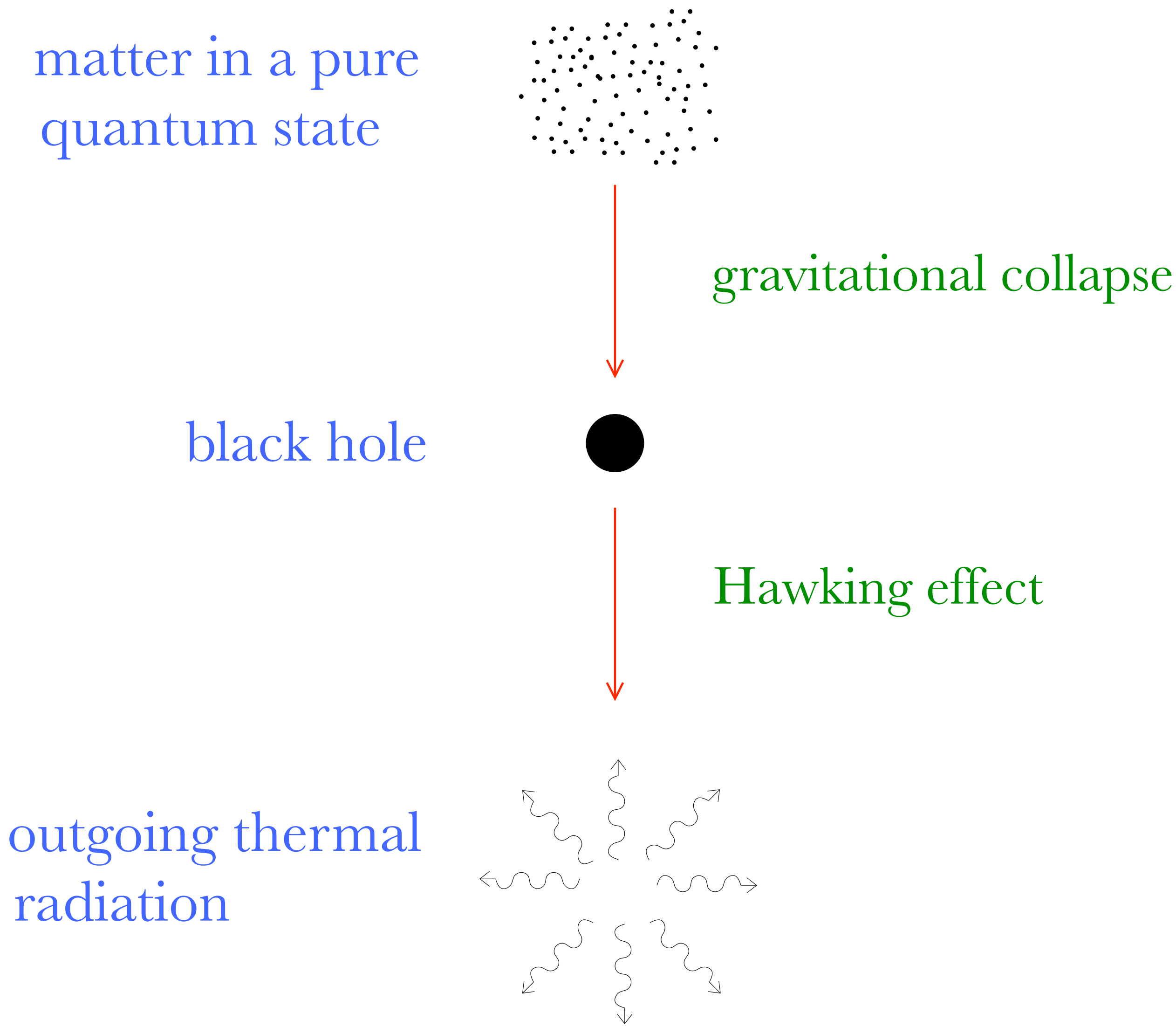
The Black Hole Information Paradox

Lárus Thorlacius

NORDITA

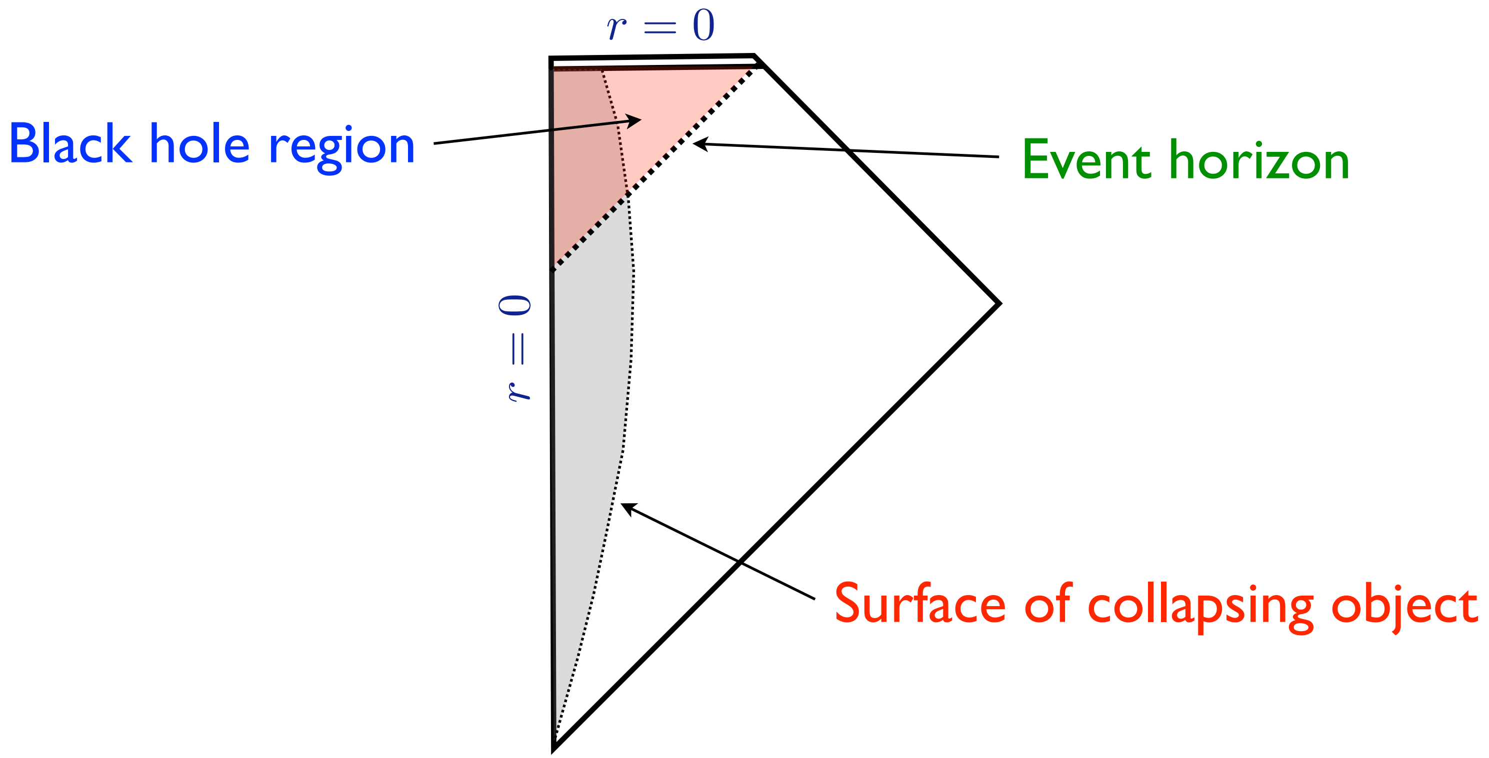
The University of Iceland

Black hole evolution



Black hole spacetime

- classical general relativity -



Schwarzschild black hole

There is a curvature singularity at r = 0

but

the geometry is non-singular at event horizon

$$R_{\mu\nu\lambda\sigma}\, R^{\mu\nu\lambda\sigma} = \frac{48M^2}{r^6} \longrightarrow \begin{cases} \infty & \text{as} \quad r \to 0 \\ \frac{3}{4M^4} & \text{as} \quad r \to 2M \end{cases}$$

Spacetime is almost flat at the horizon of a large black hole!

$$R_{\mu\nu\lambda\sigma}\, R^{\mu\nu\lambda\sigma}\Big|_{r=2M} \longrightarrow 0 \quad \text{as} \quad M \to \infty$$

Black hole evaporation

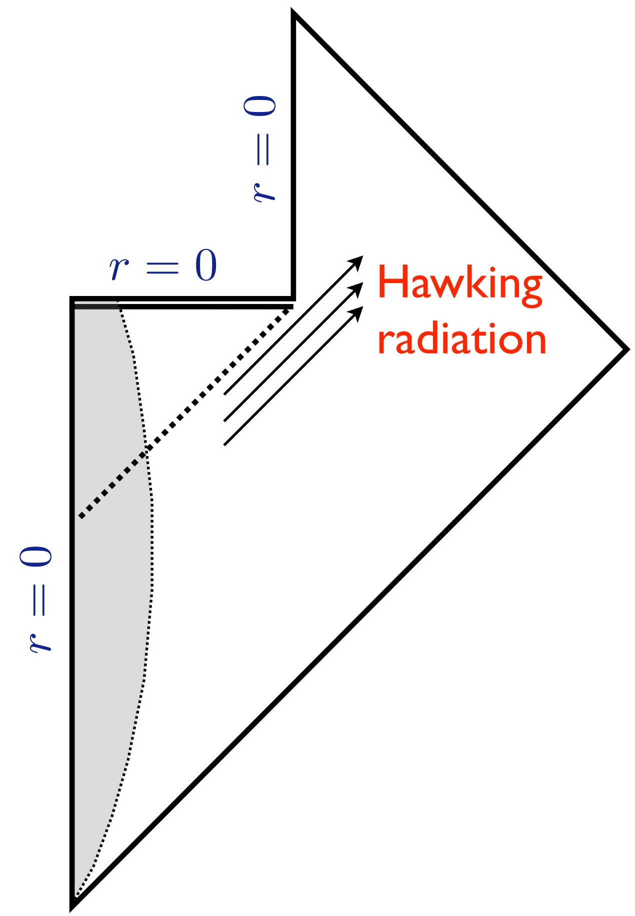
According to Hawking's semi-classical calculation, black hole radiation is thermal

Hawking temperature: $$T_H = 6 \times 10^{-8} \left(\frac{M_\odot}{M} \right) \mathrm{K}$$

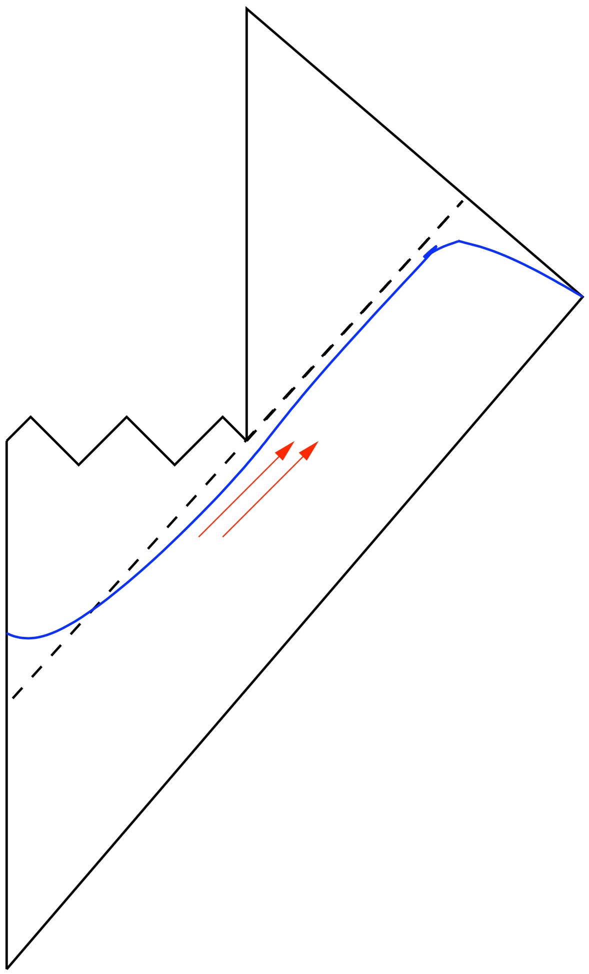
Black hole lifetime: $$\tau \sim 10^{71} \left(\frac{M}{M_\odot} \right)^3 \mathrm{s}$$

Age of universe $\sim 5 \times 10^{17}$ s

Semi-classical black hole



Effective field theory



- assume that local effective field theory can be applied in regions of weak curvature, away from black hole singularity

- the explicit form of the effective field theory is not needed

- construct a convenient set of Cauchy surfaces

  'nice' time slices

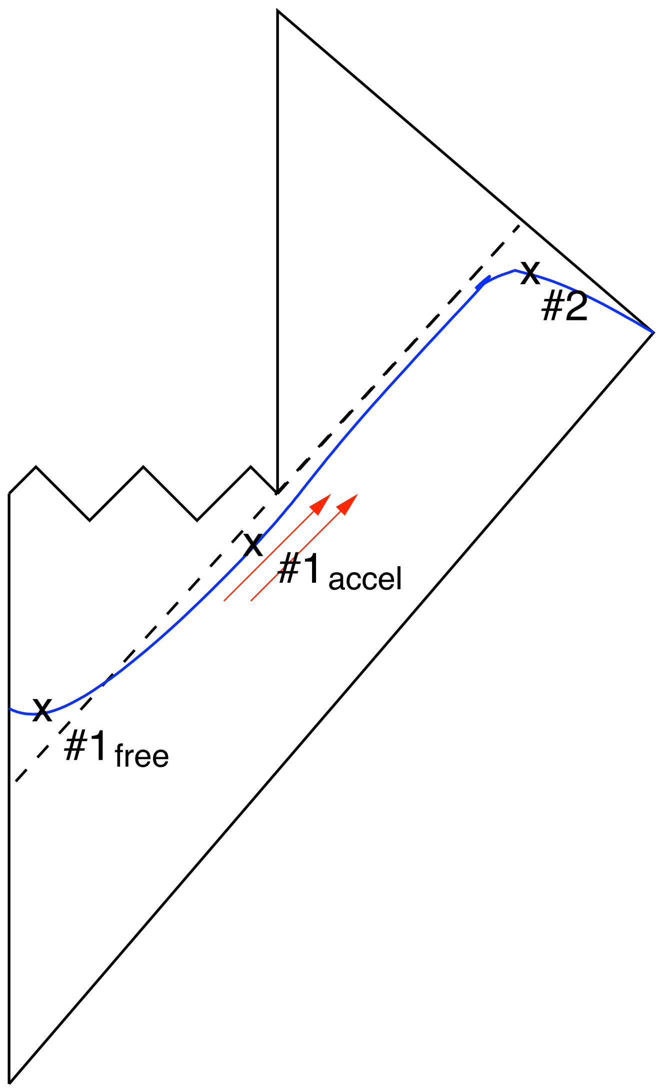
  Wald '93
  Lowe, Polchinski, Susskind, LT, Uglum '95

- effective field theory Hamiltonian generates unitary evolution of states

- nice slice Hamiltonian is time-dependent

  ---> Hawking emission

Formulation of the paradox



- prepare singlet pair (#1,#2)
- keep #2 outside and send #1 into black hole
- $\#1_{\text{free}}$ and $\#1_{\text{accel}}$ measure spin along z-axis
- #2 measures spin either along z-axis or x-axis
- local qft $\Rightarrow$ independent measurements by $\#1_{\text{free}}$ and $\#1_{\text{accel}}$
- if they disagree they discover that #2 measured along x-axis $\Rightarrow$ acausal signal from #2 to #1

Some suggested resolutions

- Non-unitary evolution Hawking '76
  - generalized quantum mechanics Hawking '82

- Black hole remnants Aharonov, Casher, Nussinov '87
  Banks, O'Loughlin '93

- Information returned in Hawking radiation Page '80, 't Hooft '91
  - black hole complementarity Susskind, LT, Uglum '93
    Kiem, Verlinde, Verlinde '93
  - eternal AdS black holes Maldacena '01
  - final state projection Horowitz, Maldacena '03

- Non-singular quantum geometry
  - supergravity fuzzballs Mathur, Saxena, Srivastava '03

Information loss

Purely thermal Hawking radiation implies non-unitary evolution

Hawking ’76

Generalized quantum mechanics   Hawking ’82

- replace states by density matrices

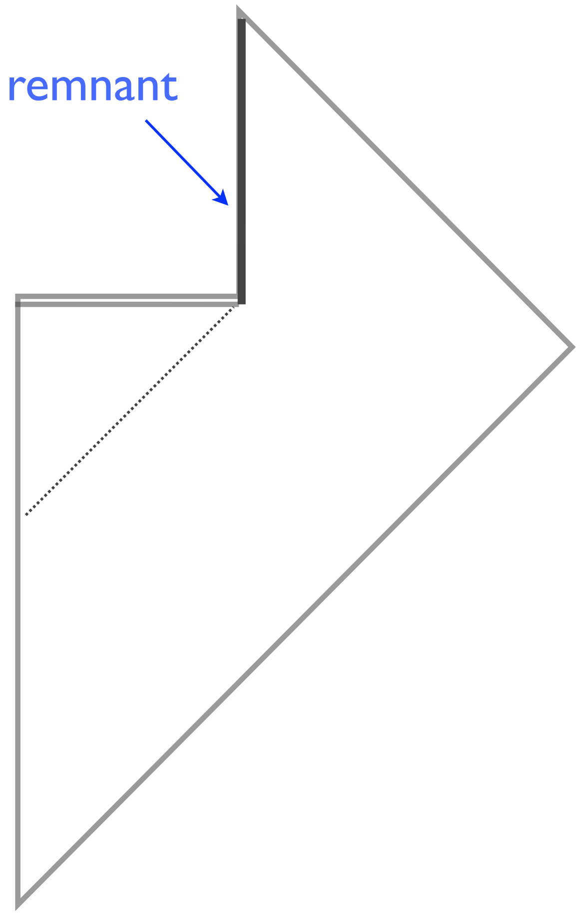
- replace S matrix by super-scattering operator $

Energy not conserved - vacuum heats up to Planck temperature

Banks, Susskind, Peskin ’84
Ellis, Hagelin, Nanopoulos, Srednicki ’84

Decoherence without dissipation   Unruh, Wald ’95; Unruh ’12

Black hole remnants

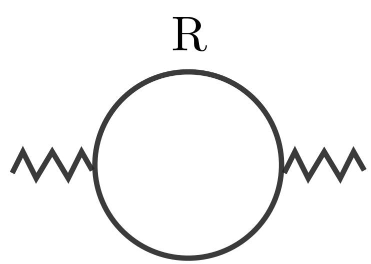


Information about initial state stored in a stable remnant Aharonov, Casher, Nussinov '87

Need a Planck scale remnant for every possible initial black hole

- infinite degeneracy of states

- divergent contribution to quantum loops



$$\text{amplitude} \sim G \sum_{R} \frac{1}{M_R^2} = \infty$$

Possible loophole: Remnants with large intrinsic geometry Banks, O'Loughlin '92
Hossenfelder, Smolin '09

Non-singular fuzzball geometry

Mathur, Saxena, Srivastava '03

Supergravity fuzzballs   Mathur, Saxena, Srivastava '03

- pure quantum states correspond to non-singular geometries

- black hole geometry, with its event horizon and singularity, arises in a course grained description

- violation of equivalence principle?

- how do 'classical' observers interact with a fuzzball geometry?

The number of smooth solutions in supergravity too small to account for the entropy of macroscopic black holes?
Balasubramanian, de Boer, El-Showk, Messamah '08   Skenderis, Taylor '08

Information return

Postulates:

’t Hooft ’90
Susskind, LT, Uglum ’93
Kiem, Verlinde, Verlinde ’93

1. Black hole evolution, as viewed by a distant observer, is described by quantum theory with a unitary S-matrix relating the state of infalling matter to that of outgoing radiation.
2. Outside the stretched horizon of a massive black hole, physics can be described to good approximation by a set of semi-classical field equations.
3. To a distant observer, a black hole appears to be a quantum system with discrete energy levels. The dimension of the subspace of states that describe a black hole of mass M is

$$\exp\left(\frac{A}{4}\right) = \exp\left(4\pi M^2\right)$$

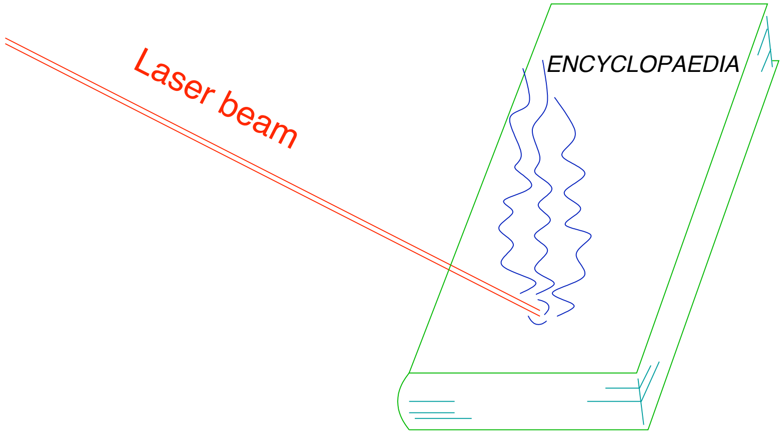
Black hole complementarity

Susskind, LT, Uglum '93

There is no contradiction between outside observers finding information encoded in Hawking radiation and infalling observers entering a black hole unharmed.

- Apparent violation of no-cloning theorem of QM
- Low energy observers in any single reference frame cannot detect duplication of information
- Contradictions only arise when descriptions in very different reference frames are compared
- BHC is consistent with known low-energy physics but implies non-locality and a new degree of relativity in spacetime physics

Information lost to black holes vs. traditional information loss



Emitted radiation appears thermal

For practical purposes information is lost in process

b u t

Final state with outgoing radiation (+ remaining ashes) contains all the information **in principle**

There are subtle correlations between early and late-time radiation

Information carried in the outgoing radiation has been removed from the book

Tests of black hole complementarity

Membrane paradigm   Thorne, Price, MacDonald '82-'86

Replace black hole by a stretched horizon -- a membrane 'near' the event horizon

In astrophysical applications 'near' means close compared to f.ex. distance to companion in a binary system

Quantum mechanical stretched horizon Susskind, LT, Uglum'93

Minimal stretching: $A_{\rm sh} = A_{\rm eh} + 1$

Unspecified microphysics with $\# \text{ of states } = \exp(A/4)$

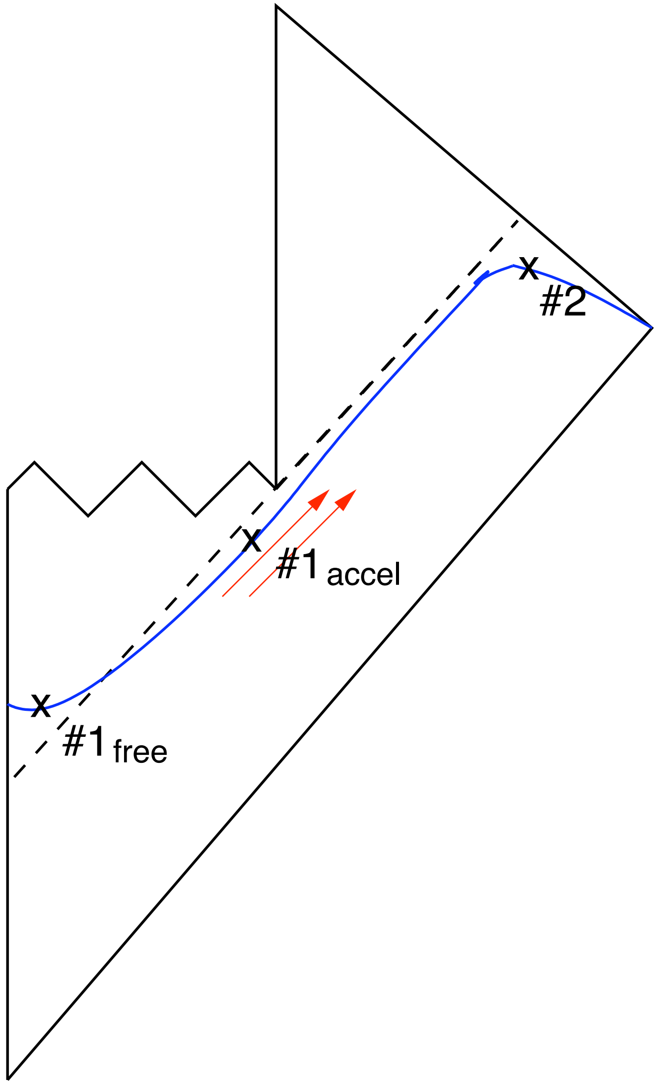
Gedanken eperiments   Susskind, LT '93

Apparent violations of BHC can be traced to assumptions about physics at Planck energy (or higher)

Information paradox involves Planck scale in subtle ways

Firewall for infalling observers?

Revisit gedanken experiment



O$_{\text{accel}}$ must wait before information can be extracted from Hawking radiation

Young BH: $t \sim r_s S_{bh}$ Page 1993

Old BH: $t \sim r_s \log r_s$ Hayden & Preskill 2007

O$_{\text{free}}$ has short time for spin measurement

Young BH: $\Delta t \sim e^{-S_{bh}}$

Old BH: $\Delta t \sim r_s^{-1}$

>> limited measurement accuracy

O$_{\text{far}}$ measures state of Hawking radiation to arbitrary accuracy

>> projects BH state into eigenstate of Hawking radiation

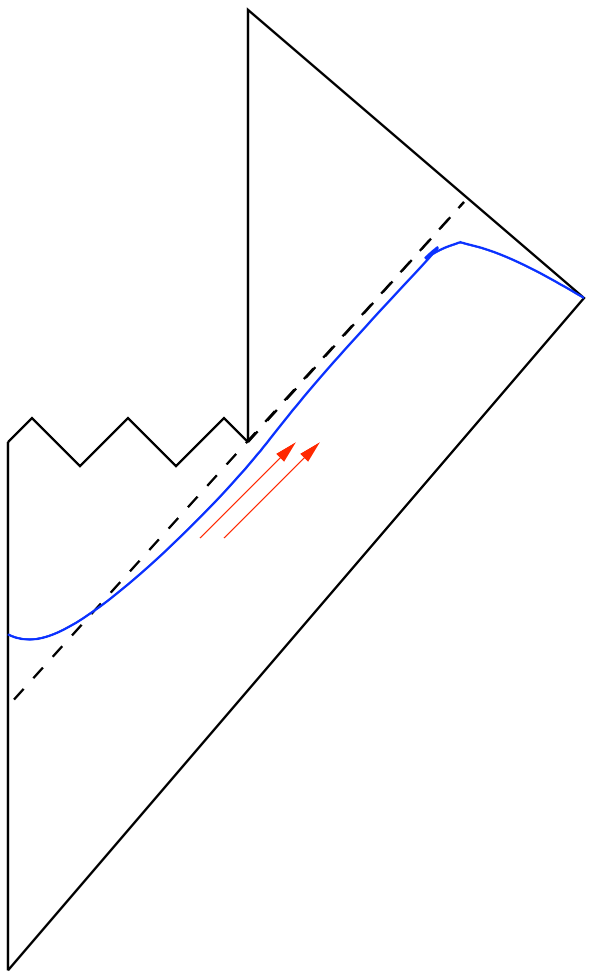
State of infalling observer is also projected

>> observation of Hawking radiation burns infalling observer at horizon D.Lowe, LT '06

A. Almheiri, D. Marolf, J. Polchinski, J. Sully '12

Limitations of local effective field theory

'Nice' time slices: Wald '93; Lowe, Polchinski, LT, Susskind, Uglum '95



Cauchy surfaces that intersect worldlines of both infalling matter and (most of) the outgoing Hawking radiation

Avoid the region of strong curvature near black hole singularity

Local extrinsic curvature of a nice slice is small everywhere

Global properties are, however, not so nice

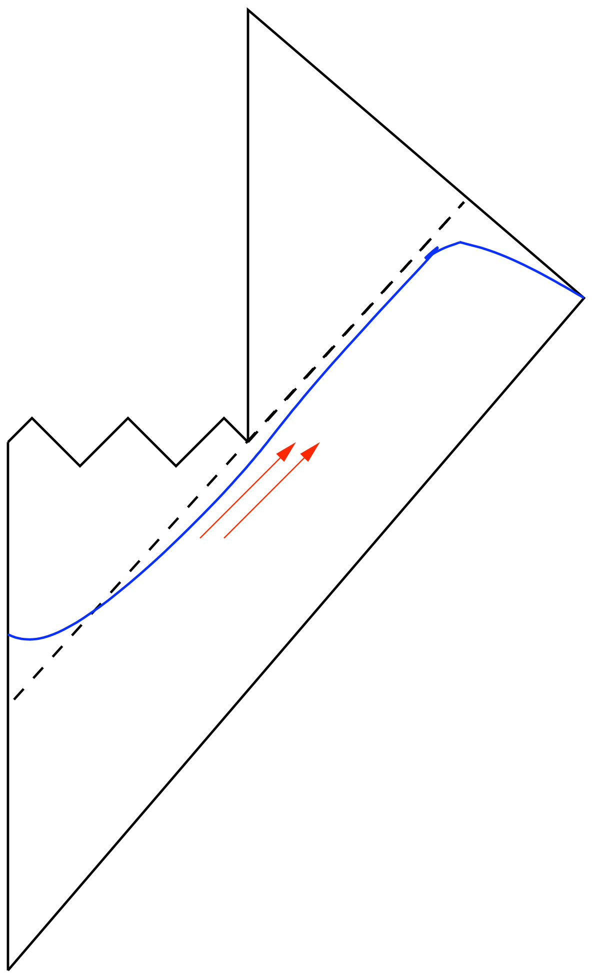
Enormous relative boost between inside and outside of black hole

Gravitational back-reaction leads to a breakdown of local effective field theory when the relative boost gets large

Giddings and Lippert '04; Lowe, LT '06

Boost bound

Rindler region $r - r_h \ll r_h$ of a large black hole is nearly flat



Consider effective field theory with cutoff Λ

Two wave-packets with energies of order Λ at arbitrary separation on a given time-slice should not produce large back-reaction

Giddings and Lippert '04

Apply hoop conjecture (Thorne '72) to wavepackets in Rindler region

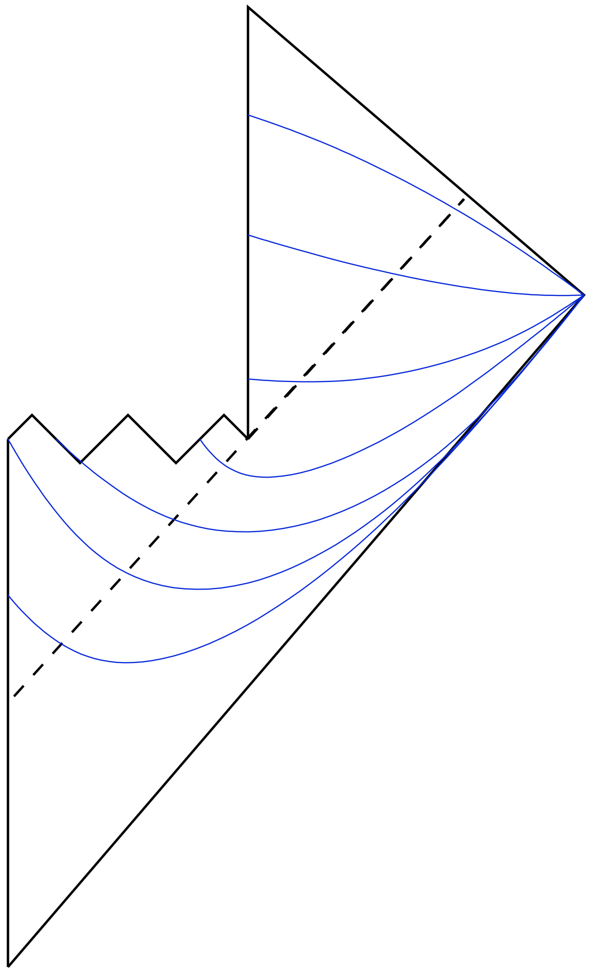
$\rightarrow$ boost bound $\Lambda \gamma_{\rm max} = M$

The bound restricts bending of time slices

Nice slices run into boost bound at

$$t_{\rm bb} \sim r_h \log\left(\frac{M}{\Lambda}\right)$$

Lowe, LT '06



Timeslices satisfying the boost bound

run into singularity before information

is returned to outside observers

Lowe, LT '06

Input from string theory

Black hole entropy   Strominger, Vafa '96

String theory provides a microphysical basis for the entropy of a certain class of (supersymmetric) black holes

$$S_{\mathrm{bh}} = \frac{A}{4} = \log\left(\#\ \text{of microstates}\right)$$

-- leaves no room for black hole remnants

Gauge theory / gravity correspondence   Maldacena '97

Non-pertubative string theory defined in terms of unitary quantum field theory

-- bounds on non-local effects in unitary black hole evolution in AdS/CFT   Lowe, LT '99 & '06