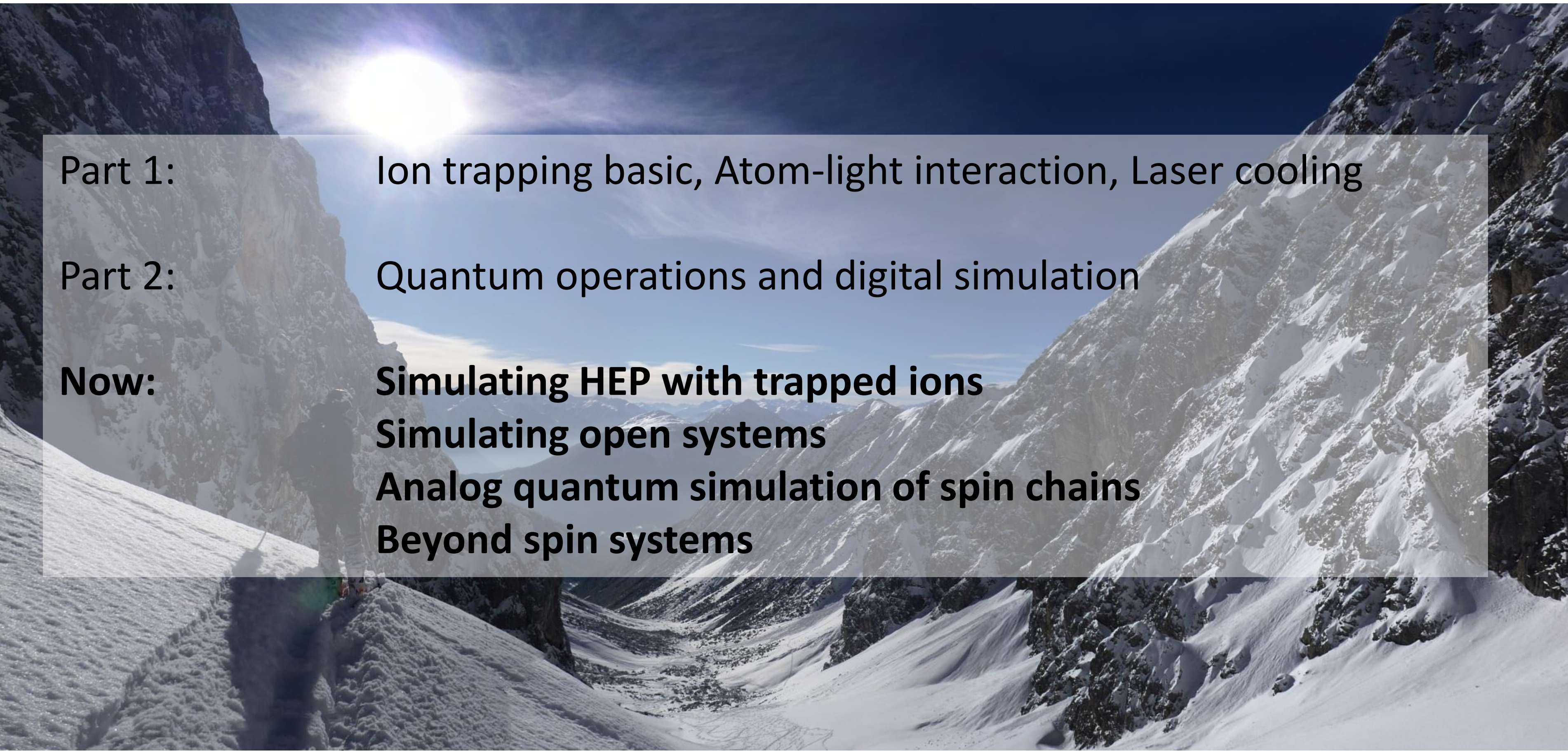
# Outline



Part 1: Ion trapping basic, Atom-light interaction, Laser cooling

Part 2: Quantum operations and digital simulation

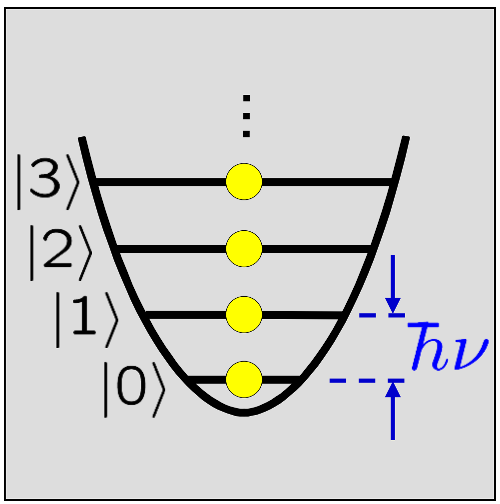
**Now:** **Simulating HEP with trapped ions**
**Simulating open systems**
**Analog quantum simulation of spin chains**
**Beyond spin systems**

http://github.com/pschindler/natal

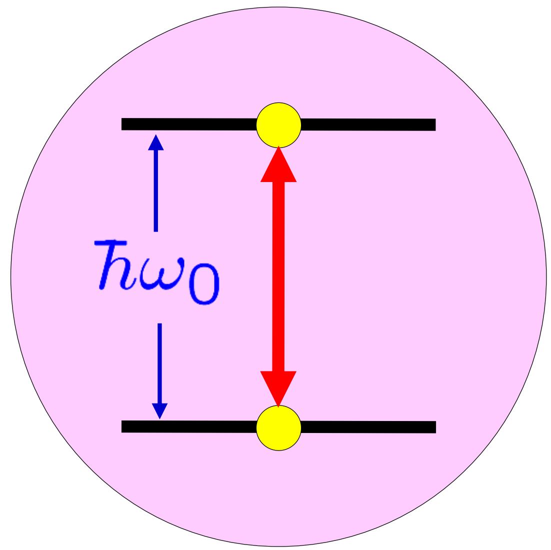
# The system

Harmonic oscillator

Quantum bit




$\otimes$




Including spontaneous decay

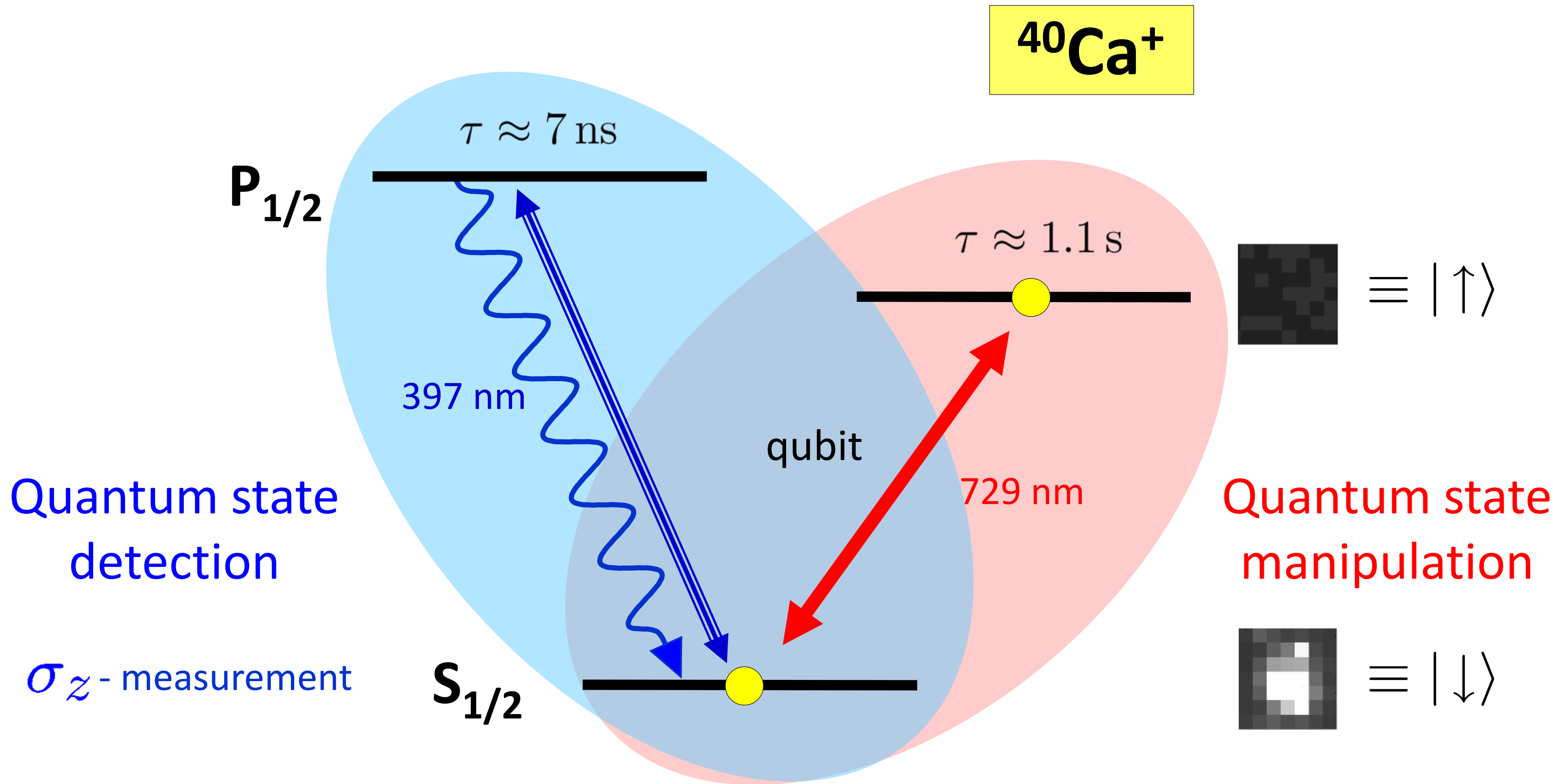
motional states

$$|0\rangle, |1\rangle, |2\rangle, |3\rangle, \ldots$$

internal states

$$|\uparrow\rangle, |\downarrow\rangle$$

# Calcium ions

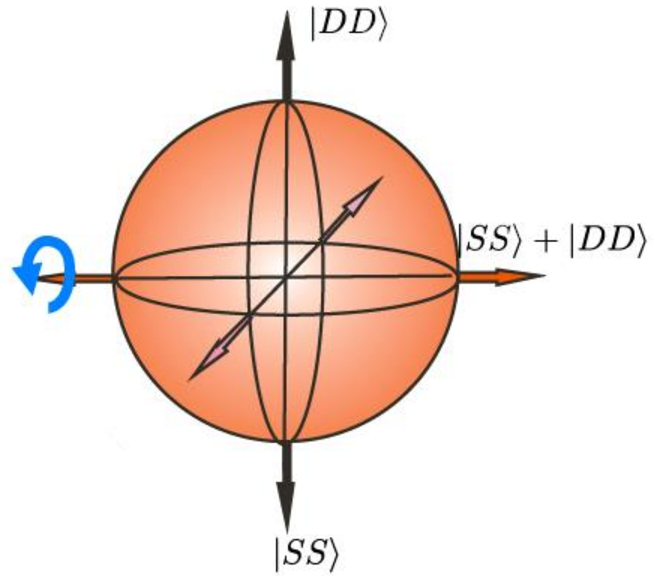


# Mølmer-Sørensen entangling operation

Based on state-dependent light forces.

Works for any number of qubits

Effective infinite range 2-body interaction.




T. Monz et al., *PRL.* **106**, 130506 (2011).

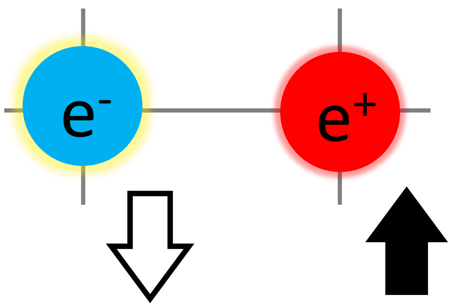
K. Mølmer and A. Sørensen, PRL 82, 1835 (1999).

# Outline

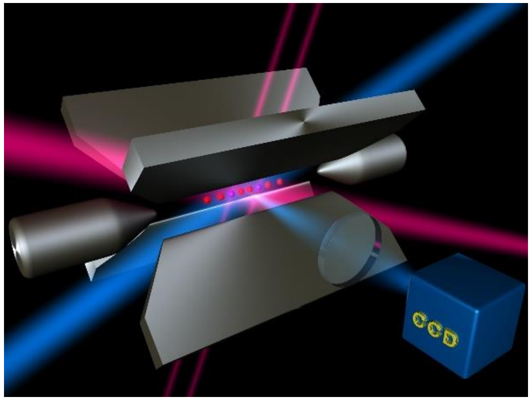
- Simulating high energy physics
- Simulating open quantum systems
- Analog simulation of spin chains
- Beyond spin systems

# Simulating the Schwinger model

The model: lattice gauge theories




Trapped-ion quantum information processing

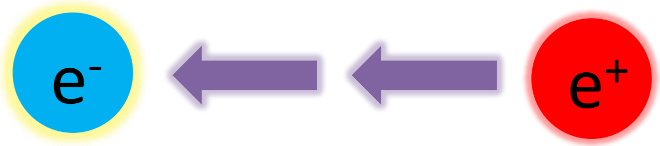


Quantum simulation of lattice gauge theories

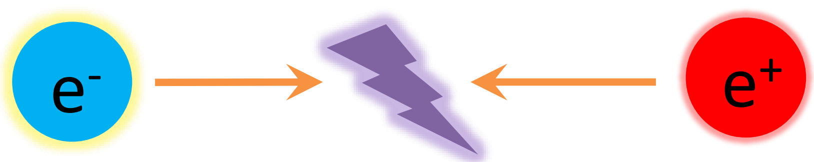
E. Martinez, C. Muschik et al, Nature **534**, 516 (2016)

# Quantum electrodynamics

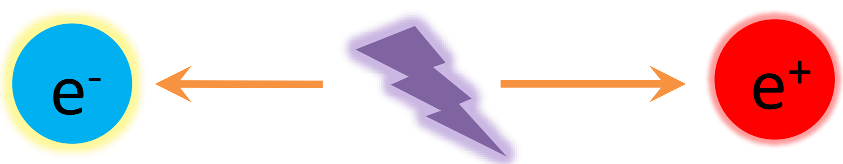
- Charged particles (electrons, $e^-$) and antiparticles (positrons, $e^+$) interact via electromagnetic force fields.




  - Particles and antiparticles can mutually annihilate.

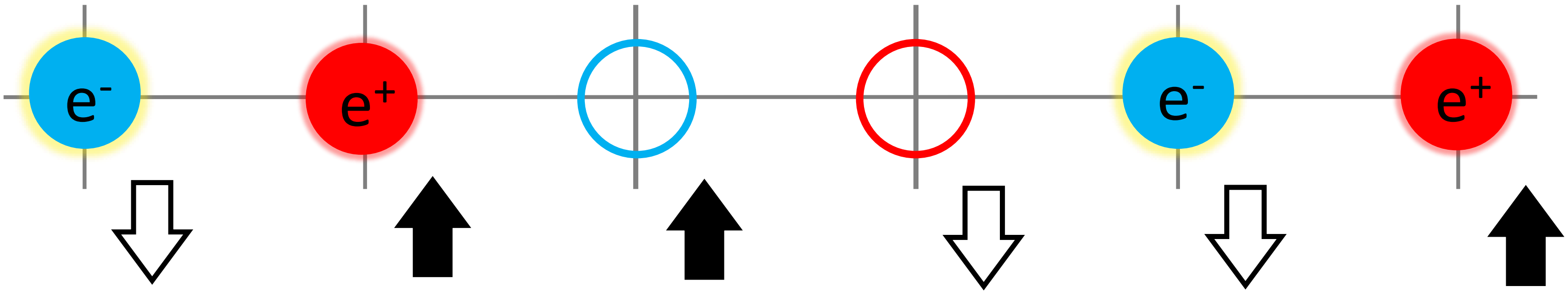



  - Prediction: spontaneous creation of particle-antiparticle pairs in strong static fields (Schwinger mechanism).

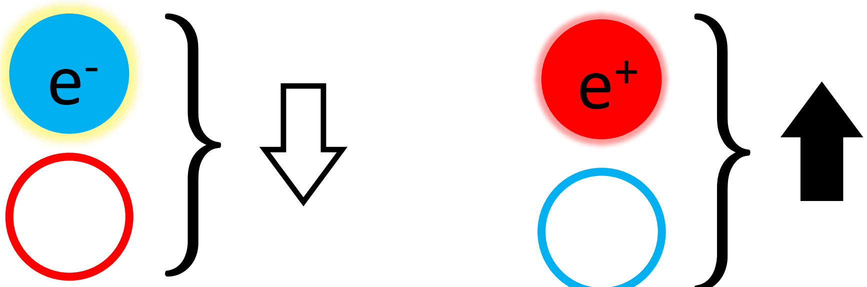


# Lattice gauge theories

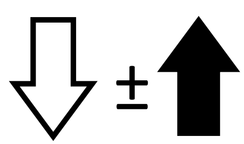
How can we simulate gauge theories?

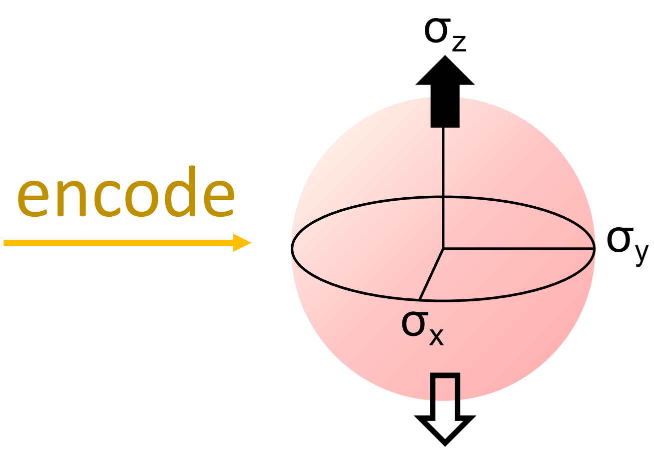



- Discretize space to a lattice (1D for simplicity).
- Blue sites hold particles, red sites hold antiparticles.
- Each site has two possible states (full/empty), encoding:



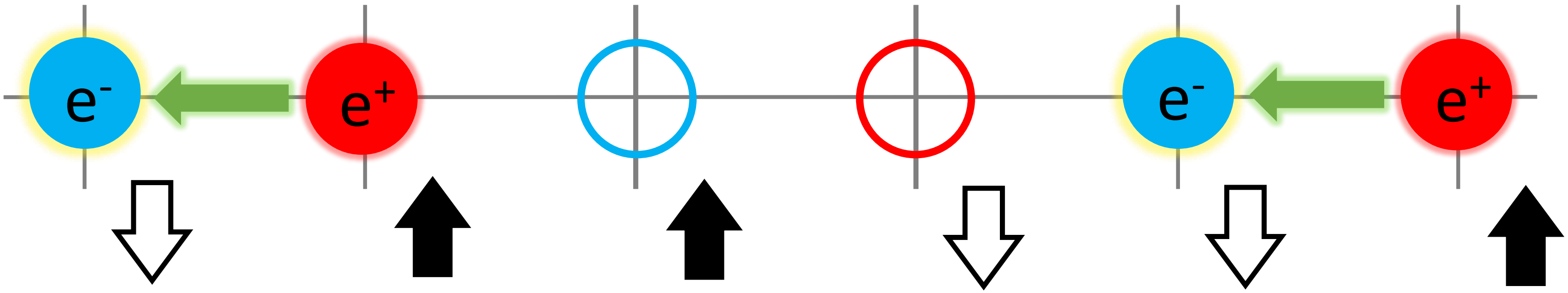

and also superpositions:



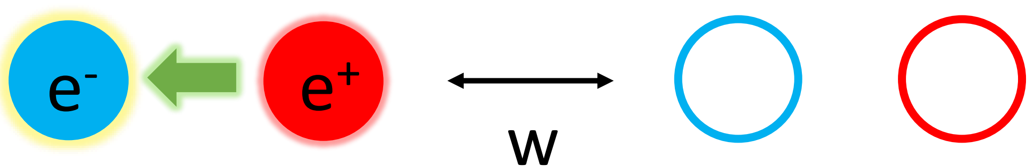



# Lattice gauge theories

How do we simulate gauge theories?

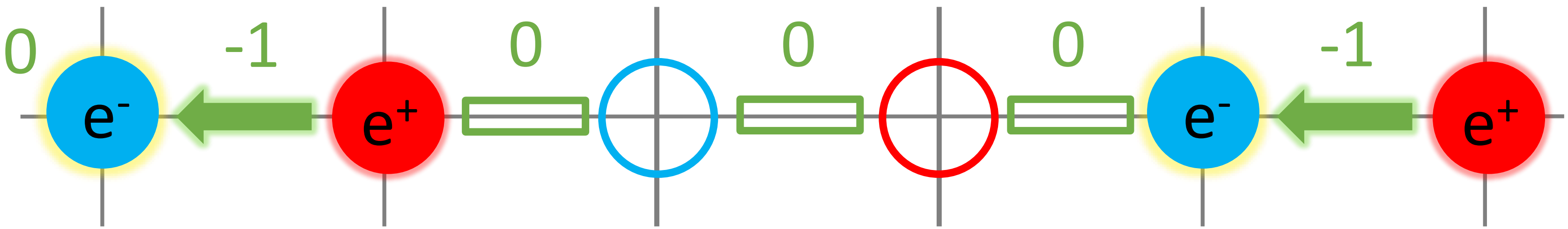



- Interactions: gauge fields on the links between the sites (electric field).
- Neighboring $e^+e^-$ pairs and fields get created/destroyed:



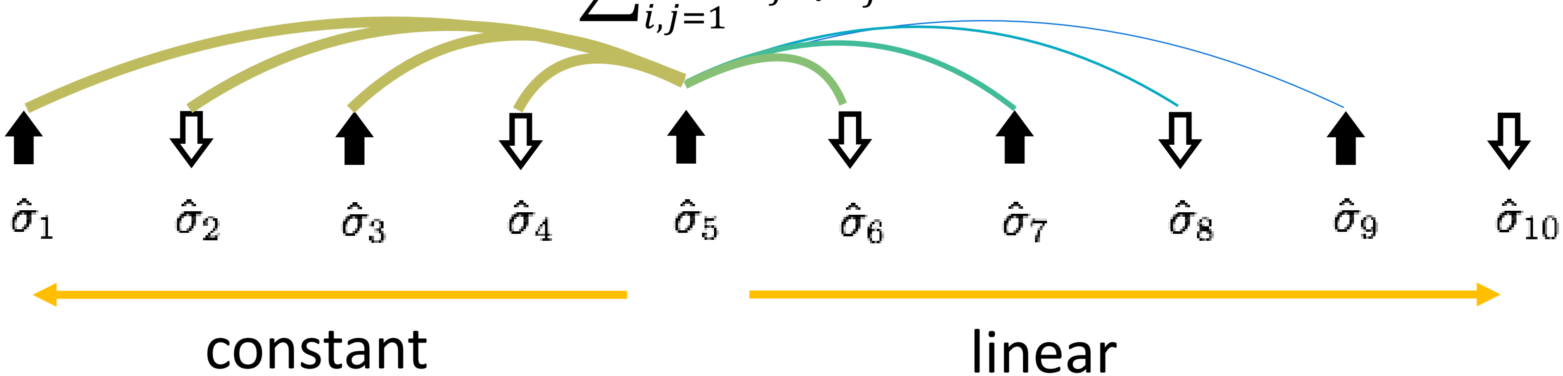
# Eliminating the gauge fields

If we know the charges and the boundary conditions, we can infer the value of the fields from Gauss’ law:



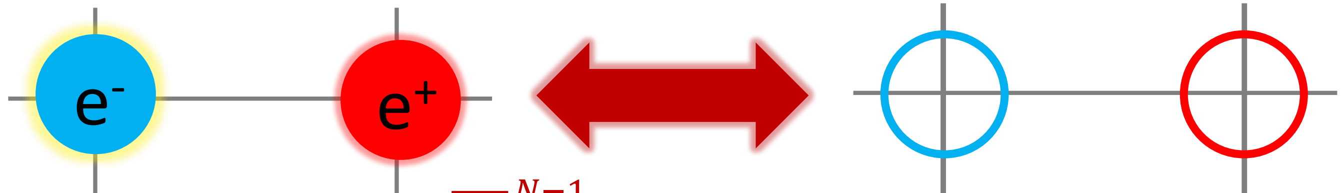

- Each charge determines the fields to its right.
- We eliminate the fields and get effective long-range interactions:

$$J \sum_{i,j=1}^{N} c_{ij}\sigma_i^z \sigma_j^z$$



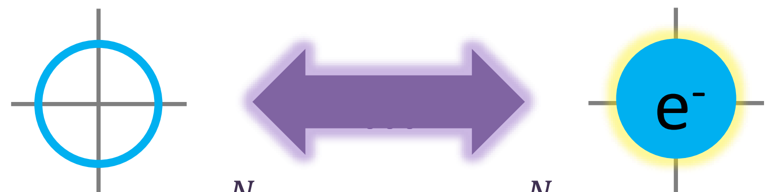
# Dynamics

- Neighboring pairs are created/annihilated at a rate *w*:



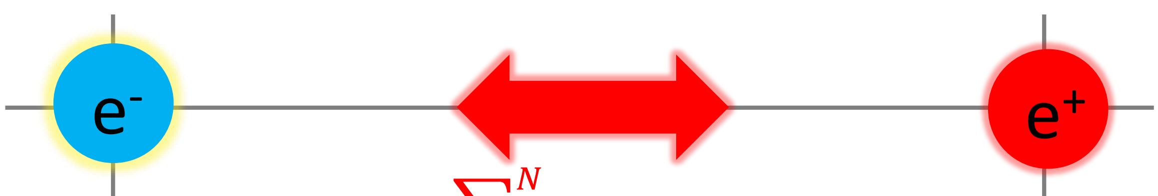

$$w\sum_{i=1}^{N-1} \sigma_i^+\sigma_{i+1}^- + \sigma_i^-\sigma_{i+1}^+$$

- Particles have mass *m*, so they take energy to create:




$$m\sum_{i=1}^{N} c_i\sigma_i^z + J\sum_{i=1}^{N} \tilde{c}_i\sigma_i^z$$

- Long-range interactions (Coulomb force) with strength *J*:




$$J\sum_{i,j=1}^{N} c_{ij}\sigma_i^z\sigma_j^z$$

# Time evolution

- The Hamiltonian of our spin system is:

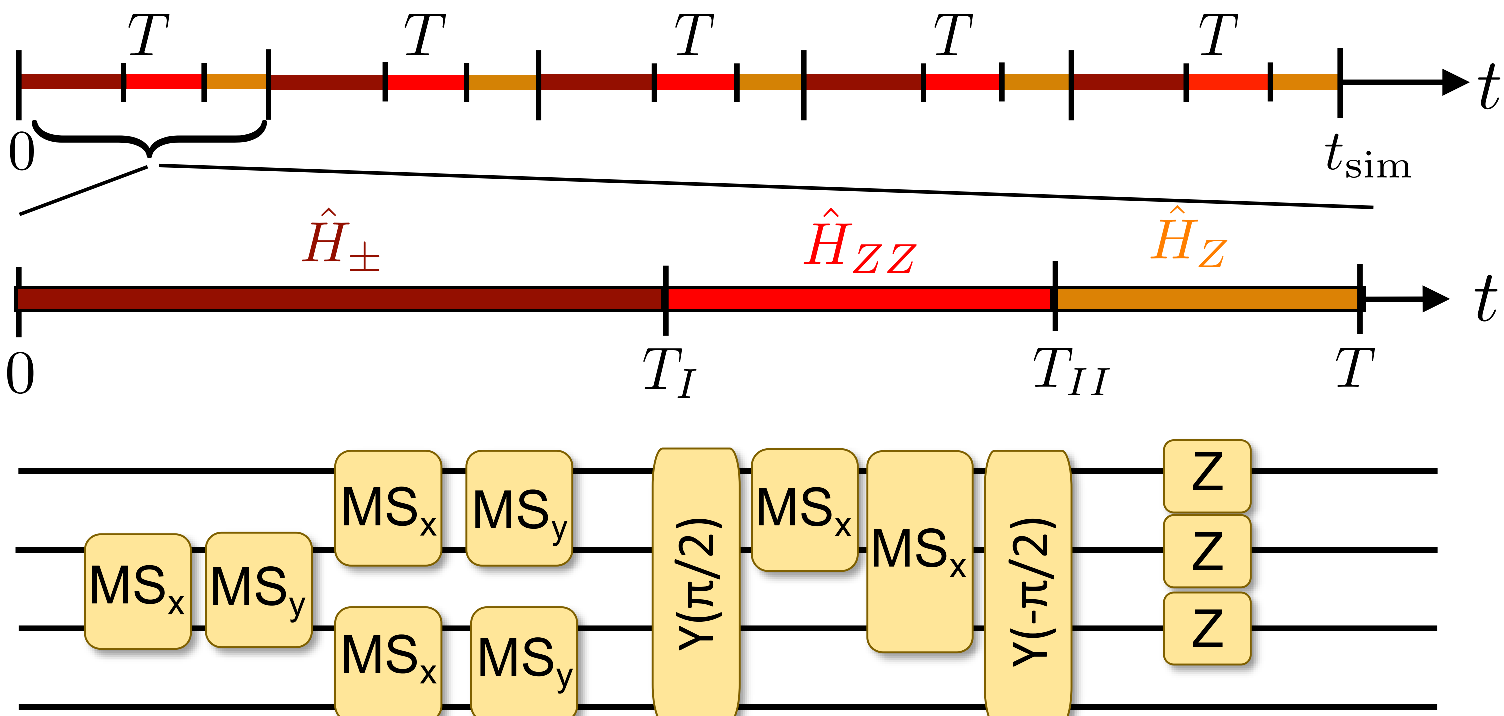
$$H = w\sum_{i=1}^{N-1} \sigma_i^+\sigma_{i+1}^- + \sigma_i^-\sigma_{i+1}^+ + J\sum_{i,j=1}^{N} c_{ij}\sigma_i^z\sigma_j^z + m\sum_{i=1}^{N} c_i\sigma_i^z + J\sum_{i=1}^{N} \tilde{c}_i\sigma_i^z$$

particle – antiparticle creation/annihilation

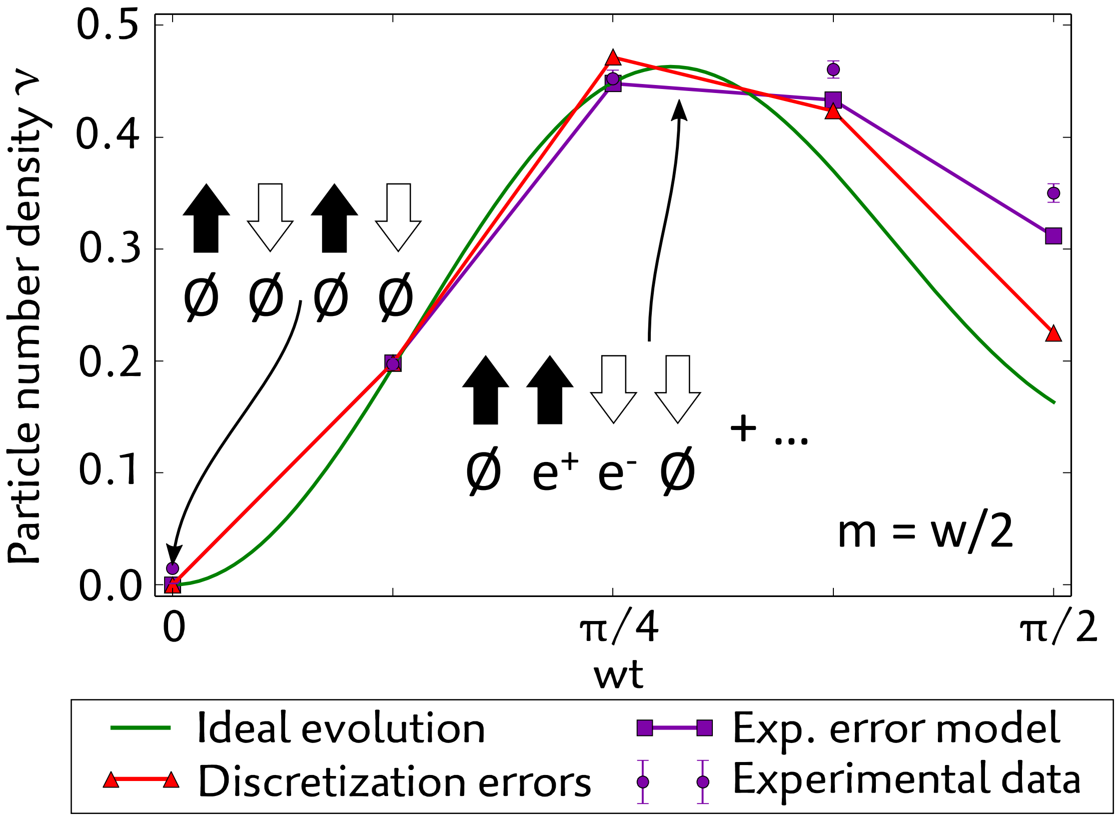
long-range interactions

effective particle masses

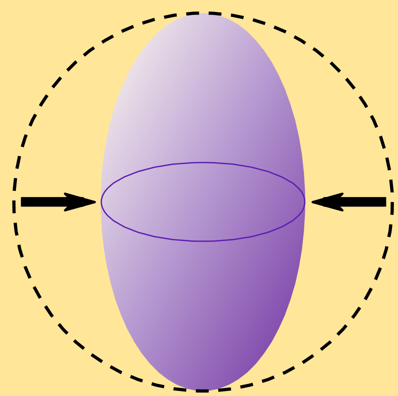
- We slice the evolution in small time steps (Trotterization):



# Dynamics of $e^+e^-$ pair creation

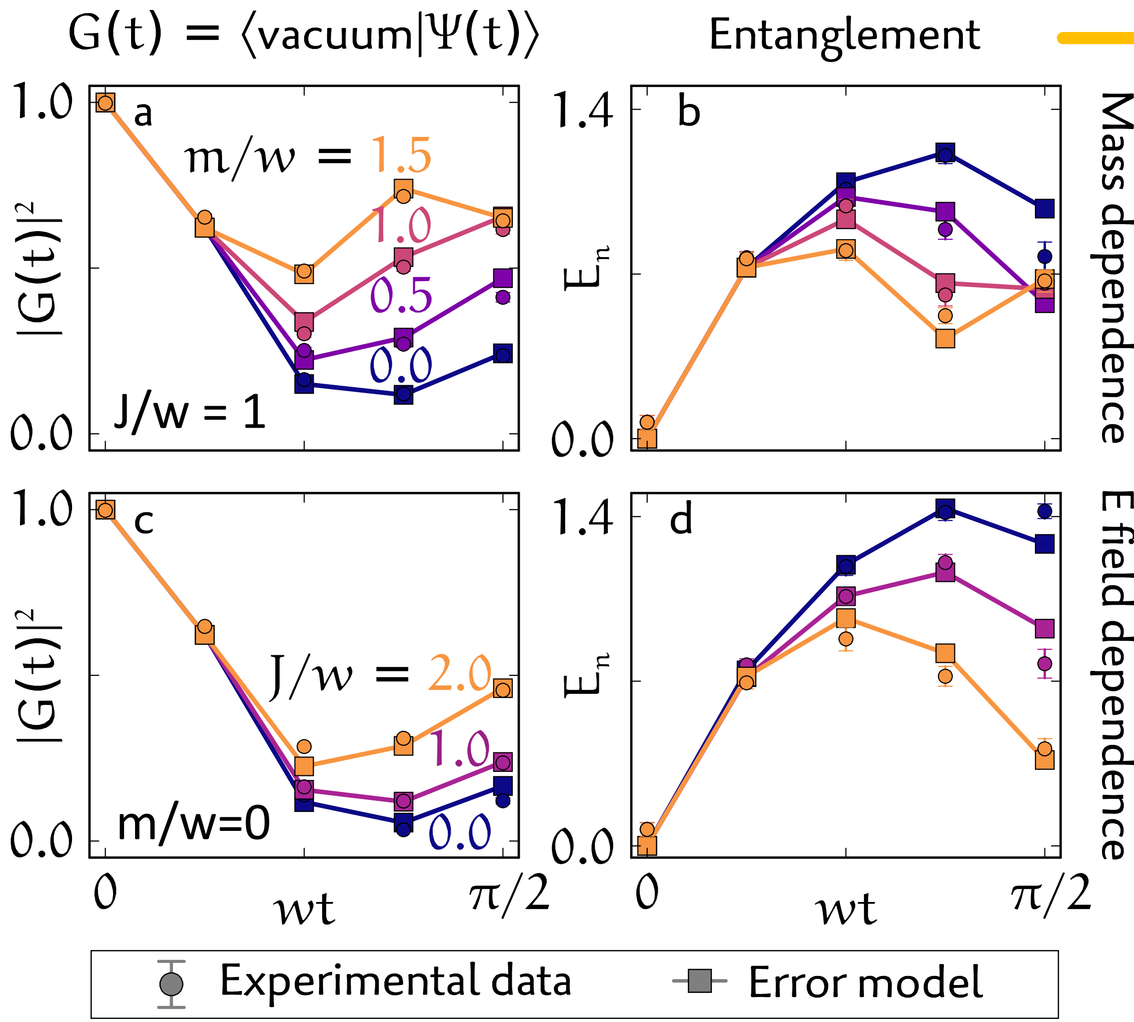


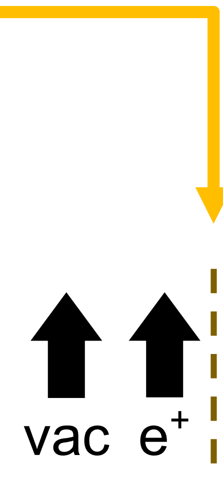

**Error model:**
uncorrelated dephasing noise with error probability $p$ = 0.038 per qubit per step.



# What you cannot see at CERN

We have full experimental access to the system wavefunction:




($E_n$ = log. negativity across this bipartition)

# Outline

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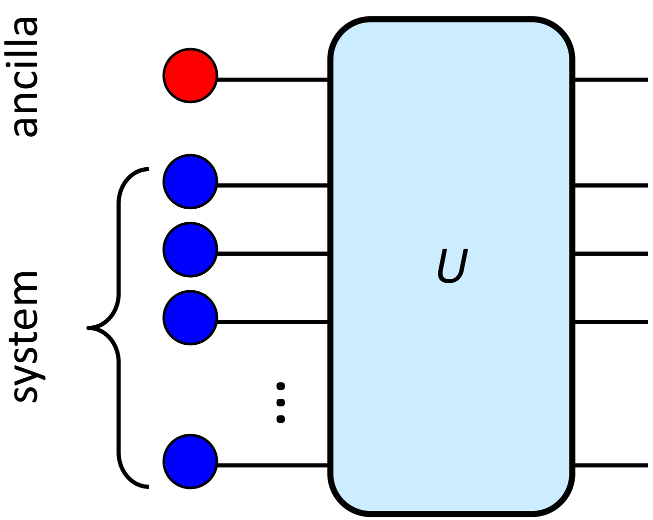
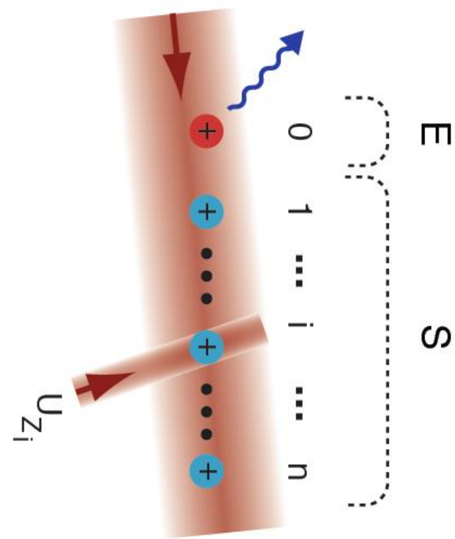
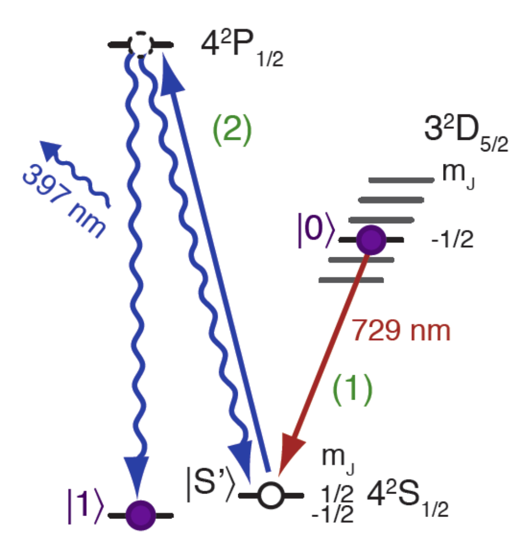
# Simulating open systems

J. Barreiro, M. Müller et al., Nature **470**, 486 (2011)



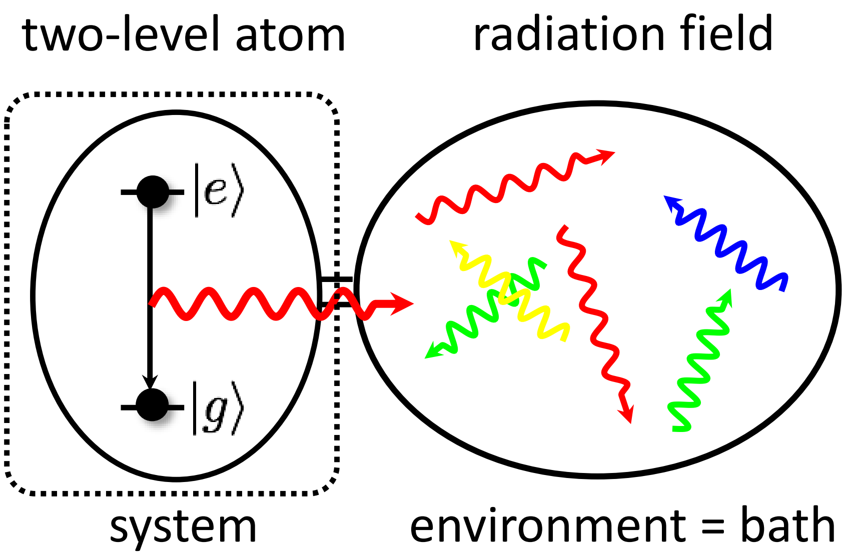



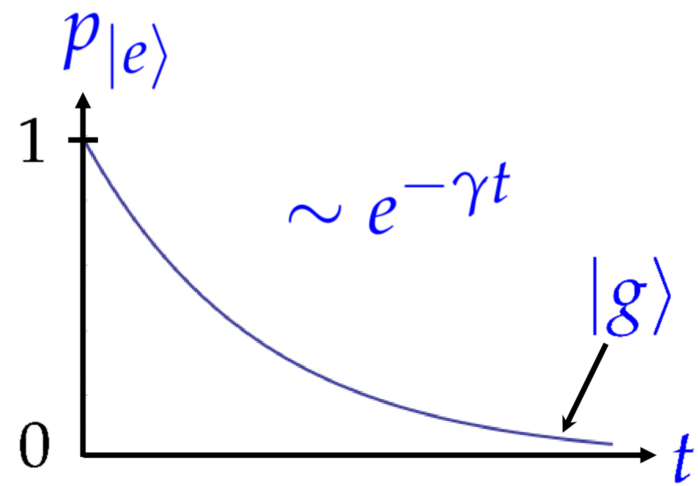




engineering many-body operations
engineering the environment
stabilizer pumping (Bell, GHZ)
QND measurements of many-body operators
dissipative state preparation

open systems
quantum simulations

# Dissipative quantum systems




**Realize an open system evolution where the steady state is entangled**

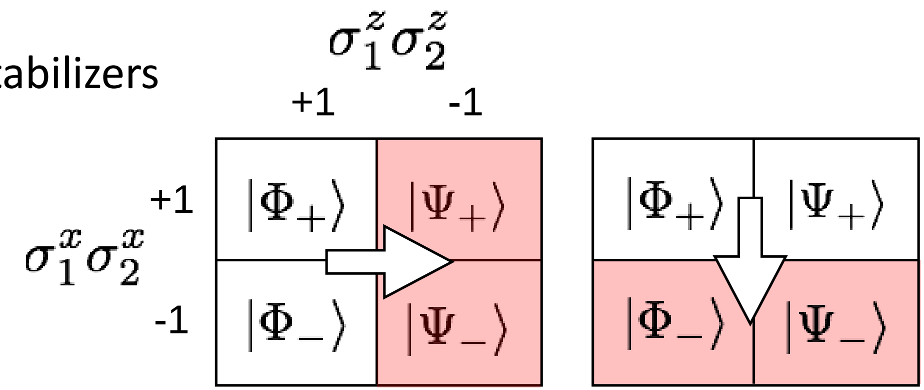
**Dissipation can be a resource!**

# Bell state pumping

Engineer dissipative dynamics that pumps a many-body system into an entangled state

M. Müller, P. Zoller (2010-11)

stabilizers




one pumping cycle

two qubits 1 2

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$$

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$$

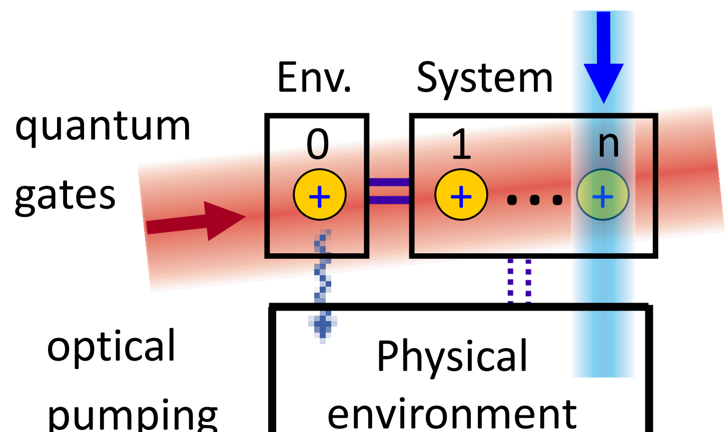
uniquely fixed by their eigenvalues with respect to $\sigma_1^z\sigma_2^z$ and $\sigma_1^x\sigma_2^x$

master equation for $\sigma_1^z\sigma_2^z$ - pumping:

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho = \gamma(c\rho c^\dagger - \frac{1}{2}c^\dagger c\rho - \rho\frac{1}{2}c^\dagger c)$$

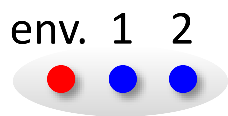
with $c = \sigma_x^{(1)} \frac{1}{2}(1 + \sigma_z^{(1)}\sigma_z^{(2)})$

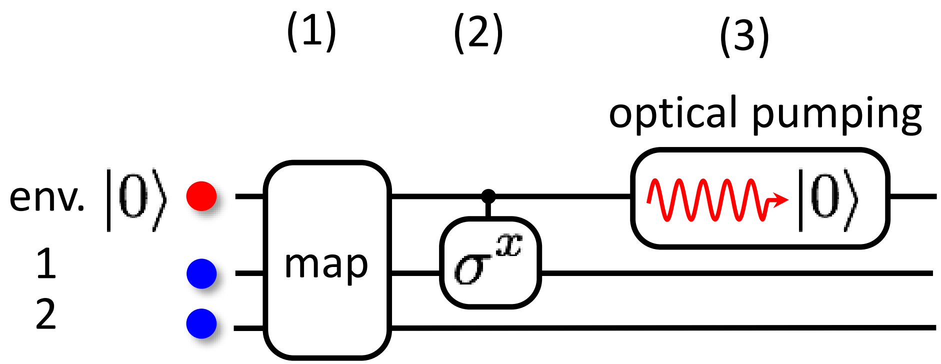
two-body quantum jump operator

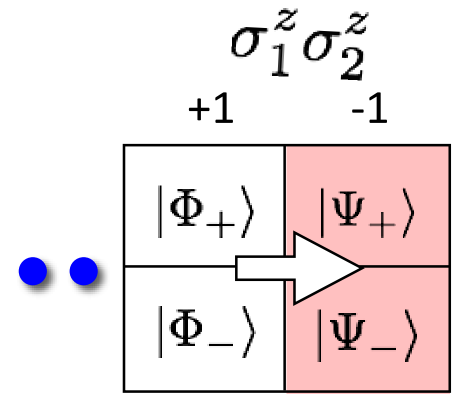


# Implementing Pumping

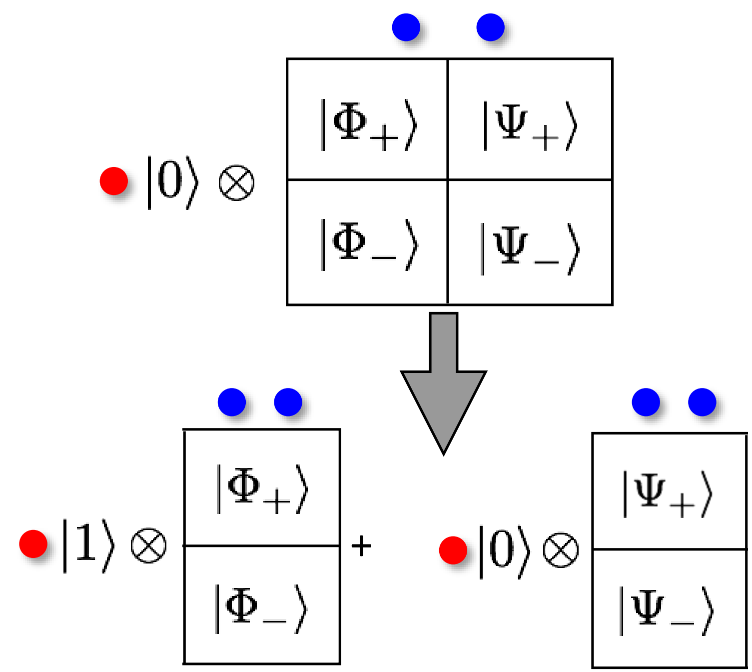
Implementation
with 1+2 ions



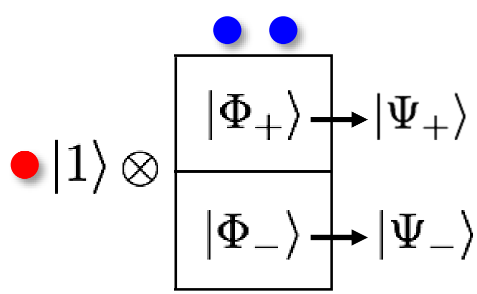




(1) coherent mapping




(2) two-qubit gate $C = |0\rangle\langle 0| \otimes 1 + |1\rangle\langle 1| \otimes \sigma_1^x$

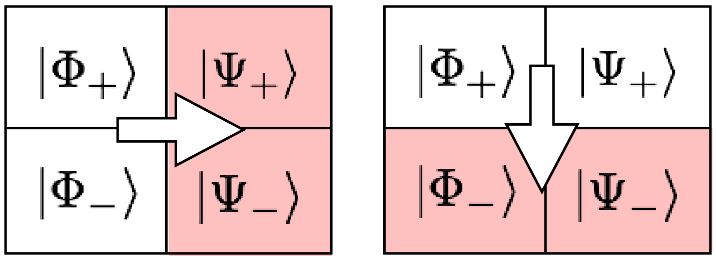



(3) optical pumping env. ion: $|1\rangle \rightsquigarrow |0\rangle$

... as the dissipative ingredient

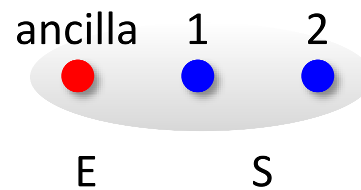
# Experimental Bell state pumping

one pumping cycle

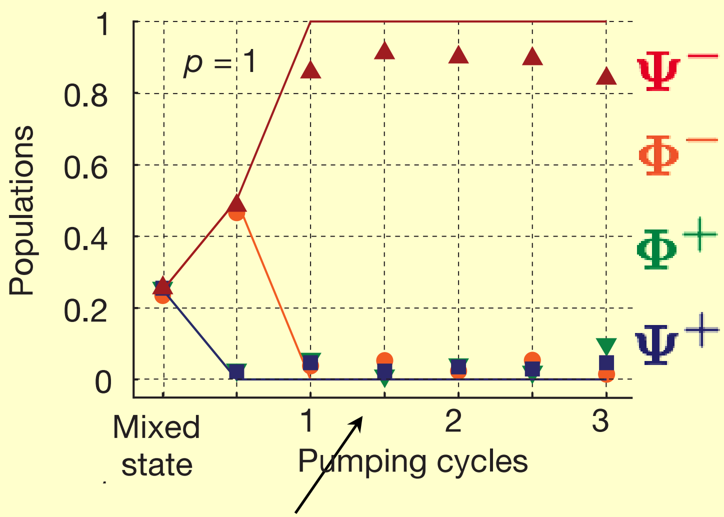



with pumping probability p

system ions

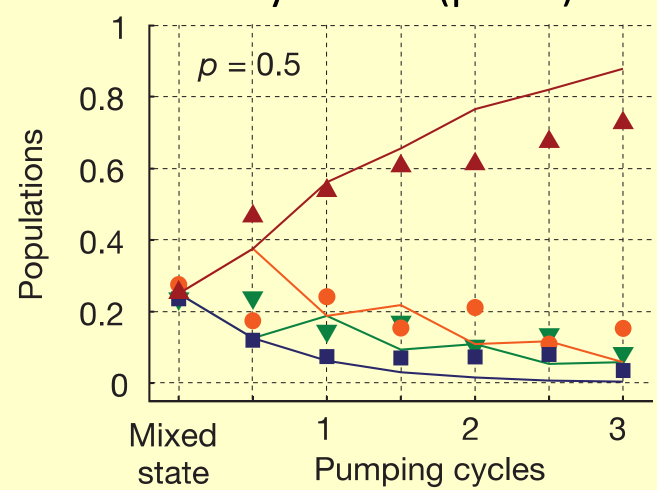



deterministic pumping (p=1)




$F_{process}$ = 87(1)%

towards master equation dynamics (p=0.5)




J. Barreiro, M. Müller et al., Nature **470**, 486 (2011)

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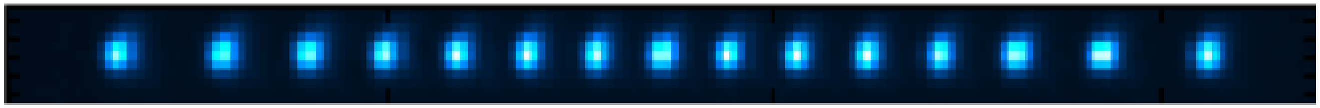
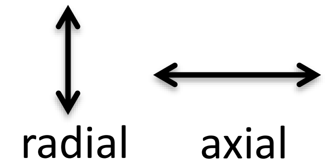
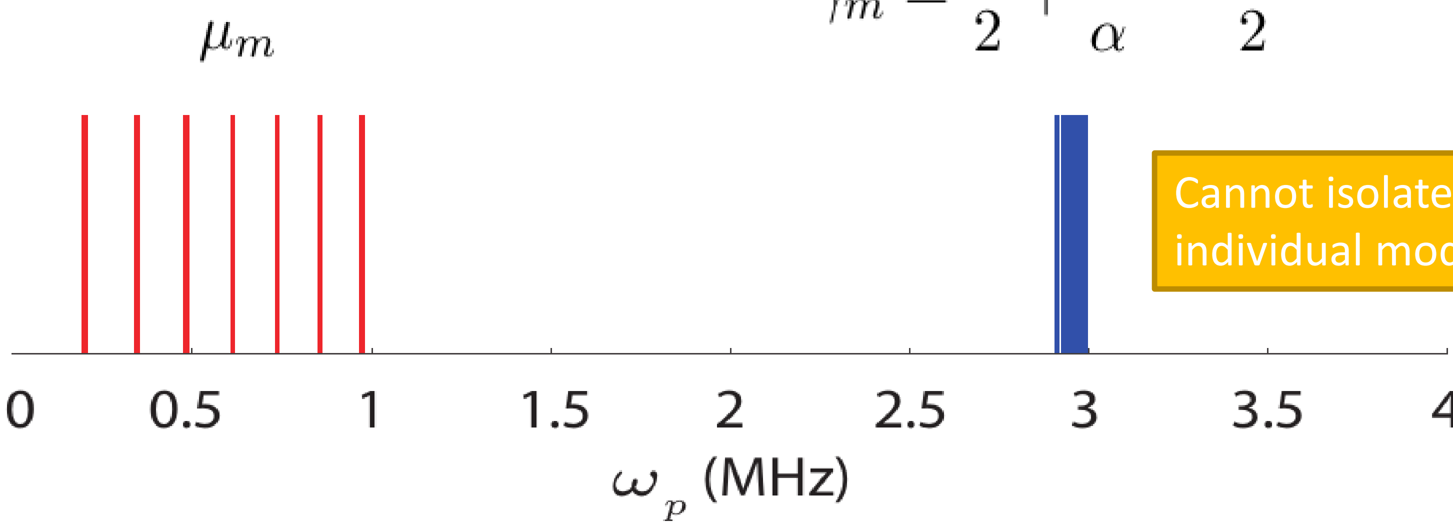
# Normal modes revisited





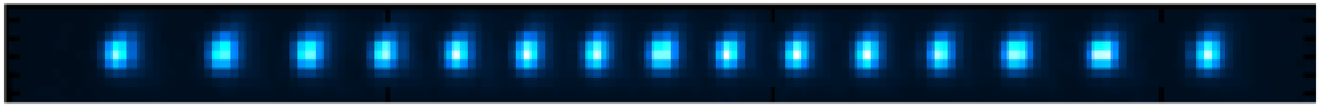

Highly anisotropic potential: $$\left(\frac{\omega_{ax}}{\omega_{rad}}\right)^2 = \left(\frac{\omega_3}{\omega_{1,2}}\right)^2 =: \alpha \ll 1$$

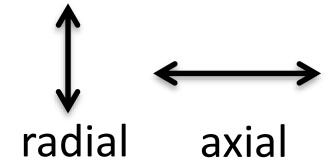
Eigenvalues (mode frequency): $$\gamma_m = \frac{1}{2} + \frac{1}{\alpha} - \frac{\mu_m}{2}$$

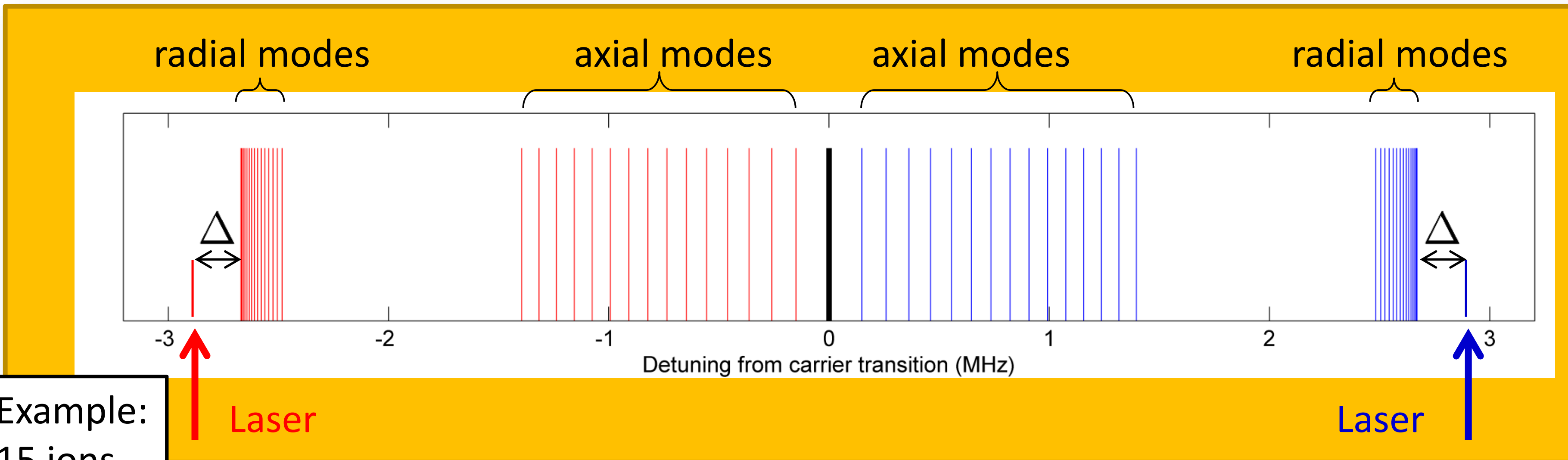



Cannot isolate individual modes

# Gate on the transverse modes






Example:
15 ions

$$H = \frac{\hbar\Omega}{2}\sum_{j=1}^{N}\sum_{m=1}^{2N}\eta_{j,m}\,\sigma_x^{(j)}\left(a_m\,e^{i\delta_m t} + a_m^{\dagger}\,e^{i\delta_m t}\right)$$

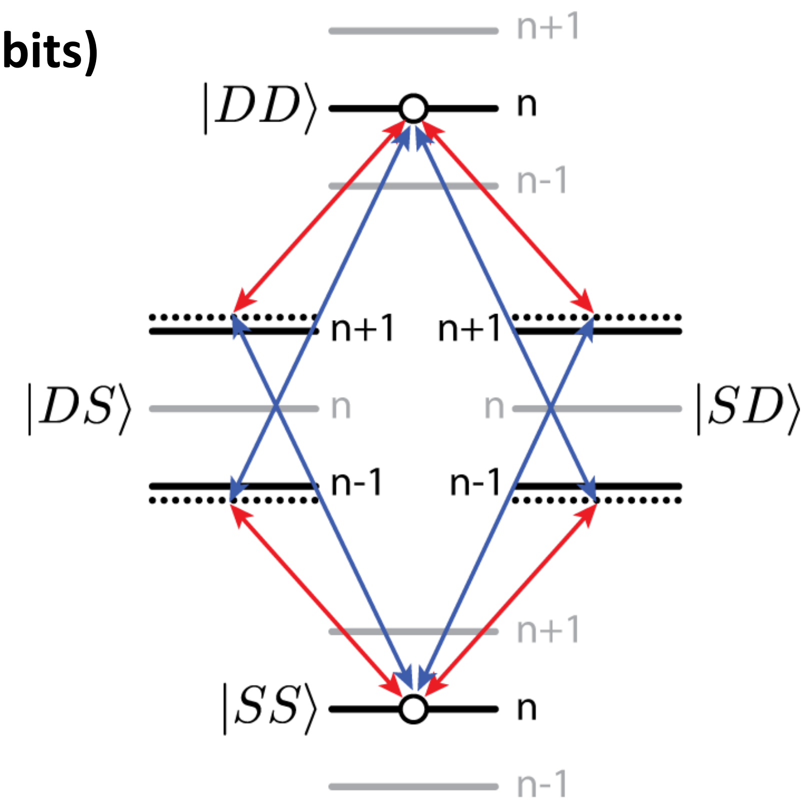
# Interacting with multiple modes

**Couple to multiple modes simultaneously: Hard to close all loops in phase space**

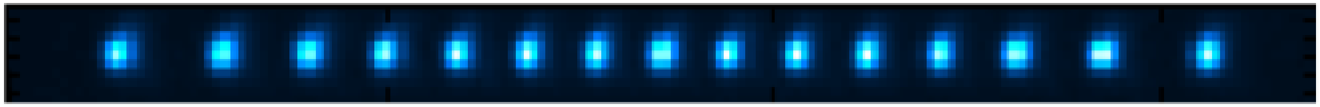
**Adiabatic elimination of motional mode (2 qubits)**

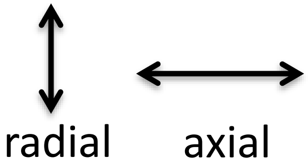
$$\eta\Omega \ll \delta$$

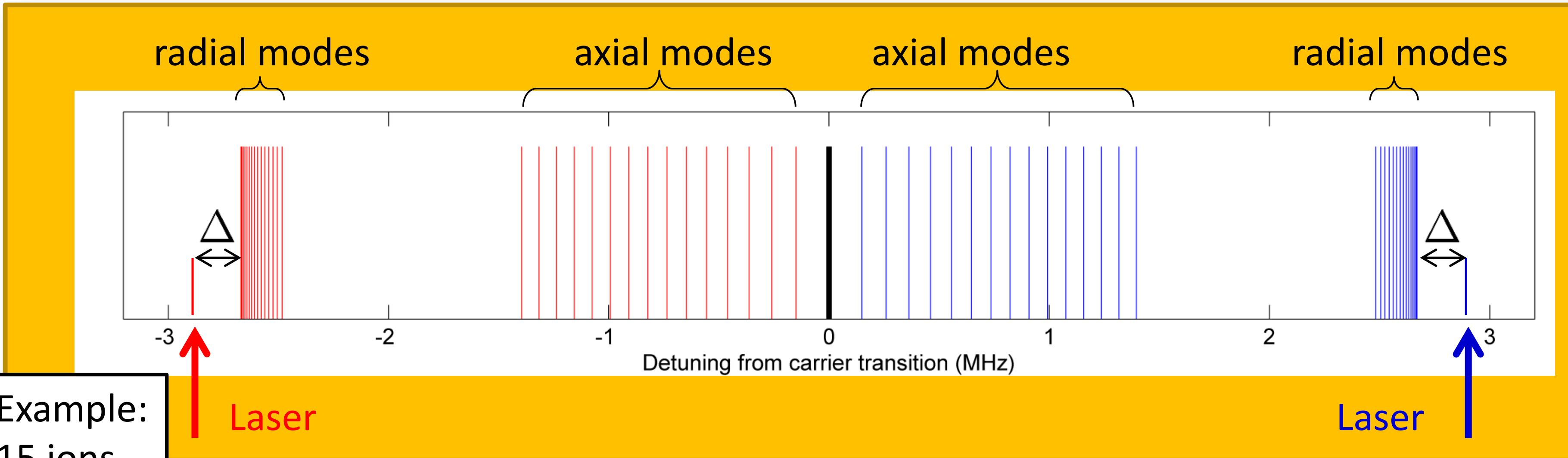
$$H = J\,\sigma_x \otimes \sigma_x \qquad J = \frac{(\eta\Omega)^2}{\delta}$$



# Gate on the transverse modes






Example:
15 ions

$$H = \sum_{i<j} J_{ij} \sigma_i^x \sigma_j^x$$ with $$J_{i,j} = \frac{\hbar\Omega^2}{2} \sum_m^{2N} \frac{\eta_{i,m}\,\eta_{j,m}}{\delta_m}$$

$$\eta_{i,m} = b_{i,j}\,\eta$$

Amplitude of ion *i* in motional mode *m*

K. Kim et al, PRL **103**, 120502 (2009)

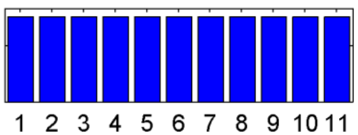
# Variable range interactions

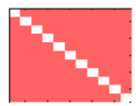
Example: 11 ions

$$H = \sum_{i<j} J_{ij} \sigma_i^x \sigma_j^x \qquad J_{i,j} = \frac{\hbar \Omega^2}{2} \sum_m^{2N} \frac{\eta_{i,m}\, \eta_{j,m}}{\delta_m}$$

vibrational mode

'COM'



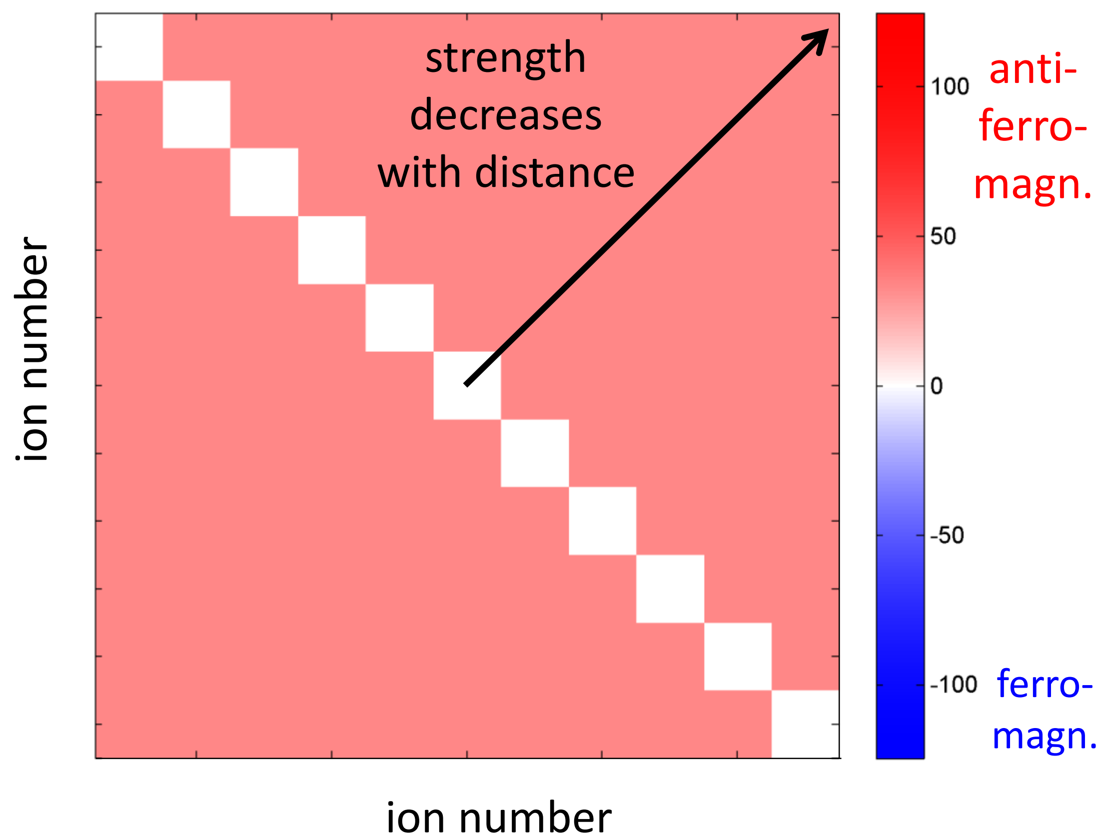



'Tilt'

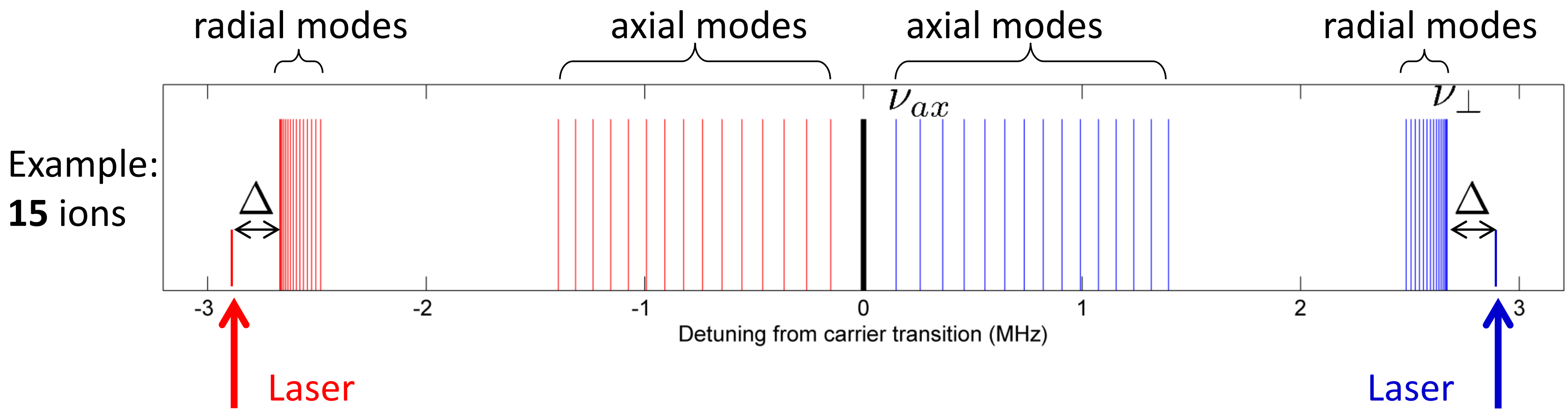
⋮

⋮

Spin-spin coupling $J_{ij}$ (Hz)



# Variable length interaction




$$H = \sum_{i<j} \hbar J_{ij} \sigma_i^x \sigma_j^x \quad \text{with} \quad J_{ij} \approx \frac{J_0}{|i-j|^\alpha}$$

Interaction range: $0 < \alpha < 3$

couple only to center-of-mass

couple to all modes equally

**Knobs to turn**:

- laser detuning $\Delta$
- spread of radial modes

K. Kim et al, PRL **103**, 120502 (2009)

J. Britton et al, Nature **484**, 489 (2012)

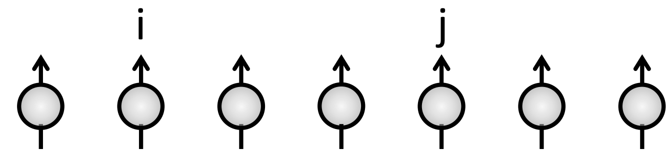
# Measuring the coupling matrix

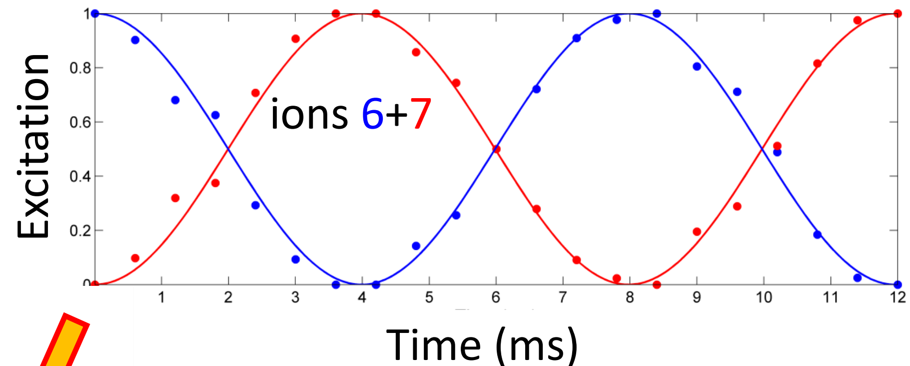
1. Initialize ions in state $|\uparrow\rangle_i|\downarrow\rangle_j$

2. Switch on Ising Hamiltonian

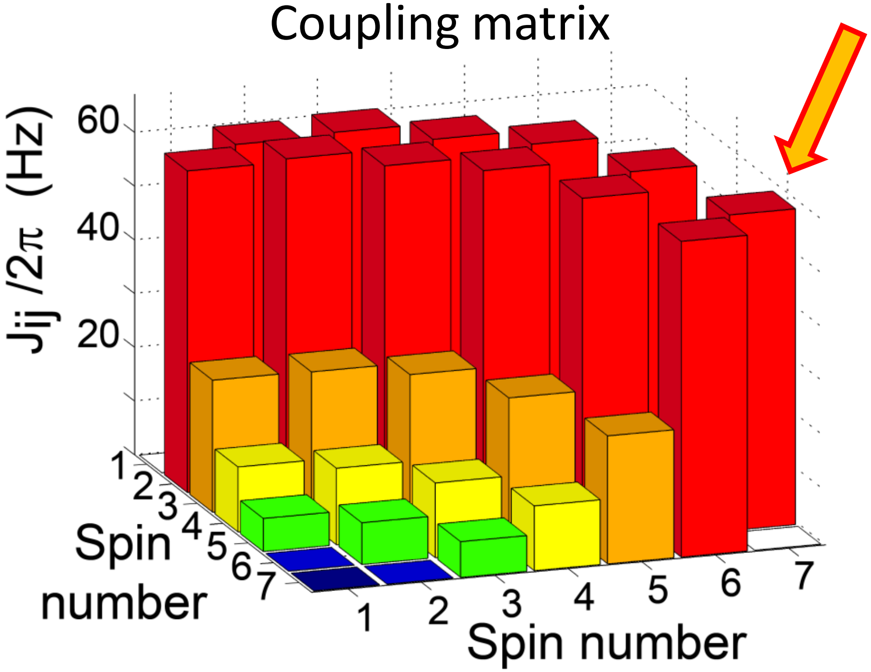
$$|\uparrow\rangle_i|\downarrow\rangle_j \longleftrightarrow |\downarrow\rangle_i|\uparrow\rangle_j$$

3. Measure coherent hopping rate

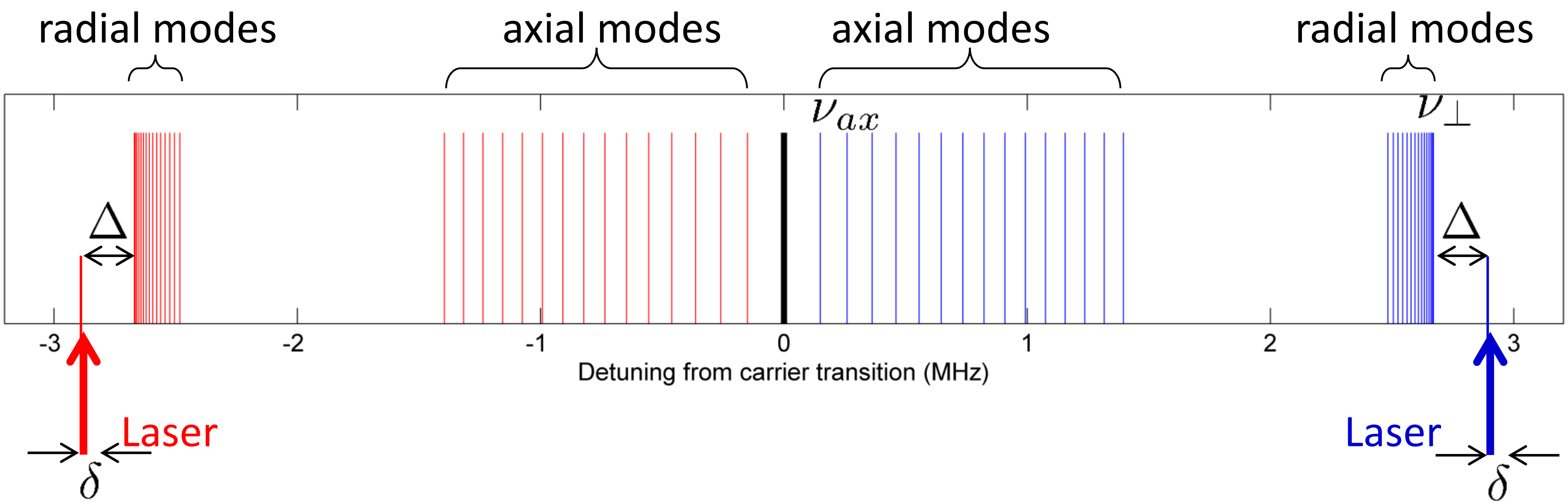



Coupling matrix



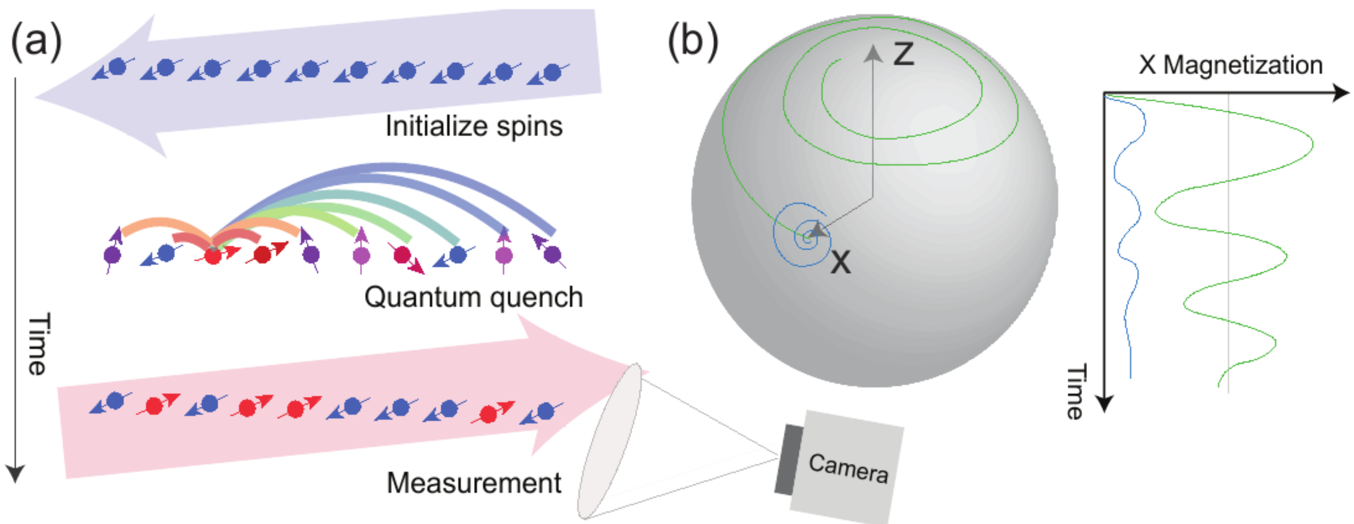
# Adding a transverse field




$$H = \sum_{i<j} \hbar J_{ij} \sigma_i^x \sigma_j^x + \hbar B \sum_i \sigma_i^z \qquad B = \delta/2$$

# Analog simulation with large spin chains

UMD - Monroe group




Switch global interaction Hamiltonian on rapidly

$$H = \sum_{i<j} J_{ij}\sigma_i^x \sigma_j^x + B_z \sum_i \sigma_i^z$$

"Observation of a Many-Body Dynamical Phase Transition in a 53-Qubit Quantum Simulator," J. Zhang et al., Nature 551, 601 (2017).

# Recent experiments

Talk next week

R. v. Bijnen

Self-Verifying Variational Quantum Simulation of the Lattice Schwinge
C. Kokail et al, arXiv:1810.03421

Probing entanglement entropy via randomized measurements,
T.Brydges et al, arXiv 1806.05747

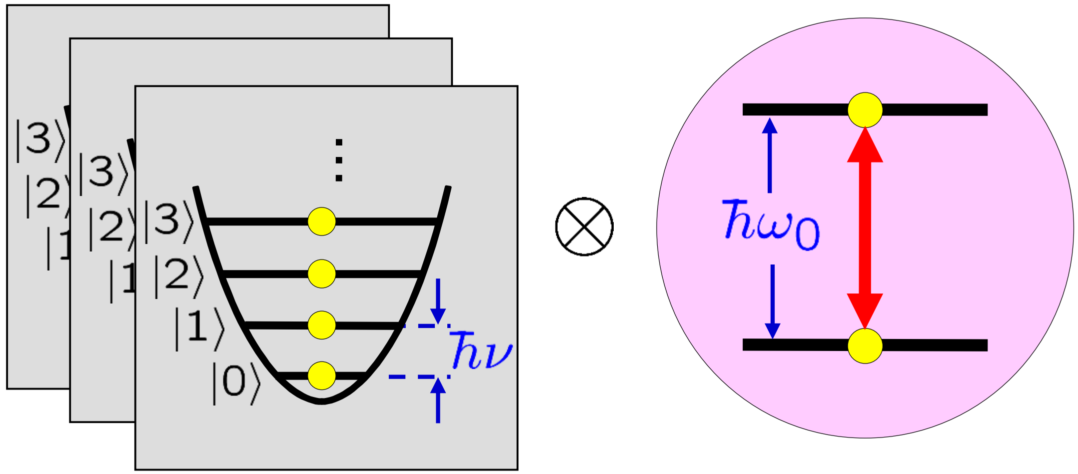
Observation of a Discrete Time Crystal,
J. Zhang et al, , Nature 543, 217 (2017)

Efficient tomography of a quantum many-body system,
B. P. Lanyon et al, Nat. Phys. 13, 1158 (2017)

# Outline

- Quantum gates on the transverse modes
- Simulating spin chains
- Beyond spin systems

# Simulation beyond spins



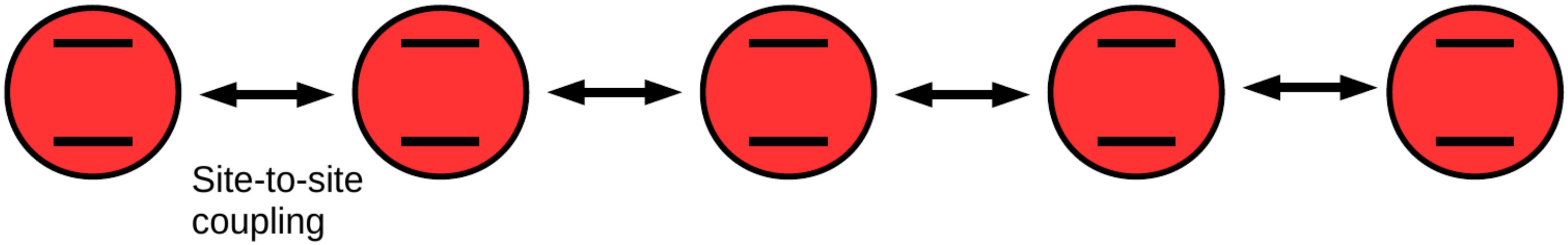

Simple idea: Use motional modes to increase the complexity of the simulation.

Spin-Boson model
A Lemmer et al, NJP 20 073002 (2018)

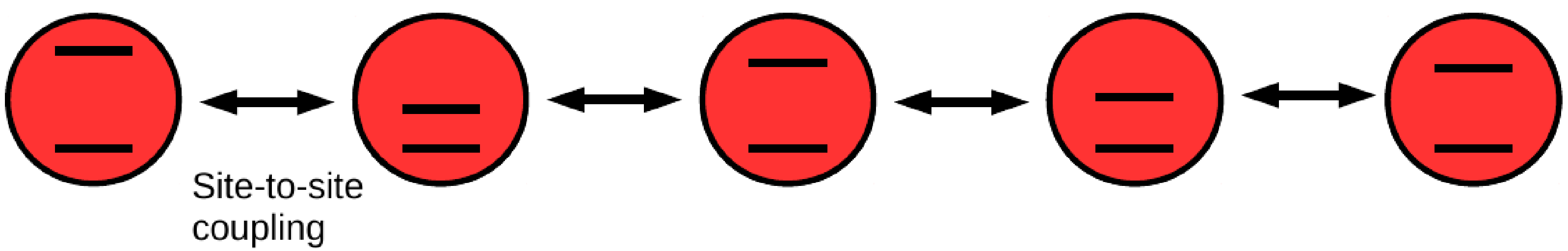
Vibrationally assisted energy transport
D. Gorman et al, PRX X 8, 011038 (2018)
Haeffner group, Berkeley

# Energy transport through chains

**On resonance**: Energy transfer between sites

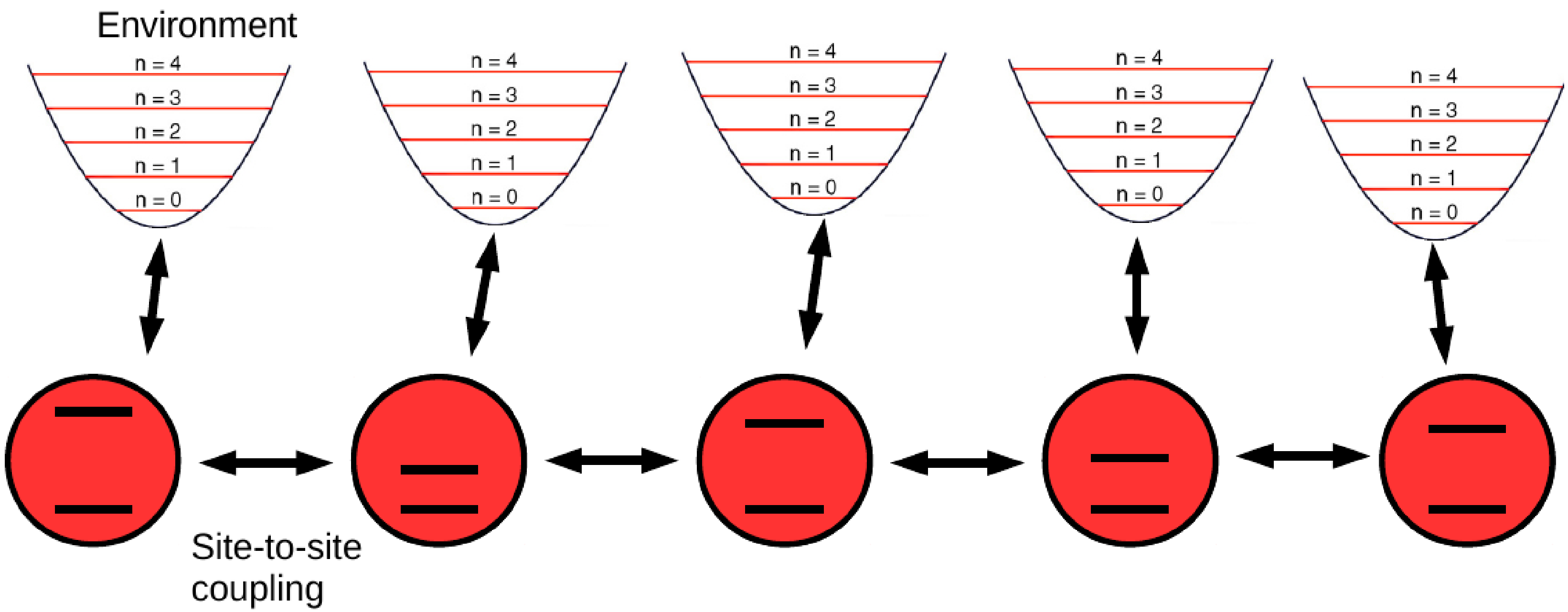



**Off resonance**: **No** energy transfer between sites



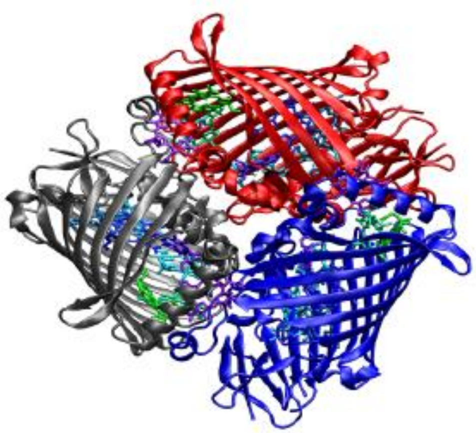
# Vibrationally assisted energy transport

**Environment can help to fulfill resonance condition**

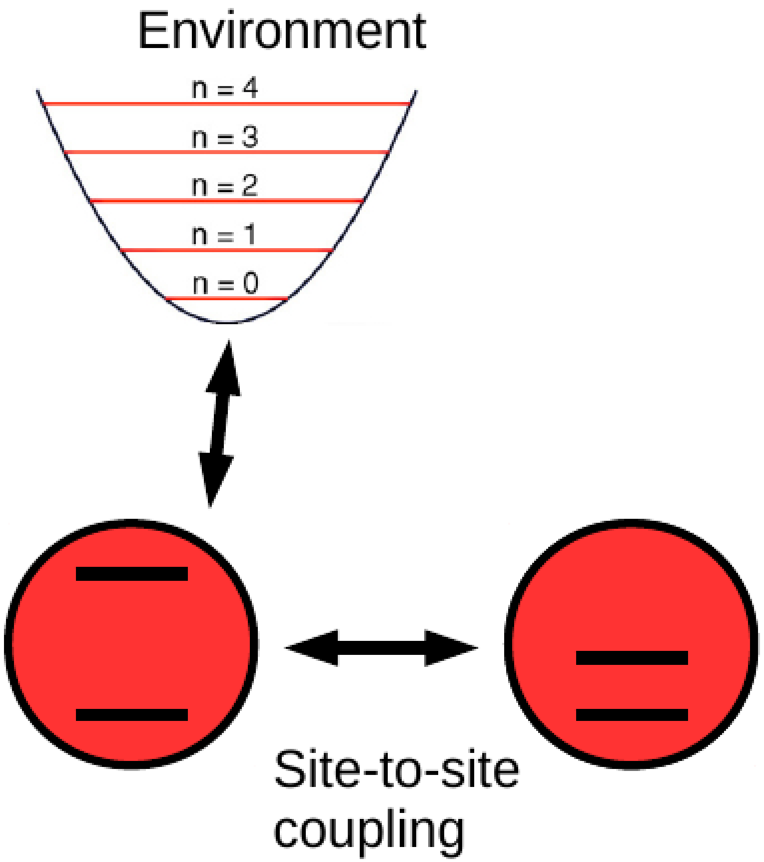



Linked to efficient energy transfer in light harvesting complexes?

Classically intractable for 10-20 spins+modes?

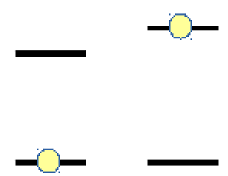


# Simplest system

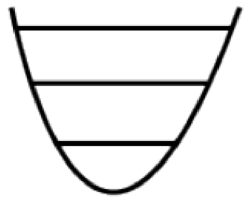



$$
\begin{aligned}
H_{\text{eff}}/\hbar = &\sum_{i,j} \frac{J_{ij}}{2} \left(\sigma_i^+ \sigma_j^- + \sigma_i^- \sigma_j^+\right) \\
&+ \sum_{i,j} \frac{K_{ij}}{2} \sigma_i^z \left(a_i + a_i^\dagger\right) \\
&+ \sum_i \frac{\Delta_i}{2} \sigma_i^z + \sum_i \nu_i a_i^\dagger a_i
\end{aligned}
$$

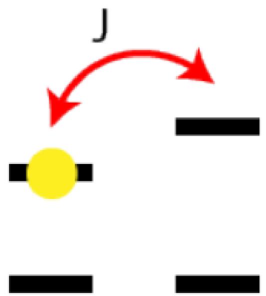
# Ion trap implementation



$$\frac{1}{2}\sum \Delta_i \sigma_z^i$$

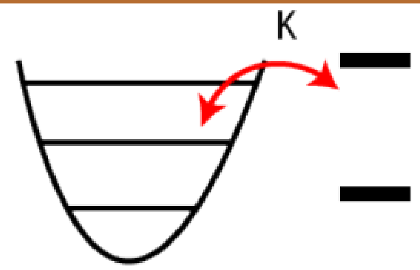


$$\sum \nu_i a^{\dagger i} a^i$$



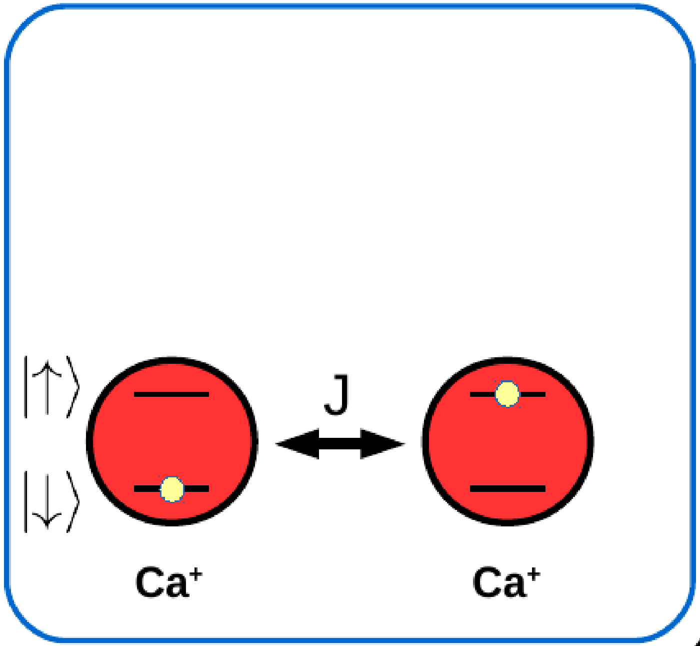

$$\frac{1}{2}\sum J_{ij}\sigma_x^i \sigma_x^j$$

Bichromatic light field with state dependent force!

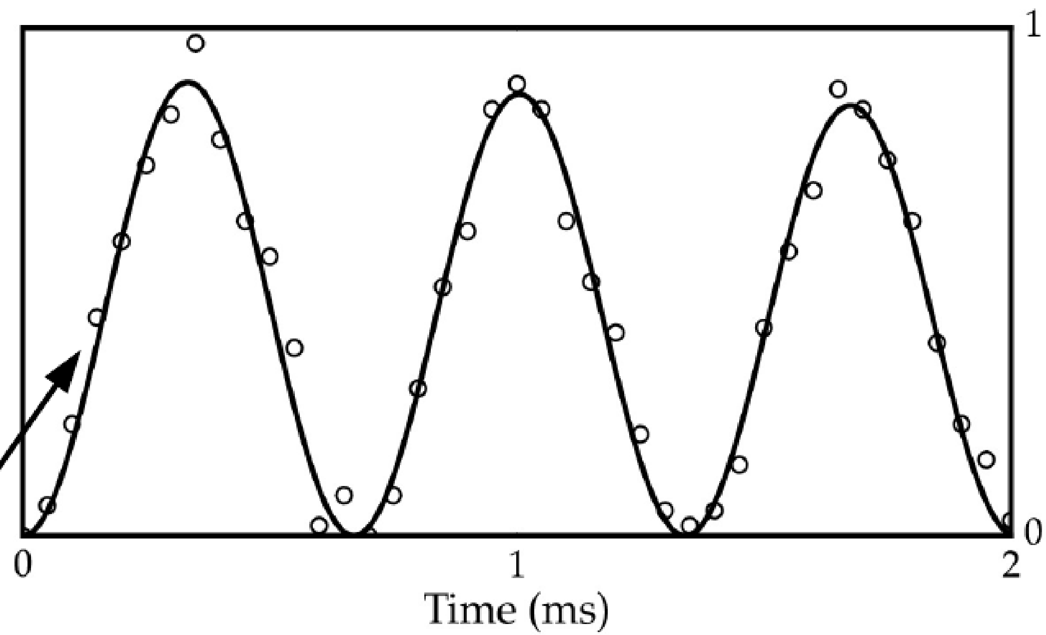



$$\frac{1}{2}\sum K_{ij}\sigma_z^i \left(a^j + a^{\dagger j}\right)$$

# Experiment: resonant transport




Measured probability of population transfer



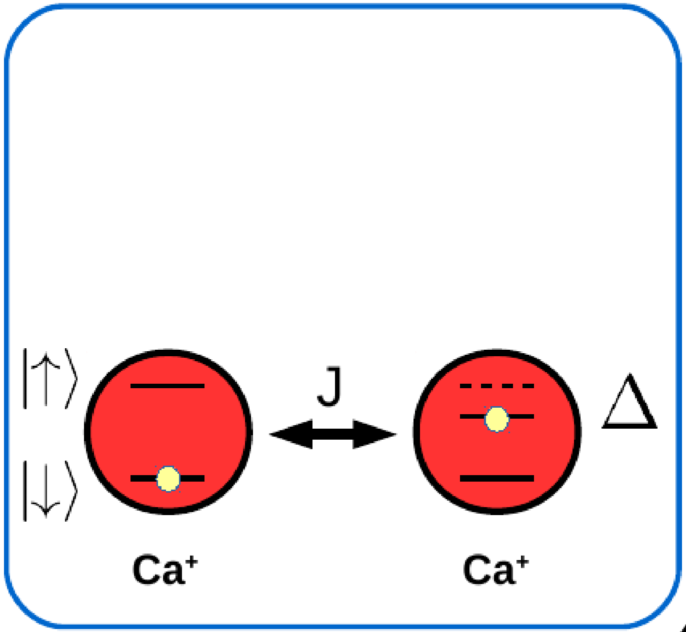

All parameters controllable!

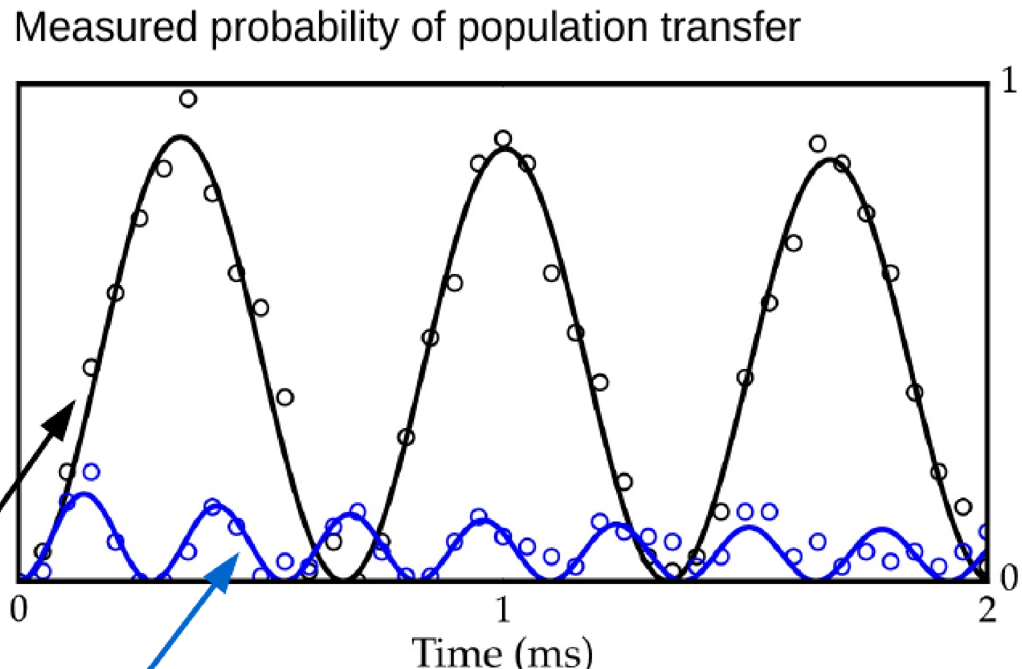
$$H = \frac{J}{2}\sigma_x^1 \sigma_x^2$$

Site-site coupling

D. Gorman et al, PRX X 8, 011038 (2018)

# Off-resonant spin without environment



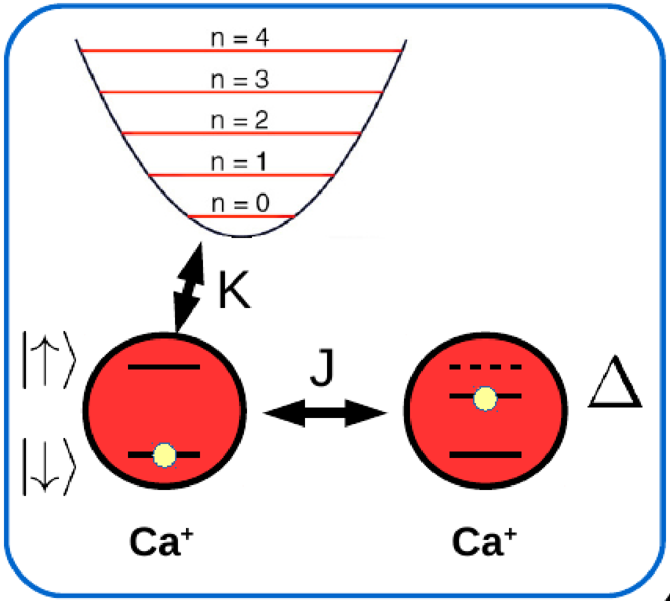




$$H = \frac{J}{2}\sigma_x^1\sigma_x^2 + \frac{\Delta}{2}\sigma_z^1$$

Site-site coupling Detuning

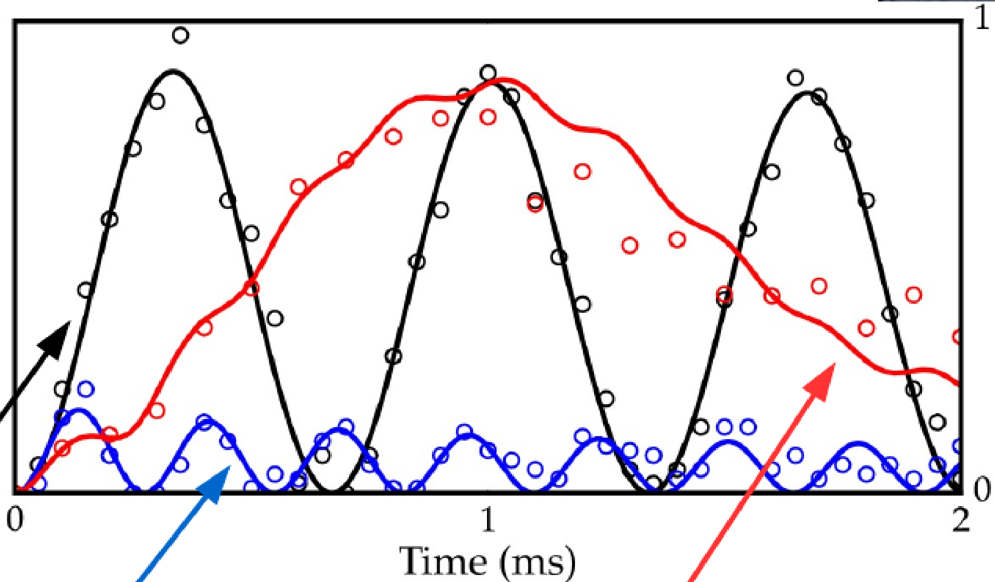
D. Gorman et al, PRX X 8, 011038 (2018)

# Vibrationally assisted transport




All parameters controllable!

Measured probability of population transfer



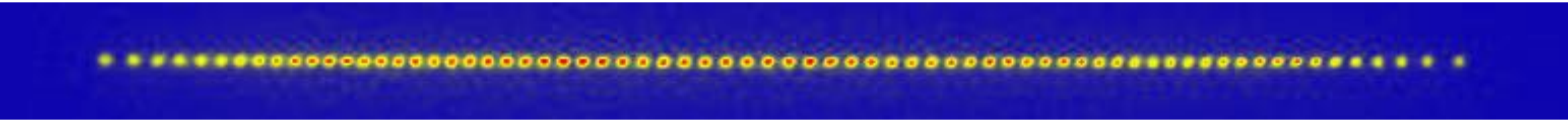

Vibrationally assisted energy transport

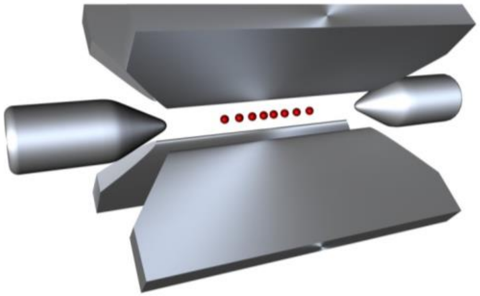
$$H = \frac{J}{2}\sigma_x^1\sigma_x^2 + \frac{\Delta}{2}\sigma_z^1 + \nu_{\text{eff}} a^\dagger a + \frac{K}{2}\sigma_z^1\left(a + a^\dagger\right)$$

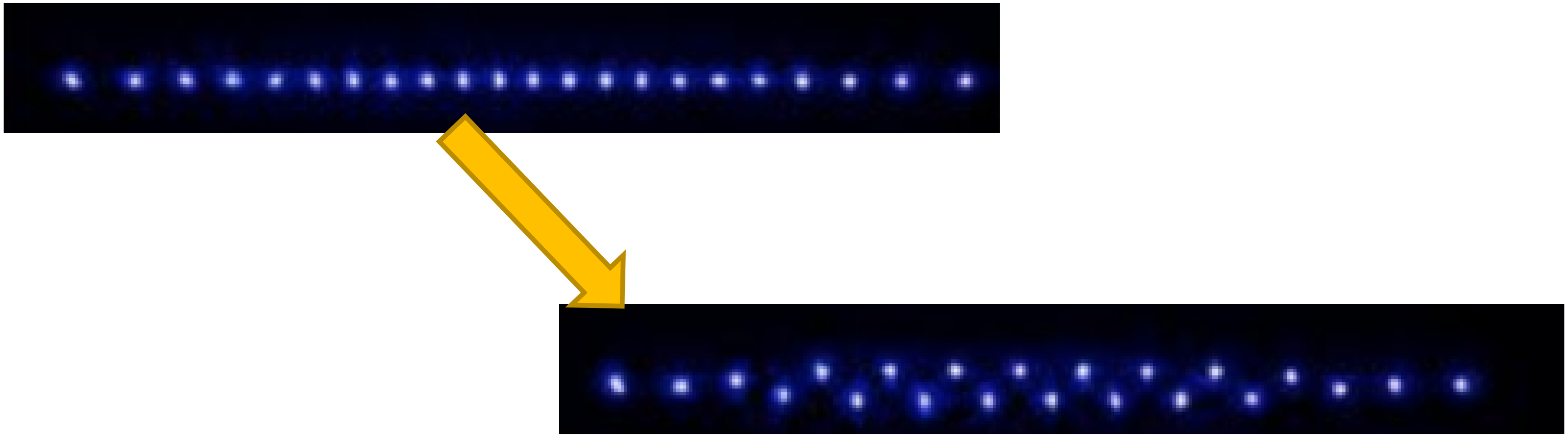
Site-site coupling — Detuning — Spin-bath coupling

D. Gorman et al, PRX X 8, 011038 (2018)

# Are ion traps scalable?







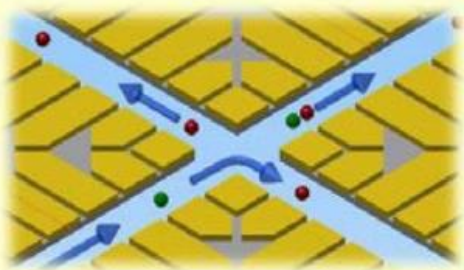
# Scaling ion traps to many particles

< 100 ions

Extended ion chains

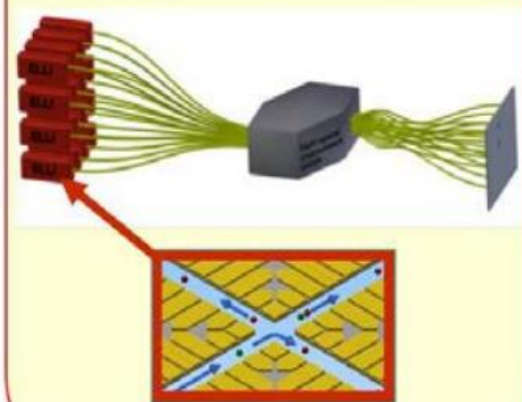
< 200 ions

Quantum CCD
- Deterministic shuttling
- Fault-tolerant

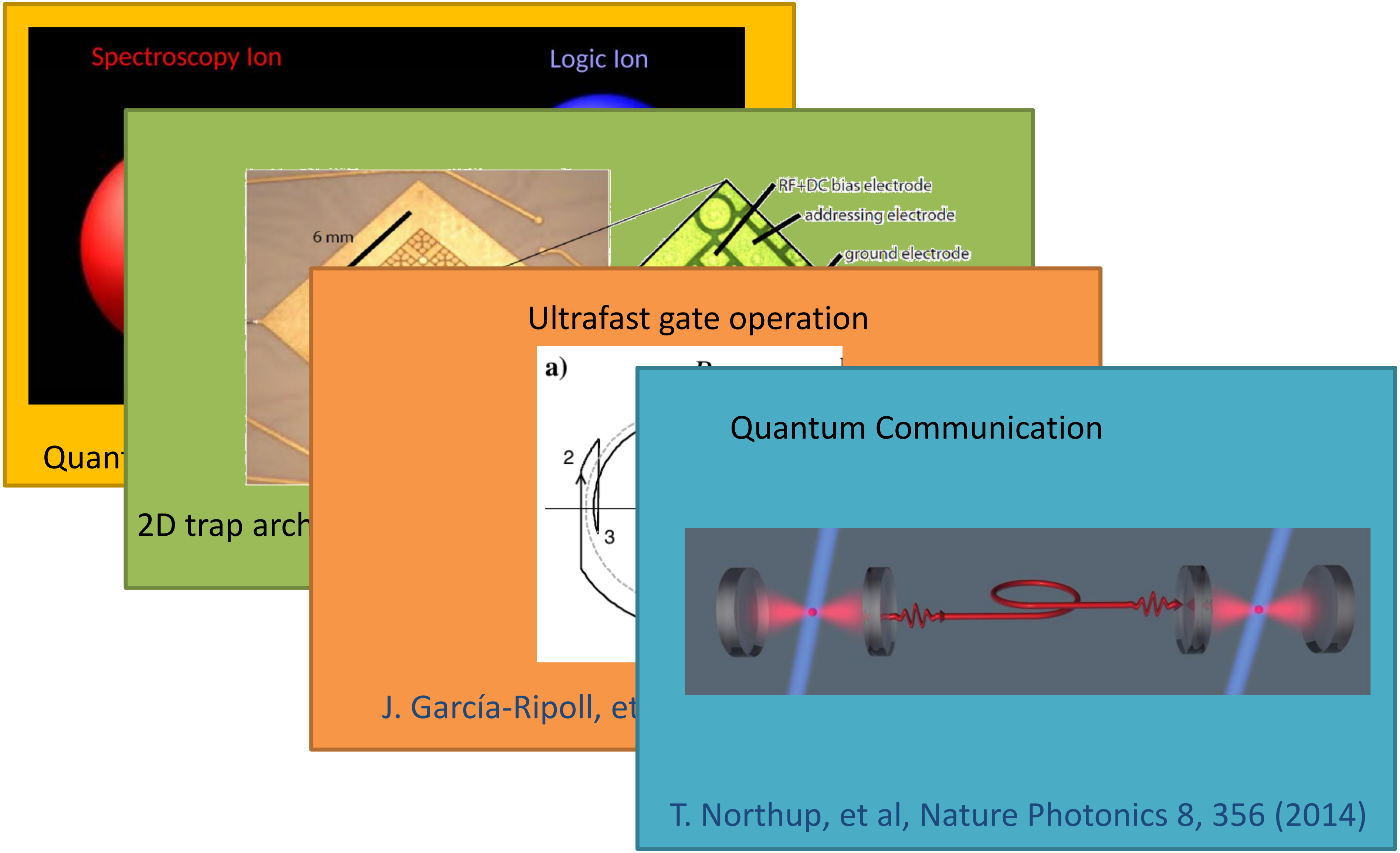


> 200 ions

Photonic links
- Entanglement distribution



# More ion trapping



# The International Team 2018

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AG Quantenoptik und Spektroskopie

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