Periodically driven array of single Rydberg Atoms

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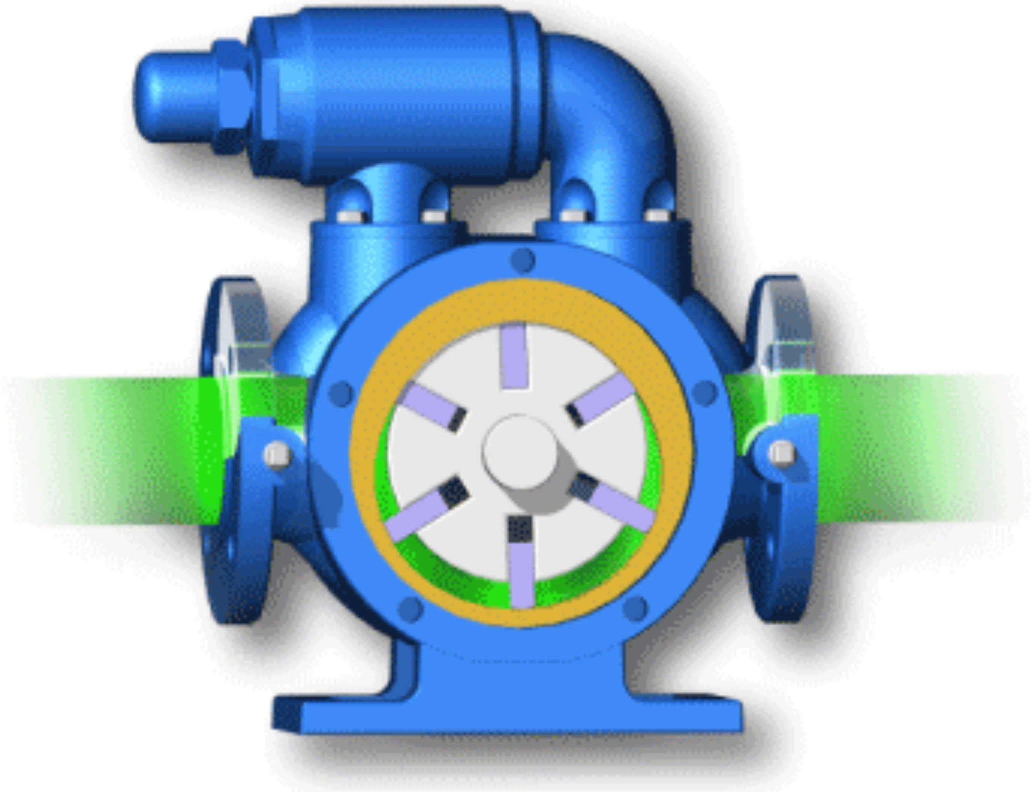
19th July 2017, ICTS Bangalore

Driven (periodically) systems

Transport

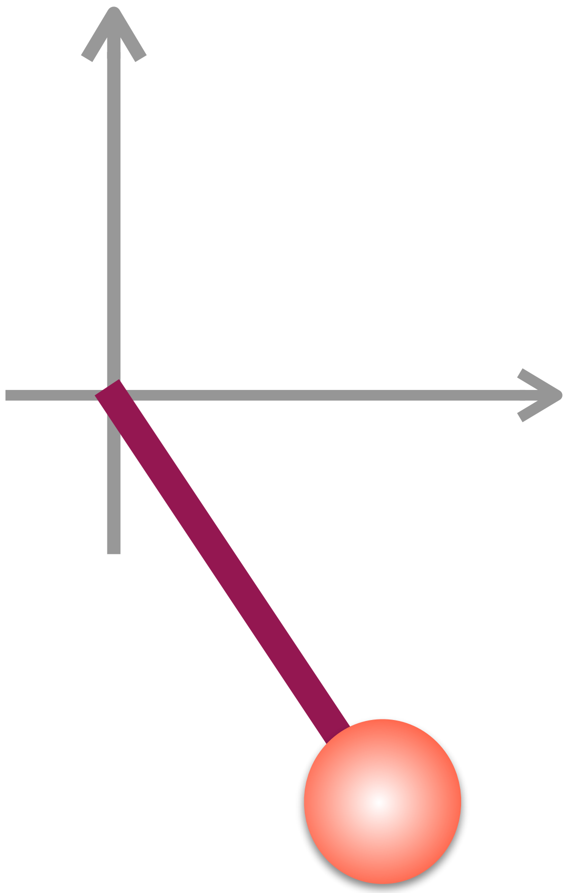
faster …..

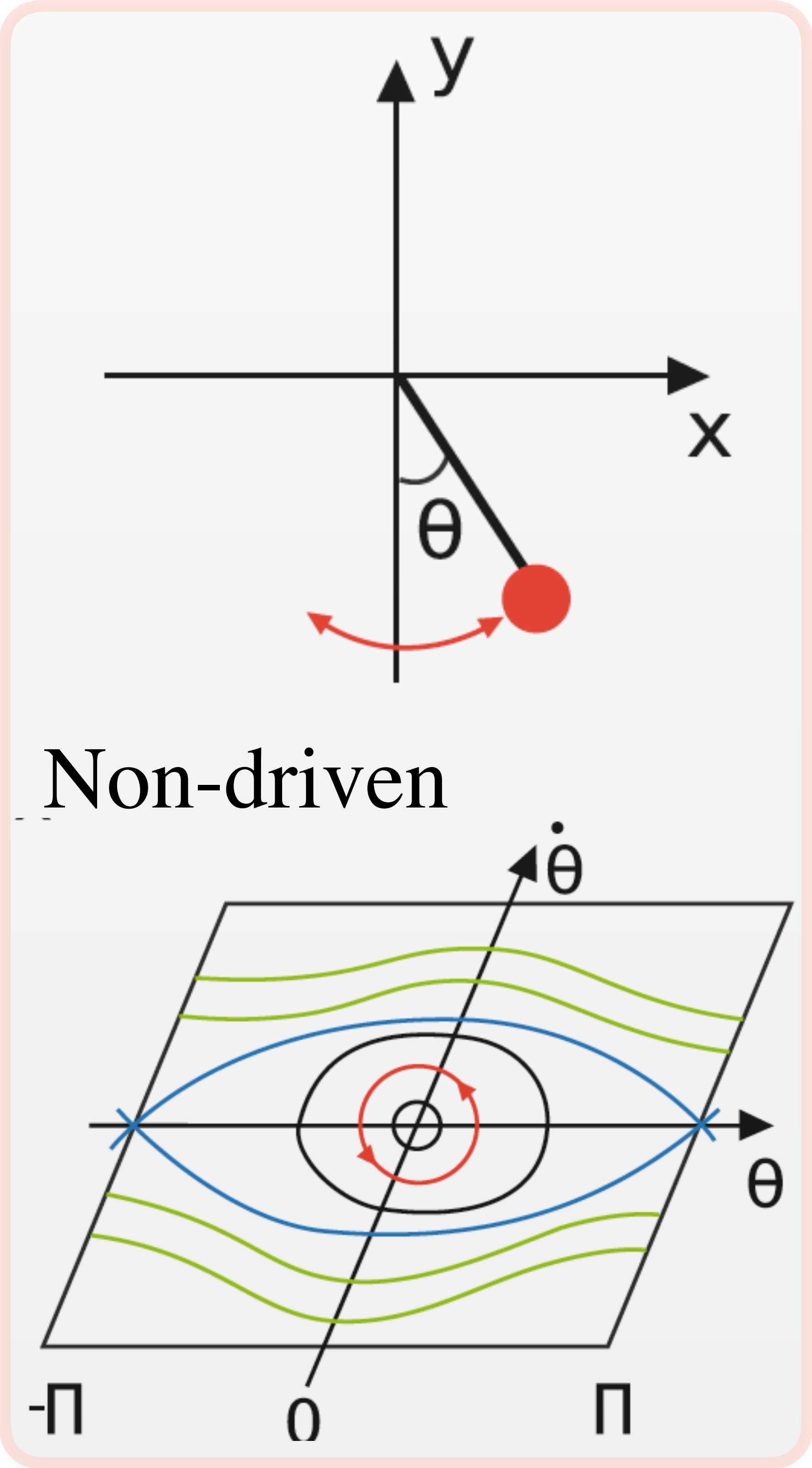


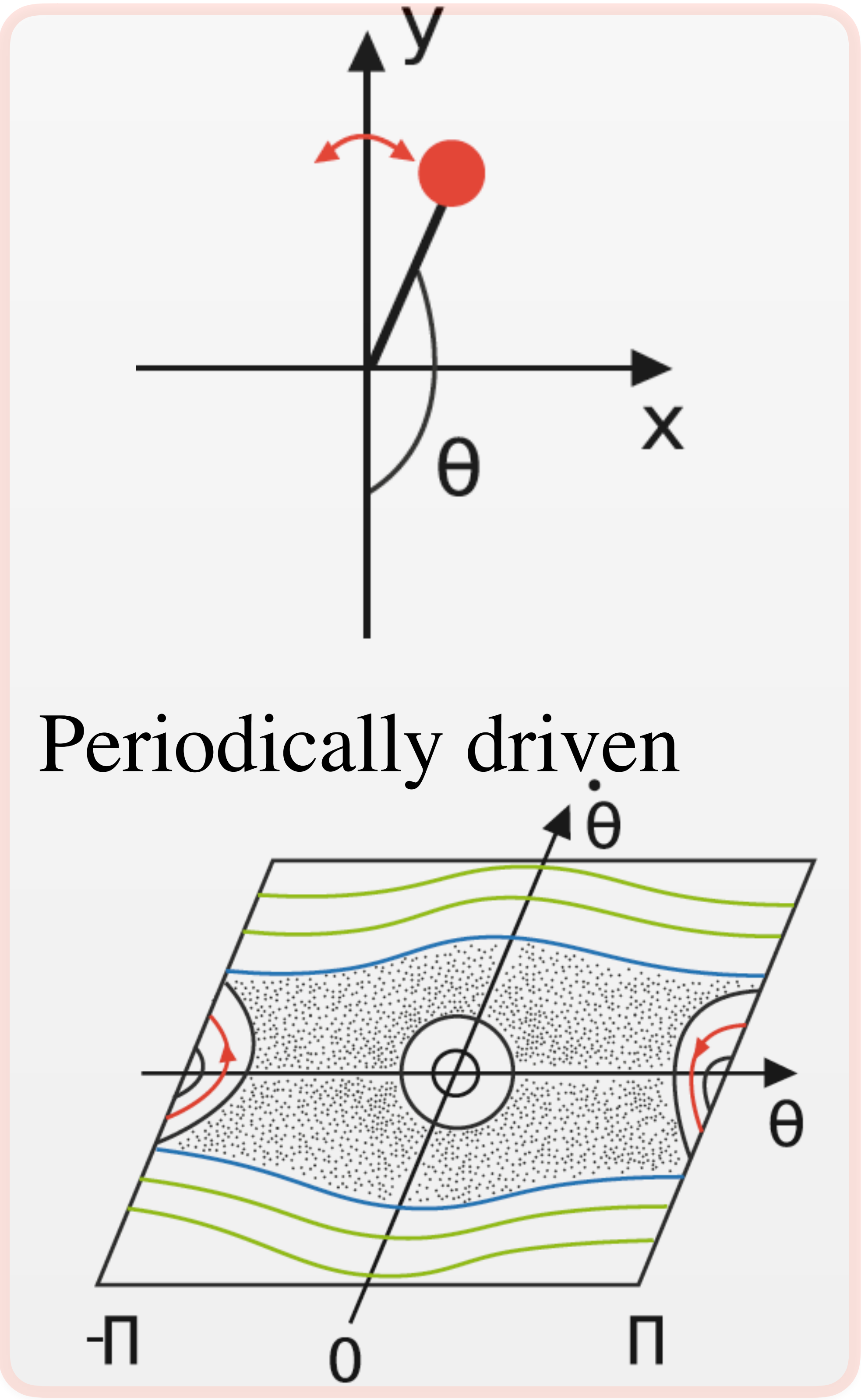
- It may also slow down ….
- Interesting classical and quantum dynamics.

We can transport matter
from one place to another.

Kapitza Pendulum



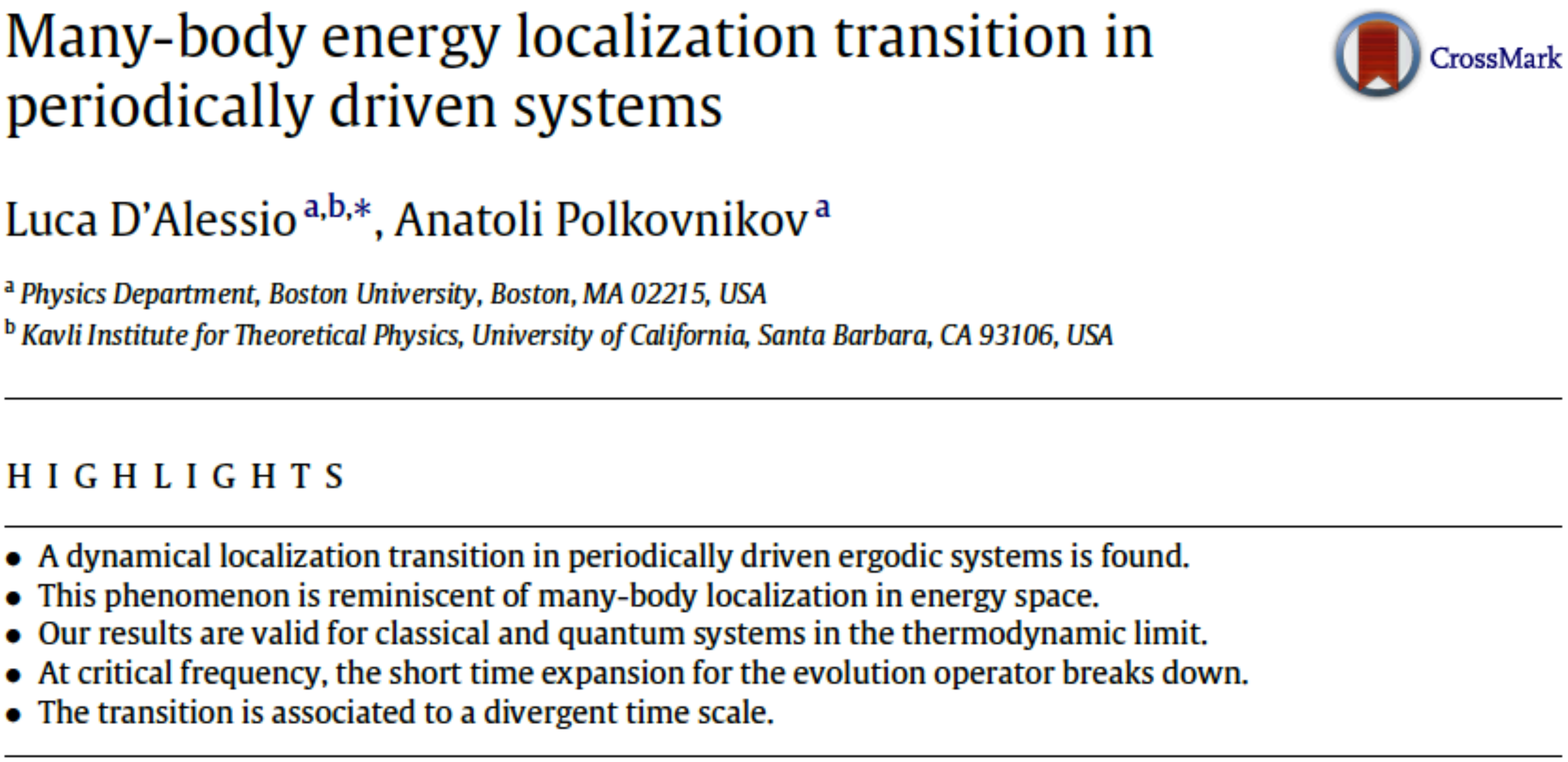




L. D'Alessio, A. Polkovnikov / Annals of Physics 333 (2013) 19–33

Dynamical stabilization

Periodically driven systems: some interesting results



Many-body energy localization transition in periodically driven systems

Luca D'Alessio [a,b,*], Anatoli Polkovnikov [a]

[a] *Physics Department, Boston University, Boston, MA 02215, USA*
[b] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA*

HIGHLIGHTS

- A dynamical localization transition in periodically driven ergodic systems is found.
- This phenomenon is reminiscent of many-body localization in energy space.
- Our results are valid for classical and quantum systems in the thermodynamic limit.
- At critical frequency, the short time expansion for the evolution operator breaks down.
- The transition is associated to a divergent time scale.

(periodically driving a system past a LZ transition)

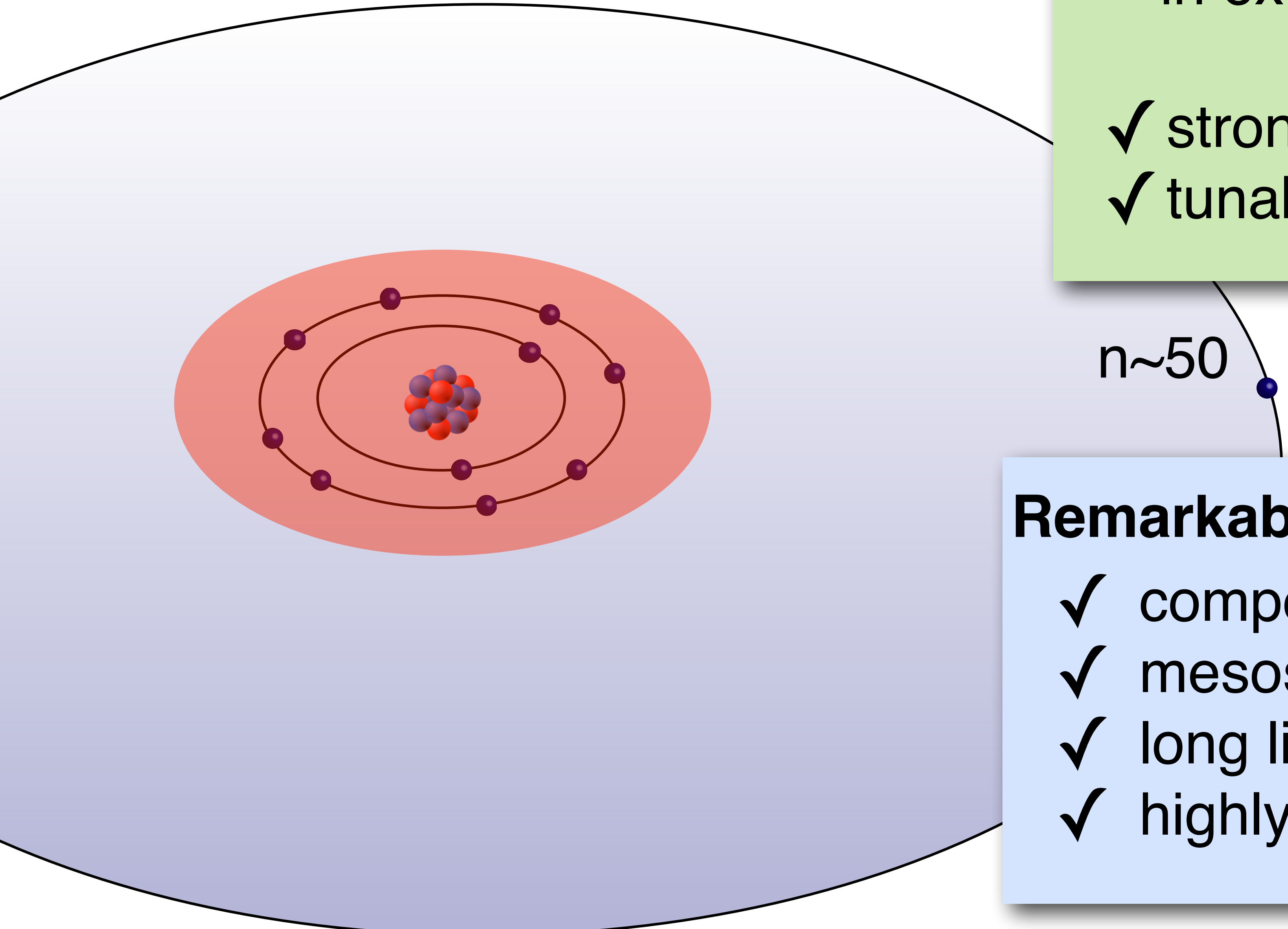
Driven quantum spin systems

In general a platform to study non-equilibrium physics.

[1] S. Kohler, J. Lehmann, and P. Hänggi, Phys. Rep. **406**, 379 (2005); M. P. Silveri, J. A. Tuorila, E. V. Thuneberg, and G. S. Paraoanu, Rep. Prog. Phys. **80**, 056002 (2017); M. Grifoni and P. Hänggi, Phys. Rep. **304**, 229 (1998).
[2] S. Shevchenko, S. Ashhab, and F. Nori, Phys. Rep. **492**, 1 (2010).

Rydberg atoms …

Rydberg atoms: short overview



Interactions:

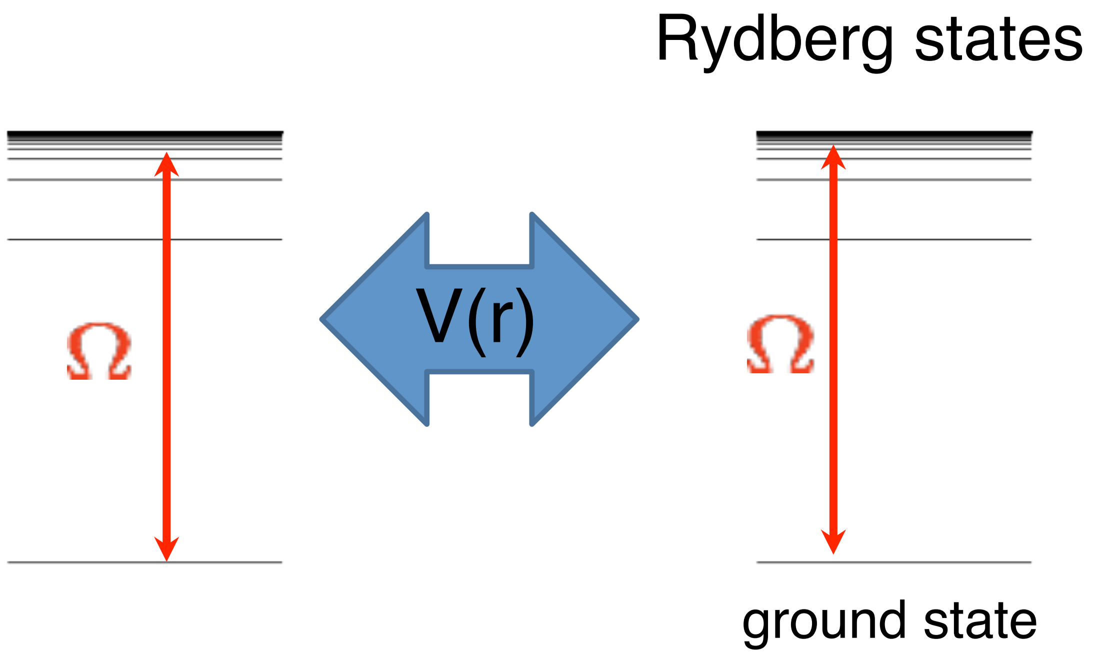
- without external fields: $V_{vdw} \sim \dfrac{n^{11}}{r^6}$
- in external fields: $V_{dip} \sim \dfrac{n^4}{r^3}$

✓ strong long-range interactions
✓ tunable and state-dependent

Remarkable properties:

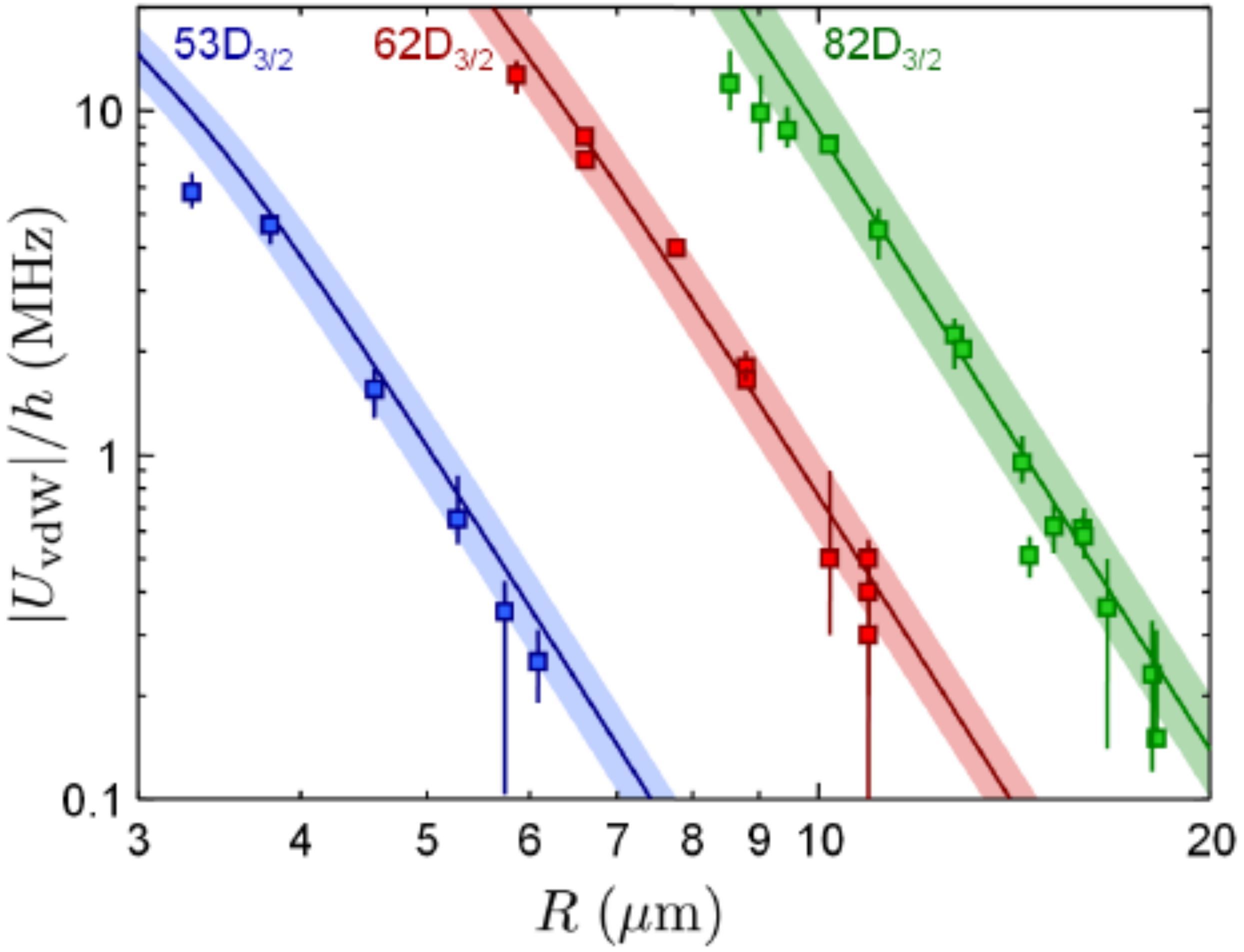
✓ composite object: single electron + cor
✓ mesoscopic object: $\langle r \rangle \sim a_0 n^2 \sim \mu\mathrm{m}$
✓ long lifetime: $\tau \sim n^3 \sim \mathrm{ms}$
✓ highly susceptible to external fields

Rydberg atoms: short overview



Rydberg states

ground state



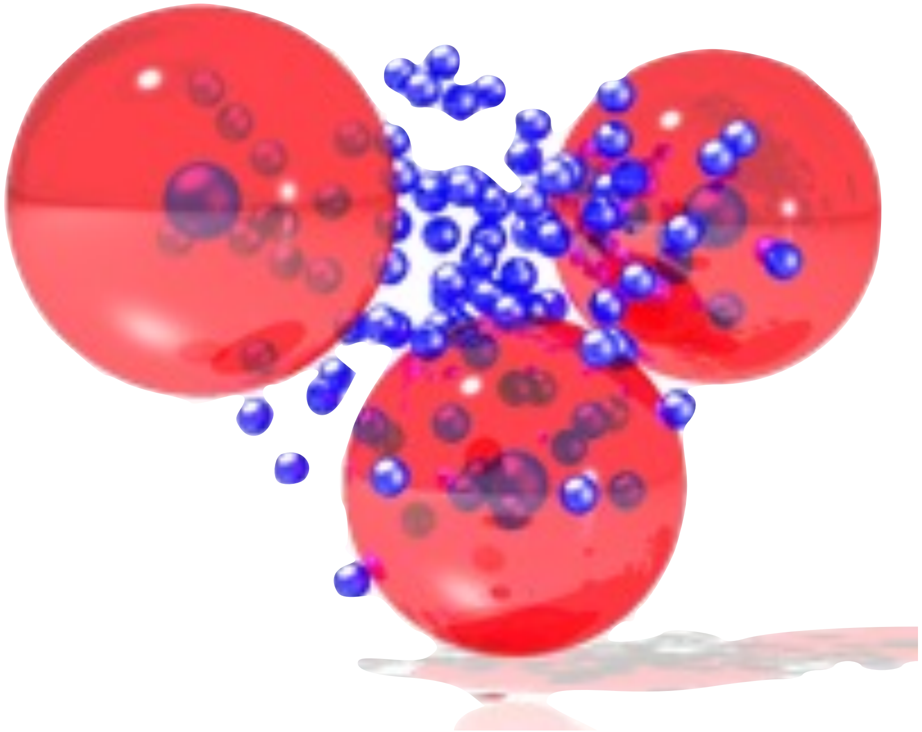
Direct measurement of Van der Waals interaction

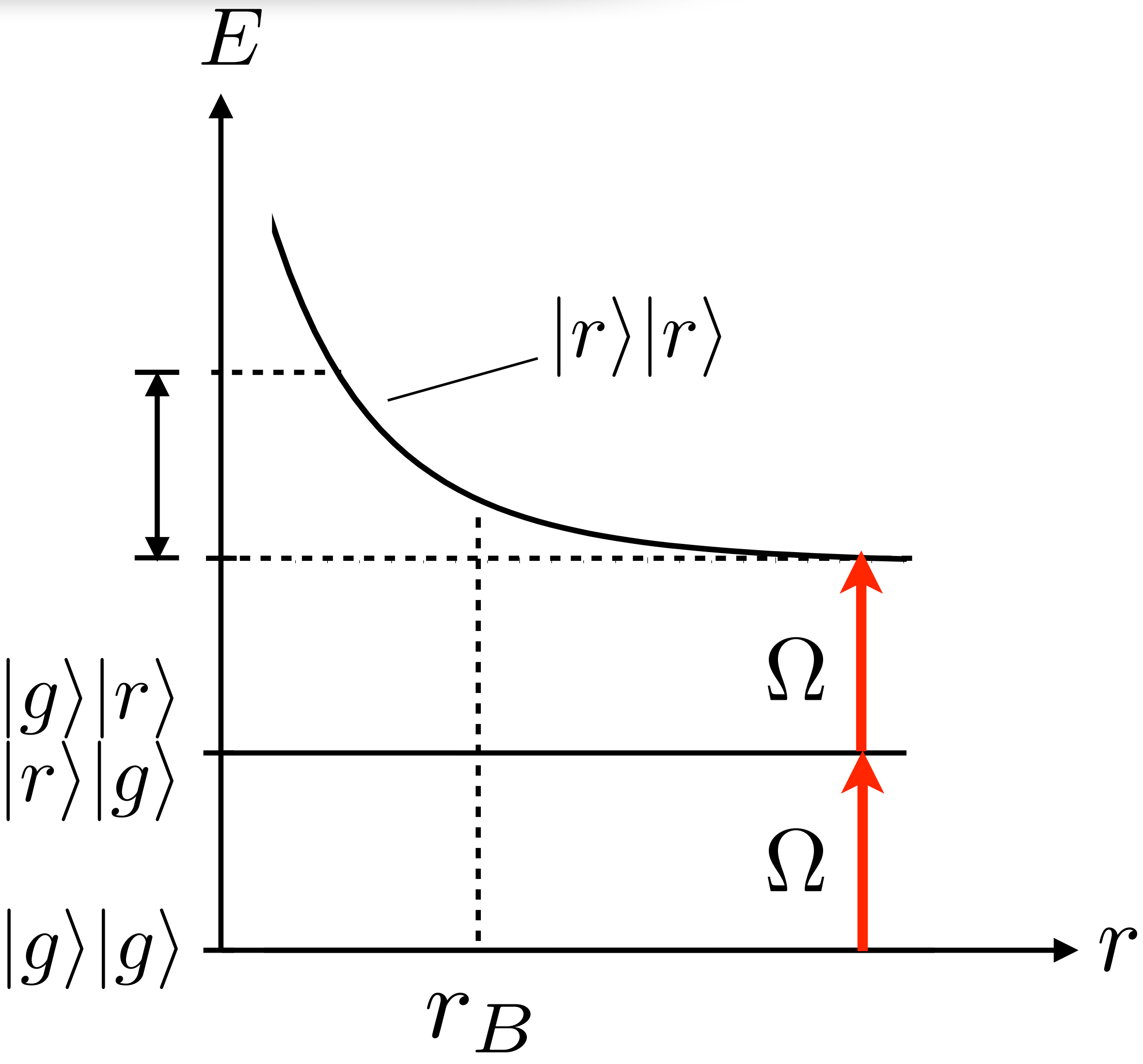
$$U_{\mathrm{vdW}}(R) = C_6/R^6$$

Phys. Rev. Lett. **110**, 263201 (201

Rydberg atoms: short overview

Blockade Effect

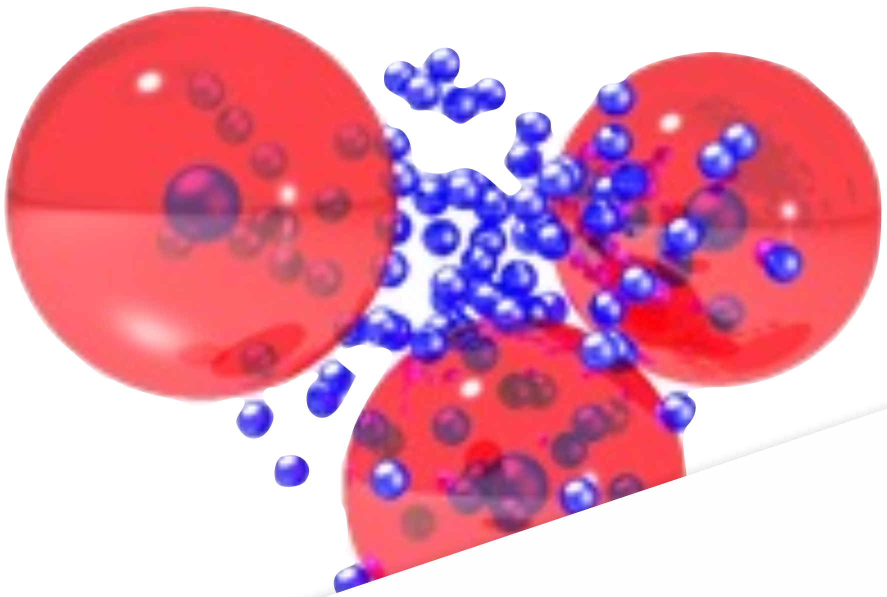


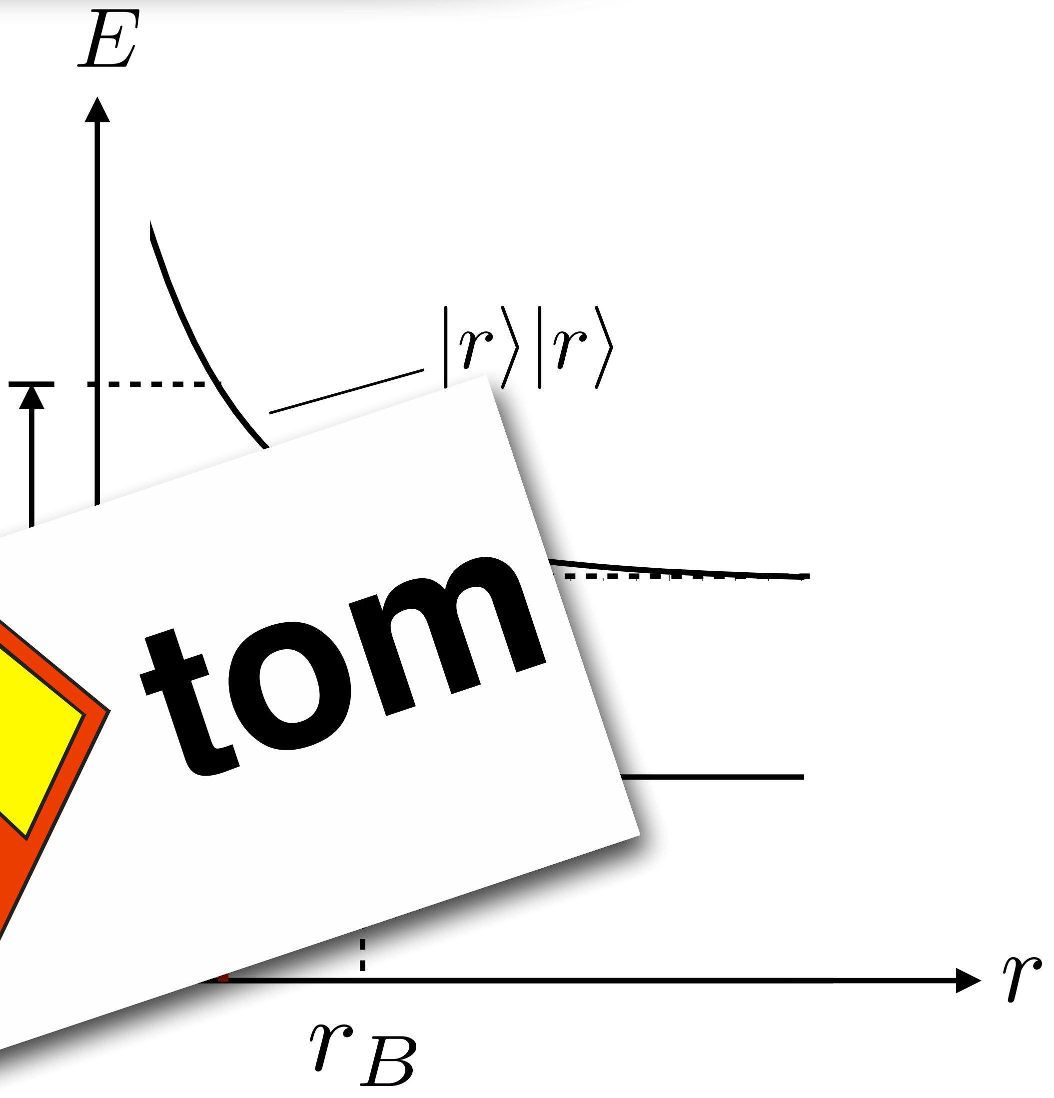


Rydberg atoms: short overview

Blockade Effect

$$V_{vdW}(r) \gg \hbar\Omega$$





SuperAtom

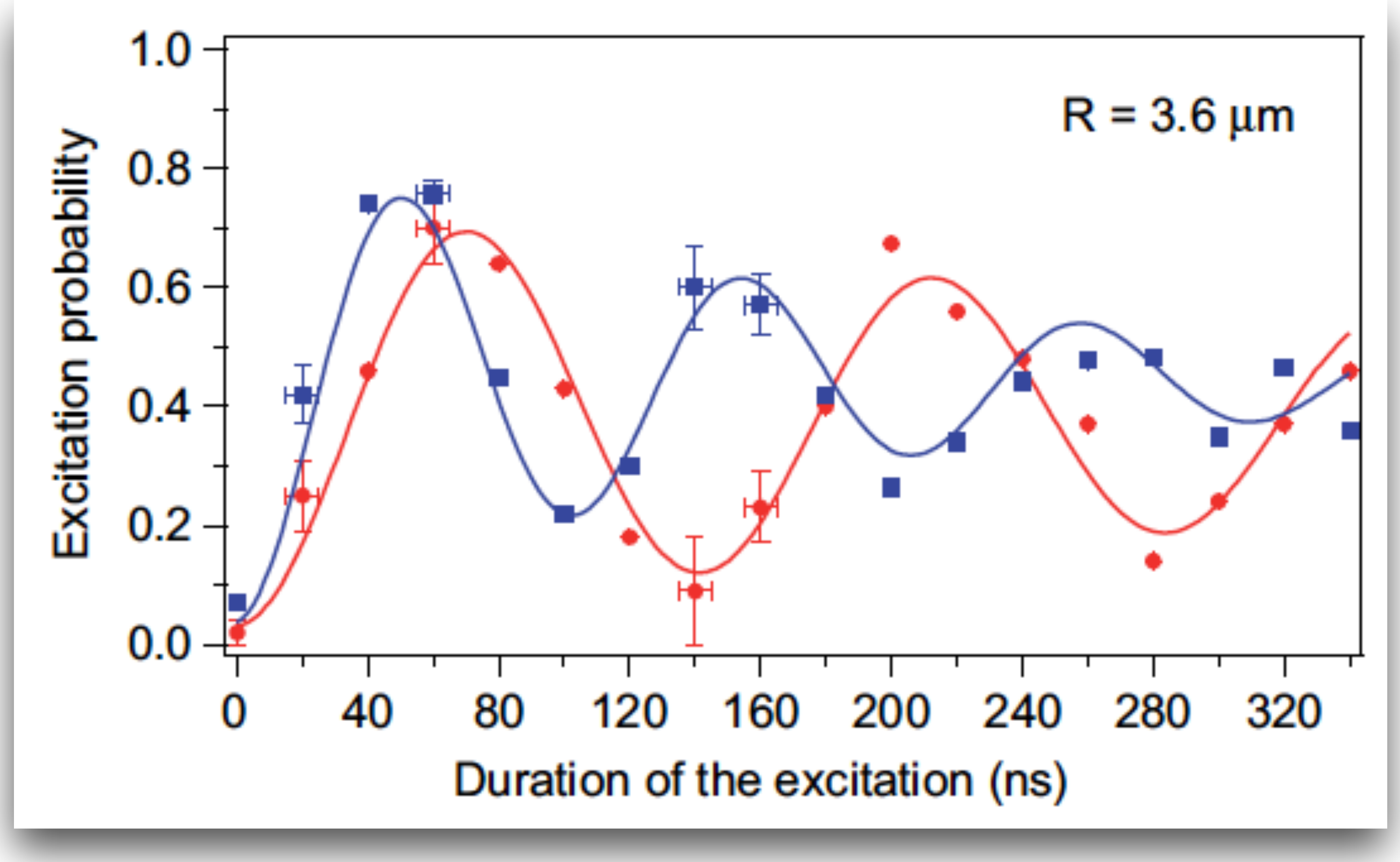
Coherent [illegible] oscillations between $|G\rangle = \otimes_{i=1}^{N} |g^{(i)}\rangle$

and $|+\rangle = \sum_i |gg...e^{(i)}...gg\rangle / \sqrt{N}$

Rydberg atoms: short overview

Coherent Rabi oscillations between $|G\rangle = \otimes_{i=1}^{N} |g^{(i)}\rangle$

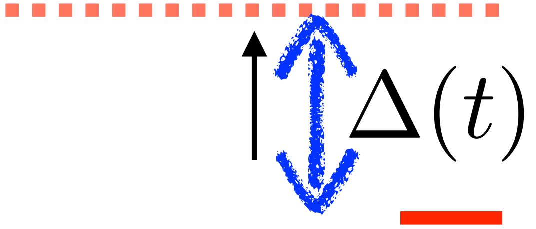
and $|+\rangle = \sum_i |gg...e^{(i)}...gg\rangle / \sqrt{N}$

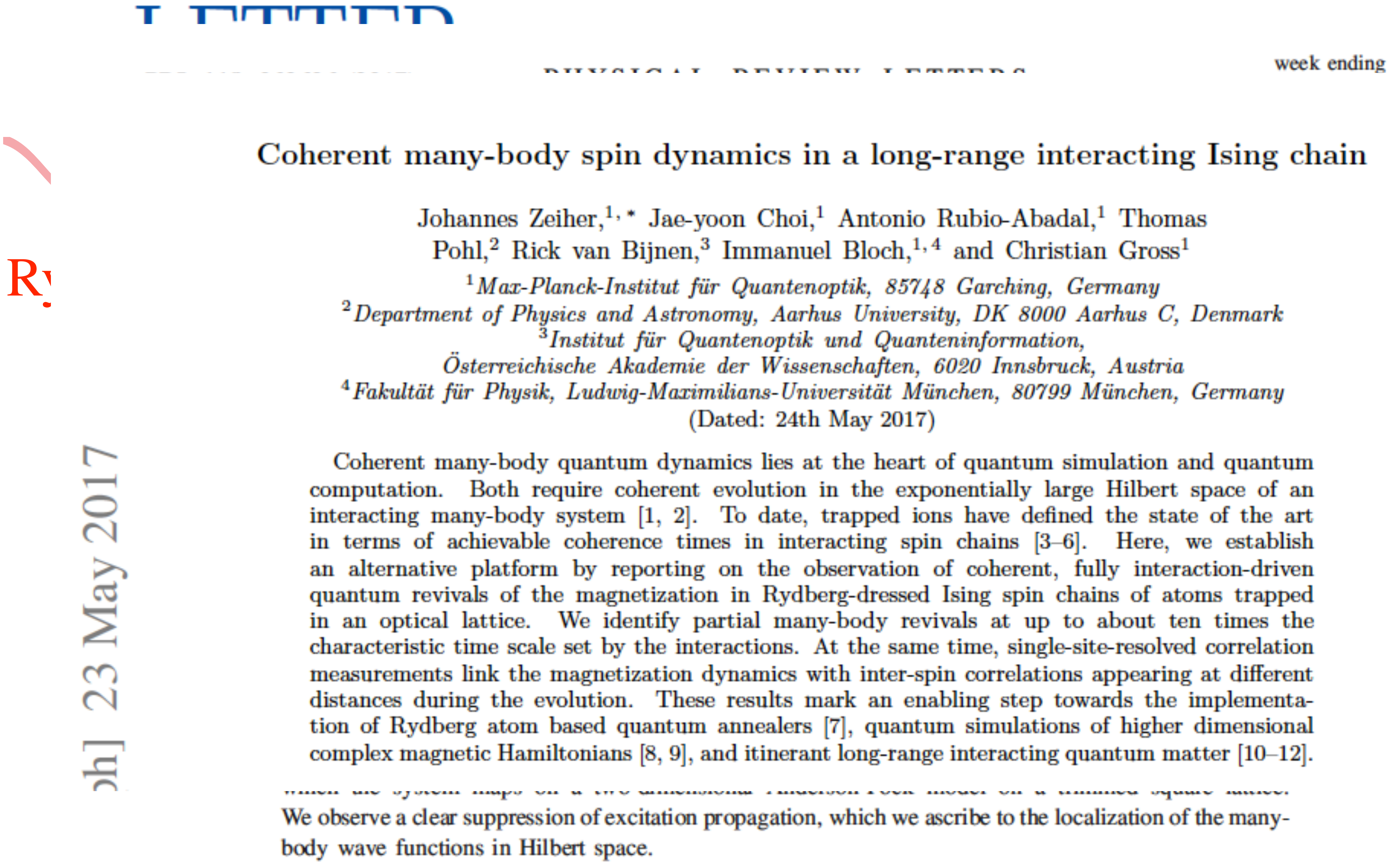


Enhancement of Rabi frequency due to the Rydberg blockade

Nature Phys. 5, 115 (2009)

Our setup





week ending

ph] 23 May 2017

Coherent many-body spin dynamics in a long-range interacting Ising chain

Johannes Zeiher,[1,*] Jae-yoon Choi,[1] Antonio Rubio-Abadal,[1] Thomas Pohl,[2] Rick van Bijnen,[3] Immanuel Bloch,[1,4] and Christian Gross[1]

[1] *Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany*
[2] *Department of Physics and Astronomy, Aarhus University, DK 8000 Aarhus C, Denmark*
[3] *Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*
[4] *Fakultät für Physik, Ludwig-Maximilians-Universität München, 80799 München, Germany*

(Dated: 24th May 2017)

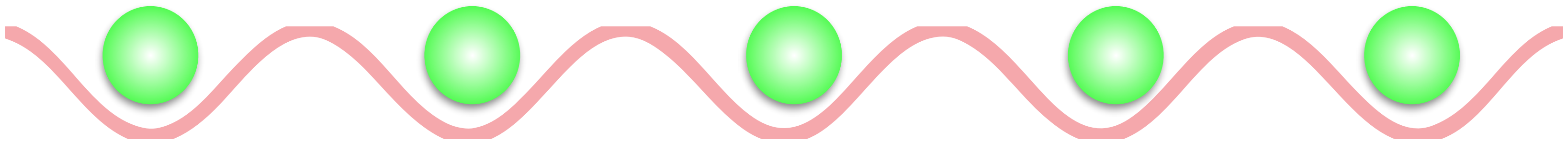
Coherent many-body quantum dynamics lies at the heart of quantum simulation and quantum computation. Both require coherent evolution in the exponentially large Hilbert space of an interacting many-body system [1, 2]. To date, trapped ions have defined the state of the art in terms of achievable coherence times in interacting spin chains [3–6]. Here, we establish an alternative platform by reporting on the observation of coherent, fully interaction-driven quantum revivals of the magnetization in Rydberg-dressed Ising spin chains of atoms trapped in an optical lattice. We identify partial many-body revivals at up to about ten times the characteristic time scale set by the interactions. At the same time, single-site-resolved correlation measurements link the magnetization dynamics with inter-spin correlations appearing at different distances during the evolution. These results mark an enabling step towards the implementation of Rydberg atom based quantum annealers [7], quantum simulations of higher dimensional complex magnetic Hamiltonians [8, 9], and itinerant long-range interacting quantum matter [10–12].

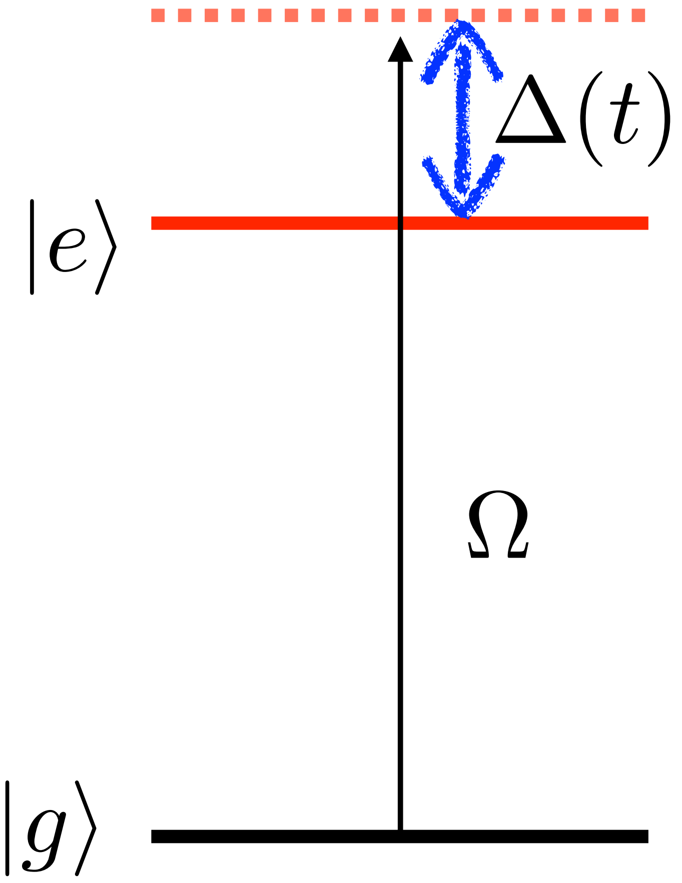
We observe a clear suppression of excitation propagation, which we ascribe to the localization of the many-body wave functions in Hilbert space.

Our setup

arXiv: 1707.01956

$$\Delta(t) = \Delta_0 + \delta\cos(\omega_0 t)$$



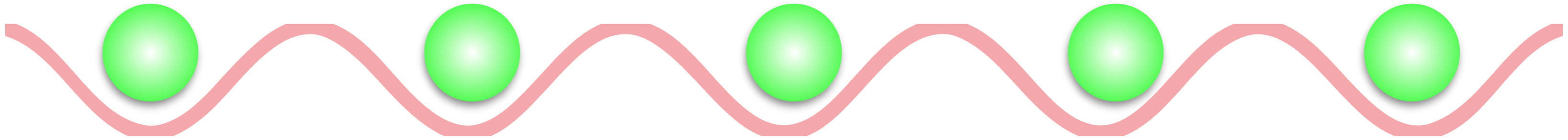


$$\hat{H} = -\hbar\Delta(t)\sum_{i=1}^{N}\hat{\sigma}^{i}_{ee} + \frac{\hbar\Omega}{2}\sum_{i=1}^{N}(\hat{\sigma}^{i}_{eg} + \hat{\sigma}^{i}_{ge}) + \sum_{i<j} V(r_{ij})\hat{\sigma}^{i}_{ee}\hat{\sigma}^{j}_{ee}$$

Our setup

arXiv: 1707.01956

$$\Delta(t) = \Delta_0 + \delta\cos(\omega_0 t)$$



$$\hat{H} = -\hbar\Delta(t)\sum_{i=1}^{N}\hat{\sigma}^i_{ee} + \frac{\hbar\Omega}{2}\sum_{i=1}^{N}(\hat{\sigma}^i_{eg} + \hat{\sigma}^i_{ge}) + \sum_{i<j} V(r_{ij})\hat{\sigma}^i_{ee}\hat{\sigma}^j_{ee}$$

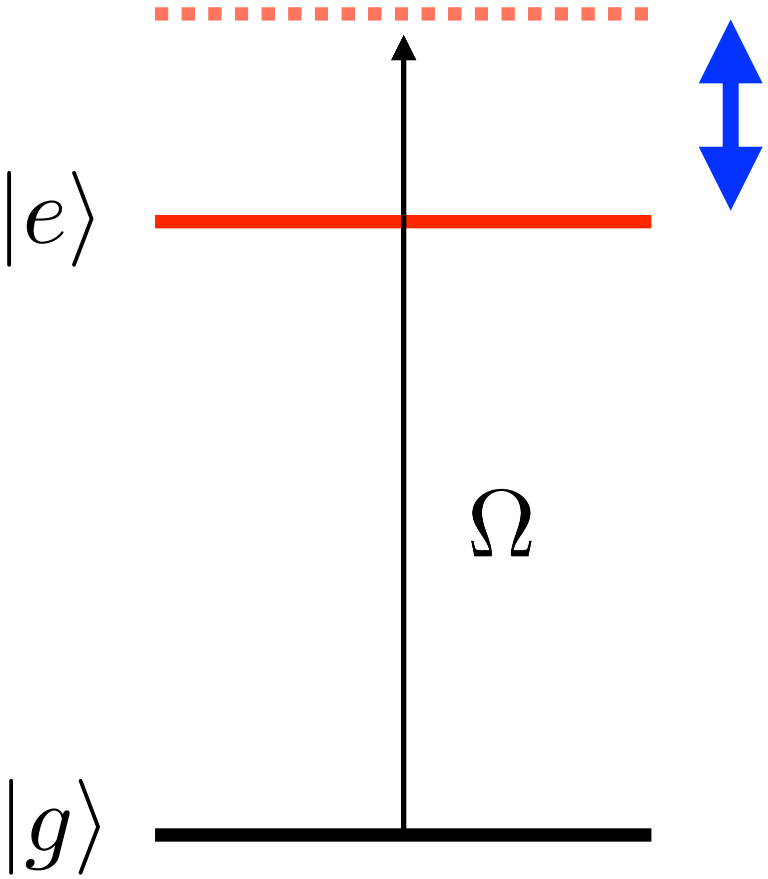
In a rotating frame:

$$\hat{H}' = \boxed{\frac{\hbar\Omega}{2}\sum_{i=1}^{N}\sum_{m=-\infty}^{\infty} J_m(\delta/\omega_0)\left(e^{i[(m\omega_0-\Delta_0)t+\pi/2]}\hat{\sigma}^i_{eg} + h.c.\right)} + \sum_{i<j} V(r_{ij})\hat{\sigma}^i_{ee}\hat{\sigma}^j_{ee},$$

Engineering the Rabi couplings by modulating the detuning.

Single driven atom: different regimes

We consider an atom in a frequency modulated light field



time-dependent detuning

$$\Delta(t) = \Delta_0 + \delta\cos(\omega_0 t)$$

$$\hat{H} = -\Delta(t)\sigma_{ee} + \frac{\Omega}{2}\sigma_x$$

What really happens depend on the amplitude and frequency of modulation.

Single driven atom: different regimes

$$\Delta(t) = \Delta_0 + \delta\cos(\omega_0 t)$$

$\delta, \omega_0 \ll \Omega$ adiabatic regime.

$$\delta \ll \Omega_{eff} = \sqrt{\Delta_0^2 + \Omega^2}$$

Weak driving or
Rabi limit

Resonance: $\omega_0 = \Omega_{eff}$

Energy separation between the
eigen-states of the un-driven Hamiltonian

Single driven atom: different regimes

$$\Delta(t) = \Delta_0 + \delta \cos(\omega_0 t)$$

$\omega_0 \gg \Omega$ High-frequency limit

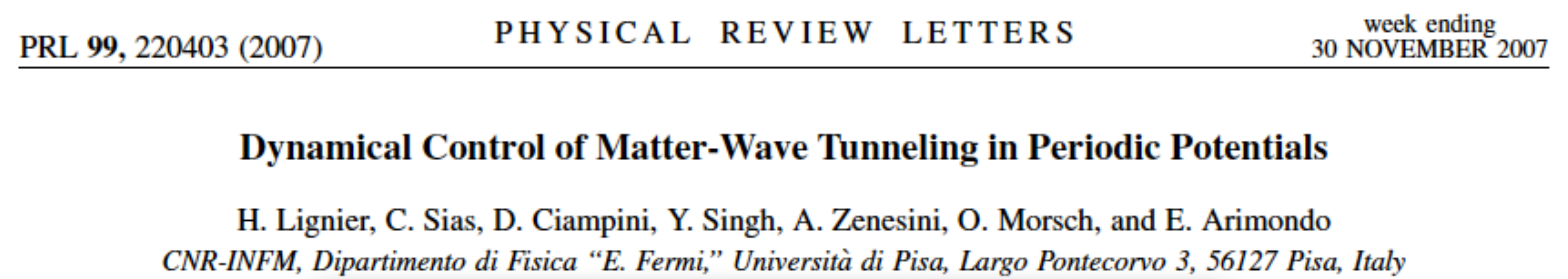
$$\hat{H}' = \frac{\hbar\Omega}{2} \sum_{m=-\infty}^{\infty} J_m(\delta/\omega_0)\left(e^{i[(m\omega_0-\Delta_0)t+\pi/2]}\hat{\sigma}^i_{eg} + h.c.\right)$$

the only term which survives: $m\omega_0 = \Delta_0$

Rabi oscillations with a frequency

$$\Omega' = \Omega J_n(\delta/\omega_0)$$

Single driven atom: different regimes



PRL **99,** 220403 (2007)
PHYSICAL REVIEW LETTERS
week ending
30 NOVEMBER 2007

Dynamical Control of Matter-Wave Tunneling in Periodic Potentials

H. Lignier, C. Sias, D. Ciampini, Y. Singh, A. Zenesini, O. Morsch, and E. Arimondo
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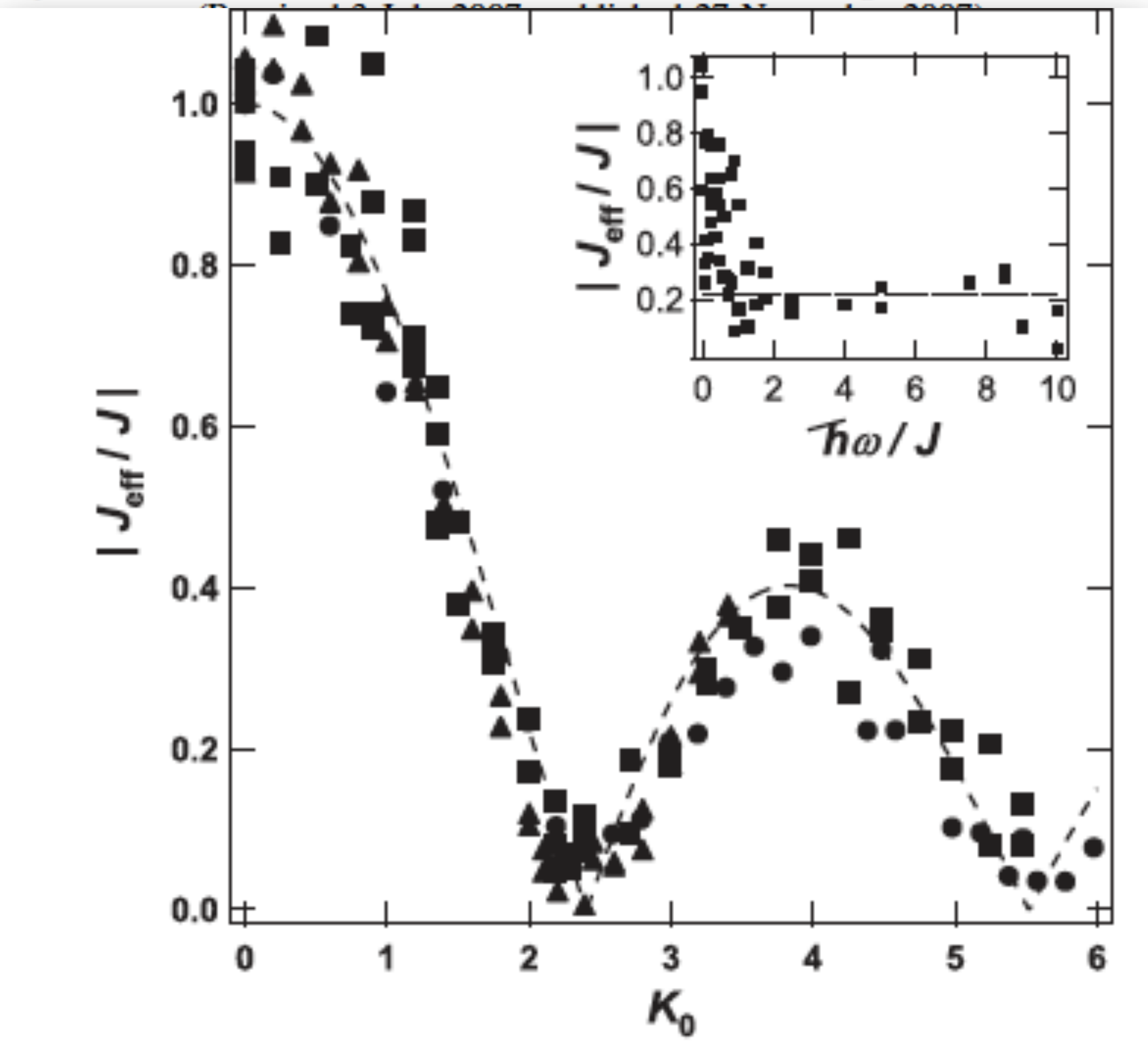
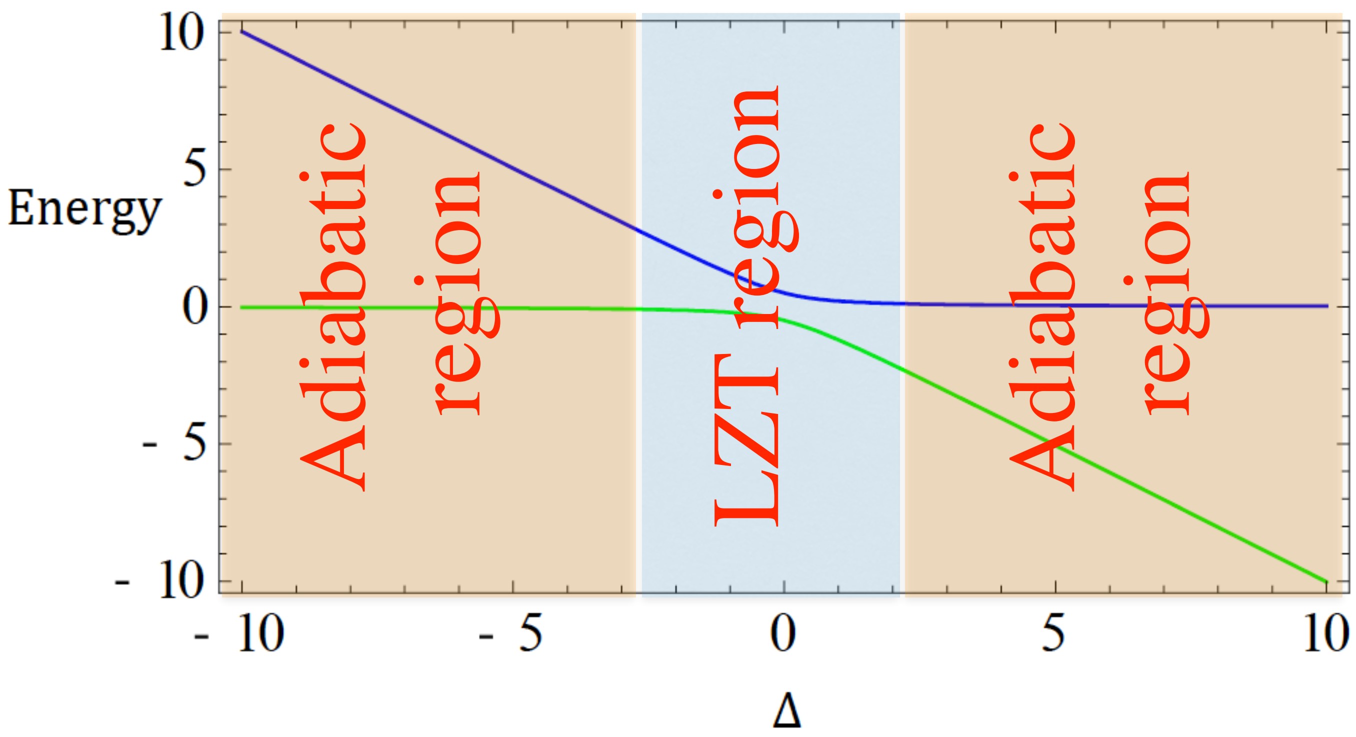


(ident

Single driven atom: Fast passage limit (FPL)

$$\hat{H} = -\Delta(t)\sigma_{ee} + \frac{\Omega}{2}\sigma_x$$



$$H(t\ ) = \frac{\Omega}{2}\sigma_x - vt\ \sigma_{ee}$$

$$v \sim \omega_0\sqrt{\delta^2 - \Delta_0^2}$$

Resonance condition

$$n\omega_0 = \Delta_0$$

$$\omega_0\sqrt{\delta^2 - \Delta_0^2} \gg \Omega^2 \text{ with } \delta - \Delta_0 \gg \Omega$$

For sufficiently large value of δ, FPL overlaps with HFL.

Single driven atom

$$\delta \ll \Omega_{eff} = \sqrt{\Delta_0^2 + \Omega^2}$$

Weak driving or
Rabi limit

Resonance: $\omega_0 = \Omega_{eff}$

$$\omega_0 \gg \Omega$$

High-frequency
limit

Resonance condition

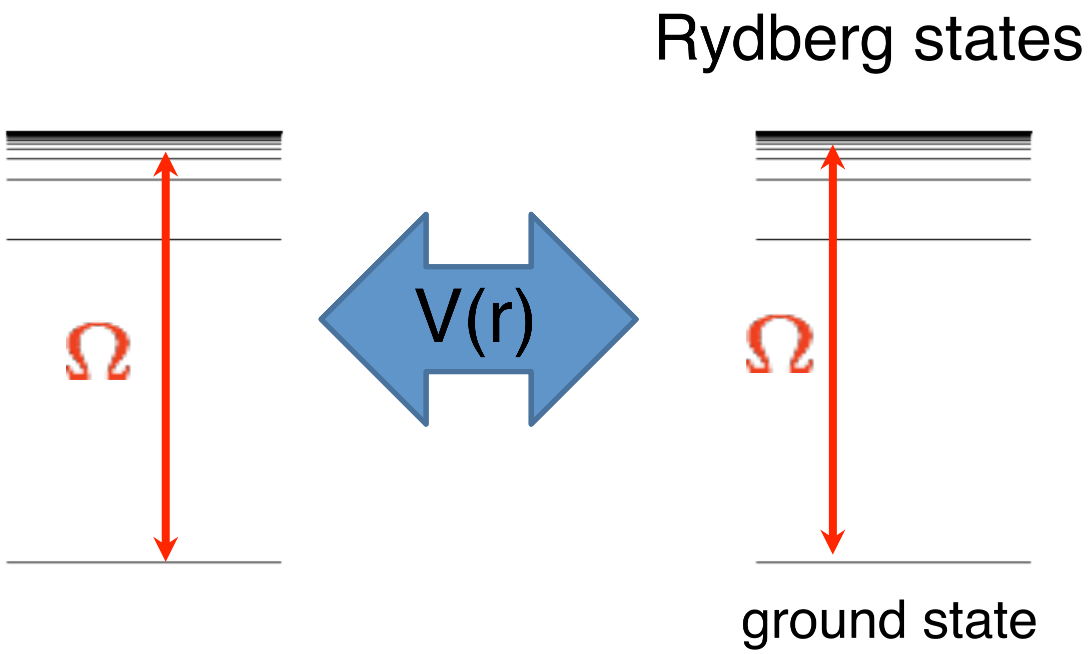
$$n\omega_0 = \Delta_0$$

$$\omega_0 \sqrt{\delta^2 - \Delta_0^2} \gg \Omega^2 \text{ with } \delta - \Delta_0 \gg \Omega$$

Fast-Passage
limit

Now we take two atoms ….

Two atoms



We consider two kinds of resonant transitions

$$|gg\rangle \leftrightarrow |+\rangle = (|eg\rangle + |ge\rangle)/\sqrt{2} \quad (S\text{-Resonance})$$

$$|gg\rangle \leftrightarrow |ee\rangle \quad (D\text{-Resonance})$$

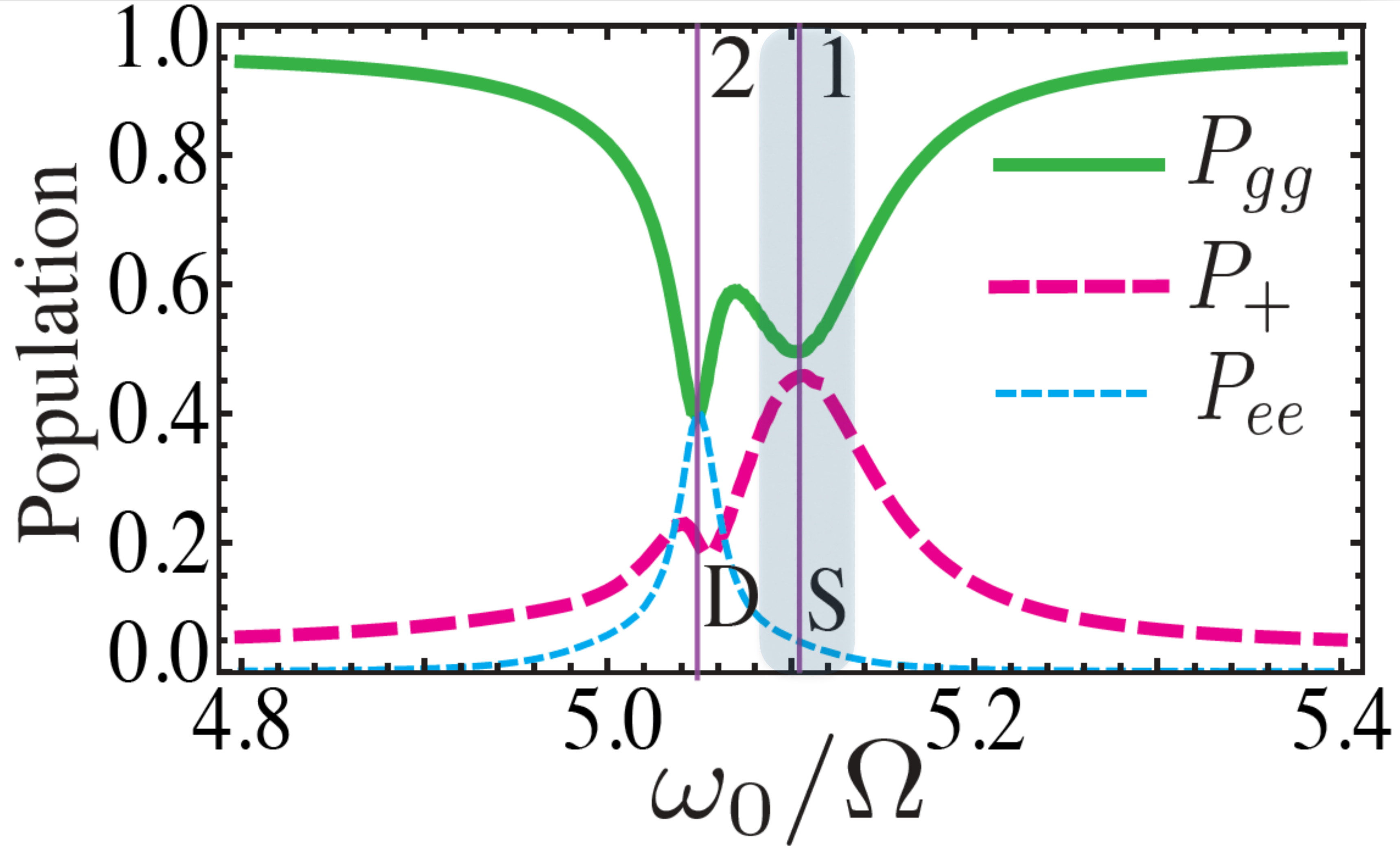
Two atoms: Weak driving limit

$$\delta \ll \Omega_{eff} = \sqrt{\Delta_0^2 + \Omega^2}$$

Weak driving or
Rabi limit

Resonance: $\omega_0 = \Omega_{eff}$

$$P_\alpha = (1/T)\int_0^T |\langle\alpha|\psi(t)\rangle|^2 dt \qquad \alpha \in \{|gg\rangle, |ee\rangle, |+\rangle\}$$

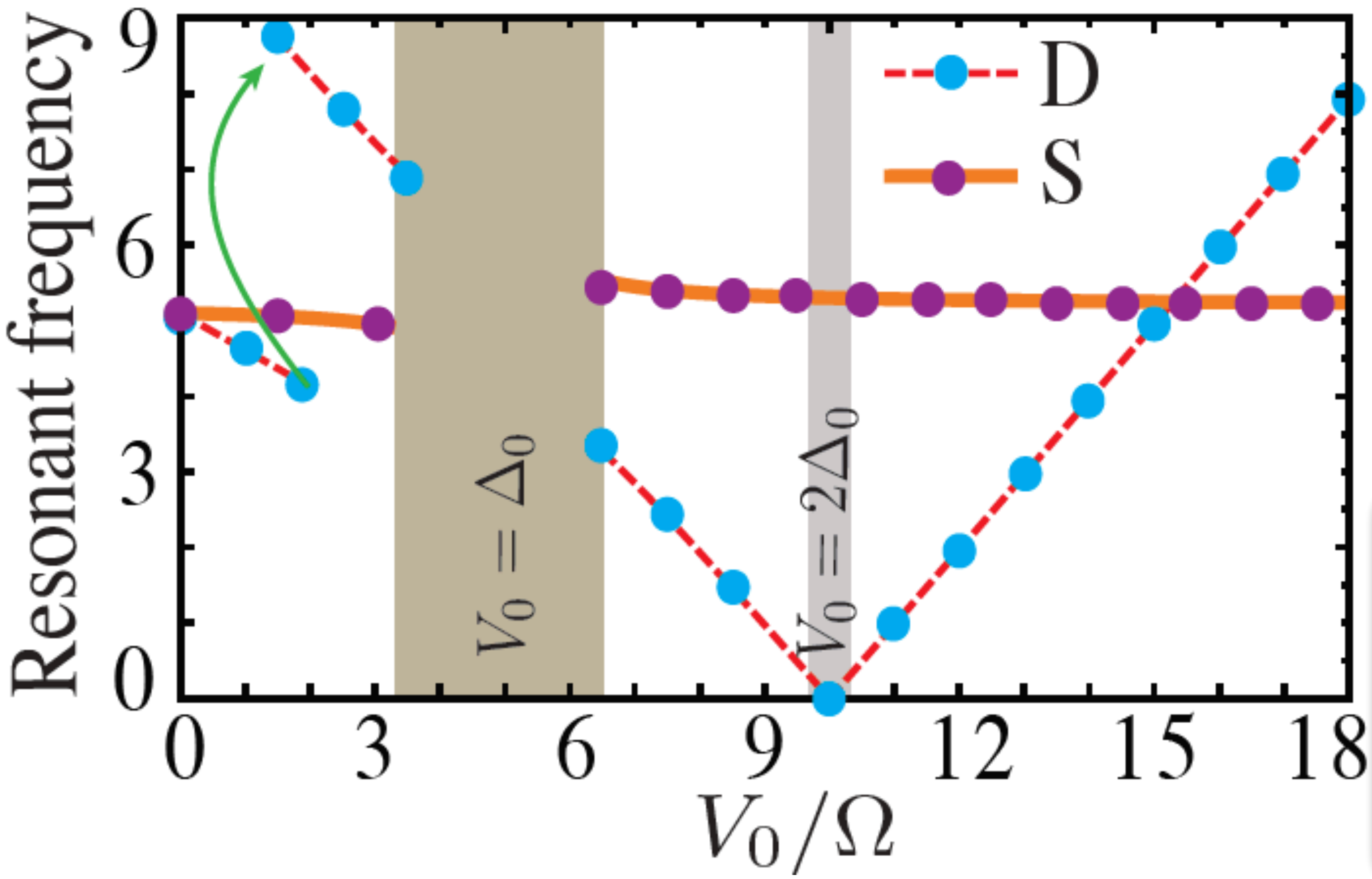


Resonances are seen as dips/peaks in the population vs ω_0

Blockade enhancement!!!

$\delta = 0.4\Omega$, $\Delta_0 = 5\Omega$, $V_0 = 0.1\Omega$

Two atoms: Weak driving limit



$$V_0 \ll \Omega_{eff}$$

S-Resonance

$$\boxed{\omega_0 = \omega_S = \Omega_{eff}}$$

D-Resonance

$$\omega_0 = \omega_D = \sqrt{\Omega^2 + (\Delta_0')^2}$$

$$\Delta_0' = \Delta_0 - V_0/2$$

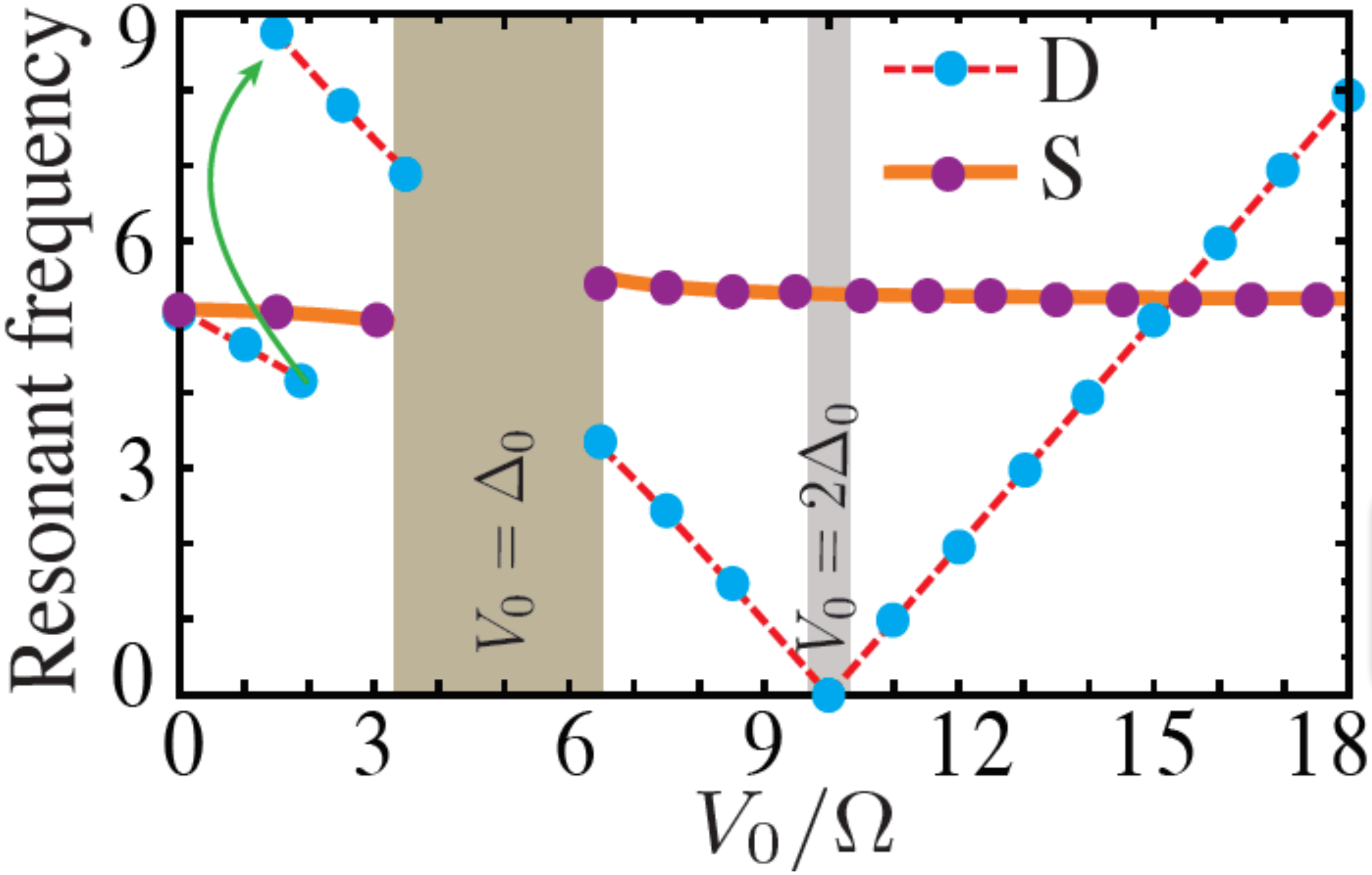
At large interactions:

$$\omega_S = |E_{gg} - E_+| \approx \Delta_0 + \frac{\Omega^2}{2}\left(\frac{2}{\Delta_0} - \frac{1}{\Delta_0 - V_0}\right) + O\left(\Omega^4\right)$$

$$\omega_D = |E_{gg} - E_{ee}| \approx |V_0 - 2\Delta_0 - \frac{\Omega^2}{2}\left(\frac{2}{\Delta_0} + \frac{1}{\Delta_0 - V_0}\right)$$

$$+\frac{\Omega^4}{4}\left(\frac{1}{\Delta_0^3} + \frac{1}{(\Delta_0 - V_0)^3}\right)|.$$

Two atoms: Weak driving limit



$$V_0 \ll \Omega_{eff}$$

S-Resonance

$$\boxed{\omega_0 = \omega_S = \Omega_{eff}}$$

D-Resonance

$$\boxed{\omega_0 = \omega_D = \sqrt{\Omega^2 + (\Delta_0')^2}}$$

$$\Delta_0' = \Delta_0 - V_0/2$$

For $V_0 \approx \Delta_0 : |+\rangle$ and $|ee\rangle$ are almost degenerate.

When $V_0 \simeq 2\Delta_0$, $|gg\rangle$ and $|ee\rangle$ are almost degenerate

Two atoms: High frequency limit

$\omega_0 \gg \Omega$ High-frequency limit

$$\hat{U}(t) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-i\left(\Delta_0 t - \frac{\delta}{\omega_0}\cos\omega_0 t\right)} & 0 \\ 0 & 0 & e^{-i\left(2\Delta_0 t - Vt - \frac{2\delta}{\omega_0}\cos\omega_0 t\right)} \end{bmatrix}$$

written in the basis $\{|gg\rangle, |+\rangle, |ee\rangle\}$

$$\tilde{\Omega} = \sqrt{2}\Omega$$

$$\Omega_1 = \tilde{\Omega} \sum_{n=-\infty}^{\infty} J_n(\delta/\omega_0) e^{i(n\omega_0 - \Delta_0)t - in\pi/2}$$

$|gg\rangle \leftrightarrow |+\rangle$

$$\Omega_2 = \tilde{\Omega} \sum_{n=-\infty}^{\infty} J_n(\delta/\omega_0) e^{i(n\omega_0 - \Delta_0 + V_0)t - in\pi/2}$$

$|+\rangle \leftrightarrow |ee\rangle$

Two atoms: High frequency limit

$$\Omega_1 = \tilde{\Omega} \sum_{n=-\infty}^{\infty} J_n(\delta/\omega_0) e^{i(n\omega_0 - \Delta_0)t - in\pi/2} \qquad |gg\rangle \leftrightarrow |+\rangle$$

$$\Omega_2 = \tilde{\Omega} \sum_{n=-\infty}^{\infty} J_n(\delta/\omega_0) e^{i(n\omega_0 - \Delta_0 + V_0)t - in\pi/2} \qquad |+\rangle \leftrightarrow |ee\rangle$$

$n_1\omega_0 = \Delta_0$ S-Resonance

$n_2\omega_0 = |\Delta_0 - V_0|$ $|+\rangle \leftrightarrow |ee\rangle$

If both resonance conditions are to be met simultaneously with any $V_0 \neq 0$, we need $n_1 \neq n_2$

Two atoms: High frequency limit

$$\Omega_1 = \tilde{\Omega} \sum_{n=-\infty}^{\infty} J_n(\delta/\omega_0) e^{i(n\omega_0 - \Delta_0)t - in\pi/2}$$

$$|gg\rangle \leftrightarrow |+\rangle$$

$$\Omega_2 = \tilde{\Omega} \sum_{n=-\infty}^{\infty} J_n(\delta/\omega_0) e^{i(n\omega_0 - \Delta_0 + V_0)t - in\pi/2}$$

$$|+\rangle \leftrightarrow |ee\rangle$$

$n_1\omega_0 = \Delta_0$ *S*-Resonance is satisfied

$$\Omega_1 \approx \tilde{\Omega} J_{n_1}(\delta/\omega_0) \qquad \Omega_2 \approx 0$$

$n_2\omega_0 = |\Delta_0 - V_0|$ is satisfied

$$\Omega_1 \approx 0 \qquad \Omega_2 \approx \tilde{\Omega} J_{n_2}(\delta/\omega_0)$$

Two atoms: High frequency limit

$$\Omega_1 = \tilde{\Omega} \sum_{n=-\infty}^{\infty} J_n(\delta/\omega_0) e^{i(n\omega_0 - \Delta_0)t - in\pi/2}$$

$|gg\rangle \leftrightarrow |+\rangle$

$$\Omega_2 = \tilde{\Omega} \sum_{n=-\infty}^{\infty} J_n(\delta/\omega_0) e^{i(n\omega_0 - \Delta_0 + V_0)t - in\pi/2}$$

$|+\rangle \leftrightarrow |ee\rangle$

$n_1\omega_0 = \Delta_0$ $\quad$ $n_2\omega_0 = |\Delta_0 - V_0|$ are satisfied

$\Omega_1 \approx \tilde{\Omega} J_{n_1}(\delta/\omega_0)$ $\quad$ $\Omega_2 \approx \tilde{\Omega} J_{n_2}(\delta/\omega_0)$

δ is the only free parameter then.

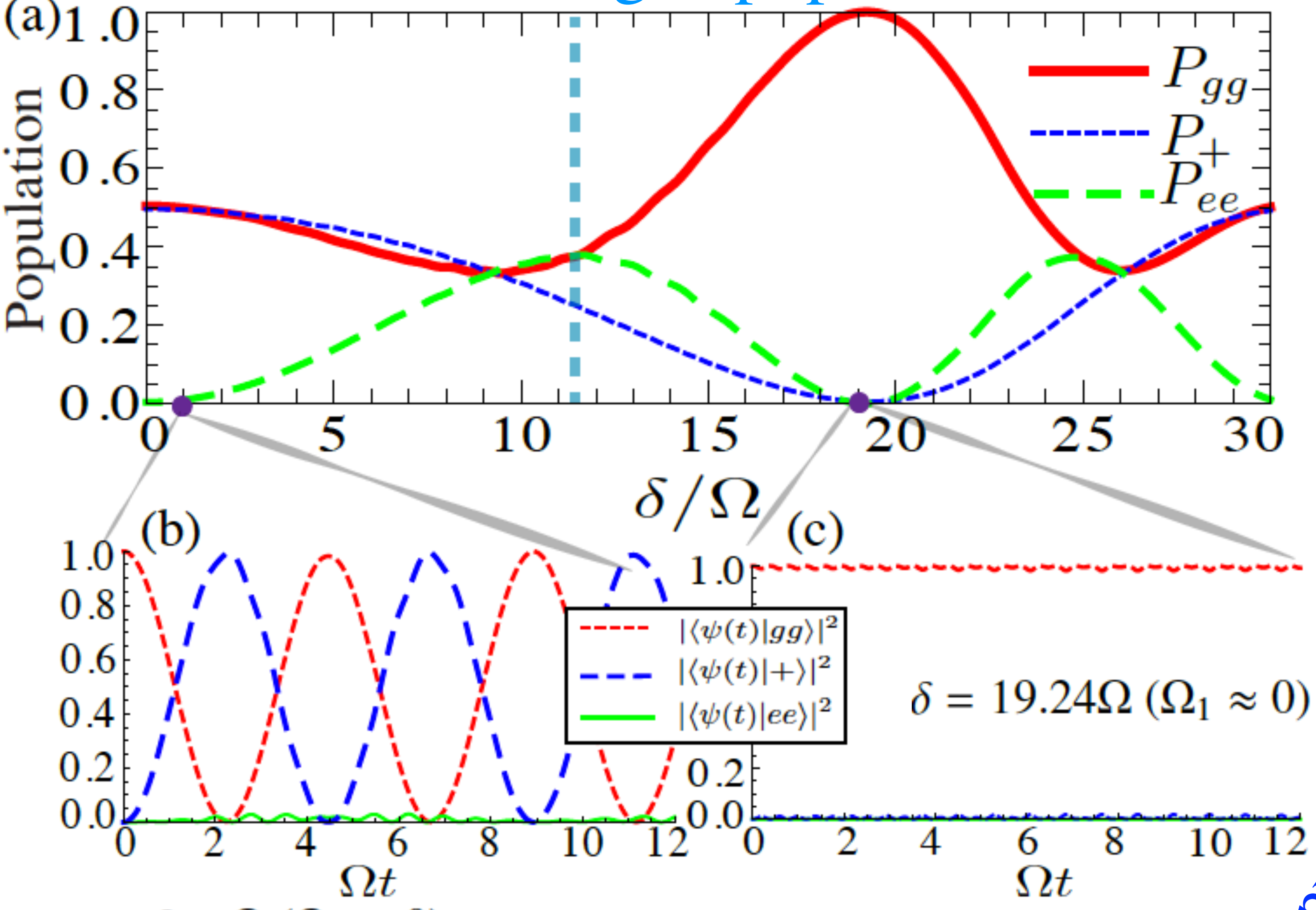
Two atoms: High frequency limit

Dynamics as a function of $\boldsymbol{\delta}$.

$n_1 = 0$ ($\Delta_0 = 0$) and $n_2 = 1$, $\Omega T = 100$

$V_0 = 8\Omega$ and $\omega_0 = 8\Omega$

Time averaged population



$\delta = 19.24\Omega$ ($\Omega_1 \approx 0$)

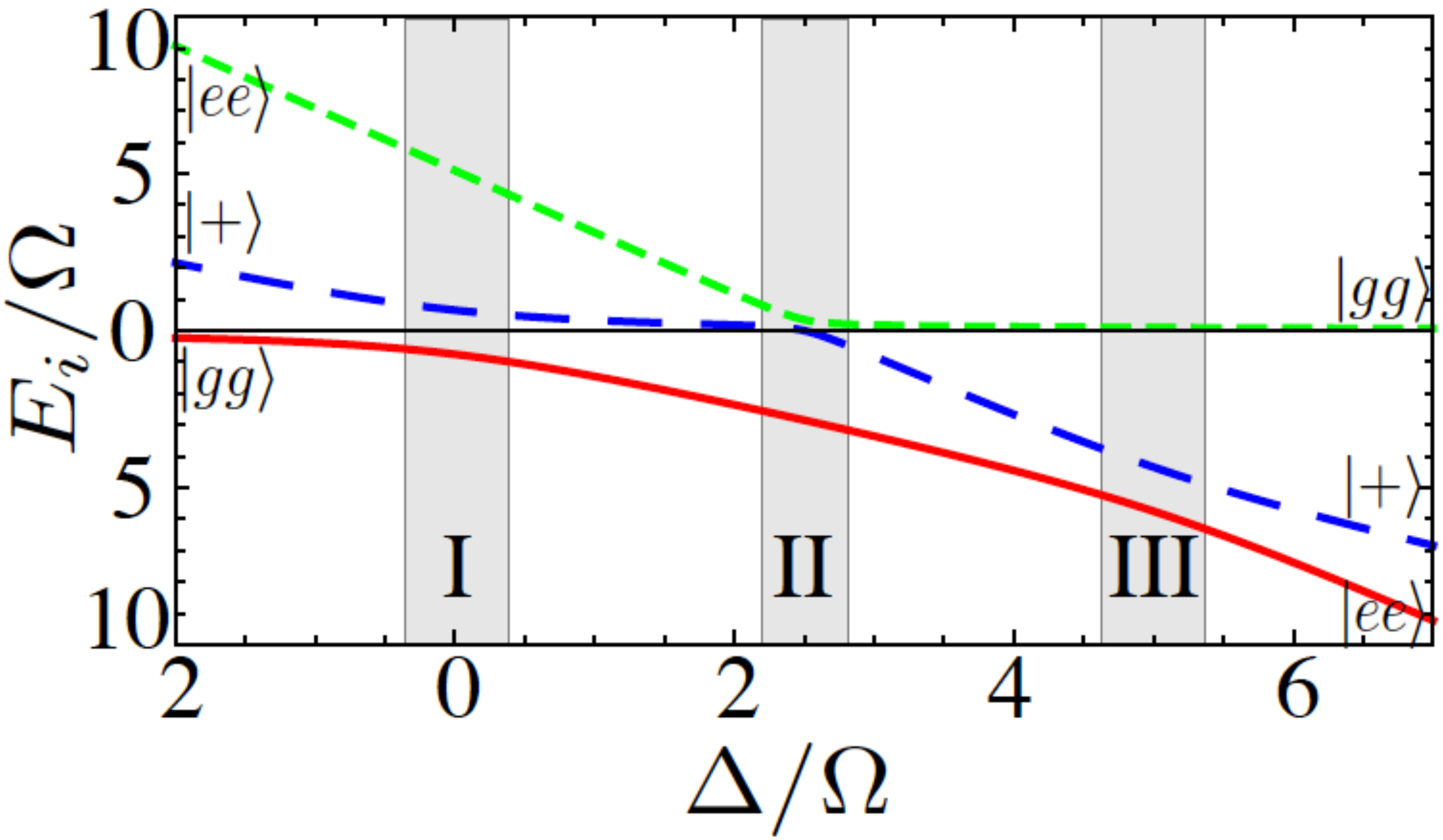
$\delta = \Omega$ ($\Omega_2 \approx 0$)

Population trapping

Two atoms: Fast passage limit

$$\omega_0 \sqrt{\delta^2 - \Delta_0^2} \gg \Omega^2 \text{ with } \delta - \Delta_0 \gg \Omega$$

multi-LZ transition points



First transition: $|gg\rangle \leftrightarrow |+\rangle$

$$\Delta_0 = n\omega_0$$

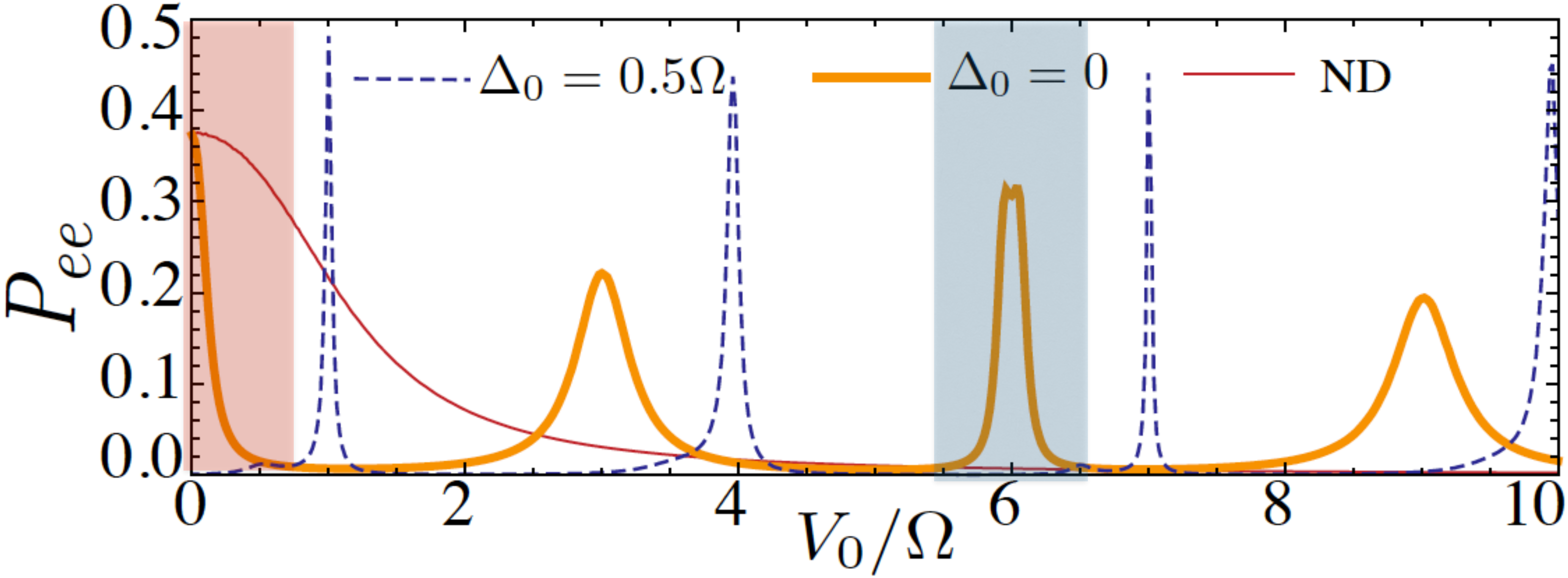
Second transition: $|gg\rangle \leftrightarrow |ee\rangle$

$$\Delta_0 - V_0/2 = n\omega_0$$

Third transition: $|+\rangle \leftrightarrow |ee\rangle$

$$\Delta_0 - V_0 = n\omega_0$$

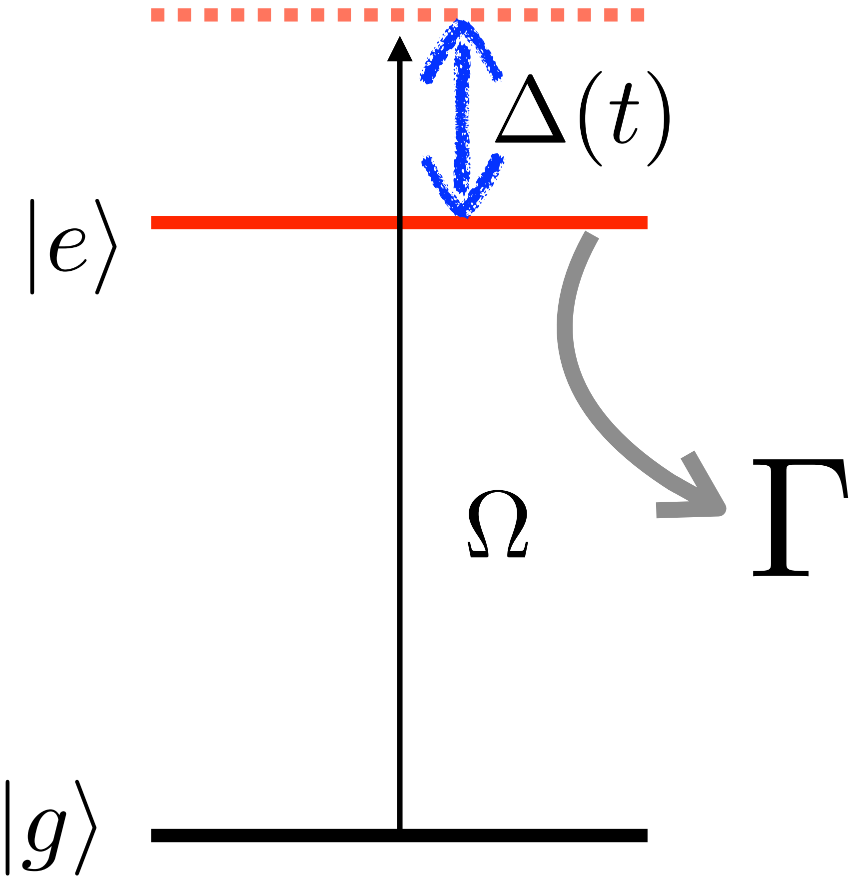
Two atoms: Fast passage limit



Blockade Enhancement

Anti-blockades at very large interactions

Blockade enhancement in Rubidium atoms

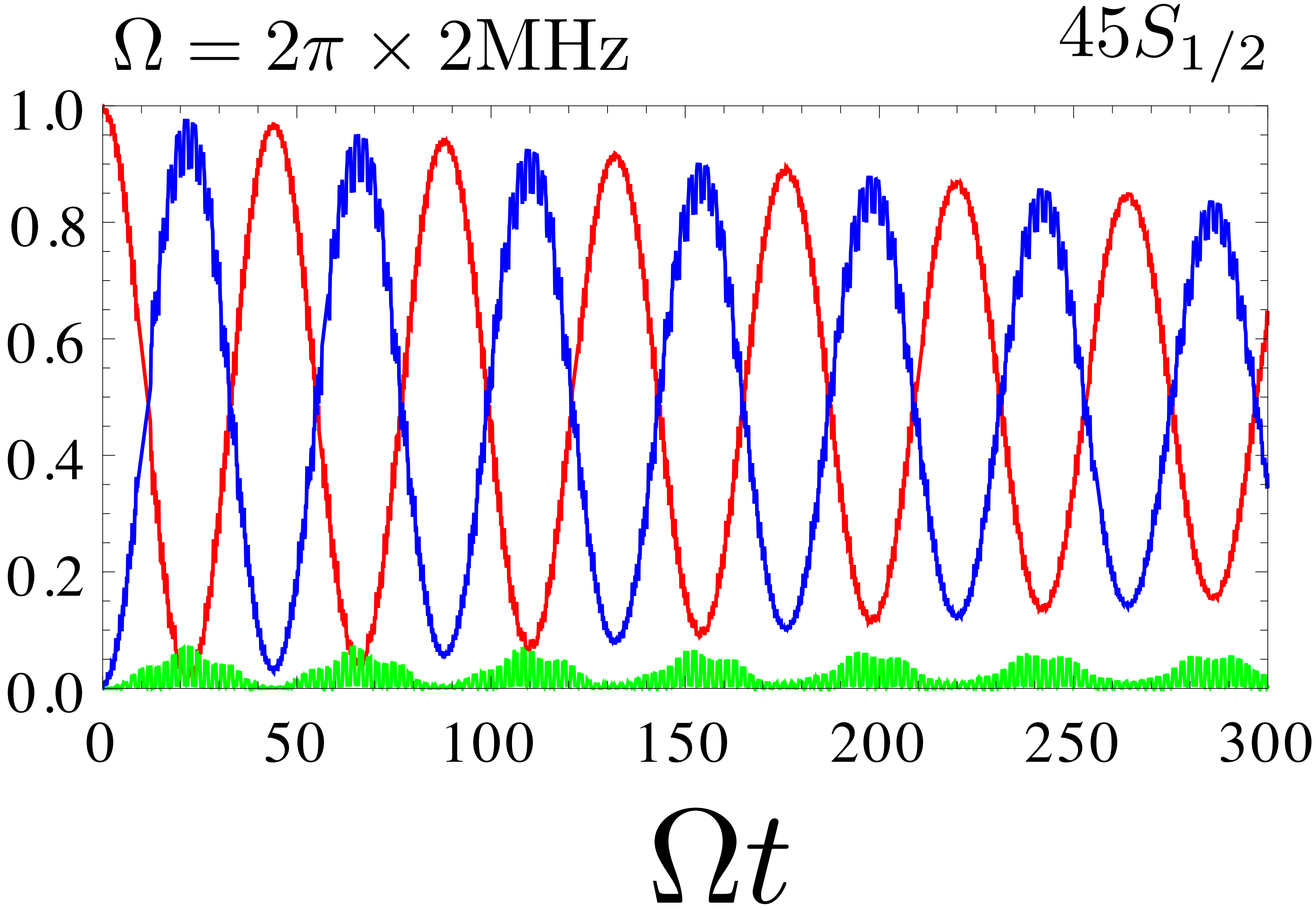


$$\Delta_0 = 0$$

$$\delta = 2\pi \times 34\text{MHz}$$

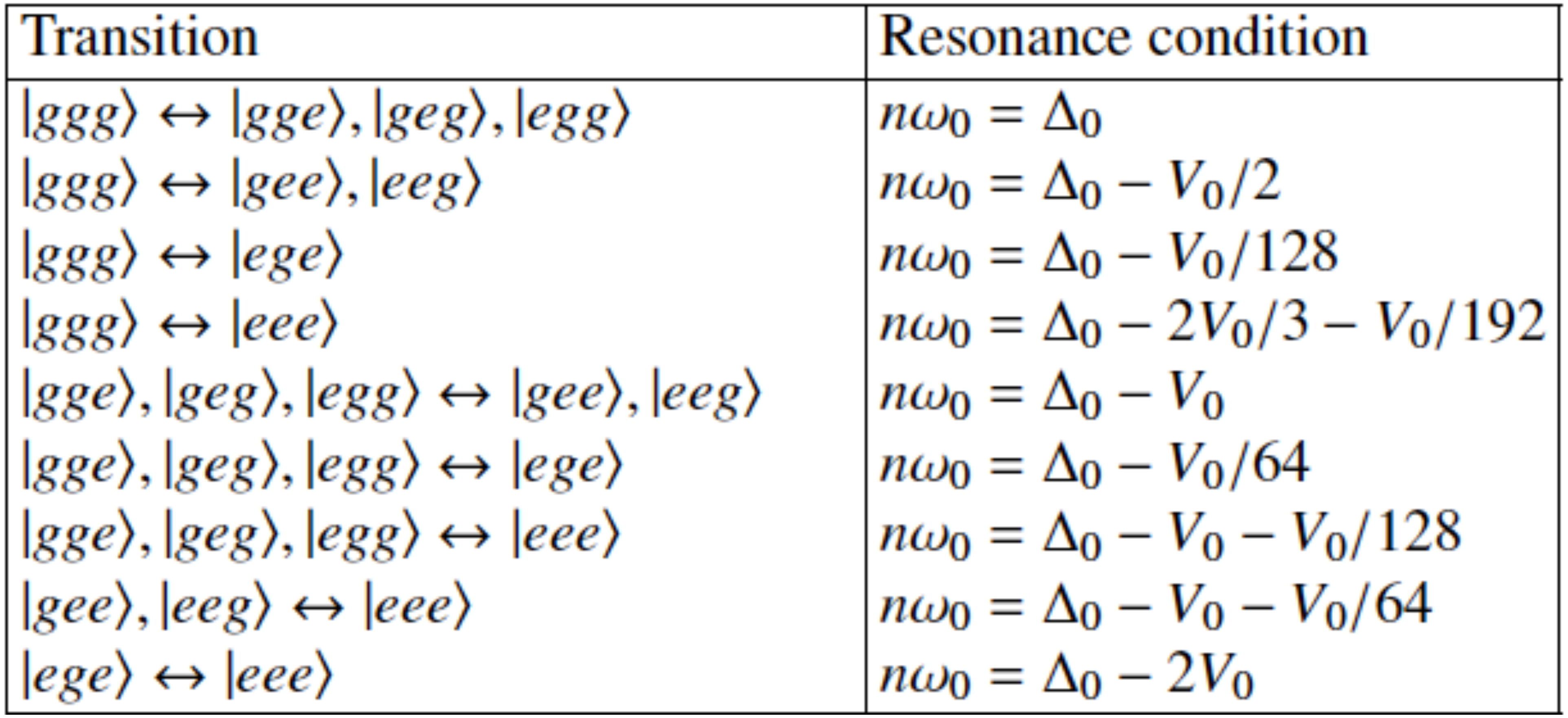
$$\omega = 2\pi \times 3\text{MHz}$$

$$V_0 = \Omega/2$$



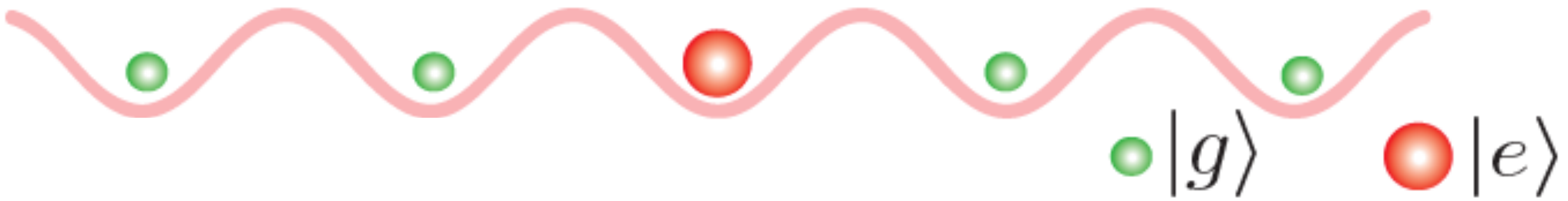
More atoms …

Nine resonances in three atoms



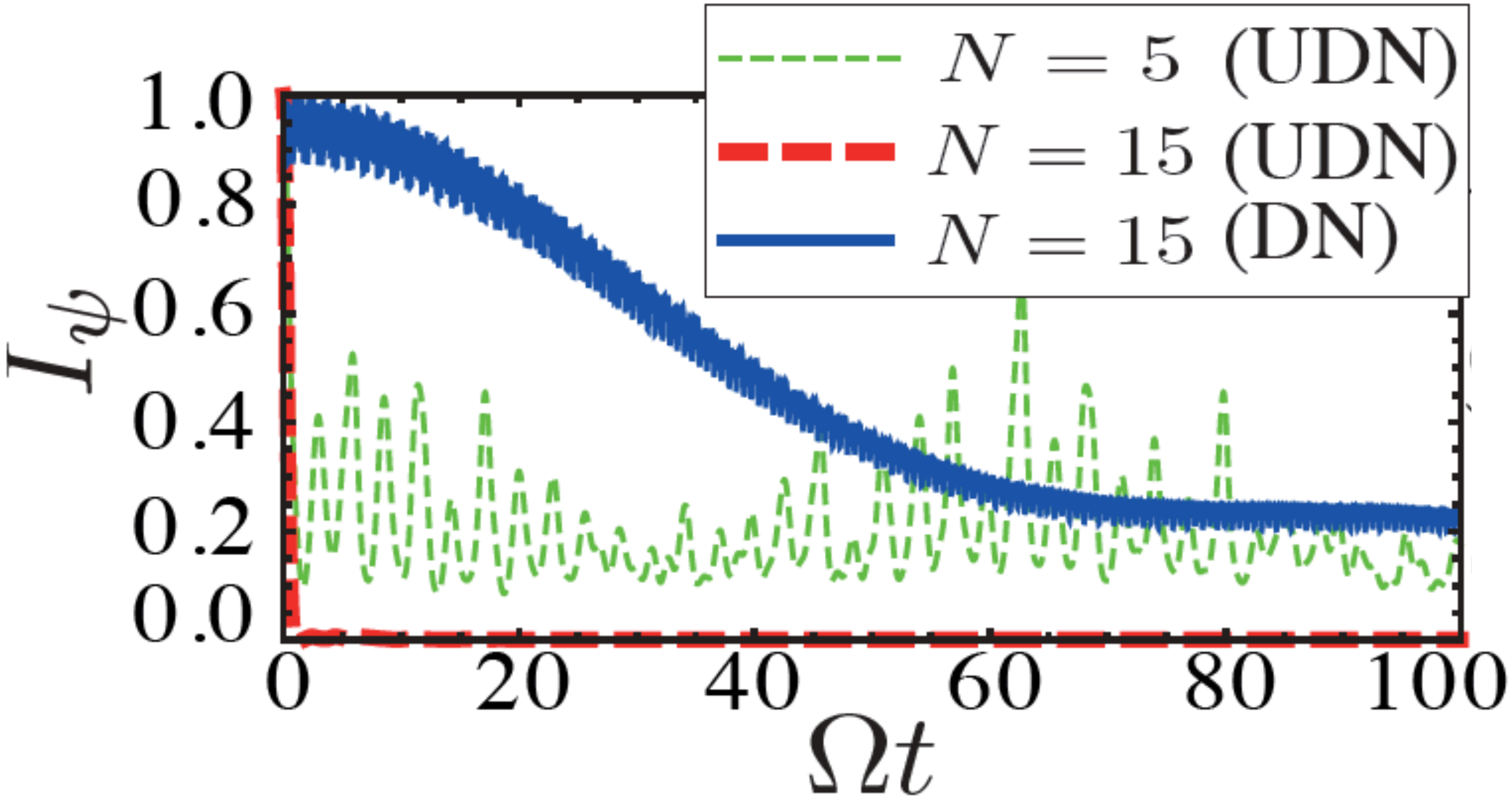
Transition	Resonance condition
$\lvert ggg\rangle \leftrightarrow \lvert gge\rangle, \lvert geg\rangle, \lvert egg\rangle$	$n\omega_0 = \Delta_0$
$\lvert ggg\rangle \leftrightarrow \lvert gee\rangle, \lvert eeg\rangle$	$n\omega_0 = \Delta_0 - V_0/2$
$\lvert ggg\rangle \leftrightarrow \lvert ege\rangle$	$n\omega_0 = \Delta_0 - V_0/128$
$\lvert ggg\rangle \leftrightarrow \lvert eee\rangle$	$n\omega_0 = \Delta_0 - 2V_0/3 - V_0/192$
$\lvert gge\rangle, \lvert geg\rangle, \lvert egg\rangle \leftrightarrow \lvert gee\rangle, \lvert eeg\rangle$	$n\omega_0 = \Delta_0 - V_0$
$\lvert gge\rangle, \lvert geg\rangle, \lvert egg\rangle \leftrightarrow \lvert ege\rangle$	$n\omega_0 = \Delta_0 - V_0/64$
$\lvert gge\rangle, \lvert geg\rangle, \lvert egg\rangle \leftrightarrow \lvert eee\rangle$	$n\omega_0 = \Delta_0 - V_0 - V_0/128$
$\lvert gee\rangle, \lvert eeg\rangle \leftrightarrow \lvert eee\rangle$	$n\omega_0 = \Delta_0 - V_0 - V_0/64$
$\lvert ege\rangle \leftrightarrow \lvert eee\rangle$	$n\omega_0 = \Delta_0 - 2V_0$

Dynamical localisation



$$|I\rangle = |...g,e,g,...\rangle$$

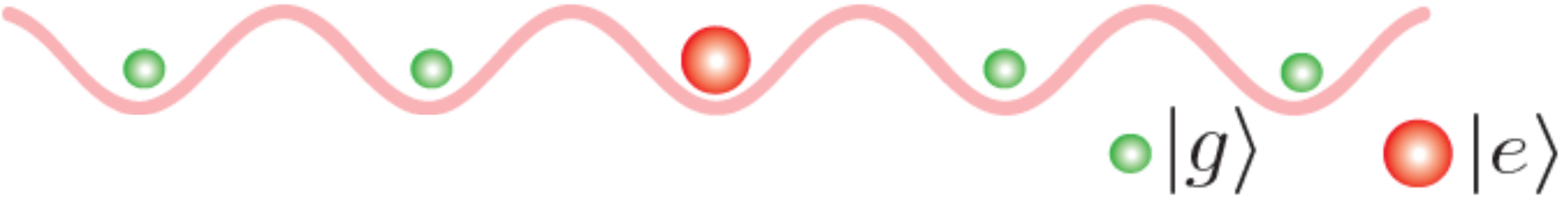
$$I_\psi = \sum_i p_i^2$$



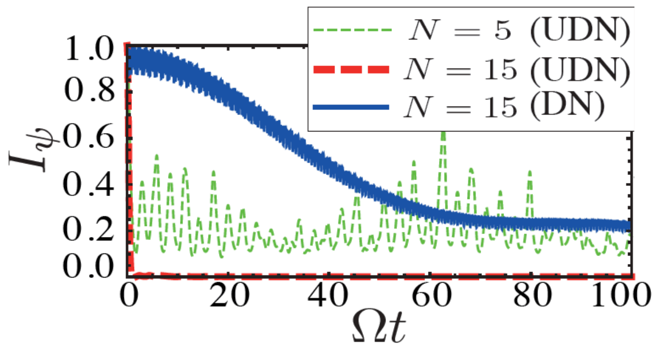
UDN - undriven

DN - driven

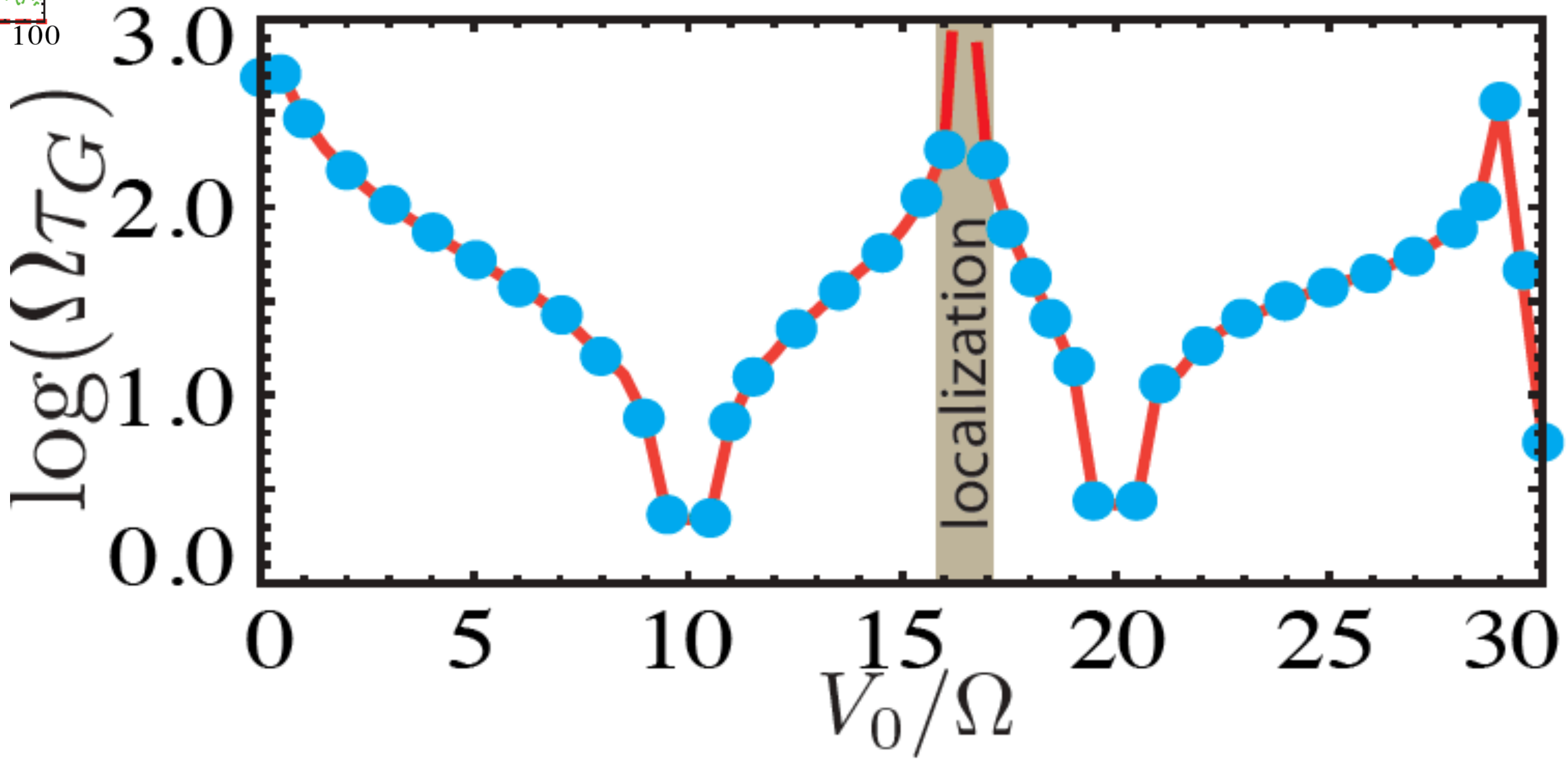
Dynamical localisation



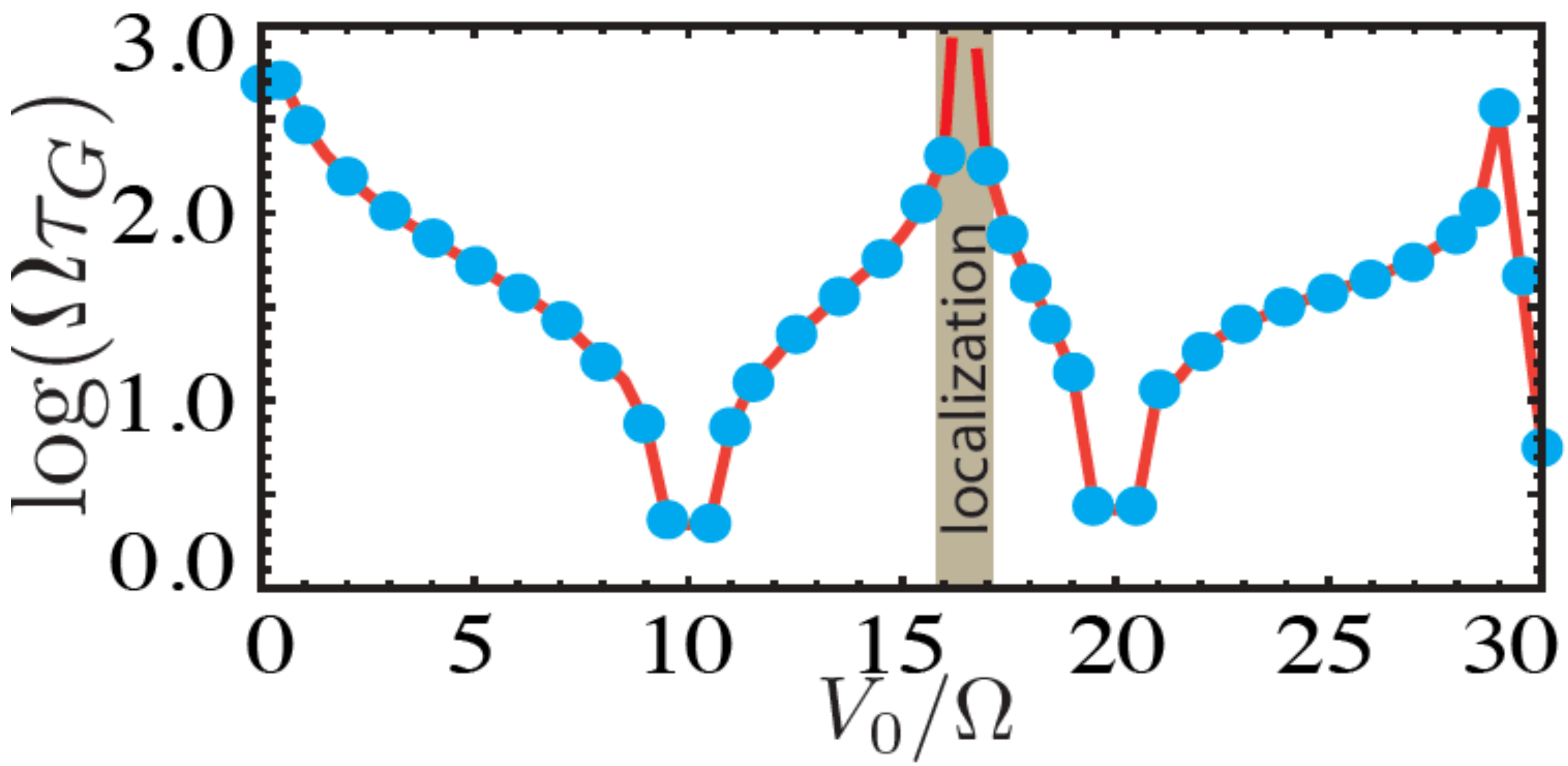
$$|I\rangle = |...g, e, g, ...\rangle$$



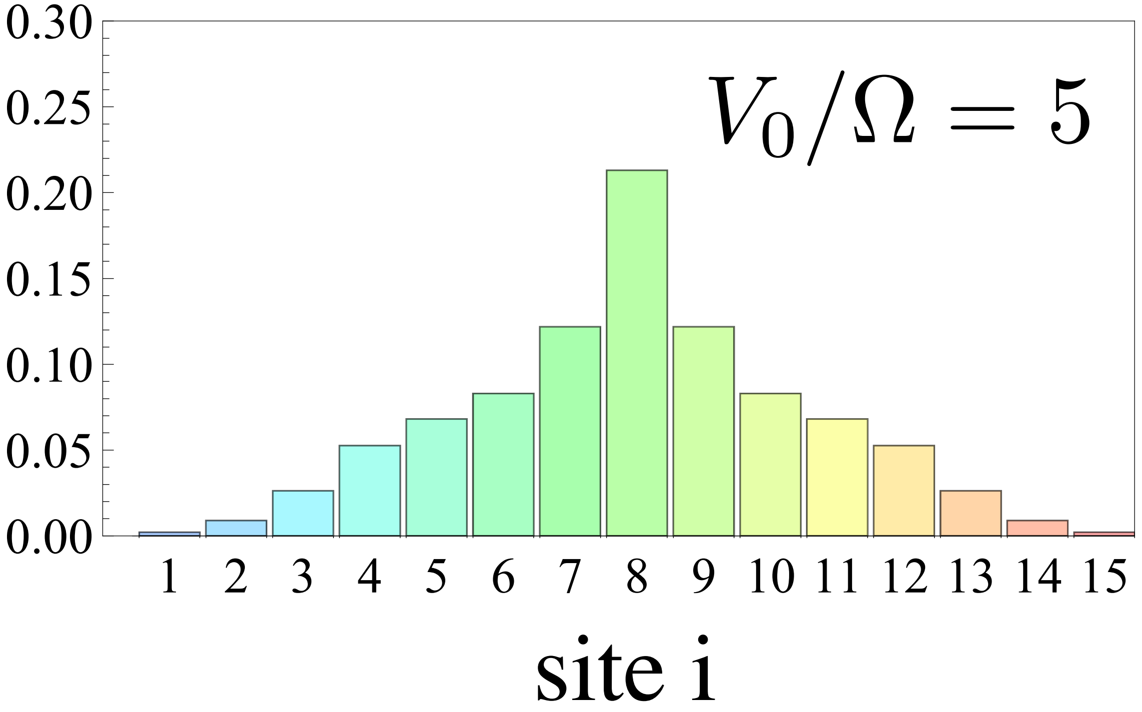
$$I_\psi = \sum_i p_i^2$$

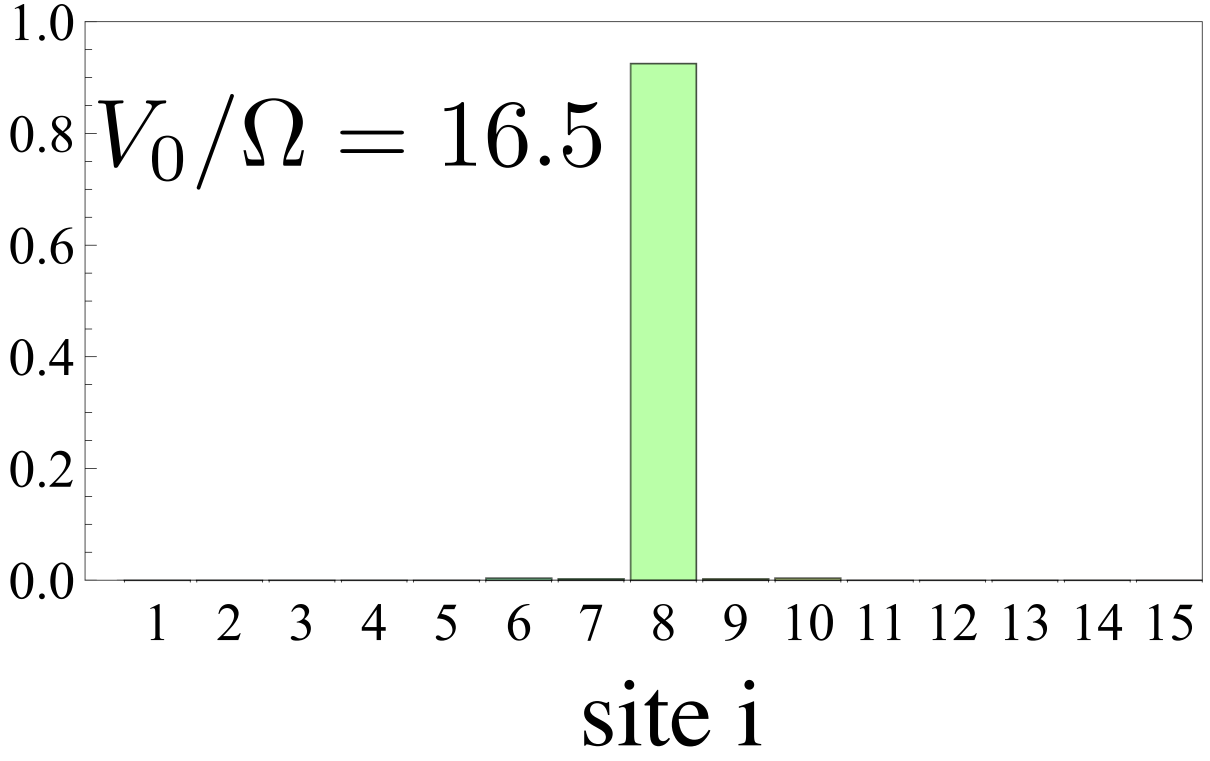


Dynamical localisation



Singly excited states time averaged populations





Conclusion

Periodic modulation of the driving field leads to interesting scenarios in a Rydberg-atoms dynamics.

Blockade Enhancement Anti-blockades at large interactions

Dynamical localisation of a many body configuration

Thank you all!!