Ionization dynamics and antiblockade of an ultracold Rydberg gas

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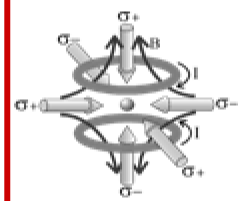
Center for
Quantum
Dynamics

Quantum Dynamics
of Atomic and Molecular Systems

Ultracold Rydberg Gases

magneto-optical trap (MOT)



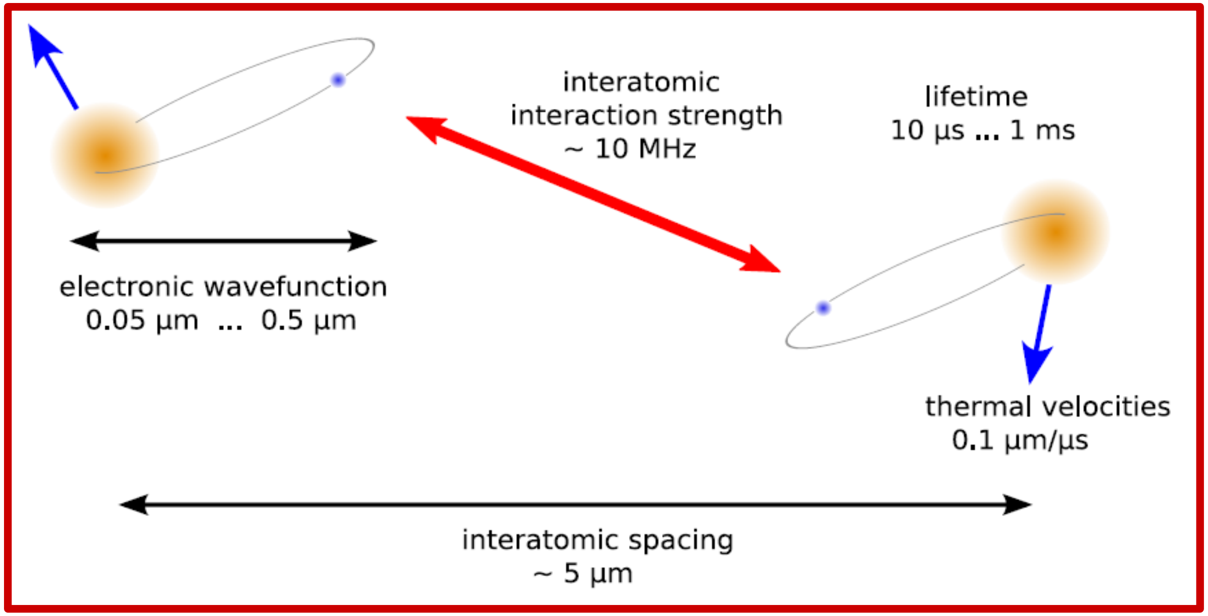
10^7-10^8 atoms

$\rho \sim 10^{10}$ cm^{-3}

T < 100 μK

ultralong range interactions:

- large polarizability $\propto n^7$
- strong dipole interaction $\propto n^4$
- strong van-der-Waals forces $\propto n^{11}$

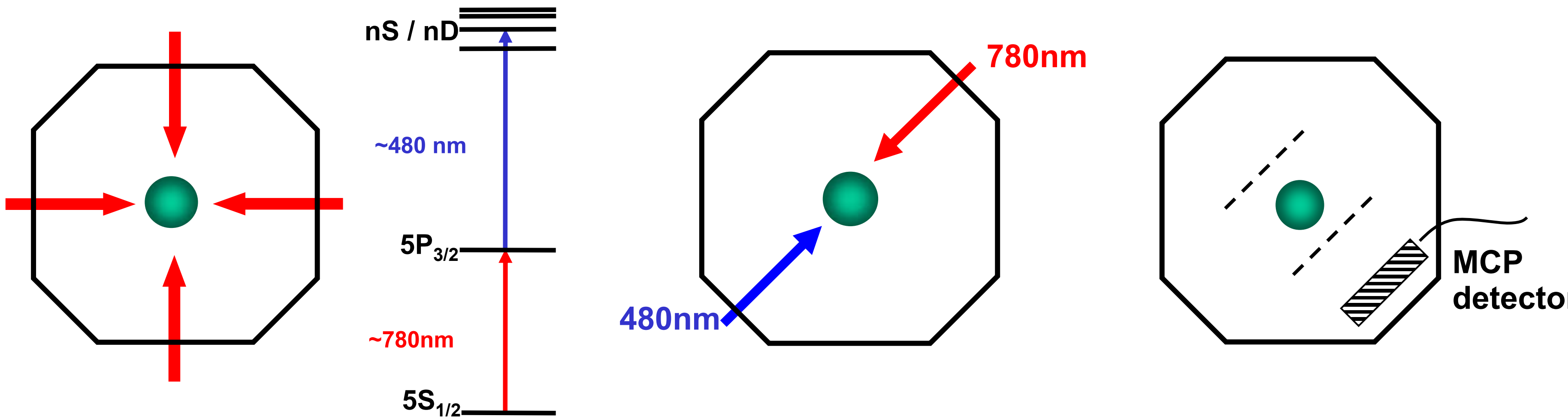


Typical experimental cycle

1. Magneto-optical trapping of ^{87}Rb

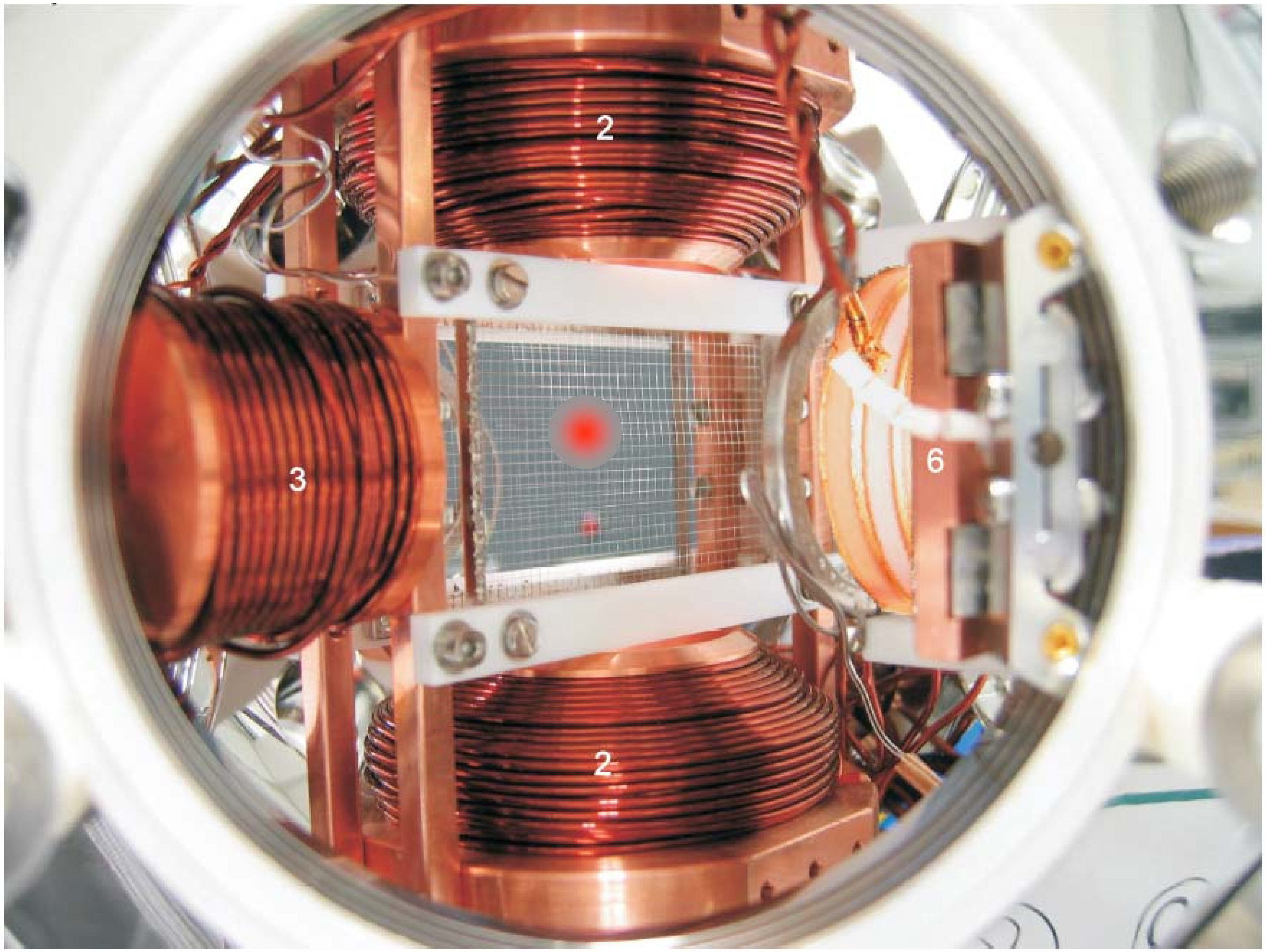
2. Excitation of Rydberg states
(~0.1µs – 10µs)

3. State-selective field ionization



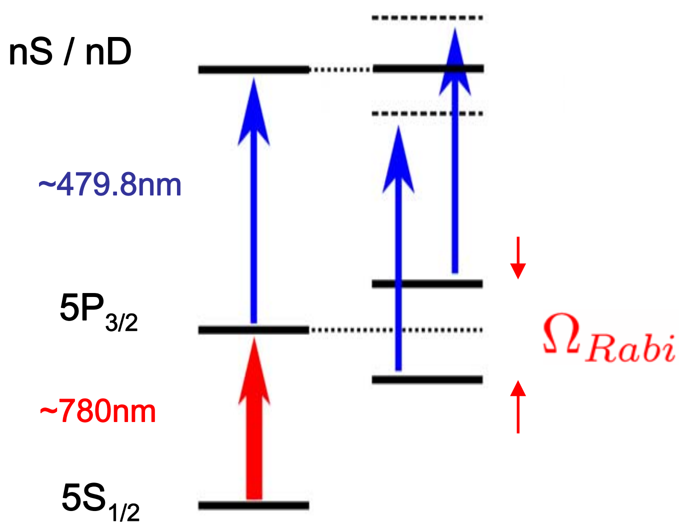
T < 100 µK
$10^7 - 10^8$ atoms
$\rho \sim 10^{10}$ cm^{-3}

Experimental Setup

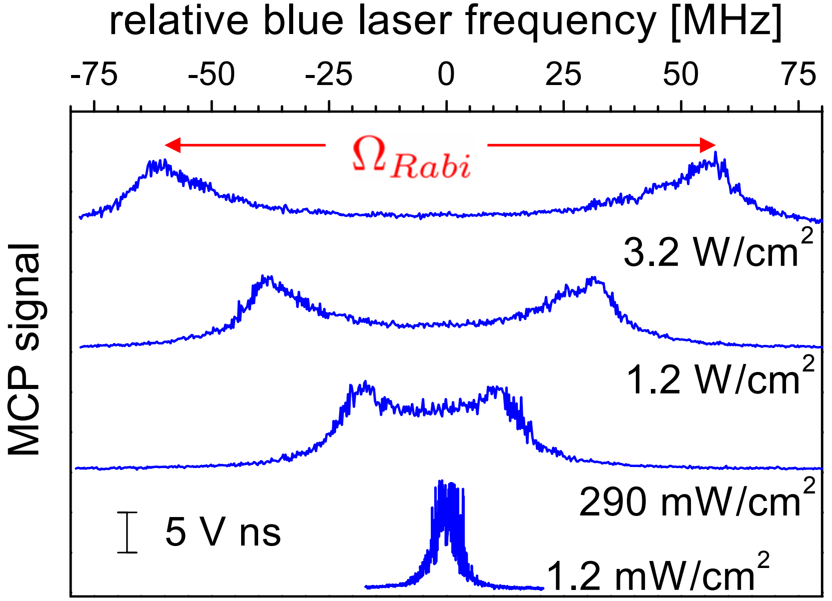


Excitation schemes I

- 2 photons & 3 levels

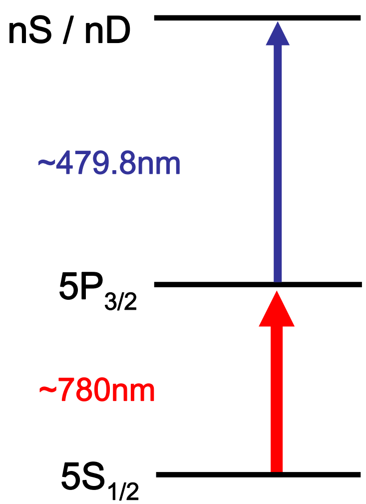


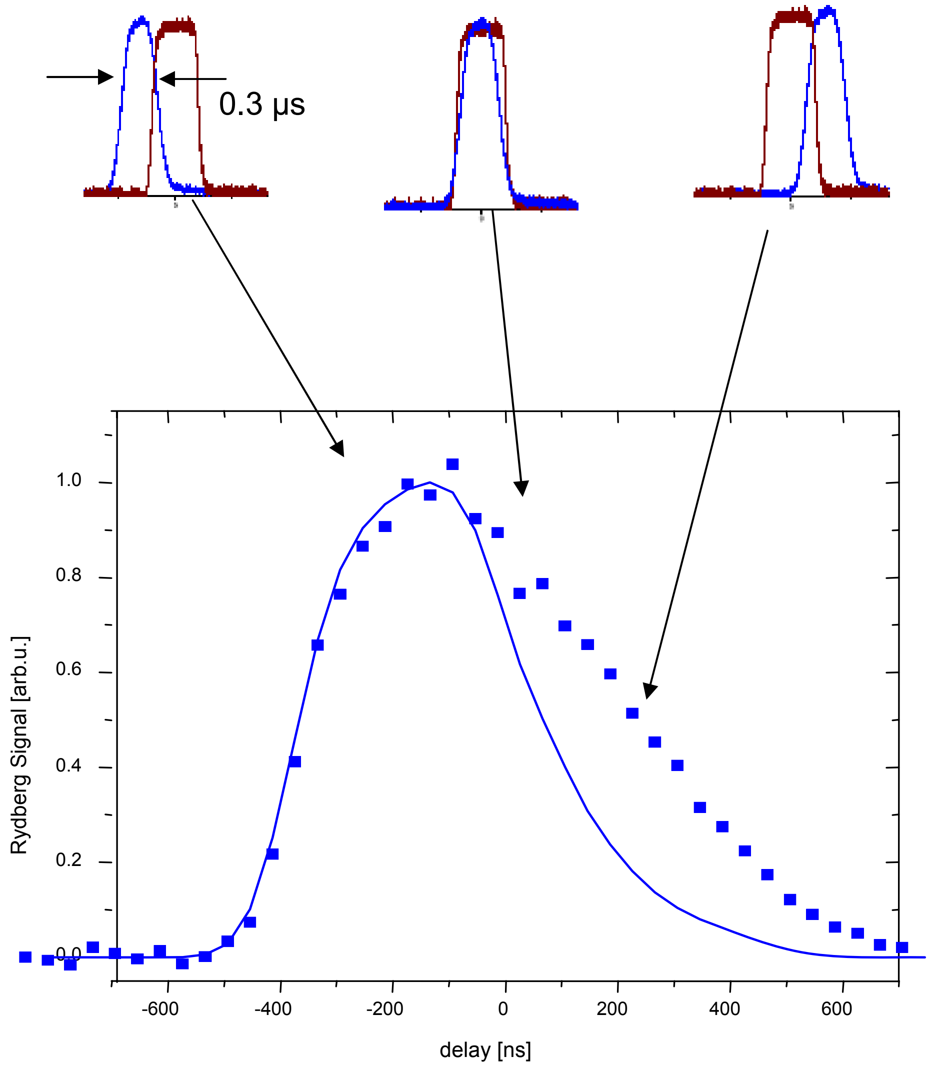
Autler-Townes-Splitting



Excitation schemes II

- 2 photons & 3 levels
- STIRAP

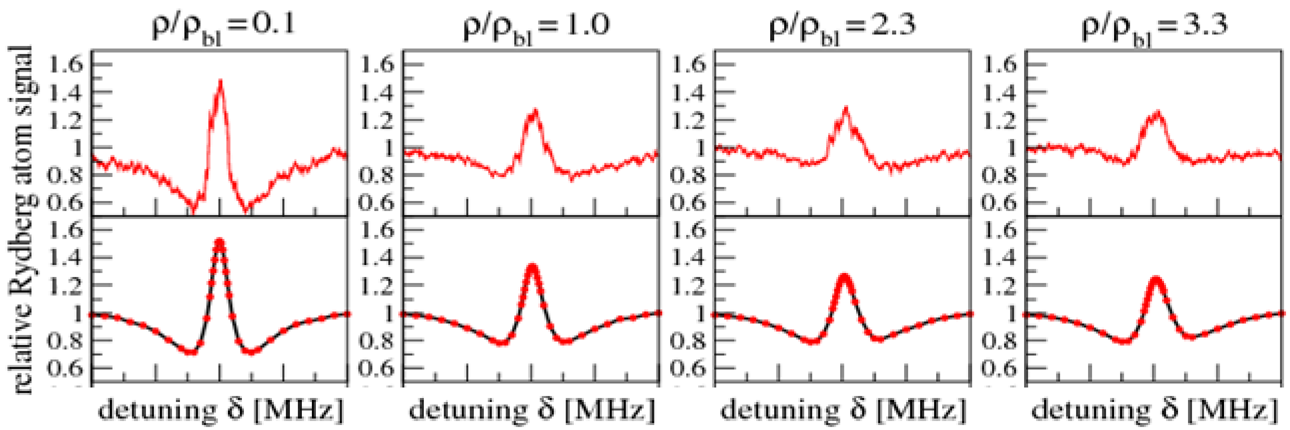


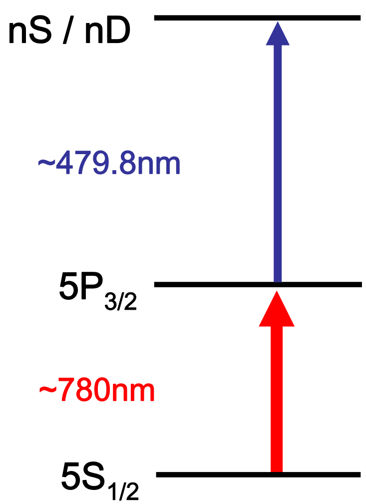


Deiglmayr *et al.*, Opt.Comm. **264**, 293 (2006), *see also* Cubel *et al, PRA* ***72****, 023405 (2005)*

Excitation schemes III

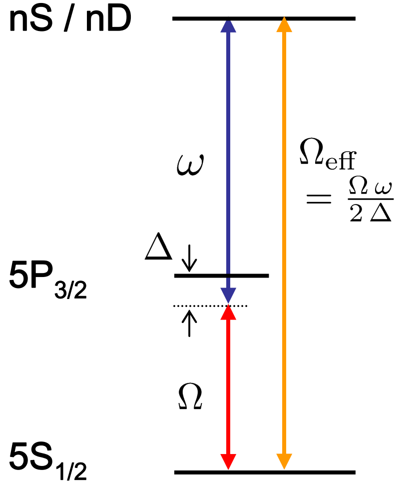
- 2 photons & 3 levels
- STIRAP
- CPT



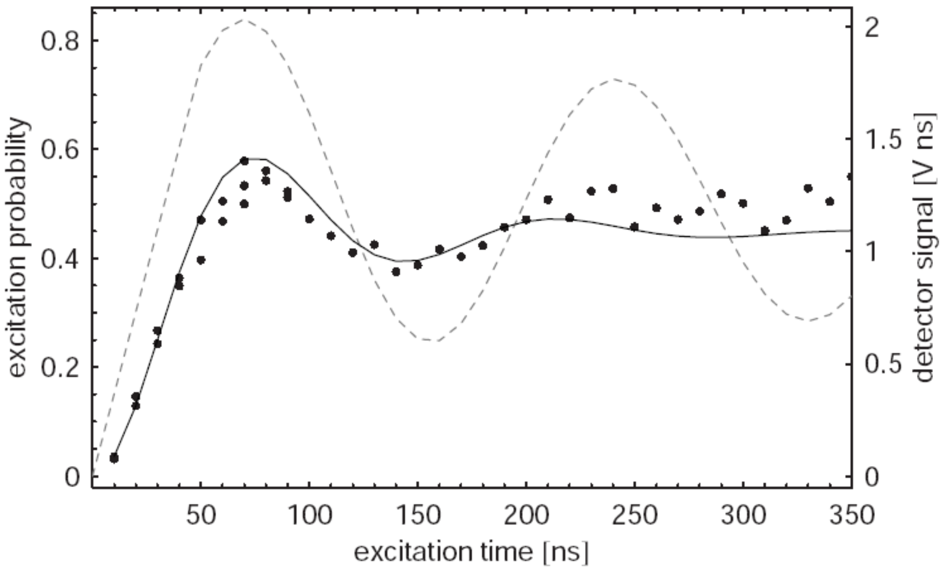


Excitation schemes IV

- 2 photons & 3 levels
- STIRAP
- CPT
- **2 photons & 2 levels**



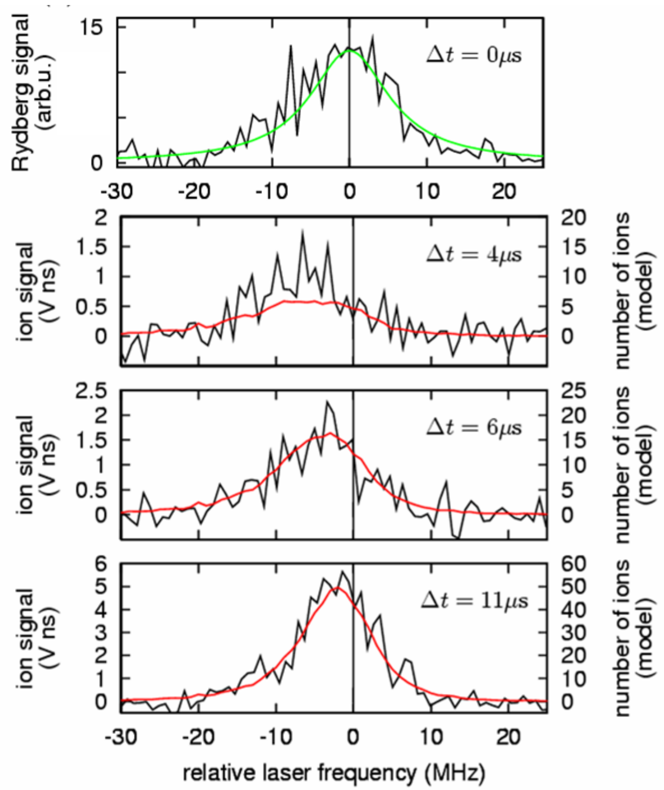
Coherent Rydberg excitation



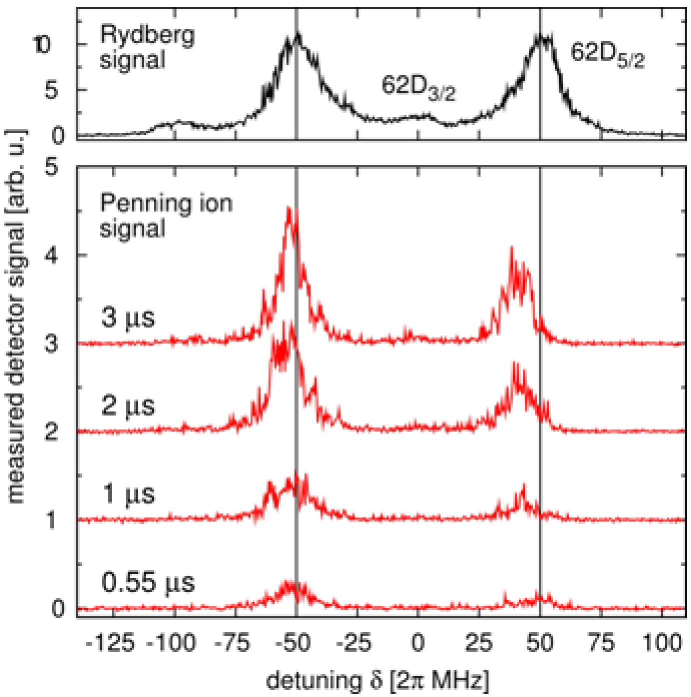
see also Johnson *et al.*, PRL **100**, 113003 (2008)
and Miroshnychenko *et al.*, PRA **82**, 013405 (2010)

Mechanical forces and Antiblockade

Real time observation of mechanical forces



Antiblockade of excitation



Amthor *et al.*, PRL **98**, 023004 (2007) & PRA **76**, 054702 (2007)

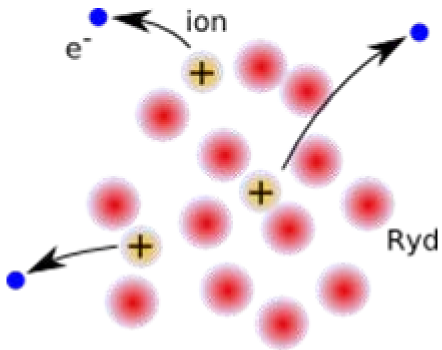
Amthor *et al.*, PRL **104**, 013001 (2010)

Overview

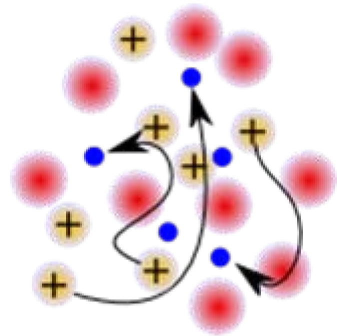
- Introduction to ultracold Rydberg physics
- Rydberg ionization dynamics observed in real time
  - attractive van-der-Waals-potientials
  - repulsive van-der-Waals-potientials
- Antiblockade of an interacting Rydberg gas
- Conclusion

Autoionization and formation of a plasma

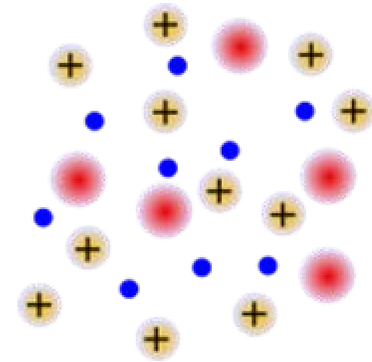
some atoms are ionized



avalanche ionization



ultracold plasma



~1μs ~10μs

Robinson *et al.*, PRL **85,** 4466 (2000

Pohl *et al.*, PRA **68**, 010703 (2003)

Li *et al.*, PRL **94**, 173001 (2005)

Killian *et al.*, Physics Reports **449**, 77 (2007)

Autoionization and formation of a plasma

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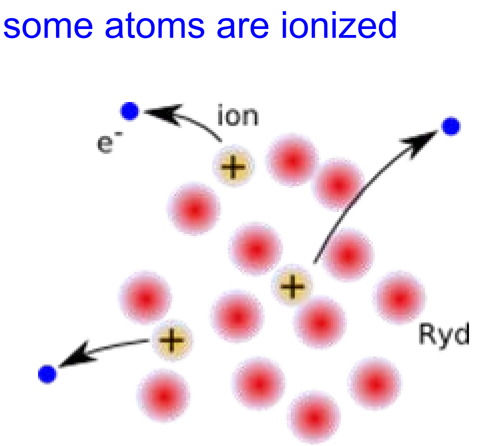

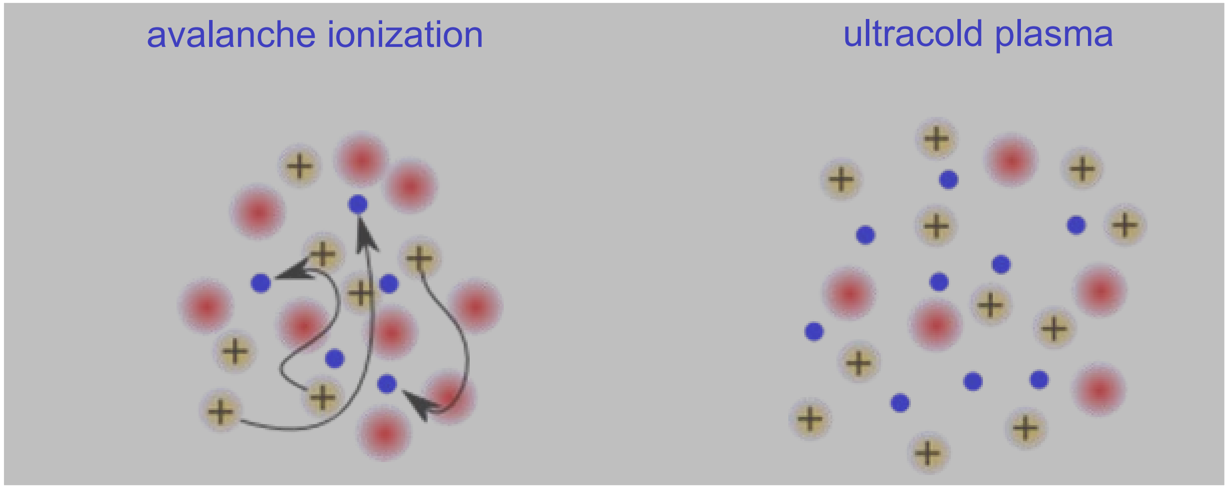

~1μs ~10μs

Initial ionization processes

- Black body radiation ~3 kHz @ n=80
- Collisions with hot background atoms ~200 Hz @ n=80
- *Cold Rydberg - cold Rydberg collisions*

First experimental observation: Robinson *et al.*, PRL **85**, 4466 (2000)

Rydberg interactions

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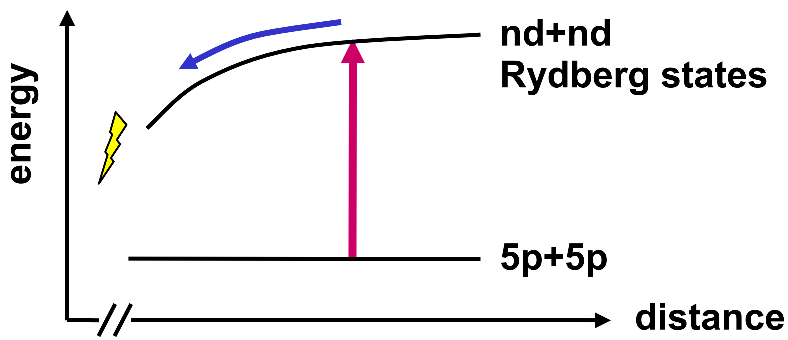
- Large polarizability $\propto n^7$
- Strong van der Waals coefficient $\propto n^{11}$

attractive or repulsive van der Waals interactions

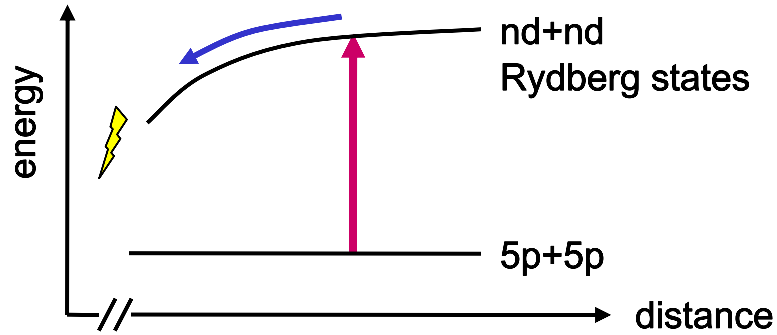
pair potential



ionizing collisions
(Penning ionization)

n ~ 60:
collision time ~ µs
for distances ~ µm

Interaction-induced ionization



IDEA:

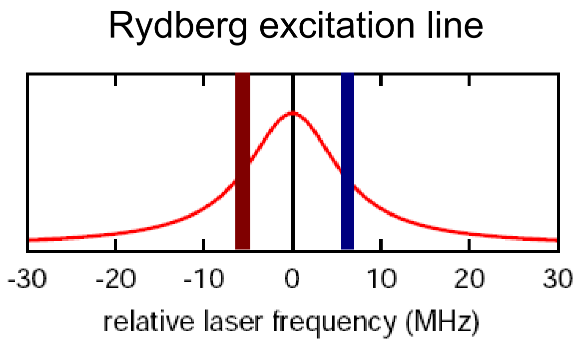
- Prepare a sample with specific distribution of pair distances

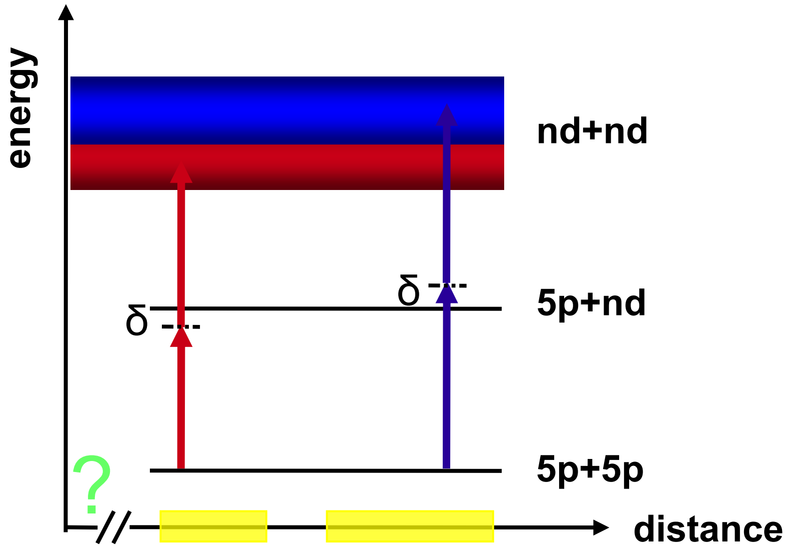
- Observe ionizing collisions in real time

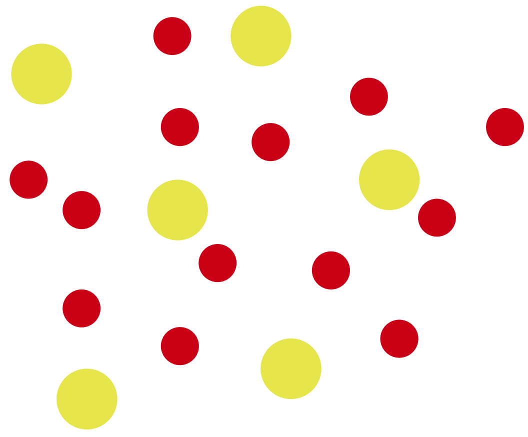
Measurement of ionization dynamics gives information about effective potentials and pair distribution

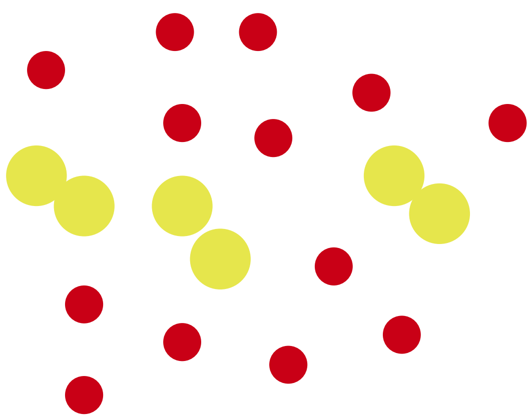
Interaction potential calculations: Singer *et al.*, J. Phys. B 38, S295 (2005)

Model excitation process



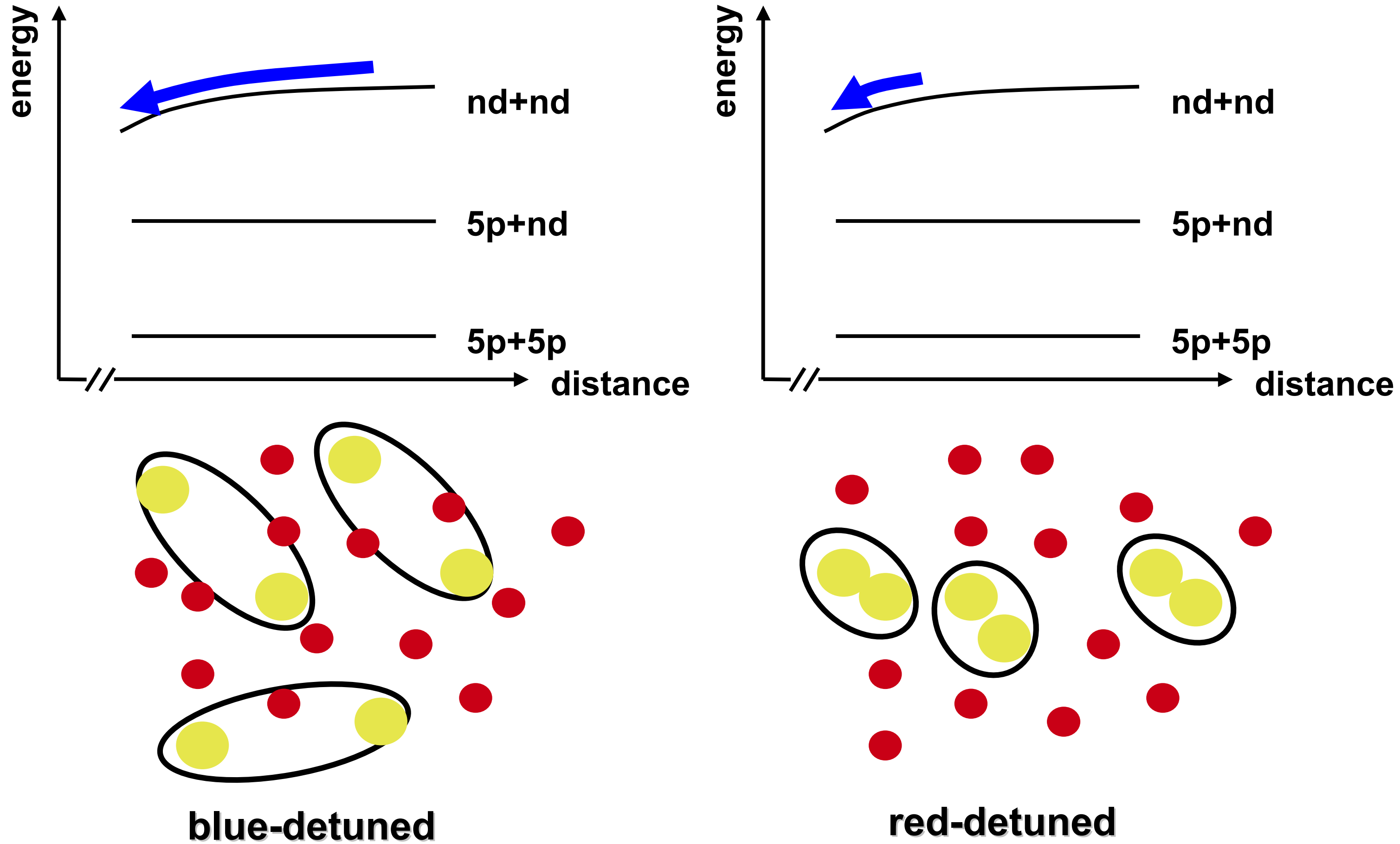




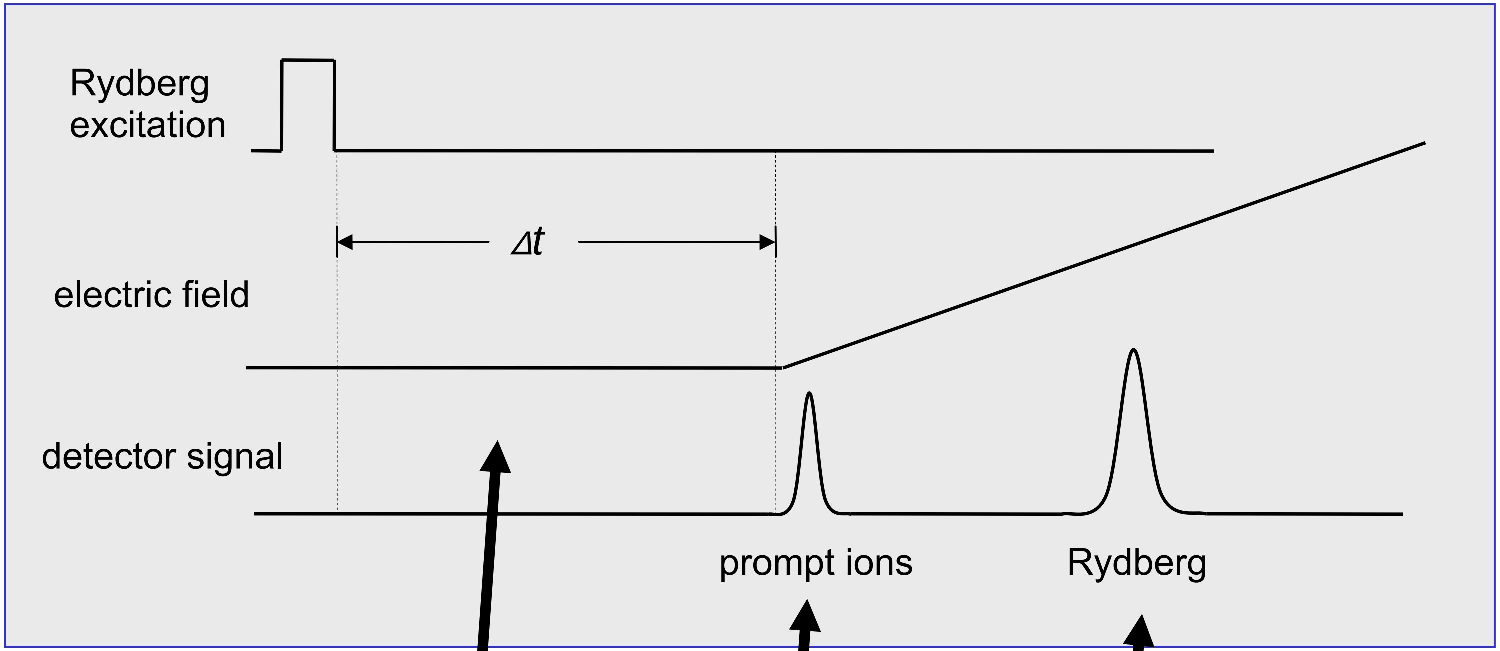


Part 2: Calculation of collision times

- **interaction distance is translated into ionization time**
- extremely sensitive to tiny changes in pair distribution



Timing of the experiment

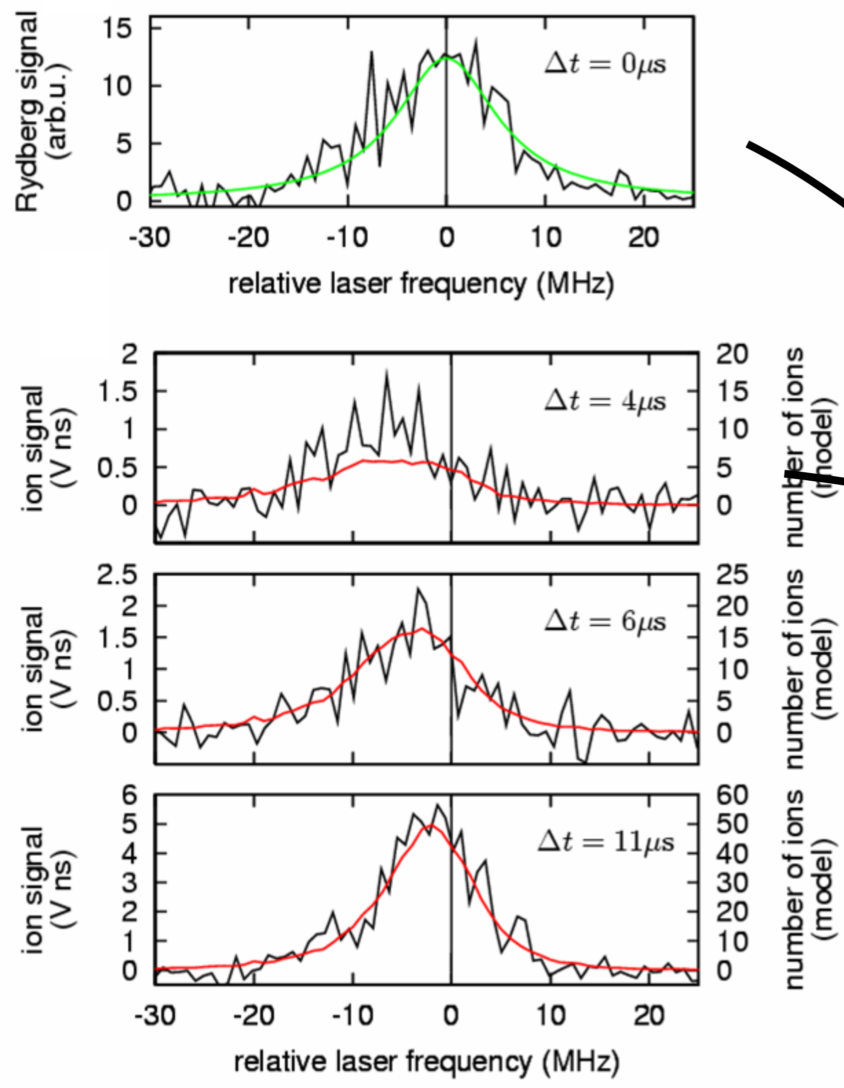


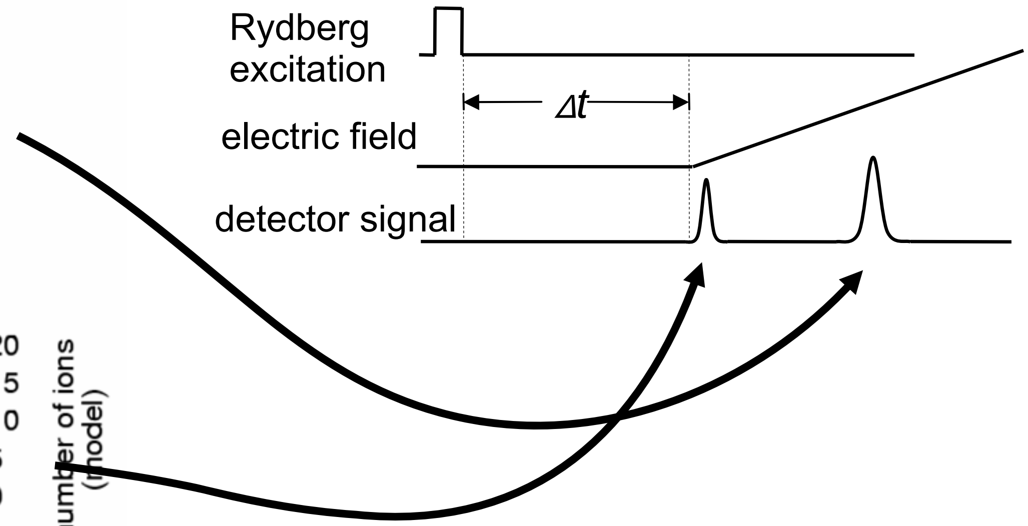
Free evolution of Rydberg gas

Free ions are detected at low electric field

Rydberg states are ionized at higher field

Measurement of $60D_{5/2}$ ionization

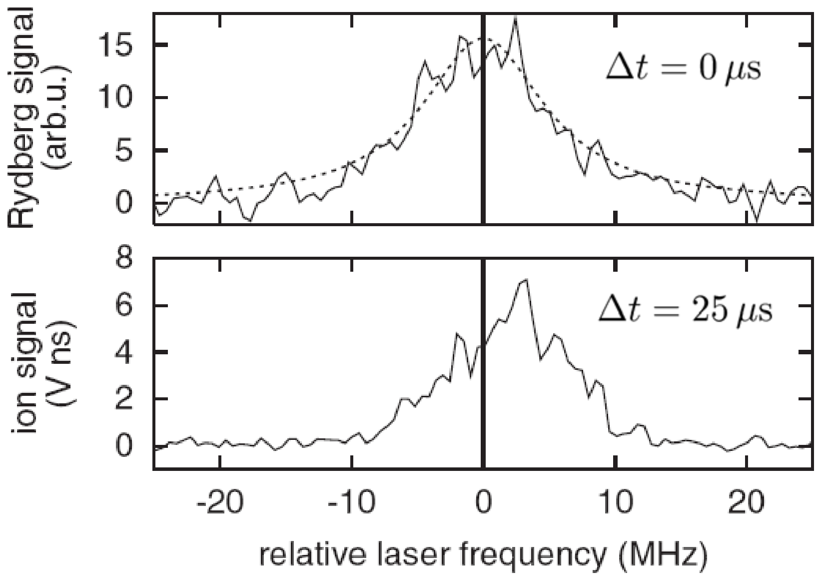


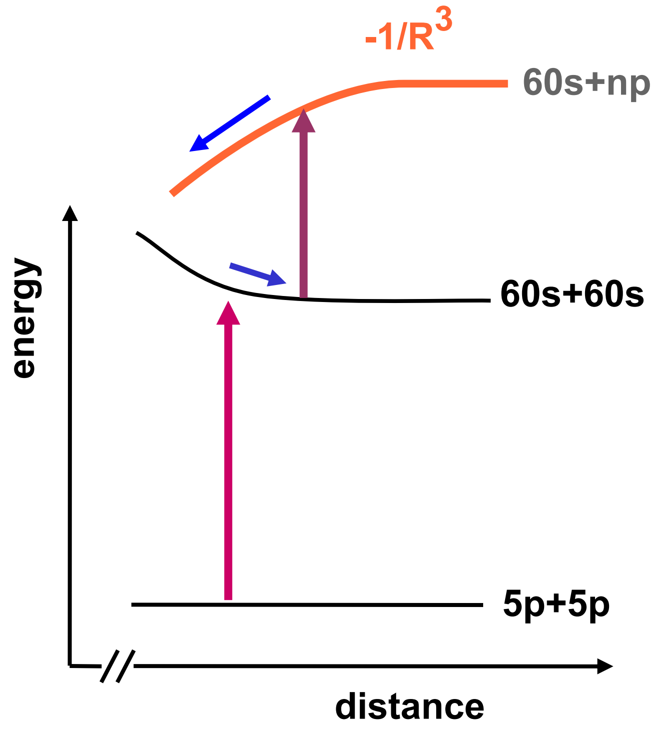


Ions appear first on the red-detuned wing of the excitation line

Amthor *et al.*, PRL **98**, 023004 (2007)

Repulsive potentials – the 60S state



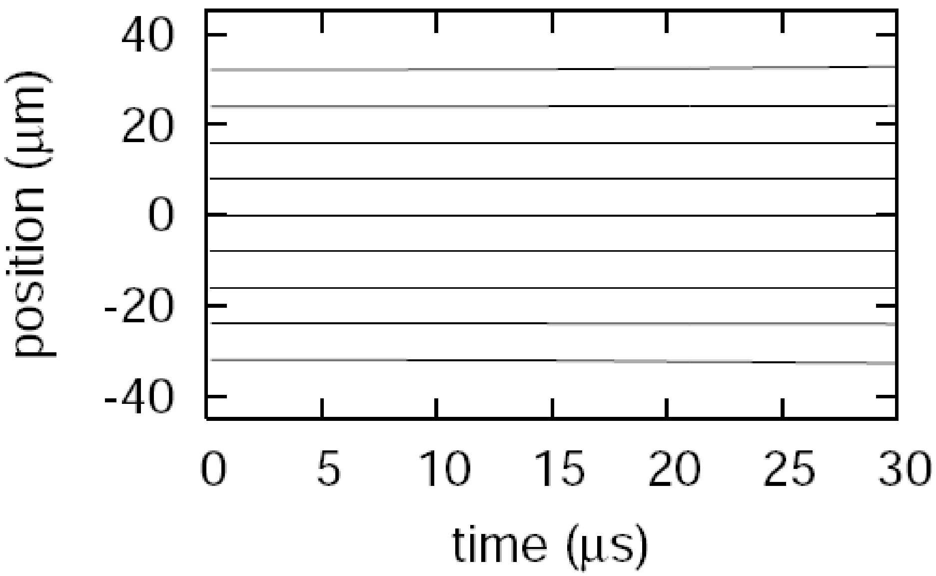


Ionization on blue-detuned side
and on longer time scales

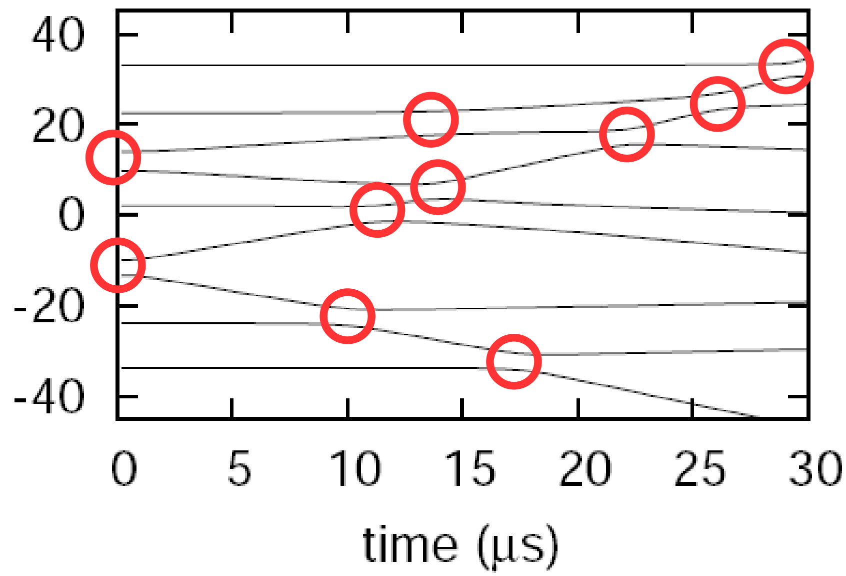
- black body radiation-induced **redistribution** to other states
  → attractive dipole-dipole interaction

Many-particle repulsive interaction (1D)

regular spacing



some close pairs

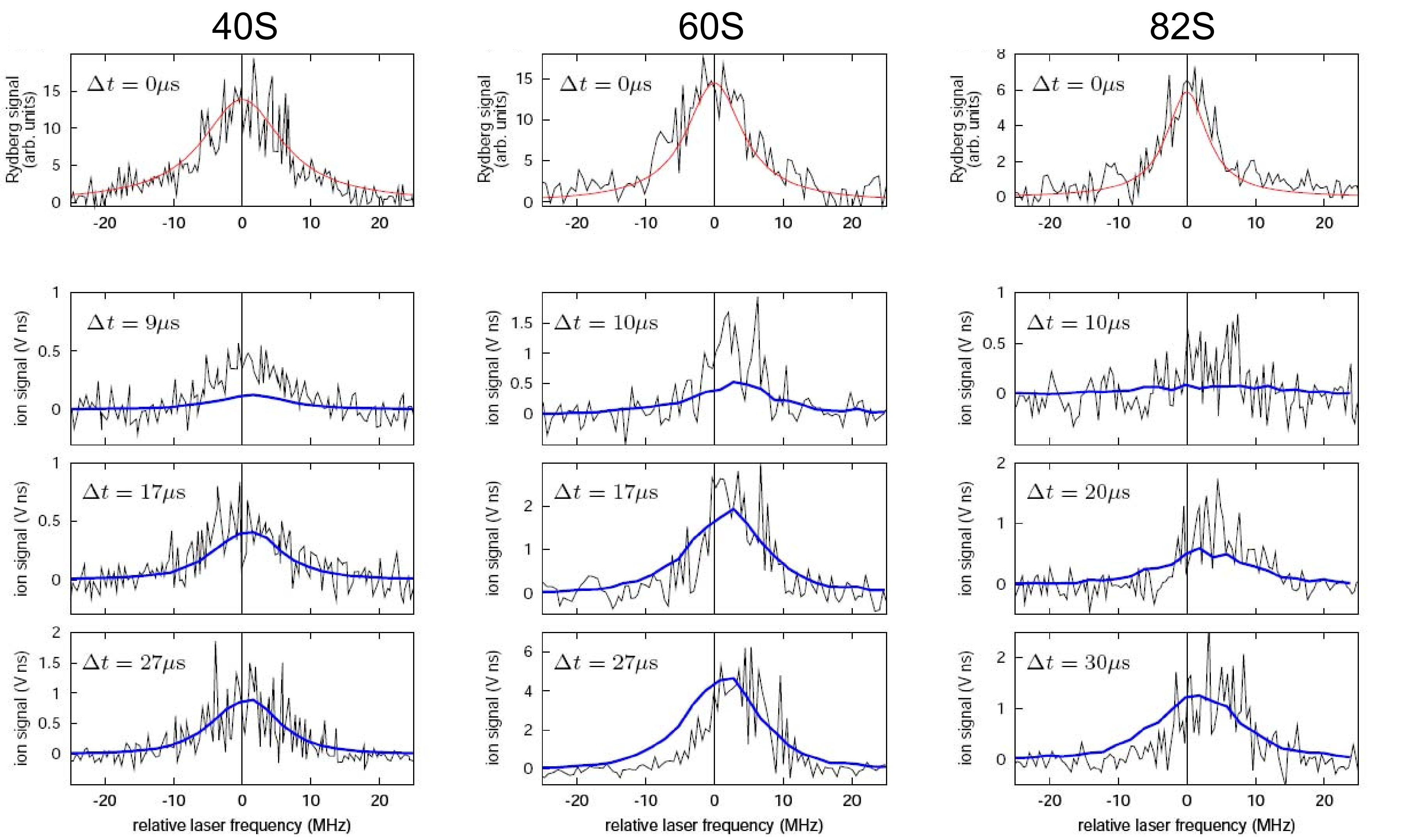


short distances always recurring

few black-body-induced collisions on relevant timescales

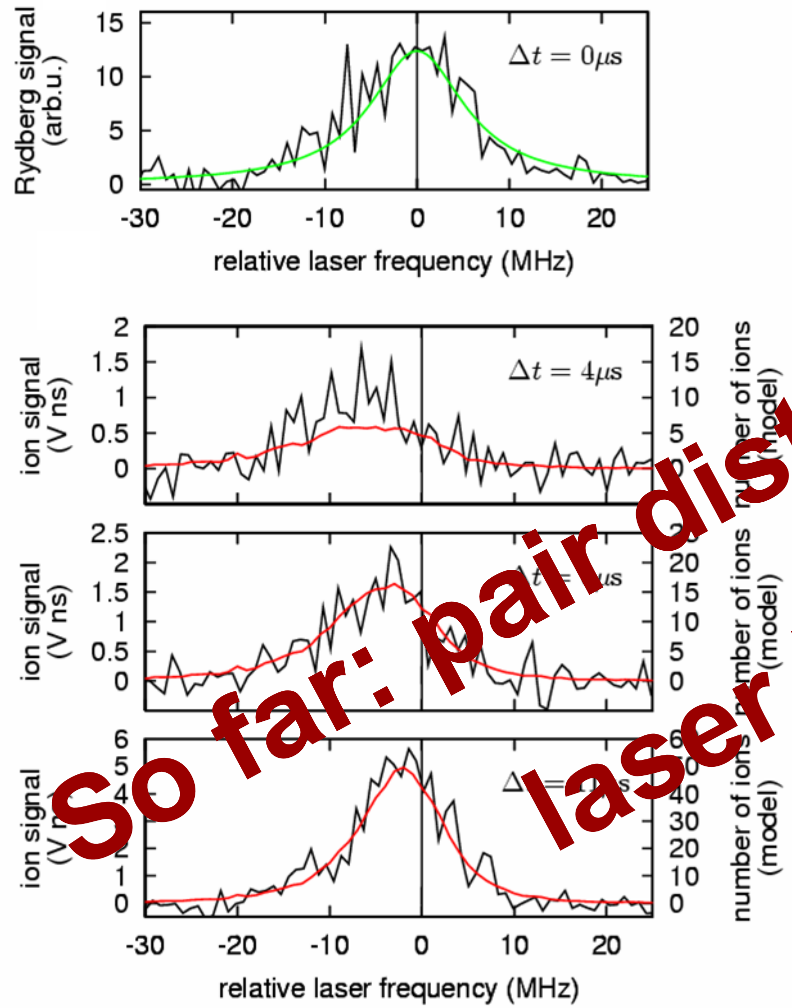
many black-body-induced collisions on relevant timescales

Ionization dynamics of repulsive states

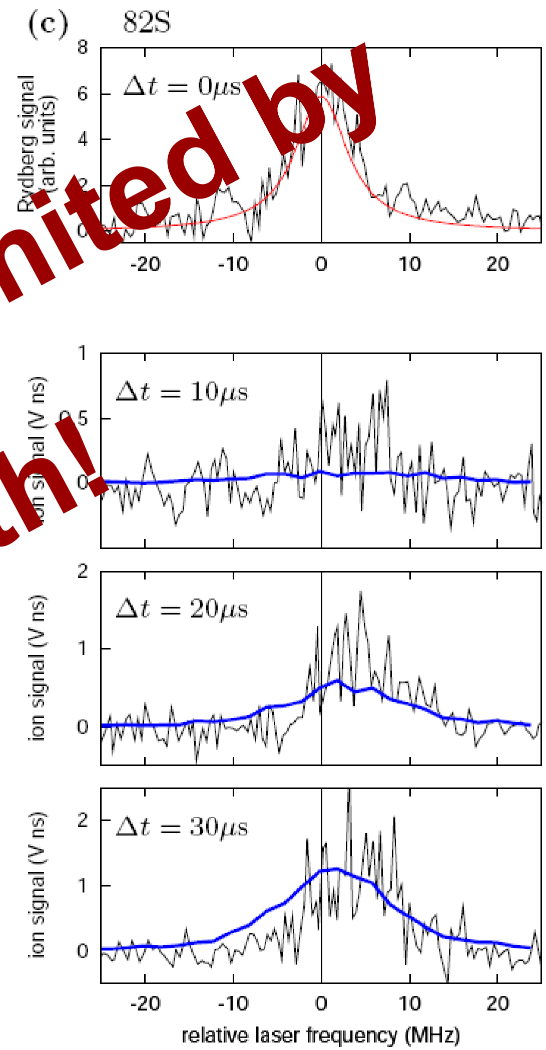


Manipulation of the pair distribution

62D (attractive)



82S (repulsive)



So far: pair distance limited by laser linewidth!

Amthor *et al.*, PRL **98**, 023004 (2007)

Amthor *et al.*, PRA **76**, 054702 (2007)

Overview

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- Rydberg ionization dynamics observed in real time
  - attractive van-der-Waals-potientials
  - repulsive van-der-Waals-potientials
- Antiblockade of an interacting Rydberg gas
- Conclusion

Antiblockade proposal

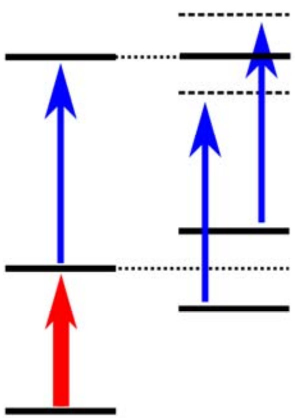
PRL **98,** 023002 (2007) PHYSICAL REVIEW LETTERS week ending 12 JANUARY 2007

Antiblockade in Rydberg Excitation of an Ultracold Lattice Gas

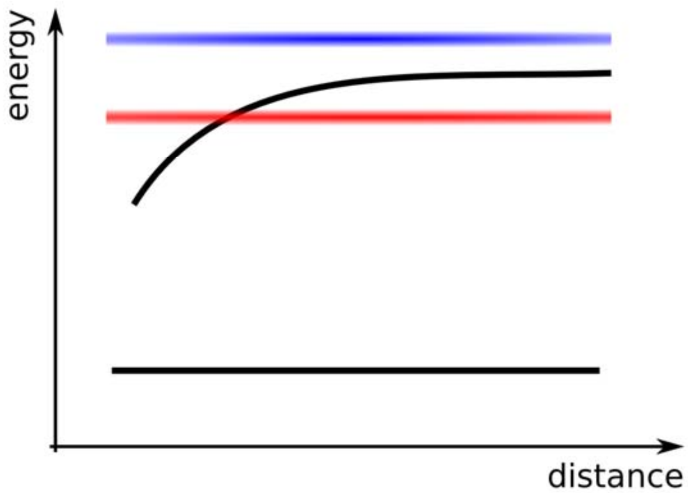
C. Ates,[1] T. Pohl,[2] T. Pattard,[1] and J. M. Rost[1]

[1]*Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Straße 38, D-01187 Dresden, Germany*
[2]*ITAMP, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA*
(Received 12 May 2006; published 8 January 2007)

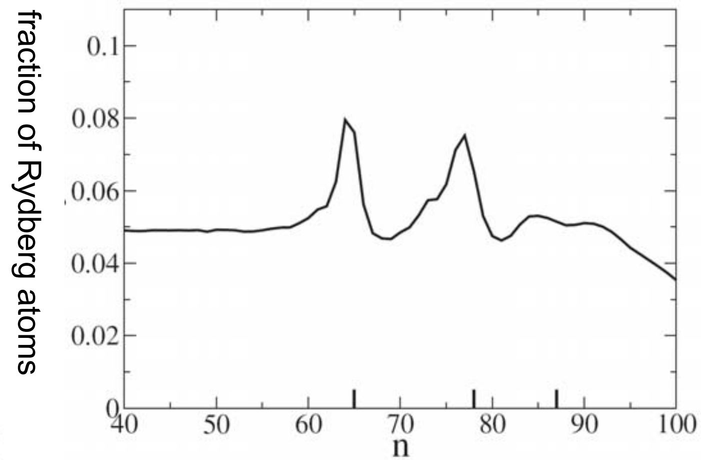
dressed atom picture



two atom picture

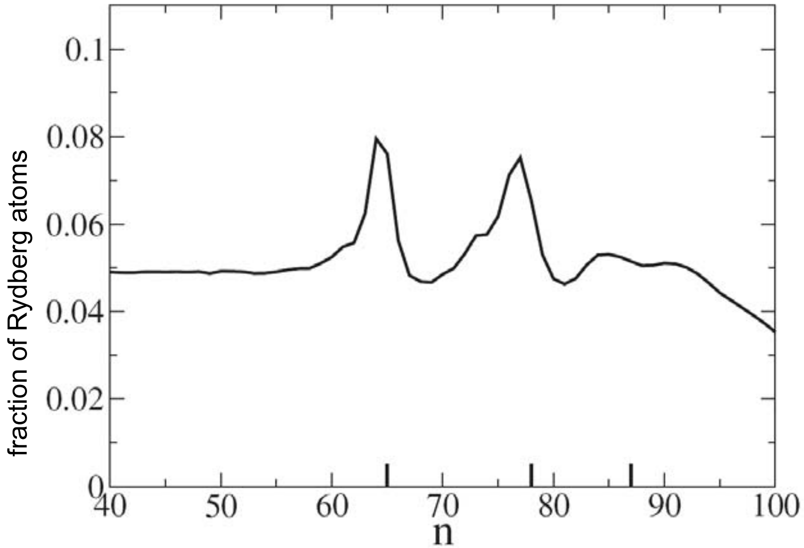


Antiblockade = enhanced Rydberg excitation



Antiblockade effect

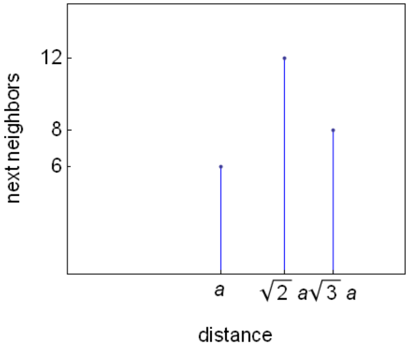
- **anti-blockade = enhanced Rydberg excitation**

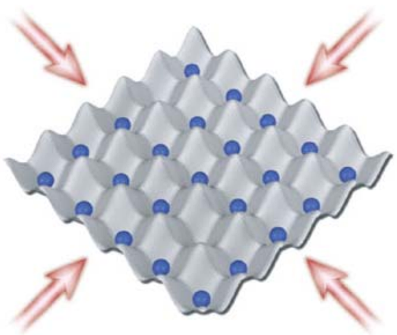


starting conditions:

→ 2-photon transition to produce AT splitting (Ω_1 = 22 MHz)

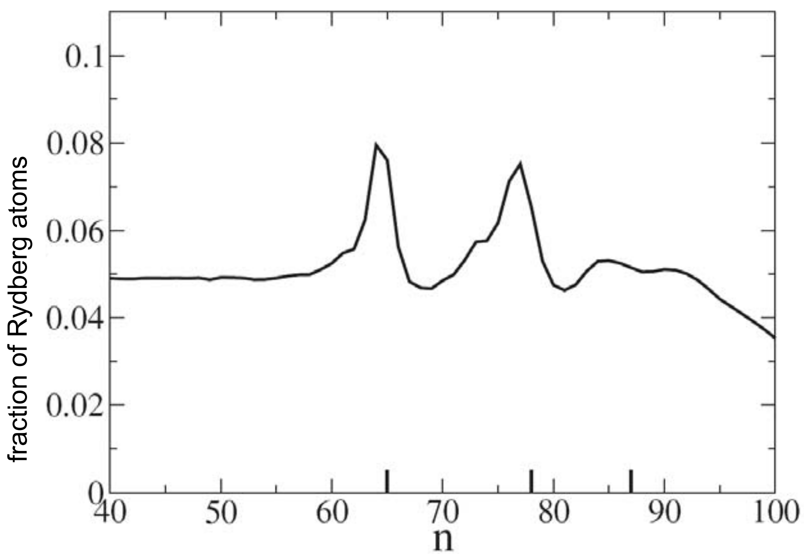
→ optical lattice (a = 5 μm)

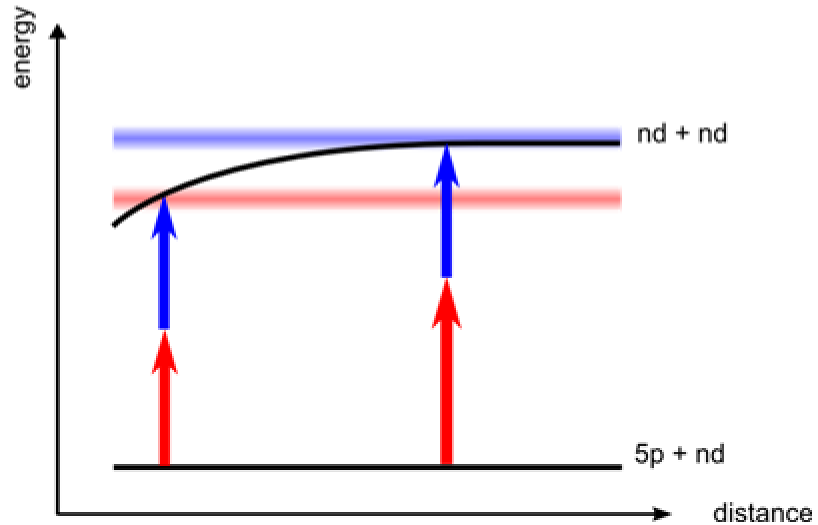




Ways to reveal the antiblockade effect

- **anti-blockade = enhanced Rydberg excitation**





→ discrete pair distribution $\delta(R, a_i)$

→ n-dependent energy shift $\Delta_R(n) \sim n^{11}$

→ resonance condition $h\Omega_1 = \Delta_R(n)$

→ continuous pair distribution $\sim R^2$

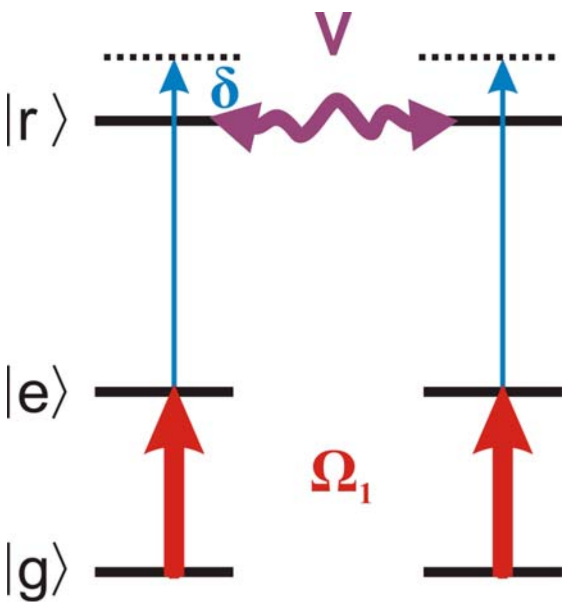
→ R-dependent energy shift $\Delta_n(R) \sim R^{-6}$

→ resonance condition $h\Omega_1 = \Delta_n(R)$

Ates *et al.* PRL 98, 023002 (2007)

Amthor *et al.* PRL 104, 013001 (2010)

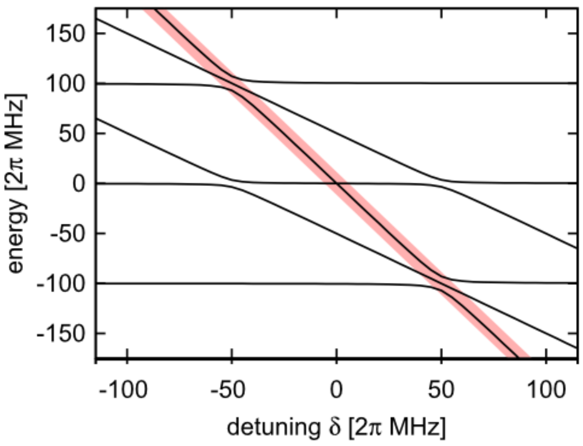
Two interacting three-level systems



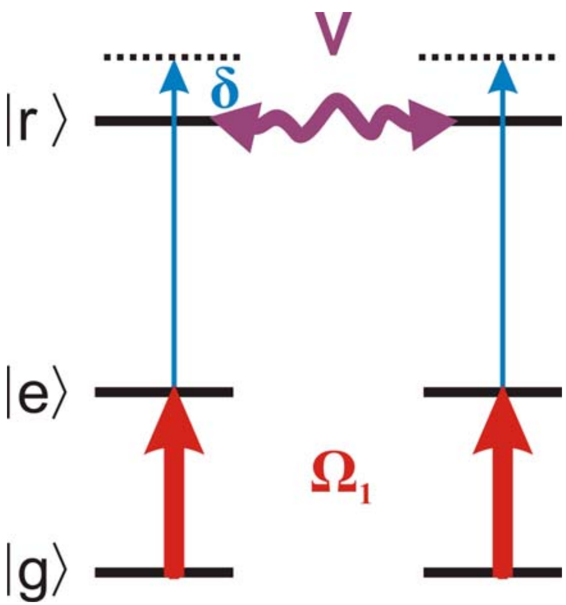
two-atom states

|rr>	- 2δ - V
|gr> |rg> |er> |re>	- δ
|ee> |ge> |eg> |gg>	0

eigenstates of coupled system
with V = 0, Ω_1 = 100 MHz



Two interacting three-level systems



two-atom states

|rr>	- 2δ - V
|gr> |rg> |er> |re>	- δ
|ee> |ge> |eg> |gg>	0

eigenstates of coupled system
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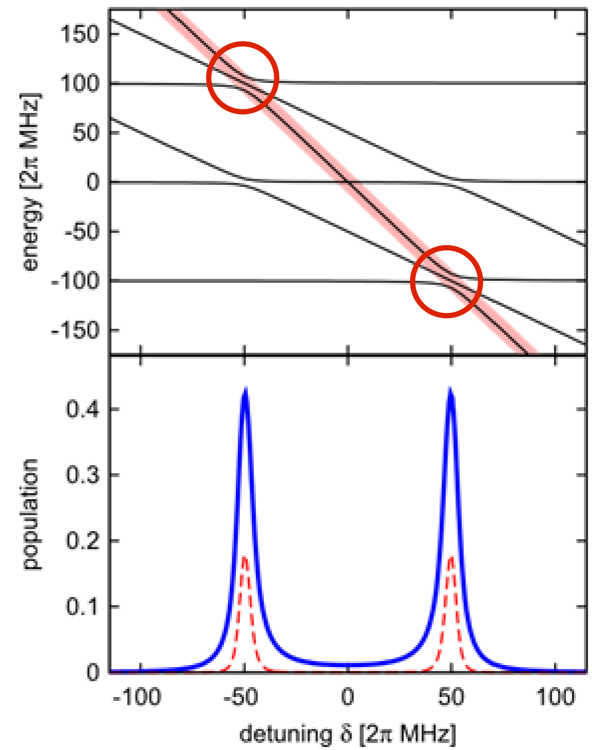
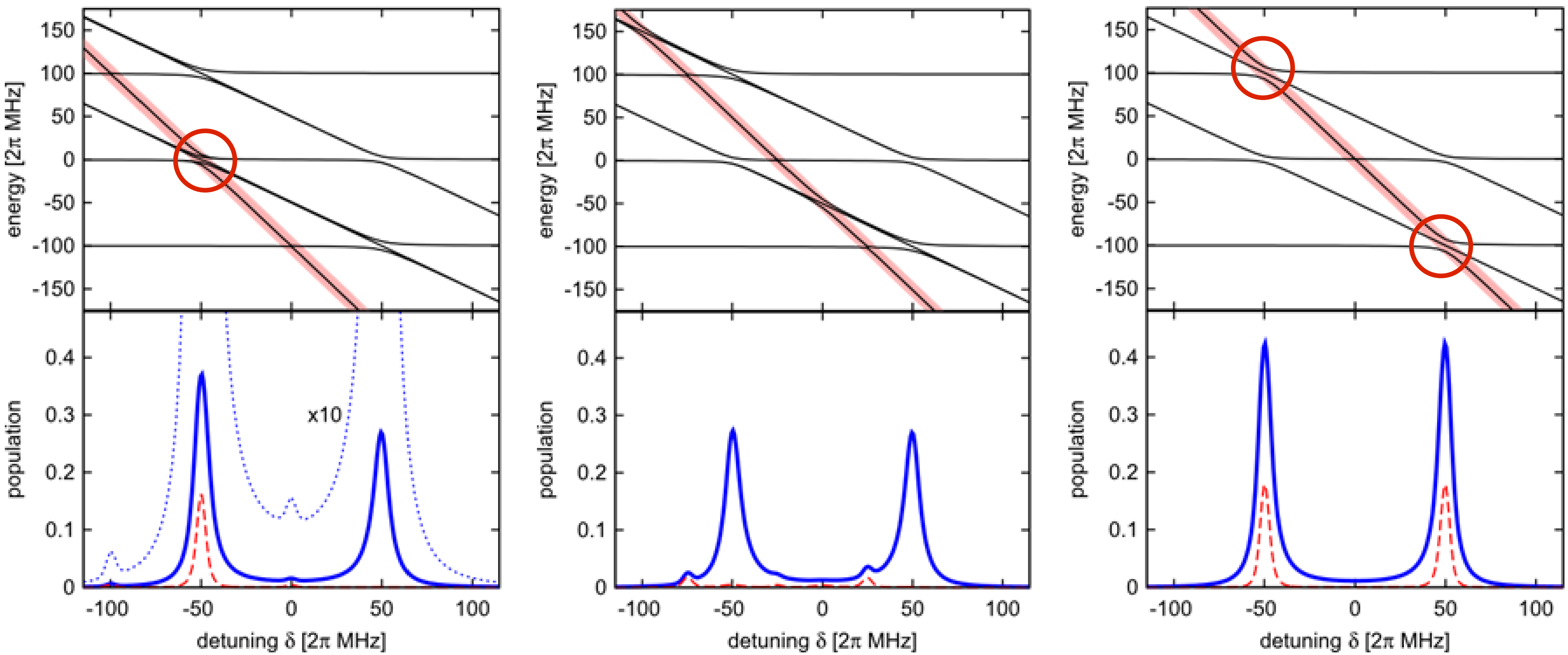


Autler-Townes-Splitting
due to Ω_1

Blockade and antiblockade

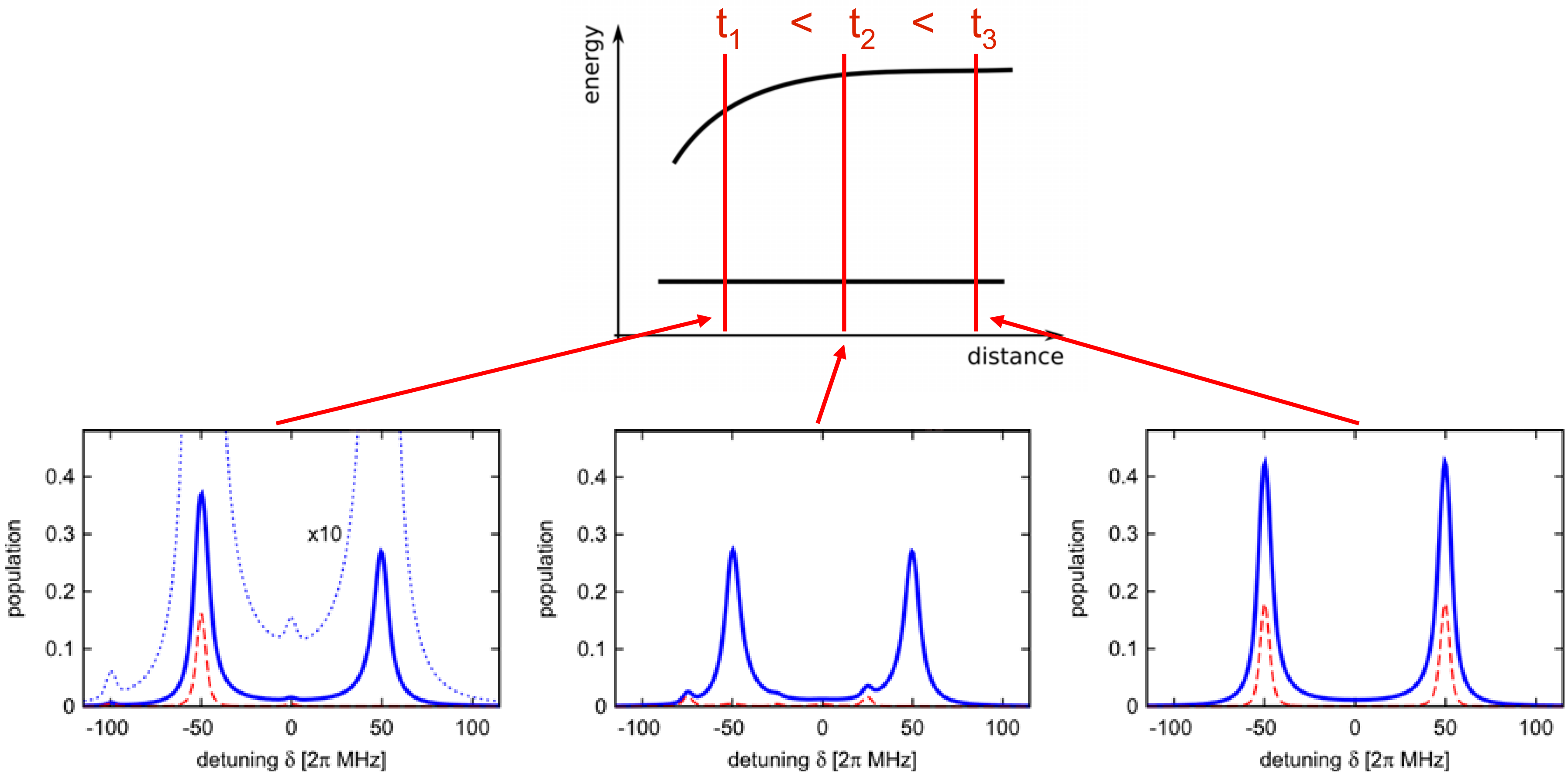
$V = \Omega_1$	$V = \Omega_1/2$	$V = 0$,
Ω_1 = 100 MHz	Ω_1 = 100 MHz	Ω_1 = 100 MHz
antiblockade	**blockade**	**no blockade**



total Rydberg population per atom

detectable as prompt ions ⟵ undergoes Penning ionization ⟵ population of |rr> only

Blockade and antiblockade



total Rydberg population per atom

detectable as prompt ions ← undergoes Penning ionization ← population of |rr> only

Average over pair distribution

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Random gas: All pair distances available

Large Rabi splitting → large interaction energies
→ only **nearest neighbors** are taken into account

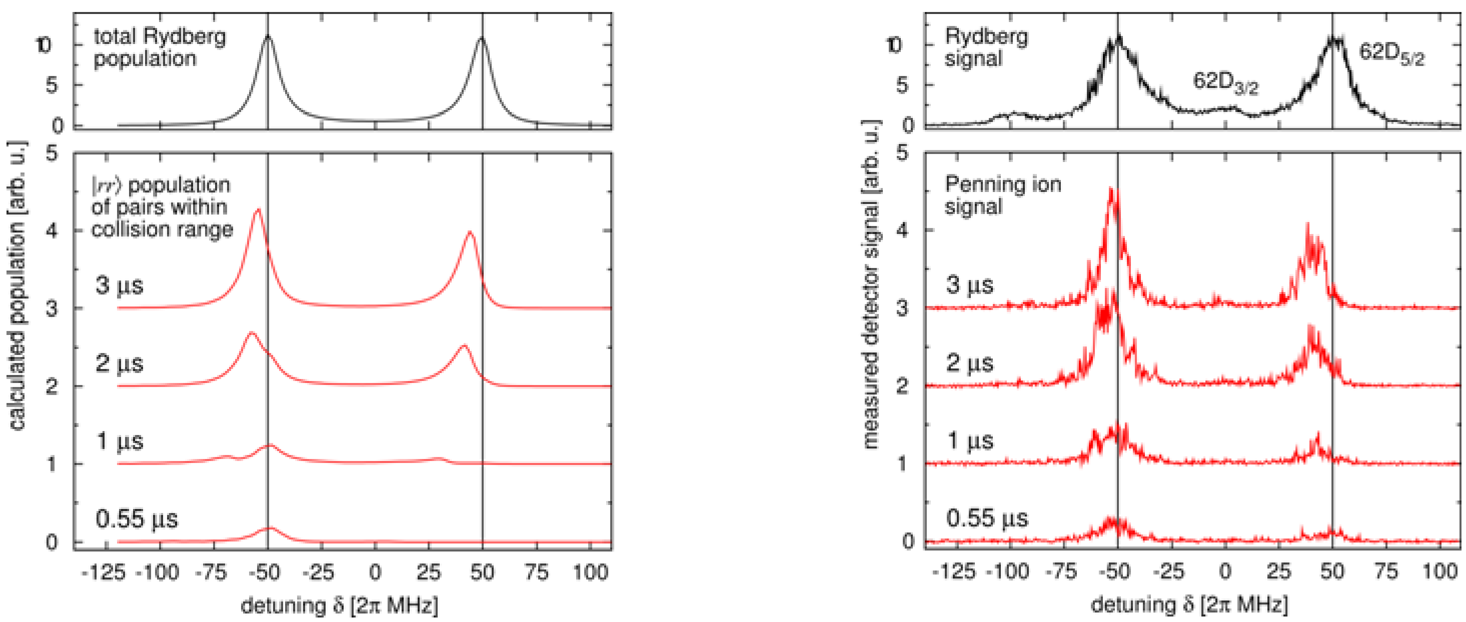
How to calculate the expected Penning ionization signal?

- Calculate excitation spectra for many pair distances
- Perform weighting with regard to nearest neighbor distribution
- Add up |rr> contribution of all spectra with a pair distance leading to a collision within a given time delay

Penning ionization signals

Theoretical prediction

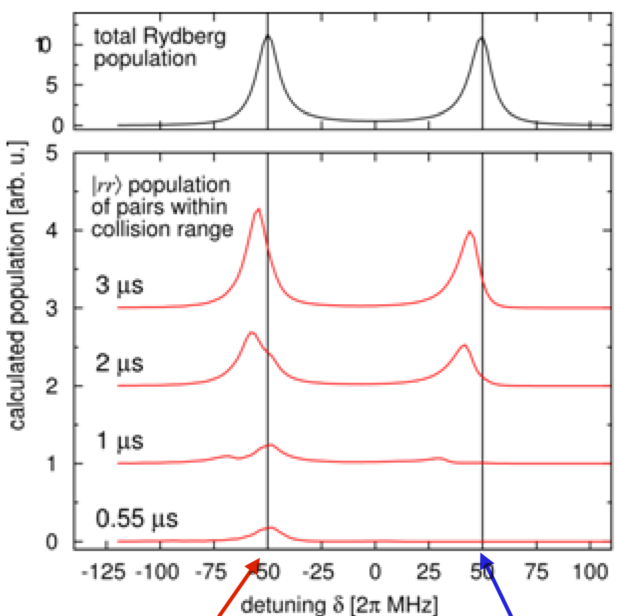
Experimental observation



Asymmetry of Autler-Townes spectra
as evidence for antiblockade

Nearest neighbor distribution

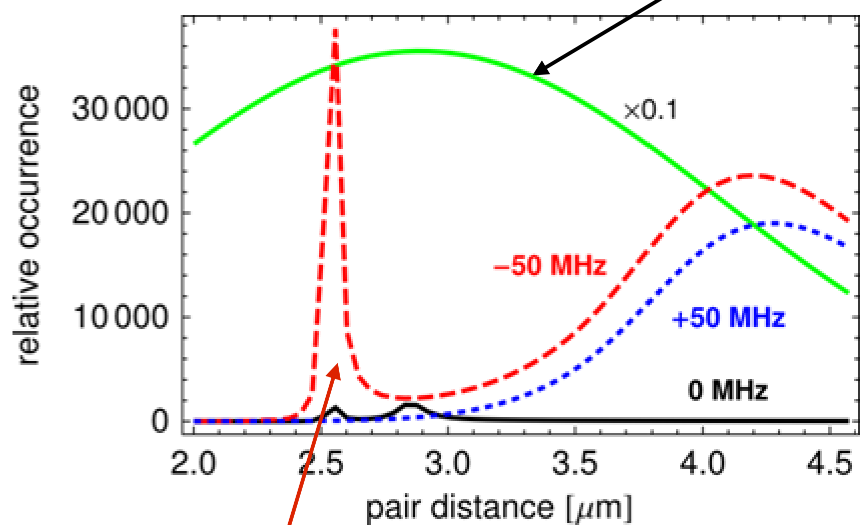
Theoretical prediction



-50 MHz

+50 MHz

total nearest neighbor distribution



antiblocked pairs that cause asymmetry of Autler-Townes spectra

Distinctness of asymmetry

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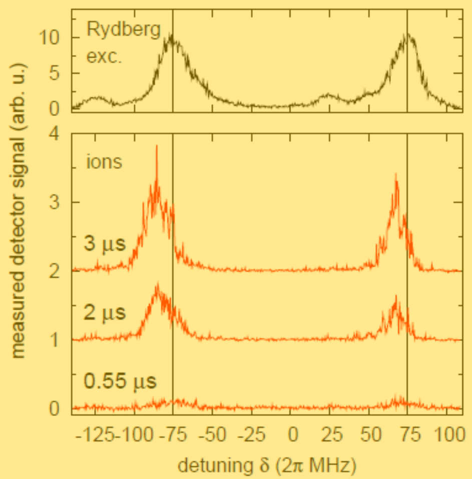
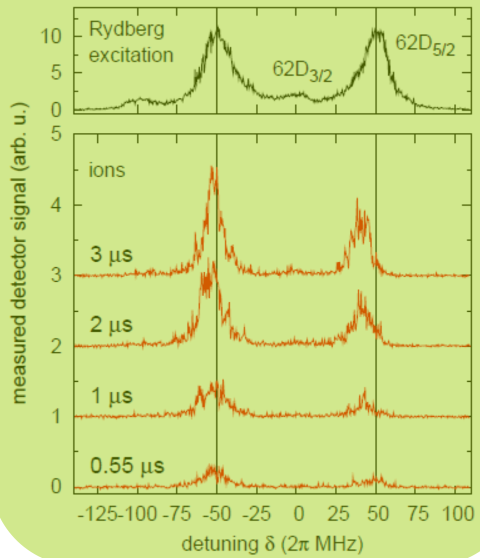
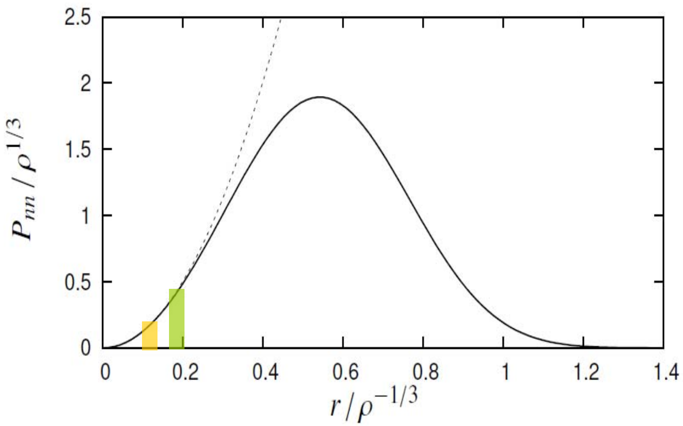
Ω_1 = 150 MHz



Ω_1 = 100 MHz



nearest neighbor distribution



$$P_{nn}(r) = 4\pi r^2 \rho e^{-\frac{4}{3}\pi\rho r^3}$$

- distinctness of the asymmetry depends on availability of atom pairs for which $\mathbf{h\Omega_1 = \Delta_n(r)}$
- more pairs are available at **larger r**
  → asymmetry more pronounced for **smaller** $\mathbf{\Omega_1}$

Conclusion

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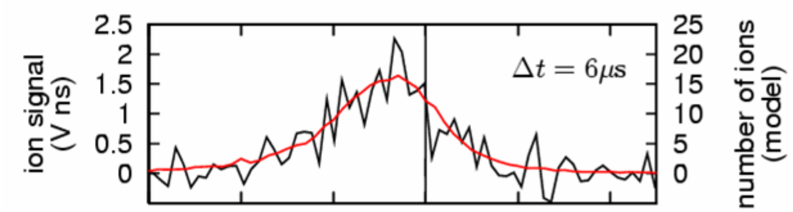
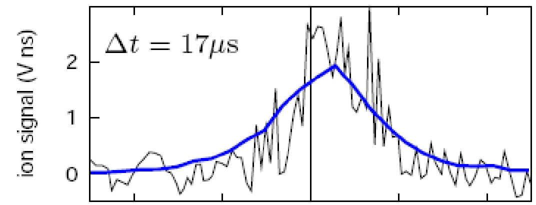
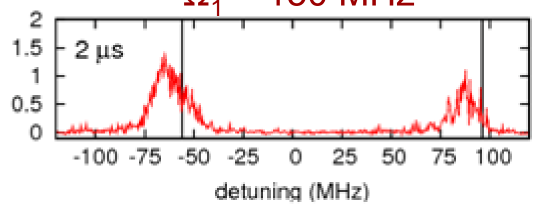
- Real time observation of Ionization dynamics



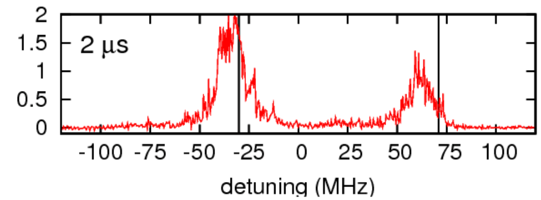


- First experimental evidence of the antiblockade

Ω_1 = 150 MHz



Ω_1 = 100 MHz



- Manipulating the pair distribution by detuned Rydberg excitation