# <span id="page-0-0"></span>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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- The problem of time
- The problem of non-normalizability.
	- 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.

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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New conceptual approach based on pilot-wave theory.

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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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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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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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$$
\begin{array}{ll}\text{Quantum State:} & \hat{H}|\psi\rangle = i\hbar\partial_t|\psi\rangle\\ \text{Configuration:} & \vec{v} = \frac{j}{|\psi|^2} \end{array}\bigg\} \text{ Law}
$$

Is of nature

Conceptual approach to key issues



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Quantum State:  $\hat{H}|\psi\rangle=i\hbar\partial_{t}|\psi\rangle$ Configuration:  $\vec{v} = \frac{j}{|\psi|^2}$  Laws of nature

#### Conceptual approach to key issues

1. The problem of time  $\overline{t}$  parameterizes variation of the configuration.



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Quantum State:  $\hat{H}|\psi\rangle=i\hbar\partial_{t}|\psi\rangle$ Configuration:  $\vec{v} = \frac{j}{|\psi|^2}$  Laws of nature

#### Conceptual approach to key issues

1. The problem of time  $\overline{t}$  parameterizes variation of the configuration.

2. The problem of non-normalizability  $\overline{\phantom{a}}$  locally conserved current.



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Quantum State:  $\hat{H}|\psi\rangle=i\hbar\partial_{t}|\psi\rangle$ Configuration:  $\vec{v} = \frac{j}{|\psi|^2}$  Laws of nature

#### Conceptual approach to key issues

1. The problem of time  $\overline{t}$  parameterizes variation of the configuration.

- 2. The problem of non-normalizability  $\overline{\phantom{a}}$  locally conserved current.
- 3. The problem of classical limit  $\longleftrightarrow$  quantum corrections in the guidance equation.



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Quantum State:  $\hat{H}|\psi\rangle=i\hbar\partial_{t}|\psi\rangle$ Configuration:  $\vec{v} = \frac{j}{|\psi|^2}$  Laws of nature

#### Conceptual approach to key issues

- 1. The problem of time  $\overline{t}$  parameterizes variation of the configuration.
	- 2. The problem of non-normalizability  $\overline{\phantom{a}}$  locally conserved current.
- 3. The problem of classical limit  $\longleftrightarrow$  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 system $^{1}$ :

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

 $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \end{array} \right.$ 

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<sup>&</sup>lt;sup>1</sup>S. Alexander et al., *Phys. Rev. D* 2022, 106, 106012.

Total constraint for interacting gravitational-fermionic system:

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

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Total constraint for interacting gravitational-fermionic system:



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Total constraint for interacting gravitational-fermionic system:

$$
\begin{array}{c}\n\int_{\mathcal{M}} (\tilde{N}\hat{\mathcal{H}} + N^a \hat{\mathcal{V}}_a) \Psi[A, \xi] = 0 \longrightarrow \text{ Ashtekar connection} \\
\downarrow \text{Shift vector} \longrightarrow 2\text{-component Weyl Spinor}\n\end{array}
$$

$$
\hat{\mathcal{H}} = \frac{1}{2} \epsilon_{ijk} \hat{E}^{bj} \hat{E}^{ai} \left( F_{ab}^k + \frac{\Lambda}{3} \epsilon_{abc} \hat{E}^{ck} \right) + (\hat{\mathcal{D}}_a \xi)_{A} \sigma_i^{AB} \hat{E}^{ai} \hat{\Pi}_B + \hat{E}^{ai} (\hat{\mathcal{D}}_a \xi)_{A} \sigma_i^{AB} \hat{\Pi}_B
$$
\n
$$
\hat{\mathcal{V}}_a = \frac{i}{2} F_{ab}^k \hat{E}_k^b + (\hat{\mathcal{D}}_a \xi)_{B} \hat{\Pi}^B
$$

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Total constraint for interacting gravitational-fermionic system:



Quantization scheme:

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

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$$
\int_{\mathcal{M}} \tilde{N} \frac{\delta}{\delta A_{ai}} \left[ \frac{\epsilon_{ijk}}{2} \frac{\delta}{\delta A_{bj}} \left( F^k_{ab} + \frac{\Lambda}{3} \epsilon_{abc} \frac{\delta}{\delta A_{ck}} \right) - 2 (\hat{\mathcal{D}}_a \xi)_{A} \sigma_i^{AB} i \frac{\delta}{\delta \xi^B} \right] \Psi[A, \xi]
$$
\n
$$
+ \int_{\mathcal{M}} i N_b \frac{\delta}{\delta A_{ai}} \left[ \frac{F^b_{ai}}{2} \Psi[A, \xi] \right] - \int_{\mathcal{M}} i N_b \frac{\Psi[A, \xi]}{2} \frac{\delta F^b_{ai}}{\delta A_{ai}} \right]
$$
\n
$$
= \int_{\mathcal{M}} N^b (\hat{\mathcal{D}}_b \xi)^B i \frac{\delta}{\delta \xi^B} \Psi[A, \xi]
$$

Where is time?

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

Where is 
$$
\lim_{\epsilon \to 0} \to \text{Kodama State}
$$
  
Use ansatz  $\Psi[A, \xi] = \Psi_K[A] \Phi[A, \xi]$ 

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$$
\int_{\mathcal{M}} \frac{1}{\Psi_K} \frac{\delta}{\delta A_{ai}} \left\{ \left[ \tilde{N} \frac{\epsilon_{ijk}}{2} \frac{\delta}{\delta A_{bj}} \left( F_{ab}^k + \frac{\Lambda}{3} \epsilon_{abc} \frac{\delta}{\delta A_{ck}} \right) + i N_b \frac{F_{ai}^b}{2} \right] \Psi_K \Phi[A, \xi] \right\} + \int_{\mathcal{M}} \frac{\delta}{\delta A_{ai}} \left[ -2 \tilde{N} (\hat{\mathcal{D}}_a \xi)_{A} \sigma_i^{AB} i \frac{\delta}{\delta \xi^B} \Phi[A, \xi] \right] = i \frac{\partial \Phi[A, \xi]}{\partial t}
$$

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

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

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

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

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

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

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

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

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

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

∂Φ[A, ξ]  $\frac{[A,\xi]}{\partial t} \equiv \int$ M δξ<sup>B</sup> δt δ  $\overline{\delta \xi^{B}}$   $\Phi[A,\xi]$  implicitly depends on  $\Psi[A,\xi]$ δξ<sup>B</sup>  $\frac{\delta \xi^B}{\delta t} \equiv N^b (\widehat{\mathcal{D}}_b \xi)^B + 2 \ell_{\rm Pl}^2 \frac{\delta \ln \Psi_K}{\delta A_{ai}}$  $\frac{\partial W}{\partial A_{ai}} \tilde{N}(\widehat{\mathcal{D}}_a \xi)_A \sigma_i^{AB}$ defines absolute simultaneity

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$$
\frac{\partial(|\Psi|^2 \Omega)}{\partial t} + \nabla^{ai} J_{ai} + \overline{\nabla}^{ai} \overline{J}_{ai} = 0
$$

$$
\nabla^{ai} \equiv \int_{\mathcal{M}} \delta / \delta A_{ai}
$$

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$$
\frac{\partial(|\Psi|^2 \Omega)}{\partial t} + \nabla^{ai} J_{ai} + \overline{\nabla}^{ai} \overline{J}_{ai} = 0
$$

$$
\nabla^{ai} \equiv \int_{\mathcal{M}} \delta / \delta A_{ai}
$$
Constraint on  $\Omega$ :
$$
-\left[\frac{\delta^2 \Omega}{\delta A_{ai} \delta A_{bj}} \frac{i \tilde{N} \epsilon_{ijk}}{2} F_{ab}^k + c.c\right] + \left[\frac{\delta^3 \Omega}{\delta A_{ai} \delta A_{bj} \delta A_{ci}} \frac{i \tilde{N} \epsilon_{ijk}}{2} \frac{\Lambda}{3} \epsilon_{abc} + c.c\right]
$$

$$
-\left[N_b \frac{\delta \Omega}{\delta A_{ai}} \frac{F_{ai}^b}{2} + c.c\right] = 0
$$

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$$
\frac{\partial (|\Psi|^2 \Omega)}{\partial t} + \nabla^{ai} J_{ai} + \overline{\nabla}^{ai} \overline{J}_{ai} = 0
$$

$$
\nabla^{ai} \equiv \int_{\mathcal{M}} \delta / \delta A_{ai}
$$

$$
\Omega[A, \overline{A}] = \frac{1}{\Psi_k \overline{\Psi_K}}
$$

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$$
\frac{\partial (|\Psi|^2 \Omega)}{\partial t} + \nabla^{ai} J_{ai} + \overline{\nabla}^{ai} \overline{J}_{ai} = 0
$$

$$
\nabla^{ai} \equiv \int_{\mathcal{M}} \delta / \delta A_{ai}
$$

$$
\Omega[A, \overline{A}] = \frac{1}{\Psi_k \Psi_K}
$$

**Implications for Unitarity:**  
\n
$$
\Psi_K \text{ naturally factored out } \rightarrow \Phi[A, \xi] = \frac{\Psi[A, \xi]}{\Psi_K[A, \xi]} \text{ may be normalizable.}
$$
\nNon-perturbative inner product.

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$$
\frac{\partial (|\Psi|^2 \Omega)}{\partial t} + \nabla^{ai} J_{ai} + \overline{\nabla}^{ai} \overline{J}_{ai} = 0
$$

$$
\nabla^{ai} \equiv \int_{\mathcal{M}} \delta / \delta A_{ai}
$$

$$
\Omega[A, \overline{A}] = \frac{1}{\Psi_k \Psi_K}
$$

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

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

Classical solution:

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

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

Classical solution:

$$
\dot{A}_{ai}=\frac{i\tilde{N}}{2}E^{bj}\epsilon_{ijk}\bigg(2\mathcal{F}^{k}_{ab}+\Lambda\epsilon_{abc}E^{ck}\bigg)-N_{b}\mathcal{F}^{b}_{ai}+2\tilde{N}(\widehat{\mathcal{D}}_{a}\xi)_{A}\sigma^{AB}_{i}\Pi^{B}
$$

For self-dual solutions,

$$
F_{ik}^j = -\frac{\Lambda}{3} \epsilon_{ikb} E^{bj}
$$

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

Classical solution:

$$
\dot{A}_{ai} = \frac{i\tilde{N}}{2} E^{bj} \epsilon_{ijk} \left( 2F_{ab}^k + \Lambda \epsilon_{abc} E^{ck} \right) - N_b F_{ai}^b + 2\tilde{N} \ell_{\rm Pl}^2 (\widehat{\mathcal{D}}_a \xi)_{A} \sigma_i^{AB} \Pi^B
$$

For self-dual solutions,

$$
F_{ik}^j = -\frac{\Lambda}{3} \epsilon_{ikb} E^{bj}
$$

$$
\ell_{\rm Pl}^2 \frac{\delta \ln \Psi_{\rm K}}{\delta A_{\rm bj}} = E^{\rm bj}
$$

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

Classical solution:

$$
\dot{A}_{ai} = \frac{i\tilde{N}}{2} E^{bj} \epsilon_{ijk} \left( 2F_{ab}^k + \Lambda \epsilon_{abc} E^{ck} \right) - N_b F_{ai}^b + 2\tilde{N} \ell_{\text{Pl}}^2 (\widehat{\mathcal{D}}_a \xi)_{A} \sigma_i^{AB} \Pi^B
$$

For self-dual solutions,

$$
F_{ik}^j = -\frac{\Lambda}{3} \epsilon_{ikb} E^{bj}
$$

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

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

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

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$$

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

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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\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{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_{bi}} \frac{\delta \ln \Psi_K}{\delta A_{ck}} + \frac{1}{\Phi} \frac{\delta^2 \Phi}{\delta A_{ck} \delta A_{bj}} \right] \right)
$$

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

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

$$
\Gamma_{ai} = \frac{1}{2} \epsilon_{ijk} E^{bk} \Big( E^j_{a,b} - E^j_{b,a} + E^c_j E^j_a E^j_{c,b} \Big) + \frac{1}{4} \epsilon_{ijk} E^{bk} \Big( 2 E^j_a \frac{\mathbf{E}_{,b}}{\mathbf{E}} - E^j_b \frac{\mathbf{E}_{,a}}{\mathbf{E}} \Big)
$$

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# Continuity equation

$$
\frac{\partial(|\Psi|^2 \Omega)}{\partial t} + \nabla^{ai} J_{ai} + \overline{\nabla}^{ai} \overline{J}_{ai} = 0
$$

$$
\nabla^{ai} \equiv \int_{\mathcal{M}} \delta / \delta A_{ai}
$$

$$
\Omega[A, \overline{A}] = \frac{1}{\Psi_k \overline{\Psi_K}}
$$

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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## Continuity equation

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## Continuity equation

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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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Exact Schrodinger equation with respect to fermionic time.

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Future directions:

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1. Quantum fluctuations on de-Sitter space.

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#### 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

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

normalizable branches of the quantum state

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

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$$

normalizable branches of the quantum state

 $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \end{array} \right.$ 

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Quantization due to decoherence.

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"Clearly, there is no lower bound on  $H$  and so there is no physical equilibrium state."<sup>2</sup>



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"Clearly, there is no lower bound on  $H$  and so there is no physical equilibrium state."<sup>2</sup>



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

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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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$$
d\vec{y} \qquad \qquad H_{pw} \equiv \int_{\mathcal{C}} \rho(\vec{y}) \ln \frac{\rho(\vec{y})}{\rho_{pw}(\vec{y})} d\vec{y}
$$

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$$
H_{\text{pw}} \equiv \int_{\mathcal{C}} \rho(\vec{y}) \ln \frac{\rho(\vec{y})}{\rho_{\text{pw}}(\vec{y})} d\vec{y}
$$

where,

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

$$
\rho_{\rho w}(\vec{y}) \equiv \begin{cases} |\psi(\vec{y})|^2/{\cal N} & , \text{ for } \vec{y} \in \Omega \\ 0 & , \text{ for } \vec{y} \in {\cal C} \setminus \Omega \end{cases}
$$

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

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

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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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$$
H_{\text{pw}} \equiv \int_{\mathcal{C}} \rho(\vec{y}) \ln \frac{\rho(\vec{y})}{\rho_{\text{pw}}(\vec{y})} d\vec{y}
$$

where,

$$
\rho_{\rho w}(\vec{y}) \equiv \begin{cases} |\psi(\vec{y})|^2 / \mathcal{N} & , \text{ for } \vec{y} \in \Omega \\ 0 & , \text{ for } \vec{y} \in \mathcal{C} \setminus \Omega \end{cases}
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H_q \equiv \int_C \rho(\vec{y}) \ln \frac{\rho(\vec{y})}{|\psi(\vec{y})|^2} d\vec{y}
$$
  
not a well-defined relative entropy  

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$$

$$
H_{\rho w}(t) \equiv \int_{\mathcal{C}} \rho(\vec{y}, t) \ln \frac{\rho(\vec{y}, t)}{\rho_{\rho w}(\vec{y}, t)} d\vec{y}
$$

where,

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

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$$

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H_{pw}(t) \equiv \int_{\mathcal{C}} \rho(\vec{y}, t) \ln \frac{\rho(\vec{y}, t)}{\rho_{pw}(\vec{y}, t)} d\vec{y}
$$

where,

$$
\rho_{pw}(\vec{y},t) = \begin{cases} |\psi(\vec{y},t)|^2 / \mathcal{N}(t) & , \text{ for } \vec{y} \in \Omega_t \\ 0 & , \text{ for } \vec{y} \in \mathcal{C} \setminus \Omega_t \end{cases}
$$
  
and 
$$
\mathcal{N}(t) = \int_{\Omega_t} |\psi(\vec{y},t)|^2 d\vec{y}.
$$
  
compact time-dependent support of  $\rho$  on  $\mathcal{C}$ 

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

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H_{\rho w}(t) \equiv \int_{\mathcal{C}} \rho(\vec{y}, t) \ln \frac{\rho(\vec{y}, t)}{\rho_{\rho w}(\vec{y}, t)} d\vec{y}
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where,

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$$
  
and  $\mathcal{N}(t) = \int_{\Omega_t} |\psi(\vec{y},t)|^2 d\vec{y}$ .

compact time-dependent support of  $\rho$  on  $\mathcal C$ 

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

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

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