Quantum information in quantum gravity: localization, transfer, and black hole evolution

Steve Giddings, CERN & U.C. Santa Barbara

CERN Theory Institute:
Black holes, quantum information, & spacetime reconstruction
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Broad themes:

How is quantum information localized in gravity?

How is it transferred?

Basic notion of localization of information:

<u>subsystems</u> of quantum system

More specific questions:

Is a black hole a quantum subsystem?

If so, how does it evolve, e.g. consistent w/ unitarity?

Subsystem structure:

- Underlies:
  - Entanglement, von Neumann entropy (eg EPR)
  - Entanglement transfer
  - Complexity
  - Observer / Observee
  - ⋮
- How locality encoded in QFT
- Plausibly a basic element in quantum structure of gravity

(see: Quantum-first gravity, 1803.04973, 1805.06900)

Usually just assumed...

But somewhat subtle in gravity.

(see e.g. "soft quantum hair" discussion)

Why?

But somewhat subtle in gravity.

(see e.g. "soft quantum hair" discussion)

Why?

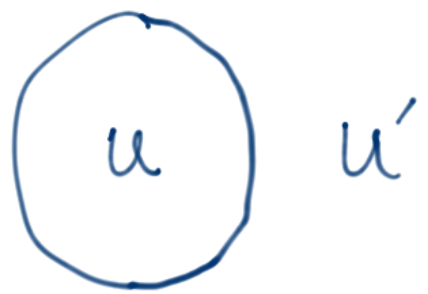
1) Subsystems in finite (or locally finite) systems:

$$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2 \otimes \cdots$$

... what is usually assumed

... wrong in QFT.

The reason:



$$|0\rangle \sim \sum_i |i\rangle_{\mathcal{U}} |i\rangle_{\mathcal{U}'}$$

infinite entanglement (UV)

e.g. $S_{vN} = \infty$

$\leftrightarrow$ type III vN algebra

(Araki, 1963-4)

The solution:

2) Subsystems in local QFT

consider $\mathcal{A}_{\mathcal{U}}$ = subalgebra of ops w/ support $\subset \mathcal{U}$.

e.g. $\phi_f = \int d^4x\, f(x)\, \phi(x)$

$\mathcal{A}_{\mathcal{U}}, \mathcal{A}_{\mathcal{U}'}$ commute (encodes locality)

describe local information;

use as LQFT def. of subsystems.

But operator def. problematic in gravity:

- $\phi(x)$ not gauge invt: $\delta_\xi \phi = -\kappa \xi^\mu \partial_\mu \phi$

- Can "dress:" use $g_{\mu\nu}(x) = \eta_{\mu\nu} + \kappa h_{\mu\nu}(x)$ *

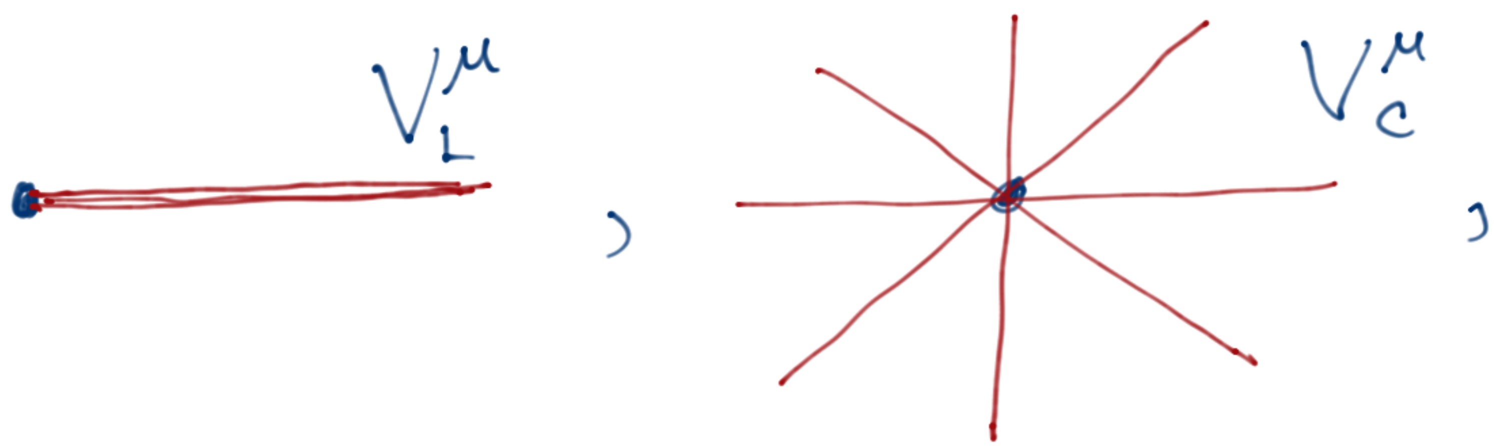
$\kappa = \sqrt{32\pi G}$

$$\hat{\phi}(x) = \phi(x^\mu + V^\mu(x)) \quad (\text{to } O(\kappa))$$

Donnelly & SG 1607.01025

$V^\mu(x)$: int. of $h_{\mu\nu}(x)$ to ∞

e.g.



etc.

Donnelly & SG 1507.07921

$$\Rightarrow \quad [\hat{\phi}(x), \hat{\phi}(x')] \neq 0 \quad \text{for } x-x' \text{ spacelike.}$$

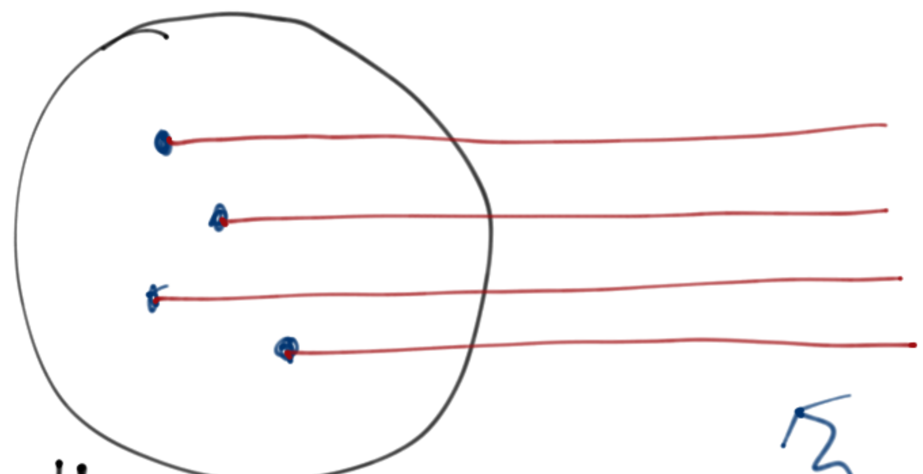
* Also, e.g., AdS: SG & Kinsella, 1802.01602

"A particle is inseparable from its gravitational field"

gauge invc.; constraints.

So: is information localized in gravity?

E.g.



U

detect config here ?

soft hair; holography.
(Marolf)

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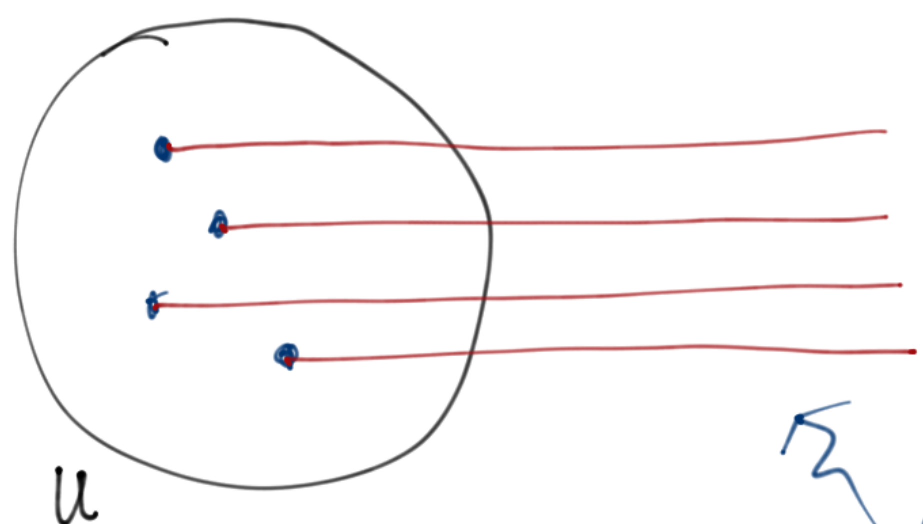
Eg.



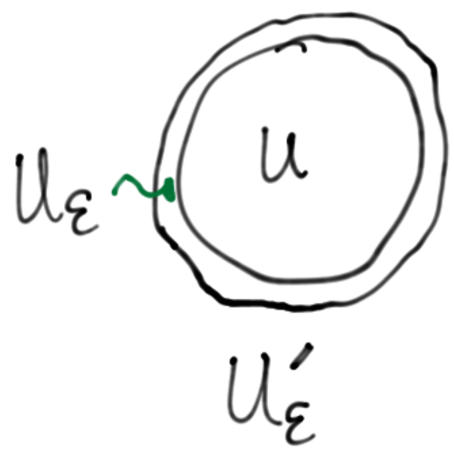
detect config here?

soft hair; holography.
(Marolf)

But: flexibility of dressing

Q: are there distinct states, indistinguishable outside $\mathcal{U}$?

First QFT ($\kappa = 0$):



$$\mathcal{H} \neq \mathcal{H}_\mathcal{U} \otimes \mathcal{H}_{\mathcal{U}'}$$

$$\mathcal{H}_\mathcal{U} \otimes \mathcal{H}_{\mathcal{U}'_\varepsilon} \hookrightarrow \mathcal{H}$$

"Split vacuum" $|\mathcal{U}_\varepsilon\rangle$:

$$\langle \mathcal{U}_\varepsilon | A \bar{A} | \mathcal{U}_\varepsilon \rangle = \langle 0|A|0\rangle \langle 0|\bar{A}|0\rangle$$

for any $A \in \mathcal{A}_\mathcal{U}$, $\bar{A} \in \mathcal{A}_{\mathcal{U}'_\varepsilon}$

So, $\bar{A}$ can't distinguish $A_I|\mathcal{U}_\varepsilon\rangle$ from $A_J|\mathcal{U}_\varepsilon\rangle$.

$\sim$ "localized qubit"

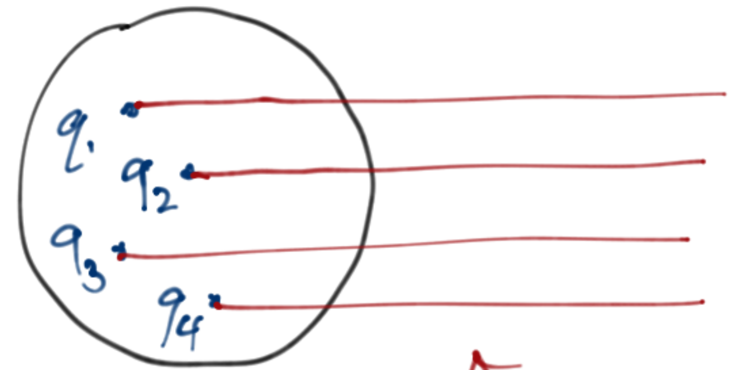
However, dressing.

Warmup w/ QED:

$$\Phi(x) = \varphi(x)\, e^{iq\int_x^\infty A}$$

$$[\Phi(x),\ \partial^\mu F_{0\mu} - J_0] = 0.$$

(gauge invt.)



Faraday lines

information?

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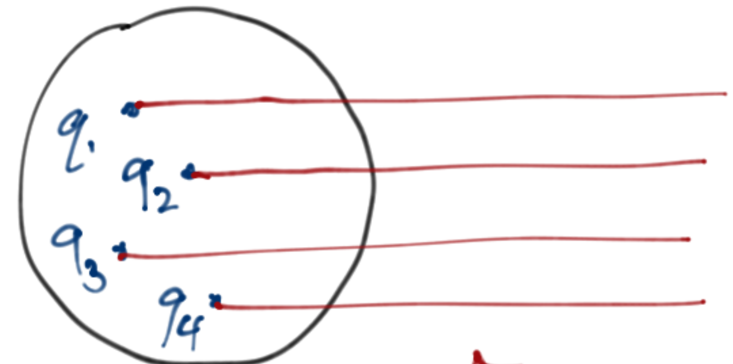

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Faraday lines

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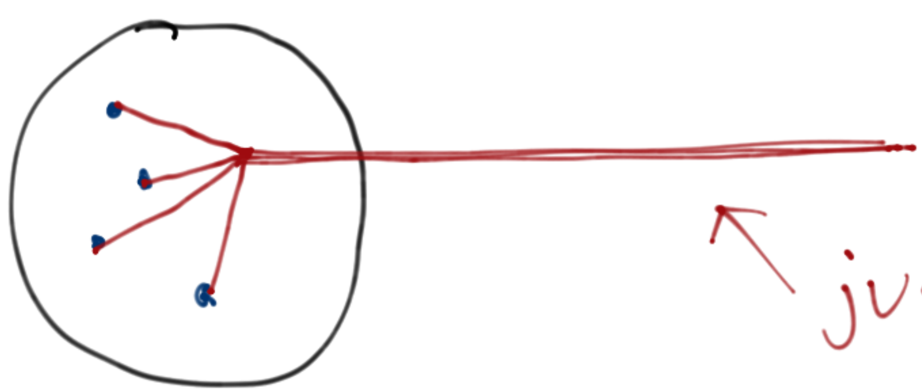
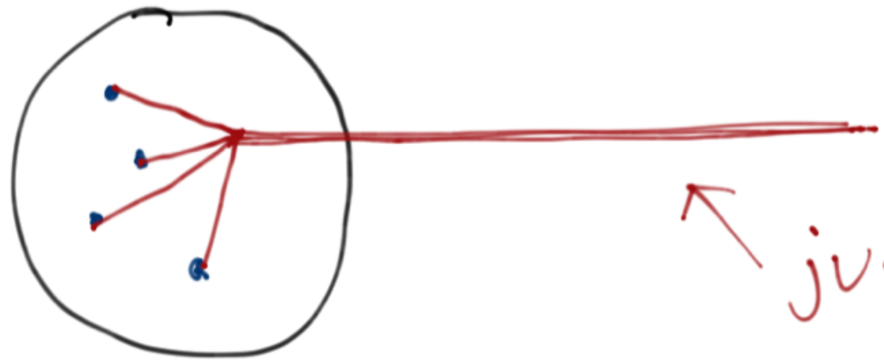
But: flexibility of dressing:



just depends on $Q = \sum_i q_i$



just depends on $Q = \sum_i q_i$

So, given B_1^Q, B_2^Q (different particle configs)

$\hat{B}_1^Q |\mathcal{U}_\varepsilon\rangle$ indistinguishable from $\hat{B}_2^Q |\mathcal{U}_\varepsilon\rangle$

by $\bar{B}$ outside ($\in \mathcal{A}_{\mathcal{U}'_\varepsilon}$):

"charged qubit"

$$\bigoplus_Q \left(\mathcal{H}_{\mathcal{U}}^Q \otimes \mathcal{H}_{\mathcal{U}'_\varepsilon}^Q \right) \hookrightarrow \mathcal{H}$$

"Electromagnetic splitting"

Analog for gravity:

classical: Donnelly & SG 1706.03104
quantum: 1805.11095

$A \in \mathcal{A}_U$.

Require: $[C_\mu(x), \hat{A}] = 0$

$C_\mu \;\hat{=}\; G_{0\mu} - \frac{\kappa^2}{4} T_{0\mu}$

dressed operator:

Let $V^\mu_{(x)}$ = some dressing. $\delta_\xi V^\mu_{(x)} = \kappa \xi^\mu(x)$

$$\hat{A} = A + i \int d^3x\, V^\mu_{(x)} [T_{0\mu}(x), A] + \mathcal{O}(\kappa^2)$$

dressed state:

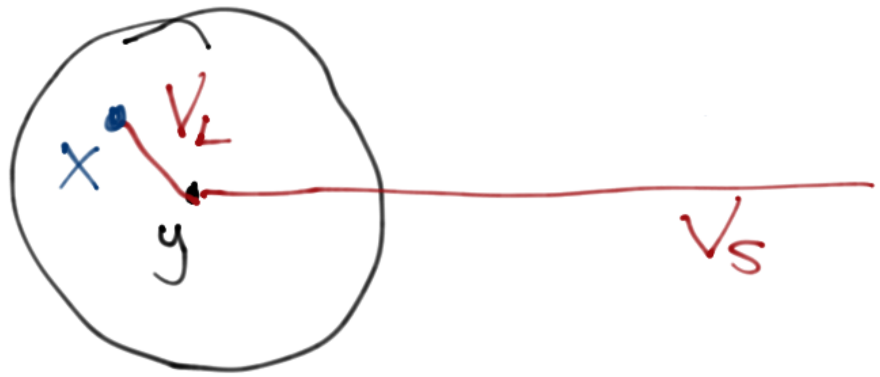
let $|\psi_I\rangle = A_I |U_\varepsilon\rangle$

$$|\hat{\psi}_I\rangle = \left[1 + i \int d^3x\, V^\mu_{(x)} T_{0\mu}(x)\right] |\psi_I\rangle + \mathcal{O}(\kappa^2)$$

$$C_\mu |\hat{\psi}_I\rangle \approx 0 .$$

cf Gupta-Bleuler

Use flexibility of dressing:



$V_S^\mu(y)$ = "standard dressing"

line or Coulomb or ...

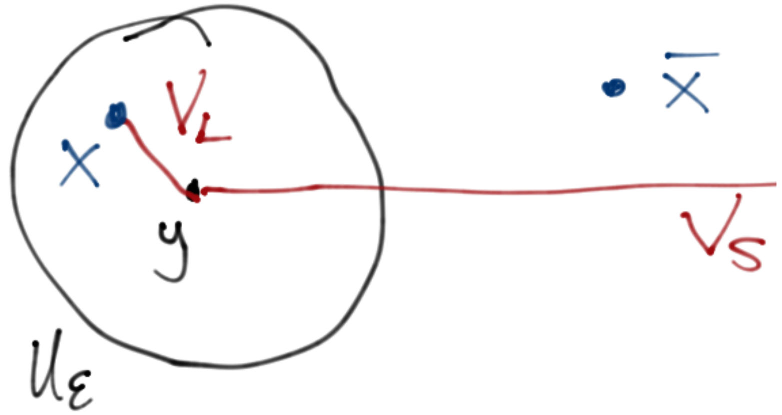
Then:

$$V^\mu(x) = V_L^\mu(x,y) + V_S^\mu(y) - \frac{1}{2}(x-y)_\nu \left[\partial^\nu V_S^\mu(y) - \partial^\mu V_S^\nu(y)\right]$$

satisfies $\quad \partial_\xi V^\mu(x) = \kappa\, \xi^\mu(x)$

with

$$V_{L\mu}(x,y) = \frac{\kappa}{2}\int_y^x dx'^\nu \left\{ h_{\mu\nu}(x') - \int_y^{x'} dx''^\lambda \left[\partial_\mu h_{\nu\lambda}(x'') - \partial_\nu h_{\mu\lambda}(x'')\right]\right\}$$



$$|\psi_I\rangle = A_I |U_\varepsilon\rangle \longrightarrow |\hat{\psi}_I\rangle$$

standard fields

$$\langle\hat{\psi}_I| h_{\mu\nu}(\bar{x}) |\hat{\psi}_J\rangle = \tilde{h}^{S\lambda}_{\mu\nu} \langle\psi_I|P_\lambda|\psi_J\rangle + \partial^\lambda_y h^{S\sigma}_{\mu\nu} \langle\psi_I|M_{\lambda\sigma}|\psi_J\rangle$$

$\therefore$ subspace w/ fixed $\langle P_\lambda\rangle$, $\langle M_{\lambda\sigma}\rangle$:
indistinguishable states.

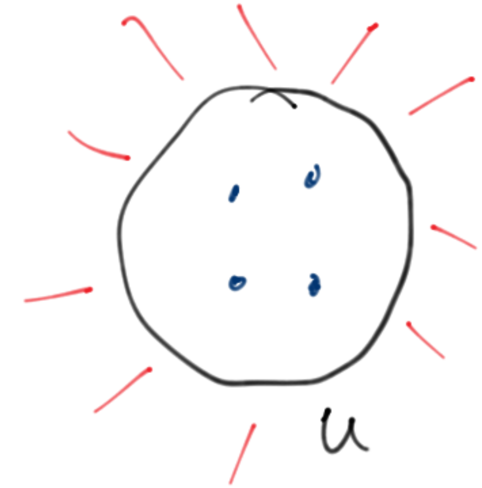
"gravitating qubit"

"Gravitational splitting" to $O(\kappa)$

(Q: what about $\langle hh\rangle$, etc.? $O(\kappa^2)$; Classical theorems...)

Contrast w/ soft-hair motivation:

Soft hair "expresses" info. in region?



Have shown for states in region,

can chose gravitational field (initial data) for $h_{\mu\nu}$ outside <u>just</u> depending on Poincaré charges.

Different superposed radiation fields $\longleftrightarrow$ Different soft charges.

(Related: Bousso & Porrati)

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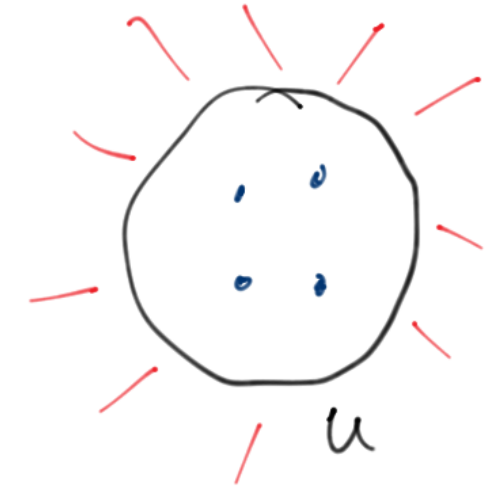

Soft hair "expresses" info. in region?

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Different superposed radiation fields $\longleftrightarrow$ Different soft charges.
(Related: Bousso & Porrati)

No obvious obstacle (though technical challenges):
extend to states inside a black hole. (WIP w/ S. Weinberg)

So, returning to general discussion:

plausibly a BH can be a quantum subsystem,

at least to order κ (i.e. w/ leading grav. effects)

(ultimately need full non-pert. story)

Moreover, plausibly:

Definition of subsystem structure is fundamental.

If take a "quantum-first" approach to gravity, need structure on $\mathcal{H}$; plausibly $\sim$ "net" of gravitational splittings.

1803.04973
1805.06900

so these ideas part of foundations of gravity?

End of part I:

localization of quantum information in gravity (approximate?)

Part II: small departures from <u>QFT</u> localization/locality, and <u>transfer</u> of information

particular focus: black hole

here this question connects to a profound problem:

"unitarity crisis" or "information paradox"

A set of guiding postulates for BH evolution:

(somewhat different from STU; AMPS) 1701.08765

1. QM

   linearity, $\mathcal{H}$, unitarity, ...

2. Subsystems, at least approximately.

   e.g. BH + environment

3. Correspondence: $\sim$ LQFT (min. departure)

4. Universality (optional? motiv.: mining, thermo.)

   any new grav effects couple universally

Follow their implications:

1. QM
2. Subsystems
3. Correspondence w/ LQFT
4. Universality

- P2 + P3 (Hawking):

  BH builds up large entanglement with environment
  (~ large information content)

- BH shrinks + P1 :

  Full evolution <u>must</u> transfer information out

Departure from LQFT localization/locality needed.
can make "minimal" ?

- P3 + P4 $\Longrightarrow$

  significant constraints.

Set up:

mass $M \pm \Delta M$

(Schrödinger pic.)

P2: $|K, M; \psi_e, T\rangle$

$K = 1, \ldots, N = e^{S_{bh}}$

$\psi_e \approx$ state of LQFT

$$H = H_{bh} + \underbrace{H_{env}}_{LQFT} + H_I$$

P3

H_I:

1) Must transfer info P1

departure from LQFT locality//localization

2) <u>Min</u> departure from LQFT P3

3) Universal P4

H_I : 1) Must transfer info P1
2) Min departure from LQFT P3
3) Universal P4

Describe in "effective" approach:

$$\rightsquigarrow \quad H_I = \int dV \sum_A \underbrace{\lambda^A}_{N\times N} T_{\mu\nu}(x) \; G_A^{\mu\nu}(x)$$

parametrize ignorance

incl. $t^h_{\mu\nu}$ P4

H_I : 1) Must transfer info P1
2) Min departure from LQFT P3
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parametrize ignorance

incl. $t^h_{\mu\nu}$ P4

$$H^{\mu\nu}(x) = \sum_A \lambda^A G_A^{\mu\nu}(x)$$

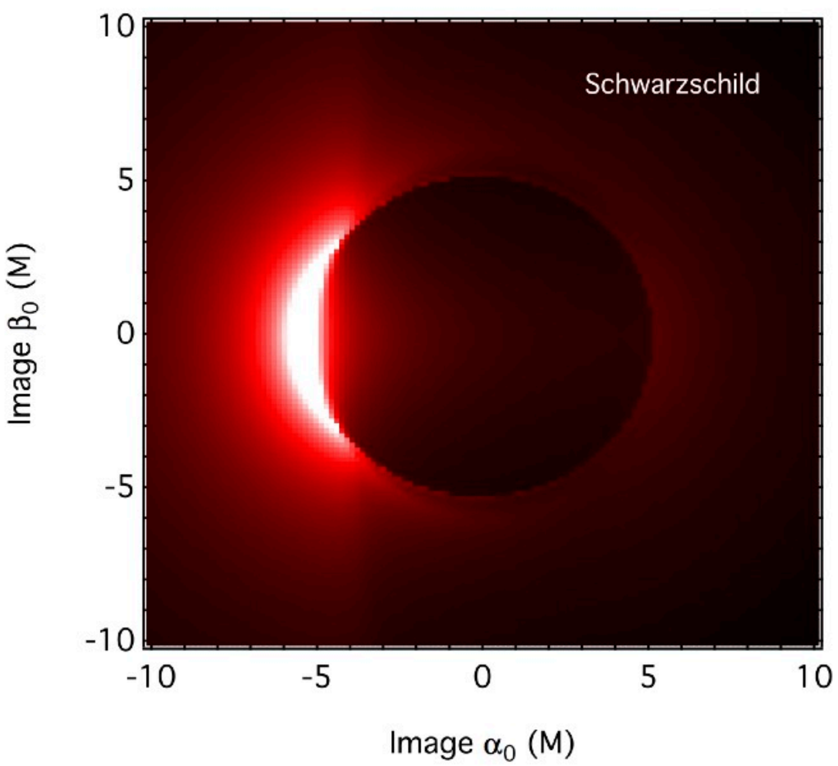
"BH state dep. metric pert."

P3: - $G_A^{\mu\nu}(x)$ supported near BH.
- not too near, e.g. $\Delta R_a \sim R$ ($\Delta R_a \sim l_{Pl}$: firewall)
- also $\Delta M \sim 1/R$.

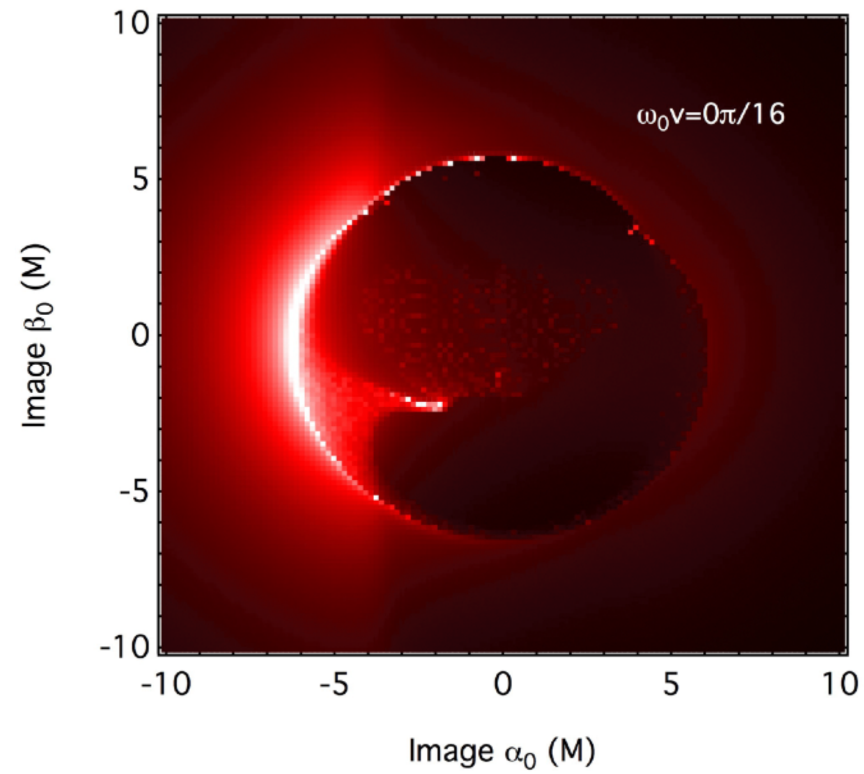
P1: $\frac{dI}{dt} \sim \frac{1}{R}$ information (entanglement) transfer to undo Hawking's entanglement

$\langle \Psi, T | H_{\mu\nu}(x) | \Psi, T \rangle = \mathcal{O}(1)$ suffices (variation scale $\Delta T \sim R$)

Such "soft, strong" couplings could produce observable effects: Event Horizon Telescope



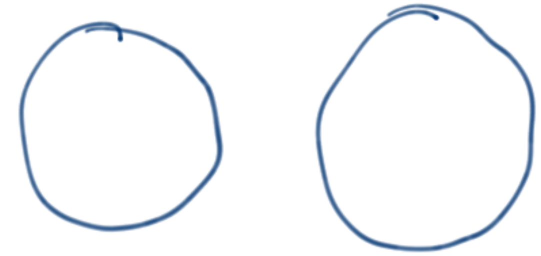
vs.



SG & Psaltis, 1606.07814

But are such strong couplings necessary?

General problem and conjecture re. information transfer:



$A \ll B$

$$H = \underbrace{H_A + H_B}_{\text{sufficiently random;}} + H_I \qquad \text{scale } \varepsilon$$

$$H_I = \varepsilon \sum_{\gamma=1}^{\chi} c_\gamma \, O_A^\gamma \, O_B^\gamma \qquad \| O_{A,B}^\gamma \| = 1$$

e.g. A = BH, Q computer, Q sensor, ... ; B = environment.

How fast does H_I transfer information* from A?

Conjecture:
1701.08765

$$\frac{dI}{dt} = C \varepsilon \sum_\gamma c_\gamma^2 \qquad (c_\gamma \lesssim 1)$$

(Evidence: 1710.00005 w/ M. Rota)

* e.g. entanglement w/ $\bar{A}$

BH application & heuristic explanation:

$$H_I = \int dV \, H^{\mu\nu}(x) \, T_{\mu\nu}(x)$$

acts on: bh env.

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

(compare atomic transition)

BH application & heuristic explanation:

$$H_I = \int dV \, \underset{\substack{\uparrow \\ \text{acts on: bh}}}{H^{\mu\nu}_{(x)}} \, \underset{\substack{\uparrow \\ \text{env.}}}{T_{\mu\nu}(x)}$$

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

want $\sim 1/R$

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

Weak couplings suffice, contrary to lore/beliefs !
(also valid for more general couplings)

(e.g. motivation for fuzzball program ...)

So: the necessary delocalization/nonlocality can be <u>exponentially</u> small.

Such "Soft, weak" gravitational structure:

... apparently bad for EHT observation

... modified GW absorpt.; LIGO tests?

more exploration to come...

Summary:

Information localization/subsystems: basic

Outlined leading perturbative definition; ⇝ ~~BH info role for soft hair~~ ?

Plausibly part of fundamental structure of theory
1803.04973, 1805.06900

Evolution for black holes

Postulates:

QM, Subsystems, Correspondence, Universality

⇒ New couplings needed

General problem + conjecture re. info. transfer

Soft, weak gravitational structure on BH suffices
(or, more general weak couplings)

Observational tests?

Interaction of "matter" w/ BH

(or gravity wave; infalling observer)

$$\frac{dP}{dt} \sim 2\pi\, \rho(E_f)\ \left| \langle \beta, \kappa | H_I | \alpha, \psi \rangle \right|^2$$

$$\underset{e^{S_{bh}}}{\wr} \qquad\qquad \underset{e^{-S_{bh}/2}}{\wr}$$

$\Rightarrow$ still $\mathcal{O}(1/R)$.

$\Delta p_{\beta\alpha} \sim 1/R$;

negligible for $R|p_\alpha| \gg 1$

But: <u>gravity waves</u> (LIGO)