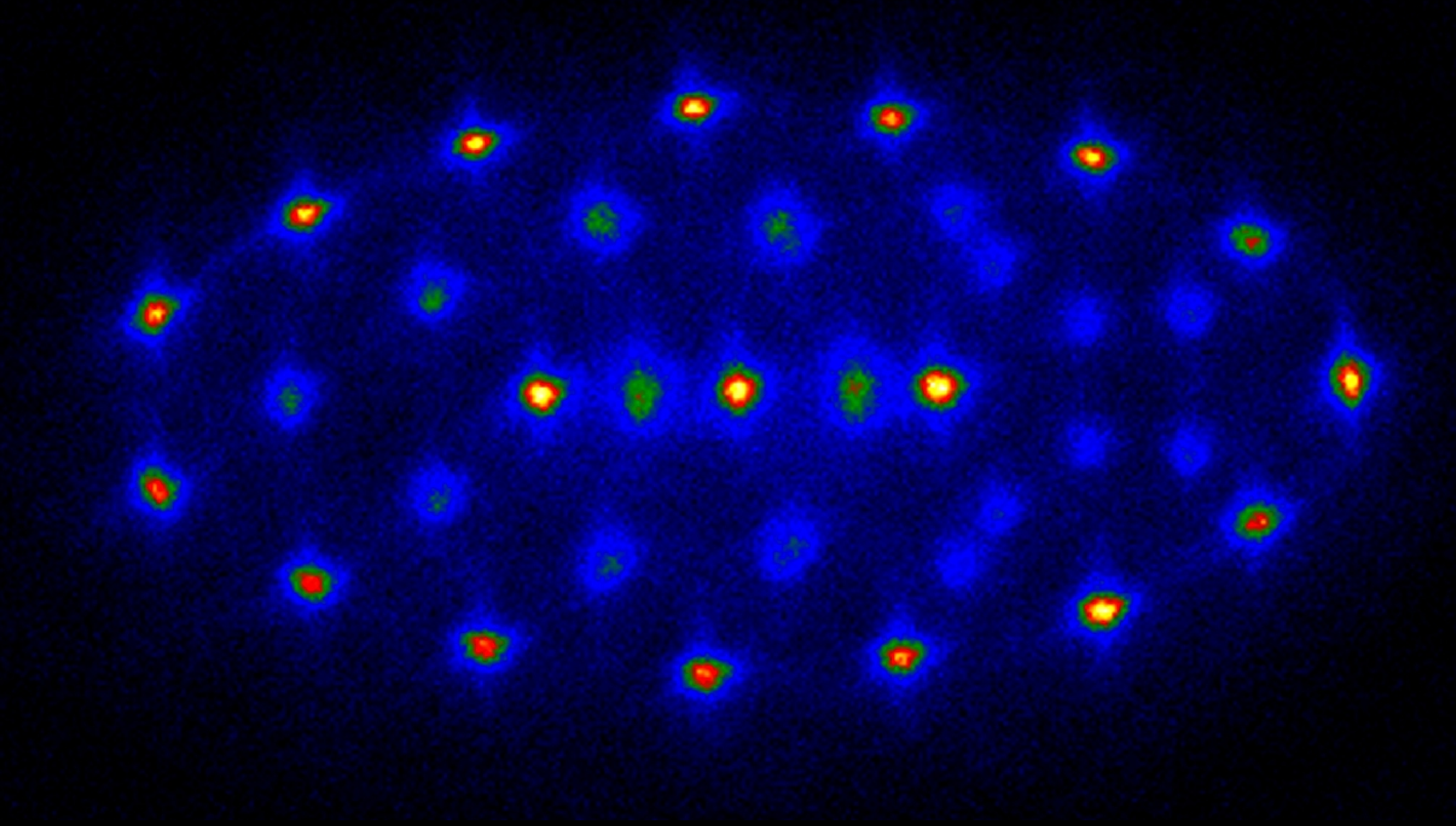
Quantum Simulator



A poor man's quantum computer?

more than one quantum simulator?

(a)addressing different questions

quantum simulator
≠
universal quantum computer

ions:

+large interaction strength
(kHz not Hz)
@ small decoherence rates

+outstanding initialization /preparation
however[1]:
-scalability
-intrinsically (**+**bosons/ **-**fermions)
however[2]:
+dream to combine advantages

(b)addressing identical questions

by different systems?

testing the "non-testable"

Didi's ('2020 visions' *Nature* **463**, 26–32; 2010)

Some promising technologies have emerged, but verifying a quantum simulation is not straightforward. Do the results demonstrate properties of the simulated model, or are they due to unrelated features of the simulator? At first, this quandary

...

But if the same physics models are simulated on different quantum simulators based on different technologies, it is quite likely that common features of all the results will be due to the quantum-physical model and not to the systematics of the simulators.

NJP-special issue on quantum simulations (04.2011)
Tillman Esslinger, Chris Monroe, Tobias Schaetz

outline: experimental Quantum Simulations (QS)

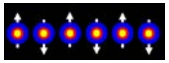
➔ **different implementations of QS (luxury?)**
➔ **different classes (intentions) of QS**
+incomplete list of examples

➔ **example for QS (quantum walk, quantum magnet)**
➔ **similarities/differences between QS and QC**

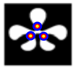
after successful exp. proof of principle
vision ➔ **outperform classical computation**
➔ **deeper insight in complex quantum dynamics**

suggesting 3 objectives

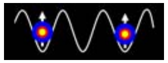
- **#1: <u>decoherence ≠ error</u>**



- **#2: <u>scaling radio-frequency (Penning) traps</u>**
  + minimizing effort



- **#3: <u>new prospects:</u>**
  <u>ions (and atoms) in optical lattices</u>



different classes of quantum simulations

class 1

explore new physics in the laboratory
(perhaps even trackable classically)

<u>simulating analogues:</u>

nonlinear interferometers

Dirac equation
+Klein paradox

Solitons

early universe

(quantum walks)

(Duffing oscillator-Roee)

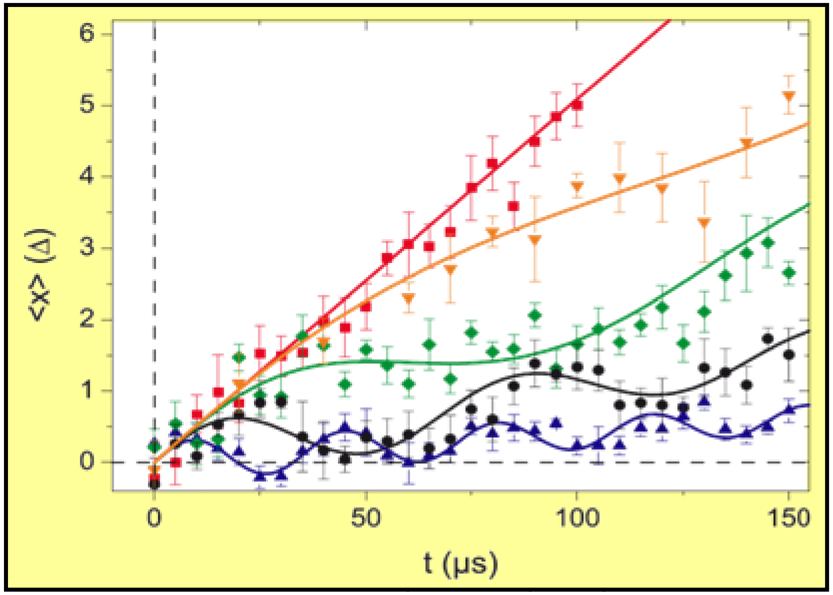
Frenkel Kontorova model

Kibble-Zureck mechanism

class 2

outperform classical computation
address the classically
non-trackabkle

L.Lamata, E.Solano,T.Schaetz et al. PRL (2007)
R.Blatt's group Nature (2010)
R.Blatt's group PRL (2011)



Blatt group (2010)

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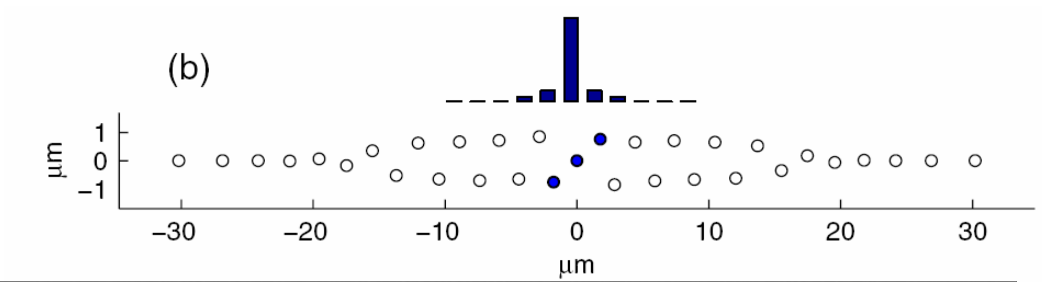
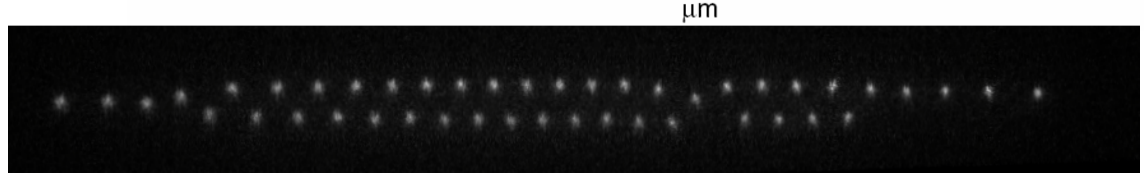
H.Landa, A.Retzker, B.Reznik et al. PRL (2010)





MPQ (2010)

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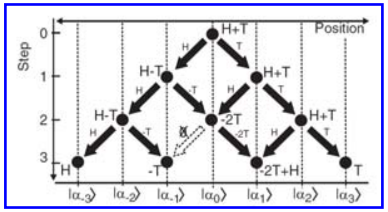
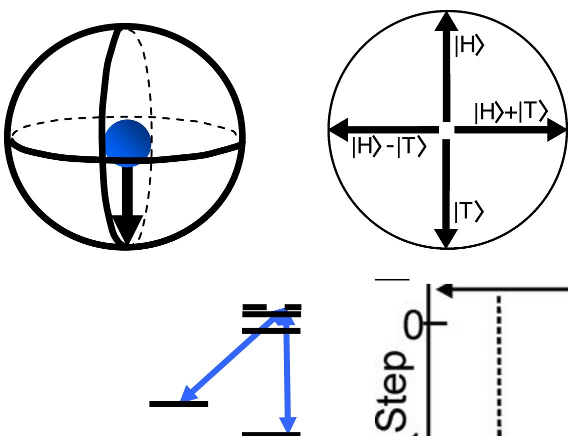
early universe	Milburn PRL 2005 R.Schuetzhold, T.Schaetz et al. PRL (2007)
(quantum walks)	Milburn PRA 2002 Ch.Schneider, T.Schaetz et al. PRL (2009) C.Sanders, D.Leibfried et al. PRL (2009) R.Blatt's group PRL (2010)
(Duffing oscillator-Roee)	R.Ozeri et al., arXiv (2010)
Frenkel Kontorova model	Garcia-Mata et al., Eur. Phys. J. D (2007) + H.Haeffner working on it
Kibble-Zureck mechanism	W.H.Zurek, P.Zoller et al. PRL (2005)



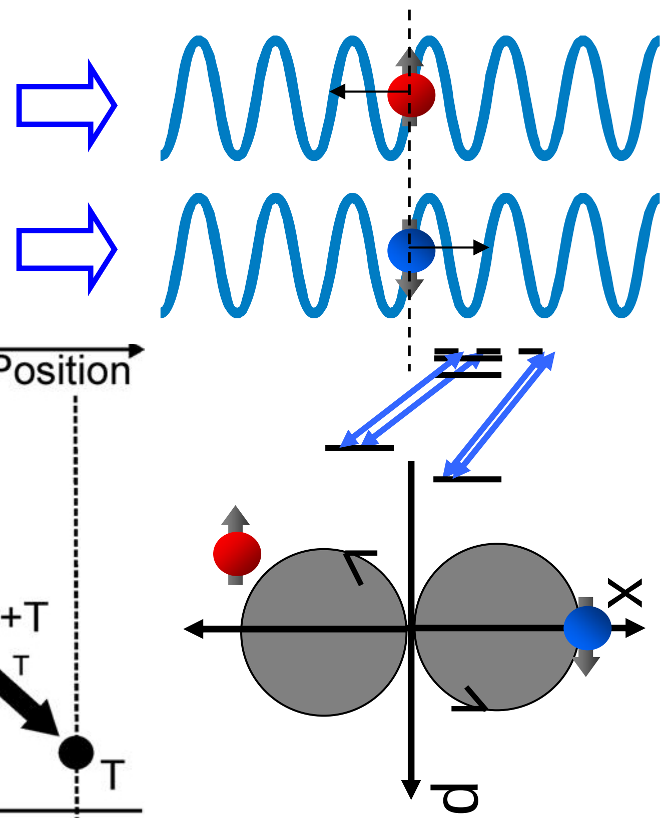
quantum walk

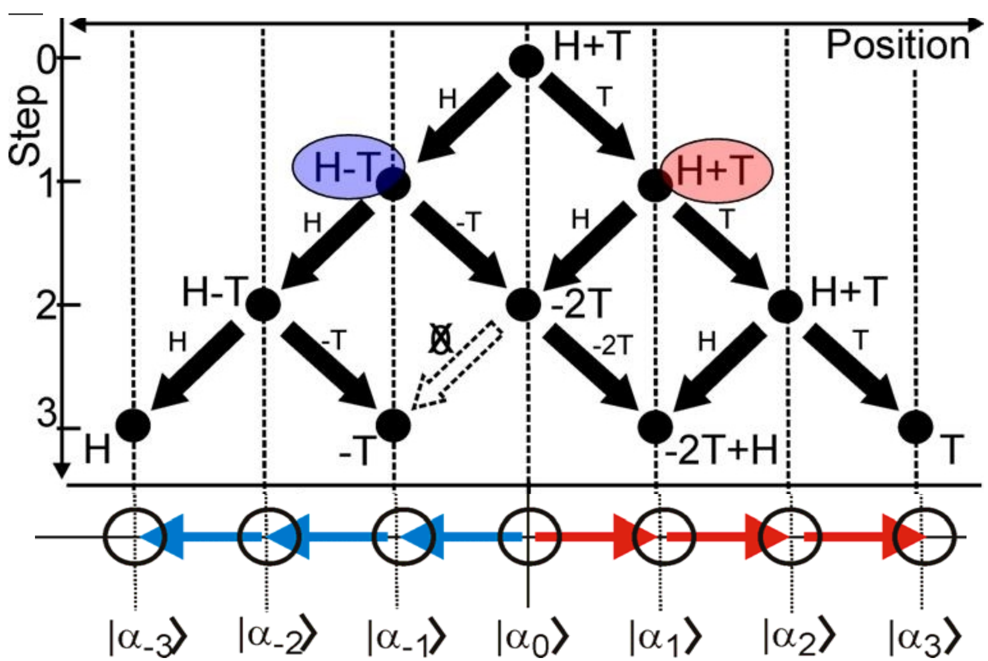
(1) qubit	$\hat{=}$	coin
(2) one qubit gate	$\hat{=}$	coin-flip
(3) conditional gate	$\hat{=}$	step

coin – operation:



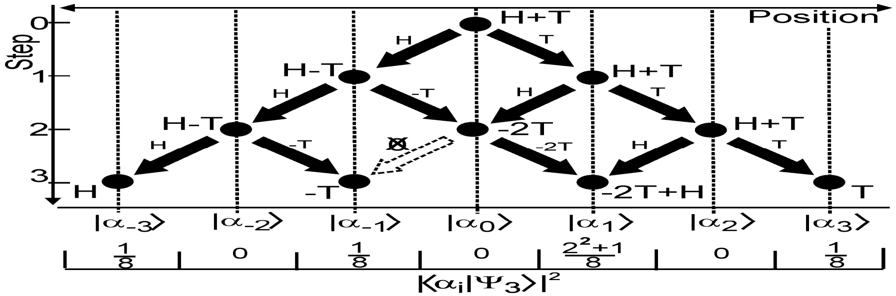
step – operation:

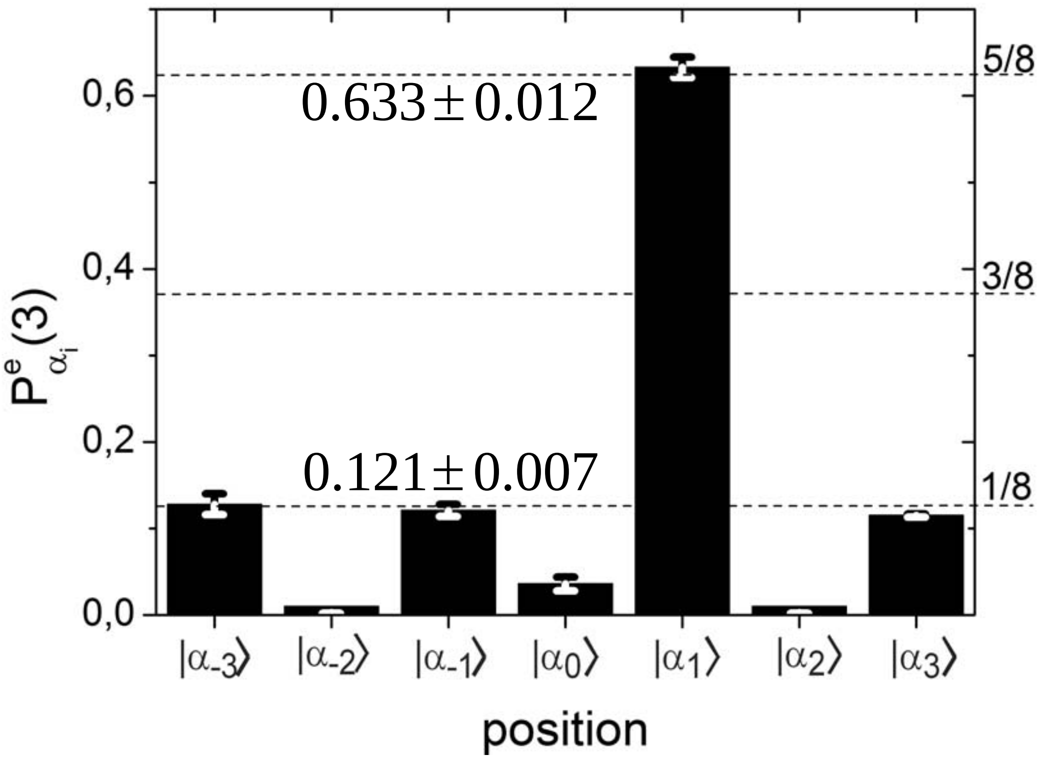




$$|\alpha_i\rangle = e^{-|\alpha_i|^2/2}\sum_{n=0}^{\infty}\frac{\alpha_i^n}{\sqrt{n!}}|n\rangle$$

quantum walk: results (position space)





$$|\Psi_3\rangle = 1/\sqrt{8}\ [\ |H\rangle\,(|\alpha_{-3}\rangle+|\alpha_1\rangle) + |T\rangle\,(-|\alpha_{-1}\rangle - 2|\alpha_1\rangle + |\alpha_3\rangle)]$$

[PRL (2009)]

see also: C.Roos et al. Innsbruck [PRL (2009)]

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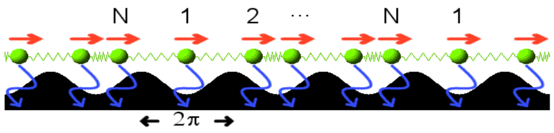

Kibble-Zureck mechanism — W.H.Zurek, P.Zoller et al. PRL (2005)

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simulating solid state physics:

D.Porras and I.Cirac PRL (2004) — Bose-Hubbard model

D.Porras, I.Cirac et al. PRA (2008) — Spin boson model

D.Porras and I.Cirac PRL (2004)
Schaetz's group Nature Physics (2008)
Monroe's group Nature (2010)
— quantum spin Hamiltonians (e.g. quantum Ising, spin frustration)

D.Porras — Anderson localization, three particle interaction

see also Bollinger et al. (+ Thompson & Segal et al.) beautiful work in Penning traps – Nature 2009

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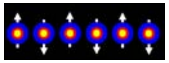

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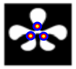

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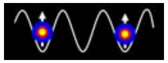


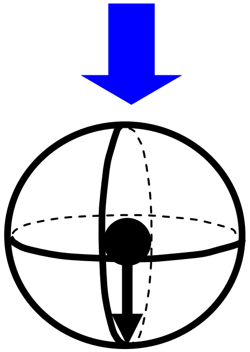
pick one: simulating quantum-spin-systems

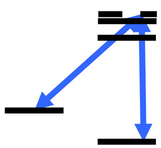
(1) qubit	≙	**spin (σ)**
(2) one qubit gate	≙	**spin-flip (B-field)**
(3) two qubit gate	≙	**spin-spin (J)**

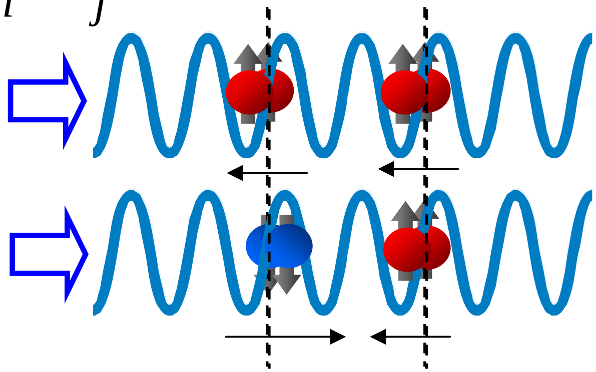
spin-flip (B-field):

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

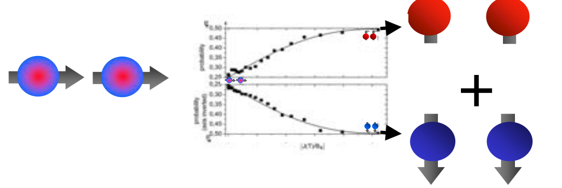
spin-spin (J):

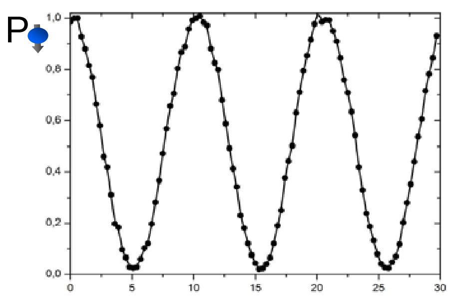






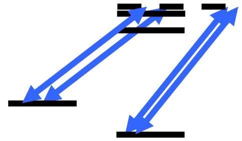
quantum Ising model





$$^x \sum_{\langle i,j \rangle} \sigma_i^x \sigma_j^x + J^y \sum_{\langle i,j \rangle} \sigma_i^y \sigma_j^y$$

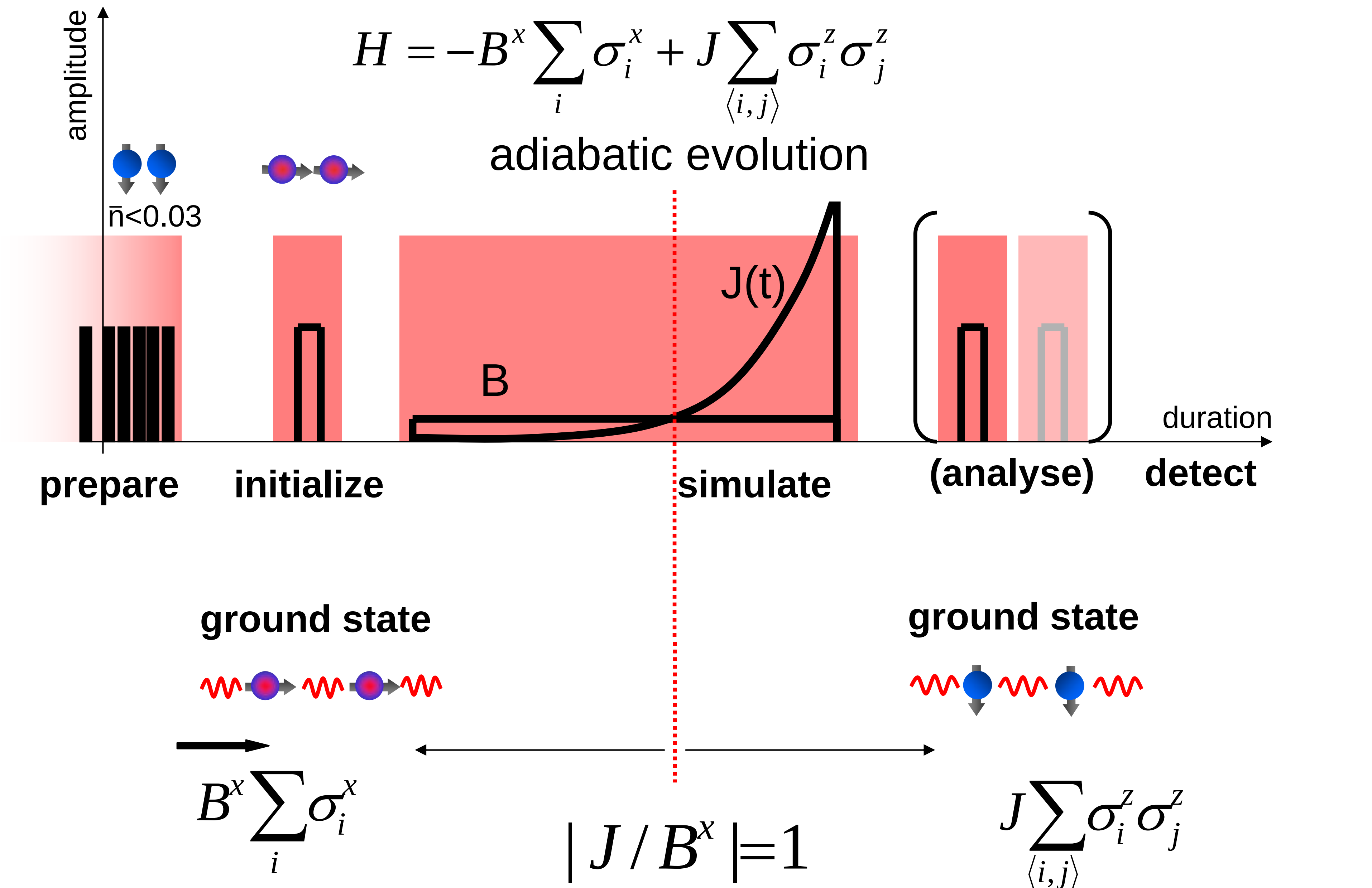
XY model



$$\sum_{\langle i,j \rangle} \sigma_i^x \sigma_j^x + J^y \sum_{\langle i,j \rangle} \sigma_i^y \sigma_j^y + J^z \sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z$$

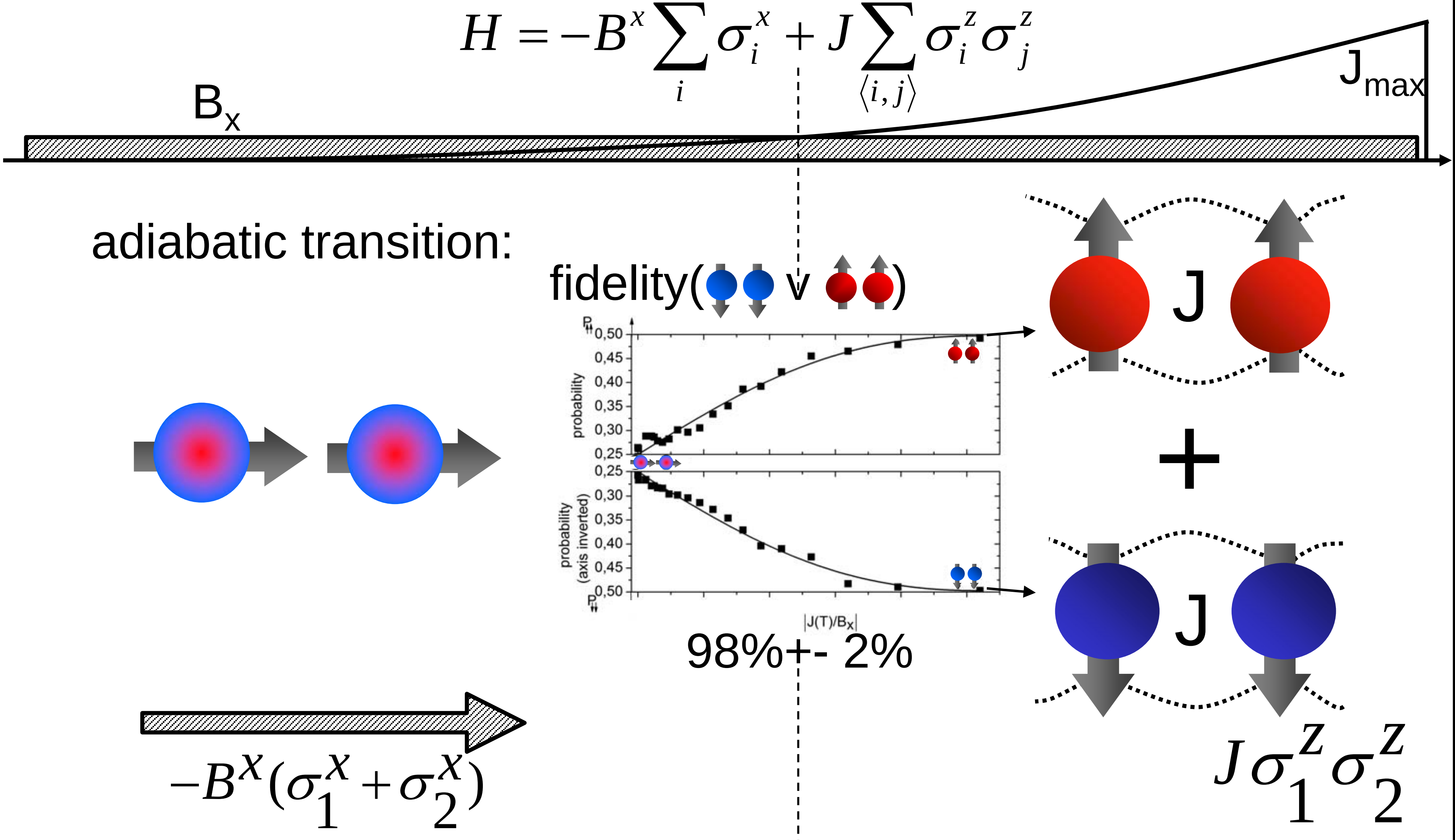
Heisenberg model

quantum magnet



summary: what's up spins?

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



simulating a quantum magnet in an ion trap

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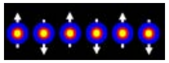

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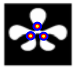

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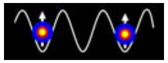
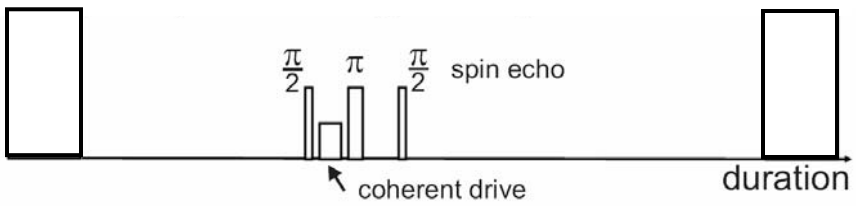
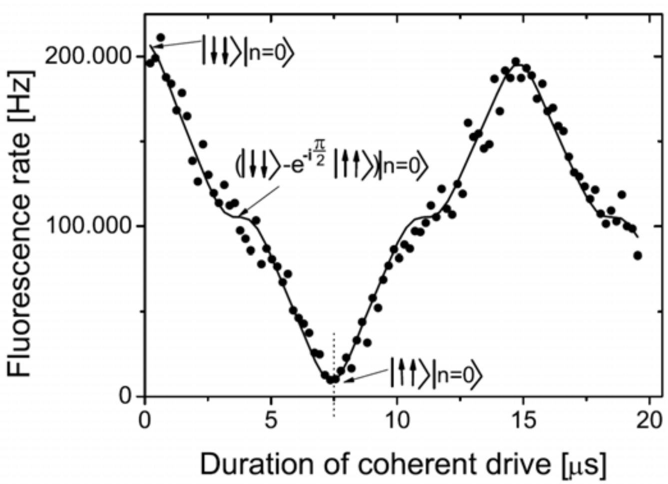
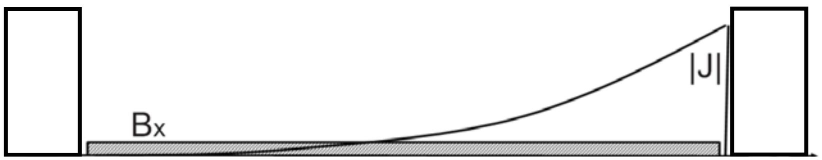
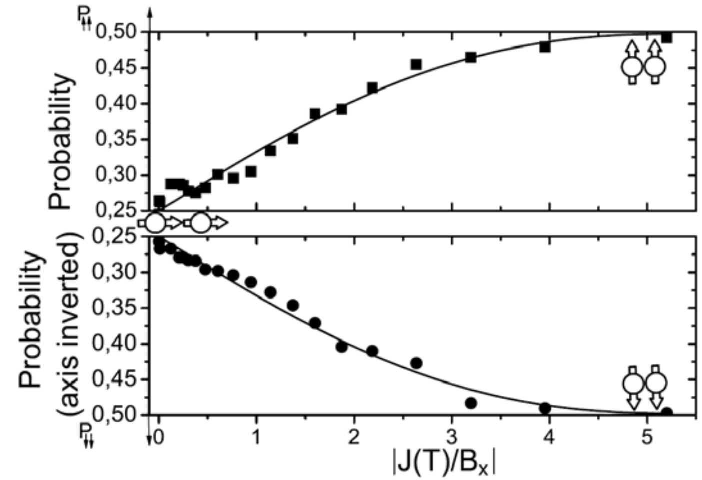


computing versus adiabatic simulation









- -stroboscopic pulses (!t!)
- -non equilibrium (oscillation)
- -error correction (e.g. spin echo)
- -decoherence = error
- -1.1 dimensional trap network

- -continuous evolution (J and B)
- -equilibrium (adiabatic)
- -robust (inherent correction)
- -decoherence = ?nature?
- -2 dimensional trap-lattice

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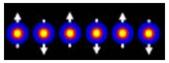

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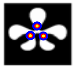

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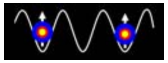
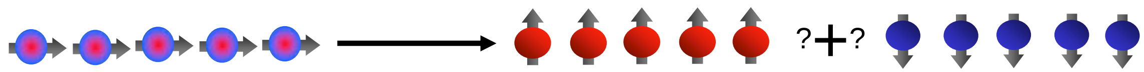


objective #1

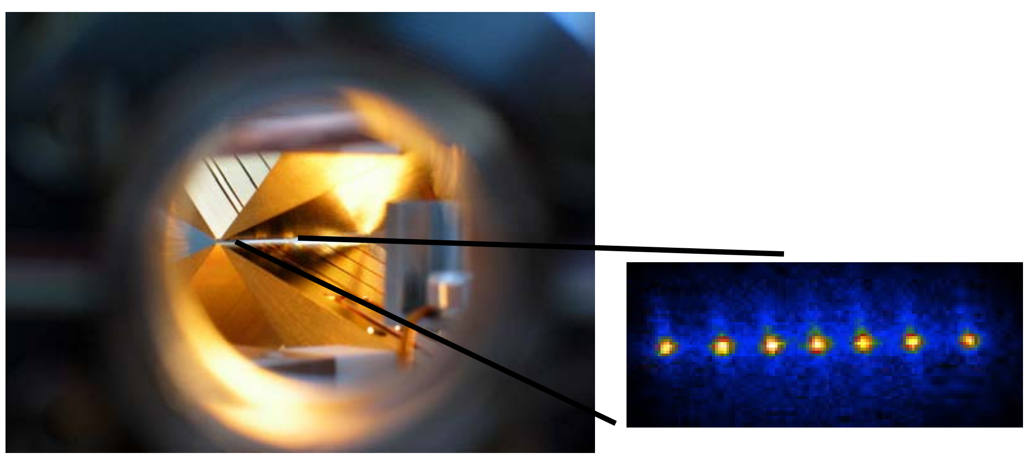
investigate/exploit decoherence

➔**robust:** reduced impact of decoherence (e.g. quantum phase transitions?)



➔**gadget:** engineered decoherence (e.g. simulate “natural” noise?)

➔**necessary:** enhanced (quantum) efficiency by decoherence (e.g. in biological systems?)



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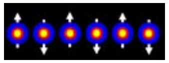

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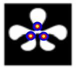

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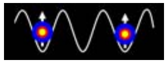
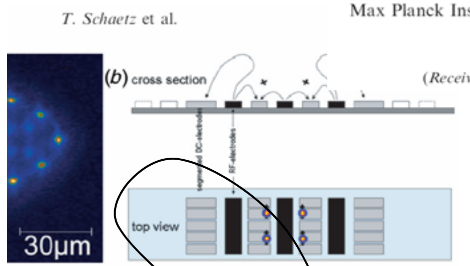


objective #2

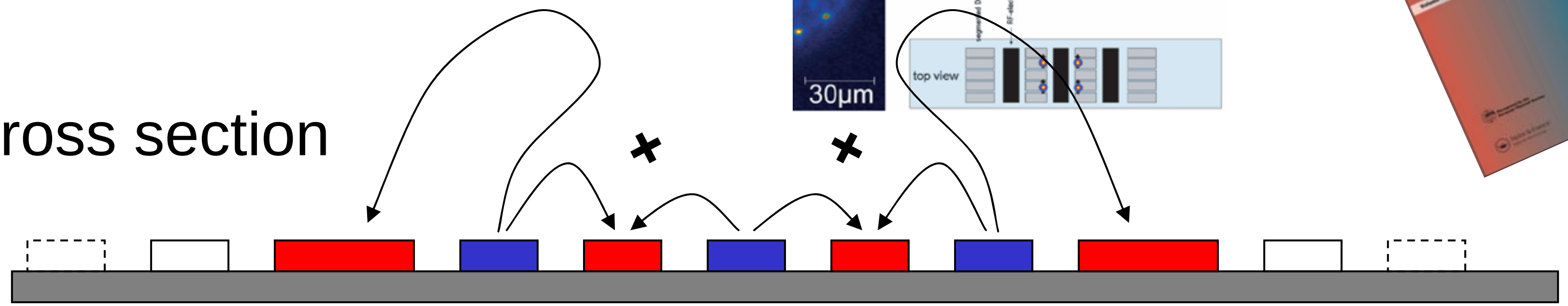
Towards (scalable) quantum simulations in ion traps

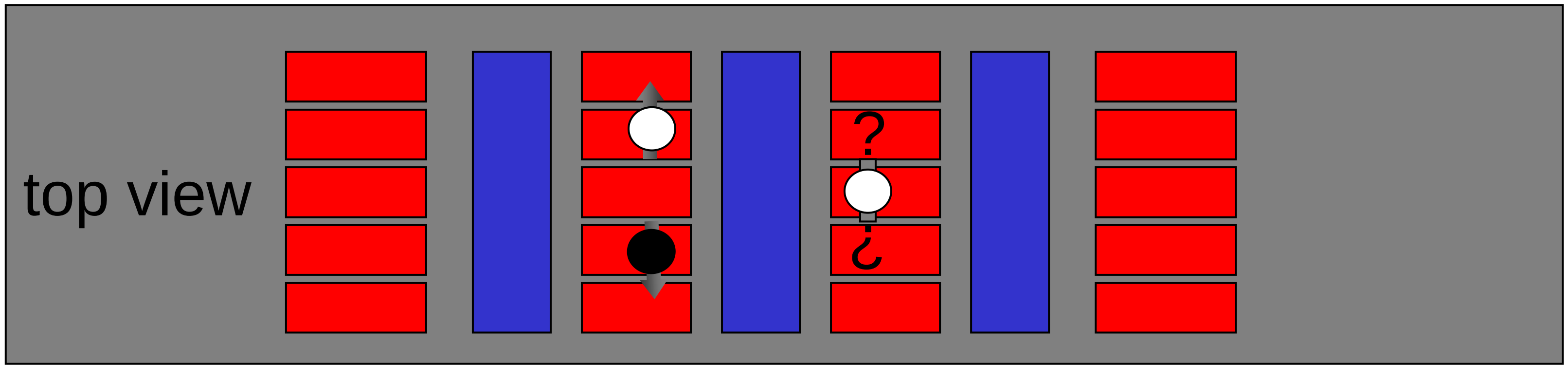
T. SCHAETZ*, A. FRIEDENAUER, H. SCHMITZ, L. PETERSEN and S. KAHRA
Max Planck Institut für Quantenoptik, Hans Kopfer... Strasse 1, 85748 Garching, German...

(Received 14 March 2007; ...



cross section





➔ **<u>extend into second dimension (arrays of ions)</u>**

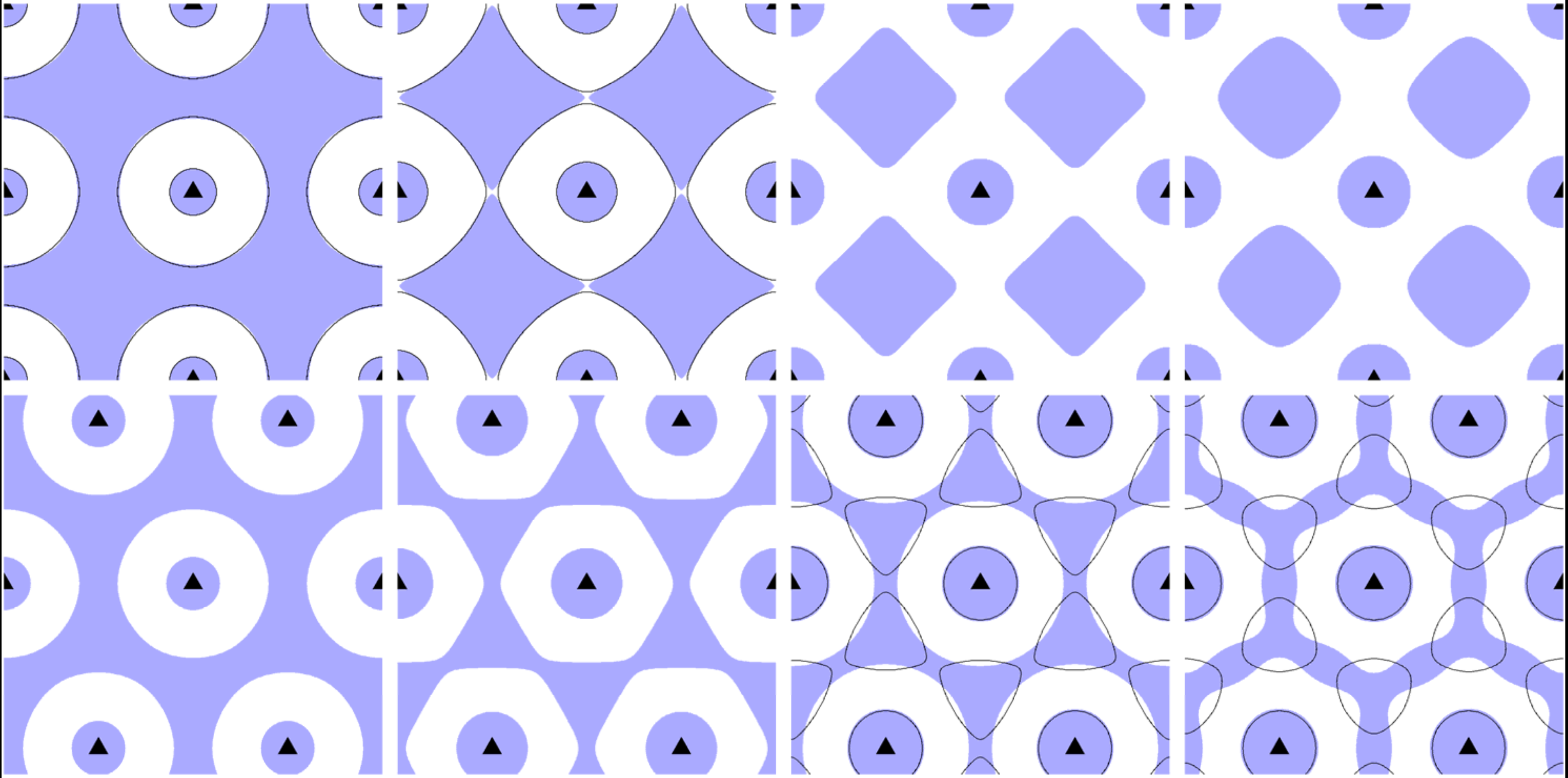
➔ **<u>optimize architecture for quantum simulations</u>** (no cryogenics, large $J_{spin/spin}$)

➔ (potentially without lasers)

trapology –theory - scaling

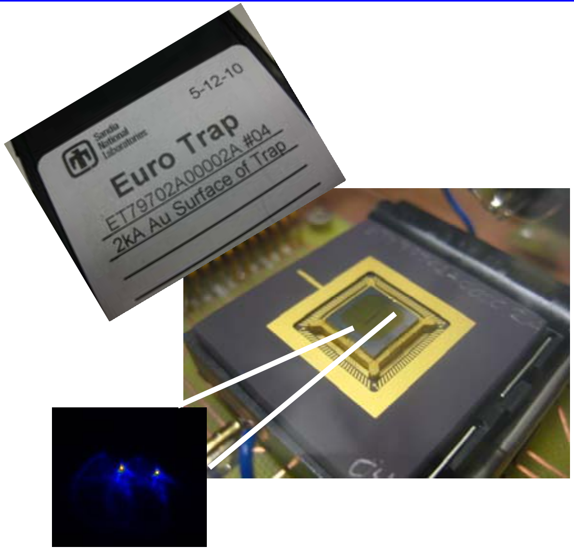
quadratic lattice

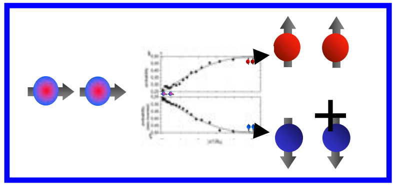
Schmied,Wesenberg, Leibfried PRL(2009)

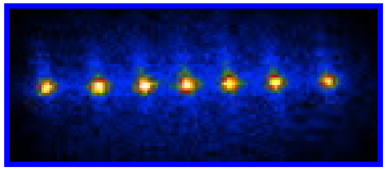


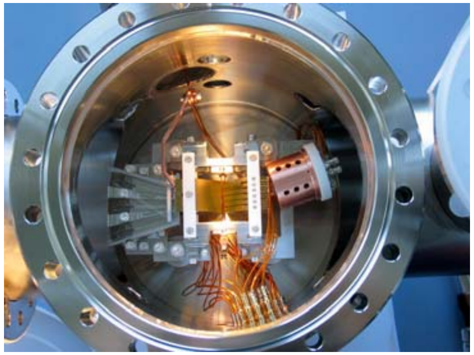
triangular lattice – collaboration: R.Schmied, NIST, Sandia

ion trapper's perspective





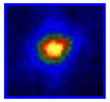




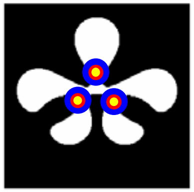
main challenge:
scaling to many ions/spins

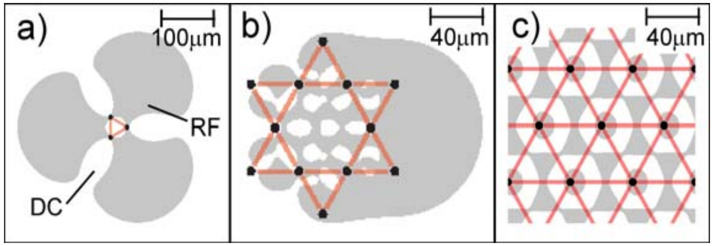
Jan 2011: trapping ions
in SANDIA'S surface trap

2010: optically trapping an ion
+ion trapped in 1D optical lattice

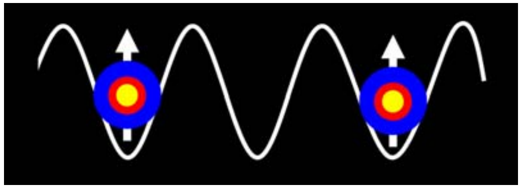


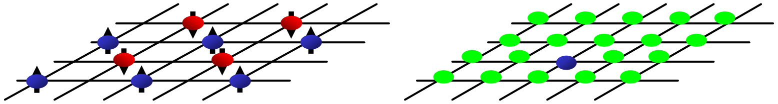
➔ions in 2D rf-surface traps





➔ions (atoms) in optical lattices





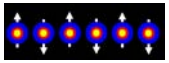
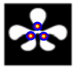
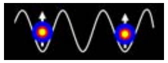
outline: experimental Quantum Simulations (QS)

➔ **different implementations of QS (luxury?)**
➔ **different classes (intentions) of QS**
+incomplete list of examples

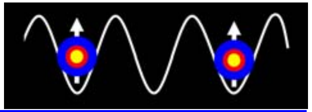
➔ **play through one example for QS (quantum magnet)**
➔ **discuss differences between QS and QC**

after successful exp. proof of principle
vision ➔ **outperform classical computation**
➔ **deeper insight in complex quantum dynamics**

suggesting 3 objectives

- **#1: <u>decoherence ≠ error</u>**

- **#2: <u>scaling radio-frequency (Penning) traps</u>**

+ minimizing effort
- **#3: <u>new prospects:</u>**

<u>ions (and atoms) in optical lattices</u>

objective #3



sharing advantages of ions and optical lattices:

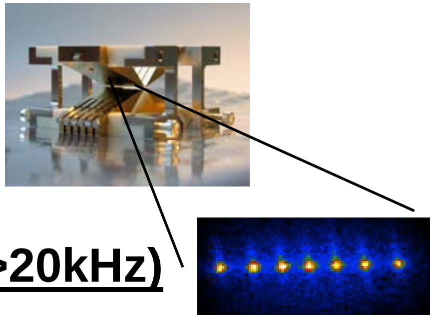
for 60 years:
ions in radio frequency fields

for 30 years:
atoms in optical fields

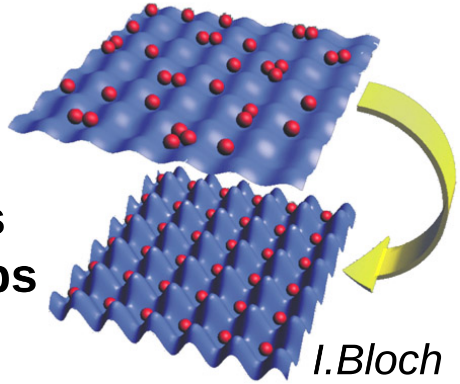
➔ individual addressability

➔ operations of high fidelity (>99%)

➔ **long range interaction ($J_{spin/spin}$>20kHz)**



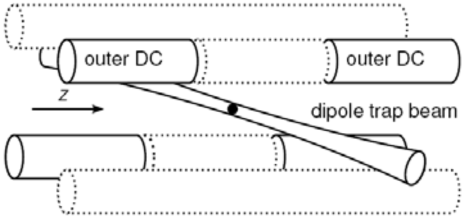
+ **arrays of traps**



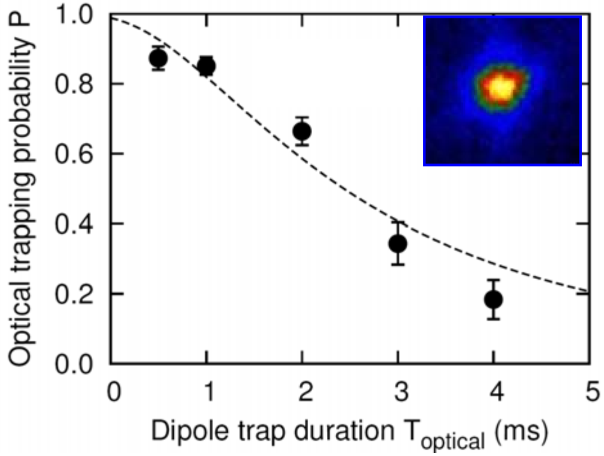
should not compete but complete

first step in our lab: trapping an ion in optical dipole trap*

-loading and cooling in rf-trap
-dipole trap on / rf-trap off



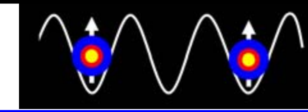
- detection in rf-trap



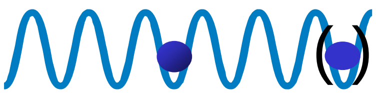
➔ lifetime limited by recoil heating only
➔ several 100s of oscillations in optical potential
➔ loading via rf-trap without heating
➔ion trapped in optical lattice

Nature Photonics (2010)

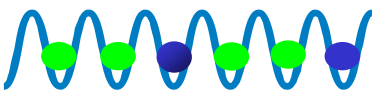
optical dreaming



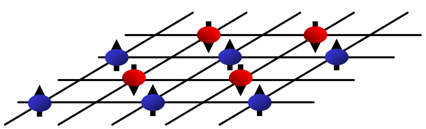
scaling quantum simulations with ions (atoms) in an optical lattice



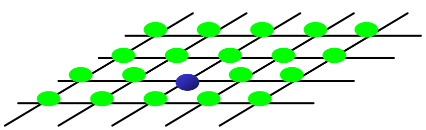
trapping and cooling ion(s) in (hybrid) optical lattice



atoms and ions in common 1D optical lattice*[1]
(e.g. electron tunnling)

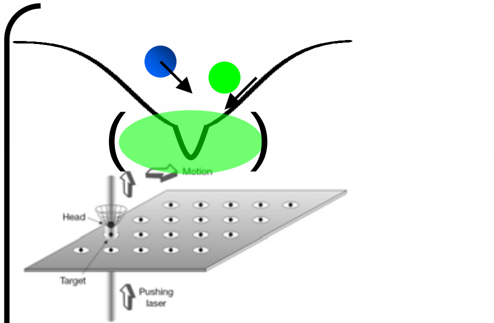


➔ions/spins in 2D/3D optical lattice*[1]
(old QS)



➔atoms and ion(s) in common 2D/3D optical lattice*[1]
(new QS)

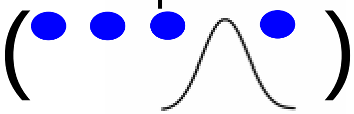
*[1]priv. com. I.Cirac and P.Zoller

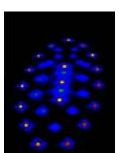
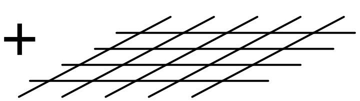


➔atom and ion in common optical trap
(no micromotion)

universal quantum computing
pushing gate*[2] for ions in optical trap array

ion separation

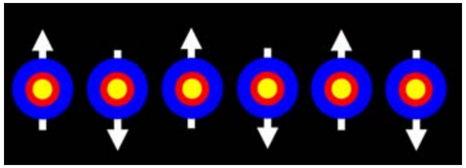


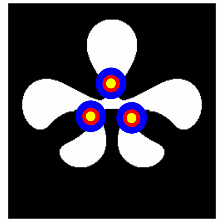
 + 

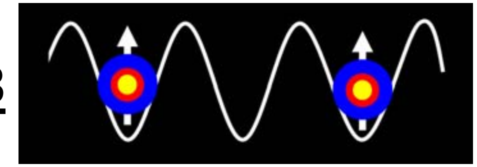
hybrid (Coulomb crystal in RF + optical lattice*[2])

*[2]Nature: Cirac,Zoller (2010)
*[3]NJP: Cirac group (2008)

summary: novel physics

#1 

#2 

#3 

decoherence ≠ error

scaling quantum simulations in ion traps

➔ proof of principle on ions (and atoms) for quantum simulations

➔ how to mitigate, how to exploit it (chemistry/biology)

➔ how to investigate (mesoscopic) decoherence

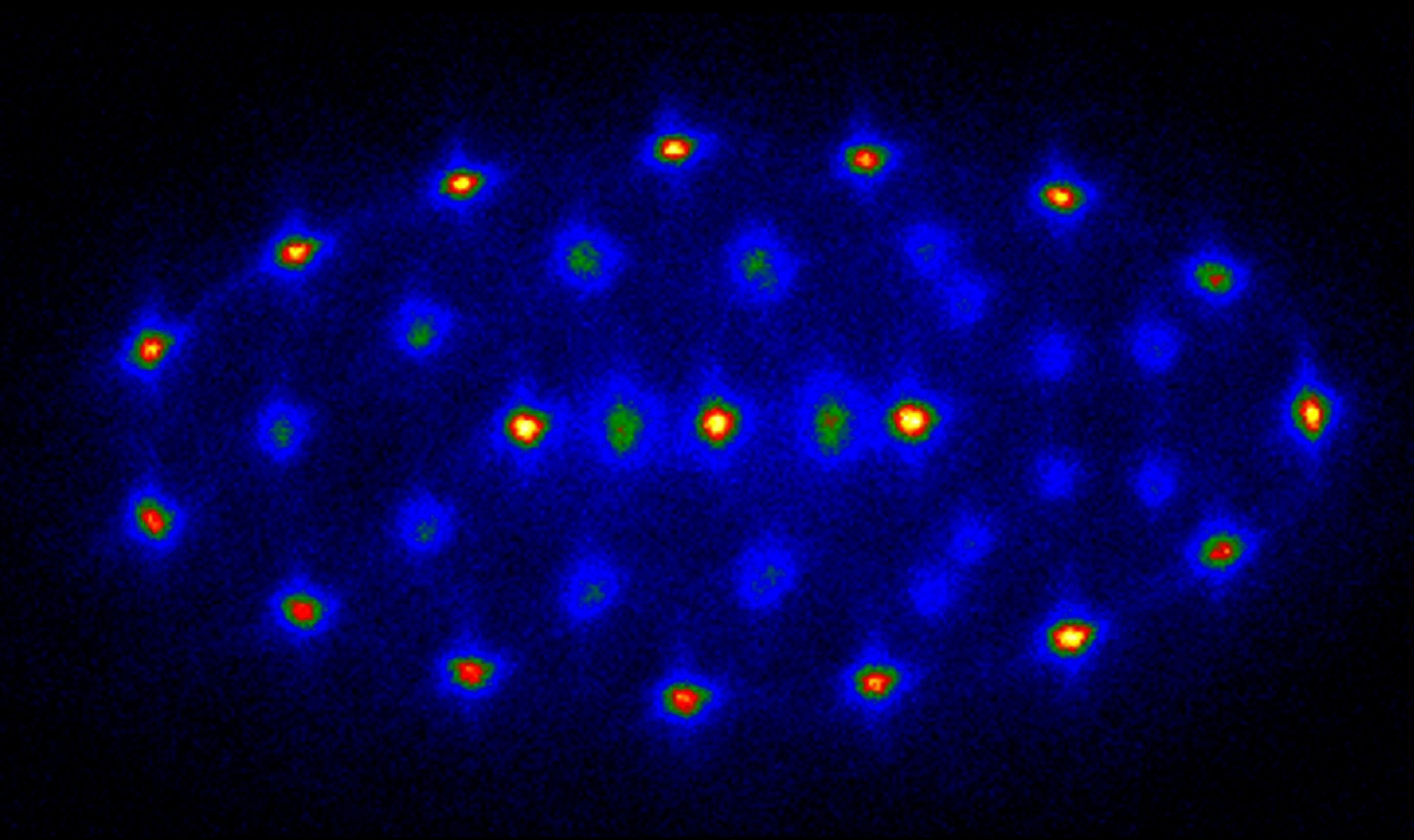
bridging the gap
(proof of principle studies and "useful" QS)

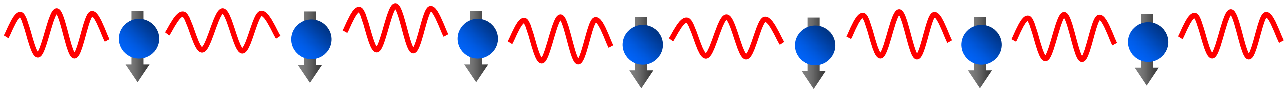
➔ outperforming classical computation

➔ deeper understanding of quantum dynamics **(10x10 spins)**

investigate the impact on:

- **solid state physics** (magnets, ferroelectrics, quantum Hall, high T_c)
  (quantum phase transitions, spin frustration, spin glasses,…)
- **quantum information** processing / **quantum metrology**
- **cold chemistry** (cold collisions)
- …





Max-Planck Institute for Quantum Optics
Garching
Deutsche Forschungsgemeinschaft

IMPRS-APS

+ Taro

TIAMO
Trapped Ions And MOlecules

news from the
3.8 fs beam line

QSim
Quantum Simulations

miac
post doc position
available