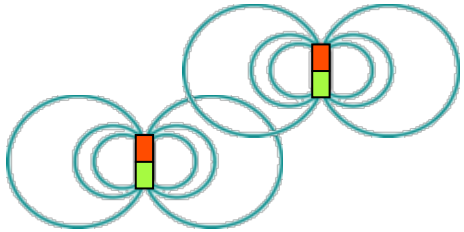
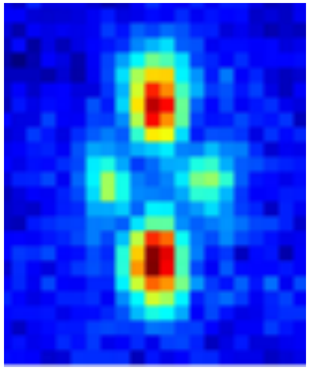
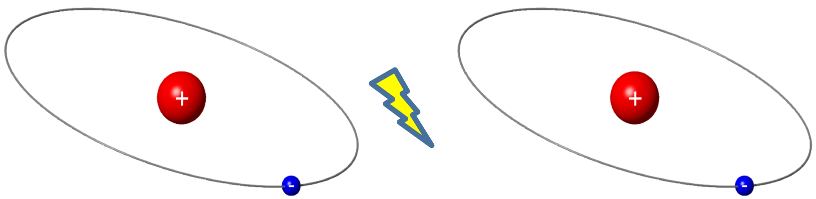
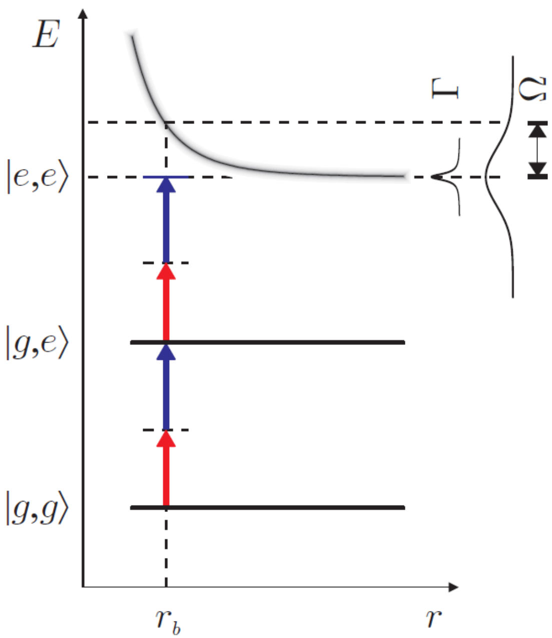
Lecture I: (magnetic) dipolar gases





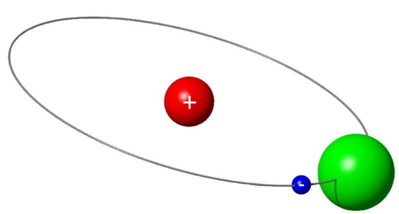
Lecture II: Rydberg Rydberg interaction





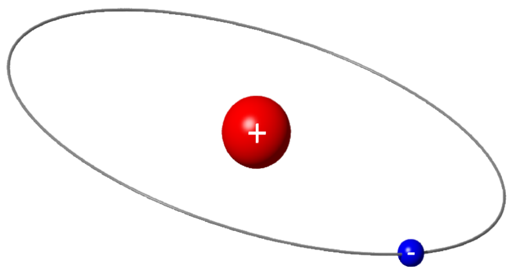
Lecture III : Rydberg ground state interaction

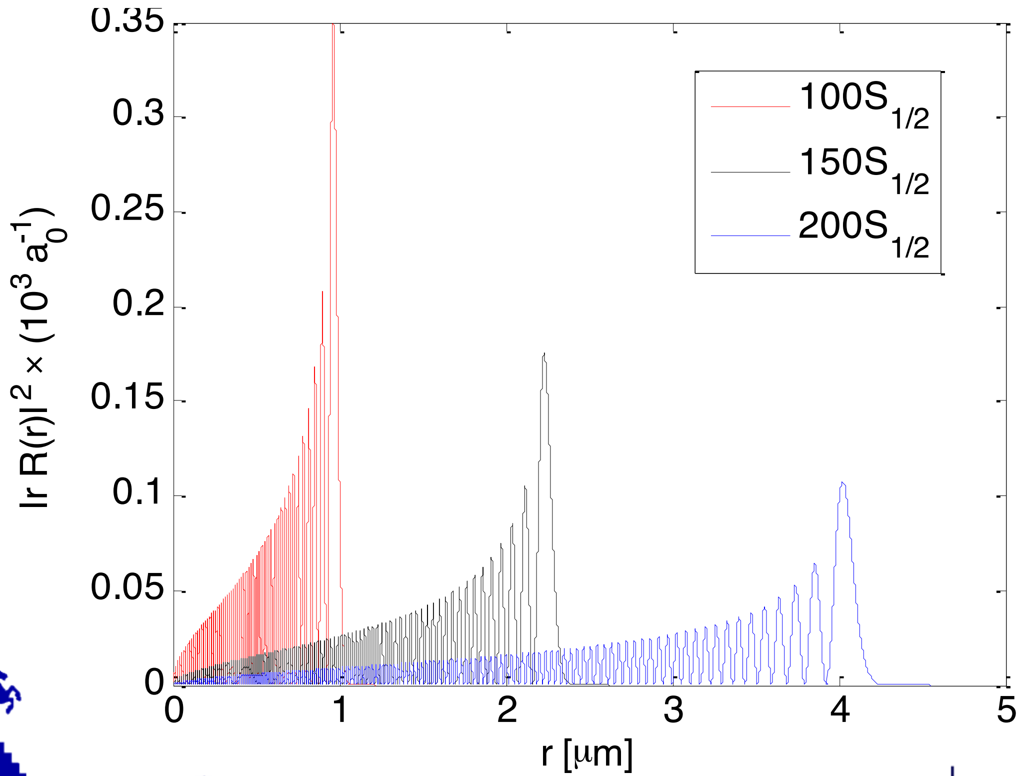
dimer:



Rydberg atoms - Size

quantity	scaling	100S-state of ^{87}Rb
radius	$\propto n^2$	~ 1 μm

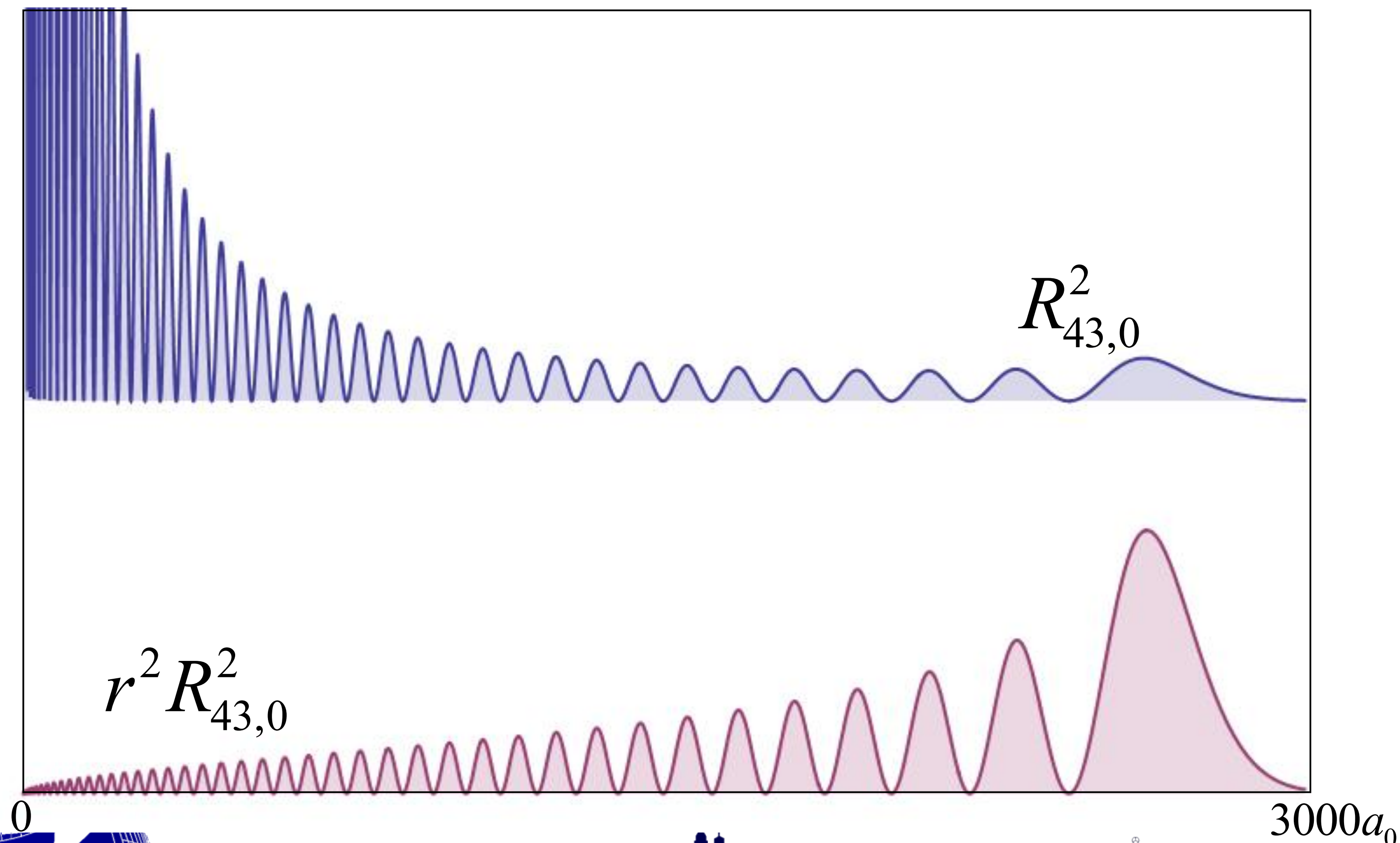




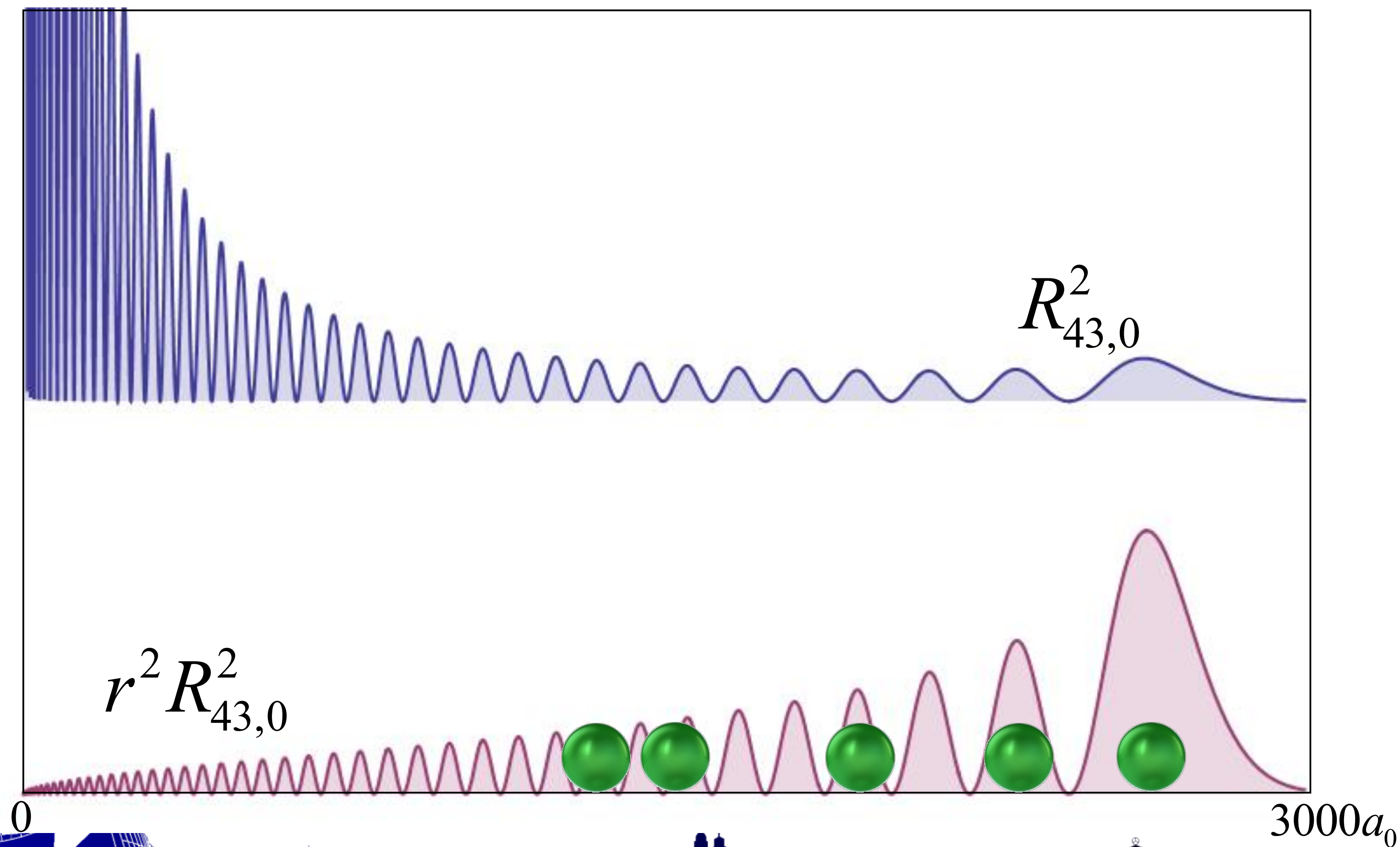
Size of Rydberg atom > 1 μm

for n > 100

Rydberg electron interacting with ground state atoms

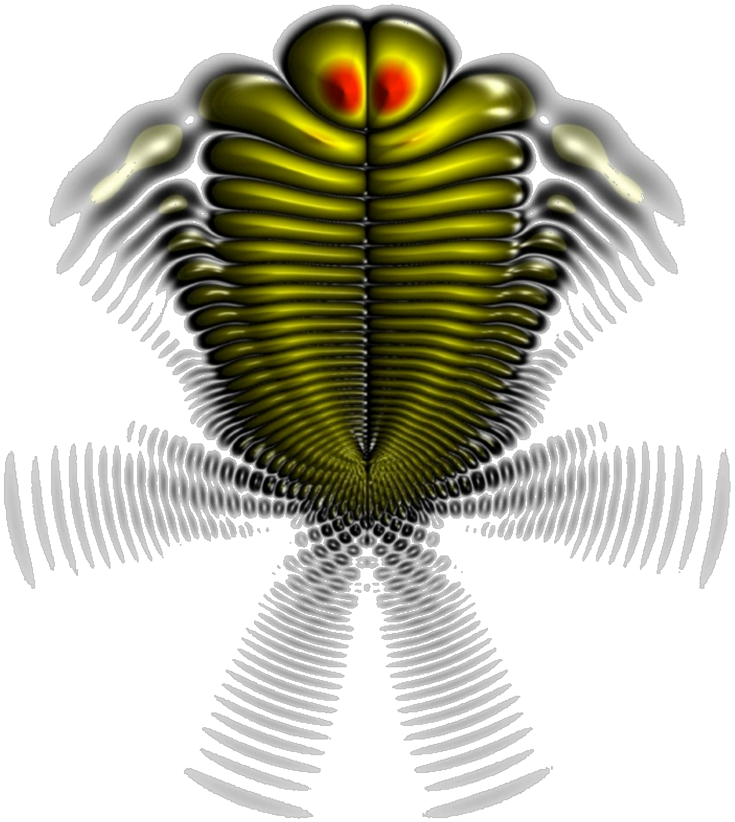


Rydberg electron interacting with ground state atoms



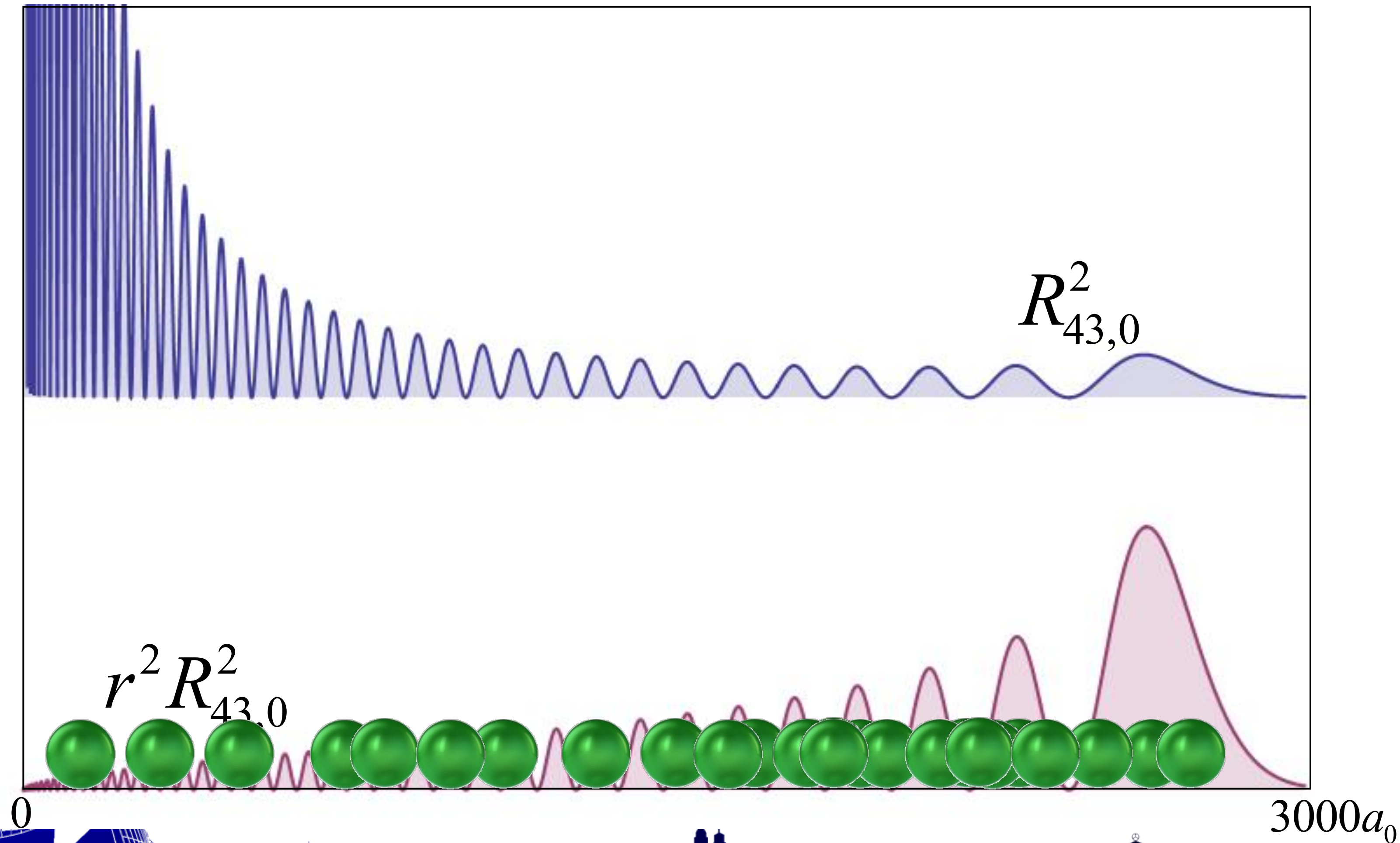
Ultracold Rydberg Chemistry

- Giant molecules

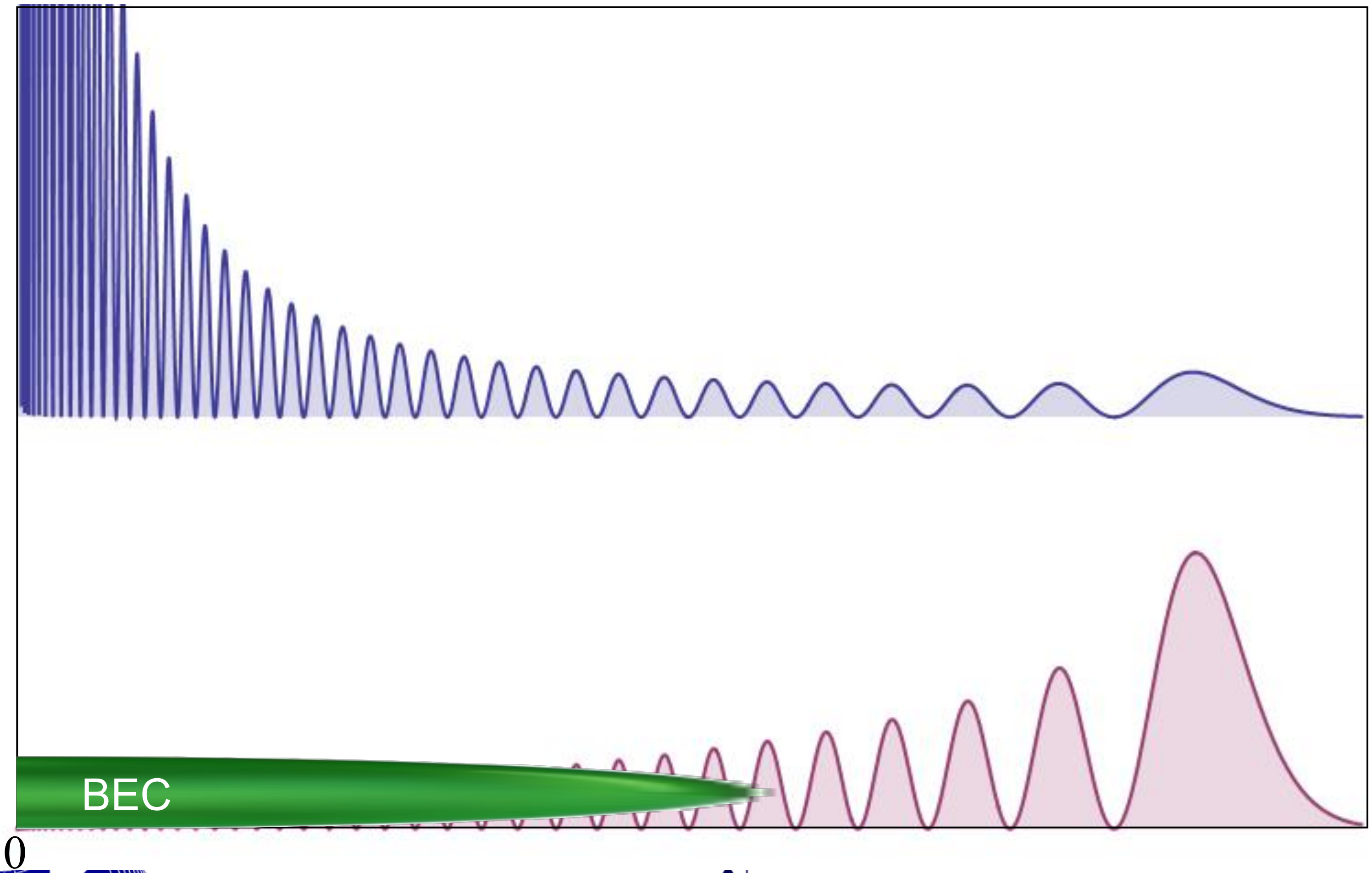


Two or few-body physics

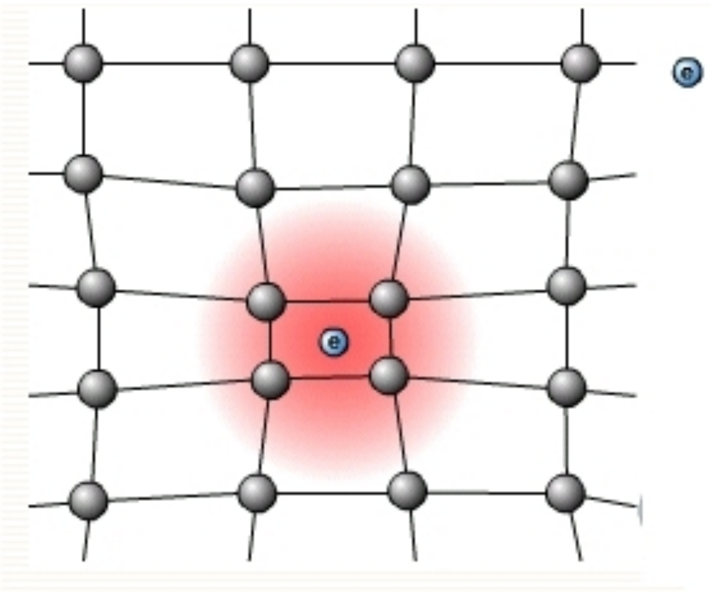
Rydberg electron interacting with ground state atoms

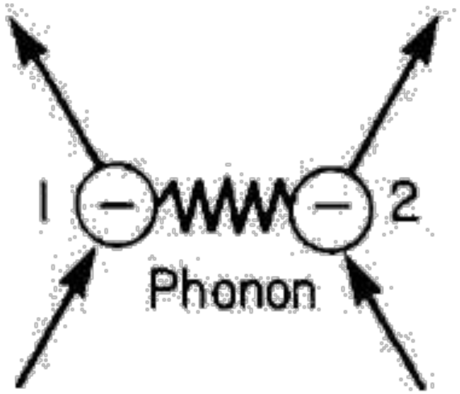


Ultimately: one electron bound by a charged BEC



Single electron in a quantum gas





Cooper pairs

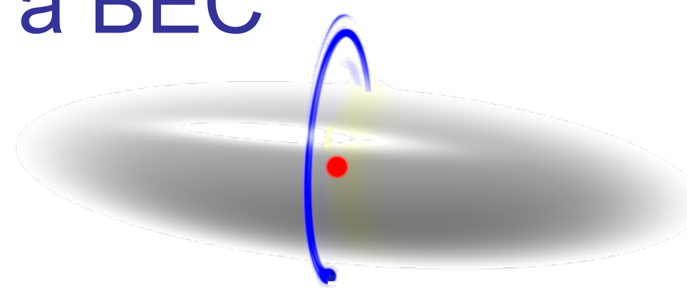
electron phonon coupling

Many-body physics

Outline

- History of Rydberg atoms in dense gases

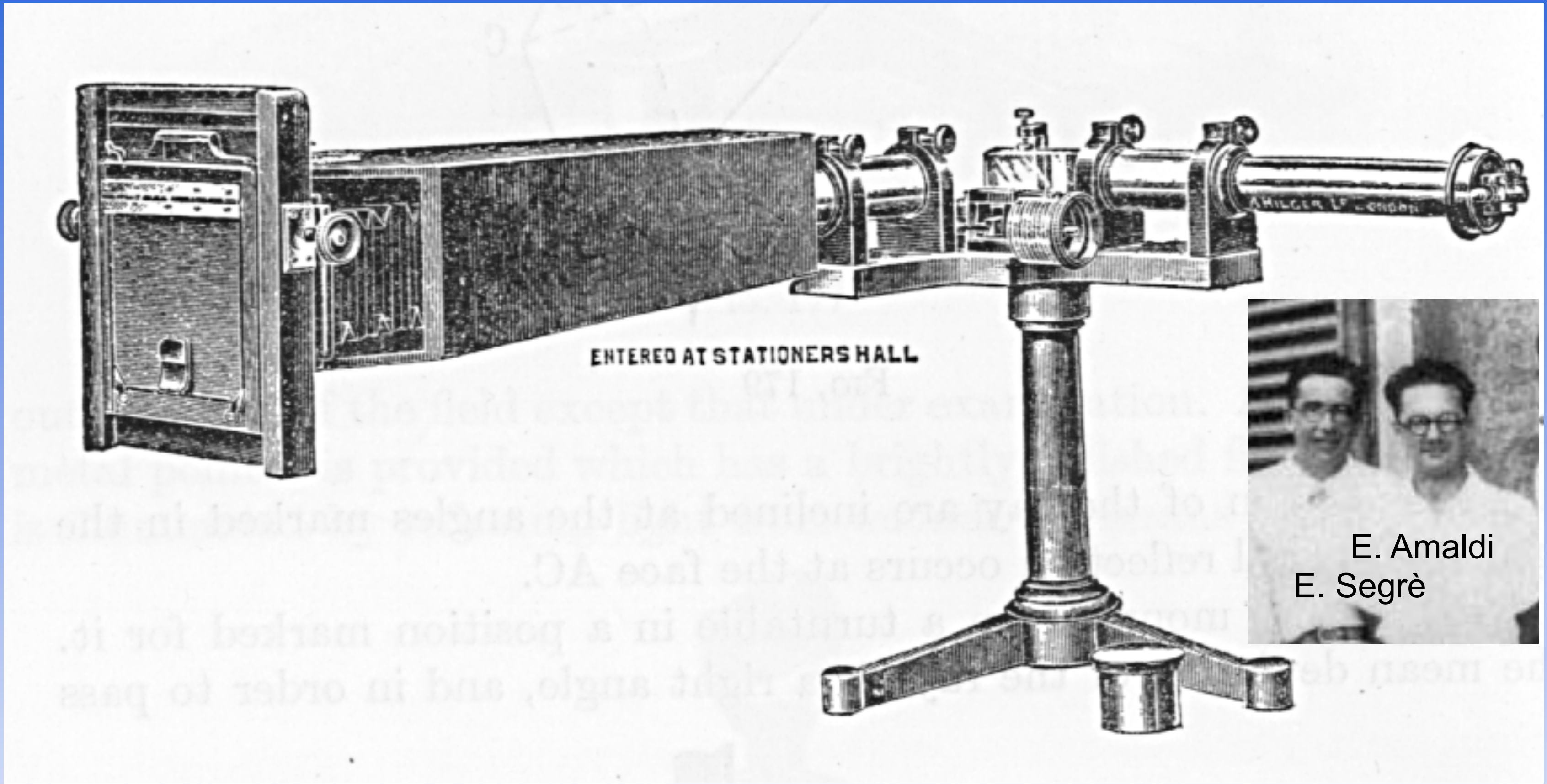
- How Rydberg electrons catch atoms
- Single Rydberg electron in a BEC



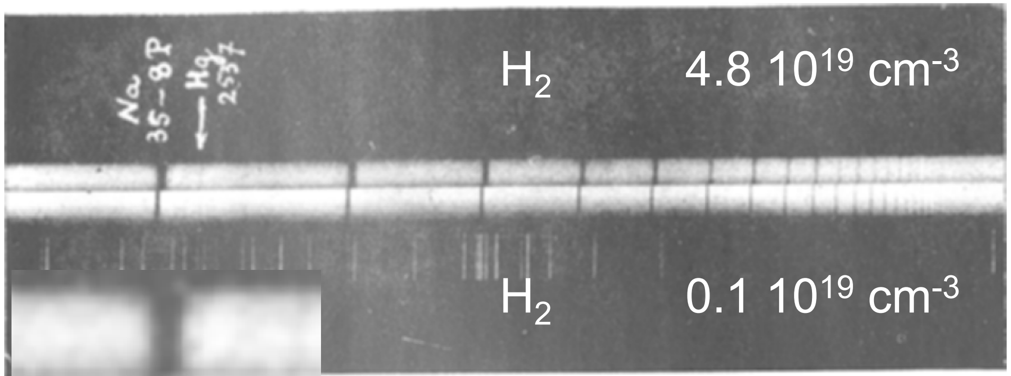
The group of Rome

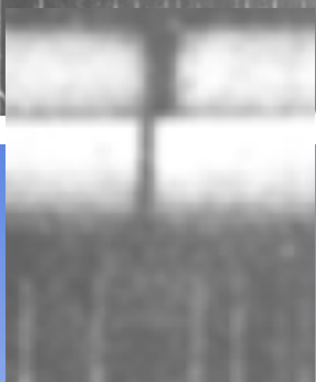
Oscar D'Agostino
Emilio Segrè,
Edoardo Amaldi
Franco Rasetti
Enrico Fermi

History of Rydberg atoms in dense gases



Hilger Ltd., London UK





EFFETTO DELLA PRESSIONE SUI TERMINI ELEVATI DEGLI ALCALINI

Nota di E. Amaldi ed E. Segrè (*)

H_2	4,80	cm^{-1}	*v*
N_2	0,00	»	
He	5,15	»	*v*
A	11,60	»	*r*

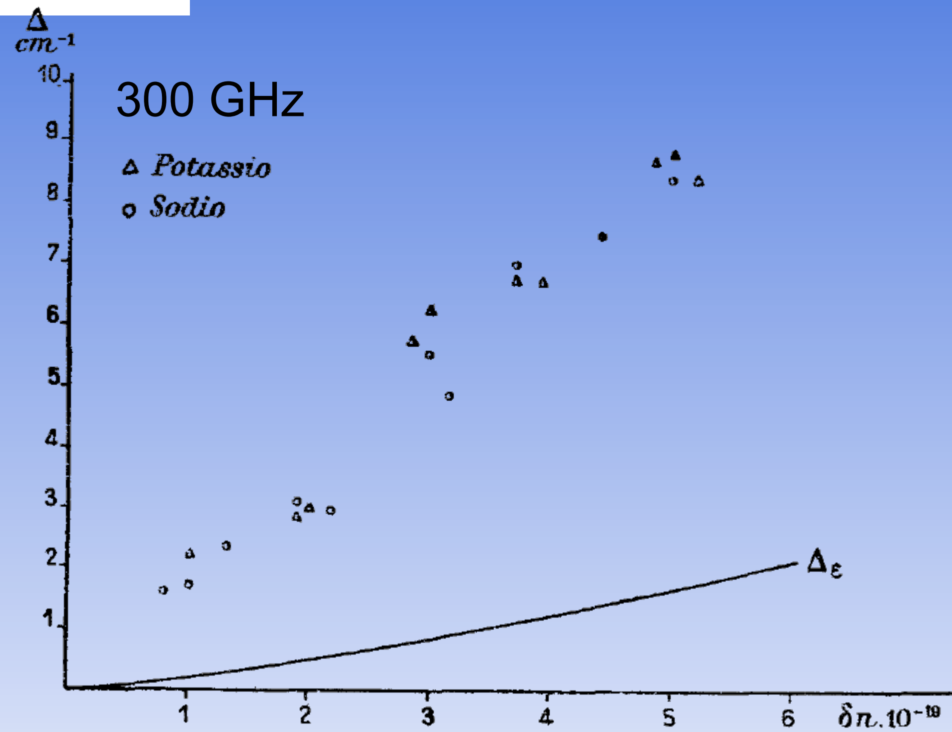
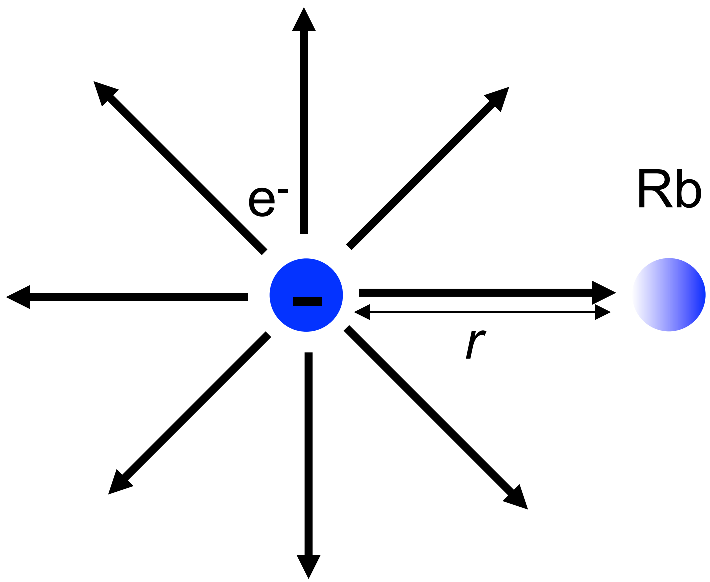


Fig. 3

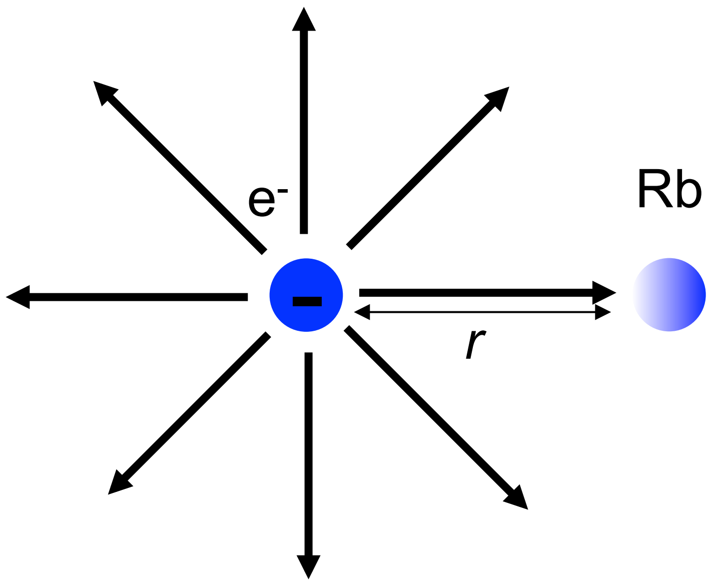
Spostamento medio delle righe in funzione della concentrazione di H_2

E. Amaldi, E. Segre: Nature **133**, 141 (1934), Nuovo Cimento **11**, 145 (1934)

Interaction between a charge and a polarizable atom



Interaction between a charge and a polarizable atom



$$V(r) = -\vec{d} \cdot \vec{E}$$

$$= -\frac{1}{2}\alpha \vec{E} \cdot \vec{E}$$

$$= -\frac{1}{(4\pi\varepsilon_0)^2}\frac{\alpha q^2}{2r^4} = -\frac{\alpha}{2r^4}$$

Interaction between a charge and a polarizable atom

$$V_{pseudo}(r) = 2\pi\, a_s\, \delta(r)$$

$$V(r) = -\frac{\alpha}{2r^4}$$

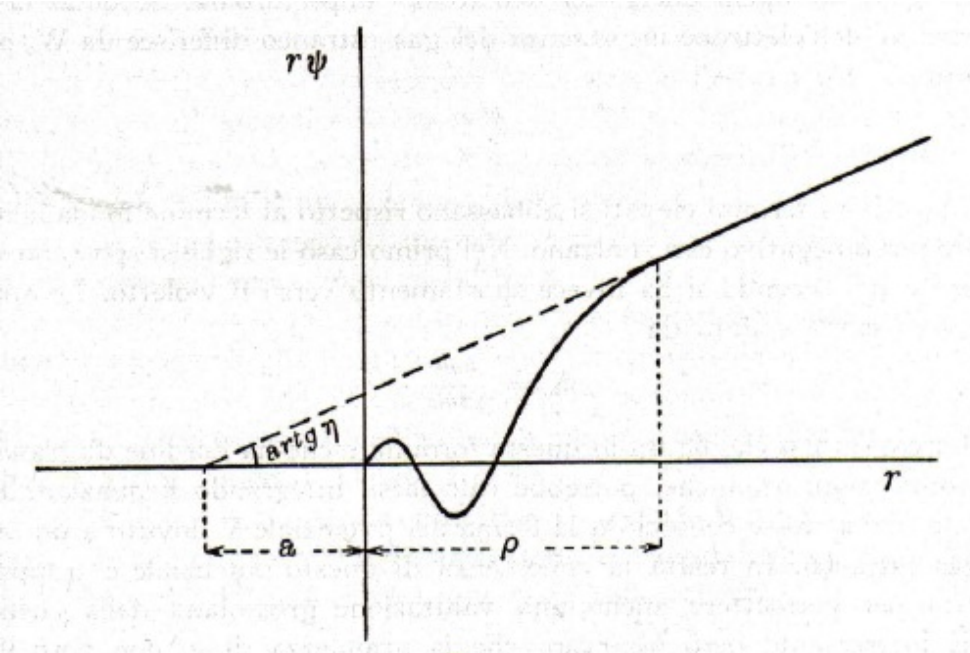


Fig. 1.

E. Fermi: Nuovo Cimento 11, 157 (1934)

Interaction between a charge and a polarizable atom

$$V_{pseudo}(r) = 2\pi\, a_s\, \delta(r)$$

$$V(r) = -\frac{\alpha}{2r^4}$$

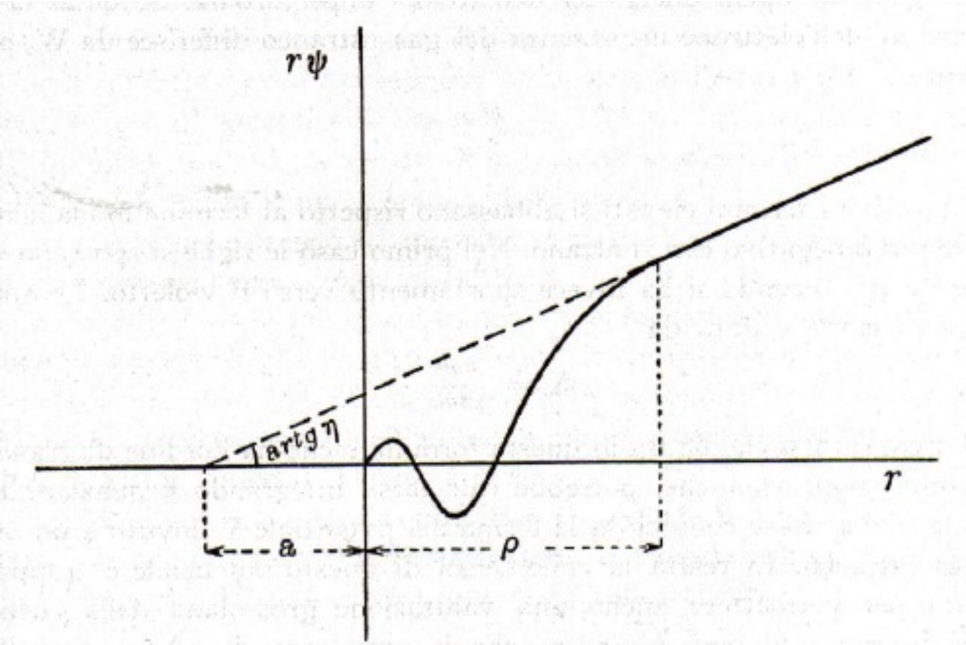


Fig. 1.

E. Fermi: Nuovo Cimento 11, 157 (1934)

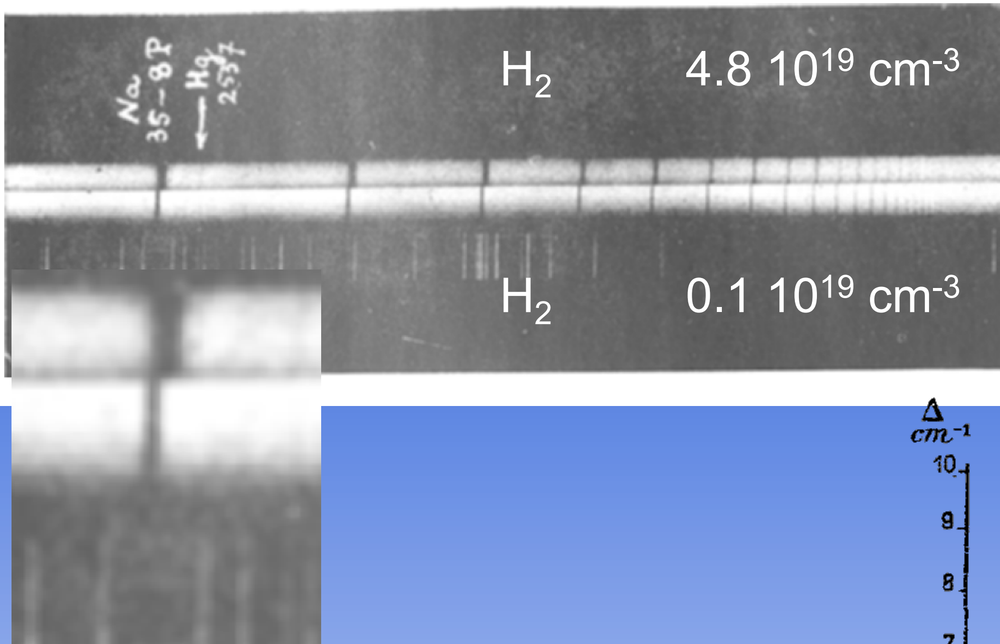
range of interaction

$$E_{kin}(r^*) = E_{pot}(r^*)$$

$$\frac{h^2}{2\mu r^{*2}} = \frac{1}{(4\pi\varepsilon_0)^2}\,\frac{\mu\alpha q^2}{2r^{*4}}$$

SI a.u.

$$r^* = \sqrt{\frac{\mu\alpha q^2}{(4\pi h\varepsilon_0)^2}} = \sqrt{\alpha} \approx 18a_0$$



EFFETTO DELLA PRESSIONE SUI TERMINI ELEVATI DEGLI ALCALINI

Nota di E. AMALDI ed E. SEGRÈ (*)

$$U_{e-atom} = \frac{2\pi h^2}{m_e} a_{e-atom} n_{atom}$$

H_2	4,80	cm^{-1}	v
N_2	0,00	»	
He	5,15	»	v
A	11,60	»	r

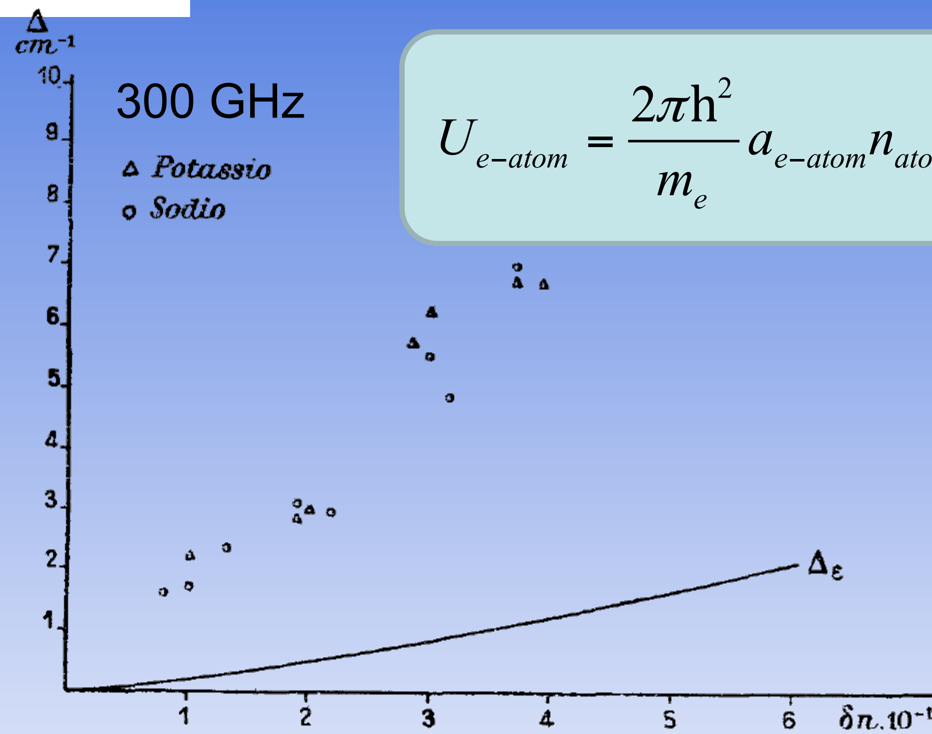


Fig. 3

Spostamento medio delle righe in funzione della concentrazione di H_2

E. Amaldi, E. Segre: Nature **133**, 141 (1934), Nuovo Cimento **11**, 145 (1934)

Verschiebung von hohen Serienlinien des Natriums und Kaliums durch Fremdgase, Berechnung der Wirkungsquerschnitte von Edelgasen gegen sehr langsame Elektronen.

Von **Chr. Füchtbauer, P. Schulz** und **A. F. Brandt** in Rostock.

Mit 4 Abbildungen. (Eingegangen am 30. Juni 1934.)

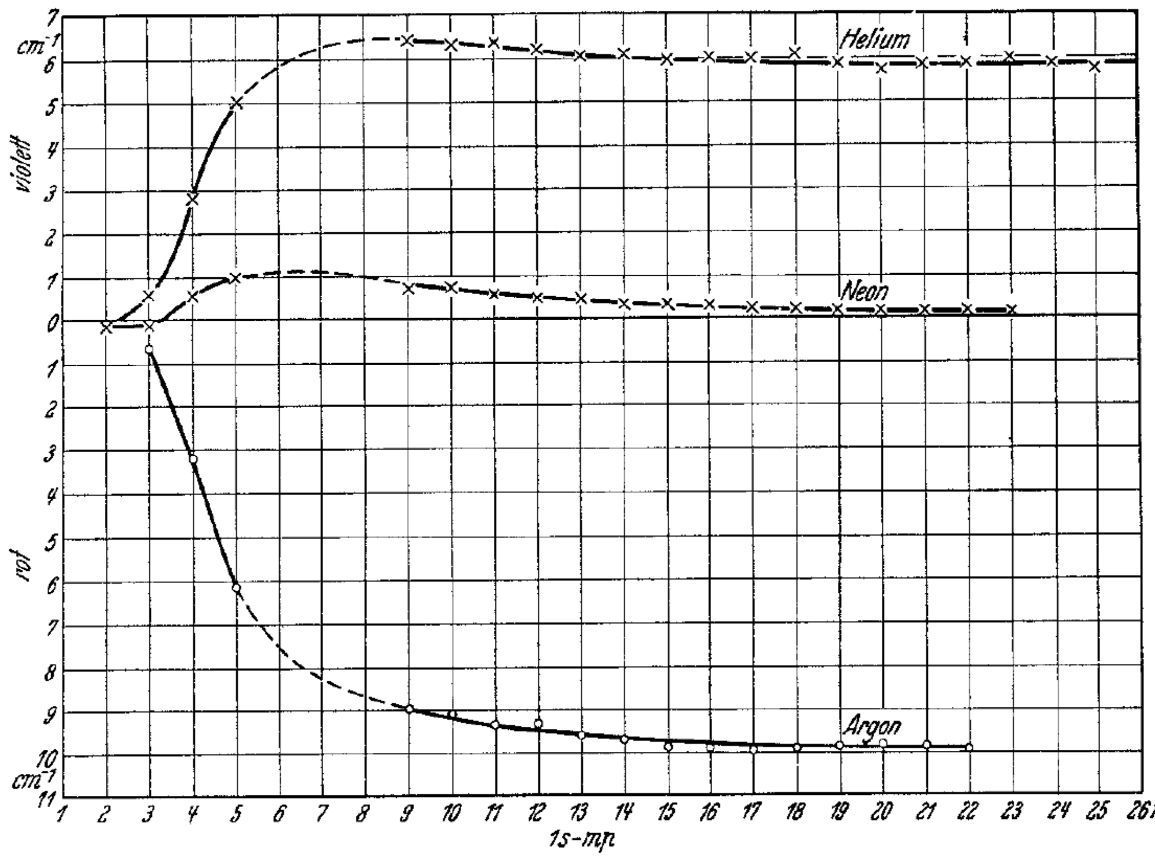
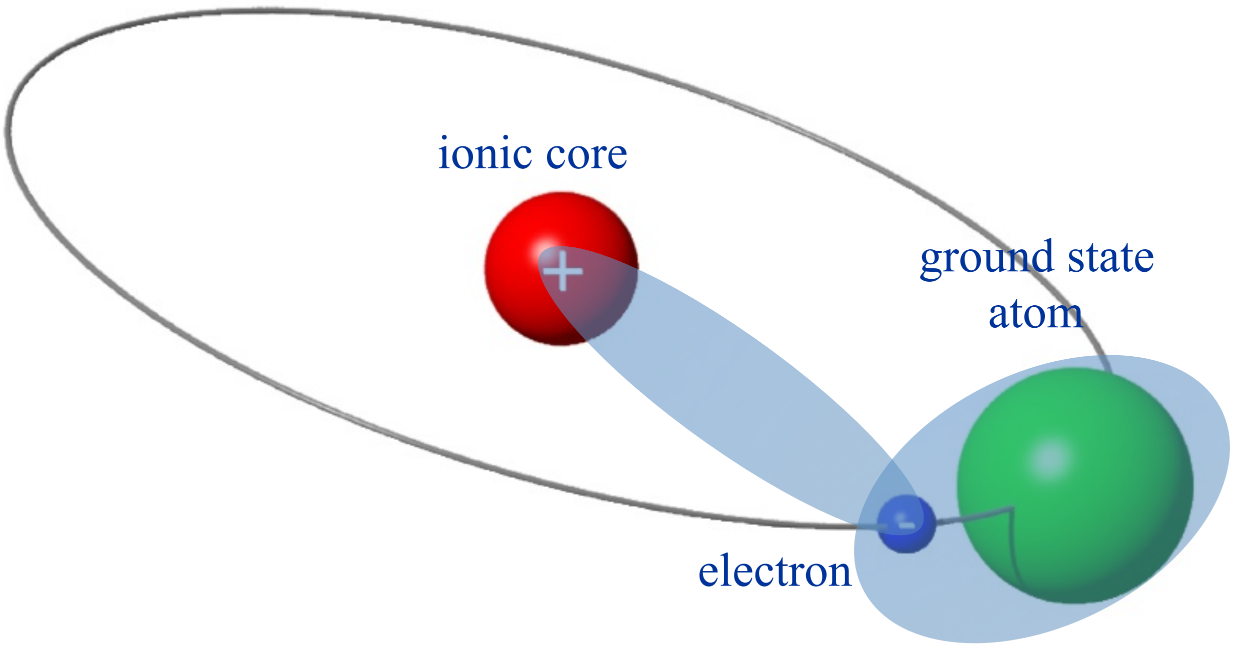


Fig. 4. Gesamtverlauf der Verschiebung bei 0⁰ und 1 Atm. für die Cäsiumhauptserie.

$$U_{e-atom} = \frac{2\pi h^2}{m_e} a_{e-atom} n_{atom}$$

Zeitschrift für Physik **90**, 403-415 (1934)

interacting Rydberg electron



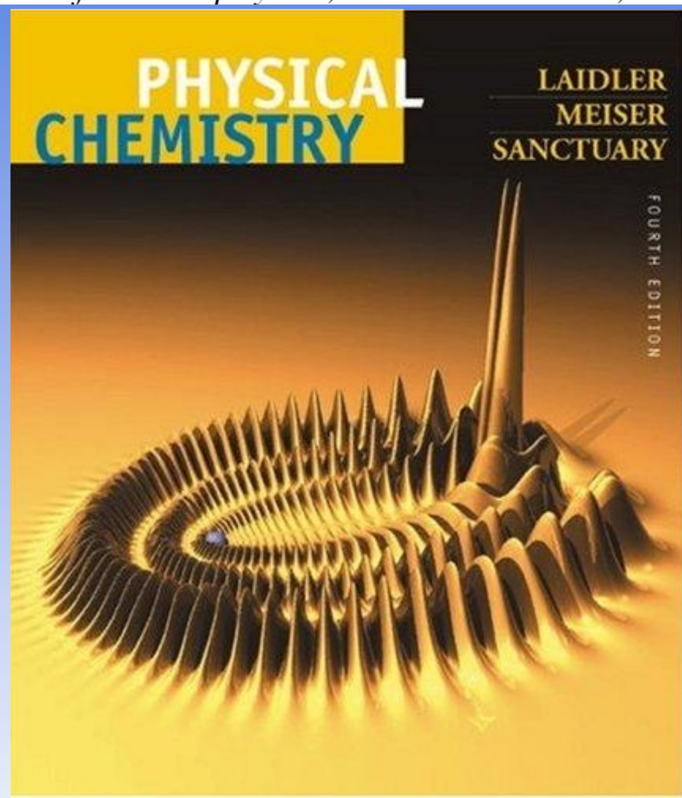
Effect on ground state atom?

Creation of Polar and Nonpolar Ultra-Long-Range Rydberg Molecules

Chris H. Greene
Department of Physics and JILA, University of Colorado, Boulder, Colorado 80309-0440

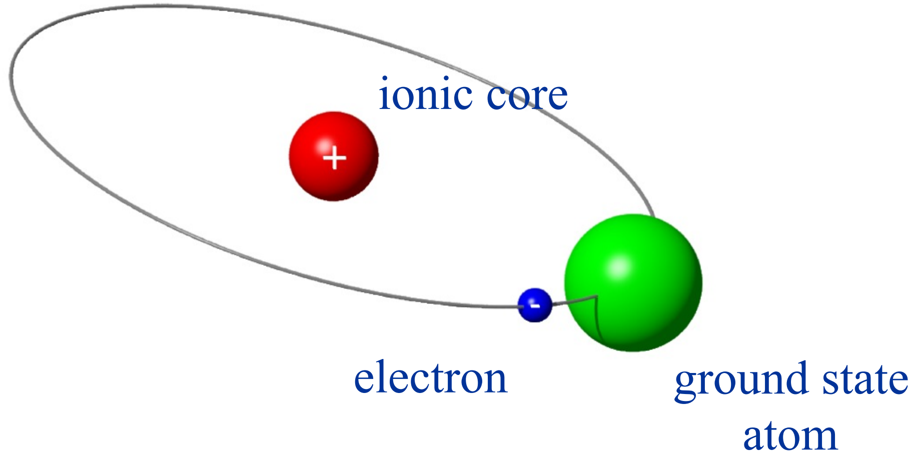
A. S. Dickinson*
JILA, University of Colorado, Boulder, Colorado 80309-0440

H. R. Sadeghpour
ITAMP, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138



PRL **85,** 2458 (2000)

density/pressure shift

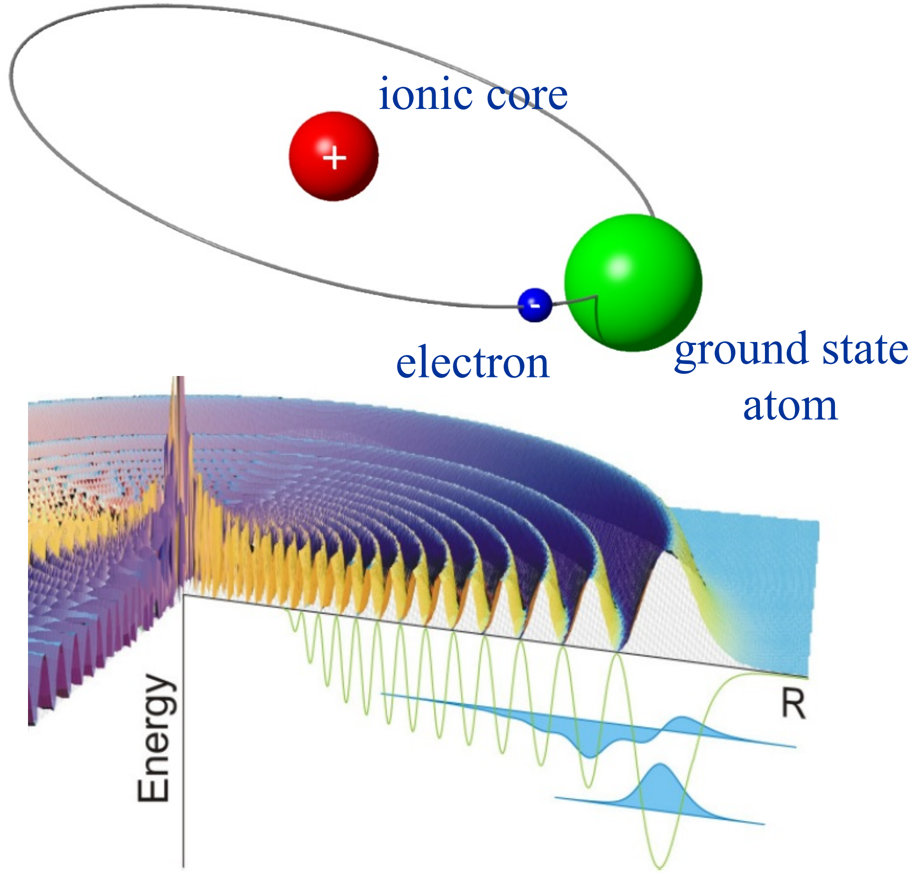


atom effects electron

$$U_{e-atom} = \frac{2\pi h^2}{m_e} a_{e-atom} n_{atom}$$

E. Fermi, Nuovo Cimento **11,** 157 (1934).
E. Amaldi, E. Segrè, Nuovo Cimento **11**, 145 (1934)
A. Omont, J. Phys. France **38**, 1343 (1977)
I. Fabrikant, J. Phys. B 19, 1527 (1986).

„Trilobite“ molecules



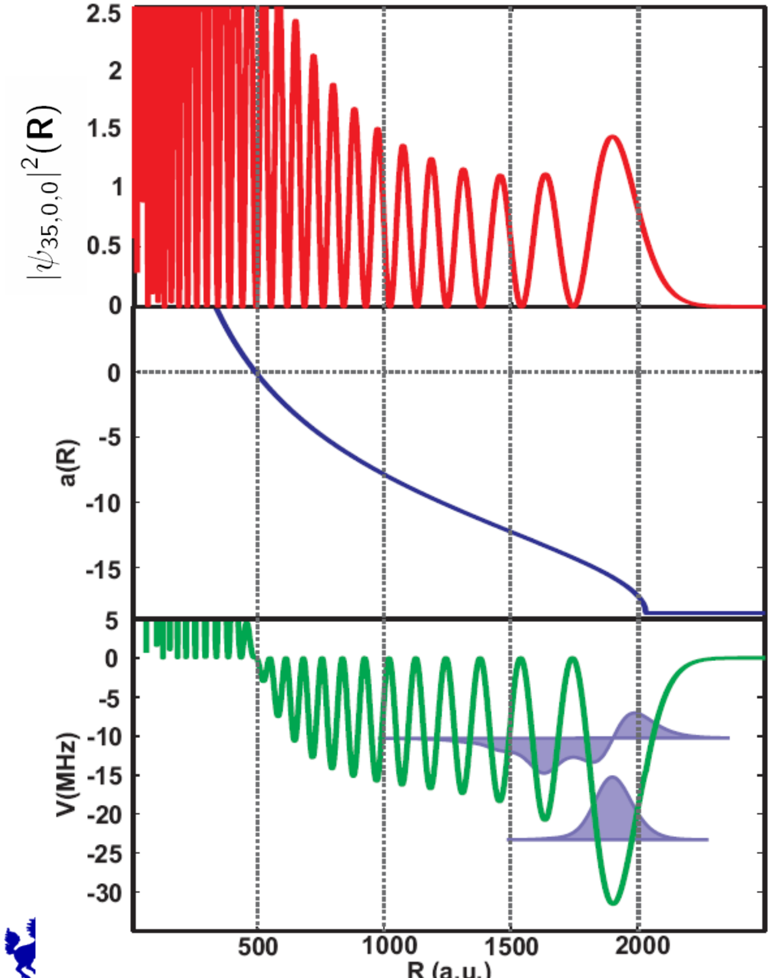
electron effects atom

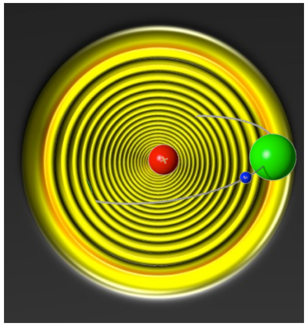
$$U_{e-atom} = \frac{2\pi h^2}{m_e} a_{e-atom} n_e$$

E. Fermi, Nuovo Cimento **11,** 157 (1934).
E. Amaldi, E. Segrè, Nuovo Cimento **11**, 145 (1934)
A. Omont, J. Phys. France **38**, 1343 (1977)
I. Fabrikant, J. Phys. B **19**, 1527 (1986).
C. Greene et al. PRL **85,** 2458 (2000)

Fermi-Greene Model

single channel





probability density

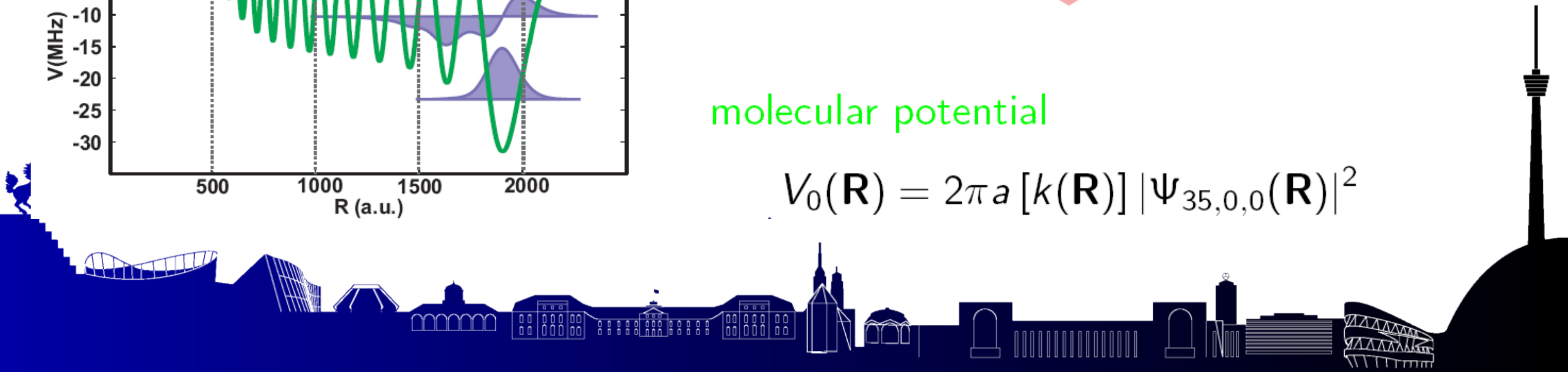
$$|\psi_{35,0,0}|^2(\mathbf{R})$$

energy-dependent scattering length

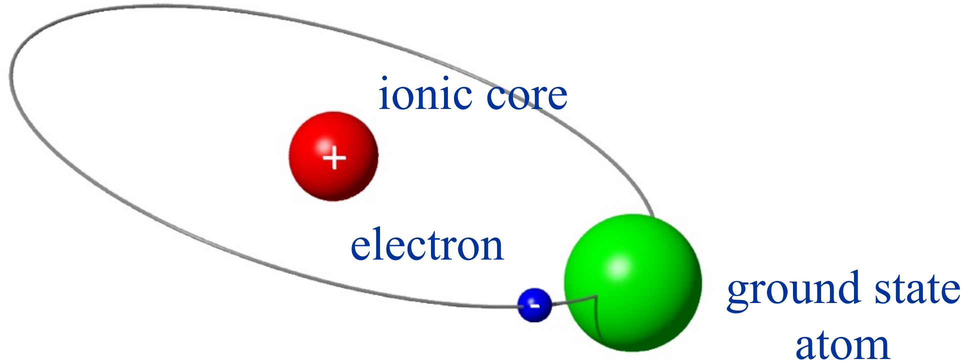
$$a\left[k(R)\right] = a_0 + \frac{\pi\alpha}{3}k(R)$$

molecular potential

$$V_0(\mathbf{R}) = 2\pi a\left[k(\mathbf{R})\right]\left|\Psi_{35,0,0}(\mathbf{R})\right|^2$$

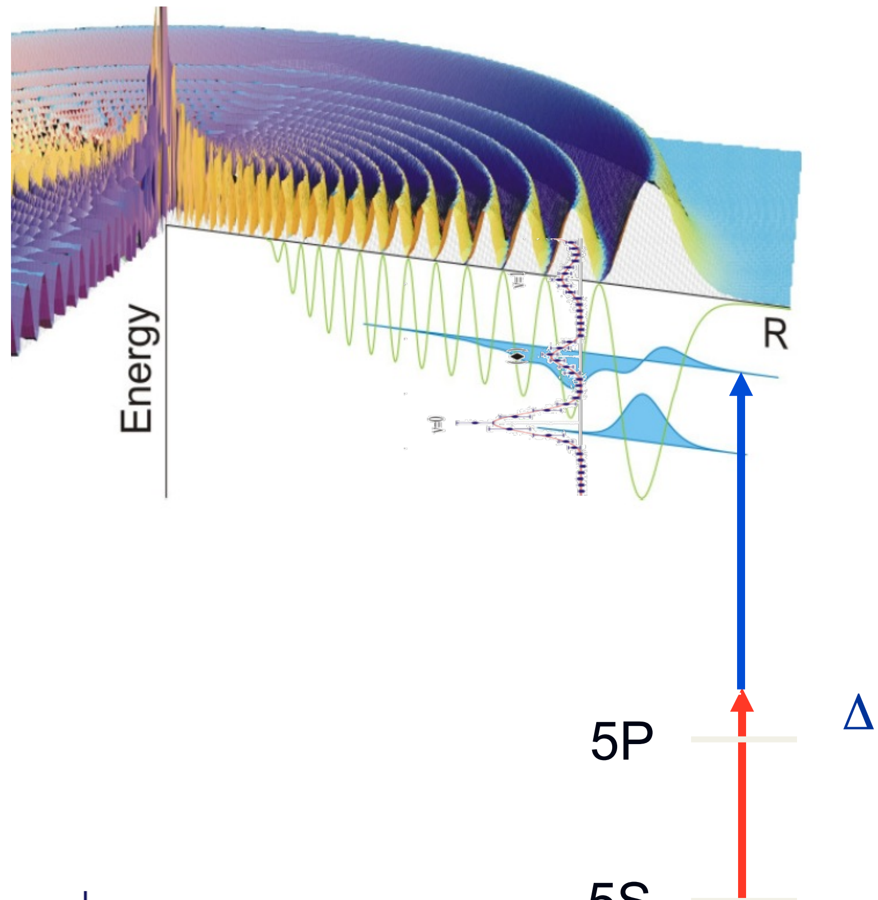


„Trilobite“ molecules



electron effects atom

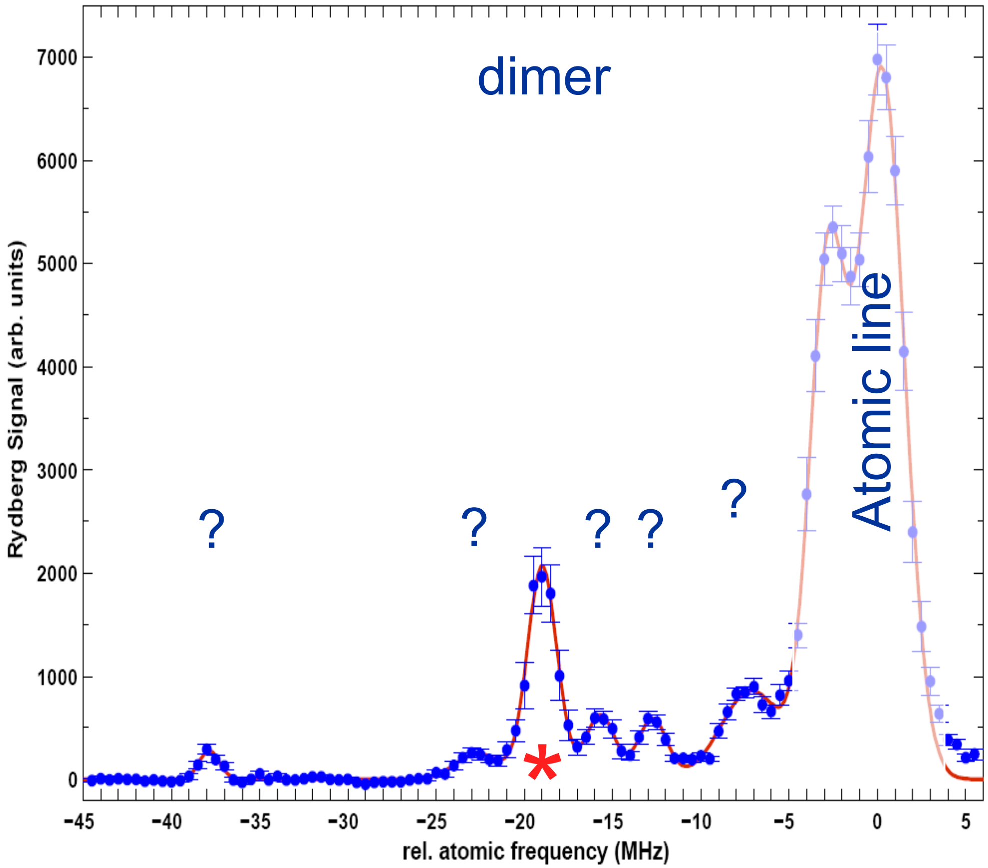
$$U_{e-atom} = \frac{2\pi h^2}{m_e} a_{e-atom} n_e$$

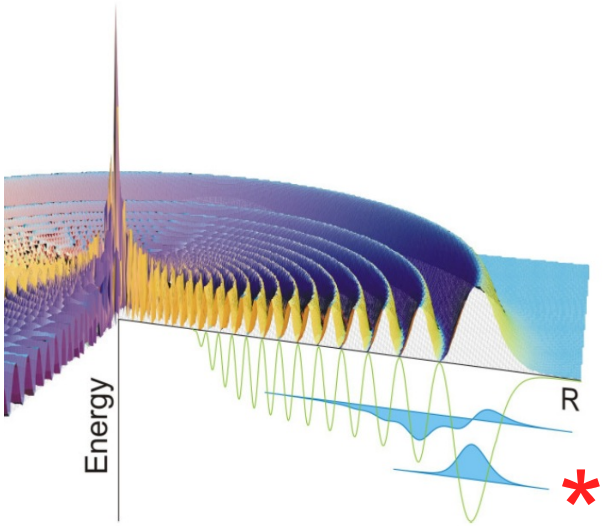


V. Bendkowsky, B. Butscher, J. Nipper,
J. P. Shaffer, R. Löw, TP,
Nature **458**, 1005 (2009)

rich molecular spectra

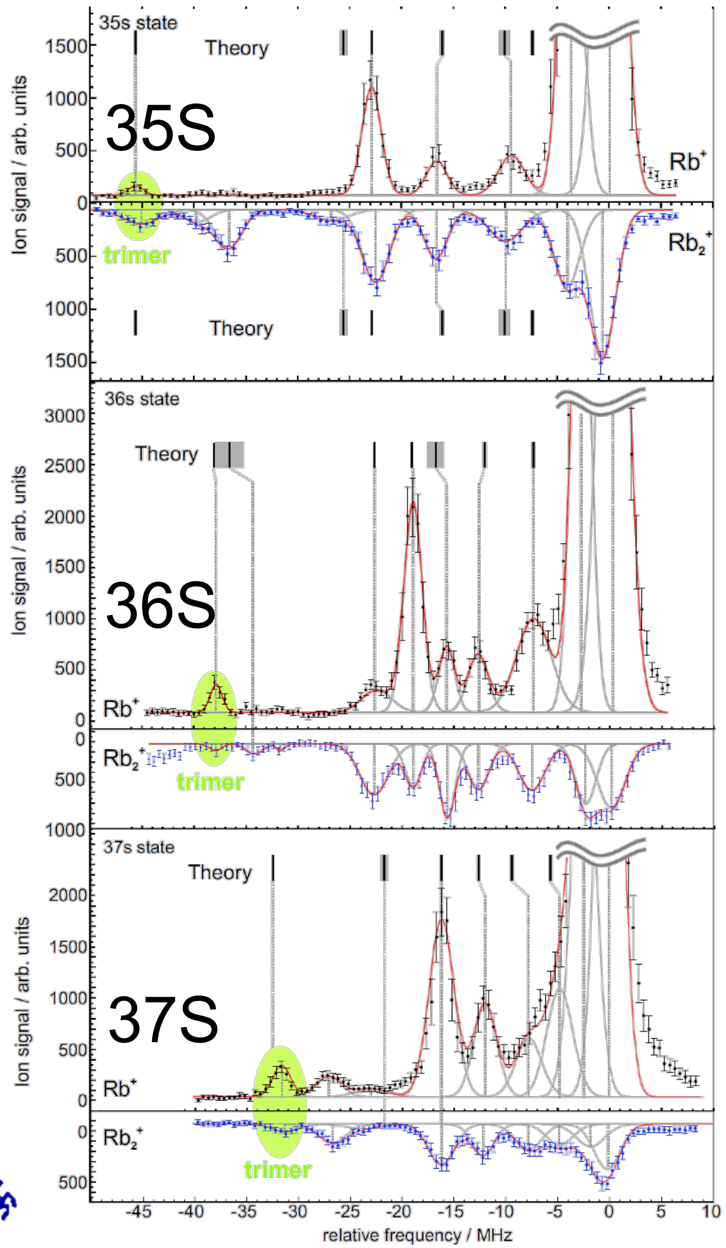
36S

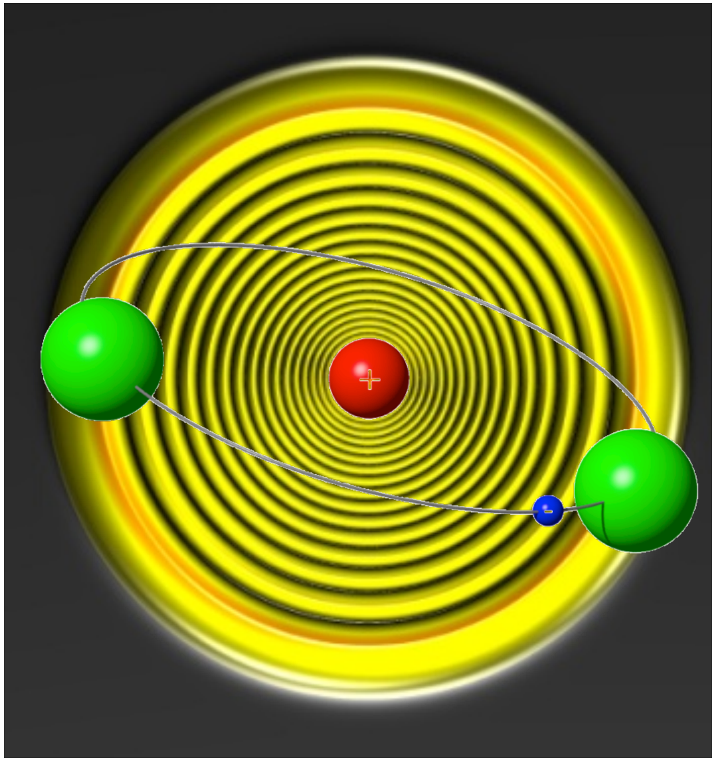




* molecule bound by s wave scattering

Ultralong-range trimers

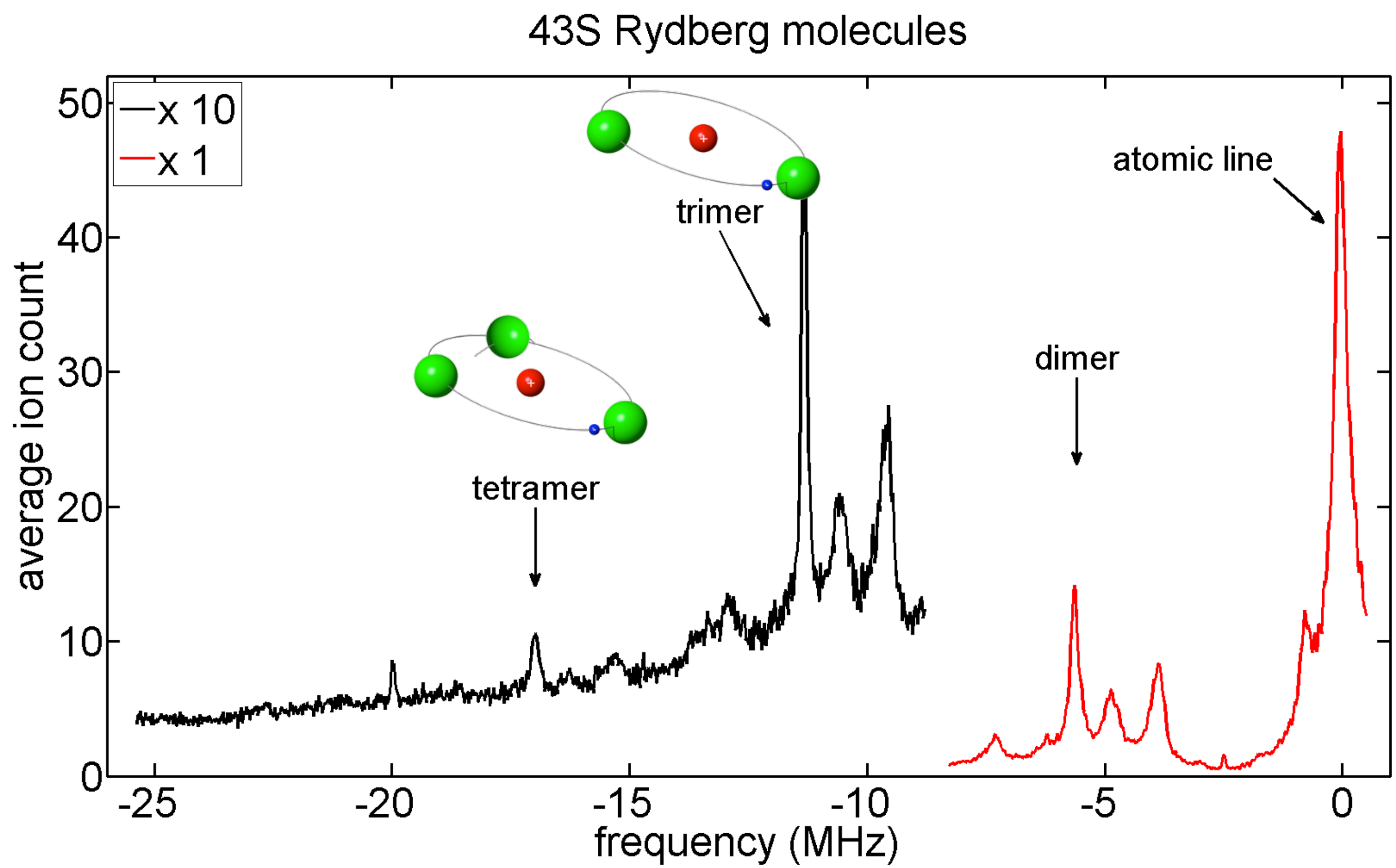




3 body photoassociation

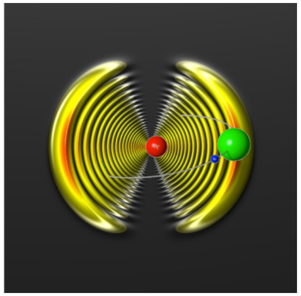
PRL **105**, 163201 (2010)

Ultralong-range trimers, and tetramers and…

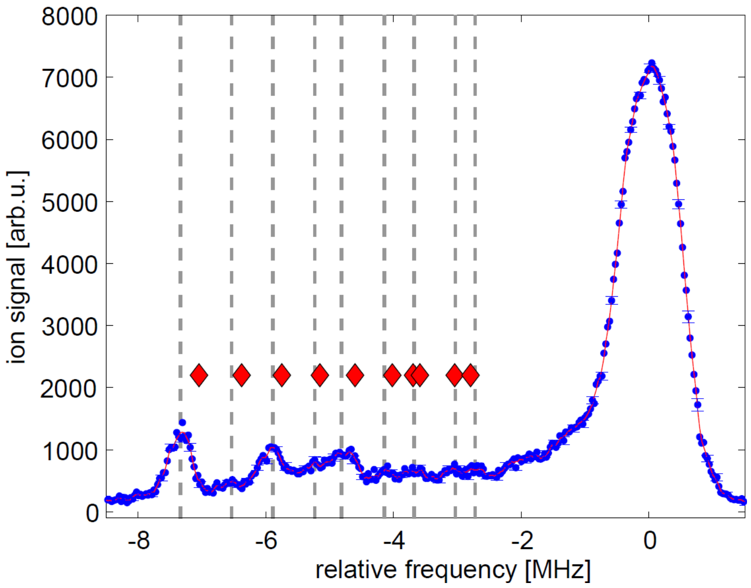


Increase l :
D state molecules show rovibrational states…

42 $D_{5/2}$ state

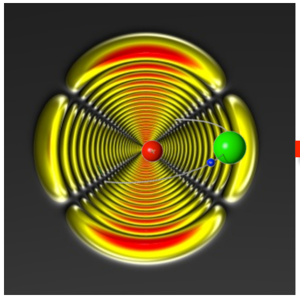


$m_J = 5/2$

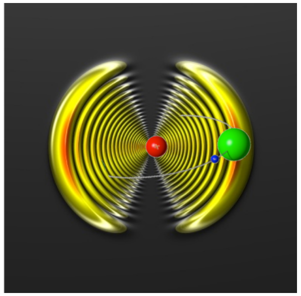


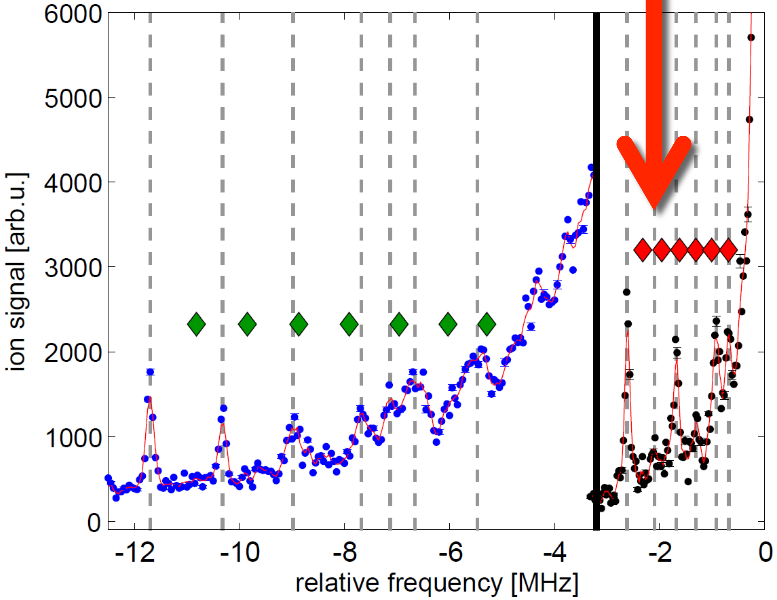
A. Krupp, M. Kurz, P. Schmelcher et al.
arXiv:1401.4111 (2014) accepted in PRL

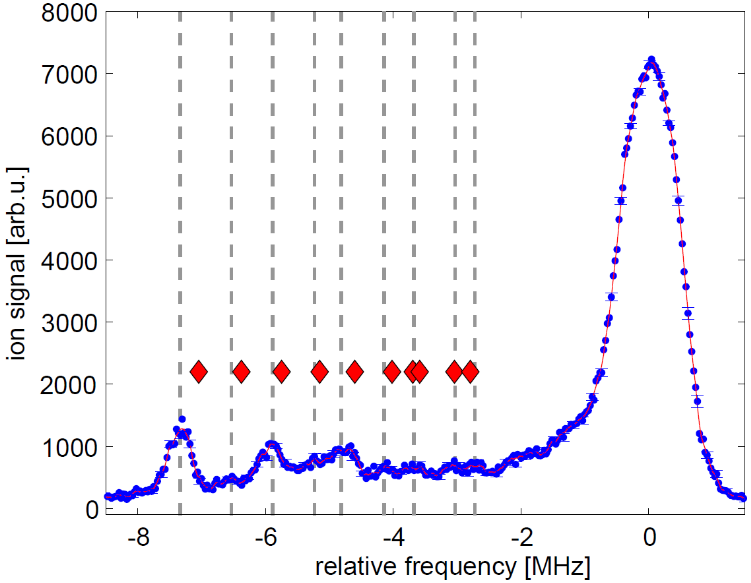
Increase l :
D state molecules show rovibrational states…



42 $D_{5/2}$ state

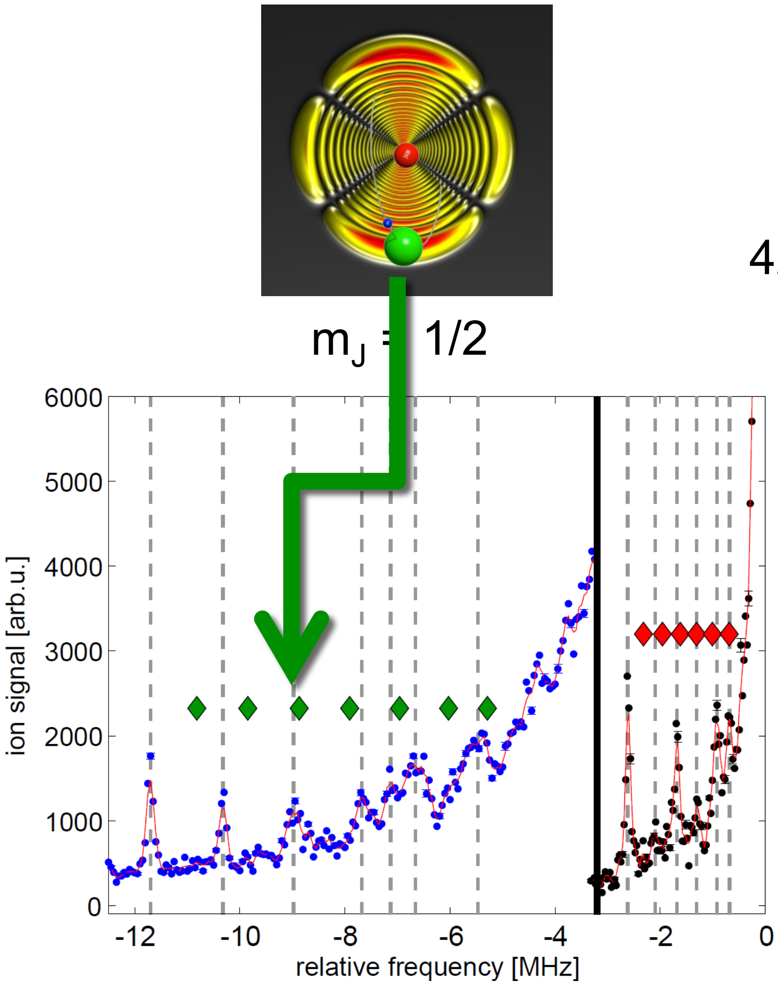




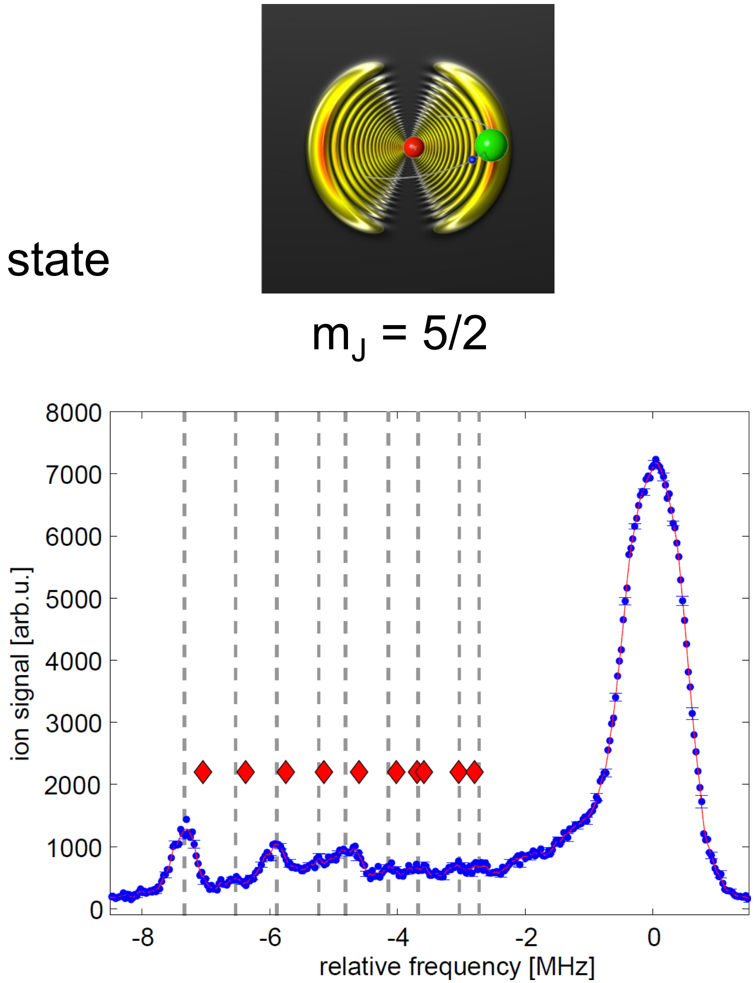


A. Krupp, M. Kurz, P. Schmelcher et al.
arXiv:1401.4111 (2014) accepted in PRL

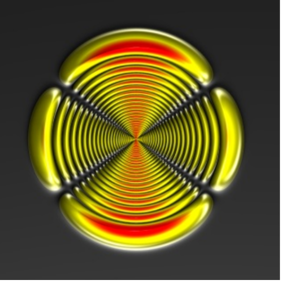
Increase l :
D state molecules show rovibrational states…



$42\ D_{5/2}$ state

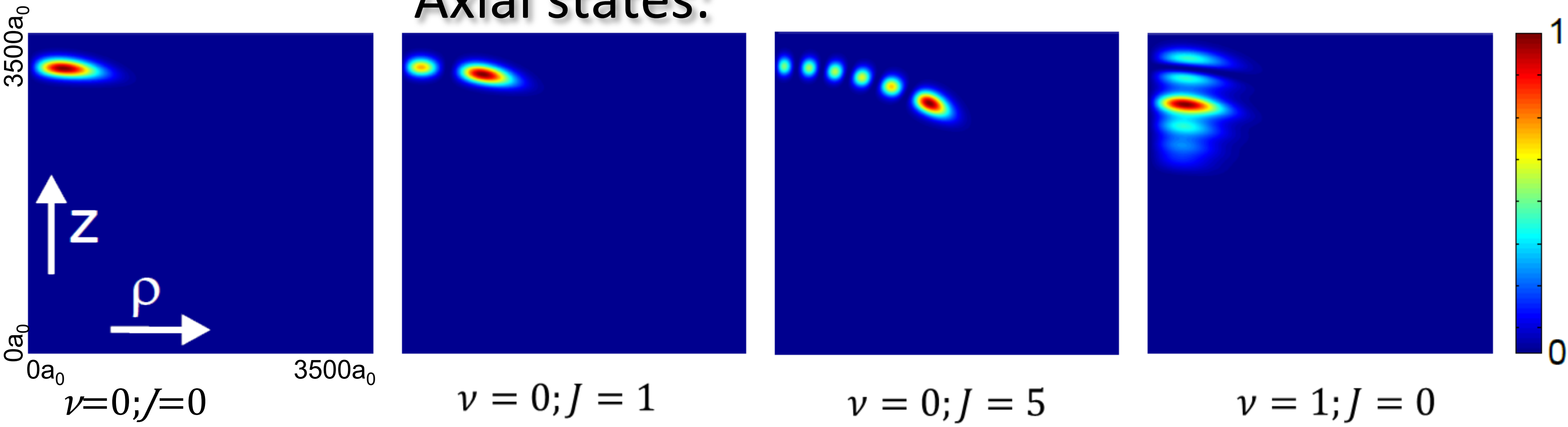


A. Krupp, M. Kurz, P. Schmelcher et al.
arXiv:1401.4111 (2014) PRL 2014

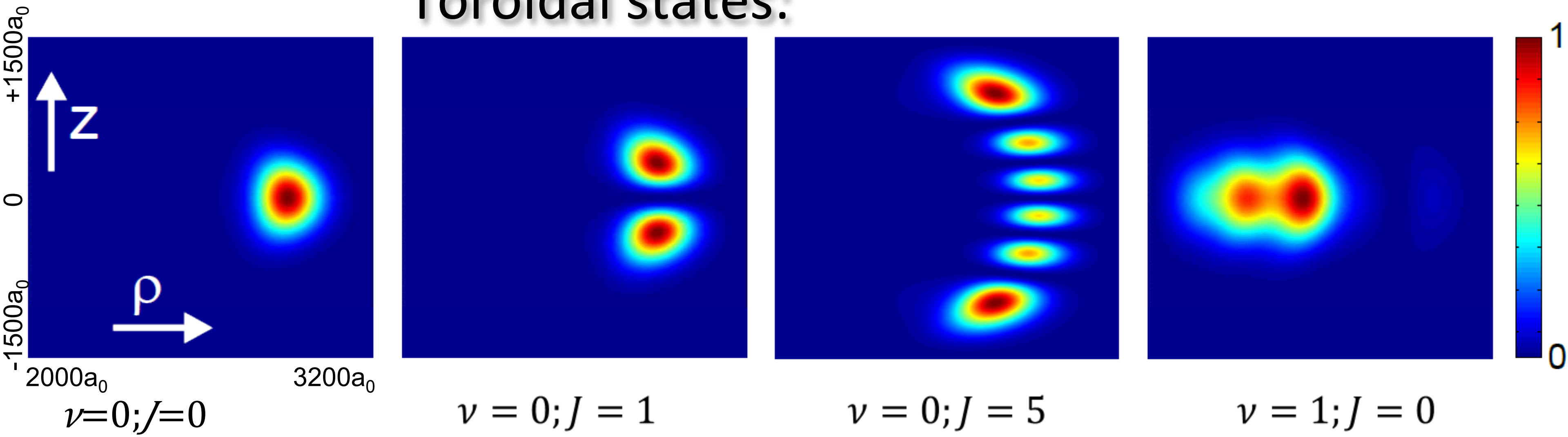


Scaled rovibrational probability densities

Axial states:



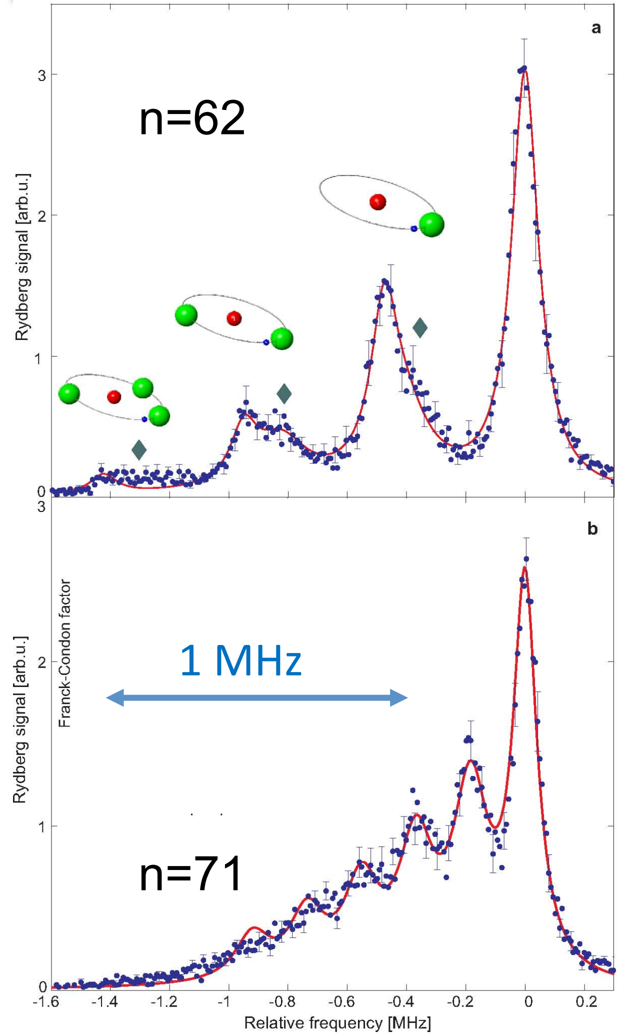
Toroidal states:



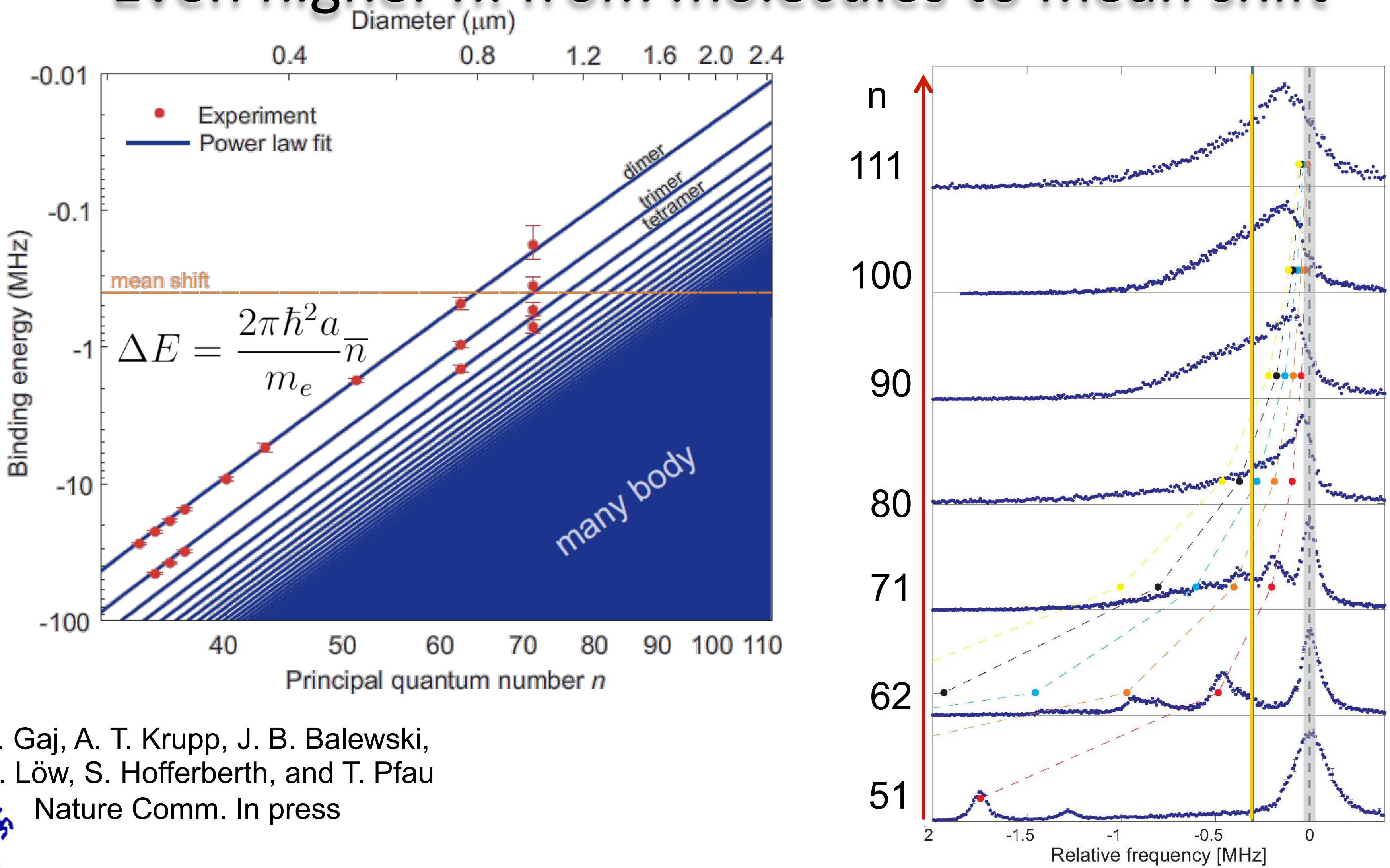
Going higher in n:
dimers, trimers, tetramers, pentamers …

Binding energy scales with principal quantum number

$$V_{\mathrm{mol}}(\vec{R}) = \frac{2\pi\hbar^2 a}{m_e}|\Psi(\vec{R})|^2 \sim n^{-6}$$

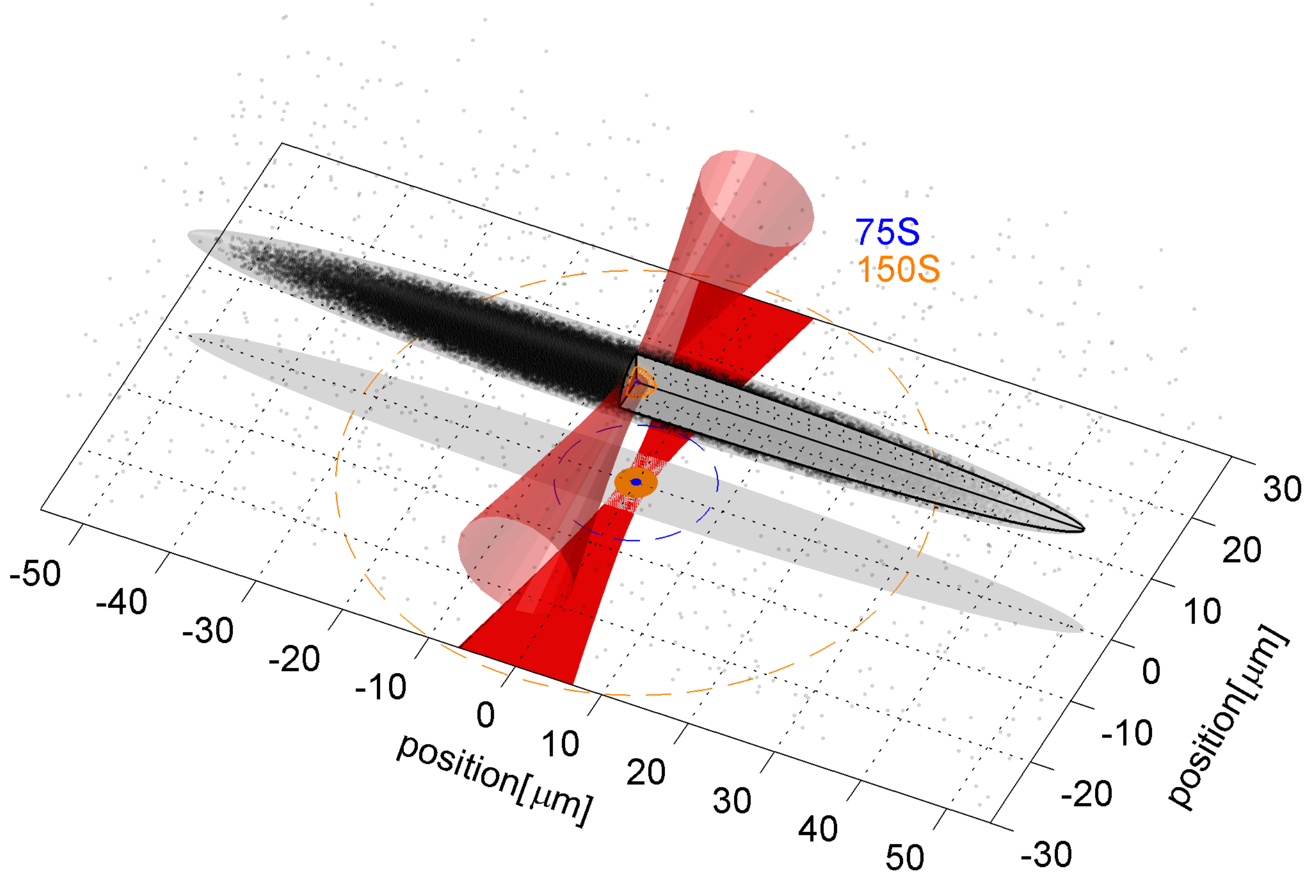


Even higher n: from molecules to mean shift

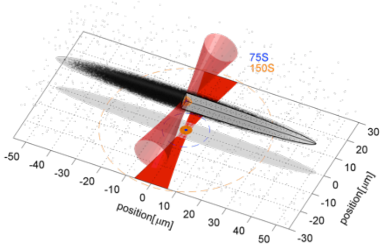


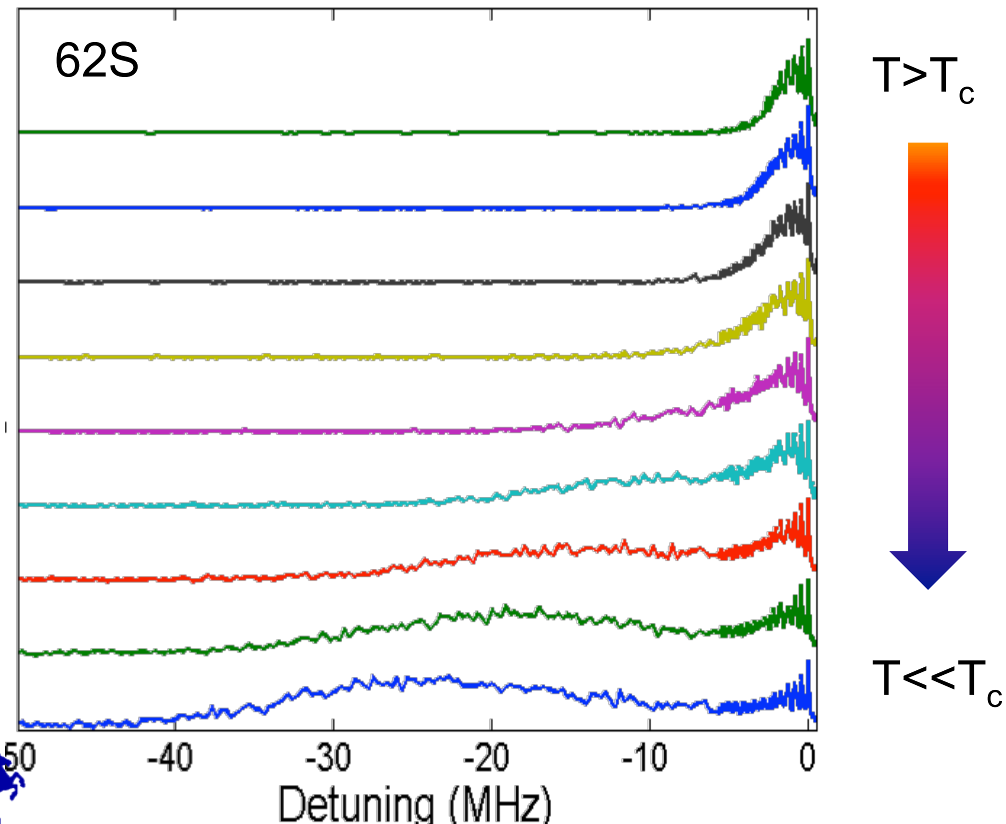
A. Gaj, A. T. Krupp, J. B. Balewski,
R. Löw, S. Hofferberth, and T. Pfau
Nature Comm. In press

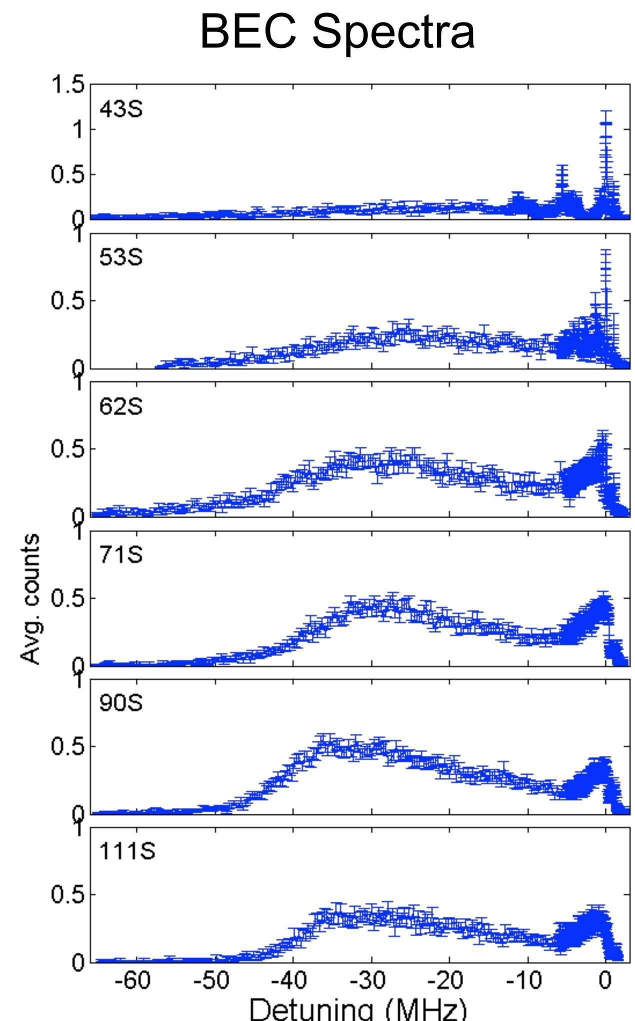
In situ Rydberg spectroscopy setup



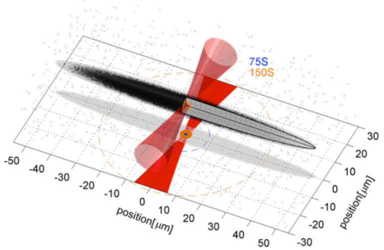
Increase density: Rydberg spectroscopy in a BEC

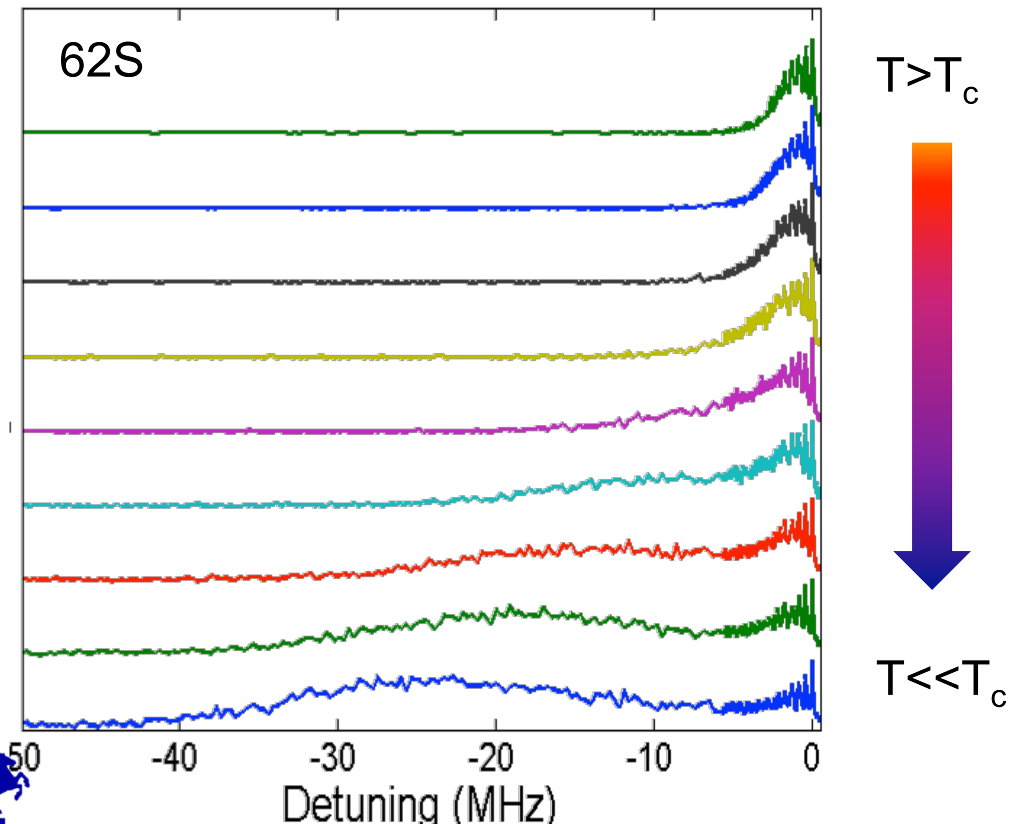


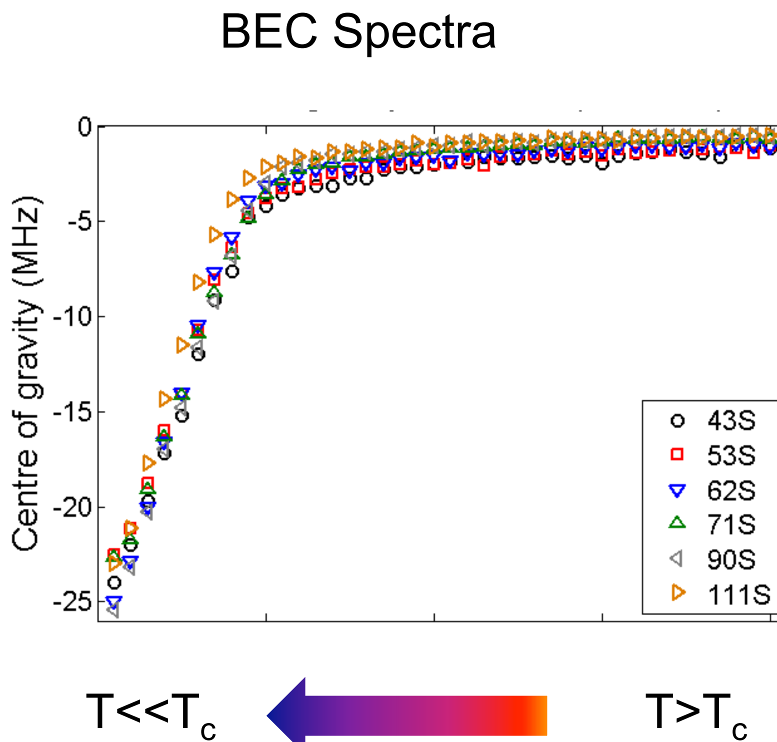




Increase density: Rydberg spectroscopy in a BEC



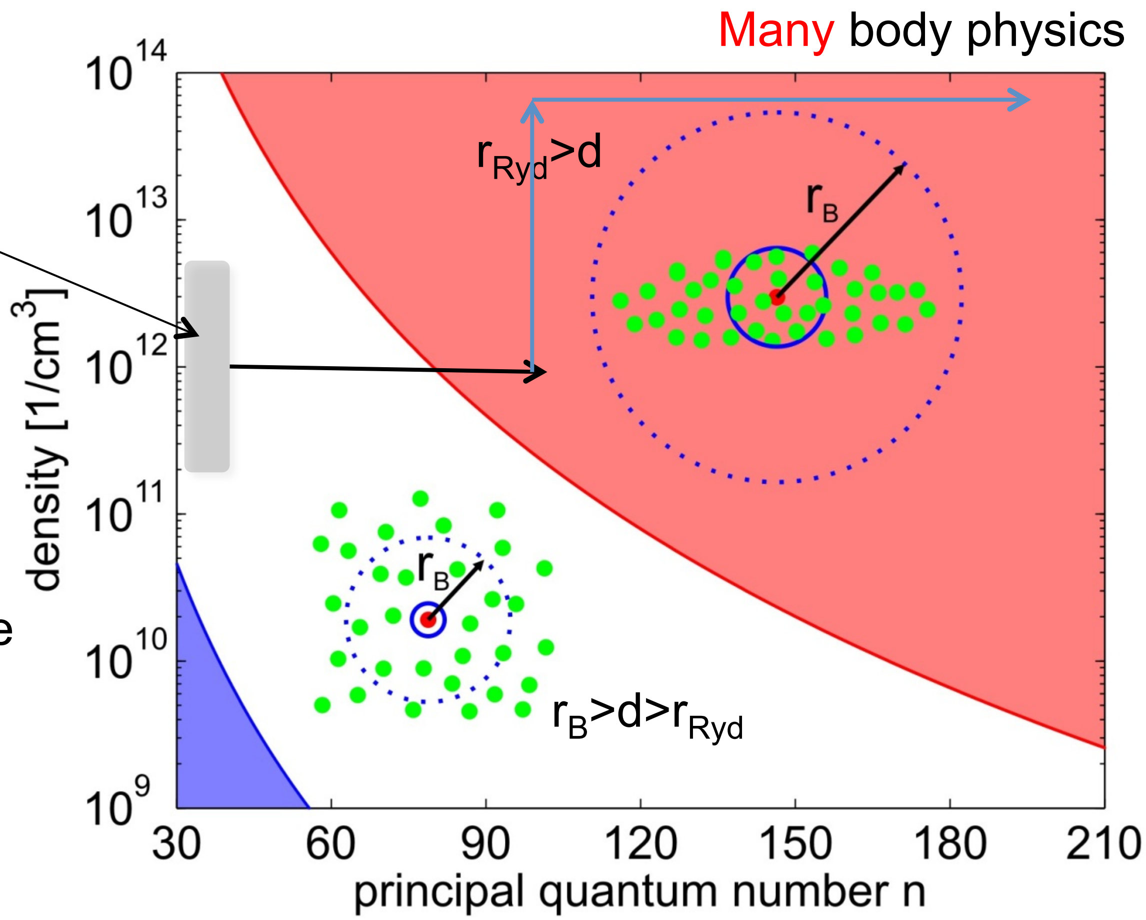




Length scales

probability to find an atom inside Rydberg electron wavefunction small, but finite!

Few body physics



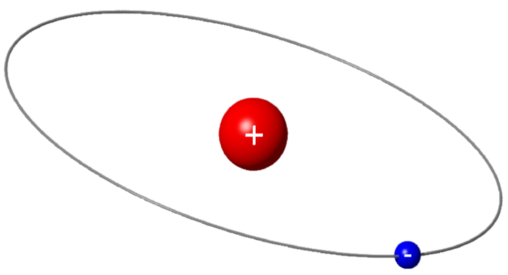
d: mean particle distance

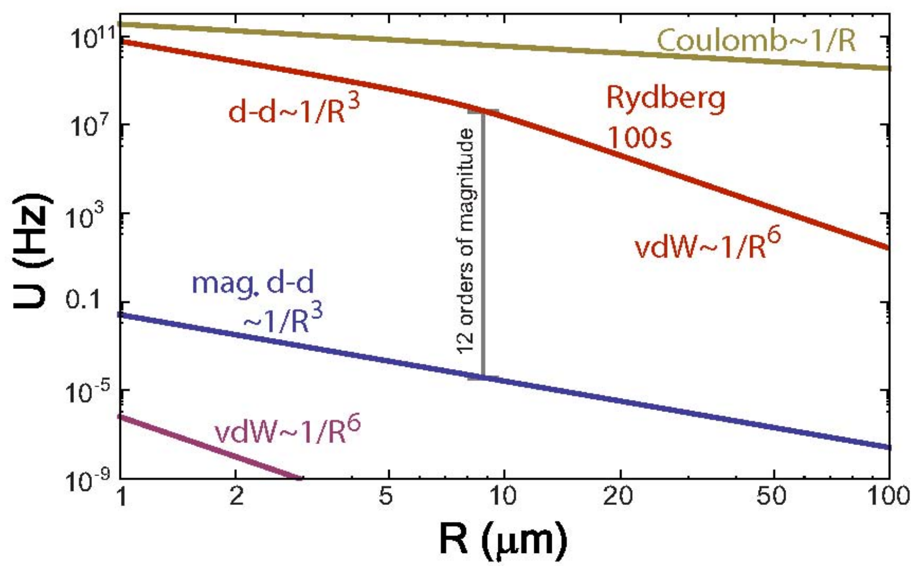
r_B: blockade radius

r_{Ryd}: size of electron orbit

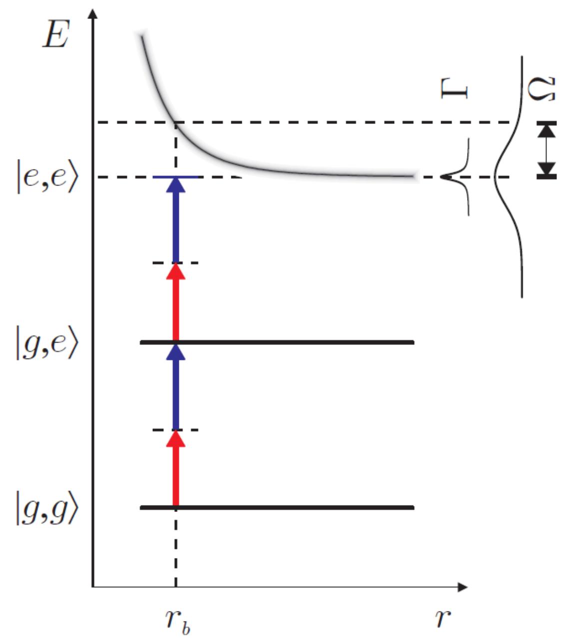
Rydberg atoms - Blockade

quantity	scaling	100S-state of ^{87}Rb
lifetime	$\propto n^3$	1.24 ms
Polarizability	$\propto n^7$	6.245 GHz $(V/cm)^{-2}$
Van der Waals C_6	$\propto n^{11}$	-3.89×10^{23} a.u.





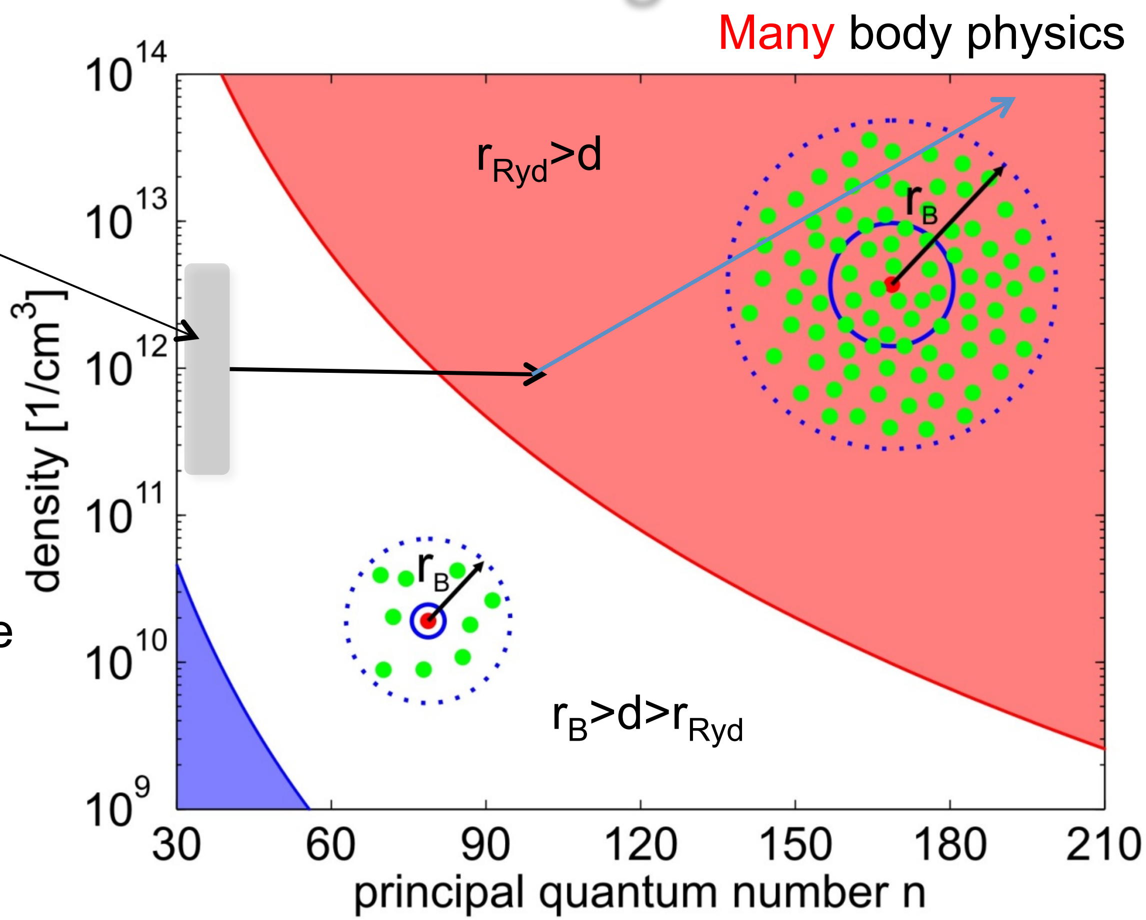
M. Saffman et al., Rev. Mod. Phys. 82, 2313 (2010)



Rydberg atoms in dense gases

probability to find an atom inside Rydberg electron wavefunction small, but finite!

Few body physics

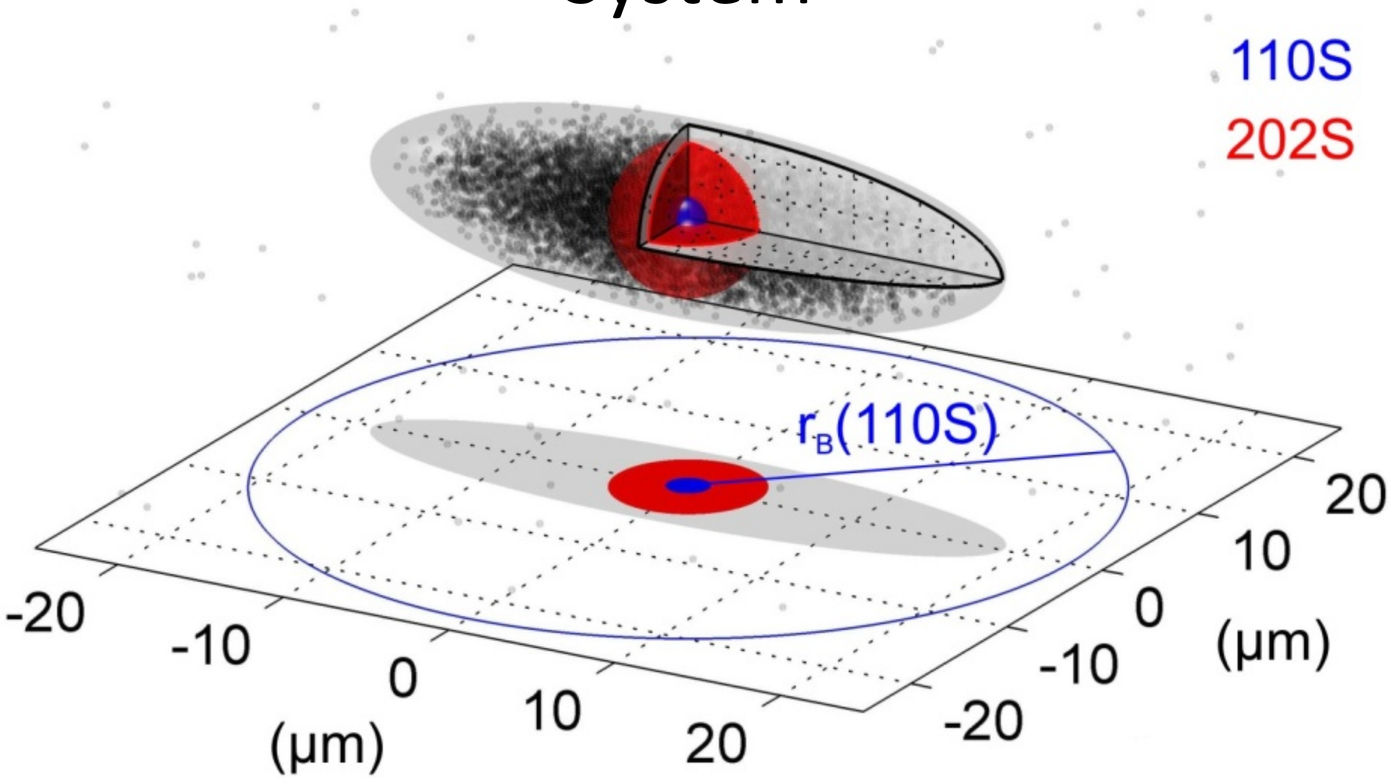


d: mean particle distance

r_B: blockade radius

r_{Ryd}: size of electron orbit

System

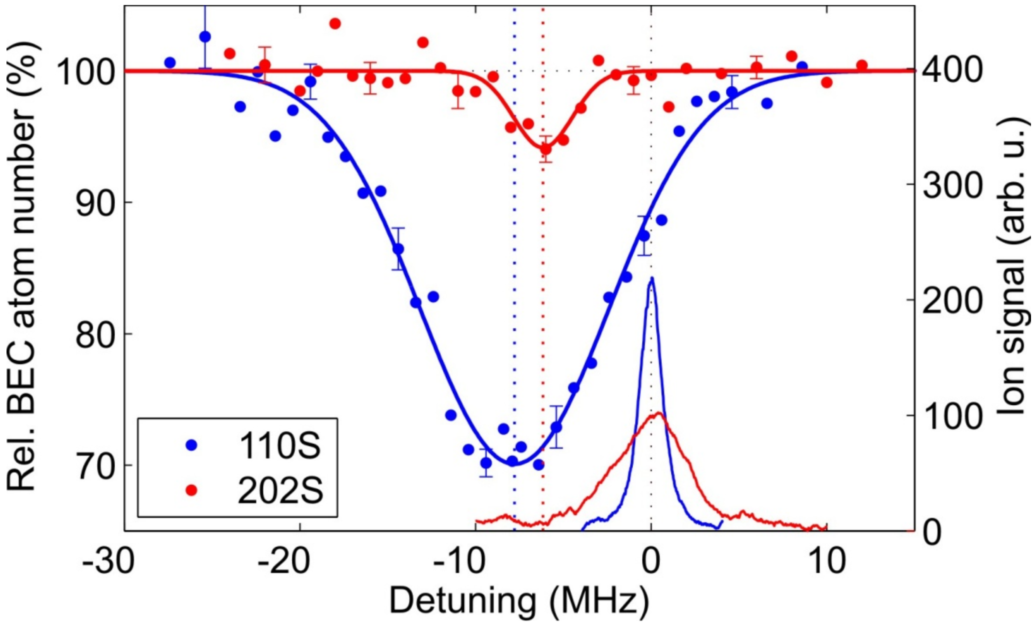


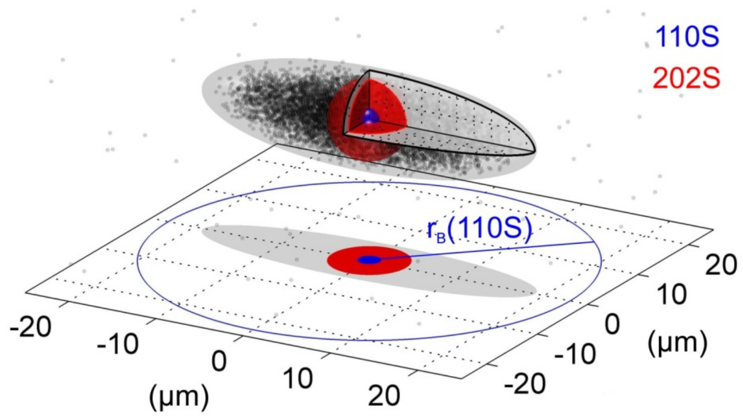
Rydberg: 1.2 µm radius / 4.2 µm radius

BEC: $8 \cdot 10^4$ atoms, 5 / 18 µm radial / axial TF-radius

$\Rightarrow$ 700 / 30000 atoms inside Rydberg atom

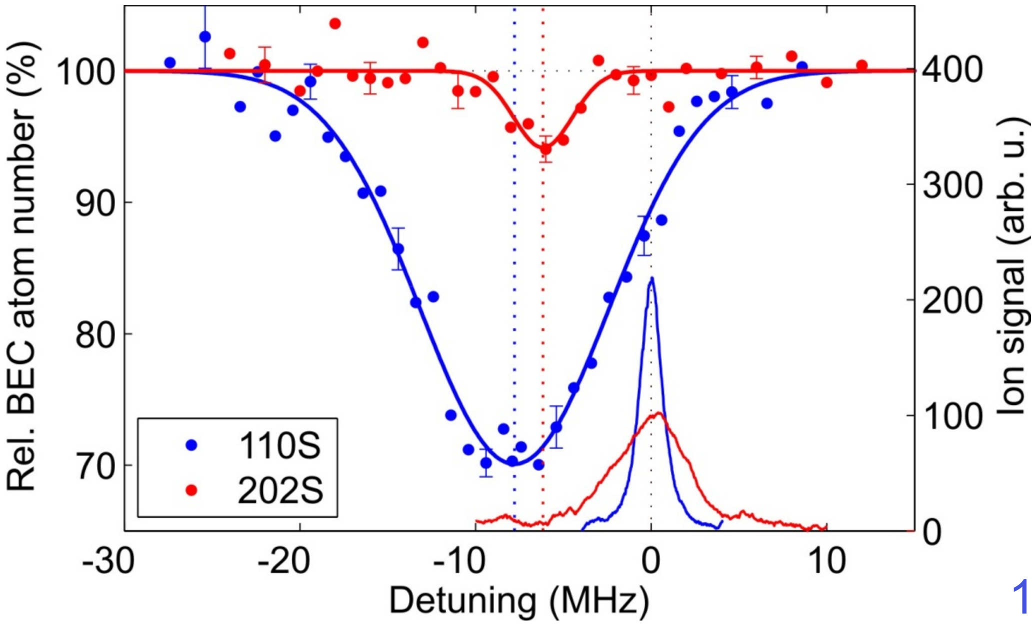
Effect of BEC on single Rydberg electron

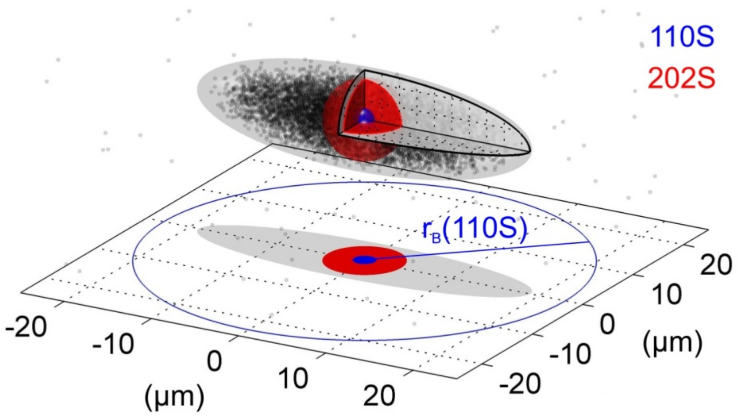




⇒ effect on Rydberg: lineshift ~10 MHz

Effect of single electron on BEC



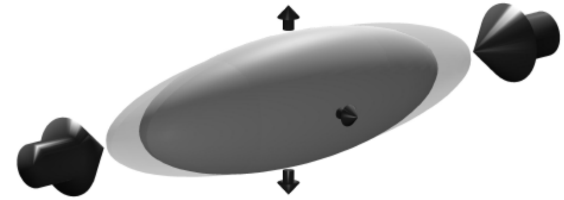


110S ~ 700 atoms inside
~ 50 atoms lost pp

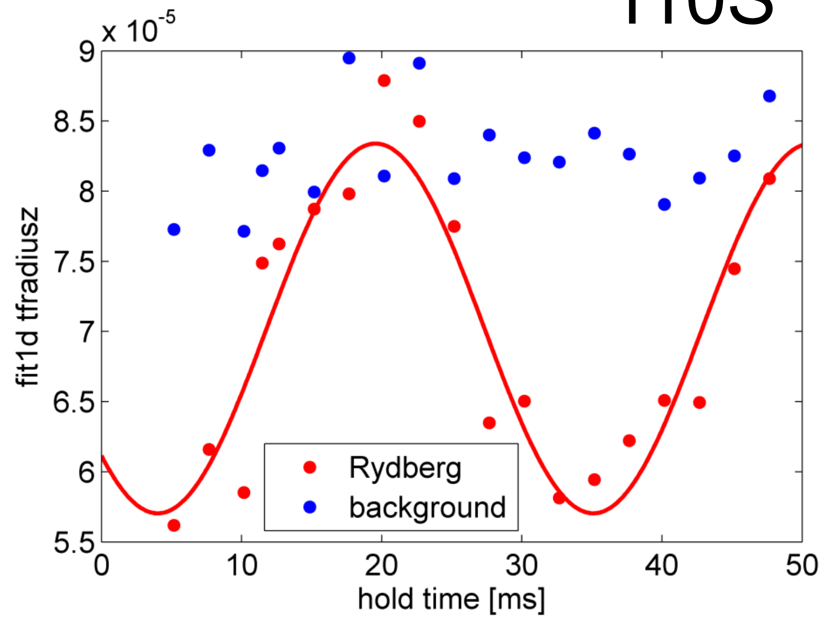
202S ~ 30000 atoms inside
~ 7 atoms lost pp

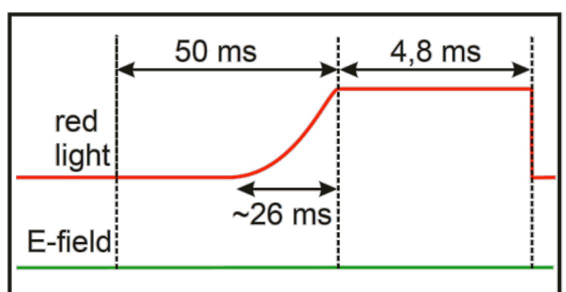
⇒ effect on Rydberg: lineshift ~10 MHz

Rydberg electron sets BEC in motion

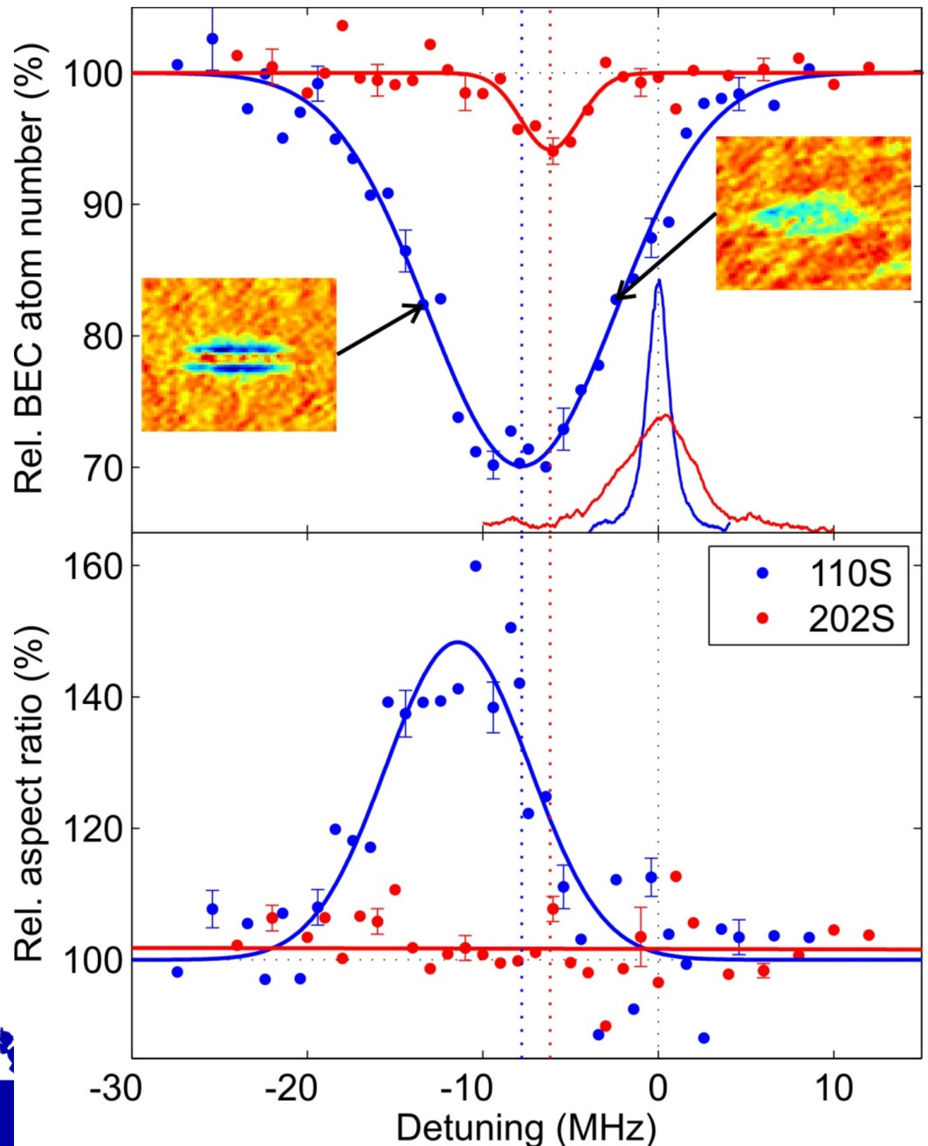


110S





Effect of single electron on BEC



110S ~ 700 atoms inside

~ 50 atoms lost pp

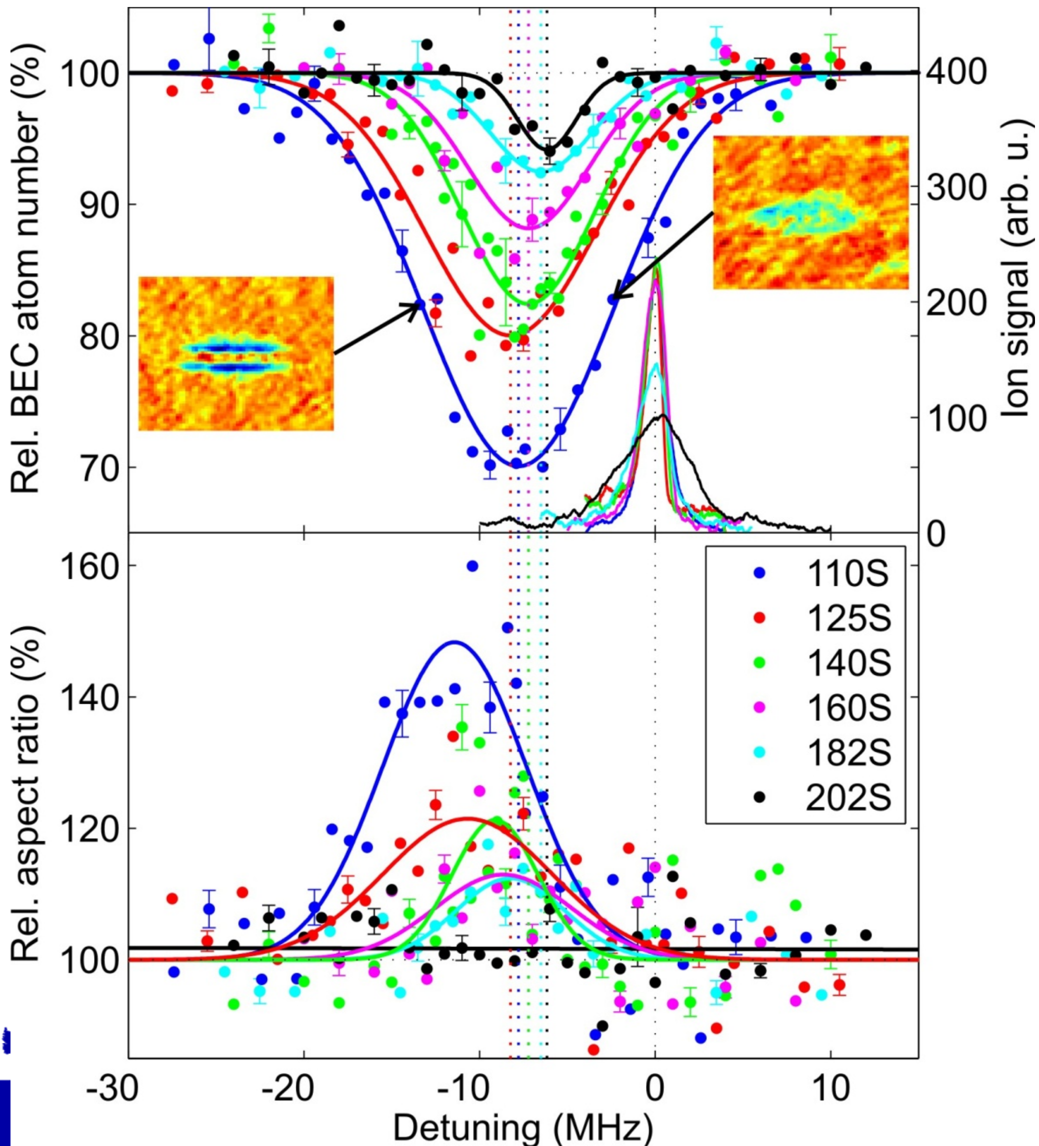
strong mechanical effects

202S ~ 30000 atoms inside

~ 7 atoms lost pp

no mechanical effects

Effect of single electron on BEC

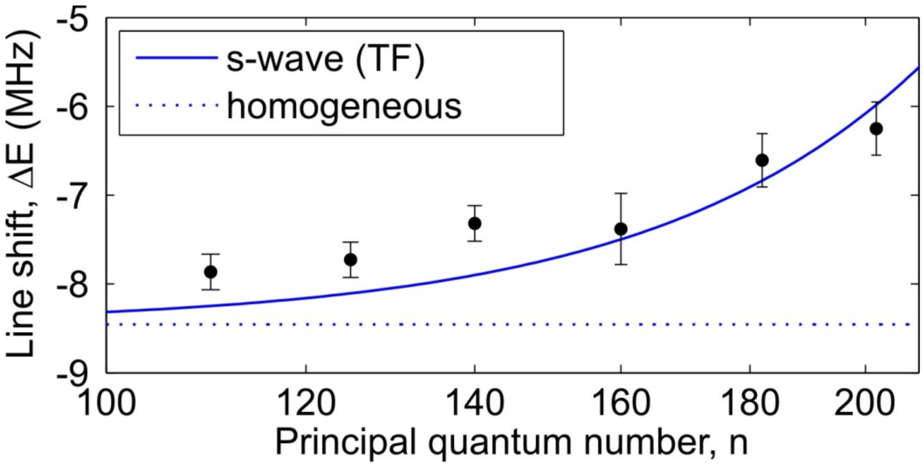


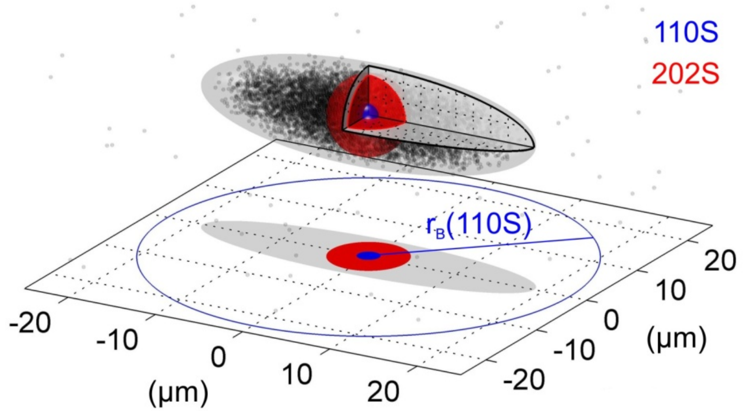
110S ~ 700 atoms inside
~ 50 atoms lost pp
strong mechanical effects

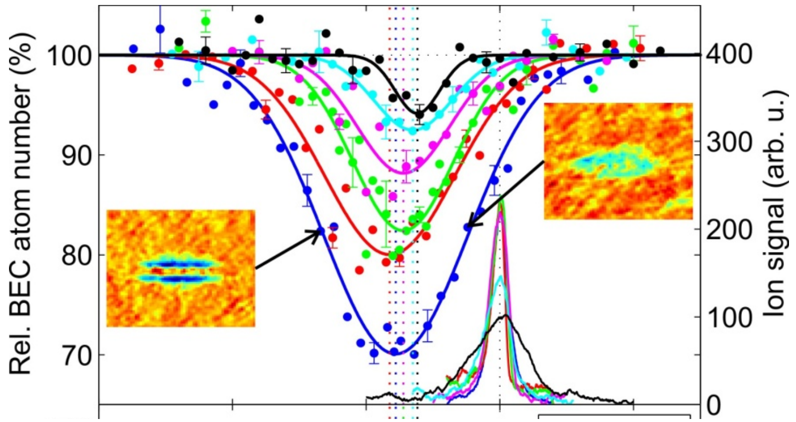
202S ~ 30000 atoms inside
~ 7 atoms lost pp
no mechanical effects

J.B. Balewski, A.T. Krupp, A.Gaj, D. Peter, H. P. Büchler, R. Löw, S. Hofferberth and T. Pfau, [Nature, **502**, 664 (2013)]

Line shift





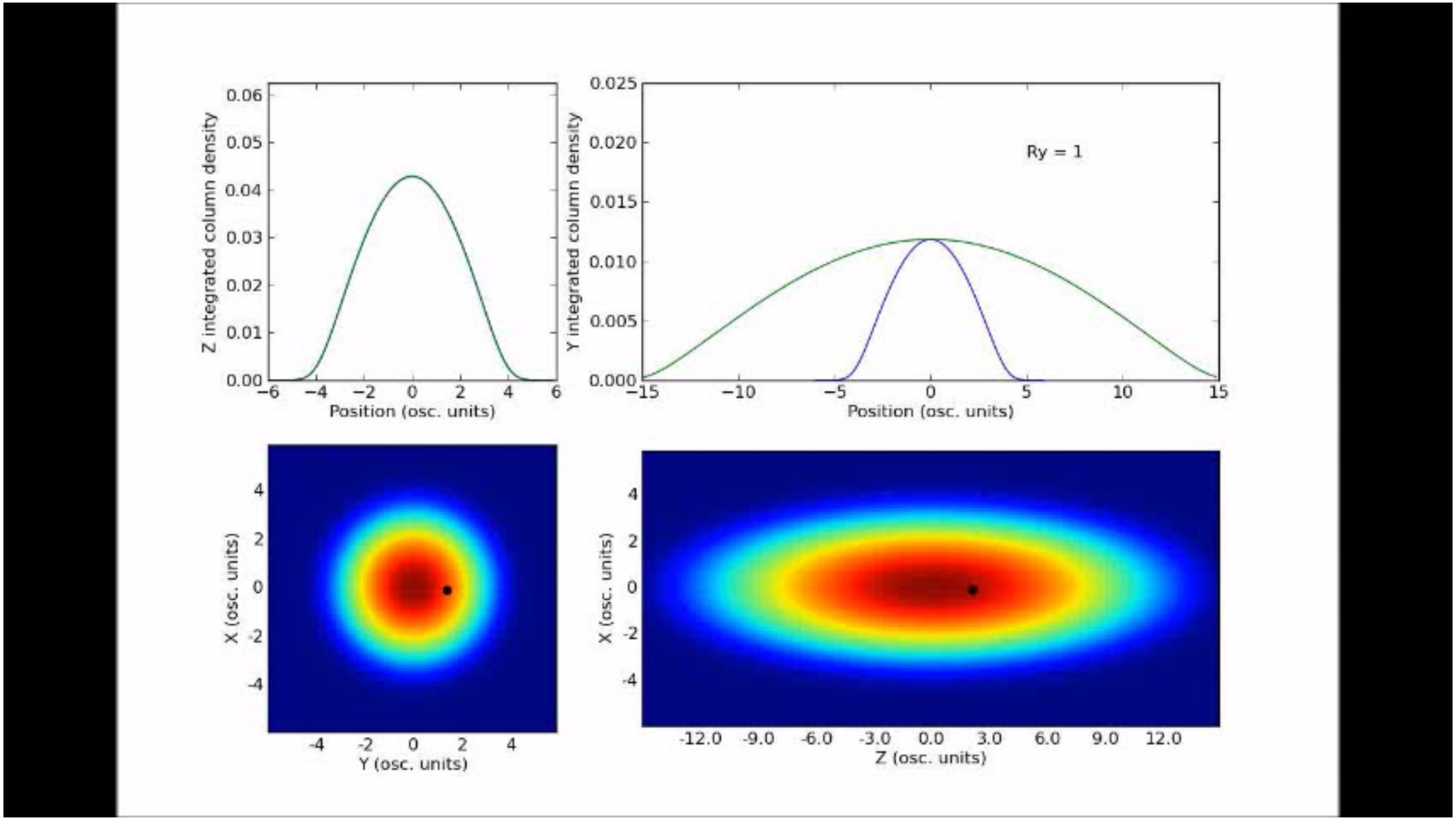


- line shift depending only on mean density n:

$$\Delta E = \frac{2\pi\hbar^2 a}{m_e}\overline{n}$$ (cf. Amaldi, Segrè, 1934)

- density not homogeneous (Thomas-Fermi)

Solving GP equation for our parameters



T. Karpiuk, M. Brewczyk, K. Rzążewski

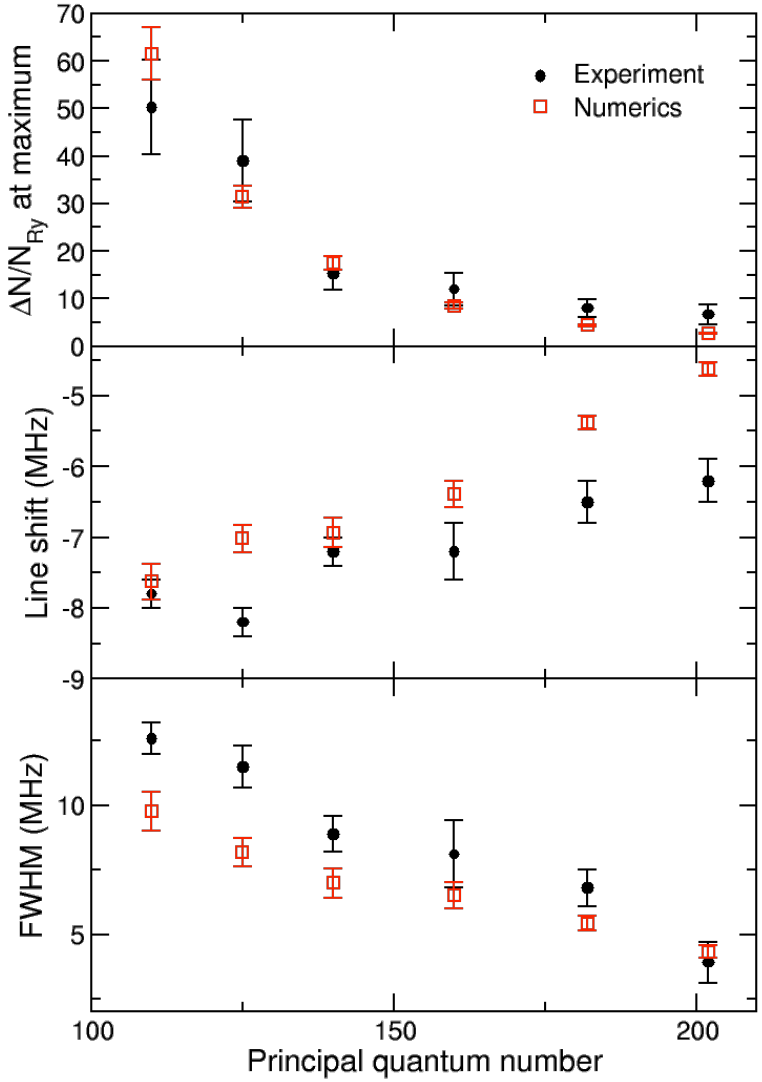
Loss after ToF – numerics

collaboration with Tomasz Karpiuk, Mirosław Brewczyk and Kazimierz Rzążewski (Warsaw, Poland) arXiv: 1402.6875

Methods:

- Monte-Carlo simulation of excitation process
- time evolution of Gross-Pitaevskii equation for BEC
- Classical field approximation to extract atom loss

PRA 81, 013629 (2010)



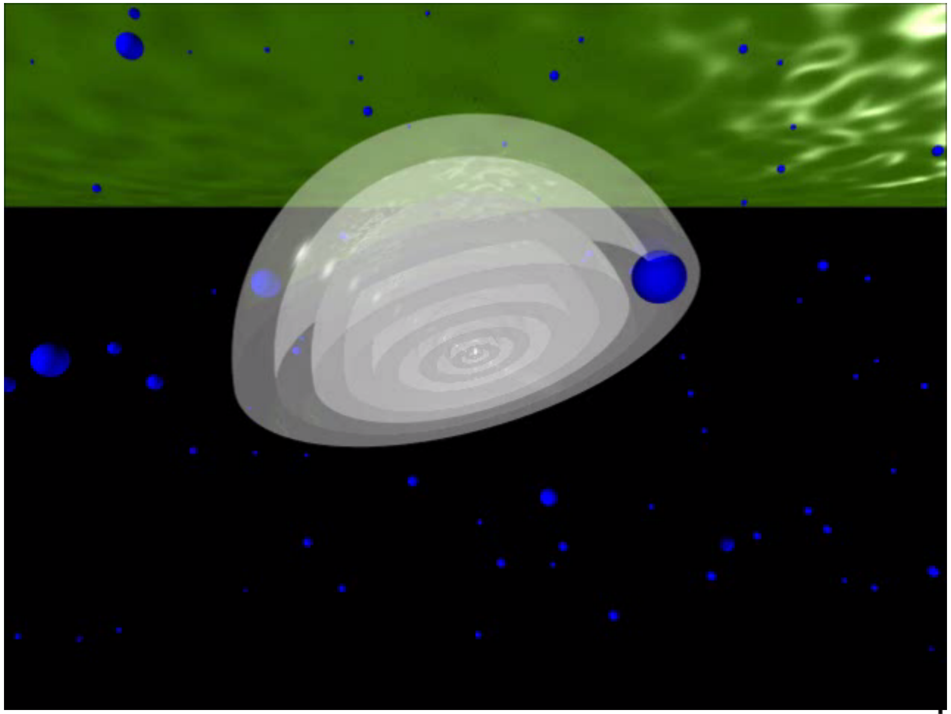
Combining high Rydberg states and BEC

- Rydberg core serves as e^- - trap

- Rydberg blockade allows only one single electron

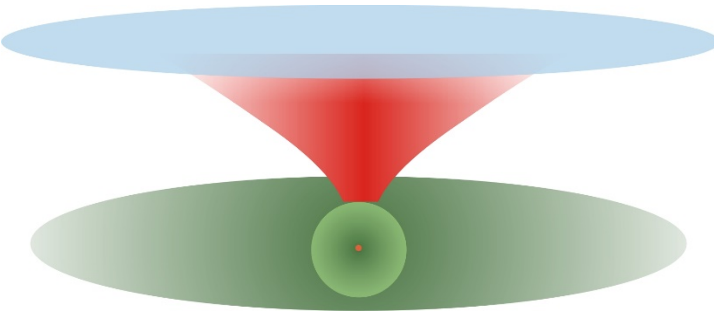
- quasifree electron in pure state

  → 700-30.000 atoms within wavefunction



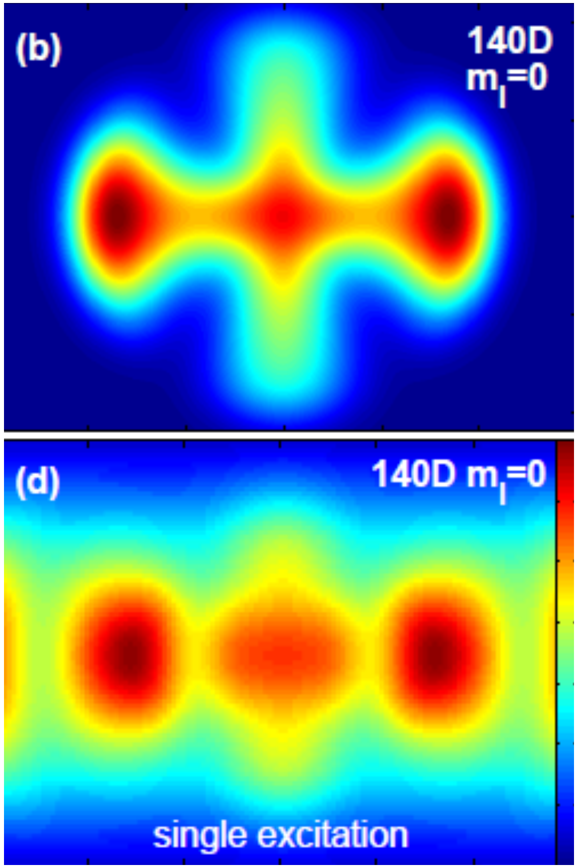
⇒ strong coupling of charged impurity to BEC excitations

Wavefunction^2 imaging of single electrons



Excite single Rydberg atom

$$\int \left|\Psi(\vec{r})\right|^2 dz$$



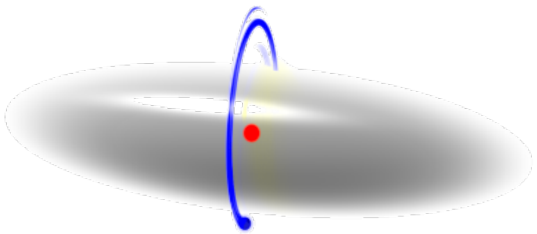
BEC as contrast agent
(GP simulation)

T. Karpiuk, M. Brewczyk, K. Rzążewski, J. B. Balewski,
A. T. Krupp, A. Gaj, M. Schlagmüller, R. Löw, S. Hofferberth, and T. Pfau
"Detecting and imaging single Rydberg electrons in a Bose-Einstein condensate"
arXiv:1402.6875

Ion – BEC interaction?

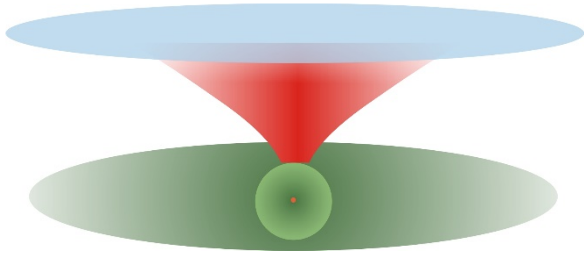
new approach to prepare a single ion in a BEC?

Idea 1:
high n circular (l>>0) state



electron outside the BEC shields ion

Idea 2:
hold ion in optical trap



„magic“ wavelength (430nm) ODT for ion

The COLD Rydberg team

W Li, T Pohl, JM Rost
ST Rittenhouse, HR Sadeghpour,
D Peter, HP Büchler,
K Rzążewski, M Brewczyk
M. Kurz, P. Schmelcher

Sebastian Hofferberth: Rydberg quantum optics

CO.CO.MAT
SFB/TRR 21