Environment-Assisted Speed-up of the Field Evolution in Cavity QED

Journal club

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This paper..

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Environment-Assisted Speed-up of the Field Evolution in Cavity Quantum Electrodynamics

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We measure the quantum speed of the state evolution of the field in a weakly driven optical cavity QED system. To this end, the mode of the electromagnetic field is considered as a quantum system of interest with a preferential coupling to a tunable environment: the atoms. By controlling the environment, i.e., changing the number of atoms coupled to the optical cavity mode, an environment-assisted speed-up is realized: the quantum speed of the state repopulation in the optical cavity increases with the coupling strength between the optical cavity mode and this non-Markovian environment (the number of atoms).

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1987 Doctorate in Physics, August 1987 under Prof. H. Jeff Kimble "*Optical Bistability with Two-Level Atoms*". University of Texas at Austin. Austin, Texas, USA.

Andres D. Cimmarusti
2014 Doctorate in Physics, under Prof. Luis. A. Orozco "*Control protocols for manipulation of ground-state quantum beats in a cavity QED system*". University of Maryland College Park. Prince George's county, Maryland, USA.

Sebastian Deffner
2011 Doctorate in Physics, August 2011 under Prof. Eric Lutz "*Nonequilibrium entropy production in open and closed quantum systems*". University of Augsburg at Universitätsviertel section of Augsburg, Germany.

QSL (Quantum Speed Limit)

"Determines the theoretical upper bound on the speed of evolution of a quantum system"

Possibility of observing *speed-ups* of the quantum evolution if an open quantum system is subject to environmental changes

Let's realize this theory proposing *environment-assisted speed-up* through an experiment

Theoretical back ground

$$\left(J_{\pm}=\sum_{j=1}^{N}\sigma^{j}{}_{\pm}\right)$$

Master equation

$$\dot{\rho}=\varepsilon\left[\left(a^{\dagger}-a\right),\rho(t)\right]+g\left[a^{\dagger}\boxed{J_{-}}-a\boxed{J_{+}},\rho(t)\right]$$

$$+\kappa\left(2a\rho(t)a^{\dagger}-a^{\dagger}a\rho(t)-\rho(t)a^{\dagger}a\right)$$

$$+\left(\frac{\gamma}{2}\right)\sum_{j=1}^{N}\left(2\sigma^{j}{}_{-}\rho(t)\sigma^{j}{}_{+}-\sigma^{j}{}_{+}\sigma^{j}{}_{-}\rho(t)-\rho(t)\sigma^{j}{}_{+}\sigma^{j}{}_{-}\right)$$

Weak field limit, $\varepsilon\ll\kappa$

$$\rho(t)\simeq\left|\psi(t)\right\rangle\left\langle\psi(t)\right|$$

$$\left|\psi(t)\right\rangle\simeq\left|00\right\rangle+\underline{A_{1}(t)}\left|10\right\rangle+\underline{A_{2}(t)}\left|01\right\rangle+O(\varepsilon^{2}/\kappa^{2})$$

$$\Rightarrow\begin{cases}\dot{A}_{1}(t)=-\kappa A_{1}(t)+g\sqrt{N}A_{2}(t)+\varepsilon\\ \dot{A}_{2}(t)=-\dfrac{\gamma}{2}A_{2}(t)-g\sqrt{N}A_{1}(t)\end{cases}$$

H. J. Carmichael, Opt. Commun. **82**, 73 (1991)

Theoretical back ground

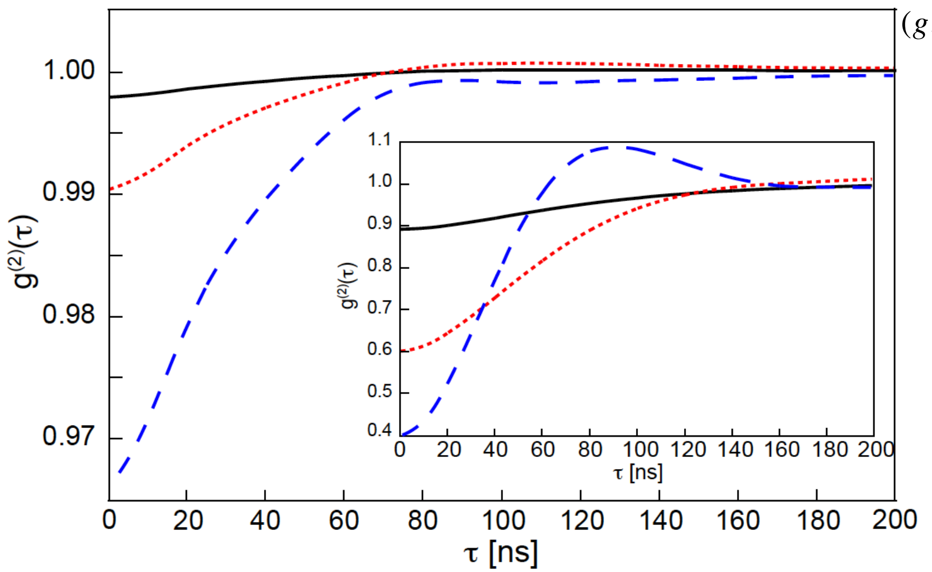
$$C = NC_1 \qquad C_1 = \frac{g^2}{\kappa\gamma}$$

The intensity correlation function

$$\boxed{g^{(2)}(\tau) = \left\{1 + \frac{\Delta\alpha}{\alpha} e^{\left[-\frac{\tau}{2}\left(\kappa+\frac{\gamma}{2}\right)\right]}\left[\cosh\left(\Omega_{VR}\tau\right) + \frac{1}{2}\left(\kappa + \frac{\gamma}{2}\right)\frac{\sinh\left(\Omega_{VR}\tau\right)}{\Omega_{VR}}\right]\right\}^2}$$

$$\frac{\Delta\alpha}{\alpha} = -2C'_1\left[\frac{2C}{1+2C-2C'_1}\right] \qquad \Omega_{VR} = \sqrt{\left[\frac{\kappa-\gamma/2}{2}\right]^2 - g^2 N}$$

$$C'_1 = \frac{C_1}{1+\gamma/2\kappa}$$



$(g,\kappa,\gamma)/2\pi = (3.2, 4.5, 6.0)$ MHz

$\Omega_{VR}/2\pi = 1.1$ MHz

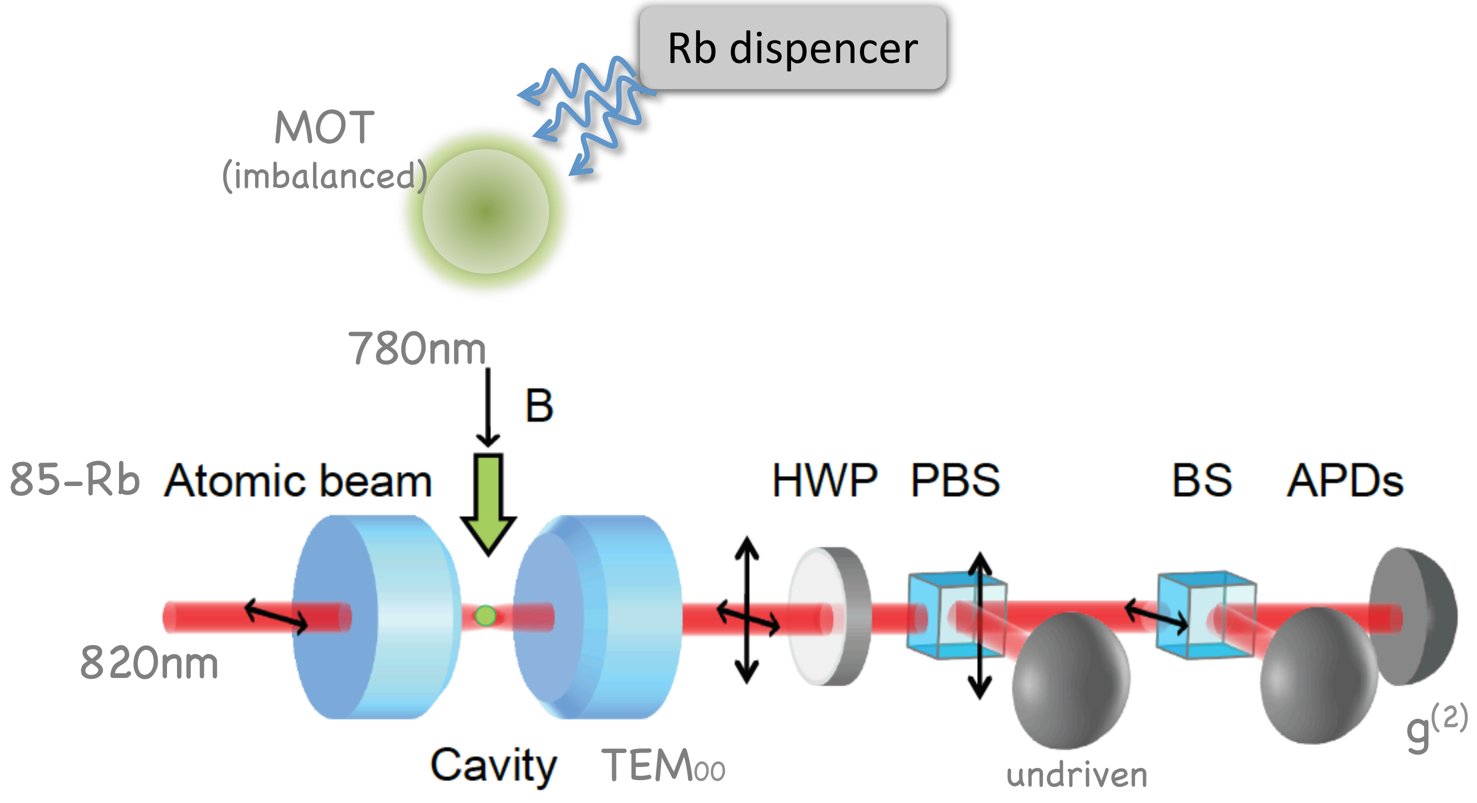
$\Omega_{VR}/2\pi = 2.8$ MHz

$\Omega_{VR}/2\pi = 5.2$ MHz

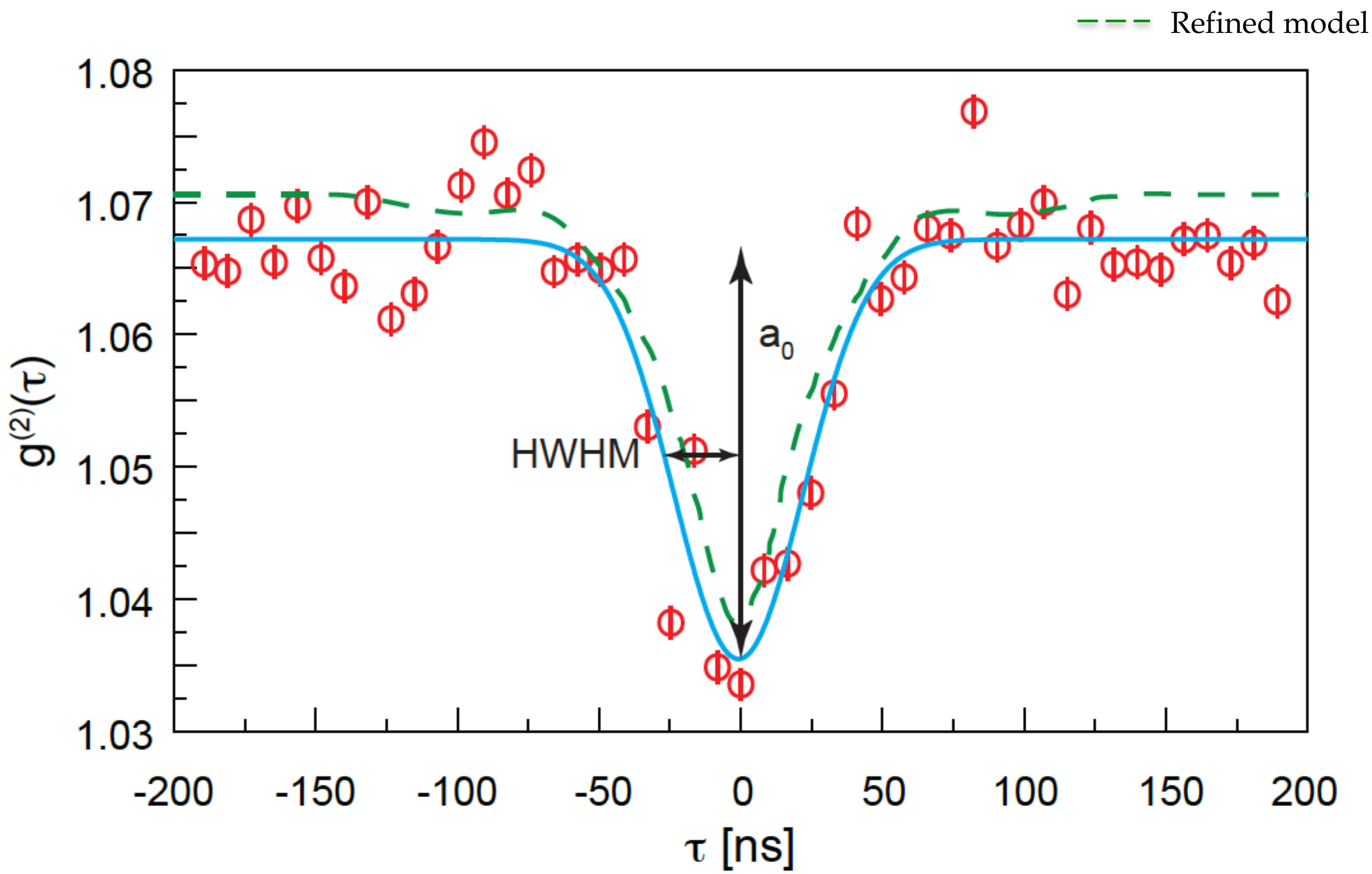
*inset : maximally coupled atom and optimal experimental comdition

H. J. Carmichael, Opt. Commun. **82**, 73 (1991)

Set-up

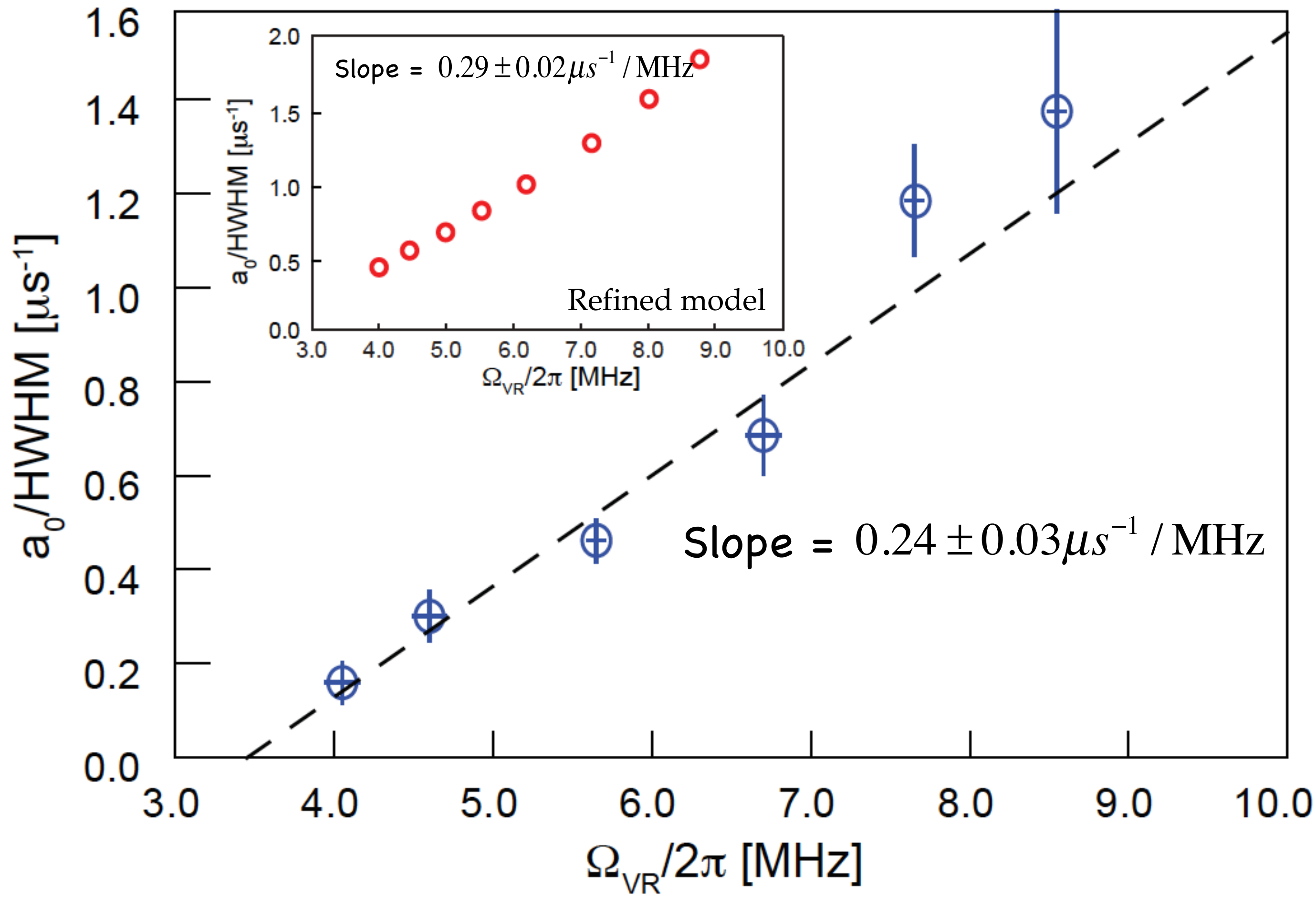

Rb dispencer
MOT
(imbalanced)
780nm
B
85-Rb
Atomic beam
HWP
PBS
BS
APDs
820nm
Cavity
TEM00
undriven
g(2)

result



Refined model
1.08
1.07
1.06
1.05
1.04
1.03
$g^{(2)}(\tau)$
HWHM
a_0
-200
-150
-100
-50
0
50
100
150
200
τ [ns]

result



* $\Omega_{VR} \simeq g\sqrt{N_{eff}}$

Non-Markovian speed-up ??

"The quantum speed-up in an open quantum system was attributed to the non-Markovian nature of the environment"

S. Deffner, Phys. Rev. Lett. **111**, 010402 (2013)

Non-Markovianity

$$N = \max_{\rho_{1,2}(0)} \int_{\sigma>0} dt\,\sigma[t,\rho_{1,2}(0)]$$

$$\sigma[t,\rho_{1,2}(0)] = \frac{1}{2}\frac{d}{dt}\mathrm{tr}\left\{\left|\rho_1(t)-\rho_2(t)\right|\right\}$$

Heinz-Peter Breuer, Phys. Rev. Lett. **103**, 210401 (2009)

Non-Markovian speed-up ??

"The quantum speed-up in an open quantum system was attributed to the non-Markovian nature of the environment"

S. Deffner, Phys. Rev. Lett. **111**, 010402 (2013)

Non-Markovianity

$$N = 0$$

$$\sigma[t,\rho_{1,2}(0)] = \frac{1}{2}\frac{d}{dt}\mathrm{tr}\left\{\left|\rho_1(t)-\rho_2(t)\right|\right\}$$

Markovian dynamics

Negative

Heinz-Peter Breuer, Phys. Rev. Lett. **103**, 210401 (2009)

Non-Markovian speed-up ??

"The quantum speed-up in an open quantum system was attributed to the non-Markovian nature of the environment"

S. Deffner, Phys. Rev. Lett. **111**, 010402 (2013)

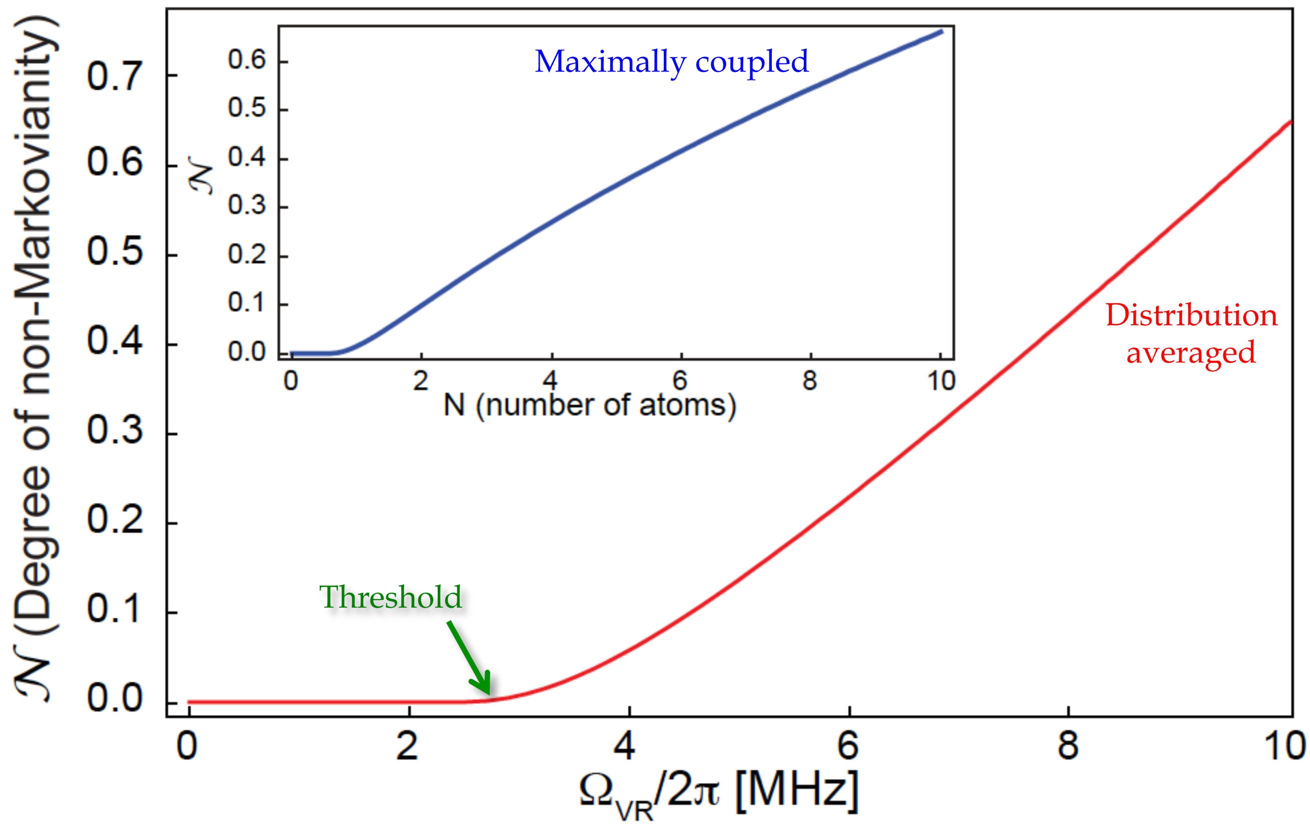
Non-Markovianity

$$N = finite$$

$$\sigma[t, \rho_{1,2}(0)] = \frac{1}{2}\frac{d}{dt}\mathrm{tr}\left\{\left|\rho_1(t) - \rho_2(t)\right|\right\}$$

Non-Markovian dynamics Positive

Heinz-Peter Breuer, Phys. Rev. Lett. **103**, 210401 (2009)



Maximally coupled
$\mathcal{N}$
N (number of atoms)
Distribution averaged
Threshold
$\mathcal{N}$ (Degree of non-Markovianity)
$\Omega_{VR}/2\pi$ [MHz]

summary

- Demonstrated the theoretically predicted environment-assisted speed-up

- Cavity field as a system, tunable environment;
  they realized a fully accessible quantum system obeying non-Markovian dynamics

- Environment engineering for optimal quantum control protocols

Q & A

Supplementary

D2-line of 85-Rb