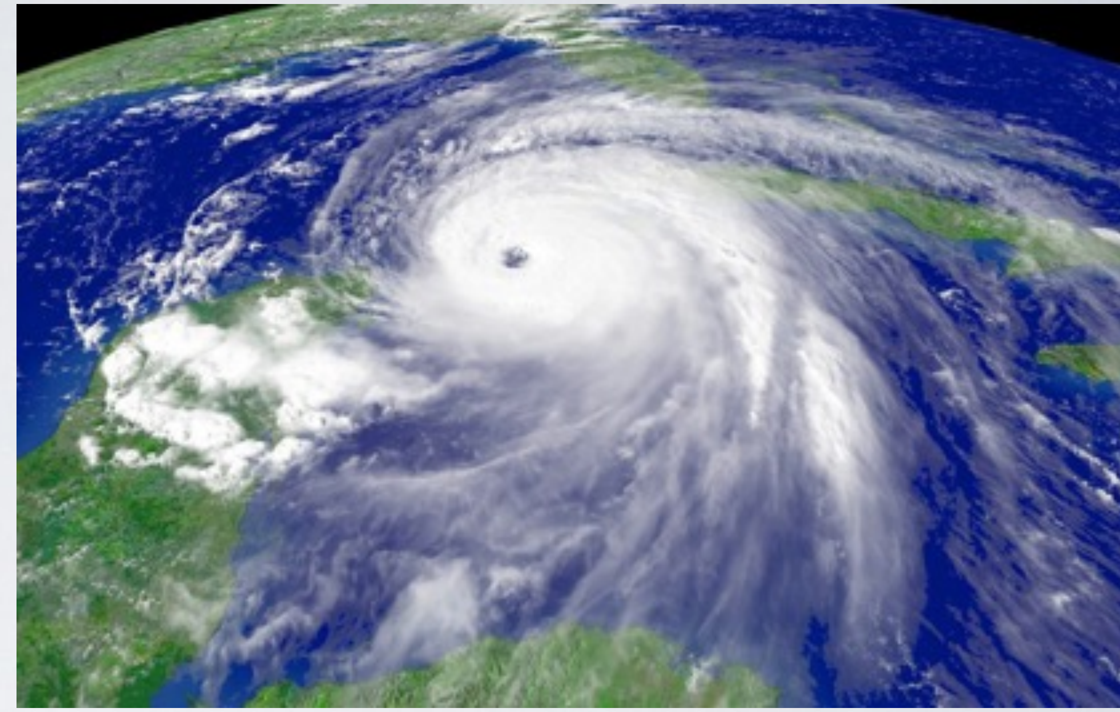
- Entanglement builds bridges: ‘ER = EPR’ [Maldacena, Susskind]



Einstein-Rosen bridge

Einstein-Podolsky-Rosen entanglement

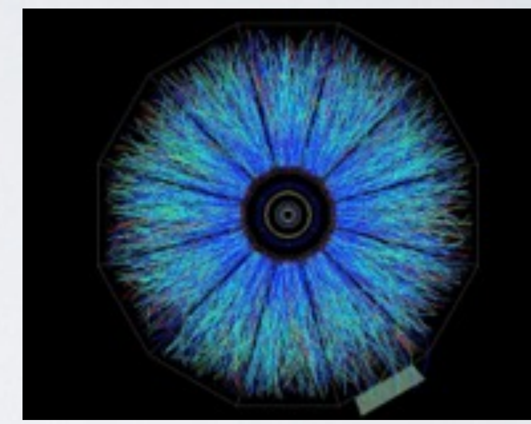
Space Ref (Harvard-Smithsonian CfA)



Hurricane Ivan, NOAA

soihub.org/itschool

Thank you!



RHIC event, LBL

Roller Wave, by William Dalton

Dancing Non-Newtonian fluid by Milo Vosch