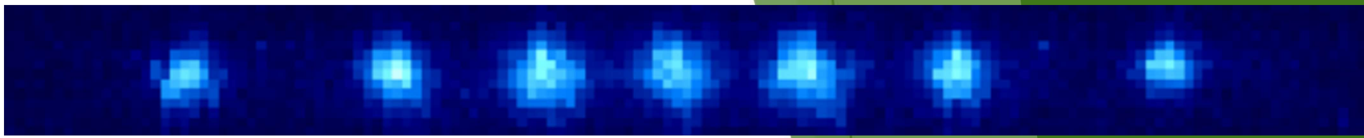
Lecture 1

Towards quantum impurity physics with atoms and ions

Rene Gerritsma

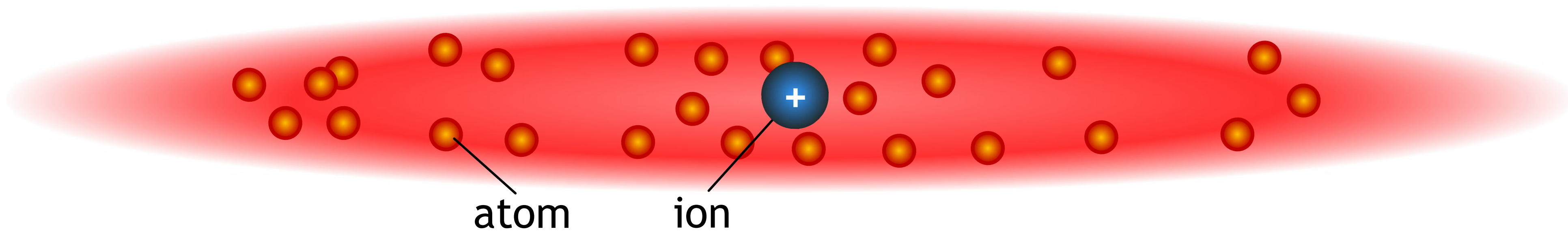


Lecture 1

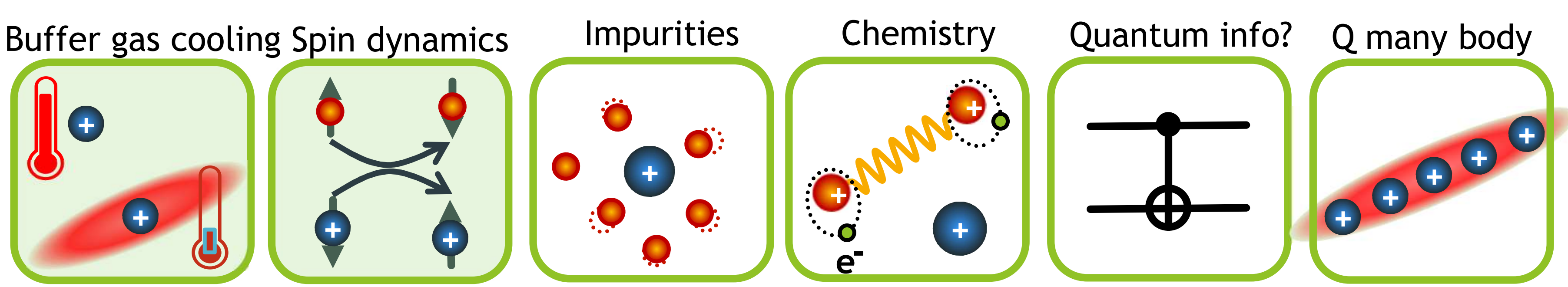
- Introduction
- Atom-ion interactions
- Ion trapping
- Reaching the quantum regime

Motivation

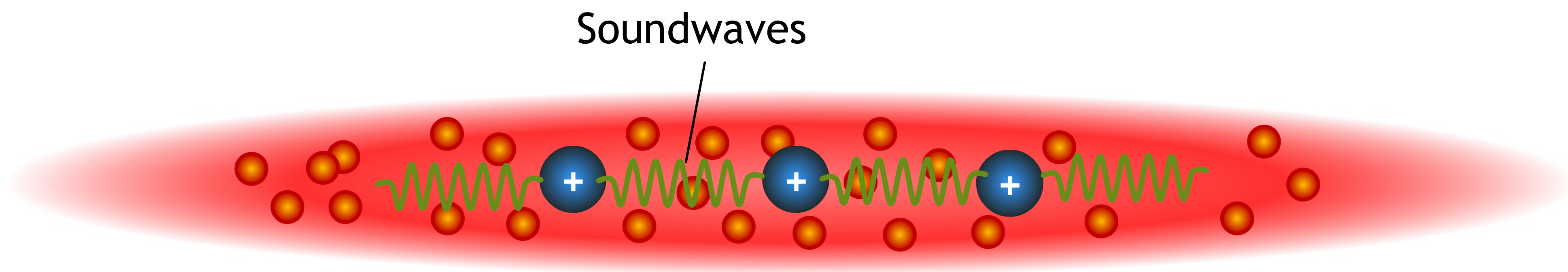
Why study atom-ion mixtures?



M. Tomza et al., RMP 91, 035001 (2019).

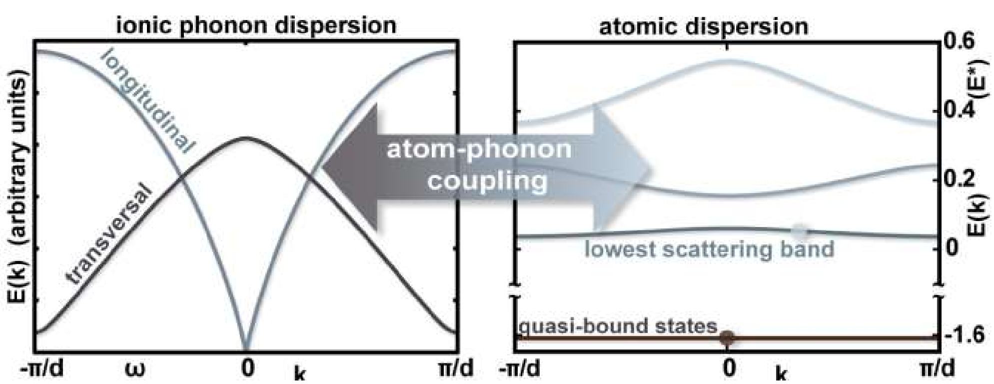


A solid look-alike?



→ A crystal of ions overlapped with a cloud of ultracold fermions: an artificial solid??

→ Mediated interactions?

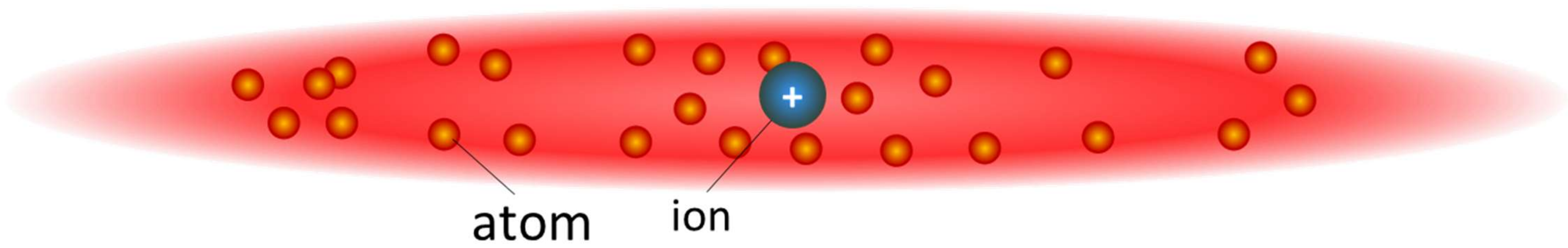


	Nat. solid	^{6}Li / ^{174}Yb^{+}
Lattice spacing d (nm)	0.3-0.6	10^3 – 10^4
Length scale R* (nm)	0.026	71
d/R*	10-20	14-140
mi / mf	10^4	29

U. Bissbort *et al.*, *PRL* 111, 080501 (2013).

Quantum chemistry with trapped ions and atoms

- Prepare ions and atoms in particular quantum state
- Detect chemical reactions at the single particle level
- Measure the output states, released or absorbed energy, branching ratios, etc…



Phys. Rev. Lett. 107, 243202 (2011).
Phys. Rev. Lett. 107, 243201 (2011).
Nat. Phys. 8, 649 (2012).

Phys. Rev. A 96, 030703(R) (2017).
Nature Communications. 9, 920 (2018)
Phys. Rev. Lett. 109, 123201 (2012)
And many more….

Atoms and ions used

- Alkali atoms and earth alkaline or alkali (i.e. same as parent atom) ions

I	II													III	IV	V	VI	VII	VIII
1	2		3	4	5	6	7	8	9	10	11	12		13	14	15	16	17	18
1 H															(np shells)				2 He
3 Li	4 Be													5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg					transition elements (nd shells)								13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn		31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd		49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57–70 *	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg		81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89–102 **	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg								

rare-earth elements (nf shells)

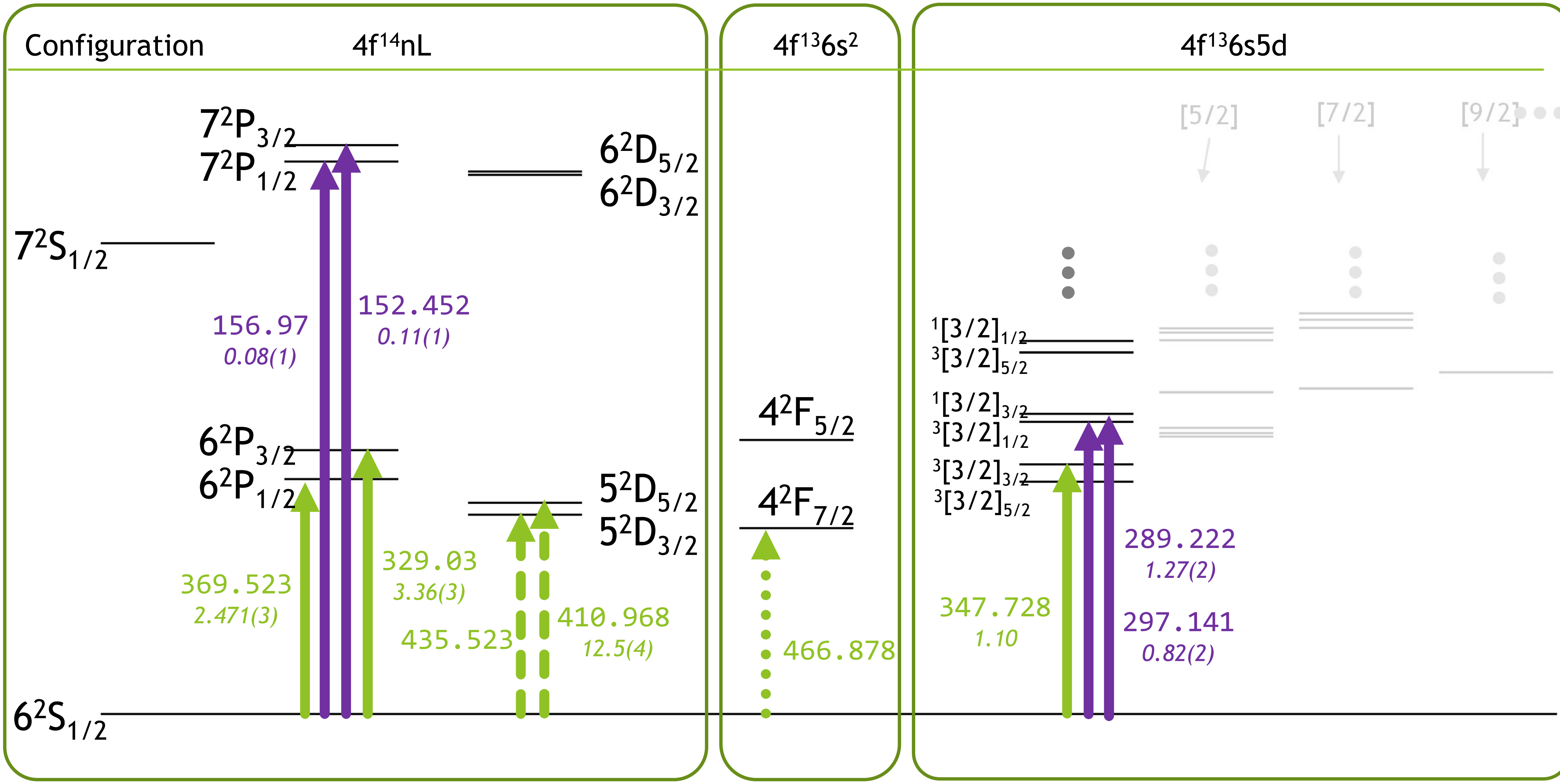
*lanthanides (4f)	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
**actinides (5f)	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

Some of the groups:
Amsterdam: Yb^+/Li, Freiburg: Ba^+/Li, LENS: Ba^+/Li, Ulm: Ba^+ and Rb^+/Rb,
Weizmann: Sr^+/Rb, Stuttgart: Rb^+/Rb, Arhus Ba^+/Li (under construction), …

Yb^+

↓ Same as earth alkaline ions

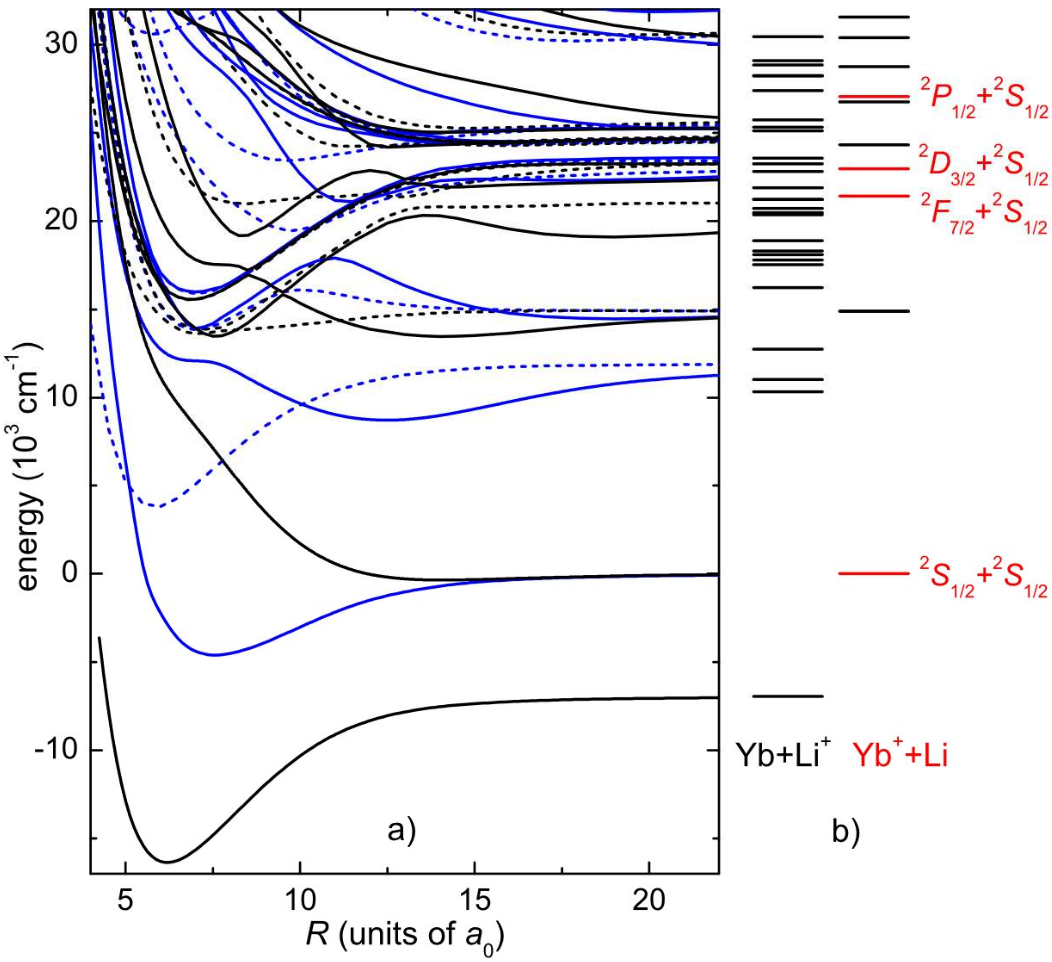
↙↓ Configuration interactions severely limit theoretical predictions



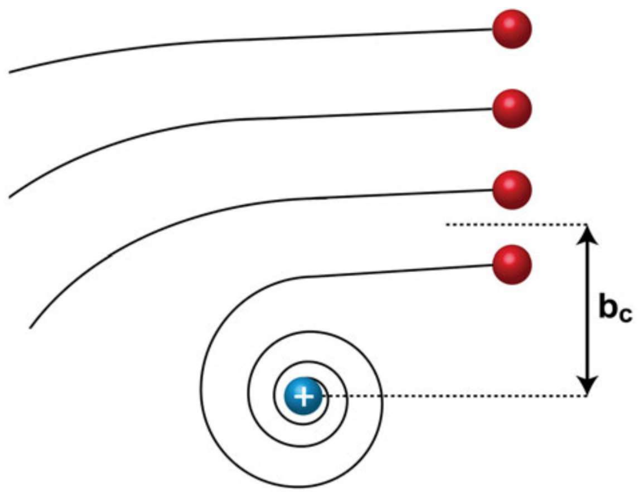
Already pretty complicated, but still a favorite in ion trapping

Atom/ion potentials

PRA 96, 030703(R) (2017)



Note: no spin-orbit!

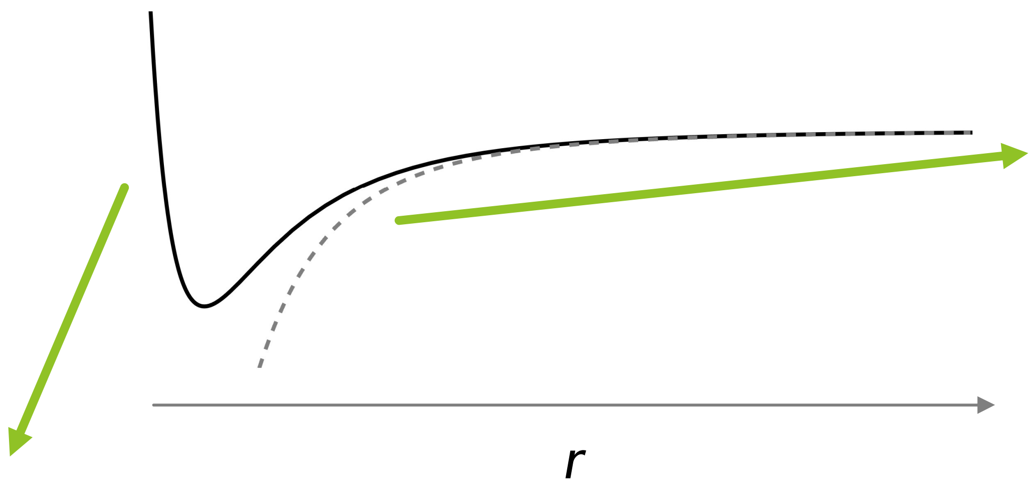


Atom-ion interactions

- Interaction potential
- The s-wave limit
- The Langevin rate

Atom-ion interactions

- An ion polarizes a nearby atom
- Leads to attraction at large distances



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

Short range repulsion

Typical units

- An ion polarizes a nearby atom
- Leads to attraction at large distances

$$\mathrm{V}_{\mathrm{a-i}}(\mathrm{r}) = -\frac{\mathrm{C}_4}{2\,r^4}$$

Equate potential energy with kinetic energy to obtain typical length and energy scales:

$$R^* = \frac{\sqrt{\mu C_4}}{\hbar}$$ ← Typical scattering length

$$E^* = \frac{\hbar^2}{2\mu(R^*)^2}$$ ← s-wave energy

Typical units

- An ion polarizes a nearby atom
- Leads to attraction at large distances

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

Equate potential energy with kinetic energy to obtain typical length and energy scales:

$$R^* = \frac{\sqrt{\mu C_4}}{\hbar}$$ ← Typical scattering length

$$E^* = \frac{\hbar^2}{2\mu(R^*)^2}$$ ← s-wave energy

Atom	Ion	Mass ratio $\frac{m_i}{m_a}$	E^*/h (kHz)	E^*/k_B (μK)	R^* (nm)	References
^{6}**Li**	^{174}Yb$^+$	28.92	178.583	8.57	69.77	[106]
	^{171}Yb$^+$	28.42	178.793	8.58	69.75	
	^{138}Ba$^+$	22.93	181.716	8.72	69.46	
^{87}**Rb**	^{174}Yb$^+$	2.00	0.924	0.044	307.23	[112, 113]
	^{171}Yb$^+$	1.97	0.935	0.045	306.33	
	^{138}Ba$^+$	1.59	1.092	0.052	294.67	
	^{88}Sr$^+$	1.01	1.624	0.078	266.80	

Langevin collisions

- Atoms that come close to the ion undergo close-range 'Langevin' collisions
- Write down Hamiltonian for the relative motion:

$$H = \frac{\vec{p}^{\,2}}{2\mu} - \frac{C_4}{2r^4}$$

Reduced mass $\mu = \frac{m_{atom} m_{ion}}{m_{atom} + m_{ion}}$

- Transform to spherical coordinates:

$$H = \frac{p_r^2}{2\mu} + \underbrace{\frac{L^2}{2\mu r^2}}_{\text{Centrifugal barrier}} - \frac{C_4}{2r^4}$$

Radial momentum

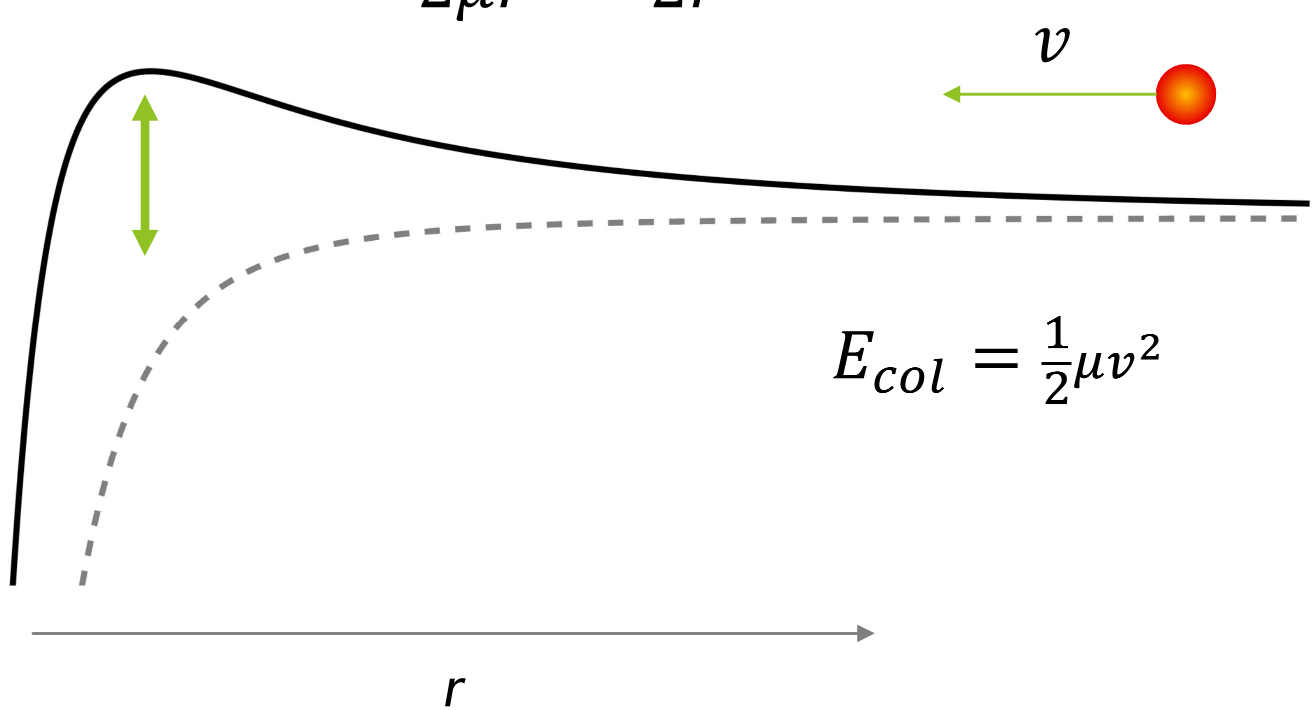
Angular momentum

Langevin collisions

- Angular momentum and collision energy determine whether particles can get close enough to each other to react
- Closeby collisions are called ‘Langevin collisions’

$$V(r) = \frac{L^2}{2\mu r^2} - \frac{C_4}{2r^4}$$

$$E_{barrier} = \frac{L^4}{8C_4\mu^2}$$

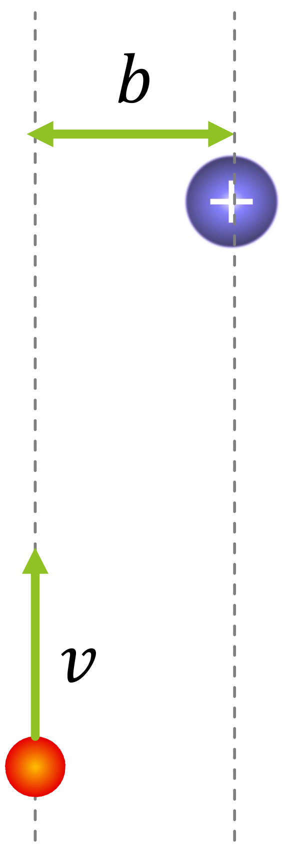


Impact parameter *b*

- When the particles are far away from each other, their motion is not affected yet by the force:

$$\vec{L} = \vec{r} \times \vec{p} \;\; \rightarrow \;\; |L| = \mu v b$$

- The particle can only make it over the barrier if the collision energy is larger than $E_{barrier}$:

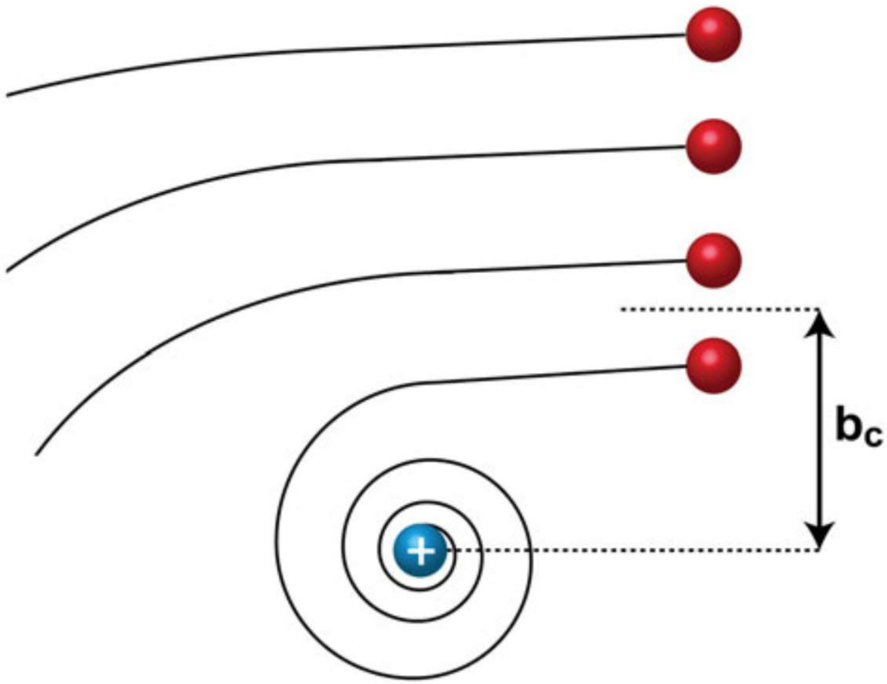


$$E_{barrier} = \frac{L^4}{8 C_4 \mu^2}$$

$$E_{col} = \frac{1}{2} \mu v^2$$

The Langevin rate

- There is a critical impact parameter below which all collisions are short range 'Langevin collisions'

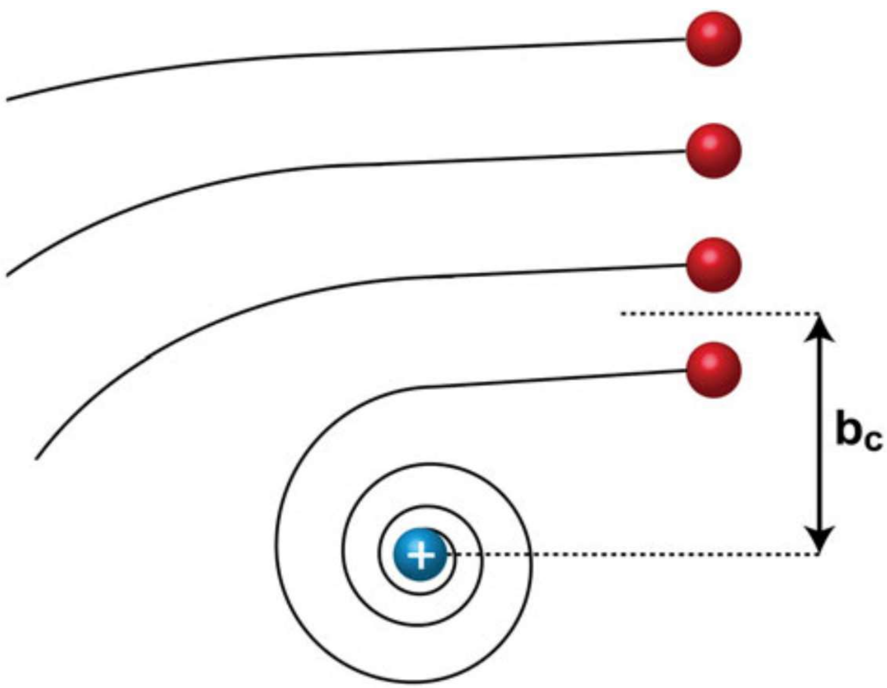


From: Contemporary Physics, 55:1, 33-4

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

The Langevin rate

- There is a critical impact parameter below which all collisions are short range ‘Langevin collisions’



From: Contemporary Physics, 55:1, 33-4

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

Langevin collision rate:

$$\gamma = nv\sigma$$

Cross section $\sigma = \pi b_c^2$

Atomic density n

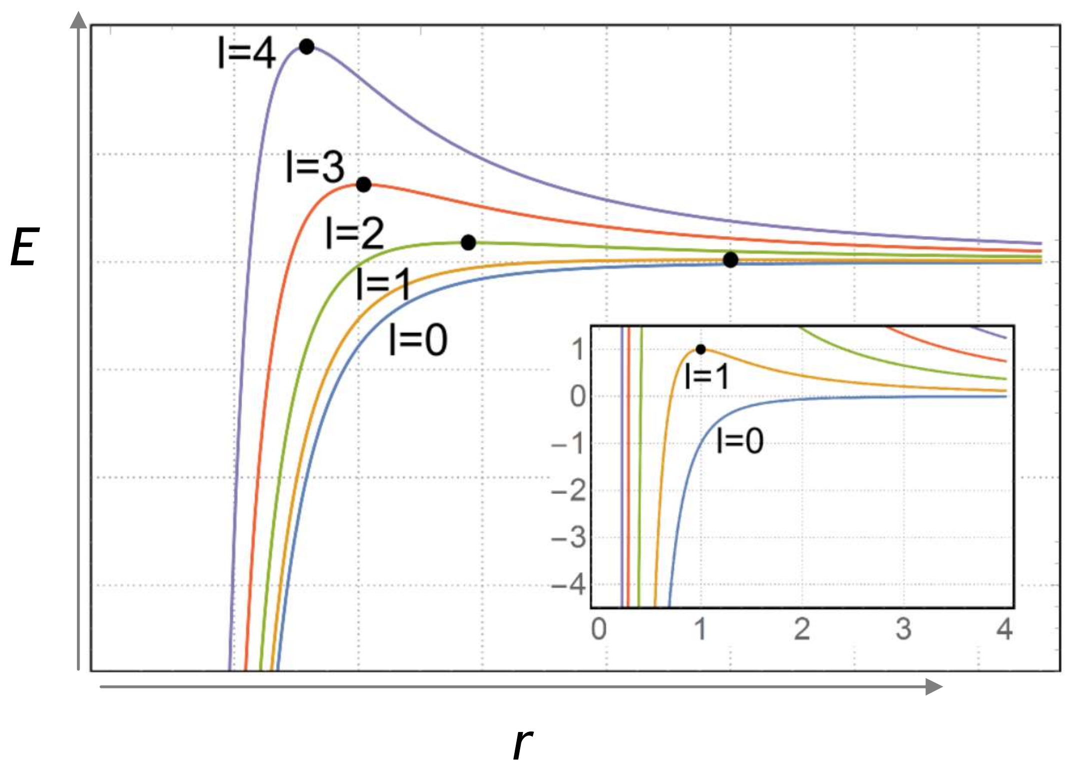
→ Langevin rate independent of Velocity (collision energy)

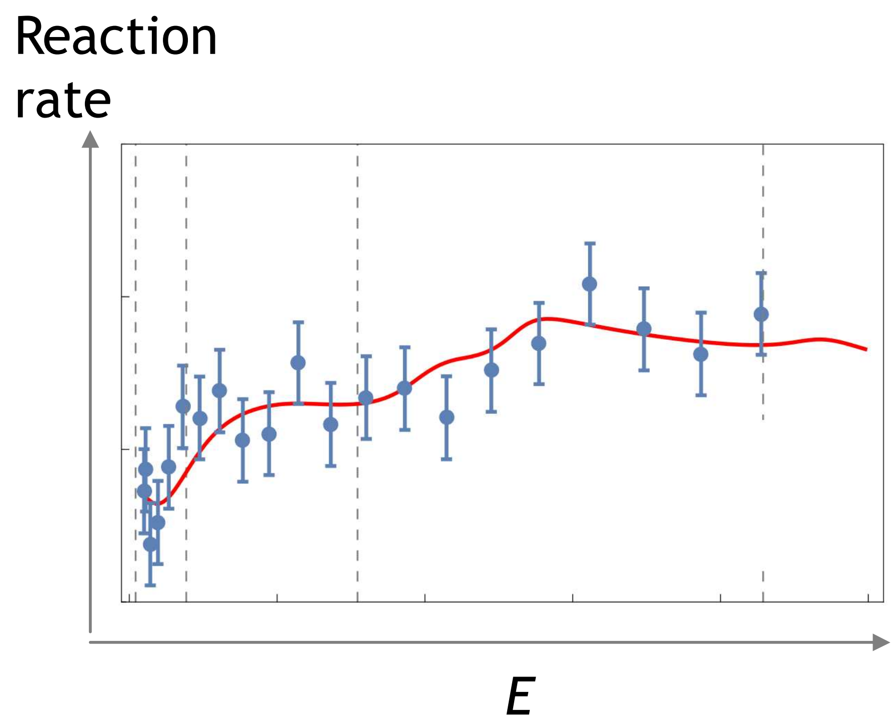
$$\gamma = 2\pi n\sqrt{C_4/\mu}$$

→ Famous result from physical chemistry: reaction rates between neutral and charged particles is independent of energy

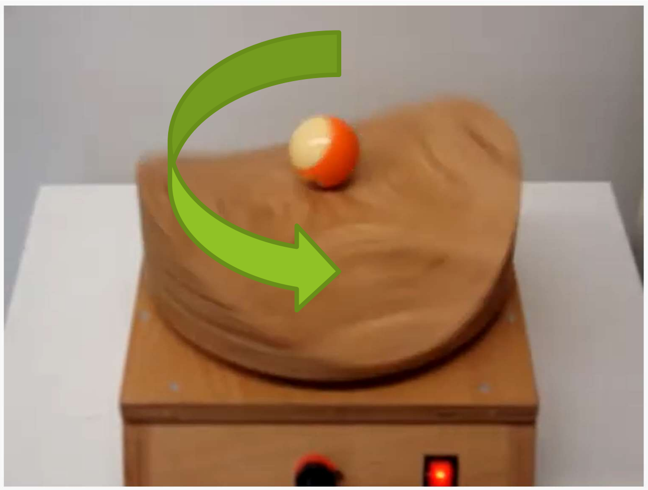
Then why look at cold chemistry?

- Quantum effects change the picture: The angular momentum is *quanitized*!
- When the collision energy gets very low, only $L = 0$ collisions are allowed → the s-wave limit
- Langevin theory breaks down! → What happens in the ultracold regime?





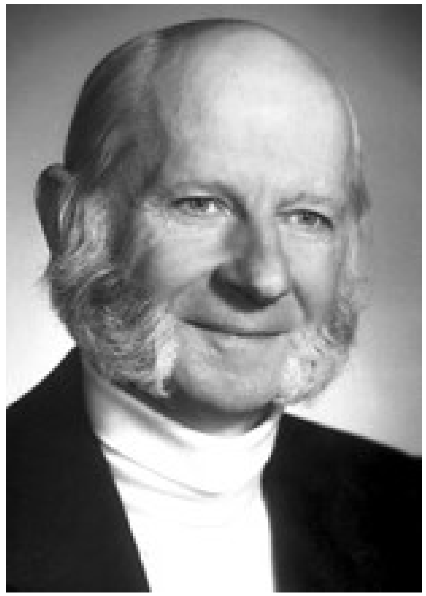
Ion trapping



- The Paul trap
- Equations of motion
- Micromotion and the secular approximation
- The quantum case and the breakdown of the secular approximation

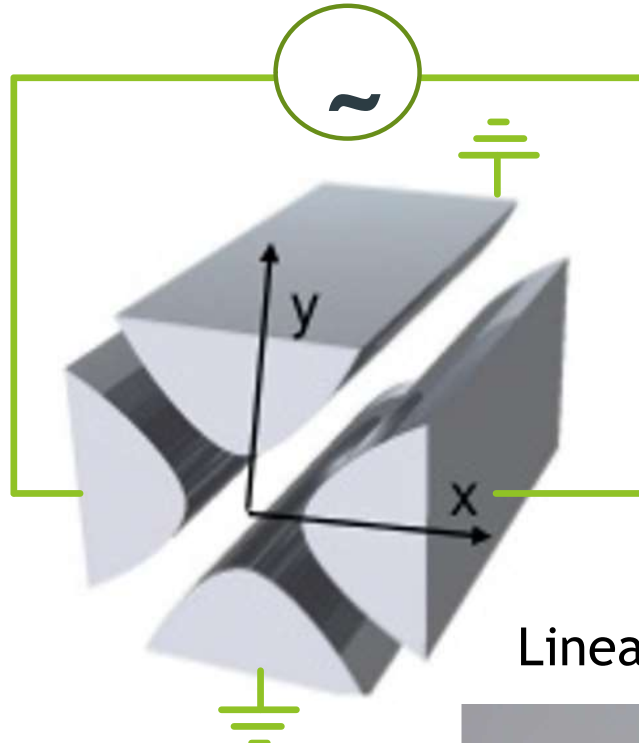
Some history

Wolfgang Paul

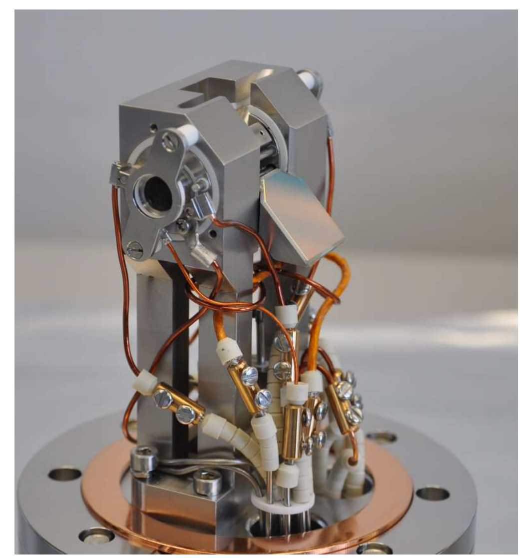


Hans Dehmelt

- Ion traps were developed by Paul and Dehmelt in the 50s
- They were awarded the Nobel price in 1989
- Two types of ion traps:
  Paul (or radio frequency) traps
  Penning traps



Linear Paul trap



Ion trapping: Paul traps

- Ions trapped by a combination of static and oscillating (rf) electric fields

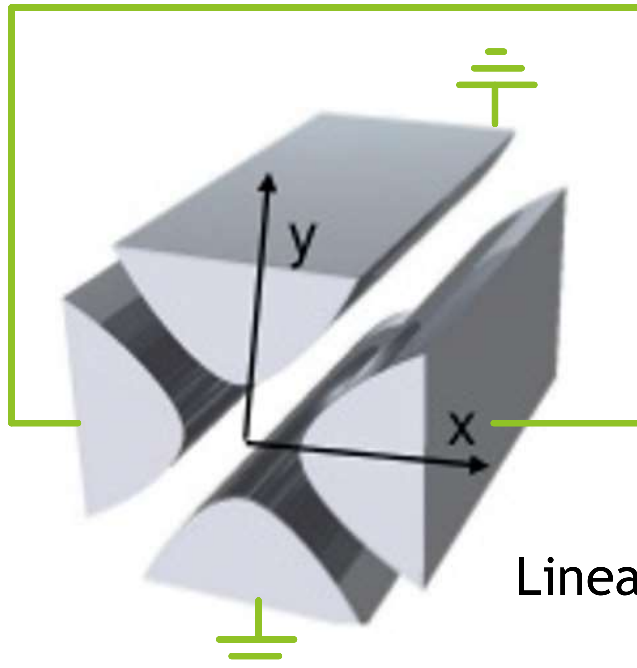
$$\mathcal{E}(t) = \mathcal{E}_{\mathrm{s}} + \mathcal{E}_{\mathrm{rf}}(t)$$

$$\mathcal{E}(t) \approx (\mathbf{G}_{\mathrm{s}} + \mathbf{G}_{\mathrm{rf}}(t)) \cdot \mathbf{r}$$

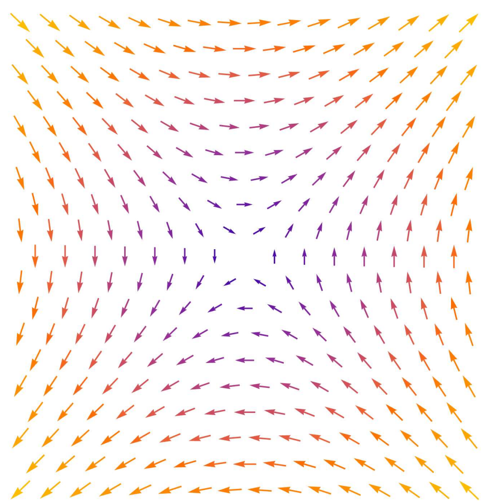
$$G_{\mathrm{s},i,j} = \frac{d\mathcal{E}_{\mathrm{s},i}}{dr_j}$$

$$G_{\mathrm{rf},i,j}(t) = \frac{d\mathcal{E}_{\mathrm{rf},i}(t)}{dr_j}$$

$$i, j \in \{x, y, z\}$$



Linear Paul trap



← Quadrupole electric field

Ion trapping: Paul traps

- Ions trapped by a combination of static and oscillating (rf) electric fields

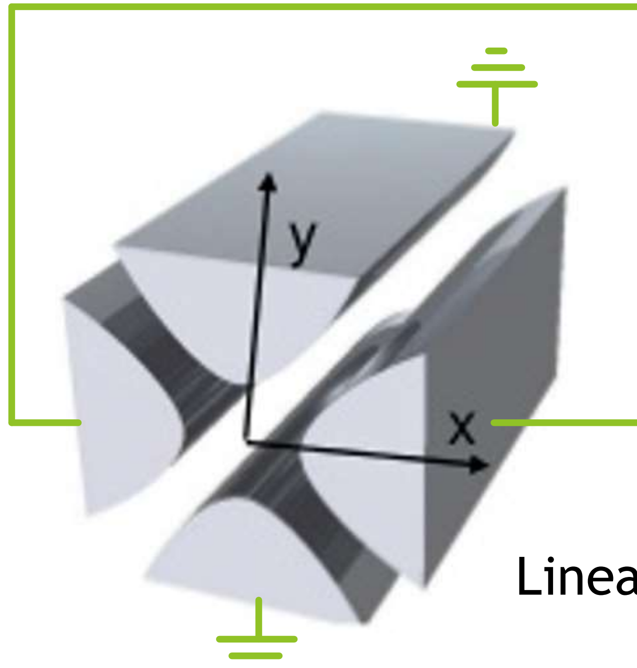
$$\boldsymbol{\mathcal{E}}(t) = \boldsymbol{\mathcal{E}}_{\mathrm{s}} + \boldsymbol{\mathcal{E}}_{\mathrm{rf}}(t)$$

$$\boldsymbol{\mathcal{E}}(t) \approx (\mathbf{G}_{\mathrm{s}} + \mathbf{G}_{\mathrm{rf}}(t)) \cdot \mathbf{r}$$

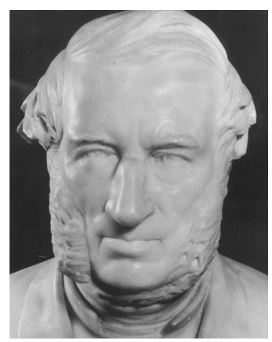
$$G_{\mathrm{s},i,j} = \frac{d\mathcal{E}_{\mathrm{s},i}}{dr_j}$$

$$G_{\mathrm{rf},i,j}(t) = \frac{d\mathcal{E}_{\mathrm{rf},i}(t)}{dr_j}$$

$$i, j \in \{x, y, z\}$$



Linear Paul trap



Notice Maxwell:

$$\nabla \cdot \boldsymbol{\mathcal{E}}_{\mathrm{s}} = 0$$

Earnshaw: cannot hold stationary charged particle with static fields alone

Solving the equations of motion

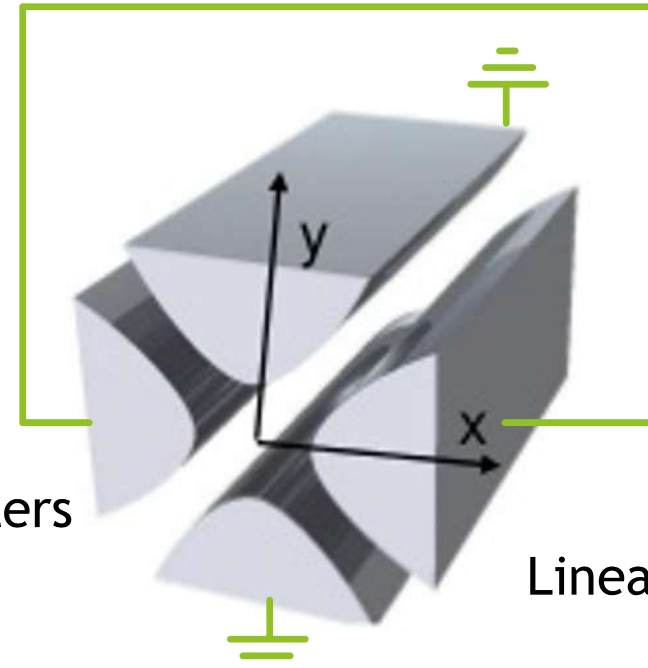
- Ions trapped by a combination of static and oscillating (rf) electric fields

$$G_{\mathrm{s},i,j} = -(m_{\mathrm{i}}\Omega_{\mathrm{rf}}^2/e)a_{ij}$$

$$G_{\mathrm{rf},i,j} = -(m\Omega_{\mathrm{rf}}^2/(2e))q_{ij}$$

Drive frequency

Stability parameters



Linear Paul trap

eqs. Of motion:

$$m_{\mathrm{i}}\ddot{\mathbf{r}}(\mathbf{t}) = e(\mathbf{G}_{\mathrm{s}} + \mathbf{G}_{\mathrm{rf}}(t)) \cdot \mathbf{r}$$

Solving the equations of motion

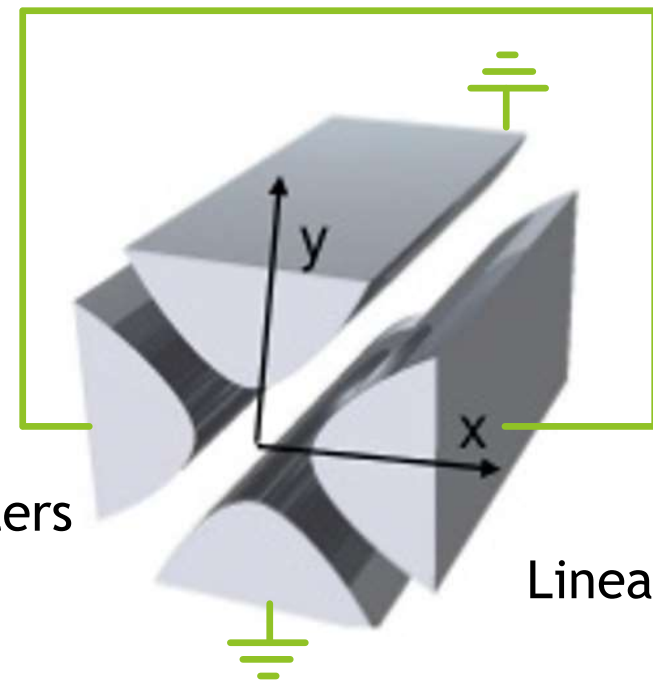
- Ions trapped by a combination of static and oscillating (rf) electric fields

$$G_{\mathrm{s},i,j} = -(m_\mathrm{i}\Omega_\mathrm{rf}^2/e)a_{ij}$$

$$G_{\mathrm{rf},i,j} = -(m\Omega_\mathrm{rf}^2/(2e))q_{ij}$$

Drive frequency

Stability parameters



Linear Paul trap

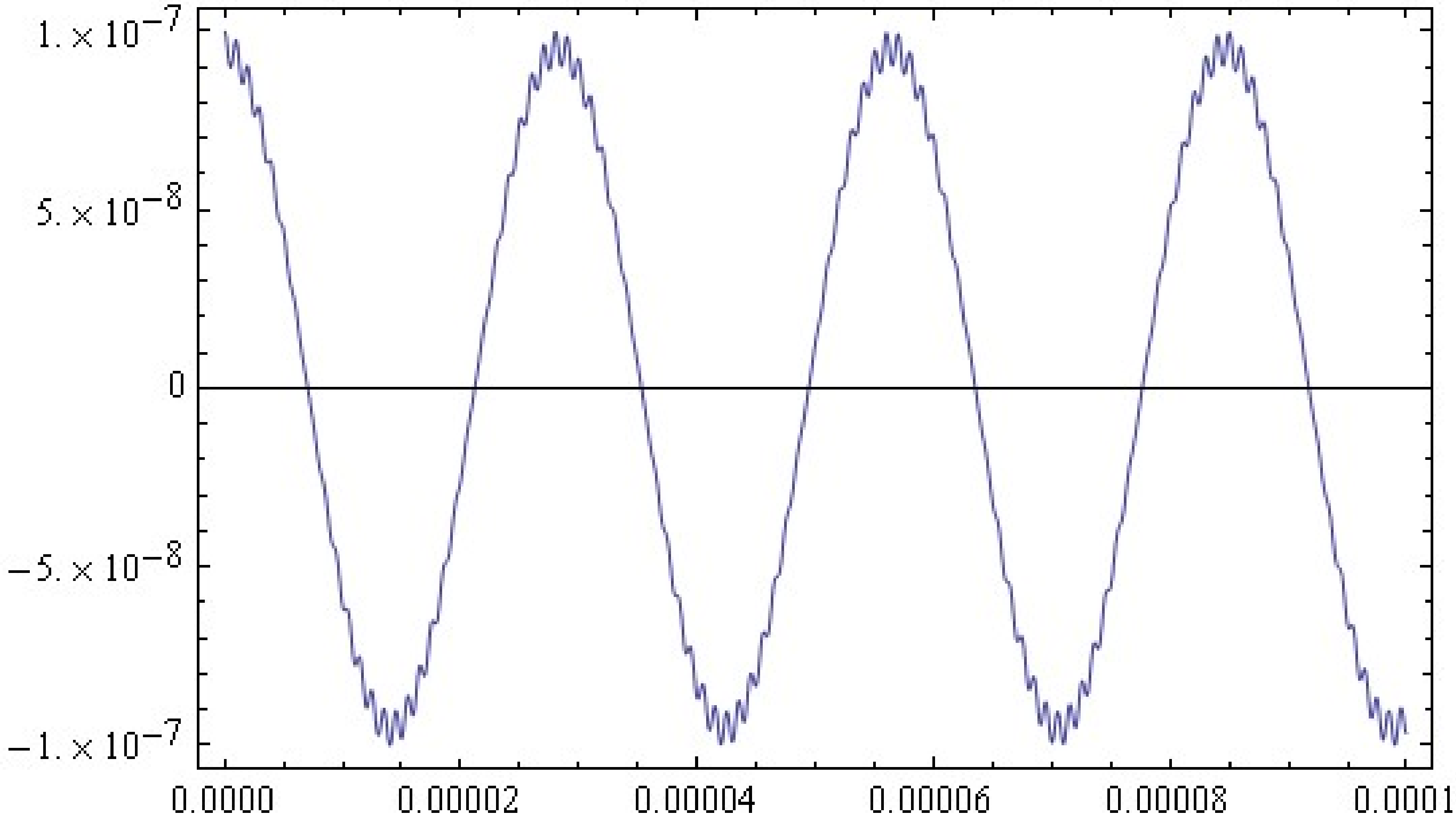
Assume gradient tensors can be simultaneously diagonalized
→ 3 uncoupled eqs. Of motion:

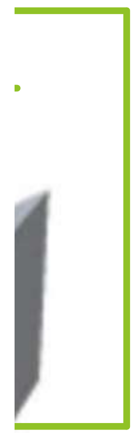
$$m_i\ddot{x} = (a_x - 2q_x\cos 2\xi)x$$

With $\xi = \Omega_{rf}t/2$

And similar for the *y* and *z* directions

Solving the equations of motion





inear Paul trap

$$\omega_j \approx (\Omega_{\mathrm{rf}}/2)\sqrt{a_j + q_j^2/2} \ll \Omega_{\mathrm{rf}}$$ ← Secular frequency

$$r_j(t) \approx A_j \cos(\omega_j t + \phi_j)\left(1 + \frac{q_j}{2}\cos(\Omega_{\mathrm{rf}} t)\right)$$

Secular motion Micromotion

Summary

- An ion in a Paul trap behaves like a harmonic oscillator with small amplitude, high frequency micromotion on top
- Just choose stability parameters such that $a \ll q^2 \ll 1$
- Build a good ion trap (there is also something called excess micromotion…..)
- And forget about micromotion ☺

"The career of a young theoretical physicist consists of treating the harmonic oscillator in ever-increasing levels of abstraction.“

Sidney Coleman (according to google)…

Summary

- An ion in a Paul trap behaves like a harmonic oscillator with small amplitude, high frequency micromotion on top
- Just choose stability parameters such that $a \ll q^2 \ll 1$
- Build a good ion trap (there is also something called excess micromotion…..)
- And forget about micromotion ☺

- Until of course…..

Micromotion-induced heating

- The quantum treatment!
- What to do about it and why

Let's do quantum

- Stick to 1D

$$H_{\text{ion}}(t) = \frac{p_i^2}{2m_i} + \frac{1}{8} m_i \Omega^2 z_i^2 [a + 2q\cos(\Omega t)]$$

Let's do quantum

- Stick to 1D

$$H_{\text{ion}}(t) = \frac{p_i^2}{2m_i} + \frac{1}{8} m_i \Omega^2 z_i^2 [a + 2q\cos(\Omega t)]$$

Cook and Shankland: Write wavefunction as:

$$\Psi(z_i, t) = \exp\left(-\frac{i}{4\hbar} m_i q \Omega z_i^2 \sin(\Omega t)\right) w(z_i, t)$$

Let's do quantum

- Stick to 1D

$$H_{\text{ion}}(t) = \frac{p_i^2}{2m_i} + \frac{1}{8} m_i \Omega^2 z_i^2 [a + 2q\cos(\Omega t)]$$

Cook and Shankland: Write wavefunction as:

$$\Psi(z_i, t) = \exp\left(-\frac{i}{4\hbar} m_i q \Omega z_i^2 \sin(\Omega t)\right) w(z_i, t)$$

The wavefunction $w(z_i, t)$ evolves according to the Hamiltonian:

$$H_{\text{eff}}(t) = \frac{p_i^2}{2m_i} + \frac{1}{2} m_i \omega_i^2 z_i^2 + H_{mm}(t)$$

$$H_{mm}(t) = -m_i g^2 \omega_i^2 z_i^2 \cos(2\Omega t) - g\omega_i \{z_i, p_i\} \sin(\Omega t)$$

$$g = [2(1 + 2a/q^2)]^{-1/2}$$

Let’s do quantum

- Stick to 1D

$$H_{\text{ion}}(t) = \frac{p_i^2}{2m_i} + \frac{1}{8} m_i \Omega^2 z_i^2 [a + 2q \cos(\Omega t)]$$

Cook and Shankland: Write wavefunction as:

$$\Psi(z_i, t) = \exp\left(-\frac{i}{4\hbar} m_i q \Omega z_i^2 \sin(\Omega t)\right) w(z_i, t)$$

The wavefunction $w(z_i, t)$ evolves according to the Hamiltonian:

$$\boxed{H_{\text{eff}}(t) = \frac{p_i^2}{2m_i} + \frac{1}{2} m_i \omega_i^2 z_i^2 + \cancel{H(t)}}$$

→ Secular approximation

$$\omega_i = \frac{\Omega}{2}\sqrt{a + \frac{q^2}{2}}$$

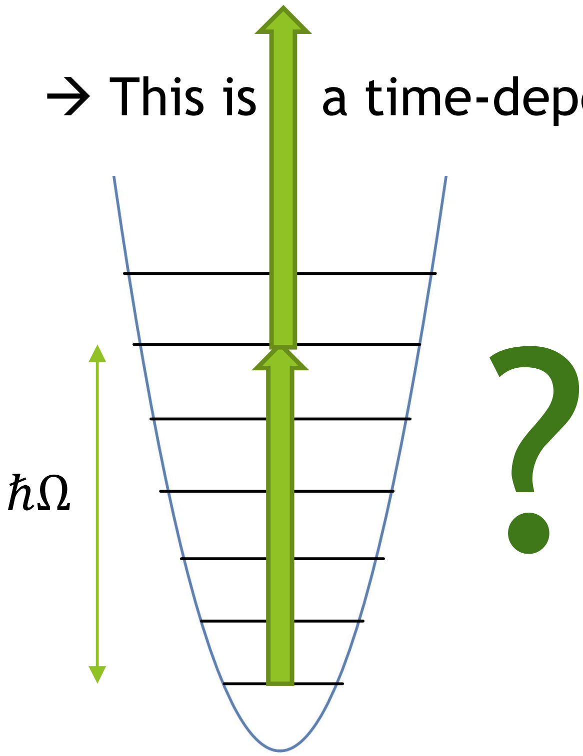
Another look….

- This extra micromotion term looks troubling though….

$$H_{\text{eff}}(t) = \frac{p_i^2}{2m_i} + \frac{1}{2} m_i \omega_i^2 z_i^2 + H_{mm}(t)$$

$$H_{mm}(t) = -m_i g^2 \omega_i^2 z_i^2 \cos(2\Omega t) - g\omega_i \{z_i, p_i\} \sin(\Omega t)$$

→ This is a time-dependent term: may cause parametric excitation?



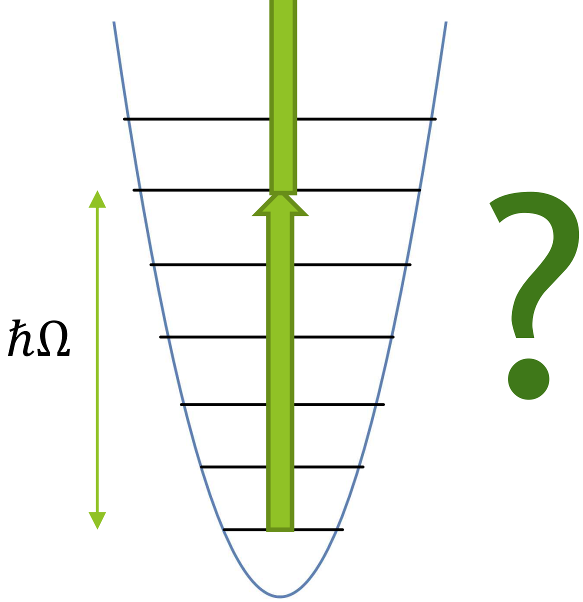
Another look….

- This extra micromotion term looks troubling though….

$$H_{\text{eff}}(t) = \frac{p_i^2}{2m_i} + \frac{1}{2} m_i \omega_i^2 z_i^2 + H_{mm}(t)$$

$$H_{mm}(t) = -m_i g^2 \omega_i^2 z_i^2 \cos(2\Omega t) - g\omega_i \{z_i, p_i\} \sin(\Omega t)$$

→ This is a time-dependent term: may cause parametric excitation?



No! Because $\Omega \gg \omega_i$
and $\langle n | H_{mm}(t) | n' \rangle = 0$ for $|n - n'| > 2$

However….

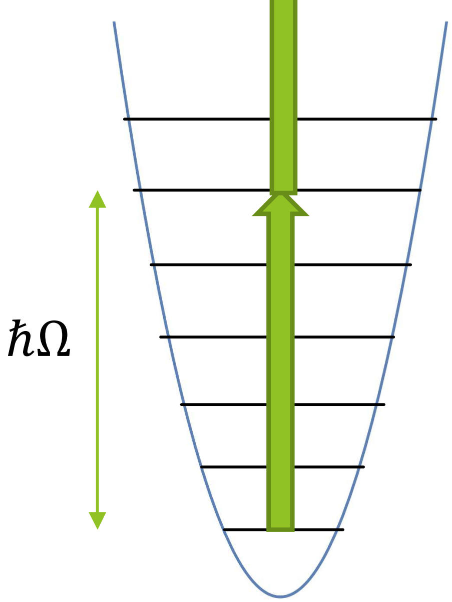
- This extra micromotion term looks troubling though….

$$H_{\text{eff}}(t) = \frac{p_i^2}{2m_i} + \frac{1}{2}m_i\omega_i^2 z_i^2 + H_{mm}(t) \; +cz_i^6$$

Anharmonicity in trap….

$$H_{mm}(t) = -m_i g^2 \omega_i^2 z_i^2 \cos(2\Omega t) - g\omega_i \{z_i, p_i\} \sin(\Omega t)$$

→ This is a time-dependent term: may cause parametric excitation?



Parametric excitation when $6\omega_i = \Omega$
and $\langle n|H_{mm}(t)|n'\rangle \neq 0$ for $|n - n'| = 6$
Because the eigenstates are no longer Fock states!

Another look….

- Parametric excitations in trapped ions: well known

← In practice, the multipole expansion never ends with quadrupole!
→ Solution: low q (or beta)
→ This is a ringtrap btw

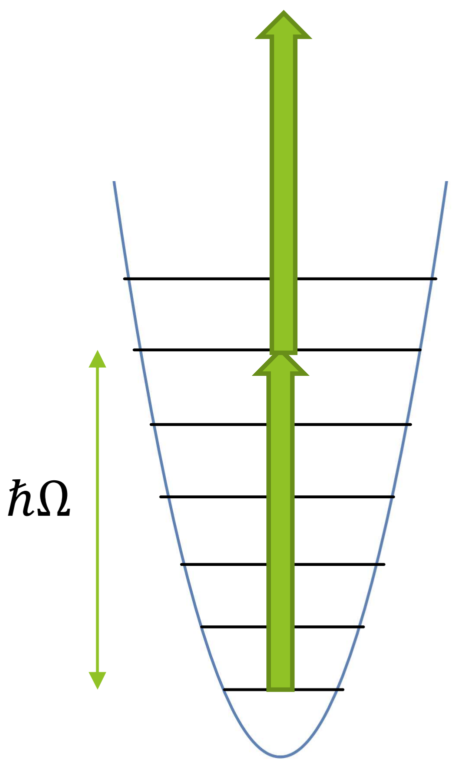
Alheit R, Hennig C, Morgenstern R, Vedel F and Werth G 1995 Appl. Phys. B **61** 277–83

What happens when we add atoms?

- Unfortunately, it is hard to imagine anything more anharmonic than $\frac{1}{r^4}$

$$H_{\text{eff}}(t) = \frac{p_i^2}{2m_i} + \frac{1}{2} m_i \omega_i^2 z_i^2 + H_{mm}(t) - \frac{C_4}{2|r_i - r_a|^4}$$

$$H_{mm}(t) = -m_i g^2 \omega_i^2 z_i^2 \cos(2\Omega t) - g\omega_i \{z_i, p_i\} \sin(\Omega t)$$

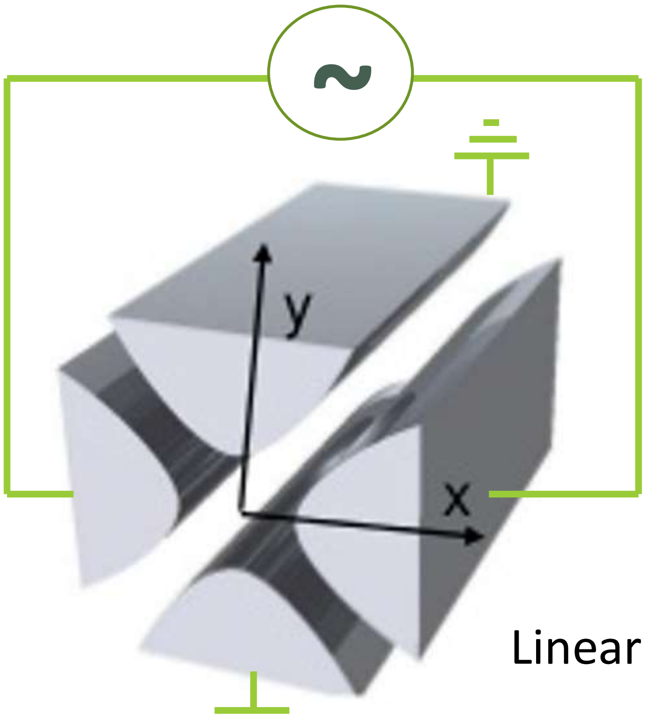


→ Interaction with an atom will cause parametric excitation all over the place….

→ Quantum explanation for micromotion induced heating

Ultracold atom-ion mixtures?

- Micromotion of ion in a Paul trap limits attainable temperatures



Linear Paul trap

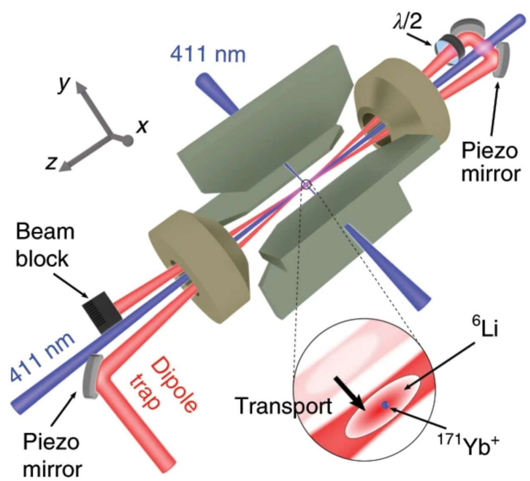
$$T_{ion} > T_{atom}$$

DeVoe, PRL 102, 063001 (2009).
Zipkes et al., NJP 13, 053020 (2011).
M. Cetina et al., PRL 109, 253201 (2012).
Chen et al., PRL 112, 143009 (2014).
Rouse & Willitsch, PRL. 118, 143401 (2017).
Höltkemeier et al., PRL 116, 233003 (2016).
Fürst et al., J. Phys. B 51, 195001 (2018).
…………

So what to do?

Live with it

The quantum regime is in reach for excellent Paul traps and some atom-ion combinations



Nature Physics 16, 413–416 (2020).

Optical traps

Optical traps eliminate micromotion -induced heating

Phys. Rev. Lett. 124, 053402 (2020).

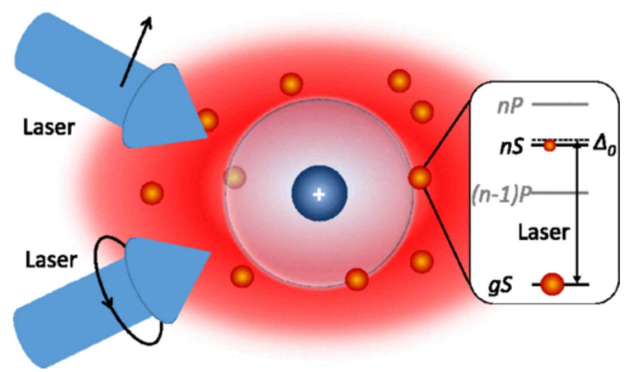
No trap

No trap, no micromotion

Phys. Rev. Lett. 126, 033401 (2021).

Crazy ideas

Create optical barrier to prevent mm-induced heating

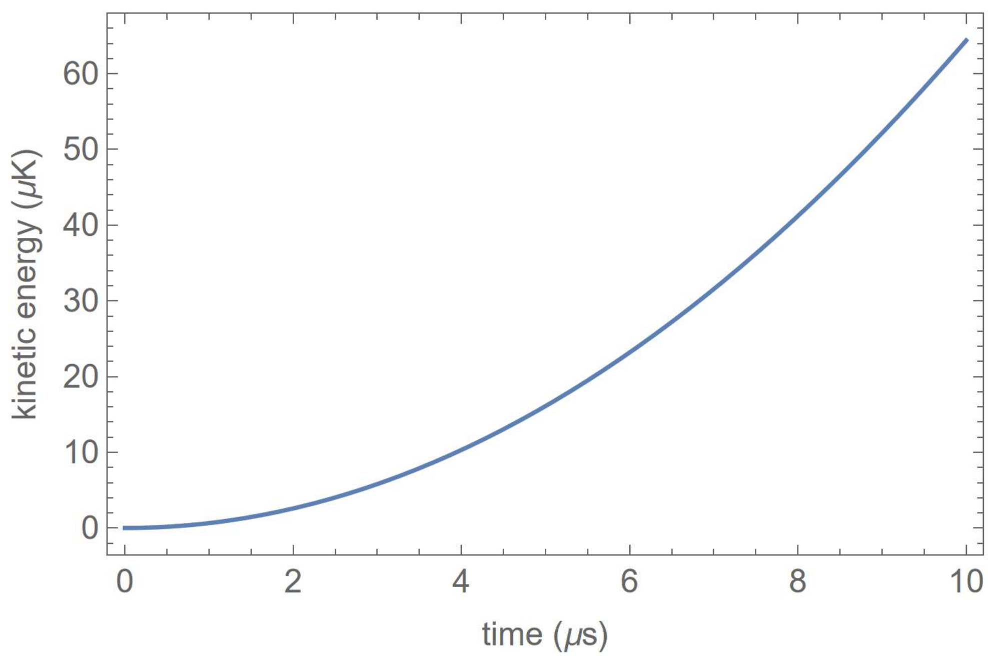


Phys. Rev. Lett. 118, 263201 (2017).

Why live with it?

- The s-wave limit can still be reached in a Paul trap
- The Paul trap offers key benefits:
  - \>100000 K deep → very long storage time
  - Can use lasers to accurately measure motion and state of ions
- Optical traps have their own disadvantages (for example photon-induced chemistry)
- Using no trap makes it hard to sustain the ultracold regime (sensitive to offset fields)

Kinetic energy of Rb^+ starting at rest in 0.01 V/m offset field →



The role of the masses

- All polarizabilities of alkalis are pretty similar (within factor ~2)
- Mass ratio between ion and atom can be varied more

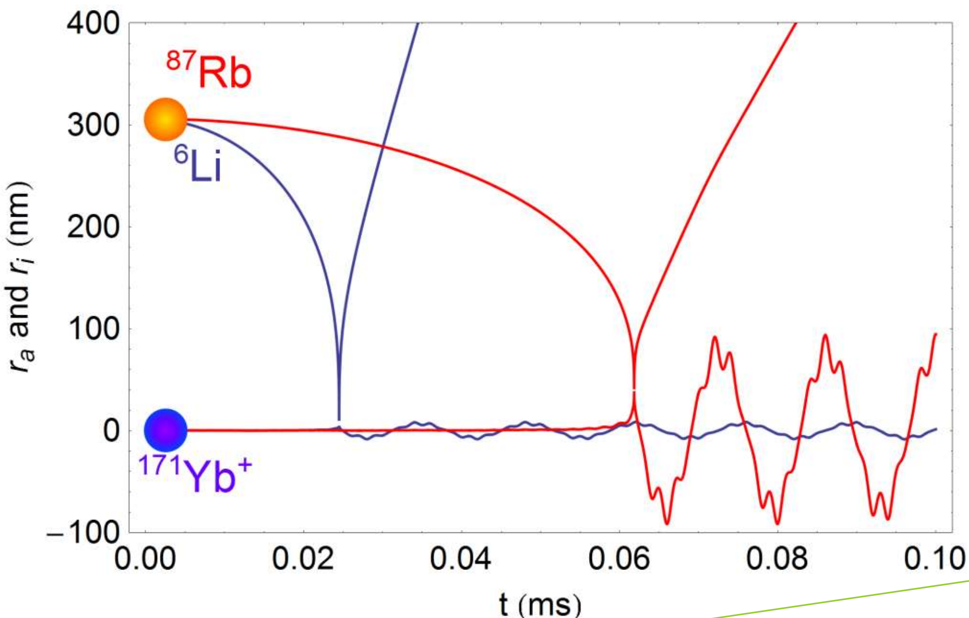
$$W_0 = 2\left(\frac{m_a}{m_i + m_a}\right)^{5/3}\left(\frac{m_i^2 \omega^4 C_4}{q^2}\right)^{1/3}$$

← Estimated minimum heating in one low energy collision, based on classical physics

Phys. Rev. Lett. 109, 253201 (2012)

The role of the masses

- All polarizabilities of alkalis are pretty similar (within factor ~2)
- Mass ratio between ion and atom can be varied more



It seems to help to use
a heavy ion and light atom

$$W_0 = 2\left(\frac{m_a}{m_i + m_a}\right)^{5/3}\left(\frac{m_i^2 \omega^4 C_4}{q^2}\right)^{1/3}$$

← Estimated minimum heating in one low energy collision, based on classical physics

Phys. Rev. Lett. 109, 253201 (2012)

The role of the masses

$$W \sim \left(\frac{m_a}{m_i + m_a}\right)^{5/3}$$

Micromotion heating effect

$$T_s \sim \frac{1}{\mu^2}$$

S-wave limit

$$E_{col} \sim \frac{\mu}{m_i} T_{ion} + \frac{\mu}{m_a} T_{atom}$$

Collision energy

- **Sticking to much used ions and atoms that can be easily laser cooled:**
- **Largest practical mass ratio → $Yb^+/^6Li$**
- **Also good choice: $Ba^+/^6Li$**

H. A. Fürst, N. V. Ewald, T. Secker, J. Joger, T. Feldker and R. Gerritsma, J. Phys. B 51, 195001 (2018).

What to expect?

Equilibrium energy of ion ↓

Ion	Atom	a_x	q	$\Omega_{\rm rf}/(2\pi)$ (MHz)	$W_0^{3D}/k_{\rm B}$ (μK)	$E_\infty^{\rm ion}/k_{\rm B}$ (μK)	Refs.
$^{171}Yb^+$	^6Li	-0.00073	0.22	2	0.31	28.0	Hirzler et al. (2020a)
$^{138}Ba^+$	^6Li	-0.00011	0.24	1.433	0.30	35.5	Weckesser et al. (2021a)
$^{40}Ca^+$	^6Li	-0.0016	0.16	4.8	3.29	87.1	Saito et al. (2017)
$^{138}Ba^+$	^{87}Rb	-0.00093	0.13	5.24	56.3	1.47×10^3	Schmid et al. (2012)
$^{138}Ba^+$	^{87}Rb	-0.00032	0.40	1.4	20.7	667	Schmidt et al. (2020b)
$^{88}Sr^+$	^{87}Rb	-0.052	0.58	4.22	104	313×10^3	Katz et al. (2022)
$^{87}Rb^+$	^{87}Rb	-0.0015	0.21	5.24	87.5	552×10^3	Schmid et al. (2012)

Molecular dynamics simulations for various combinations and traps in a dilute atomic bath of 2 μK with realistic excess micromotion

R.S. Lous and R. Gerritsma, Advances In Atomic, Molecular, and Optical Physics 71, 65-133 (2022).

What to expect?

Equilibrium energy of ion ↓

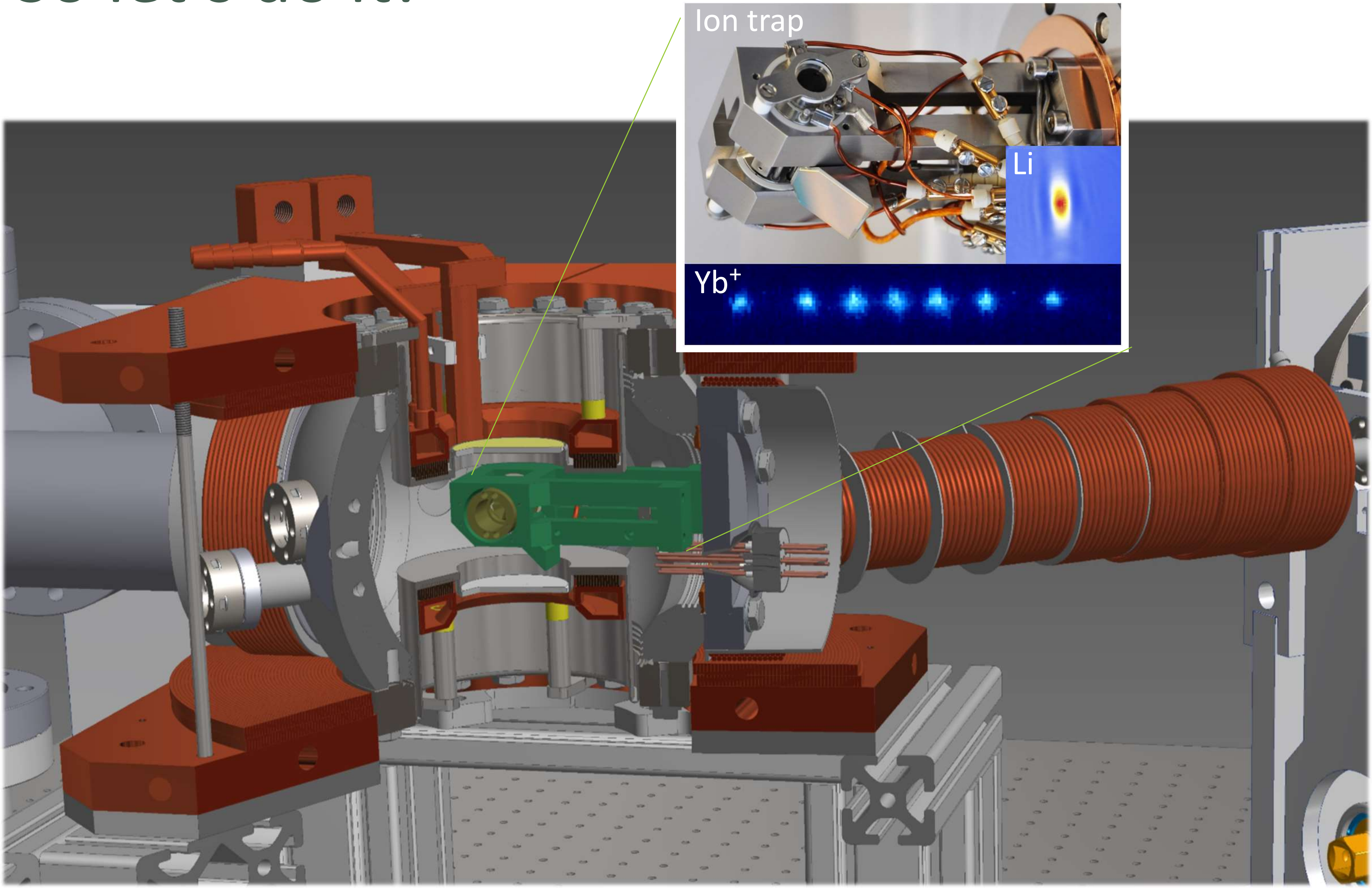
Ion	Atom	a_x	q	$\Omega_{\mathrm{rf}}/(2\pi)$ (MHz)	W_0^{3D}/k_B (μK)	$E_\infty^{\mathrm{ion}}/k_B$ (μK)	Refs.
$^{171}Yb^+$	^6Li	-0.00073	0.22	2	0.31	28.0	Hirzler et al. (2020a)
$^{138}Ba^+$	^6Li	-0.00011	0.24	1.433	0.30	35.5	Weckesser et al. (2021a)
$^{40}Ca^+$	^6Li	-0.0016	0.16	4.8	3.29	87.1	Saito et al. (2017)
$^{138}Ba^+$	^{87}Rb	-0.00093	0.13	5.24	56.3	1.47×10^3	Schmid et al. (2012)
$^{138}Ba^+$	^{87}Rb	-0.00032	0.40	1.4	20.7	667	Schmidt et al. (2020b)
$^{88}Sr^+$	^{87}Rb	-0.052	0.58	4.22	104	313×10^3	Katz et al. (2022)
$^{87}Rb^+$	^{87}Rb	-0.0015	0.21	5.24	87.5	552×10^3	Schmid et al. (2012)

Molecular dynamics simulations for various combinations and traps in a dilute atomic bath of 2 μK with realistic excess micromotion

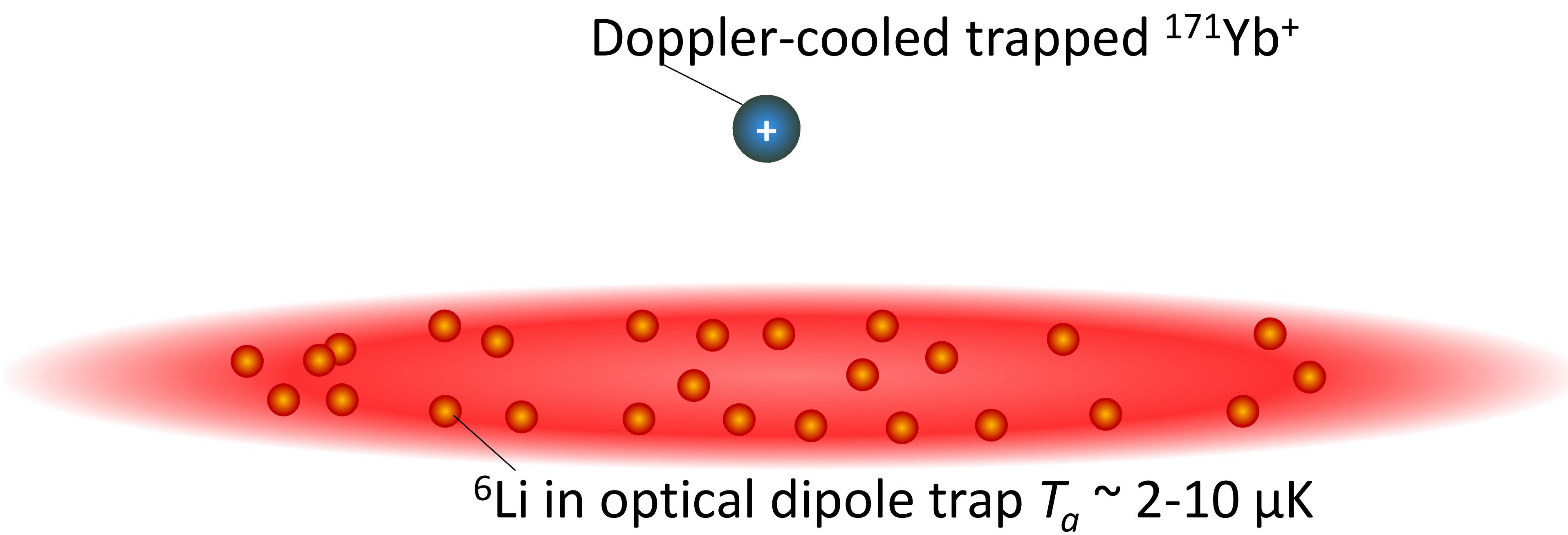
Collision energy below s-wave

R.S. Lous and R. Gerritsma, Advances In Atomic, Molecular, and Optical Physics 71, 65-133 (2022).

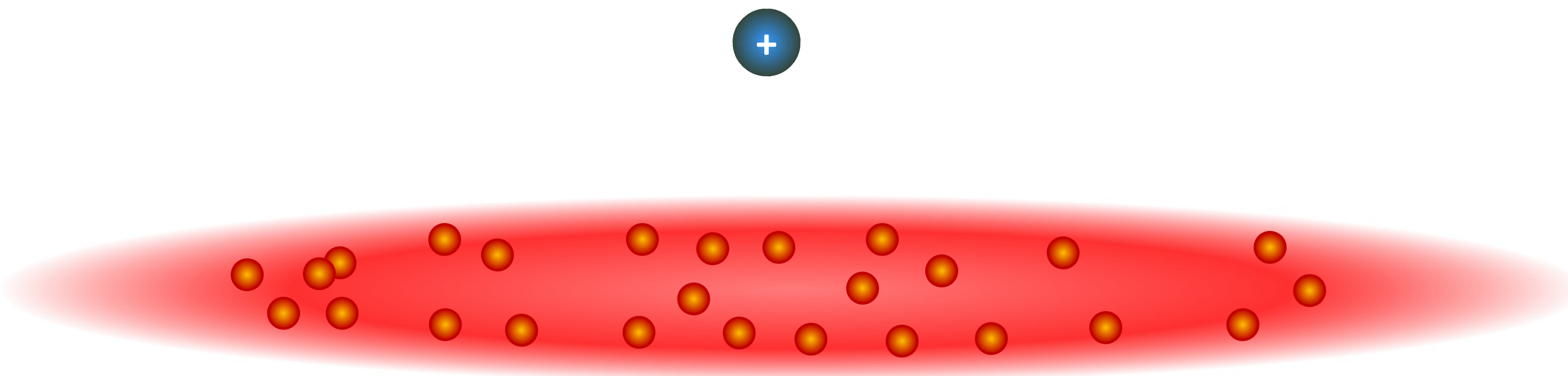
So let’s do it!



Buffer gas cooling of $^{171}Yb^+$

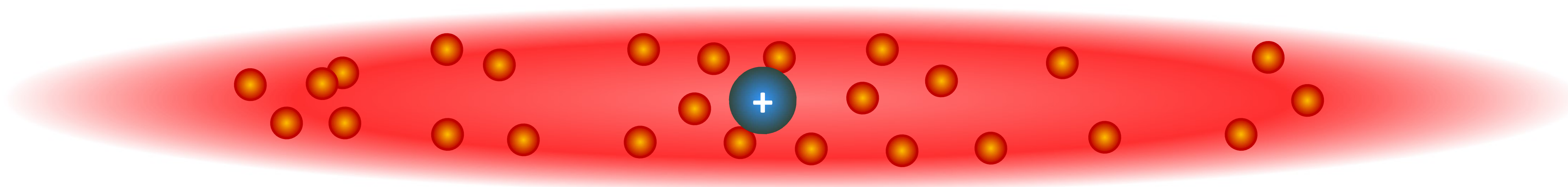


Buffer gas cooling of $^{171}Yb^{+}$



Transport up using piezo-controlled mirrors

Buffer gas cooling of $^{171}Yb^+$

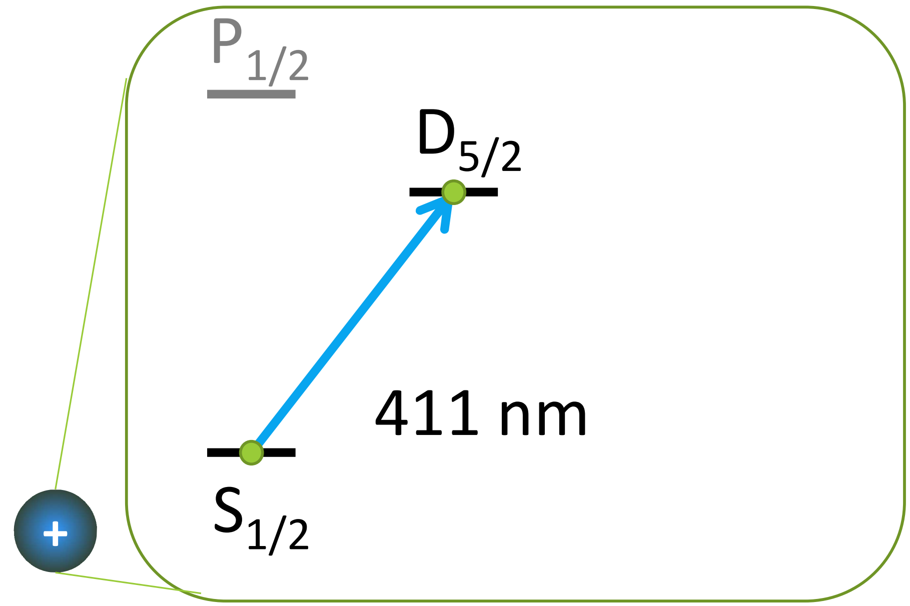


Buffer gas cooling

Buffer gas cooling of $^{171}Yb^+$

Release atoms

Buffer gas cooling of $^{171}Yb^{+}$



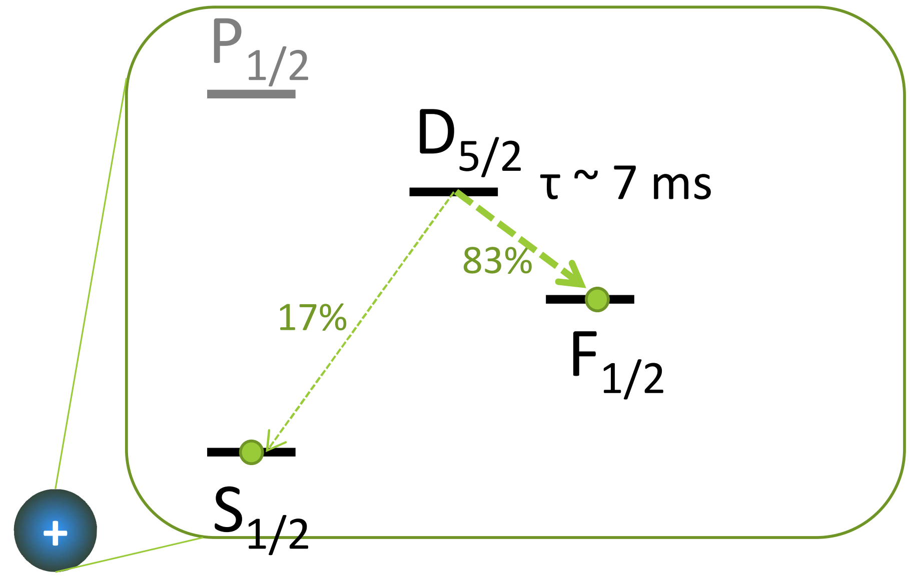
Rabi frequency depends on motional quantum number *n*

$$\Omega \approx \Omega_0(1 - \eta^2 n)$$

Spectroscopy on ion

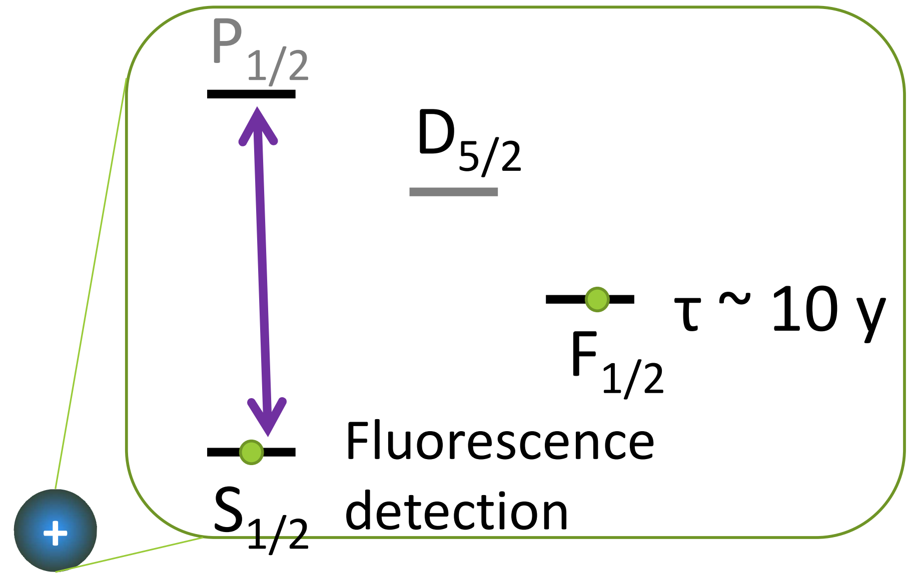
Leibfried et al., PRL 77, 4281{4285 (1996).
Meir, Z. et al. PRL 117, 243401 (2016).

Buffer gas cooling of $^{171}Yb^{+}$



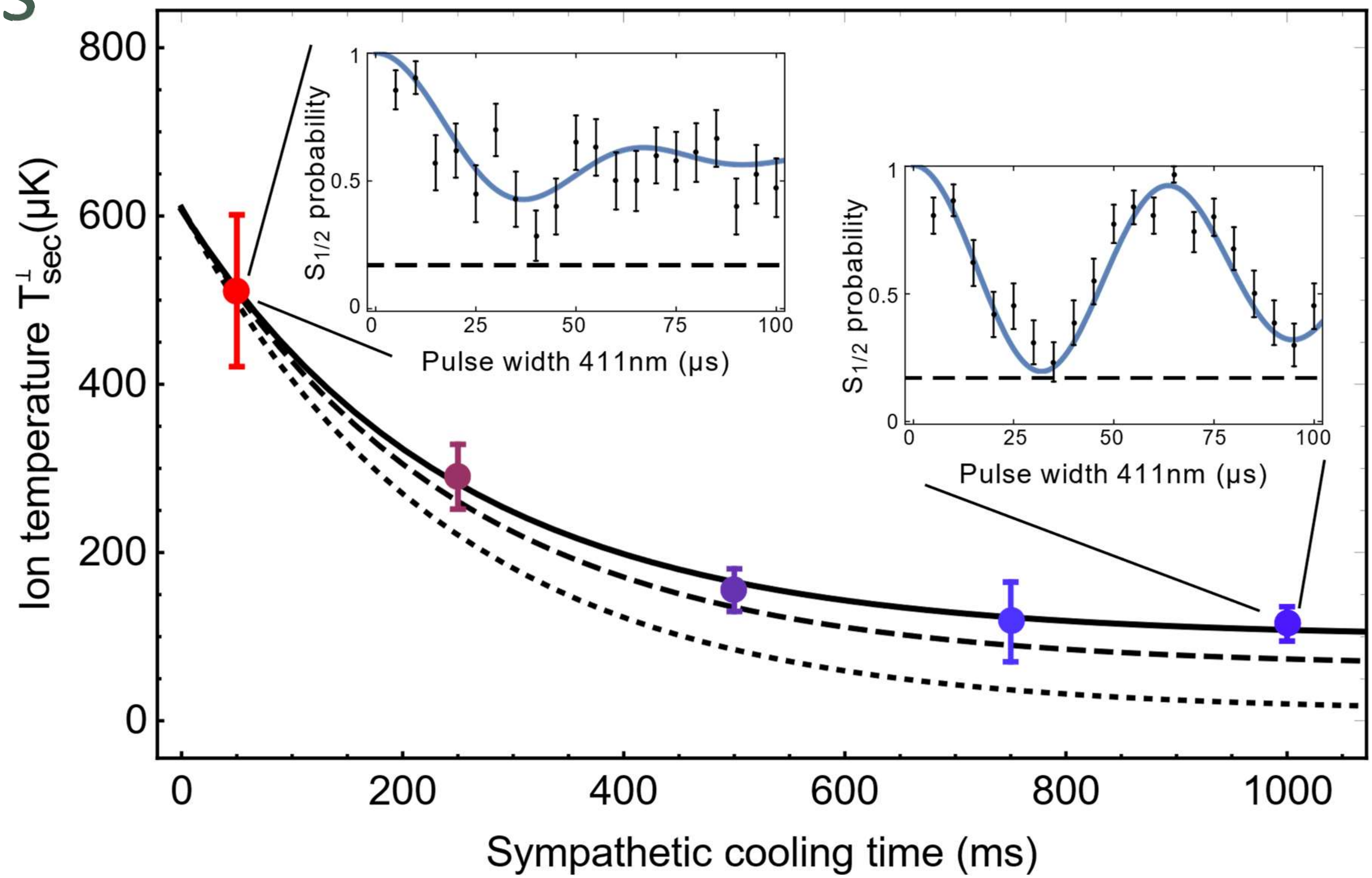
Wait for decay of $D_{5/2}$ state

Buffer gas cooling of $^{171}Yb^+$



State detection

Results



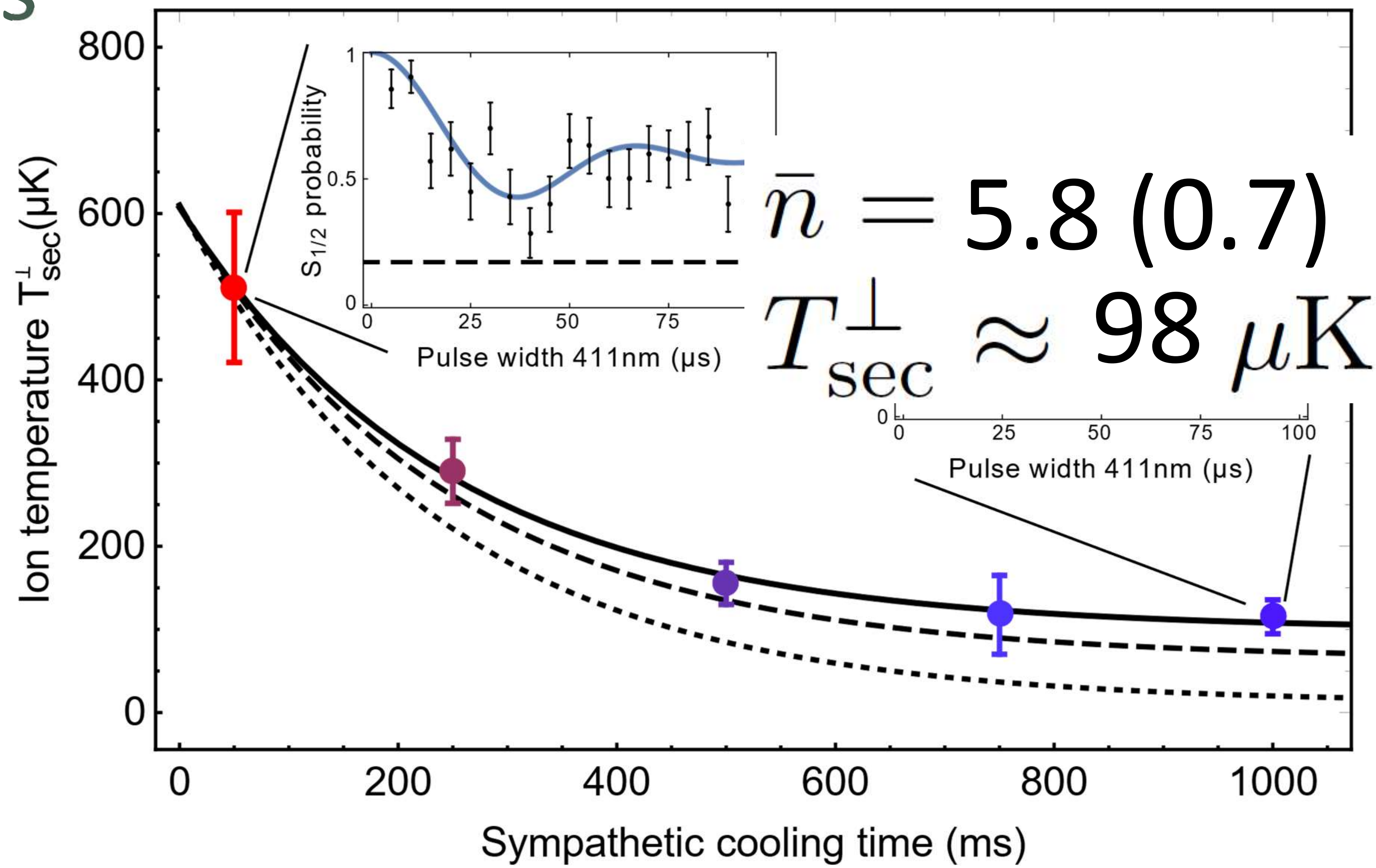
········ simulation without trap rf-field

- - - - Simulation with trap rf-field + background heating (85 μK/s)

—— exponential fit

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

Results



simulation without trap rf-field

Simulation with trap rf-field + background heating (85 μK/s)

exponential fit

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

Interactions in quantum regime

Type of motion	$E_{\mathrm{kin}}/\mathrm{k_B}(\mu\mathrm{K})$	$E_{\mathrm{col}}/\mathrm{k_B}(\mu\mathrm{K})$
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

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

Crossover to quantum regime

Coldest results

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

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, $Yb^+/{}^6Li$ and $Ba^+/{}^6Li$ that have reached the crossover into the quantum regime

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