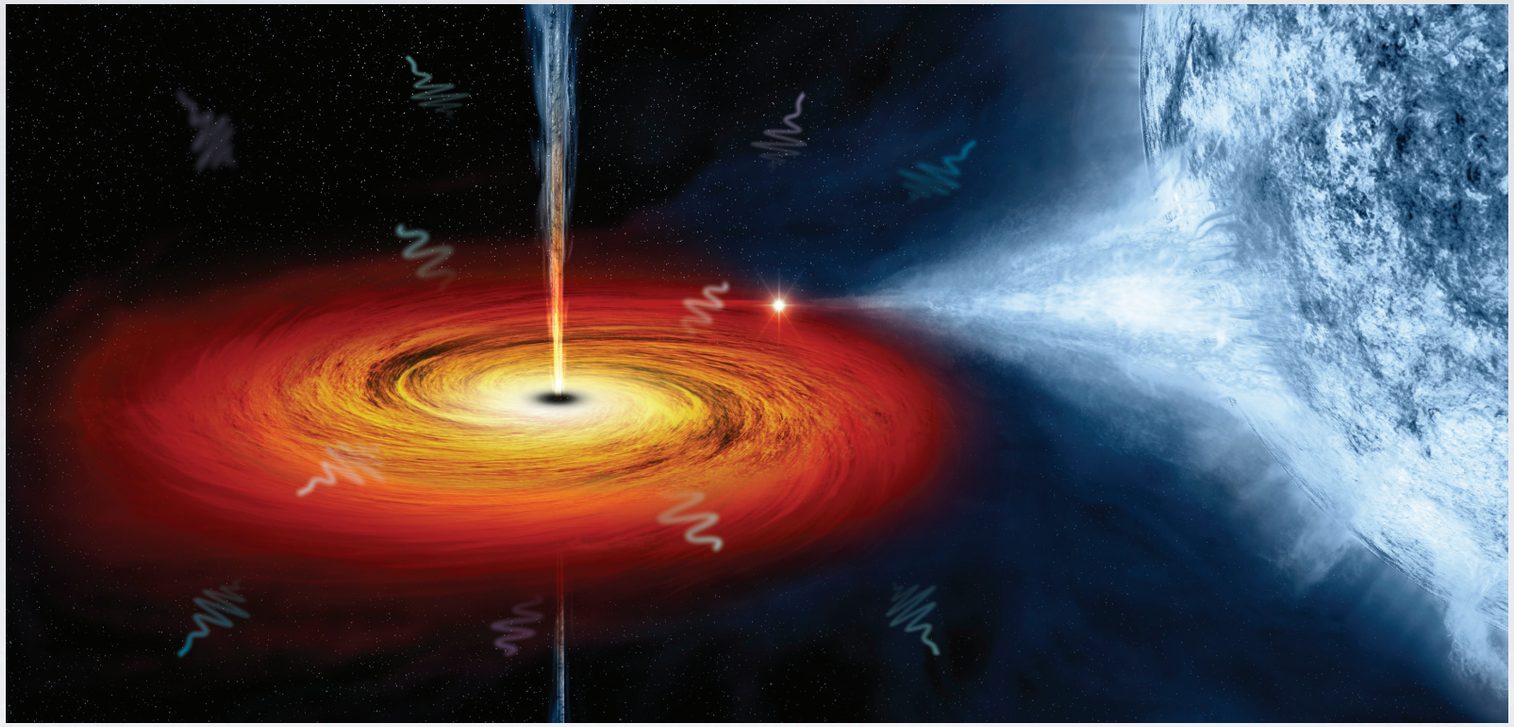
# QUANTUM INFORMATION TRANSFER FROM BLACK HOLES: VIOLENT VS. NONVIOLENT NONLOCALITY



Based on an image from NASA/CXC/M. Weiss

Physics Today April 2013

S.B. Giddings, UC Santa Barbara

## Black hole horizons and quantum information

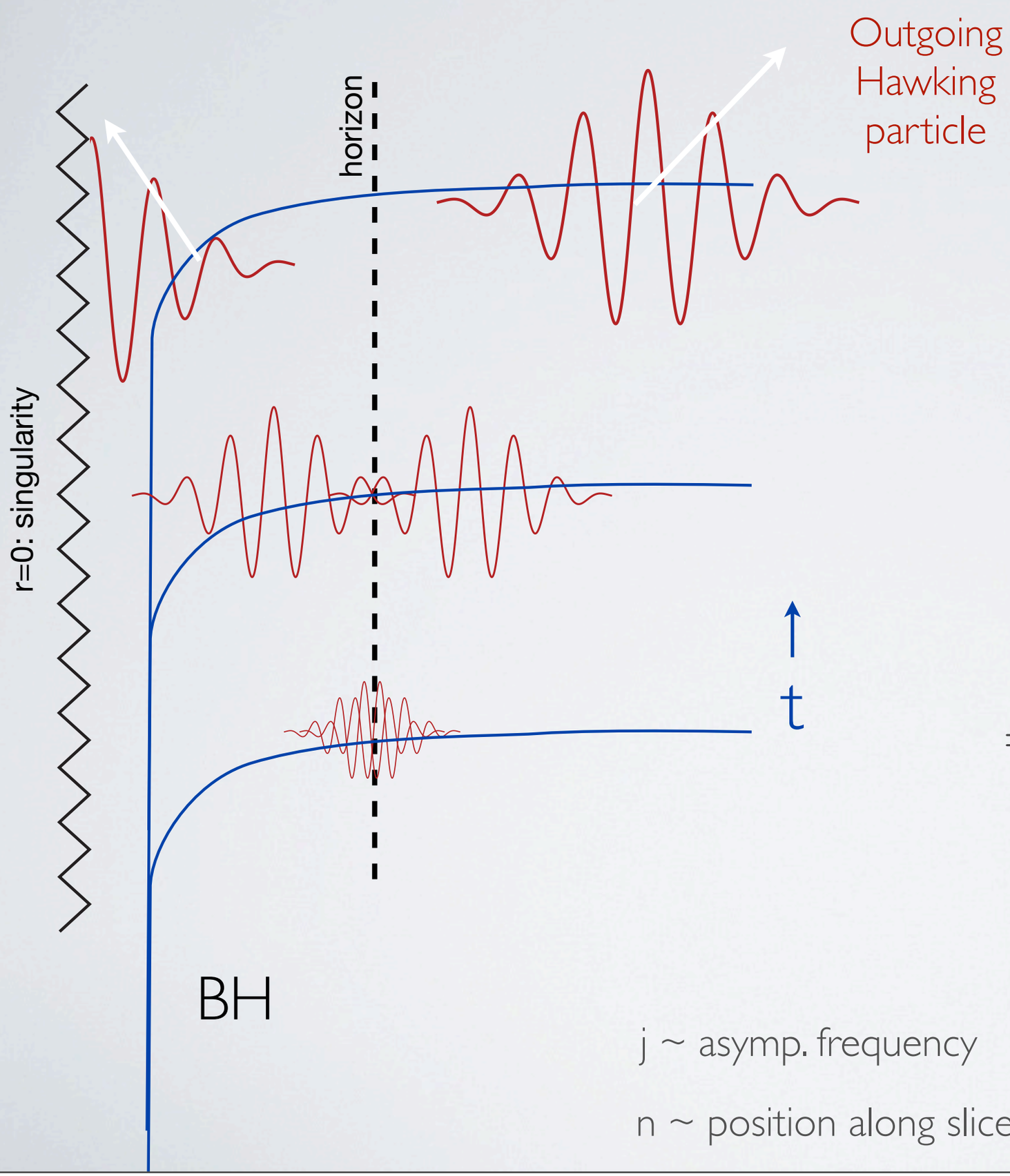
CERN, Mar 25, 2013

Refs: SBG 1201.1037; 1211.7070; 1302.2613
SBG & Y. Shi; SBG & Brown -- work in progress

## This talk:

1. The gravitational unitarity crisis (quick review)
2. Modifying locality
3. Nonviolent nonlocality - motivation and basic picture
4. NVNL -- candidate effective parameterization
5. Thoughts on a fundamental framework

# I. Review




$$\frac{\delta M}{M} \sim \frac{1}{S_{BH}}$$

"Hawking state"

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

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

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

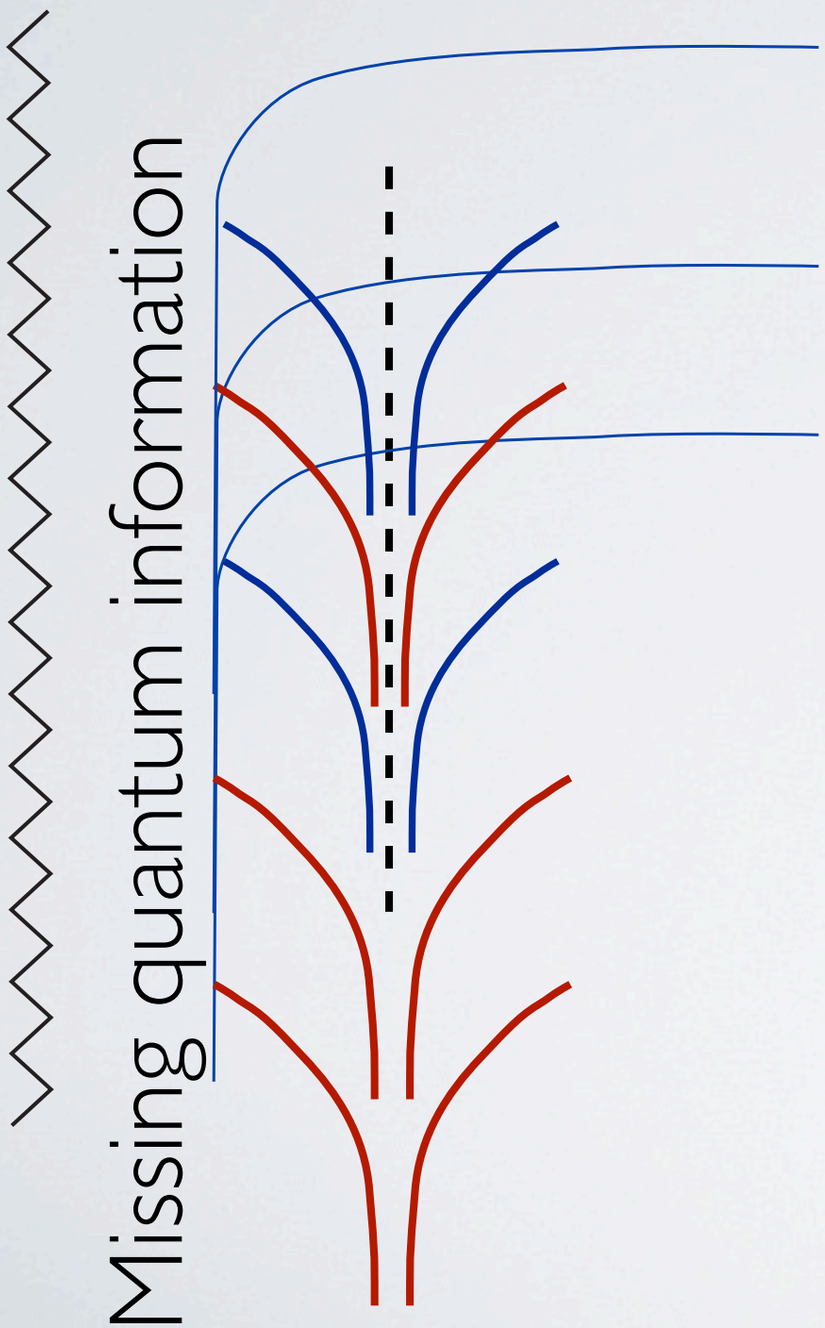
j ~ asymp. frequency

n ~ position along slice

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

# simplified picture ("qubit models;" cf Mathur)

$$|\psi\rangle \sim \prod_i \left(|\hat{R}R\rangle + |\hat{B}B\rangle\right)_i$$




$$\rho_{ext} = \mathrm{Tr}_{in}(|\psi\rangle\langle\psi|)$$

$$S_{vN} = -\mathrm{Tr}(\rho_{ext}\log\rho_{ext}) \sim t/R$$

If black hole disappears:

Missing quantum information $\sim S_{BH}$

Massive failure of unitarity

*Breakdown of quantum mechanics*

# The information "paradox"* in a nutshell:

Information that falls into a black hole:

- can't be destroyed — QM; energy conserv.

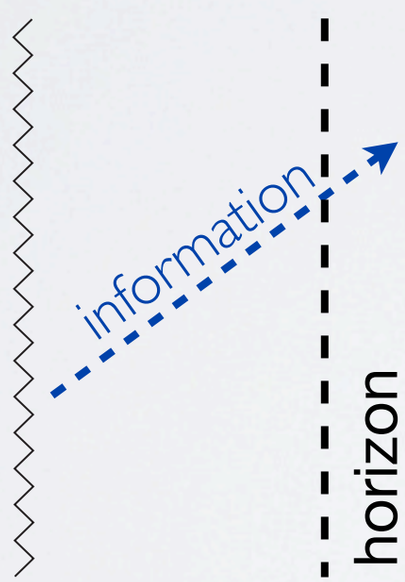
Banks, Peskin, Susskind

- can't be left in remnant — catastrophic instabilities

see e.g SBG hep-th/9310101, hep-th/9412159; also Susskind hep-th/9501106

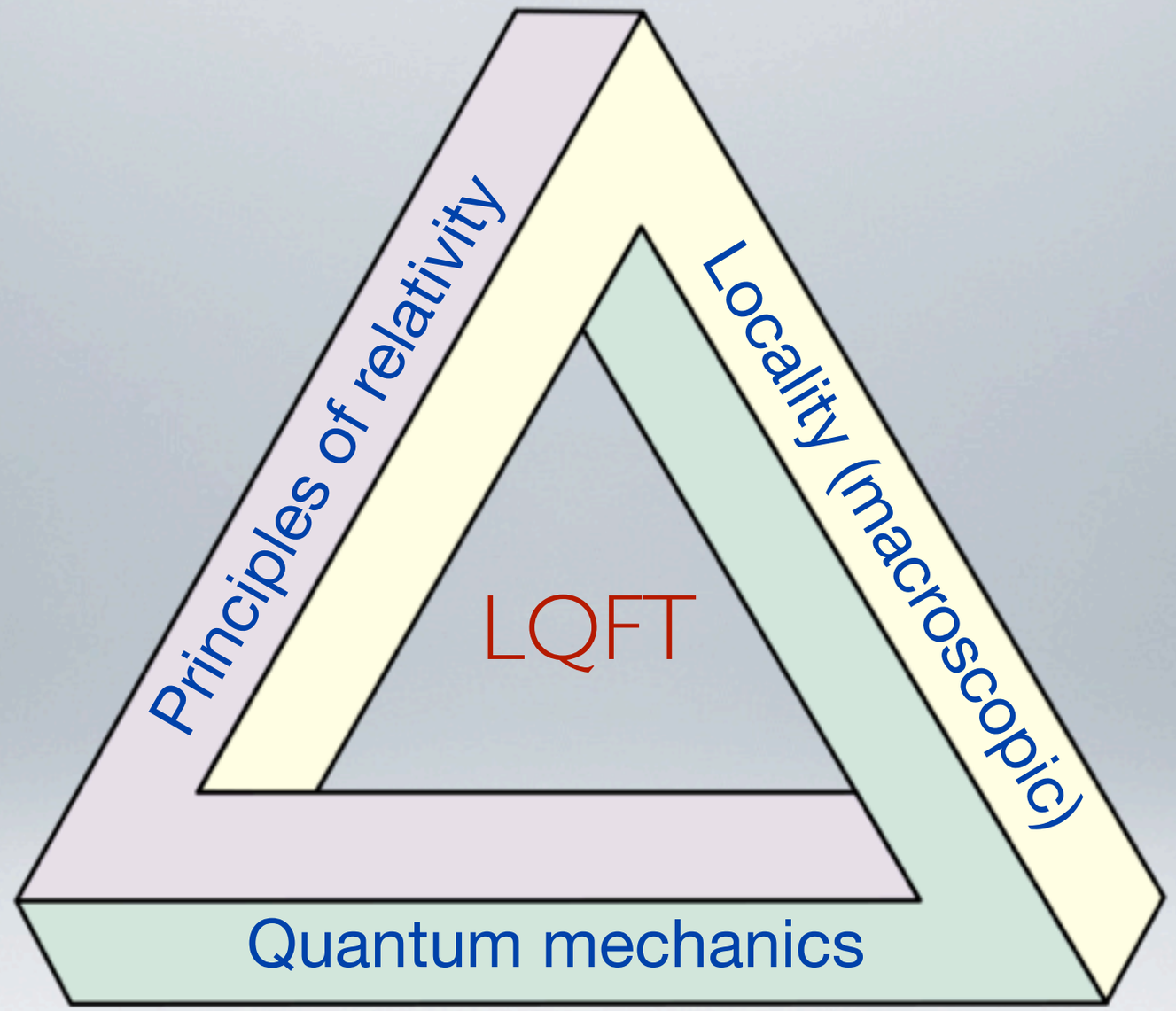
- can't get out — QFT locality

Quantum information does not propagate faster than the speed of light




*not a true paradox: no sharp calc. of missing info at times t>RS: SBG hep-th/0703116; 0911.3395; see also Arkani-Hamed et al

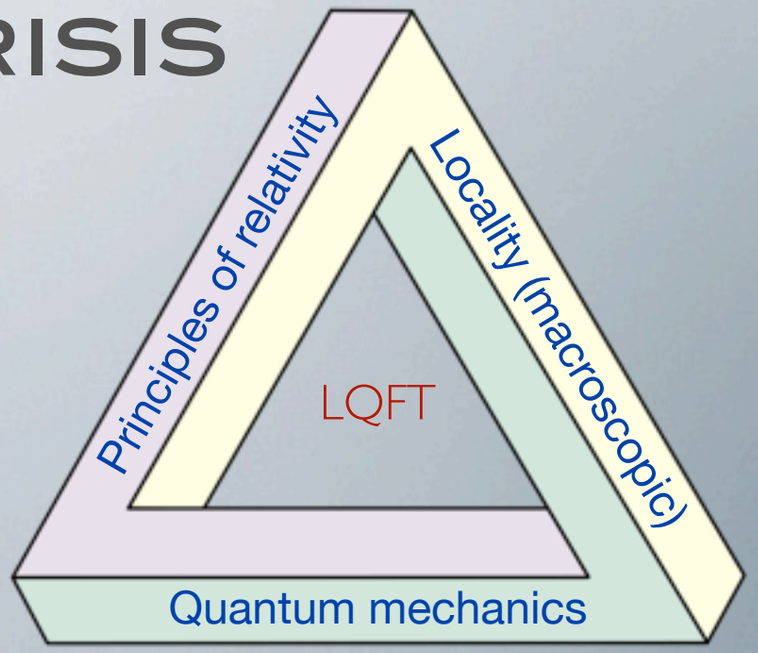
# Gravitational Unitarity Crisis




Escher: "impossible object"

Conflict between fundamental principles

# Gravitational Unitarity Crisis




Some thoughts:

- It's not about singularities, renormalizability? Long distance.
- QM; LI, etc.: hard to modify (consistency, observation). Locality?
- The need to account for quantum BH formation/evaporation:
  a key guide? (compare atomic stability crisis --> QM)

Theoretical probes

gravitational scattering/S-matrix

localized description of BHs

# 2. Modifying semiclassical locality

- locality is not a sharp concept in quantum gravity -

Info not localized

Quantum info transfer

# 2. Modifying semiclassical locality

- locality is not a sharp concept in quantum gravity -

Info not localized

## Complementarity

more radical than necessary 0911.3395

at odds w/ quantum reality

ruled out? AMPS 1207.3123

Quantum info transfer

## Massive remnants/violent nonlocality

fuzzballs, firewalls

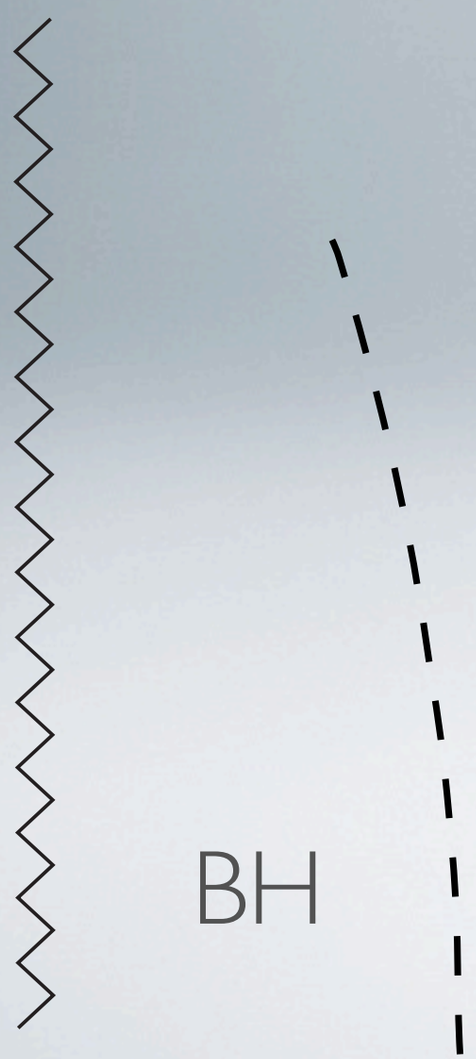
"black holes no longer black holes"

## Nonviolent nonlocality

# "Nonlocal" information transfer

A proposal from 1992: hep-th/9203059

(early 90's: attempt to characterize possible general scenarios)

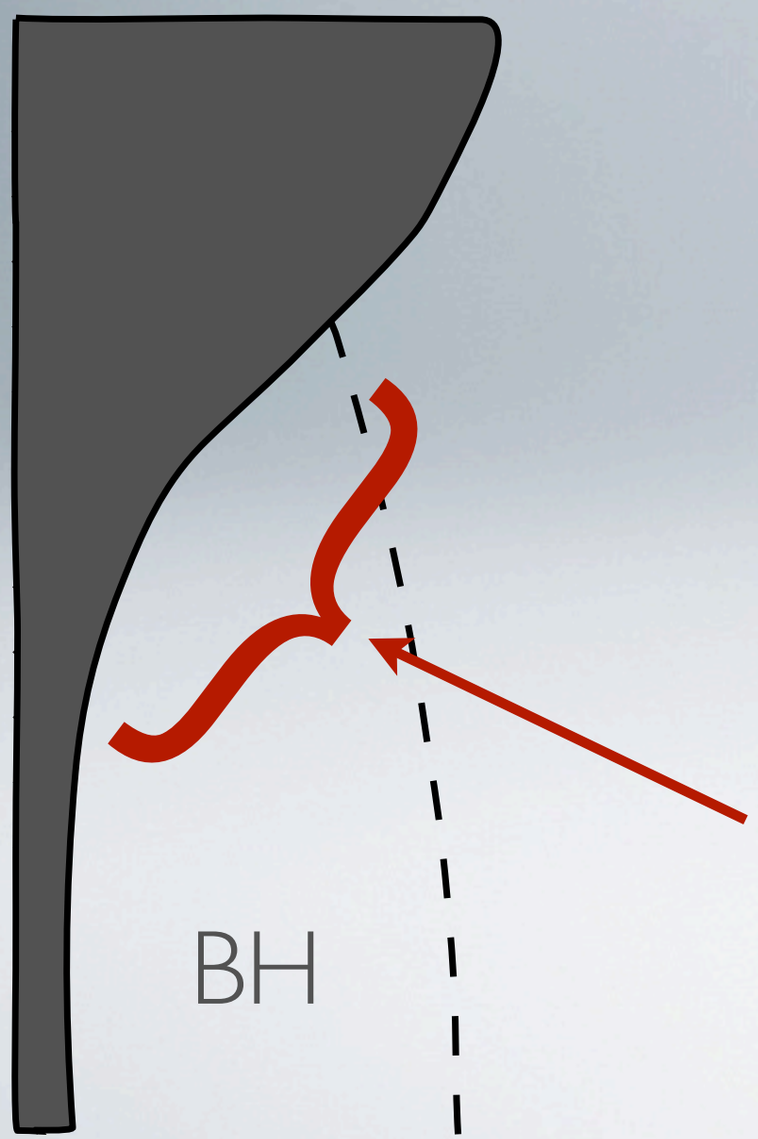


# "Nonlocal" information transfer

A proposal from 1992: hep-th/9203059

(early 90's: attempt to characterize possible general scenarios)

Massive Remnant




(G) *The Hawking process terminates with the production of a large, massive remnant which carries all of the information missing from the outgoing radiation. Whether the remnant subsequently decays or whether it is long lived, the information stored in it becomes accessible.*

"star-like"

Nonlocal information transfer

"New, unknown, nonlocal physics"

Basic points:

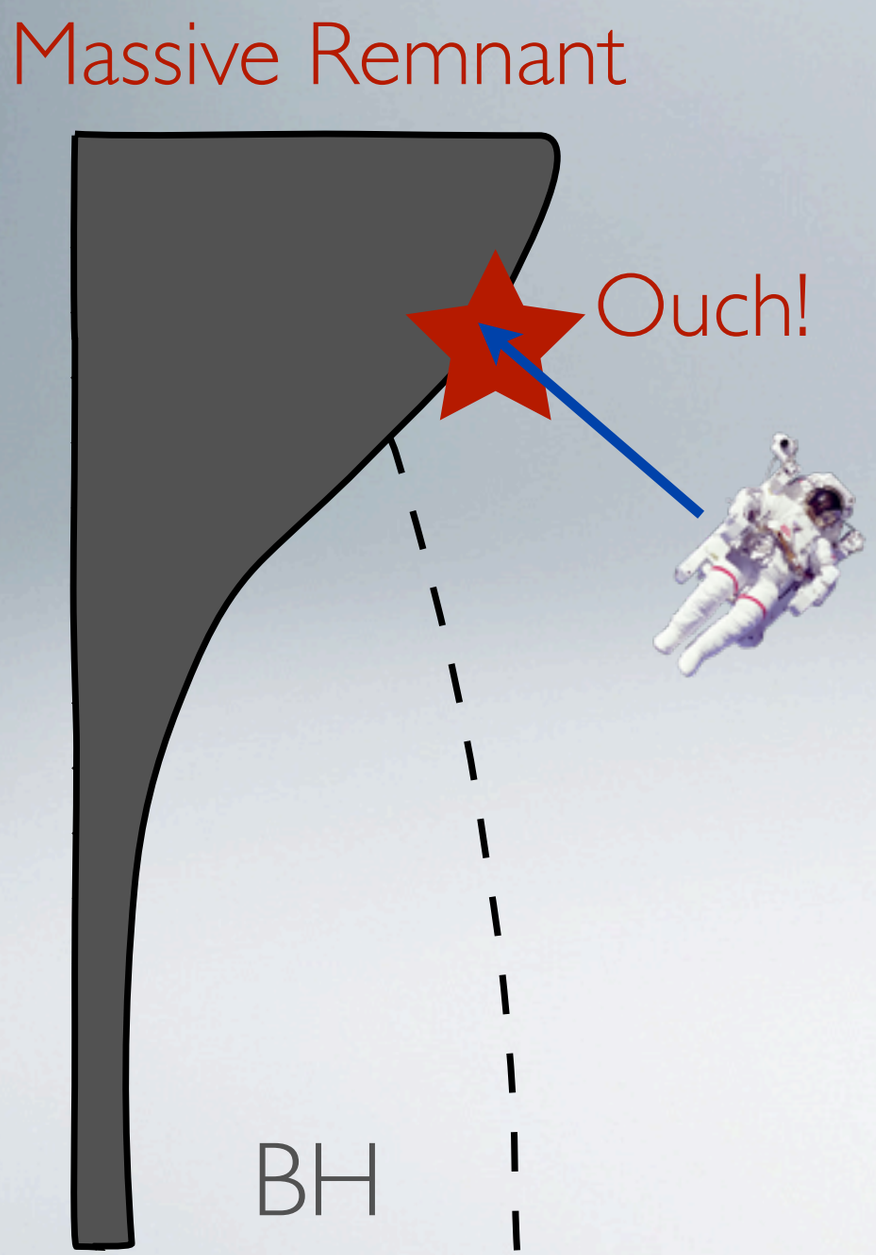
1. Specific realizations:

- Fuzzball

  stringy geometries

- Firewall (degenerate limit)

  wall of quanta




2. Violent

- to physics
- to infalling observers

(conjectured otherwise for fuzzballs- Mathur ...)

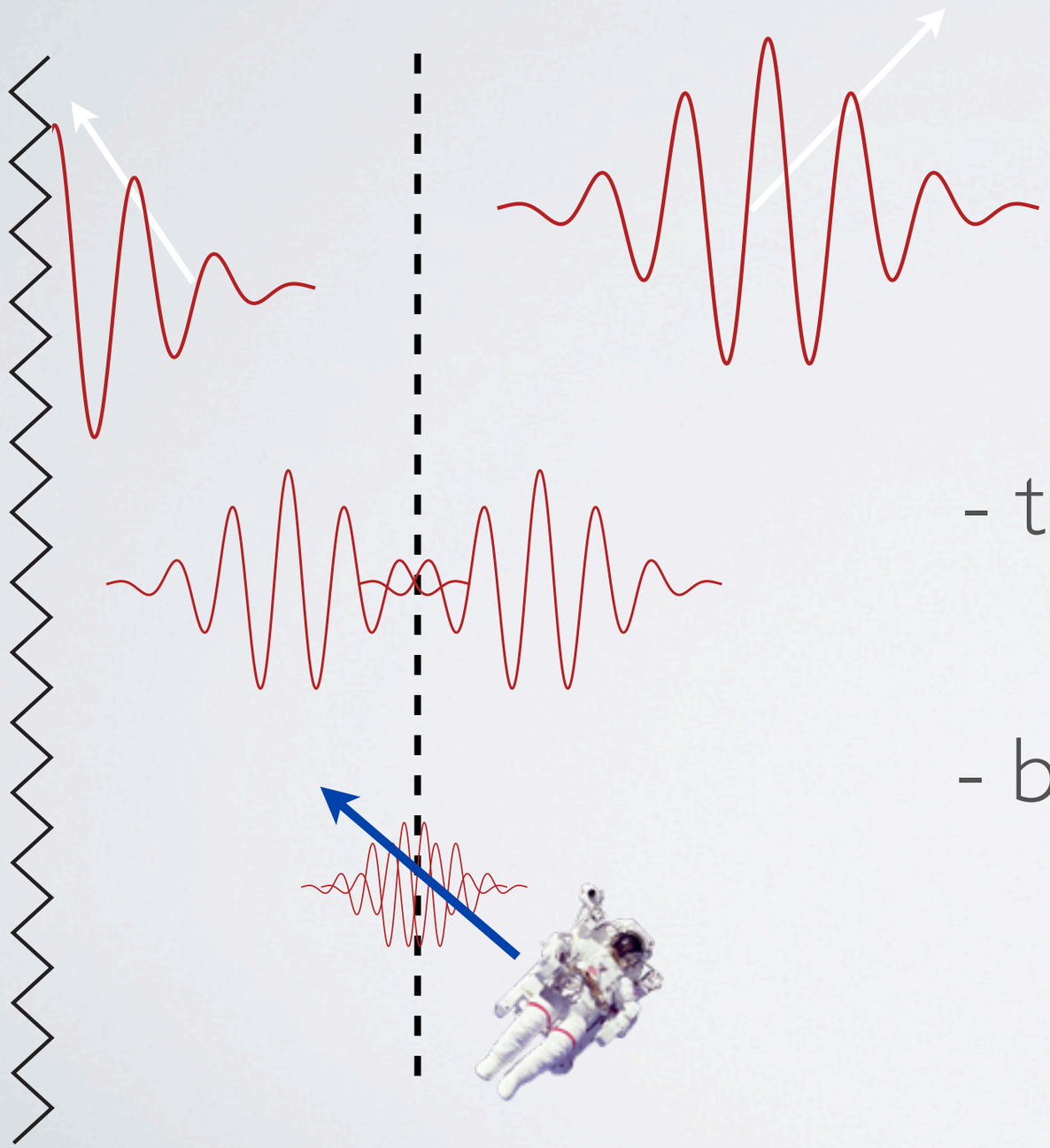
"Violent nonlocality"

Is there a nonviolent alternative?

# pre-AMPS argument for violent horizon (now: firewall)

(see e.g. SBG, hep-th/0605196; Mathur; 1108.2015, 1201.1037)

## Consider first:



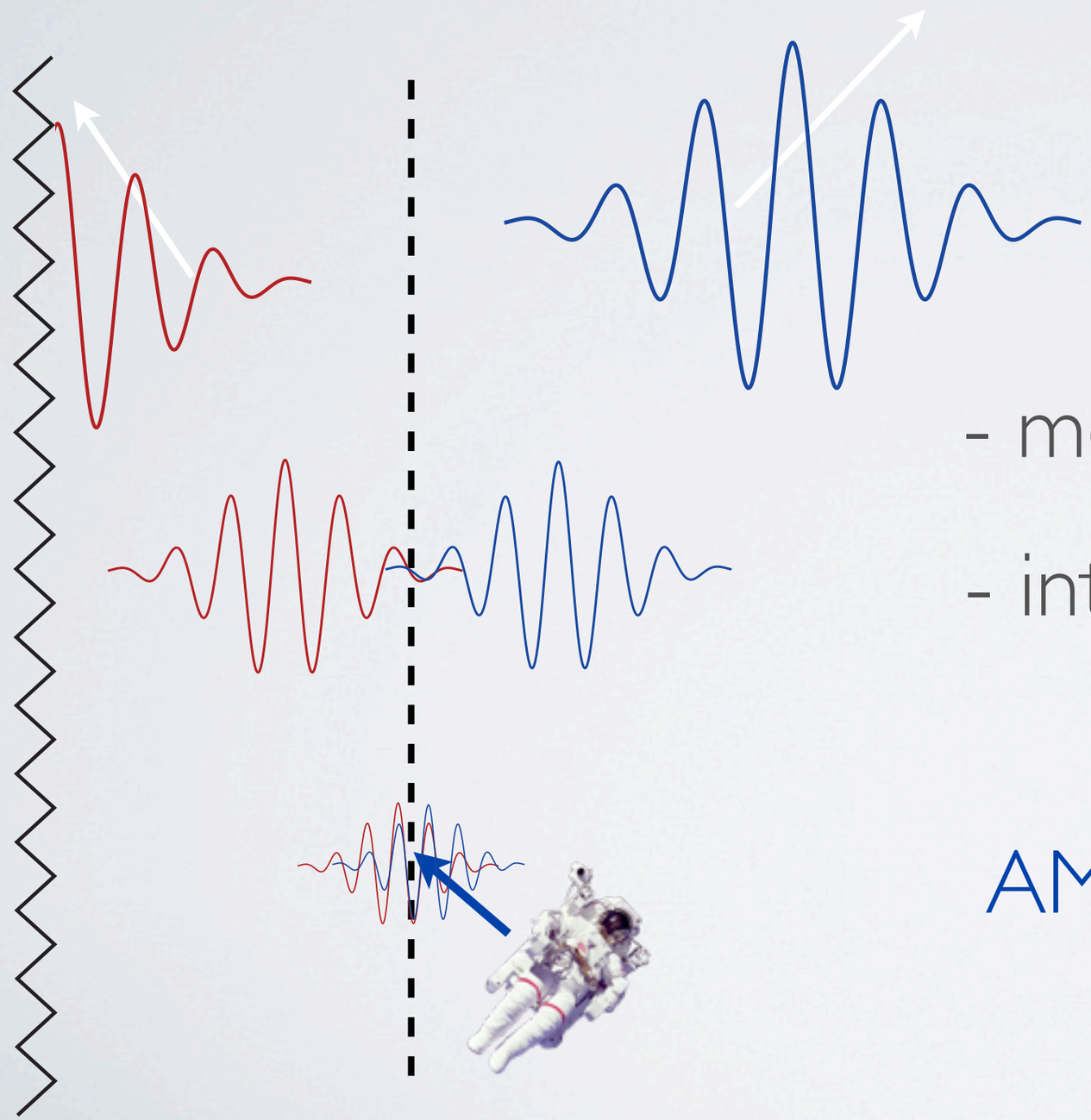
Hawking state:

- track back: modes blueshift to high energy
- but interactions cancel

hep-th/0605196

Now, suppose 1) different state: missing information out

2) LQFT holds outside horizon



Outgoing information:

modified Hawking quanta

- modes blueshift to high energy

- interactions don't cancel

violent

AMPS: rederivation, rebranding

unavoidable?

# Observations:

1. The problem is info. transfer right *to* the horizon

2. This is nonlocal -- why stop there?

# 3. Nonviolent nonlocality: motivation; basic picture

How to save quantum mechanics,
+ minimize violence to equivalence principle?
(more fundamental formulation?)

- Assume quantum info localized; e.g.
quantum subsystems $\mathcal{H}_{BH} \otimes \mathcal{H}_{ext}$

- quantum information transfers out

("entanglement transfer:" Hayden-Preskill;
SBG & Shi 1205.4732; Susskind 1210.2098)

- not described by LQFT

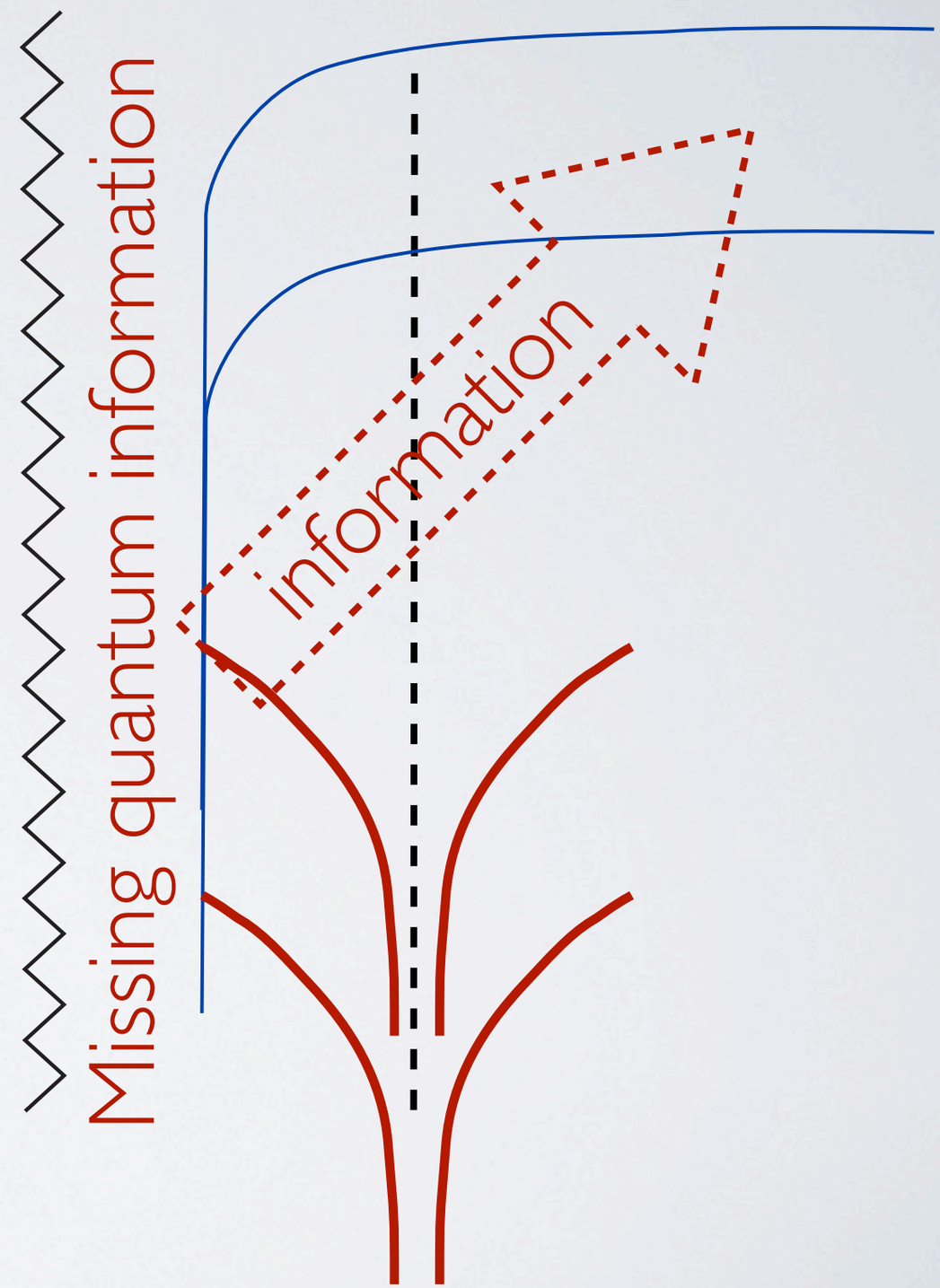
- semiclassical geom. picture
  likely not correct

  (more basic pic:
  Q. subsystems?)

- but -

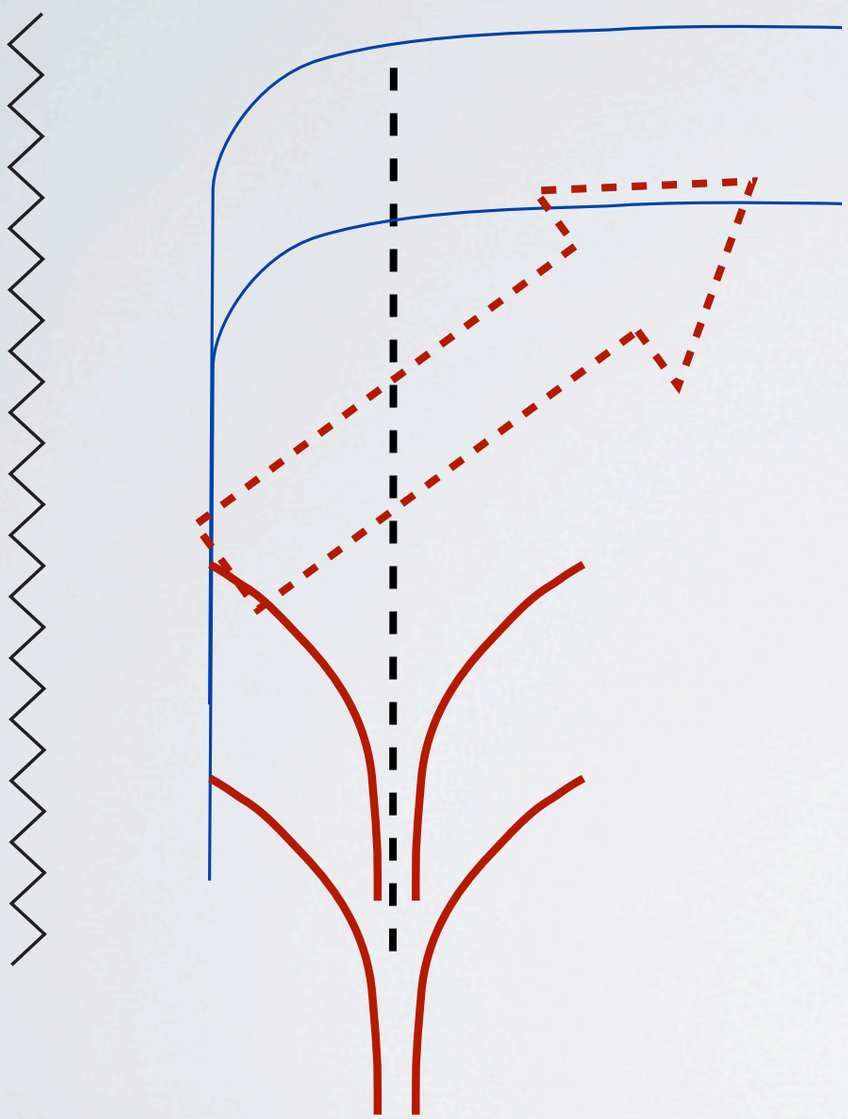
- try to describe in
approximate LQFT picture

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



# Basic aspects

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



## Unitary evolution:

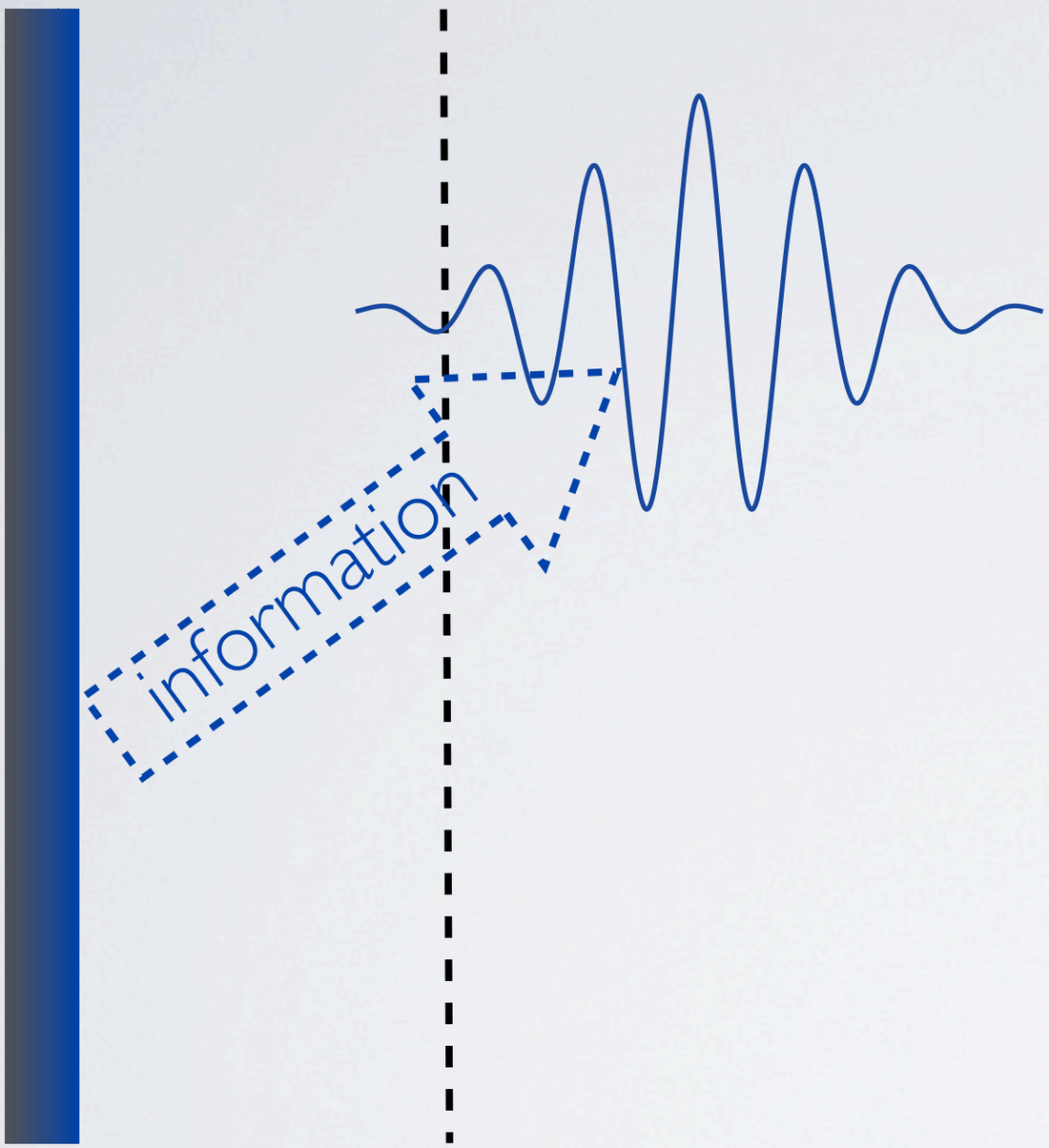
1. $\dim(\mathcal{H}_{BH}) \downarrow$

2. Entanglement w/ early radiation transfers out
   - unitary evolution

- Most basic version: subsystem transfer (cf SBG & Shi)
- Multiple constraints

Can be nonviolent?

# Basic picture (approximate): nonviolent nonlocality




1. Nonlocality not just confined inside horizon

(why should it stop there?)

2. Information transfers into modes when "soft"

e.g. $\lambda \sim R^p$

$0 < p \leq 1$

information-dense black hole "core"

possible basic framework - shortly

# 4. NVNL - candidate effective parameterization

(See also qubit models, and generalization to modes: 1108.2015, 1201.1037)

Note: LQFT/semiclassical geometry is likely not the correct fundamental framework to describe the physics. Nonetheless, parameterize/approximate the information transfer as a correction to such physics.

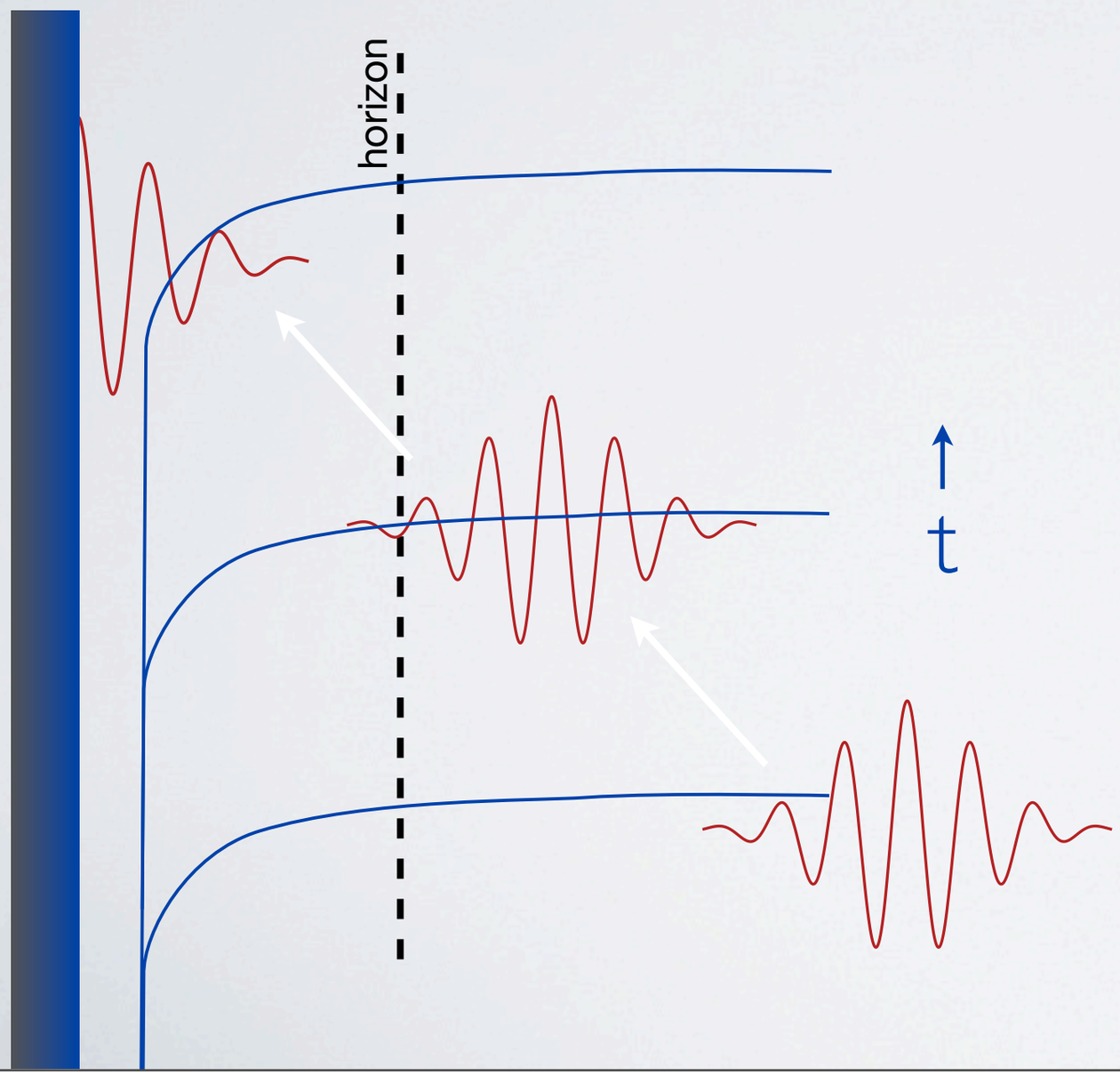
# Usual LQFT evolution

$$\phi(x,t) = \sum_I \left[ a_I U_I(x,t) + a_I^\dagger U_I^*(x,t) \right]$$

## Subdivide modes $U_I = \{\hat{u}_i, u_a, u_\alpha\}$

BH atmosphere asymptotic

$\hat{u}_i$ $u_a$ $u_\alpha$

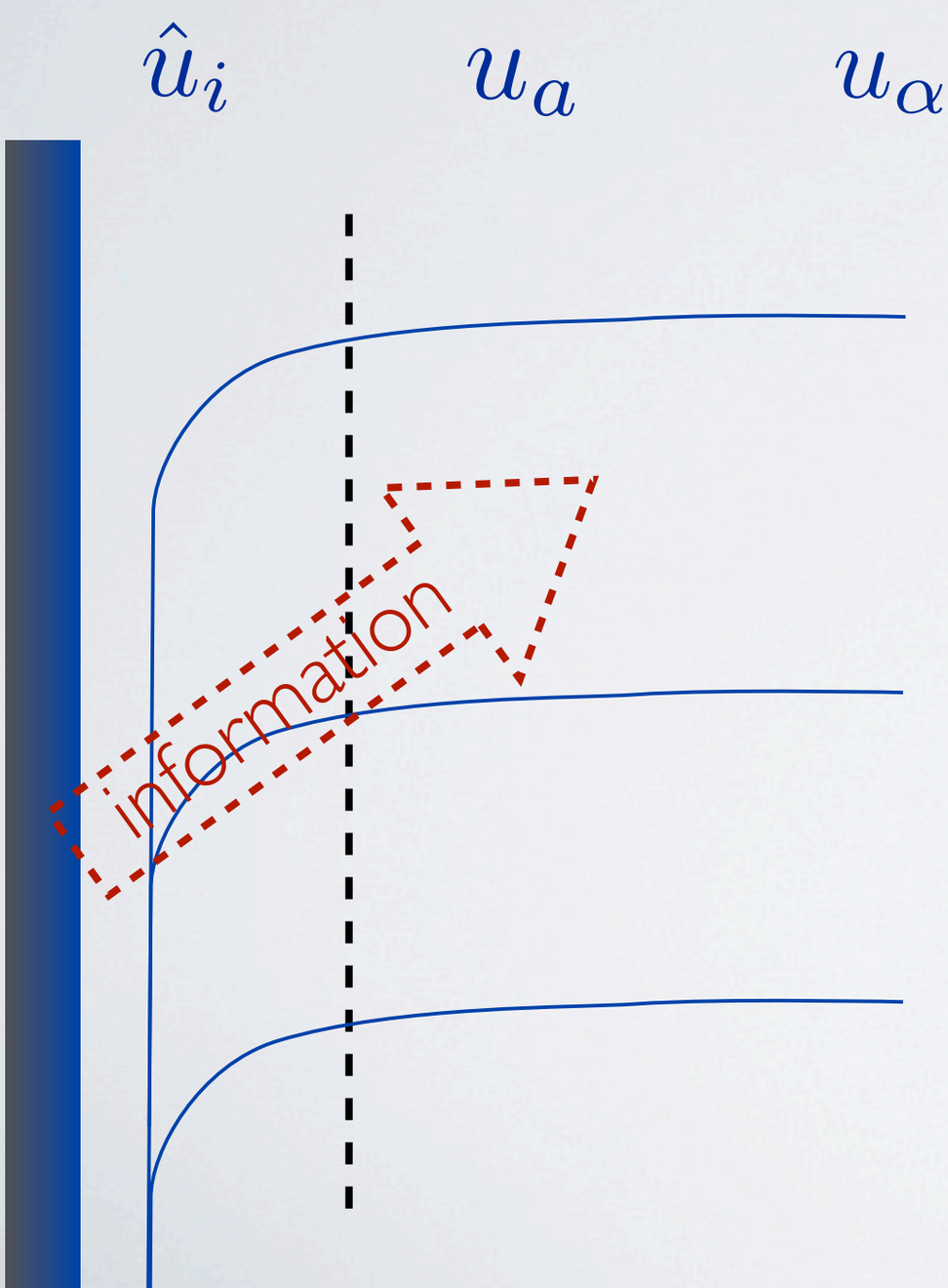



$$H \sim \hat{a}_i^\dagger a_a + \cdots$$

Note

- BH chooses frame
- dynamics not T invt

# Modifications to LQFT hamiltonian:




1) Need to transfer information:

$$H_{trans} = \frac{1}{R}\sum_{i,a} \mathcal{N}_{\bar{a}i}(t) a_a^\dagger \hat{a}_i \; + h.c.$$

(note: not into asymp. modes)

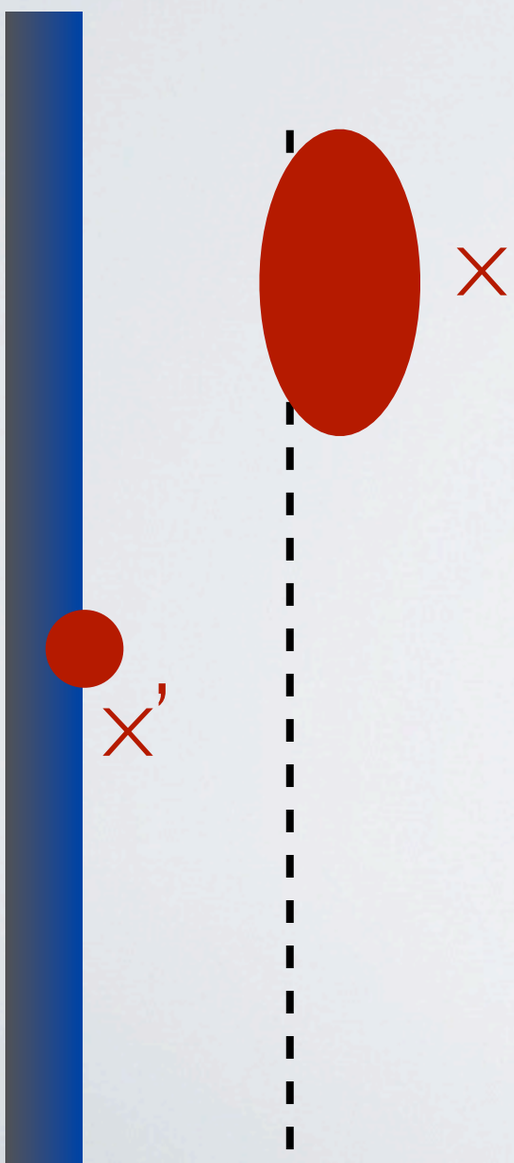
2) Can also scramble (or, not):

$$H_{sc} = \frac{1}{R}\sum_{i,j} \mathcal{S}_{\bar{\imath}j} \hat{a}_i^\dagger \hat{a}_j$$

# Alternate ~equivalent parameterization:

$$\int dt H_{NL} = \int dV_4 dV_4' \mathcal{O}_A(x) G_{AB}(x,x') \mathcal{O}_B(x')$$

e.g. $\mathcal{N} \leftrightarrow G_{AB}(x,x')$




- for G=const., ~wormholes: no info transfer but for BH dependent G(x,x'), can transfer

- interactions: could have multilocals

- clearly a lot of latitude in pheno. model of G.

constraints?

Some particular questions:

Can describe sufficient info transfer?

Appearance to outside observers?

Violent?

Focus on outside:

$$\int dV_4 \mathcal{O}_A(x) \underbrace{\int dV_4' G_{AB}(x,x')\mathcal{O}_B(x')}_{J_A(x)}$$

"Effective source description"

E.g.

$$\int dV_4 J^I(x)\Phi^I(x) \quad , \quad \int dV_4 J^{\mu\nu}(x)T_{\mu\nu}(x) \quad \ldots$$

Simple model: free scalar, $\int dt H_{NL} \to \int dV_4 J(x)\phi(x)$

Describe effect in terms of modes created:

$$\phi(x) = \sum_A a_A U_A + h.c.$$

$$U_A \sim Y_{lm}(\Omega)\frac{u_l(r,t)}{r}$$

radial problem: motion in effective potential, in new coordinates

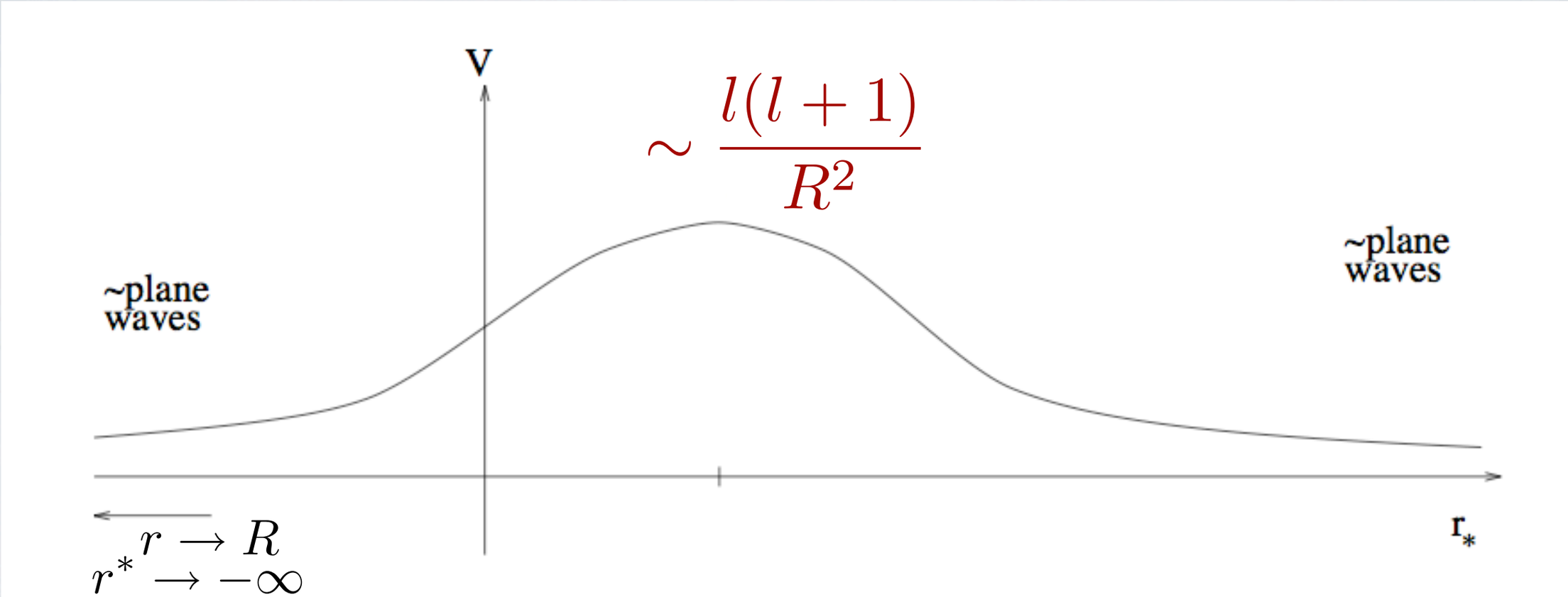
$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2$$

$$= -f(r)(dt^2 + dr^{*2}) + r^2 d\Omega^2$$

$$f(r) = 1 - \frac{R}{r}$$

"tortoise coordinate"

$$\left(-\frac{\partial^2}{\partial t^2}+\frac{\partial^2}{\partial r^{*2}}\right)u_l = V_l(r^*)u_l$$




Let $\quad J(x) = Y_{lm} j_l(t,r)$

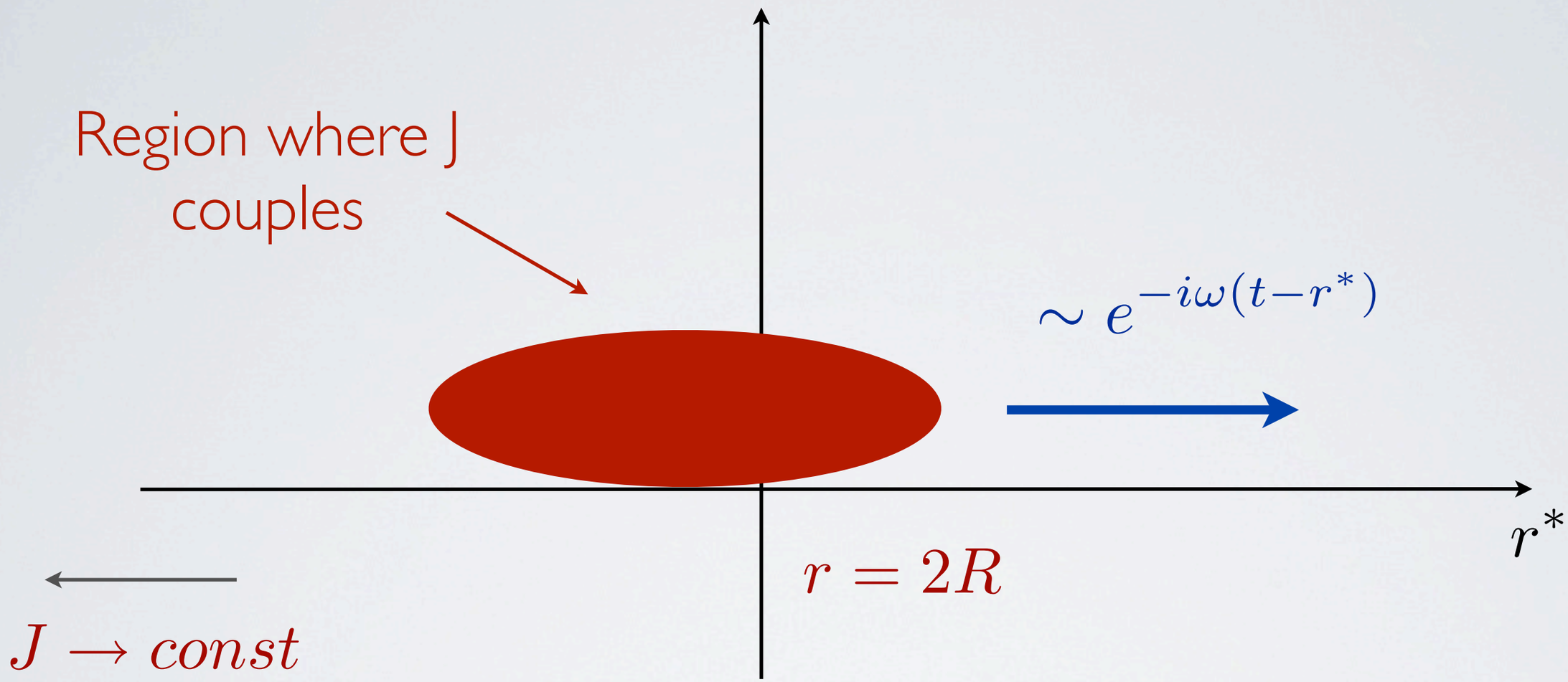
$$\Rightarrow \quad \int dV_4 J\phi \sim a^\dagger_{lm} \int r f dt dr^* j_l(t,r) u^*_l(t,r)$$

Specifically, consider J's that are:

A) smooth at r=R and

B) vanish rapidly for r>>2R (outside "atmosphere")

First, $l = 0, \quad \omega \sim 1/R$



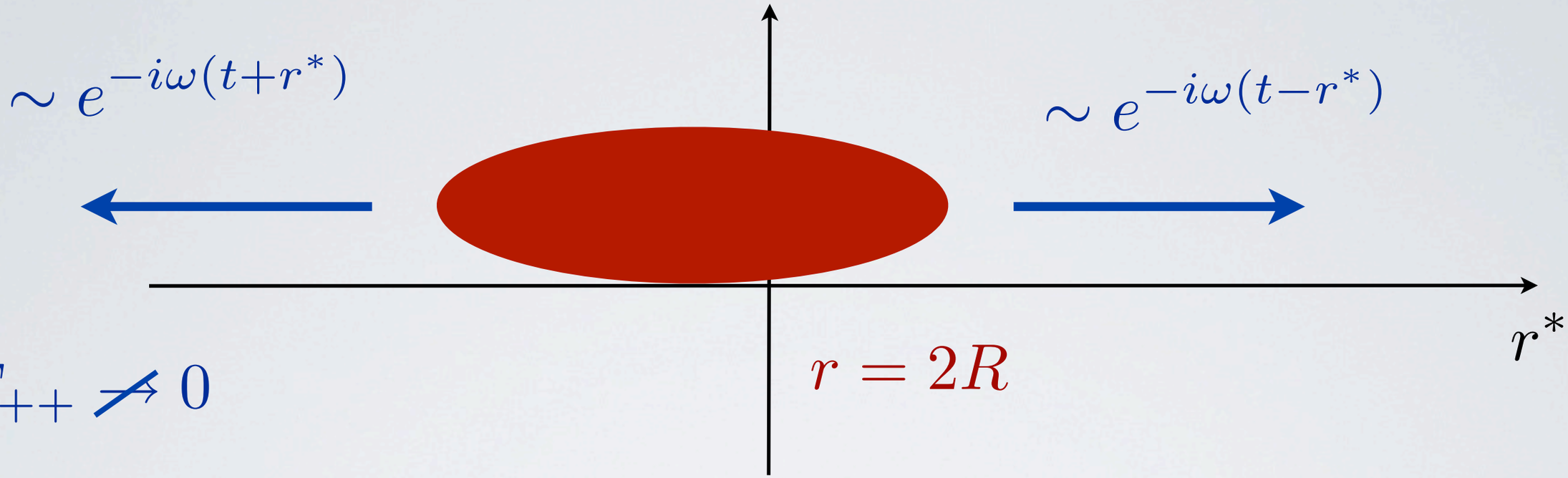

$$\int J u^* \to 0$$

Can arrange ~ one quantum of energy 1/R per time R: benchmark transfer rate

Outgoing energy density: $\sim 1/R^4$ "tiny"

# Singular horizon?

Let $x^{\pm} = t \pm r^*$




$T_{++} \not\to 0$

$T_{--} \to 0$

Good coords, infalling observer: $X^{\pm} = \pm 2Re^{\pm x^{\pm}/2R}$

Kruskal

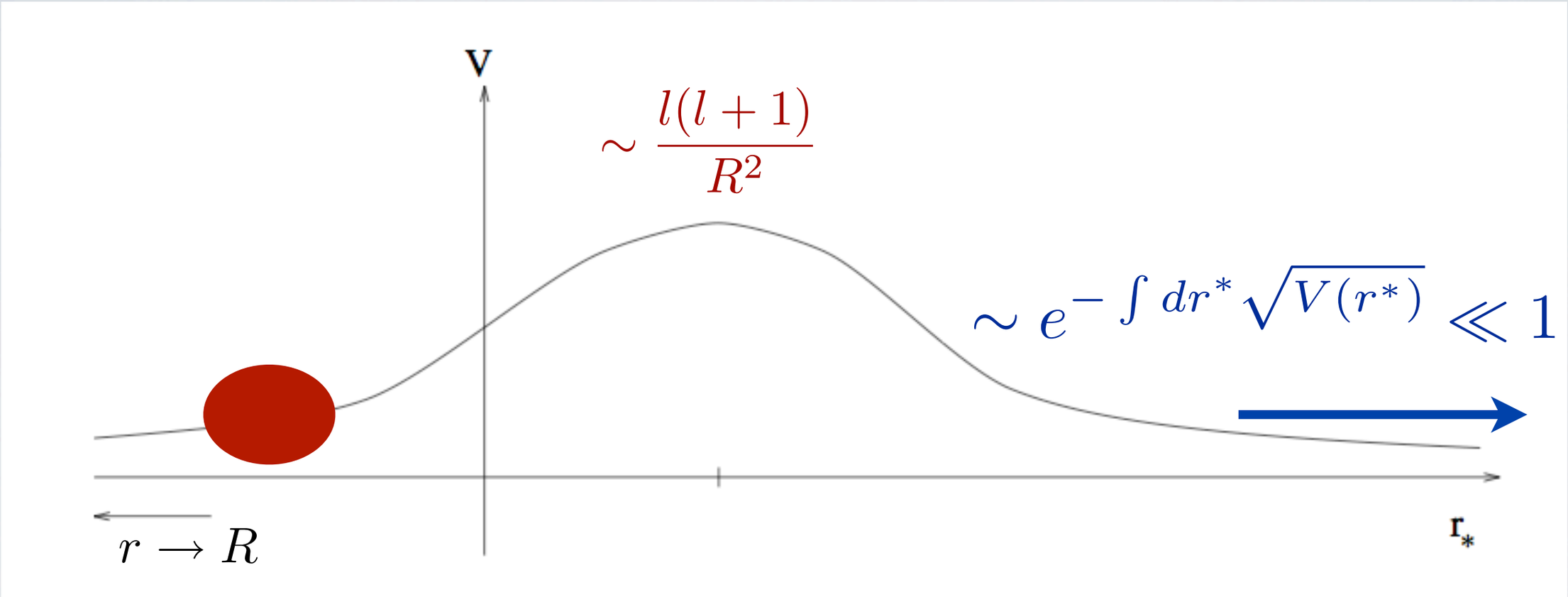
$$T_{--}^{\text{Krusk}} = \left(\frac{\partial x^-}{\partial X^-}\right)^2 T_{--}$$

$\to \infty$ at r=R

No singularity!

holds for arbit. l

Next, consider $l > 0, \quad \omega \ll l/R$ (e.g. $\omega \sim 1/R$ )




Therefore:

Effective sources $\sim j_l(t,r)Y_{lm}$ can be present, even with large magnitude compared to s-wave, without significant energy/information flux

This may help address one challenge to the scenario of nonviolent nonlocality

Mining: AMPS:

"... disagree with [11] that this new physics can be innocuous ..."

Naive version (see Unruh, Wald):

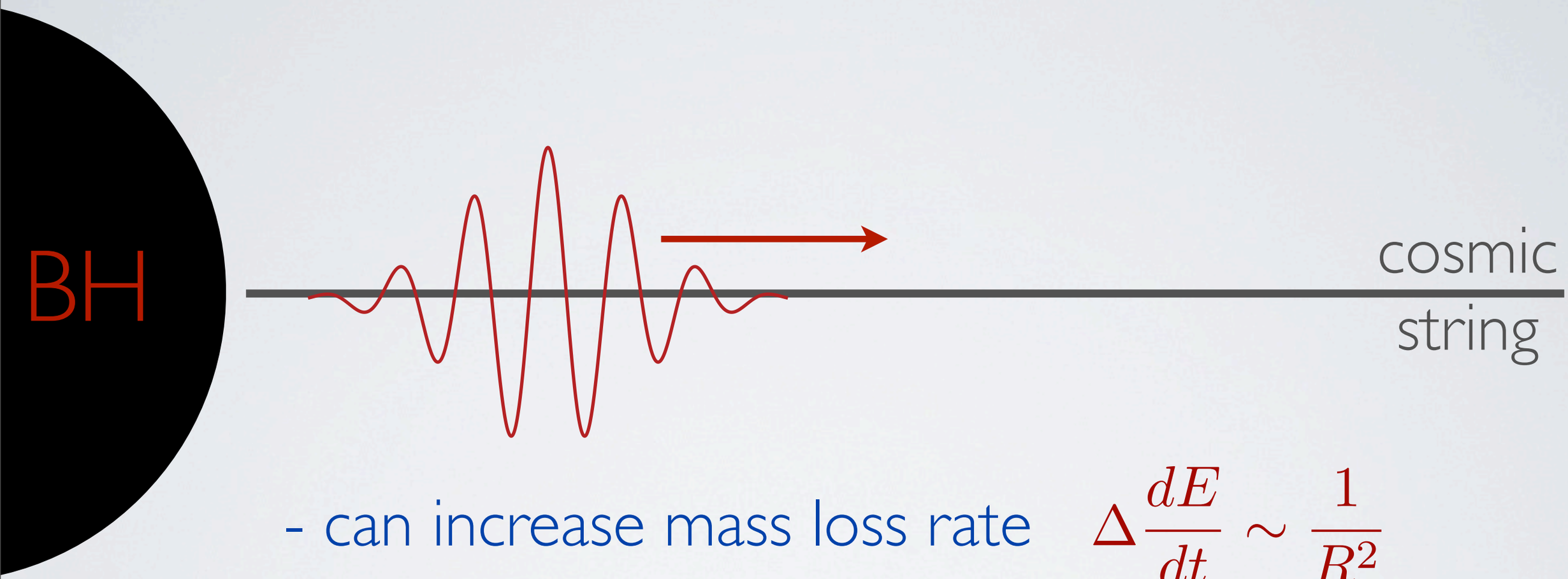

- can increase mass loss rate

- if do to a black hole after Page time, risk of "overfull" BH

$$S_{vN} > S_{BH}$$

This is a little too naive. E.g. Brown, 1207.3342

Mining, sharp version




- can increase mass loss rate $\Delta \frac{dE}{dt} \sim \frac{1}{R^2}$

- if do to a black hole after Page time, risk of "overfull" BH

$$S_{vN} > S_{BH}$$

- with ~R strings, get maximal possible mining rate

But, suppose:

1) Effective sources $\sim j_l(t,r)Y_{lm}$ are present, up to high l.

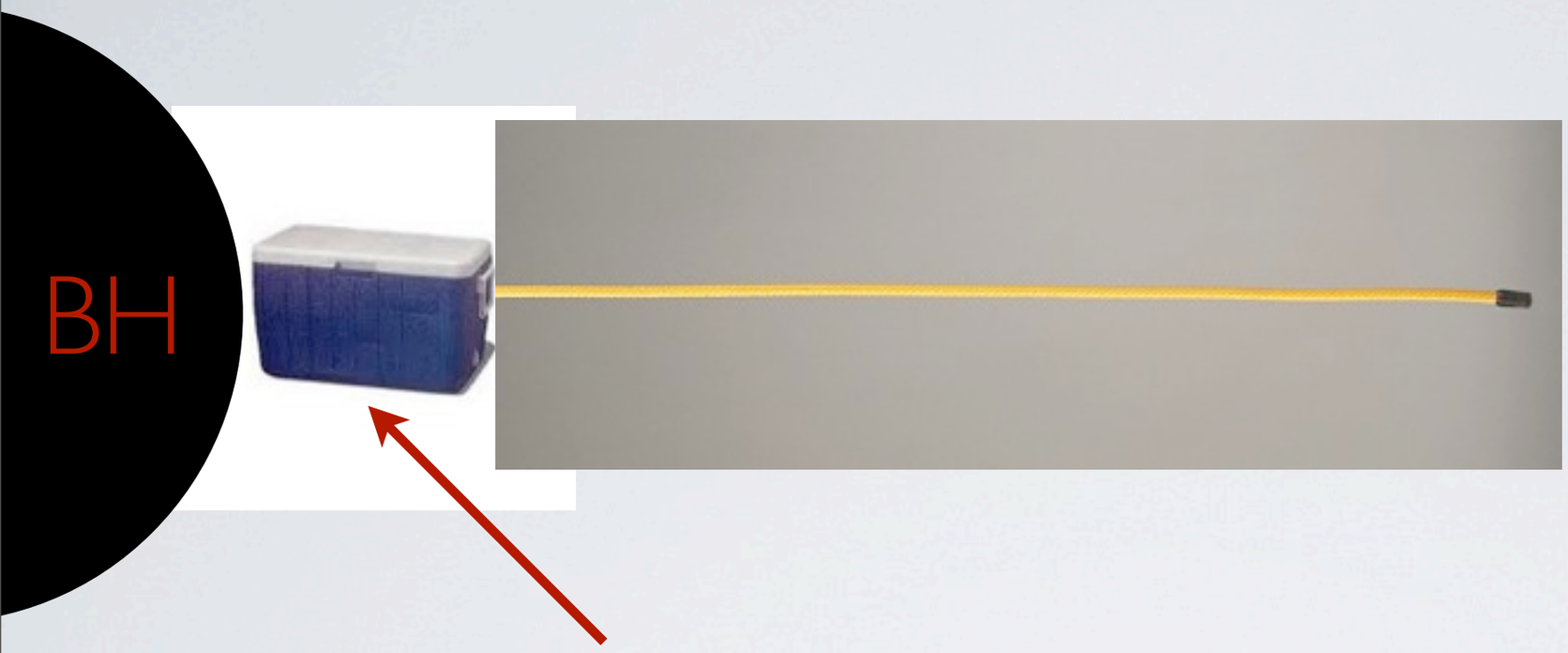
2) These couple to all matter (or, at least cosmic string matter)

Then: - introduction of cosmic string introduces extra channel for information flow, along with energy flow (new barrier-free mode, like s-wave)

- so, information flow increases commensurate with energy loss: natural, parametric resolution of overfilling problem

(note, information flow could also begin earlier; less natural?)

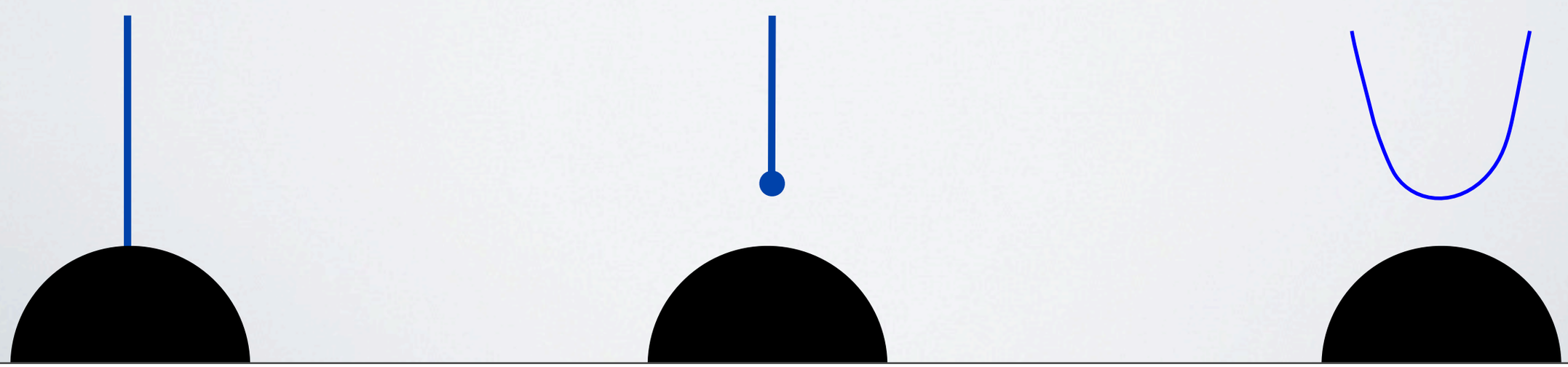
# Another objection from mining



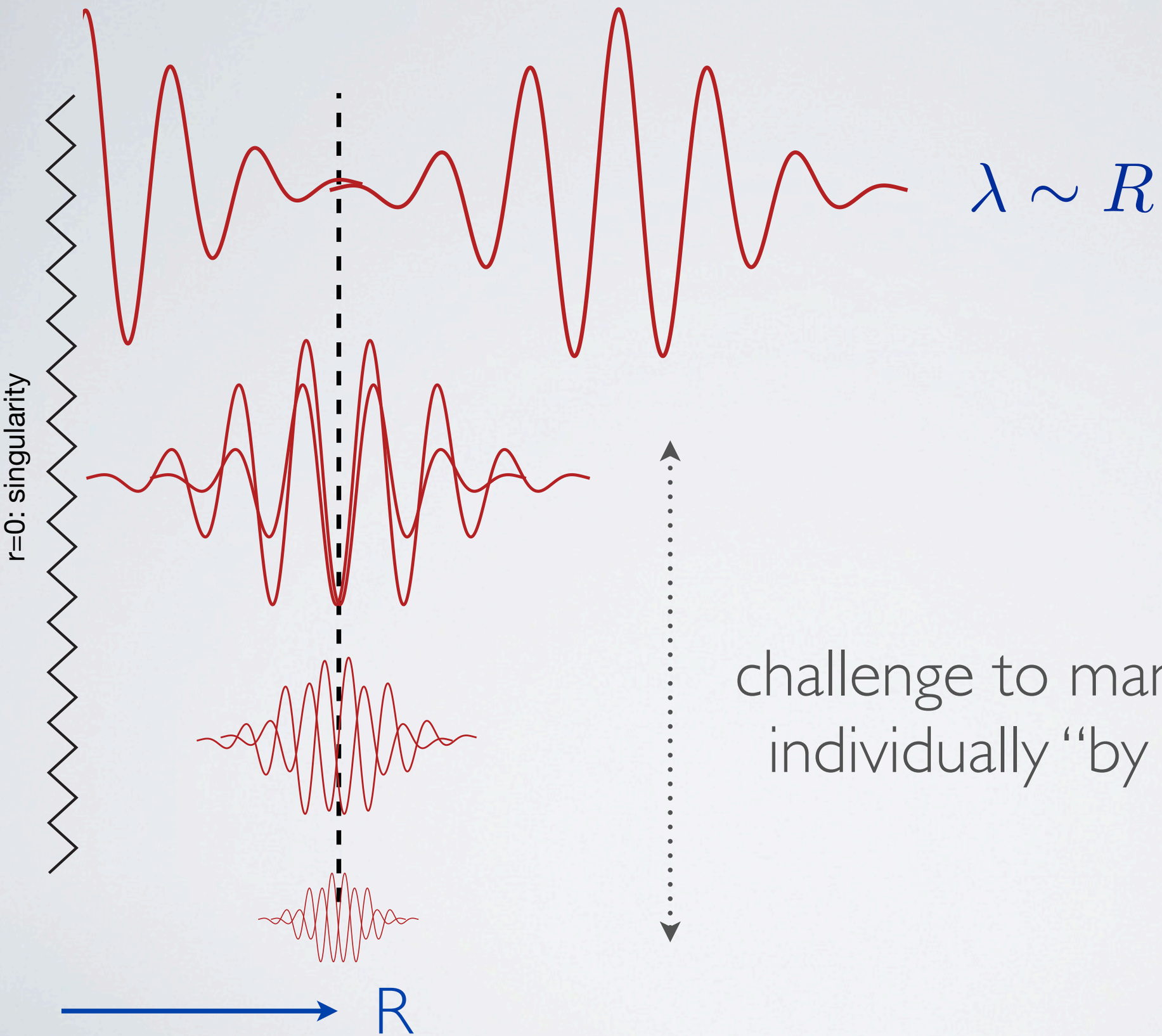

naive picture: capture, manipulate quanta/bits

## Sharper version: significant limitations

A. Brown and SBG (& Bousso?) WIP



- don't just "grab" HE quanta




challenge to manipulate individually "by hand"

# Important questions to answer:

1. Is this fundamentally inconsistent with anything we know?

   Sharp objections?

   if not: 


2. Generic prediction: extra energy flux, beyond Hawking

   problematic? avoidable?

   (special qubit models)

   (Potentially alters BH thermodynamics; though, compare stars)

3. What is the correct general framework for such physics?

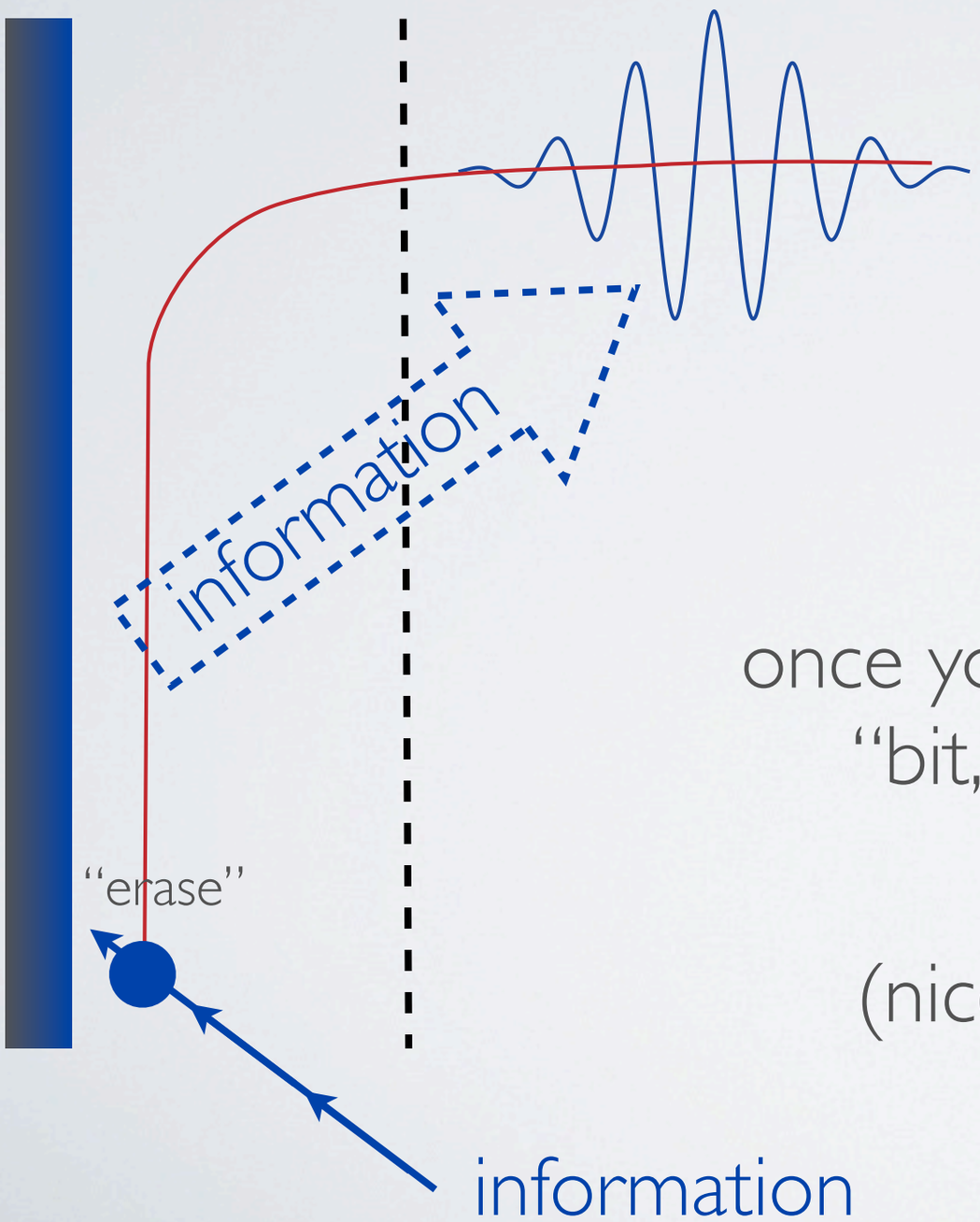
   (Black holes as guides to quantum gravity ...)

# Comment re. complementarity:

## AMPS seems regarded as posing a severe challenge to complementarity

(Complementarity, as stated, didn't make sense to me ...)

(see, e.g., arXiv:0911.3395)



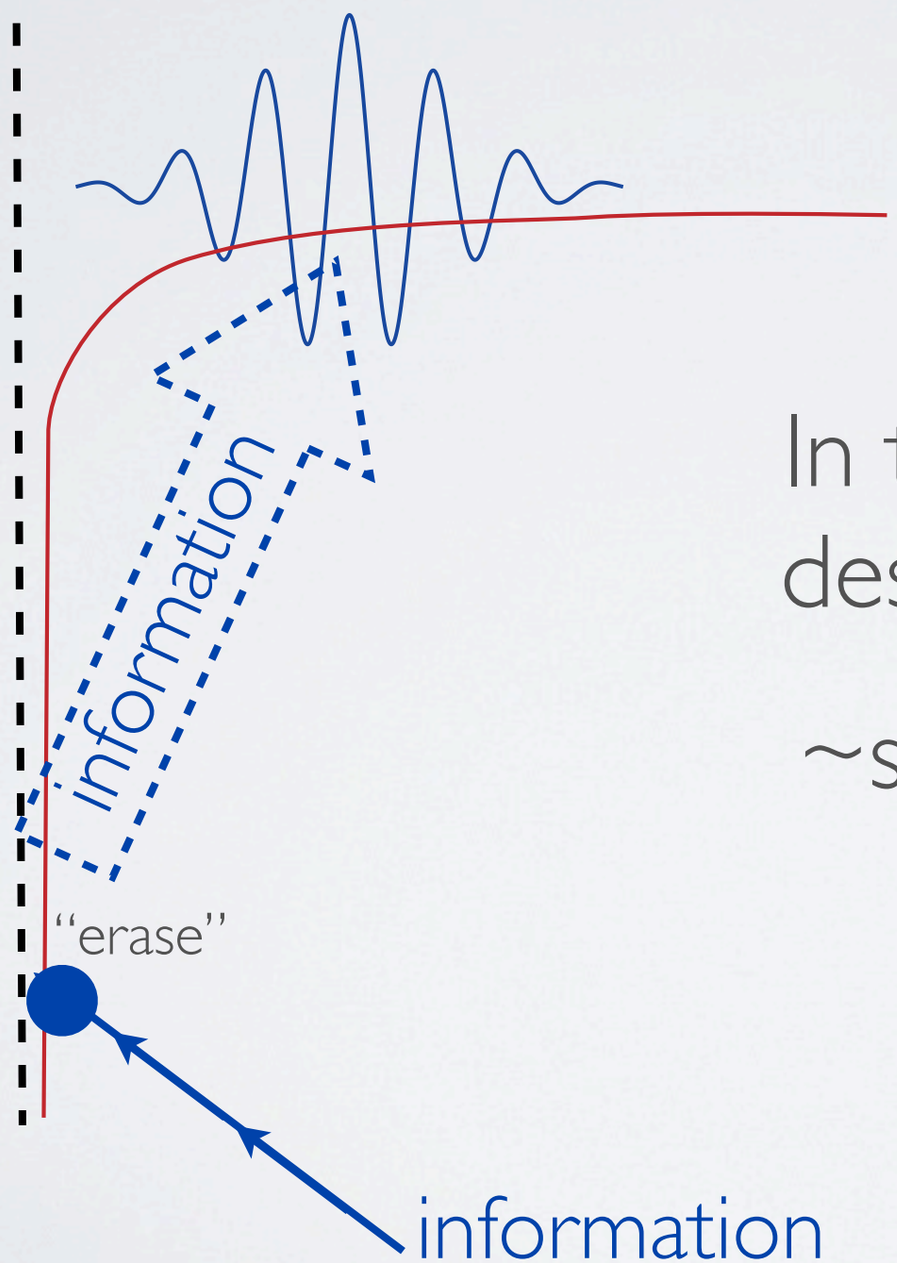

"Weak complementarity:"

once you pass the info. transfer time for a given "bit," it should no longer have an internal description

(nice-slice description bad at long times)

# Comment re. complementarity, cont'd:

The basic physics may allow a different choice of gauge:




In this gauge: no manifest description of BH interior

~strong complementarity

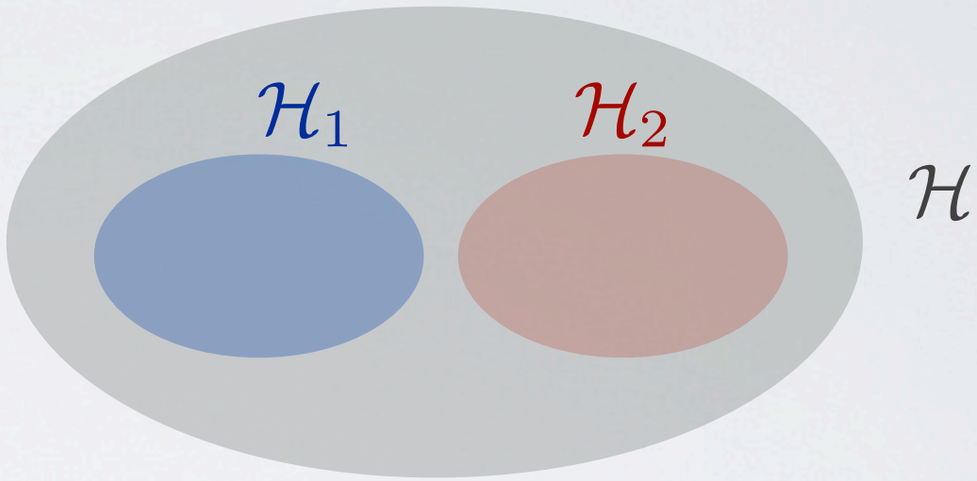
(1211.7070)

# 5. Thoughts on a fundamental framework:

## Hilbert space networks

- Quantum states more basic than spacetime -

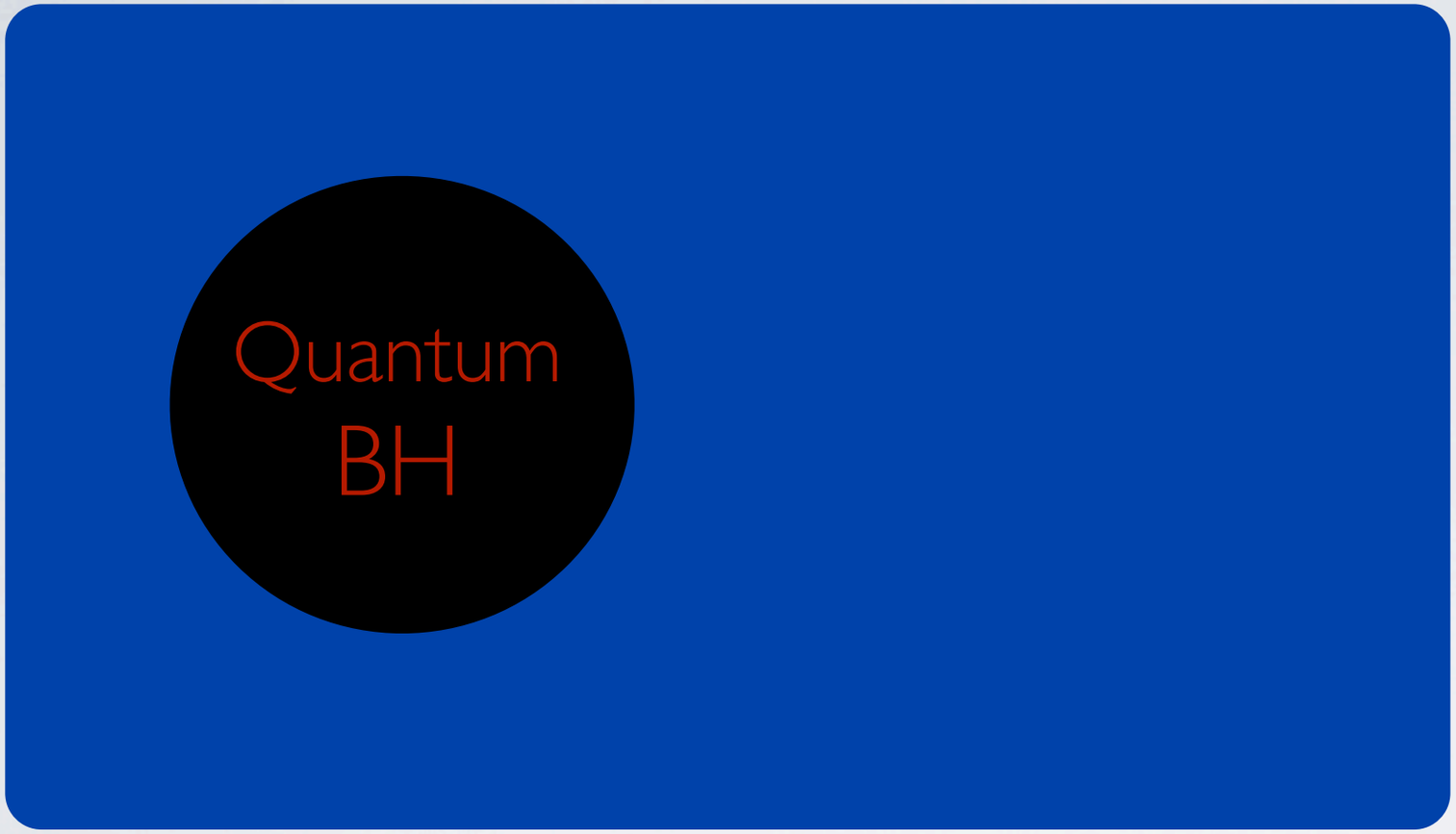
Approximate "localization:"
subsystem structure




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

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

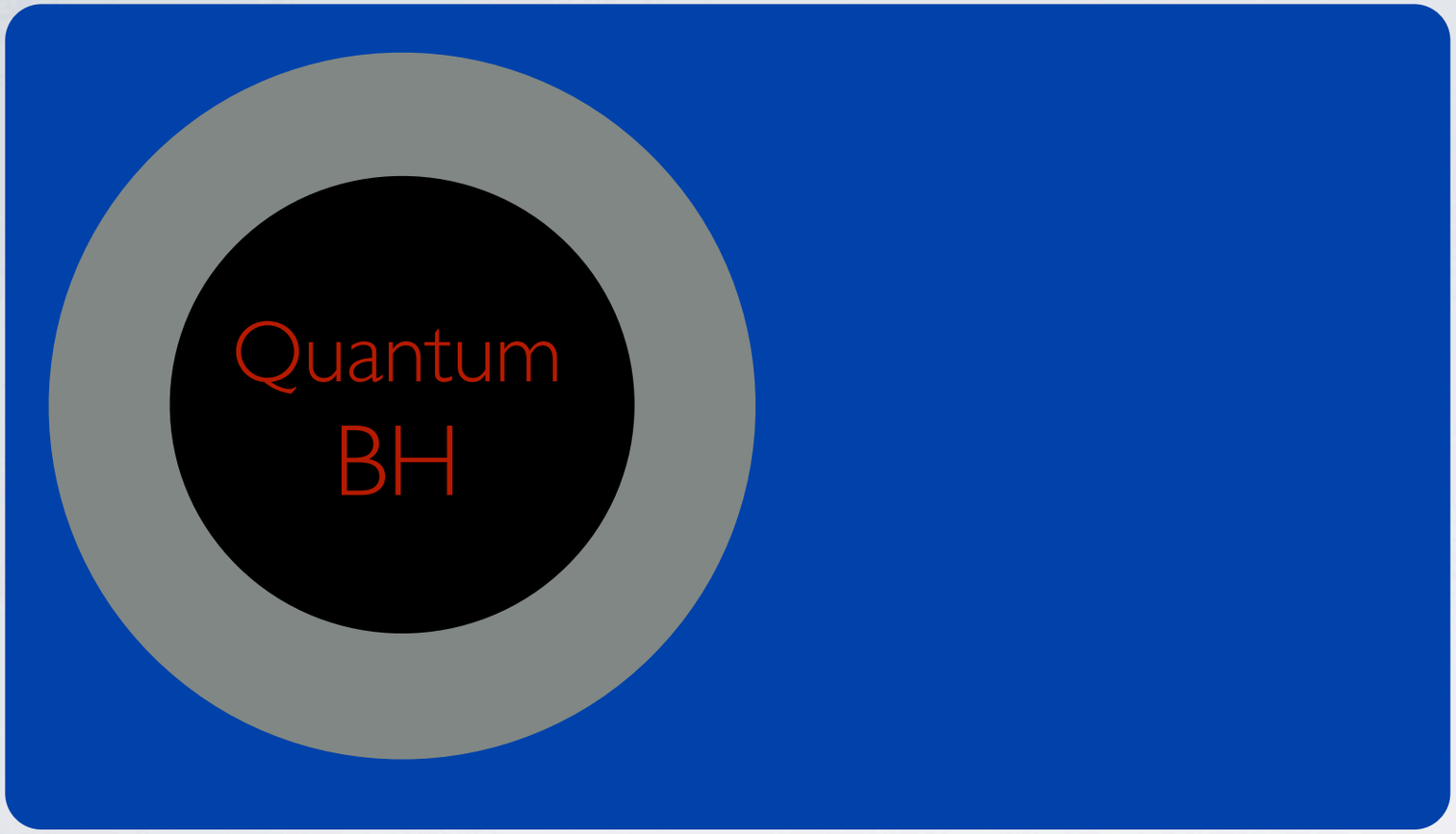
# Example: black hole plus environment




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

(nb: AdS/CFT could work this way)

# Example: black hole plus environment




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

(nb: AdS/CFT could work this way)

Some expectations:

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

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

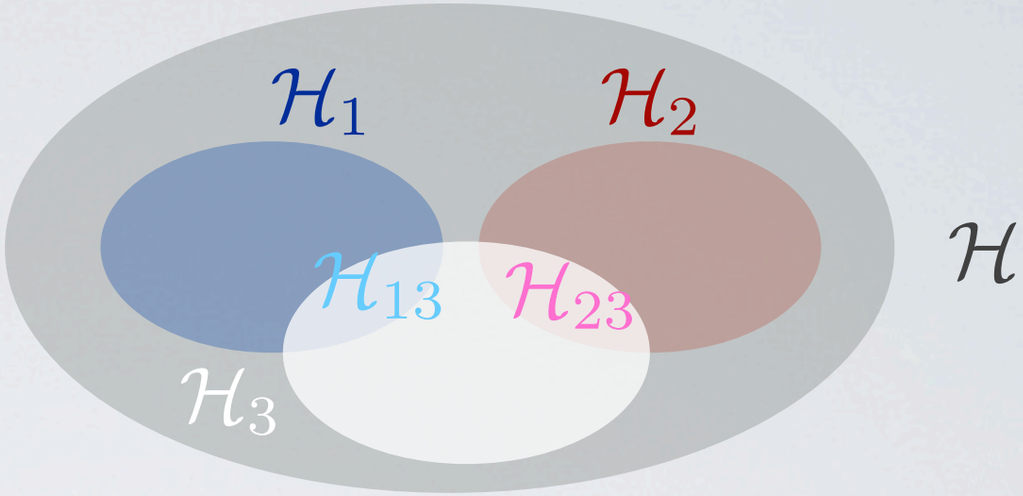
$$\mathcal{H}_{BH} \neq LQFT$$

$$U \approx LQFT$$

$$U \neq LQFT$$

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

~ quantum analog of manifold:




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

- Unitary evolution; ~local, LQFT

- Locality: conditions on evolution

- Symmetries

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

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

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

Conclusions:

To save QM, we apparently must transfer quantum information out of black holes.

(unless never localized to begin with -- hard to understand?)

This requires nonlocality, with respect to a description via semiclassical geometry

One scenario (violent) involves large deviation from semiclassical geometry, and replaces BHs with "star-like" objects - massive remnants

fuzzballs, firewalls, ...

In the "nonviolent nonlocality" scenario, the semiclassical geometry remains a good approximation for some aspects of the description. The quantum information transfer has "minimal" effect.

- Can parameterize in effective QFT framework

hamiltonian; bi- (multi-) local interactions

- Outside description:

  ~ Effective source

  Information carrying capacity easily met

  Nonsingular stress tensor; "small" effect

  Flux of modes w/ info increases w/ string mining

- Generic such couplings: predict extra flux, beyond Hawking

- Other physical constraints...

Fundamental description: likely *not* based on spacetime