Weak convergence proof (in progress)

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Theorem 1. *Let $\nu_t^{(1:N)}$ denote the offspring numbers in an interacting particle system satisfying the standing assumption and such that, for any N sufficiently large, for all finite t, $\mathbb{P}\{\tau_N(t) = \infty\} = 0$. Suppose that there exists a deterministic sequence $(b_N)_{N\geq 1}$ such that $\lim_{N\to\infty} b_N = 0$ and*

$$\frac{1}{(N)_3} \sum_{i=1}^{N} \mathbb{E}_t\{(\nu_t^{(i)})_3\} \leq b_N \frac{1}{(N)_2} \sum_{i=1}^{N} \mathbb{E}_t\{(\nu_t^{(i)})_2\} \tag{1}$$

for all N, uniformly in $t \geq 1$. Then the rescaled genealogical process $(G_{\tau_N(t)}^{(n,N)})_{t\geq 0}$ converges weakly to Kingman's n-coalescent as $N \to \infty$.

Proof. Define $p_t := \max_{\xi\in E}\{1 - p_{\xi\xi}(t)\} = 1 - p_{\Delta\Delta}(t)$, where Δ denotes the trivial partition of $\{1,\dots,n\}$ into singletons. For a proof that the maximum is attained at $\xi = \Delta$, see Lemma 1. Following Möhle (1999), we now construct the two-dimensional Markov process $(Z_t, S_t)_{t\in\mathbb{N}}$ with transition probabilities

$$\mathbb{P}(Z_t = j, S_t = \eta \mid Z_{t-1} = i, S_{t-1} = \xi) = \begin{cases} 1 - p_t & \text{if } j = i \text{ and } \xi = \eta \\ p_{\xi\xi}(t) + p_t - 1 & \text{if } j = i+1 \text{ and } \xi = \eta \\ p_{\xi\eta}(t) & \text{if } j = i+1 \text{ and } \xi \neq \eta \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

The construction is such that the marginal (S_t) has the same distribution as the genealogical process of interest, and (Z_t) has jumps at all the times (S_t) does plus some extra jumps. (The definition of p_t ensures that the probability in the second case is non-negative, attaining the value zero when $\xi = \Delta$.)

Denote by $0 = T_0^{(N)} < T_1^{(N)} < \dots$ the jump times of the rescaled process $(Z_{\tau_N(t)})_{t\geq 0}$, and $\omega_i^{(N)} := T_i^{(N)} - T_{i-1}^{(N)}$ the corresponding holding times ($i \in \mathbb{N}$).

... $\square$

Lemma 1. $\max_{\xi\in E}(1 - p_{\xi\xi}(t)) = 1 - p_{\Delta\Delta}(t)$.

Proof. Consider any $\xi \in E$ consisting of k blocks ($1 \leq k \leq n-1$), and any $\xi' \in E$ consisting of $k+1$ blocks. From the definition of $p_{\xi\eta}(t)$ (Koskela et al., 2018, Equation (1)),

$$p_{\xi\xi}(t) = \frac{1}{(N)_k} \sum_{\substack{i_1,\dots,i_k \\ \text{all distinct}}} \nu_t^{(i_1)} \cdots \nu_t^{(i_k)}. \tag{3}$$

Similarly,

$$\begin{aligned} p_{\xi'\xi'}(t) &= \frac{1}{(N)_{k+1}} \sum_{\substack{i_1,\dots,i_k,i_{k+1} \\ \text{all distinct}}} \nu_t^{(i_1)} \cdots \nu_t^{(i_k)} \nu_t^{(i_{k+1})} \\ &= \frac{1}{(N)_k (N-k)} \sum_{\substack{i_1,\dots,i_k \\ \text{all distinct}}} \left\{ \nu_t^{(i_1)} \cdots \nu_t^{(i_k)} \sum_{\substack{i_{k+1}=1 \\ \text{also distinct}}}^{N} \nu_t^{(i_{k+1})} \right\}. \end{aligned} \tag{4}$$

Discarding the zero summands,

$$p_{\xi'\xi'}(t) = \frac{1}{(N)_k(N-k)} \sum_{\substack{i_1,\dots,i_k \\ \text{all distinct:} \\ \nu_t^{(i_1)},\dots,\nu_t^{(i_k)}>0}} \left\{ \nu_t^{(i_1)} \cdots \nu_t^{(i_k)} \sum_{\substack{i_{k+1}=1 \\ \text{also distinct}}}^{N} \nu_t^{(i_{k+1})} \right\}. \tag{5}$$

The inner sum is

$$\sum_{\substack{i_{k+1}=1 \\ \text{also distinct}}}^{N} \nu_t^{(i_{k+1})} = \left\{ \sum_{i=1}^{N} \nu_t^{(i)} - \sum_{i\in\{i_1,\dots,i_k\}} \nu_t^{(i)} \right\} \leq N-k \tag{6}$$

since $\nu_t^{(i_1)},\dots,\nu_t^{(i_k)}$ are all at least 1. Hence

$$p_{\xi'\xi'}(t) \leq \frac{N-k}{(N)_k(N-k)} \sum_{\substack{i_1,\dots,i_k \\ \text{all distinct:} \\ \nu_t^{(i_1)},\dots,\nu_t^{(i_k)}>0}} \nu_t^{(i_1)} \cdots \nu_t^{(i_k)} = p_{\xi\xi}(t). \tag{7}$$

Thus $p_{\xi\xi}(t)$ is decreasing in the number of blocks of ξ, and is therefore minimised by taking $\xi = \Delta$, which achieves the maximum n blocks. This choice in turn maximises $1 - p_{\xi\xi}(t)$, as required. $\square$

Lemma 2. *For any $t > 0$,*

$$\lim_{N\to\infty} \mathbb{E}\left[\prod_{r=1}^{\tau_N(t)} (1-p_r) \right] = e^{-\alpha t} \tag{8}$$

where $\alpha := n(n-1)/2$.

Proof. The strategy is to find upper and lower bounds on $\mathbb{E}\left[\prod_{r=1}^{\tau_N(t)}(1-p_r)\right]$, both of which converge to $e^{-\alpha t}$.

Lower Bound

From Brown et al. (2020, Equation (14)), taking $\xi = \Delta$, we have

$$1 - p_t = p_{\Delta\Delta}(t) \geq 1 - \alpha(1 + O(N^{-1}))\,[c_N(t) + B_n D_N(t)] \tag{9}$$

where $B_n > 0$ and the $O(N^{-1})$ term does not depend on t. In particular,

$$1 - p_t = p_{\Delta\Delta}(t) \geq 1 - \frac{N^{n-2}}{(N-2)_{n-2}}\alpha c_N(t) - \frac{N^{n-3}}{(N-3)_{n-3}} B_n D_N(t) \tag{10}$$

Hence, by a multinomial expansion,

$$\begin{aligned}
\prod_{r=1}^{\tau_N(t)} (1-p_r) &\geq \prod_{r=1}^{\tau_N(t)} \left\{1 - \alpha(1+O(N^{-1}))\,[c_N(r) + B_n D_N(r)]\right\} \\
&= 1 + \sum_{k=1}^{\tau_N(t)} \sum_{\substack{r_1<\dots<r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k} \left\{-\alpha(1+O(N^{-1}))\,[c_N(r_j) + B_n D_N(r_j)]\right\} \\
&= 1 + \sum_{k=1}^{\tau_N(t)} \left\{-\alpha(1+O(N^{-1}))\right\}^k \sum_{\substack{r_1<\dots<r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k} \left\{c_N(r_j) + B_n D_N(r_j)\right\}. \qquad (11)
\end{aligned}$$

Taking expectations,

$$\mathbb{E}\left[\prod_{r=1}^{\tau_N(t)} (1-p_r)\right] \geq 1 + \sum_{k=1}^{\tau_N(t)} \left\{-\alpha(1+O(N^{-1}))\right\}^k \mathbb{E}\left[\sum_{\substack{r_1<\dots<r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k} \left\{c_N(r_j) + B_n D_N(r_j)\right\}\right]. \tag{12}$$

We want to show that the expectation on the right converges to $t^k/k!$, for reasons that will become clear. The strategy is to upper and lower bound this expectation by quantities that converge to $t^k/k!$.

First the lower bound. Assume that $k \leq \tau_N(t)$, i.e. the sum is non-empty. From Koskela et al. (2018, Equation (8)),

$$
\begin{aligned}
\sum_{\substack{r_1 < \cdots < r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k} \{c_N(r_j) + B_n D_N(r_j)\} &\geq \sum_{\substack{r_1 < \cdots < r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k} c_N(r_j) \\
&\geq \frac{1}{k!} \left(\sum_{s=1}^{\tau_N(t)} c_N(s) \right)^k - \frac{1}{k!} \binom{k}{2} \left(\sum_{s=1}^{\tau_N(t)} c_N(s)^2 \right) \left(\sum_{s=1}^{\tau_N(t)} c_N(s) \right)^{k-2} \\
&\geq \frac{1}{k!} t^k - \frac{1}{k!} \binom{k}{2} (t+1)^{k-2} \left(\sum_{s=1}^{\tau_N(t)} c_N(s)^2 \right) \qquad (13)
\end{aligned}
$$

by the definition of τ_N. Then

$$
\mathbb{E}\left[\sum_{\substack{r_1 < \cdots < r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k} \{c_N(r_j) + B_n D_N(r_j)\} \right] \geq \frac{1}{k!} t^k - \frac{1}{k!} \binom{k}{2} (t+1)^{k-2} \mathbb{E}\left[\sum_{s=1}^{\tau_N(t)} c_N(s)^2 \right] \longrightarrow \frac{1}{k!} t^k \qquad (14)
$$

as $N \to \infty$ using Brown et al. (2020, Equation (5)), which is shown to hold via lemmata 1 and 3 therein.

Now for the upper bound. We start with a multinomial expansion and some manipulations of the sums:

$$
\begin{aligned}
\sum_{\substack{r_1 < \cdots < r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k} \{c_N(r_j) + B_n D_N(r_j)\} &= \frac{1}{k!} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}}^{\tau_N(t)} \prod_{j=1}^{k} \{c_N(r_j) + B_n D_N(r_j)\} \\
&= \frac{1}{k!} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}}^{\tau_N(t)} \sum_{\mathcal{I} \subseteq \{1,\ldots,k\}} (B_n)^{k-|\mathcal{I}|} \left\{ \prod_{i \in \mathcal{I}} c_N(r_i) \right\} \left\{ \prod_{j \notin \mathcal{I}} D_N(r_j) \right\} \\
&= \frac{1}{k!} \sum_{\mathcal{I} \subseteq \{1,\ldots,k\}} (B_n)^{k-|\mathcal{I}|} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}}^{\tau_N(t)} \left\{ \prod_{i \in \mathcal{I}} c_N(r_i) \right\} \left\{ \prod_{j \notin \mathcal{I}} D_N(r_j) \right\} \\
&= \frac{1}{k!} \sum_{I=0}^{k} \binom{k}{I} (B_n)^{k-I} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}}^{\tau_N(t)} \left\{ \prod_{i=1}^{I} c_N(r_i) \right\} \left\{ \prod_{j=I+1}^{k} D_N(r_j) \right\} \\
&= \frac{1}{k!} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}}^{\tau_N(t)} \left\{ \prod_{i=1}^{k} c_N(r_i) \right\} \\
&\quad + \frac{1}{k!} \sum_{I=0}^{k-1} \binom{k}{I} (B_n)^{k-I} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}}^{\tau_N(t)} \left\{ \prod_{i=1}^{I} c_N(r_i) \right\} \left\{ \prod_{j=I+1}^{k} D_N(r_j) \right\}. \qquad (15)
\end{aligned}
$$

Then, using that $D_N(s) \le c_N(s)$ for all s (Koskela et al., 2018, p.9), along with the definition of τ_N,

$$\begin{aligned}
\frac{1}{k!}\sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}}^{\tau_N(t)} \left\{\prod_{i=1}^{k} c_N(r_i)\right\} &+ \frac{1}{k!}\sum_{I=0}^{k-1}\binom{k}{I}(B_n)^{k-I} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}}^{\tau_N(t)} \left\{\prod_{i=1}^{I} c_N(r_i)\right\}\left\{\prod_{j=I+1}^{k} D_N(r_j)\right\} \\
&\le \frac{1}{k!}\left(\sum_{r=1}^{\tau_N(t)} c_N(r)\right)^k + \frac{1}{k!}\sum_{I=0}^{k-1}\binom{k}{I}(B_n)^{k-I} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}}^{\tau_N(t)} \left\{\prod_{i=1}^{k-1} c_N(r_i)\right\} D_N(r_k) \\
&\le \frac{1}{k!}\left\{t + c_N(\tau_N(t))\right\}^k + \frac{1}{k!}\sum_{I=0}^{k-1}\binom{k}{I}(B_n)^{k-I} \left\{\sum_{\substack{r_1 \neq \cdots \neq r_{k-1} \\ \text{all distinct}}}^{\tau_N(t)} \prod_{i=1}^{k-1} c_N(r_i)\right\}\left(\sum_{r_k=1}^{\tau_N(t)} D_N(r_k)\right) \\
&\le \frac{1}{k!}\left\{t + c_N(\tau_N(t))\right\}^k + \frac{1}{k!}\sum_{I=0}^{k-1}\binom{k}{I}(B_n)^{k-I} \left(\sum_{r=1}^{\tau_N(t)} c_N(r)\right)^{k-1}\left(\sum_{r=1}^{\tau_N(t)} D_N(r)\right) \\
&\le \frac{1}{k!}\left\{t + c_N(\tau_N(t))\right\}^k + \frac{1}{k!}\sum_{I=0}^{k-1}\binom{k}{I}(B_n)^{k-I}(t+1)^{k-1} \left(\sum_{r=1}^{\tau_N(t)} D_N(r)\right). \qquad (16)
\end{aligned}$$

Taking expectations,

$$\begin{aligned}
\lim_{N\to\infty}\mathbb{E}\left[\sum_{\substack{r_1<\cdots<r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k}\left\{c_N(r_j) + B_n D_N(r_j)\right\}\right] &\le \frac{1}{k!}\lim_{N\to\infty}\mathbb{E}[\{t + c_N(\tau_N(t))\}^k] \qquad (17) \\
&\quad + \frac{1}{k!}\sum_{I=0}^{k-1}\binom{k}{I}(B_n)^{k-I}(t+1)^{k-1}\lim_{N\to\infty}\mathbb{E}\left[\left(\sum_{r=1}^{\tau_N(t)} D_N(r)\right)\right] \\
&= \frac{1}{k!}t^k.
\end{aligned}$$

The limit follows from Brown et al. (2020, Equations (3),(4)) along with the fact that, since $c_N(s) \in [0,1]$ for all s, $\mathbb{E}[c_N(s)^k] \le \mathbb{E}[c_N(s)]$ for all $k \ge 1$, and the expansion

$$\mathbb{E}\left[\frac{1}{k!}\{t + c_N(\tau_N(t))\}^k\right] = \frac{1}{k!}\sum_{i=0}^{k}\binom{k}{i} t^i\, \mathbb{E}\left[c_N(\tau_N(t))^{k-i}\right] \longrightarrow \frac{1}{k!}t^k. \qquad (18)$$

Combining these upper and lower limits, we conclude that

$$\lim_{N\to\infty}\mathbb{E}\left[\sum_{\substack{r_1<\cdots<r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k}\left\{c_N(r_j) + B_n D_N(r_j)\right\}\right] = \frac{1}{k!}t^k \qquad (19)$$

and thus

$$\begin{aligned}
\lim_{N\to\infty}\mathbb{E}&\left[1 + \sum_{k=1}^{\tau_N(t)}\left\{-\alpha(1+O(N^{-1}))\right\}^k \sum_{\substack{r_1<\cdots<r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k}\left\{c_N(r_j) + B_n D_N(r_j)\right\}\right] \\
&= 1 + \lim_{N\to\infty}\sum_{k=1}^{\infty}\left\{-\alpha(1+O(N^{-1}))\right\}^k \mathbb{E}\left[\mathbb{I}_{\{k \le \tau_N(t)\}} \sum_{\substack{r_1<\cdots<r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k}\left\{c_N(r_j) + B_n D_N(r_j)\right\}\right] \\
&= 1 + \sum_{k=1}^{\infty}(-\alpha)^k \lim_{N\to\infty}\mathbb{E}\left[\sum_{\substack{r_1<\cdots<r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k}\left\{c_N(r_j) + B_n D_N(r_j)\right\} \middle| k \le \tau_N(t)\right] \times \lim_{N\to\infty}\mathbb{P}[k \le \tau_N(t)] \\
&= 1 + \sum_{k=1}^{\infty}(-\alpha)^k \frac{t^k}{k!} \times 1 = e^{-\alpha t} \qquad (20)
\end{aligned}$$

as $N \to \infty$, where the last line follows from (19) and Lemma [??].

Upper Bound
From Koskela et al. (2018, Lemma 1 Case 1), taking $\xi = \Delta$, we have

$$1 - p_t = p_{\Delta\Delta}(t) \leq 1 - \alpha(1 + O(N^{-1}))\left[c_N(t) - B_n' D_N(t)\right]. \tag{21}$$

A multinomial expansion as before yields

$$\prod_{r=1}^{\tau_N(t)} (1 - p_r) \leq 1 + \sum_{k=1}^{\tau_N(t)} \left\{-\alpha(1 + O(N^{-1}))\right\}^k \sum_{\substack{r_1 < \cdots < r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k} \left\{c_N(r_j) - B_n' D_N(r_j)\right\}. \tag{22}$$

Analogously to (15), assuming $k \leq \tau_N(t)$ we can write

$$\begin{aligned} \sum_{\substack{r_1 < \cdots < r_k \\ =1}}^{\tau_N(t)} \prod_{j=1}^{k} \left\{c_N(r_j) - B_n' D_N(r_j)\right\} &= \frac{1}{k!} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}}^{\tau_N(t)} \left\{\prod_{i=1}^{k} c_N(r_i)\right\} \\ &\quad + \frac{1}{k!} \sum_{I=0}^{k-1} \binom{k}{I} (-B_n')^{k-I} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}} \left\{\prod_{i=1}^{I} c_N(r_i)\right\} \left\{\prod_{j=I+1}^{k} D_N(r_j)\right\}. \end{aligned} \tag{23}$$

We start by dealing with the second term:

$$\begin{aligned} &\frac{1}{k!} \sum_{I=0}^{k-1} \binom{k}{I} (-B_n')^{k-I} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}} \left\{\prod_{i=1}^{I} c_N(r_i)\right\} \left\{\prod_{j=I+1}^{k} D_N(r_j)\right\} \\ &\qquad = \frac{1}{k!} \sum_{\substack{I=0: \\ k-I \text{ even}}}^{k-1} \binom{k}{I} (B_n')^{k-I} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}} \left\{\prod_{i=1}^{I} c_N(r_i)\right\} \left\{\prod_{j=I+1}^{k} D_N(r_j)\right\} \\ &\qquad\quad - \frac{1}{k!} \sum_{\substack{I=0: \\ k-I \text{ odd}}}^{k-1} \binom{k}{I} (B_n')^{k-I} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}} \left\{\prod_{i=1}^{I} c_N(r_i)\right\} \left\{\prod_{j=I+1}^{k} D_N(r_j)\right\}. \end{aligned} \tag{24}$$

This is lower bounded by

$$0 - \frac{1}{k!} \sum_{\substack{I=0 \\ k-I \text{ odd}}}^{k-1} \binom{k}{I} (B_n')^{k-I} (t+1)^{k-1} \left(\sum_{s=1}^{\tau_N(t)} D_N(s)\right) \tag{25}$$

using that $c_N(r), D_N(r) \geq 0$ for all r to bound the even terms below, and arguments from (16) to bound the odd terms above. The same arguments lead to the upper bound

$$\frac{1}{k!} \sum_{\substack{I=0 \\ k-I \text{ even}}}^{k-1} \binom{k}{I} (B_n')^{k-I} (t+1)^{k-1} \left(\sum_{s=1}^{\tau_N(t)} D_N(s)\right) - 0. \tag{26}$$

By Brown et al. (2020, Equation (4)), both bounds have vanishing expectation as $N \to \infty$. We are left with the first term in (23), which is upper bounded by

$$\frac{1}{k!} \sum_{\substack{r_1 \neq \cdots \neq r_k \\ \text{all distinct}}}^{\tau_N(t)} \left\{\prod_{i=1}^{k} c_N(r_i)\right\} \leq \frac{1}{k!} \left(\sum_{s=1}^{\tau_N(t)} c_N(s)\right)^k \leq \frac{1}{k!} \{t + c_N(\tau_N(t))\}^k \tag{27}$$

the expectation of which converges to $t^k/k!$ as in (18). We use Koskela et al. (2018, Equation (8)) to construct a lower bound:

$$\frac{1}{k!}\sum_{\substack{r_1\neq\cdots\neq r_k\\ \text{all distinct}}}^{\tau_N(t)}\left\{\prod_{i=1}^{k}c_N(r_i)\right\} \geq \frac{1}{k!}\left(\sum_{s=1}^{\tau_N(t)}c_N(s)\right)^k - \frac{1}{k!}\binom{k}{2}\left(\sum_{s=1}^{\tau_N(t)}c_N(s)^2\right)\left(\sum_{s=1}^{\tau_N(t)}c_N(s)\right)^{k-2}$$
$$\geq \frac{1}{k!}t^k - \frac{1}{k!}\binom{k}{2}(t+1)^{k-2}\left(\sum_{s=1}^{\tau_N(t)}c_N(s)^2\right) \tag{28}$$

The expectation of this bound also converges to $t^k/k!$, using Brown et al. (2020, Equation (5)). We can now conclude that

$$\lim_{N\to\infty}\mathbb{E}\left[\sum_{\substack{r_1<\cdots<r_k\\=1}}^{\tau_N(t)}\prod_{j=1}^{k}\{c_N(r_j)-B_n'D_N(r_j)\}\right] = \frac{1}{k!}t^k \tag{29}$$

and thus, by calculations analogous to (20),

$$\lim_{N\to\infty}\mathbb{E}\left[1+\sum_{k=1}^{\tau_N(t)}\left\{-\alpha(1+O(N^{-1}))\right\}^k\sum_{\substack{r_1<\cdots<r_k\\=1}}^{\tau_N(t)}\prod_{j=1}^{k}\{c_N(r_j)-B_n'D_N(r_j)\}\right] = 1+\sum_{k=1}^{\infty}(-\alpha)^k\frac{1}{k!}t^k = e^{-\alpha t} \tag{30}$$

as $N\to\infty$.

We now have upper and lower bounds on $\lim_{N\to\infty}\mathbb{E}\left[\prod_{r=1}^{\tau_N(t)}(1-p_r)\right]$, both of which are equal to $e^{-\alpha t}$, and the result follows. □

References

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