Pilot-wave approach to key issues in non-perturbative quantum gravity

Dr. Indrajit Sen

May 9, 2024

1. I. Sen, S. Alexander and J. Dressel. A realist interpretation of unitarity in quantum gravity. *Class. Quantum Grav.* 41, 115005 (2024).

2. I. Sen. Physical interpretation of non-normalizable harmonic oscillator states and relaxation to pilot-wave equilibrium. *Nat. Sci. Rep.* 14, 669 (2024).



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1 The problem of time

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- 1 The problem of time
- 2 The problem of non-normalizability.

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- 1 The problem of time
- 2 The problem of non-normalizability.
 - 3 The problem of classical limit.

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- 1 The problem of time
- 2 The problem of non-normalizability.
 - 3 The problem of classical limit.
- 4 The problem of reality conditions.

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All major approaches to resolving these problems based on orthodox quantum mechanics.

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- 1 The problem of time
- 2 The problem of non-normalizability.
 - 3 The problem of classical limit.
- 4 The problem of reality conditions.



New conceptual approach based on pilot-wave theory.

- 1 The problem of time \checkmark
- 2 The problem of non-normalizability. \checkmark
 - 3 The problem of classical limit. \checkmark
- 4 The problem of reality conditions. \checkmark

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Pilot-wave theory

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Pilot-wave theory

Quantum State: $\hat{H}|\psi\rangle = i\hbar\partial_t|\psi\rangle$

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Quantum State: $\hat{H}|\psi\rangle = i\hbar\partial_t|\psi\rangle$ Configuration: $\vec{v} = \frac{j}{|\psi|^2}$

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Quantum State: $\hat{H}|\psi\rangle = i\hbar\partial_t|\psi\rangle$ Configuration: $\vec{v} = \frac{j}{|\psi|^2}$

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Pilot-wave theory

Quantum State: $\hat{H}|\psi\rangle = i\hbar\partial_t|\psi\rangle$ Configuration: $\vec{v} = \frac{j}{|\psi|^2}$

Laws of nature



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Pilot-wave theory

 $\begin{array}{l} \mbox{Quantum State:} \ \hat{H} |\psi\rangle = i \hbar \partial_t |\psi\rangle \\ \mbox{Configuration:} \ \vec{v} = \frac{j}{|\psi|^2} \end{array} \end{array} \right\} \ \mbox{Laws of nature} \label{eq:Quantum state}$

Conceptual approach to key issues



Pilot-wave theory

 $\left. \begin{array}{l} \mbox{Quantum State:} \ \hat{H} |\psi\rangle = i \hbar \partial_t |\psi\rangle \\ \mbox{Configuration:} \ \vec{v} = \frac{j}{|\psi|^2} \end{array} \right\} \ \mbox{Laws of nature} \label{eq:configuration}$

Conceptual approach to key issues

1. The problem of time \longleftarrow t parameterizes variation of the configuration.



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Pilot-wave theory

 $\left. \begin{array}{l} {\rm Quantum \ State: \ } \hat{H} |\psi\rangle = i \hbar \partial_t |\psi\rangle \\ {\rm Configuration: \ } \vec{v} = \frac{j}{|\psi|^2} \end{array} \right\} \ {\rm Laws \ of \ nature \ } \end{array} \right\}$

Conceptual approach to key issues

1. The problem of time \downarrow parameterizes variation of the configuration.

2. The problem of non-normalizability ______ locally conserved current.



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 $\left. \begin{array}{l} {\rm Quantum \ State: \ } \hat{H} |\psi\rangle = i \hbar \partial_t |\psi\rangle \\ {\rm Configuration: \ } \vec{v} = \frac{j}{|\psi|^2} \end{array} \right\} \ {\rm Laws \ of \ nature \ } \end{array} \right\}$

Conceptual approach to key issues

- 1. The problem of time \leftarrow t parameterizes variation of the configuration.
 - 2. The problem of non-normalizability ______ locally conserved current.
- 3. The problem of classical limit *quantum* corrections in the guidance equation.



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Pilot-wave theory

 $\left. \begin{array}{l} {\rm Quantum \ State: \ } \hat{H} |\psi\rangle = i \hbar \partial_t |\psi\rangle \\ {\rm Configuration: \ } \vec{v} = \frac{j}{|\psi|^2} \end{array} \right\} \ {\rm Laws \ of \ nature \ }$

Conceptual approach to key issues

- 1. The problem of time \downarrow parameterizes variation of the configuration.
 - 2. The problem of non-normalizability ______ locally conserved current.
- 3. The problem of classical limit \rightarrow quantum corrections in the guidance equation.
- 4. The problem of reality conditions _______ implement at the level of guidance equation.



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Total constraint for interacting gravitational-fermionic system¹:

$$\int_{\mathcal{M}} (ilde{N} \hat{\mathcal{H}} + N^{a} \hat{\mathcal{V}}_{a}) \Psi[A,\xi] = 0$$

¹S. Alexander et al., Phys. Rev. D 2022, 106, 106012.

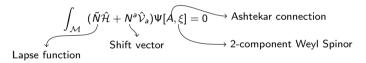
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Total constraint for interacting gravitational-fermionic system:

$$\int_{\mathcal{M}} \underbrace{(\tilde{N}\hat{\mathcal{H}} + N^{a}\hat{\mathcal{V}}_{a})\Psi[A,\xi]}_{\text{Shift vector}} = 0$$

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Total constraint for interacting gravitational-fermionic system:



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Total constraint for interacting gravitational-fermionic system:

$$\int_{\mathcal{M}} (\tilde{N}\hat{\mathcal{H}} + N^{a}\hat{\mathcal{V}}_{a})\Psi[A,\xi] = 0 \rightarrow \text{Ashtekar connection}$$

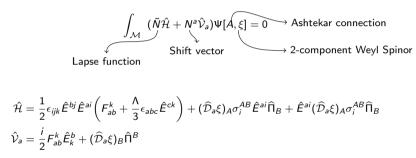
Shift vector 2-component Weyl Spinor Lapse function

$$\begin{aligned} \hat{\mathcal{H}} &= \frac{1}{2} \epsilon_{ijk} \hat{\mathcal{E}}^{bj} \hat{\mathcal{E}}^{ai} \left(\mathcal{F}^{k}_{ab} + \frac{\Lambda}{3} \epsilon_{abc} \hat{\mathcal{E}}^{ck} \right) + (\widehat{\mathcal{D}}_{a} \xi)_{A} \sigma^{AB}_{i} \hat{\mathcal{E}}^{ai} \widehat{\Pi}_{B} + \hat{\mathcal{E}}^{ai} (\widehat{\mathcal{D}}_{a} \xi)_{A} \sigma^{AB}_{i} \widehat{\Pi}_{B} \\ \hat{\mathcal{V}}_{a} &= \frac{i}{2} \mathcal{F}^{k}_{ab} \hat{\mathcal{E}}^{b}_{k} + (\widehat{\mathcal{D}}_{a} \xi)_{B} \widehat{\Pi}^{B} \end{aligned}$$

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Total constraint for interacting gravitational-fermionic system:



Quantization scheme:

$$\hat{E}^{ai}
ightarrow rac{\delta}{\delta A_{ai}}, \qquad \widehat{\Pi}_A
ightarrow -irac{\delta}{\delta \xi^A}$$

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$$\begin{split} &\int_{\mathcal{M}} \tilde{N} \frac{\delta}{\delta A_{ai}} \left[\frac{\epsilon_{ijk}}{2} \frac{\delta}{\delta A_{bj}} \left(F_{ab}^{k} + \frac{\Lambda}{3} \epsilon_{abc} \frac{\delta}{\delta A_{ck}} \right) - 2(\widehat{\mathcal{D}}_{a}\xi)_{A} \sigma_{i}^{AB} i \frac{\delta}{\delta \xi^{B}} \right] \Psi[A, \xi] \\ &+ \int_{\mathcal{M}} i N_{b} \frac{\delta}{\delta A_{ai}} \left[\frac{F_{ai}^{b}}{2} \Psi[A, \xi] \right] - \int_{\mathcal{M}} i N_{b} \frac{\Psi[A, \xi]}{2} \frac{\delta F_{ai}^{b}}{\delta A_{ai}} \\ &= \int_{\mathcal{M}} N^{b} (\widehat{\mathcal{D}}_{b}\xi)^{B} i \frac{\delta}{\delta \xi^{B}} \Psi[A, \xi] \end{split}$$

Where is time?

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$$\begin{split} &\int_{\mathcal{M}} \tilde{N} \frac{\delta}{\delta A_{ai}} \left[\frac{\epsilon_{ijk}}{2} \frac{\delta}{\delta A_{bj}} \left(F_{ab}^{k} + \frac{\Lambda}{3} \epsilon_{abc} \frac{\delta}{\delta A_{ck}} \right) - 2(\widehat{\mathcal{D}}_{a}\xi)_{A} \sigma_{i}^{AB} i \frac{\delta}{\delta \xi^{B}} \right] \Psi[A, \xi] \\ &+ \int_{\mathcal{M}} i N_{b} \frac{\delta}{\delta A_{ai}} \left[\frac{F_{ai}^{b}}{2} \Psi[A, \xi] \right] - \int_{\mathcal{M}} i N_{b} \frac{\Psi[A, \xi]}{2} \frac{\delta F_{ai}^{b}}{\delta A_{ai}} \\ &= \int_{\mathcal{M}} N^{b} (\widehat{\mathcal{D}}_{b}\xi)^{B} i \frac{\delta}{\delta \xi^{B}} \Psi[A, \xi] \end{split}$$

Where is time? Kodama State
$$\Psi[A,\xi] = \Psi_K[A] \Phi[A,\xi]$$

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$$\begin{split} &\int_{\mathcal{M}} \frac{1}{\Psi_{K}} \frac{\delta}{\delta A_{ai}} \left\{ \left[\tilde{N} \frac{\epsilon_{ijk}}{2} \frac{\delta}{\delta A_{bj}} \left(F_{ab}^{k} + \frac{\Lambda}{3} \epsilon_{abc} \frac{\delta}{\delta A_{ck}} \right) + i N_{b} \frac{F_{ai}^{b}}{2} \right] \Psi_{K} \Phi[A, \xi] \right\} \\ &+ \int_{\mathcal{M}} \frac{\delta}{\delta A_{ai}} \left[-2 \tilde{N}(\widehat{D}_{a}\xi)_{A} \sigma_{i}^{AB} i \frac{\delta}{\delta \xi^{B}} \Phi[A, \xi] \right] = i \frac{\partial \Phi[A, \xi]}{\partial t} \end{split}$$

Where is time? Kodama State
Use ansatz
$$\Psi[A, \xi] = \Psi_{K}[A]\Phi[A, \xi]$$

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$$\begin{split} &\int_{\mathcal{M}} \frac{1}{\Psi_{K}} \frac{\delta}{\delta A_{ai}} \left\{ \left[\tilde{N} \frac{\epsilon_{ijk}}{2} \frac{\delta}{\delta A_{bj}} \left(F_{ab}^{k} + \frac{\Lambda}{3} \epsilon_{abc} \frac{\delta}{\delta A_{ck}} \right) + i N_{b} \frac{F_{ai}^{b}}{2} \right] \Psi_{K} \Phi[A, \xi] \right\} \\ &+ \int_{\mathcal{M}} \frac{\delta}{\delta A_{ai}} \left[-2 \tilde{N}(\widehat{\mathcal{D}}_{a}\xi)_{A} \sigma_{i}^{AB} i \frac{\delta}{\delta \xi^{B}} \Phi[A, \xi] \right] = i \frac{\partial \Phi[A, \xi]}{\partial t} \end{split}$$

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$$\Psi[A, \xi] = \Psi_K[A]\Phi[A, \xi]$$

$$\frac{\partial \Phi[A,\xi]}{\partial t} \equiv \int_{\mathcal{M}} \frac{\delta \xi^B}{\delta t} \frac{\delta}{\delta \xi^B} \Phi[A,\xi]$$

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$$\frac{\partial \Phi[A,\xi]}{\partial t} \equiv \int_{\mathcal{M}} \frac{\delta \xi^B}{\delta t} \frac{\delta}{\delta \xi^B} \Phi[A,\xi]$$

$$\frac{\delta\xi^B}{\delta t} \equiv N^b (\widehat{\mathcal{D}}_b \xi)^B + 2\ell_{\rm Pl}^2 \frac{\delta \ln \Psi_K}{\delta A_{ai}} \widetilde{N} (\widehat{\mathcal{D}}_a \xi)_A \sigma_i^{AB}$$

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$$\begin{split} &\int_{\mathcal{M}} \frac{1}{\Psi_{K}} \frac{\delta}{\delta A_{ai}} \left\{ \left[\tilde{N} \frac{\epsilon_{ijk}}{2} \frac{\delta}{\delta A_{bj}} \left(F_{ab}^{k} + \frac{\Lambda}{3} \epsilon_{abc} \frac{\delta}{\delta A_{ck}} \right) + i N_{b} \frac{F_{ai}^{b}}{2} \right] \Psi_{K} \Phi[A, \xi] \right\} \\ &+ \int_{\mathcal{M}} \frac{\delta}{\delta A_{ai}} \left[-2 \tilde{N} (\hat{\mathcal{D}}_{a} \xi)_{A} \sigma_{i}^{AB} i \frac{\delta}{\delta \xi^{B}} \Phi[A, \xi] \right] = i \frac{\partial \Phi[A, \xi]}{\partial t} \end{split}$$

Where is time? Kodama State Use ansatz
$$\Psi[A,\xi] = \Psi_K[A]\Phi[A,\xi]$$

 $\frac{\partial \Phi[A,\xi]}{\partial t} \equiv \int_{\mathcal{M}} \frac{\delta \xi^B}{\delta t} \frac{\delta}{\delta \xi^B} \Phi[A,\xi] \quad \text{implicitly depends on } \Psi[A,\xi]$ defines absolute simultaneity $\frac{\delta \xi^B}{\delta t} \equiv N^b (\widehat{\mathcal{D}}_b \xi)^B + 2\ell_{\text{Pl}}^2 \frac{\delta \ln \Psi_K}{\delta A_{ai}} \widetilde{N}(\widehat{\mathcal{D}}_a \xi)_A \sigma_i^{AB}$

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$$rac{\partial (|\Psi|^2 \Omega)}{\partial t} +
abla^{ai} J_{ai} + \overline{
abla}^{ai} \overline{J}_{ai} = 0$$
 $abla^{ai} \equiv \int_{\mathcal{M}} \delta / \delta A_{ai}$

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$$\begin{split} \frac{\partial(|\Psi|^2\Omega)}{\partial t} + \nabla^{ai}J_{ai} + \overline{\nabla}^{ai}\overline{J}_{ai} &= 0\\ \nabla^{ai} &\equiv \int_{\mathcal{M}} \delta/\delta A_{ai}\\ \text{Constraint on }\Omega:\\ - \left[\frac{\delta^2\Omega}{\delta A_{ai}\delta A_{bj}} \frac{i\tilde{N}\epsilon_{ijk}}{2}F_{ab}^k + c.c \right] + \left[\frac{\delta^3\Omega}{\delta A_{ai}\delta A_{bj}\delta A_{ck}} \frac{i\tilde{N}\epsilon_{ijk}}{2}\frac{\Lambda}{3}\epsilon_{abc} + c.c \right] \\ - \left[N_b \frac{\delta\Omega}{\delta A_{ai}} \frac{F_{ai}^b}{2} + c.c \right] = 0 \end{split}$$

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$$\begin{split} \frac{\partial (|\Psi|^2 \Omega)}{\partial t} + \nabla^{ai} J_{ai} + \overline{\nabla}^{ai} \overline{J}_{ai} = 0 \\ \nabla^{ai} \equiv \int_{\mathcal{M}} \delta / \delta A_{ai} \\ \Omega[A, \overline{A}] = \frac{1}{\Psi_k \overline{\Psi_K}} \end{split}$$

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$$rac{\partial (|\Psi|^2 \Omega)}{\partial t} +
abla^{ai} J_{ai} + \overline{
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 $abla^{ai} \equiv \int_{\mathcal{M}} \delta / \delta A_{ai}$
 $\Omega[A, \overline{A}] = rac{1}{\Psi_k \overline{\Psi_K}}$

Implications for Unitarity:

$$\Psi_K$$
 naturally factored out $\rightarrow \Phi[A, \xi] = \frac{\Psi[A, \xi]}{\Psi_K[A, \xi]}$ may be normalizable.
Non-perturbative inner product.

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$$rac{\partial (|\Psi|^2 \Omega)}{\partial t} +
abla^{ai} J_{ai} + \overline{
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$$\begin{split} &\frac{\delta A_{ai}}{\delta t} \equiv \frac{J_{ai}}{|\Psi|^2 \Omega} = \frac{i\tilde{N}\ell_{\rm Pl}^2}{2} \frac{\delta \ln \Psi_K}{\delta A_{bj}} \epsilon_{ijk} \left(2F_{ab}^k + \ell_{\rm Pl}^2 \Lambda \epsilon_{abc} \frac{\delta \ln \Psi_K}{\delta A_{ck}} \right) - N_b F_{ai}^b + 2\tilde{N}\ell_{\rm Pl}^2 (\hat{\mathcal{D}}_a \xi)_A \sigma_i^{AB} \frac{\delta \ln \Phi}{\delta \xi^B} \\ &+ \frac{i\tilde{N}\ell_{\rm Pl}^2}{2} \epsilon_{ijk} \left(2F_{ab}^k \frac{\delta \ln \Phi}{\delta A_{bj}} + \frac{\ell_{\rm Pl}^2 \Lambda}{3} \epsilon_{abc} \left[2\frac{\delta \ln \Phi}{\delta A_{bj}} \frac{\delta \ln \Psi_K}{\delta A_{ck}} + \frac{1}{\Phi} \frac{\delta^2 \Phi}{\delta A_{ck} \delta A_{bj}} \right] \right) \end{split}$$

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$$\begin{split} \frac{\delta A_{ai}}{\delta t} &\equiv \frac{J_{ai}}{|\Psi|^2 \Omega} = \frac{i \tilde{N} \ell_{\rm Pl}^2}{2} \frac{\delta \ln \Psi_K}{\delta A_{bj}} \epsilon_{ijk} \left(2F_{ab}^k + \ell_{\rm Pl}^2 \Lambda \epsilon_{abc} \frac{\delta \ln \Psi_K}{\delta A_{ck}} \right) - N_b F_{ai}^b + 2 \tilde{N} \ell_{\rm Pl}^2 (\widehat{\mathcal{D}}_a \xi)_A \sigma_i^{AB} \frac{\delta \ln \Phi}{\delta \xi^B} \\ &+ \frac{i \tilde{N} \ell_{\rm Pl}^2}{2} \epsilon_{ijk} \left(2F_{ab}^k \frac{\delta \ln \Phi}{\delta A_{bj}} + \frac{\ell_{\rm Pl}^2 \Lambda}{3} \epsilon_{abc} \left[2 \frac{\delta \ln \Phi}{\delta A_{bj}} \frac{\delta \ln \Psi_K}{\delta A_{ck}} + \frac{1}{\Phi} \frac{\delta^2 \Phi}{\delta A_{ck} \delta A_{bj}} \right] \right) \end{split}$$

Classical solution:

$$\dot{A}_{ai} = \frac{i\tilde{N}}{2} E^{bj} \epsilon_{ijk} \left(2F^{k}_{ab} + \Lambda \epsilon_{abc} E^{ck} \right) - N_b F^{b}_{ai} + 2\tilde{N} (\hat{D}_a \xi)_A \sigma^{AB}_i \Pi^B$$

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$$\begin{split} \frac{\delta A_{ai}}{\delta t} &\equiv \frac{J_{ai}}{|\Psi|^2 \Omega} = \frac{i \tilde{N} \ell_{\rm Pl}^2}{2} \frac{\delta \ln \Psi_K}{\delta A_{bj}} \epsilon_{ijk} \left(2F_{ab}^k + \ell_{\rm Pl}^2 \Lambda \epsilon_{abc} \frac{\delta \ln \Psi_K}{\delta A_{ck}} \right) - N_b F_{ai}^b + 2 \tilde{N} \ell_{\rm Pl}^2 (\hat{\mathcal{D}}_a \xi)_A \sigma_i^{AB} \frac{\delta \ln \Phi}{\delta \xi^B} \\ &+ \frac{i \tilde{N} \ell_{\rm Pl}^2}{2} \epsilon_{ijk} \left(2F_{ab}^k \frac{\delta \ln \Phi}{\delta A_{bj}} + \frac{\ell_{\rm Pl}^2 \Lambda}{3} \epsilon_{abc} \left[2 \frac{\delta \ln \Phi}{\delta A_{bj}} \frac{\delta \ln \Psi_K}{\delta A_{ck}} + \frac{1}{\Phi} \frac{\delta^2 \Phi}{\delta A_{ck} \delta A_{bj}} \right] \right) \end{split}$$

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For self-dual solutions,

$$F^{j}_{ik} = -rac{\Lambda}{3}\epsilon_{ikb}E^{bj}$$

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For self-dual solutions,

$$F^{j}_{ik} = -rac{\Lambda}{3}\epsilon_{ikb}E^{bj}$$

$$\ell_{\mathrm{Pl}}^2 rac{\delta \ln \Psi_K}{\delta A_{bj}} = E^{bj}$$

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$$\begin{split} \frac{\delta A_{ai}}{\delta t} &\equiv \frac{J_{ai}}{|\Psi|^2 \Omega} = \frac{i \tilde{N} \ell_{\rm Pl}^2}{2} \frac{\delta \ln \Psi_K}{\delta A_{bj}} \epsilon_{ijk} \left(2F_{ab}^k + \ell_{\rm Pl}^2 \Lambda \epsilon_{abc} \frac{\delta \ln \Psi_K}{\delta A_{ck}} \right) - N_b F_{ai}^b + 2 \tilde{N} \ell_{\rm Pl}^2 (\hat{\mathcal{D}}_a \xi)_A \sigma_i^{AB} \frac{\delta \ln \Phi}{\delta \xi^B} \\ &+ \frac{i \tilde{N} \ell_{\rm Pl}^2}{2} \epsilon_{ijk} \left(2F_{ab}^k \frac{\delta \ln \Phi}{\delta A_{bj}} + \frac{\ell_{\rm Pl}^2 \Lambda}{3} \epsilon_{abc} \left[2 \frac{\delta \ln \Phi}{\delta A_{bj}} \frac{\delta \ln \Psi_K}{\delta A_{ck}} + \frac{1}{\Phi} \frac{\delta^2 \Phi}{\delta A_{ck} \delta A_{bj}} \right] \right) \end{split}$$

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For self-dual solutions,

$$F^{j}_{ik} = -rac{\Lambda}{3}\epsilon_{ikb}E^{bj}$$

$$\ell_{\mathrm{Pl}}^2 \frac{\delta \ln \Psi_{K}}{\delta A_{bj}} = E^{bj} \qquad \qquad \ell_{\mathrm{Pl}}^2 \frac{\delta \ln \Phi}{\delta \xi^B} = \Pi^B$$

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$$\begin{split} \frac{\delta A_{ai}}{\delta t} &\equiv \frac{J_{ai}}{|\Psi|^2 \Omega} = \frac{i\tilde{N}\ell_{\rm P1}^2}{\delta \ln \Psi_K} \frac{\delta \ln \Psi_K}{\delta A_{bj}} \epsilon_{ijk} \left(2F_{ab}^k + \ell_{\rm P1}^2 \Lambda \epsilon_{abc} \frac{\delta \ln \Psi_K}{\delta A_{ck}} \right) - N_b F_{ai}^b + 2\tilde{N}\ell_{\rm P1}^2 (\hat{\mathcal{D}}_a \xi)_A \sigma_i^{AB} \frac{\delta \ln \Phi}{\delta \xi^B} \\ &+ \frac{i\tilde{N}\ell_{\rm P1}^2}{2} \epsilon_{ijk} \left(2F_{ab}^k \frac{\delta \ln \Phi}{\delta A_{bj}} + \frac{\ell_{\rm P1}^2 \Lambda}{3} \epsilon_{abc} \left[2\frac{\delta \ln \Phi}{\delta A_{bj}} \frac{\delta \ln \Psi_K}{\delta A_{ck}} + \frac{1}{\Phi} \frac{\delta^2 \Phi}{\delta A_{ck} \delta A_{bj}} \right] \right) \end{split}$$

Classical limit is obtained when $\Phi = \Phi_{SC}[\xi]$.

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Reality Conditions $(A_{ai} + \overline{A}_{ai} = 2\Gamma_{ai}, E_{ai} = \overline{E}_{ai})$ implemented at the level of guidance equation.

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Reality Conditions $(A_{ai} + \overline{A}_{ai} = 2\Gamma_{ai}, E_{ai} = \overline{E}_{ai})$ implemented at the level of guidance equation.

$$\Gamma_{ai} = \frac{1}{2} \epsilon_{ijk} E^{bk} \left(E^{j}_{a,b} - E^{j}_{b,a} + E^{c}_{j} E^{J}_{a} E^{J}_{c,b} \right) + \frac{1}{4} \epsilon_{ijk} E^{bk} \left(2E^{j}_{a} \frac{\mathbf{E}_{,b}}{\mathbf{E}} - E^{j}_{b} \frac{\mathbf{E}_{,a}}{\mathbf{E}} \right)$$

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Continuity equation

$$\begin{split} \frac{\partial (|\Psi|^2 \Omega)}{\partial t} + \nabla^{ai} J_{ai} + \overline{\nabla}^{ai} \overline{J}_{ai} &= 0\\ \nabla^{ai} \equiv \int_{\mathcal{M}} \delta / \delta A_{ai}\\ \Omega[A, \overline{A}] &= \frac{1}{\Psi_k \overline{\Psi_K}} \end{split}$$

Implications for Unitarity:

$$\Psi_K$$
 naturally factored out $\rightarrow \Phi = \frac{\Psi}{\Psi_K}$ may be normalizable.
Non-perturbative inner product.

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Probabilities stay normalized in minisuperspace.

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Global time in pilot-wave approach \longleftrightarrow Relational time approaches.

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Global time in pilot-wave approach \longleftrightarrow Relational time approaches.

Kodama state has a purely dynamical role in the theory.

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Global time in pilot-wave approach \longrightarrow Relational time approaches.

Kodama state has a purely dynamical role in the theory.

Exact Schrodinger equation with respect to fermionic time.

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Future directions:

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Future directions:

1. Quantum fluctuations on de-Sitter space.

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Future directions:

1. Quantum fluctuations on de-Sitter space. 2. Insights for singularities.

3

Global time in pilot-wave approach \longleftrightarrow Relational time approaches.

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Future directions:

Quantum fluctuations on de-Sitter space.
 Insights into singularities.

THANK YOU!

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Low-energy physics: Emergence of quantization in the early universe.

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Low-energy physics: Emergence of quantization in the early universe.

$$\psi(\vec{y},t) = e^{-i\hat{H}_0t/\hbar}\psi^K(\vec{y}) - \frac{ie^{-i\hat{H}_0t/\hbar}}{\hbar} \int_0^t dt' e^{i\hat{H}_0t'/\hbar} \delta V(\vec{y},t') e^{-i\hat{H}_0t'/\hbar}\psi^K(\vec{y}) + \mathcal{O}(\delta V^2)$$

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For realistic perturbations

$$\psi(\vec{y},t) = e^{-iE_{K}t/\hbar}\psi^{K}(\vec{y}) - \frac{ie^{-i\hat{H}_{0}t/\hbar}}{\hbar} \int_{0}^{t} dt' \sum_{ij} e^{i(E_{j}-E_{K})t'/\hbar}c_{j}(t')\psi^{j}(\vec{y}) + \mathcal{O}(\delta V^{2})$$

normalizable branches of the quantum state

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Low-energy physics: Emergence of quantization in the early universe.

$$\psi(\vec{y},t) = e^{-i\hat{H}_0t/\hbar}\psi^{K}(\vec{y}) - \frac{ie^{-i\hat{H}_0t/\hbar}}{\hbar} \int_0^t dt' e^{i\hat{H}_0t'/\hbar} \delta V(\vec{y},t') e^{-i\hat{H}_0t'/\hbar}\psi^{K}(\vec{y}) + \mathcal{O}(\delta V^2)$$

For realistic perturbations

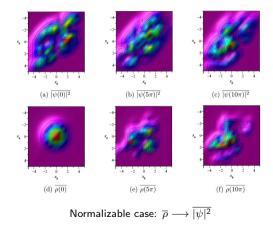
$$\psi(\vec{y},t) = e^{-iE_{K}t/\hbar}\psi^{K}(\vec{y}) - \frac{ie^{-i\hat{H}_{0}t/\hbar}}{\hbar} \int_{0}^{t} dt' \sum_{i} e^{i(E_{j}-E_{K})t'/\hbar}c_{j}(t')\psi^{j}(\vec{y}) + \mathcal{O}(\delta V^{2})$$

normalizable branches of the quantum state

Quantization due to decoherence.

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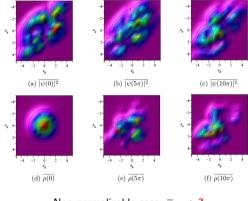
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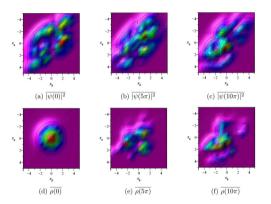


Non-normalizable case: $\overline{\rho} \longrightarrow$?

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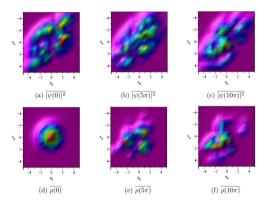


"Clearly, there is no lower bound on H and so there is no physical equilibrium state."²

² A.	Valentini,	arXiv:2104.07966	2021.
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$$H_q \equiv \int_{\mathcal{C}}
ho(ec{y}) \ln rac{
ho(ec{y})}{|\psi(ec{y})|^2} dec{y}$$

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$$H_q \equiv \int_{\mathcal{C}} \rho(\vec{y}) \ln \frac{\rho(\vec{y})}{|\psi(\vec{y})|^2} d\vec{y}$$
not a well-defined relative entropy

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$$H_q \equiv \int_{\mathcal{C}} \rho(\vec{y}) \ln \frac{\rho(\vec{y})}{|\psi(\vec{y})|^2} d\vec{y}$$
 not a well-defined relative entropy

$$ho_{pw}(ec{y}) \equiv egin{cases} |\psi(ec{y})|^2/\mathcal{N} & ext{, for } ec{y} \in \Omega \ 0 & ext{, for } ec{y} \in \mathcal{C} \setminus \Omega \end{cases}$$

and $\mathcal{N}\equiv\int_{\Omega}|\psi(ec{y})|^{2}dec{y}.$

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$$H_{
m pw}\equiv\int_{\mathcal{C}}
ho(ec{y})\lnrac{
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ho_{
m pw}(ec{y})}dec{y}$$

where,

$$H_q \equiv \int_{\mathcal{C}} \rho(\vec{y}) \ln \frac{\rho(\vec{y})}{|\psi(\vec{y})|^2} d\vec{y}$$
 not a well-defined relative entropy

$$\begin{split} \rho_{pw}(\vec{y}) &\equiv \begin{cases} |\psi(\vec{y})|^2/\mathcal{N} &, \text{ for } \vec{y} \in \Omega \\ 0 &, \text{ for } \vec{y} \in \mathcal{C} \setminus \Omega \end{cases} \\ & \text{ and } \mathcal{N} \equiv \int_{\Omega} |\psi(\vec{y})|^2 d\vec{y}. \\ & \uparrow \\ & \text{ compact support of } \rho \text{ on } \mathcal{C} \end{cases} \end{split}$$

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$$H_{q} \equiv \int_{C} \rho(\vec{y}) \ln \frac{\rho(\vec{y})}{|\psi(\vec{y})|^{2}} d\vec{y}$$

not a well-defined relative entropy
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$$H_{
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where,

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where,

$$\begin{split} \rho_{\mathcal{P}\mathcal{W}}(\vec{y}) &\equiv \begin{cases} |\psi(\vec{y})|^2/\mathcal{N} & \text{, for } \vec{y} \in \Omega \\ 0 & \text{, for } \vec{y} \in \mathcal{C} \setminus \Omega \end{cases} \\ & \text{and } \mathcal{N} \equiv \int_{\Omega} |\psi(\vec{y})|^2 d\vec{y}. \\ & \uparrow \\ & \text{compact support of } \rho \text{ on } \mathcal{C} \end{split}$$

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$$H_q \equiv \int_{\mathcal{C}} \rho(\vec{y}) \ln \frac{\rho(\vec{y})}{|\psi(\vec{y})|^2} d\vec{y}$$

(not a well-defined relative entropy)
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and $\mathcal{N}(t) = \int_{\Omega_t} |\psi(ec{y},t)|^2 dec{y}.$

compact time-dependent support of ρ on ${\mathcal C}$

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compact time-dependent support of ρ on ${\mathcal C}$

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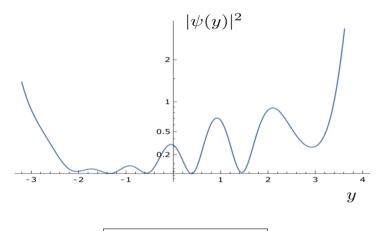
and
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compact time-dependent support of ρ on ${\mathcal C}$

$$\mathcal{N}(t) = \int_{\Omega_t} |\psi(ec{y},t)|^2 dec{y} = \mathcal{N}(0)$$

Pilot-wave approach to key issues in non-perturbative c

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Indrajit Sen

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