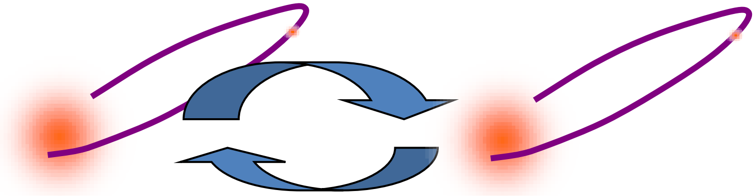


Applications of Cold Rydberg atoms

From cold Rydberg atoms to ultra-cold plasmas

Daniel.Comparat@lac.u-psud.fr

ICQIO’2010
Kyiv
1 June 2010

Experiments in « Cold atoms, Rydberg and molecules group »

- Cesium Magneto-Optical Trap (D. Comparat, H. Lignier)
  - Cold cesium molecules (formation, vibrational cooling, trapping, ..)
  - Cold Rydberg atoms (dipole blockade, ….)
  - Cold plasma (ionic and electronic temperature, dynamics, …..)
- Stark & Zeeman decelerators (N. Vanhaecke)
  - Zeeman decelerator for atoms and molecules
  - Stark decelerator for Rydberg atoms and molecules
- Production of ion and electron sources from cold atoms

  (A. Fioretti, D. Comparat)
- Project: Ytterbium MOT: (D. Comparat, P Cheinet)

  YbCs molecules + two-electrons Rydberg

Thibault Vogt
Matthieu Viteau
Amodsen Chotia

Leila Kime
Joshua Gurian
Andréa Fioretti

Patrick Cheinet
Daniel Comparat
Nicolas Vanhaecke
Pierre Pillet

Collaboration on Rydbergs with:
Anti hydrogen experiments: (AEGIS)
Thomas F. Gallagher, University of Virginia
Ducan Tate, Colby College
Jia Suotang, Shanxi University, China
Philippe Grangier, Antoine Browaeys et al., Institut d'Optique

Talk
Yevhen Miroshnychenko
18:00 Mo31D(A)b3

Outline

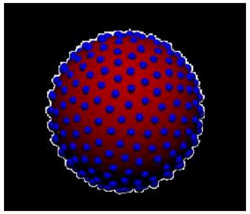
- Historical motivations (why cold Rydberg atoms ?)
- Quantum control with Dipole blockade: exp +model
- Ultra-cold plasmas: model, realization, application
- Prospects and conclusion

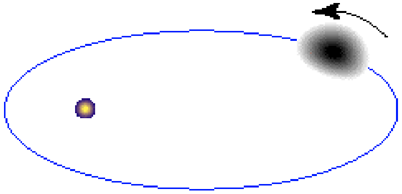
Cold Rydberg atoms at the crossing of atomic, molecular, solid state and plasma physics …

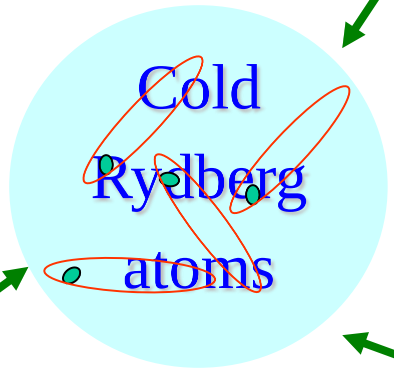
size ~ $2 n^2 a_0 \sim 1\ \mu m\ (n=100)$
dipole $\mu \sim n^2 e a_0 \sim 10000$ D
Lifetime $\propto n^3 \sim 1$ ms
$E_{ion} \propto n^{-4} \sim 10$ V/cm

Dipole-dipole interactions:
Dipolar gas
- migration of the excitation,
-spin glass
- cold collisions:
Penning ionization
- **dipole blockade**
…

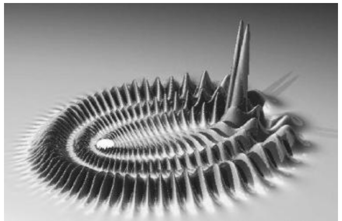
Transition
Rydberg ↔ plasma



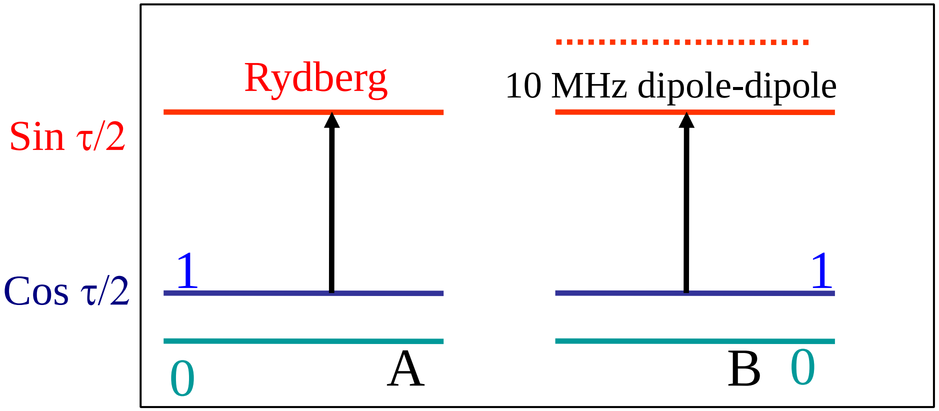




Rydberg
photoassociation



Dipole-dipole $\propto \mu\mu'/R^3$



Cold Rydberg gaz (*exp* + th): Review QOIT (Today) JOSA B

1998 *Dipole-Dipole interaction in a cold sample (Broadening + diffusion ?)*

Pillet (PRL 80 253), Gallagher (PRL 80 249)

1999 *Dipolar Forces → Dynamics → Non Frozen Gaz !*

Pillet (PRL 82 1839)

2000 *Rydberg → plasma* *1999 Ultra cold Plasma: photo-ionisation (NIST)* (PRL 83, 4776)

Pillet + Gallagher (PRL 85 4466)

2000-2001 Quantum gate using dipole-dipole shifting « dipole blockade »

Lukin, Fleischhauer, Côté, Jaksch, Cirac, Zoller (PRL 87 037901)

Molecules
(Côté, Greene)

2004 *Van der Waals (2nd order): blockade (saturation of excitation) + spectroscopy (broadening)*

Eyler Gould (PRL 93 063001) + Weidemüller (PRL 93 163001) Martin (PRL 93 23300)

2006 *Dipole blockade (1er order) (saturation of excitation)* + th (Rost, Pohl, Robicheaux …)

Pillet : permanent dipole (PRL 99 073002) + transition dipole (Förster) (PRL 97 083003)

2007 *Coherent collective excitation + spin-echo*

Pfau (PRL 99 163601)

Superradiance (Gould), EIT (Adams),
STIRAP (Raithel, Weidemüller), …

2008 *Rabi oscillation* Weidemüller (NJP 10 045026) + *(1 at)* Saffman,Walker (PRL 100 113003)

3D trapping of Rydberg atoms Merkt (PRL 100 043001)

2009 *Dipole blockade (2 at)* Saffman,Walker + Browaeys, Grangier (Nat. Phys 5, 110-115)

Molecules (2,3 atoms) Pfau (arXiv:0809.2961)

2010 *Intrication* Browaeys, Grangier, *quantum gate* Saffman,Walker (PRL 104 010502-010503)

Quantum simulator, repeater, … Zoller, Büchler, ….

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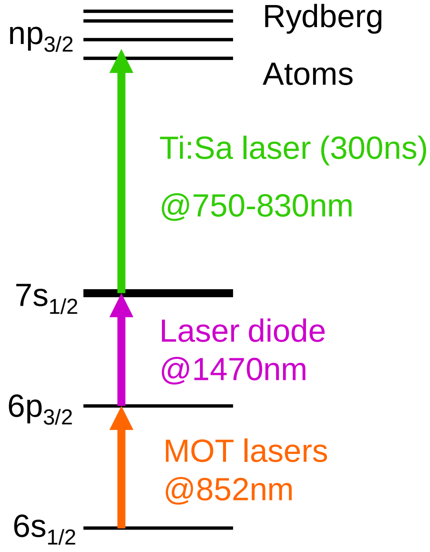
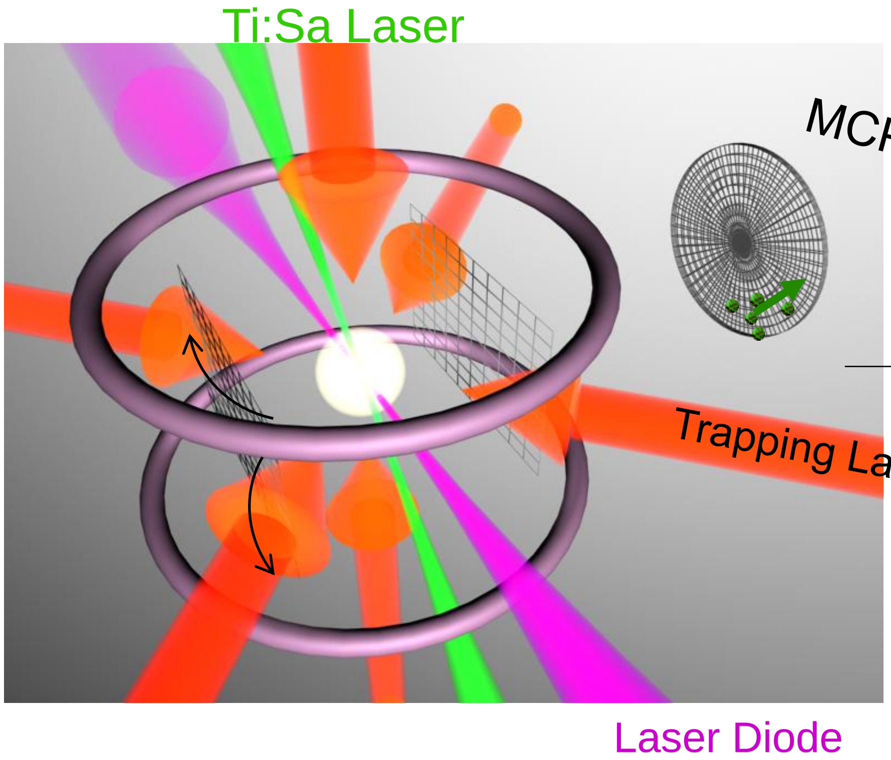
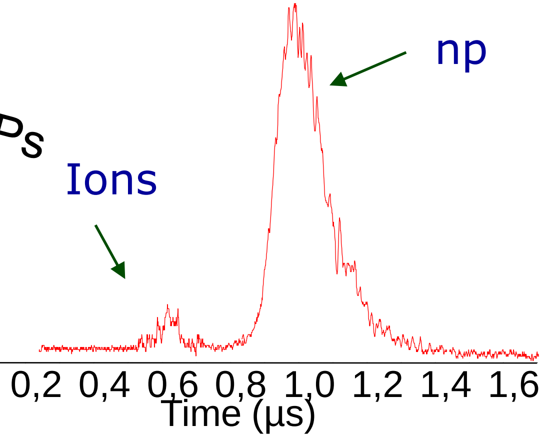
Dipole blockade in a cold atomic sample (Cs MOT)





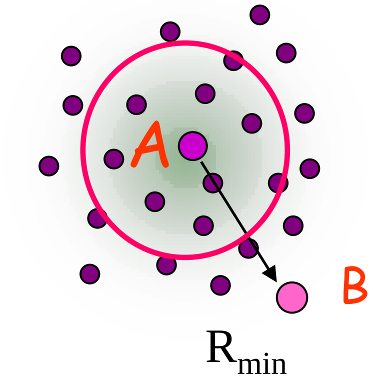


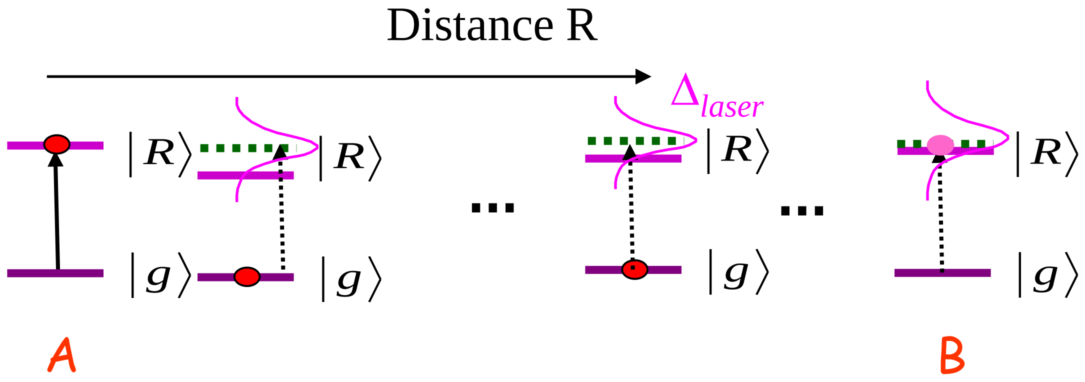
CW laser excitation

→dipole-dipole interaction

→ selective field ionization

Blockade sphere radius: $\hbar\Delta_{\mathbf{laser}} \sim V_{\text{dip-dip}} \propto \boldsymbol{\mu}^2 / \mathbf{R}_{\mathbf{min}}{}^3$

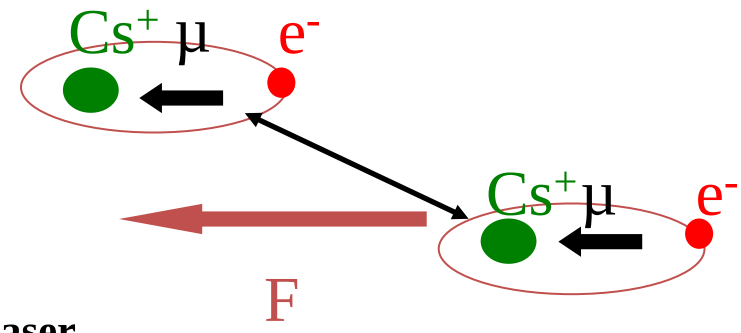




Electric field: control (blockade) of Rydberg excitation

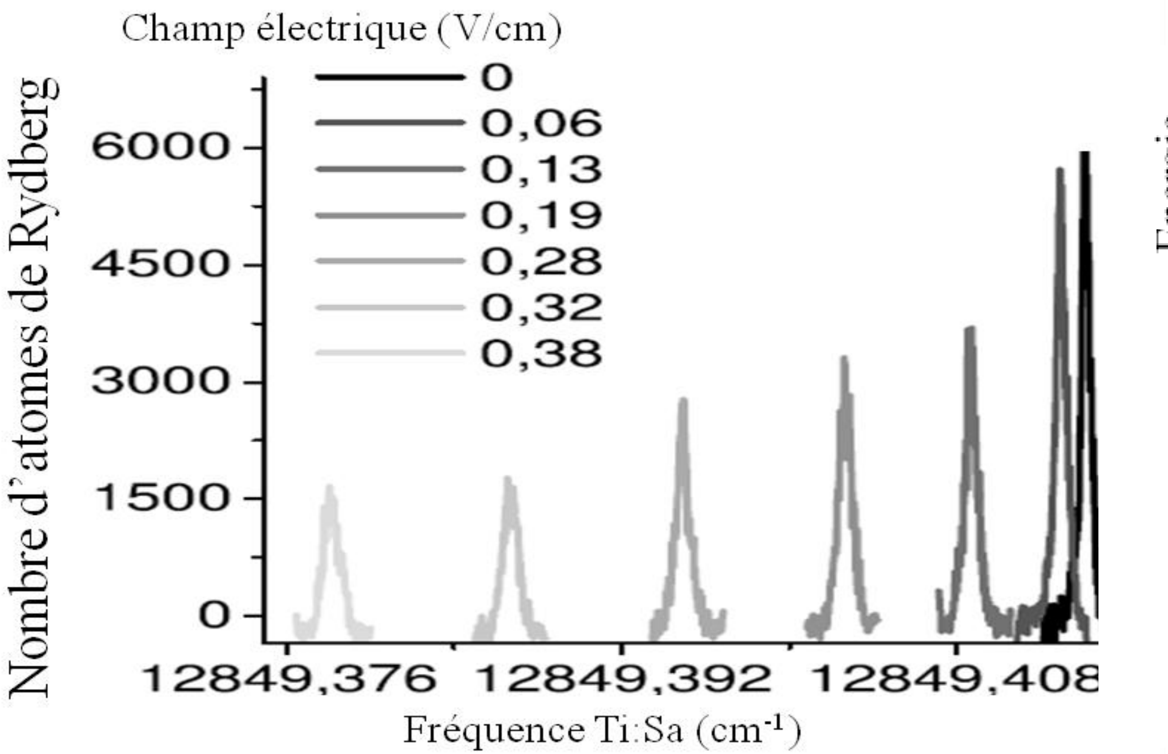
Permanent dipole

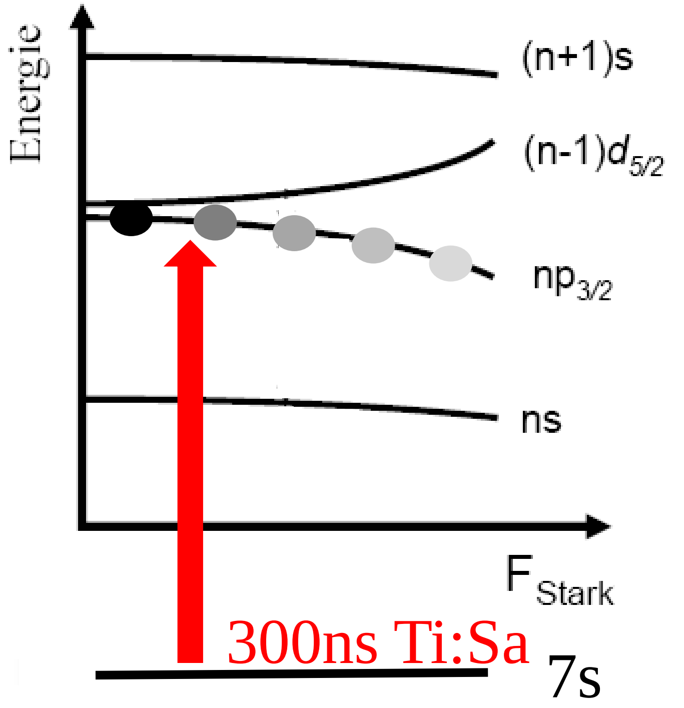
Vogt *et al.* PRL 99 073002 (2007)



$$\mathbf{V_{dd} \propto \mu^2 / R^3 \sim \hbar\Delta_{laser}}$$

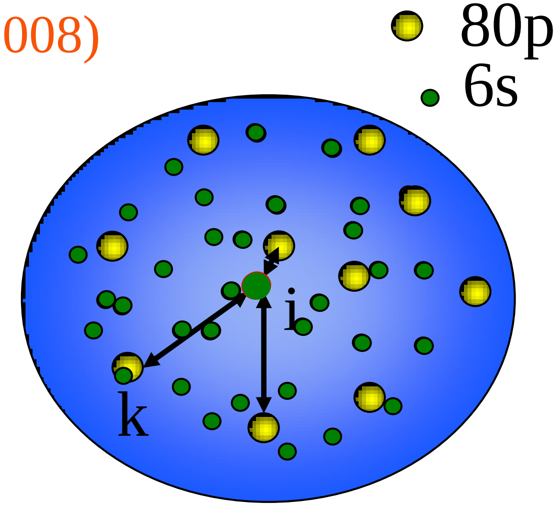
$$\mathbf{n_{Ryd} \propto \Delta_{laser}/\mu^2}$$





Model of dipole blockade

A. Chotia *et al*. NJP 10, 045031 (2008)



Rate excitation → Kinetic Monte Carlo

(Exact and faster than « classical » Monte Carlo)

Interaction between all paires

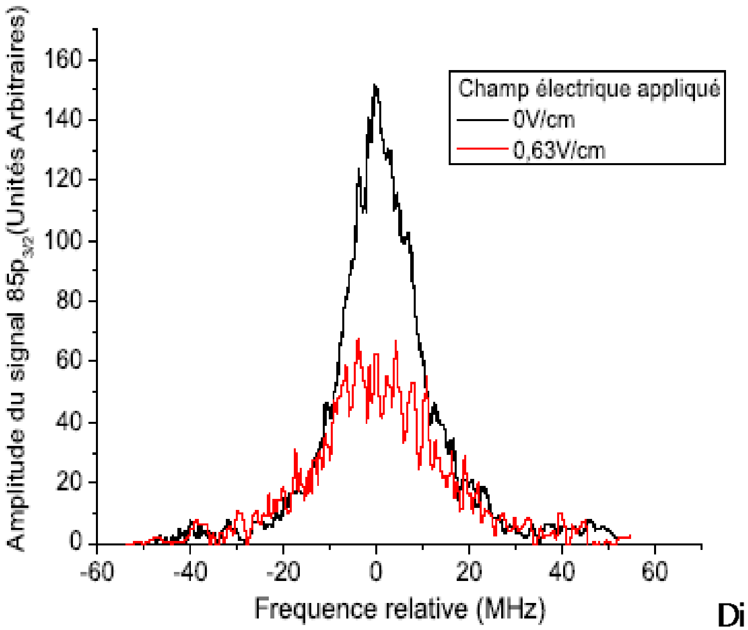
$\delta_i \sim \delta_{Laser} + \Sigma_k\, \mu^2\, (1\text{-}3\ Cos^2\ \theta_{ik})/R_{ik}^3$

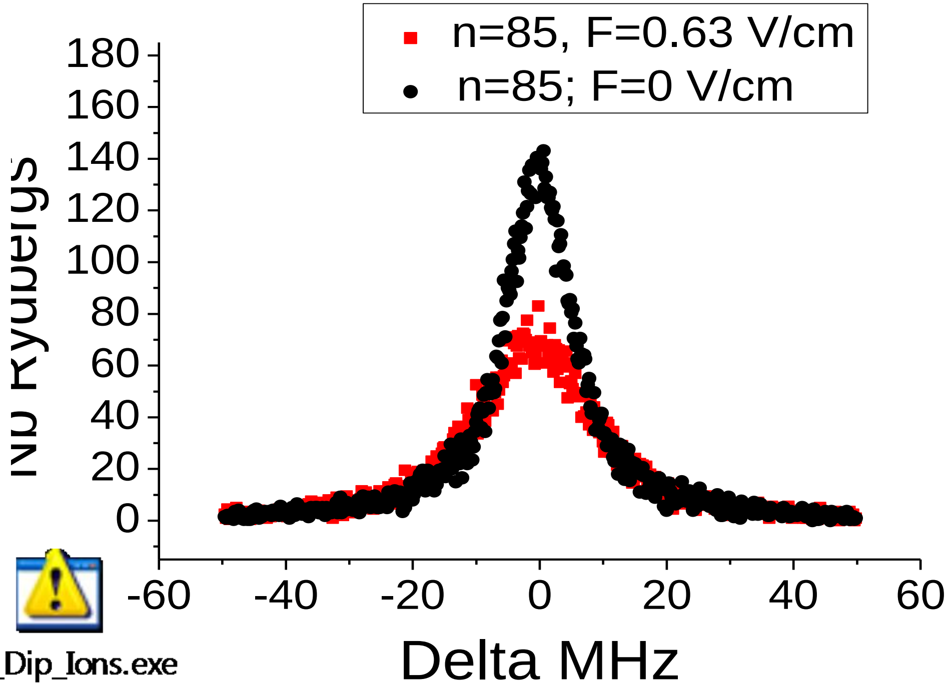
+ N-body:

LeapFrog-Verlet

Nearest neigbourg interaction dominates

Ions can mimic dipole effects: 1 ion = 150mV/cm @ 10 µm ~ 100 X n=50 dipole





Dip_Dip_Ions.exe

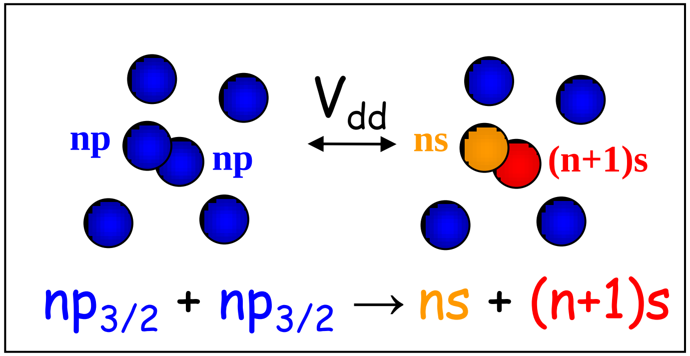
Electric field: control of internal states + blockade

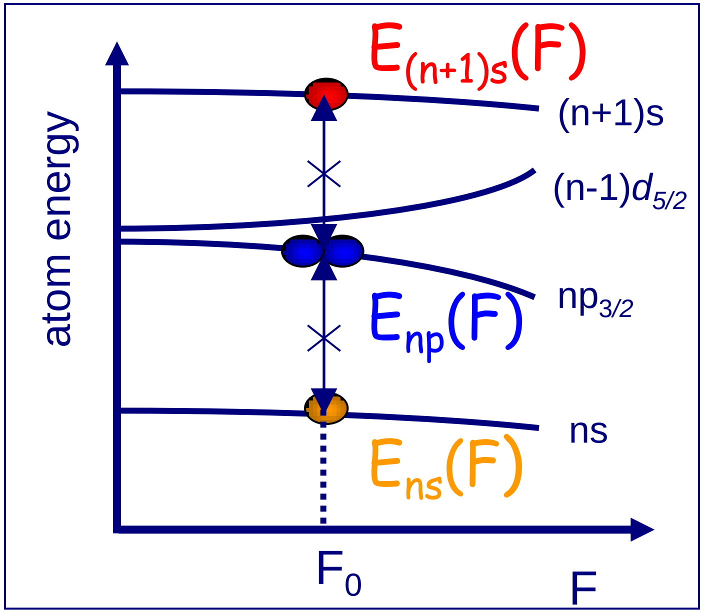
Transition Dipole(Förster, np middle of ns (n+1)s)

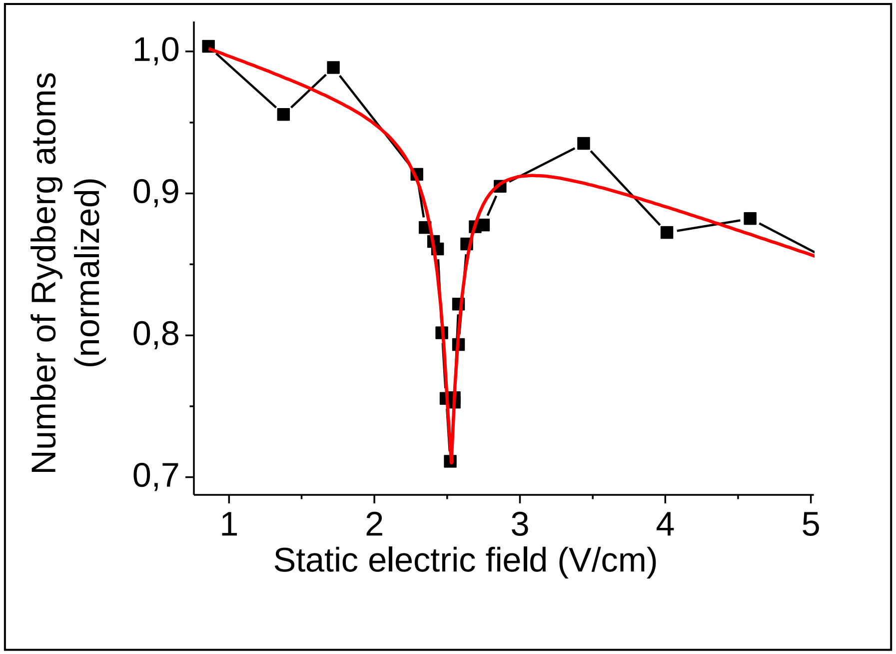
Vogt *et al.* PRL 97 083003 (2006)

FRET (Förster resonance energy transfer)

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





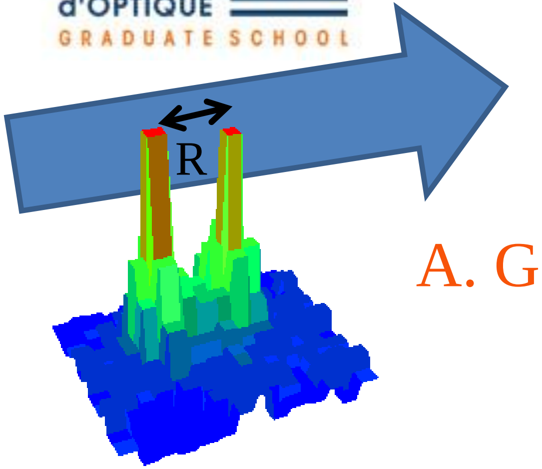


2 trapped atoms: coherent blockade

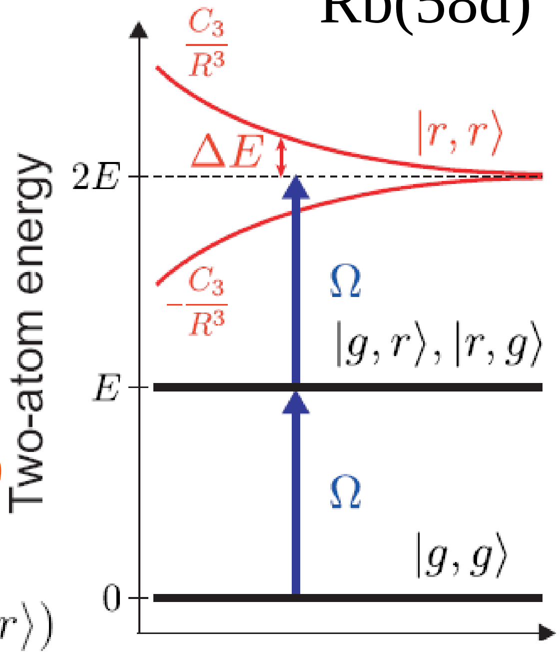
Rb(58d)

INSTITUT d'OPTIQUE GRADUATE SCHOOL

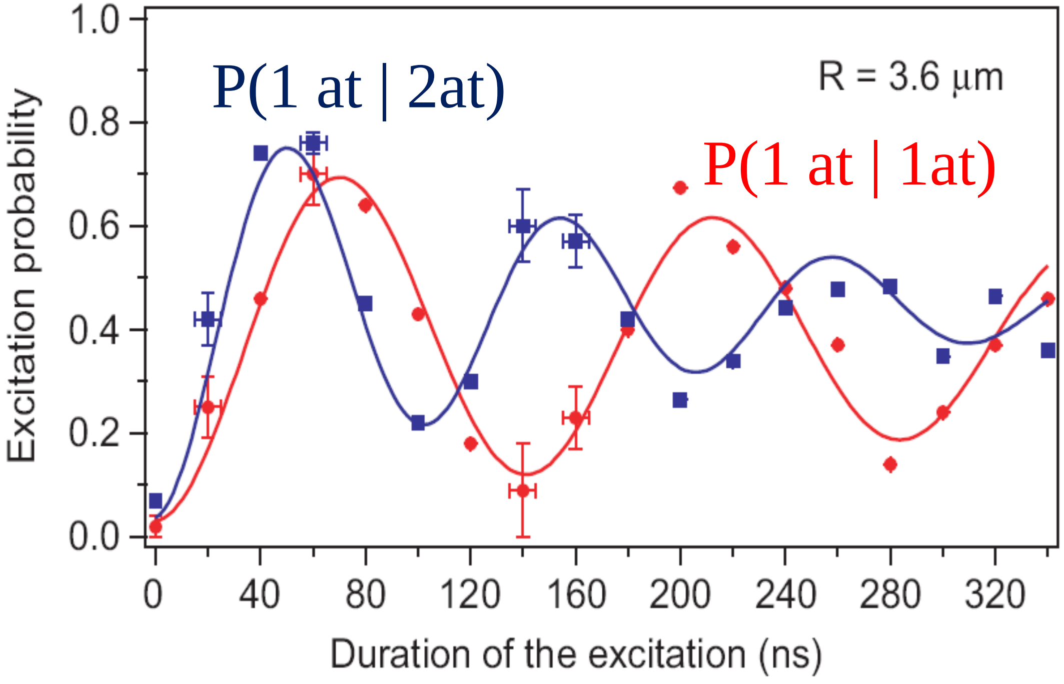
Browaeys, Grangier

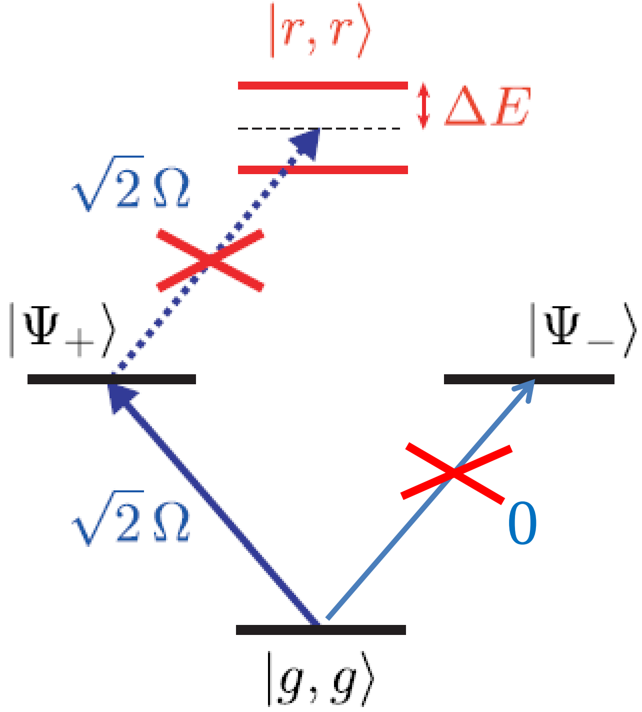


A. Gaëtan *et al. (Nat. Phys 5, 110)*



$$|\Psi_\pm\rangle = \frac{1}{\sqrt{2}}(e^{i\mathbf{k}\cdot\mathbf{r}_a}|r,g\rangle \pm e^{i\mathbf{k}\cdot\mathbf{r}_b}|g,r\rangle)$$





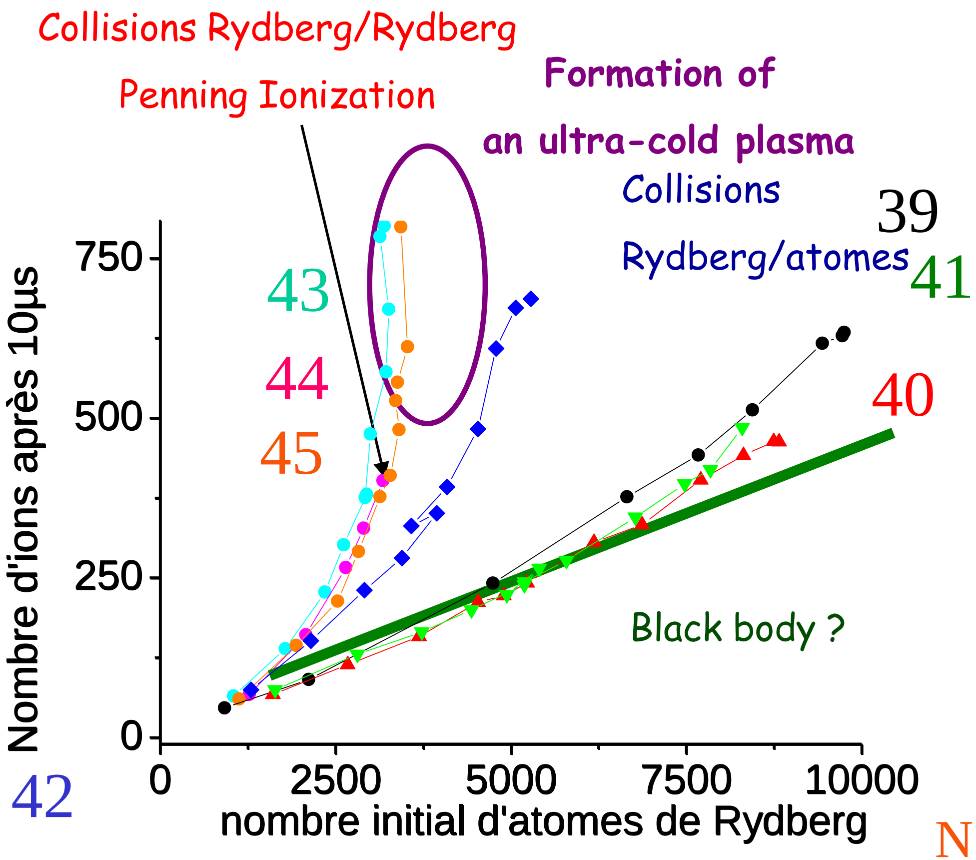
Controled ionization

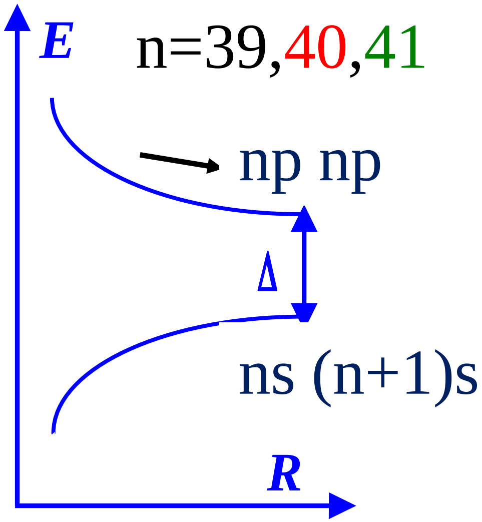
Study in electric field: C_3/R^3

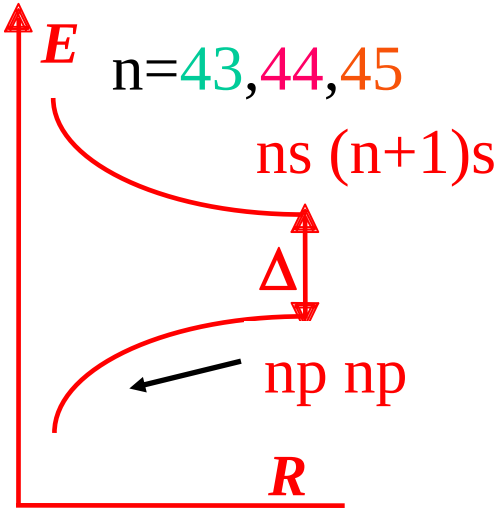
M. Mudrich *et al.* PRL 95 233002 (2005)

Study in zero electric field: C_6/R^6

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







N. Vanhaecke *et al.* PRA 71 013416 (2005)

Control of ion kinetic energy (Ice-Rydberg) ?

T. Pohl *et al.* EPJD 40 45 (2006)

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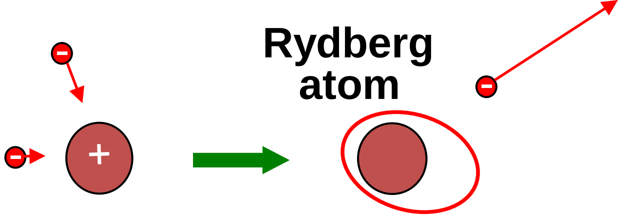
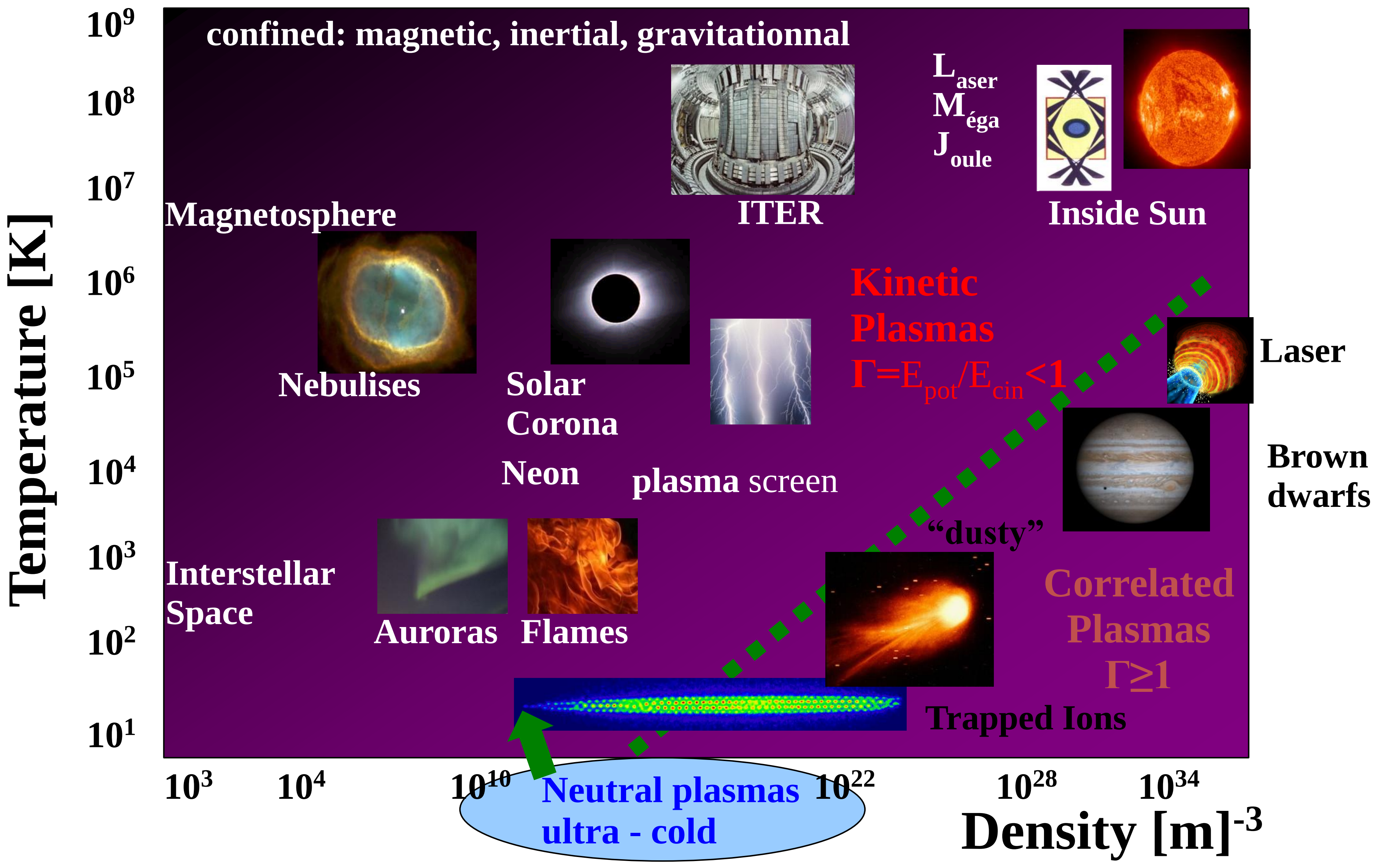
- Ultra-cold plasmas: model, realization, application
- Prospects and conclusion

Ultra-cold plasma (non T>1K!)

Three body recombinaison

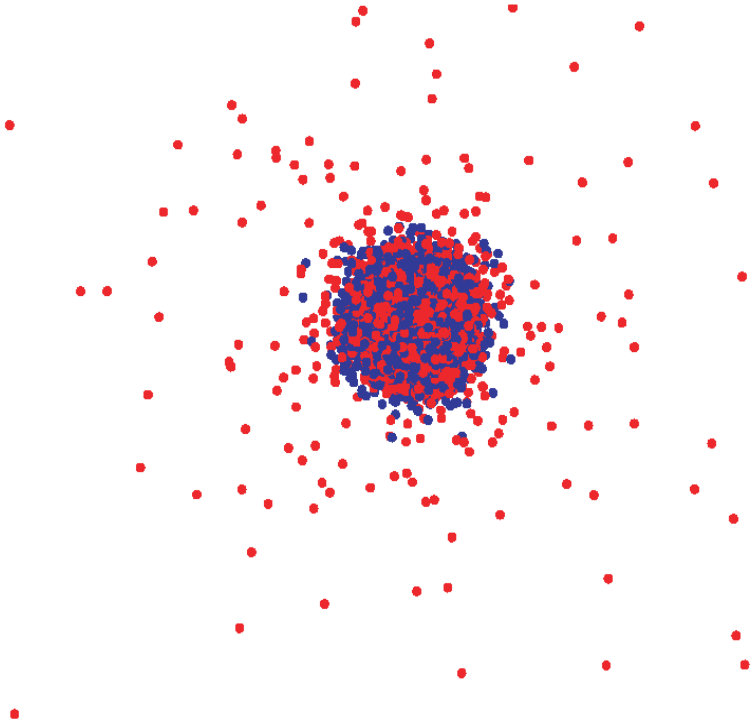


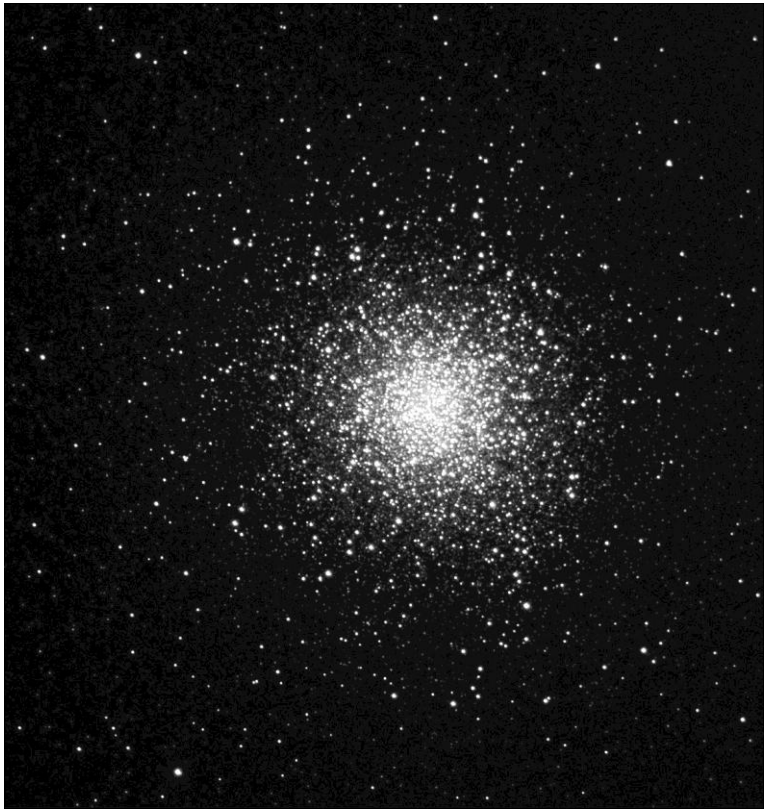


Ultra Cold Neutral Plasma: Model system

D. Comparat *et al.* MNRAS 361, 1227 (2005)

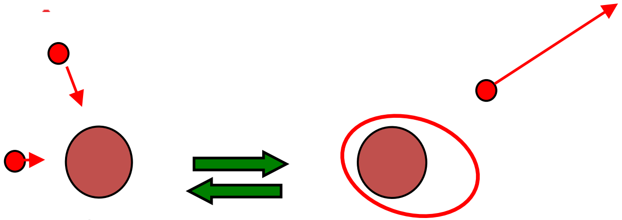
Globular star cluster analogy (back in 1957)





Ultra cold Plasma

$F= (q_e^2 / 4 \pi \varepsilon_0)/r^2$



Globular star

$F= (-G M^2)/ r^2$

Same equation Boltzmann (Vlasov) for electrons (trapped by ions) ↔ stars

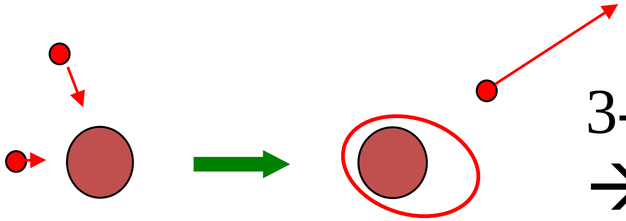
Lowered Maxwellian at equilibrium (Kramers-Michie-King) $f(E) \sim e^{-E/kT} - e^{-E0/kT}$

Same collisional laws : dissociation of binary systems (Rydberg,stars) if $E_{binding} < 4 k_B T$

Rydberg/Plasma:Antihydrogen

A. Kellerbauer *et al.*
NIMB 266 351 (2008)

2002 CERN ATRAP (Antihydrogen Trap) + ATHENA (AnTiHydrogEN Apparatus)



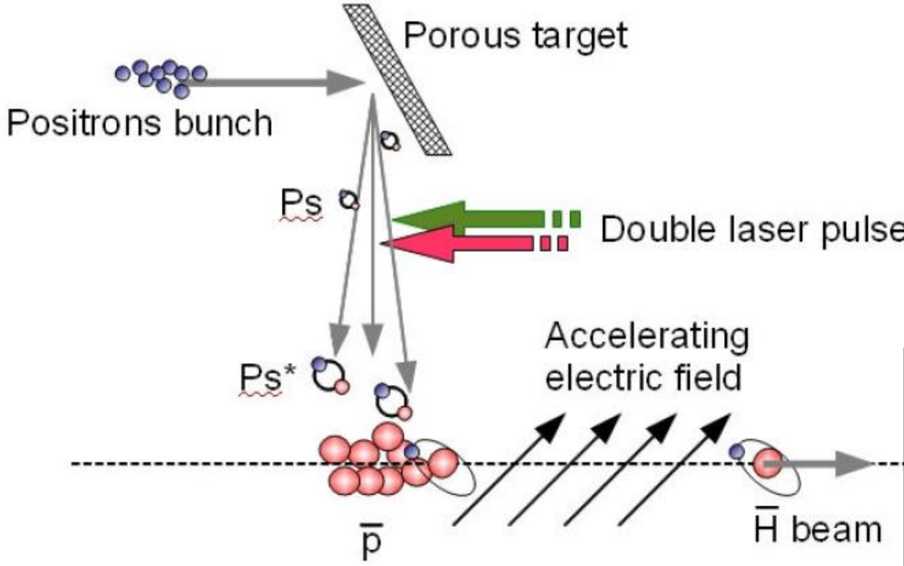
3-body recombination (antiprotons + 2 positrons)
→ Antihydrogen

2006 AEGIS (Antimatter Experiment : Gravity, Interferometry, Spectroscopy)

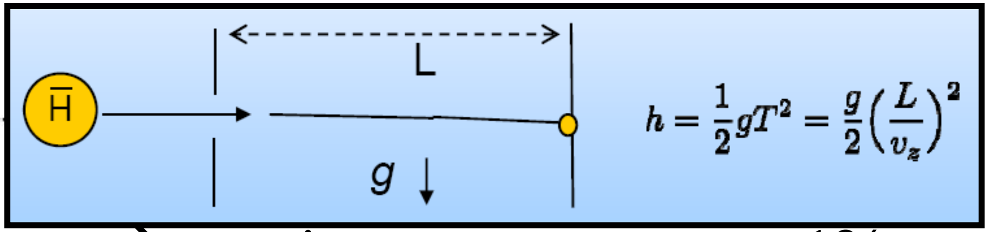
1) Charge exchange (1998) : $Ps(nl) + \bar{p} \rightarrow \bar{H}(n'l')$

2) "Stark-acceleration" of anti-Rydberg

3) Gravity measurement with antimatter (+ violation CPT ?)



Rydberg Excitation Ps= ($e^+ e^-$)
F. Castelli *et al.* PRA, 78, 052512 (2008)



$$h = \frac{1}{2} g T^2 = \frac{g}{2}\left(\frac{L}{v_z}\right)^2$$

→ gravity measurement at 1%

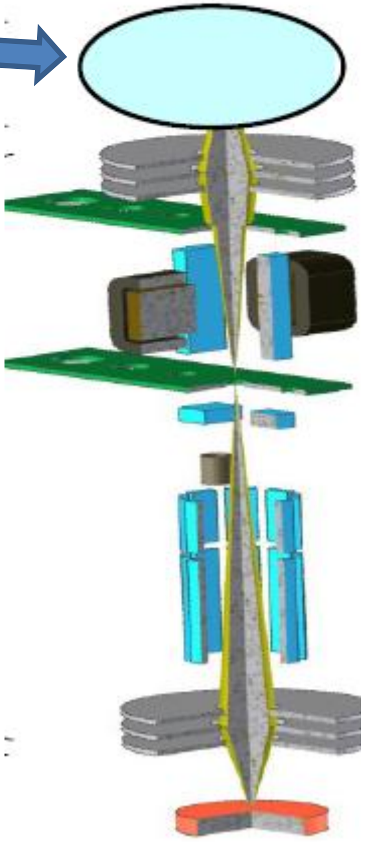
Cold Ion or e^- Beam

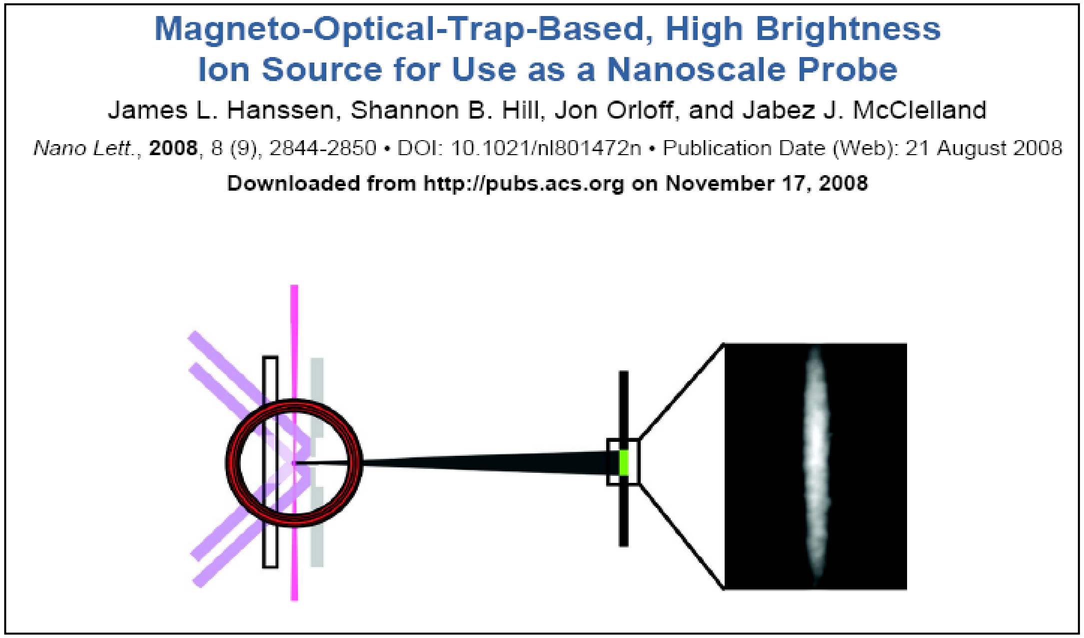
Ultra cold plasma → ion or electron beams

Less energy dispersion (<0.1 eV compare to ~0.3-5eV)

→ low energy beam + small probe beam

Non contaminant (rare gaz) source (compare to Galium)





Magneto-Optical-Trap-Based, High Brightness Ion Source for Use as a Nanoscale Probe

James L. Hanssen, Shannon B. Hill, Jon Orloff, and Jabez J. McClelland

Nano Lett., **2008**, 8 (9), 2844-2850 • DOI: 10.1021/nl801472n • Publication Date (Web): 21 August 2008

Downloaded from http://pubs.acs.org on November 17, 2008

PRL **102,** 034802 (2009) PHYSICAL REVIEW LETTERS week ending 23 JANUARY 2009

Low-Energy-Spread Ion Bunches from a Trapped Atomic Gas

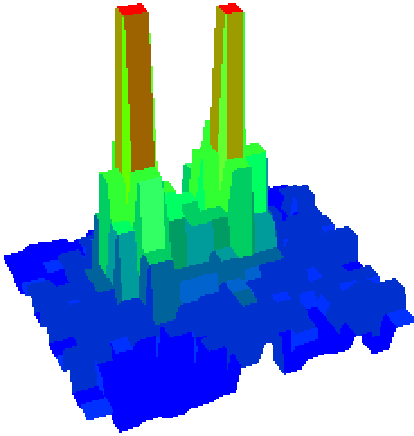
M. P. Reijnders, P. A. van Kruisbergen, G. Taban, S. B. van der Geer, P. H. A. Mutsaers,
E. J. D. Vredenbregt, and O. J. Luiten*

Department of Applied Physics, Eindhoven University of Technology, P.O Box 513, 5600 MB Eindhoven, The Netherlands
(Received 30 September 2008; published 22 January 2009)

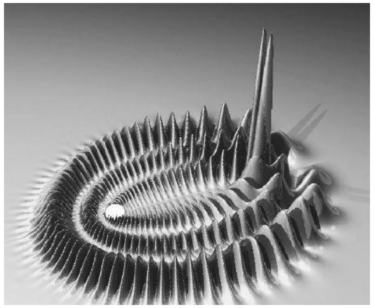
Outline

- Historical motivations (why cold Rydberg atoms ?)
  - *Use and control of long range dipole-dipole interactions*
- Quantum control with Dipole blockade: exp +model
  - *Electric field control of dipole (induced,permanent, transition)*
  - *Many-body coherent effects*
  - *Dynamics and Penning ionization*
- Ultra-cold plasmas: model, realization, application
  - *« controled » Model system for plasma dynamics and excitation*
  - *Anti hydrogen formation*
  - *Ions and electrons beam*
- Prospects and conclusion

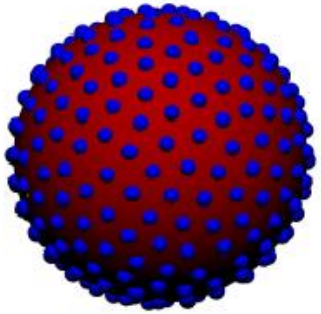
Conclusion and Perspectives



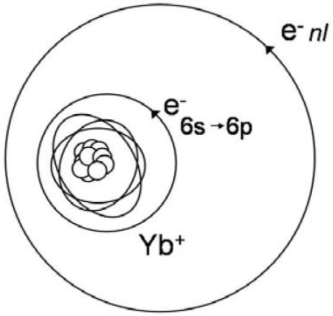
- Quantum control
  - Dipole blockade →entanglement of two (few) atoms
  - Förster (transition dipole), Landau-Zener transitions: few, many-body (dynamical) effects
  - Quantum simulators
  - Quantum engineering, photoassociation



- Ionization → Ultra-cold (neutral) plasmas
  - Penning ionization, control of the interatomic forces
  - Evolution towards an ultracold plasmas, heating processes → highly correlated plasmas…,
  - Anti-hydrogen beam formation, gravity or CPT test
  - Rydberg production of ion and electron sources



- New experimental devices
  - Lattice + Rydberg excitation of quantum gases
  - Stark-Rydberg decelerator of supersonic beams
  - Two-electrons Rydberg (Sr,Yb, …): one Rydberg electron, another to image, manipulate

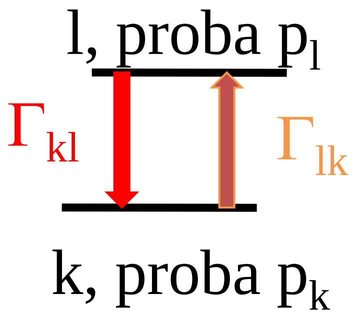


How to solve a master (rate) equation

1) Master equation

Rate equation

$$\frac{dP_k}{dt} = \sum_{l=1}^{N} \Gamma_{kl} P_l = \sum_{l=1}^{N} \Gamma_{kl} P_l - \sum_{l=1}^{N} \Gamma_{lk} P_k$$



l, proba p_l

Γ_{kl}

Γ_{lk}

k, proba p_k

2) Usual way to solve (Monte Carlo): dt << Γ

$$P_k(t+dt) = P_k(t) - \sum_{l=1}^{N} \Gamma_{lk}(t) P_k(t) dt + \sum_{l=1}^{N} \Gamma_{kl}(t) P_l(t) dt$$

New Journal of Physics
10 (2008) 045031

random number r between 0 and 1. If $r < \Gamma_{lk}(t)\,dt$ → change k->l.

Huge time for nothing (no reaction). Not exact !

2) Much better way to solve: Kinetic Monte Carlo model

2 steps:

a) Reaction time t' calculated by $\int_t^{t'} \sum_{l=1}^{N} \Gamma_{kl}(\tau) d\tau = -\ln r$

b) Reaction l chosen proportional to its rate $\Gamma_{kl}(t)$

Every step a reaction occurs. EXACT SOLUTION !