Universität Stuttgart

COHERENCE

Rydberg molecules

Pisa

Sept, 18th - 2012

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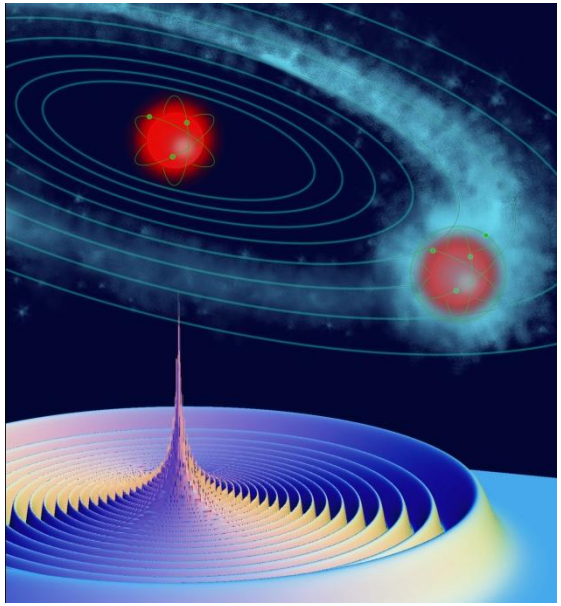
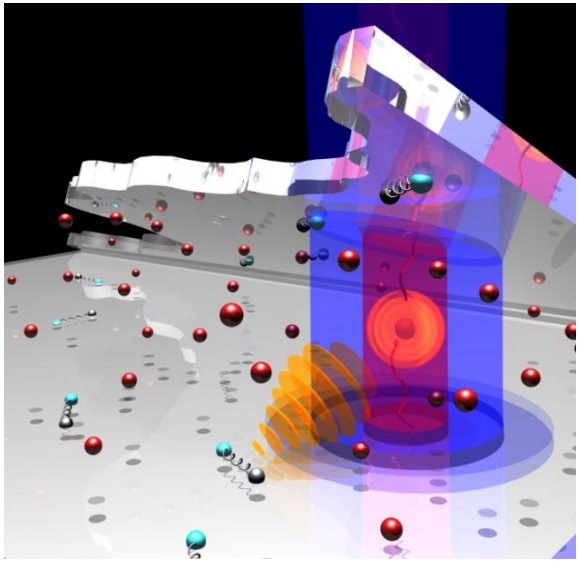
H Sadeghpour, JM Rost, T Pohl, S Rittenhouse, W Li, J Shaffer

Research topics



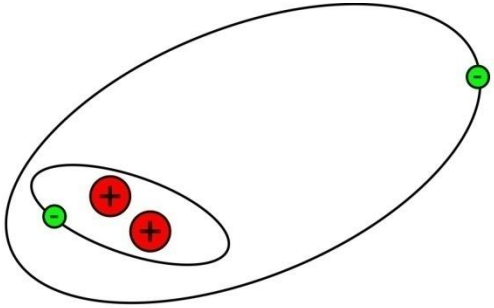
Rydberg molecules

Frozen Rydberg gases

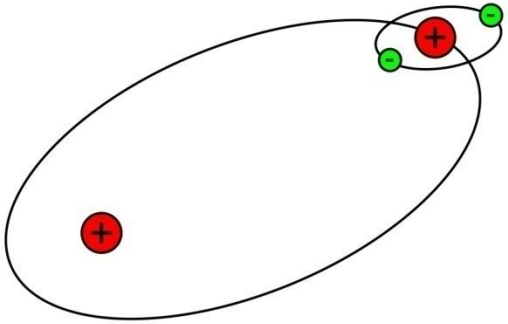


μ-cells

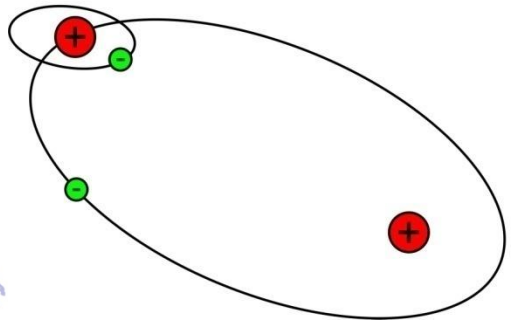
Rydberg molecules



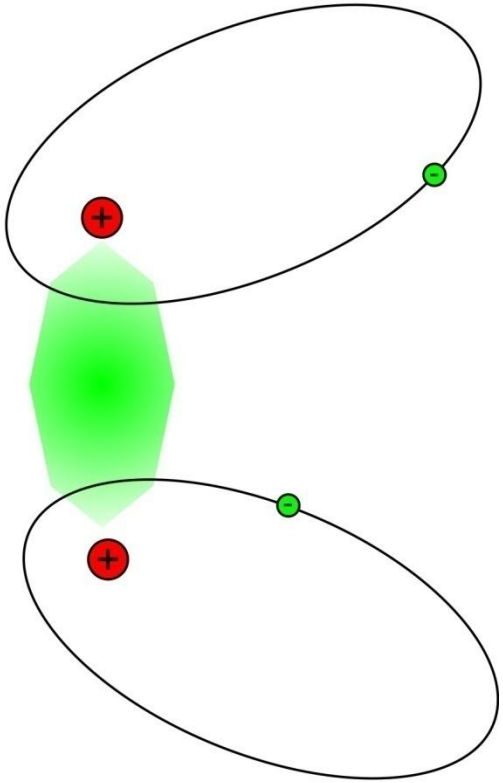
Ordinary Rydberg molecules



Heavy Rydberg

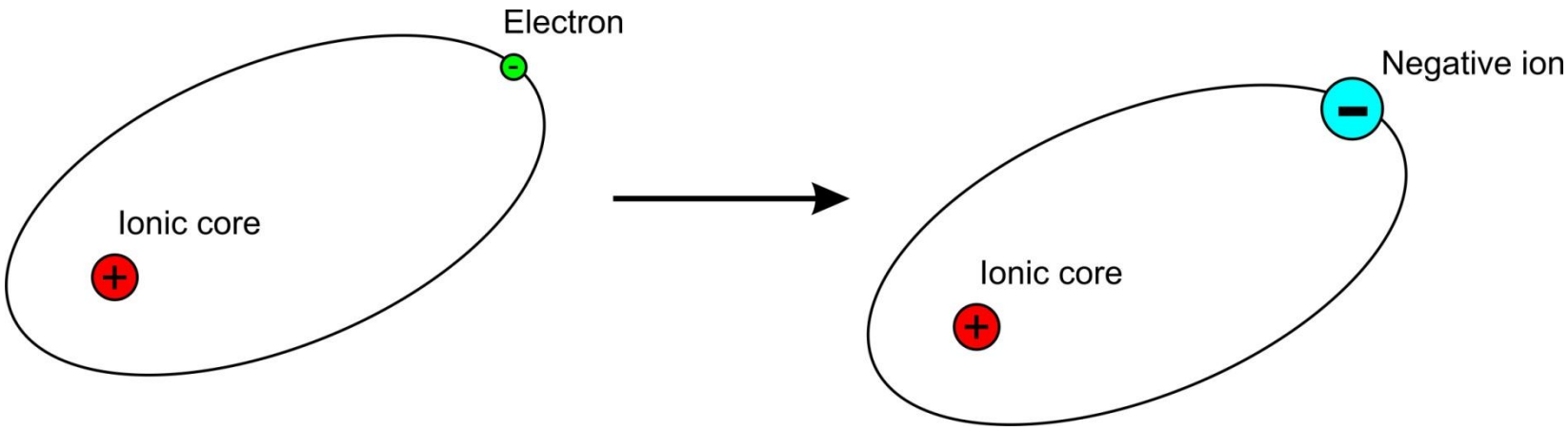


Trilobite Rydberg molecules



Rydberg-Rydberg molecules

Heavy Rydberg



$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$

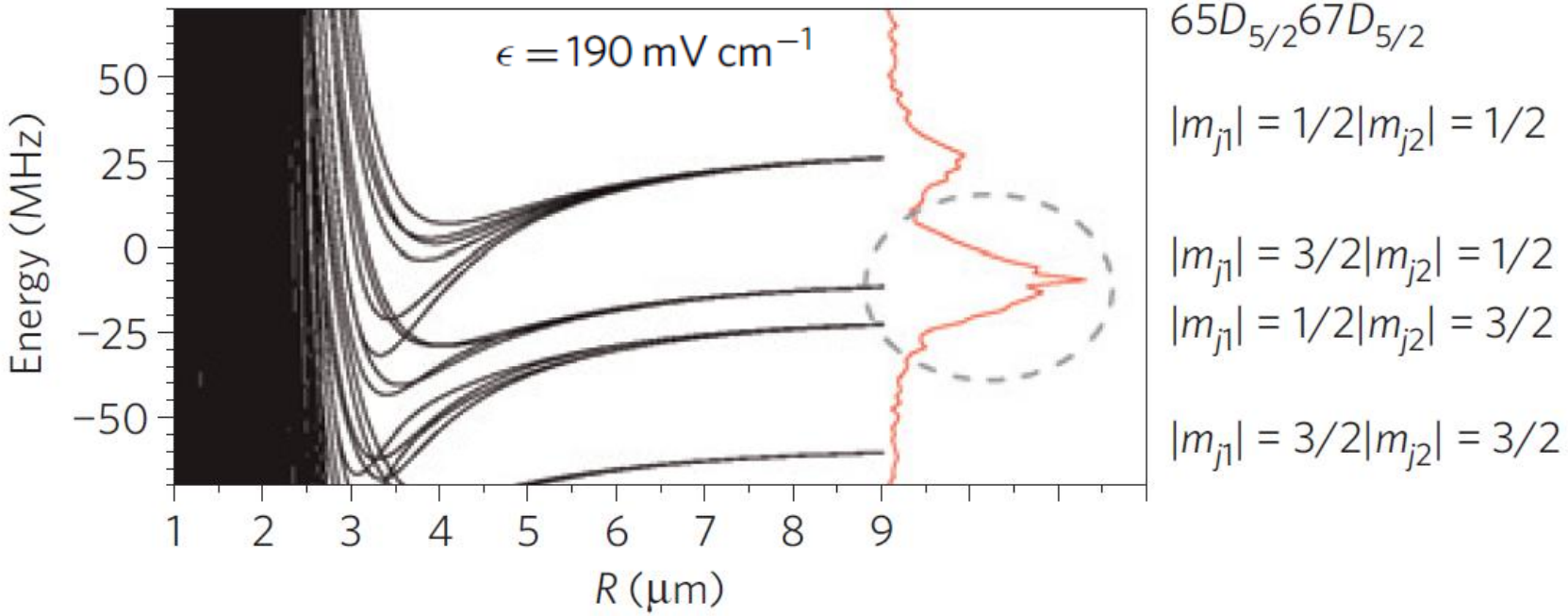
Larger reduced mass

$$\tau^2 = \frac{16\pi^3 \varepsilon_0 \mu}{Ze^2} a^3$$

Kepler‘s third law -> larger time periods

Wim Ubachs
Amsterdam

Observation of Cs Rydberg atom macrodimers

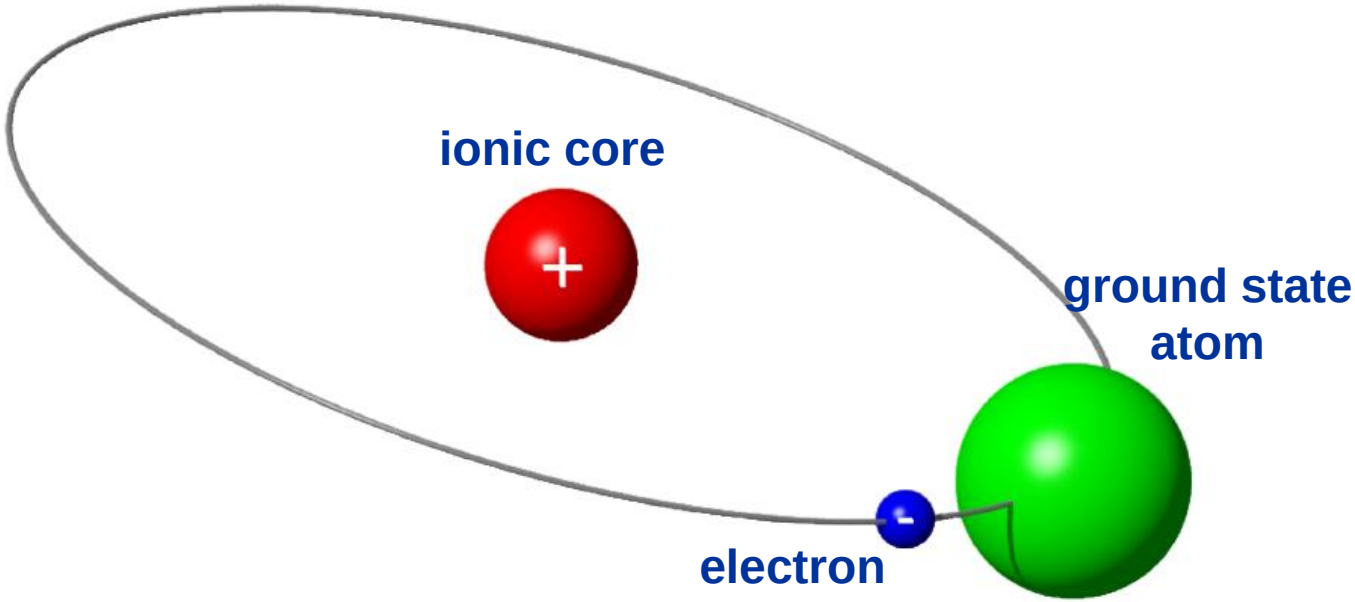


Nature Physics **5**, 581 - 585 (2009)

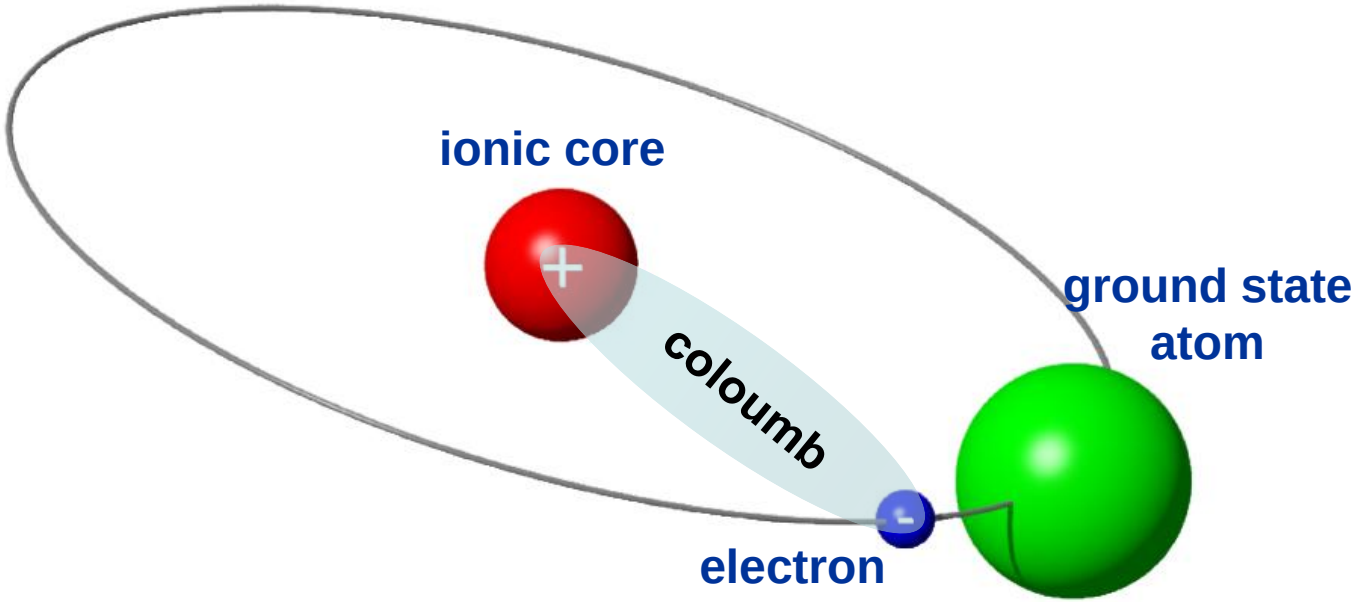
Oklahoma

Jim Shaffer
Oklahoma

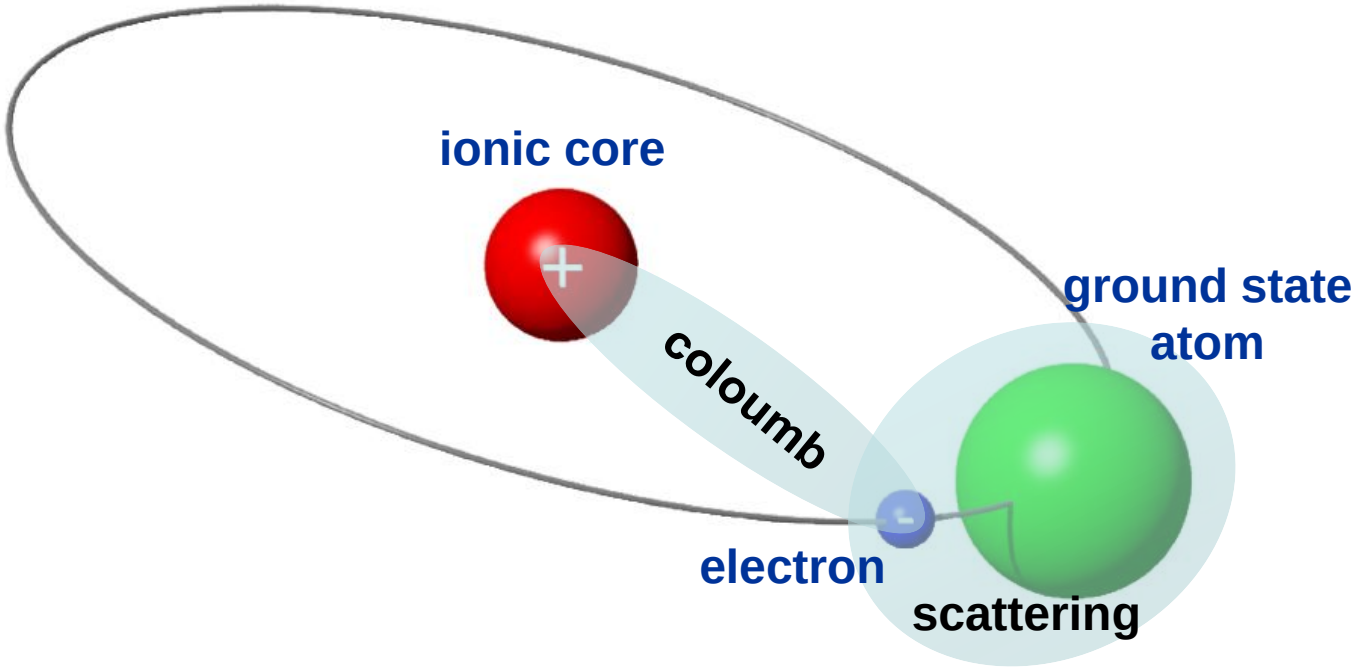
Rydberg molecules



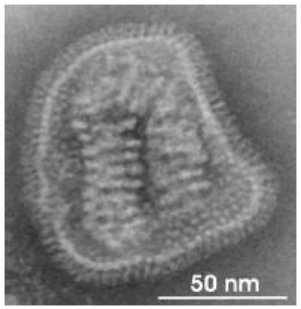
Rydberg molecules



Rydberg molecules



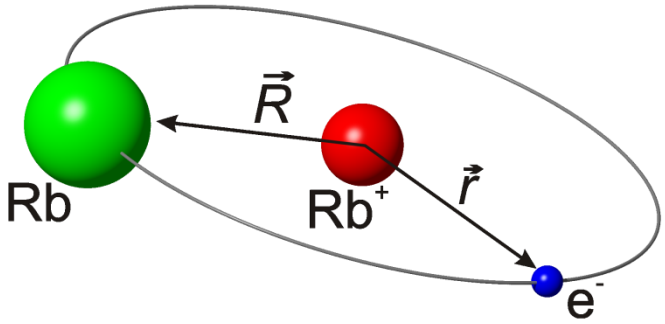
Rydberg molecules



Electron-atom scattering

neutral Rb polarized by electron

$$V_{pol}(\vec{r},\vec{R}) = -\frac{1}{2}\alpha\vec{E}^2 \propto \frac{1}{|\vec{R}-\vec{r}|^4}$$



quantum mechanical s-wave scattering

- **pseudopotential**

$$V_{pseudo}(\vec{r},\vec{R}) = 2\pi a(k)\delta(\vec{r}-\vec{R})$$

E. Fermi: Nuovo Cimento 11 (1934)

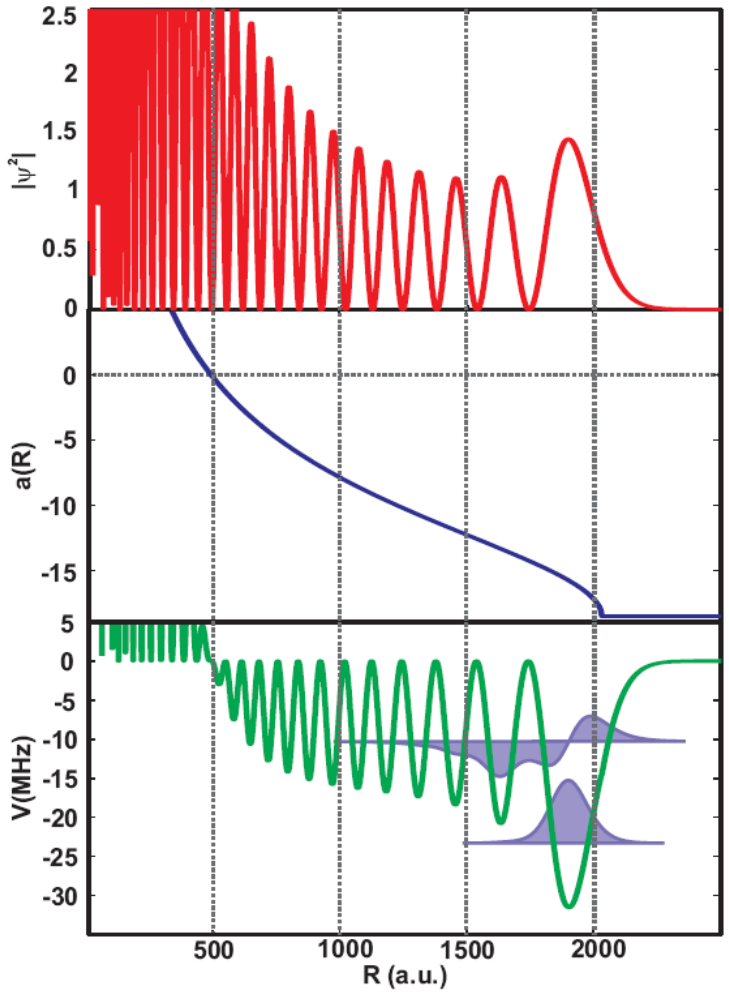
- **scattering length**

$$a\left[k(R)\right] = a_0 + \frac{\pi\alpha}{3}k(R) + O(k^2)$$

- **classical k-dependence of Rydberg electron**

$$\frac{1}{2}k^2(R) = -\frac{1}{2n^2} + \frac{1}{R}$$

Simplest possible model for the molecular potential



probability density

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

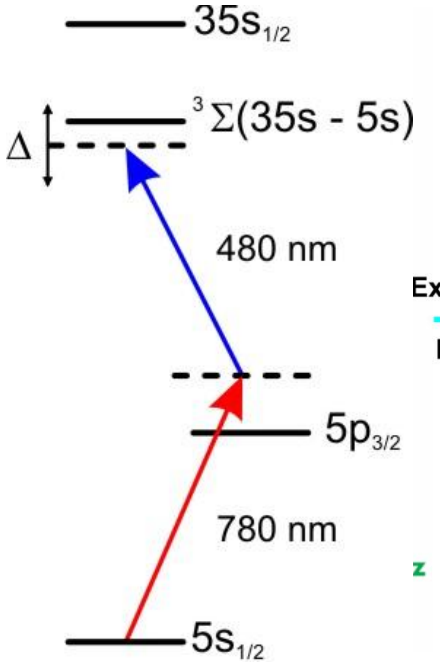
energy-dependent scattering length

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

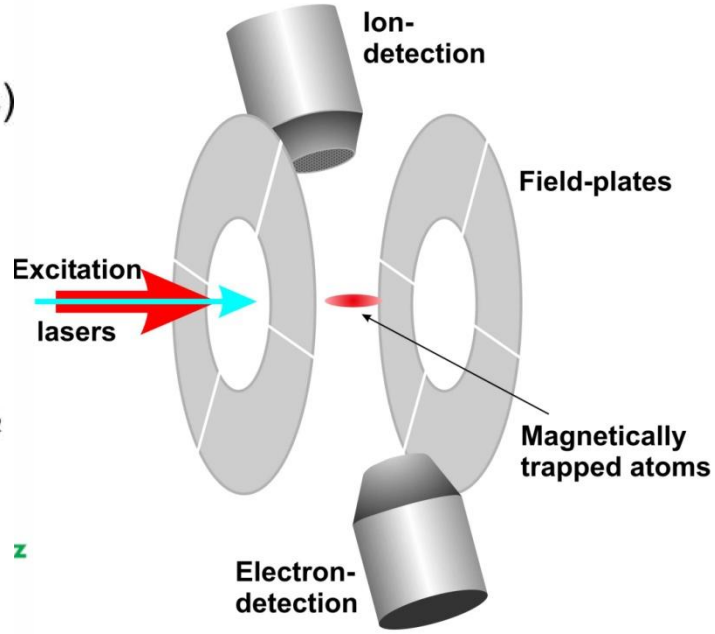
molecular potential

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

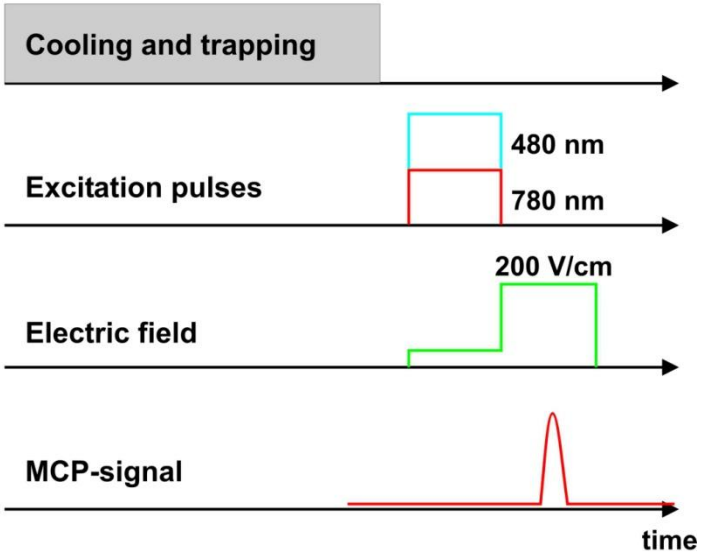
Some experimental details



Excitation scheme

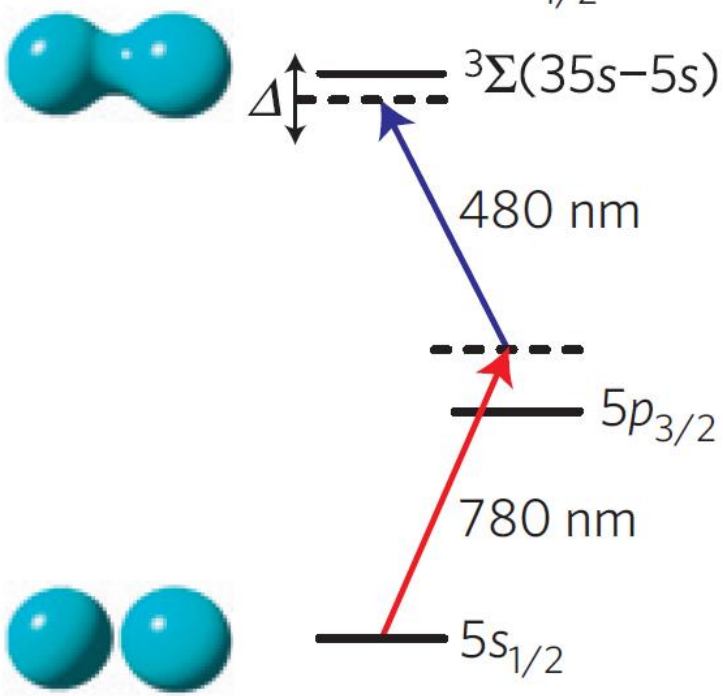


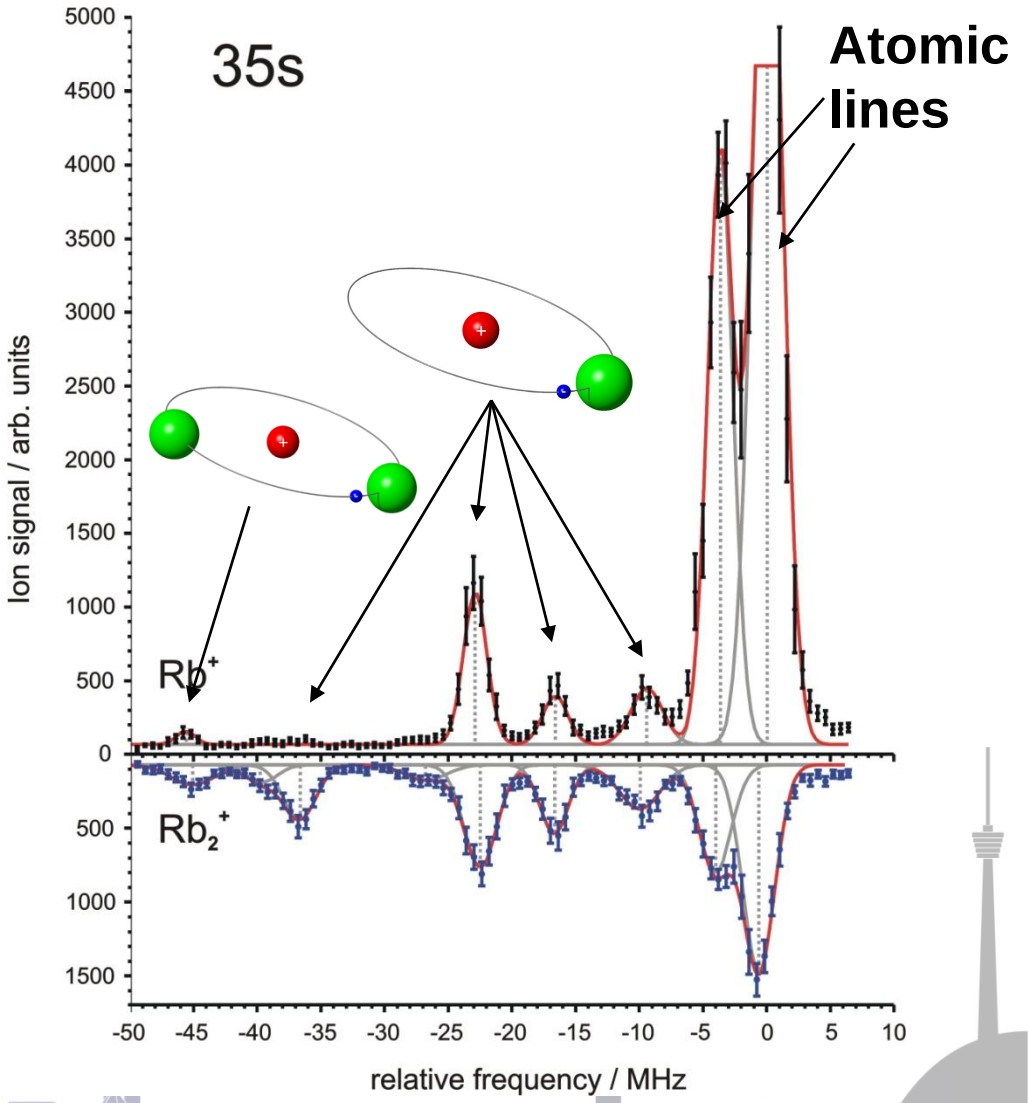
Experimental setup



Experimental sequence

Photo association of Rydberg molecules

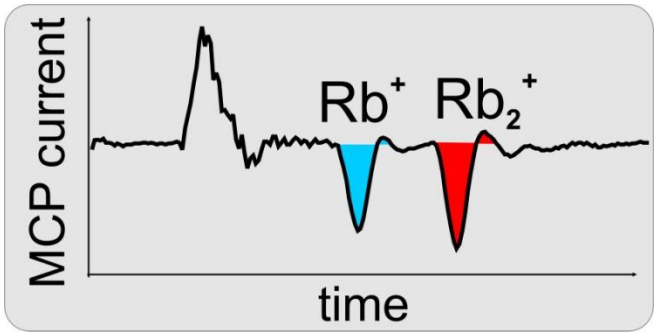




Nature 458 1005 (2009)

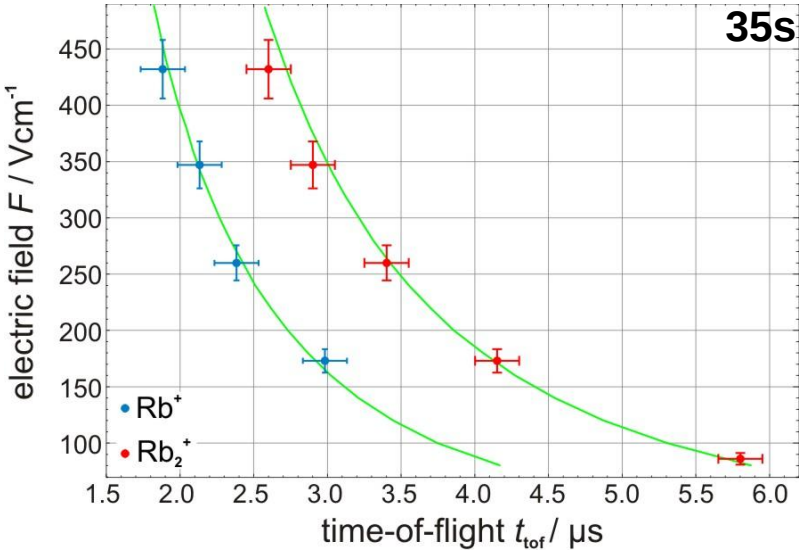
Two kinds of ions signals

detected ion signal



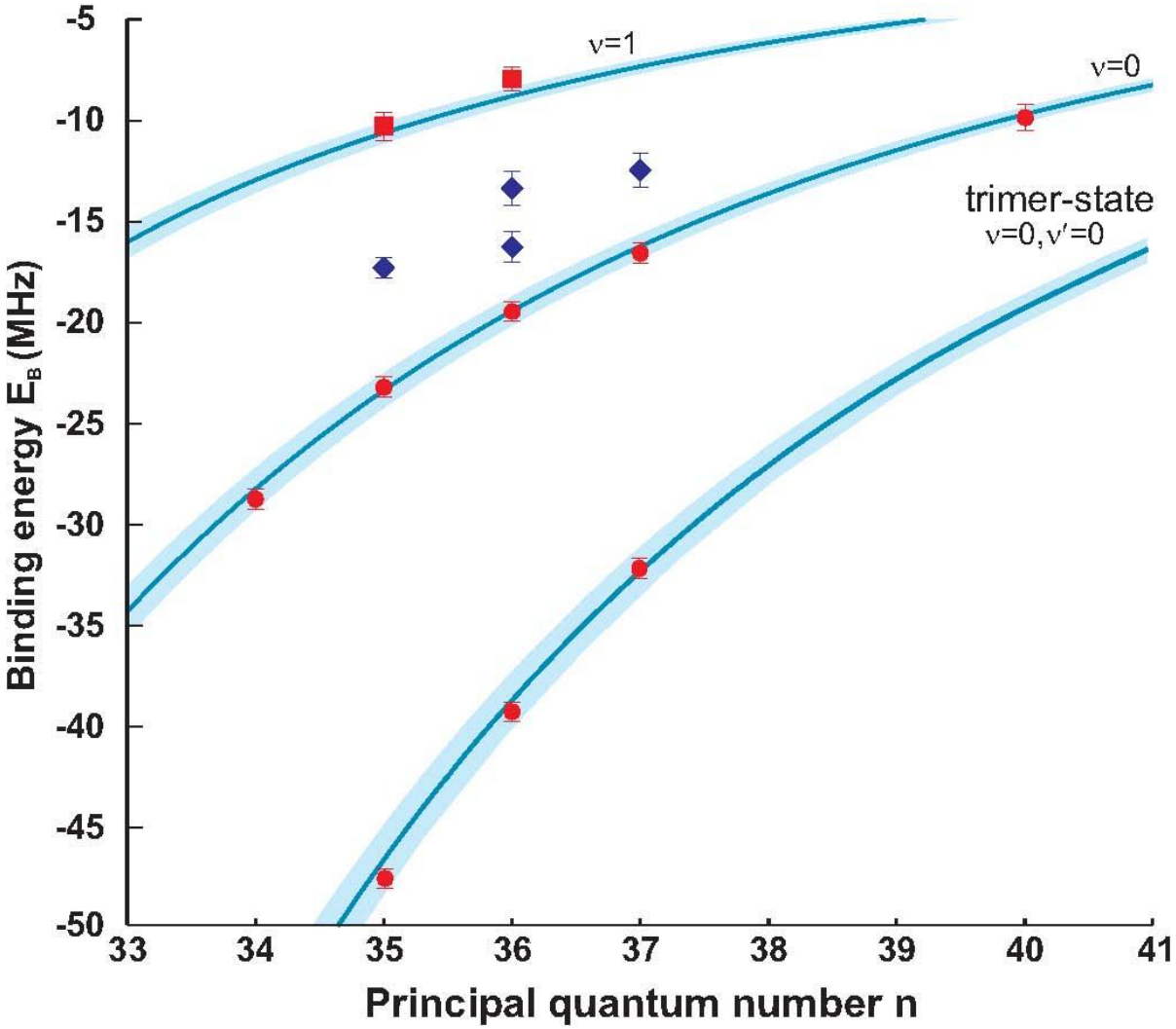
two signals:
- **atomic ion signal Rb^+**
- **molecular ion signal Rb_2^+**

time-of-flight measurement



source of Rb_2^+:

$$Rb(ns) + Rb(5s) \rightarrow Rb_2^+ + e^-$$

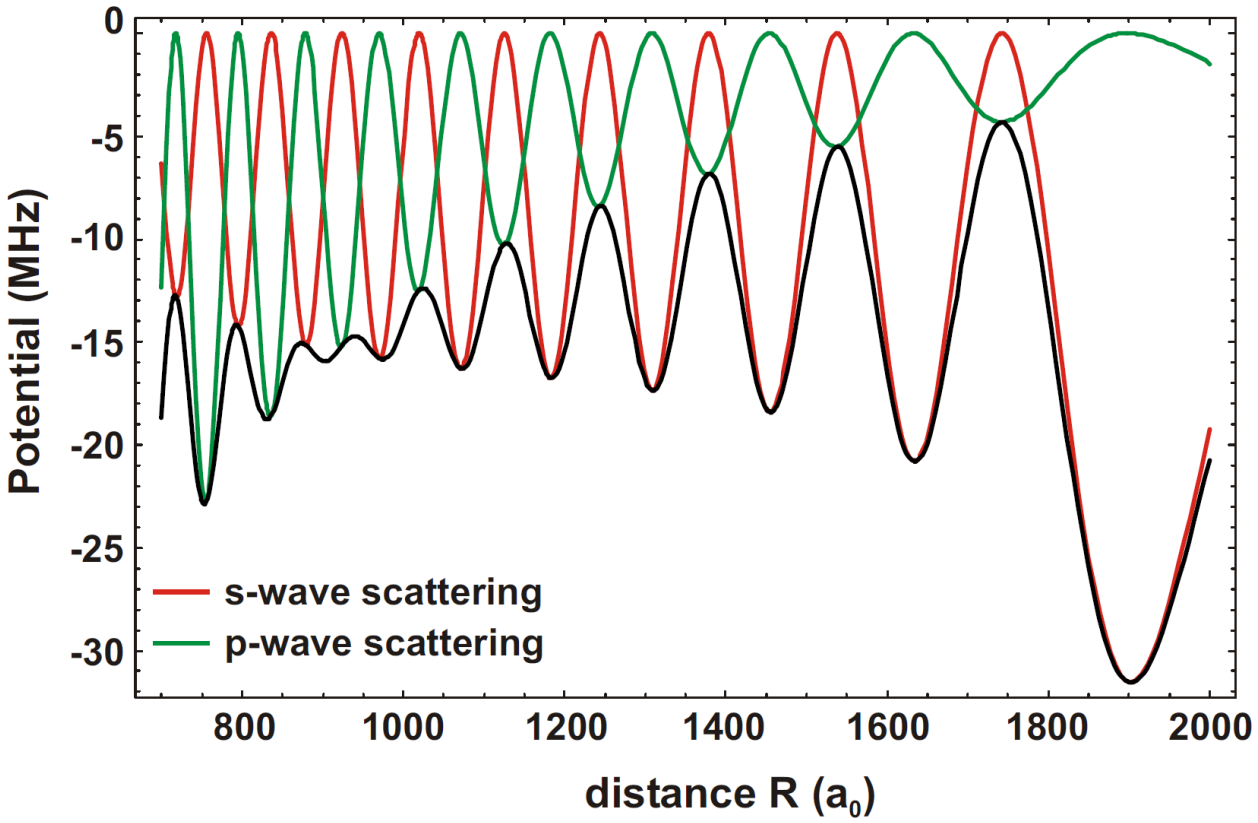

ν=1
ν=0
trimer-state
ν=0,ν′=0
Binding energy E_B (MHz)
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
33
34
35
36
37
38
39
40
41
Principal quantum number n

A closer look on the potential

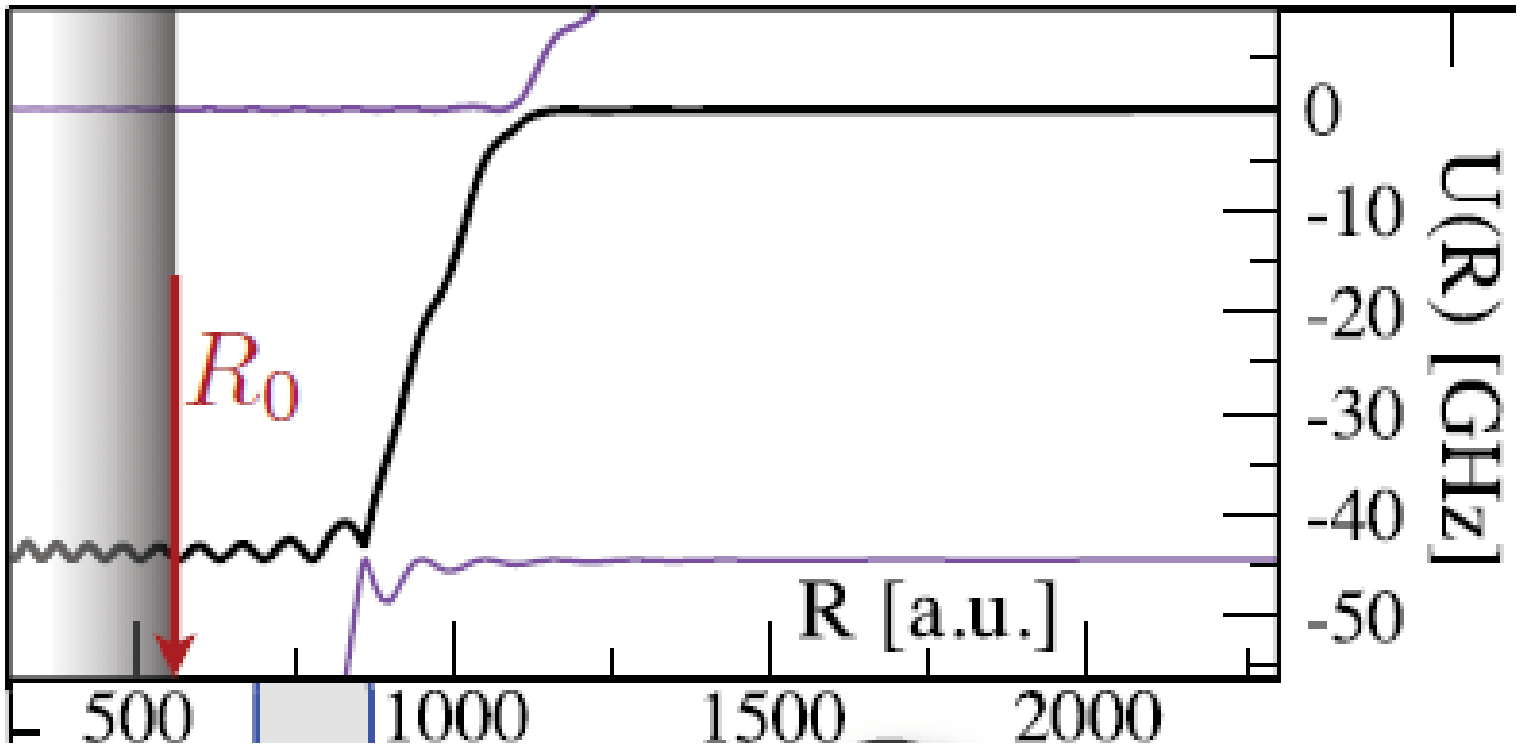
s-wave potential $$\mathbf{V_0}(\vec{\mathbf{R}}) = \mathbf{2\,\pi a\,[k\,(R)]} \cdot \left|\mathbf{\Psi_{n,l,m}}(\vec{\mathbf{R}})\right|^{\mathbf{2}}$$

p-wave potential $$\mathbf{V_1}(\vec{\mathbf{R}}) = -\frac{\mathbf{2\,\pi^2\,\alpha}}{\mathbf{5\,k(R)}} \cdot \left|\nabla\mathbf{\Psi_{n,l,m}}(\vec{\mathbf{R}})\right|^{\mathbf{2}}$$

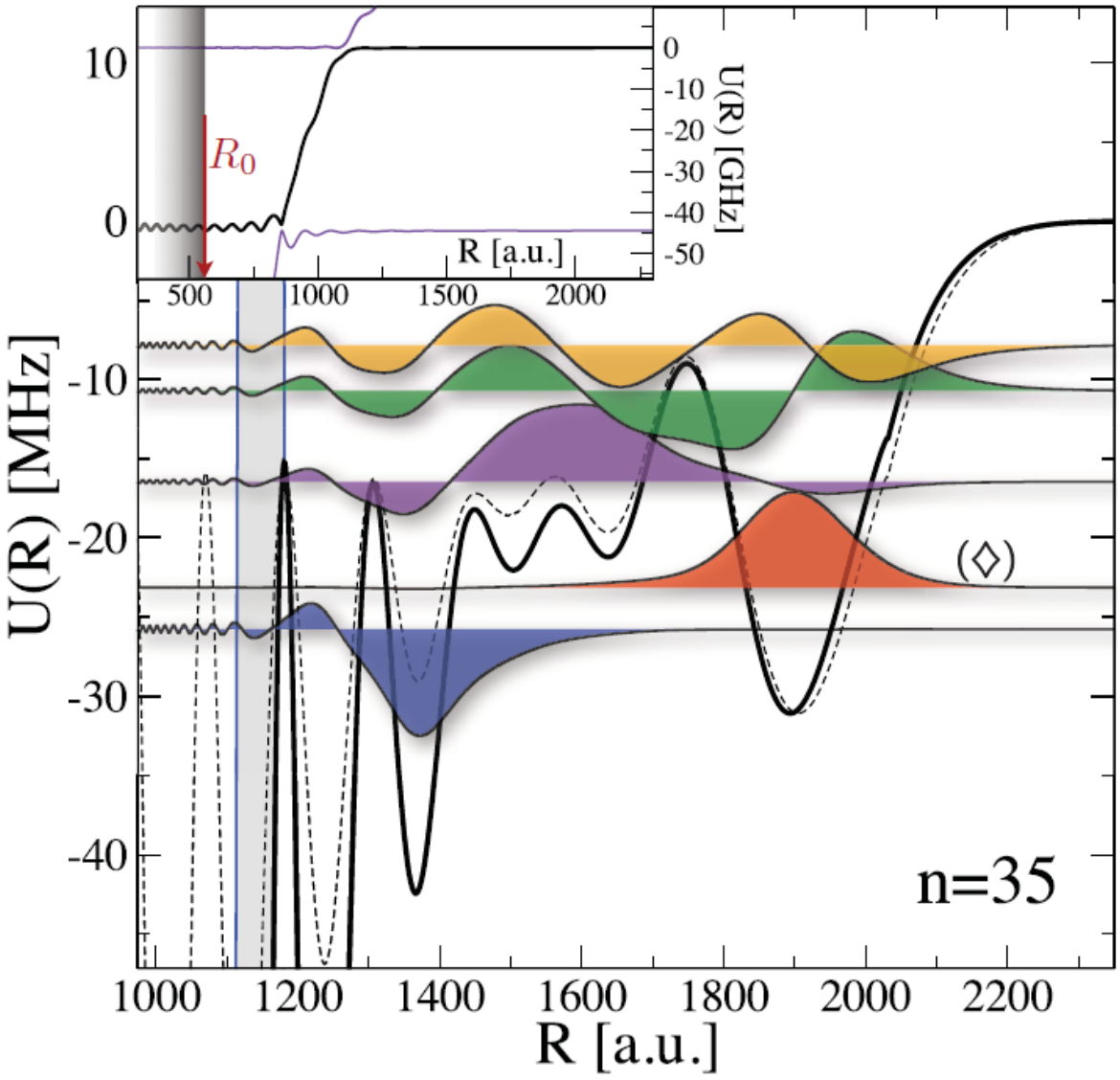
Omont, J. Physique **38**, 1343 (1977)



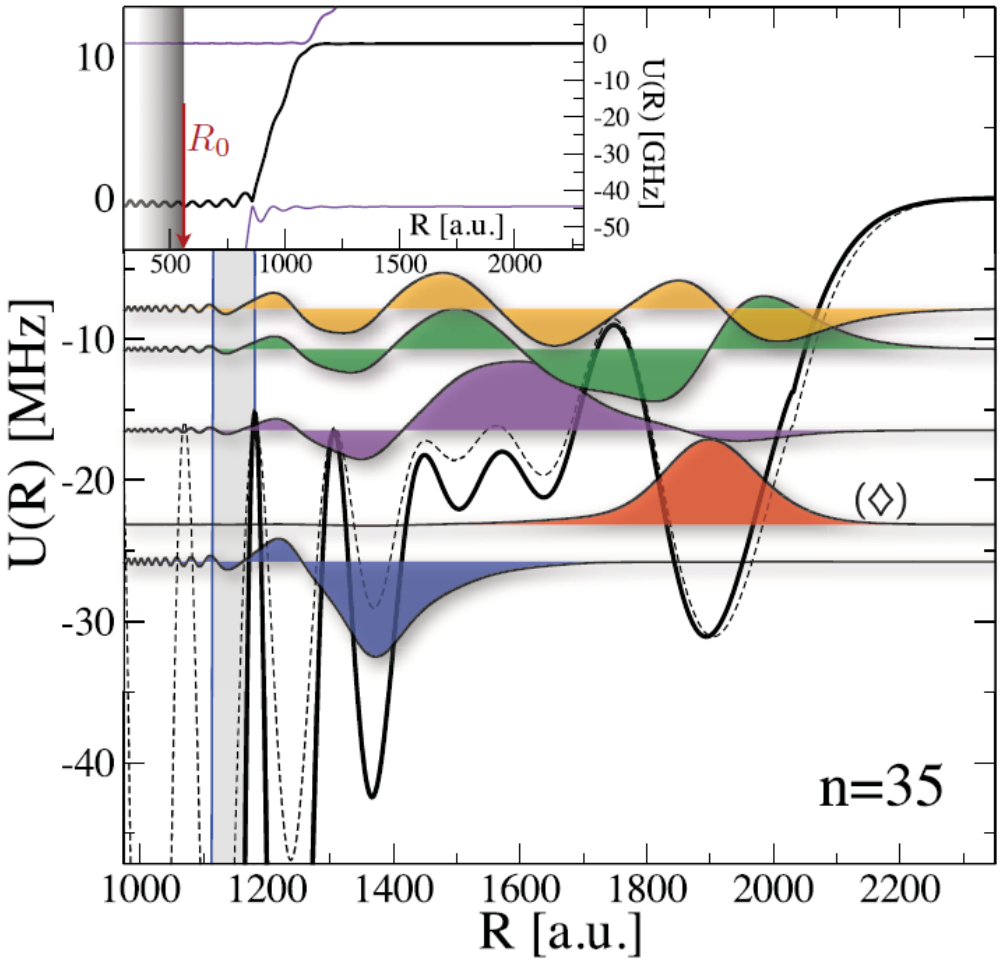
A wider look on the potential

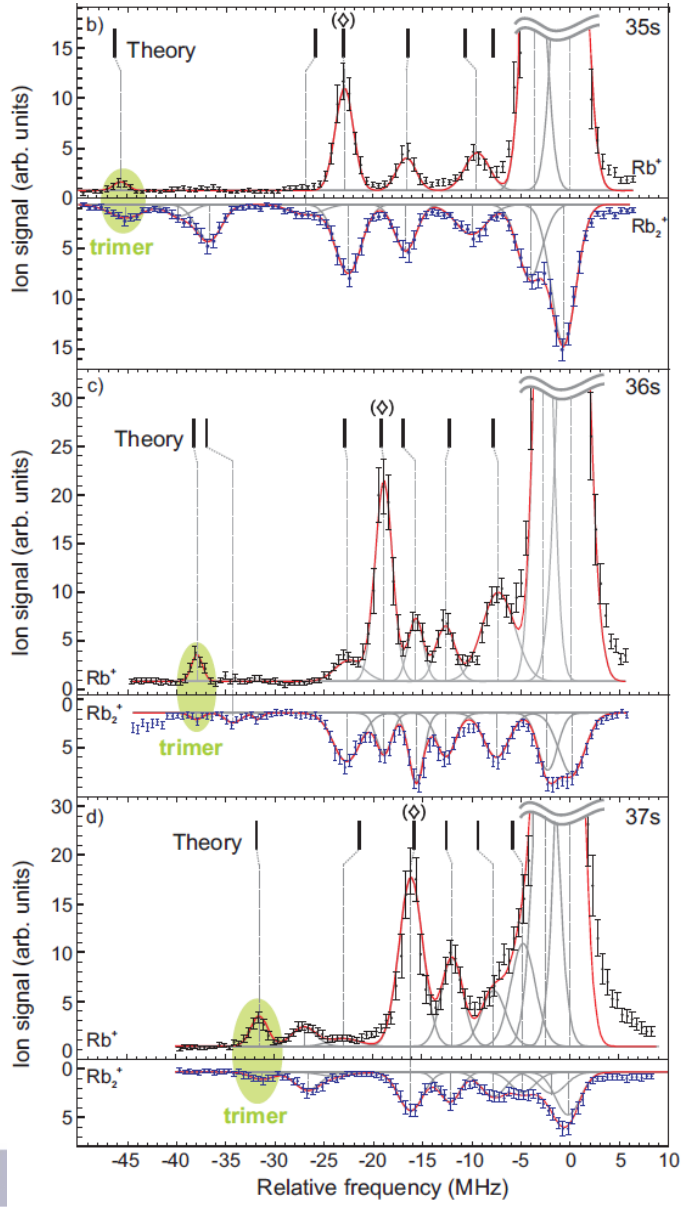


Exact calculation of the potential



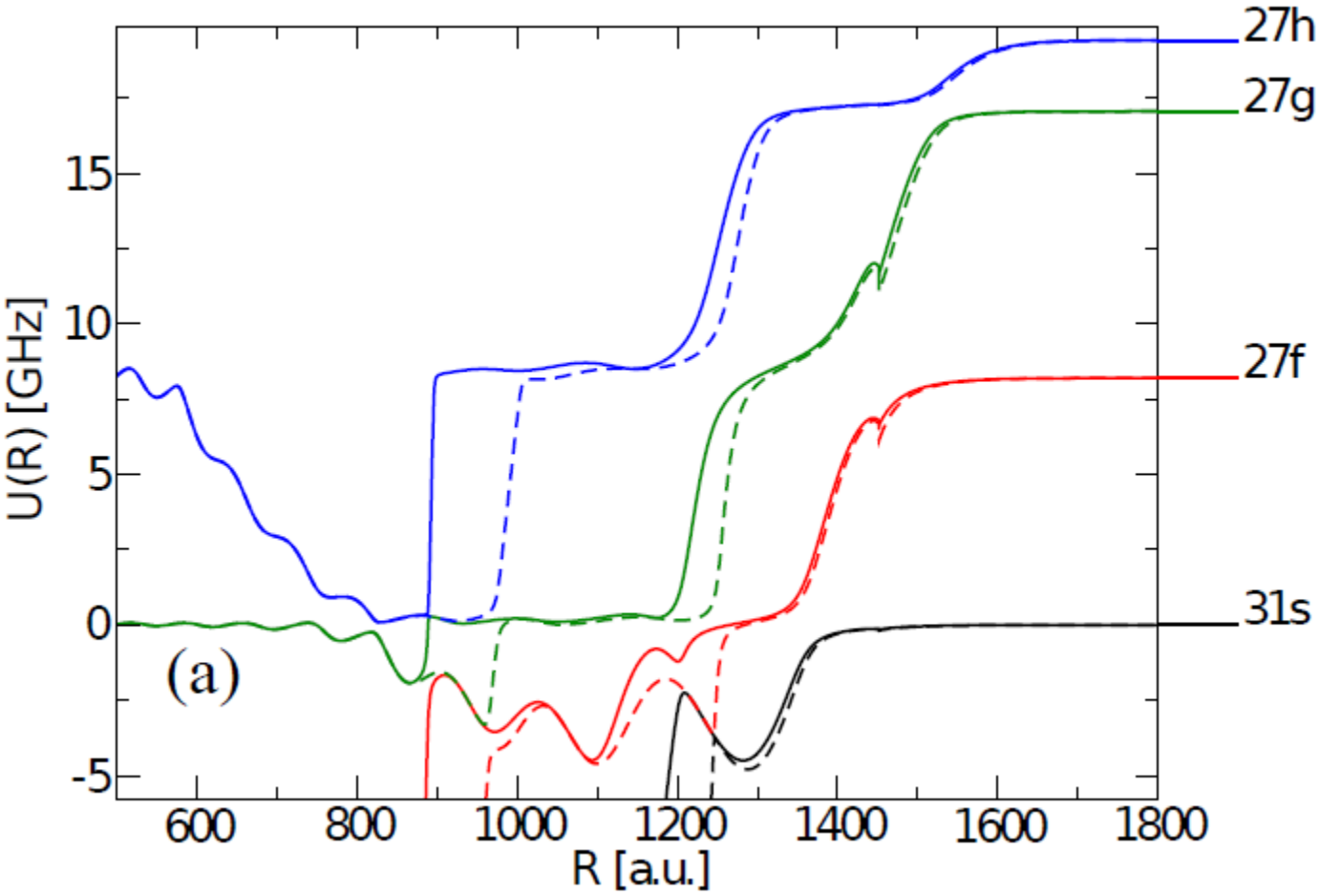
Exact calculation of the potential



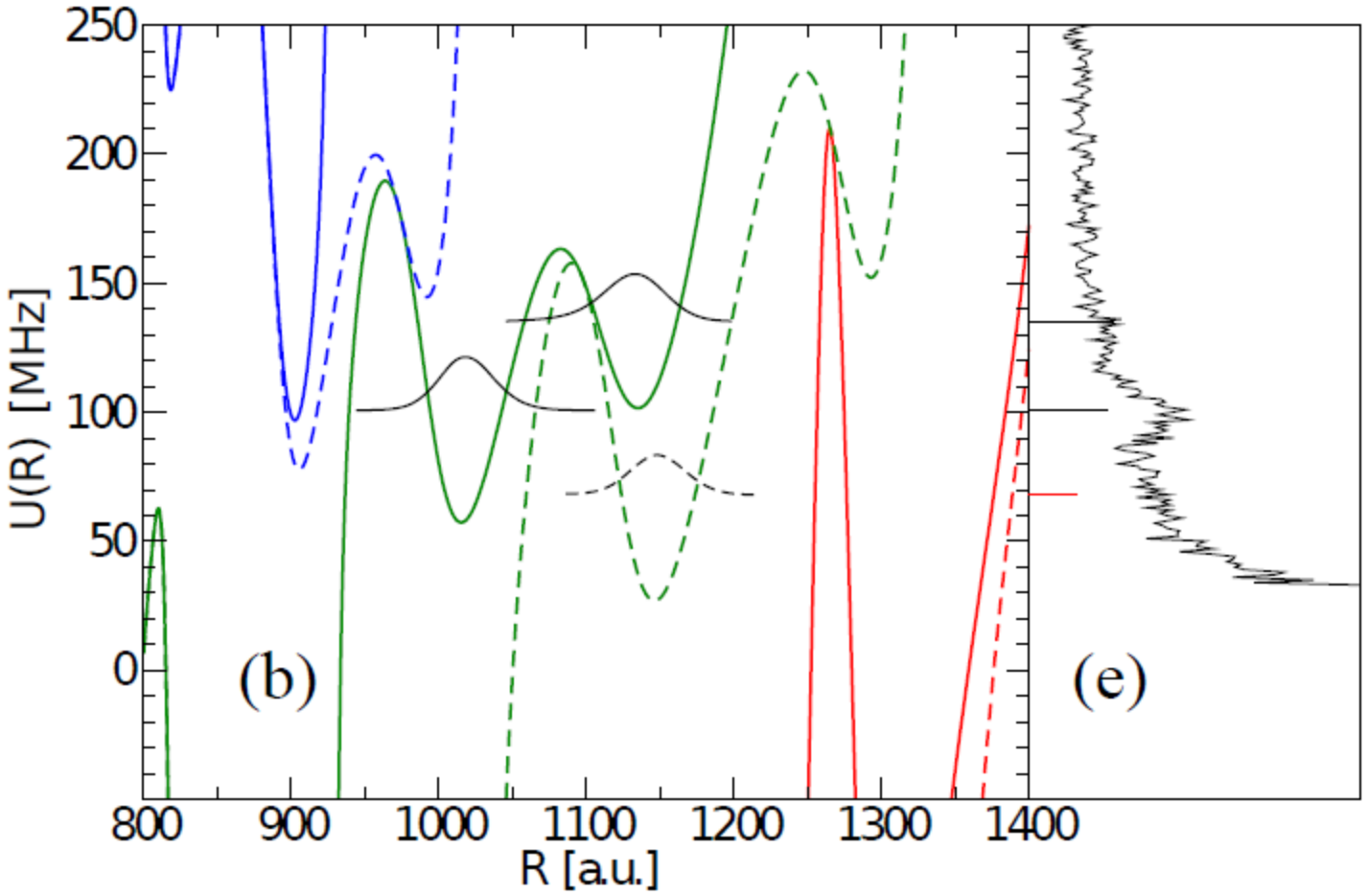


Phys. Rev. Lett. 105, 163201 (2010)

How about Cesium

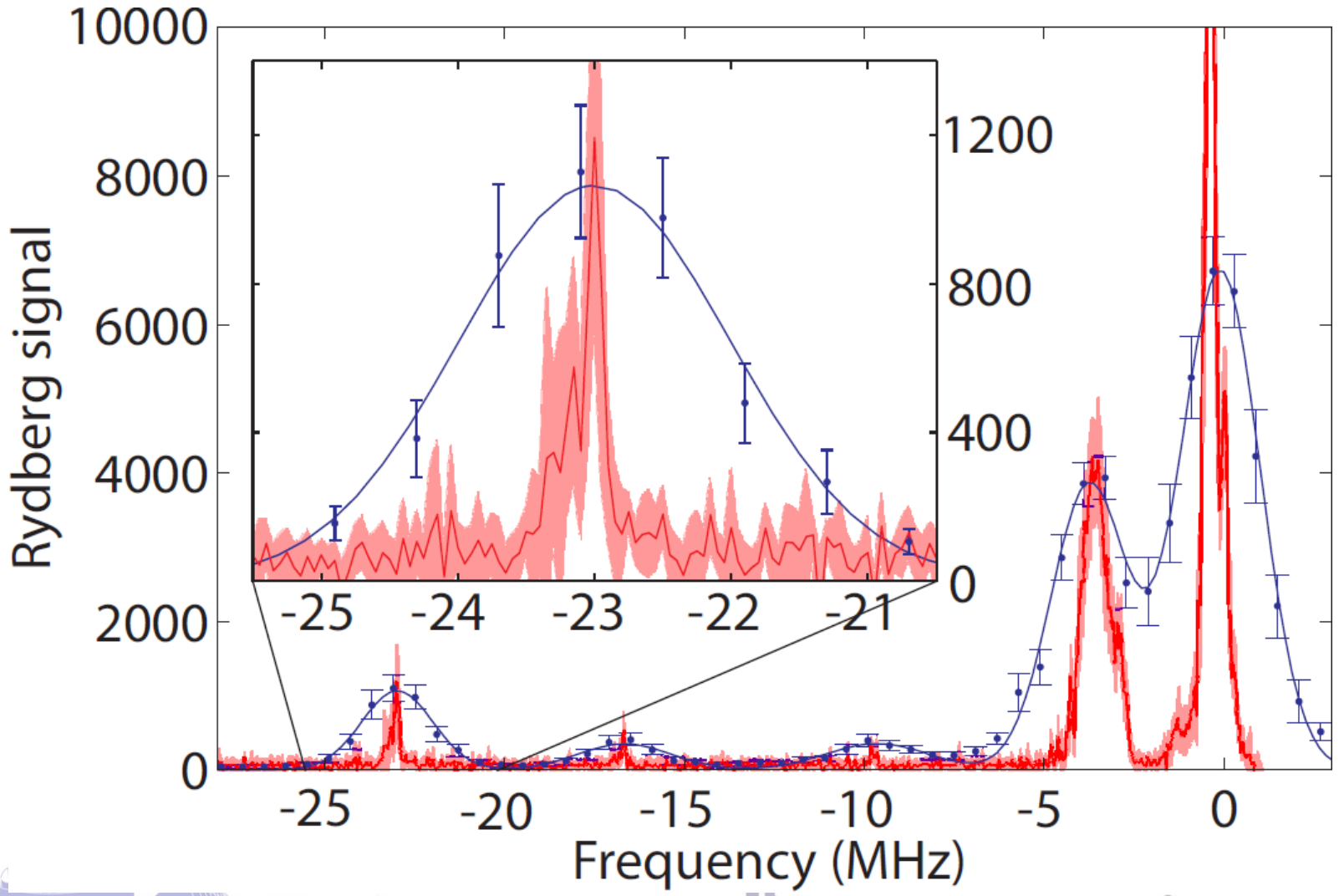


How about Cesium

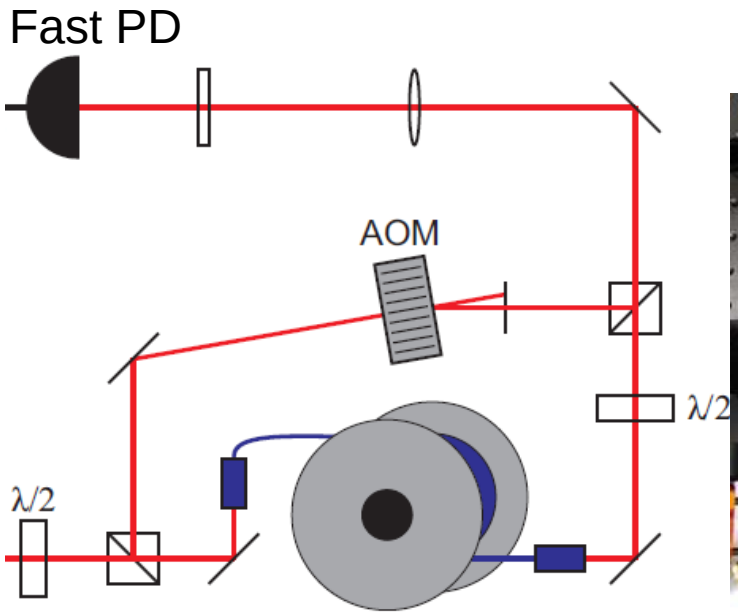


Shaffer, Arxiv1205.4974

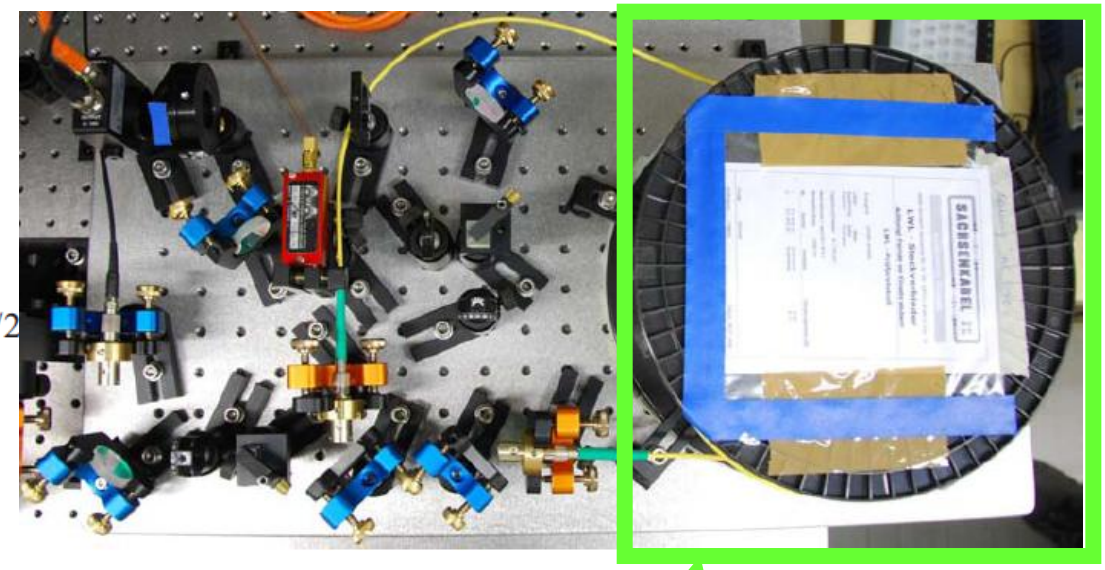
High resolution photoassociation spectrum



Characterization by selfheterodyne detection

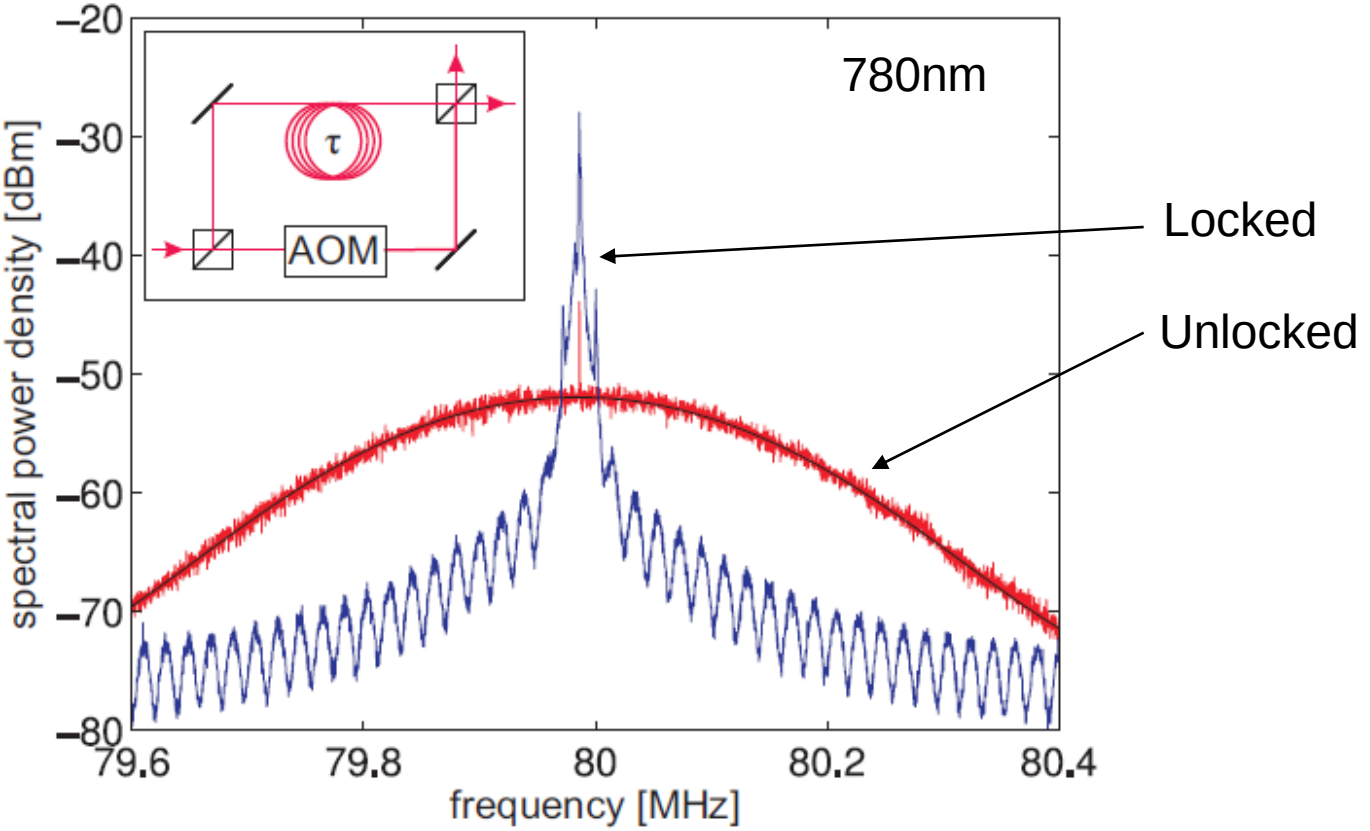


10 km fiber
τ=52µs

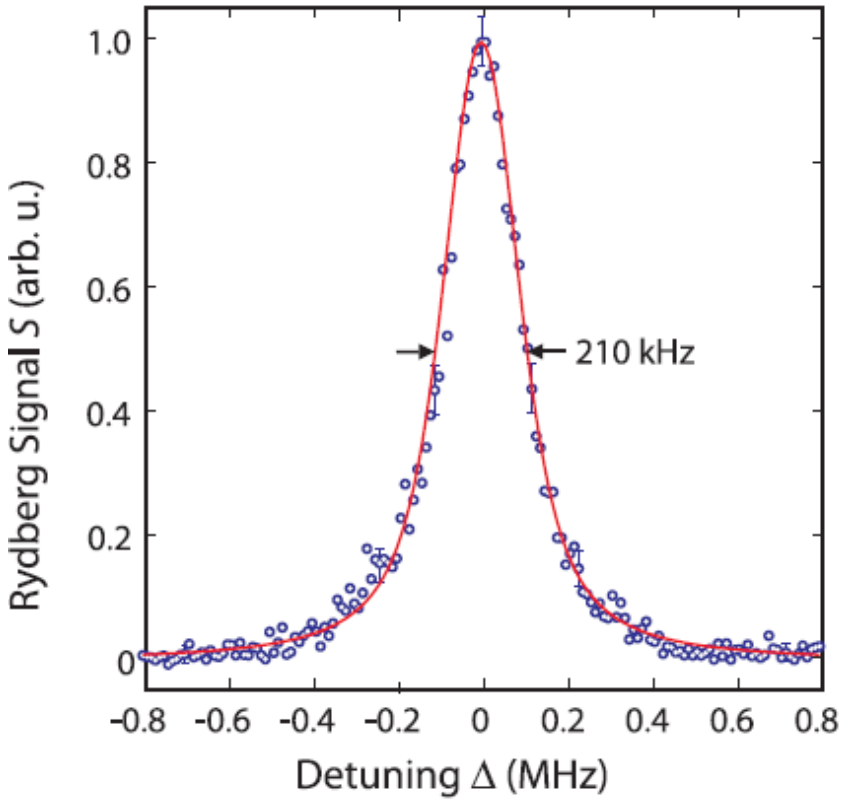


Acoustic shielding
(foam) necessary!

Characterization by selfheterodyne detection

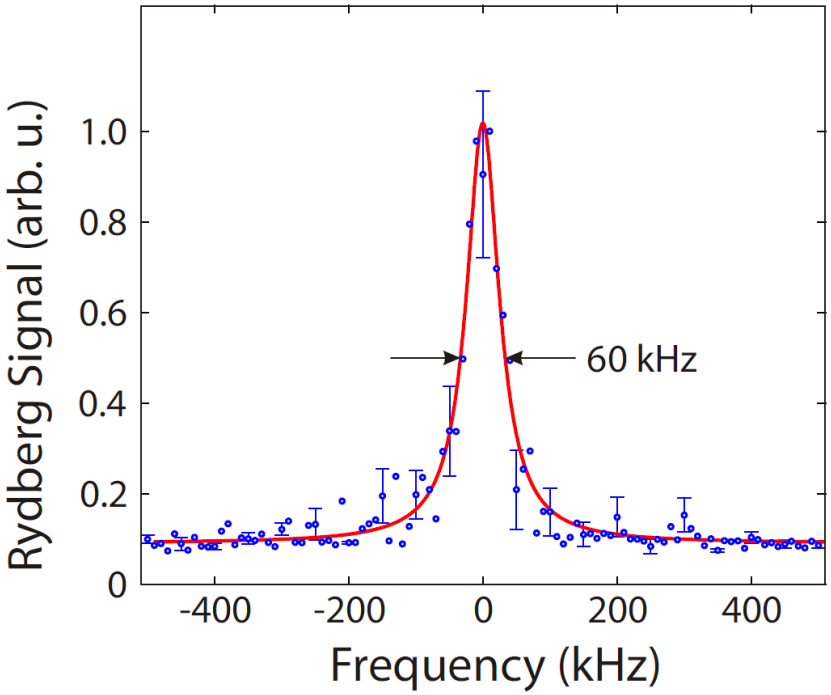


Rydberg molecules



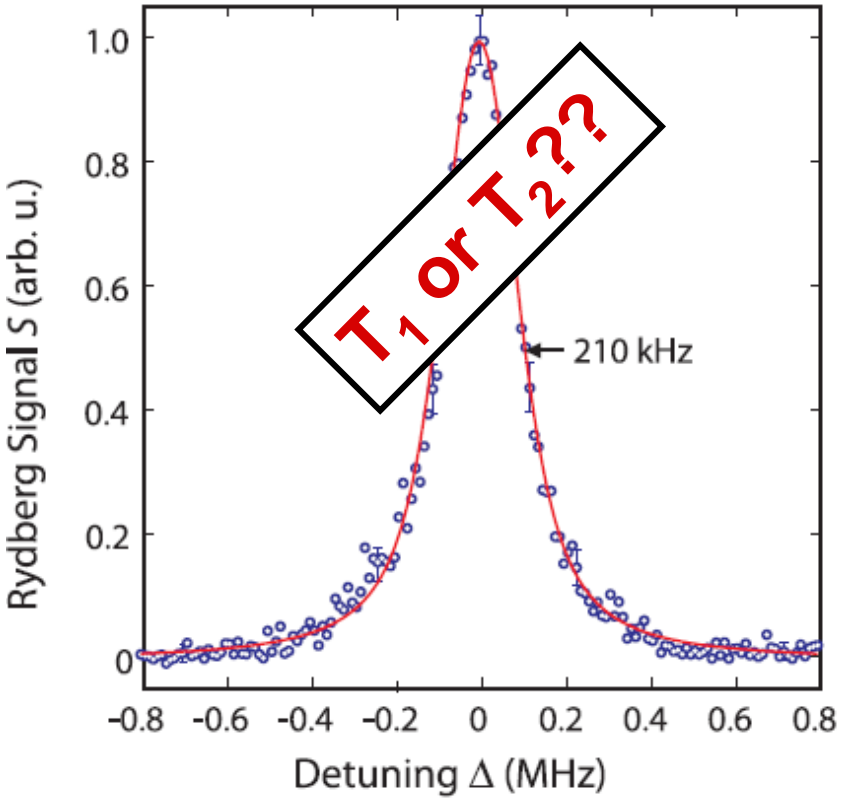
Voigt Fit for fixed 3 μK:
142 kHz Lorentz linewidth

Rydberg atoms



Limited by Laser linewidth

Rydberg molecules



Voigt Fit for fixed 3 μK:
142 kHz Lorentz linewidth

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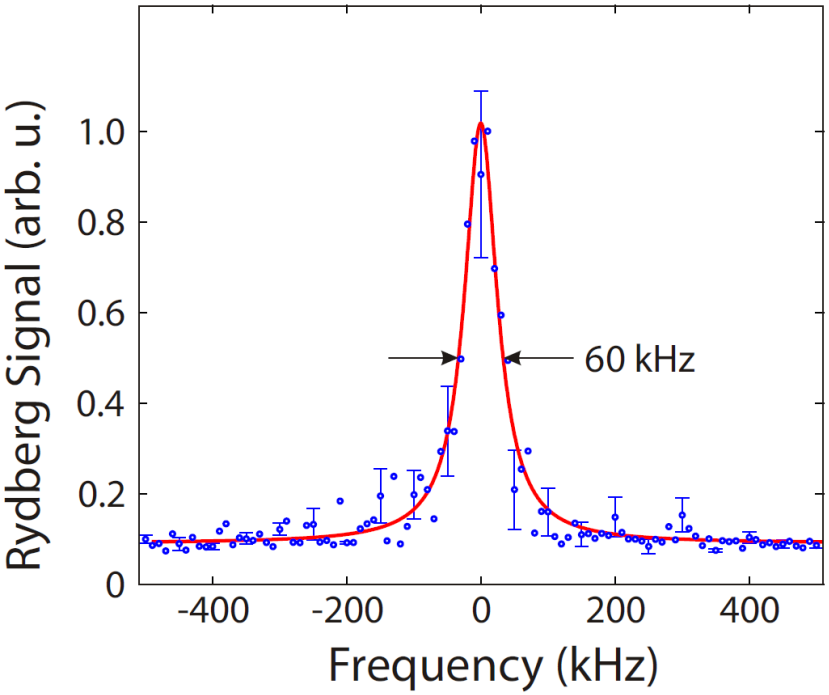
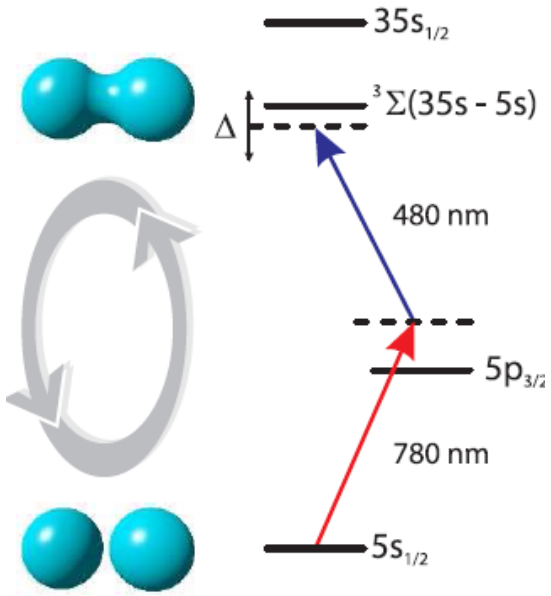
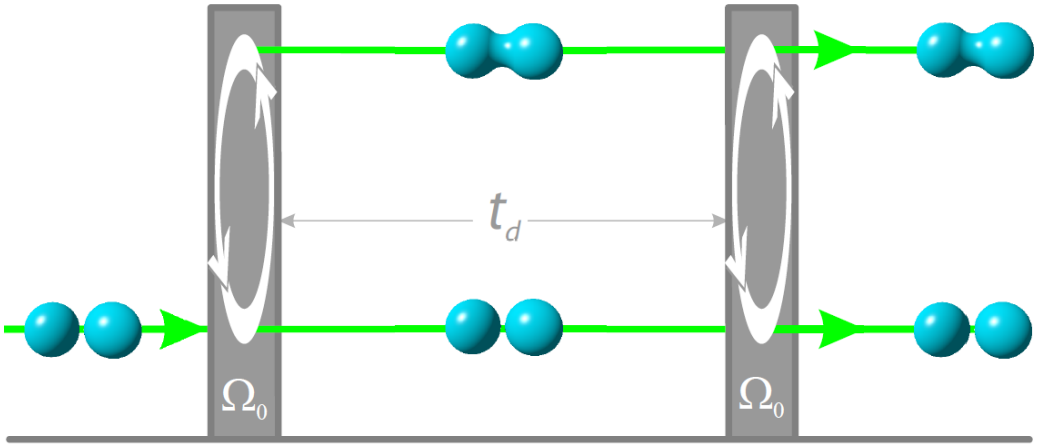


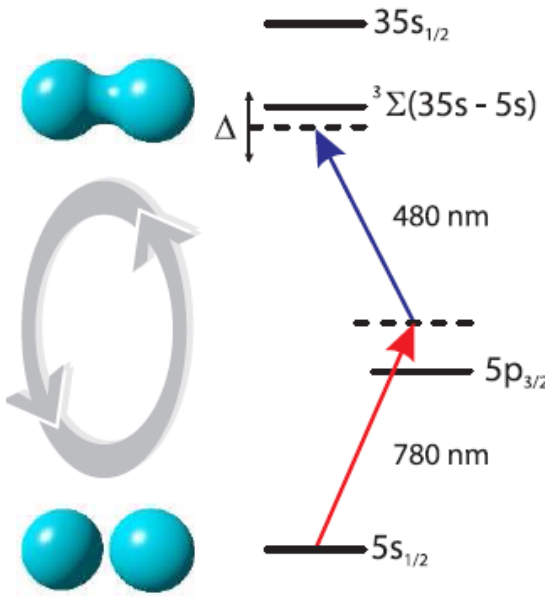
Limited by Laser linewidth

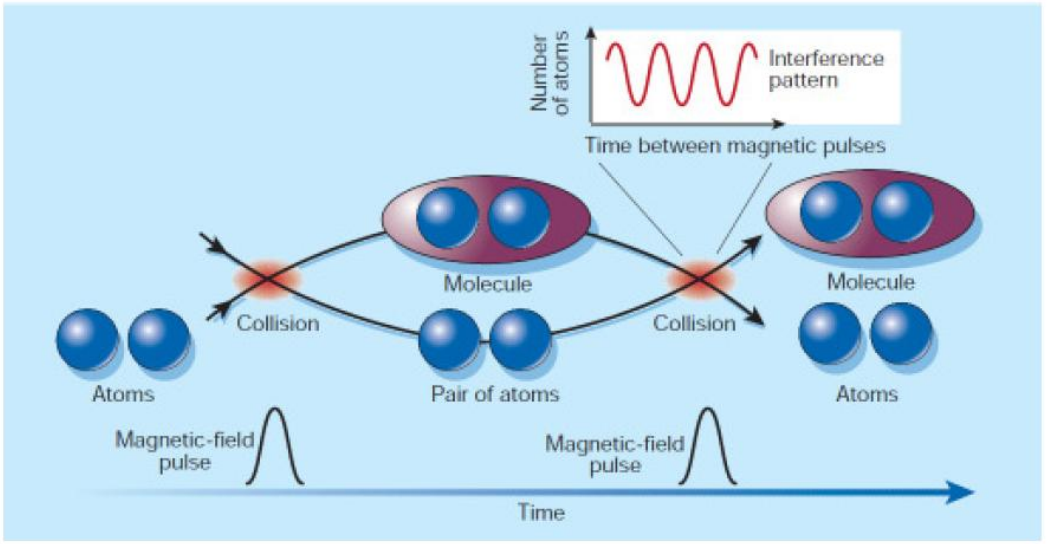
Ramsey interferometry with Rydberg molecules





Ramsey interferometry with Rydberg molecules



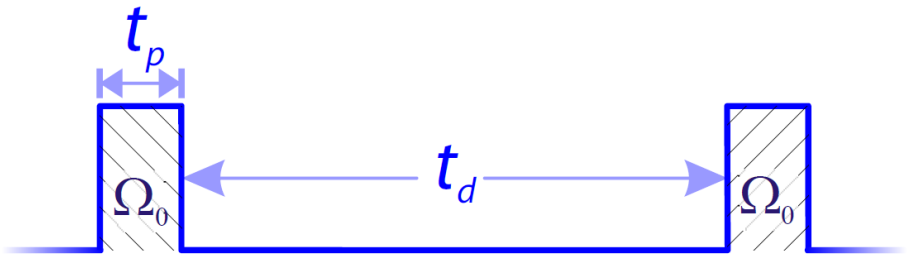


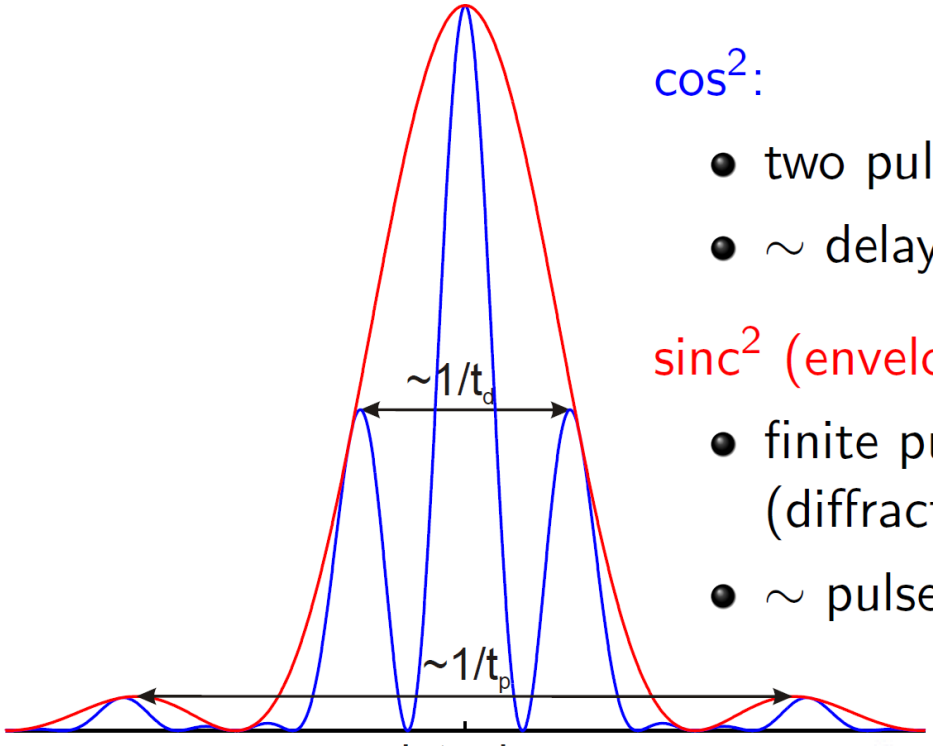
P. Zoller, Nature, **417** 493 (2002)

First experiment with Feshbach molecules (JILA) Nature, **417** 529 (2002)

Ramsey fringes: (cf. Young's double slit)

separate two pulses by variable delay time:





$\cos^2$:

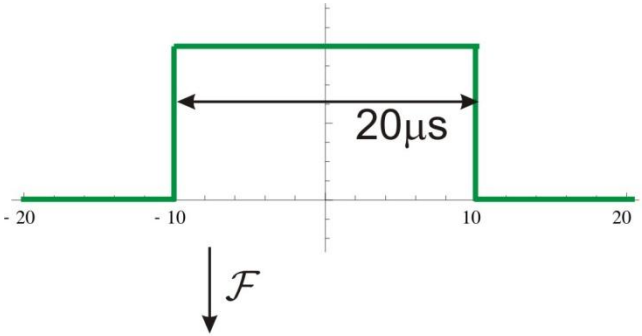
- two pulses (interference of two slits)
- $\sim$ delay time t_d (slit distance)

sinc^2 (envelope):

- finite pulse length (diffraction at single slit)
- $\sim$ pulse length t_p (slit width)

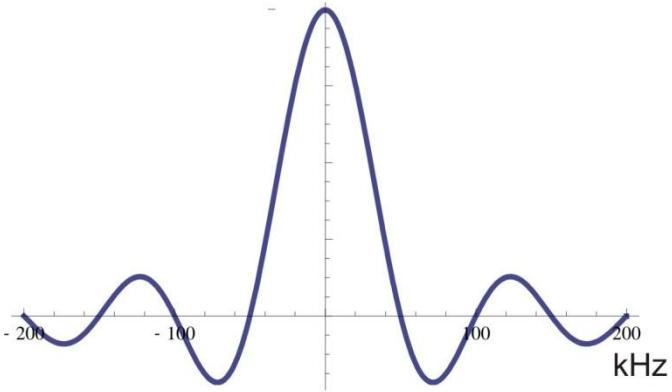
Excitation time broadening

Pulse shape



$\mathcal{F}$

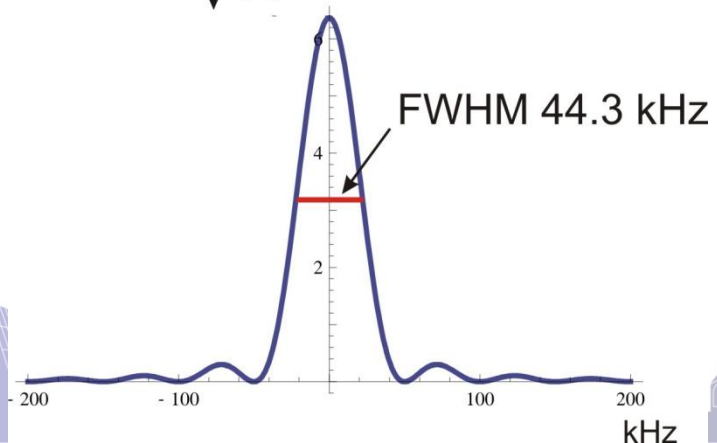
Amplitude of electric field



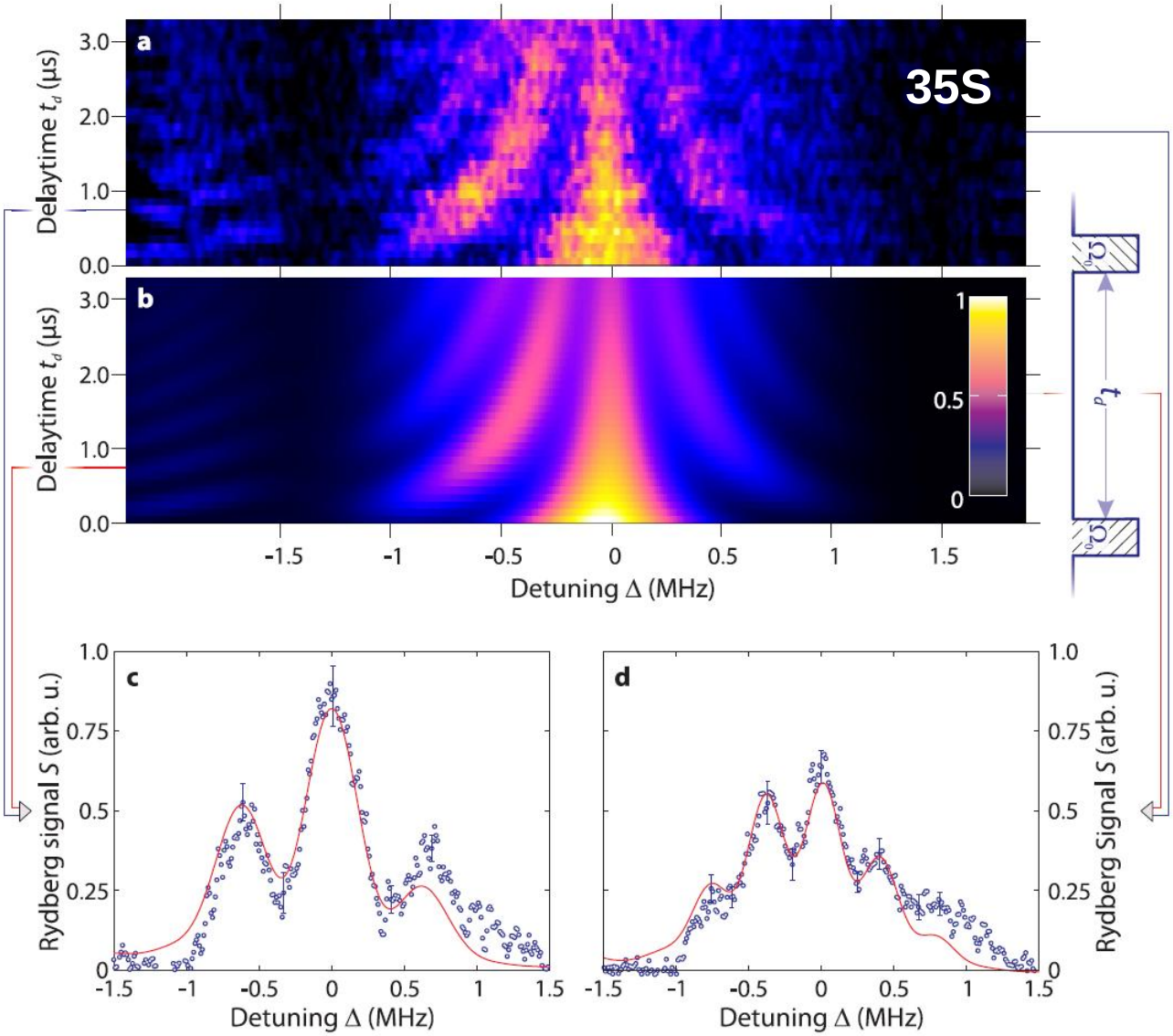
$$\frac{1}{\sqrt{2\pi}}\tau\mathrm{sinc}\left(\pi\upsilon\tau\right)$$

$()^2$

Intensity of light field



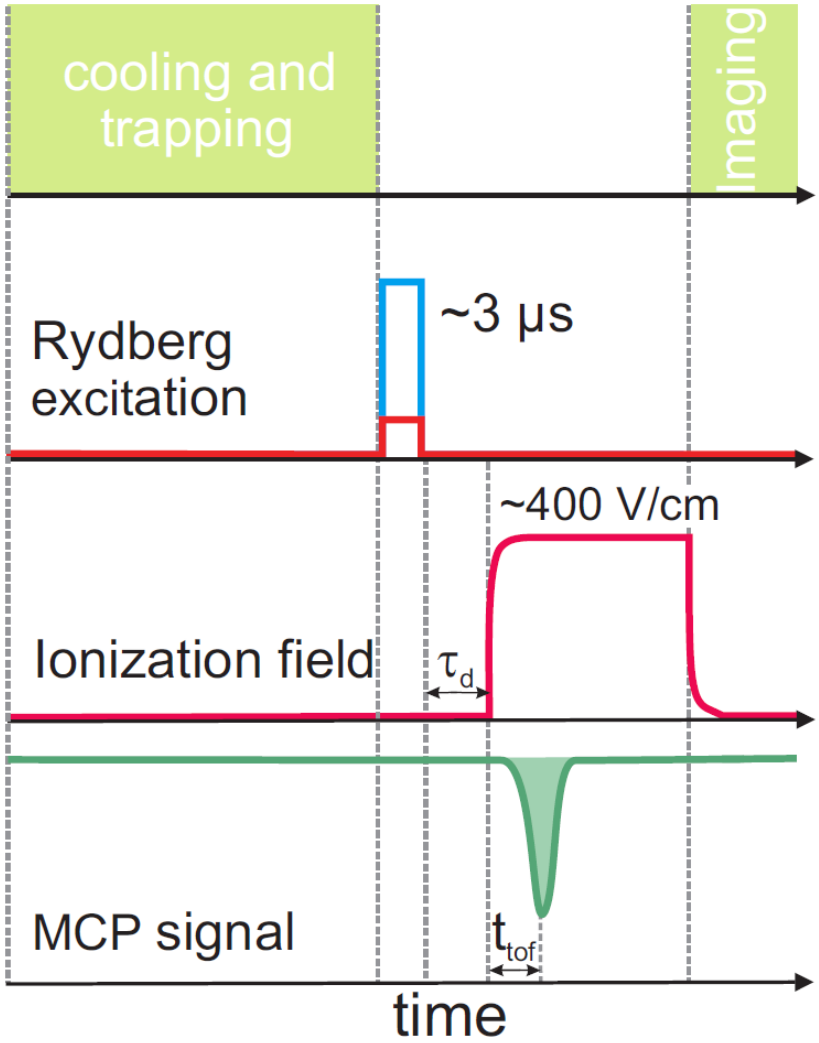
$$\left(\frac{1}{\sqrt{2\pi}}\tau\mathrm{sinc}\left(\pi\upsilon\tau\right)\right)^2$$



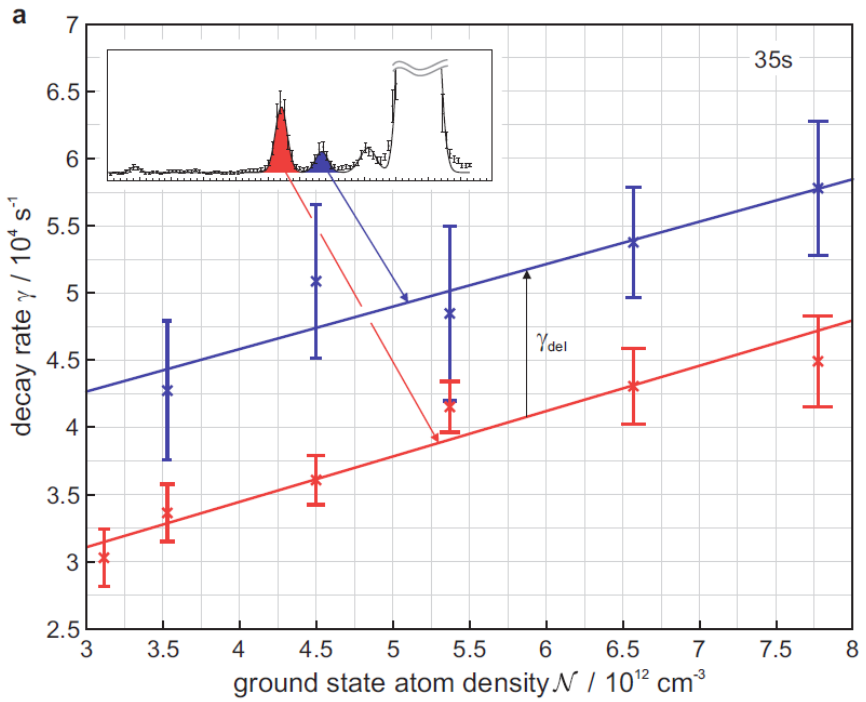
T_1= 6.4(9) µs T_2= 1.5(2) µs

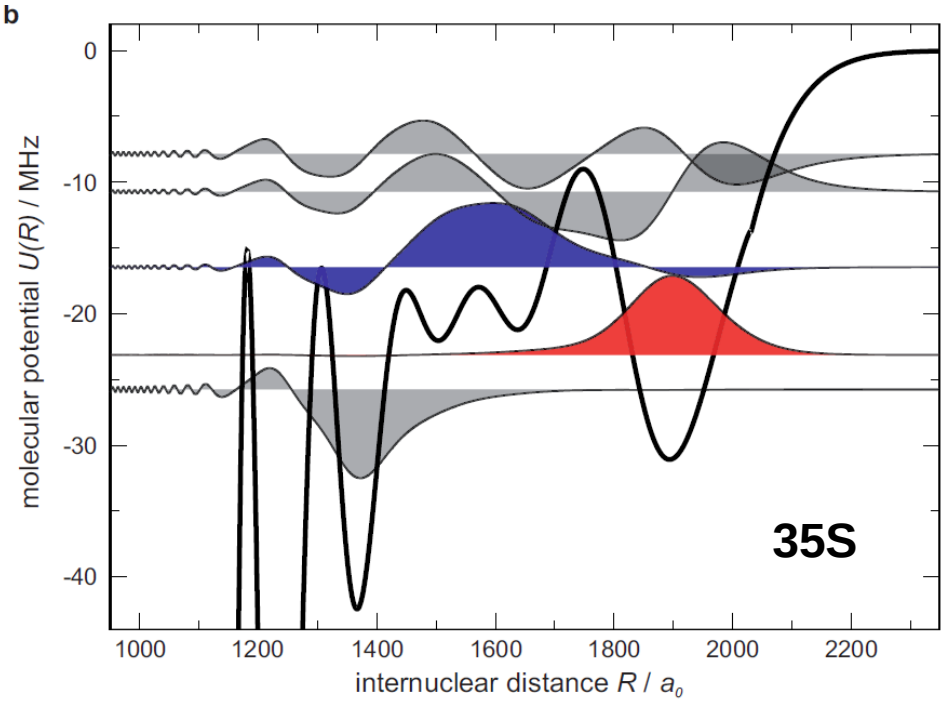
Nature Physics 6, 970–974 (2010)

Lifetimes of Rydberg molecules



Lifetimes of Rydberg molecules

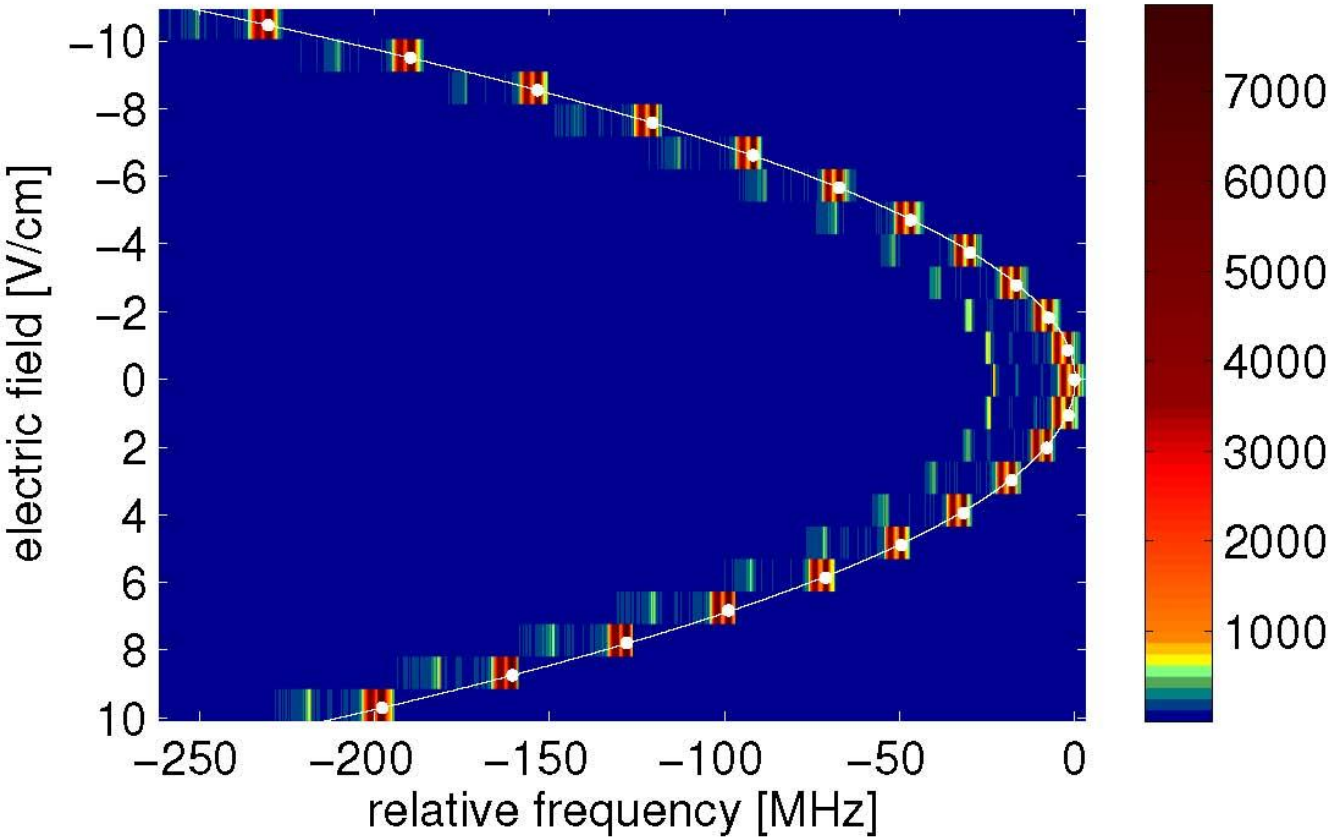




$$\gamma = \gamma_{\text{radiative}} + \underbrace{\gamma_{\text{collision}}}_{n\sigma v} + \gamma_{\text{transmission}}$$

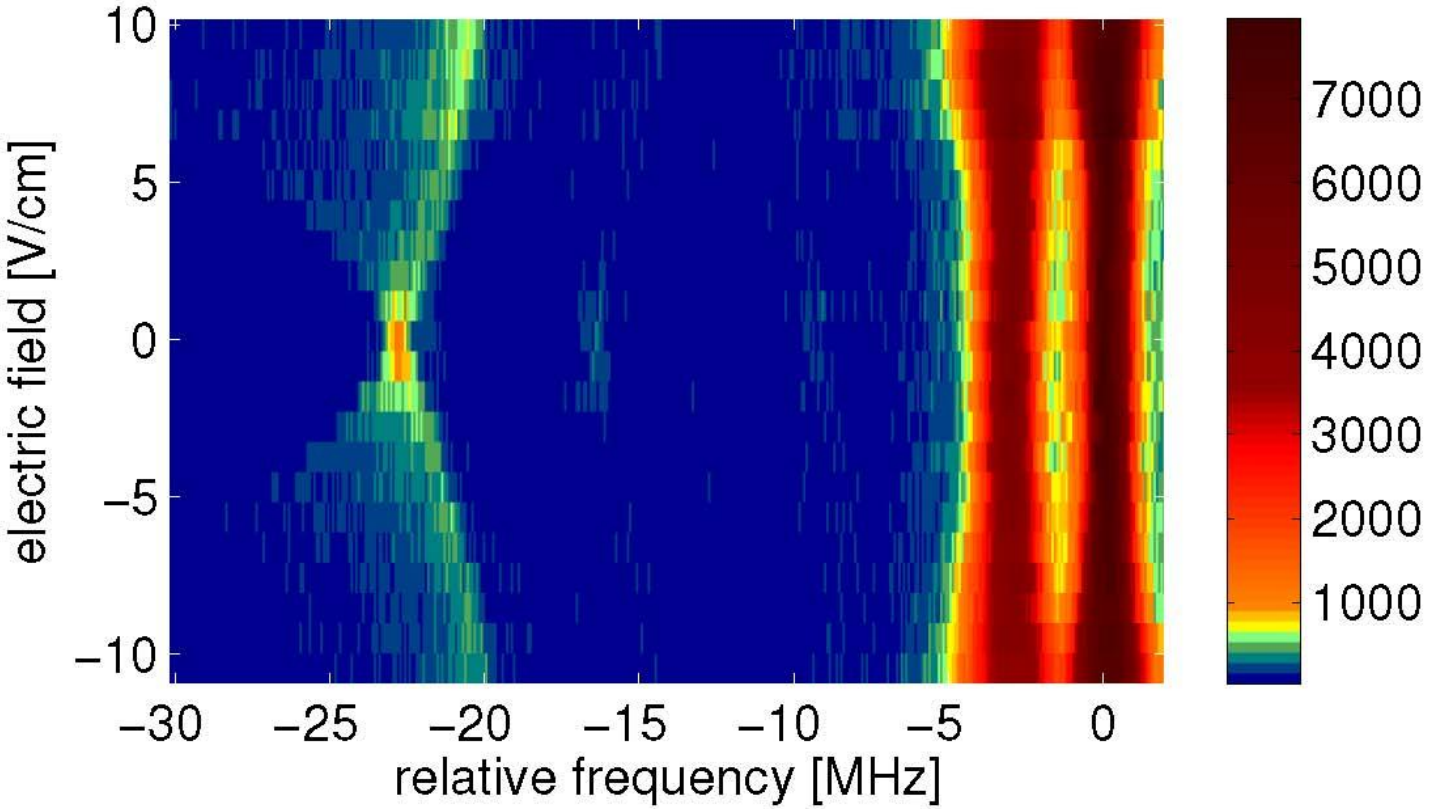
J. Phys. B. 44 184004 (2011)

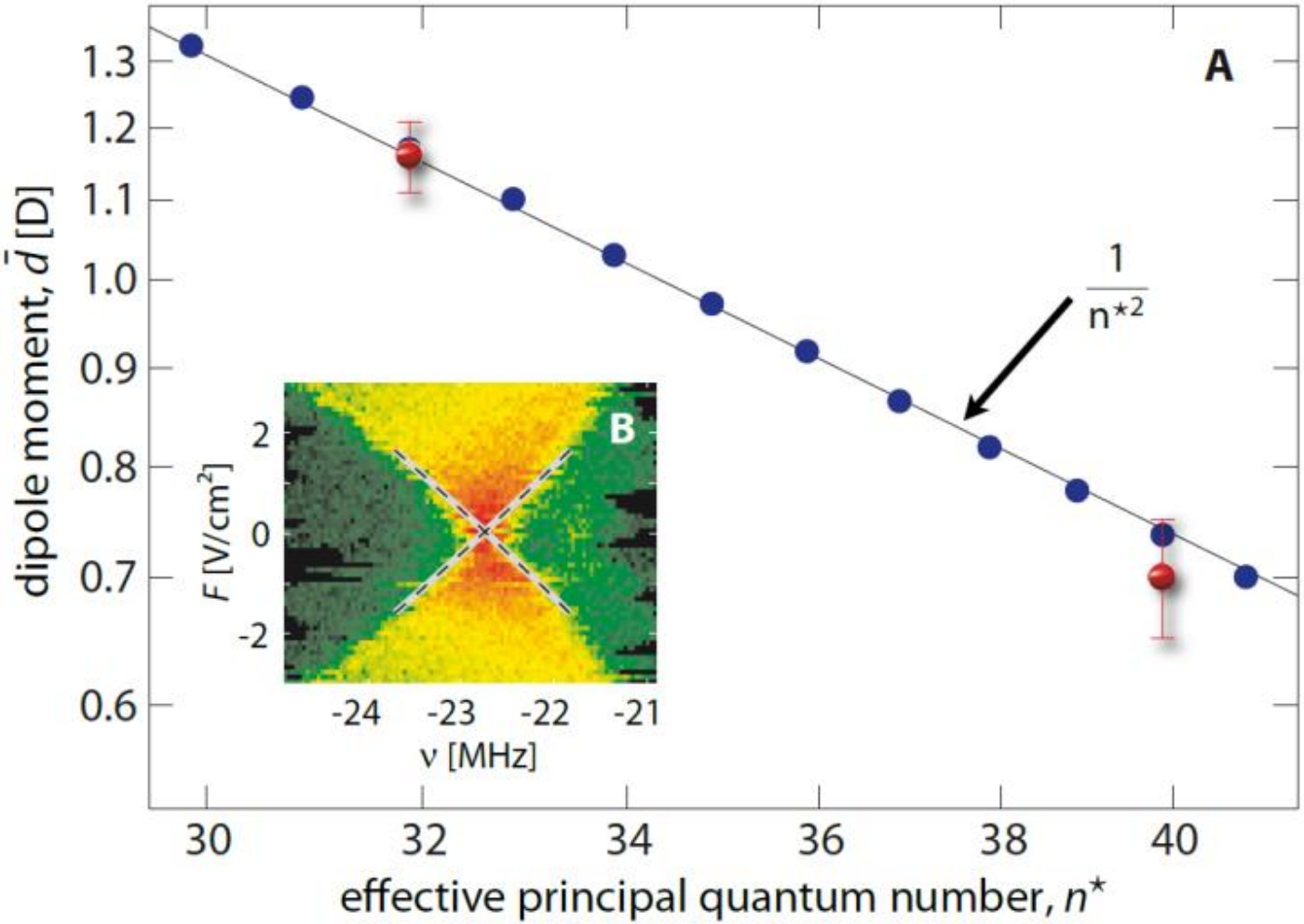
Stark effect



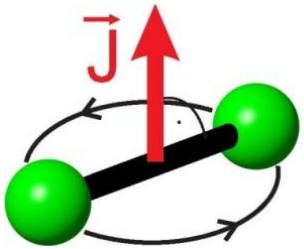
$$\Delta\nu = -\frac{1}{2}\alpha E^2 \qquad \alpha = 4.19\frac{MHz}{(V/cm)^2}$$

„Subtracted“ Stark effect

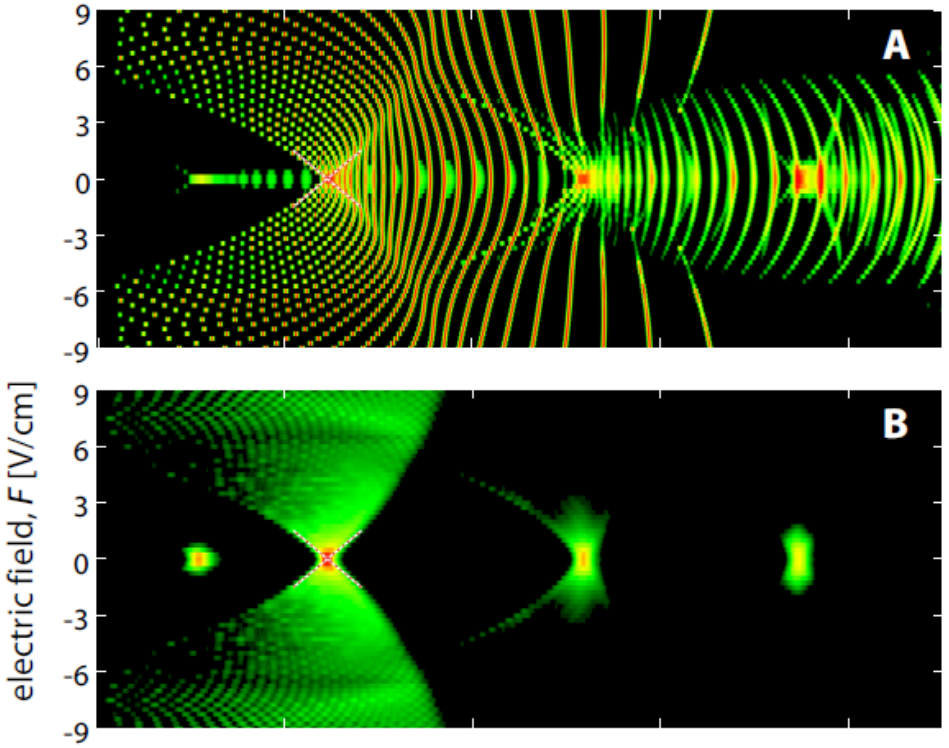


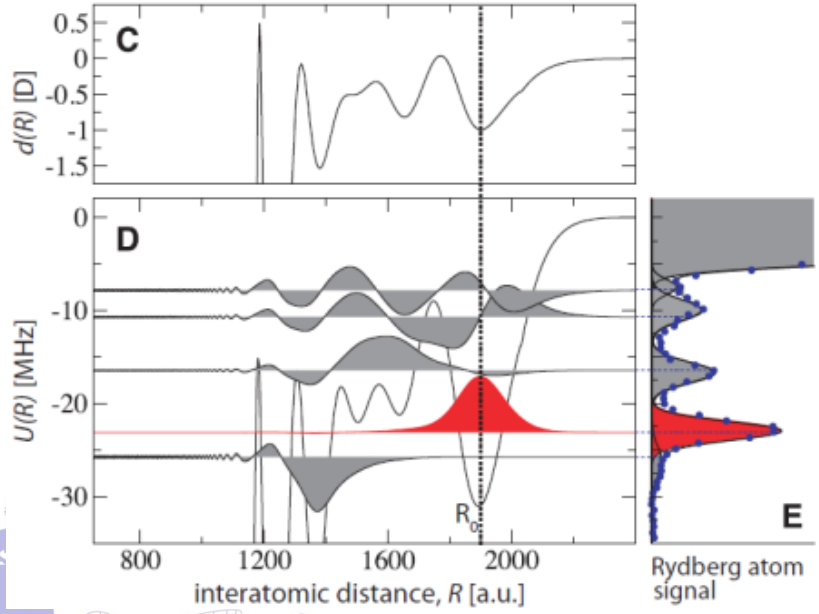

A
B
dipole moment, $\bar{d}$ [D]
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
$\frac{1}{n^{\star 2}}$
F [V/cm²]
2
0
-2
-24
-23
-22
-21
ν [MHz]
30
32
34
36
38
40
effective principal quantum number, $n^{\star}$

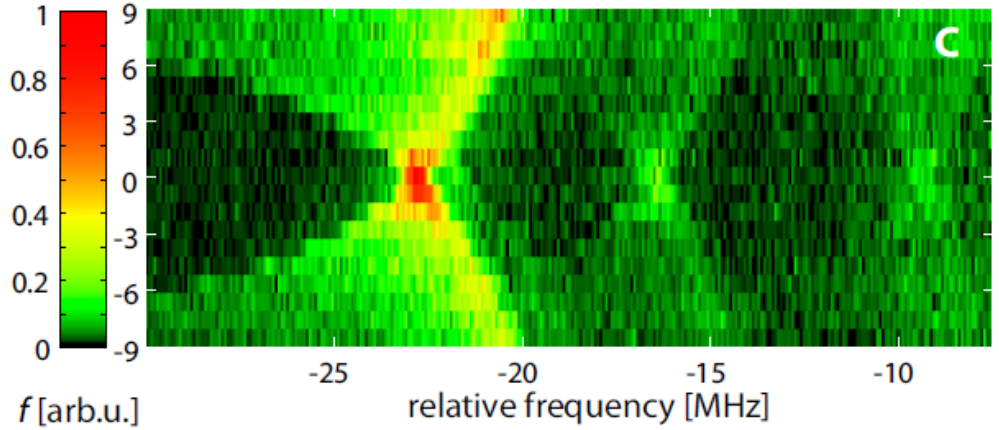
Full theory



B=11.5 kHz
T=3 μK
γ=142 kHz

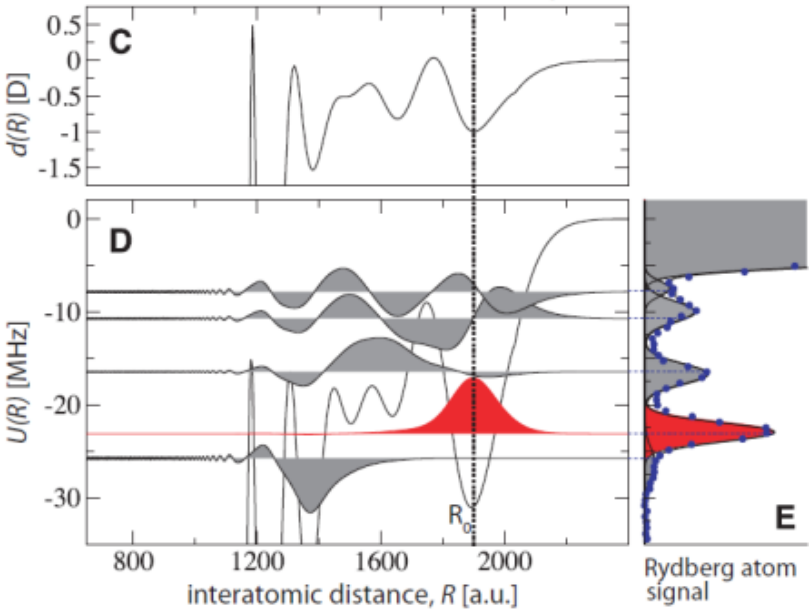


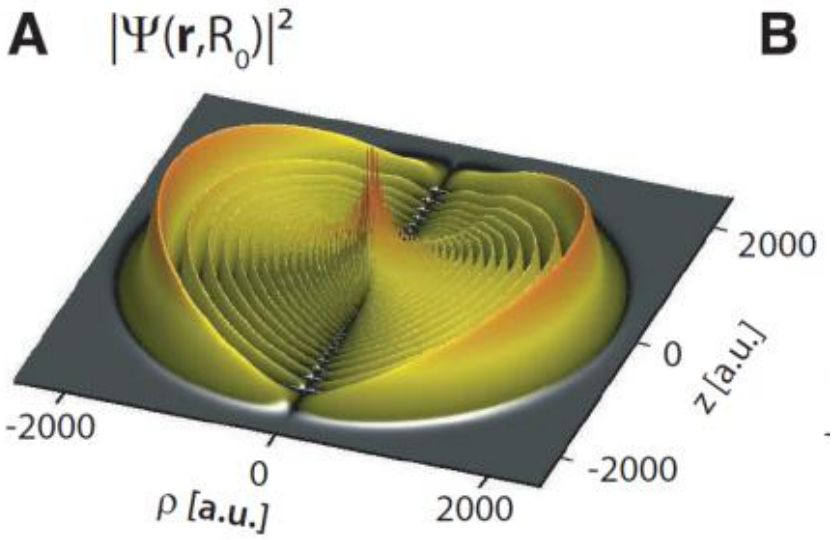


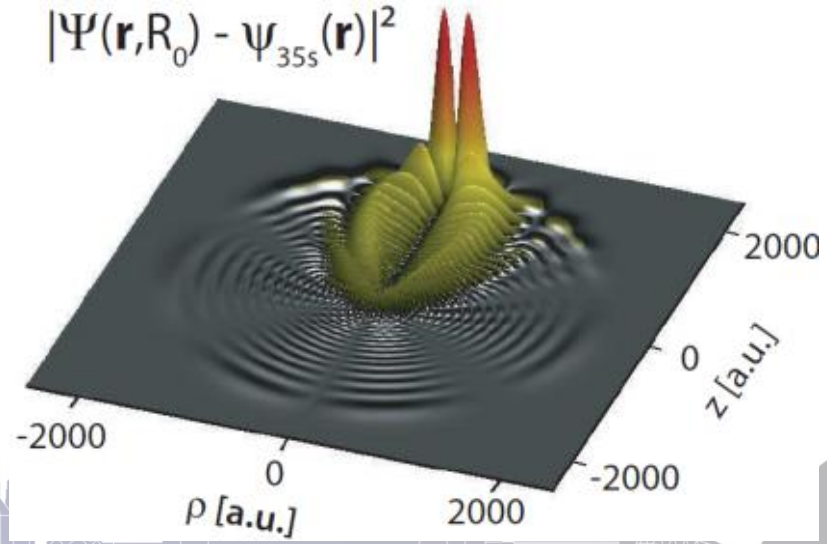


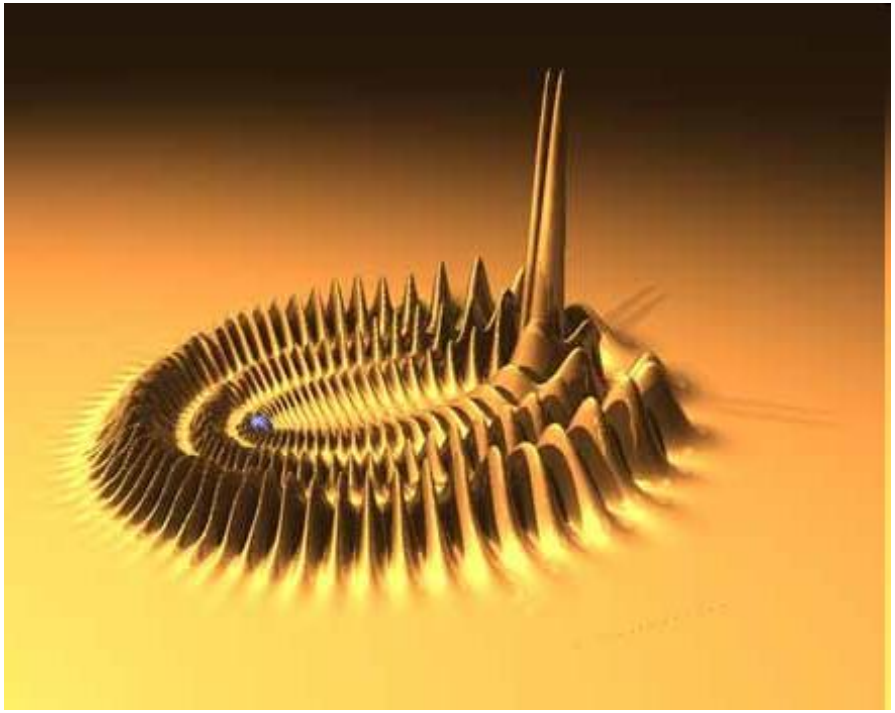
Origin of the permanent dipole moment

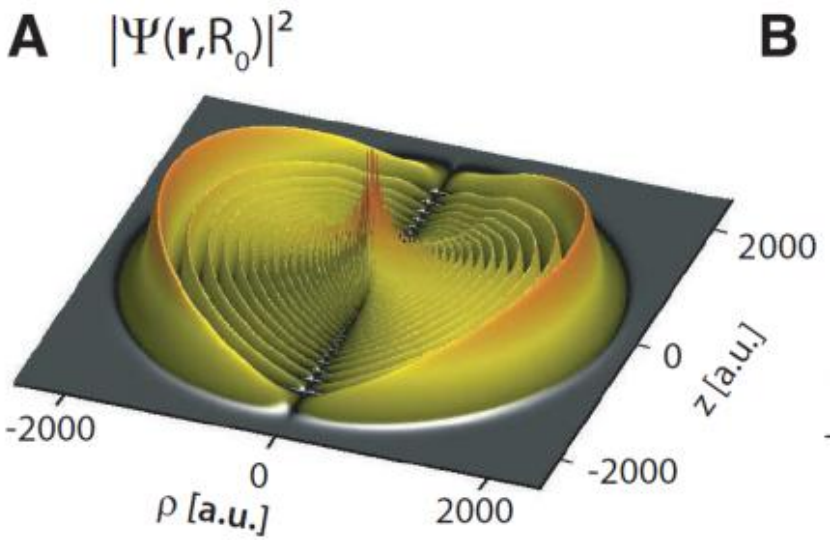
$$d(R) = \langle \Psi(r,R) | ez | \Psi(r,R) \rangle$$

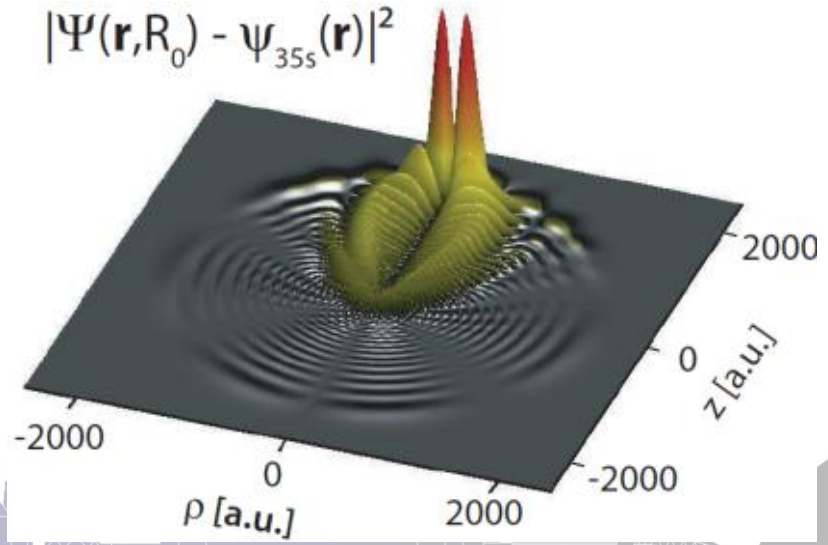




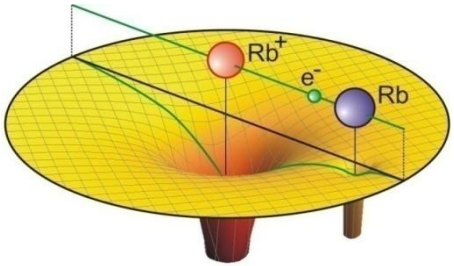




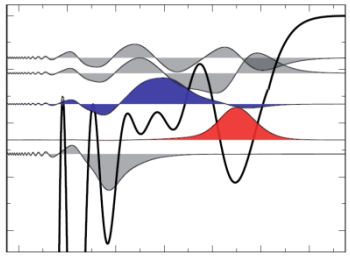

A
$|\Psi(\mathbf{r},R_0)|^2$
B
2000
0
z [a.u.]
-2000
-2000
0
2000
ρ [a.u.]


$|\Psi(\mathbf{r},R_0) - \psi_{35s}(\mathbf{r})|^2$
2000
0
z [a.u.]
-2000
-2000
0
2000
ρ [a.u.]

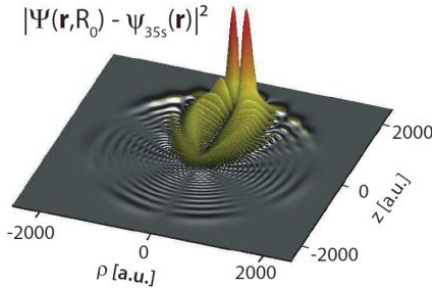
Conclusion



Ultra-longrange Rydberg Molecules

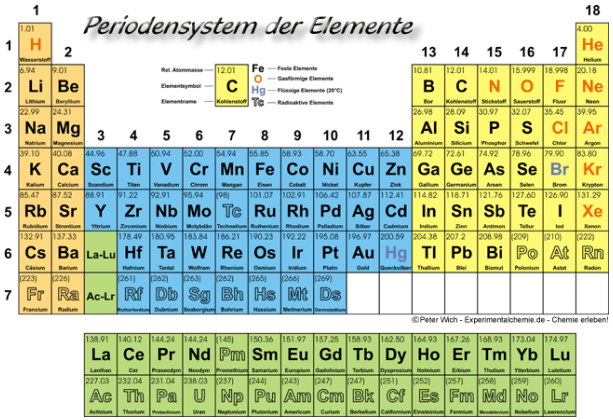


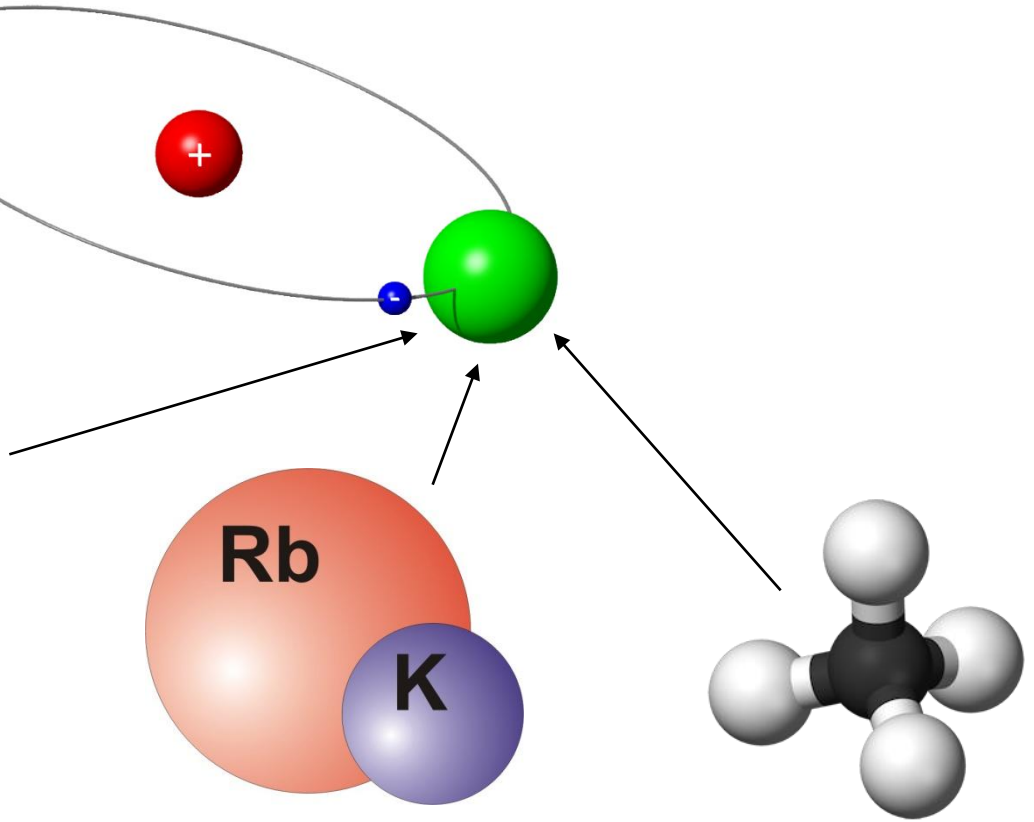
Decay mechanism of Rydberg molecules



Trilobite states

More exotic molecules ?





Radial dynamics