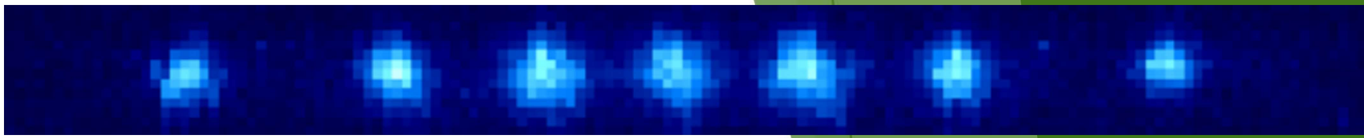
Lecture 2

UNIVERSITY OF AMSTERDAM

QuSoft
Research Center for Quantum Software

Towards quantum impurity physics with atoms and ions

Rene Gerritsma



Lecture 2

- Can we get colder?
- Spin dynamics
- Controlling interactions: Rydbergs
- Quantum chemistry: Trapped ions interacting with Feshbach dimers
- Conclusions

Crossover to quantum regime

Type of motion	$E_{\rm kin}/k_B(\mu K)$	$E_{\rm col}/k_B(\mu K)$
Radial secular ion	$2 \times 21(9)$	1.4(0.6)
Intrinsic micromotion	$2 \times 21(9)$	1.4(0.6)
Axial secular ion	65(18)	2.2(0.4)
Excess micromotion	44(13)	1.5(0.4)
Total ion energy	**193(42)**	**6.6(1.4)**
Atom temperature	$3/2 \times 2.3(0.4)$	3.3(0.6)
Total collision energy	—	**9.9(2.0)**

Measurement of all types of motion

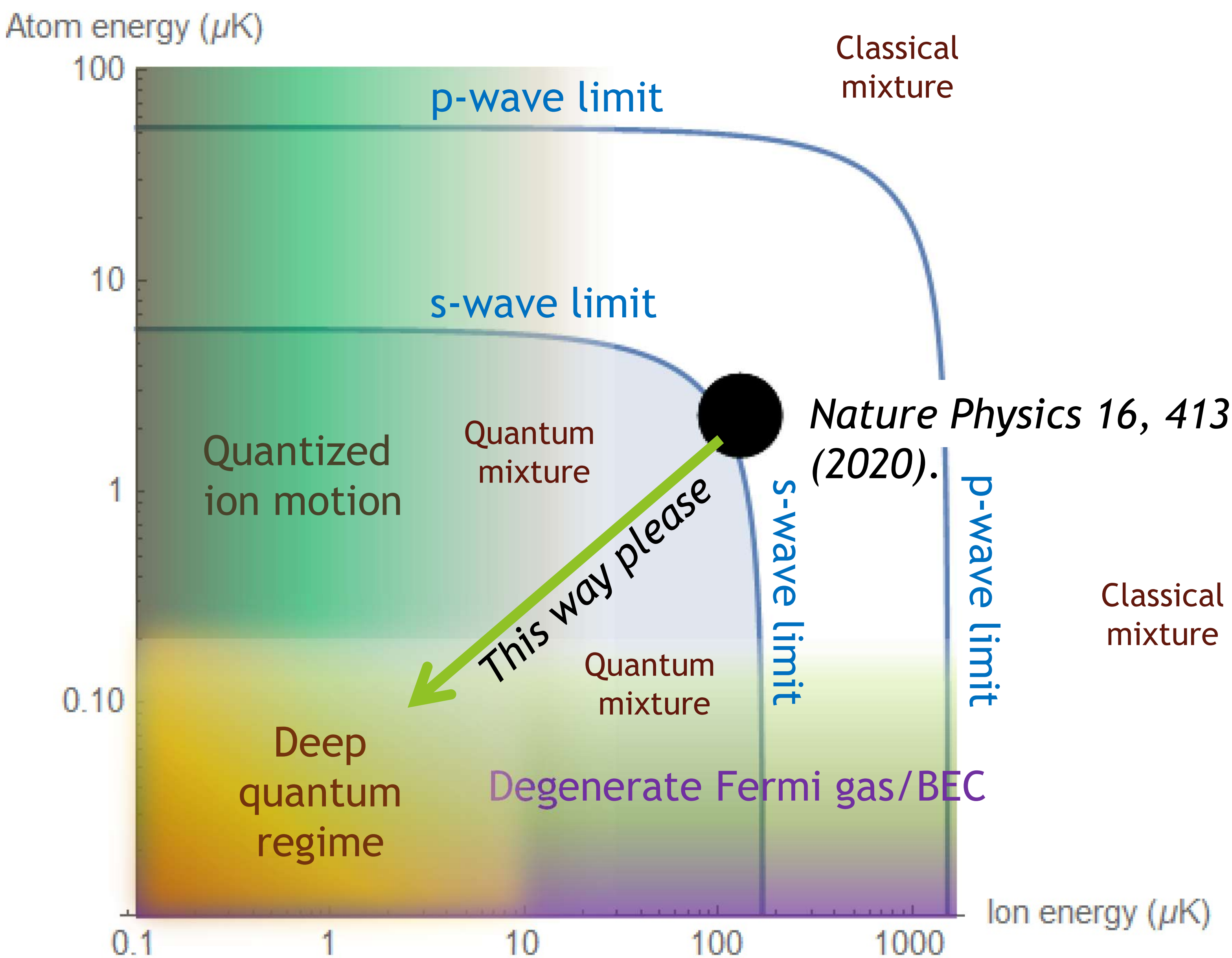
$$E_{col} = 1.15(23) \times E_s$$

Coldest results

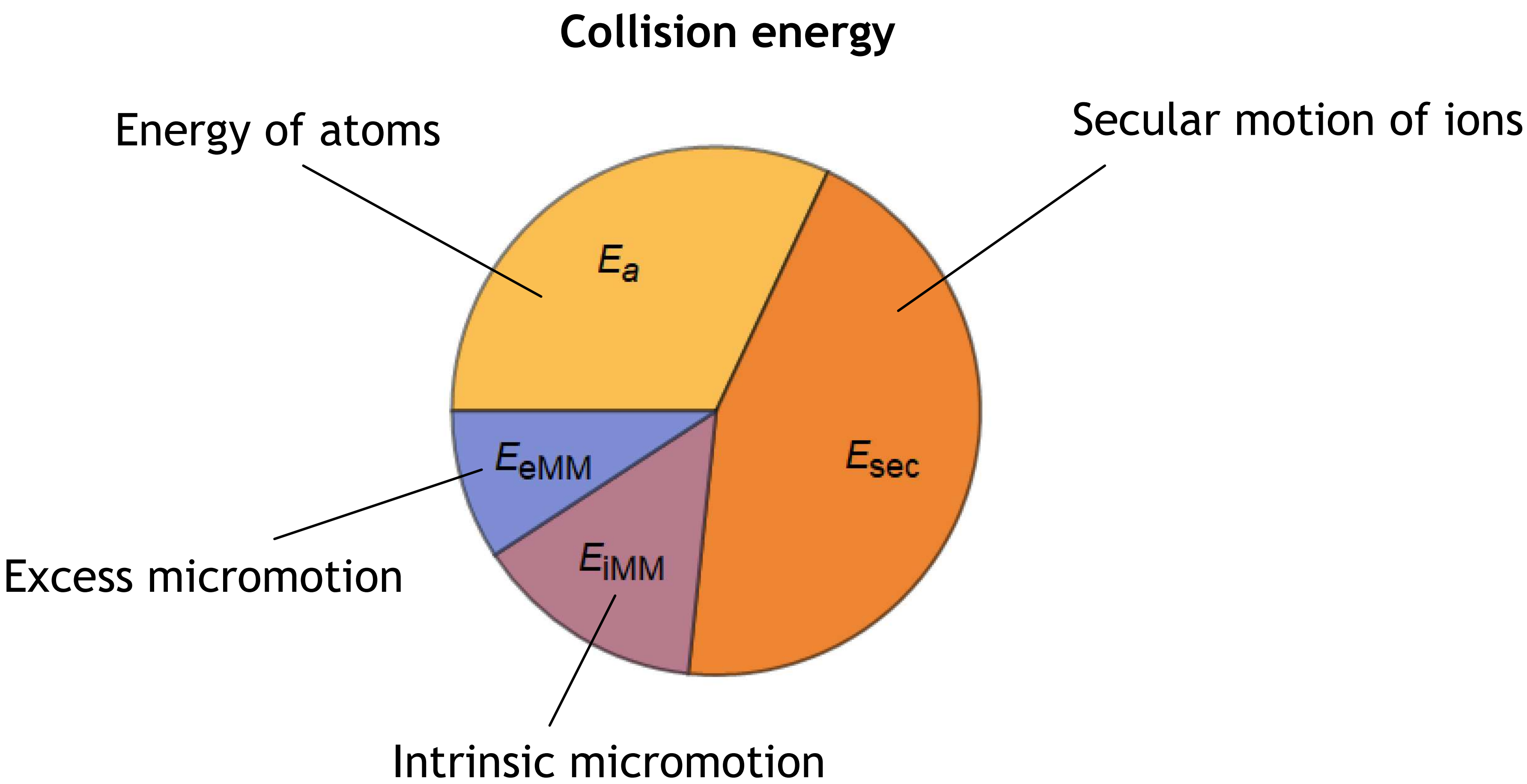
Crossover into quantum regime, can we get colder?

T. Feldker et al., *Nature Physics, 16, 413-416 (2020)*.

Prospects for getting colder



Prospects for getting colder

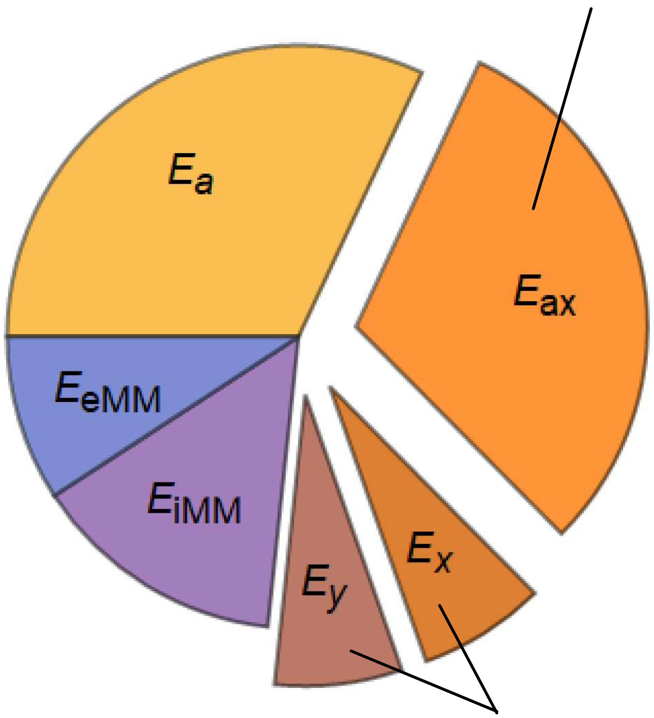


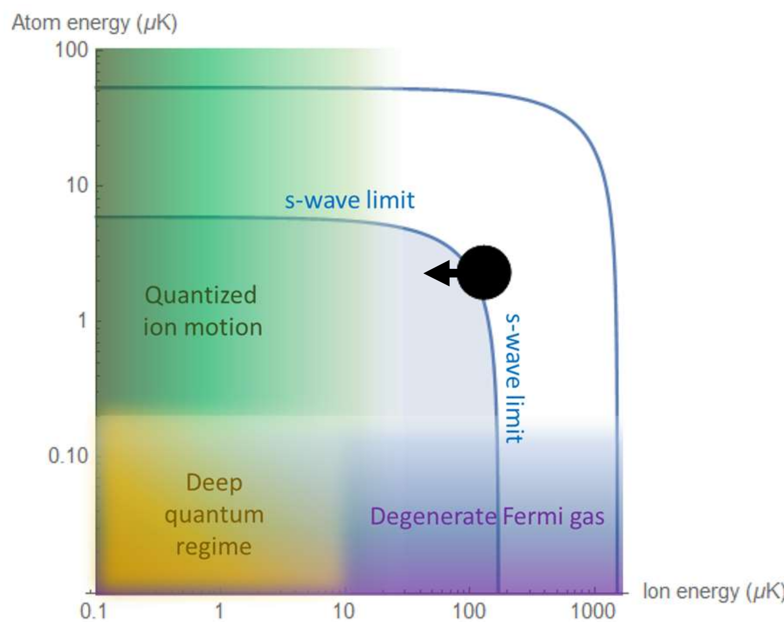
Experimentally determined collision energy

Prospects for getting colder

Collision energy

Axial motion of ions
→ Background heating
~ 200 μK/s



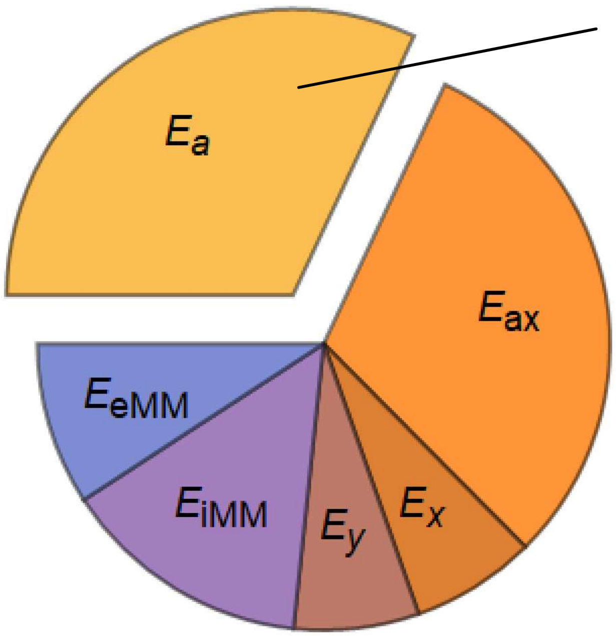


Radial motion of ions
→ Background heating
~ 85 μK/s

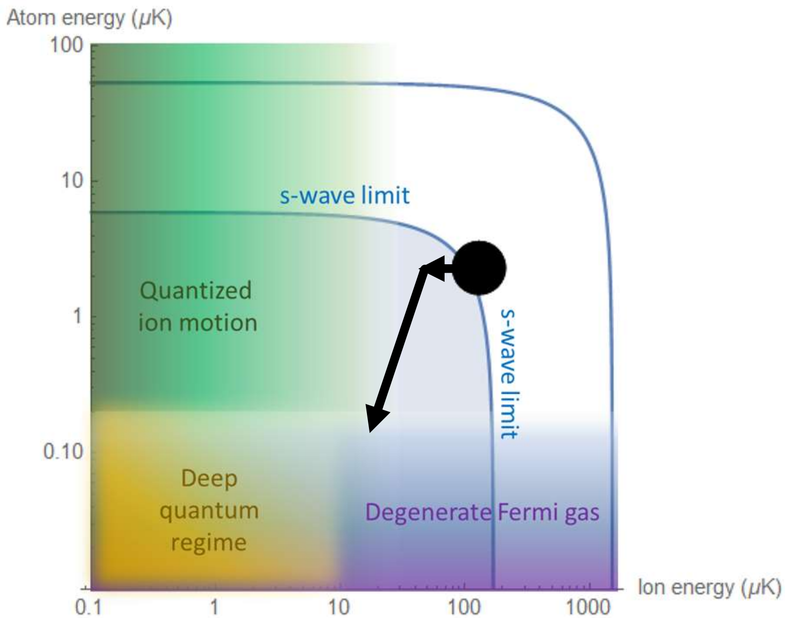
→ Denser gas eliminates background heating lims
→ Faster repetition of experiments reduces overestimation } factor 2?

Prospects for getting colder

Collision energy



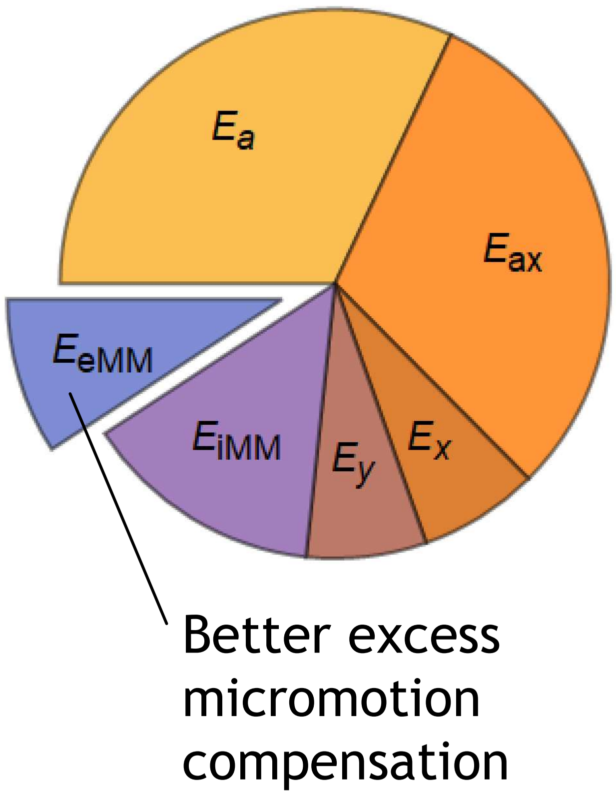
Make colder atoms!
→ More efficient evaporation
→ Need denser gas

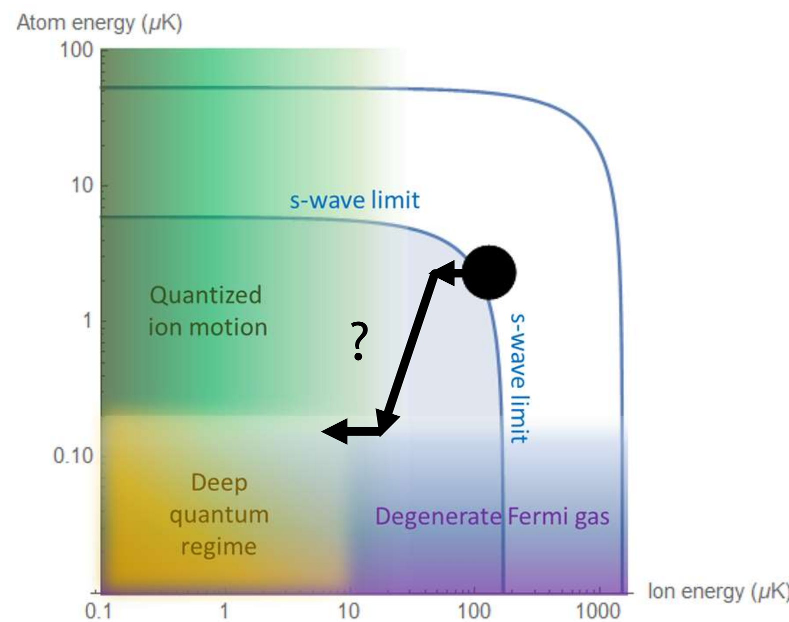


→ Colder gas eliminates atomic energy → another factor of 2?

Prospects for getting colder

Collision energy

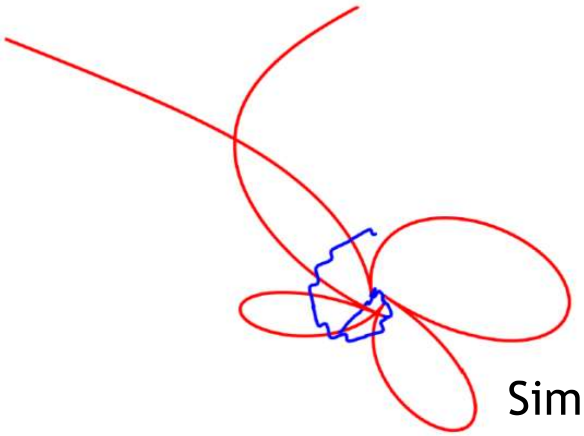




→ Simulations suggest another factor of 2 within reach

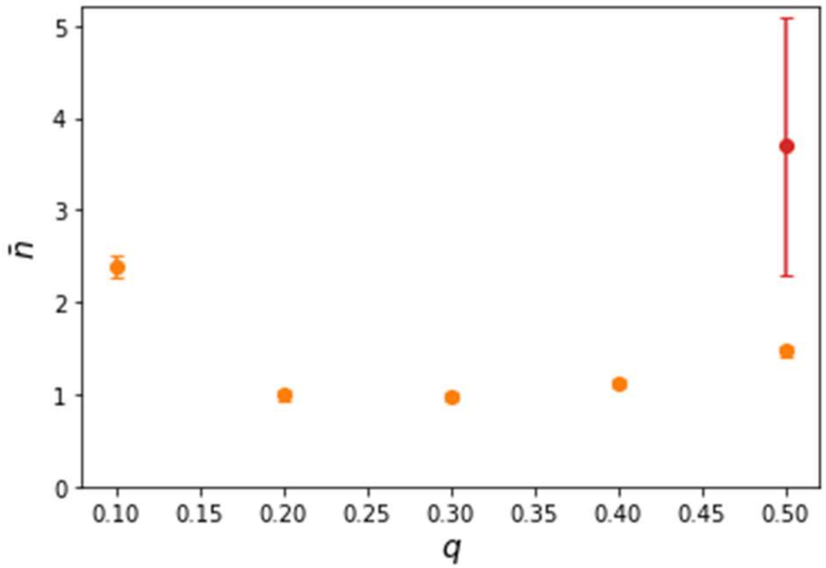
Simulations:
Parameter optimization of trap voltage

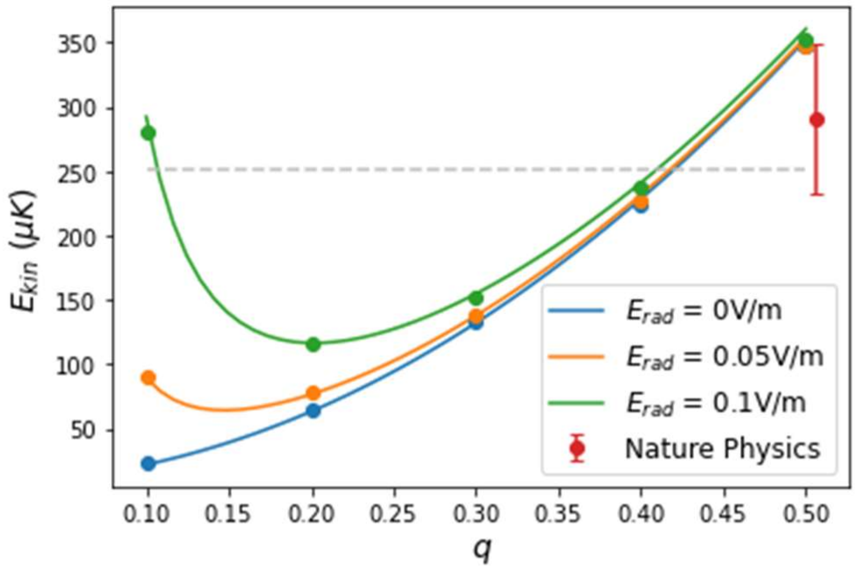
- Optimal q depends on excess micromotion
  - Measure micromotion -> select q
- Can feasibly decrease ion temperature by factor 2
- Can also decrease $\bar{n}$ through choice of q



Simulated trajectory

Classical molecular dynamics simulations



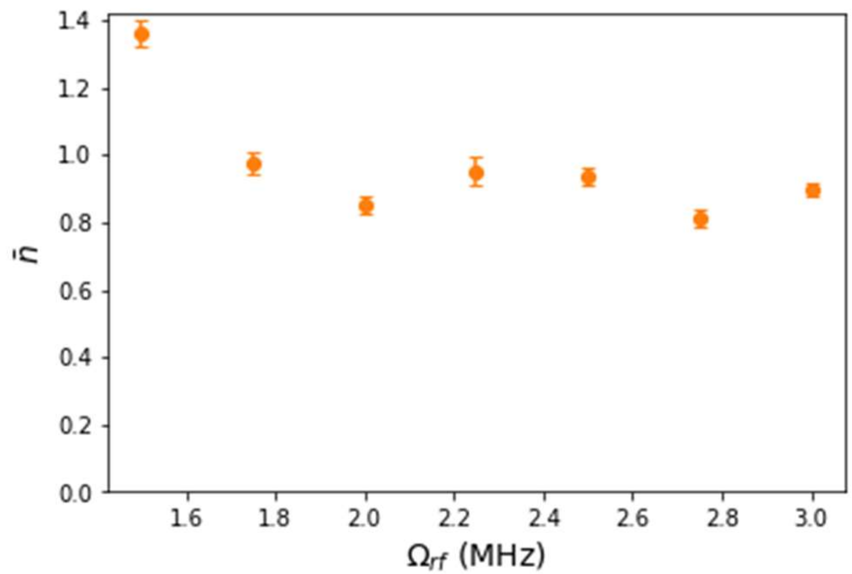


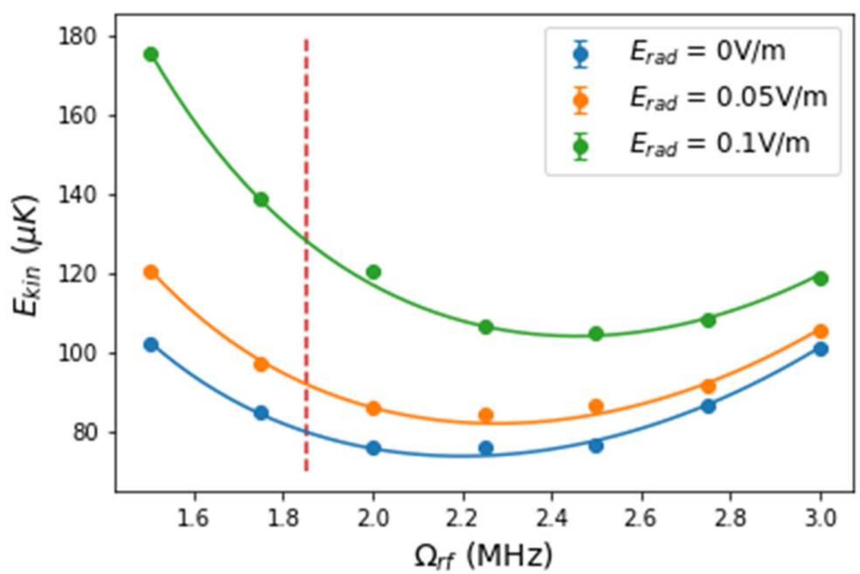
$T_a = 2\mu K$
$\Omega_{rf} = 2MHz$

NJP 24, 035004 (2022).

Simulations:
Parameter optimization of Paul trap drive freq.

- Optimal Ω_{rf} also depends on excess micromotion



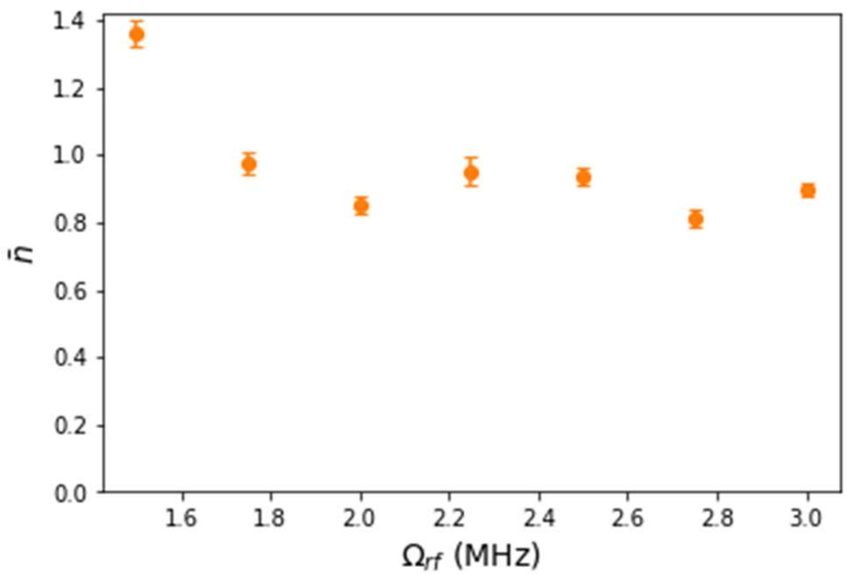


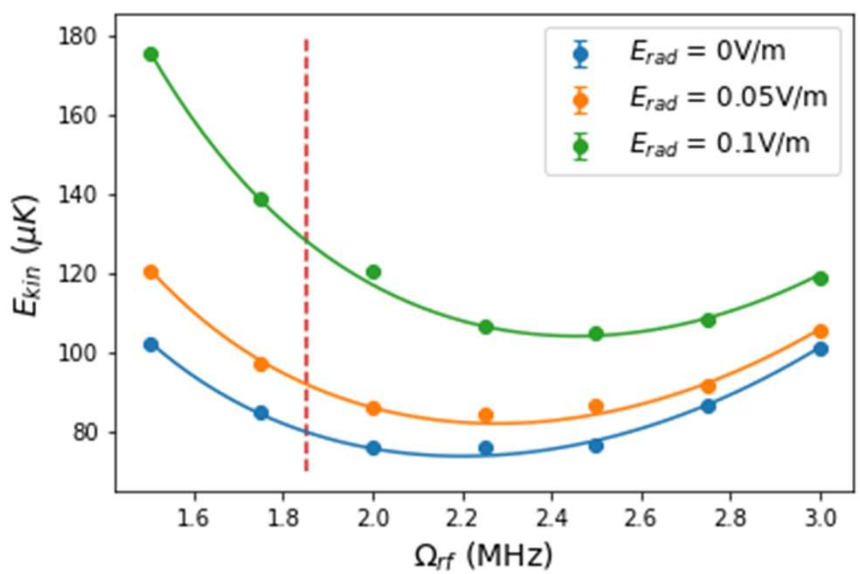
$T_a = 2\mu K$
$q = 0.219$

NJP 24, 035004 (2022).

Simulations:
Parameter optimization of Paul trap drive freq.

- Optimal Ω_{rf} also depends on excess micromotion





$T_a = 2\mu K$
$q = 0.219$

→ The simulations show that $\bar{n} \sim 1$ are possible:
Buffer gas cooling is competitive w.r.t. sub-Doppler cooling?
→ What will be the role of quantum effects?

NJP 24, 035004 (2022).

Interactions in quantum regime

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Measurement of all types of motion

$$E_{col} = 1.15(23) \times E_s$$

Coldest results

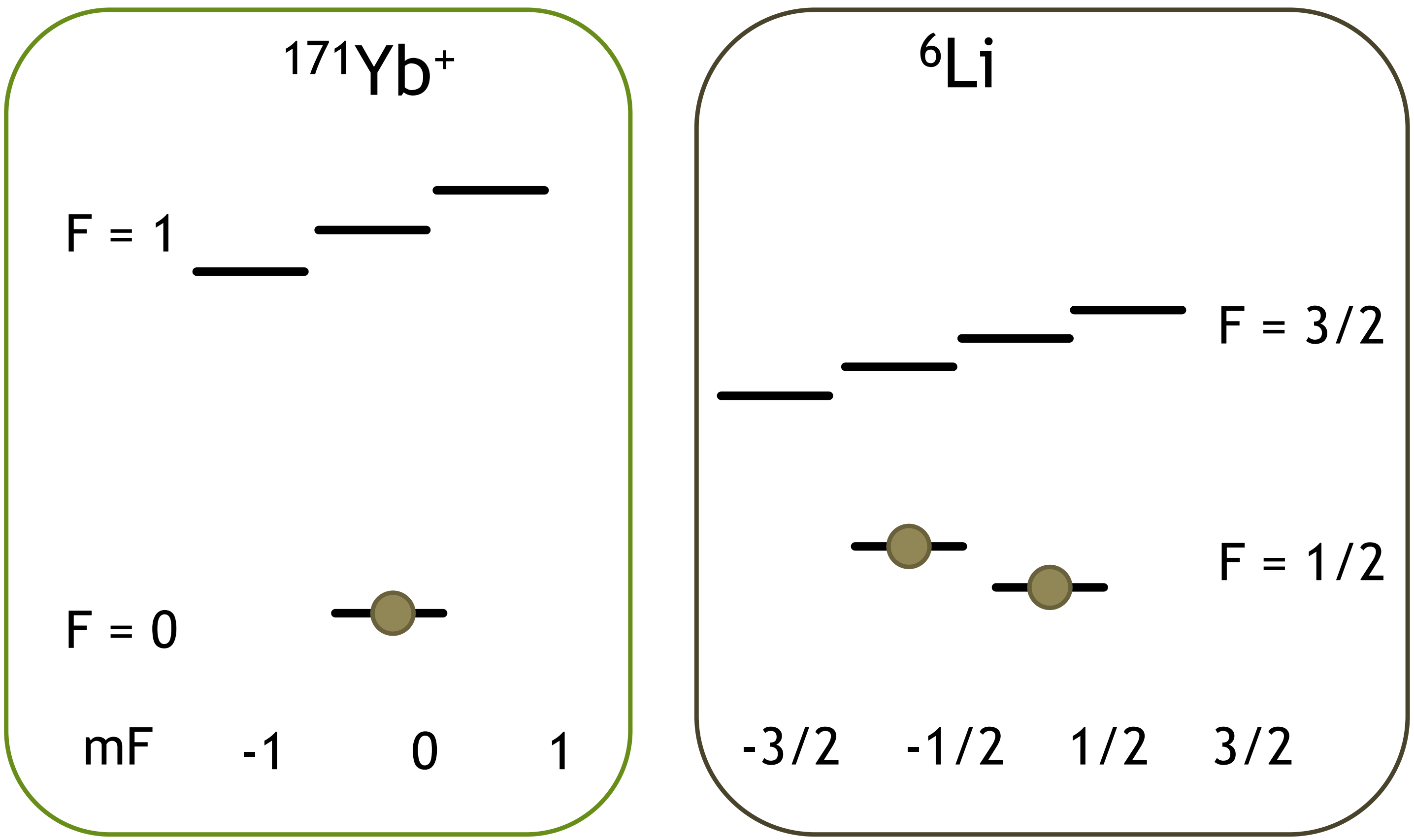
So can we measure something 'quantum' about it?

T. Feldker et al., *Nature Physics, 16, 413-416 (2020)*.

Quantum effects in atom-ion collisions?

→ Spin exchange rates

→Prepare spin in ion after buffer gas cooling, detect spin flip



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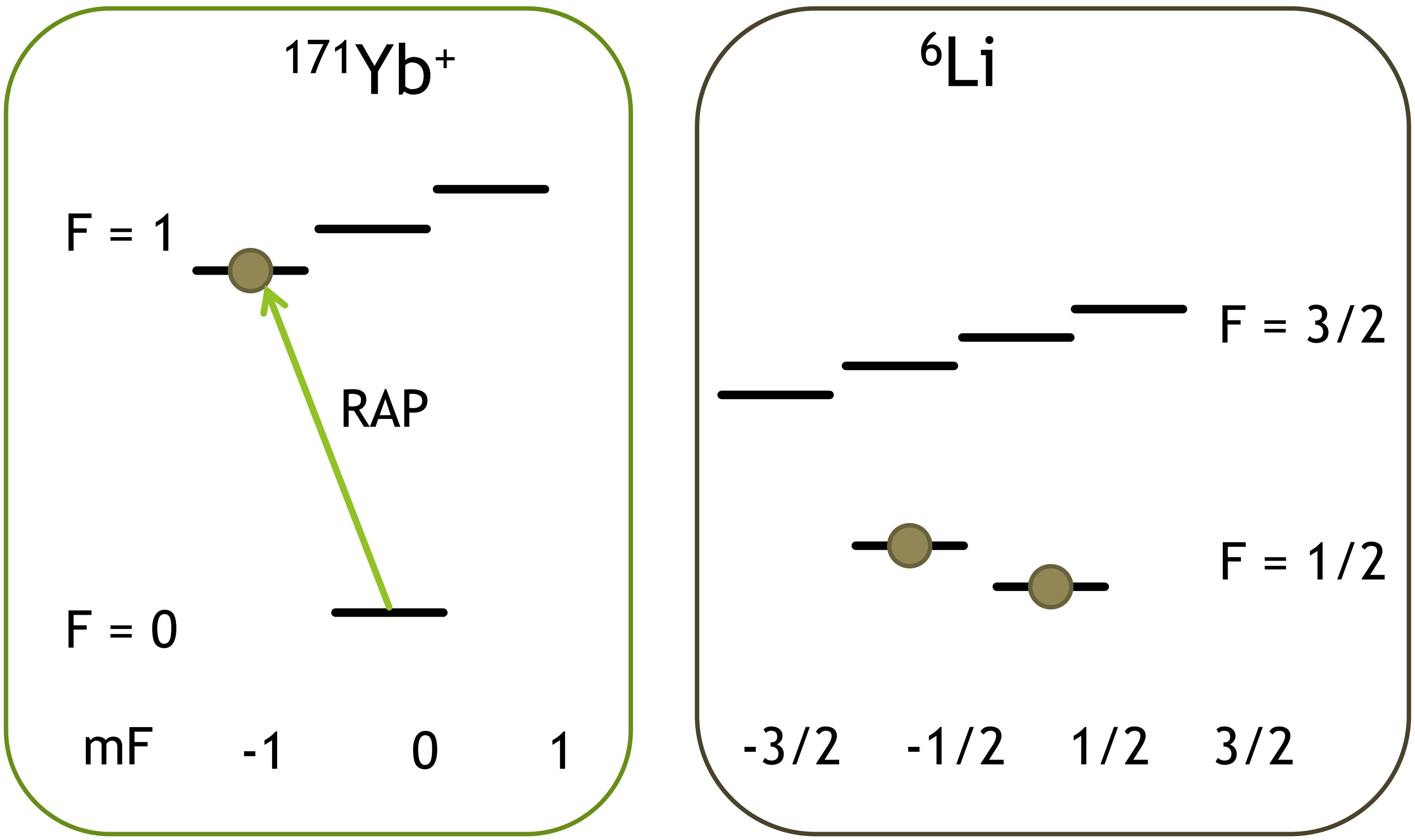

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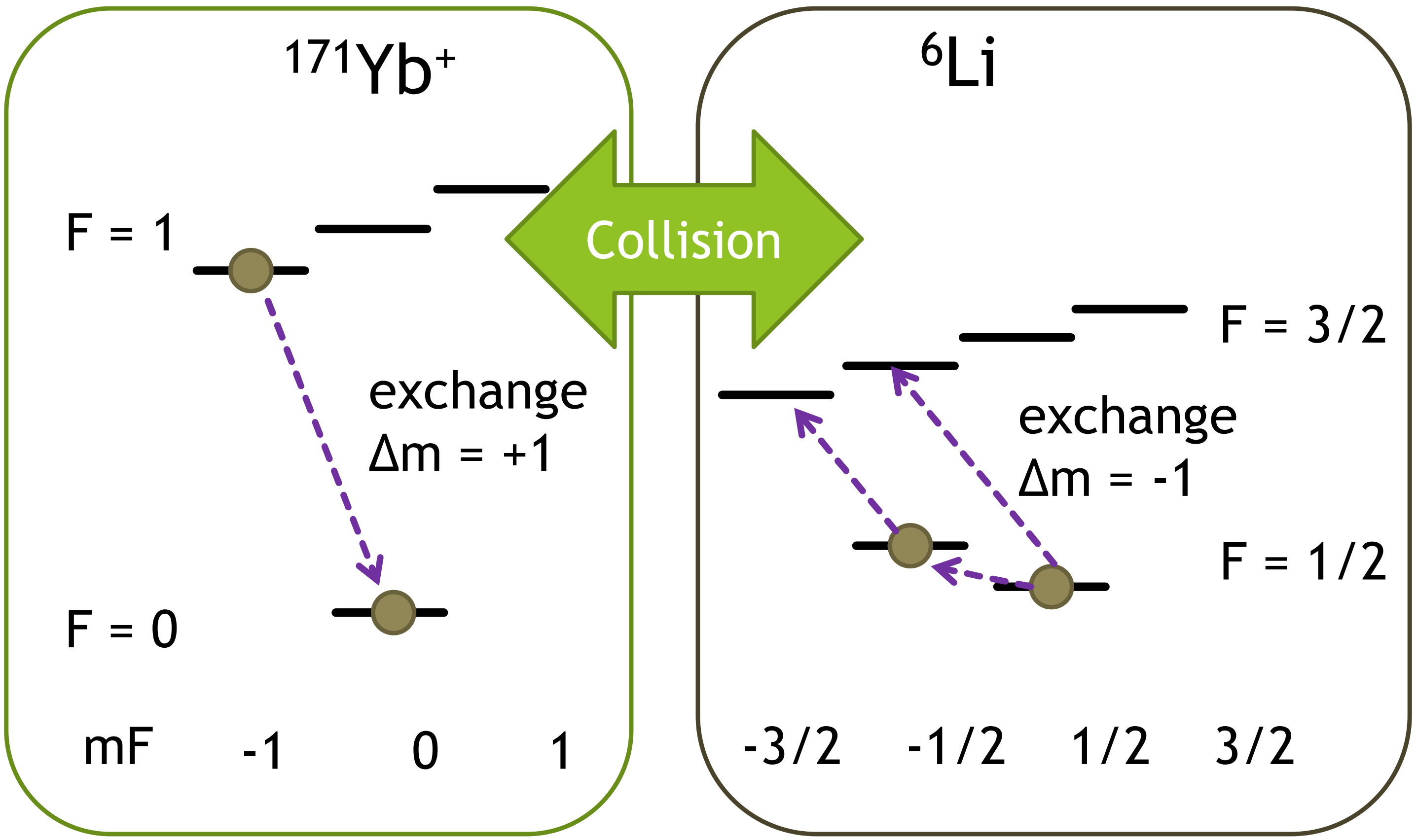

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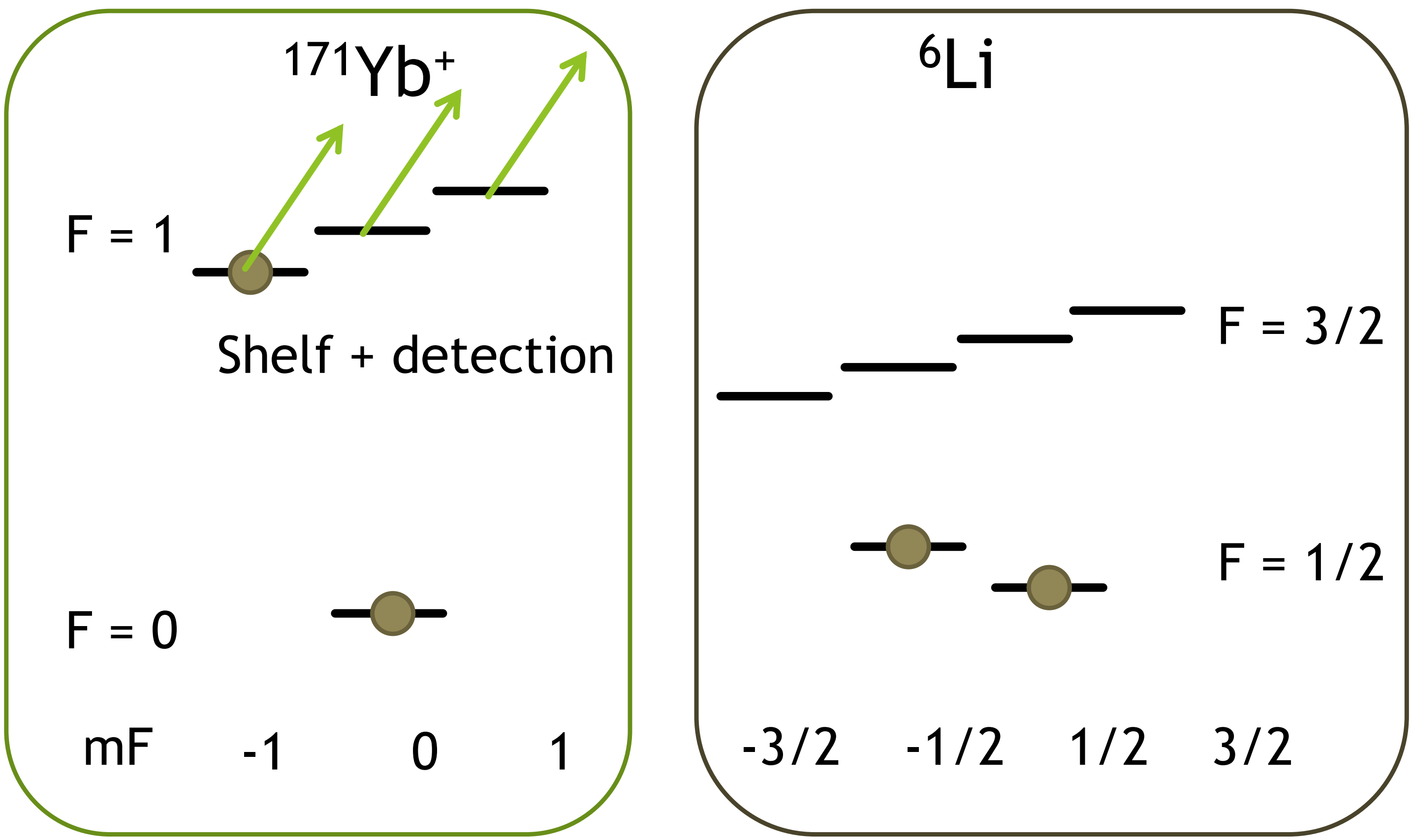
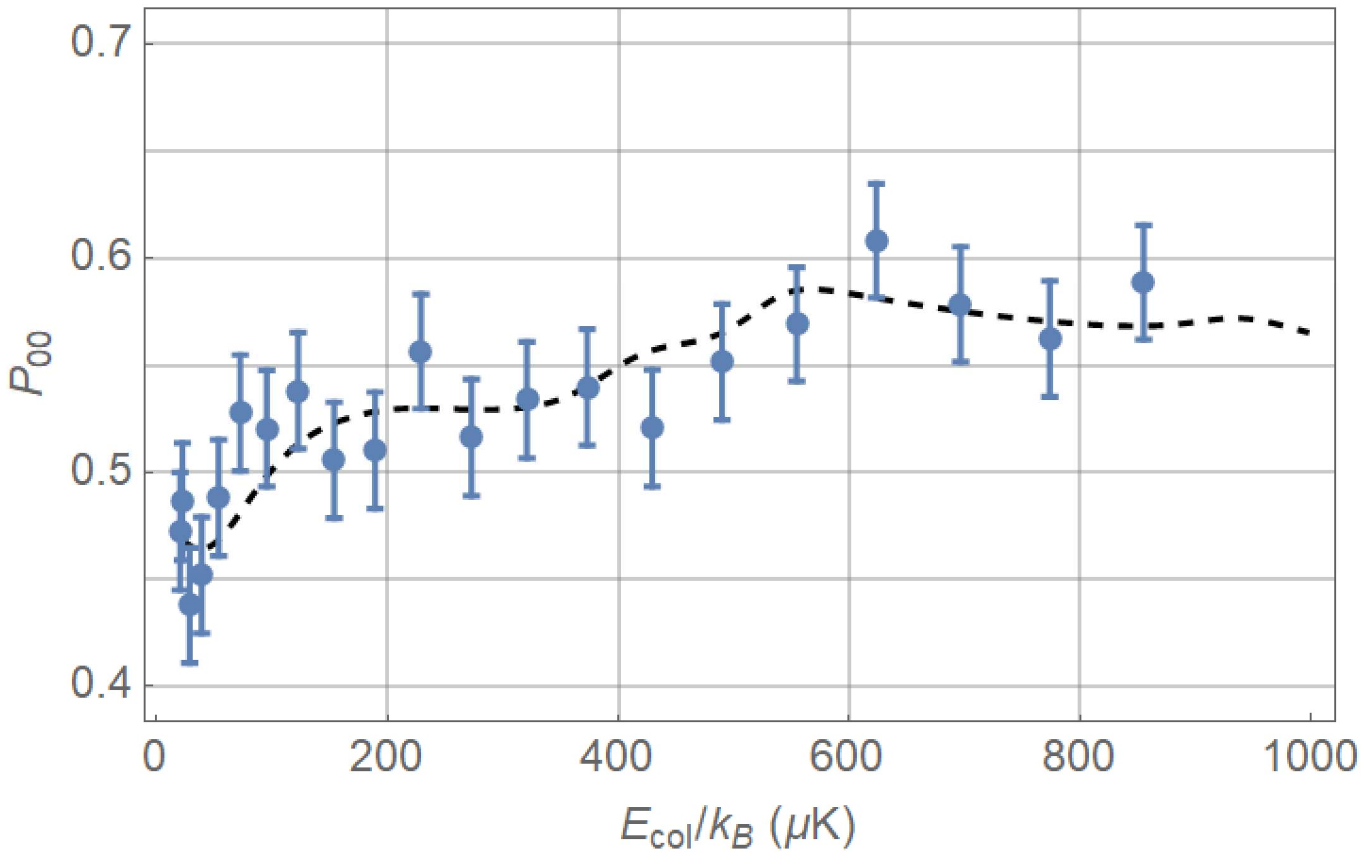


Quantum effects in atom-ion collisions?

→ Scan collision energy via radial excess MM



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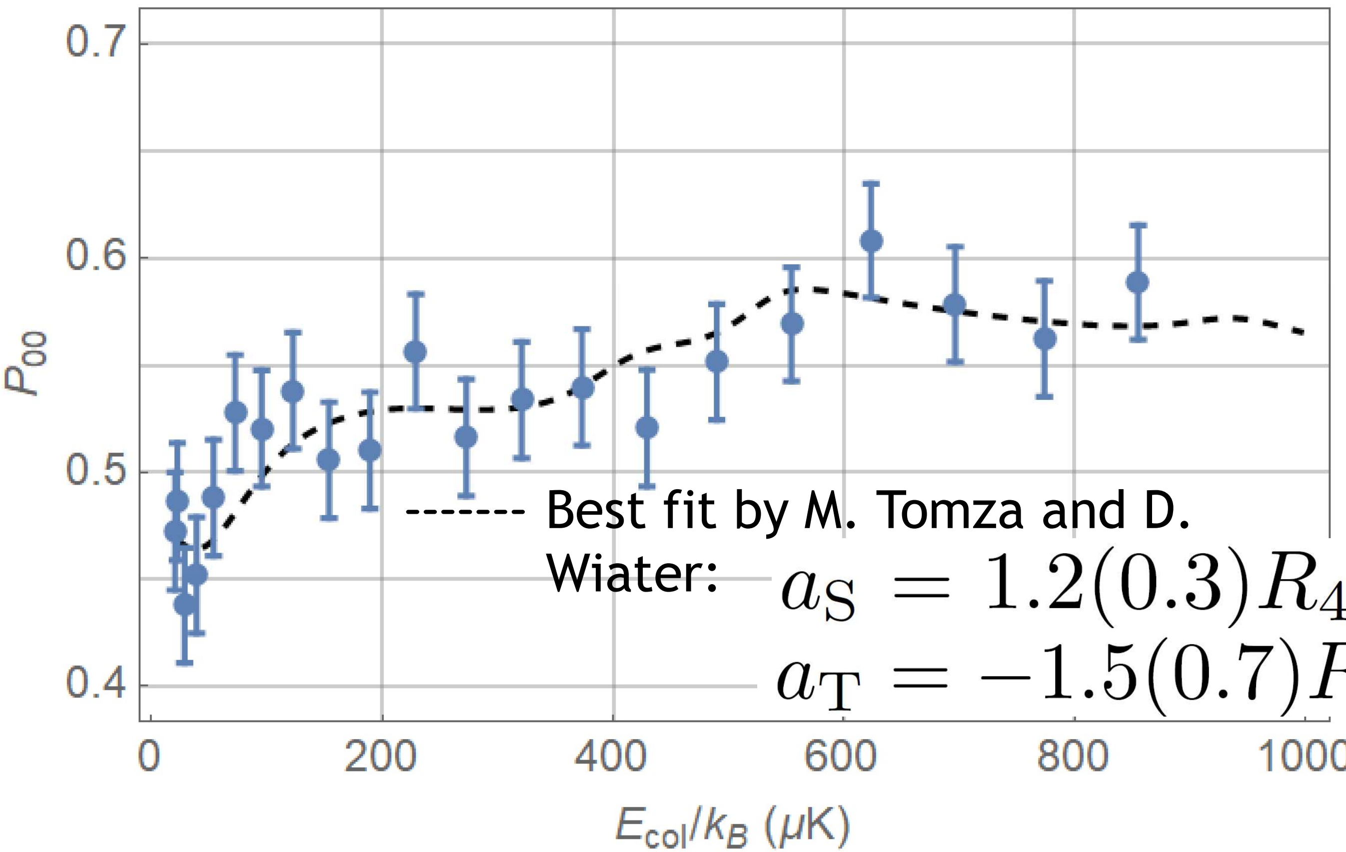


------- Best fit by M. Tomza and D. Wiater:

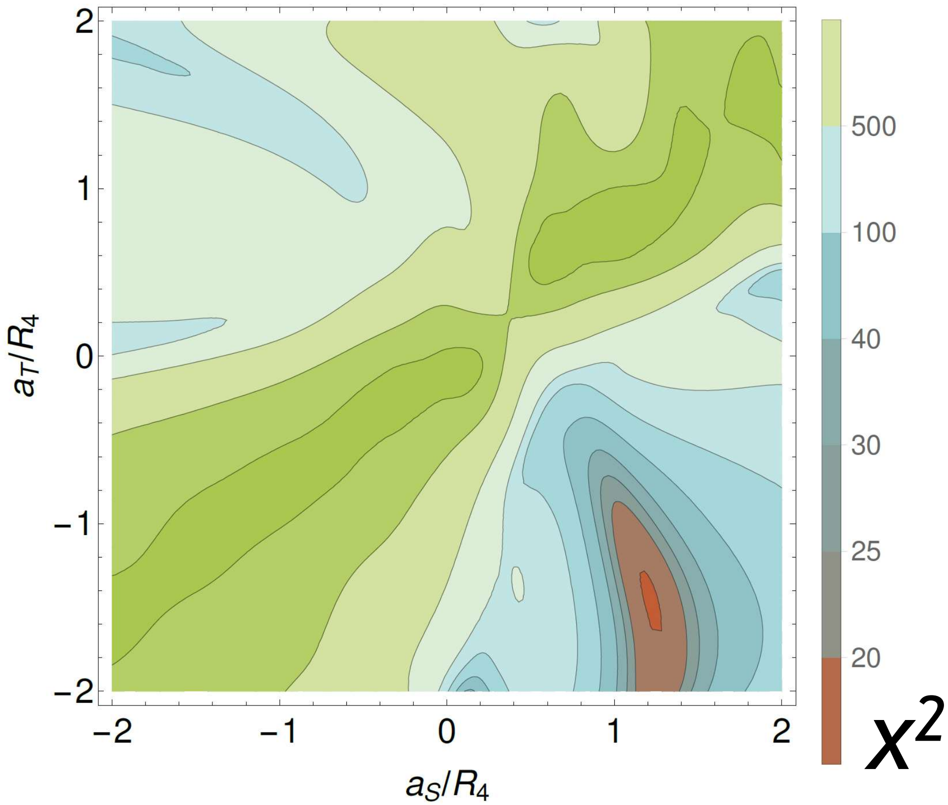
$$a_S = 1.2(0.3)R_4$$
$$a_T = -1.5(0.7)R_4$$

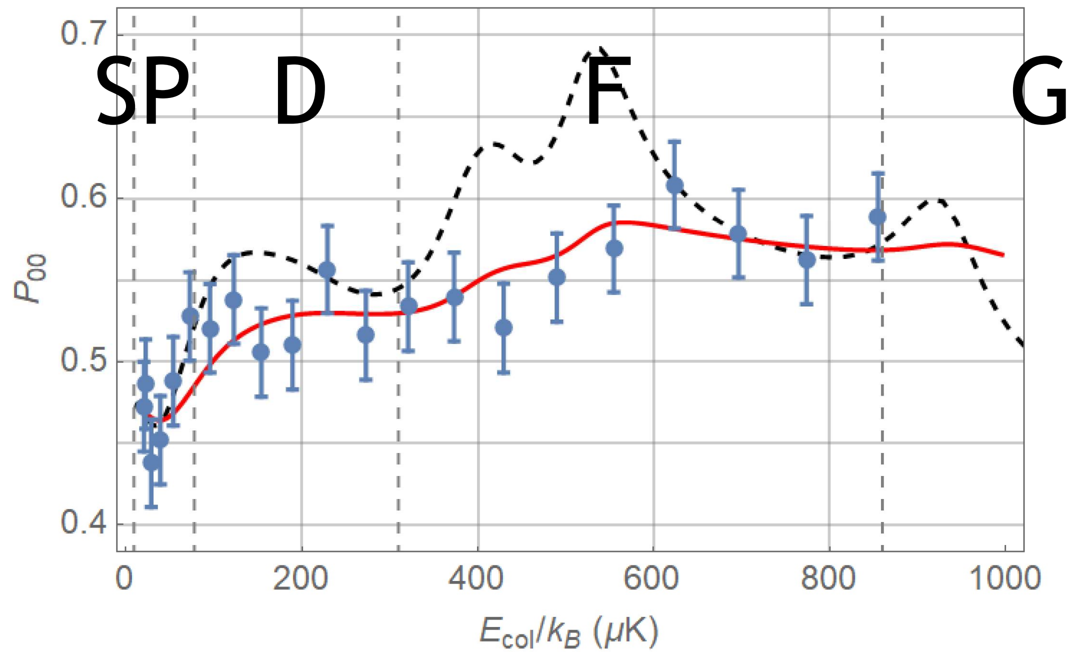
} Scattering lengths

R_4 = 1320 a_0

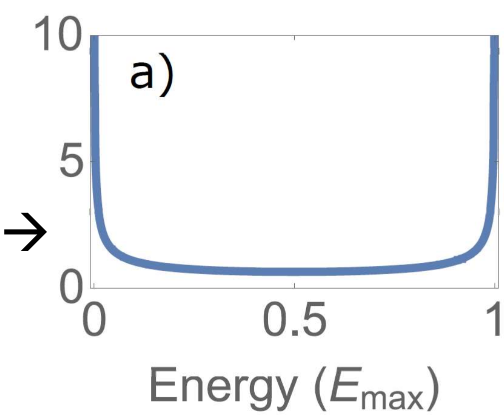
Estimates on scattering lengths

Work by M. Tomza and D. Wiater





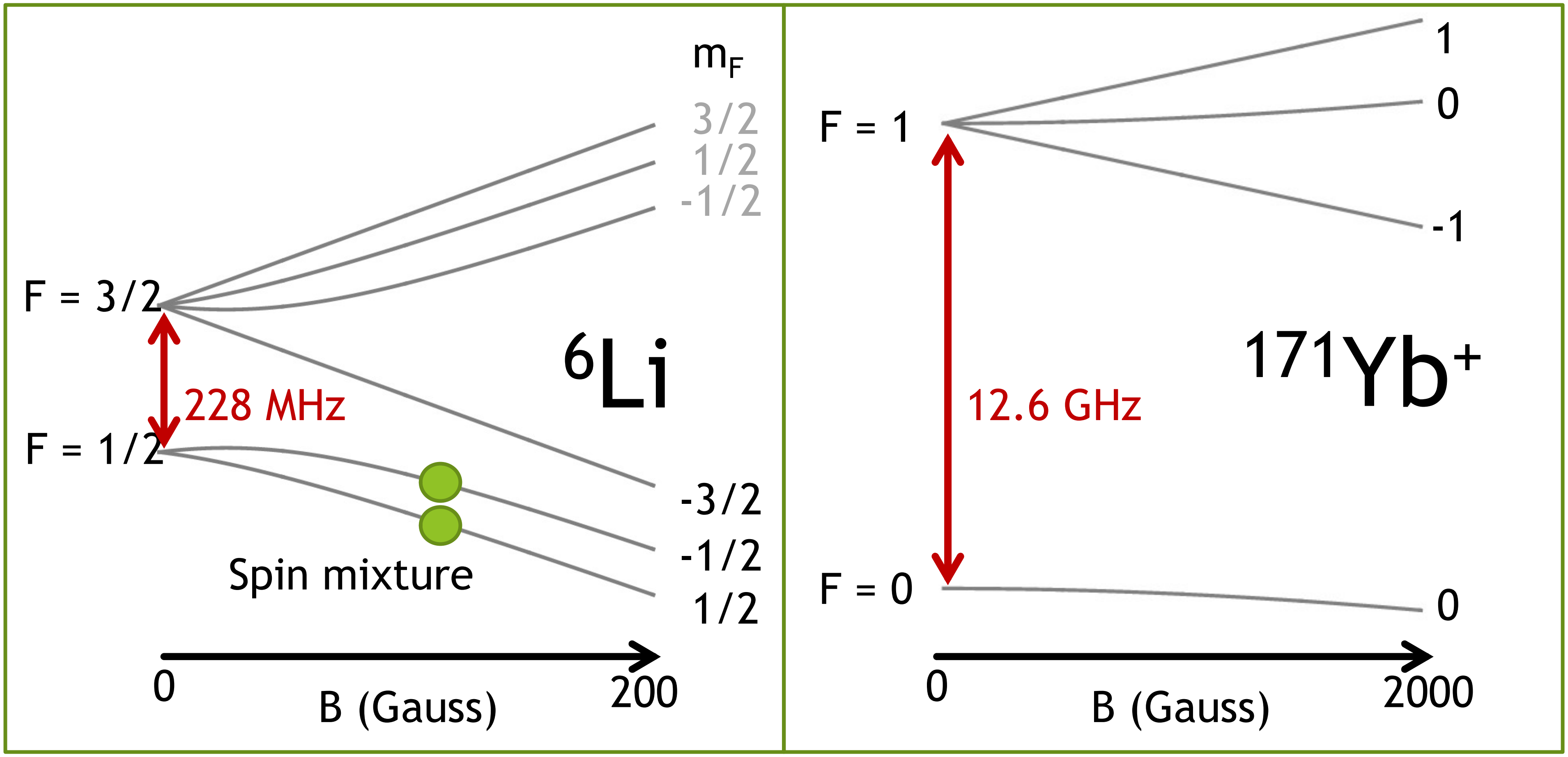
Energy distribution →



Note: almost every collision results in spin-exchange!

T. Feldker et al., *Nature Physics, 16, 413-416 (2020)*.

Candidates for Feshbach in $Yb^+/^6Li$



Spin-exchange: $|1,-1\rangle_{ion}|1/2,1/2\rangle_{atom} \longleftrightarrow |1,0\rangle_{ion}|1/2,-1/2\rangle_{atom}$

B < 15 G, v = -1 → low field, strong resonance

Motion ($^{174}Yb^+$): $|1/2,-1/2\rangle_{ion}|1/2,1/2\rangle_{atom} \longleftrightarrow |1/2,1/2\rangle_{ion}|1/2,-1/2\rangle_{atom}$

B < 10 G, v = -1 or B = 10-50 G for v = -2

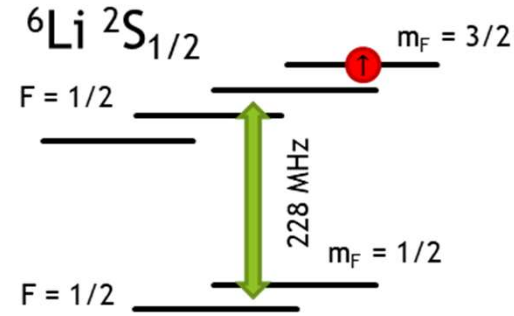
Spin dynamics in atom-ion mixtures

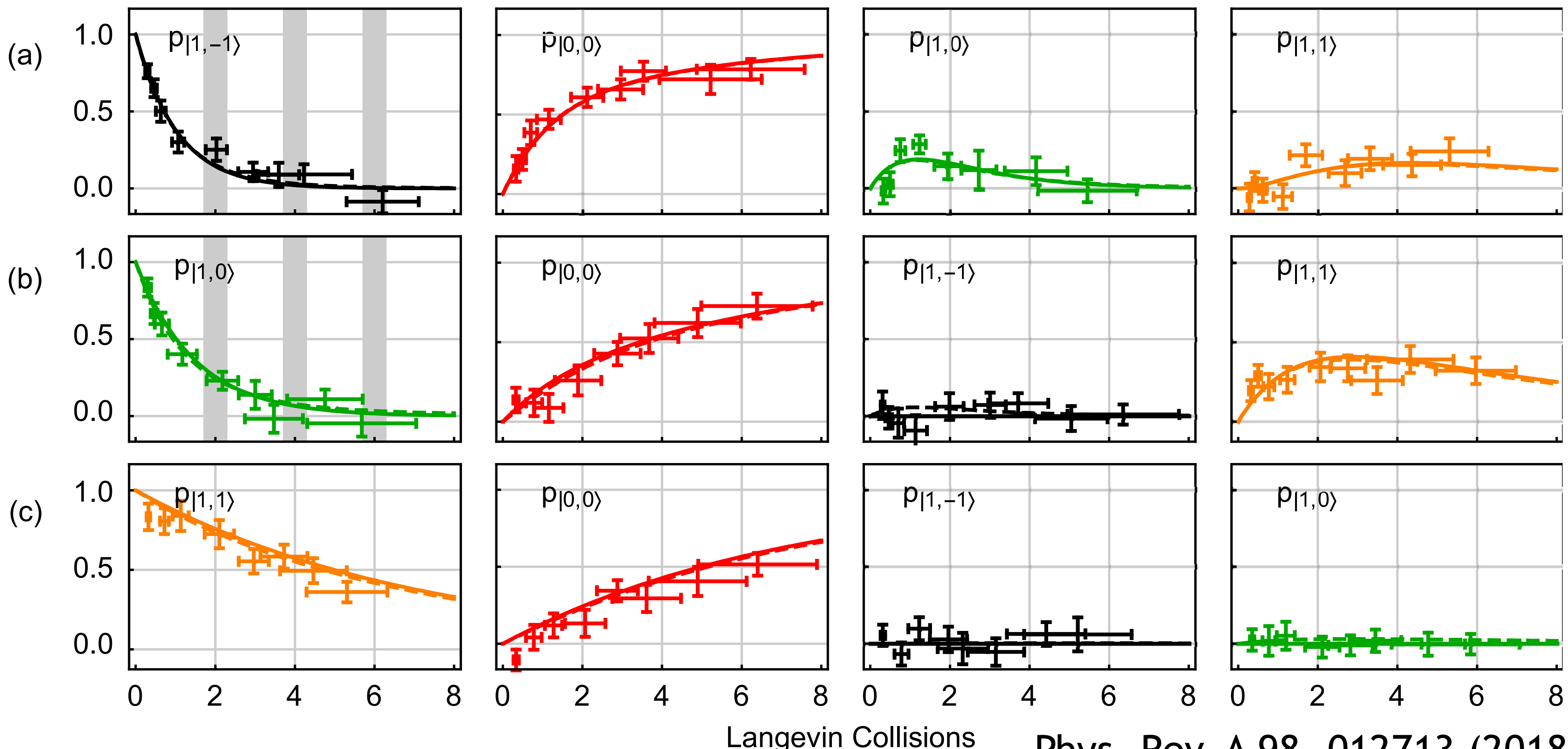
→ Things are a bit different than in neutral mixtures….

From: L. Ratschbacher, C. Sias, L. Carcagni, J. M. Silver, C. Zipkes, and M. Köhl Phys. Rev. Lett. 110, 160402 (2013).

Spin dynamics of $^{171}Yb^{+}$

These results are for 600 μK atoms in the $\left|\frac{3}{2}\,\frac{3}{2}\right\rangle$ stretched state





Phys. Rev. A 98, 012713 (2018)

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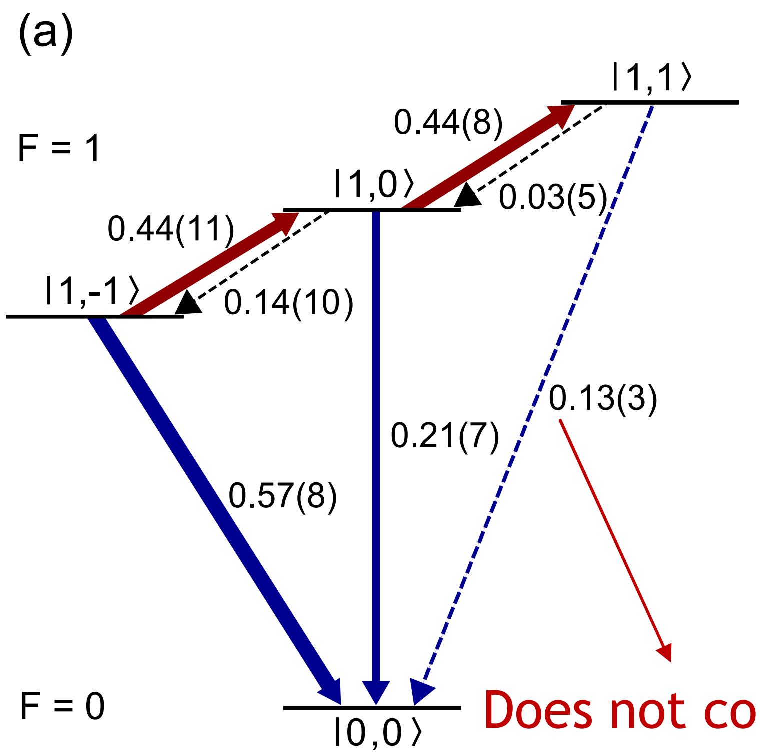
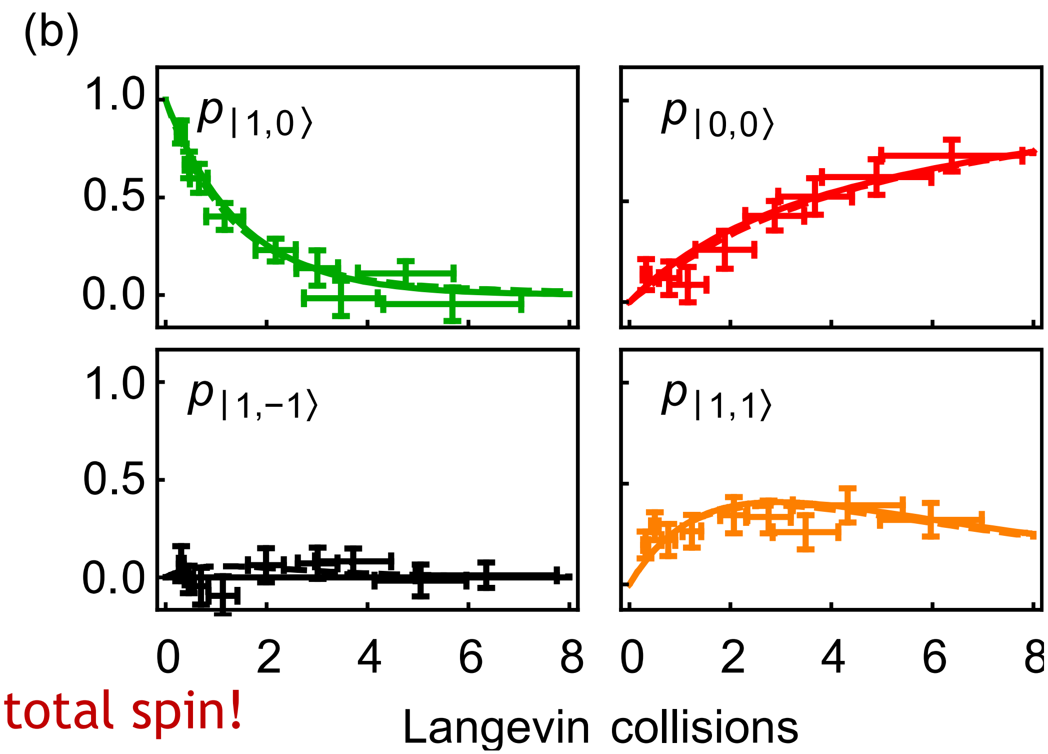


Does not conserve total spin!



$^{171}Yb^{+}$ $^{2}S_{1/2}$ hyperfine ground states and transition rates in units of the Langevin rate

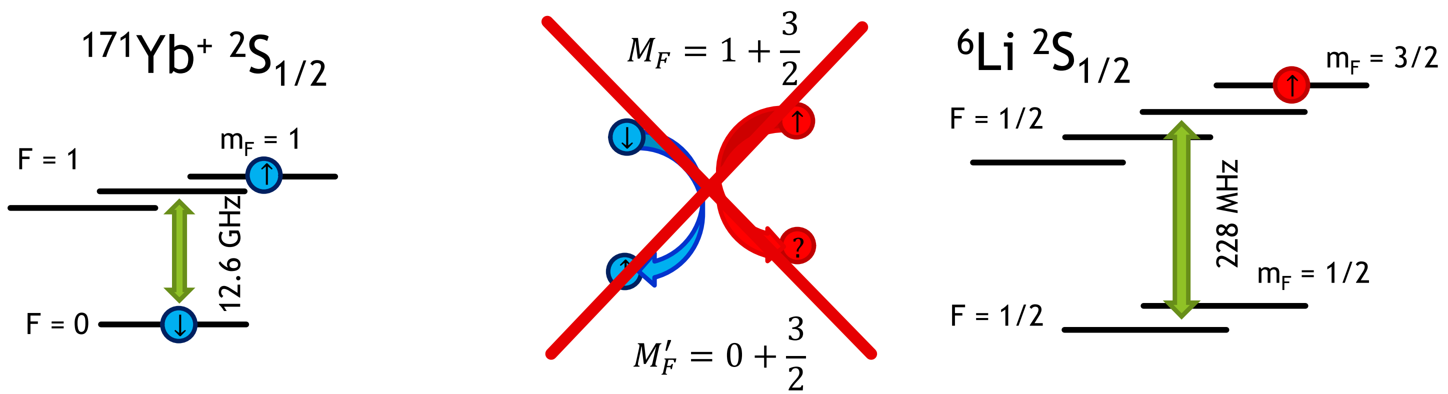
Population dynamics for starting in the $^{171}Yb^{+}$ $^{2}S_{1/2}$ $|1,0\rangle$ state

- Almost every Langevin collision flips the Spin when in $|1,-1\rangle$

Phys. Rev. A 98, 012713 (2018)

Spin exchange and relaxation

- Hyperfine qubit in $^{171}Yb^{+}$ + ^{6}Li:



These states should be protected by spin and energy conservation

→ But they are not, what is happening?

Previous Work on Rb-Yb^+ and Rb-Sr^+

L. Ratschbacher et al., Phys. Rev. Lett. **110**, 160402 (2013)
T. Sikorski et al., Nature Communications. 9, 920 (2018)

Rb in streched state $|1,1\rangle_a$
Yb ion in either $|{}^1/_2, {}^1/_2\rangle_i$ or $|{}^1/_2, -{}^1/_2\rangle_i$

Yb^+ is in a mixed state after interaction
→ Spin relaxation dominates exchange
→ total spin is not conserved!

Similar results in Rb-Sr^+: Exchange is 5 times faster than relaxation

Mechanism

Second order spin-orbit coupling T. V. Tscherbul et al., Phys. Rev. Lett. **117**, 143201 (2016)

Causes effective spin-spin interaction
Made worse by crossing of potential lines and heavy ions
→ **qubits in atomic gases seems not sustainable**

Controlling the interactions between atoms and ions

- Feshbach resonances
- Rydberg dressing

↑ The group of Tobias Schaetz observed Feshbach resonances between ^6Li and Ba^+
Nature 600, 429–433 (2021).

Controlling the interactions

→ Interaction between atoms and ion proportional to polarizability

$$V_{a,i}(r) = -\frac{C_4}{2\,r^4}$$

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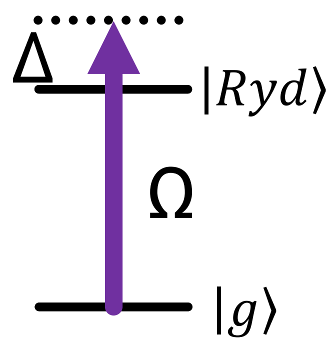


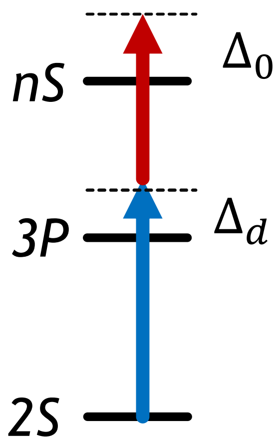
Rydberg dressing: Polarizability scales as *n^7*

Can be many orders of magnitude larger even for weak dressing

Rydberg dressing and ions

→ Weakly couple atom to Rydberg state → increased range and strength of potential, but not limited by Rydberg lifetime

$$H_{3-level} = \begin{pmatrix} 0 & \hbar\Omega_d(\mathbf{r}_a) & \hbar\Omega \\ \hbar\Omega_d(\mathbf{r}_a) & -\hbar\Delta_d & 0 \\ \hbar\Omega & 0 & -\hbar\Delta_0 - \frac{C_4^{|R\rangle}}{R^4} \end{pmatrix}$$



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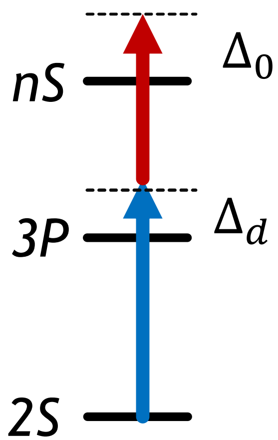
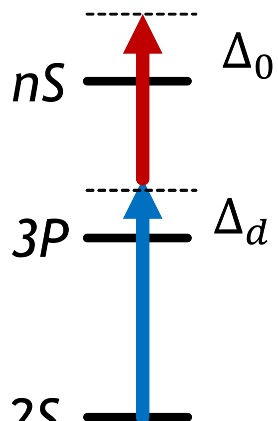
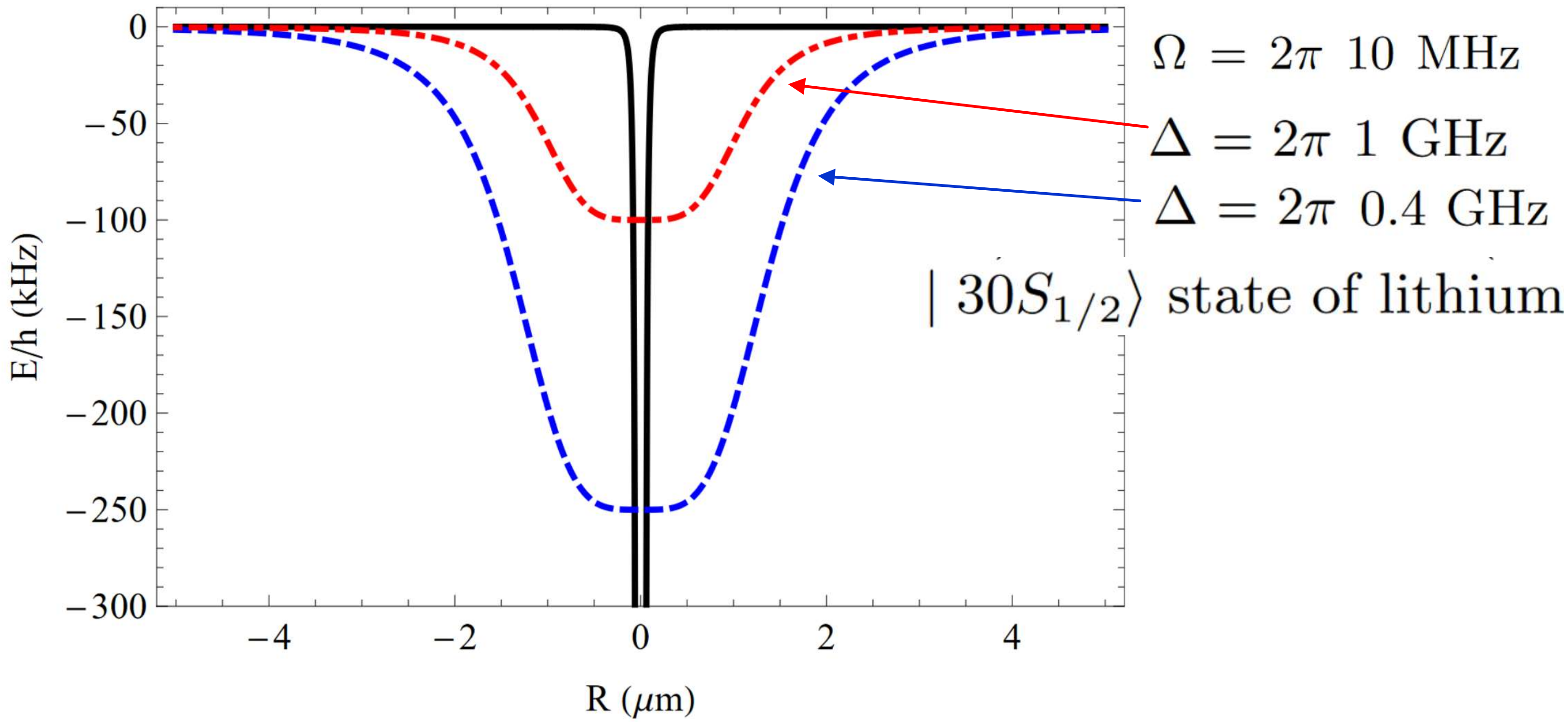


Neglect ground state atom-ion interaction

Rydberg polarizability

Rydberg dressing and ions





$$V(R) = -\frac{AR_w^4}{R^4 + R_w^4}$$ ← Adiabatic potential

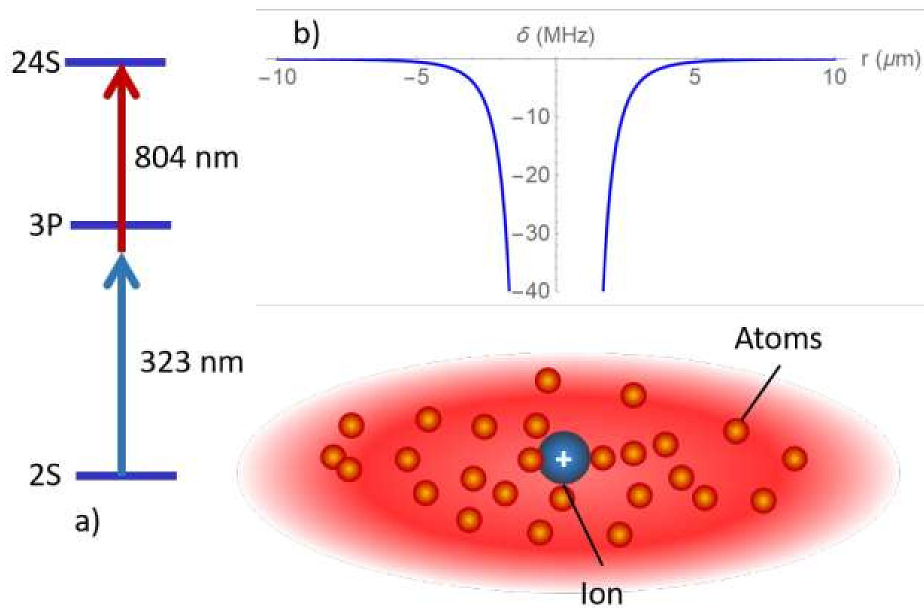
$$A = \hbar\Omega^2/\Delta_0$$

$$R_w = (C_4^{|R\rangle}/\hbar\Delta_0)^{1/4}$$

PRA 94, 013420 (2016)

Let's try it: start with Rydberg excitation

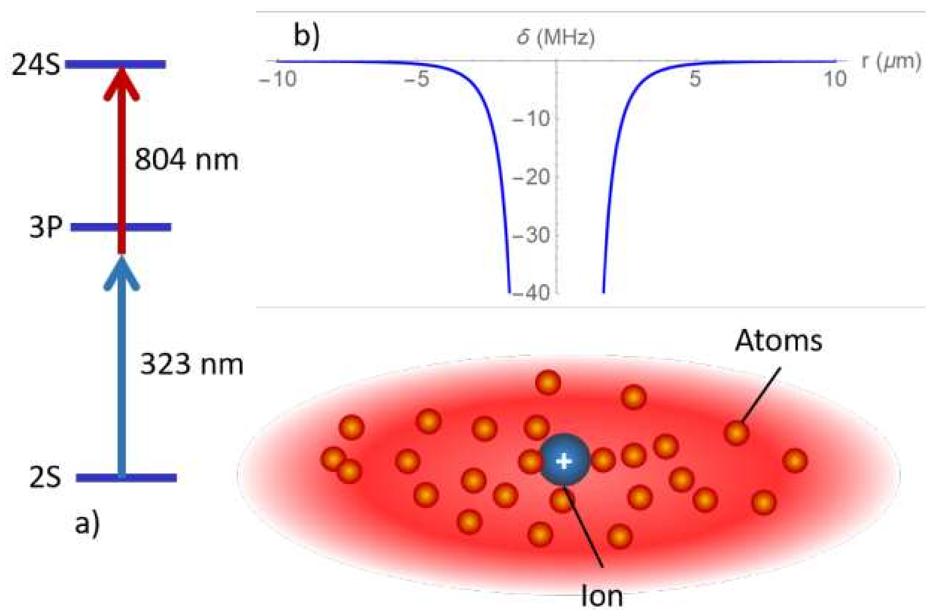
→ Two photon Rydberg excitation to $24S_{1/2}$
→ Image atoms and ions



Polarizability of 24S state is about 10^8 times larger than for the ground state

Exciting Rydbergs

→ Two photon Rydberg excitation to $24S_{1/2}$
→ Image atoms and ions: Losses?



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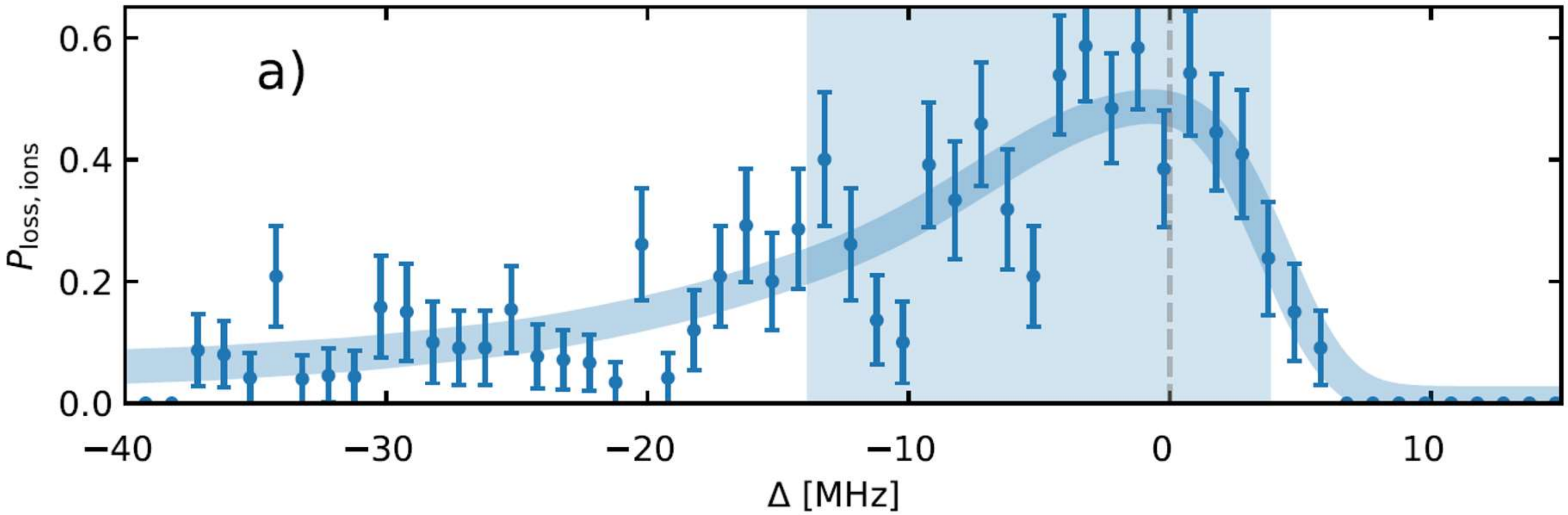
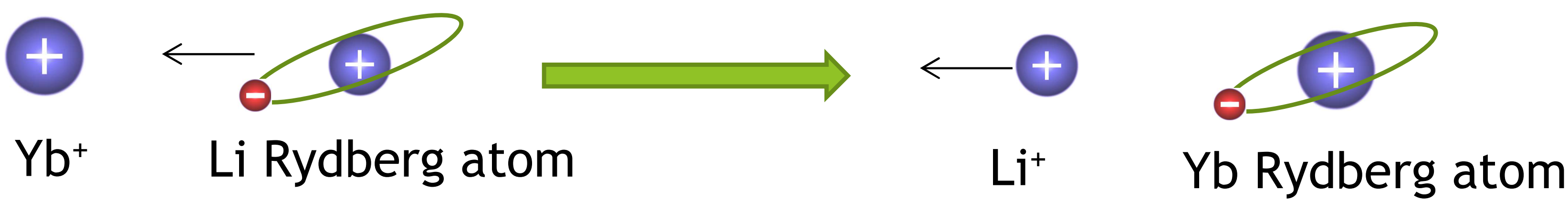
Rydberg atom-ion interactions

Ion loss spectrum for 20 μs excitation pulse





Rydberg atom-ion interactions

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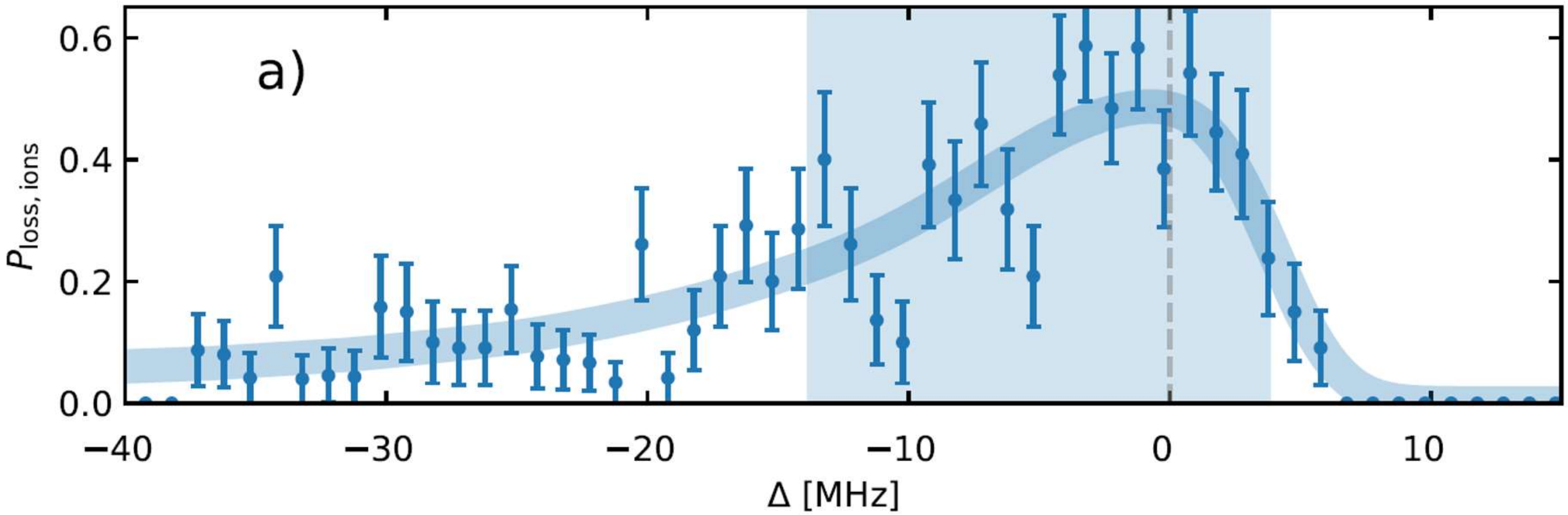

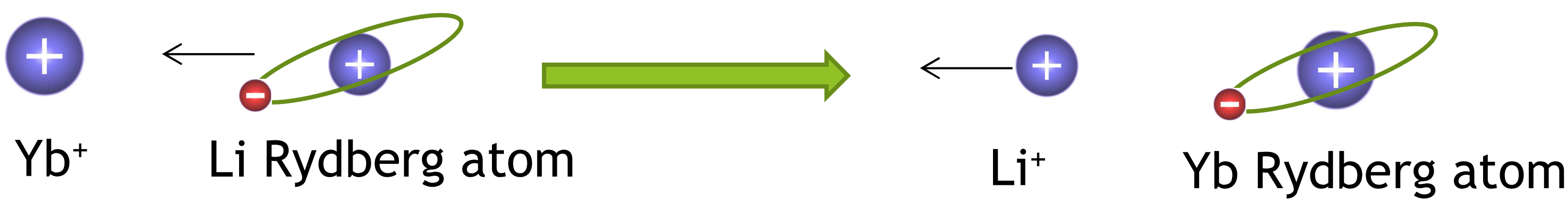

Ion loss exceeds Langevin collision rate for ground state atoms by factor ≈10^3
We have boosted the interaction strength!

Repulsive interactions

→ **We boosted the interactions ☺, but we lose our ions ☹**
→ **We should use repulsive interactions: Prevent charge transfer**

Rydberg state with opposite dipole moment

Unfortunately in Li, transitions to such states are not allowed

Repulsive interactions

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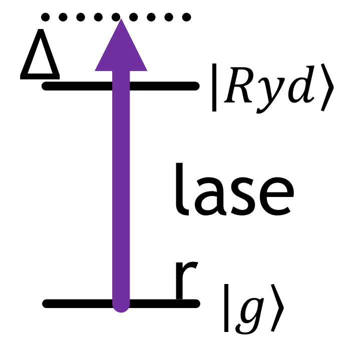
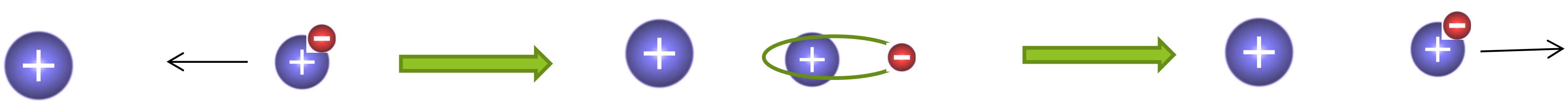
Rydberg state with opposite dipole moment



Unfortunately in Li, transitions to such states are not allowed

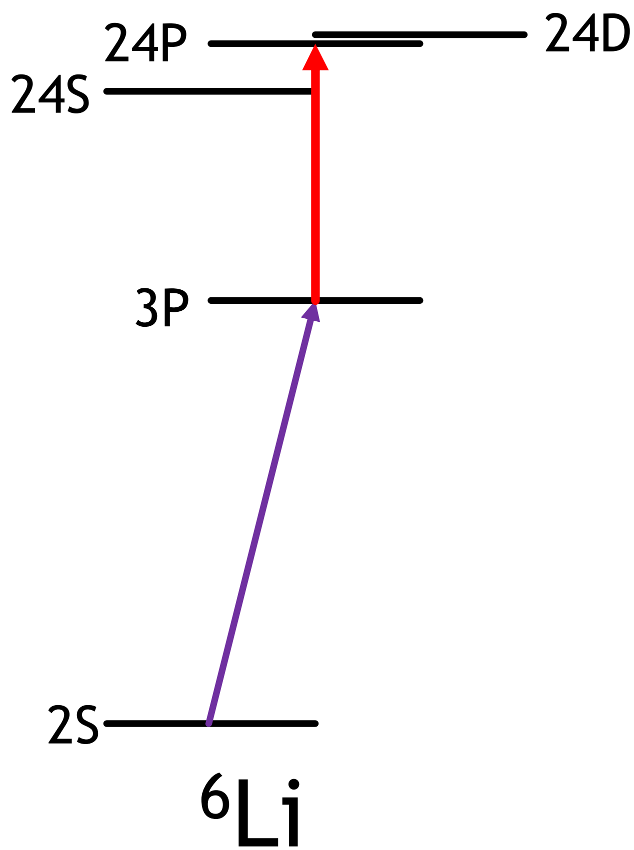
Unless of course, the atom is in a strong electric field

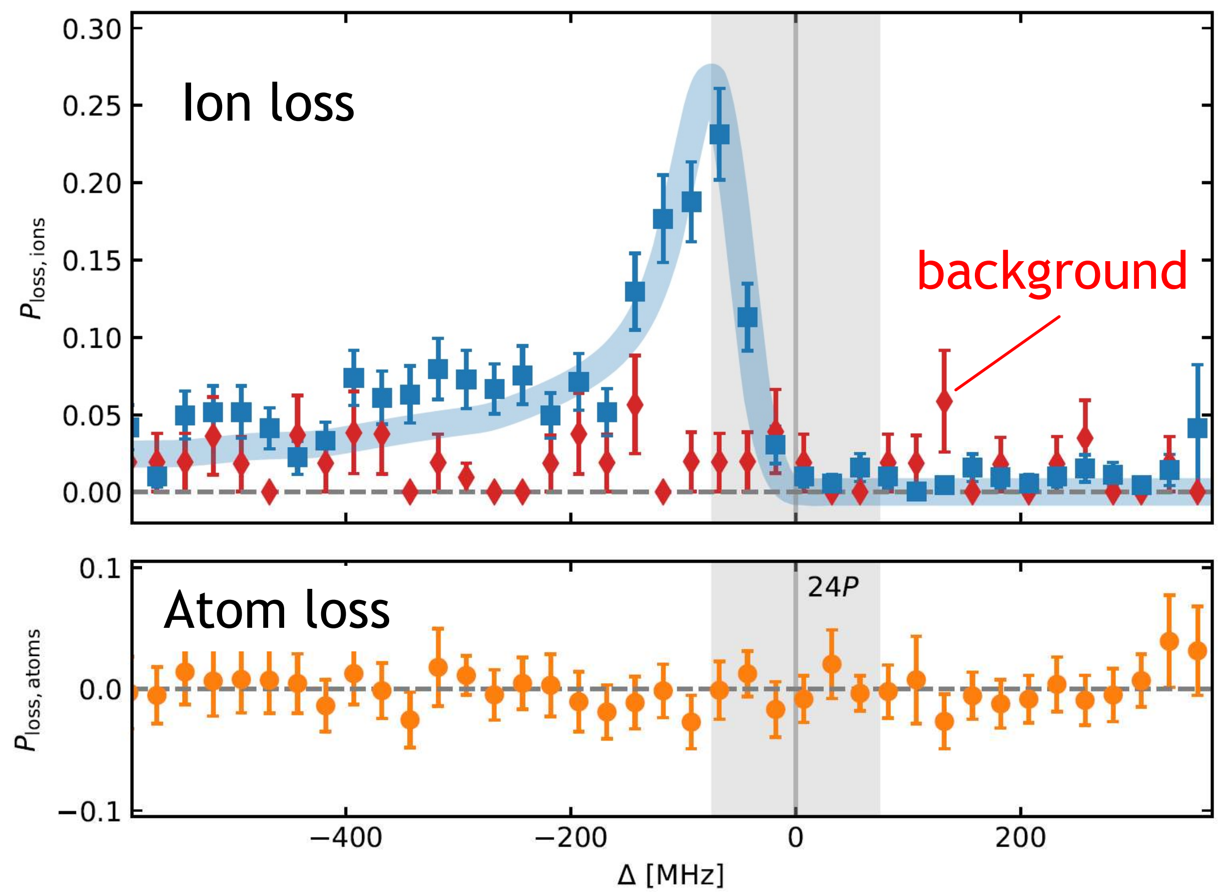


ion Atom Rydberg atom

Phys. Rev. Lett. 118, 263201 (2017).

Excitation on a dipole forbidden transition in the field of a single Ion: first attempt

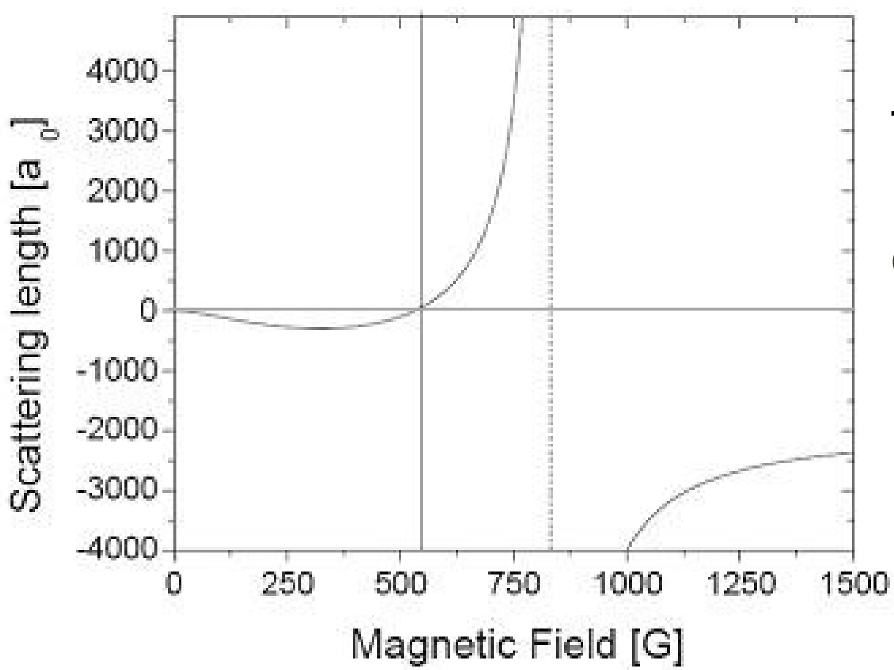




Note: The P state has the wrong sign of the polarizability so we still lose ions
Prospect: Engineer repulsive interaction

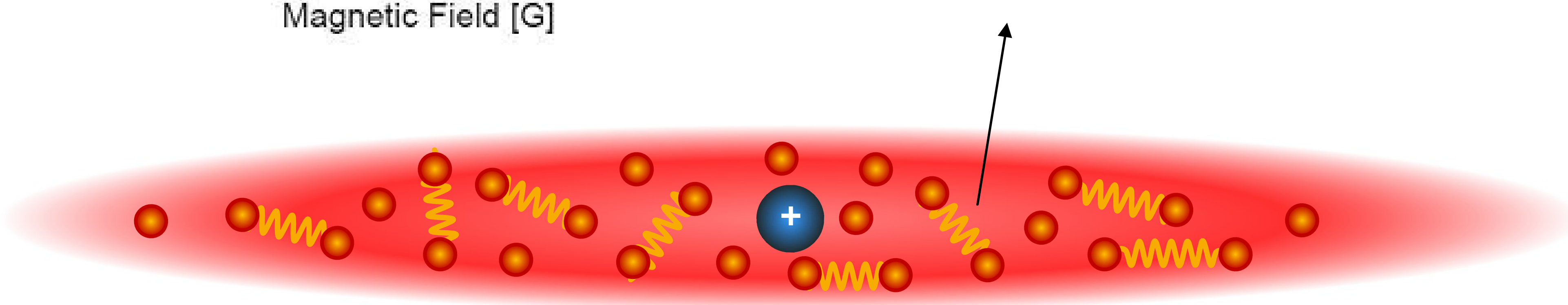
Phys. Rev. Lett. 122, 253401 (2019).

Now for some chemistry

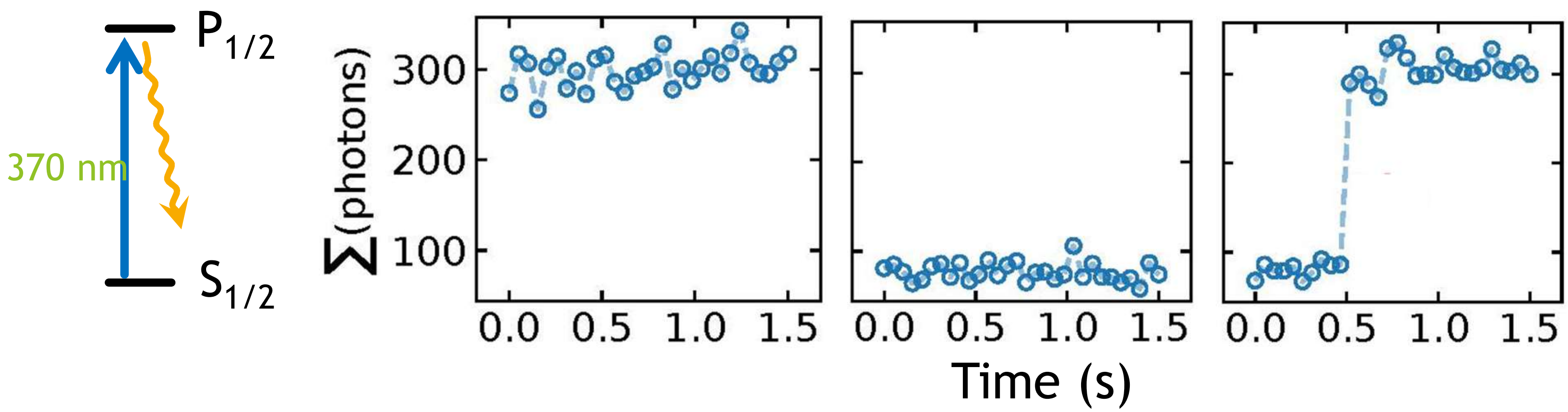


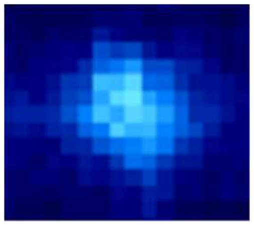
← ^{6}Li Feshbach resonances
Taken from R. Grimm:
Proceedings of the International School of Physics "Enrico Fermi"

Trace amounts of Li_2 dimers
Due to Li + Li' + Li ⇔ Li_2 + Li



Ion in a bath of Feshbach Dimers





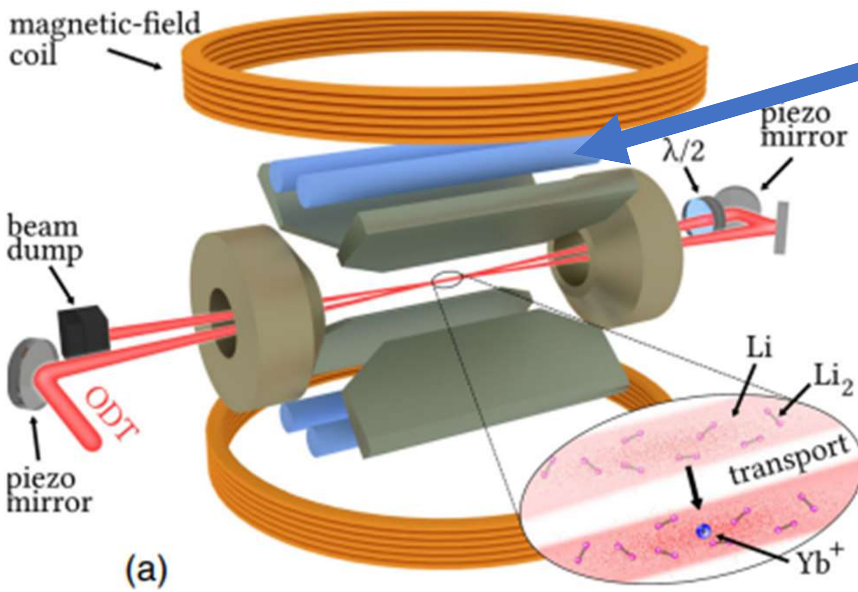
$LiYb^+$

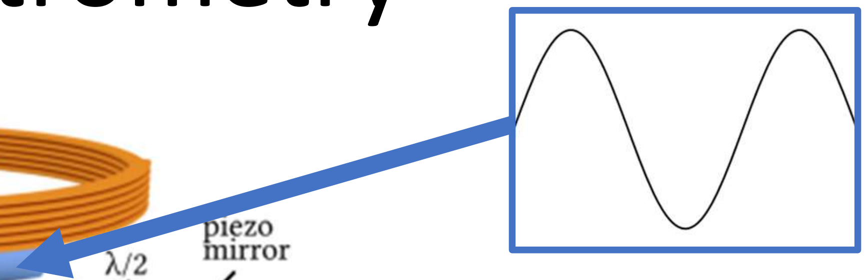
$Li + Li + Yb^+ \rightarrow LiYb^+ + Li$

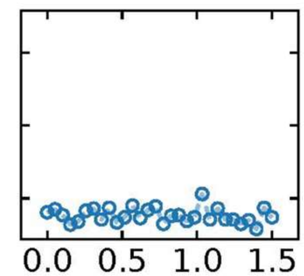
$Li_2 + Yb^+ \rightarrow LiYb^+ + Li$

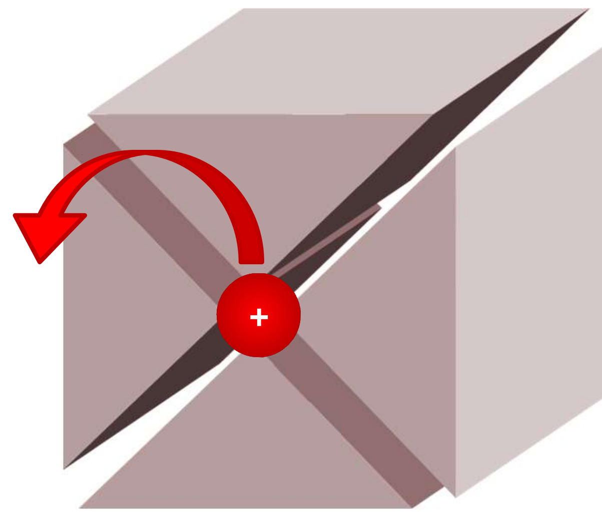
H. Hirzler et al, Phys. Rev. Lett. 128, 103401 (2022).

Mass Spectrometry



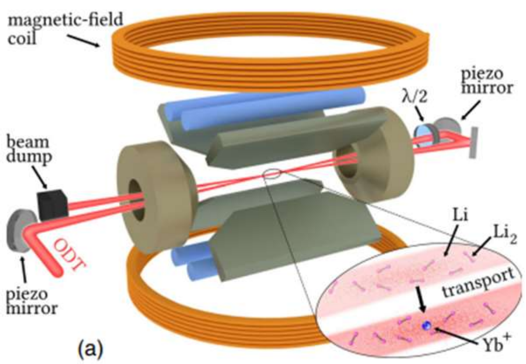




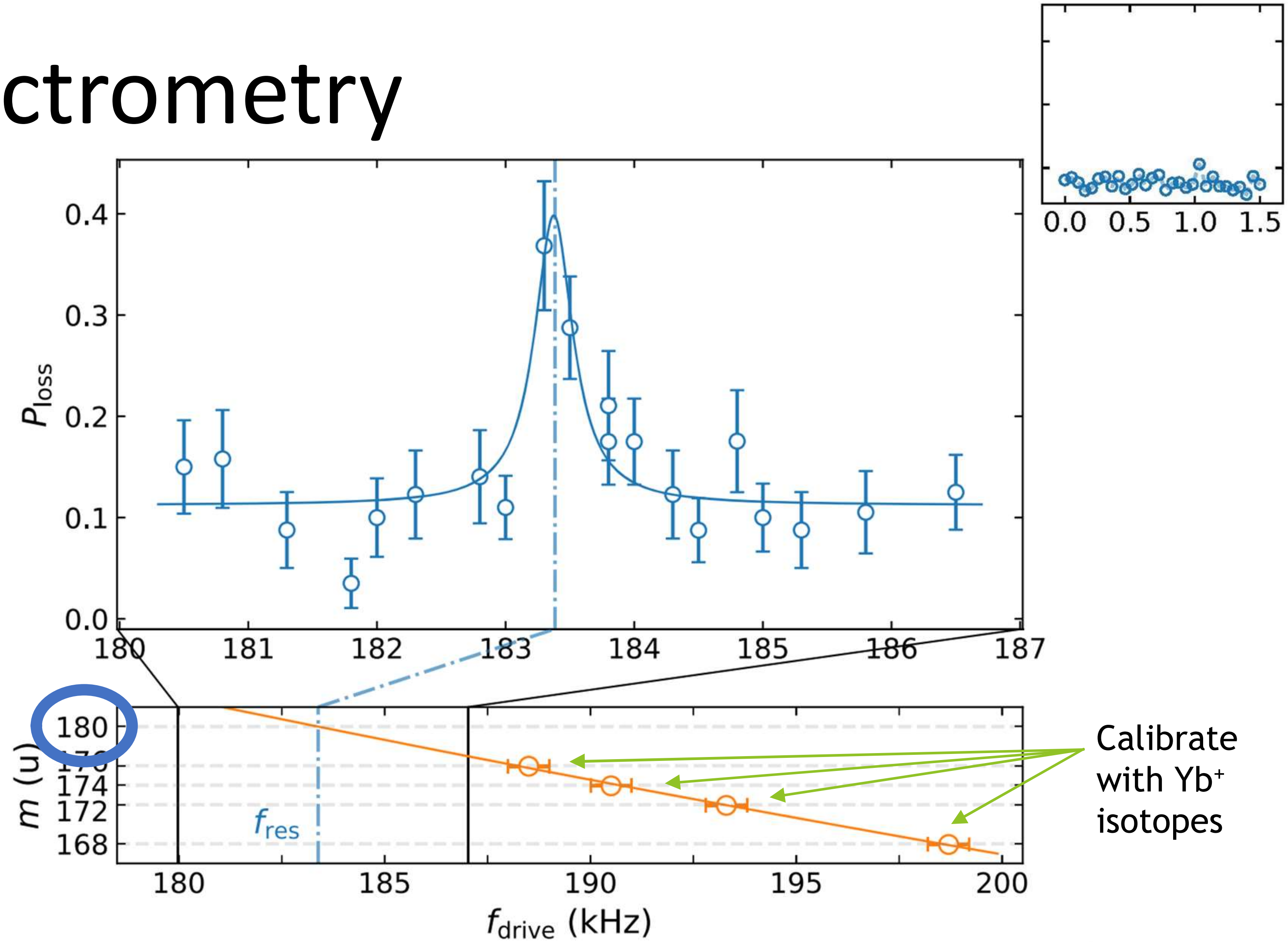


H. Hirzler et al, Phys. Rev. Lett. 128, 103401 (2022).

Mass Spectrometry

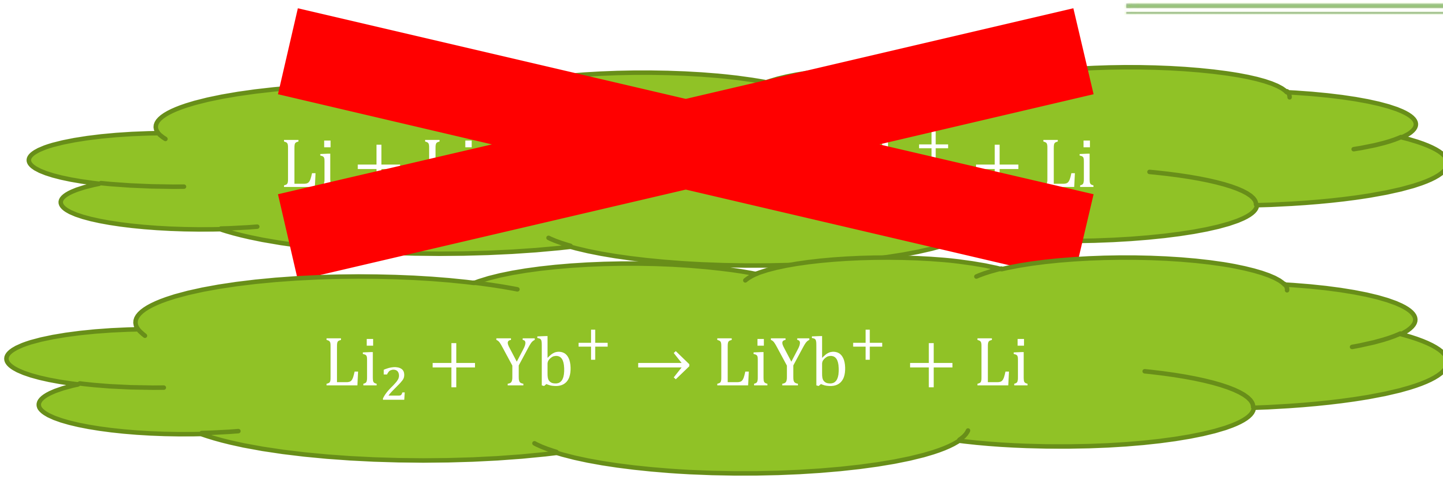


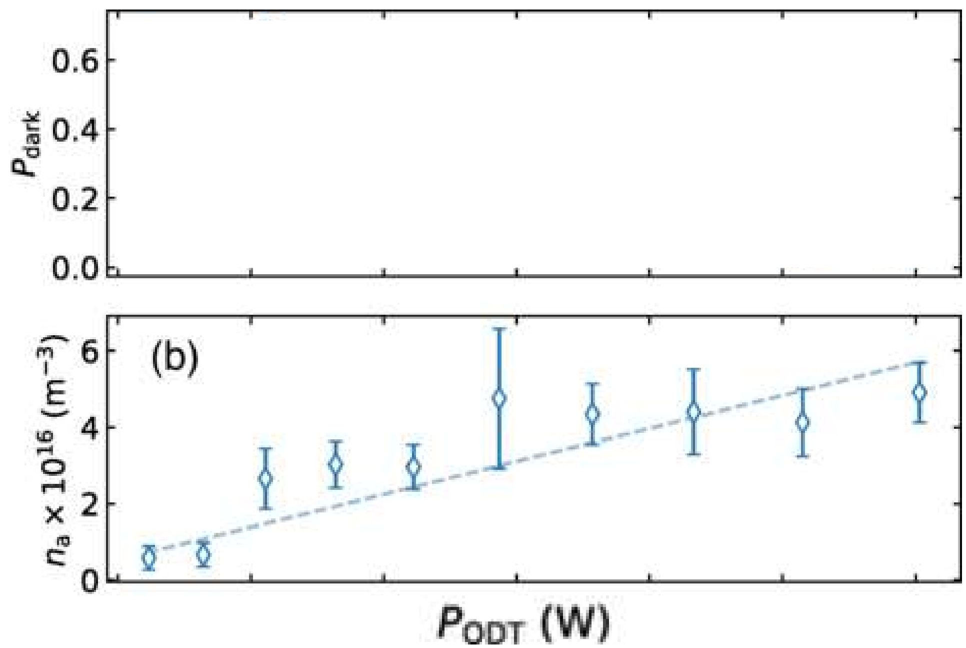
LiYb$^+$



Calibrate with Yb$^+$ isotopes

H. Hirzler et al, Phys. Rev. Lett. 128, 103401 (2022).



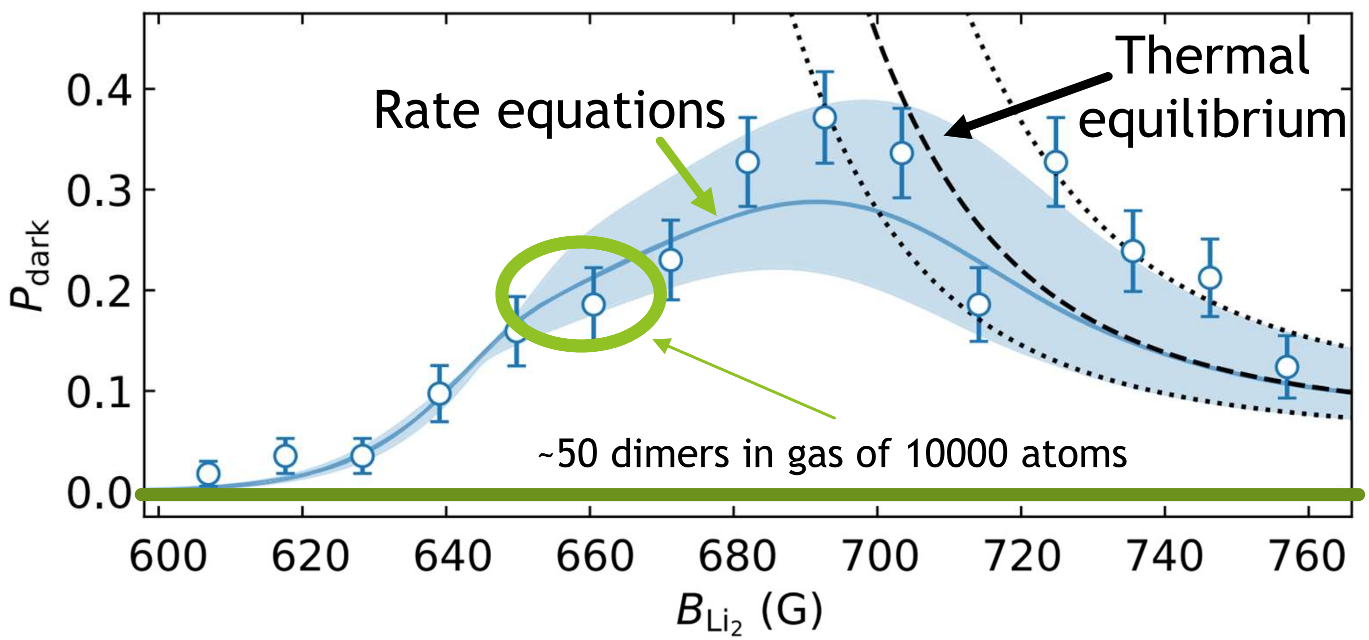


Change $P_{ODT}(W)$

Change in atom density

Change in LiYb+ formation?

Dimer Density



Change B (G)

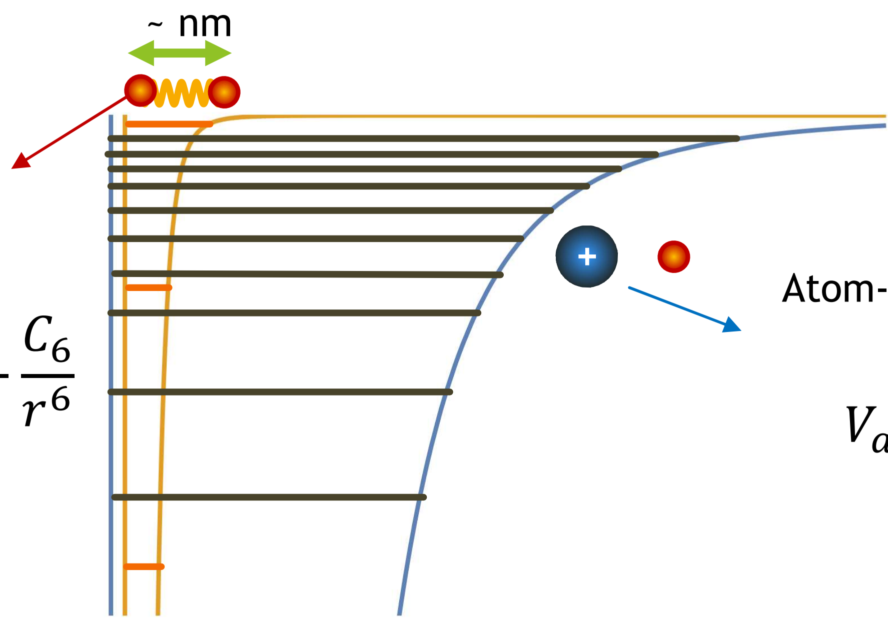
Change in dimer density

Change in LiYb+ formation

→ No fit parameters, but we assume all dimer-ion collisions lead to dark ions

Theory based on: Jochim et al., Science **302** (2003); Chin and Grimm, PRA **69** (2004);

Density of states



Atom-atom potential

$$V_{a-a}(r) = -\frac{C_6}{r^6}$$

Atom-ion potential

$$V_{a-i}(r) = -\frac{C_4}{r^4}$$

→Density of states much larger for atom-ion potential
→Expect molecular ions to be formed

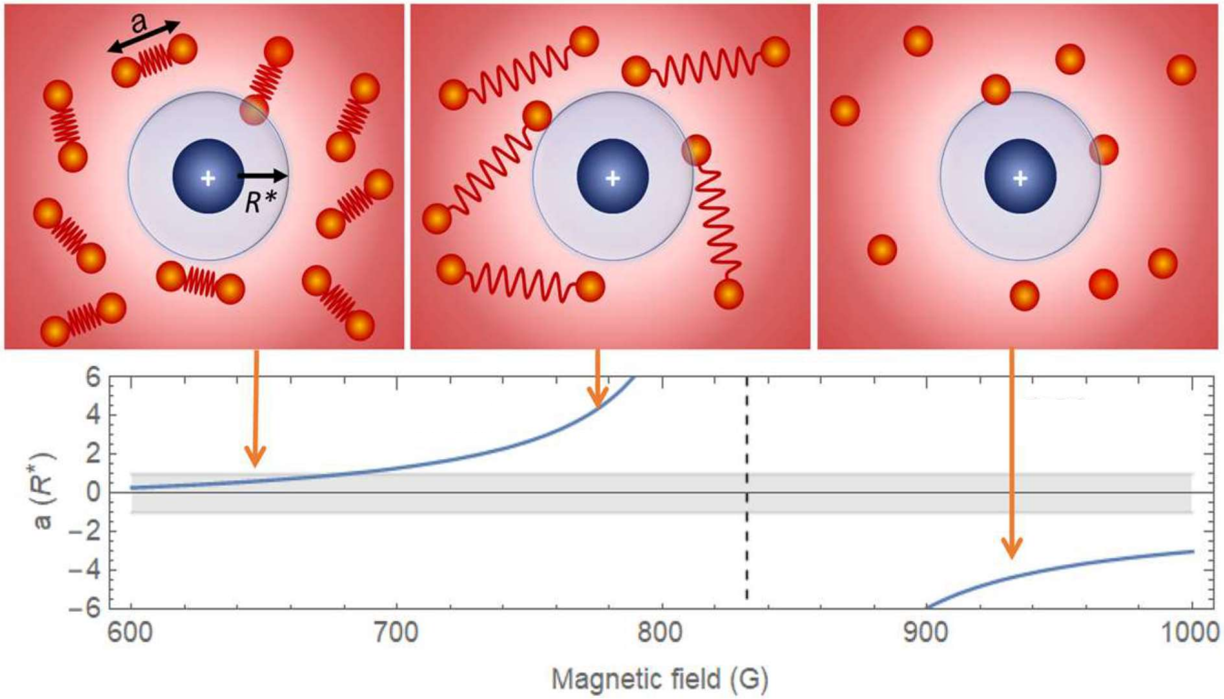
Feshbach dimers

← Taken from
Chin et al., RMP 82, 1225 (2010).

Li_2 dimers created by
three-body recombination

Up until now, we ramp the B-field to 0....

Trapped ions in a bath of Feshbach dimers



→Tune size of Feshbach dimers with magnetic field

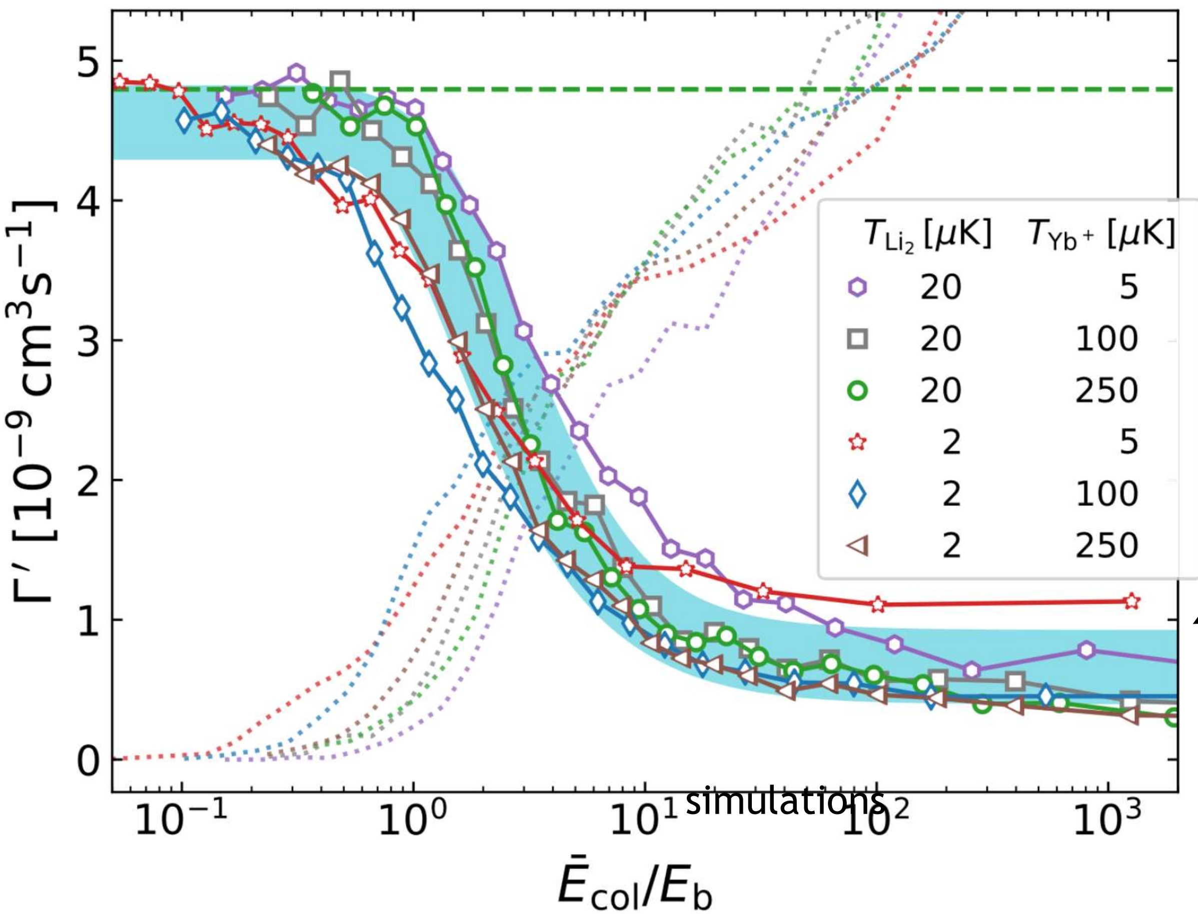
→Interesting crossover of length scales: $E^*_{atom\text{-}ion} = E_{binding\ Li\text{-}Li}$ @ B = 704 G

→Crossover from atom-ion to molecule-ion collisions

Theory

Yb⁺ + Li + Li

Our data is for B = 0 up until now



(LiYb)⁺ + Li

→Efficient creation of molecular ions!

→Impurity physics on BEC side: losses?

→Quantum effects?

Classical theory by:
H. Hirlzer and Jesús Pérez-Ríos

Summary

- Plenty of interesting physics to explore with atoms and ions!
- We introduced the atom-ion interaction potential
- We introduced ion trapping
- We explored micromotion-induced heating and what to do about it
- We now have two systems, $Yb^{+}/^{6}Li$ and $Ba^{+}/^{6}Li$ that have reached the crossover into the quantum regime

- Tomorrow: Some quantum chemistry and controlling interactions between atoms and ions