Cold Rydberg atoms

Dipole-dipole interactions with cold Rydberg atoms

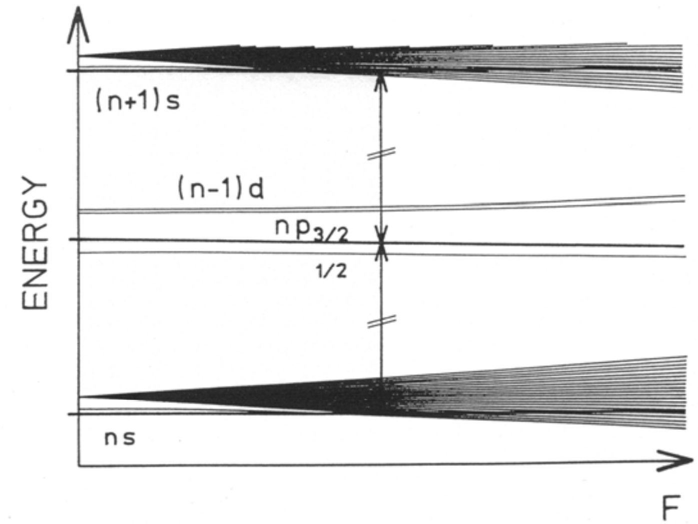
Frozen Rydberg gas or dipole gas

Resonant collisions (Cs: *n* < 42)

by adding a small electric field 2 x E($np_{3/2}$) = E(ns) + E((n+1)s)

Resonant Rydberg-Rydberg atom collisions
(T.F. Gallagher et al., P.R.L. 40, 1362 (1981) with Na)

Resonant transfer of internal energy **n < 42**
Cs [$np_{3/2}$] + Cs [$np_{3/2}$] –> Cs [ns] + Cs [(n+1)s]



Long-range dipole-dipole interaction:

$$W = \frac{\vec{\mu}_1 \cdot \vec{\mu}_2}{r^3} - \frac{3(\vec{\mu}_1 \cdot \vec{r})(\vec{\mu}_2 \cdot \vec{r})}{r^5} \approx \frac{\mu_1 \mu_2}{r^3}$$

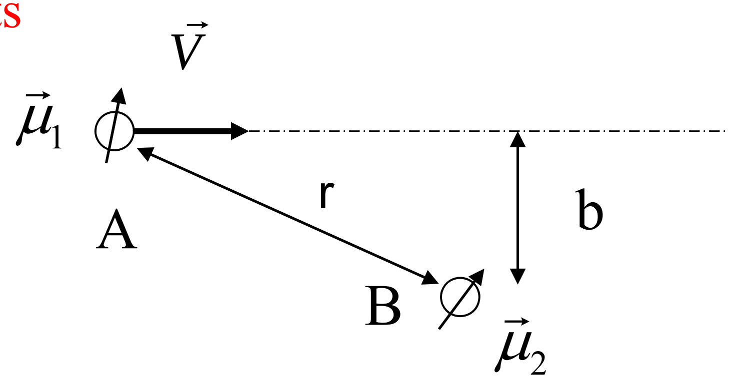
Characterized by huge Rydberg dipole moments

$$\langle ns | \mu_i | np \rangle \approx \langle ns | \mu_i | (n-1)p \rangle \sim n^2 a.u.$$

Characteristic time: $\tau_C \approx \frac{b}{v}$; $W_C \tau_C \sim 1$

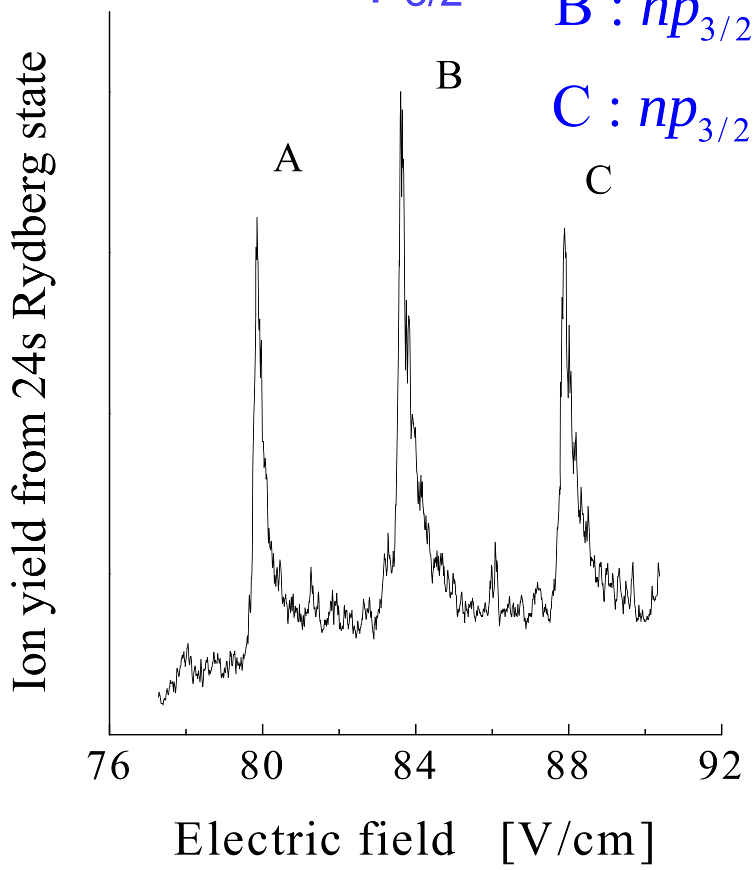
Impact parameter: $b \approx \sqrt{\frac{\mu_1 \mu_2}{v}}$

COLLISION



Resonant collisions in an atomic beam
(10 ns pulsed excitation and hot atoms)

Cs $23p_{3/2}$



$$A: np_{3/2}\,|m| = 1/2 + np_{3/2}\,|m| = 1/2 \rightarrow ns + (n+1)s$$

$$B: np_{3/2}\,|m| = 1/2 + np_{3/2}\,|m| = 3/2 \rightarrow ns + (n+1)s$$

$$C: np_{3/2}\,|m| = 3/2 + np_{3/2}\,|m| = 3/2 \rightarrow ns + (n+1)s$$

Electric field selective detection of ns level

$T \approx 300$ K, $v \approx 300$ m/s

Huge impact parameter: $b_0 \sim 1\ \mu$m

Long collision time: $\tau_C \sim 10$ ns

The width depends of the velocity

Dipole-dipole interaction between cold Rydberg atoms (Försters resonances)

(10 ns pulsed excitation)

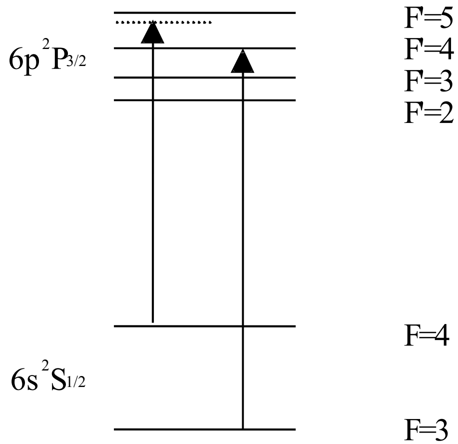
- Large impact parameter (40 μm) comparable to the size of the volume (300μm): ***many-body effects?***

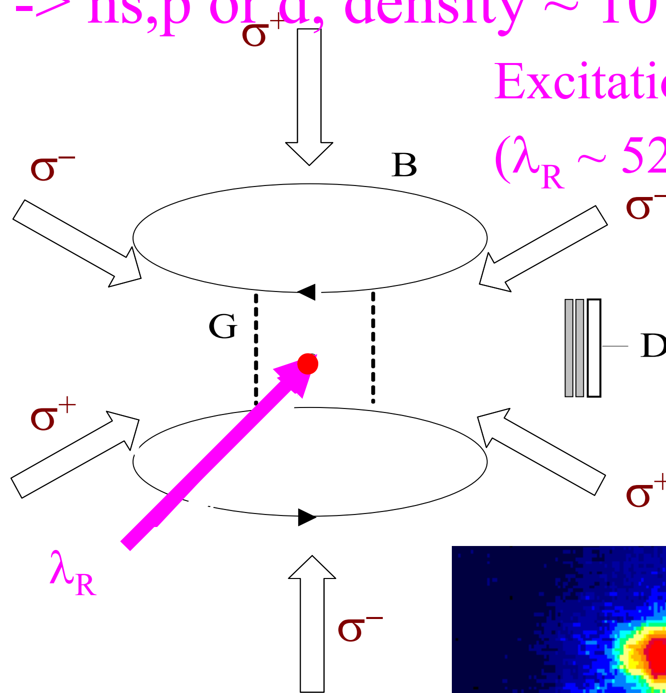
- ***No collision!***

  Approximation of frozen Rydberg gas:
  - small displacement (100 nm) of the atoms in 1μs compared to the average distance of two atoms (5-50 μm).
  - but « too long » collisionnal time (500 μs) compared to the life time (~ a few 10 μs).

Experimental set-up: Cs (Rb) magneto-optical trap (T ~ 20-200 μK)

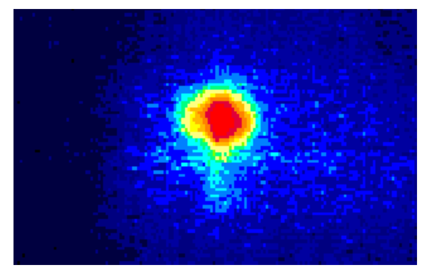
Cs(Rb) : $6(5)p_{3/2} + h\nu_R \rightarrow$ ns,p or d; density ~ 10^{7-10} cm^{-3}

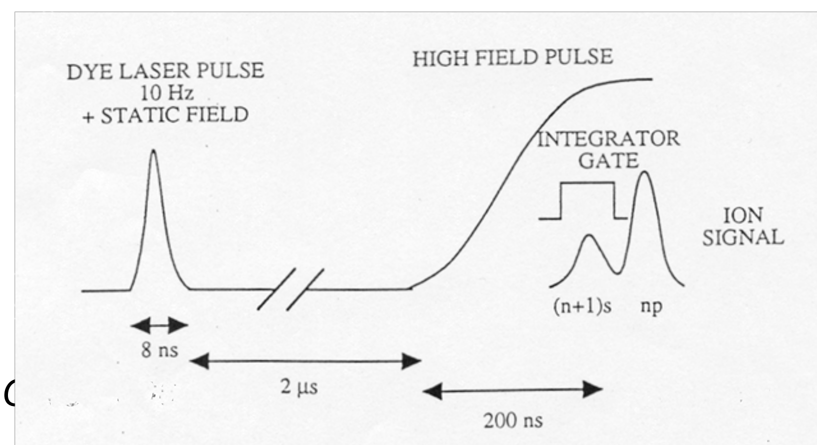




Excitation: pulsed dye-laser

(λ_R ~ 520 nm, 10 Hz)

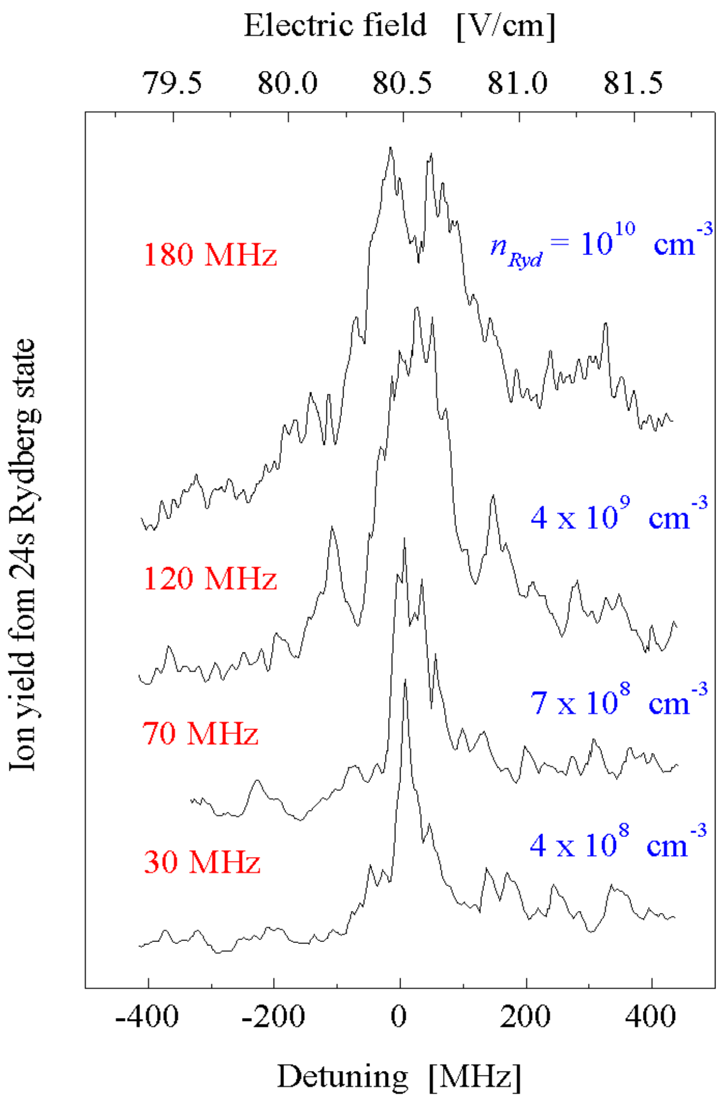




Selective detection

by electric-field ionization

Dipole-dipole interactions in a frozen Rydberg gaz



$$23p_{3/2}(|m_j| = 1/2) + 23p_{3/2}(|m_j| = 1/2)$$

$$\rightarrow 23s + 24s$$

Population Transfer ~ 10-15 %

Interaction between the closest neighbors leads to a too small width: $W_{typ} \approx \dfrac{\mu_1 \mu_2}{\bar{R}_{AB}^3} < 1.5$ MHz

The frozen Rydberg gas cannot be explained in the framework of two-body effects

- Many-body effects in a frozen Rydberg, I. .Mourachko, D. Comparat, F . de Tomasi,, A. Fioretti, P. Nosbaum, V. Akulin et P. Pillet, Phys. Rev. Lett., 80, 253 (1998)
- Resonant dipole-dipole energy transfer in a nearly frozen Rydberg gas, W.R. Anderson, J.R. Veale, and T.F. Gallagher, Phys. Rev. Lett., 80, 249 (1998)

Many-body effects

Interplay with a two-body effect and many-body phenomena

Elementary processes:

I - Resonant transfer of internal energy

$Cs_A\ [np_{3/2}] + Cs_B\ [np_{3/2}]$

$\quad\quad\quad\quad \to Cs_A\ [ns] + Cs_B\ [(n+1)s]$

(resonant for a given electric field)

II - **Migration of the reaction products**

$Cs_C\ [np_{3/2}] + Cs_A\ [ns] \to Cs_C\ [ns] + Cs_A\ [np_{3/2}]$

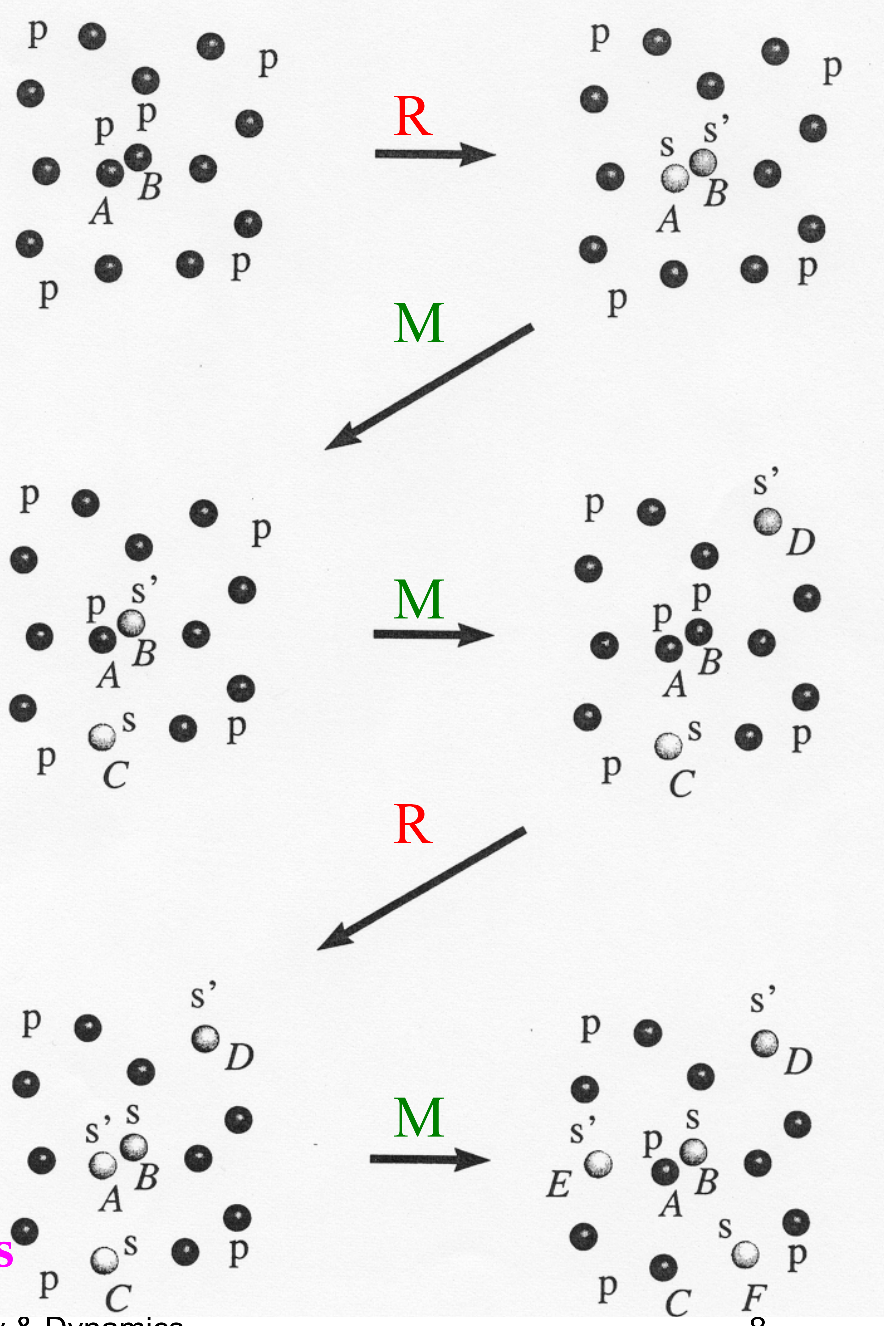
$Cs_D\ [np_{3/2}] + Cs_B\ [(n+1)s]$

$\quad\quad\quad\quad \to Cs_D\ [(n+1)s] + Cs_B\ [np_{3/2}]$

(no sensitive to the electric field)

Mourachko et al., PRA 70, 031401 (2004)

Importance of the "fluctuations" in the Rydberg density of pairs of close atoms



Rb (Virginia)

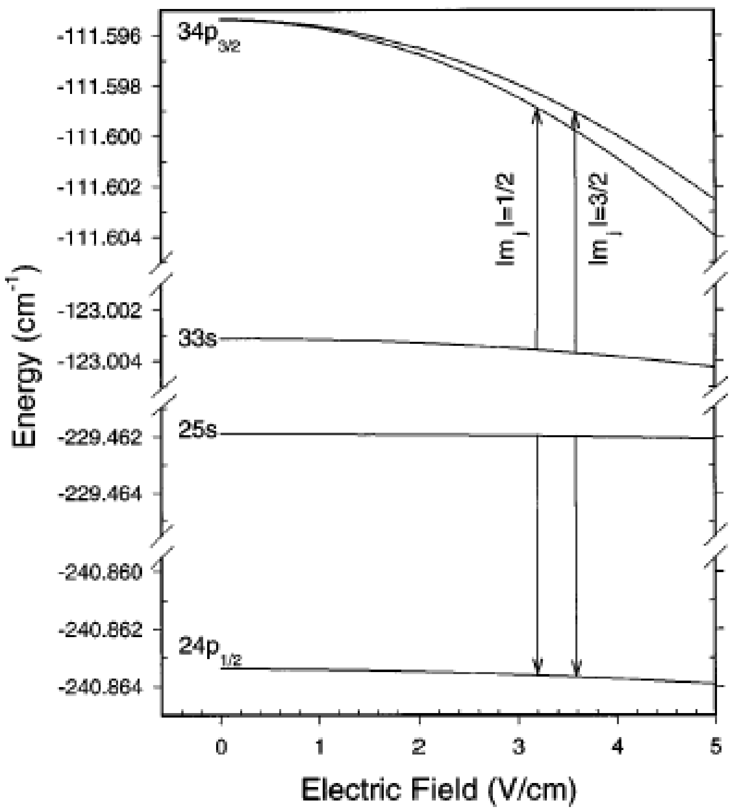


FIG. 1. Energy levels of Rb in an electric field showing the two energy transfer resonances of Eq. (1).

$$33s + 25s \rightarrow 34p_{3/2} + 24p_{1/2}$$

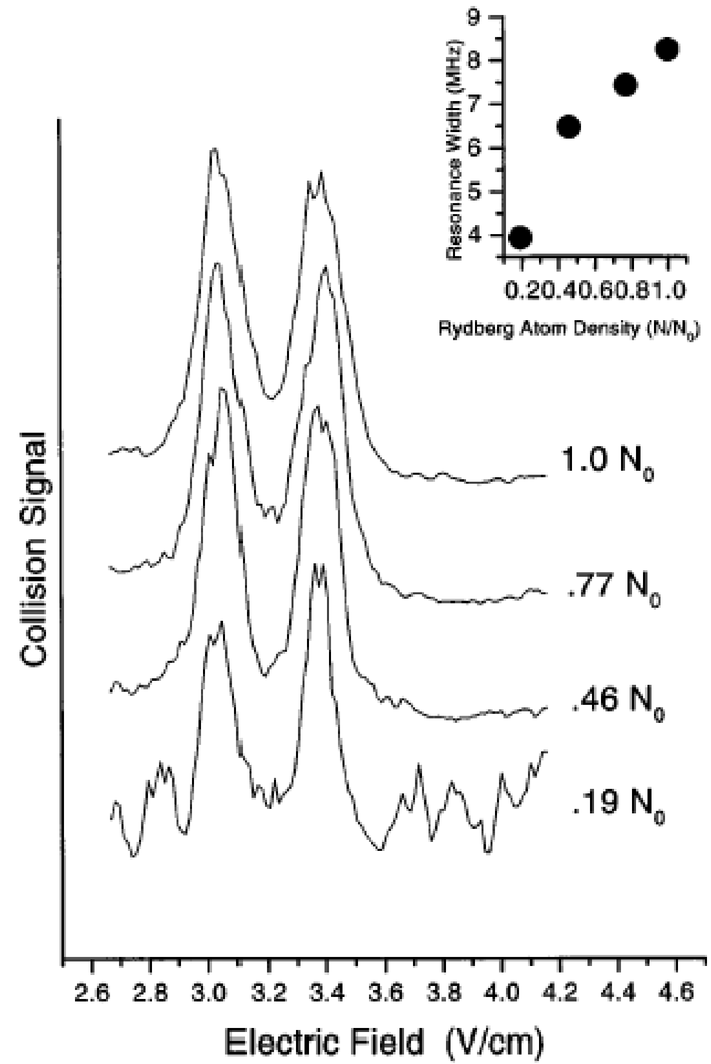


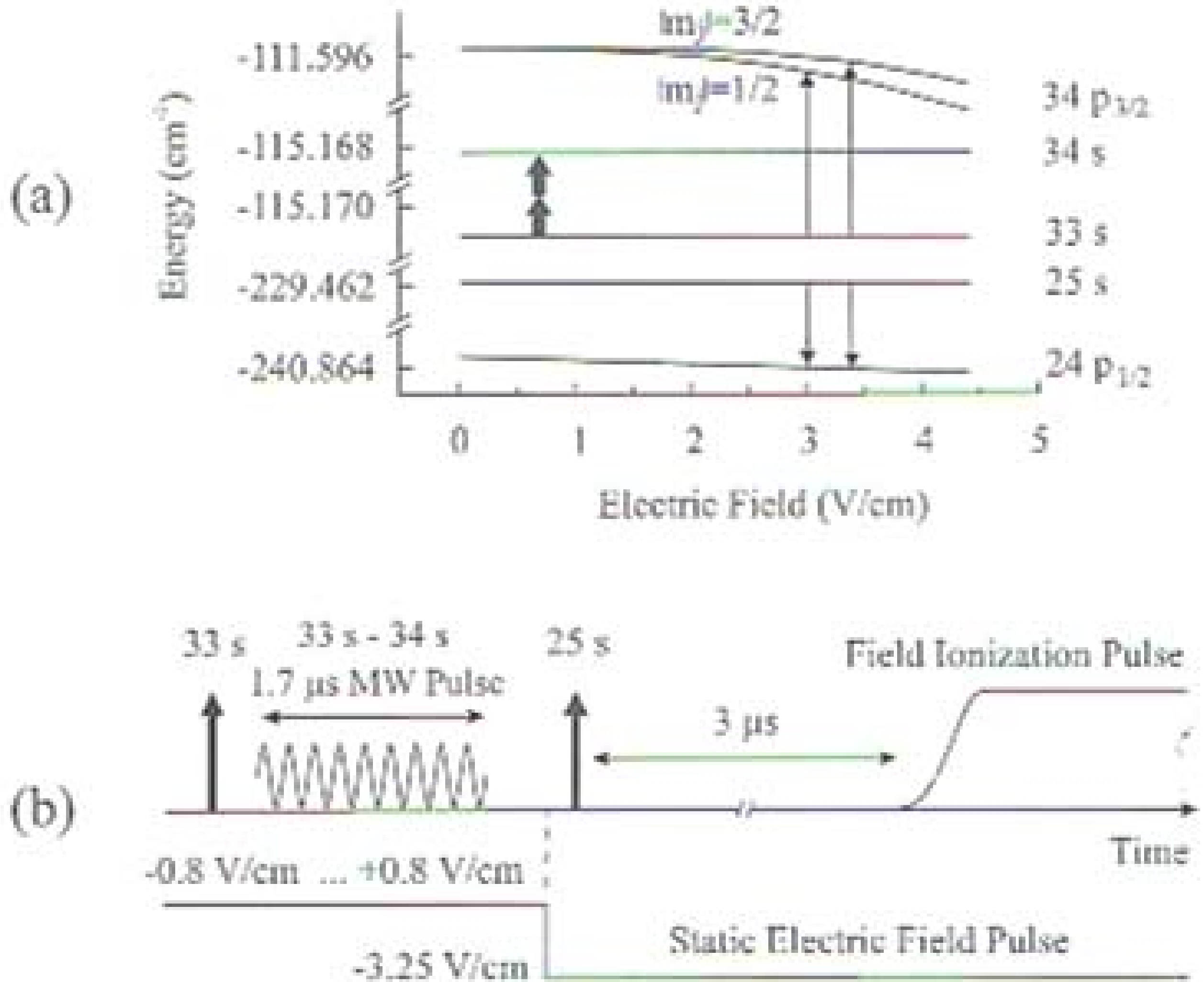
FIG. 2. The $25s_{1/2} + 33s_{1/2} \rightarrow 24p_{1/2} + 34p_{3/2}$ resonances at 300 μK observed in the MOT at four densities, $0.19N_0$, $0.46N_0$, $0.77N_0$, and N_0. The inset shows the width of the observed resonances vs relative density.

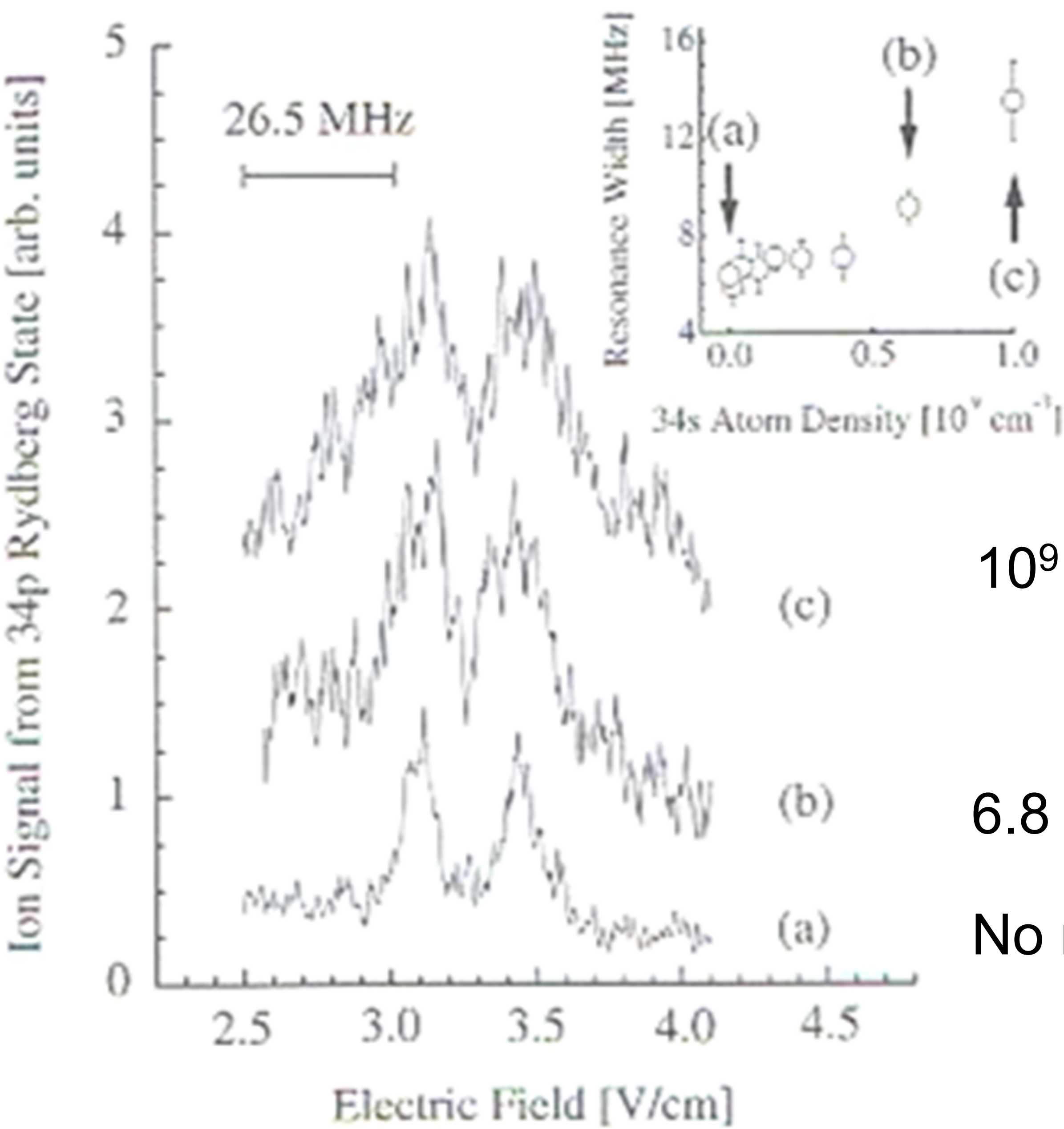
Control of many-body intercations

μ_{33s34p}=126 a.u.
μ_{34s34p}=930 a.u.

μ_{25s24p}=492 a.u.

Microvawe:
117 GHz





10^9 cm^{-3}

6.8 10^8 cm^{-3}

No microwave

How to test the coherence

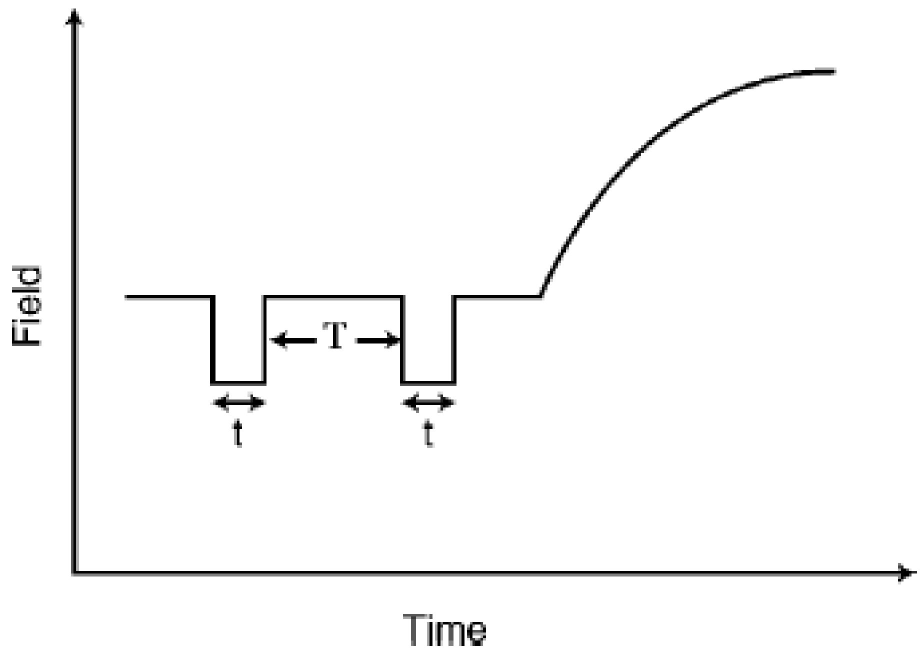


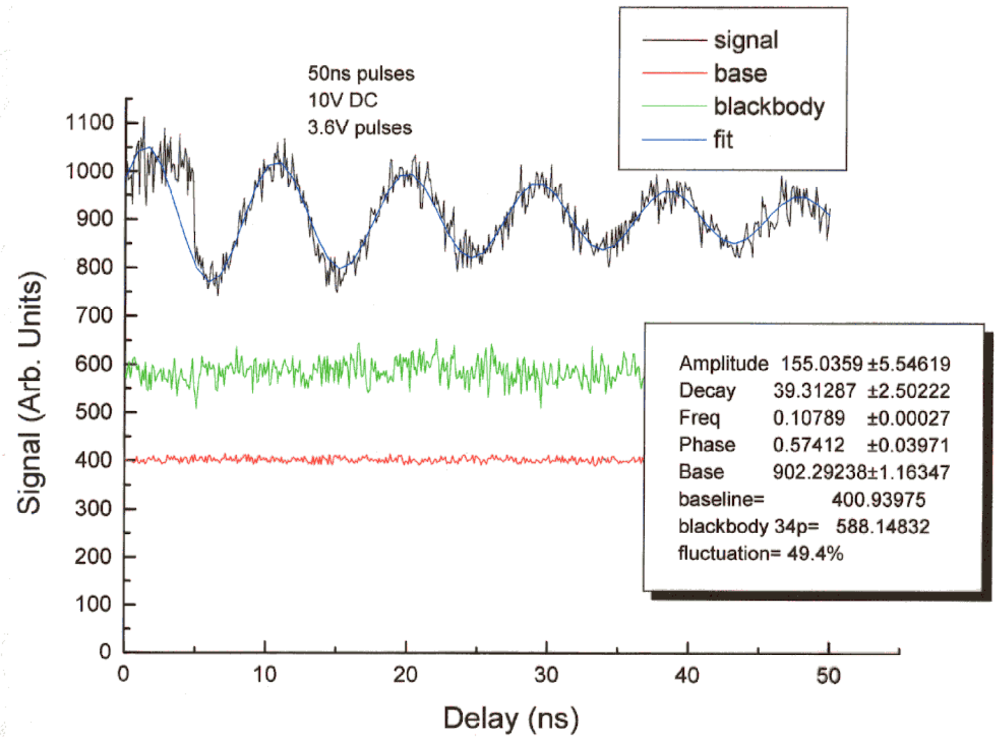
FIG. 4. Timing diagram for the Ramsey double field pulse and subsequent field ionization pulse. $T = 0-50$ ns and $t = 50$ ns.

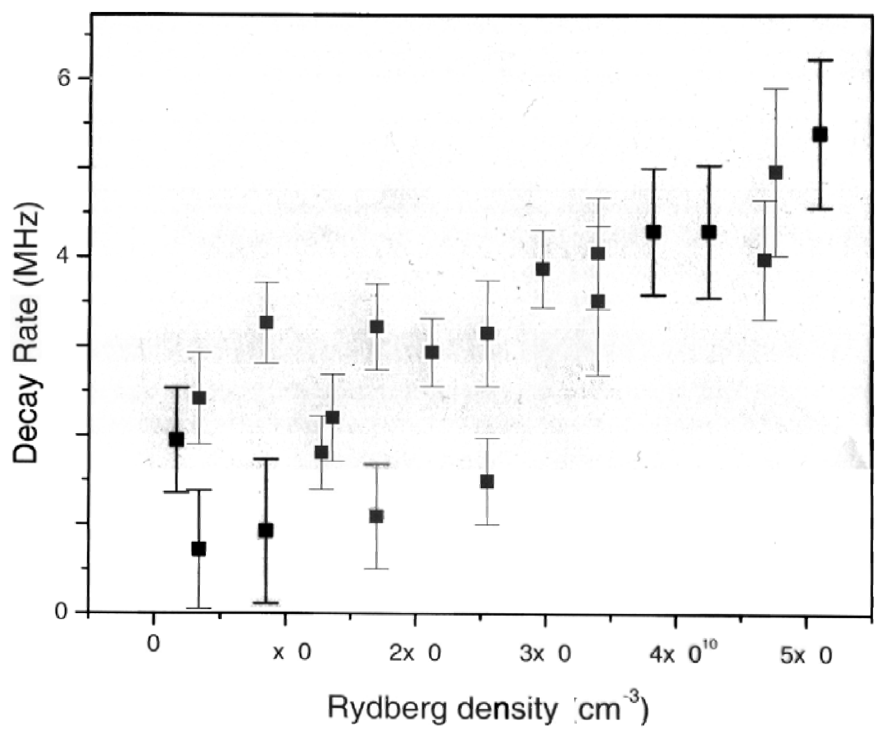
Ramsey scheme

The migration of the reaction product has been tested by T.F. Gallagher (Charlottesville, Virginia) through a Ramsey experiment

Rb: 25s +33s -> 24p + 34p (Stark tuned, 34p selectively detected)
Rb: 25s + 24p -> 24p +25s and 33s + 34s -> 34s + 33s (always resonant)

Charlottesville: W.R. Anderson et al., PRA65, 063404 (2002)





Why cold Rydberg atoms?

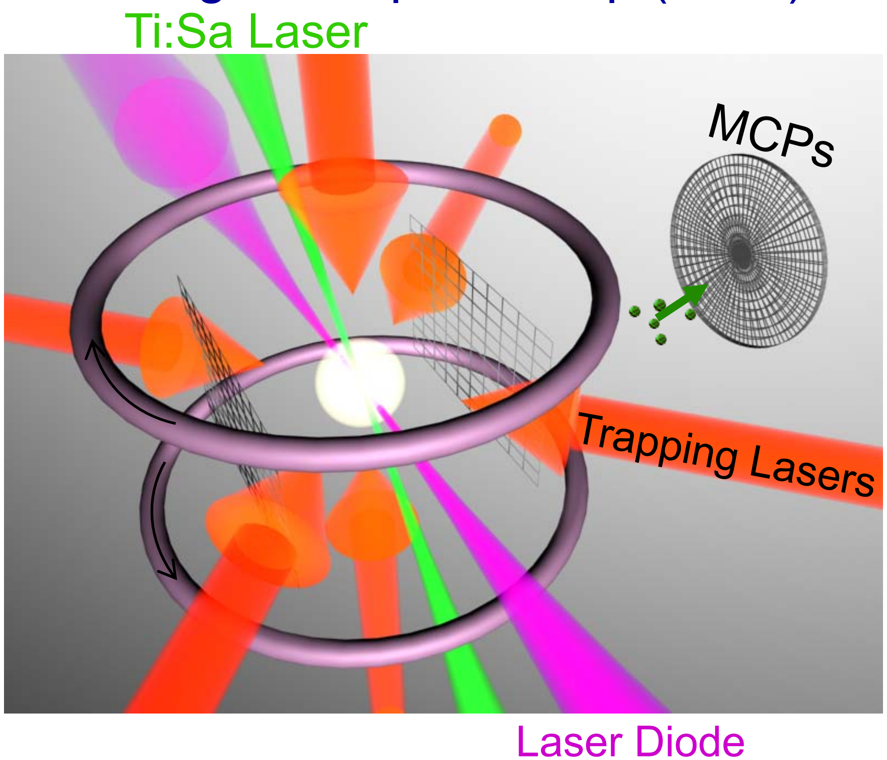
- Crucial role of cold collisions in a cold atomic sample: losses, photoassociation, evaporative cooling, sympathetic cooling, Feshbach resonance, three-body collisions…

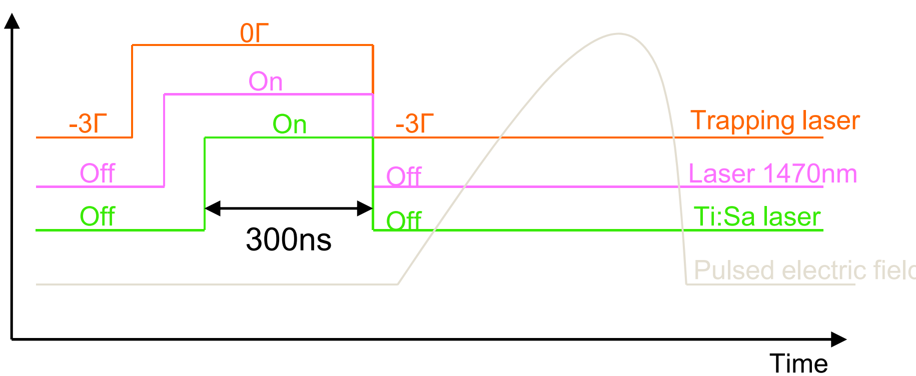
  Long time interaction!
- Rydberg atoms: huge electric dipole, long-range interactions,… *Two-body collisions*.
- Cold Rydberg atoms: *What new?*

  Frozen Rydberg gas, many-body effects…

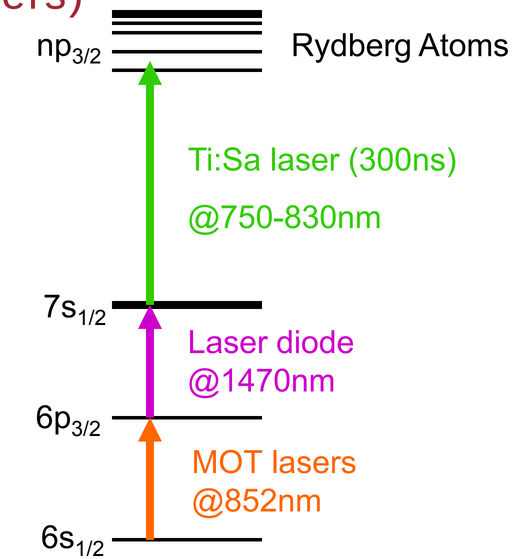
High-resolution laser excitation of Rydberg atoms

- # Cs Magneto-Optical Trap (MOT)

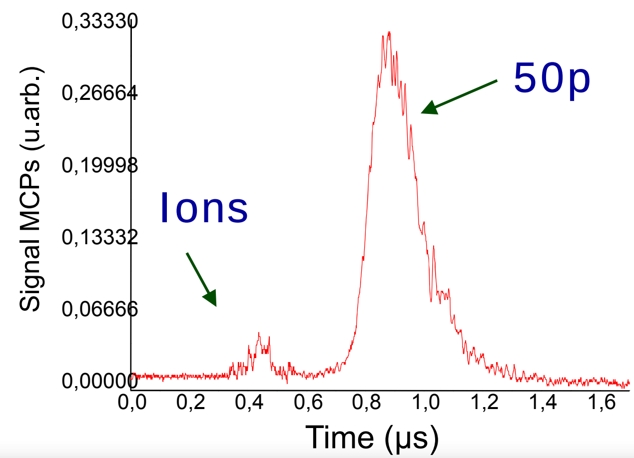




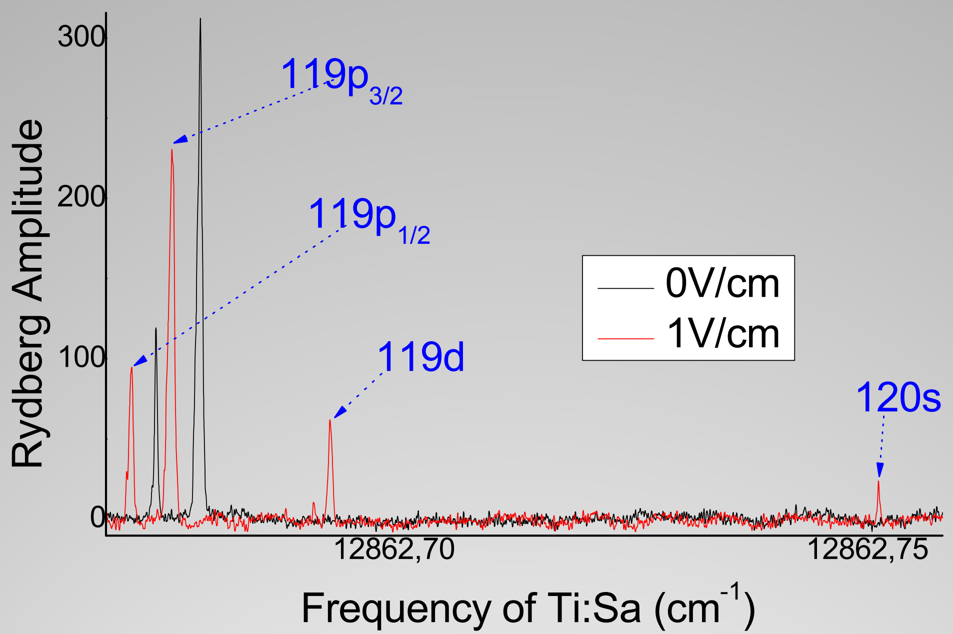
Excitation scheme (with cw lasers)



Selective field ionization



High n Rydberg spectra



- *Need to compensate spurious electric field better as F<<1 mV/cm*
- *Δ_{Laser} ~ 5MHz*
- *No ion during the 300 ns excitation (repetition rate 80 Hz)*

Dipole Blockade of the high-resolution excitation

The cold Rydberg atoms have the properties of both cold atoms and Rydberg atoms

Frozen Rydberg gases (no motion) at the frontier of the solid state physics

- Stark-Rydberg manifold states have permanant dipole (High *l*)

$$\mu = -\frac{3}{2}n\left(n_1 - n_2\right) \;,\; \mu_{\max} \sim \pm\frac{3}{2}n^2$$

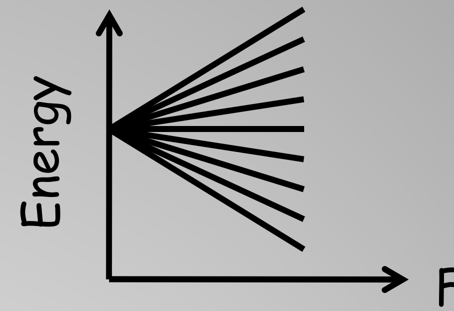
$$n = n_1 - n_2 + |m| + 1$$

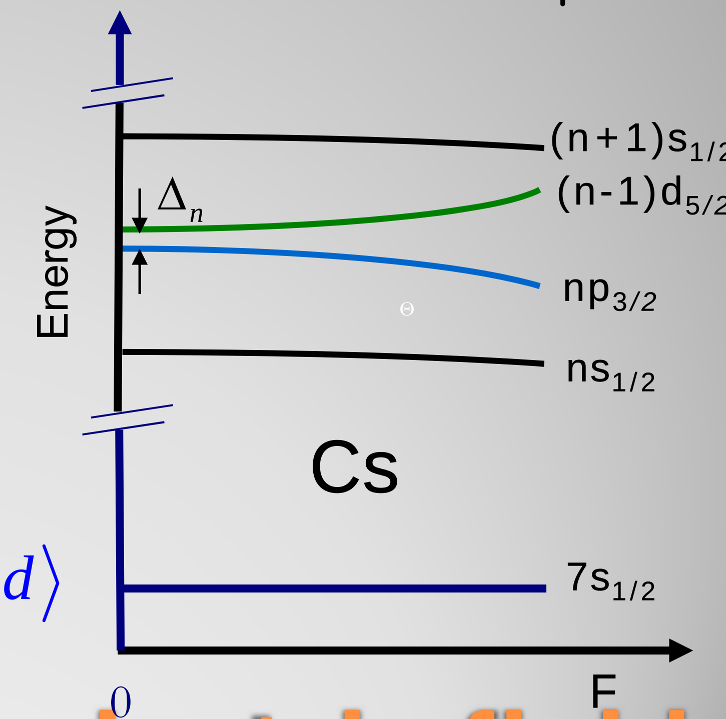
- *p* and *d* strongly Stark-coupled

$$\mu \approx \mu_{dp}\sin\theta \quad , \quad \mu_{dp} \sim n^2 (a.u.)$$

$$\tan(\theta) = \frac{|W_n|}{\Delta_n / 2} \;,\; W_n = -\mu_{dp}F_z$$

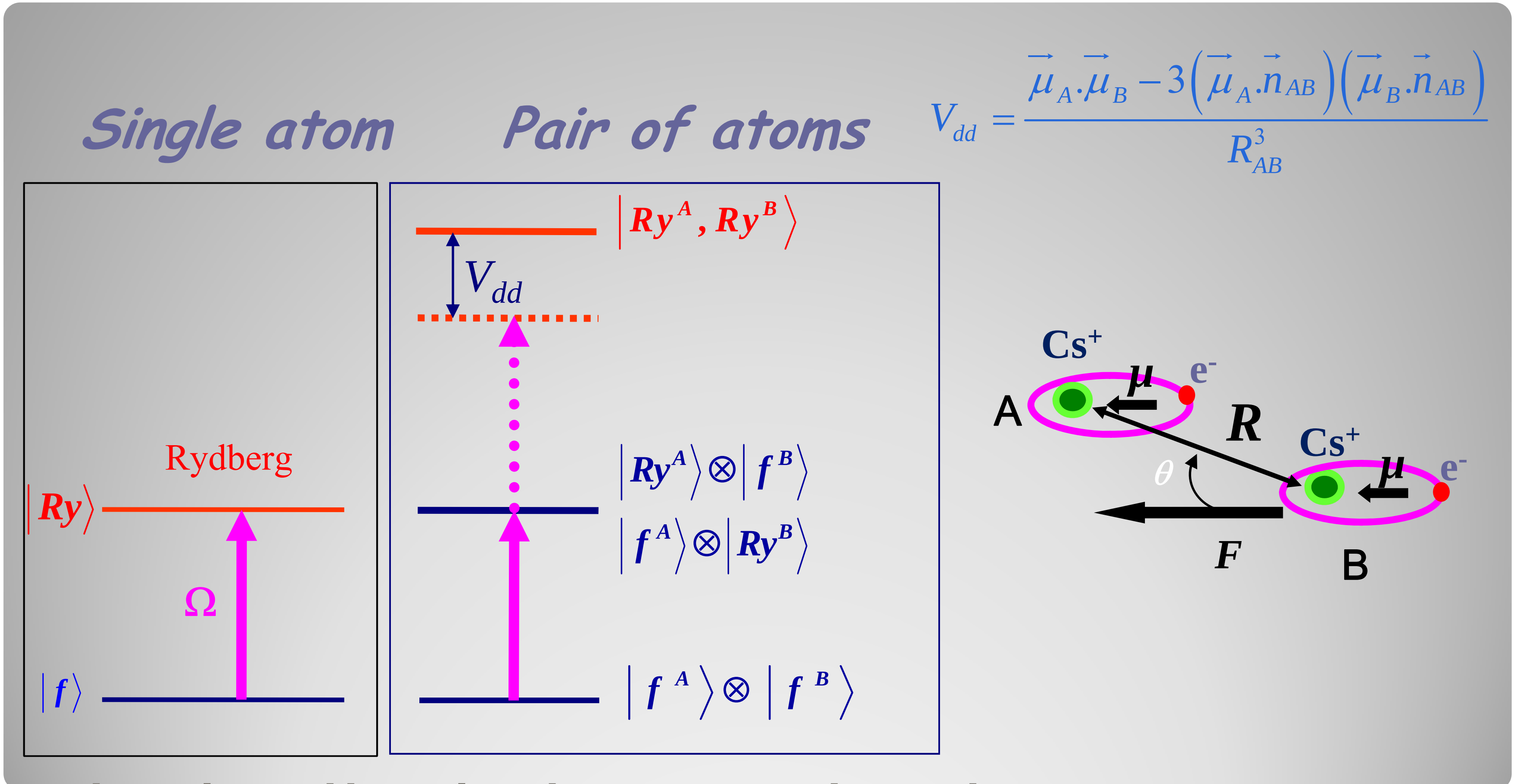
$$|np,F\rangle \approx \cos\left(\frac{\theta}{2}\right)|np\rangle - \sin\left(\frac{\theta}{2}\right)|(n-1)d\rangle$$





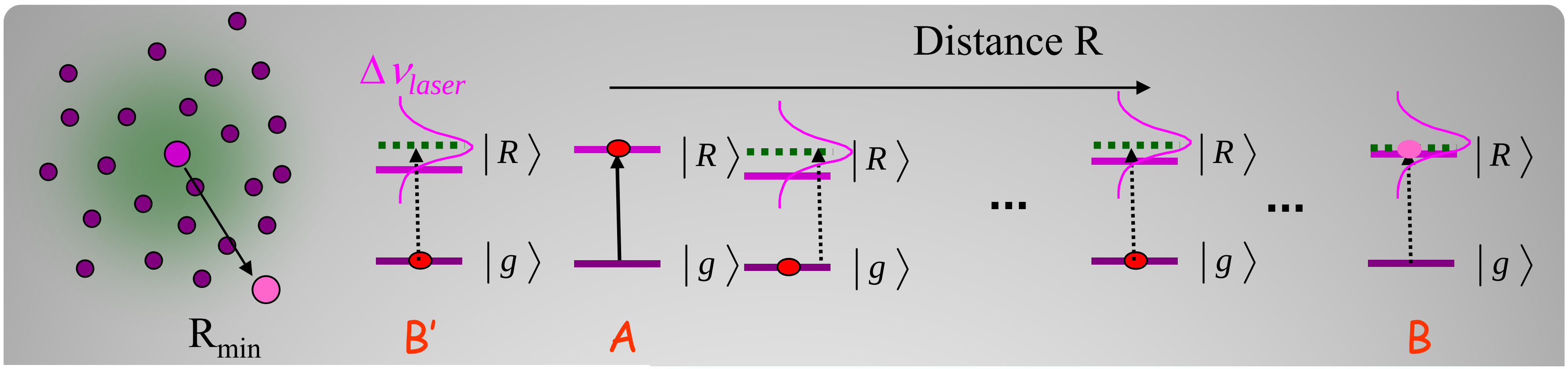
Dipole induced by electric field

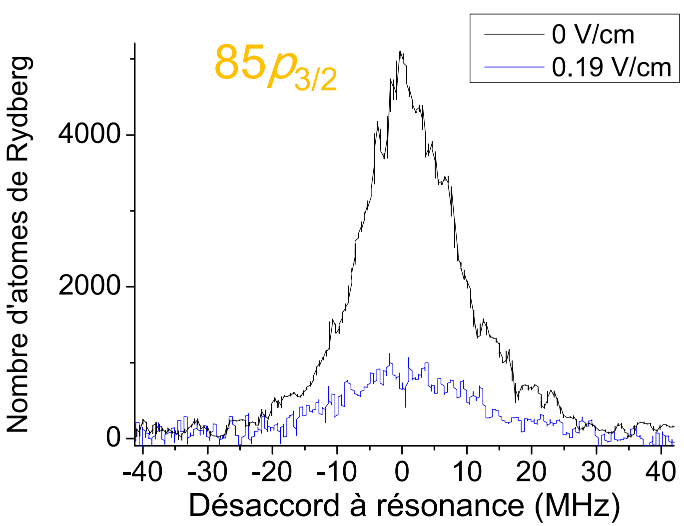
n = 30 μ_{max} ~ 3500 Debye ; n = 100 μ_{max} ~ 38000 Debye

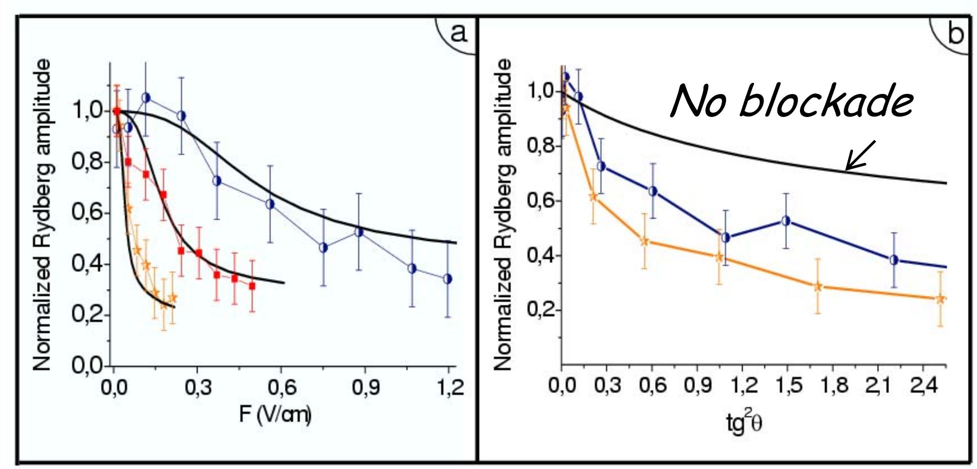


Dipole-dipole interaction between two atoms

Dipole blockade of the excitation / Conditionnal excitation







60, 70 and 85 $p_{3/2}$

Dipole blockade in an atomic sample

Spectraly broadband excitation: band of levels

Limitation of the high-resolution excitation

Role of the nearest neighbor

$$\text{Recall}: \tan(\theta) = \frac{|W_n|}{\Delta_n / 2}$$

Dipole-dipole interaction

Förster resonance

$$H = H_R + \sum_{i=1}^{N} \left(H_{Ai} + H_{RAi} \right)$$

$$H_R = \sum_{kl} hcka_{kl}^{+} a_{kl} \quad ; \quad H_{Ai} = \hbar\omega_0 \left|2,i\right\rangle\left\langle 2,i\right| \quad ; \quad H_{RAi} = -\vec{E}.\vec{\mu}_i$$

$$\vec{E} = i \sum_{kl} \sqrt{\frac{hck}{2\varepsilon_0 L^3}} a_{kl} \vec{e}_l \exp\left(i\vec{k}.\vec{x}_i \right) + h.c.$$

$$\vec{\mu}_i = \vec{\mu}_i^{+} + \vec{\mu}_i^{-} \ ; \ \vec{\mu}_i^{+} = \left\langle 2\right|\vec{\mu}\left|1\right\rangle \left|2,i\right\rangle\left\langle 1,i\right| = \left\langle 2\right|\vec{\mu}\left|1\right\rangle r_i^{+} \ ; \ \vec{\mu}_i^{-} = \left(\vec{\mu}_i^{+} \right)^{+}$$

Master equation in Born-Markov approximation (interaction representation)

$$\frac{d\sigma}{dt} = -\frac{\Gamma}{2} \sum_{i=1}^{N} \left(\left[r_i^{+} r_i^{-}, \sigma(t) \right]_{+} - 2 r_i^{-} \sigma(t) r_i^{+} \right) - \frac{1}{i\hbar} \sum_{j \neq i} \left[\vec{E}_j^{+} . \vec{\mu}_i^{-} \sigma(t) - \sigma(t) \left(\vec{E}_j^{+} \right)^{+} . \vec{\mu}_i^{-} \right]$$

$\vec{E}_j^{+}$ electric dipole field creared by j in i

$$\vec{E}_j^{+} = \frac{1}{4\pi\varepsilon_0} \left\{ k_0^2 \left(\frac{\vec{x}_{ij}}{x_{ij}} \times \vec{\mu}_i^{+} \right) \times \frac{\vec{x}_{ij}}{x_{ij}} \frac{e^{ik_0 x_{ij}}}{x_{ij}} + \left[3 \frac{\vec{x}_{ij}}{x_{ij}} \left(\frac{\vec{x}_{ij}}{x_{ij}} . \vec{\mu}_i^{+} \right) - \vec{\mu}_i^{+} \right] \left(\frac{1}{x_{ij}^3} - \frac{ik_0}{x_{ij}^2} \right) e^{ik_0 x_{ij}} \right\}$$

N two-level (1,2) atoms (i)

Master equation $\frac{d\sigma}{dt} = -\frac{\Gamma}{2}\sum_{i=1}^{N}\left(\left[r_i^+ r_i^-, \sigma(t)\right]_+ - 2r_i^- \sigma(t) r_i^+\right)$

$$-\frac{\Gamma}{2}\sum_{j\neq i}\left(\left[r_i^+ r_j^-, \sigma(t)\right]_+ - 2r_i^- \sigma(t) r_j^+\right) + \frac{1}{i\hbar}\sum_{j\neq i}\left[H_{dd}^{(i,j)}, \sigma(t)\right]$$

We have the terms of cooperative spontaneous emission (superradiance) and those cooresponding to dipole-dipole interaction ($H_{dd}^{(i,j)}$)

$$H_{dd}^{(i,j)} = \frac{\mu_i \mu_j}{4\pi\varepsilon_0}\left\{\left(1-3\cos^2\theta_{ij}\right)\frac{1}{x_{ij}^3} - \frac{\left(1+\cos^2\theta_{ij}\right)}{2}\frac{k_0^2}{x_{ij}}\right\}$$

We have the classical term of dipole-dipole interaction

+ another term a priori much smaller when $k_0 x_{ij} << 1$

$\omega_0 \sim 1/(2n^3)\ a.u.\ ;\ k_0^{-1} = ƛ = \lambda/2\pi = 115\mu m\ (n=20),\ 390\ (n=30),\ 930\ (n=40),$
$1.8mm\ (n=50),\ 3\ (n=60),\ 7.5\ (n=80),\ 14.5\ (n=100)$

Small volume: $K_0 x_{ij} < 1$

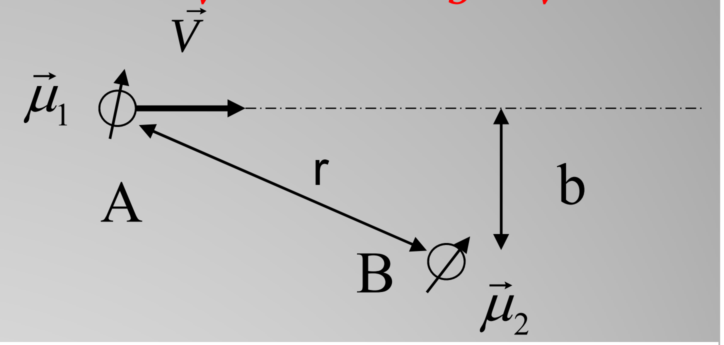
Förster resonances

Dipole-dipole coupling

Förster resonances

- **Resonant Rydberg-Rydberg atom collisions** (T.F. Gallagher et al., P.R.L. 40, 1362 (1981) with Na Impact parameter *b* ~ μ/v$^{1/2}$ ~ 1 μm at T ~ 500 K)
- Cs [$np_{3/2}$] + Cs [$np_{3/2}$] –> Cs [ns] + Cs [(n+1)s]

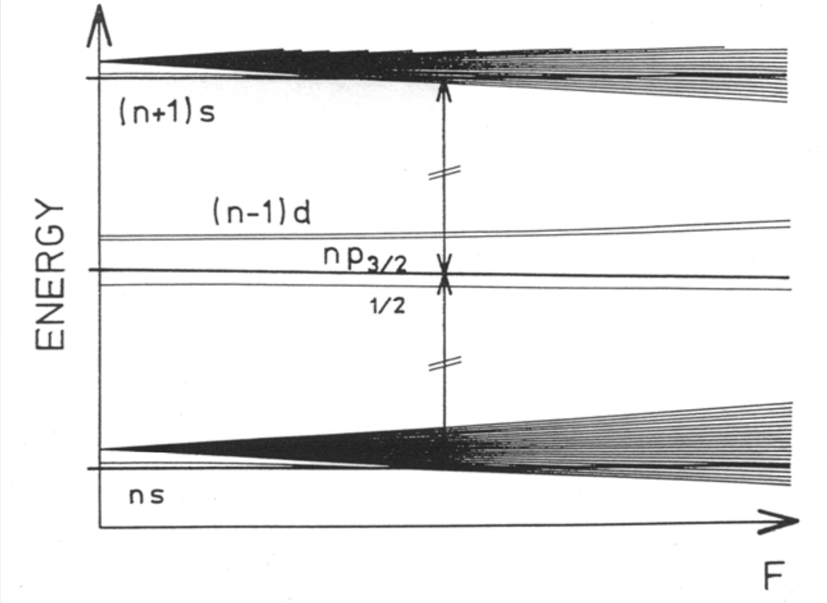
$$\tau_C \approx \frac{b}{v};\ V_C\tau_C \sim \frac{\mu_1\mu_2}{b^3}\frac{b}{v} \sim 1$$



$$V_{dd} = \frac{\vec{\mu}_A.\vec{\mu}_B - 3\left(\vec{\mu}_A.\vec{n}_{AB}\right)\left(\vec{\mu}_B.\vec{n}_{AB}\right)}{R_{AB}^3}$$

$$\left\langle ns,(n+1)s \middle| V_{dd} \middle| np_{3/2}, np_{3/2} \right\rangle \sim$$

$$\frac{\left\langle ns \middle| \vec{\mu}_A \middle| np_{3/2} \right\rangle \left\langle (n+1)s \middle| \vec{\mu}_B \middle| np_{3/2} \right\rangle}{R^3} \sim \frac{n^4}{R^3}$$

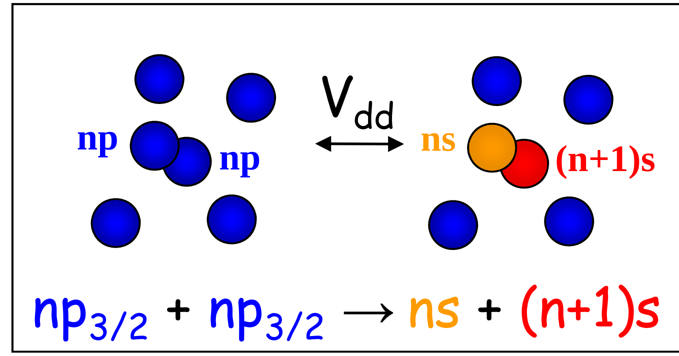


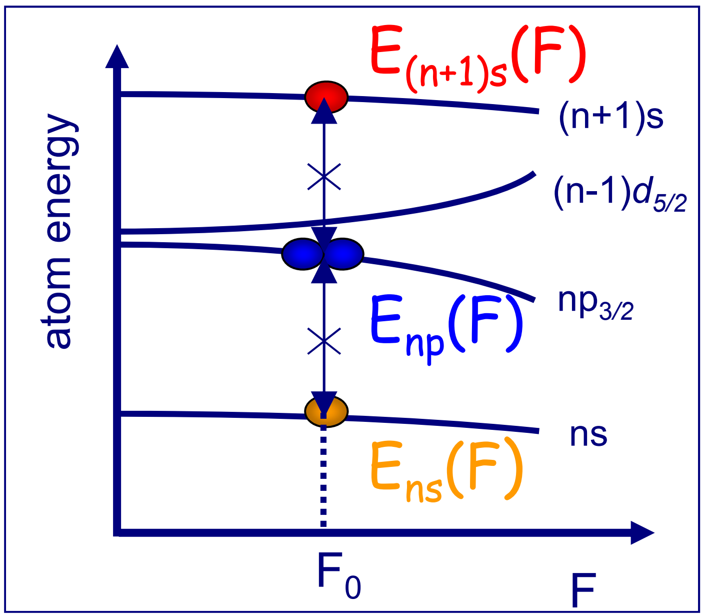
n =60 R = 1 μm V_{dd} ~ 14 GHz

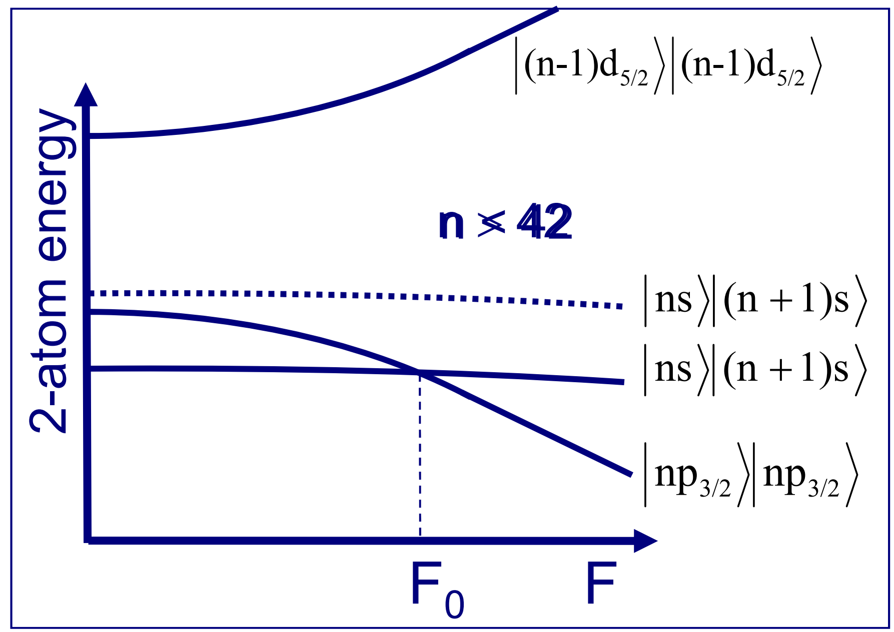
Föster resonances – dipole dipole interaction

Resonance at F_0

$$Cs: \; 2\,E_{np}(F_0) = E_{ns}(F_0) + E_{(n+1)s}(F_0)$$

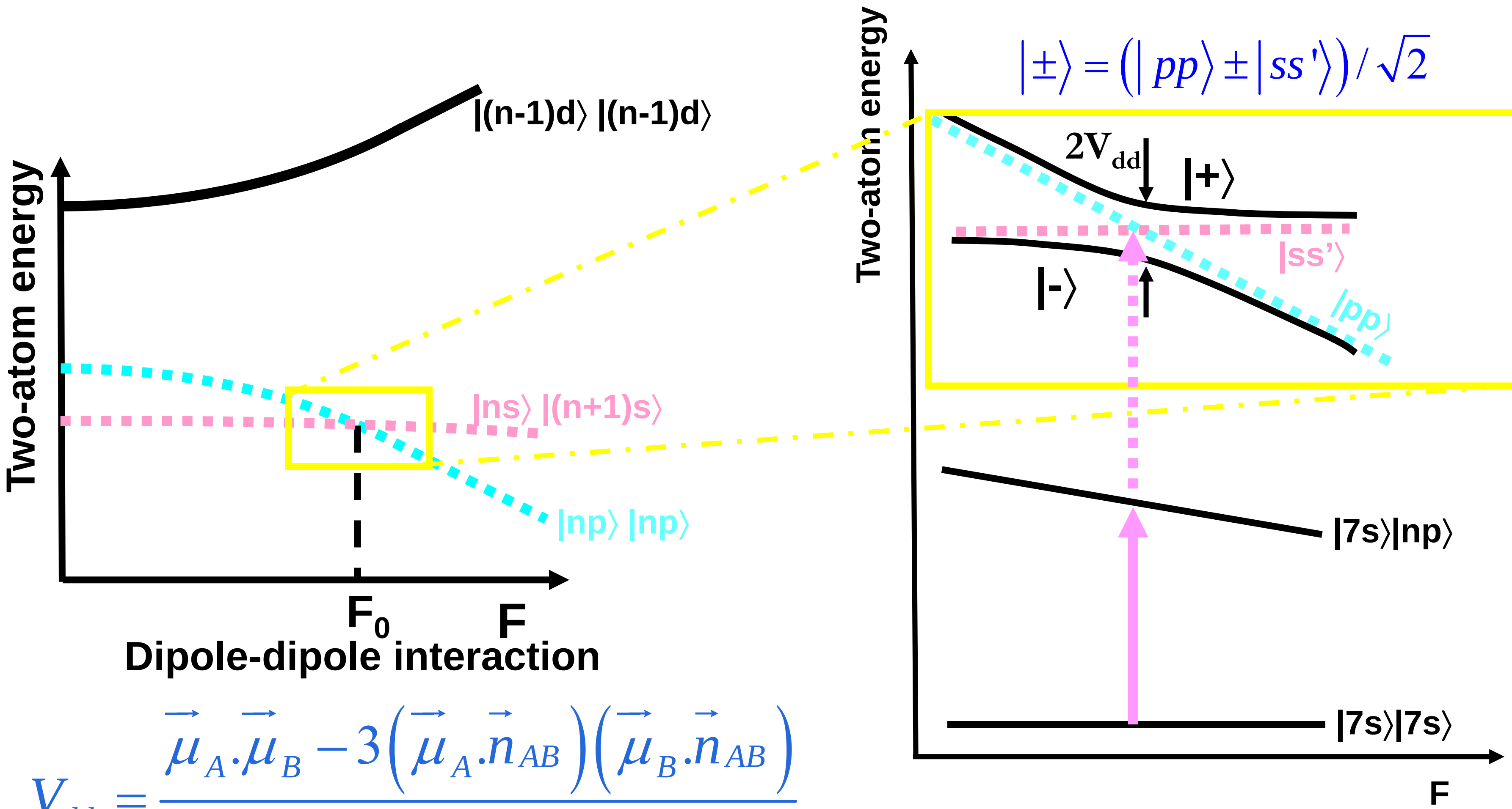






FRET (Förster resonance energy transfer)

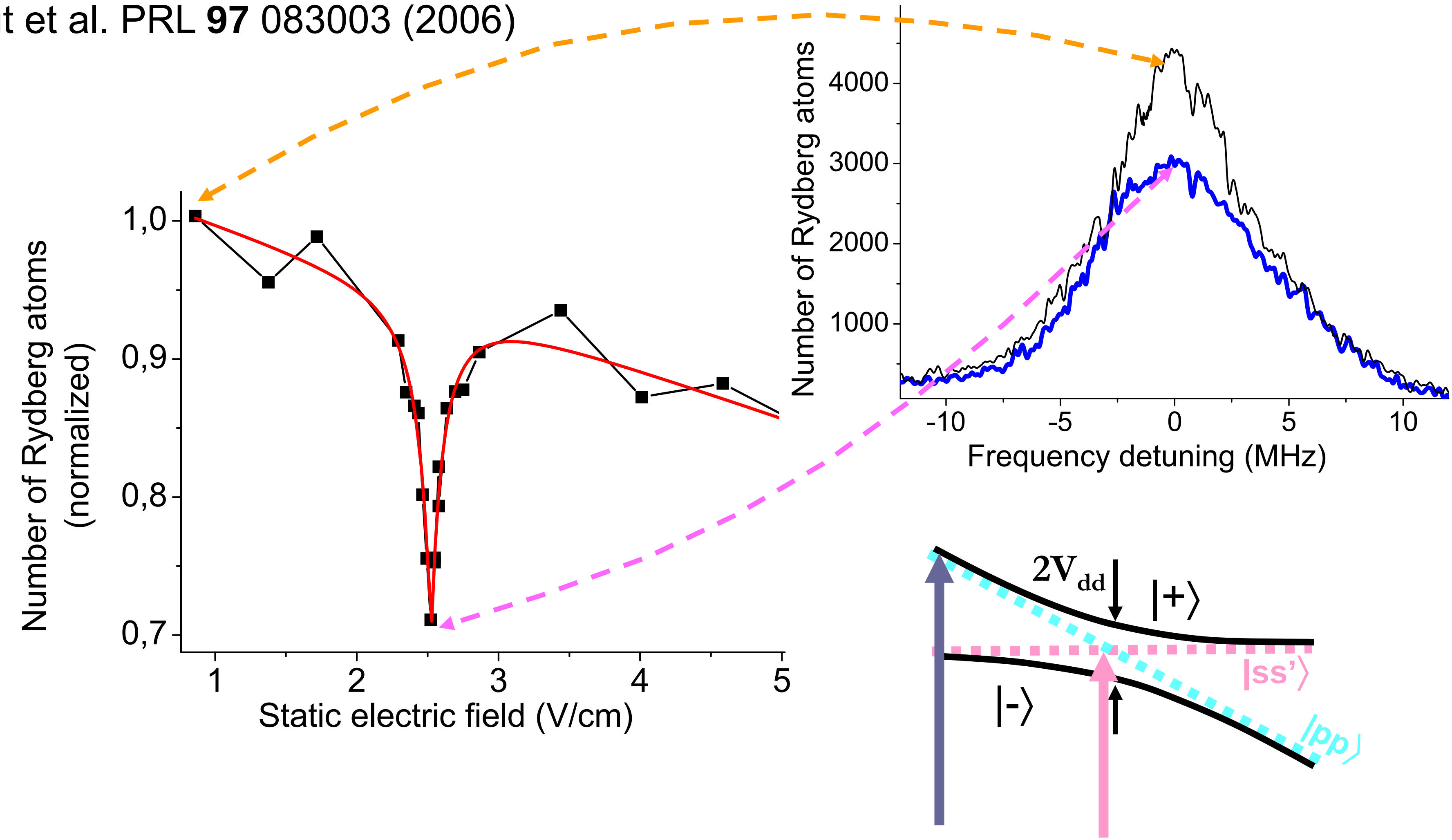
Excitation of a pair of atoms at a Förster resonance



$$V_{dd} = \frac{\vec{\mu}_A.\vec{\mu}_B - 3\left(\vec{\mu}_A.\vec{n}_{AB}\right)\left(\vec{\mu}_B.\vec{n}_{AB}\right)}{R_{AB}^3}$$

Dipole blockade of the high-resolution Rydberg excitation ($36p_{3/2}$)

Vogt et al. PRL **97** 083003 (2006)

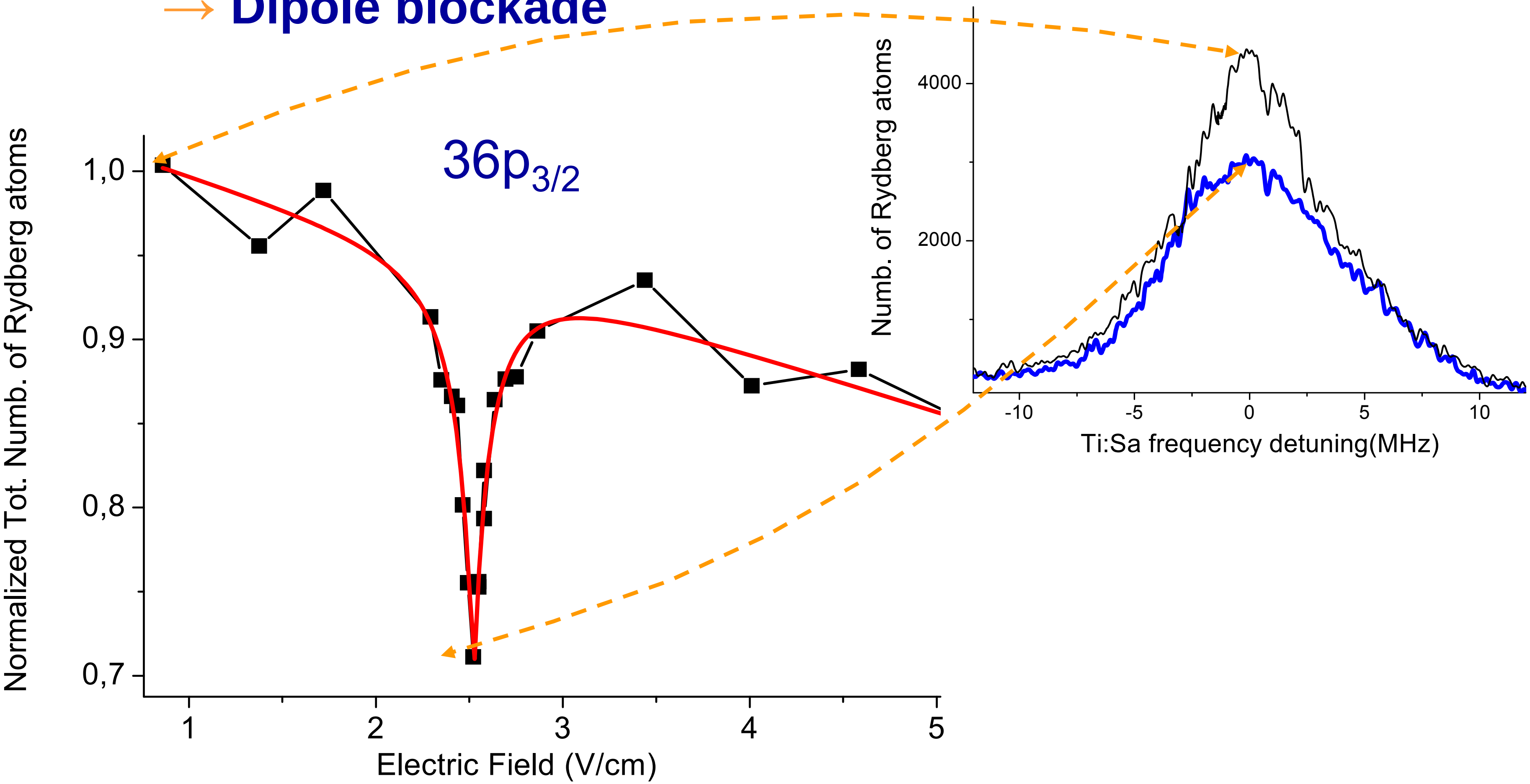


Demonstration of the dipole blockade

300ns cw laser excitation

- Rydberg atoms excited at Förster resonance

→ **Dipole blockade**

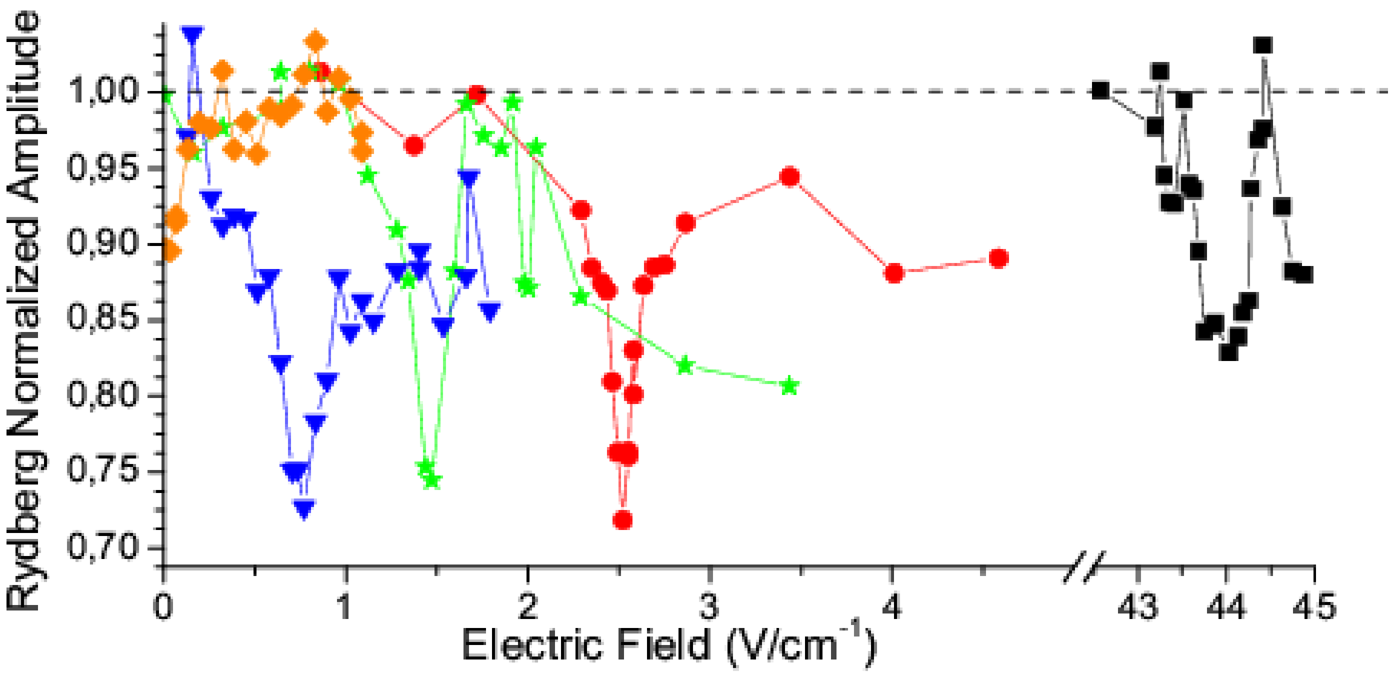


Dipole blockade from 25 to 42p

30 % for n = 34 - 41

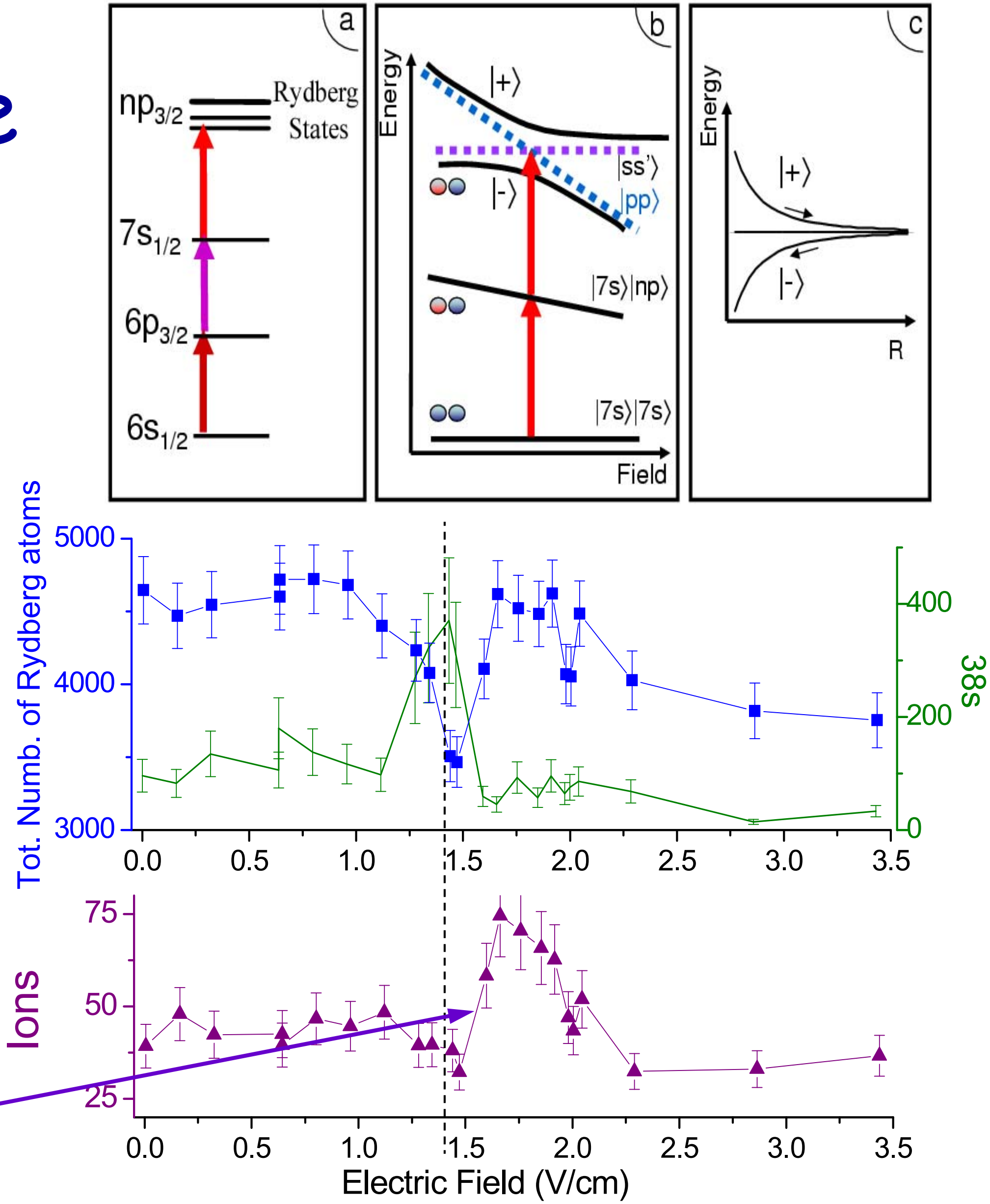
$$\Delta_L \sim W \Rightarrow R_{\min} \approx 4\,\mu m$$

n = 42, 40, 38, 36 n = 25



Dipole blockade

- Dipole blockade at Förster resonance 38 $p_{3/2}$
- Transfer *p –> s state*
  $np_{3/2} + np_{3/2} \rightarrow ns + (n+1)s$
- Few Ions (<1%) ⟶ no broadening of the lines.
  Number of ions increases at the right of the resonance ⟶ attractive force



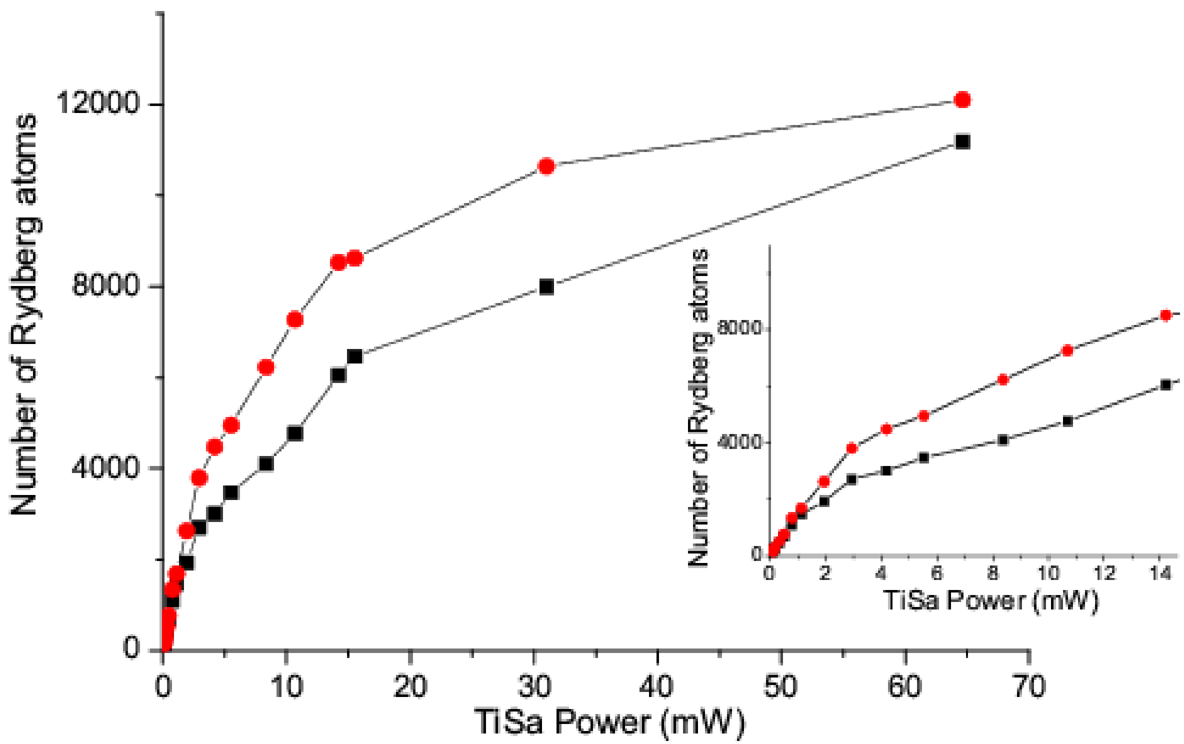
Properties of dipole blockade

At Förster resonance

Dipole blockade and saturation of the excitation

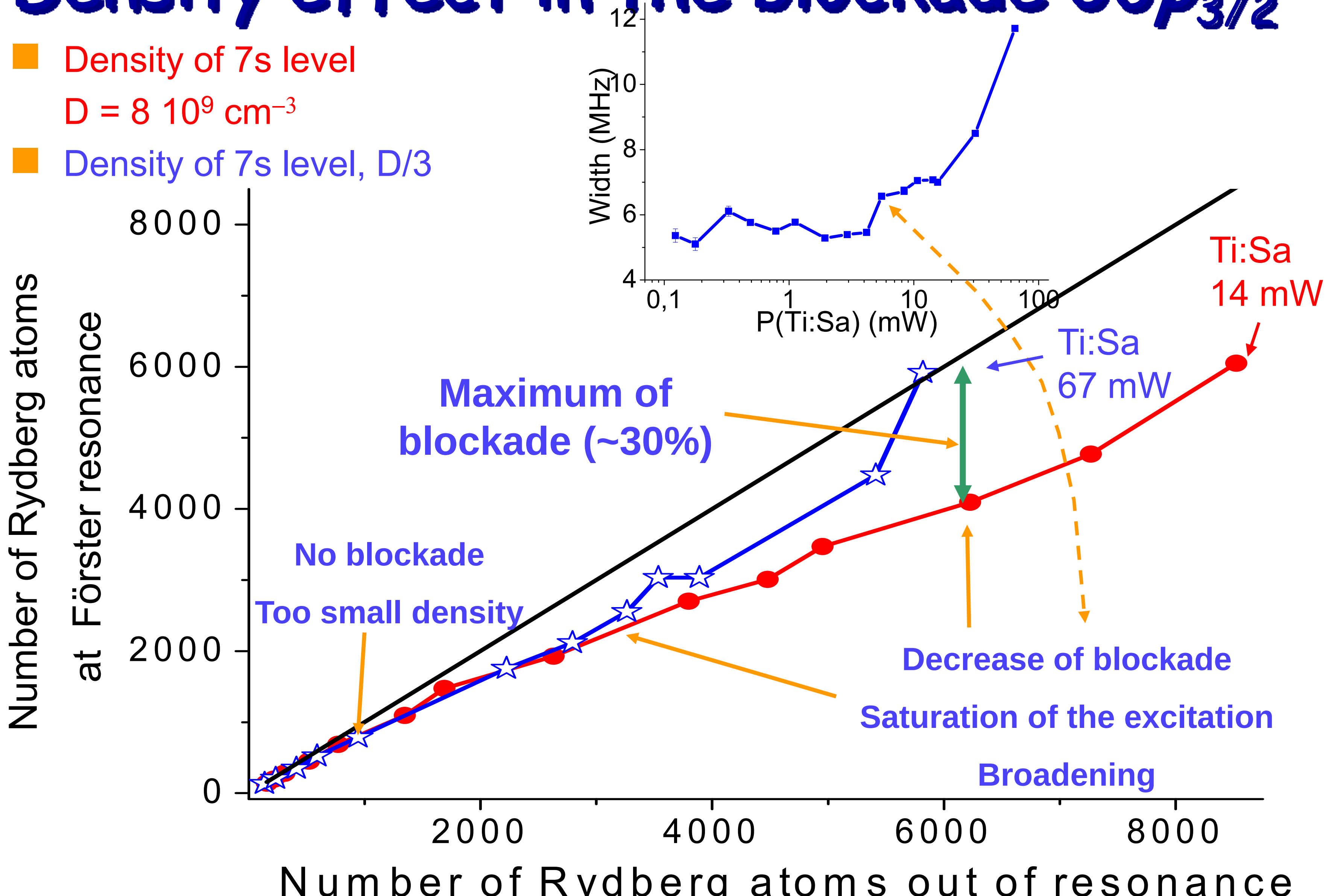
due to the “short” lifetime of 7s level

$36p_{3/2}$



Density effect in the blockade 36$p_{3/2}$

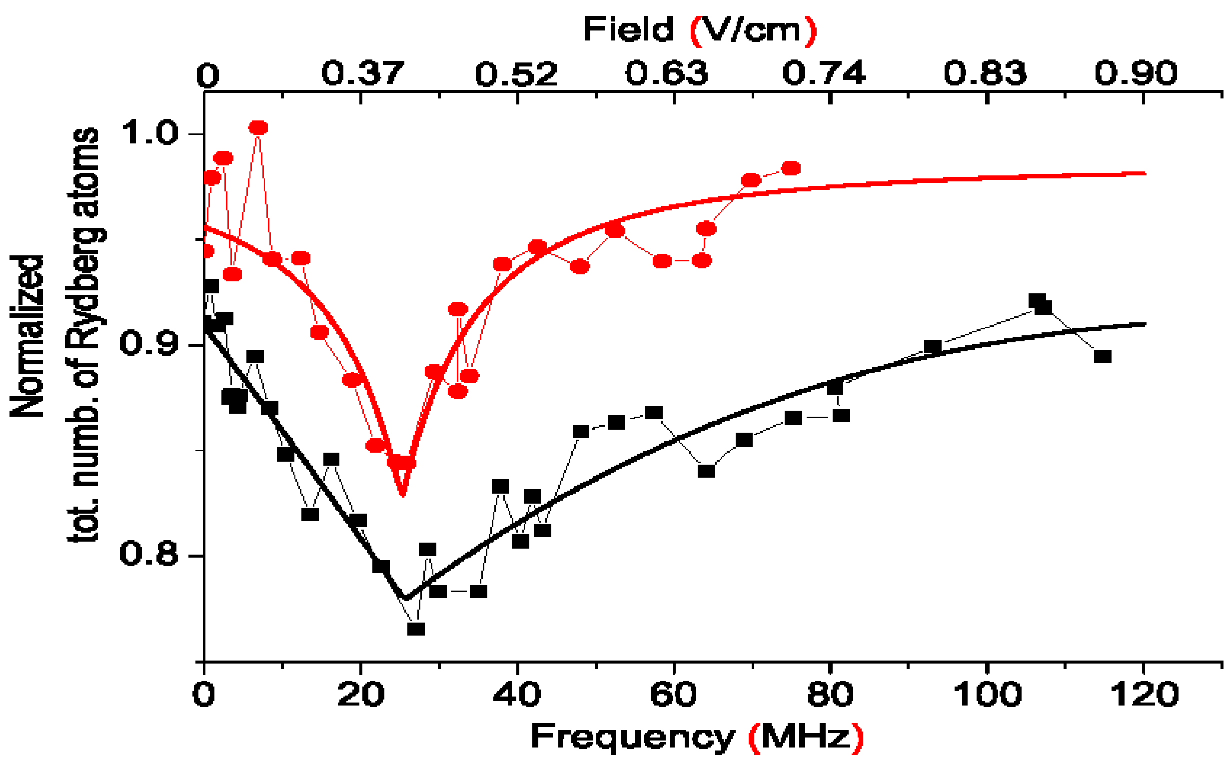
- Density of 7s level
  D = 8 10^9 cm^{-3}
- Density of 7s level, D/3



Resonance in field

10 times larger than laser ones.

Similar as pulsed excitation: Many-body effects

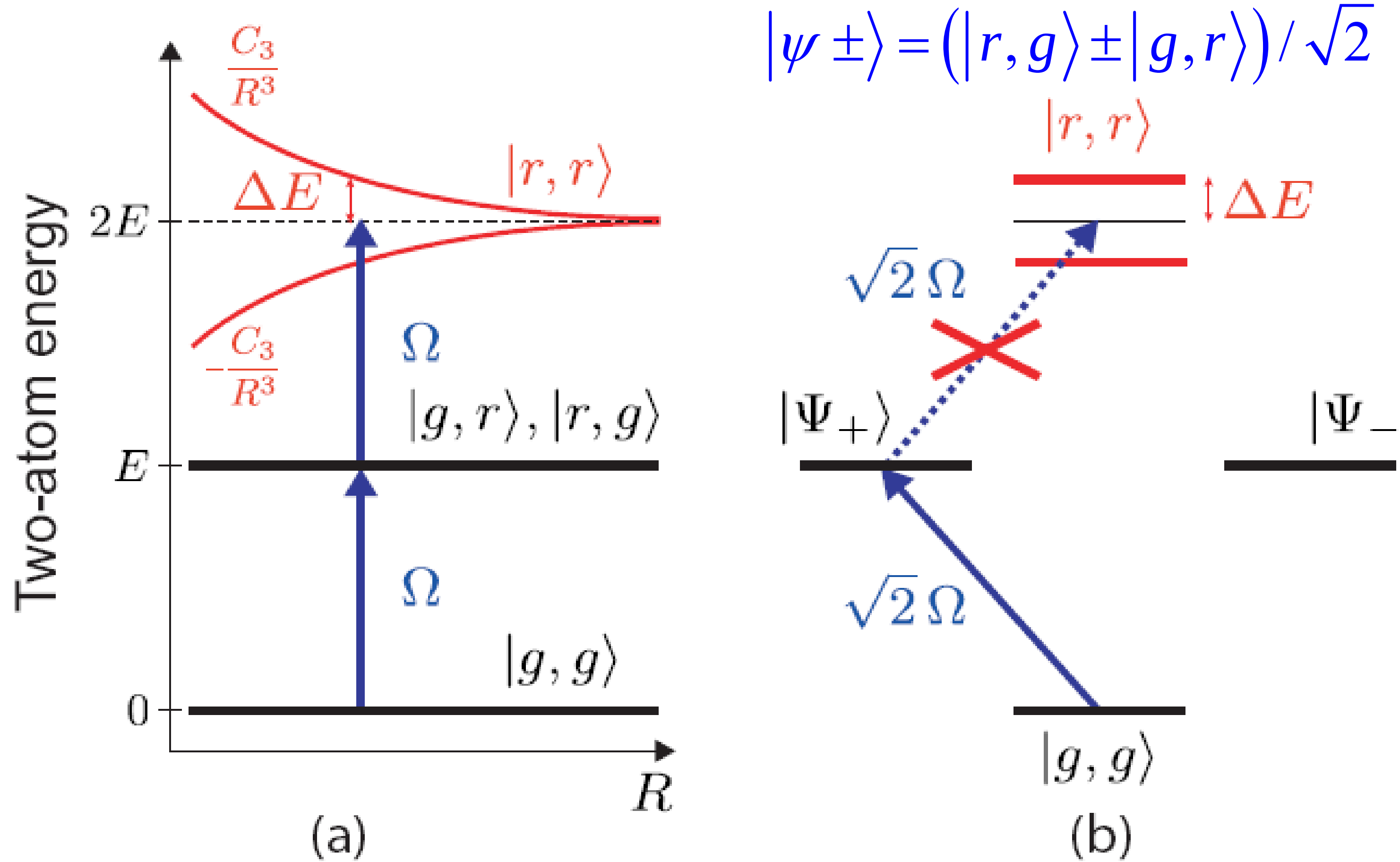


$41p_{3/2}$

3000 Rydberg atoms

5000

Conclusion and frontiers

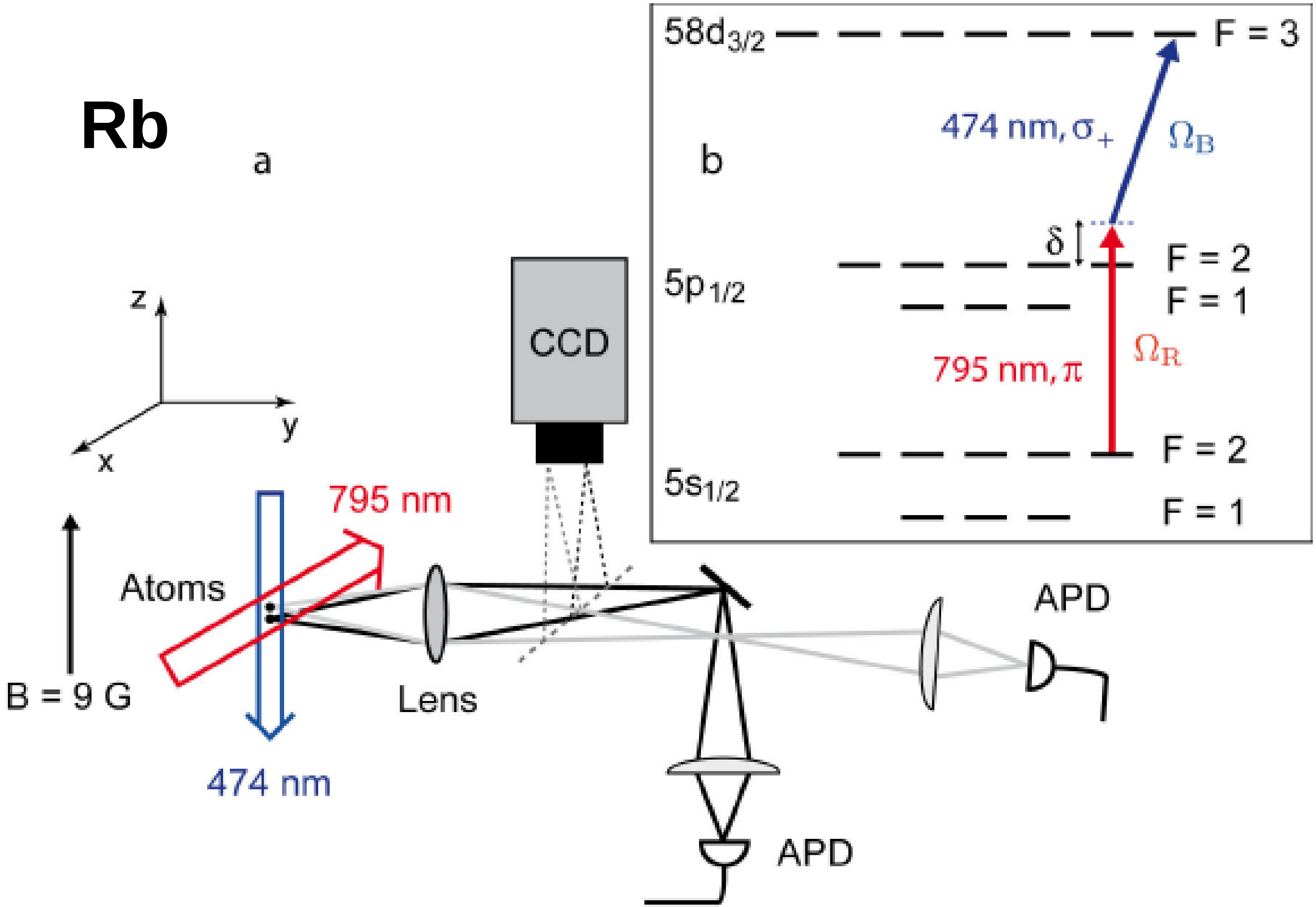


Dipole blockade at Förster resonance

The case of two atoms: conditionnal excitation (a) or collective excitation (b)

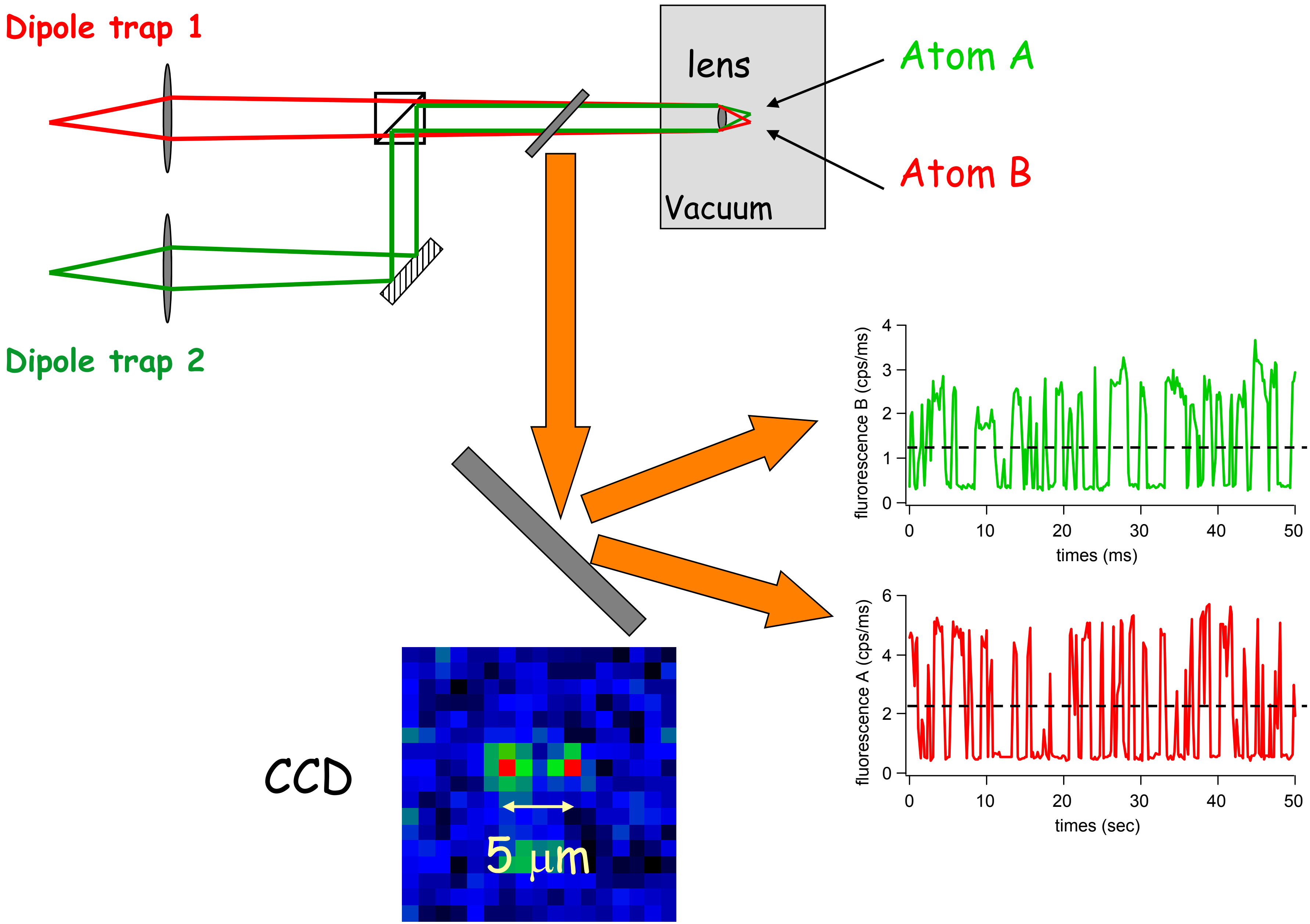
Collective excitation in the dipole blockade regime

Rb



a
z
y
x
CCD
795 nm
Atoms
B = 9 G
Lens
474 nm
APD
APD
b
58d3/2
F = 3
474 nm, σ+
ΩB
δ
5p1/2
F = 2
F = 1
795 nm, π
ΩR
5s1/2
F = 2
F = 1

Detecting and "heralding" two single trapped atoms



Experimental protocol

1. Trap 2 atoms in 2 tweezers and optically pump them

2. Excite the two atoms

3. Measure if they are still trapped after the excitation

Repeat 100 times

Atom A : 0, 1, 0, 1, 0, 0, 0, 1, 1, …
Atom B : 0, 1, 1, 1, 0, 0, 1, 1, 0, …

Experimental protocol

1. Trap 2 atoms in 2 tweezers and optically pump them

2. Excite the two atoms

3. Measure if they are still trapped after the excitation

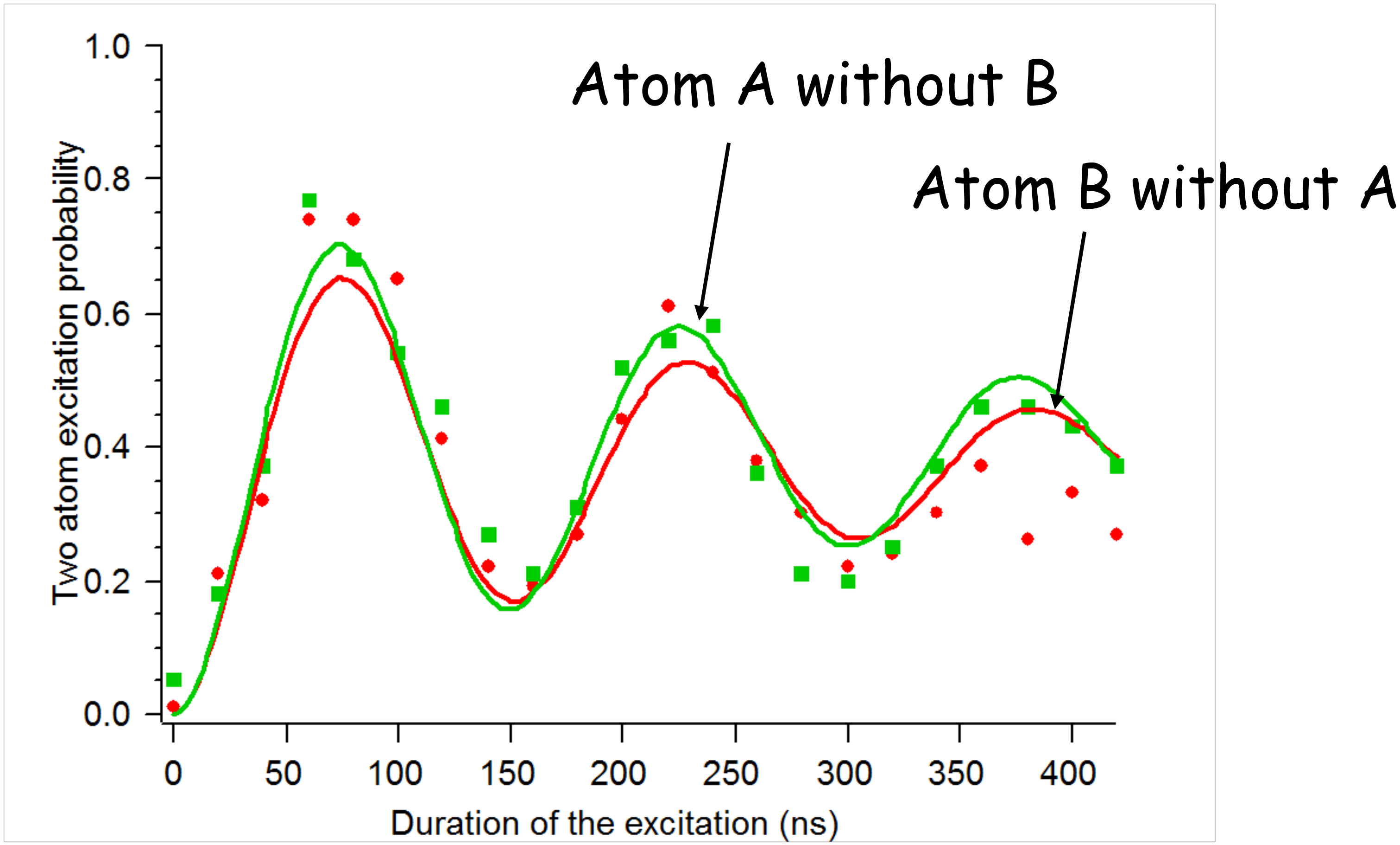
Repeat 100 times

Atom A : 0, 1, 0, 1, 0, 0, 0, 1, 1, ...
Atom B : 0, 1, 1, 1, 0, 0, 1, 1, 0, ...

Extract

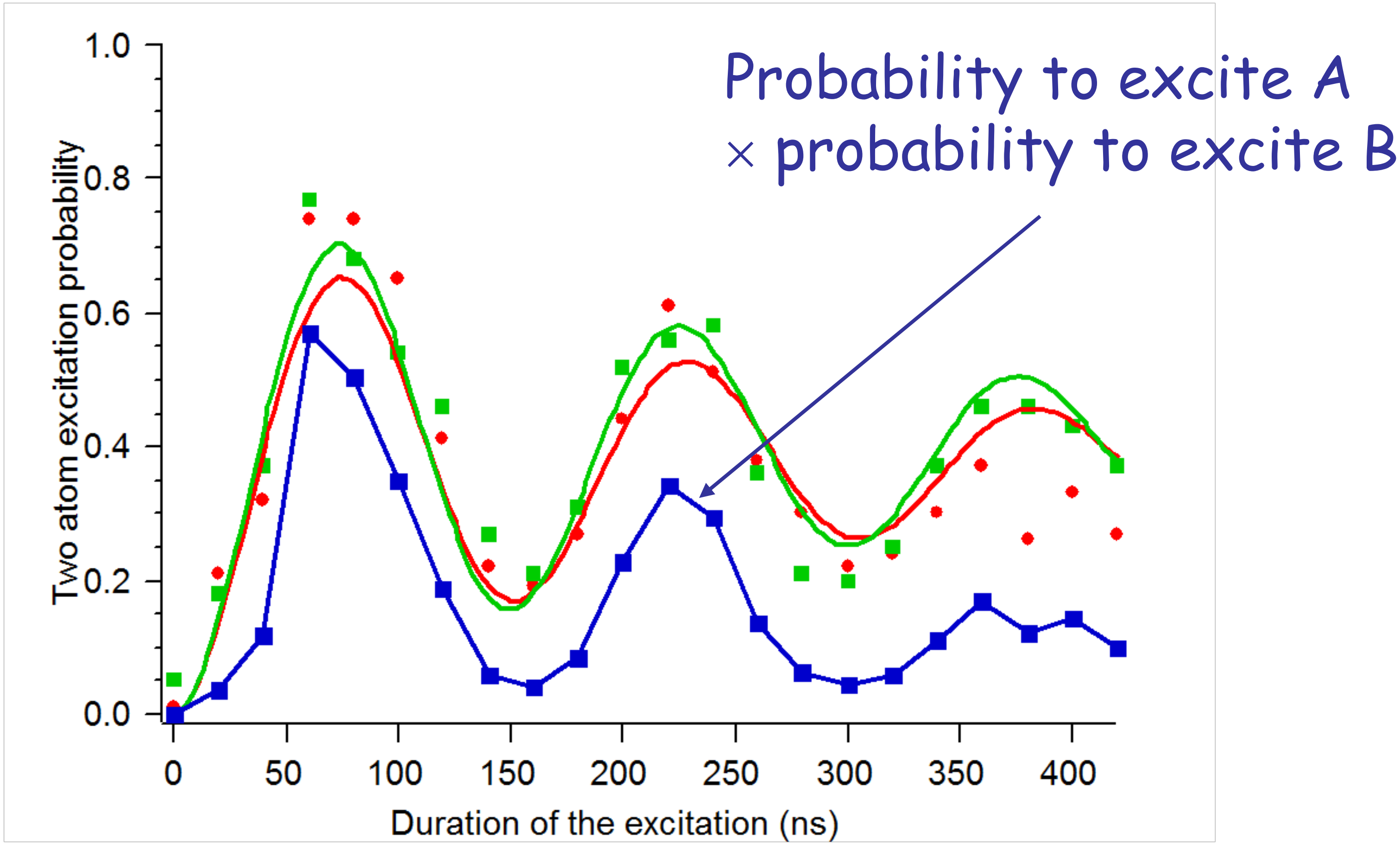
P to excite no Rydberg's
P of exciting two Rydberg's simultaneously
P to excite only one Rydberg

Excitation of two atoms at R = 18 μm

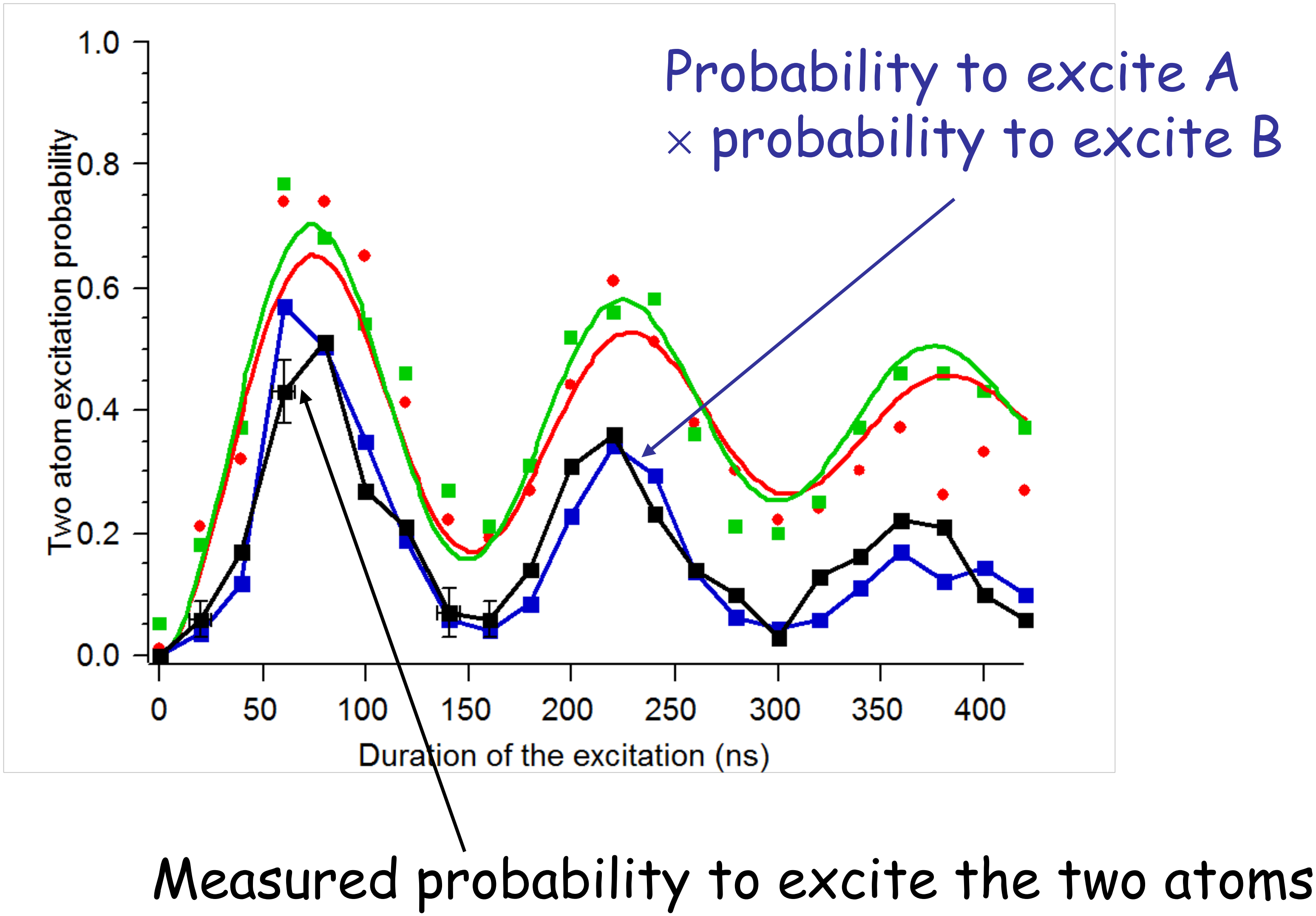


Single atom Rabi oscillation
between ground and Rydberg state

Excitation of two atoms at R = 18 μm

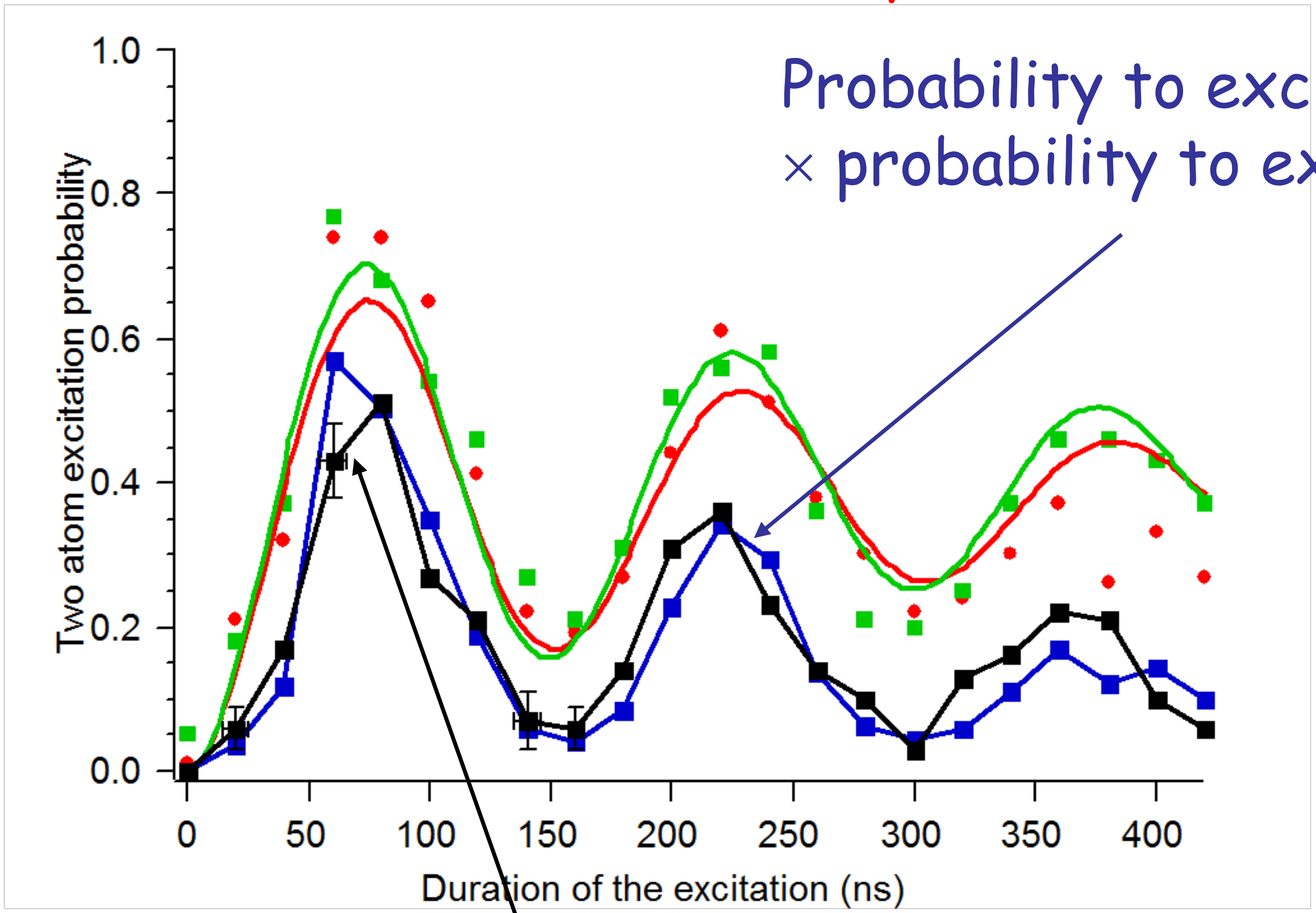


Excitation of two atoms at R = 18 μm



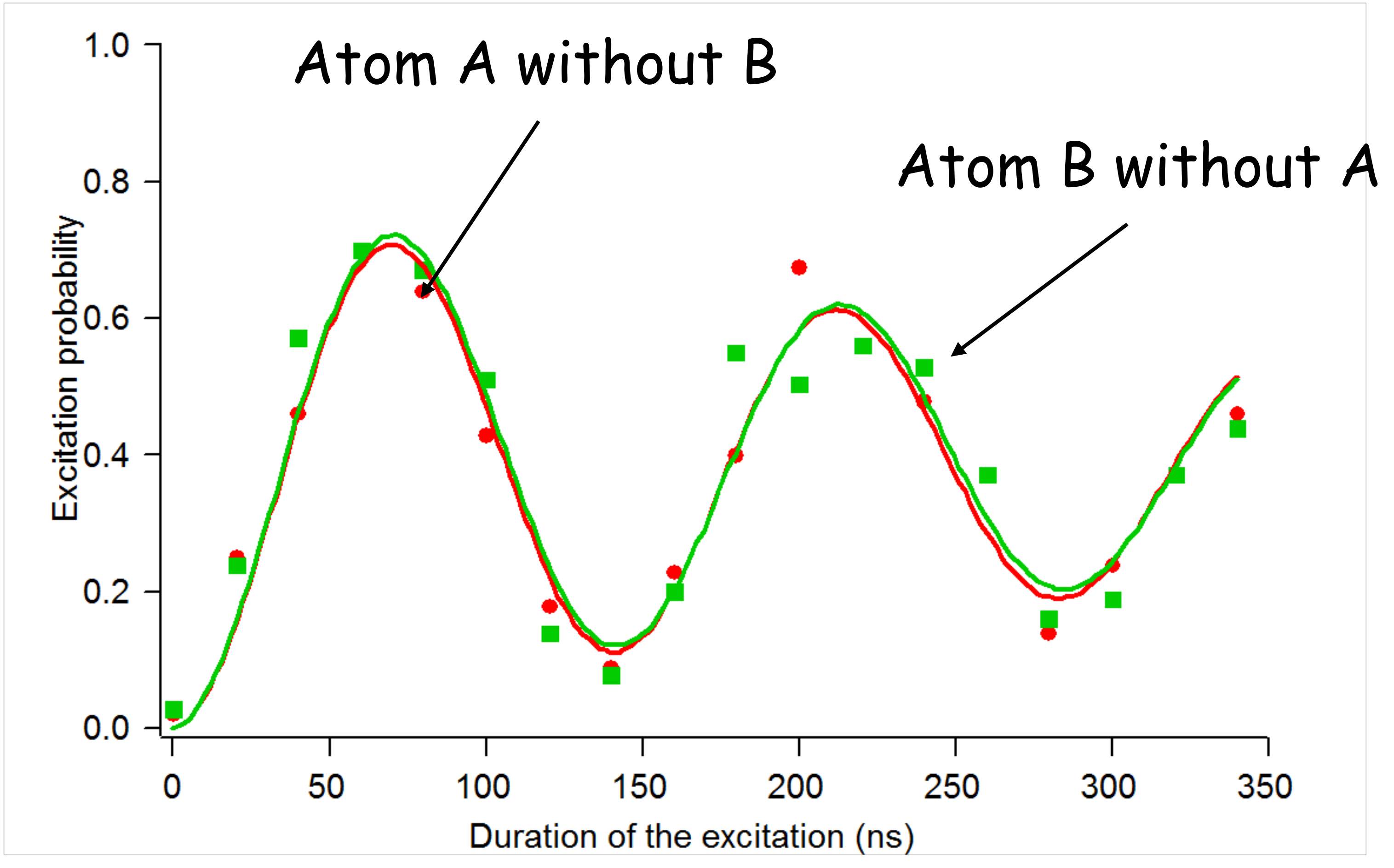
Excitation of two atoms at R = 18 μm

The atoms are « independent »

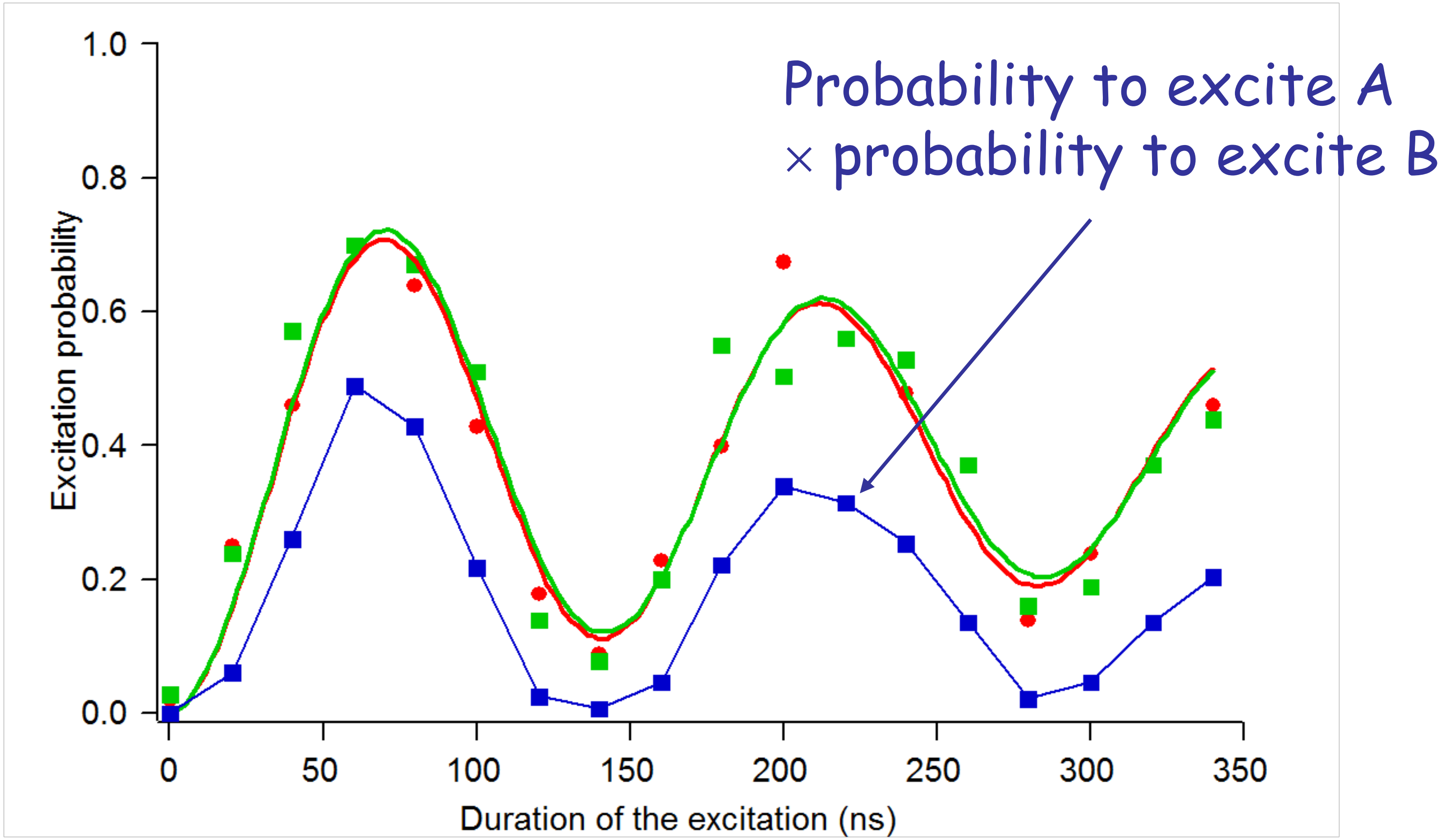


Measured probability to excite the two atoms

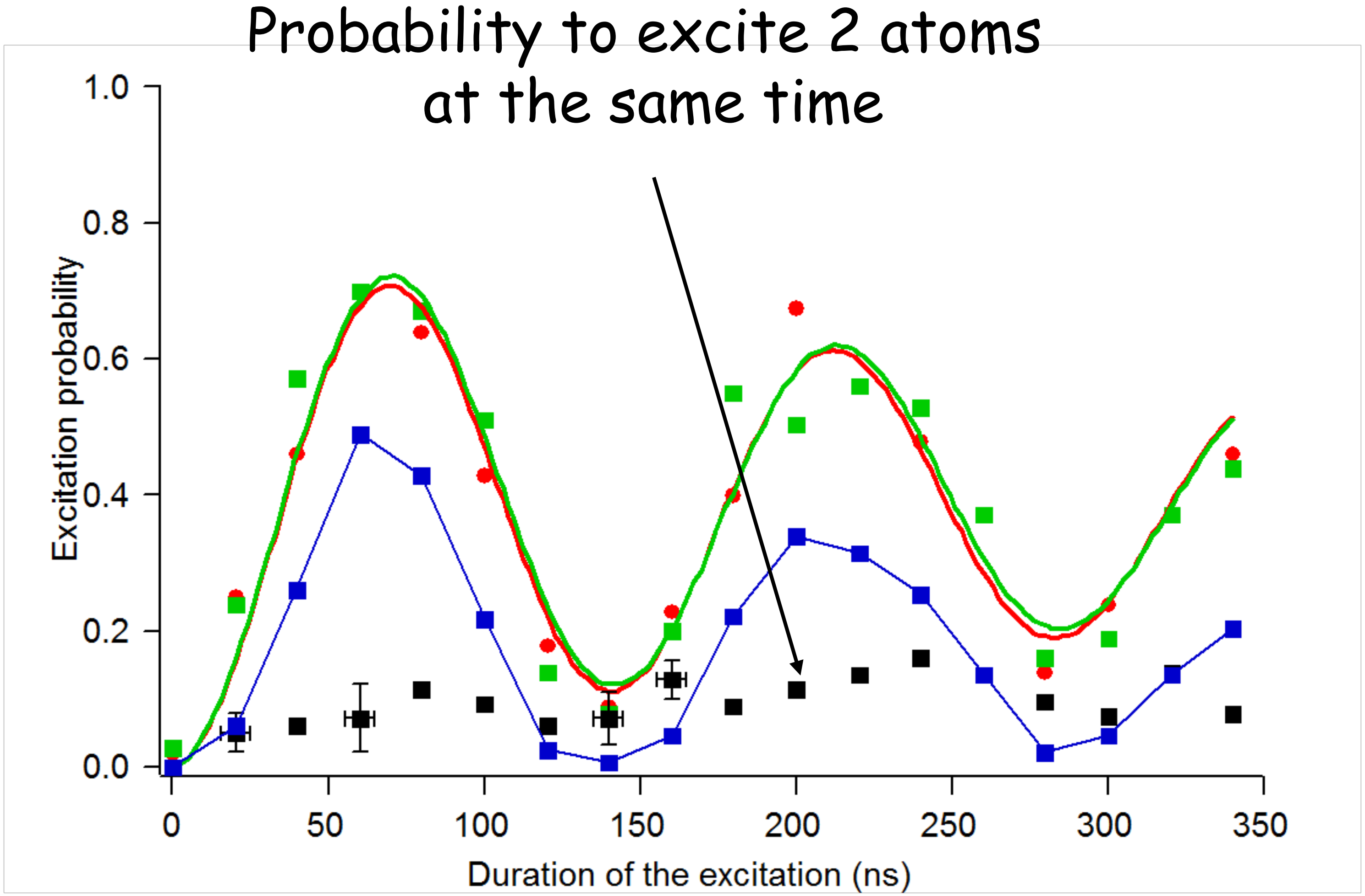
Excitation of two atoms at R = 3.6 μm



Excitation of two atoms at R = 3.6 μm



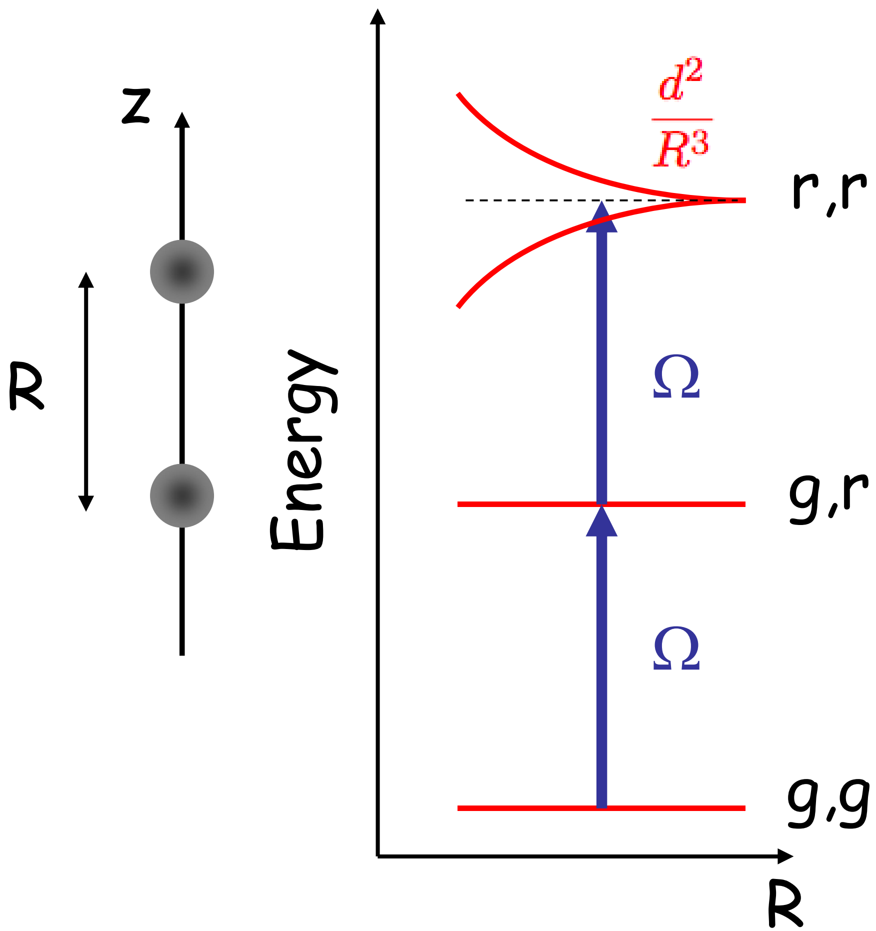
Excitation of two atoms at R = 3.6 μm



« Blockade » range

Two atoms excited to
$|58d_{3/2}\,;\,M_J = 3/2\rangle$

Δ=7 MHz $|58\,d\,3/2; 58\,d\,3/2\rangle$ $|60p\,1/2; 56\,f\,5/2\rangle$

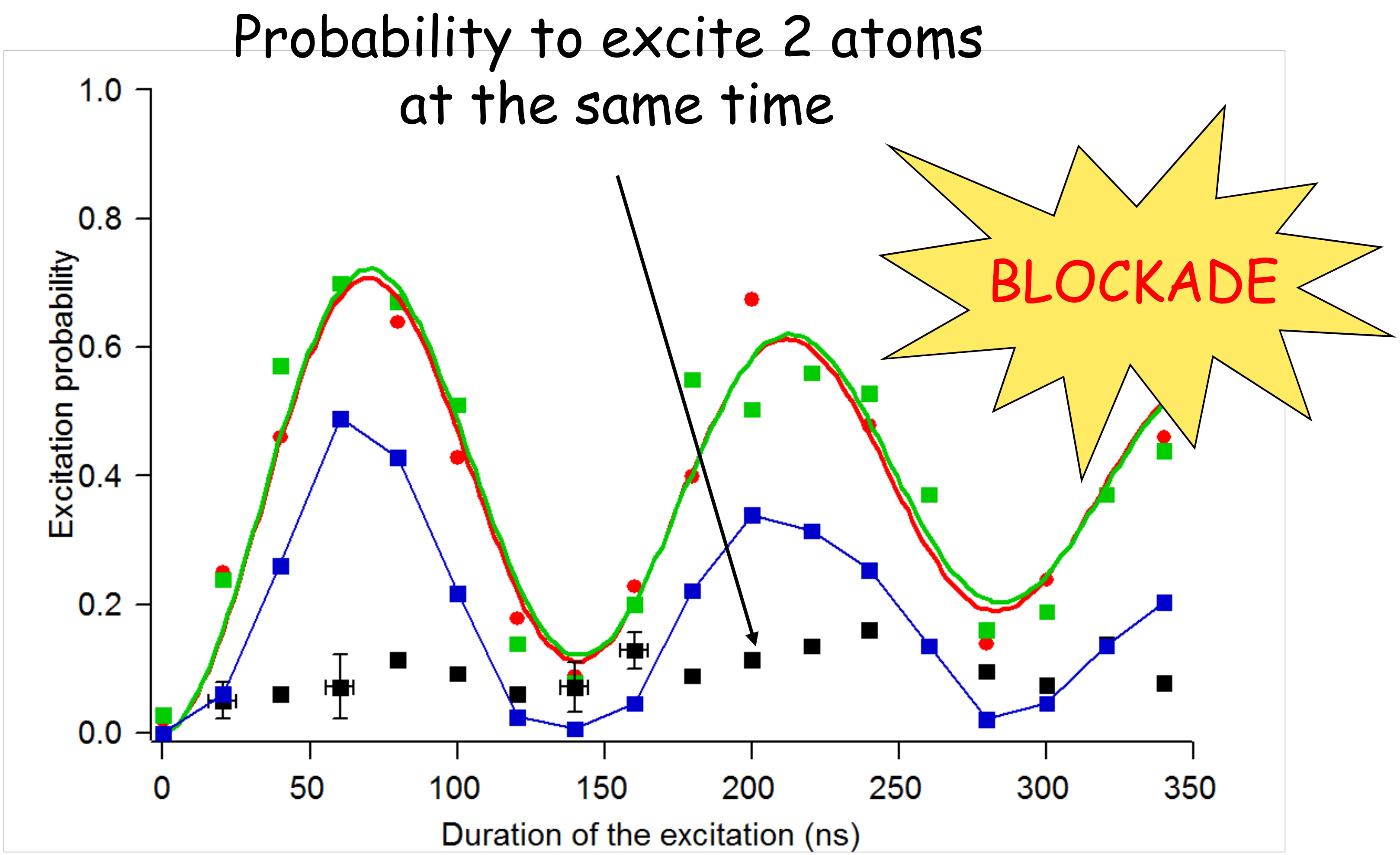


Blockade stops when

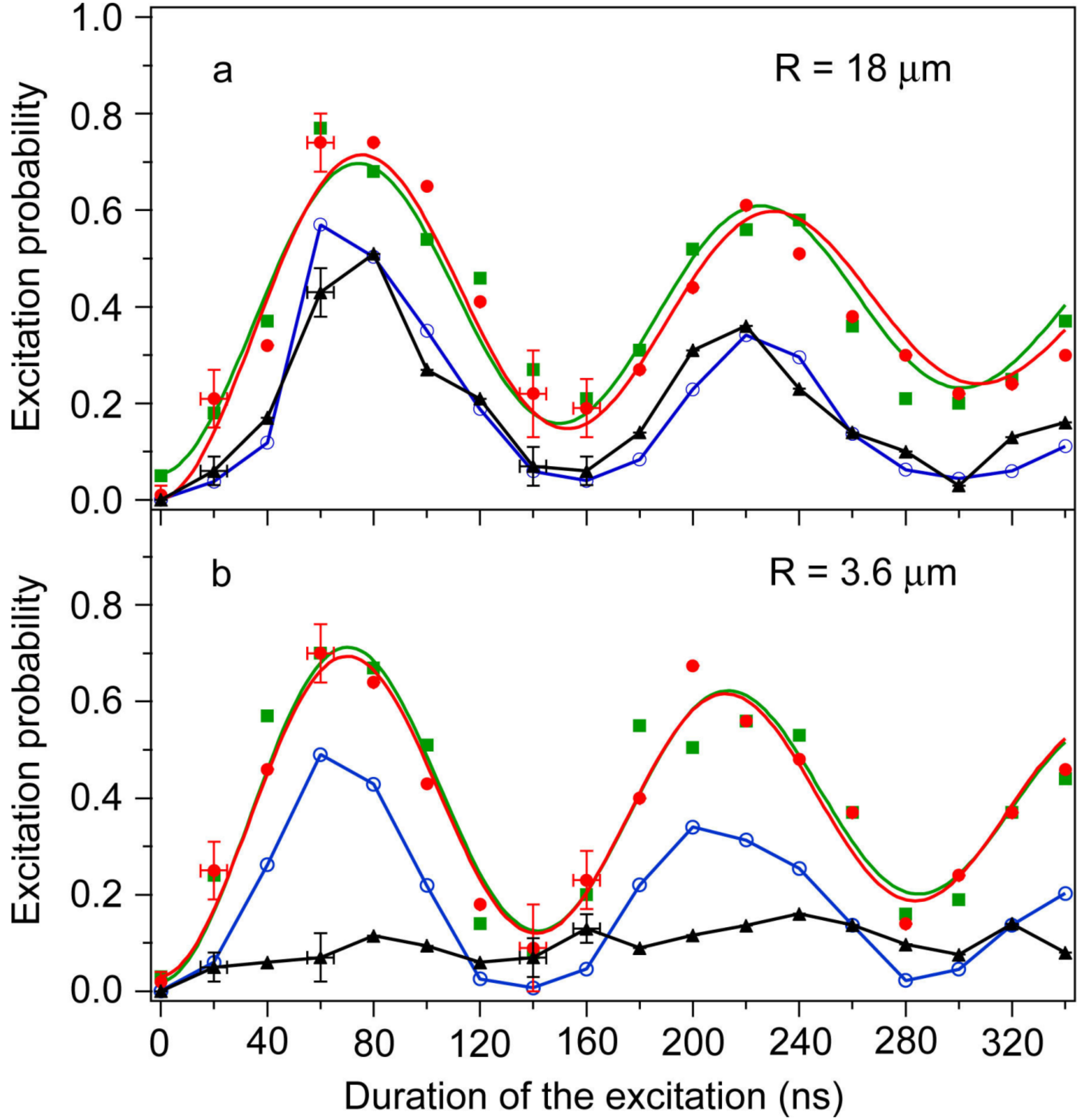
$$\hbar\Omega \approx \frac{d^2}{R^3}$$

$\Omega = 2\pi \times 7$ MHz
$\Rightarrow$ Rmax = 8 μm

Excitation of two atoms at R = 3.6 μm



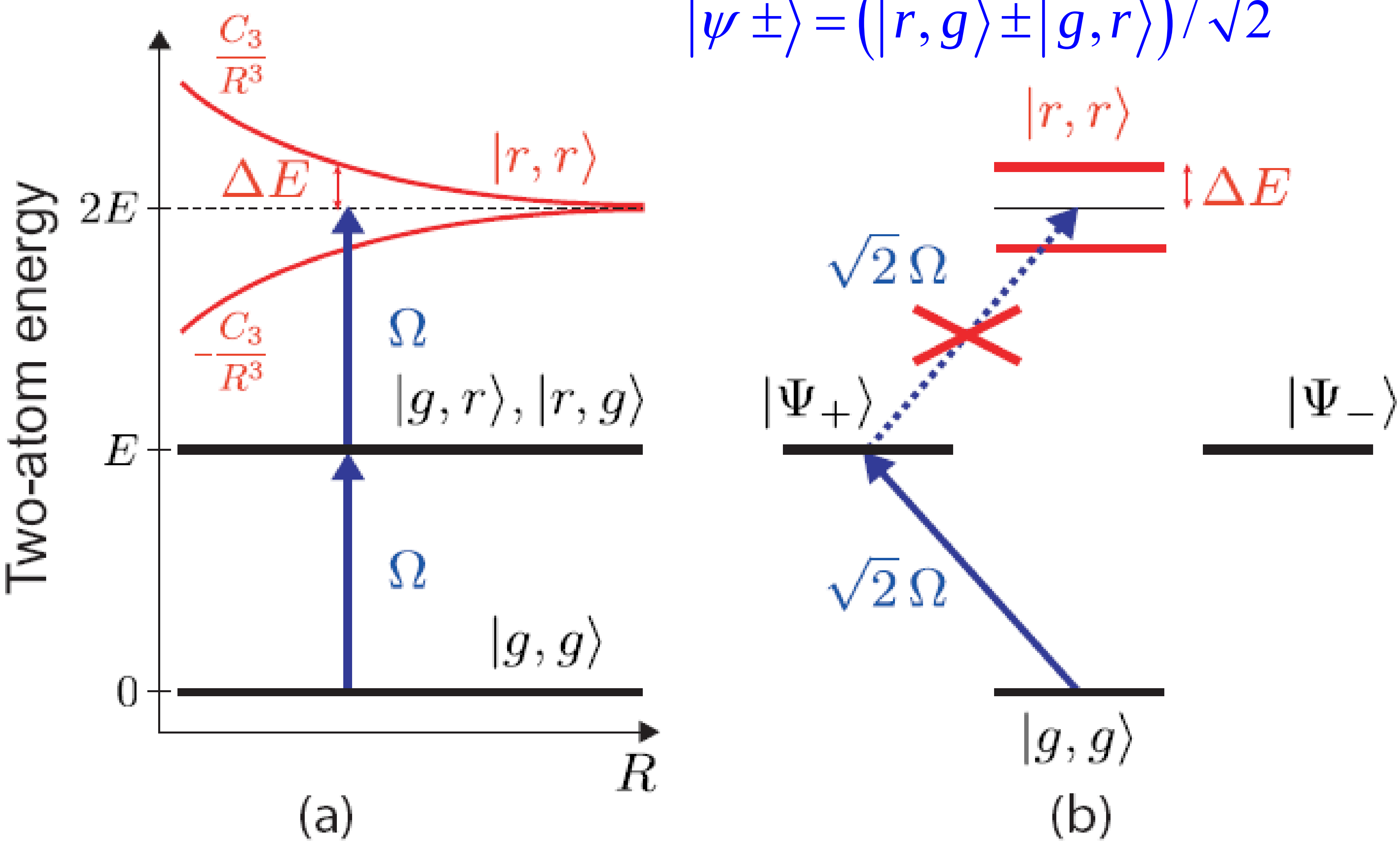
« Observation of collective excitation of two individual atoms in the Rydberg blockade regime », A. Gaëtan, Y. Miroshnychenko, T. Wilk, A. Chotia, M. Viteau, D. Comparat, P. Pillet, A. Browaeys, and P. Grangier, Nature Physics **5**, 115 (2009).



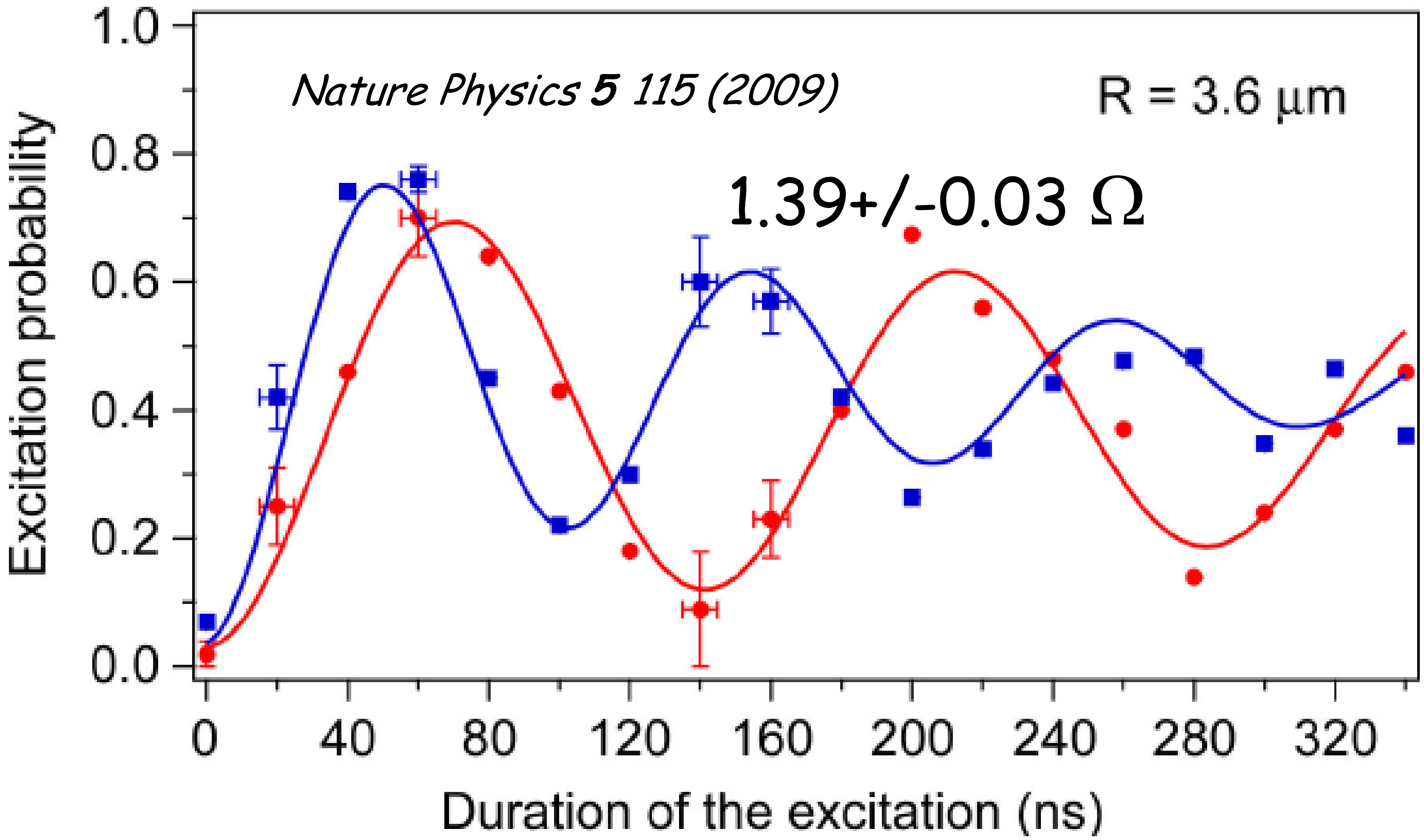
a
R = 18 μm
b
R = 3.6 μm
Excitation probability
Excitation probability
1.0
0.8
0.6
0.4
0.2
0.0
0 40 80 120 160 200 240 280 320
Duration of the excitation (ns)

Rb : Förster résonance ($58d_{3/2}$, $58d_{3/2}$) et ($60p_{1/2}$, $56f_{5/2}$)

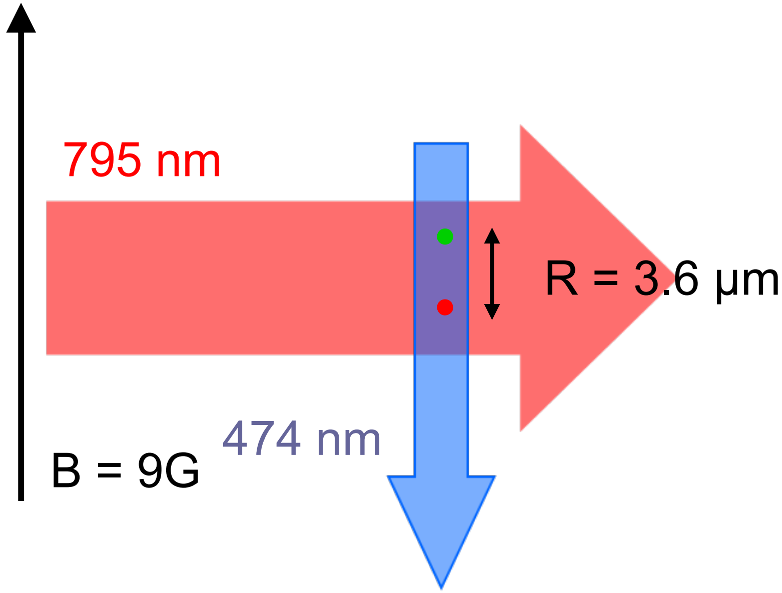
$$|\psi\pm\rangle = \left(|r,g\rangle \pm |g,r\rangle\right)/\sqrt{2}$$

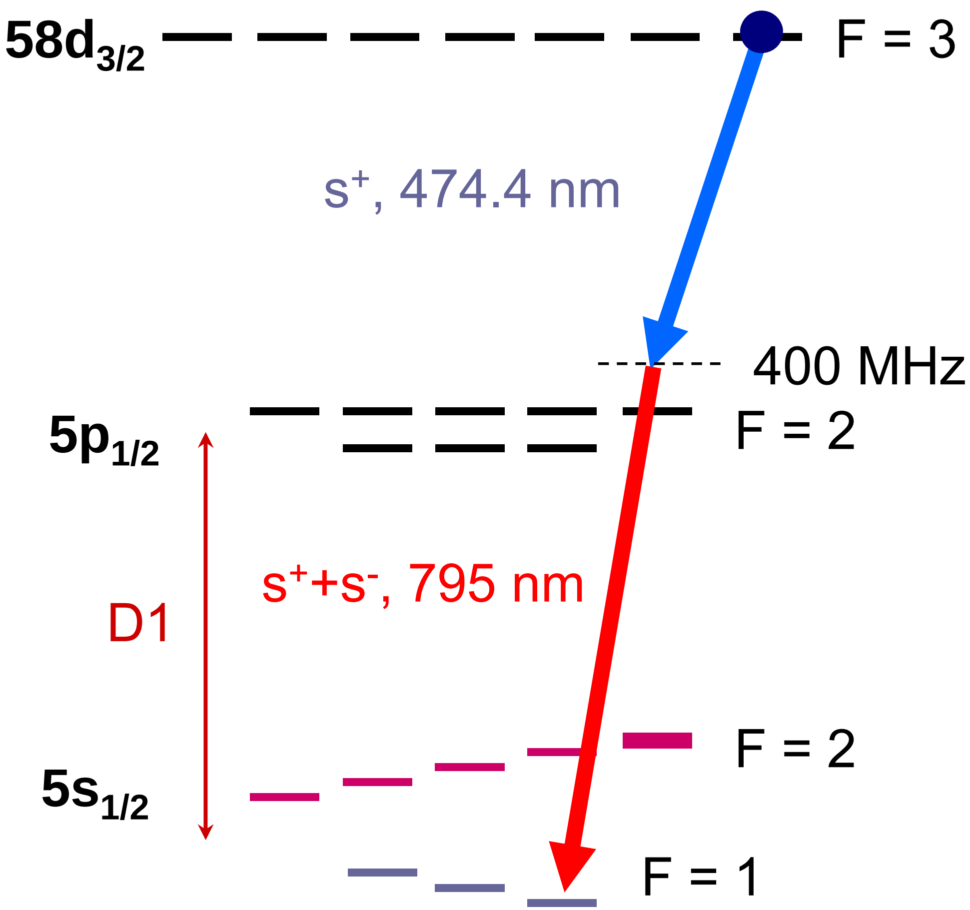


Collective excitation: Alpha Gaëtan, Yevhen Miroshnychenko, TatjanaWilk, Amodsen Chotia, Matthieu Viteau, Daniel Comparat, Pierre Pillet, Antoine Browaeys and Philippe Grangier



To prepare a quantum bit



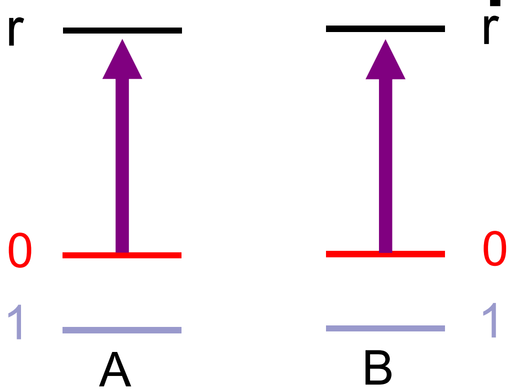


$$\frac{1}{\sqrt{2}}(|r,1\rangle + |1,r\rangle)$$

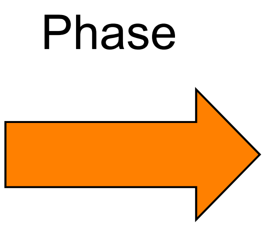
$$\rightarrow \quad |\psi_B\rangle = \frac{1}{\sqrt{2}}\left(|1,0\rangle + |0,1\rangle\right)$$

Scalable quantum gate

Jaksch, *et al.*
PRL **85**, 2208 (2000)



$|1\ 1\rangle$
$|0\ 1\rangle$
$|1\ 0\rangle$
$|0\ 0\rangle$



$|1\ 1\rangle$
$-|0\ 1\rangle$
$-|1\ 0\rangle$
$-|0\ 0\rangle$

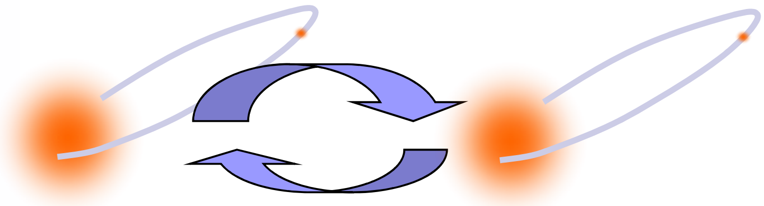
Blockade

π - excitation on A
2π - excitation on B
π - excitation on A

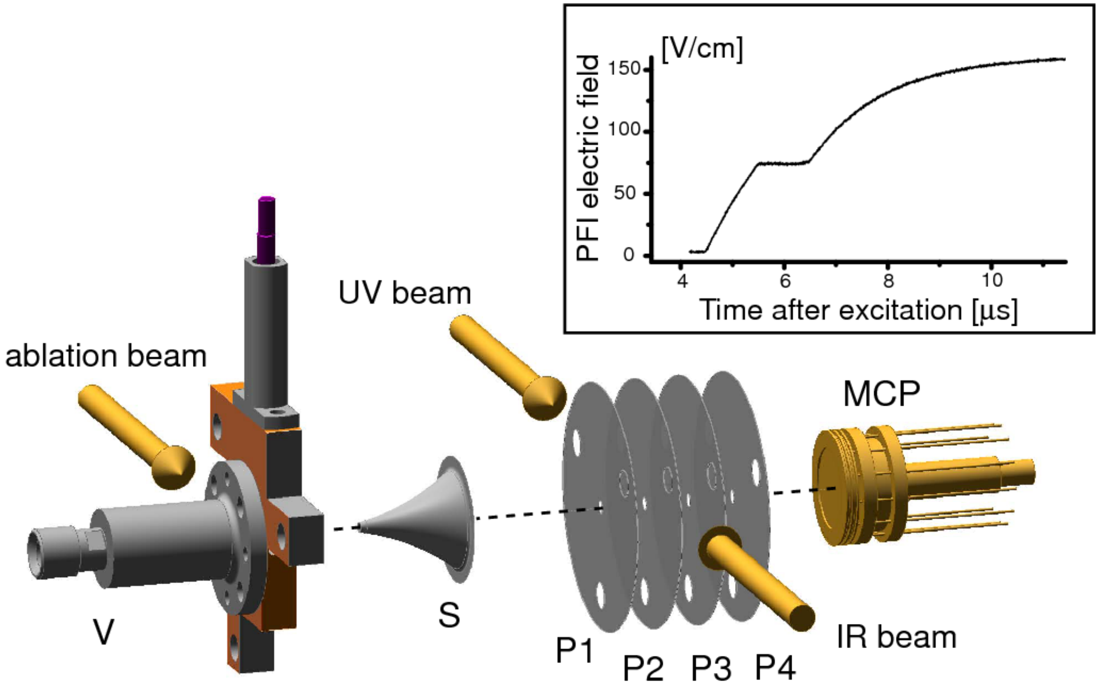
* Requires « adressability ». Very fast gate
* Can (easily ?) be turned into a CNOT gate

Work in progress… (U. Wisconsin, Institut d'Optique)

Foster resonance: Collisions, Landau-Zener transitions, or Interactions



Experiments with a Na supersonic beam



<v> = 1900 m/s

T_{trans} = 1 K

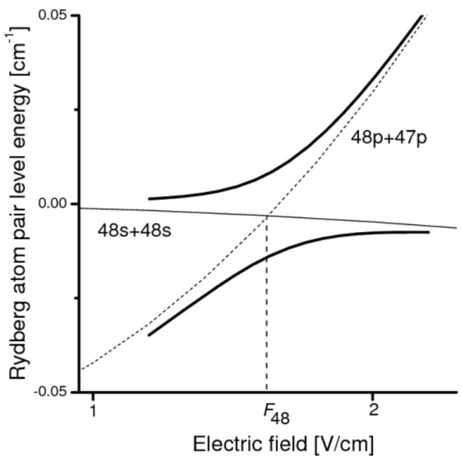
Excitation

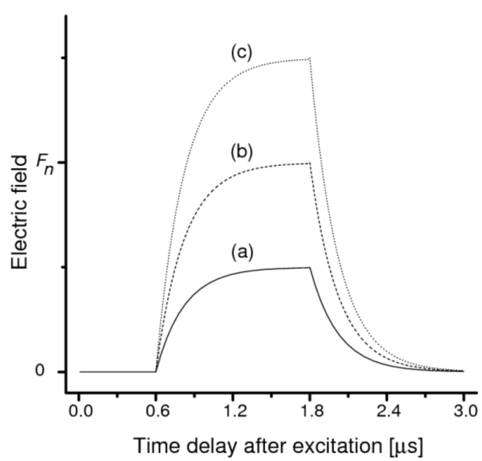
3s -> $4p_{3/2}$ -> ns

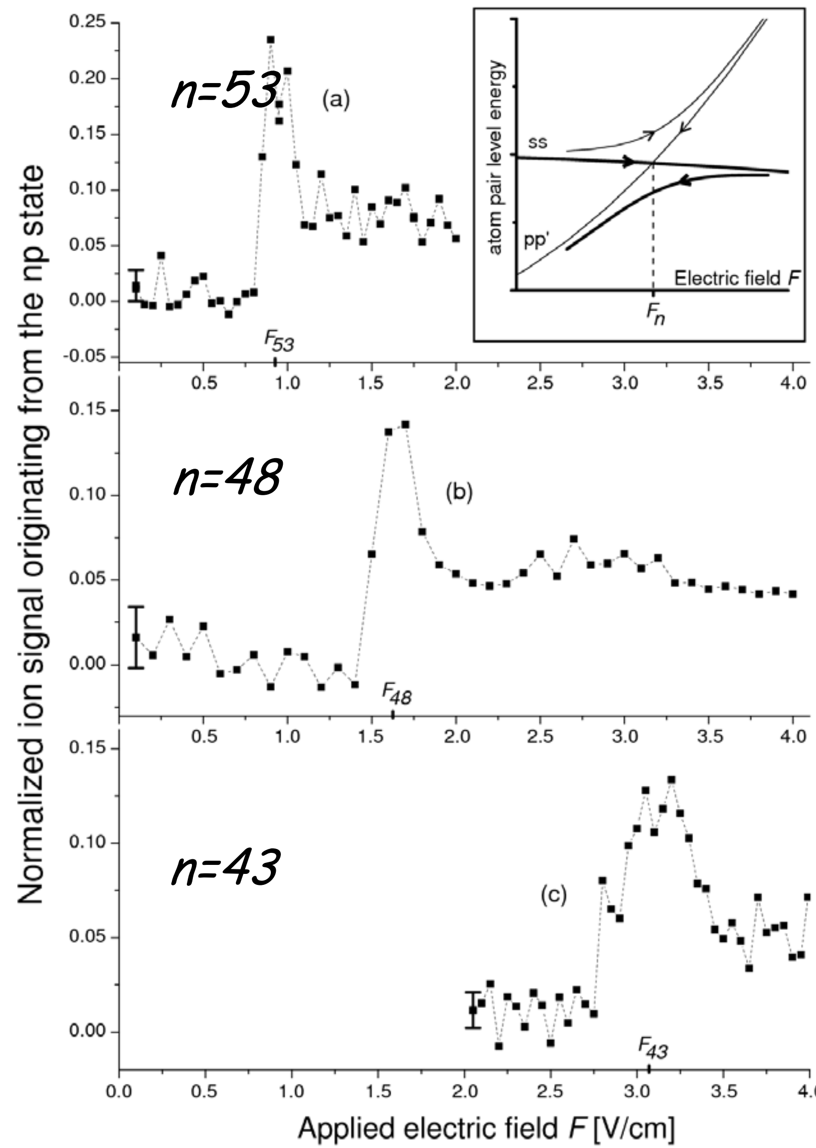
Föster resonance

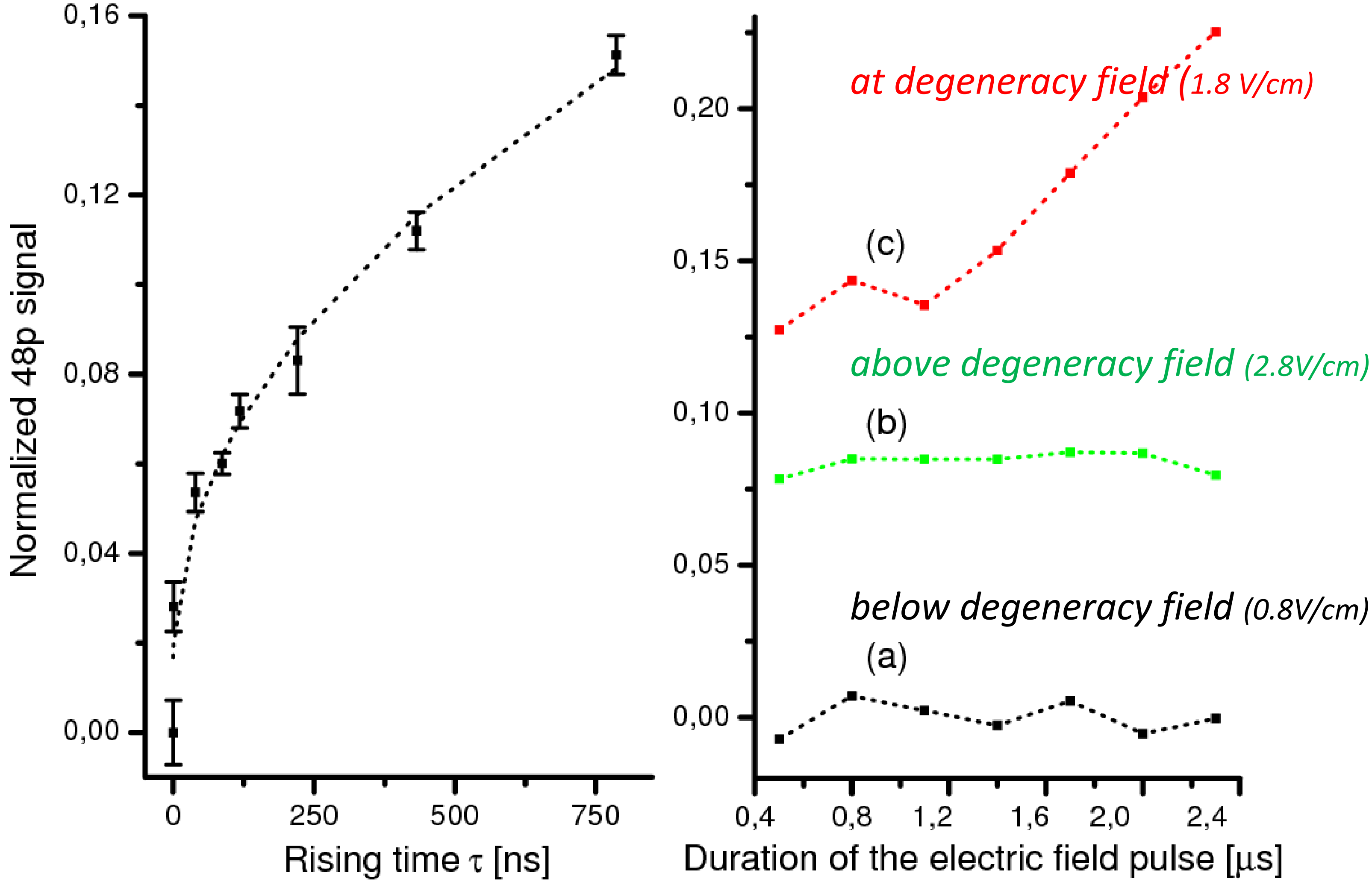
ns+ns -> np+(n-1)p

Landau-Zener transitions at Föster resonance



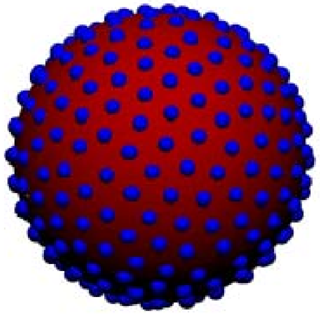




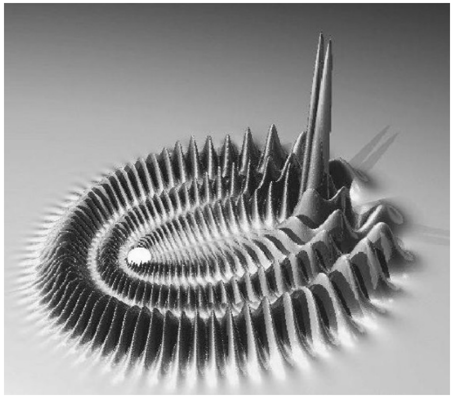


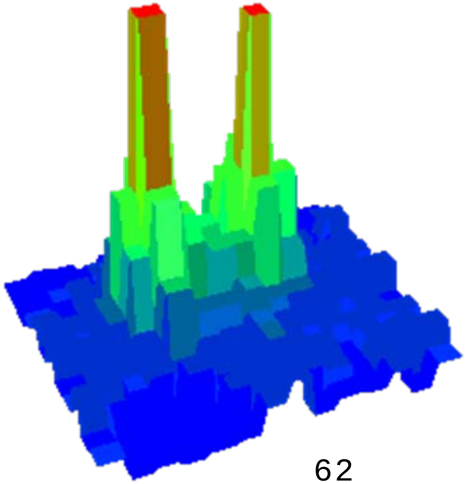
0,16
0,12
0,08
0,04
0,00
Normalized 48p signal
0
250
500
750
Rising time τ [ns]
0,20
0,15
0,10
0,05
0,00
at degeneracy field (1.8 V/cm)
(c)
above degeneracy field (2.8V/cm)
(b)
below degeneracy field (0.8V/cm)
(a)
0,4
0,8
1,2
1,6
2,0
2,4
Duration of the electric field pulse [μs]

Perspectives and conclusion



- A very rich physics
- ….
- Penning ionization, control of the interatomic forces, evolution towards an ultracold plasmas, highly correlated plasmas…
- Application of dipole blockade for quantum gates : P. Gangrier, A. Browaeys *et al.* entanglement of two atoms with a fidelity of 75 %
- Landau-Zener transitions: selection of pairs, few-body effects
- Stark-Rydberg decelerator of supersonic beams
- …





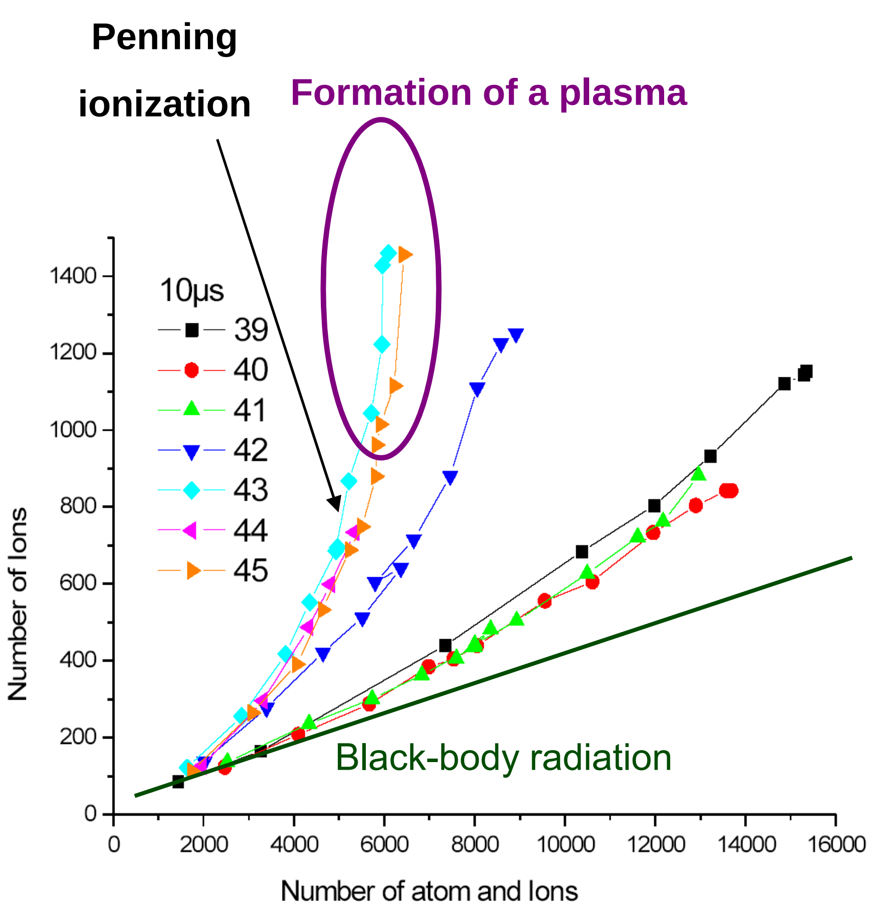
Frontier between cold Rydberg gases and ultracold plasmas

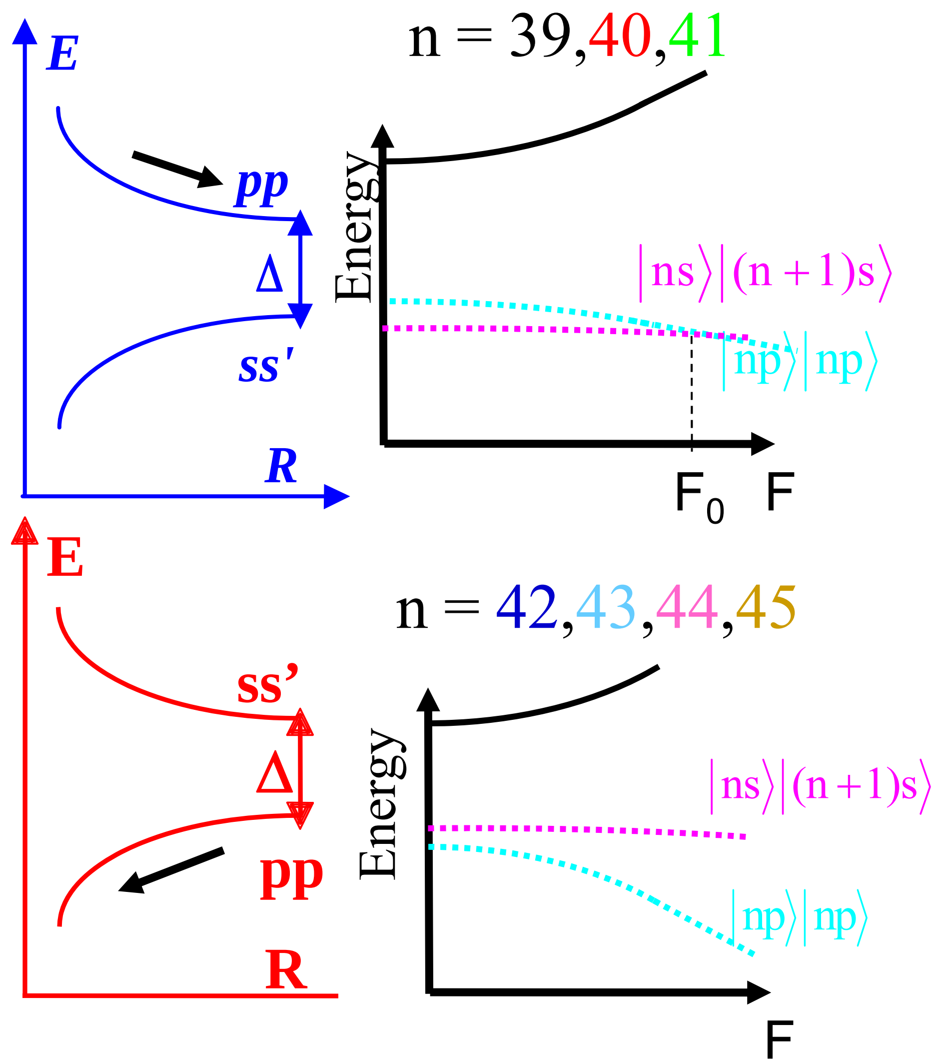
Limit of the frozen Rydberg gas picture
Dipole forces

Penning ionization
nl + nl -> n'l' + ion + e (n'<n)

Dipole-dipole collisions (after 10μs)

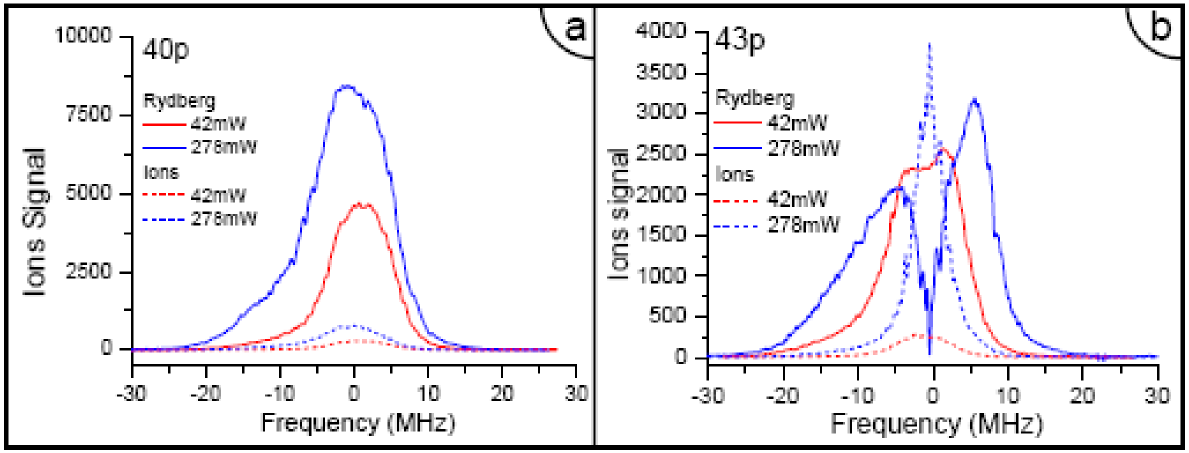
- ***Excitation of $np_{3/2}$ at zero field (F = 0V/cm)***
  van der Waals or second order dipole-dipole coupling

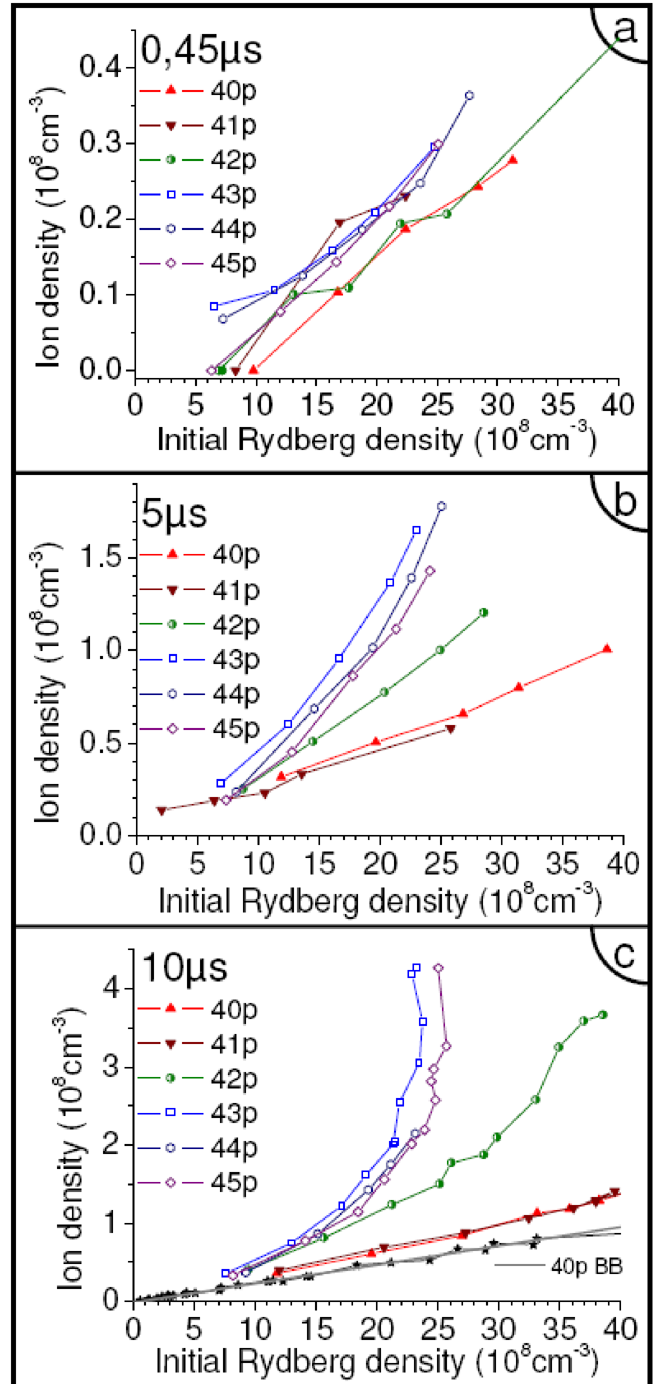




From 40p to 43p: Spectacular change in the behavior of the Rydberg gas

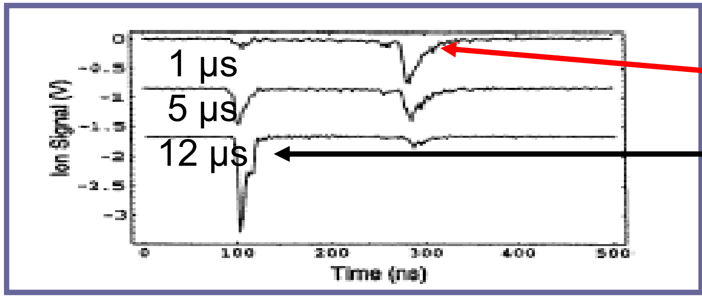
Viteau et al. PRA **78** 040704(R) (2008)





For 43p: The pairs of close atoms collide to form an ion space charge which can trap the electrons, leading to avalanche ionization up to the formation of an ultracold plasma

Spontaneous evolution of a Rydberg atomic gas into an ultracold plasma

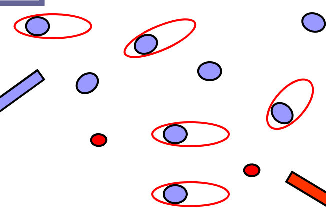


Two signals
- Rydberg atoms
- Ions

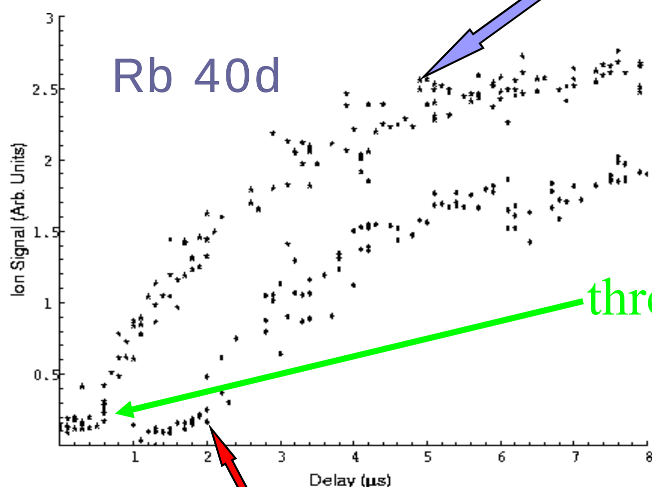
PRL 85 4466 (2000)

Ion detection

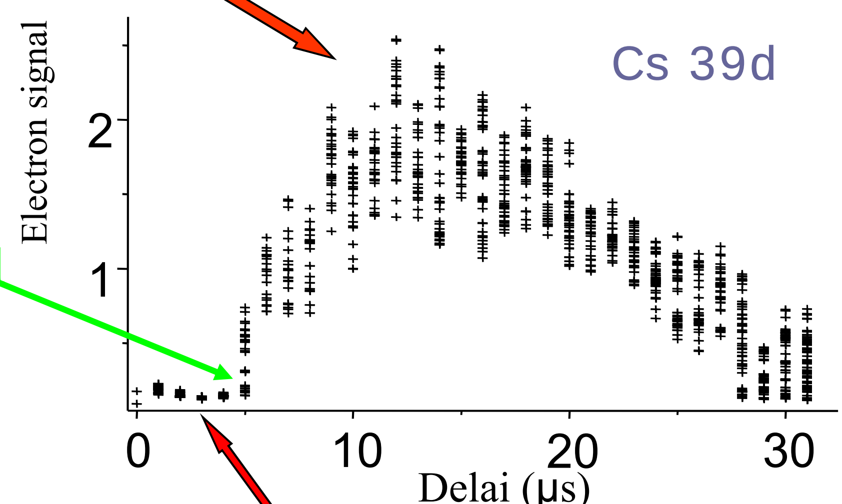
3.3 et 2.4 10^5 atoms



Electron detection

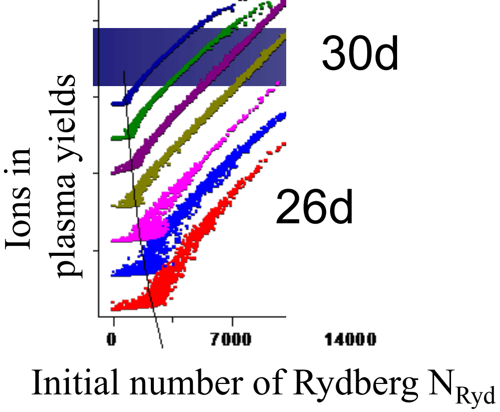


threshold

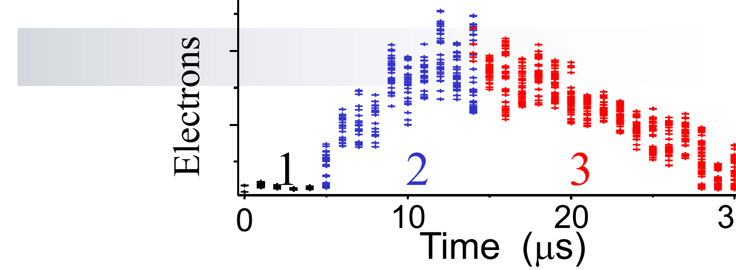


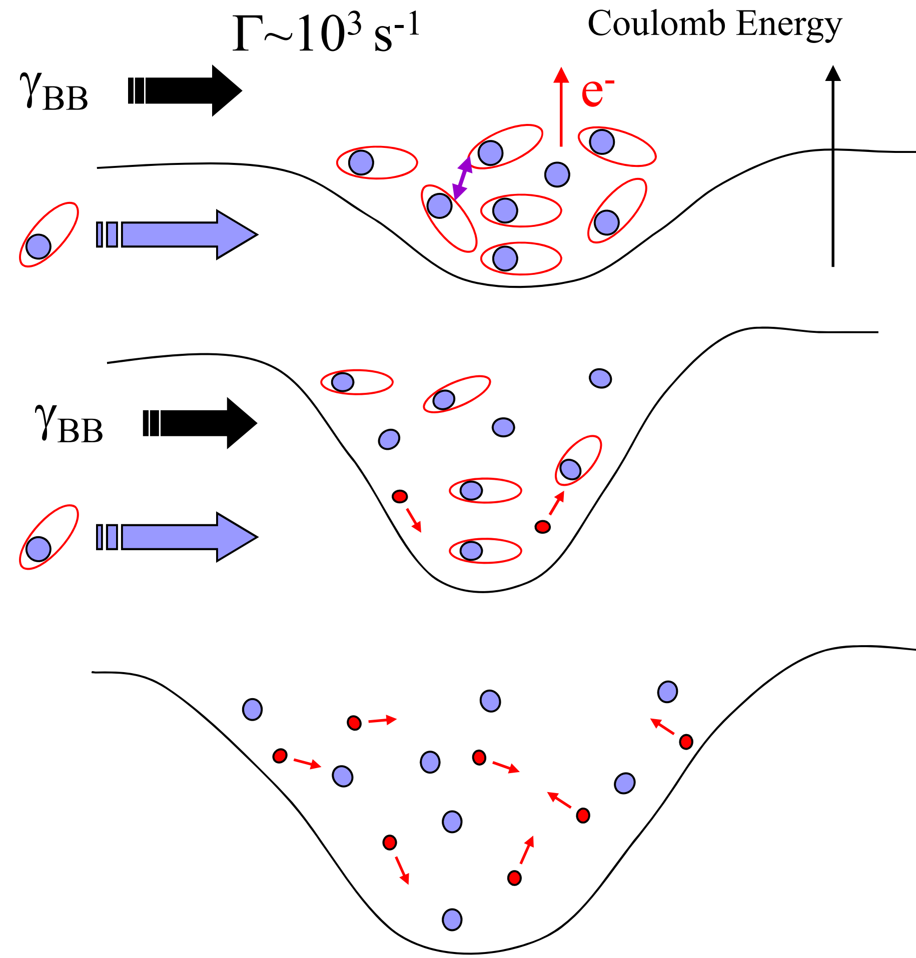
A few ions

No electrons



Scenario





1) Ionization and ignition

Blackbody radiation
Collisions between hot and cold atoms
Collisions between cold Rydberg atoms

2) Avalanche ionization

Electrons trapped by the space charge
Collisions electrons – Rydberg atoms: ionization , super-elastic collisions

3) Expansion

Electron pressure + Coulomb explosion
3-body recombination (heating)
Evaporation of electrons

Plasma parameters

$E_{cin} \sim k_B T_e$ $E_{pot} \sim e^2/a$

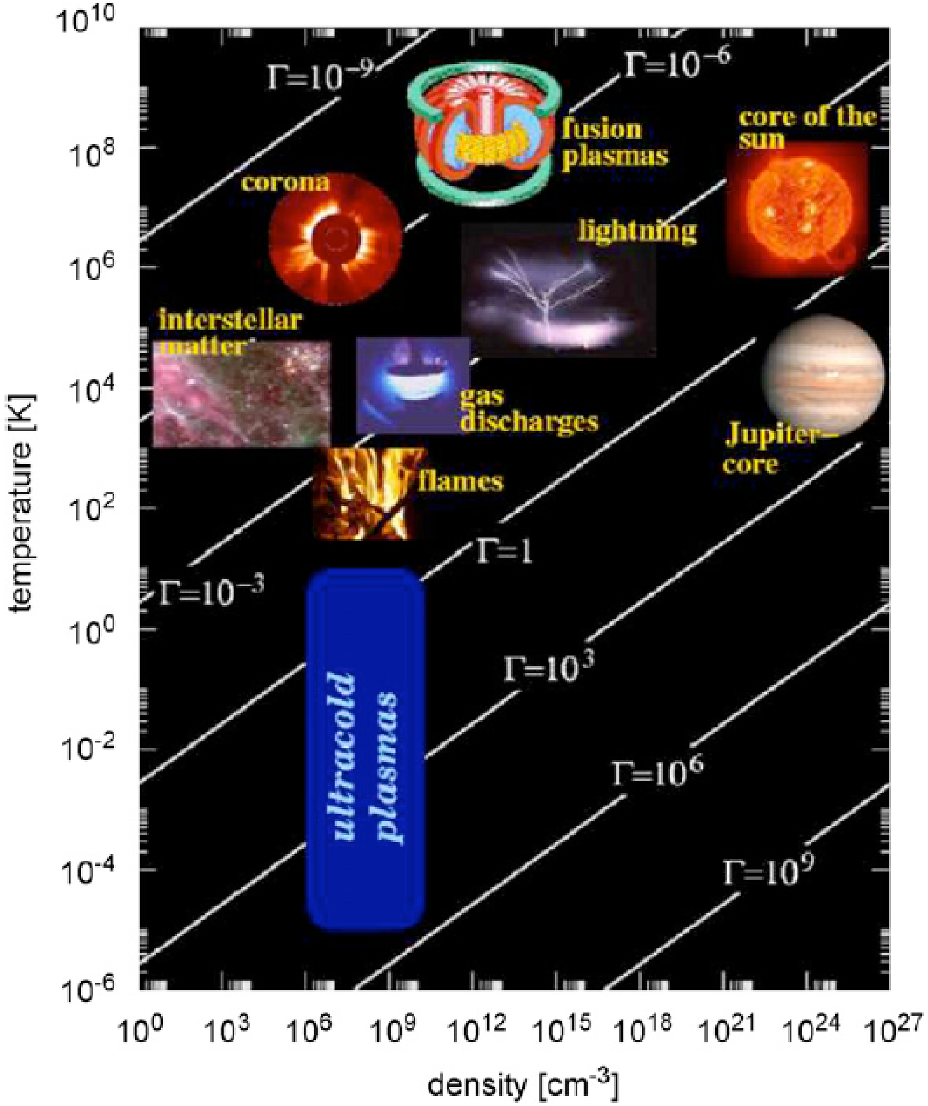
$(e^2 = q_e^2/4\pi\varepsilon_0)$
$a = (4\pi n_e/3)^{-1/3}$

$\Gamma = E_{pot}/E_{cin}$

$\Gamma < 1$; $n_e \lambda_{Debye}^3 > 1$

$\lambda_{Debye} = (\varepsilon_0 k_B T_e / e^2 n_e)^{1/2}$

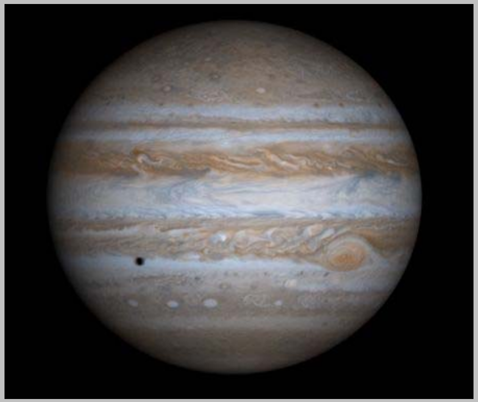
Plasmas



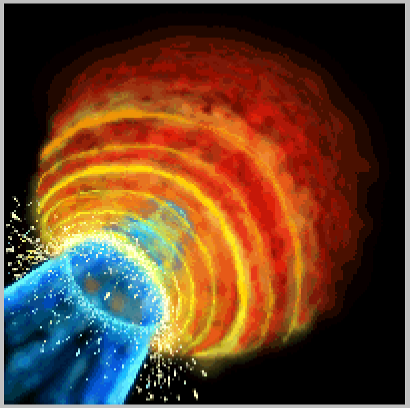
Correlated plasmas $\Gamma \geq 1$

White dwarfs:
$T \sim 10^7$ K, $n \sim 10^{40}$ m^{-3},
$\Gamma_{ion} \sim 300$

Braun dwarfs:
$T \sim 10^4$ K, $n \sim 10^{30}$ m^{-3}
$\Gamma \sim 20$



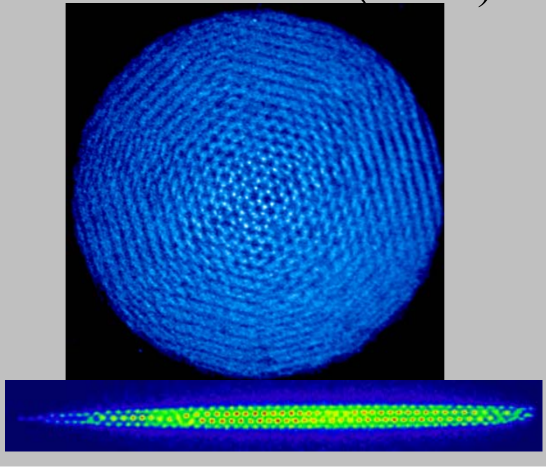
Laser plasmas (ps):
$T \sim 10^4$ K, $n \sim 10^{30}$ m^{-3}
$\Gamma \sim 20$



$\Gamma \geq 172$ Coulomb crystal

Non neutral plasma

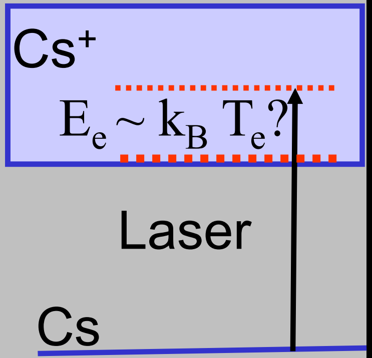
Coulomb cluster (EBIT)

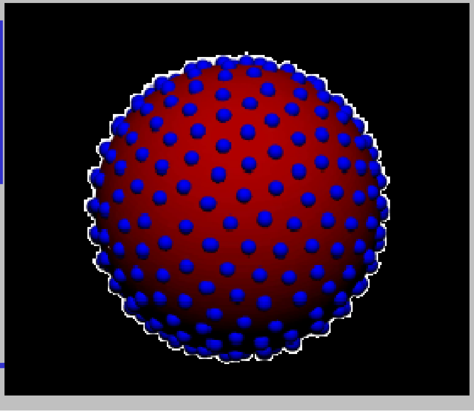


$\Gamma \geq 1$ Ultra-cold plasmas

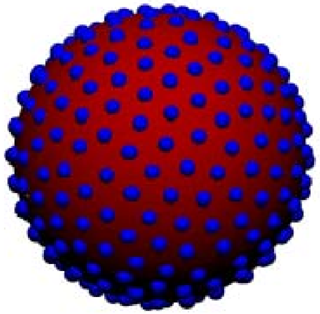
$n_e \sim n_i \sim 10^{16}$ m^{-3}

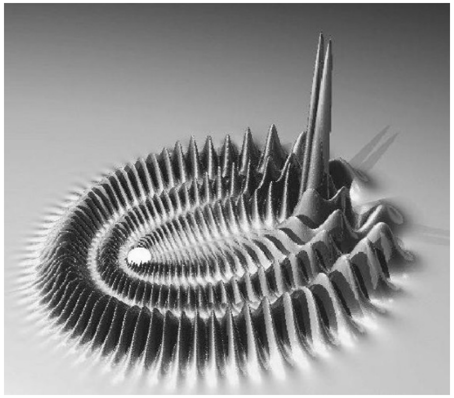
$T_e \sim T_i \sim 100$ μK

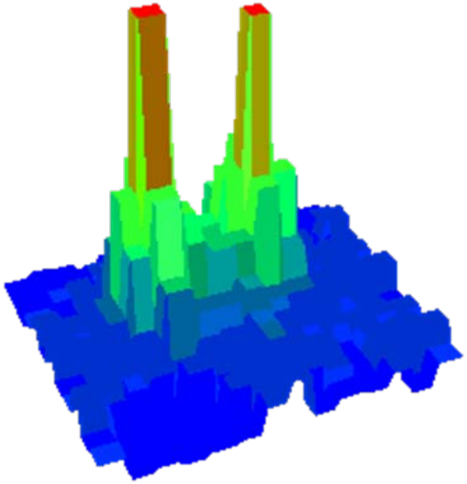




Perspectives and conclusion

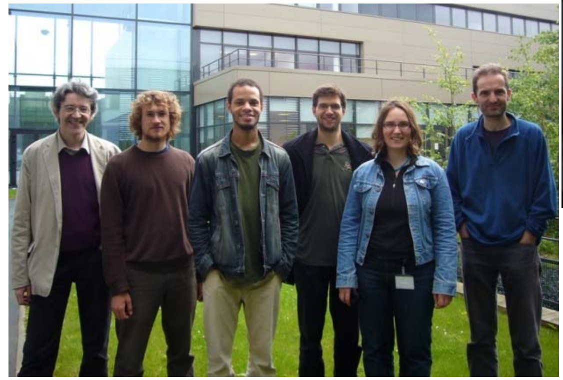


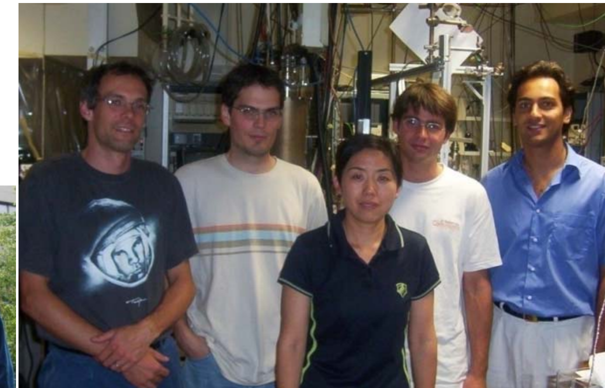




- A very rich physics: cold Rydberg atoms as quantum simulators, cold Rydberg matter?
- ….
- Penning ionization, control of the interatomic forces, evolution towards an ultracold plasmas, highly correlated plasmas…, heating processes
- Application of dipole blockade for quantum gates : P. Gangrier, A. Browaeys *et al.* entanglement of two atoms with a fidelity of 75 % (quantum engineering)
- Rydberg photoassociation of cold atoms
- Landau-Zener transitions: few-body effects
- Stark-Rydberg decelerator of supersonic beams
- Rydberg excitation of quantum gases
- …

Cold Rydberg atoms / Ultracold plasmas





Thibault Vogt
Matthieu Viteau
Amodsen Chotia
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Collaboration on ultracold plasmas with Thomas F. Gallagher, University of Virginia and Ducan Tate, Colby College

Collaboration on collective excitation of a pair of atoms in the dipole blockade regime with Philippe Grangier, Antoine Browaeys et al., Institut d'Optique

IAC 80 ans 1927-2007

UNIVERSITE PARIS-SUD XI

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IFRAF

The end

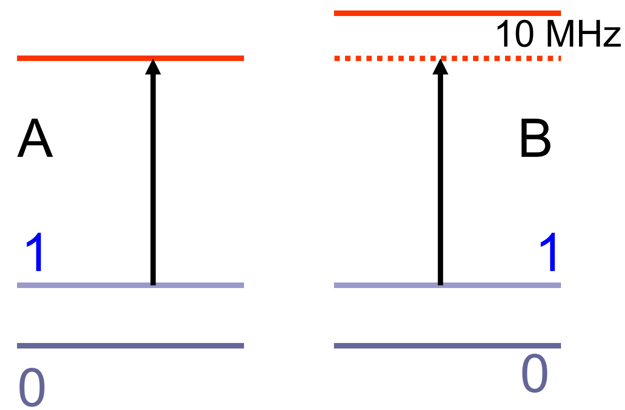
Thank you for your attention

Dipole blockade of the Rydberg excitation

Application: quantum information

Dipole blockade and quantum information

- Rydberg atoms, *nl*, are giant atoms (*n^2 a.u.*) and have huge polazaribilities
- **Two atoms: Long-range dipole-dipole interaction shifts the Rydberg energy from its isolated value**
- **and prevents the excitation of the second atom in narrow bandwidth excitation: Dipole blockade**
- ….
- *Application for scalable quantum logic gates*



Jaksch et al., PRL 85 2208 (2000)

Lukin et al., PRL 87 037901 (2001)

Phase Gate

$|0\rangle\otimes|0\rangle \to +|0\rangle\otimes|0\rangle$

$|0\rangle\otimes|1\rangle \to$ ▬ $|0\rangle\otimes|1\rangle$

$|1\rangle\otimes|0\rangle \to$ ▬ $|1\rangle\otimes|0\rangle$

$|1\rangle\otimes|1\rangle \to$ ▬ $|1\rangle\otimes|1\rangle$

1) π pulse atom A

2) 2π pulse atom B

3) π pulse atom A

|00>	|00>	|00>	|00>
|01>	|01>	-|01>	-|01>
|10>	|R0>	|R0>	-|10>
|11>	|R1>	|R1>	-|11>

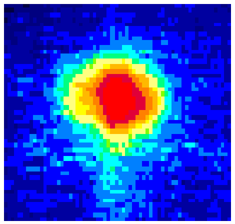
Dipole Blockade in a mesoscopic Rydberg *nl* ensemble?

- In zero electric field, no permanant electric dipole: no interaction? no blockade?
- By adding an electric field, Rydberg atoms acquire a permanant dipole: control of dipole blockade
- **Förster resonances: to control and to have a strong dipole-dipole interaction**

- Need high-resolution laser excitation ($\Delta\nu_L$).
  Need to have motionless atoms: cold atoms
  $\Delta\nu_L \sim W \approx \mu_1 \mu_2 / R^3$
- To avoid the line-broadening due to saturation
- To limit the ionization processes

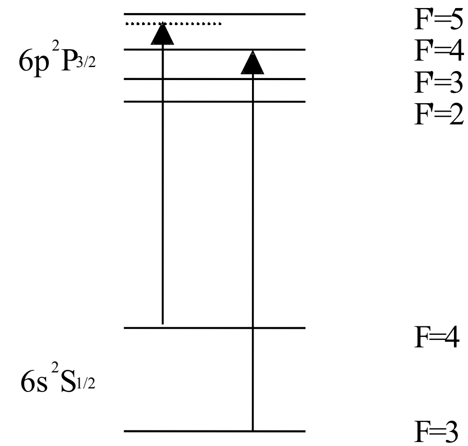
Evolution toward an ultracold plasma (Robison *et al.*, PRL85, 1408 (2000)) LAC-Charlottesville.

Cold Rydberg atoms at a Förster resonance



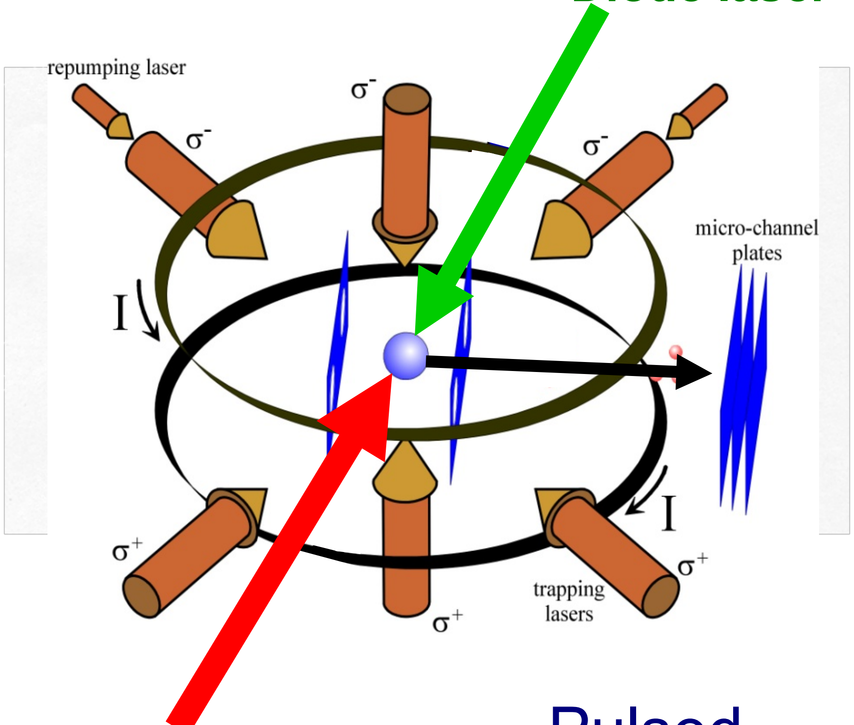
Experimental setup

Cs vapor loaded MOT



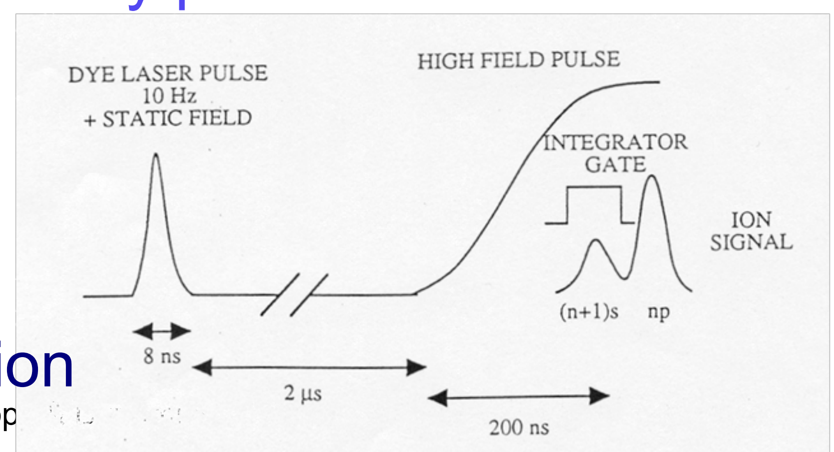
Cs

Diode laser



Ti:Sa laser

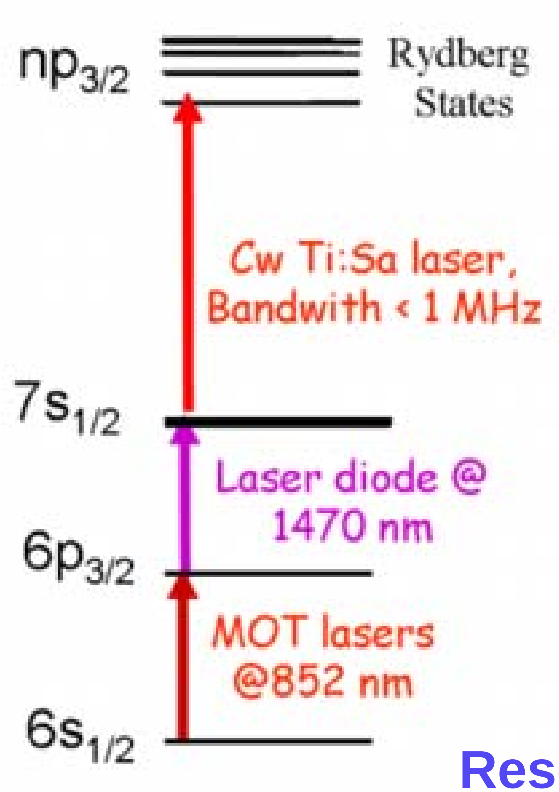
Selective ionization
by pulsed electric field

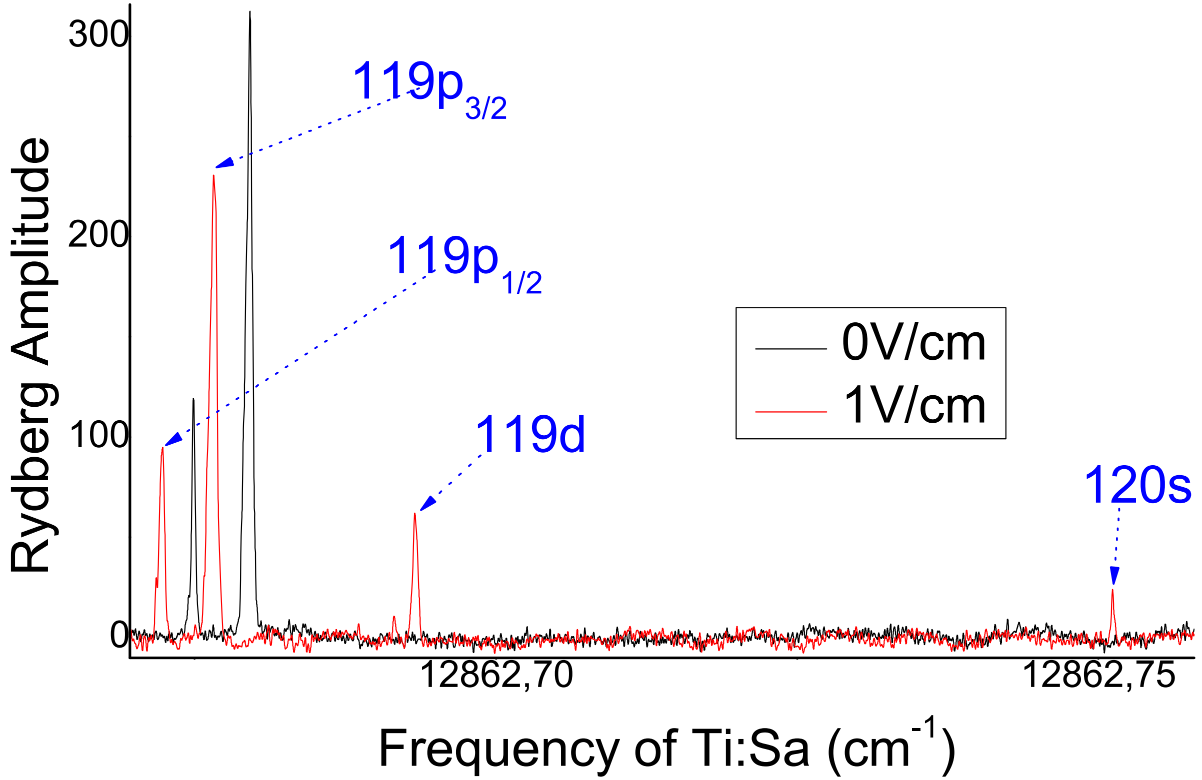


Pulsed
or cw excitation

High-resolution laser-excitation of an ensemble of Rydberg atoms

n =25 - 130





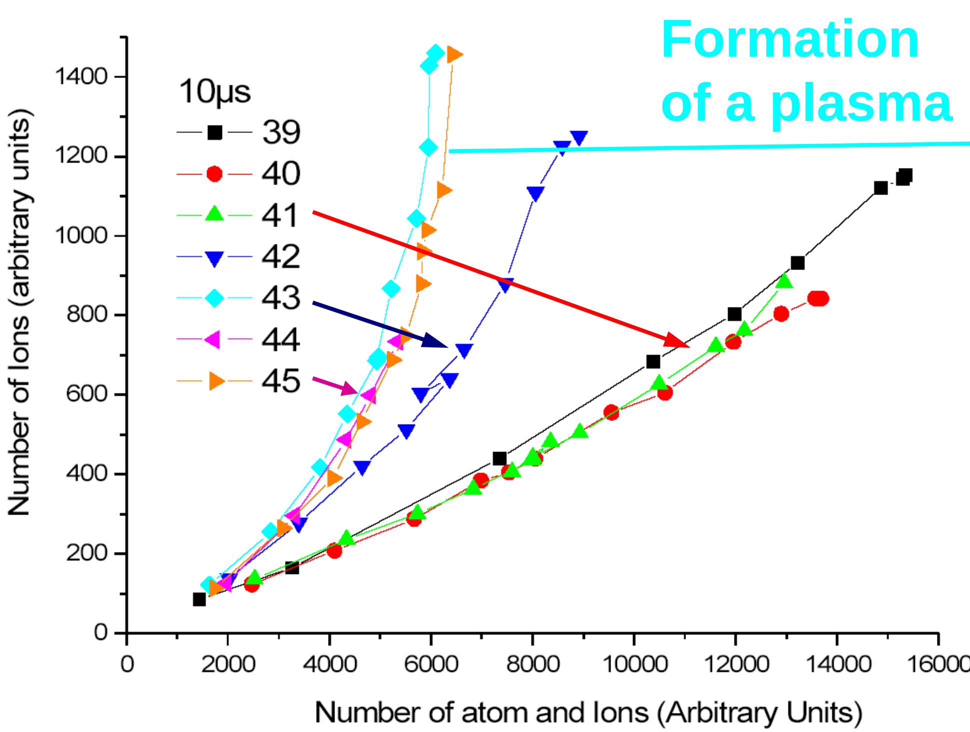
Resolution limited by the lifetime of 7s level: 56.5 ns: $\Delta\nu_L$ = 5 – 6 MHz. Duration of the excitation: τ = 300 ns

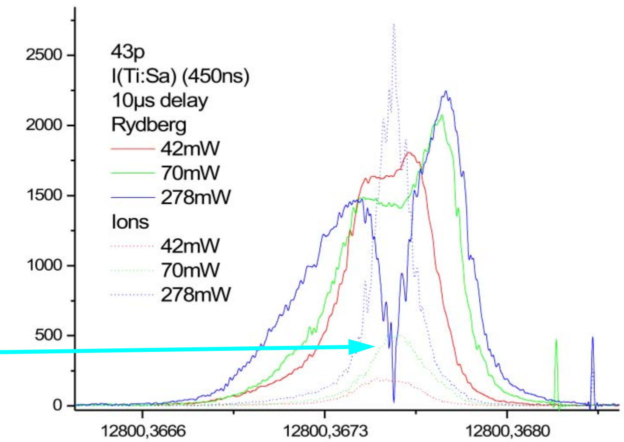
Cold collisions between cold Rydberg atoms and ionization (in zero field)

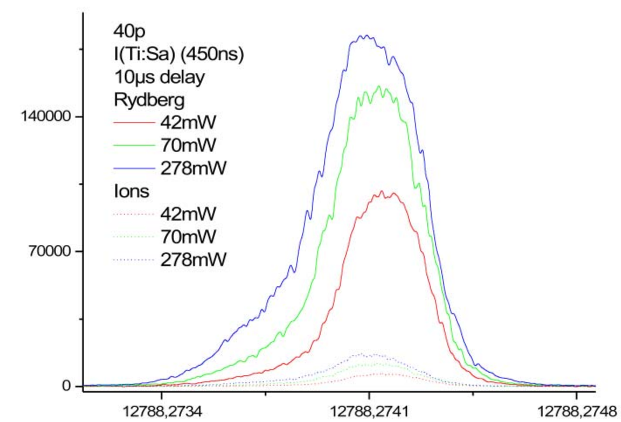
(excitation duration 10 μs)

$$Cs(np_{3/2}) + Cs(np_{3/2}) \rightarrow Cs^{+} + Cs(n'l')$$

$$n' << n$$







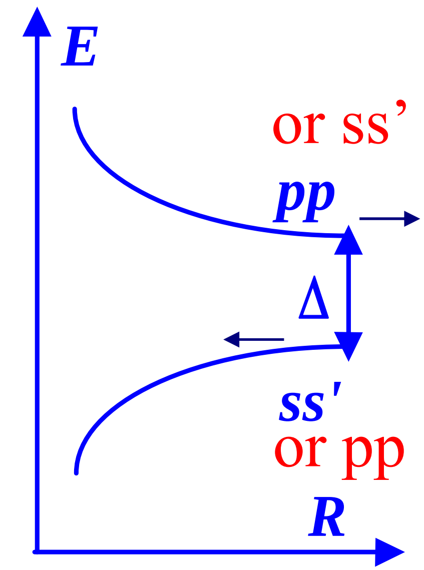
Dipole gas / Rydberg atomic gas

- Quasi-resonance
  2 x E(*np*) ~ E(*ns*) + E((*n*+1)*s*)
  Second order dipole-dipole coupling

$$V \approx \frac{W^2}{\Delta} \quad \text{avec} \quad W \approx \frac{\mu\mu'}{R_{AB}^3}$$

$$\mu = \langle np | \mu | ns \rangle \quad , \quad \mu' = \langle np | \mu | (n+1)s \rangle$$

$$\Delta = 2E_{np} - (E_{(n+1)s} + E_{ns})$$



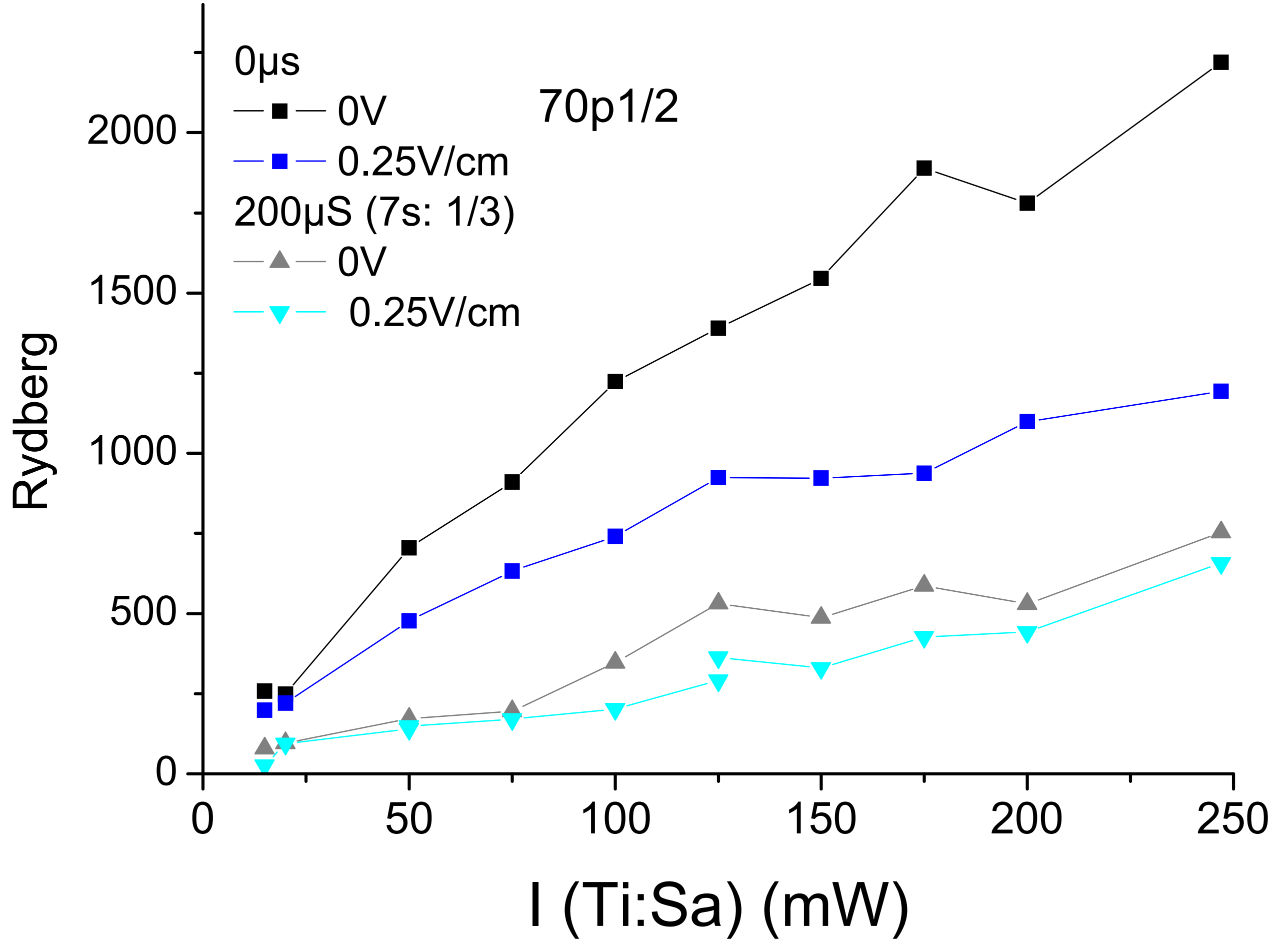
- ***n* < 42:** 2 x E(*np*) > E(*ns*) + E((*n*+1)*s*), which corresponds to a weak <u>repulsive force</u> between close Rydberg atoms. The slow ionization is the result of blackbody radiation (ionization, BR assisted collisions)
- ***n* > 42:** 2 x E(*np*) < E(*ns*) + E((*n*+1)*s*), which corresponds to an <u>attractive force</u> leading to Penning ionization, then to the *evolution of an ultracold plasma* (not the subjet) **~ Dipole gas.**

$$Cs(np_{3/2}) + Cs(np_{3/2}) \rightarrow Cs^+ + Cs(n'l') \qquad n' << n$$

New schemes:
Dipole blockade controled by electric field

Dipole-dipole interaction due *p - d mixing*

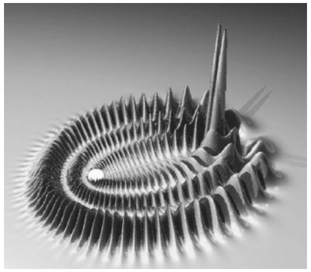
In progress



Conclusion

- Examples of dipole – dipole interaction
- Demonstration of the dipole blockade for Förster resonances

  T. Vogt, M. Viteau, J. Zhao, A. Chotia, D. Comparat and P. Pillet, PRL 97, 083003 (2006)
- Quantum gate: collaboration with the group of Philippe Grangier
- A singly excited collective state
- Rydberg photoassociation (trilobite state)…



- Development of a Stark decelerator for Rydberg atoms or molecules (Nicolas Vanhaecke, Christian Jungen,… LAC)