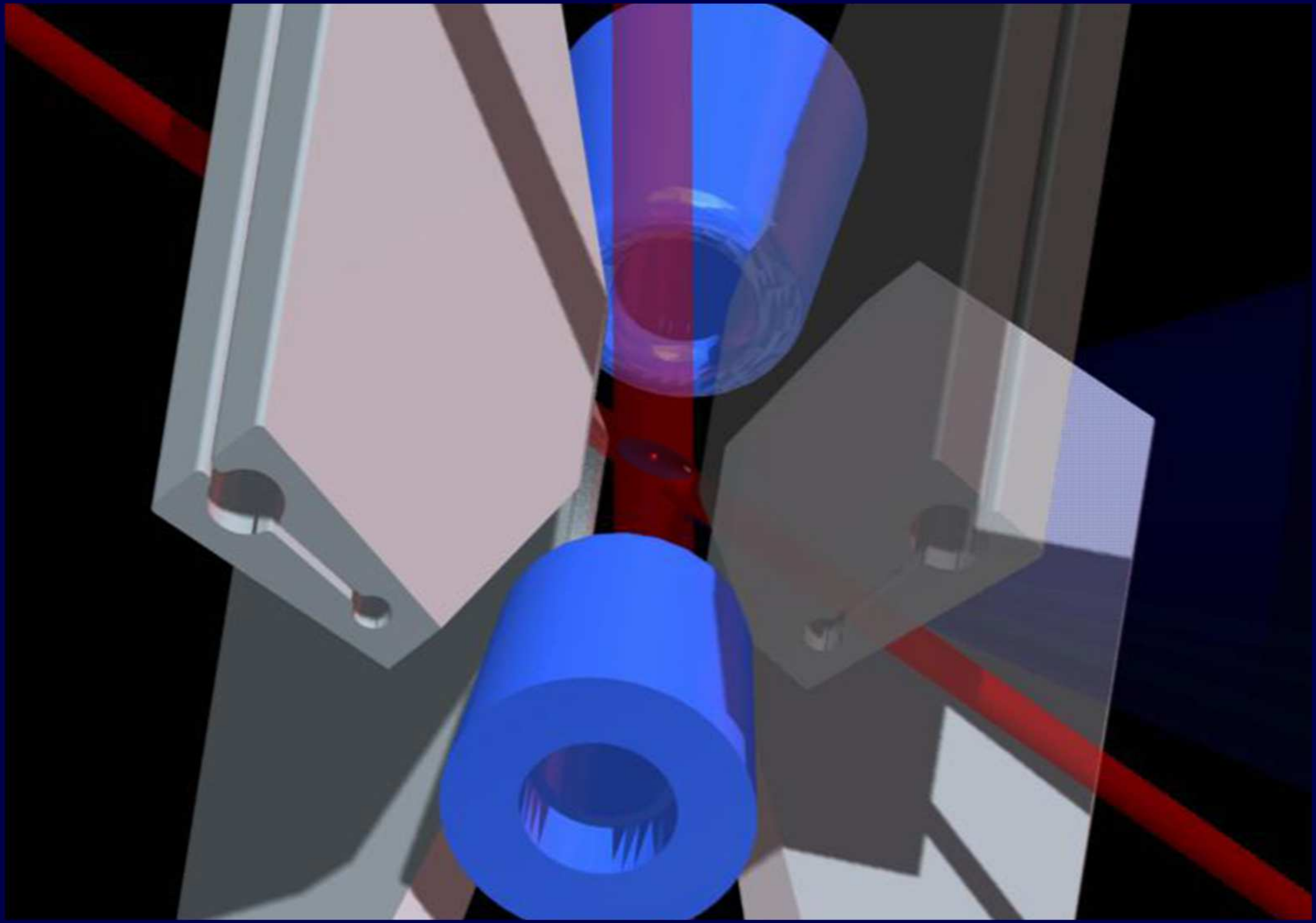
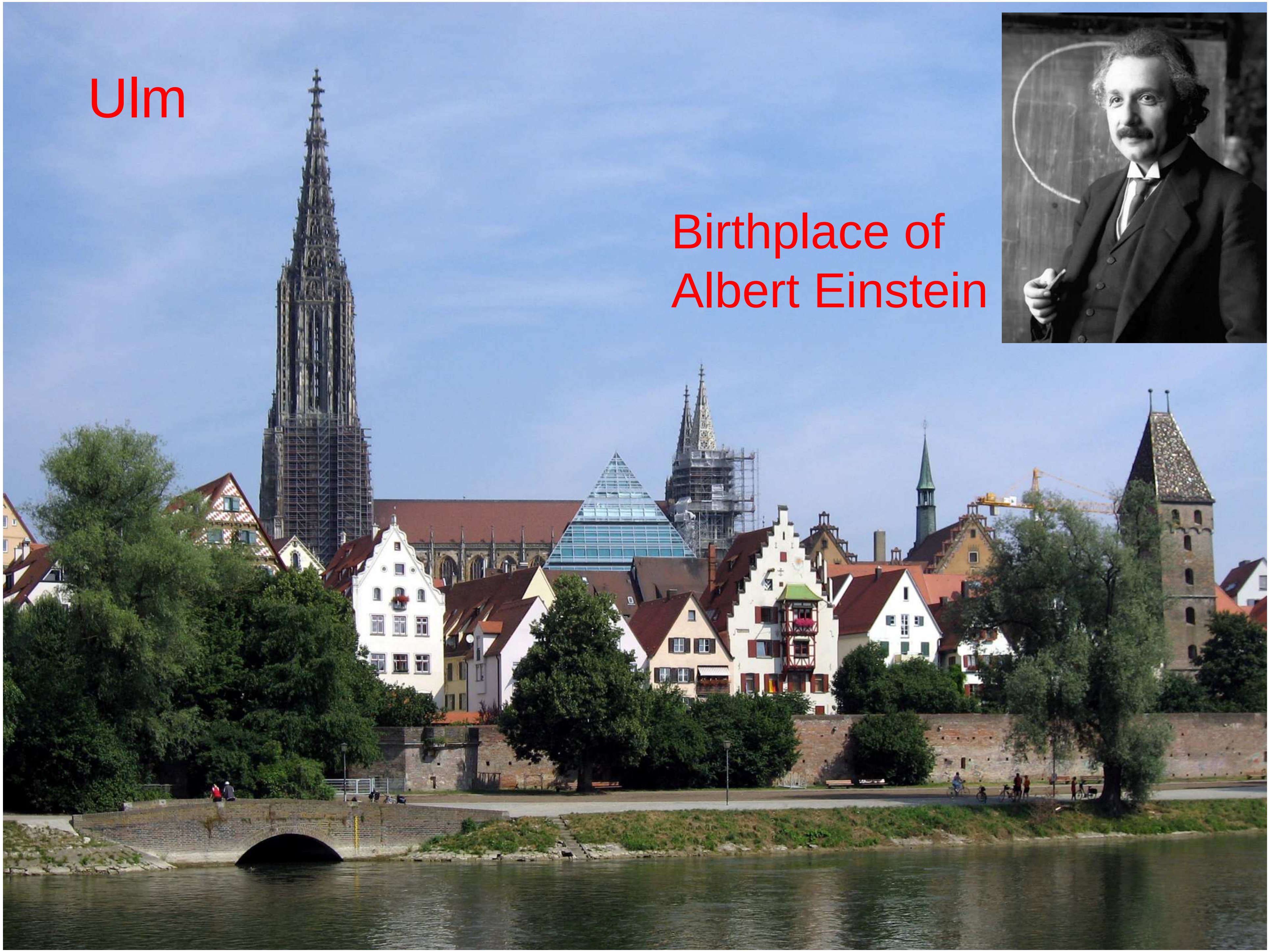
SFB/ TRR21

Cold few-body collisions between atoms, ions and molecules



Johannes Hecker Denschlag
Seattle, April 15, 2014



Ulm

Birthplace of
Albert Einstein

ULM

170.000 people

Danube

Albert Einstein

Great Summer Festival

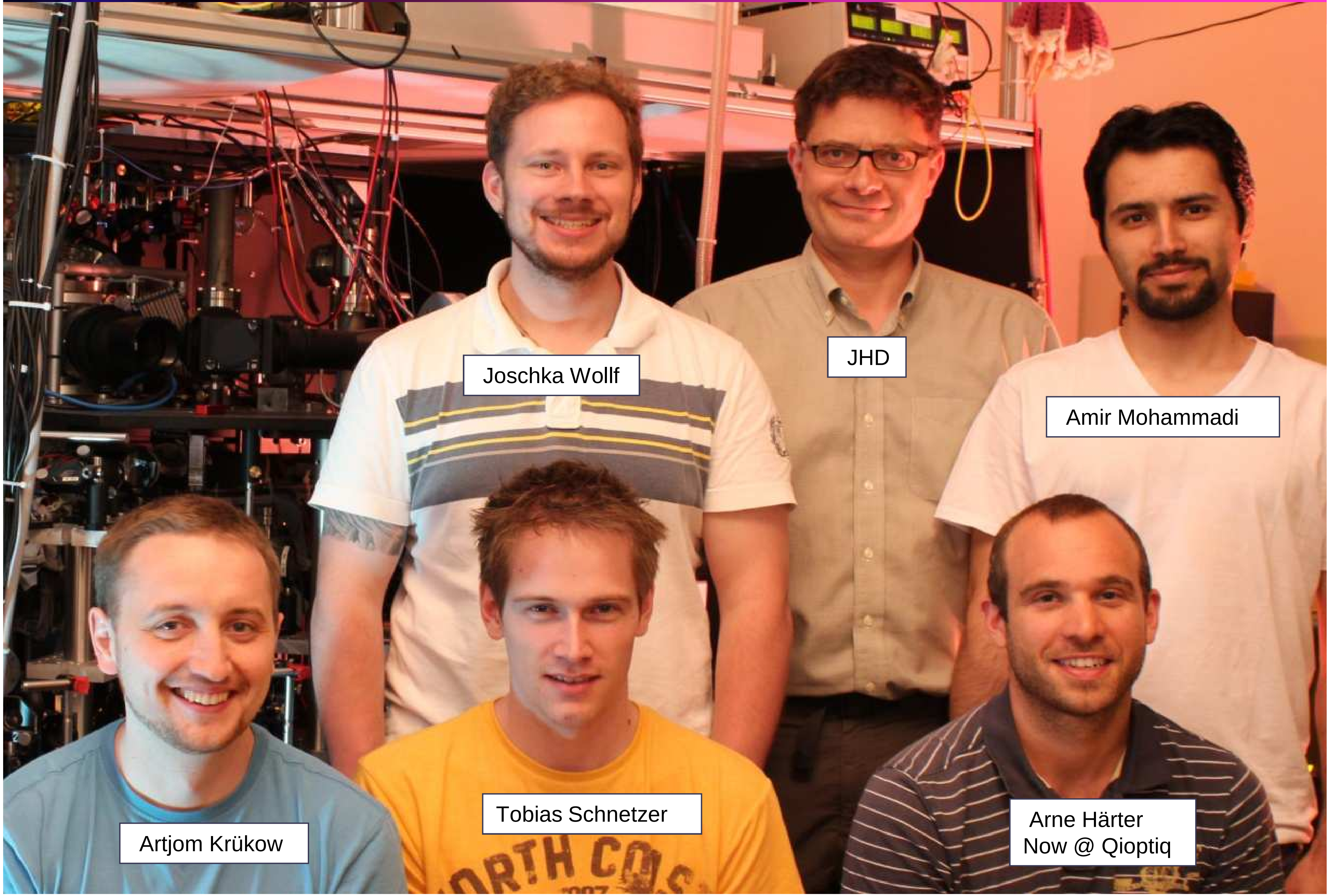
Caves

… another good thing
from Ulm

(besides Einstein)


Seattle, NE 42 St

The BaRbIe-Team



Joschka Wollf

JHD

Amir Mohammadi

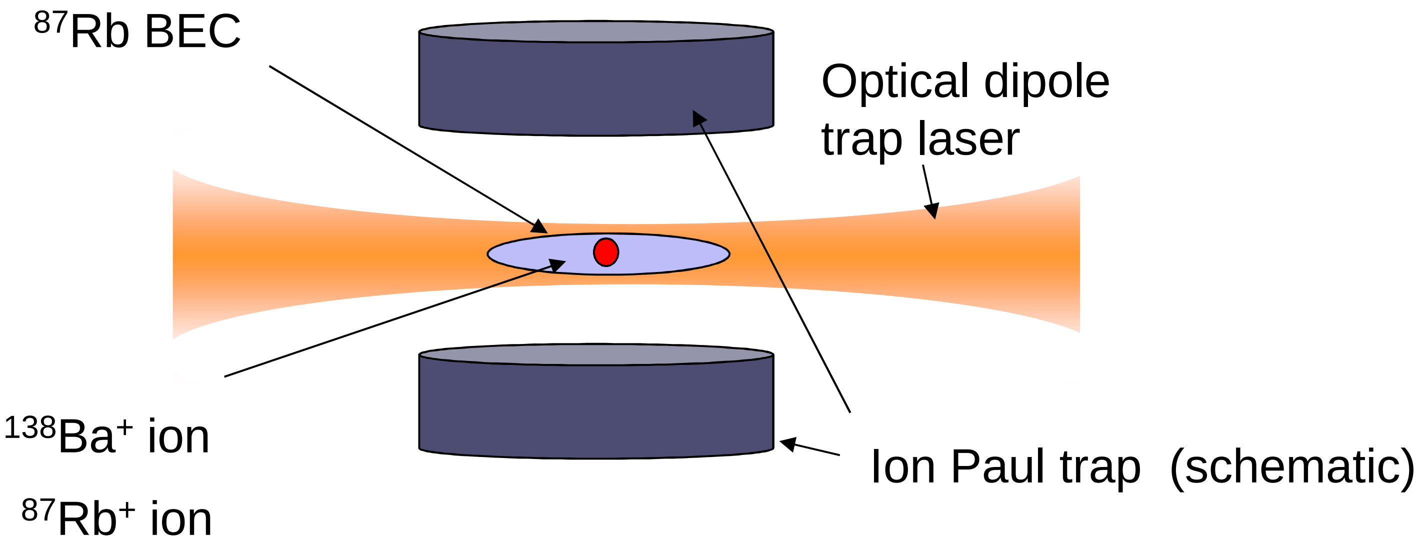
Artjom Krükow

Tobias Schnetzer

Arne Härter
Now @ Qioptiq

Combining cold atoms and ions: a new field

Trapped Ions and **Ultracold neutral Atoms**



^{87}Rb BEC

Optical dipole trap laser

^{138}Ba^{+} ion

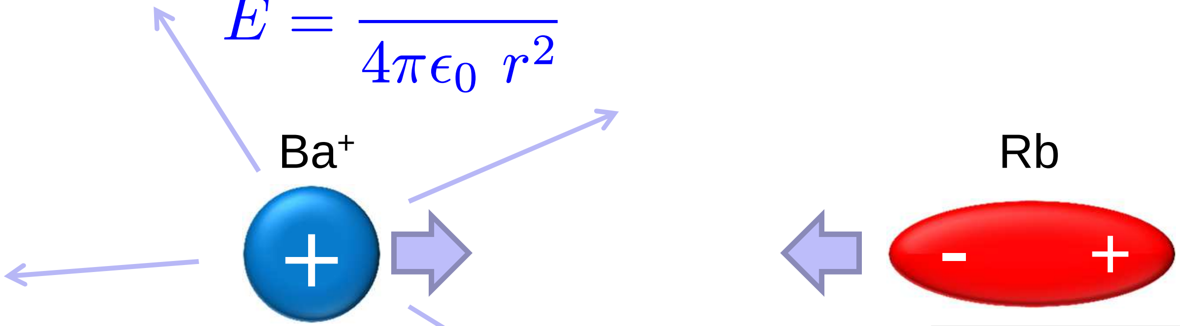
^{87}Rb^{+} ion

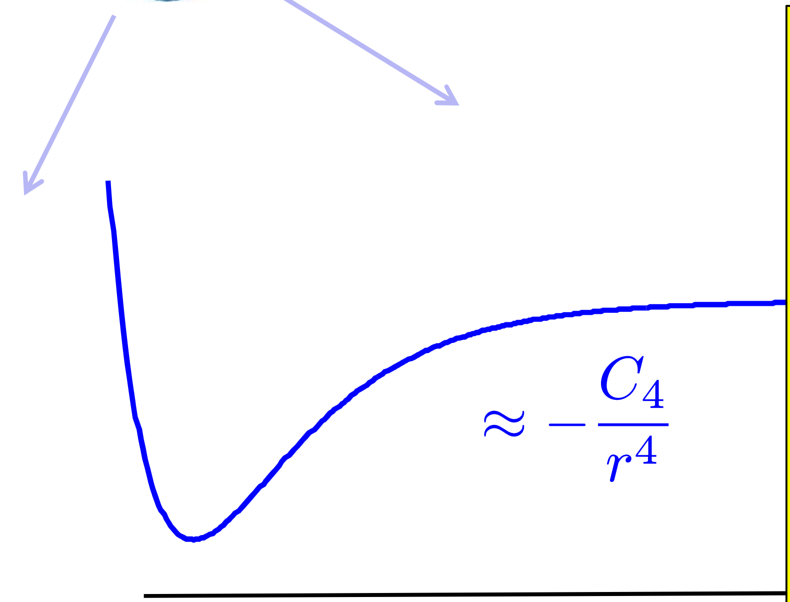
Ion Paul trap (schematic)

Good compatibility of traps!

Long range atom – ion interaction

$$E = \frac{e}{4\pi\epsilon_0\ r^2}$$

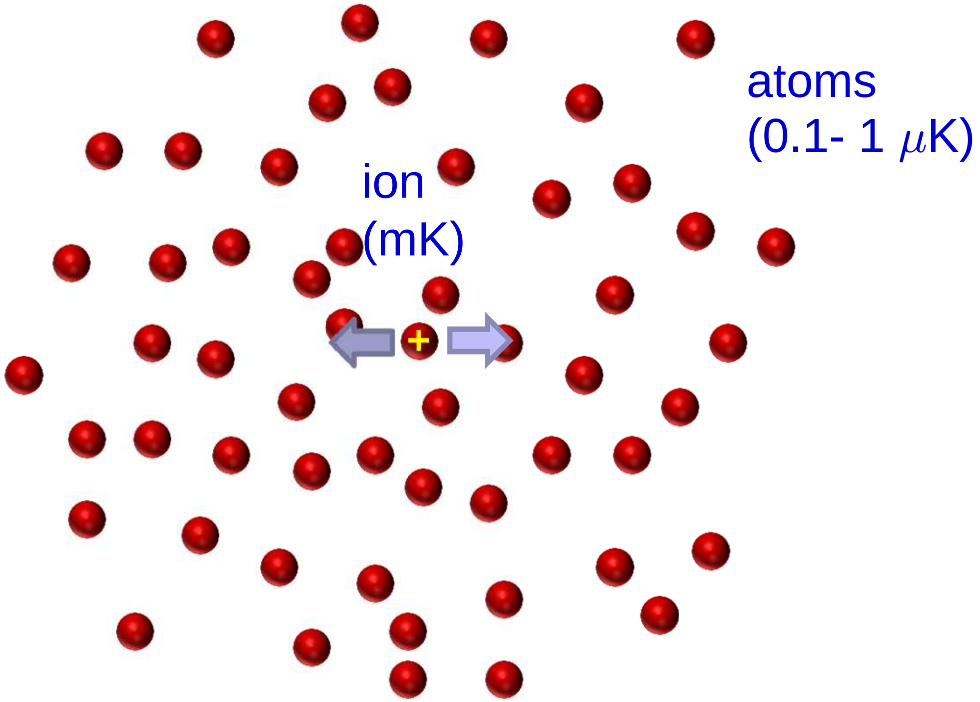




$$\approx -\frac{C_4}{r^4}$$

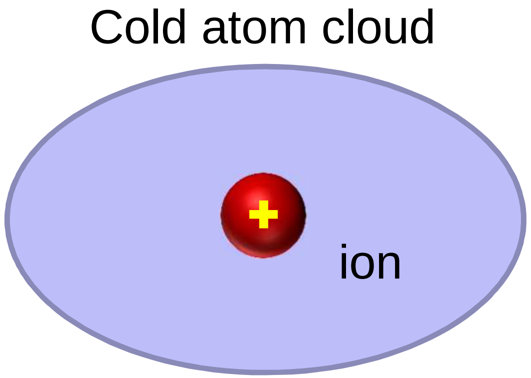
- Pure s- wave regime only at ~ 100nK (at our energies 0.1- 10 mK several partial waves contribute)
- Large scattering lengths of ~5000 a_0 (large cross sections and many body effects at even at moderate densities)

An ion in a cloud of atoms, naive picture

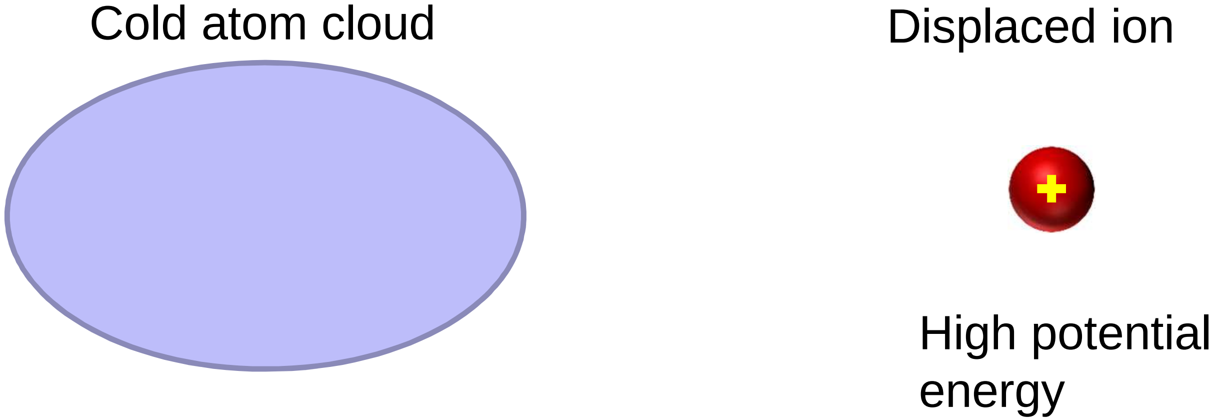


- Thermalization of ion within a few collisions, sympathetic cooling
- No further dynamics afterwards….

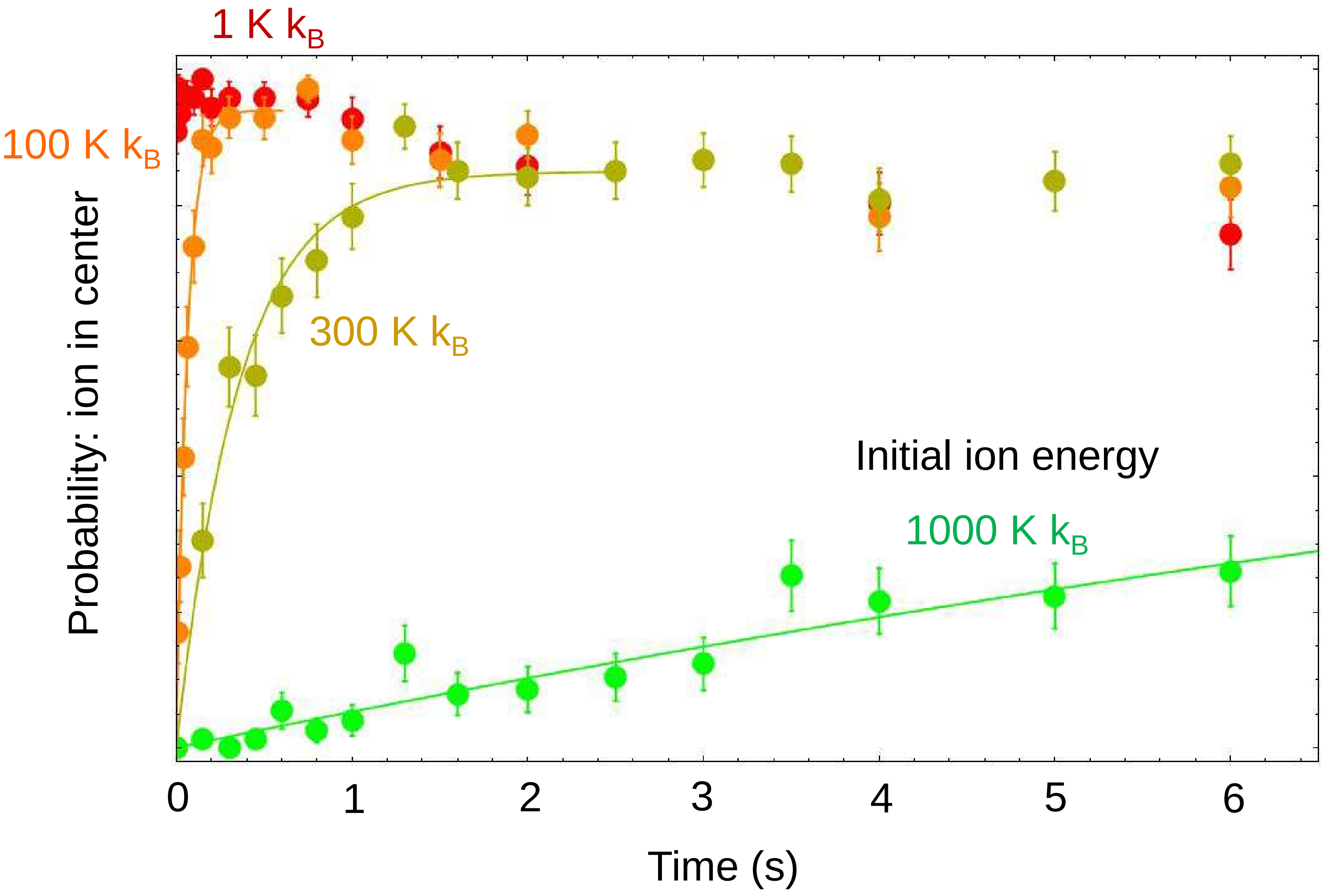
Can atoms cool hot ions?



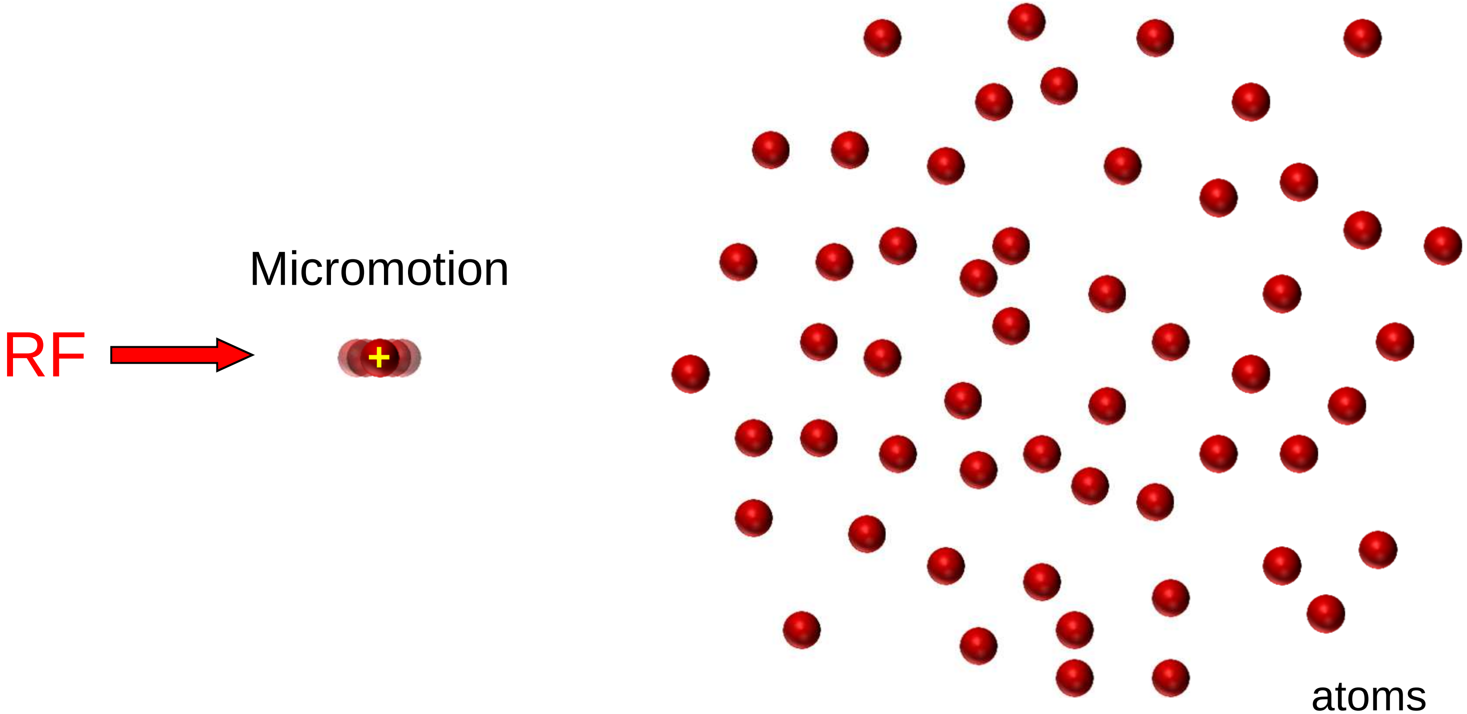
Can atoms sympathetically cool hot ions?



Sympathetic cooling of a hot ion



The role of excess micromotion



atoms $T \sim 1\,\mu\mathrm{K}$
confined by
shallow dipole trap
$U_{\mathrm{dip}} \sim 10\mu\mathrm{K}$

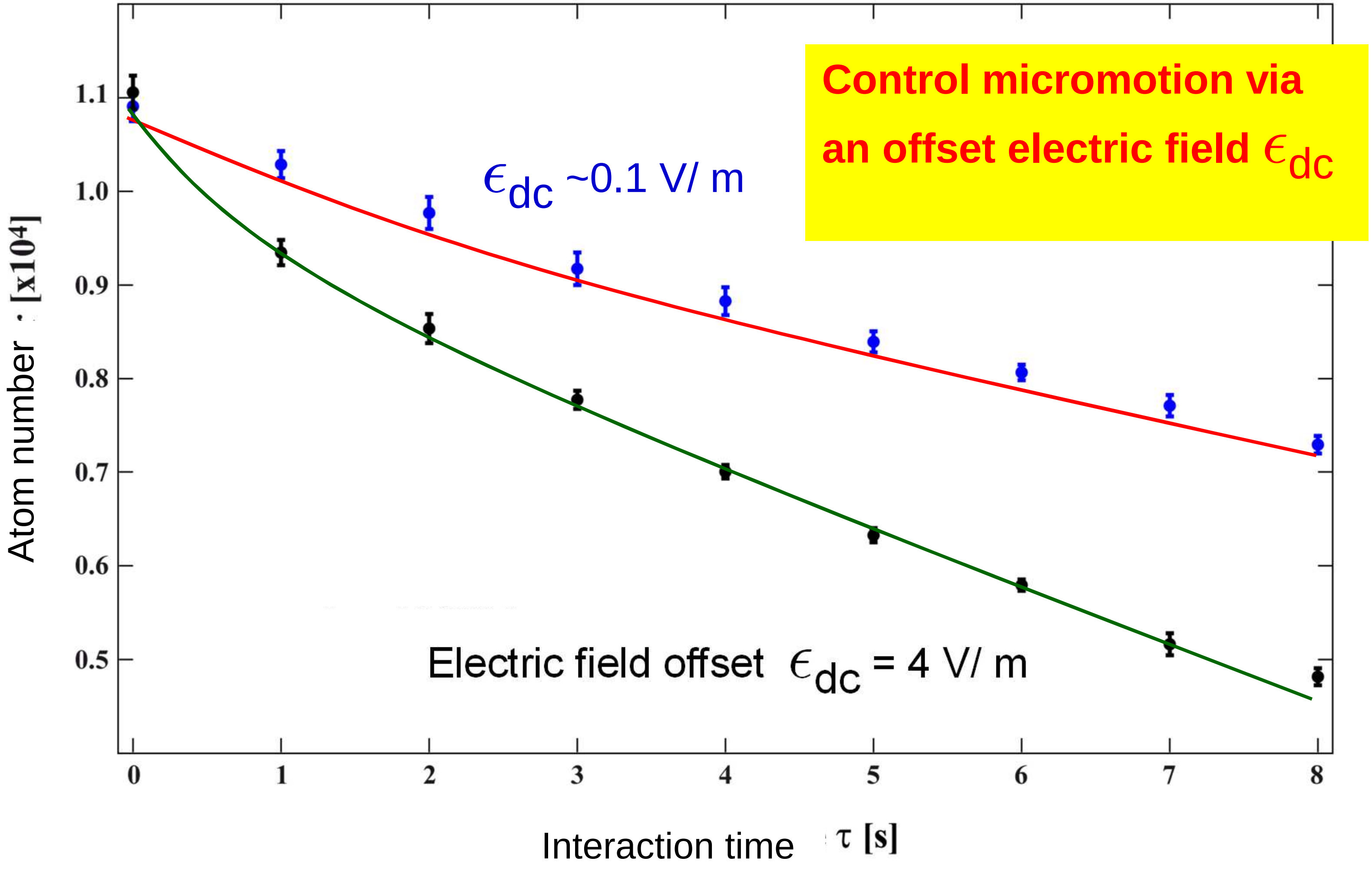
- coherent trap drive (4 MHz) accelerates stopped ion again

- ion energy is set by excess micromotion which we can control $E_{\mathrm{ion}} \sim 0.1 - 10\mathrm{mK}\ \mathrm{k_B}$

We set collision energy by controlling micromotion !

Elastic two-body atom-ion collisions

Thermal atom cloud T ~ 100nK

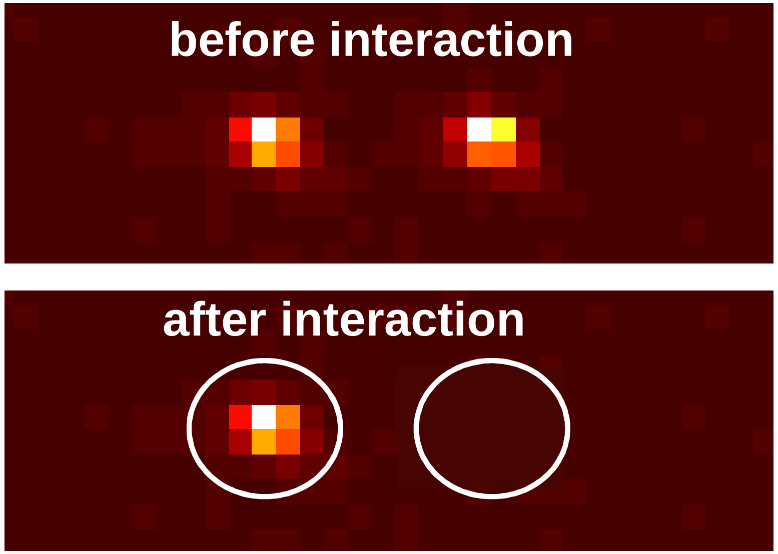


Control micromotion via an offset electric field ϵ_{dc}

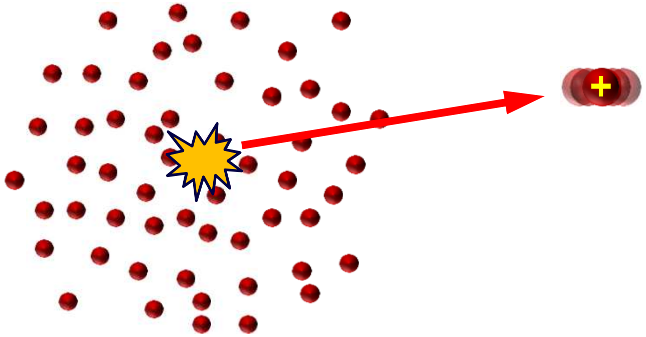
Reactions

How do we detect a reaction?

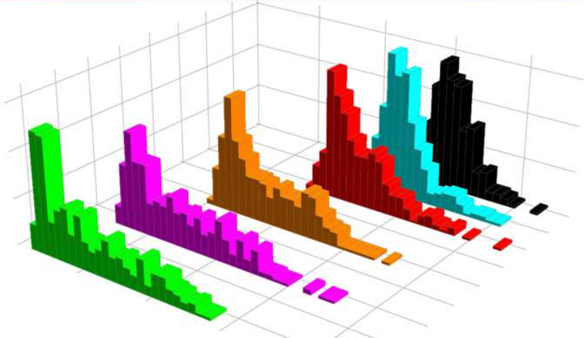
- Ion turns dark,
  changes mass



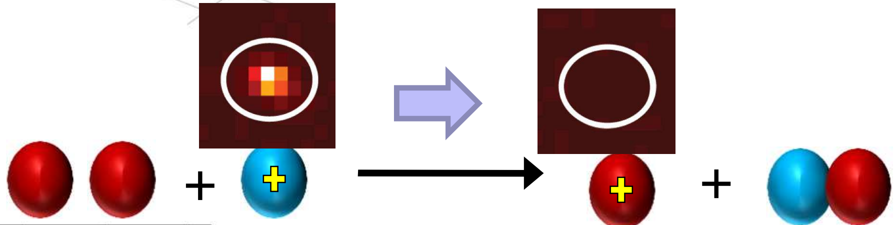
- Release of energy
  - ion orbits outside of atoms
  - change in atom loss



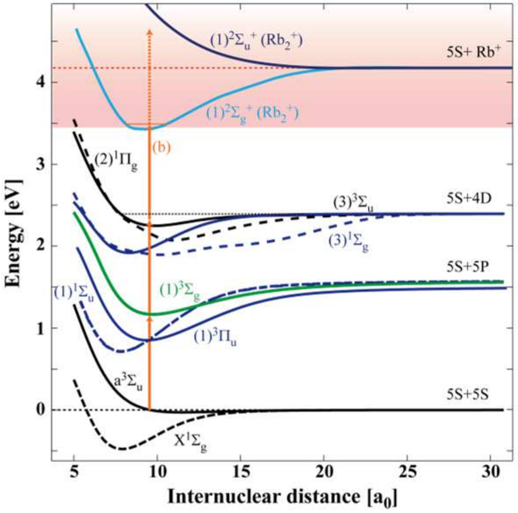
few-body reactions



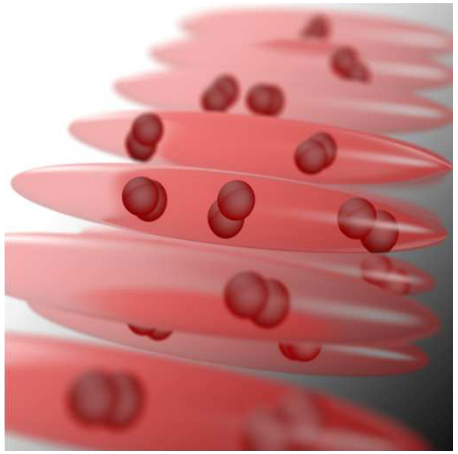
1) $Rb^+ + 2Rb \rightarrow Rb^+ + (2Rb)$



2) Three-body charge exchange
$Ba^+ + 2Rb \rightarrow Rb^+ + ?$

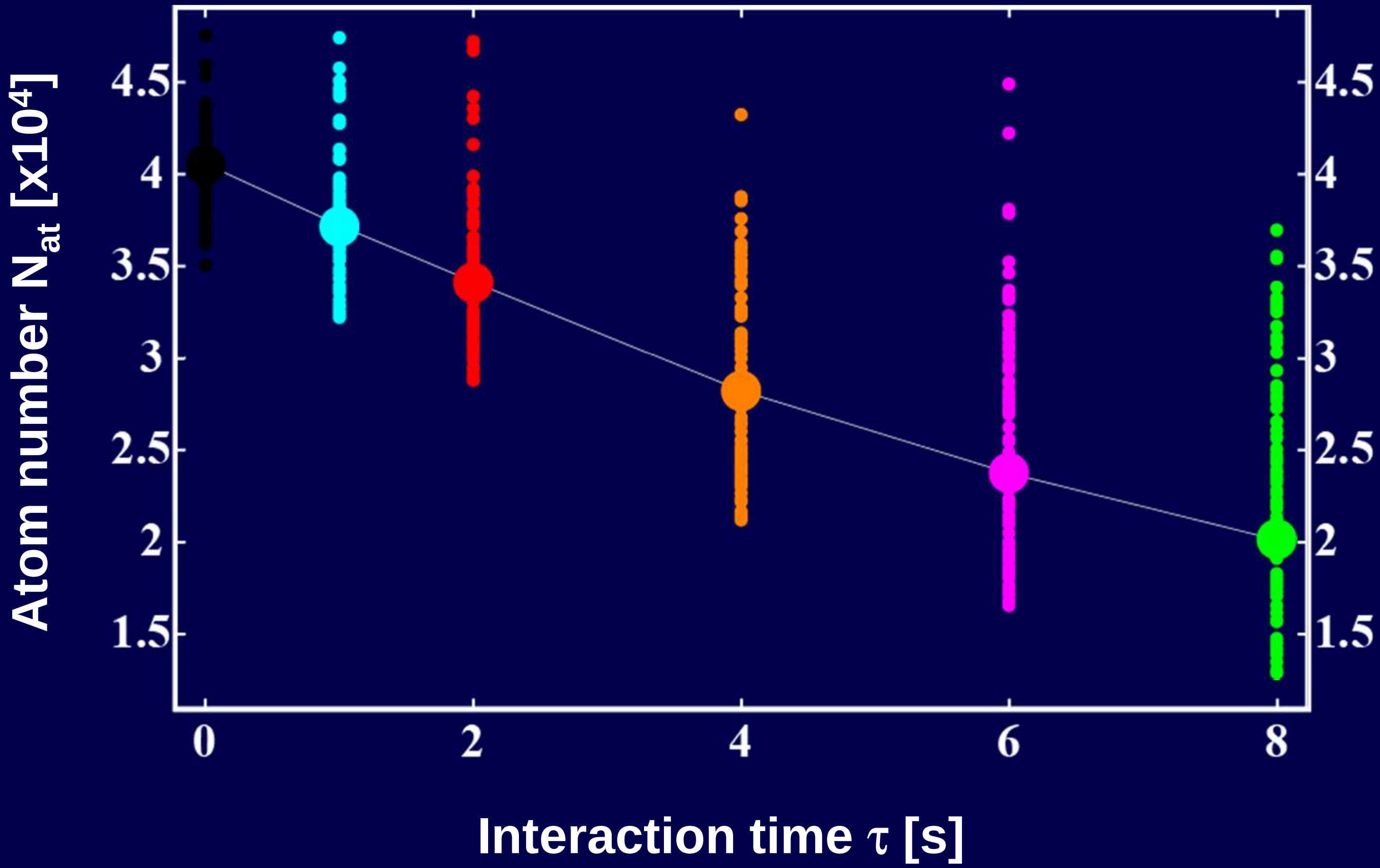


3) Reaction products
$3\,Rb \rightarrow Rb_2 + Rb$

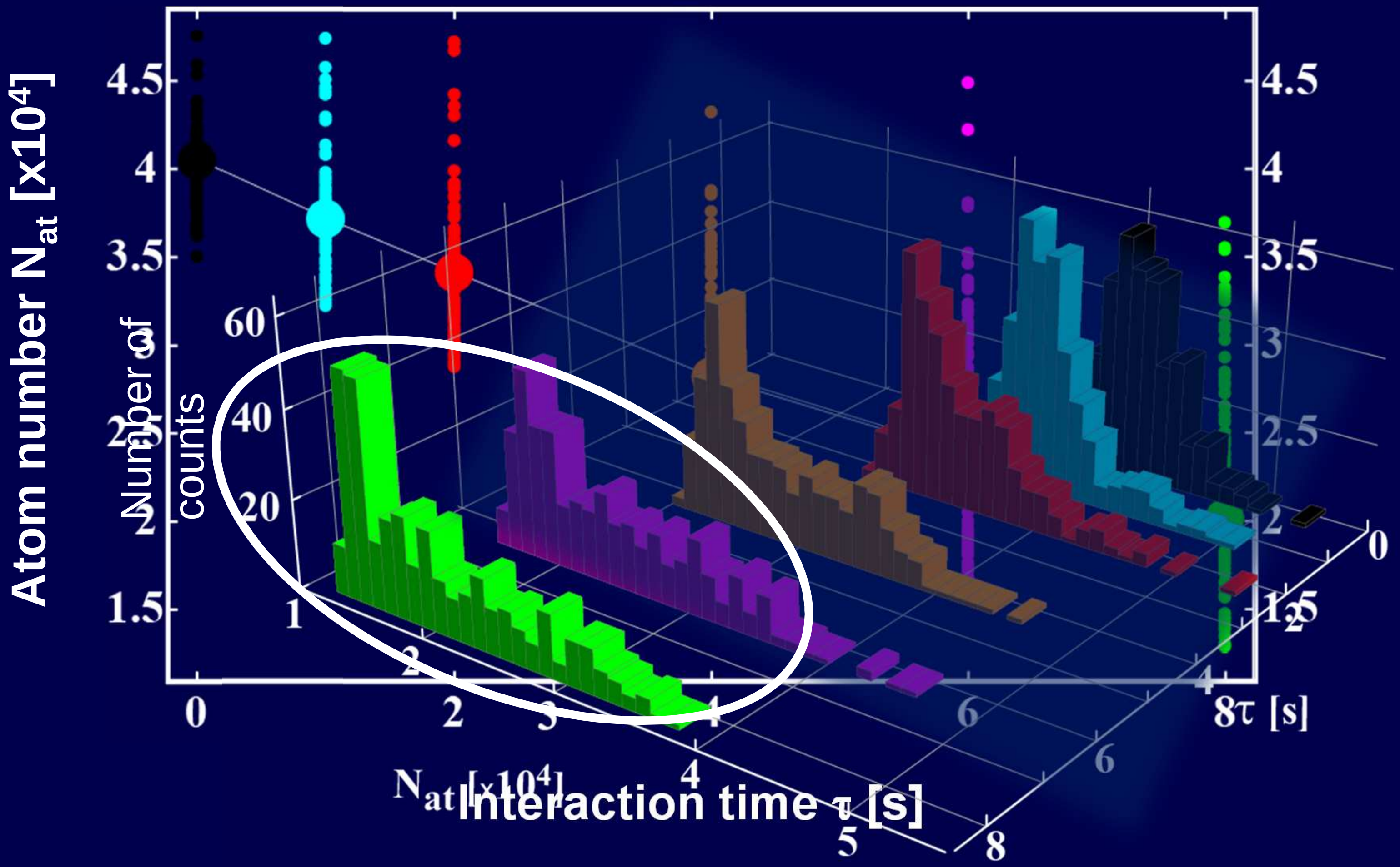


4) Cold molecule collisions
$Rb_2 + Rb_2$

Ion-induced atom loss
Rb^+ in cold Rb cloud

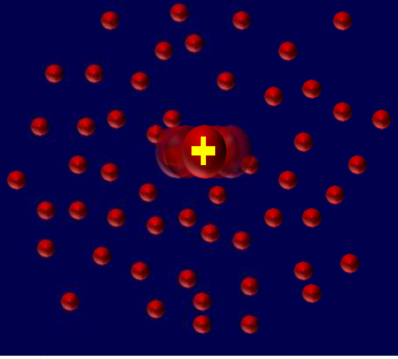


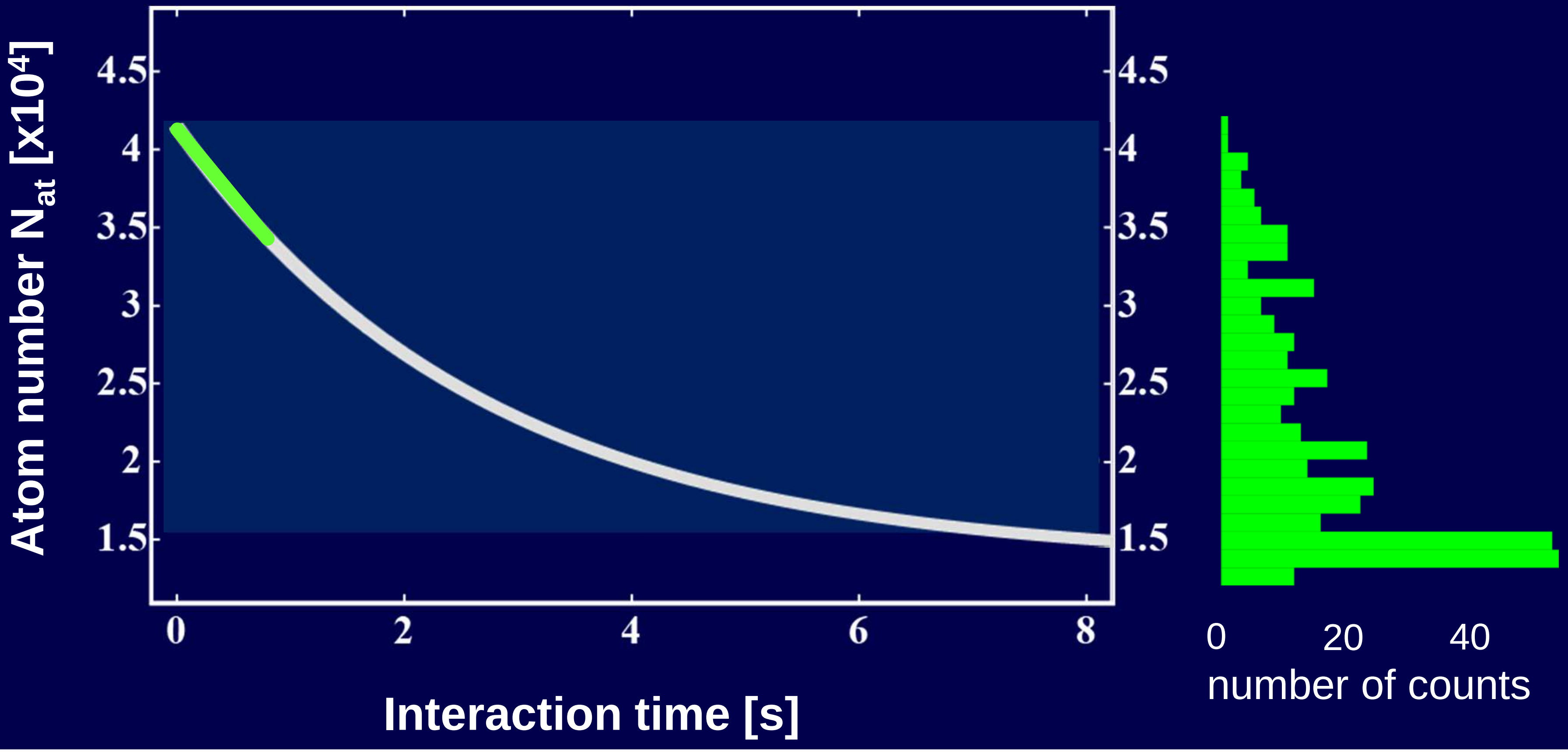
Atom number distributions



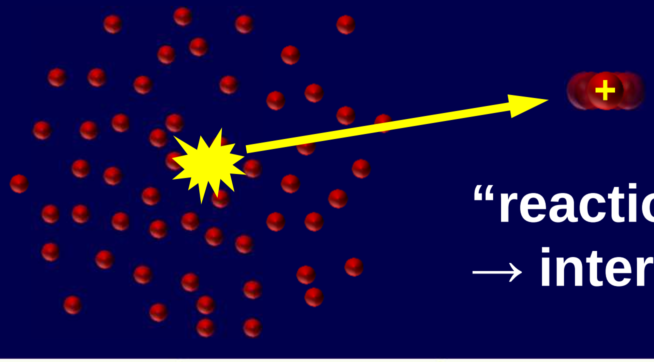
A. Härter et al. PRL 2012

Collision dynamics

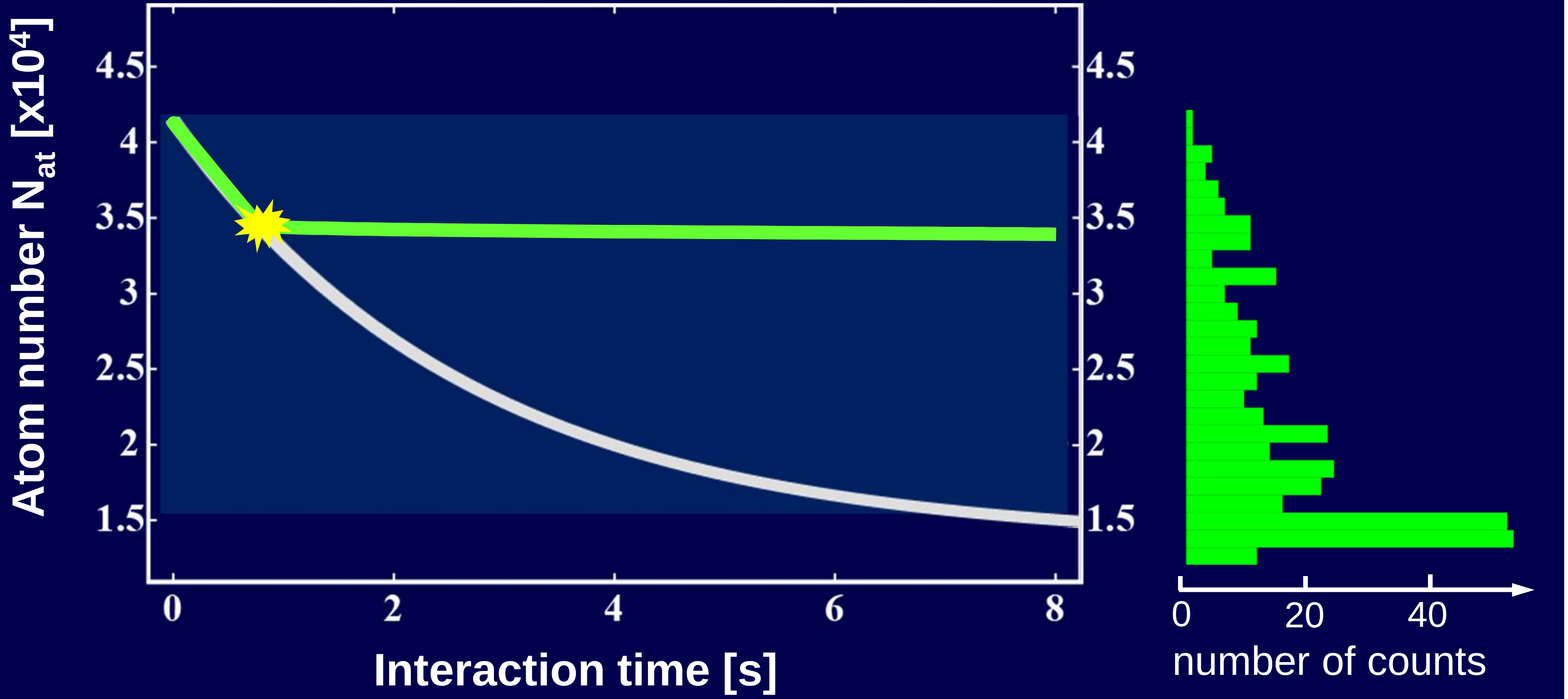




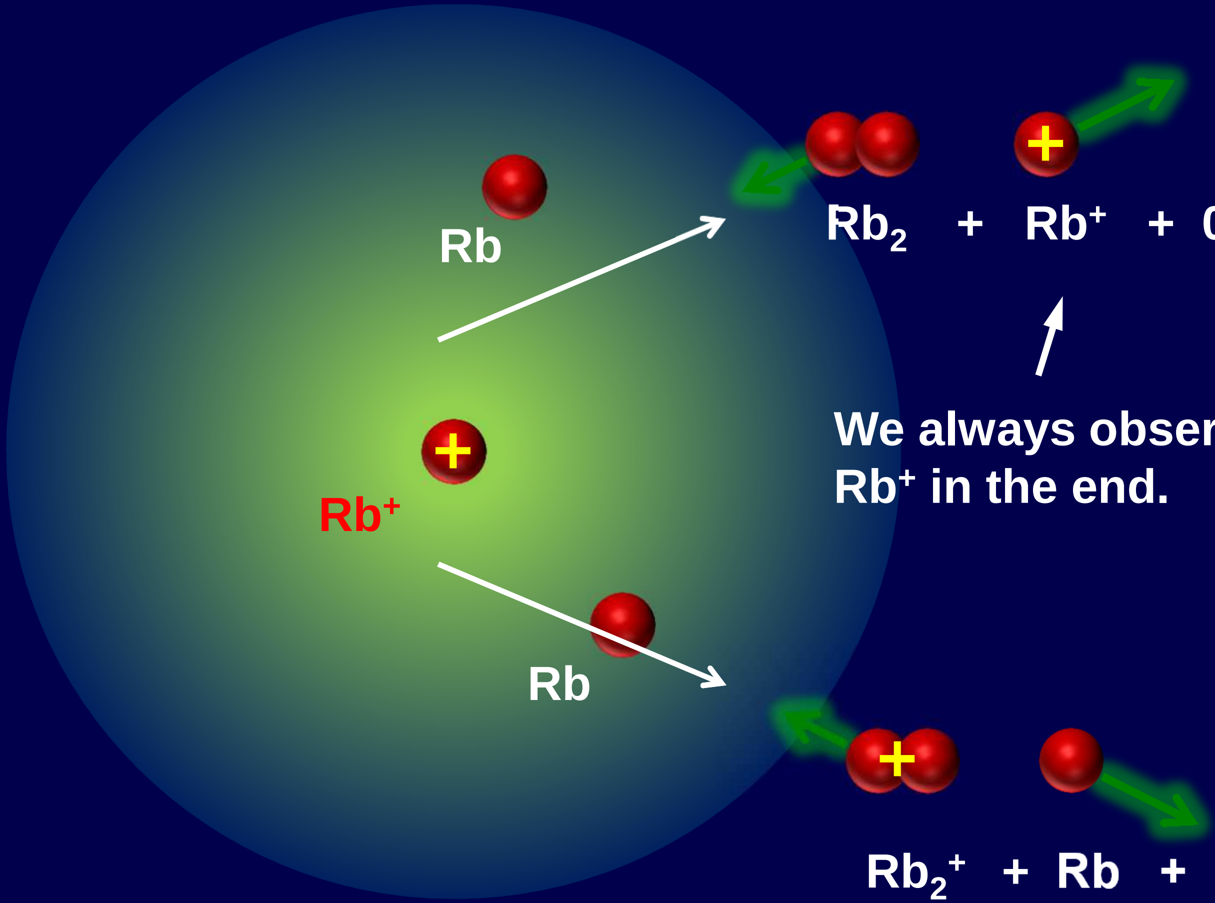
Collision dynamics



“reaction“ event
→ interaction stops!



Atom-atom-ion three-body recombination

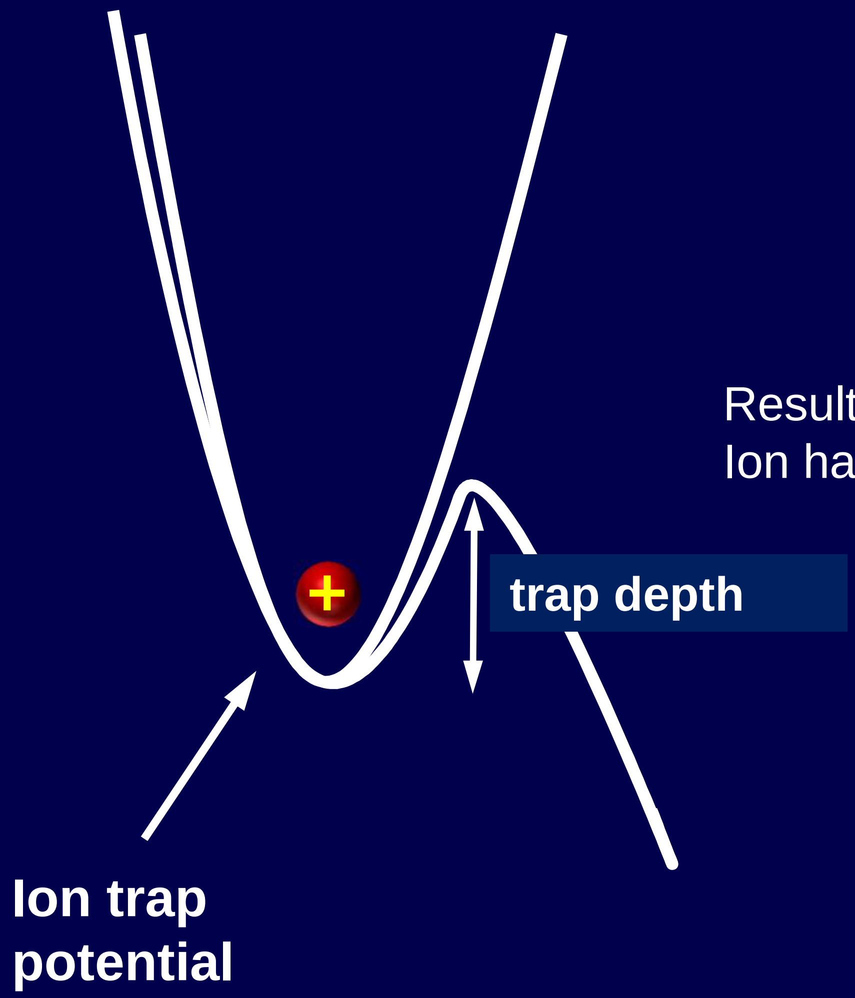


Rb_2 + Rb^+ + 0.48eV

We always observe Rb^+ in the end.

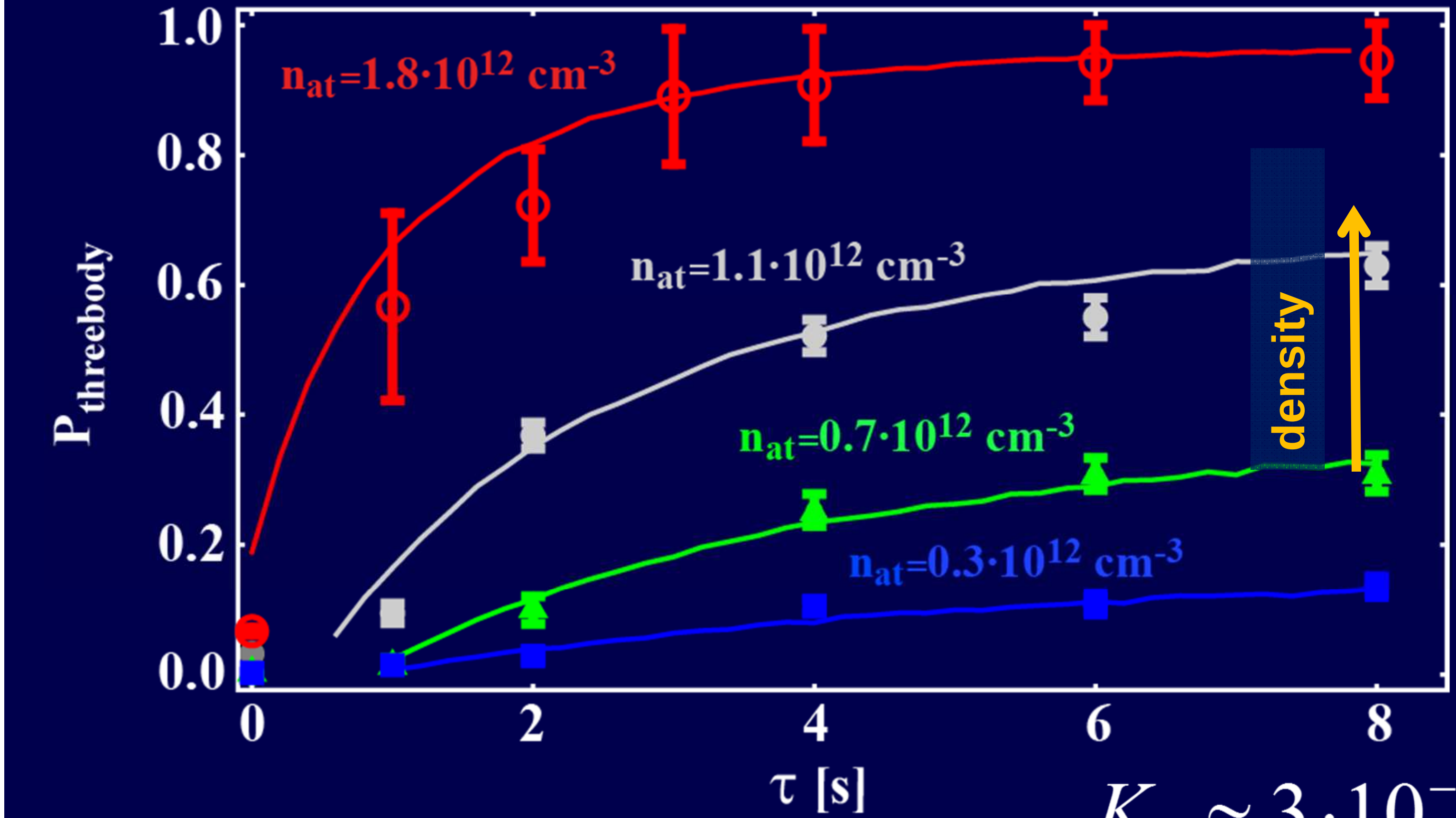
Rb_2^+ + Rb + 0.7eV

Measurement of the reaction energy



Result:
Ion has typical energy of a few 0,1 eV.

Data well described by three-body recombination dynamics

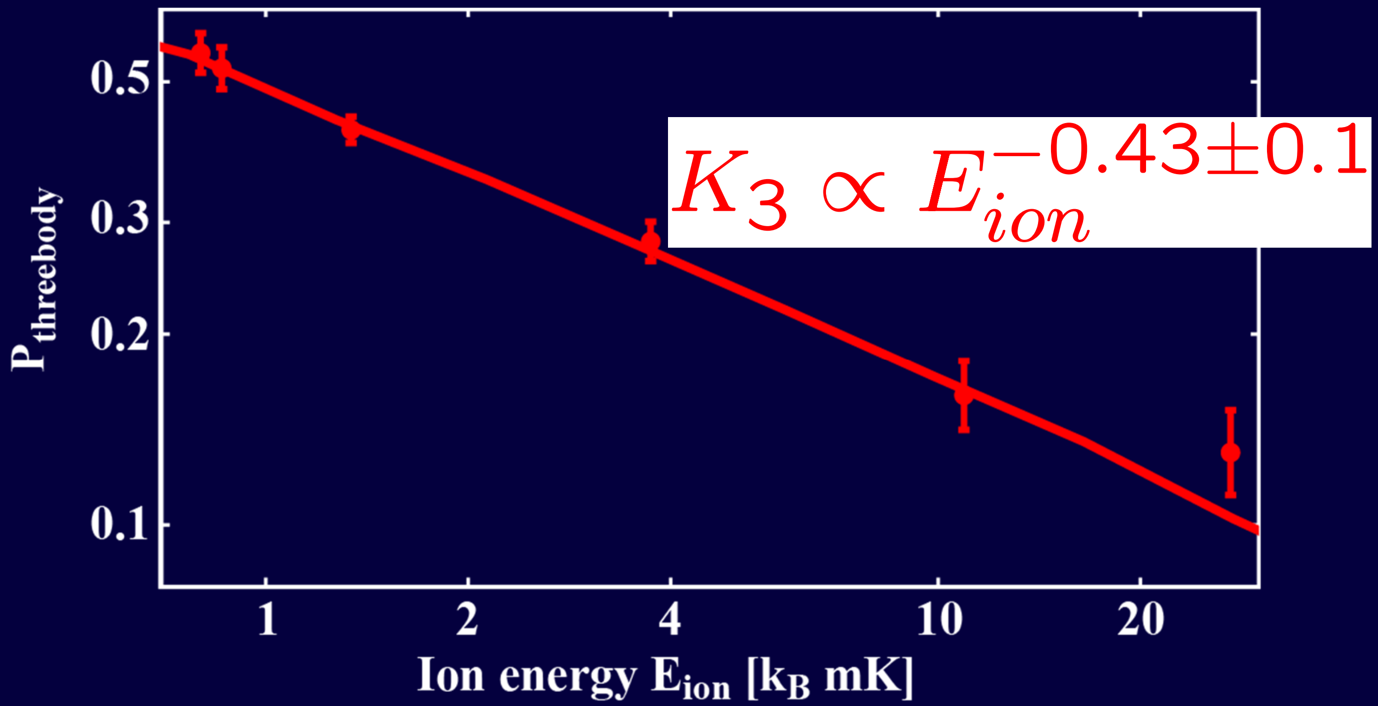


$$K_3 \approx 3\cdot 10^{-25}\ cm^6 s^{-1}$$

quadratic density dependence → atom-atom-ion three-body coefficient

A. Härter et al. PRL 2012

Energy dependence



$$K_3 \propto E_{ion}^{-0.43\pm0.1}$$

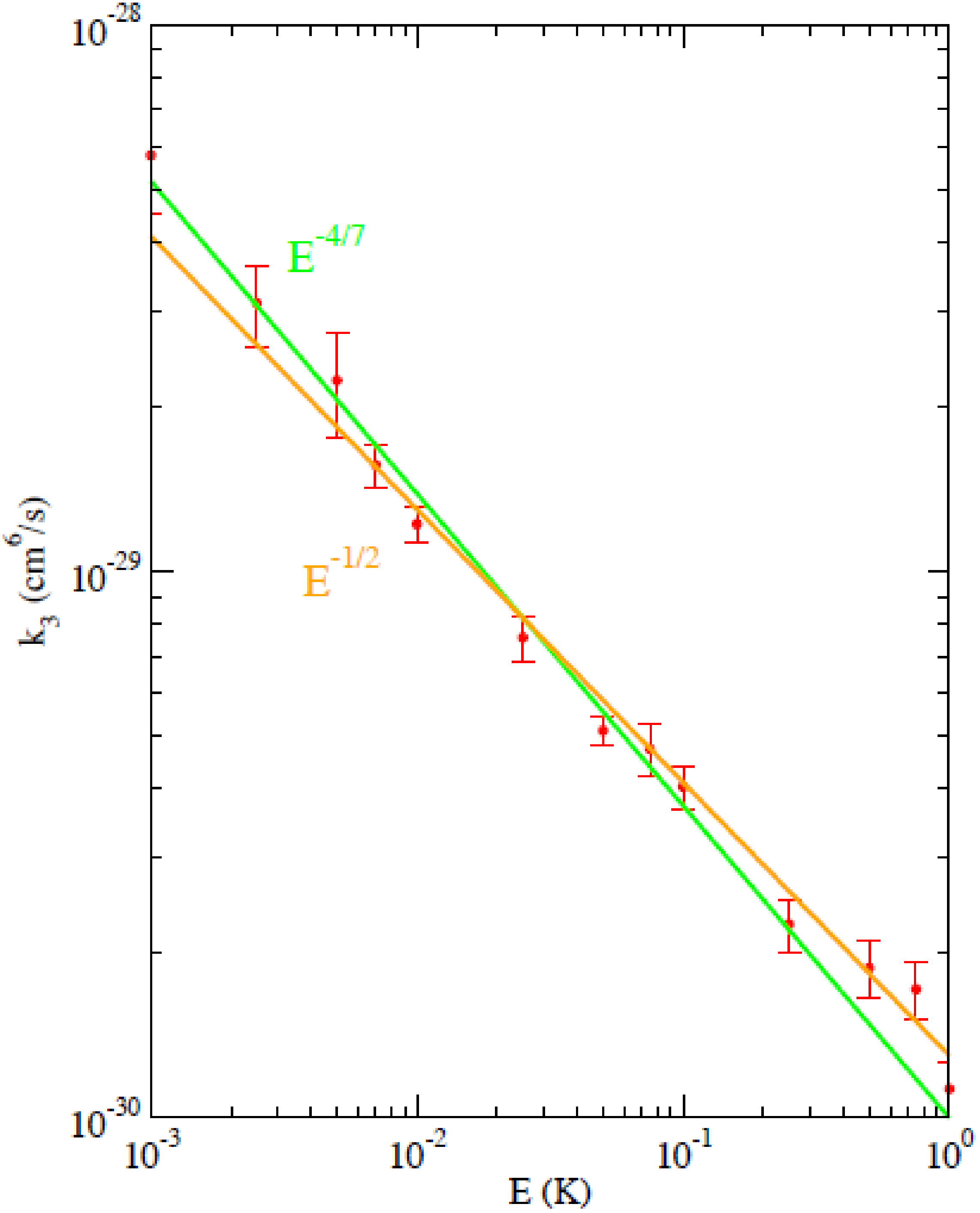
Similar as for Ba* + 2 Rb!

Chris Green and Jesus Perez-Rios
can theoretically confirm this dependence!

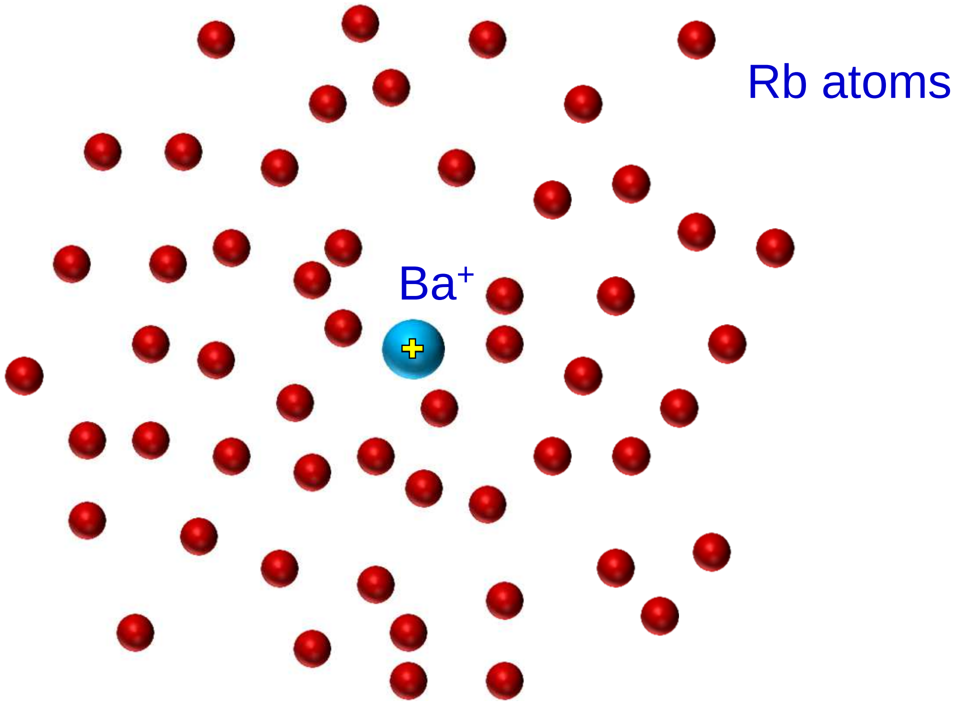
Calculations by
Chris Greene and
Jesus Perez-Rios
(14. 5. 2014)

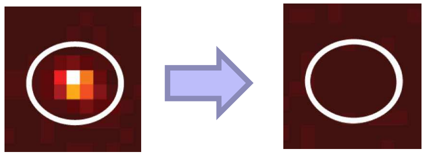
- Classical trajectory
- Monte-Carlo

- Heuristic argument
  for $E^{-4/7} = E^{-5.7}$
  dependence

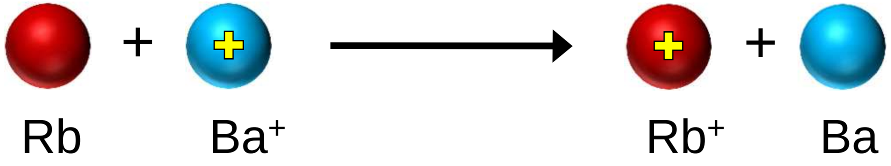


Reaction: Ba^+ with Rb cloud

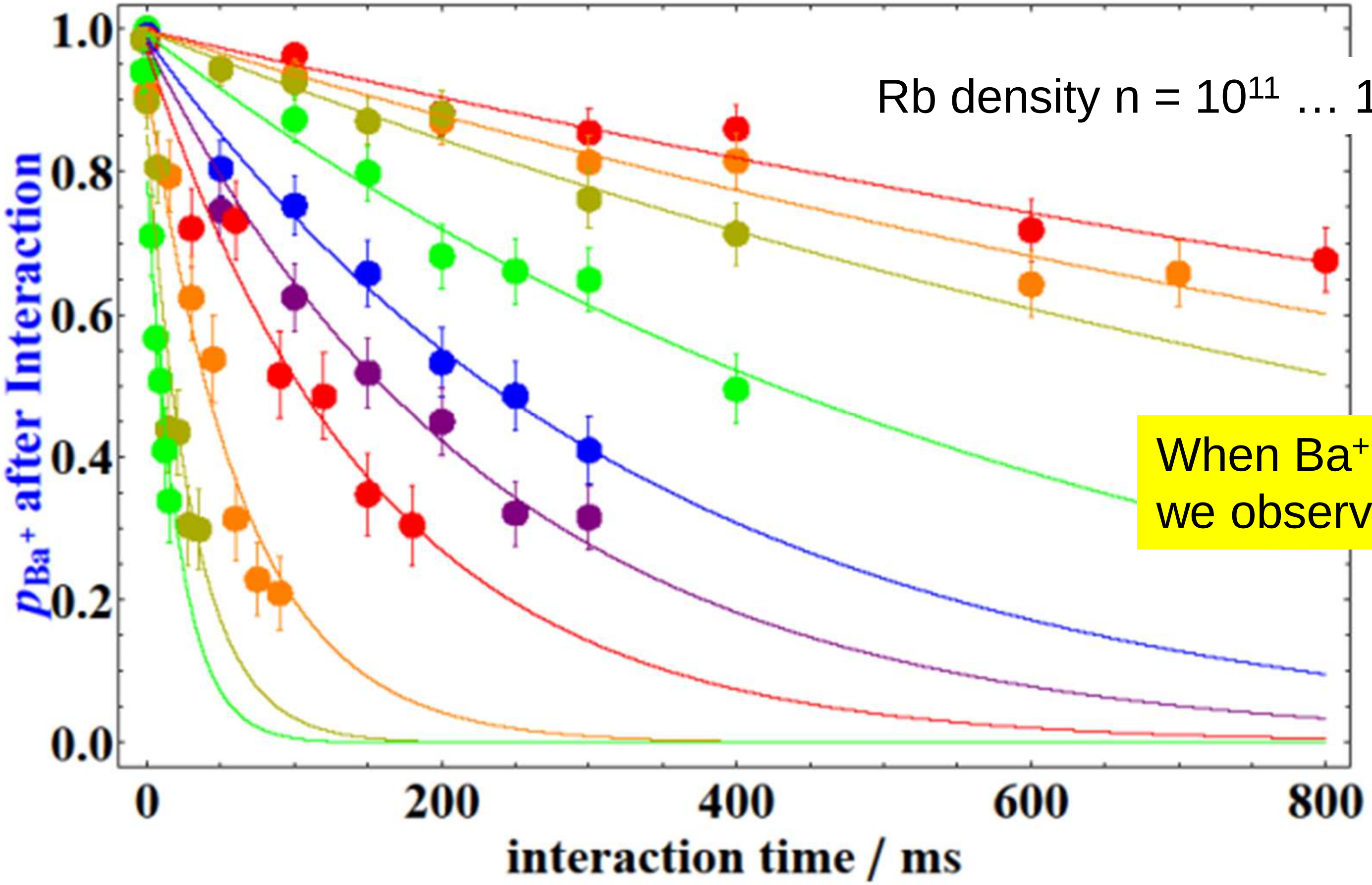




Typical reaction: charge exchange



Decay of Ba^+ in atomic clouds of various densities



Rb density n = 10^{11} … 10^{13} cm^{-3}

When Ba^+ is lost we observe Rb^+.

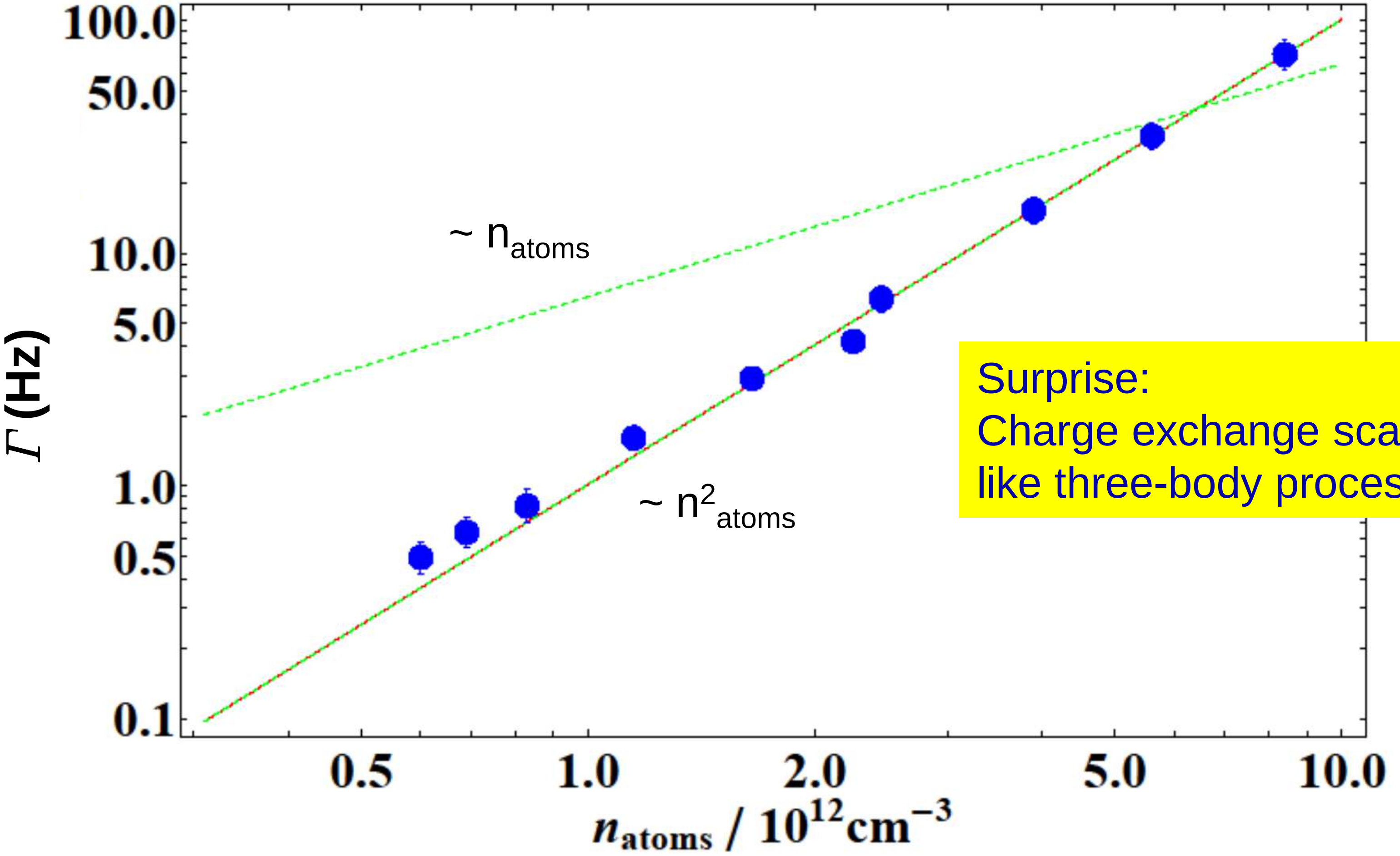
Exponential decay

$$p_{Ba^+}(t) = e^{-\Gamma \cdot t}$$

Decay constant

$$\Gamma = \Gamma(n)$$

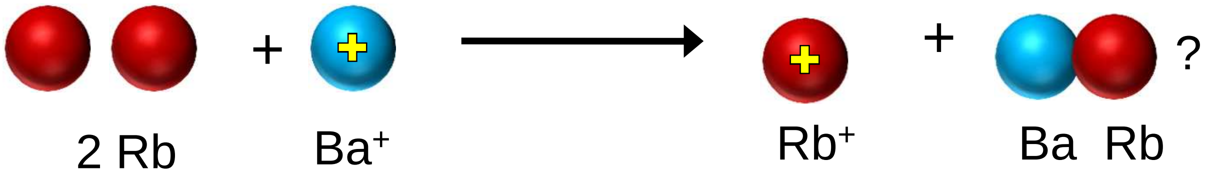
Charge exchange in three-body process!



Surprise:
Charge exchange scales like three-body process!

$$\Gamma = K_2 \times n_{atoms} + K_3 \times n_{atoms}^2$$

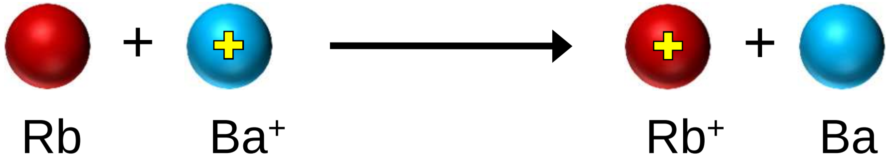
$$K_2 < 9\times 10^{-14}\, cm^3 s^{-1} \quad K_3 = 1.02(1)\times 10^{-24}\, cm^6 s^{-1}$$



High densities favor three-body process.

$$K_3 = 1.02(1)\times10^{-24}\,cm^6 s^{-1}$$

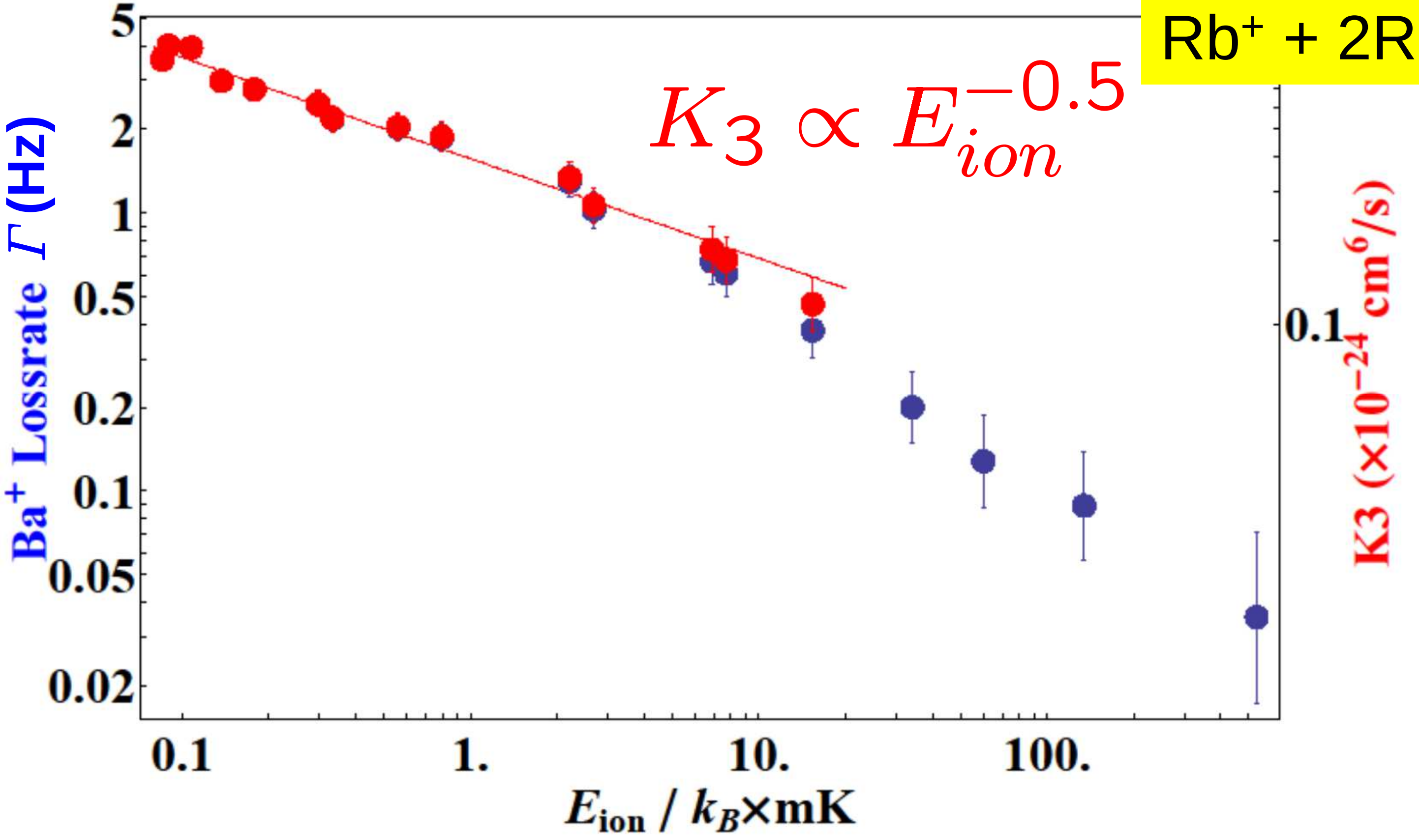
vs



Langevin collision:
The rate Γ
should be energy independent!

$$K_2 < 9\times10^{-14}\,cm^3 s^{-1}$$

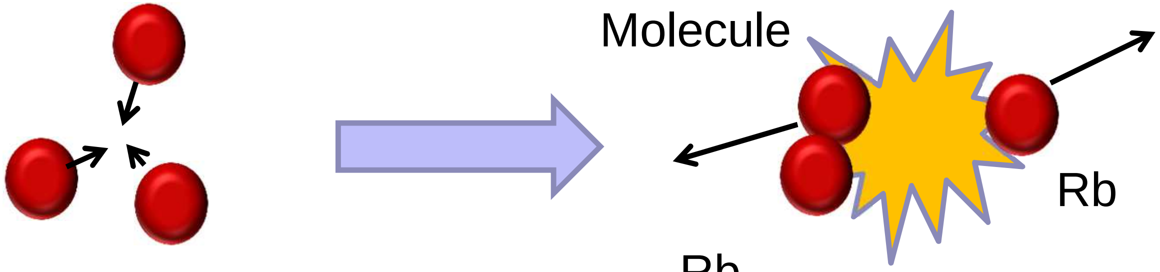
Energy dependence of three-body charge exchange



$$K_3 \propto E_{ion}^{-0.5}$$

Similar as for Rb$^+$ + 2Rb !

Investigate reaction product states



Three-body recombination

3Rb

Molecule

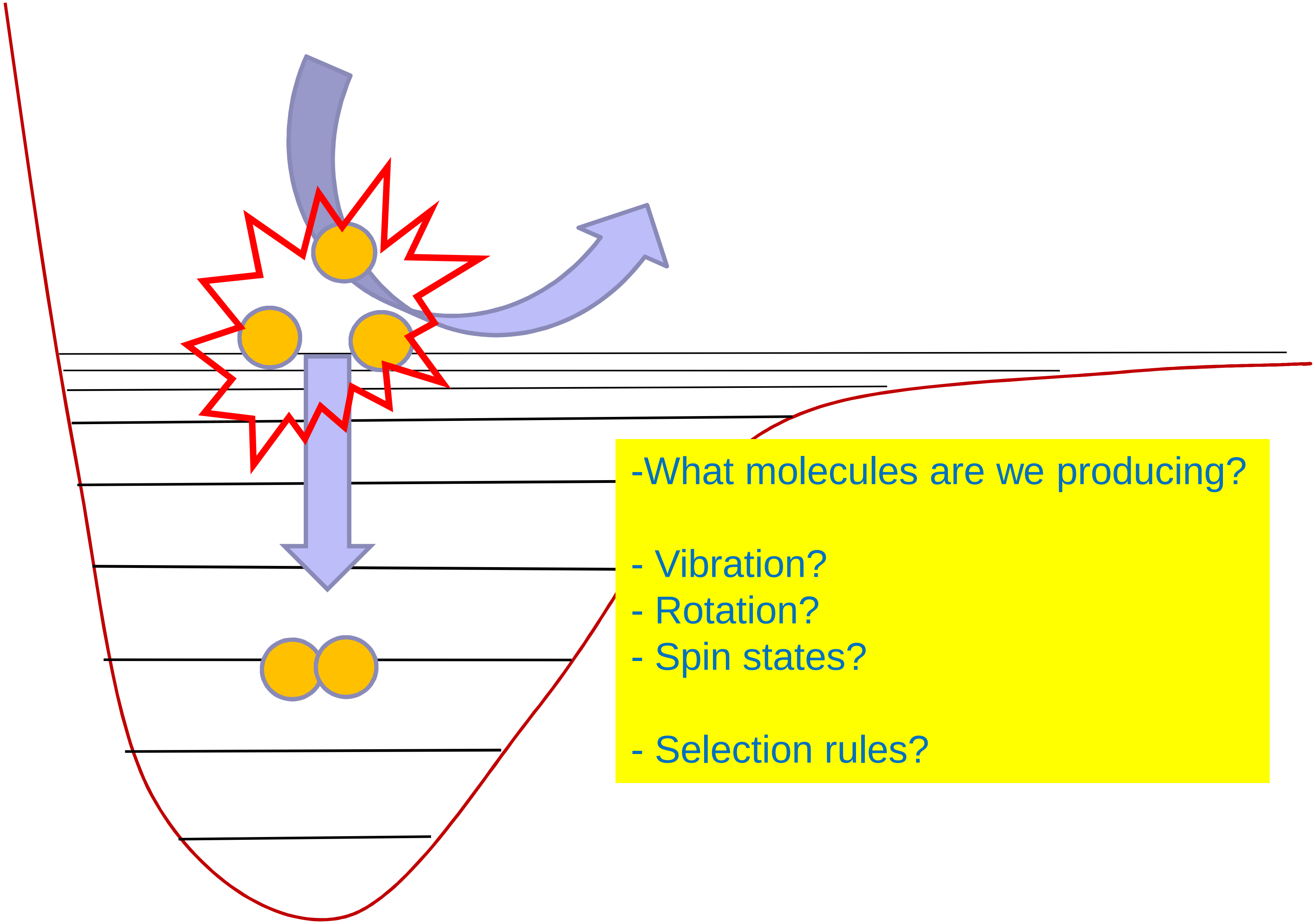
Rb_2

Rb

energy

Question:
What quantum state is the molecule in?

Three-body recombination

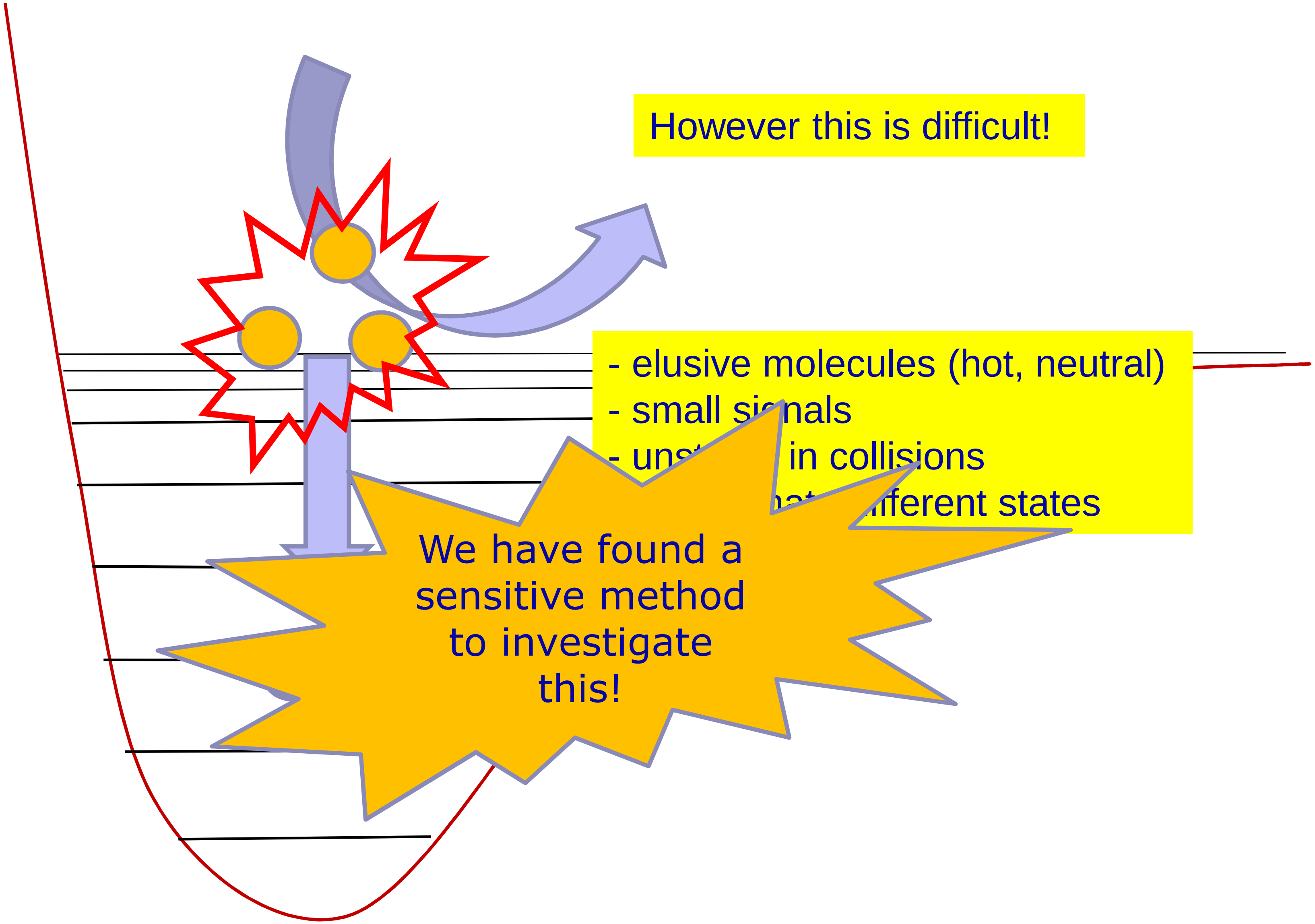


-What molecules are we producing?

- Vibration?
- Rotation?
- Spin states?

- Selection rules?

Three-body recombination away from Feshbach resonance



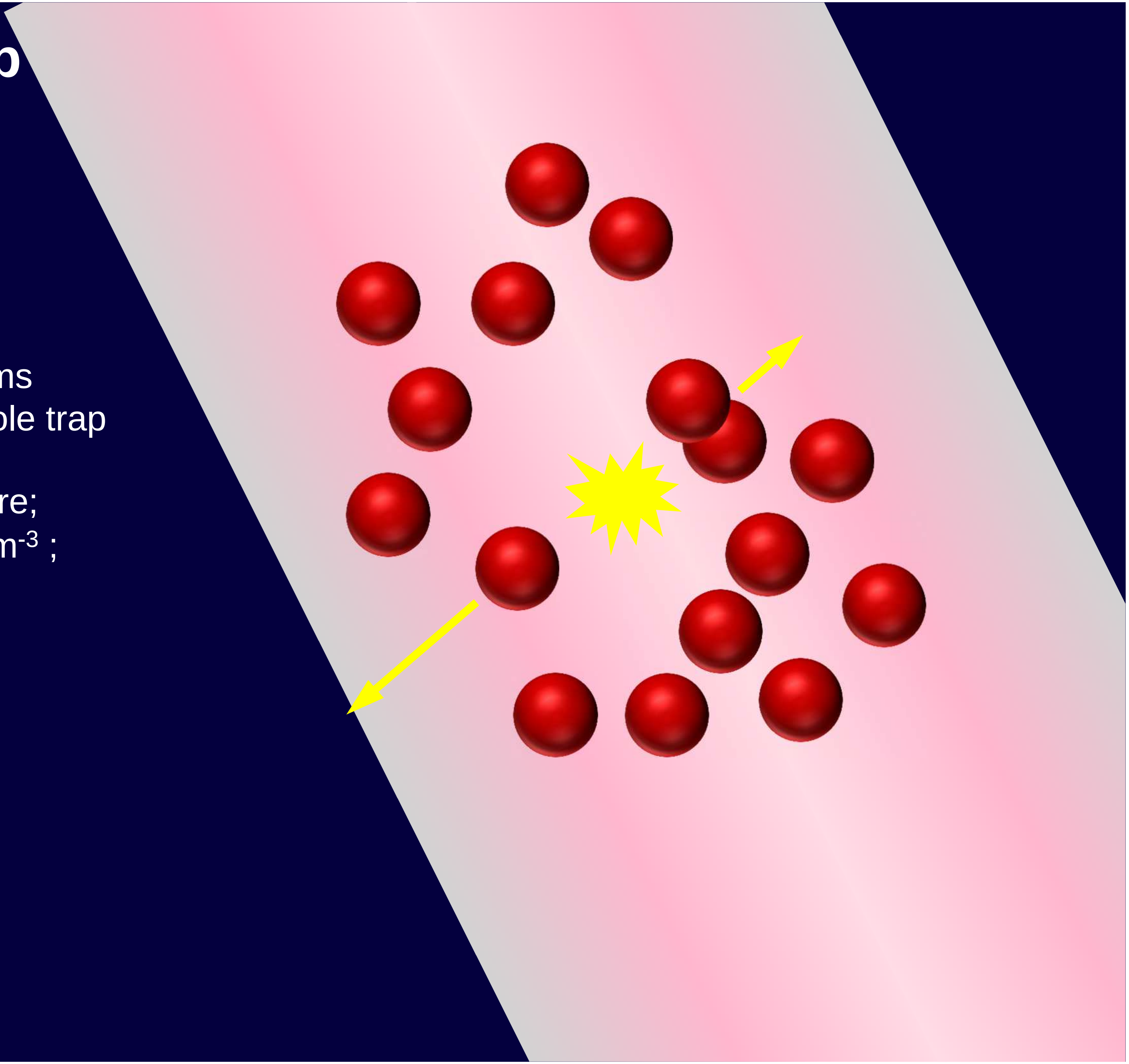
However this is difficult!

- elusive molecules (hot, neutral)
- small signals
- unst in collisions

hat ifferent states

We have found a sensitive method to investigate this!

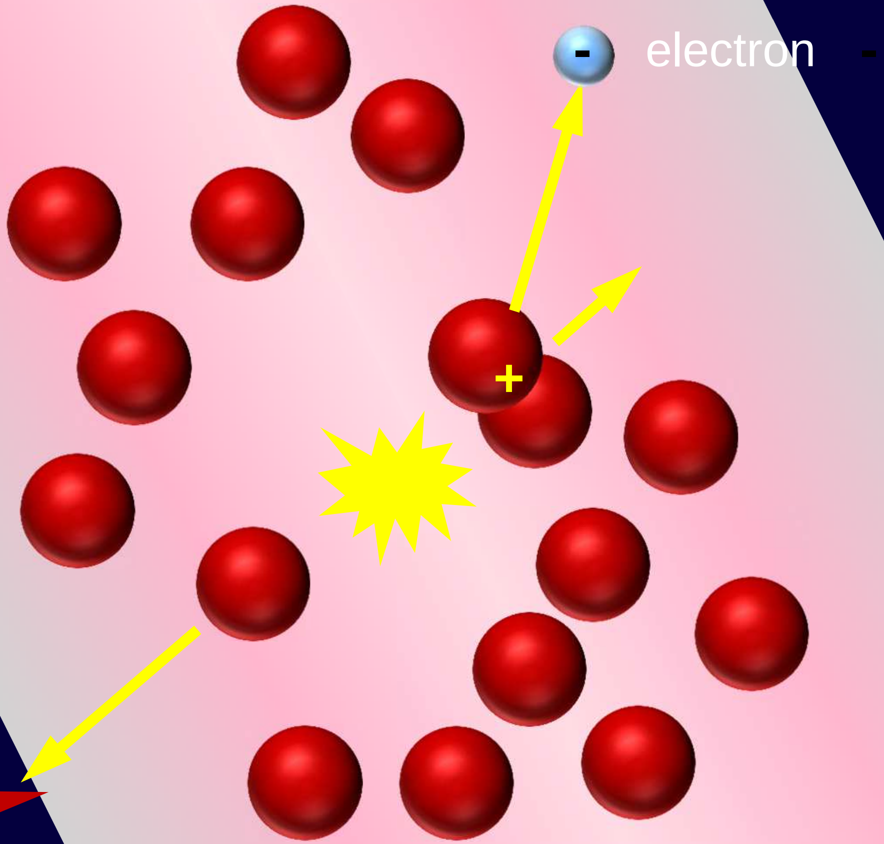
The set-up



4×10^4 ^{87}Rb atoms
in an optical dipole trap
at 1064nm;
~1μK temperature;
density ~ 10^{13} cm^{-3} ;

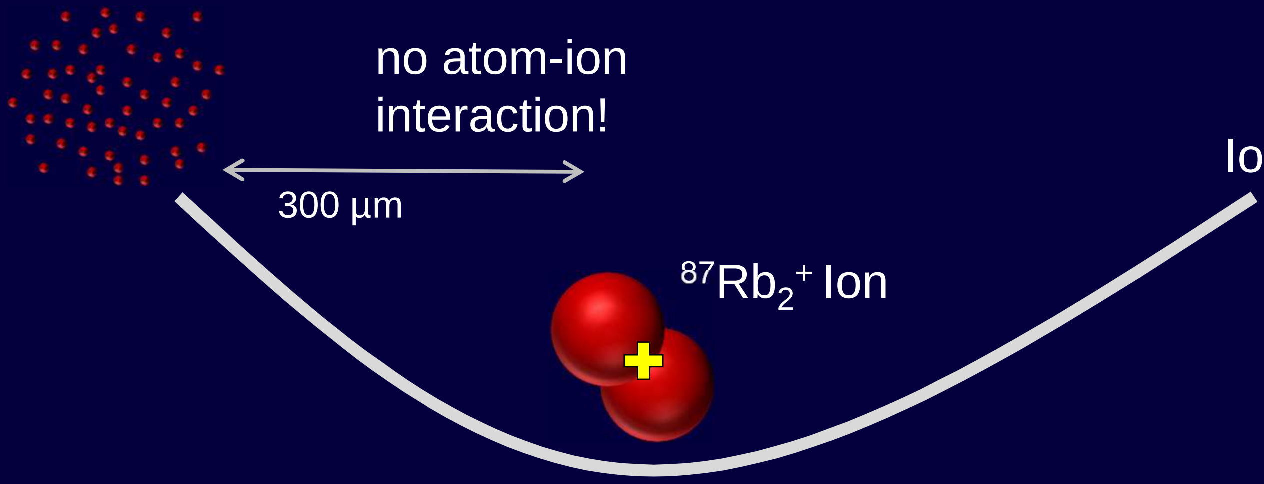
The set-up

4×10^4 ^{87}Rb atoms
in an optical dipole trap
at 1064nm;
~1μK temperature;
density ~ 10^{13} cm^{-3} ;



State-selectively ionize molecule!

Rb$_2^+$ ion is trapped!



atom cloud

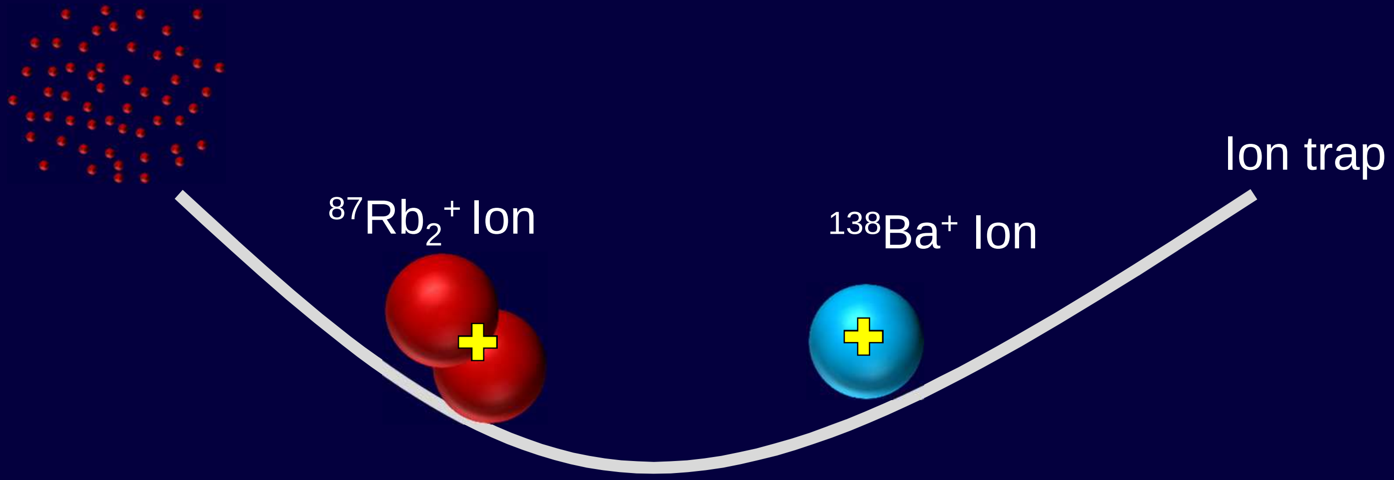
no atom-ion interaction!

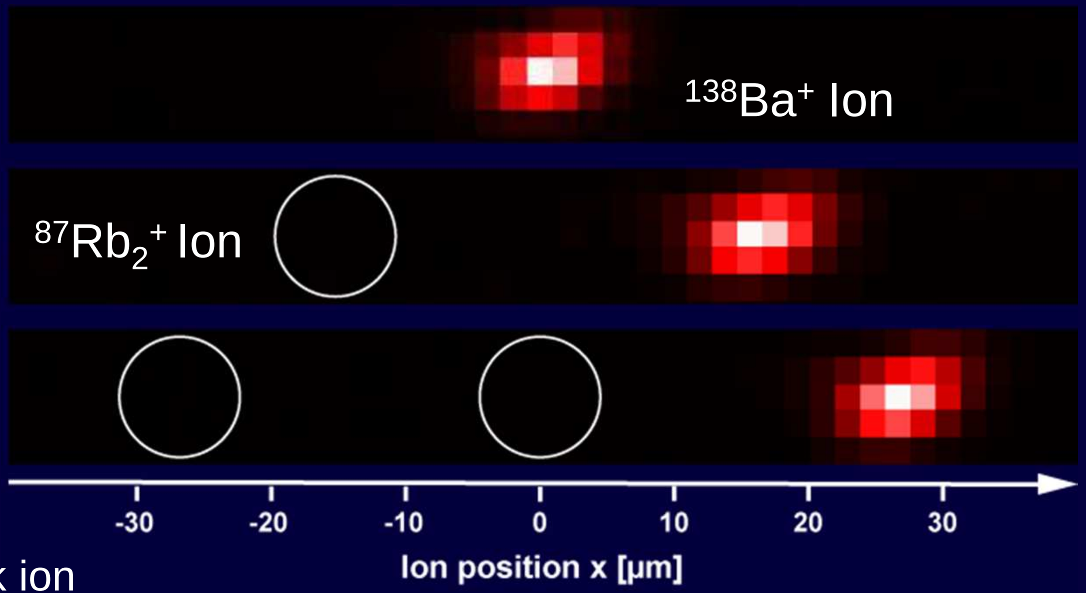
300 µm

Ion trap

^{87}Rb$_2^+$ Ion

Detecting dark ions





Measure mass of dark ion
(modulation spectroscopy)

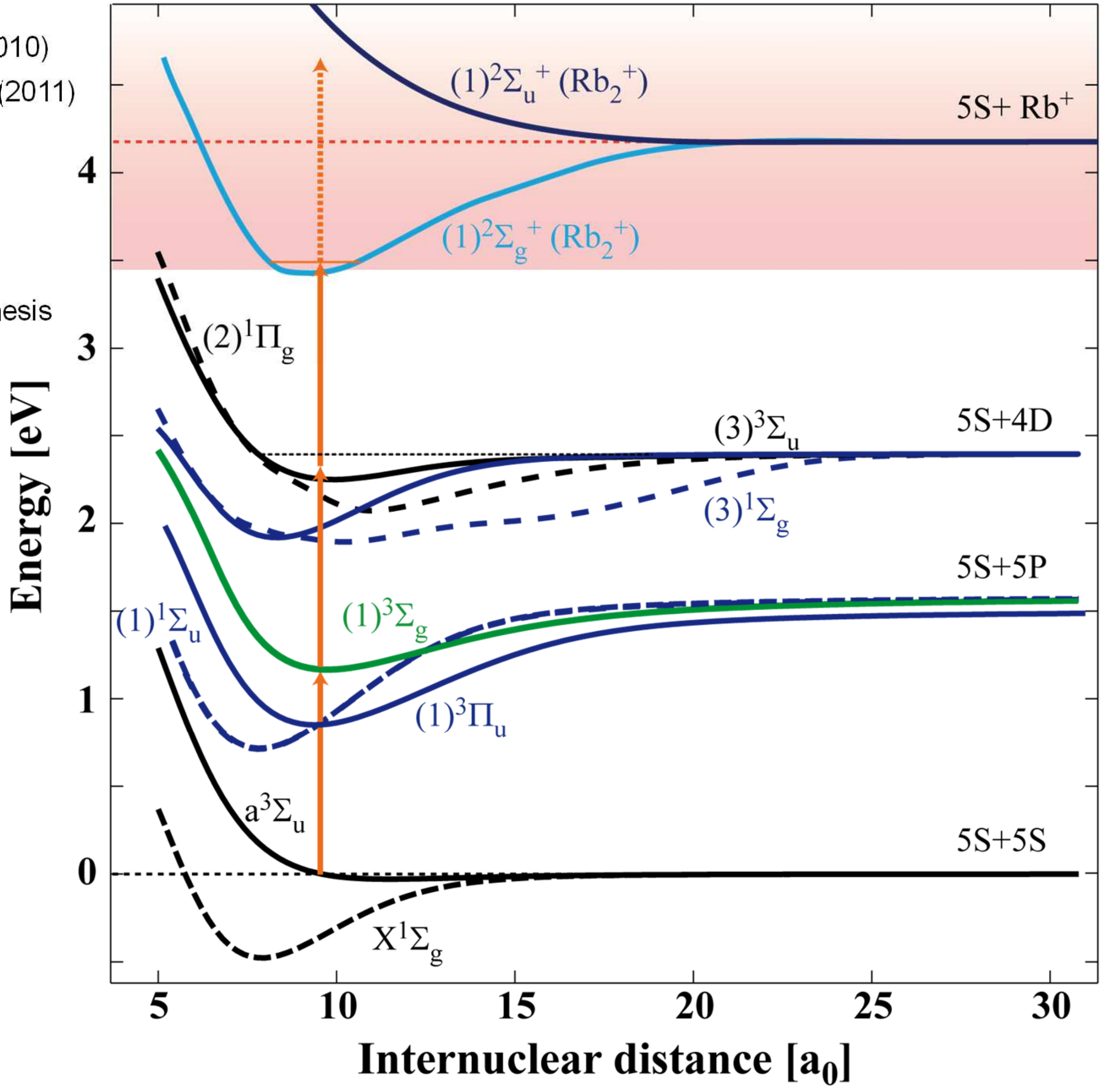
Use resonance enhanced multi-photon ionization!

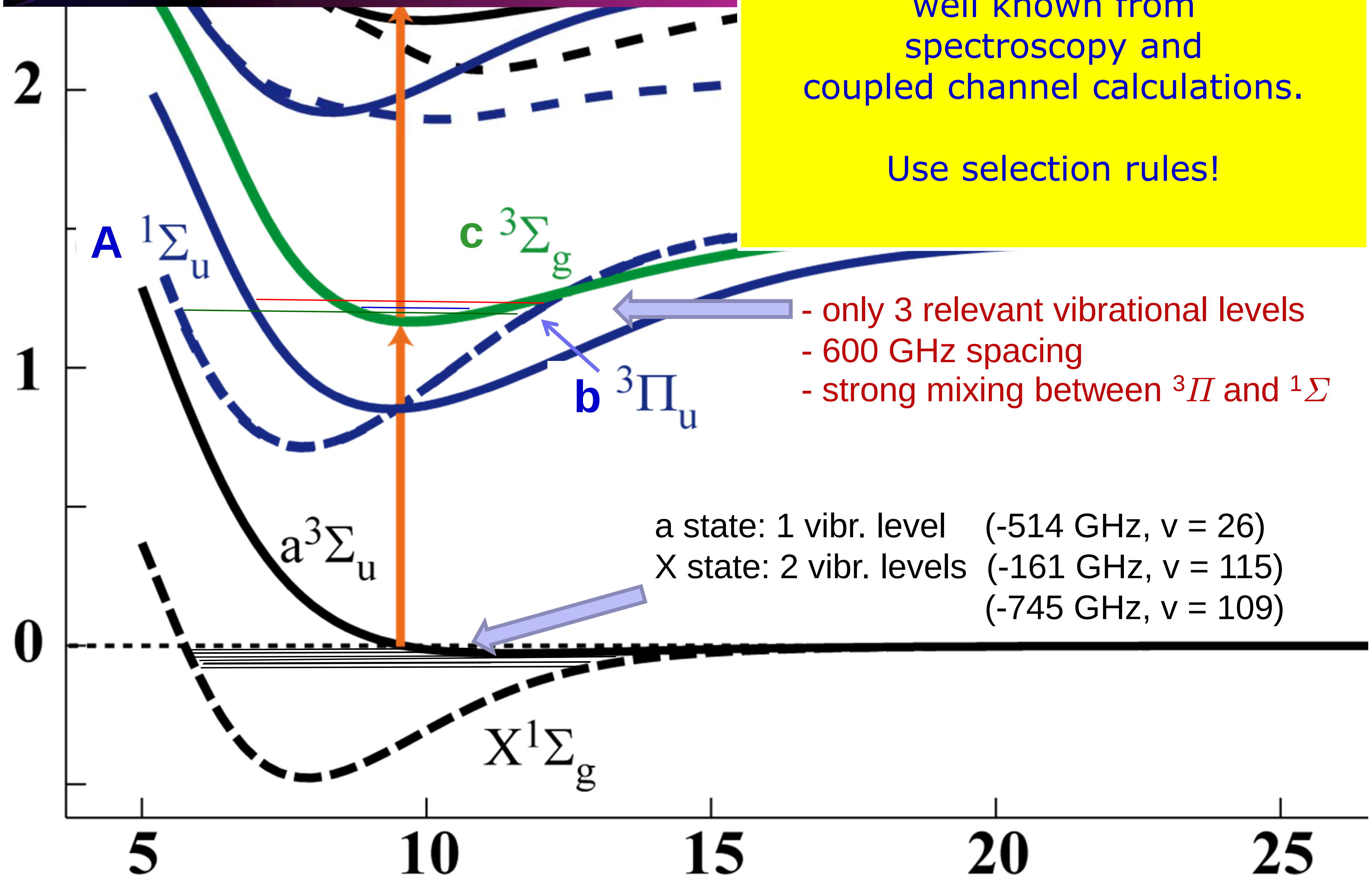
Strauss et al., PRA (2010)

Takekoshi et al., PRA (2011)

collaboration
with E. Tiemann

A. Drozdova, PhD Thesis





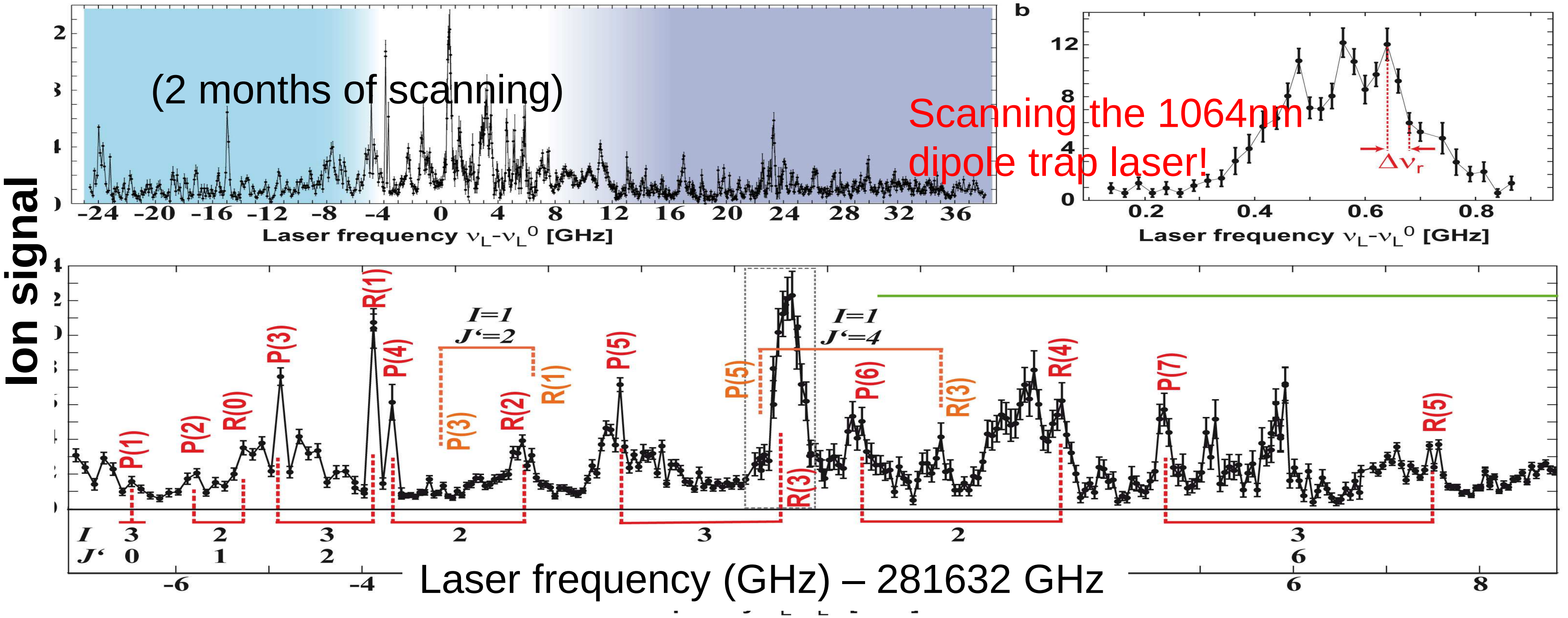
Substructure (hyperfine, rotation)
well known from
spectroscopy and
coupled channel calculations.

Use selection rules!

- only 3 relevant vibrational levels
- 600 GHz spacing
- strong mixing between $^3\Pi$ and $^1\Sigma$

a state: 1 vibr. level (-514 GHz, v = 26)
X state: 2 vibr. levels (-161 GHz, v = 115)
(-745 GHz, v = 109)

Plenty of resonances!



(2 months of scanning)

Scanning the 1064nm dipole trap laser!

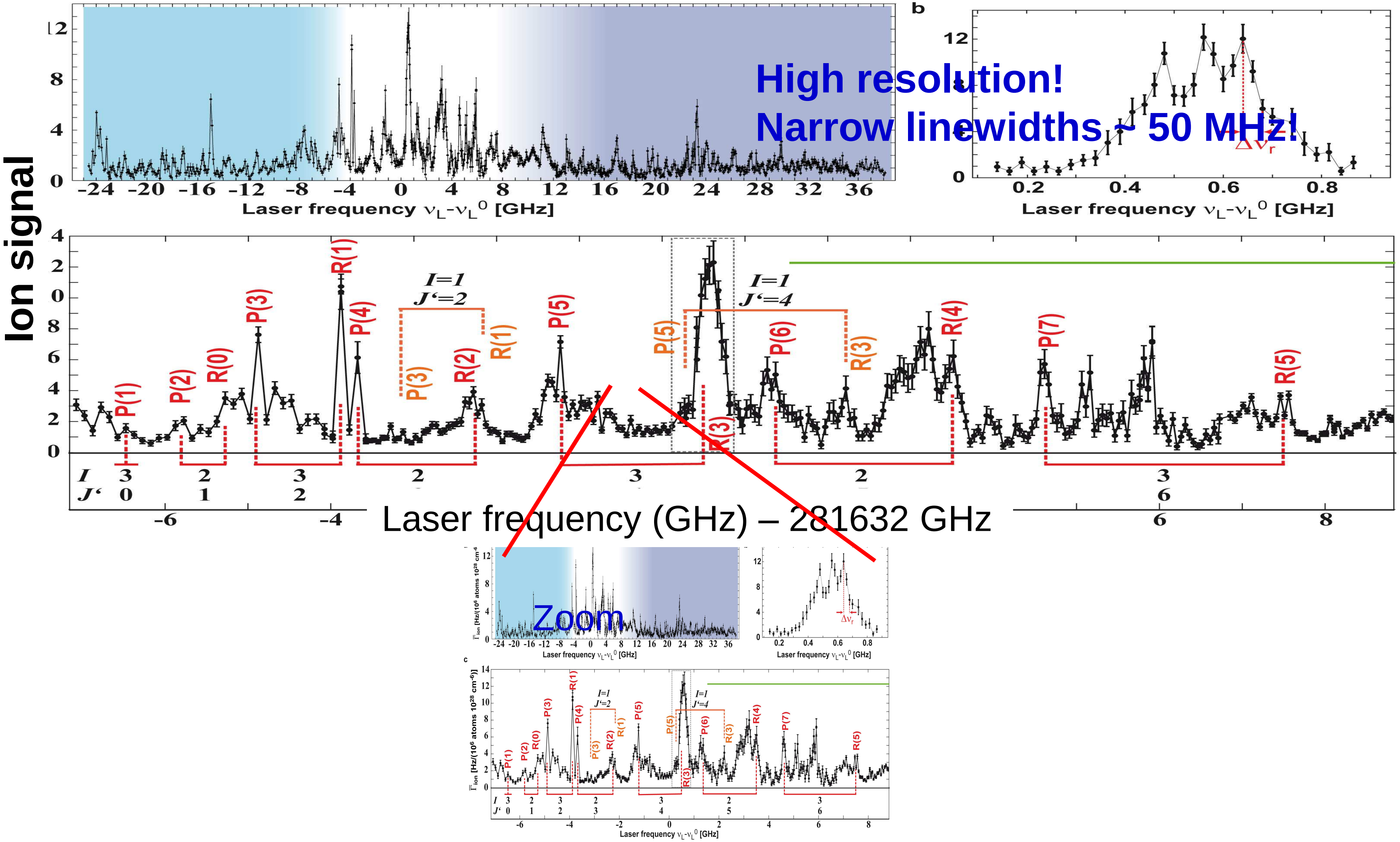
Ion signal

Laser frequency (GHz) – 281632 GHz

- very dense and fairly irregular spectrum (> 100 lines)
- distribution over many initial states
- selection rules: each level only gives rise to two or three lines

A. Härter, A. Krükow, M. Deiß, B. Drews, E. Tiemann, and J. Hecker Denschlag, Nature Physics (2013)

Study the line shape!



Ion signal

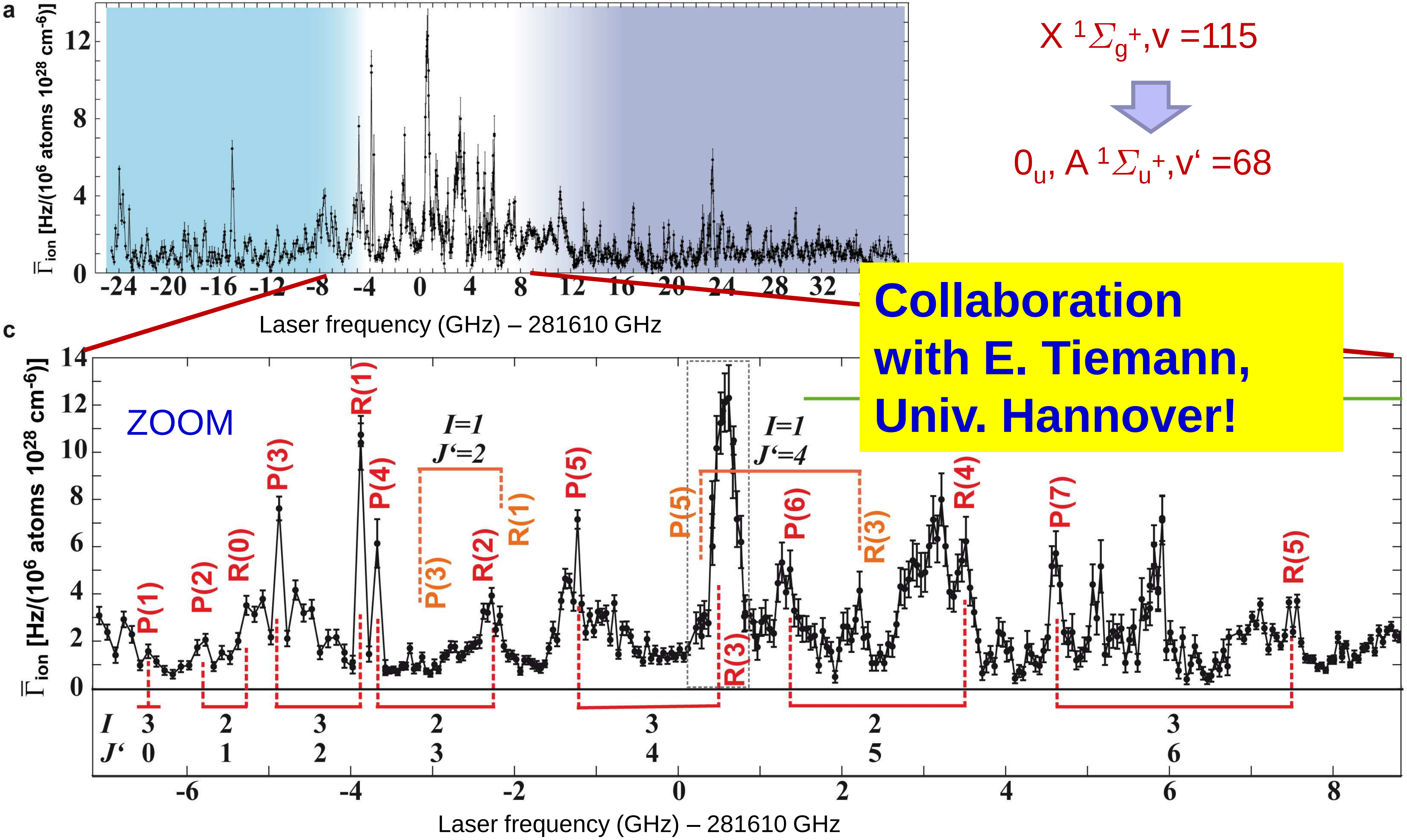
Laser frequency (GHz) – 281632 GHz

High resolution!

Narrow linewidths ~ 50 MHz!

Zoom

First assignment of rotational line spectrum



$X\ {}^1\Sigma_g^+, v = 115$

⇩

$0_u,\ A\ {}^1\Sigma_u^+, v' = 68$

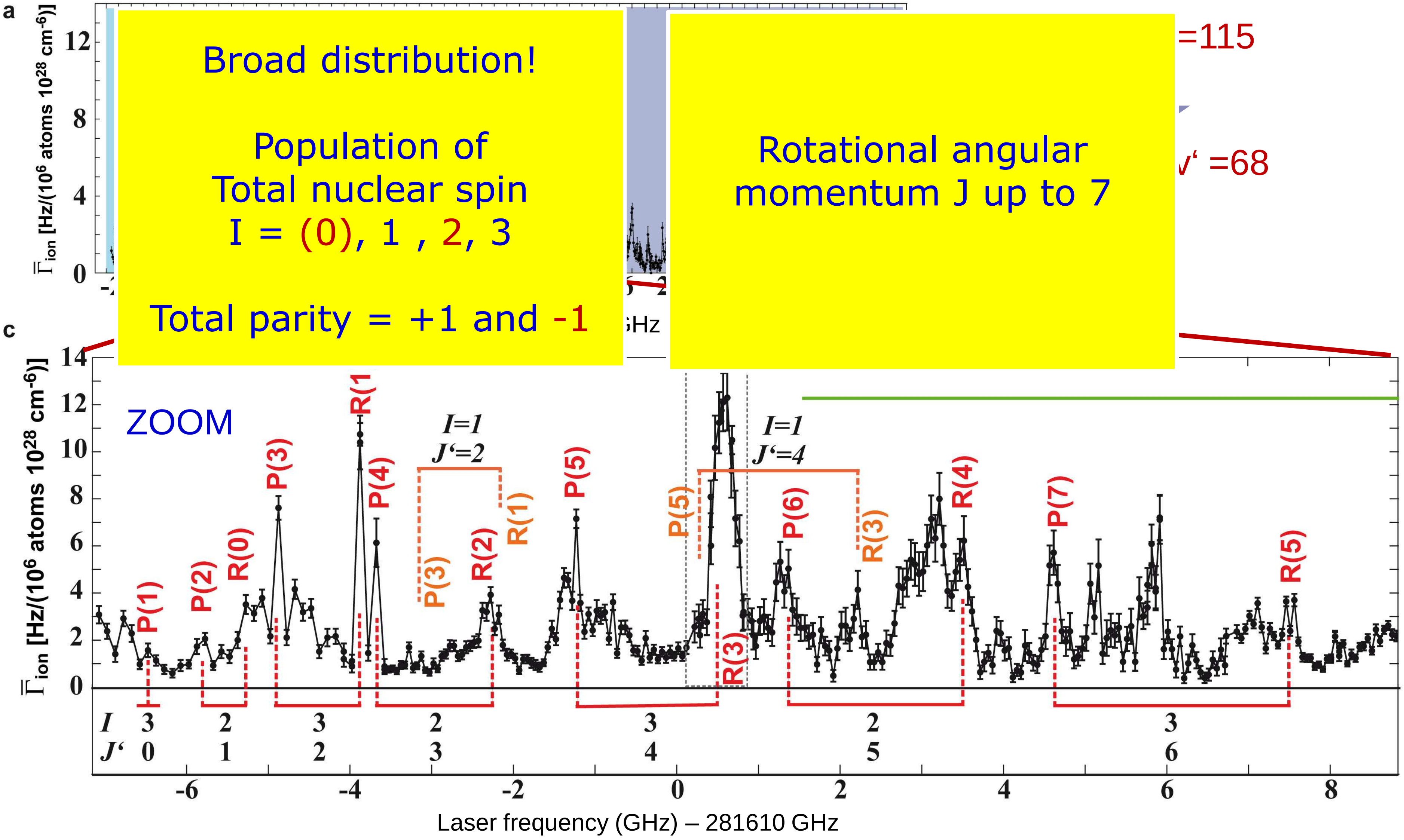
Collaboration with E. Tiemann, Univ. Hannover!

P, R branches

P(J): J –> J -1

R(J): J –> J +1

First assignment of rotational line spectrum



Broad distribution!

Population of
Total nuclear spin
I = (0), 1 , 2, 3

Total parity = +1 and -1

Rotational angular
momentum J up to 7

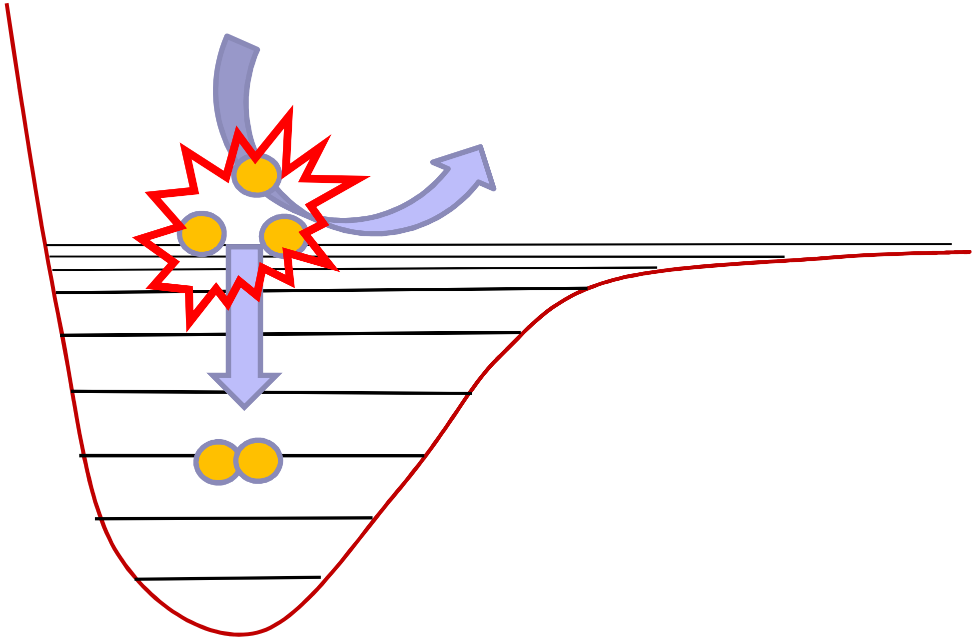
P, R branches

P(J): J –> J -1

R(J): J –> J +1

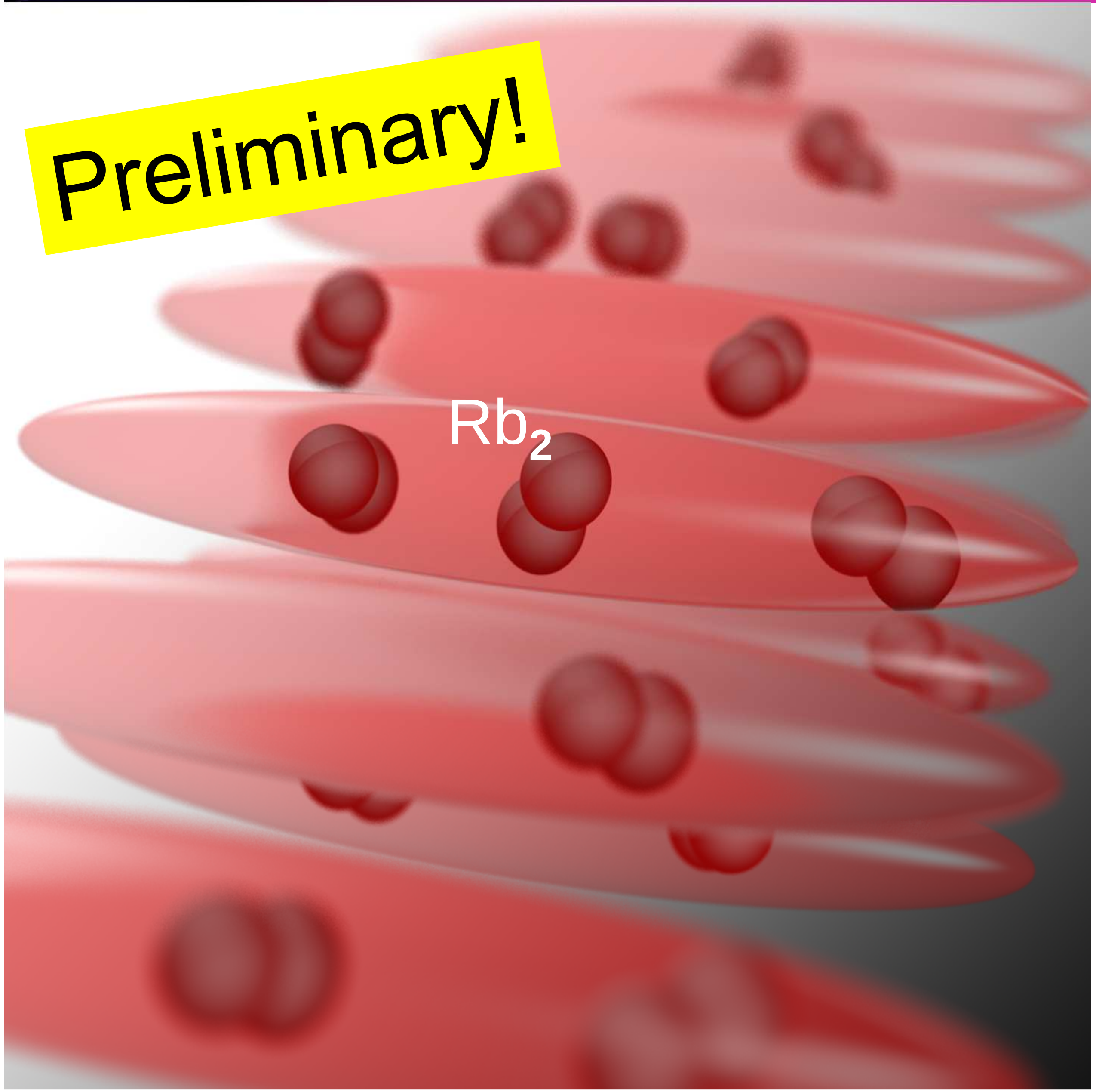
This scheme can be extended!

- Understand reaction pathways in all details
- Test theoretical models/ predictions
  for three-body recombination



A. Härter, A. Krükow, M. Deiß, B. Drews, E. Tiemann,
and J. Hecker Denschlag, Nature Physics (2013)

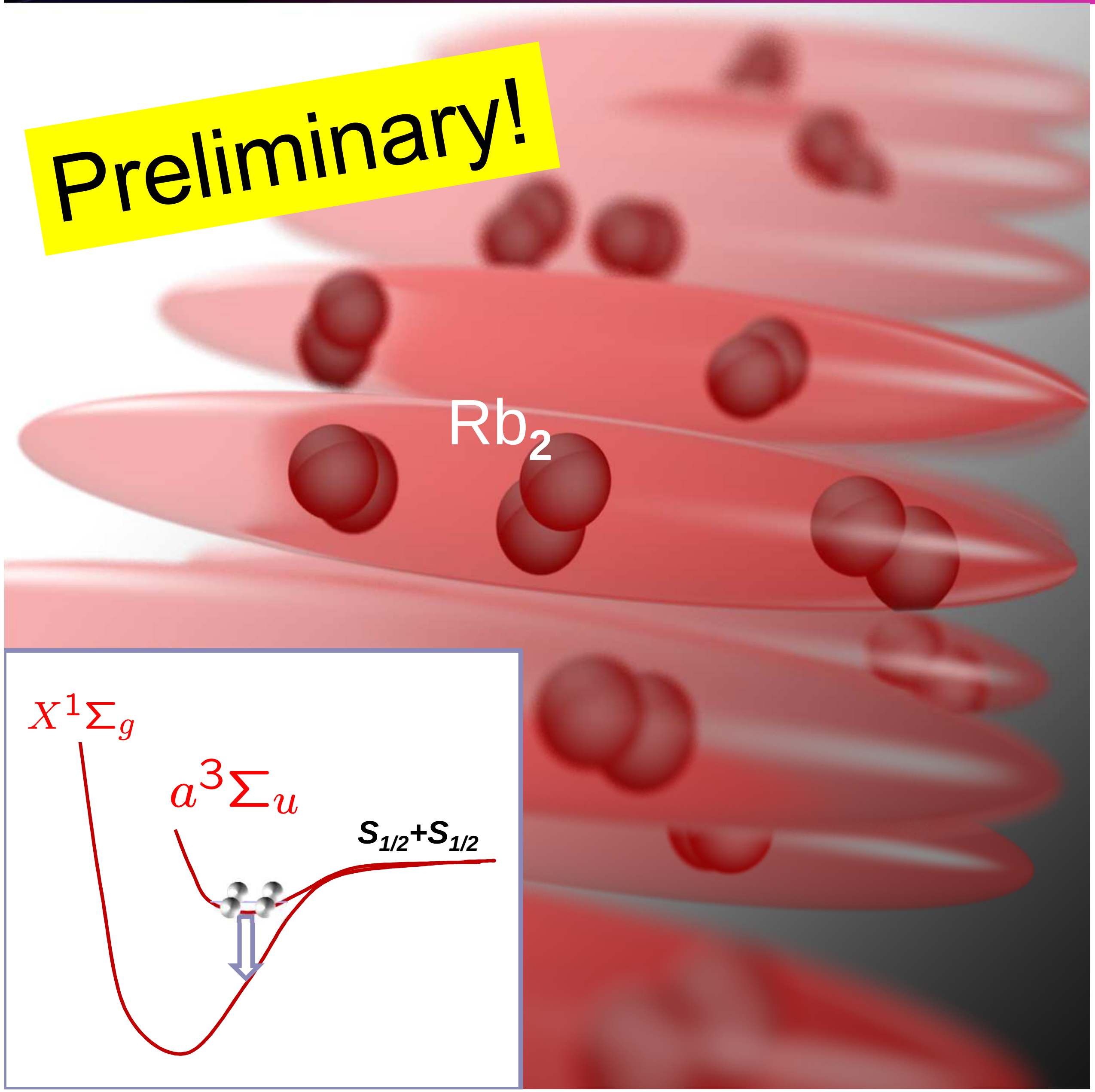
Collisions of ultracold Rb_2 molecules



Björn Drews
Markus Deiss

Krzysztof Jachymski
Tommaso Calarco
Zbigniew Idziaszek

Collisions of ultracold Rb_2 molecules



Preliminary!

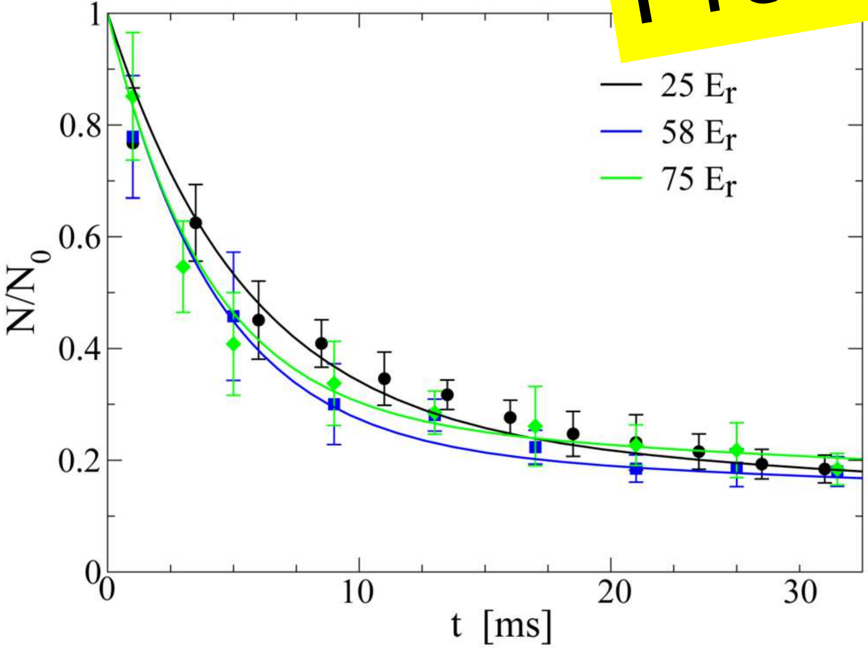
$$a^3\Sigma_u$$

- -Vibrational ground state
- Molecule rotation
  R =0 or R = 2
- Precisely defined quantum state: R, I, F, J, m_F, …
- Quasi 1D
  trap ground state
  in transverse direction
  (~100 E_r)
- Longitudinal energy
  ~ 100nK k_B

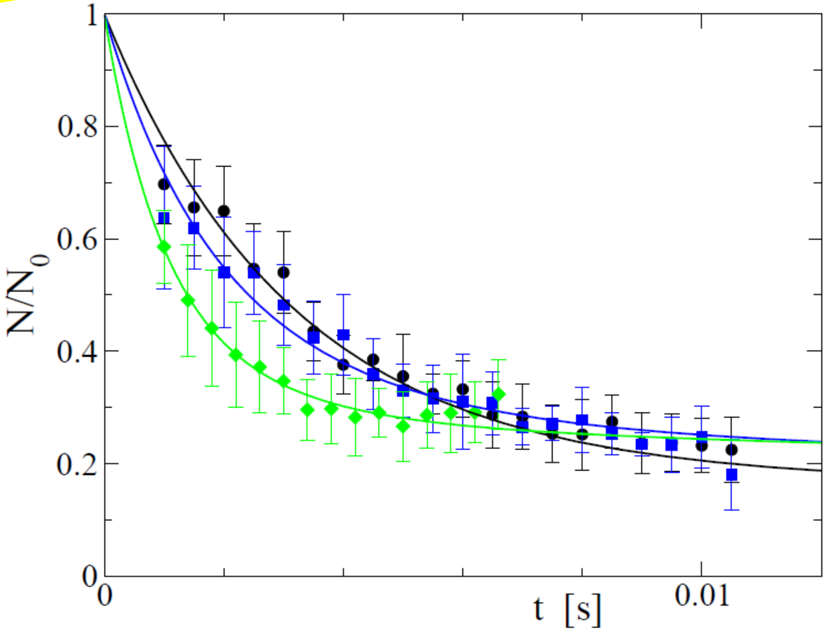
Decay of Rb_2 molecules

Preliminary!

R = 0



R = 2



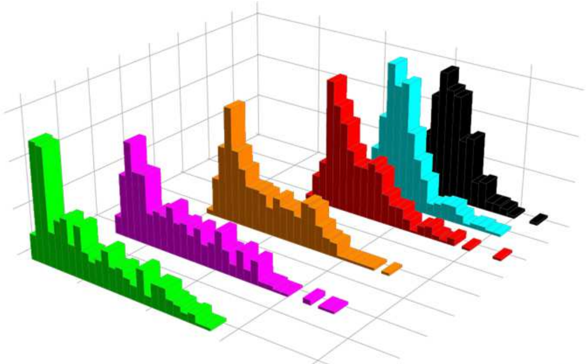
Data compatible with universal collisions?

$$a_{3D} = \bar{a}(1 - i)$$

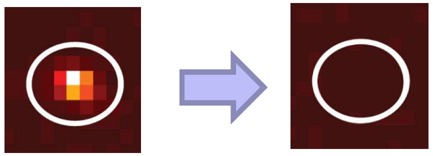
$$\bar{a} = 2\pi/\Gamma(1/4)^2 R_6$$

$$R_6 = (2\mu C_6/\hbar)^{1/4} \approx 270 a_0$$

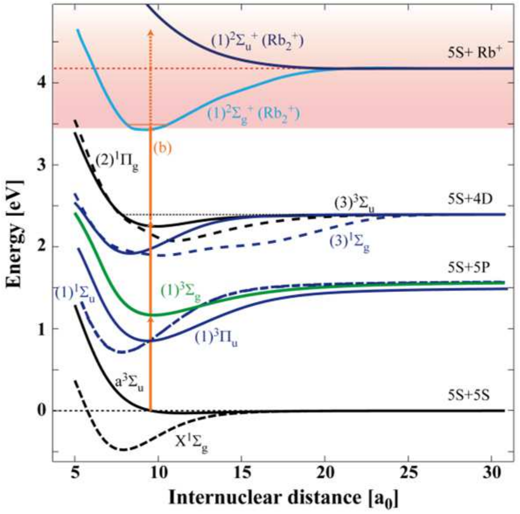
Four stories



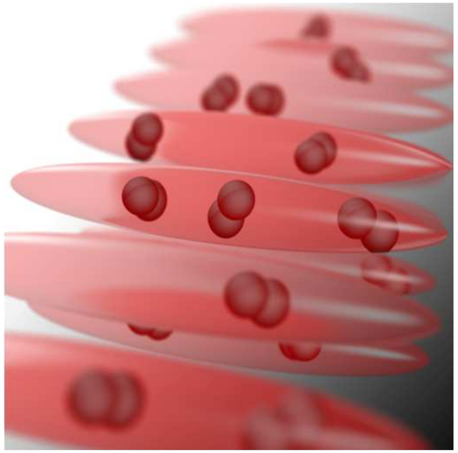
1) Three-body recombination
$Rb^+ + 2Rb \rightarrow Rb^+ + \text{energy} + (2Rb)$



2)
$Ba^+ + 2Rb \rightarrow Rb^+ + ?$



3) Analyse quantum states
of reaction products
$3Rb \rightarrow Rb_2 + Rb$



4) Cold collisions of Rb_2 triplet molecules
$2\,Rb_2 \rightarrow$ loss