THE STATUS OF THE WAVE FUNCTION IN DYNAMICAL COLLAPSE MODELS

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¹This raises the objection that the q-bar history is not really properly defined at all as it contains a white noise term. One could fall back on the argument that spacetime is widely expected to be fundamentally discrete and this discreteness would provide a physical cutoff for the frequency of the white noise. Or turn the argument around and say that if the Bell ontology for collapse models is desirable, this suggests the necessity of fundamental discreteness.

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a unitary QFT on a 1+1 null lattice, making it into a collapse model
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the field values 0 and 1 to represent the absence or presence (resp.) of
 "bare particles" on the lattice.
A quantum state $|\psi_n\rangle$ on surface σ_n is an element of the 2^{2N} R-matrices.) $\mathrm{d}\mathrm{i}$ imensional Hilbert spaces on each link cut by σ_n . The basis vectors
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J_0 = \frac{1}{\sqrt{1+X^2}} \begin{pmatrix} 1 & 0 \\ 0 & X \end{pmatrix}, \quad J_1 = \frac{1}{\sqrt{1+X^2}} \begin{pmatrix} X & 0 \\ 0 & 1 \end{pmatrix}, \tag{2}
$$

jection operators for measurements in (1) by positive operators (for

"unsharp measurements") and adopting the resulting formula as the

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space associa other components of the full Hilbert space. The probability of the field that the corresponding fields that the corresponding fields (i.e., ated with a link) the two condition of $\sqrt{1+X^2}$ $\begin{pmatrix} 1 & 0 \\ 0 & X \end{pmatrix}$, J ≤ 1 . Note that $J_0^2 + J_1^2 =$ sure. Then we define the importance on space associated with a link) the two operators J_0 and J_1 where
 $J_0 = \frac{1}{\sqrt{1 + X^2}} \begin{pmatrix} 1 & 0 \\ 0 & X \end{pmatrix}$, $J_1 = \frac{1}{\sqrt{1 + X^2}} \begin{pmatrix} X & 0 \\ 0 & 1 \end{pmatrix}$, (2)

with $0 \le X \le 1$. Note that $J_0^2 + J_1^2 = 1$ and this is a $J_0 = \frac{1}{\sqrt{1 + X^2}} \left(0 X \right)$, $J_1 = \frac{1}{\sqrt{1 + X^2}} \left(0 1 \right)$,
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ued measure. Then we define the jump operator $J(\alpha_{v_k})$ on the

nensional Hilbert sp $0 \le X \le 1$. Note that $J_0^2 + J_1^2 = 1$ and this is a positive operator
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luct of the tw dimensional Hilbert space on the outgoing links from v_k as the tensor
product of the two relevant 2-dimensional jump operators, e.g., when it 2-dimensional jump operators, *e.g.*, when
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ill Hilbert space. The probability on the Hilbert space of any spatial surface containing those two links
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broduct with the identity operators on all the

e full Hilbert space. The probability of the field
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 $= ||J(\alpha_{v_n})U(v_n)...J(\alpha_{v_1})U(v_1)|\psi_0\rangle||^2$. (3)

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$$
\mathbf{P}(\alpha_{v_1},\ldots,\alpha_{v_n})=\|J(\alpha_{v_n})U(v_n)\ldots J(\alpha_{v_1})U(v_1)|\psi_0\rangle\|^2.
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 (3)

From this we can see the importance of the fact the jump operators form a positive operator valued measure, which ensures consistency:

other components of the full Hilbert space. The probability of the field configuration
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\mathbf{P}(\alpha_{v_1}, \ldots \alpha_{v_n}) = ||J(\alpha_{v_n})U(v_n)\ldots J(\alpha_{v_1})U(v_1)|\psi_0\rangle||^2.
$$
\n(3)

\nFrom this we can see the importance of the fact the jump operators form a positive operator valued measure, which ensures consistency:

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\mathbf{P}(\alpha_{v_1}, \ldots \alpha_{v_{n-1}}) = \sum_{\alpha_{v_n}} \mathbf{P}(\alpha_{v_1}, \ldots \alpha_{v_n})
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= \sum_{\alpha_{v_n}} \langle \psi_0 | \ldots J(\alpha_{v_n}) J(\alpha_{v_n}) \ldots | \psi_0 \rangle
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$$
= ||J(\alpha_{v_{n-1}})U(v_{n-1})\ldots J(\alpha_{v_1})U(v_1)|\psi_0\rangle||^2.
$$
\n(6)

\nAgain, (3) depends only on the (partial) causal order of the vertices because any other choice of natural labelling of the same vertices.

$$
= \sum_{\alpha_{v_n}} \langle \psi_0 | \dots J(\alpha_{v_n}) J(\alpha_{v_n}) \dots | \psi_0 \rangle \tag{5}
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= ||J(\alpha_{v_{n-1}})U(v_{n-1})\dots J(\alpha_{v_1})U(v_1)|\psi_0\rangle||^2. \qquad (6)
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 $\begin{align*}\n\mathbf{y} &= \|\mathbf{J}(\alpha_{v_n})U(v_n)\dots J(\alpha_{v_1})U(v_1)|\psi_0\rangle\|^2. \tag{3} \\
\text{the importance of the fact the jump operators} \\
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&= \sum_{\alpha_{v_n}} \langle \psi_0 | \dots J(\alpha_{v_n}) J(\alpha_{v_n}) \dots | \psi_0 \rangle \tag{5} \\
&= \|\mathbf{J}(\alpha_{v_{n-1}})U(v_{n-1})\dots J(\alpha_{v_1})U(v_1)|\psi_0$ on all stems are enough, via the standard methods of measure theory, From this we can see the importance of the fact the jump operators
form a positive operator valued measure, which ensures consistency:
 $\mathbf{P}(\alpha_{v_1},... \alpha_{v_{n-1}}) = \sum_{\alpha_{v_n}} \mathbf{P}(\alpha_{v_1},... \alpha_{v_n}$ 4)
 $= \sum_{\alpha_{v_n}} \langle \psi_0 | ... J(\alpha_{v_n})$ to define a unique probability measure on the sample space of all field From this we can see the importance of
form a positive operator valued measure,
 $\mathbf{P}(\alpha_{v_1},... \alpha_{v_{n-1}}) = \sum_{\alpha_{v_n}} \mathbf{P}(\alpha_{v_1},... \alpha_{v_n})$
 $= |\mathcal{J}(\alpha_{v_{n-1}})U(v_{n-1})|$.
Again, (3) depends only on the (pa
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 $= \sum_{\alpha_{v_n}} \langle \psi_0 | \dots J(\alpha_{v_n}) J(\alpha_{v_n}) \dots | \psi_0 \rangle$ (5)
 $= ||J(\alpha_{v_{n-1}}) U(v_{n-1}) \dots J(\alpha_{v_1}) U(v_1) | \psi_0 \rangle ||^2$. (6)

gain, (3) depe $\mathbf{P}(\alpha_{v_1}, \dots \alpha_{v_{n-1}}) = \sum_{\alpha_{v_n}} \mathbf{P}(\alpha_{v_1}, \dots \alpha_{v_n})$
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Eq. (3) is interpreted, in the Bell ontology, as the probability for the

Dynamical Wave Function Collapse Models 505

Dynamical Wave Function Collapse Models
 $\{\alpha_{v_1}, \dots \alpha_{v_n}\}$ have been realised is the normalised state $\{\alpha_{v_1}, \ldots \alpha_{v_n}\}\$ have been realised is the normalised state

Dynamical Wave Function Collapse Models 505
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\{\alpha_{v_1}, \dots \alpha_{v_n}\} \text{ have been realised is the normalised state}
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|\psi_n\rangle = \frac{J(\alpha_{v_n})U(v_n)\dots J(\alpha_{v_1})U(v_1)|\psi_0\rangle}{\|J(\alpha_{v_n})U(v_n)\dots J(\alpha_{v_1})U(v_1)|\psi_0\rangle\|}.
$$
\n(7)
\nThus, the probability for state (7) on hypersurface σ_n is (3). In order

to make predictions about the field on the lattice to the future of σ_n **Dynamical Wave Function Co:**
 $\{\alpha_{v_1}, \dots \alpha_{v_n}\}$ have been $\ket{\psi_n} = \frac{J(\psi_n)}{\|J(\psi_n)\|}$

Thus, the probability for **ollapse Models** 505

realised is the normalised state
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 $(\alpha_{v_n})U(v_n) \dots J(\alpha_{v_1})U(v_1)|\psi_0\rangle ||$ (7)

r state (7) on hypersurface σ_n is (3). In order

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{ $\alpha_{v_1}, \ldots \alpha_{v_n}$ } have been realised is the normalised state
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Thus, the probabili $\rm bv$ **Pynamical Wave Function Collapse Models** 505

{ $\alpha_{v_1}, \ldots \alpha_{v_n}$ } have been realised is the normalised state
 $|\psi_n\rangle = \frac{J(\alpha_{v_n})U(v_n)\ldots J(\alpha_{v_1})U(v_1)|\psi_0\rangle}{\|J(\alpha_{v_n})U(v_n)\ldots J(\alpha_{v_1})U(v_1)|\psi_0\rangle\|}$. (7)

Thus, the probability { $\alpha_{v_1}, \ldots \alpha_{v_n}$ } have been realised is the normalised state
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Thus, the probability for state (7) on hypersurface σ_n is (3). to make predictions about the held on the lattice to the tuture of σ_n

- conditional on the past values $\{\alpha_{v_1}, \ldots \alpha_{v_n}\}$ - it is sufficient to know
 $|\psi_n\rangle$. Indeed, the conditional probability of $\{\alpha_{v_{n+1}}, \ldots \alpha_{$

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\mathbf{P}(\alpha_{v_{n+1}},\ldots,\alpha_{v_{n+m}})=\|J(\alpha_{v_{n+m}})U(v_{n+m}\ldots J(\alpha_{v_{n+1}})U(v_{n+1})|\psi_n\rangle\|^2.
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\n(8)

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state vector provides these conditional probabilities, and is there-

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The state vector provides these conditional profore a convenient way of keeping the probability given past events.
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506 Dowker and Herbauts

Dowker and Herbauts
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\| |\psi_n^2, \alpha(n) \rangle - \lambda |\psi_n^1, \alpha(n) \rangle \| \to 0 \text{ as } n \to \infty \tag{9}
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Conjecture (density matrix form):

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Conjecture: There exists a complex phase λ such that
 $|||\psi_n^2, \alpha(n)\rangle - \lambda |\psi_n^1, \alpha(n)\rangle|| \rightarrow 0$ as $n \rightarrow \infty$ (9)
for all $\alpha(n)$ except those which almost surely do not occur according
to both \mathbf{P}_1 and \mathbf{P}_2 .
Conjecture (density matrix form):

$$
\|\sum_{\alpha(n)} \mathbf{P}_1(\alpha(n))|\psi_n^1, \alpha(n)\rangle \langle \psi_n^1, \alpha(n)|
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-\sum_{\alpha(n)} \mathbf{P}_1(\alpha(n))|\psi_n^2, \alpha(n)\rangle \langle \psi_n^2, \alpha(n)|| \rightarrow 0
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 as $n \rightarrow \infty$, (10)
where $||\cdot||$ is the operator norm, and similarly with 1 and 2 interchanged.
Note that we already know that the conjectures cannot be true
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Conjecture (density matrix form):
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the R-matrices preserved only particle num
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When there are superselection sectors, an initial quantum state a quantum state in each sector, in the familiar way. Without loss selection sectors (even and odd p
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Dynamical Wave Function Collapse Models 507
\n**4. THE SIMULATIONS**
\nWe sought evidence for the conjecture in the following way. We chose a unitary R-matrix, uniform across the lattice, of the form
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R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & i \sin \theta & \cos \theta & 0 \\ 0 & \cos \theta & i \sin \theta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.
$$
\nThis gives a particle number preserving dynamics for the state, since the hit operators J also preserve particle number.
\nWe chose σ_0 to be a constant time surface and we chose two initial states, $|\psi_0^1\rangle$ and $|\psi_0^2\rangle$ (in the same superselectron sector, which here meant the same particle number sector). We generated, at random according to the probability distribution P_1 or P_2 field configurations

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article number preserving dynamics for the state, sin We sought evidence for the conjecture in the following way. We chose
a unitary R-matrix, uniform across the lattice, of the form
 $R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & i \sin \theta & \cos \theta & 0 \\ 0 & \cos \theta & i \sin \theta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$. (11)
This gives a states $|\psi_n^a, \alpha(n)\rangle$, $a = 1, 2$ on the surface σ_n which is the nth surface in a sequence of surfaces chosen according to the stochastic rule "choose" *n* R-matrix, uniform across the lattice, of the form
 $R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & i \sin \theta & \cos \theta & 0 \\ 0 & \cos \theta & i \sin \theta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ (11)

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We chose σ_0 to be a constant time This gives a particle number preserving dynamics for the state, since
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the hit operators J also preserve particle number.
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would like to show that the two states $|\psi_n^a, \alpha(n)\rangle$, $a = 1, 2$
ose, up to a phas choice for ease of calculation. We will comment on what significance
this has for our results below.
We would like to show that the two states $|\psi_n^a, \alpha(n)\rangle$, $a = 1, 2$
become close, up to a phase, as n gets large and more this has for our results below.
We would like to show that become close, up to a phase, as *n* gets
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does not sample uniformly in the space of surfaces, as mentioned above, the two states $|\psi_n^a, \alpha(n)\rangle$, $a = 1, 2$
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like to know how the difference behaves with *n*. One can argue that it is
not the states themselves that should be compared but the probability
d probabilities, not for the whole future field configuration but only for is to know how the difference behaves with *n*. One can argue that the states themselves that should be compared but the probastributions for the field variables that they produce. Indeed, terpretation in which only the f tates themselves that should be compared but the probability
ions for the field variables that they produce. Indeed, in an
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be very gentle and superpositions of microscopically different 508 $\frac{1}{2}$ and $\frac{1}{2$ **Dowker and Herbauts**
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evoluti g close to each other. Indeed, let the link in question be denoted
suppose, at some stage in the dynamics, *l* is one of the outgoing
from the vertex that has just been evolved over. Let the state on
urrent spacelike surf α surface through l be denoted

$$
|\Psi\rangle = a|0\rangle + b|1\rangle,\tag{12}
$$

evolution to that stage) is *l* and suppose
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d in state 2 we will obtain

($|b_1|^2 - |b_2|$

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 $\frac{2}{x^2}$ - $\frac{1}{x^2}$
 $\frac{2}{x^2}$
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f the field on l is 0 (1).
(conditional on the past
 $\frac{1-X^2}{1+X^2}$. (13)
for a 1 on link l in state
 $-X^2$). (14)
). (15)

The probability that the field will be 1 on *l* (conditional on the past
evolution to that stage) is

$$
\frac{|a|^2X^2+|b|^2}{1+X^2} = \frac{X^2}{1+X^2} - |b|^2 \frac{1-X^2}{1+X^2}.
$$
(13)
So, for the difference between the probability for a 1 on link *l* in state
1 and in state 2 we will obtain

$$
(|b_1|^2 - |b_2|^2)(1-X^2)/(1+X^2).
$$
(14)
When ϵ is small, this becomes

$$
(|b_1|^2 - |b_2|^2)(\epsilon + \mathcal{O}(\epsilon^2)).
$$
(15)
From this we see that the appropriate quantity to calculate for
each link is $|b_1|^2 - |b_2|^2$; that gives a measure of the difference of the

So, for the difference between the probability for a 1 on link l in state 1 and in state 2 we will obtain

$$
(|b_1|^2 - |b_2|^2)(1 - X^2)/(1 + X^2). \tag{14}
$$

$$
(|b_1|^2 - |b_2|^2)(\epsilon + \mathcal{O}(\epsilon^2)). \tag{15}
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From this we see that the appropriate quantity to calculate for lution to the
for the different in state 2
nen ϵ is small
From think is $|b_1|$ each link is $|b_1|^2 - |b_2|^2$: that gives a measure of the difference of the probability distributions that affects the coarse grained, renormalised $\frac{|a|^2X^2+|b|^2}{1+X^2} = \frac{X^2}{1+X^2} - |\n$

So, for the difference between the probabil

1 and in state 2 we will obtain
 $(|b_1|^2 - |b_2|^2)(1 - X^2)/(\n$

When ϵ is small, this becomes
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From this we $|b|^2 \frac{1-X^2}{1+X^2}$. (13)

lity for a 1 on link *l* in state
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s a measure of the difference $\frac{|A_1|^2 + |B_2|^2}{1 + X^2} =$

So, for the difference between

1 and in state 2 we will obtain
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When ϵ is small, this becomes
 $(|b_1|^2 - |b_2|^2)$:

From this we see that the

each link is $|b_1|^2 - |b_2|^2$: t between the states themselves. First 1+X² 1+X² 1+X² 1+X² 1+X² 1+X²

difference between the probability for a 1 on link *l* in state

te 2 we will obtain
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mall, this becomes
 $(|b_1|^2 - |b_2|^2)(\epsilon + \mathcal{O}(\epsilon^2))$ So, for the difference between the probability for a 1 on link l in state

1 and in state 2 we will obtain
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When ϵ is small, this becomes
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From in state 2 we will obtain
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From this we see that the appropriate quantity to calculate for

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From this we see that the

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l configuration (see [9]) and if

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Thus,
 v_1, v_2, \ldots is

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mall, this becomes
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this we see that the appropriate quantity to calculate for
 $|b_1|^2 - |b_2|^2$: that gives a measure of the difference of the

dis

link, *l*, from v_n , the quantity $|b_1|^2 - |b_2|^2$ which we denote by $B(\tilde{l})$. Of course this is a very approximate measure of the difference between the states and, this becomes
 $(|b_1|^2 - |b_2|^2)(\epsilon + \mathcal{O}(\epsilon^2))$. (15)

From this we see that the appropriate quantity to calculate for

ch link is $|b_1|^2 - |b_2|^2$: that gives a measure of the difference of the

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Thus,
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In this we see that the appropriate quantity to calculate for
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From this we see that the appi
each link is $|b_1|^2 - |b_2|^2$: that gives a
probability distributions that affects
field configuration (see [9]) and indeed
between the states themselves.
Thus, we calculat the width of the whole spatial lattice: nat the appro
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 $B_m(t) \equiv \sum_{n=1}^{\infty}$ priate quantity to calculate for
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B_m(t) \equiv \sum_l B(l),\tag{16}
$$

Dynamical Wave Fur **Dynamical Wave Function Collapse Models 509**

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SECUTE: Solver all links with lattice time coordinate from the solver all links with lattice time coordinate from the solver t **the sum is over all links with lattice time coordinate from the lattice time step is 1). Our convergence criterion namical Wave Function Collapse Models**

ere the sum is over all links with lattice time coordinate from t

cough $t+m-1$ (the lattice time step is 1). Our convergence criterion

s $B_m(t) < \delta$ and we define the convergence t **Dynamical Wave**
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the sum is over all links what $t+m-1$ (the lattice time s
 $h(t) < \delta$ and we define the coint that $B_m(t) \leq \delta$, $\forall t > T_c$. **Collapse Models** 509

all links with lattice time coordinate from t

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convergence of states for field configurations not generated according **Dynamical Wave Function Collapse Models**

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where the sum is over all links with lattice time coordinate from t
through $t+m-1$ (the lattice time step is 1). Our convergence criterion
was $B_m(t) < \delta$ and we define the conv configuration (a) of all 1's, (b) of all 0's and (c) randomly generated **Dynamical Wave Function Collapse Models**
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the help of n where the sum is over all links with lattice time coordinate from t
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cal simulations of T_c .
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periodic sectors. In total about 600 simulations were run. We also studied the convergence of states for field configurations not generated according to the probability distributions from either state, for example the field config with uniform probability distribution of $1/2$ for a 1 on each link. We failed to find convergence only in the cases (a) and (b) mentioned above inded to find convergence only in the cases (a) and (b) mentioned above
then the field configuration was all 1's or all 0's which is consistent with
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5. RE or and configuration was all 1's or all 0's which is consistent with
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mvergence occurred but was slower for the field configurations
(c) than for those genera when the field configuration was all 1's or all 0's which is consistent with
the conjecture because they almost surely do not occur in P_1 and in

boundary conditions of the lattice stimulate convergence remains open. For conjecture because they almost surely do not occur in \mathbf{P}_1 and in
 \mathbf{P}_2 . Convergence occurred but was slower for the field configurations

f type (c) than for those generated by (and therefore likely in) the \mathbf{P}_2 . Convergence of type (c) than for
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probability distibut
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5. RESULTS
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lations we were limited as to lattice size by the ex-

of the problem in vertex number, of type (c) tha
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5. RESULT:
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Discussed in the conver-
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ch cell corresponds
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In our simulations we were limited as to latt

ponential growth of the problem in vertex number, a

unclear whether the limited size of the lattice has

cations for our results, cations for our results, in particular the question whether the periodic

5. RESULTS 5_l

proportional to $|b|^2$ (see equation (12)). In plot (a) we show the evolution of state 1, which begins as an eigenstate with 4 particles on the tice size by the exand it is at present
is important impli-
hether the periodic
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ons run, the conver-
ons run, the conver-
consisting cell is (positively)
a) we show the evo-
h 4 particles on the In our simulations we were limited as to lattice size by the exponential growth of the problem in vertex number, and it is at present unclear whether the limited size of the lattice has important implications for our resu left hand side of the lattice in the leftmost panel, time proceeds up the ponential growth of the problem in verte-
unclear whether the limited size of the
cations for our results, in particular the to-
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5. **RESULTS**
To begin by giving a flavour of the Examples and it is at present

Example lattice has important impliquestion whether the periodic

date convergence remains open.

of simulations run, the conver-

of simulations run, the conver-

of Fig. 2. Each cell corres inclear whether the limited size of the lattice has important implications for our results, in particular the question whether the periodic boundary conditions of the lattice stimulate convergence remains open.
5. **RESULT** so on. Plot (b) shows the evolution of state 2, which begins as a state ions for our results, in particular the question whether the periodic
indary conditions of the lattice stimulate convergence remains open.
 RESULTS

begin by giving a flavour of the kind of simulations run, the conver-
 boundary conditions
5. **RESULTS**
To begin by giving a
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lution of state 1, where the page and then the lat
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so s of the lattice stimulate convergence remains open.

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states is illustrated in Fig. 2. Each cell corresponds

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To begin by giving a flavour of the kind of simulations run, the
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To begin by giving a flavour of the kind of simulations run, the convergence of two initial states is illustrated in Fig. 2. Each cell corresponds to a single link of the lattice word are twice as many cells first panel in each. The plots after this time are somewhat superfluous **RESULTS**
begin by giving a flavour of the kind of simulations run, the conver-
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to the probability distribution of $|\psi_1\rangle$, with $X = 0.65$ and $\theta = 0.26\pi$.

 $\sum_{i=1}^{n} \binom{n}{i}$ and (b) are plots of the evolution of four-particle is consistent with $X = 0.65$ and $|\psi_2\rangle$ respectively, in a field configuration generation of $|\psi_1\rangle$, with $X = 0.65$ and $|\psi_2\rangle$ respectively, in The evolution of four-particle eigenstates
the evolution of four-particle eigenstates
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a consequence of the evolution of four-particle eigenstates
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T_c \propto 1/\epsilon^2 \tag{17}
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5. Convergence time vs θ .

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6. DISCUSSION

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Fig. 6. Plot of log 7

Fig. 6. Plot of log 7

6. **DISCUSSION**

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number of elementary motions. The data is from the same run as shown in Fig. 8.

Fig. 10. Plot of $B_{10}(t)$, against

Fig. 10. Plot of $B_{10}(t)$, against

lattice time t, for $X = 0.95$,
 $\theta = 0.25\pi$ and two different

one-particle eigenstates for initial

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lattice time t, for $X = 0.95$,
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number of elementary motions. The data is from the same run as shown in Fig. 10. 0 as we did for some runs described in

limit where the lattice spacing $a \to 0$ and $\epsilon = O(\sqrt{a})$ then the physical convergence timescale, aT_c would remain finite and the dynamics would
be approximately Markovian for time scales larger than this.

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Elementary motions x 10⁴

Fig. 11. Plot of C_n , against the

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The data is from the same run as

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It would be valuable to check all our results by redoing the sim-
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