Holography inside the horizon

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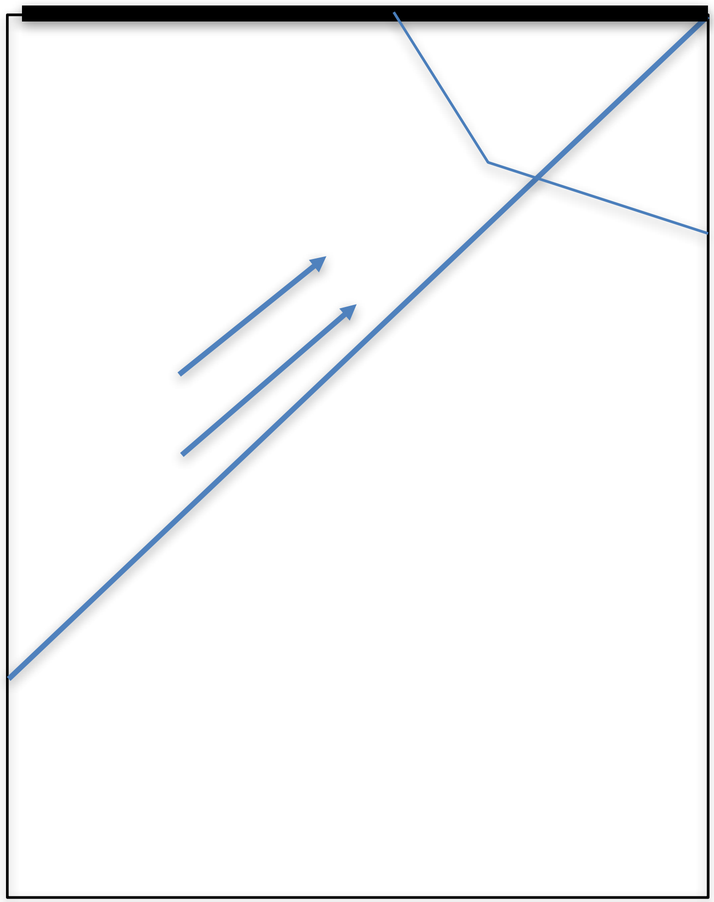
Outline

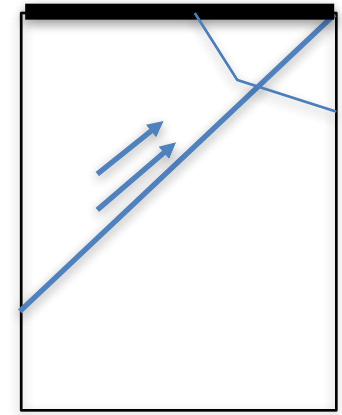
- Goal: define interior horizon quasilocal operators for pure states dual to black holes
- Part 1: Bulk perspective
  – Reviews obstacles (firewalls, etc.)
  – Need for UV cutoff in bulk
  – Scrambling time emerges as a maximum interior lifetime
- Part 2: Holographic perspective
  – Test idea in a simple model with fast scrambling
  – Bulk Hamiltonian dual to mean field Hamiltonian
  – Quantum coherence of infalling lab preserved for a scrambling time

Part 1: Bulk perspective

- Obstacles to black hole complementarity



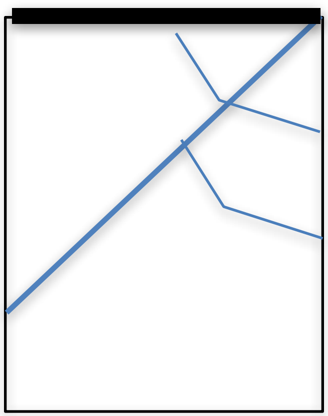
Bulk UV cutoff



- Cutoff is essential. Without cutoff:
  - Modes with arbitrarily short λ but low ω
  - Infinite number of such modes come into contact with late time infaller
  - Shockwave problems (Shenker et al.)
  - Infinite entanglement entropy
- Planck length spatial cutoff
  - Eliminates these modes
  - Renders entropy finite (‘t Hooft)

Infalling Planck lattice

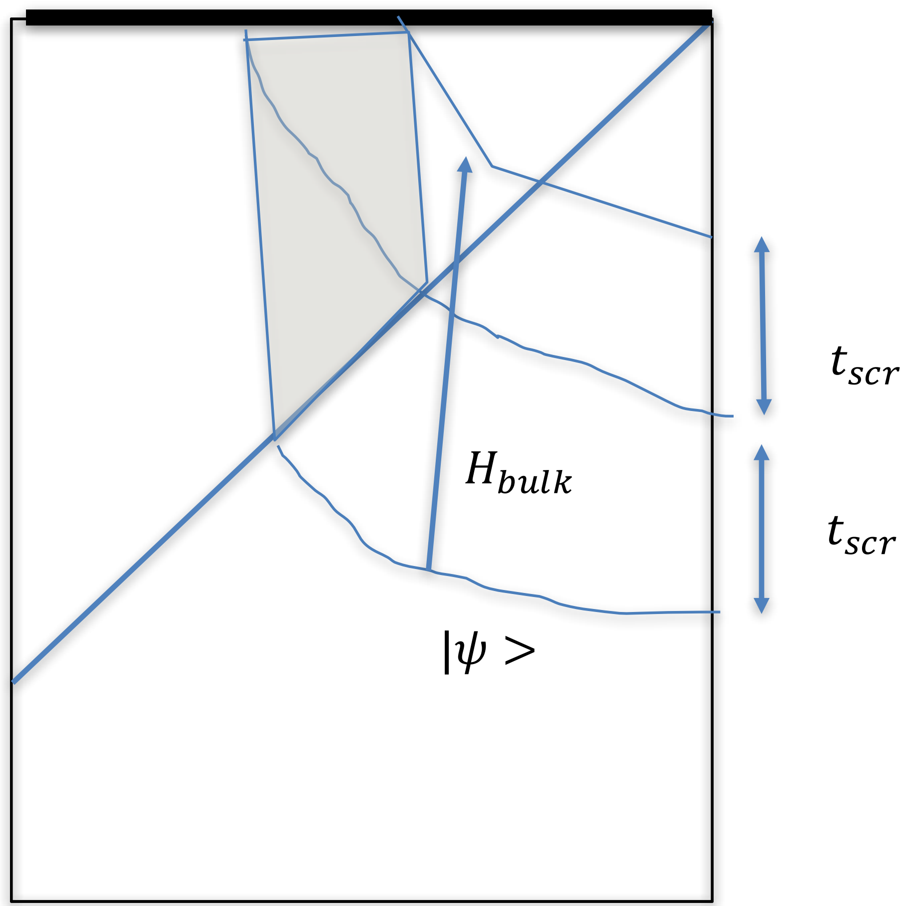
- Corley Jacobson
  - For Schwarzschild = lattice in Gulstrand-Painleve coordinates
    - $ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + 2\sqrt{\frac{2M}{r}} dtdr + r^2 d\Omega^2$
  - Each lattice point falls along a timelike geodesic at rest at infinity
  - No coordinate singularity at future horizon
  - Conclude Hawking radiation unaffected
- LT
  - Minimal version of bulk cutoff in holographic theory
  - Match t to holographic time (at r of order a few M)
  - Implications for interior propagation
  - Predictions for violations of general covariance



Scrambling time emerges

- Lattice leads to finite group velocity
- Most dangerous modes short λ but low ω
- Hit singularity in scrambling time
    - $t \sim \beta \log S$
- After a scrambling time, all information about the interior state is "erased"
    - Hits singularity
    - "Frozen vacuum" argument is a real effect

Proposal for interior operators



Objections

- A priori no reason why proposal immune from acausal decoherence
  - Hayden-Preskill tell us information leaks out after a scrambling time
  - Hawking radiation dual to interior operators doesn't get far, so "measurements" must be conducted in a compact spacetime region
  - Can try to argue interior operators immune from such measurements, since apparatus must be lighter than black hole
  - Real test holographic computation

Part 2: Holographic perspective

- Near horizon holographic model
  - Only includes interior and near region exterior degrees of freedom
  - Doesn’t need SUSY (BFSS) or conformal symmetry (AdS/CFT) because modes near infinity not included
- Should exhibit fast scrambling

Toy model

- Simple toy model: spin lattice with nonlocal pairwise interactions $N = O(S_{BH})$
- Kitaev model (minus the averaging) special case
- Each spin has pairwise interactions with $O(N)$ other spins
- Interaction strength scales as $1/N$ so energy density stays finite

- Can try to cast BFSS model in this way

$$H = \sum_{a=1..9} Tr\left(\dot{X}_a\right)^2 + \sum_{a,b} Tr[X_a, X_b]^2$$

$$= \sum_{a=1..9, i,j=1..N} \dot{X}_{aij}\,\dot{X}_{aji} + \cdots$$

But interactions involve 4-fold couplings. And X's are unbounded.

- Expect similar story for AdS/CFT if you integrate out asymptotic degrees of freedom

Analysis

- Lieb-Robinson (1972) found general methods to bound commutators of operators in general lattice models
- Result holds in any state

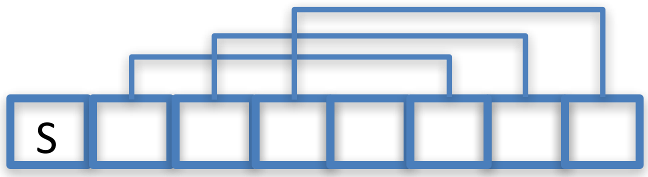
$$\sup_{O_A} \|[O_A(t), O_B(0)]\| / \|O_A\| \leq \frac{4|A|\|O_B\|}{N} e^{8ct}$$

Scrambling

- Lashkari, Stanford, Hastings, Osbourne and Hayden applied this to study scrambling
- Goal, consider some subsystem S with some reduced density matrix $\Psi_S(t)$ and find the time when it is close to maximally mixed
- Use trace distance

$$\|\Psi_S(t) - \mathbb{I}_S/\mathrm{dim}\mathcal{H}_S\| < \varepsilon$$

- Highly entangled initial states show fast scrambling



- Apply Lieb-Robinson to trace distance
  - Time to scramble S is $t \sim \log N$

Decoherence

- LT, Goal is to test whether an infalling product state will decohere. Quantify this in a basis independent way using trace distance

$$\left\| \Psi_S(t) - \Psi_S^{bulk}(t) \right\| > \varepsilon$$

Where S is our infalling "lab" degrees of freedom

- Natural candidate for Ψ_S^{bulk}, set

$\Psi_S(0) = \Psi_S^{bulk}(0)$ but use mean field evolution

Mean field H=Bulk H

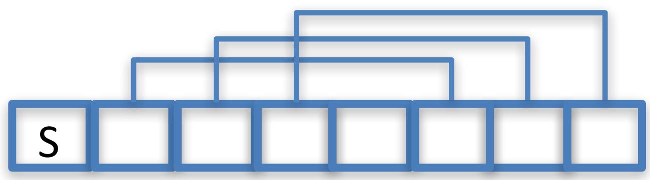
- Mean field by definition freely propagates product (unentangled states) matches free propagation in the bulk
- Candidate mean field Hamiltonian for general density matrix

$$H_{MF} = \sum_{x,y} \mathrm{tr}_y(H_{x,y} \Psi_y^{MF}(t))$$

- Note state dependence!
- Bound trace distance using Dyson expansion in $H - H_{MF}$

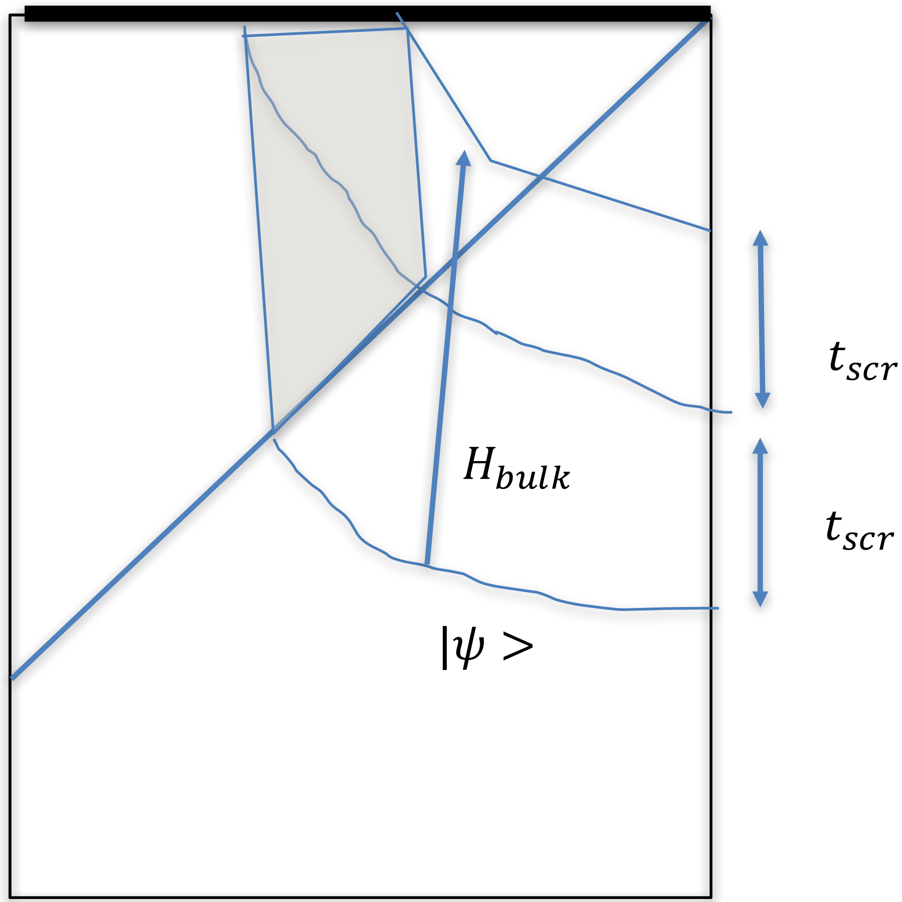
Mean field calculation

- Again take highly entangled initial state to model an old black hole



- Firewall would predict rapid decoherence on timescale of order 1.
- Instead we find decoherence time matches scrambling time

Dictionary matches bulk calculation



Negligible difference between exact and H_{bulk} evolution for a scrambling time

Conclusions

- Decoherence time of infalling, initially unentangled, “lab” state = scrambling time = maximum bulk lifetime in slicing with physical UV cutoff
- Decoherence of lab state = singularity approach
- Results give rise to a nonperturbative Bulk/boundary map
  - time dependent
  - time asymmetric
  - State dependent
  - Evades objections of firewall advocates