Information Loss in Quantum Field Theory

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Outline

Black Hole Information Loss

- Nothing can escape from the interior of a black hole event horizon.
- Semi-classical calculations predict that black holes evaporate through radiation.
- Is this process unitary?
  - YES
    - Information from infalling matter somehow escaped the event horizon.
    - Need to modify space-time geometry.
    - Protect unitarity by holography: AdS-CFT correspondence.
  - NO
    - This breaks QM as we know it.
    - How do we prevent such non-unitary processes from trickling down to every day QM?
- Current trend is to assume evaporation is unitary.
- I'm going to assume it's not.
  - What assumptions are required for alternative to unitarity.
  - Models to guide experiments in quantum gravitational effects.

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  - etc.
- Also related to collapse models, widely studied.

Setting: Lindblad equation at a fundamental level

$$\dot{\rho} = \int -i[\mathcal{H}(x), \rho] + \sum_a L(x)_a \rho L_a(x)^\dagger - \frac{1}{2}\{L_a(x)^\dagger L_a(x), \rho\} d^3x$$

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No-go results

BPS (and others)

Local, Lorentz-covariant Lindblad field theory cannot preserve energy.

- Energy conservation: not even defined!
  - Hamiltonian = time translation generator, but not here!
  - The Hamiltonian is not uniquely defined: add jump operator $L = I + iA \quad \Leftrightarrow \quad H' = H + A$.
  - The vacuum is unstable, particle creation at infinite rate.
- Locality: do we need it?
  - Locality is how we enforce causality in (unitary) QFT.
  - The relation between locality and causality breaks down in irreversible theories.
  - E.g. relaxation into singlet state is non-local but does not enable signaling (PR box).
- See also Beckman, Gottesman, Nielsen, and Preskill *Phys. Rev. A* 2001; Oppenheim & Reznik arXiv:0902.2361 2009.

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  - E.g. relaxation into singlet state is non-local but does not enable signaling (PR box).
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BPS (and others)

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Our goal

Construct a well defined non-unitary QFT that does not conflict with experiments.

- I do not mind breaking theoretical constructs that build on the premise that QM is unitary.
  - Noether's theorem.
  - Cluster decomplsition, etc.
- I do mind breaking these relations under well tested conditions: recover ordinary QFT at low energy and/or flat space.
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Outline

Lorentz covariance

- In ordinary field theory, H transforms like the 0-th component of a 4-vector $T^\mu = (H, \mathbf{P})$, so evolution is covariant:
  - For a 4-vector b_μ, define CPTP map $\mathcal{E}_b(\rho) = e^{-ib_\mu T^\mu}\rho e^{ib_\mu T^\mu}$.
  - For Lorentz transform Λ, we have $U_\Lambda \mathcal{E}_b(\rho) U_\Lambda^\dagger = \mathcal{E}_{\Lambda^{-1}b}(U_\Lambda \rho U_\lambda^\dagger)$.
- Generalizing, we need a superoperator L that transforms like the 0-th component of a 4-vector.
  - Space-like translations use ordinary displacement operators.
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A model

- Start with a free scalar theory $H = \frac{1}{2}\int \frac{d^3p}{(2\pi)^3}(\pi^2 + m^2\phi^2 + (\nabla\phi)^2)$.
- Consider positive frequency component of field operators $\pi^+(x)$.
- Use them as jump operators

$$\dot{\rho} = -i[H,\rho] + \gamma \int d^3x \left[2\pi^-\rho\pi^+ - \{\pi^+\pi^-,\rho\}\right]$$

- In momentum space,

$$\dot{\rho} = \int \frac{d^3p}{(2\pi)^3}\omega_p\left(\gamma a_p\rho a_p^\dagger - \frac{\gamma}{2}\{a_p^\dagger a_p,\rho\} - i[a_p^\dagger a_p,\rho]\right)$$

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Energy conservation

- Vacuum is stable, in fact, it is the fixed point: $\mathcal{E}(\Omega) = \Omega$
  - All (most?) previous models had only considered Hermitian jump operators, in which case the resulting CPTP map is unital: $\mathcal{E}(I) = I$.
  - Previous no-go results $\Leftrightarrow$ unital CPTP map have infinite temperature fixed point, hence no stable vacuum.
- Decay rate of mode p is $\gamma\omega_p$.
  - By setting γ small enough, we can imagine having negligible decay in everyday experiments, but fast entropy production at Plankian energies or on cosmological scales.
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Locality and Causality

- This is NOT a local Lindblad equation, $\pi^+(x)$ is not a local operator.
  - $[\pi^+(x), \phi(y)]$ does not vanish when $x \neq y$, but decays exponentially with range $1/m$.
  - $[\mathcal{E}_t^\dagger(\phi(x)), \phi(y)]$ has an exponential tail outside the lightcone.
- Causality is violated on a microscopic length scale $1/m$.
  - Motivation to consider heavy field, e.g. $m = m_P$?
  - Information loss on other species would be highly suppressed at low energy since this heavy field is far off shell.

$$\mathcal{L} = \mathcal{H}_{Ordinary\ fields} + \mathcal{L}_{Heavy,\ damped\ field} + \mathcal{H}_{Hybridization}$$

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- Is the theory stable when we add interactions, e.g. ϕ^4?
  - In general, Lindblad QFT can be renormalized, see e.g. Avinash, Jana, Loganayagam, and Rudra 2017 (based on DP&Preskill).
  - The action of our model does not quite fit the formalism

$$\int d^4x \left(\partial_\mu \phi_c \partial^\mu \phi_q + i\gamma(m^2\phi_q^2 + \dot{\phi}_q^2 + (\nabla\phi_q)^2) - V(\phi_L) + V(\phi_R) \right),$$

    where $\phi_q = (\phi_L - \phi_R)/\sqrt{2}$ and $\phi_c = (\phi_L + \phi_R)/\sqrt{2}$.
  - Heuristically, if there is a gap and we adiabatically turn on $V(\phi)$, we should dress the vacuum and the jump operators simultaneously, and preserve a stable vacuum.
- This remains an important open question.
- Non-unitary QFT with irrelevant jump operators?
  - In principle, jump operators with large mass dimension.
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Outline

Why quantize gravity?

- In unitary QM, if A is quantum mechanical and the state of A influences the evolution of B, then B must be quantum mechanical:

$$\left.\begin{array}{l} \psi_A^1\Omega_B \xrightarrow{time} \phi_A^1\Lambda_B^1 \\ \psi_A^2\Omega_B \xrightarrow{time} \phi_A^2\Lambda_B^2 \end{array}\right\} \Rightarrow (|\psi_A^1\rangle + |\psi_A^2\rangle)|\Omega_B\rangle \xrightarrow{time} |\phi_A^1\rangle|\Lambda_B^1\rangle + |\phi_A^2\rangle|\Lambda_B^2\rangle$$

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- Assume now that B is a classical system, and that α label a phase space coordinate, e.g., $\alpha = (x, p)$.
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Classical-Quantum field theory

- In field theory, there is a sub-normalized density matrix of some quantum field $\Psi_q(x)$ associated to every configuration of a classical field ϕ_c and its conjugate momentum π_c: $\langle\Psi_q|\rho(\phi_c,\pi_c)|\Psi'_q\rangle = \rho(\phi_c,\pi_c,\Psi_q,\Psi'_q)$.
- Local equation $\alpha(x) = (\phi(x),\pi(x))$,

$$\dot{\rho}(\alpha) =$$

$$\int d^3x \left[\mathcal{L}(x)[\rho(\alpha)] + \sum_j \mathcal{L}_j(x)\left[\frac{\partial}{\partial\alpha_j(x)}\rho(\alpha)\right] + \Big\{H(x),\rho(\alpha)\Big\}_{\text{Poisson}}\right]$$

Quantum Matter & Classical Gravity?

- In principle possible if coupling is dissipative.
  - No constraint on how gravity influences matter.
  - Matter has only stochastic effect on gravity.
- In our free-field theory example, we can imagine that the decay rate γ is a gravitational degree of freedom, e.g. scalar curvature.
  - Unitary evolution in flat space, high decoherence near black hole singularity.
  - With Lindblad term $L(p) = a_p$, rate equation of gravitational field is controlled by energy density $\langle L^\dagger L \rangle = \langle a_p^\dagger a_p \rangle$.
- Classical-Quantum coupling

$$g^{\mu\nu}\left(2\pi_\mu^- \rho \pi_\nu^+ - \{\pi_\nu^+ \pi_\nu^-, \rho\}\right)$$

where $\pi_\mu = \delta L / \delta(\partial_\mu \phi)$.

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  - Recover invariance when decay rate are gravitational degrees of freedom.
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- Black holes: they evaporate from the inside.
  - Entangled partner of photon in Hawking radiation disapears near singularity, so Hawking radiation becomes truly mixed.
- Black hole entropy still counts micro-states.
- Inflation: dissipation as a mean to obtain smooth, isotropic universe with no heavy magnetic monopoles?
- Offset in astronomical distance measures: what if photons had a finite dissipation rate?
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- Inflation: dissipation as a mean to obtain smooth, isotropic universe with no heavy magnetic monopoles?
- Offset in astronomical distance measures: what if photons had a finite dissipation rate?
- Dark matter: what if the vacuum is not exactly a fixed point of the dynamics?

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  - Further justifies non-unitary evolution since dissipative terms can be controlled by classical gravitational variables: turn on only in extreme conditions.
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