

Bangalore, ICTS conference on OQS, 18. 7. 2017



ulm university universität
uulm

An ion in a sea of ultracold atoms

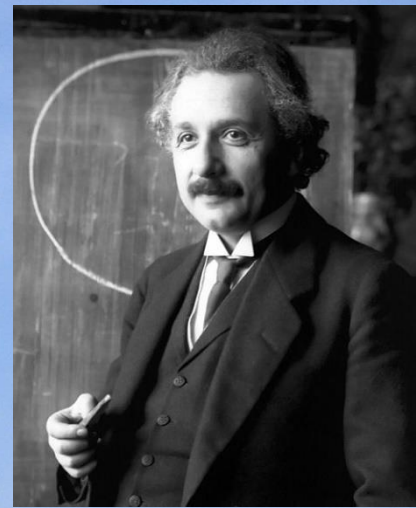
Johannes Hecker Denschlag



Institut für Quantenmaterie
Universität Ulm, Germany

Ulm

Birthplace of
Albert Einstein



ULM

170.000 people

Danube

Albert Einstein

Great Summer
Festival

Caves



The BaRbl Team



Markus Deiss

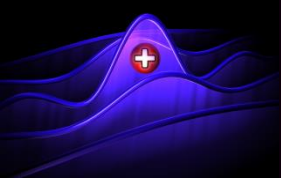
Artjom Krüchow

Johannes Hecker Denschlag

Joschka Wolf

Amir Mahdian

Amir Mohammadi

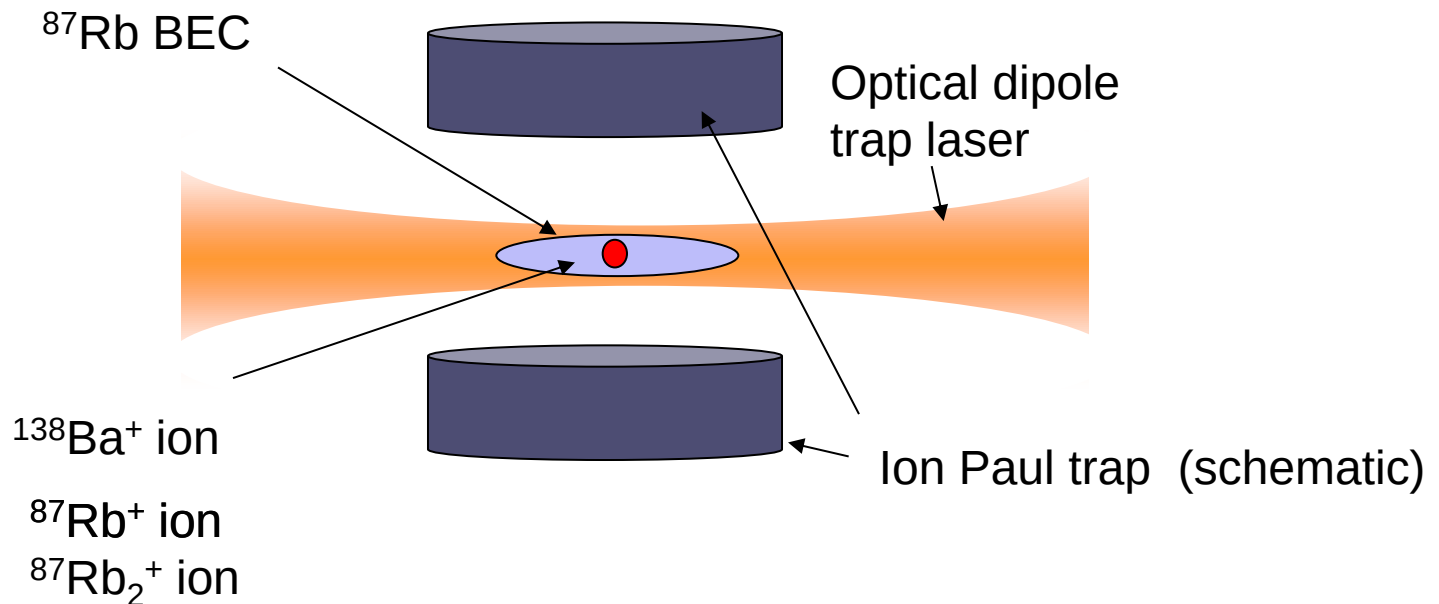


Combining cold atoms and ions: a young field

Trapped Ions

and

Ultracold neutral Atoms

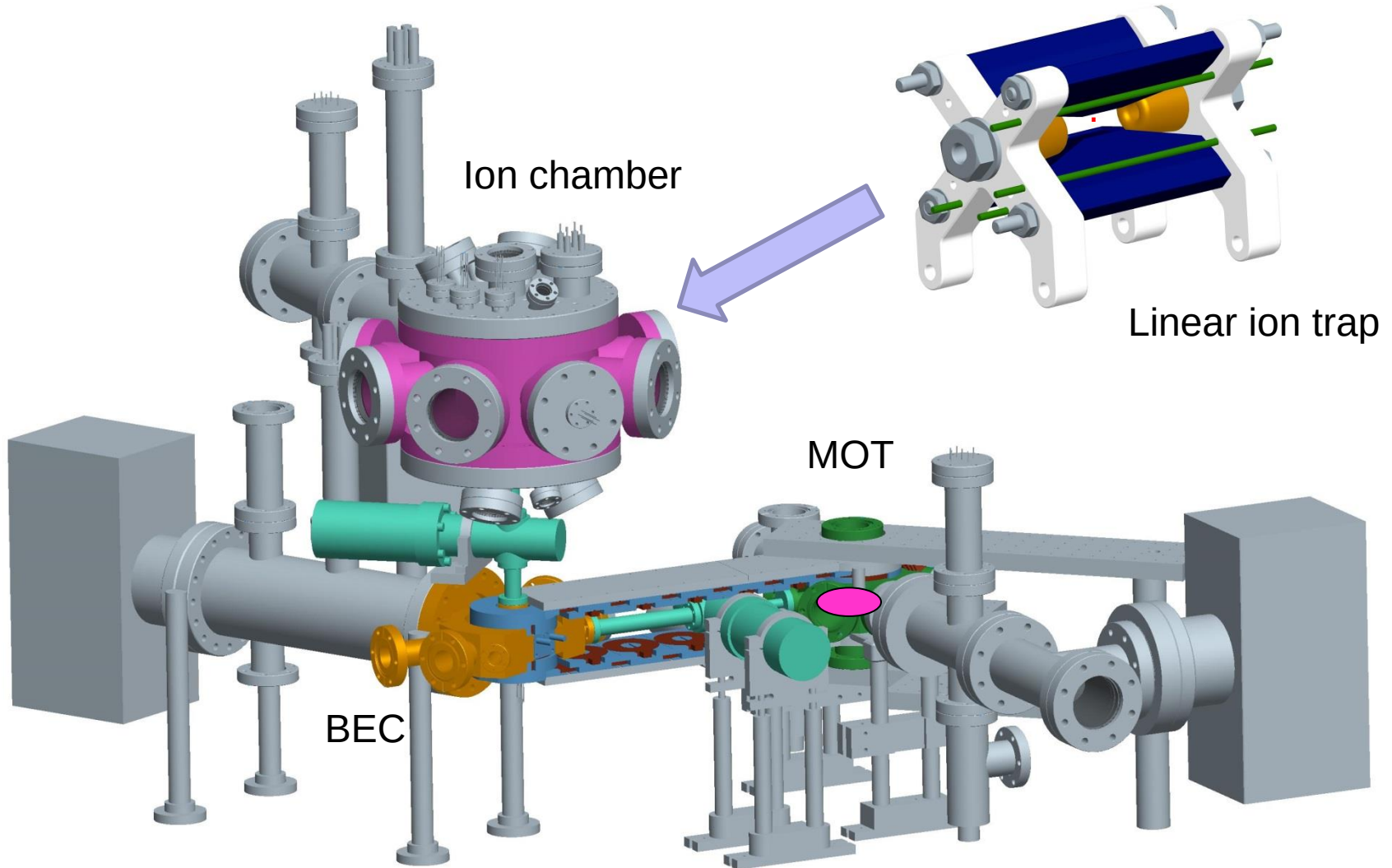


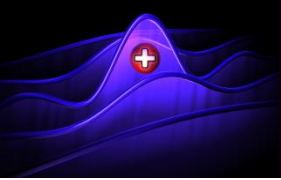
Good compatibility of traps!

$$\begin{aligned}\omega_{\text{ion trap}} &\sim 200 \text{ kHz} \\ \omega_{\text{atom trap}} &\sim 200 \text{ Hz}\end{aligned}$$



Ion in a Sea: Set up in Ulm



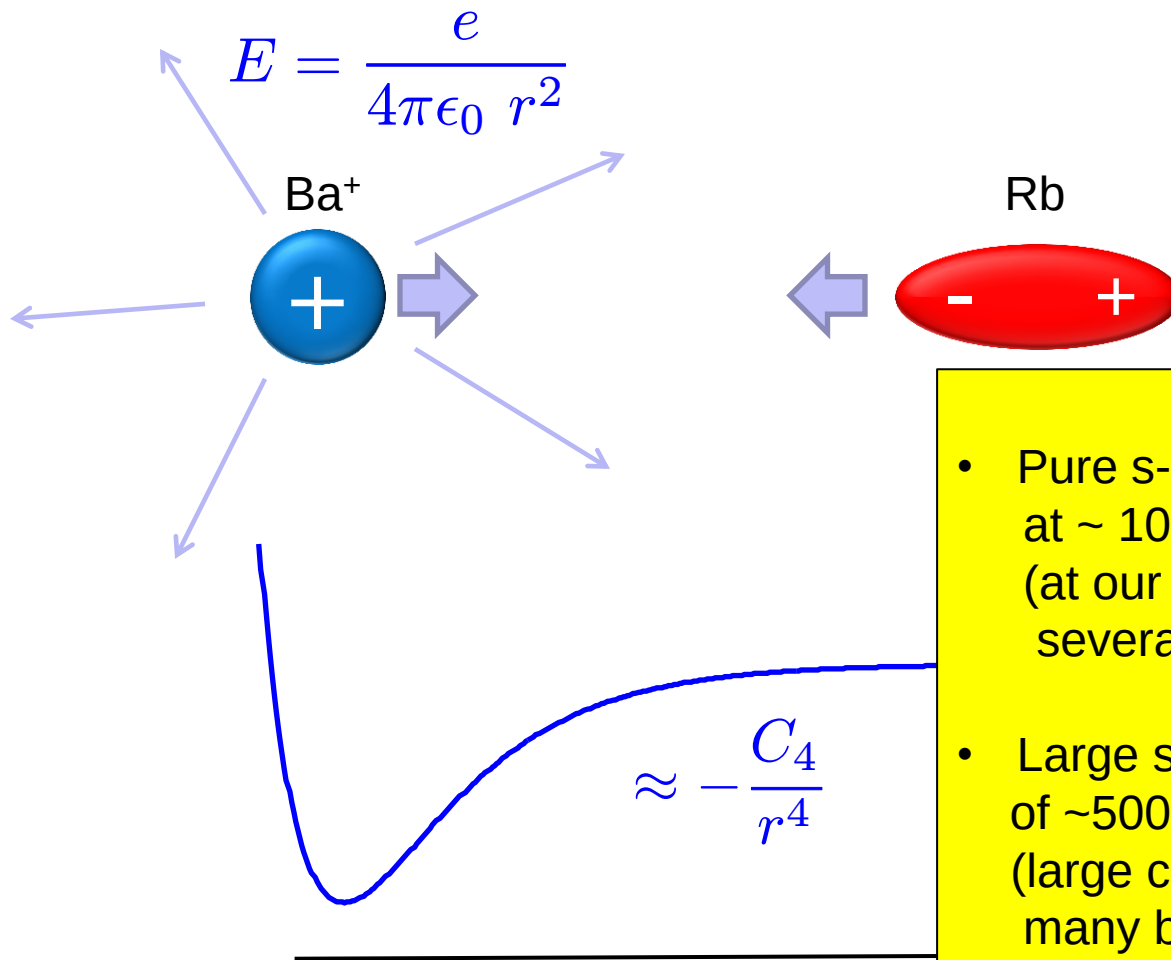


NEW FIELD: Growing community:

Experiment

- a) V. Vuletic/ I. Chuang, MIT
- b) M. Köhl, U Bonn
- c) W. Smith, UCon
- d) S. Rangwala, RRI Bangalore
- e) S. Willitsch, U Basel
- f) T. Softley, U Oxford
- g) E. Hudson, UCLA
- h) T. Mukaiyama, U ElCom, Chofu
- i) R. Ozeri, Weizmann
- j) T. Schätz, U Freiburg
- k) G. Raithel, U Ann Arbor
- l) R. Wester, U Innsbruck
- m) M. Weidemüller, U Heidelberg
- g) F. Schmidt-Kaler, U Mainz
- h) R. Gerritsma, U Amsterdam
- i) C. Sias, LENS
- j) B. Odom, Northwestern U
- k) ...

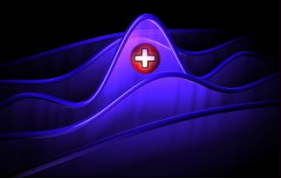
Long range atom – ion interaction



- Pure s- wave regime only at $\sim 100\text{nK}$ (at our energies $0.1\text{-}10\text{ mK}$ several partial waves contribute)
- Large scattering lengths of $\sim 5000\text{ a}_0$ (large cross sections and many body effects at even at moderate densities)

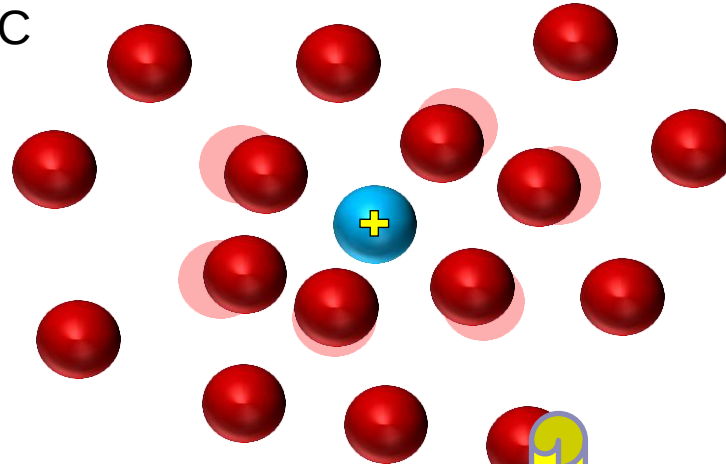
Impurity in a bath

- Polaron/ Few body bound states
- Transport
- Sensing
- Decoherence/ dissipation
- Coupling of various quantum systems/ Entanglement
- Non-thermal distributions

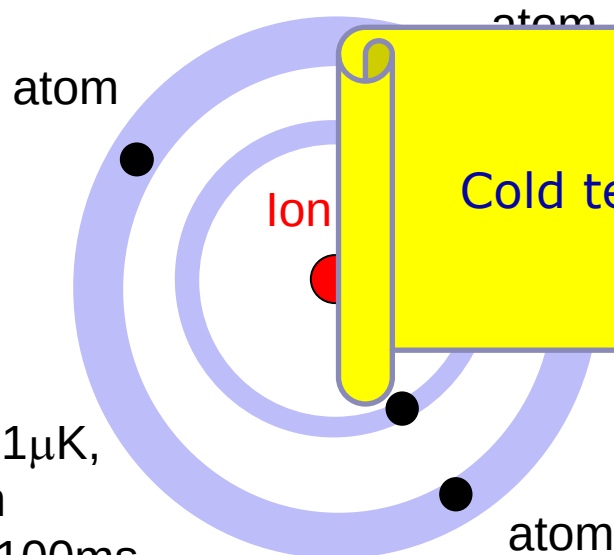


Polaron

- Dressing of ion, corrugation of BEC
- Reach strong-coupling regime
- Self-trapping
- Change of effective mass



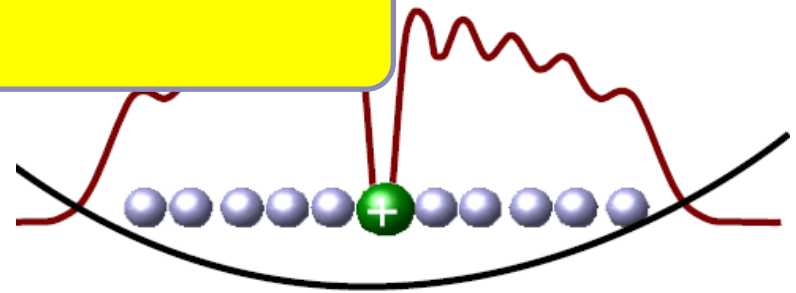
Mesoscopic molecular ion



Cold temperatures needed!

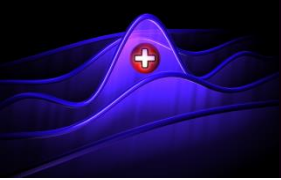
- energy $\sim 1\mu\text{K}$,
- size $1\mu\text{m}$
- Lifetime 100ms

Cote et al., Phys. Rev. Lett. 89, (2002)

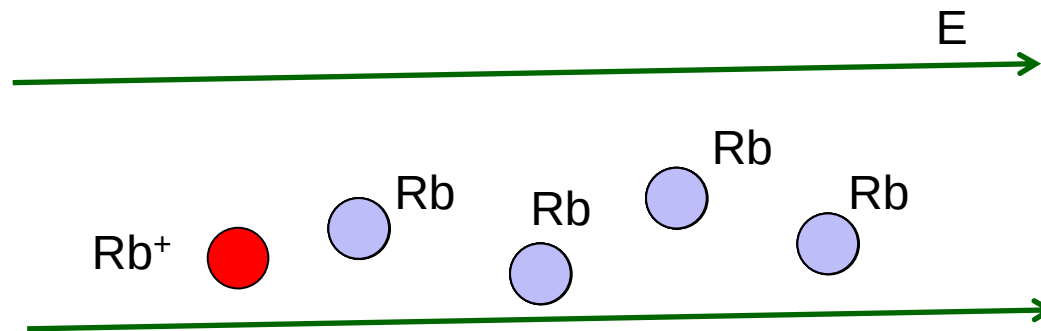


Goold et al, PRA **81**, (2010)

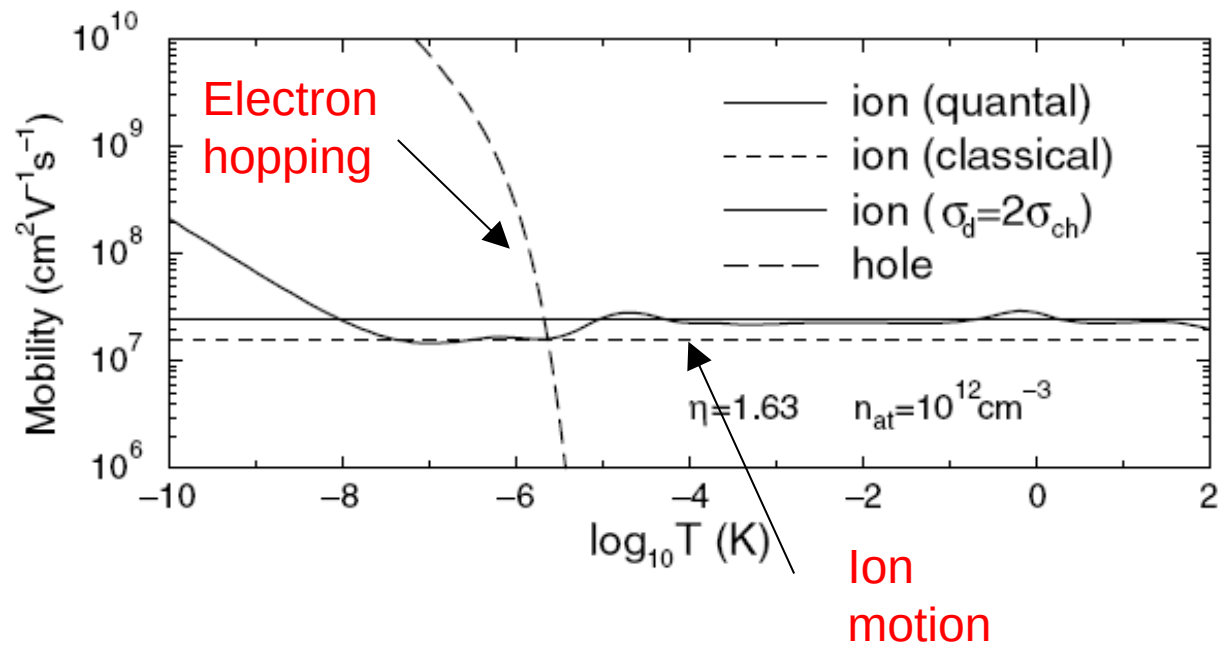
Casteels et al, JLowTempPhys, (2011)

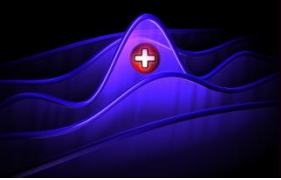


Transport

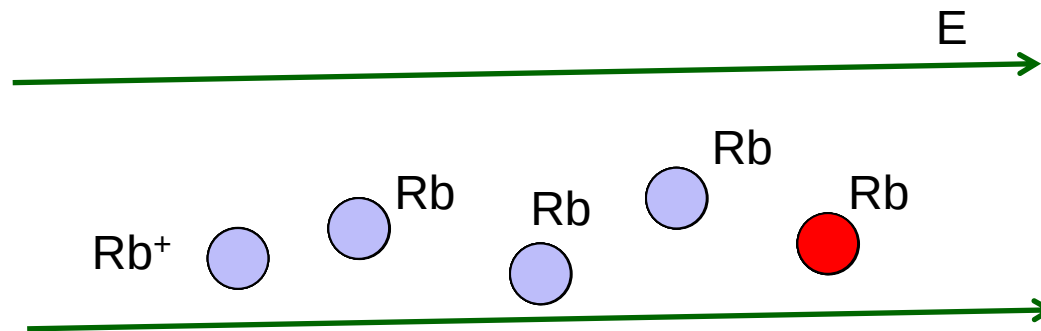


Cote et al, PRL **85**, 2000

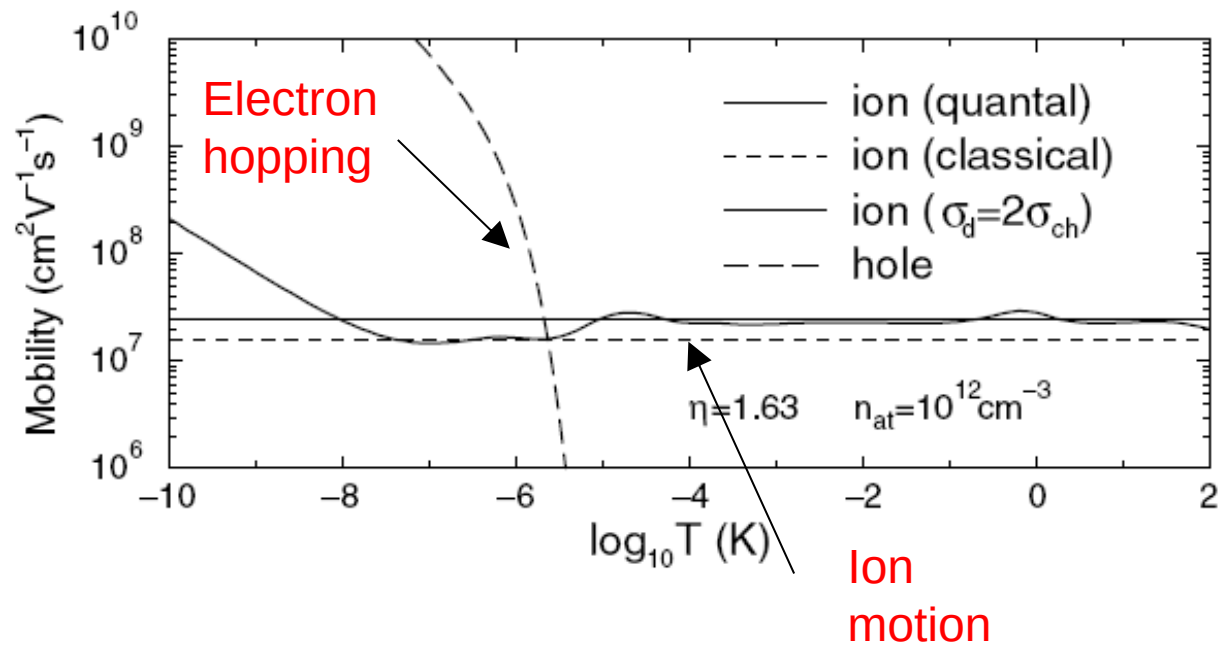


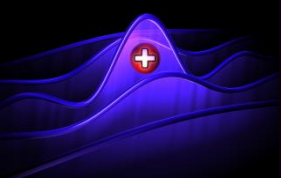


Transport



Cote et al, PRL **85**, 2000

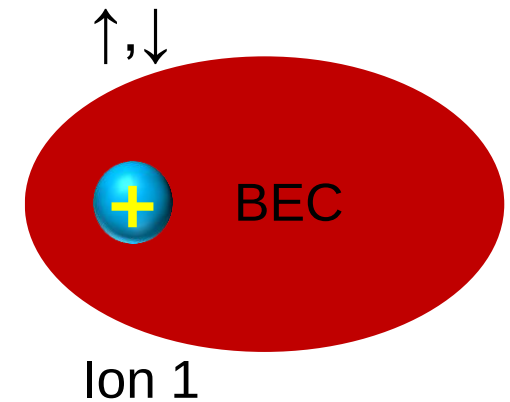
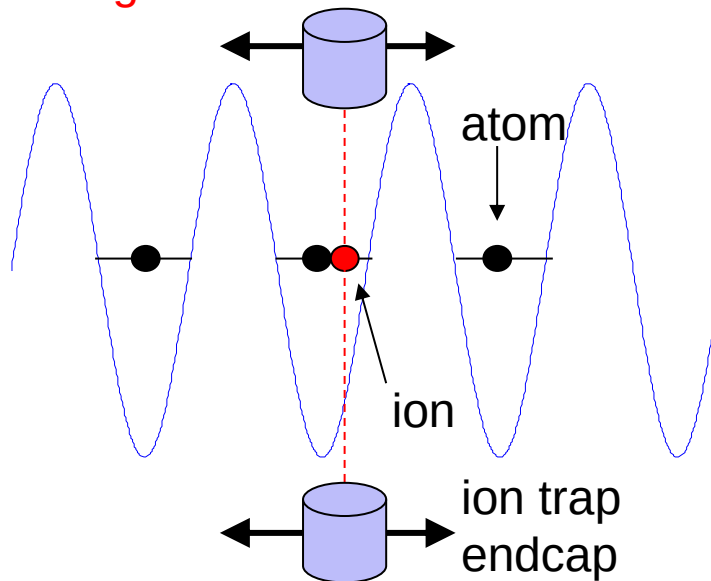




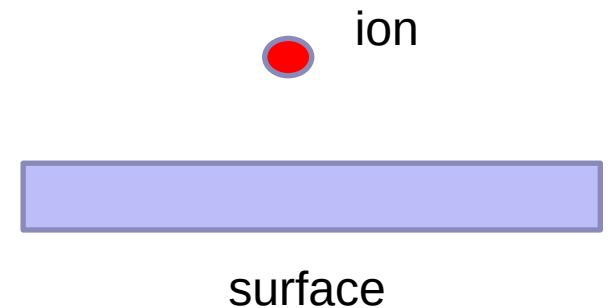
Sensing

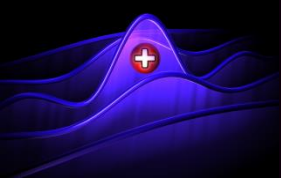
- Measure magnetic field and fluctuations of BEC with Ramsey interferometry
- Use entangled ion pair for decoupling from background

Single atom regime



Ion coupling to surface





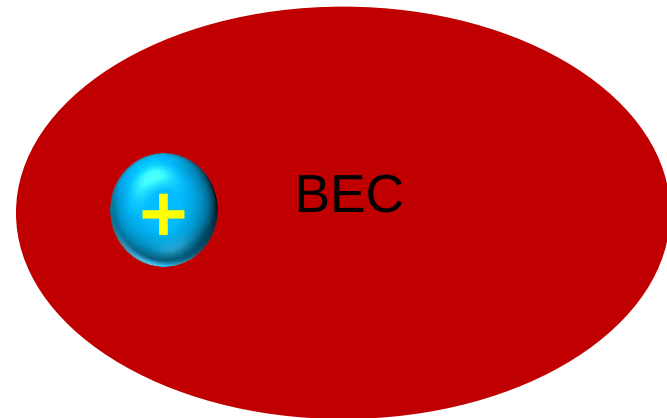
Decoherence and dissipation

decoherence of $\frac{1}{\sqrt{2}} (|\uparrow\rangle + |\downarrow\rangle)$

$\uparrow, \downarrow$

Measure how quickly
coherent superposition
state of ion decays

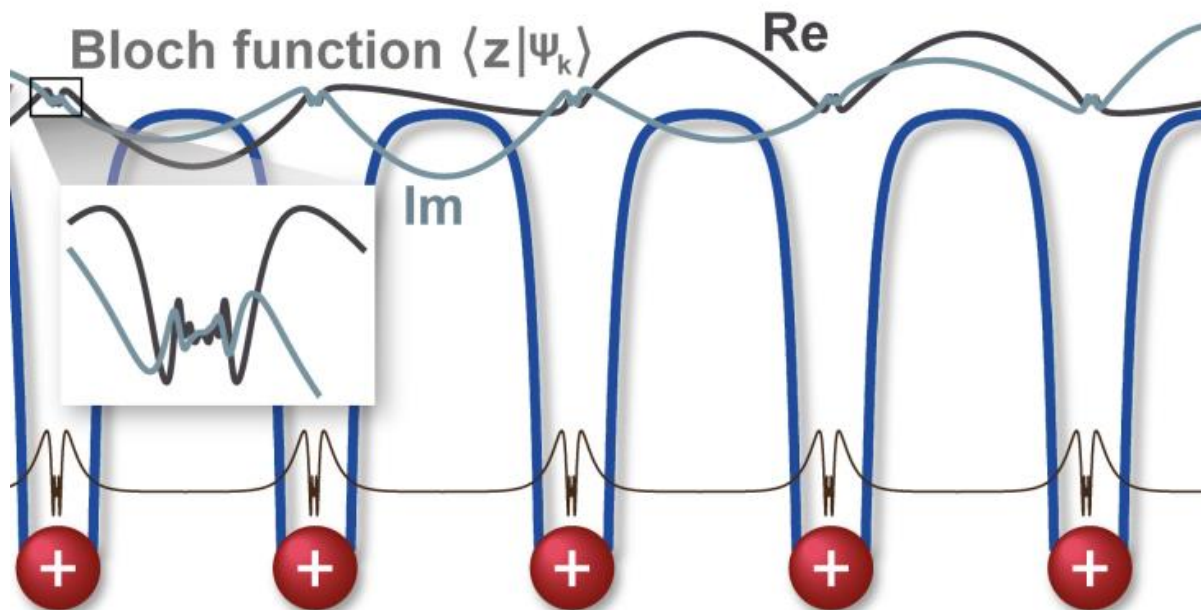
Consequence of collisions
With cold atoms



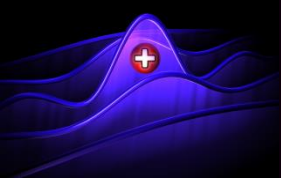
Ion 1

More advanced systems...

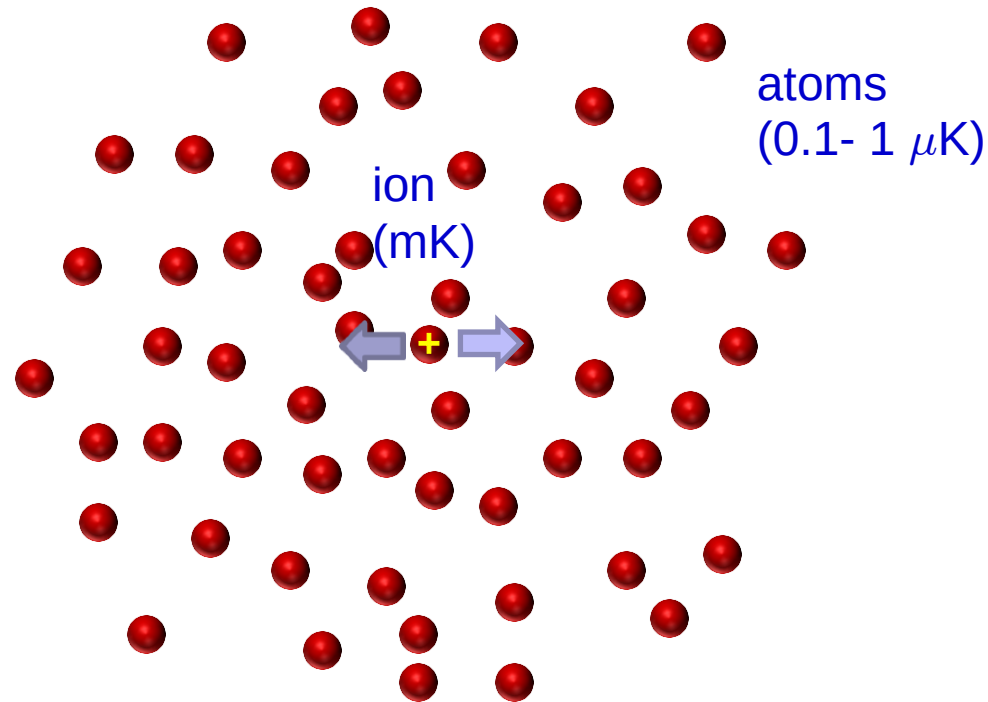
Atom phonon coupling



Bisbort et al, arxiv:1304.4972



Non-Maxwell Boltzmann distributions



- Sympathetic cooling
- Micromotion of ion heats atomic cloud and ion



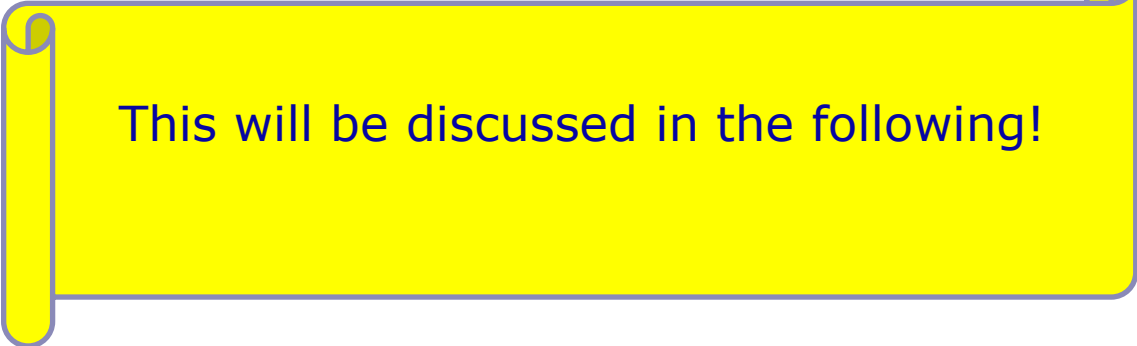
Experimental requirements:

Reach low temperatures!

- in order to observe low energy phenomena / bound states
- in order to gain control over particle interactions:
s-wave collisions + Feshbach resonances

Achieve long ion lifetimes!

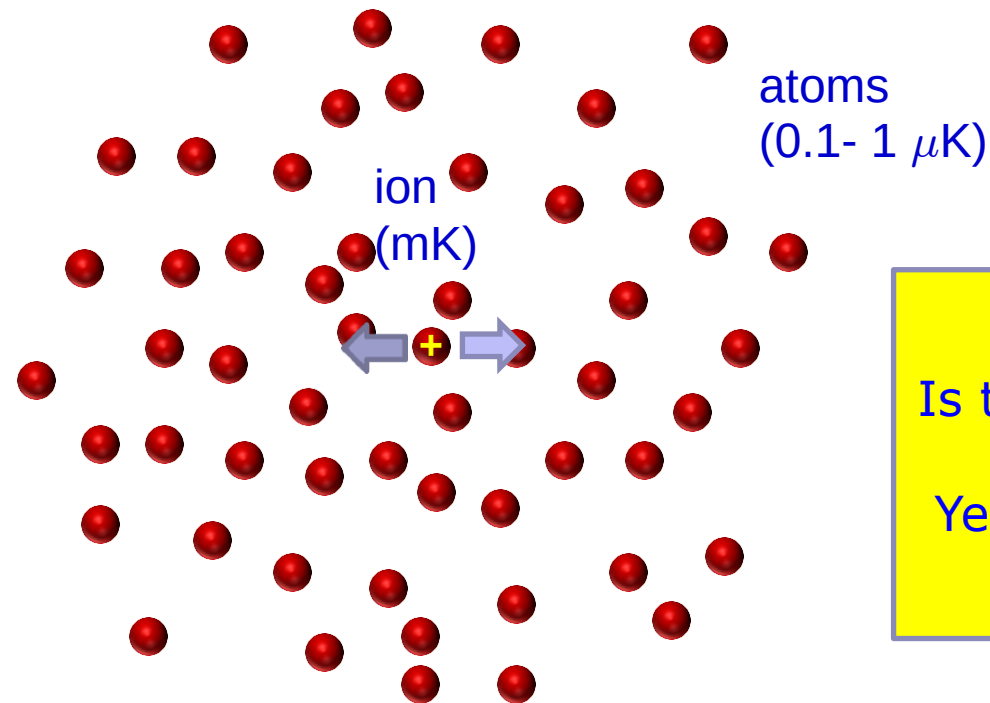
- Chemical reactions
- Spin flips



This will be discussed in the following!



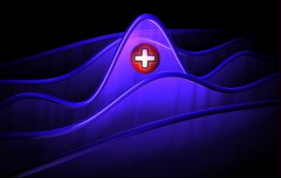
An ion in a cloud of atoms, naive picture



Is that right?

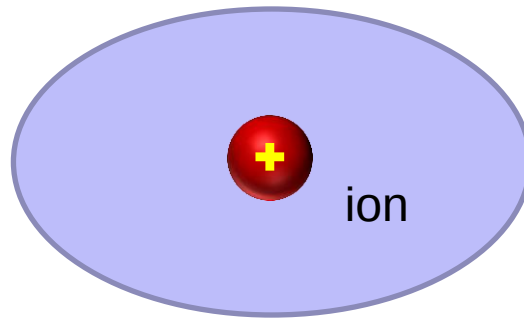
Yes and no!

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

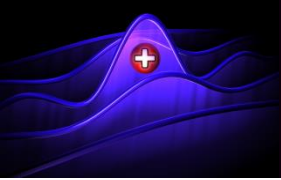


Can atoms cool hot ions?

Cold atom cloud

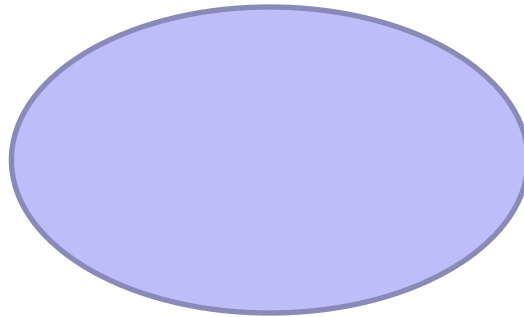


Related experiments also by Rangwala et al.



Can atoms sympathetically cool hot ions?

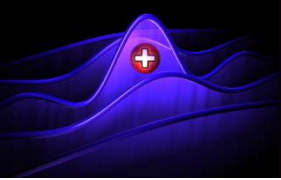
Cold atom cloud



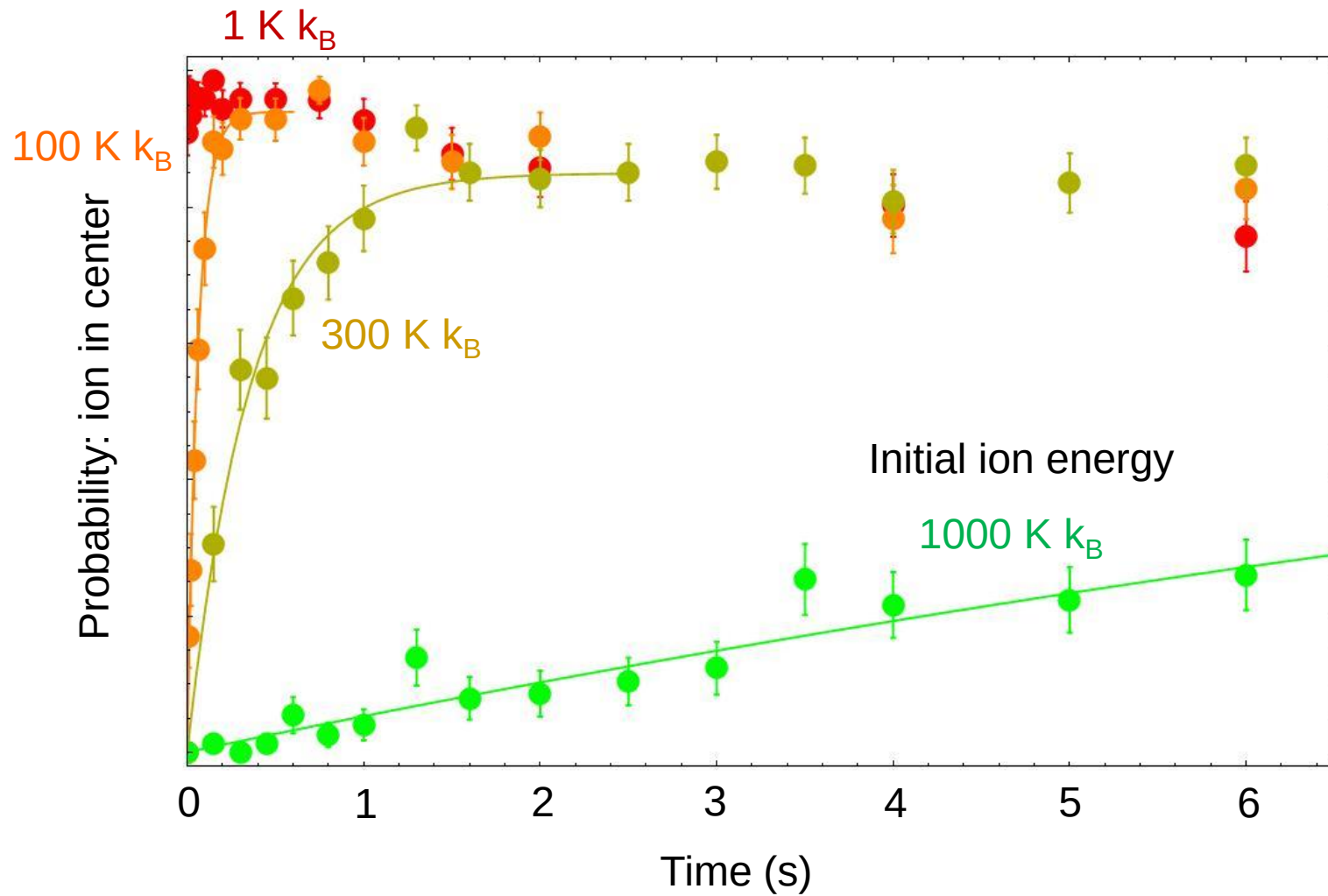
Displaced ion



High potential
energy



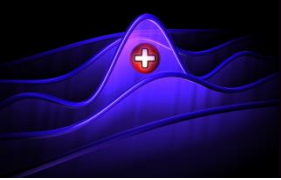
Sympathetic cooling of a hot ion



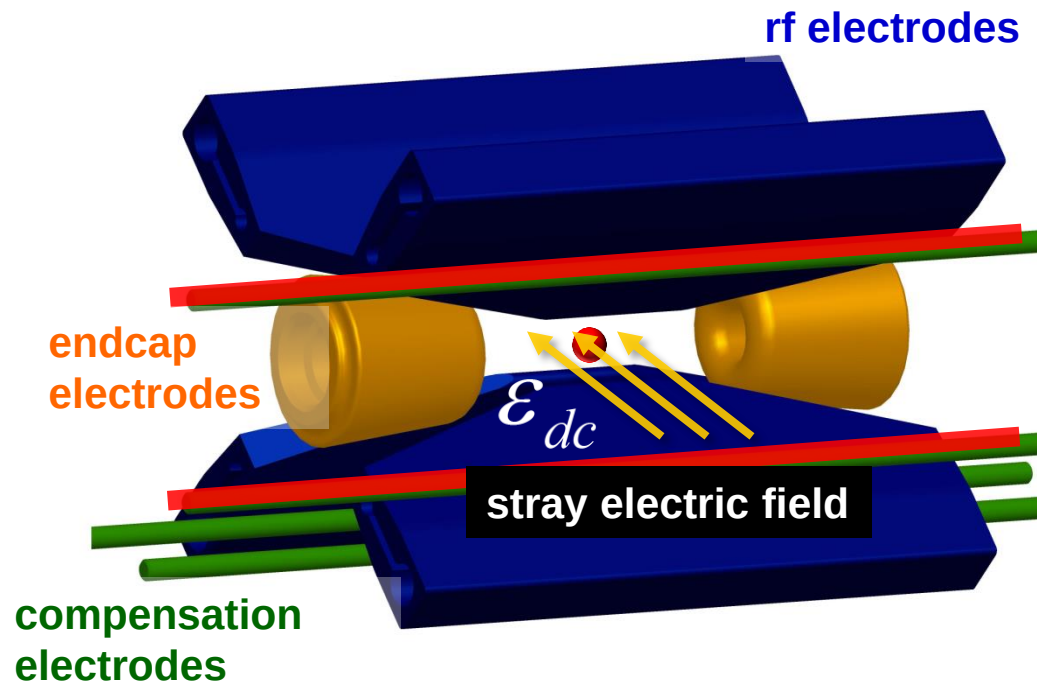


How low in temperature can we go?

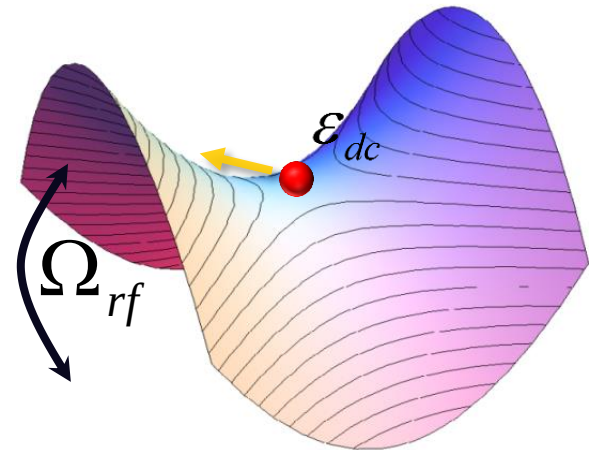
This is determined by the micromotion!



Stray electric fields -> excess micromotion

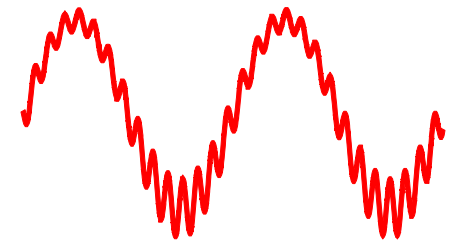


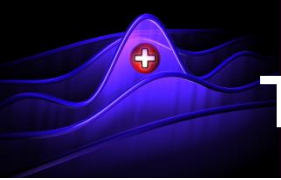
saddle potential



→ driven motion

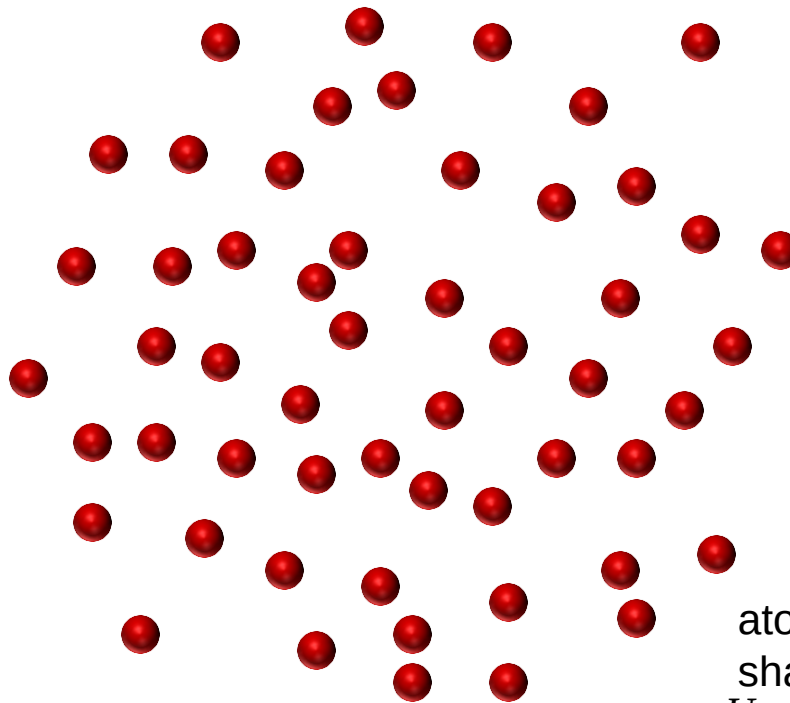
can be minimized by applying appropriate compensation voltages





The role of excess micromotion

RF



atoms confined by
shallow dipole trap

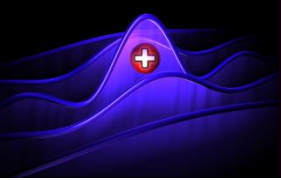
$$U_{\text{dip}} \sim 10 \mu\text{K}$$

$$T \sim 1 \mu\text{K}$$

- coherent trap drive (5MHz) accelerates stopped ion again

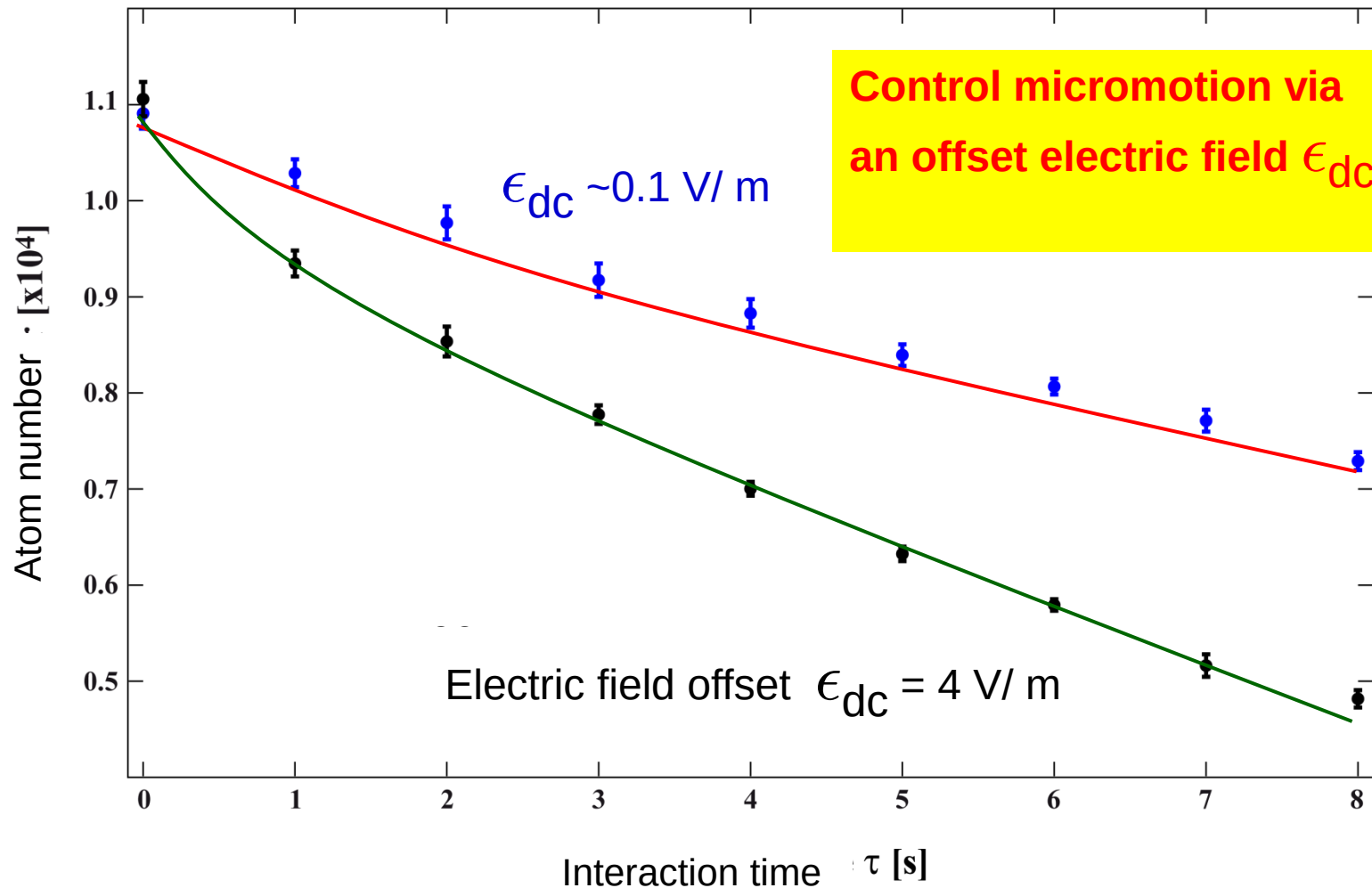
- ion energy is set by excess micromotion

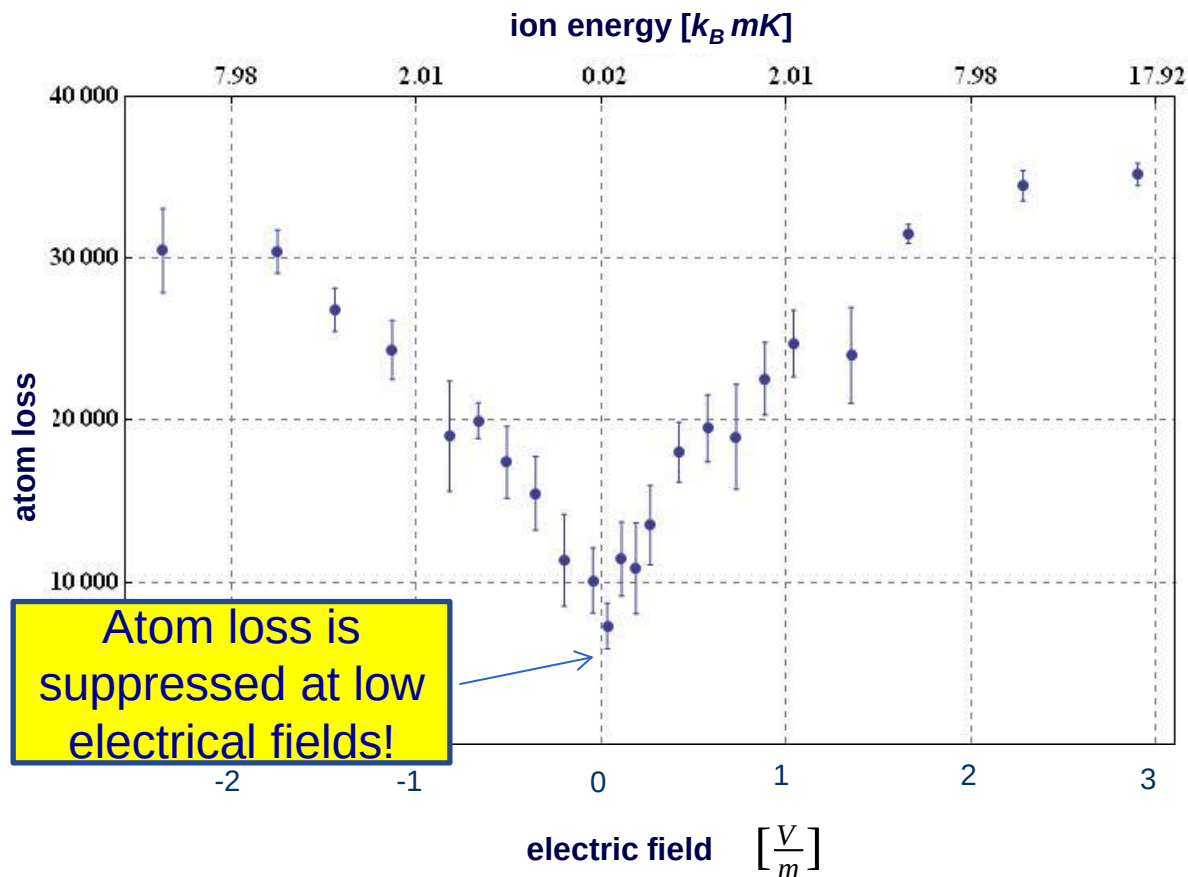
$$E_{\text{ion}} \sim \text{mK } k_{\text{B}}$$



Elastic two-body atom-ion collisions

Thermal atom cloud $T \sim 100\text{nK}$





You can use cold atoms to compensate micromotion!

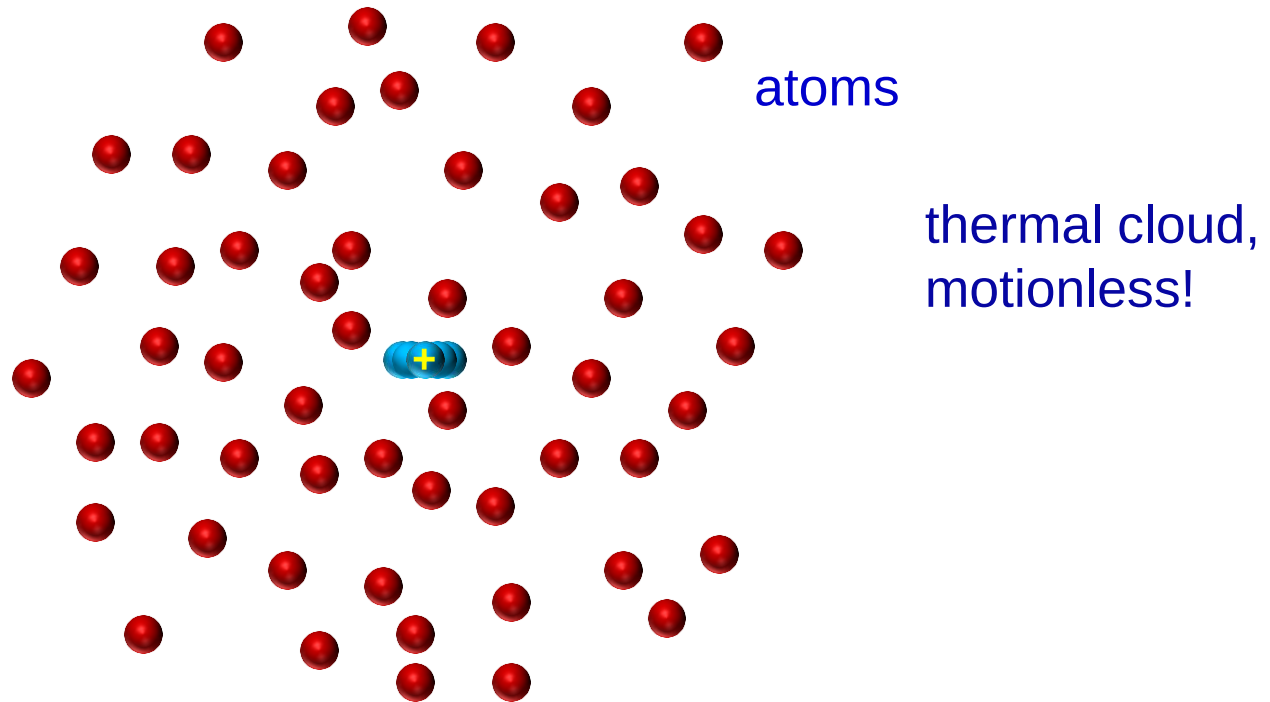
Sensitivity down to 0.03 V/m for stray electrical fields
→ micromotion energies $\sim 1\mu K$

However, preliminary analysis indicates that some micromotion $\sim 500\mu K$ remains, probably due to rf phase difference on electrodes.



Ion Pin Ball Game

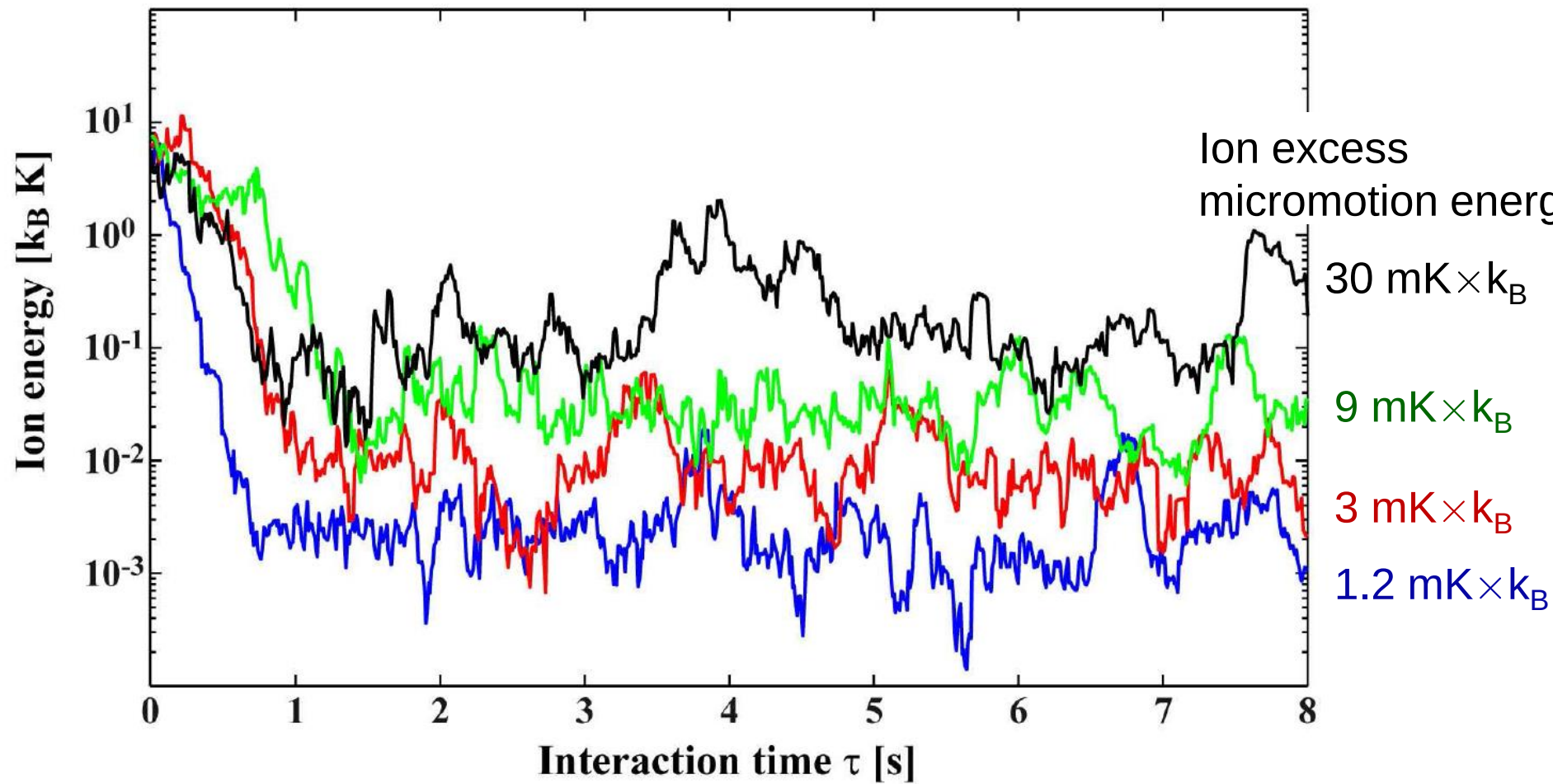
Ion energy distribution?

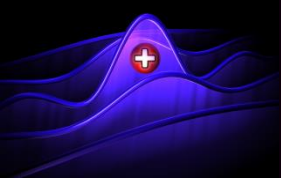


Average ion energy set by micro-motion

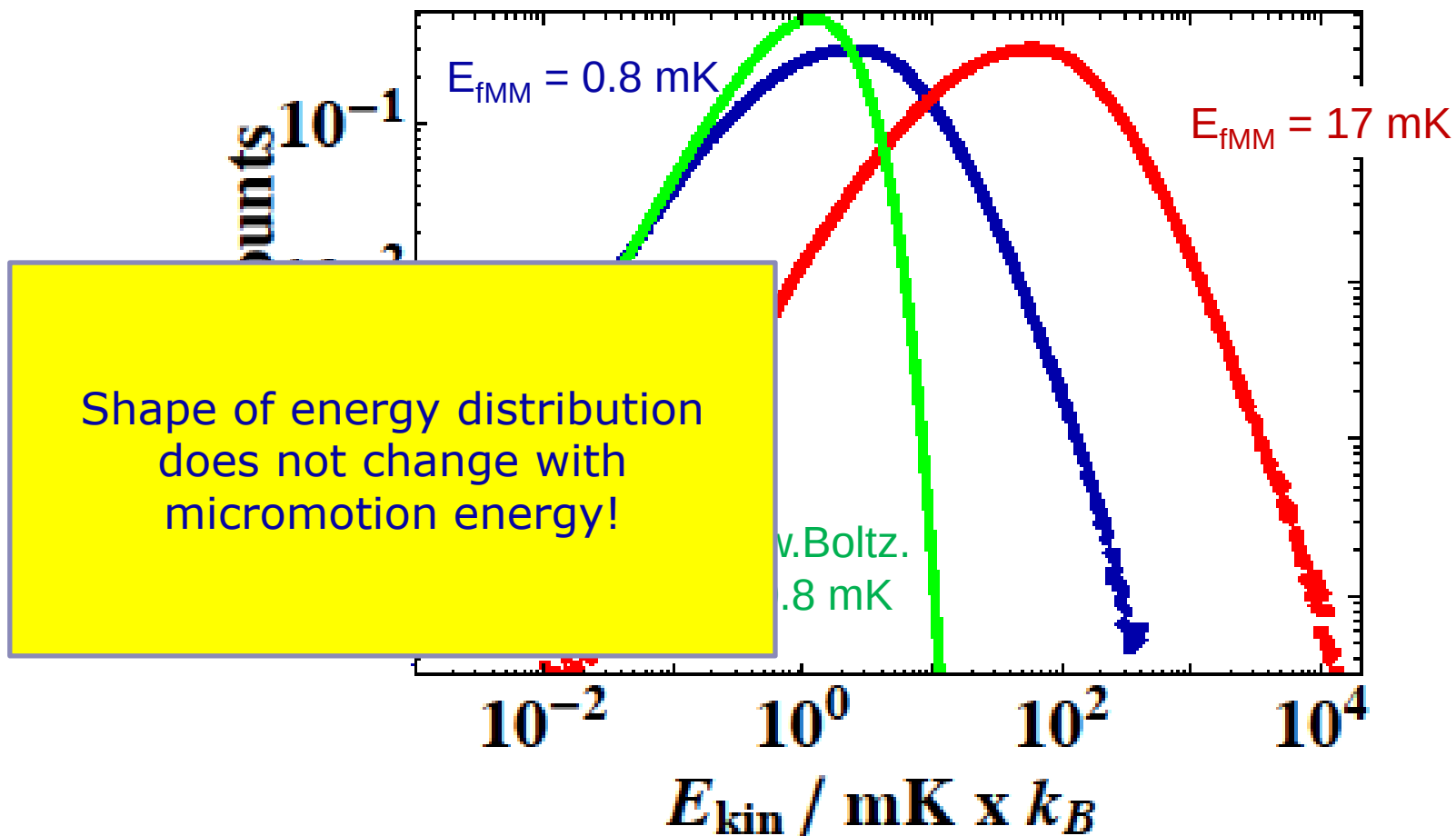


A few trajectories



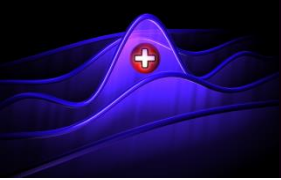


Ion energy distribution

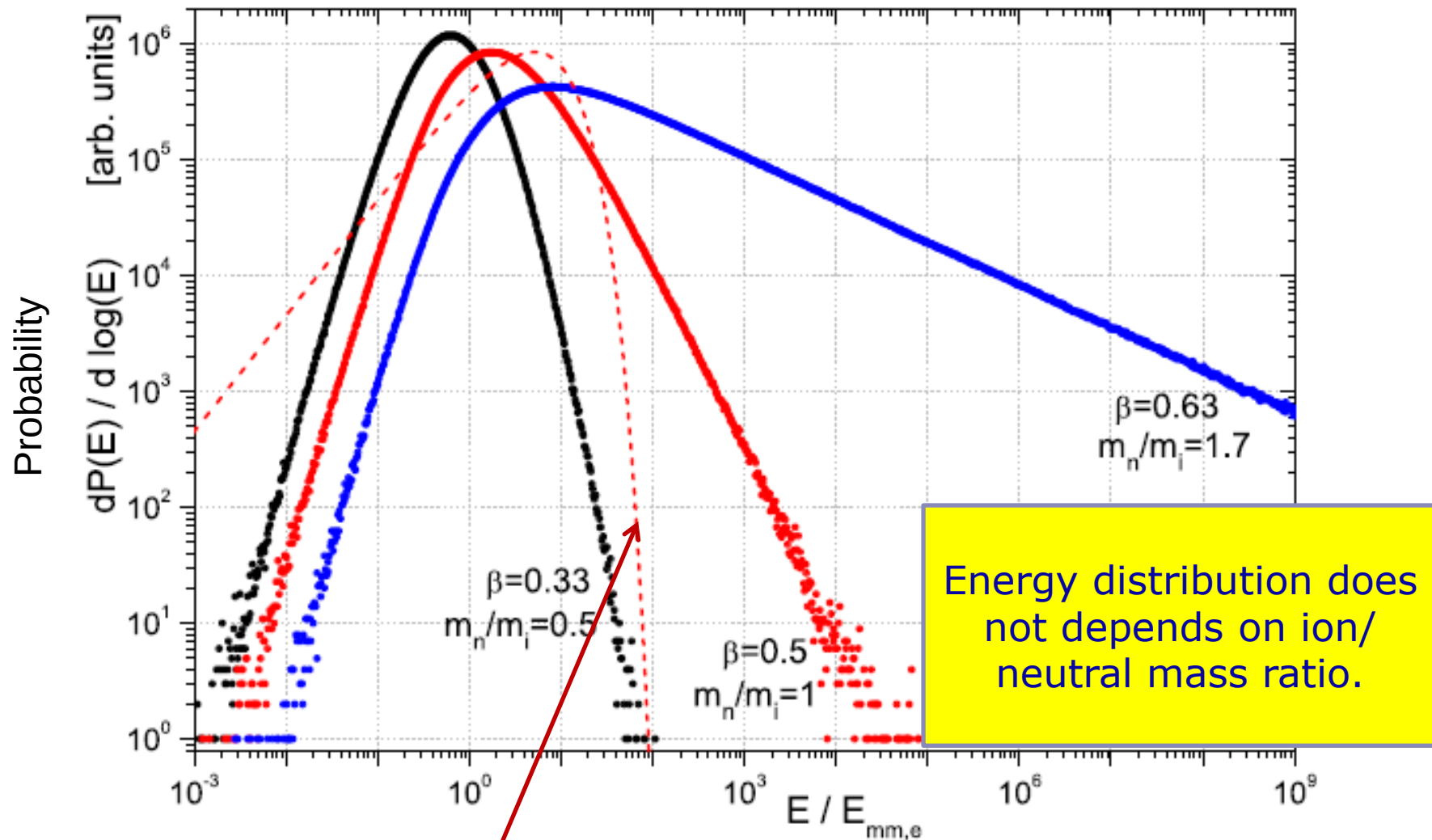


Non-Maxwell-Boltzmann energy distribution. $\langle E_{\text{ion}} \rangle \approx 5 E_{\text{fMM}}$ for Rb/ Ba⁺

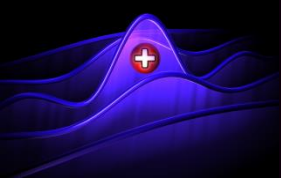
Micromotion energy determines ion energy. (energy scale)



Non-thermal energy distribution of ion



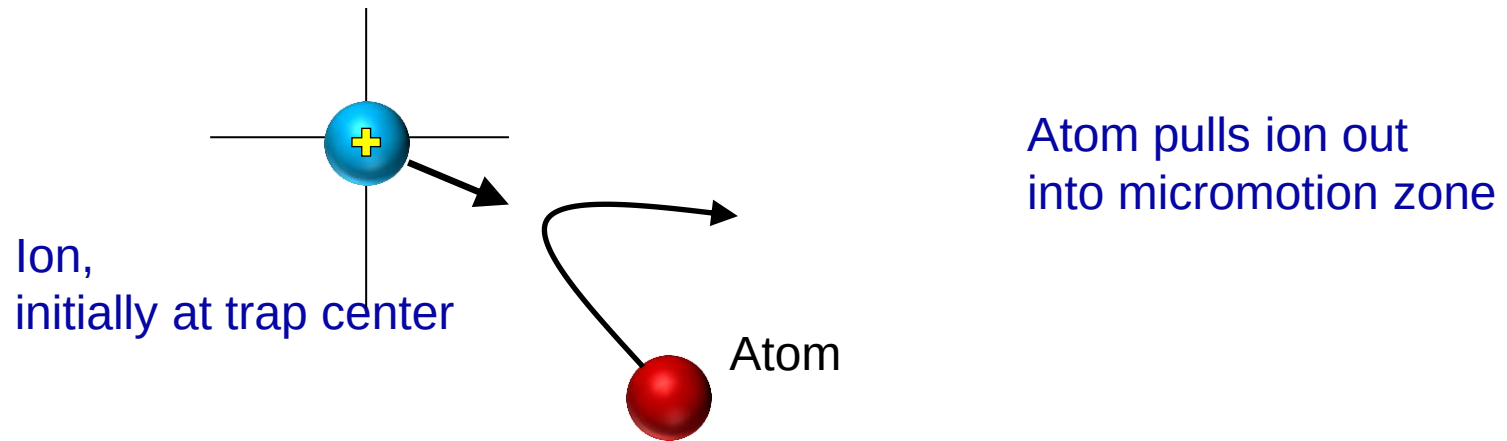
Thermal,
Maxwell-Boltzmann



How cold can we get?

Even if micromotion is perfectly compensated limits have been predicted....

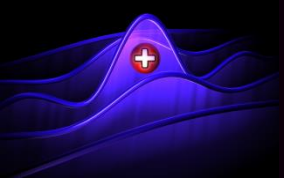
M. Cetina et al.
PRL 109 (2012)



Prediction for our parameters: $E_{\text{final}} \sim 100 \mu\text{K}$

We think that we are already very close to that!

A. Krüchow et al., Phys. Rev. A 94, 030701(R) (2016)
Thomas Sikorsky et al, arXiv:1705.00453.
Z. Meir, et al, PRL 117, 243401 (2016)



Further challenges

Ok, low temperature is an issue....

How about stability/ lifetime of the ion?

Loss due to

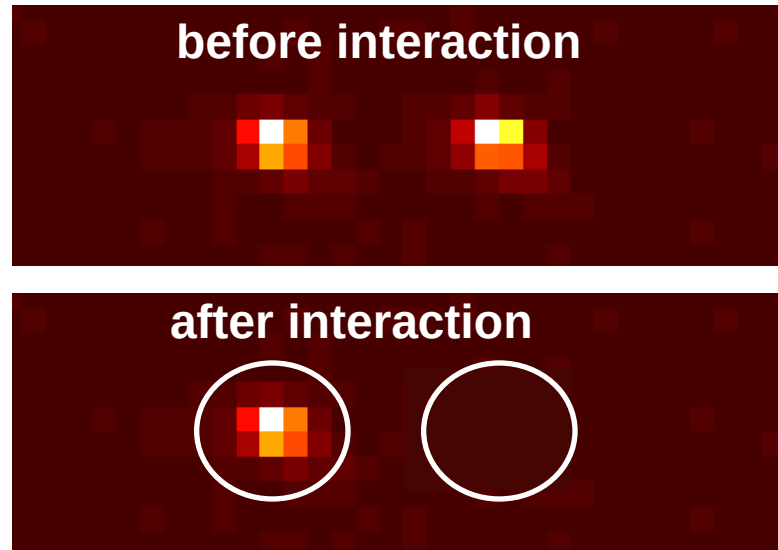
- chemical reactions
- spin flip



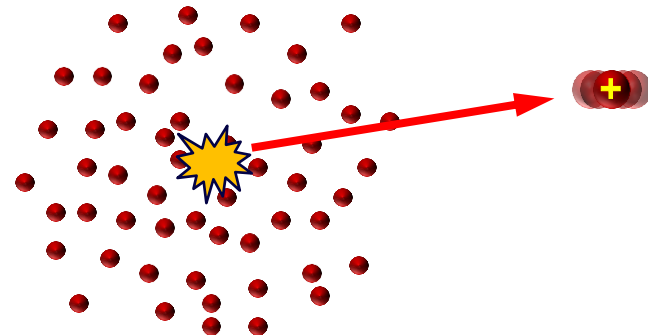
Reactions

How do we detect a reaction?

- Ion turns dark, changes mass

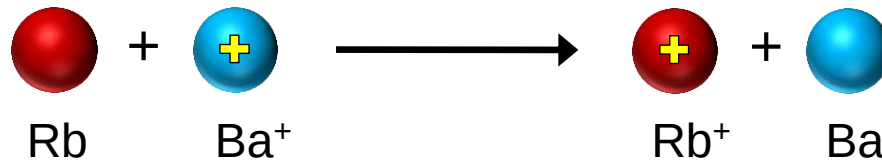


- Release of energy
 - ion orbits outside of atoms
 - change in atom loss



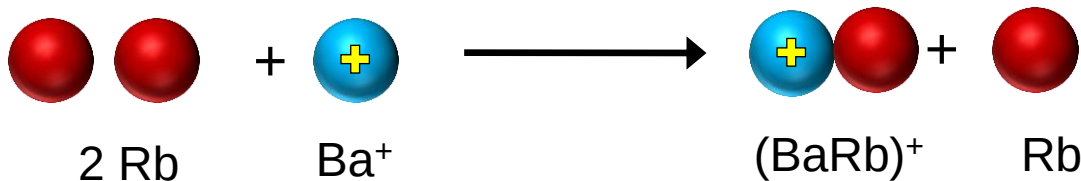


Some reactions that we have observed



$$K_2 < 9 \times 10^{-14} \text{ cm}^3 \text{ s}^{-1}$$

At densities of 10^{14} cm^{-3}
the ion lifetime is 100 ms!



$$K_3 = 1.02(1) \times 10^{-24} \text{ cm}^6 \text{ s}^{-1}$$

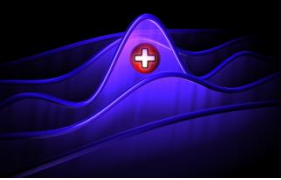
High densities favor
three-body process.

At densities of 10^{14} cm^{-3}
the ion lifetime is only
100 μs !

A. Krüchow et al., Phys. Rev. Lett. 116, (2016)

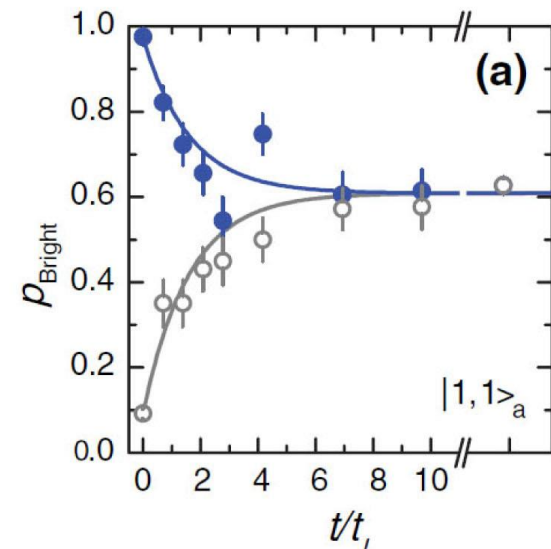
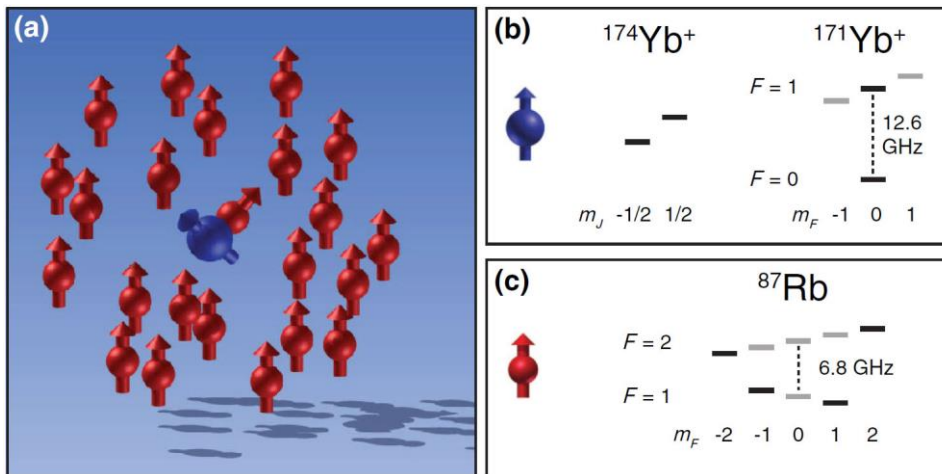
A. Krüchow et al., Phys. Rev. A 94, 030701(R) (2016)

A. Härter, et al., Phys. Rev. Lett. 109, 123201 (2012)



Loss due to spin relaxation

Immerse ion spin qubit into spin polarized atom gas.
Fast relaxation of qubit in Langevin collision. (Strong spin-orbit coupling?)



Ratschbacher et al., PRL 110 (2013)

Problem: relaxation despite being fully stretched

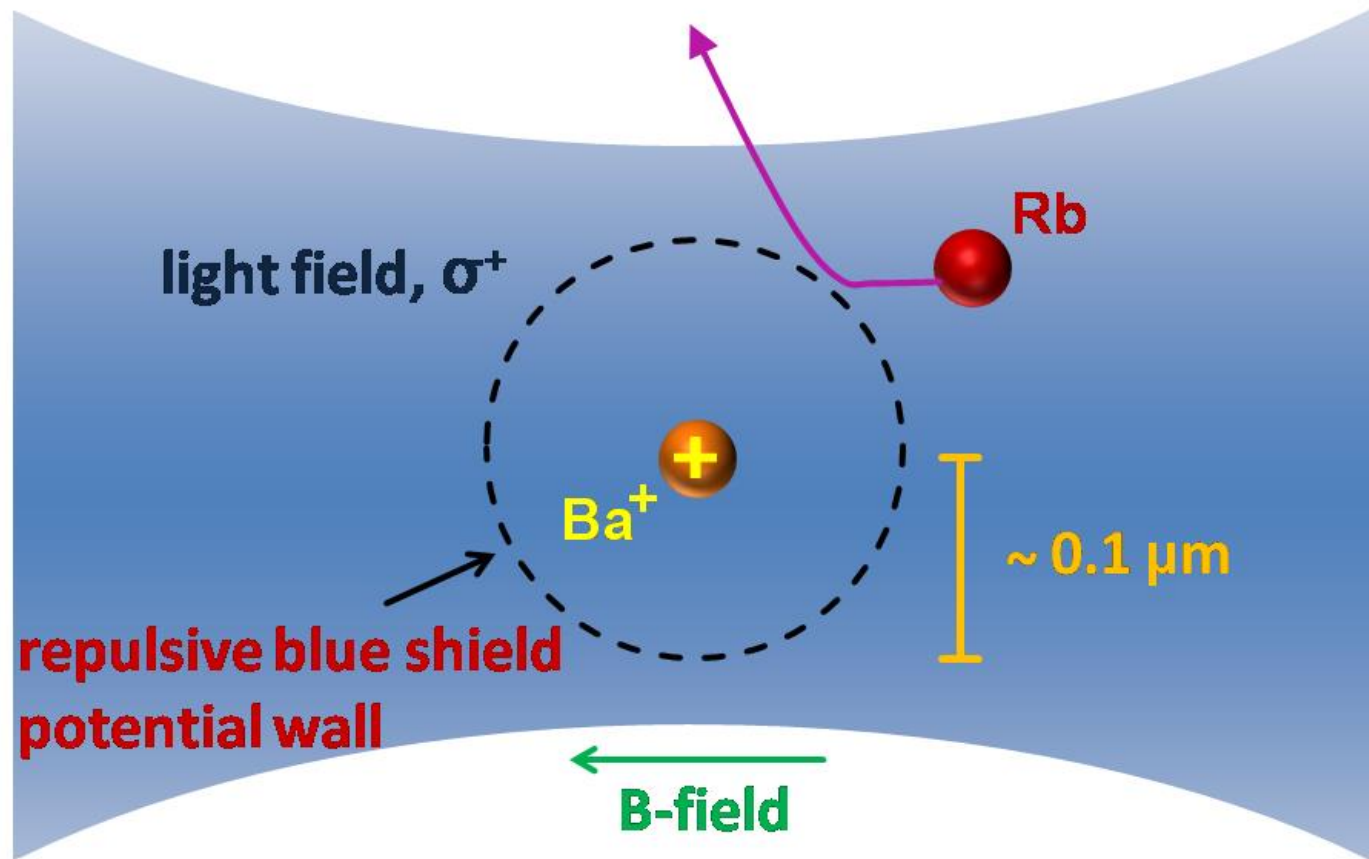


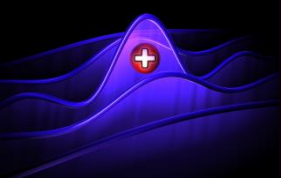
Spin angular momentum dissipates into mechanical angular momentum.

Idea: Preventing reactions/ inelastic collisions using Rydberg states

Ba^+ ion trapped in Paul trap ($\sim \text{nm}$), laser cooled

10^5 Rb atoms trapped in dipole trap ($\sim 1 \mu\text{K}$)

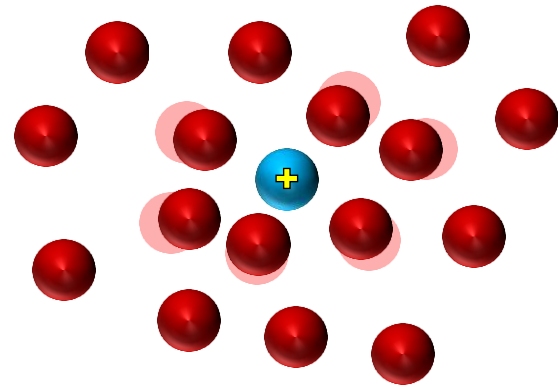




Summary

Atom–ion hybrid system is interesting for research of open quantum systems

- Polaron/ Few body bound states
- Transport
- Sensing
- Decoherence/ dissipation
- Coupling of various quantum systems
- Non-thermal distributions



Challenges

- get cold (~ 1 μ K)
- loss due to chemical reactions
- loss due to spin flips

