Cooling methods in ion traps

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What is cooling ?

- decrease the kinetic energy ?

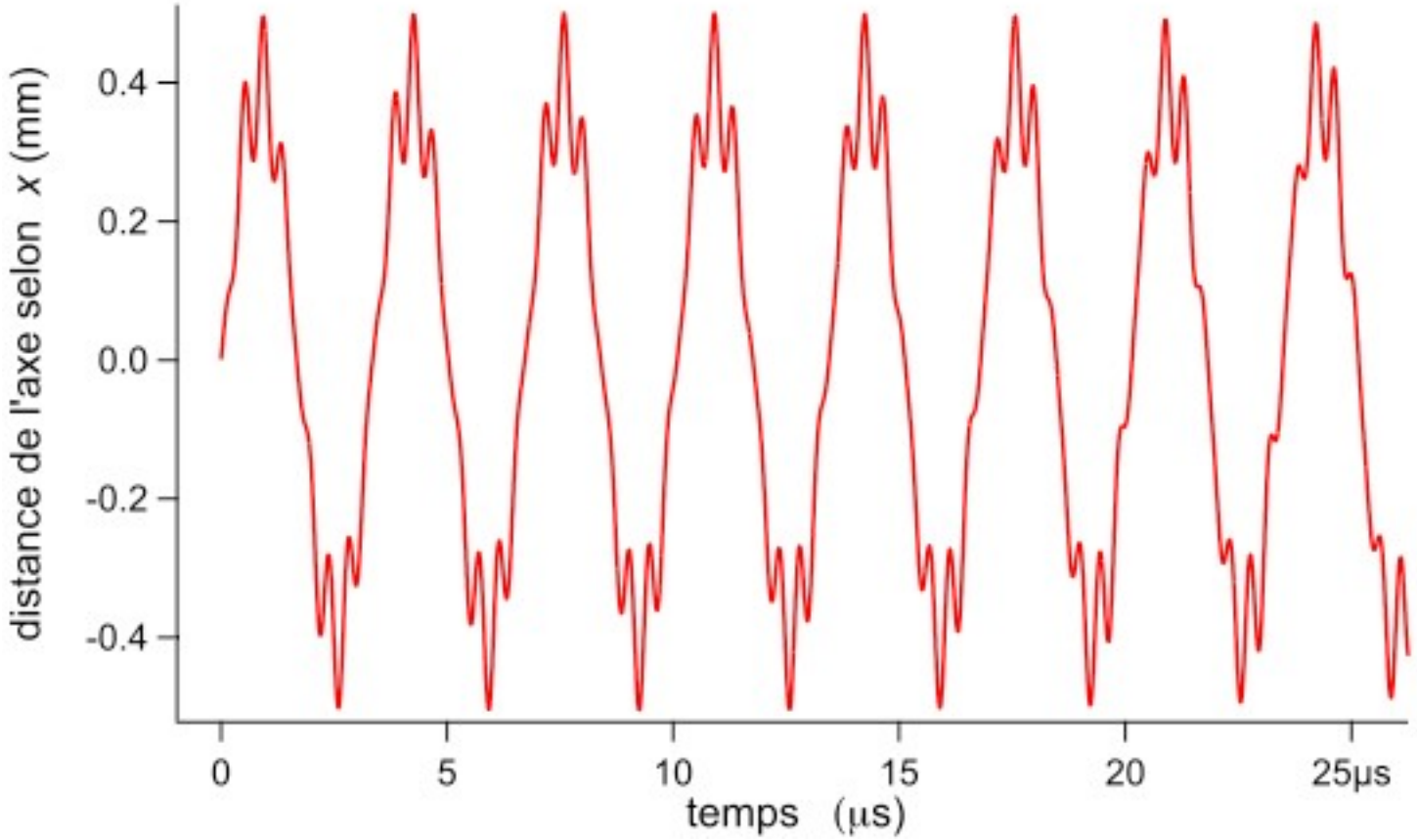
- increase the phase space density ?

What is cooling ?

→ reducing the kinetic energy...

...at fixed trap condition
and
fixed atom number

What is cooling in a RF Paul trap?



Typical motion of an ion in a Paul trap.

A secular large amplitude low frequency motion is modulated by a high frequency (trap RF) low-amplitude so called *micro-motion*.

What is cooling ?

Definition of the temperature
for atom and ion trappers ?

- no equilibrium with a thermal bath
- exotic velocity distribution
- anisotrope temperature

…

→ width of the velocity distribution (clouds)
→ average quantum number (few ions)

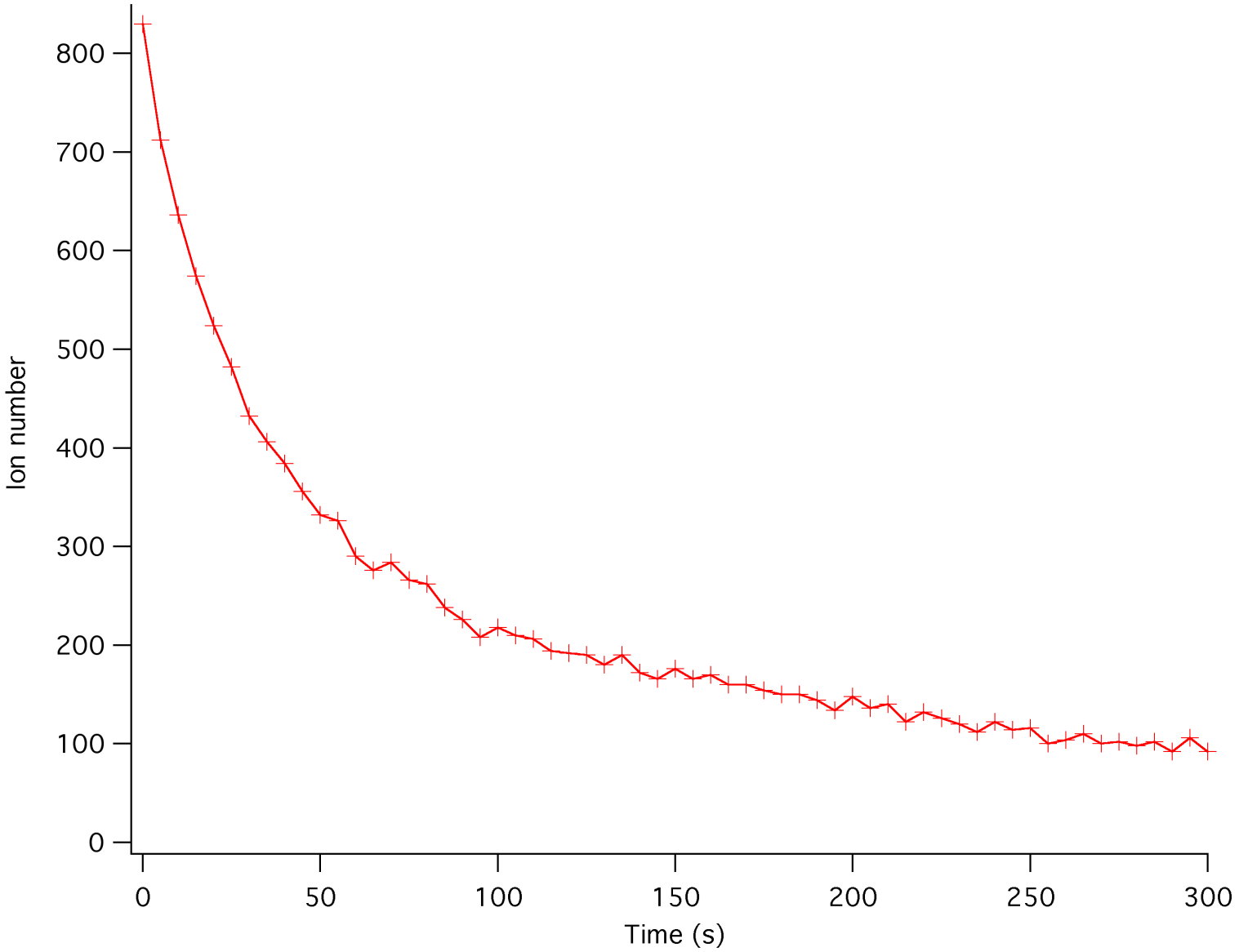
Why cooling ?

- Very high temperature ions can be trapped (eV)

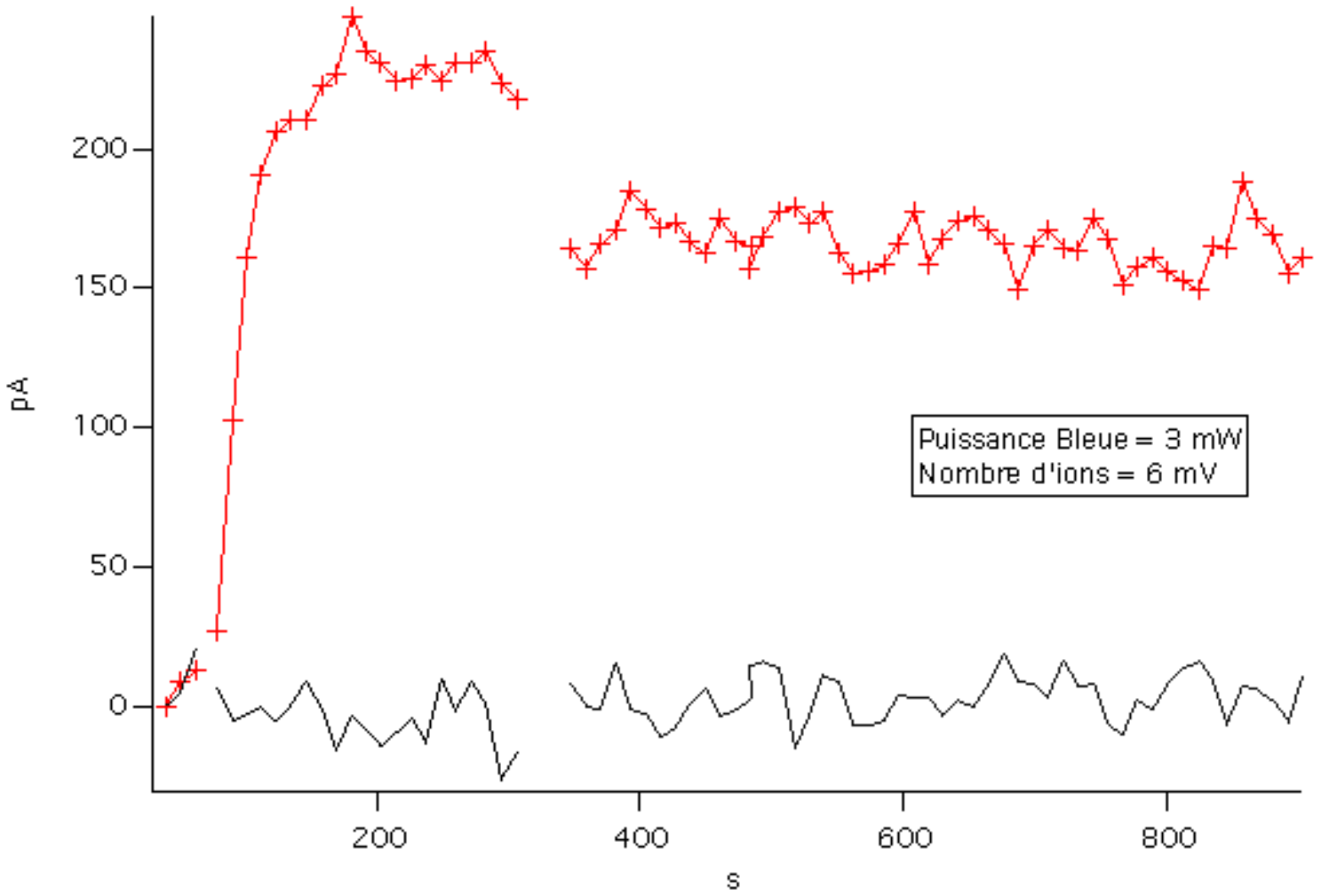
  Goal of cooling :
  hold ions for very long times and controlling the interaction with their environnement.

- Cooling has several benefits...

lifetime...



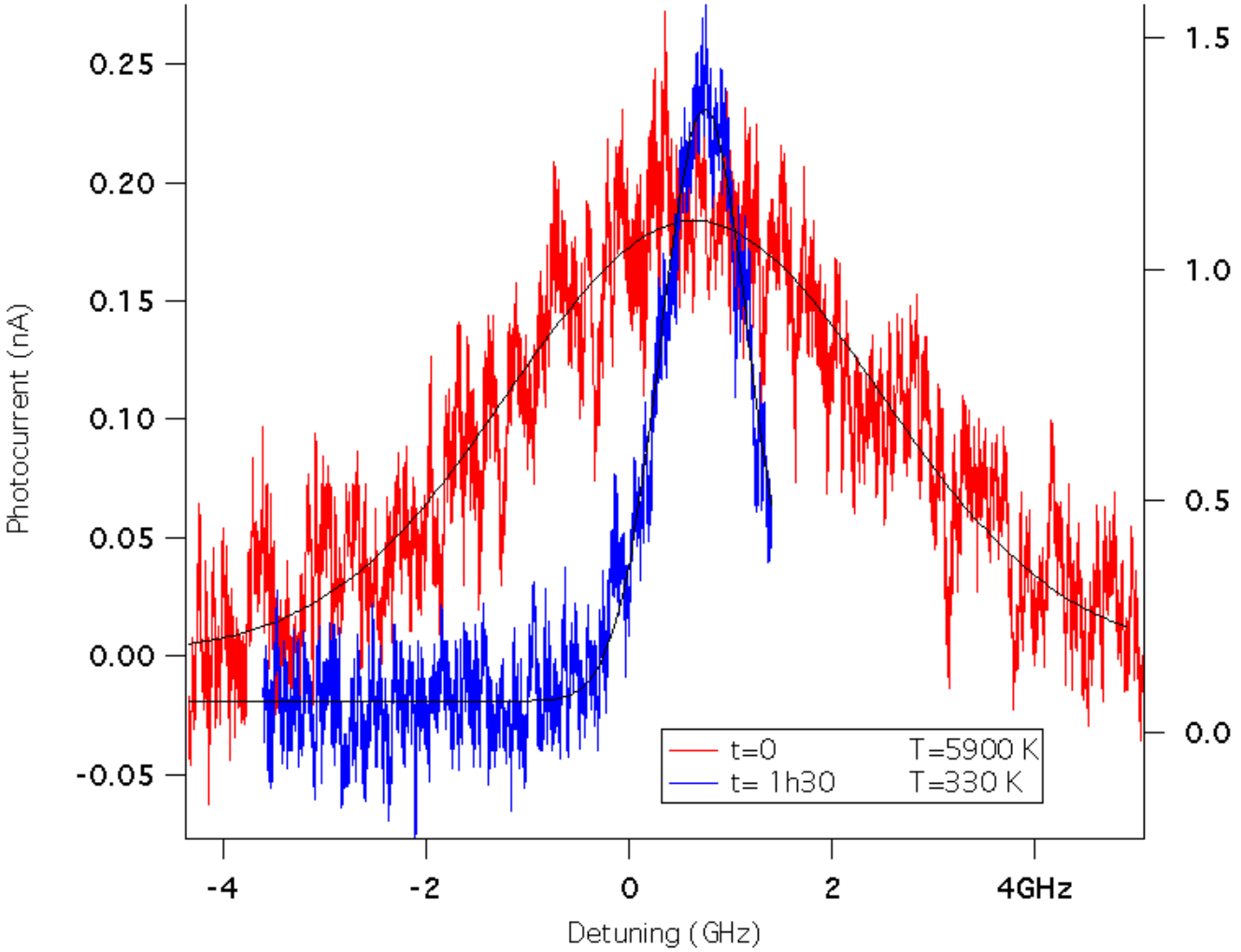
Hot cloud of trapped ions (lifetime < min.)



Lifetime of a laser-cooled ion cloud (can be hours...)

(remark : 2 different sets of experimental parameters are presented here)

ion/laser interaction...

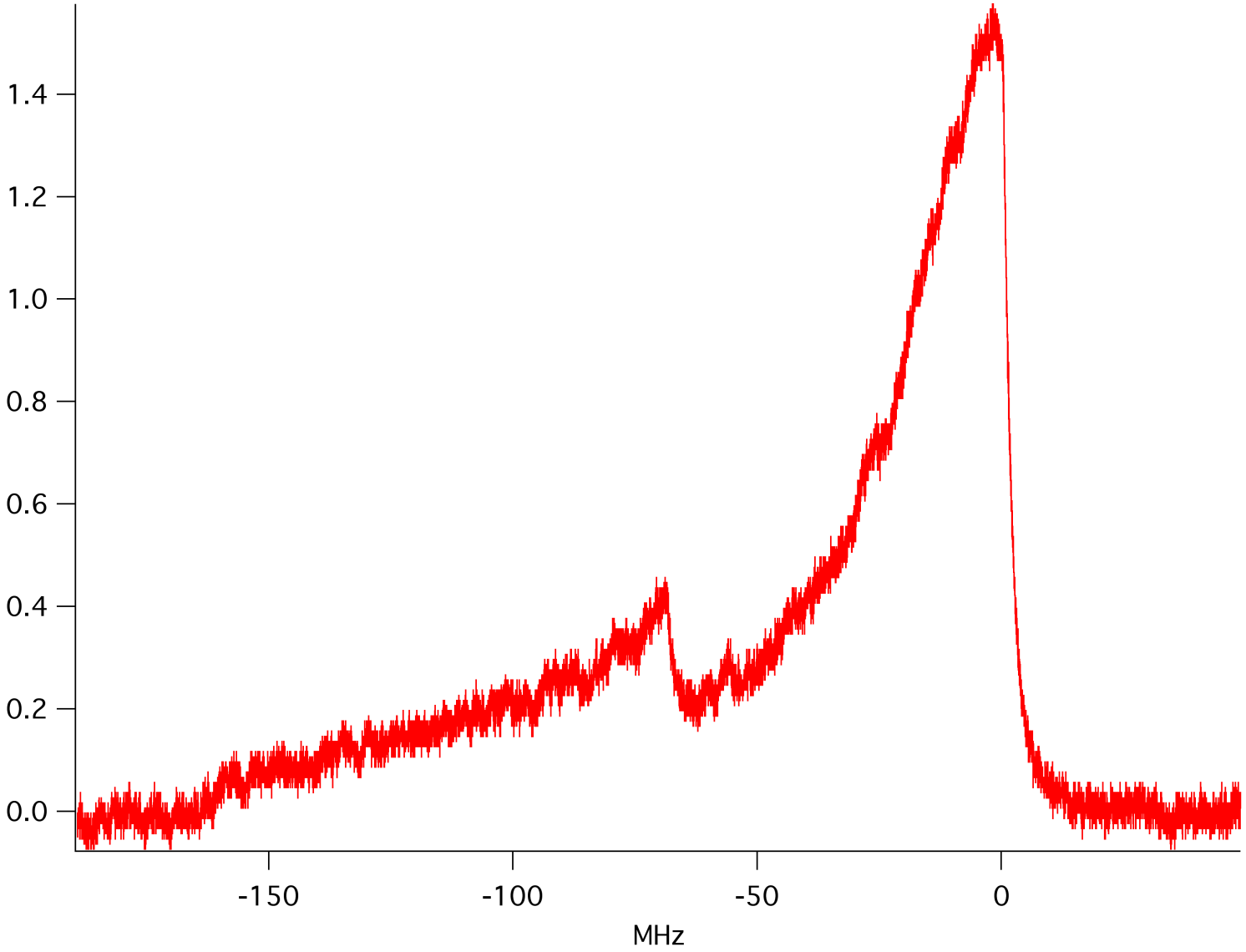


Fluorescence spectrum of « hot » and « cold » trapped ion clouds (vs. laser detuning)

Horizontal : laser detuning from atomic transition.

Red : hot cloud

Blue : cooled cloud (low pressure buffer gas)



Fluorescence spectrum of an efficiently laser-cooled trapped ions cloud (vs cooling laser detuning).

Horizontal : laser detuning from atomic transition.

Why cooling ions ?

- Increased lifetime
- Increased precision of measurements (clocks or high-res spectroscopy)
- Strong localization of ions in spatially ordered structures (individual manipulation)
- Preservation of quantum coherence (even of external degrees of freedom)
- Because it's fun!

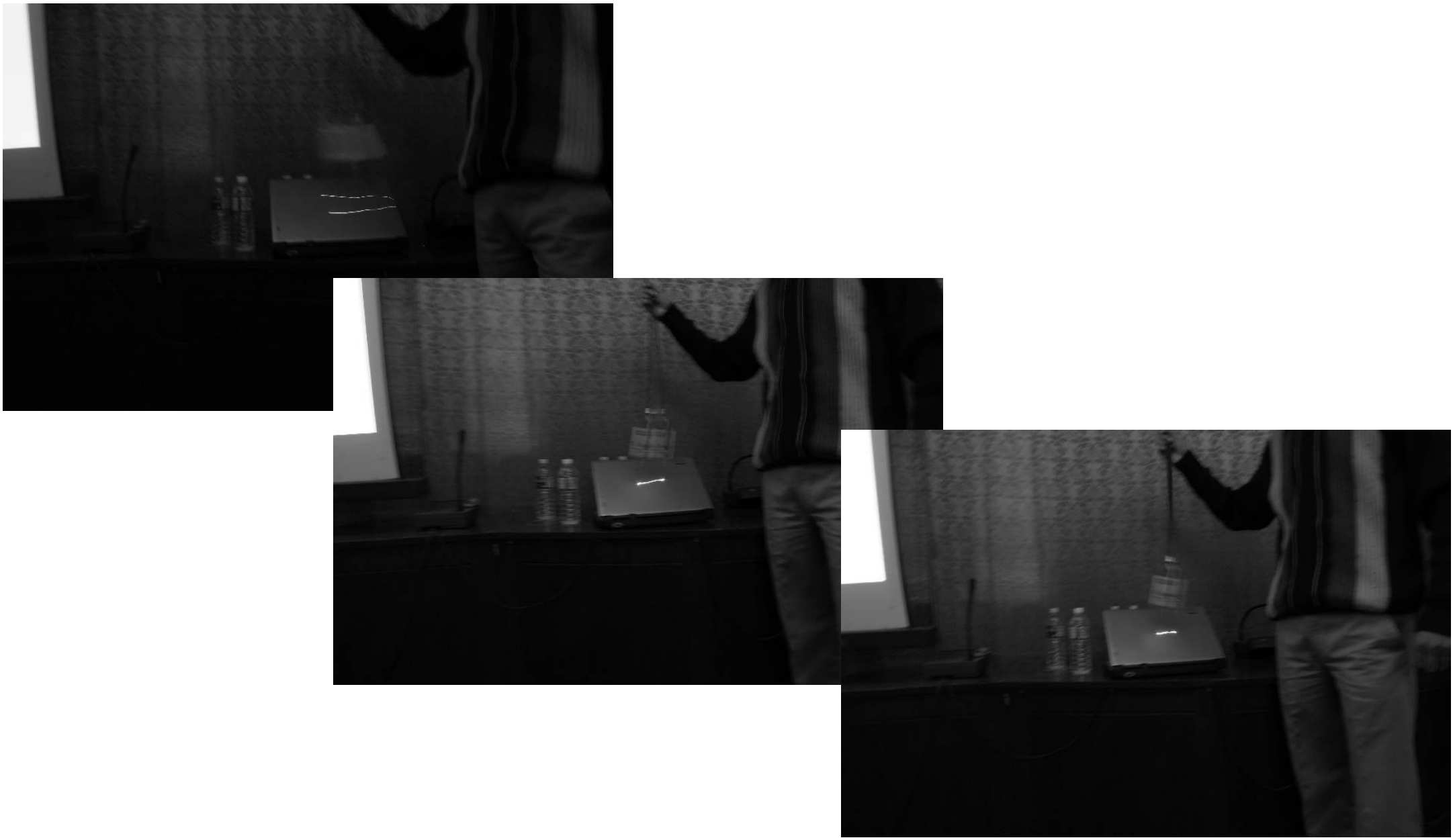
Trapped ions diagnostics and measurements methods

- Direct ion detection and time of flight
- Fluorescence imaging
  - few hot ions → temperature
  - many (or some) cold ions → number
- Laser excitation spectrum analysis
- Fluorescence spectrum (at fixed laser excitation)
- Resonant excitation of the secular motion
  - trap-loss detection
  - fluorescence detection

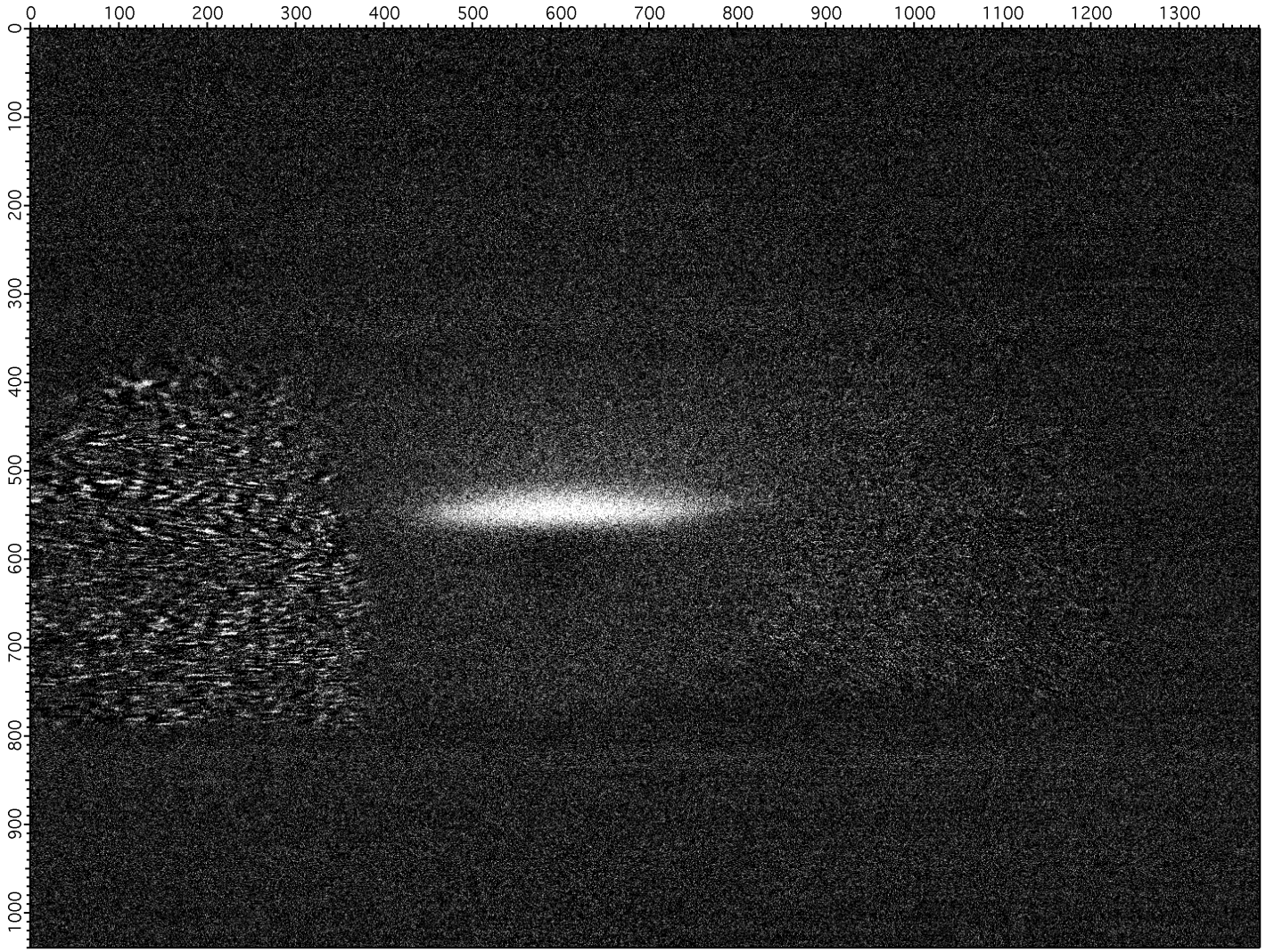
Ion imaging

Let's imagine a trapped ion...

Laser cooling ;-) (by buffer gas cooling)

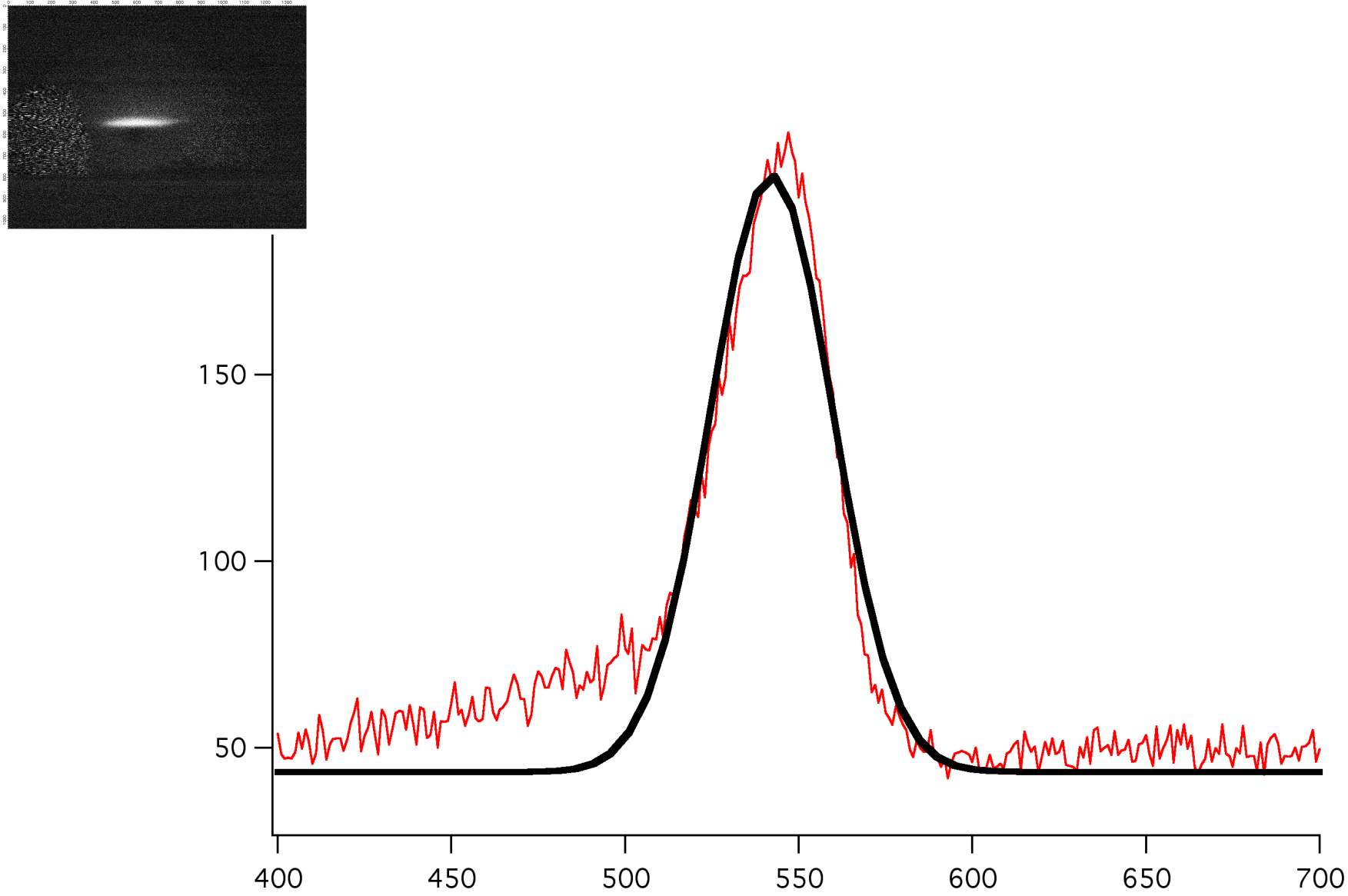


And now...
perform useful measurements !



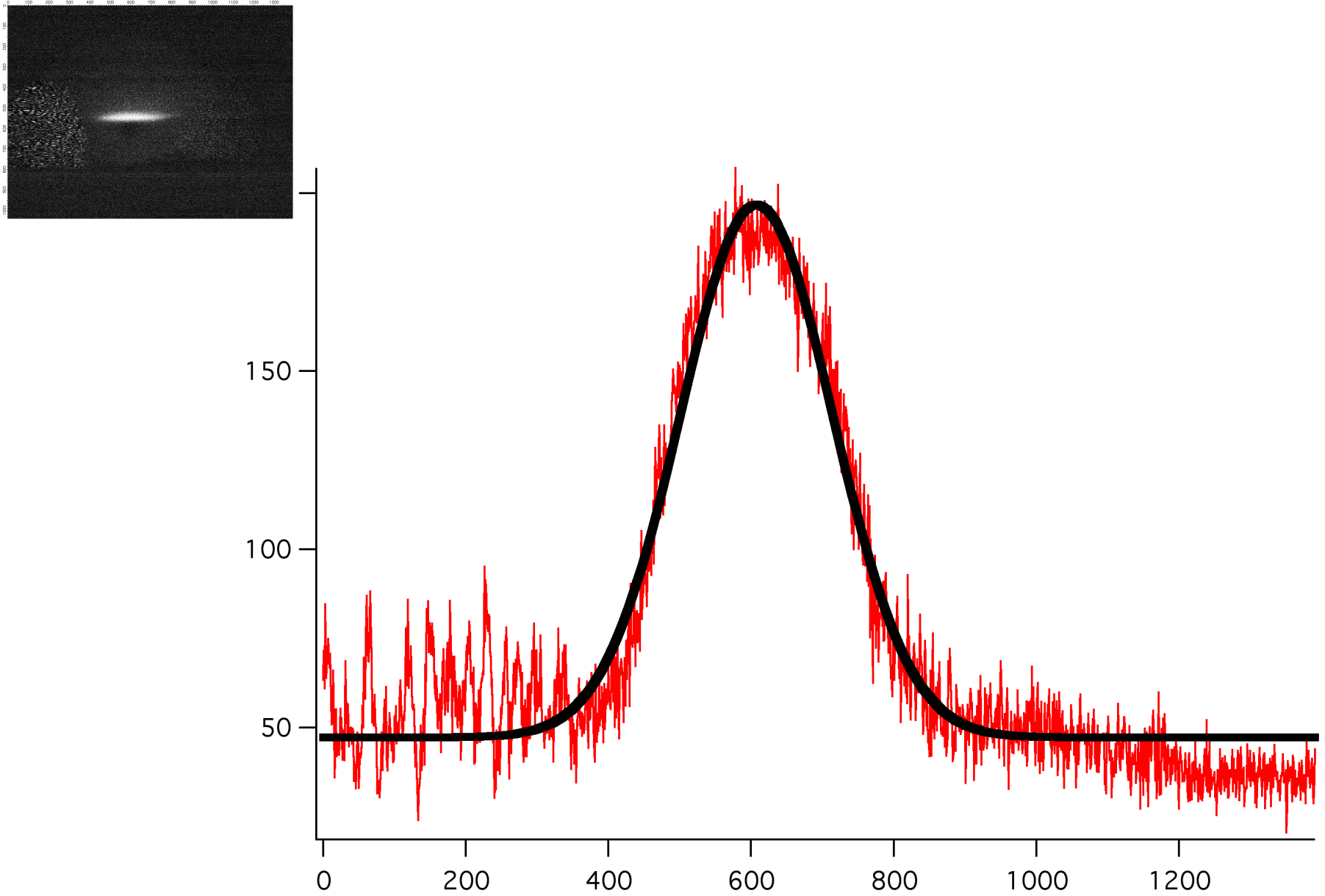
Hot trapped $^{88}Sr+$ ion cloud (6.6microns/px)

Trap oscillation frequencies : axial 33kHz, radial 200kHz



Hot trapped ion cloud

vertical profile, width = 25 px (0.165 mm)



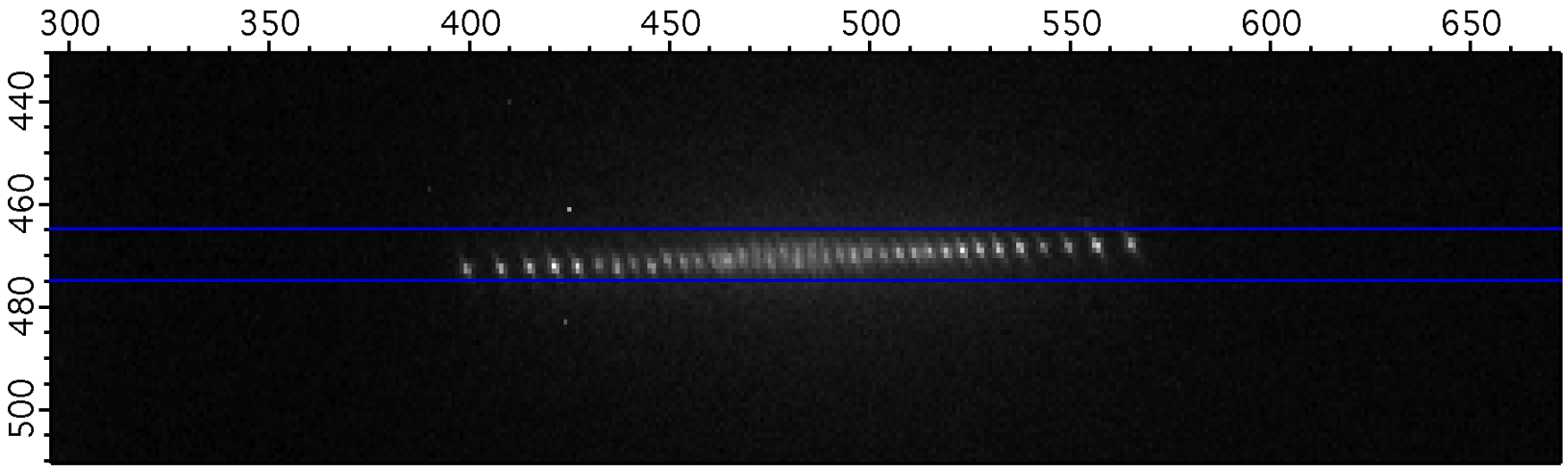
Hot trapped ion cloud

horizontal profile width = 150 px (1mm)

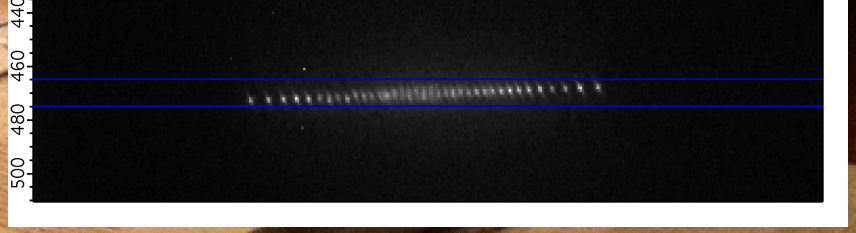
Interpret the measurement...

What is the temperature of
this trapped ion cloud ?

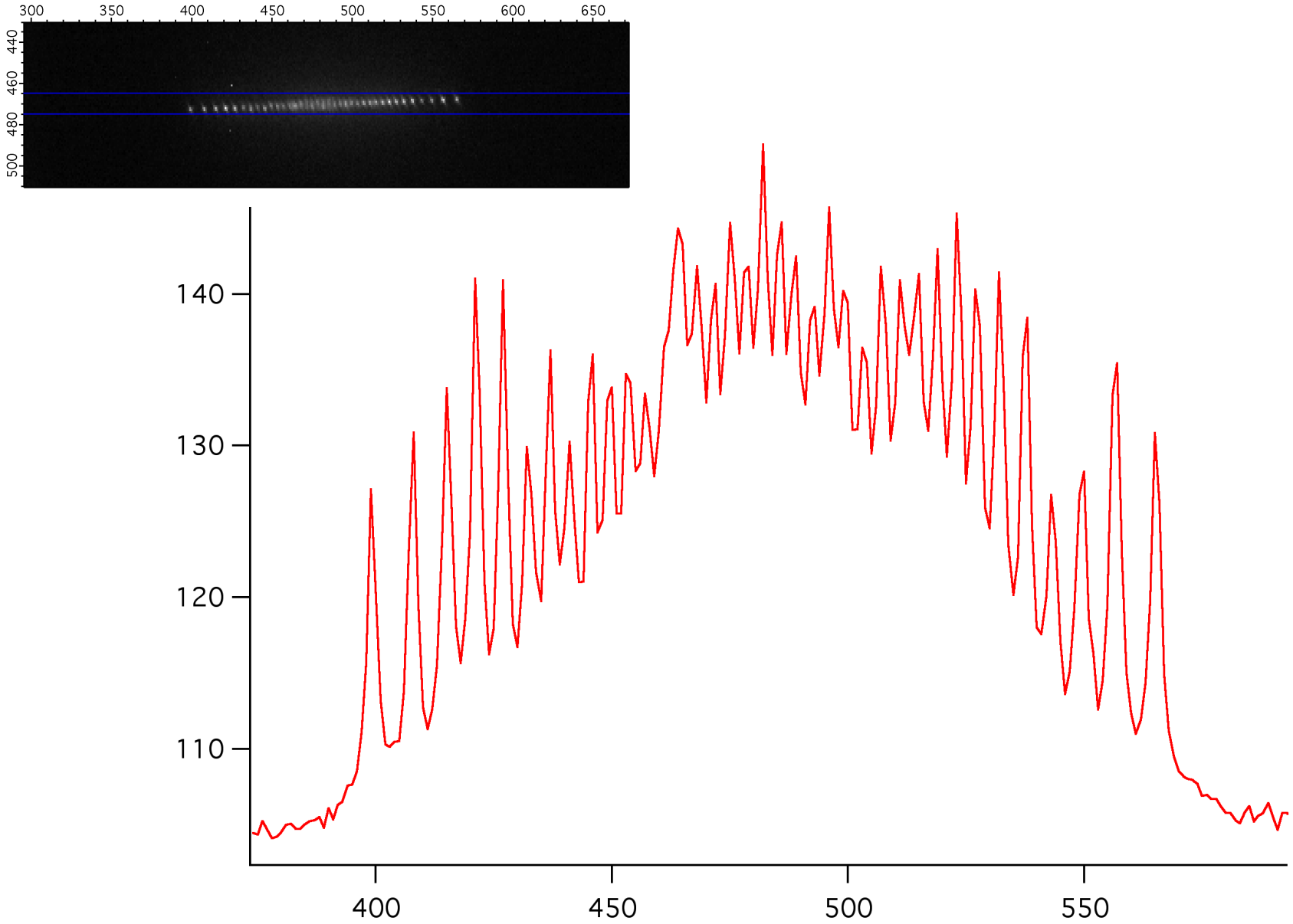
400K !
Let's cool these ions !



Laser-cooled trapped $^{88}Sr+$ ions
(same trap as before)



What could be the distance between two consecutive ions of this string ?



Ion string profile. $\Delta X\_avrg = 7px \rightarrow 45\mu m$

Cooling methods

- **Electrical cooling**
  - Resisitive
  - Active feedback
- **Collisional cooling**
  - (Evaporative)
  - Buffer gas
  - Sympathetic
- **Laser cooling**
  - Doppler
  - Resolved sideband

Electrical cooling

- Resistive

Characteristic time $\tau = 4mz_0^2/q^2R$

Final ion temperature : circuit temperature (needs cryogenic...)

- Active feedback

Time is divided by the gain of the loop

...but noise is increased by the same factor

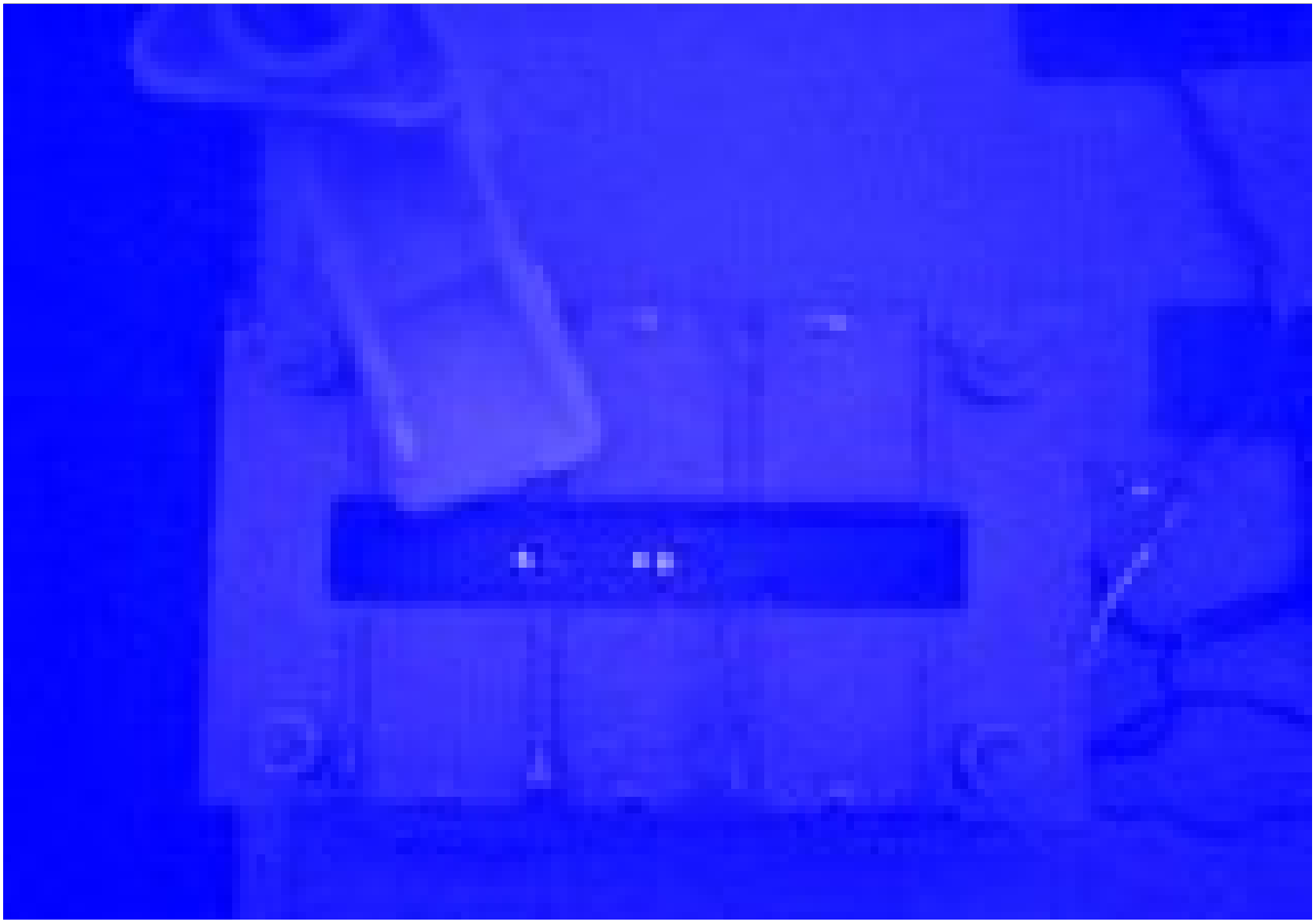
Buffer gas cooling

- Takes advantage of the collisions with a neutral gas of light particles...

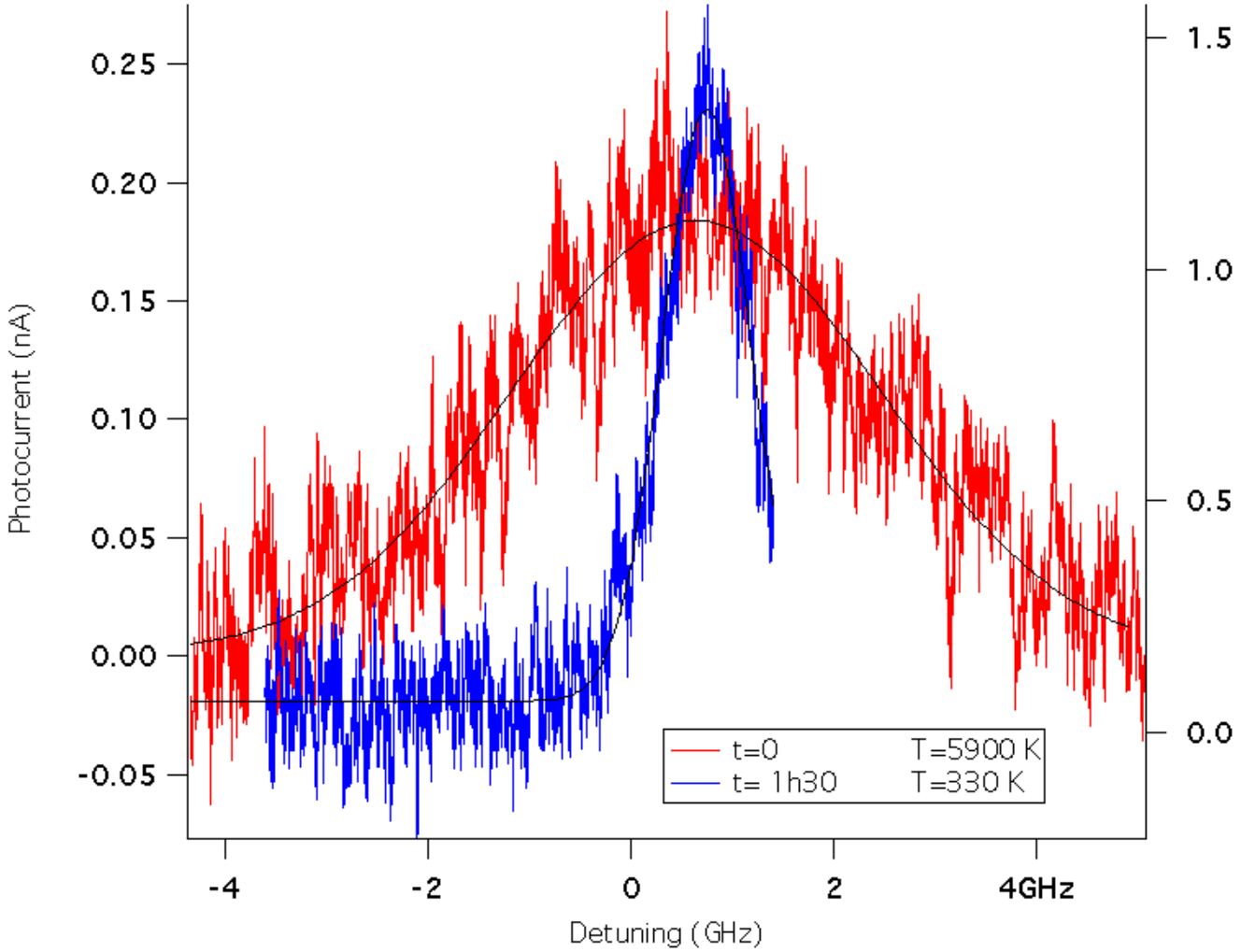
Buffer gas cooling...
an other experiment

Thermal oscillation amplitude at equilibrium ???

Ambient pressure buffer gas cooling a simple experiment...

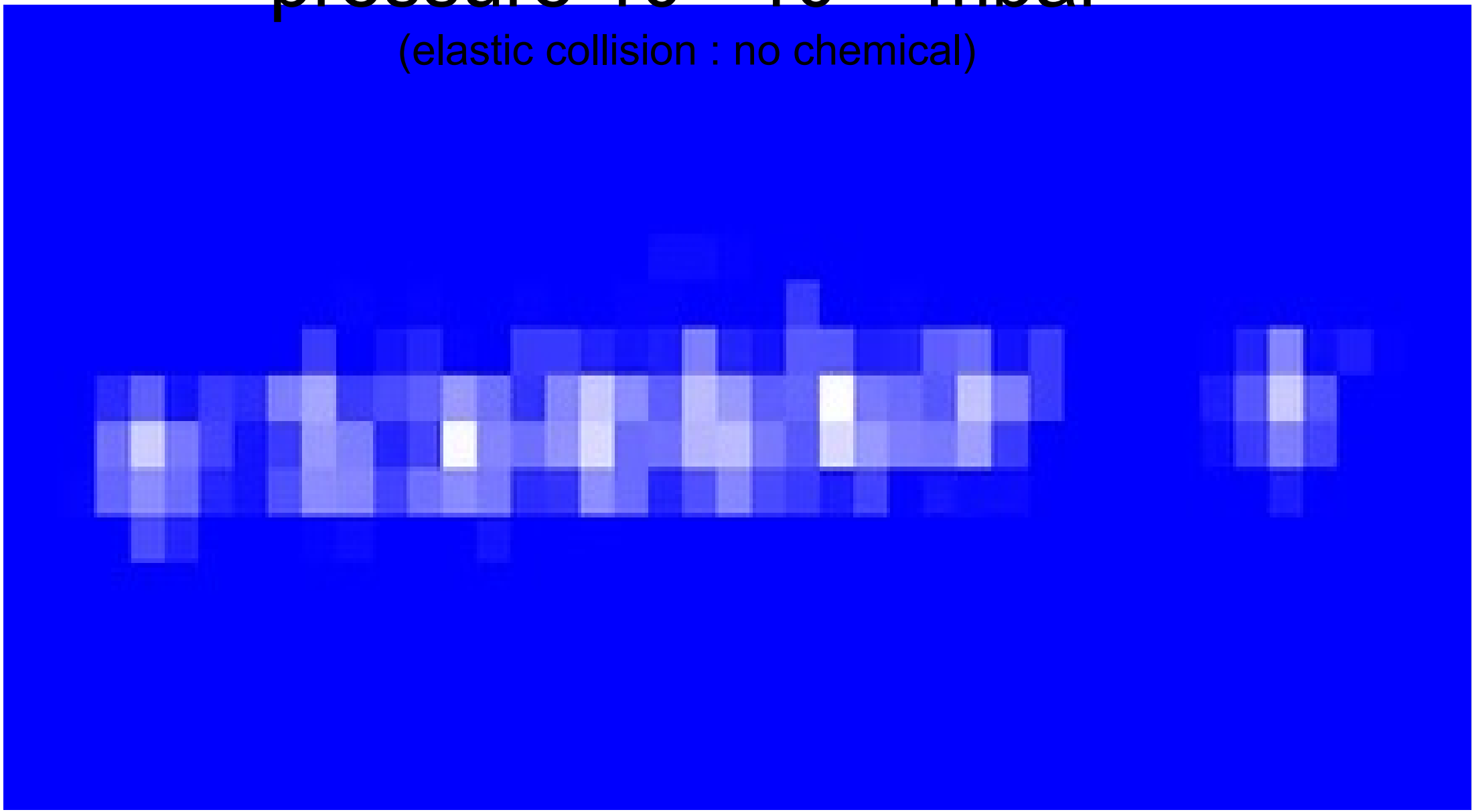


Collisional cooling effect and characteristic time



Background gas collision evidence pressure 10^{-9}-10^{-10} mbar

(elastic collision : no chemical)



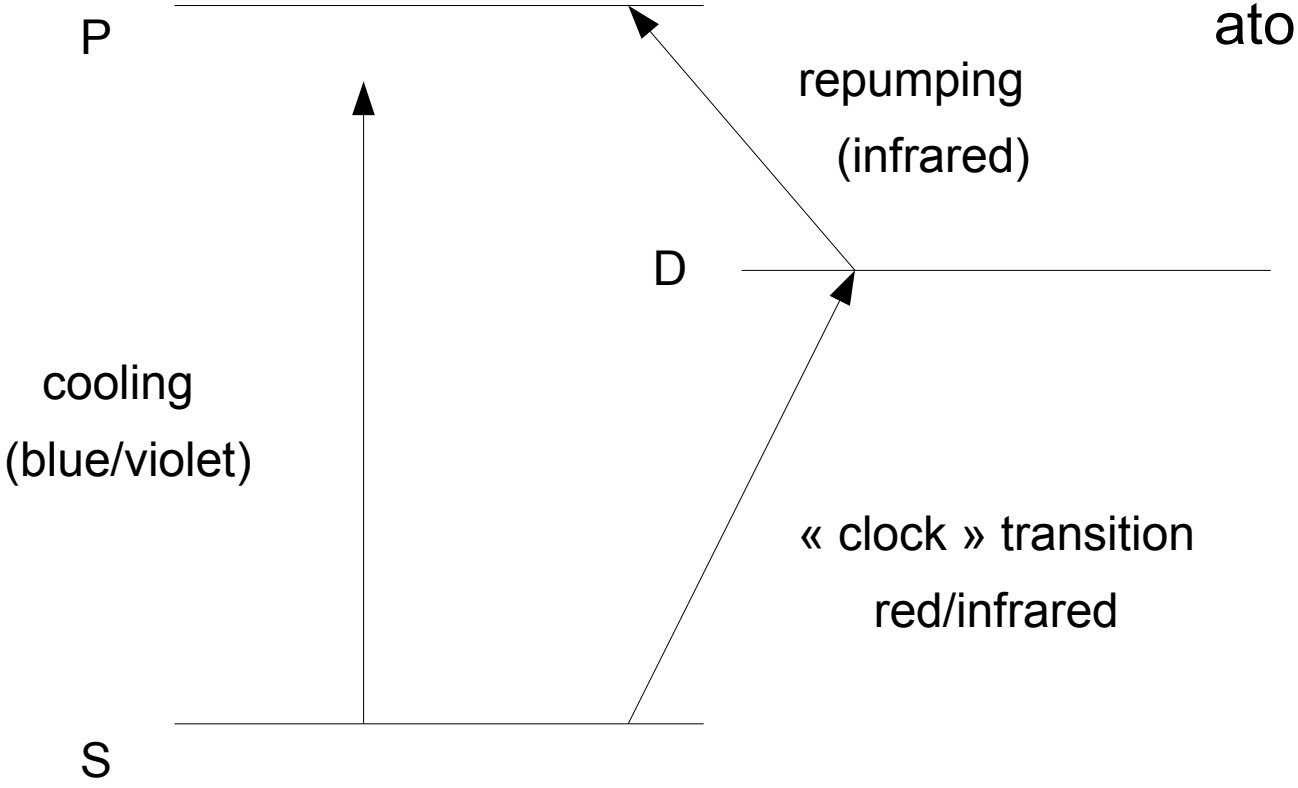
Laser cooling

- Doppler cooling the same way as for neutral atoms
- Confinement adds supplementary properties and constraints

Ion doppler cooling
Typical level scheme

Alkaline-earth ion

Very similar to alkaline atoms structure



Doppler cooling

- Doppler Limit temperature : $\hbar\Gamma/2$
- Crystallization temperature ?
- Doppler broadening at limit temperature ?
- Average # of occupied vibrational quantum states ?

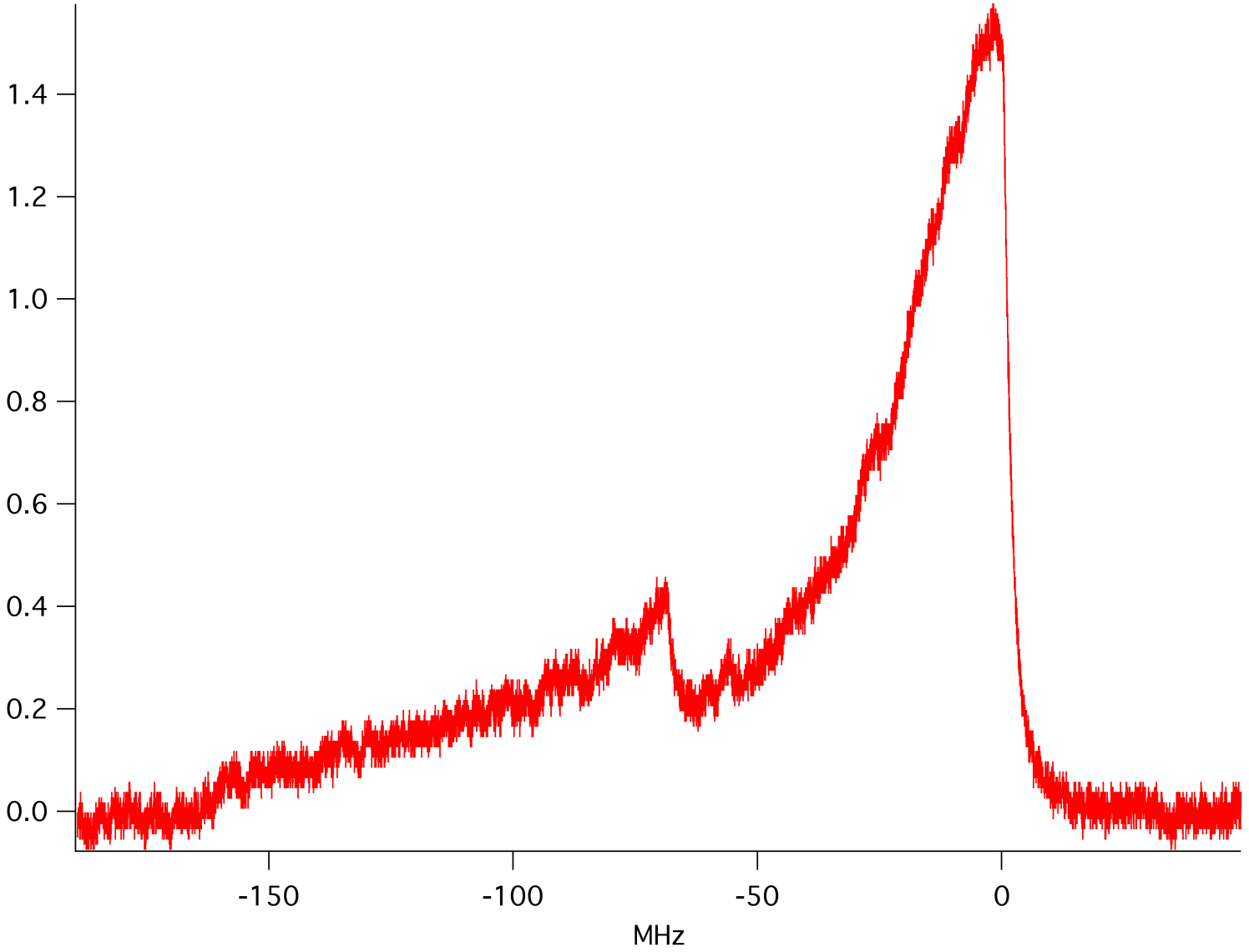
Influence of the trap loading technique

- Loading by electron bombardement or by photoionization

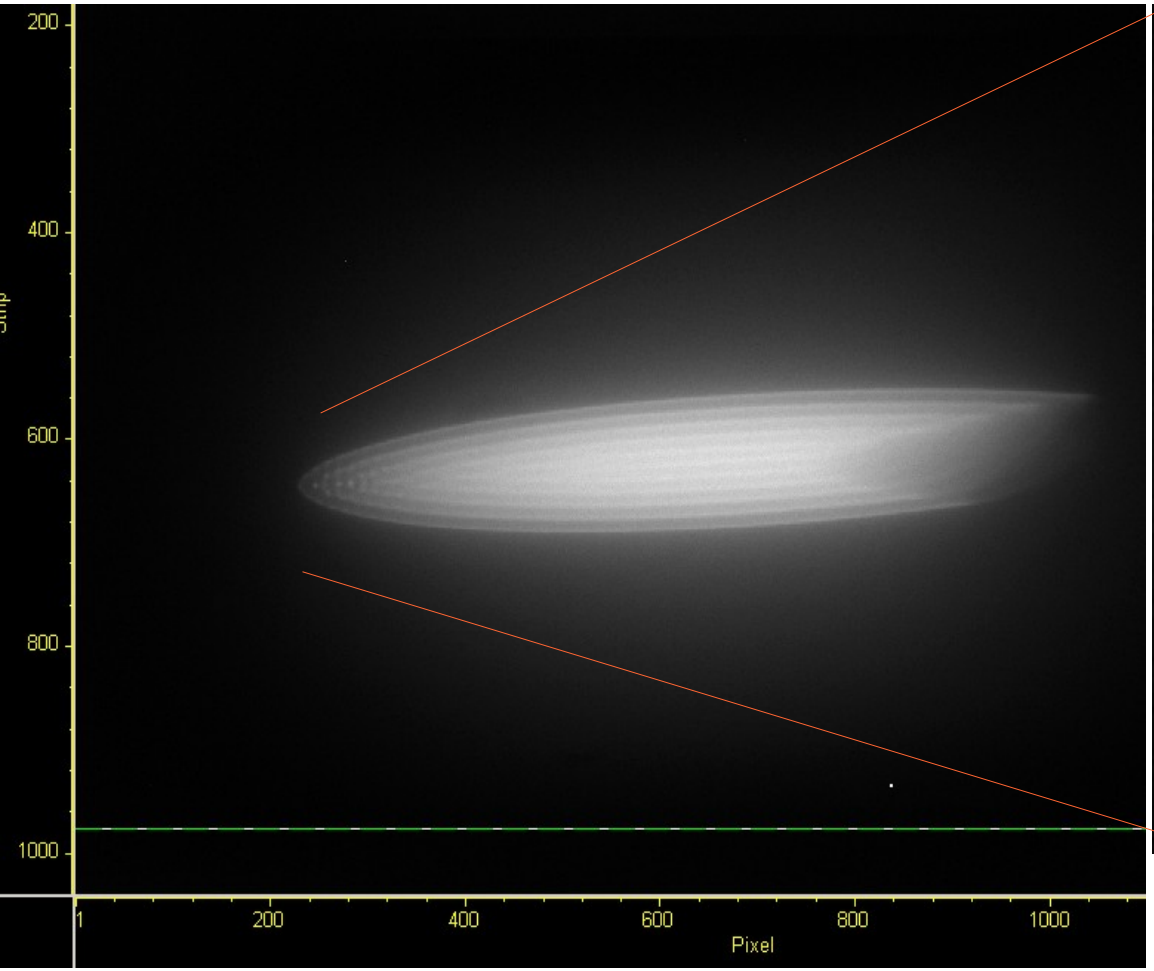
  → initial temperature

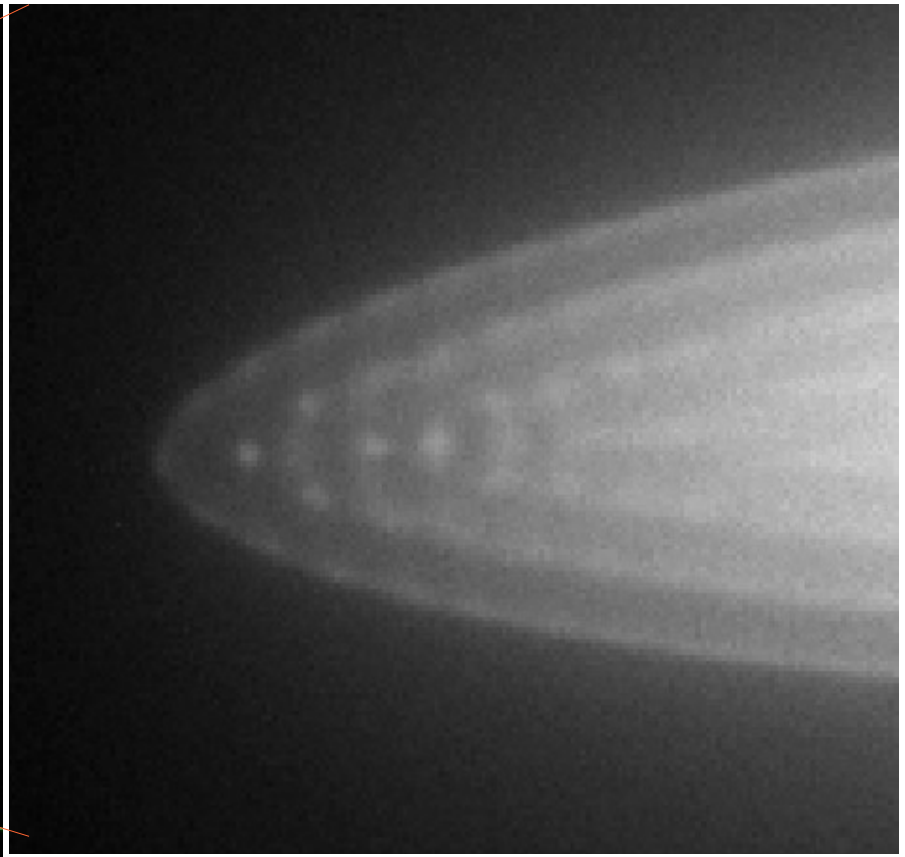
  → perturbating electric charges

Doppler cooling



Doppler cooling down to the formation of a 3D crystal





MPQ, Paris

Resolved sideband cooling

- Tight confinement → Lamb-Dicke effect
- Few ions
- Quantization of the ion vibrational motion

Lamb-Dicke effect

PHYSICAL REVIEW VOLUME 89, NUMBER 2 JANUARY 15, 1953

The Effect of Collisions upon the Doppler Width of Spectral Lines

R. H. DICKE
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received September 17, 1952)

Quantum mechanically the Doppler effect results from the recoil momentum changing the translational energy of the radiating atom. The assumption that the recoil momentum is given to the radiating atom is shown to be incorrect if collisions are taking place. If the collisions do not cause broadening by affecting the internal state of the radiator, they result in a substantial narrowing of the Doppler broadened line.

QUANTUM mechanically, the Doppler effect results from the recoil momentum given to the radiating system by the emitted photon.[1] This recoil momentum implies a change in the kinetic energy of the

would, within limits, be pressure-independent. Actually, under certain circumstances, this assumption is far from correct. Collisions which do not affect the internal state of the radiating system have a large effect

Lamb-Dicke effect

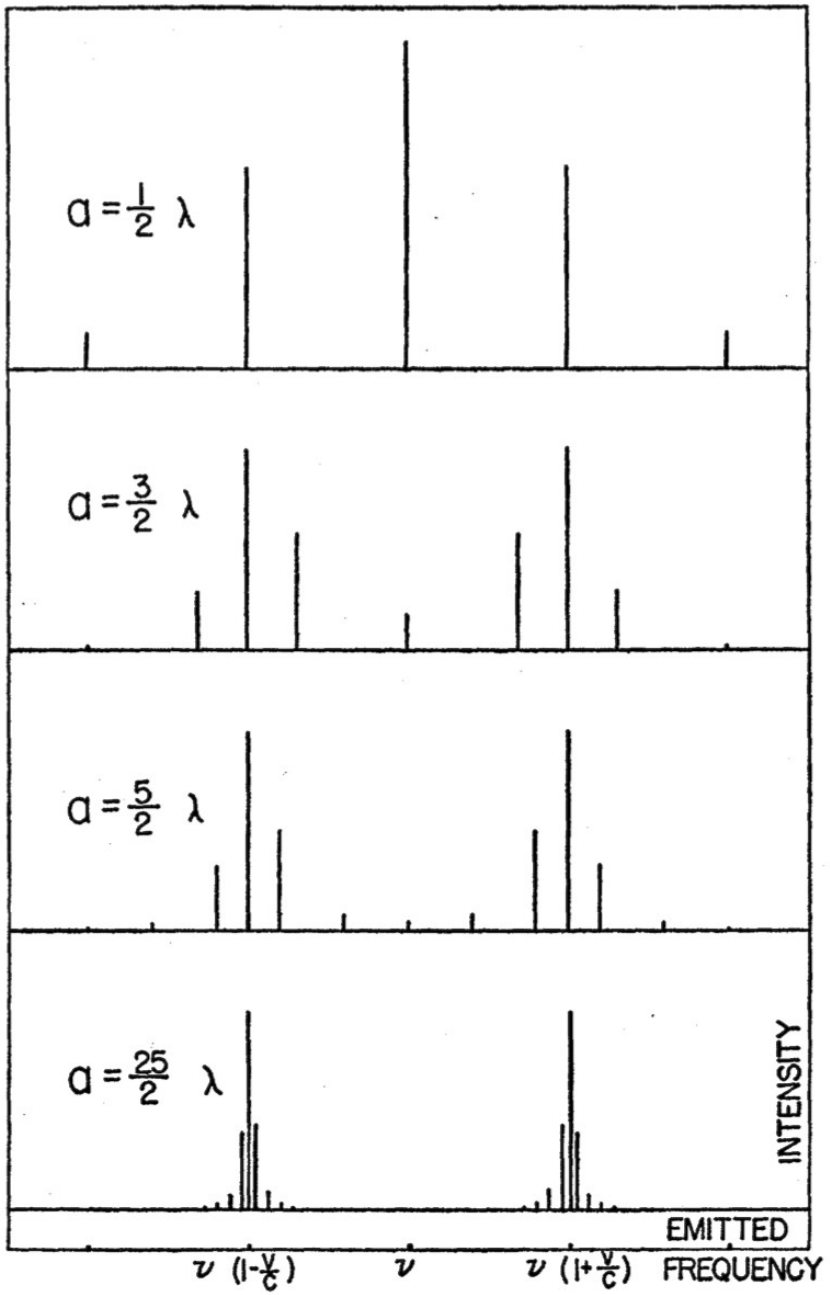


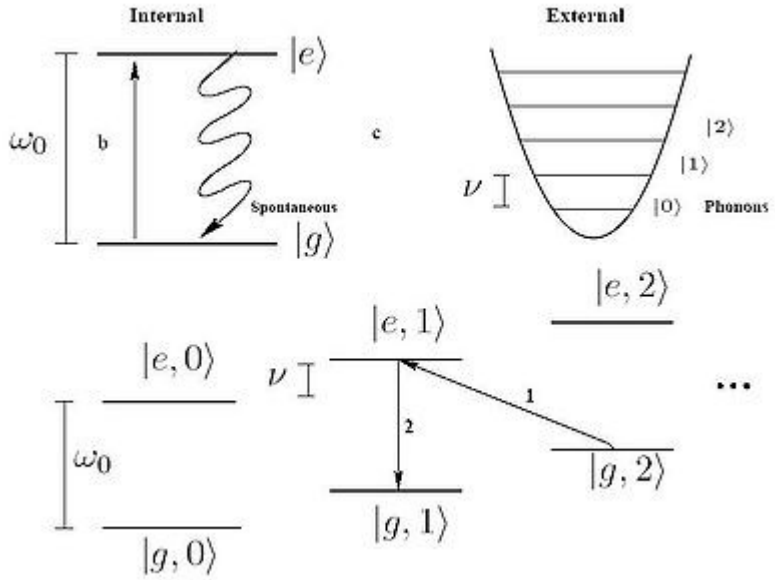
FIG. 1. Spectral distribution of radiation emitted by an atom confined to a one-dimensional box of width *a*.

Lamb-Dicke effect

Strong confinement ($\Delta X/\lambda << 1$)

$\rightarrow$ No vibrational level change in spontaneous emission processes

Sideband cooling principle



Requirements :

- Lamb-Dicke regime
- Linewidth of the optical transition smaller than the vibrational levels spacing...

....But needs to have a sufficient excitation rate to be efficient.

Sideband cooling
Relevant levels and transitions

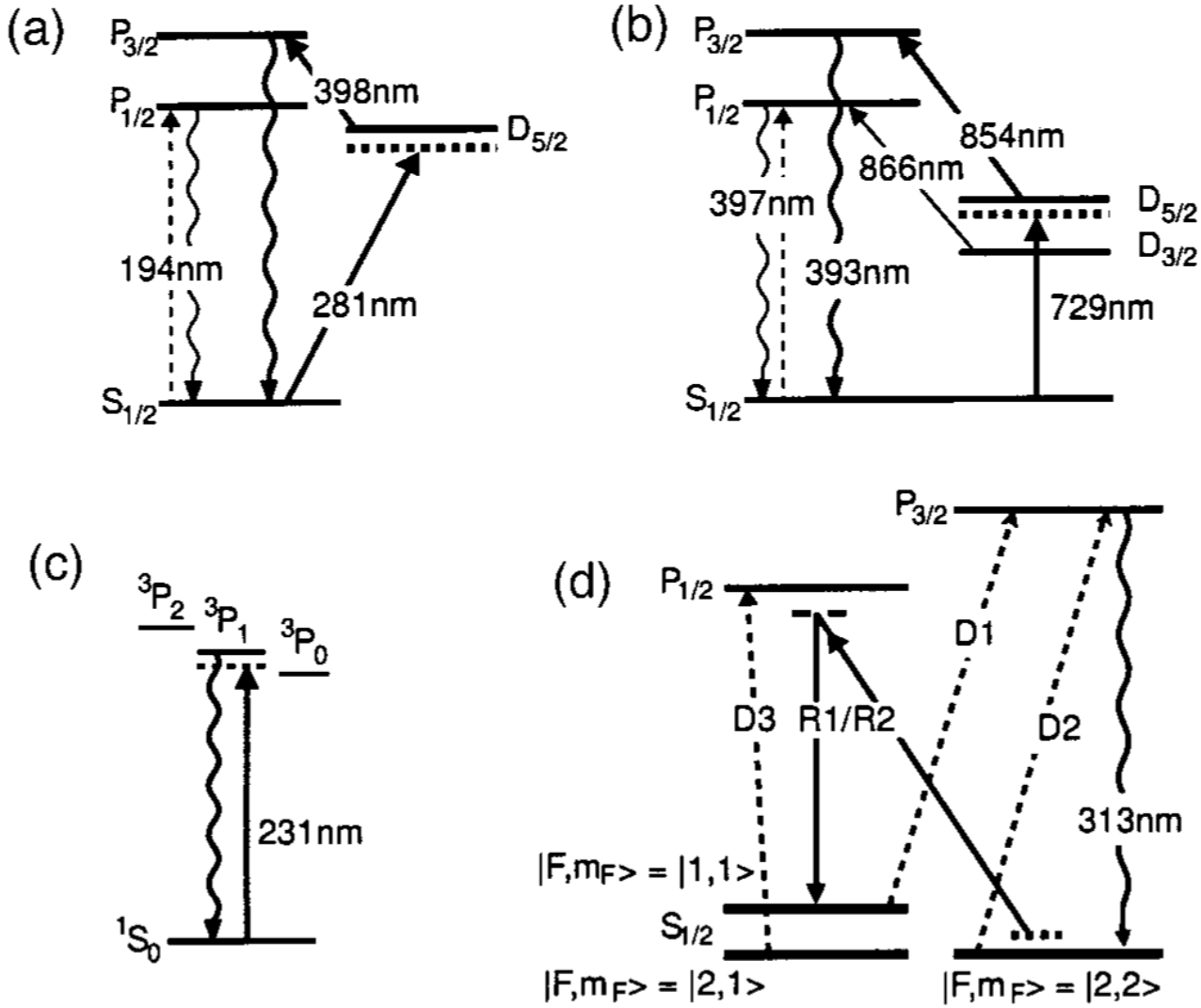


Fig. 3. Levels and transition wavelengths relevant for resolved-sideband cooling in various ion species: (a) With a single $^{198}Hg^{+}$ ion, Doppler cooling is performed on the transition near 194 nm. For sideband cooling, laser light near 281 and 398 nm is used. The red sideband of the $S_{1/2}$–$D_{5/2}$ transition is indicated with a dashed horizontal line. (b) For Doppler cooling of $^{40}Ca^{+}$ ions, the dipole transitions near 397 and 866 nm are employed. Resolved-sideband cooling is performed on the quadrupole transition near 729 nm while the dipole transition near 854 nm is used to increase the cooling rate. (c) For resolved-sideband cooling of $^{115}In^{+}$ ions, the intercombination line near 231 nm is used. (d) Levels relevant for optical cooling of $^{9}Be^{+}$ ions. Transitions D1, D2, and D3 are used for Doppler cooling and optical pumping. Raman sideband cooling is performed with laser pulses alternately driving the transitions R1, R2, and D1, D3. All wavelengths are near 313 nm; the hyperfine splitting of both P states is 1.250 GHz.

Taken from review paper Eschner et al., Vol. 20, No. 5/May 2003/J. Opt. Soc. Am. B, 1003, Laser cooling of trapped ions

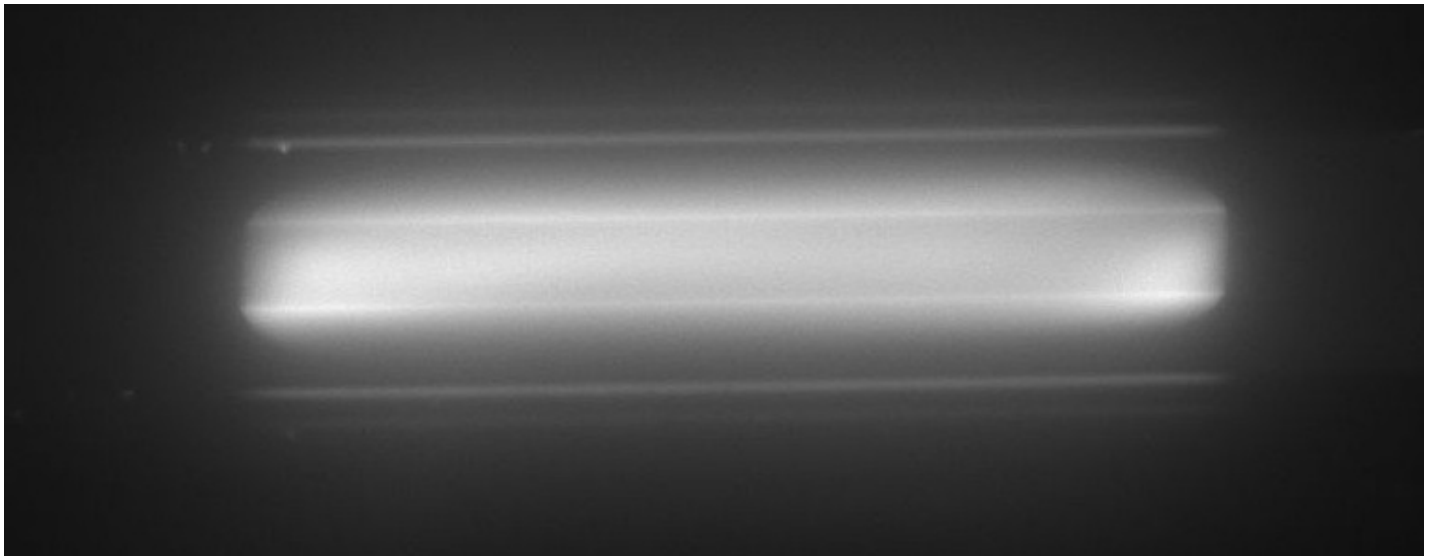
Sideband cooling principle

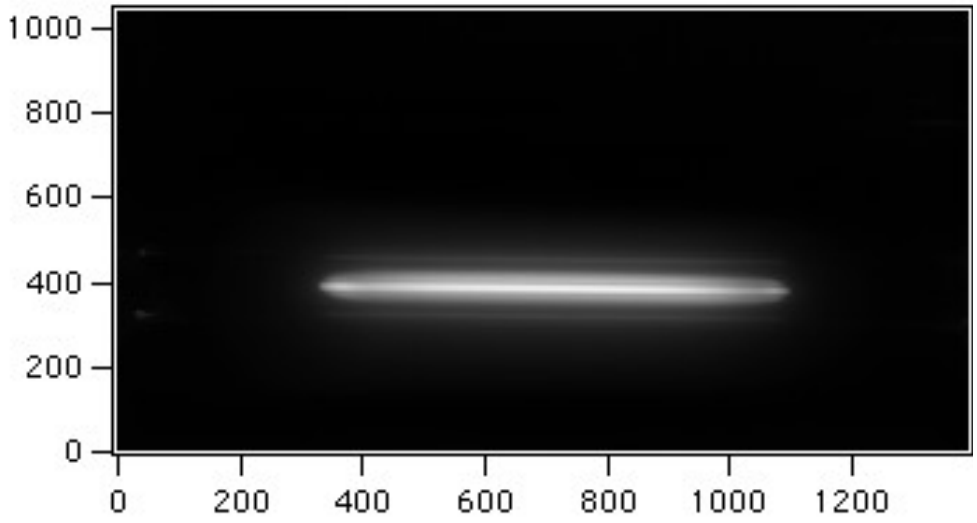
- Vibrational level population measurement by sideband excitation intensity

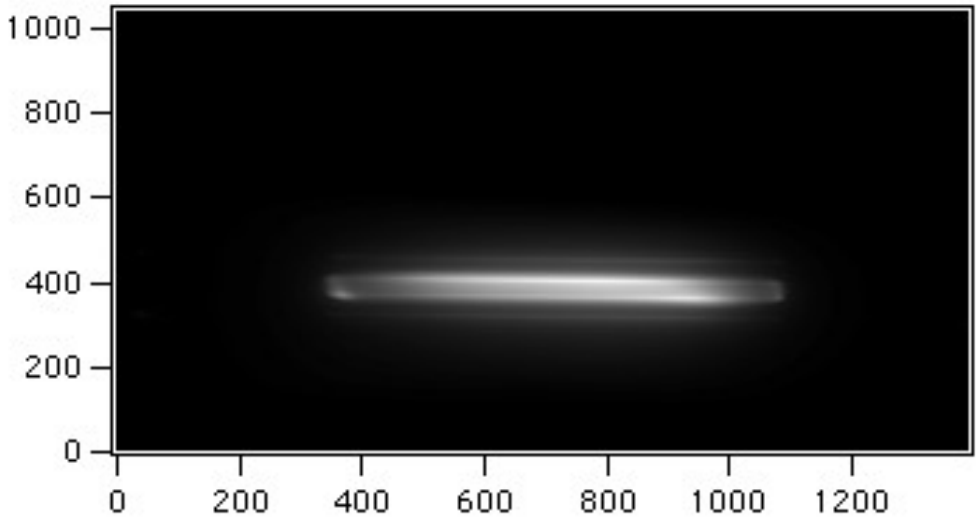
Sympathetic cooling

- Different ion species in the same trap, one is laser-cooled...

Multi-iosotope trap : sympathetic cooling







$^{86}Sr+$

$^{88}Sr+$

Sympathetic cooling

Translational cooling and storage of protonated proteins in an ion trap at subkelvin temperatures

D. Offenberg, C. B. Zhang, Ch. Wellers, B. Roth, and S. Schiller (2009)

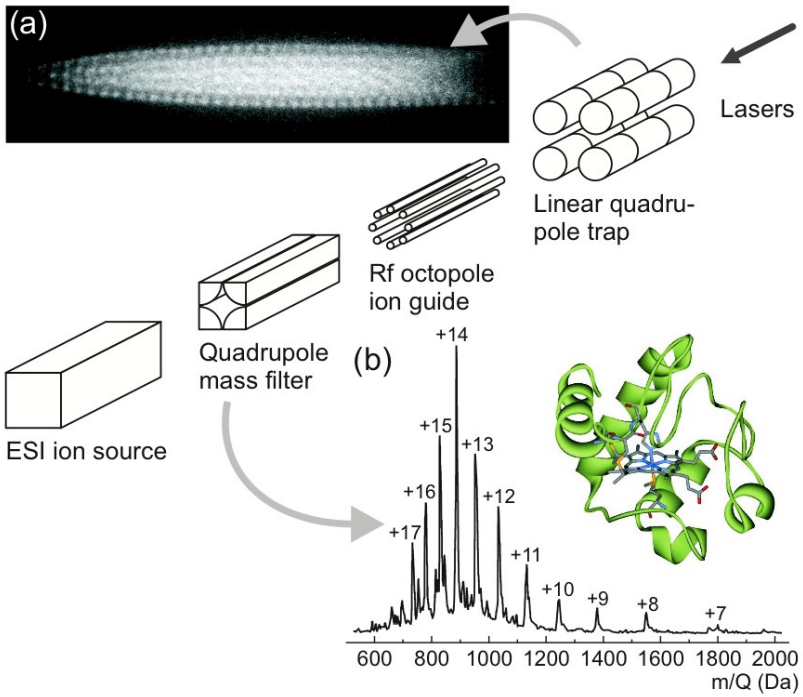


FIG. 1: (Color online) Schematic overview of our setup. Singly or multiply protonated molecular ions from an ESI ion source are selected by a quadrupole mass filter and transferred via a RF octopole ion guide to a linear quadrupole trap in an UHV chamber. (a) CCD image of a typical trapped barium ion Coulomb crystal used as coolant for the molecular ions. (b) Secondary structure and ESI mass spectrum of cytochrome c showing the distribution of the different grades of protonation.

Sympathetic cooling

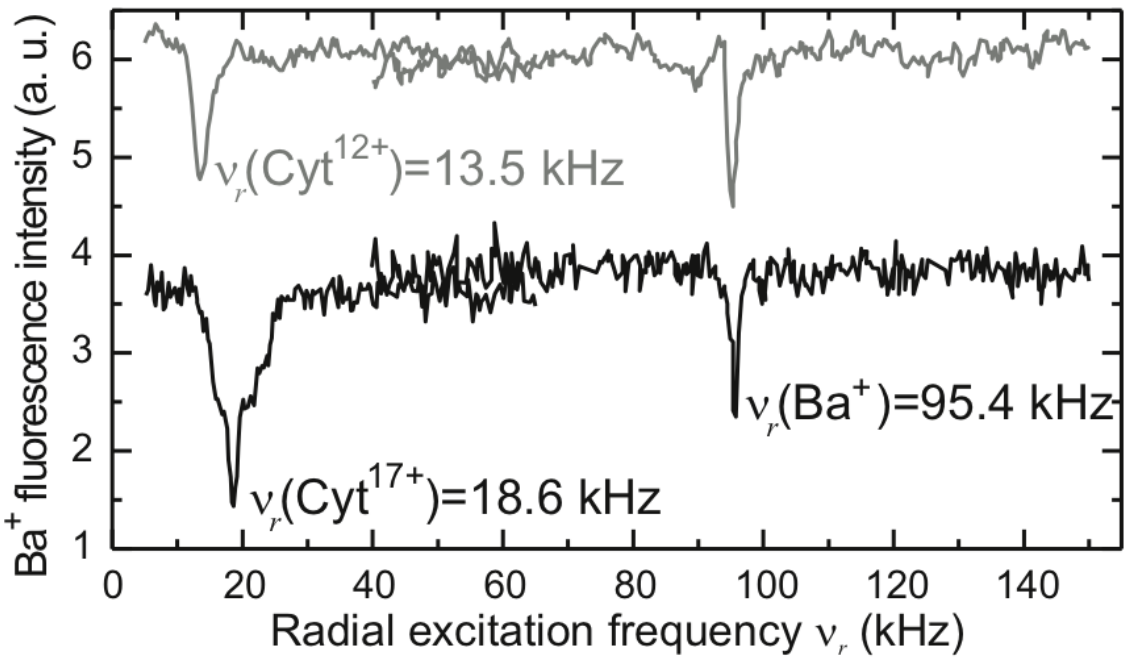


FIG. 2: Radial excitation spectra of barium crystals containing differently protonated cytochrome ions. The upper (Cyt^{12+}) and lower (Cyt^{17+}) curves were acquired at the same trap parameters and yield the same barium frequency of 95.4 kHz used for calibration. The obtained cytochrome frequencies are well confirmed by their theoretical values.

Sympathetic cooling

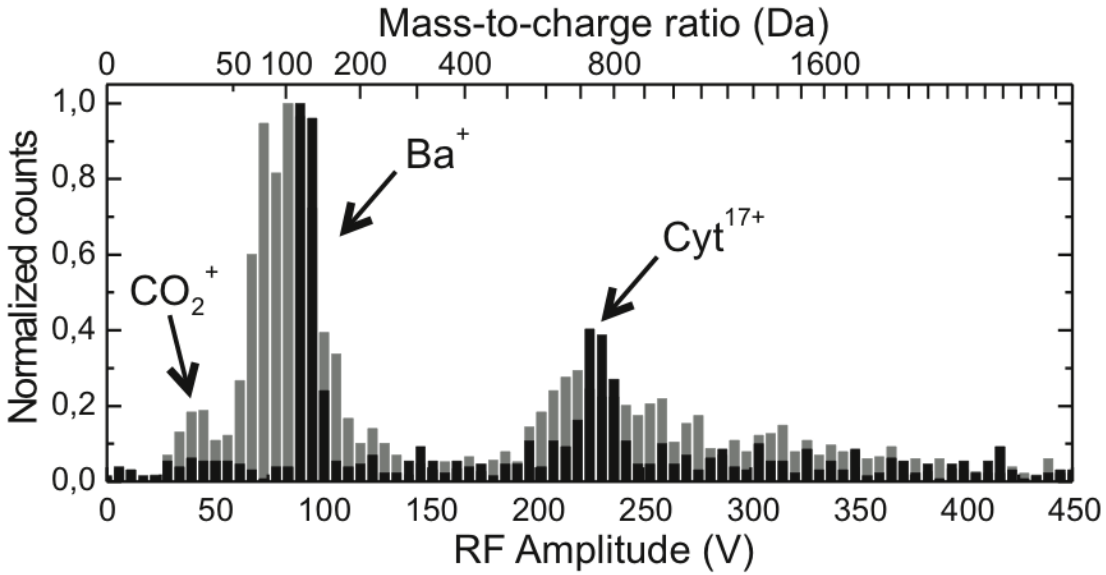


FIG. 3: Ion extraction mass spectra of Ba^+/Cyt^{17+} ensembles at different temperatures. In the noncooled case (gray) the mass spectrum is broadened compared to the laser-cooled case (black). Here, not only the peak of the laser-cooled Ba^+ ions, but also that of the simultaneously trapped Cyt^{17+} ions is narrower, which is a proof of their sympathetic cooling.

Sympathetic cooling

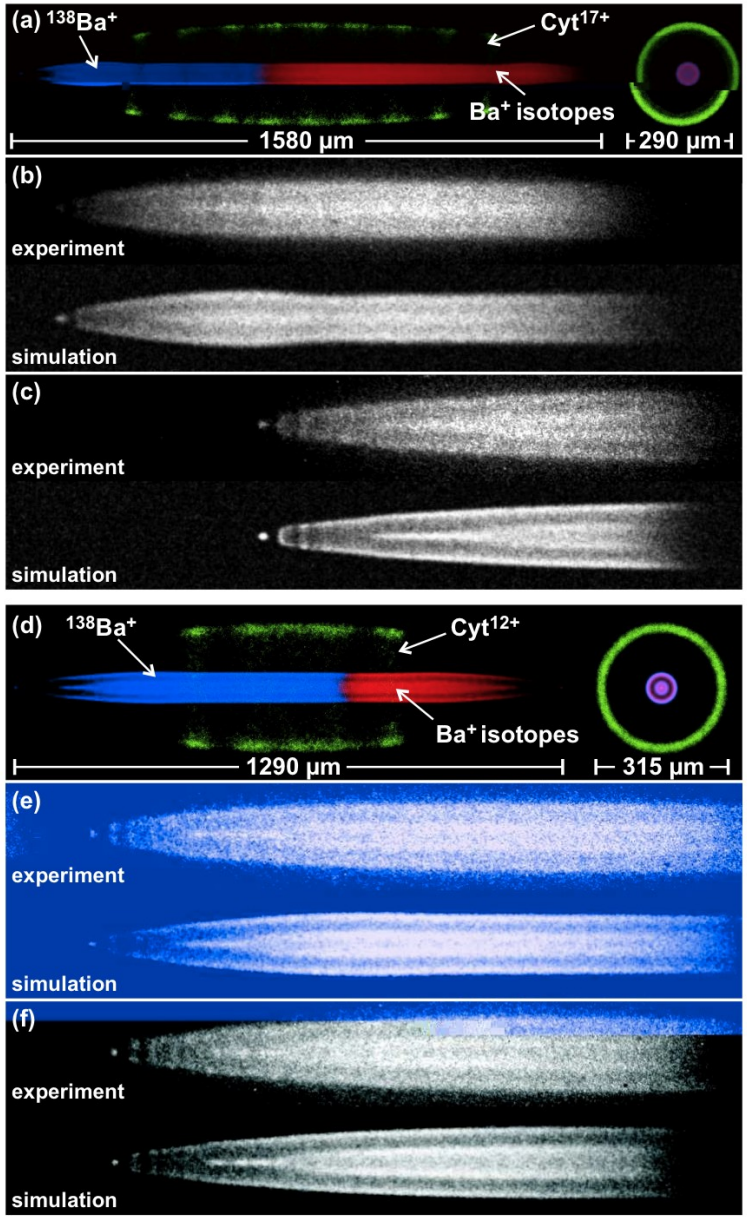


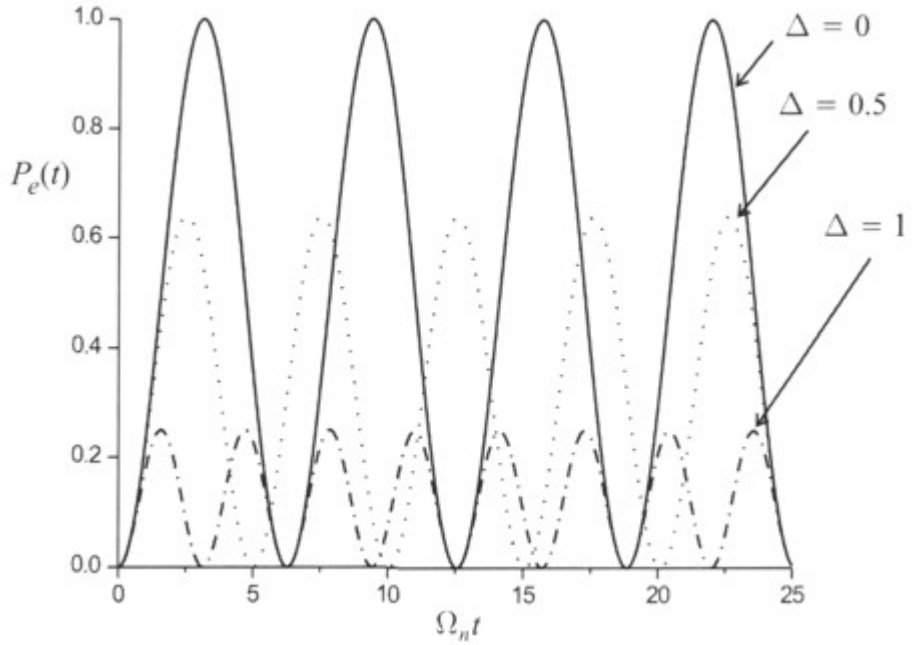
FIG. 4: (color online) Experimental and simulated CCD images of a Ba^+/Cyt^{17+} and a Ba^+/ Cyt^{12+} ion crystal. (a, d) Simulated images in radial (left) and axial view (right), as they would appear if all ions would fluoresce. The cooling lasers propagate to the left, separating the $^{138}Ba^+$ ions (blue) and the barium isotopes (red) axially due to the light pressure force. The cytochrome ions (green) form a sheath around the barium ion subensemble. (b, e) Experimental image of the barium-cytochrome ion crystal and its simulation, showing only the fluorescing $^{138}Ba^+$ ions. (c, f) Crystals after the removal of the cytochrome ions. Here, the barium ion ensemble is no longer deformed nor heated by the molecular ions.

(Two) level system coupled to laser light...

Optical Bloch equations
&
Rabi frequency

Rabi oscillations

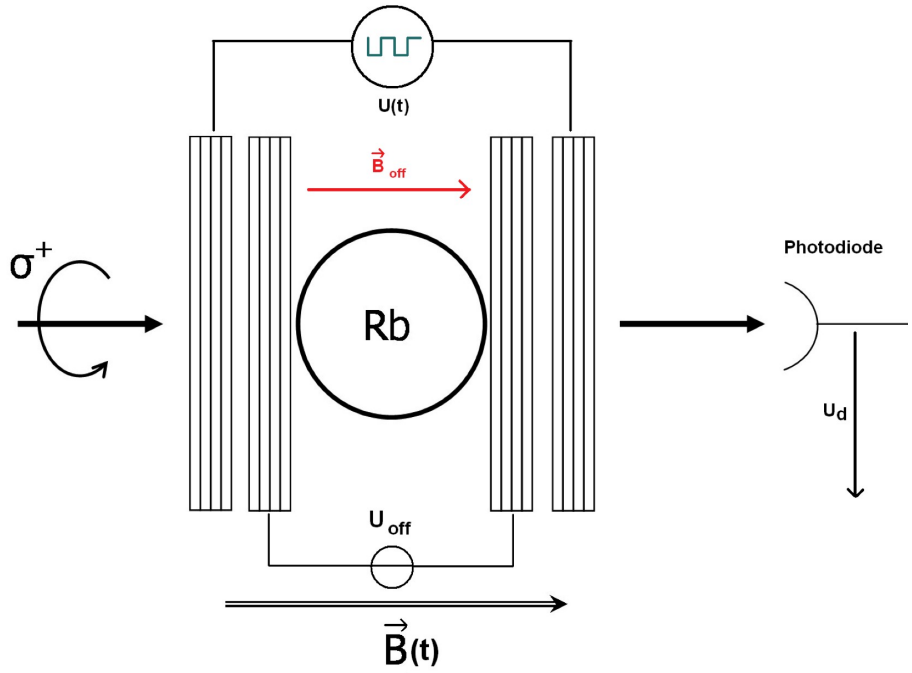
Coherent oscillations in the population of the 2 coupled states

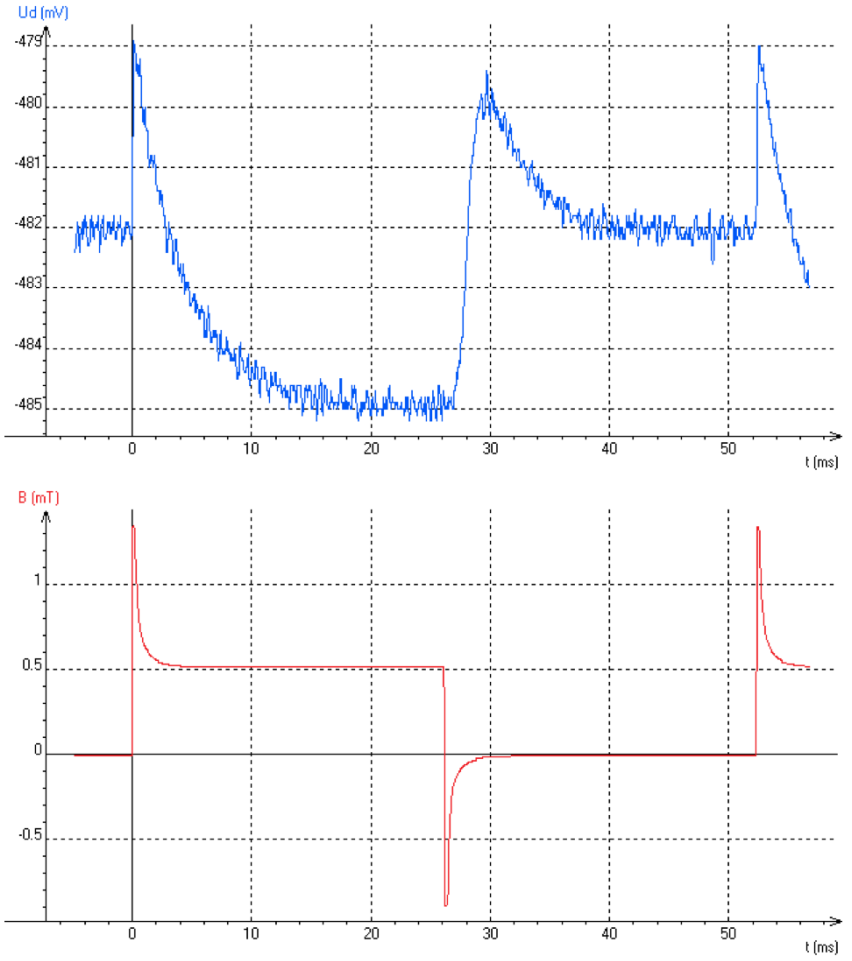


Used to manipulate qubits (2-level system) in the experiments of quantum computation with trapped ions

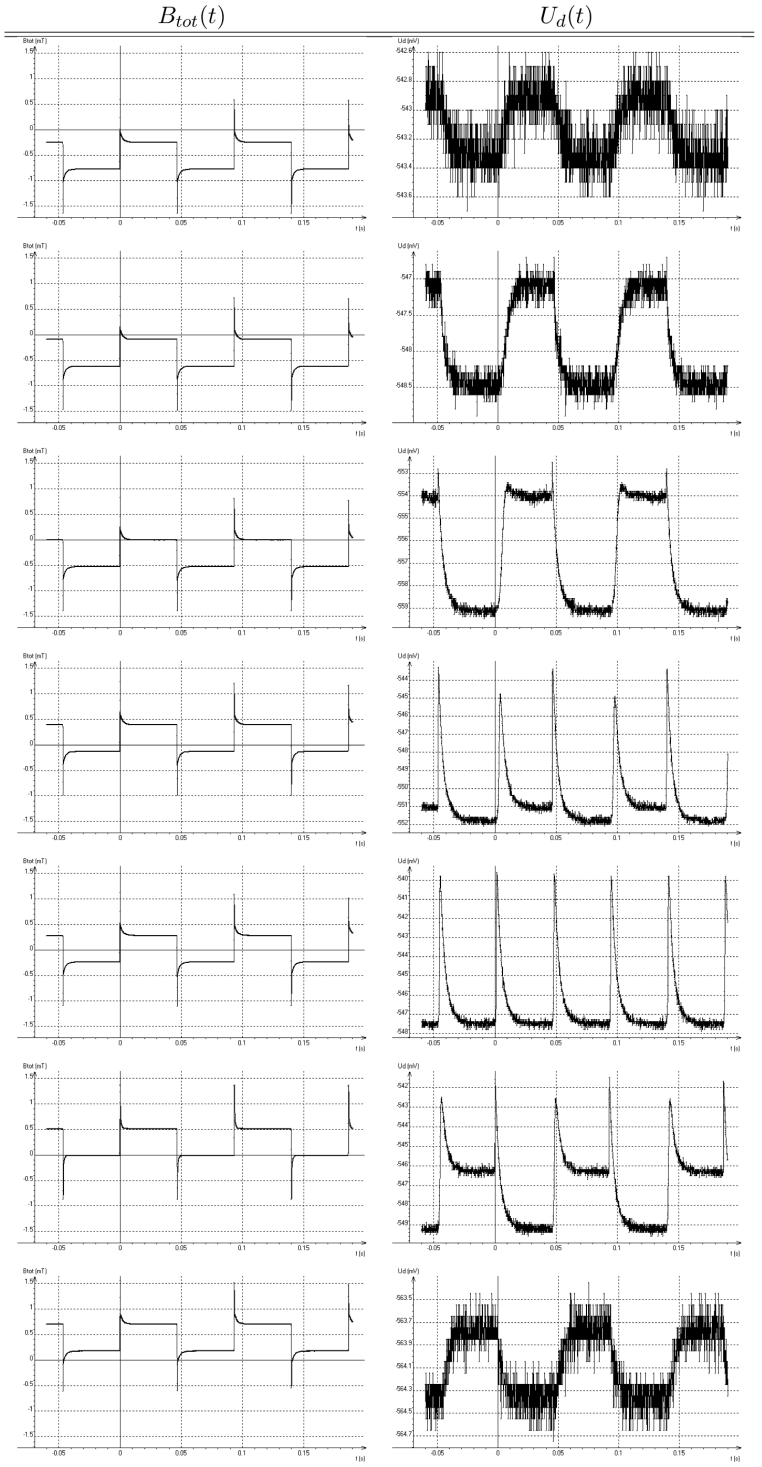
A more than 2-levels phenomenon: Optical pumping

Example :
Polarized light transmission through a rubidium cell under pulsed longitudinal magnetic field



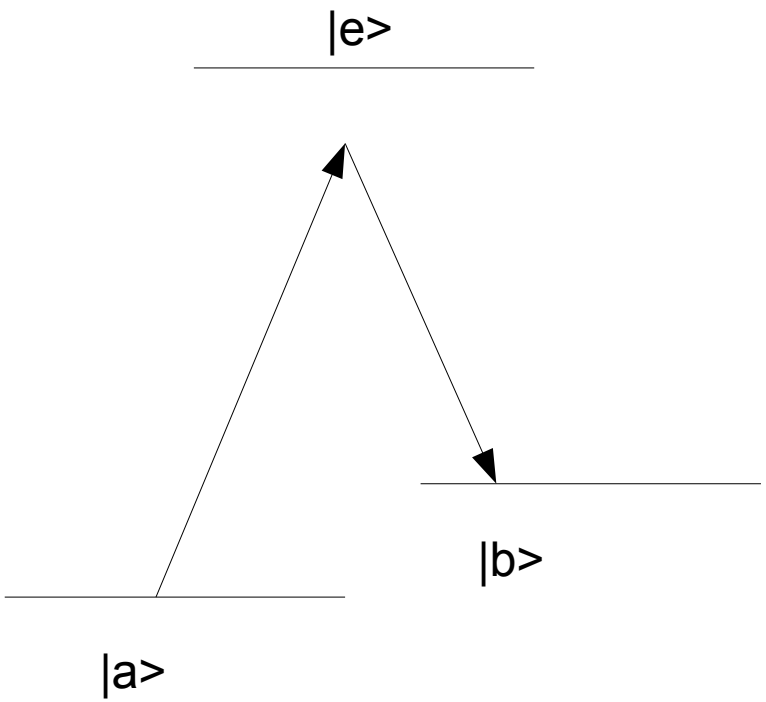


Optical pumping (continued)



Dark states

- 2 ground states & 1 excited state (Λ scheme)



Raman resonance condition between |a> and |b>

→ Coherent superposition of |a> and |b> uncoupled to |e>

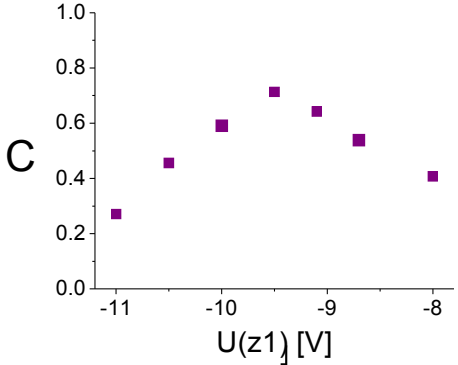
→ No population in the excited state

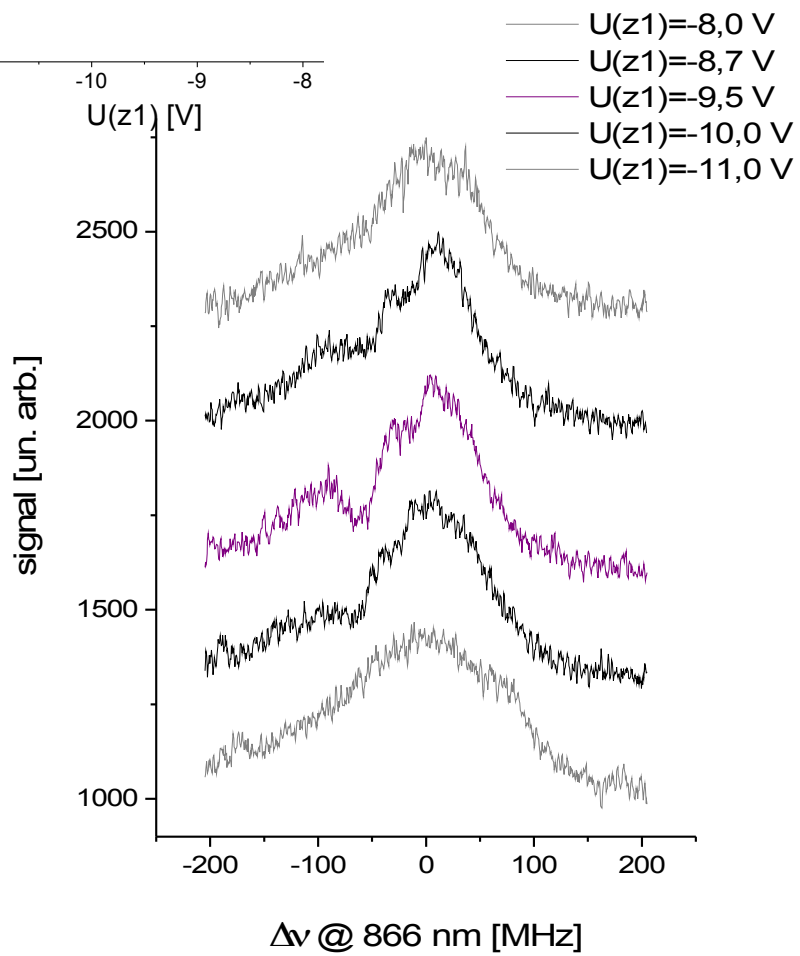
→ No more absorption and fluorescence cycles

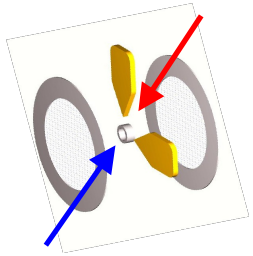
→ dark state reached randomly

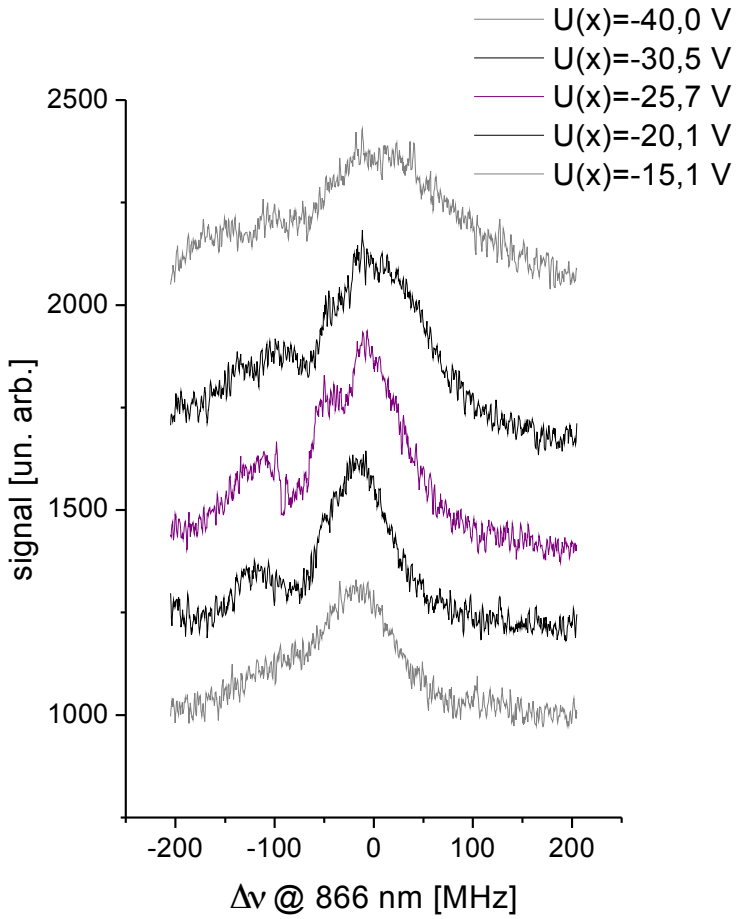
A medium which is absorbing for each of the two laser fields individually becomes transparent through the electromagnetic interaction : "electromagnetically induced transparency"

Electric field compensation via dark resonance









Dark resonance

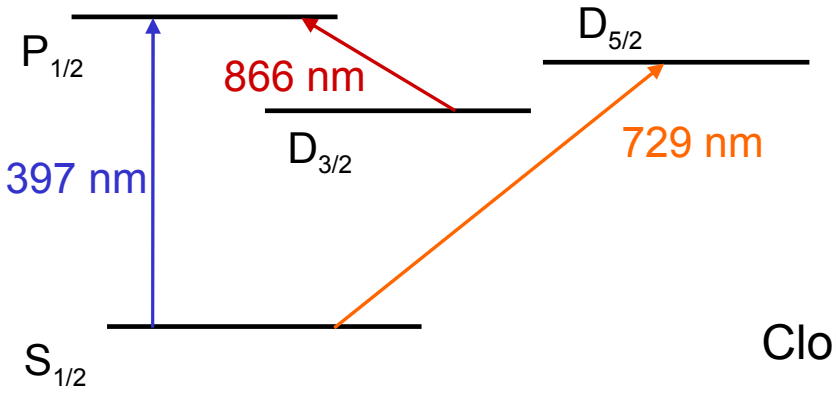
- May reduce or cancel the fluorescence of trapped ions

  → should be avoided !

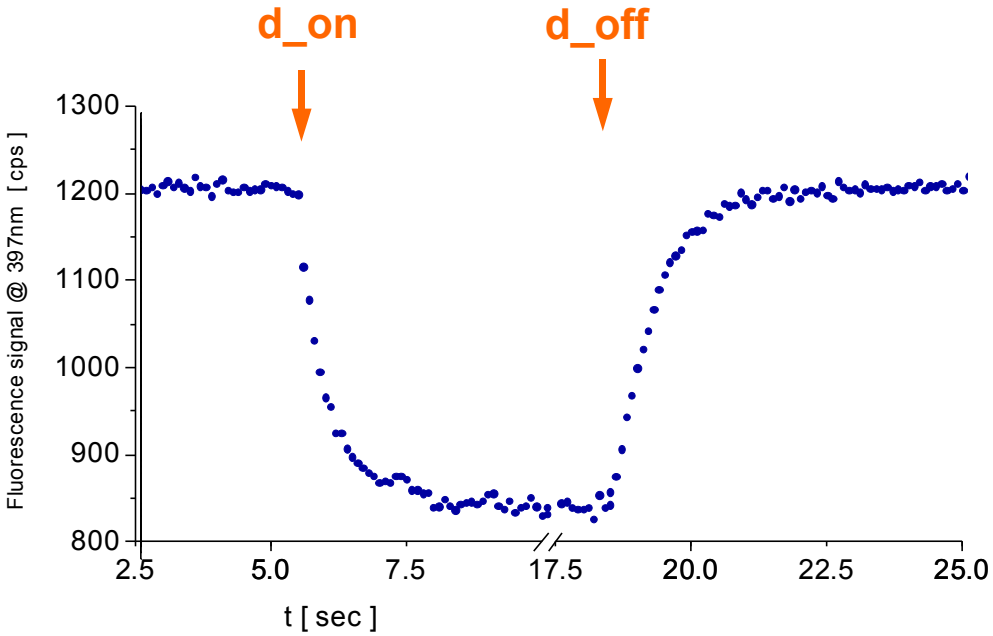
- Magnetic field
- Polarization fluctuation

Electron shelving

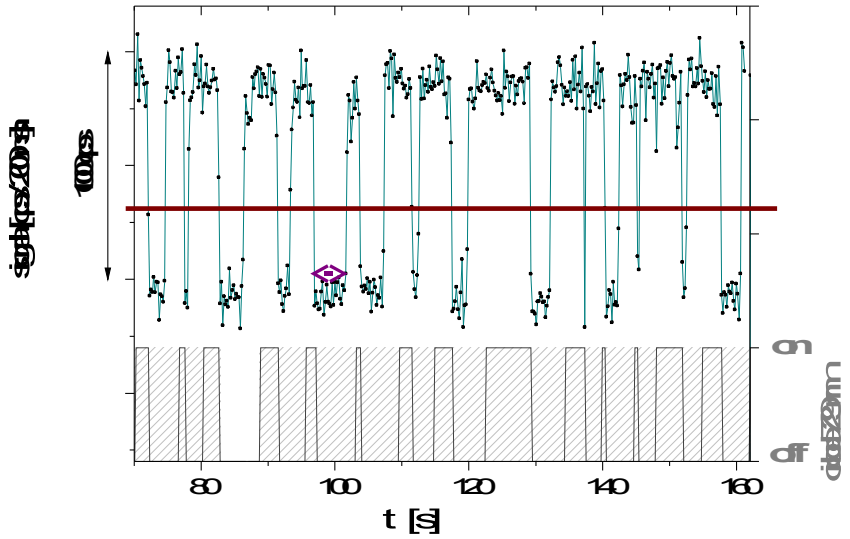
Metastable level lifetime measurement



Cloud



Single ion



Single ion Fluorescence

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Heterodyne measurement of the fluorescent radiation of a single trapped ion

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Abstract

The spectrum of the fluorescent radiation of a single trapped $^{24}Mg^{+}$-ion at low excitation intensity was investigated. The measurement was performed by heterodyning the fluorescent radiation with a sideband of the single mode laser radiation used to excite the ion, resulting in a linewidth of 6 Hz. Under identical experimental conditions, the antibunching in the photon statistics of the fluorescent radiation was also investigated. Heterodyne detection and photon correlation measurement are complementary featuring either the wave or the particle nature of the radiation. The combination of both techniques will allow to measure squeezing in resonance fluorescence.

Single ion Fluorescence

- Classical properties

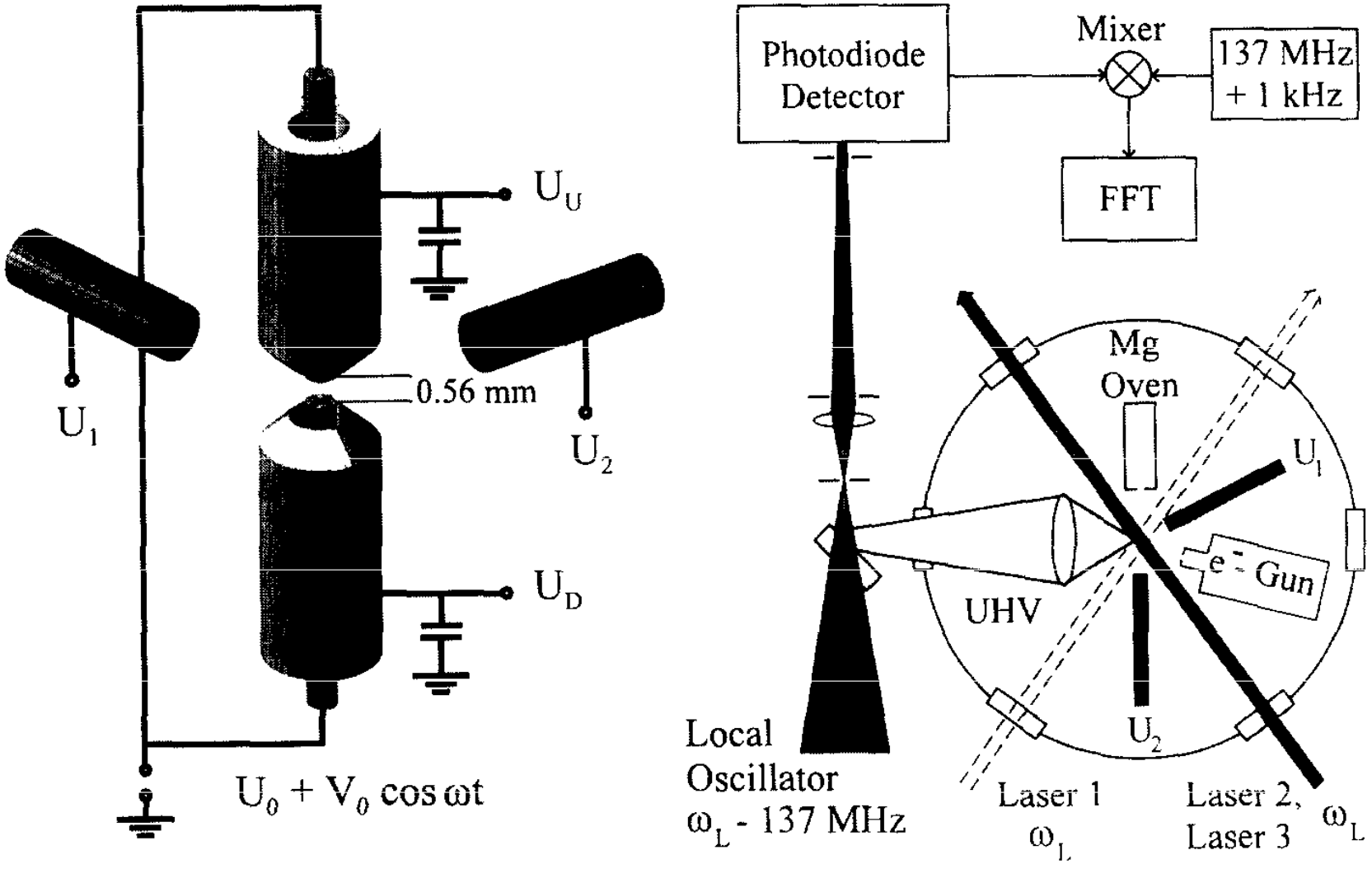
  → coherent elastic scattering

&

- Quantum properties

  → Photon anti-bunching

Single ion Fluorescence setup



Single ion Fluorescence heterodyne spectrum

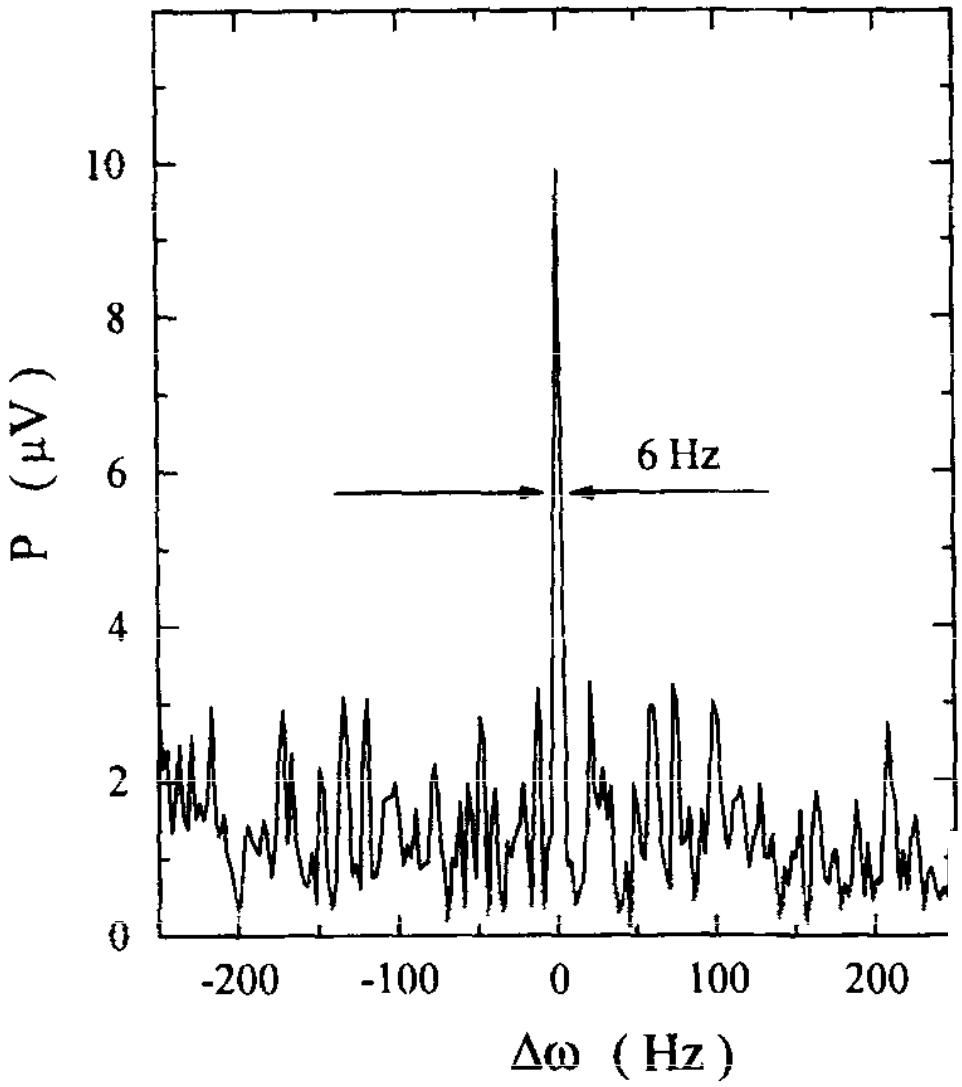


Fig. 2. Heterodyne spectrum of the elastic fluorescence component from a single trapped $^{24}Mg^{+}$-ion for $s = 0.9$, $\Delta = -2.3\,\Gamma$, $\Omega = 3.2\,\Gamma$ and integration time = 267 ms. $\Delta\omega$ is the frequency difference deviation of the heterodyne signal from the 137 MHz driving frequency of the AOM.

Single ion Fluorescence photon correlation (hanbury-brown and twiss)

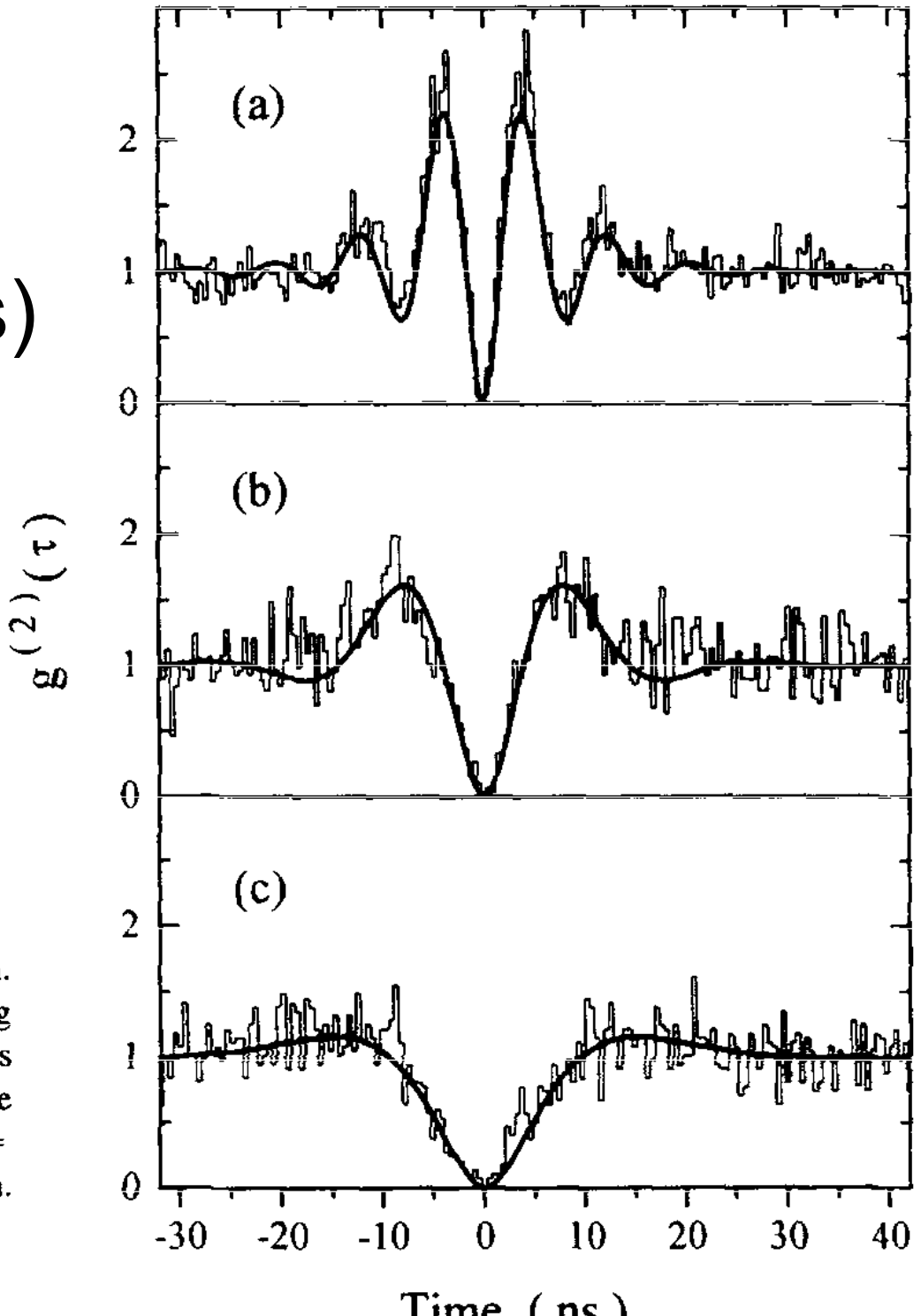


Fig. 3. Photon correlation measurements for a single $^{24}Mg^{+}$-ion. The detunings and Rabi frequencies were determined by fitting the formula given in Ref. [20] (smooth curve) to the measurements (histograms). The integration time t_0 was limited by the storage time of the ion. (a) $\Delta = -2.3\,\Gamma$, $\Omega = 2.8\,\Gamma$, $s = 0.7$ and $t_0 =$ 165 min. (b) $\Delta = -1.1\,\Gamma$, $\Omega = 1.0\,\Gamma$, $s = 0.3$ and $t_0 =$ 95 min. (c) $\Delta = -0.5\,\Gamma$, $\Omega = 0.6\,\Gamma$, $s = 0.4$ and $t_0 =$ 220 min.

Single ion fluorescence

- Heterodyne measurement :

  → Wave detection of the radiation

- Photon correlation :

  → Particle detection

Quantum state engineering

- **Coupling between spin and motional states**

2-photon polarization-dependent stimulated interaction.

- **Motional states manipulation**
  - **Fock (number) states**

These are the eigenstates of the harmonic oscillator hamiltonian, labelled |n>, n being the vibrational quantum number.

  - **Thermal states**

Superposition of Fock states with a Boltzman distribution for P(n)

  - **Coherent states**

Displaced ground state wave packet. Minimal uncertainty state. In the case of large amplitude coherent state it is referred to a quasi-classical state.

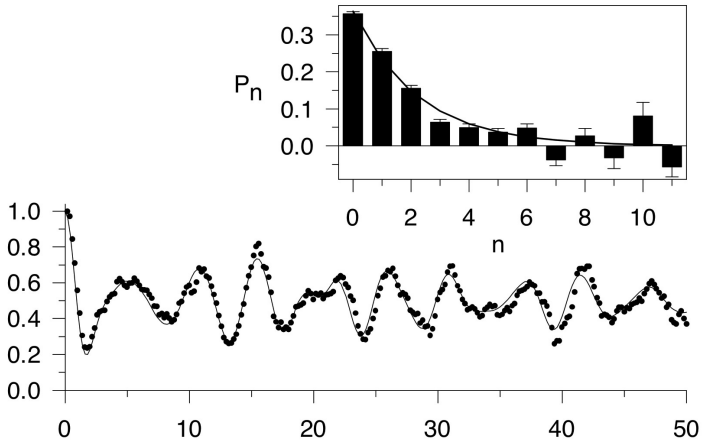
  - **Squeezed states**

Coherent state of which the uncertainty disc has been modified into an ellipse. It is created through a parametric (an so non-) excitation (modulation of the trap frequency).

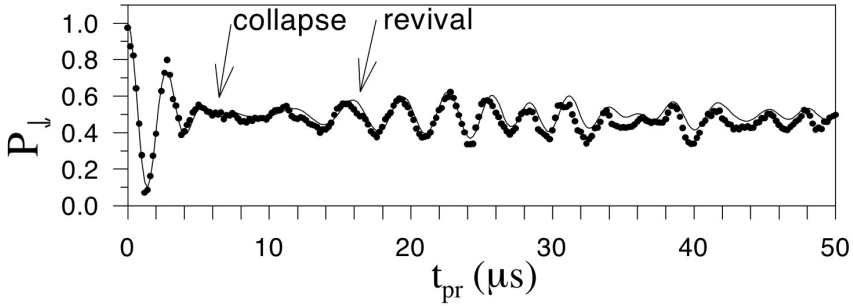
Quantum state engineering

diagnostic : map the |n> state to the spin state and measure the Rabi oscillation

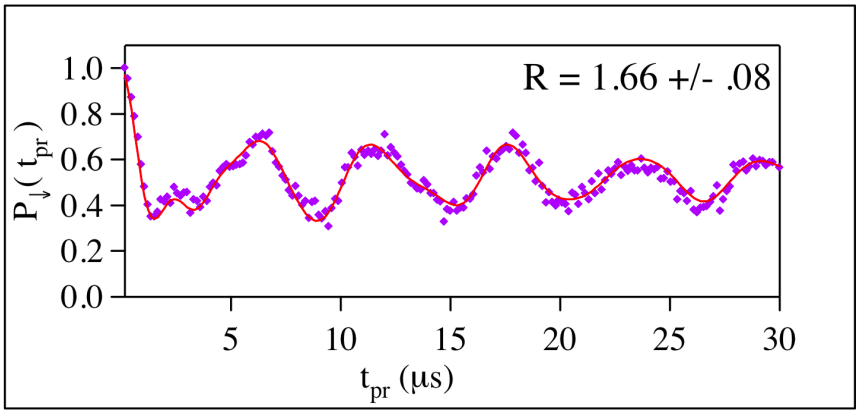
Thermal state



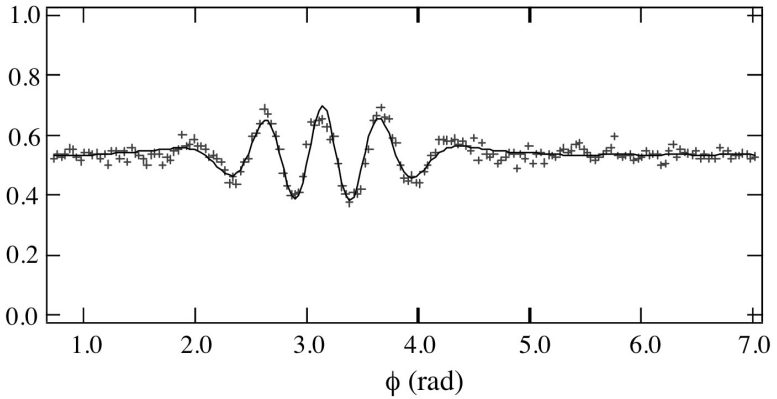
Coherent state



Squeezed state



Schrödinger cat (spin/motion)



S. Guibal

Cooling methods in ion traps

Introduction

What ?

What does the term “cooling” refers to ?

“Cooling is decreasing the average kinetic energy of a sample of particules”

Yes! but... adiabatic reducing of a trap stiffness leads to such an average kinetic energy reduction... however is it really favorable to the experiments (high resolution spectroscopy, metrology, quantum manipulation) atomic and molecular physicists intend to carry-out ?

No! Actually, what is usually needed in the atomic physics experiments is to increase the phase-space density of the trapped sample, *ie* decreasing the average kinetic energy while keeping or incerasing the spatial density.

So what we want is to decrease the average kinetic energy at a given trap stiffness and depth and without loss of particle (we won't consider here the special situation of the runaway regime in evaporative cooling leading to BEC of cold neutral atoms).

In the case of trapped ions in a Paul trap, the motion is described by a secular motion (harmonic oscillator) superimposed with a micro-motion at the trap RF frequency. The micro-motion amplitude depends only of the ion position (RF amplitude) and thus can not be cooled directly. It does decrease however when the secular oscillation amplitude decrease under the effect of the cooling process.

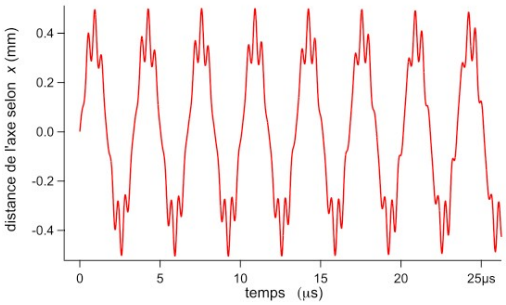


Figure : Typical motion of an ion in a Paul trap. A secular large amplitude low frequency motion is modulated by a high frequency (trap RF) low-amplitude so called micro-motion.

It is worth noting that the term “cooling” has not necessarily the meaning of usual thermodynamics. In particular it does not imply that the ions are in thermal equilibrium with each other or with a thermal bath. The temperature may not even be well defined since the velocity distribution may be exotic due to the presence of random motional modes (secular motion) and of coherent motional modes (micro-motion). So what we will refer to a “temperature” in the field of cold ions (it is true for cold atoms as well) will usually be the width of the velocity distribution or, in the few-ions quantum regime, to the average vibrational quantum number or even the relative population of the ground vibrational state.

Why ?

Contrary to neutral atoms trapping experiments, the ions can be trapped efficiently without the need of being cooled down. The trap depth are on the order of the eV which corresponds to 12000K, much larger than the initial temperature of the atomic vapour from which the ions are created.

So, the ion trap works without cooling!

However, the goal in trapping ion experiments is to make measurements that are impossible to perform by other techniques. The main benefit is to hold ions for long times in a well controlled environment. Cooling the trapped ions may have several beneficial effects for such experiments :

- Increased lifetime
- Increased precision of measurements (clocks or high-res spectroscopy)
- Strong localization of ions in spatially ordered structures (individual manipulation)
- Preservation of quantum coherence (even of external degrees of freedom)

…

Now let's have a look at some experimental signatures of such effects...

Lifetime

Comparison of the lifetime of an un-cooled cloud of ions vs a laser-cooled ion cloud

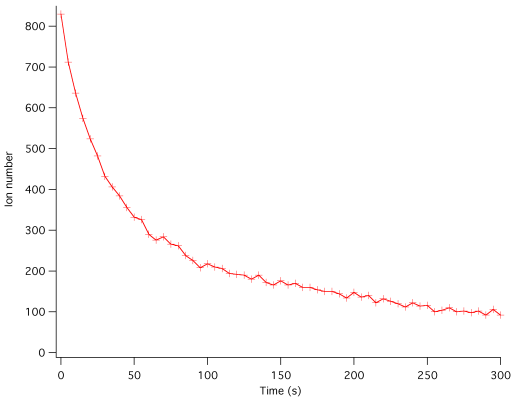


Figure : Hot cloud of trapped ions (<min.)

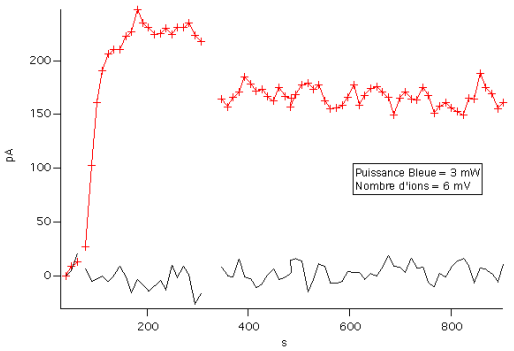


Figure : Lifetime of the laser-cooled ion cloud (can be hours...)

Doppler broadening

In experiences involving light – atom/ion/molecule interaction, the particle velocity affects the actual frequency of the radiation seen by the particle or the frequency of the light it emits as received by the experimentalist. In a vapour or a trapped sample, the velocity distribution is assumed to be gaussian and the spectral width of the radiation takes a gaussian shape of width :

$\Delta\nu=k\langle v^2\rangle$ where k is the wavevector of the radiation and $\langle v^2\rangle$ the mean square velocity of the sample at the temperature T. It appears that the spectral broadening is inversely proportional to the wavelength.

The Doppler broadening affects considerably the experiments in the optical domain because of their short wavelength. As mentioned by Professor G. Werth in his lecture, experiments carried-out in the microwave domain are not affected by thermal Doppler broadening at usual temperatures for which cooling is thus not crucial.

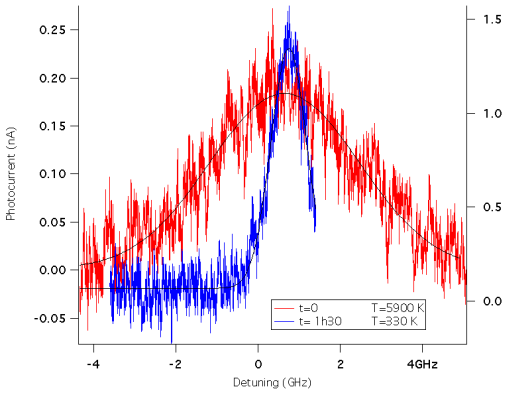


Figure : Fluorescence spectrum of a « hot » trapped ions cloud (vs. excitation laser detuning)

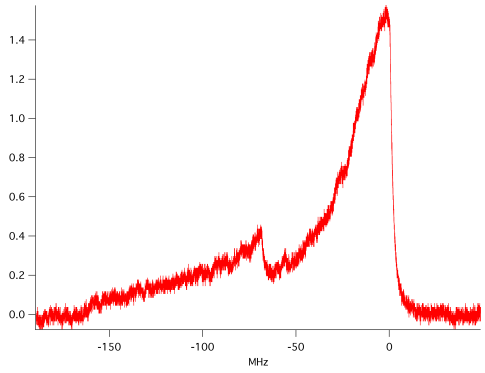


Figure : Fluorescence spectrum of a laser-cooled trapped ions cloud (vs cooling laser detuning)

Confinement and spatial order

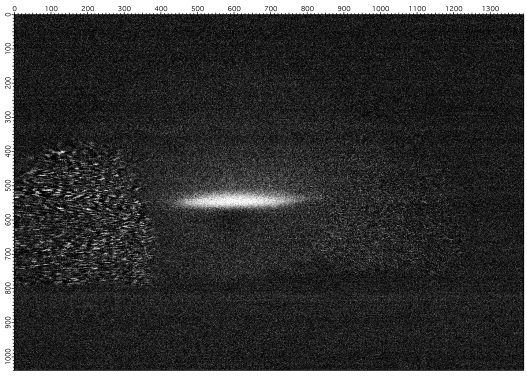


Figure : Hot trapped few ions cloud (6.6microns/px)

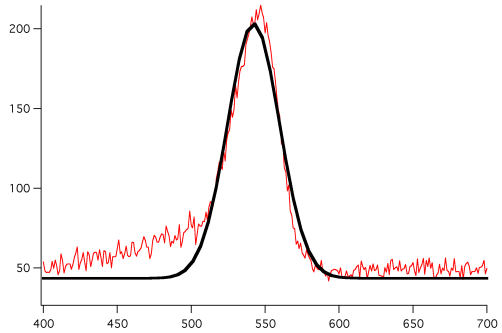


Figure : vertical profile, width = 25 px (0.165 mm)

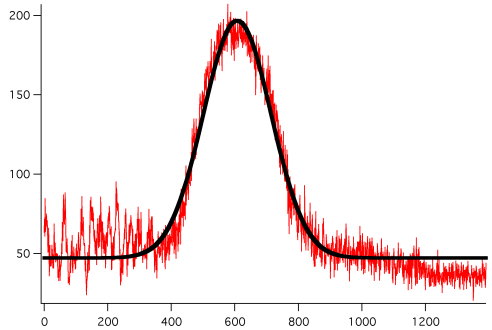


Figure : horizontal profile width = 150 px (1mm)

Exercice : what is (approx.) the longitudinal trap stifness in the following experiment with strontium ions ?

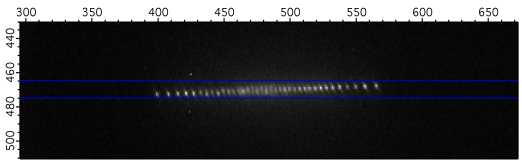


Figure : Cold trapped ion string

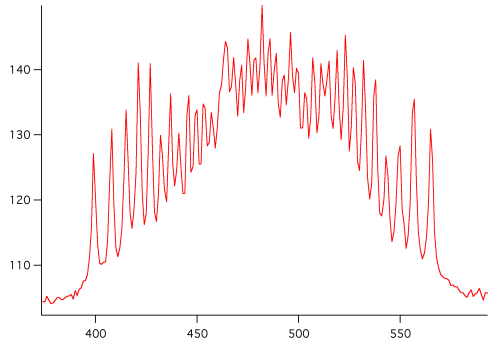


Figure : Ion string profile. $\Delta X\_avrg = 7px$

How ?

Trapped particules are expected to be well isolated from interaction with any environment. It means that the usual thermodynamics view of sight which involves an equilibrium of the studied system with a thermal reservoir via a strong coupling, is probably not the most appropriate way of controlling the temperature of a trapped particule ensemble.

The laser-cooling methods to extract energy from a trapped sample have proven to be very effective and satisfactory to this extent. Although these methods have already been introduced in the previous courses on neutral atoms laser-cooling, we will discuss here their application in the very special case of trapped ions. These methods are undoubtedly the most efficient when applicable, but several others involving a weaker level of control may also apply. However these latter methods deserve a particular attention since they are applicable in a very general way to any trapped charged particule, which is not the case of laser-cooling techniques whose requirements are extremely restrictive. Some example of situation where laser-cooling is not adapted or feasible are : complex heavy particules, ionic molecules, atoms not easily laser-addressable or in the case where the trapped ions of interest have to remain optically uncoupled to the environment like in quantum manipulation experiments.

Among these methods, we will discuss here the **electrical cooling method** (resistive or active feedback), **collisional cooling** either mediated by a neutral **buffer gas** or by other cooled and trapped species (**sympathetic cooling**).

We will also discuss the application of the **laser-cooling** methods in the particular case of trapped ions. In particular, the simple **Doppler cooling** and the **resolved sideband cooling**.

But at first a brief review of some common and useful diagnostic and measurement methods suitable for trapped ions.

Trapped ions diagnostic and measurement

- Direct ion detection and time of flight
- Fluorescence imaging – trapped-ion peculiarities

Two limit cases for the ion cloud size interpretation : few hot ions → temperature / many (or some) cold ions → number

Laser excitation spectrum analysis is useful but coupling with cooling effect and interpretation not always obvious.

Fluorescence spectrum (at fixed excitation) may be rich but the natural linewidth is usually large and hides some features (discussed below with the sideband cooling)...

- Resonant excitation of the secular motion

- trap-loss detection
- fluorescence detection

Resistive cooling

The trap electrodes act as a condensator and the ion charge displacement in the trap leads to time-dependent induced charges to appear on the electrodes. If the electrical circuit is closed by a resistor placed in between the electrodes, these induced charges will lead to induced current which can dissipate into the resistor. This is a non reversible energy loss from the ion system and thus induces a cooling of the ion motion. The limit of this cooling method is that the ion ends (at best) in a thermal equilibrium with the resistor temperature and that the cooling power may be very low due to non-optimal coupling which leads to long thermalization times. Furthermore, at some point the RF-heating may compete and prevent an efficient cooling.

The resistive cooling effect is characterized by a time constant $\tau=4mz_0^2/q^2R$ which shows that it is most efficiently applied to light and/or highly charged particles...

Optimizing the coupling of the ion motion to the electrical circuitry appears to be a crucial point. This is achieved by designing a resonant circuit at the ion motion eigen-frequency... Of course this is complicated by the fact that the ion motion is characterized by several frequencies...

It has to be noticed that this method is sensitive to the global charge displacement and then only the motion of the center of mass of an ion cloud is cooled down... However, the velocity spread among the sample can be indirectly cooled, provided that the energy redistribution rate due to electrostatic collisions is high enough.

This method has been experimentally demonstrated. However its relative complexity and its intrinsic limitations makes it non-competitive with others and must be reserved to particles where laser-cooling is not available (molecules, clusters...) or where collisions with other species (buffer gas cooling) have to be absolutely avoided.

Active feedback cooling

This is an extension of the resistive cooling. The idea is to measure the current produced by the ion , to amplify it and to apply the amplified signal to the electrode with an appropriate phase. It can be seen as an error signal to lock the ion position. This method decrease the resistive cooling time by a factor in the order of the gain but since the thermal noise of the circuitry is also amplified, the final temperature will be higher.

This methods applies to single ion cooling or to the center of mass motion of a cloud. The velocity spread among the cloud is not directly affected.

Buffer gas cooling

The principle of buffer gas cooling is to inject a controlled pressure of a neutral non-reactive buffer gas inside the vacuum chamber in which the trap resides. The collision between the trapped ions and the neutral gas are expected to drive the system to thermal equilibrium, and the ion sample should end at the chamber temperature.

This method has been demonstrated experimentally, the main diagnostic was an increasing of the trapped ion lifetime depending on the buffer gas pressure.

Although this method is very simple and efficient, the main drawback is that it is limited by the chamber temperature and that the collision may affect the experiment to be carried-out with the ion sample, in particular in high resolution spectroscopy or metrology experiments where collisions

may affect the energy levels of interest. Of course it is not suitable for experiments where quantum coherence of the various degrees of freedom of the trapped ions is a concern.

The buffer gas atom must be lighter than the trapped ion in order to roduce an efficient cooling.

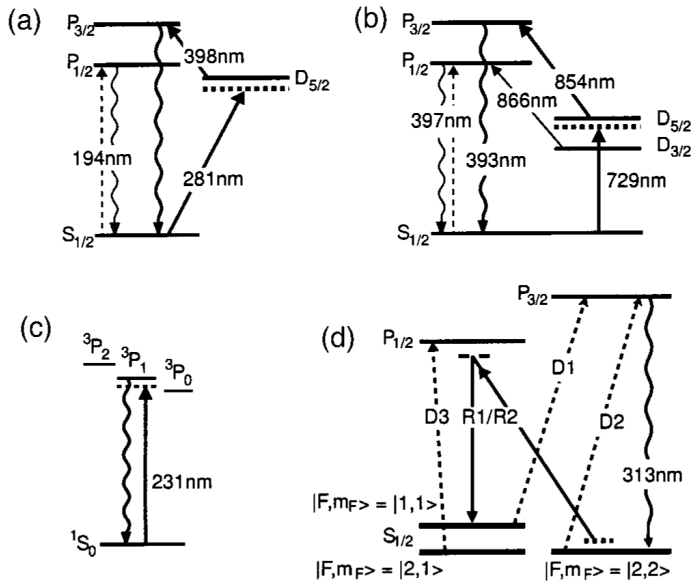
An interesting parameter for buffer gas cooling is the mean free path of an ion inside the buffer gas vapour. The theory of Langevin for the collisions gives a calculation of the mean free path or equivalently of the average time between collision (which depends on the atomic polarizability, pression and temperature...). This average time must remain long compared to the trap characteristic time in order to avoid destabilization of the trap. The typical pressure suitable for buffer gas cooling of usual atomic ions are in the range 10-5 to 10-4 mbar.

Doppler cooling

Principle (already seen in the neutral atom laser-cooling course). Main results : order of magnitude of the acceleration (1000-10000g), limit Doppler temperature

How cool ? → crystallization temperature vs doppler limit
Is Doppler Cooling enough for Coulomb crystals observation ? → yes! (cf line above)
Is Doppler cooling enough for Lamb-Dicke regime (quick definition of LD regime: linewidth narrowing thanks to confinement) ? → possibly yes (depending on the stiffness of the trap)

Sideband cooling



Levels and transitions for sideband cooling

Fig. 3. Levels and transition wavelengths relevant for resolved-sideband cooling in various ion species: (a) With a single $^{198}Hg^{+}$ ion, Doppler cooling is performed on the transition near 194 nm. For sideband cooling, laser light near 281 and 398 nm is used. The red sideband of the $S_{1/2}$–$D_{5/2}$ transition is indicated with a dashed horizontal line. (b) For Doppler cooling of $^{40}Ca^{+}$ ions, the dipole transitions near 397 and 866 nm are employed. Resolved-sideband cooling is performed on the quadrupole transition near 729 nm while the dipole transition near 854 nm is used to increase the cooling rate. (c) For resolved-sideband cooling of $^{115}In^{+}$ ions, the intercombination line near 231 nm is used. (d) Levels relevant for optical cooling of $^{9}Be^{+}$ ions. Transitions D1, D2, and D3 are used for Doppler cooling and optical pumping. Raman sideband cooling is performed with laser pulses alternately driving the transitions R1, R2, and D1, D3. All wavelengths are near 313 nm; the hyperfine splitting of both P states is 1.250 GHz.

Sympathetic cooling

Principle, experimental demonstrations and possible numerical approach by n-body simulation (S. Schiller, Dusseldorf).
Paper review : http://arxiv.org/pdf/0810.5102v2

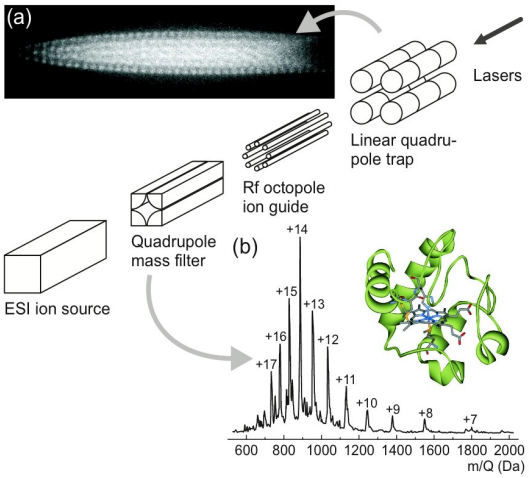


FIG. 1: (Color online) Schematic overview of our setup. Singly or multiply protonated molecular ions from an ESI ion source are selected by a quadrupole mass filter and transferred via a RF octopole ion guide to a linear quadrupole trap in an UHV chamber. (a) CCD image of a typical trapped barium ion Coulomb crystal used as coolant for the molecular ions. (b) Secondary structure and ESI mass spectrum of cytochrome c showing the distribution of the different grades of protonation.

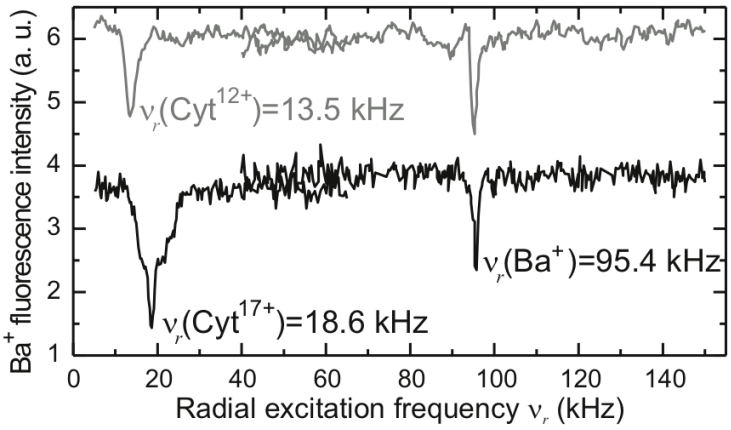


FIG. 2: Radial excitation spectra of barium crystals containing differently protonated cytochrome ions. The upper (Cyt^{12+}) and lower (Cyt^{17+}) curves were acquired at the same trap parameters and yield the same barium frequency of 95.4 kHz used for calibration. The obtained cytochrome frequencies are well confirmed by their theoretical values.

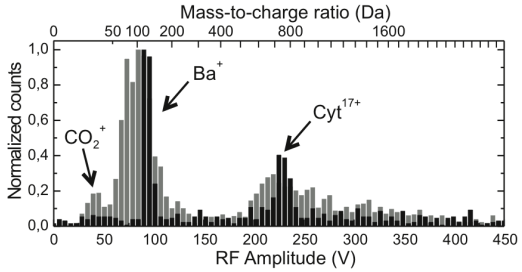


FIG. 3: Ion extraction mass spectra of Ba^+/Cyt^{17+}ensembles at different temperatures. In the noncooled case (gray) the mass spectrum is broadened compared to the laser-cooled case (black). Here, not only the peak of the laser-cooled Ba^+ ions, but also that of the simultaneously trapped Cyt^{17+} ions is narrower, which is a proof of their sympathetic cooling.

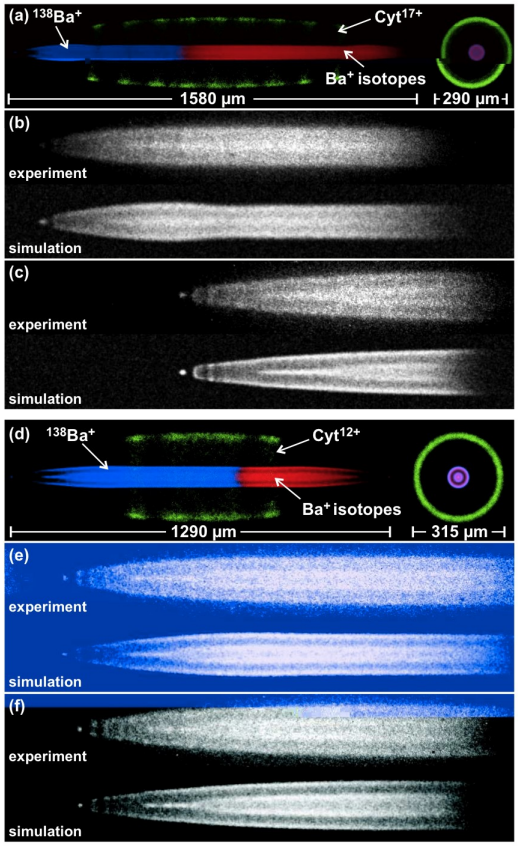


FIG. 4: (color online) Experimental and simulated CCD images of a Ba^+/Cyt^{17+} and a Ba^+/ Cyt^{12+} ion crystal. (a, d) Simulated images in radial (left) and axial view (right), as they would appear if all ions would fluoresce. The cooling lasers propagate to the left, separating the $^{138}Ba^+$ ions (blue) and the barium isotopes (red) axially due to the light pressure force. The cytochrome ions (green) form a sheath around the barium ion subensemble. (b, e) Experimental image of the barium-cytochrome ion crystal and its simulation, showing only the fluorescing $^{138}Ba^+$ ions. (c, f) Crystals after the removal of the cytochrome ions. Here, the barium ion ensemble is no longer deformed nor heated by the molecular ions.

Trapped two level system coupled to laser light

Introduction

Theoretical description of a 2-level system coupled to a light field

Dipolar interaction hamiltonian

Optical Bloch equations

(mention also the dressed atom approach)

Rabi frequency and Rabi oscillations

Light-shift, Rabi-splitting, Autler-Townes effect (dressed atom or Bloch equations)

Real world : some experimental facts

Multilevel atom effects

Optical pumping and dark-states

- Optical pumping : Kastler experiment presentation and interpretation

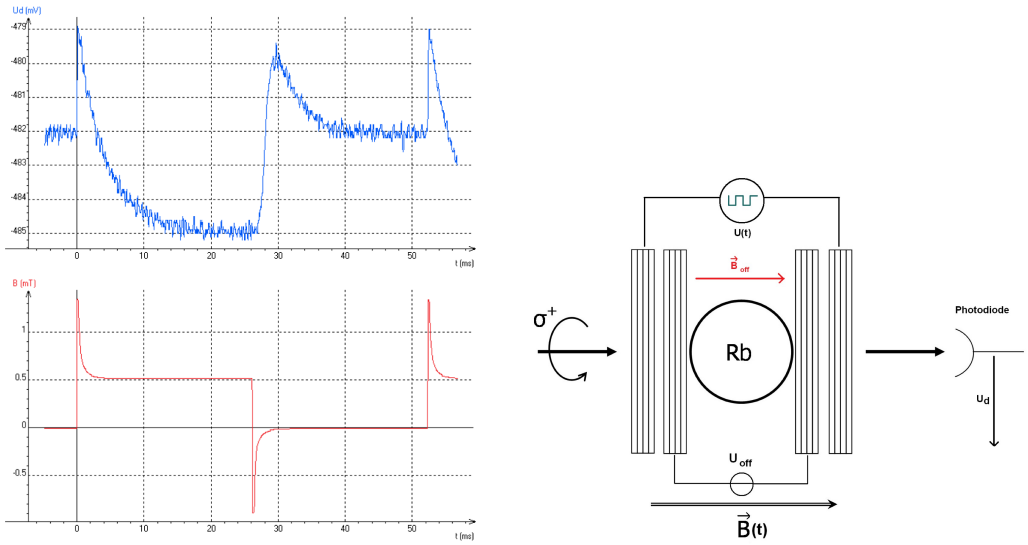


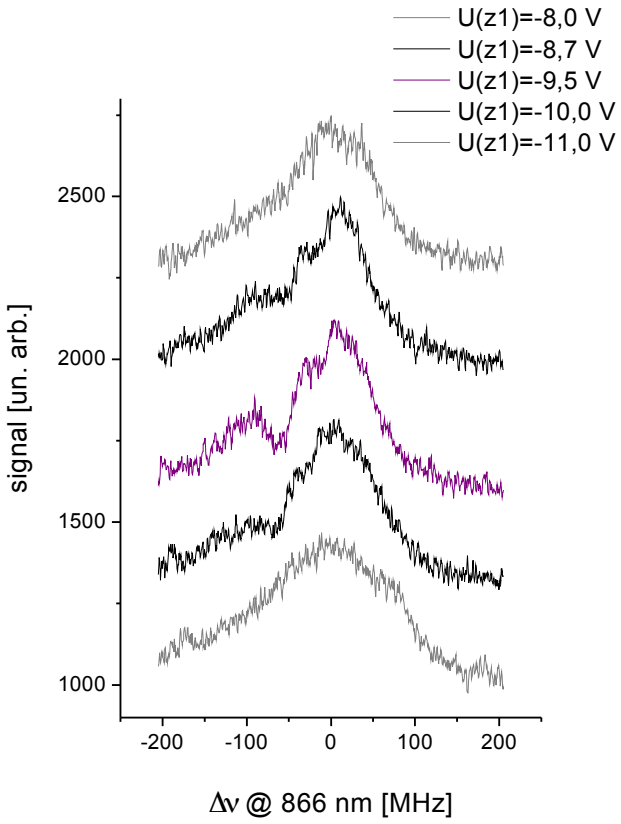
Figure : Circularly polarized resonant beam absorption (upper, blue) in a rubidium cell as a fonction of magnetic field (lower, red)

- Dark resonance : quantum interference between two possible optical transitions

Figure : Dark state observation in the fluorescence spectrum of an ion

The dark resonance are very sensitive to the atom velocity.

This property has been exploited as a diagnostic tool for reducing the micromotion (by fine tuning of the electrical compensation).



Quantum jumps : electron shelving

Fluorescence statistics : discrete (few ions) or continuous (large ion ensembles)

Relation between Internal and external degrees of freedom

Fluorescence spectrum of a trapped ion

Let us consider the secular ion motion. It is an harmonic oscillator and the ion position is described by a sine function. Of course the ion velocity is modulated the same way and if we consider the ion as a light emitter at a given well defined frequency, the light frequency observed in the lab frame will be affected by the Doppler effect due to the ion velocity. The effect of this motion will be a modulation of the observed light frequency. A complete treatment shows that the emission spectrum observed in the lab frame exhibits sidebands around the natural emission line shifted by the secular oscillation frequency. The amplitude of these sidebands depends on the oscillation amplitude.

This can also be described in term of quantum transition involving both internal electronic states and external vibrational states of the harmonic oscillator. (LEVEL SCHEME)

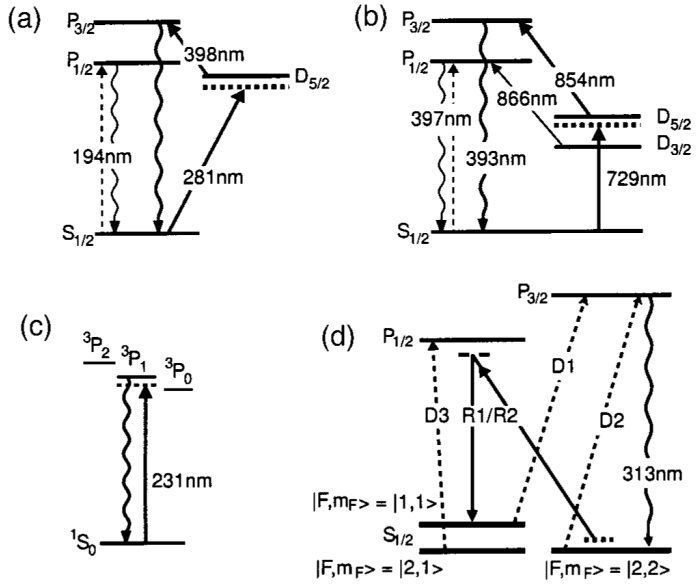
(opt. classical sideband calculation in FM)

Lamb-Dicke regime : tight confinement in optical lattices and trapped ion

Increasing of the motional coherence of neutral atoms in bright optical lattices (schematic of Sisyphus cooling and consecutive confinement)

Reduction of vibrational sidebands amplitude.

Sideband cooling



Single ion fluorescence

Paper presentation : “heterodyne measurement of the fluorescent radiation of a single trapped ion”, Höghes et al, optics comm '96 : interesting because they perform simultaneous observation of quantum and classical properties of the fluorescent light emitted by the single ion.

Introduction to experimental techniques : ion trap, heterodyne detection, single photon detection and statistics, photon correlation for classical sources or single photon emitters (hanburry brown and twiss intensity interferometer)

Definition of squeezing : optical bloch equation represented in the bloch sphere. Acoustic representation of squeezing

Quantum state engineering

Stimulated Raman sideband cooling allows the ion to be cooled down to the ground vibrational state of the ion. It is the tool of choice for achieving a complete control of the whole quantum state of the ion, both for internal and external degrees of freedom.

This ground state preparations open the ways to coherently manipulate the ion in order to create some more complex quantum states. That's what we call “quantum engineering” : once a simple well determined eigenstate (typically ground state) of a quantum system has been prepared, one can apply coherent transformation to the system and tailor arbitrary stationary or not quantum state. This is the basic necessary tool for quantum information processing experiments. It is also a way to study other quantum phenomena such as decoherence and aproaching the frontier between quantum and classical phenomena often related to the size of the system : one question (one experimental challenge!) is how much can you increase the size of a quantum system while keeping its quantum properties long enough to be able to observe them.

We will discuss now the ways to control and measure the motional and electronic degrees of freedom of an ion. We will discuss several state configuration of interest : the thermal states, the Fock states, the coherent states and the squeezed states.

Coupling between spin and motional states

As seen in the previous chapter on laser-cooling, the ion-laser interaction involves the electronic degrees of freedom of the ion but may affect the ion motion. In particular in the case of resolved sideband cooling, the laser interaction is made dependent on the vibrational state of the ion. In order to go further in the ion state control, we will consider now 2-photon polarization-dependent stimulated interaction. This allows to manipulate the ion spin state in a coherent manner since it drives polarization-dependent transitions without spontaneous emission.

Fock (number) states

These are the eigenstates of the harmonic oscillator hamiltonian, labelled $|n\rangle$, n being the vibrational quantum number.

Thermal states

Superposition of Fock states with a Boltzman distribution for P(n)

Coherent states

Displaced ground state wave packet. Minimal uncertainty state. In the case of large amplitude coherent state it is referred to a quasi-classical state.

Squeezed states

Coherent state of which the uncertainty disc has been modified into an ellipse. It is created through a parametric (an so non-) excitation (modulation of the trap frequency).