Light-matter interaction with atomic ensembles

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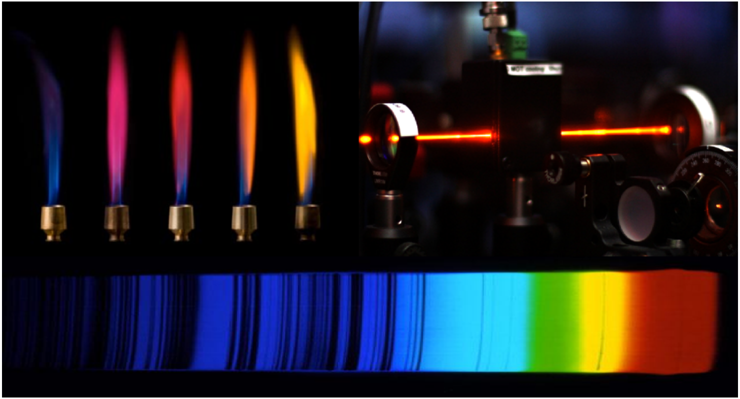
Interaction with light and matter

- How light is generated from matter ?
- How light is absorbed ?
- Which information is exchanged ?



Interaction with light and matter

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- How light is absorbed ?
- Which information is exchanged ?

Numerous implications

- Spectroscopy
- Metrology
- Quantum mechanics
- Technologies (Clocks, Laser)

Light and matter as quantum objects

Fundamental interest

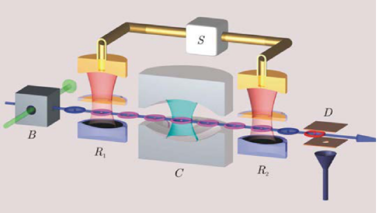
- Study of entanglement
- Understanding of decoherence
- Border quantum/classical

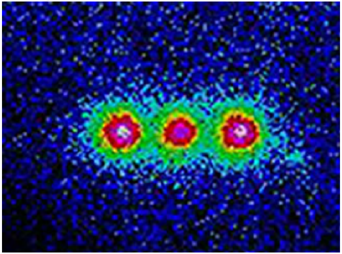
A tool for quantum technology

- Quantum communication
- Quantum computation

Singles particles ...

Individual quantum systems can be generated and measured





Single Photons (LKB, Paris) Single ions (NIST, Boulder)

… or ensembles

Control of millions of such systems could allow

- Study of collective entanglement e.g. squeezing
- Study of decoherence mechanisms
- Stronger interaction between light and matter

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The non classical behavior of such systems is difficult to reach

Outline

Storing light in a large ion Coulomb crystal

- Large Coulomb crystals in a linear Paul trap
- Signature of Electromagnetically Induced Transparency (EIT)
- Residual temperature

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Detection of Non-Gaussian states in trapped atoms

Non-classical, Non-Gaussian states
Measurement of distributions
Cumulants to detect non-Gaussian states in trapped atoms

Storing light in a large ion Coulomb crystal

Cold trapped ions: a good system for quantum manipulations

Cold trapped ions properties

- Isolation from the environment
- Good detectability
- Long trapping times (days)

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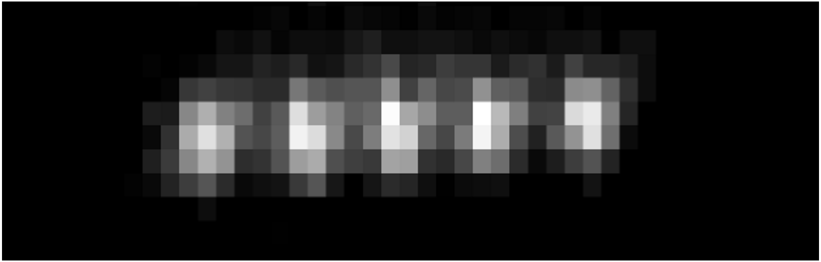
Allowed the demonstration of:

- High fidelity quantum gates
- Single photon - single ion entanglement
- Ultra precise clocks ($\approx 10^{-17}$)

Large Coulomb crystals: a good candidate for a quantum memory

The strong Coulomb repulsion forces the ions to organize



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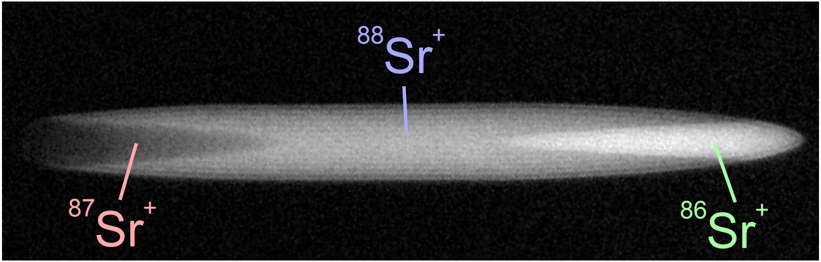

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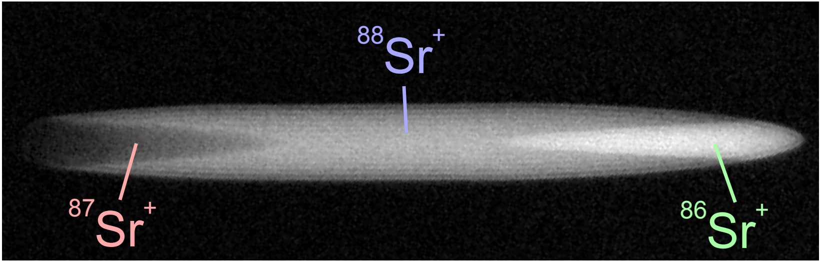
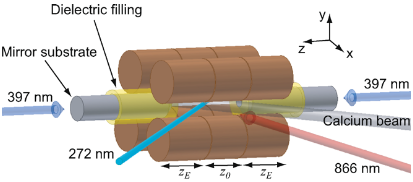


- No collisions, reduced motion
- Long coherence times of internal sub-levels are expected
- Need for high light matter interaction

Increasing the interaction with ion Coulomb crystals

Cavity enhanced interaction (Aarhus)



Collective effects mediated by the cavity

Increasing the interaction with ion Coulomb crystals

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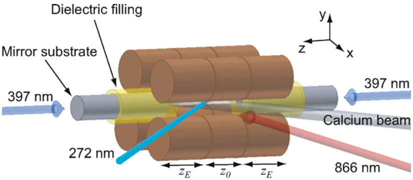


Collective effects mediated by the cavity

Free space with large crystals

Wide bandwidth for light storage

- Frequency
- Spatial modes

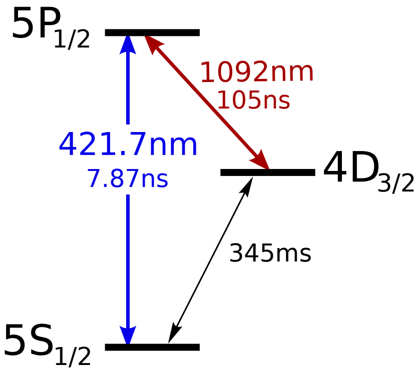
Storing light in a large ion Coulomb crystal

Large Coulomb crystals in a linear Paul trap

Signature of Electromagnetically Induced Transparency (EIT)

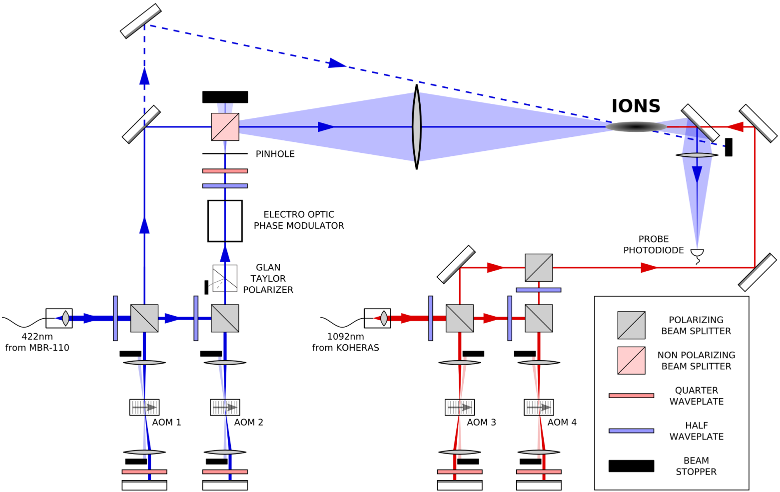
Residual temperature

Experimental setup: Strontium level structure



Sr^+ ion energy levels

Experimental setup: Lasers



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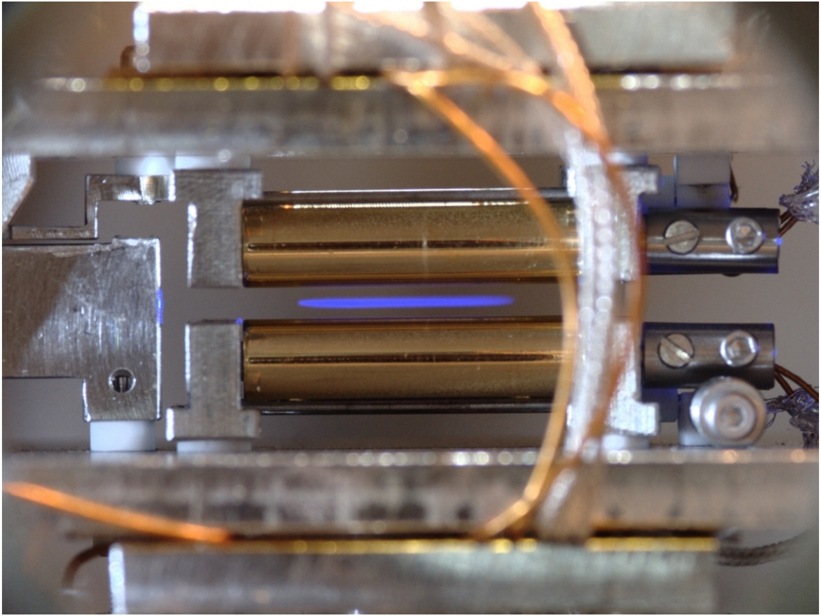

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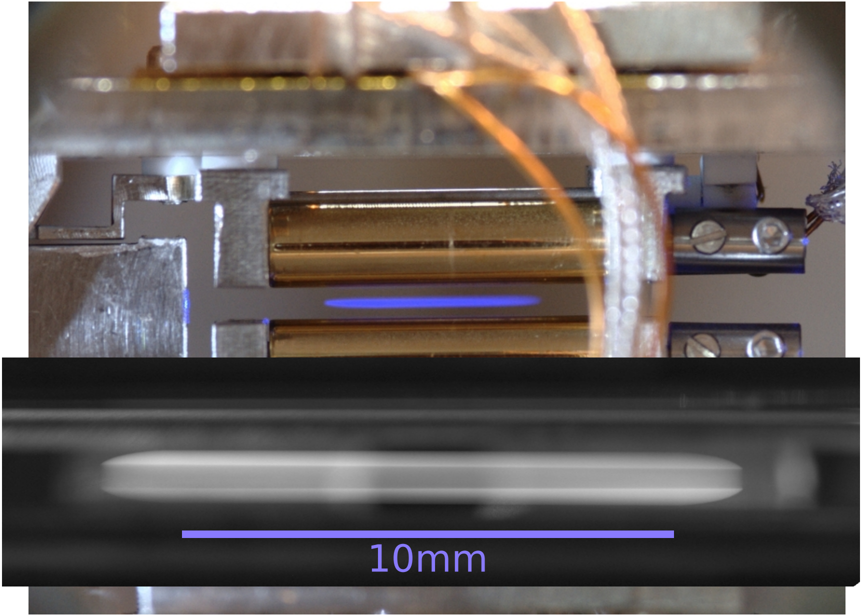
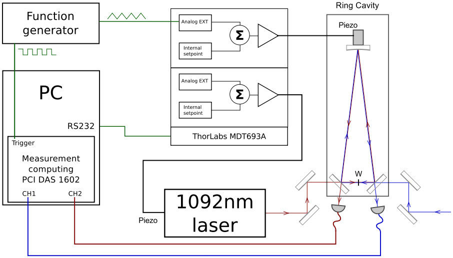


Trapped ion topics

Topics covered during the thesis

- Trap and laser system improvements



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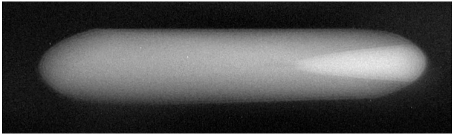

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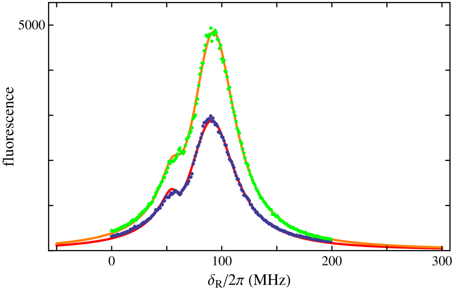

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- Isotopic enrichment
- Spectroscopy
- Absorption measurements

Storing light in a large ion Coulomb crystal

Large Coulomb crystals in a linear Paul trap

Signature of Electromagnetically Induced Transparency (EIT)

Residual temperature

The absorption expected in a large cloud is on the order of 10%

Expected absorption with ideal 2-level model

$$I(z) = I(0).\exp -\sigma \rho_0 z$$

With an absorption cross section

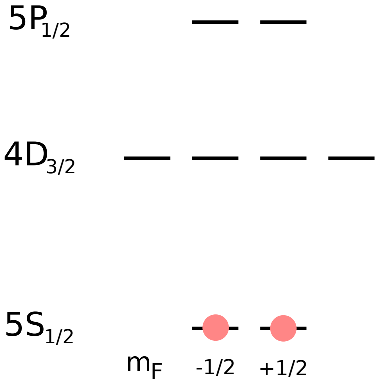
$$\sigma = 2.8 \times 10^{-14}\,\mathrm{m}^2$$

and a density

$$\rho_0 \approx 3 \times 10^{14}\,\mathrm{m}^{-3}$$

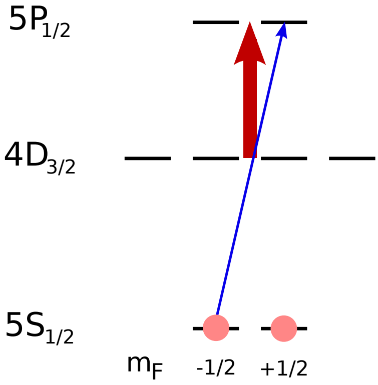
We expect 8% absorption in a 10 mm long cloud on the 422 nm transition.

Absorption measurement method



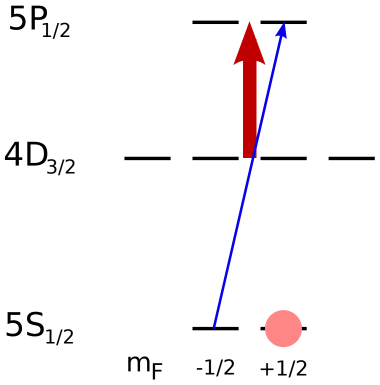
Preparation

Absorption measurement method



Pumping

Absorption measurement method



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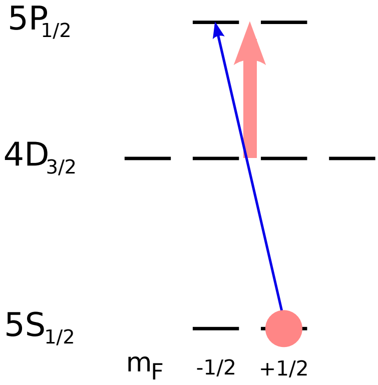
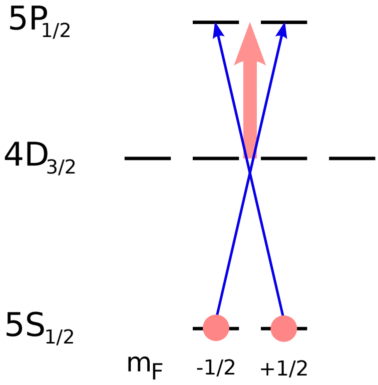


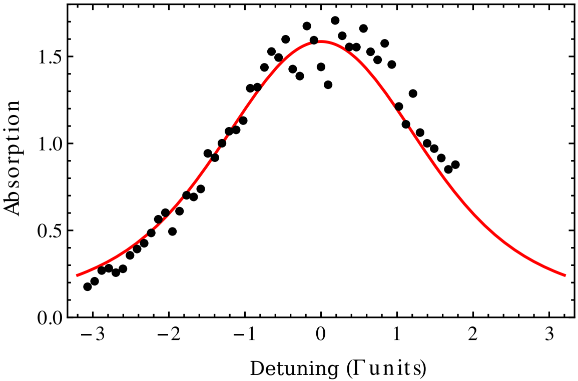
Probing

Absorption measurement method



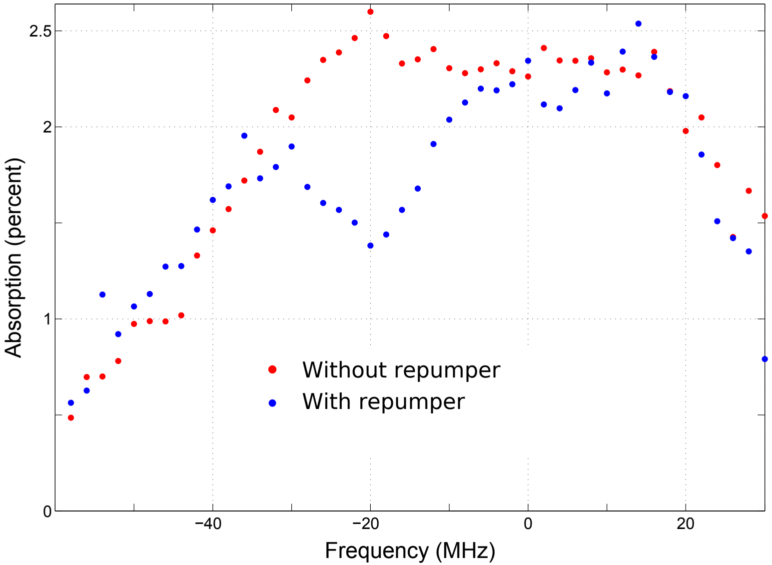
Probing with linear polarization

Significant absorption levels have been measured



Fit results
Absorption: 1.6%
Expected absorption: 2.8%
Width: 45 MHz (2.1 Γ)

A signature of EIT has been observed in a large Coulomb crystal



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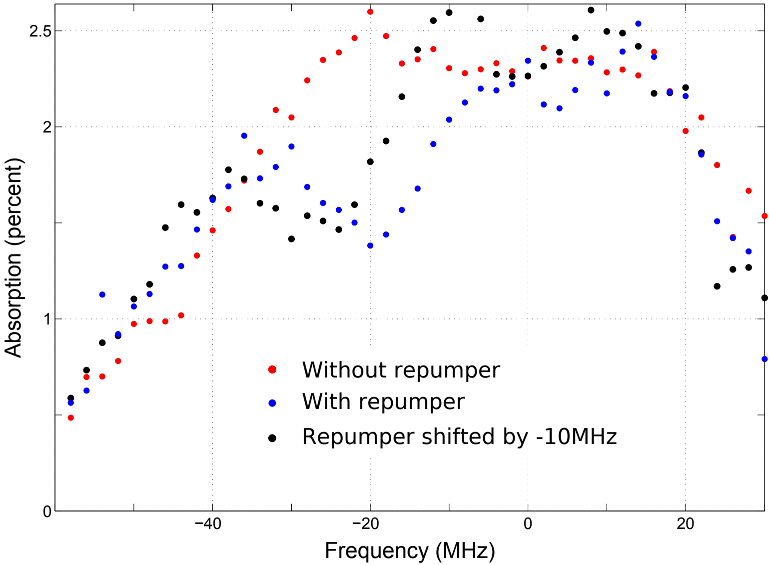


Storing light in a large ion Coulomb crystal

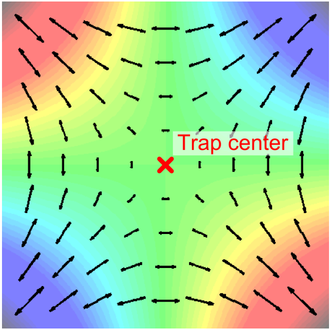
Large Coulomb crystals in a linear Paul trap

Signature of Electromagnetically Induced Transparency (EIT)

Residual temperature

Radio Frequency heating

Radio-frequency field in a Paul trap



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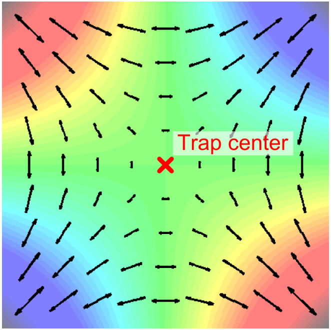
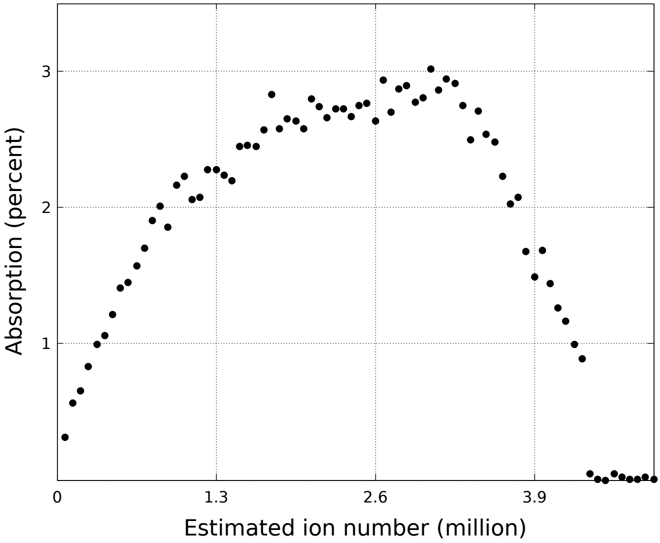


The energy of the trapping field can be transferred to the ion crystal

- Due to the dephasing induced by collisions between the ions
- Depends on the crystal size

Absorption is limited by heating



Without heating, increase of absorption then a plateau are expected

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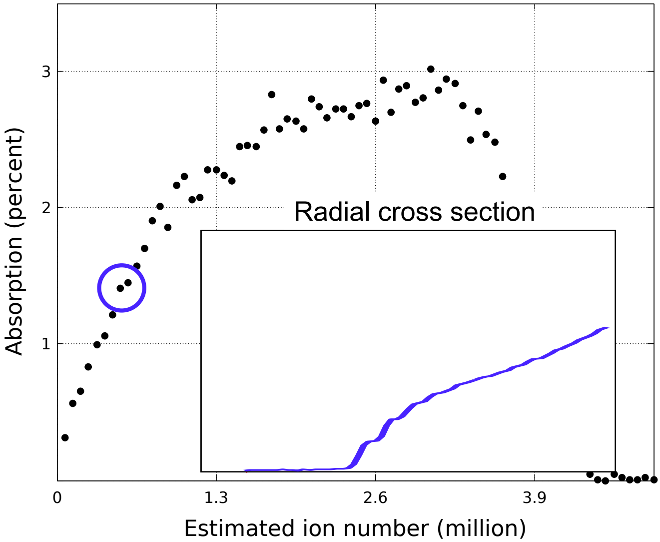

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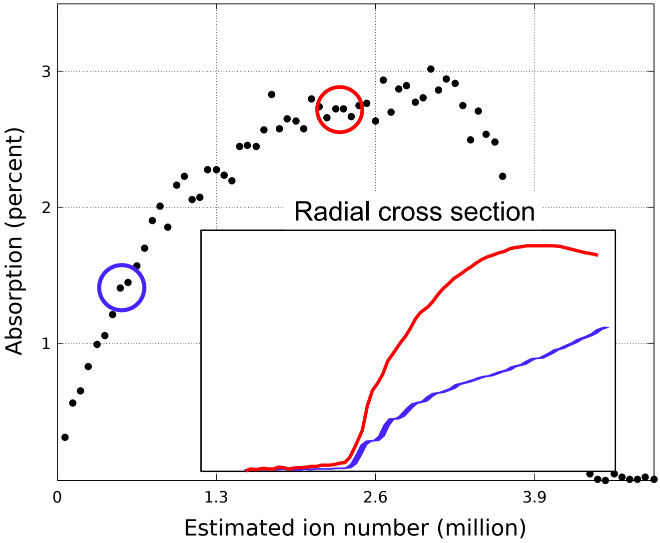

Without heating, increase of absorption then a plateau are expected

Conclusion and outlook

Summary

- Large Coulomb crystals demonstrated
- Significant absorption levels measured
- Signature of electromagnetically induced transparency observed
- Limited by radio frequency heating

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- Large Coulomb crystals demonstrated
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Several ways are possible to improve this result

- Better understanding of RF heating in large Coulomb crystals
- Improved cooling
- Reduced heating via trap geometry and RF field

Detection of Non-Gaussian states in trapped atoms

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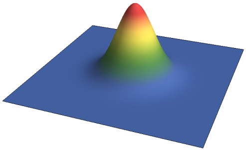
Non-classical, Non-Gaussian states

Measurement of distributions

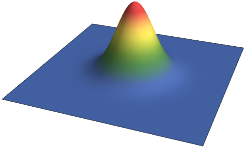
Cumulants to detect non-Gaussian states in trapped atoms

Non-classical, Non-Gaussian states



Coherent state
Classical

Non-classical, Non-Gaussian states



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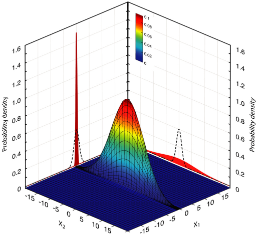

Squeezed state
Collective
entanglement

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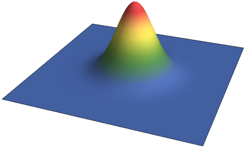

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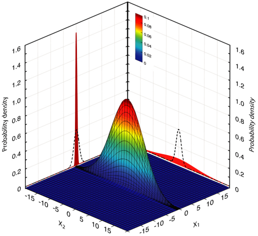

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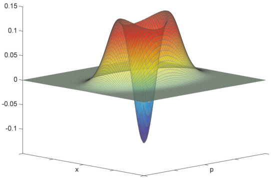
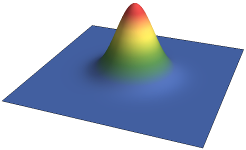


Non-Gaussian state
More "quantumness"

Non-classical, Non-Gaussian states



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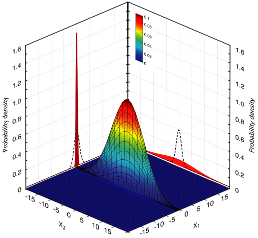

Squeezed state
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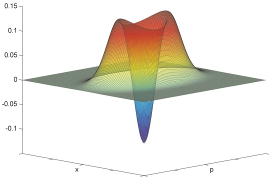
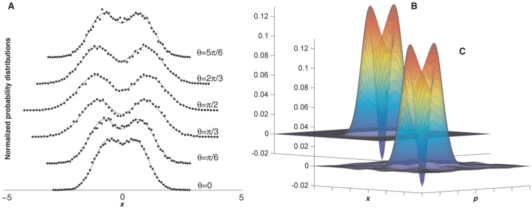


Non-Gaussian state
More "quantumness"

Resource for quantum computation and quantum communication

Non-classical, Non-Gaussian states

- Photonic non-Gaussian states have been produced



- Experiments are being pursued to produce atomic non-Gaussian states, necessary for efficient quantum computation

Non-classical, Non-Gaussian states

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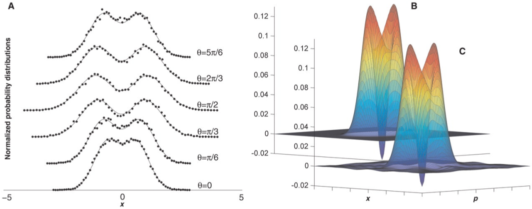

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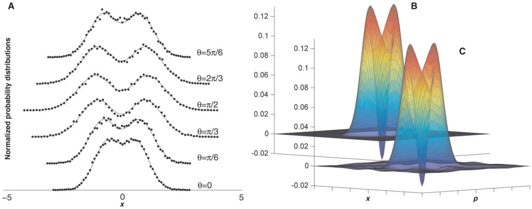

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- The measurement time and the measurement noise are significantly higher in atomic systems
- Need for an efficient measure of non-Gaussianity

Detection of Non-Gaussian states in trapped atoms

Non-classical, Non-Gaussian states

Measurement of distributions

Cumulants to detect non-Gaussian states in trapped atoms

The non-gaussianity of a state can be measured by different ways

Histograms

- Simplest method
- Qualitative

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State tomography

- General method allowing to reconstruct the quantum state
- Need to perform a large number of measurements

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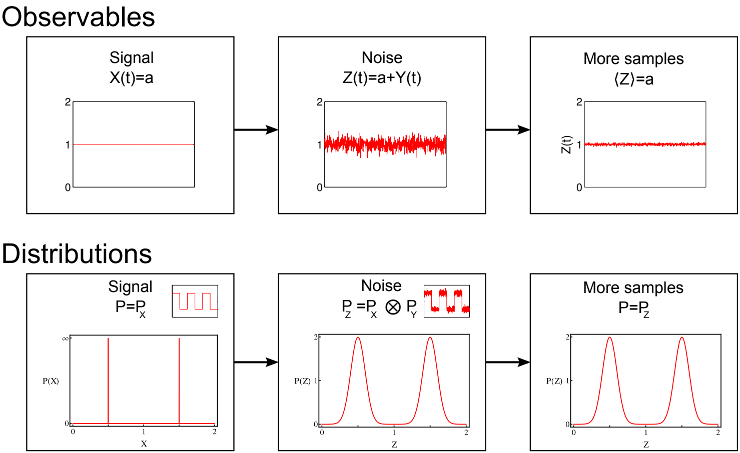
Our approach

- New approach based on cumulants and k-statistics

Distributions exhibit a different noise behavior than observables



Statistical tools to extract distribution properties

Cumulants

- General measure on the shape of a distribution
- κ_1: mean; κ_2: variance

Statistical tools to extract distribution properties

Cumulants

- General measure on the shape of a distribution
- κ_1: mean; κ_2: variance
- $\kappa_{n>2} = 0$ for Gaussian distributions
- High order ($n > 2$) cumulants are unaffected by Gaussian measurement noise

The fourth order cumulant

Fourth order cumulant

- Combination of moments:

$$\kappa_4 = \mu_4 - 4\mu_1\mu_3 - \mu_2^2 + 12\mu_1^2\mu_2 - 6\mu_1^4$$

- Simplest cumulant revealing non gaussianity for symmetric distributions

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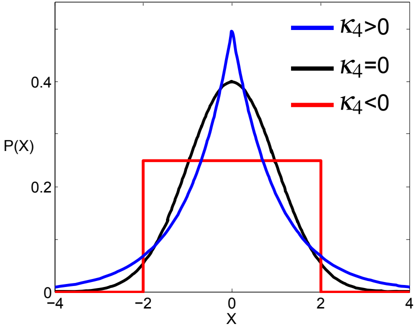

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- Simplest cumulant revealing non gaussianity for symmetric distributions
- Unbiased estimators: Fisher's k-statistics
- The variance on the estimator value can be computed
- Can reveal non-classicality

κ_4 reveals characteristic values of a non-Gaussian state

State of a quantum memory with (maybe) one photon

$$\rho = (1-p)\,|0\rangle\langle 0| + p\,|1\rangle\langle 1|$$

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State of a quantum memory with (maybe) one photon

$$\rho = (1-p)\,|0\rangle\langle 0| + p\,|1\rangle\langle 1|$$

- Marginal distribution

$$P_p(X) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{x^2}{2\sigma^2}\right]\left[1 + p\left(\frac{x^2}{\sigma^2} - 1\right)\right]$$

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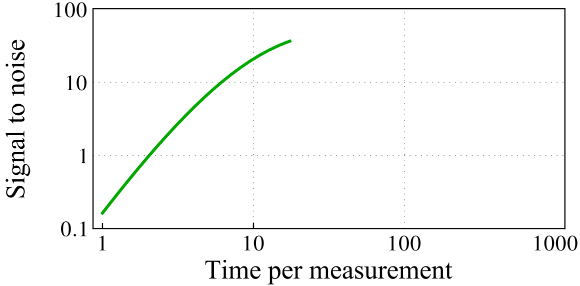
- $\kappa_4 = -12p^2\sigma^4$
- Negative Wigner function for $p > 0.5$

Optimal use of resources

With limited measurement time two strategies are possible



- Many measurements: un-precise but large statistical information

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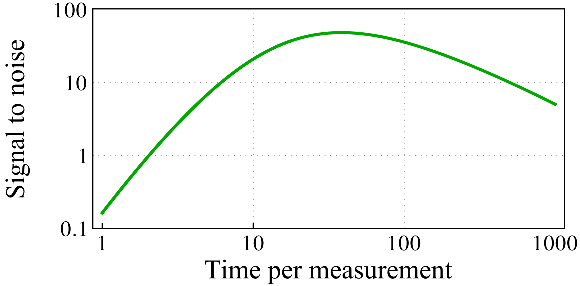

- Many measurements: un-precise but large statistical information
- Few measurements: very precise but low statistical information

Optimal use of resources

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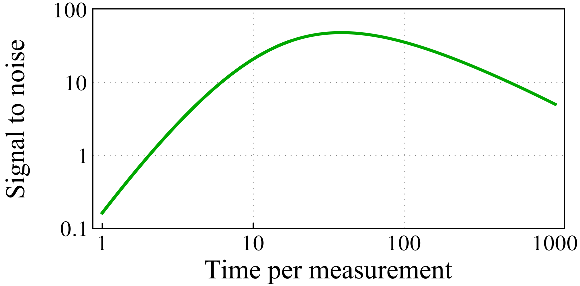

Optimum when:

Measurement precision ≈ distribution characteristic features

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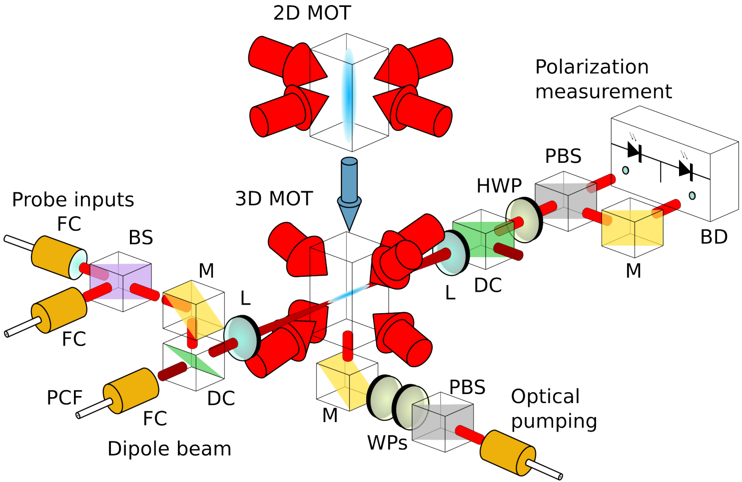
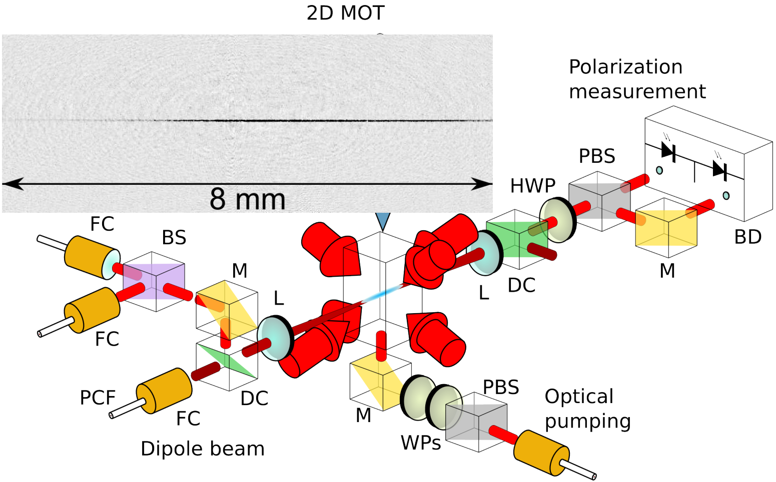
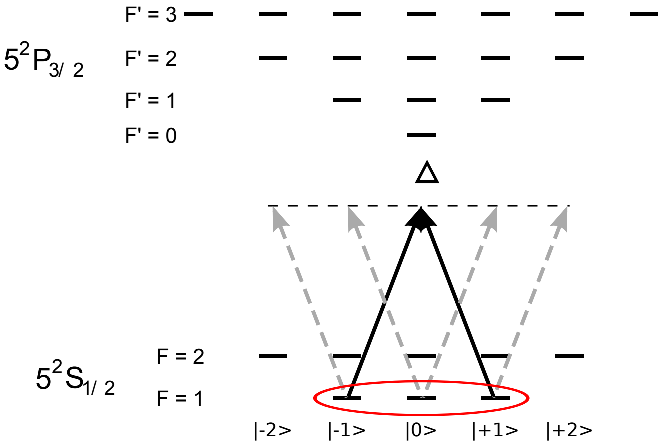
Experimental setup: cold rubidium atom trap



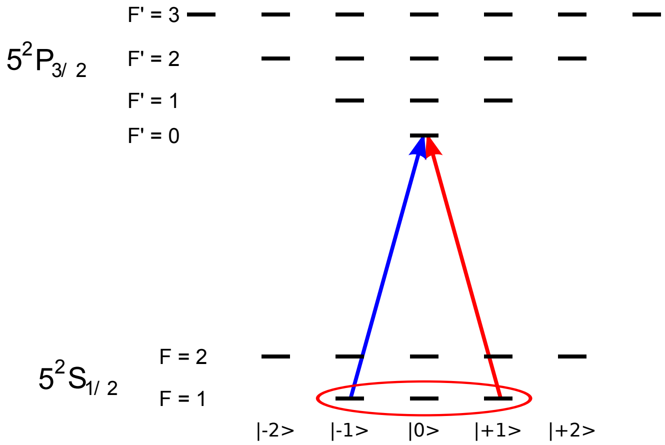
Experimental setup: cold rubidium atom trap



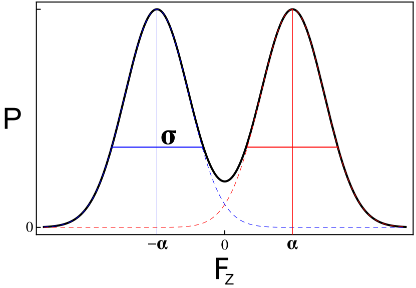
Atoms are measured using Faraday rotation



State preparation: optical pumping

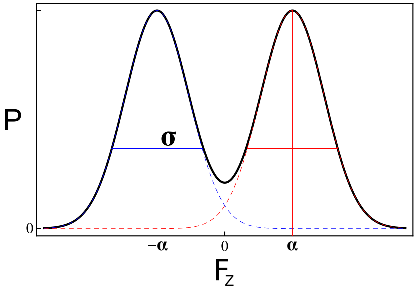


Non-Gaussian test distribution



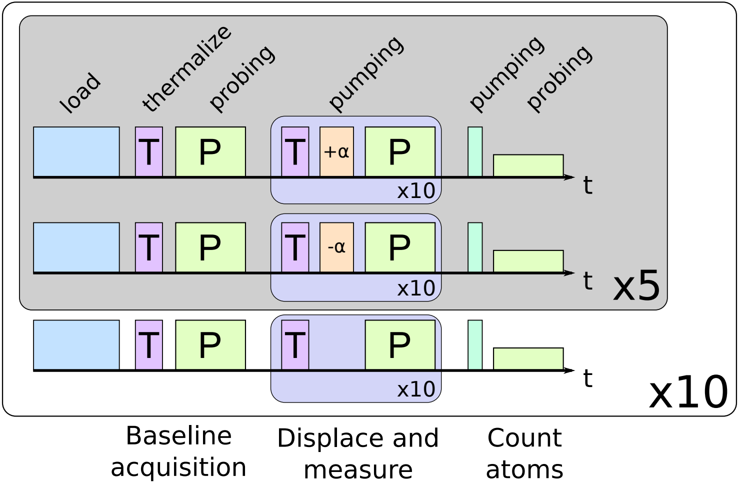
- Statistical mixture of two displaced Thermal states

Non-Gaussian test distribution



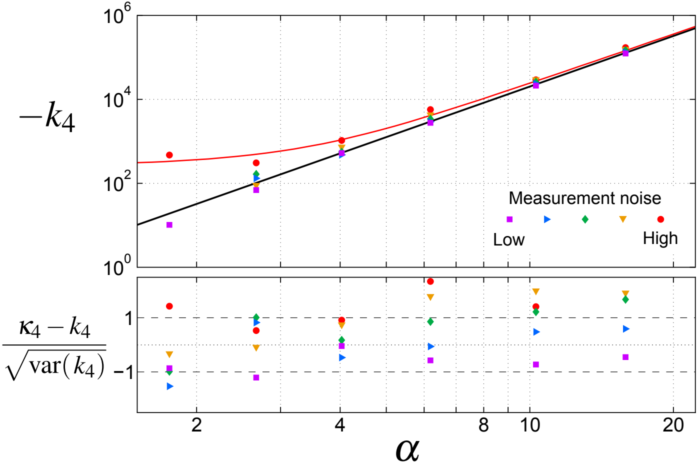
- Statistical mixture of two displaced Thermal states
- $\kappa_4 = -4\alpha^4$
- Can be characterized independently

Experimental sequence

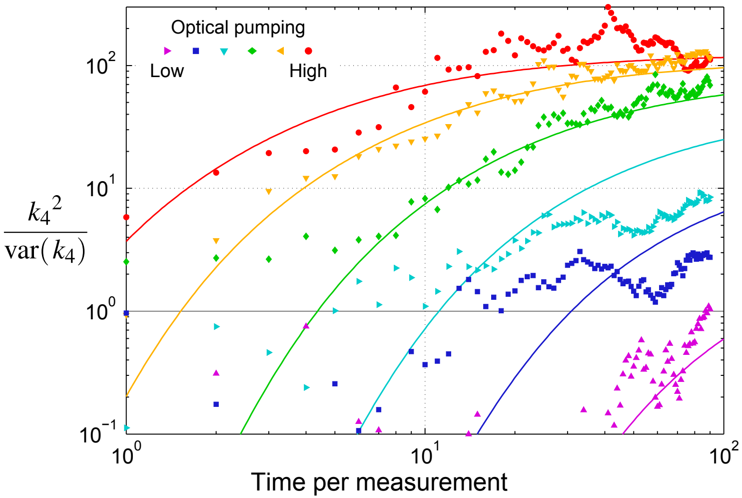


The value of k_4 corresponds to the expectations

Measured value of k_4 compared with the value computed from the distribution characteristics for different measurement noise



The signal to noise can be accurately predicted



Conclusion

- The use of cumulants and k-statistics allows to detect efficiently Non-Gaussian states in atomic ensembles.
- The variance of the measurement can be estimated for a proof of non-gaussianity
- An optimal use of the resources can be determined for experimental design

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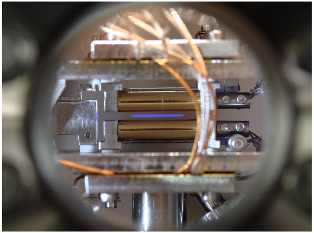
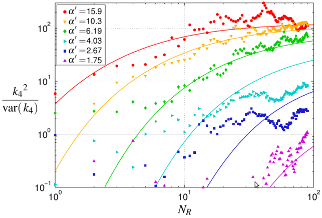
Outlook

- Determine a simple link between negative Wigner function and the value of k_4 on different observables

Two aspects of light-matter interaction have been studied

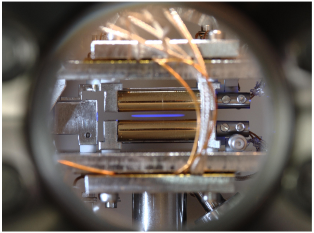


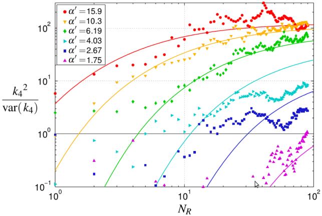


Two aspects of light-matter interaction have been studied

Storing light in an ion Coulomb crystal

- Significant absorption levels and EIT were reached in a ion Coulomb crystal
- Future improvements via the reduction of RF heating





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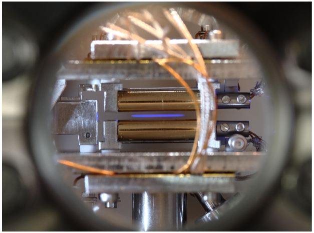
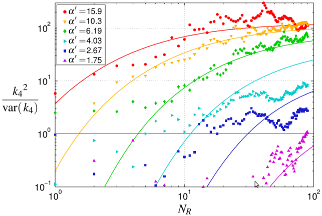


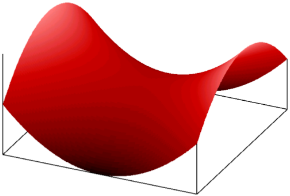
Detecting non-Gaussian states in trapped atoms

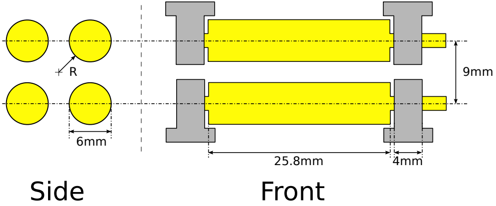
- Efficient tool to detect non-Gaussianity in atomic systems
- Noise properties can be accurately predicted



Appendix

Appendix

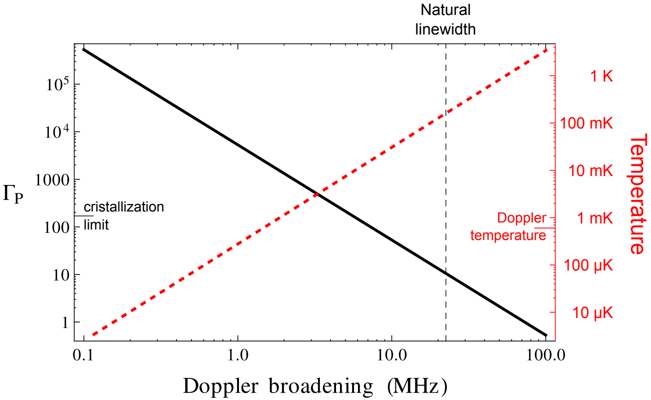




$$\Phi(x, y, t) = \left(V_{RF}\,\cos(\omega_{RF}t) - V_{DC}\right)\frac{x^2 - y^2}{R^2}$$

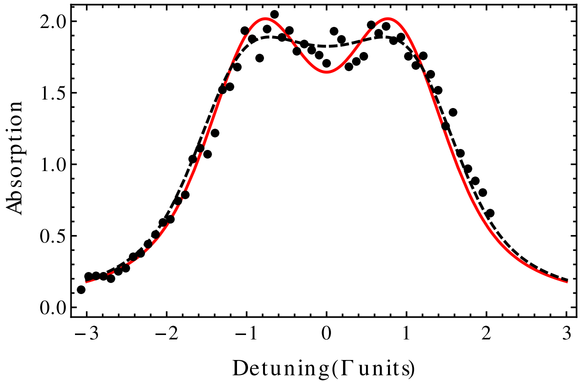
$$q = \frac{ZeV_{RF}}{mR^2\omega_{RF}^2} \qquad a = \frac{ZeV_{DC}}{mR^2\omega_{RF}^2}$$

Appendix

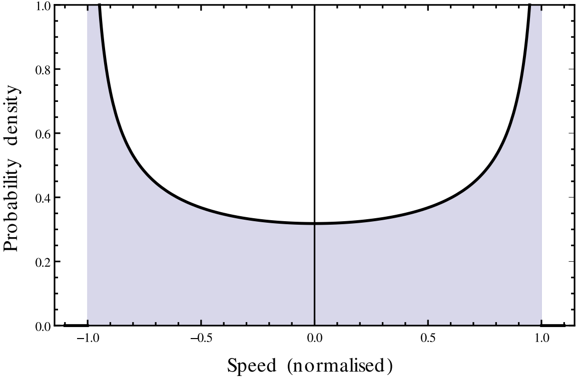


Natural
linewidth
10^5
10^4
1000
100
10
1
Γ_P
cristallization
limit
1 K
100 mK
10 mK
1 mK
100 μK
10 μK
Doppler
temperature
Temperature
0.1
1.0
10.0
100.0
Doppler broadening (MHz)

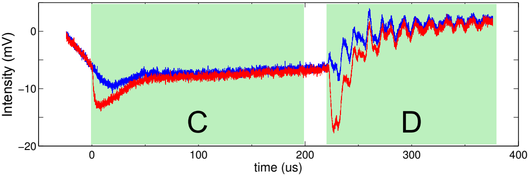
Appendix



Appendix

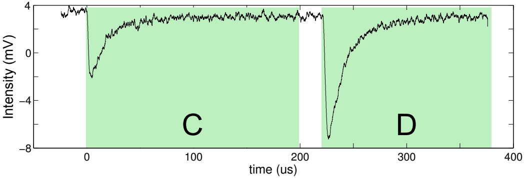

1.0
0.8
0.6
0.4
0.2
0.0
Probability density
−1.0
−0.5
0.0
0.5
1.0
Speed (normalised)

Appendix



Intensity (mV)
0
−10
−20
0
100
200
300
400
time (us)
C
D

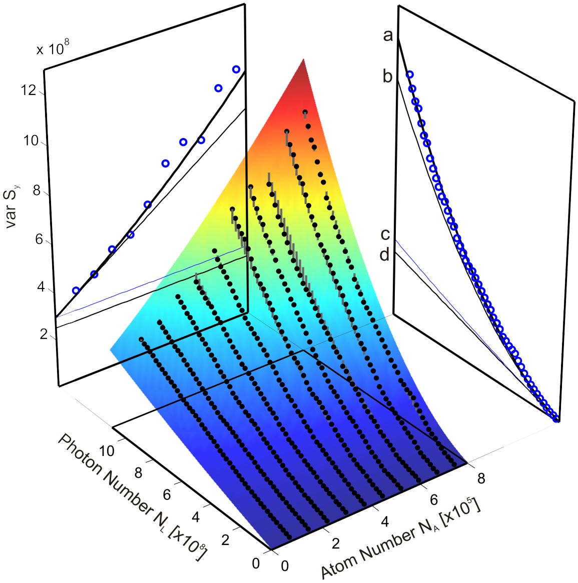
(a)



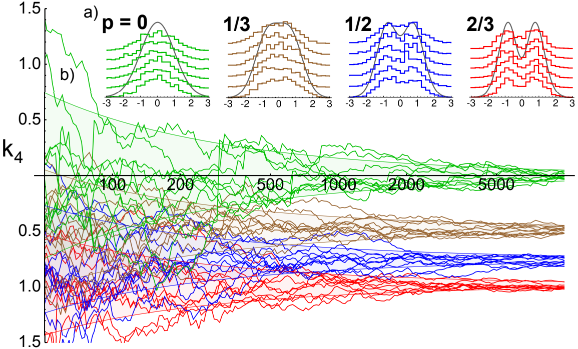
Intensity (mV)
4
0
−4
−8
0
100
200
300
400
time (us)
C
D

(b)

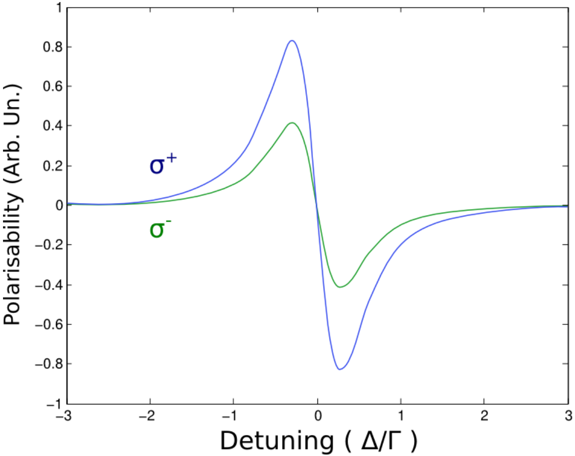
Characterization of the noise contributions



Cumulants versus histograms



Appendix



Polarisability (Arb. Un.)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−3
−2
−1
0
1
2
3
σ^+
σ^-
Detuning (Δ/Γ)

Appendix

$$
\begin{aligned}
k_4 &= \frac{N^2(N+1)S_4 - 4N(N-1)S_1S_3 - 3N(N-1)S_2^2}{N(N-1)(N-2)(N-3)} \\
&\quad + \frac{12NS_1^2S_2 - 6S_1^4}{N(N-1)(N-2)(N-3)}
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{var}(k_4) &= \frac{\kappa_8}{N} + 2N\frac{8\kappa_6\kappa_2 + 24\kappa_5\kappa_3 + 17\kappa_4^2}{N(N-1)} \\
&\quad + 72N^2\frac{\kappa_4\kappa_2^2 + 2\kappa_3^2\kappa_2}{N(N-1)(N-2)} \\
&\quad + \frac{24N^2(N+1)\kappa_2^4}{N(N-1)(N-2)(N-3)}.
\end{aligned}
$$