Correlated Dynamics of Rydberg atoms

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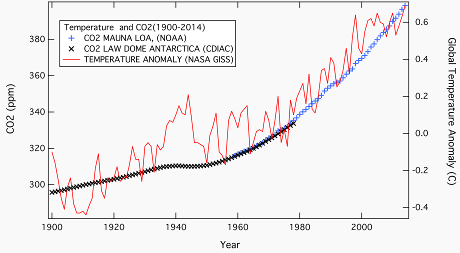
Outline

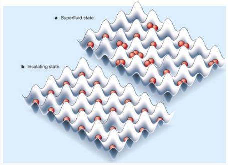
Correlation in Nature

Correlated systems:

- LinkedIn's connection $\sim$ job opportunities
- supply $\sim$ demand $\sim$ price
- $C0_2$ conc. $\sim$ global temperature



- superconductors
- 1D electron systems
- superfluid-MOTT insulators



Correlation creates new and unexpected behaviour

A simple game

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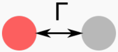

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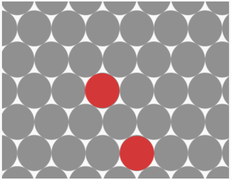

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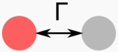

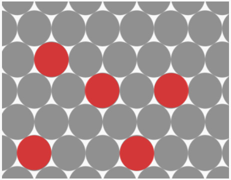

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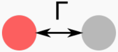

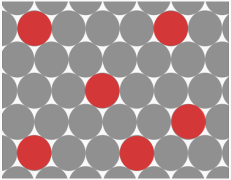

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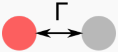

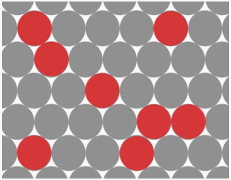

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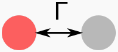

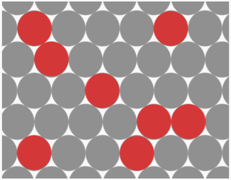

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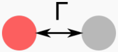

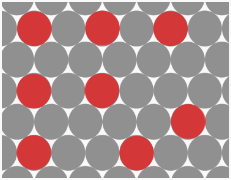

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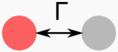

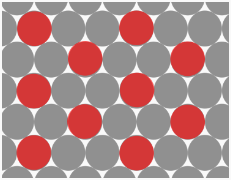

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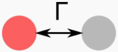

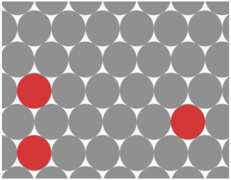

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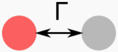

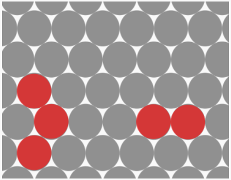

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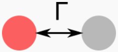

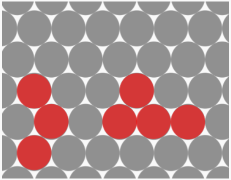

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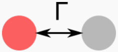

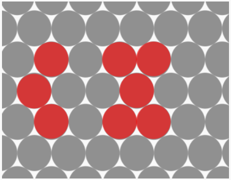

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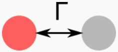

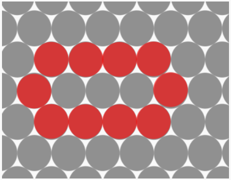

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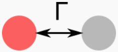

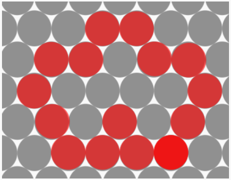

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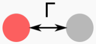
Correlation in atomic physics



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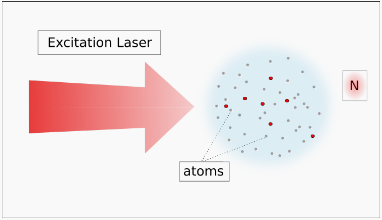

Excitation rate per unit volume

$$\Gamma = \frac{dn}{dt}$$

and number of excitations

$$N = \int_V \int_0^{t_{ex}} \Gamma dt dV$$

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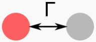

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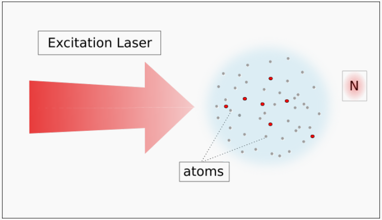

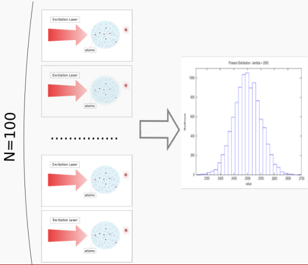

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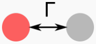

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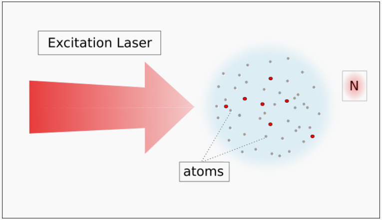

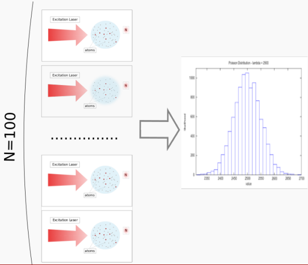

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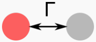

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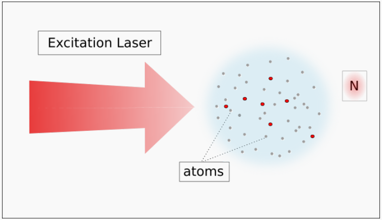

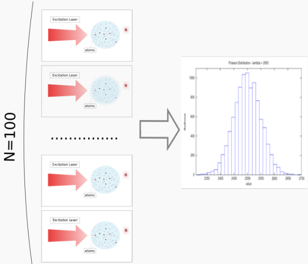

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Excitations distribution $\rho(r_1, r_2, .., r_k, ..., r_N)$ determines the dynamics.

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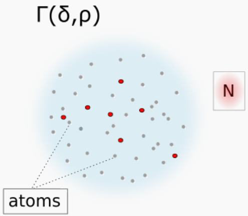
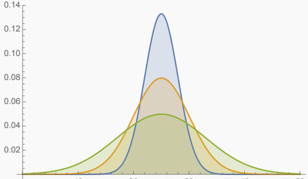


As in the game, we have:

- no rules → uncorrelated dynamics
- facilitation → correlated dynamics
- constraint → anti-correlated dynamics

Mandel Q Parameter (1979) $Q = \frac{\sigma^2}{\langle N \rangle} - 1$



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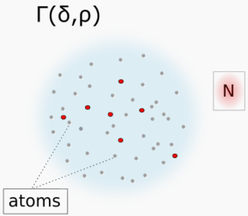

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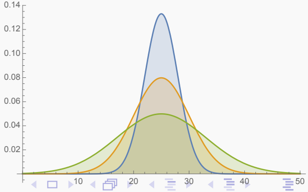

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Cold gas of Rydberg Atoms!

General proprieties

"Cold"

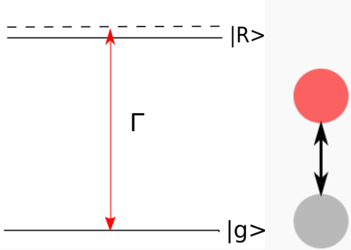
- kinetic energy $\ll$ interaction energy

"Rydberg atoms" (our pieces)

- atoms excited to high principal quantum number ($n > 20$) state
- strong Interactions $U_{VdW} = \frac{C_6}{|r-r|^6}$ ($C_6 \sim n^{11}$)
- long lifetime $\tau \sim n^3$

Rydberg Atoms Excitation Scheme

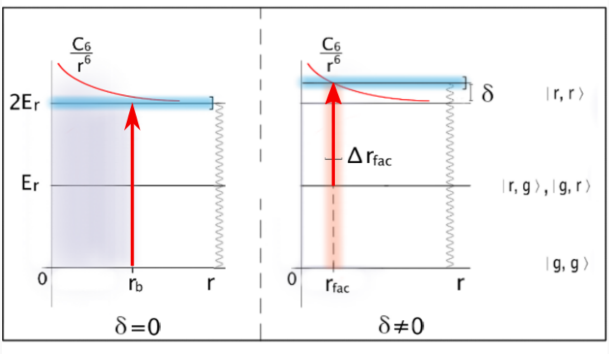
We describe the dynamic in terms of an excitation rate Γ_k ($\gamma_{\|} >> \gamma_{\perp}$)



$$\Gamma_k = \frac{\Omega^2}{\gamma_\perp} \frac{1}{1 + R^{12}[\Delta - \sum_{j \neq k} \frac{n_j}{|\hat{r}_k - \hat{r}_j|^6}]^2}$$

$$R = \frac{r_b}{a} \quad r_b = \left(\frac{C_6}{\hbar \gamma_\perp} \right)^{1/6}$$

How to realize the rules of the games



Two different processes and two important length scales

- on resonance $\rightarrow$ *blockade radius* r_b
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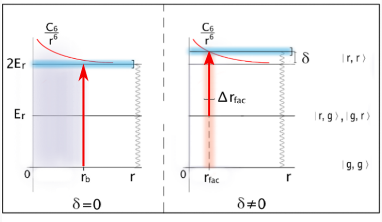

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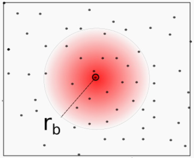
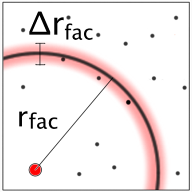


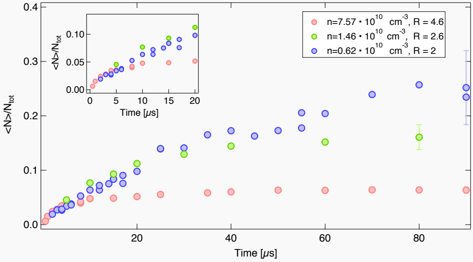
- *anti-correlated* dynamic for $\delta = 0 \rightarrow$ *kinetic constraint*

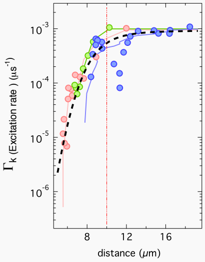


- *correlated* dynamic for $\delta > 0 \rightarrow$ *facilitation process*

Kinetic Constraint

$$\Gamma_k = \frac{\Omega^2}{\gamma_\perp} \frac{1}{1 + \underline{R^{12}\left[\sum_{j\neq k} \frac{n_j}{|\hat{r}_k - \hat{r}_j|^6}\right]^2}}$$





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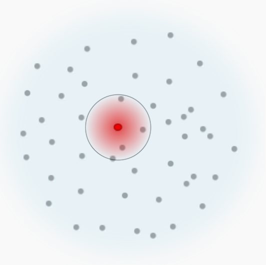

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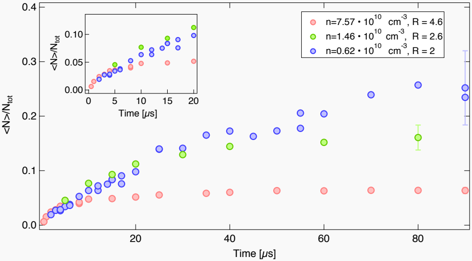

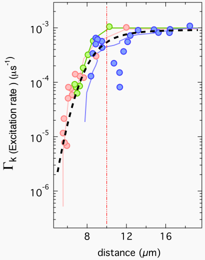

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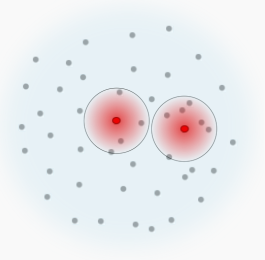

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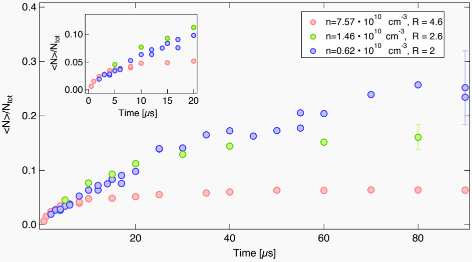
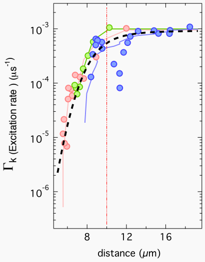
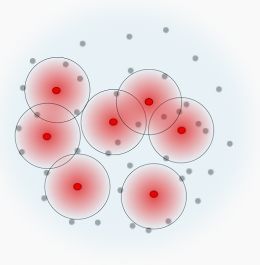




Kinetic Constraint



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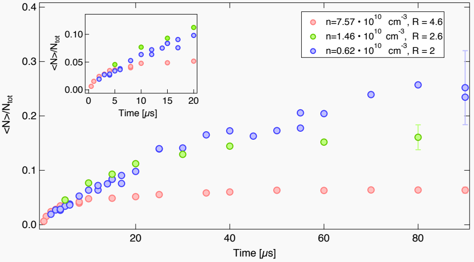
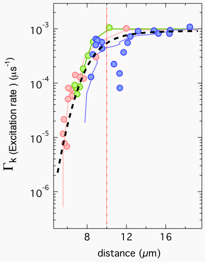
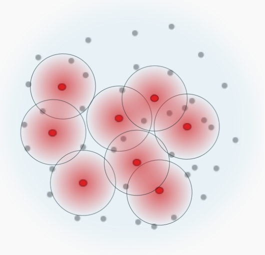


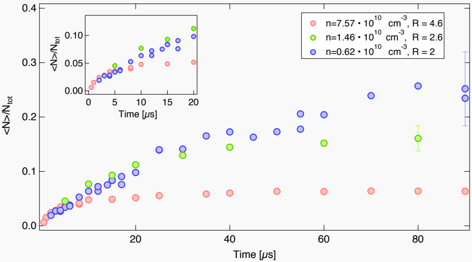


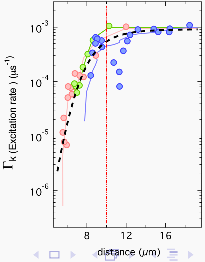
Kinetic Constraint

"*you can't flip to Red if the neighbour is Red*"



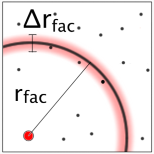
$$\Gamma_k = \frac{\Omega^2}{\gamma_\perp} \frac{1}{1 + R^{12}\left[\sum_{j \neq k} \frac{n_j}{|\hat{r}_k - \hat{r}_j|^6}\right]^2}$$

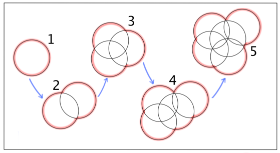




Facilitation process

"*you can only flip to Red if the neighbour is Red*"

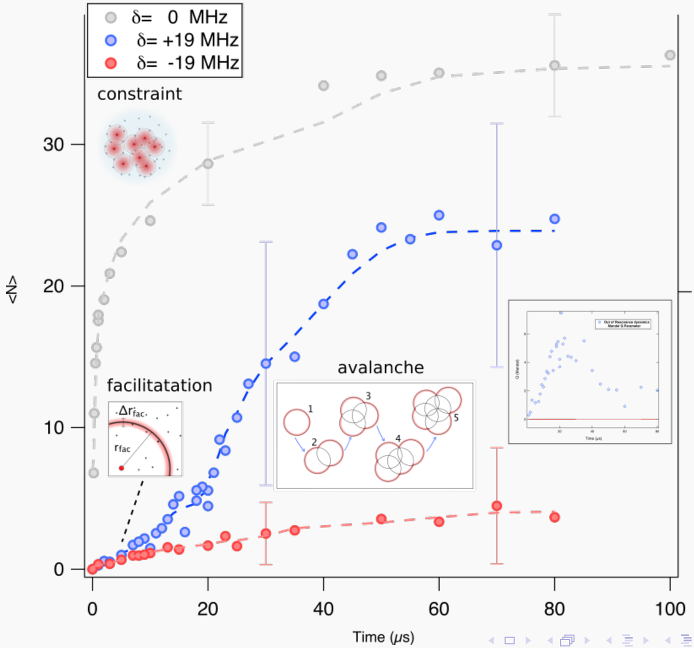




Interactions compensate the detuning at r_{fac}

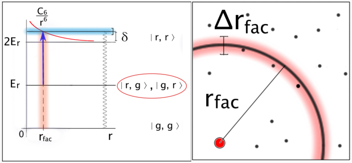
$$\Gamma_k = \frac{\Omega^2}{\gamma_\perp}\frac{1}{1 + R^{12}[\Delta - \sum_{j\neq k}\frac{n_j}{|\hat{r}_k - \hat{r}_j|^6}]^2} \rightarrow \frac{\Omega^2}{\gamma_\perp}$$

Facilitation leads to an *Avalanche excitation process*

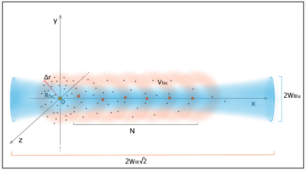


δ= 0 MHz
δ= +19 MHz
δ= -19 MHz
constraint
facilitatation
Δr_fac
r_fac
avalanche
1
2
3
4
5
⟨N⟩
0
10
20
30
0
20
40
60
80
100
Time (μs)

1D avalanche simple Model

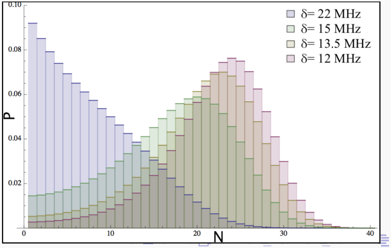


"intuitive idea" $\rightarrow$ To step forward the important parameter is $\tilde{N} = n(x, y, z) \cdot V_{fac}$



Basic HP of the 1D model

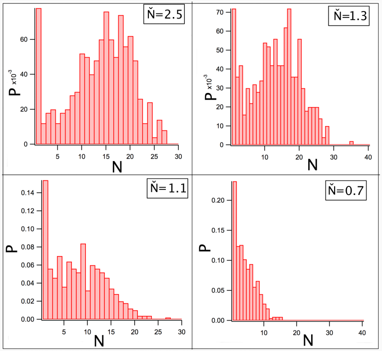
- $\tilde{P}(0) = e^{-<\tilde{N}>}$
- $P_+ = 1 - \tilde{P}(0)$ is the step forward probability
- the number of steps determines the number of the excitations $< N >$



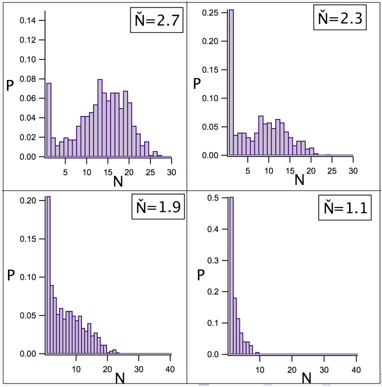
Experimental Counts Distributions

$$t_{exc} = 100\mu s \text{ for different } \tilde{N} = n(x,y,z) \cdot V_{fac}$$

Changing $n(x,y,z)$



Changing V_{fac}



Experimental Counts Distributions

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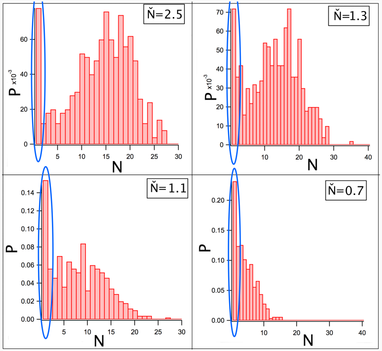
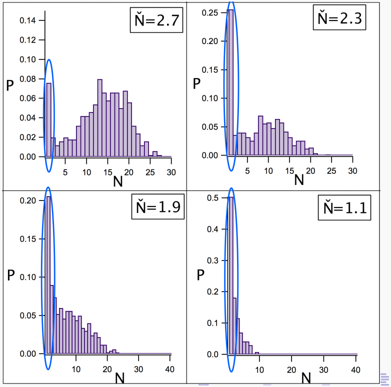


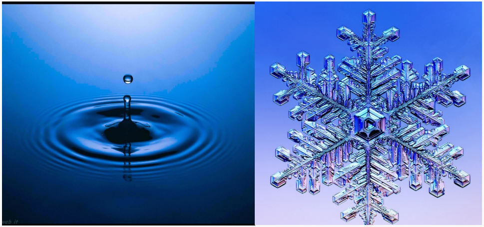
Changing V_{fac}



Triggering the avalanche

Very common system: water.

- liquid water $\rightarrow$ ice
- temperature
- nucleation center



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Nucleation is the first step in the formation of a new structure via self-assembly.

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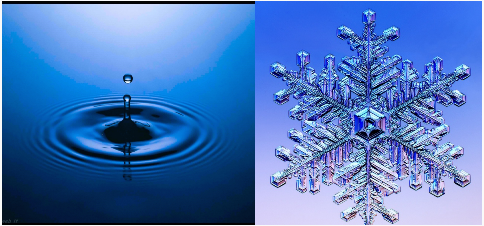


Nucleation is the first step in the formation of a new structure via self-assembly.

Can we do the same?

Triggering the avalanche

Very common system: water.

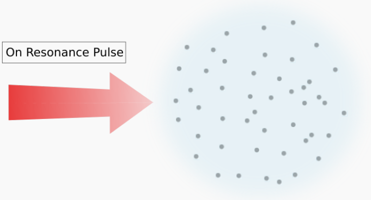
- liquid water $\rightarrow$ ice
- temperature
- nucleation center

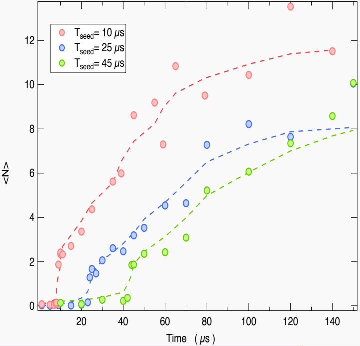
Nucleation is the first step in the formation of a new structure via self-assembly.

Can we do the same?
Yes we can!

Triggering the avalanche

Avalanche needs an initial excitation to begin $\rightarrow$ *Seed*





- short On resonance excitation pulse $\rightarrow$ seed/seeds
- pulse duration $\rightarrow < N >_{seed}$
- pulse starting point $\leftrightarrow$ avalanche starting point

Triggering the avalanche

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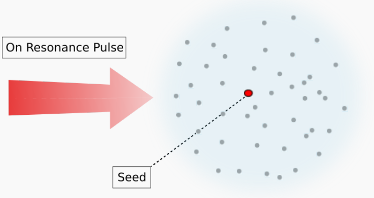

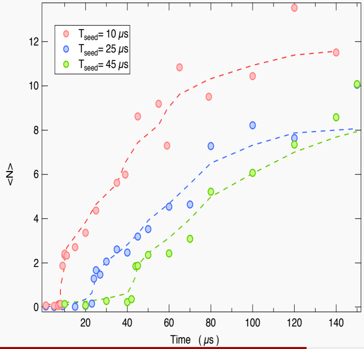

- short On resonance excitation pulse → seed/seeds
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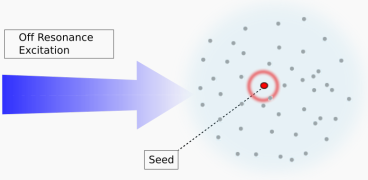
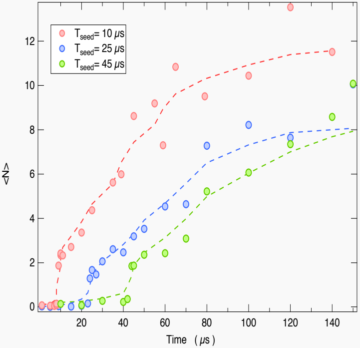
Triggering the avalanche

Avalanche needs an initial excitation to begin $\rightarrow$ *Seed*
The avalanche grows in the sample





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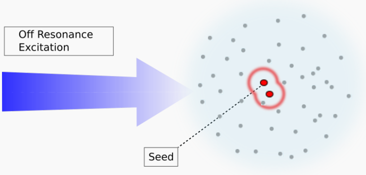

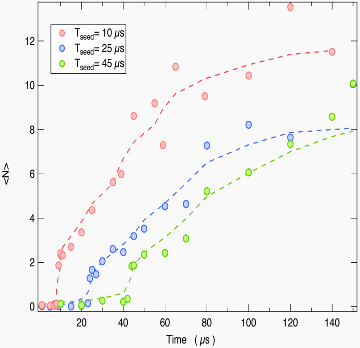

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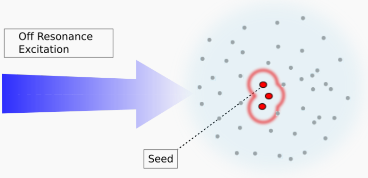

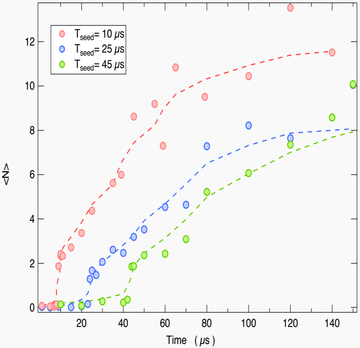

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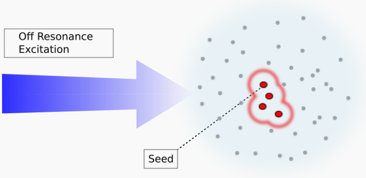

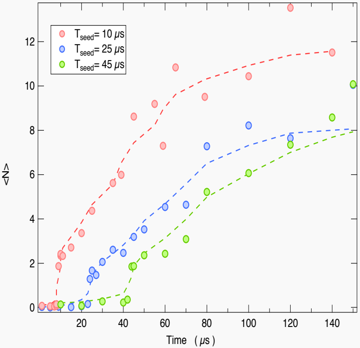

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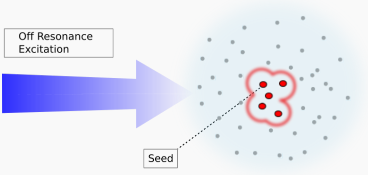

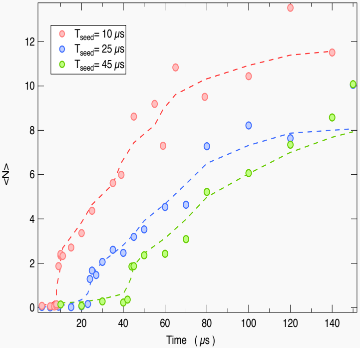

- short On resonance excitation pulse $\rightarrow$ seed/seeds
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Conclusion:

- Correlation creates new and unexpected behaviour
- Rydberg atoms provide a flexible platform
- Induce or block the excitations
- qualitative difference in the statistics

What's next?

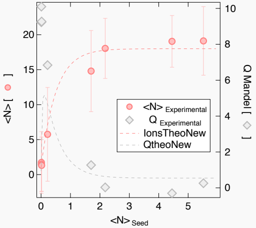
- other correlations of Rydberg atoms
- van der Waals interaction effect
- Quantum Computation and Simulation
- ....

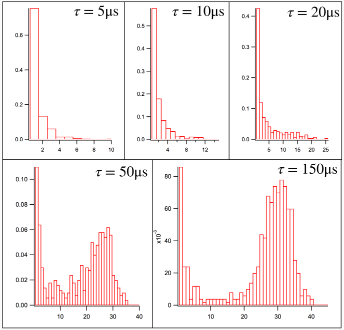
thanks for your attention!

The Bimodal Model

Hp Bimodal Model

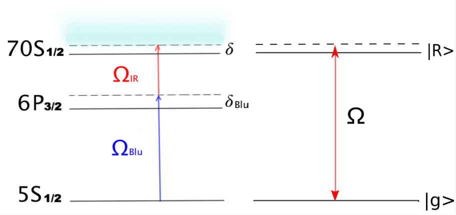
- $< N > = \mu_1 P(0) + \mu_2 (1 - P(0))$
- $P(0) = e^{-<N>_{seed}}$
- $< N >_{seed} = 0 \rightarrow < N > = \mu_1$





- Bimodal model well approximates $< N >$ and Q
- Signature of the avalanche in the counts distribution

Rydberg Atoms Excitation Scheme



Two photons excitation scheme

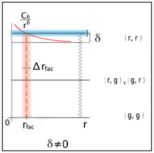
- $\delta_{Blu} \sim 1GHz$ avoid population of the intermediate level $6P_{3/2}$
- *generalized* Rabi frequency

$$\Omega = \sqrt{\frac{\Omega_{IR}^2 \Omega_{Blu}^2}{\delta_{Blu}^2} + \delta^2}$$

We describe the dynamic in terms of an excitation rate Γ_k ($\gamma_{||} >> \gamma_{\perp}$)

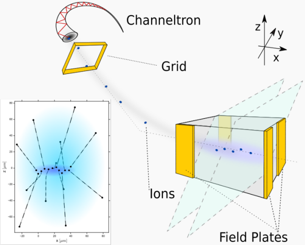
$$\Gamma_k = \frac{\Omega^2}{\gamma_\perp} \frac{1}{1 + R^{12}[\Delta - \sum_{j \neq k} \frac{n_j}{|\hat{r}_k - \hat{r}_j|^6}]^2} \qquad \Delta = \frac{\delta}{R^6 \gamma_\perp}, \quad R = \frac{1}{a}(\frac{C_6}{\hbar \gamma_\perp})^{(1/6)}$$

Measuring the Van der Waal's force effect

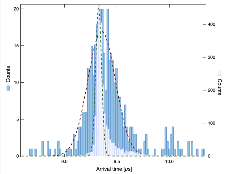


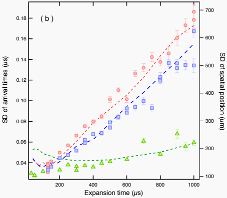
- Excited Atoms have potential energy
- Atoms cloud expands

How do we detect the cloud expansion?



- Excite
- Evolve
- Detect





interaction strength