Title: Locality in Quantum Gravity

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Abstract:

SUBSYSTEMS & LOCALITY IN QUANTUM GRAVITY

- The low-energy problem: find propagating modes in a background-independent quantum theory of gravity (e.g. spin foam, LQG). Necessary, in order to make contact with physics.
- Quantum Information Theory ⇒ these are "noiseless subsystems"
  - Definition
  - Example: the Schwarzchild black hole in LQG.
- Implications for background-independence & locality

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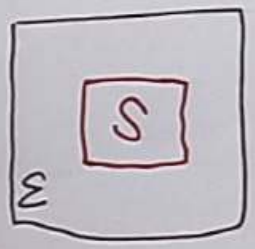
QUANTUM EVOLUTION OF AN OPEN SYSTEM.



$$\mathcal{H}^{TOTAL} = \mathcal{H}^S \otimes \mathcal{H}^E$$

$$H = H^{int} + H^E + H^S$$

Reduced dynamics on $\mathcal{H}^S$:

$$\phi : \mathcal{H}^S \rightarrow \mathcal{H}^{S'}$$

$$\rho_f^S = \phi[\rho_i^S] = tr_E\left[U(\rho_i^S \otimes \rho_i^E)U^\dagger\right]$$

PROPAGATING MODE: A SUBSYSTEM OF S THAT IS CONSERVED UNDER ϕ, ie. EVOLVES UNITARILY.

We will see that this is a NOISELESS SUBSYSTEM.

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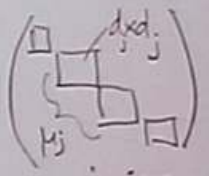
PROPAGATING MODES AND THE INTERACTION COMMUTANT.

INTERACTION ALGEBRA: $\phi[\rho^S] = \sum_k A_k \rho^S A_k^\dagger \qquad \sum_k A_k^\dagger A_k = 1$

The A_k generate $\mathcal{A}^{int} \subseteq \mathcal{B}(\mathcal{H}^S)$.

$$\mathcal{A}^{int} \simeq \bigoplus_j \mathbb{1}_{M_j} \otimes \mathcal{B}(\mathbb{C}^{d_j})$$



INTERACTION COMMUTANT: $\mathcal{A}^{int\prime} \subseteq \mathcal{B}(\mathcal{H}^S)$

$$\mathcal{A}^{int\prime} \simeq \bigoplus_j \mathcal{B}(\mathbb{C}^{M_j}) \otimes \mathbb{1}_{d_j}.$$

Any $\rho \in \mathcal{A}^{int\prime}$ is a fixed point of ϕ:

$$\phi[\rho^S] = \sum_k A_k \rho^S A_k^\dagger = \sum_k A_k A_k^\dagger \rho^S = \rho^S$$

i.e. $\boxed{\phi[\rho^S] = \rho^S \iff \rho^S \in \mathcal{A}^{int\prime}}$

Hence, $\mathcal{H}^S \simeq \bigoplus_j \mathbb{C}^{M_j} \otimes \mathbb{C}^{d_j}$ and the $\boxed{\mathbb{C}^{M_j}\text{'s}}$ are conserved = A NOISELESS SUBSYSTEM.

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(with D. Poulin)

- NS are useful for describing the long-term behavior of the system because they are conserved.
- If we divide the quantum gravitational field into subsystems, those properties that are CONSERVED under interactions btw THE SUBSYSTEMS will characterize the low-energy limit spacetime geometry.

$\Rightarrow$ The commutant $A^{int'}$ should include the symmetries that characterize classical spacetime (e.g. Poincaré).

EXAMPLE ...

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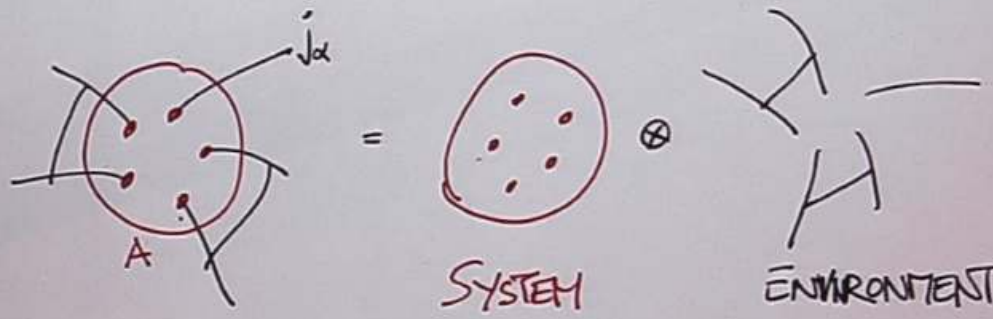
O. Dreyer, FM + L. Smolin, hep-th/0409056.

EXAMPLE OF A NS: THE SCHWARZCHILD BLACK HOLE IN LQG.



Ashtekar-Baez-Corichi-Krasnov

$\mathcal{H}^S_A$ = invariant states of U(1) Chern-Simons on punctured S^2

$\mathcal{H}^E_{\{j_\alpha\}}$ = diff-classes of spinnets ending on horizon

$$\mathcal{H}^{TOTAL} = \sum_{\{j_\alpha\}} \mathcal{H}^S_A \otimes \mathcal{H}^E_{\{j_\alpha\}}$$

Q: WHICH STATES IN $\mathcal{H}^S_A$ CORRESPOND TO THE QUANTUM ANALOGUE OF A SCHWARZCHILD BLACK HOLE ?

A classical SBH has SO(3) symmetry.

→ if there is a microscopic analogue of a SBH, there must be a microscopic analogue, G_q, of SO(3), that becomes SO(3) in the classical limit. ← IN THE DYNAMICS

→ This corresponds to a non-trivial $A^{int'}$ that identifies the QSBH as a NS, ie.,

$$G_q \subseteq A^{int'}$$

We do not know $\mathcal{B}(\mathcal{H}_A^S)$ or A^{int}, but it is possible to restrict it sufficiently to find the NS corresponding to G_q.

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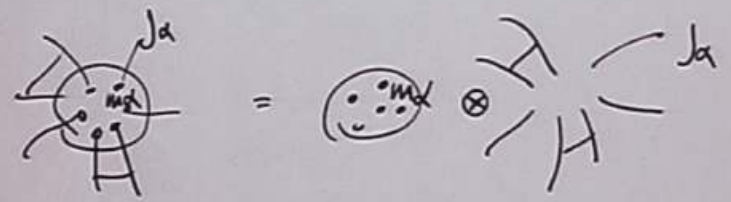
G_q = MICROSCOPIC So(3)

- G_q is a discrete symmetry group.
- A_k and A_t^{int} must { act simultaneously on $\mathcal{H}^S \& \mathcal{H}^E$ / act locally

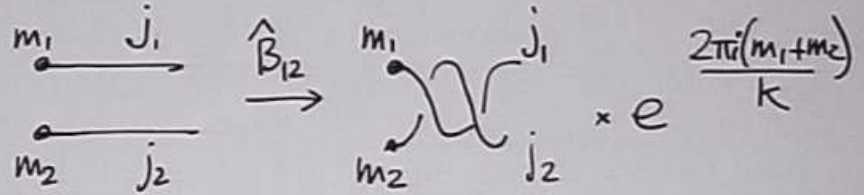
- 

$|m_\alpha| \leq j_\alpha \qquad \sum_\alpha m_\alpha = 0$

Level of Chern-Simons : $k = \frac{a_0[\{j_\alpha\}]}{4\pi\gamma}$

$\Rightarrow$ A sufficient set of GENERATORS for A^{int} is

1. Add / remove punctures
2. Braid



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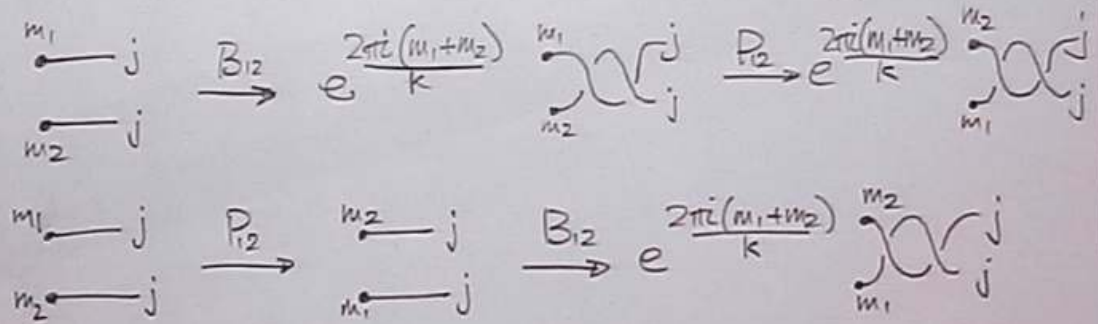
- G_q must not change the horizon area, $G_q : \mathcal{H}_A^S \to \mathcal{H}_A^S$.

$\Rightarrow$ Generate A^{nat} by braidings only.



ie Permute · Braid = Braid · Permute for same j

$\Rightarrow \boxed{G_q \subset \prod_j P_{K_j}}$ $\quad K_j = \#\text{punctures } j$

- G_q is transitive : for every $\cdot\cdot$, there is $\cdot \overset{G_q}{\to} \cdot$

$\Rightarrow K_j = \#$ punctures on surface — ALL j THE SAME.

$\Downarrow$

QUANTUM SCHWARZCHILD BLACK HOLE

$$\mathcal{H}_A^{QSBH} = \mathcal{H}_j^{QBH} = \mathcal{H}_{j_{min}}^{QBH}$$

THE NOISELESS SUBSYSTEM

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NAMELY,

the state space of the quantum Schwarzschild BH is the noiseless subsystem corresponding to the G_q symmetries of the dynamics.

Quasinormal modes: excited states in the NS.

LESSONS:

- The NS is a dynamical construction.
  (without using A^{int}, you could have obtained $\mathcal{H}_m^{BH}$.)
  Cf. using class. observables to distinguish BH.
- For the low-energy behavior, we only need the interaction dynamics, and from that, we only need the symmetries.
- A^{int} depends on the energy level/approximation/observables we are interested in.
- Conversely, in model-building, we can use the low-energy symmetries to constrain the microscopic dynamics.

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PROPAGATING MODES vs BACKGROUND INDEPENDENCE.

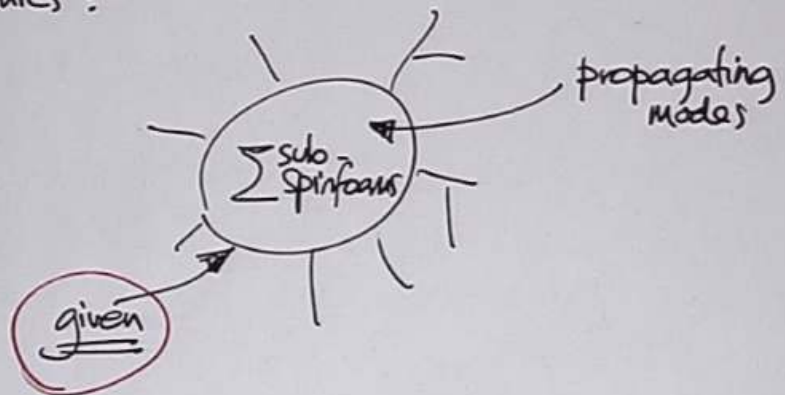
Stachel: "Background independence means there is no dynamics-independent kinematics".

The NS method is background-independent in the sense that it does not rely on a particular graph / state, there is a genuine superposition of spinfoams / states inside the boundary & is defined via the dynamics.

But:

The NS is a subsystem of a subsystem = $\mathcal{H}_A^{SBH}$ in $\mathcal{H}_A^{BH}$.
It finds the first if you give the second

[redacted] It does need the boundary / interaction dynamics:



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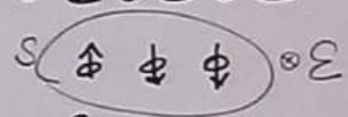
NS & LOCALITY, or, MICROSCOPIC vs MACROSCOPIC LOCALITY.

One can try to assign geometric/local/causal properties to the subfoams/subgraphs.

But they are not eigenstates of the dynamics.

We <u>have</u> to take into account the quantum sum over geometries.

<u>Locality in a NS example</u> : $\mathcal{H}^S = \mathbb{C}^2 \otimes \mathbb{C}^2 \otimes \mathbb{C}^2$ with Z_3 symmetry in $\mathcal{A}^{int'}$.

S  $\otimes \mathcal{E}$

$\rightarrow \mathcal{H}^{NS} \simeq \mathbb{C}^2$, but it's <u>none</u> of the originals.

cf Perez's talk

NS SUGGESTS:

- give boundary (interaction) dynamics
- look at appropriate symmetries & extract NSs.
- assign locality/geometric/causal properties to the effective NSs.

Outlook:

- Black Hole case:
  - excitations in $\mathcal{H}^{QSBH}$ that correspond classically to QNM.
  - Rotating BH.
  - BH in spin foams/other models
  - $G_q \to SO(3)$.
- Propagating modes in quantum gravity with boundary.
- Weaves (Dynamical) from translation symmetry in A^{int}.
- Separate scales: environment $\leftrightarrow$ small-scale fluct^{ns} system $\leftrightarrow$ coarse-grained weave
- Theory of noiseless subsystems:
  - aprox/emergent NS definition
  - Poincaré

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