Ion-atom physics

Carlo Sias

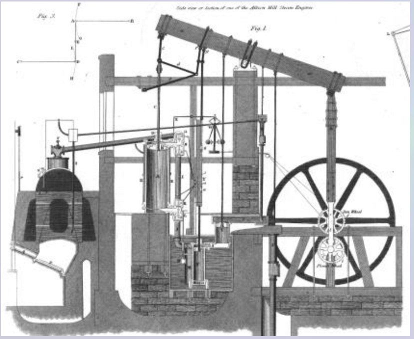
Istituto Nazionale di Ricerca Metrologica - INRIM
European Laboratory for Nonlinear Spectroscopy - LENS

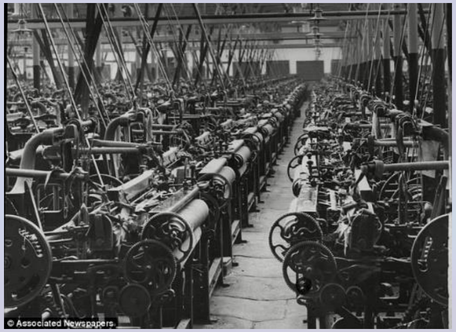
Gressoney, 13 September 2018

Roots..

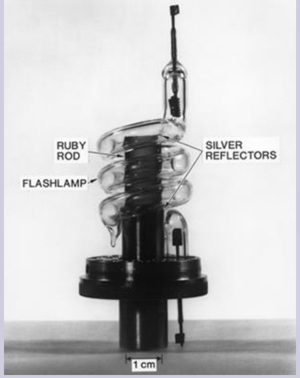
Understanding physics enables new technology

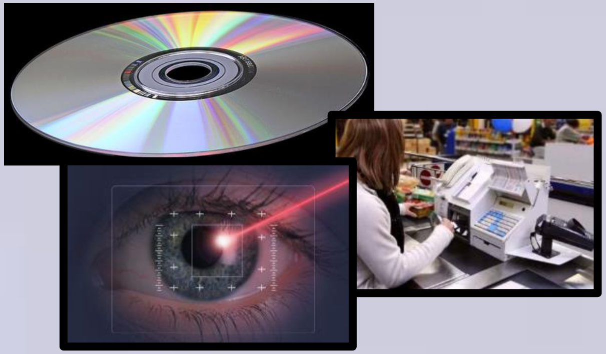
Thermodynamics





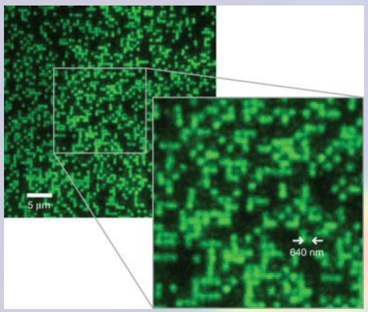
Optics, spectroscopy



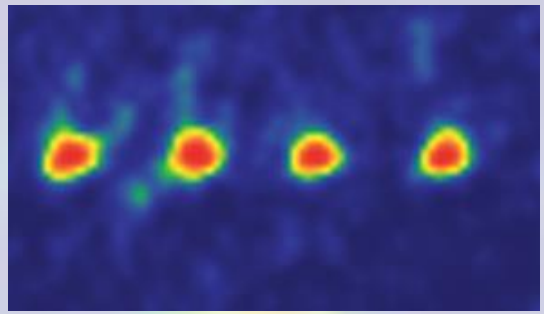


Were are we with quantum mechanics?

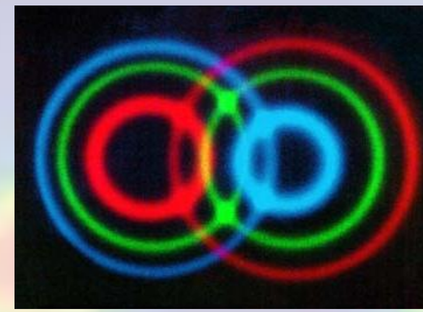
Neutral atoms



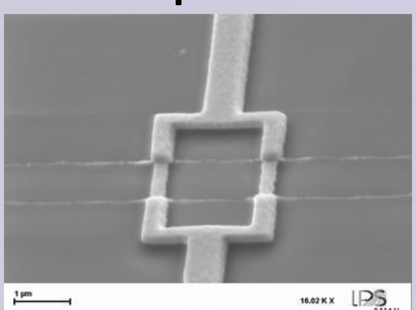
Ions



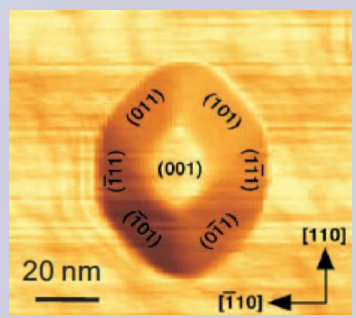
Photons



Squids



Quantum dots



... and many others

..at a good point!

..and future

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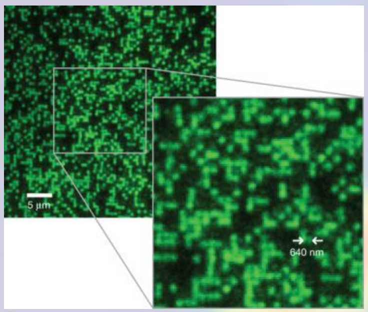
Neutral atoms



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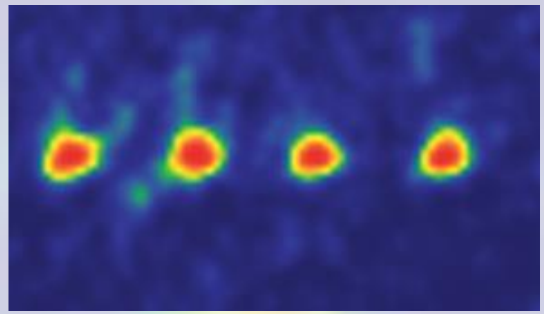

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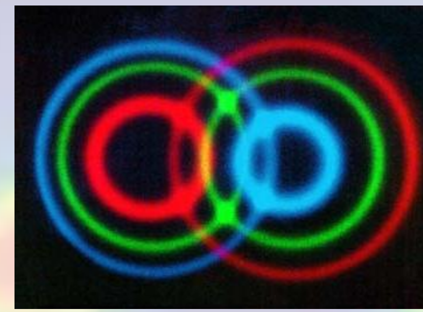

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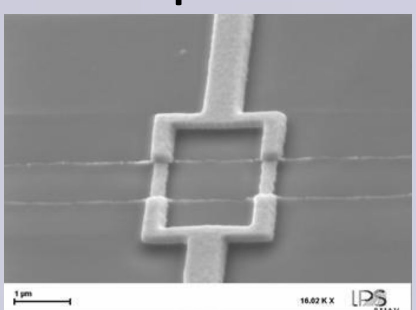

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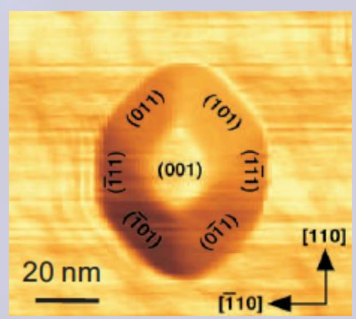

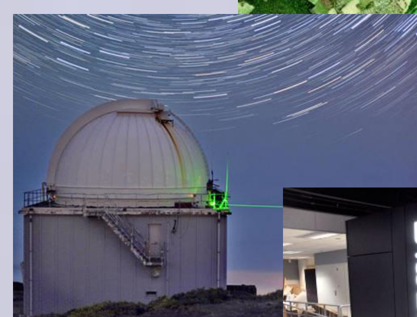

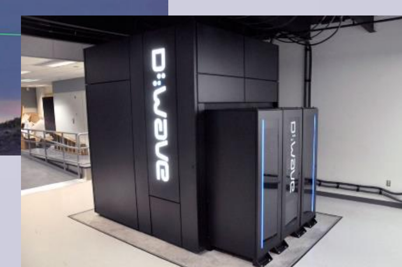

..at a good point!

..and future

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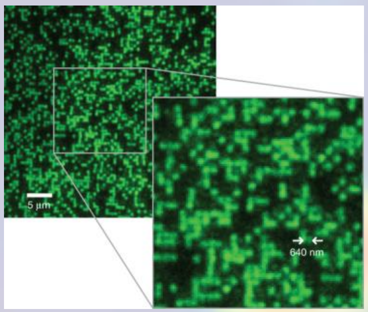

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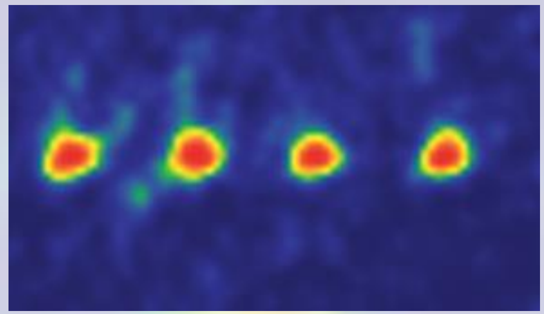
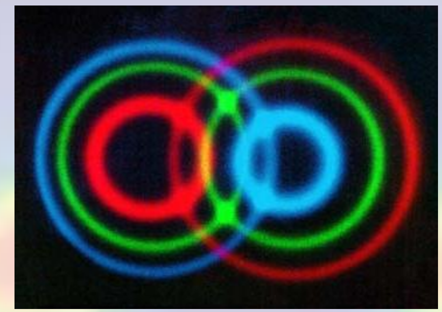
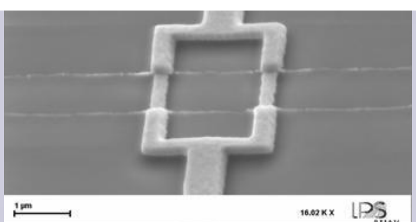
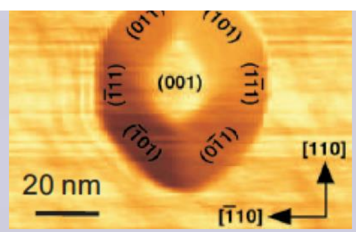


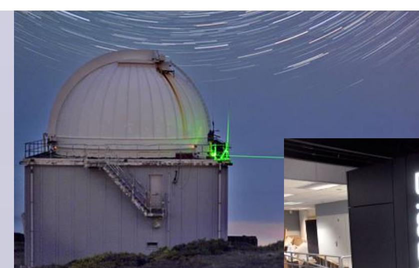
Photons

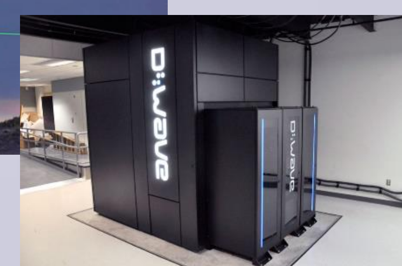


Can we think of a composite system formed by two **coupled** quantum systems?





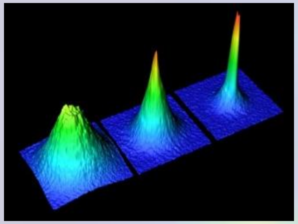




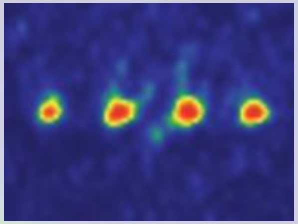
..at a good point!

Ultracold atoms - overview

Same fields, different approaches



Coherent matter



Single particles

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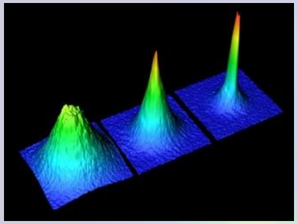

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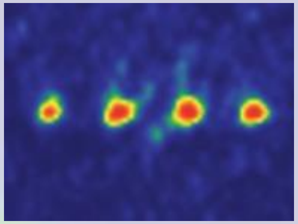

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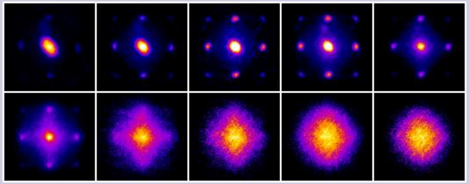
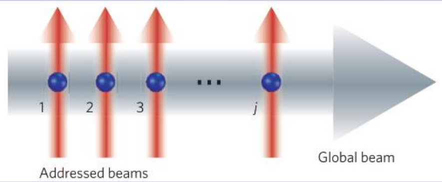


Many-body physics



Blatt, Roos Nat. Phys. 2012

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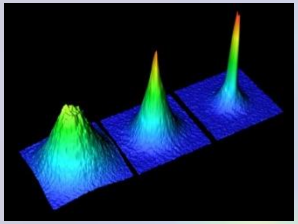
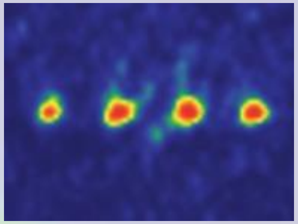
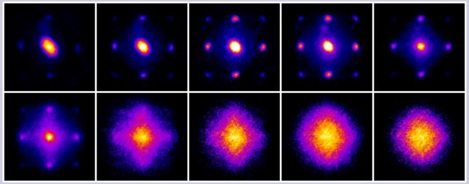




Coherent matter

Single particles



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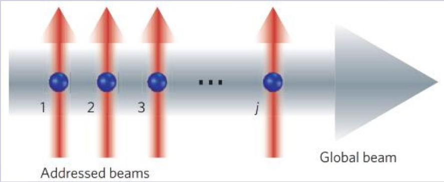

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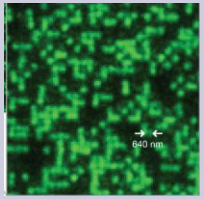
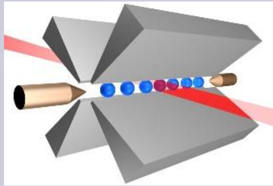


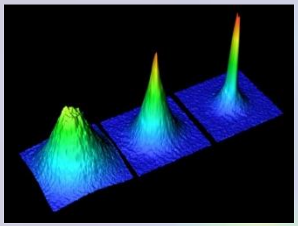
Greiner group

Single particle manipulation



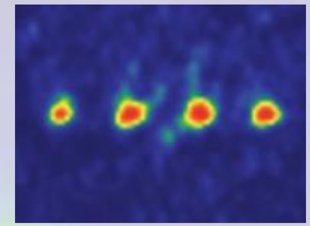
Blatt group

Same fields, different approaches



Coherent matter

CLOCKS!



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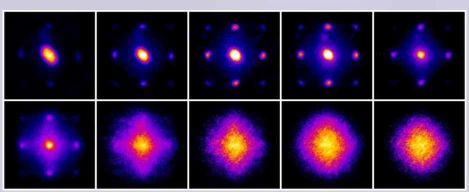

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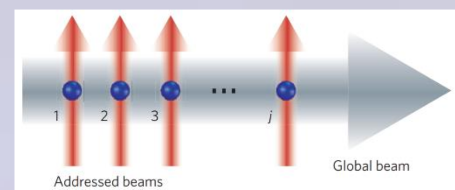

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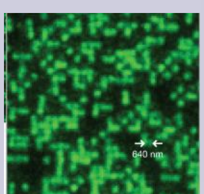

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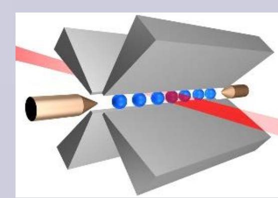
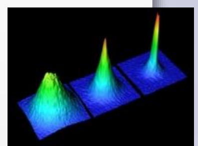


Blatt group

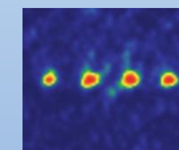
Hybrid quantum systems

Quantum degenerate atoms



- Macroscopic quantum system at nano Kelvin temperature
- Collective quantum states of 10^6 particles
- Very long coherence times

Ultracold trapped ions



- Single particle detection and manipulation
- Pristine source for quantum information processing & precision spectroscopy

+ Interactions

Hybrid quantum system

A new approach to

- **Ultracold collisions & quantum chemistry**
- **Quantum information processing and decoherence**
- **Quantum many-body physics with impurities**
- **Metrology**

Review: C. Sias, M. Koehl, arXiv 1401.3188

Ion-neutral interactions

An old problem in physics..

Ion-neutral collisions (1905)

UNE FORMULE FONDAMENTALE DE THÉORIE CINÉTIQUE;

PAR M. P. LANGEVIN.

Ion-neutral interactions

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Scattering of Ions by Polarization Forces

ERICH VOGT* AND GREGORY H. WANNIER
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received May 19, 1954)

Scattering from neutral-ion potential

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Bell Telephone Laboratories, Murray Hill, New Jersey
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Scattering from neutral-ion potential

First atom-ion experiment (He^{+}-Cs)

Exchange-Collision Technique for the rf Spectroscopy of Stored Ions*†

F. G. MAJOR‡ AND H. G. DEHMELT
Department of Physics, University of Washington, Seattle, Washington 98105
(Received 6 September 1967)

Buffer gas sympathetic cooling

First application: sympathetic cooling of charged particles

Increase of confinment lifetime of Hg^+ by buffer gas cooling (Ne)

The Three-Dimensional Quadrupole Ion Trap

P. H. DAWSON and N. R. WHETTEN

Received December 16, 1968

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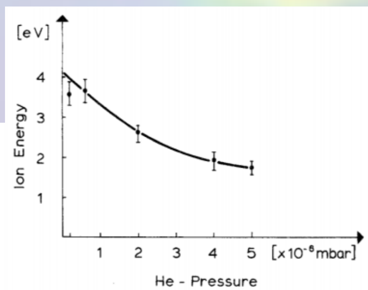
P. H. Dawson and N. R. Whetten

Received December 16, 1968

Appl. Phys. 25, 249–251 (1981)

Trapped Ion Density Distribution in the Presence of He-Buffer Gas

H. Schaaf, U. Schmeling, and G. Werth



Cooling of Ba^+ by the presence of He buffer gas

+ theoretical analysis

Computed energy and spatial statistical properties of stored ions cooled by a buffer gas

F. Vedel, J. André, M. Vedel, and G. Brincourt

Brownian Motion of a Parametric Oscillator: A Model for Ion Confinement in Radio Frequency Traps

R. Blatt[1], P. Zoller[2], G. Holzmüller[2], and I. Siemers[1]

Ion-neutral quantum mixtures

Can we exploit our knowledge in trapping and cooling particles to study collisions at lower temperature?

Ion-neutral quantum mixtures

Can we exploit our knowledge in trapping and cooling particles to study collisions at lower temperature?

Yes!

PRL **102,** 223201 (2009) PHYSICAL REVIEW LETTERS

Observation of Cold Collisions between Trapped Ions and Trapped Atoms

Andrew T. Grier, Marko Cetina, Fedja Oručević, and Vladan Vuletić

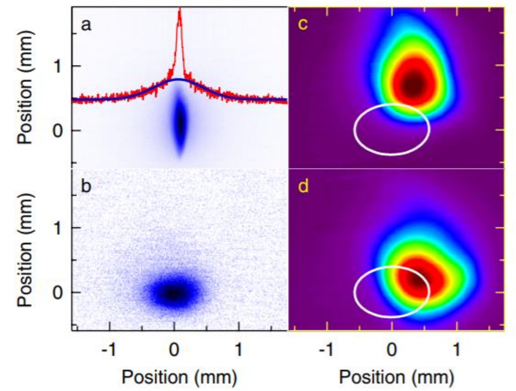


FIG. 3 (color online). (a) (1,0,1) camera image of the ion crystal (blue or dark gray) and cross-section showing highly non-Gaussian shape of crystal (red or gray). (b) (0,1,1) camera image of the ion crystal. (c) Typical low-overlap setting between MOT (colored or shaded contours) and $1/e^2$ contour of ions (white). (d) Same as (c) but for a higher overlap setting.

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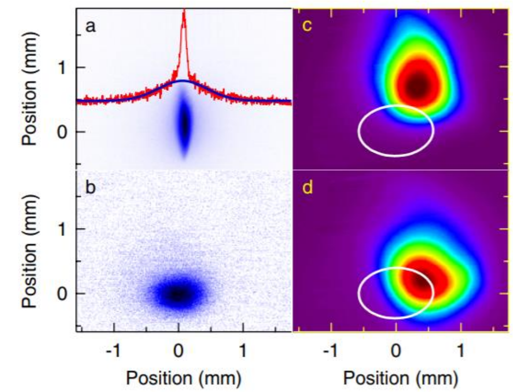

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A fast growing community

Yb-Yb^+	Rb-Rb^+	Rb-N_2^+
Rb-Yb^+	Rb-Ca^+	Li-Ca^+
Li-Yb^+	Ca-Yb^+	Ca-$BaCl^+$
Rb-Ba^+	Rb-Sr^+	Rb-K^+
Yb-Yb^+	Na-Na^+	....

Outline

A brief intro of atom-ion collisions

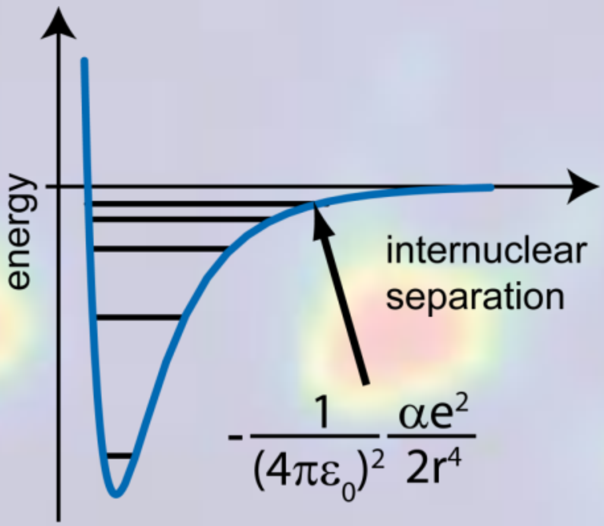
Hybrid atom-ion experiments – state-of-the-art

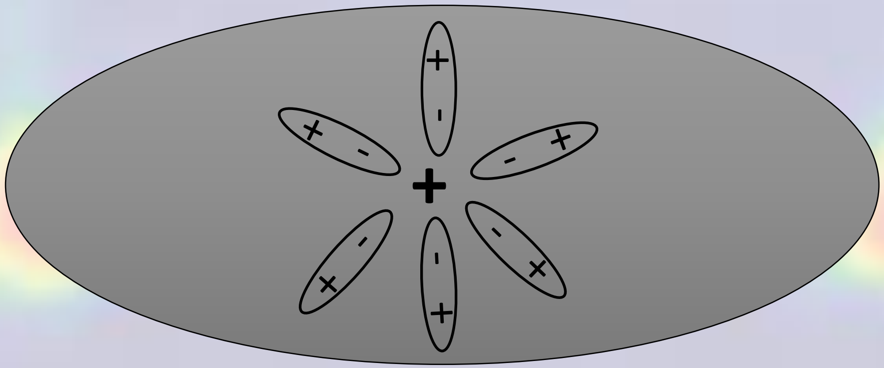
Hybrid atom-ion experiments: perspectives

Atom-ion systems for improving ion clocks

Atom-ion interactions

Charge-induced dipole interaction: R^{-4} scaling





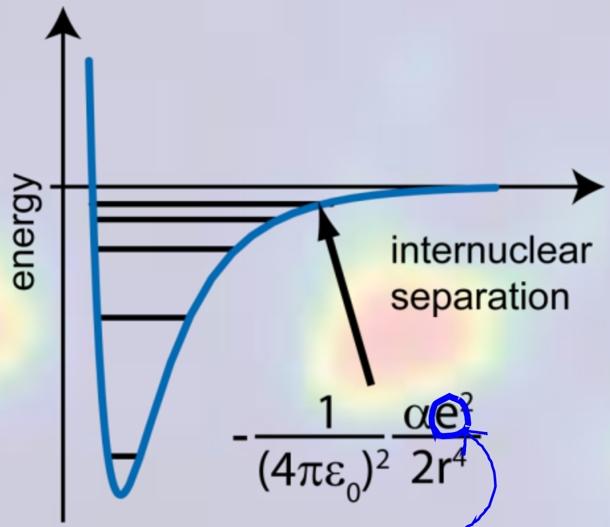
Longer ranged than atom-atom interactions!

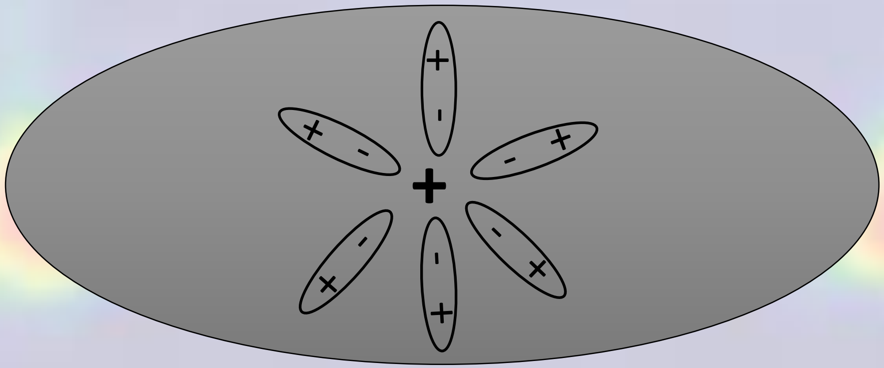
$R^* \gtrsim 100\mathrm{nm}$

For atom-atom interactions
typically $R^* \approx 1\,\mathrm{nm}$

Atom-ion interactions

Charge-induced dipole interaction: R^{-4} scaling





Longer ranged than atom-atom interactions!

<u>$R^* \gtrsim 100nm$</u>

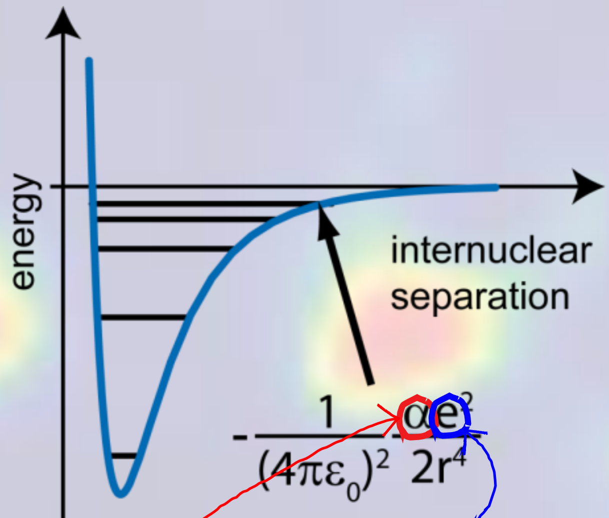
For atom-atom interactions typically $R^* \approx 1nm$

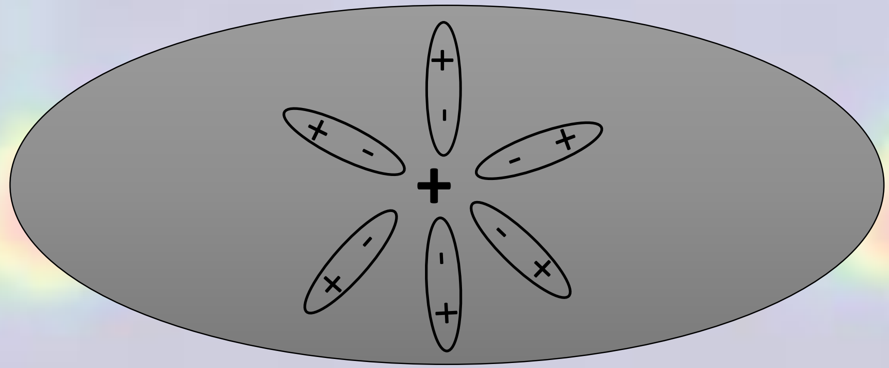
Depends only from:

- **The ion's charge**

Atom-ion interactions

Charge-induced dipole interaction: R^{-4} scaling





Longer ranged than atom-atom interactions!

$R^* \gtrsim 100\text{nm}$

For atom-atom interactions
typically $R^* \approx 1\text{nm}$

Depends only from:

- **The ion's charge**
- **The DC polarizability of the neutral particle**

→ independent from the ion's element!

Atom-ion collisions

First theory by Langevin (classical)

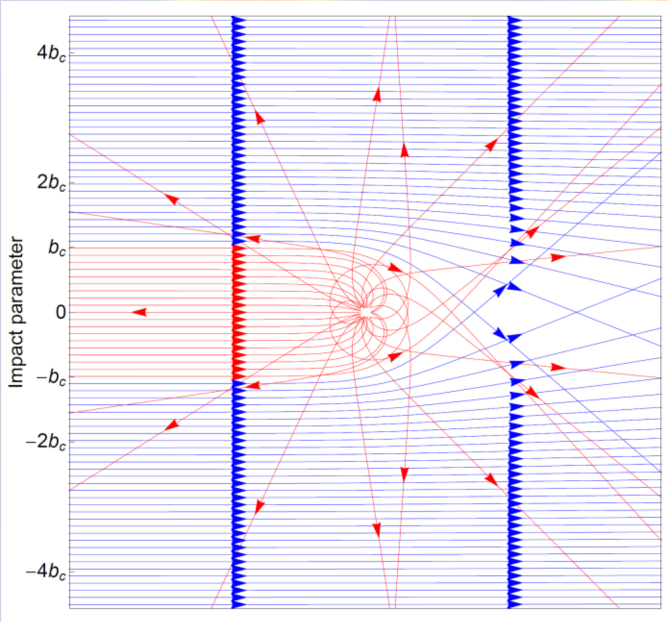
$$V(r) = -\frac{C_4}{2\,r^4} \qquad C_4 = \frac{\alpha\, e^2}{(4\pi\varepsilon_0)^2}$$

We can define a *critical impact parameter*

$$b_c = \left(\frac{2\,C_4}{E_c}\right)^{1/4}$$

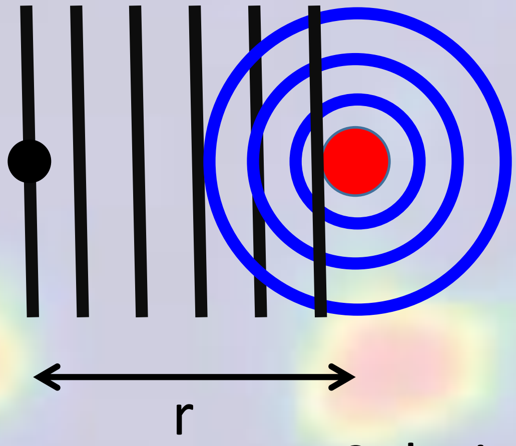
Large deflection $b < bc$

Small deflection $b > bc$



C. Zipkes, Ph.d. Thesis, University of Cambridge

..a bit of theory



Colliding particles – Schroedinger eq.

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + V(\boldsymbol{r})\right)\Psi(\boldsymbol{r}) = \frac{\hbar^2 k^2}{2\mu}\Psi(\boldsymbol{r})$$

Solution (at large r):

In: plane wave

Out: spherical wave

$$\Psi(\boldsymbol{r}) \sim e^{ikz} + f(\theta)\frac{e^{ikr}}{r}$$

..a bit of theory

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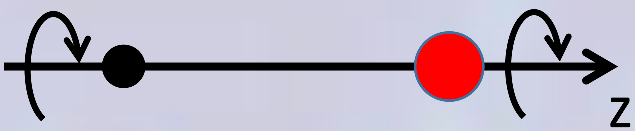

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Out: spherical wave

$$\Psi(\boldsymbol{r}) \sim e^{ikz} + f(\theta)\frac{e^{ikr}}{r}$$

Hypothesis: V(r) is central → cylindrical simmetry

Ok in atom-atom, atom-ion NOT in dipole-dipole!

→ Noether theorem, a quantity is conserved: angular momentum

..a bit of theory

Expansion in partial waves

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$$\Psi(\boldsymbol{r}) \sim e^{ikz} + f(\theta)\frac{e^{ikr}}{r}$$

(from expansion of spherical Bessel function)

$$e^{ikz} \sim \frac{1}{2ikr}\sum_{l=0}^{\infty}(2l+1)\left(e^{ikr} - (-1)^l e^{-ikr}\right)P_l(\cos\theta)$$

..a bit of theory

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Expansion in partial waves

$$\Psi(\boldsymbol{r}) \sim e^{ikz} + f(\theta)\frac{e^{ikr}}{r}$$

Here is the physics

$$f(\theta) = \sum_{l=0}^{\infty}(2l+1)\, f_l P_l(\cos\theta)$$

Legendre polynomials

$$e^{ikz} \sim \frac{1}{2ikr}\sum_{l=0}^{\infty}(2l+1)\left(e^{ikr} - (-1)^l e^{-ikr}\right)P_l(\cos\theta)$$

Let's re-write these terms $f_l = \frac{1}{k}e^{i\delta_l}\sin\delta_l$ and solve the S.E.

(crunch crunch..)

Phase acquired in the collision

Incoming wave

$$R_l(r) \sim \frac{1}{2ikr}\frac{1}{\sqrt{4\pi(2l+1)}}\left(e^{2i\delta_l}e^{ikr} - (-1)^l e^{-ikr}\right)$$

Radial part of $\Psi(\boldsymbol{r})$

Scattered wave

..a bit of theory

Cross section: $$\sigma = \frac{4\pi}{k^2}\sum_l (2l+1)(\sin\delta_l)^2$$

..a bit of theory

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<u>Summarizing</u>: a plane wave – written in terms of sum of spherical waves – is changed after the collision since each spherical wave of the expansion gets a **different** phase shift

..a bit of theory

Cross section: $$\sigma = \frac{4\pi}{k^2}\sum_l (2l+1)(\sin\delta_l)^2$$

Summarizing: a plane wave – written in terms of sum of spherical waves – is changed after the collision since each spherical wave of the expansion gets a **different** phase shift

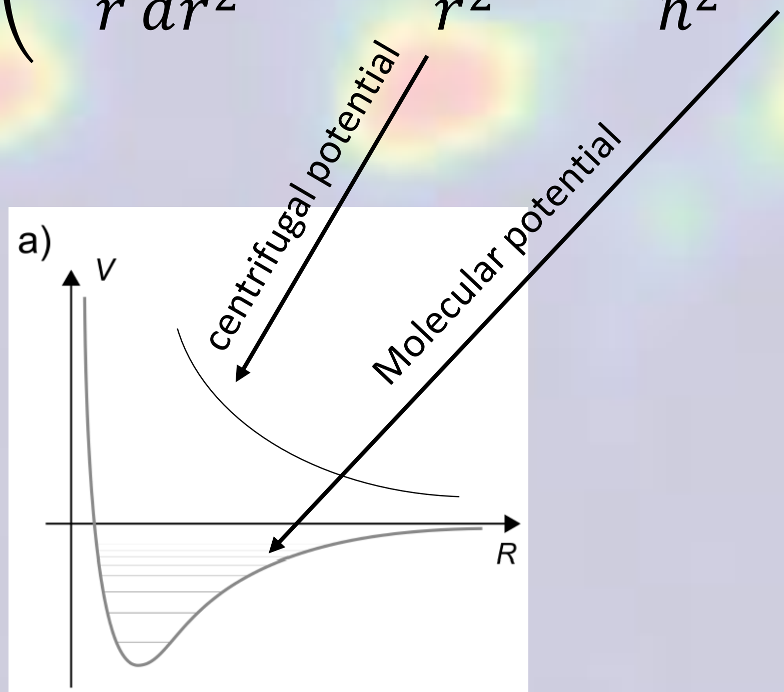
Important: energy conservation! The only effect of collisions are phase shifts that modify the «envelope» of the wave but not its amplitude!

..a bit of theory

How do we calculate the phase shifts?

We solve the Schroedinger equation! (radial part)

$$\left(-\frac{1}{r}\frac{d^2}{dr^2}r+\frac{l(l+1)}{r^2}+\frac{2\,\mu}{\hbar^2}V(r)\right)R_l(r)=k^2R_l(r)$$



Inguscio, Fallani «*Atomic Physics*», Oxford University Press

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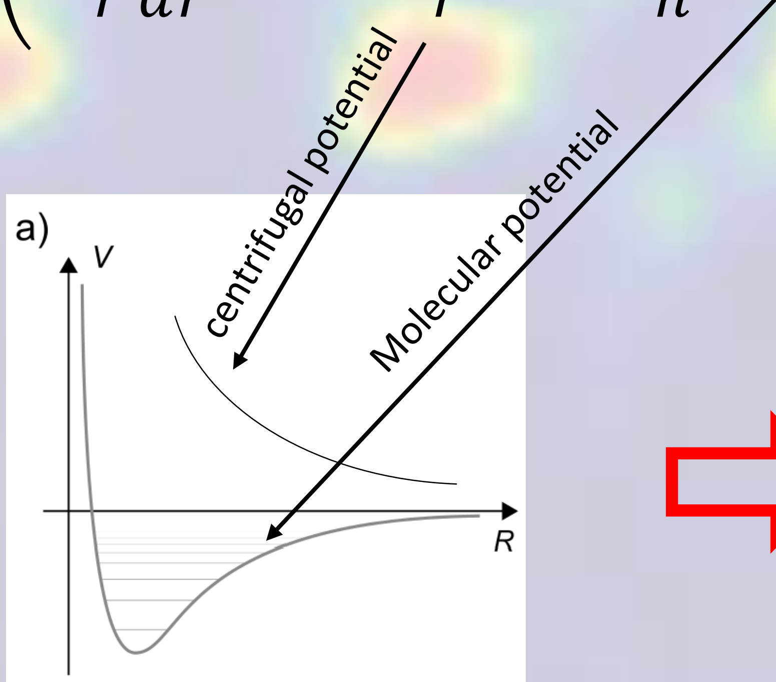

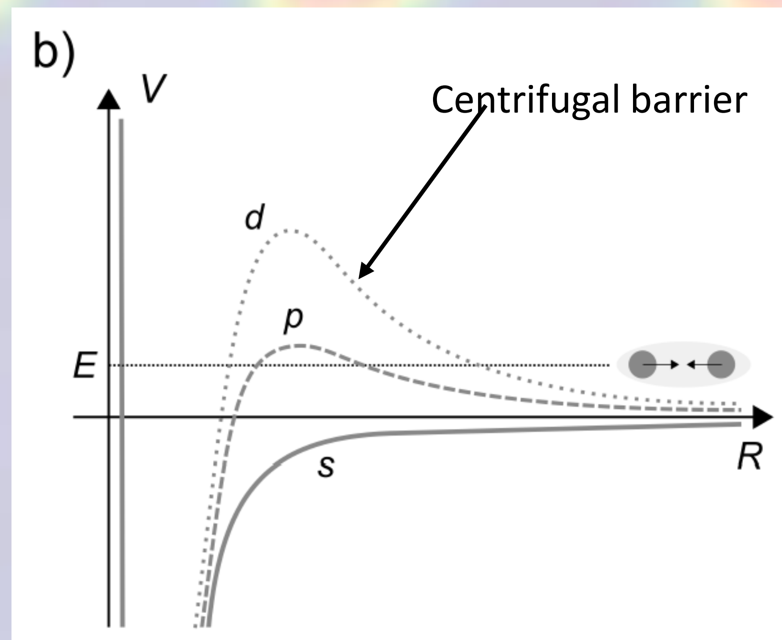

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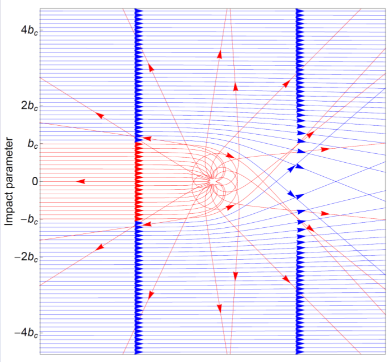
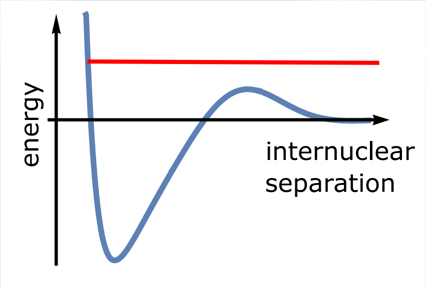
Atom-ion collisions

Large deflection

$b < bc$



Collisions from the hard wall



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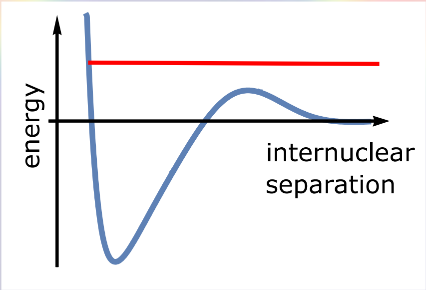

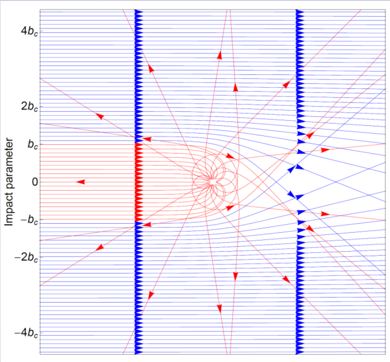

Small deflection

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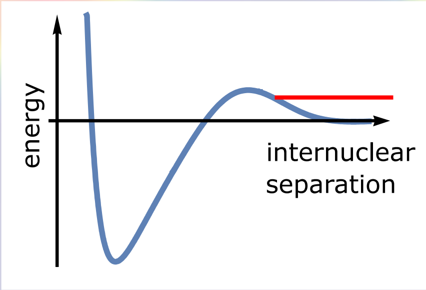
Collisions from the centrifugal barrier



Atom-ion collisions

Large deflection

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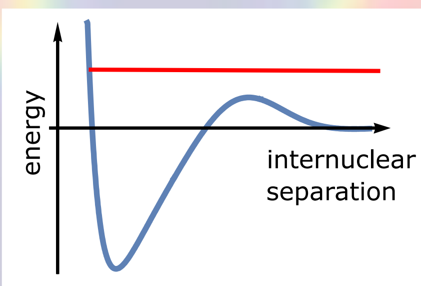
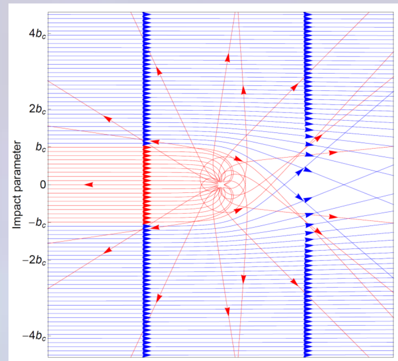


$$\sigma_L = \pi\, b_c^2 = \pi \sqrt{\frac{2C_4}{E_c}}$$

(classical)



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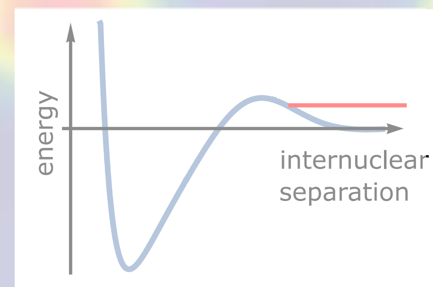

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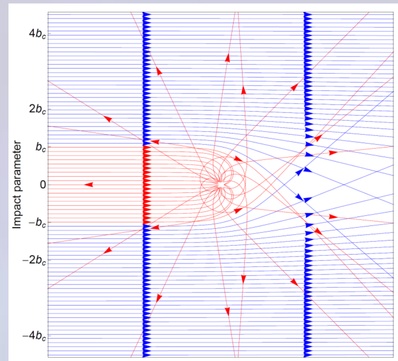

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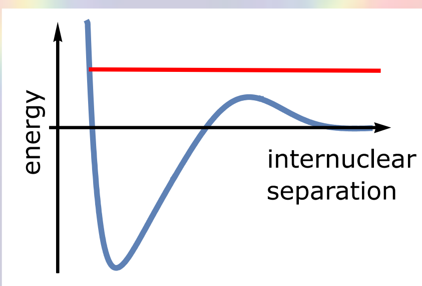

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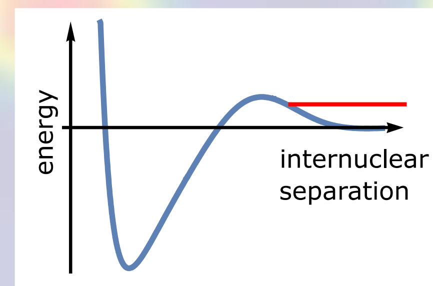

$$\sigma_{tot} = \pi \left(1 + \frac{\pi}{16}\right) \left(\frac{\mu C_4^2}{\hbar^2}\right)^2 E_c{}^{-1/3}$$

(semiclassical)

Atom-ion collisions

Large deflectio

$b < bc$

Collisions from t
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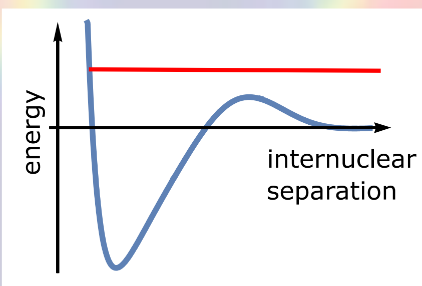

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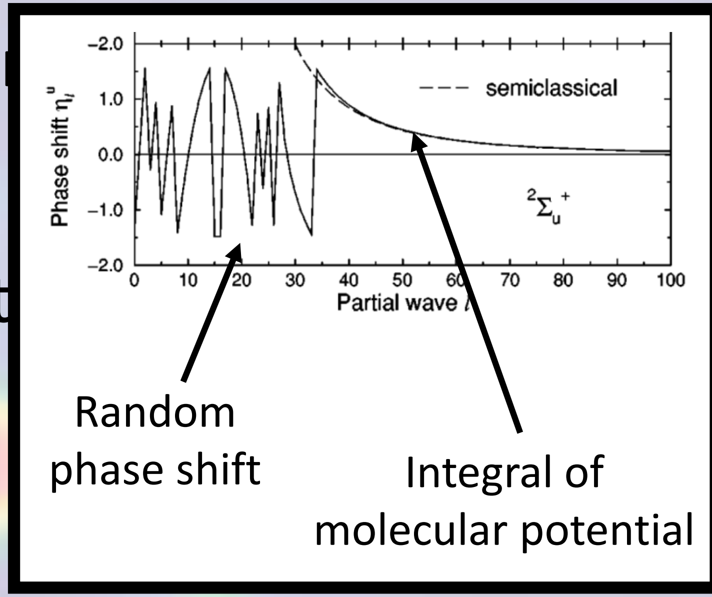

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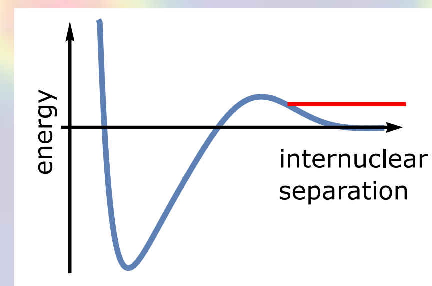

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(semiclassical)

Atom-ion collisions

Large deflection

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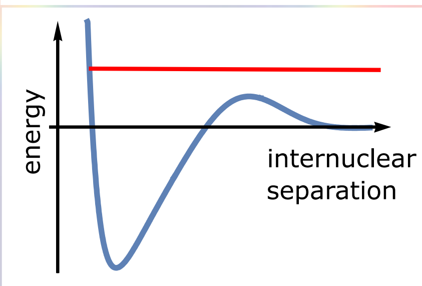
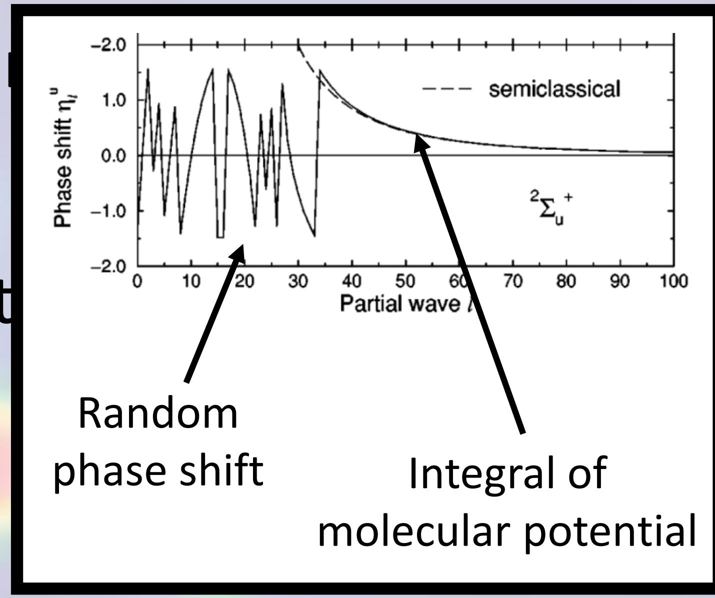
Langevin collisions

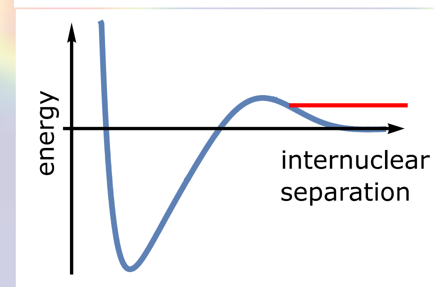




Small deflection

$b > bc$

soft collisions



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Atom-ion collisions

Cross section

$$\sigma_{tot} = \pi\left(1+\frac{\pi}{16}\right)\left(\frac{\mu C_4^2}{\hbar^2}\right)^2 E_c^{-1/3}$$

Langevin cross section

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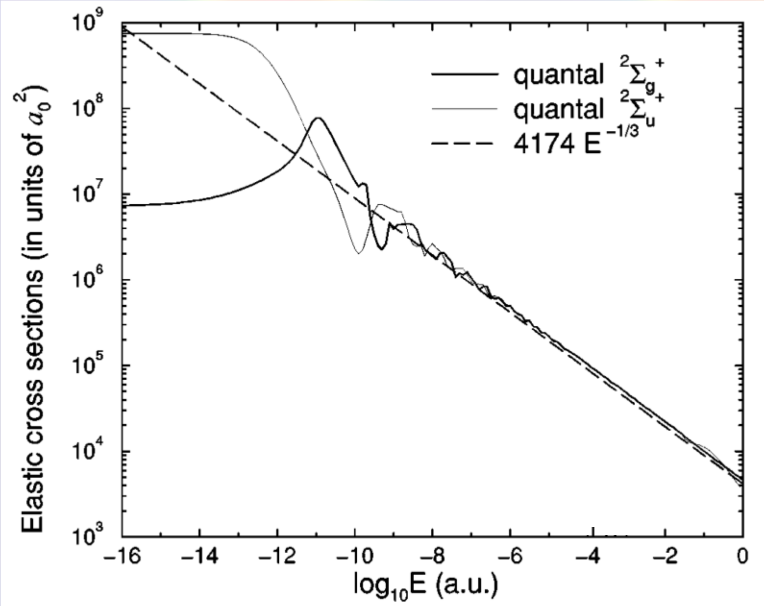

R. Côté, A. Dalgarno, PRA 2000

Atom-ion collisions

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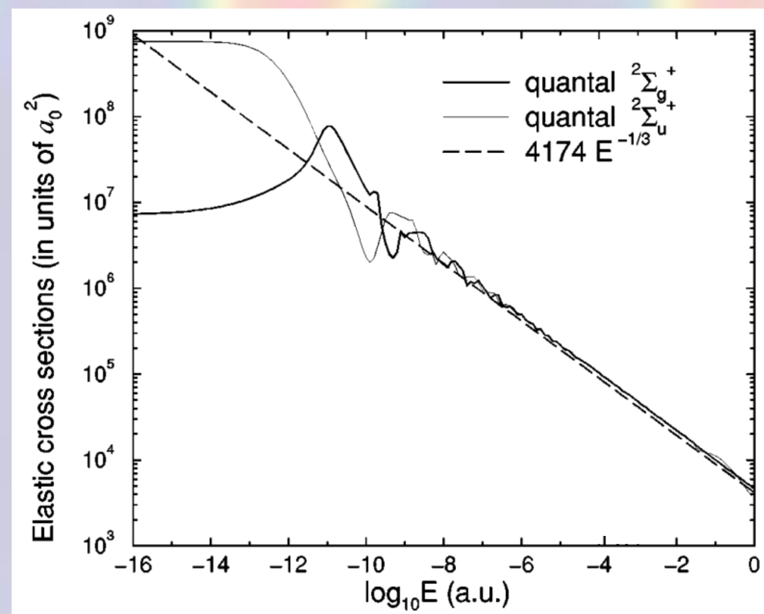

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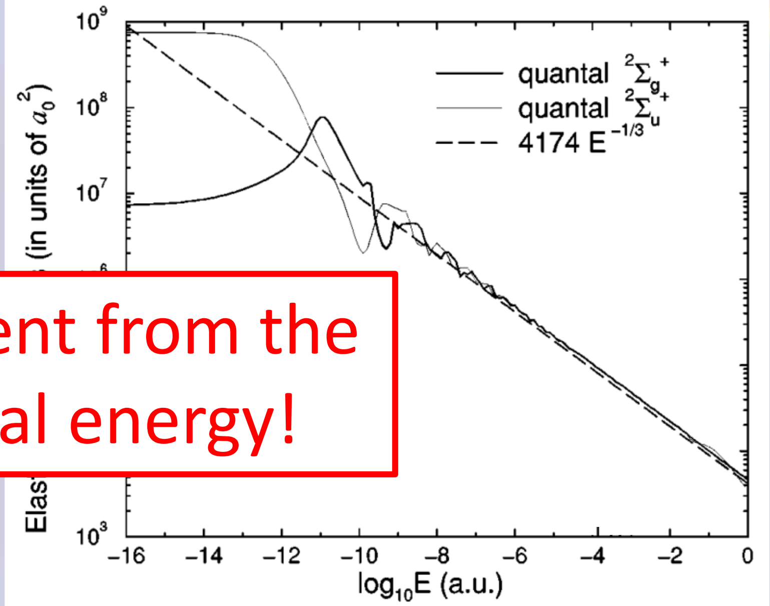
Independent from the collisional energy!



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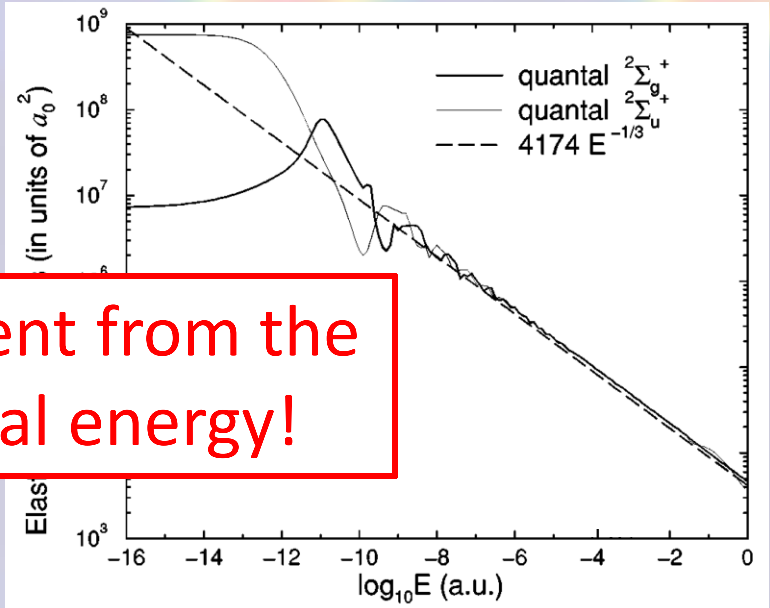

R. Côté, A. Dalgarno, PRA 2000

At large collisional energies soft collisions are the most frequent

Outline

A brief intro of atom-ion collisions

Hybrid atom-ion experiments – state-of-the-art

Hybrid atom-ion experiments: perspectives

Atom-ion systems for improving ion clocks

The experiments

Paul trap + Atom trap

(Magneto-optical trap,
magnetic trap, optical trap..)

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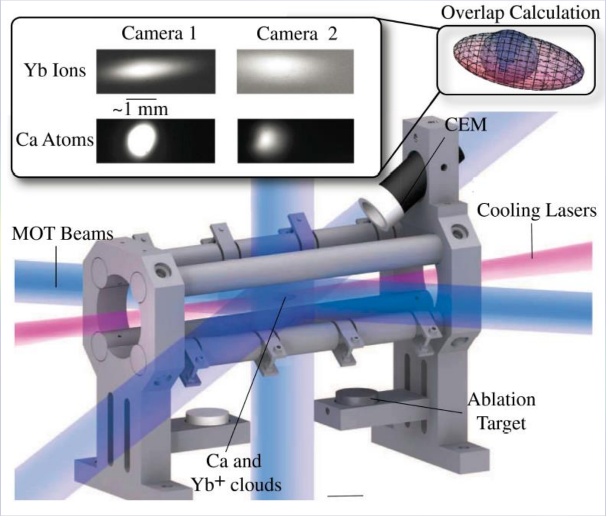

Hudson group, UCLA

The experiments

Paul trap + Atom trap

(Magneto-optical trap,
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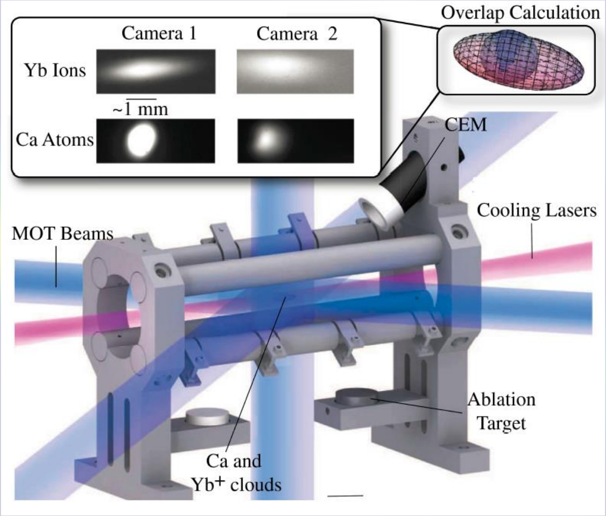

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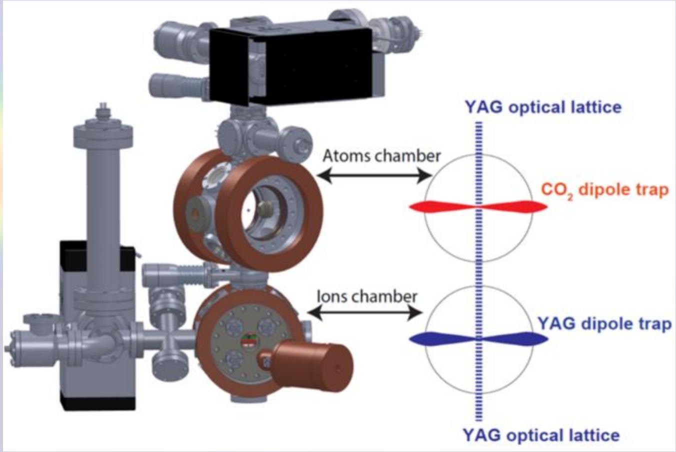
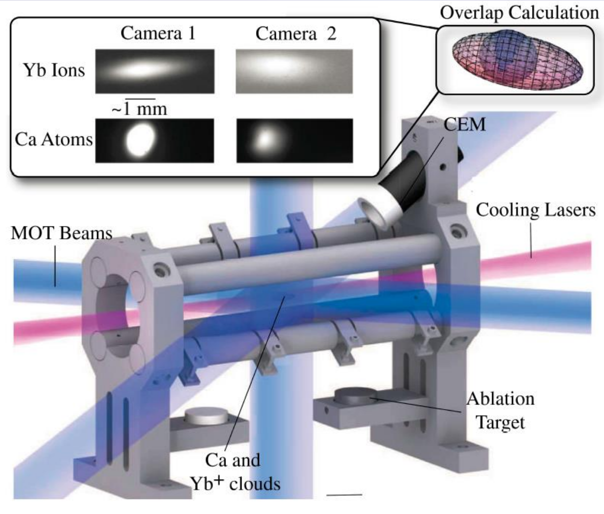


Ozeri group, Weizmann

The experiments

Paul trap + Atom trap

(Magneto-optical trap, magnetic trap, optical trap..)



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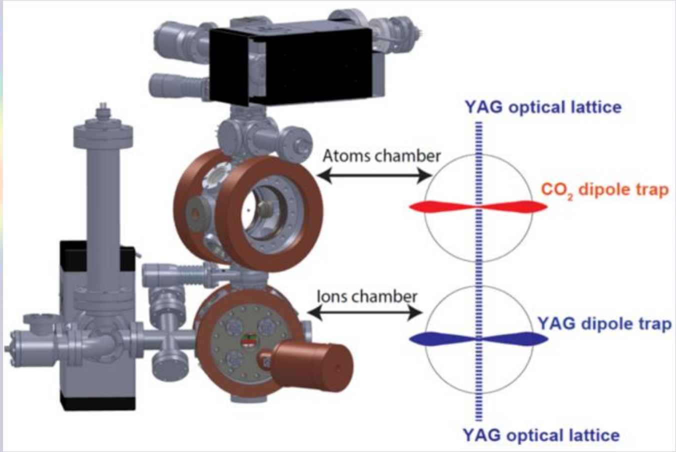

Ozeri group, Weizmann

PROs: high repetition rate
large atom number
CONs: relatively high temperature,
poor control of internal state

The experiments

Paul trap + Atom trap

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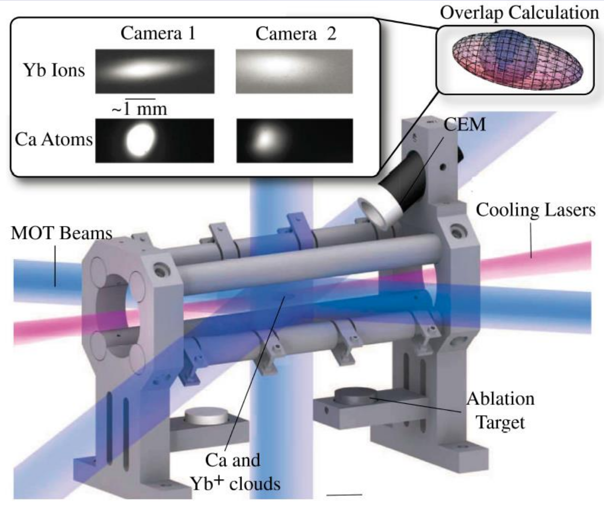

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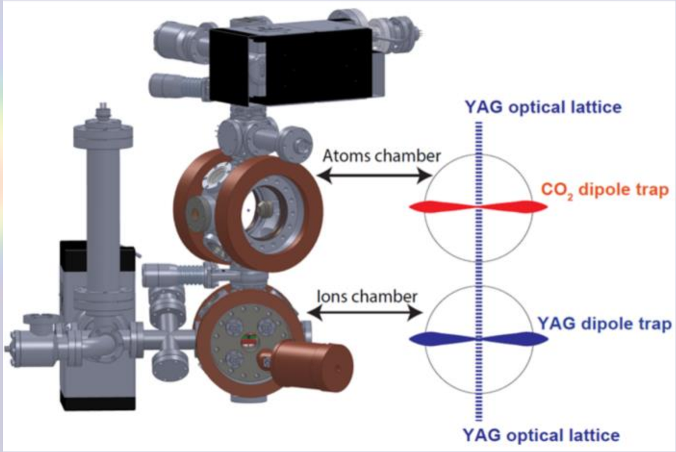
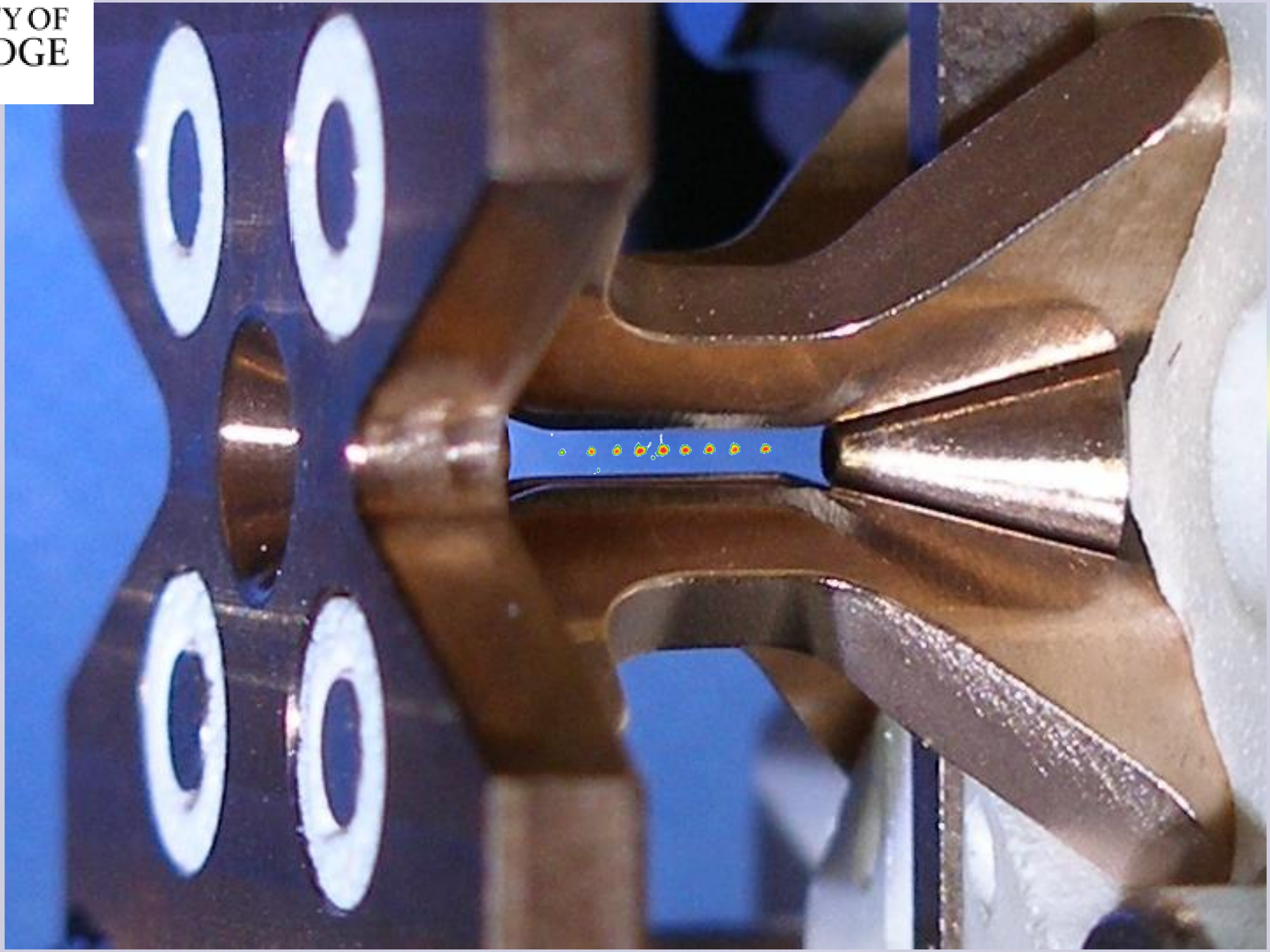


Ozeri group, Weizmann

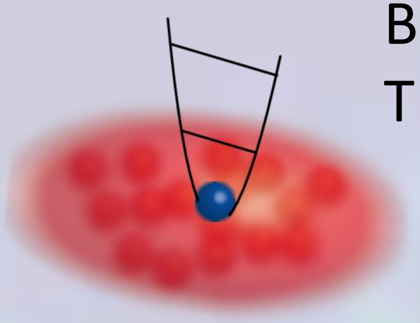
PROs: high repetition rate
large atom number
CONs: relatively high temperature,
poor control of internal state

PROs: lower temperature,
coherence
CONs: slower repetition rate,
high collisional rate

A hybrid apparatus



Elastic collisions: sympathetic cooling

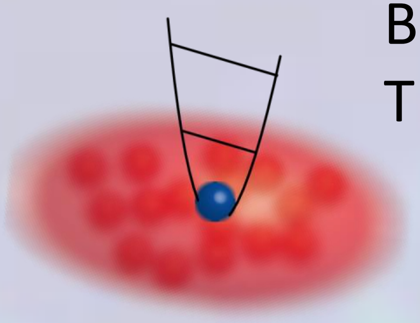


Bose-Einstein condensate
T ≈ 100 nK

Ion trap
(level spacing ≈ 5 mK)

Goal: continuous cooling of an ion-based quantum hardware

Elastic collisions: sympathetic cooling



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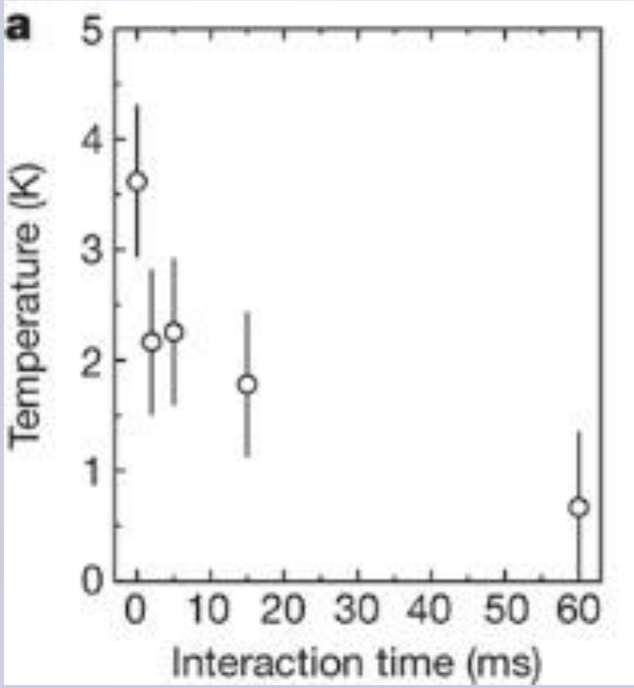
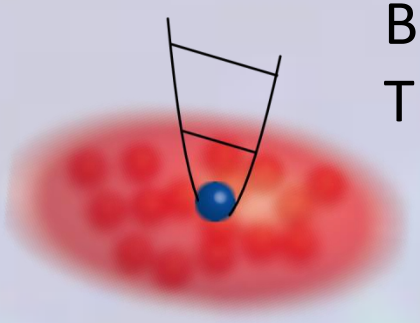


C. Zipkes, et al. Nature 2010; C. Zipkes et al. PRL 2010; S. Schmid et al. PRL 2010

<u>Elastic</u> collisions: sympathetic cooling



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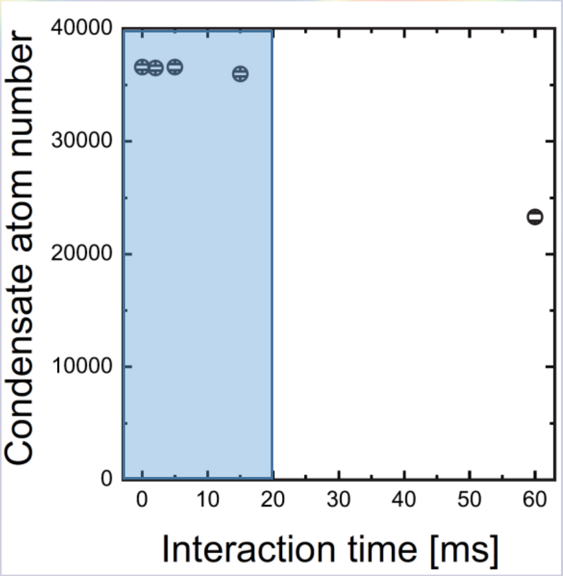
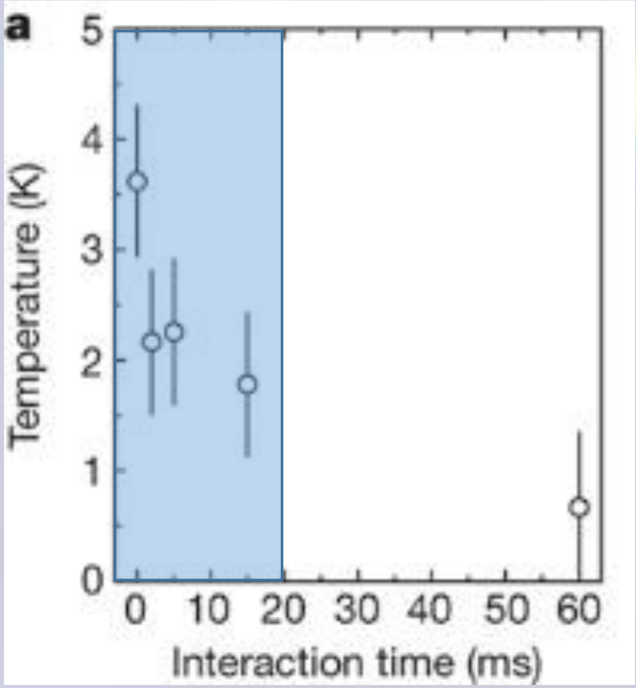


Very efficient!
(at the beginnging)



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Inelastic collisions: chemical reactions

Possible effects of inelastic collisions: (example: Rb-Yb^+ mixture)

- $Yb^+ + Rb \rightarrow Yb + Rb^+$ — Charge Exchange
- $Yb^+ + Rb \rightarrow (YbRb)^+$ — Molecular association
- $(Yb^+)^* + Rb \rightarrow Yb^+ \; Rb$ — Collisional quenching

L. Ratschbacher et al. Nat. Phys. 2011, F.H.J. Hall et al. PRL (2011), L. Ratschbacher et al. PRL 2012

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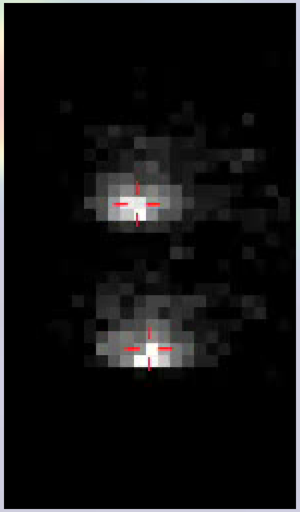
Problems: 1. New ion invisible to spectroscopy
2. Non-radiative decays cause trap losses
3. Heating mechanism

L. Ratschbacher et al. Nat. Phys. 2011, F.H.J. Hall et al. PRL (2011), L. Ratschbacher et al. PRL 2012

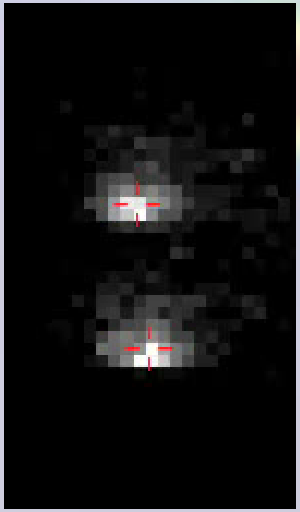
Inelastic collisions: chemical reactions

Detection of inelastic processes

Creation of a dark ion



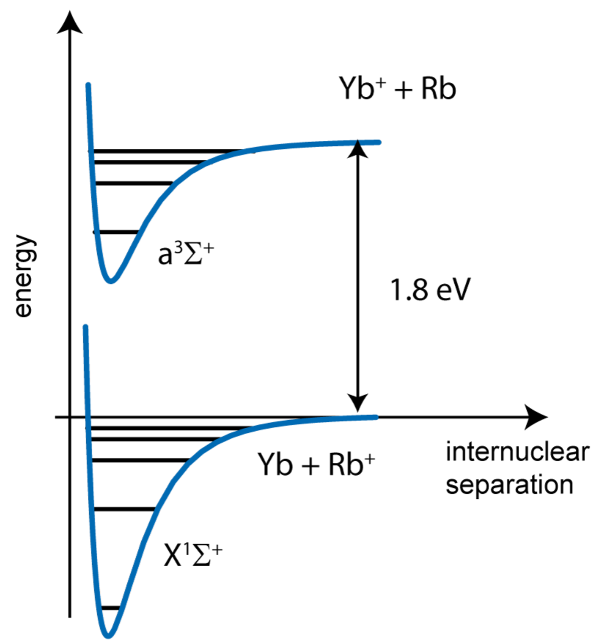
Ion loss



Not enough to ascertain what happened

Inelastic collisions: chemical reactions

Detection of inelastic processes

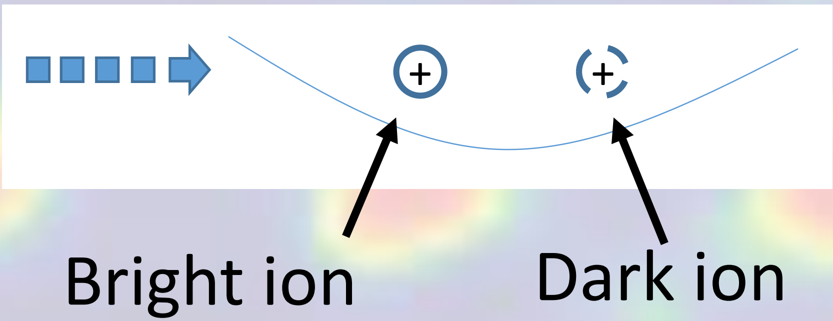


Only purely radiative processes make the ion survive

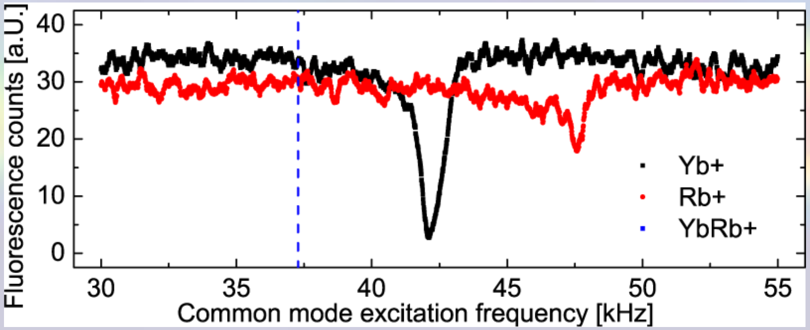
Not enough to ascertain what happened

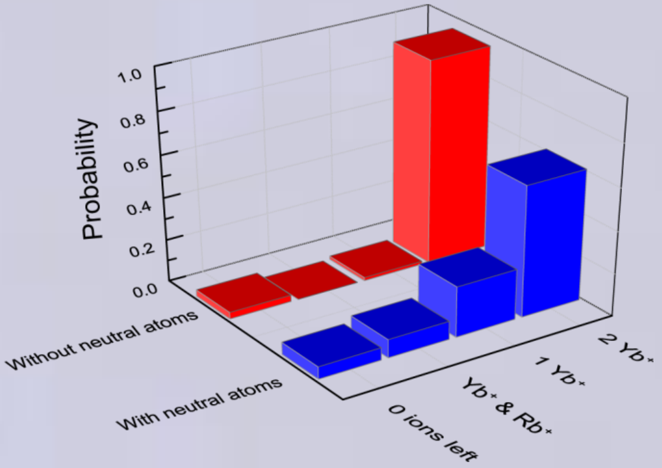
Inelastic collisions: chemical reactions

We can perform mass spectrometry of a dark ion by modulating e.g. the cooling laser of an ancillary ion



Example: Rb-Yb^+





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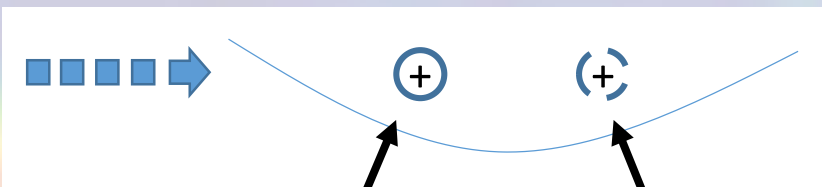
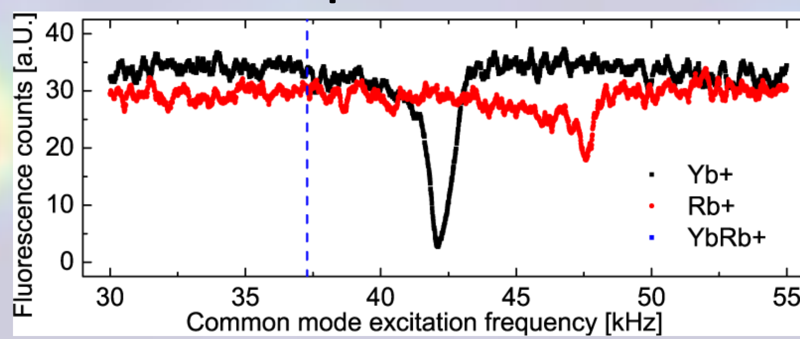
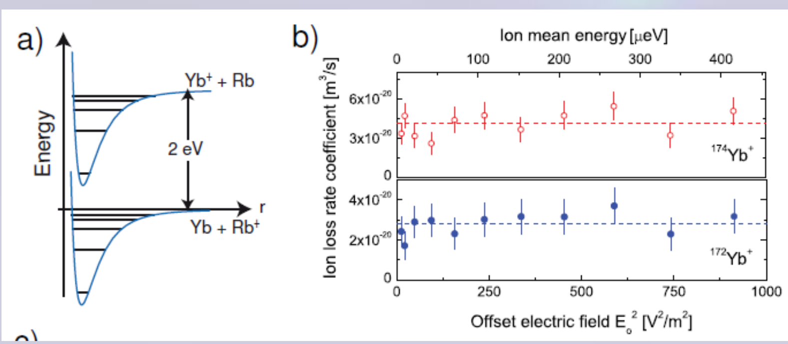


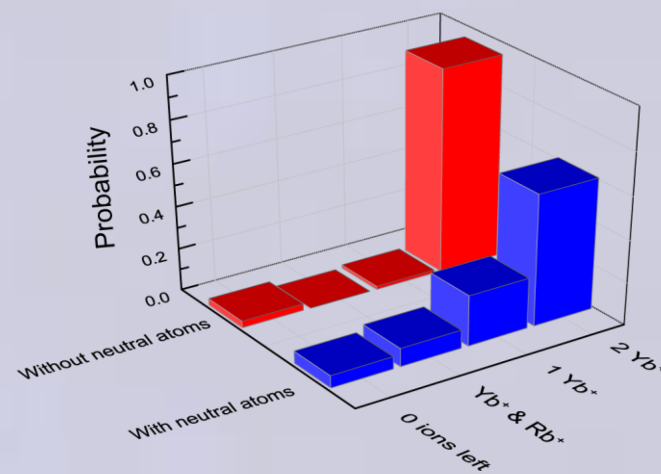
Bright ion

Dark ion

Example: Rb-Yb^+







Reaction rate independent from collisional energy: Langevin!

Controlling chemical reactions

everything depends on the ion-neutral pair

	Rb-Yb⁺ (Cambridge)	**Rb-Sr⁺** (Weizmann)	**Rb-Ca⁺** (Basel)
Charge exchange rate	$\sim 10^{-5}\gamma_L$	$\sim 2 \times 10^{-5}\gamma_L$	$< 10^{-3}\gamma_L$
Creation of molecules	✗	✗	✓

Controlling chemical reactions

everything depends on the ion-neutral pair
… and on the state

Table 1 | Measured proportionality constant ϵ and branching ratios.

	$^2S_{1/2}$	$^2D_{3/2}$	$^2F_{7/2}$	$^2P_{1/2}$
ϵ	$10^{-5\pm0.3}$	1.0 ± 0.2	0.018 ± 0.004	0.1 ± 0.2
Charged particle lost	65%	87%	84%	
Rb^+ identified	35%	12%	15%	
Dark Yb^+ identified		$<1\%$		
Hot ion (unidentified)			1%	
Number of events	283	754	225	

Rb-Yb$^+$
(Cambridge)

$$\gamma_{react} = \gamma_L \epsilon$$

State-dependent reactivity

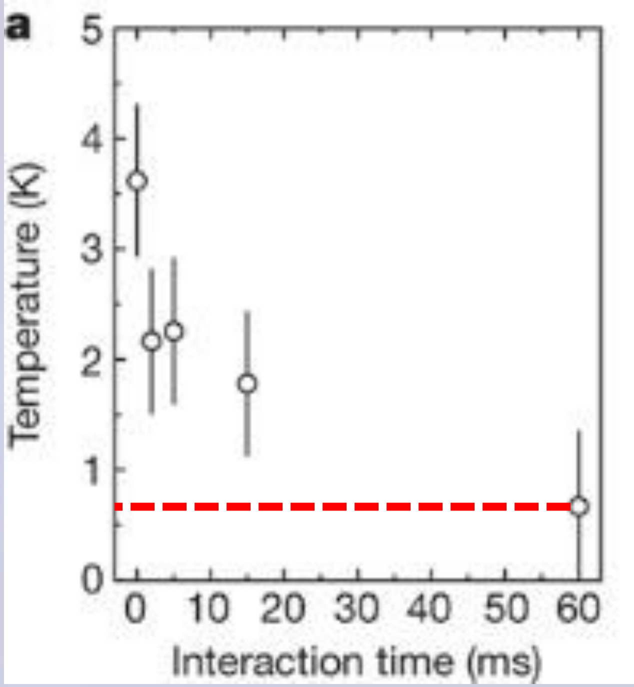
L. Ratschbacher et al. Nature Phys. 2012; T. Sikorsky et al. Nature Comm. 2018

.. a problematic story

<u>How COLD can we get?</u>

.. a problematic story

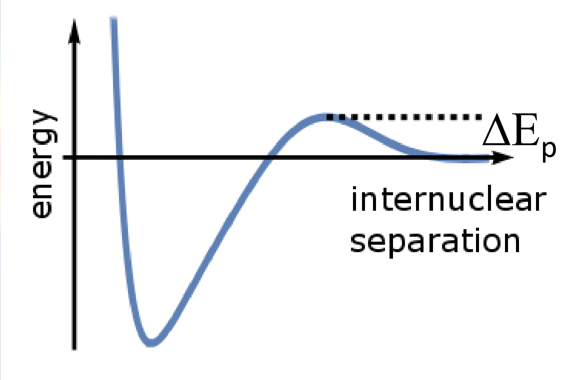
How COLD can we get?



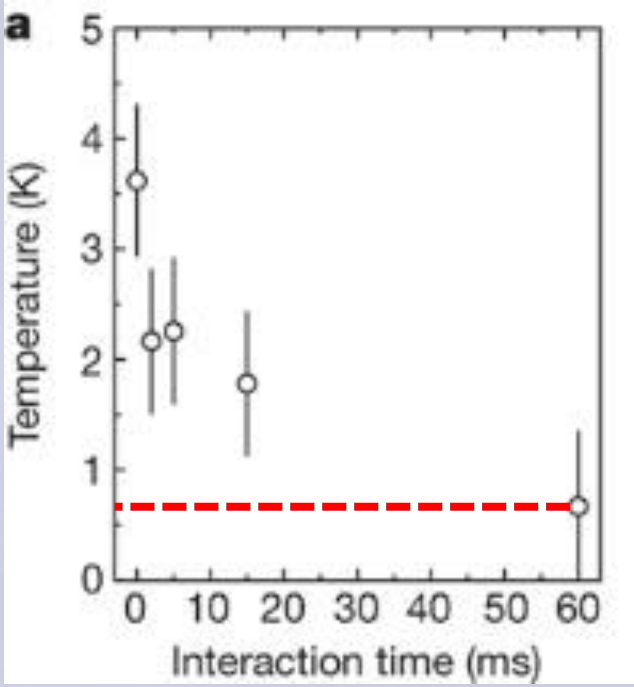
.. a problematic story

How COLD can we get?

At these temperature atom-ion collisions are CLASSICAL



$\Delta E_p / k_B \approx$ **1-10uK**



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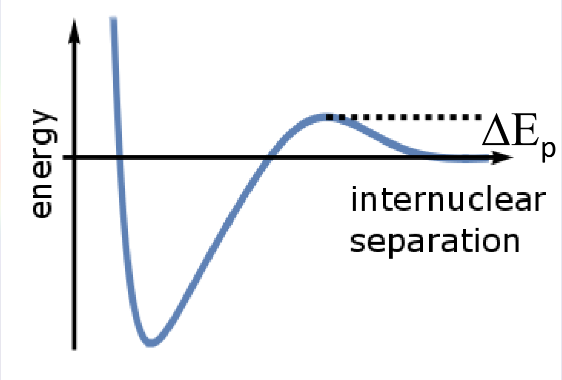

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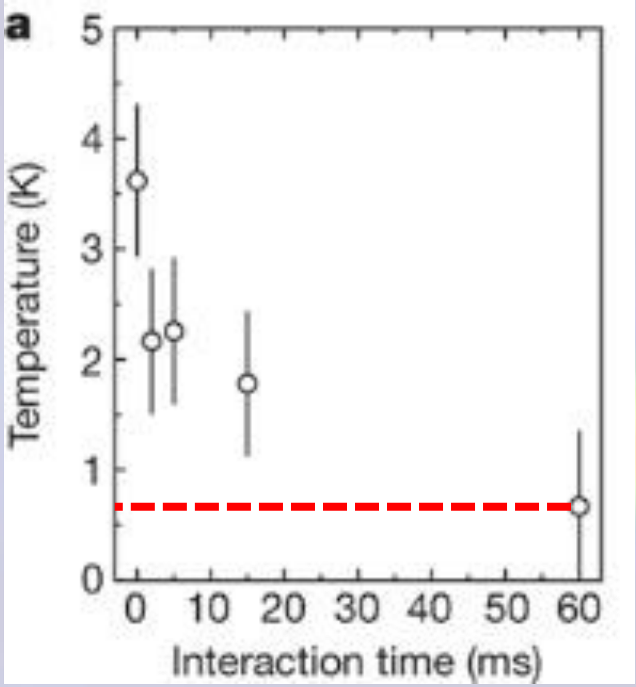

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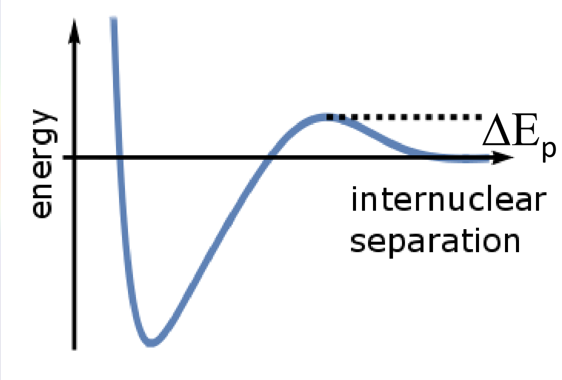

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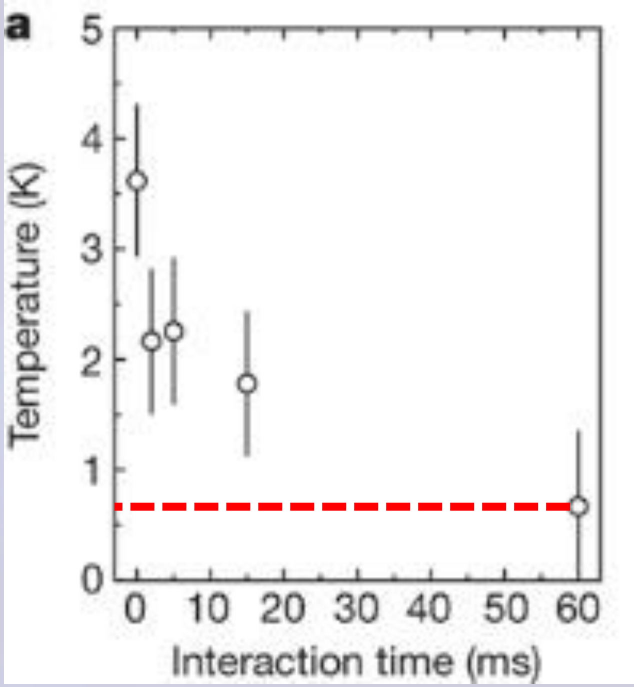

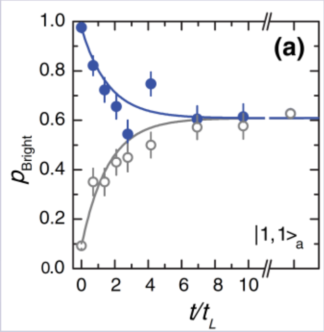

→ **Problem 1**: coherence does not survive

L. Ratschbacher et al. PRL 2013

.. a problematic story

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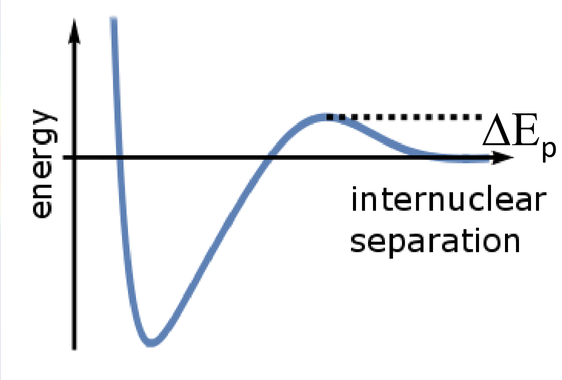

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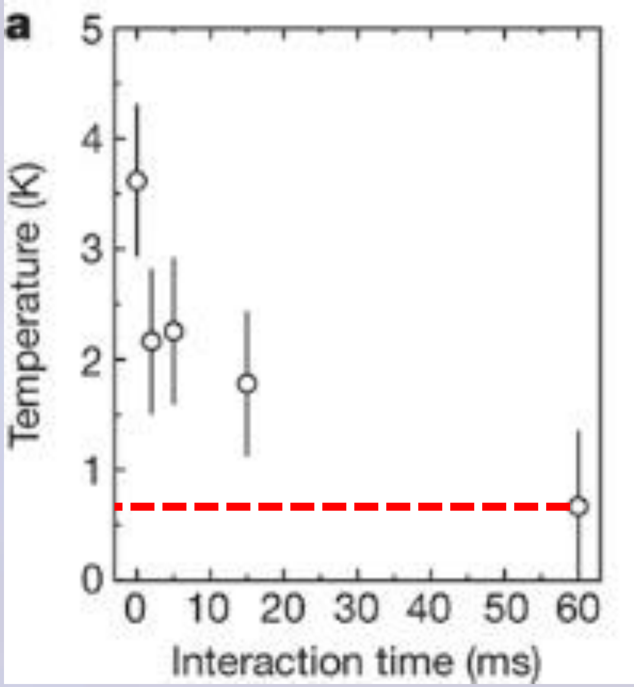
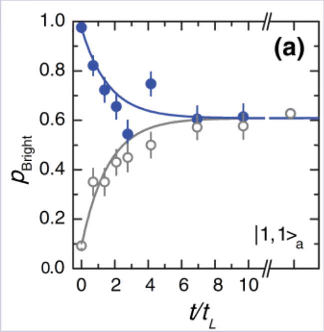
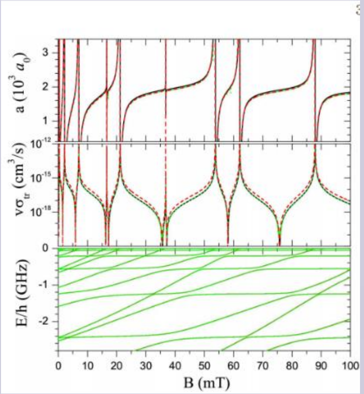




→ **Problem 1**: coherence does not survive

Problem 2 ←
We can't see/use Feshbach resonances



L. Ratschbacher et al. PRL 2013

Z. Idziaszek et al. PRA 2009

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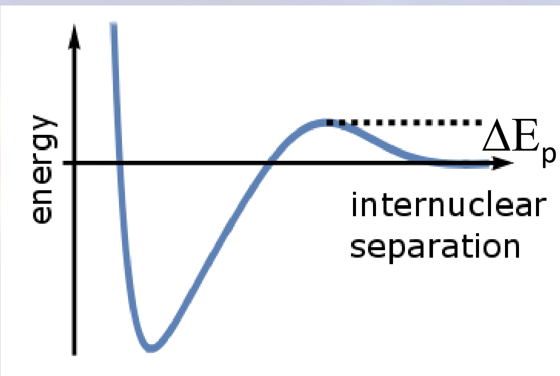

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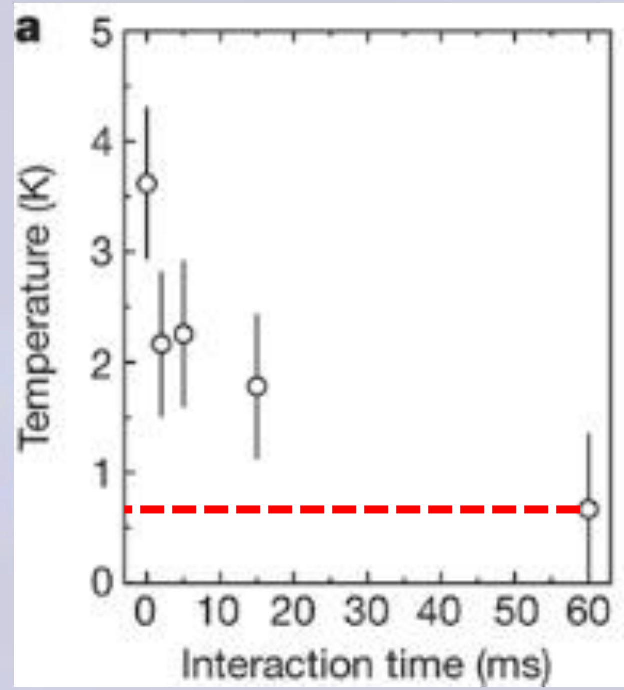
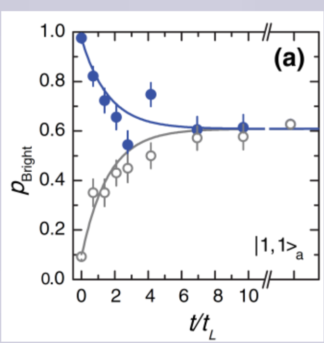




→ **Problem 1**: coherence

c

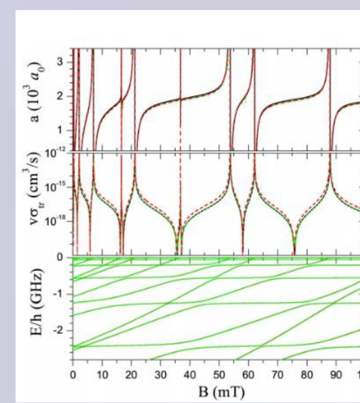
Physical problem:

We cannot bring atom-ion physics to a quantum level

⟵

se

Feshbach resonances



L. Ratschbacher et al. PRL 2013

Z. Idziaszek et al. PRA 2009

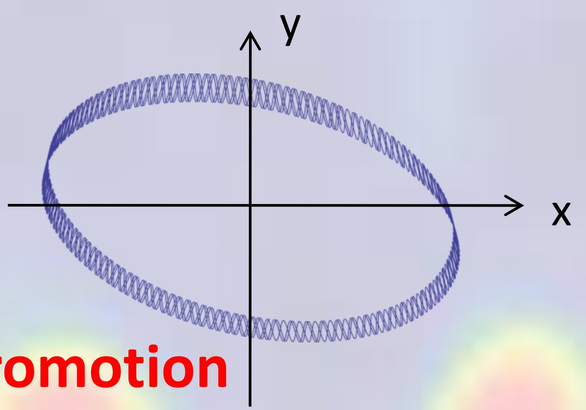
Origin of problems: micromotion

$$r_{ion,x} = A_x \sin(\omega_x t + \varphi_x) \left[1 + \frac{q}{2}\sin(\Omega_T t)\right]$$

$$r_{ion,y} = A_y \sin(\omega_y t + \varphi_y) \left[1 - \frac{q}{2}\sin(\Omega_T t)\right]$$

Secular motion

Micromotion



.. a problematic story

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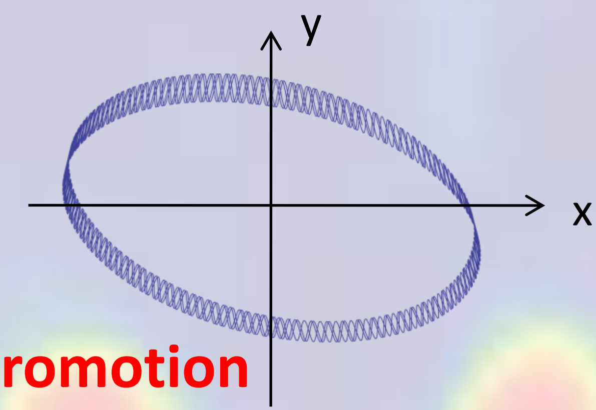

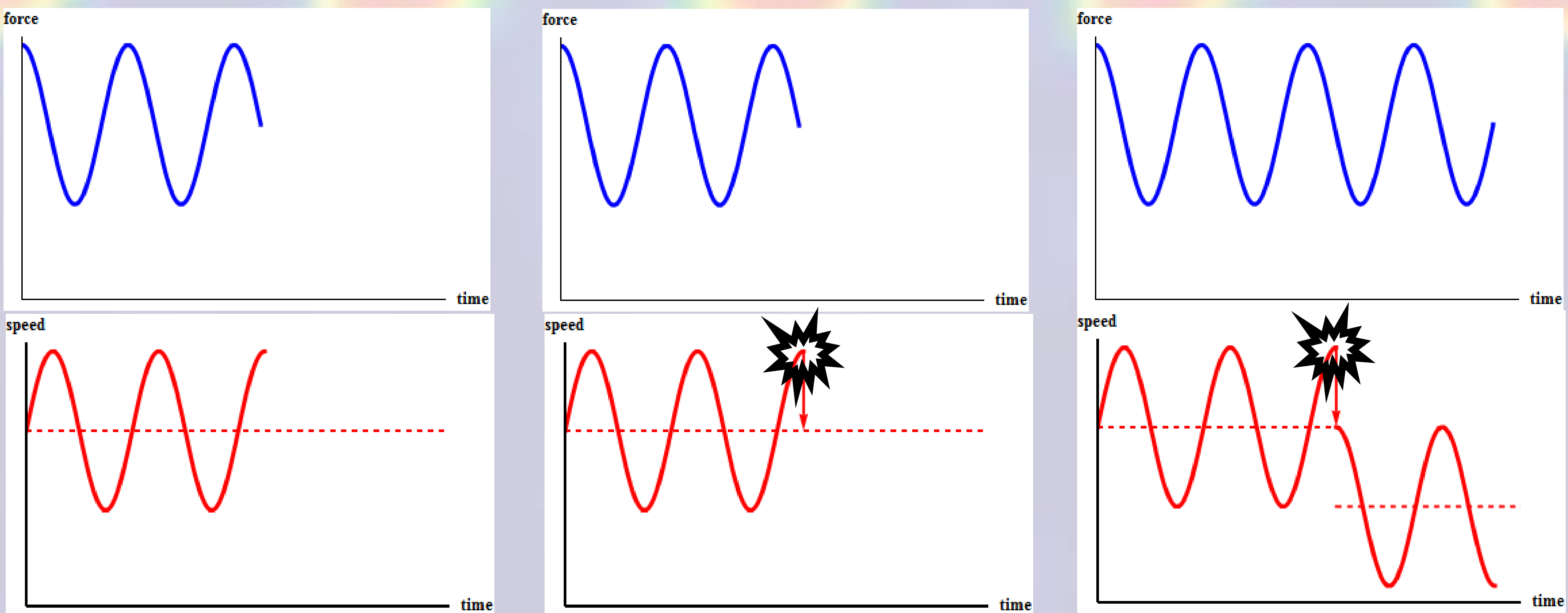

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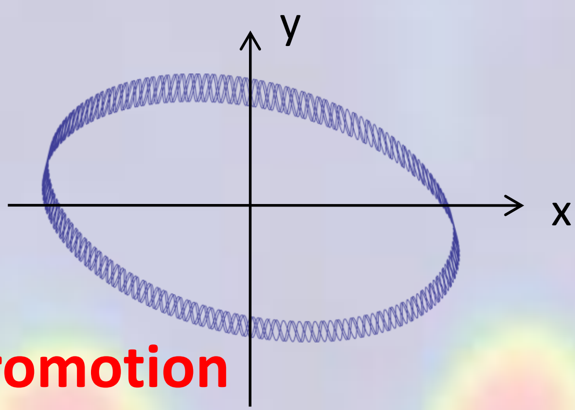

Collisions in the presence of micromotion can couple energy from the radiofrequency field to the colliding particles

.. a problematic story

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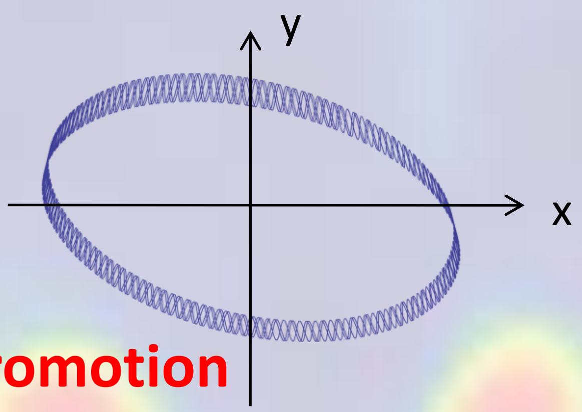


Secular motion

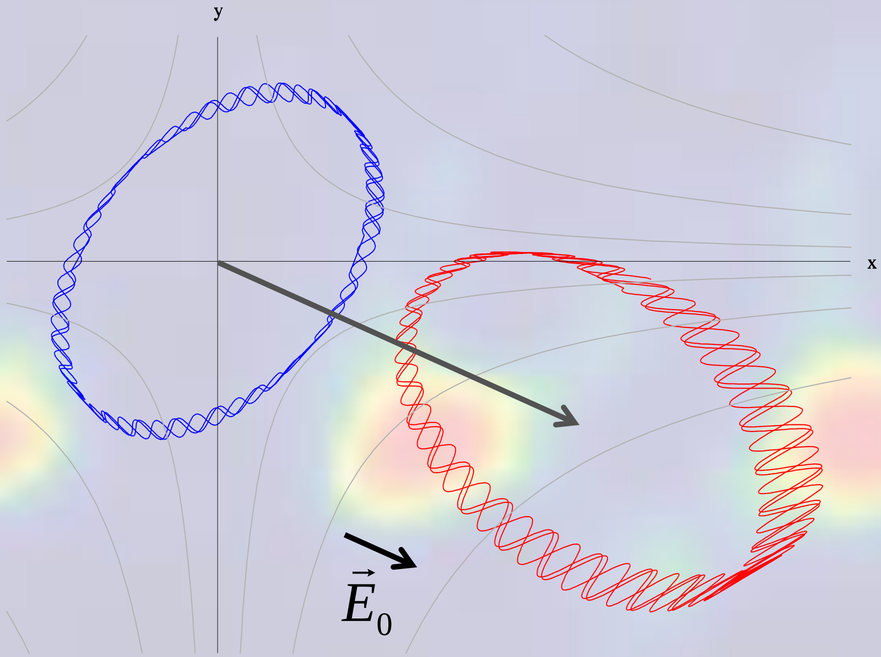
Micromotion

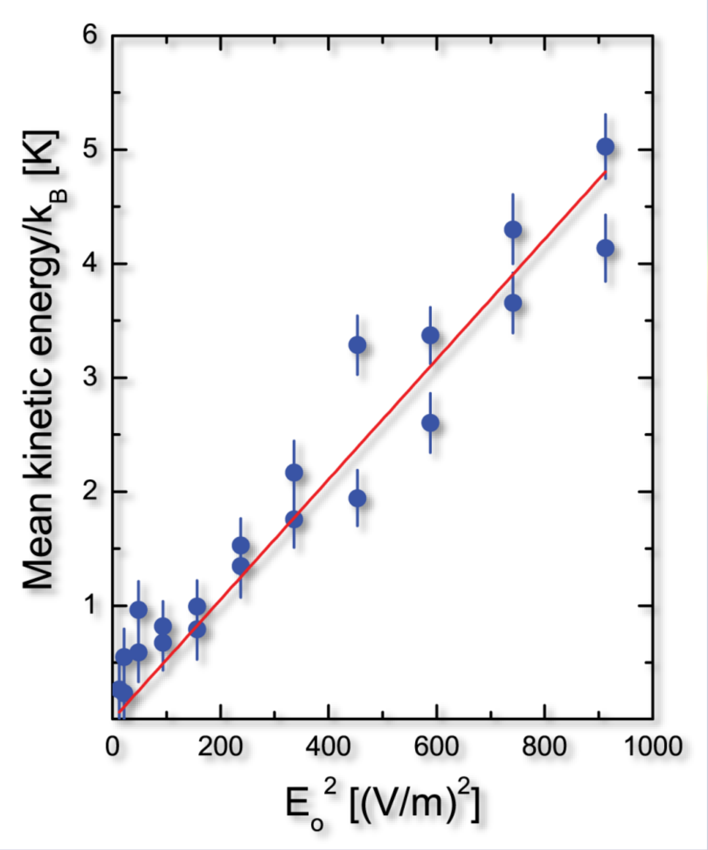
Collisions in the presence of micromotion can couple energy from the radiofrequency field to the colliding particles

Problem = Opportunity!

We can use micromotion to tune the collisional energy

Tuning the collisional energy





By applying an offset electric field $\vec{E}_0$ the mean kinetic energy changes:

$$\Delta E \approx \tfrac{1}{2} m\Omega^2 a_{mm}^2 \propto E_0^2$$

Where a_{mm} is the micromotion amplitude

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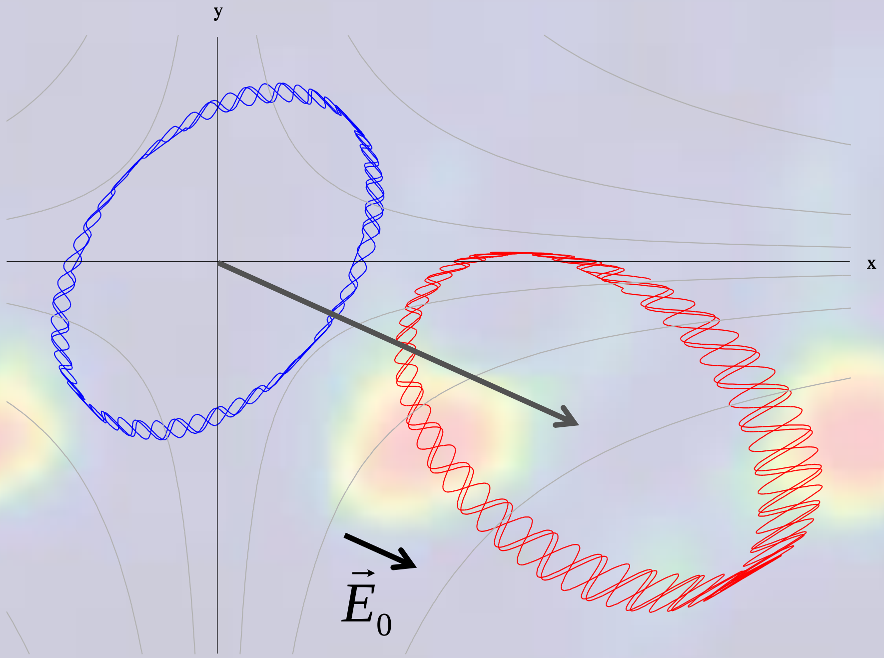

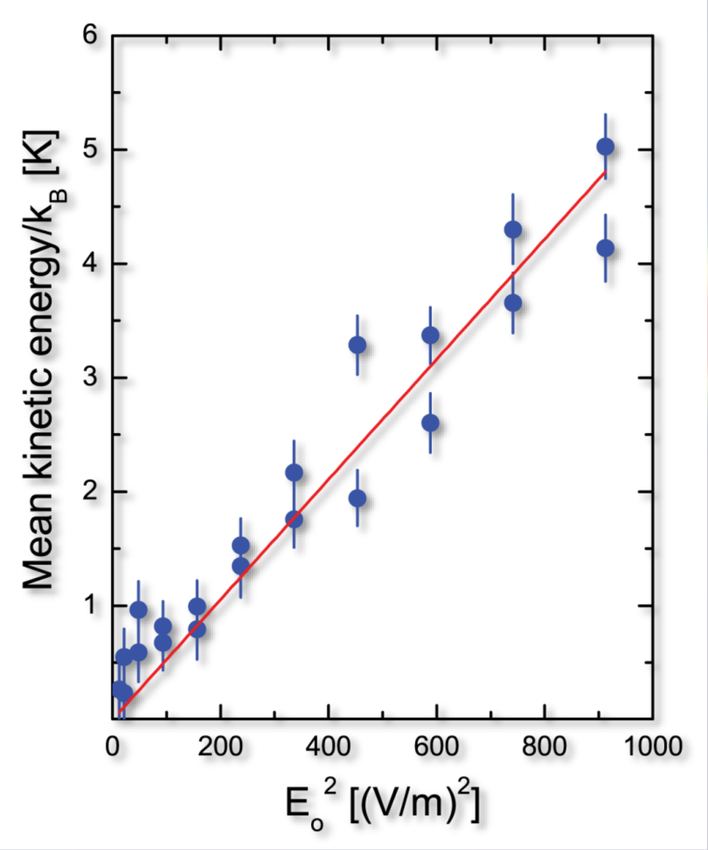

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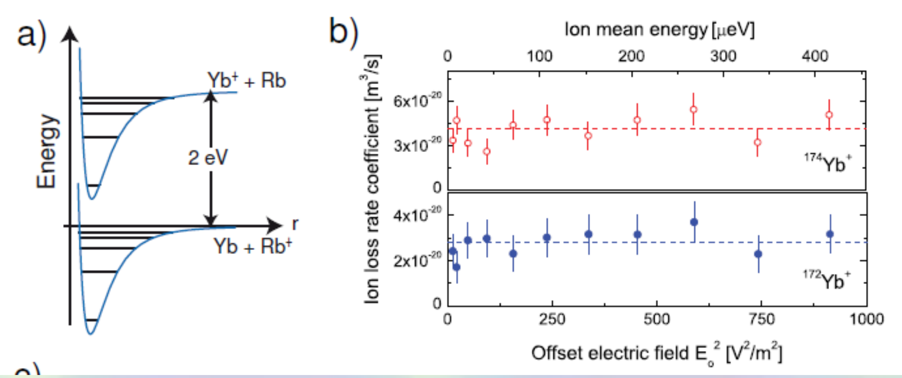
Studying ion-neutral collisions

Langevin collisions (no energy dependence of the scattering rate constant)



C. Zipkes, S. Palzer, L. Ratschbacher, C.S., M. Koehl PRL 105, 133201 (2010)

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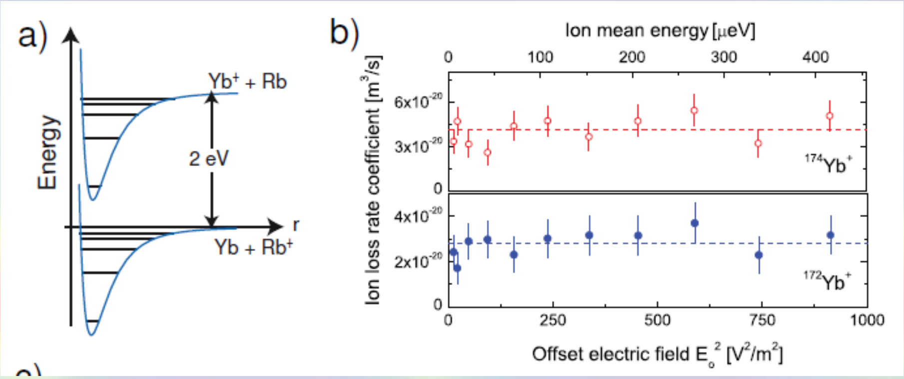
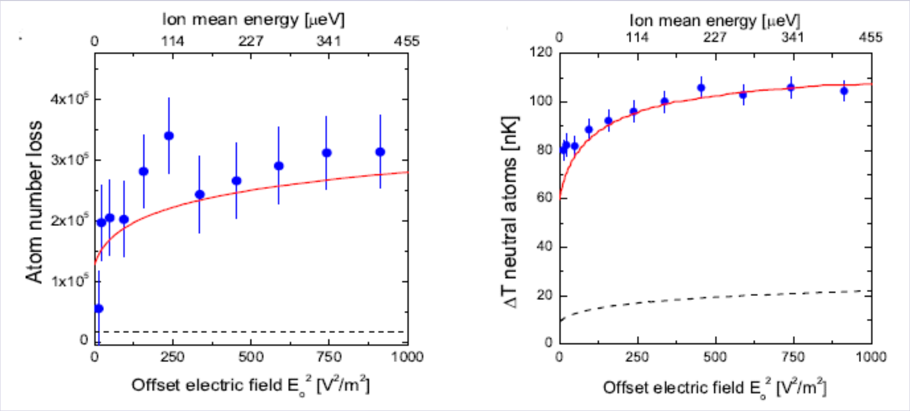


«Soft» collisions (energy dependent scattering rate constant)



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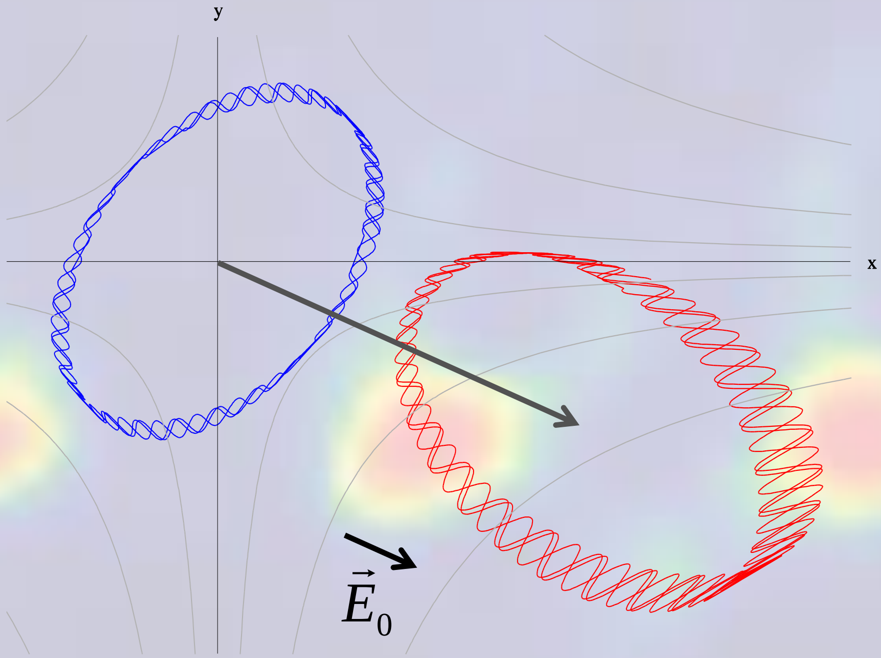

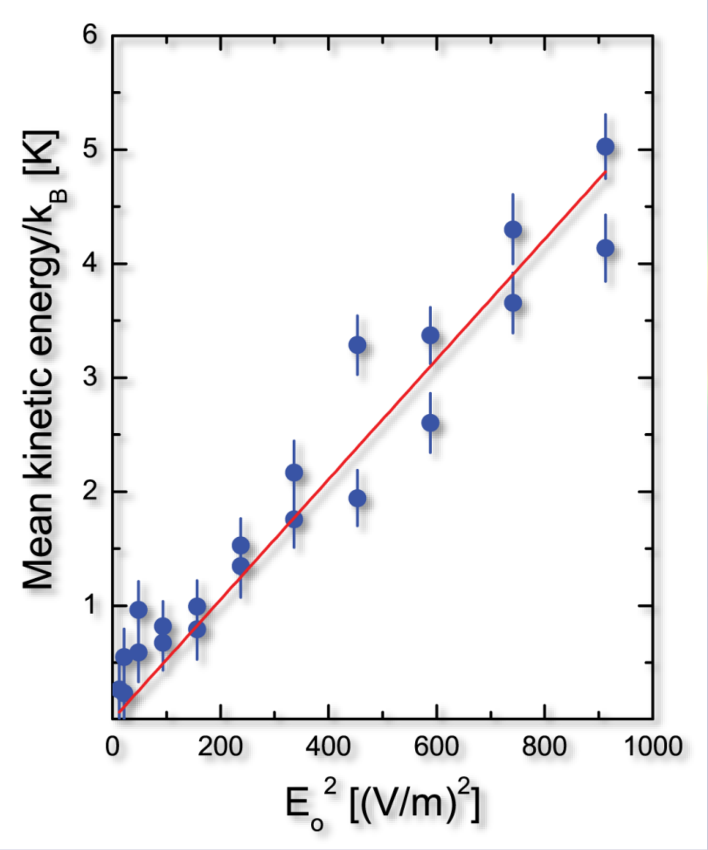

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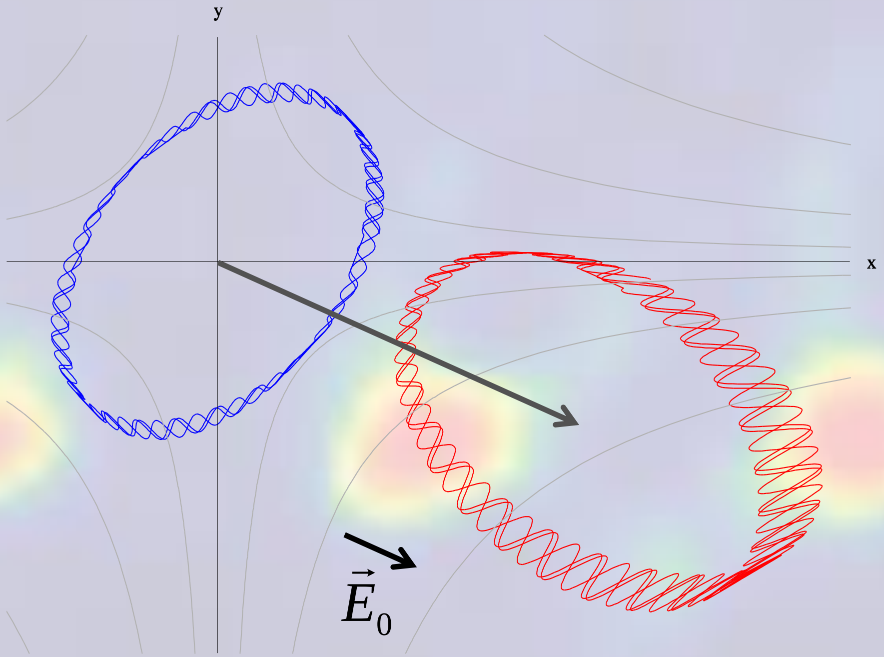

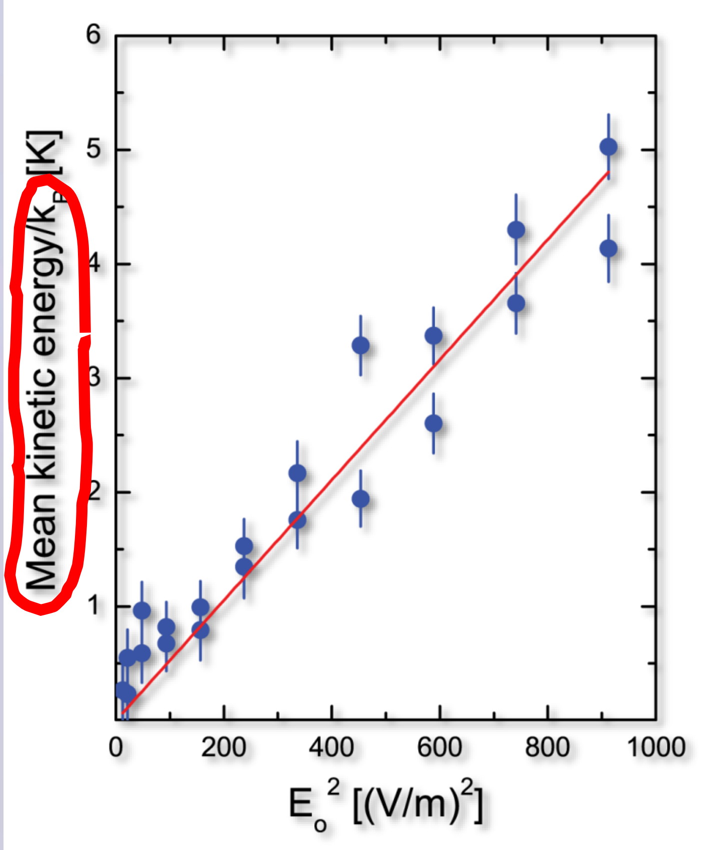

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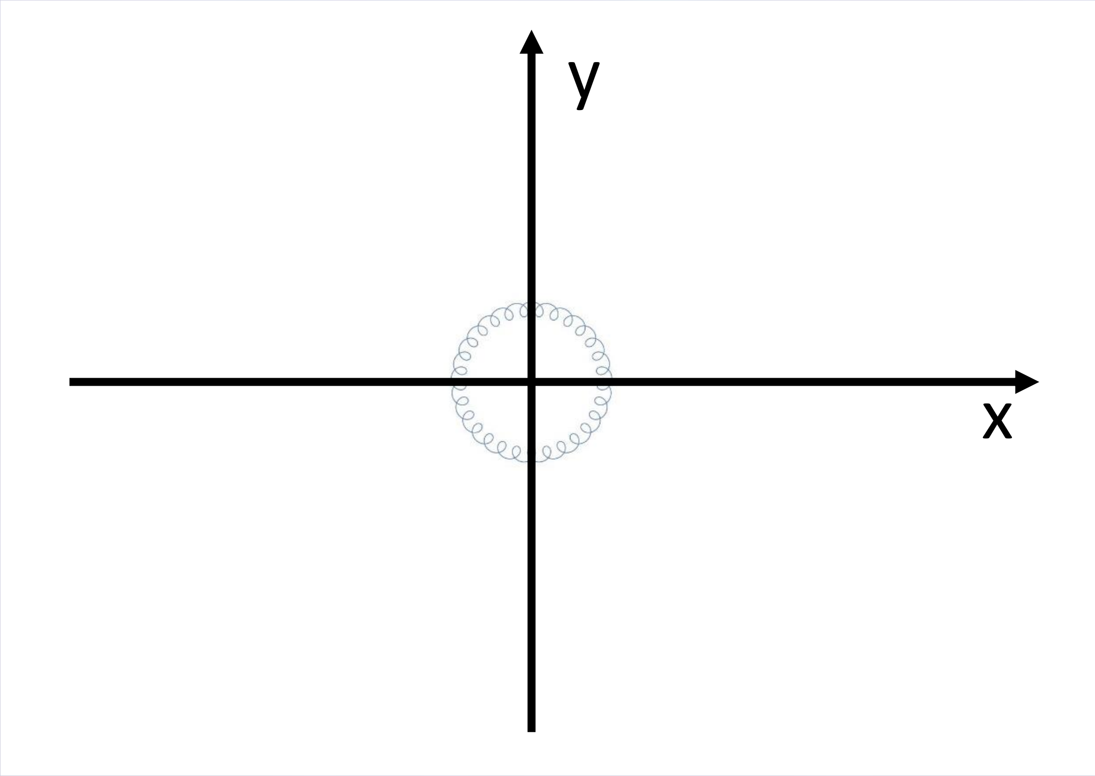
Distribution energy

The energy distribution of an ion in a buffer gas is *not* a thermal distribution



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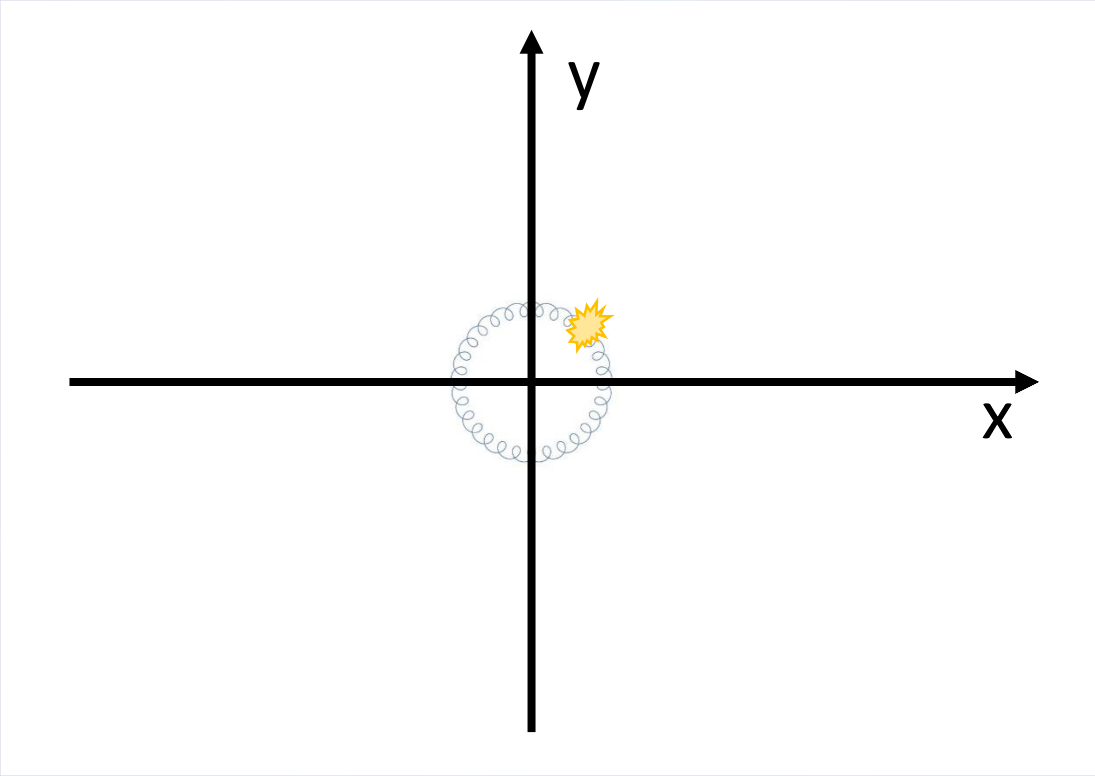

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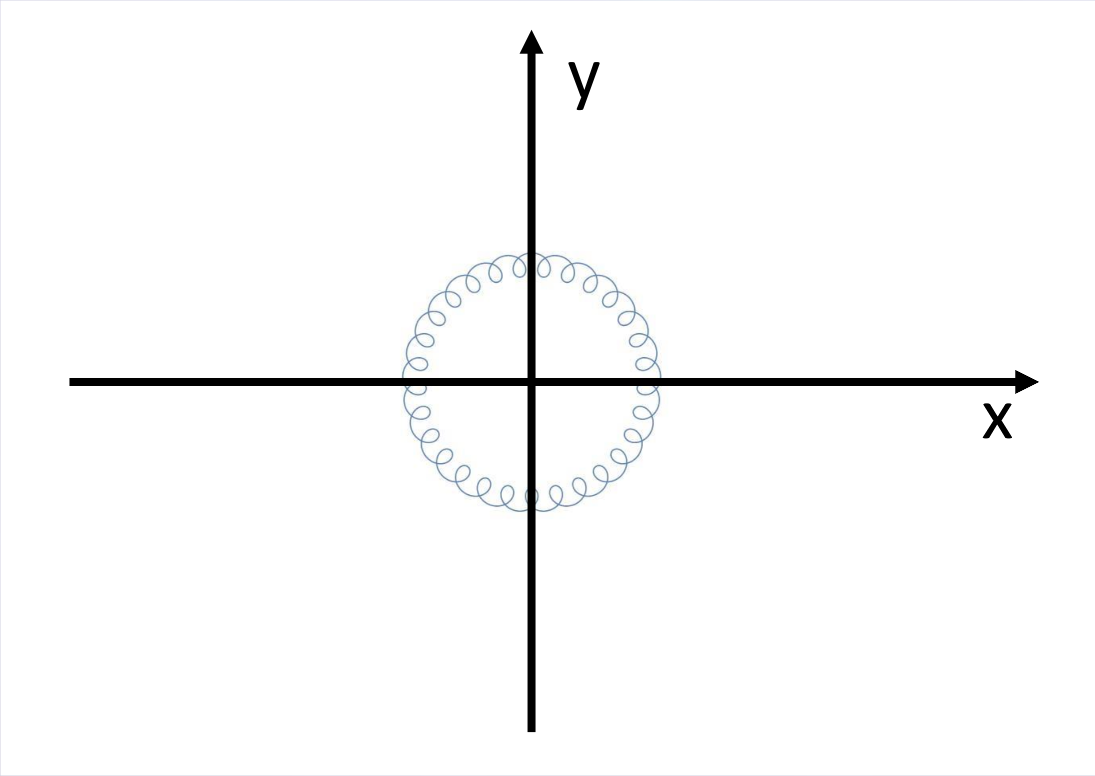

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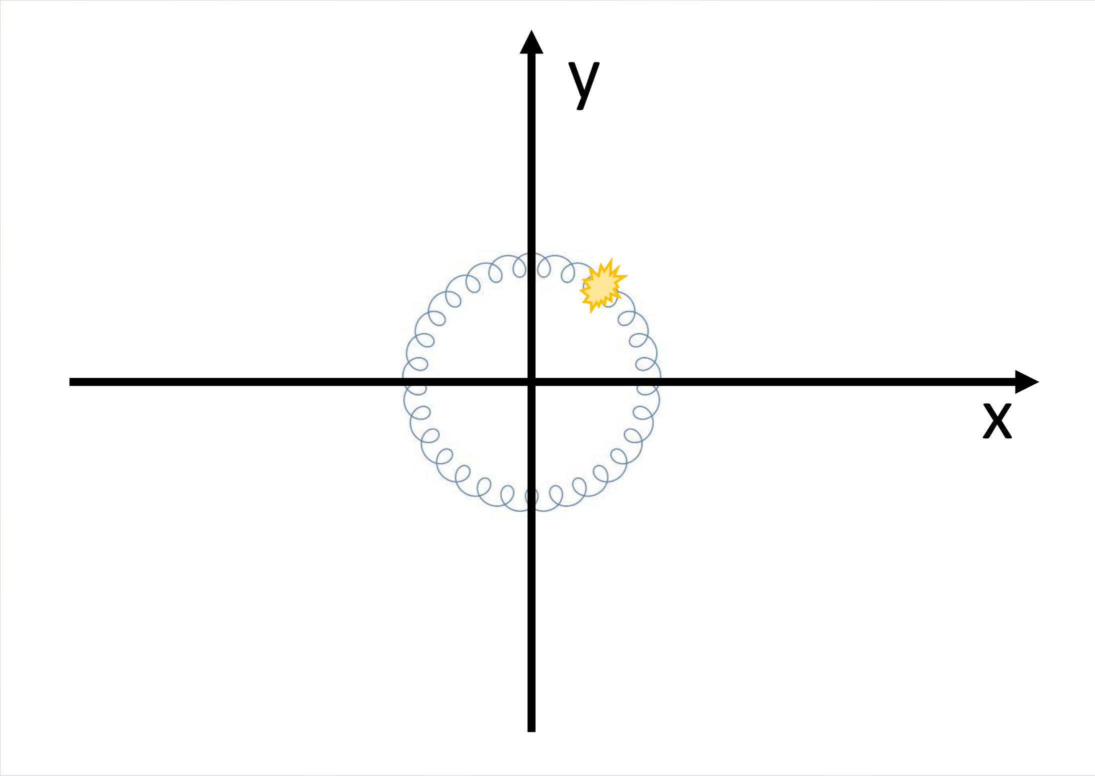

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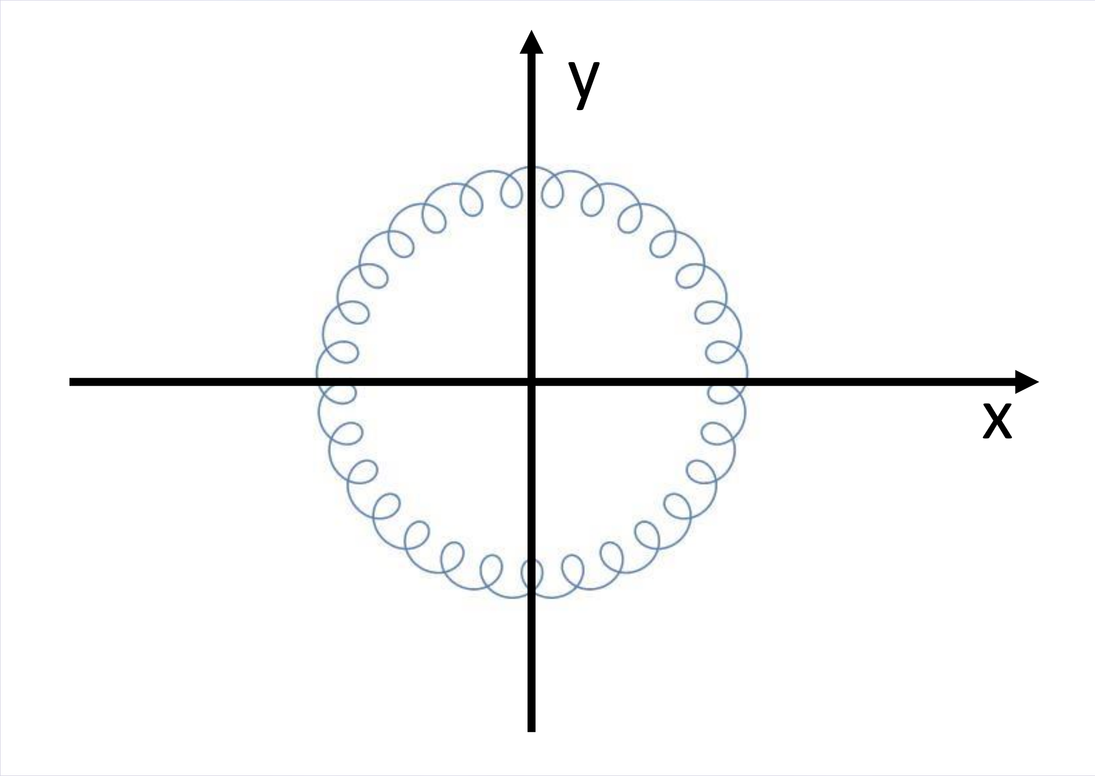

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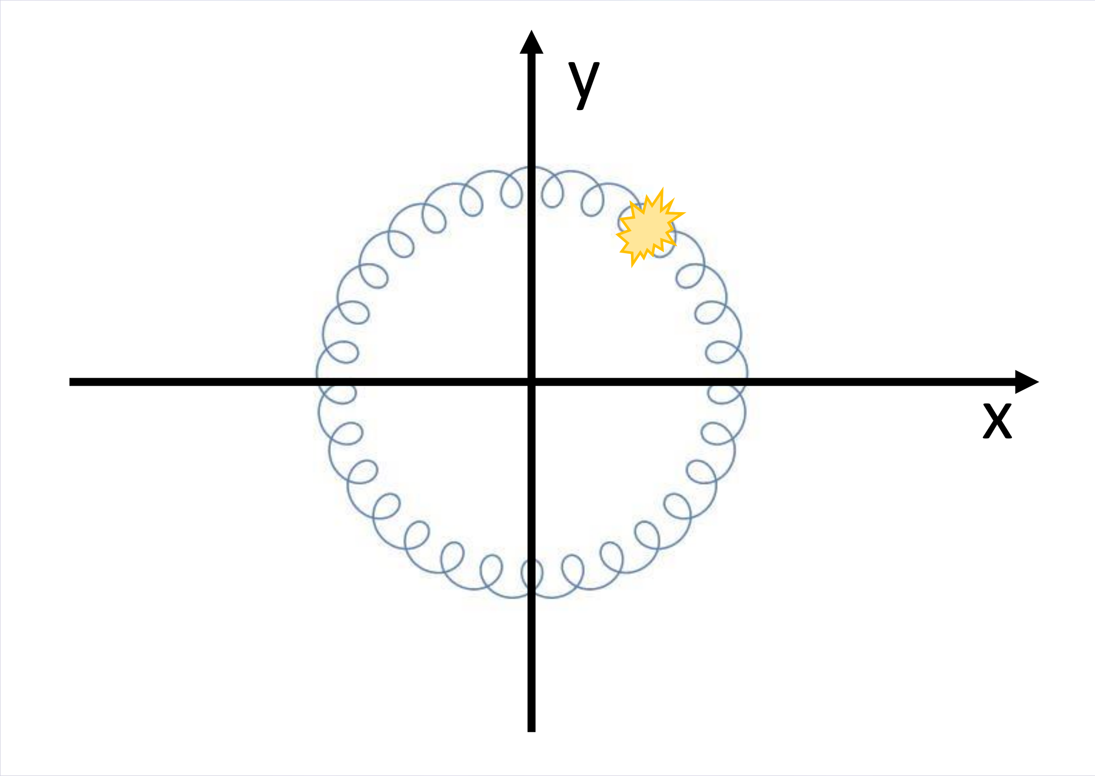

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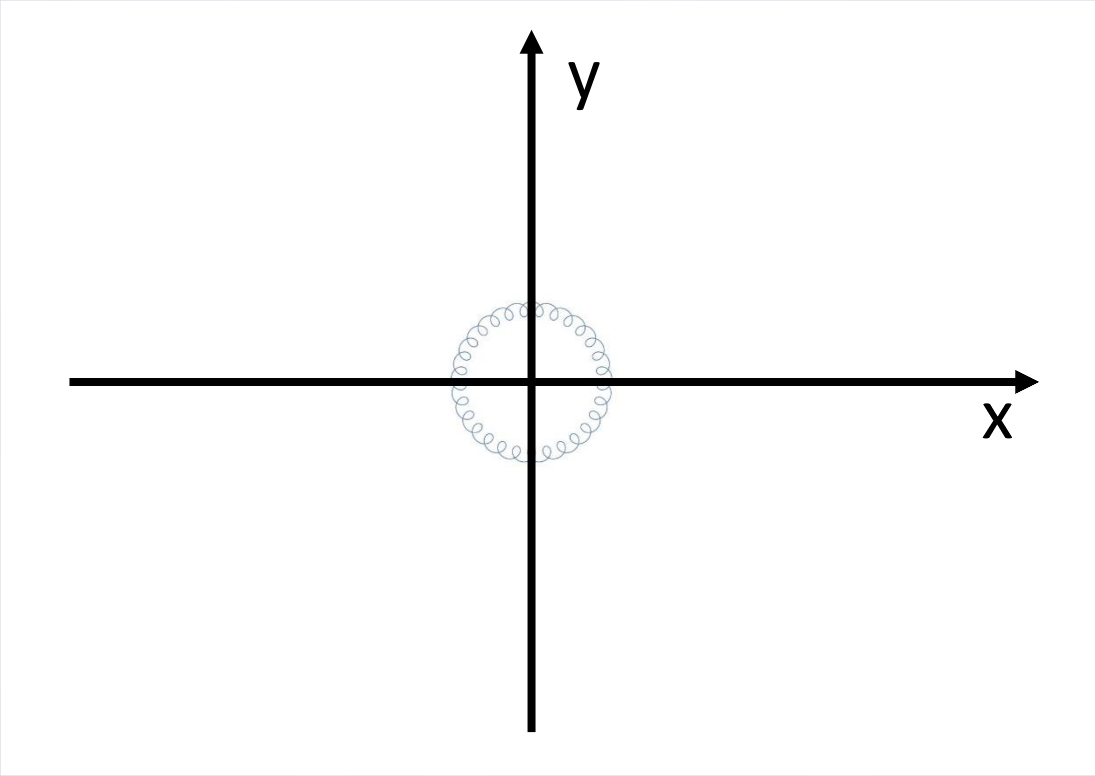

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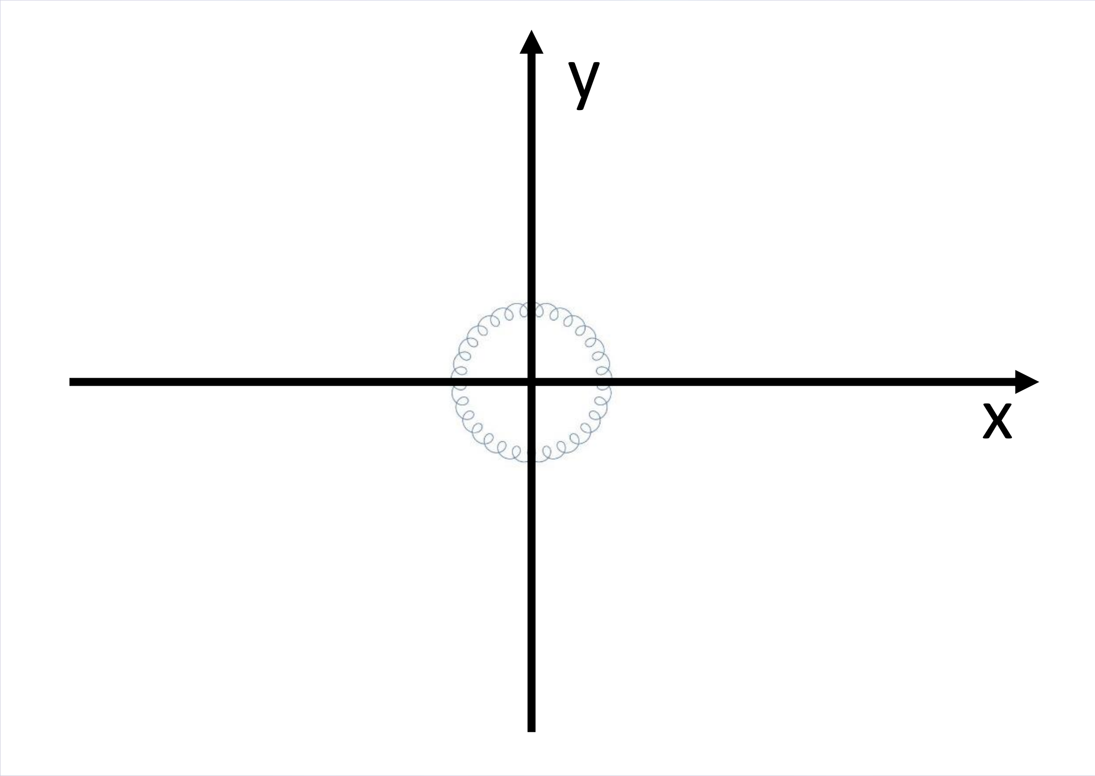

It's like playing Texas hold'em only with all-ins!

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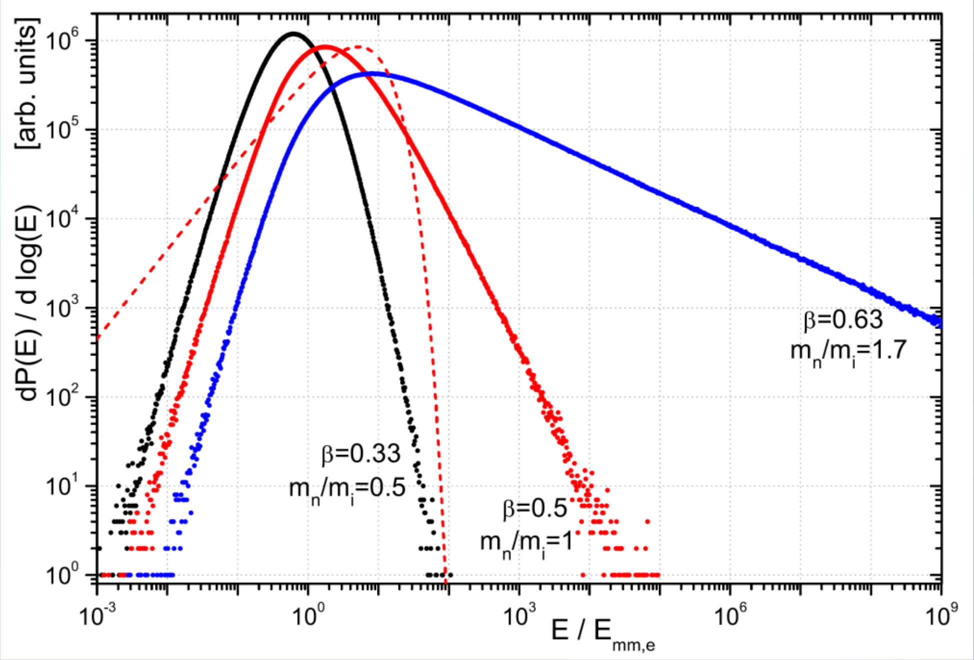

C. Zipkes et al., New J. Phys. 2011

It's a power law distribution.. This is complex physics!

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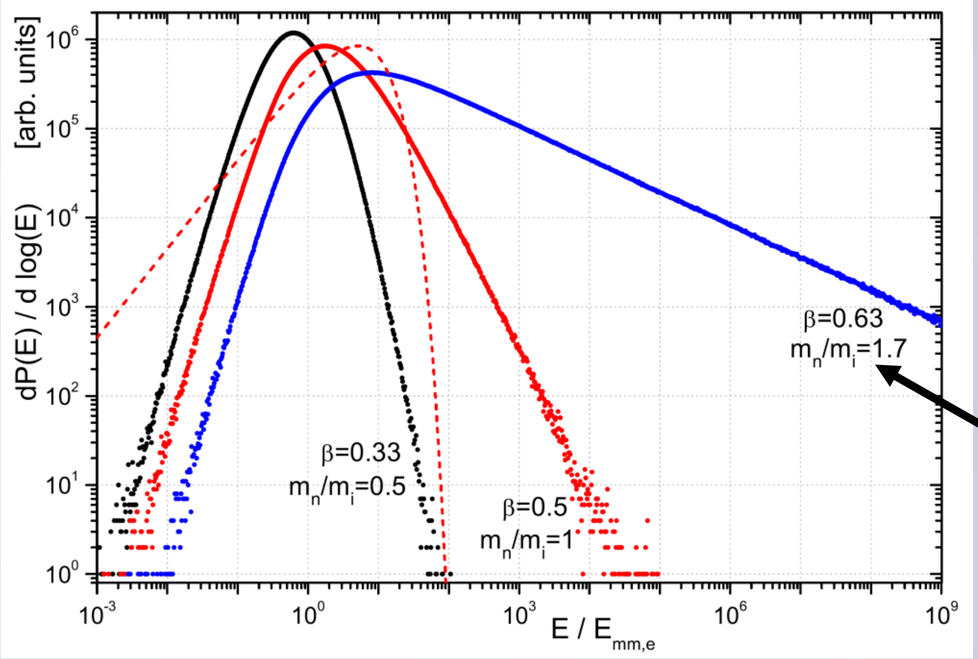

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Ion trapping feasible only for “light” atoms and “heavy” ions

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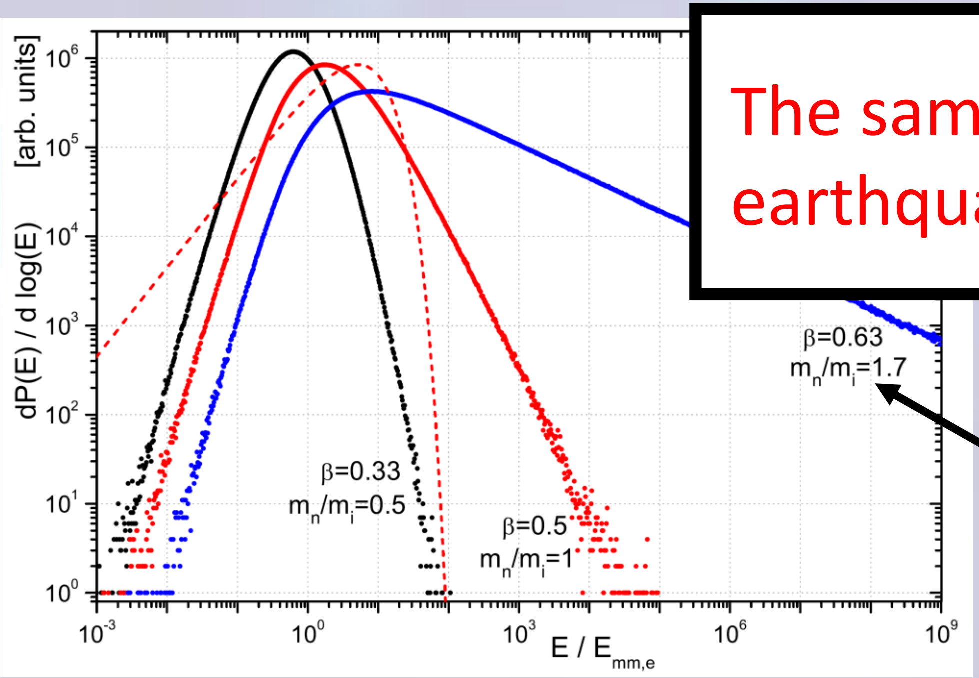

C. Zipkes et al., New J. Phys. 2011

The same energy distribution of earthquakes and cosmic rays!

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Outline

A brief intro of atom-ion collisions

Hybrid atom-ion experiments – state-of-the-art

Hybrid atom-ion experiments: perspectives

Atom-ion systems for improving ion clocks

Open problems

Still many issues:

- Can we enter a full quantum regime (few partial waves) in atom-ion interactions?

- Can we reach a coherent evolution of the ion-neutral mixture?

- Can we control (in a more deterministic way) inelastic processes?

- ……

Reducing micromotion

Atoms are an exceptional tool to measure micromotion!

Method	$\Delta\varepsilon$ (V/m)
Photon-correlation spectroscopy	0.9
Micromotional sideband spectroscopy	7 / 1 / 0.4
Ion-cavity emmission spectroscopy	1.8
Parametric excitation of secular motion	6 / 0.4
Neutral atom loss	0.02
Monitor displacement	$\leq$ 11.8
Trajectory analysis	0.09

Gloger et al. PRA **92**, 043421 (2015)

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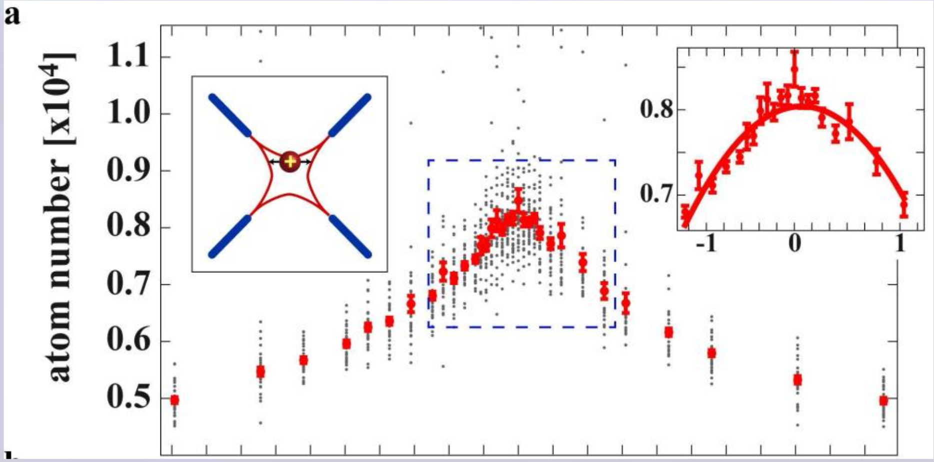

Haerter et al. APL **102**, 221115 (2013)

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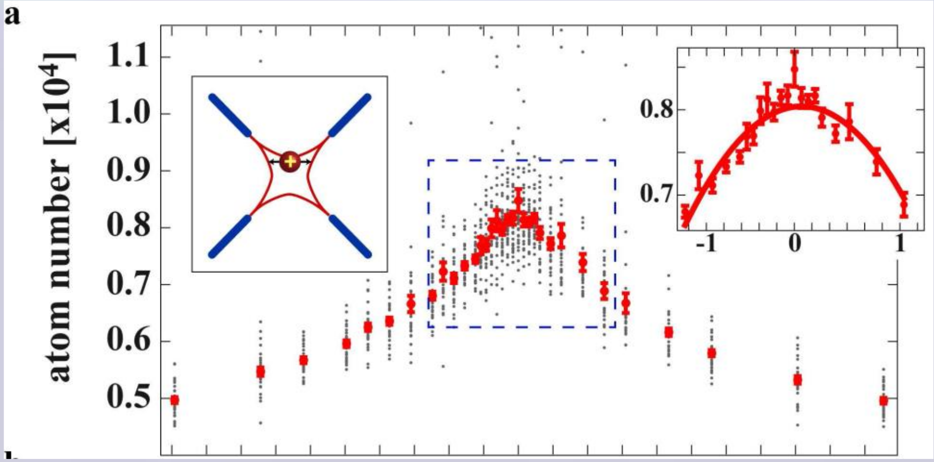
Gloger et al. PRA **92**, 043421 (2015)

<u>Is that sufficient?</u>



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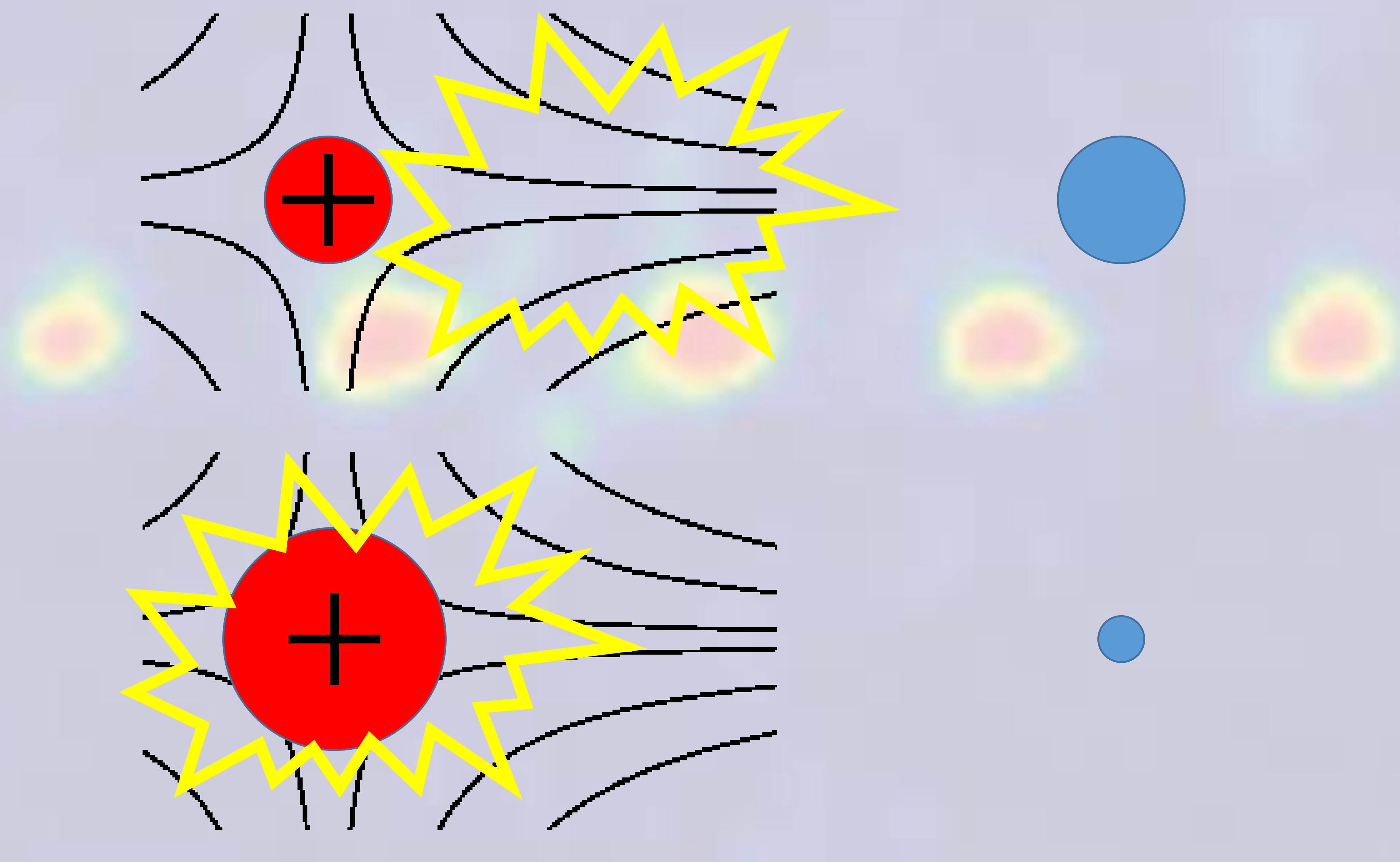
Reducing micromotion



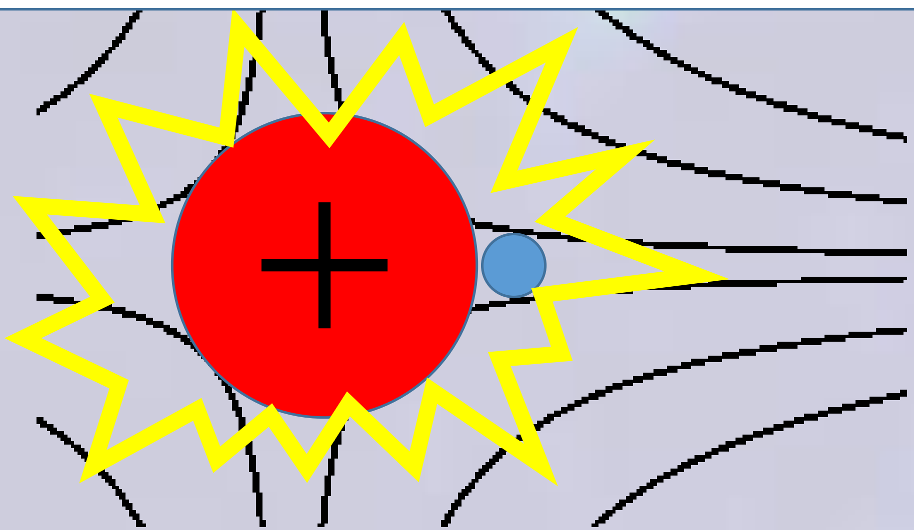
Reducing micromotion

What mass ratio to reach s-wave scattering?

Cetina et al. PRL **109**, 253201 (2012) → **Yb^+ - Li**

Krych et al. PRA **91**, 023430 (2015) → **Yb^+ - Li**

→ **Ba^+ - Li**



Static ion trapping

Paul trap → dipolar trap

Optical trapping of an ion

Ch. Schneider, M. Enderlein, T. Huber and T. Schaetz*

First demonstrated in 2010

Static ion trapping

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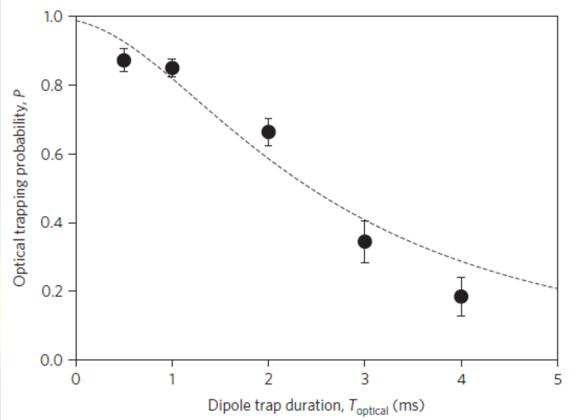
PROS:

Intrinsically without micromotion

No limitations in mass ratio

Static ion trapping

Paul trap → dipolar trap



Optical trapping of an ion

Ch. Schneider, M. Enderlein, T. Huber and T. Schaetz*

First demonstrated in 2010

CONS:

SHORT lifetime because of difficulties in laser cooling

BUT atoms can provide cooling!

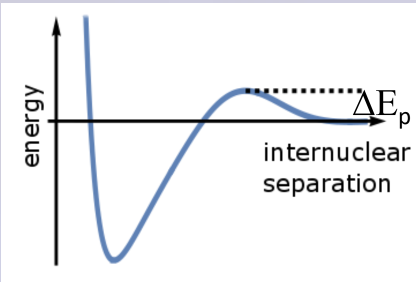
PROS:

Intrinsically without micromotion

No limitations in mass ratio

Control of ion-neutral interactions

Elastic collisions



S-wave regime - collisions described by a single phase shift: scattering length

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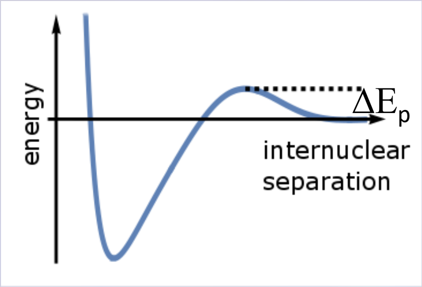

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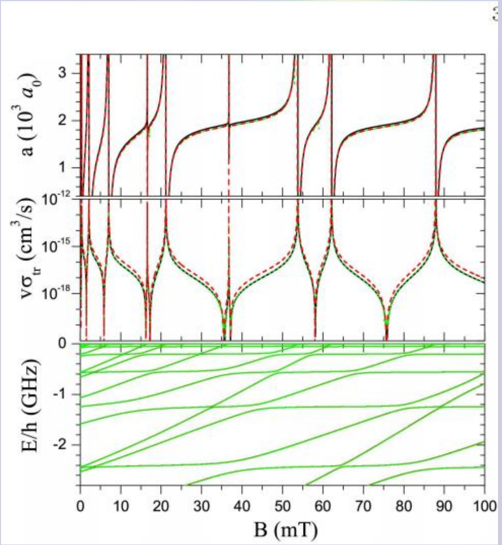
Observe Feshbach resonances to control ion-neutral interactions



Z. Idziaszek et al. PRA 2009

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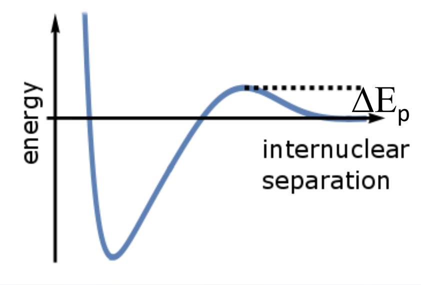

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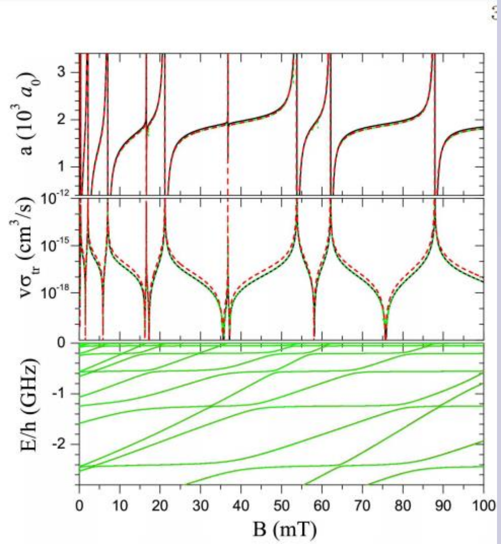

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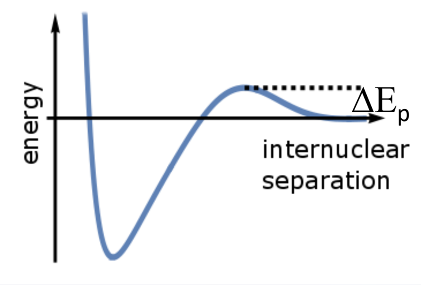
Some advice:

- Use atom-ion pair with "tall" (>10uK) p-wave barrier

Control of ion-neutral interactions

Elastic collisions



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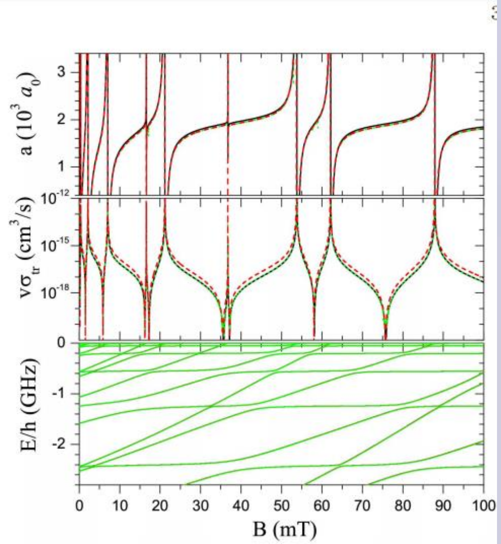

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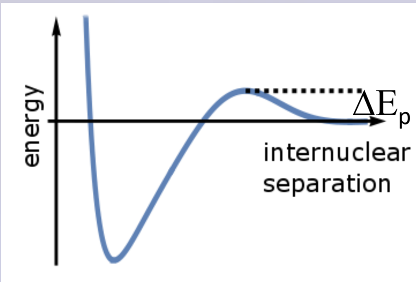
Elastic collisions



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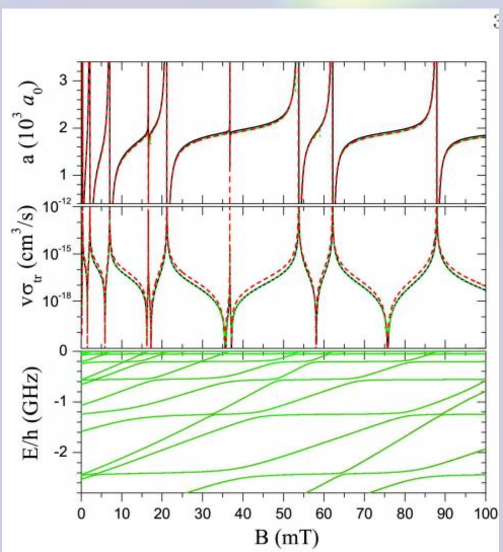

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- Beware of possible devils entering from the back door!

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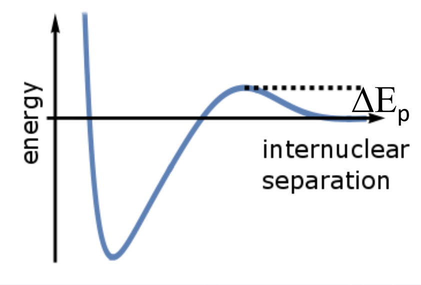

S-wave regime - collisions described by a single phase shift: scattering length

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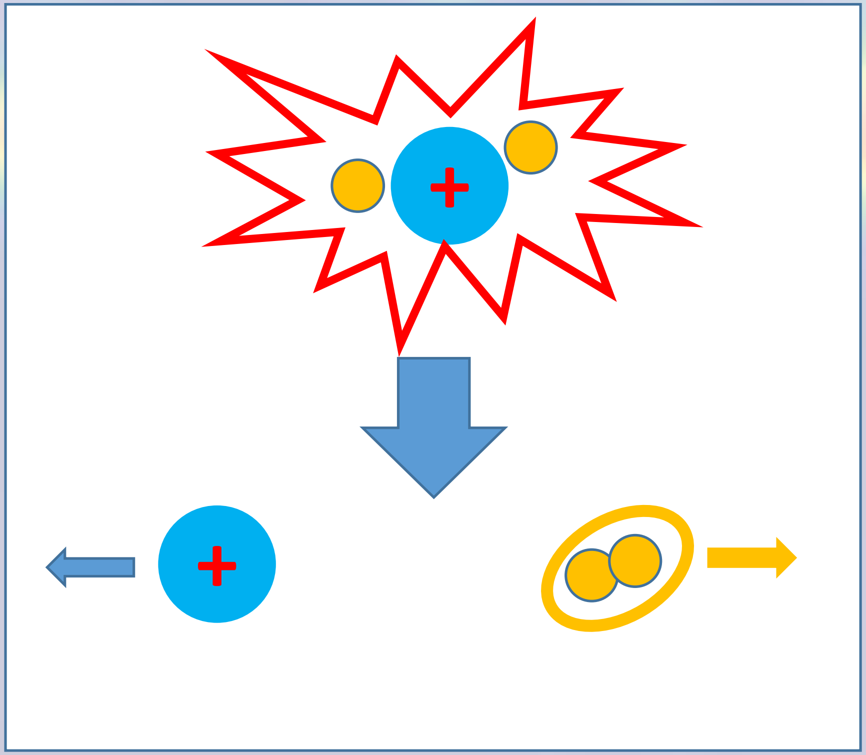

See works by Denschlag group

Some advice:

- Use atom-ion pair with “tall” (>10uK) p-wave barrier
- Use atom-ion pair with a sufficiently large mass ratio OR optical trap for the ions
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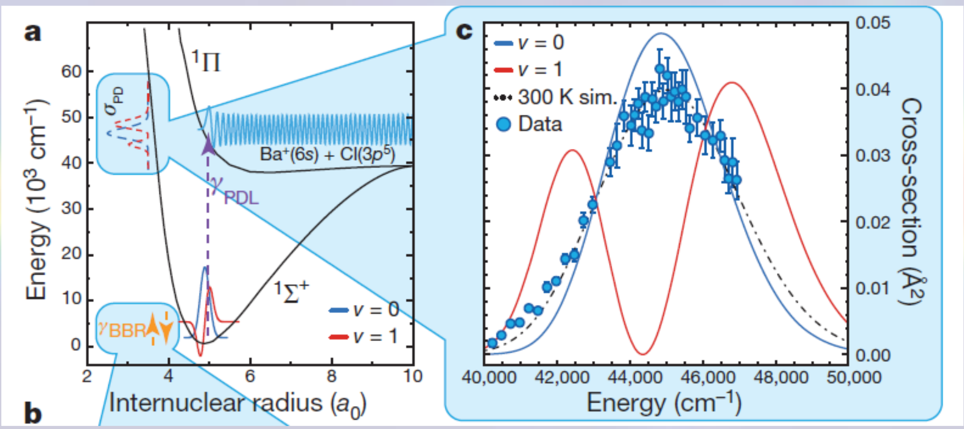
Control of ion-neutral interactions

Inelastic collisions

Control the formation of molecules and achieve sympathetic cooling



W.G. Rellergert et al. Nature 2013

Photodissociation thermometry of a BaCl+ ions immersed in a Ca MOT

Also Heidelberg, Basel, Bangalore, …

More pieces of advice:

- Use atom-ion pairs for which you know you get a molecule
- Alternatively: begin from molecules!

Outline

A brief intro of atom-ion collisions

Hybrid atom-ion experiments – state-of-the-art

Hybrid atom-ion experiments: perspectives

Atom-ion systems for improving ion clocks

Effects of collisions on a clock

Effects: Decoherence (Langevin, soft collisions)
Quench (Langevin collisions)

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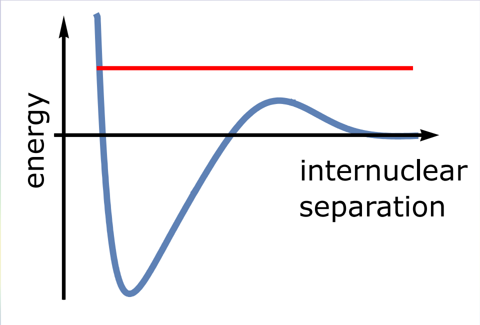
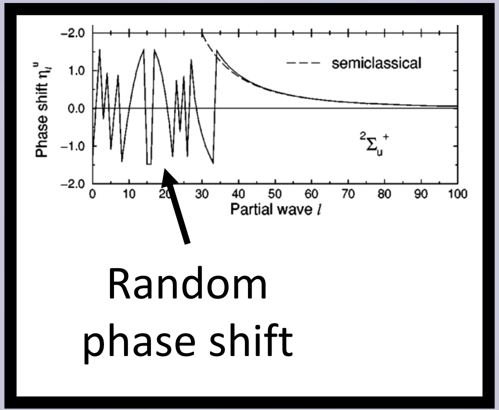


Langevin: phase shift during clock operation



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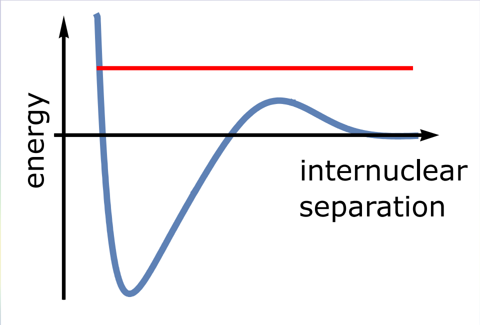

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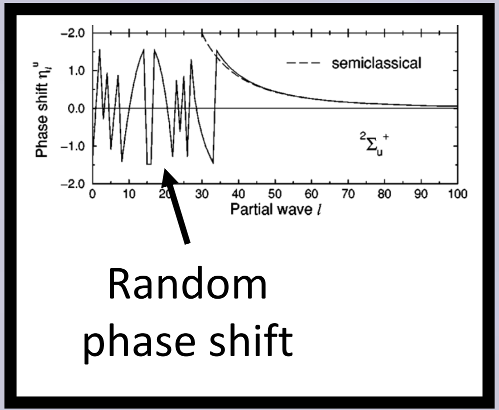

Model (Rosenband et al. Science 2008):

1. assume pi/2 phase shift at each Langevin collision
2. Integrate over optical Bloch equation

→ Average frequency shift:

$$\Delta\nu_{coll}=0.15\,\gamma_L$$

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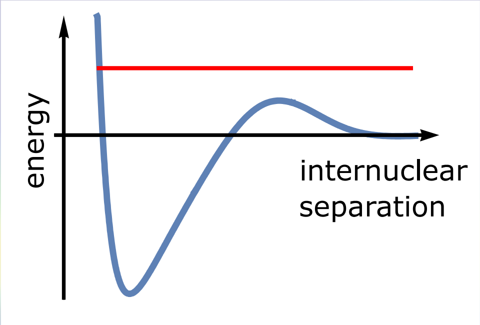

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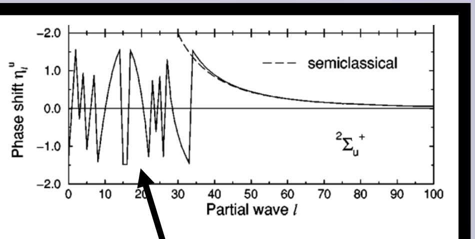


Random phase shift

Model (Rosenband et al. Science 2008):

1. assume pi/2 phase shift at each Langevin collision
2. Integrate over optical Bloch equation

→ Average frequency shift:

estimated shift $\Delta\nu_{coll}=0.15\ \gamma_L$

uncertainty

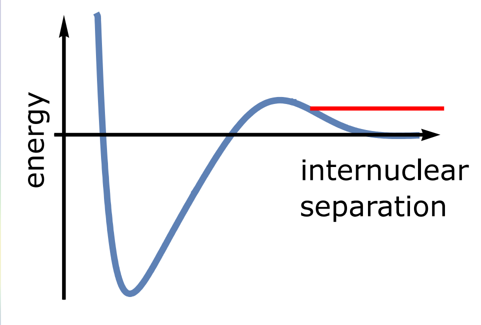
Al^+ : 0.5 x 10^{-18}

Sr^+ : 2 x 10^{-18}

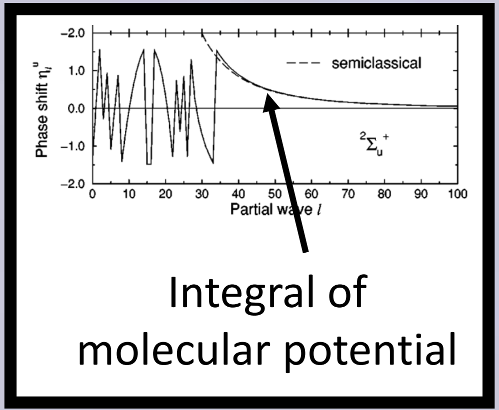
More refined model:
Vutha et al. PRA 2017

Effects of collisions on a clock

Effects: Decoherence (Langevin, soft collisions)
Quench (Langevin collisions)



Soft collisions:
differential phase



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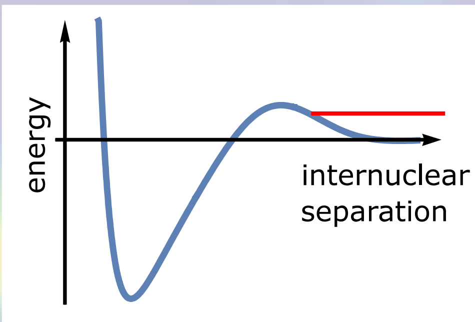

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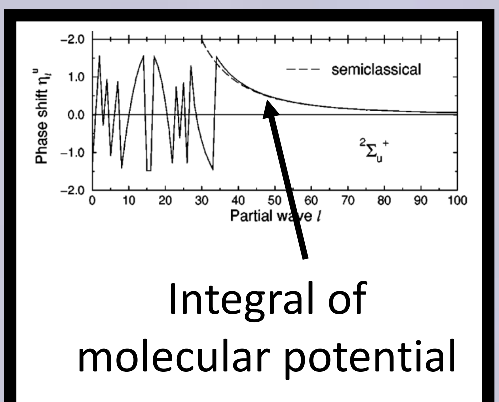
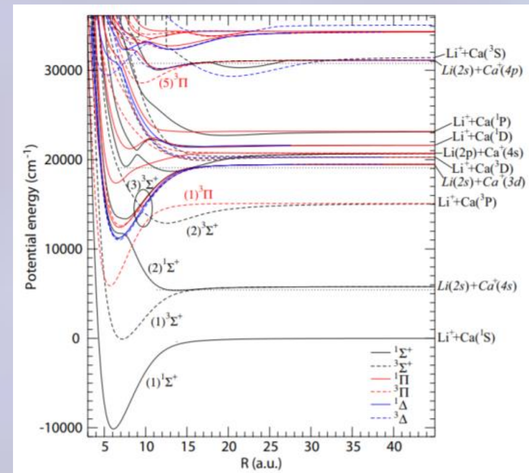


Complicated structure!



Li-Ca^+ (Mukaiyama, Dulieu)

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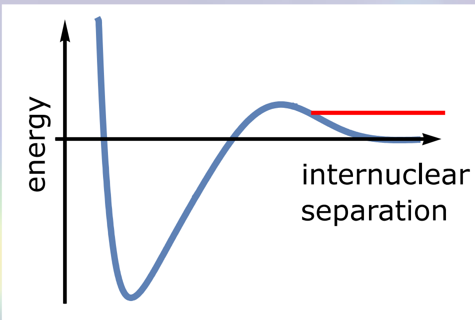

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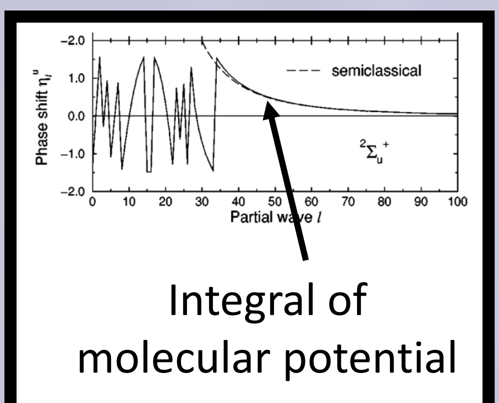

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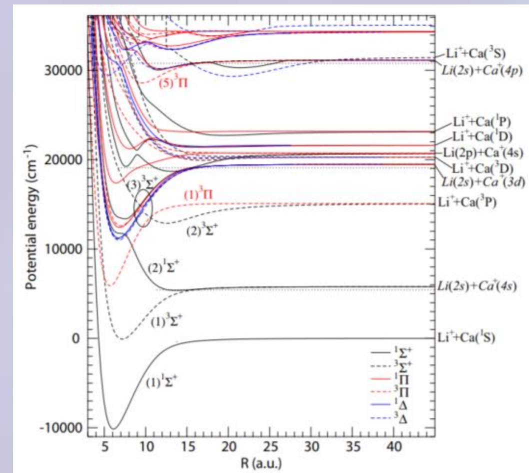

Li-Ca^+ (Mukaiyama, Dulieu)

Model (Rosenband et al. Science 2008):

Consider the induced dipole on the atom as a fluctuating E-field

estimated shift uncertainty

$Al^+ < 1 \times 10^{-19}$

Effects of collisions on a clock

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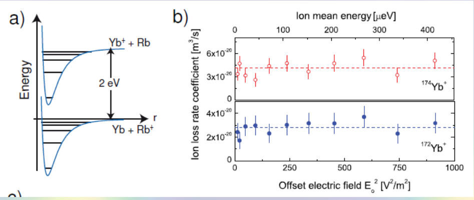
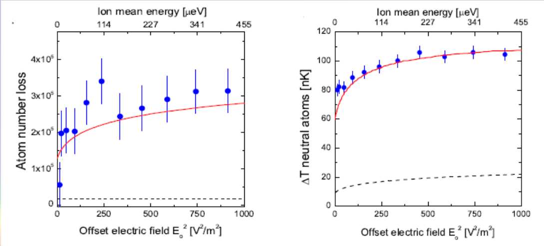


Precise detection of Langevin and soft collisions rates



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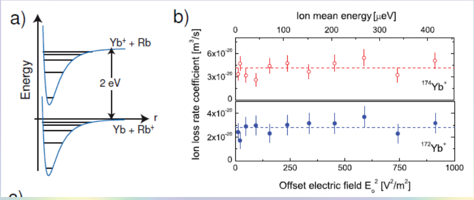

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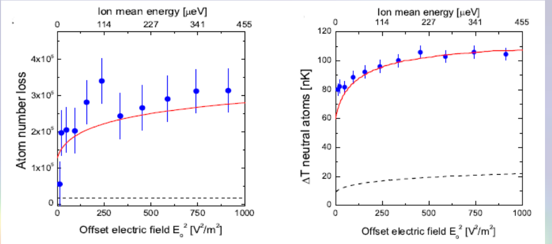

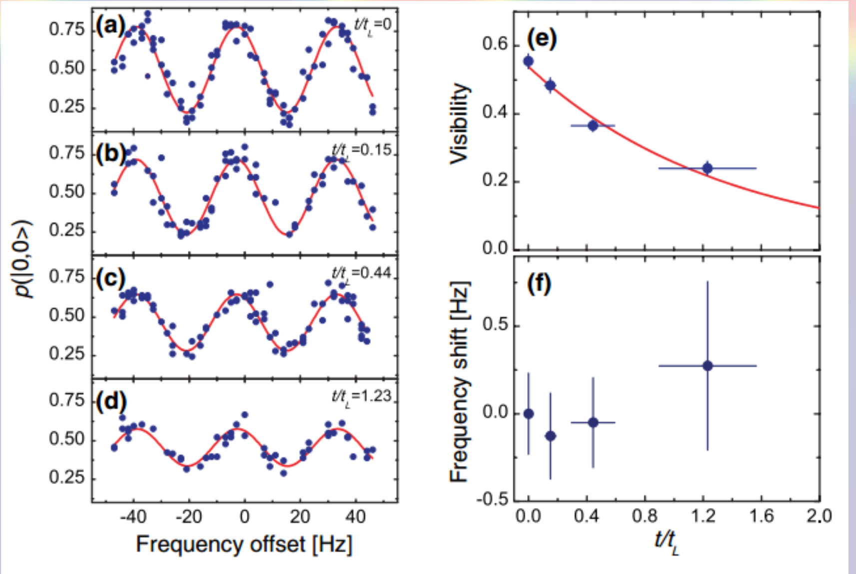

"knobs" that we can use:

- Density of the neutrals
- Collisional energy
- Optical transitions
- Internal states of the ions

L. Ratschbacher, et al. PRL 110, 160402 (2012)
Similar on Sr^+-Rb measurements at Weizmann

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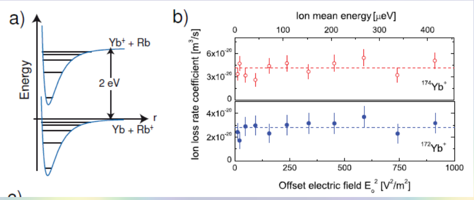

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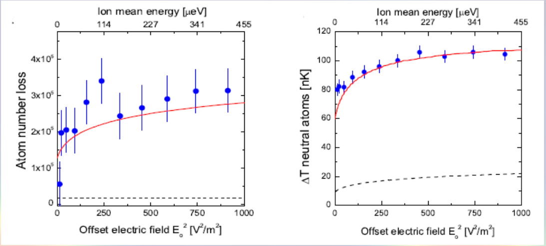

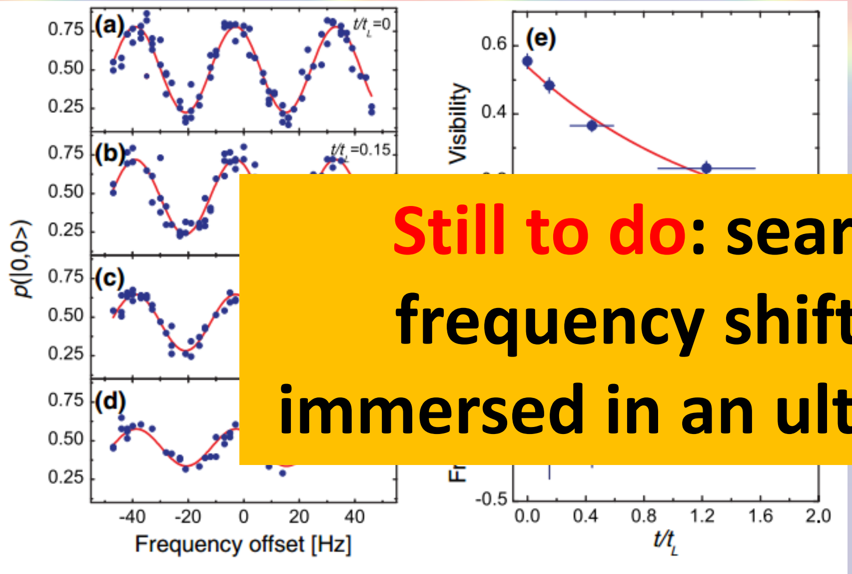

Still to do: search for optical frequency shifts with an ion immersed in an ultracold buffer gas

"knobs" that we can use:

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- ...rgy
- ...ons
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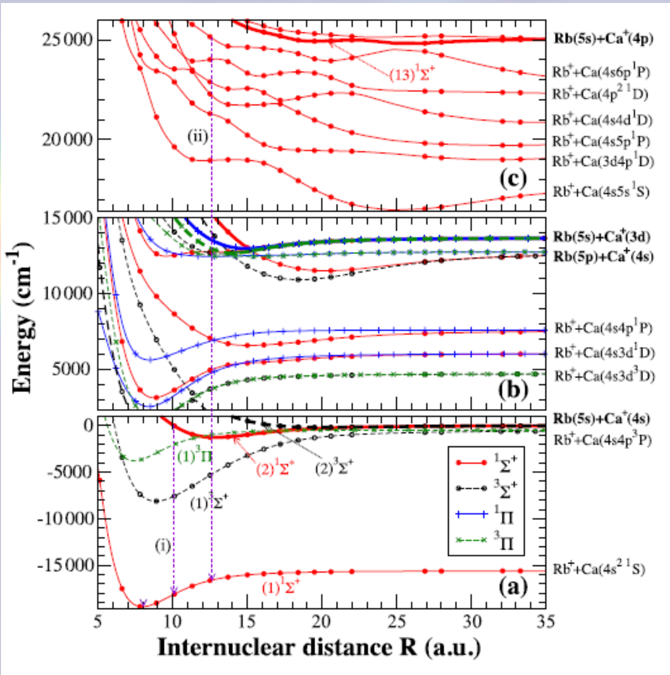

F.H.J. Hall et al. PRL **107**, 243202 (2011)

Are collisionally-created molecular ions a common phenomena?

NO: Yb^+-Rb, Ba^+-Rb, Sr^+-Rb, Yb^+-Li, …

YES: Ca^+-Rb, many hydrates (like YbH^+)

→ A problem in HCI, since C_4 depends *quadratically* on the charge

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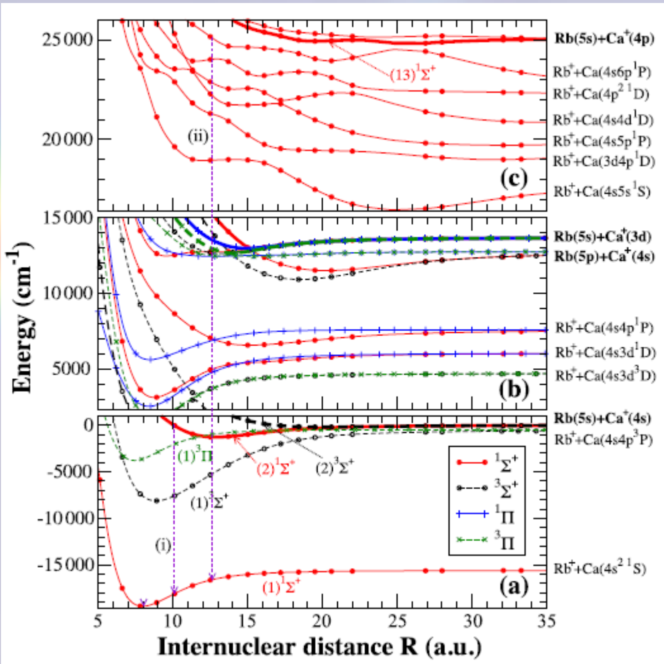

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Questions: How big can Coulomb crystals be before being too much affected by these inelastic processes?
Can we photodissociate these molecules and recycle the ion?

Conclusions

- Neutral-ion interaction's main term is a long-range R-4 potential
- Collisions can be of two types: Langevin and soft collisions
- Langevin collisions' scattering rate is independent from the collisional energy, while soft collisions' scattering rate is not
- Hybrid atom-ion experiments have dramatically advanced our understanding of neutral-ion collisions
- In hybrid experiments we can control the density, collisional energy, the internal state of the colliding particles, the occurrence of chemical reactions
- Applications to ion clocks: searching for frequency shifts and for procedures to "recycle" an ion undergoing a chemical reaction

The group and funds

Elia Perego

Amelia Detti

Lucia Duca

Massimo Inguscio

PhD and postdoc opportunities!

www.ultracoldplus.eu

quantumgases.lens.unifi.it

Funds:

PlusOne

Ultracoldplus

CC4C

UltraCrystals

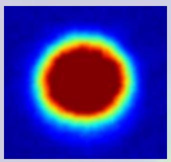
Our experiment

Our experimental setup: a novel atom-ion mixture

Our experiment

Our experimental setup: **a novel atom-ion mixture**

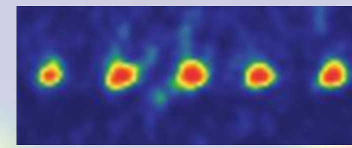
Ultracold gas



Lithium

(bosons, fermions)

Trapped ions



Barium

(several isotopes)

Li-Ba$^+$

absolute ground state

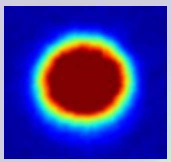
NO CHARGE-EXCHANGE

Reactive collisions only "on demand", i.e. only by placing the ions or the atoms in a different internal state

Our experiment

Our experimental setup: a novel atom-ion mixture

Ultracold gas



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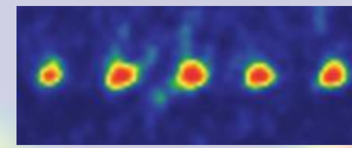


Barium

(several isotopes)

NO CHARGE-EXCHANGE

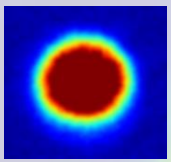
NO 3-BODY RECOMBINATION

By using a spin-polarized Fermi gas, 3-body collisions (in s-wave) are suppressed by Pauli principle → less heating

Our experiment

Our experimental setup: a novel atom-ion mixture

Ultracold gas



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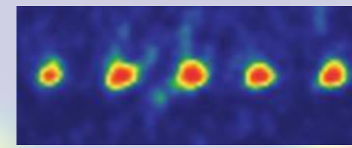

Barium
(several isotopes)

NO CHARGE-EXCHANGE

NO 3-BODY RECOMBINATION

FAVOURABLE FOR COOLING

Large mass ratio + no spin exchange in the ground state (Landé factor of opposite sign)