# Towards Quantum Simulations in ion traps

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## idea:

### motivation - Feynman's approach:

**classical two-level system : 0 or 1**
**quantum two-level system : 0 or 1 but also |0 |1 superposition**

e.g, to describe the state of N spin-1/2 particles requires $2^N$ parameters

$_0|000...0> + _1|000...1> + ... + _{2^N-1}|111...1>$

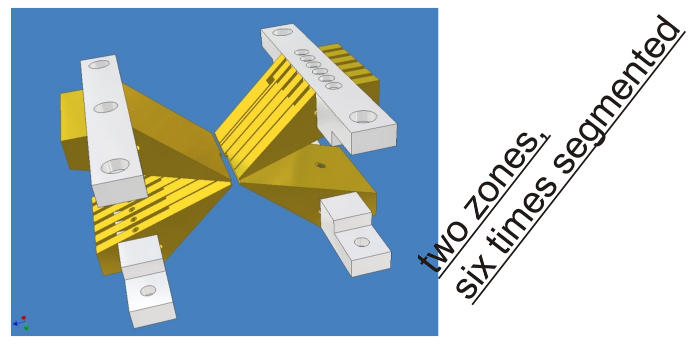
maximum size of system to be simulated classically: N~30 ($2^{30}$ parameters)

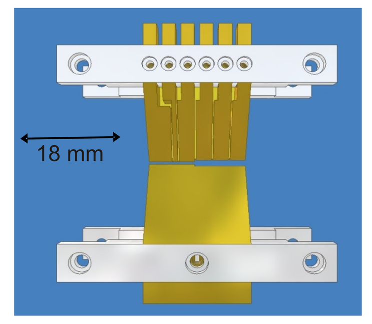
(note: for 300 particles: $2^{300}$ is the guestimated number of protons in the universe)

**deeper insight into quantum dynamics** ← **quantum jump in computer sience**

## work horse:

### ion trap (linear Paul-trap)

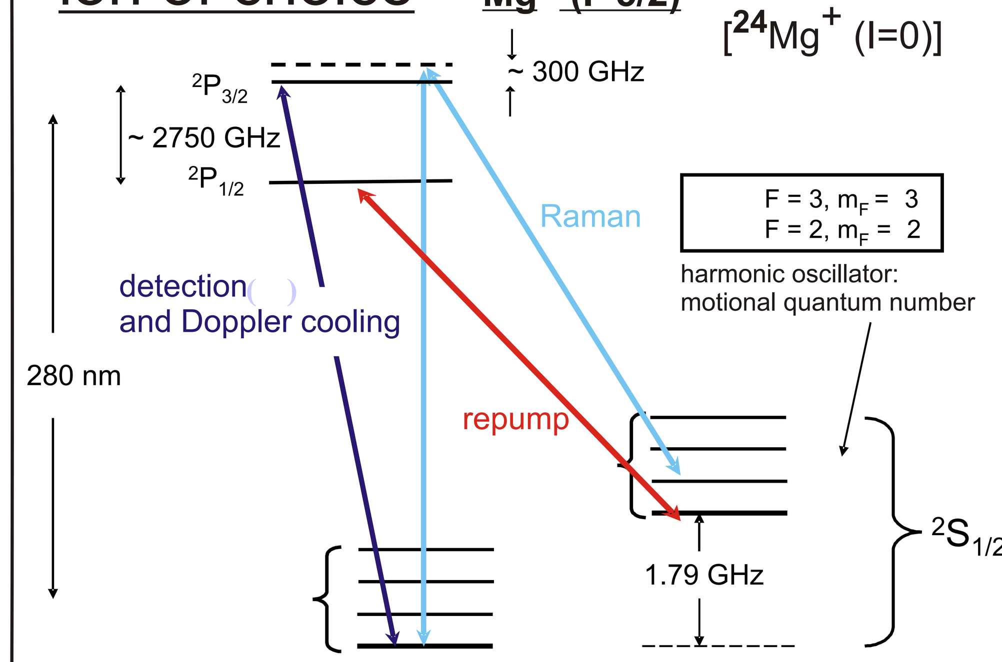



r = 400 m
or 800 m
~ 2 5MHz
sec
= 2 56 Mhz

### ion of choice $^{25}Mg^+$ (I=5/2)

$[^{24}Mg^+$ (I=0)]

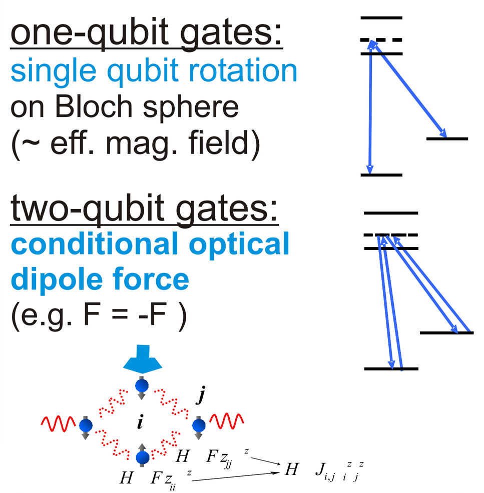



### laser tools

two-photon stimulated Raman transition
(single photon: laser stability limited by life time)

one-qubit gates:
single qubit rotation on Bloch sphere (~ eff. mag. field)

two-qubit gates:
conditional optical dipole force
(e.g. F = -F )



(~ eff. spin-spin interaction)

### laser systems

(I) Raman-laser (4 beams)

532nm pump laser — 5W — 560nm dye laser — 650mW fiber (500mW) — 280nm SHG (BBO) — >100mW — acusto-optical-modulators (switch - splitter - frequency shifter)
Doppler free iodine spect.

(II) detection and Doppler-cooling laser (1 beam)
(III) repump laser (2 beams)
(IV) photo-ionization or sympathetic cooling laser (1 beam each)

1120nm Yb-fiber laser — 1.8W — 560nm SHG (LBO) — 950mW — 280nm SHG (BBO) — >250mW — acusto-optical-modulators
Doppler free iodine spect.

factor 3 cheaper system

thank you, Jim and Didi

## realizing Quantum Simulations on:

| universal quantum computer | analog quantum computer |
|---|---|
| quantum dynamic of a system is translated into an quanten-algorithm consisting of gate-operations | choose a system, that can be controlled and manipulated, governed by the same Hamiltonian as the system to be simulated |

motivation:
test the security of our standard encoding = work towards the implementation of Shor's algorithm (factorizing large numbers)

**BUT:**
pre-condition
1000 logical qubits
~100 ancilla qubits per logical qubit (for necessary fault-tollerance)

**$10^5$ qubits necessary**

could be used to perform universal quantum simulations — shortcut → analog quantum simulator

**similar techniques, but:**

+ **less severe constraints on fidelities:** not aiming for results of quantum algorithms, but robust effects, e.g.quantum phase transitions

+ **30-50 qubits sufficient to outperform classical computers**

proposal PRL 2004
D. Porras and I. Cirac

### advantages:

(1) tunable strength of interaction
(2) ferro/antiferromagnetic interaction
(3) tunable range of interaction

impossible in solid state magnetic systems

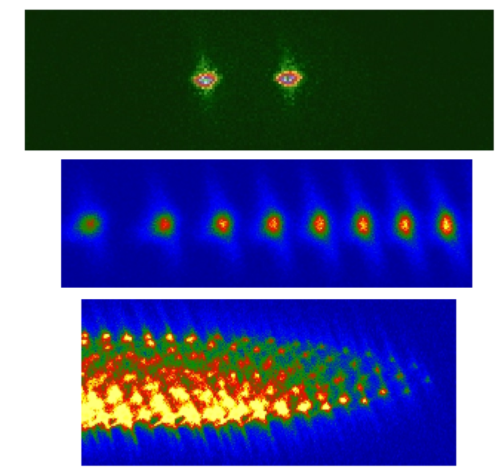
### in ion traps:

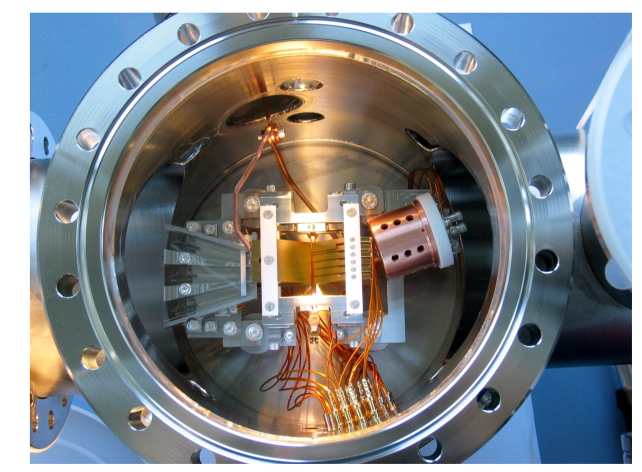
population of each lattice site known;
efficient cooling, manipulation and detection;
(4) manipulable single eff. spins
[e.g. initialize as excited system]
(5) measurable single eff. spins

## road map:

(1) build up of dye- and fiber-laser systems and simple trap in $10^{-10}$mbar vacuum — ok

(2) start up trap with $^{24}Mg^+$ for calibration and setup of detection, test of photo-ionization, characterize the trap — ok





(3) build up of all laser paths, loading $^{25}Mg^+$

(4) build up of data acquisition and computer control, ground-state-cooling of $^{25}Mg^+$, diagnosis of its state

### simulations with one ion:

(*) tunneling process in "Leibfried simulator" [Leibfried, *PRL* 2003]
(*) quantum random walk [Milburn, *PRA* 2002]
(*) MASER simulation (VASER) [Toschek, *PRA* 1996]
(*) quantum particle coupled to boson-bath [Porras and Cirac, *PRL* 2004]

## quantum-spin Hamiltonians

$H = J \sum_{\langle i,j\rangle} \sigma_i^z \sigma_j^z + B^x \sum_i \sigma_i^x$ — quantum Ising model

$H = \sum_{\langle i,j\rangle} J^x \sigma_i^x \sigma_j^x + \sum_{\langle i,j\rangle} J^y \sigma_i^y \sigma_j^y$ — XY model

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quantum-spin Hamiltonians describe the evolution of many solid-state systems:
- magnets
- high Tc superconductors
- quantum Hall ferromagnets
- ferroelectrics
- ...

e.g.

### e.g. quantum Ising model:

$H = J \sum_{\langle i,j\rangle} \sigma_i^z \sigma_j^z + B^x \sum_i \sigma_i^x$

effective magnetic field $B^x$: realized by global qubit rotation

effective spin-spin interaction J: realized by conditional optical dipole force

## quantum-phase-transition:

ground state:

$J \sum_{\langle ij\rangle} \sigma_i^z \sigma_j^z$ — $J = B^x$ — $B^x \sum_i \sigma_i^x$

➡ **not thermal fluctuations responsible (only for T>0) but quantum-fluctuations (also for T=0)**
➡ **degenerate ground state:**
⋮
**( |101⟩ + |010⟩ ) entanglement**

## complete control of parameters (e.g. quantum Ising model):

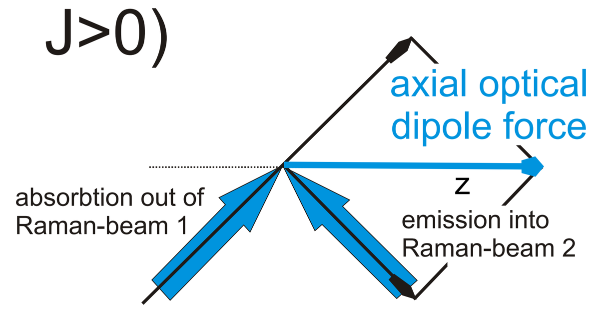
### amplitude of J (and $B_x$):

**intensity** and **detuning** of **Raman beams** control Raman rate, conditional optical dipol force and |J|, respectively.

$|J| \sim F^2_{dipol} \sim {}^2_{Raman}$

### sign of J:

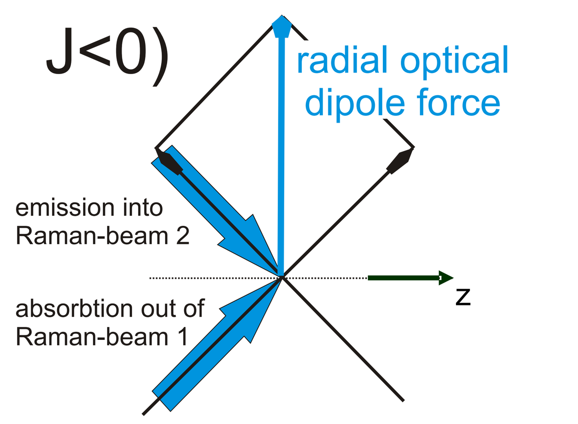
J>0)




anti-ferromagnetic order would increase mutual Coulomb energy

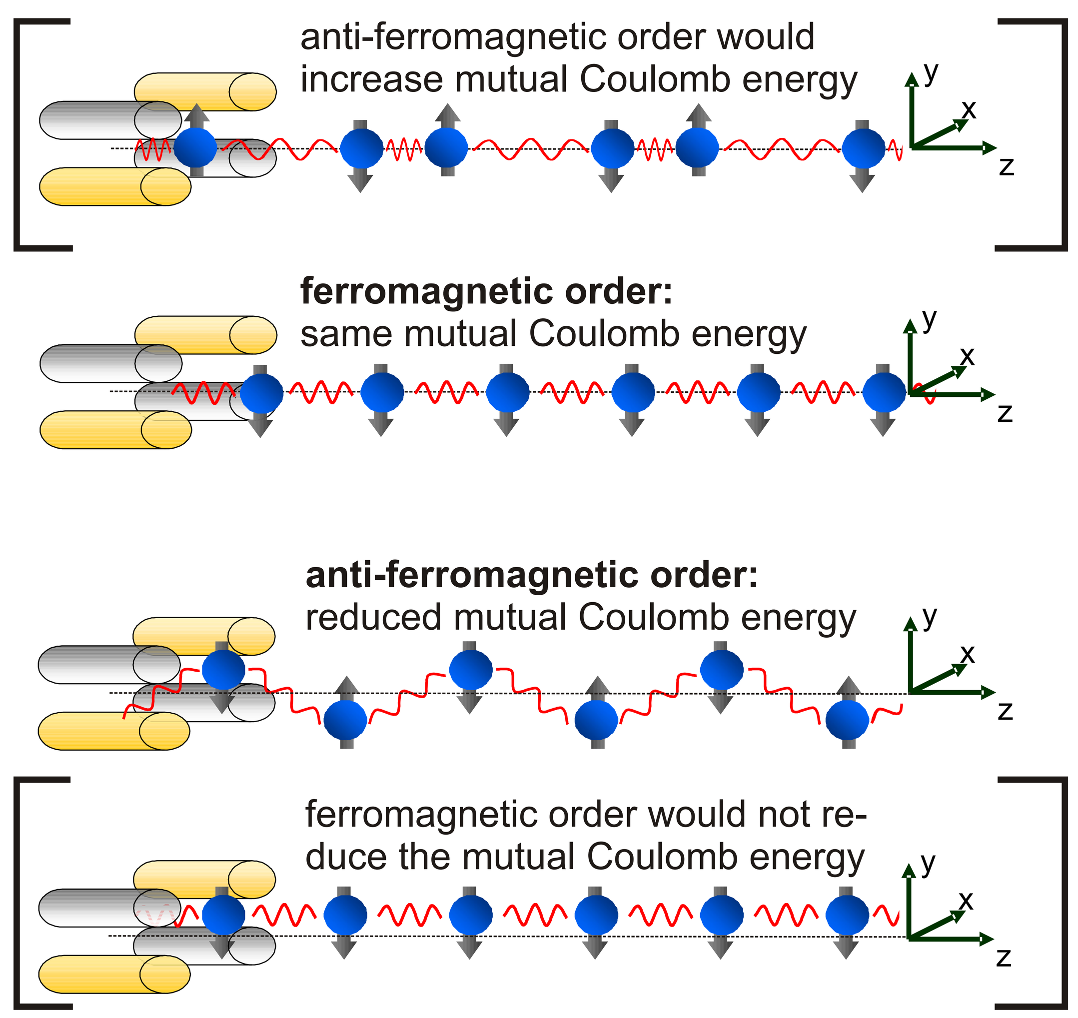
**ferromagnetic order:** same mutual Coulomb energy

J<0)




**anti-ferromagnetic order:** reduced mutual Coulomb energy

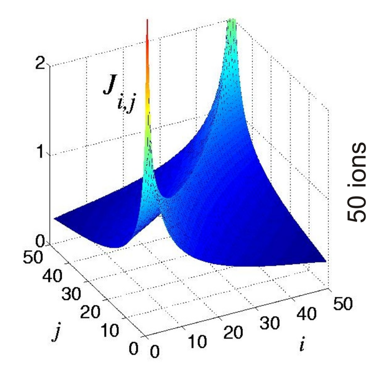
ferromagnetic order would not reduce the mutual Coulomb energy



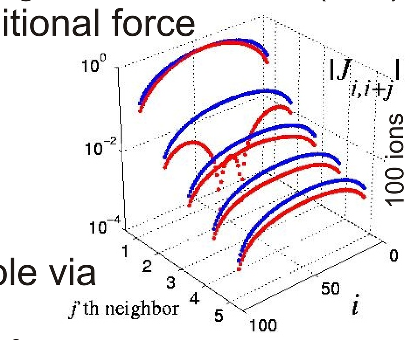
### range of interaction

long range ferromagnetic interaction (J>0) induced by axial conditional force

classical simulations by Porras and Cirac




short range antiferromagnetic interaction (J<0) induced by radial conditional force

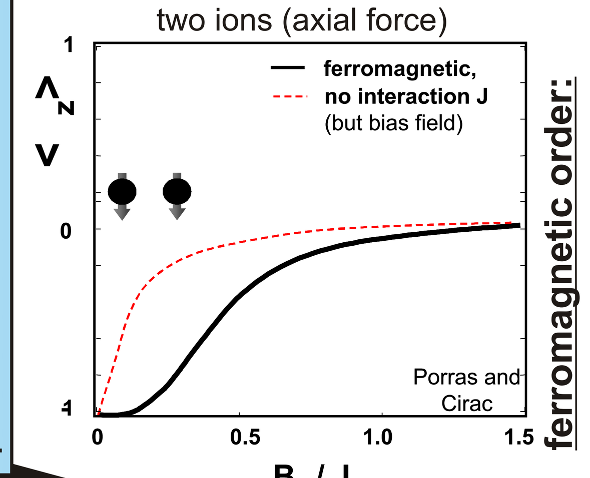



interaction range tunable via radial confinement
e.g. dipolar decay (~$1/r^3$- blue set of data)
or second nearest neighbor interaction strongly suppressed (red set of data)

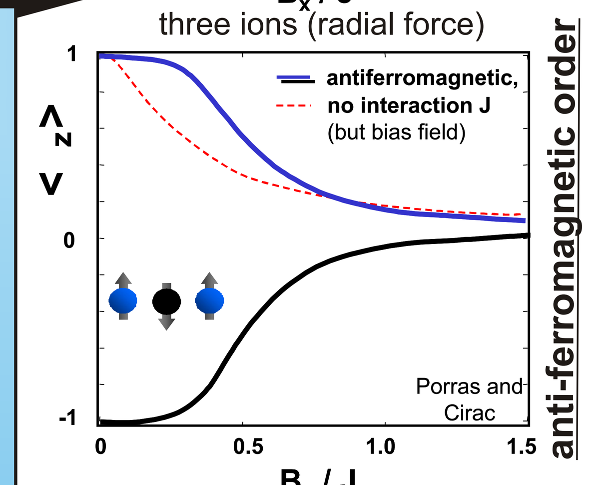
### simulations with two/three ions:

e.g.

two ions (axial force)




three ions (radial force)




### Ising-quantum simulator:

protocol:

1; initialize state, e.g.|↓ ... ↓⟩
2; (adiabatically) switch on $B_x$
3; (adiabatically) switch on J
4; measure global fluorescence
-; alter amplitude of J for constant $B_x$

**"proof of principle" of simulation of quantum spin systems**
[Porras and Cirac, *PRL* 2004;
Milburn, arXiv/0401137 2004]
(1) quantum-Ising model
(2) quantum XY-Heisenberg model

**towards quantum-phase-transition**

### simulations with >10 ions:

**towards a better understanding of quantum-dynamics**
(+) non-equilibrium dynamics
- non-adiabatic evolution
- evolution of excited states (spin systems)
- spontaneous symmetry breaking
- ...