BLACK HOLES, QUANTUM INFORMATION TRANSFER, AND HILBERT-SPACE NETWORKS

S.B. Giddings
UCSB

Black Holes and Information
KITP
May 21, 2012

Refs: SBG 1108.2015, 1201.1037;
SBG and Y. Shi, 1205.xxxx

The information “paradox,” in a nutshell:

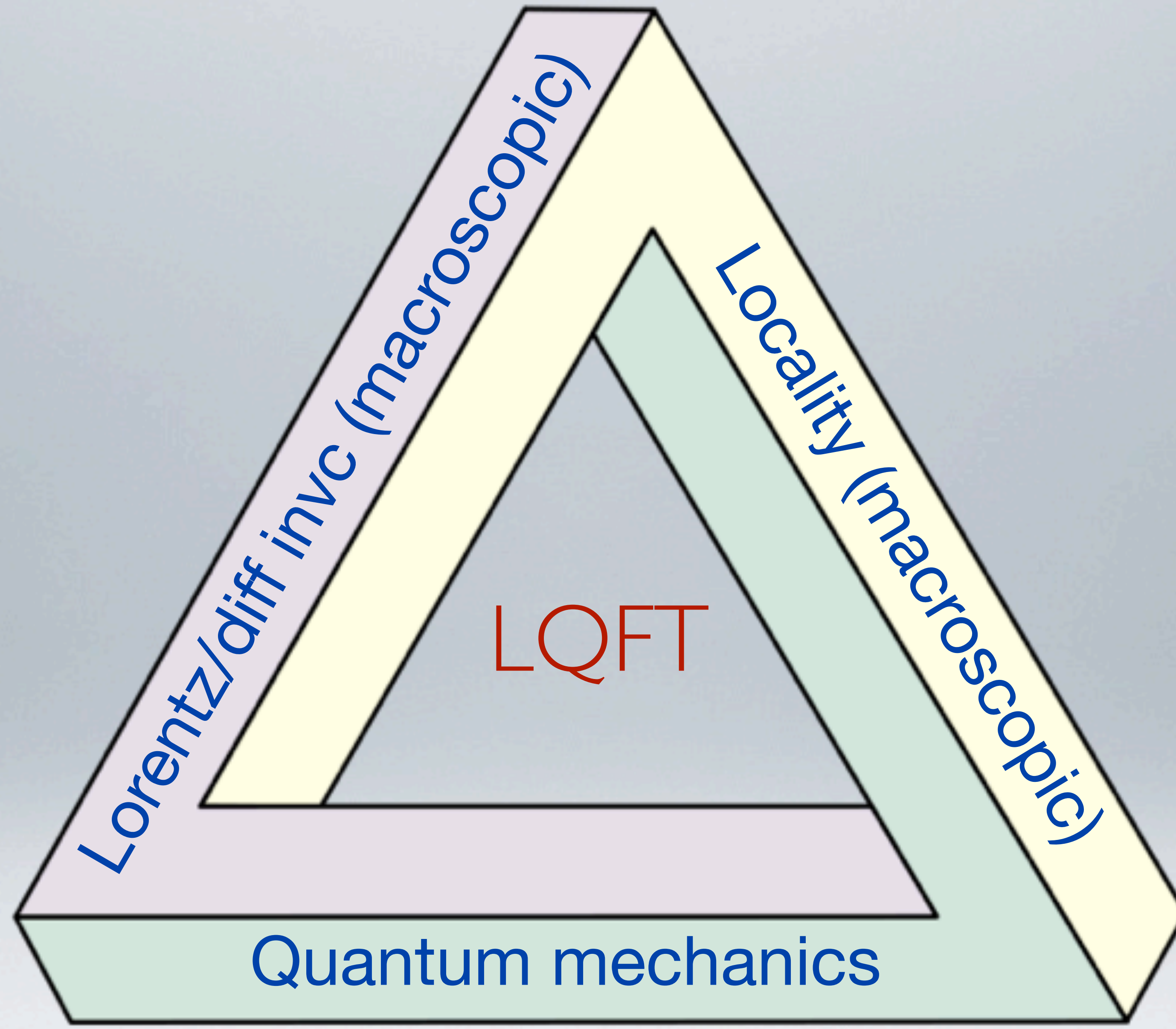
Information cast into a black hole

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

Stupid mistake?

Harbinger of new physics?

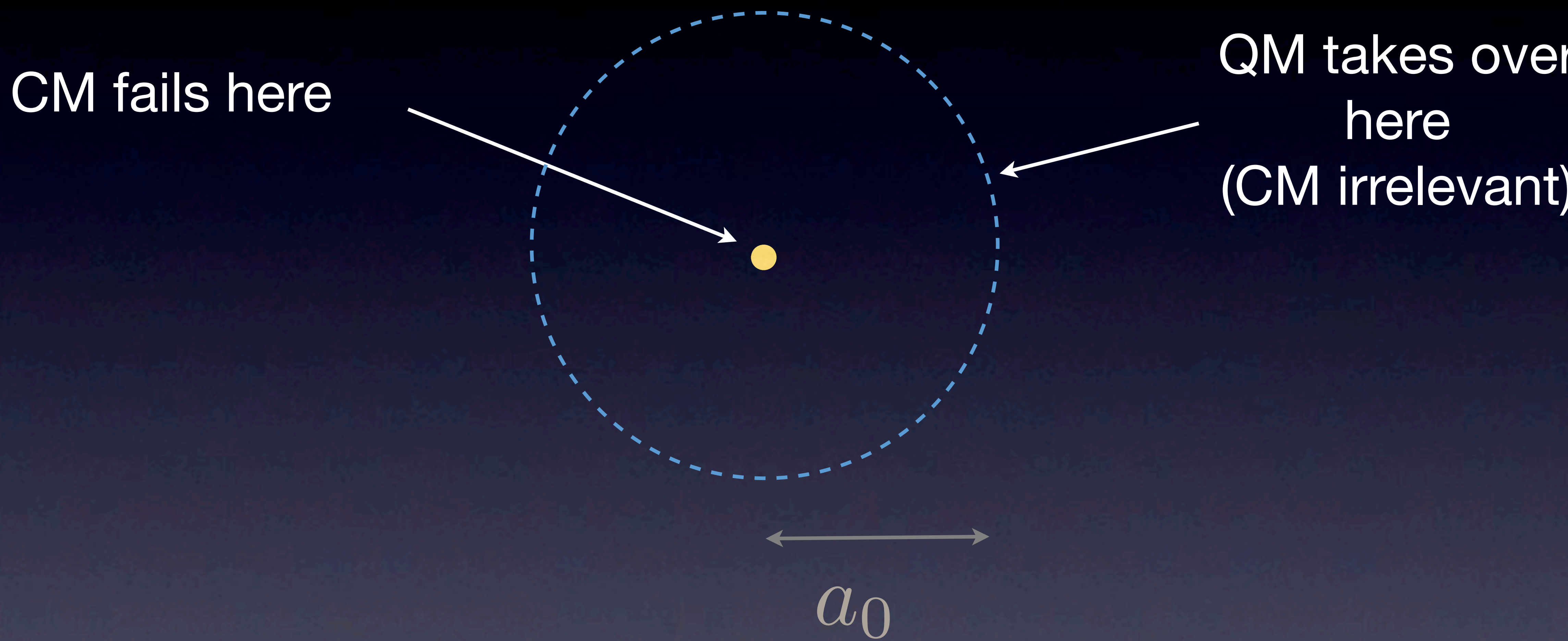
A Viewpoint: represents a fundamental conflict



- QM, LI: hard to modify (consistency, observation). Locality?
- It's not about singularities, renormalizability? Long distance.

A SEEMINGLY SIMILAR CRISES:

Classical atom



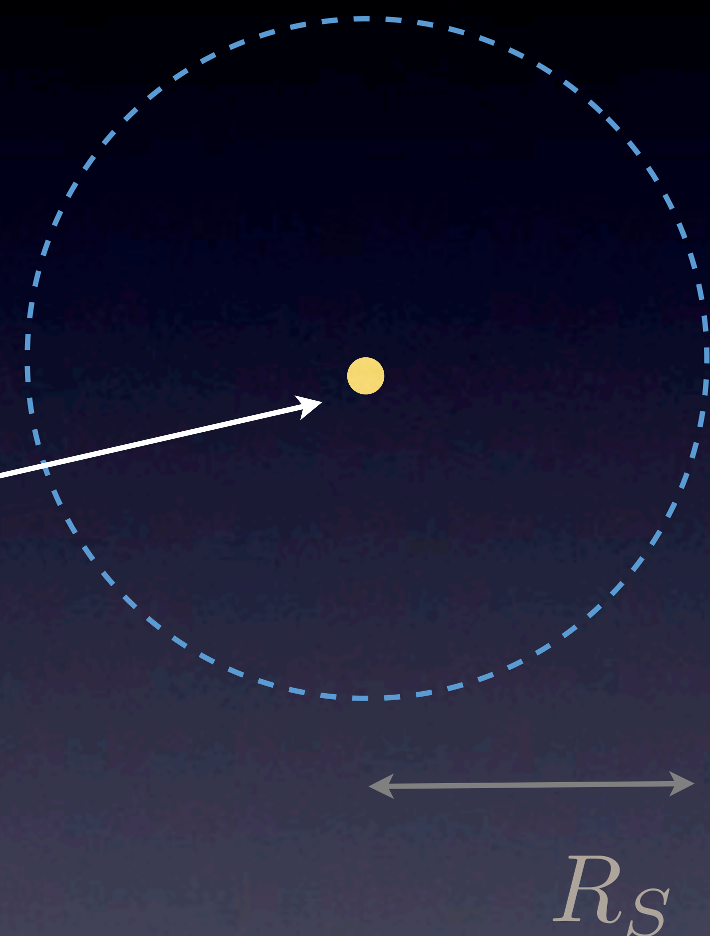
New physics was needed:

Uncertainty principle

Wave mechanics...

A seemingly similar crises:

Black hole



LQFT fails here

QG relevant here?
(subtle breakdown LQFT?)

New physics ~~was~~ needed:

is

~~Uncertainty principle~~

~~Wave mechanics...~~

???

“Classical instability paradox”

“Black hole information paradox”

The information problem 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??	workshop/conference
Cosmological comparisons; tests?	workshop/conference
Locality/ local observables	e.g. hep-th/0512200, w/ Marolf and Hartle
S-matrix	Erice lectures: 1105.2036
Amplitude magic??	previous workshop; nonperturbative?
Correspondence	
Quantum info. transfer from BHs	

What other guides do we have?

AdS/CFT??

Microstates?? — workshop/conference

Cosmological comparisons; tests? — workshop/conference

Locality/ local observables — e.g. hep-th/0512200, w/ Marolf and Hartle

S-matrix — Erice lectures: 1105.2036

Amplitude magic?? — previous workshop; 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 observers falling in?

Need:

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

interacting

1-1, unitary

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

Unitary bulk evolution?

Approaches:

(~) local bulk observables

challenge in QG

much discussion at workshop

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

S-matrix (flat space limit)

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

not much discussion at workshop

there are challenges

(more discussion: 1106.3553 w/ M. Gary)

More general approaches:

1. Investigate correspondence boundary

2. Quantum information transfer

3. The gravitational S-matrix

Correspondence

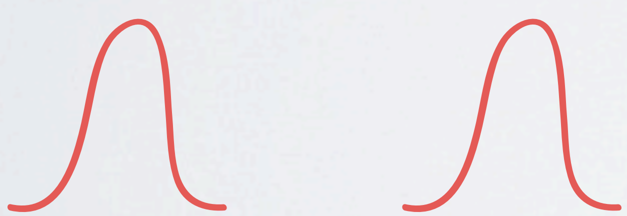
Existing theory: LQFT, semiclassical background

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

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

(min uncertainty wavepackets)

Where description fails?



$\phi_{x,k}$ $\phi_{x',k'}$

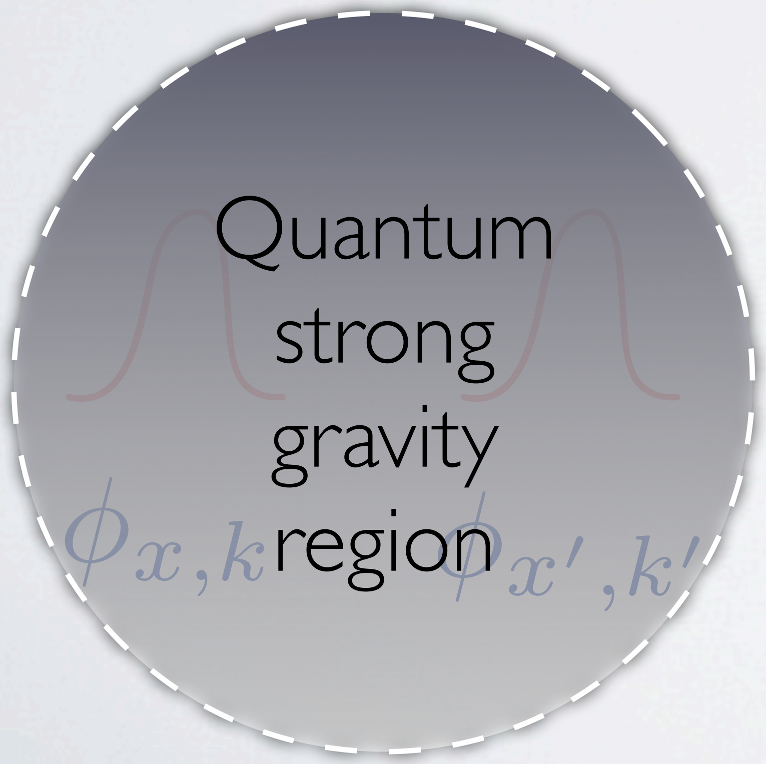
Correspondence

Existing theory: LQFT, semiclassical background

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

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

(min uncertainty wavepackets)



Where description fails?

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

"locality bound"

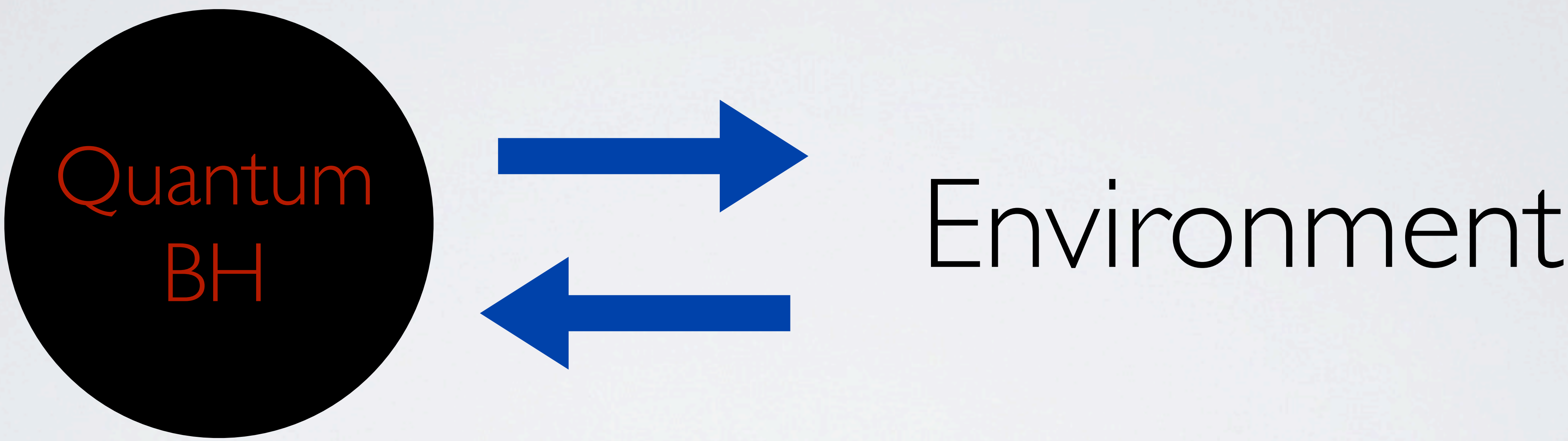
~ Heisenberg microscope

(multiparticle generalizations)

We seek guides to this regime.

Assume: quantum mechanics (take seriously)

Also assume: quantum subsystems

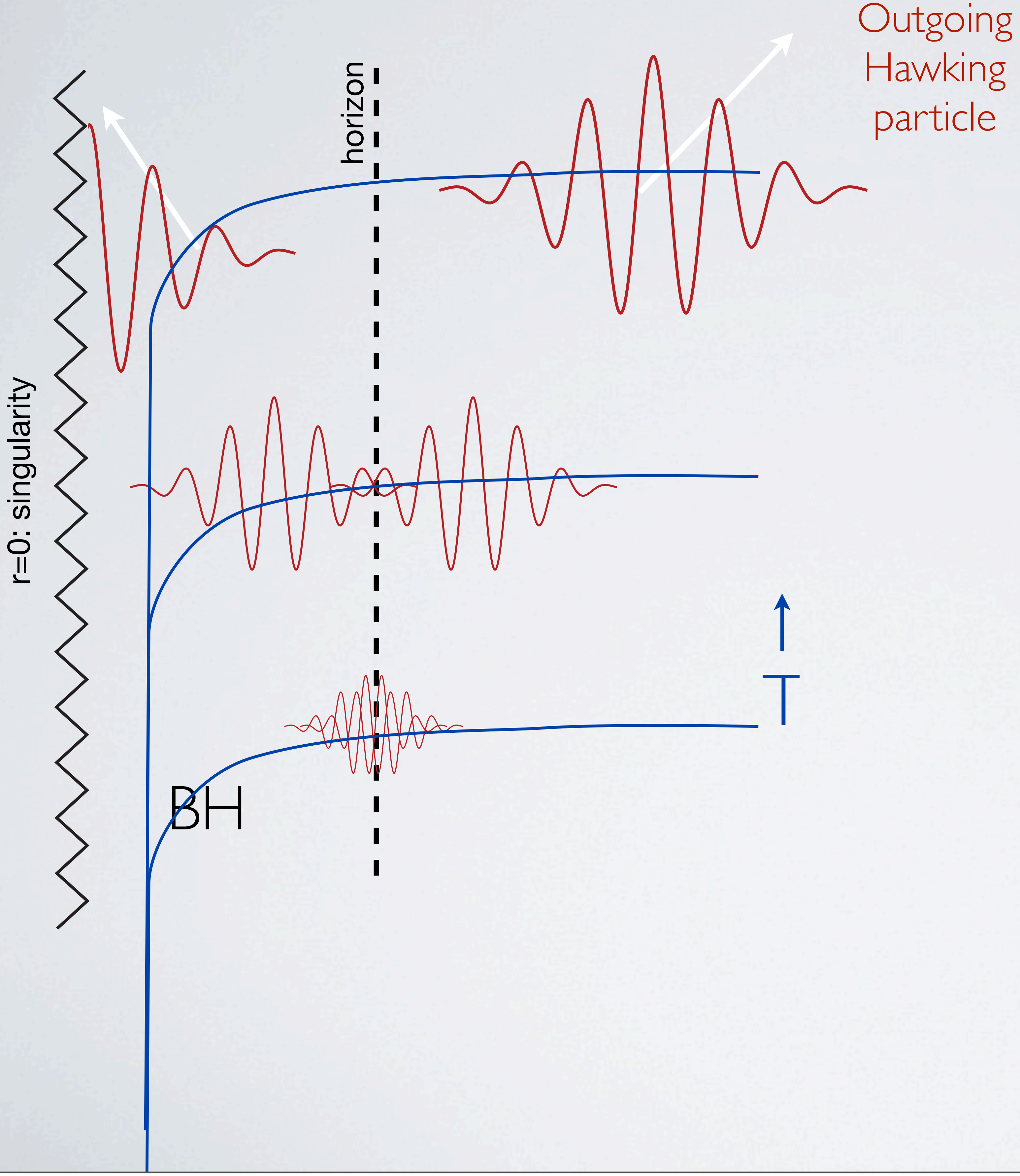


$$\mathcal{H}_{BH} \otimes \mathcal{H}_{ext}$$

Information exchange; unitary

"Effective quantum theory;" and more
(recall: "QM+locality+Poincare $\Rightarrow$ QFT")

Another guide: “as close as possible” to LQFT



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)

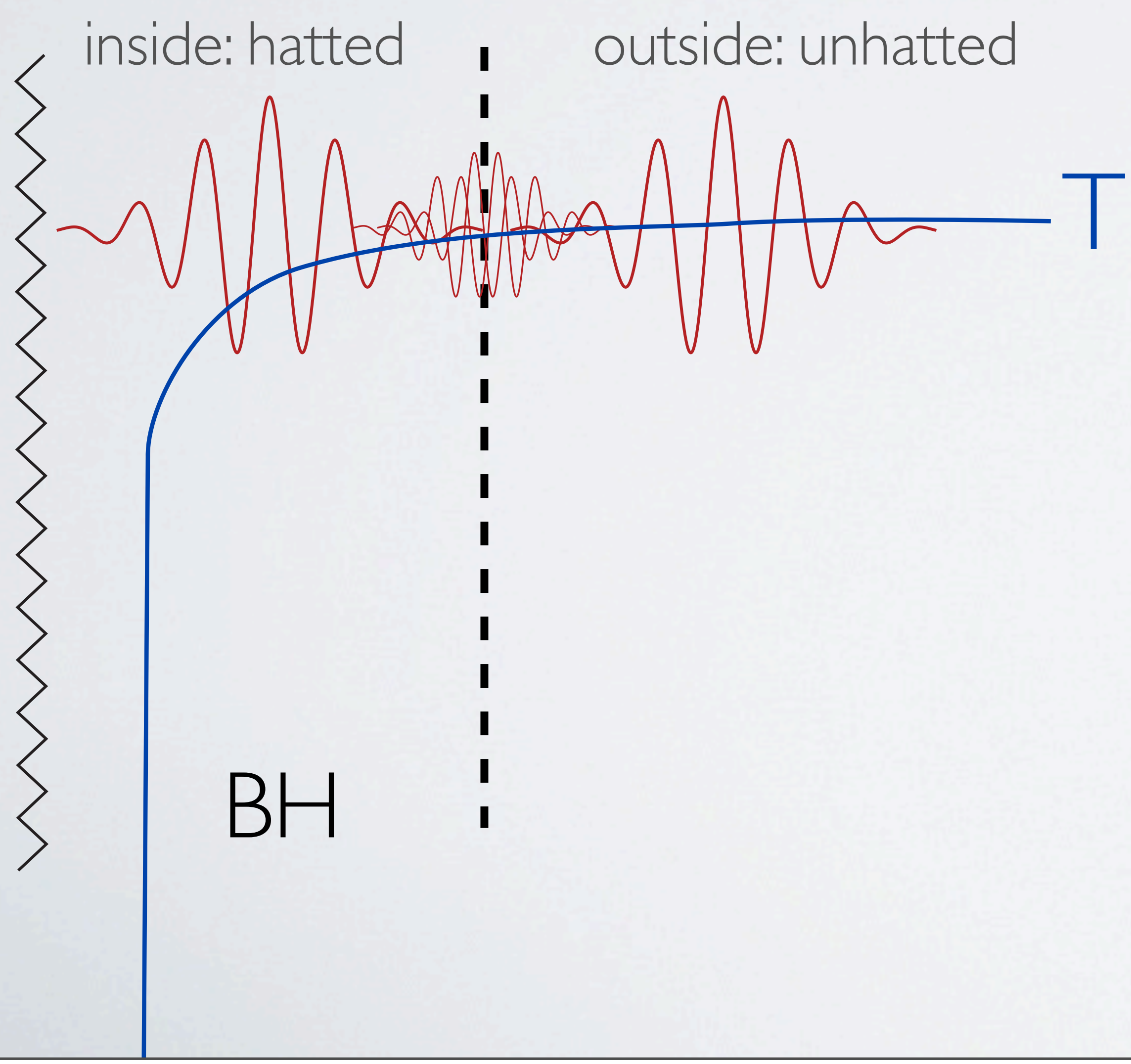
$$|\psi\rangle_{\mathrm{Hawk}} = \prod_{jn} S_{jn}|\hat{0}\rangle|0\rangle$$

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

j ~ asymp. frequency

n ~ position along slice

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



For given T:

$$n \to \infty \quad \leftrightarrow \quad \to \mathrm{horizon}$$

Regularize:

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

Shorter modes "look like" vacuum

"Hawking state" (cont'd):

So rewrite:

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

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

As discussed

- $|0\rangle_N$ 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

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"

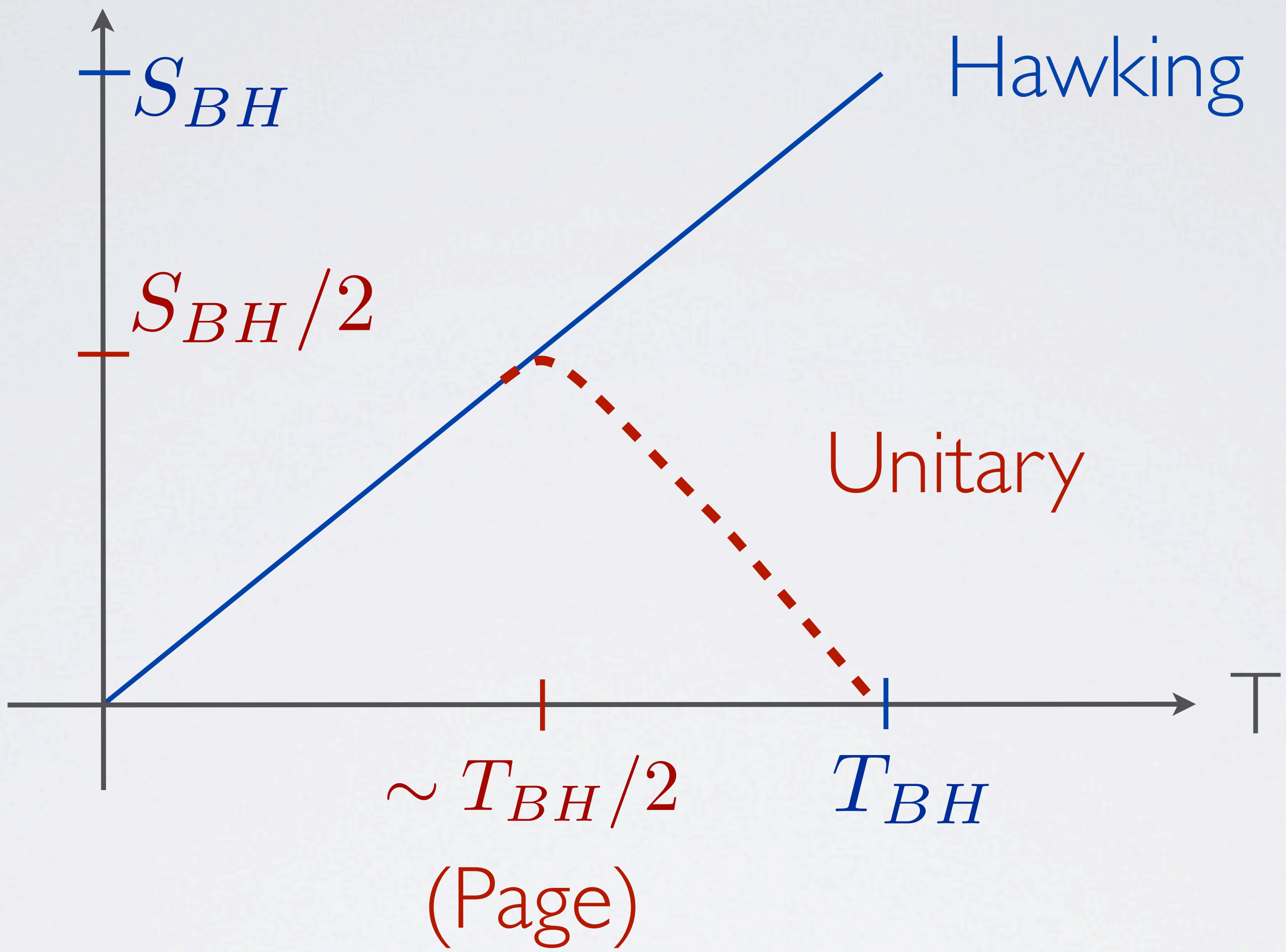
pairs produced

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

Nonunitarity

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

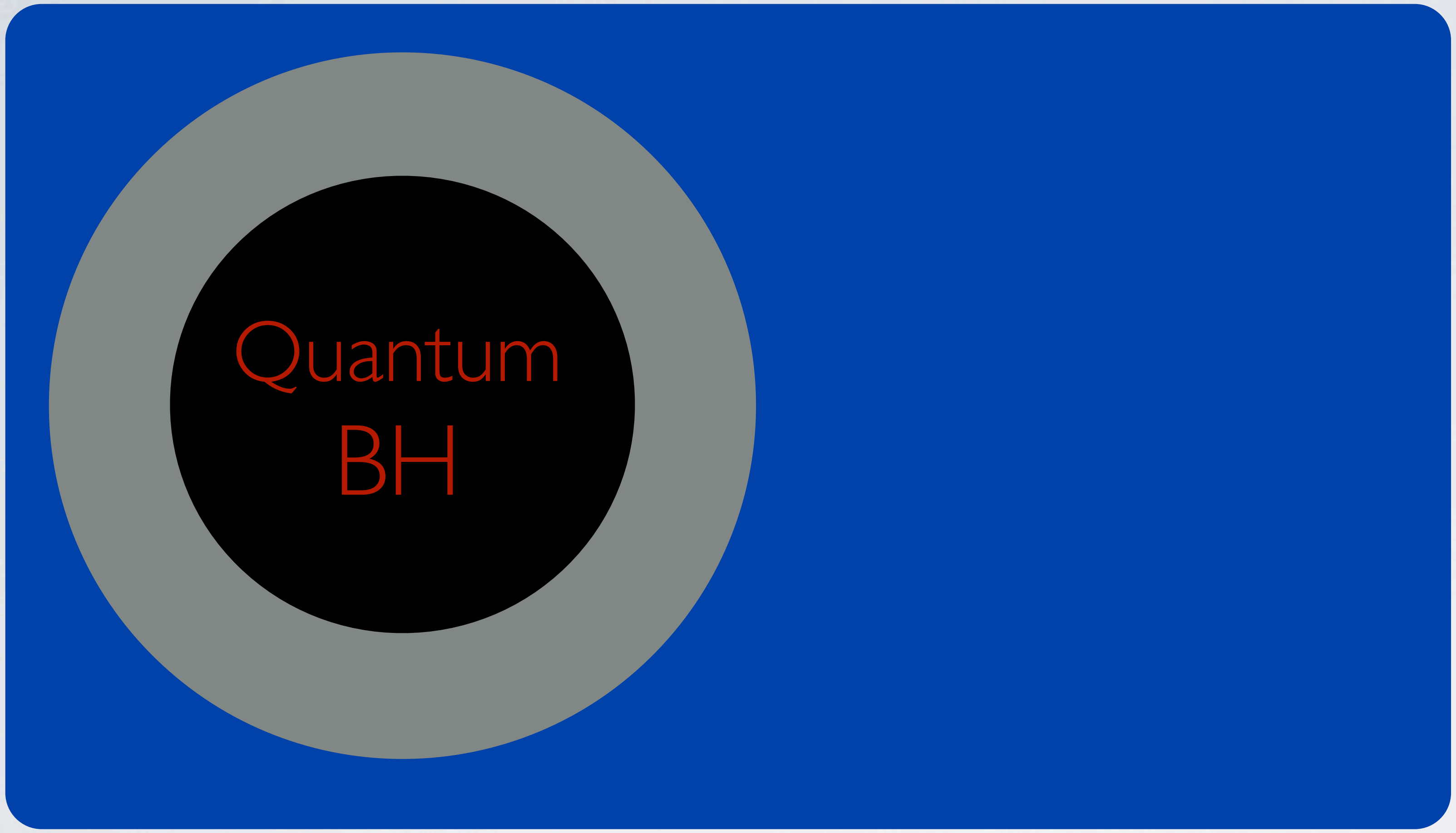
$$S_{ext} = -\mathrm{Tr}\rho_{ext}\ln\rho_{ext}$$



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

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

But how do we describe presumably correct unitary evolution?



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

(nb: AdS/CFT could work this way)

Some expectations:

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

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

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

$$U \approx LQFT$$

$$U \neq LQFT$$

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

Physical constraints on evolution:

A) $S \to 0$

B) Innocuous to infalling observers (?) (preserve "pain-free" horizon)

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

D) Near-Hawking; ~thermodynamic (?)

E) Correspondence limit: LQFT + GR

F) Energy conservation

G) Complete, consistent

...

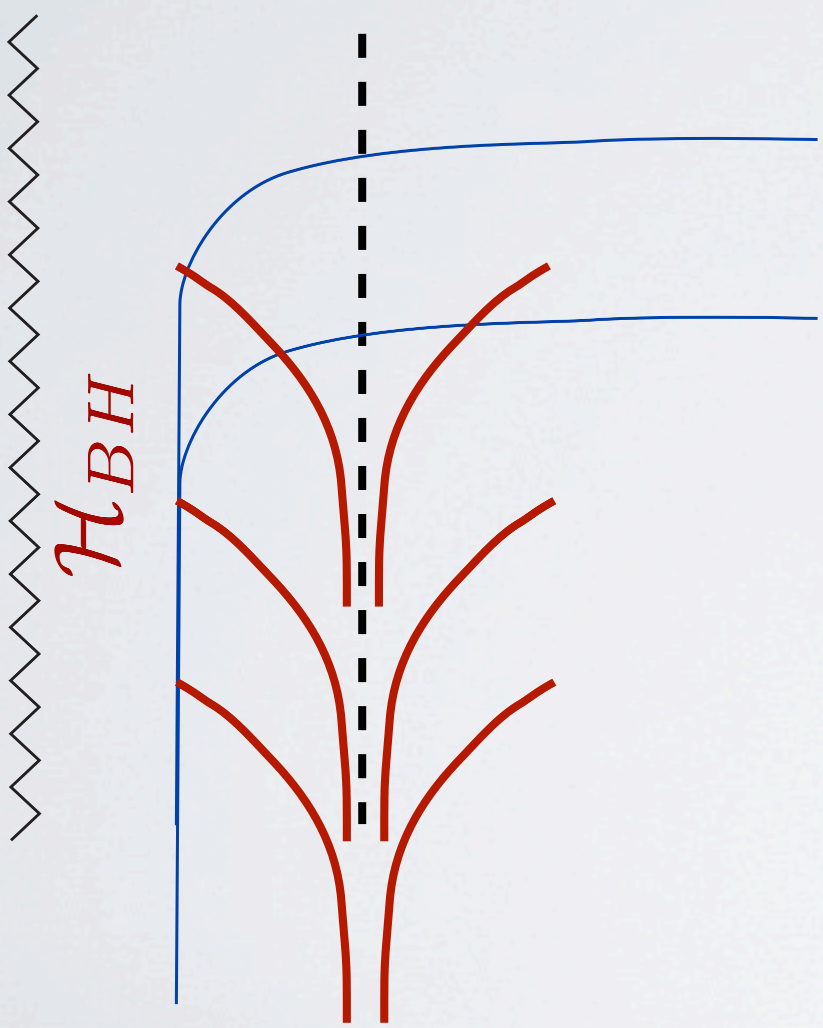
Basic guideline: be as conservative as possible!

What is "as close as possible to LQFT"?

Explore examples (e.g. qubit models)

most conservative?

Recap:



Explore examples
(e.g. qubit models)

Not most conservative?

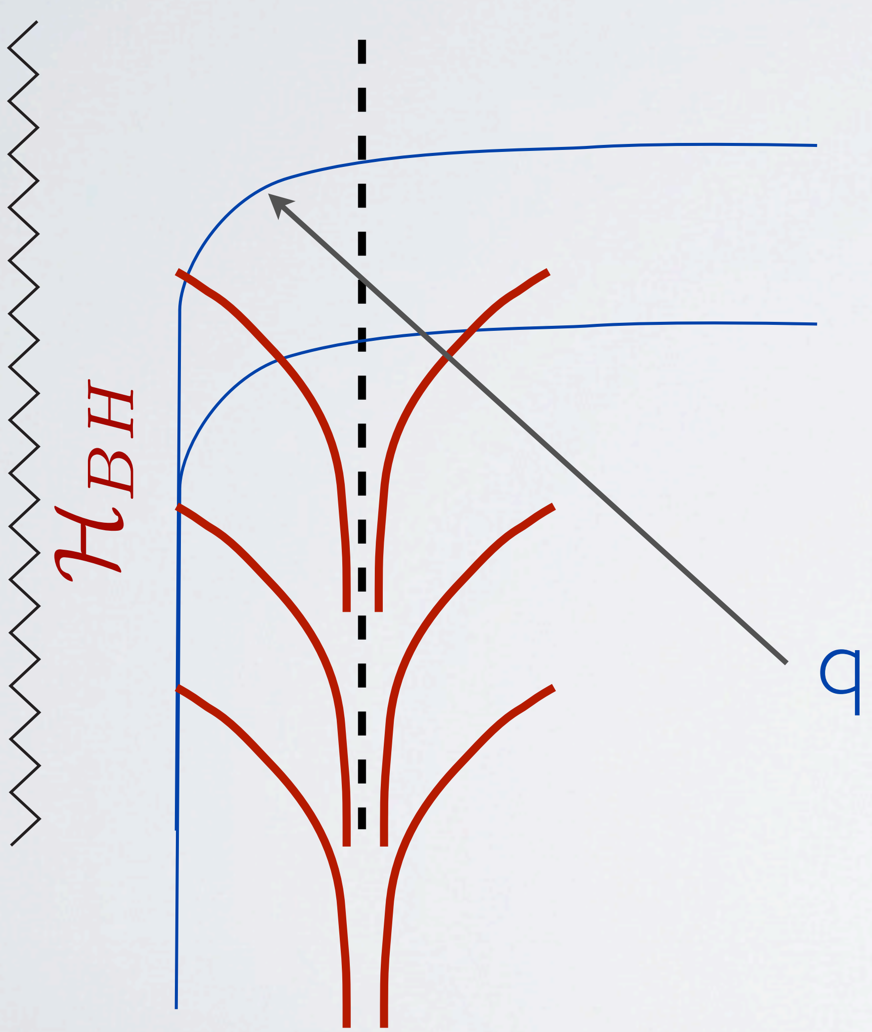
Recap:

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

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

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

"Fast scrambling" (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)

(these are representative of more general finite dim models)

Not most conservative?

Big departure from LQFT evolution

($\leftrightarrow$complementarity?)

Indeed, Hayden/Preskill:

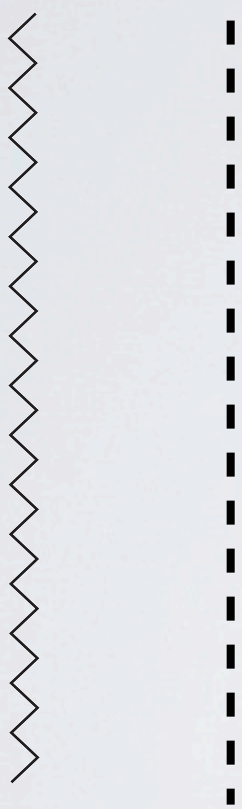
After sufficient evolution, a BH behaves as an information mirror on the scrambling time!

One classification:

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

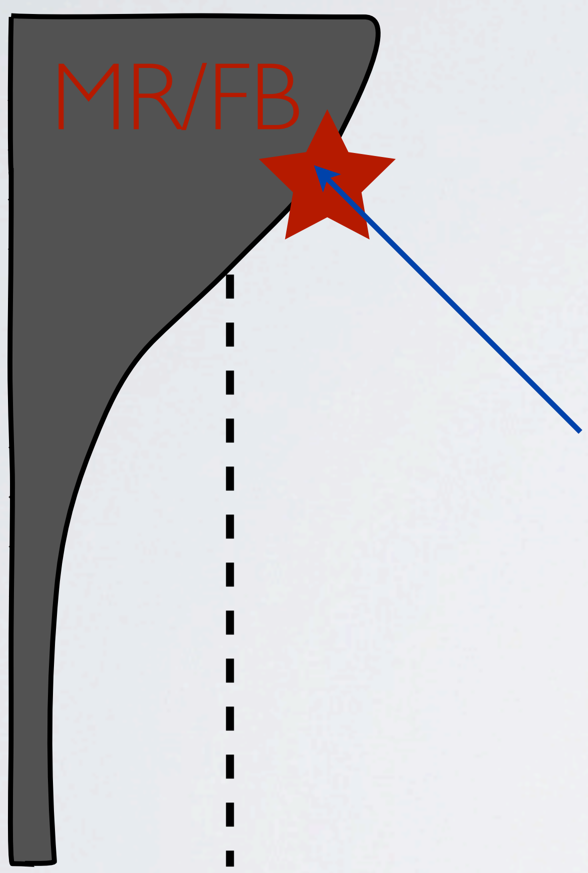
Not most conservative? (cont'd)

1B) Massive remnant; fuzzball



Not most conservative? (cont'd)

1B) Massive remnant; fuzzball



expect:

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

rapidly varying microstructure
outside horizon

rapid, more limited(?) scrambling

(~ "neutron star")

Unitary models: "more conservative"

2)

$$|\hat{0}\hat{0}\hat{a}\rangle|a\rangle \to \hat{U}|\hat{a}\rangle\frac{(|\hat{0}0\rangle + |\hat{1}1\rangle)}{\sqrt{2}}U|a\rangle$$

e.g. LQFT

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

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

e.g. "leftmost" qubits

$$|\hat{1}\hat{1}\hat{a}\rangle|a\rangle \to \hat{U}|\hat{a}\rangle\frac{(|\hat{0}0\rangle - |\hat{1}1\rangle)}{\sqrt{2}}U|a\rangle$$

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

(and e.g. extra unitaries)

"Hawking-like" "minimal" mods to evolution

- info imprinted in typical Hawking modes
- $\langle T^0_r\rangle = \langle T^0_r\rangle_{Hawking}$

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

(again, modulo unitaries)

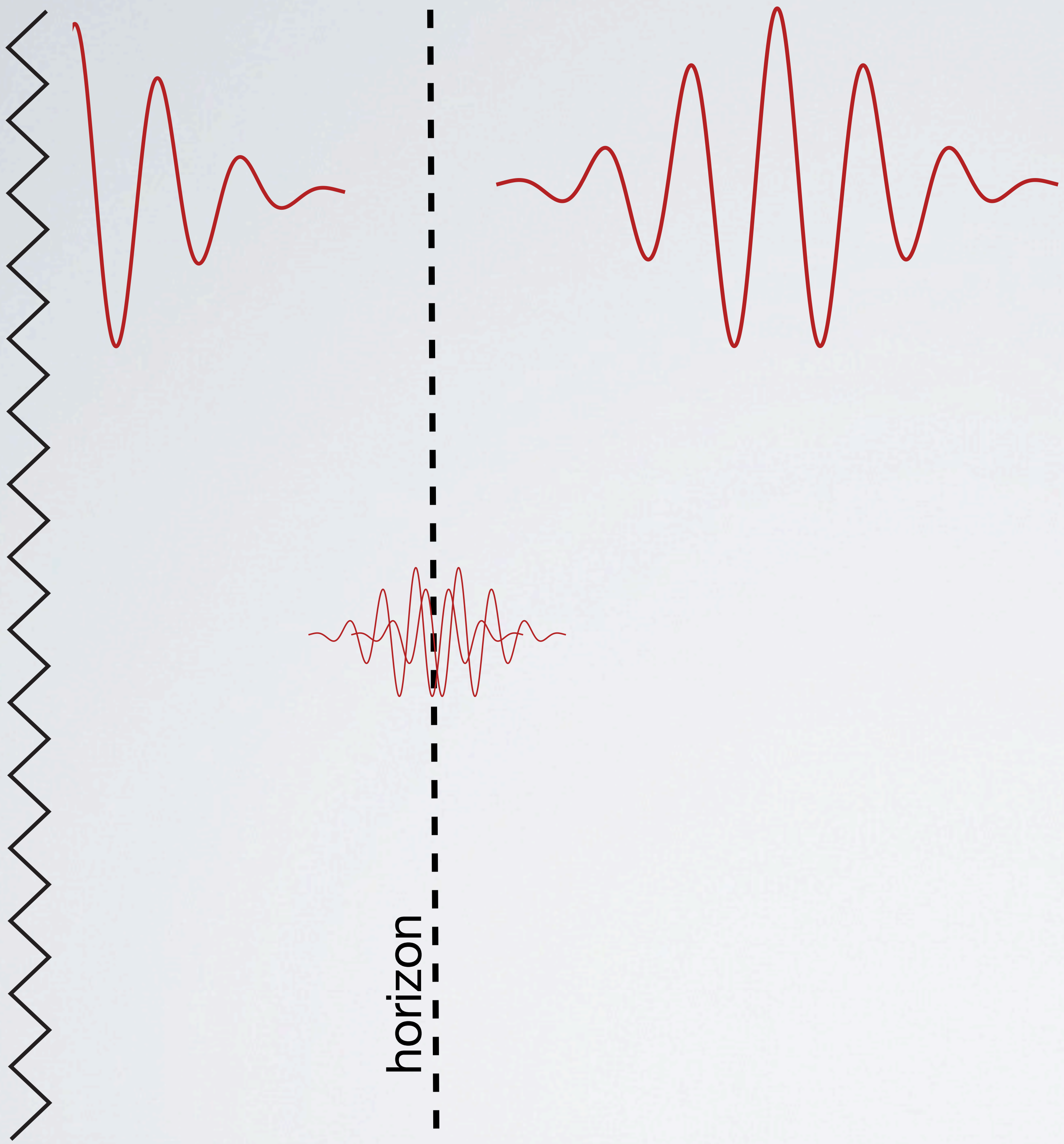
... representative of more general (e.g. multimode) models:

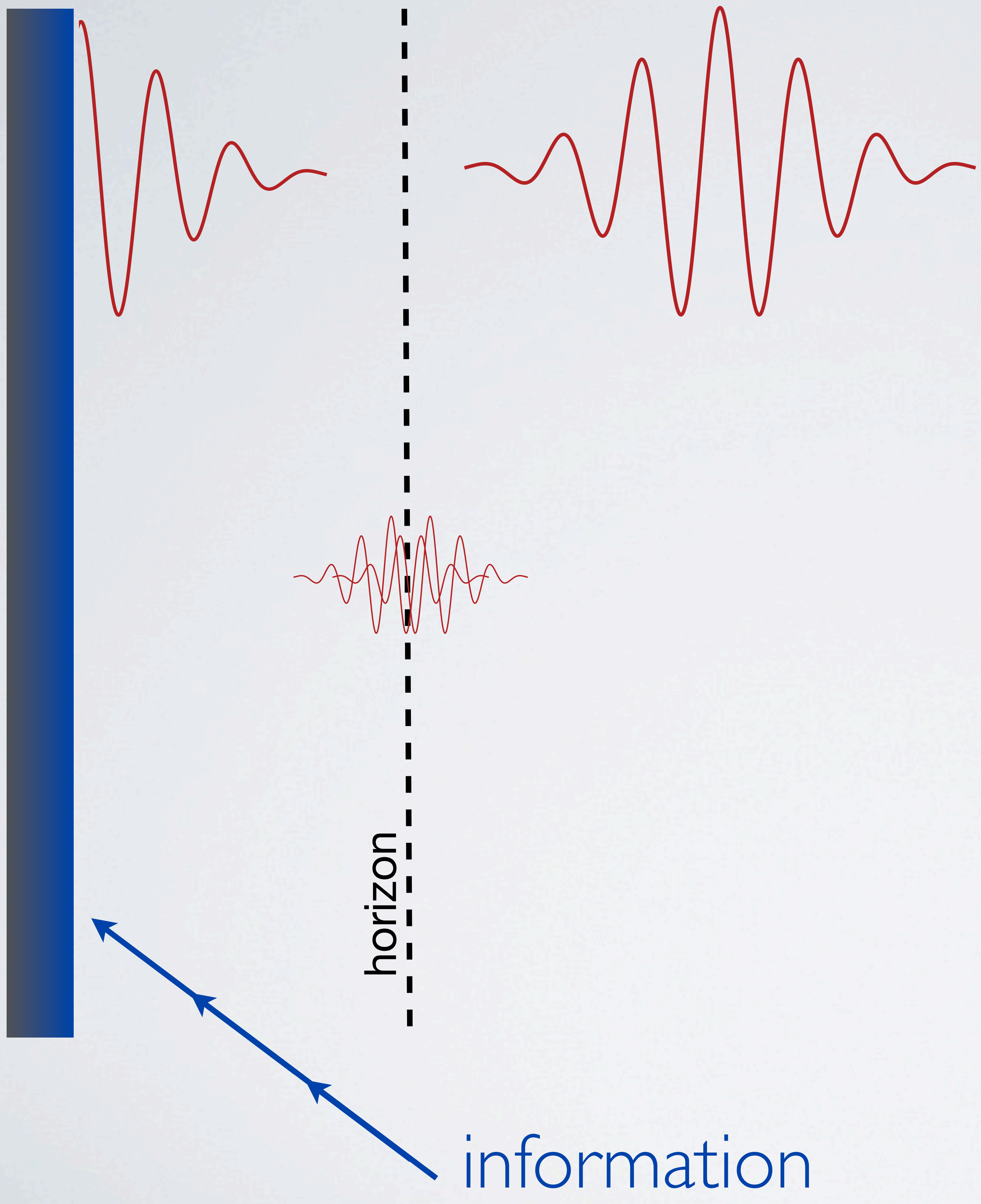
- more generic
- yield extra energy flux

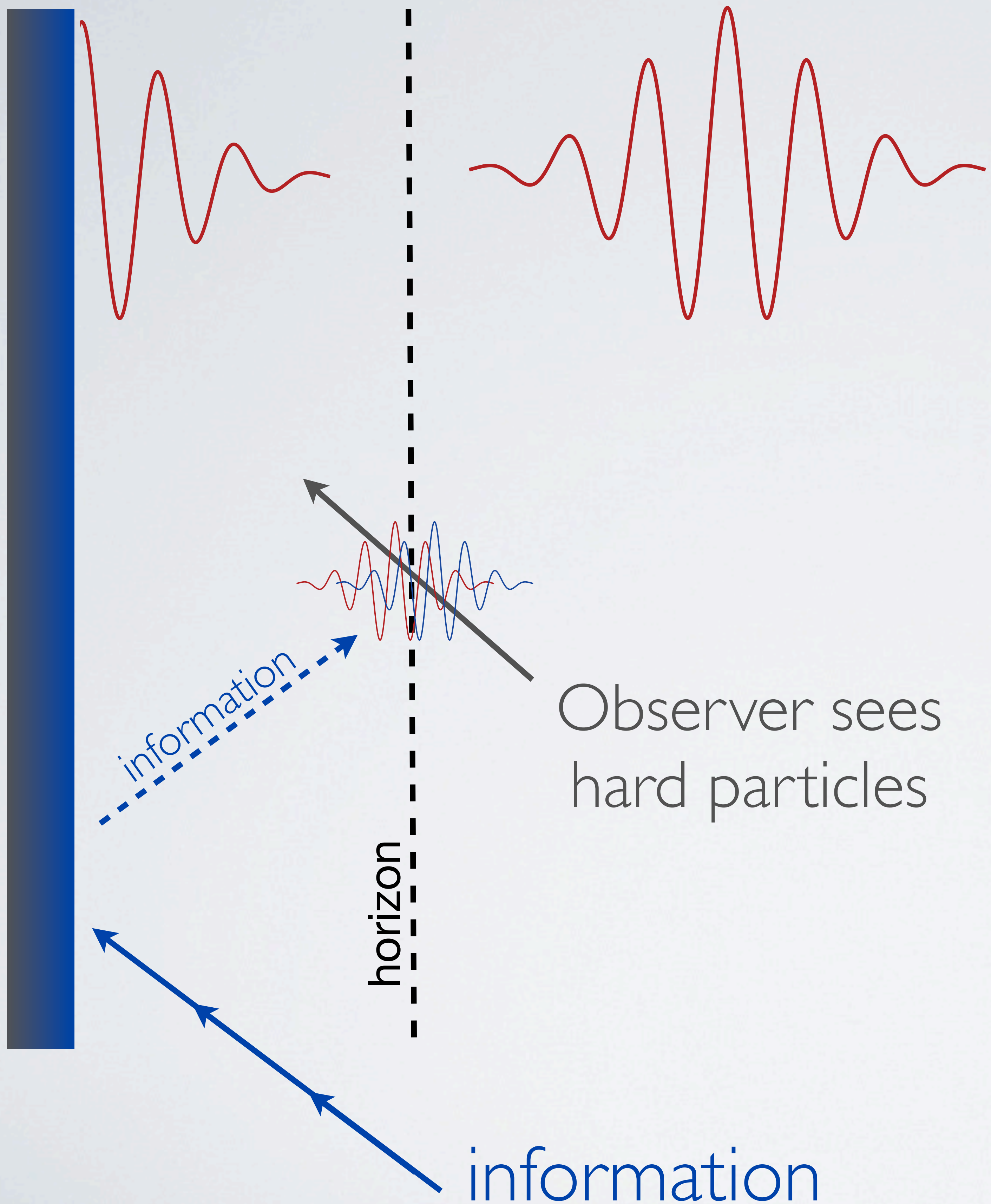
(But: $dE/dI > 1/R$?)

- This evolution is not local with respect to the semiclassical geometry

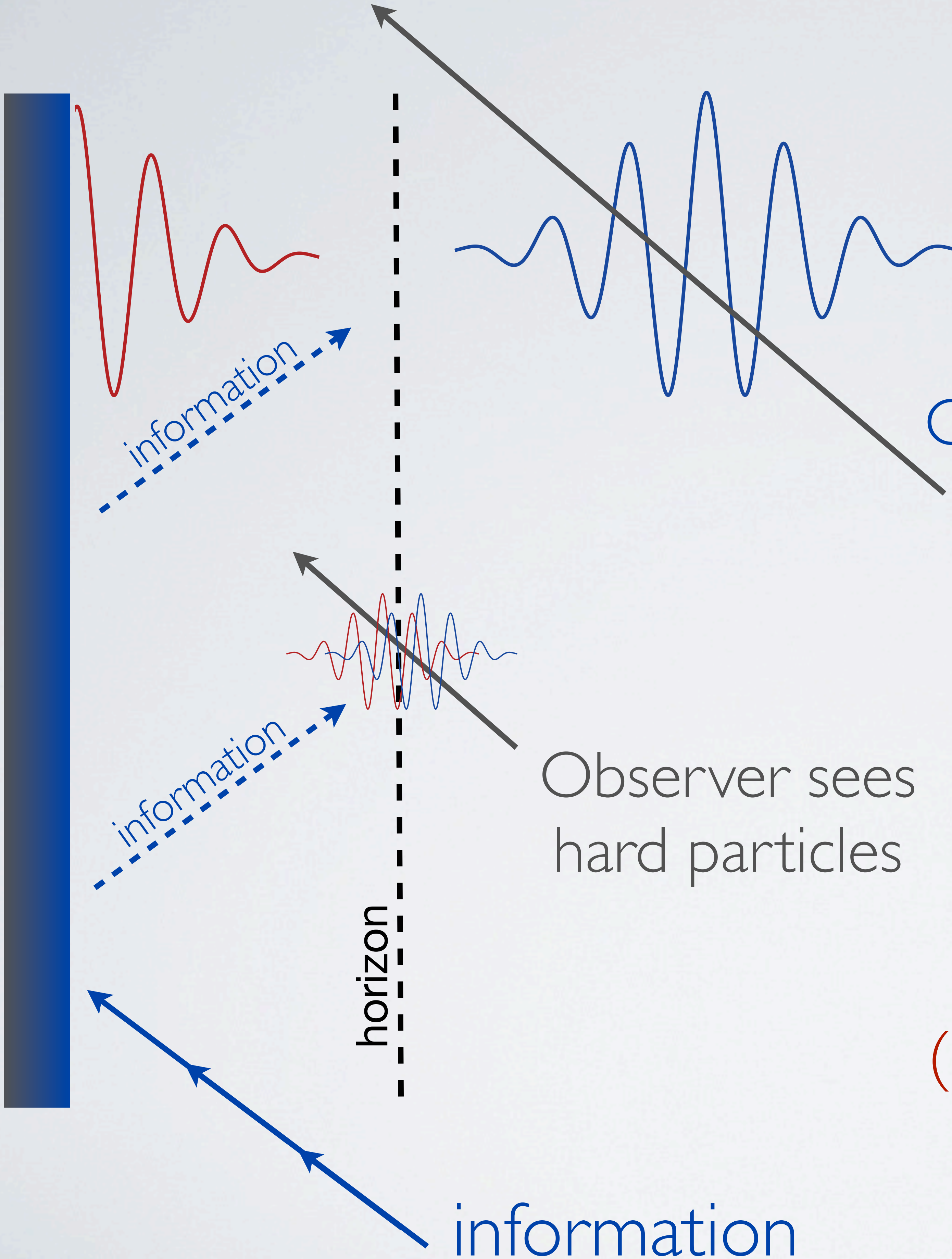
- “Pain-free” horizon?


horizon


horizon
information



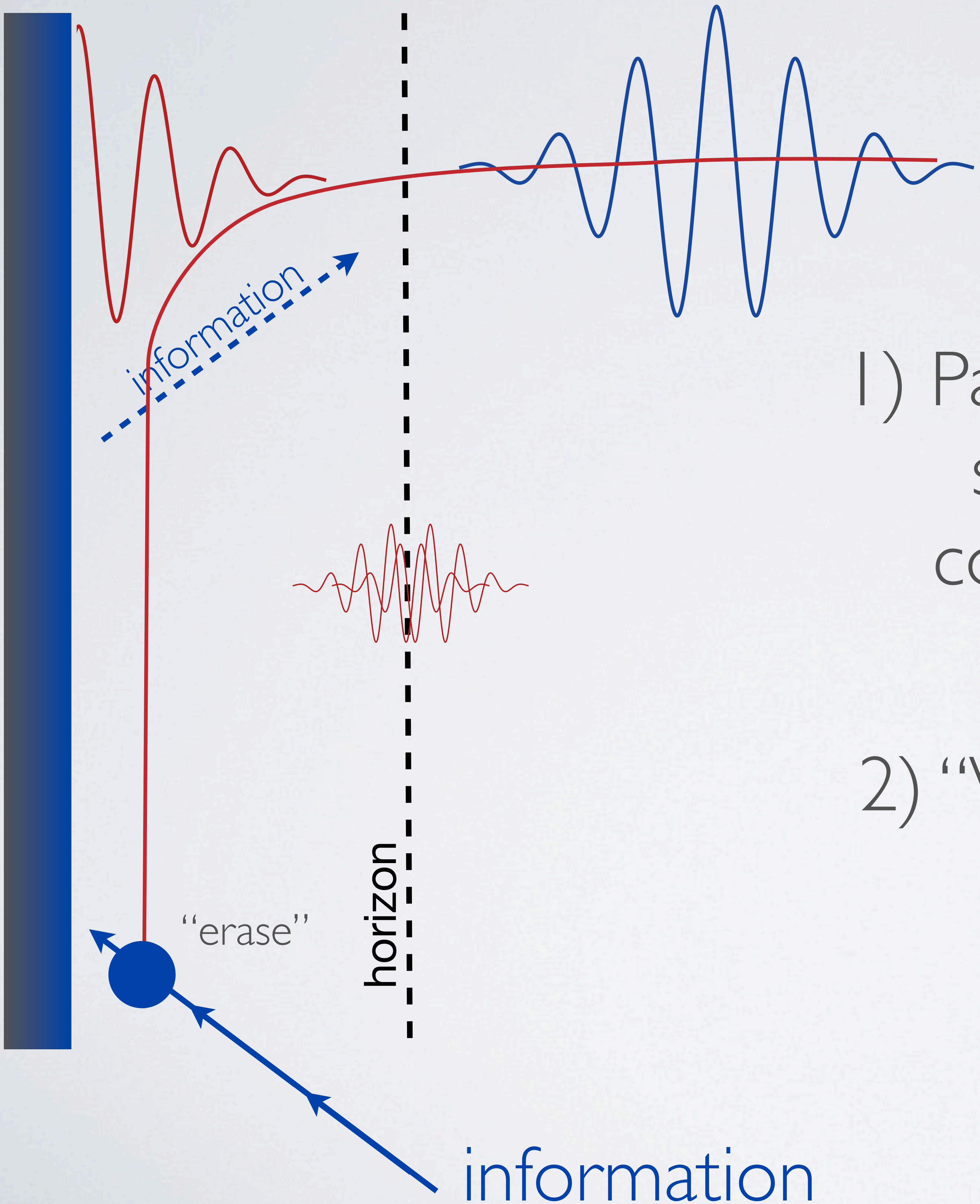
information
horizon
Observer sees
hard particles
information



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

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

Two further comments:



1) Pain-free 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.xxxx & WIP)

E.g. characterize information transfer

Minimal -- Simplest, most efficient form:

- Can explore other restrictions from physical + q. info-theoretic requirements (SBG & Shi 1205.xxxx & WIP)

E.g. characterize information transfer

Minimal -- Simplest, most efficient form:

$A = A_1 \otimes A_2$ $\qquad\qquad\qquad$ B

- Can explore other restrictions from physical + q. info-theoretic requirements (SBG & Shi 1205.xxxx & WIP)

E.g. characterize information transfer

Minimal -- Simplest, most efficient form:

$A = A_1$ $\qquad\qquad$ $A_2 \otimes B$

"Subspace transfer"

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

Contrast nonminimal:

$$\begin{aligned} |\hat{0}\rangle|0\rangle &\rightarrow |\hat{0}\rangle|0\rangle \\ |\hat{1}\rangle|0\rangle &\rightarrow |\hat{1}\rangle|1\rangle \end{aligned}$$

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)

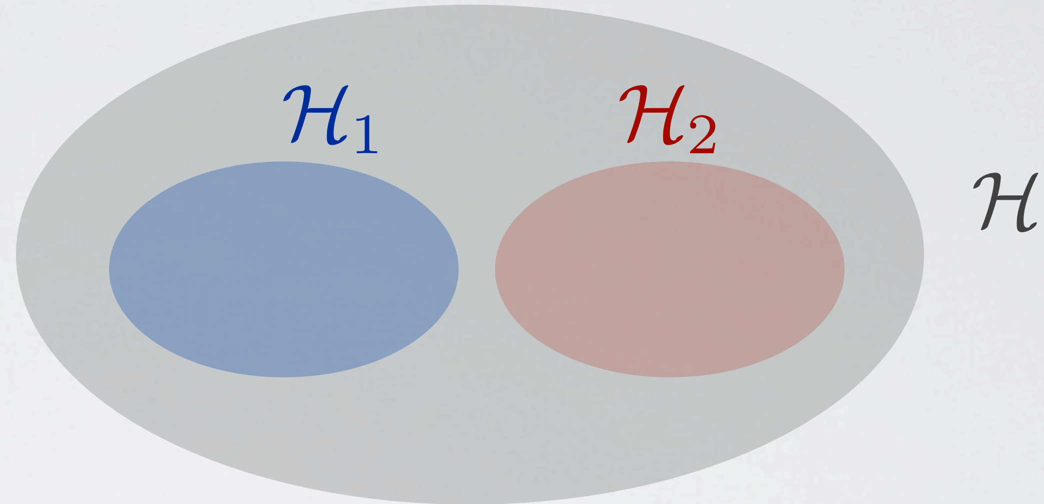
Possible reasons to expect (near-)minimal:

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

A proposed broader picture:

Quantum states more basic than spacetime

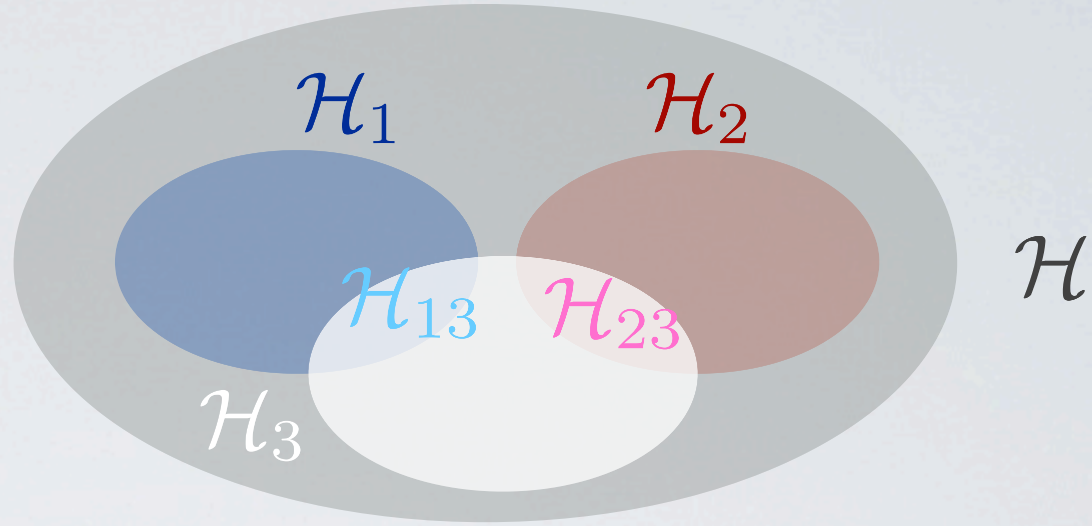
Approximate "localization"



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

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?")

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