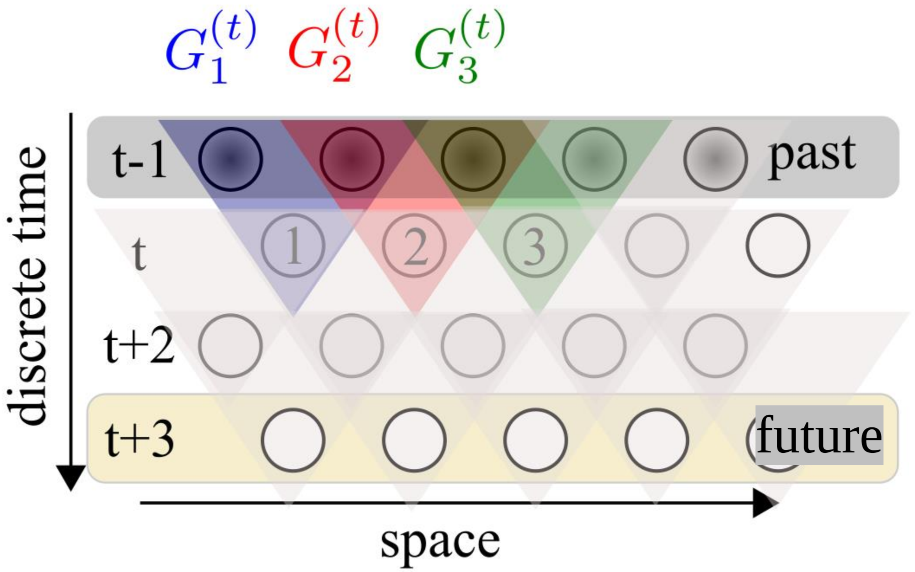
# Exploring non-equilibrium physics with synthetic quantum systems




**Igor Lesanovsky**

Quantum Science Seminar

11/02/2021

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

www.open-quantum-systems.com

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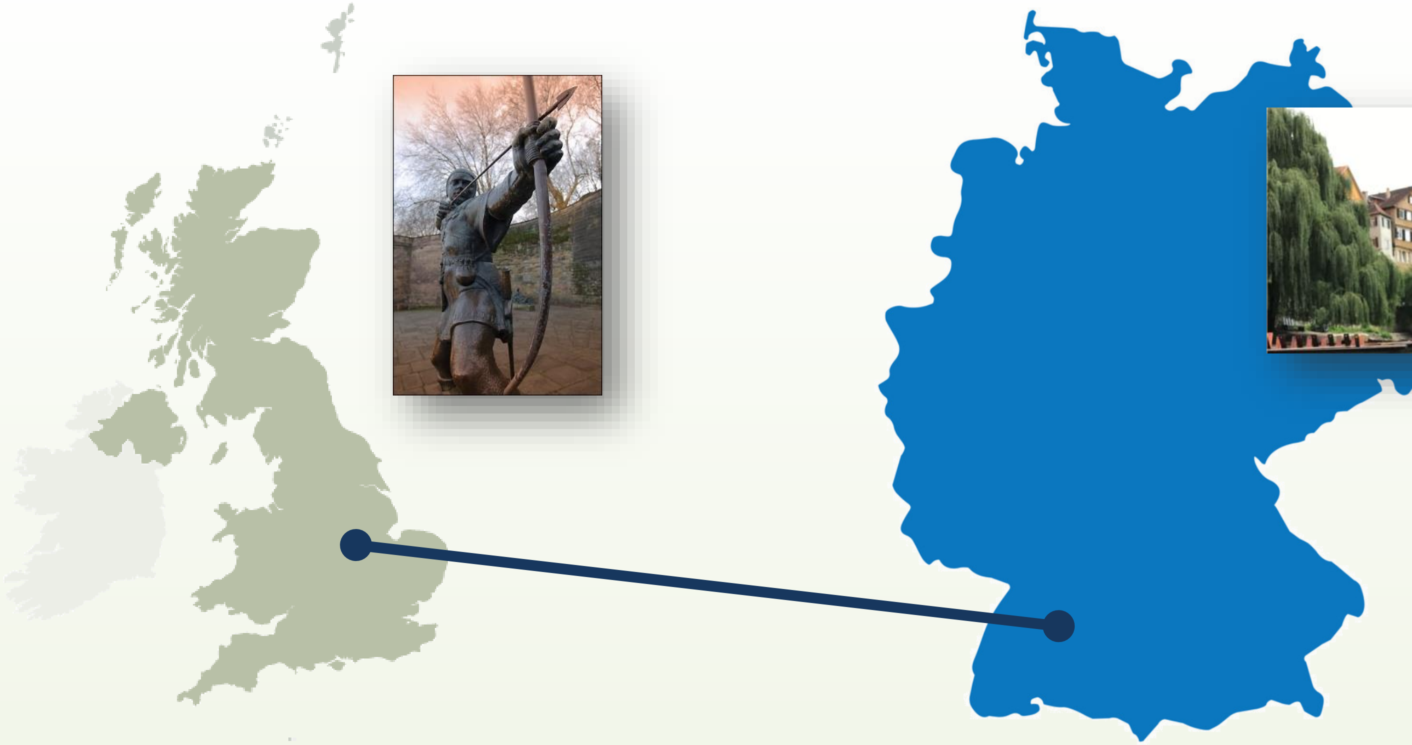

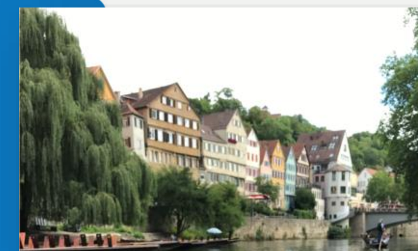

J. P. Garrahan
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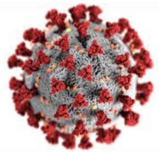
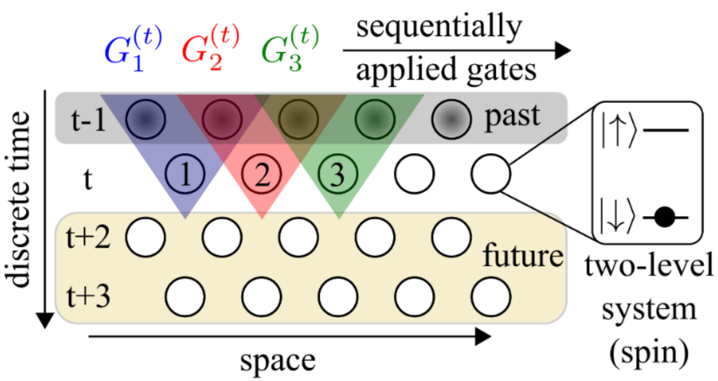
# This talk

- Synthetic quantum systems – Rydberg quantum simulators
- Classical vs. Quantum non-equilibrium processes (Quantum contact process)



- (Open) Quantum cellular automata
  - Definition
  - Non-equilibrium phase transitions
  - Non-classical correlations
- Outlook

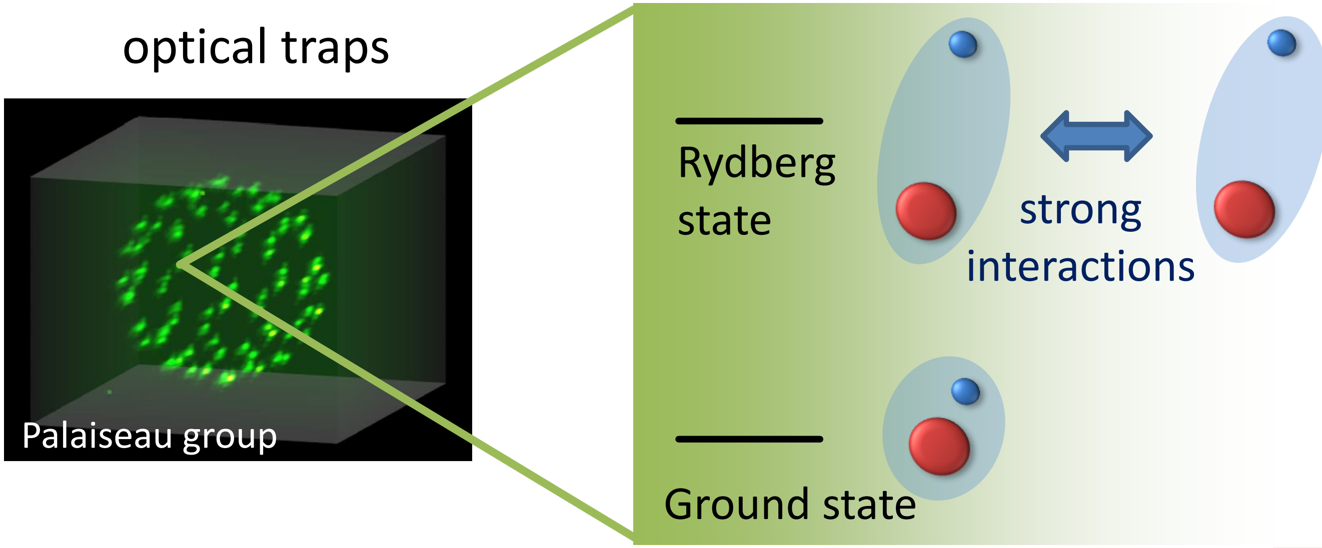

Physical Review Letters **116**, 245701 (2016)
Quantum Science and Technology **4**, 02LT02 (2019)
Physical Review Letters **123**, 100604 (2019)
Physical Review Letters **125**, 100403 (2020)
arXiv:2010.10954 (2020)

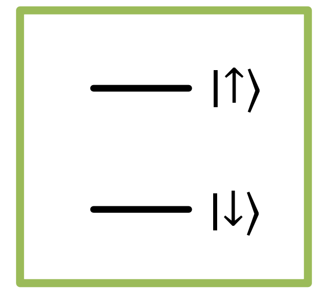
# Synthetic quantum systems

## Rydberg atoms quantum simulator

optical traps




Artificial spin degree of freedom




$$\vec{S} = (S_x, S_y, S_z)$$

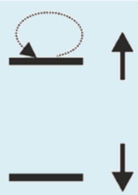
**Coherent dynamics:**

$$H_{\text{atom}} = \sum_k \vec{B}_k \cdot \vec{S}_k + \sum_{km} \vec{S}_k \cdot \boldsymbol{J}_{km} \cdot \vec{S}_m$$

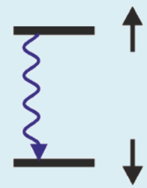
external fields — interactions

**Dissipative processes:**

dephasing




decay



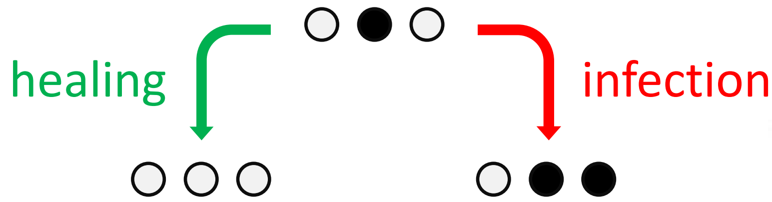

- Phase transitions
- Topological phases
- Quantum scars
- Time crystals
- Quantum information
- Kinetic constraints
- Quantum engines
- Quantum annealing

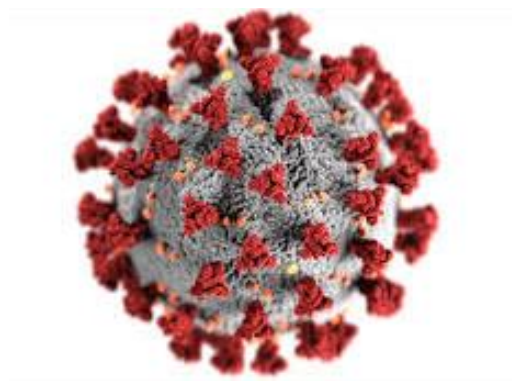
…

# Non-equilibrium processes

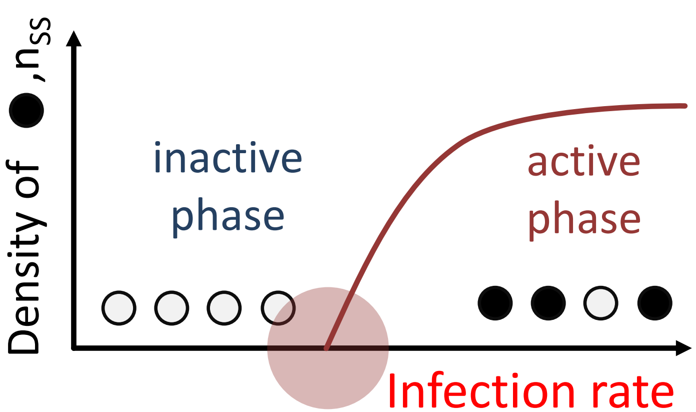
**Lattice dynamics**

○ healthy
● infected



- Dynamics described by rate equation (master equation): $\partial_t \rho(t) = L\, \rho(t)$
- Stationary state: $\rho(\infty) = \lim_{t\to\infty} e^{Lt} \rho(0)$
- Order parameter: density of infected sites, $n(t)$
- Absorbing state phase transition




**Continuous phase transition**

- Observables show power-law behavior
- Set of critical exponents characterises the universality class

| $n_{SS} \propto \lvert\lambda - \lambda_c\rvert^{\beta}$ | $n(t) \propto t^{-\delta}$ |
| --- | --- |
| Stationary density | Time-dependence at critical point |

# Non-equilibrium processes

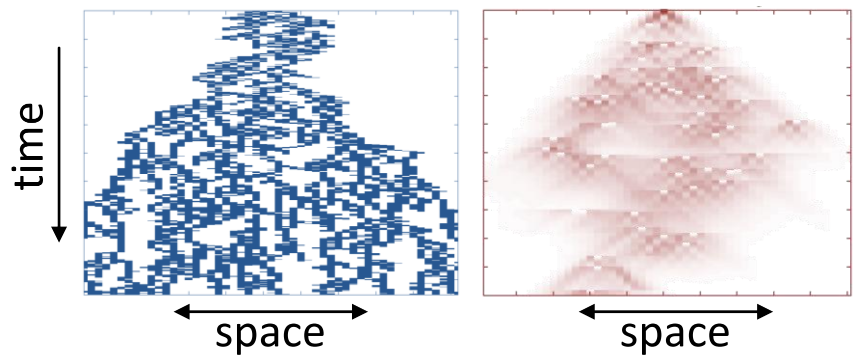
- What if infection was a quantum process ? (healing remains classical)

$$|\bullet\circ\rangle \longrightarrow a|\bullet\circ\rangle + b|\bullet\bullet\rangle$$

- Dynamics starting from a single infected site (super-critical region):

- Also in quantum version: phase transition from competition between healing and infection

Infection process is classical | Infection process is quantum




- Universality class depends on whether infection is classical or quantum

<u>1d classical/quantum contact process:</u>
Directed percolation universality (1d) vs.
Tricritical directed percolation universality (2d)

PRL **123**, 100604 (2019)
PRL **116**, 245701 (2016)

M. Jo et al., 2004.02672

# Open quantum cellular automata

Unitary and Nonunitary Quantum Cellular Automata with Rydberg Arrays

T. M. Wintermantel, Y. Wang, G. Lochead, S. Shevate, G. K. Brennen, and S. Whitlock
Phys. Rev. Lett. **124**, 070503 – Published 21 February 2020

## (Open) Quantum Cellular Automata

Nanotechnology 4 (1993) 49–57. Printed in the UK

**Quantum cellular automata**

**Craig S Lent, P Douglas Tougaw, Wolfgang Porod and Gary H Bernstein**
Department of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556, USA

Weyl, Dirac, and Maxwell equations on a lattice as unitary cellular automata

Iwo Bialynicki-Birula
Phys. Rev. D **49**, 6920 – Published 15 June 1994

arXiv:quant-ph/0405174 [pdf, ps, other] quant-ph

**Reversible quantum cellular automata**

**Authors:** B. Schumacher, R. F. Werner

*Complex Systems* **2** (1988) 197–208

Quantum Cellular Automata

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Quantum
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A review of Quantum Cellular Automata

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Citation: Quantum 4, 368 (2020).

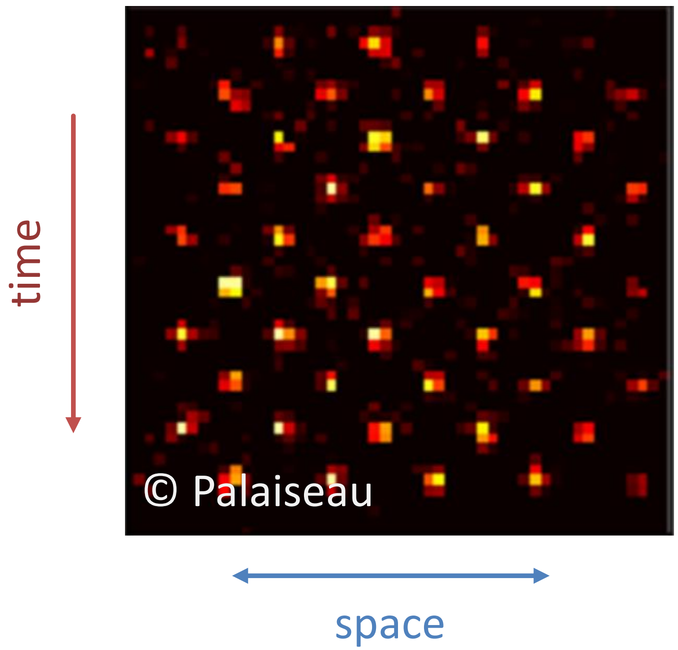
arXiv:2005.01763 [pdf, other] quant-ph cond-mat.quant-gas cond-mat.stat-mech nlin.CG nlin.PS

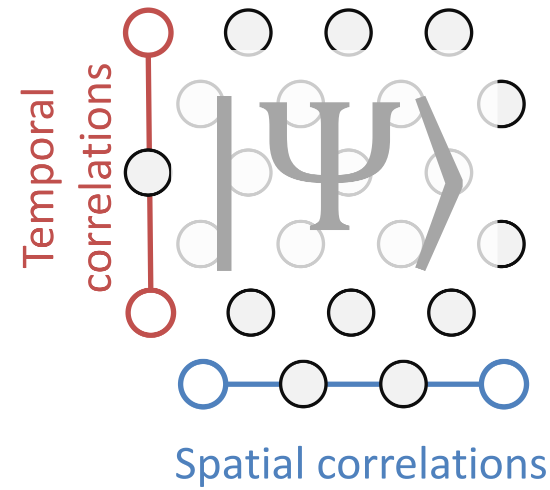
**Entangled quantum cellular automata, physical complexity, and Goldilocks rules**

**Authors:** Logan E. Hillberry, Matthew T. Jones, David L. Vargas, Patrick Rall, Nicole Yunger Halpern, Ning Bao, Simone Notarnicola, Simone Montangero, Lincoln D. Carr

# Open quantum cellular automaton

- Quantum cellular automata for the purpose of this talk …

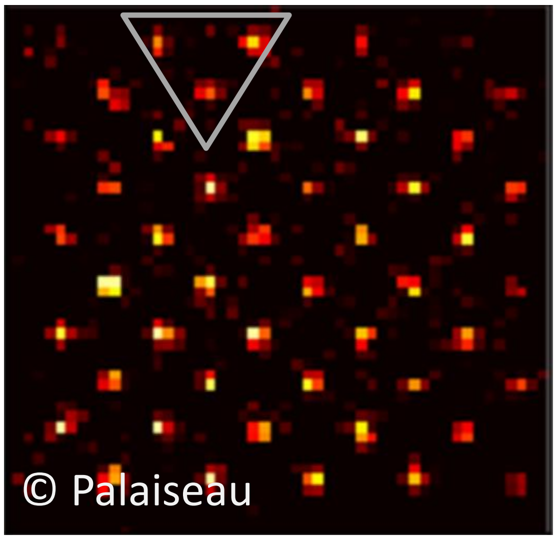


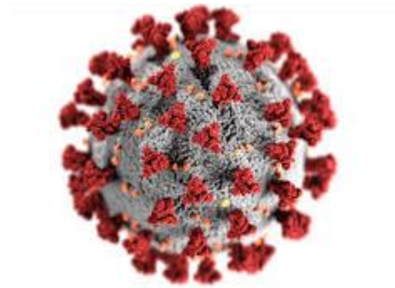



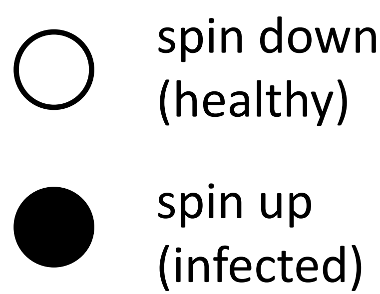

- Inspired by 2d lattice Rydberg quantum simulators
  [Browaeys, Lukin, Groß, Bloch, Ahn, Saffmann, …]
- 1+1d dynamics is propagated by quantum gates
- Space-time correlations are encoded in a single 2d quantum states (PEPS)
- Possess close connection to classical probabilistic cellular automata
  [see e.g. Hinrichsen, Adv. Phys. **49**, 815 (2000)]

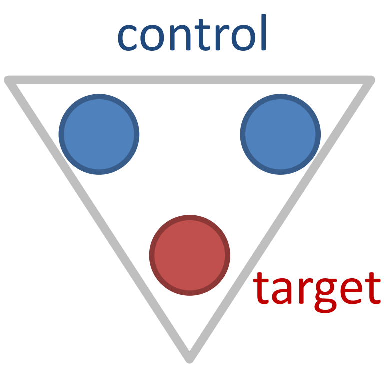
# Open quantum cellular automaton

- Rydberg states permit to implement conditional spin rotations by exploiting state-dependent interactions (here facilitation/anti-blockade)

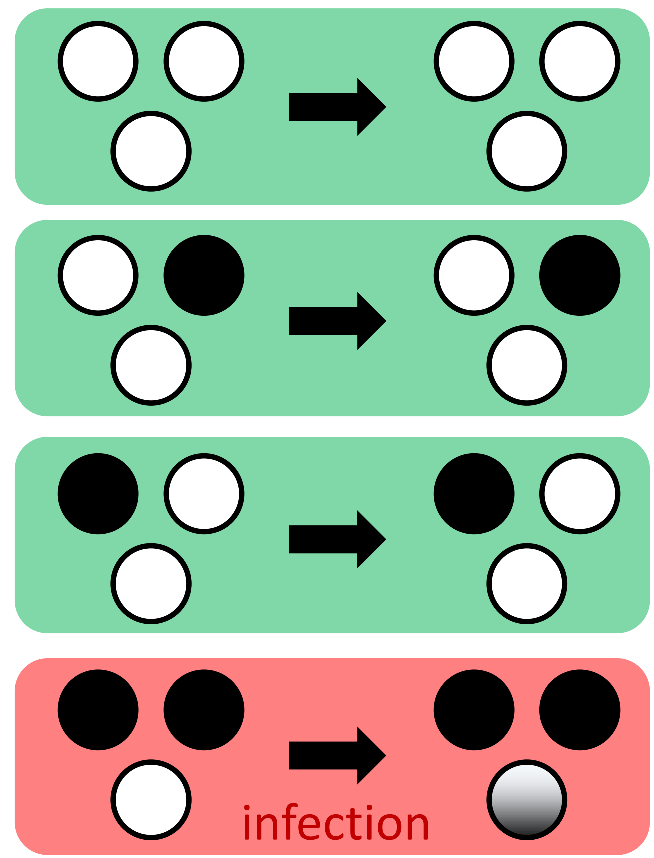




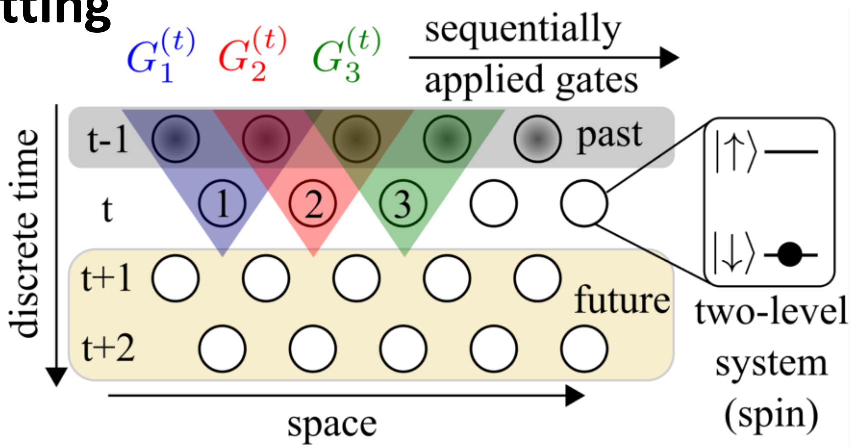




**Conditional spin rotation**




# Open QCA dynamics

**Setting**




- lattice spins initialised in state where all spins are down
- application of gates to coherently propagate state
- different gates commute here

**Fundamental 3-body gate**

t-1 slice

t slice

$$G_m^{(t)} = P_{m,m+1}^{(t-1)} \otimes U_m^{(t)} + Q_{m,m+1}^{(t-1)} \otimes \mathbb{I}_m$$

checks if at least one spin is in up-state

$U = \exp(-i\alpha S_y)$

flips target spin from down to up with probability $\sin^2\left(\frac{\alpha}{2}\right)$

if there is no up-spin on time slice t-1 don't do anything on time slice t

**state of target spin**

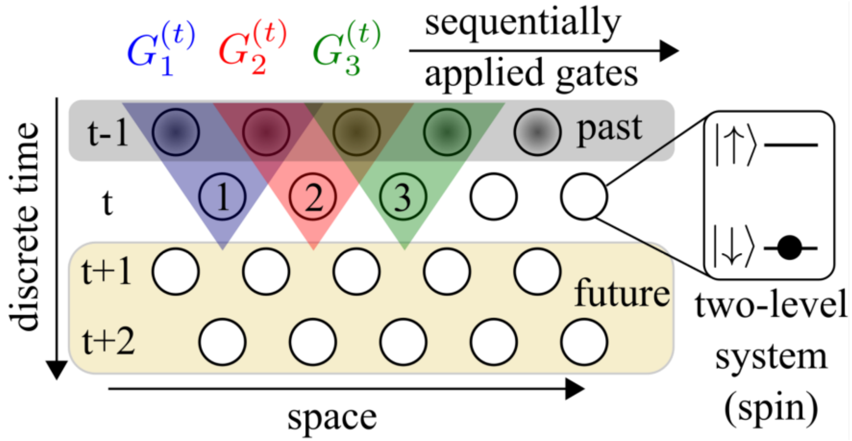
$\rho^{(1)} = |\downarrow\rangle\langle\downarrow|$

**state of target spin**

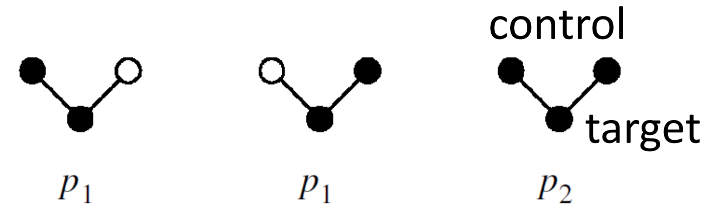
$\rho^{(0)} = |\alpha\rangle\langle\alpha|$

Quant. Sci. Tech. **4**, 02LT02 (2019)

# Non-equilibrium phase transition



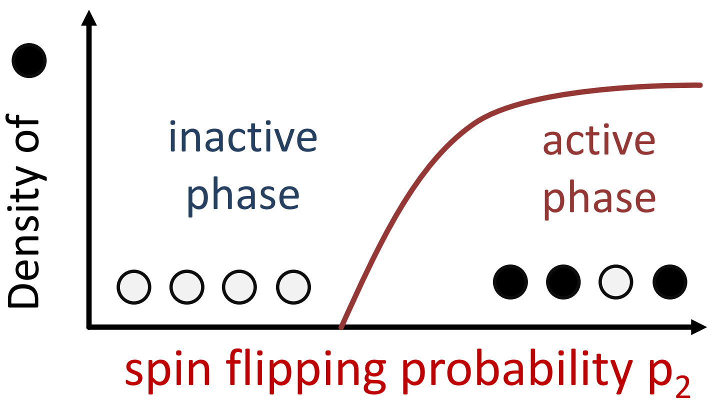

- dynamics can be mapped on classical probabilistic Domany-Kinzel cellular automaton
[Quant. Sci. Tech. **4**, 02LT02 (2019)]

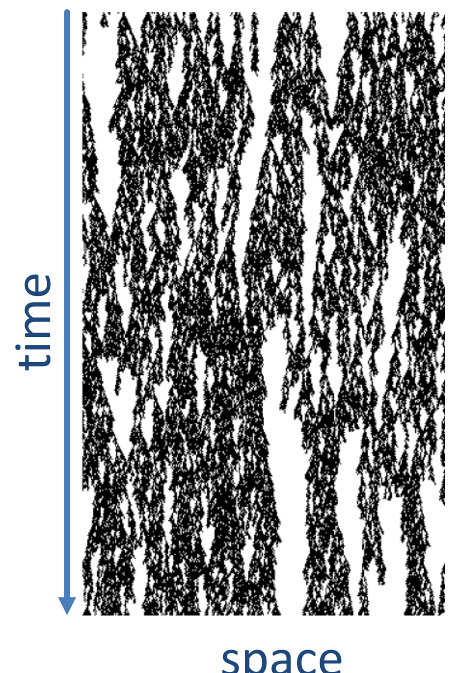



[Hinrichsen, Adv. Phys. **49**, 815 (2000)]

- Domany-Kinzel cellular automaton shows phase transition in stationary state

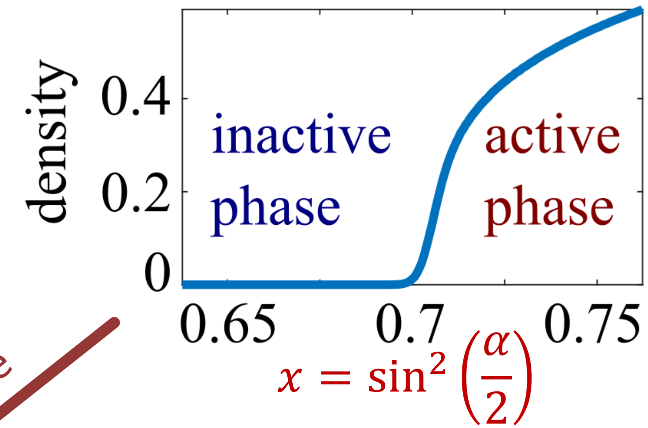
- Universality class (@$p_1$=0): directed percolation



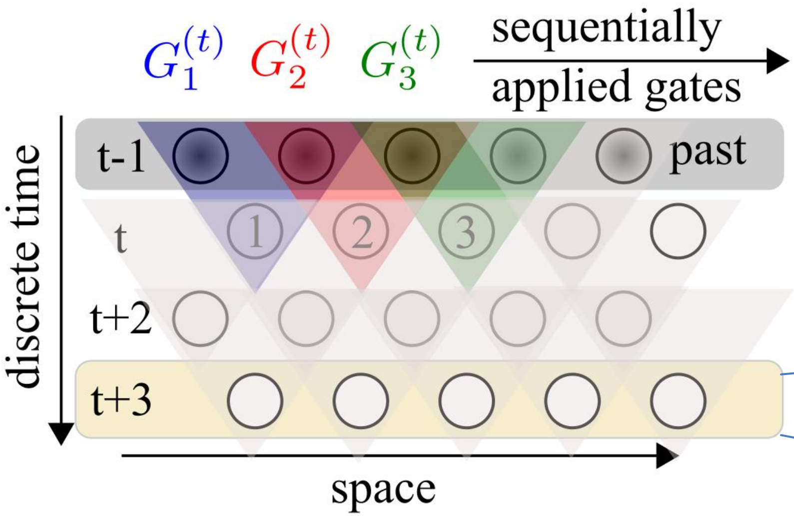
# Quantum correlations

- also quantum cellular automaton shows phase transition
- note, that dynamics is fully coherent




Gate rotation angle

Final time slice




Reduced state in each time slice is separable, i.e. not entangled

$$X_k^{(0)} = P_{k,k+1} \rightarrow \rho^{(0)}$$

$$X_k^{(1)} = Q_{k,k+1} \rightarrow \rho^{(1)}$$

$$\rho_t = \sum_{i_1,\ldots i_N=0,1} \mathrm{Tr}\left[X_1^{(i_1)} \ldots X_N^{(i_N)} \rho_{t-1}\right] \rho^{(i_1)} \otimes \ldots \otimes \rho^{(i_N)}$$

Expectation value take on previous time slice

- however, reduced state is non-classical: **non-classical correlations**

# Quantum correlations

- Quantum correlations are quantified via '**Local Quantum Uncertainty**'

[Adesso, PRL **110**, 240402 (2018)]

- Uncertainty due to non-commutativity between observable and state
- Calculated via maximum eigenvalue of operator

$$W^{ij}_{\alpha\beta} = \mathrm{Tr}\left(\rho^{1/2}_{ij}\sigma^i_\alpha \rho^{1/2}_{ij}\sigma^i_\beta\right)$$

Reduced two-spin density matrix

$$\rho_{ij} = \begin{pmatrix} c_{ij} & x\,c_{ij} \\ x\,c_{ij} & 1-c_{ij} \end{pmatrix} \otimes \begin{pmatrix} c_{ij} & x\,c_{ij} \\ x\,c_{ij} & 1-c_{ij} \end{pmatrix} + [\langle n\rangle - c_{ij}] \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & x \\ 0 & 0 & 1 & x \\ 0 & x & x & -2 \end{pmatrix}$$

$x = \sin^2\left(\frac{\alpha}{2}\right)$ = excitation probability; $c_{ij} = \sqrt{\langle n_i n_j\rangle}$ = density-density correlations;

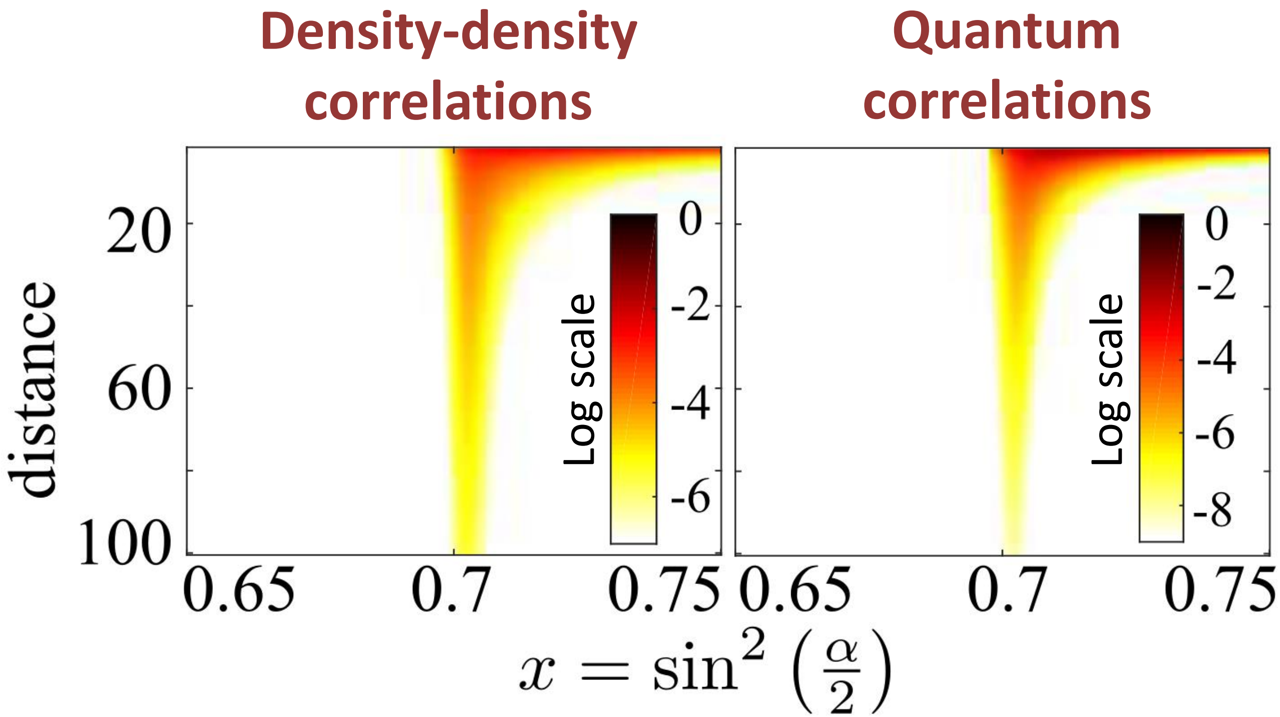
$\langle n\rangle$ = excitation density

- Product state if $c_{ij} = \sqrt{\langle n_i\rangle\langle n_j\rangle} = \langle n\rangle$, i.e. when sites are uncorrelated
- $c_{ij} \neq \langle n\rangle$ in vicinity of phase transition

# Quantum correlations

- Quantum cellular automaton exhibits quantum correlations
- **Quantum correlations** linked to **density-density correlations**:

  present when $\langle n \rangle - \sqrt{\langle n_i n_j \rangle} \neq 0$



# Beyond quantum discord

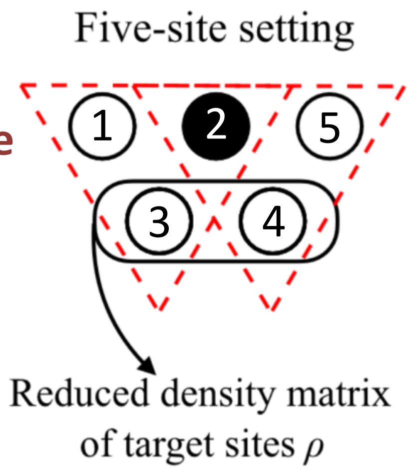
- entanglement can be introduced by modifying gate (add unitary on the control time slice)

**General gate**

$$G = \exp[-i\alpha(\sigma_3^+ U^{12} P^{12} + \mathrm{h.c.})]$$

Control time slice

Target time slice

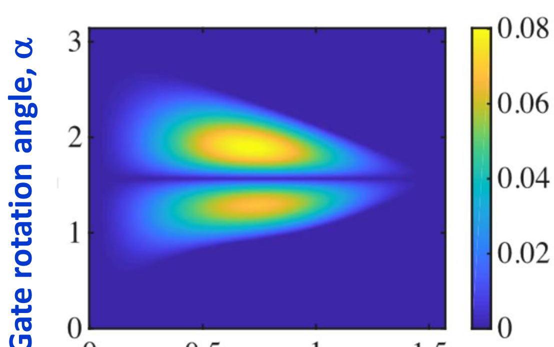



**Unitary generating entanglement**

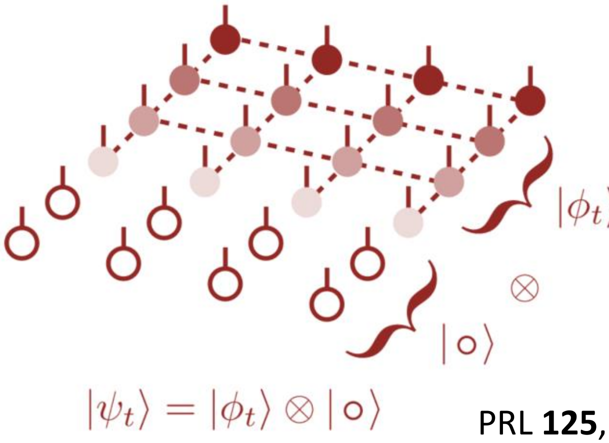
$$U^{12} \equiv U^{12}(\omega) = \exp\left(-i\omega\left[\sigma_z^1\sigma_y^2 + \sigma_y^1\sigma_z^2\right]\right)$$

- Degree of entanglement is quantified through concurrence
- Controlled by rotation angle ω

**Concurrence between 3 and 4**



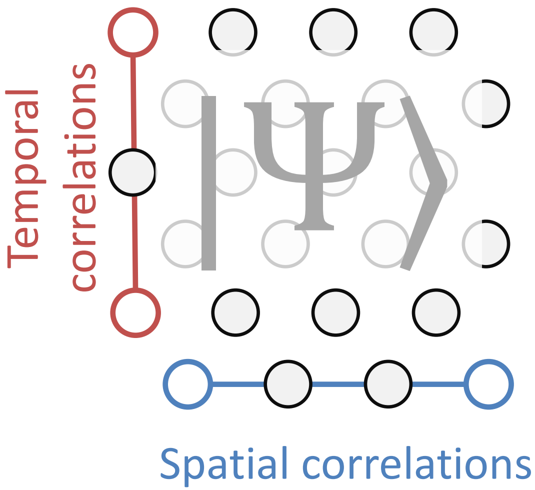

- **Problem:** mapping to classical Domany-Kinzel CA no longer possible
- 1+1d quantum state of encoded in **Projected Entangled Pair State**




PRL **125**, 100403 (2020)

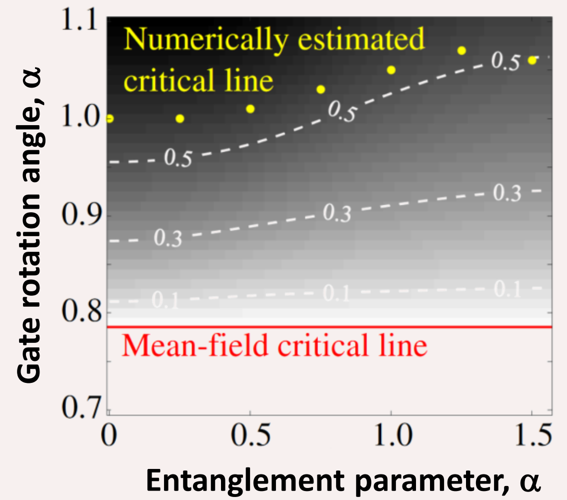
# Beyond quantum discord

**„Complexity“ of dynamics**

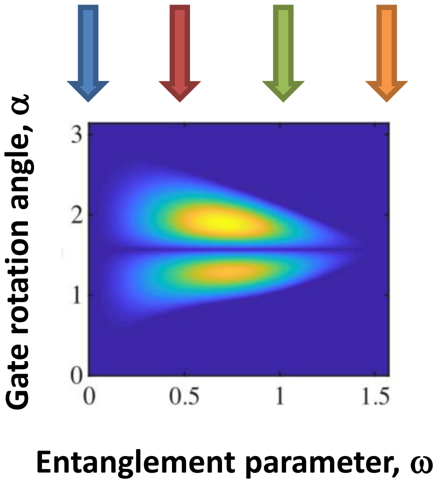


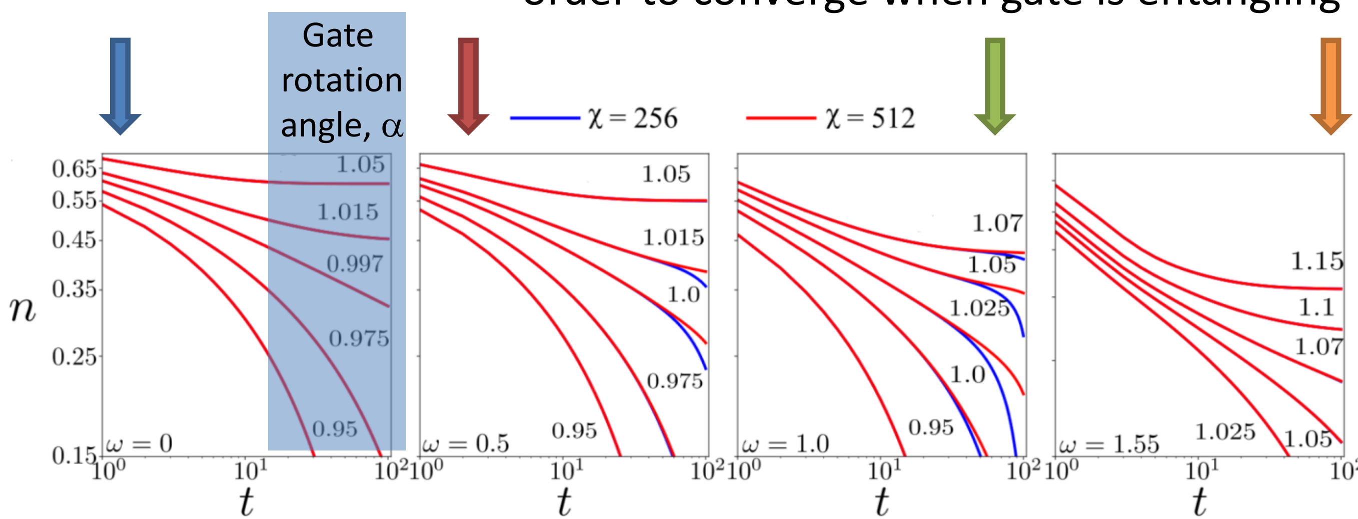

**Phase diagram**

- Introduction of entanglement changes phase boundary
- No change of universality class



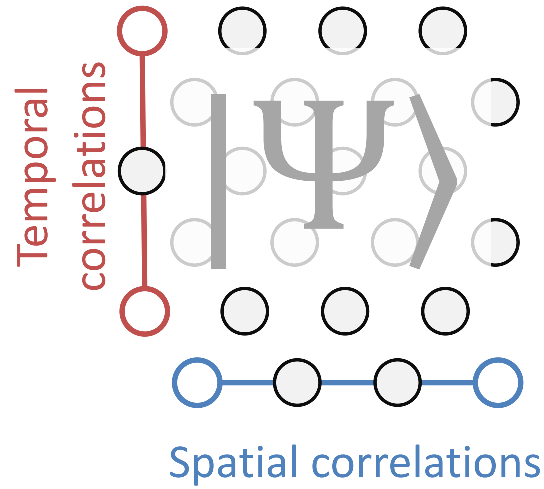

- PEPS needs higher bond dimension $X$ in order to converge when gate is entangling



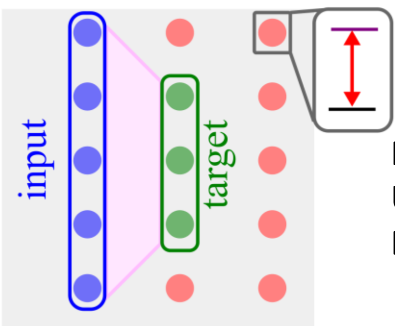



# Summary and outlook

- Open Quantum CA in 1+1d are a convenient setting for exploring non-equilibrium physics
- Allows access to full space-time correlations at once
- Allow introduction of „quantumness“ from „classical limit“
- Concept bears resemblance of a **feed-forward neural network**
  → open QCA may offer framework for understanding role/impact/usefulness of quantum correlations




Positions available




E. Torrontegui and J. J. García-Ripoll
Unitary quantum perceptron as efficient universal approximator
EPL **125**, 30004 (2019)

**Many-body quantum engines**
PRL **125**, 240602 (2020)
PRL **124**, 170602 (2020)
**Time crystals**
PRE **100**, 060105(R) (2019)
PRL **122**, 015701 (2019)
arXiv:2102.02719

**Kinetically constrained systems**
PRL **125**, 033602 (2020)
arXiv:2010.07825
**Sub- and superradiance**
PRL **124**, 093601 (2020)
PRA **102**, 043711 (2020)
**Machine learning**
arXiv:2101.08591

**Many-body interactions**
PRL **125**, 133602 (2020)
PRL **124**, 043402 (2020)
**„Synthetic molecules“ with Rydberg ions**
arXiv:2012.01834

**Quantum Neural network dynamics**
PRL **125**, 070604 (2020)
arXiv:2009.13932