Locality &
Black hole information

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PNW String Seminar

Hawking's 1974 discovery of black hole radiance began an apparent crisis in theoretical physics. This crystallized shortly after publication of his 1976 paper on information loss in black hole evaporation, leading to the black hole information paradox.

Many, particularly in the string community, now believe that resolution of the paradox arises through the ideas of black hole complementarity and holography

There is significant circumstantial evidence for this:

- Counting black hole states (Strominger-Vafa, ...)
- AdS/CFT (Maldacena)

⋮

* * *

But, so far, no one has given a sharp argument about where the loophole lies in Hawking's original argument for information loss. This would resolve the paradox.

* * *

(Recently Hawking has made such a proposal; not yet published.)

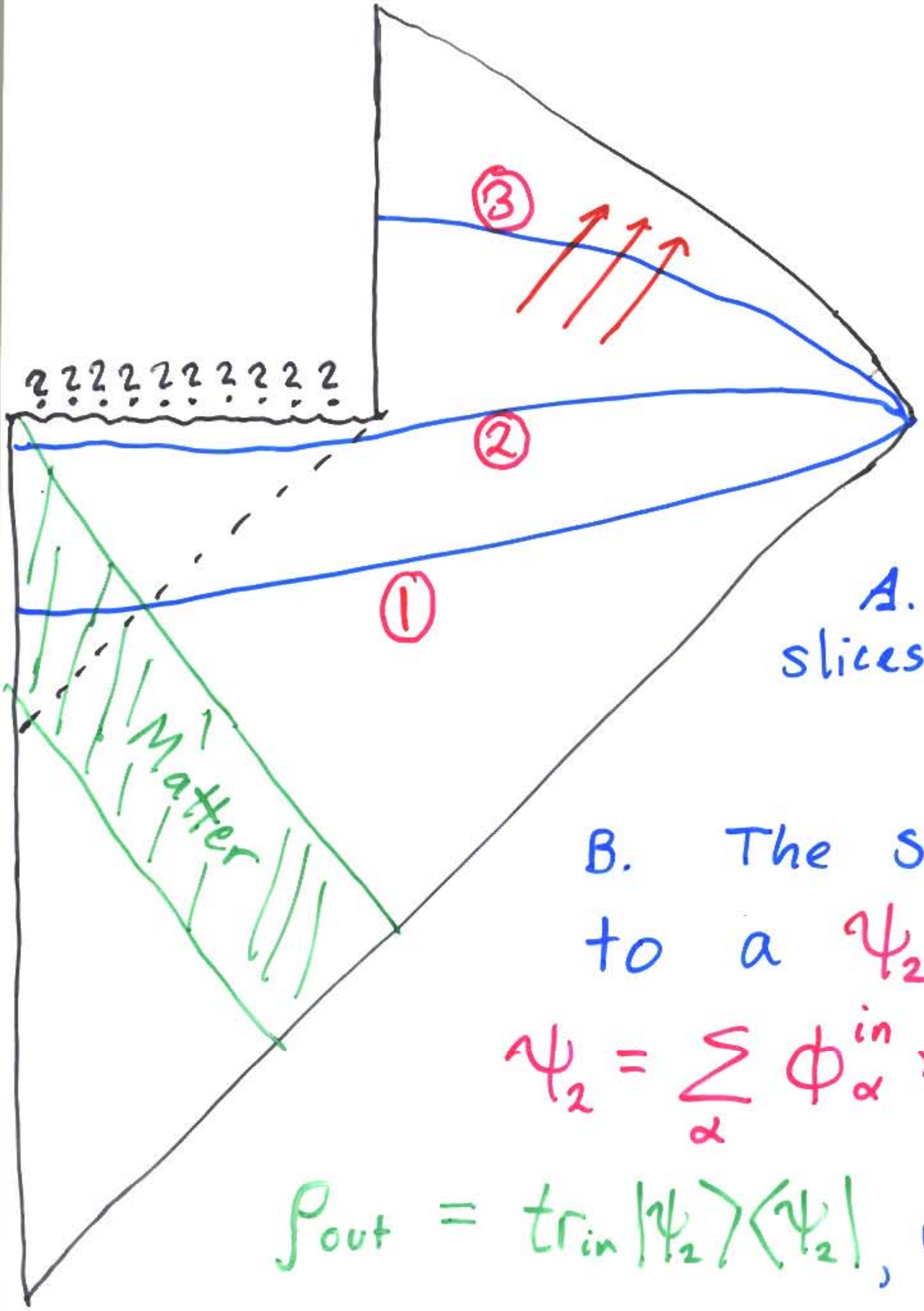
This talk will summarize an argument about where locality fails in black hole evaporation, and its relevence to information loss.

hep-th/0402073, w/ Matt Lippert

Key idea:

The "locality bound," which summarizes where local field theory fails in gravitational physics.

Review of Hawking's argument (slightly modernized):



A. On family of spacelike slices, can decompose:

$$\mathcal{H} = \mathcal{H}_{in} \times \mathcal{H}_{out}$$

B. The state Ψ_1 evolves to a Ψ_2 of the form

$$\Psi_2 = \sum_\alpha \Phi^{in}_\alpha \times \Psi^{out}_\alpha ;$$

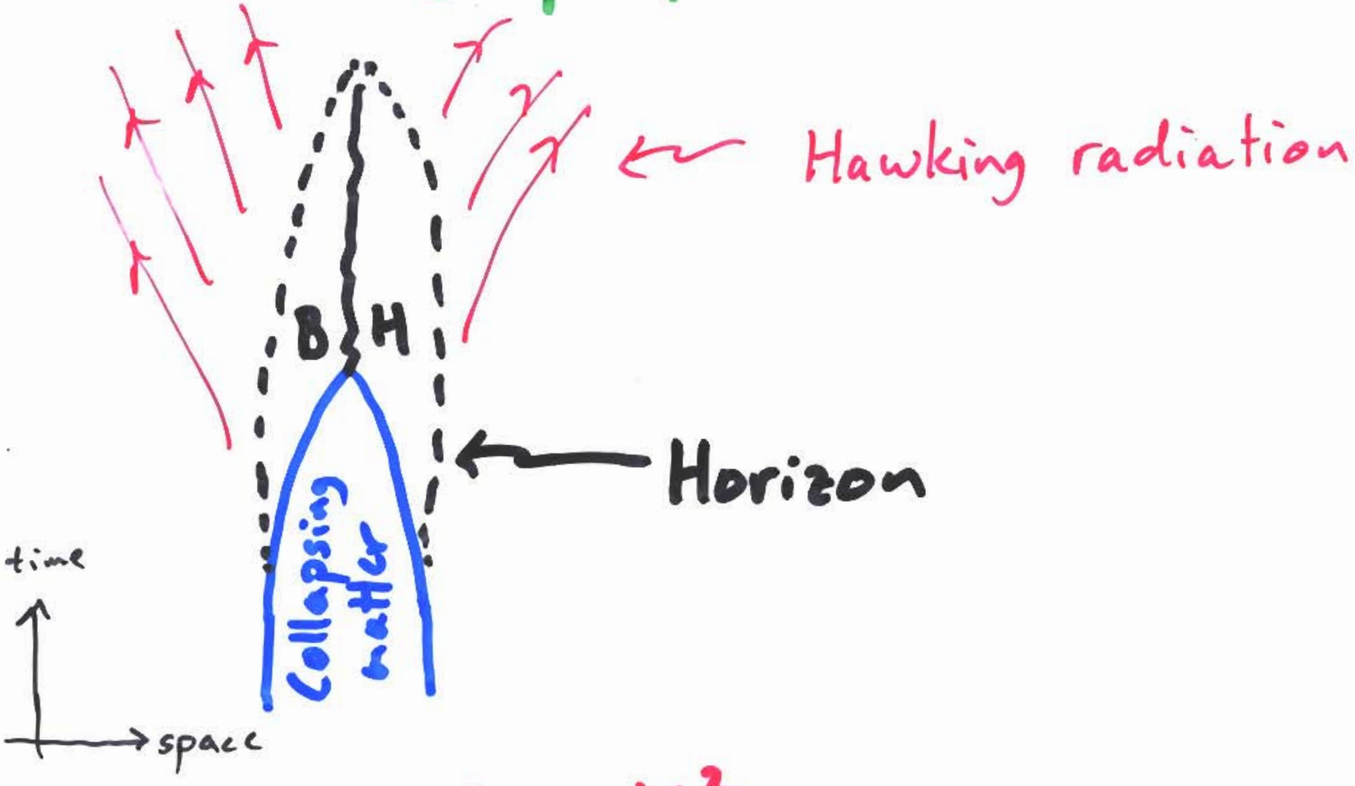
$\rho_{out} = tr_{in} |\Psi_2\rangle\langle\Psi_2|$, w/ $S_{out} = -tr\, \rho_{out} \ln \rho_{out} \sim M^2$

C. The information in $\mathcal{H}_{in}$ on slice ② is not recovered (energetics; remnants unphysical)

So: $S \sim M^2$

More on the paradox (review):

Hawking proposed



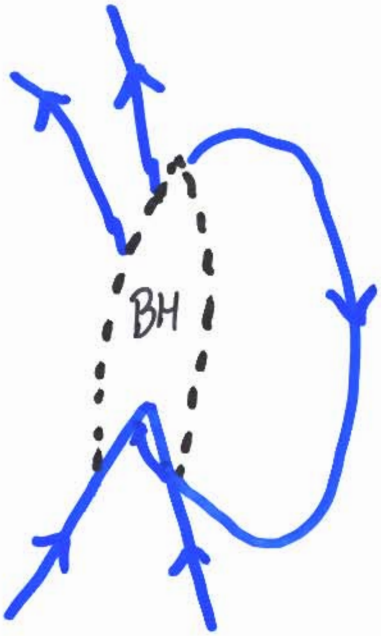
$$\Delta I \sim S_{BH} \sim M^2$$

But: $\Delta E \, \Delta t \gtrsim 1 \Rightarrow$

To lose one bit of information in time Δt, must also pay ΔE

Big deal ?? $\tau_{BH} \sim M^3$ ...

But Quantum processes



⇝ information los
all the time ...

$\Delta E \sim m_{pl}$

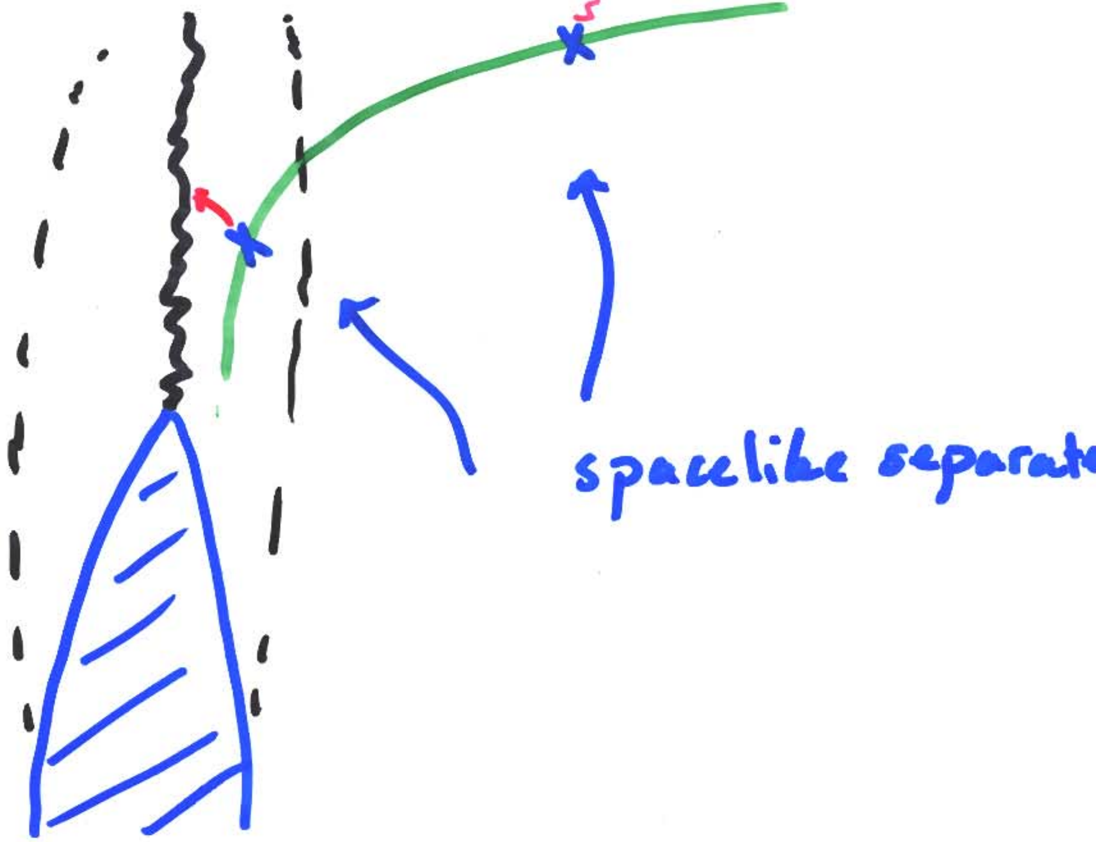
Indeed, Banks, Peskin, Susskind argued

$\sim$ thermal bath at $T \sim M_{pl}$

Disaster
for energy conservation

Outs?

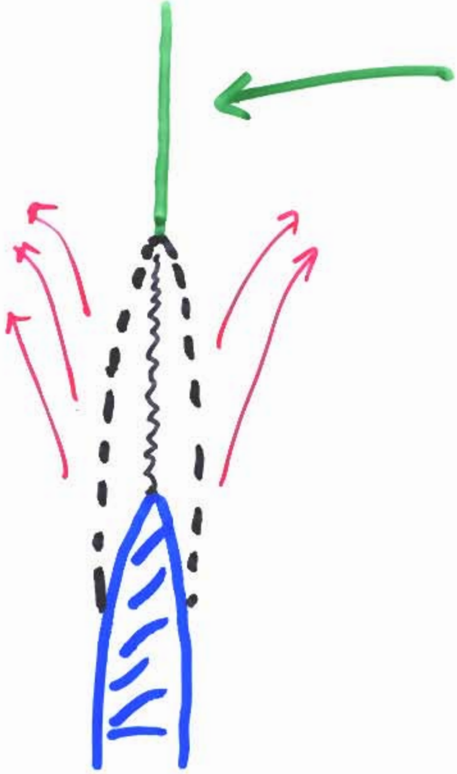
Information return?



⇒ to escape during semiclassica
evolution (up to $M_{BH} \sim M_{pl}$)
requires macroscopic locality
violation . . .

But . . .

Remnants ?

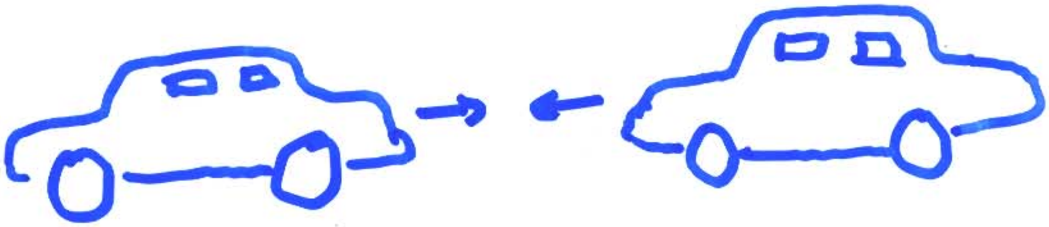


Remnant,
containing information
in internal quantum sta

Remnant properties :

1. $M_R \sim m_{Pl}$
2. Long lived, $\tau \gg m_{Pl}^{-1}$
3. ∞ # internal states

Consider car-car scattering



$E > E_{\text{threshold}} \sim m_{\text{pe}}$

Remnant production rate:

$$r \sim \underset{\substack{\uparrow \\ \text{Rate per species: } \underline{\text{tiny}}}}{r_0} \times N_{\text{remnants}} = \infty \,!!$$

To summarize:

Info loss ⇒ Energy nonconserv.

Info return ⇒ Locality violation

Remnants ⇒ Instability

Paradox

How do we know $\mathcal{H} = \mathcal{H}_{in} \times \mathcal{H}_{out}$?

Standard QFT:

$$[\mathcal{O}_i(x), \mathcal{O}_j(y)] = 0 \qquad (x-y)^2 >$$

Of course, to study BH info, <u>must</u> include gravity. $\rightsquigarrow$

$\hat{\mathcal{O}}_i(x)$: ~ local observables "gravitationally dressed"

... reduce to QFT observables in semiclassical limit.

(For Hawking's argument must assume their existence or equivalent to get $\mathcal{H}_{in} \times \mathcal{H}_{out}$)

(Examples of constructions: SG, Hartle, Marolf, WIP

When does $[\hat{O}_i(x), \hat{O}_j(y)] \neq 0$, or
locality break down?

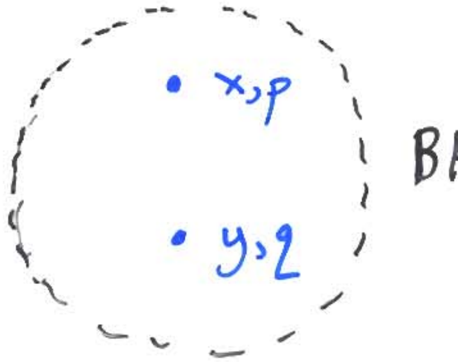
E.g. "free" scalar field

$\phi(x) \longrightarrow \quad \phi_{x,p}$ ← creates/annihilates particles

(e.g. minimum uncertainty wavepacke

QFT: $[\phi_{x,p}, \phi_{y,q}] \sim e^{-|x-y|^2/\delta^2}$

But can't say $[\hat{\phi}_{x,p}, \hat{\phi}_{y,q}] = 0$
for $|x-y| < |p+q|$: strong
gravitational backreaction



"locality bound"

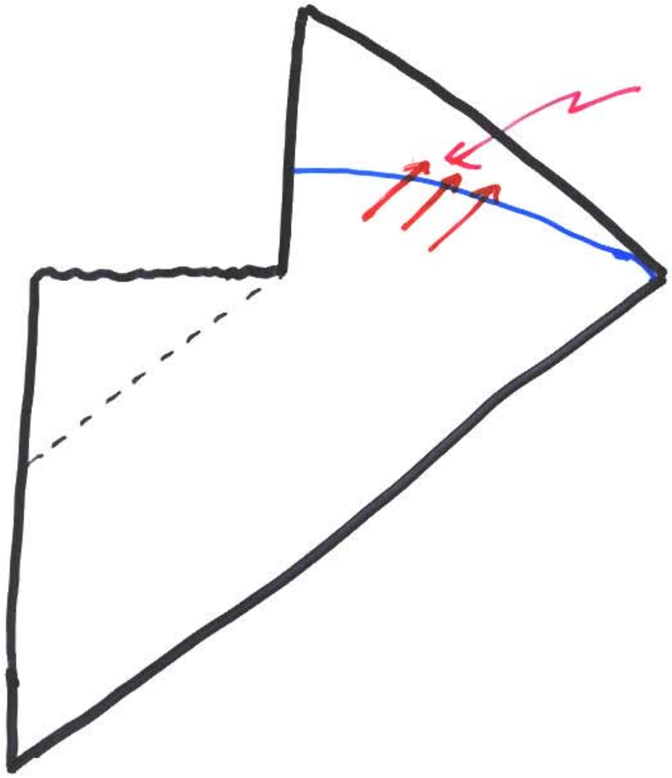
(which constant, l_s or l_p ?
Belief: l_p — strong gravity, not long strings
Discuss another time — brief comment later

So: $$\mathcal{H} \approx \mathcal{H}_{in} \times \mathcal{H}_{out}$$

approximate statement: Only known to be true for certain states, not violating locality bound.

What states are relevant for the information paradox?

First, how to determine information:



ρ_3:
pure or mixed?

E.g. 2×2: $\rho = \alpha|\downarrow\rangle\langle\downarrow| + \beta|\uparrow\rangle\langle\downarrow| + \beta^*|\downarrow\rangle\langle\uparrow| + \gamma|\uparrow\rangle\langle\uparrow|$

pure $\Longleftrightarrow$ $1 = \langle\sigma_z\rangle^2 + \langle\sigma_x\rangle^2 + \langle\sigma_y\rangle^2$

w/ $\langle\sigma_i\rangle = \mathrm{Tr}(\rho\sigma_i)$

Example of <u>general statement</u>: need precise combo of expect. values; <u>phase information</u>, etc.

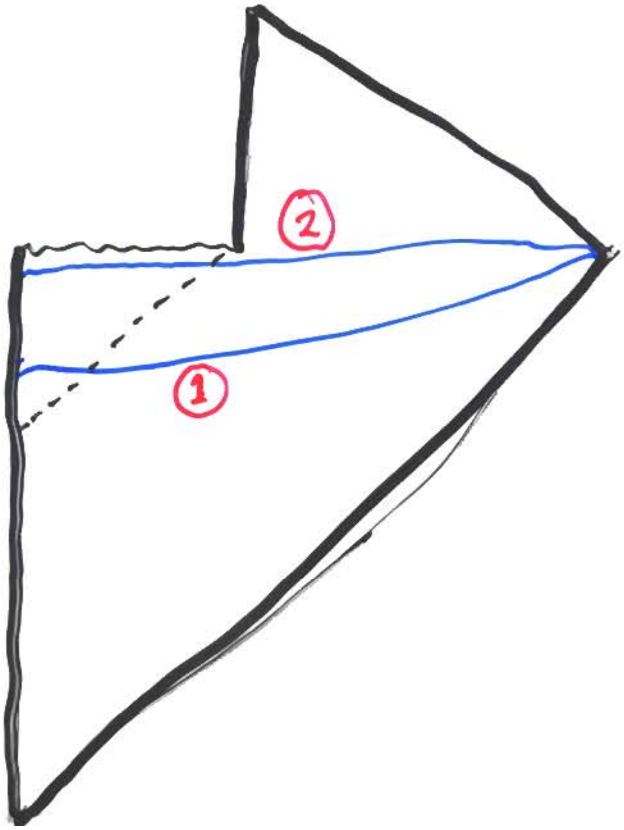
(Alternately: ρ_{AB}, $S = -\mathrm{Tr}(\rho \ln \rho)$)

Analagous statement here:

Need $\left\langle \hat{\phi}^{n_1}_{x_1 p_1} \hat{\phi}^{n_2}_{x_2 p_2} \cdots \right\rangle$

Here Hawking argues mixed because

$$[\hat{\phi}_{x,p}, \hat{\phi}_{y,q}] \simeq 0 \longleftrightarrow \mathcal{H} = \mathcal{H}_{in} \times \mathcal{H}_{out}$$



and

$\psi_1 \longrightarrow$

$$\psi_2 = \sum_\alpha \phi_\alpha \times \psi_\alpha$$

- Need to know $[\hat{\phi}_{x,p}, \hat{\phi}_{y,q}] \simeq 0$

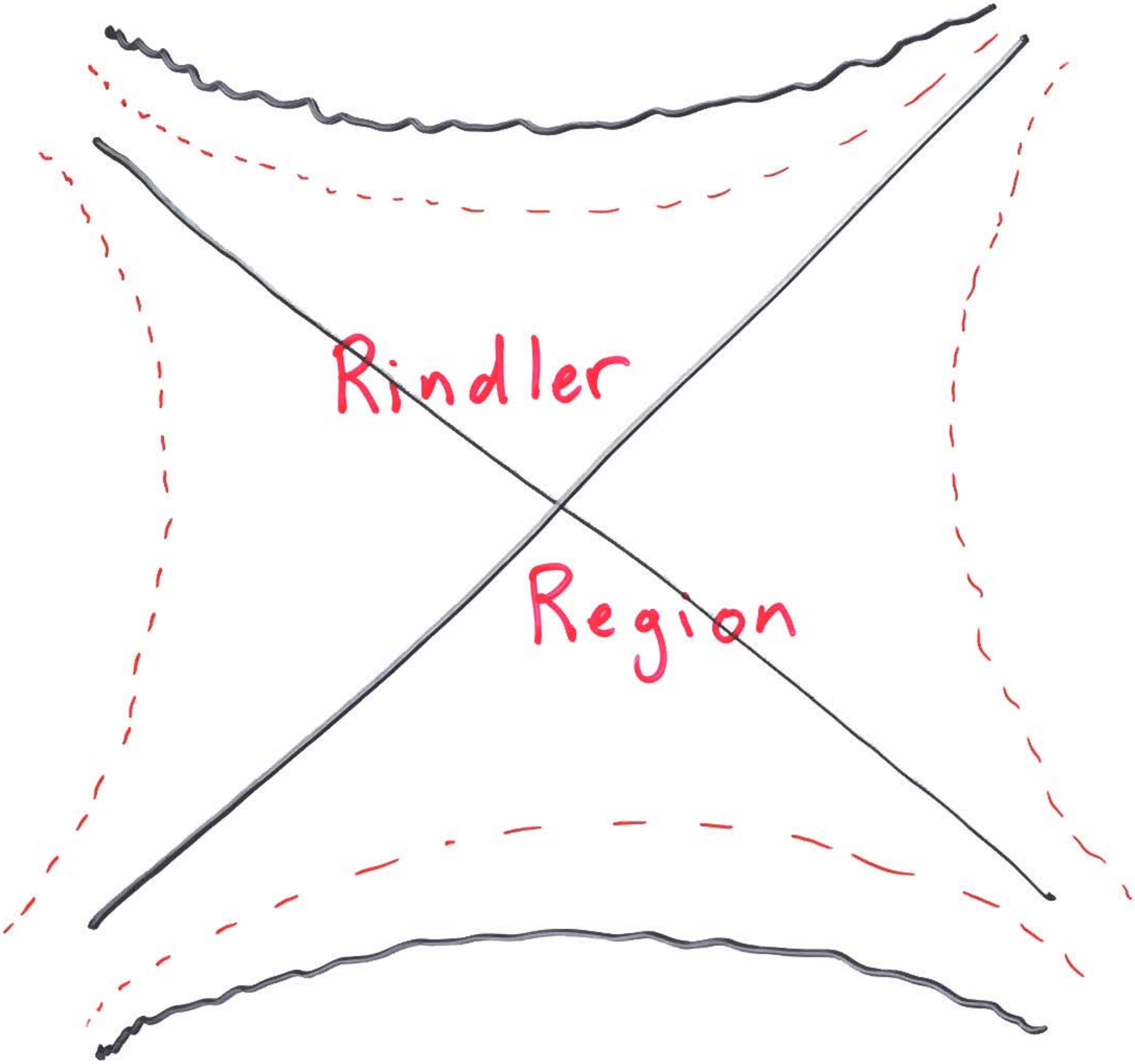
- Needs to be true on slices 1 and 2 for all (x,p) and (y,q) relevant to describing matrix elements / degrees of freedom.

(Need a product Hilbert space before & after, and evolution between)

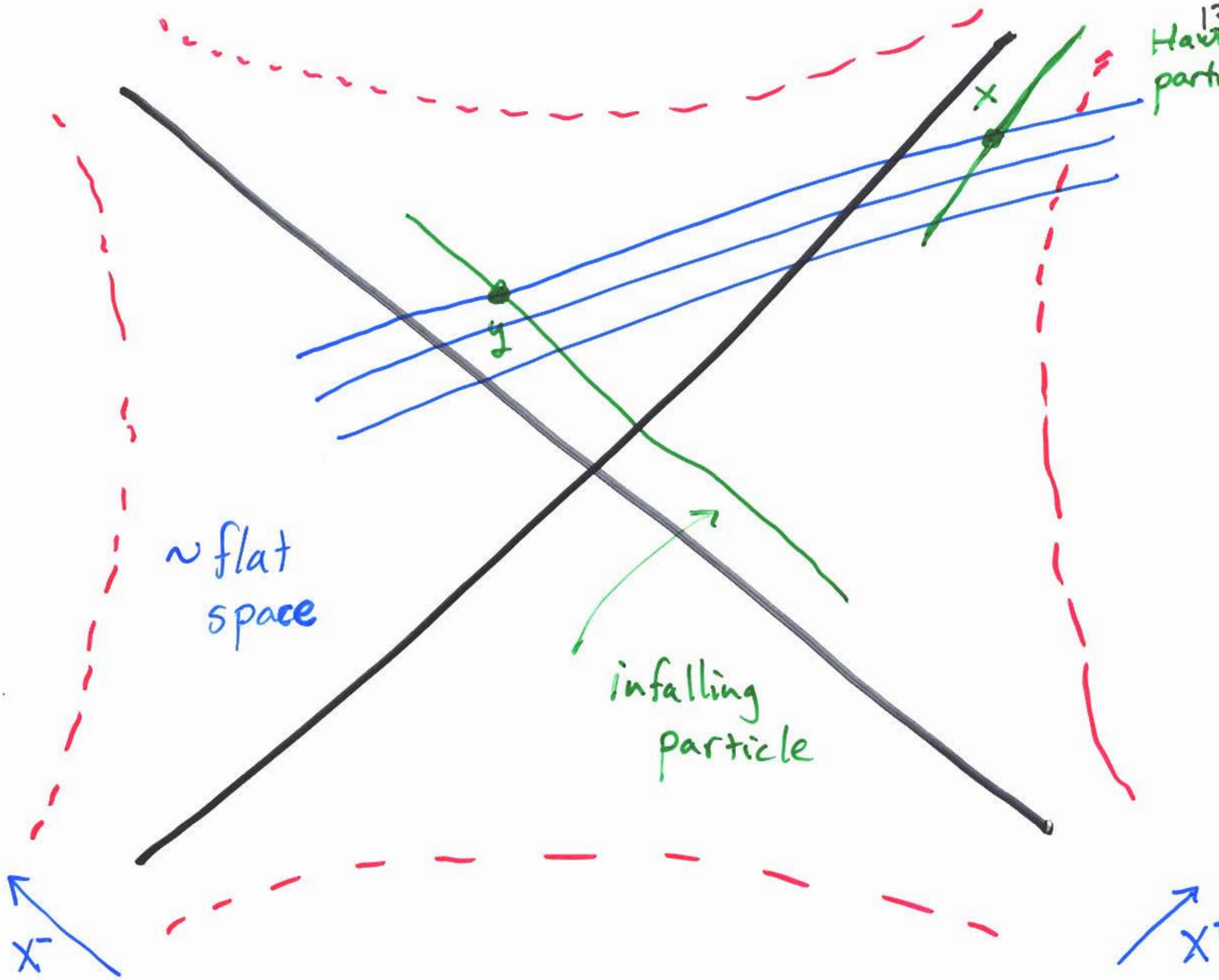
In accord w/ locality bound?

... Hard to apply in curved space; much easier in flat space.

Fortunately, the relevant questions can be addressed in a region ≈ flat ...



$|r-2M| << M$



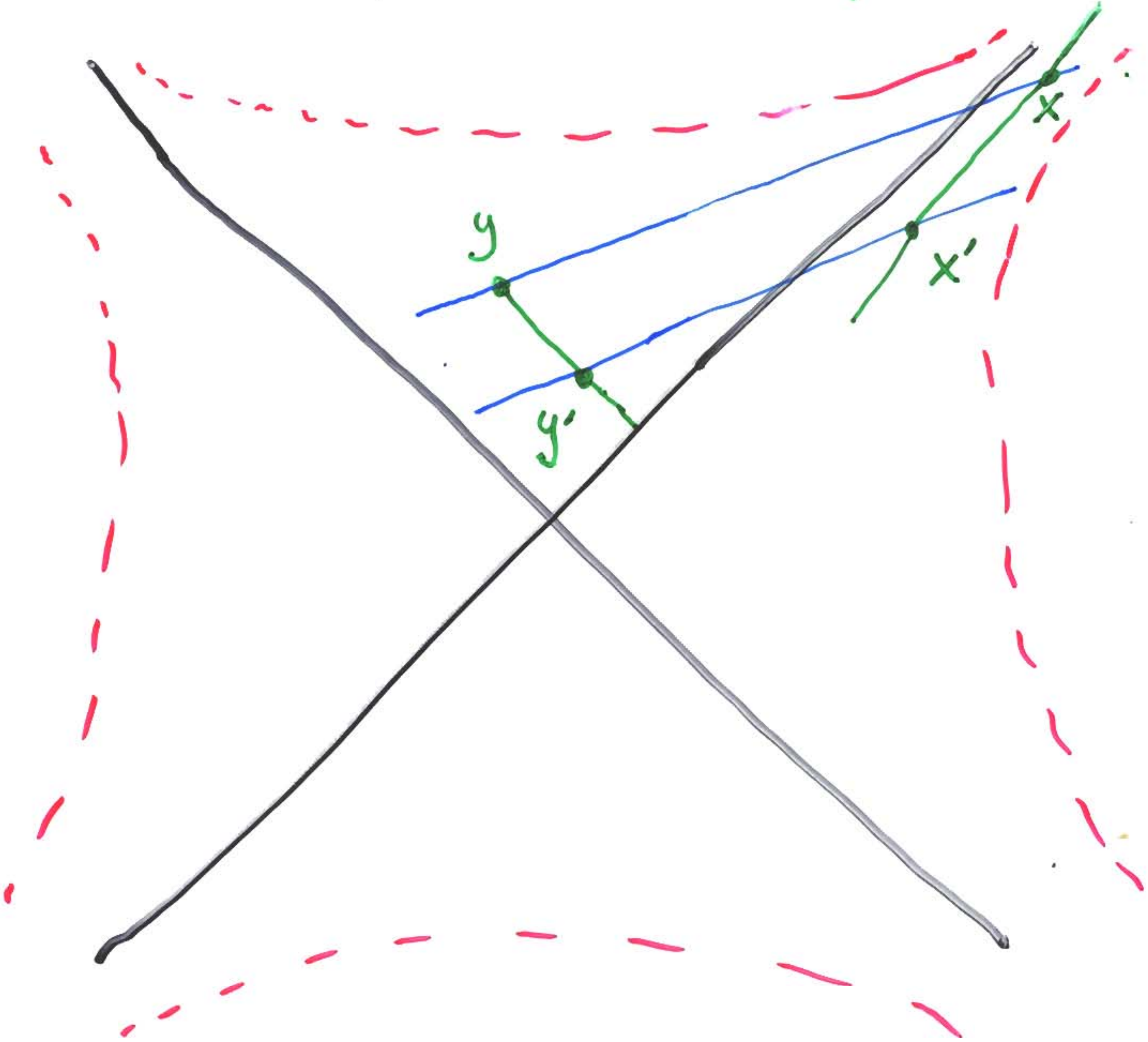
$X^\pm = \pm \rho e^{\pm\theta}$

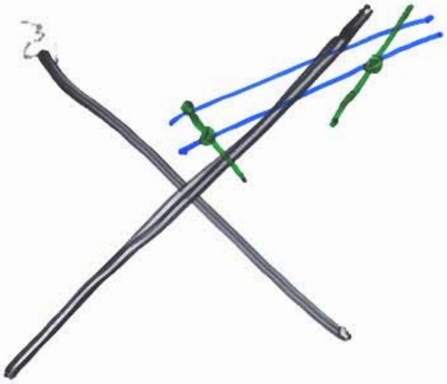
Infalling particle $(\rho_y, 0)$

Outgoing particle $(\rho_x, \tau/4M)$ $\tau \gg M$

In standard QFT:

$$[\phi_{x,p}, \phi_{y,q}] = 0 \iff [\phi_{x',p}, \phi_{y',q}] = 0$$





Work in CM frame

Apply locality bound:

Violated @ CM time T'

Where $p_{CM} \gtrsim |x' - y'|$

For Hawking particle, $E \sim 1/M$, τ

$$T' \sim \frac{1}{M} e^{\tau/8M} \,, \quad R_{CM} \sim \frac{1}{M} e^{\tau/8M}$$

e.g. $\tau \sim M^3$ (Page) $\Longrightarrow \frac{1}{M} e^{\tau/8M} \sim \frac{e^{M^2}}{M} \gg R_{BH} \sim M$

So:

- Can't conclude $[\phi_{x',p}, \phi_{y',q}] = 0$
- Can't conclude $[\phi_{x,p}, \phi_{y,q}] = 0$
- Can't say state inside horizon is independent of the state outside

Can ask: for what Schwarzschild emission time τ does such a mode violate the locality bound with a generic infalling particle?

Just need $E_{cm} \gtrsim M \rightsquigarrow$

$$\tau_{lb} \sim M \log M^2$$

... holographic spreading time of Susskind

This is the single-mode analysis; it's quite plausible that in studying full correlators

$$\langle \phi^{n_1}_{x_1 p_1} \, \phi^{n_2}_{x_2 p_2} \cdots \rangle$$

$\sim M^2$ insertions

the locality bound is directly saturated even for slightly later times

e.g. $T_{CM} \sim M e^{M^2}$

(CM time corresponding to measured Hawking particle)

Relation to earlier work

't Hooft et al, Verlindes, ...

related arguments, based on large blueshift

but here : 1. Connection to issue of measuring mat. elements (purity

2. Correct HE physics of grav. scatt is B.H. formatio not "shifts"

Lowe, Polchinski, Susskind, Thorlacius, Uglum

1. Even the authors of the paper couldn't agree they'd found a gauge invt. signal for requisite locality violation

2. Based on long string creation contributing to relevant correlators, instead of strong gravity / black holes

Indeed, which locality bound?

D dim

String $|x-y| \lesssim \ell_s^2 |p+q|$

Strong grav/ black hole $|x-y|^{D-3} < \ell_P^{D-2} / |p+q|$

There seems to be evidence (partly circumstantia that at long distances gravity bound is the relevant one

($\leftrightarrow$ High energy BH formation, not long string

And if so: the genericity of these arguments for why info. inside and outside the horizon is not independent is a very satisfying mirror of the genericity of Hawkings arguments for BH evaporatio and information loss.

(Independent of specific microscopic theory of gravity)

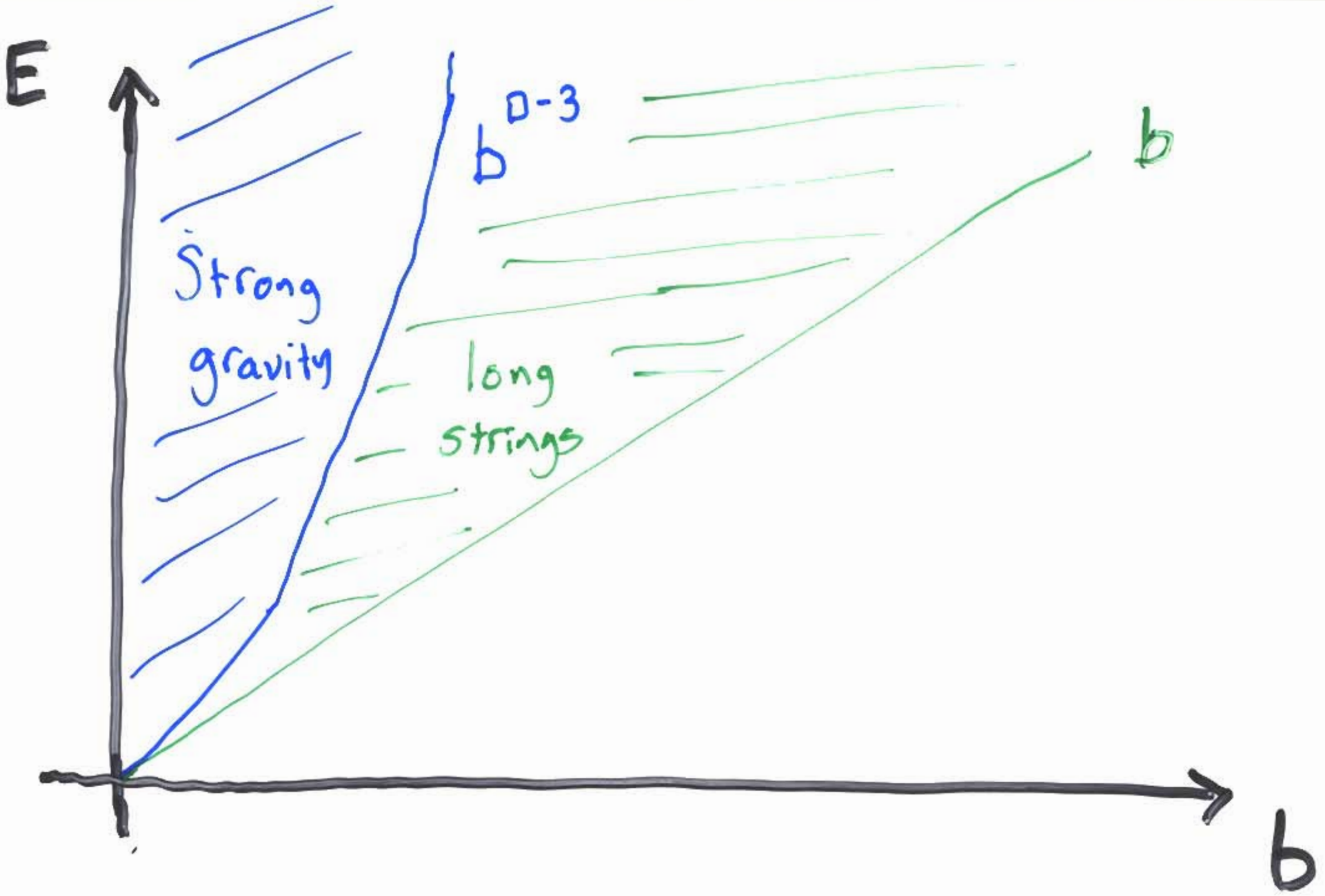
String vs gravitational nonlocality

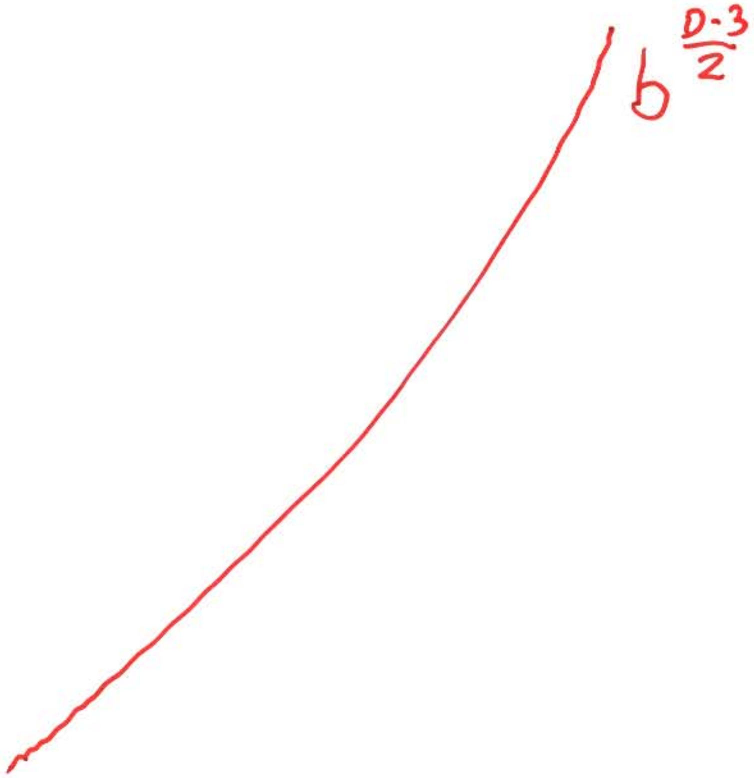
Consider scattering:

What is dominant effect at large b?

If long strings, $b \sim E$

If strong gravity, $b \sim E^{1/D-3}$


E
b^{D-3}
b
Strong gravity
long strings
b



Amati, Ciafaloni, Veneziano:

studied string scattering at fixed t, large s

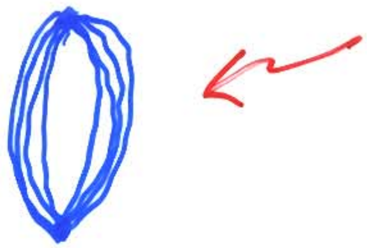
so analysis valid for $E \lesssim b^{D-3/2}$

They find: scattering agrees with that described by long-distance gravity, with corrections $\sim \frac{R_{schw}}{b}$, as expected.

What's going on?

Hint from Gross-Mende (large s, fixed θ)

At genus g, find



g strings, size $\sim E/g$

Then Mende & Ooguri found sum dominated at large g, $\sim E$, so size $\sim$ constant $\sim \ell_s$.

(Though analysis fails at $E \gtrsim \left[\log[1/g^2]\right]^{3/2}$)

So: when last seen, string scattering

$\not\rightarrow$ long strings

Finally, we've grappled a great deal with the ideas of "holography," and in particular have sought to understand how to holographically describe spacetime processes.

Perhaps the locality bound, and appropriate generalizations, provide the beginning of a deeper underpinning for implementation of holographic ideas. (~ uncertainty principle ?)

Slogan:

Semiclassical QFT techniques are good for computing $\langle T_{\mu\nu} \rangle$, $\cdots$, which determine Hawking flux, but break down when computing $\left\langle \Phi^{n_1}_{x_1 p_1} \Phi^{n_2}_{x_2 p_2} \cdots \right\rangle$ which determine its purity. (Or equivalently: ρ_{AB} ... all matrix elements).

The origin of the breakdown is strong gravitational backreaction.

This is our proposal for how the information paradox is resolved in favor of unitary evolution.