UNITARITY, NEAR-LOCALITY, AND HILBERT SPACE NETWORKS

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THE HOLOGRAPHIC WAY
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Refs: SBG 1108.2015, 1201.1037;

SBG and Y. Shi, 1205.4732; WIP

This talk:

1. Introductory/motivational comments

   - comments on AdS/CFT

2. Review Hawking/nice slice description

3. Restoring unitary

   "nonviolent" nonlocalty vs. complementarity, massive remnants (fuzzballs, firewalls)

4. Comments on Hilbert space networks

The information "paradox," in a nutshell:

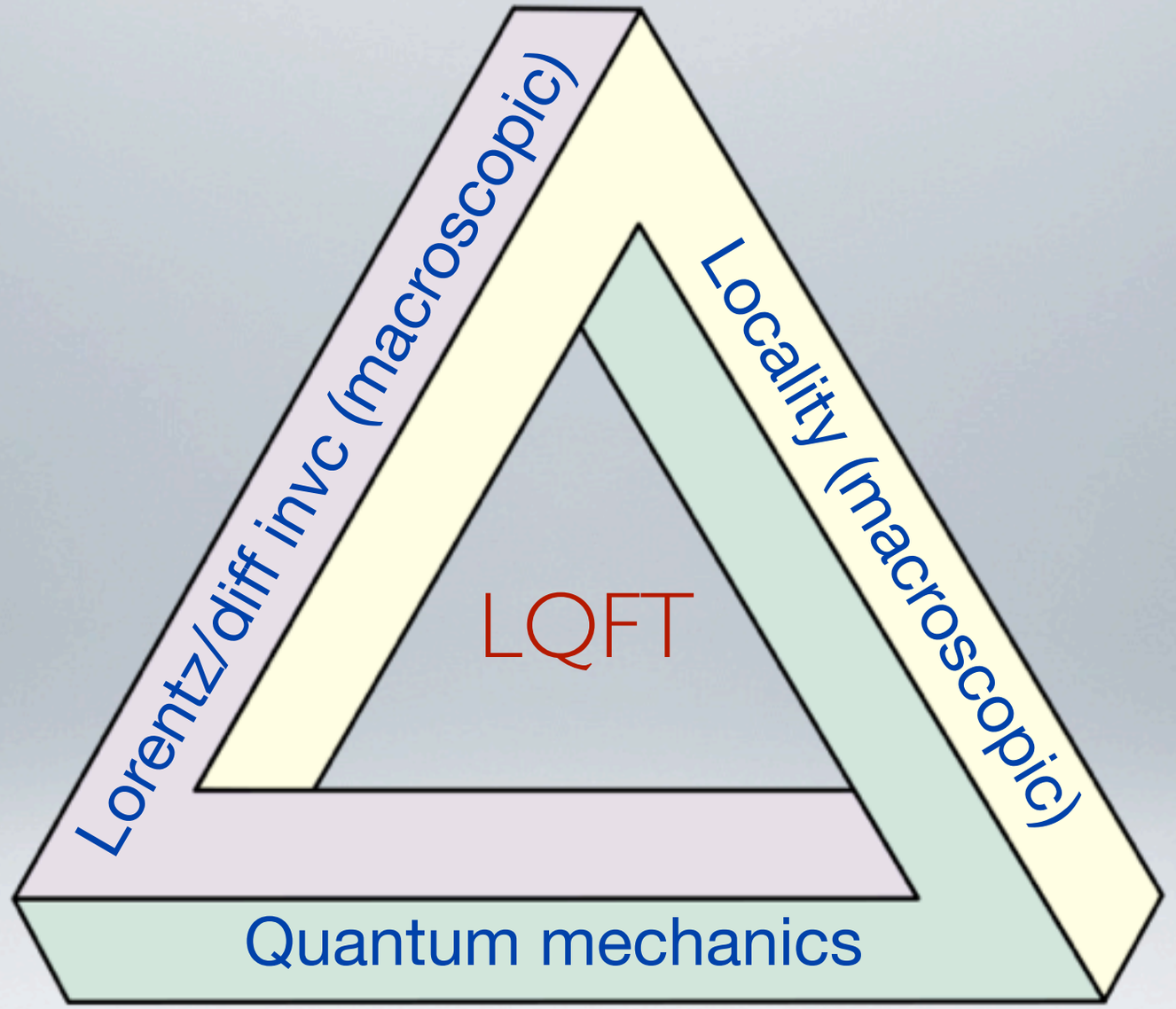
Information cast into a black hole

- can't get out — locality
- can't be destroyed — QM; energy conserv.
- can't be left in remnant — catastrophic instabilities

Stupid mistake?

Guide to new physics?

Apparently a fundamental conflict:



- QM, LI: hard to modify (consistency, observation). Locality?

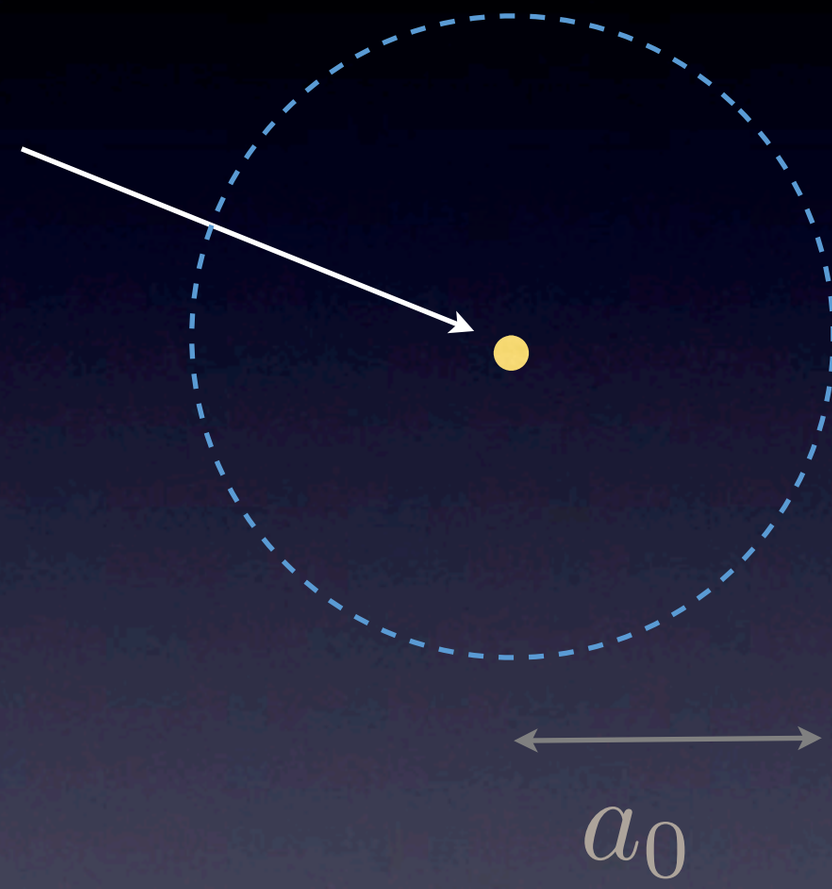
- It's not about singularities, renormalizability? Long distance.

A SEEMINGLY SIMILAR CRISES:

Classical atom

CM breaks down here

QM takes over here (CM irrelevant)



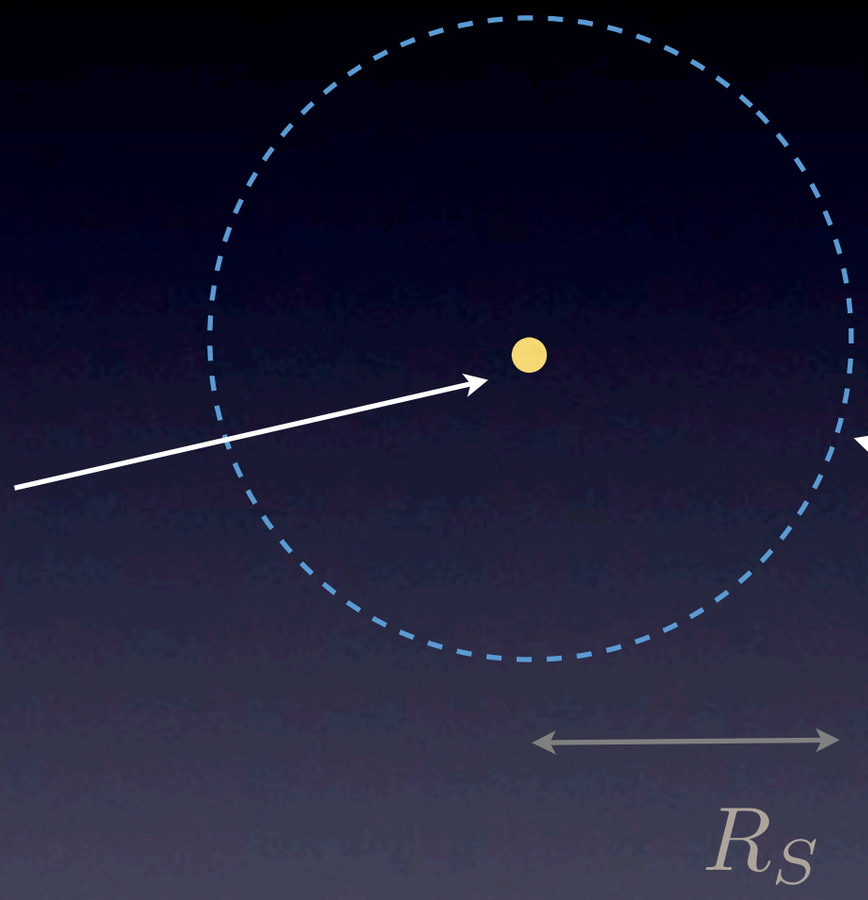
New physics was needed:

Uncertainty principle

Wave mechanics...

A SEEMINGLY SIMILAR CRISES:

Black hole



LQFT breaks down here

QG relevant here? (subtle breakdown LQFT?)

New physics ~~was~~ needed:

is

Uncertainty ~~principle~~

~~Wave mechanics...~~

???

“Classical instability paradox”

“Black hole information paradox”

This unitarity crisis is likely an important guide to understanding new principles/mechanisms.

(As was the stability problem of the atom)

What other guides do we have?

AdS/CFT??

Microstates??

Cosmological comparisons; tests?

SBG and Sloth; many others

Locality/ local observables

e.g. hep-th/0512200, w/ Marolf and Hartle

S-matrix

Erice lectures: 1105.2036

Amplitude magic??

nonperturbative?

Correspondence

Quantum info. transfer from BHs

Comments on AdS/CFT (More detail: 1105.6359)

- many regard as resolution -

A question: can we recover from the boundary theory a sufficiently fine-grained bulk description, e.g., of evolution of a small (<< R) BH, and of infalling observers?

Need:

$$M : \mathcal{H}_{\rm bulk} \to \mathcal{H}_{\rm bdy}$$

interacting

1-1, unitary

$$U_{bulk} = M^\dagger U M \qquad U$$

Unitary bulk evolution?

Approaches:

(~) local bulk observables

- challenge in QG

- much discussion at recent KITP workshop

- general "relational" approach: e.g SBG, Marolf, Hartle hep-th/0512200; used in inflation

- no clear and general story

S-matrix (flat space limit)

- Problem: construct scattering states from boundary data; extract fine-grained S-matrix

- there are obstacles

(more discussion: 1106.3553 w/ M. Gary)

More general approaches (e.g. beyond AdS/CFT):

1. Investigate correspondence boundary

2. Quantum information transfer

3. The gravitational S-matrix

Correspondence

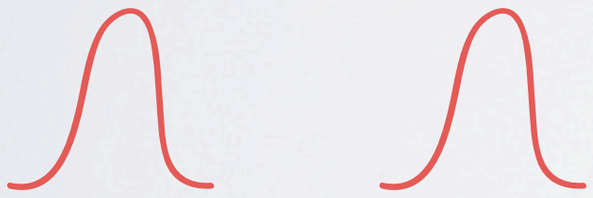
Existing theory: LQFT, semiclassical background

correspondence point - various proposals: planckian curvature, modified/string uncertainty, modified dispersion, holographic bounds ...

Configurations: $\phi_{x,k}\phi_{x',k'}|0\rangle$

(min uncertainty wavepackets)

Where is description untrustworthy?



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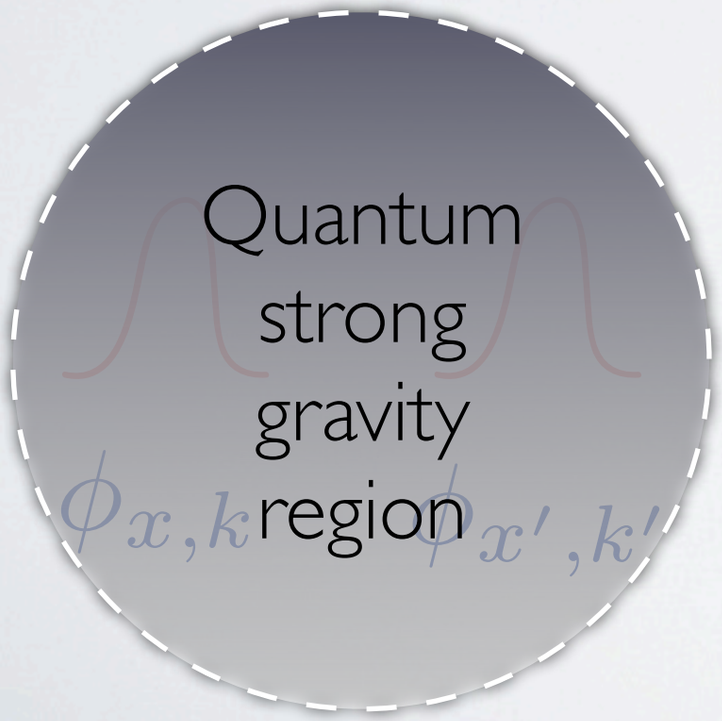


Where is description untrustworthy?

$$|x - x'|^{D-3} < (\hbar G)|k - k'|$$

"locality bound"

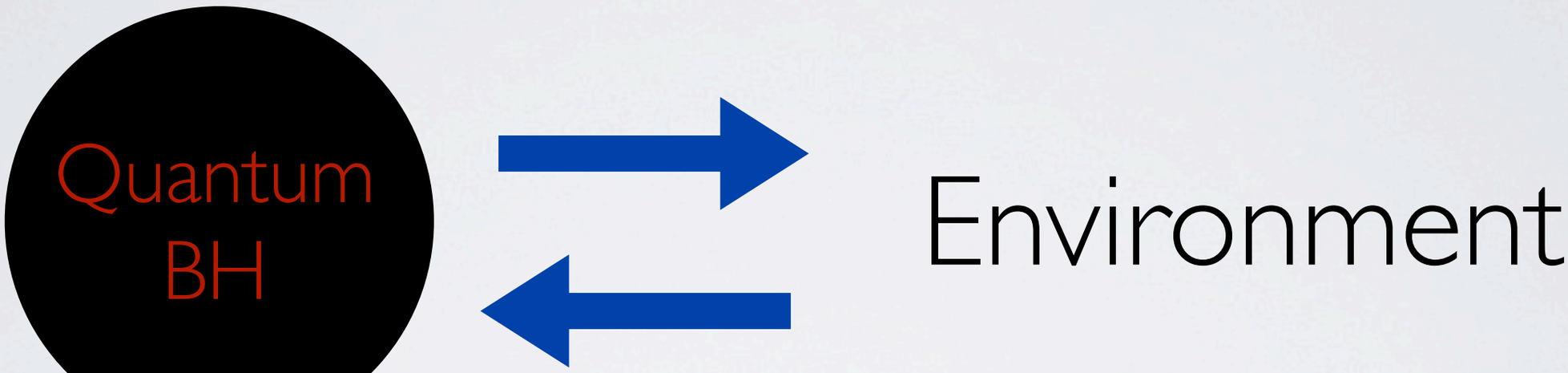
~ Heisenberg microscope

(multiparticle generalizations)

How do we describe physics in this regime?

Assume: quantum mechanics (take seriously)

Also assume: quantum subsystems (~localization)



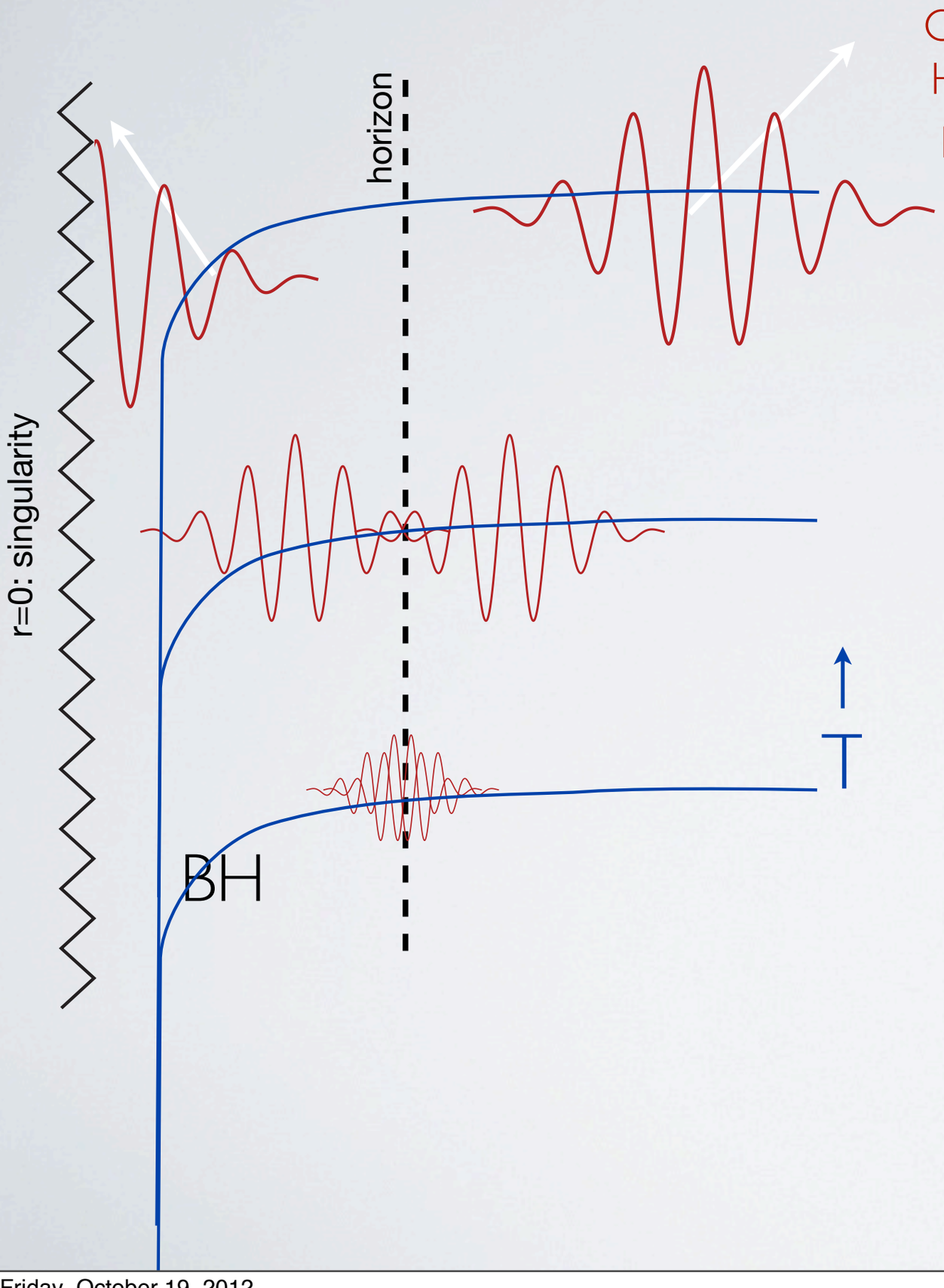
$$\mathcal{H}_{BH} \otimes \mathcal{H}_{ext}$$

Information exchange; unitary

"Effective quantum theory" -- but more?

(recall: "QM+locality+Poincare $\Rightarrow$ QFT")

Another guide: "as close as possible" to LQFT. Review



nice-slice description
-- sharpens tension

$X^+,\ X^-$: null, Kruskal

$$X^+(X^- + e^{-2T}X^+) = R_c^2$$

"Hawking state"

(explicit in 2d:
SBG and Nelson, 1992)

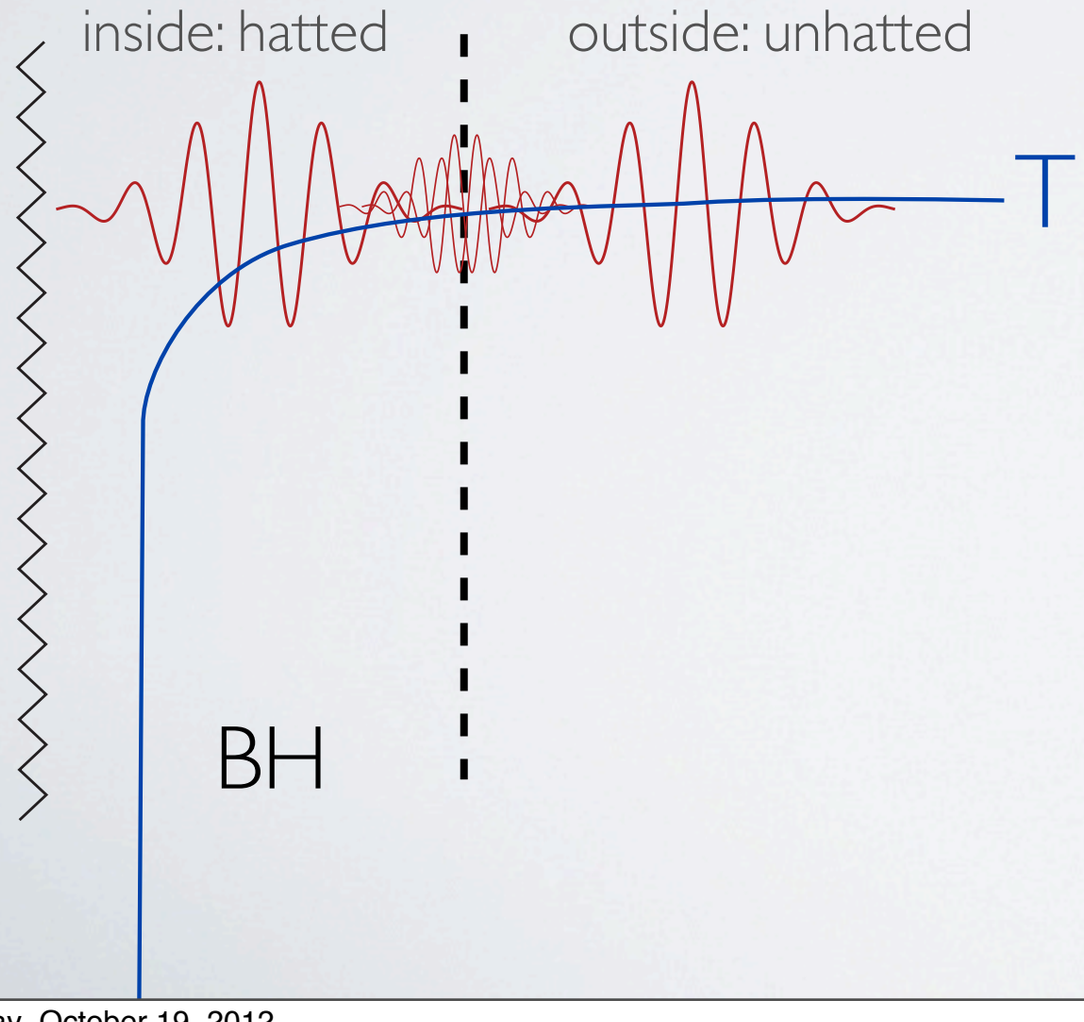
$$|\psi\rangle_{\rm Hawk} = \prod_{jn} S_{jn} |\hat{0}\rangle|0\rangle$$

$$\exp\left\{ tanh^{-1}[e^{-\omega_j/2T}] \left(\hat{b}^\dagger_{jn} b^\dagger_{jn} - \text{h.c.} \right) \right\}$$

$$= \frac{1}{Z} \sum_{\{n_{jn}\}} e^{-\beta H/2} |\widehat{\{n_{jn}\}}\rangle |\{n_{jn}\}\rangle$$

j ~ asymp. frequency

n ~ position along slice



Regularization:

For given T:

$$n \to \infty \;\; \leftrightarrow \to \text{horizon}$$

cutoff: $n < N(T) \;\sim\; \lambda > L$

Shorter modes "look like" vacuum

"Hawking state" (cont'd):

So rewrite:

$$|\psi\rangle_{\rm Hawk} = \prod_{jn} S_{jn}|\hat{0}\rangle|0\rangle = |0\rangle_N \prod_j \prod_n^{N-1} \left(S|\hat{0}\rangle|0\rangle\right)_{jn}$$

UV modes: "in vacuum"

$\in \mathcal{H}_{BH} \otimes \mathcal{H}_{ext}$

As advocated

- $|0\rangle_N$ can either go with BH, or "ancillary"
- Hilbert spaces effectively finite dim. (if finite time)

Evolution: e.g 2d: $U = 1$

$$|\psi\rangle_{\rm Hawk} = |0\rangle_N \prod_j \prod_n^{N-1} \left(S|\hat{0}\rangle|0\rangle\right)_{jn}$$

$$= \frac{|0\rangle_N}{Z} \sum_{\{n_{jn}\}, n<N} e^{-\beta H/2} |\widehat{\{n_{jn}\}}\rangle |\{n_{jn}\}\rangle$$

more generally: U_{LQFT}

(also, can include infalling matter)

and: $N \to N+1$

Note: "generalized" unitary transform: dimensions of $\mathcal{H}_{BH},\ \mathcal{H}_{ext}$ change ("isometry")

Cartoon: timestep ~R

(See also Mathur)

$$|0\rangle_N \to |0\rangle_{N+1} \left(|\hat{0}0\rangle + |\hat{1}1\rangle\right)_{n=N}$$

"qubit model"

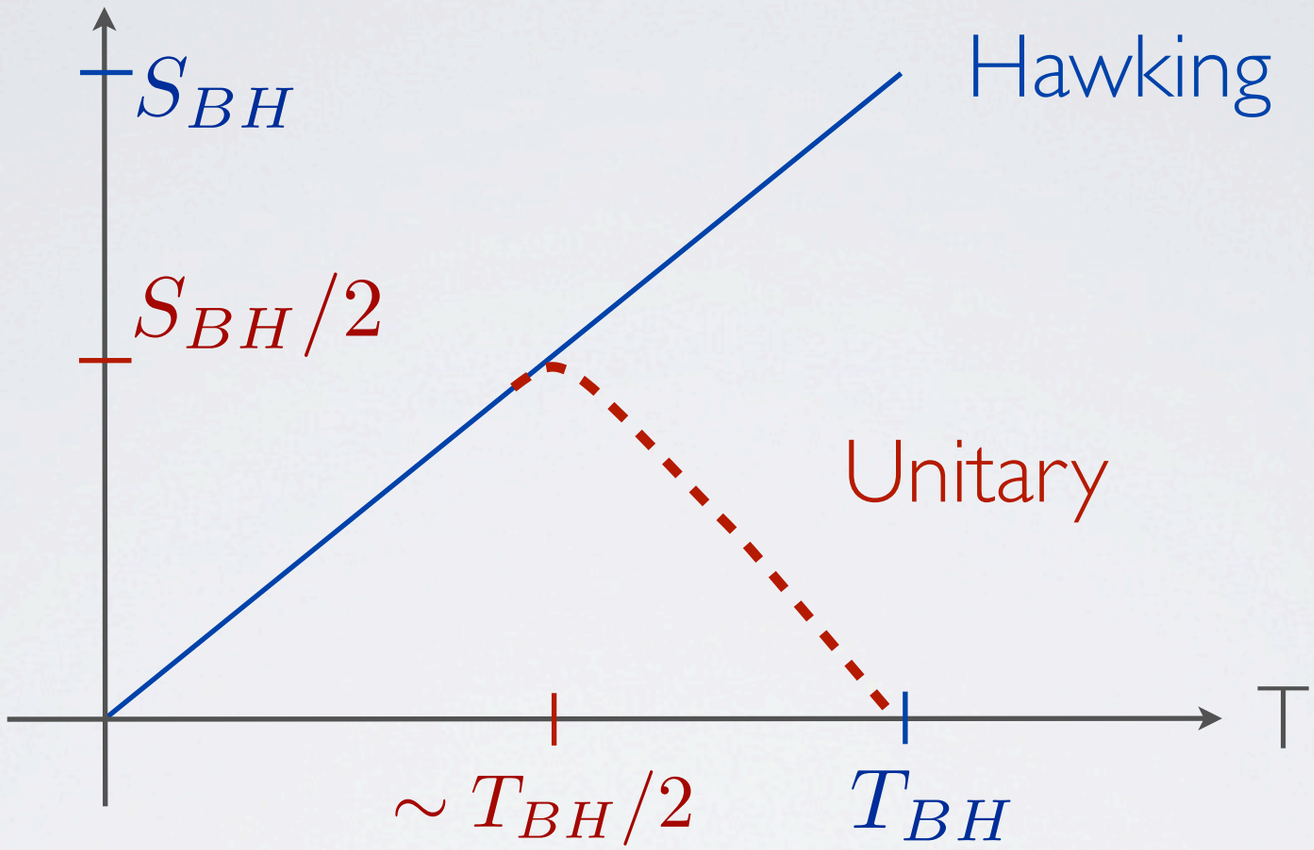
pairs produced

$(\omega_j \simeq 1/\beta)$

Nonunitarity

$$\rho_{ext} = \mathrm{Tr}_{BH}\left(|\psi\rangle_{\mathrm{Hawk}}\langle\psi|\right) \propto \sum_{\{n_{jn}\},n<N} e^{-\beta H}|\{n_{jn}\}\rangle\langle\{n_{jn}\}|$$

$$S_{ext} = -\mathrm{Tr}\rho_{ext}\ln\rho_{ext}$$



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arguments for failure of LQFT/nice-slice description
(hep-th/0703116, 0911.3395, etc.)

- problems making gauge invariant
- problems w/ perturbative quant.

How is unitarity restored?

General scenarios:

Massive remnants

includes fuzzballs, firewalls

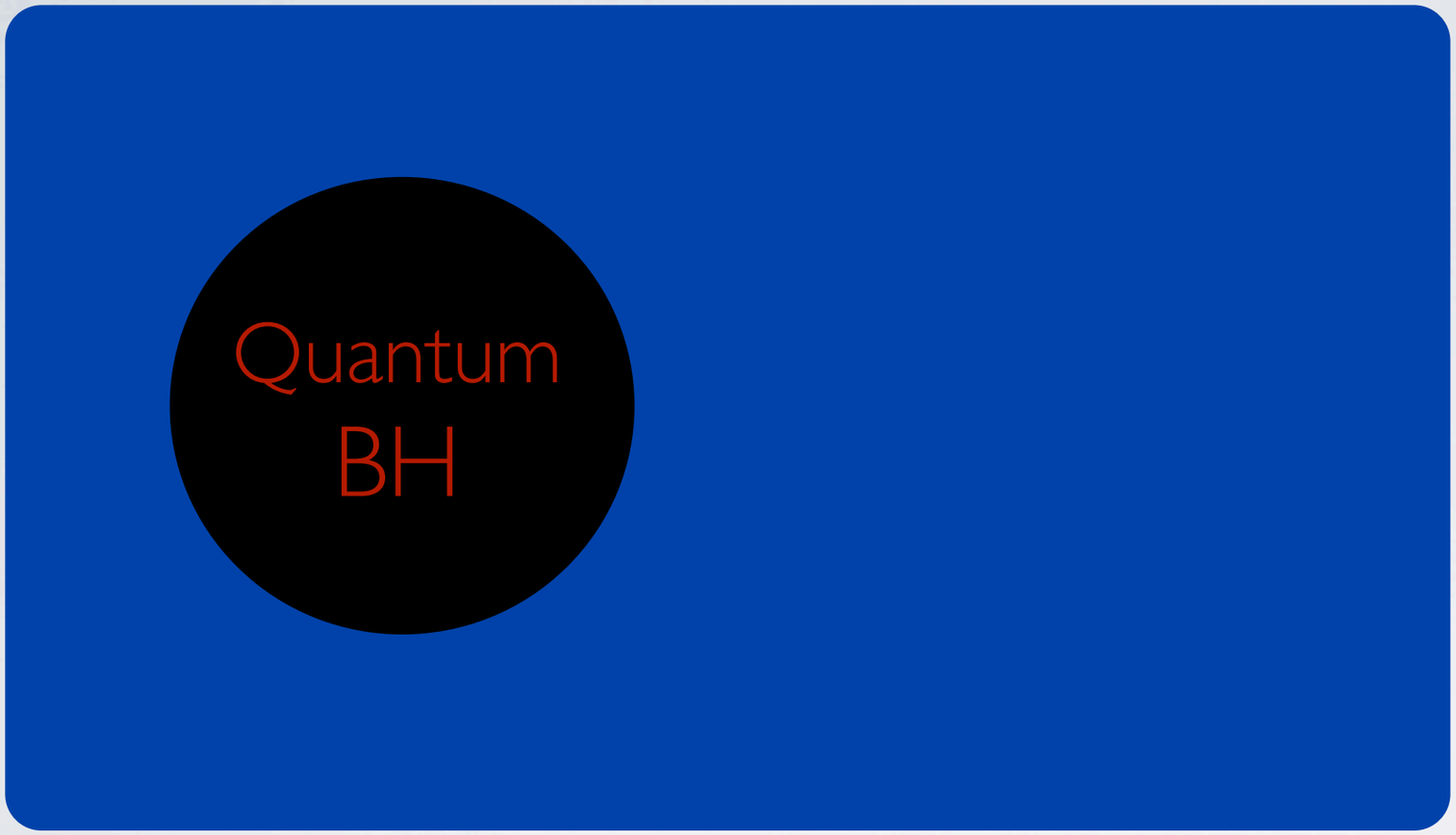
Complementarity (holography)

"Nonviolent" nonlocality

All approaches nonlocal. How to describe physics?

(No fundamental spacetime?)

General framework -- not necessarily based on spacetime

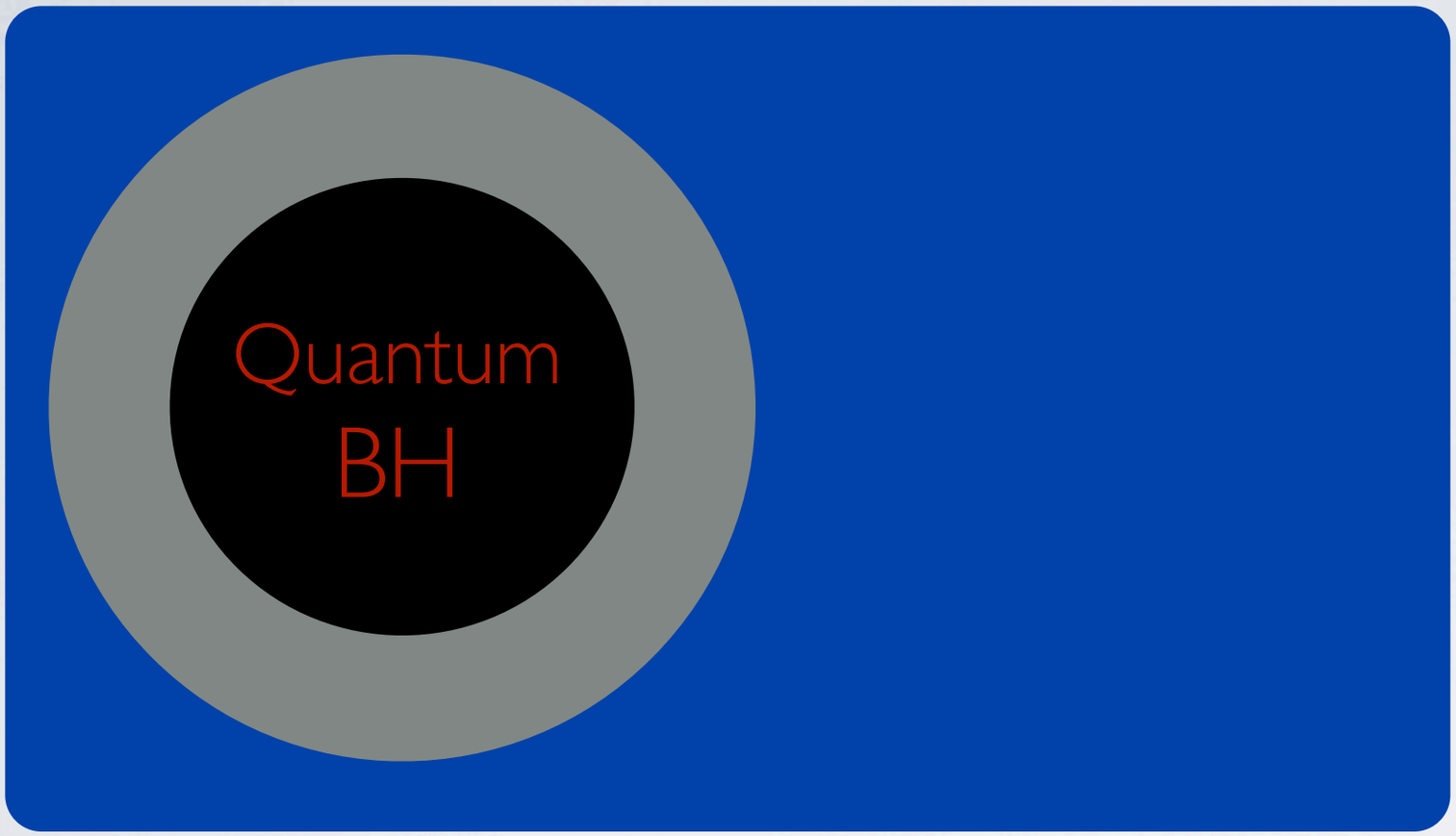


"Hilbert space network"

$$\mathcal{H}_{BH} \otimes \mathcal{H}_{ext}$$

(nb: AdS/CFT could work this way)

General framework -- not necessarily based on spacetime



"Hilbert space network"

$$\mathcal{H}_{BH} \otimes \mathcal{H}_{near} \otimes \mathcal{H}_{far}$$

(nb: AdS/CFT could work this way)

Some expectations:

$$\mathcal{H}_{far} \approx LQFT \qquad U \approx LQFT$$

$$\mathcal{H}_{near} \sim LQFT$$

$$\mathcal{H}_{BH} \neq LQFT \qquad U \neq LQFT$$

$\mathcal{H}_{BH}$, $\mathcal{H}_{near}$ finite dimensional; $\log \dim \mathcal{H}_{BH} = S_{BH}$?

Physical constraints on evolution:

A) $S \to 0$

B) Innocuous to infalling observers (?) (uneventful horizon)

C) $dS/dt \sim 1/R$ (?)

D) Near-Hawking; ~thermodynamic (?)

E) Correspondence limit: LQFT + GR

F) Energy conservation

G) Complete, consistent

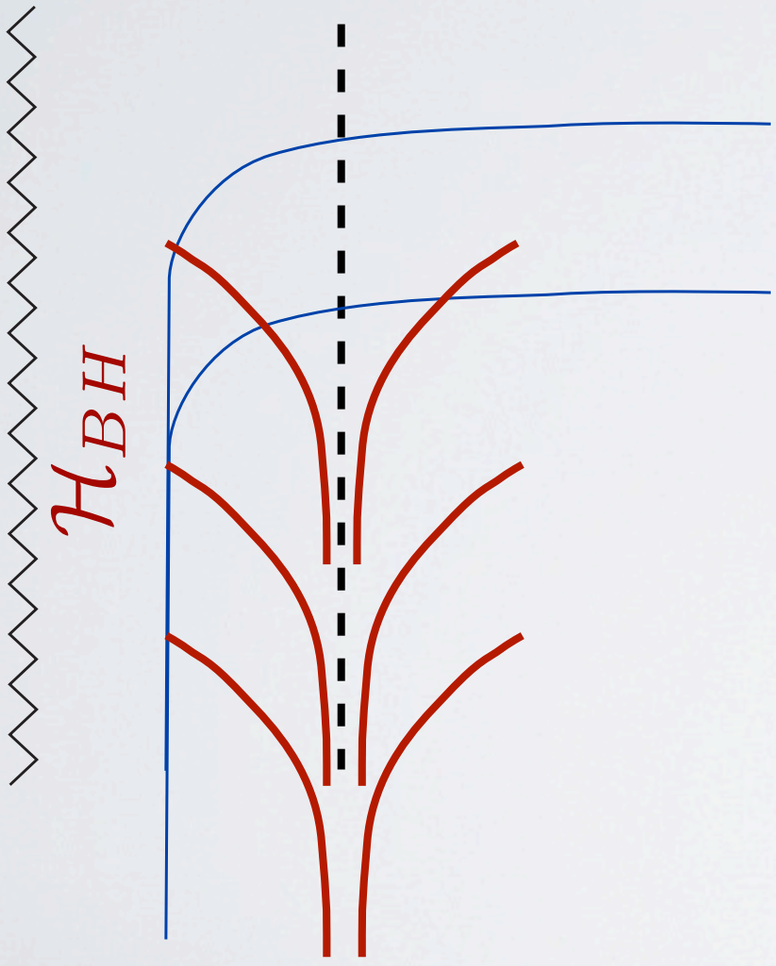
...

Basic guideline: be as conservative as possible!

What is "as close as possible to LQFT"?

Explore examples (e.g. qubit models)

Recap:



Explore examples
(e.g. qubit models)

Not most conservative?

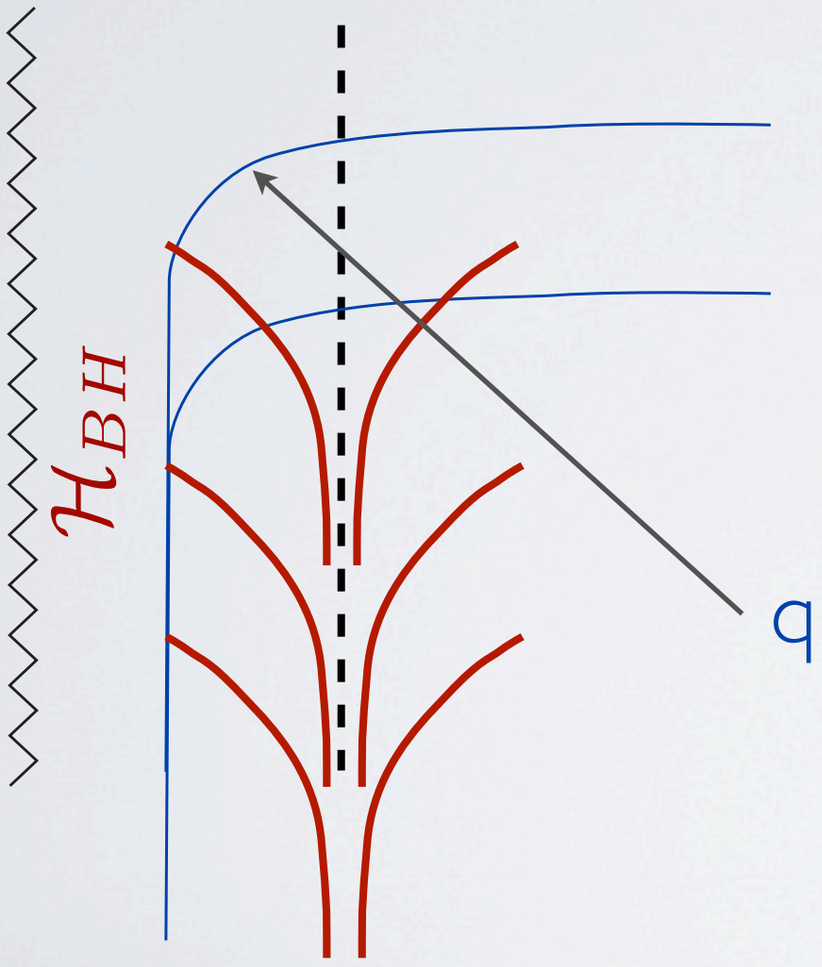
1A) "Fast scrambling"
(complementarity)

e.g. qubit "q=0,1" in:

$$|\hat{a}\rangle|\psi\rangle \rightarrow \underbrace{|\hat{a}\rangle|\hat{q}\rangle}|\psi\rangle$$

$$\hat{U}\left(|\hat{a}\rangle|\hat{q}\rangle\right) \qquad \Delta t \sim R$$

(or, w/ $|\hat{0}0\rangle + |\hat{1}1\rangle$)



then: $|\hat{q}'\hat{a}'\rangle|\psi\rangle \rightarrow |\hat{a}'\rangle|q'\rangle|\psi\rangle$

(separate scrambling/transfer)

Not most conservative?

Big departure from LQFT evolution

Indeed, Hayden/Preskill:

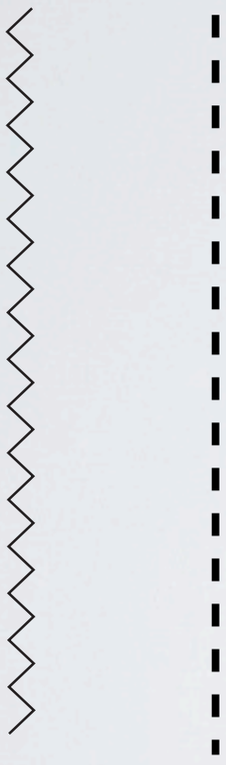
After sufficient evolution, a BH behaves as an information mirror on the scrambling/transfer time!

One classification of scenarios:

	$T_{scramble}$	$T_{transfer}$
Susskind	$R \ln R$	$R \ln R$
Page		$< \mathcal{O}(RS)$
HR, nat. slice	$\sim R$?	∞
HR, nice slice	∞	∞

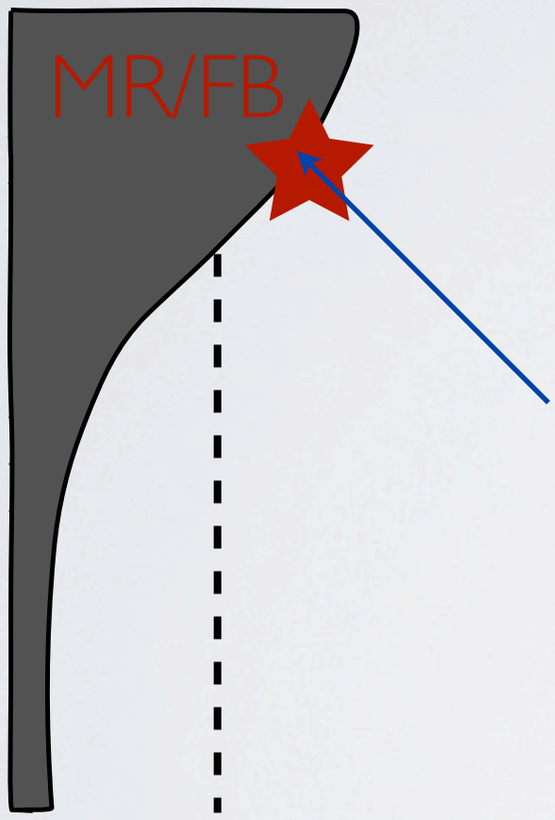
Not most conservative? (cont'd)

1B) Massive remnant; fuzzball; firewall



Not most conservative? (cont'd)

1B) Massive remnant; fuzzball; firewall



expect:

big mods. to $\mathcal{H}_{BH}$

rapidly varying microstructure outside horizon

rapid, more limited(?) scrambling

(~ "neutron star")

Unitary models: "more conservative"

2)

$$|\hat{0}\hat{0}\hat{a}\rangle|a\rangle \rightarrow |\hat{a}\rangle \frac{|\hat{0}0\rangle + |\hat{1}1\rangle}{\sqrt{2}}|a\rangle$$

$$|\hat{0}\hat{1}\hat{a}\rangle|a\rangle \rightarrow |\hat{a}\rangle|\hat{0}1\rangle|a\rangle$$

$$|\hat{1}\hat{0}\hat{a}\rangle|a\rangle \rightarrow |\hat{a}\rangle|\hat{1}0\rangle|a\rangle$$

$$|\hat{1}\hat{1}\hat{a}\rangle|a\rangle \rightarrow |\hat{a}\rangle \frac{|\hat{0}0\rangle - |\hat{1}1\rangle}{\sqrt{2}}|a\rangle$$

e.g. "leftmost" qubits transfer

(toy model)

Oversimiplified, but:

$$|\hat{0}\hat{0}\hat{a}\rangle|a\rangle \rightarrow \hat{U}|\hat{a}\rangle \frac{|\hat{0}0\rangle + |\hat{1}1\rangle}{\sqrt{2}} U|a\rangle$$

$$|\hat{0}\hat{1}\hat{a}\rangle|a\rangle \rightarrow \hat{U}|\hat{a}\rangle|\hat{0}1\rangle U|a\rangle$$

$$|\hat{1}\hat{0}\hat{a}\rangle|a\rangle \rightarrow \hat{U}|\hat{a}\rangle|\hat{1}0\rangle U|a\rangle$$

$$|\hat{1}\hat{1}\hat{a}\rangle|a\rangle \rightarrow \hat{U}|\hat{a}\rangle \frac{|\hat{0}0\rangle - |\hat{1}1\rangle}{\sqrt{2}} U|a\rangle$$

- can include unitary evol. acting inside, outside

- can generalize to more realistic modes (arXiv: 1201.1037) (not just qubits)

Also:

"Hawking-like" "minimal" mods to evolution

- info imprinted in typical Hawking modes

- $\langle T^0_r \rangle = \langle T^0_r \rangle_{Hawking}$

3) More general information transfering models:

$$|\hat{q}_1\hat{q}_2\hat{a}\rangle|a\rangle \rightarrow |\hat{a}\rangle \underbrace{\frac{|\hat{0}\rangle|0\rangle + |\hat{1}\rangle|1\rangle}{\sqrt{2}}}_{\text{Usual Hawking particles}} \underbrace{|\hat{0}'\hat{0}''\rangle}_{\text{Not typically occupied}}|q_1'q_2''\rangle|a\rangle$$

(again, modulo unitaries)

... again, representative of more general (e.g. multimode) models:

- more generic

- yield extra energy flux

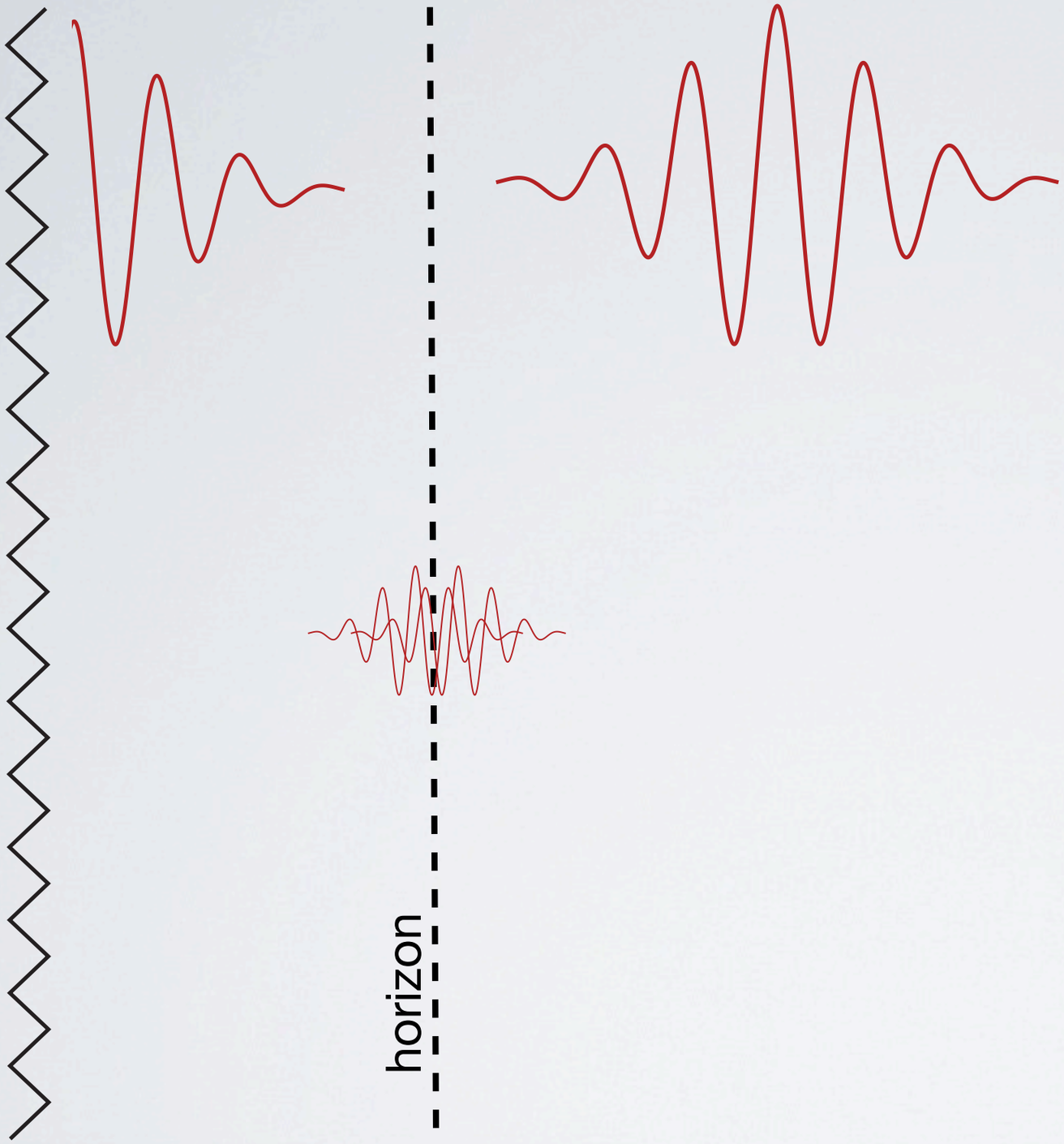
(But: $dE/dI > 1/R$?)

Important points:

- These forms of evolution are not local with respect to the semiclassical geometry

- "Nonviolent" or uneventful horizon?

Uneventful horizons:



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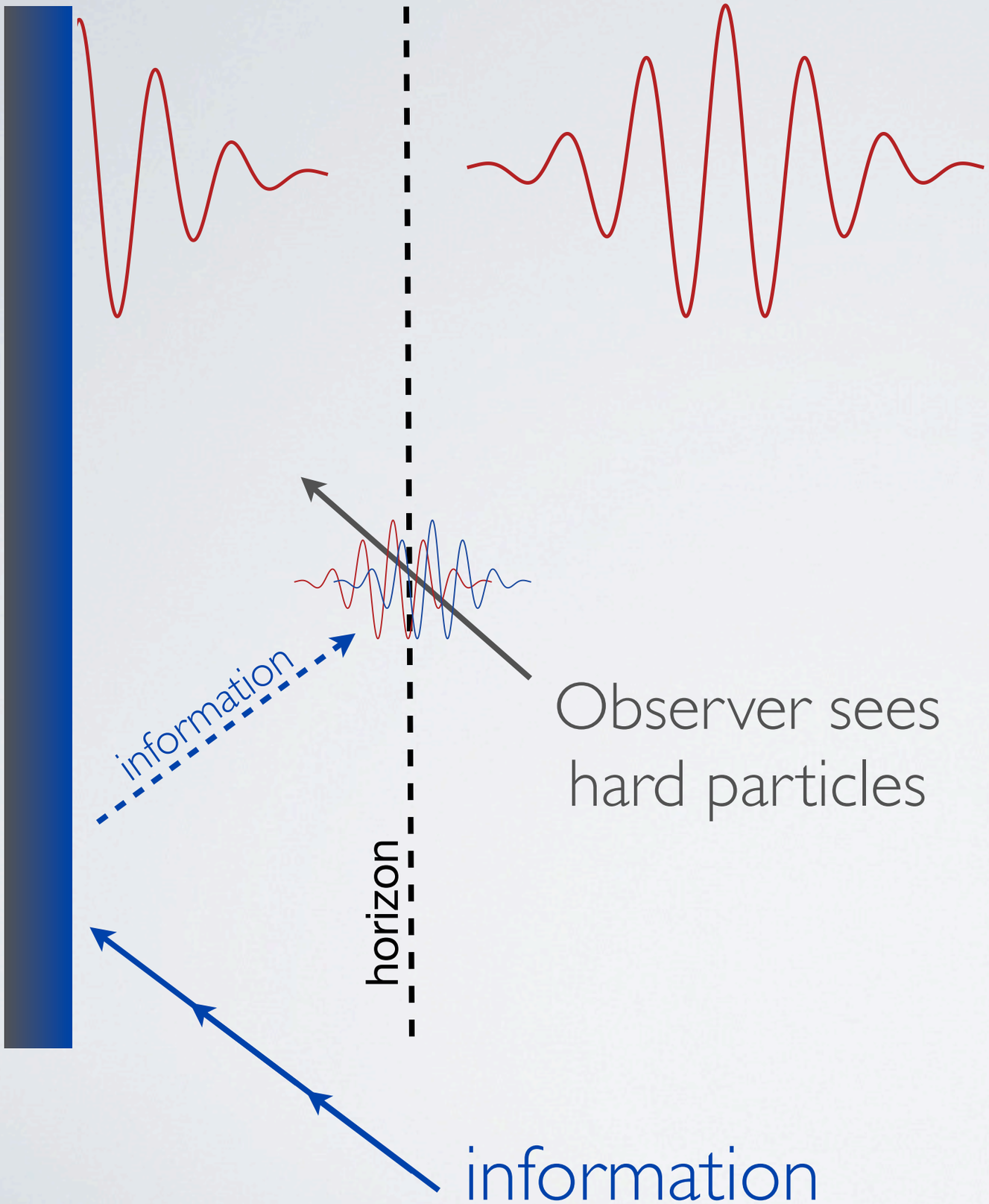
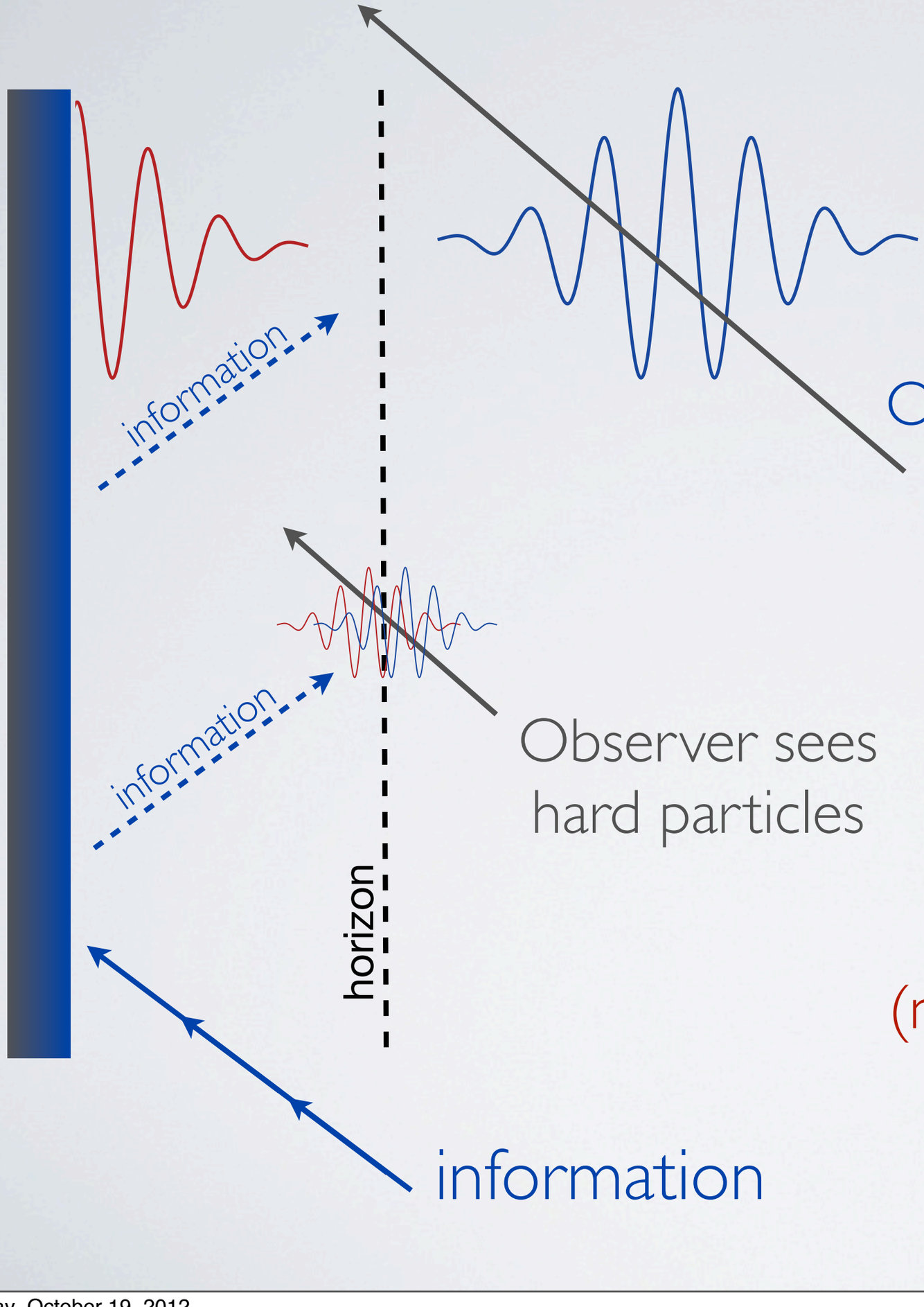


Observer sees hard particles

(recently rebranded: "firewall")

Uneventful horizons:

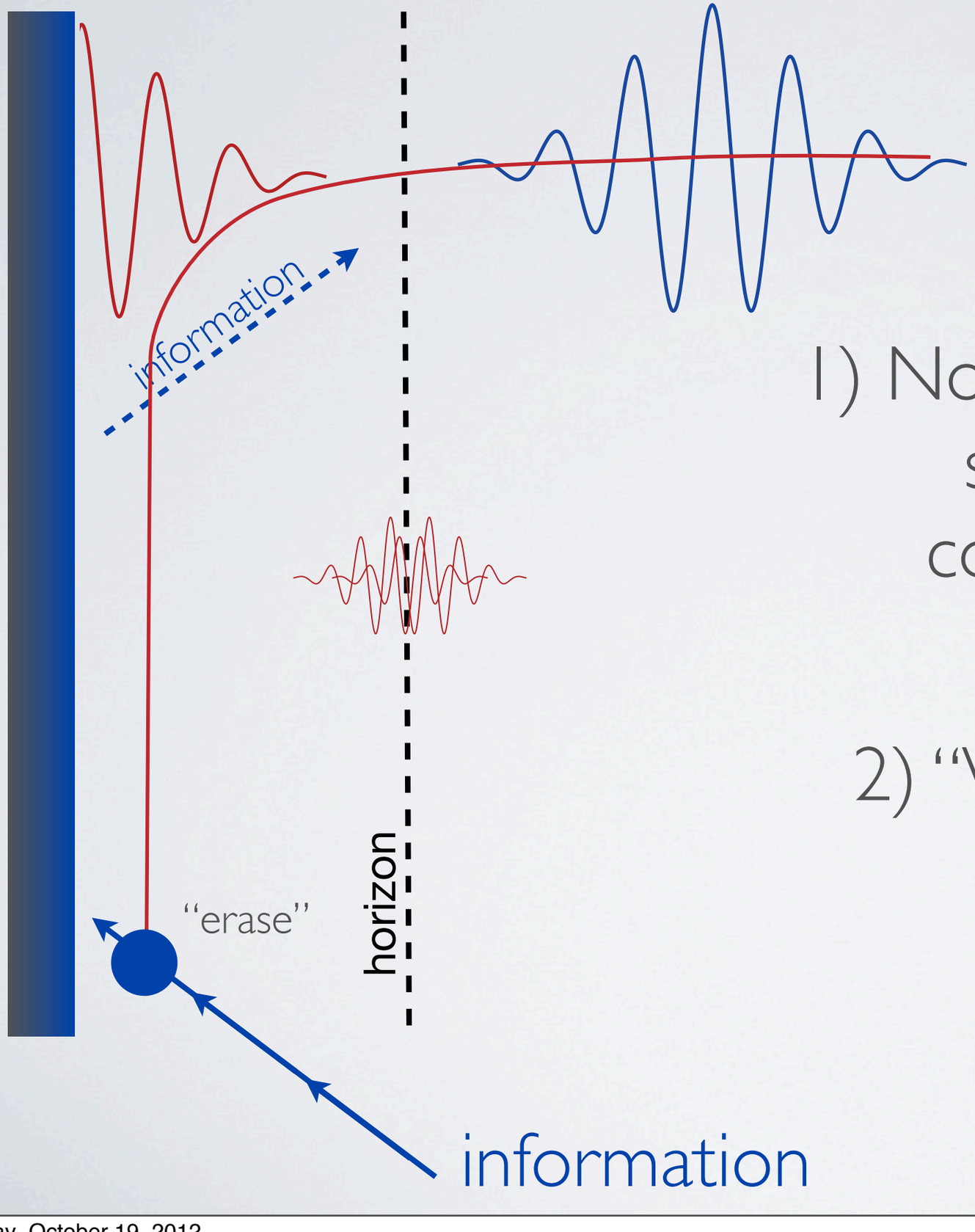


Observer sees ~1 extra quantum of energy ~1/R per time R (~innocuous)

(recently rebranded: "firewall")

(n.b.: idea is: geometry not strictly correct picture of physics - spacetime=approx.!);

Two further comments:



1) Nonviolent horizon:
small dim of $\mathcal{H}_{near}$
constraint on evolution

2) "Weak complementarity"
As long as T ~ RS

(e.g. nice slice descript.
not good at long times)

- Can explore other restrictions from physical + q. info-theoretic requirements (SBG & Shi 1205.4732 & WIP)

E.g. characterize information transfer

Minimal -- Simplest, most efficient form:

A B

- Can explore other restrictions from physical + q. info-theoretic requirements (SBG & Shi 1205.4732 & WIP)

E.g. characterize information transfer

Minimal -- Simplest, most efficient form:

$A = A_1 \otimes A_2$

B

- Can explore other restrictions from physical + q. info-theoretic requirements (SBG & Shi 1205.4732 & WIP)

E.g. characterize information transfer

Minimal -- Simplest, most efficient form:

$A = A_1$ $A_2 \otimes B$

"Subsystem transfer"

Mod unitaries U_A, U_B etc. Saturates a subadd. condition

Contrast nonminimal:

$$|\hat{0}\rangle|0\rangle \rightarrow |\hat{0}\rangle|0\rangle$$
$$|\hat{1}\rangle|0\rangle \rightarrow |\hat{1}\rangle|1\rangle$$

Might allow you to measure dead or alive Schrodinger's cat inside a black hole, but doesn't transfer quantum information ...

Example 2 was minimal; Example 3 was not

(extra flux)

Possible reasons to expect (near-)minimal:

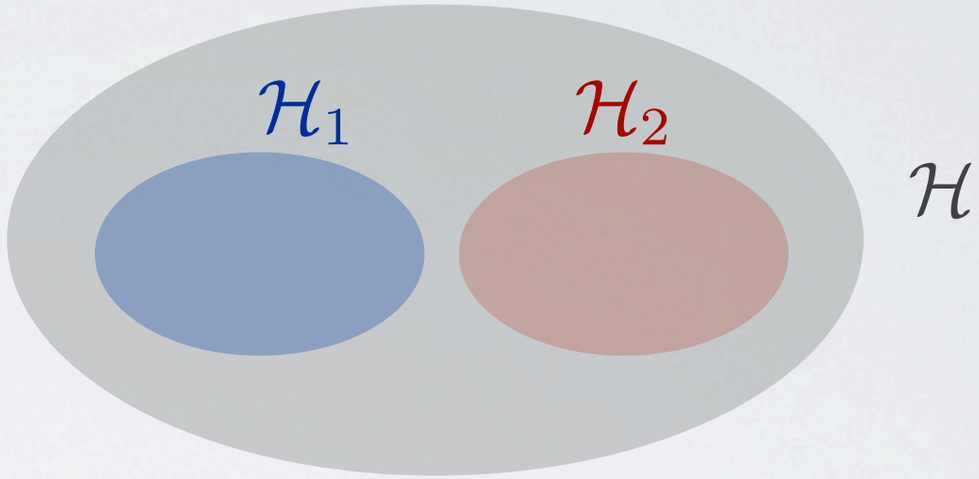
Weak coupling; ~ thermodynamic; small $\mathcal{H}_{near}$

Comments on Hilbert space networks:

A proposed broad picture -

Quantum states more basic than spacetime

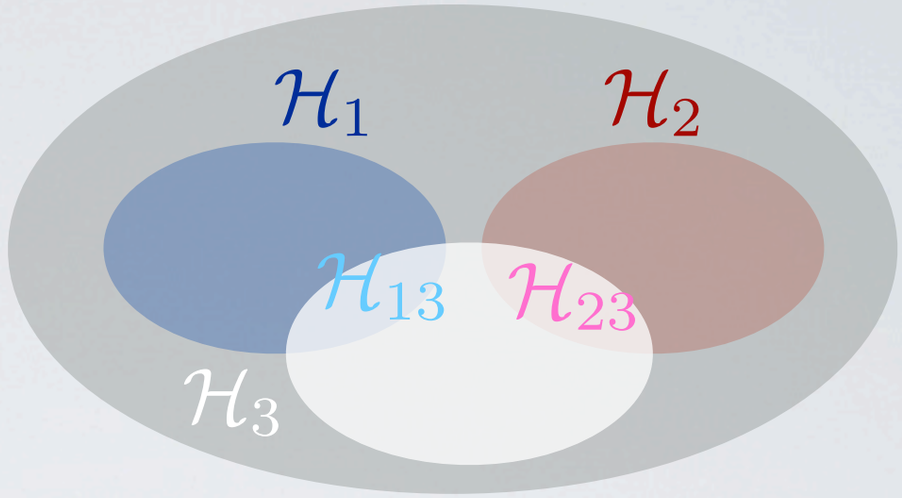
Approximate "localization"



$$\mathcal{H}_1 \otimes \mathcal{H}_2 \in \mathcal{H}$$

Compare LQFT: $[\mathcal{O}(x), \mathcal{O}(y)] = 0 \quad , \quad (x-y)^2 > 0$

~ quantum analog of manifold:



(some common ideas w/ algebraic QFT; also Banks "HST" -- though important differences)

- Unitary evolution; ~local, LQFT

- Symmetries

$$\mathcal{H} \to \mathcal{S}\mathcal{H} \qquad \text{global}$$

$$\mathcal{H} \to \mathcal{S}_{loc}\mathcal{H} = \mathcal{S}_1\mathcal{H}_1 \otimes \mathcal{S}_2\mathcal{H}_2 \cdots \qquad \text{local}$$

Hilbert space networks: a possible framework for a unitary theory of quantum gravity

Summary:

The information problem appears foundational.

A "most conservative" approach is to modify macroscopic locality. (not QM, LI)

Unitarity can be restored through QI transfer from BH subsystem ... not LQFT (but "nearly local," nonviolent?)

Proposal: approximate spacetime emerges from a broader framework - Hilbert space network