# Entanglement transfer from black holes via *small* couplings: basic postulates to "soft quantum structure"

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1701.08765, + predecessor papers

(A pure QI problem: 1710.00005 w/ M. Rota)

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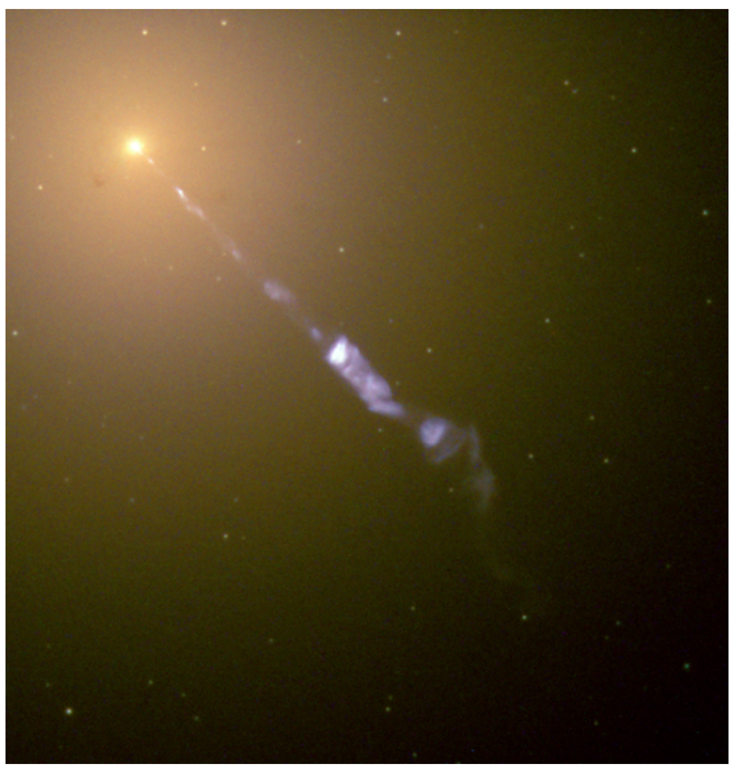
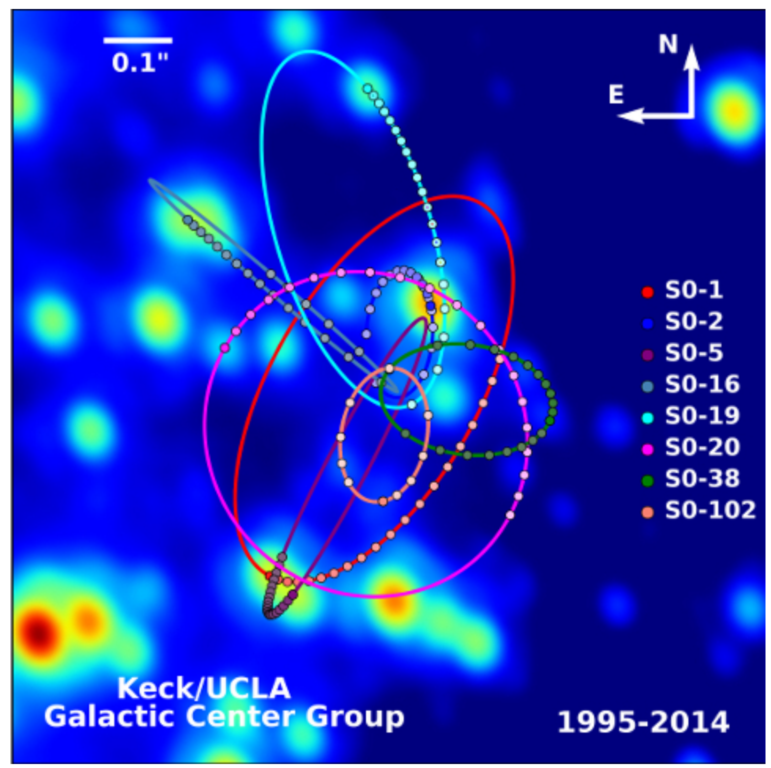
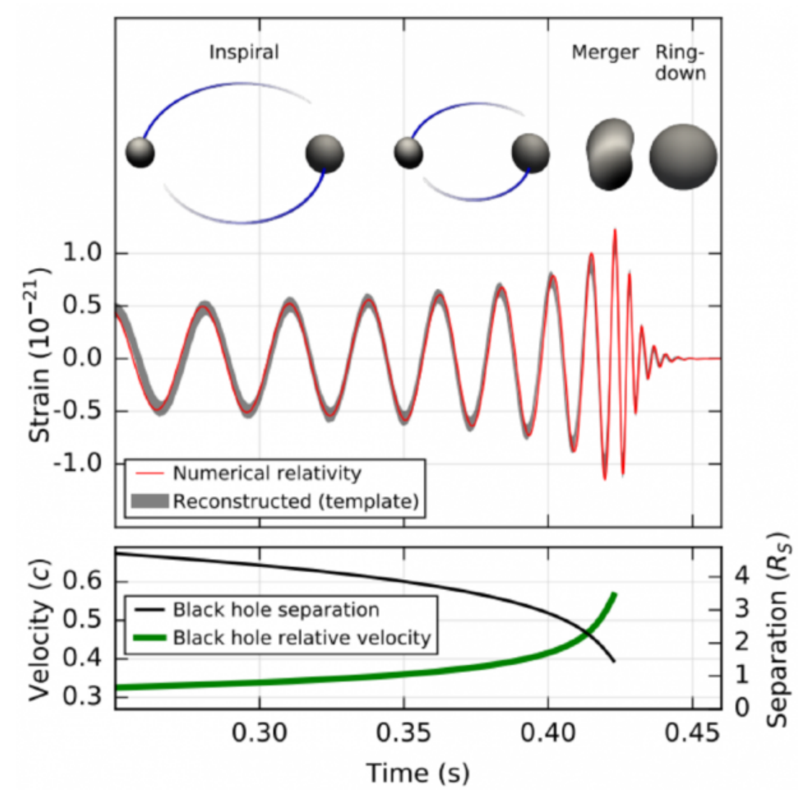
# The Black Hole "Information Paradox" has been a major driver for investigating QI/QG connections

- BHs appear to exist:






- No known description of their evolution, consistent with Quantum Mechanics

I’ll take an approach that can be motivated by QI theory

Subsystems, Hamiltonian evolution,…

Big question: how to reconcile with what we know (or believe) about BHs and gravity

“Info. paradox” reveals a contradiction between principles underlying LQFT

1) Relativity 2) QM 3) Locality

… why the problem is so interesting

## Lay out some basic assumptions:

Postulate I, *Quantum mechanics*: linear space of states, unitary S-matrix (in appropriate circumstances) …

Need further structure.

## Suggested approach:

A BH is just another kind of quantum subsystem of a quantum system (the Universe) — at least to good approximation

Likewise for its environment.

*This is a subtle point in a theory with gravity.*

QFT: Subsystems $\leftrightarrow$ local subalgebras of observables

Gravity: No local observables

such subtleties in localization help motivate various proposals:

"Soft hair" - Hawking, Perry, Strominger

ER=EPR

But, have seen some indications working perturbatively for a notion of localized subsystems in gravity.

1706.03104, w/ Donnelly; also WIP with S. Weinberg

and, so far, no strong evidence for a resolution based on its failure

So,

Postulate II, *Subsystems*: The Universe can be divided into distinct quantum subsystems, at least to a good approximation

"What about AdS/CFT?"

After 20 years, don't know how it works; will investigate from "bulk" viewpoint, which is closest to what we observe and really understand

We'd like to be "close" to such a description via GR+LQFT:

Postulate III, *Correspondence with LQFT*: Observations of small freely falling observers in weak curvature regimes are approximately well described by a local quantum field theory lagrangian. They find "minimal" departure from relativistic LQFT.

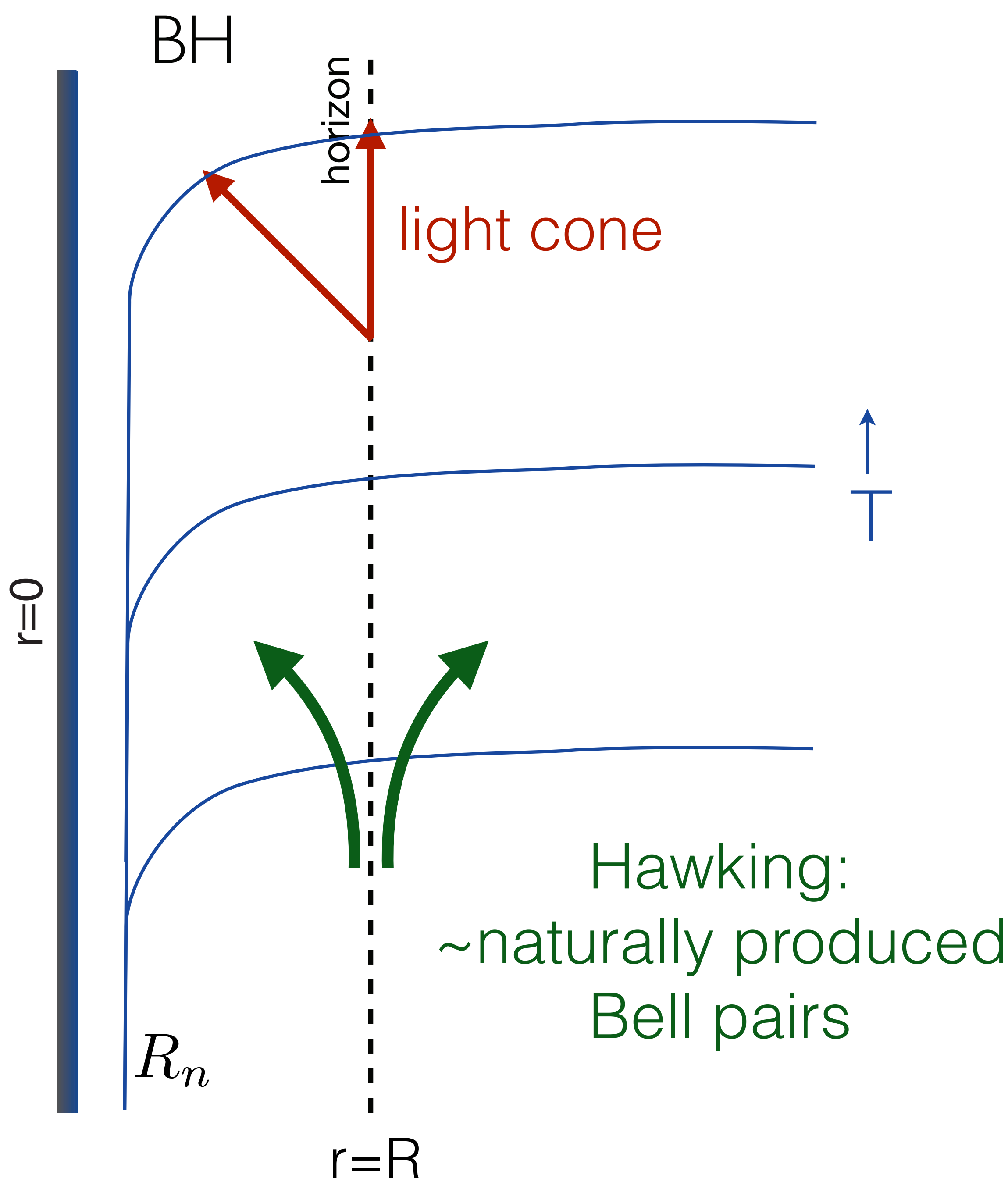
*Includes observers crossing big horizons.*

("nonviolent")

But this is where things get challenging.

# Illustrate postulates and problem w/ a warmup:

## Schrodinger evolution, LQFT in BH background




$$ds^2 = -N^2 dT^2 + q_{ij}(dx^i + N^i dT)(dx^j + N^j dT)$$

E.g. evolution of scalar matter:

$$U(T) = \exp\left\{-i \int dT H\right\}$$

$$H = H(\phi, \pi)$$

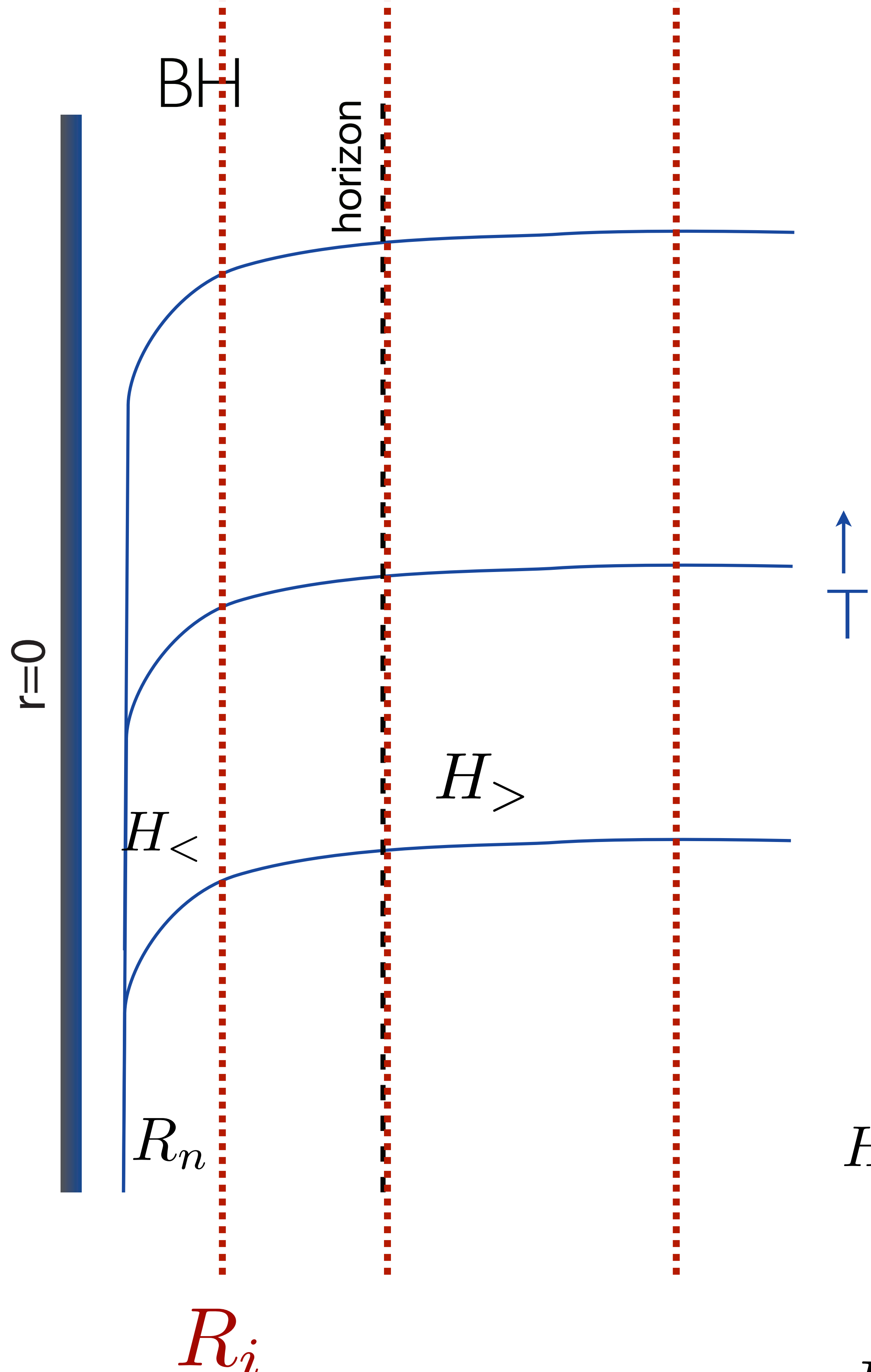
$$\pi(x) = -i\frac{\delta}{\delta\phi(x)}$$

(Unitary on these slices, w/G=0)

QM ✓

## Subsystems:

In LQFT, subregions ⟷ subalgebras “subsystems”




Subtlety in gravity: dressing

Small effect? $\sim GE_{cm}/r$

[SBG and Lippert; Donnelly and SBG, 1507.07921]

Assume: good approx.

1706.03104 w/Donnelly; in progress w/ S. Weinberg

Subsystem evolution:

$$H = H_{<} + H_{>} + H_i$$

$$H_{\lessgtr} = \int_{r \lessgtr R_i} d^{D-1}x\sqrt{q}\left[\frac{1}{2}N(\pi^2 + q^{ij}\partial_i\phi\partial_j\phi) + N^i\pi\partial_i\phi\right]$$

$H_i$ : local at $R_i$

The problem w/ this LQFT description:

Unitarity ultimately fails (violates Postulate I)   $G \neq 0$

Why?

1) H only increases entanglement with BH subsystem

Transfers info in;

Hawking radiation builds up entanglement

2) BH subsystem has unbounded dimension

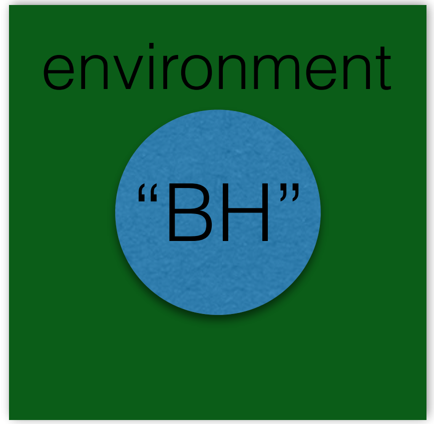
When BH disappears, unitarity violated

So, *modifications needed to save QM ("unitarize")*

# *Unitarization:*

## Structural modifications needed — *follow postulates (+1)*

Postulate II:




$$|K, M; \psi_e, T\rangle$$

$H_I$

Postulate I:

1) Interactions must allow information (entanglement) transfer out $\quad H_I$

2) BH Hilbert space must behave finite-dimensionally

$$K = 1, \cdots, N \sim e^{S_{bh}} \quad \text{in} \quad \Delta M \sim 1/R$$

~1 qubit/R

"To beat Hawking"

Have assumed subsystems and Hamiltonian evolution.

Next, postulate III: Correspondence w/ LQFT description.

"environment" *approximately* described via LQFT $(r > R_i)$

$$H = \underbrace{H_<}_{\uparrow\ ?} + \underbrace{H_> + H_i}_{\sim\text{LQFT}} + H_I$$

$H_I$ ← what structure?

(work in spirit of effective field theory…)

Bilinear needed to transfer entanglement:

$$H_I = \sum_{Ab} \int d^{D-1}x \sqrt{q}\, G_{Ab}(x) \quad \lambda^A\, O^b(x)$$

$\lambda^A$: U(N) generators    $O^b(x)$: Act on > subsystem

$G_{Ab}(x)$ :    parameterize ignorance

Will constrain these.

$$H_I = \sum_{Ab} \int d^{D-1}x \sqrt{q}\, G_{Ab}(x)\, \lambda^A\, O^b(x)$$

Constraints:

1) Postulate III: “Minimize” departure from LQFT

- Supported near the BH scale $R_a$

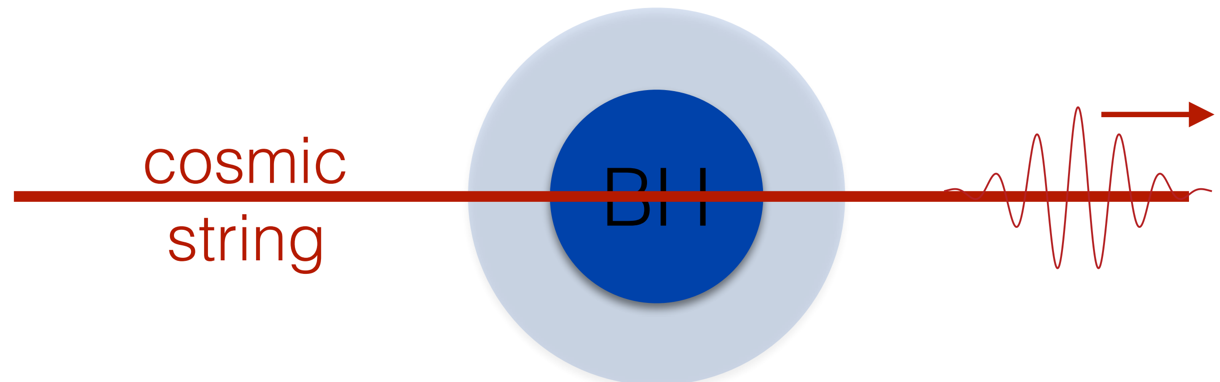
- Not confined too near the BH

$R_a = R + l_{pl}$ : “FW” (tuned) vs. $R_a \sim R$ : nonviolent

- Simplest implementation: characteristic scales ~R,

also $\Delta M \sim 1/R$

# 2) Consistency with mining; approx. w/ BH thermo.




Suggests: (optional??)

Postulate IV, *Universality*: Departures from the usual LQFT description influence matter and gauge fields in a universal fashion.

E.g.:

$$H_I = \int d^{D-1}x \sqrt{q} \underbrace{\sum_A \lambda^A G_A^{\mu\nu}(x)}_{H^{\mu\nu}(x)} T_{\mu\nu}(x)$$

also want pert. gravitons

~ "BH state-dependent metric perturbation"

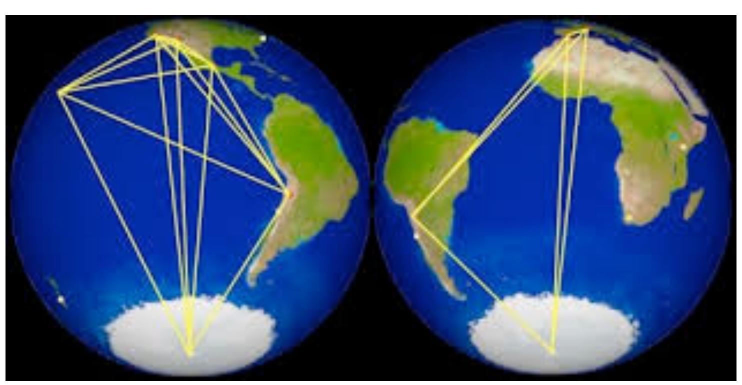
# 3) Need sufficient information transfer ~1/R

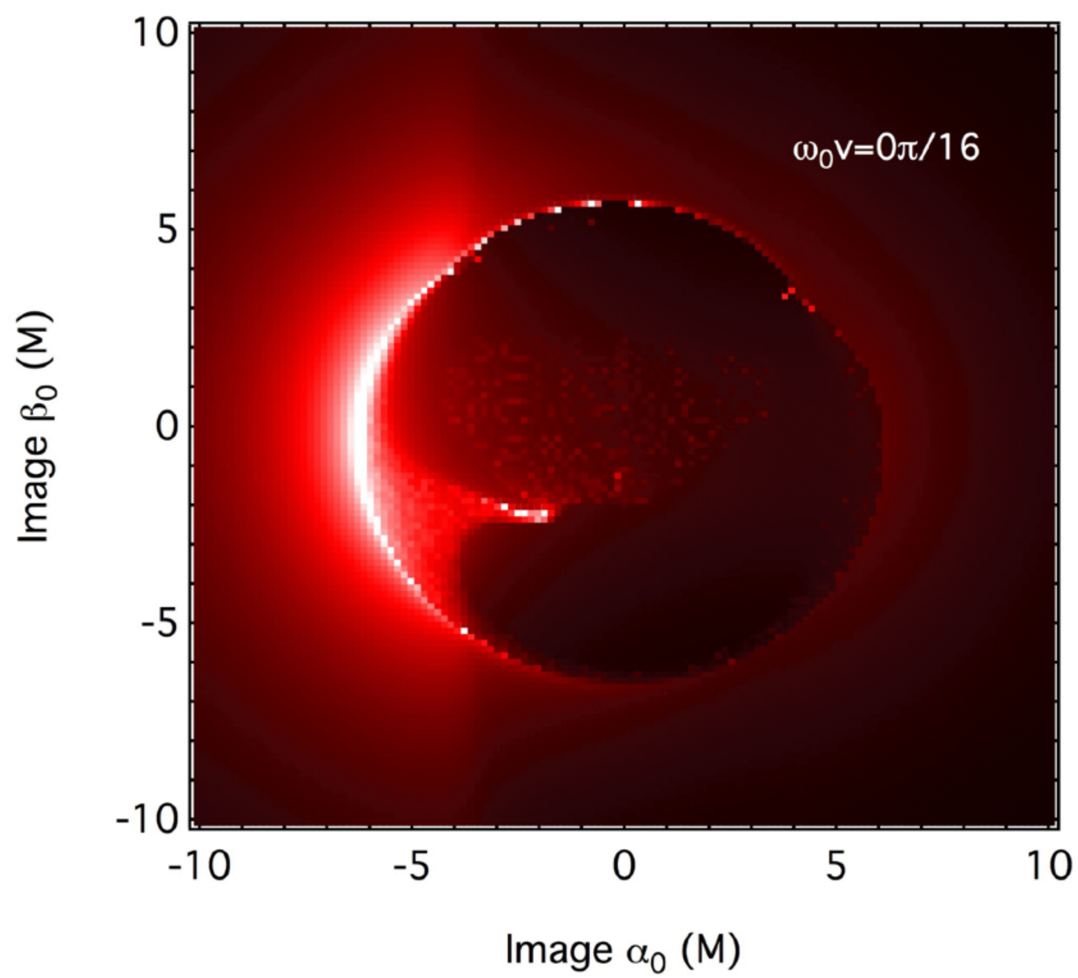
What would easily *suffice*: $\langle\psi, T|H^{\mu\nu}(x)|\psi, T\rangle \sim 1$

(fluctuation scales ~ R)

arXiv:1401.5804

This could also produce observable effects, e.g. to Event Horizon Telescope! (Sgr A*, M87)






[SG/Psaltis]
1606.07814

# But, are such large effects *necessary*?

$$H_I = \int d^{D-1}x \sqrt{q} \sum_A \lambda^A G_A^{\mu\nu}(x)\, T_{\mu\nu}(x)$$

## Reorganize:

Expand: $$G_A^{\mu\nu}(x) = \sum_{\gamma=1}^{\chi} c_{A\gamma} f_\gamma^{\mu\nu}(x)$$

Small basis of functions
(Postulate III-NV)

$$O_\gamma = \sum_A \lambda^A c_{A\gamma}$$

$$\mathcal{T}_\gamma = \frac{1}{\mathcal{E}} \int d^{D-1}x \sqrt{q} f_\gamma^{\mu\nu}(x) T_{\mu\nu}(x)$$

$$\mathcal{E} \sim 1/R$$

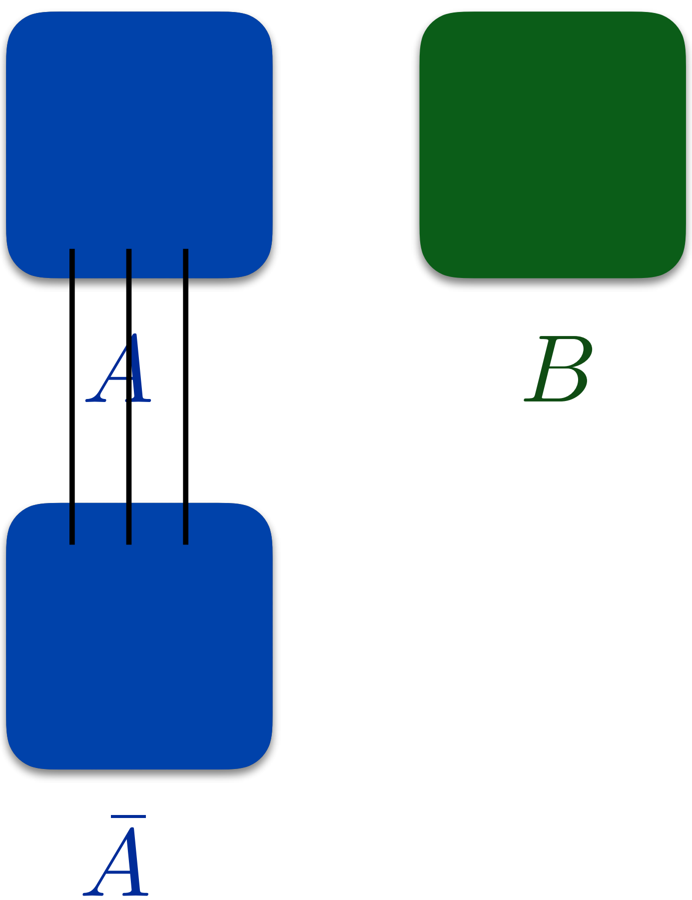
$$H_I = \mathcal{E} \sum_{\gamma=1}^{\chi} O_\gamma \mathcal{T}_\gamma$$

$\chi$ “channels” or “pathways”

How do we see that sufficient information transfers?

# A problem and conjecture in quantum information theory:

Subsystems




$e.g.\ |A| \ll |B|$

$$H = H_A + H_B + H_I$$

$$H_I = \mathcal{E} \sum_{\gamma=1}^{\chi} c_\gamma O_A^\gamma O_B^\gamma$$

Common scale

$$\|O_{A,B}^\gamma\| = 1$$

How fast transfers information?

$$I(\bar{A} : B) = S_{\bar{A}} + S_B - S_{\bar{A}B}$$

Take, e.g., $H_A = \mathcal{E} \sum_a h_a \lambda^a$

$\sum_a (h_a)^2/|A| = 1$

~"random"

## Conjecture:

$$\frac{dI}{dt} = C\mathcal{E}\sum_{\gamma=1}^{\chi} c_\gamma^2 \qquad \text{for} \quad c_\gamma \lesssim 1$$

- working on checking (WIP w/ Rota and Nayak)
- evidence in 1710.00005 w/ Rota
- applications to decoherence, thermo.
- will explain some motivation shortly

future discussion?

Black holes: $$H_I = \mathcal{E} \sum_{\gamma=1}^{\chi} O_\gamma \mathcal{T}_\gamma$$

let $\|O_\gamma\| = 1$ $\|\mathcal{T}_\gamma\| \sim 1$

$$\Rightarrow \frac{dI}{dt} \sim \mathcal{E} \sim \frac{1}{R}$$ ✓

Rewrite: $$H_I = \mathcal{E} \sum_{\gamma, A} \lambda^A c_{A\gamma} \mathcal{T}_\gamma$$ $(\mathcal{O}_\gamma \sim \text{random})$

$\wr$ couplings to BH states

$c_{A\gamma} \sim \sqrt{1/N} \sim e^{-S_{bh}/2}$ tiny

(contrast previous arguments)

# Some motivation: Fermi's Golden Rule

$$\frac{dP}{dt} = 2\pi\rho(E_f)|H_I|^2$$

decay rate ~ info transfer rate

( see 1710.00005 w/ Rota)

(many final states)(tiny couplings)$^2$ ~ O(1) rate

Also means

$$\langle\psi, T|H^{\mu\nu}(x)|\psi, T\rangle \sim \frac{1}{\sqrt{N}} \sim e^{-S_{bh}/2}$$

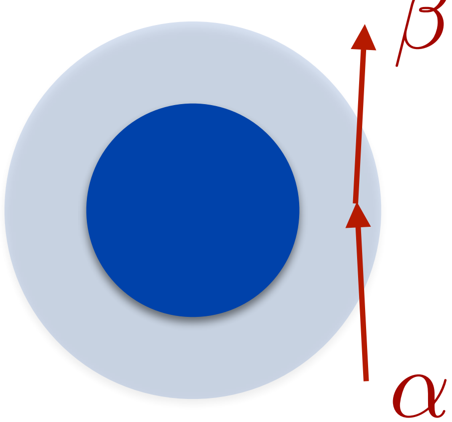
Compare previous: ~ incoherent, vs. coherent effect

# Observational constraints?

-no large ~classical fluctuations

-estimate effect on matter, light: ~ Golden Rule:

$$\Gamma \sim \omega^{bh}(M)\mathcal{E}^2 \sum_\gamma |\langle K|O_\gamma|\psi\rangle|^2 \; |\langle\beta|\mathcal{T}_\gamma|\alpha\rangle|^2$$




- also can be $\mathcal{O}(1/R)$

- typical $\Delta p \sim (1/R)$ ("nonviolent")

- tiny effect on matter, light

- but: possible signal in GWs - LIGO/VIRGO??

# To summarize,

## Investigated postulates:

Postulate I, *Quantum mechanics*: linear space of states, unitary S-matrix (in appropriate circumstances) …

Postulate II, *Subsystems*: The Universe can be divided into distinct quantum subsystems, at least to a good approximation

Postulate III, *Correspondence with LQFT*: Observations of small freely falling observers in weak curvature regimes are approximately well described by a local quantum field theory lagrangian. They find "minimal" departure from relativistic LQFT.

Postulate IV, *Universality*: Departures from the usual LQFT description influence matter and gauge fields in a universal fashion.

(incidentally: III+IV ~ "weak quantum equivalence principle")

- lead to "soft quantum structure" of BHs
- very weak interactions that can transfer information out
- an interesting connection with a problem in QI theory

# Questions:

## Refine description of such "entropy-enhanced" transfer

also, size of exterior effects - GWs, etc.: more systematic

## Observability

LIGO/VIRGO; EHT?

$$\langle H_{\mu\nu} \rangle \sim 1 \quad \text{vs.} \quad \langle H^{\mu\nu}(x) \rangle \sim 1/\sqrt{N} \sim e^{-S_{bh}/2}$$

becoming empirical question …

## Beyond effective description to more complete description

Connection w/ subsystem subtleties/dressing

maybe soft quantum hair ??

but, 1706.03104 w/ Donnelly…

More complete thermodynamic tests

Gauge independence

## Foundational picture for QG, respecting principles

# Backups

Comment on approach: working *towards* fundamental framework, don't have complete story

"Effective" description — parameterize departures from current best-tested framework, LQFT

Some questions premature.

Follow postulates to logical conclusions

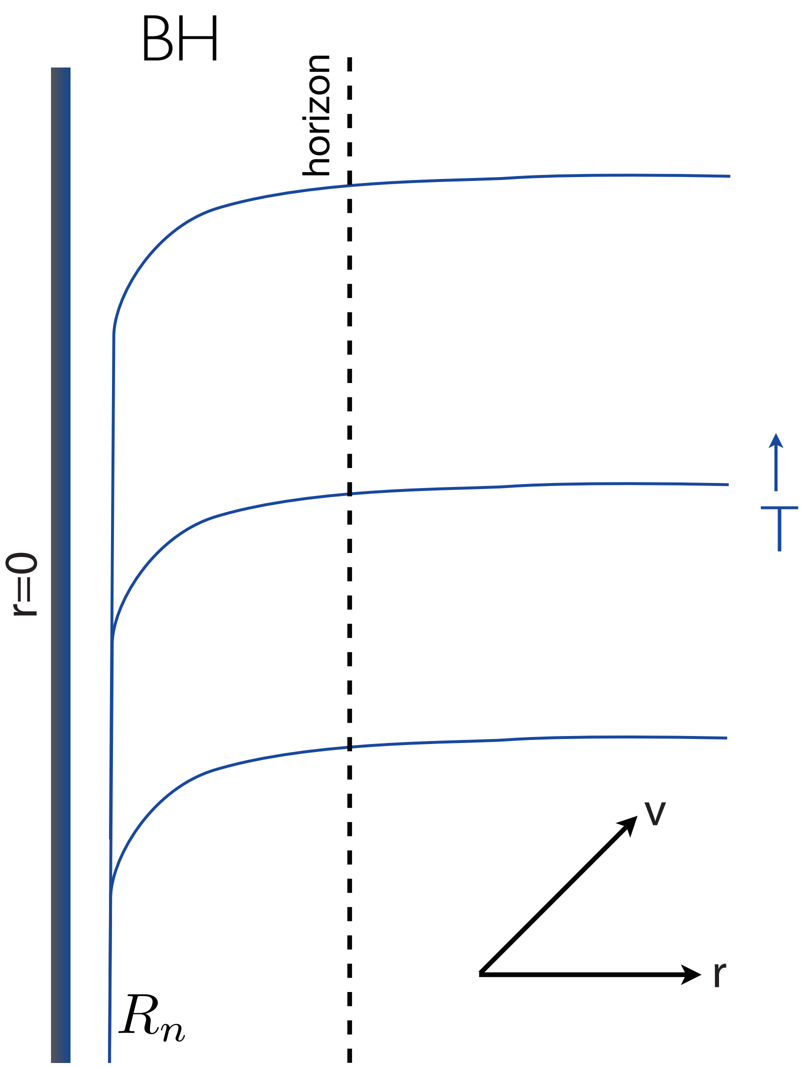
If the conclusions are wrong, either:

One or more of these Postulates wrong: *interesting.*

Logic wrong. Also interesting?

If right, also interesting.

# BH slicing: explicit description




$$ds^2 = -f(r)dv^2 + 2dvdr + r^2 d\Omega^2_{D-2}$$

$$f(r) = 1 - \mu(r)$$

$$\mu(r) = \left(\frac{R}{r}\right)^{D-3}$$

$$v = T + s(r)$$

arbitrary; e.g. $s(r) = r$

$$ds^2 = -N^2 dT^2 + q_{ij}(dx^i + N^i dT)(dx^j + N^j dT)$$

$$N^2 = \frac{1}{s'(2-fs')} \quad , \quad N_r = 1 - fs' \quad , \quad q_{rr} = s'(2-fs')$$

$s(r) = r:$ $$N^2 = \frac{1}{1+\mu(r)} \quad , \quad N_r = \mu(r) \quad , \quad q_{rr} = 1 + \mu(r)$$