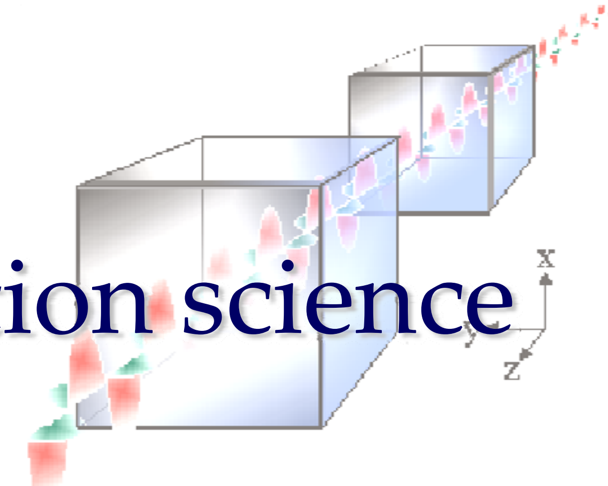
Dissipation:
a new tool in
quantum information science



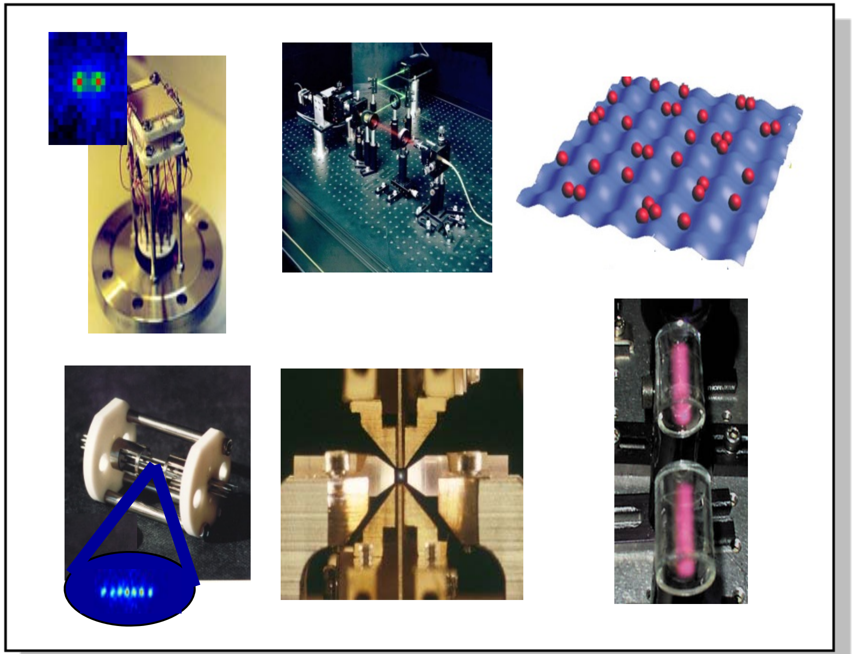
J. IGNACIO CIRAC

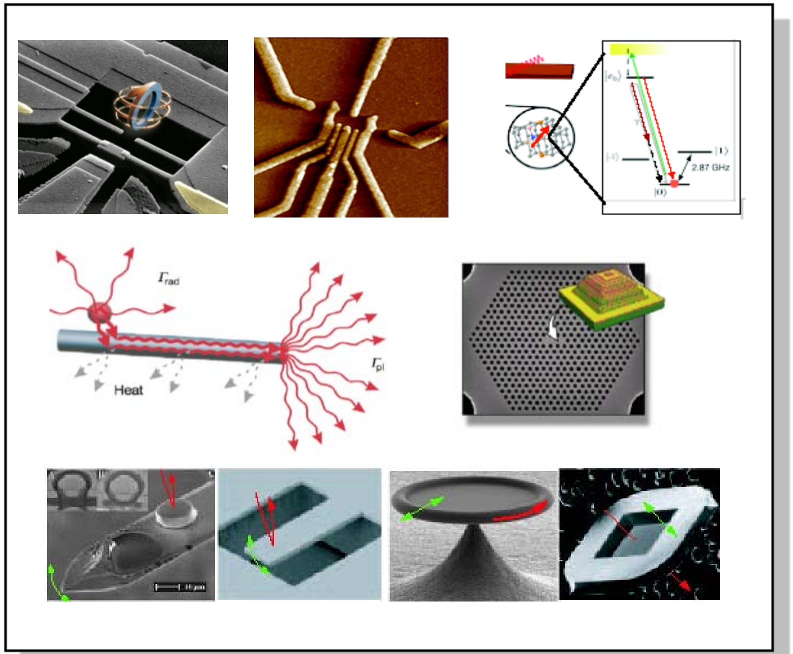
MPQ
Max-Planck-Institut
für Quantenoptik

Physics Colloquium,
Israel Institute of Technology, December 3rd, 2012

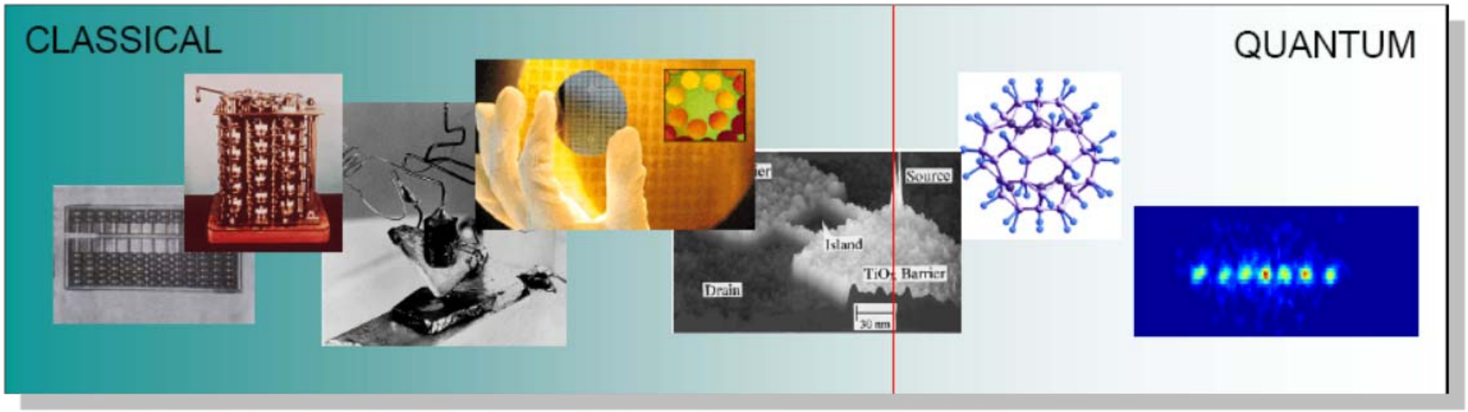
QUANTUM PHYSICS

- Progress in theory / experiment
- Control single / few quantum systems





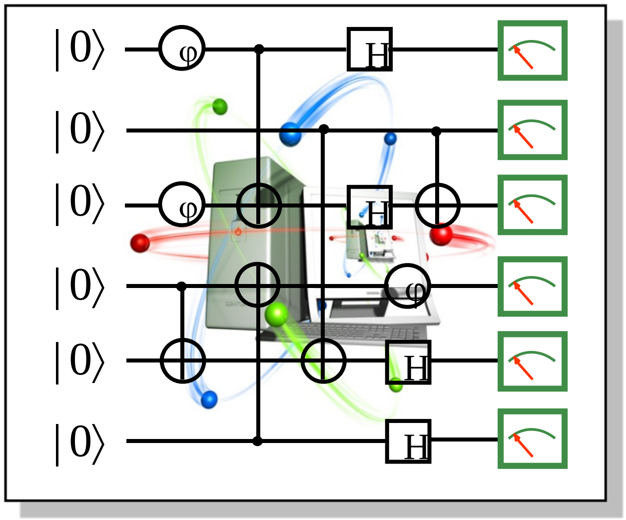
QUANTUM PHYSICS



- Access to new laws of Physics
- Applications

QUANTUM INFORMATION

COMPUTING



Hard problems

1881988129206079638386972394616504398071635633794173827007633564229888597152346654853190606065047430453173880113033967161996923212057340318795506569962213051687593076502570591

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39807508642406493739712550055038649119906436234252670840638518957594638895726176858331

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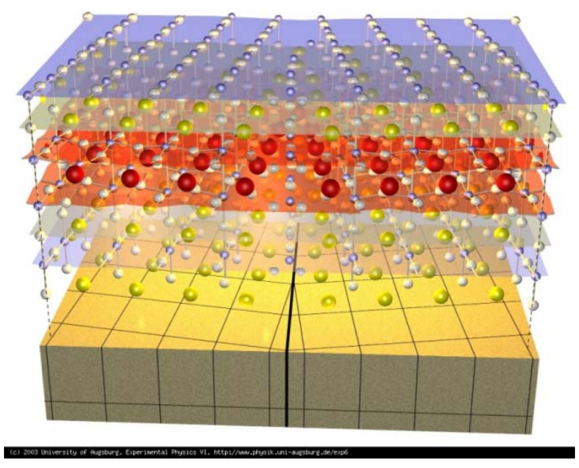
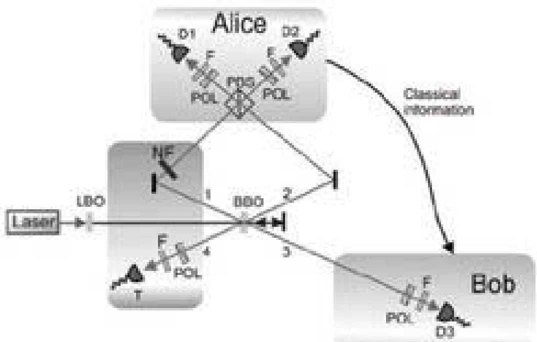
472772146107435302536223071973048224632914695302097116459852171130520711256363590397527

Quantum Simulations

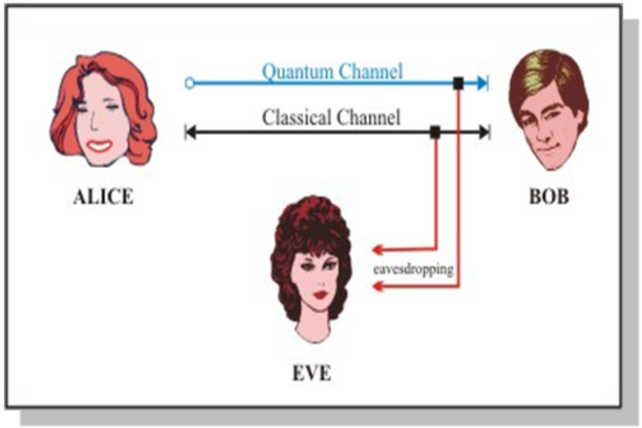


QUANTUM INFORMATION

COMMUNICATION



Cryptography



Networks

REQUIREMENTS:

- Qubits (quantum systems)
- Initialization (pure state)
- Quantum gates (coherent interaction)
- Read-out (measurement)

- Ideally no-decoherence
  - Decouple from the environment
  - Strategies to correct/purify the state

THIS TALK: Quantum information based on dissipation

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REQUIREMENTS:

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- Engineer the coupling.

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THIS TALK: Quantum information based on dissipation

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  - ~~Strategies to correct/purify the state~~

DISSIPATION IS THE CENTRAL MECHANISM

OUTLINE

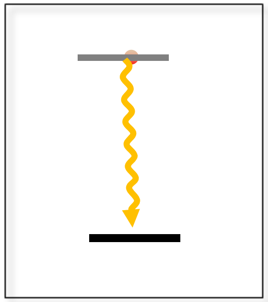
- DISSIPATION IN QUANTUM OPTICS:
- ENTANGLEMENT DISTRIBUTION:
  - Atomic ensembles
- QUANTUM MEMORIES:
  - NV-centers
  - Money, tickets and credit cards
- OTHER APPLICATIONS:
  - Repeaters
  - Many-body quantum systems
  - Computers

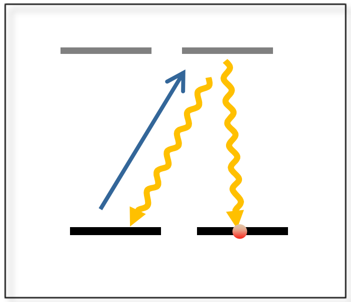
DISSIPATIVE PROCESSES
IN QUANTUM OPTICS

DISSIPATIVE PROCESSES

- Dissipation may help:

ATOM + ELECTROMAGNTIC FIELD





DISSIPATIVE PROCESSES

- Reservoir engineering:

VOLUME 77, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1996

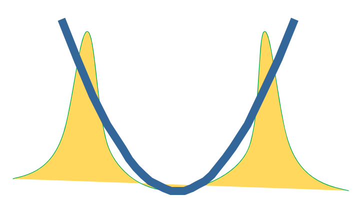
Quantum Reservoir Engineering with Laser Cooled Trapped Ions

J. F. Poyatos,* J. I. Cirac,* and P. Zoller

Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

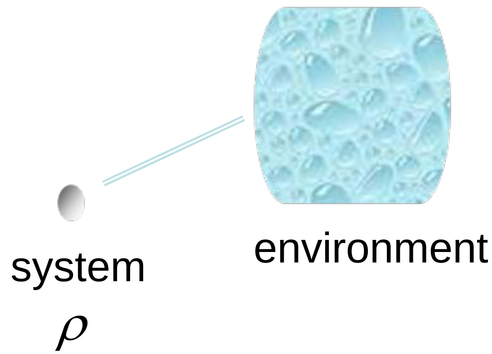
(Received 28 June 1996)

become identical [15]; moreover, there exist interactions which allow Schrödinger cat states to be stable, and, what is more surprising, dissipation can drive a system into a steady state of the form (1) [15]. For example, in



DISSIPATIVE PROCESSES

- Idea:



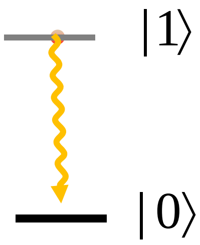
  - Irreversibility: The environment has infinite degrees of freedom
  - Steady state ($t \to \infty$):

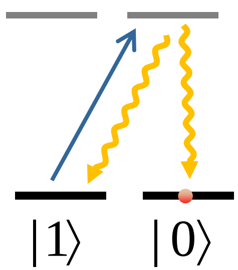
  - Engineer the coupling of the system with an environment.
  - Dark state: system decouples from environment

$$\rho = |\Psi\rangle\langle\Psi|$$

DISSIPATIVE PROCESSES

- Example: spontaneous emission





- Environment: Electromagnetic field
- Steady state: $\rho_{ss} = |0\rangle\langle 0|$

ENTANGLEMENT DISTRIBUTION

$$|0,0\rangle + |1,1\rangle$$

ENTANGLEMENT DISTRIBUTION

- Long distance quantum communication: quantum repeaters
- Quantum networks

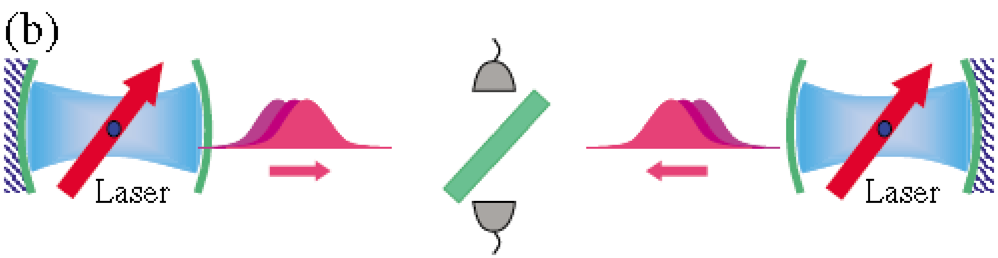
ENTANGLEMENT DISTRIBUTION

- Long distance quantum communication: quantum repeaters
- Quantum networks
- Quantum cryptography:

ENTANGLEMENT DISTRIBUTION

- Methods:

Cirac, Zoller, Mabuchi, Kimble, PRL 97

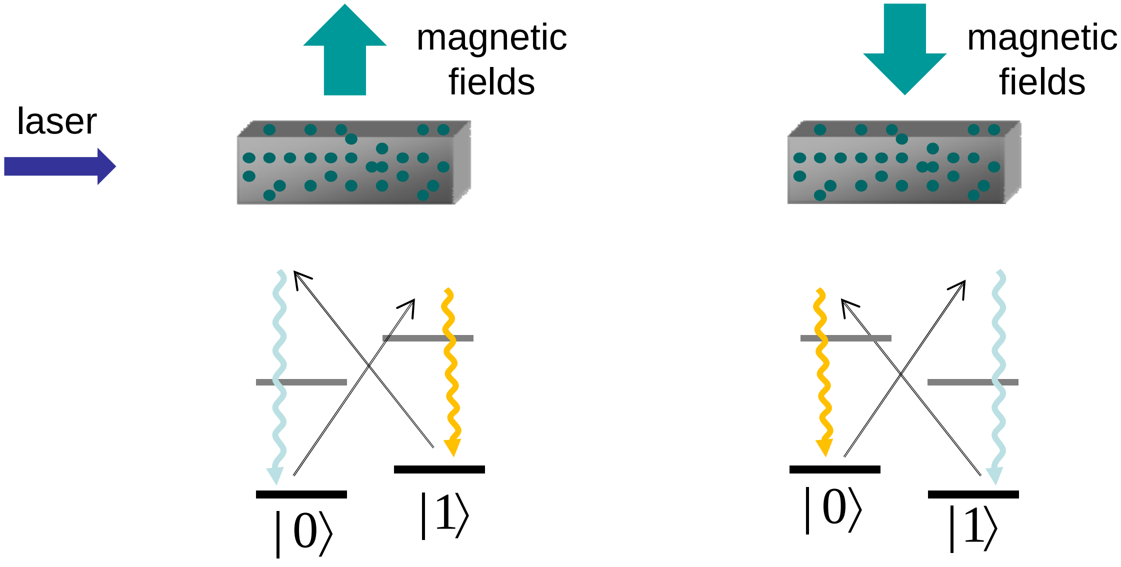


Cabrillo, Cirac, Garcia, Zoller, PRA 99

ENTANGLEMENT DISTRIBUTION
ATOMIC ENSEMBLES

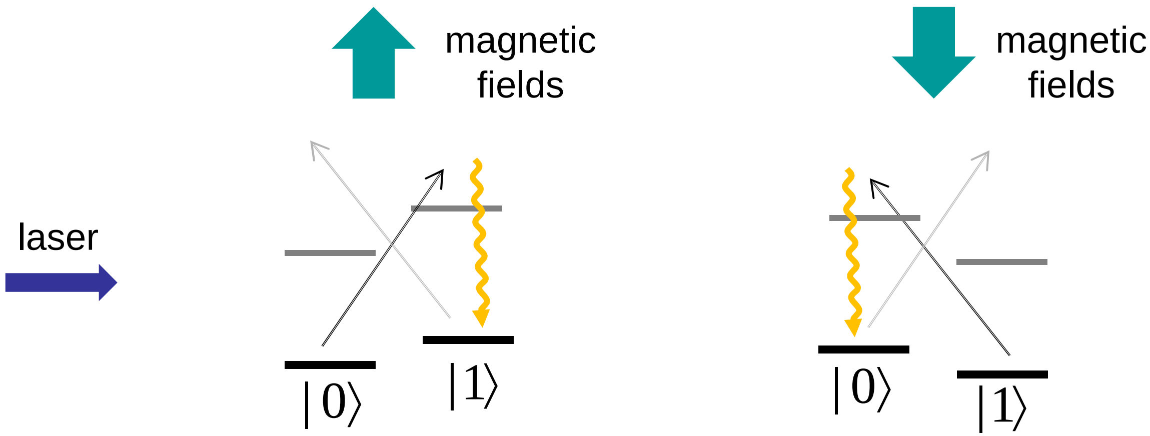
H. Krauter, C. Muschik, et al, PRL 2011

- Set-up:



ENTANGLEMENT DISTRIBUTION
ATOMIC ENSEMBLES

- One atom: forward scattering



- Processes 1:

$$|0,0\rangle \rightarrow |0,0\rangle + \varepsilon |1,0\rangle$$
$$|1,1\rangle \rightarrow |1,1\rangle + \varepsilon |1,0\rangle$$

$$\Rightarrow \quad |0,0\rangle - |1,1\rangle \rightarrow |0,0\rangle - |1,1\rangle$$

entangled state is dark

ENTANGLEMENT DISTRIBUTION
ATOMIC ENSEMBLES

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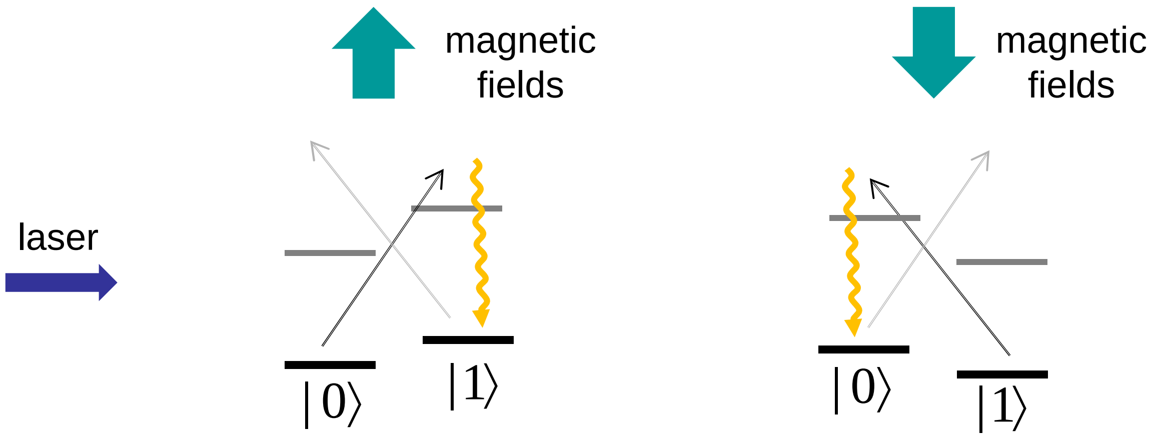

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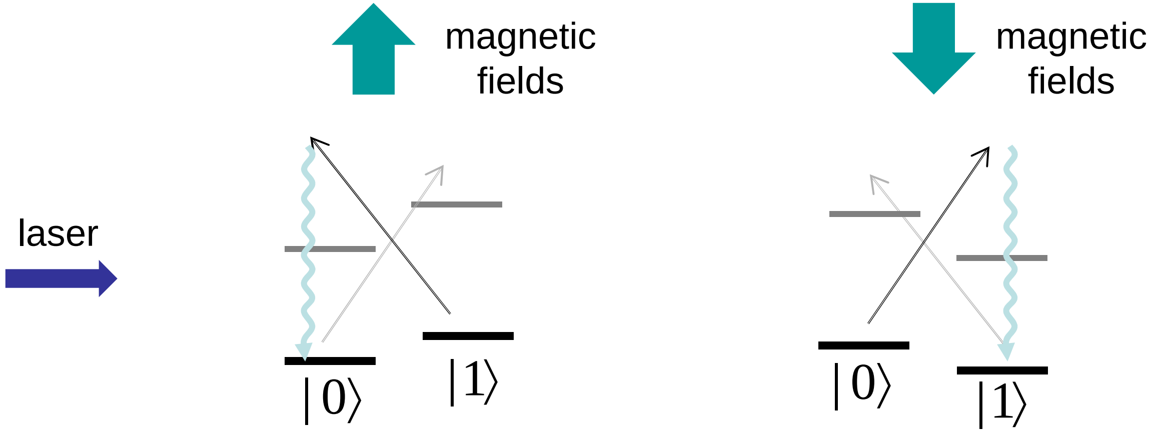
$$|0,0\rangle - |1,1\rangle \rightarrow |0,0\rangle - |1,1\rangle$$

entangled state is dark

$$|1,0\rangle \rightarrow |1,0\rangle$$

product state is also dark

- One atom: forward scattering



- Processes 2:

$$|0,0\rangle \rightarrow |0,0\rangle + \varepsilon\,|0,1\rangle$$
$$|1,1\rangle \rightarrow |1,1\rangle + \varepsilon\,|0,1\rangle$$

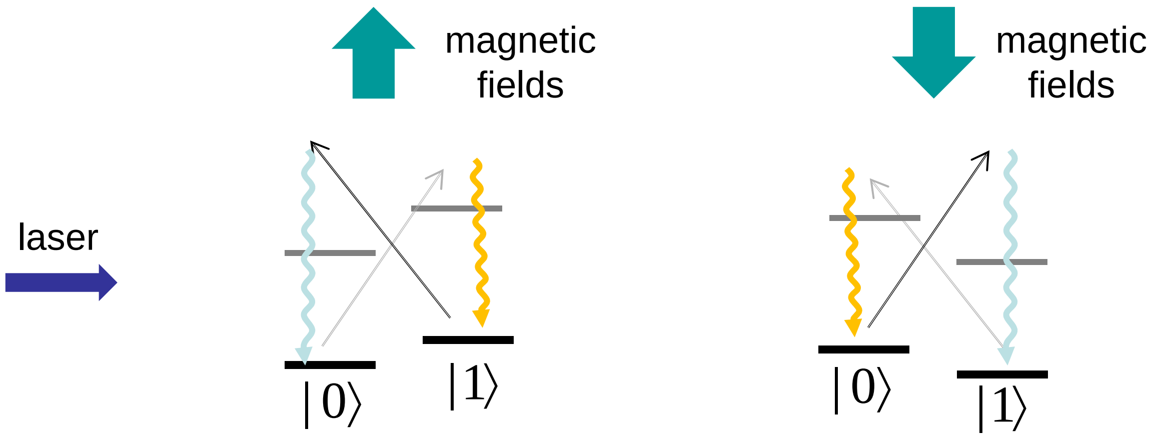
$$\Rightarrow \quad |0,0\rangle - |1,1\rangle \rightarrow |0,0\rangle - |1,1\rangle$$

entangled state is dark

$$|1,0\rangle \rightarrow |1,0\rangle$$

The state is no longer dark

- One atom: forward scattering



- Processes 1&2:

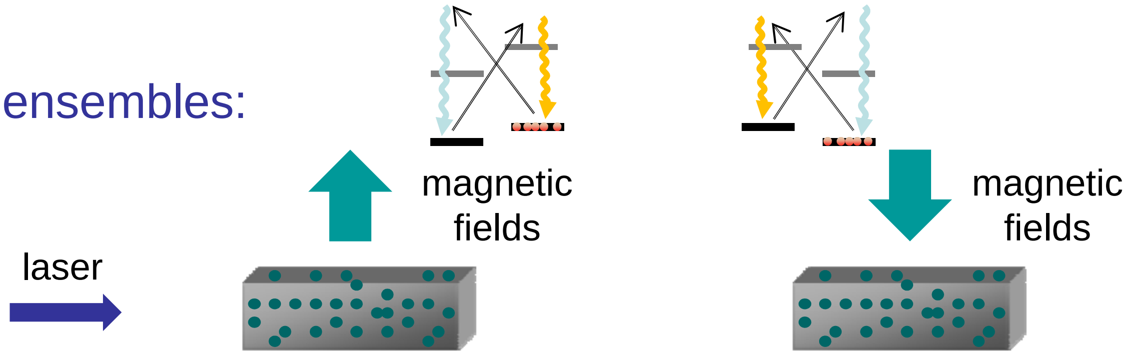
$$|0,0\rangle - |1,1\rangle$$ is the only dark state

But this is only in forward scattering

ENTANGLEMENT DISTRIBUTION

ATOMIC ENSEMBLES

- Atomic ensembles:



- Collective states: $|0\rangle = |00\ldots\rangle$

$$|1\rangle = (|100\ldots\rangle + |010\ldots\rangle + \ldots)/\sqrt{N}$$

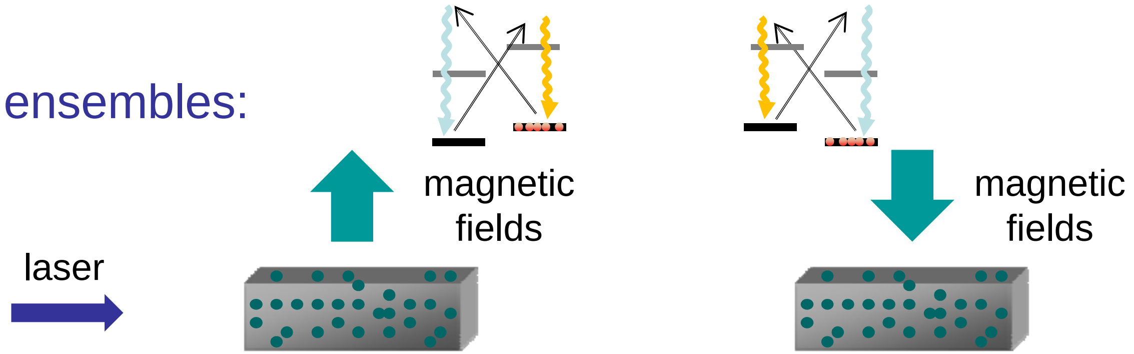
- Inerference in the forward scattering:

$$|1\rangle \rightarrow |1\rangle + \varepsilon N\,|0\rangle/\sqrt{N}$$

- Scattering in other directions has random phases: no interference

ENTANGLEMENT DISTRIBUTION
ATOMIC ENSEMBLES

- Atomic ensembles:



- Steady state: $|0,0\rangle - \lambda|1,1\rangle + \lambda^2|2,2\rangle + \ldots$

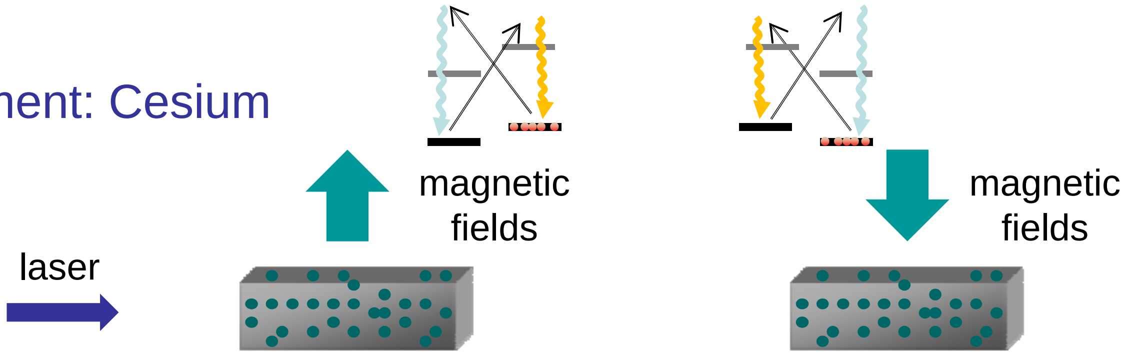
- Entanglement:

$$\xi = \frac{\mathrm{var}(J_{z,1} + J_{z,2}) + \mathrm{var}(J_{y,1} - J_{y,2})}{\langle J_{x,1}\rangle + \langle J_{x,2}\rangle}. < 1$$

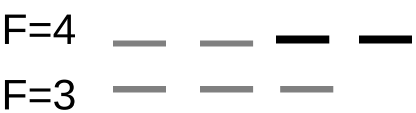
Duan, Giedke, Cirac and Zoller, 2000
Simo, 2000
Sanders et al, 2003

ENTANGLEMENT DISTRIBUTION
ATOMIC ENSEMBLES

- Experiment: Cesium



- Many levels:

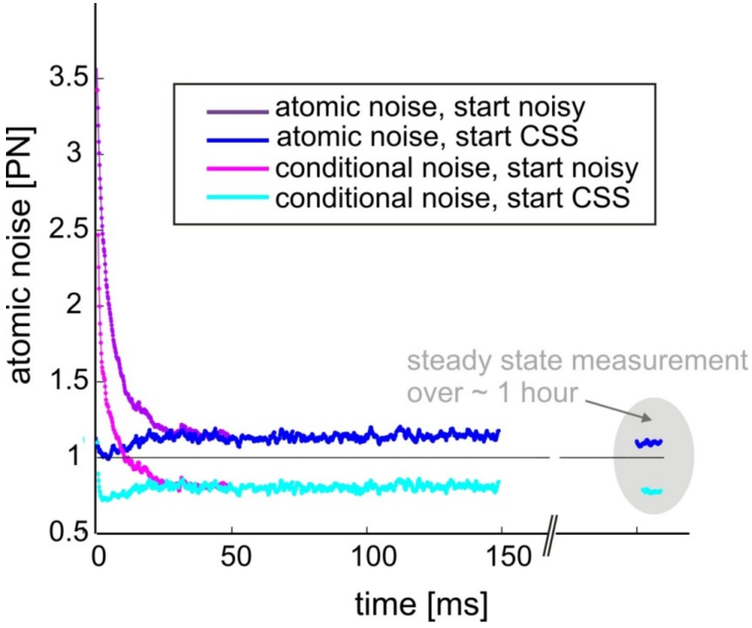


- Imperfections, etc:

ENTANGLEMENT DISTRIBUTION
ATOMIC ENSEMBLES

H. Krauter, C. Muschik, et al, PRL 2011

- Experiment: Cesium



- First demonstration of entanglement by dissipation.
- Entanglement:lifetime > 1 hour
- Several orders of magnitude longer than any previous experiment

See also Blatt's experiment on trapped ions

QUANTUM MEMORIES

(courtesy G. Rempe)

QUANTUM MEMORIES

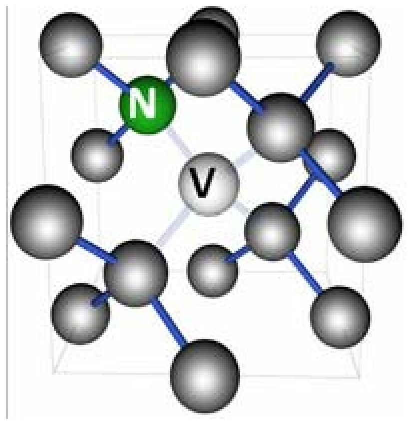
Goal:

$$|\Psi\rangle = a|0\rangle + b|1\rangle \qquad\qquad |\Psi'\rangle \approx |\Psi\rangle$$

- Memory time: as long as possible
- Trapped ions: 1 hour (NIST)

QUANTUM MEMORIES

NV Centers:



Electronic excited states

$|-1\rangle$ $|1\rangle$

$|0\rangle$

Electronic spin states

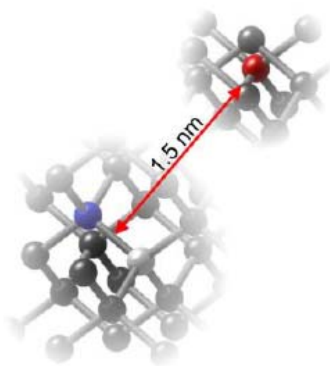
- Electron: atomic structure
- Preparation: using light, |0> dark state.
- Detection: using light: fluorescence = |1>, |-1>
- Electronic spin manipulation: MW pulses.

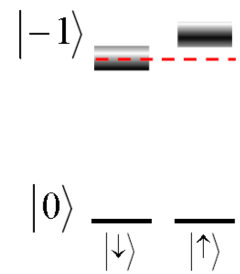
- Electron spin lifetime :T1=T2= 8 ms

At room temperature!

QUANTUM MEMORIES

NV Centers: Nuclear spins



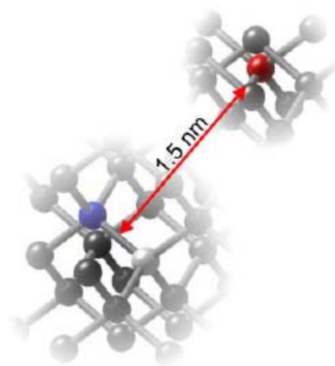


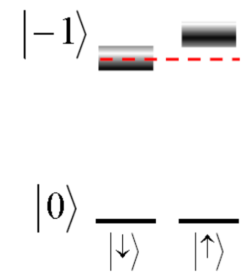
$$H = AS_z I_z$$

- Purified diamond: 99% C(12).
- C(13) has nuclear spin 1/2
- Use hyperfine interaction to purify nuclear spin
- Use RF waves to prepare nuclear spin
- Use again hyperfine interaction to detect nuclear spin

- Nuclear spin lifetime (T1)= hours

NV Centers: Nuclear spins





$$H = AS_zI_z$$

- Problem: hyperfine interaction + electron spin polarization = decoherence

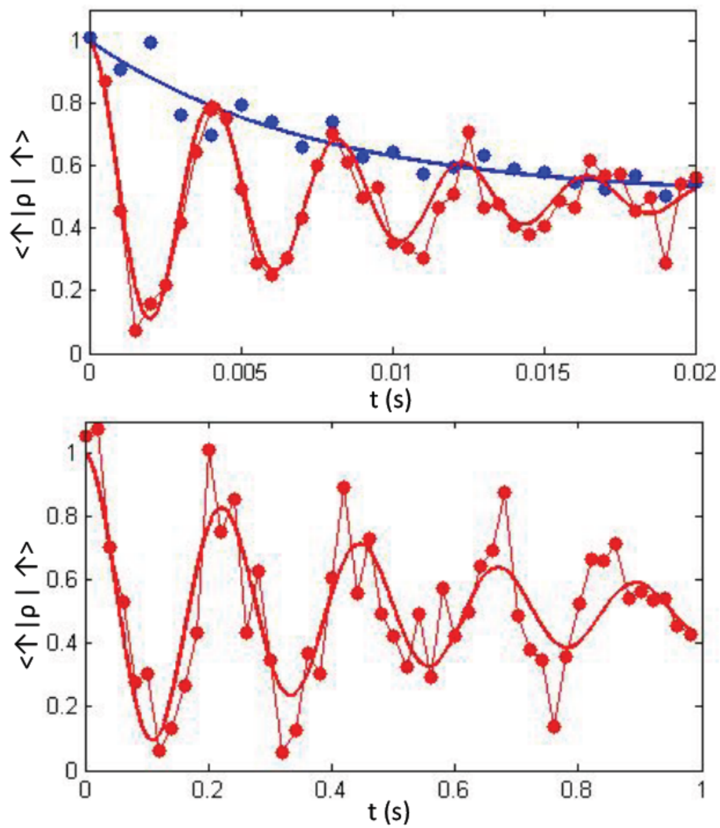
  Nuclear spin T2 = Electronic spin T1= 8 ms

- Solution: use dissipation to depolarize electronic spin

QUANTUM MEMORIES

Mauer, Kuksko, Latta (Lukin‘s lab)

Nuclear spin Ramsey experiment:



without dissipation

$$T_{2,n} = 8.2 \pm 1.3 \text{ ms}$$

with dissipation

$$T_{2,n} = 0.53 \pm 0.14 \text{ s}$$

Memory time extended by almost two orders of magnitude

QUANTUM MEMORIES

Mauer, Kuksko, Latta (Lukin‘s lab)

Nuclear spin Ramsey experiment:

- Limitation: Other nuclear spins
- Solution: Decoupling RF pulses

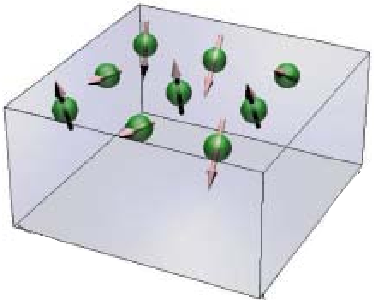
$$T_{2,n} = 1.7 \text{ s}$$

What could we do with a quantum memory of several days?

QUANTUM MEMORIES

Pastawski, Liang, Yao, Lukin, IC

NV Centers:



- Room temperature
- No vacuum, etc
- Magnetic shielding
- Many qubits

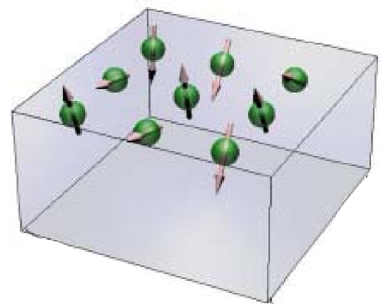
- Product sate:

$$|\alpha\rangle|\beta\rangle...$$

QUANTUM MEMORIES

Pastawski, Liang, Yao, Lukin, IC

NV Centers:



- Room temperature
- No vacuum, etc
- Magnetic shielding
- Many qubits

- Product sate:

$$|\alpha\rangle|\beta\rangle...$$

- Quantum money

A quantum bank note, containing a secret set of polarized photons, cannot be copied by counterfeiters, who would disturb the photons by attempting to measure them.

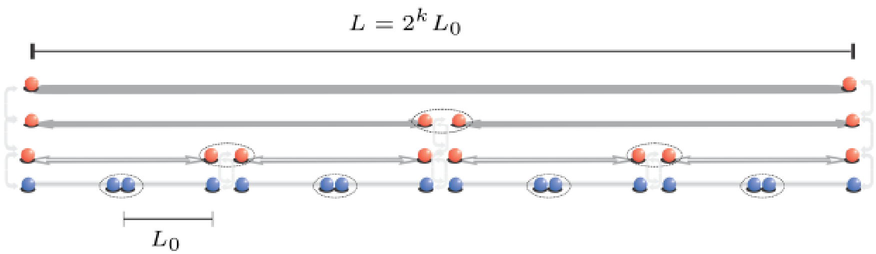
Protocols: Wiesner (ca 1970),
Mosca et al, 2007, Gavinsky 2011

OTHER APPLICATIONS

OTHER APPLICATIONS

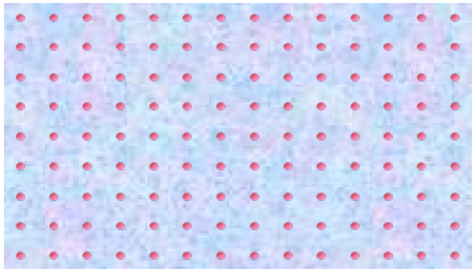
QUANTUM REPEATERS

Vollbrecht, Muschik, and IC, PRL 2011



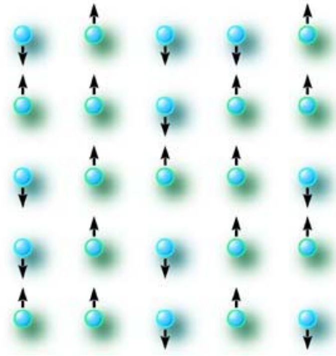
QUANTUM MEMORIES

Pastawski, Clemente, and IC, PRA 2011



MANY-BODY SYSTEMS

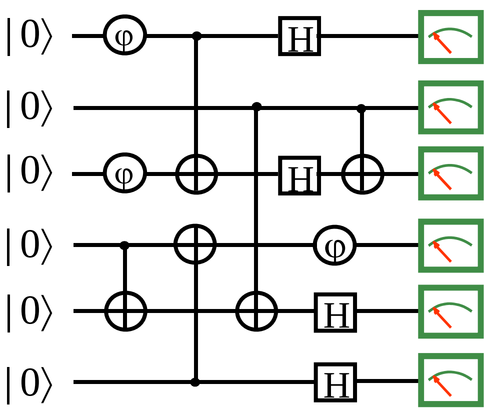
Verstraete, Wolf, IC, Nat. Phys. 2009



ENTANGLEMENT DISTRIBUTION
ATOMIC ENSEMBLES

Verstraete, Wolf, IC, Nat. Phys. 2009

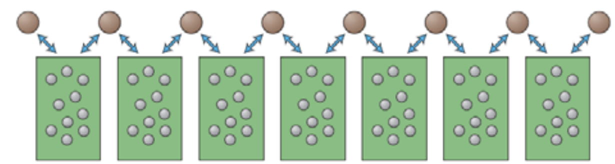
Standard QC



$$|\Psi_M\rangle = U_M \dots U_2 U_1 |00\dots0\rangle$$

M gates

Dissipative QC



- Unique steady state: ρ_{ss}
- The steady state after $O(M^{-2})$
- Ψ_M from ρ_{ss} with prob. $1/M$
- No gates (only enough patience).
- No need for initialization.

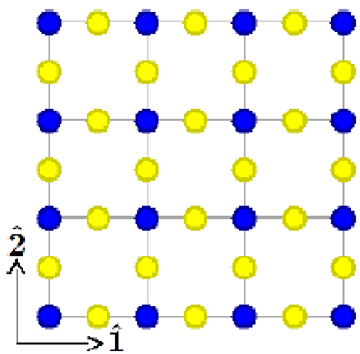
Other activities at MPQ

ATOMIC PHYSICS

COLD ATOMS

Quantum simulation of HEP

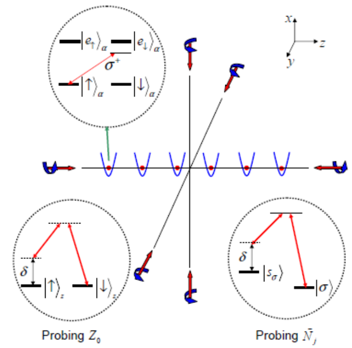
ZOHAR, REZNIK



TRAPPED IONS

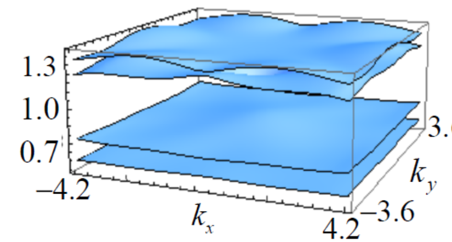
Polaron Physics

SHI, STOJANOVIC, BRUDER



Topological Insulators

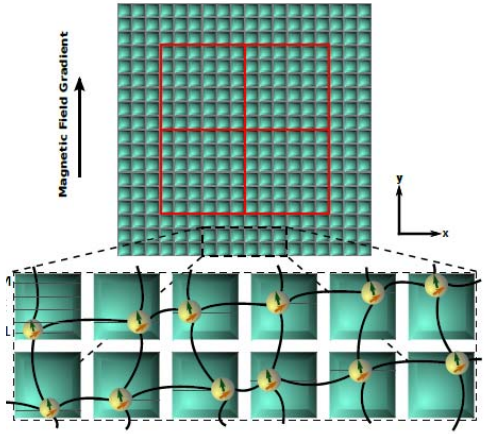
SHI



NV-CENTERS

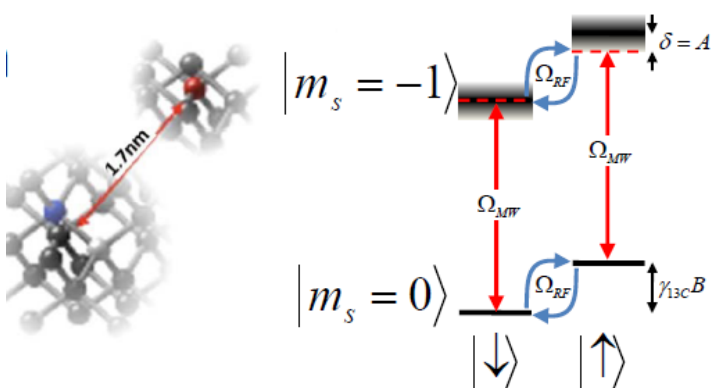
QC at room temperature

GIEDKE, LUKIN'S GROUP



MEMORIES

PASTAWSKI, LUKIN'S GROUP

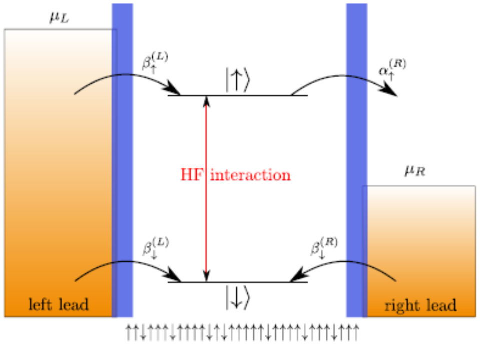


OTHER SYSTEMS

QUANTUM DOTS

Electric super-radiance

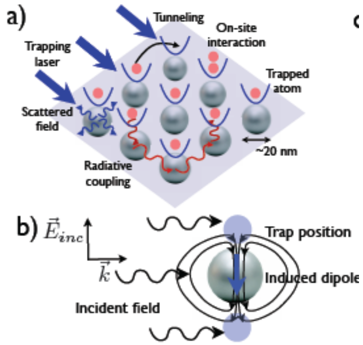
SCHUTZ, KESSLER; GIEDKE



NANO-PLASMONS

Nano-lattices

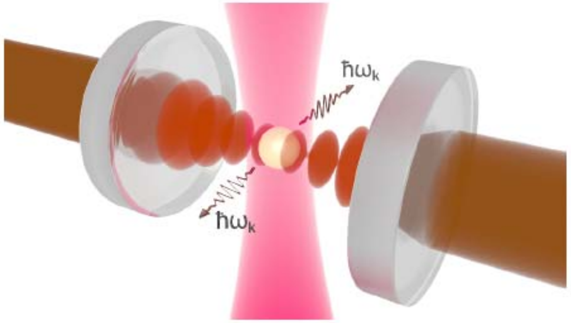
LUKIN's GROUP, ZOLLER



NANO MECHANICS

Quantum Mie theory

PFLANZER, ROMERO



MAGNETIC LEVITATION

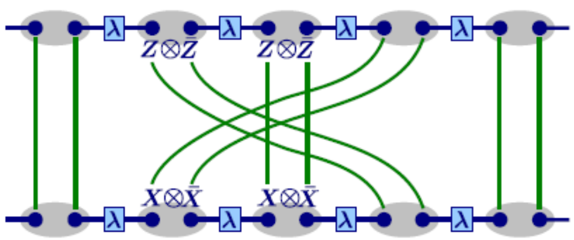
ROMERO, CLEMENT, NAVAU, SANCHEZ

MANY-BODY THEORY

PHASES OF MATTER

Order parameter

HAEGEMAN,SCHUCH,PEREZ-GARCIA



SPIN LIQUIDS

Laughlin spins in a lattice

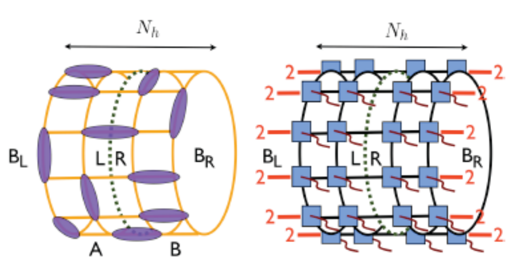
NIELSEN, SIERRA

$$H_i = \frac{1}{2}\sum_{j(\neq i)} |w_{ij}|^2 - \frac{2i}{3}\sum_{j\neq k(\neq i)} \bar{w}_{ij} w_{ik}\, \mathbf{S}_i \cdot (\mathbf{S}_j \times \mathbf{S}_k) + \frac{2}{3}\sum_{j(\neq i)} |w_{ij}|^2 \mathbf{S}_i \cdot \mathbf{S}_j + \frac{2}{3}\sum_{j\neq k(\neq i)} \bar{w}_{ij} w_{ik} \mathbf{S}_j \cdot \mathbf{S}_k, \quad (4)$$

PEPS

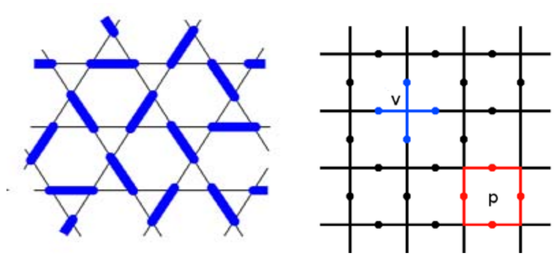
Holographic Priniple

SCHUCH,PEREZ-GARCIA;POILBLANC



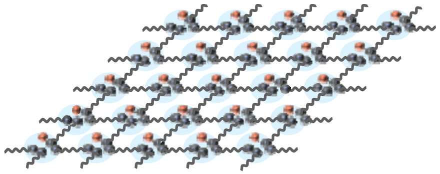
Kagome RVB = toric code

SCHUCH,PEREZ-GARCIA;POILBLANC



Uncle-Hamiltonians

SCHUCH,PEREZ, WOLF

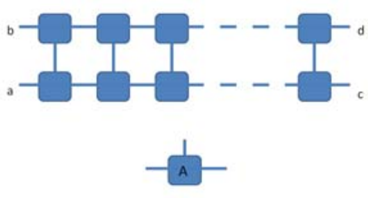


QUANTUM INFORMATION

ENTANGLEMENT

Fractionalization, long-range

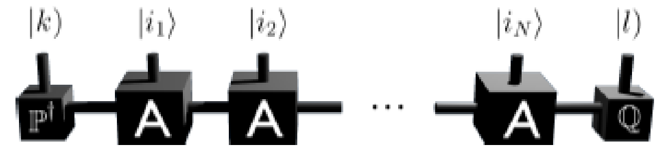
CADARSO, WOLF, PEREZ-GARCIA



LOCALIZABLE ENTANGLEMENT

Long-range

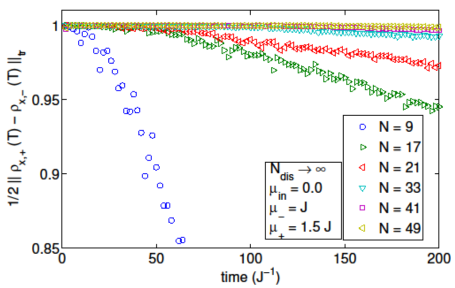
WAHL,PEREZ-GARCIA



QUANTUM MEMORIES

Robustness

PASTAWSKI, MAZZA, RIZZI, LUKIN



Security Proofs

PASTAWSKI,JIANG,YAO,LUKIN

CONCLUSION and OUTLOOK

- Most applications within QIS science can be performed using dissipation
- In some cases, the advantage is clear:
  - Entanglement distribution
  - Memories
- Some theoretical proposals have already been implemented
- Some open problems:
  - Repeaters: implementations
  - Computer: error correction
  - Memories: 2D + implementations
    + longer times + applications

THANKS

Entanglement distribution:

MPQ (ICFO)

C. Muschik

NBI

E. POLZIK
H. Krauter
K. Jensen
W. Wasilewski
J. Petersen

Memories: NV-centers:

MPQ

F. Pastawski

Harvard

M. LUKIN
N. Yao
P. Maurer
G. Kuksko
G. Latta

CALTECH

L. Yang

Quantum computing + state preparation

NBI (TUM)

M. Wolf

Vienna

F. Verstraete

Quantum repeaters:

MPQ (ICFO)

C. Muschik
K. Vollbrecht

Quantum Memories:

MPQ

F. Pastawski
L. Clemente