The Lossy Road to Entangled States

Klaus Mølmer

POLARYS, France, December, 2014

Without friction, damping and loss …

If all conductors were superconductors …

If atoms and molecules conserved their energy…

This talk

How to make good use of damping, decay, decoherence and loss processes

With the purpose of enabling quantum coherent dynamics, entanglement, … .

Examples with interacting Rydberg atoms

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 . . .

Theory:

→ Unitary dynamics of larger system
→ Non-unitary dynamics of small system (density matrix)
→ Einstein / Weisskopf-Wigner (perturbation) theory of atomic decay
→ Master equation with rates /
Trajectories with random quantum jumps

Intimately connected with measurements

We use dissipation …

To prepare an initial state of a quantum system

Cryoegenic cooling ($kT << E_{exc}$)

Optical pumping

Buffer gas and laser cooling …

To read out a quantum state (environment = meter)

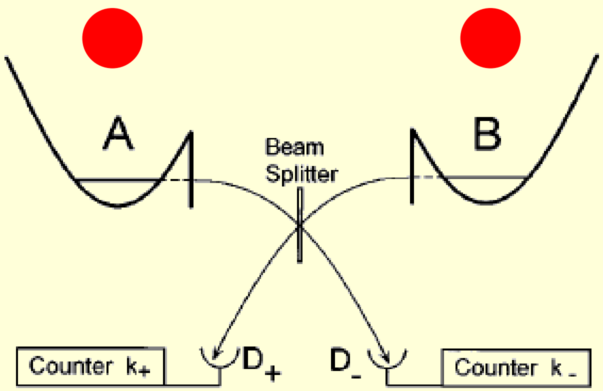
Measurements, spectroscopy

Projective preparation (by measurement)

Measurement and feedback, error correction …

Entangling atoms by seeing the light.

(Cabrilo et al, PRA 1998)



- Two excited atoms |e,e>
- Detection of spontaneously emitted photon:

  → |*g,e*> + |*e,g*>, entangled.

  …

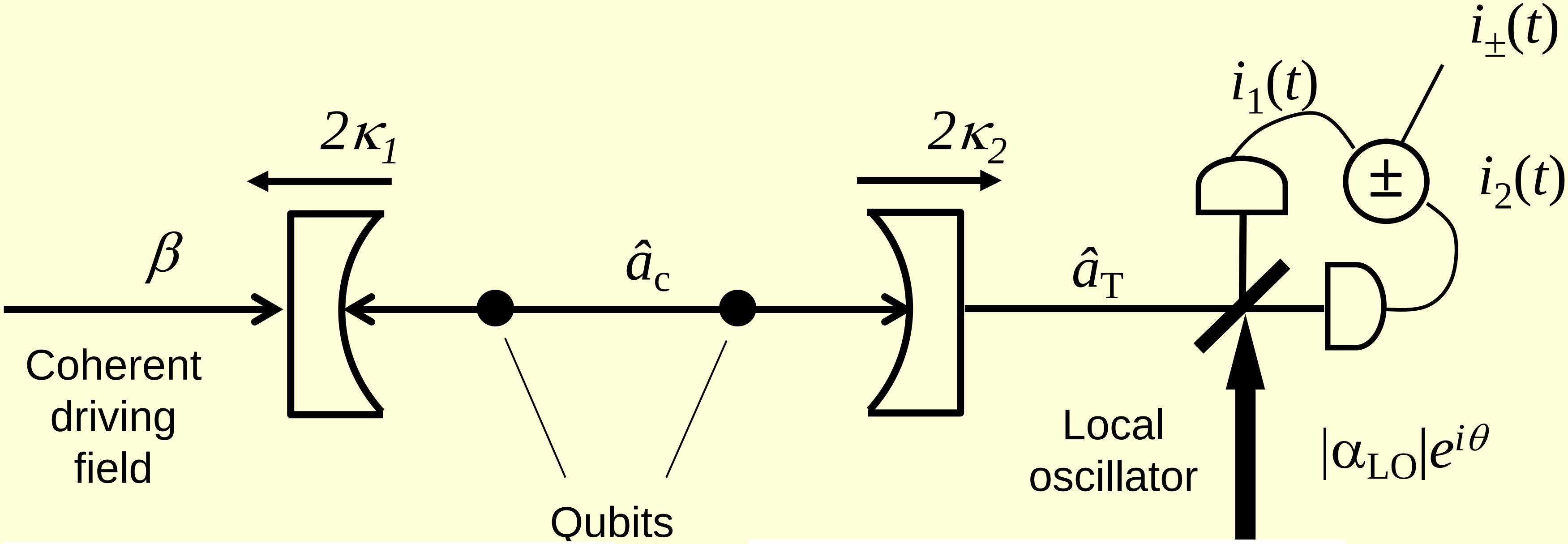
Experiments:

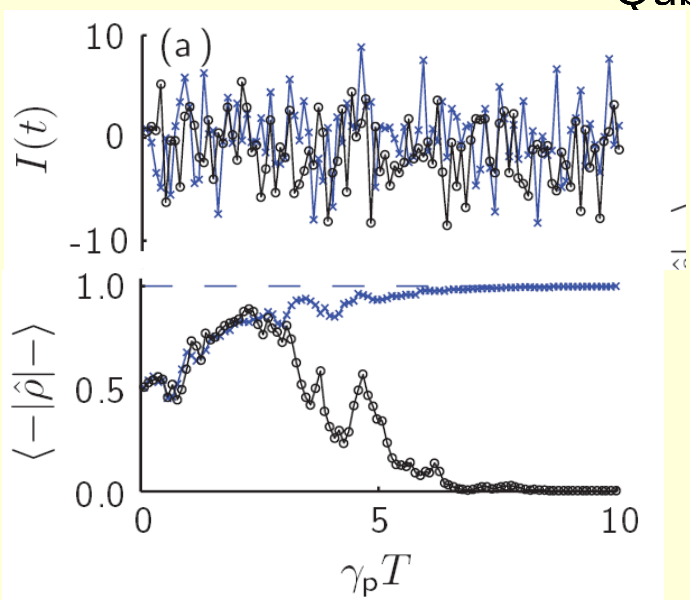
Chris Monroe: trapped ions

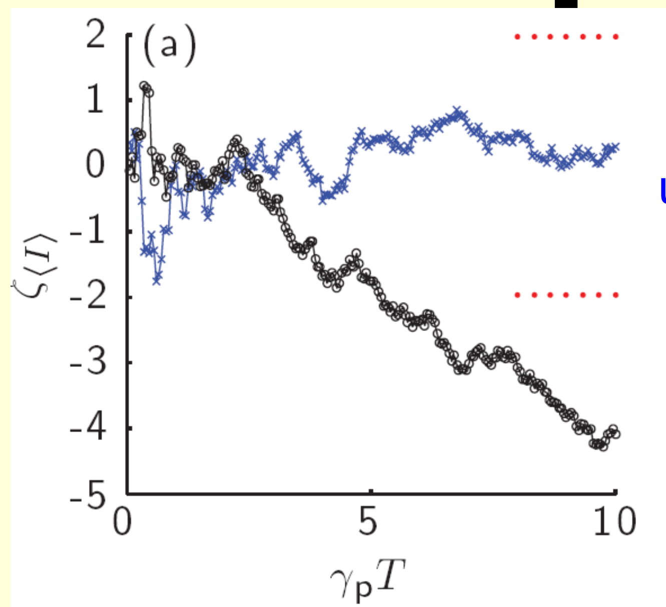
Michael Köhl: an ion and a quantum dot

…

Entangling atoms by continuous probing







|ge>-|eg> uncoupled

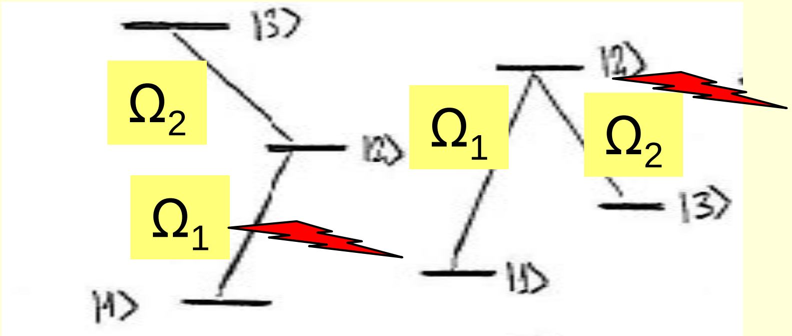
|gg>, |ee>, |ge>+|eg> coupled

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

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

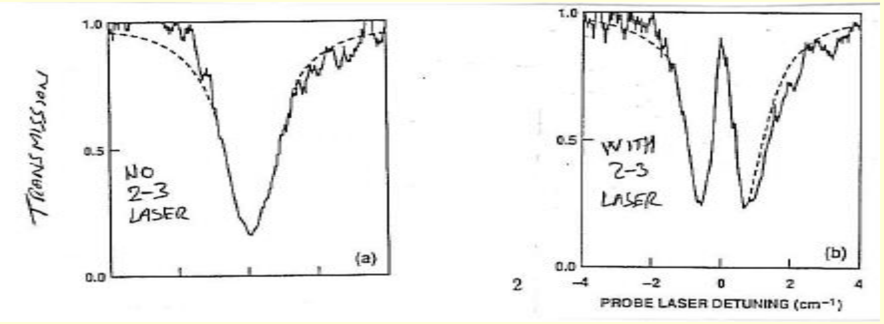
Yes, we can!

3 > 2



Dark state: $\Omega_2|1\rangle - \Omega_1|3\rangle$

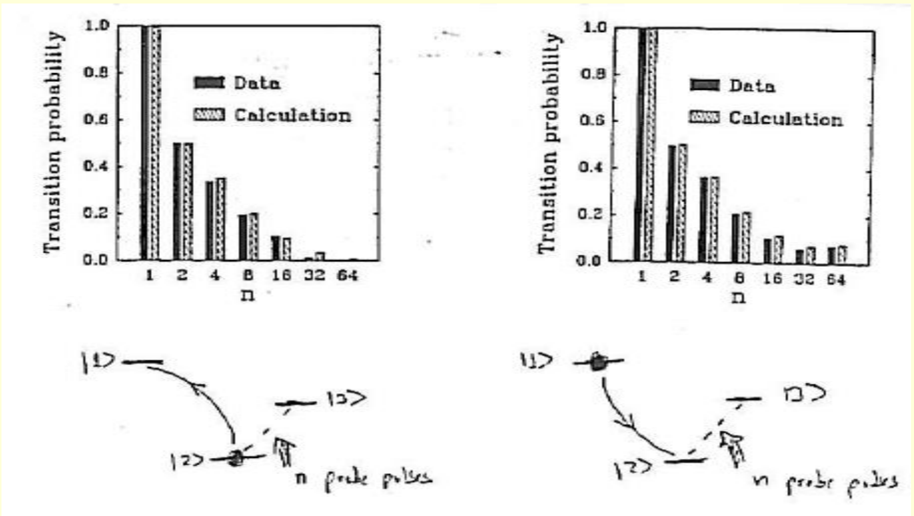
Electromagnetically induced transparency



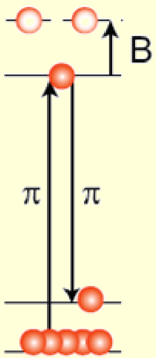
Dark state cooling
(Cohen-Tannoudji

Lasing without inversion

Quantum Zeno effect
Null-measurements

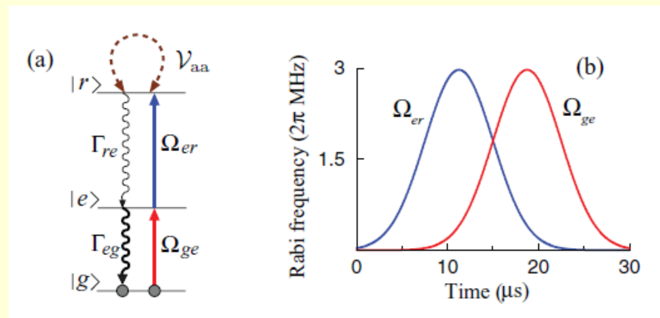


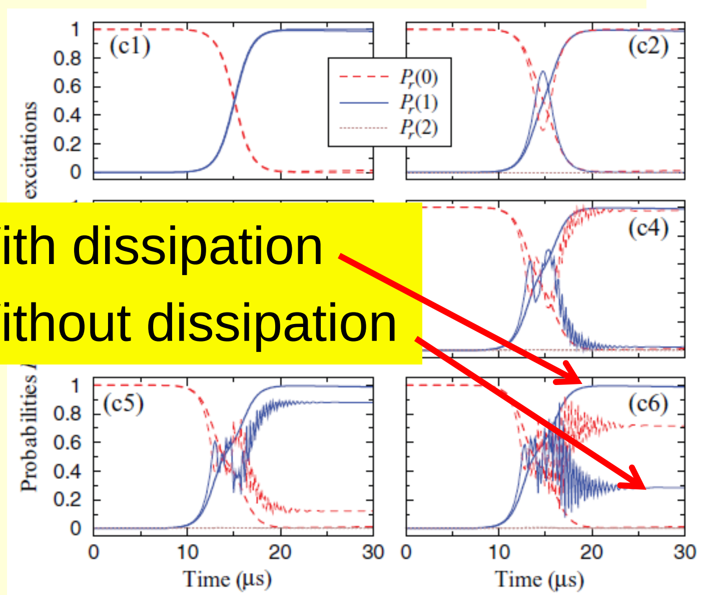
Rydberg blockade filter for atoms



Turn N>1 atoms into precisely 1 atom

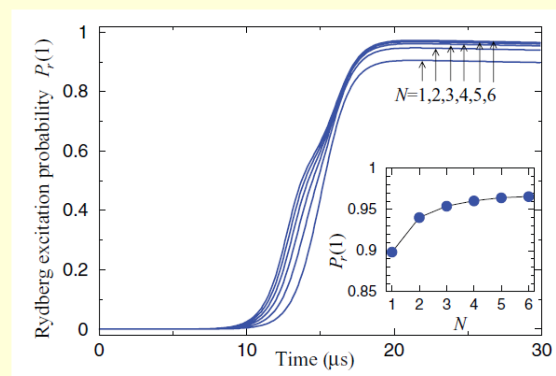
Unitary process, prone to decoherence and decay





With dissipation

Without dissipation



”One man’s loss …

D. Petrosyan, KM, PRA 87, 033416 (2013)

Can dissipation entangle different particles ?

Decay into common reservoir (superradiance)

Interaction between particles (+ decay)

Tricks

How complicated things can we do with dissipation (without measurements) ?

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

nature physics

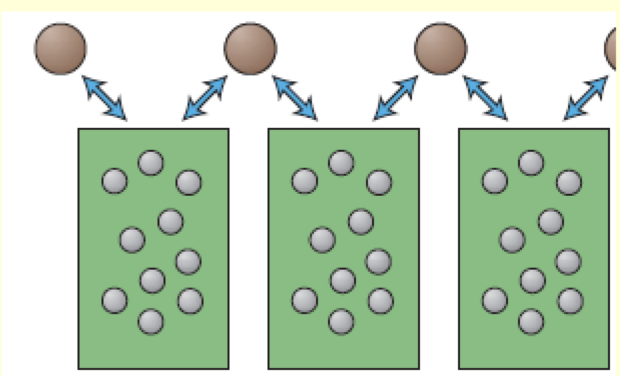
LETTERS

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]*

Related work by Zoller et al



→ Steady state

= dark state of many-qubit dynamics

= result of hard computation

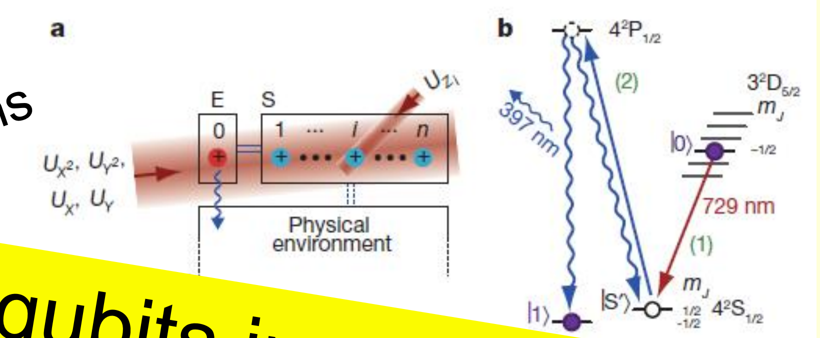
Experiments with trapped ions:

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]



... Zoller teams

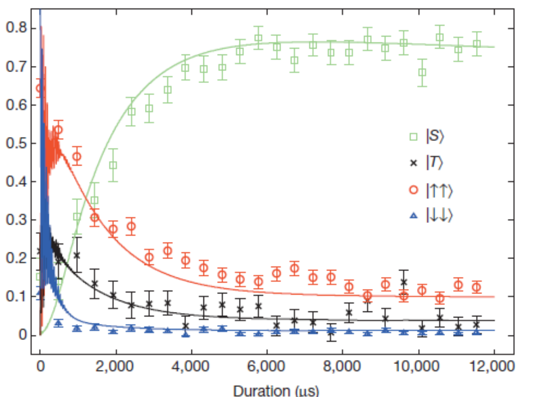
Superconducting qubits in cavitites

LETTER

doi:10.1038/nature12801

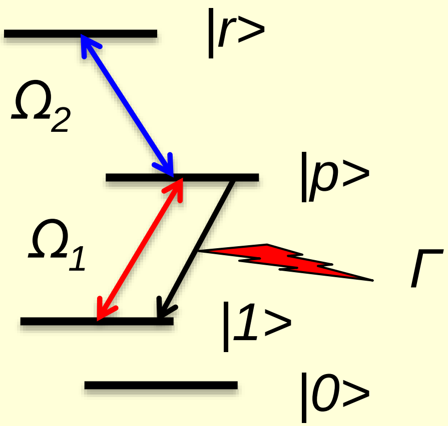
Dissipative production of a maximally entangled steady state of two quantum bits

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]



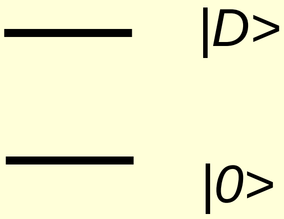
Wineland and Sørensen teams

Entanglement from dissipation



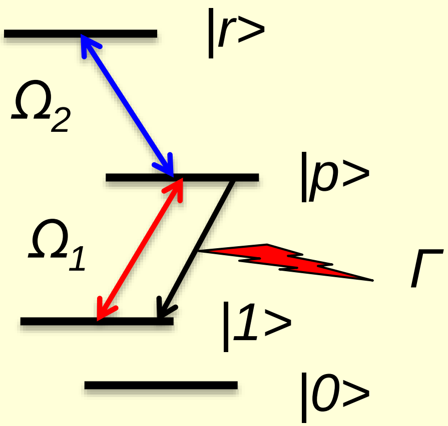
Single atom dark states:

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



D. D. Bhaktavatsala Rao and K. Mølmer, Phys. Rev. Lett 2013.

Entanglement from dissipation

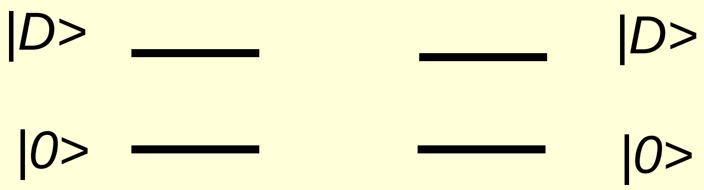


Single atom dark states:

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

Two atom dark states:

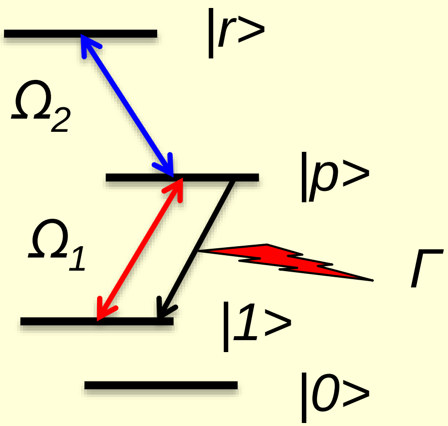
$|00\rangle$, $|0D\rangle$, $|D0\rangle$, $|DD\rangle$



ANY Rydberg interaction: $|DD\rangle$ not dark

D. D. Bhaktavatsala Rao and K. Mølmer, Phys. Rev. Lett 2013.

Entanglement from dissipaton



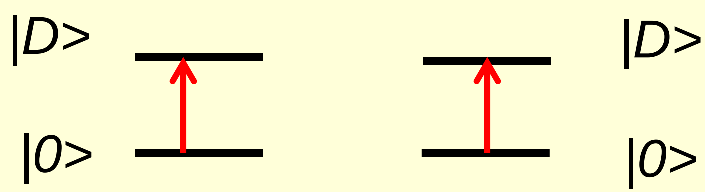
Single atom dark states:

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

Two atom dark states:

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

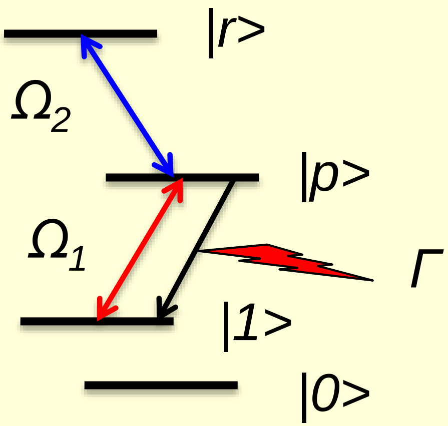
Add Raman



ANY Rydberg interaction: |DD> not dark

D. D. Bhaktavatsala Rao and K. Mølmer, Phys. Rev. Lett 2013.

Entanglement from dissipaton

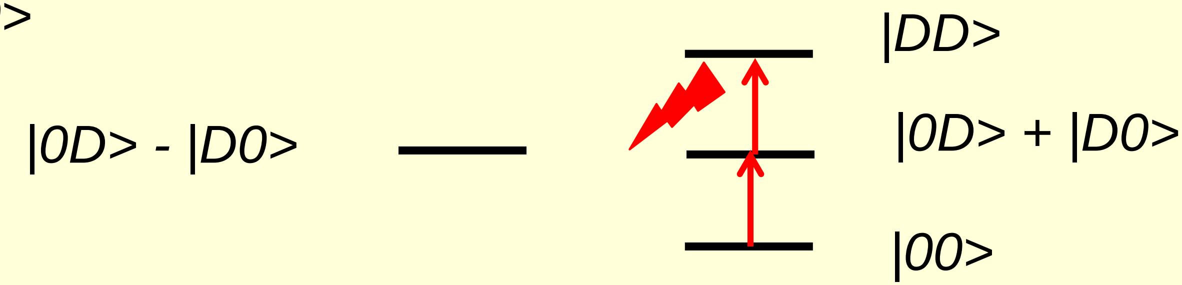


Single atom dark states:

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

Two atom dark states:

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



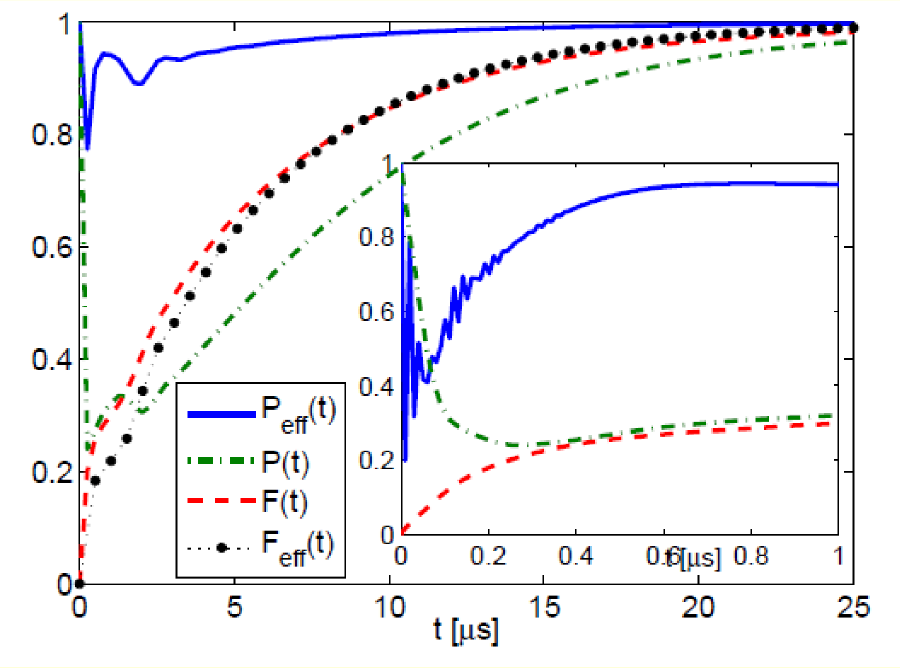
ANY Rydberg interaction: |DD> not dark

D. D. Bhaktavatsala Rao and K. Mølmer, Phys. Rev. Lett 2013.

Steady state entanglement

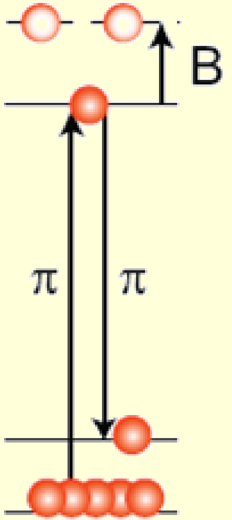
Raman coupling ω, only "singlet" |*0D*>-|*D0*>, is dark.

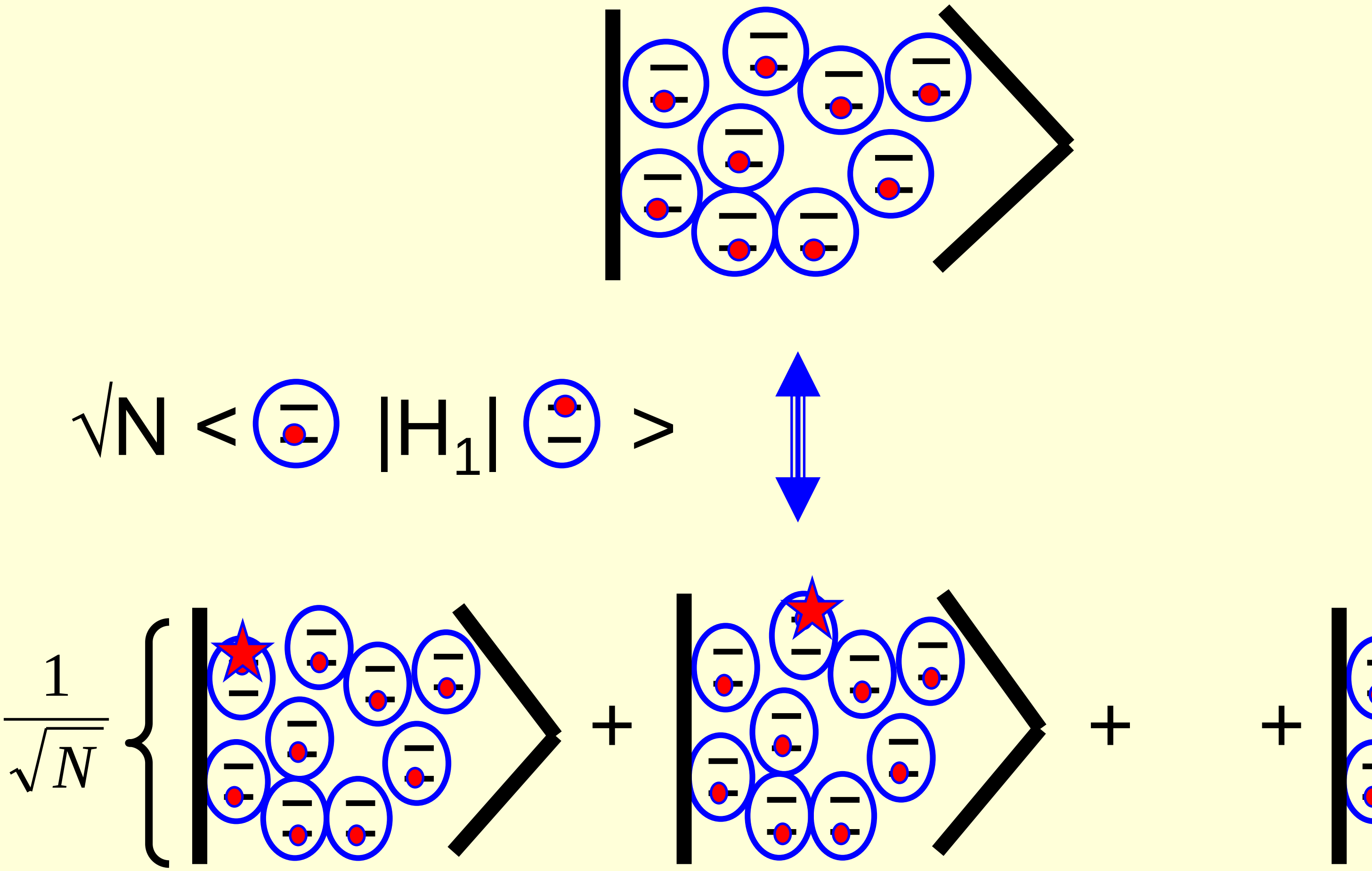
Any state decays into steady state singlet



D. D. Bhaktavatsala Rao and K. Mølmer, Phys. Rev. Lett 2013.

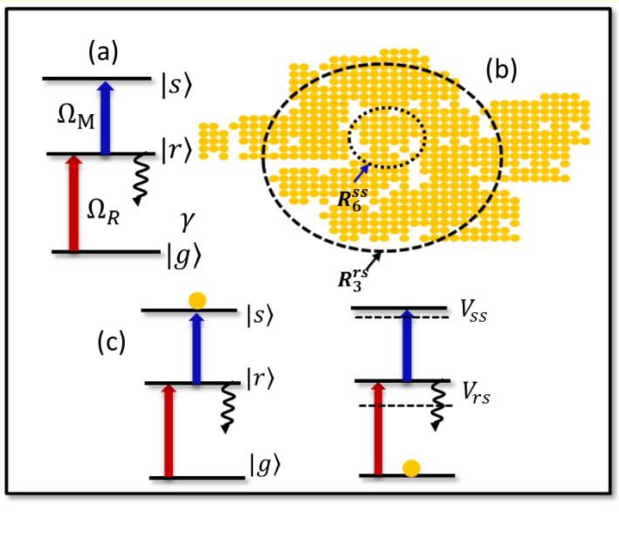
Super atom





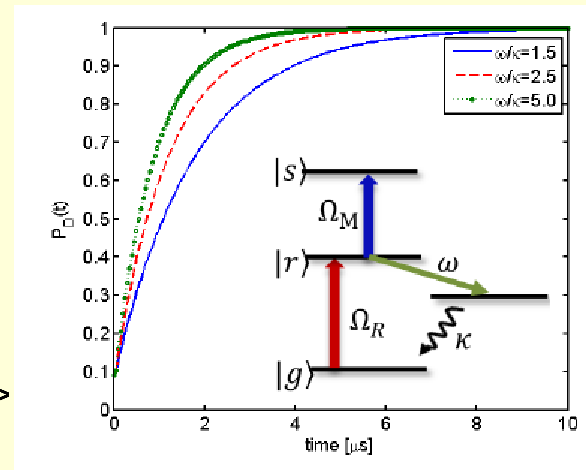
Multi-atom entangled states ?

D. D. Bhaktavatsala Rao and Klaus Mølmer, arXiv:1407.1228



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

← Single atom in |s>



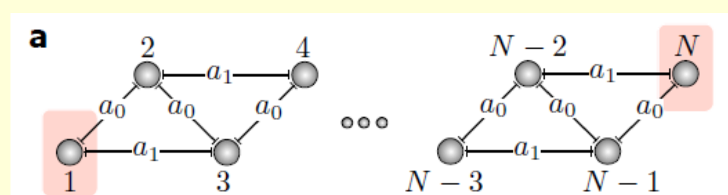
Decay of |r> and blockade of |s>

→ unique dark steady state

Current efforts: short range interaction → anti-ferromagnetic order, polaritons, ..

See also work by: Zoller, Weimer, Büchler, Saffman, Häffner, Choi, ..

K. S. Choi et al, arXiv:1401,0028



Summary/conclusion

- Dissipation projects, or gradually transforms, quantum states in ways complementary to unitary evolution.
- Applications in state preparation, memory protection, continuous time error correction, ancilla-driven gate operations, metrology and parameter estimation.
- Dissipation strengths and operator character may be optimized, heuristically or systematically.
- Intuition:
  - Think: ”jumps/no-jumps”
  - Dark states as final state of evolution
  - Zeno mechanism, suppresses unwanted dynamics
- Measurement and feedback strategies