Title: Black holes, fundamental destruction of information and conservation laws

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Abstract: Theories which have fundamental information destruction or decoherence are motivated by the black hole information paradox. However they have either violated conservation laws, or are highly non-local. Here, we show that the tension between conservation laws and locality can be circumvented by constructing a relational theory of information destruction. In terms of conservation laws, we derive a generalization of Noether's theorem for general theories, and show that symmetries imply a restriction on the type of evolution permissible. With respect to locality, we distinguish violations of causality from the creation or destruction of separated correlations. We show that violations of causality need not occur in a relational framework -- the only non-locality is that correlations decay faster than one might otherwise expect or can be created over spatial distances. The theories can be made time-symmetric, thus imposing no arrow of time.

Non-unitary evolution

Black holes, fundamental information destruction, and conservation laws.

J. Oppenheim, B. Reznik

Quantum mechanics and QFT are unitary. Pure states evolve into pure states.

$$\dot{\rho}(t) = -i[H, \rho]$$

But does it have to be this way? Are there more general evolution laws?

① That which is not forbidden is required

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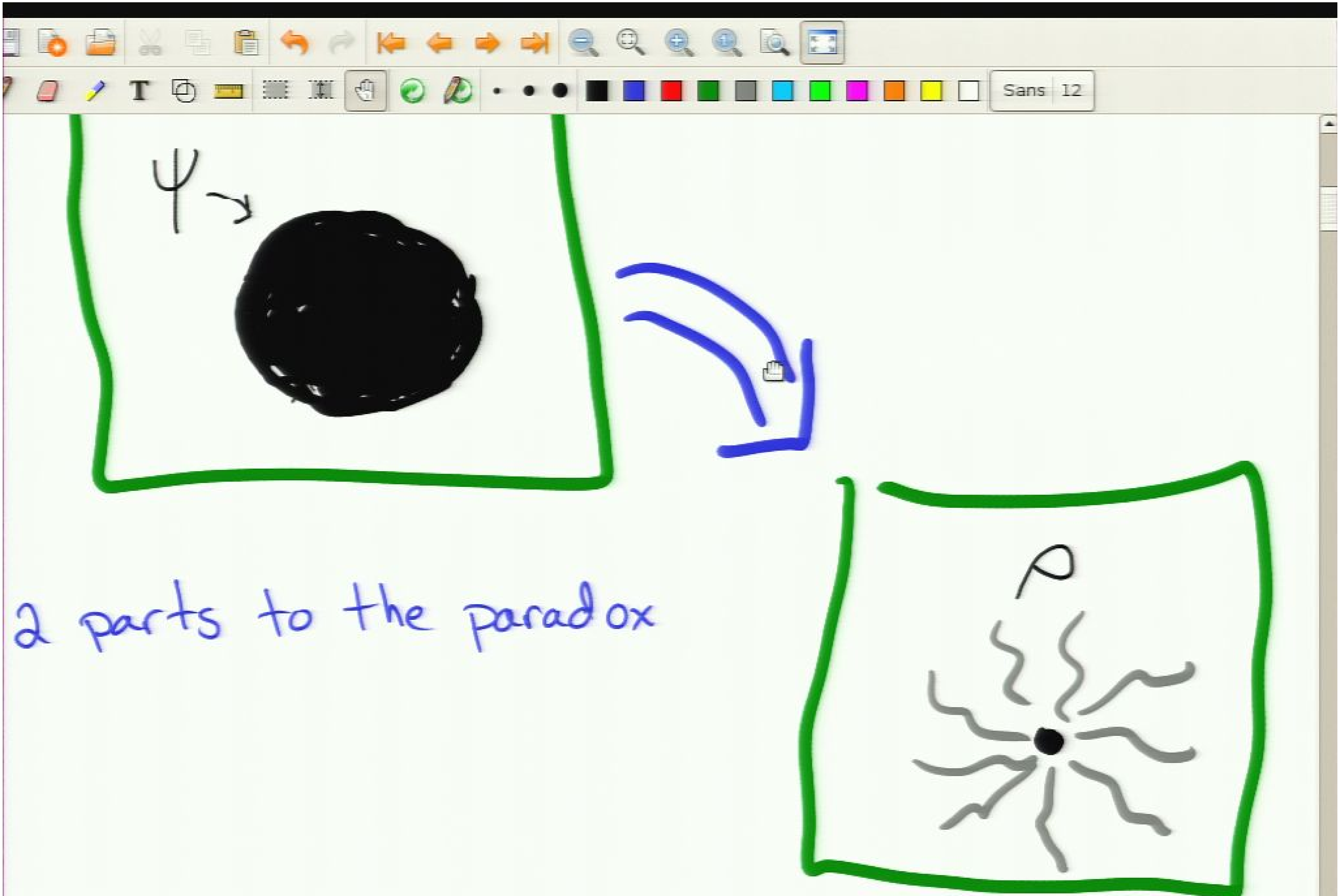
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2 parts to the paradox

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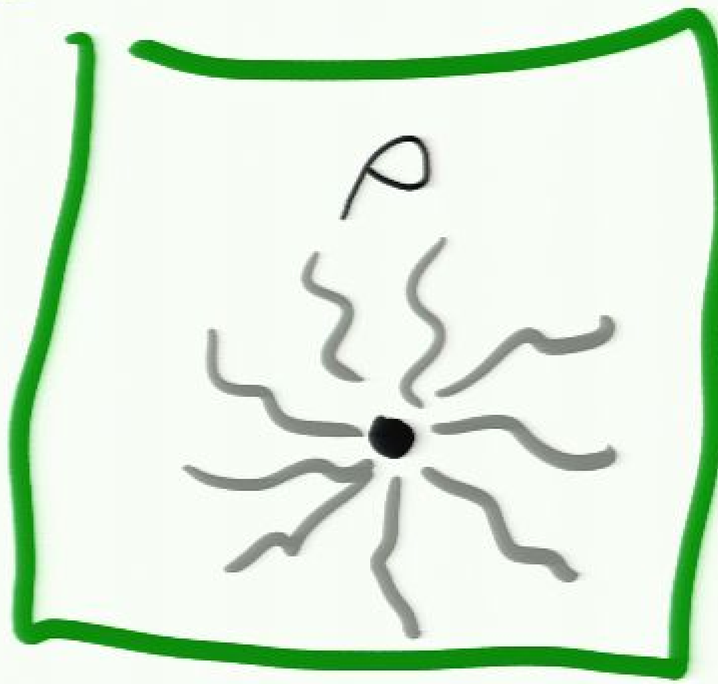

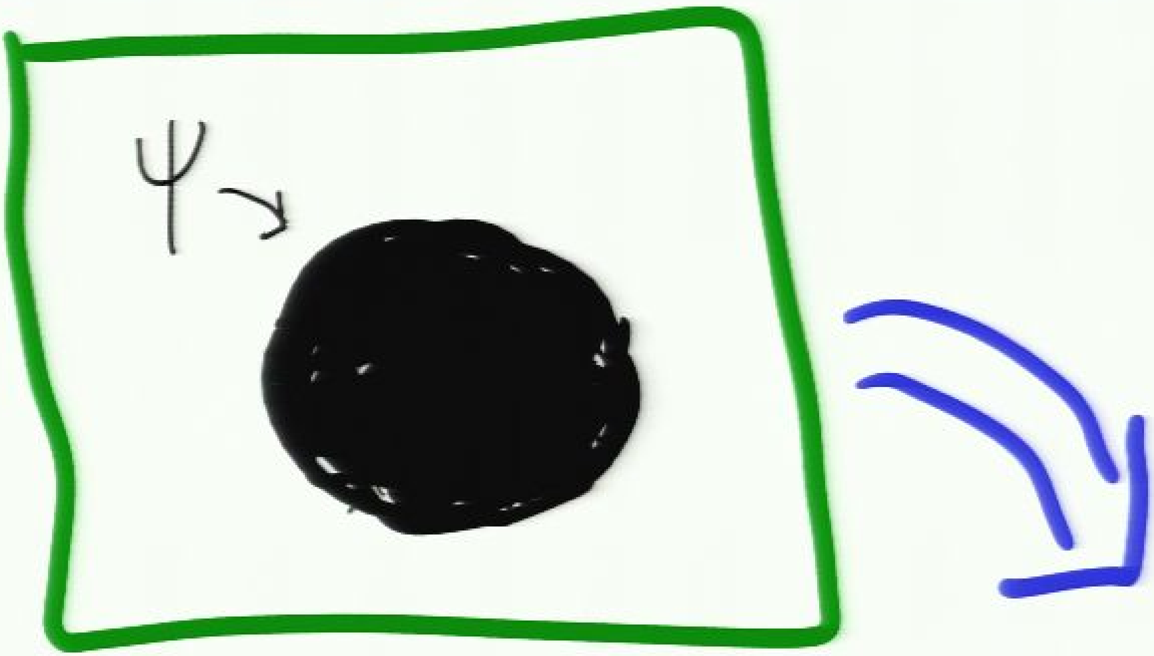

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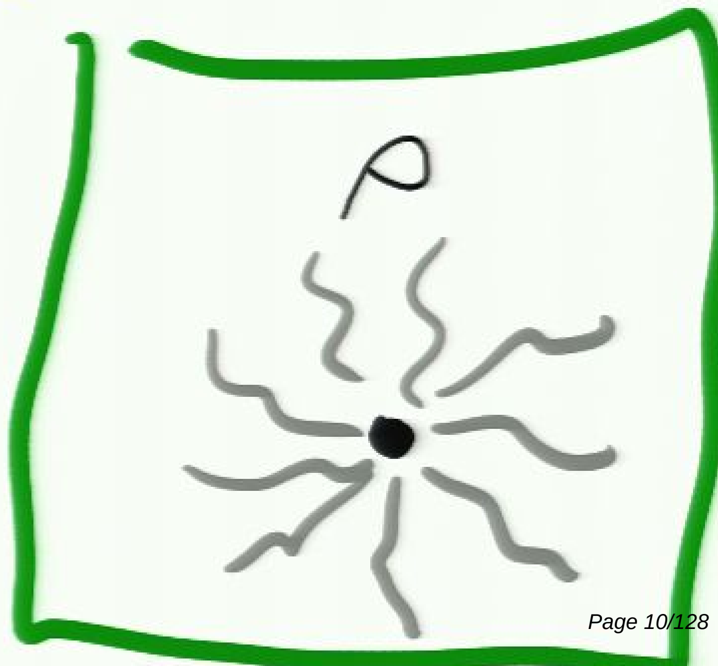
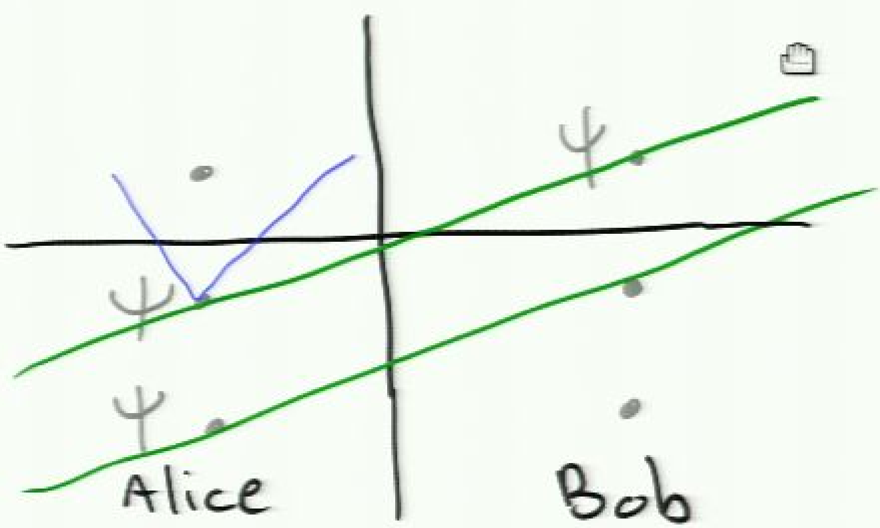
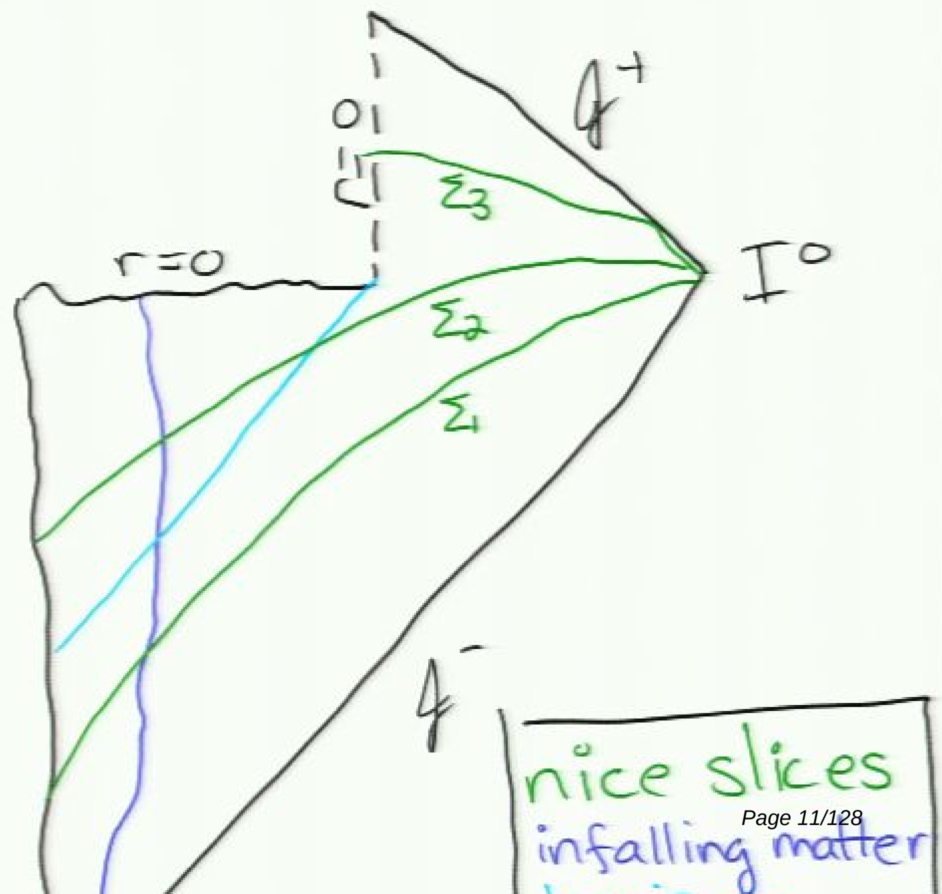


① Either information is destroyed in which case, the evolution is <u>non-unitary</u>, or information comes out, in which case it is cloned, and the evolution must be <u>non-unitary</u>.





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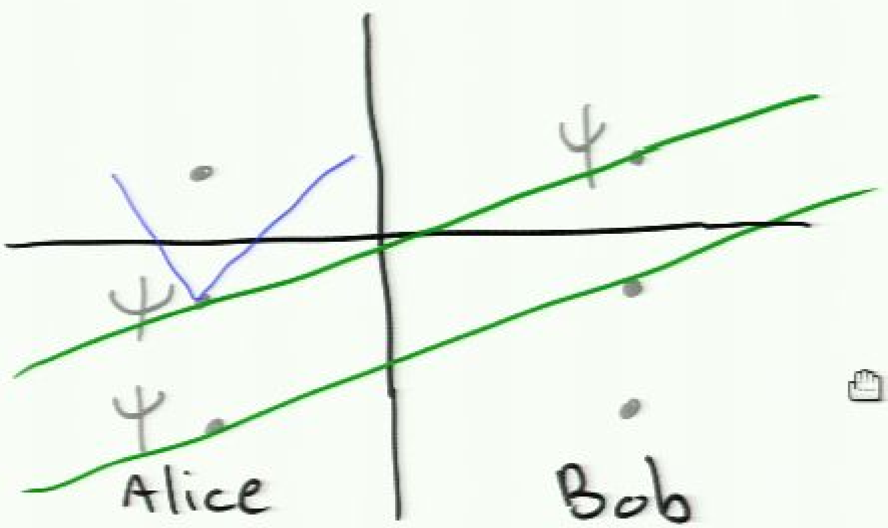

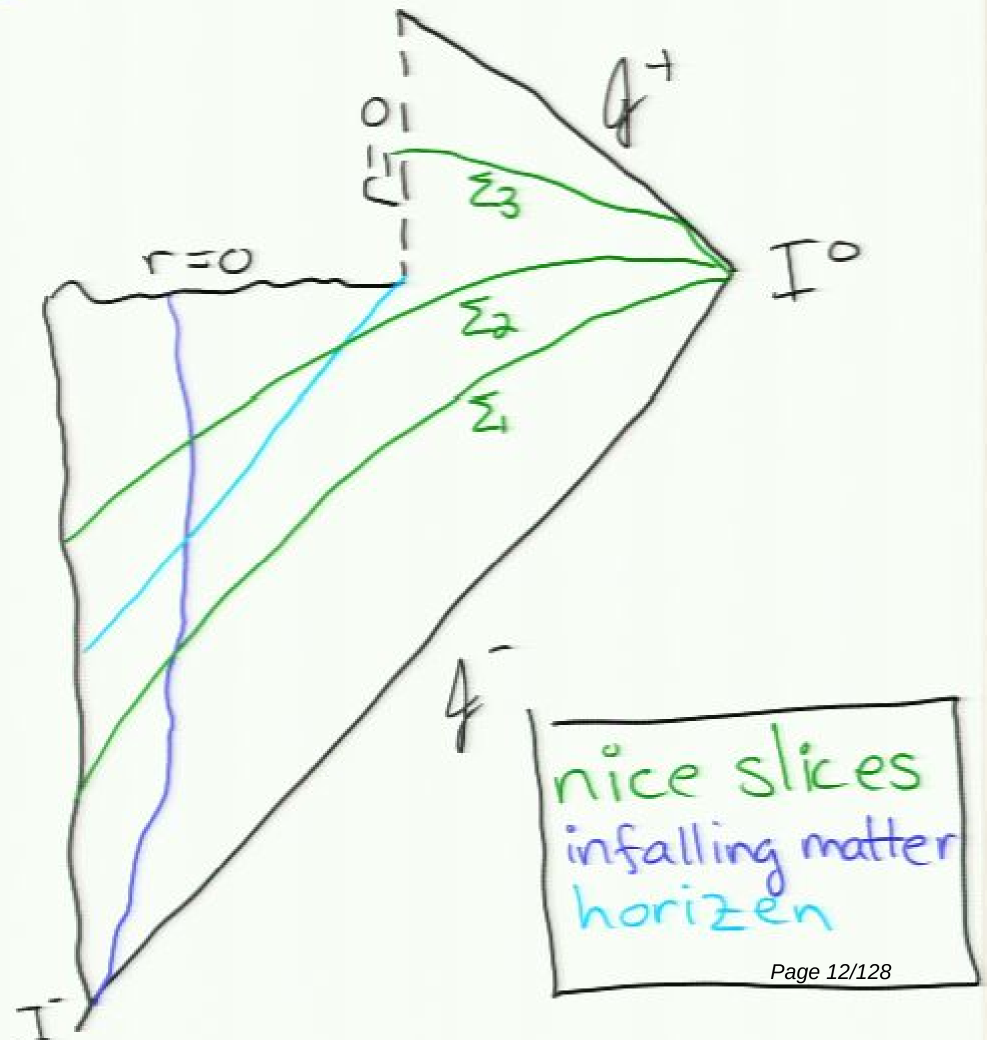

Yes!

1. That which is not forbidden is required
2. Black hole evaporation
3. Quantum measurement: "which branch"

No!

1. God is not a gambler.
2. AdS/CFT
3. Banks, Peskin and Susskind (84)

You must either violate locality or conservation laws.

Can evolution be ^non unitary?

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Outline

- non-unitary theories
- the objection of BPS
- A way out: relational theories
  - QM
  - QFT
  - Energy vs. others
- Noether's Theorem
- Coupling to gravity
- Lorentz invariance

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- Time Symmetric
- Open questions

Lindblad Equation

$$\dot{\rho} = \mathcal{L}\rho = -i[H,\rho] - \frac{1}{2}\sum_k \sigma_k (L_k^\dagger L_k \rho + \rho L_k^\dagger L_k - 2L_k^\dagger \rho L$$

$\mathcal{L}$ is the most general form of a semi-group generator if K is countable and $\mathcal{L}$ bounded.

Recall: A semi-group is a continuous, one parameter family of CPT maps $\Lambda(t)$ which are Markovian

$$\Lambda(t_1)\Lambda(t_2) = \Lambda(t_1 + t_2)$$

Pure Decoherence

Eg. $L_k = P_k$ a projector

$H = 0$ $\quad \gamma_k = \gamma$

$$\dot{\rho} = -\gamma \rho + \gamma \sum P_k \rho P_k$$

$$\rho = \sum \sigma_{ij} |i\rangle\langle j|$$

$$\sigma_{ij}(t) = \begin{cases} \sigma_{ij}(0) & \text{for } i=j \\ e^{-\gamma t}\sigma_{ij}(0) & \text{for } i \neq j \end{cases}$$

Like a measurement in P_k basis

$$[|x_k\rangle\langle x_k|, P] \neq 0$$

Hawking 82

$$\dot{\rho} = -i[H_0, \rho] - \frac{a}{2m_p^4}\int d^3x \, [F^{\mu\nu}F_{\mu\nu}(x), [F^{\mu\nu}F_{\mu\nu}(x), \rho]]$$

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- all theories suffer from this tension
- you can only decohere into boring observables (~~total~~ momentum)

A relational theory

~~QM~~

$$L = |x\rangle\langle x| \longrightarrow Q = \int_{-\infty}^{\infty} |x\rangle_{1\,1}\langle x| \otimes |x\rangle_{2\,2}\langle x| \, dx$$

A coincidence detector

$$e^{-iPx} Q e^{iPx} = Q$$

$$[P_{total}, Q] = 0$$

$$Q = \int e^{-iPx} L e^{iPx} dx$$

$$\dot{\rho}_{12} = -i[H, \rho_{12}] - \frac{\gamma}{2}[Q, [Q, \rho_{12}]]$$

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"local"

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QFT

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Hawking $\delta\alpha$

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Hawking et al

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Examples

QM $$Q = \int |x\rangle_{11}\langle x| \otimes |x\rangle_{22}\langle x| \, dx$$

QM, QFT $$Q_k = \int L_k^{(1)}(x) \otimes |x\rangle_{22}\langle x| \, dx$$

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QFT

$$Q_k = \int L_k^{(1)}(x) \otimes L_k^{(2)}(x) \, dx$$

$$\psi(x) = \phi(x) + i\pi(x)$$

$$|1_x\rangle = \psi^{\dagger}(x)|0\rangle$$

QM

$$Q = \int |x\rangle_{1\,1}\langle x| \otimes |x\rangle_{2\,2}\langle x|\, dx$$

QM, QFT

$$Q_k = \int L_k^{(1)}(x) \otimes |x\rangle_{2\,2}\langle x|\, dx$$

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Locality in more detail

What do we mean by locality??

① Causality $[A(x), B(y)] = \Delta(x-y)$

$$\Delta(x-y) = 0 \text{ for } (x-y)^2 < 0$$

② Non-local correlations

$$\frac{dA(\bar{x})}{dt} = f(\bar{x}) \quad \text{but} \ldots$$

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O w/ $f^0 \equiv g$

ad evolution

$\Sigma \gamma_i \Delta_i N_i(x)$ w/ $L_i^\dagger L_i = \int dv\, N(x)$

$K(x)$ eg. $g^\mu = T^{\mu 0}$

$= K^\mu(x)$ → couple to gravity??

upling" to gravity (toys)

to curvature (more decoherence

Sans 12

Causality is proven by a fictitious but relati[...] environment and tracin[...] to go from a unitary the[...] to a Lindblad equation

The environment

infinite spatial co[...]

Unruh and Wald

Poulin and Preski

– Introduce memory e

non-Markovian theory

(non-locality in time)

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Causality is proven by adding a fictitious but relativistic environment and tracing it out to go from a unitary theory U_{SE} to a Lindblad equation $\mathcal{L}_S$

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- infinite spatial correlation
- infinitely many fields
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② Non-local creation/destruction of correlations

For $\frac{d}{dt}A(x)B(y) = i[H, A(x)B(y)]$ $H = \int d\bar{x}\, \mathcal{H}(x)$

$$\frac{d}{dt}A(x)B(y) = \dot{A}B + A\dot{B}$$ but ....

For $Q_k = \int dx\, L_k(x)$ Hermitian

$$\frac{dA(\bar{x})B(\bar{y})}{dt} = \frac{dA(\bar{x})}{dt}B(\bar{y}) + A(\bar{x})\frac{dB(\bar{y})}{dt} + V(A(\bar{x})B(\bar{y}))$$

$$V(A(\bar{x})B(\bar{y})) = -\frac{1}{2}\sum \gamma_{ij}\int dz\,[L_i(z), A(\bar{x})]\int dz\,[L_j(z), B(\bar{y})]$$

Sans 12

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... in the extreme

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Relationalism in the extreme

$V(A \otimes B)$ reflects the fact that there may be no way to distinguish x from y if all [illegible] values at x and y are the

CMB?

Horizon Problem: correlations at space-like separated violate causality.

No!

The creation of correlation does not necessarily allow signaling

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But not for time translation.

① Time translation no longer generated by H. Evolution is via the Lindblad equation. No Noether's theorem

② $$[L(\bar{x},t), L(\bar{x}',t)] = 0$$

but $$[L(\bar{x},t), L(\bar{x},t')] \neq 0$$

$\therefore$ $Q = \int e^{-iHt} L e^{iHt}$ is not local

③ t appears on LHS of Lindblad eqn

$$\frac{d\rho}{dt} = -i[H,\rho] - \frac{1}{2}\sum \gamma_i [Q_i,[Q_i,\rho]]$$

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Symmetry + unitary evolution → conservation
Gross (84) this breaks down in non-unitary theories

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Continuity Equation

$$\frac{dg(x)}{dt} = i[H, g(x)]$$

$\therefore \quad [H, G] = 0 \qquad i[H, g] = \nabla f^i$

$$\boxed{\partial_\mu f^\mu = 0}$$

w/ $f^0 \equiv g$

For Lindblad evolution

$K(x) \equiv \sum \gamma_i \Delta_i N_i(x)$ w/ $L_i^\dagger L_i = \int dx\, N(x)$

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$$\boxed{T^{\mu\nu}{}_{;\nu}(x) = K^\mu(x)}$$

$\to$ couple to gravity??

$\partial_\mu J = 0$

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$\rightarrow$ couple to gravity??

"Coupling" to gravity (toys)

- couple to curvature (more decoherence at high curvature)

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- "couple to singularity"

$$Q = \int L(x)\, |\bar{x}\rangle\langle\bar{x}|\, |\tau\rangle\langle\tau|\, d\bar{x}\, dt$$

- decoherence terms act at high energy

Black holes as microscopes

Continuity Equation

$$G = \int dx\, g(x)$$

$$\frac{dg(x)}{dt} = i[H, g(x)]$$

$$\therefore \quad [H, G] = 0 \qquad\qquad i[H, g] = \nabla f^i$$

$$\boxed{\partial_\mu f^\mu = 0} \qquad w/ \quad f^0 \equiv g$$

For Lindblad evolution

$$K(x) \equiv \sum \gamma_i \Delta_i N_i(x) \qquad w/ \quad L_i^\dagger L_i = \int dx\, N(x)$$

$$\partial_\mu f^\mu = K(x) \qquad \text{eg.} \quad g^\mu = T^{\mu 0}$$

Black holes as

Lorentz Invariance?

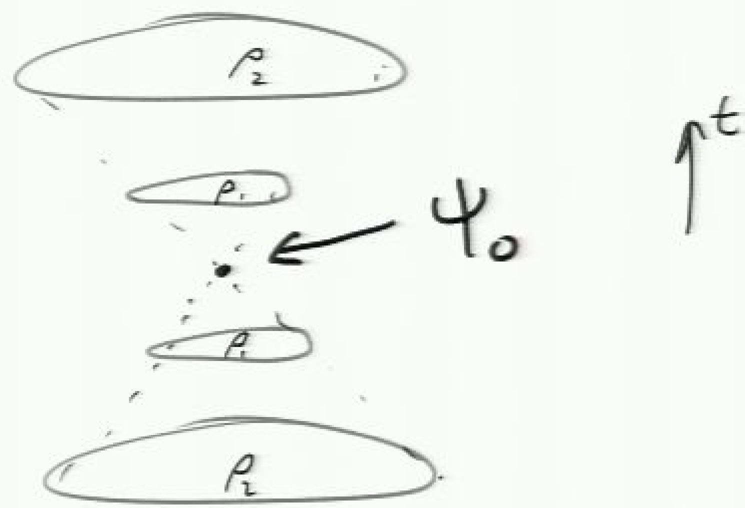
$$\partial_0 \phi(x) = -i[H, \phi(x)] + \mathcal{D}^0(\phi(x))$$

$$\partial_{\bar{0}} \bar{\phi}(\bar{x}) = -i[\bar{H}, \bar{\phi}(\bar{x})] + \bar{\mathcal{D}}^0(\bar{\phi}(\bar{x})) \quad \text{(invariance)} \qquad \bar{x} = \Lambda x$$

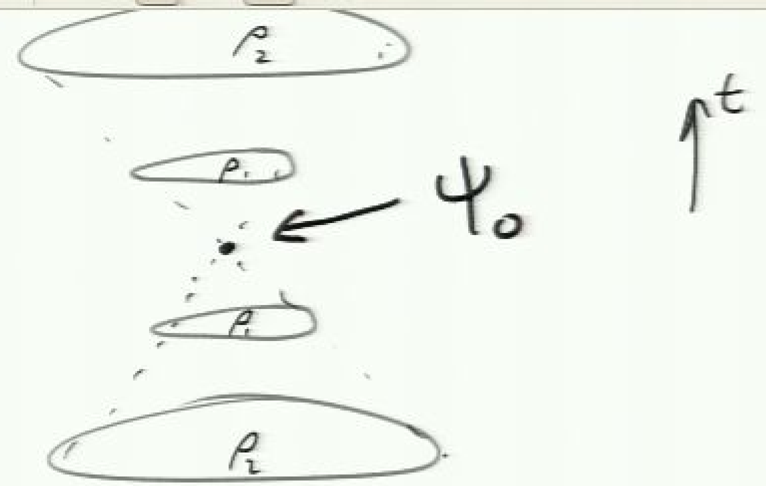
assume $\mathcal{D}^0$ transforms as a time component of $\mathcal{D}^\mu$

Time Symmetric

Increasing entropy does not give a direction in time



$$-\frac{1}{2}\int_0^t (L^\dagger L\rho + \rho L^\dagger L - 2L^\dagger \rho L)\,dt \qquad t \geq 0$$



$$\rho(t) = \rho(0) \begin{cases} -\frac{1}{2}\int_0^t \left(L^\dagger L\rho + \rho L^\dagger L - 2L^\dagger\rho L\right)dt & t \geq 0 \\ +\frac{1}{2}\int_0^t \left(L^\dagger L\rho + \rho L^\dagger L - 2L^\dagger\rho L\right)dt & t < 0 \end{cases}$$

Conclusions

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- Clarify locality: causality vs correlations
- time/energy vs other symmetries/conserved quantities
- generalized Noether's theorem
- violation of Lorentz invariance
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- resolves many of the problems in collapse models

conflict between ... g

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- are ... rich enough?

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  eg. full information destruction : 2d projectors

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Sans 12

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CMB?

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