Black Holes as harbingers of new gravitational physics

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

Physics Today April 2013

Steve Giddings,
University of California, Santa Barbara, and CERN

2018 Arnold Sommerfeld School
Black holes and quantum information

Oct. 10, 2018

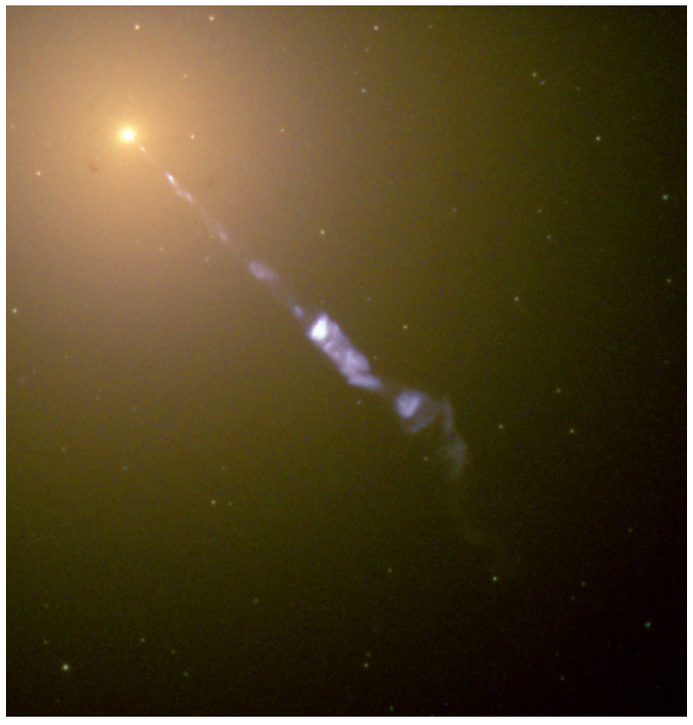
Supported in part by the US DOE

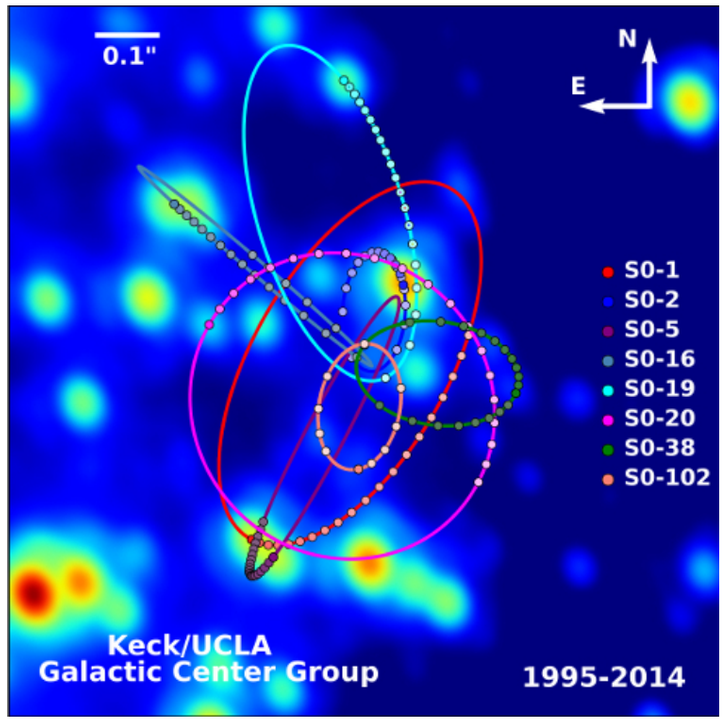
First a word from my “sponsor:”

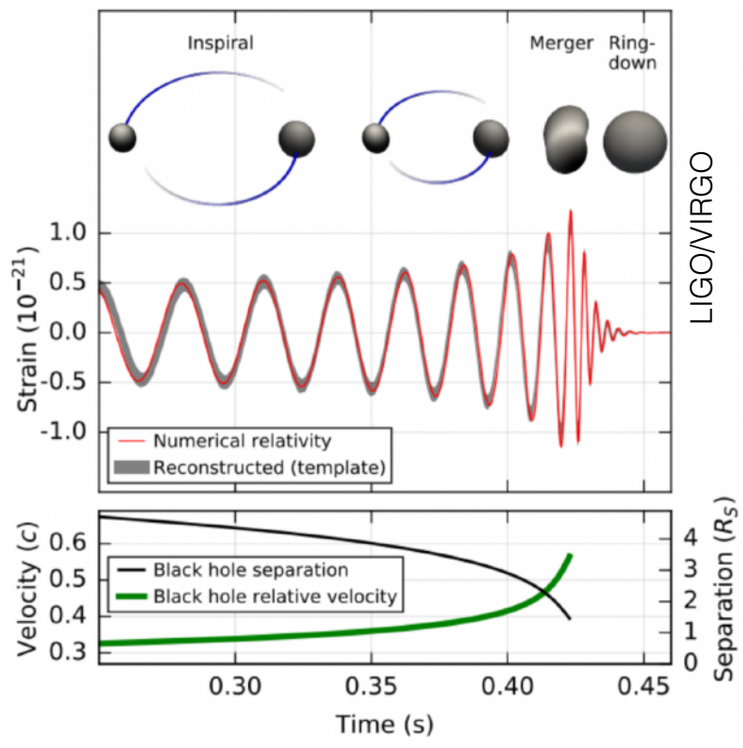
Talented and motivated postdoc (and grad school) applicants: *apply here!*

A *profound* problem in current theory:

- BHs appear to exist:







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

Plausibly provides guidance for problem of Quantum Gravity

Here, many perceive the need for a conceptual revolution

"quantum mechanics vs. spacetime"

Historical focus: infinities/nonrenormalizability

(e.g. large motivator of string theory)

short distance; plausibly the "wrong problem"

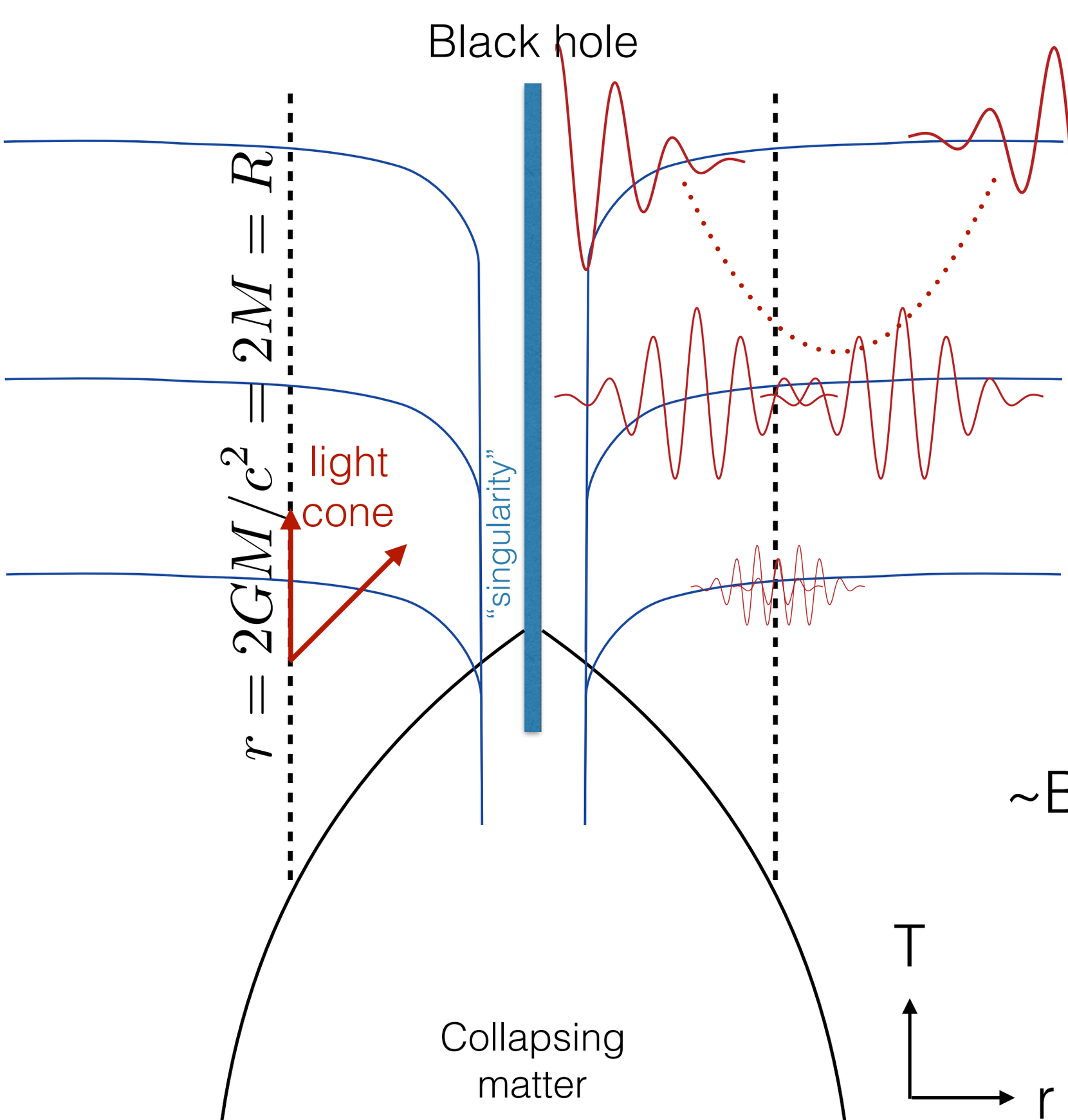
Black holes - present a more profound problem:

- glaring conflict w/ QM (unitarity)

- problem in *long distance* physics

The essential problem:

Hawking radiation



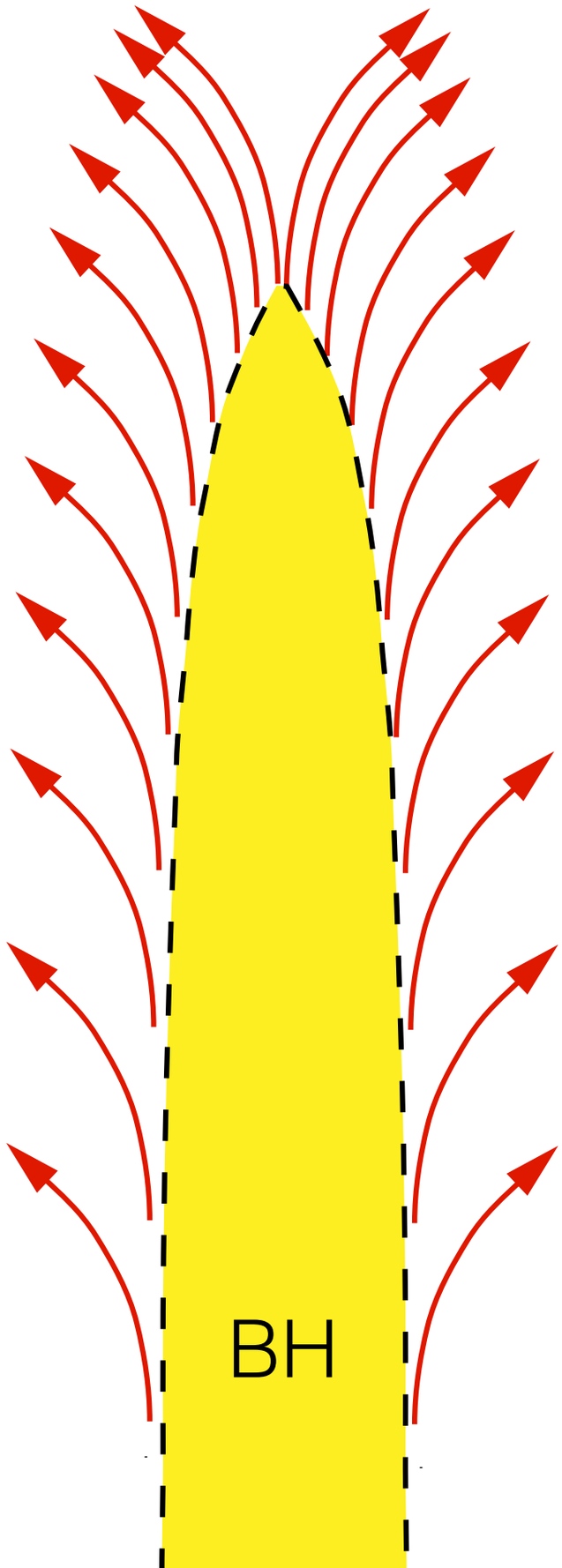
$$E \sim T_H \sim \frac{1}{R}$$

$$|\Psi\rangle_{\text{Hawking}}$$

$$\sim |\hat{0}\rangle|0\rangle + |\hat{1}\rangle|1\rangle$$

~Bell state, EPR pair

Entangled



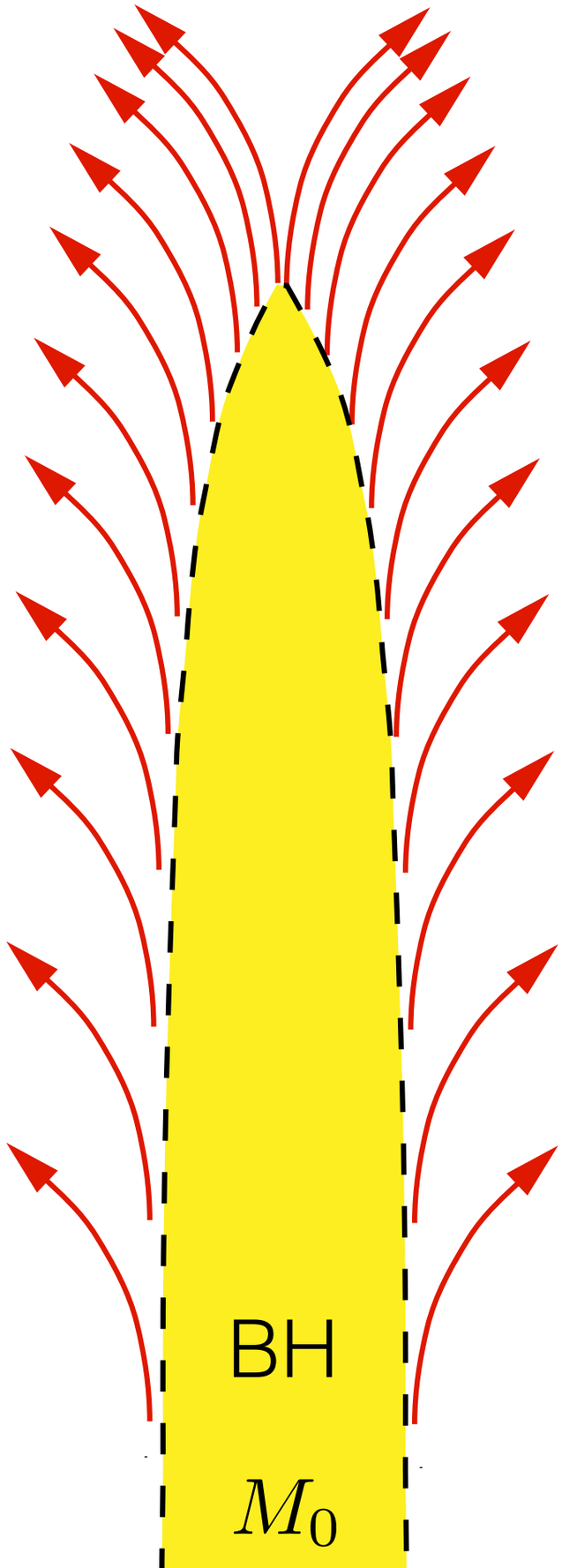
~1 Hawking quantum per time R

$$|\Psi\rangle_{\rm Hawking} \sim \left(|\hat{0}\rangle|0\rangle + |\hat{1}\rangle|1\rangle\right)^{\otimes N}$$

BH disappears

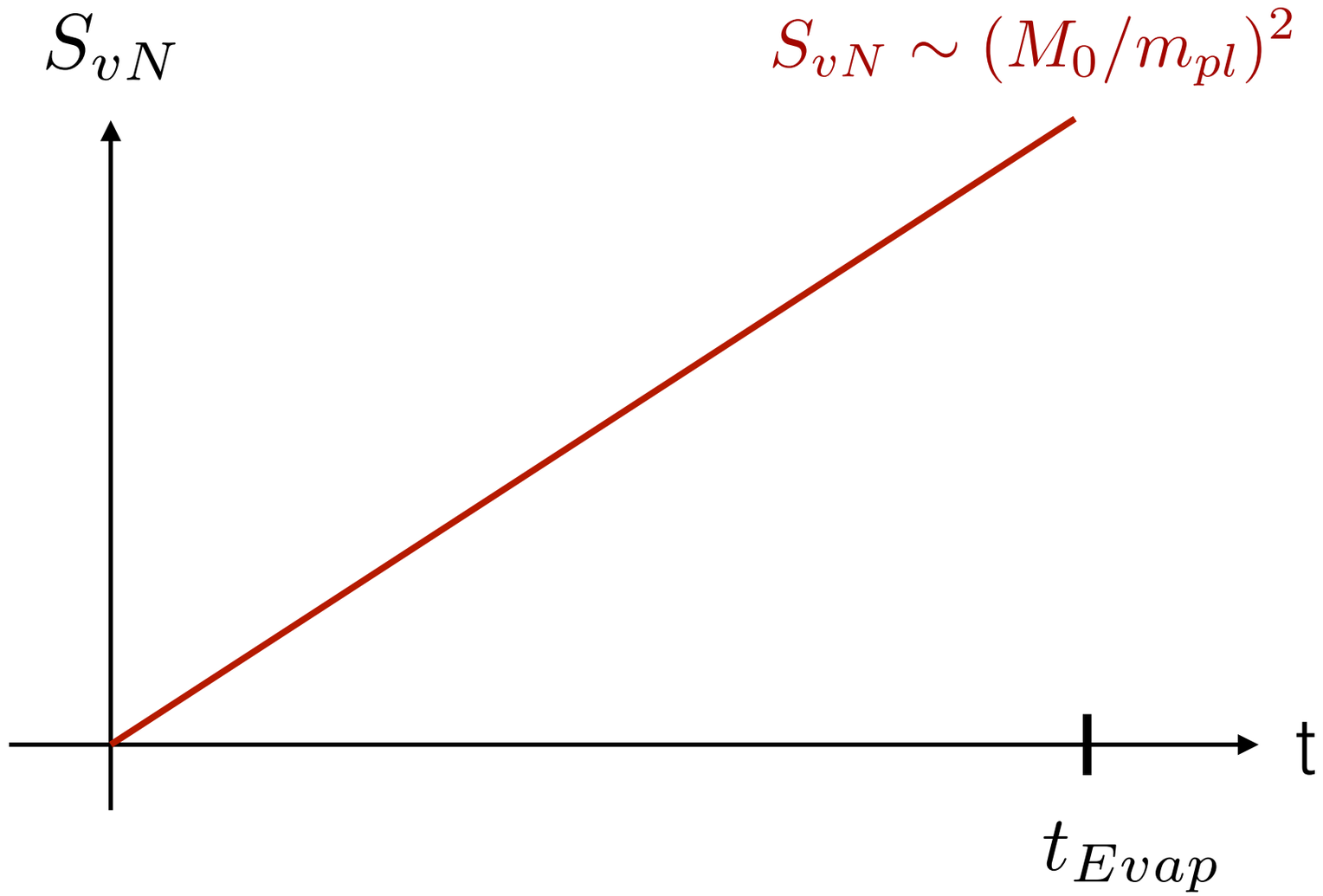
$$\rho_{\rm Hawking} = {\rm Tr}_{BH}\left(|\Psi\rangle\langle\Psi|\right) \sim \left(|0\rangle\langle 0| + |1\rangle\langle 1|\right)^{\otimes N}$$

$|\psi\rangle \to \rho$: violates QM (unitarity)



Quantified by:

$$S_{\text{von Neumann}} = -Tr(\rho \log \rho) = -\Delta I$$



So breakdown in QM (unitary evolution):

$$\longleftrightarrow \quad S_{vN} \sim (M_0/m_{pl})^2 \sim A(M_0)/4G_N$$

Crisis. Possible resolutions:

1) “Mundane” resolution, e.g. microscopic black hole remnants

… apparently ruled out (physics unstable: infinite degen.)

2) Error in reasoning

… very unlikely, after 40+ years (but see later)

3) Error in principles

… increasingly likely

→ New physical principles, associated with gravity …

Exciting; black holes as guides.

Apparently, this “unitarity crisis” reveals a contradiction between foundational principles underlying Local Quantum Field Theory (LQFT)

1) Relativity 2) QM 3) Locality

… why the problem is so interesting

If so, one or more of these principles must be modified …

Our analog of the hydrogen atom in classical physics?

Fundamentally new physics of quantum gravity!

Error in principles - first suggestion:

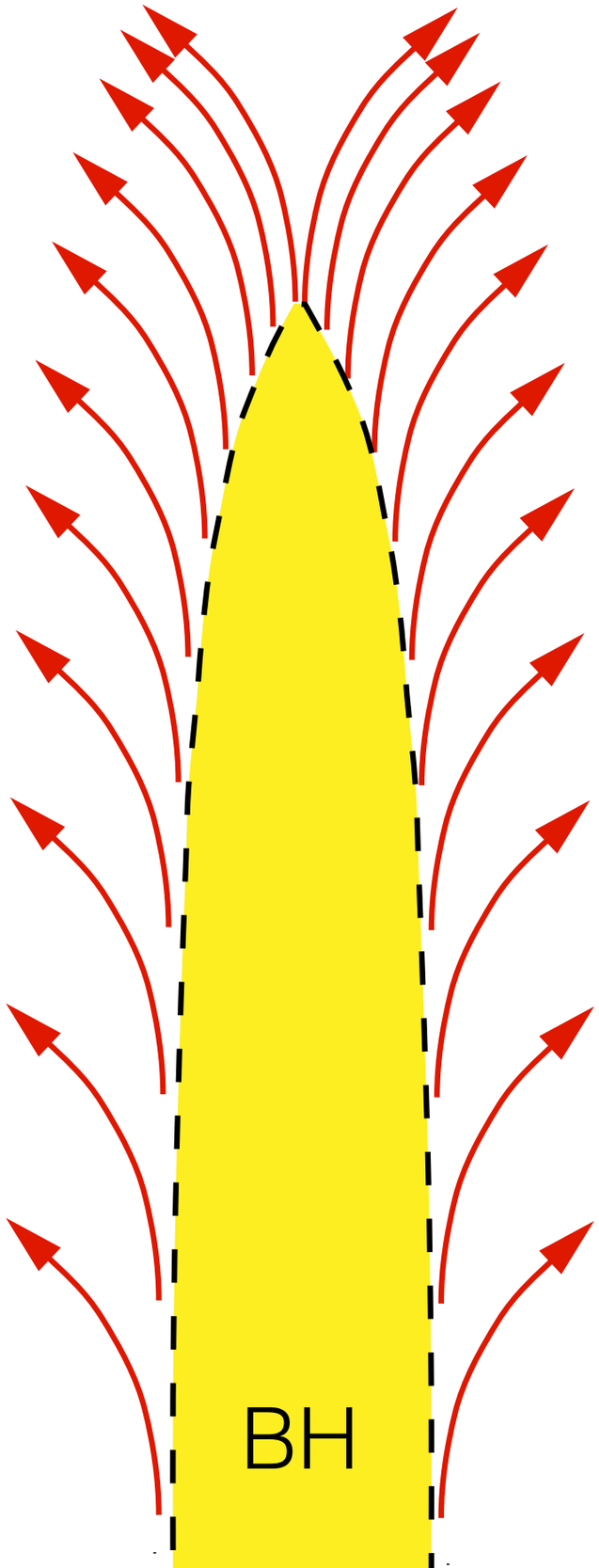
Hawking (1976): breakdown of unitary quantum evolution
(principle of QM)

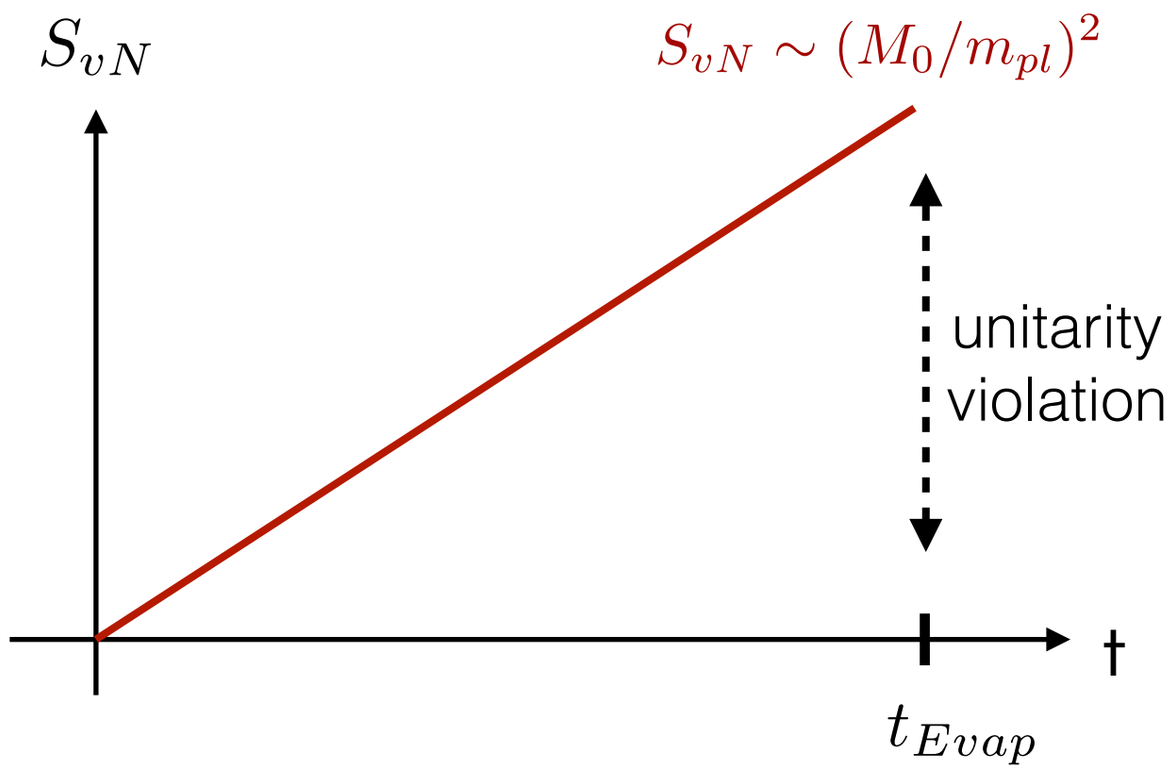
But, Banks, Peskin, Susskind (1984):

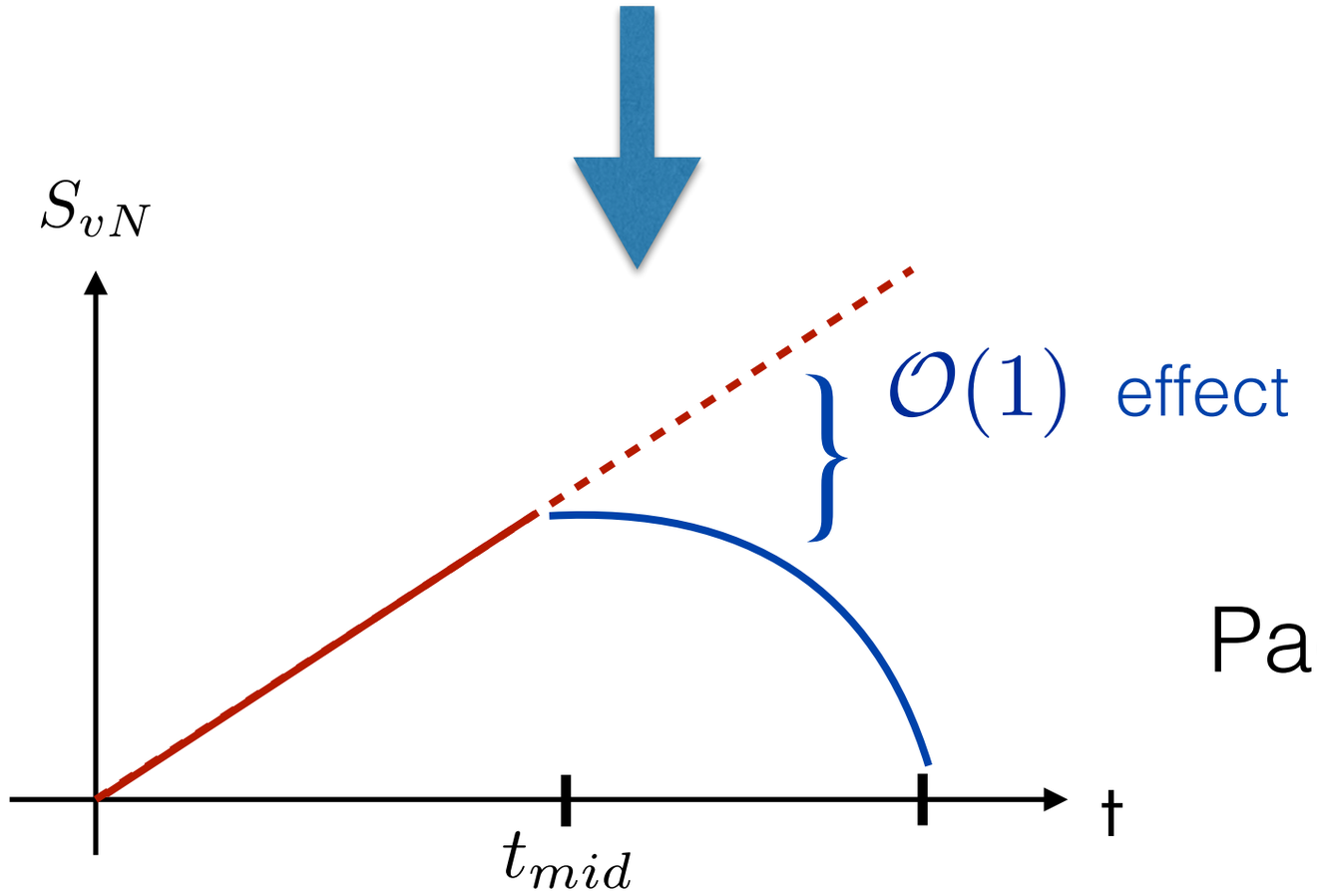
This implies massive breakdown of energy conservation,
in violent disagreement with experience

So, I'll stick with quantum mechanics.

What's needed to save QM:







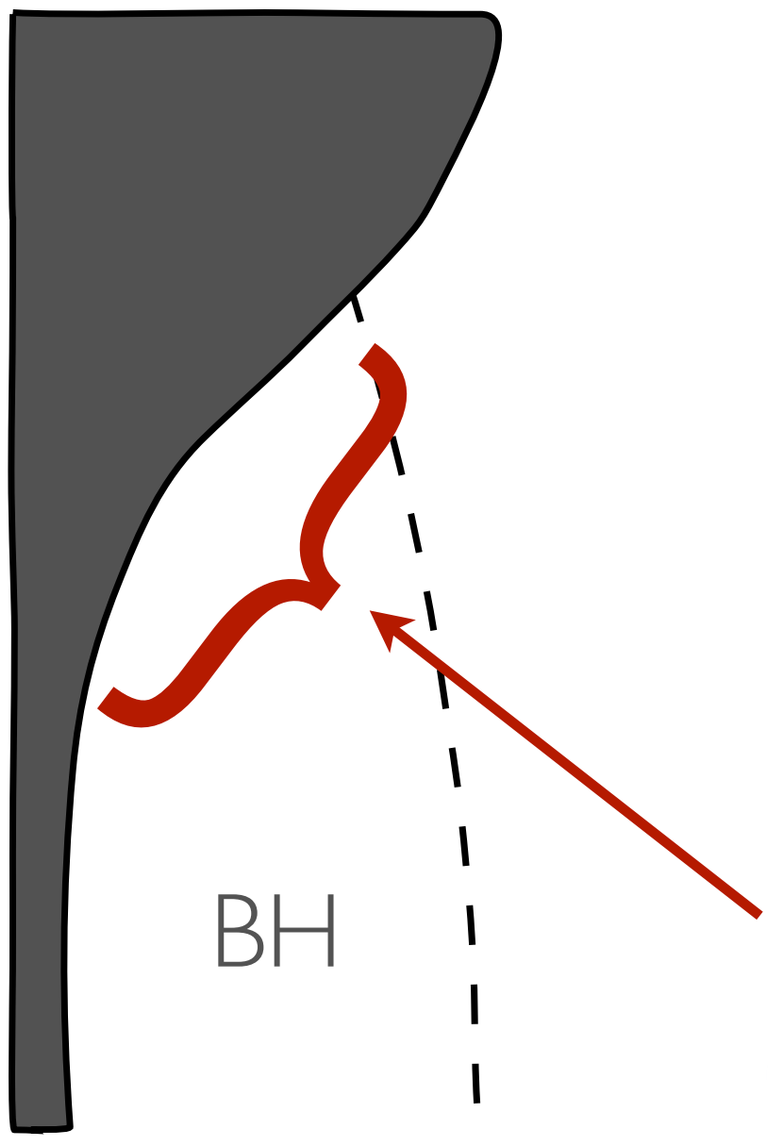
Page, 1993

(another version: Mathur,"small corrections theorem")

Alternative #1: dramatic modifications to BH structure

Basic Scenario:
(hep-th/9203059)

Massive Remnant



(or, BH never forms)

Versions:

- gravastar (Mazur/Mottola)

- fuzzball (Mathur + …)

- firewall (AMPS)

- Planck star (Rovelli/Vidotto, …)

Nonlocal information transfer

"New, unknown, nonlocal physics"

Questions about such “massive remnant” scenarios:

1) What new “nonlocal” physics responsible?

2) How to reconcile with observation?

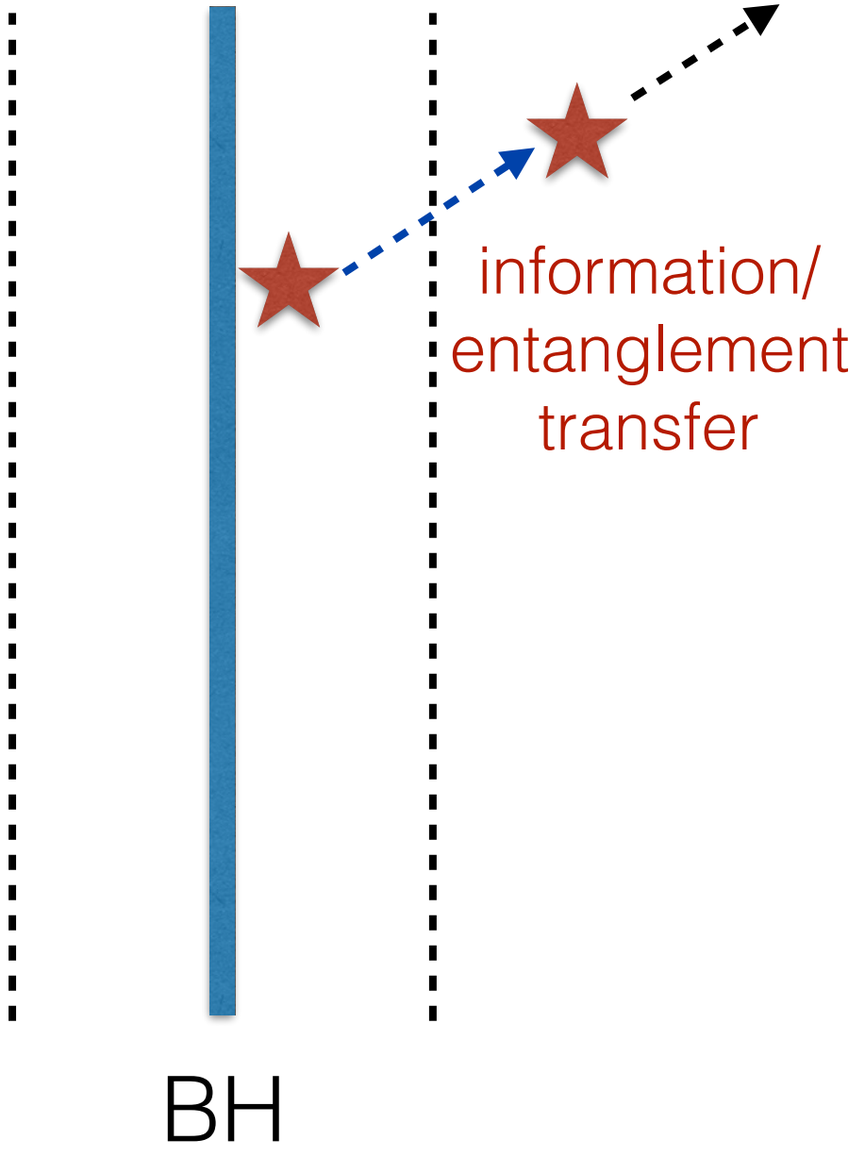
LIGO detections! Look like BHs …

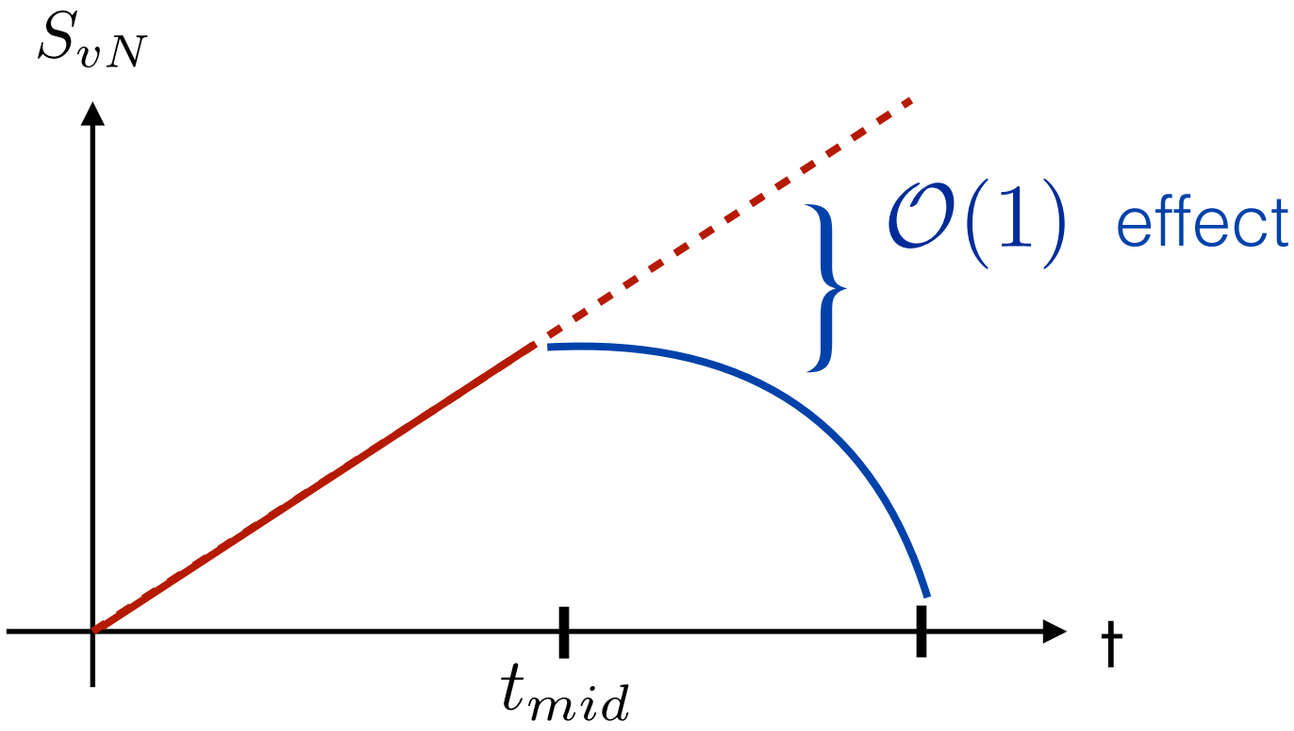
3) Is such a dramatic departure necessary?

Explore the possibility of more subtle, quantum, resolution:

Back to what is needed -

in semiclassical picture:



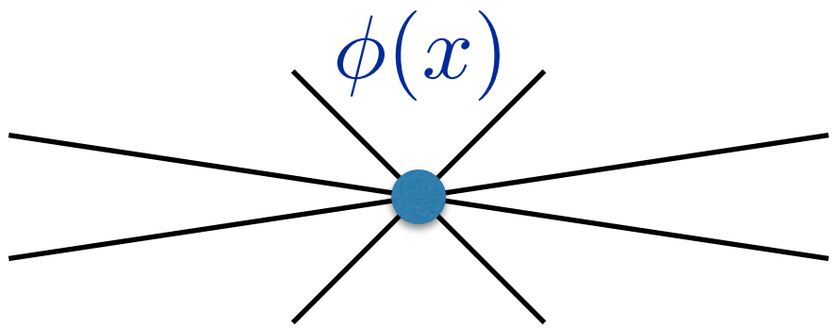


Prohibited in Local QFT:

$$[\phi(x), \phi(y)] = 0 \ , \ (x-y)^2 > 0$$

Locality - forbids such transfer

But: what is locality in *gravity*?



gravitational field

Operators don't commute [Donnelly & SBG, 1507.07921]

Some information contained in grav. field of particle

This has lead to a soft hair proposal: [Hawking, Perry, Strominger]

1) Information contained in "soft hair" (grav. field)

2) Mechanism to avoid losing information to BH

Notes: $\mathcal{O}(G_N)$ effect!

"Mistake in *reasoning*"

Closer examination suggests (though still refining/discussing):

[1706.03104,1805.11095 w/ Donnelly]

Not sufficient information in $\mathcal{O}(G_N)$ "hair"

But still, a moral:

localization of information is very subtle in gravity.

So: can small "delocalization" of information resolve the crisis?

Focus on what is *necessary*. Will find: $\mathcal{O}(e^{-1/G_N})$!

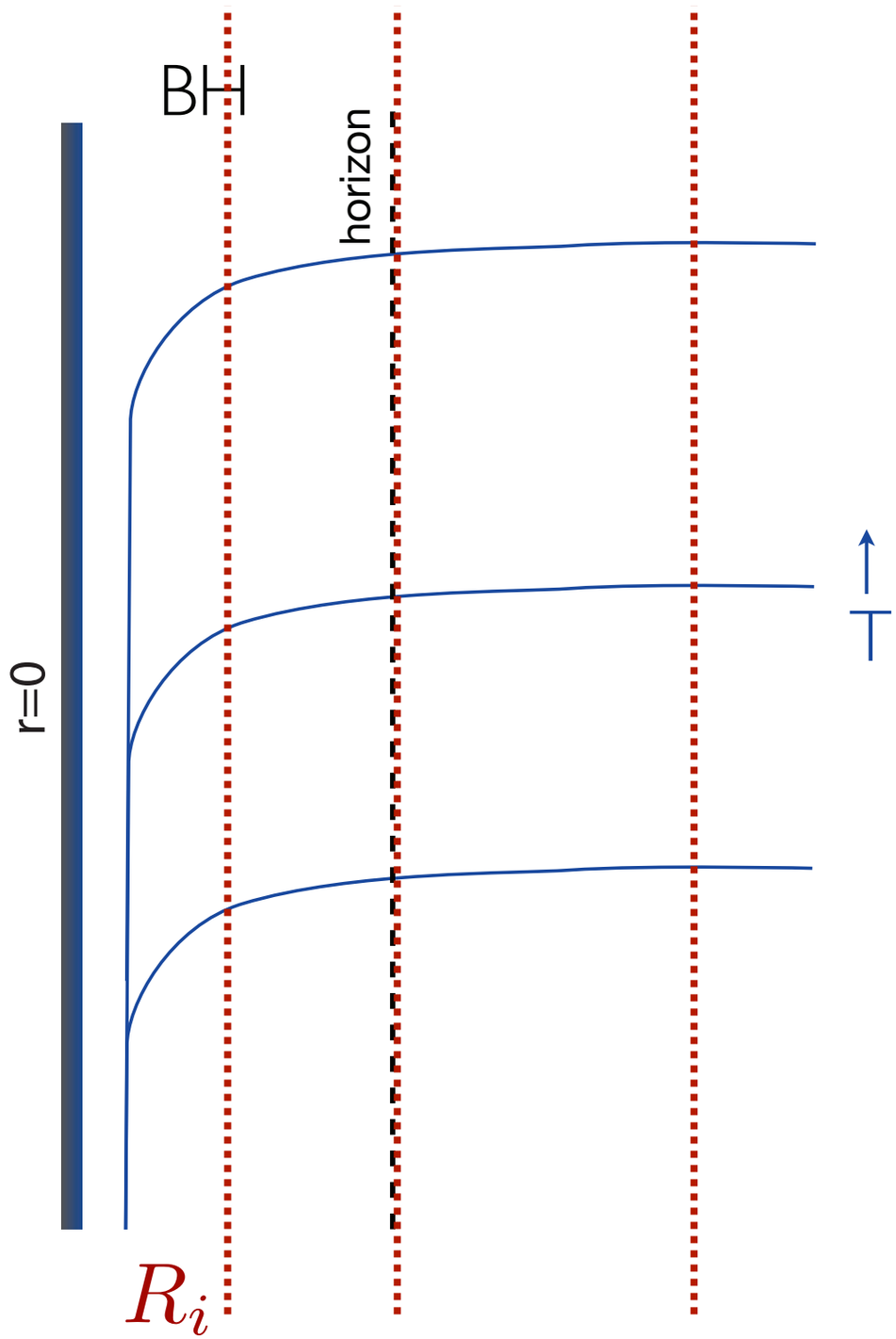
To explore, model BHs using some simple postulates for gravitational physics:

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

More structure needed (e.g. ~ “locality”)…

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

E.g: BH + its environment:



In LQFT:

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

H_i : local at R_i

Unitary evolution,

for $G_N = 0$

But, for $G_N \neq 0$ unitarity fails
(the original problem)

Violate postulate I

To restate *why* unitarity ultimately fails in LQFT description (violating Postulate I):

$$G_N \neq 0$$

1) H_{LQFT} only increases entanglement with BH subsystem:

Hawking radiation builds up entanglement;

Transfers info in

2) BH subsystem has unbounded dimension

When BH disappears, unitarity violated

Modifications to these needed to save QM ("unitarize")

Postulate I: "what goes in must come out"

Unitary dynamics must also have interactions *decreasing* entanglement

But, we'd like to be "close" to the standard 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")

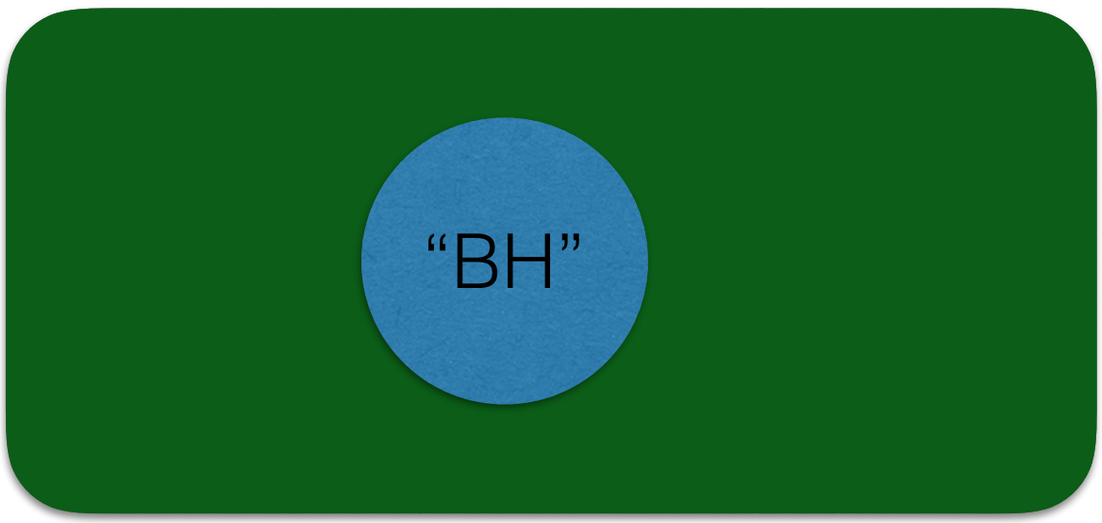
This is where things get a little challenging.

Structural modifications needed for “unitarization”

— follow postulates (+1)

arXiv:1701.08765

Postulate II:



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

H_I

Postulate I:

1) BH Hilbert space must behave finite-dimensionally

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

2) Interactions must allow information (entanglement) transfer out: H_I

~1 qubit/R

“To rescue QM”

Have assumed subsystems and Hamiltonian evolution.

Next, postulate III: Correspondence w/ LQFT description.

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

$$H = H_< + H_> + H_i + H_I$$

$H_<$: ?

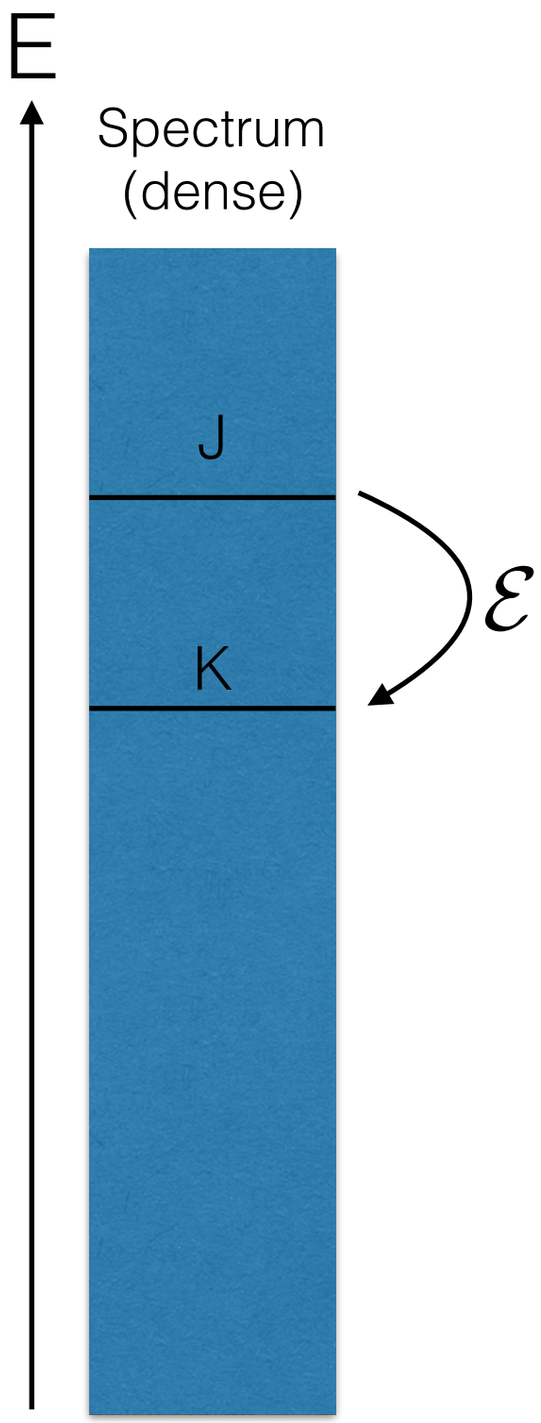
$H_> + H_i$: ~LQFT

H_I: what structure?

(work in spirit of effective field theory…)

Think of BH as a quantum subsystem, like e.g. an atom.

Bilinear interaction transfers entanglement:



$$H_I = \sum_{Ab} \int dV \quad \lambda^A \quad O^b(x) \quad G_{Ab}(x)$$

U(N) generators (basic matrices between BH states)

Act on "environment"

$$\langle K|\lambda^A|J\rangle = \begin{pmatrix} 0 & 0 & 1 & 0 & \cdots \\ 0 & 0 & 0 & 0 & \cdots \\ 1 & 0 & 0 & 0 & \cdots \\ & & \cdots & & \end{pmatrix}$$

$G_{Ab}(x)$: { couplings
parameterize ignorance
will constrain these.
how large?

$$H_I = \sum_{Ab} \int dV \; G_{Ab}(x) \lambda^A O^b(x)$$

Constraints:

1) Postulate III: “Minimize” departure from LQFT $G_{Ab}(x)$:

- Supported near the BH scale R_a

- Not confined too near the BH

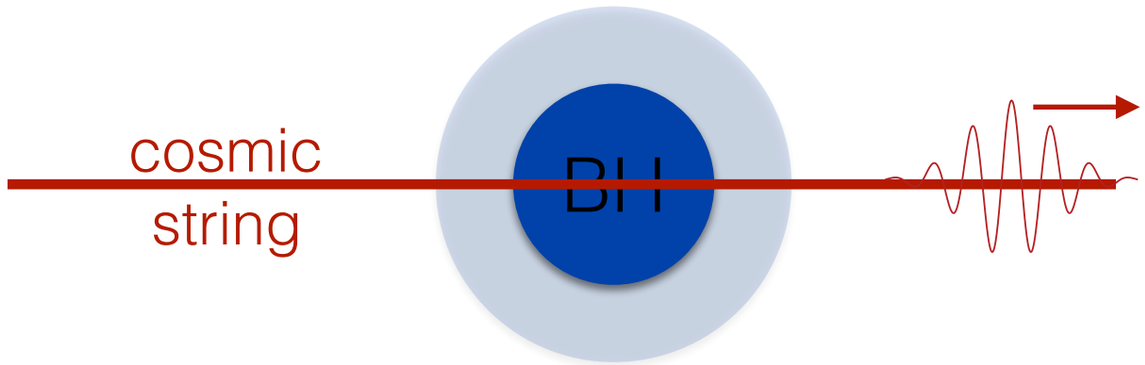
$R_a = R + l_{pl}$: “Firewall” vs. $R_a \sim R$: Nonviolent

(tuned)

- Simplest implementation: characteristic scales ~R,

also $\mathcal{E} = \Delta M \sim 1/R$

2) Consistency with mining; approx. w/ BH thermodynamics



Suggests: (optional??)

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

E.g.: $$H_I = \int dV \underbrace{\sum_A \lambda^A G_A^{\mu\nu}(x)} T_{\mu\nu}(x)$$

$H^{\mu\nu}(x)$ ~ "BH state-dependent metric perturbation"

also include pert. gravitons

E.g. $$\langle H_{\mu\nu}(x)\rangle_{\rm typ} = {}_{\rm typ}\langle\psi|H_{\mu\nu}(x)|\psi\rangle_{\rm typ}$$

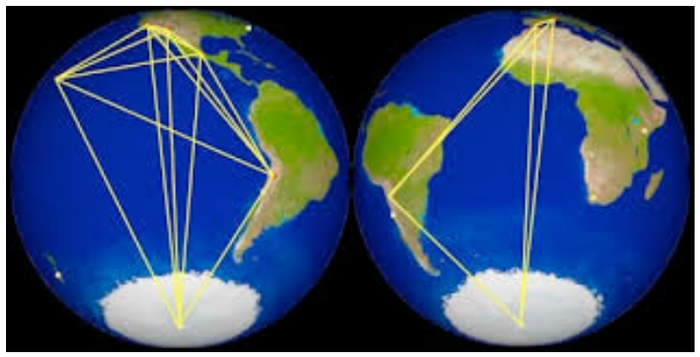
3) Need sufficient information transfer ~1/R

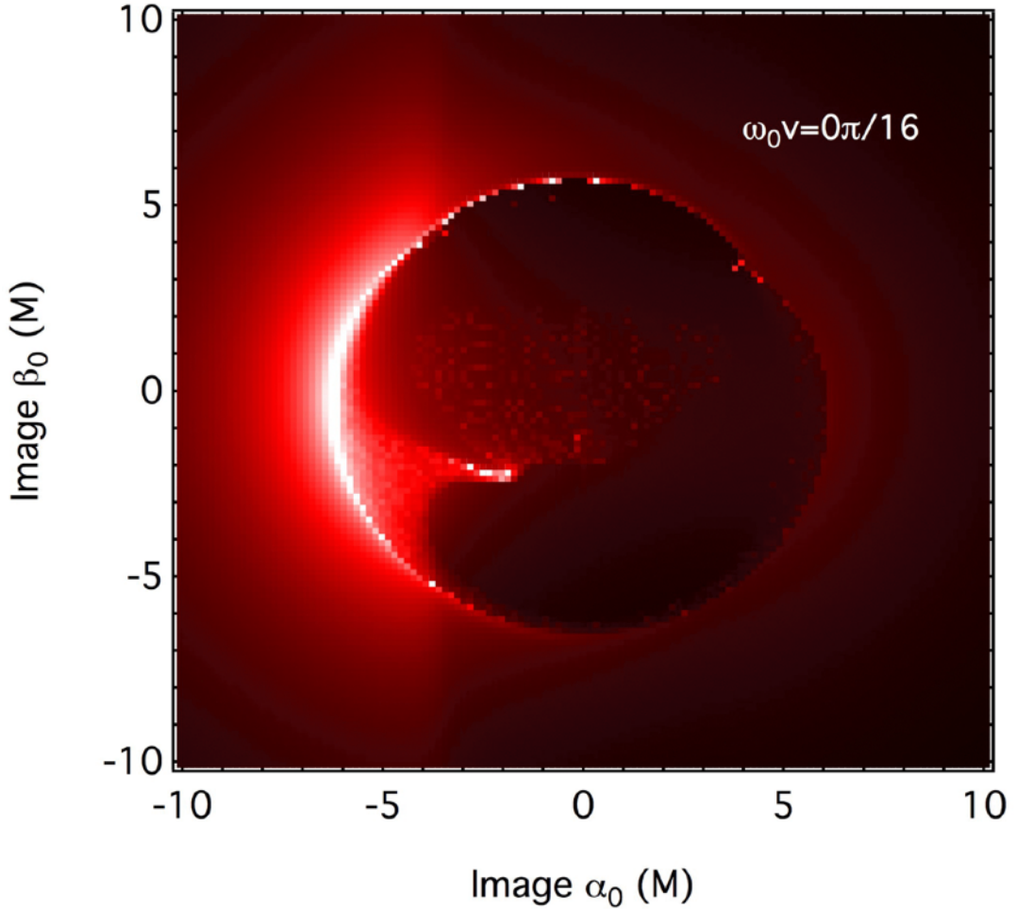
What would easily *suffice*: $\langle \psi, T | H^{\mu\nu}(x) | \psi, T \rangle \sim 1$

(distance, time scales ~ R)

arXiv:1401.5804

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





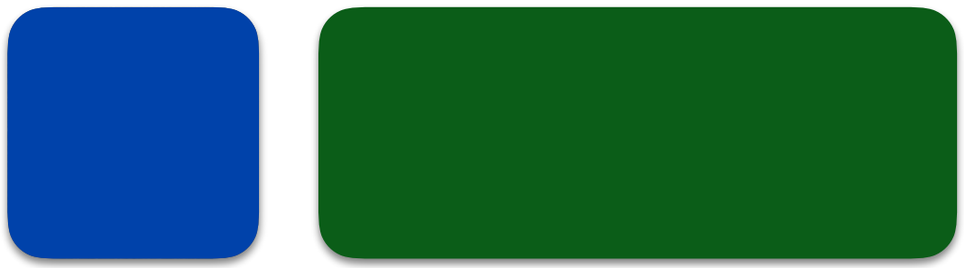
[SG/Psaltis] 1606.07814

But, what is a *necessary* condition for adequate information transfer?

A problem and conjecture in quantum information theory:

Subsystems

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



A B

BH environment

Q. sensor

Q. computer

thermal subsystem

$$H = H_A + H_B + H_I$$

Common scale

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

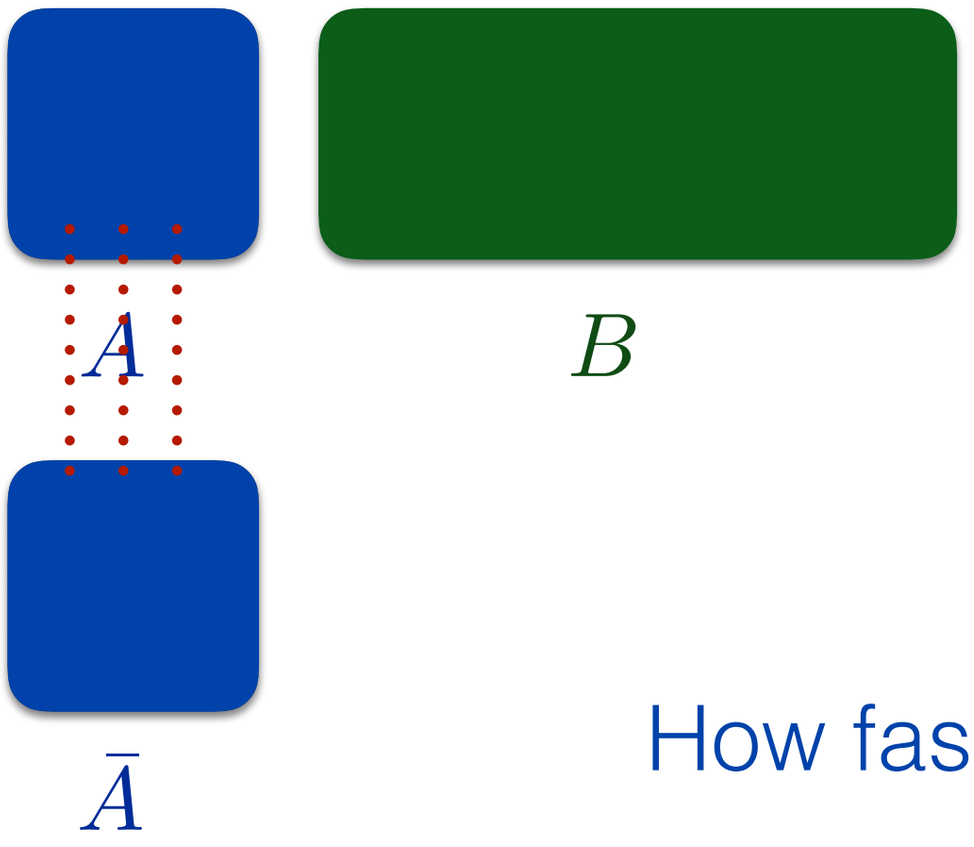
$$\|O_{A,B}^\gamma\| = 1$$

How fast transfers information?

A problem and conjecture in quantum information theory:

Subsystems

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



$$\frac{1}{\sqrt{|A|}} \sum_i |\bar{i}\rangle |i\rangle$$

$$H = H_A + H_B + H_I$$

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

How fast transfers information?

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

$$S_{\bar{A}} = S_{\rm vN}(\rho_{\bar{A}})\ ,\ \text{etc.}$$

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

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

~“random”

Conjecture:

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

arXiv:1701.08765

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

BH case: $$H_I = \int dV \sum_A \underbrace{\lambda^A G^{\mu\nu}_A(x)}_{H^{\mu\nu}(x)} T_{\mu\nu}(x)$$

e.g. Fermi's rule:
(~simplified explanation)

$$\frac{dI}{dT} \sim \frac{dP}{dT} = 2\pi\rho(E_f)|H_I|^2 \qquad \sim 1/R$$

$$\rho_{bh}(E) \sim e^{S_{bh}} \quad \Rightarrow \quad \langle K|H_{\mu\nu}|\psi\rangle \sim e^{-S_{bh}/2}$$

$$\leftrightarrow \quad G^A_{\mu\nu} \sim e^{-S_{bh}/2} \qquad \mathcal{O}(e^{-1/G_N})$$

contrary to previous lore and beliefs …

I.e. *not* "small correction" (Page, Mathur) but from *small interaction*

Likewise

$$\langle H_{\mu\nu}(x)\rangle_{\rm typ} = \langle\psi|H_{\mu\nu}(x)|\psi\rangle \sim \frac{1}{\sqrt{N}} \sim e^{-S_{bh}/2}$$

Q1: How to understand such effects?

Modification of "locality of information," compared to semiclassical geometrical description.

- new gravitational physics -

Likely need a more *intrinsically quantum* view of information localization and transfer, and spacetime

Some initial exploration:

"Quantum-first gravity," 1803.04973

"Quantum gravity: a quantum-first approach" 1805.06900

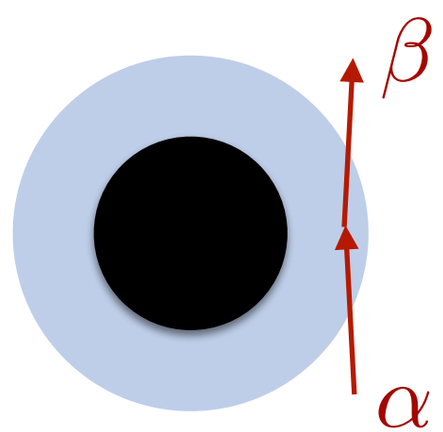
Somehow realized in AdS/CFT? (see e.g. Papadodimas)

Q2: Observational constraints?

-no large ~classical fluctuations $\langle H_{\mu\nu} \rangle \sim e^{-S_{bh}/2}$

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

$$\frac{dP}{dt} \sim \rho^{bh}(M) \left| \int dV \langle K | H^{\mu\nu} | \psi \rangle \langle \beta | T_{\mu\nu} | \alpha \rangle \right|^2$$



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

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

- tiny effect on matter, light (mm vs. $10^7\ km$)

- but: possible signal in GWs - LIGO/VIRGO??
(e.g. change absorption cross section, etc.)

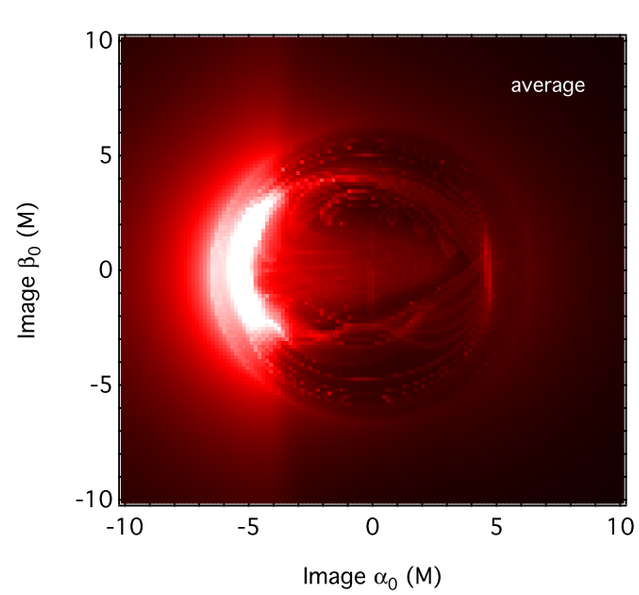
So,

1) QM 2) Subsystems 3) Correspondence and 4) Universality

have led us to “quantum gravitational atmospheres”
for black holes

coherent:

possibly visible in electromagnetic channels



incoherent:

hard to see in electromagnetic channels

possibly gravitational waves?

More generally, consider our present situation:

(indep. of my postulates)

1) There is common agreement that reconciling BHs with QM requires modifying QFT at scales ~R

2) We are now acquiring *two* observational windows on scales ~R, VLBI and GW

Something to really think about!

(see, e.g., arXiv:1703.03387…)

More general exploration of constraints and possible clues

Summary

- The “unitarity crisis” appears to point to error of *principles*

Guide to new quantum physics of gravity

Plausibly: Intrinsically more quantum notion of localization of information, spacetime

Further thoughts: 1803.04973, 1805.06900

- Not just a short distance problem — new physics needed on *horizon scales*, ~R

A simple, plausible set of postulates for quantum gravity:

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

"Information can get in, but must get out"

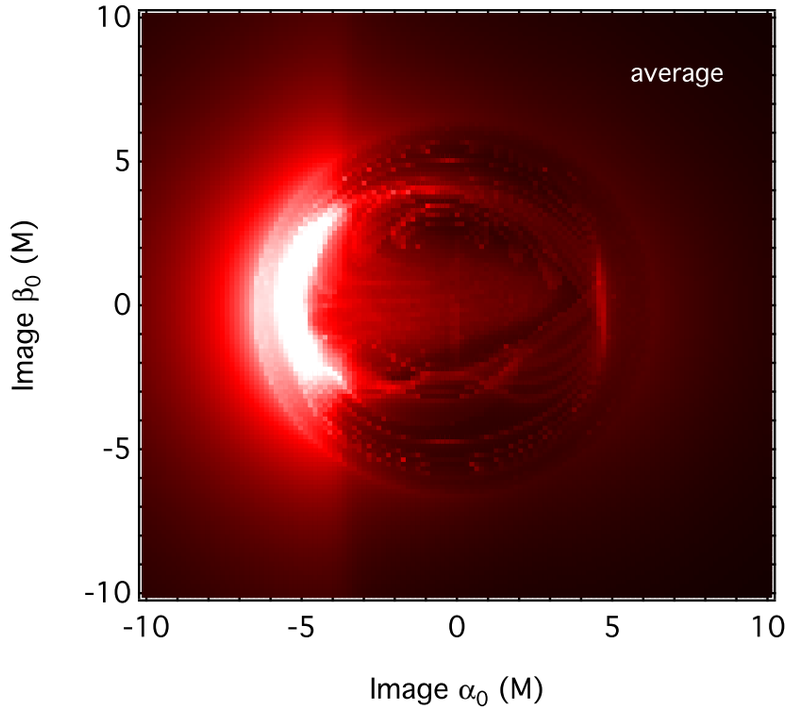
Postulate III, *Correspondence with LQFT*: Observations of small freely falling observers in weak curvature regimes are approximately well described by a local quantum field theory lagrangian. They find "minimal" departure from relativistic LQFT.

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

III+IV ~ "weak quantum equivalence principle"

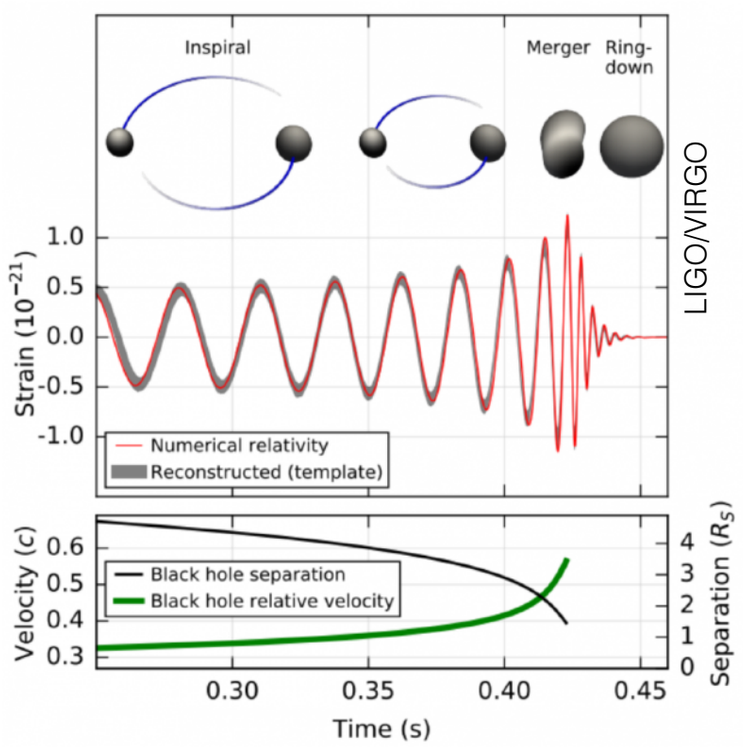
- lead to "soft quantum structure" of BHs
- very *weak* interactions can transfer information out
  (contrary to some prior thinking)
- an interesting connection with general problem of transferring Q info between subsystems

There are prospects for observational probes of/constraints on this foundational problem:



Event Horizon Telescope

(coherent atmosphere)



LIGO/VIRGO

(incoherent atmosphere?)