Quantum simulations with trapped ions

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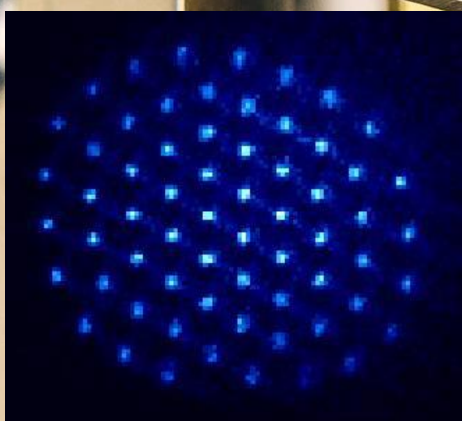

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Outline

- Quantum simulation approaches
  - Digital gate-based simulations
  - Crystal geometries
  - Analog simulations: engineering of long-range spin models
  - Detection and characterization of entangled states
  - Variational quantum simulation
  - Scaling quantum simulations to larger particle numbers

Simulating quantum physics

If there are quantum algorithms that run exponentially faster than their classical counterparts:

What stops us from simulating a quantum computer on a classical computer to find a solution in a much shorter time than with the classical algorithm?

Obstacle: There is no solution for simulating general quantum dynamics efficiently on a classical computer.

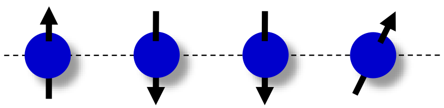
⇨ Maybe we should use a quantum processor to simulate the physics of quantum systems which is hard to simulate on classical computers

Quantum simulation

Quantum simulations with trapped ions

Simulating quantum many-body systems

How can we study the physics of quantum many-body systems?



Approaches:

- In some cases: Analytical techniques
- Numerical simulation methods on a computer using approximations

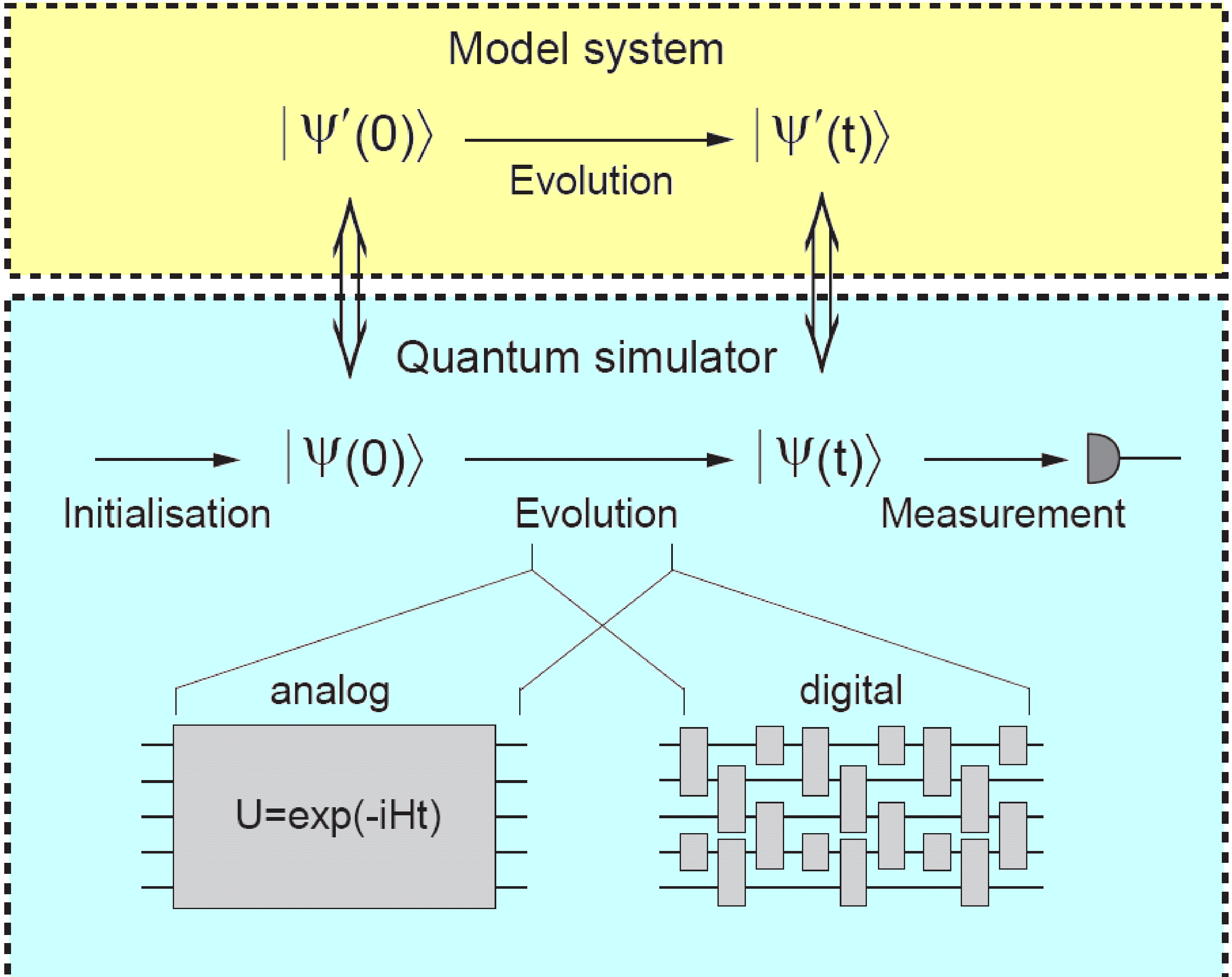
But: Exponential scaling of resources with the system size severely restricts the number of particles that can be exactly simulated.

Interacting spins: exact diagonalization techniques limited to N ~ 40 spins

- Feynman (1982), Lloyd (1996): **Quantum simulators**

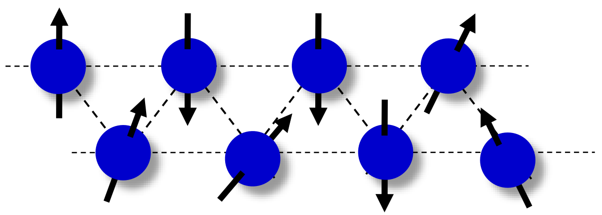
Use a precisely controlled quantum system for simulating a model of interest

Quantum simulation principle



Simulating quantum spin systems

Hamiltonians:



• Ising model (with transverse field)

$$H = \frac{1}{2}\sum_{i,j} J_{ij}\sigma_i^x\sigma_j^x + B\sum_i \sigma_i^z$$

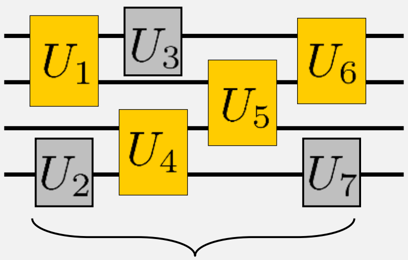
•XY model

$$H = \frac{1}{2}\sum_{i,j} J_{ij}^x\sigma_i^x\sigma_j^x + \frac{1}{2}\sum_{i,j} J_{ij}^y\sigma_i^y\sigma_j^y + B\sum_i \sigma_i^z$$

•Heisenberg model

$$H = \frac{1}{2}\sum_{i,j} J_{ij}^x\sigma_i^x\sigma_j^x + \frac{1}{2}\sum_{i,j} J_{ij}^y\sigma_i^y\sigma_j^y + \frac{1}{2}\sum_{i,j} J_{ij}^z\sigma_i^z\sigma_j^z + B\sum_i \sigma_i^z$$

Trapped-ion quantum simulations: Gate-based approach



$$U_{\text{sim}} = \prod_{j=1}^{N} U_j$$

Decompose dynamics induced by system Hamiltonian into sequence of quantum gates

$$U_{\text{sim}} \propto U_{\text{sys}} \qquad U_{\text{sys}} = e^{-\frac{i}{\hbar} H_{\text{sys}} \tau}$$

Quantum gate toolbox:

- Single qubit-gates
- Entangling two-qubit gates

Building up Hamiltonians

Spin-spin interaction $H_{xx} = J\,\sigma_x^{(1)}\sigma_x^{(2)}$

Can we add a transverse field? No… it would perturb the effective Hamiltonian H_{xx}

$$H = J\,\sigma_x^{(1)}\sigma_x^{(2)} + H_z$$

$$H_z = B\,(\sigma_z^{(1)} + \sigma_z^{(2)})$$

Solution: use ‚Trotterization' to generate the dynamics corresponding to $H_{xx} + H_z$

$$U = e^{-i(H_{xx}+H_z)t} \approx e^{-iH_{xx}\Delta t}e^{-iH_z\Delta t}\ldots e^{-iH_{xx}\Delta t}e^{-iH_z\Delta t}$$

How many steps?

N=2

H_{xx}	H_z	H_{xx}	H_z

N=4

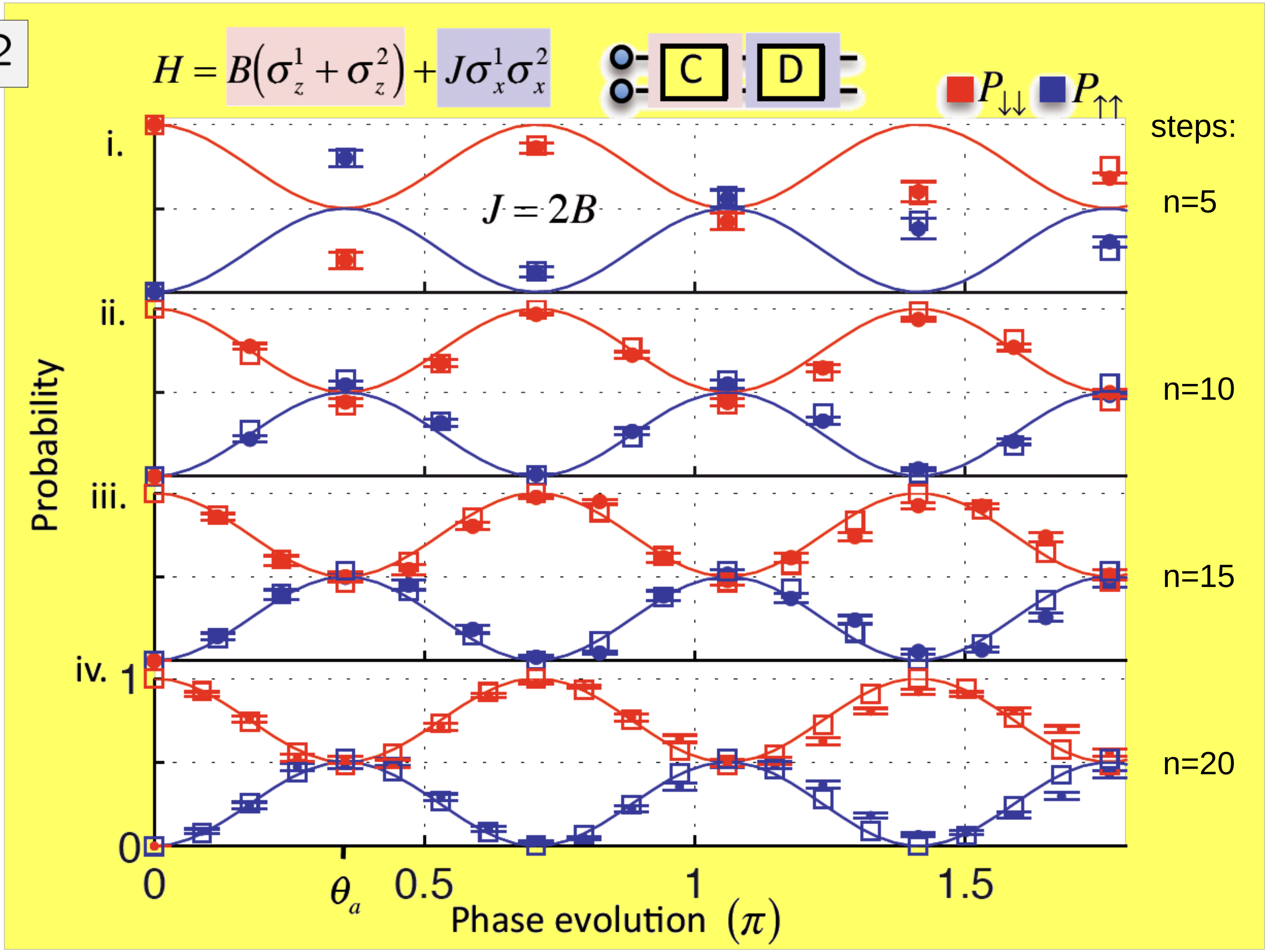
H_{xx}	H_z	H_{xx}	H_z	H_{xx}	H_z	H_{xx}	H_z

⋮

Time

Experimental ‚Trotterization' of $H_{xx} + H_z$

$J/B = 2$

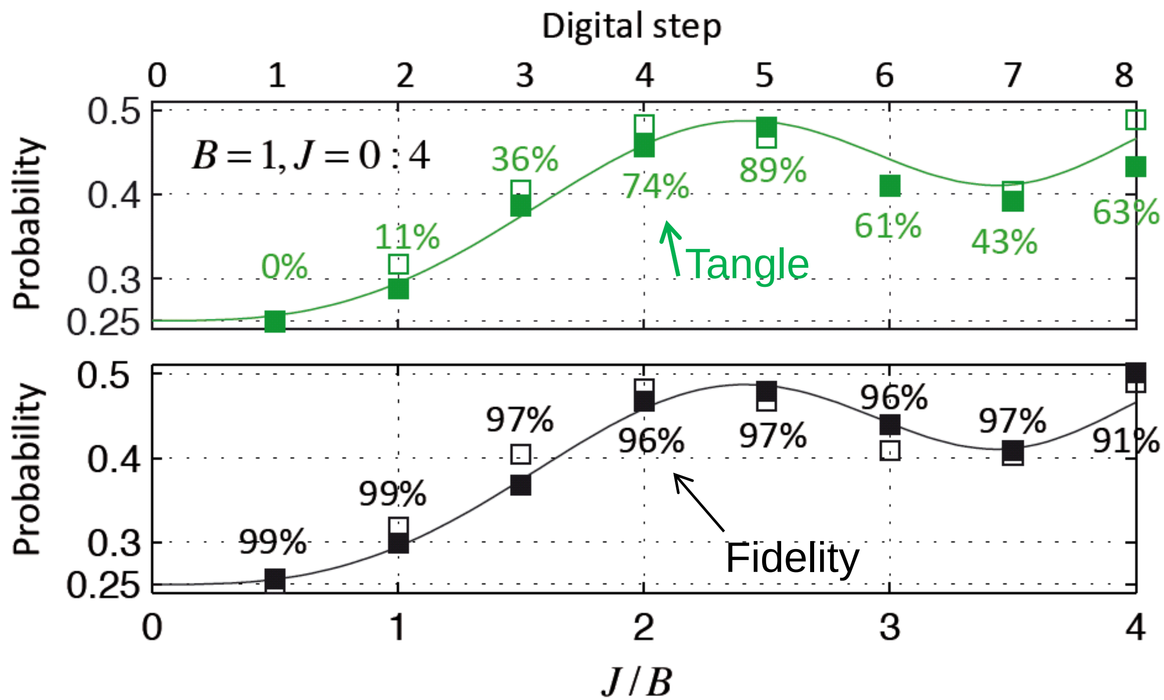


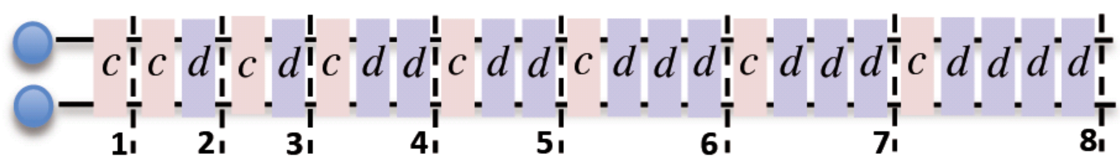
B. Lanyon *et al*, Science **334**, 57 (2011)

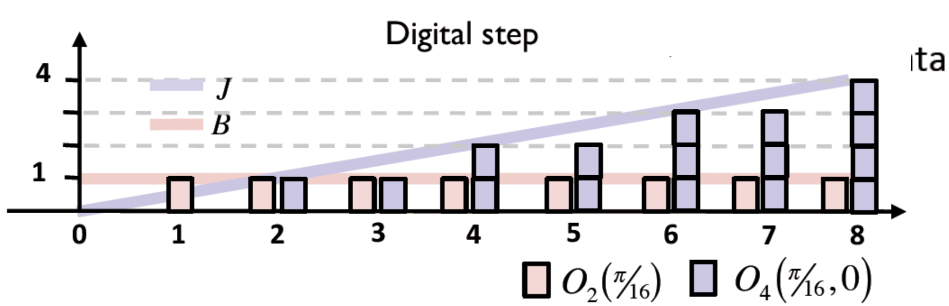
Trotterization of (non-)adiabatic evolution

$$H = B\left(\sigma_z^1 + \sigma_z^2\right) + J\sigma_x^1\sigma_x^2$$

$$\boxed{J/B = 0 \rightarrow 4}$$

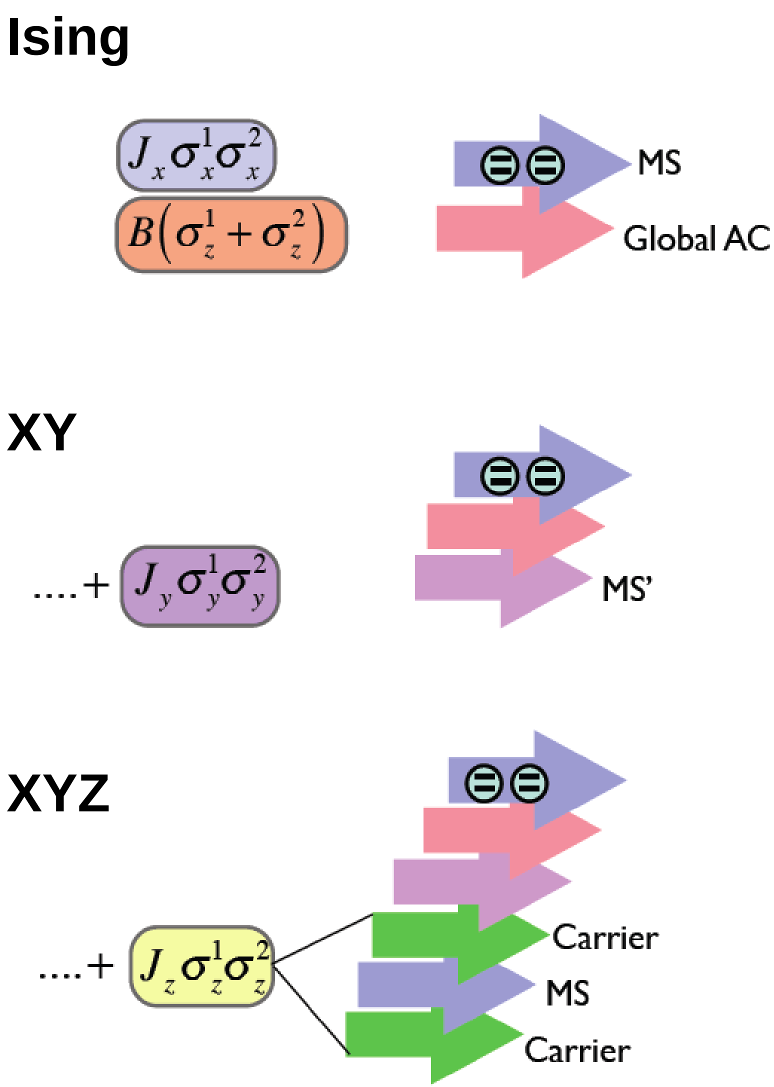


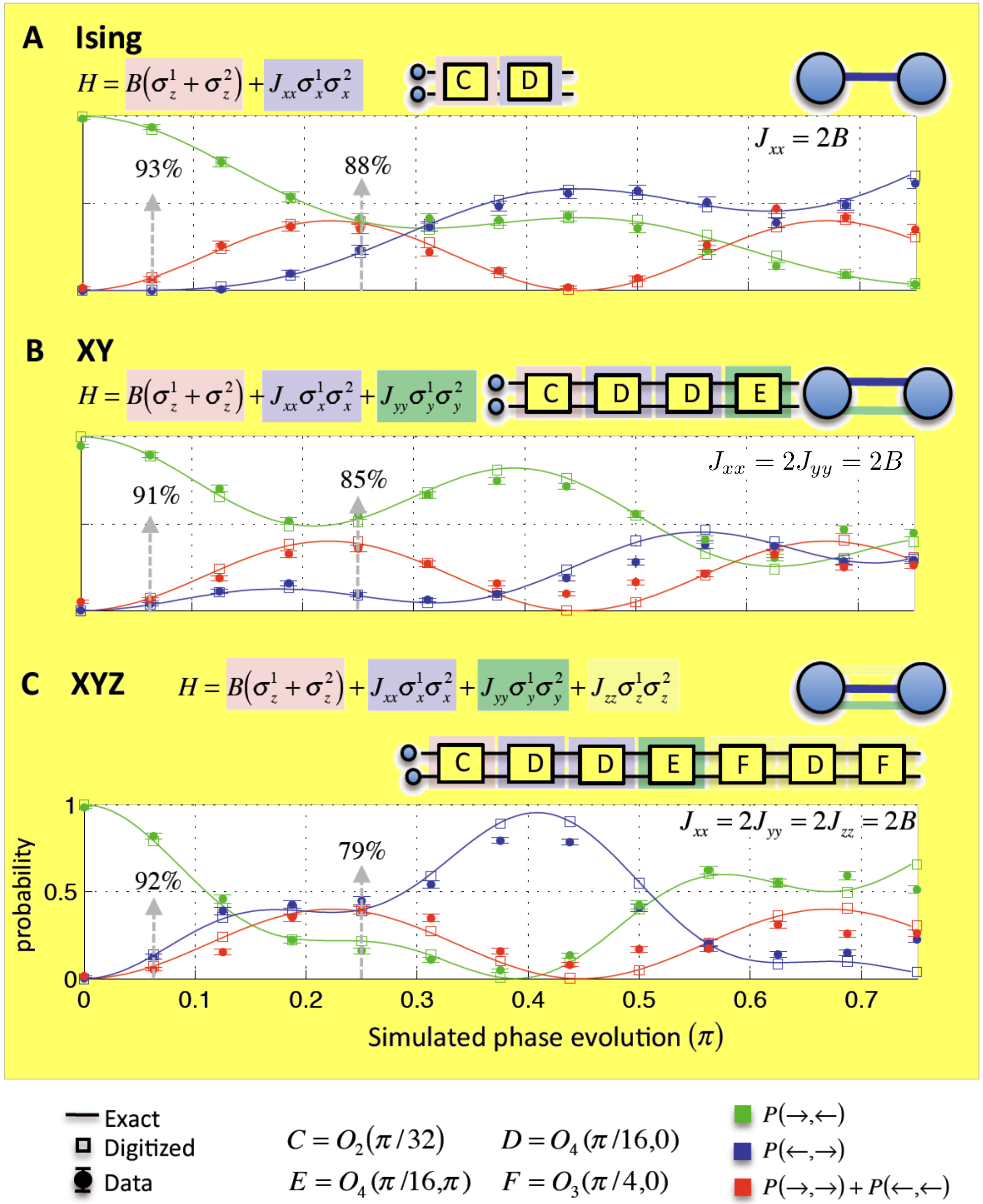




B. Lanyon *et al*, Science **334**, 57 (2011)

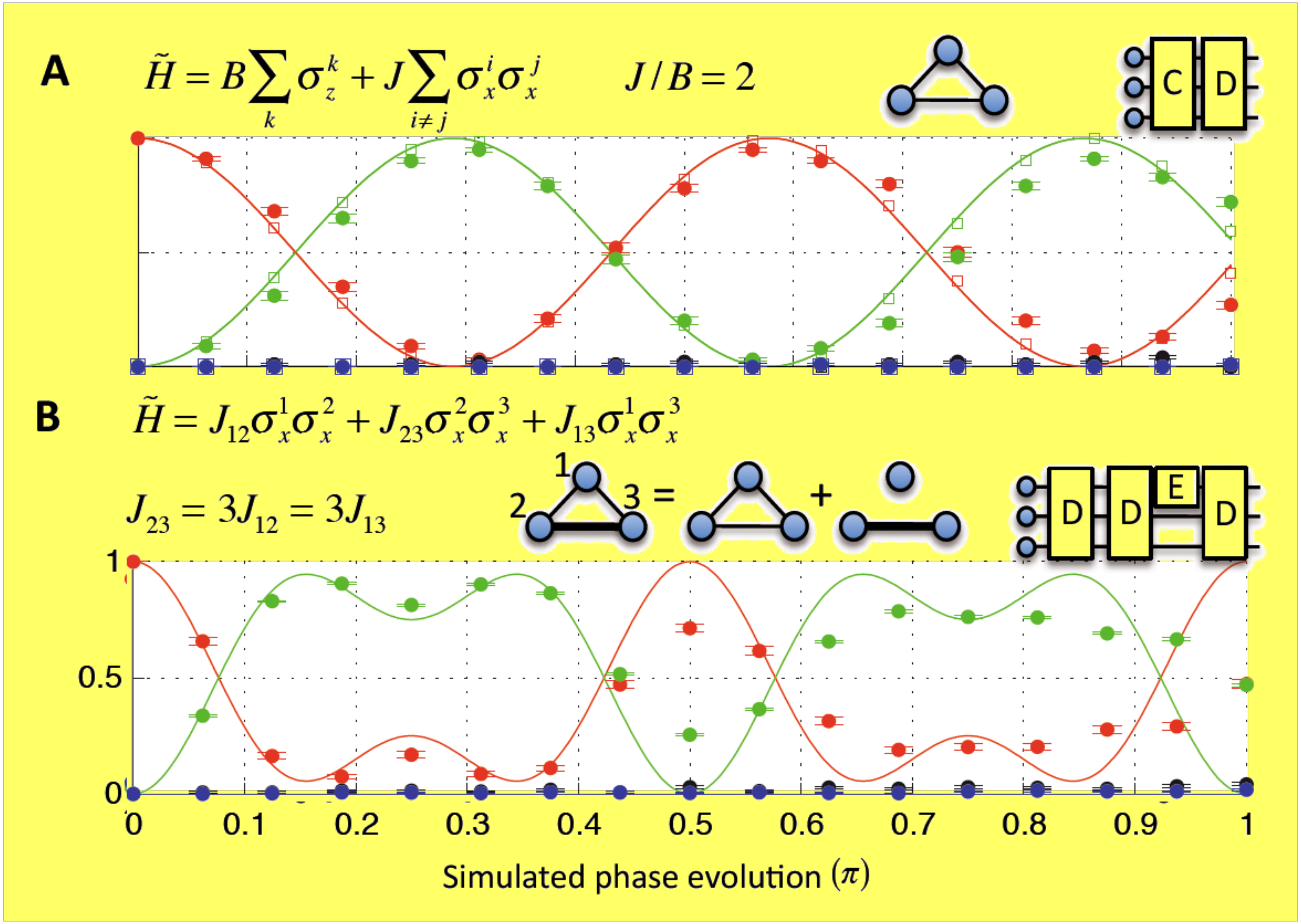
Building new interactions by Trotter technique





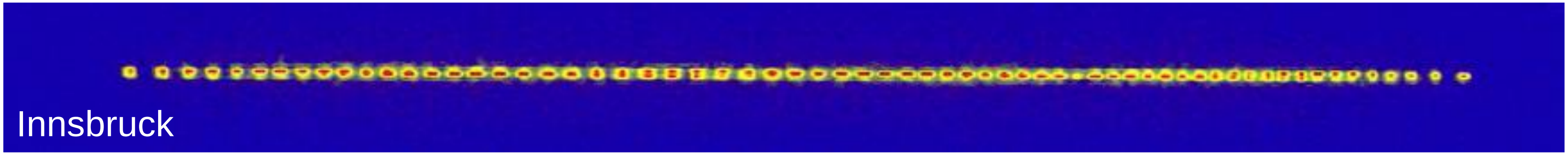
B. Lanyon *et al.*, Science **334**, 57 (2011)

Increasing the number of spins

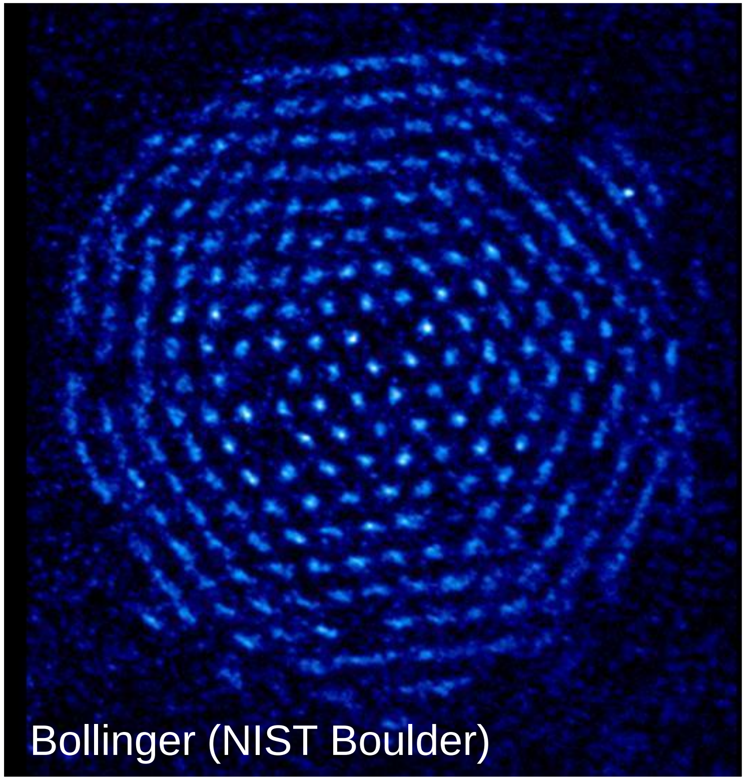


B. Lanyon *et al*, Science **334**, 57 (2011)

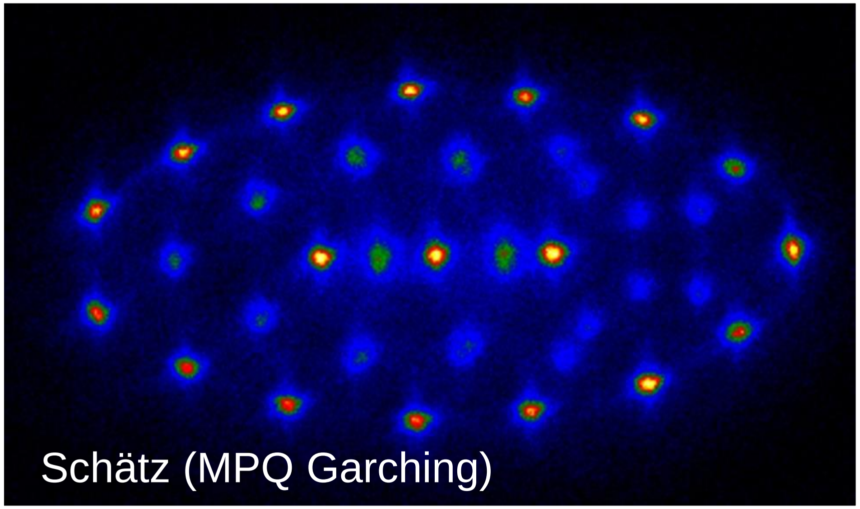
Trapped ions for simulating quantum magnetism



Challenges:



- Controlling the geometry
- Keeping decoherence low
- Engineering interactions



Trapping geometries: rf traps

Linear traps: Harmonic anisotropic potentials

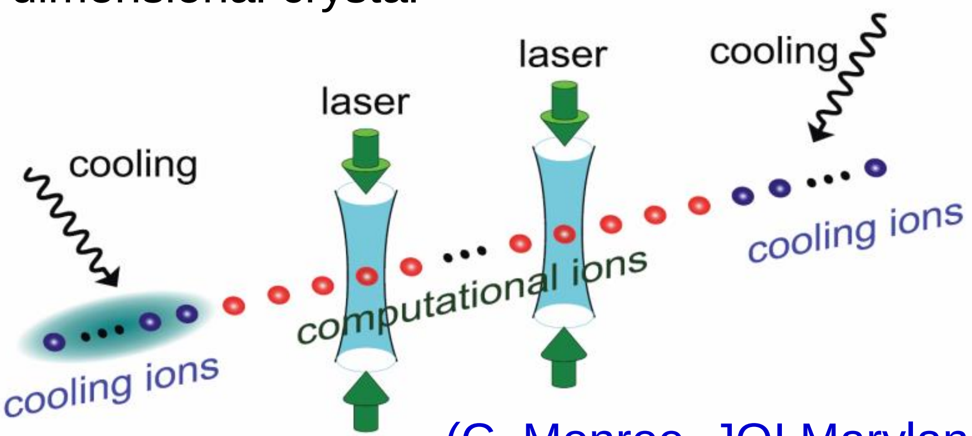
N = 2…100(?) ions in a one-dimensional crystal

$$\frac{\omega_r}{\omega_z} > 0.77\frac{N}{\log N}$$

longer crystals require very anisotropic potentials

Segmented microtraps: Anharmonic potentials for linear ion strings with equal spacing

N > 100(?) ions in a one-dimensional crystal

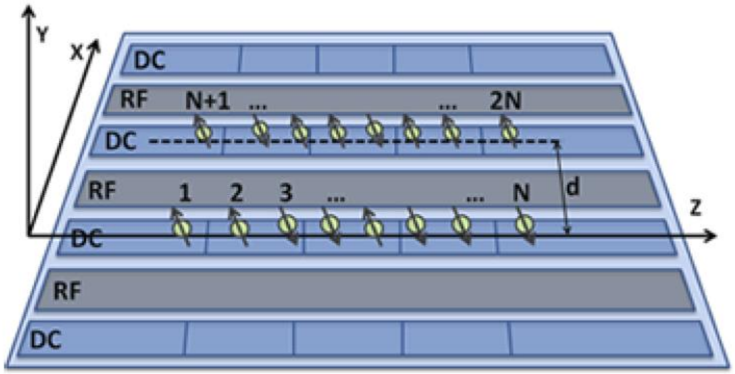


(C. Monroe, JQI Maryland)

G.-D. Lin, et al., Europhys. Lett. 86, 60004 (2009)

Trapping geometries: rf traps

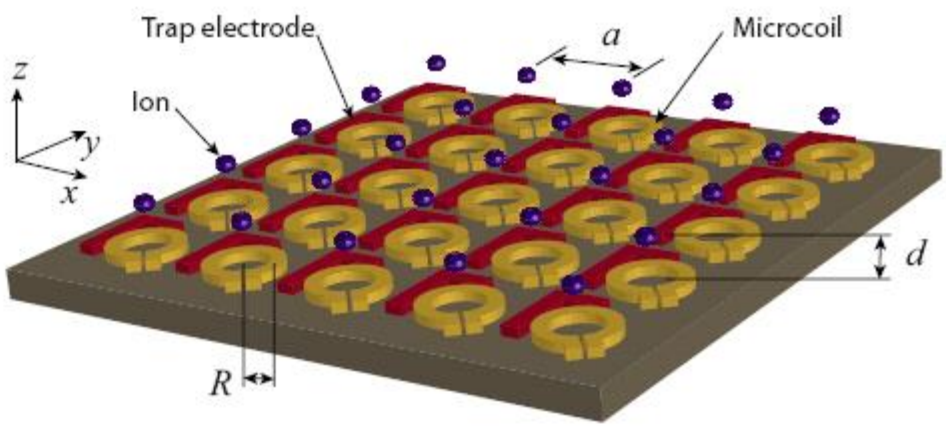
Segmented microtraps for Potentials with multipole trapping sites



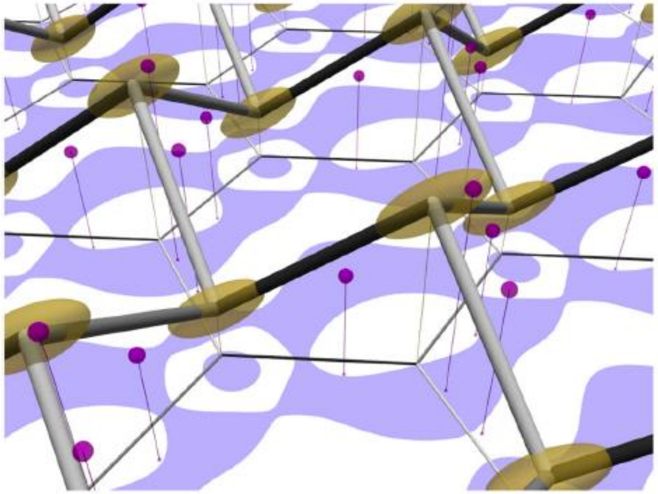
Multiple linear strings in close proximity

J. Welzel *et al*., EPJD **65**, 285 (2011)

2d-lattices of trapping sites



Chiaverini and Lybarger, Phys. Rev. A **77**, 022324 (2008)

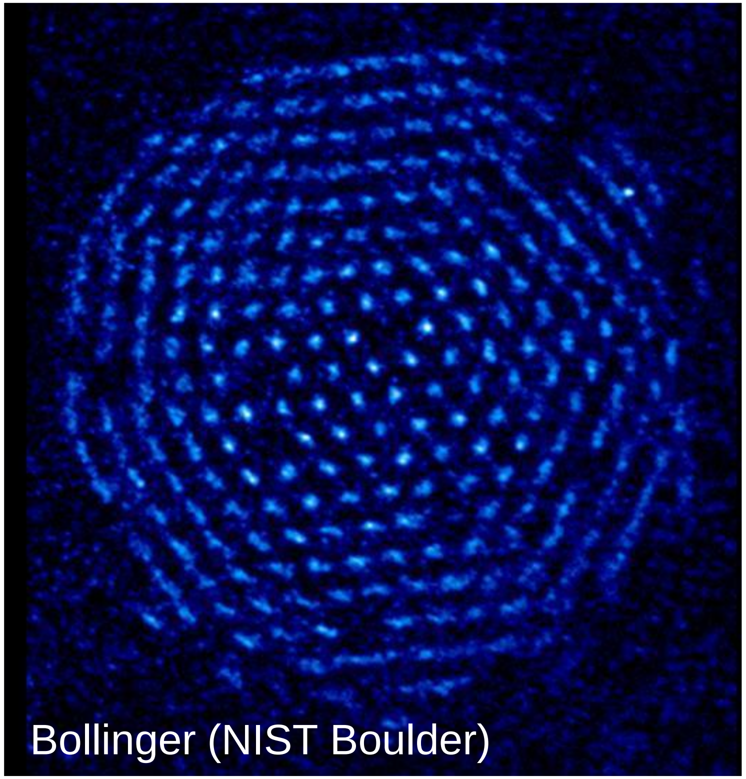


R Schmied *et al*, PRL **102**, 233002 (2009)

Trapping geometries: Penning traps

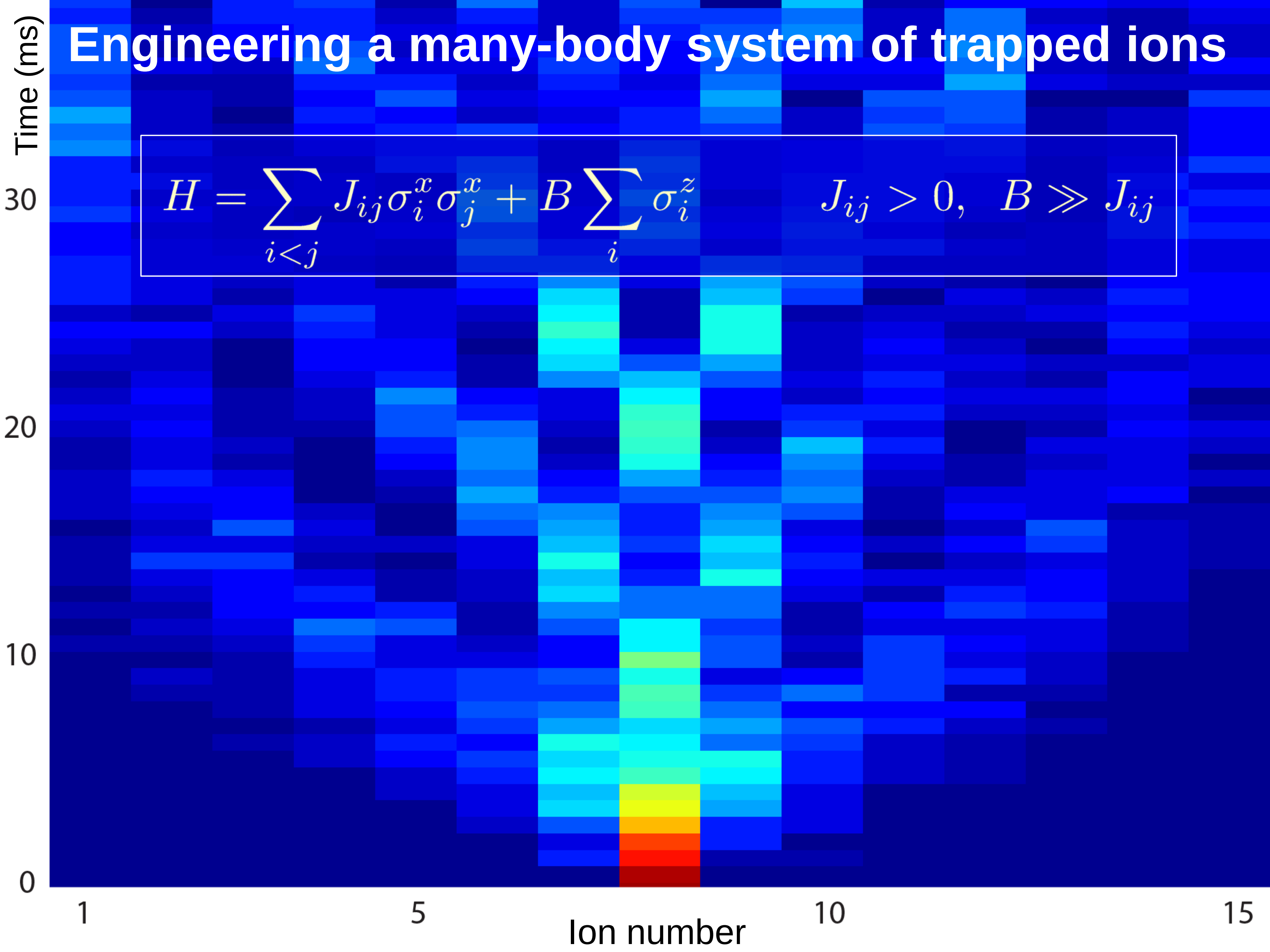
Penning trap: anisotropic potential for trapping 2d crystals

- N≈ 100 – 300 ions possible
- low internal state decoherence
- challenge: demonstrate same kind of
  quantum control as in rf-traps



Engineering a many-body system of trapped ions

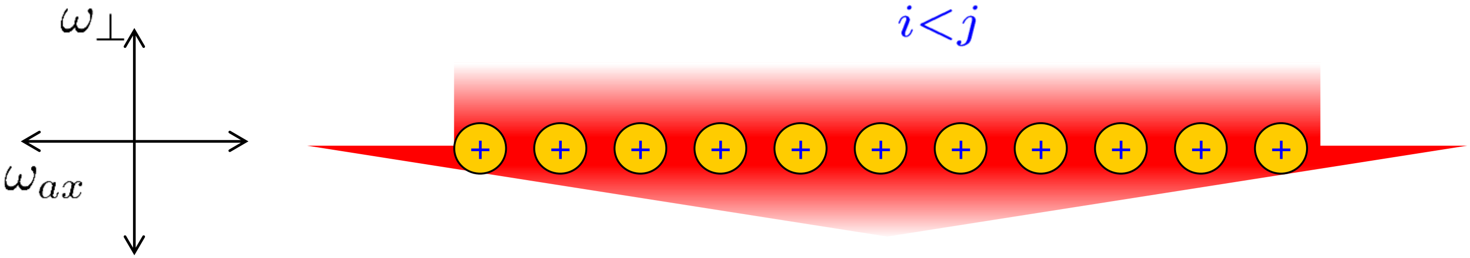
$$H = \sum_{i<j} J_{ij}\sigma_i^x\sigma_j^x + B\sum_i \sigma_i^z \qquad J_{ij} > 0, \quad B \gg J_{ij}$$



Geometry of laser-ion interaction

spin-spin coupling

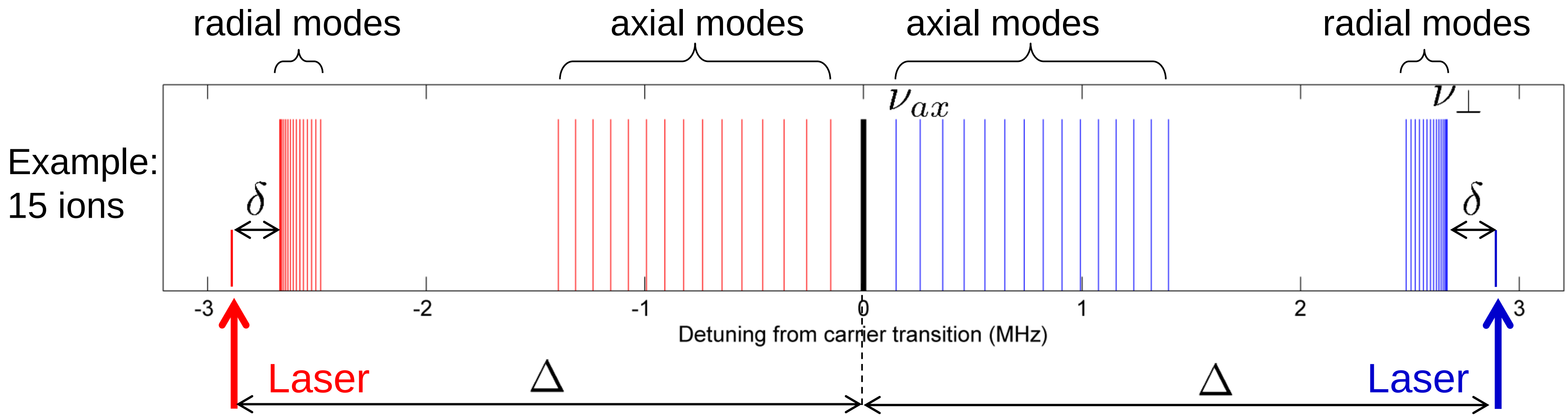
$$H = \sum_{i<j} J_{ij} \sigma_i^x \sigma_j^x$$

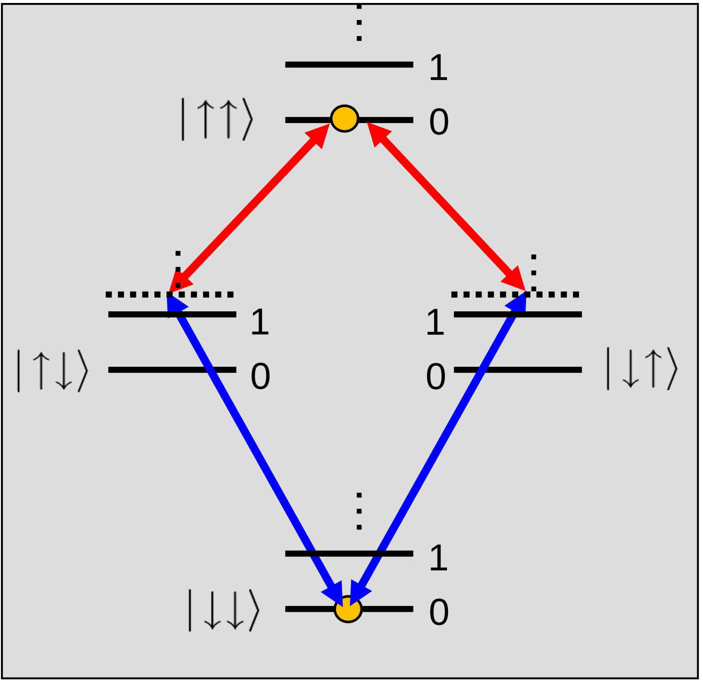


Features:

- Long strings $\Rightarrow$ strongly anistropic trapping potentials: $\omega_\perp / \omega_{ax} \approx 15 - 20$
- weak axial confinement $\Rightarrow$ 'hot' axial modes $\Rightarrow$ all laser beams $\perp$ to ion string

Variable-range interactions by coupling to transverse modes





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

with $$J_{ij} = \Omega^2 \frac{(\hbar k)^2}{2m} \sum_m \frac{b_{i,m} b_{j,m}}{\Delta^2 - \nu_m^2}$$

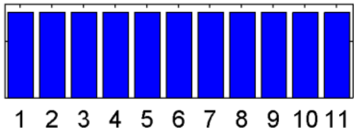
Variable-range interactions by coupling to transverse modes

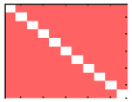
Example: 11 ions

$$J_{ij} = \Omega^2 \frac{(\hbar k)^2}{2m} \sum_m \frac{b_{i,m} b_{j,m}}{\Delta^2 - \nu_m^2}$$

vibrational mode

'COM'



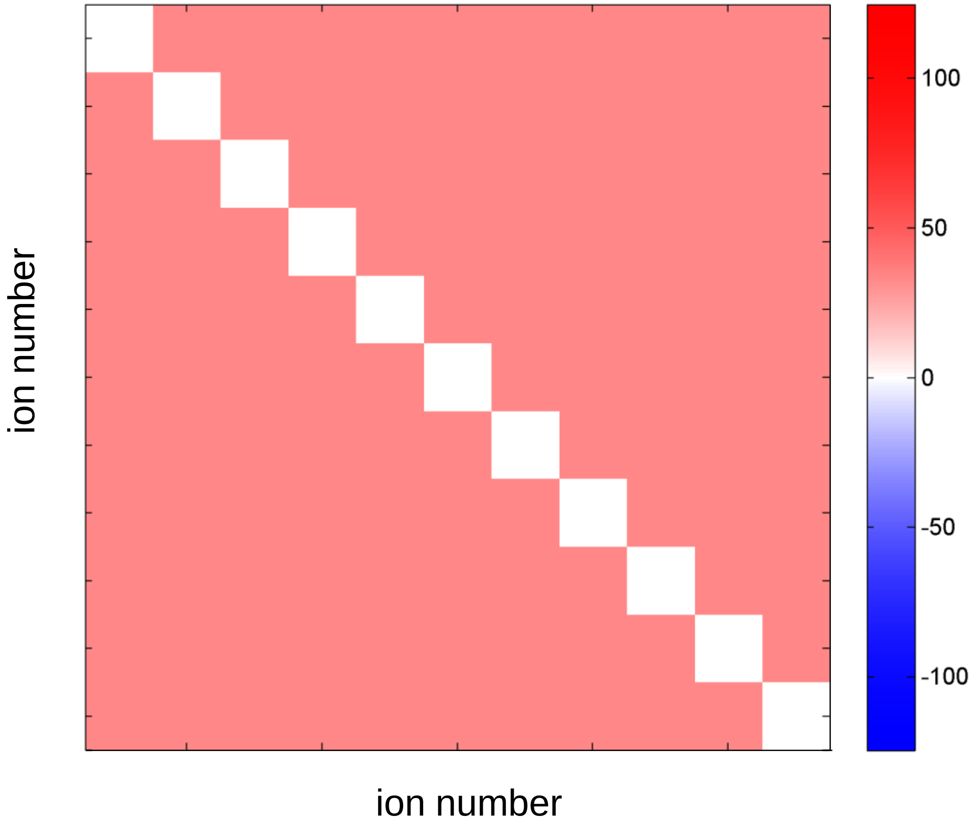


'Tilt'

⋮

⋮

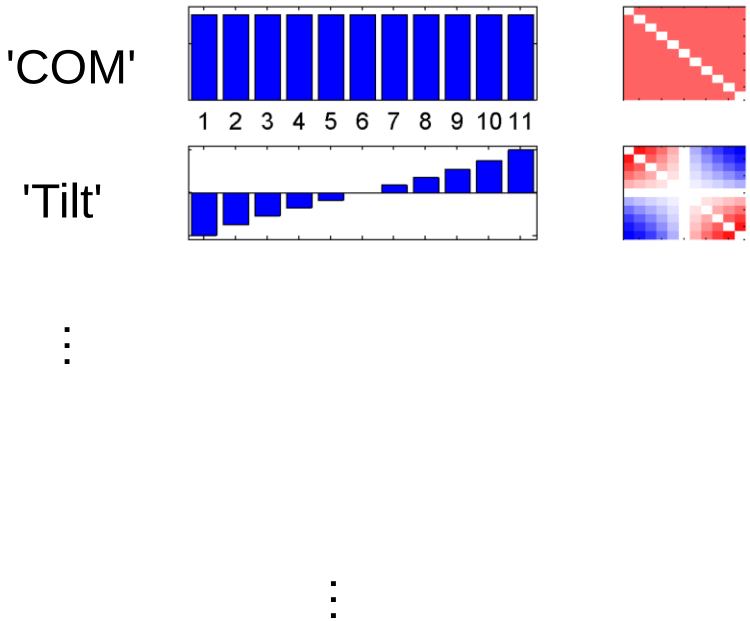
Spin-spin coupling matrix J_{ij} (Hz)



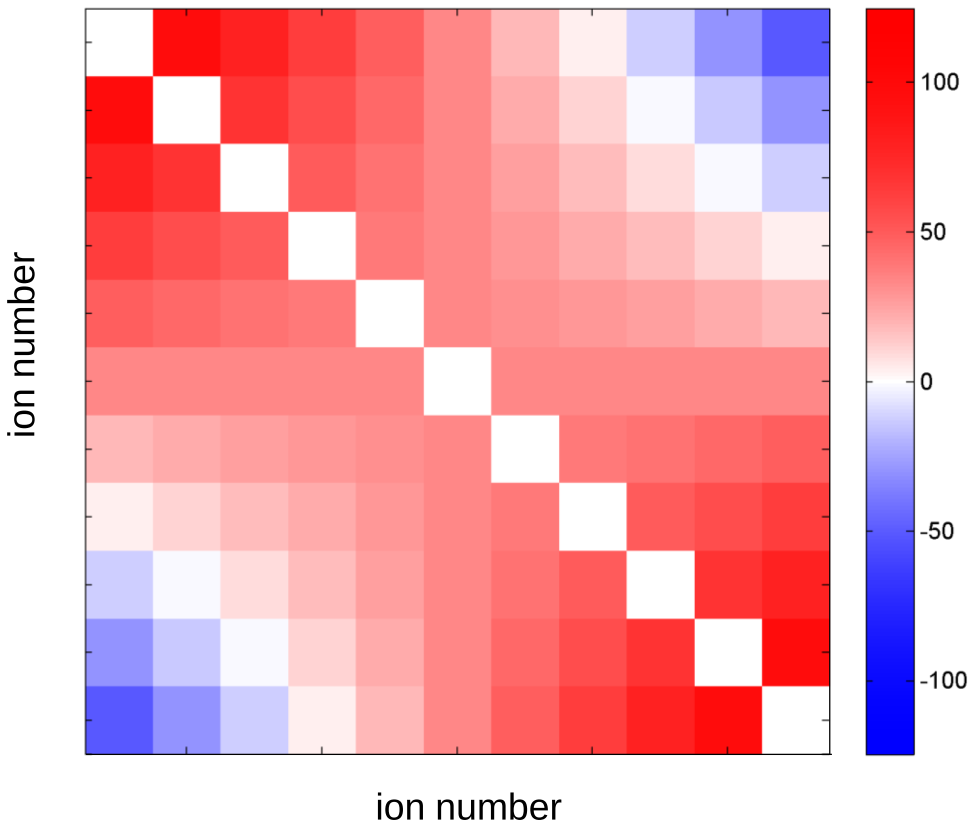
Variable-range interactions by coupling to transverse modes

Example: 11 ions

$$J_{ij} = \Omega^2 \frac{(\hbar k)^2}{2m} \sum_m \frac{b_{i,m} b_{j,m}}{\Delta^2 - \nu_m^2}$$



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



Variable-range interactions by coupling to transverse modes

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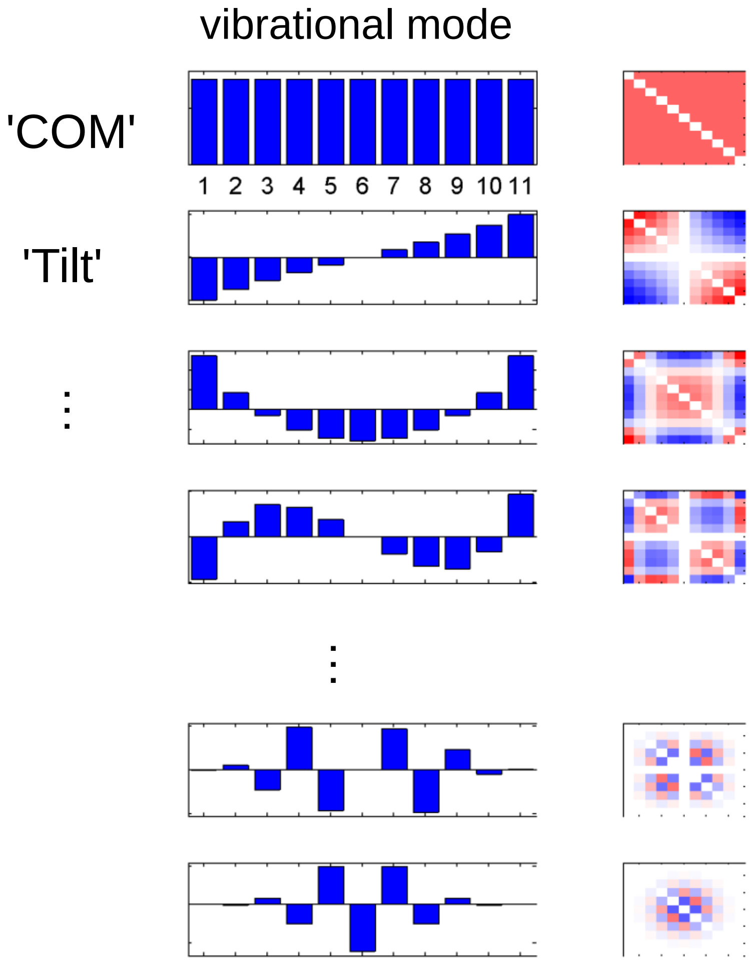
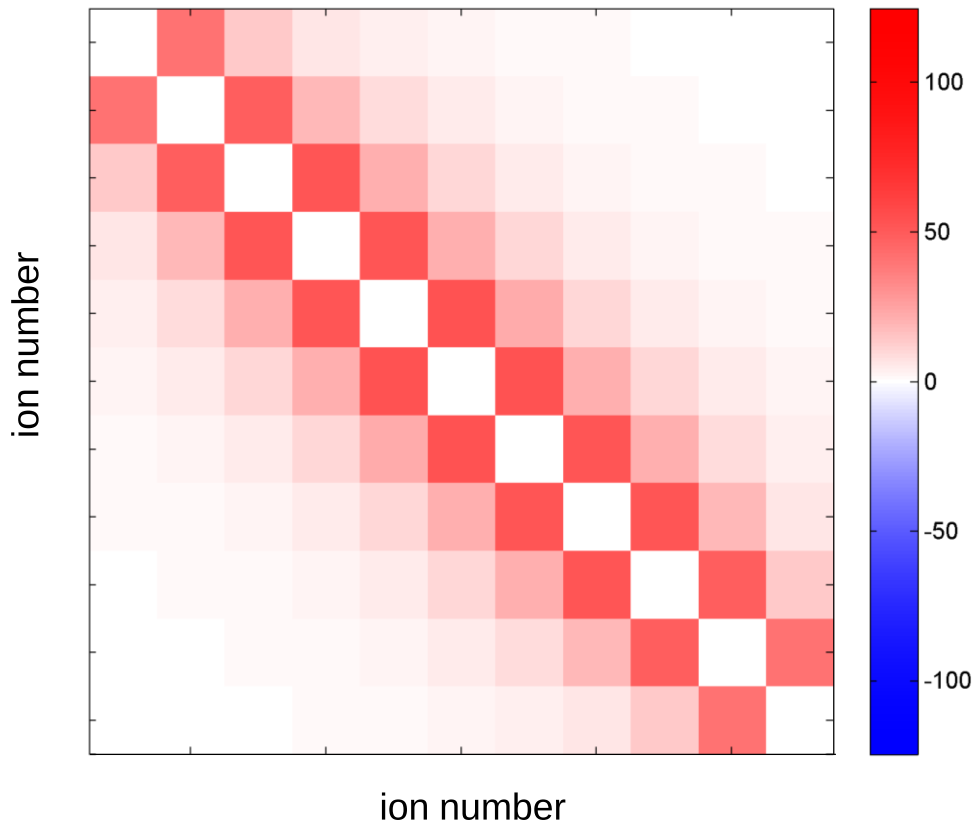
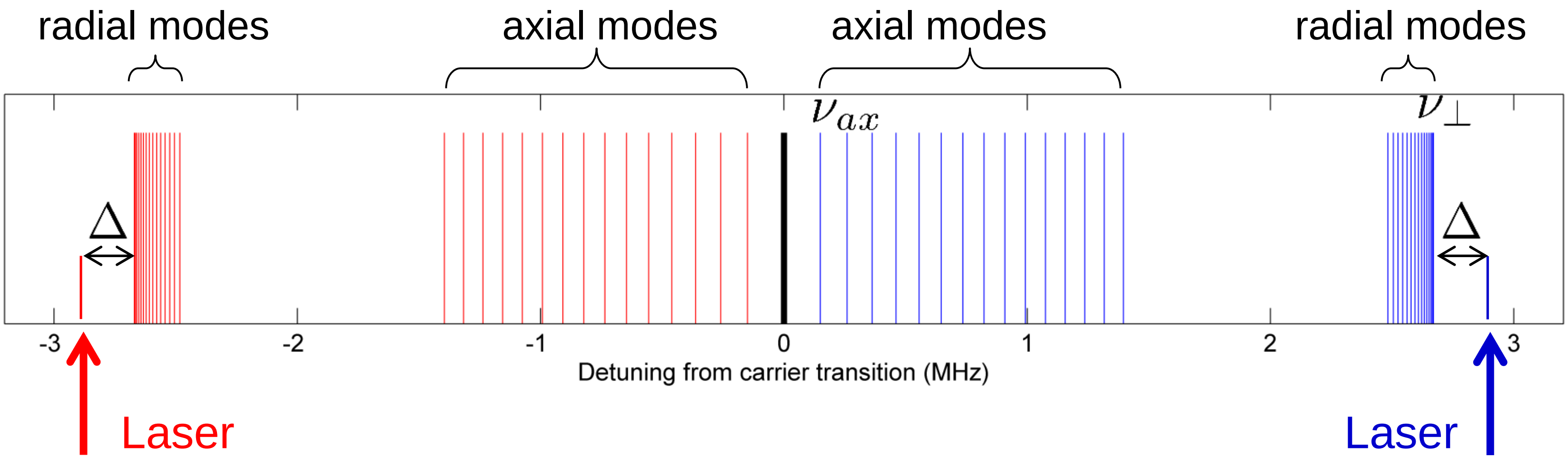


Spin-spin coupling matrix J_{ij} (Hz)



Variable-range interactions by coupling to transverse modes

Example:
15 ions



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

Interaction range: $0 < \alpha < 3$

couple only to center-of-mass

couple to all modes equally

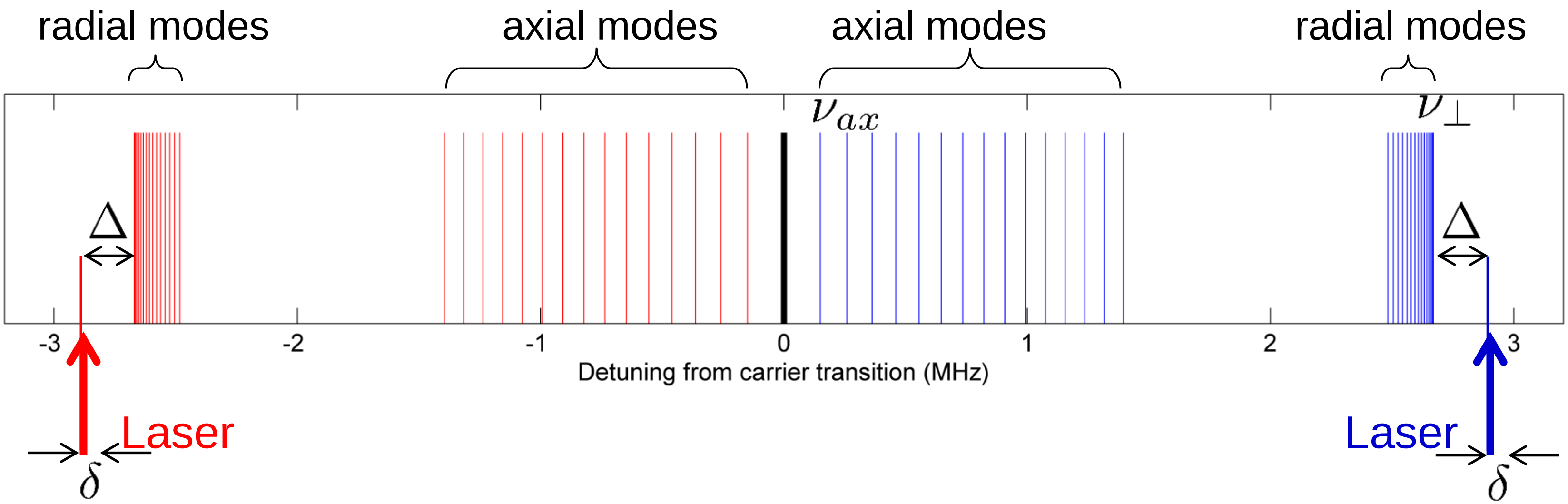
Knobs to turn:

- laser detuning Δ
- spread of radial modes

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

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

Ising model with transverse field



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

$$\approx \sum_{i<j} J_{ij} (\sigma_i^+ \sigma_j^- + h.c.) + B \sum_i \sigma_i^z \quad \text{for} \quad B \gg J$$

„XY model“: hopping of spin excitations

Measurement of the coupling matrix

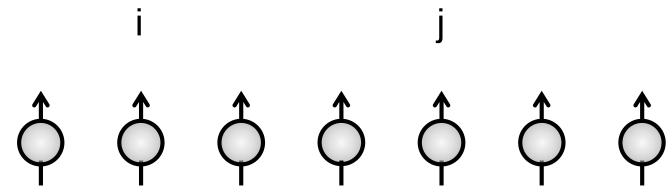
Protocol:

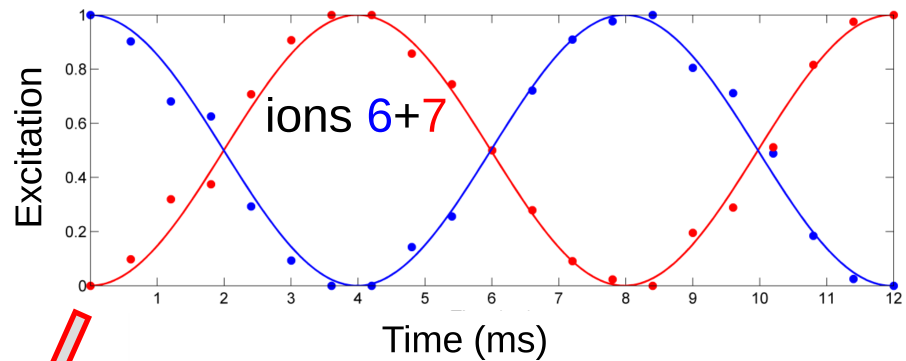
1. Initialize ions in state $|\uparrow\rangle_i|\downarrow\rangle_j$

2. Switch on Ising Hamiltonian

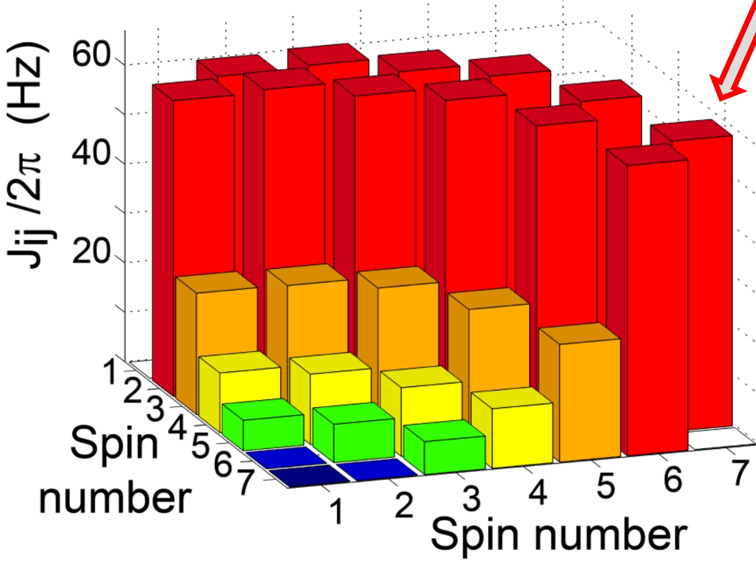
$$|\uparrow\rangle_i|\downarrow\rangle_j \longleftrightarrow |\downarrow\rangle_i|\uparrow\rangle_j$$

3. Measure coherent hopping rate





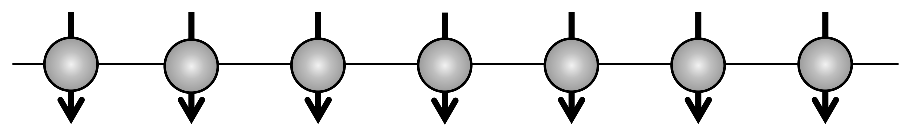
Coupling matrix



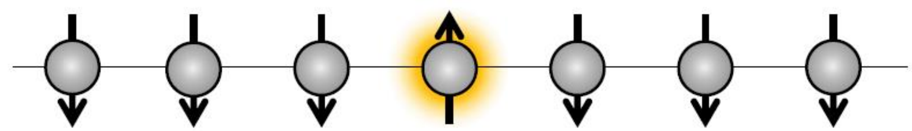
Spread of correlations after local quenches

$$H_{XY} = \sum_{i<j} J_{ij}(\sigma_i^+ \sigma_j^- + h.c.) \,+\, B \sum_i \sigma_i^z$$

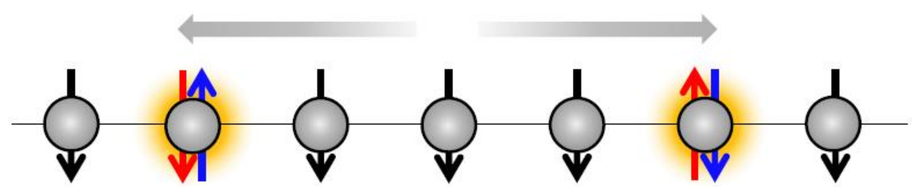
Ground state: all spins aligned with transverse field



1. Local quench: flip one spin

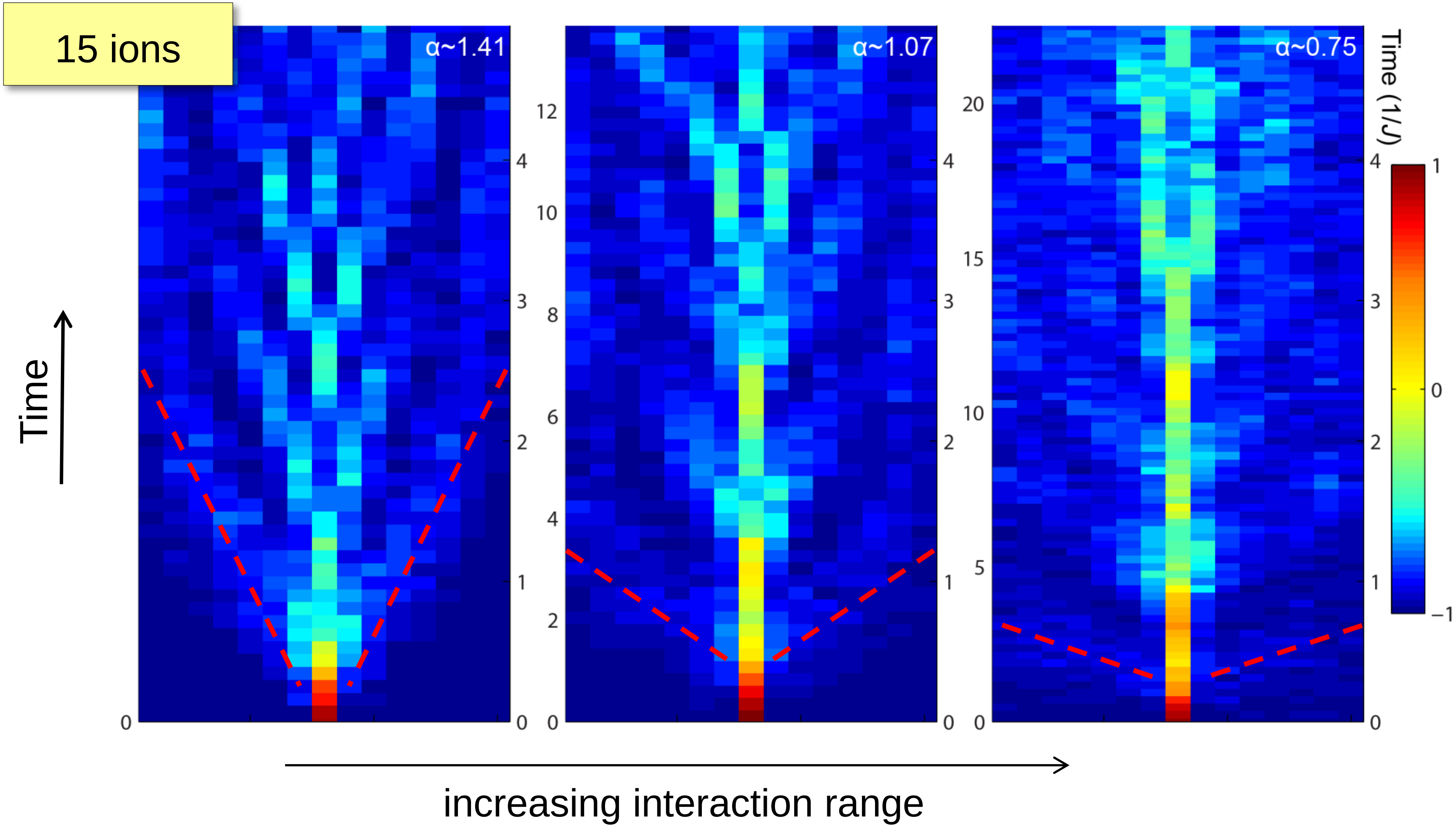


2. Spread of entanglement



3. Measure magnetization or spin-spin correlations

Magnetization dynamics after a local quench

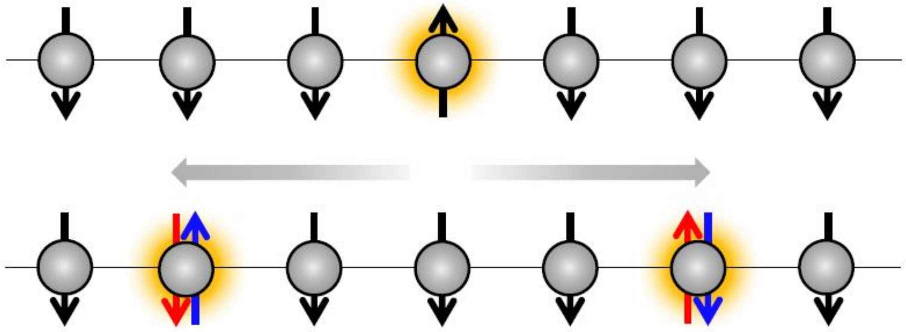


P. Jurcevic et al., Nature **511**, 202 (2014)

see also: P. Richerme et al., Nature **511**, 198 (2014)

$$J_{ij} \approx J_0 \frac{1}{|i-j|^\alpha}$$

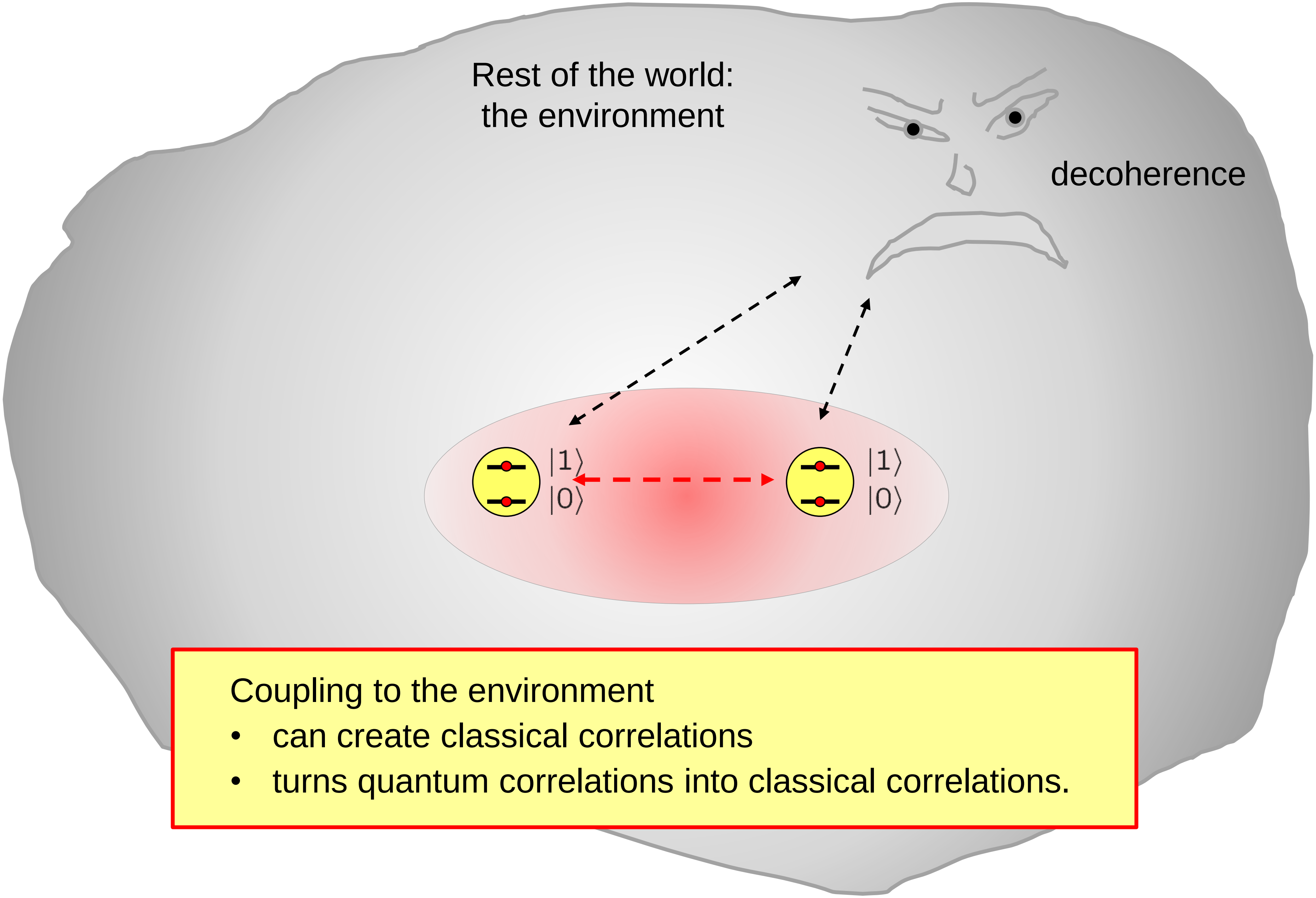
Entanglement generation in many-body dynamics



The quantum dynamics induced by a many-body Hamiltonian creates entanglement.

How can we demonstrates that this really happens in our experiment?

Classical vs quantum correlations



Coupling to the environment

- can create classical correlations
- turns quantum correlations into classical correlations.

Classical vs quantum correlations

Example: Comparison of two different states

$$\Psi_- = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

$|\uparrow\downarrow\rangle$ or $|\downarrow\uparrow\rangle$

50% 50%

Both state have the same expectation values when measured in z-basis:

$$\langle\sigma_z^{(i)}\rangle = 0$$
$$\langle\sigma_z^{(1)}\sigma_z^{(2)}\rangle = -1$$

Only measurements along x or y reveal the difference:

$$\langle\sigma_x^{(1)}\sigma_x^{(2)}\rangle = -1$$
$$\langle\sigma_y^{(1)}\sigma_y^{(2)}\rangle = -1$$

$$\langle\sigma_x^{(1)}\sigma_x^{(2)}\rangle = 0$$
$$\langle\sigma_y^{(1)}\sigma_y^{(2)}\rangle = 0$$

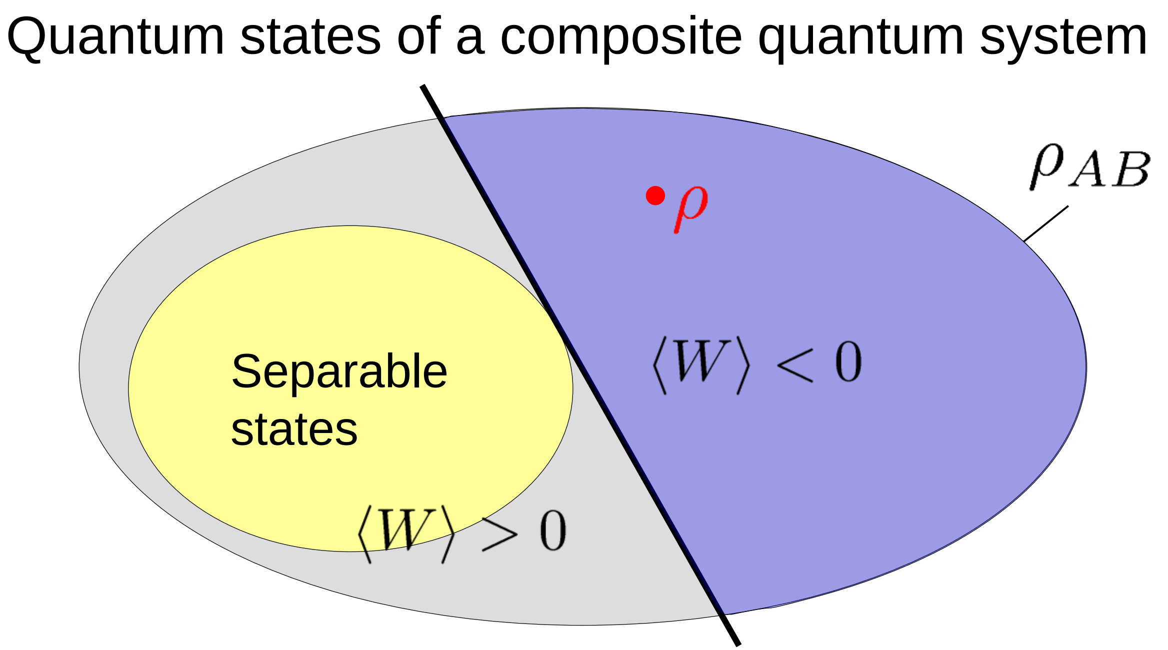
Detecting entanglement

Deciding whether a state is entangled or not is a hard task.

Entanglement detection techniques:

- **Positive partial trace (PPT) cryterion**: check whether a density matrix after partial transposition has negative eigenvalues.
- **Entanglement witnesses**: Particular observables that have negative expectation value for some entangled states, but are positve for separable states.
- **Entanglement measures (for example: concurrence)**: Nonlinear functions of the density matrix that are zero for separable mixed states and positive for entangled states. Entanglement measures quantify entanglement but can be hard to calculate even if the density matrix is known; for two qubits, closed expressions exist.

Detecting entanglement by witness operators



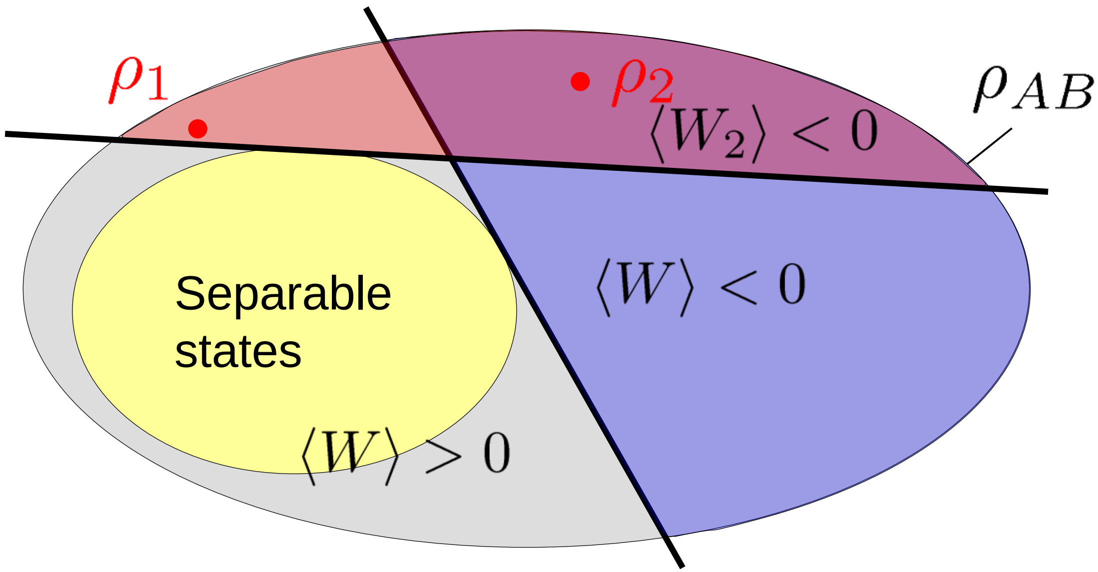
Witness: An observable W whose expectation value is positive for all separable states

$$\langle W \rangle = \mathrm{Tr}(\rho W) \geq 0$$

If we measure $\langle W \rangle < 0$ in an experiment, we can conclude that the state is entangled.

Detecting entanglement by witness operators

Quantum states of a composite quantum system



- Not every entangled state is detected by a witness $\longrightarrow \rho_1$

$$\mathrm{Tr}(\rho_1 W) \geq 0$$

- An entangled state can be detected by more than one witness $\longrightarrow \rho_2$

$$\mathrm{Tr}(\rho_2 W) < 0 \quad \mathrm{Tr}(\rho_2 W_2) < 0$$

Tomographic reconstruction of the density matrix

Representation of ρ as a sum of orthogonal observables A_i :

$$\rho = \sum_i \lambda_i A_i \text{ with } Tr(A_i A_j) = \delta_{ij}$$

ρ is completely detemined by the expectation values $<A_i>$:

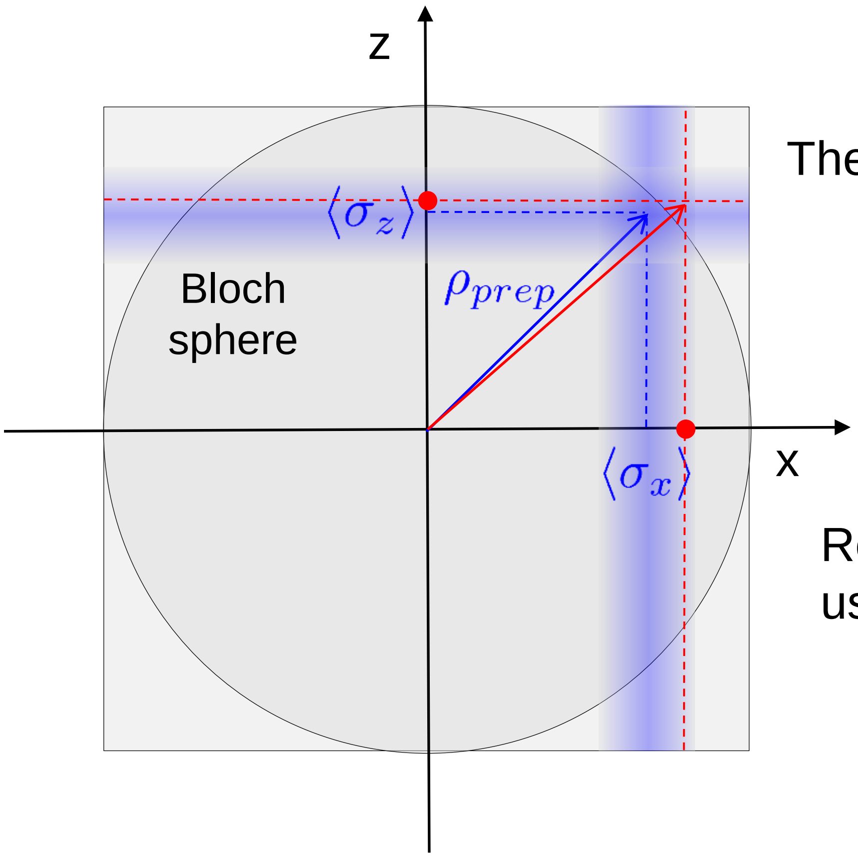
$$\langle A_j \rangle = Tr(\rho A_j) = \sum_i \lambda_i Tr(A_i A_j) = \lambda_j$$

For a two-ion system : $A_i \in \{\sigma_i^{(1)} \otimes \sigma_j^{(2)}, \sigma_i \in \{I, \sigma_x, \sigma_y, \sigma_z\}\}$

$\longrightarrow$ Joint measurements of all spin components $\sigma_i^{(1)} \otimes \sigma_j^{(2)}$

$$\rho_R = \sum_{i=1}^{16} \langle A_i \rangle A_i$$

Example: Tomography of a qubit



The experimental procedure prepares the state ρ_{prep}

$$\rho_{prep} = \frac{1}{2}(I + \langle\sigma_x\rangle\sigma_x + \langle\sigma_y\rangle\sigma_y + \langle\sigma_z\rangle\sigma_z)$$

Reconstruction by estimation of $\langle\sigma_x\rangle, \langle\sigma_y\rangle, \langle\sigma_z\rangle$ using a finite number of copies of the state:

$$s_z = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \ , \ s_x = \ldots, \ s_y = \ldots$$

$$\rho_{tomo} = \frac{1}{2}(I + s_x\sigma_x + s_y\sigma_y + s_z\sigma_z) \neq \rho_{prep}$$

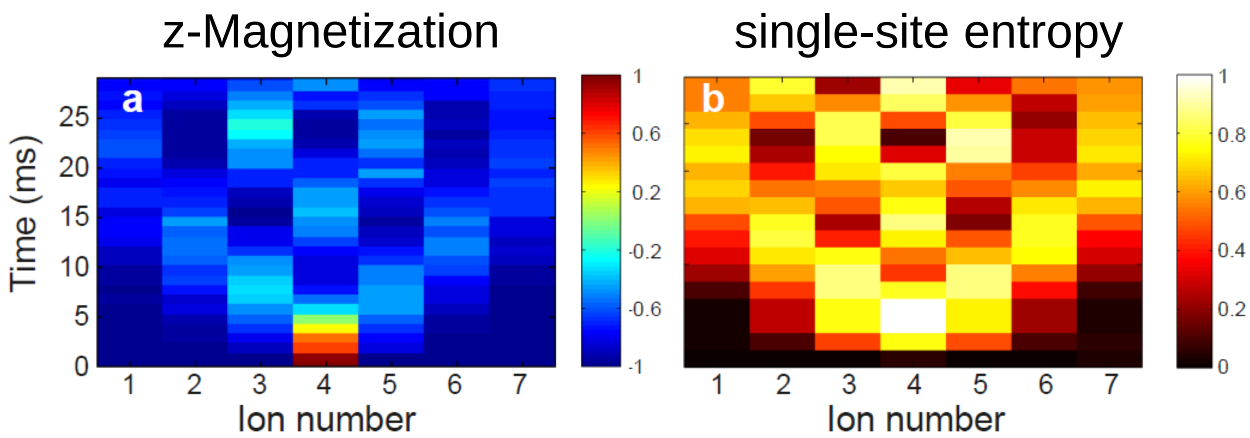
ρ_{tomo} might not be within the Bloch sphere !

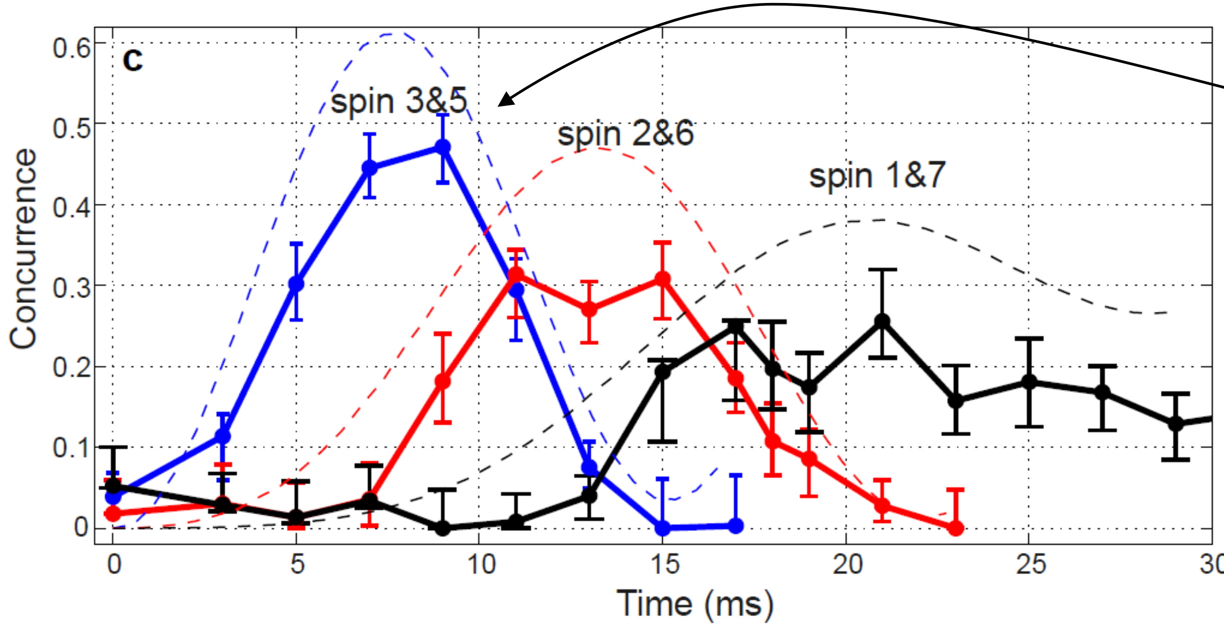
DISASTER !!!

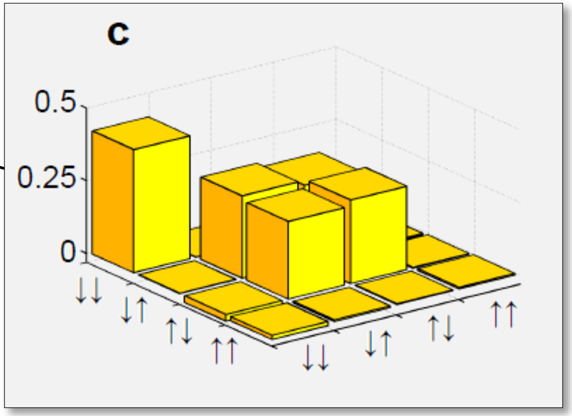
⇒ Nonlinear combination of measurement results!

Spread of entanglement after a local quench

7 ions
a ≈1.75





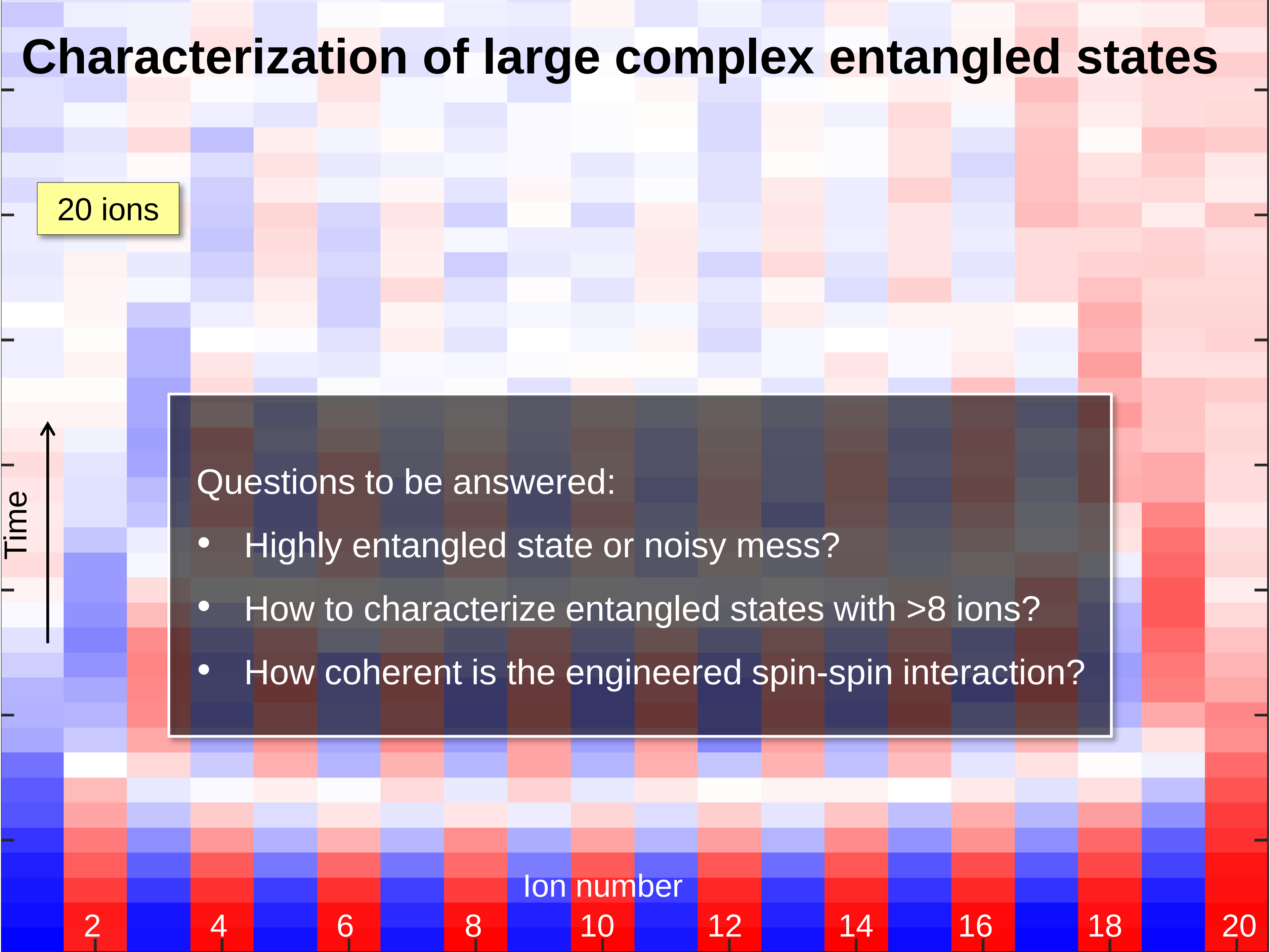


density matrix reconstruction
of spins 3 + 5
9 ms after the quench

$$\mathcal{F} = Tr(\rho|\psi\rangle\langle|\psi|) = 0.975$$

P. Jurcevic et al., Nature **511**, 202 (2014)

Characterization of large complex entangled states



Questions to be answered:

- Highly entangled state or noisy mess?
- How to characterize entangled states with >8 ions?
- How coherent is the engineered spin-spin interaction?

Characterization of large complex entangled states

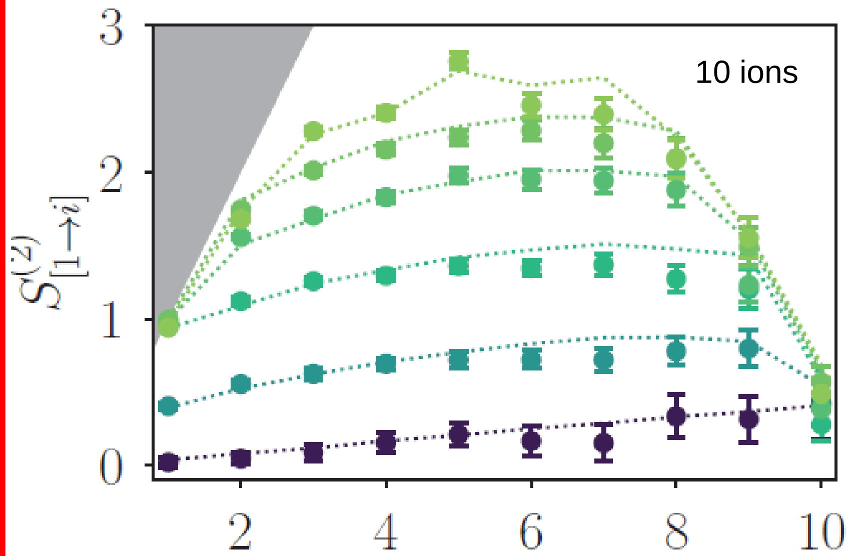
20 ions

Time

Ion number

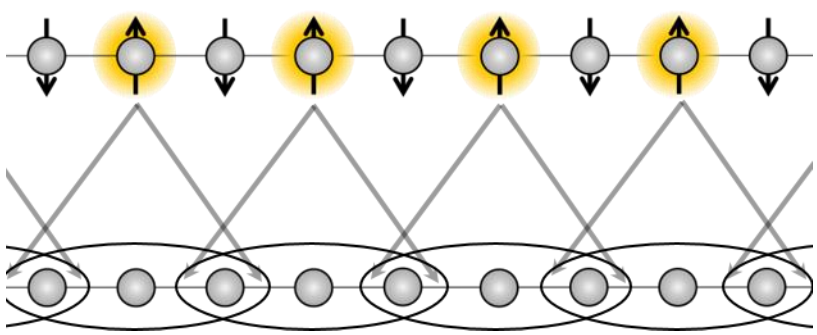
2 4 6 8 10 12 14 16 18 20

Entropy measurements by random unitaries



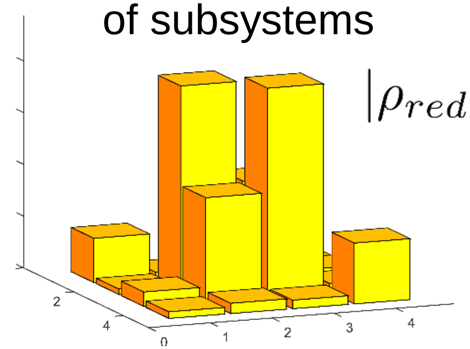
T. Brydges et al., Science **364**, 260 (2019)

Matrix-product state tomography



B. Lanyon *et al*., Nat. Phys. **13**, 1158 (2017)

Quantum state tomography of subsystems



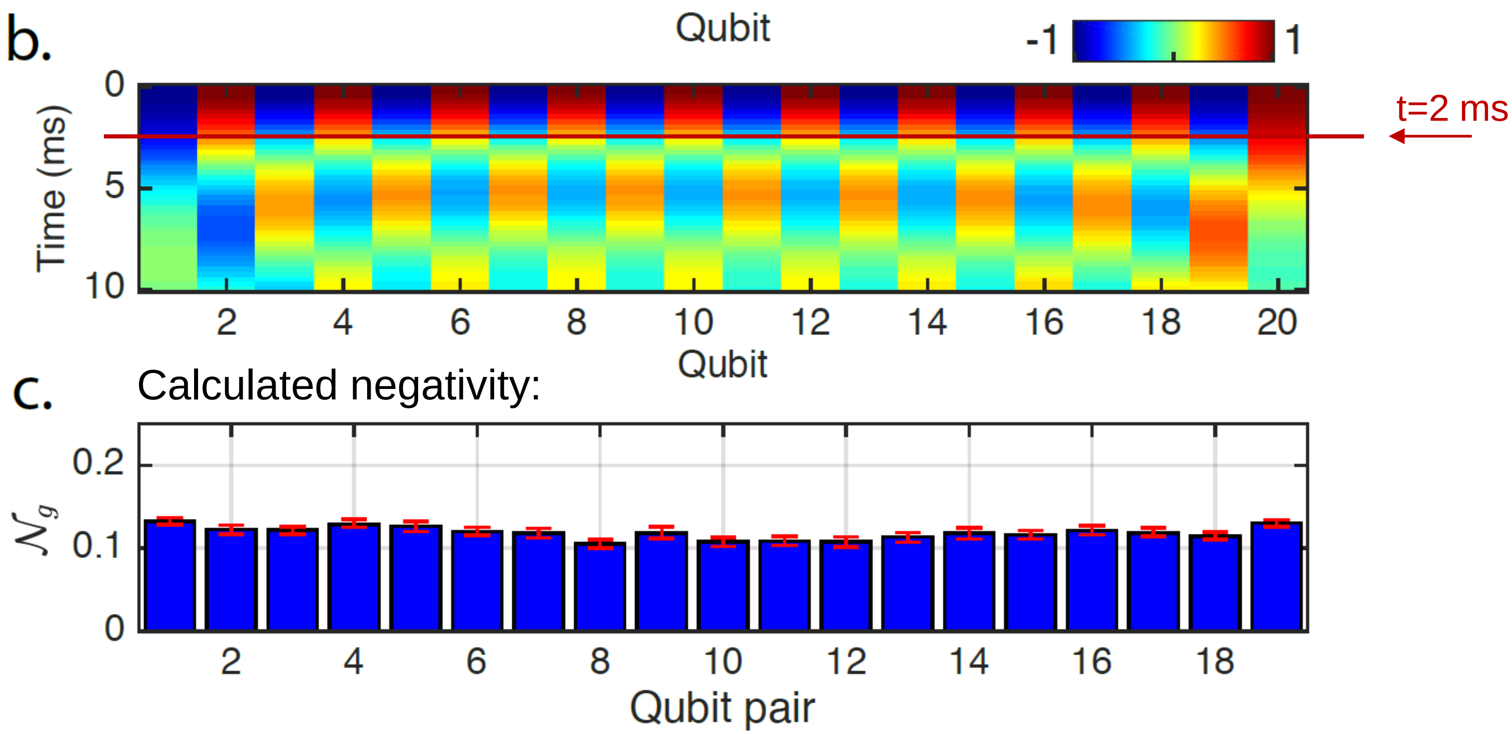
N. Friis *et al*., PRX **8**, 021012 (2018)

Entanglement detection in multi-ion experiments

Local characterization of the beginning of entanglement spreading

Option 1: Quantum state tomography to reconstruct the density matrix of subsystems

Reconstruction of all density matrices of nearest-neighbour pairs

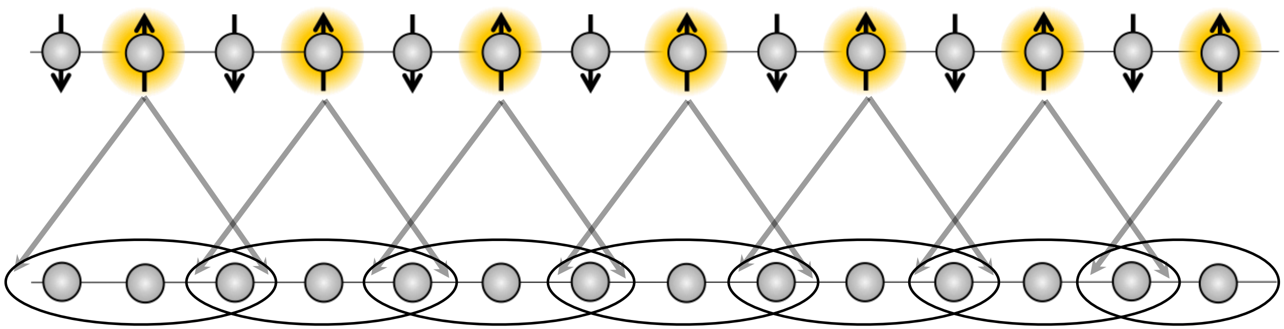


→ After 2 ms of time evolution, all ions are entangled with their neighbours

N. Friis et al., Phys. Rev. X 8, 021012 (2018)

Entanglement detection in multi-ion experiments

Local characterization of the beginning of entanglement spreading



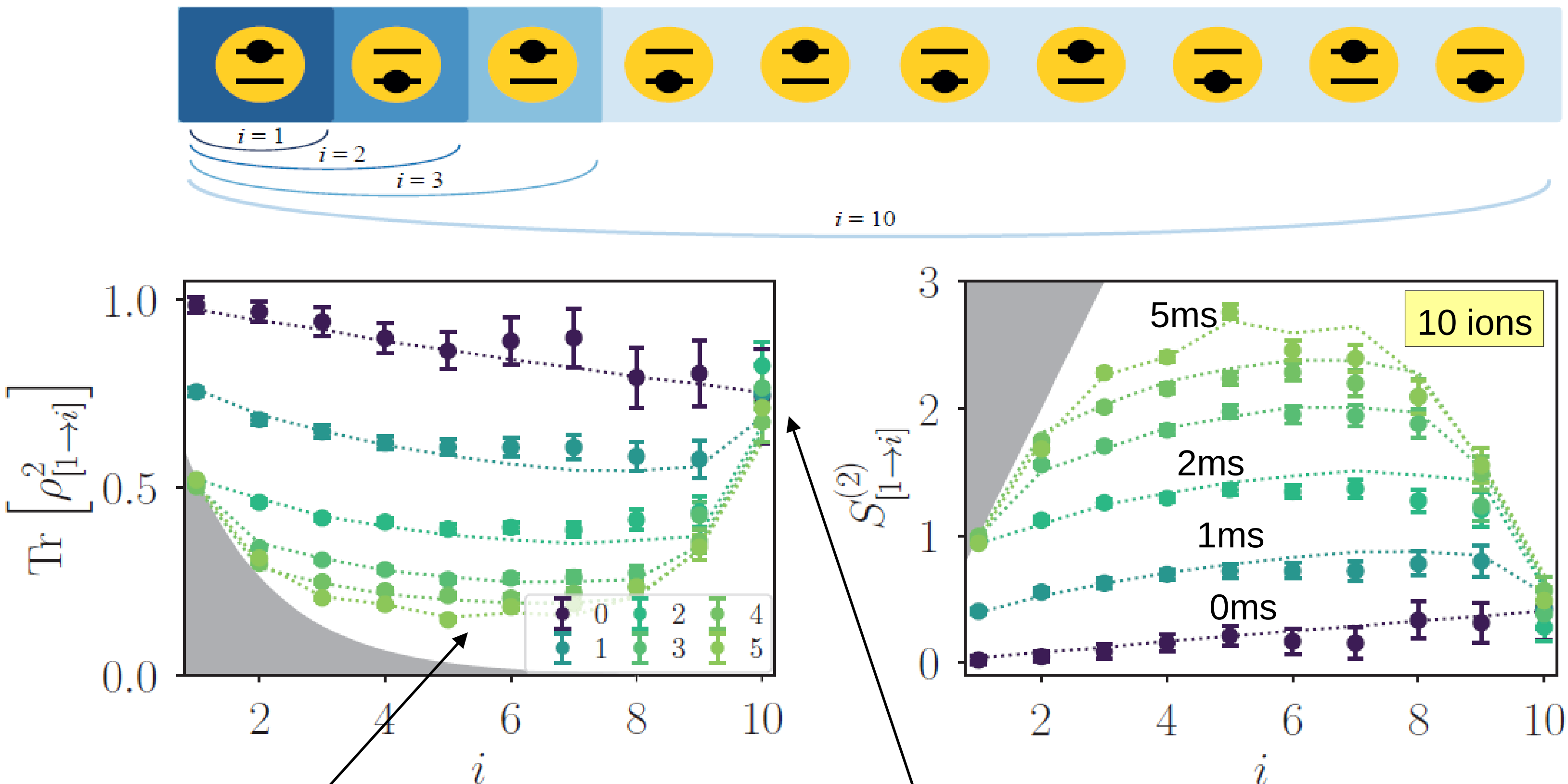
Option 2: Measure all correlation functions between groups of neighbouring ions (pairs, triplets,...) and try to build up a global representation of the quantum state using a suitable parametrization of the state

→ Matrix product state tomography

B. Lanyon, C. Maier et al, Nature Physics **13**, 1158 (2017)

Entanglement detection in multi-ion experiments

Option 3: Compare the purity of density matrices describing subsystems to the purity of the overall density matrix

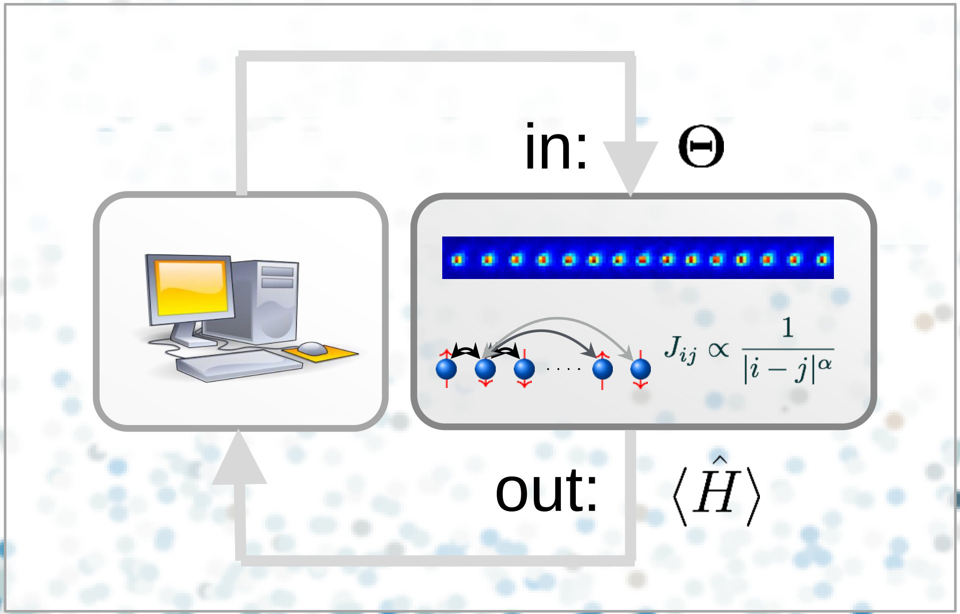


Entanglement growth

Total purity nearly invariant

T. Brydges, A. Elben et al., Science 364, 260 (2019)

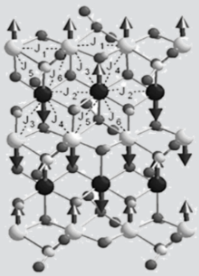
Entanglement as a computational resource: Variational quantum simulation



C. Kokail, C. Maier et al., Nature **569**, 355 (2019)

Variational quantum simulation

Target



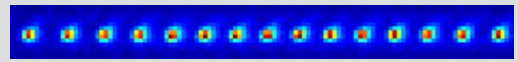
spin Hamiltonian

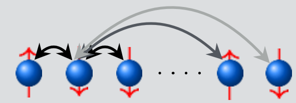
$$\hat{H}_T = \sum_{n=1}^{M} \hat{h}_n$$

$$\hat{h}_n = a_n \, \hat{\sigma}_i^x \hat{\sigma}_j^y \hat{\sigma}_k^z \cdots$$

$\rightarrow$ sums of Pauli products:

Quantum Resource



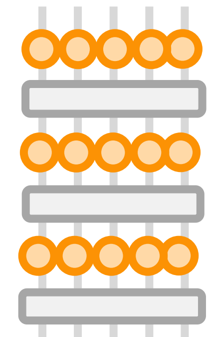


$$J_{ij} \propto \frac{1}{|i-j|^\alpha}$$

$$U_1(\Theta) = \exp\left(-\,\mathrm{i}\Theta \sum_{i<j} J_{ij}(\sigma_i^+\sigma_j^- + \mathrm{h.c.})\right)$$

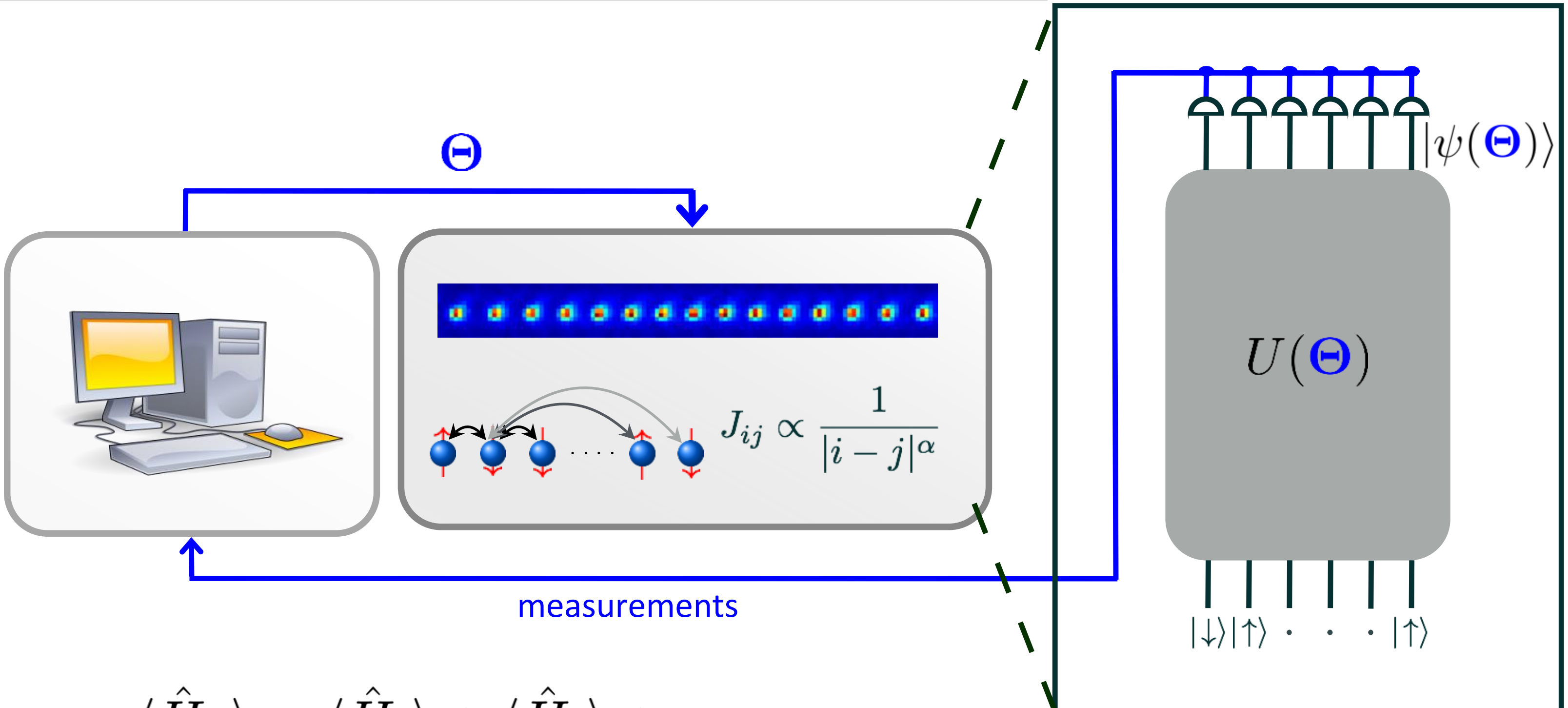
$$U_{2,i}(\Theta) = \exp\left(-\mathrm{i}\Theta\sigma_i^z\right)$$

$$|\psi(\Theta)\rangle = \hat{U}_N(\Theta_N)\cdots\hat{U}_2(\Theta_2)\hat{U}_1(\Theta_1)|\psi_0\rangle$$



Variational quantum simulation

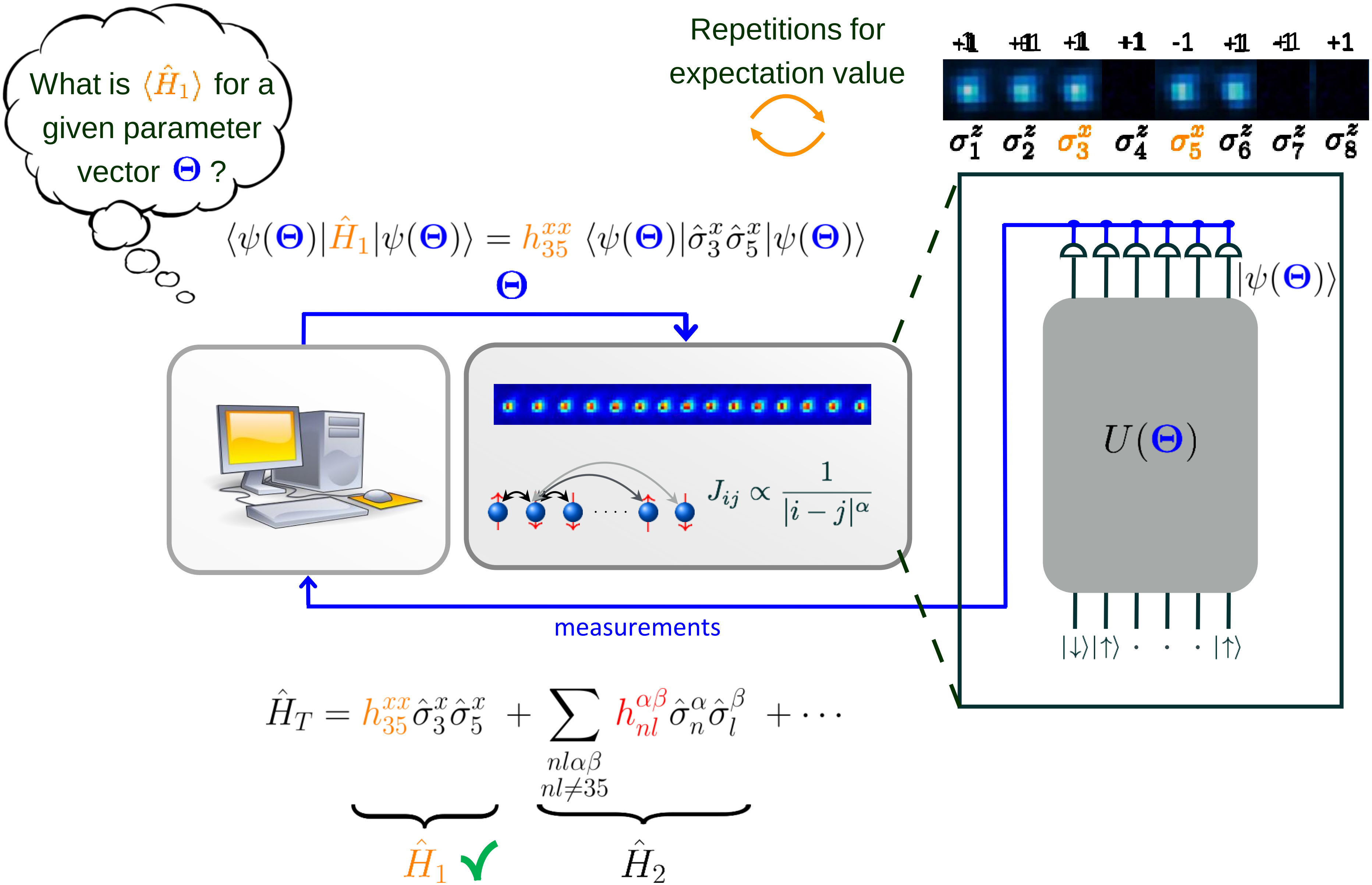
The goal of Variational Quantum Simulation	
Prepare ground state of $\hat{H}_T$ by minimising	$\langle\psi(\boldsymbol{\Theta})\vert\hat{H}_T\vert\psi(\boldsymbol{\Theta})\rangle$



$$\langle\hat{H}_T\rangle = \langle\hat{H}_1\rangle + \langle\hat{H}_2\rangle + \cdots$$

Peruzzo et al., Nature Comm. 5, 4213 (2014)
Farhi et al., arXiv:1411.4028 (2014)
McClean et al., NJP 18, 023023 (2016)

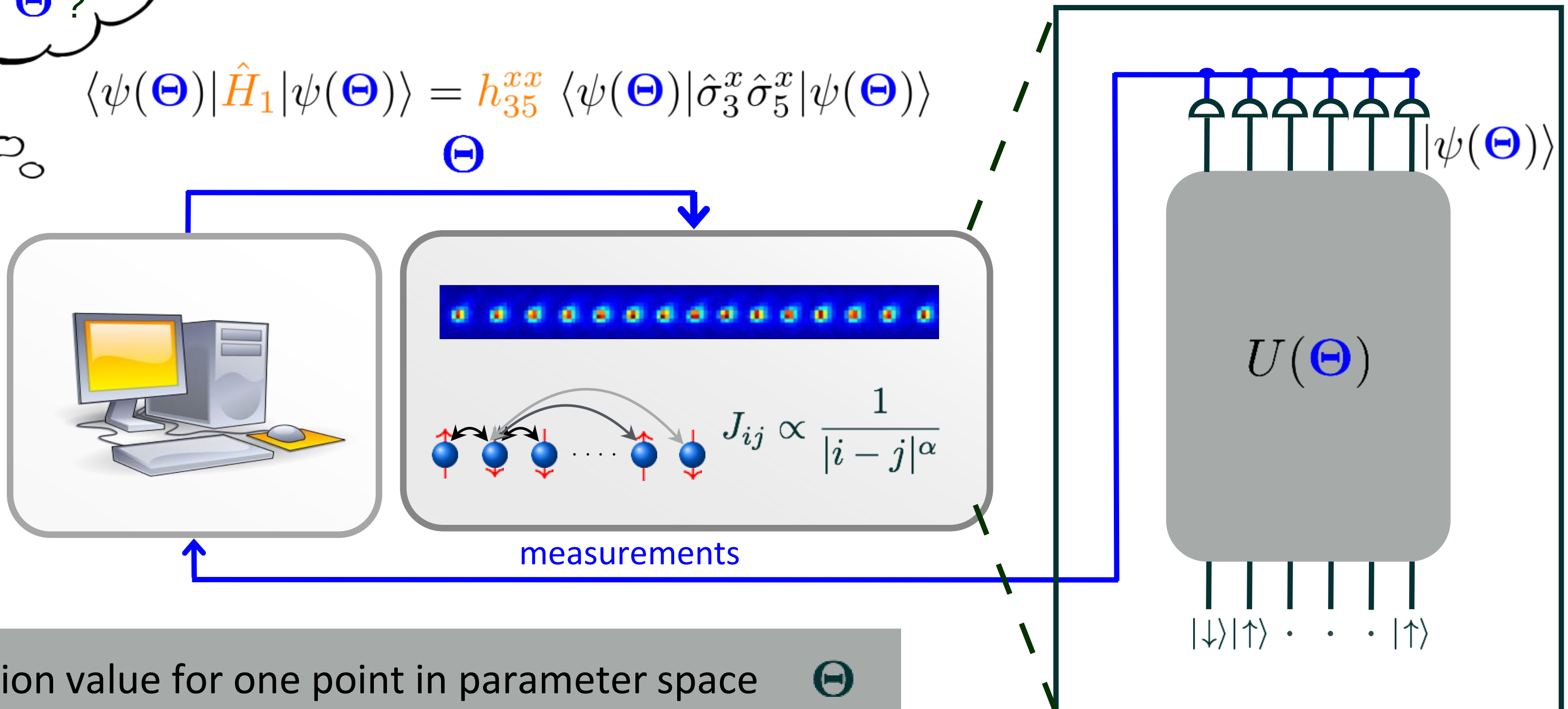
Variational quantum simulation



Variational quantum simulation

What is $\langle \hat{H}_1 \rangle$ for a given parameter vector $\boldsymbol{\Theta}$?

$$\langle \psi(\boldsymbol{\Theta}) | \hat{H}_1 | \psi(\boldsymbol{\Theta}) \rangle = h_{35}^{xx} \, \langle \psi(\boldsymbol{\Theta}) | \hat{\sigma}_3^x \hat{\sigma}_5^x | \psi(\boldsymbol{\Theta}) \rangle$$



Expectation value for one point in parameter space $\boldsymbol{\Theta}$

$$\langle \psi(\boldsymbol{\Theta}) | \hat{H}_T | \psi(\boldsymbol{\Theta}) \rangle = \underbrace{\langle \hat{H}_1 \rangle}_{\hat{H}_1 \checkmark} + \underbrace{\langle \hat{H}_2 \rangle + \cdots}_{\hat{H}_2}$$

Quantum resources for variational search: ground state energy of Schwinger lattice model

Entangling operations

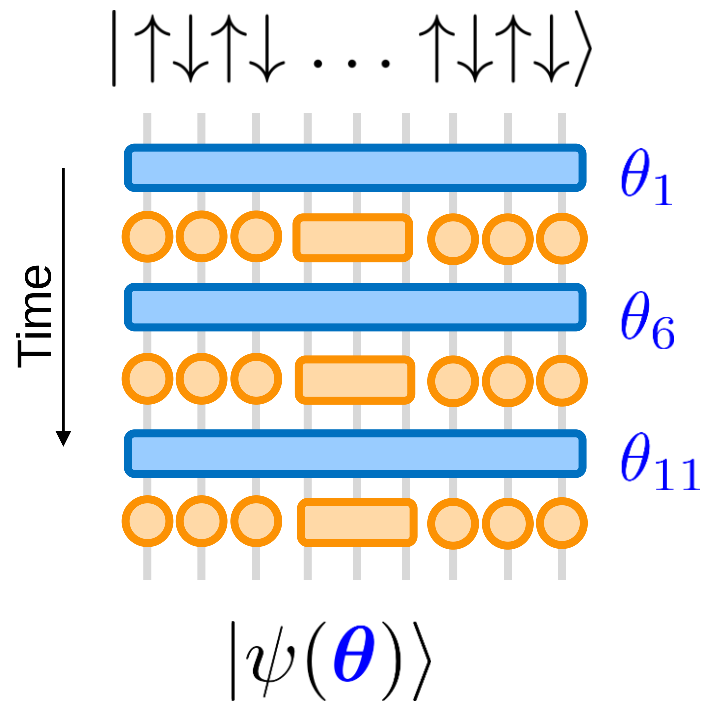
$$U(\theta) = \exp(i\theta \sum_{i<j} J_{ij}(\sigma_i^+ \sigma_j^- + \sigma_i^- \sigma_j^+))$$

Single-qubit rotations

$$U(\theta) = \exp(i\theta\, \sigma_i^z)$$

Collective qubit rotations

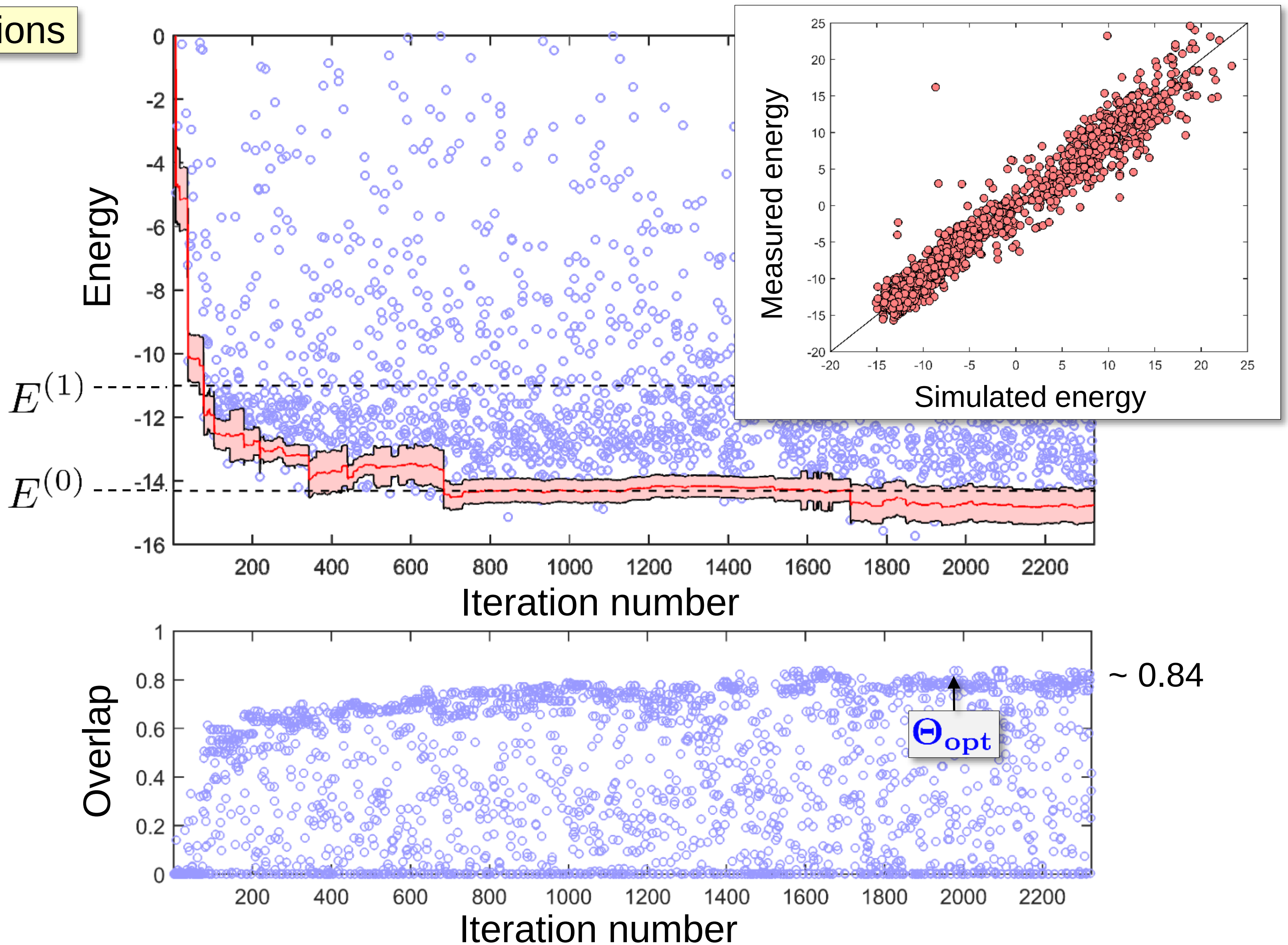
$$U(\theta) = \exp(i\theta \sum_i \sigma_i^x)$$



20 ions, 6 layers of operations, 15 variational parameters

Experimental results: energy minimization

20 ions

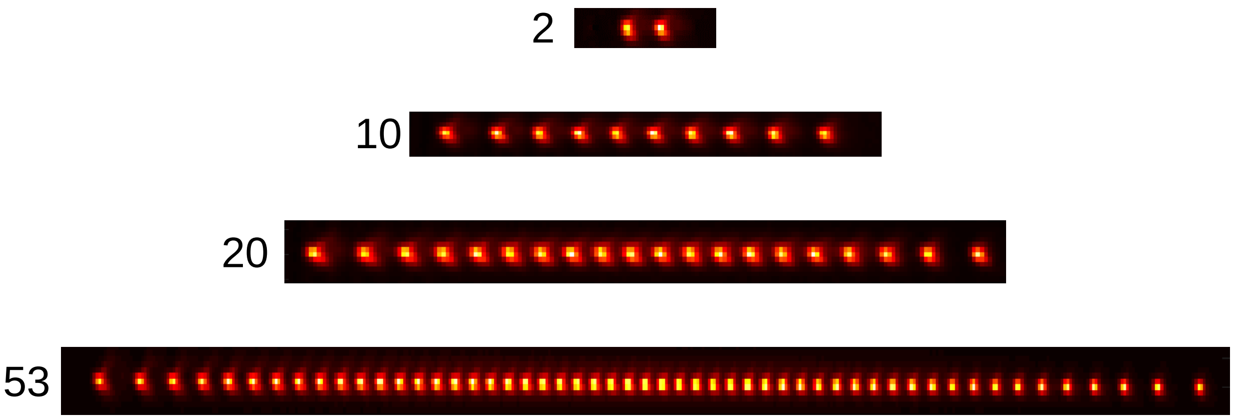


C. Kokail, C. Maier et al., Nature **569**, 355 (2019)

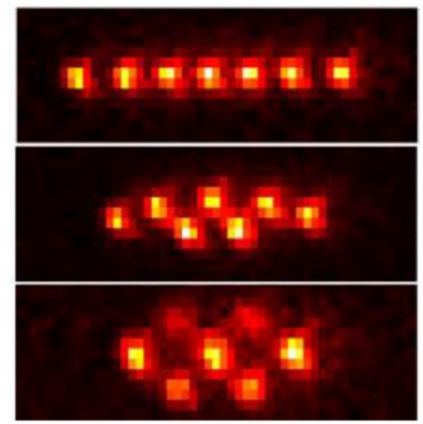
Scaling up trapped-ion quantum simulations

Options for experimenting with larger ion crystals:

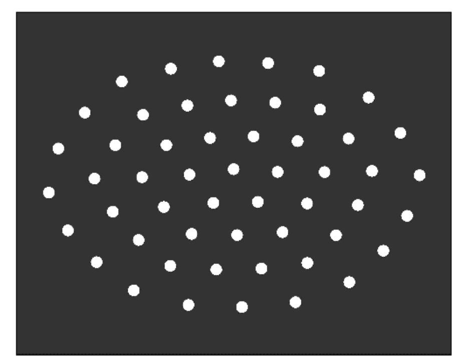
Longer linear ion strings



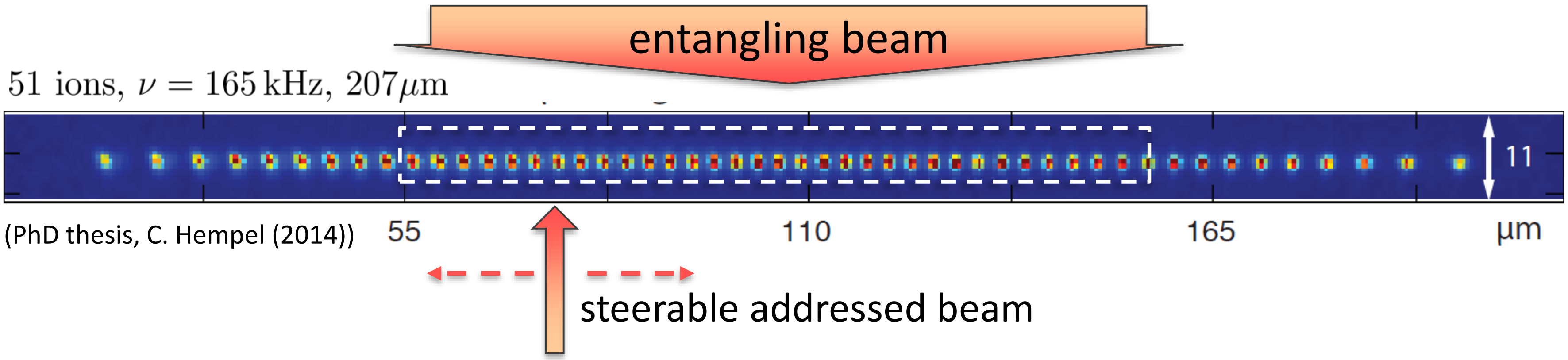
Two-dimensional crystals



53

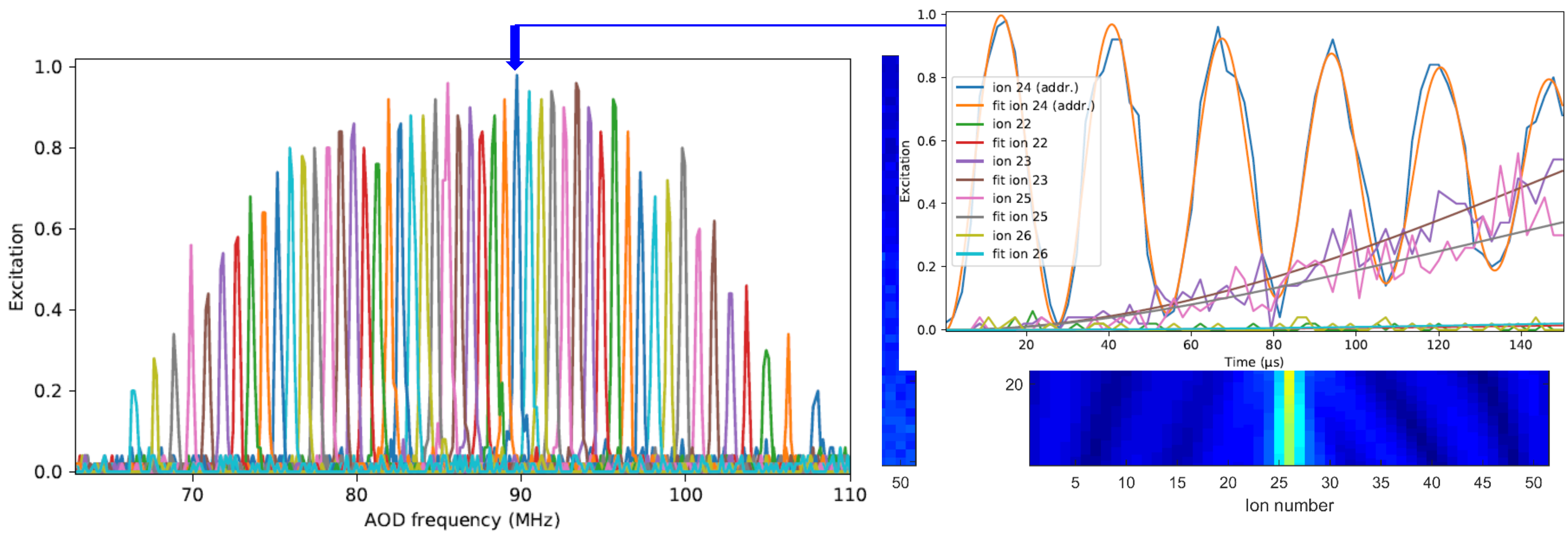


Ion strings with larger ion numbers:

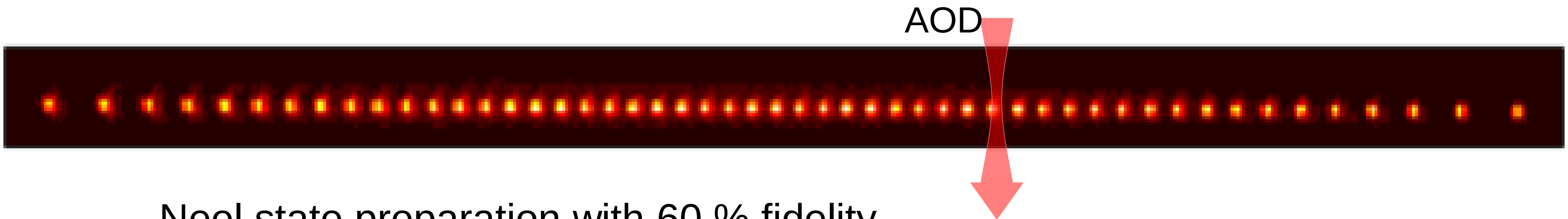


Until very recently: Only 20 ions fully controlled ions

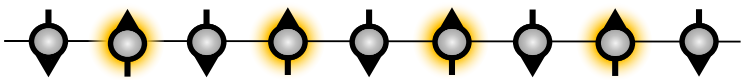
Improved addressing setup ➡ 50 addressable ions



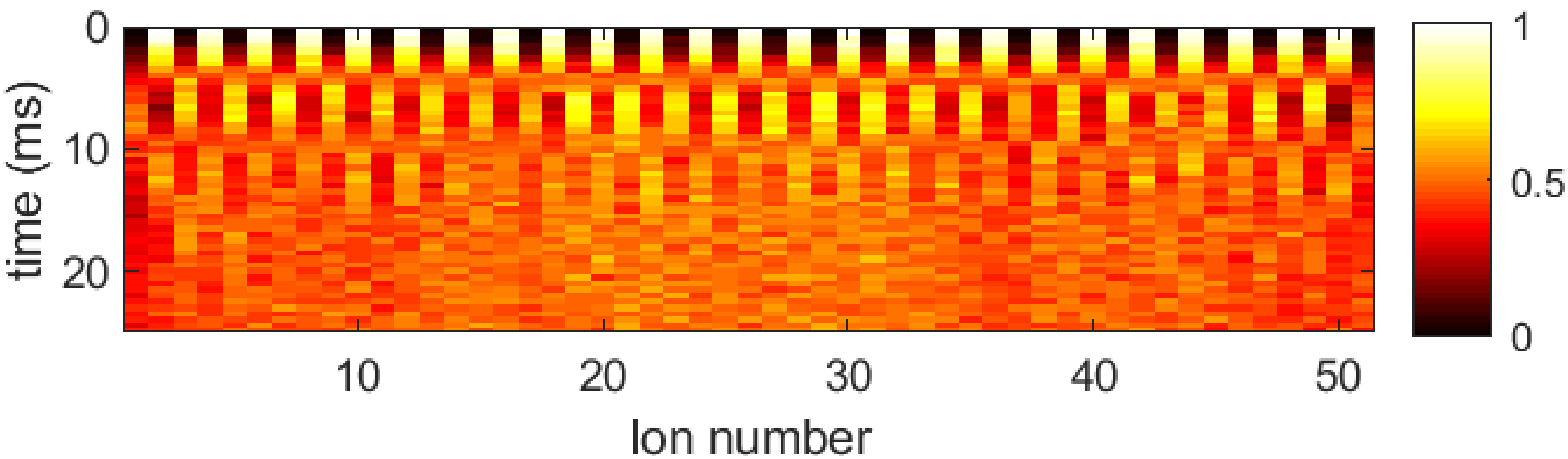
Entanglement in 50-ion strings



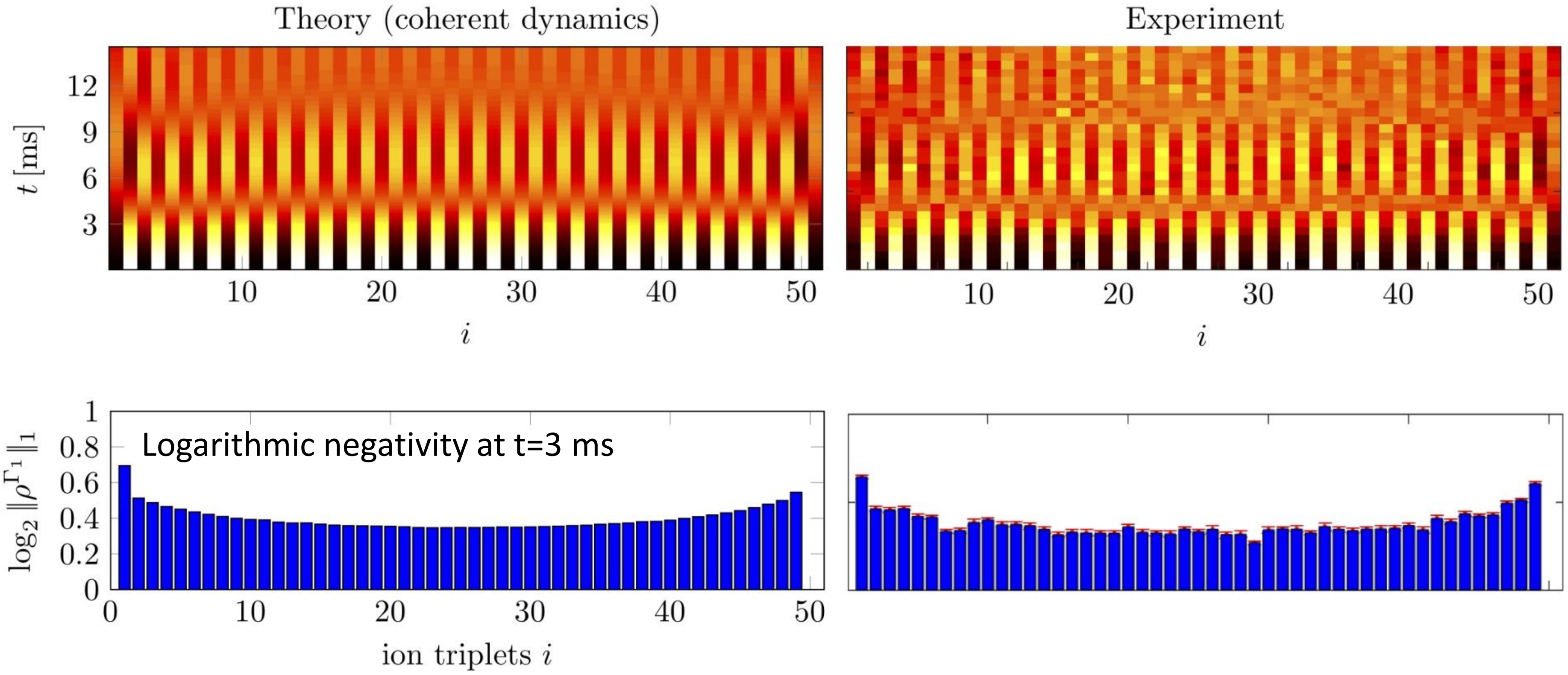
Neel state preparation with 60 % fidelity



Néel-state dynamics under long-range XY model: z-magnetization

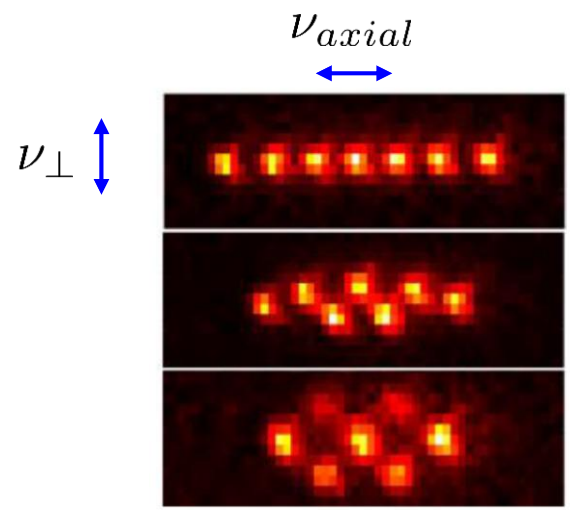


Entanglement in 50-ion strings



in collaboration with P. Zoller and co-workers

Scaling up trapped-ion quantum simulations



1d ion crystals:

- Very anistropic trapping potentials needed for keeping the ion string linear:

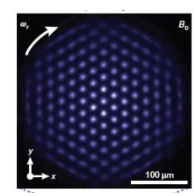
$$\nu_{\perp}/\nu_{axial} > N \log N$$

$\longrightarrow$ low axial confinement

$\longrightarrow$ tricky to control axial motion

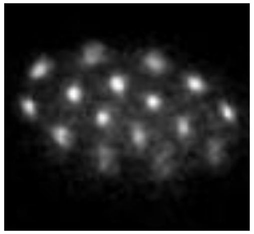
$\longrightarrow$ length of string complicates addressing

2d ion crystals:

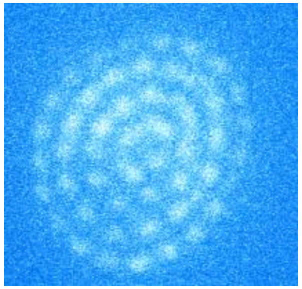


- Penning traps $\longrightarrow$ addressing of rotating crystals
- rf microtrap arrays $\longrightarrow$ electric field noise due to proximity to trap surfaces
- rf linear trap $\longrightarrow$ micromotion

Planar ion crystals

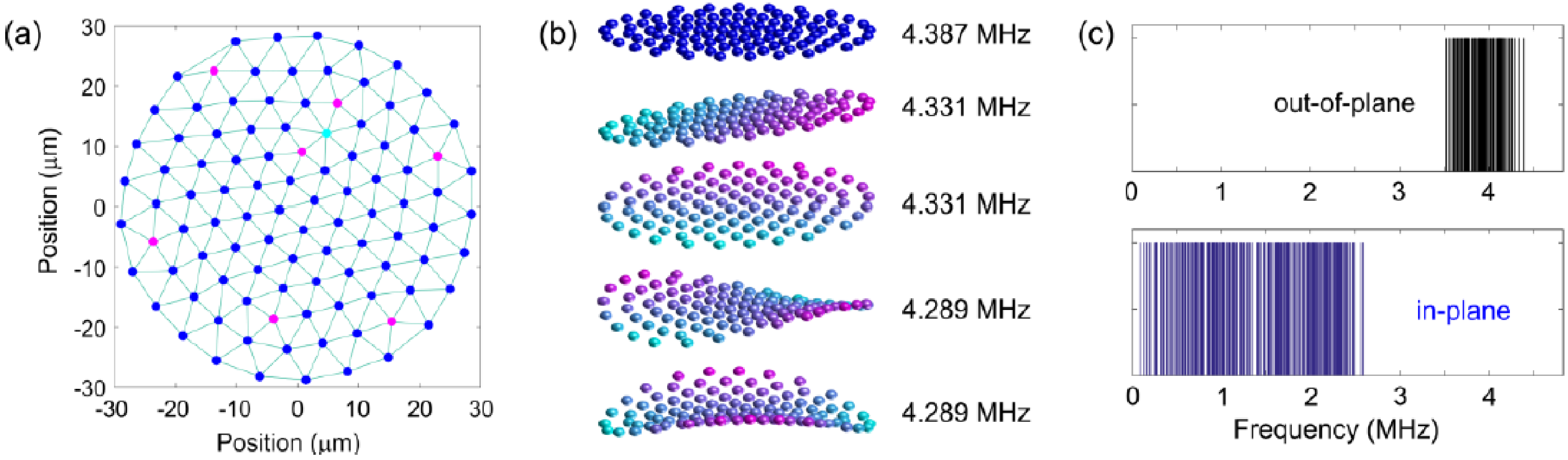


M. Block et al.
J. Phys. B **33,** L375 (2000)



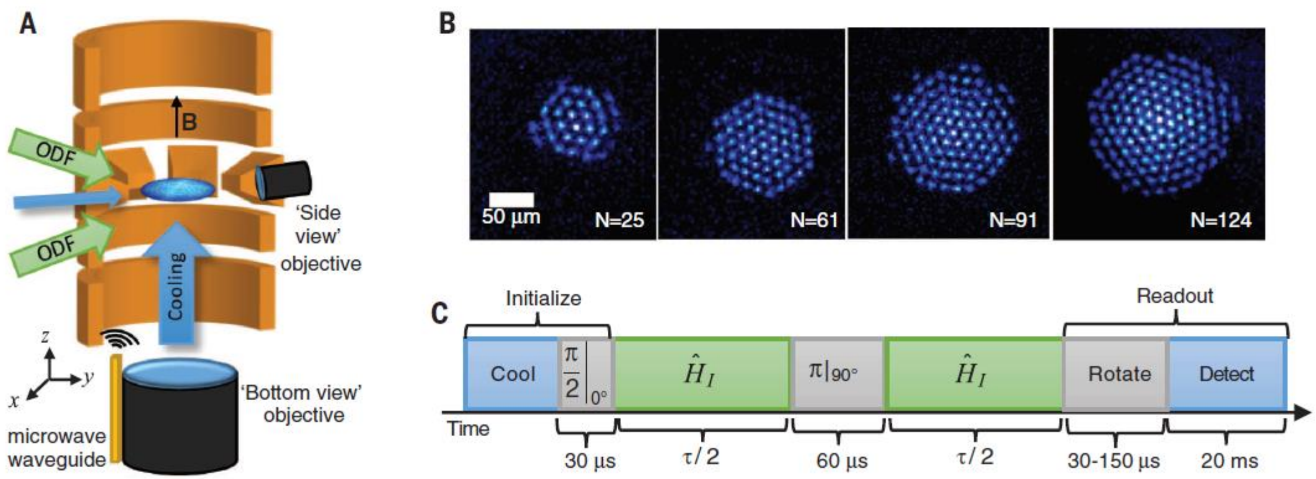
(Campbell group, UCLA)

Ions form triangular lattices with defects



Effective long-range spin-spin interactions by lasers coupling to the out-of-plane modes of vibration

Penning trap: spin dynamics in planar crystals

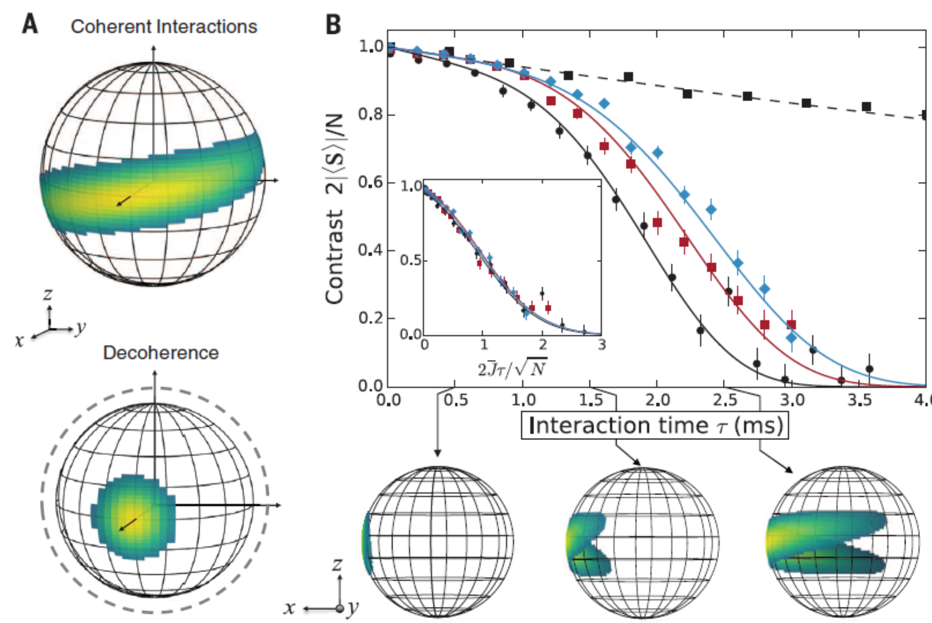


Experiment at NIST, Boulder (USA):

Quantum spin dynamics with >100 ions:

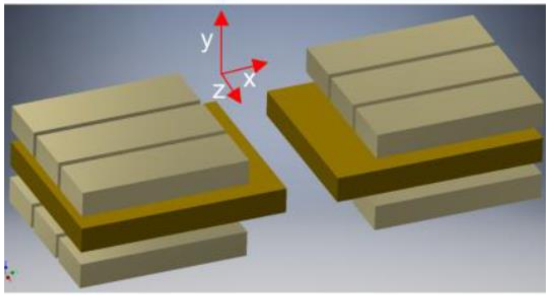
- Optical dipole force inducing spin squeezing
- Measurement of collective spin operators (rotating crystals)

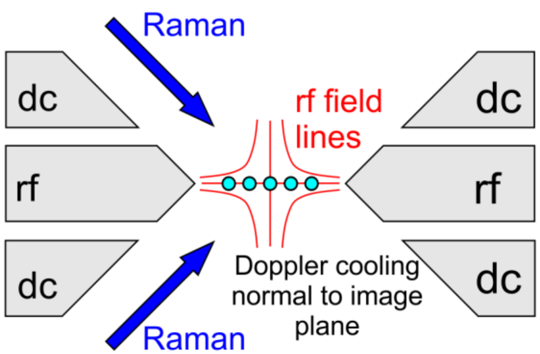
J. G. Bohnet et al, Science 253, 1297 (2016)

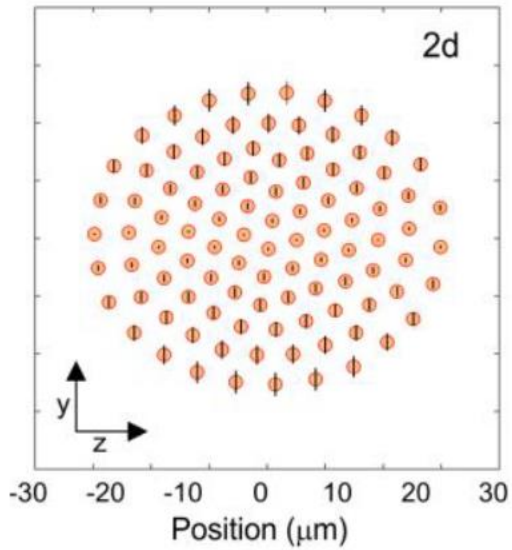


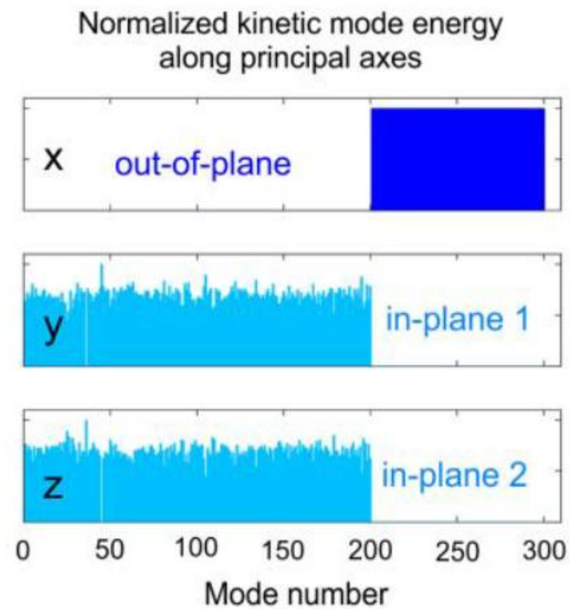
ig. 2. **Depolarization of the collective spin from spin-spin interactions and decoherence.** (**A**) The

Planar ion crystals in rf-traps: Micromotion







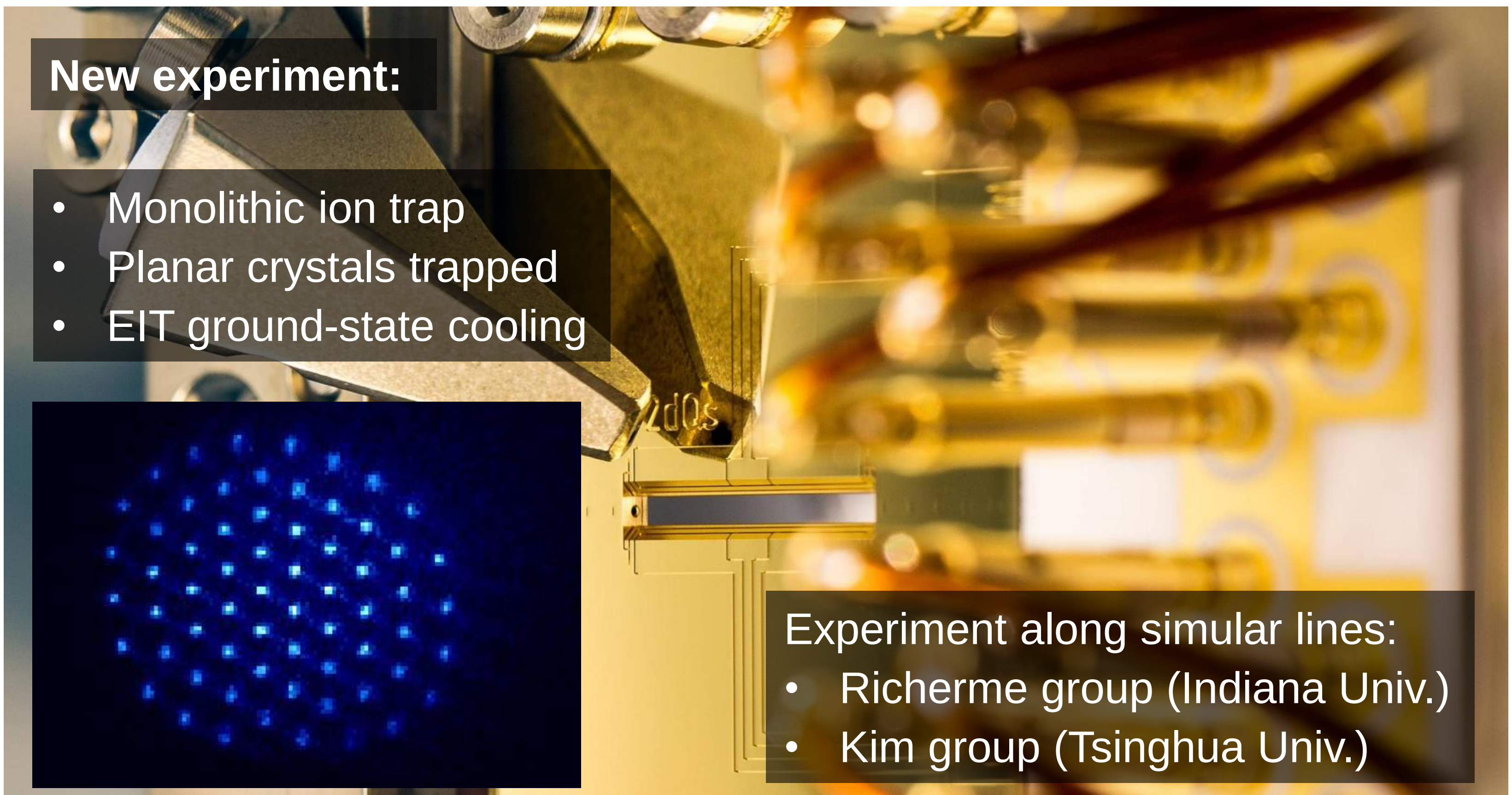


- no micromotion in direction of out-of-plane normal modes
- for certain geometries, laser cooling of in-plane modes not affected by MM

Spin-spin simulations with planar crystals in rf-traps

Challenges:

- melting of crystals by background gas collisions + recrystallization
- Laser cooling of in-plane modes
- Motional heating



New experiment:

- Monolithic ion trap
- Planar crystals trapped
- EIT ground-state cooling

Experiment along simular lines:

- Richerme group (Indiana Univ.)
- Kim group (Tsinghua Univ.)

Summary and outlook

Trapped-ion quantum simulations

- Quantum simulation approaches: digital vs analog
- Realization of long range spin models in trapped ions
- Entanglement creation and characterization in multi-ion strings
- Scaling up quantum simulations to larger ion numbers
- Variational quantum simulation

Outlook:

- Exploration of non-equilibrium quantum dynamics in systems with >50 qubits
- Experiments with planar ion crystals with single-ion control

J. I.Cirac, P. Zoller, “Goals and opportunities in quantum simulation",
Nat. Phys. 8, 264 (2012)

R. Blatt, C. F. Roos, "Quantum simulations with trapped ions", Nat. Phys. 8, 277 (2012)

C. Monroe et al., "Programmable quantum simulations of spin systems with trapped ions"
Rev. Mod. Phys. 93, 025001 (2021)

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QUANTUM FLAGSHIP

FWF

erc

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A. Schuckert, I. Lovas, M. Knap	Theory (Munich)
B. Lanyon, R. Blatt	Experiment