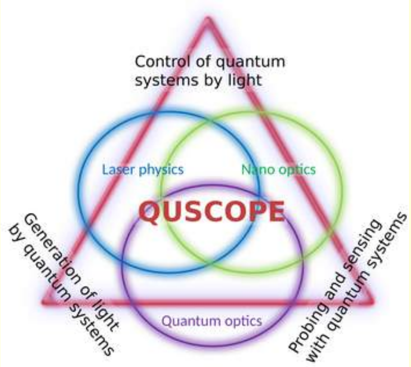
A relaxed approach to quantum state engineering



Klaus Mølmer
Aarhus University

College de France
May, 2017

Without friction, damping and loss …

Quantum state engineering

Unitary evolution

- decay into final state
- measurement and feedback
- error correction
- Zeno dynamics

|Ψ(t=0)>

|Ψ(t=T)>

- cryoegenic cooling (kT << E_{exc})
- optical pumping
- buffer gas and laser cooling …

→ ”Interesting state”

entangled state

topological state

squeezed state

→”Interesting dynamics”

quantum gate

sensing

clock

Dissipation in quantum mechanics

System coupling to an environment

Atom emitting light; atoms or molecules colliding with background gas; molecules moving in a solvent; excitons coupled to phonons and photons; light mode absorbed by mirrors …

We use dissipation to prepare an initial state of a quantum system

Dissipation is intimately connected with measurements (environment = meter)

Damping rates, master equations, quantum jumps, heralded/conditioned state

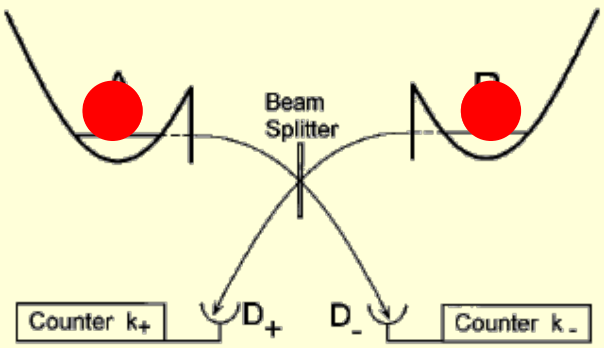
This talk

Make use of damping, decay, decoherence and loss processes
to enable quantum coherent dynamics, entanglement, … .

1. Entangling systems that never met (with measurements)

2. Dissipative entanglement without looking
   - Dissipation is not as incoherent as it seems
   - Dark state mechanisms
   - Quantum Zeno Dynamics
   - Quantum Zeno Training (with Durga Dasari, Stuttgart)

Entangling atoms by seeing the light.



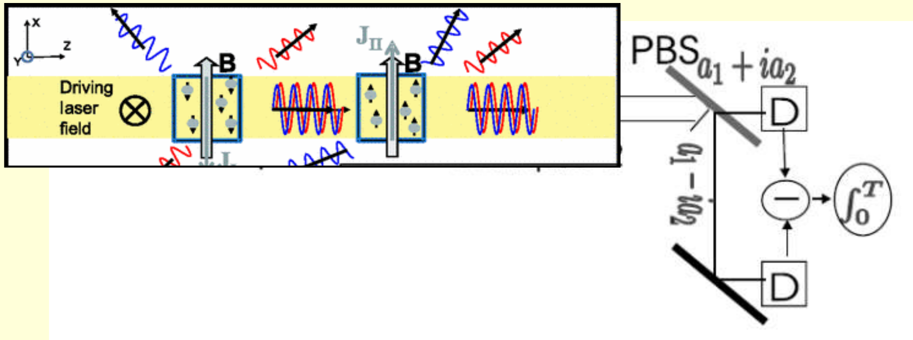
C. Cabrillo, J. I. Cirac, P. García-Fernández, and P. Zoller
Phys. Rev. A 59, 1025 (1999)

Two excited atoms |e,e>
Detection of spontaneously
emitted photon:
→ |*g,e*> + |*e,g*>, entangled.

Experiments:
Chris Monroe: trapped ions
NV-centers, atom-quantum dot, …

Two atomic ensembles
Detection of total phaseshift:
→ *Gaussian entangled state*.

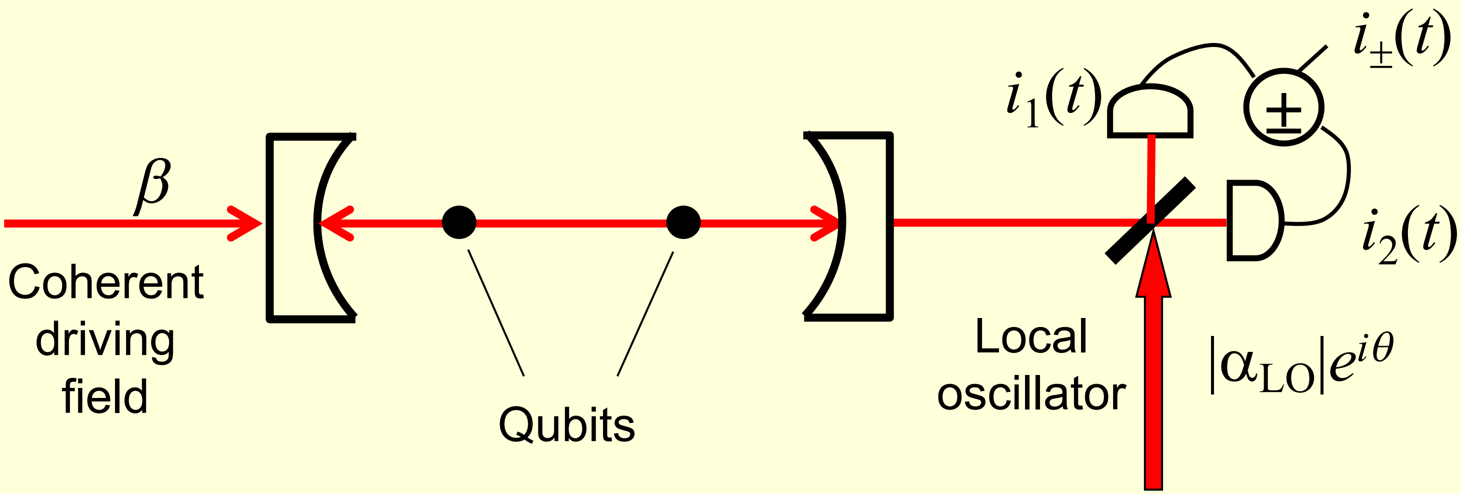
Experiments:
Eugene Polzik: atomic clouds
atom-light, …

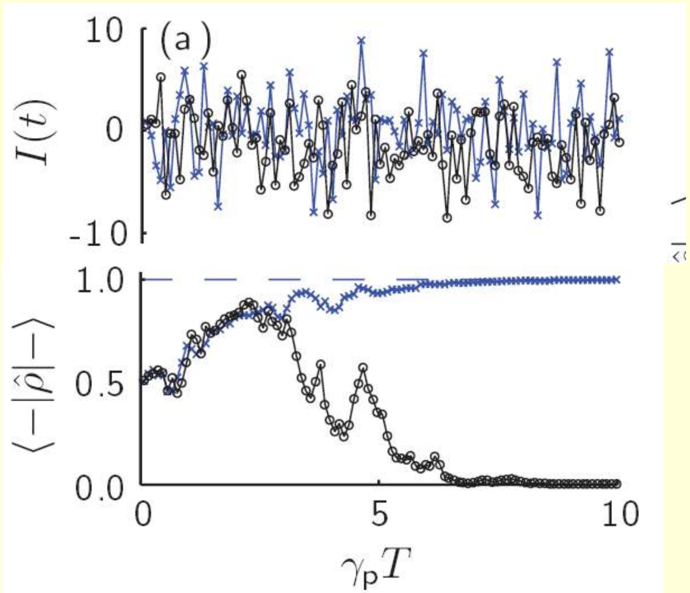


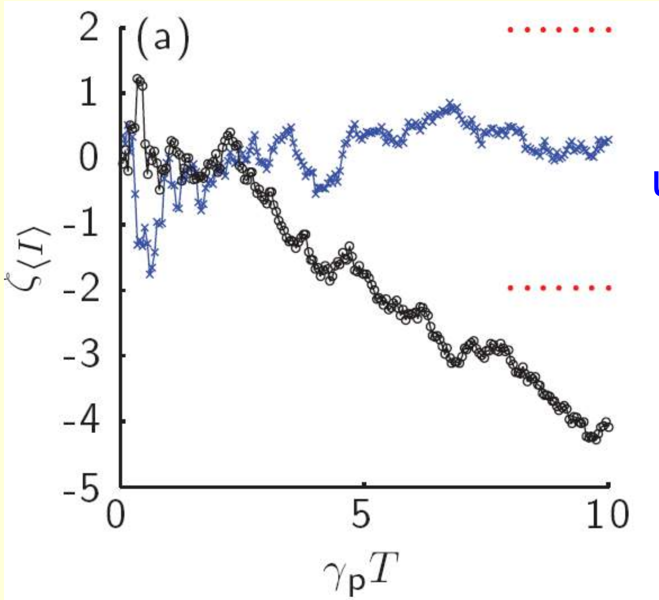
Lu-Ming Duan, J. I. Cirac, P. Zoller, and E. S. Polzik
Phys. Rev. Lett. 85, 5643 (2000)

Entangling atoms by continuous probing

Brian Julsgaard and Klaus Mølmer, Phys. Rev. A 85, 032327 (2012)



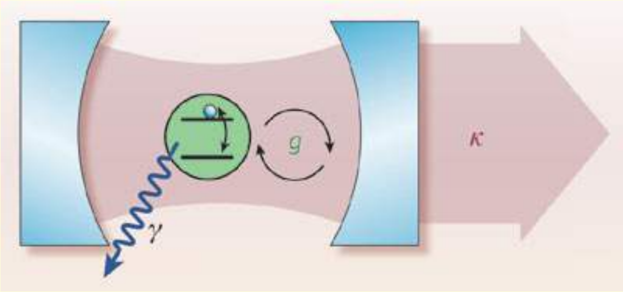




|ge>-|eg>
uncoupled

|gg>, |ee>,
|ge>+|eg>
coupled

Entanglement in cavity QED interaction vs measurement

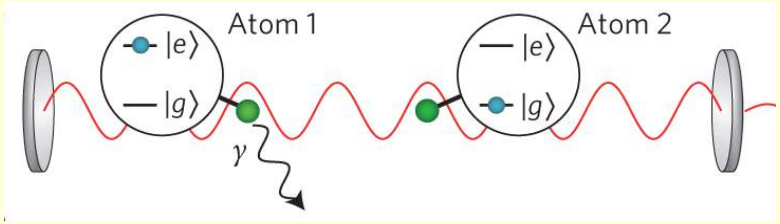


$g >> \gamma$

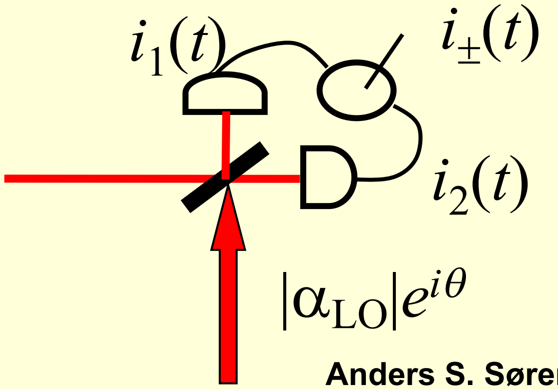
$g >> \kappa$

$C = g^2 / \kappa\gamma >> 1$

Deterministic entanglement via field mode: *F ~ 1-1/√C*



”Trade success probability for fidelity”



F ~ 1-1/C

Anders S. Sørensen and Klaus Mølmer
Phys. Rev. Lett. 90, 127903 (2003)

Anders S. Sørensen et al: arXiv:1612.06812; Phys. Rev. A 93, 040303(R) (2016); Phys. Rev. A 92, 012307 (2015)

Light =environment

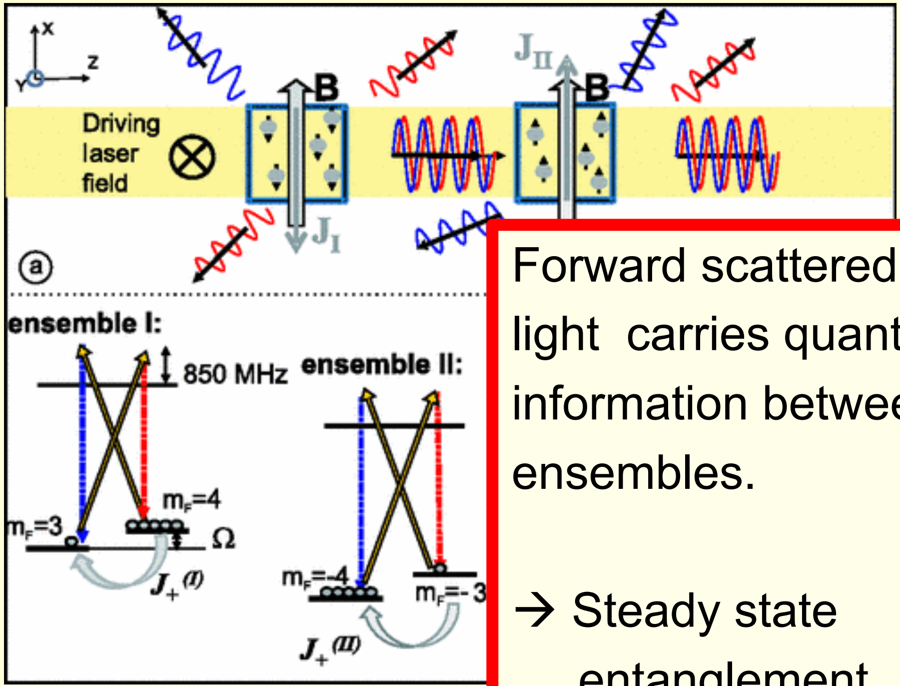
Atom-light interaction = dissipation on atomic state

Measuring the light ‘’re-purifies the system state’’

Can we make interesting quantum states using dissipation *without* measurements ?

Yes, we can!

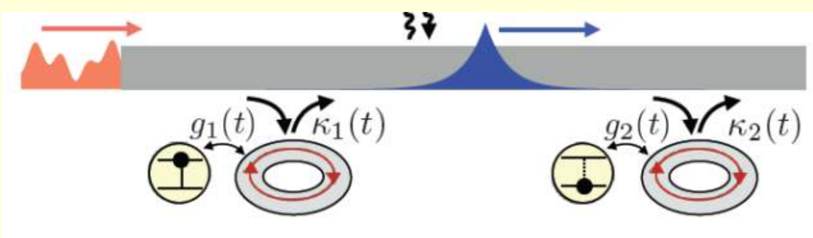
Dissipation is not as incoherent as it seems



Forward scattered light carries quantum information between ensembles.

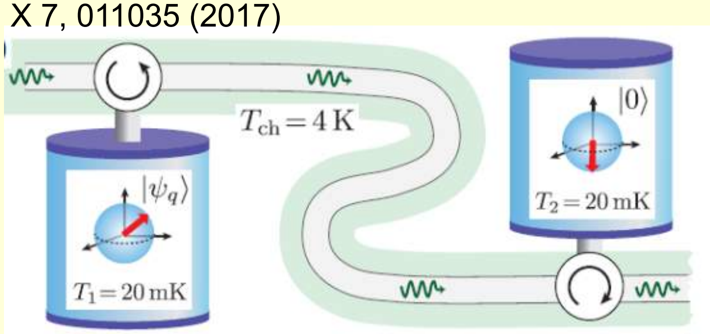
→ Steady state entanglement

Hanna Krauter, Christine A. Muschik, … , J. Ignacio Cirac, and Eugene S. Polzik
Phys. Rev. Lett. 107, 080503 (2011)

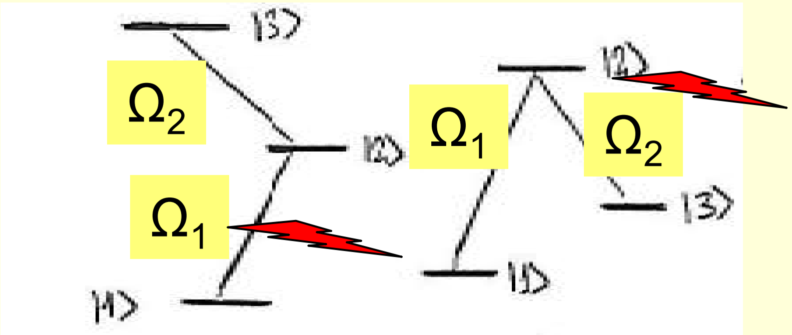


Benoît Vermersch, Pierre-Olivier Guimond, Hannes Pichler, Peter Zoller
Phys. Rev. Lett. 118, 133601 (2017)

Ze-Liang Xiang, Mengzhen Zhang, Liang Jiang, Peter Rabl
Phys. Rev. X 7, 011035 (2017)



Dark state mechanisms



« Dark » steady state: $\Omega_2|1> - \Omega_1|3>$

Generalize this to larger systems, more particles, …

What can we do without measurements ?

Pretty much everything, if we can engineer the right dissipation.

ARTICLES

Quantum states and phases in driven open quantum systems with cold atoms

S. DIEHL[1,2]*, A. MICHELI[1,2], A. KANTIAN[1,2], B. KRAUS[1,2], H. P. BÜCHLER[3] AND P. ZOLLER[1,2]

B. Kraus, H. P. Büchler, S. Diehl, A. Kantian, A. Micheli, and P. Zoller, Phys. Rev. A 78, 042307 (2008)

nature physics

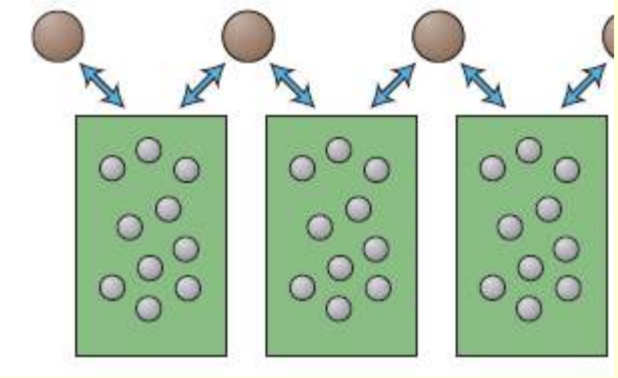
LETTERS

PUBLISHED ONLINE: 20 JULY 2009 | DOI:10.1038/NPHYS1342

Quantum computation and quantum-state engineering driven by dissipation

Frank Verstraete[1]*, Michael M. Wolf[2] and J. Ignacio Cirac[3]*

→ Steady state of many-qubit dynamics



Experiments with trapped ions

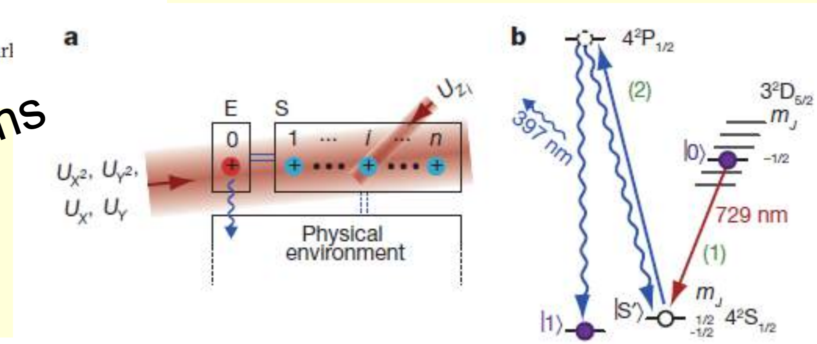
…and with SC qubits

ARTICLE

doi:10.1038/nature09801

An open-system quantum simulator with trapped ions

Julio T. Barreiro[1]*, Markus Müller[2,3]*, Philipp Schindler[1], Daniel Nigg[1], Thomas Monz[1], Michael Chwalla[1,2], Marl
Christian F. Roos[1,2], Peter Zoller[2,3] & Rainer Blatt[1,2]



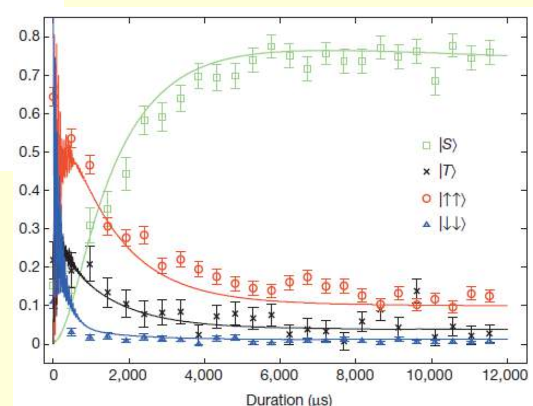
Blatt and Zoller teams

LETTER

doi:10.1038/nature12801

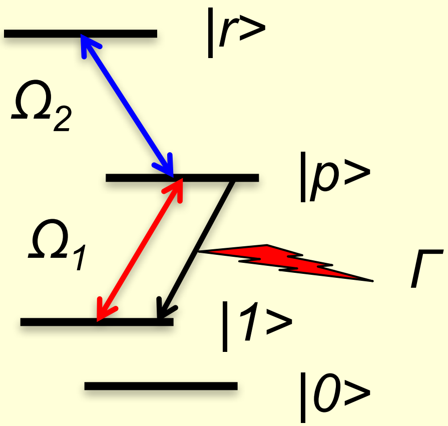
Dissipative production of a maximally entangled steady state of two quantum bits

Y. Lin[1]*, J. P. Gaebler[1]*, F. Reiter[2], T. R. Tan[1], R. Bowler[1], A. S. Sørensen[2], D. Leibfried[1] & D. J. Wineland[1]



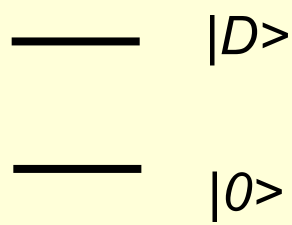
Wineland and Sørensen teams

Entanglement from dissipation



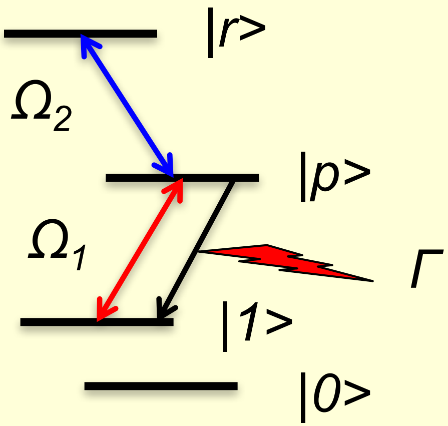
Single atom dark states:

$|0\rangle$ and $|D\rangle = \Omega_2|1\rangle - \Omega_1|r\rangle$



D. D. Bhaktavatsala Rao and Klaus Mølmer, Phys. Rev. Lett. 111, 033606 (2013)

Entanglement from dissipation

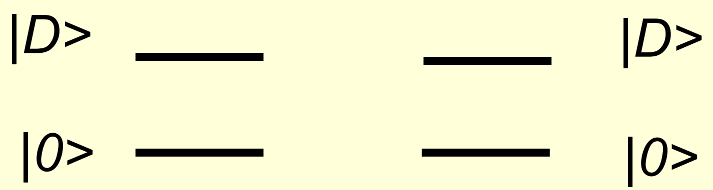


Single atom dark states:

$|0\rangle$ and $|D\rangle = \Omega_2|1\rangle - \Omega_1|r\rangle$

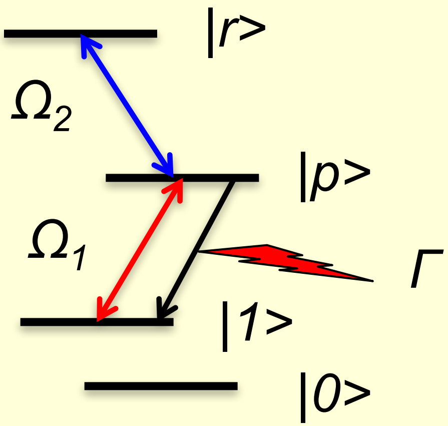
Two atom dark states:

$|00\rangle, |0D\rangle, |D0\rangle, |DD\rangle$



D. D. Bhaktavatsala Rao and Klaus Mølmer, Phys. Rev. Lett. 111, 033606 (2013)

Entanglement from dissipaton



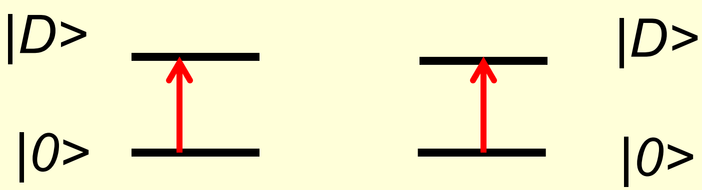
Single atom dark states:

$|0\rangle$ and $|D\rangle = \Omega_2|1\rangle - \Omega_1|r\rangle$

Two atom dark states:

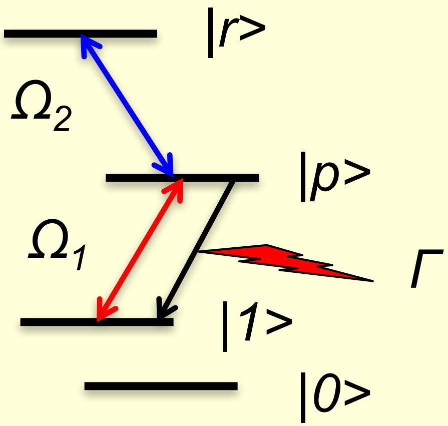
$|00\rangle, |0D\rangle, |D0\rangle, |DD\rangle$

Add Raman



D. D. Bhaktavatsala Rao and Klaus Mølmer, Phys. Rev. Lett. 111, 033606 (2013)

Entanglement from dissipaton

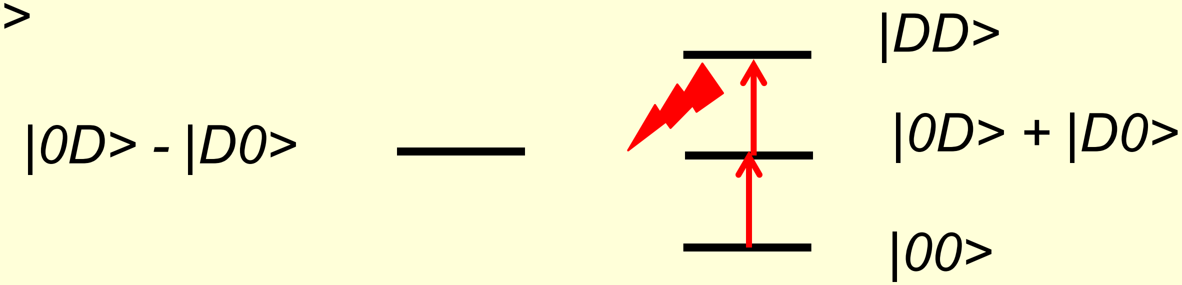


Single atom dark states:

|0> and |D> = Ω_2|1>-Ω_1|r>

Two atom dark states:

|00>, |0D>, |D0>, |DD>



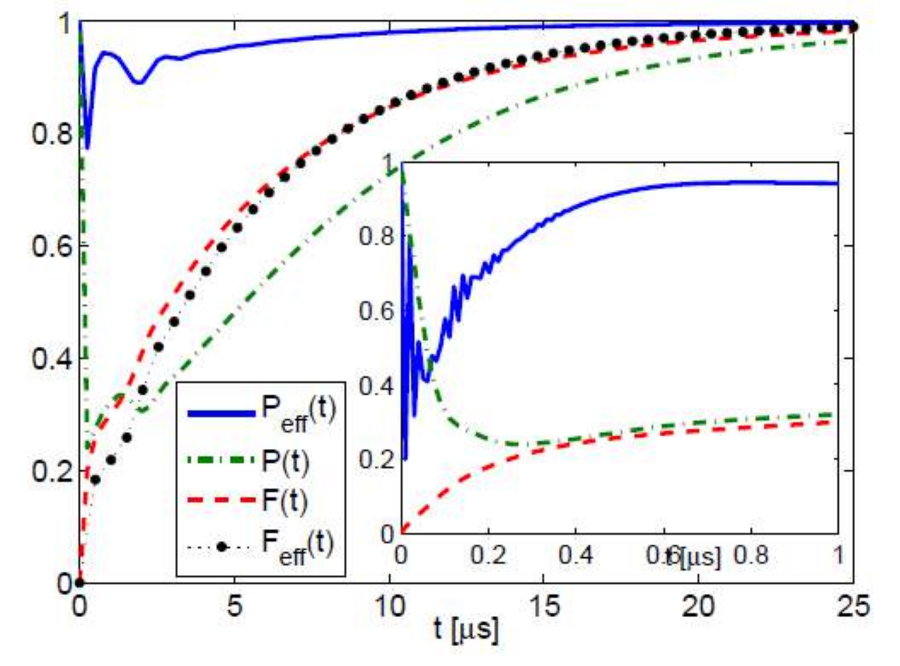
|rr>: Rydberg interaction: |DD> not dark

D. D. Bhaktavatsala Rao and Klaus Mølmer, Phys. Rev. Lett. 111, 033606 (2013)

Steady state entanglement

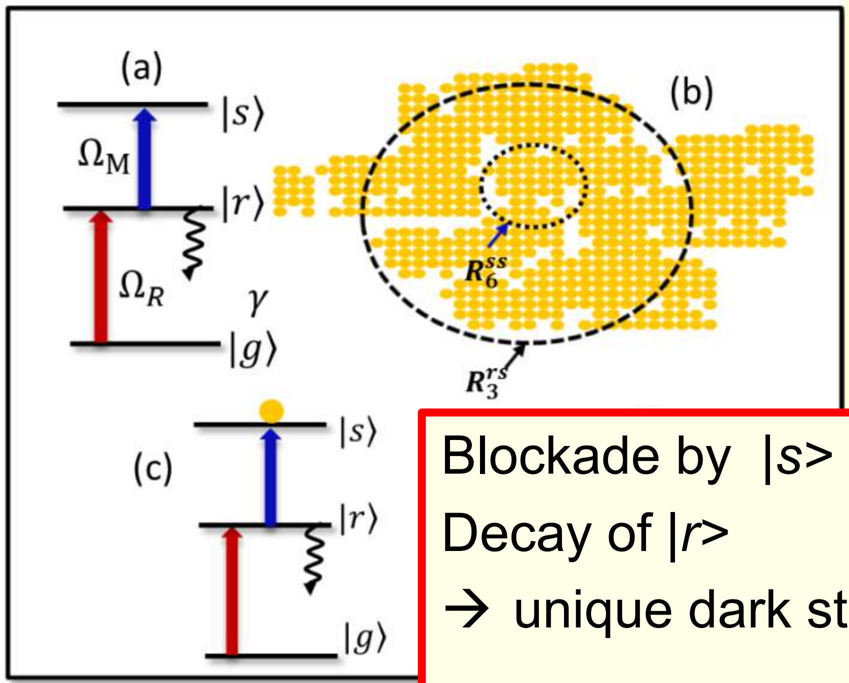
Raman coupling ω, only "singlet" |*0D*>-|*D0*>, is dark.

Any state decays into steady state singlet



D. D. Bhaktavatsala Rao and Klaus Mølmer, Phys. Rev. Lett. 111, 033606 (2013)

Multi-atom entangled states ?



Blockade by |*s*>

Decay of |*r*>

→ unique dark steady state

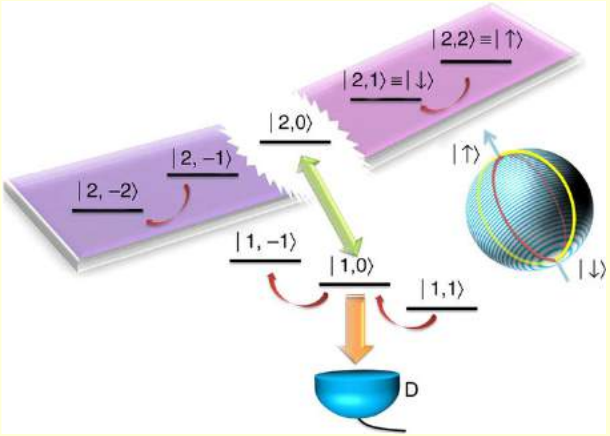
$$|\psi_D^{(N)}\rangle = \frac{1}{\Omega_N}\left[\Omega_M|G\rangle - \sqrt{N}\Omega_R|S\rangle\right]$$

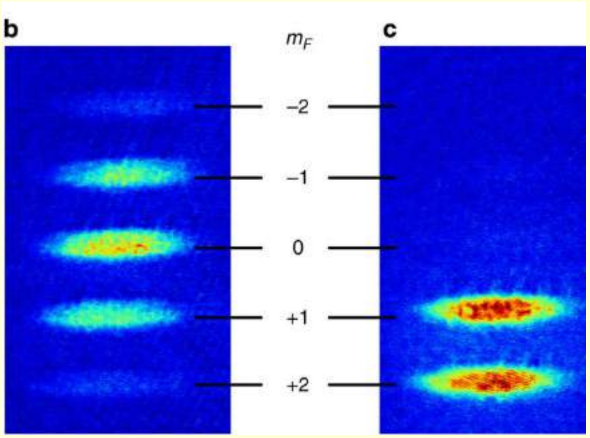
← W-state with single atom in |s>

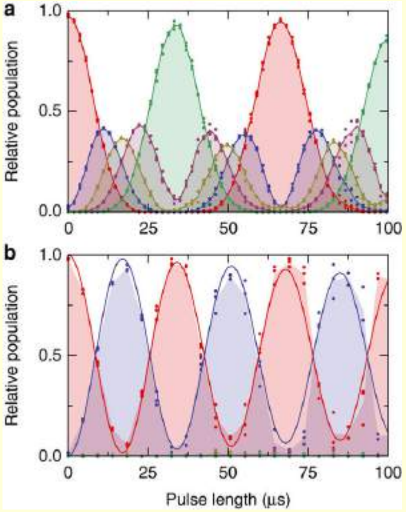
D. D. Bhaktavatsala Rao and Klaus Mølmer, Phys. Rev. A 90, 062319 (2014)

Quantum Zeno Dynamics

By measuring if a system occupies a certain state, one may block transfer of population into that state.



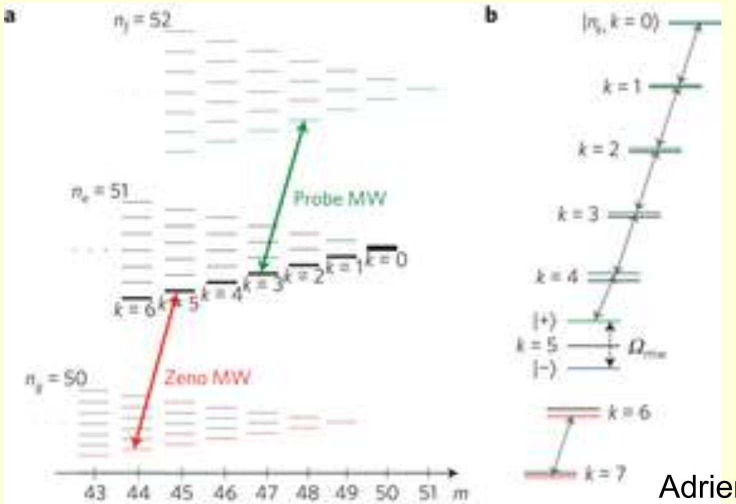


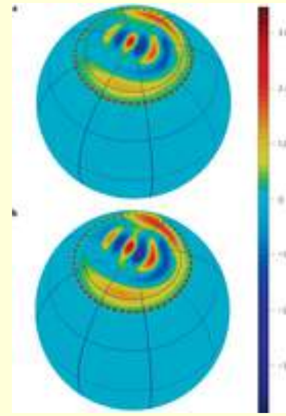


F. Schafer, I. Herrera, S. Cherukattil, C. Lovecchio, F.S. Cataliotti, F. Caruso & A. Smerzi.
NATURE COMMUNICATIONS | 5:3194 | DOI: 10.1038/ncomms4194

Yes, this can also be done by dephasing, or detuning of the state –
so we can have long fights about the reference to "Quantum Zeno Effect"

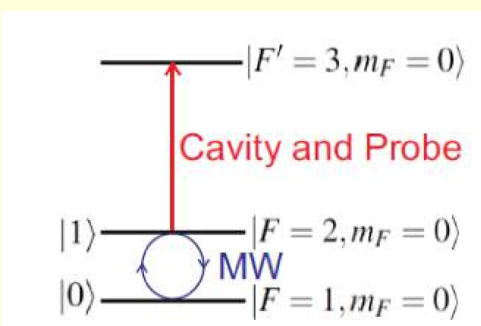
A cat-like angular momentum state

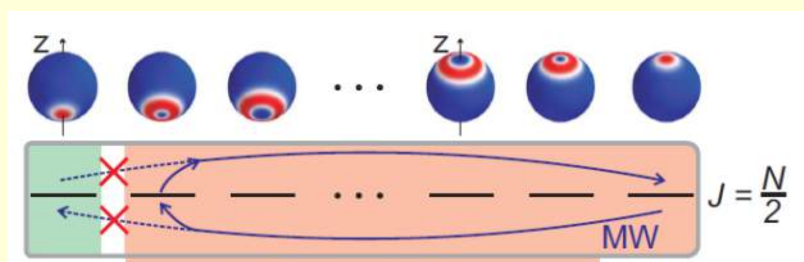




Adrien Signoles, Adrien Facon, Dorian Grosso, Igor Dotsenko,
Serge Haroche, Jean-Michel Raimond, Michel Brune and Sébastien Gleyzes,
NATURE PHYSICS, 10, 714 (2014)

A multi-atom entangled state





Giovanni Barontini, Leander Hohmann, Florian Haas, Jérôme Estève, Jakob Reichel:
Science 349, 1317 (2015)

”Quantum Zeno Training”

(With Durga Dasari, Stuttgart)

Javier Sotomayor, jumps 2.45 metres in 1995

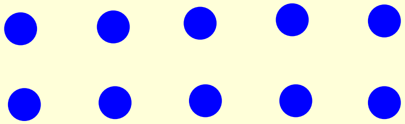
Through training (and during a tournament), you can progressively accomplish higher and higher achievements

Each move is big and ”discrete” – but the advancement is ”adiabatic”

”Quantum Zeno Training”

(With Durga Dasari, Stuttgart)

Two-level atoms with nearest
neigbour blockade interaction.
Can we make a global, entangled state ?

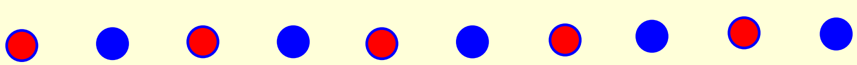


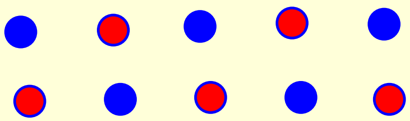
Recipe:

Start all qubits in |*0*>

Apply infinitesimal unitary U_Θ coupling states |0> and |1>

- Dephase/damp all states with a nearest neigbour |*1*>|*1*> pair
- Increase angle $\Theta \rightarrow \Theta + d\Theta$
- Apply new unitary U_Θ



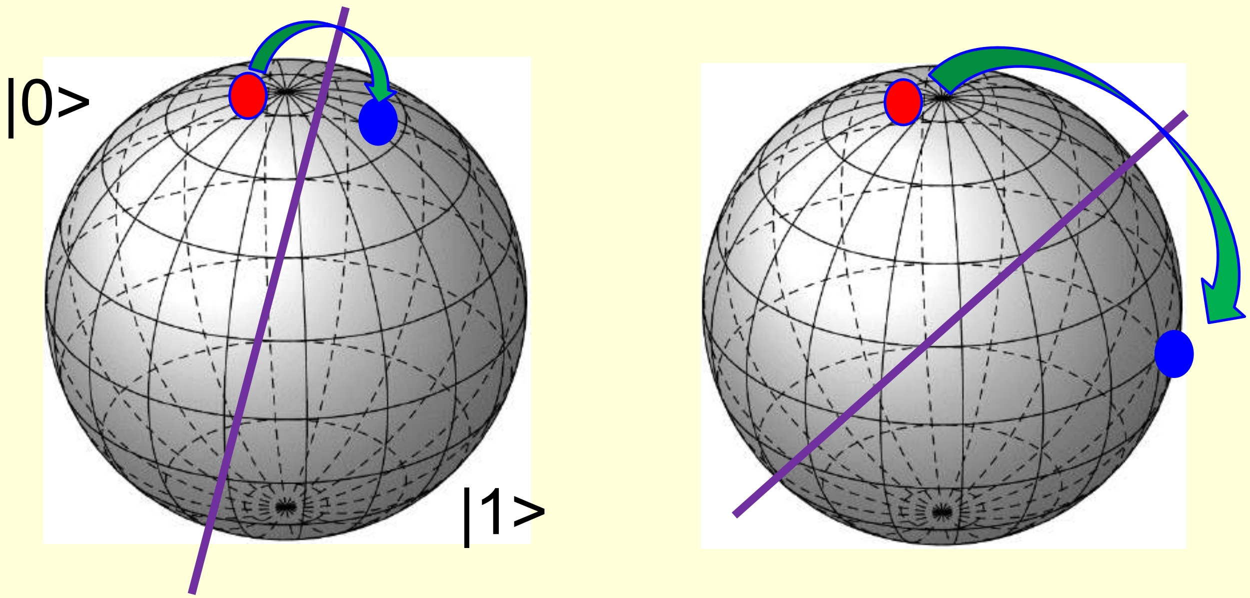


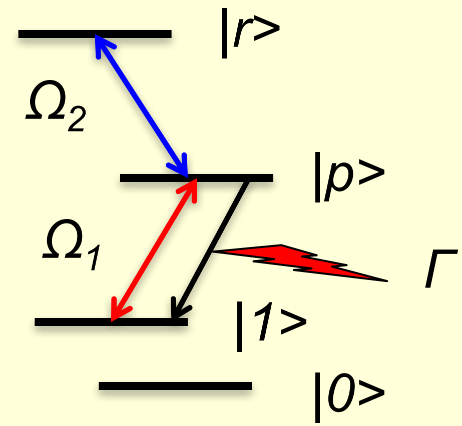
"Quantum Zeno Training"

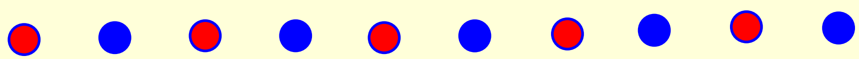
(With Durga Dasari, Stuttgart)

One-qubit operation U_{Θ}:

Rotate 180 degrees around axis at direction Θ







No nearest neigbor |1>|1>

Θ=0: |00 … 00>

→ Θ=π/2: |0101 …. 01> + |1010 … 10> (GHZ)

Summary/conclusion

- Dissipation transforms, quantum states in ways complementary to unitary evolution.
- State preparation, memory protection, error correction, gate operations, metrology and parameter estimation.
- Dissipation strengths and character may be optimized, heuristically or systematically.
- Intuition:
  - Think: ”jumps/no-jumps”
  - Dark states as final state of evolution
  - Zeno mechanism, suppress unwanted dynamics, train system