Interactions between cold Rydberg atoms.

Matthieu Viteau

Thibault Vogt

Nassim Zahzam

Marcel Mudrich

Daniel Comparat

Pierre Pillet

Recherche sur les Atomes Froids

Institut Francilien de

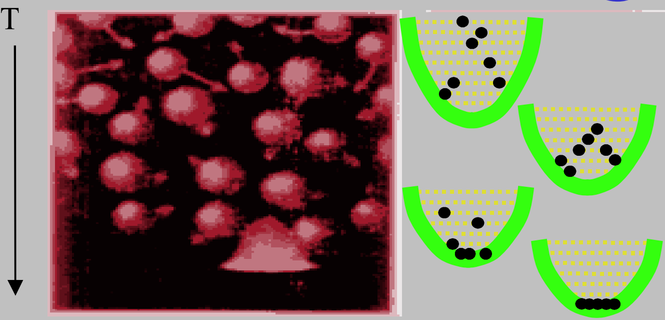
IFRAF

LAC

CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

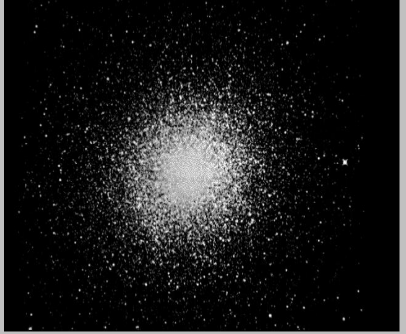
€€€: European Research and Training Network QUACS

Our experiments

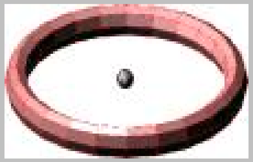


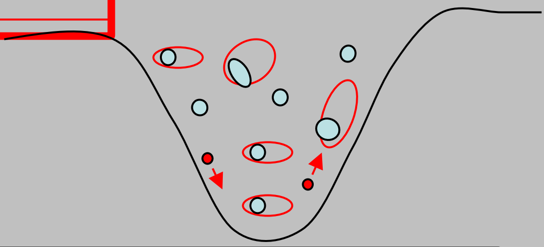
Cs BEC

arxiv

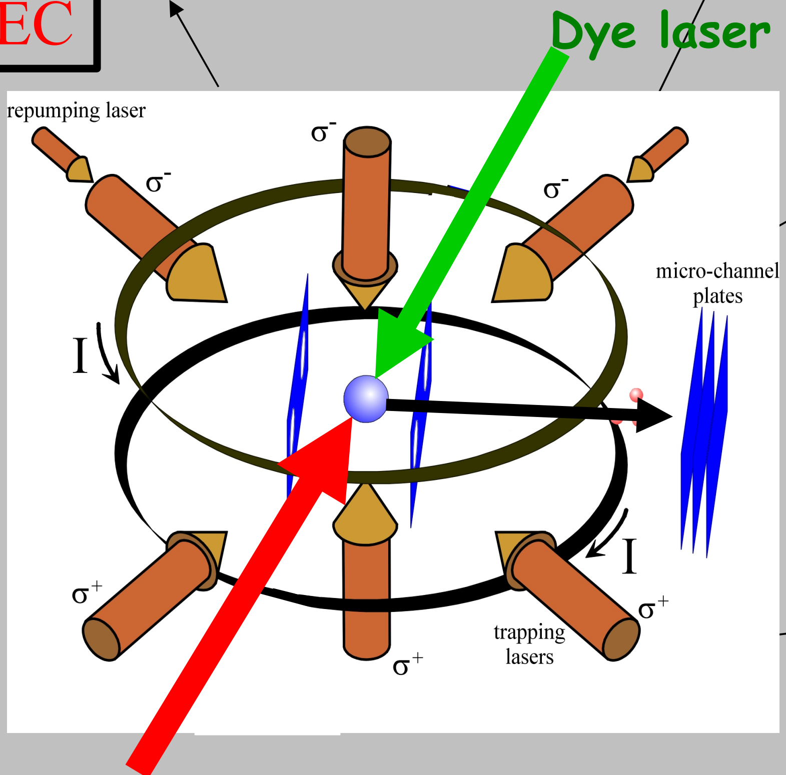


Dipole Blockade with Rydberg Atoms, Quantum information





Ultra-cold Plasma (+Rydberg)



Ti:Sa laser

Cs_2 Molecules (T~μK), Photoassociation (1998)

Magnetic trapping (2002)

laser trapping CO_2 (2005)

New (Rydberg) Stark decelerator

Outline

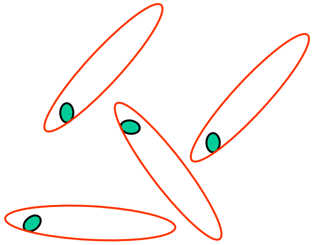
- Motivation
- Stark control of the dipole-dipole interaction
- Coherence dynamics of dipolar Rydberg gas
- Electric control of the dipole blockade
- Conclusion and Outlook

Outline

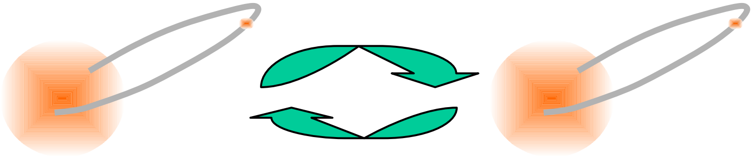
- Motivation
- Stark control of the dipole-dipole interaction
- Coherence dynamics of dipolar Rydberg gas
- Electric control of the dipole blockade
- Conclusion and Outlook

Why Rydberg atoms ?

- Large size: $\propto 2\, n^2\, a_0 \sim 1\ \mu m\ (n=100)$



- Large dipole moments: $\propto n^2\, ea_0 \sim 10000\ D\ (H_2O - 2.6\ D)$



- Long lifetime: $\propto n^3 \sim 1\ ms$

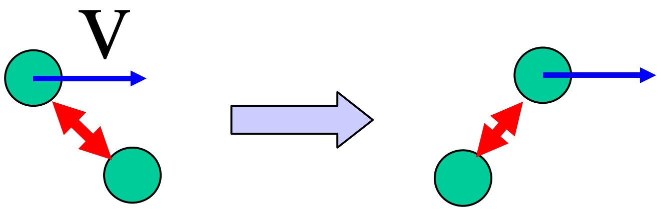
- Easy to ionize $E_{ion} \propto n^{-4} \sim 10\ V/cm$

Rydberg atoms: "Semi-classical atoms"

Why COLD Rydberg atoms ?

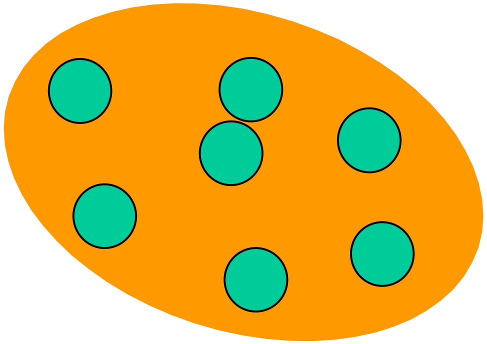
- High temperature: Binary collisions

  $t_{coll} \ll t_{life}$; $E_{mean\ interaction} \ll E_{kin}$



- Low temperature: Many-body interaction

  $t_{coll} \gg t_{life}$; $E_{mean\ interaction} \geq E_{kin}$

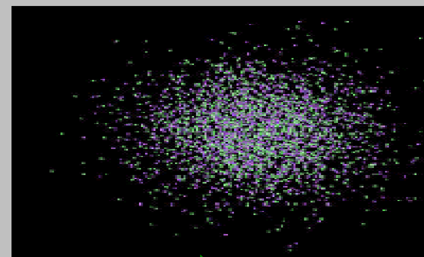


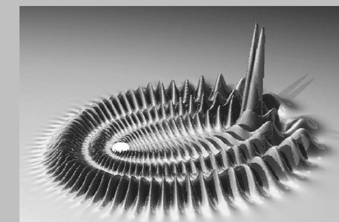
2 ms >> 10 µs;   up to 100 MHz ≥ 2 MHz

Cold Rydberg sample: Intermediate state between atoms, solid, plasma

Rydberg atoms – Interest and applications

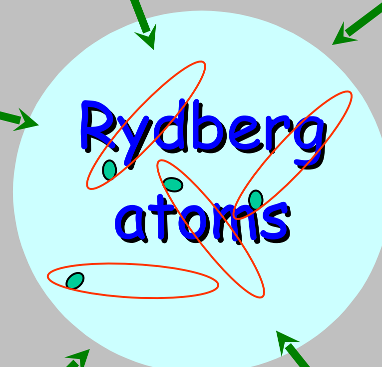
Phase transitions
Rydberg ↔ plasma



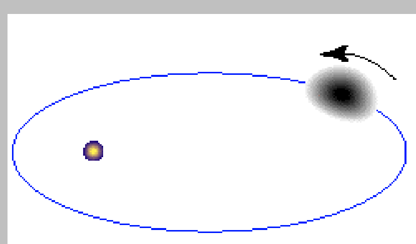


Exotic states of matter
Rydberg molecules

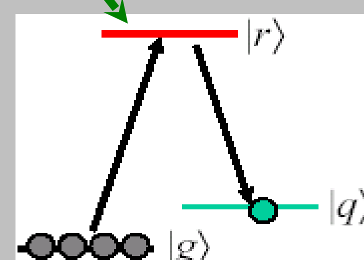
Astrophysics



Cavity QED



Quantum chaos
Wave-packet dynamics



Quantum information
processing

Quantum Information: dipole blockade

Phase gate for atoms

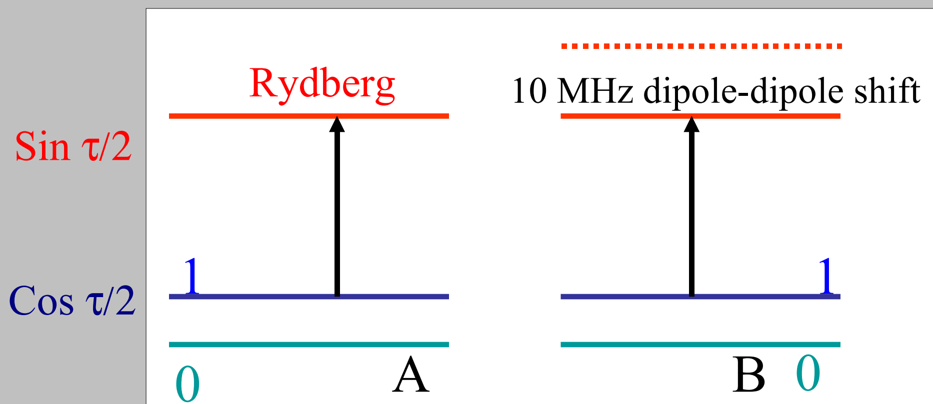
Jaksch et al. PRL 85 2208

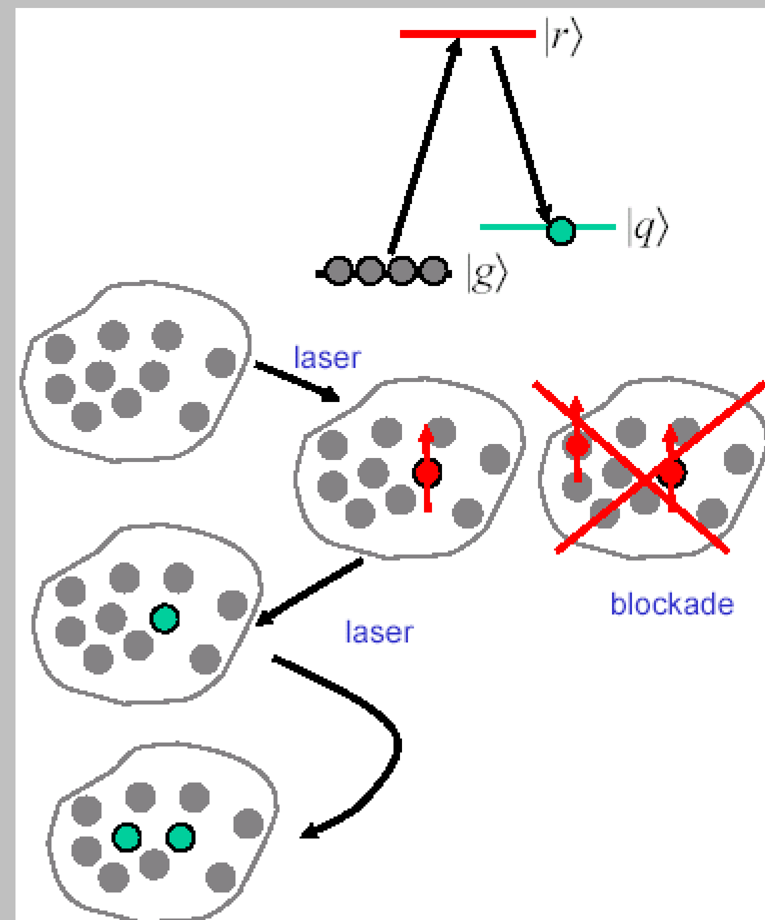
... mesoscopic ensemble of atoms

Lukin et al. PRL 87 037901

No double excitation = dipole blockade

No Force





Phase Gate

$|0\rangle\otimes|0\rangle \rightarrow +|0\rangle\otimes|0\rangle$

$|0\rangle\otimes|1\rangle \rightarrow$ ■ $|0\rangle\otimes|1\rangle$

$|1\rangle\otimes|0\rangle \rightarrow$ ■ $|1\rangle\otimes|0\rangle$

$|1\rangle\otimes|1\rangle \rightarrow$ ■ $|1\rangle\otimes|1\rangle$

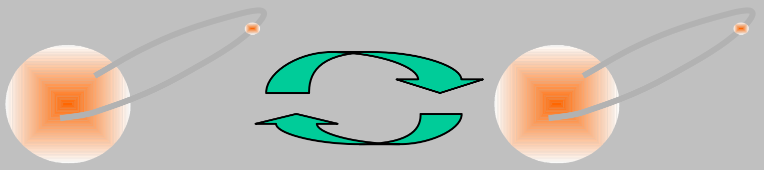
1) π pulse atom A
2) 2π pulse atom B
3) π pulse atom A

Outline

- Motivation
- Stark control of the dipole-dipole interaction
- Coherence dynamics of dipolar Rydberg gas
- Electric control of the dipole blockade
- Conclusion and Outlook

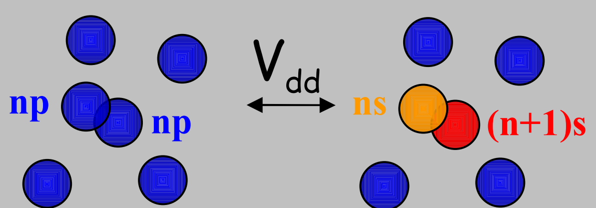
Resonant energy transfer

$$V_{dd} \approx \frac{\mu_{np-ns}\ \mu_{np-(n+1)s}}{R^3}$$



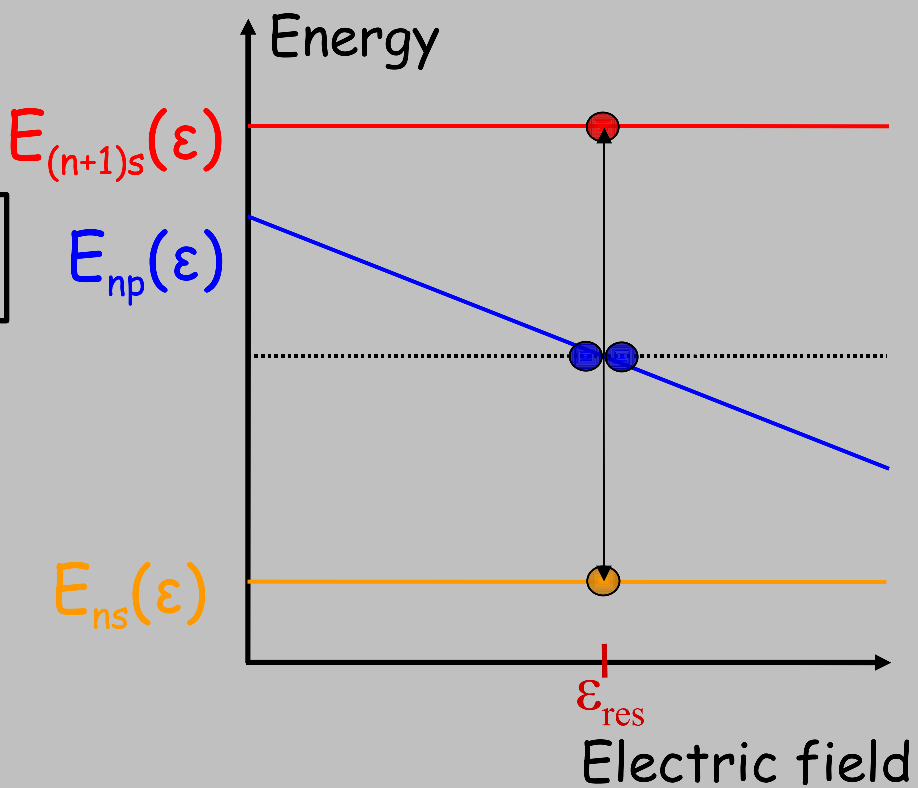
Resonance for $\varepsilon = \varepsilon_{res}$:

$$2\,E_{np}(\varepsilon_{res}) = E_{ns}(\varepsilon_{res}) + E_{(n+1)s}(\varepsilon_{res})$$



np + np ↔ ns + (n+1)s

Stark diagram:

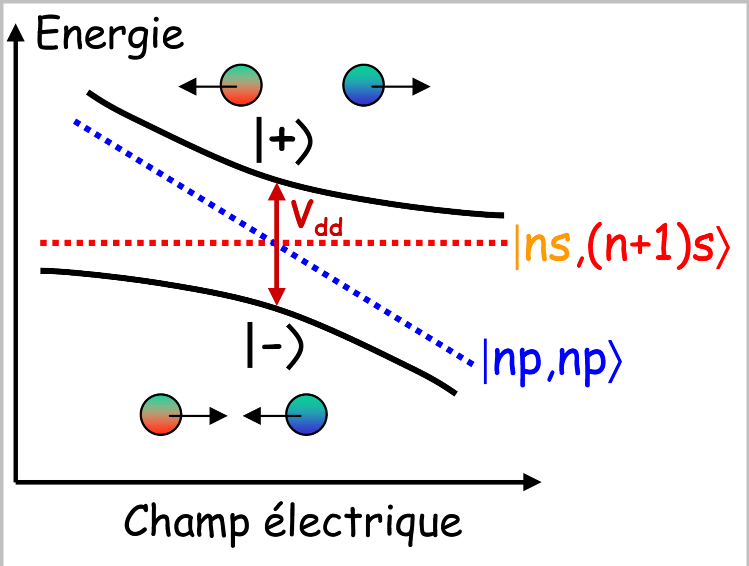


Dipole interactions for a quantum computer ?

Coherent superposition

$$|+\rangle \propto |np,np\rangle + |ns,(n+1)s\rangle$$

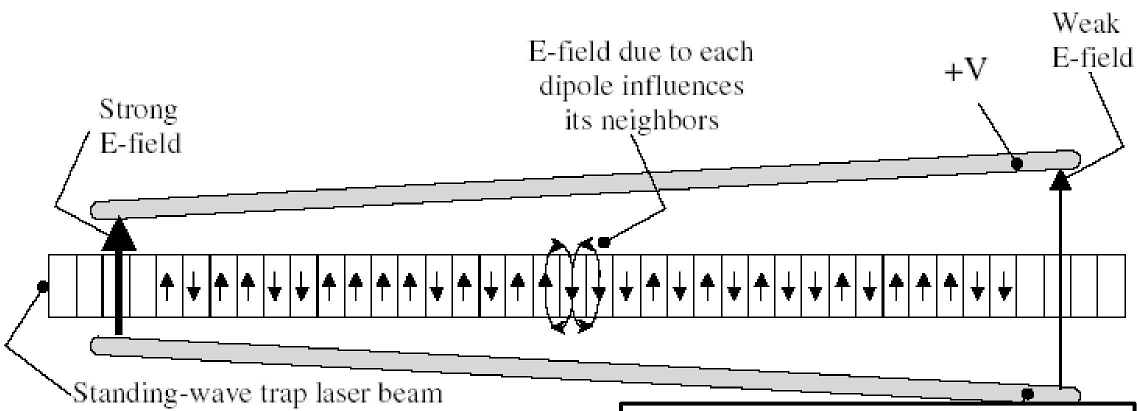
$$|-\rangle \propto |np,np\rangle - |ns,(n+1)s\rangle$$



Resonant dipole-dipole interaction

→ *Strong, ~C_3/R^3*

→ ***Tunable with electric field***

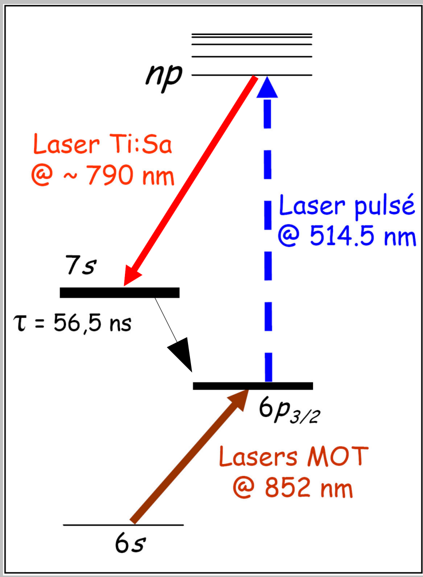


D. DeMille, PRL 88, 067901

Outline

- Motivation
- Stark control of the dipole-dipole interaction
- Coherence dynamics of dipolar Rydberg gas
  - Phys. Rev. Lett. **95**, 233002 (2005)
- Electric control of the dipole blockade
- Conclusion and Outlook

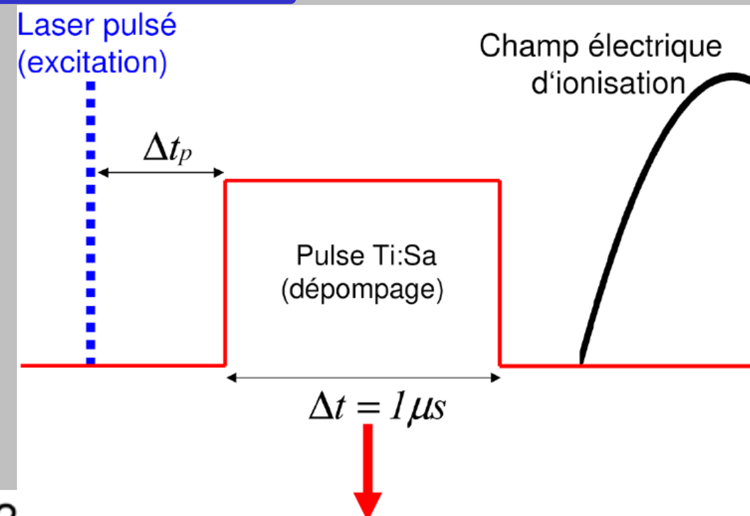
Depumping (high resolution) spectroscopy

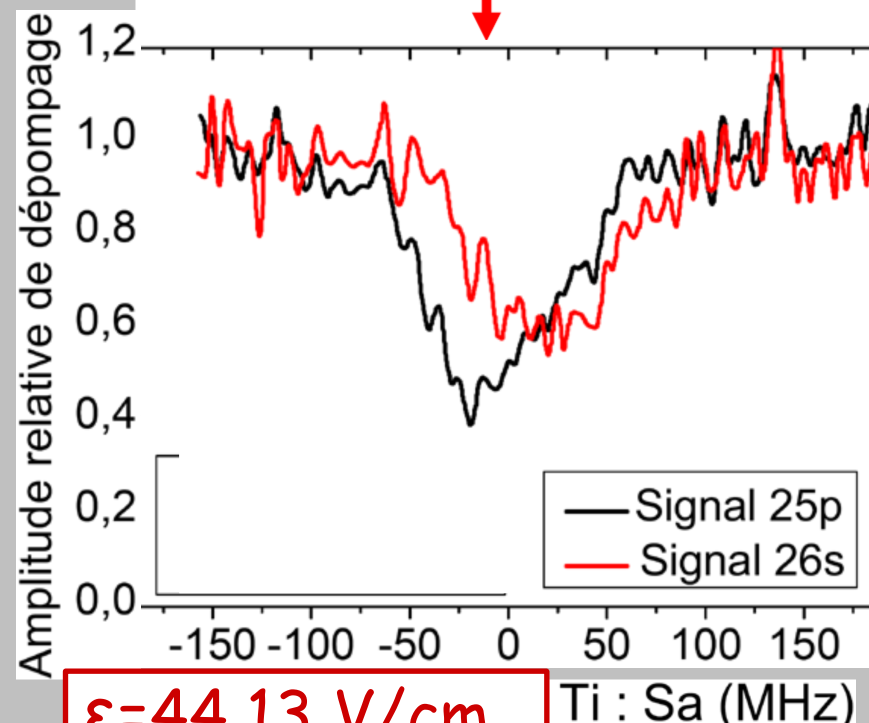


25p + 25p ↔ 26s + 25s

with ε_{res} = 44,03 V/cm

Depumping of p states only





ε=44,13 V/cm

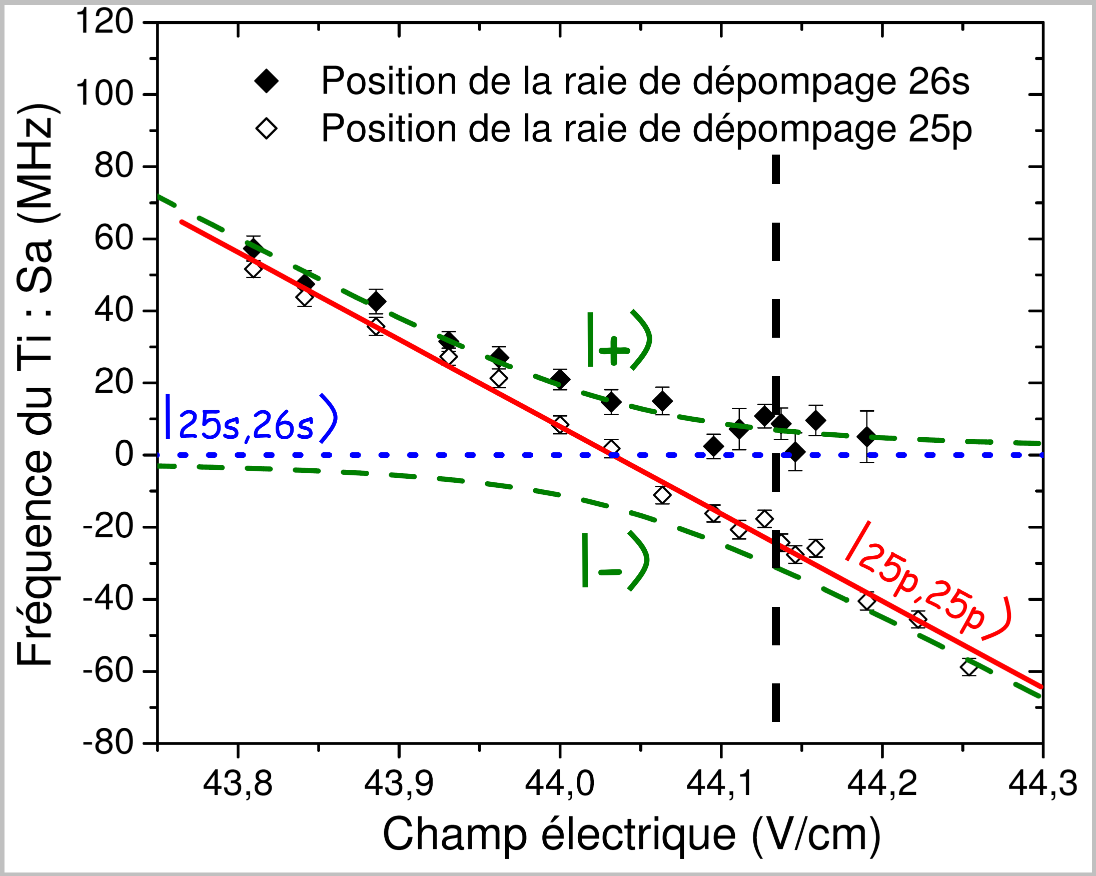
But Rydberg s signal decrease !

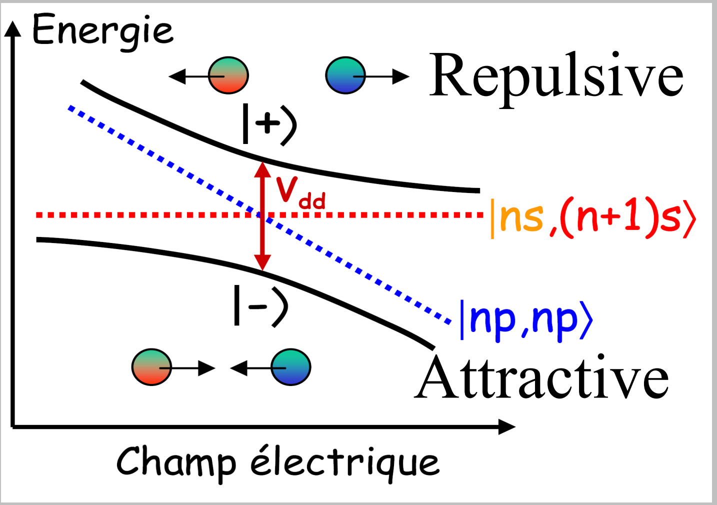
''Coherent'' oscillation between s and p

$|\psi\rangle \propto |25p,25p\rangle \pm |25s,26s\rangle$

s signal shifted from p signal ?

Coherence destroyed by attractive forces !





- No s decrease for |->
  ⇒ collisions
  ⇒ state changing (ions)
- Coherence for |+>

How long ?

- $V_{dd\ (measure)}$ ~15 MHz >> V_{th} ~ 0,5 MHz ⇒ N Body effects

Dipole-Dipole Excitation and Ionization in an Ultracold Gas of Rydberg Atoms — Wenhui Li et al., Phys. Rev. Lett. 94, 173001 (2005)
Colliding atomic pair distribution in an ultralong-range Rydberg potential — L. G. Marcassa et al., Phys. Rev. A 71, 054701 (2005)

Decoherence due to many body effects (migration)

- Resonant energy transfert :

$$p + p \rightarrow s + s' \quad (T)$$

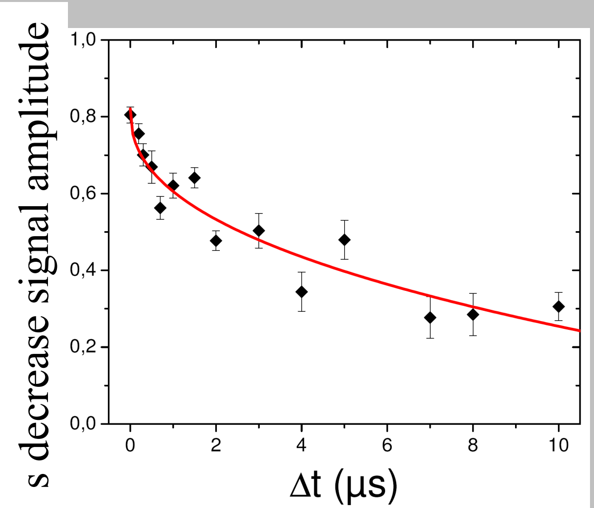
- Excitation migration :

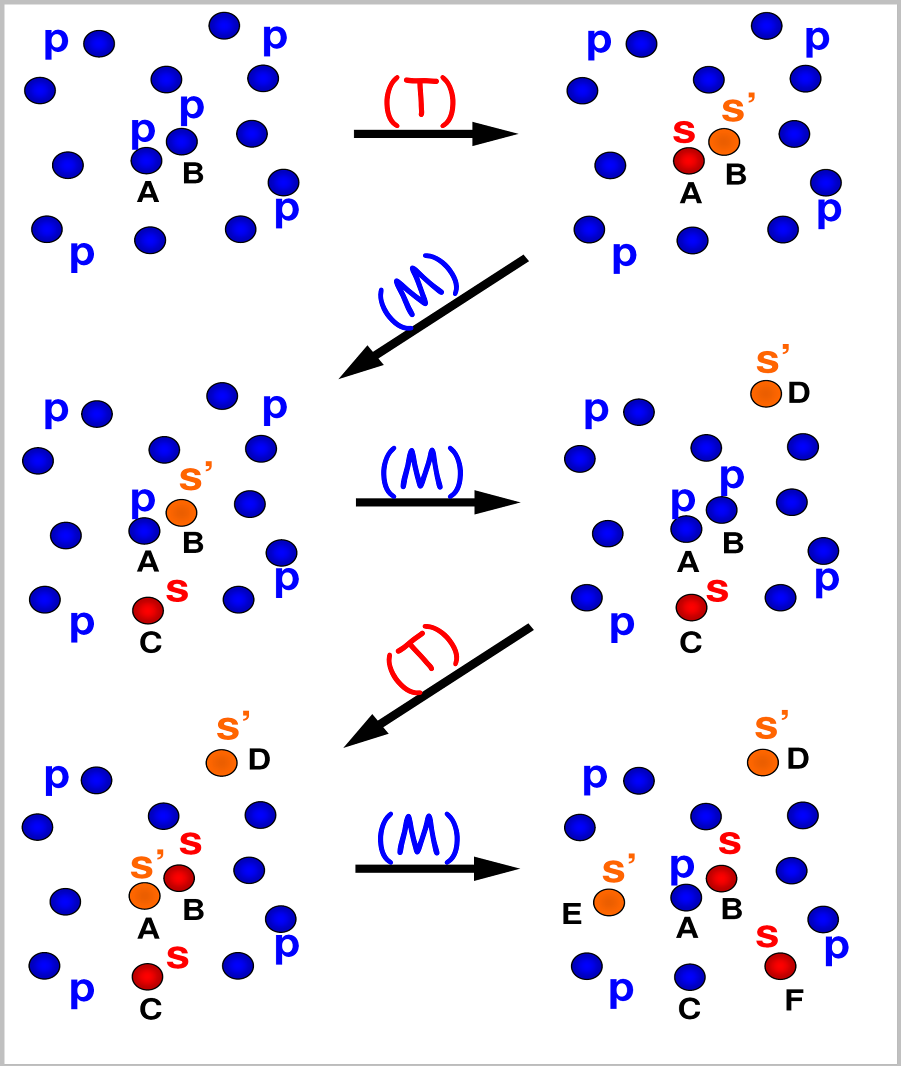
Always resonant

$$p + s \rightarrow s + p$$
$$p + s' \rightarrow s + p \quad (M)$$

⇒ Reaction product migrates

⇒ Decoherence in ~1 μs





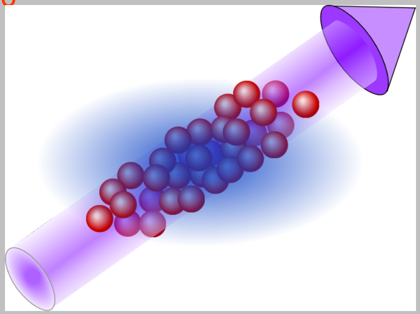
Outline

- Motivation
- Stark control of the dipole-dipole interaction
- Coherence dynamics of dipolar Rydberg gas
- Dipole blockade
- Conclusion and Outlook

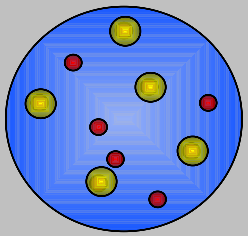
Dipole blockade – Saturation of excitation

Van-der-Waals

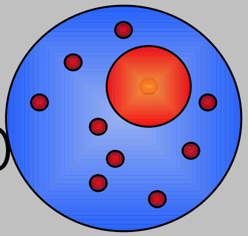
C_6/R^6 blockade



Weak interactions/low *n*

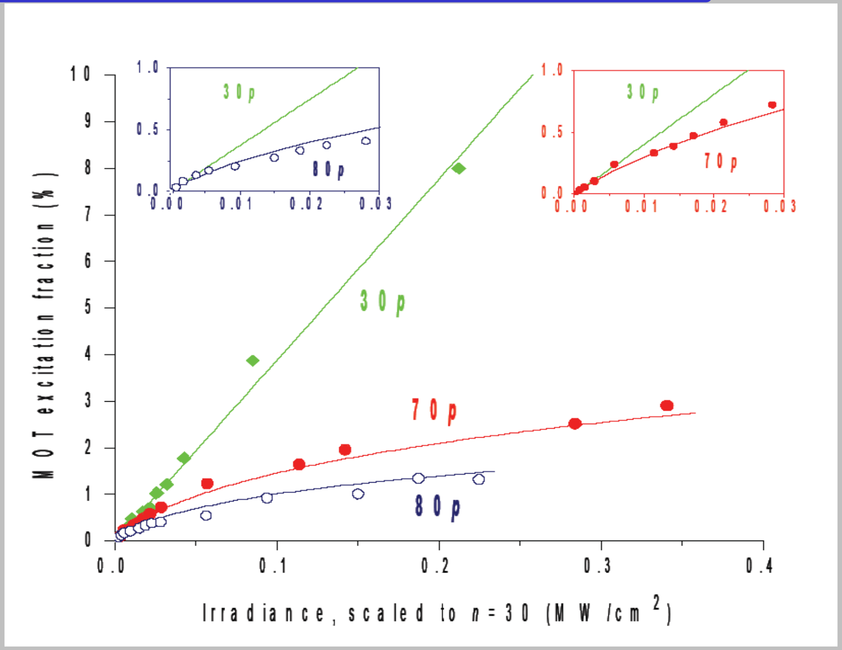


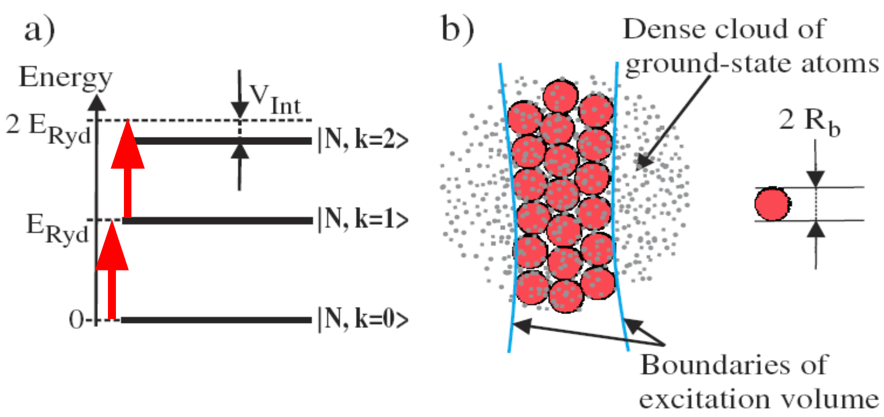
Strong interactions/high *n*

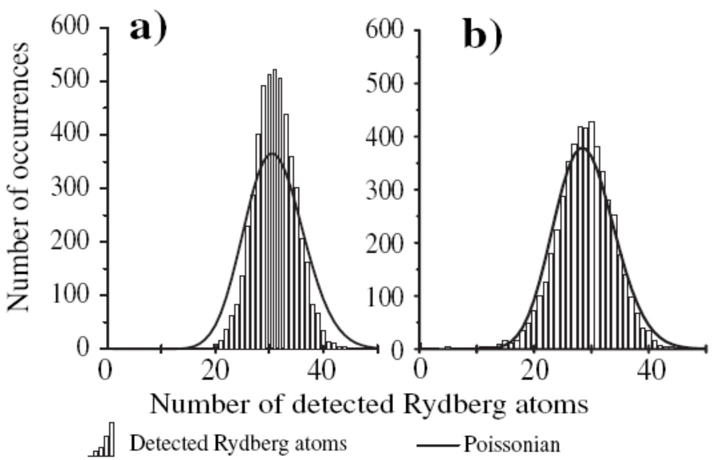


Tong, et al. PRL**93**, 063001 (2004)

Fourier transform 7ns UV pulse



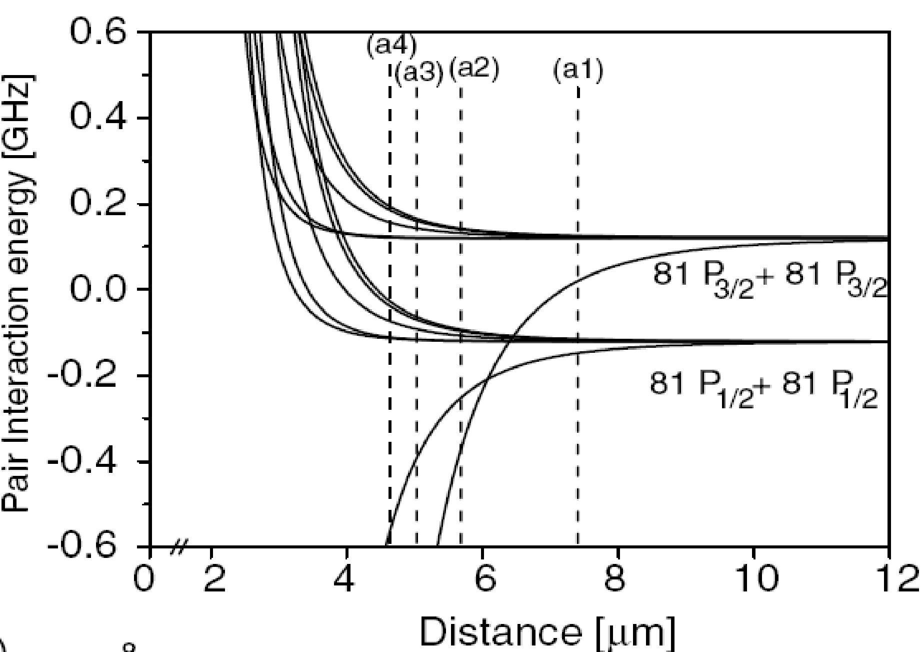


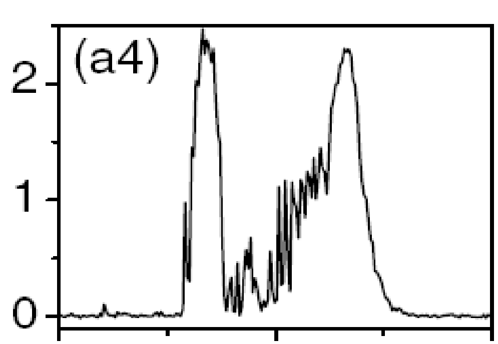


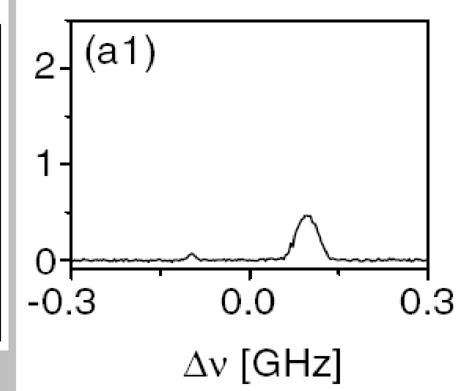
Sub Poissonian Statistics T. Cubel Liebisch et al., Phys. Rev. Lett. 95, 253002 (2005)

(5*S* -> 5*P*, 780 nm) + (5*P* -> *nD*, 480 nm) 100 ns CW

Dipole blockade – Spectral broadening



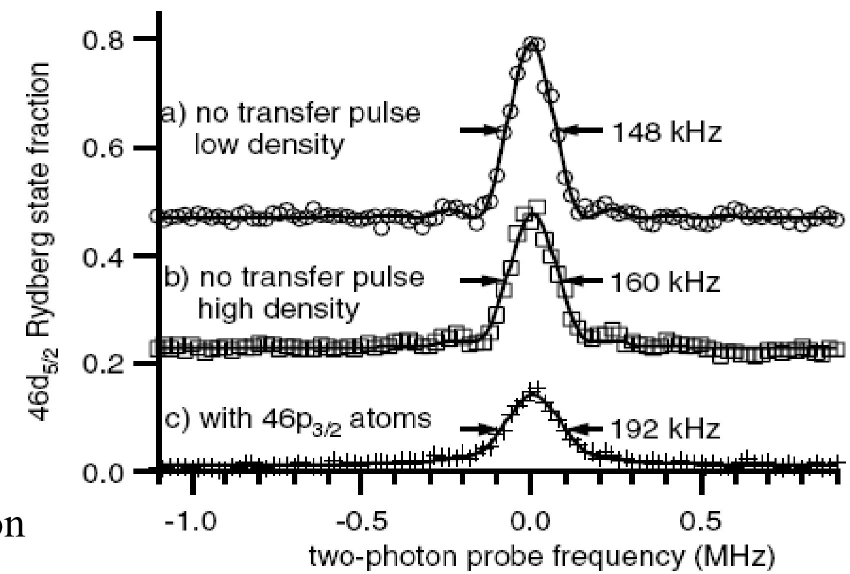




Van-der-Waals ?

Kilian Singer et al., Phys. Rev. Lett. 93, 163001 (2004)

(*5P -> nD*, 480 nm) 10 µs CW



Resonant Electric Dipole-Dipole Interactions

K. Afrousheh et al., PRL 93, 233001 (2004)

(*5P -> 45D*, 480 nm) pulsed laser

(45D -> *46P*, µ-wave) creat the dipole dipole

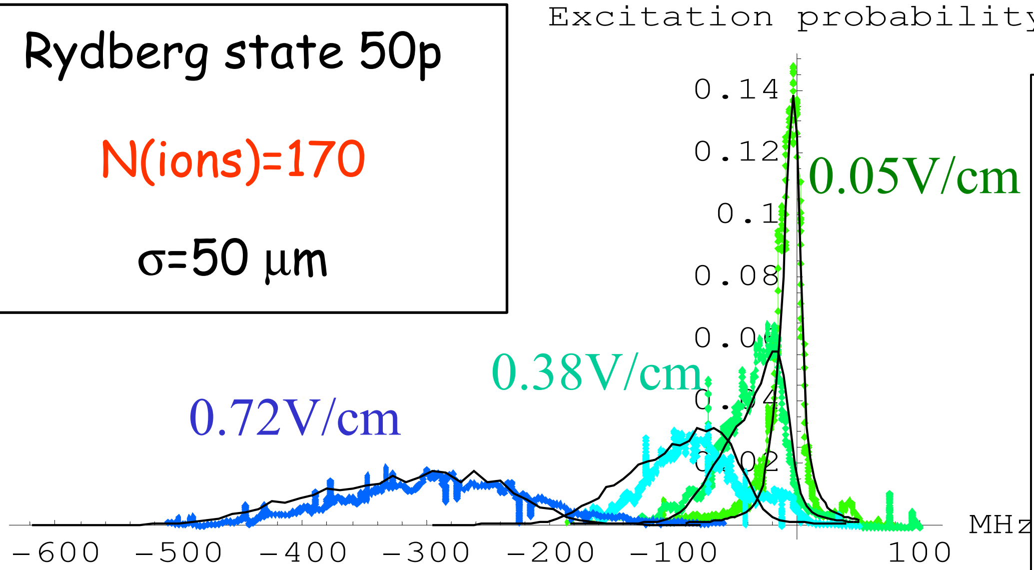
(45D -> -> *46D*, µ-wave) probe the 45D population

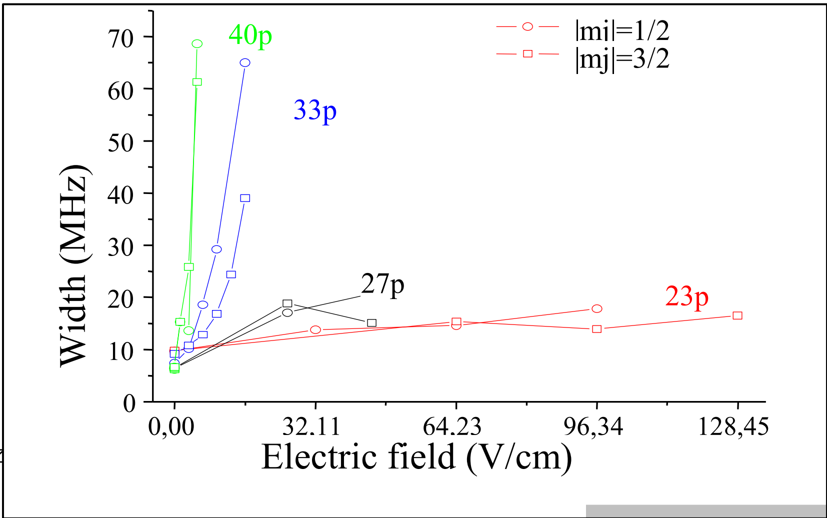
Watch the ions !!!!

Rydberg state 50p

N(ions)=170

σ=50 μm





Very few ions can broaden the transition and match a ''blockade'' effect !!

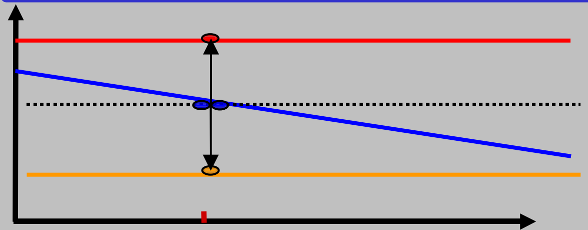
→Narrow-band spectroscopy is very sensitive to ions !

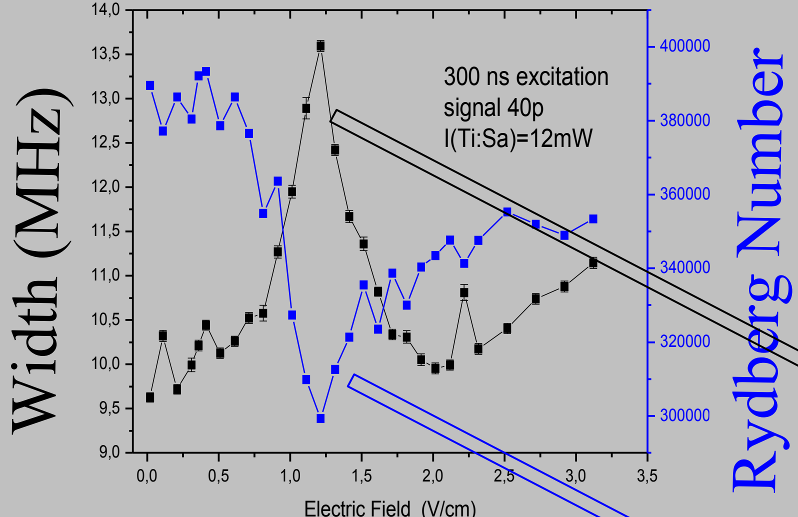
→Rydbergs as probe for weak fields

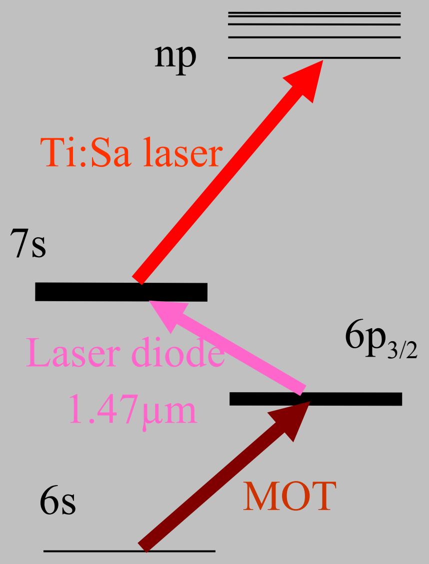
Outline

- Motivation
- Stark control of the dipole-dipole interaction
- Coherence dynamics of dipolar Rydberg gas
- Electric control of the dipole blockade
- Conclusion and Outlook

Electric control of Dipole blockade

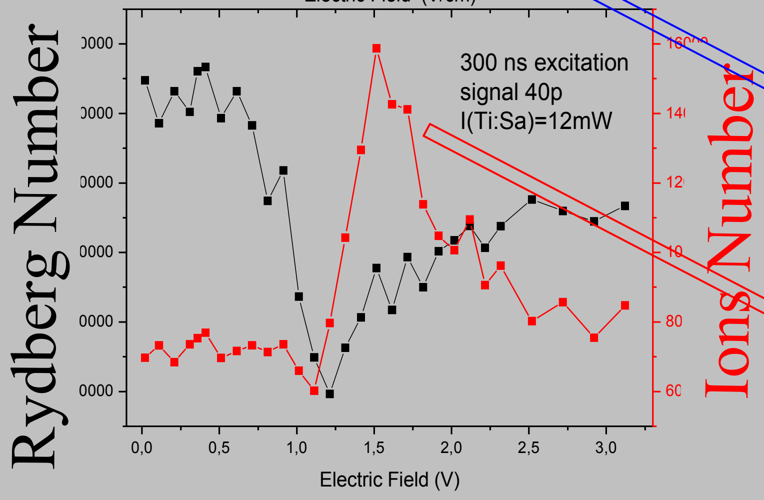






CW scheme

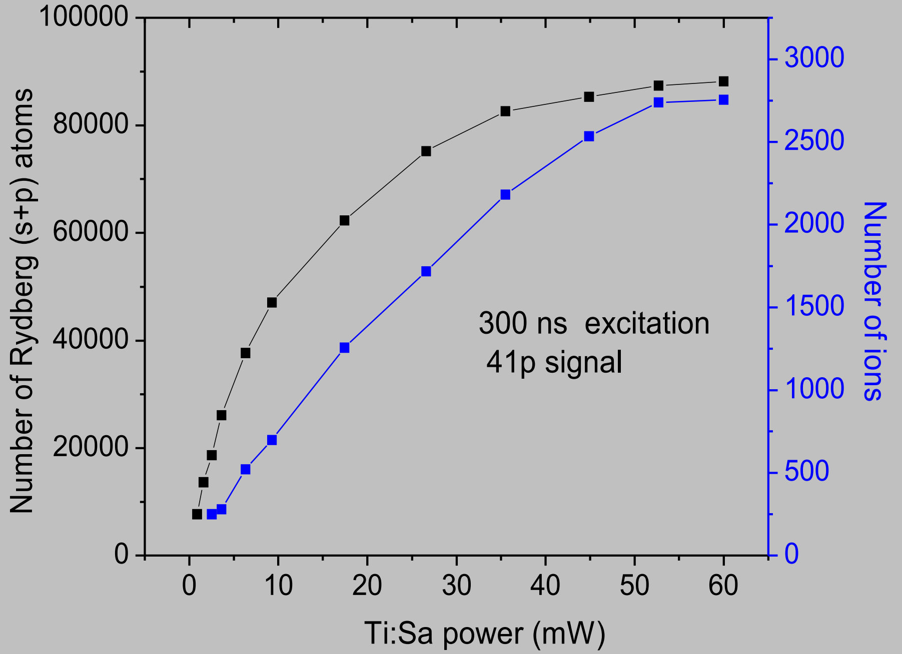
Broadening of the line at resonance

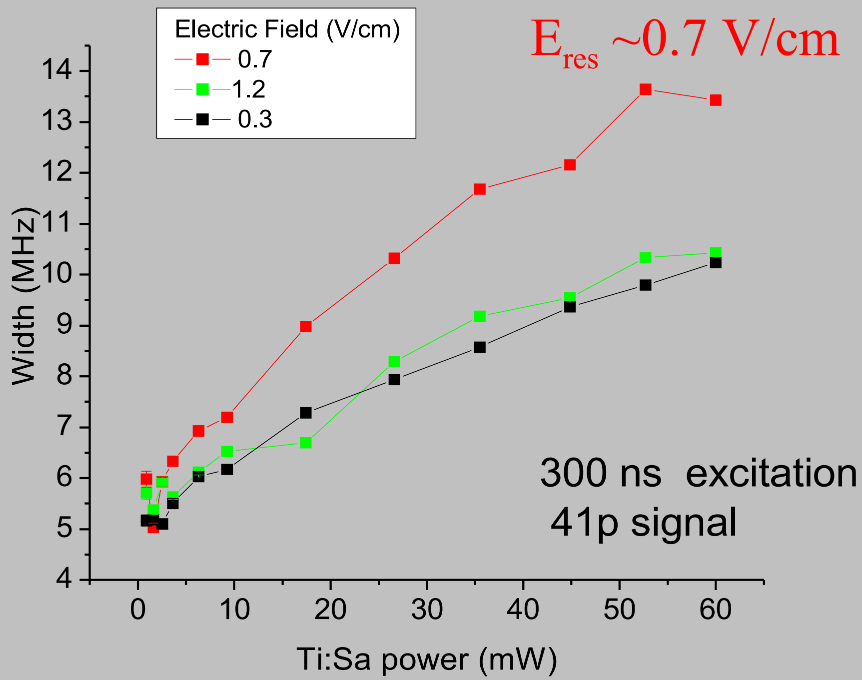


Saturation of the Rydberg number

No effect of the ions !!!

Power control of dipole blockade

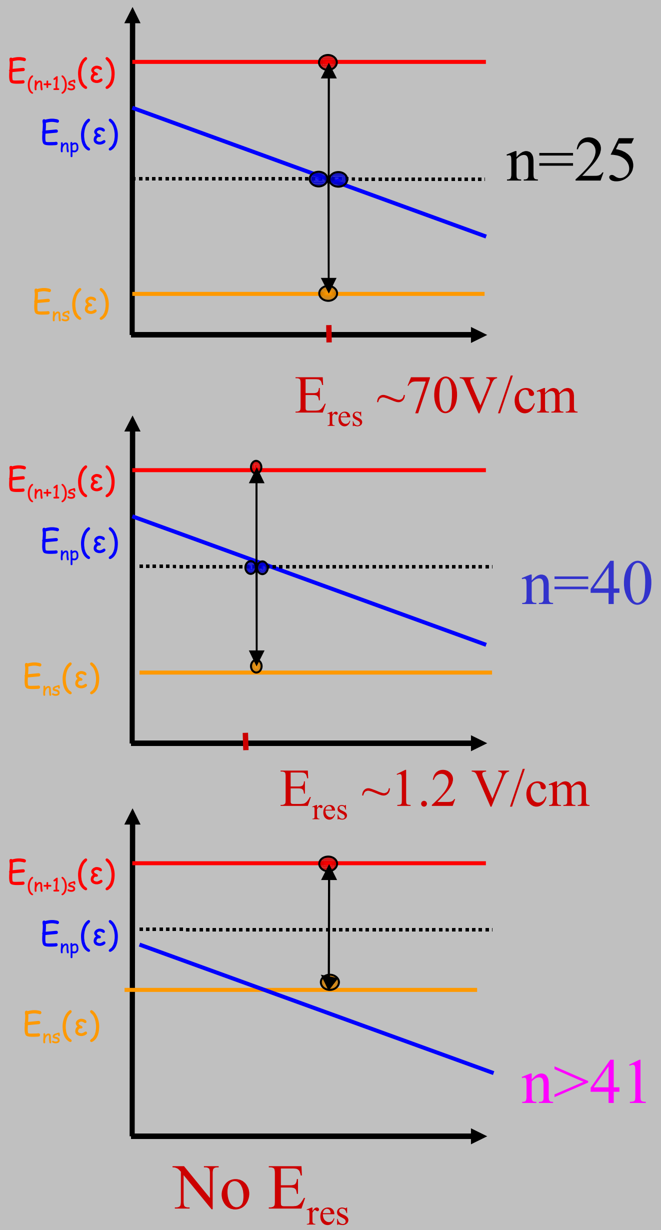


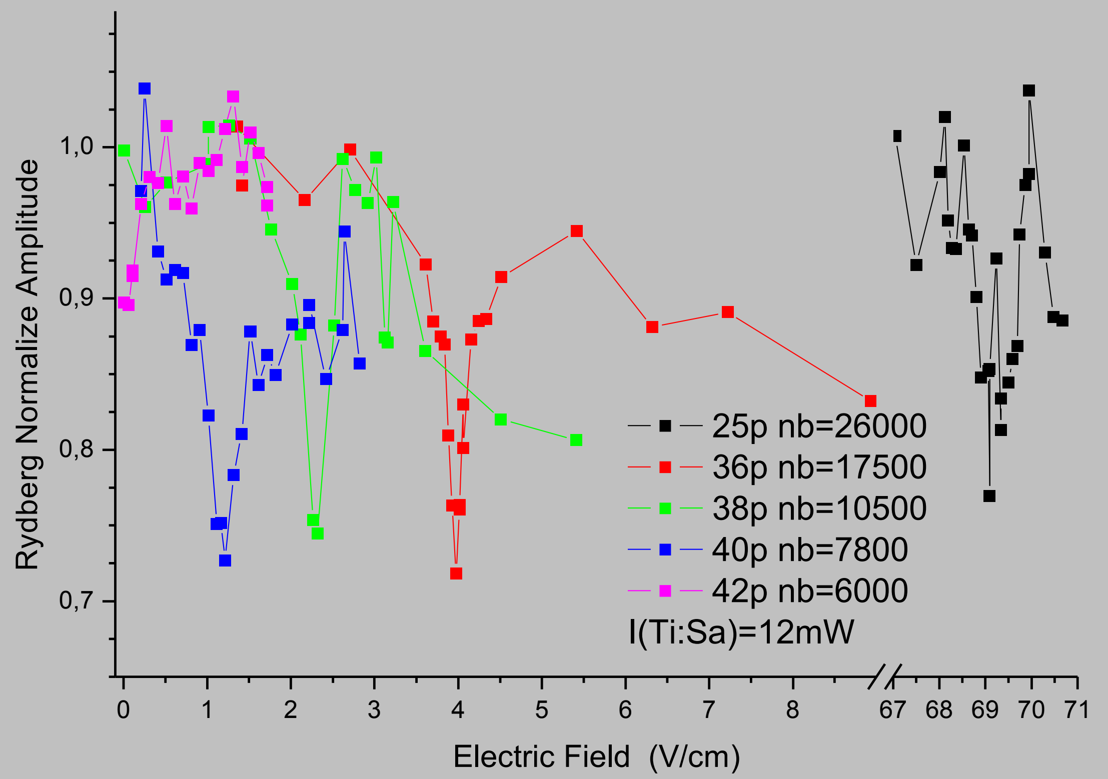


E_{res} ~0.7 V/cm

Saturation and broadening of Rydberg number at resonance

High resolution CW spectroscopy





At zero field, $F = 0 : \langle np | \mu | np \rangle = 0$

For $F \neq 0 : \langle np, F | \mu | np, F \rangle \neq 0$

$$| np, F \rangle \approx \alpha(F) | np \rangle + \beta(F) | (n-1)d \rangle$$

Outline

- Motivation
- Stark control of the dipole-dipole interaction
- Coherence dynamics of dipolar Rydberg gas
- Electric control of the dipole blockade
- Conclusion and Outlook

Conclusion

- Coherence study for ultracold Rydberg sample

- Dipolar force play a major role: Frozen Rydberg gas VS dipole gas
  - Coherence << 1 μs for (attractive) |-> state
  - Coherence for ~ 1 μs for |+> state
  - Decoherence due to migration

- Watch out for ions when doing Rydberg spectroscopy !

- Evidence for Resonant Dipole blockade (C_3/R^3)
  - Broadening and blockade controlled by electric field

Futur

- Quantum gate with only 2 atoms ?

High resolution CW spectroscopy