⟨Quantum|Gravity⟩Society

"Quantum-First" Approach to Gravity and Black Holes

Steve Giddings

"Quantum first" approach to gravity and black holes

Steve Giddings
UC Santa Barbara

QUANTUM MECHANICS & GRAVITY: MARRYING THEORY & EXPERIMENT
Aug. 15-19 2022, Vancouver, Canada

⟨Quantum|Gravity⟩
Society

Funded in part by:
US DOE, Heising-Simons Foundation

Our goal:

A quantum theory of gravity (space and time)

Traditional approach:

Begin with classical theory, and "quantize"

General relativity, w/ or w/out new variables (Ashtekar)

String theory

etc.

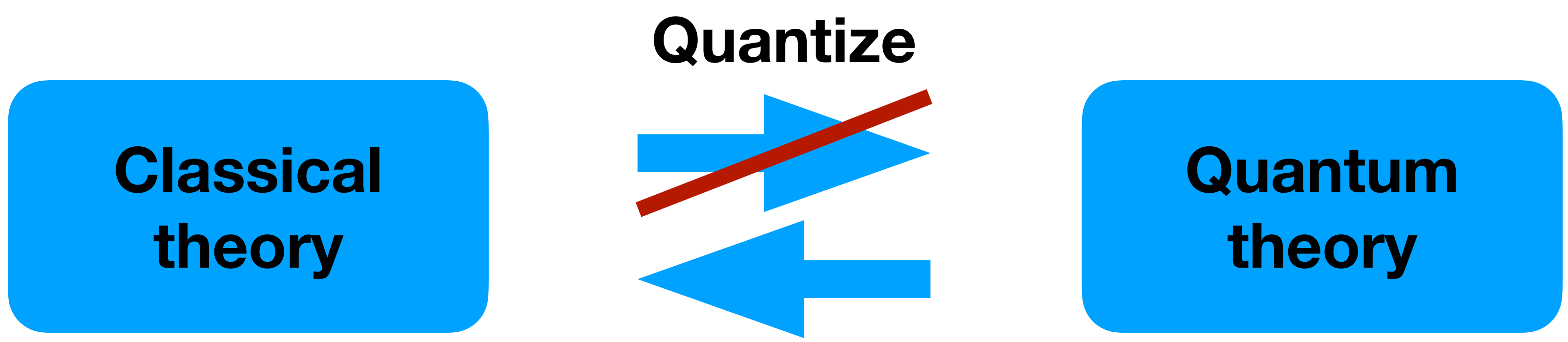
Leads to vexing problems:

Nonrenormalizability ~ nonpredictivity

(though, 1. short distance 2. e.g. string theory addresses)

Nonunitarity: long distance, more profound

"black hole information paradox"/"unitarity crisis"



Why not begin with key features of quantum mechanics, and ask what additional structure is needed to describe a theory matching onto gravity in "classical situations"

A "quantum first" approach

[0711.0757, 1503.08207,1803.04973 ...]

[related discussion: S. Carroll, w/ Cao Michalakis, Singh, ...]

We are perhaps being too classical in our thinking:
let's think like *quantum* physicists

(Possibly, AdS/CFT realizes, if we can make it precise, but still a big question)

One inspiration: a “derivation” of local QFT (and thus the standard model):

Perspective described by S. Coleman; S. Weinberg

(also, algebraic approach to QFT - Haag, etc.)

1. Quantum mechanics

2. Locality

3. Poincare symmetry

folk theorem

Local quantum field theory

(~how some of us teach QFT)

I.e. quantum field theory is *the answer to a question:*
how to formulate a quantum theory with certain properties

What properties does a quantum theory have to have in order to describe gravity?

Clues

- Strong constraints of quantum mechanics
  - Linearity
  - Unitarity

[0711.0757]

- Classical behavior of gravity
- Expected weak-field (perturbative) quantum behavior

"correspondence"

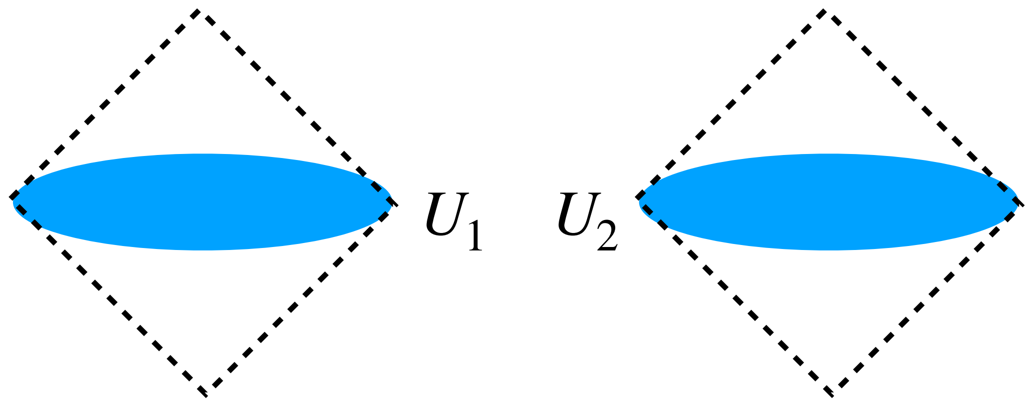
- Behavior of black holes
- Consistency
- Observation?

Questions

- What replaces locality?
- What symmetries?

What replaces locality?

Locality in LQFT:



Subalgebras:

$\mathscr{A}_1, \mathscr{A}_2$ **commute**

E.g.

$$\phi_1 = \int d^3x f_1(x)\phi(x) \qquad \phi_2 = \int d^3x f_2(x)\phi(x)$$

Quantum gravity observables:

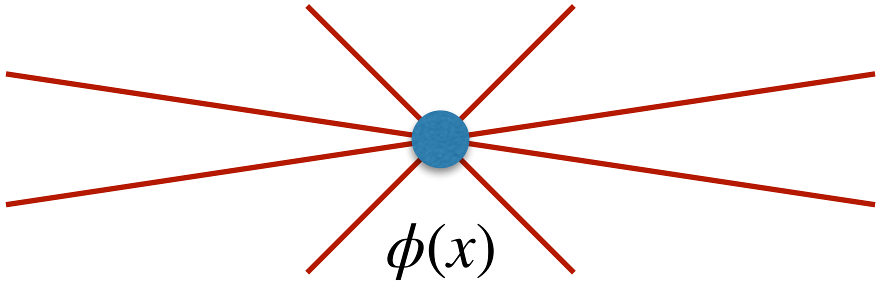
- $\phi(x)$ **not gauge invariant, so not physical observable**
- **Gauge invariant: ~ commute with constraints**

$$C_\mu = T_{0\mu} - \frac{1}{8\pi G} G_{0\mu}$$

$\Rightarrow$ ***Relational* observables** $\left\{ \begin{array}{l} \text{gravitationally dressed} \\ \text{“field-relational”} \end{array} \right.$

Very different properties from those of LQFT, even in weak gravity limit

Dressed observables:



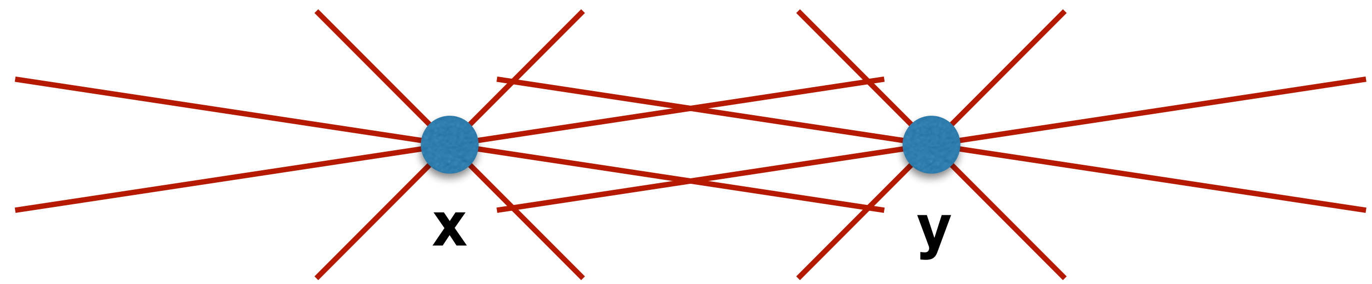
$$\hat{\mathcal{O}} = e^{i\int d^3x V^\mu(x) T_{0\mu}(x)}\ \mathcal{O}\ e^{-i\int d^3x V^\mu(x) T_{0\mu}(x)}$$

$$V_\mu[g,0,\vec{x}) \sim \int d^3x' \check{h}^{ij}(\vec{x}')_{\vec{x}}\ \Gamma_{\mu,ij}(0,\vec{x}')$$

(Leading order in $\kappa = \sqrt{32\pi G}$)

[1503.08207; SG + Donnelly; 1805.06900]

Generically don't commute:



[1507.07921 w/ Donnelly]

Can't localize information in quantum gravity??

Connection with (explanation of??) "holography" in gravity?

[Marolf, 2008; Jacobson, 2013; 2004.07843 …]

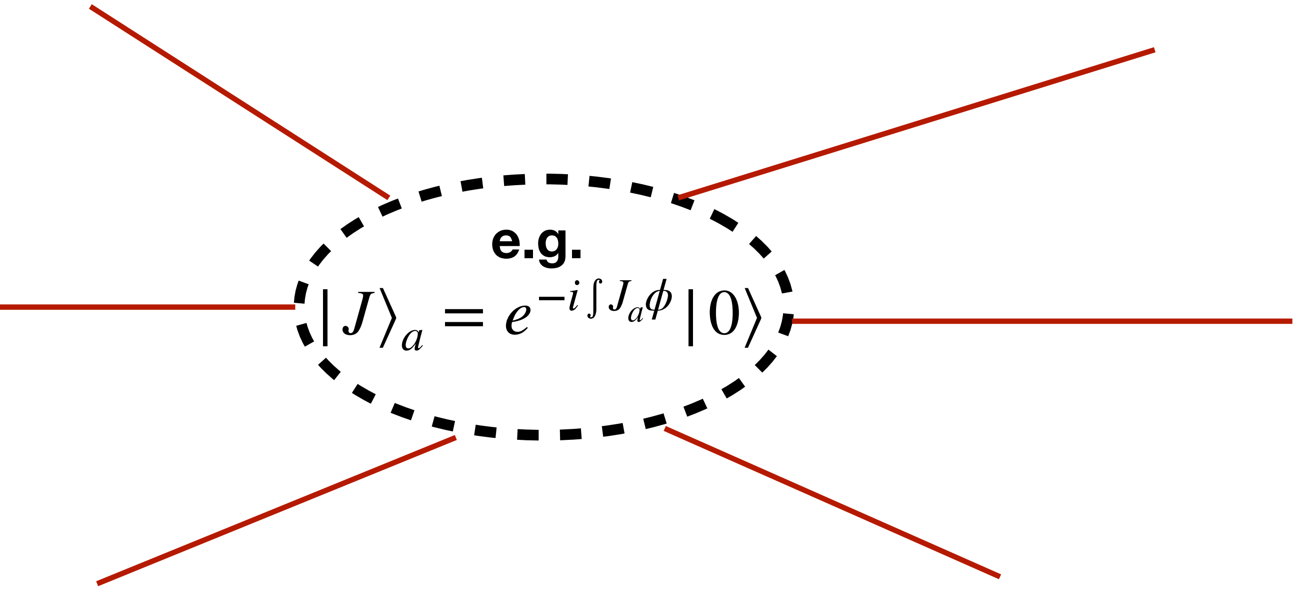
Using $$P_\mu = P_\mu^{ADM}[g(\infty)] + \int d^3x\, C_\mu$$

Maybe not so fast: can define (approximately?) subsystems in quantum gravity?

(i.e. localization of information)

Different structure, on *Hilbert space*

[1805.11095 w/ Donnelly; 1903.06160]



Dressing: can choose only depending on *Poincare charges*

(~ classical results: Corvino-Schoen, Carlotto-Schoen)

"Gravitational splitting;" so far, perturbative

Though, nonperturbatively:

$$\underbrace{{}_a\langle \hat{J}\,|\,\phi(x)\, e^{iP_i^{ADM}c^i}}_{\text{observables at infinity}}|\,\hat{J}\,\rangle_a$$

can "measure" details of state for $x \to \infty$

[1706.03104 w/ Donnelly]

(even perturbative observables?, though effects tiny: Raju et al; SG: 2112.03207)

What more complete mathematical structure? Part of basic structure of QG?

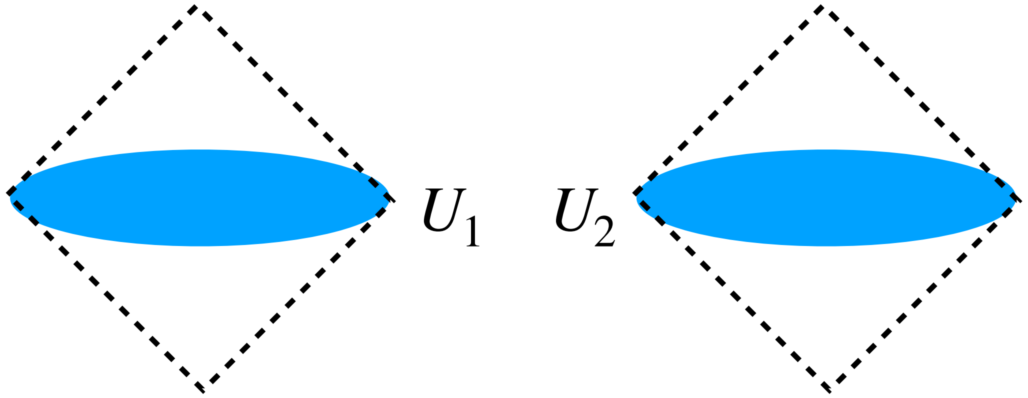
"Further, it appears to be essential for this arrangement of the things introduced in physics that, at a specific time, these things claim an existence independent of one another, insofar as these things 'lie in different parts of space.' Without such an assumption of the mutually independent existence (the 'being-thus') of spatially distant things, an assumption which originates in everyday thought, physical thought in the sense familiar to us would not be possible. Nor does one see how physical laws could be formulated and tested without such a clean separation."

- A. Einstein, 1948

LQFT: network of type III von Neumann algebras on Hilbert space $\mathscr{H}$

[see AQFT, e.g., Haag]

$\longleftrightarrow$ **mirrors open sets of spacetime manifold**



QG:

Certainly modification of algebra

S.G. and Donnelly;

Witten et al - type II (just part of story)

Possibly other structure *on Hilbert space*?

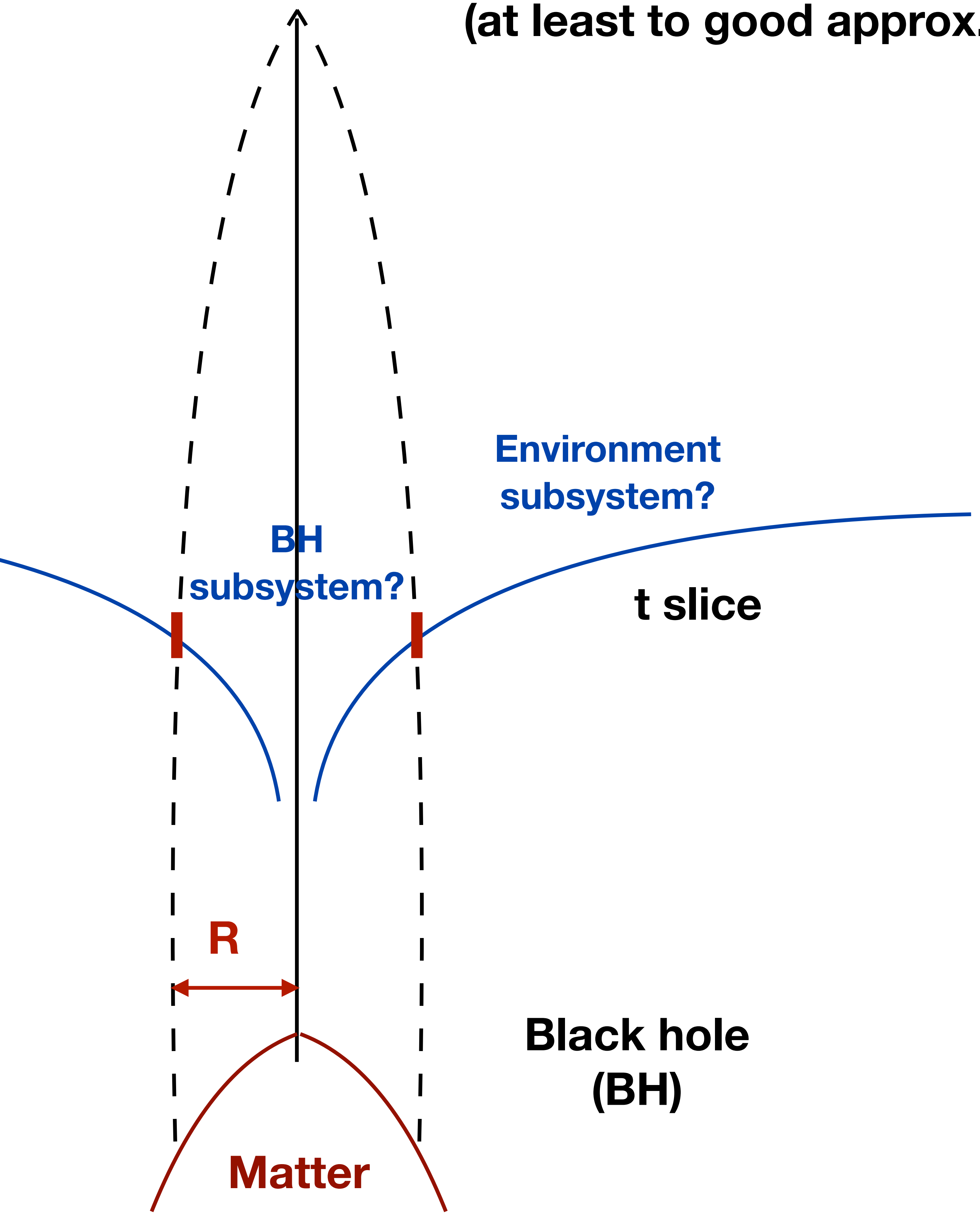
[1803.04973, 1805.06900, 1903.06160, 2112.03207]

Subtleties remain…

Turn attention to black holes:

Is a black hole a quantum subsystem?

(at least to good approx.)



If so, black hole theorem:

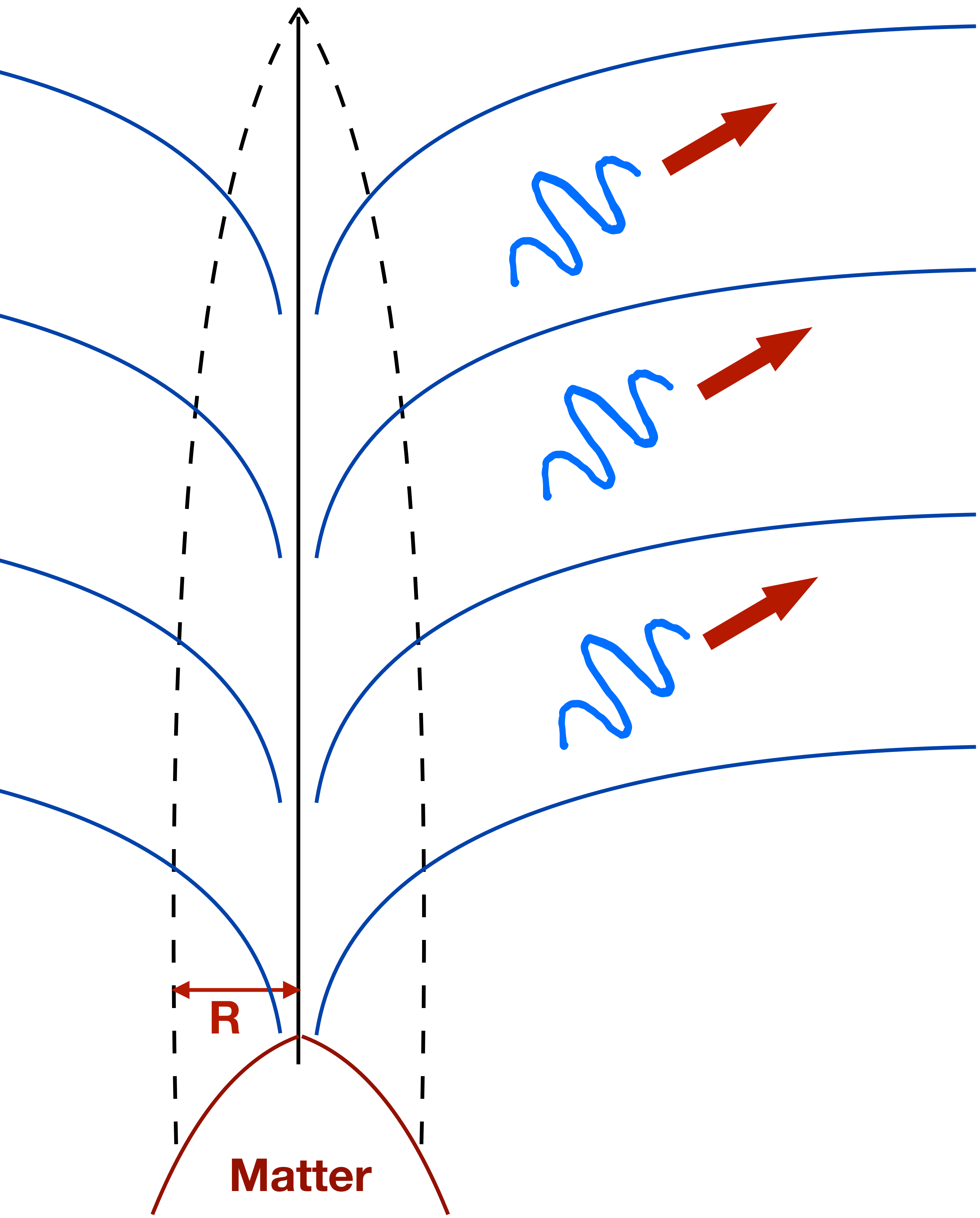
(encapsulates "information paradox"/"unitarity crisis")

[2110.10690]

> 0. Quantum mechanics (unitarity)
> 1. BHs are subsystems
> 2. Different BH states have identical exterior evolution
> 3. BHs disappear at end of their evolution

Are inconsistent

Quantized GR description:



hamiltonian evolution:

$$|\psi[g_{ij},\phi]\rangle$$

$$i\frac{\partial}{\partial t}|\psi\rangle = H|\psi\rangle$$

$$H = \int d^3x \left(\mathscr{H}_g + \mathscr{H}_m\right)$$

$$= \int d^3x\sqrt{g}\,\left(NC_n + N^iC_i\right) + H_\partial$$

w/ $C_\mu(x) = \left(-\frac{1}{8\pi G}G_{\mu n} + T_{\mu n}\right)$

N, N^i **lapse and shift**

(Gauge dependent)

Apparently respects 1,2

Apparently *must* be modified

[More explicit treatment: SG and Perkins, to appear]

Shift of perspective (quantum first!):

“Locality in classical spacetime forbids information escape”

to:

“If a black hole is a quantum subsystem, unitarity (QM) requires its interactions to describe information escape”

But, can we reconcile this with the expectation that big black holes are “nearly classical” near the horizon, and how do we describe this dynamics?

Principled parameterization of ignorance (or, effective description)

Again, quantum first

"Nonviolent unitarization"

E.g. 1108.2015, 1211.7070, 1302.2613, 1401.5804, 1701.08765;

Overview: 1905.08807

Assume ~subsystem structure $|\, i, \psi_{env}\rangle$

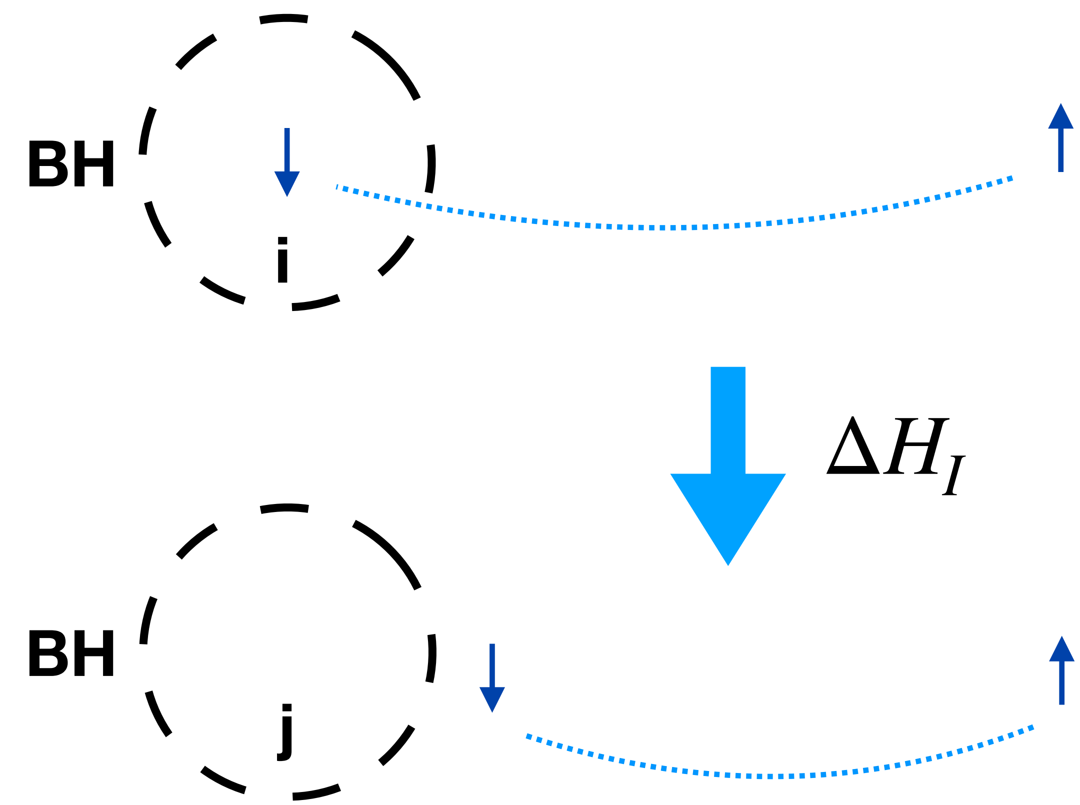
i,j, … label BH states

independent state of environment; ~LQFT description

$$H = H_{LQFT} + \Delta H_{BH} + \Delta H_I$$

described earlier

"small"



Simplest example

$$\Delta H_I = \sum_A \lambda_{ij}^A \mathcal{O}_A^{env}$$

Universality, ~locality

$$\mathcal{O}_A^{env} = \int dV G_A^{\mu\nu}(x) T_{\mu\nu}$$

"form factors" (localize near BH)

stress tensor

Reorganize: $\Delta H_I = \int dV\, H^{\mu\nu}(x)\, T_{\mu\nu}(x)$ **with** $H^{\mu\nu}(x) = \sum_A \lambda^A G_A^{\mu\nu}(x)$

***Operator:* ~state dependent metric perturbation**

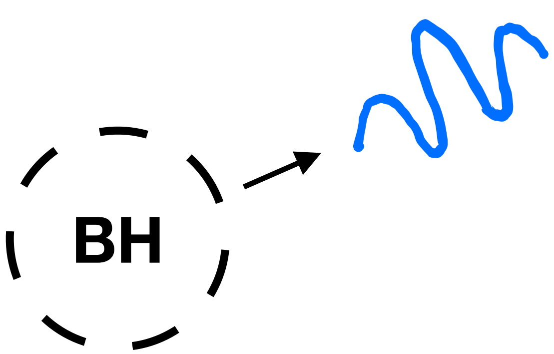
Natural scales $\langle \psi_{BH}, t \,|\, H_{\mu\nu}(x) \,|\, \psi_{BH}, t \rangle$ **varies on x, t scales ~R**

(thus "nonviolent" to infalling observers; e.g. no firewalls)

Sufficient transfer $\frac{dI}{dt} \sim \frac{1}{R}$

1) $\langle \psi_{BH}, t \,|\, H_{\mu\nu}(x) \,|\, \psi_{BH}, t \rangle \sim 1$ ***clearly suffices***

"Strong scenario"



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

$\rho(E_f) \propto e^{S_{bh}} \quad \Rightarrow \quad |\,\Delta H_I| = \mathcal{O}(e^{-S_{bh}/2})$

"Weak scenario"

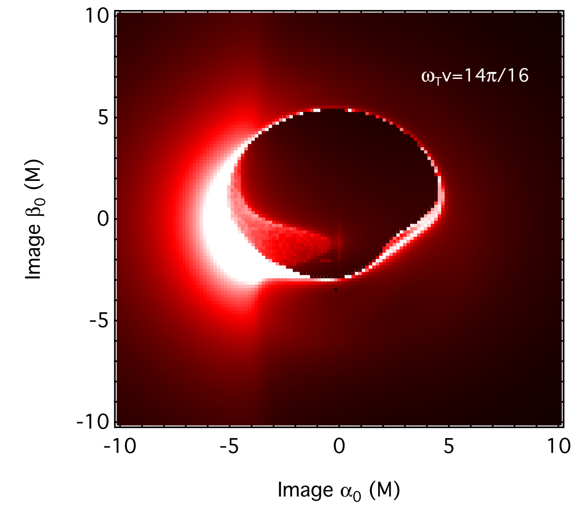
Observational signatures?

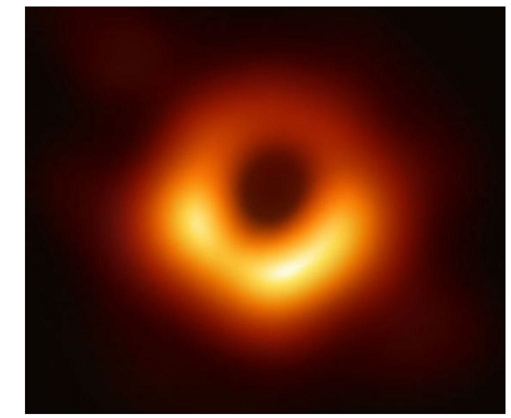
Strong scenario:

$$\langle \psi_{BH}, t \,|\, H_{\mu\nu}(x) \,|\, \psi_{BH}, t \rangle \sim 1$$

$\Rightarrow$ **Possible time dependent distortions of BH image**

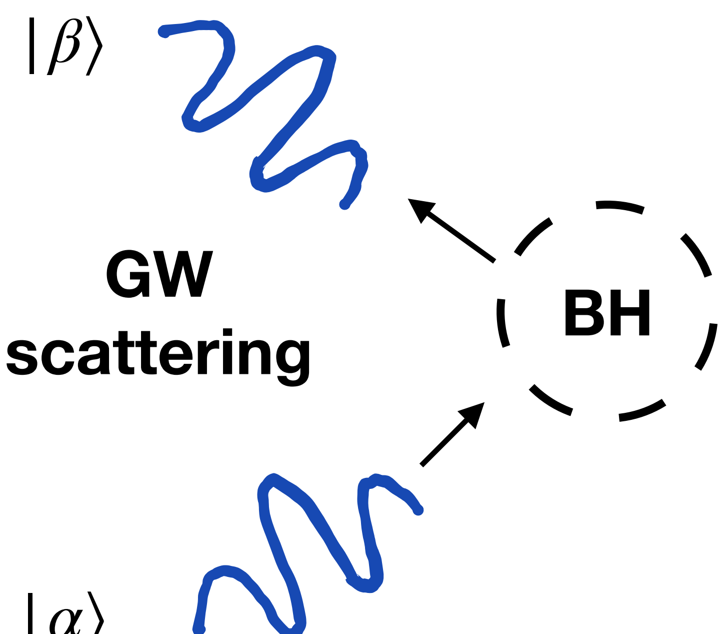
SBG and Psaltis - models [1606.07814]





Some ranges of parameters clearly ruled out by EHT images

Weak scenario:



$e^{S_{bh}}$ $\quad$ $e^{-S_{bh}/2}$

$$\frac{dP}{dt} = 2\pi\rho(E_f)\,|\langle \beta \,|\, \Delta H_I \,|\, \alpha \rangle|^2 \sim \mathcal{O}(1)$$

$$\Delta q \sim 1/R$$

Modified GW absorption/reflection

$\Rightarrow$ **Correction to GW signals**

Being investigated ...

Where do such effects "come from?"

One idea: parameterize simple failure of accuracy of classical description

Compare: classical description of atom (can parameterize but not describe)

(where does uncertainty principle "come from")

(Though, another idea: connected with "replica wormholes"/baby universes)

Returns to earlier question

What mathematical structure on Hilbert space?

Role for holography??

What symmetries?

What does unitary evolution of this structure look like?

Role of gauge invariance?

Does it describe these effects?

Summary

A possibly promising approach to quantum gravity is to try to understand properties of a quantum theory needed to describe gravity

“Quantum first …”

In fact, we seem to have a lot of clues … ***reason for optimism***

Novel mathematical structure! **Very different algebras of observables**

What is it? Possible key question

How to think about locality, subsystems? What symmetries?

If consider black holes, and they are ~subsystems, “BH theorem”:

New interactions between BH and environs needed, beyond LQFT

Such modifications of physics ***on event horizon scale*** **could be observable**

LIGO/Virgo/KAGRA; Event Horizon Telescope probe these scales

Other BH fates considered:

Microscopic remnants

Objection: infinite production instabilities in generic physical processes

[Preskill; hep-th/9412159; Susskind]

Fundamental loss of coherence [originally Hawking; Unruh/Wald, …]

Objection: if describe *repeatable* loss in BH decay experiments, drastic energy non conservation (very bad!)

[Originally Banks, Peskin, Susskind, with additional insights from baby universes: Coleman; SG, Strominger]

Massive remnants (fuzzballs, gravastars, firewalls…) [SG; Mathur…; Mazur/Mottolla; AMPS …]

Objection: still "nonlocal," and much more drastic departure from classical spacetime picture of BHs


⟨Quantum|Gravity⟩Society