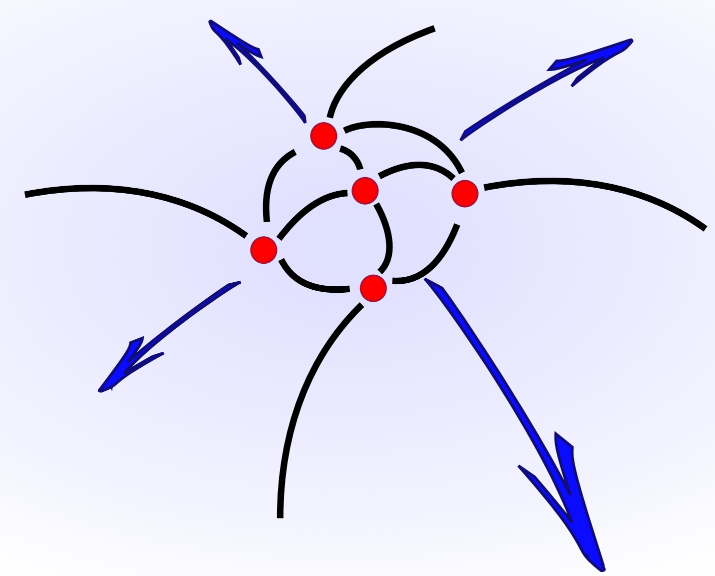
Dissipative and non-dissipative many-body dynamics in a cold Rydberg gas

Cristiano Simonelli
INO-CNR and Dipartimento di Fisica, Pisa, Italy 28/09/2016



- C. Simonelli, M. Archimi, L. Asteria, D. Capecchi, G. Masella, F. Castellucci, E. Arimondo, D. Ciampini, O. Morsch
- I. Lesanovsky, J. Garrahan; P. Pillet, R. Faoro
- **Funding:** FET-RYSQ, ITN-COHERENCE, PRIN

Overview

- Non equilibrium dynamics of a many body system

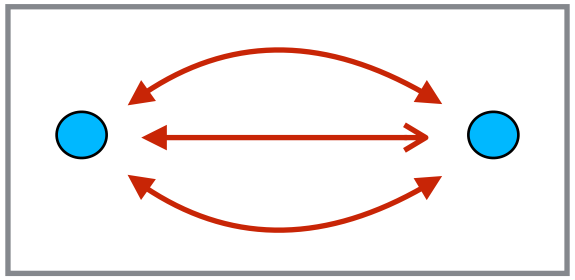
- Non dissipative regime: Observation of the kinetic constraint and the facilitation

- Seeded avalanche process

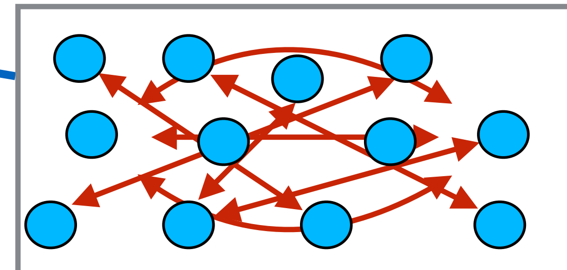
- Dissipative regime: preliminary results of percolation process

- Conclusions and outlook

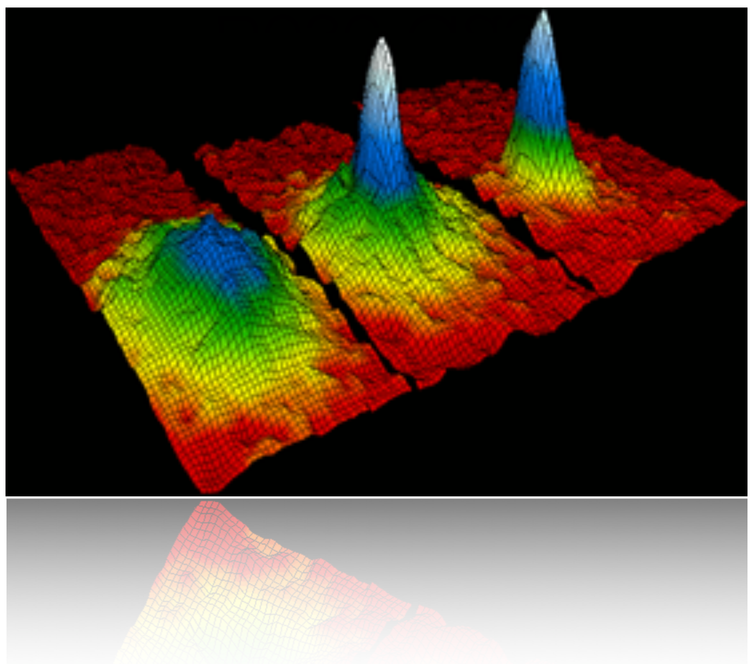
Many body systems



Many body systems

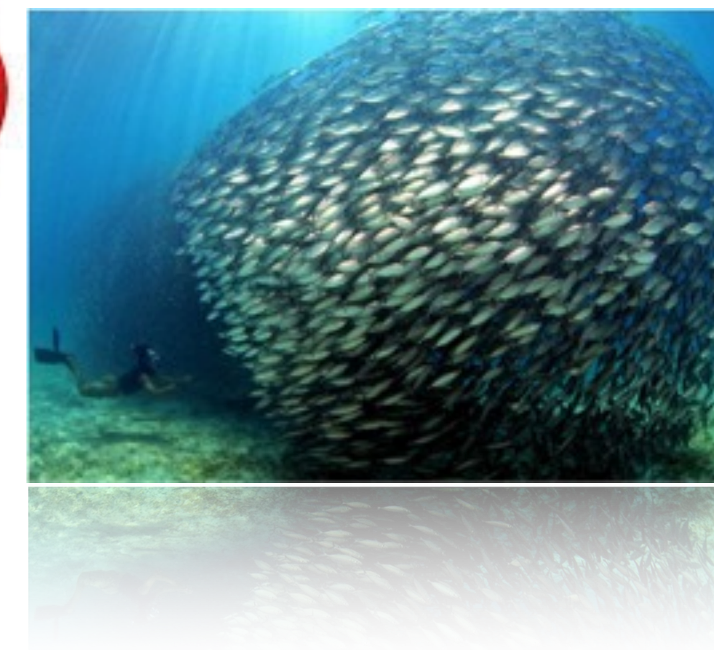


Bose Gas



“More is different”*

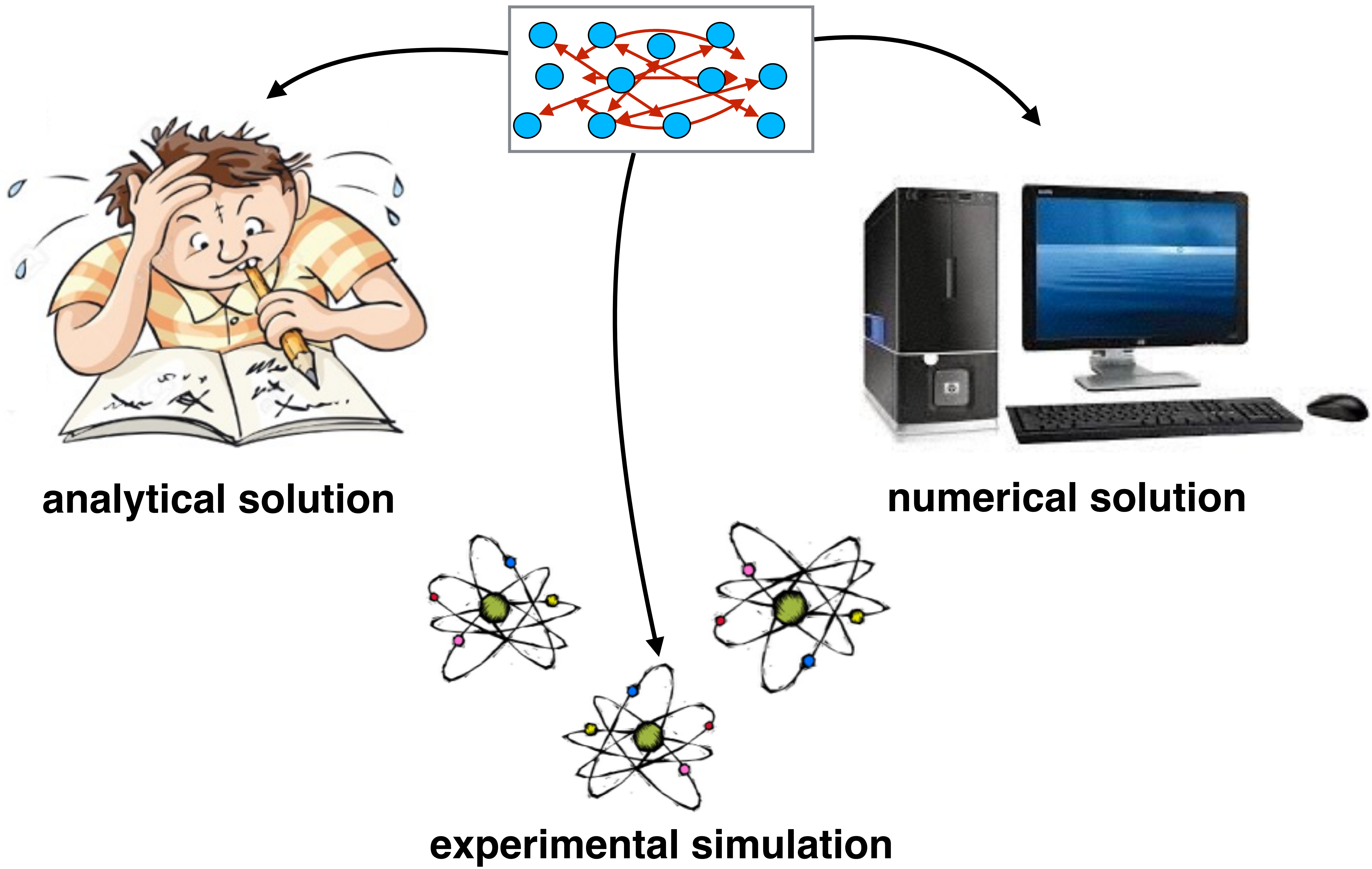
Herding behaviour



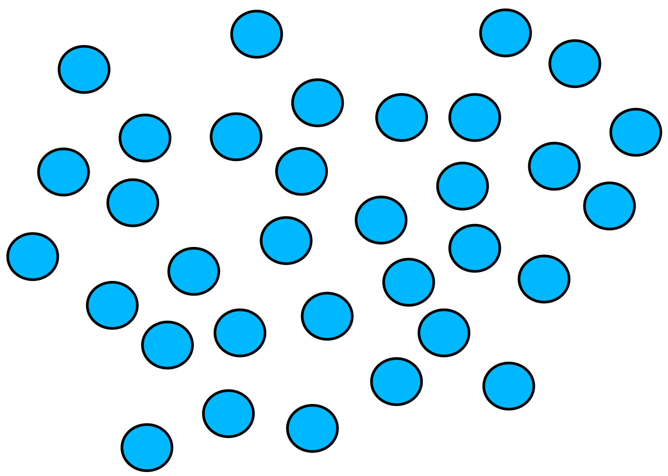
Neural network

* P. W. ANDERSON, *SCIENCE,* 04 AUG 1972, 393-396

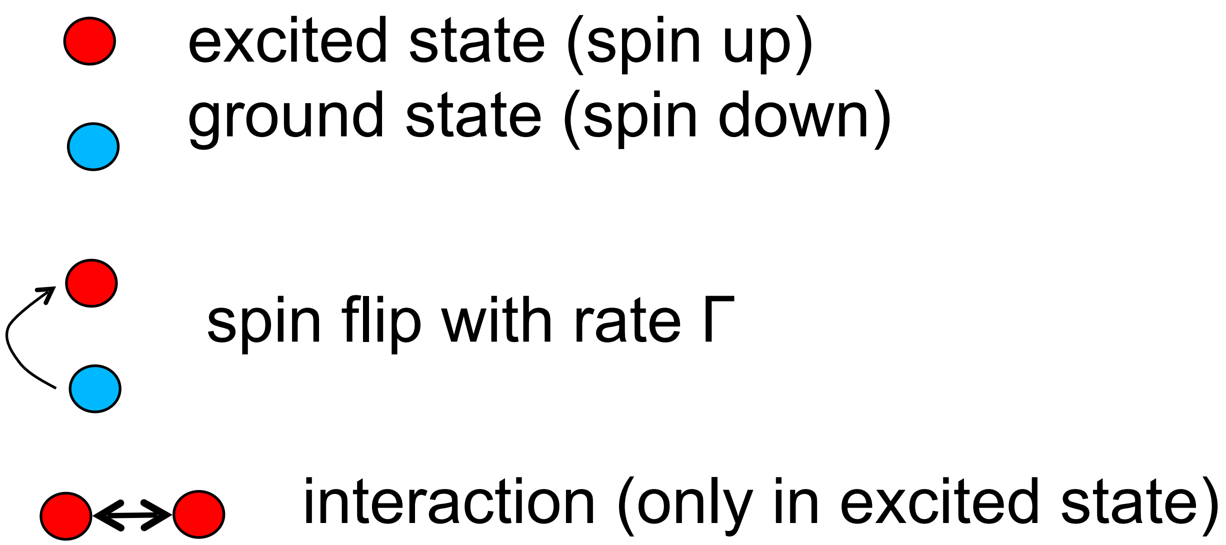
Many body problem



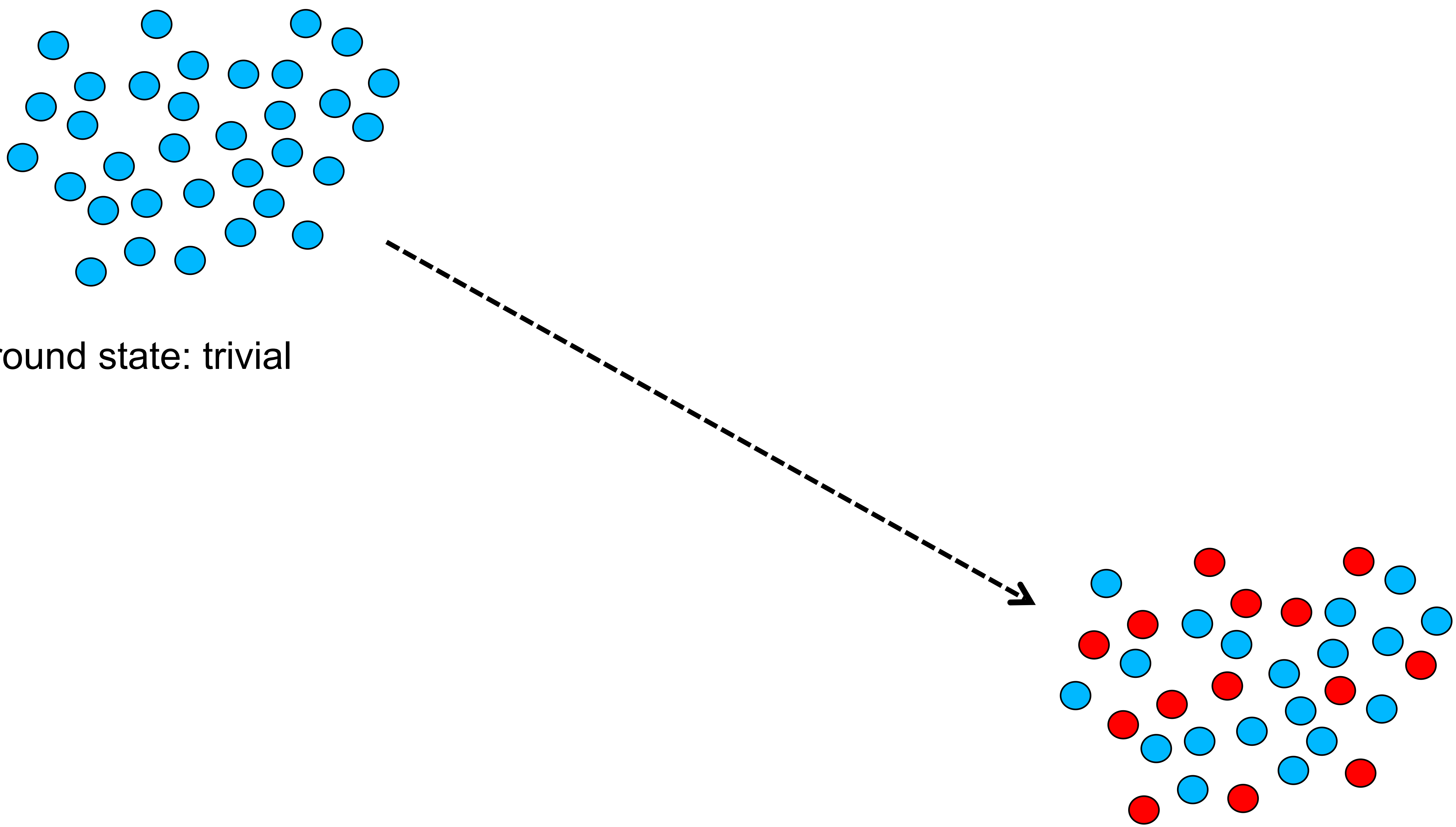
Non-equilibrium dynamics of a many-body system



ground state: trivial



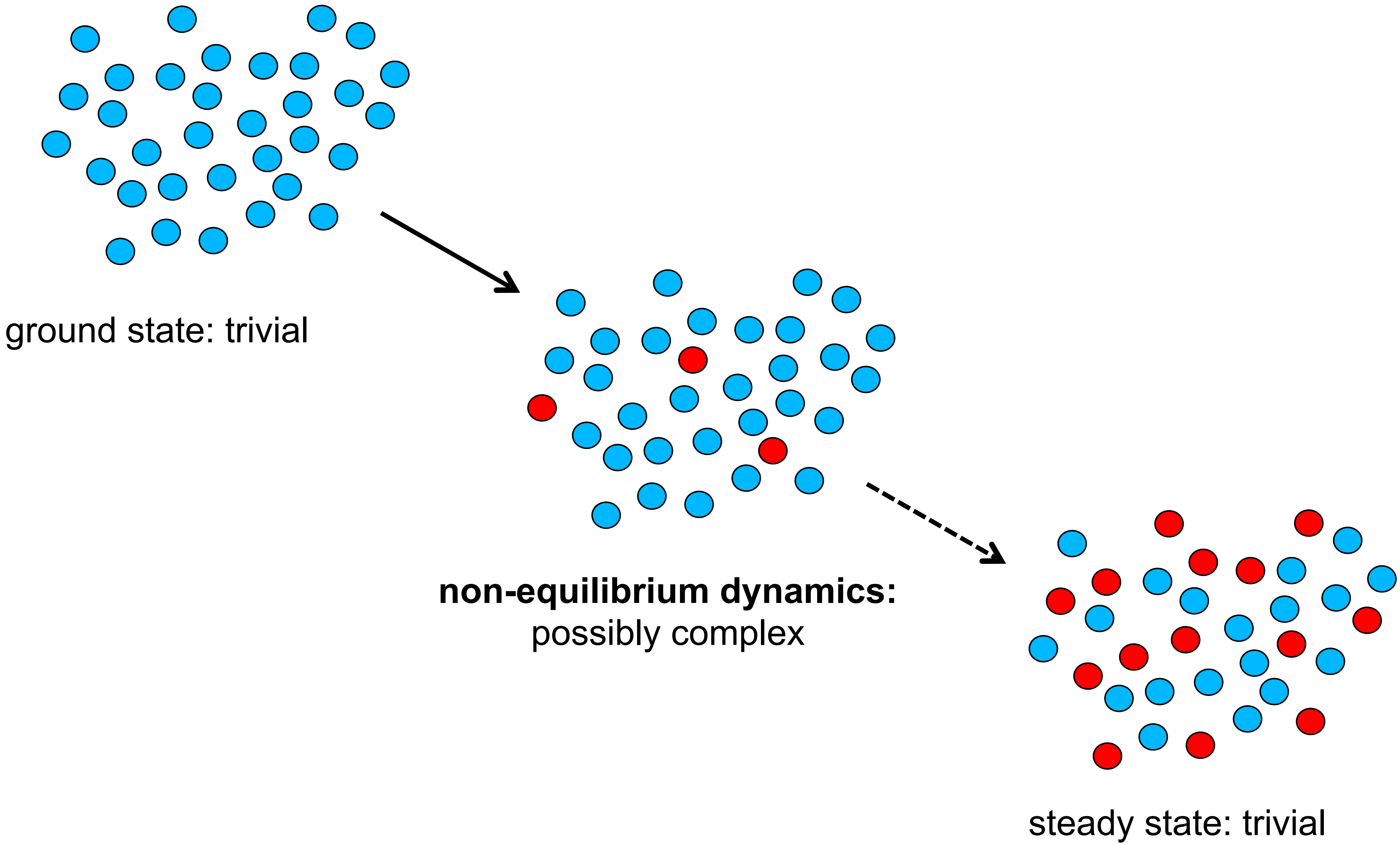
Non-equilibrium dynamics of a many-body system



ground state: trivial

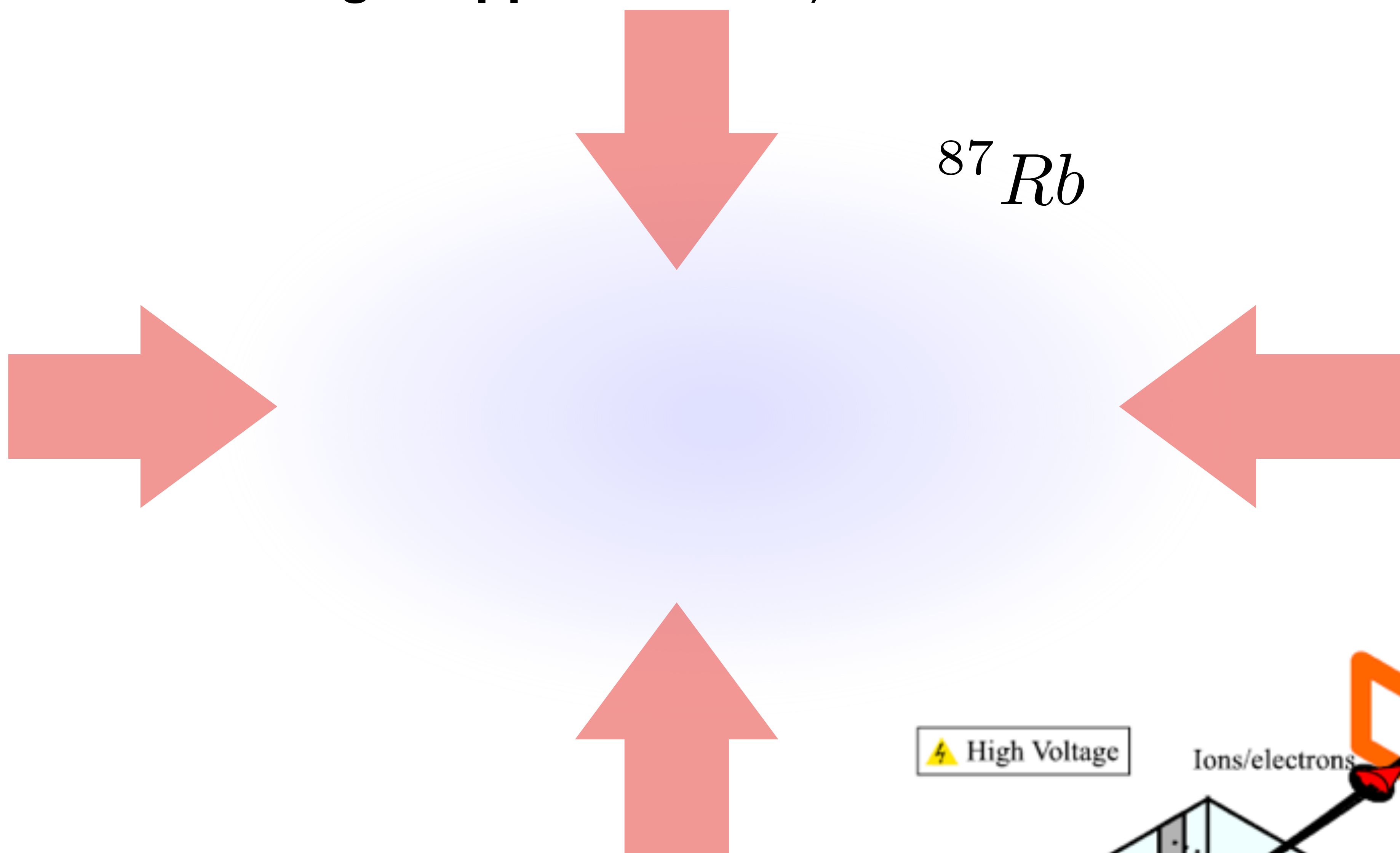
steady state: trivial (fully mixed)

Non-equilibrium dynamics of a many-body system

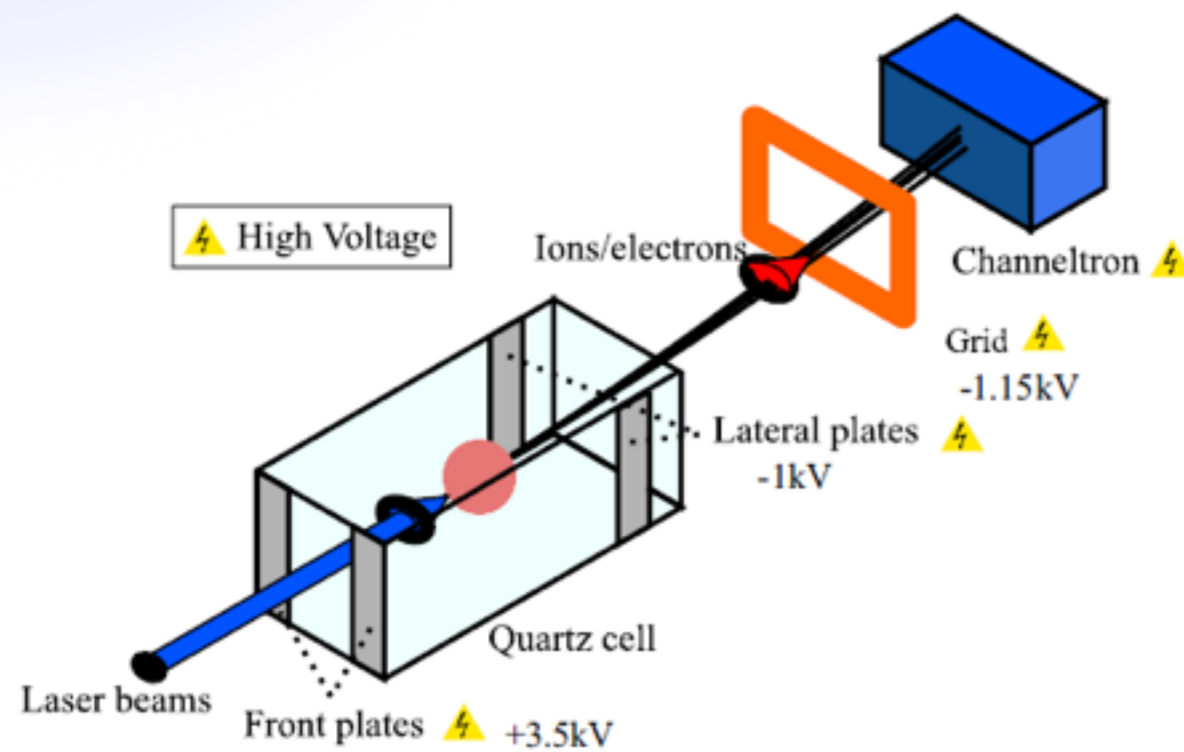


Cold cloud of ground state atoms

Ultra-cold atoms in magneto optical trap at T around 150 μK
(assume positions of atoms to be stationary on timescale of the experiment of a few microseconds -> **frozen gas approximation**)



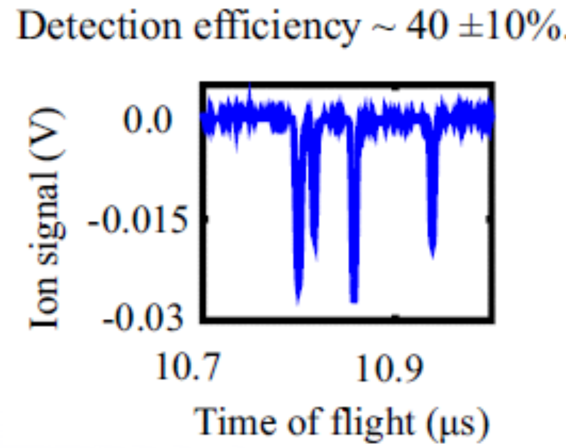
- **size of cloud 20-300 μm with up to 3,000,000 atoms**; possibility of focusing one beam tightly to realize quasi 1D geometry

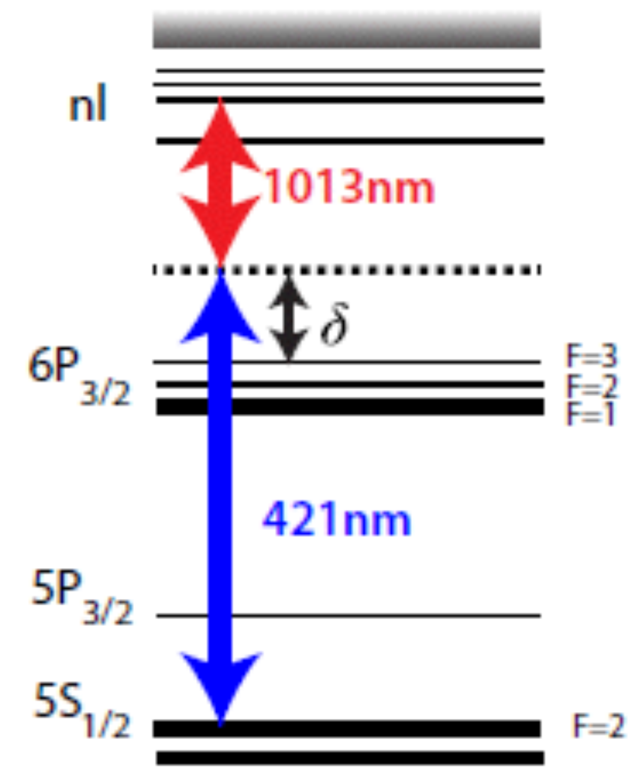


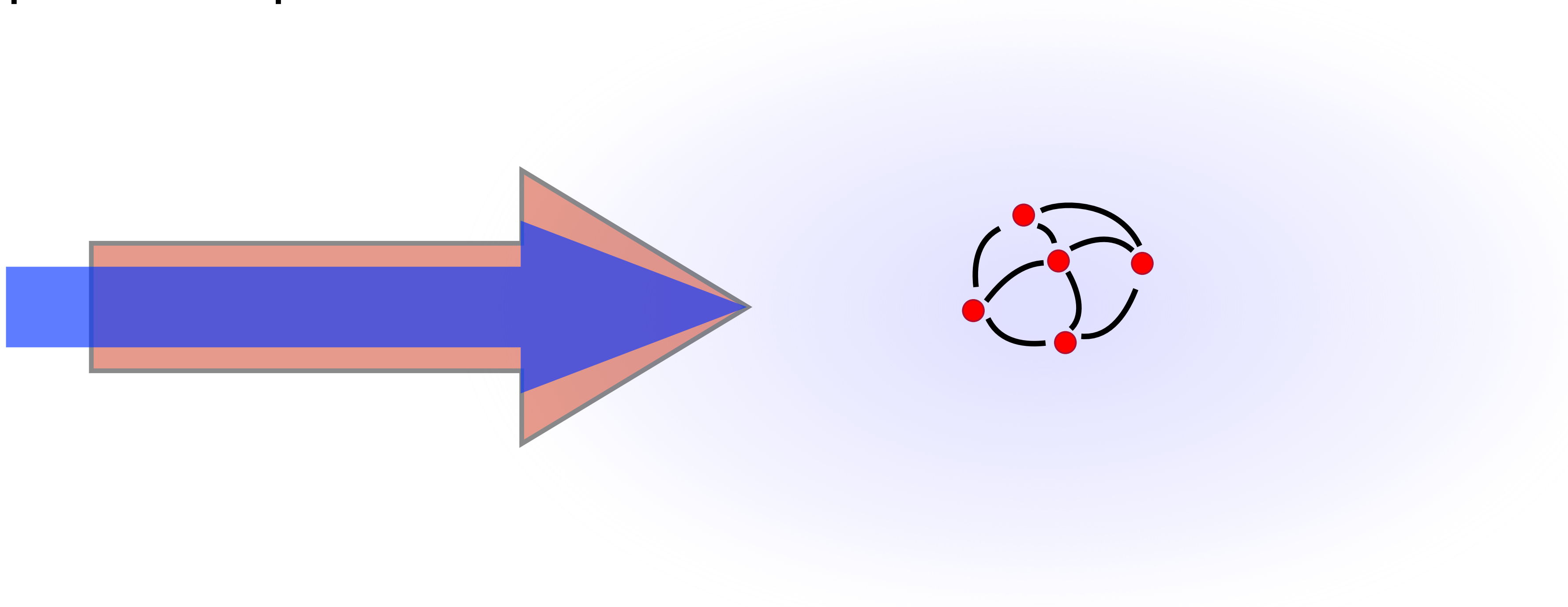
Cold cloud of ground state atoms

- in experiments reported here: **70S (repulsive interaction) Rb atoms**

- two-photon excitation scheme with Rabi frequencies up to 500 kHz

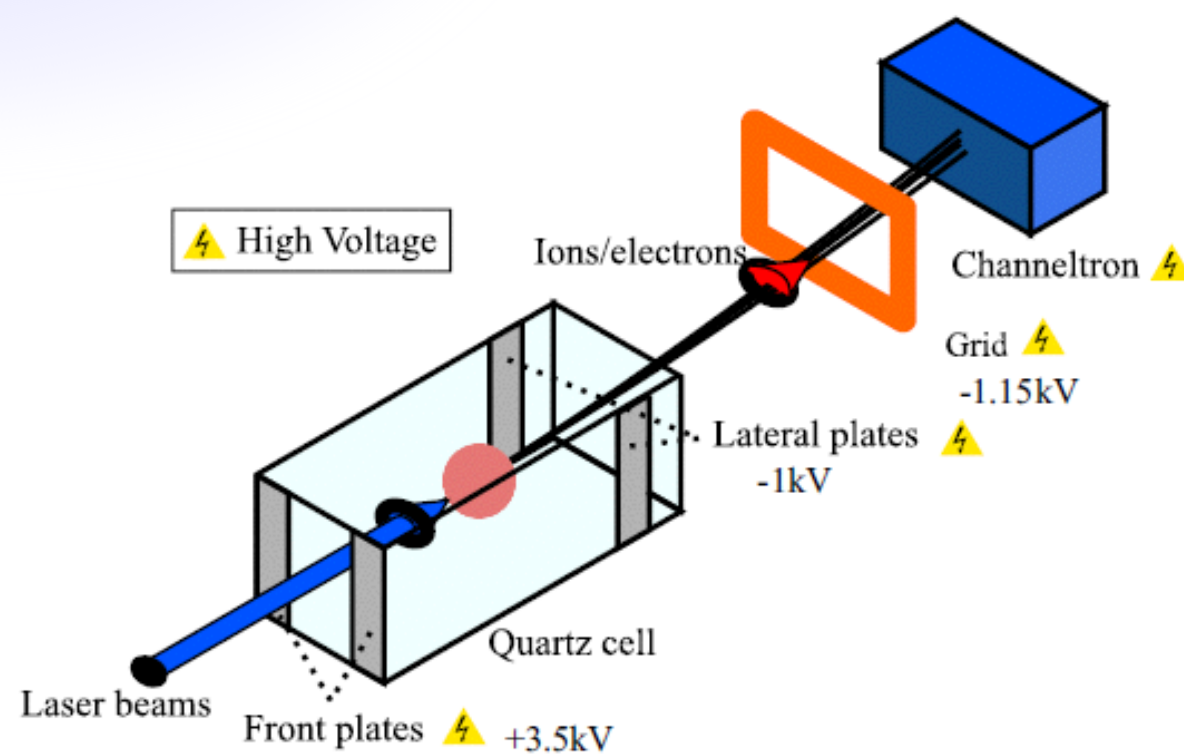






- laser line-width around 500 kHz -> coherence times around 0.5 μs

- **size of cloud 20-300 μm with up to 3,000,000 atoms**; possibility of focusing one beam tightly to realize quasi 1D geometry



Cold cloud of ground state atoms

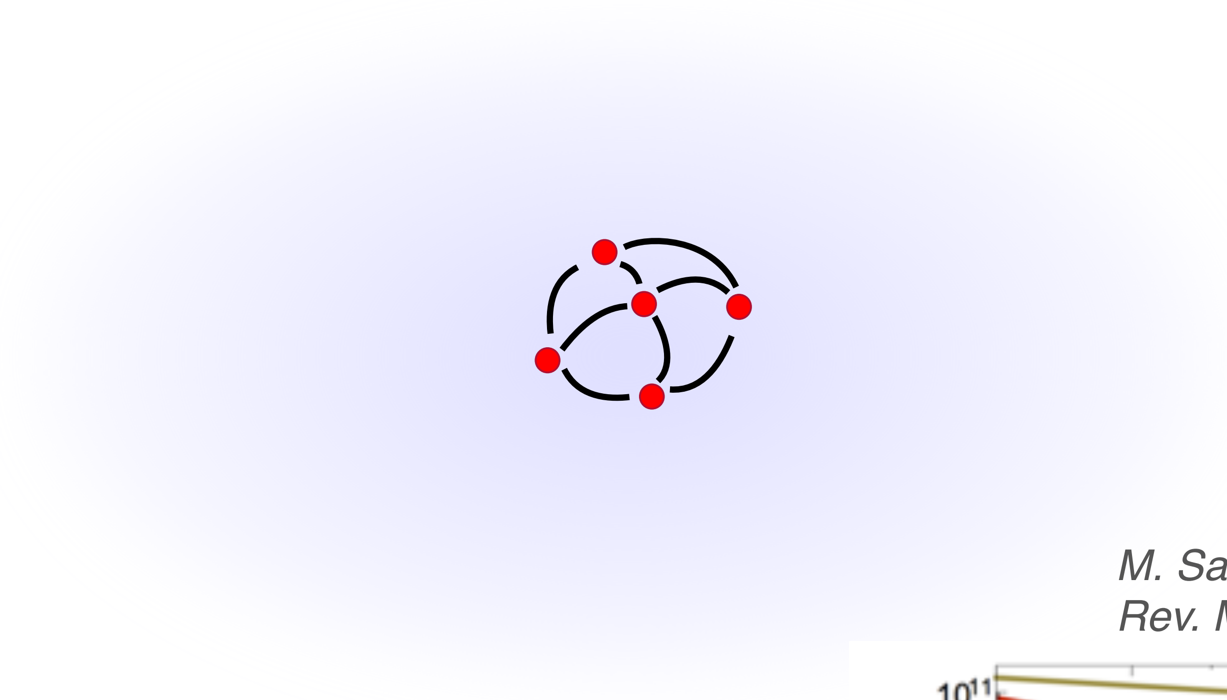
Lifetime: ~ n^3
n=70 ~ 150 µs

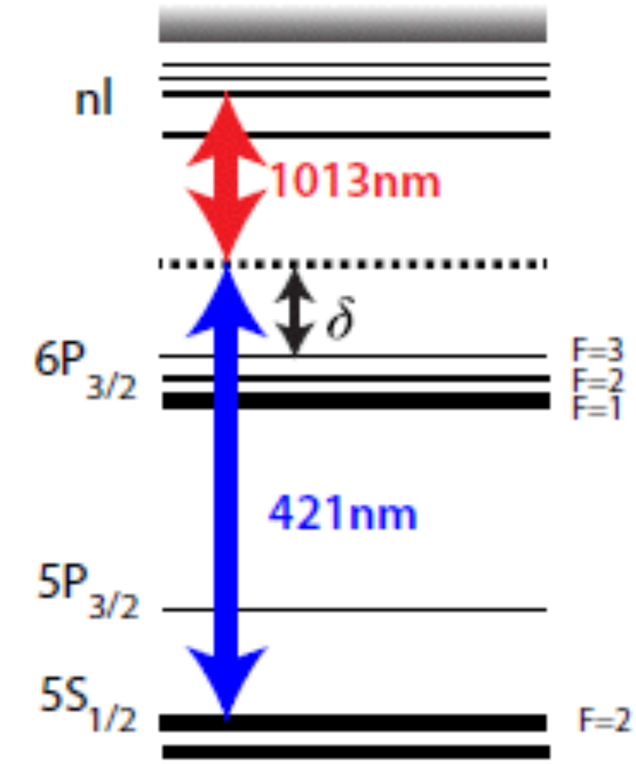
Polarizability ~ n^7
van der Waals C_6 coefficient ~ n^{11}

Interaction

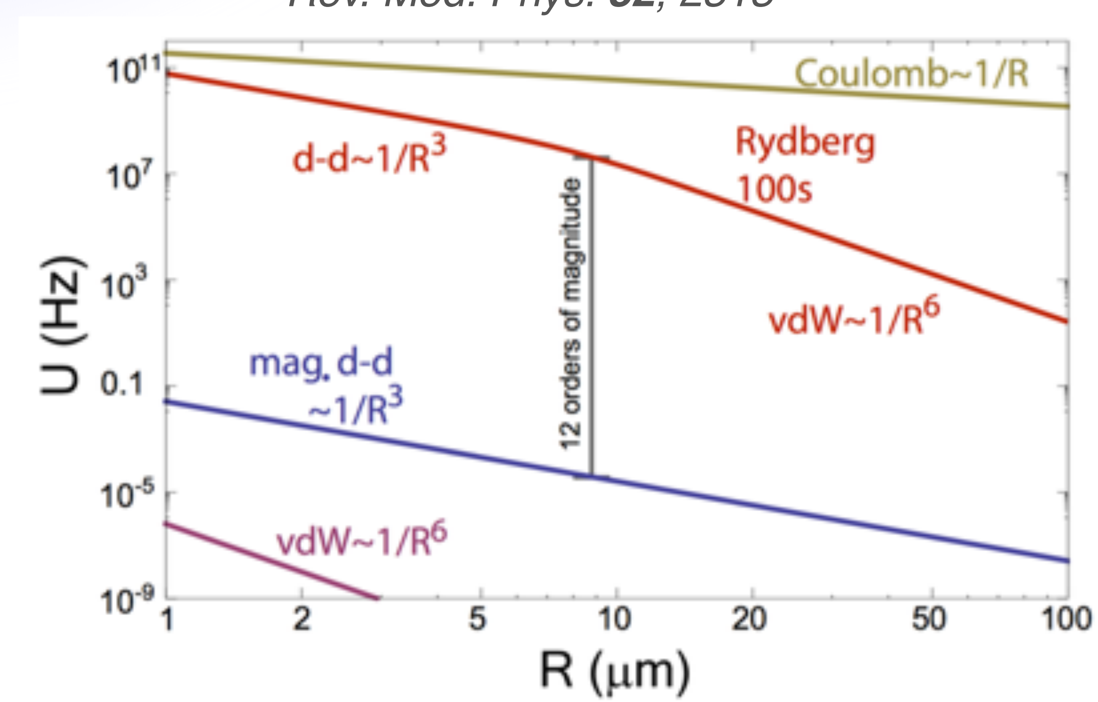
$$V_{i,k} = \frac{C_6}{|r_i - r_k|^6}$$

Rydberg atom



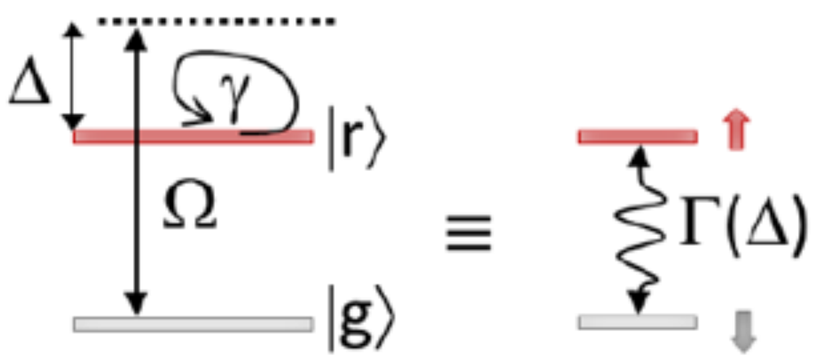


M. Saffman, T. G. Walker, and K. Mølmer, *Rev. Mod. Phys.* ***82**, 2313*



→ strong van-der-Waals or dipole-dipole interaction; **orders of magnitude larger** than contact interaction in ultra-cold gases **(up to GHz at micrometer distances)!**

Kinetic constraints in Rydberg gases



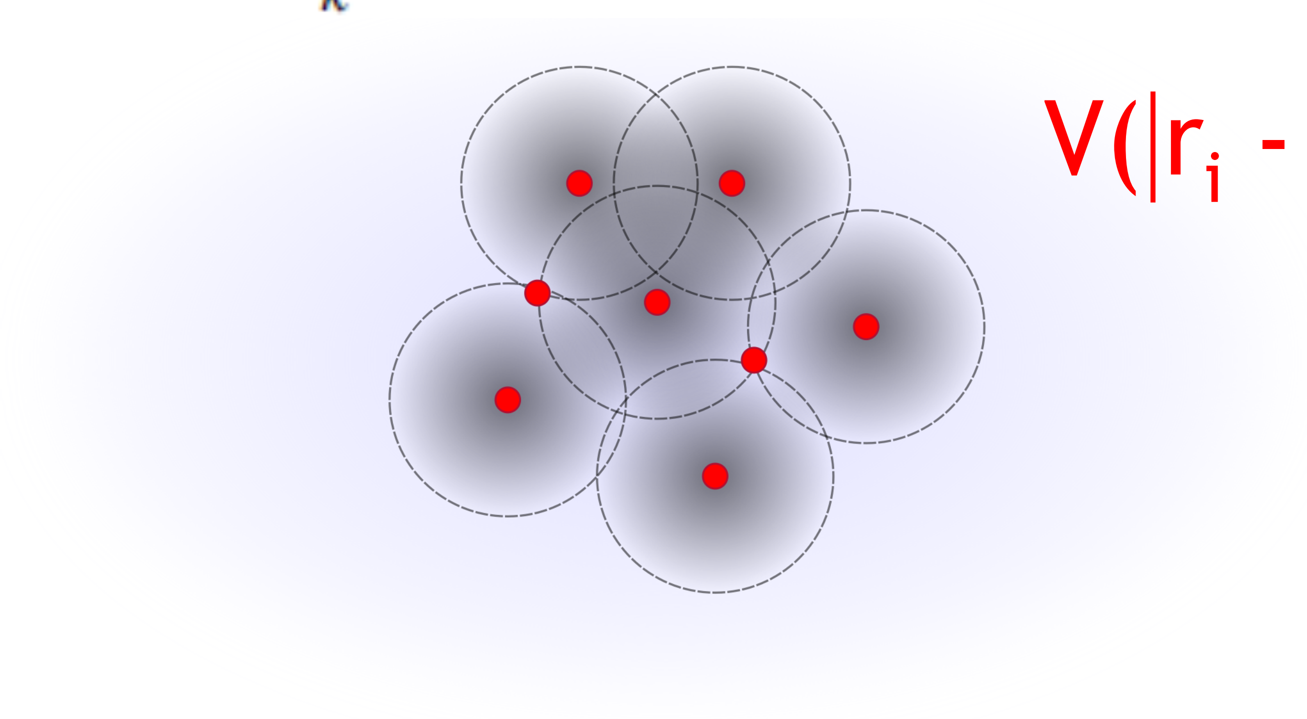
Semiclassical approximation (incoherent excitation):
Rabi oscillations with Ω ->
Spin flips with rate

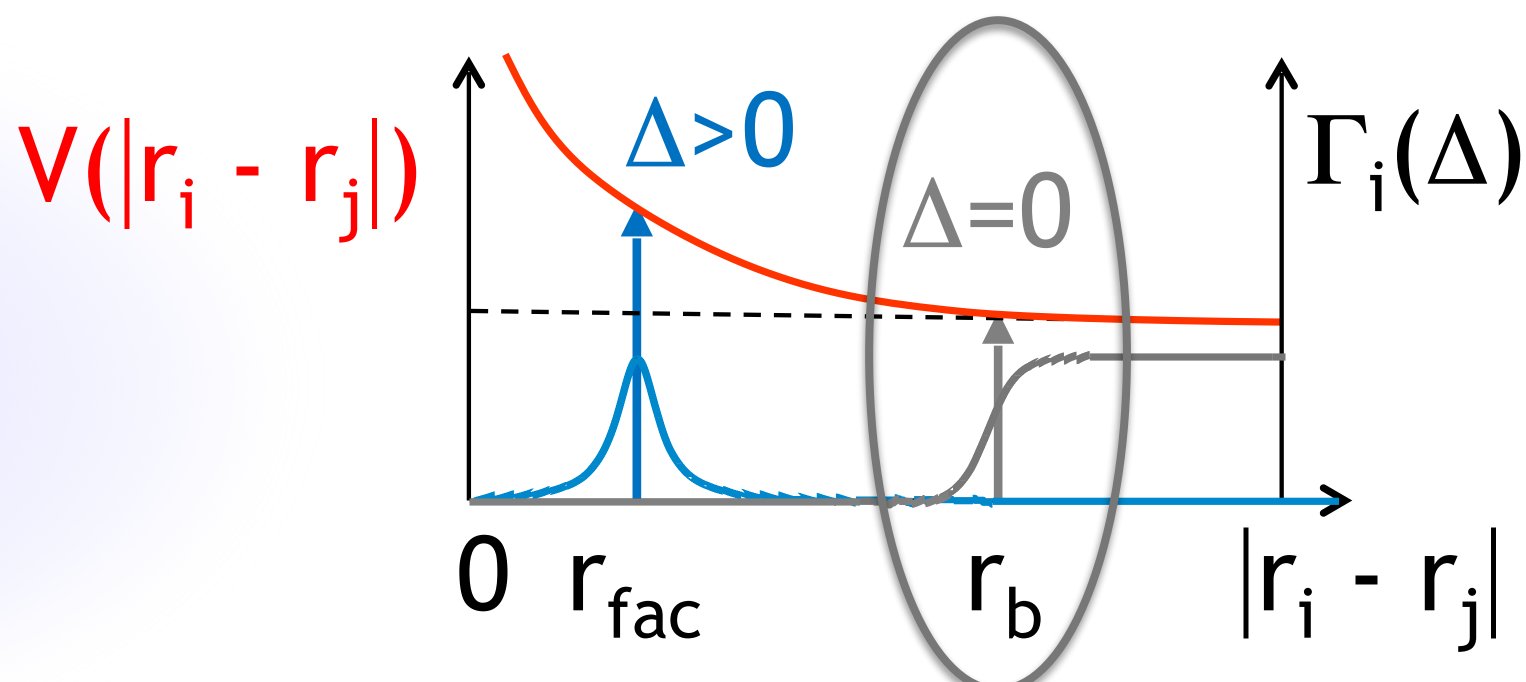
$$\Gamma_i(\Delta) = \frac{\Omega^2}{2\gamma}\left[1+\left(\frac{\Delta - \frac{1}{\hbar}\sum_{i\neq j} V_{ij} n_j}{\gamma}\right)^2\right]^{-1}$$

if γ>> Ω

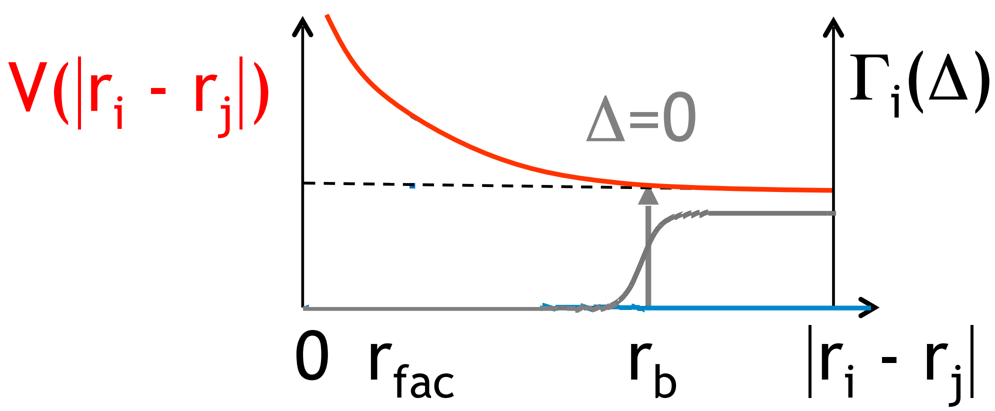
In the presence of Rydberg-Rydberg interactions, Γ now depends on the interparticle distance and on the detuning Δ

$$\partial_\tau \mu = \sum_k \Gamma_k (\sigma_x^k \mu \sigma_x^k - \mu)$$



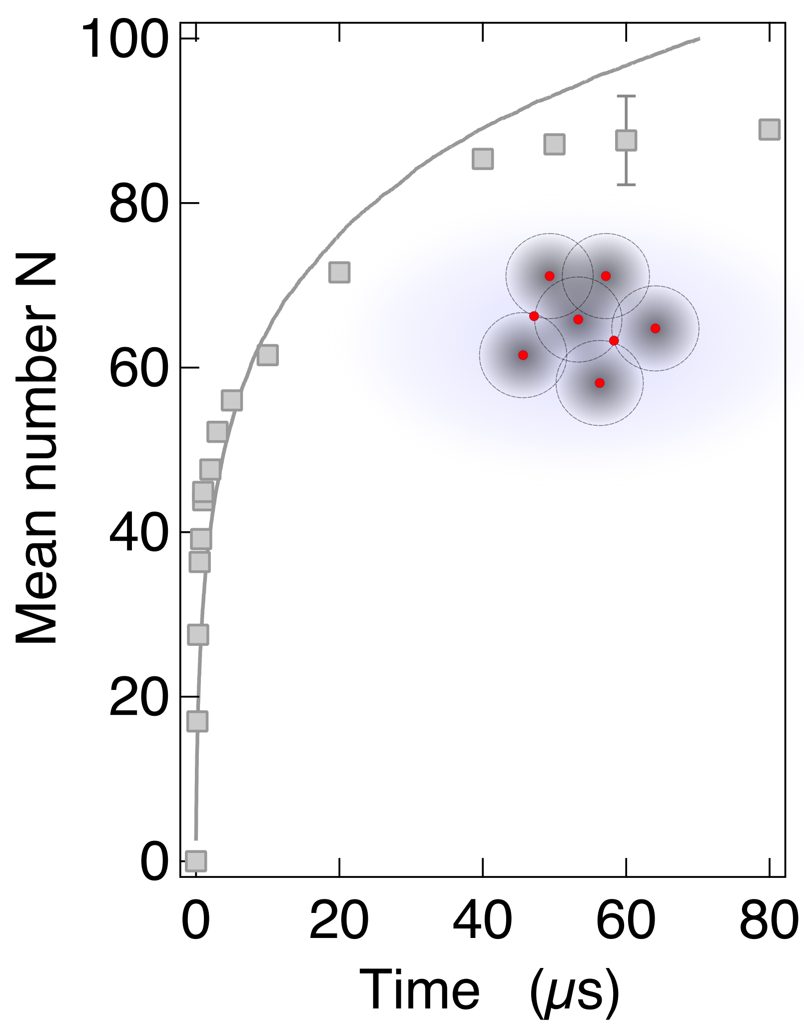


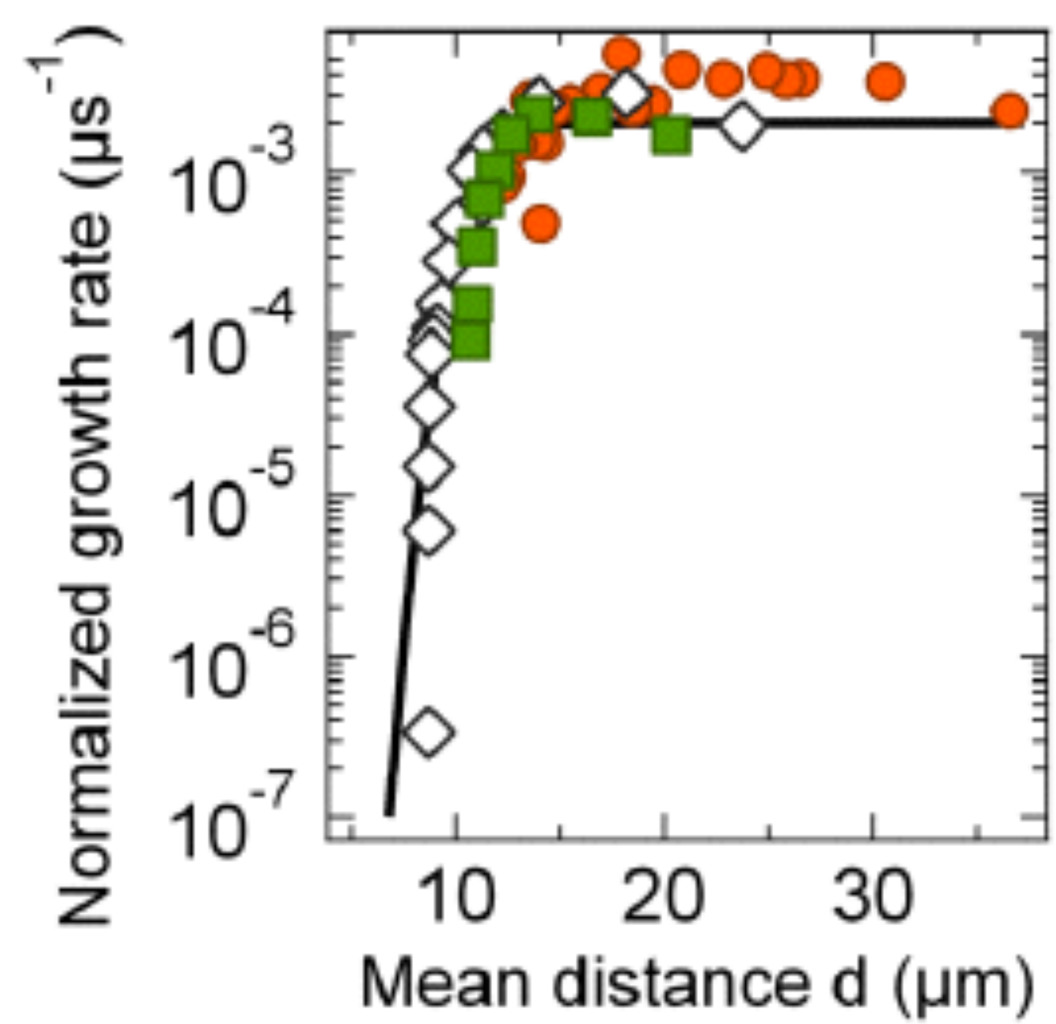
Blockade constraint:anti-correlated dynamics



$$\Gamma_i(\mathrm{N}) = \frac{\Omega^2}{2\gamma}\left[1 + \left(\frac{\frac{1}{\hbar}\sum_{i\neq j} V_{ij} n_j}{\gamma}\right)^2\right]^{-1}$$

$$V_{i,k} = \frac{C_6}{|r_i - r_k|^6}$$

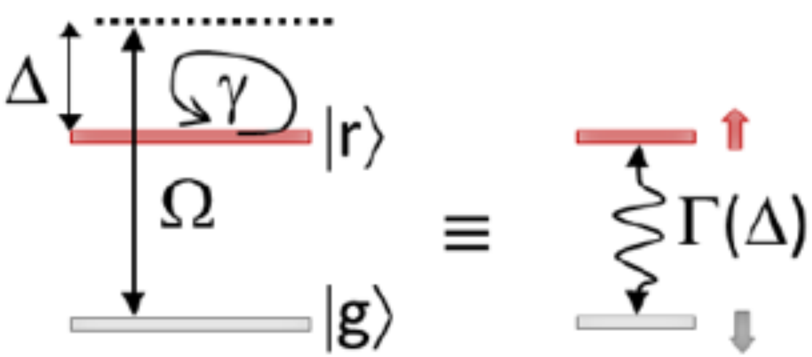




- growth rate per atom only depends on mean distance d between excited atoms

M.M. Valado et al., Phys. Rev. A ***93****, 040701(R) (2016)*

Facilitation constraint: correlated dynamics



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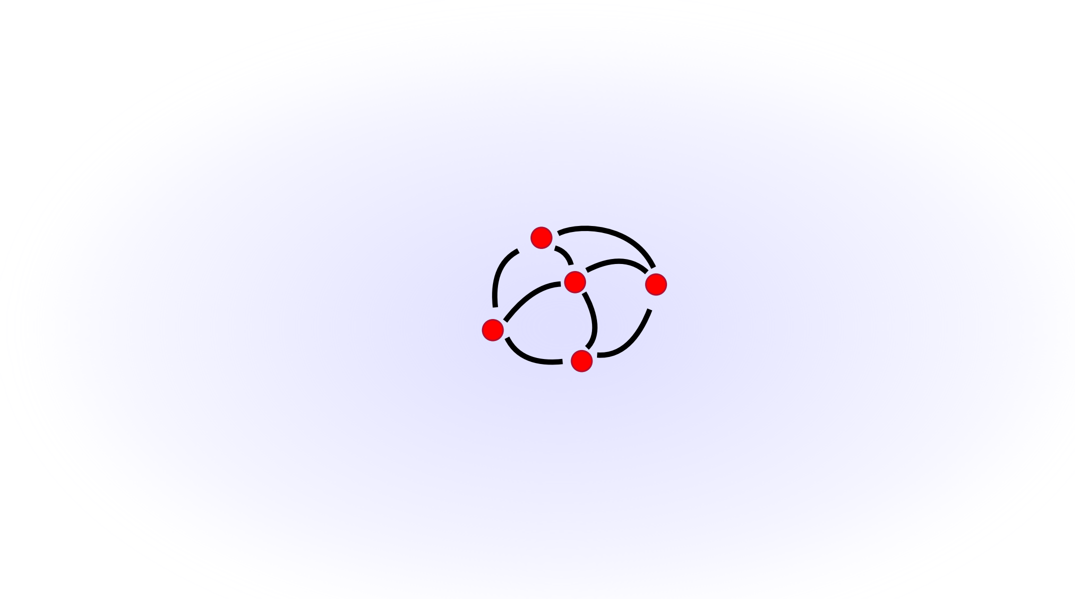
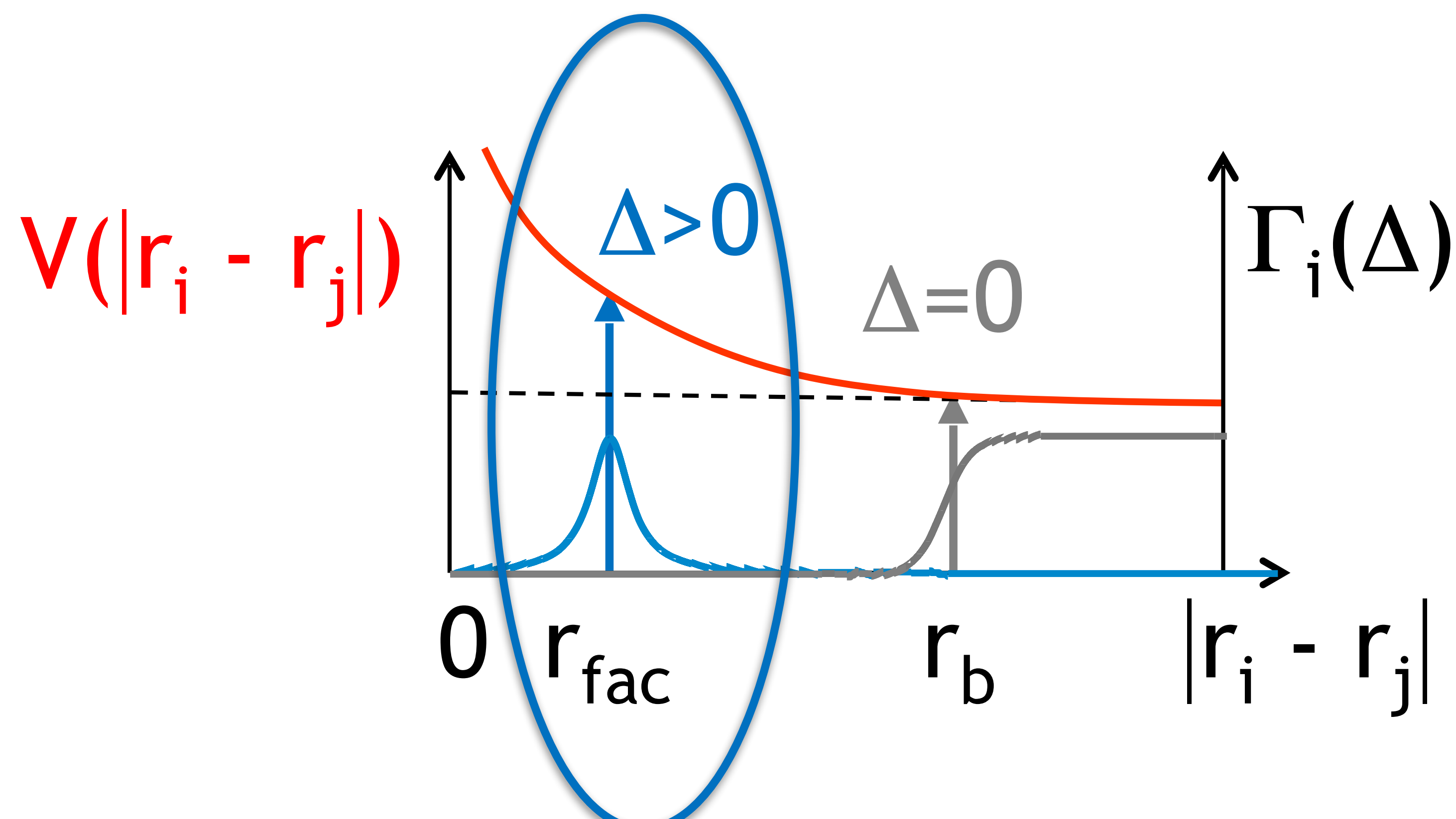
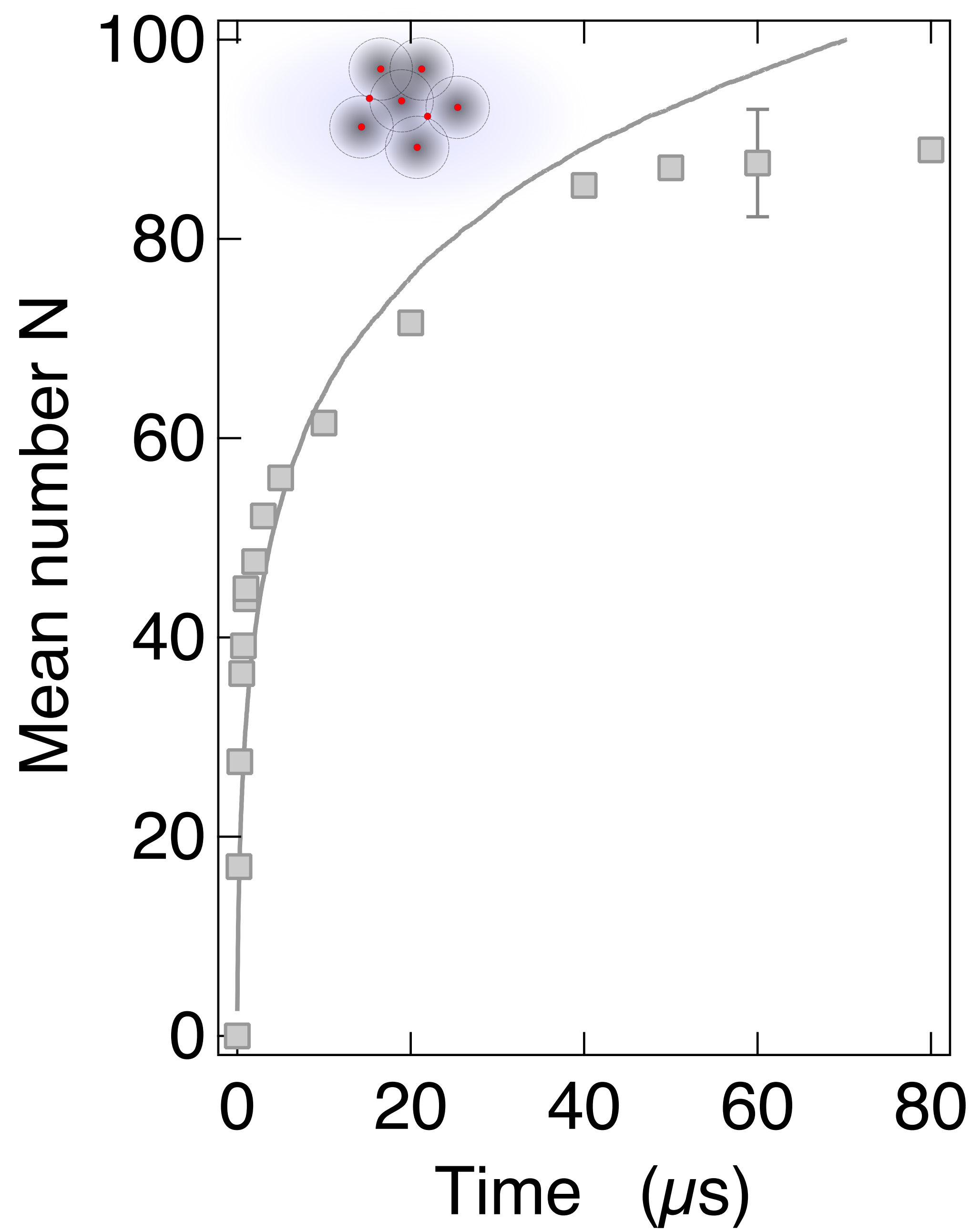


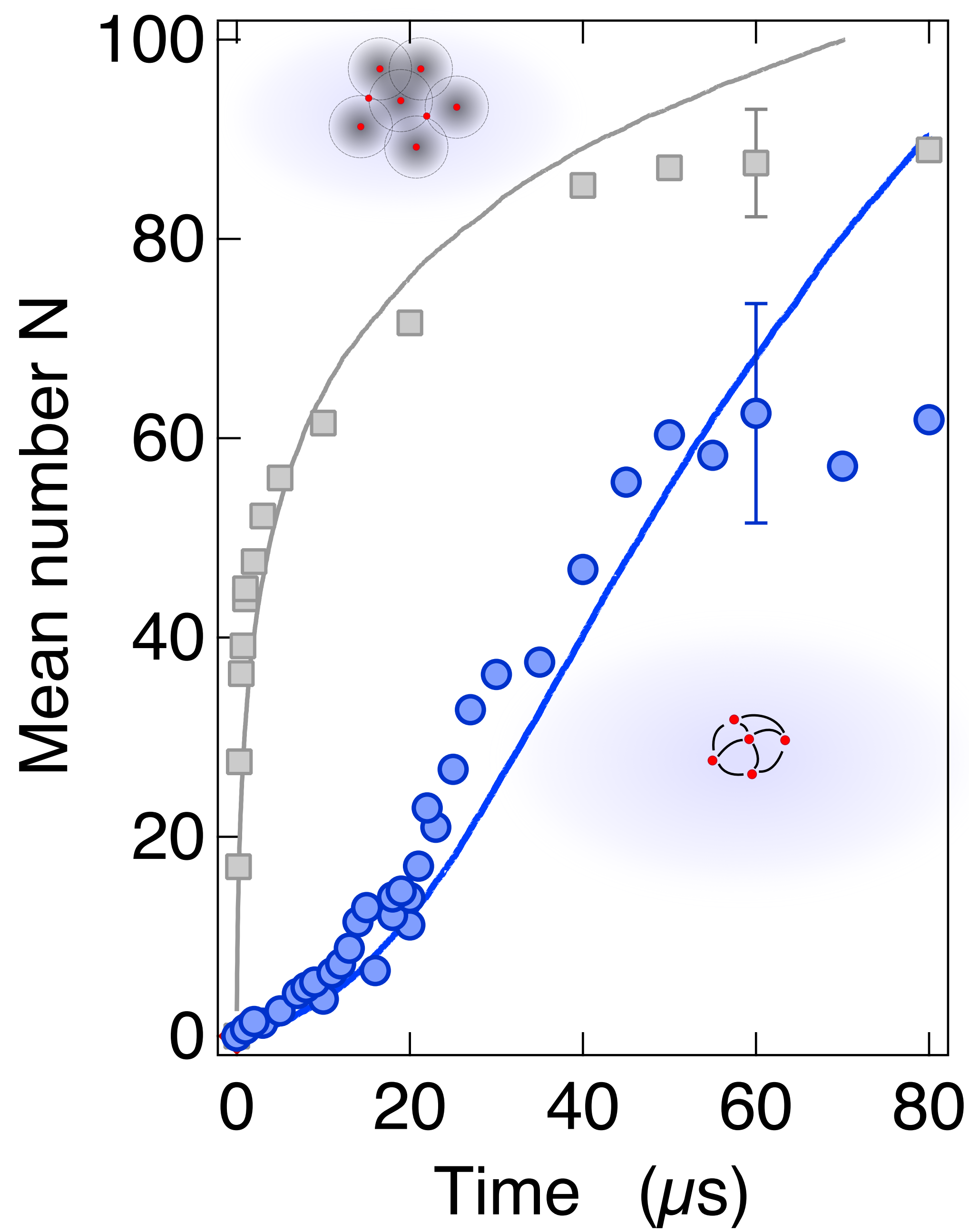


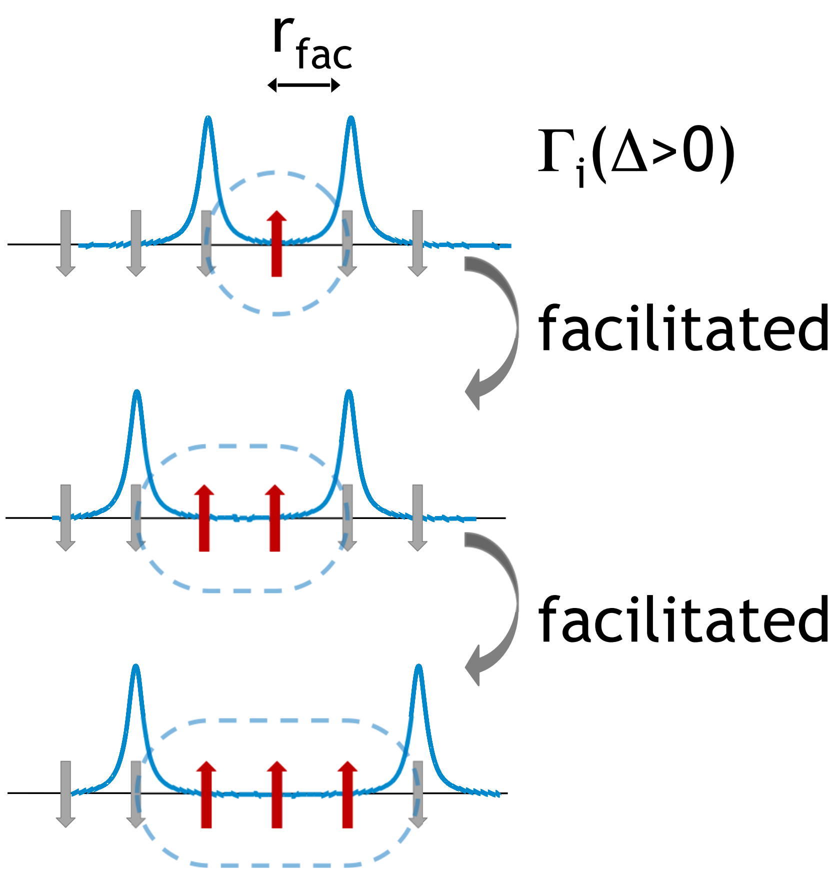
Kinetic constraints in Rydberg gases



M.M. Valado et al., Phys. Rev. A **93**, *040701(R) (2016)*

Facilitation constraint: correlated dynamics

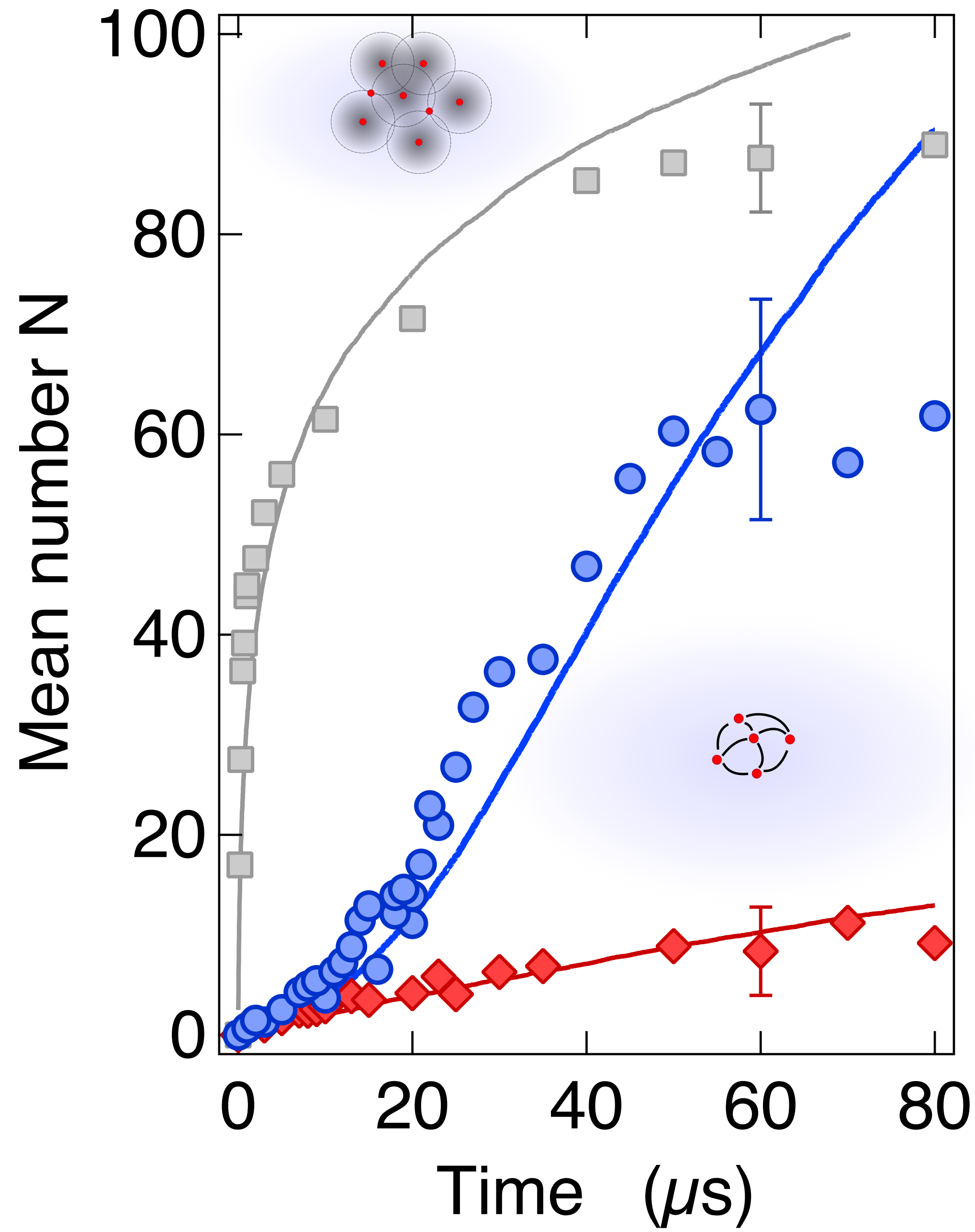


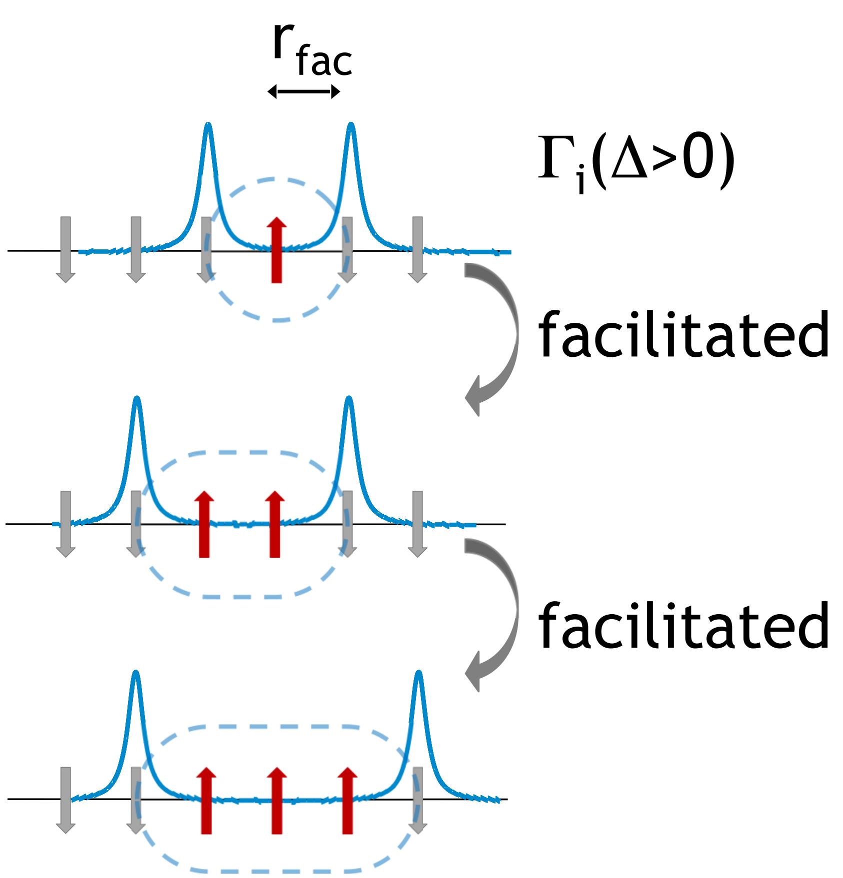


three stages:
nucleation, facilitation and saturation reflect the nature of the constraint

M.M. Valado et al., Phys. Rev. A ***93****, 040701(R) (2016)*

Facilitation constraint: correlated dynamics





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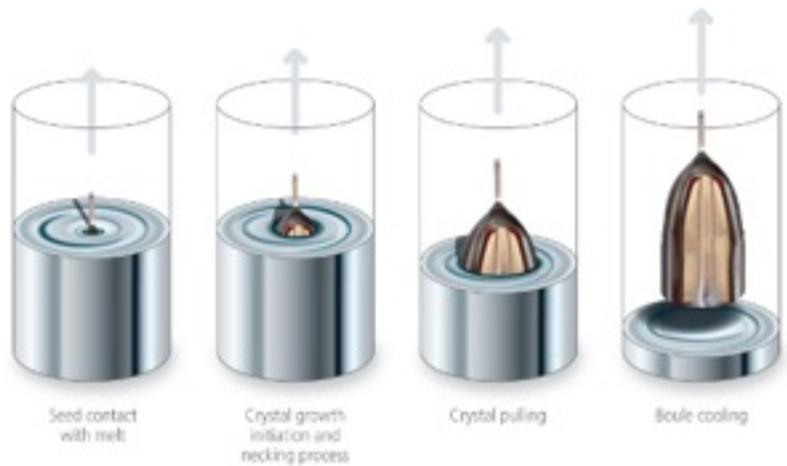
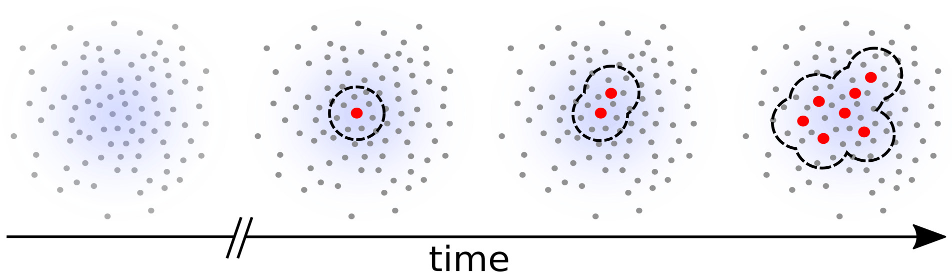
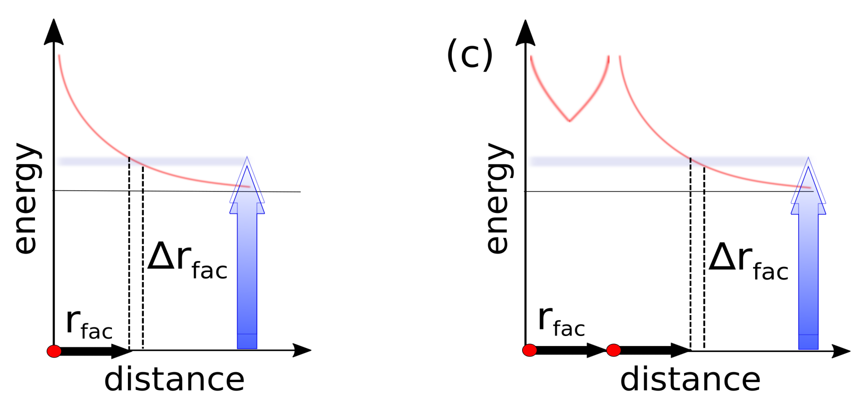
M.M. Valado et al., Phys. Rev. A ***93****, 040701(R) (2016)*

Seeded avalanche process







Probability to have at least one excitation

$$P(N > 0) = 1 - e^{-\langle N_{seed} \rangle}$$

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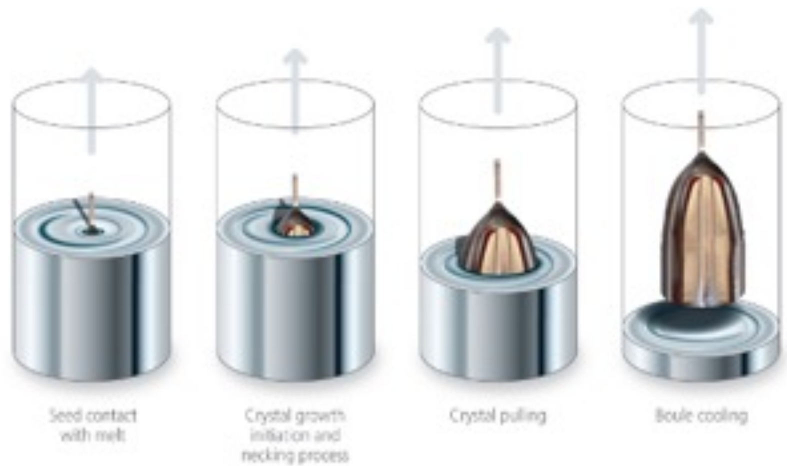

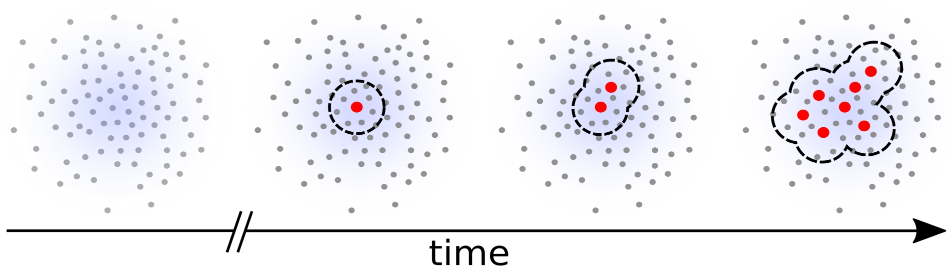

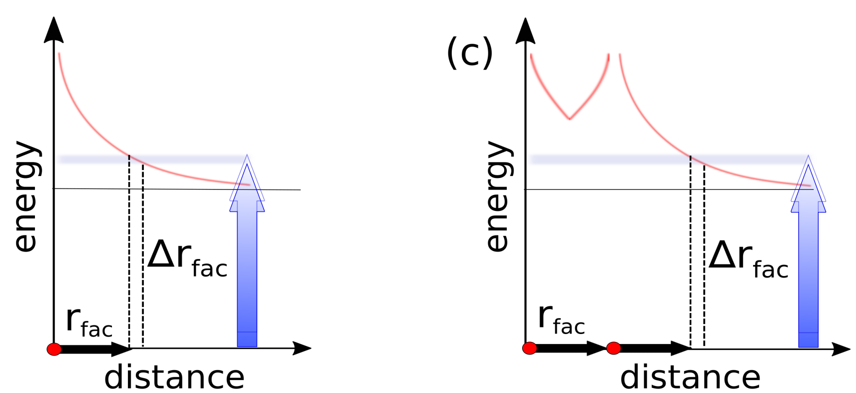

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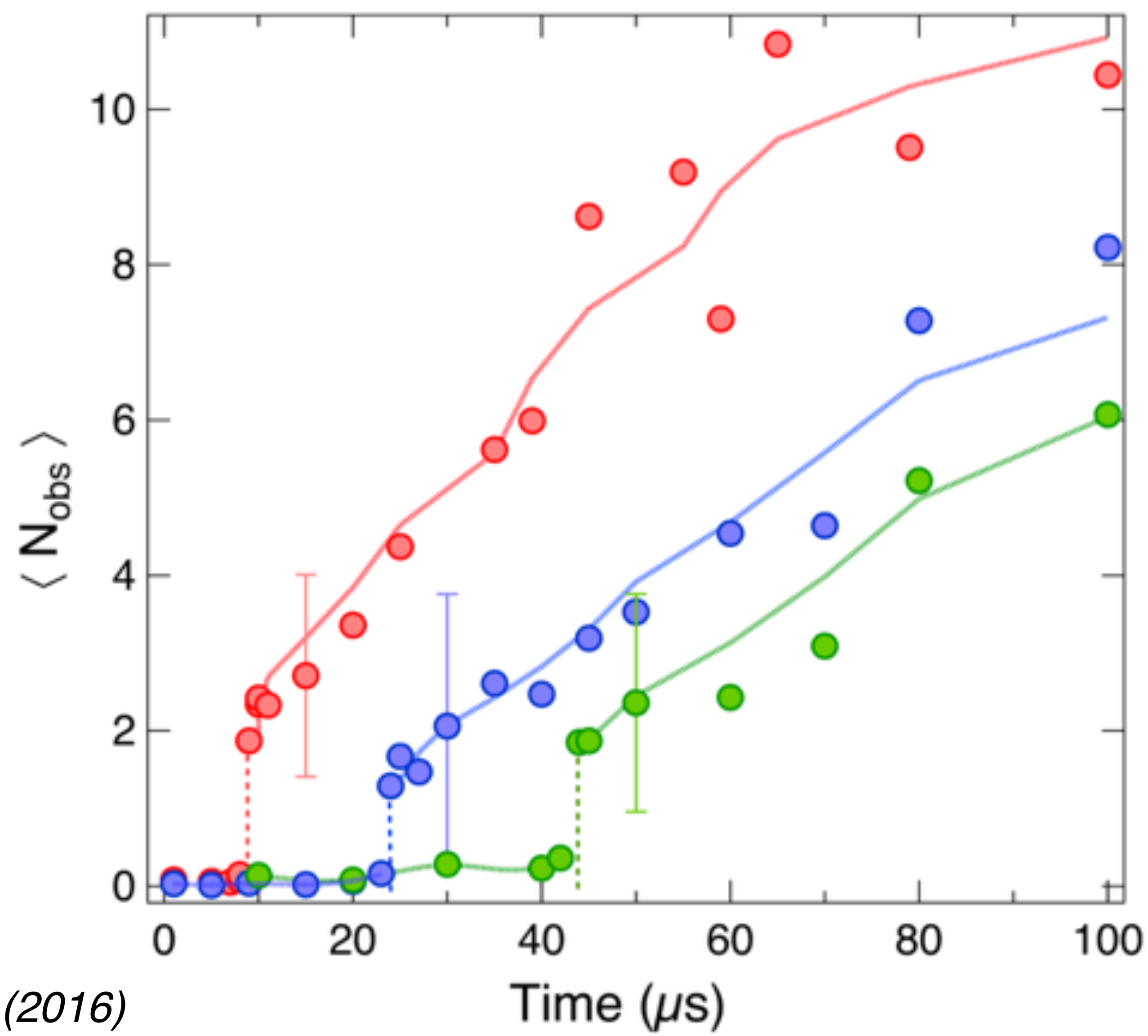
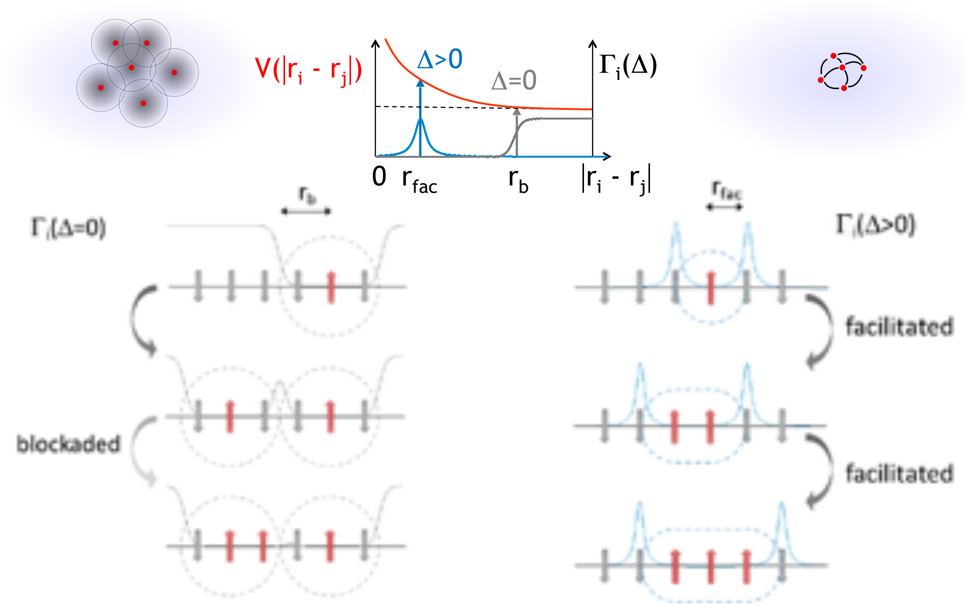


Triggered the avalanche process:

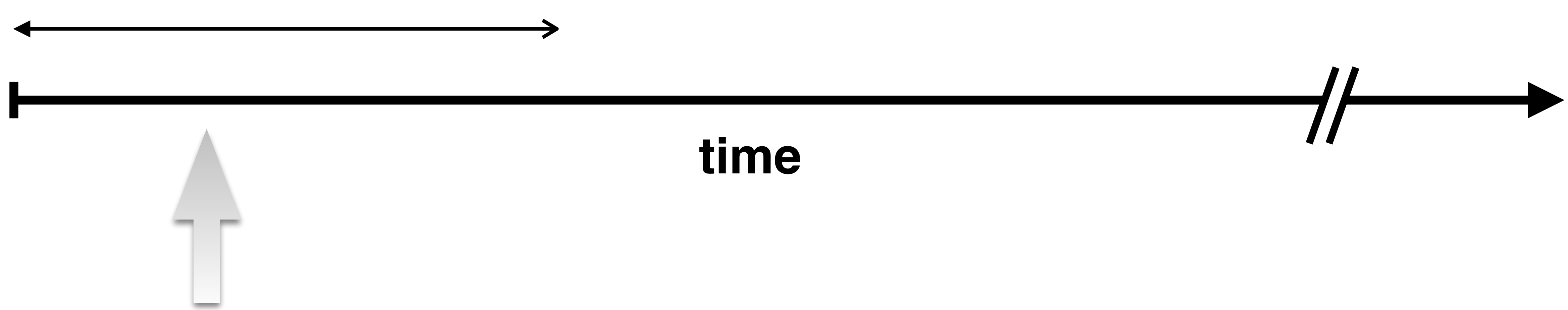
- t_{seed} =10 μs (red)
- t_{seed} =25 μs (blue)
- t_{seed} =45 μs (green)

C. *Simonelli et al., J. Phys. B: At. Mol. Opt. Phys.* **49** *154002 (2016)*

Towards the dissipative regime



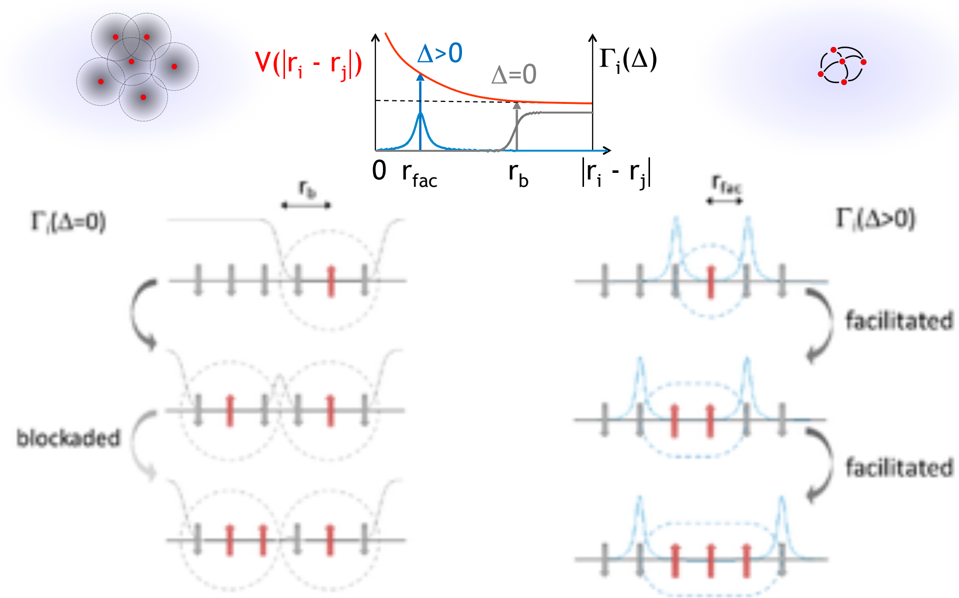
τ_{life} (70S Rydberg state lifetime)



t << τ_{life}

Non Dissipative Regime

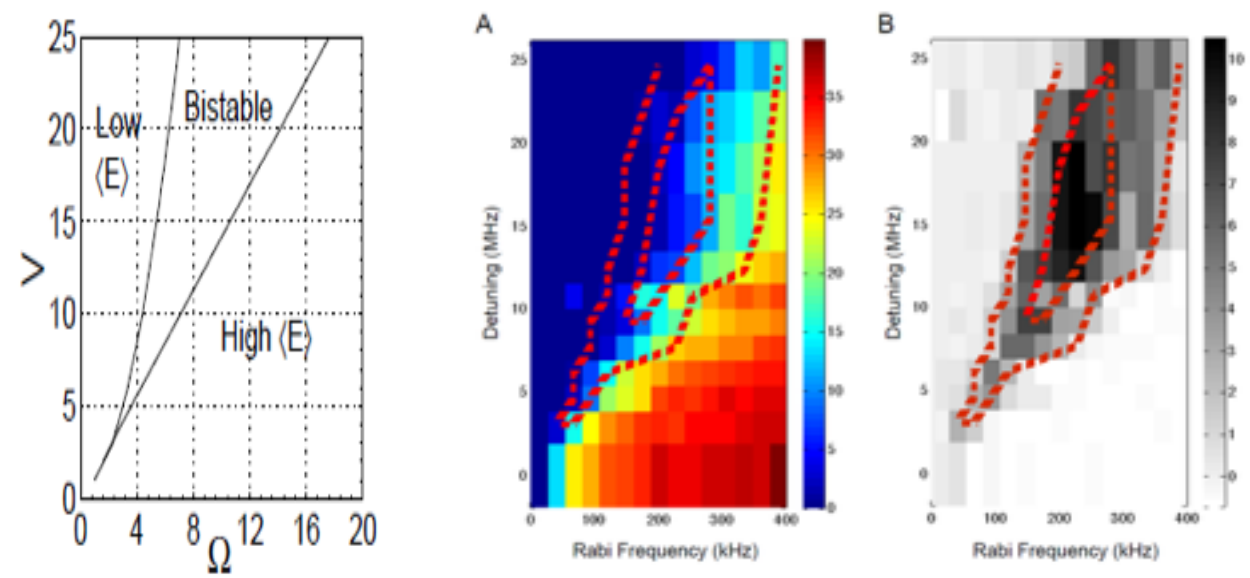
Towards the dissipative regime



Malossi, N. et al. Phys. Rev. Lett. **113**, *023006 (2014)*

see also Schempp, H. *et al. Phys. Rev. Lett.* 112, 013002 (2014)

and H. Weimer, Phys. Rev. A 91, 063401 (2015)



τ_{life} (70S Rydberg state lifetime)

time

$t \ll \tau_{life}$

$t \gg \tau_{life}$

Non Dissipative Regime

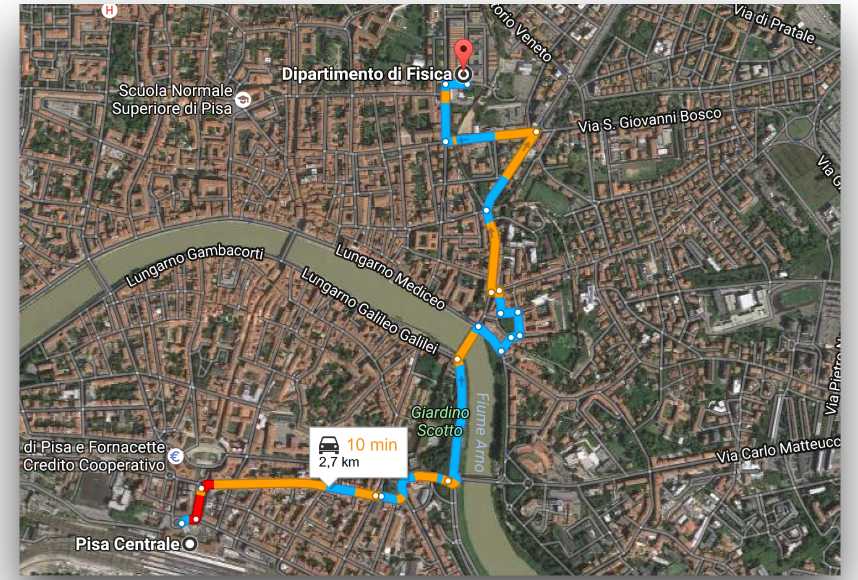
Dissipative Regime

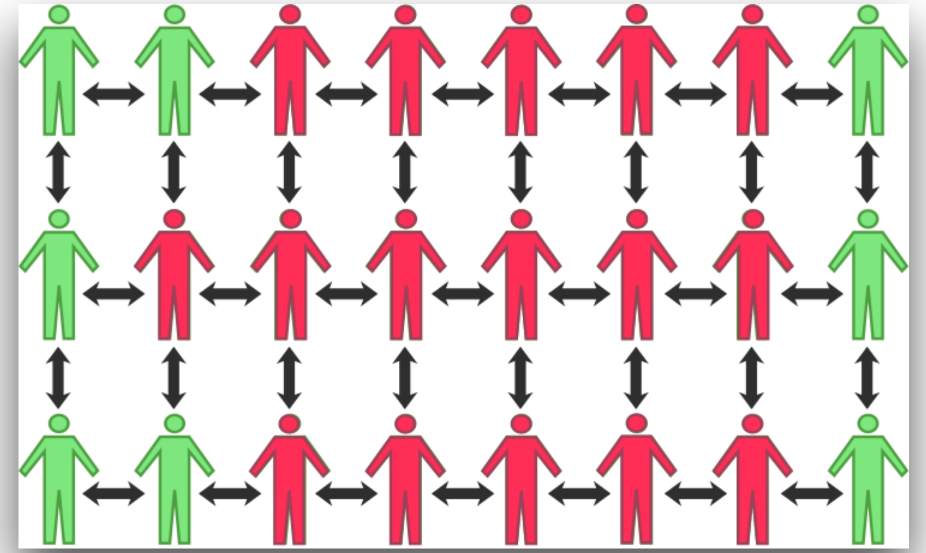
Percolation Process

The percolation is one of the simplest process showing a phase transition.

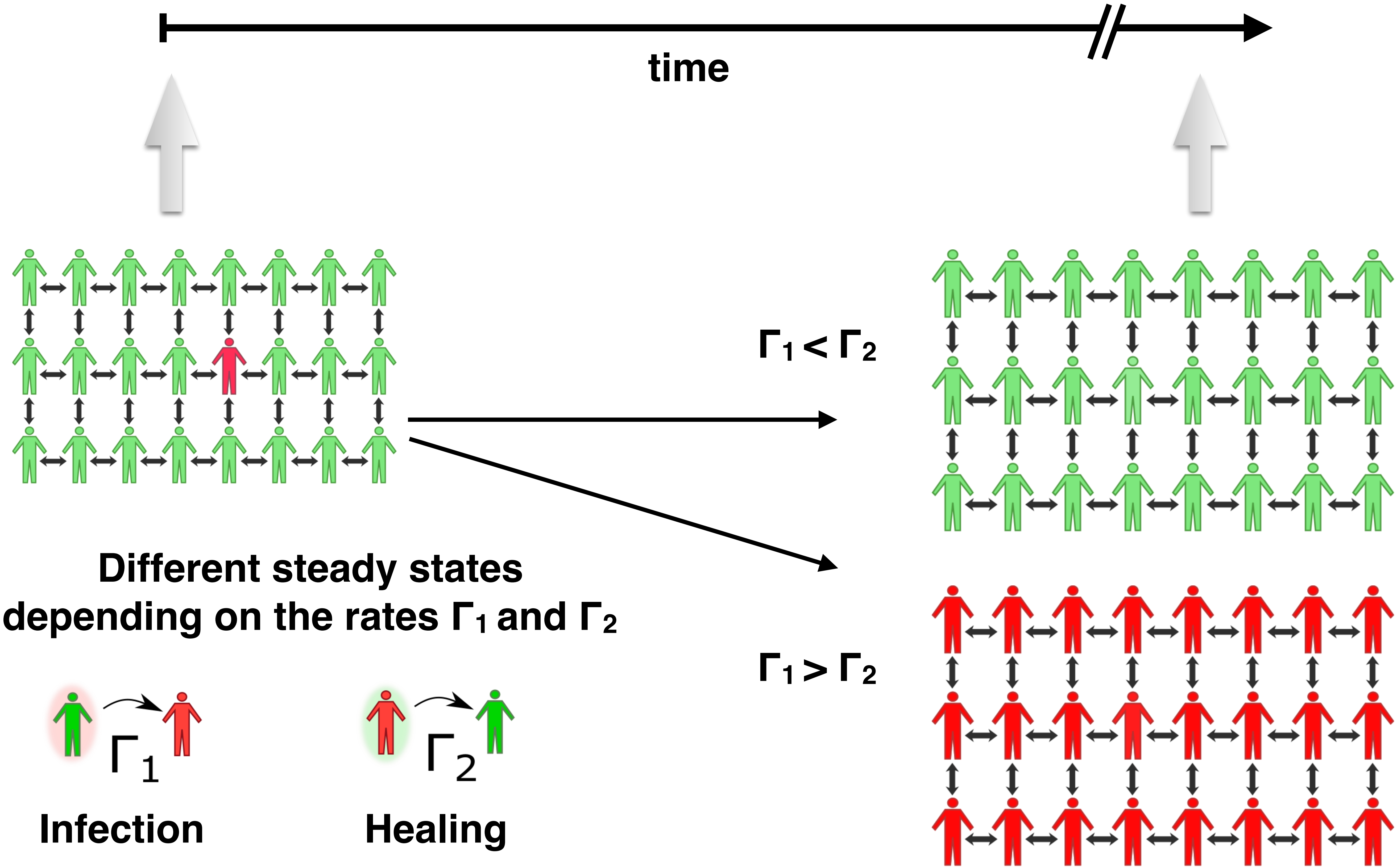
- ***Isotropic Percolation*** (any preferred direction)

- ***Directed Percolation* (DP)** (one preferred direction in space or in time)



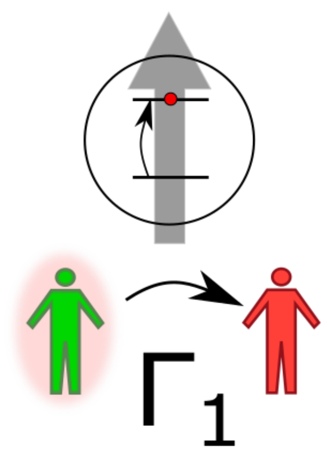


Infection spreading process (DP)

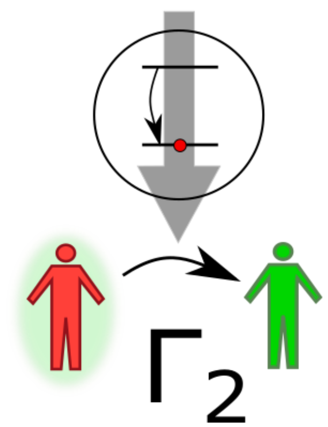


Facilitation in dissipative Regime

- Off resonant excitation to the Rydberg state and decay to the ground state mimic the basic infection mechanisms

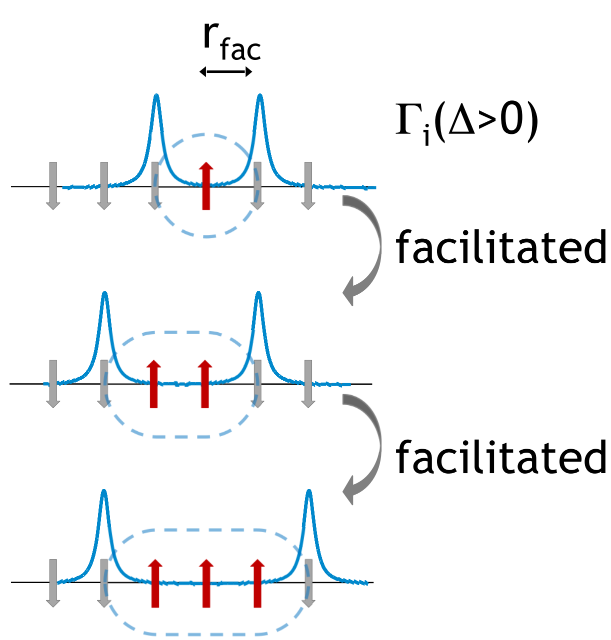


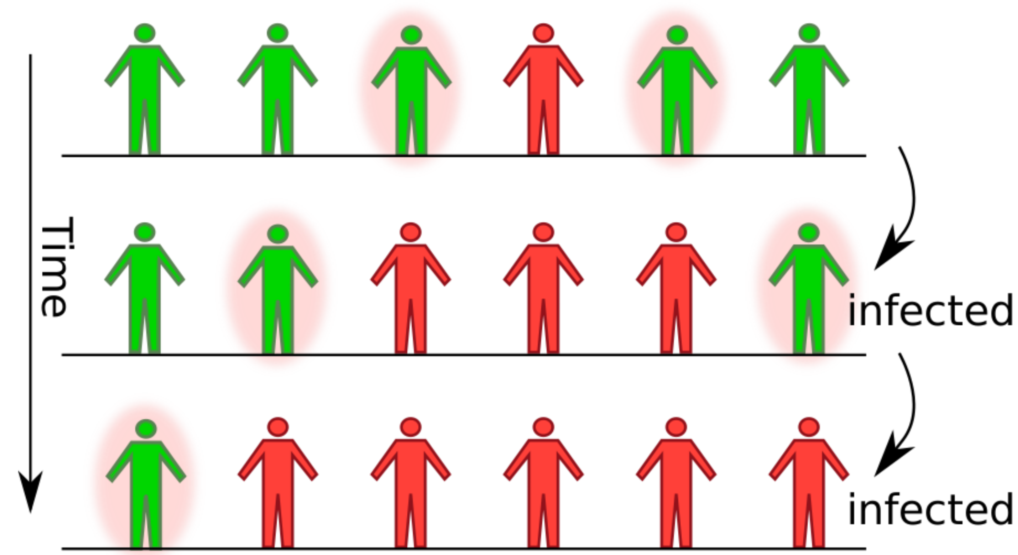
Infection



Healing

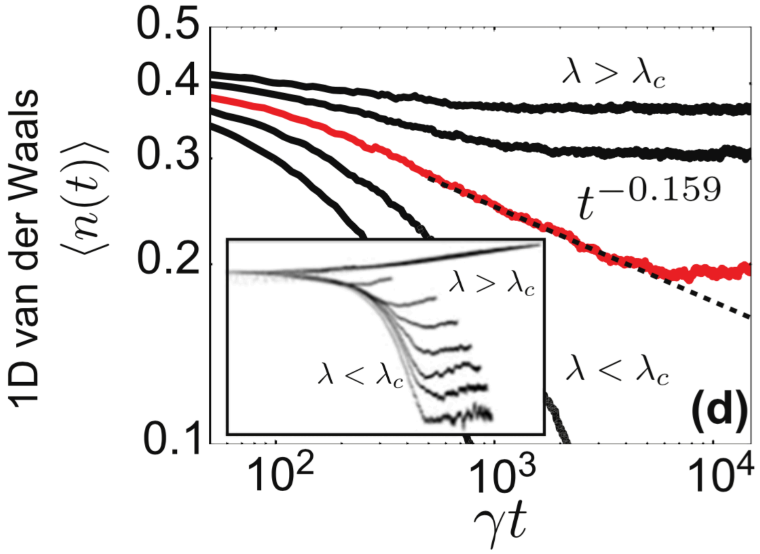
- Interaction dependence of the excitation rate Γ(Δ) simulate the connections between sink people

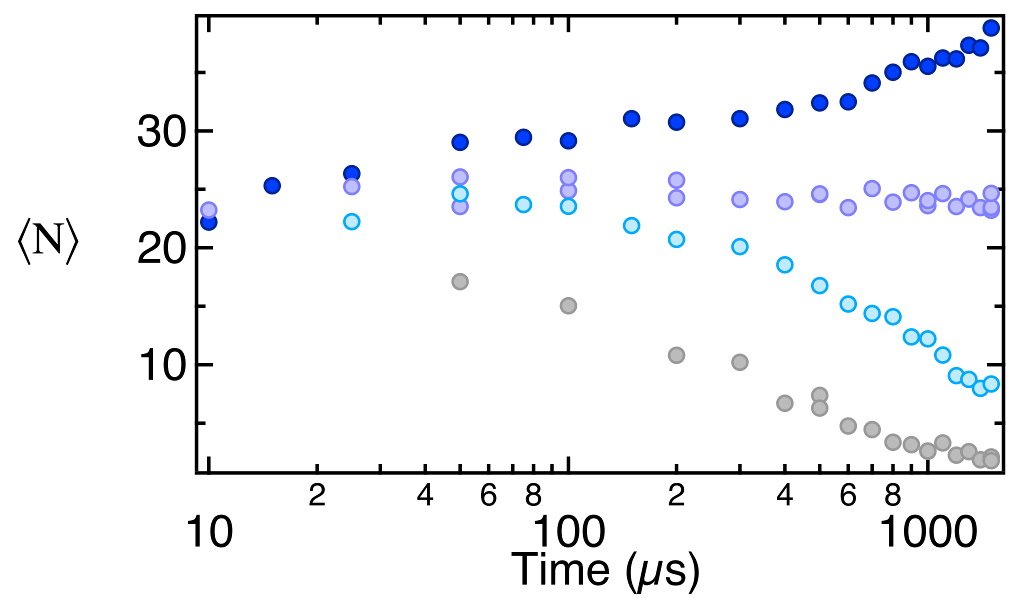




Preliminary Results of DP in 1D Rydberg atom system

- Time dependence with different excitation rates
- Off resonant excitation $\Delta/2\pi$ = +10 MHz





M. Marcuzzi et al., New J. Phys. **17** *072003 (2015)*

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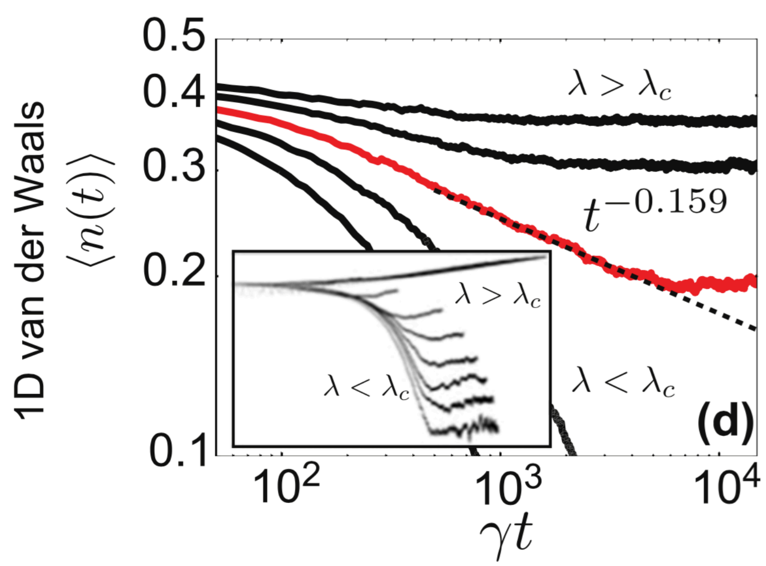
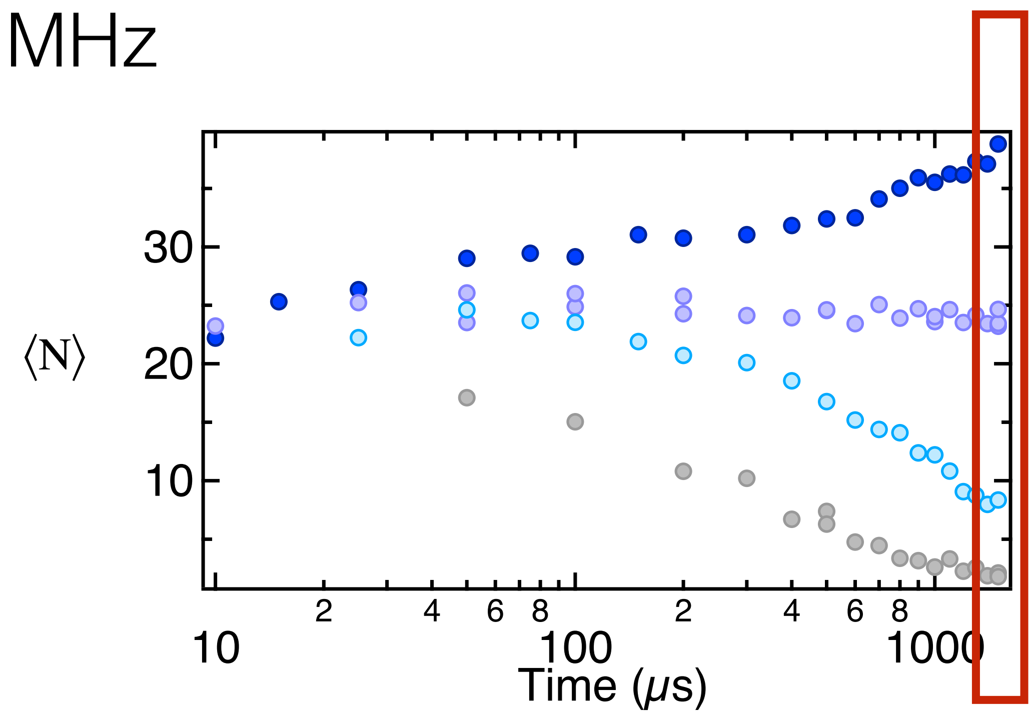
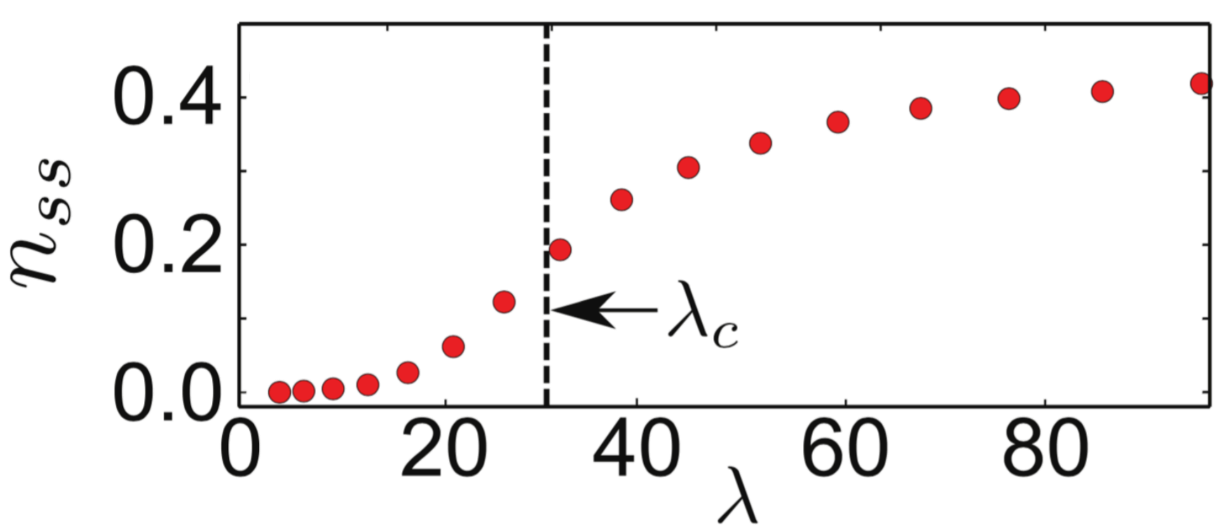
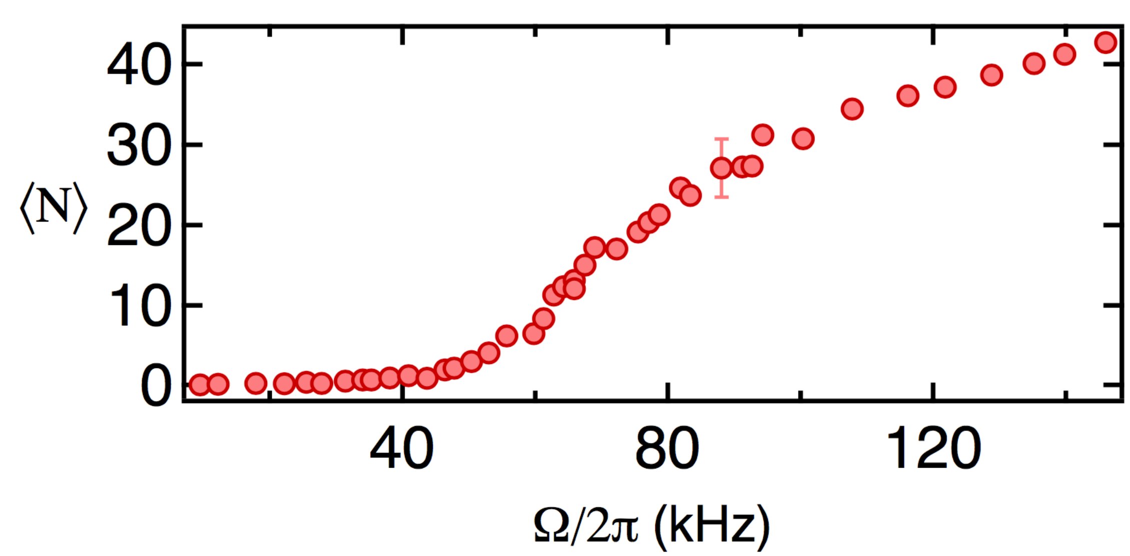




- Power dependence at 1500 μs excitation laser pulse >> decay time (around 150 μs for the 70S)





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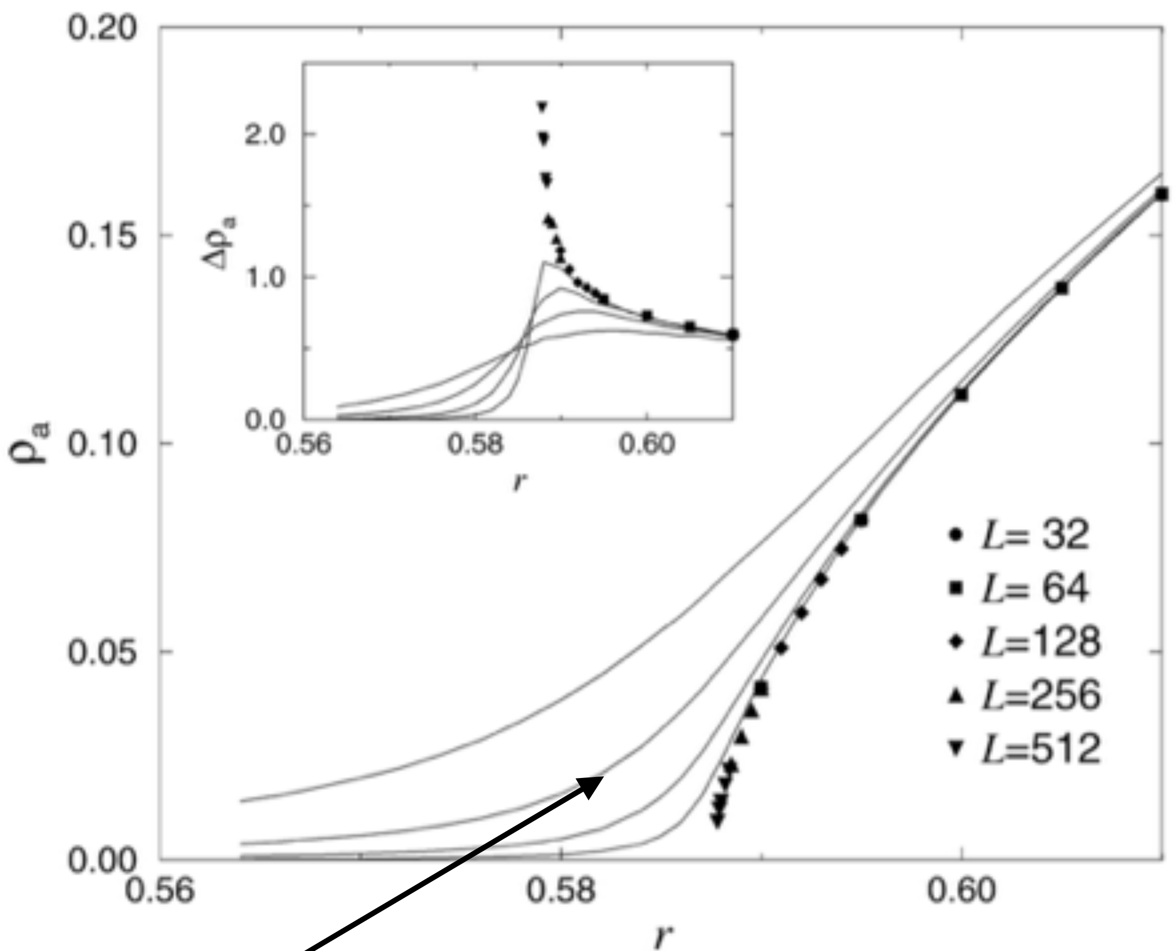
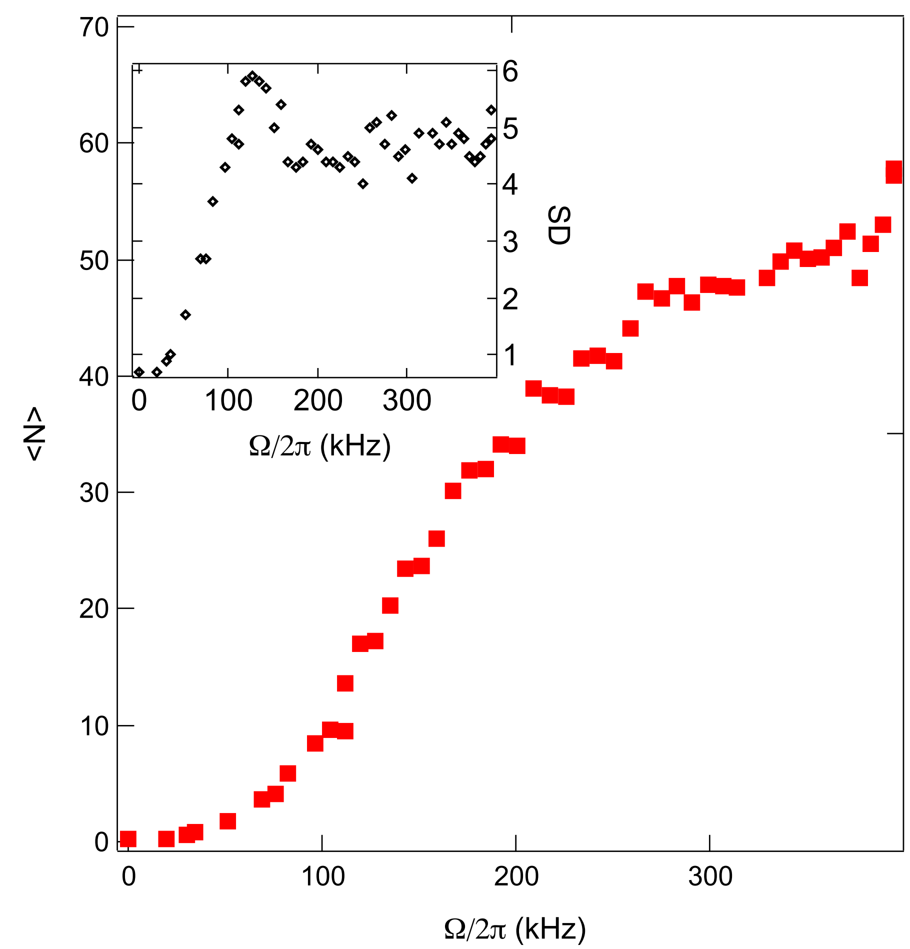
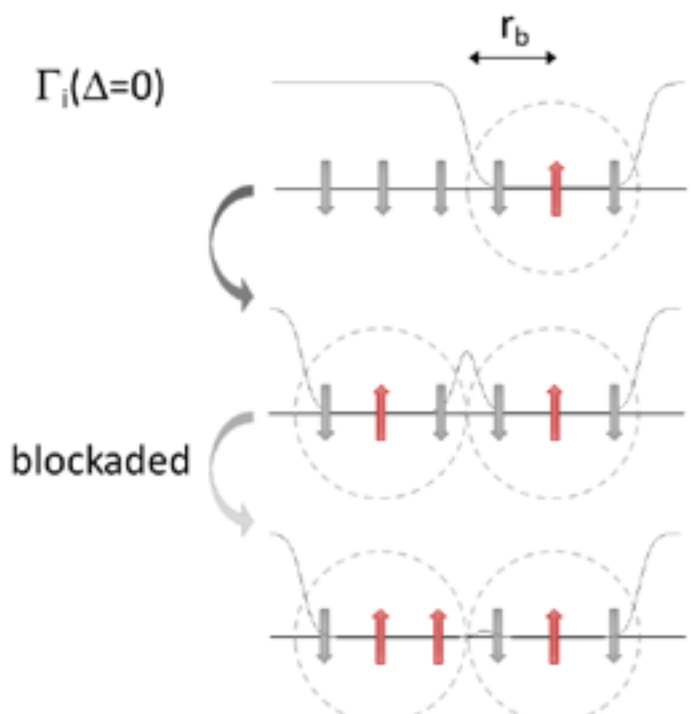


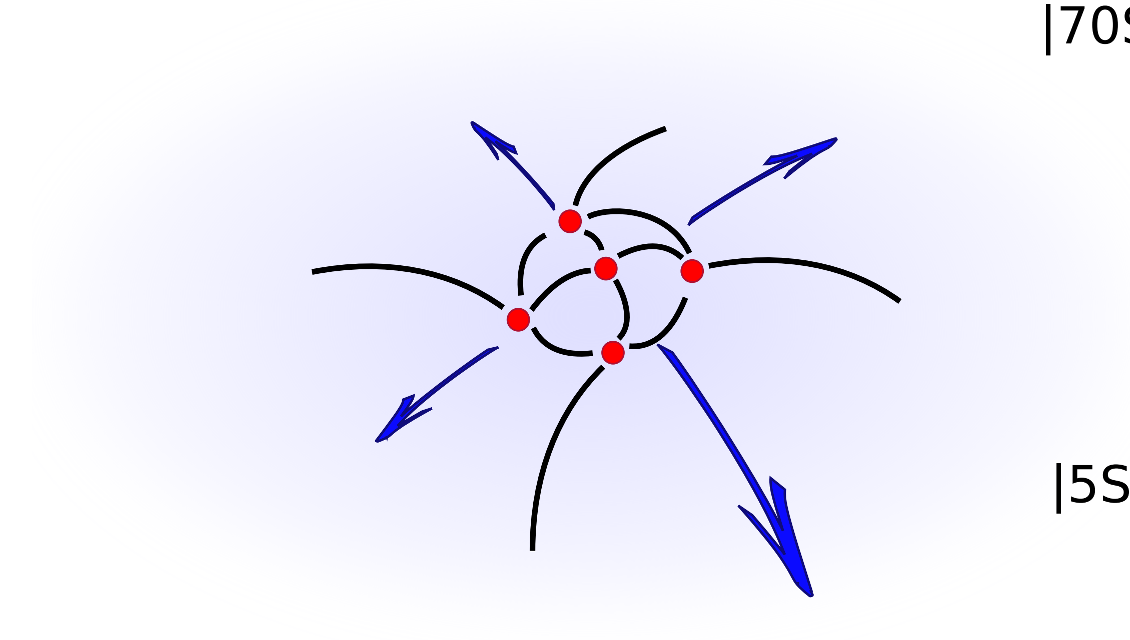


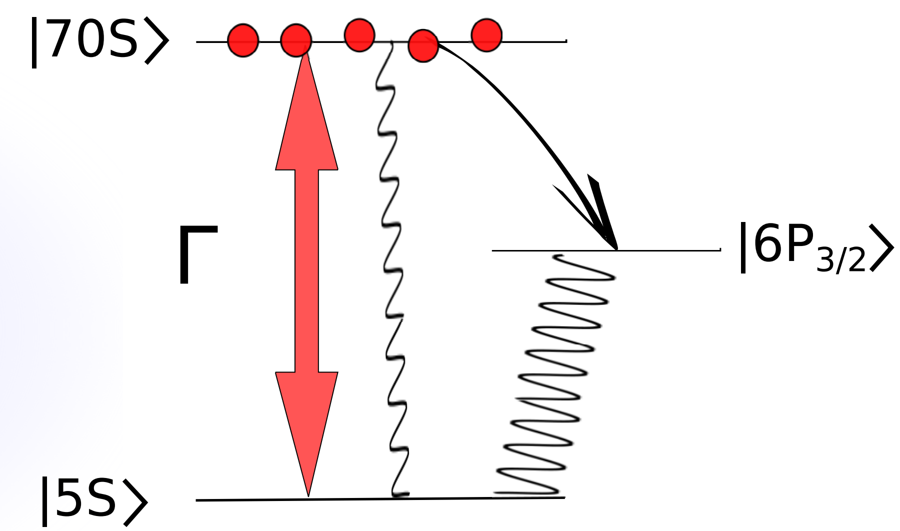
Perturbation of the model:
spontaneous generation of seeds

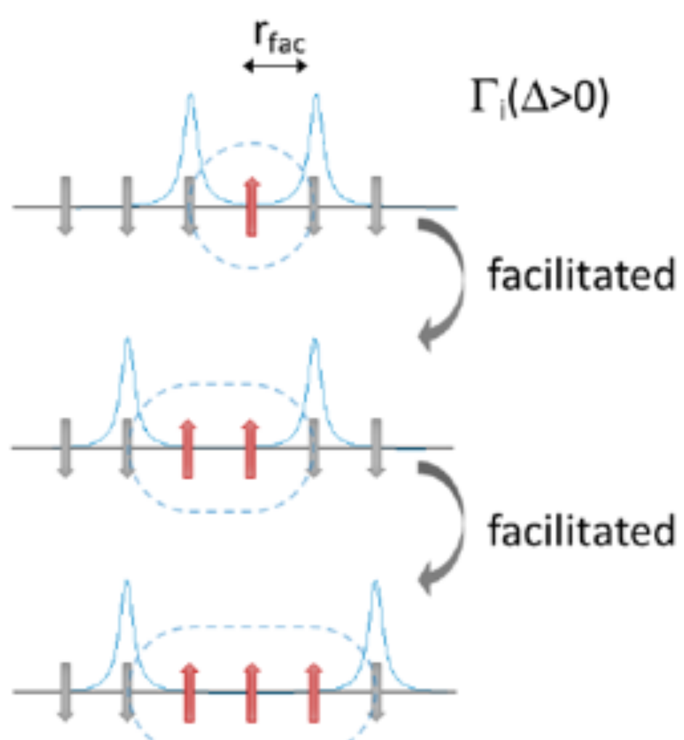
S. Lübeck, R.D. Willmann / Nuclear Physics B 718 [FS] (2005) 341–361

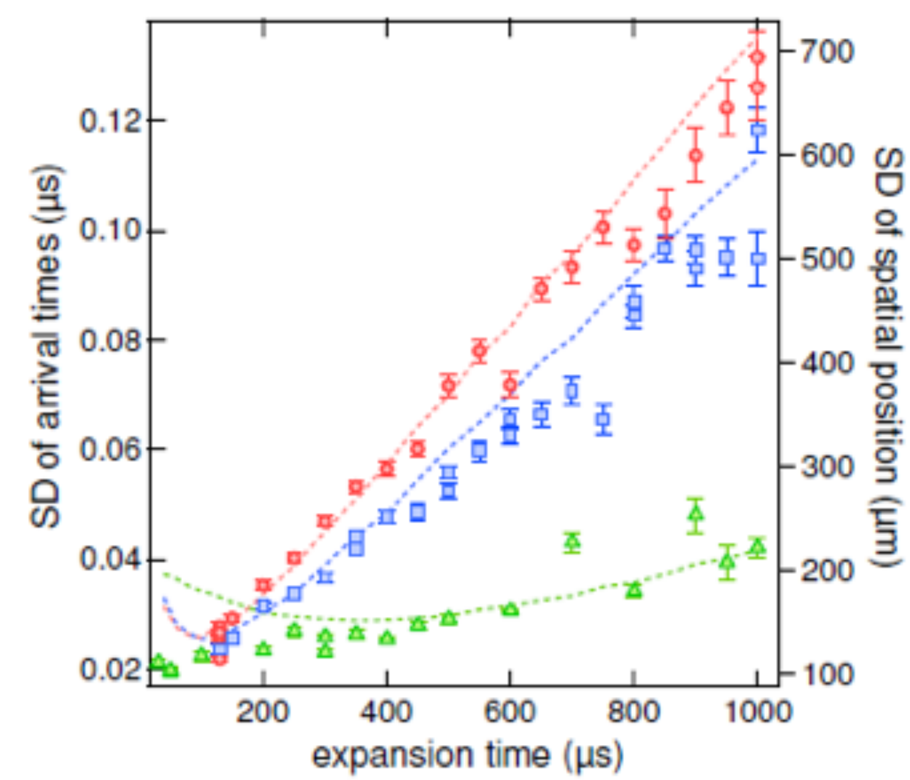
The Rydberg atom system











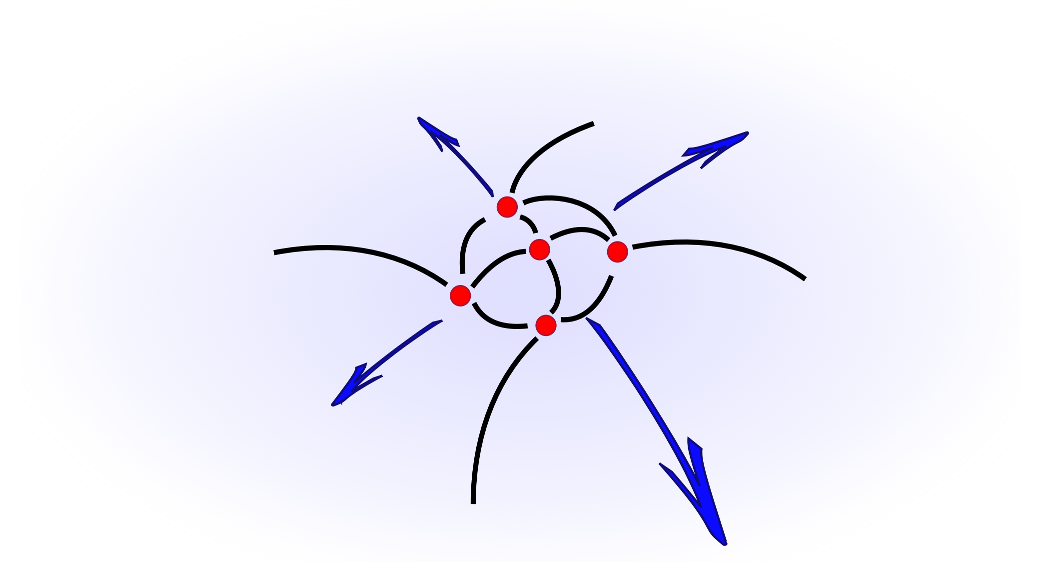
Conclusions

✓ **many body dynamics** can be studied in Rydberg gases: (anti-) correlated excitations

✓ interpretation in terms of **kinetic constraints and facilitation** in the non dissipative regime

✓ seeded **avalanche** mechanism

✓ **seeded avalanche** in the dissipative regime: absorbing state transition



Last PhD year plan

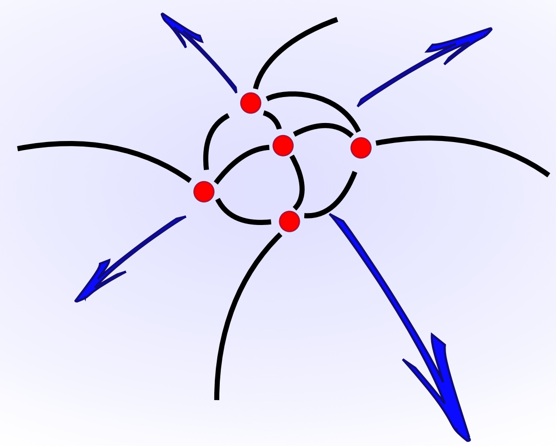
- **Use the de-excitation technique to make state selective measurement: lifetime of the target Rydberg state, coupling to different Rydberg states…**

(*The ionisation field does not distinguish states with n>40)*

- **Broad band controlled dissipation via the de-excitation technique**

(*The dissipative regime comes too late:*
vdW repulsion, Rydberg excitation migration)

thanks for your attention



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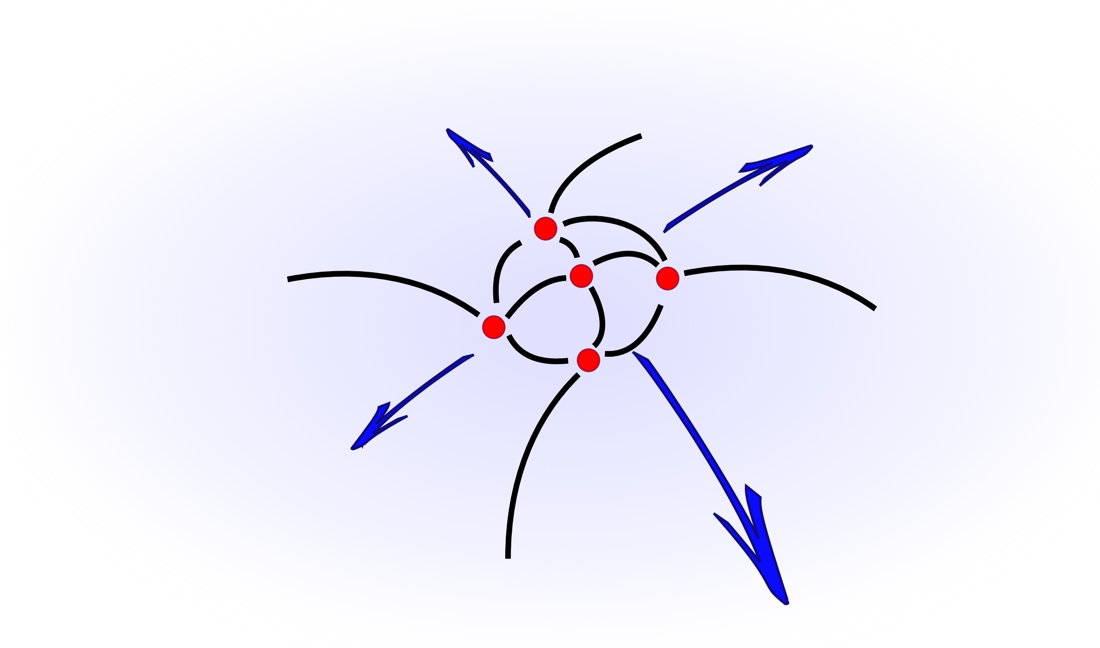
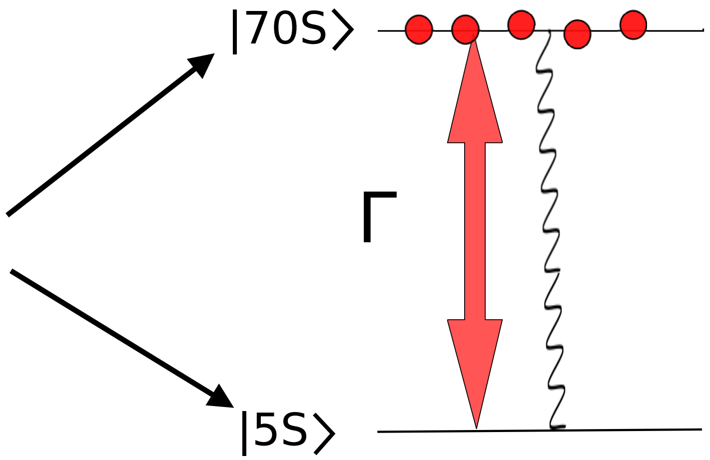
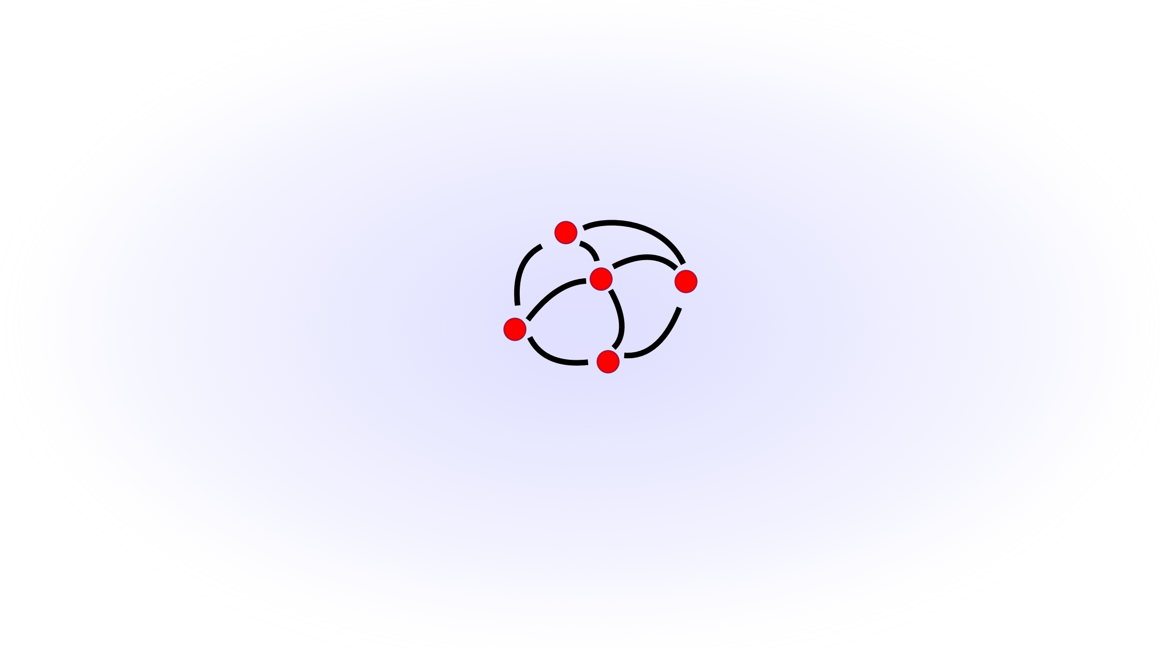


Open many body system

two levels system





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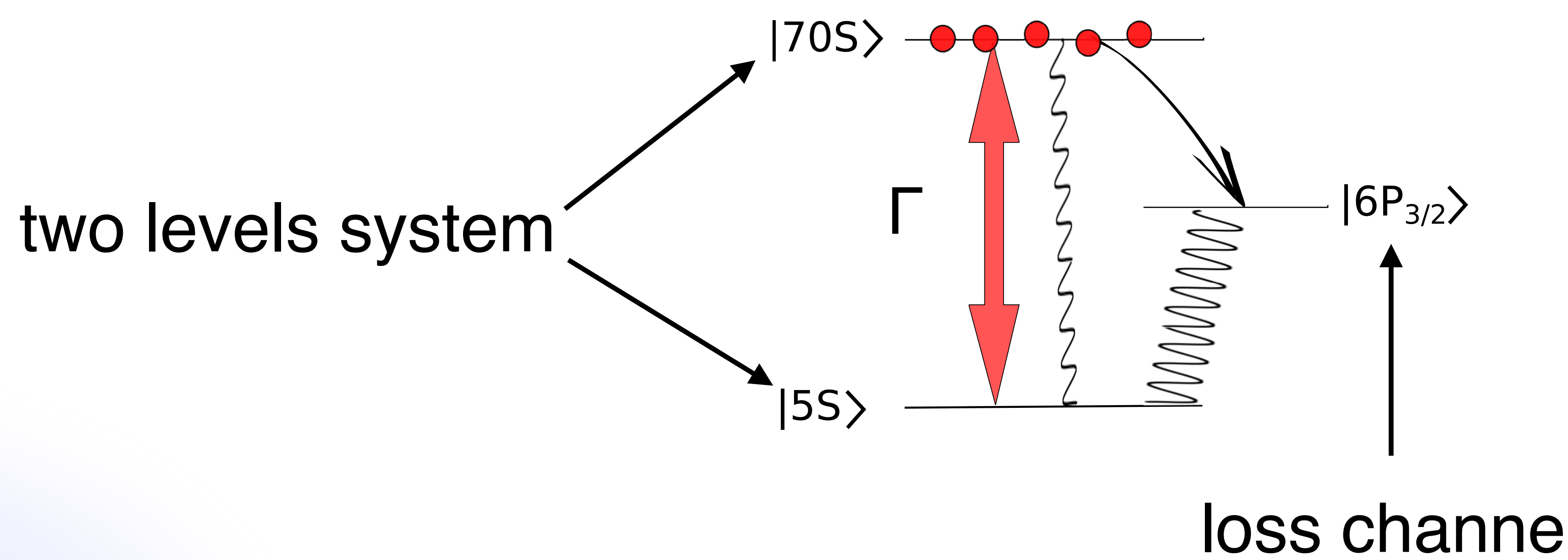
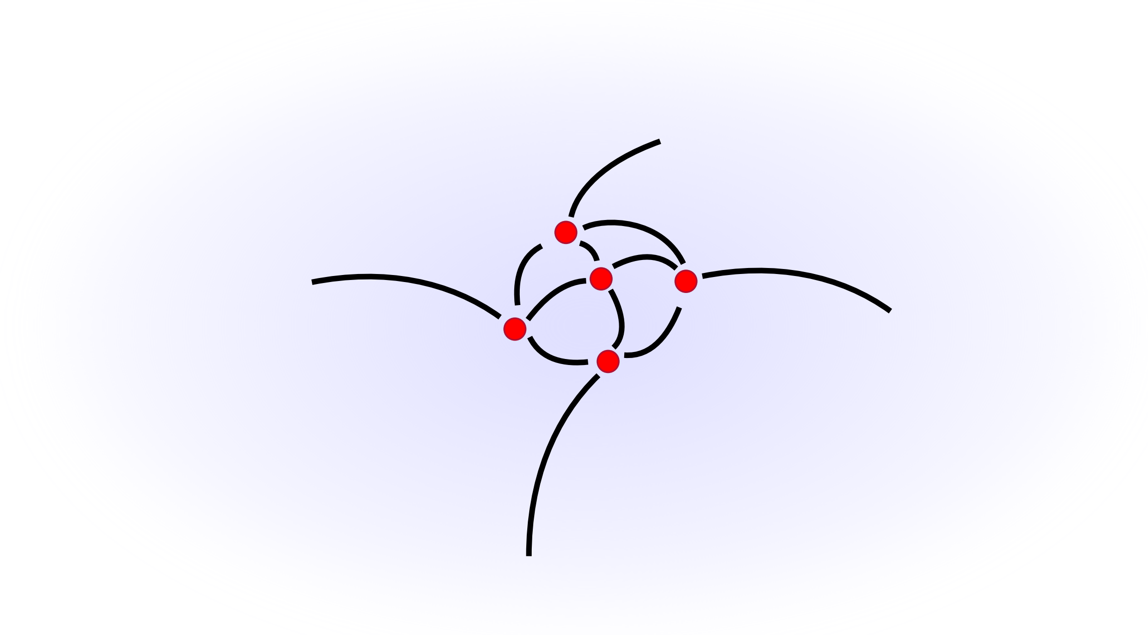
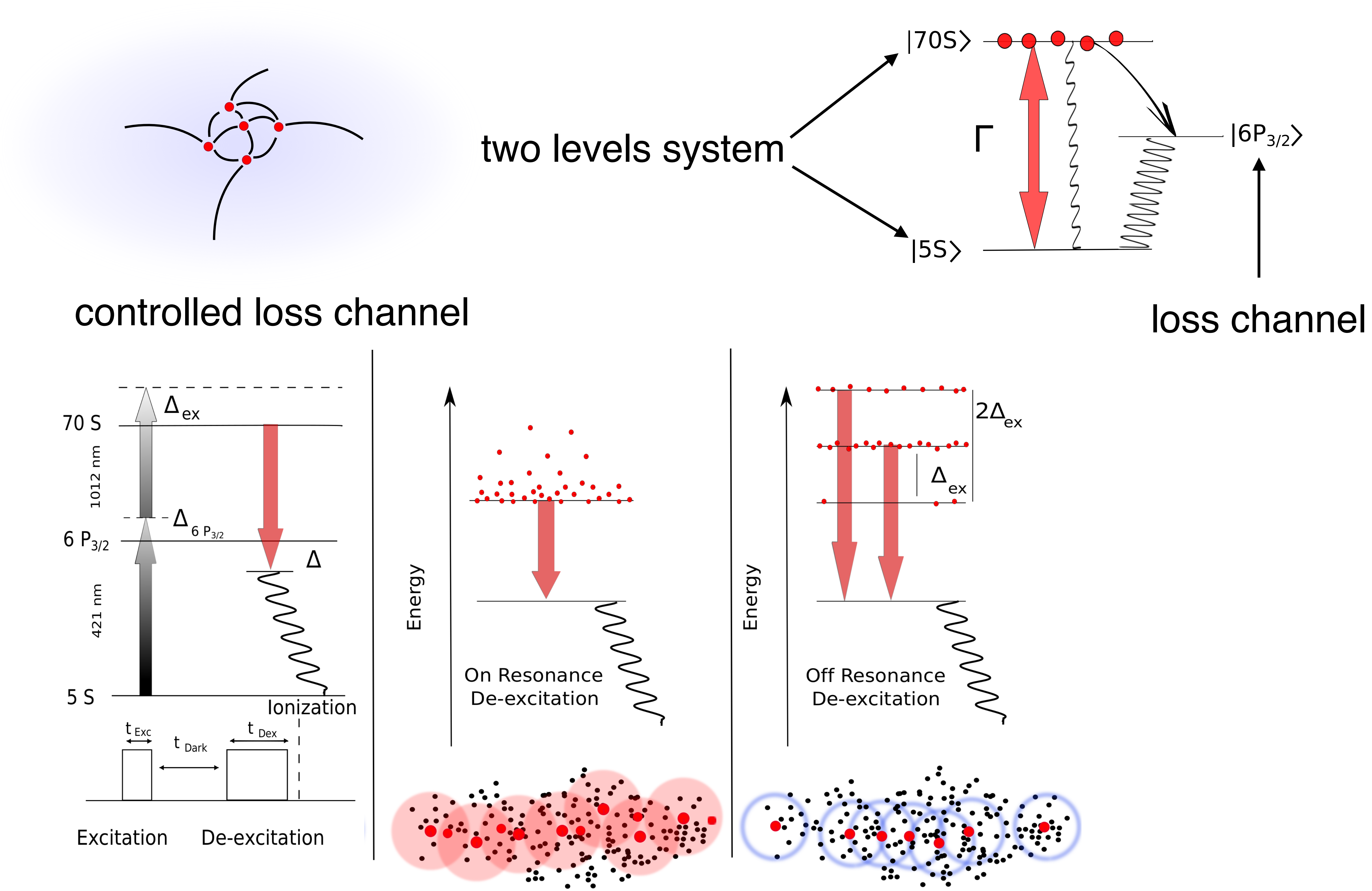
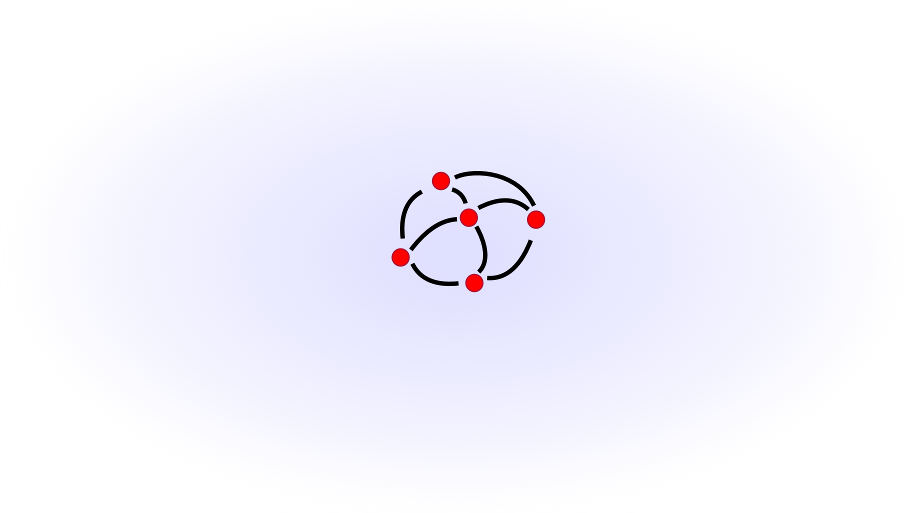


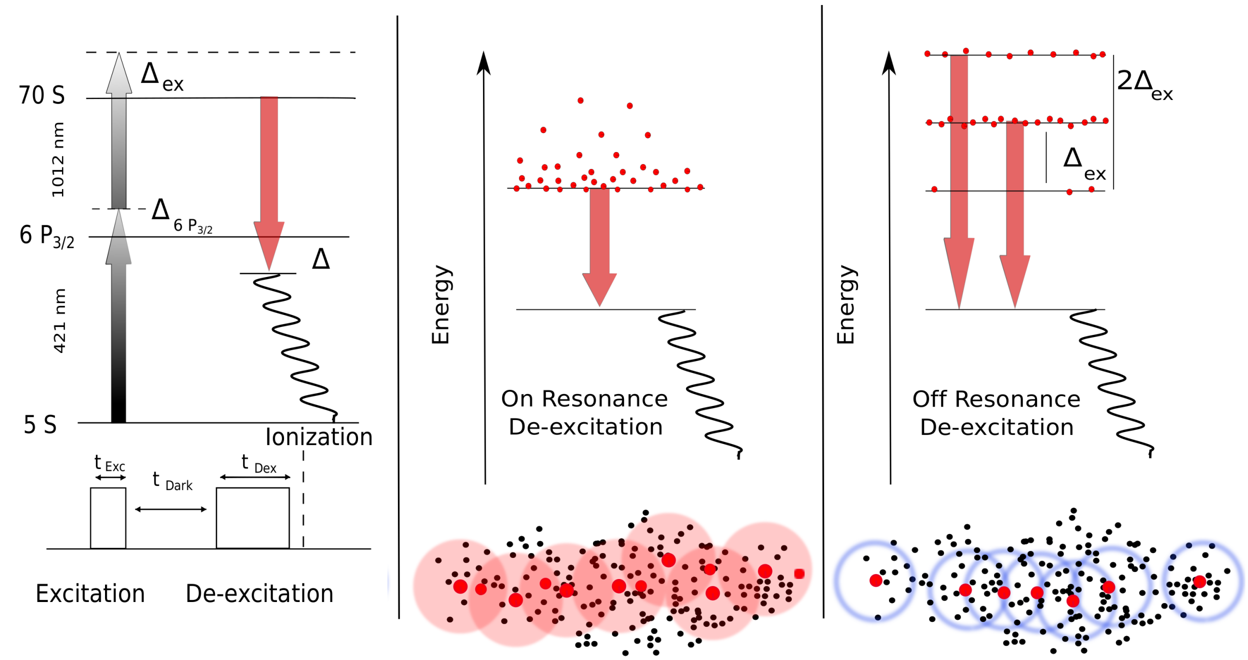


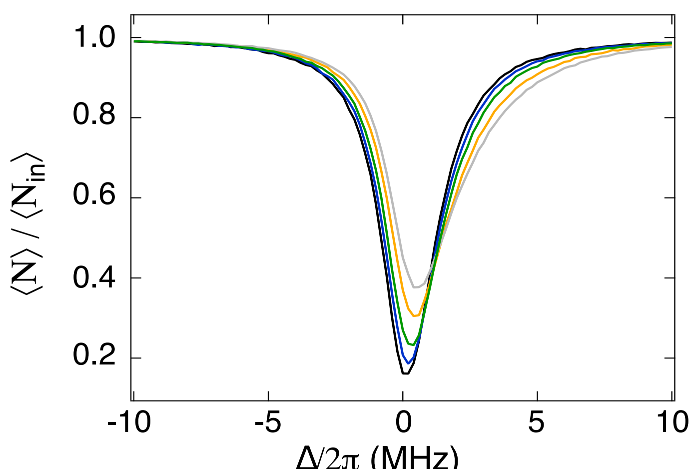
De-excitation process

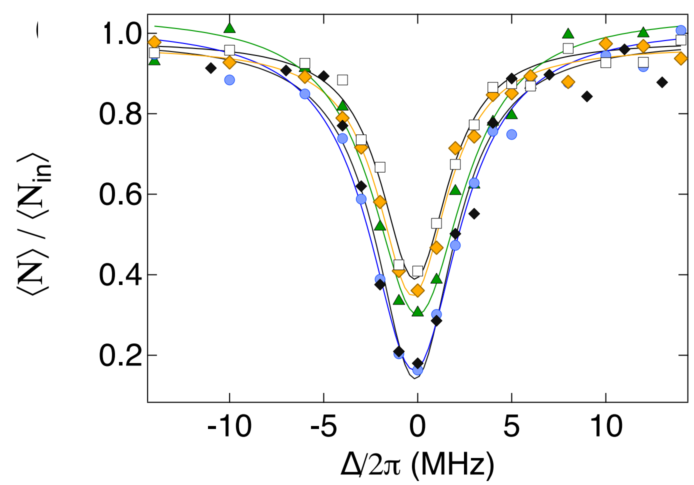


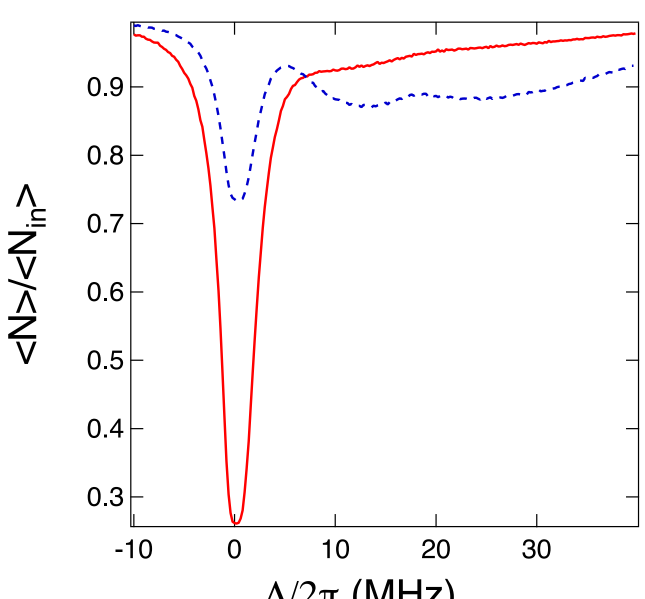
De-excitation process

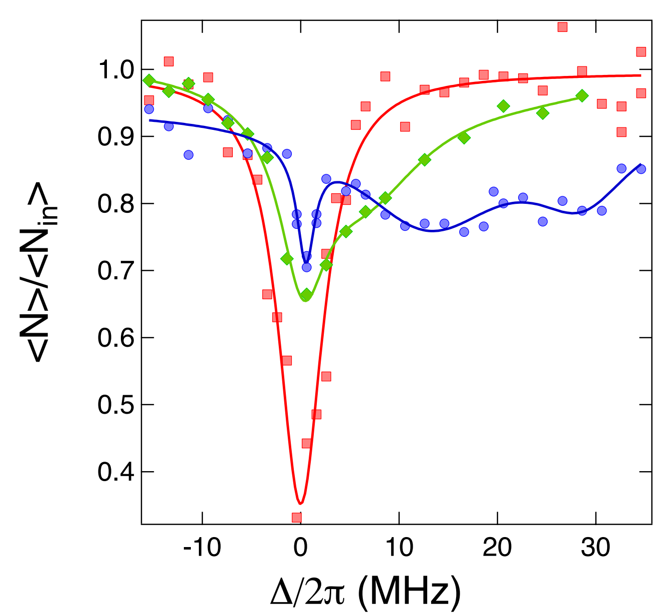






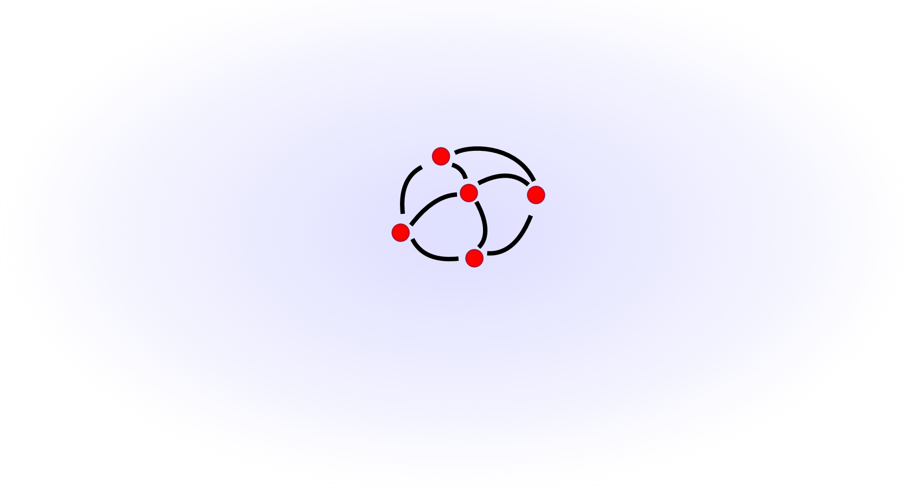


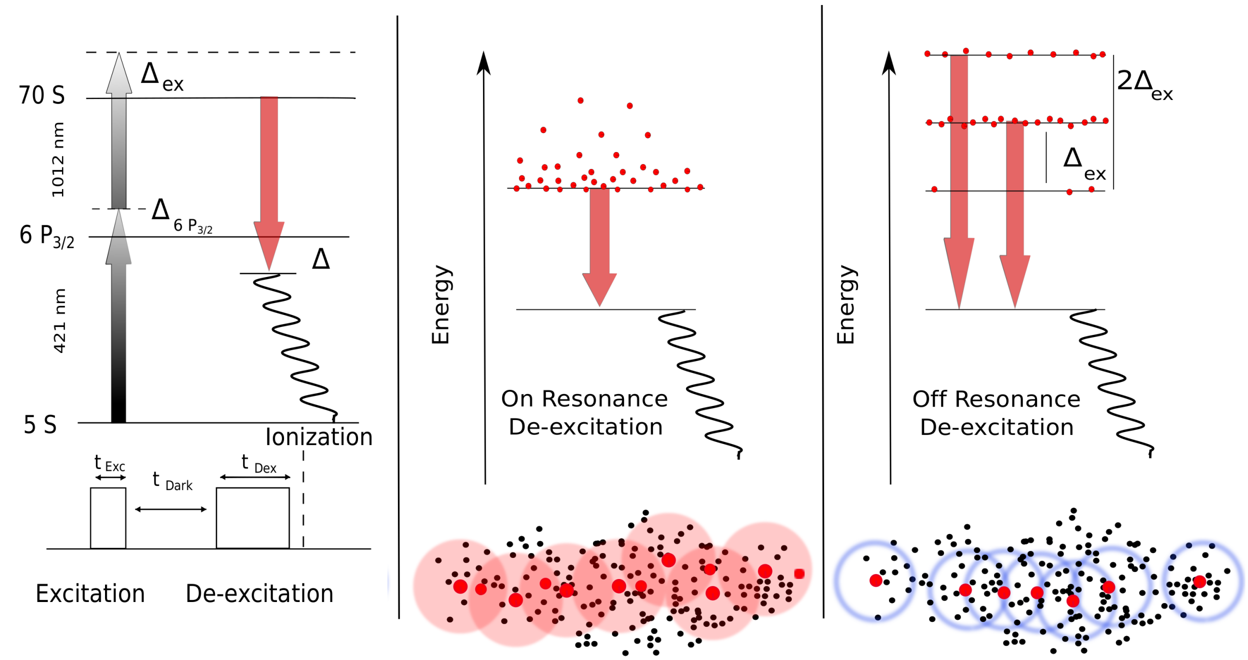


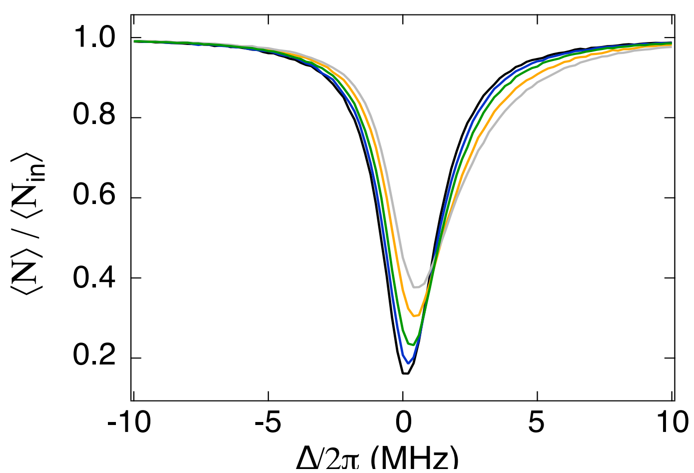


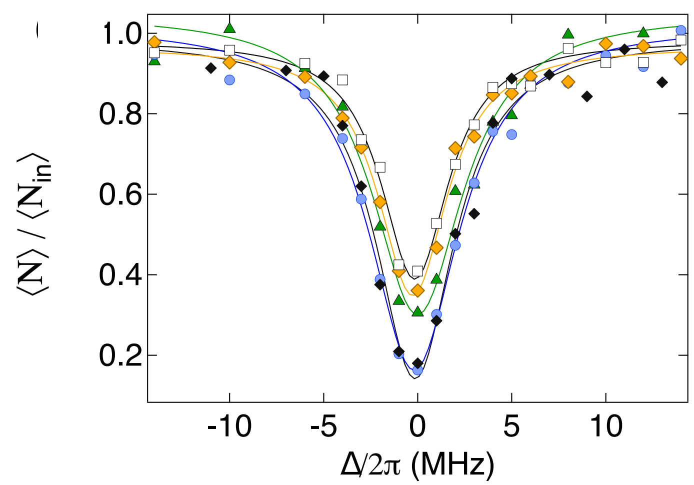
due to the interactions the de-excitation process reflects the energy distribution

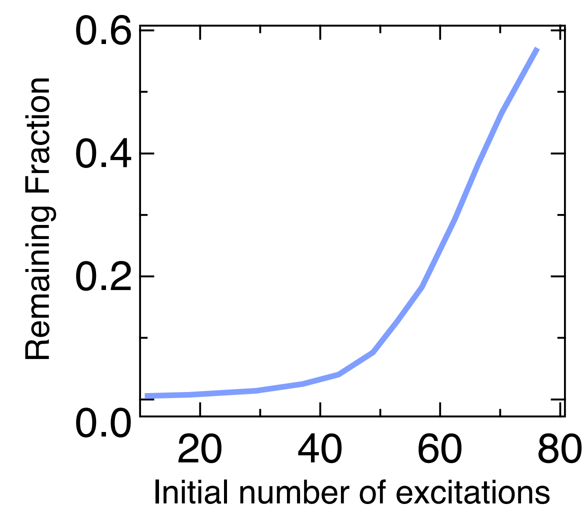
De-excitation process

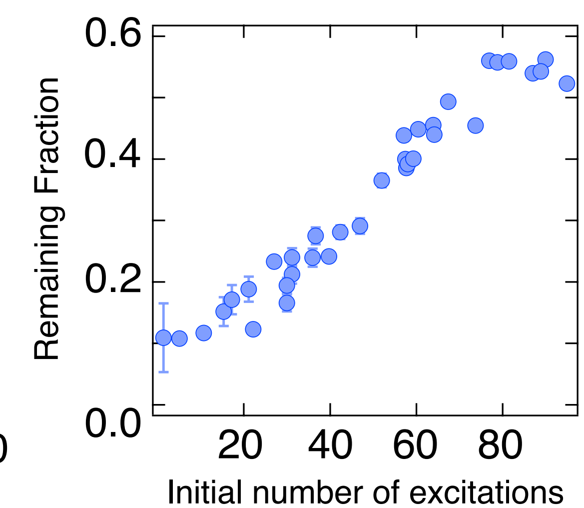


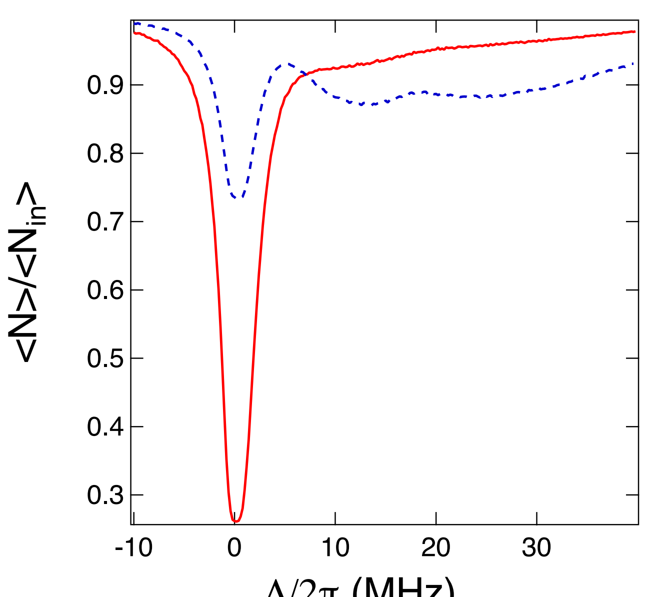


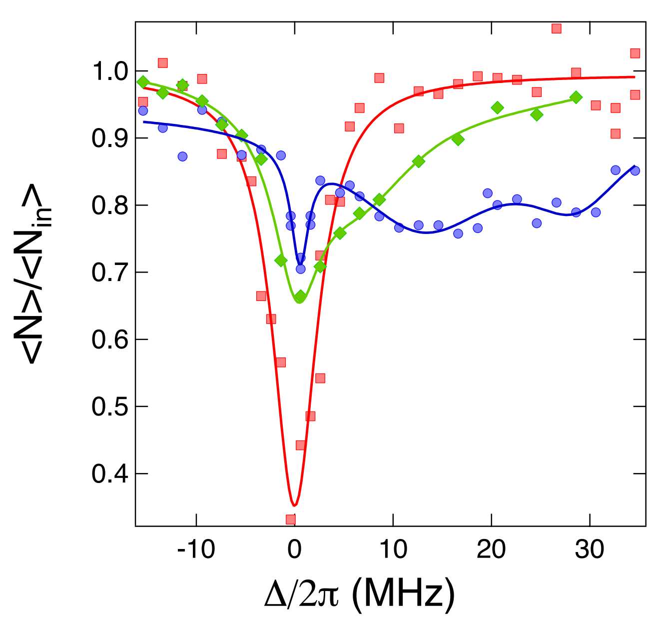








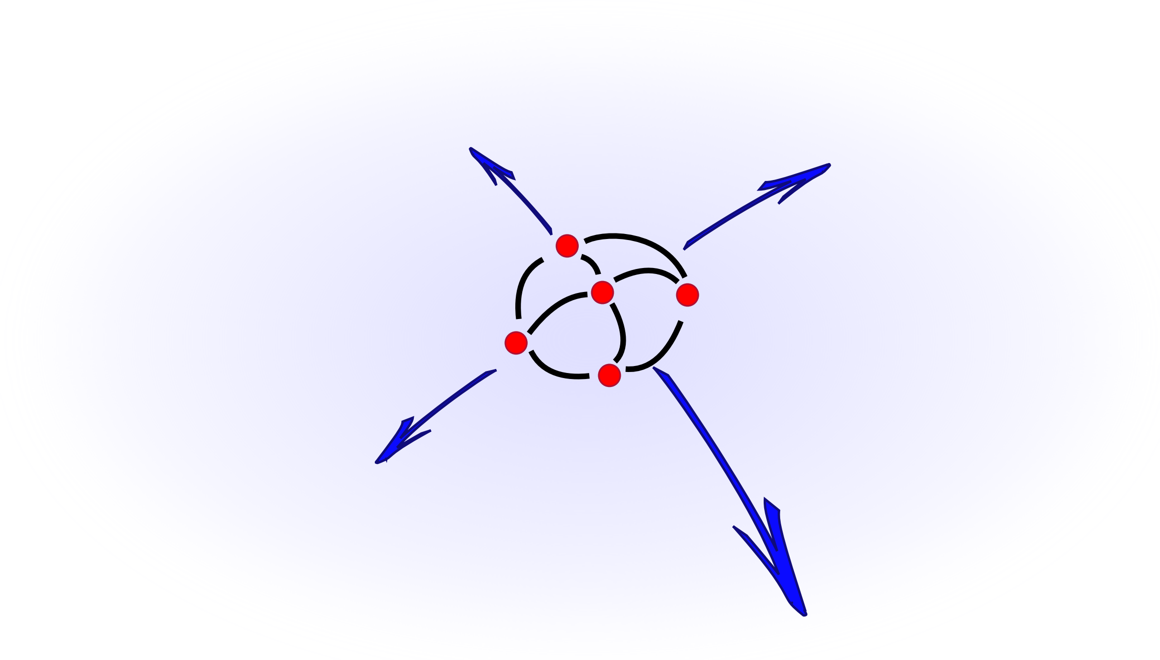


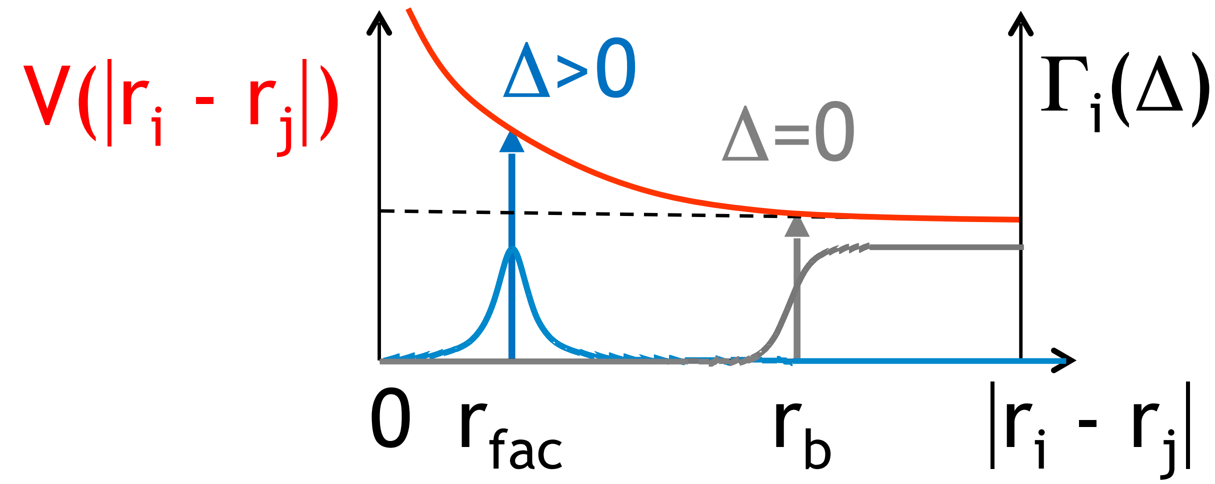


due to the interactions the de-excitation process reflects the energy distribution

Mechanical effects in Rydberg gases

Off resonant excitation cluster converts 99% of the potential energy in kinetic energy in few microseconds





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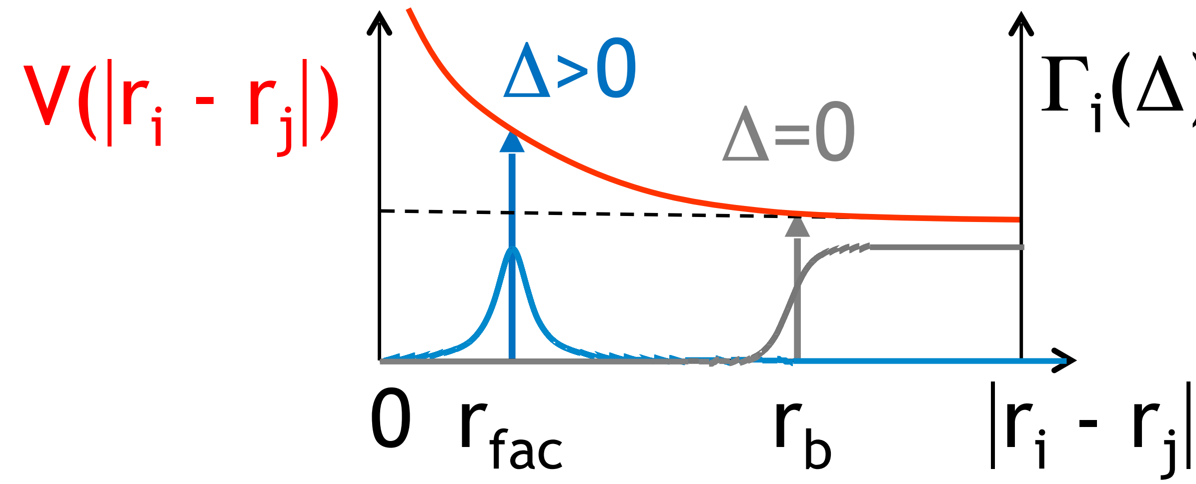
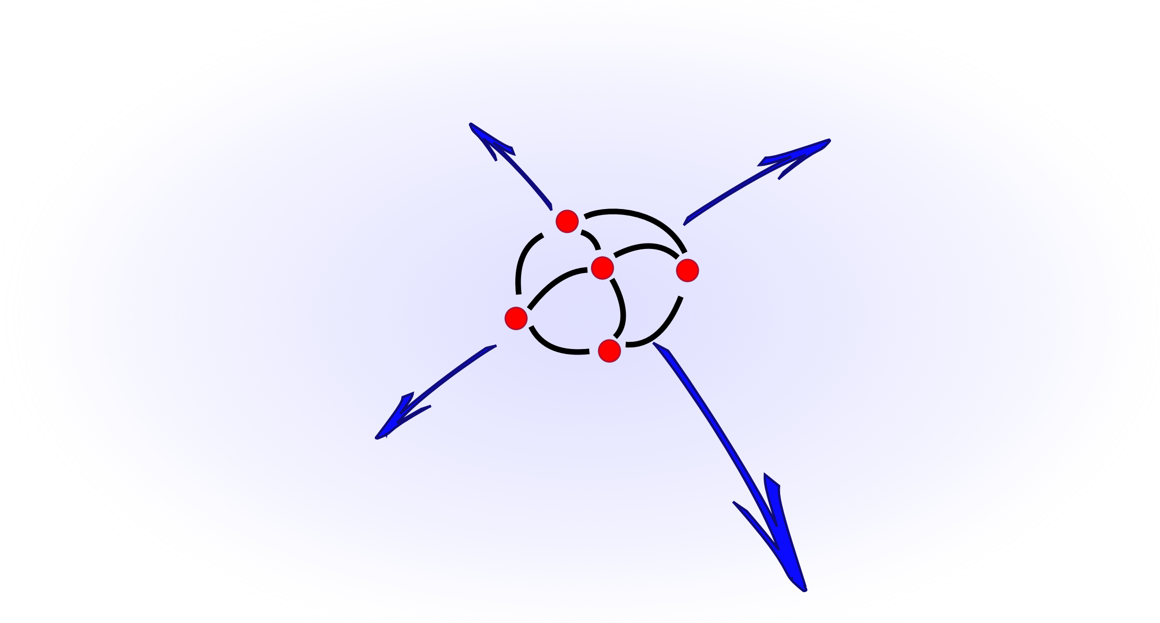
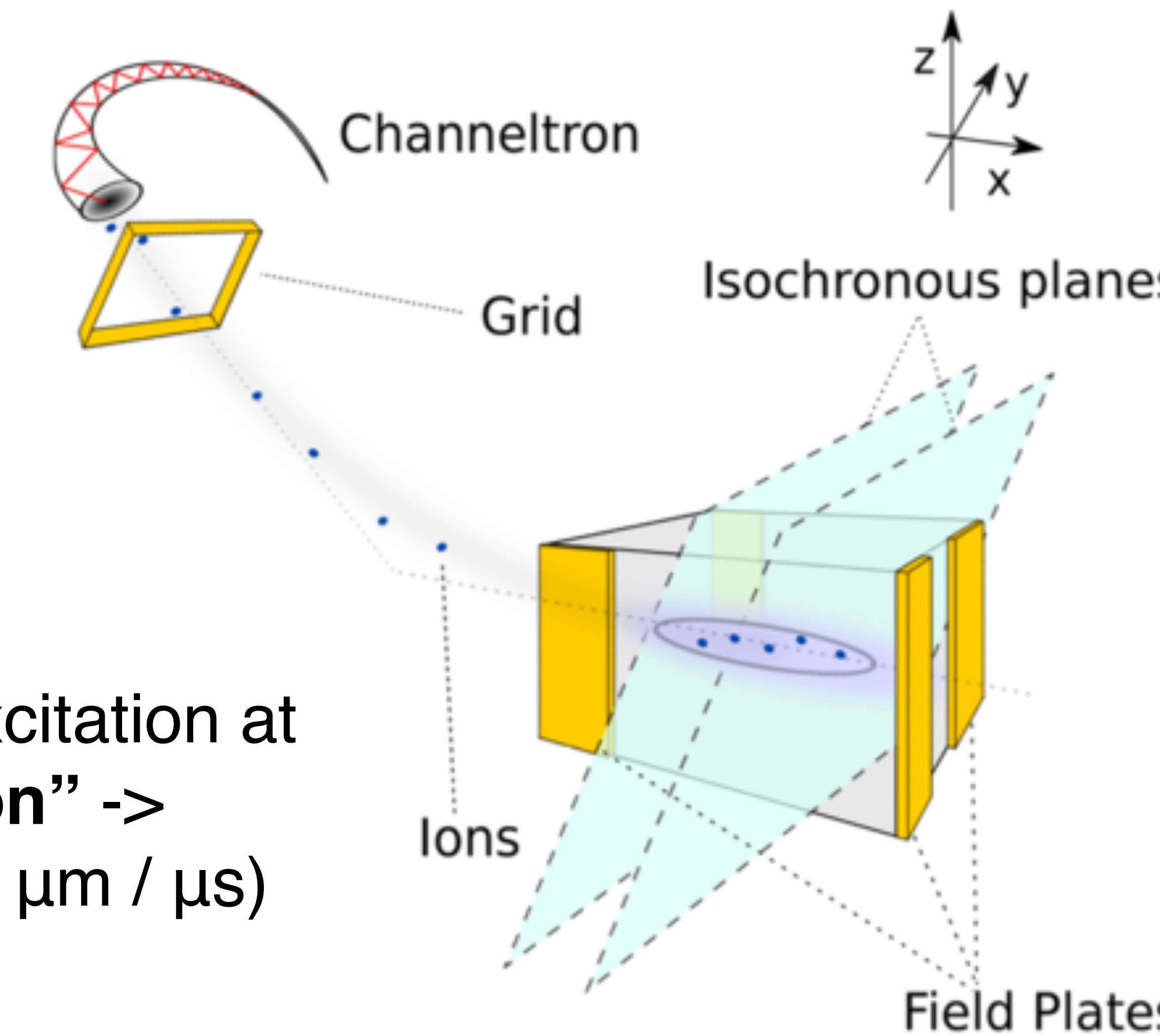
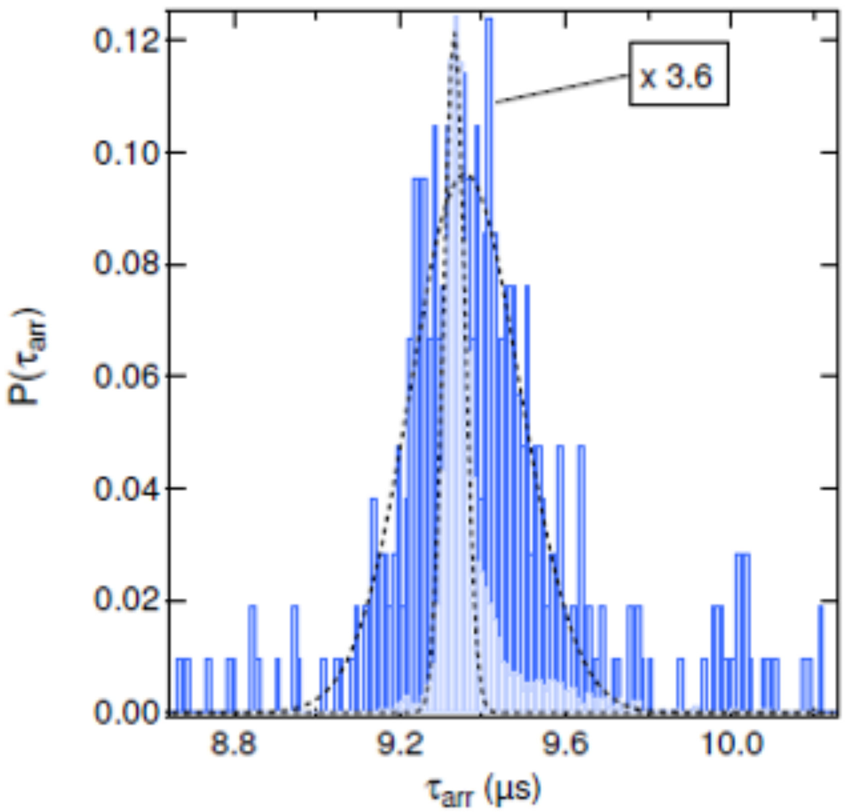




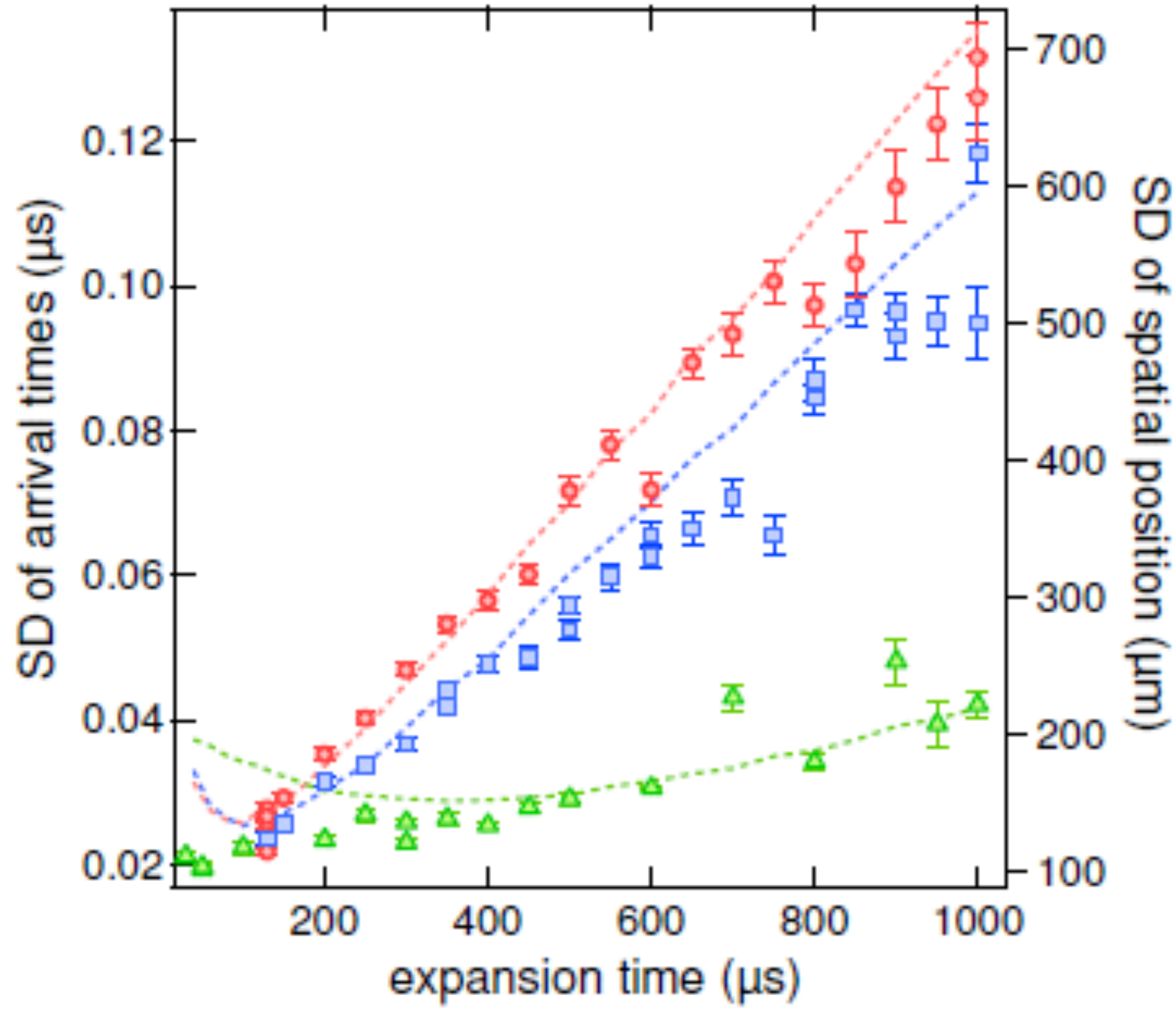


large forces ($a \sim 10^4$ g!) due to off-resonant excitation at 50-80 MHz leads to **"van der Waals explosion"** -> breakdown of frozen gas approximation ($v \sim 1$ µm / µs)

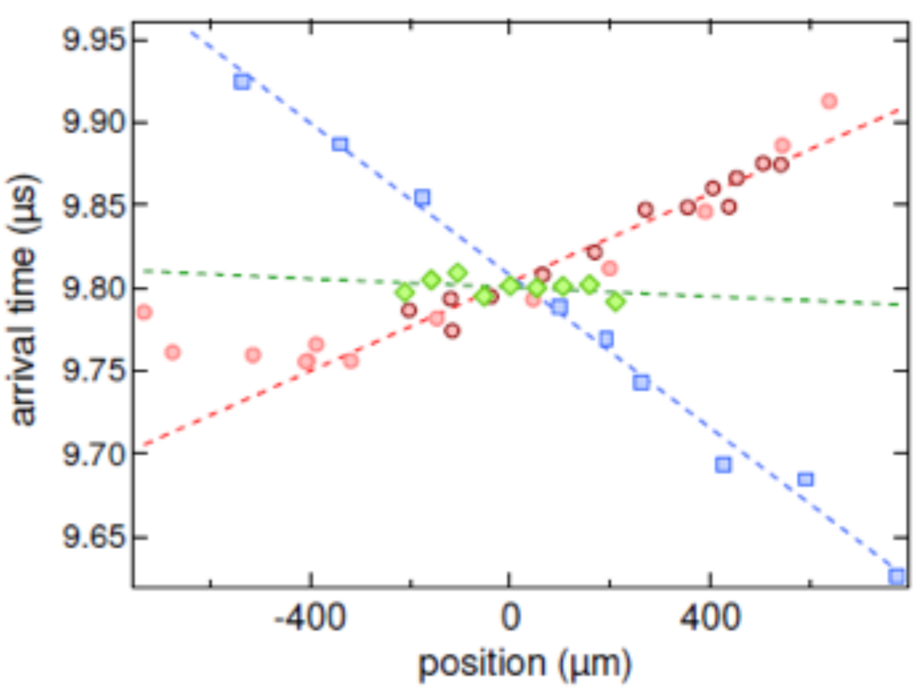
Mechanical effects in Rydberg gases



Ion time-of-flight (TOF) distribution reflects the spatial distribution of the Rydberg atoms

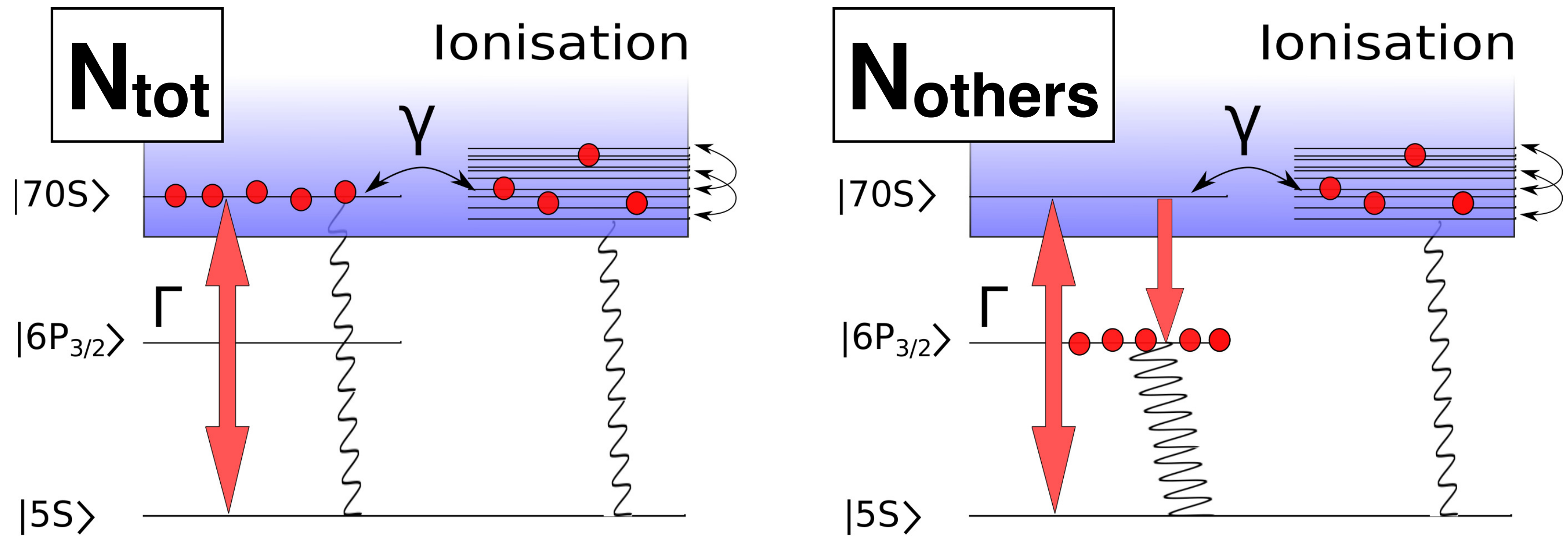


Calibration Time-Space



R. Faoro et al., Phys. Rev. A ***93****, 030701(R) (2016)*

Measuring the lifetime with de-excitation technique



simple idea: de-excitation is state selective

Measuring the lifetime with de-excitation technique

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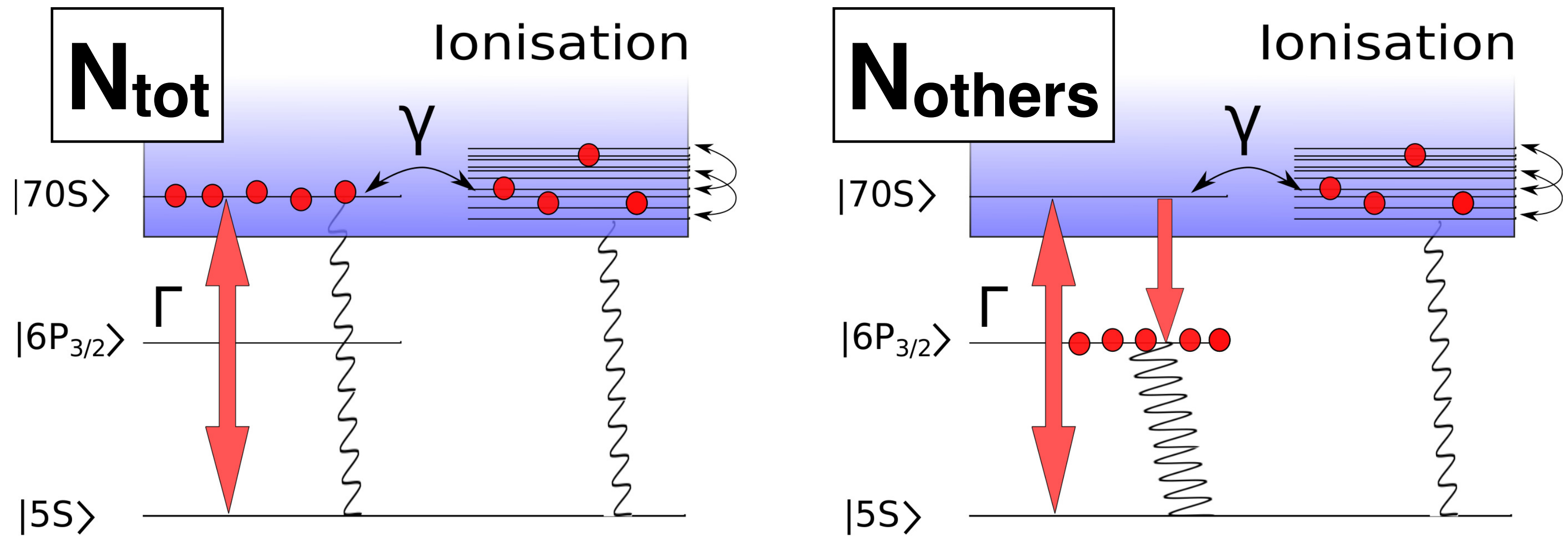
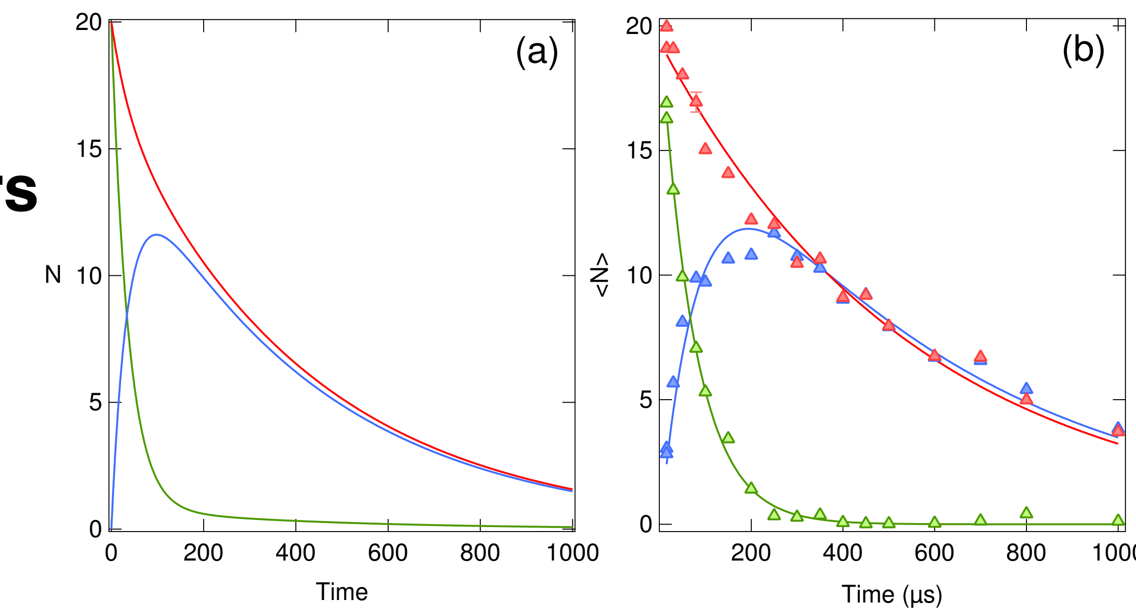


$$N_{70S} = N_{tot} - N_{others}$$



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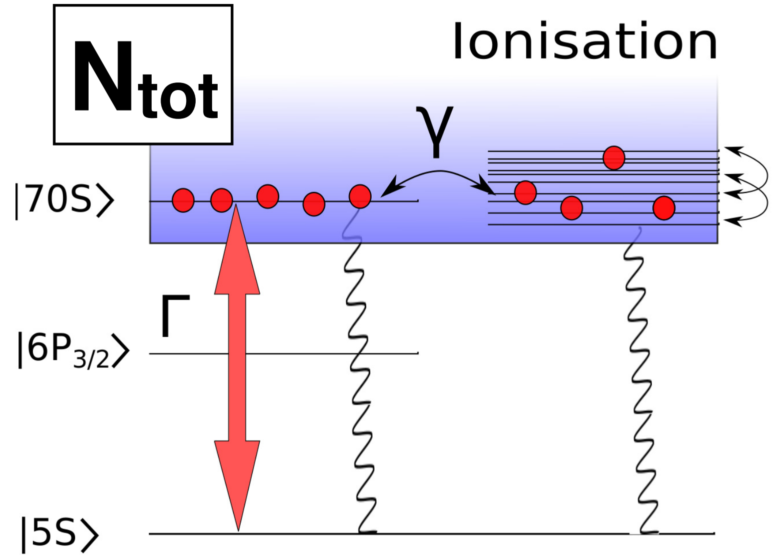

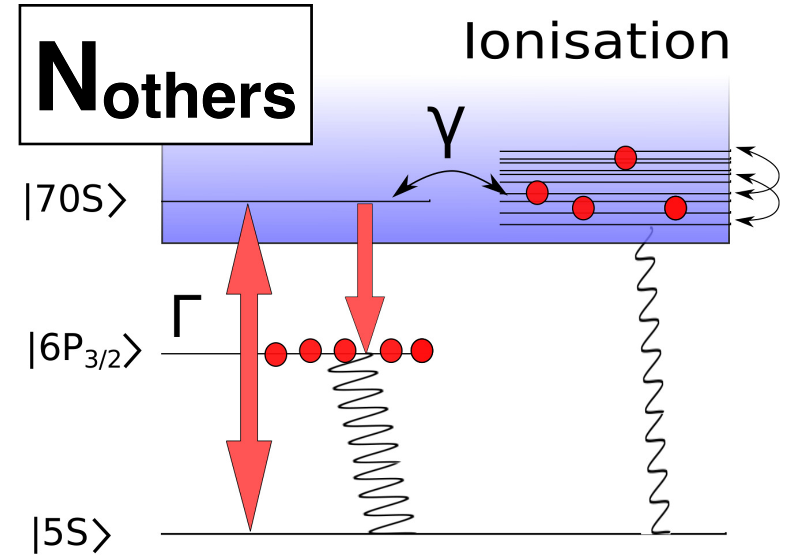

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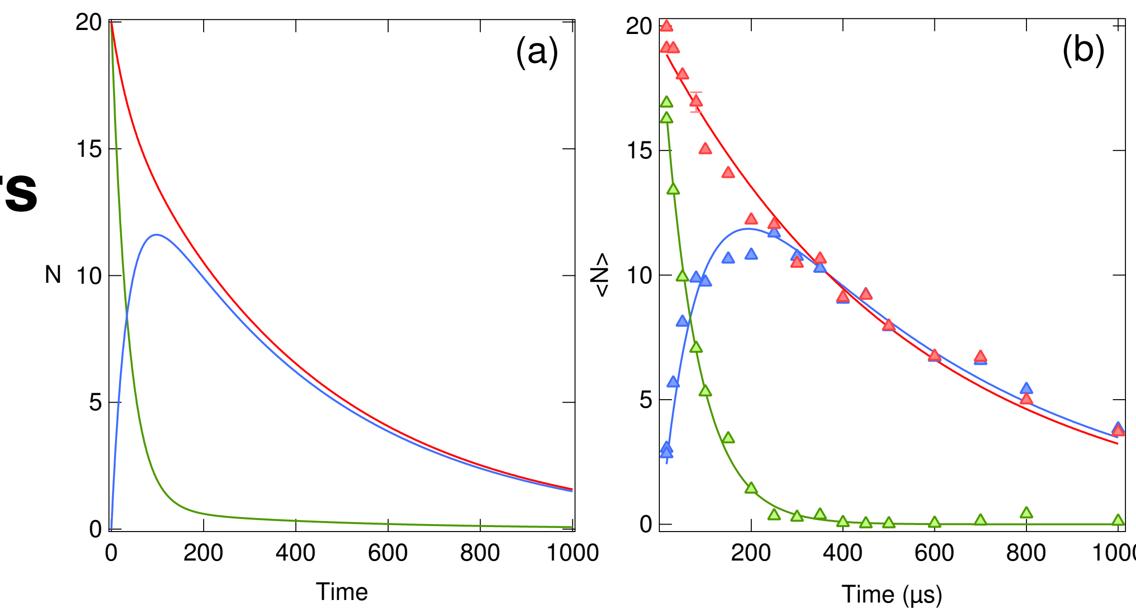

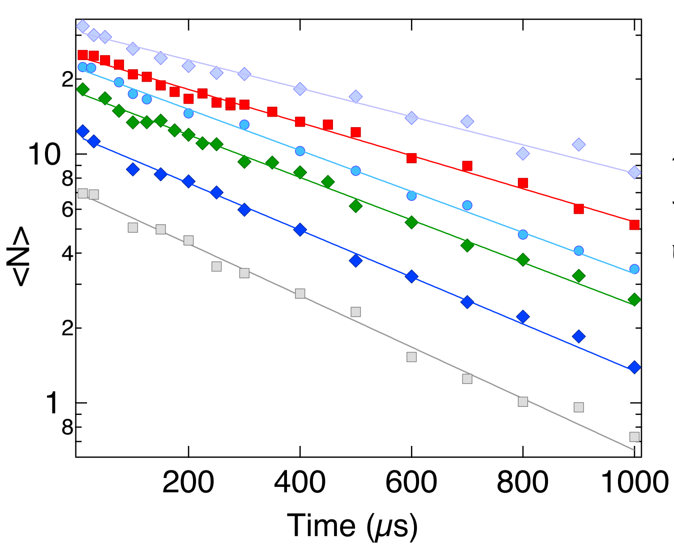

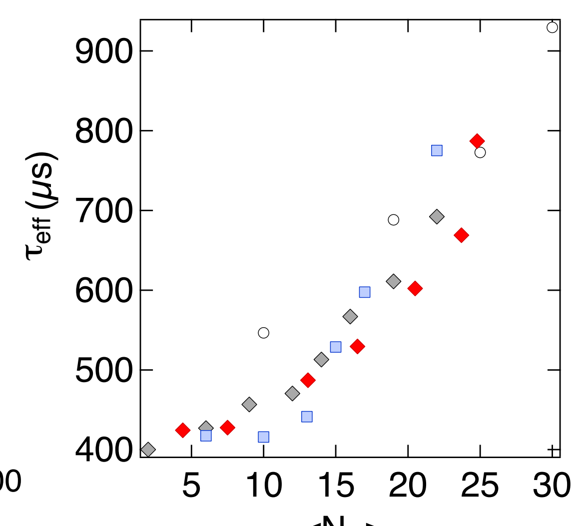

Blackbody coupling?