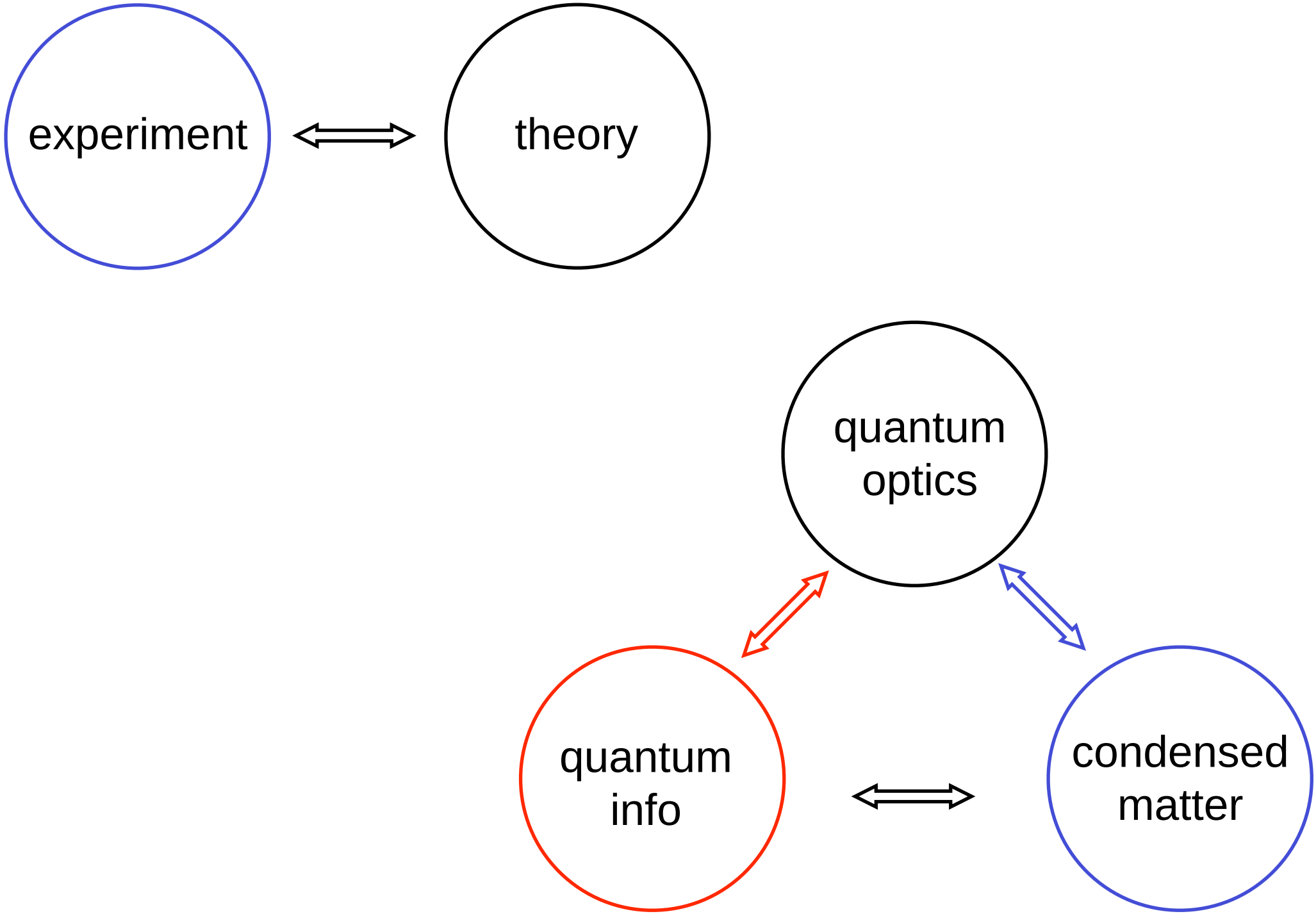

experiment
theory
quantum optics
quantum info
condensed matter

Entangled States

- entanglement

Schrödinger:
Verschränkung

states: $|0\rangle \otimes |0\rangle$

$|1\rangle \otimes |1\rangle$

... product states

but also ...

$$\frac{1}{\sqrt{2}}\left(|0\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle\right)$$

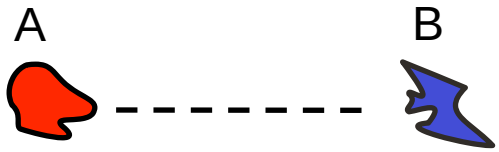
... entangled

- fundamental aspects of quantum mechanics
- applications
  - quantum computing & communication, quantum simulation
  - precision measurement

Engineering Entangled States

We need …

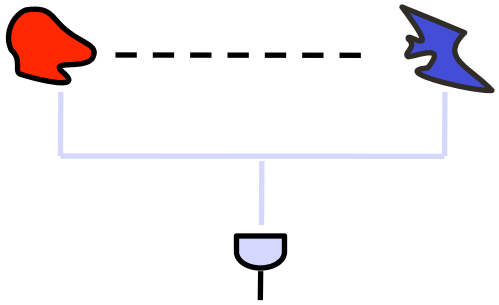
- quantum state engineering



$$|a\rangle_A|b\rangle_B \rightarrow \sum c_{ab}|a\rangle_A|b\rangle_B$$

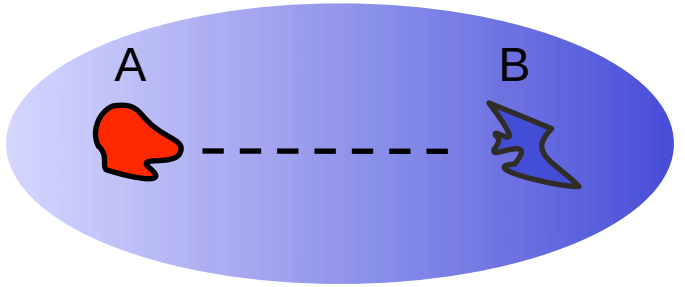
Hamiltonian evolution

- or: “quantum gambling”



measurement

- isolation



environment

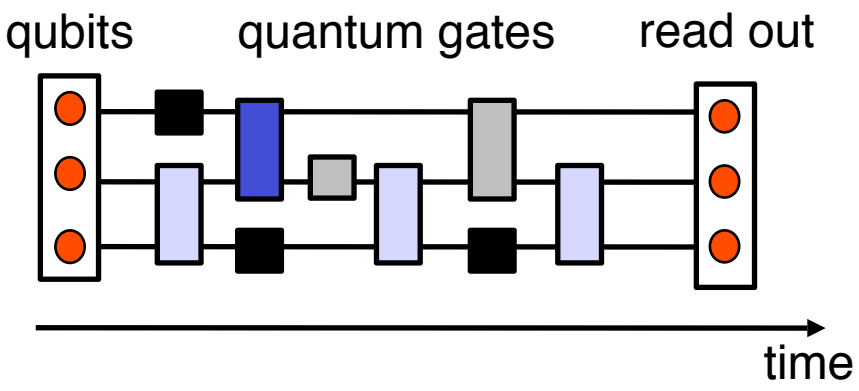
$$|\phi\rangle_A|\varphi\rangle_B|E\rangle \rightarrow |\Psi\rangle_{ABE}$$

$$\rho_{AB} = \mathrm{tr}_E|\Psi\rangle_{ABE}\langle\Psi| \neq |\Psi\rangle_{AB}\langle\Psi|$$

Quantum optical systems provide one of the best set-ups to create entangled states in a controlled way.

Quantum Computing

- quantum computing: logic network



- general purpose quantum processor

✓qubits

✓single qubit gate

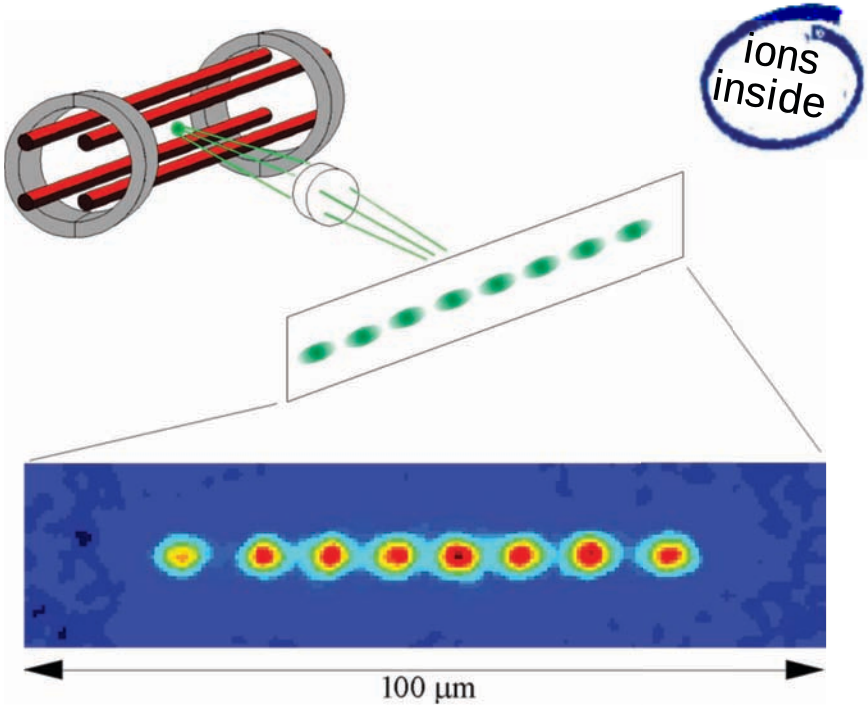
✓two qubit gate = entanglement

✓read out

✓(no decoherence)

Quantum Optics

- laser cooled trapped ions I. Cirac & P.Z.



… 2 internal state / ion

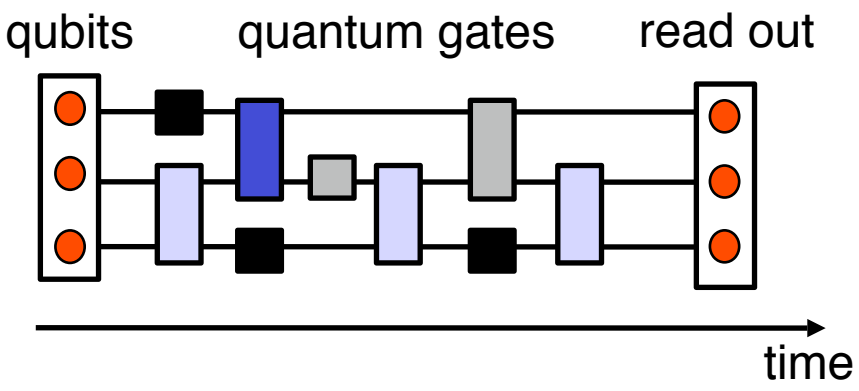
… with laser pulses

… via collective phonon modes

… with quantum jump technique

Quantum Computing

- quantum computing: logic network



- general purpose quantum processor

✓qubits

✓single qubit gate

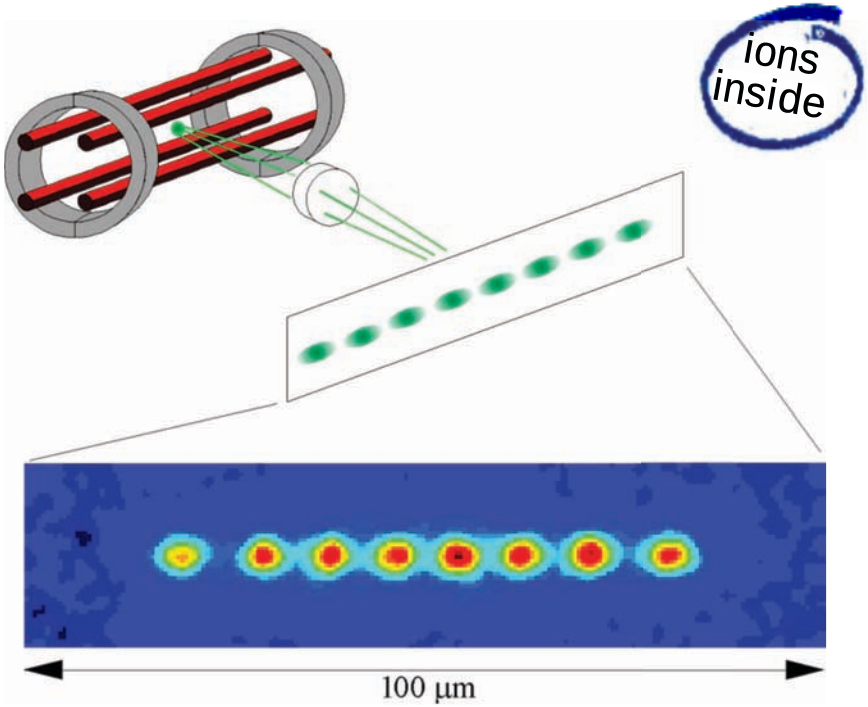
✓two qubit gate = entanglement

✓read out

✓(no decoherence)

Quantum Optics

- laser cooled trapped ions I. Cirac & P.Z.



… 2 internal state / ion

… with laser pulses

… via collective phonon modes

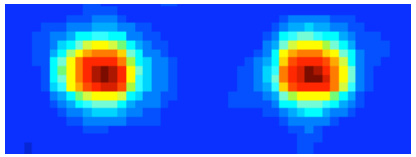
… with quantum jump technique

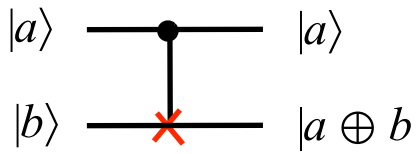
"phonon data bus"

Ion Trap QC: Achievements

D. Wineland NIST Boulder
R. Blatt Innsbruck

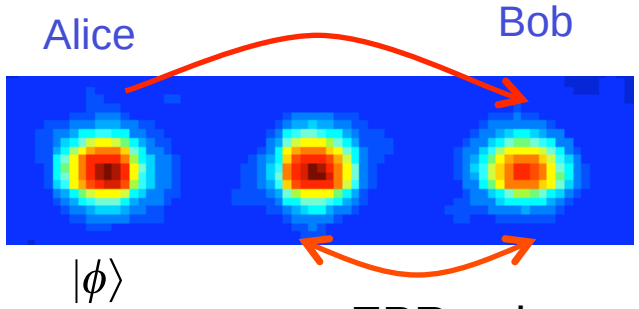
- 2 ion addressable Controlled-NOT





Controlled-NOT

- 3 ions: deterministic teleportation, error correction



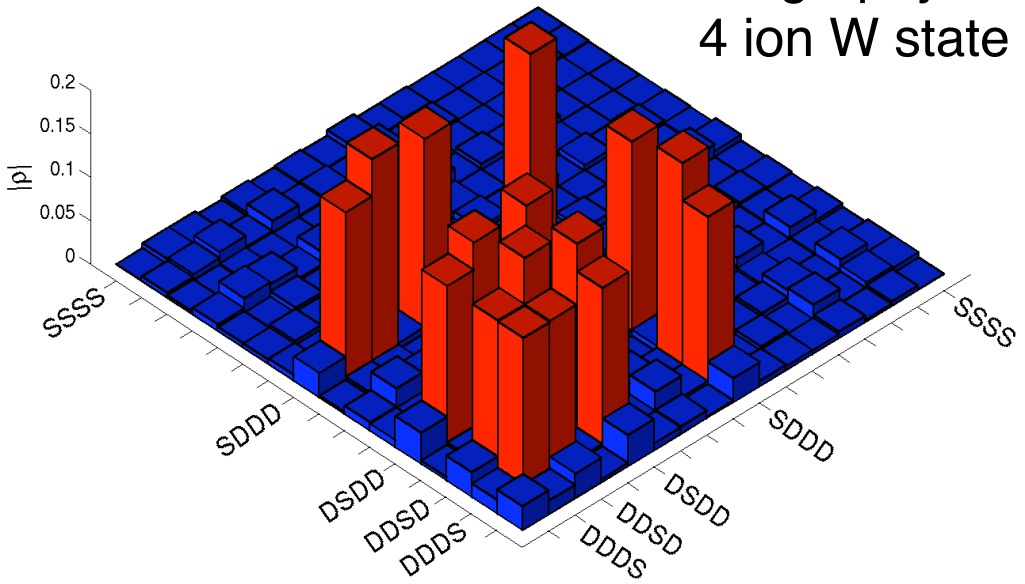
EPR pair

$$|\text{EPR}\rangle \sim |0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B$$

- lifetime of EPR states ~ 60 sec

- 6 ions GHZ state
- 8 ions: W-state

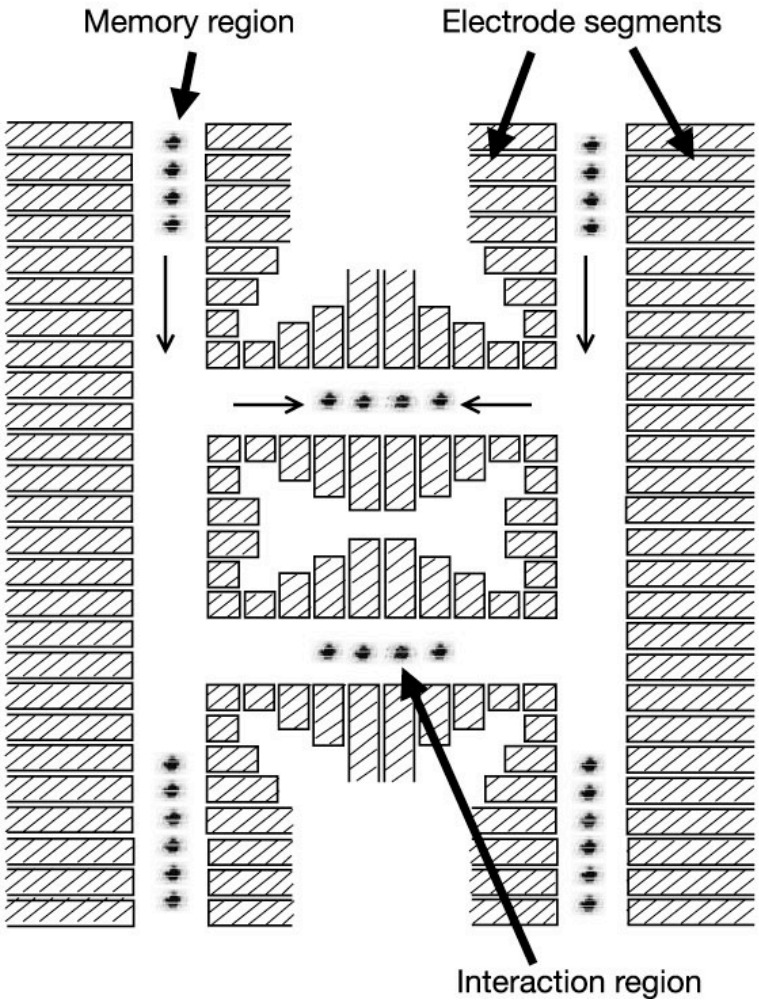
tomography of a 4 ion W state



$$|\Psi_4\rangle = \frac{1}{2}(|SDDD\rangle + |DSDD\rangle + |DDSD\rangle + |DDDS\rangle)$$

Ion Trap QC: Future

- scalable quantum computing



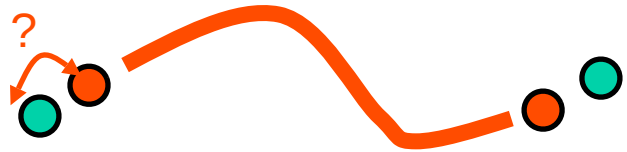
move ions

Wineland et al., I. Cirac and PZ

- interfaces

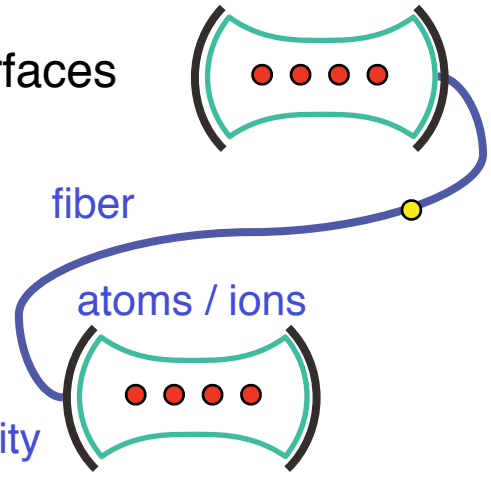
-quantum optics / solid state interfaces

connecting two quantum optical qubits by
a (passive) solid state bus



interfacing active devices

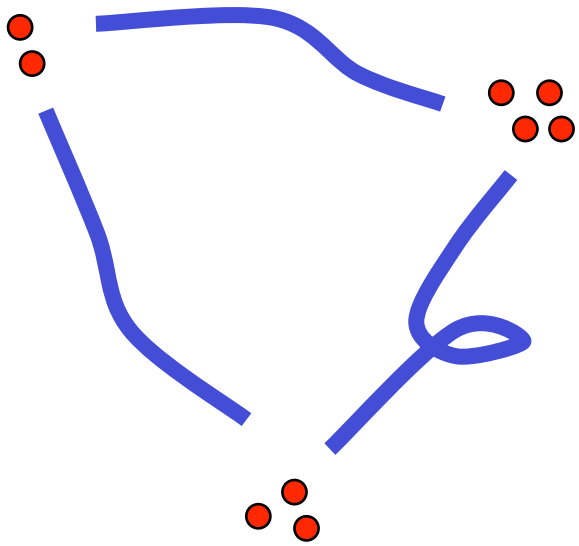
-ion / photon interfaces



I. Cirac, PZ,
J Kimble, H. Mabuchi

Quantum Communication

- quantum communication & quantum networks

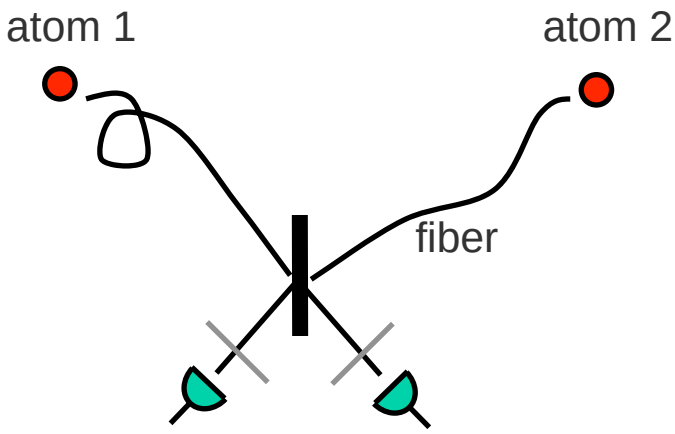


- Nodes: local quantum computing
  - store quantum information
  - local quantum processing

- Channel: quantum communication
  - transmit quantum information

Quantum Optics

- entanglement over a distance



$$|\Psi\rangle \sim |01\rangle - |10\rangle$$

probabilistic generation of EPR state

quantum repeater protocols for long distance quantum communication

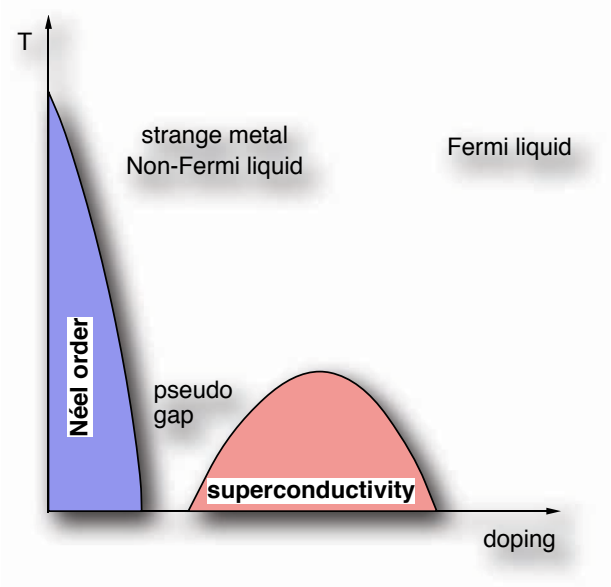
- generation and purification of long distance EPR pairs
- teleportation

Duan, Cirac, Lukin & PZ

exp: Kimble, Kuzmich, Lukin, Polzik; Monroe

Condensed Matter Physics

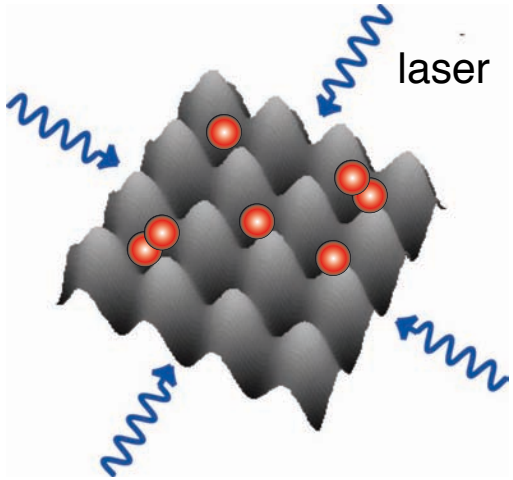
- cond mat models: strong correlation ...



Fermi Hubbard in 2D

Quantum Optics

- atoms in an optical lattices



Bose & Fermi Hubbard

$$H = -t\sum_{i,j,\sigma}(c^{+}_{i\sigma}c_{j\sigma} + c^{+}_{j\sigma}c_{i\sigma}) + U\sum_{i} n_{i\uparrow}n_{i\downarrow}$$

AMO Hubbard toolbox

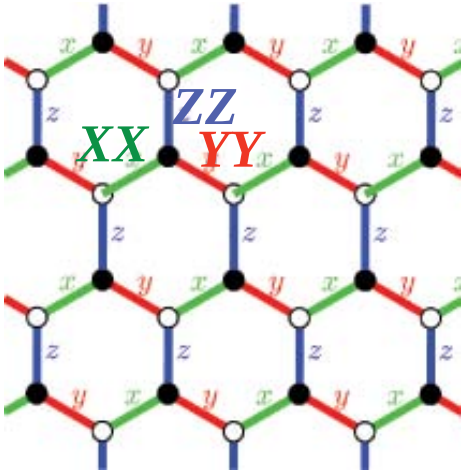
✓engineer interactions

✓controllable parameters

(1D/2D/3D, time dependence, …)

Condensed Matter Physics

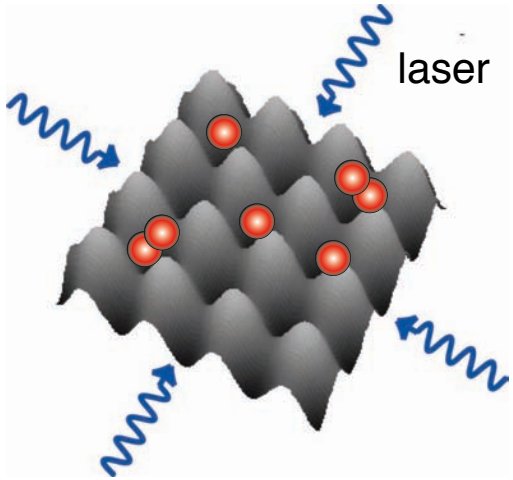
- cond mat models: strong correlation ...



exotic “materials” and quantum phases

Quantum Optics

- atoms in an optical lattices

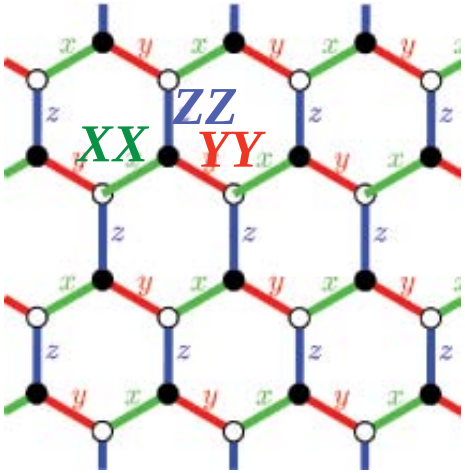


Bose & Fermi Hubbard

- “quantum simulators”
  - analog & digital
- measurement based quantum computing
- topological phases and qc (?)

Condensed Matter Physics

- cond mat models: strong correlation ...

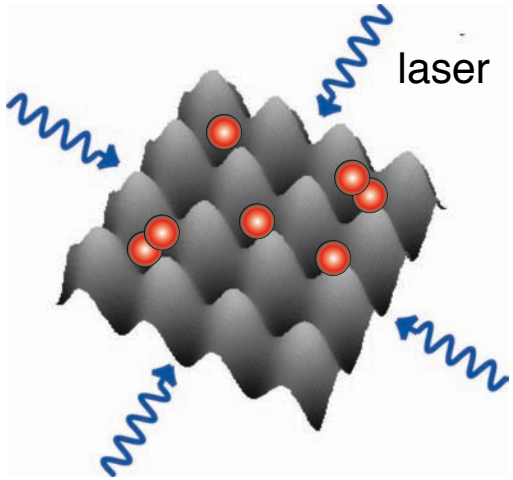


exotic “materials” and quantum phases

- “quantum simulators”
  - analog & digital
- measurement based quantum computing
- topological phases and qc (?)

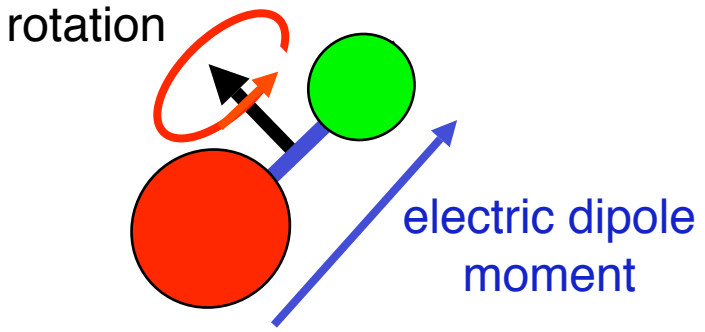
Quantum Optics

- atoms in an optical lattices



Bose & Fermi Hubbard

- polar molecules

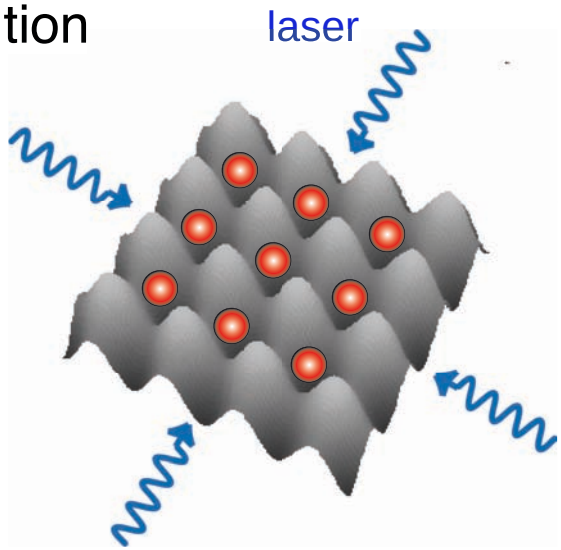


new system

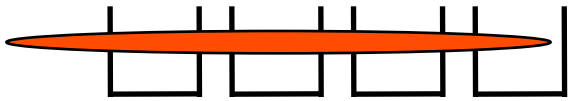
Atoms in Optical Lattices: Achievements

- Superfluid - Mott insulator quantum phase transition

$$H = -\sum_{\alpha\neq\beta} J_{\alpha\beta} b_\alpha^\dagger b_\beta + \tfrac{1}{2}U \sum_\alpha b_\alpha^\dagger b_\alpha^\dagger b_\alpha b_\alpha$$



- shallow lattice: superfluid t>>U
- deep lattice: Mott insulator t<<U



$$\left(b_1^\dagger + \ldots + b_M^\dagger\right)^N |\mathrm{vac}\rangle$$

delocalized atoms: BEC

(weakly interacting)

quantum phase transition

$$b_1^\dagger b_2^\dagger \ldots b_M^\dagger |\mathrm{vac}\rangle$$

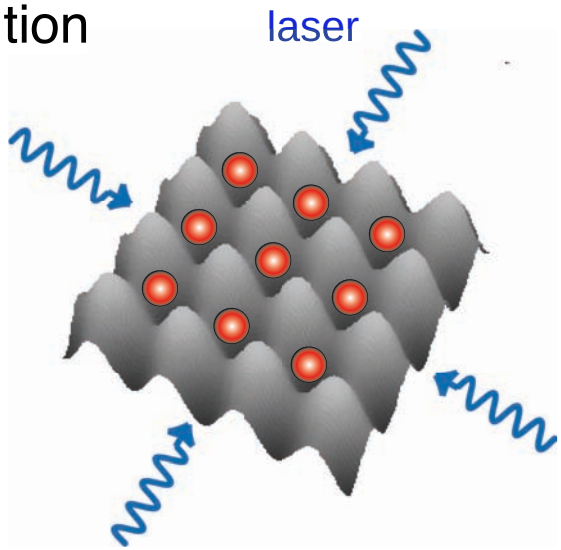
"Fock states"

(strongly interacting)

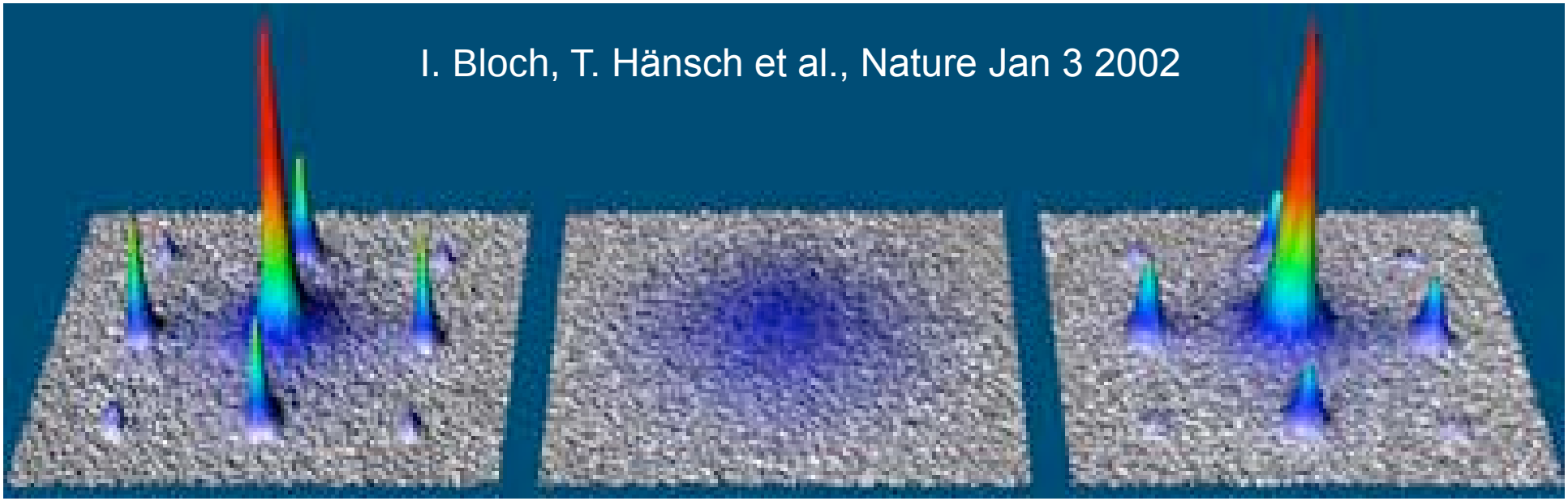
Atoms in Optical Lattices: Achievements

- Superfluid - Mott insulator quantum phase transition

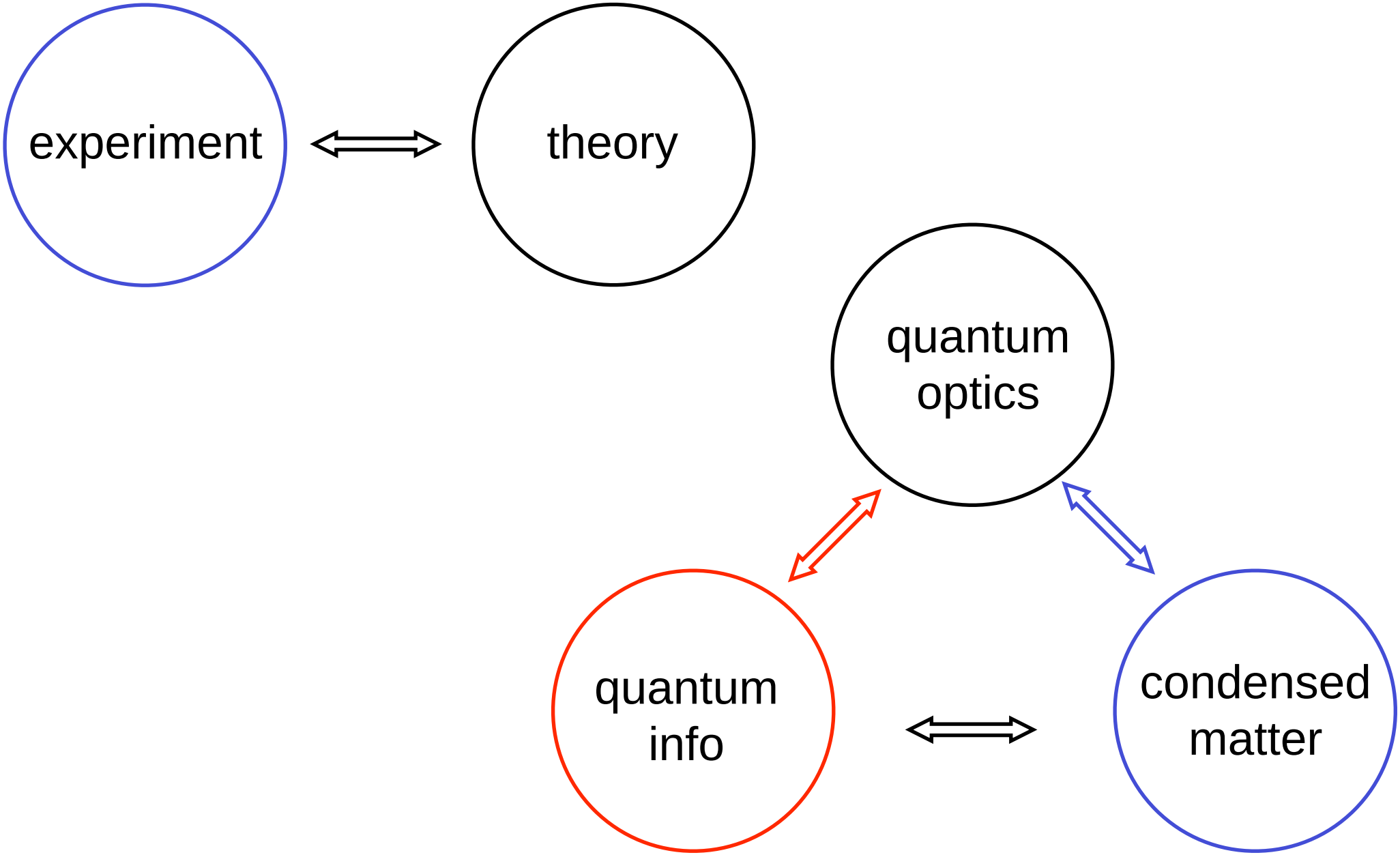
$$H = -\sum_{\alpha\neq\beta} J_{\alpha\beta} b_\alpha^\dagger b_\beta + \tfrac{1}{2}U \sum_\alpha b_\alpha^\dagger b_\alpha^\dagger b_\alpha b_\alpha$$

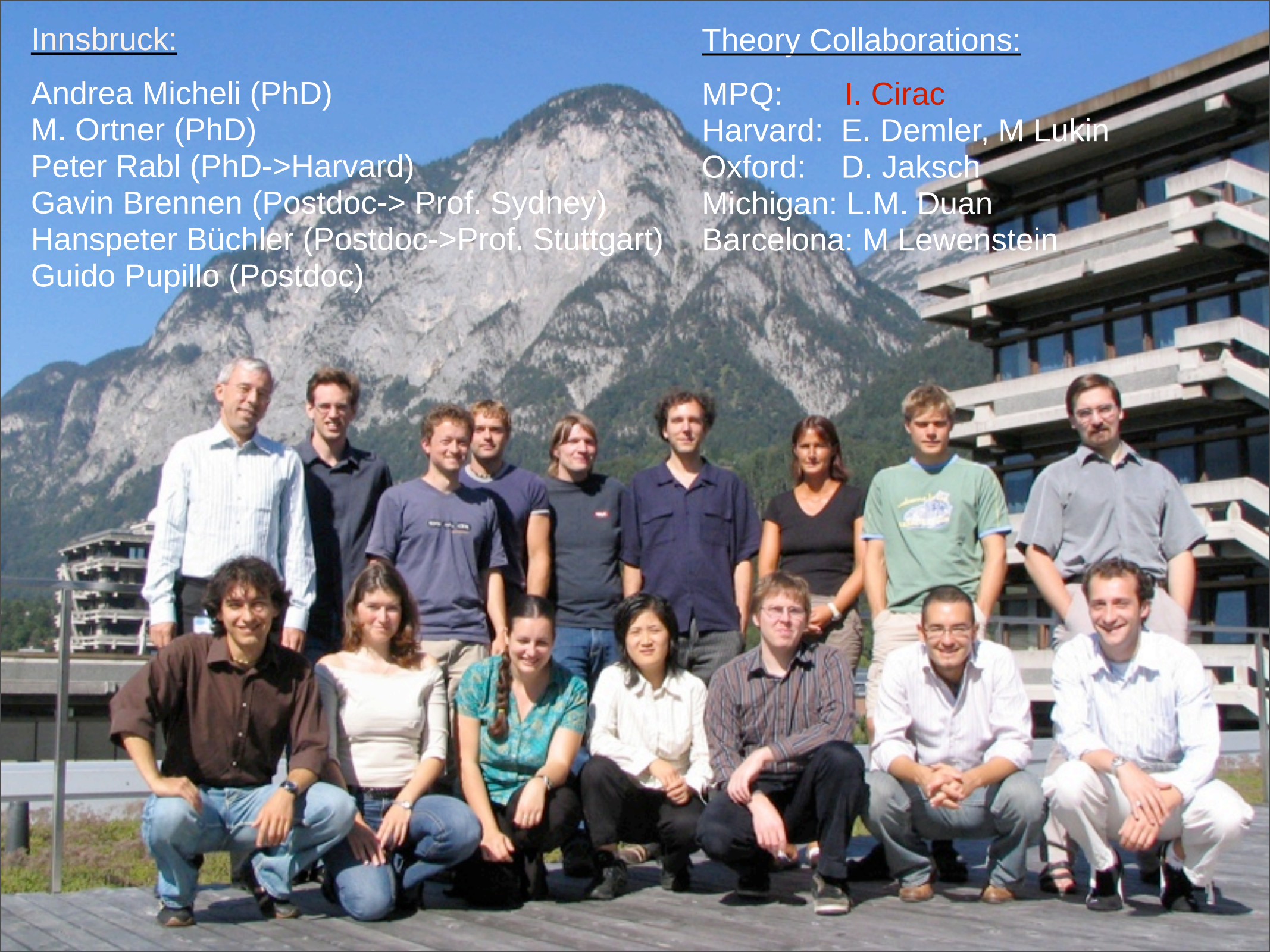


interference: SF NO interference: Mott interference: SF



Summary & Outlook




Innsbruck:
Andrea Micheli (PhD)
M. Ortner (PhD)
Peter Rabl (PhD->Harvard)
Gavin Brennen (Postdoc-> Prof. Sydney)
Hanspeter Büchler (Postdoc->Prof. Stuttgart)
Guido Pupillo (Postdoc)
Theory Collaborations:
MPQ: I. Cirac
Harvard: E. Demler, M Lukin
Oxford: D. Jaksch
Michigan: L.M. Duan
Barcelona: M Lewenstein