Controllable long-range entanglement in a lossy qubit array

Shovan Dutta
University of Cambridge
(now at MPI-PKS)

SD & Nigel Cooper, PRL 125, 240404 (2020)
PRR 3, L012016 (2021)

SD, Stefan Kuhr, & Nigel Cooper, coming soon

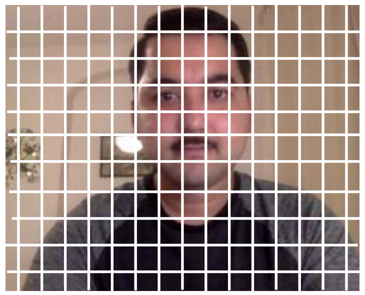
EPSRC Engineering and Physical Sciences Research Council

DesOEQ

SIMONS FOUNDATION

Qubits and Entanglement

Classical bit — unit of information: 0 or 1



Data stream $\ldots 0010110101 \ldots$

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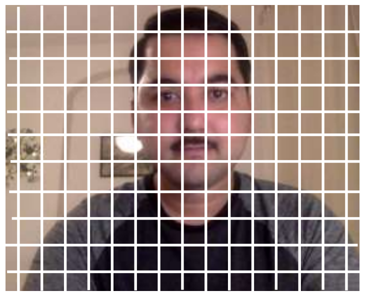

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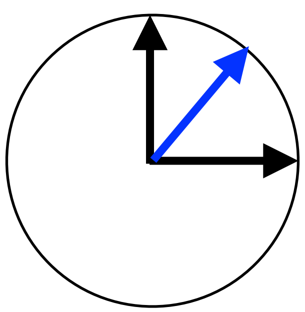

Measurement gives:

$|0\rangle$: probability $|\alpha|^2$

$|1\rangle$: probability $|\beta|^2$

Spin: $\alpha\,|\downarrow\rangle + \beta\,|\uparrow\rangle$

Lattice site: $\alpha\,|\;\rangle + \beta\,|\;\rangle$

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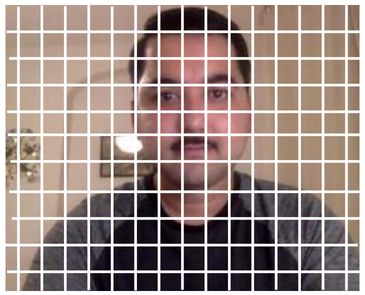

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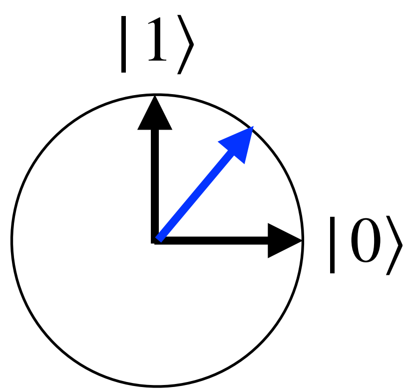

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$|\alpha| = |\beta|$: "Bell pair"

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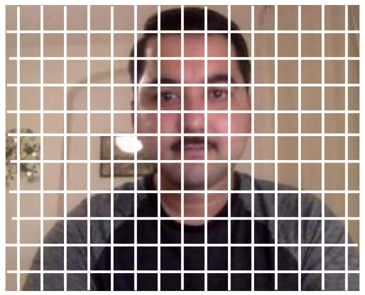

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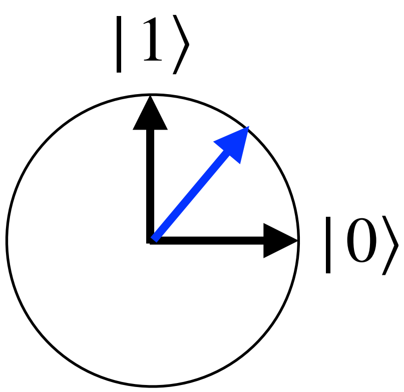

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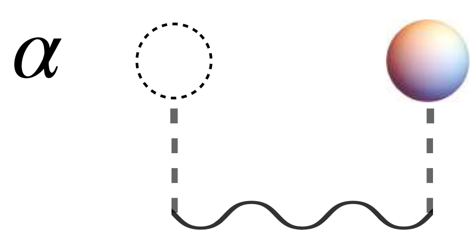

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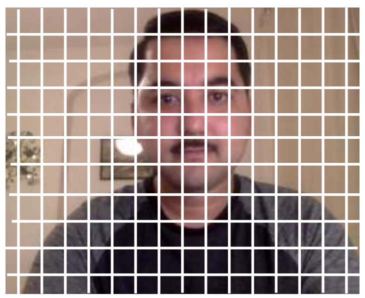

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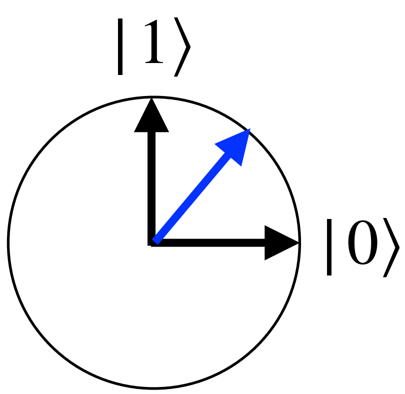

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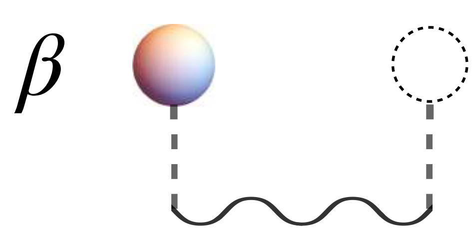

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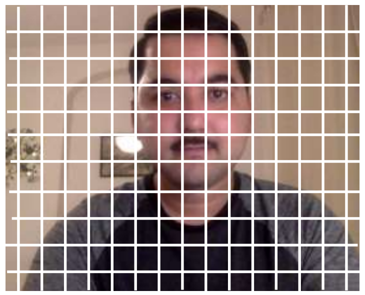

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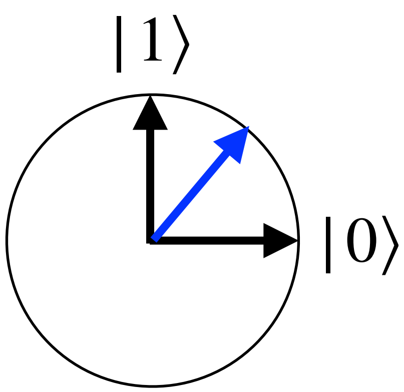

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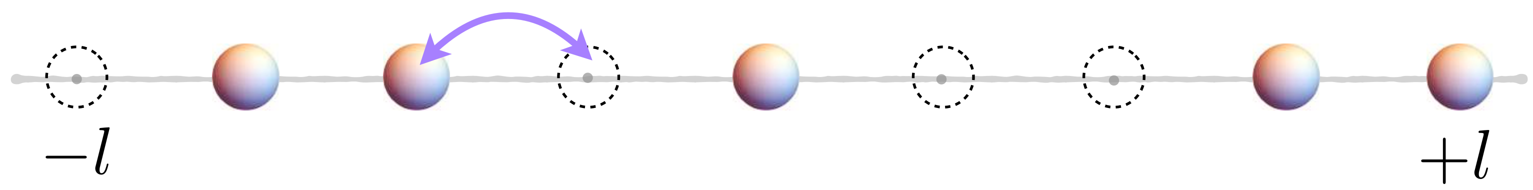
Entangled pair of qubits $\alpha|01\rangle + \beta|10\rangle$ $\quad$ $|\alpha| = |\beta|$: "Bell pair"

At the heart of quantum communication/computing — but hard to stabilise

Main result

Array of coupled qubits:



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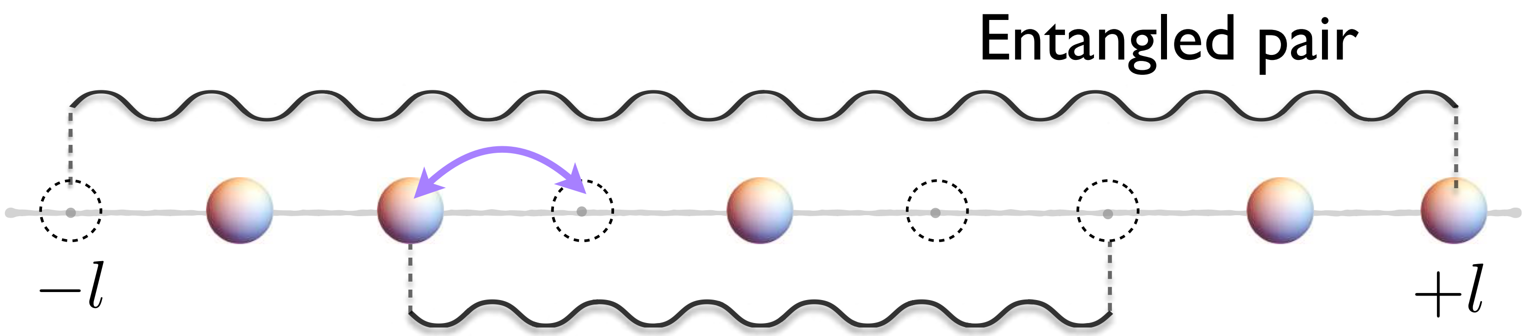
Multiple Bell pairs:



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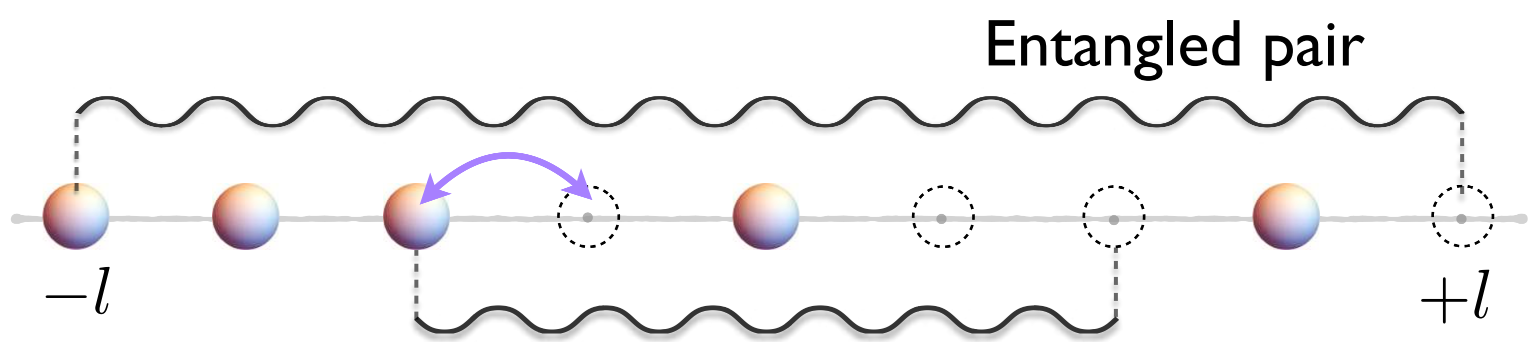

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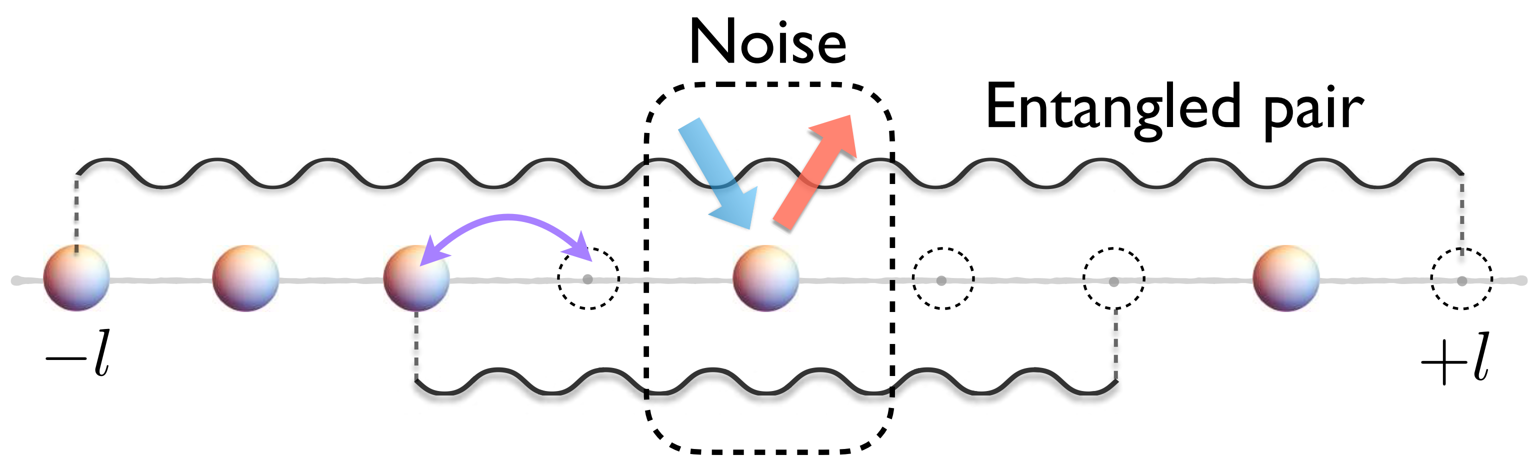
Multiple Bell pairs protected from noise by a symmetry:



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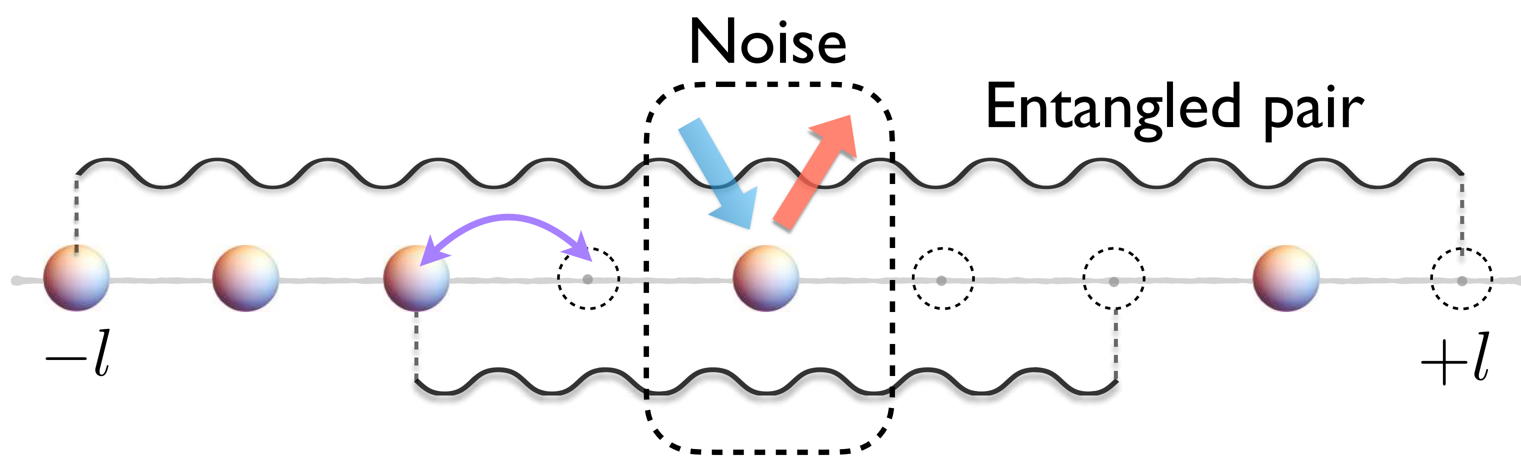

Hidden symmetry could be key to more robust quantum systems,...

https://www.cam.ac.uk/research/news/hidden-symmetry-could-be-key-to-more-robust-quantum-systems-researchers-find

9 Dec 2020: The researchers, from the University of Cambridge, have shown that microscopic particles can remain intrinsically linked, or entangled, over long distances even if there are random disruptions between them.

By: @cambridge_uni

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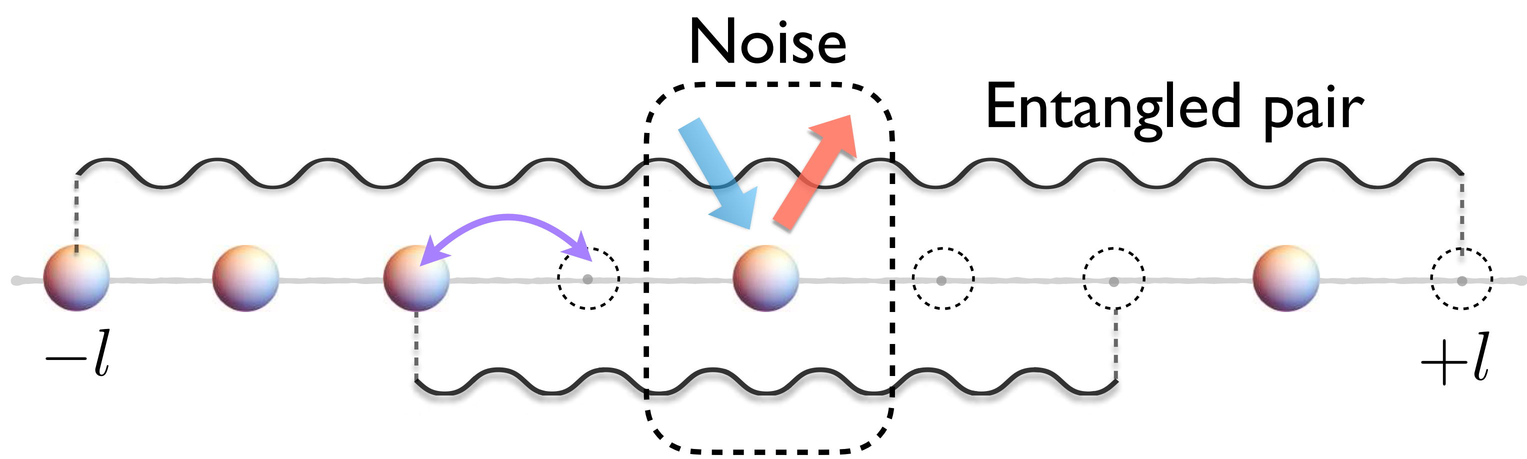

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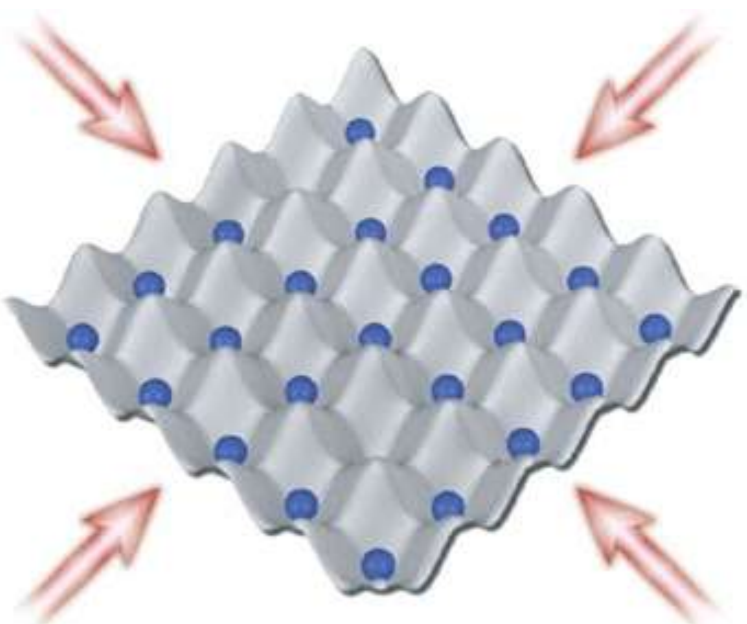
$\Rightarrow$

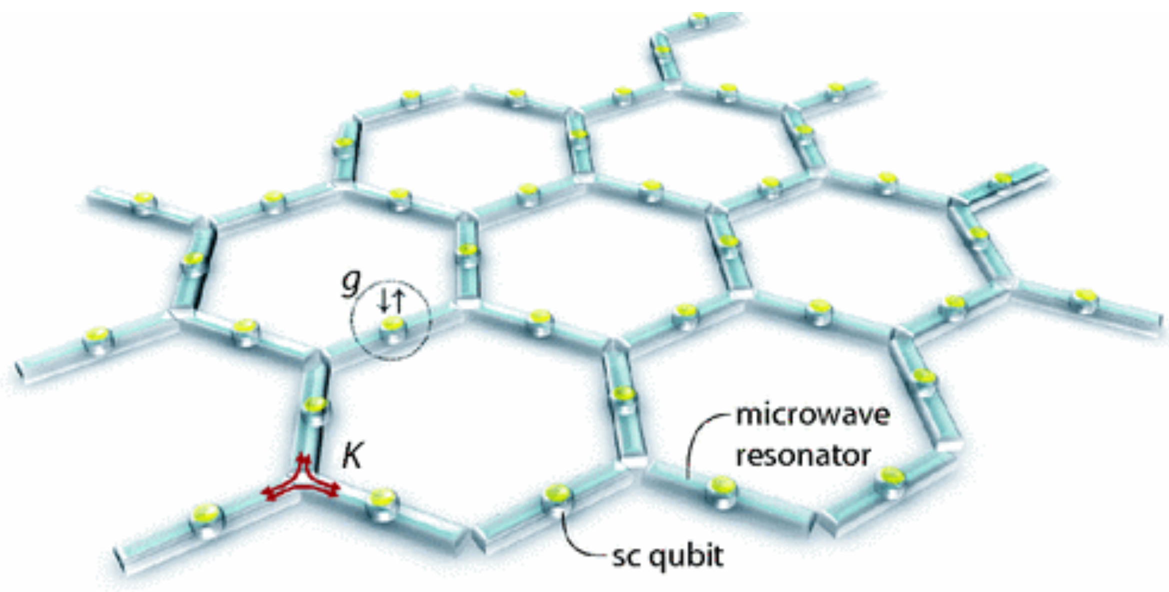
- Entanglement can be stable for certain types of noise
- Symmetry can be a resource

Big picture — engineering quantum systems

Designer experimental platforms



cold atoms [Bloch, Nature '08]



superconducting circuits [Koch *et al*, PRA '10]

- Simulating idealised models
- Novel many-body quantum phenomena
- Quantum technologies

Lewenstein *et al*, Adv Phys '07
Müller *et al*, Adv At Mol Opt Phys '12
Georgescu *et al*, RMP '14

Long-range entanglement — resource for quantum information processing

Horodecki *et al*, RMP '09

Big picture — engineering <u>open</u> quantum systems

Environmental noise typically destroys quantum correlations

$$\downarrow \quad \uparrow \quad \downarrow \quad \downarrow \quad \uparrow \quad \uparrow \quad \downarrow \quad \uparrow$$

random spin flips $\Longrightarrow$ infinite-temperature state

Big picture — engineering open quantum systems

Environmental noise typically destroys quantum correlations …But

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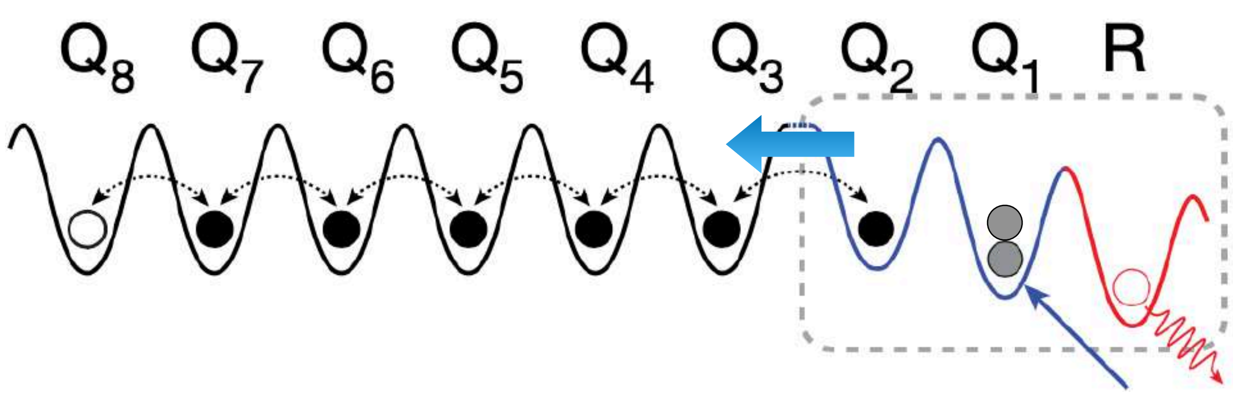
1) It is possible to engineer environment as resource — Sieberer *et al*, Rep. Prog. Phys. '16

Mott insulator of photons [Ma *et al*, Nature '19]



Photon source

Big picture — engineering open quantum systems

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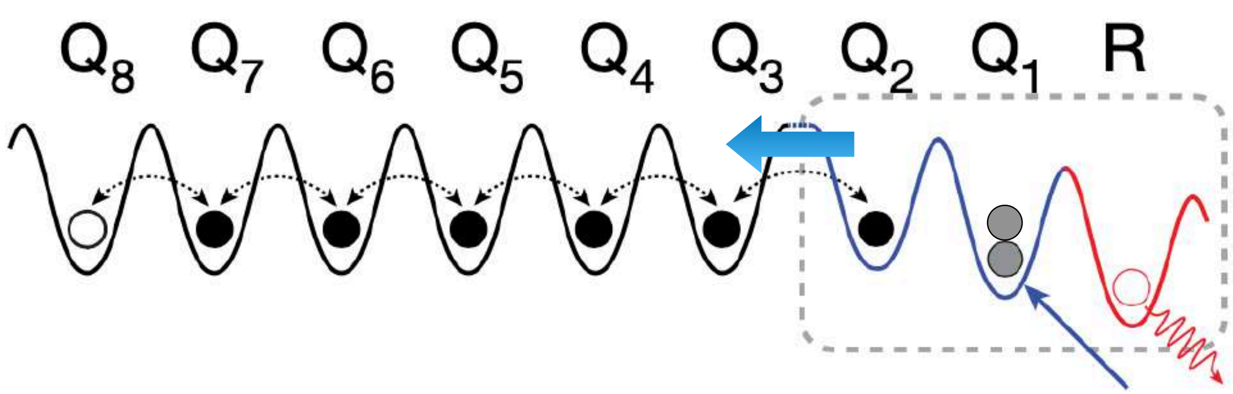
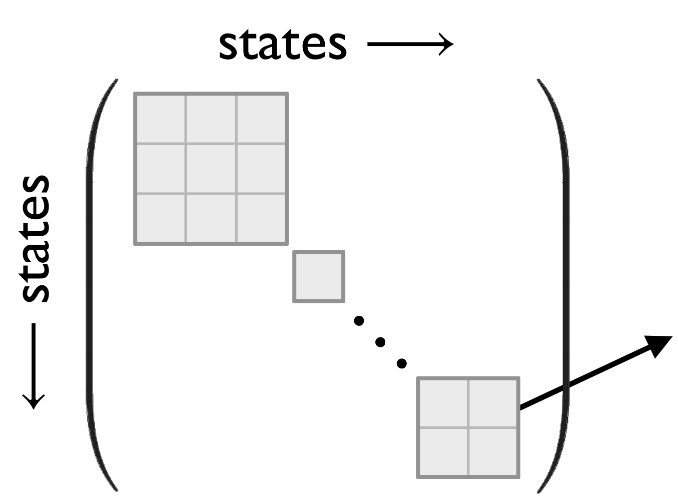


Photon source

2) Symmetry can lead to decoupled sectors

Buca, Prosen, NJP '12
Albert, Jiang, PRA '14

Symmetry
$\updownarrow$
Conservation law

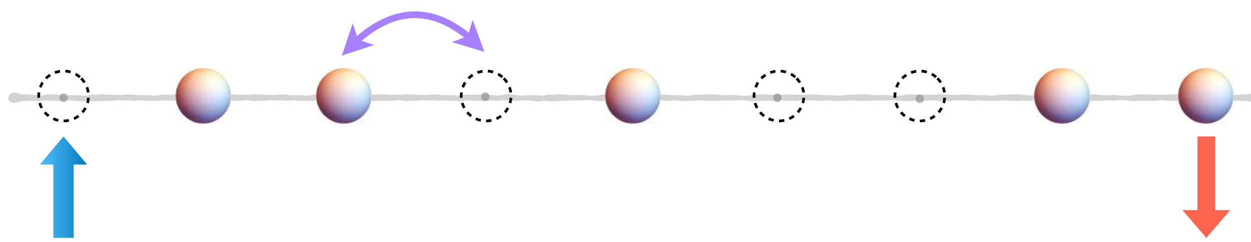


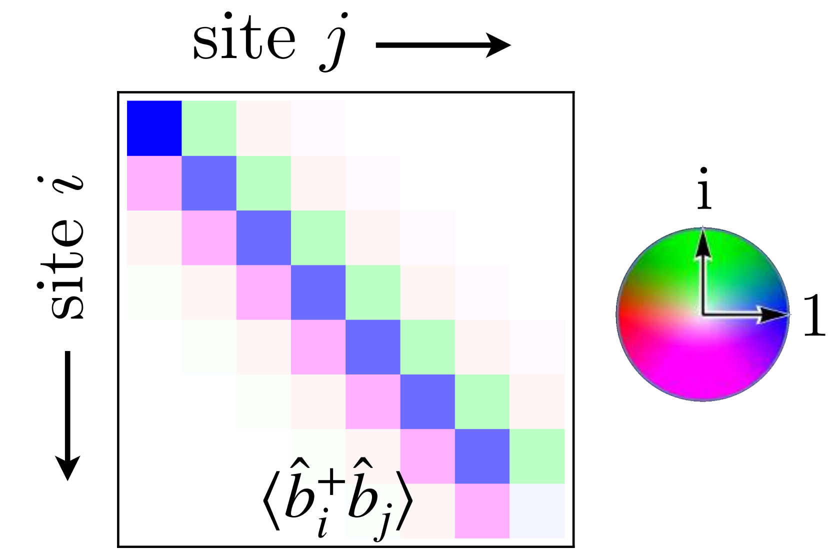
What if all states are highly entangled?

Context — steady state with pump & loss

Boundary-driven chain

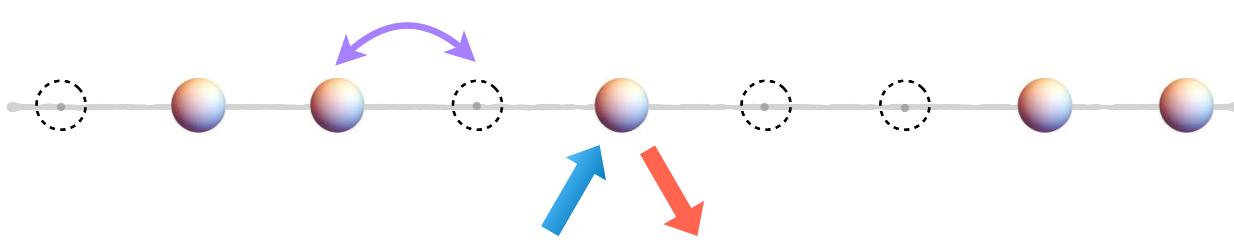
[Prosen, NJP ’08; PRL ’08; J Stat Mech ’17]

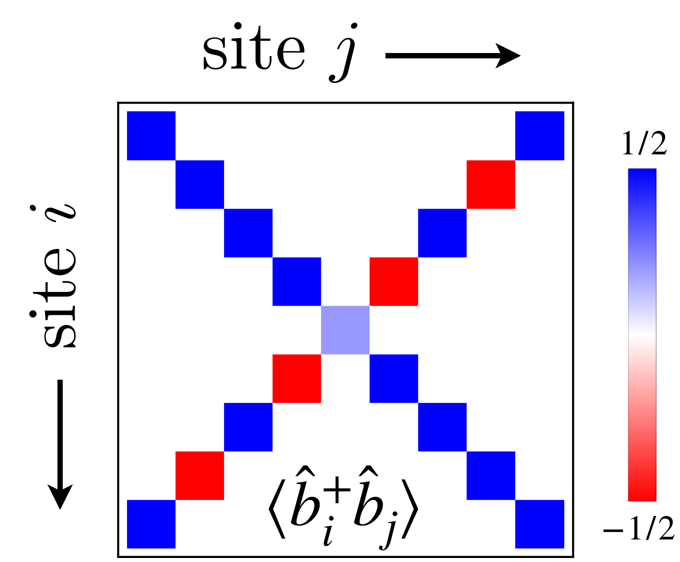




- Dynamics reduce to non-interacting fermions
- Unique steady state w/ short-range correlations

Here: Pump & loss not on the boundaries





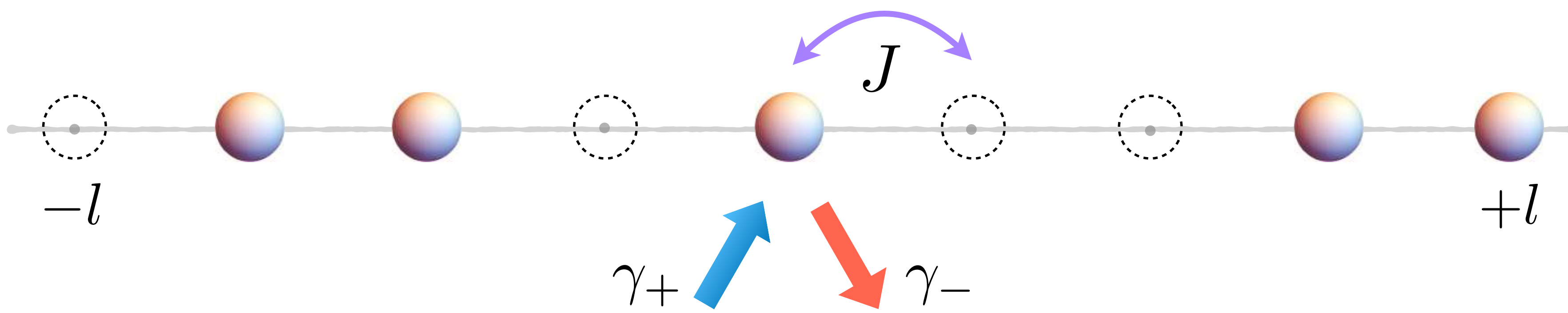
- Does not reduce to non-interacting system
- Multiple steady states (hidden symmetry)
- Stable long-range entanglement

Rare!

Model

Model — centre-driven qubit array

"Hard-core bosons" with localised pump and loss



$$\hat{b}_i^{\dagger 2} = 0$$

$$\hat{H} = -J \sum_{i=-l}^{l-1} \left(\hat{b}_i^\dagger \hat{b}_{i+1} + \hat{b}_{i+1}^\dagger \hat{b}_i \right)$$

Master equation for a Markovian environment:

$$\frac{d\hat{\rho}}{dt} = -i\,[\hat{H}, \hat{\rho}] + \sum\nolimits_\alpha \hat{L}_\alpha \hat{\rho} \hat{L}_\alpha^\dagger - \{\hat{L}_\alpha^\dagger \hat{L}_\alpha, \hat{\rho}\}/2$$

$$\hat{L}_+ = \sqrt{\gamma_+}\,\hat{b}_0^\dagger\,, \quad \hat{L}_- = \sqrt{\gamma_-}\,\hat{b}_0$$ (Lindblad)

Not essential

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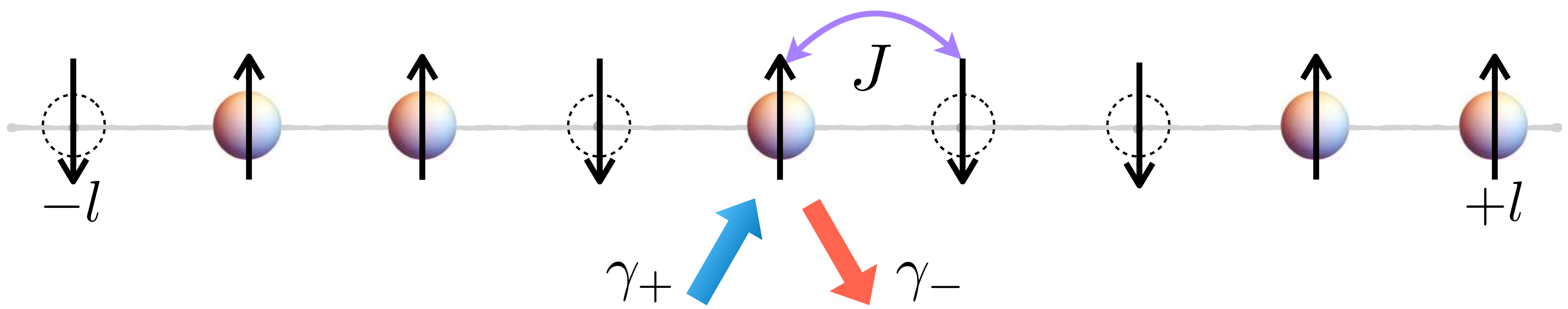

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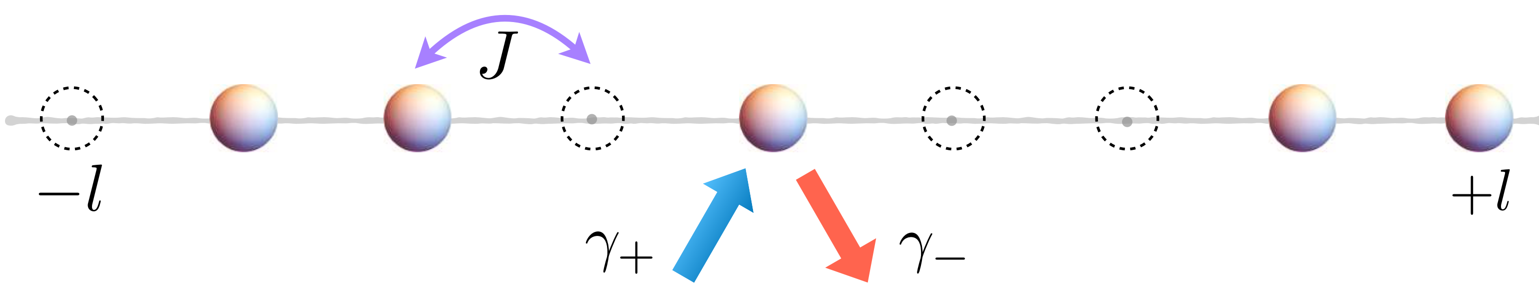
Not essential

Equivalent to XY spin-1/2 chain with spin-flip “errors”

- Two-component bosons in a deep lattice [Duan, Demler, Lukin PRL ’03]
- Spin-orbit coupled fermions [Mamaev, Kimchi, Nandkishore, Rey ’20]
- Rydberg arrays [Browaeys, Lahaye Nat. Phys. ’20]

Distinction from non-interacting fermions



$\hat{H} = -J \sum_i \hat{b}_i^\dagger \hat{b}_{i+1} + \mathrm{H.c.}$ $\hat{L}_+ = \sqrt{\gamma_+}\, \hat{b}_0^\dagger \,, \quad \hat{L}_- = \sqrt{\gamma_-}\, \hat{b}_0$

Jordan-Wigner transformation:

$\hat{f}_j = (-1)^{\sum_{i<j} \hat{n}_i} \hat{b}_j$ $[\hat{n}_i := \hat{b}_i^\dagger \hat{b}_i = \hat{f}_i^\dagger \hat{f}_i]$

$\Rightarrow$ Hamiltonian maps to free fermions $\hat{H} = -J \sum_i \hat{f}_i^\dagger \hat{f}_{i+1} + \mathrm{H.c.}$

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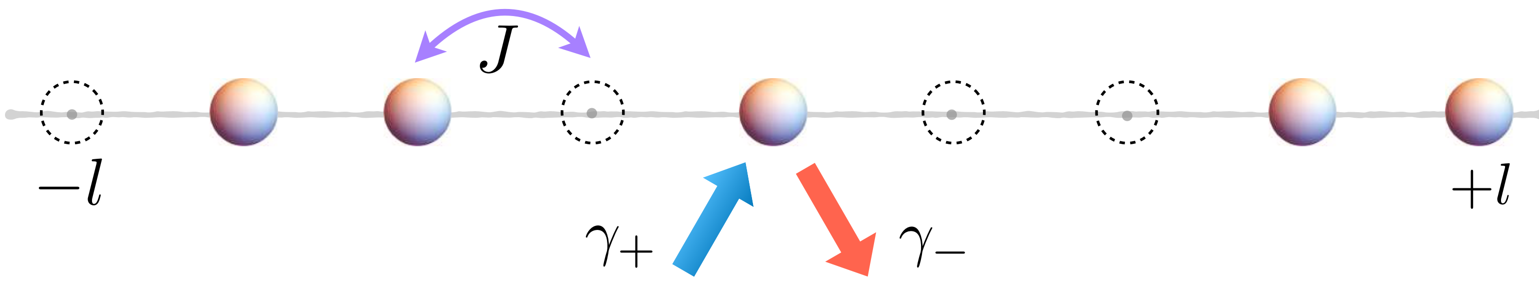

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But pump/loss mediates interactions

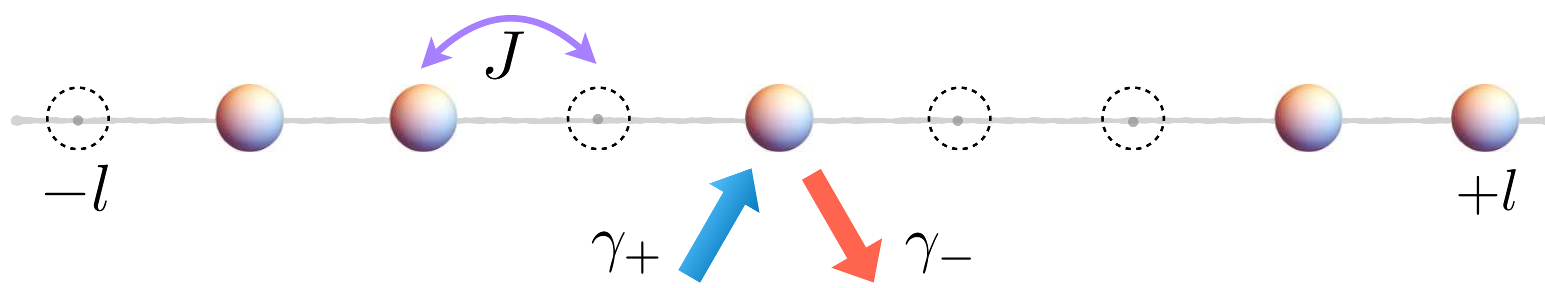
$$\hat{L}_+ := \sqrt{\gamma_+}\,\hat{b}_0^\dagger = \sqrt{\gamma_+}\,(-1)^{\sum_{i<0} \hat{n}_i} \hat{f}_0^\dagger \qquad (\neq \hat{f}_0^\dagger)$$

$$\hat{L}_- := \sqrt{\gamma_-}\,\hat{b}_0 = \sqrt{\gamma_-}\,(-1)^{\sum_{i<0} \hat{n}_i} \hat{f}_0 \qquad (\neq \hat{f}_0)$$

$\Rightarrow$ Dynamics strongly nonlinear

Symmetry

Hidden symmetry



$\hat{L}_+ = \sqrt{\gamma_+}\hat{b}_0^\dagger$
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Symmetry operator $\hat{C} := -1/2 + \sum_{i=-l}^{l} \hat{f}_i^\dagger \hat{f}_{-i}$

$\hat{C}^2$ is a "strong" symmetry:

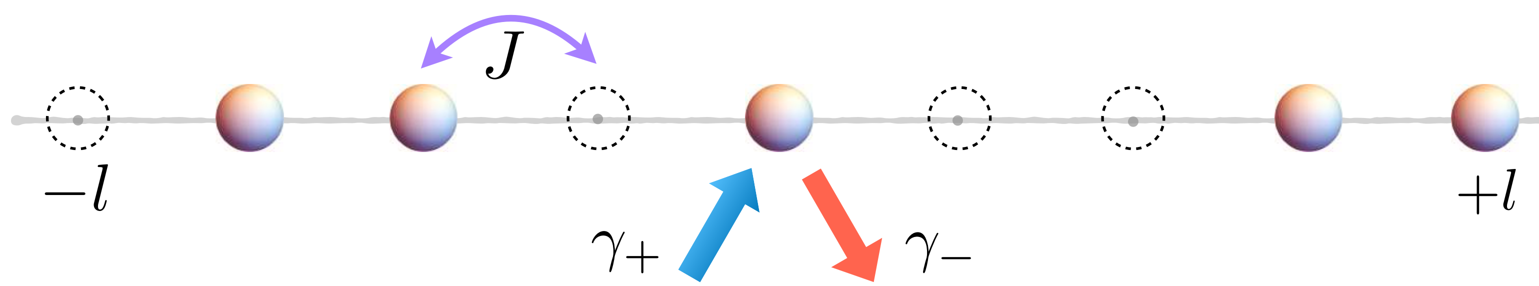
Strong/weak symmetries: Buca, Prosen, NJP '12

- $[\hat{H}, \hat{C}] = 0 \implies$ hopping J does not affect $\hat{C}$ (or $\hat{C}^2$)
- $\hat{C} = (-1)^{\hat{n}_0} \mathrm{func}(\{\hat{b}_j, \hat{b}_j^\dagger : j \neq 0\}) \implies [\hat{b}_0^{(\dagger)}, \hat{C}^2] = 0$

$\left[\hat{f}_j = (-1)^{\sum_{i<j} \hat{n}_i} \hat{b}_j \right.$

$\implies$ $\hat{C}^2$ is independent of the centre site

Hidden symmetry



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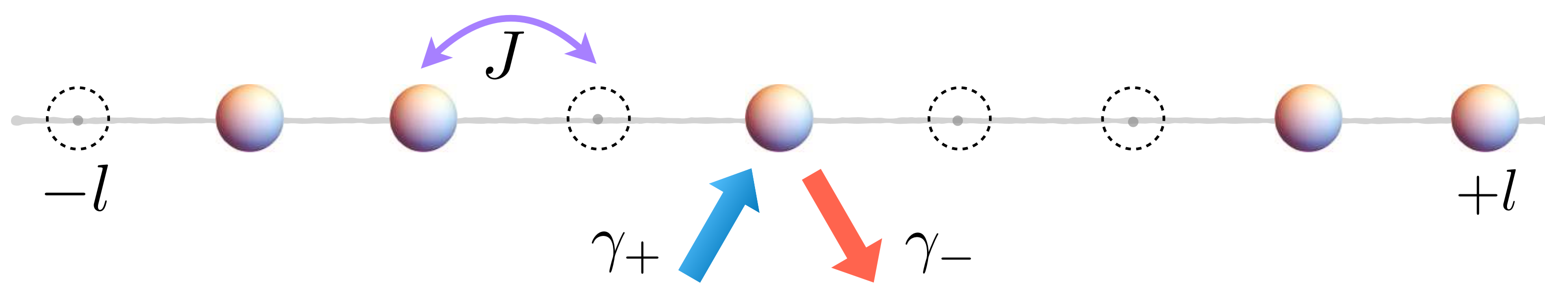
$\implies$ $\hat{C}^2$ is independent of the centre site

$\therefore$ Any coupling to centre site conserves $\hat{C}^2$

Dynamics split into different sectors of $\hat{C}^2 \Rightarrow$ multiple steady states

Hidden symmetry



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$\implies$ $\hat{C}^2$ is independent of the centre site

$\therefore$ Any coupling to centre site conserves $\hat{C}^2$ $\leftrightarrow$ number of Bell pairs

Dynamics split into different sectors of $\hat{C}^2 \Rightarrow$ multiple steady states

Interpretation of symmetry — Bell pairs

$$\hat{C} = -1/2 + \hat{n}_0 + \sum_{i=1}^{l} \hat{a}^\dagger_{i,+}\hat{a}_{i,+} - \hat{a}^\dagger_{i,-}\hat{a}_{i,-}$$

$$\hat{a}_{i,\pm} := \frac{1}{\sqrt{2}}(\hat{f}_i \pm \hat{f}_{-i})$$

$\hat{a}^\dagger_{i,\pm}|0\ldots0\rangle \sim |0_i 1_{-i}\rangle \pm |1_i 0_{-i}\rangle$ — Bell pair at sites i and $-i$

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$\hat{a}^\dagger_{i,\pm}|0\ldots 0\rangle \sim |0_i 1_{-i}\rangle \pm |1_i 0_{-i}\rangle$ — Bell pair at sites i and $-i$ with “charge” ± 1

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$\hat{a}^\dagger_{i,\pm}|0\ldots0\rangle \sim |0_i 1_{-i}\rangle \pm |1_i 0_{-i}\rangle$ — Bell pair at sites i and $-i$ with "charge" ± 1

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$\hat{C}^2$ has eigenvalues $\Lambda = (\nu + n_0 - 1/2)^2$

$\implies$ $l+1$ distinct sectors $\Lambda \in \{(\eta + 1/2)^2 : \eta = 0, \ldots, l\}$

$\eta = 0$: minimally entangled $\qquad$ $\eta = l$: maximally entangled

Steady states

Steady states

Unique steady state in each sector

$$\hat{\rho}_\eta = \text{const.}\ (\gamma_+/\gamma_-)^{\hat{N}}\hat{P}_\eta$$

$\left[\begin{array}{l}\hat{N}: \text{ total particle number} \\ \hat{P}_\eta: \text{ projector onto sector } \eta\end{array}\right.$

— Fully mixed + chemical potential $\mu = \ln(\gamma_+/\gamma_-)$ within a given sector!

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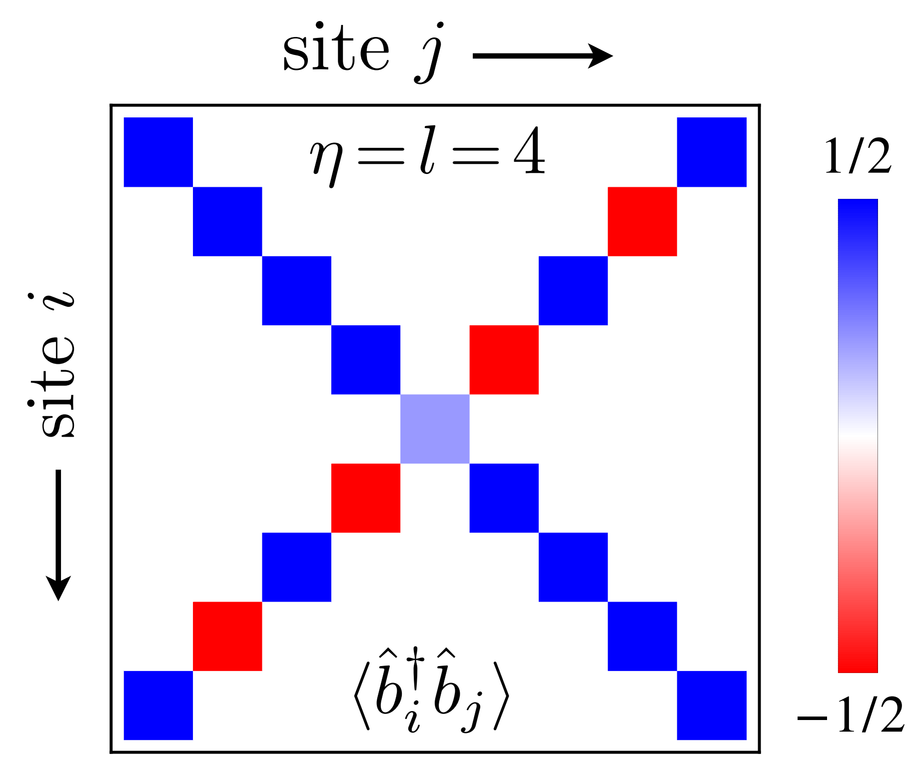
example: $\eta = l$



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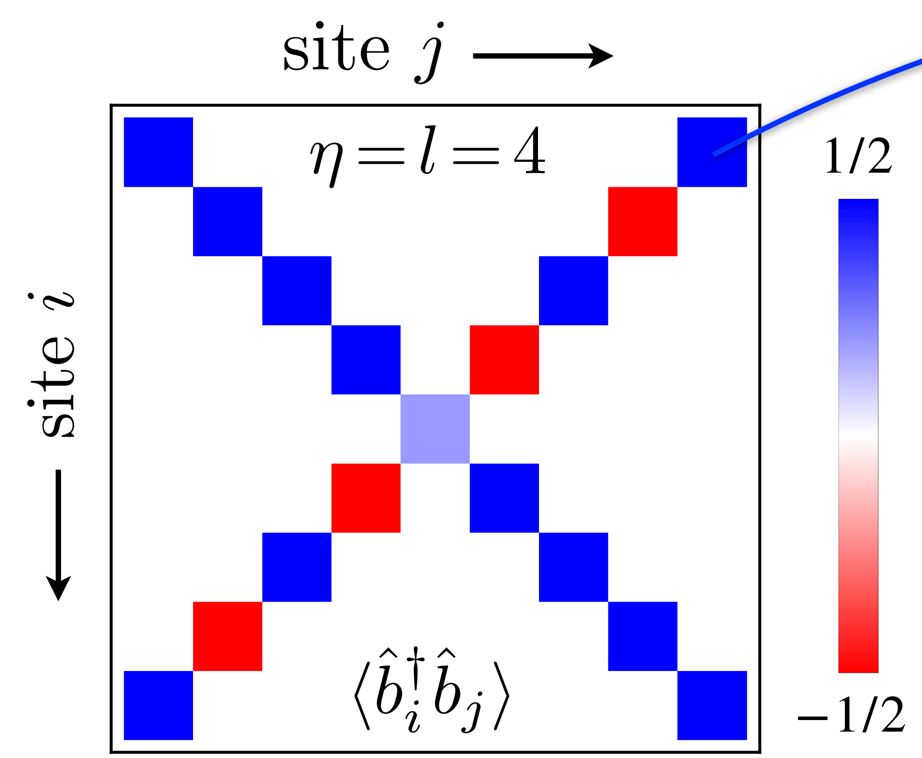

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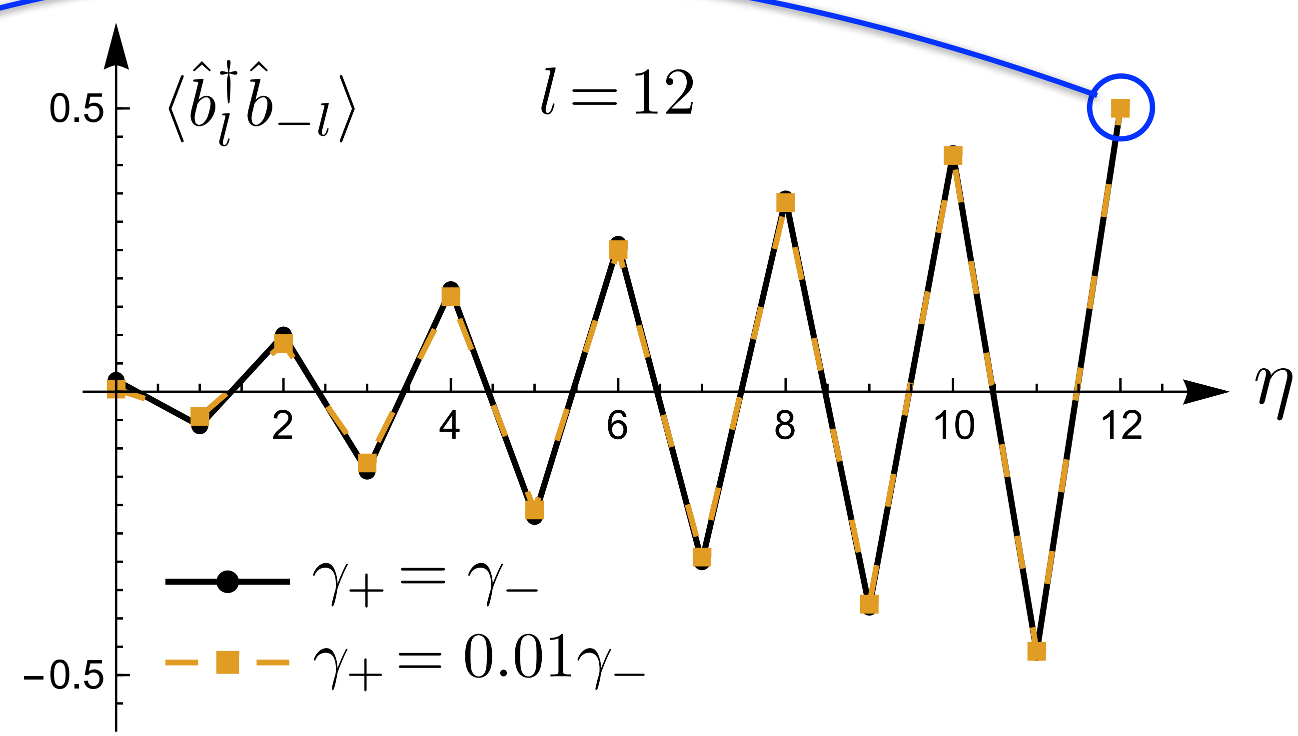
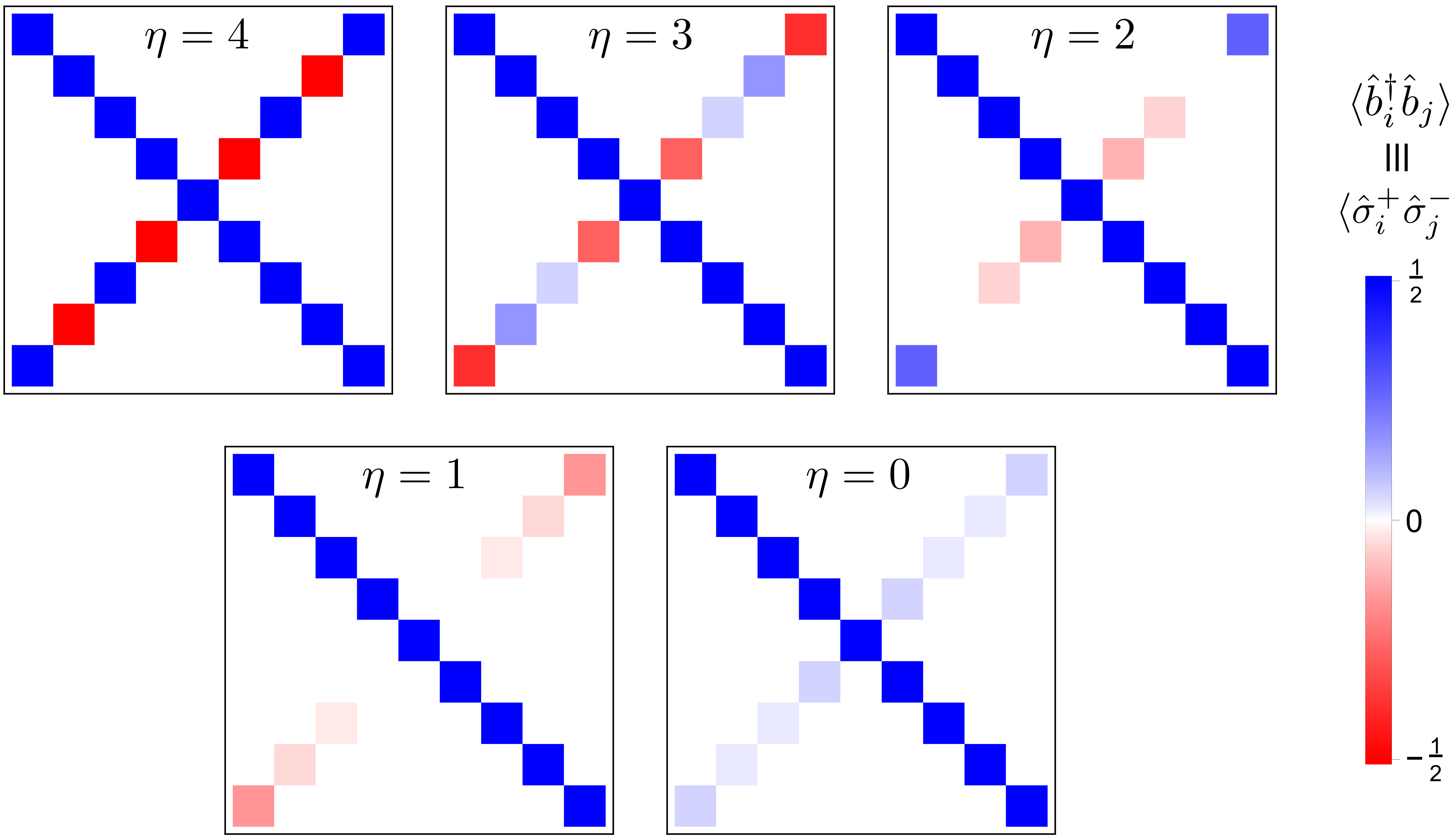


End-to-end correlation in different sectors

Steady states

$$l = 4,\ \gamma_+ = \gamma_-$$



Similar signatures in density-density correlations $\equiv \langle \hat{\sigma}_i^z \hat{\sigma}_j^z \rangle$

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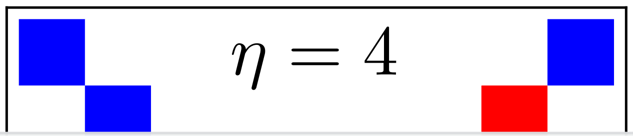
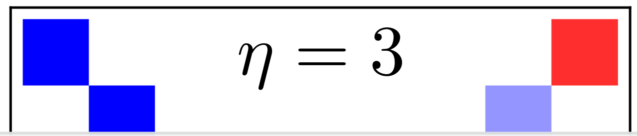
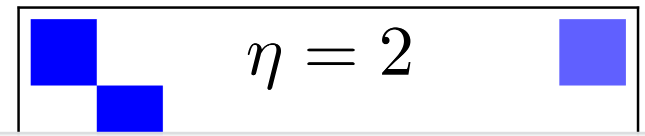
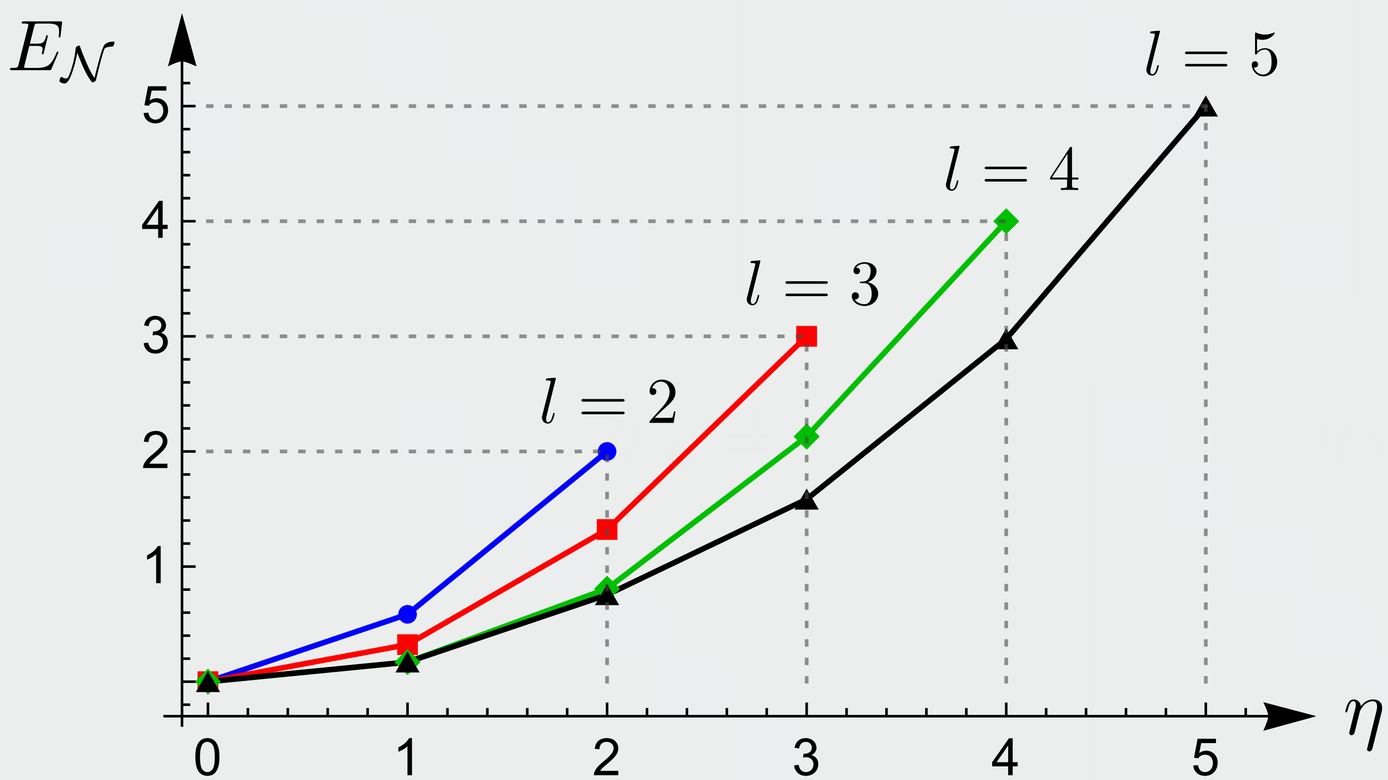






Entanglement



Log negativity $E_{\mathcal{N}}$: entanglement between left and right halves (max number of distillable Bell pairs)


Similar signatures in density-density correlations $\equiv \langle \hat{\sigma}_i^z \hat{\sigma}_j^z \rangle$

Selective Preparation

How to prepare

If initial state has sector weights w_η, final state $\hat{\rho}_\infty = \sum_\eta w_\eta \hat{\rho}_\eta$

— how to prepare a given sector?

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Exact solution using engineered loss: PRL 125, 240404 (2020)

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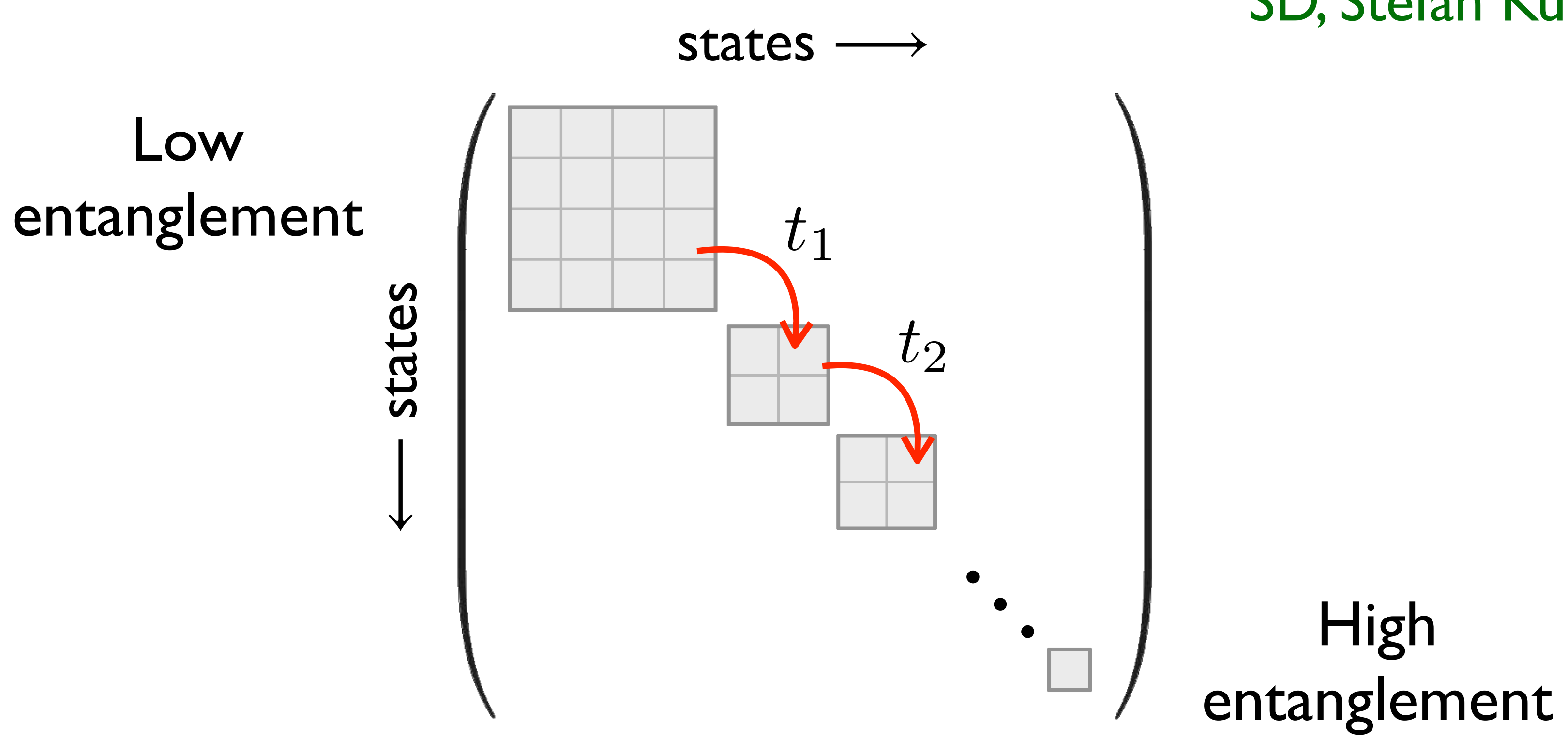
Here, approximate solution — pump C using timed pulses

SD, Stefan Kuhr, & Nigel Cooper, in prep



Generalises to other symmetries: e.g., η pairing Hubbard model

How to prepare — schematic

$$\hat{C} = \hat{\sigma}_0^z/2 \; + \sum_{i \neq 0} \hat{f}_i^\dagger \hat{f}_{-i} \qquad \bullet \equiv \uparrow \qquad \circ \equiv \downarrow$$

$\downarrow \; \downarrow \; \downarrow \; \downarrow \; \downarrow \; \downarrow \; \downarrow \; \downarrow \; \downarrow \; \downarrow \; \downarrow$ $\qquad C = -1/2$

Time

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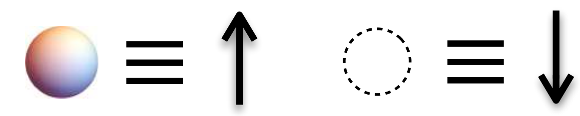

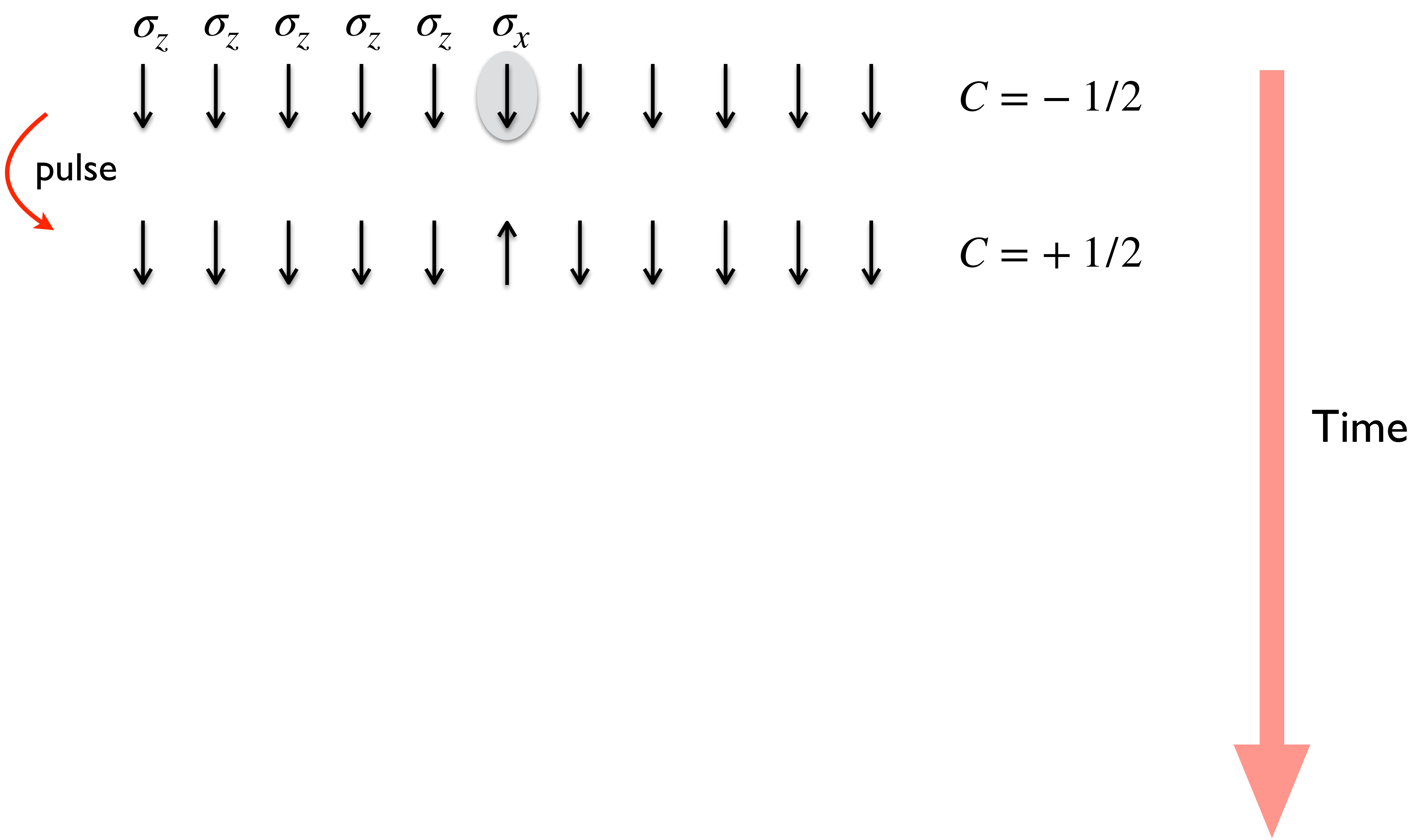

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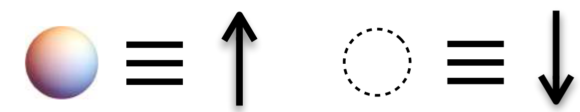

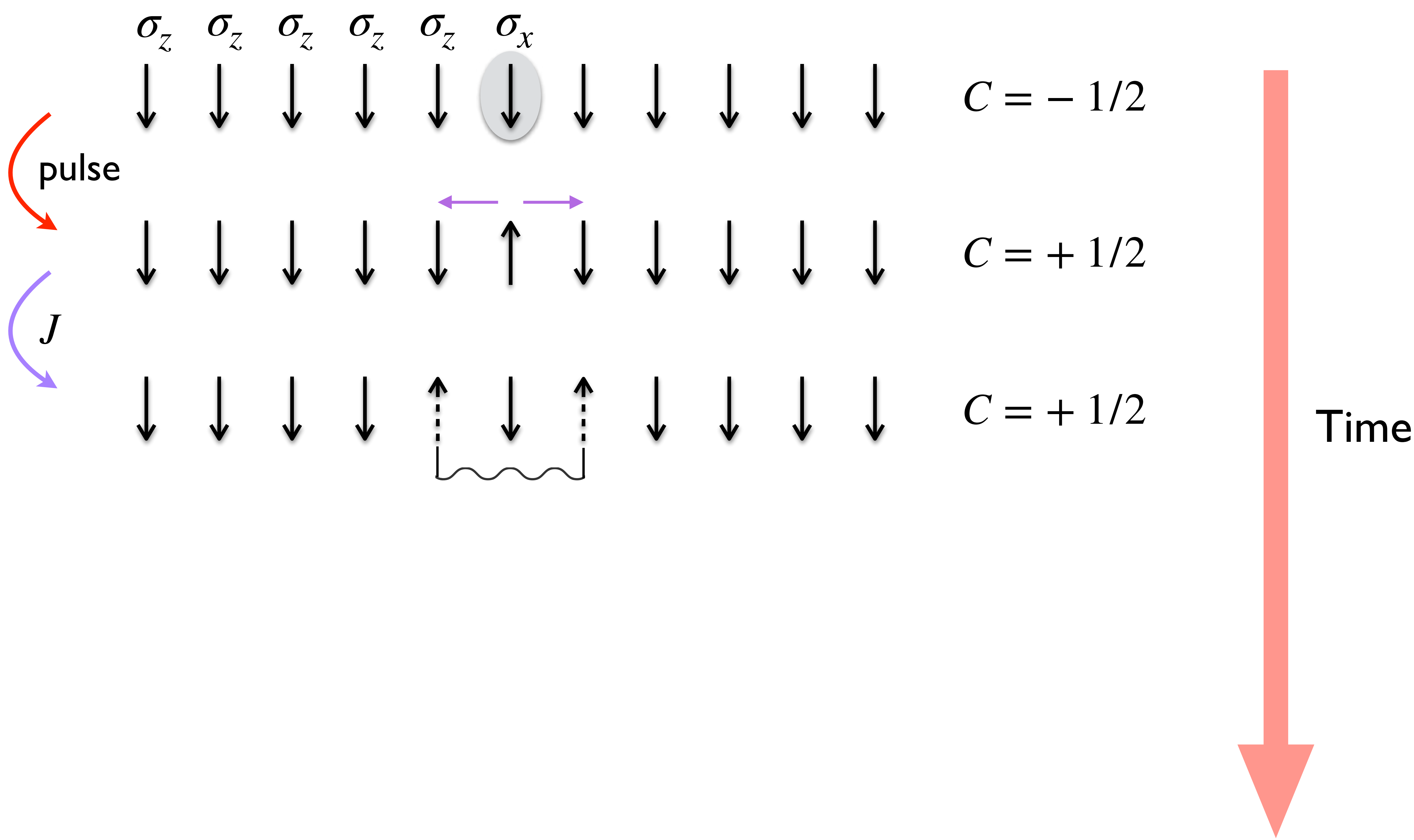

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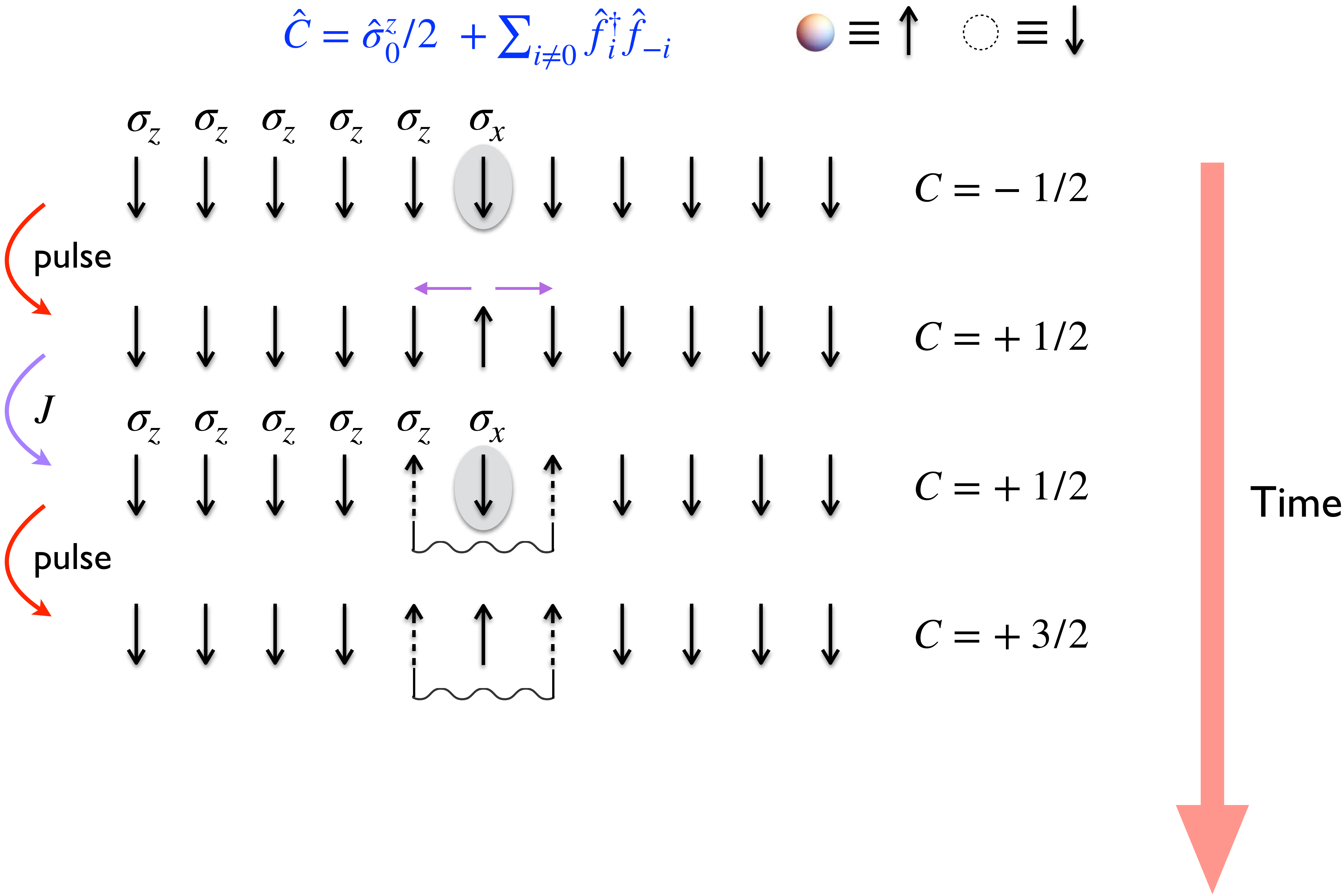

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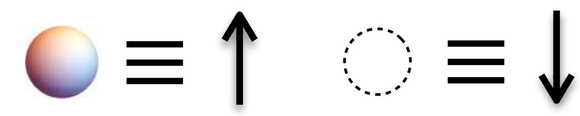
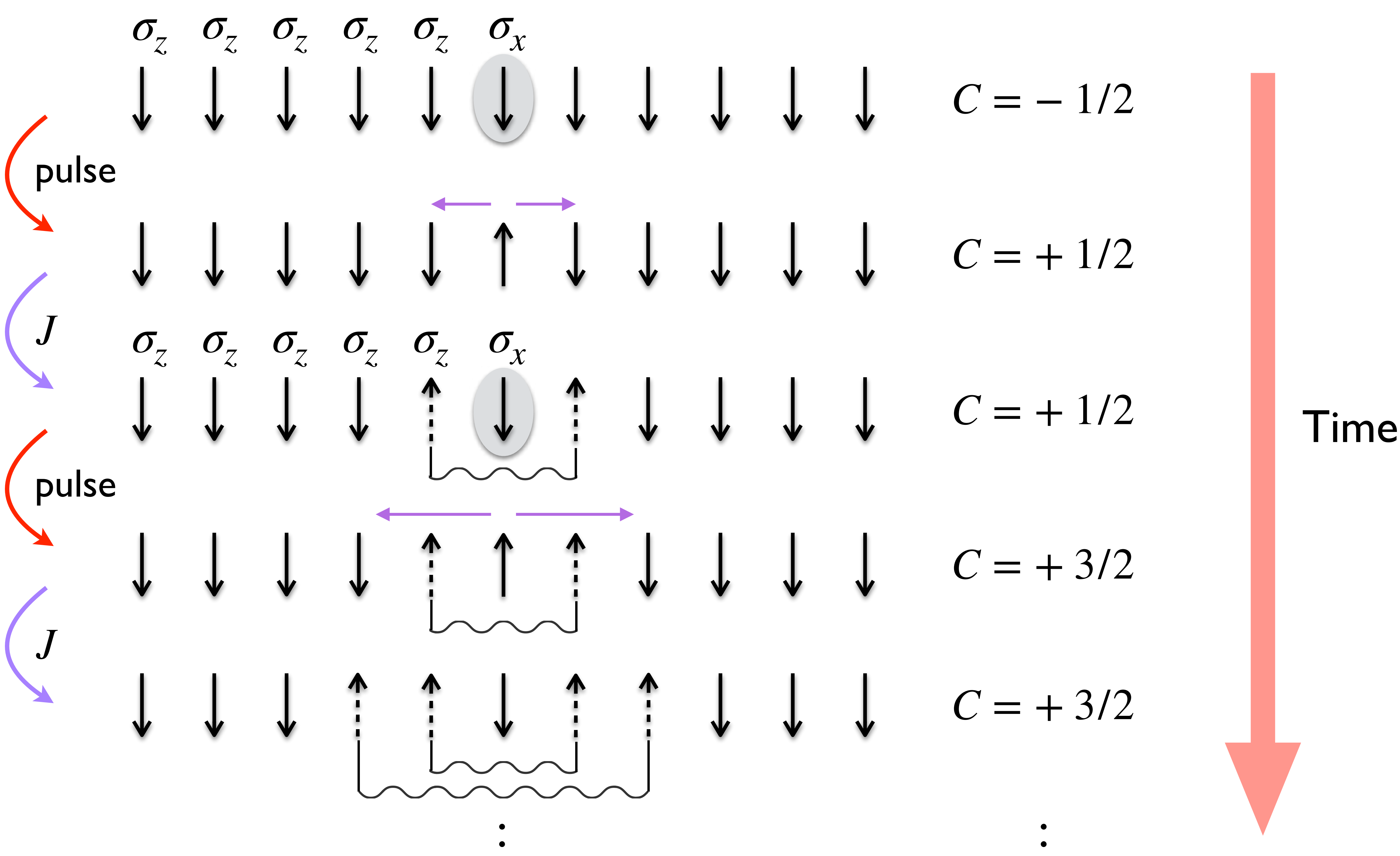
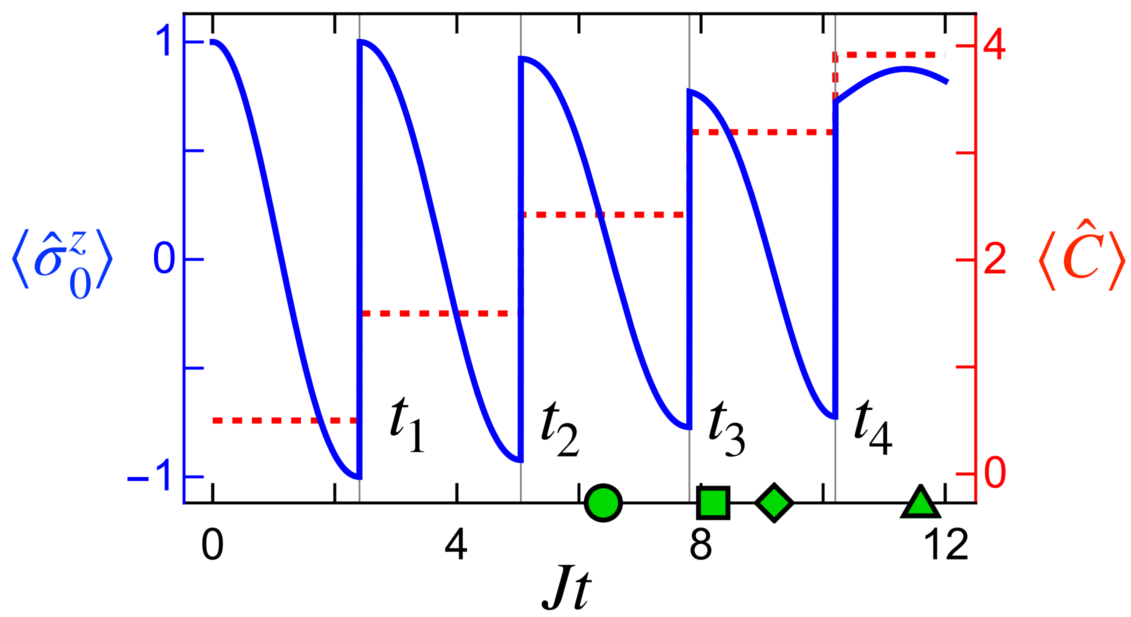
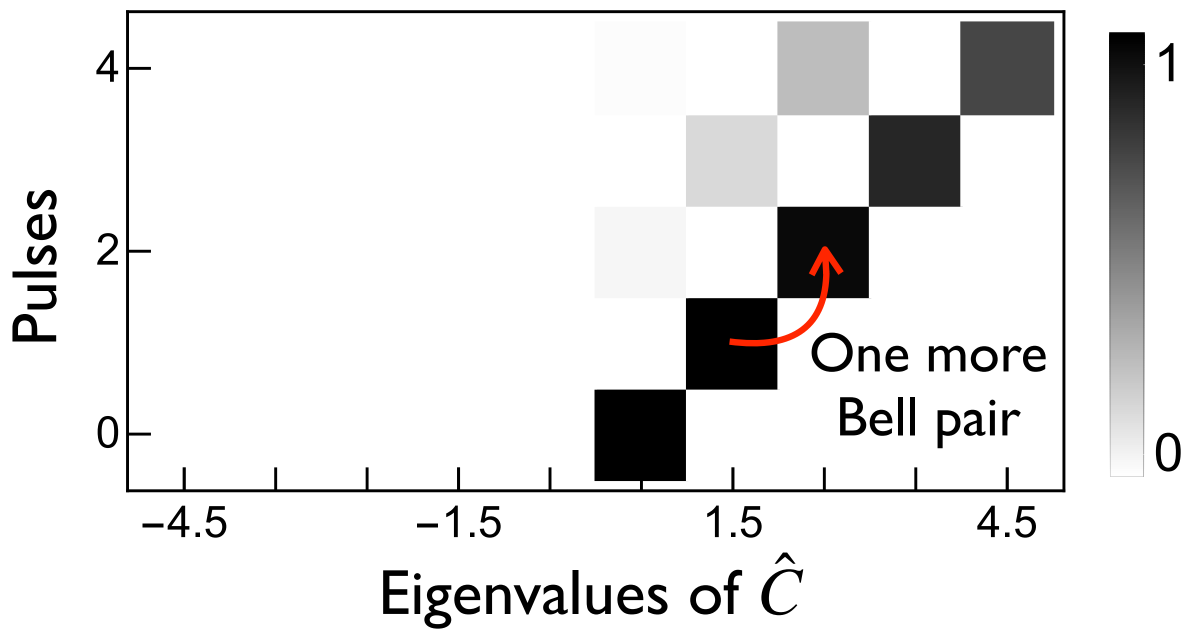




How to prepare — exact numerics

Pulse whenever centre site is mostly ↓, up to l times





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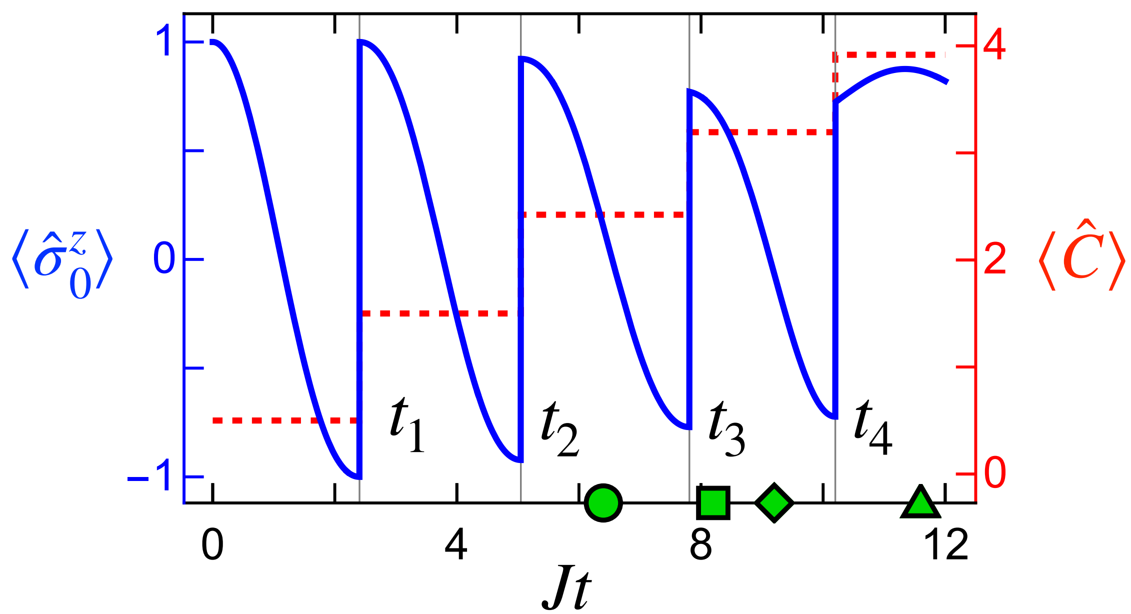
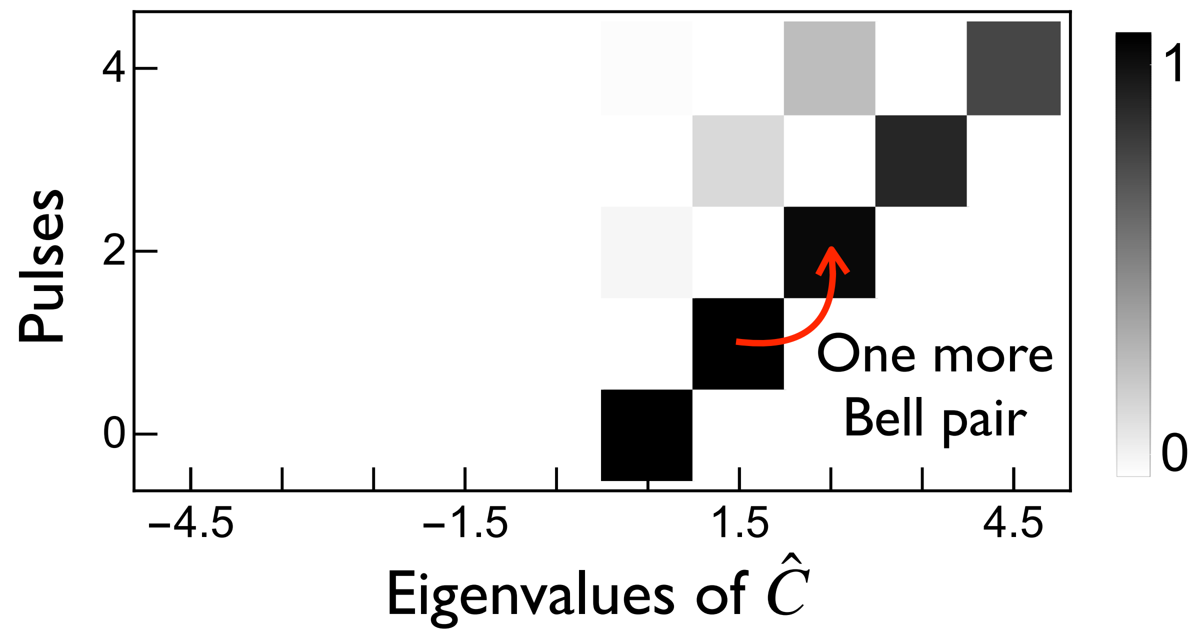
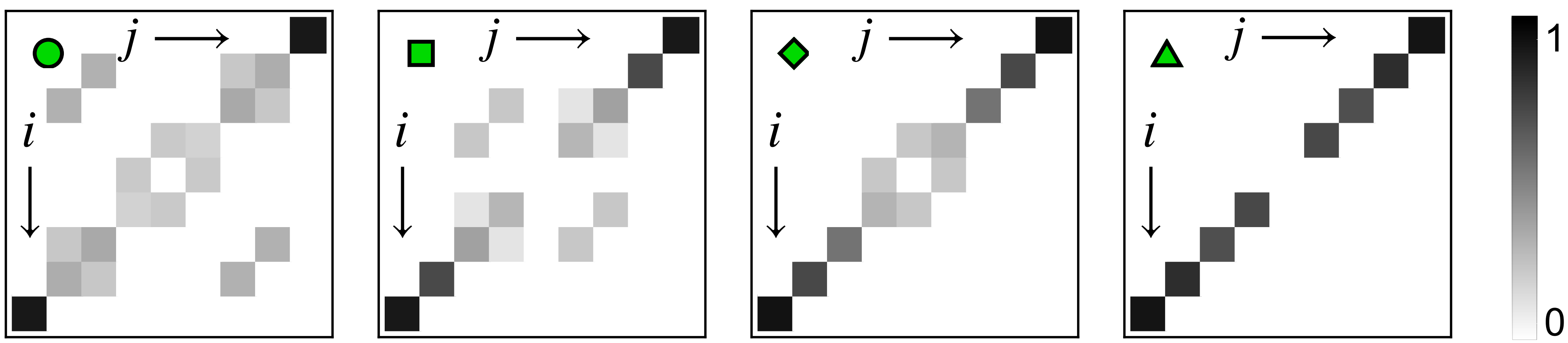




Concurrences $\mathscr{C}_{i,j}$ show Bell pairs are successively stacked inward

(same reflected in two-site correlations)



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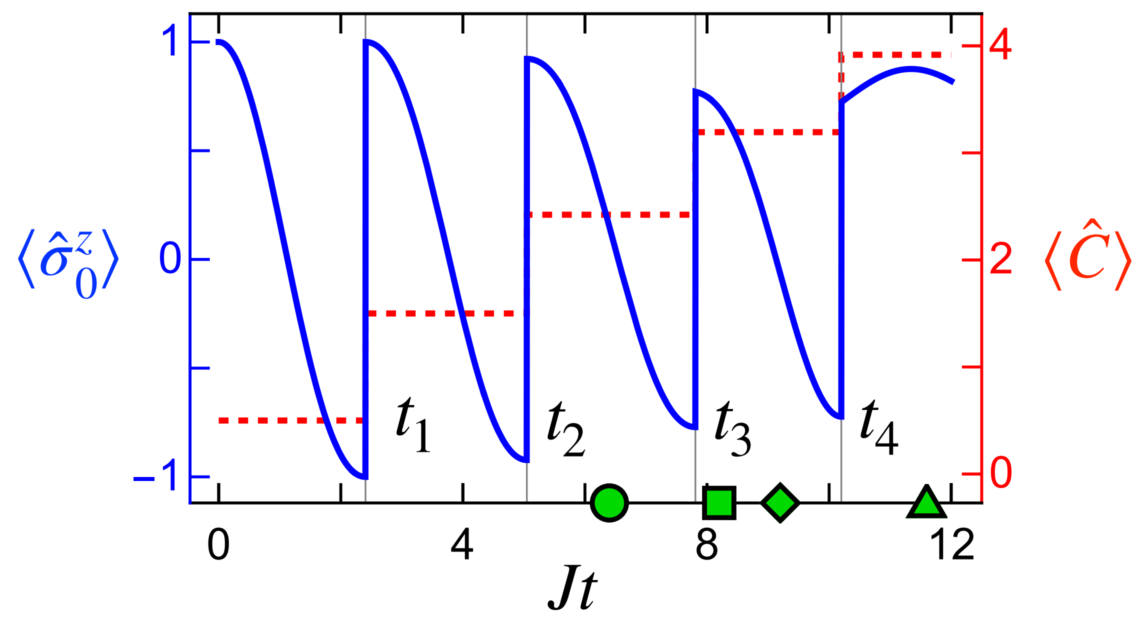

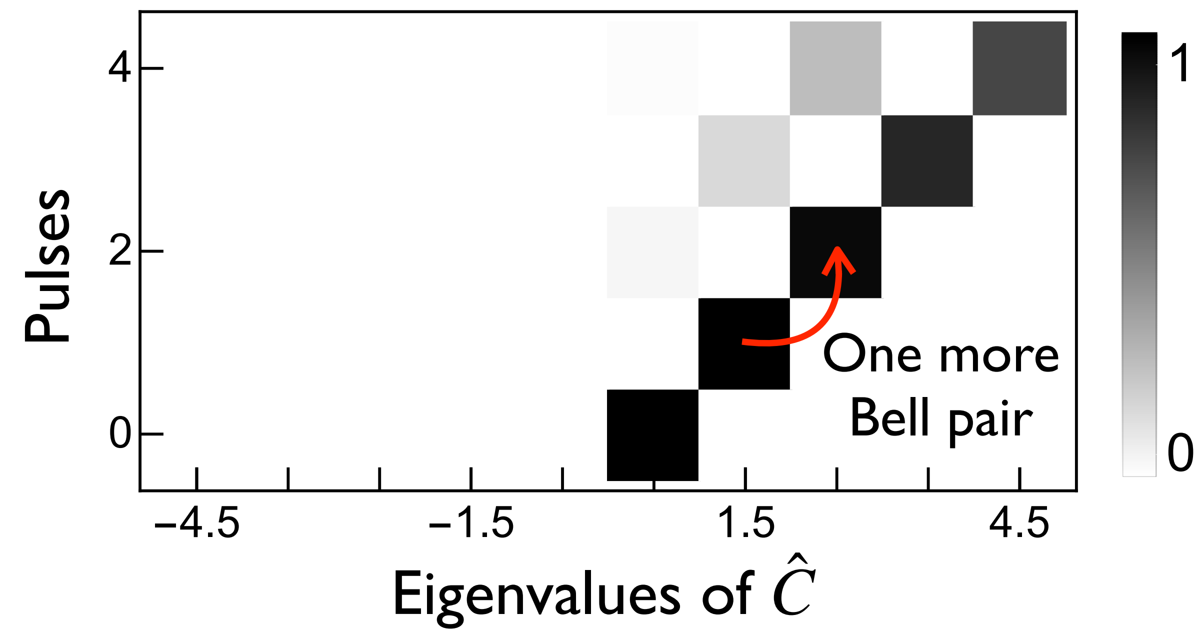

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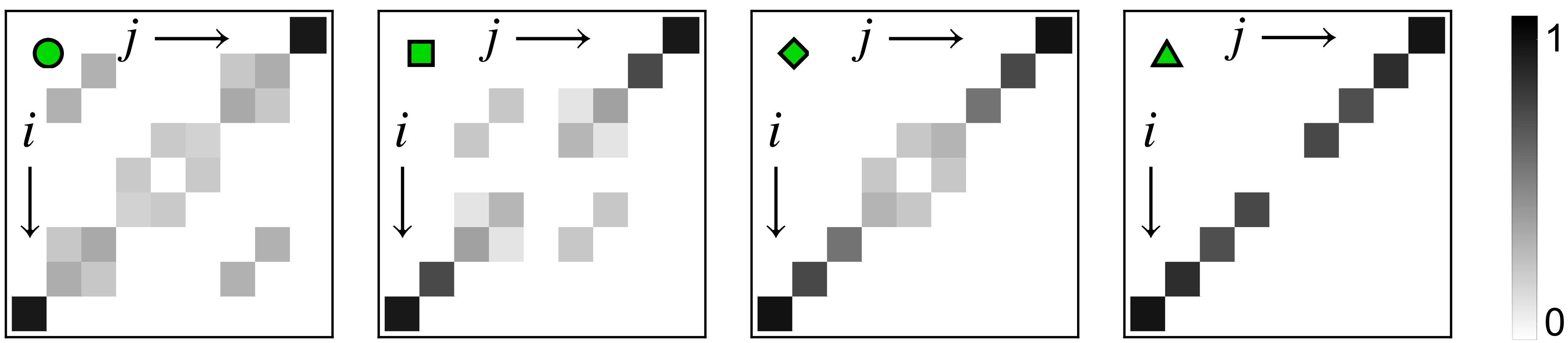


Number of Bell pairs and preparation time both linear in l

Robustness

$\hat{C}^2$ remains a symmetry for

- Hamiltonians quadratic in the JW fermions and reflection symmetric

  — symmetric traps, XY spin-1/2 chain

  — transverse-field Ising model $\leftrightarrow$ Kitaev chain

- Periodic boundary conditions

- Any coupling at the centre site

- Any function of "pair occupations" $\hat{n}_k + \hat{n}_{-k}$

- . . .

$\hat{C}^2$ symmetry is broken for

- Dissipation away from centre $\leftarrow$ uniform dephasing] decay rate $\sim \varepsilon$

- Nearest-neighbour interactions $\leftarrow$ XXZ chain

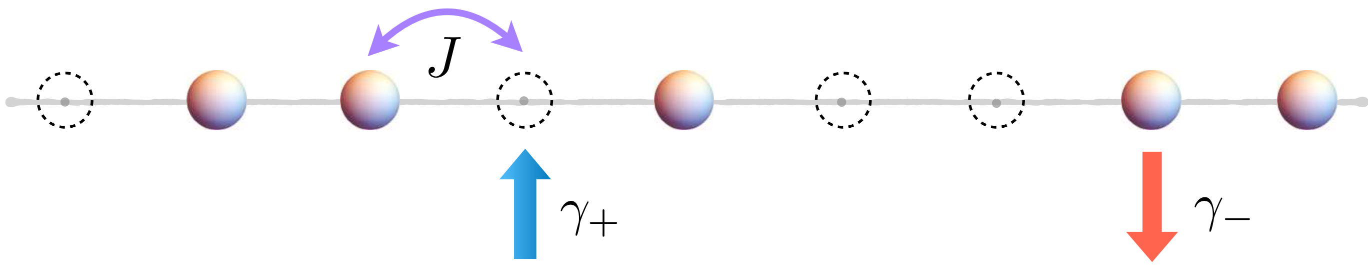
- Long-range tunnelling $\leftarrow$ Rydberg arrays

] decay rate $\sim \varepsilon^2$

Other pump-loss configurations

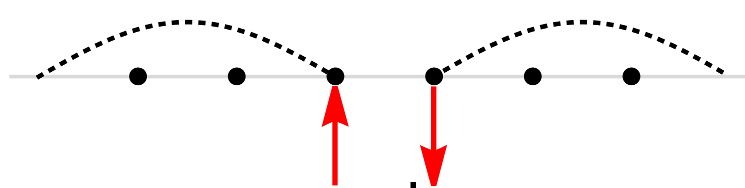
Long-range order in other configurations

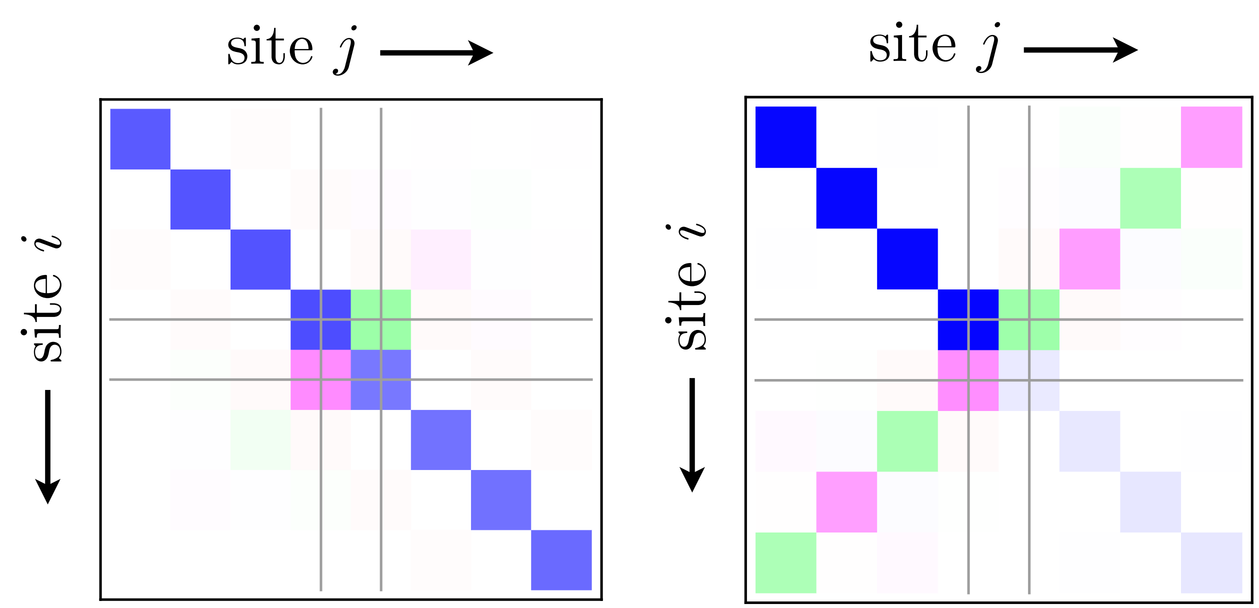
PRR 3, L012016 (2021)



No symmetry $\Rightarrow$ Unique steady state

Pump/loss-*induced* long-range correlation

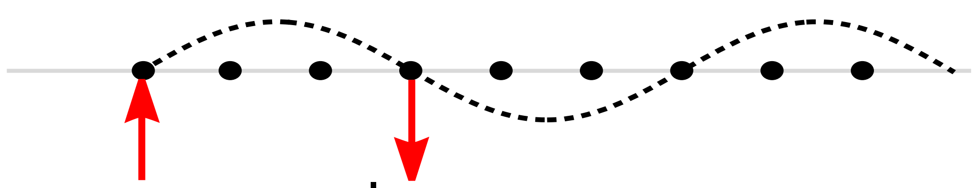


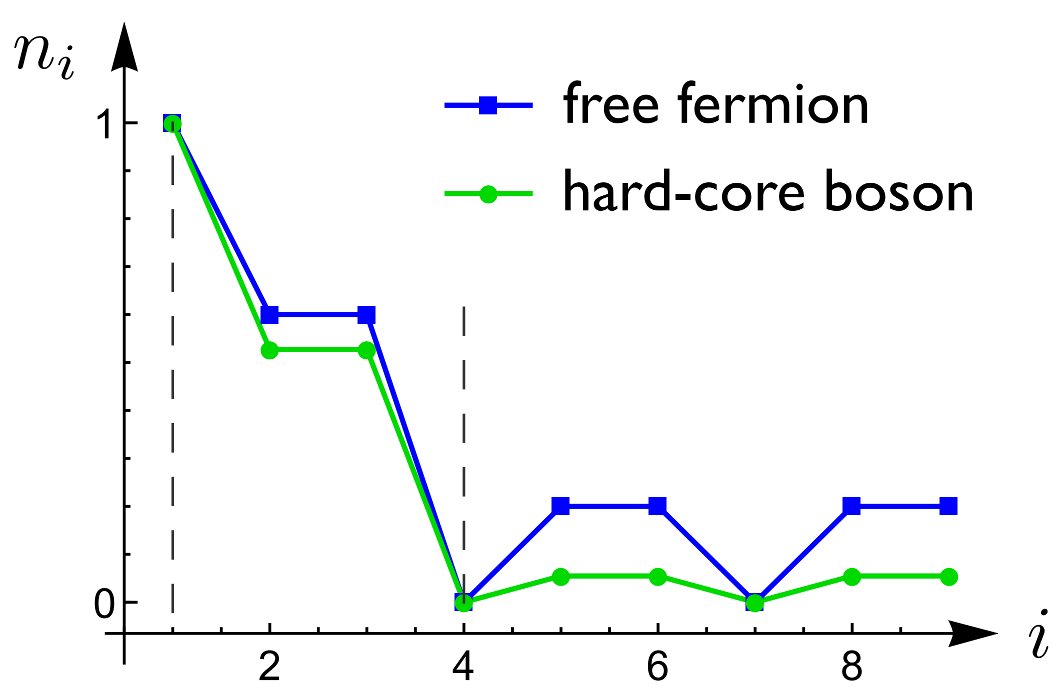


weak pump-loss

strong pump-loss

Density wave in "resonant" geometries





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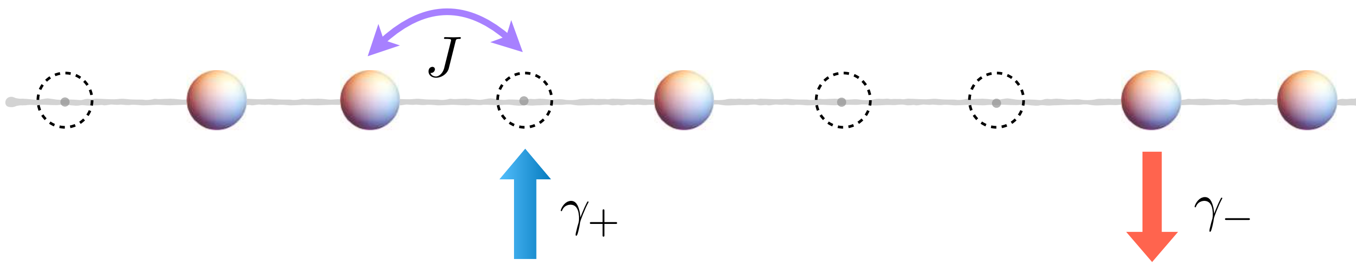
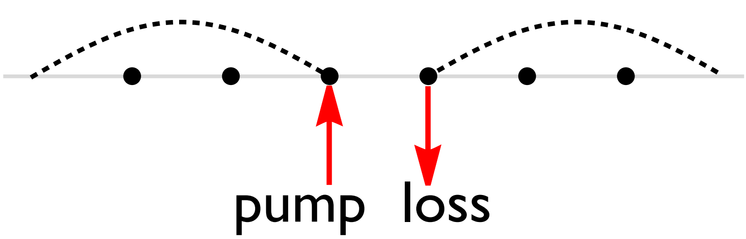
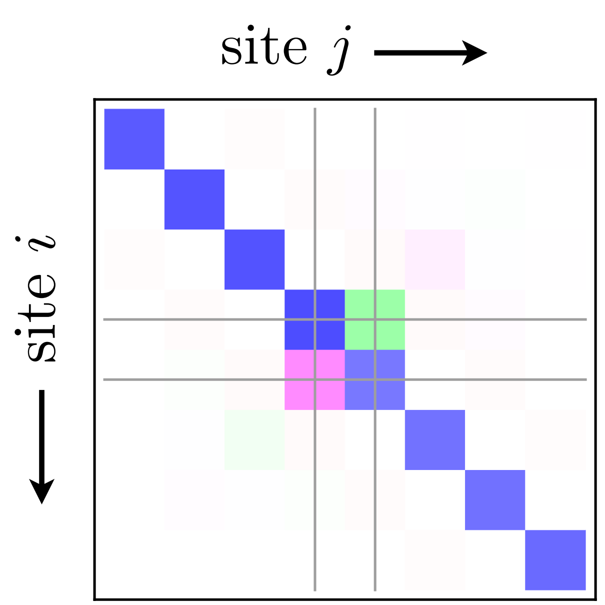


No symmetry $\Rightarrow$ Unique steady state

Techniques:
- DMRG + quantum trajectories
- Effective rate eqns

Pump/loss-*induced* long-range correlation





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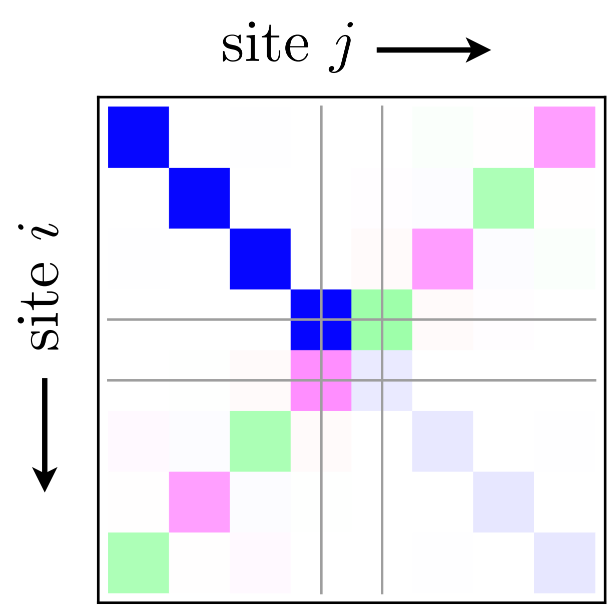

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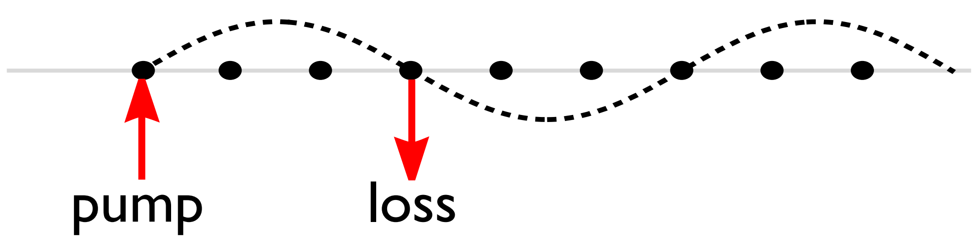
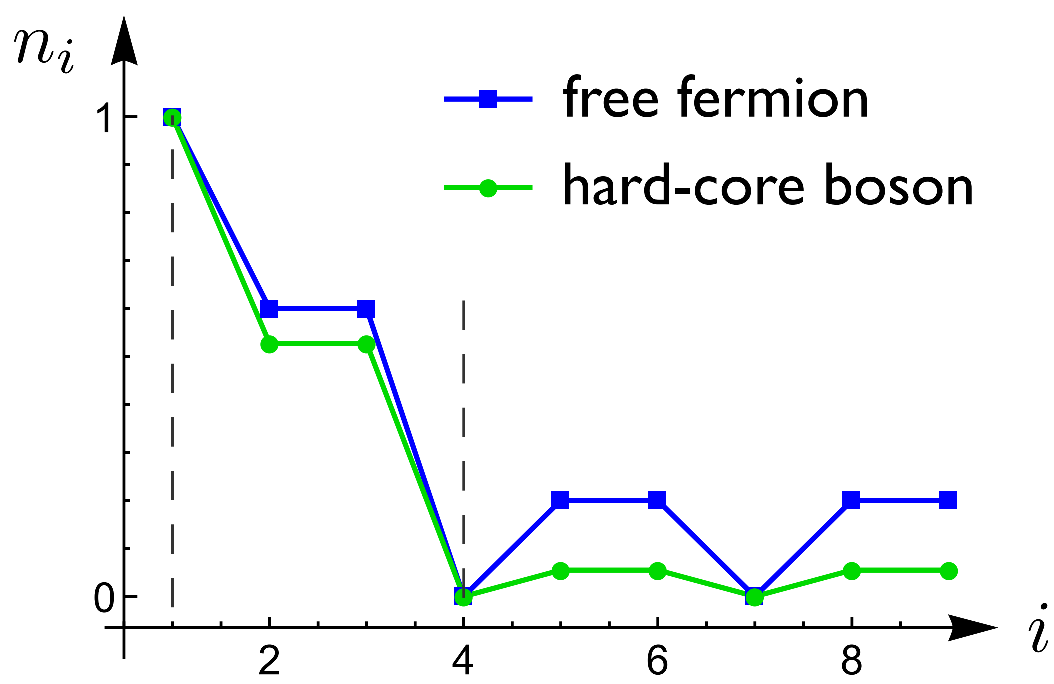


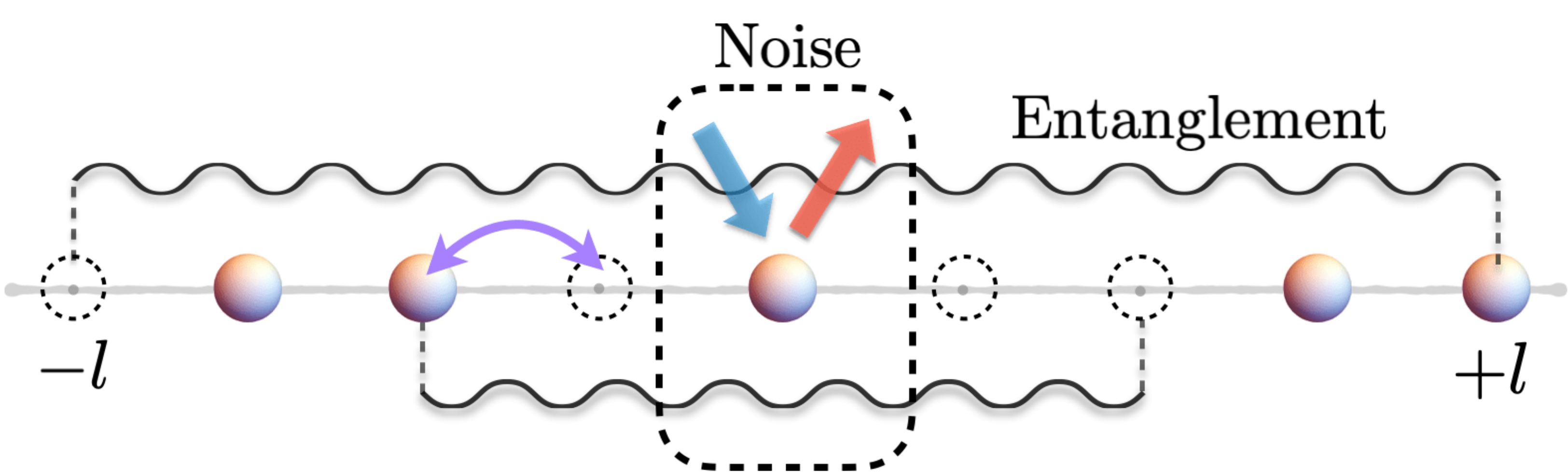


Summary

- Multiple (exactly solvable) steady states with long-range entanglement in a lossy qubit array — highly unusual

- Symmetry in open system protecting Bell pairs — applies to wider class of models

- Can be selectively prepared using timed pulses in cold atoms, superconducting circuits,… — symmetry harnessing



Shovan Dutta & Nigel Cooper, PRL 125, 240404 (2020)

SD, Stefan Kuhr, & NC, coming soon!

- Counterintuitive features in other geometries — PRR 3, L012016 (2021)