# COMPAS meeting
# November 30th – December 1st
# Hotel Le Dôme, Brussels

Christine Muschik

J.Ignacio Cirac
Max-Planck-Institut für Quantenoptik

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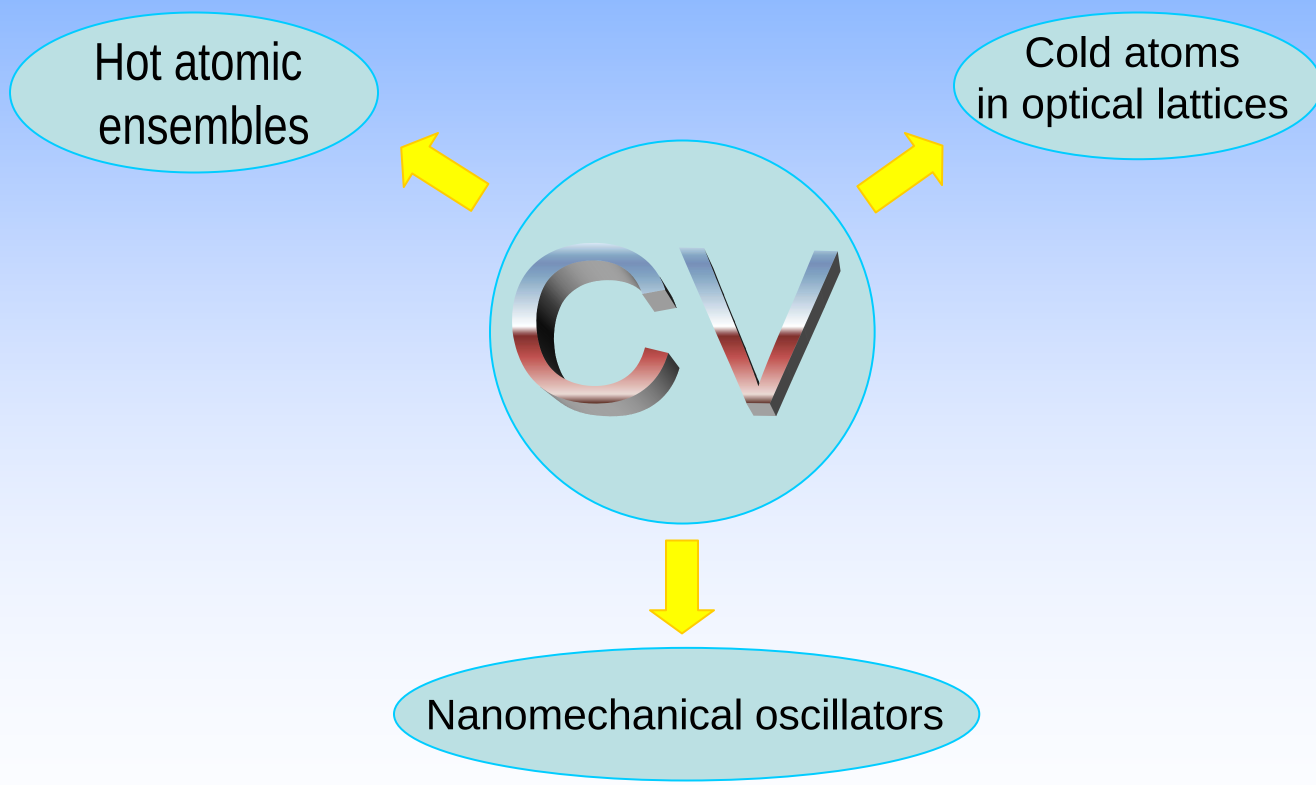

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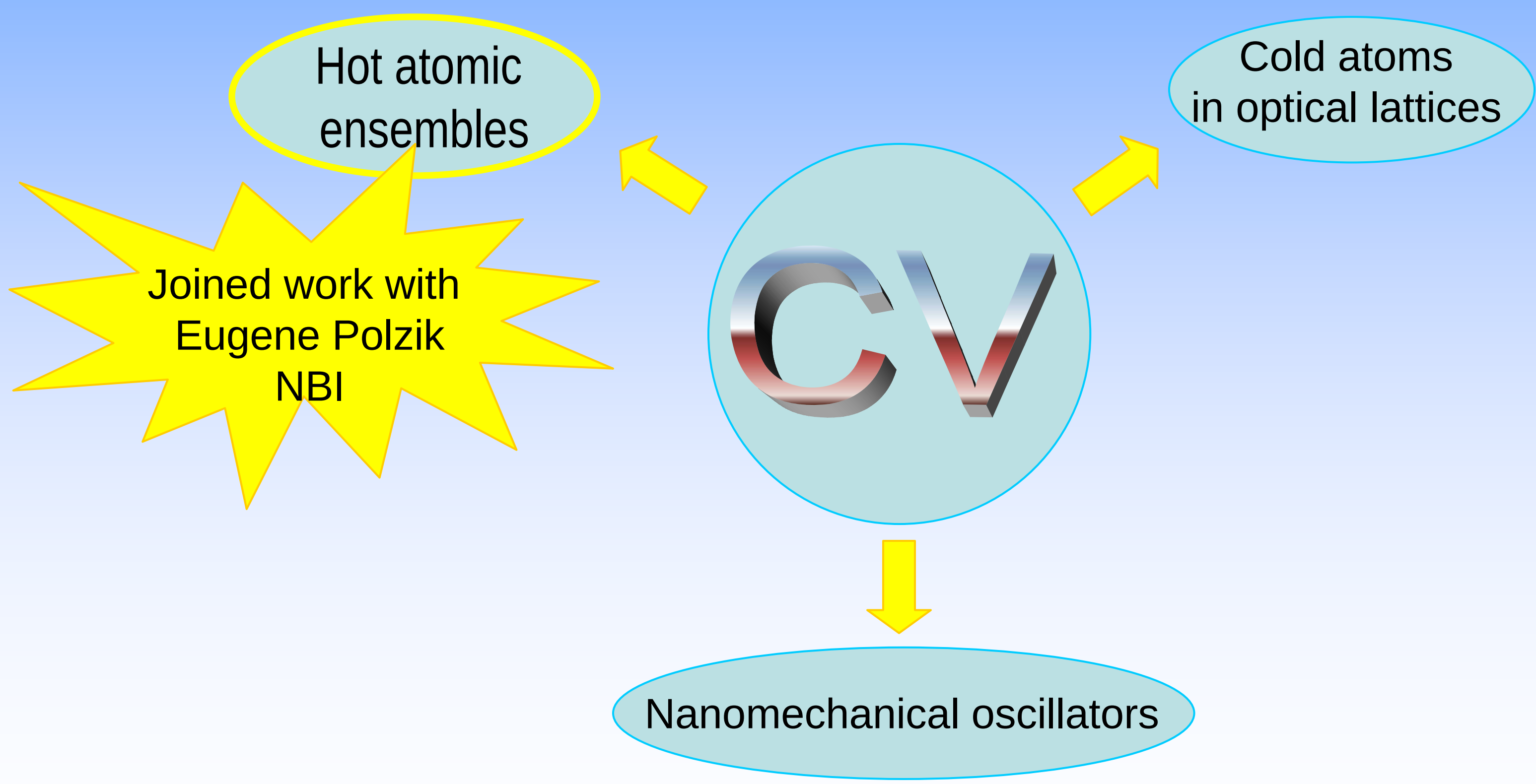

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# Steady –state entanglement with atomic ensembles

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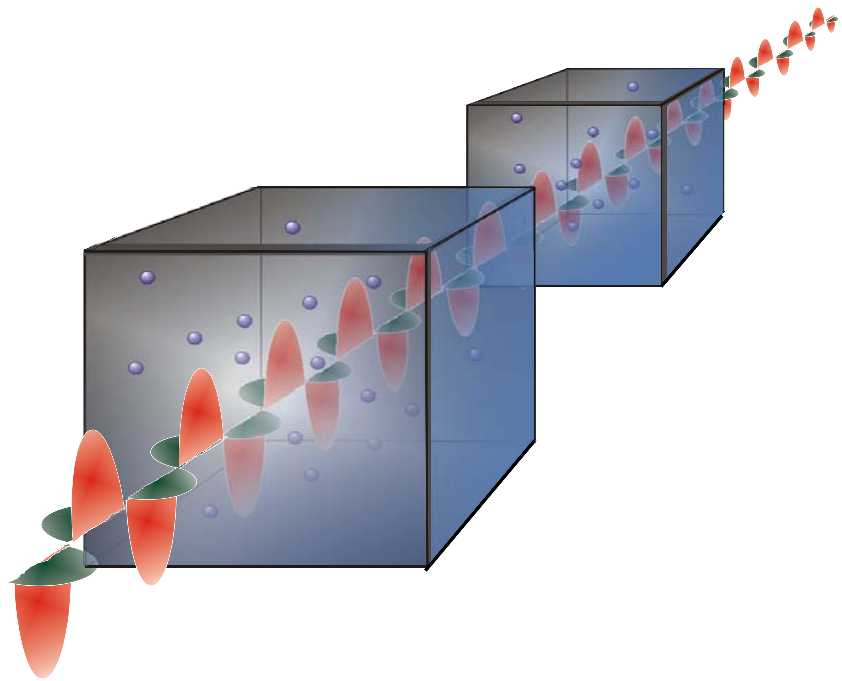
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany

Hanna Krauter, Kasper Jensen, Wojciech Wasilewski,
Jelmer Renema and Eugene Polzik
Niels Bohr Institute, Danish Research Foundation Center for Quantum Optics (QUANTOP),
Blegdamsvej 17, DK-2100 Copenhagen, Denmark

# Overview:

Steady state entanglement with atomic ensembles

- Motivation
- Main idea
- Theoretical model
- Experimental realization



# Motivation:

Quantum entanglement

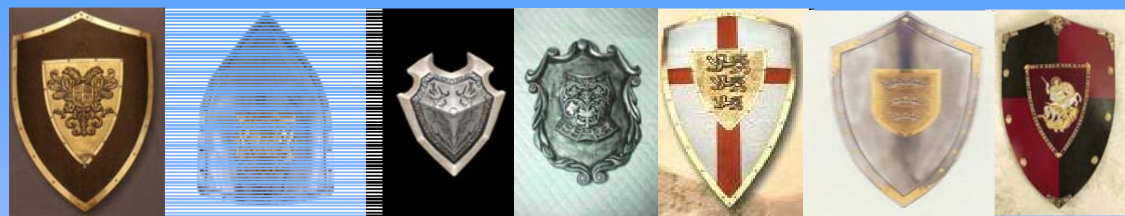
- Basic ingredient in most applications in the field of quantum information
- But: Lifetimes are usually very short
- Therefore: Need for much longer lifetimes!

Typically:

- Quantum states are fragile under decoherence
- Avoidance of dissipation by decoupling the system from the environment
- Strict isolation!

# ENVIRONMENT

# Motivation:



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New approaches

S. Diehl, A. Micheli, A. Kantian, B. Kraus, H.P. Büchler, P. Zoller

F. Verstraete, M.M. Wolf, J.I. Cirac,

→ <u>Use</u> the interaction of the system with the environment

# Motivation:

New approaches

➡ Use the interaction of the system with the environment

➡ Dissipation drives the system into the desired state

# Motivation:

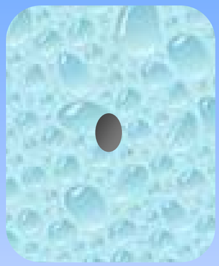
New approaches

- Use the interaction of the system with the environment
- Dissipation drives the system into the desired state
- Robust method to create extremely long-lived and robust entanglement

# Motivation:

## Procedure:

- Engineer the coupling
- Steady state = desired state
- Arbitrary initial state



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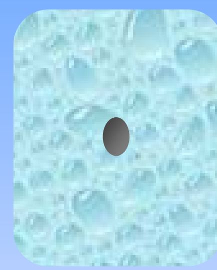

## Proposals:

- Single trapped ion
  J. F. Poyatos, J. I. Cirac and P. Zoller, Phys. Rev. Lett. 77, 4728 (1996)
- Atoms in two cavities
  B. Kraus and J. I. Cirac, Phys. Rev. Lett. 92, 013602 (2004)
- Many-body systems
  S. Diehl, A. Micheli, A. Kantian, B. Kraus, H.P. Büchler, P. Zoller, Nature Physics 4, 878 (2008)
  F. Verstraete, M.M. Wolf, J.I. Cirac, Nature Physics 5, 633 (2009)

→ Quantum phase transitions
→ State preparation
→ Quantum computing

# Main idea:

Dissipative evolution:

$$d_t\rho(t) = \Gamma\left(2A\rho(t)A^+ - A^+A\rho(t) - \rho(t)A^+A\right)$$

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$A|\Psi\rangle = 0 \quad \Rightarrow \quad \rho_{\Psi} = |\Psi\rangle\langle\Psi|$ is the unique steady state

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$$A|\Psi_{EPR}\rangle = B|\Psi_{EPR}\rangle = 0$$

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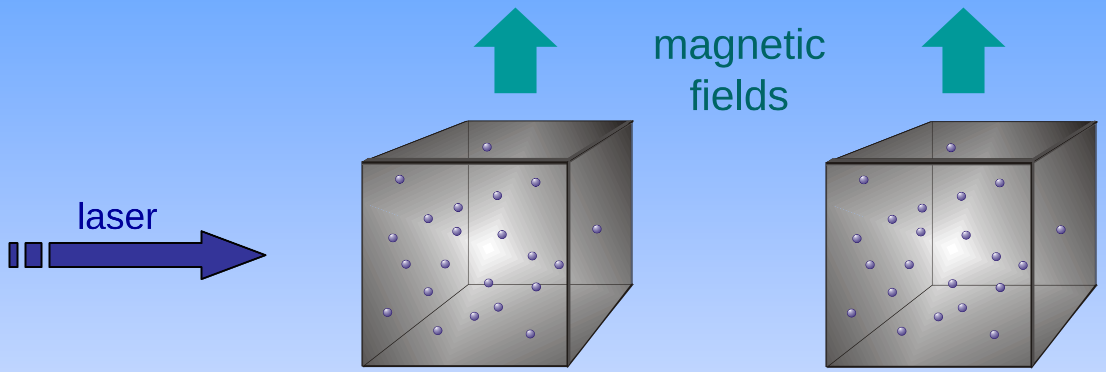
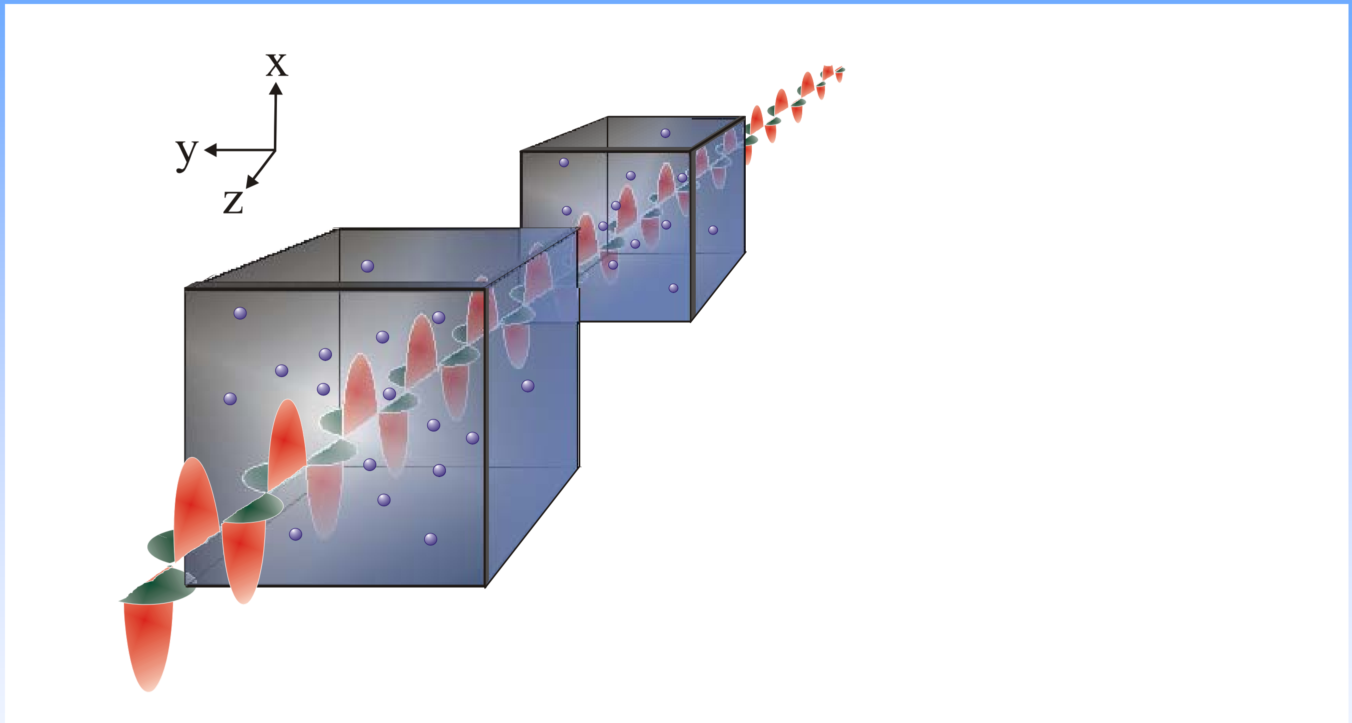
$$d_t\rho(t) = \Gamma\left(2A\rho(t)A^+ - A^+A\rho(t) - \rho(t)A^+A\right) + \Gamma\left(2B\rho(t)B^+ - B^+B\rho(t) - \rho(t)B^+B\right)$$

# Setup:




- Reservoir: common modes of the electromagnetic field.
- Control: Laser and magnetic fields

# Setup:



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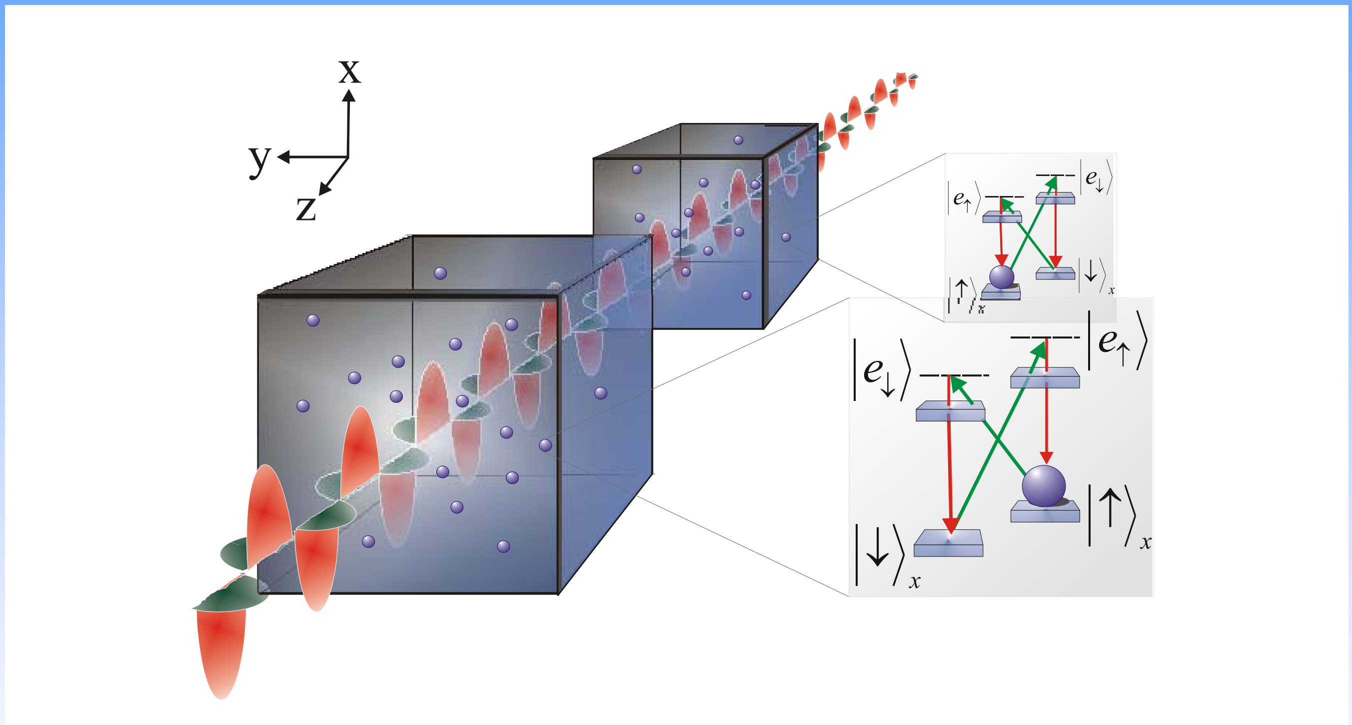
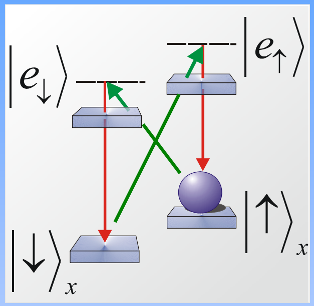
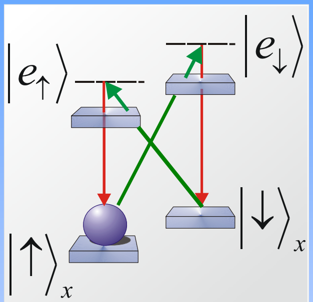

x
y
z
$|e_\uparrow\rangle$
$|e_\downarrow\rangle$
$|\downarrow\rangle_x$
$|\uparrow\rangle_x$
$|e_\downarrow\rangle$
$|e_\uparrow\rangle$
$|\downarrow\rangle_x$
$|\uparrow\rangle_x$

# Model:

Ensemble 1




Ensemble 2



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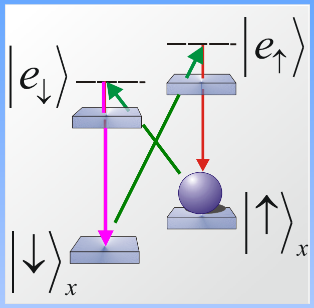
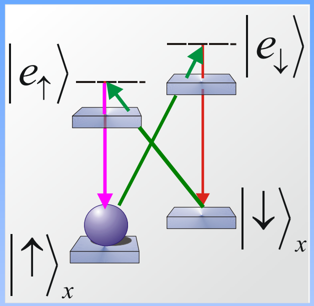
Ensemble 1

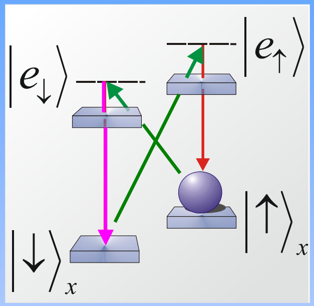



Ensemble 2

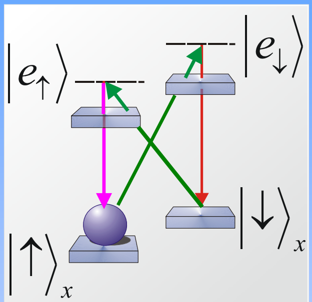


# Theory:

Ensemble 1




Ensemble 2

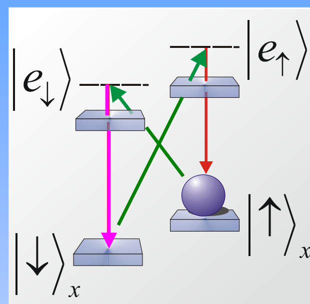



Processes:

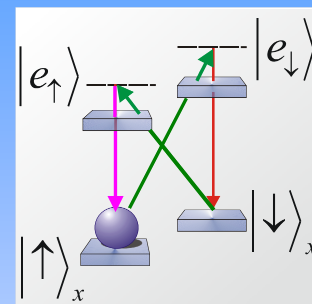
$$\left(\mu\sigma_1^- + \nu\sigma_2^+\right)a_k \qquad \left(\nu\sigma_1^+ + \mu\sigma_2^-\right)a_k$$

# Theory:

Ensemble 1




Ensemble 2




Processes: $A^+a_k$ $B^+a_k$

$$A = \mu \frac{1}{\sqrt{N}} \sum_i \sigma_{1,i}^+ + \nu \frac{1}{\sqrt{N}} \sum_j \sigma_{2,j}^-$$

$$\mu^2 - \nu^2 = 1$$

$$B = \nu \frac{1}{\sqrt{N}} \sum_i \sigma_{1,i}^- + \mu \frac{1}{\sqrt{N}} \sum_j \sigma_{2,j}^+$$

# Theory:

⇒ Masterequation:

$$\frac{d\rho}{dt} = \Gamma d(2A\rho A^{+} - A^{+}A\rho - \rho A^{+}A) + \Gamma d(2B\rho B^{+} - B^{+}B\rho - \rho B^{+}B)$$

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+undersired processes

- Adiabatic ellimination excited states
- Two independent bands of modes
- Born-Markov approximation
- Room temperature (average atomic motion)

# Theory:

$\Rightarrow$ Masterequation:

$$\frac{d\rho}{dt} = \Gamma d(2A\rho A^{+} - A^{+}A\rho - \rho A^{+}A) + \Gamma d(2B\rho B^{+} - B^{+}B\rho - \rho B^{+}B)$$

+undesired processes

- Dark state: $A|\Psi\rangle = 0$
  $B|\Psi\rangle = 0$

- Entanglement: ideal case

$$\xi = \frac{\mathrm{var}\left(J_{z,I} + J_{z,II}\right) + \mathrm{var}\left(J_{y,I} - J_{y,II}\right)}{\left\langle J_{x,I}\right\rangle + \left\langle J_{x,II}\right\rangle} = (\mu - \nu)^2$$

# **Theory:**

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- Entanglement: including undesired processes

$$\xi = \frac{1}{P_2}\frac{\tilde{\Gamma} + d\Gamma P_2^2\left(\mu - \upsilon\right)^2}{\tilde{\Gamma} + d\mathrm{T}P_2} \xrightarrow{d>>1} \left(\mu - \nu\right)^2$$

$\tilde{\Gamma}$ : noise rate

$P_2$ : polarization

# Theory:

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$\bar{\Gamma}$ : noise rate

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Effective ground state Hamiltonian:

$$H = \int_{\Delta\omega_{us}} d\vec{k}\cdot g(\omega_k)\left(\mu\sum_{i=1}^{N}\sigma_{I,i}e^{i\Delta\vec{k}\vec{r}_i} + \nu\sum_{j=1}^{N}\sigma_{II,j}^{\perp}e^{i\Delta\vec{k}\vec{r}_j}\right)a_{\vec{k}}^{\perp} + \int_{\Delta\omega_{ls}} d\vec{k}\cdot g(\omega_k)\left(\nu\sum_{i=1}^{N}\sigma_{I,i}^{\perp}e^{i\Delta\vec{k}\vec{r}_i} + \mu\sum_{j=1}^{N}\sigma_{II,j}e^{i\Delta\vec{k}\vec{r}_j}\right)a_{\vec{k}}^{\perp} + H.C.$$

Master equation:

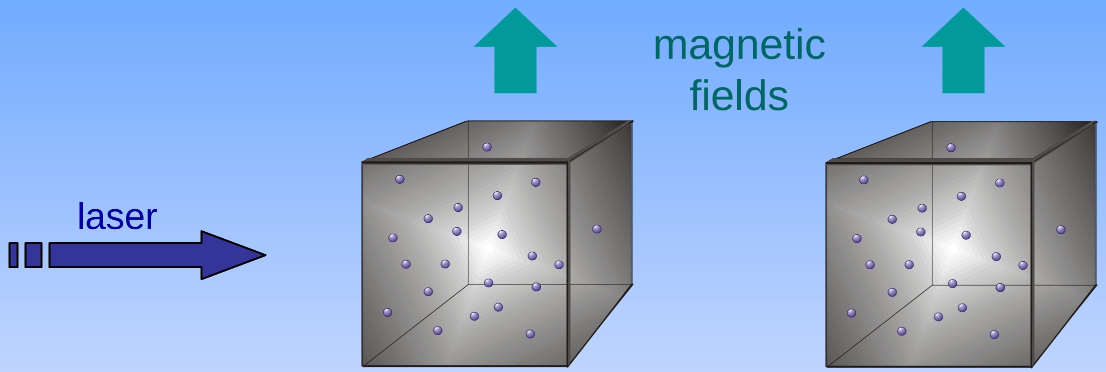
$$\begin{aligned} d_t\rho(t)_{first\cdot term} &= 2d\Gamma A\rho(t)A^{\perp} + 2d\Gamma B\rho(t)B^{\perp} \\ &+ 2\Gamma_{cool}\sum_{i=1}^{N}\left(\sigma_{I,i}\rho(t)\sigma_{I,i}^{\perp} + \sigma_{II,i}\rho(t)\sigma_{II,i}^{\perp}\right) \\ &+ 2\Gamma_{heat}\sum_{i=1}^{N}\left(\sigma_{I,i}^{\perp}\rho(t)\sigma_{I,i} + \sigma_{II,i}^{\perp}\rho(t)\sigma_{II,i}\right) \\ &+ 2\Gamma_{deph}\sum_{i=1}^{N}\left(\sigma_{I,i}\sigma_{I,i}^{\perp}\rho(t)\sigma_{I,i}\sigma_{I,i}^{\perp} + \sigma_{II,i}\sigma_{II,i}^{\perp}\rho(t)\sigma_{II,i}\sigma_{II,i}^{\perp}\right) \end{aligned}$$

Entanglement:

$$\xi(t) = \frac{e^{-2\left(\tilde{\Gamma}+d\Gamma P_2(t)\right)t}}{P_2(t)} + \frac{n_2(t)}{P_2(t)}\frac{\tilde{\Gamma}+d\Gamma P_2^2(t)(\mu-\nu)^2}{\tilde{\Gamma}+d\Gamma P_2(t)}\left(1-e^{-2\left(\tilde{\Gamma}+d\Gamma P_2(t)\right)t}\right)$$

$$\tilde{\Gamma} = \Gamma_{cool} + \Gamma_{heat} + \Gamma_{deph}$$

# Theory:




Result:

- Steady-state is an entangled state
- Immune to noise
- Long-lived entanglement

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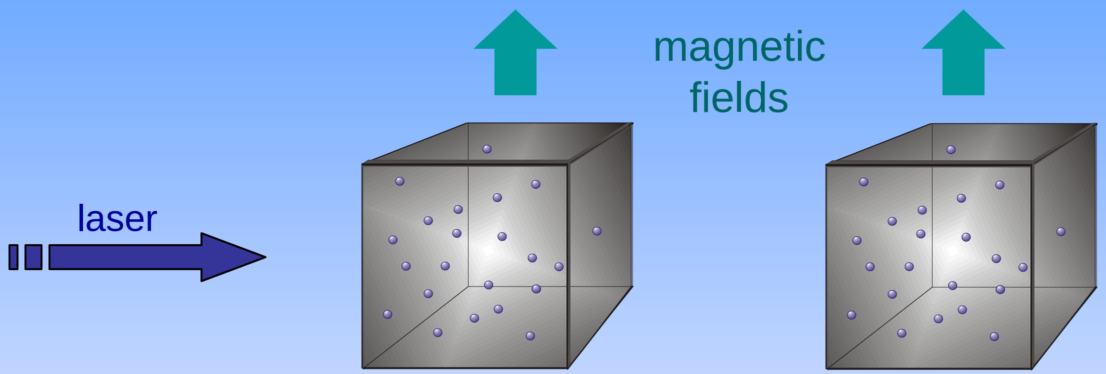


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“Standard procedure“:

- Pure state (cooling, polarization, etc.)
- Coherent interaction (gate)
- Isolation (no decoherence)

# Experimental realization of purely dissipation based entanglement:

Theory: Two-level model ⟷ Experiment: Multi-level structure

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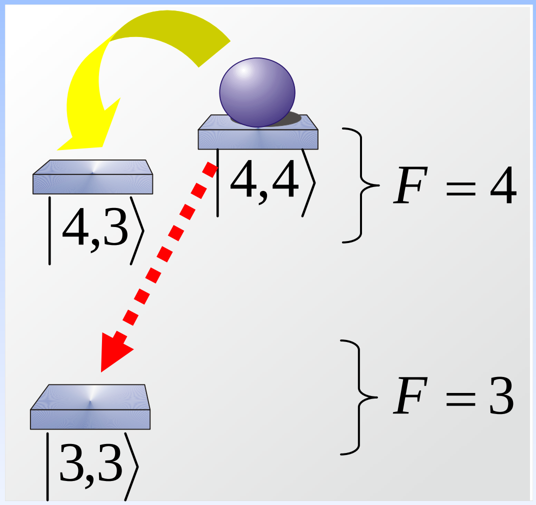
Theory: Two-level model ⟷ Experiment: Multi-level structure

$^{133}Cs$ (nuclear spin I=7/2)



# Experimental realization of purely dissipation based entanglement:

Theory: Two-level model ⟷ Experiment: Multi-level structure

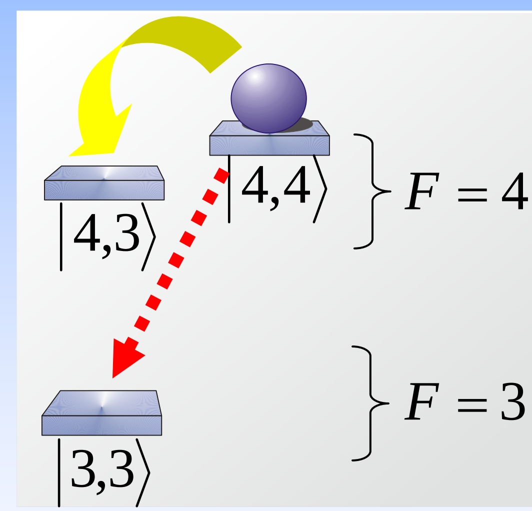
Quasi steady-state:

$$\xi = \frac{8}{P_2+7}\,\frac{\tilde{\Gamma} + d\Gamma P_2^2(\mu-\upsilon)^2}{\tilde{\Gamma} + d\mathrm{T}P_2}$$

$P_2(t)$: polarization

$n_2(t)$: depopulation

$^{133}Cs$ (nuclear spin I=7/2)



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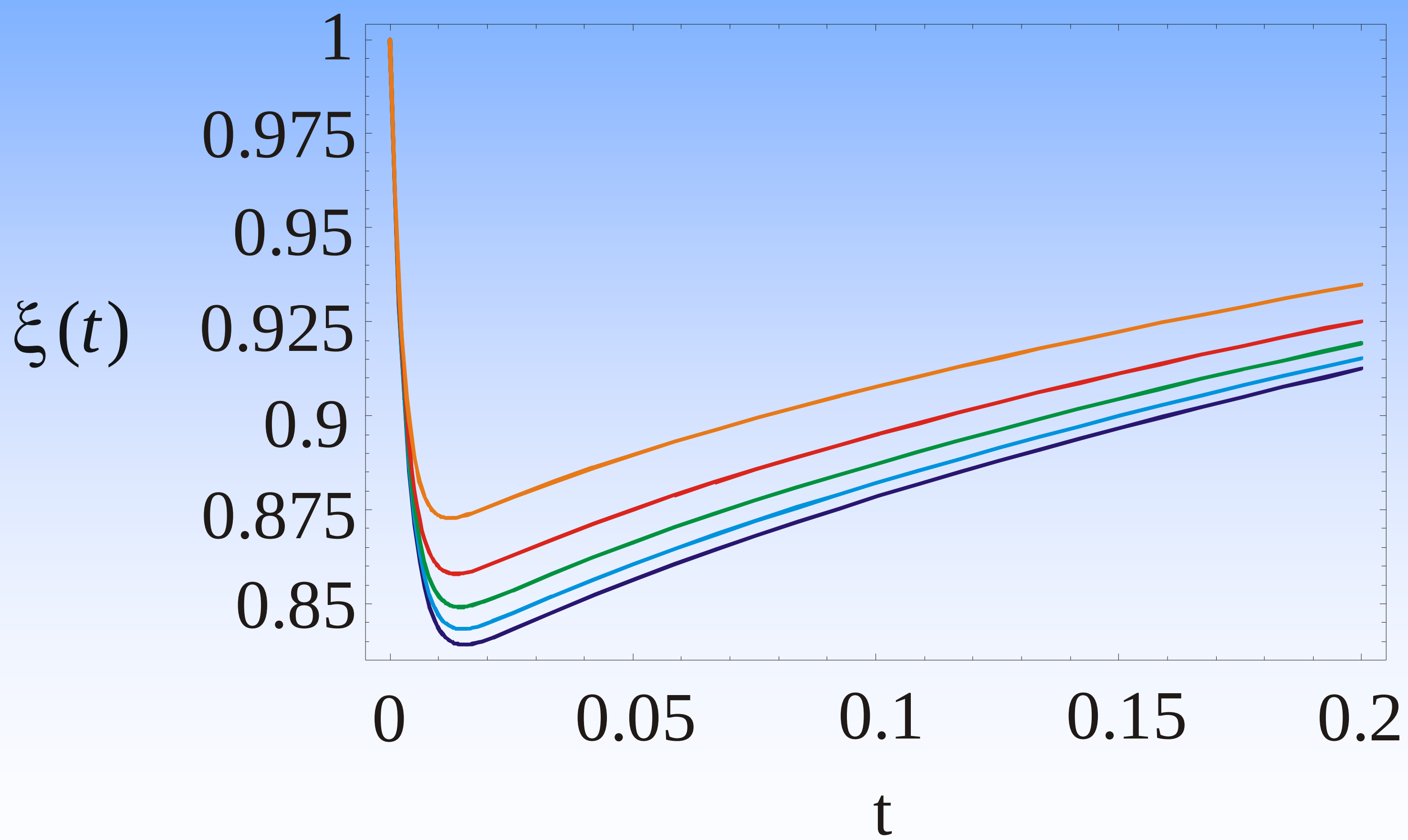


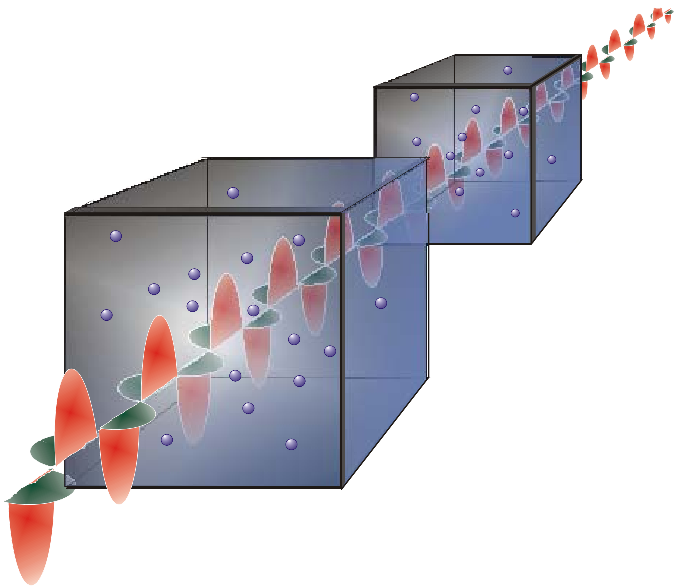
# Summary:

## Proposal for long-lived entanglement

- Atomic ensembles at room temperature
- Dissipatively driven entanglement
- Environment = vacuum modes of the electromagnetic field

## Experimental results

- Quasi steady state



## Future

- Multi-level systems
- More systems

***Thank you very much for your attention***