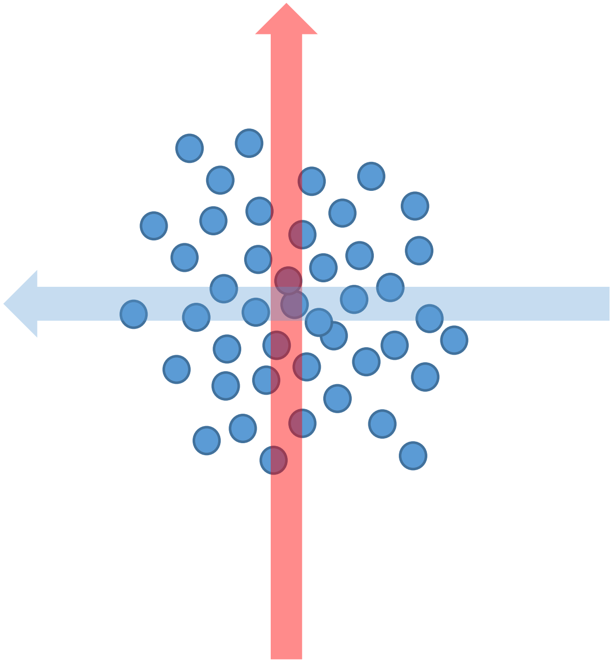
Characterizing cold atomic clouds using Rydberg excitation

Oliver Morsch

CNR-INO and Dipartimento di Fisica, Pisa

Atomtronics 2024, Benasque, 28/05/2024



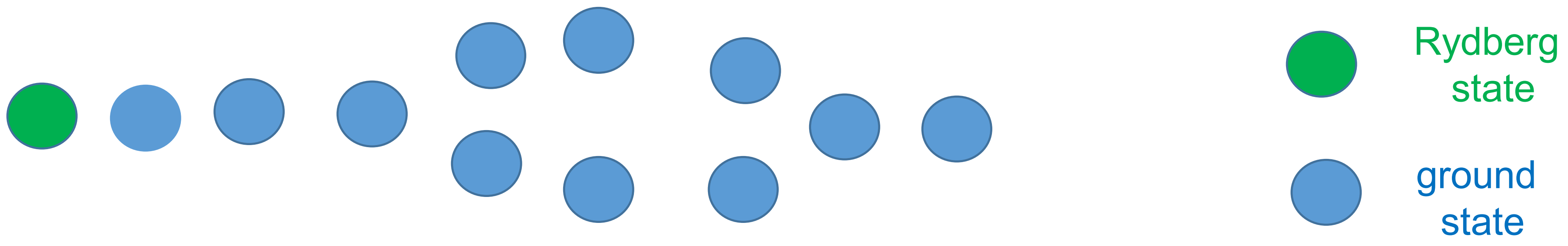
People: B. Bégoc, K. N. Trivedi, M. Carminati, T. Bonaccorsi, R. Donofrio

Collaborators: I. Lesanovsky, L. Amico, D. Rossini, F. Perciavalle

Funding: MOQS Molecular Quantum Simulations; JSF Julian Schwinger Foundation; NQSTI National Quantum Science and Technology Institute

On the road to Rydberg atomtronics…

«Rydberg Atomtronics»



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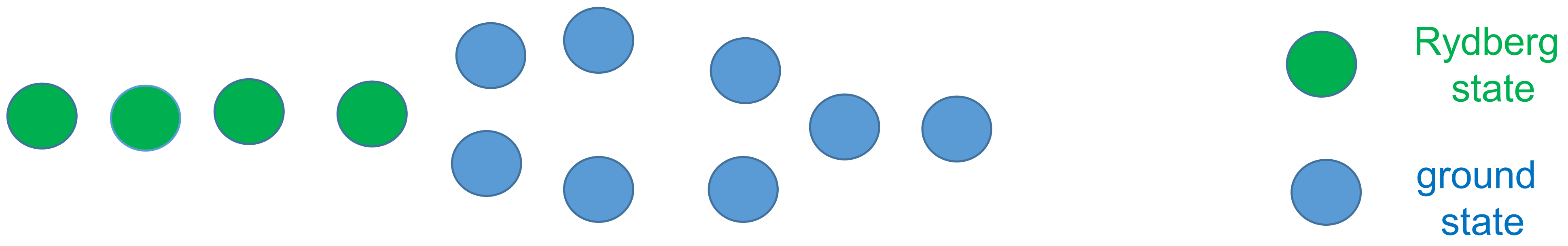

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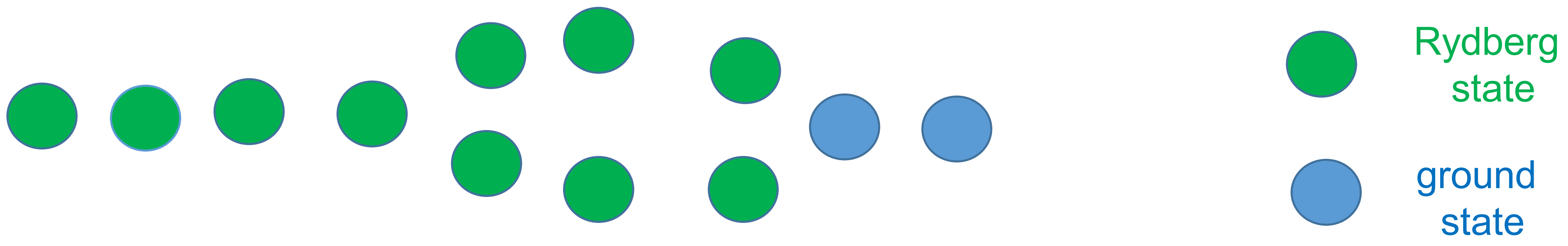

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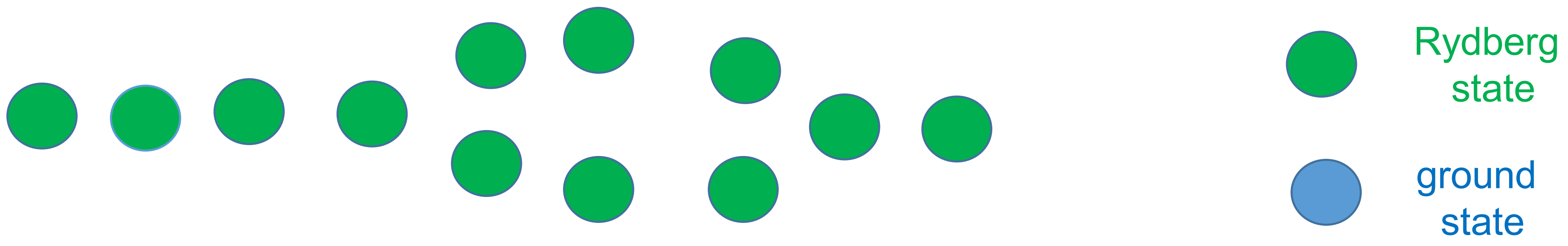

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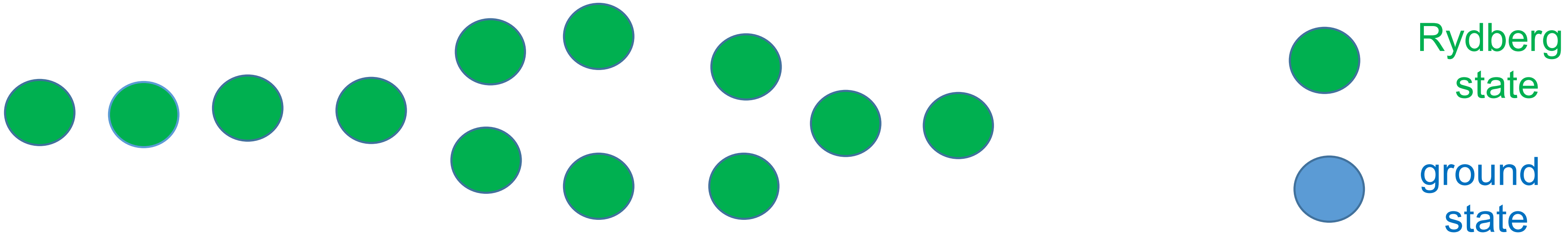

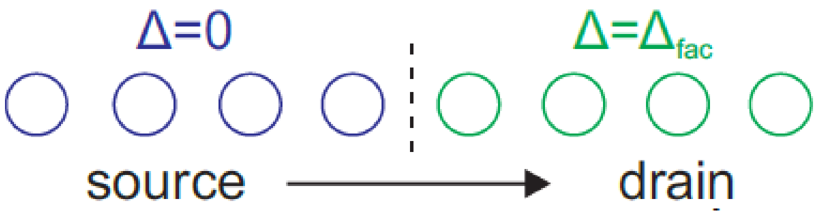

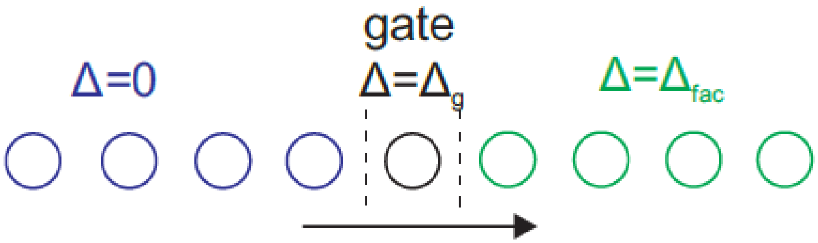

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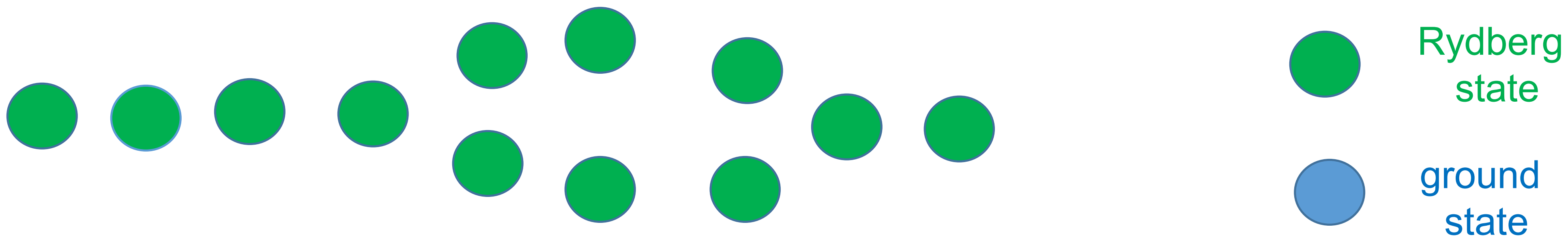

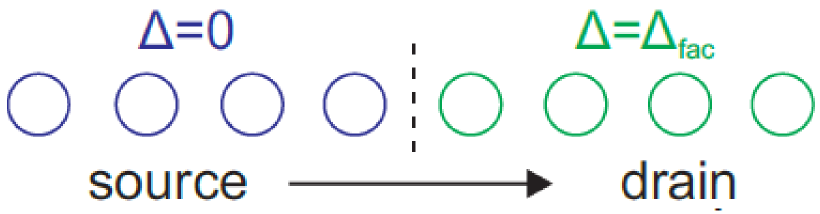

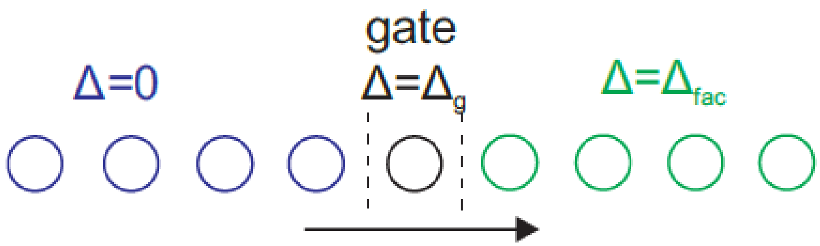

PHYSICAL REVIEW A **108**, 023305 (2023)

Controlled flow of excitations in a ring-shaped network of Rydberg atoms

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Rydberg atomtronic devices

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ArXiv: 2310.18242

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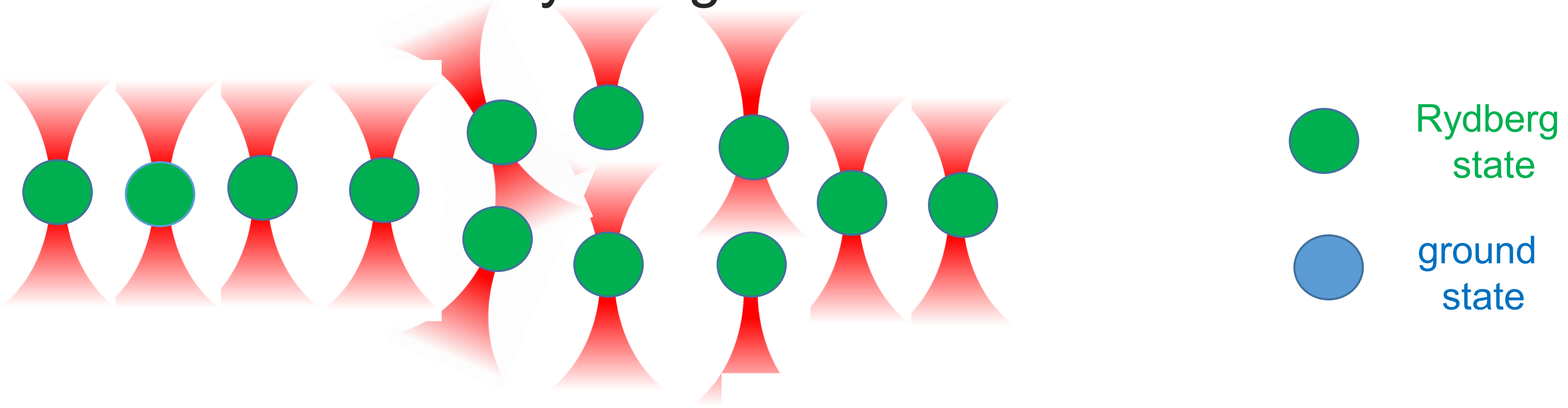

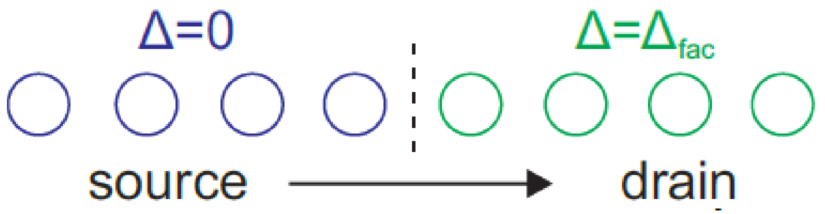

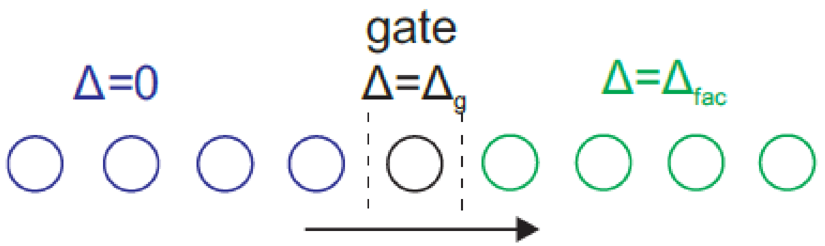

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... we've got as far as one dipole trap

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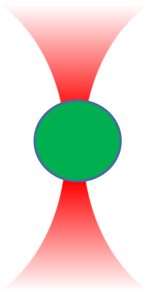

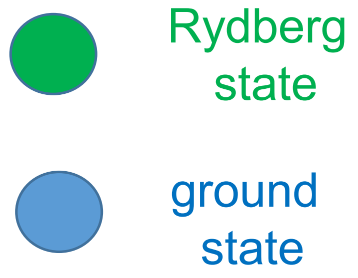

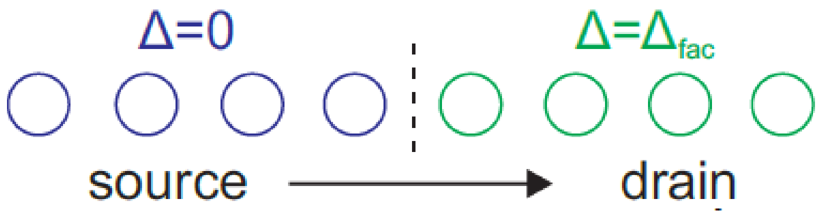

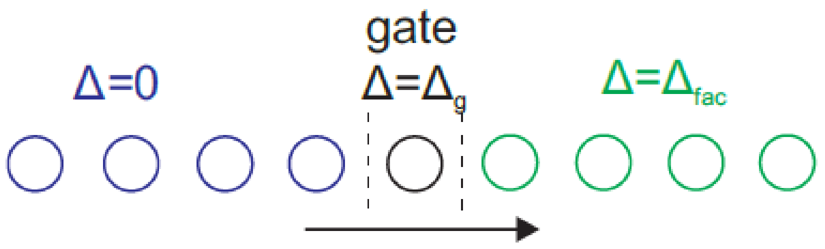

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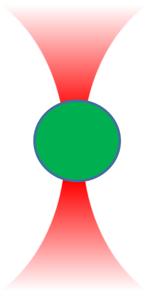
... we’ve got as far as one dipole trap



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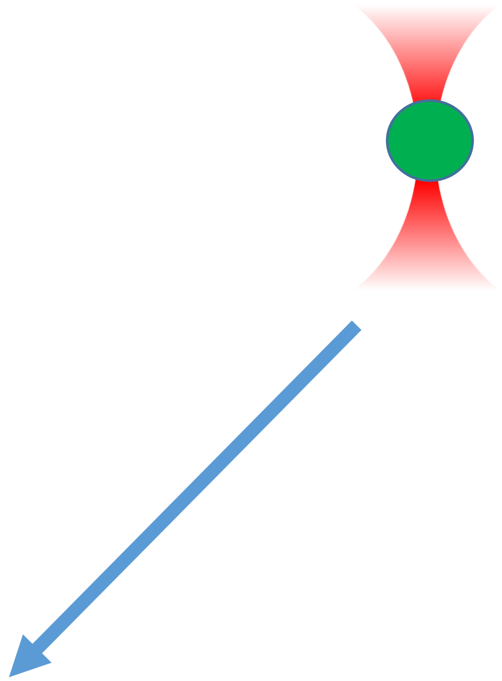

characterize dipole trap
using Rydberg excitations

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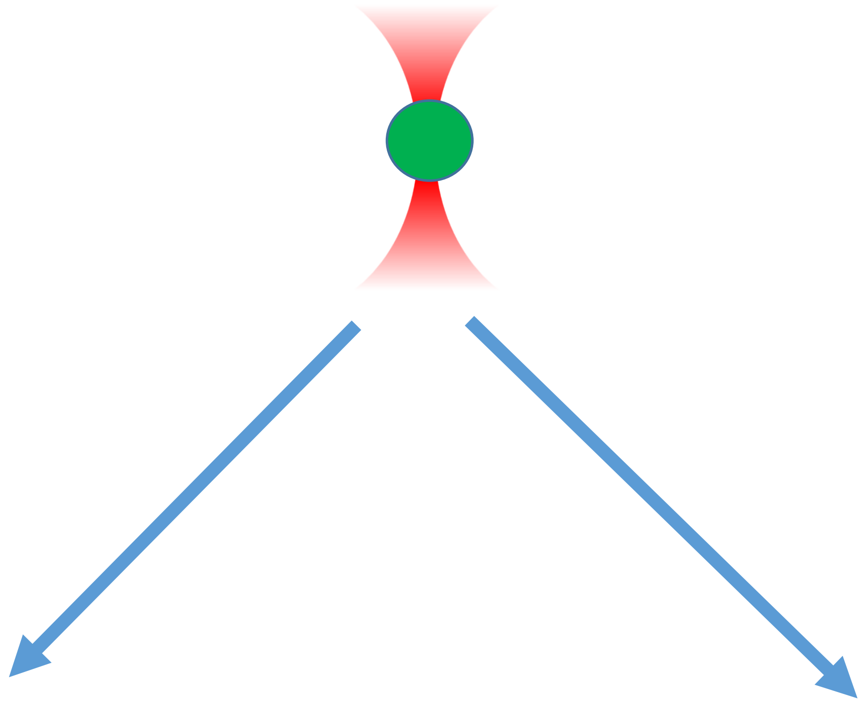


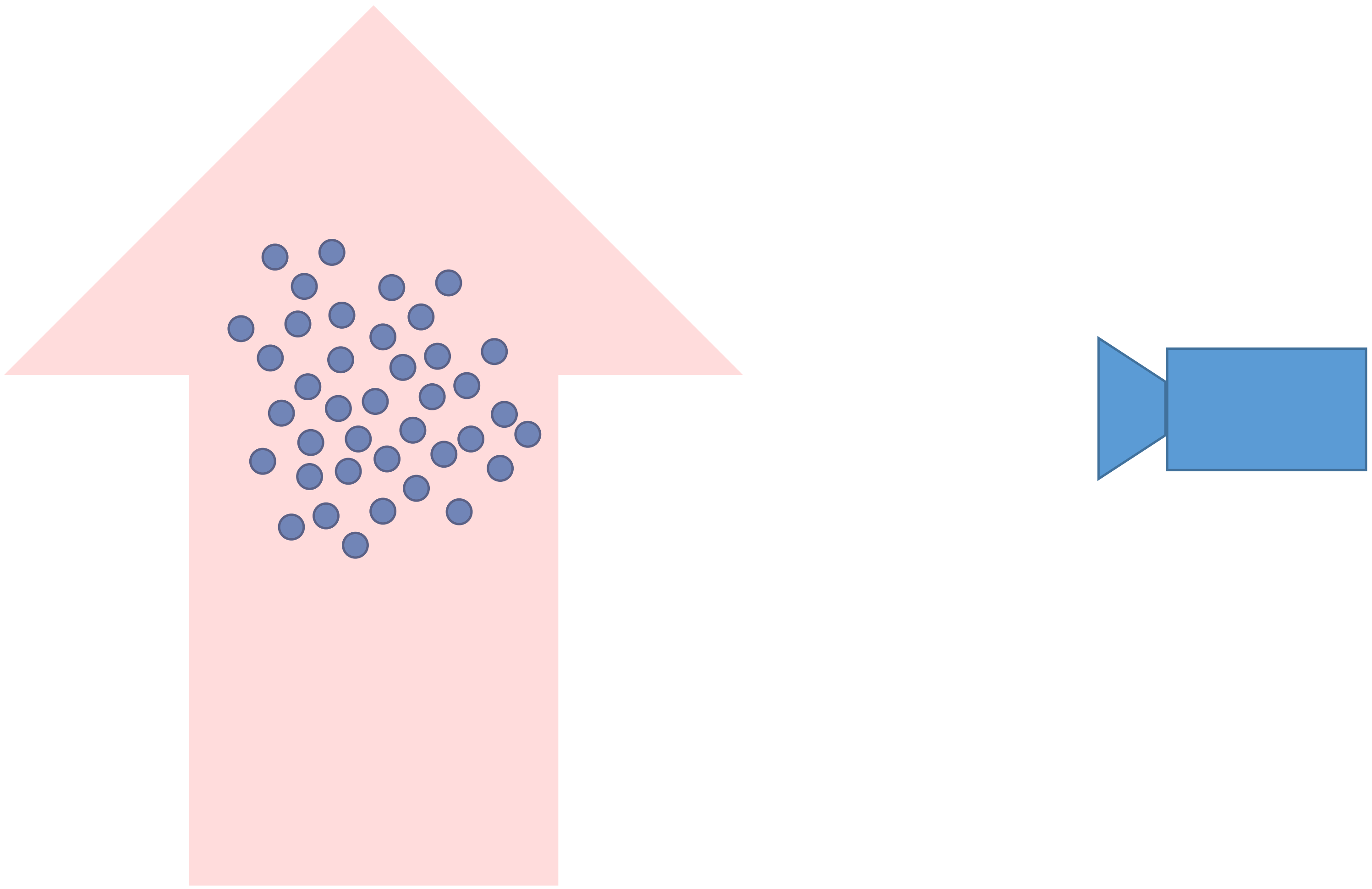
characterize dipole trap using Rydberg excitations

use Rydberg excitations to characterize cold atoms: temperature measurement

Exciting and detecting Rydberg atoms

^{87}Rb atoms in a magneto-optical trap (MOT)
T ~ 150 micro Kelvin («frozen gas»)
N ~ few 10^5
size around 150 microns

Exciting and detecting Rydberg atoms



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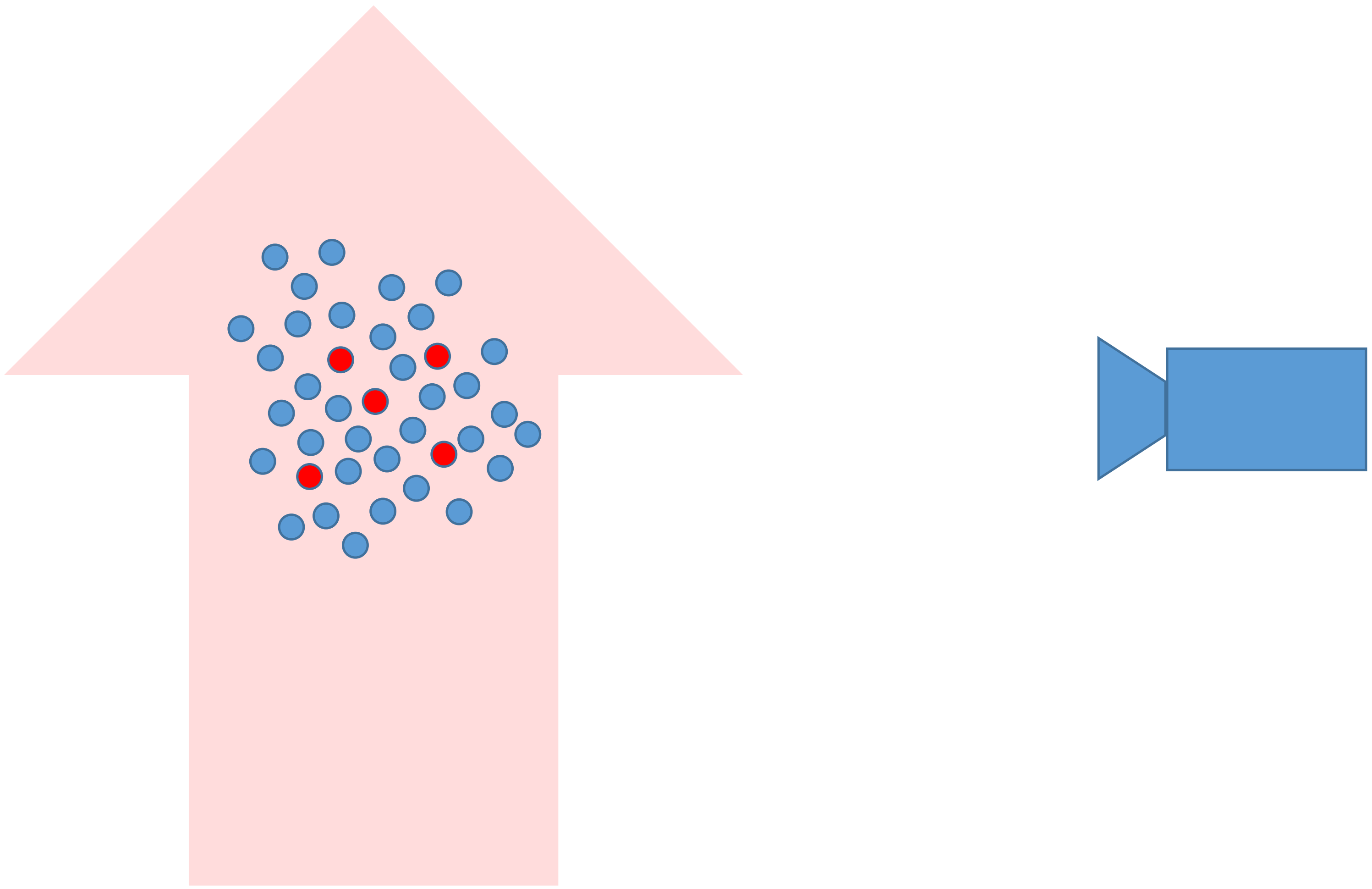

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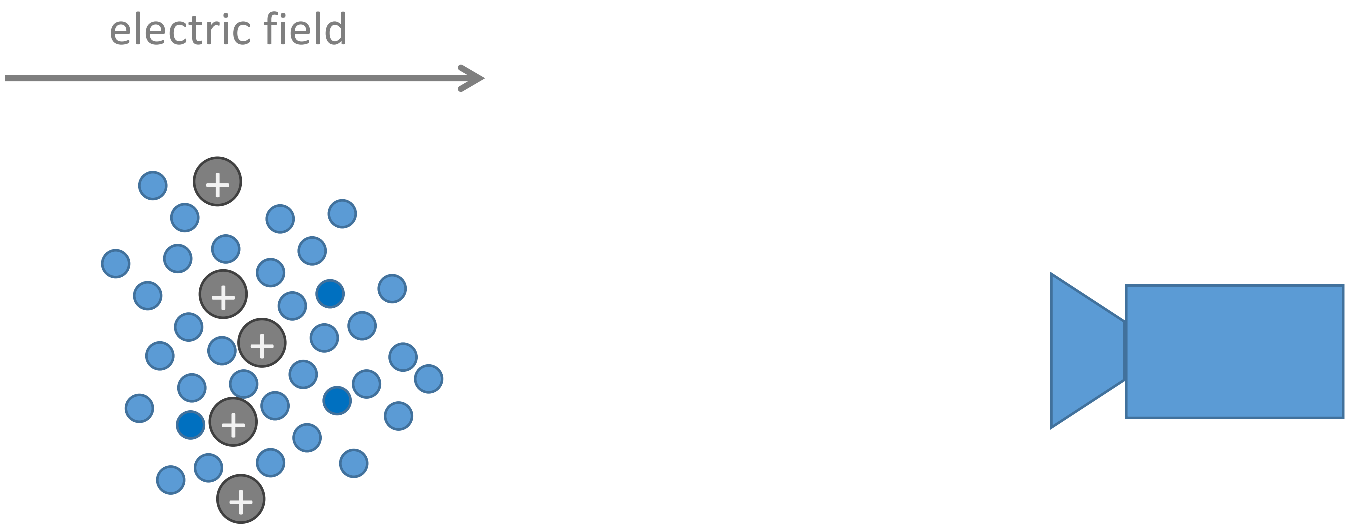
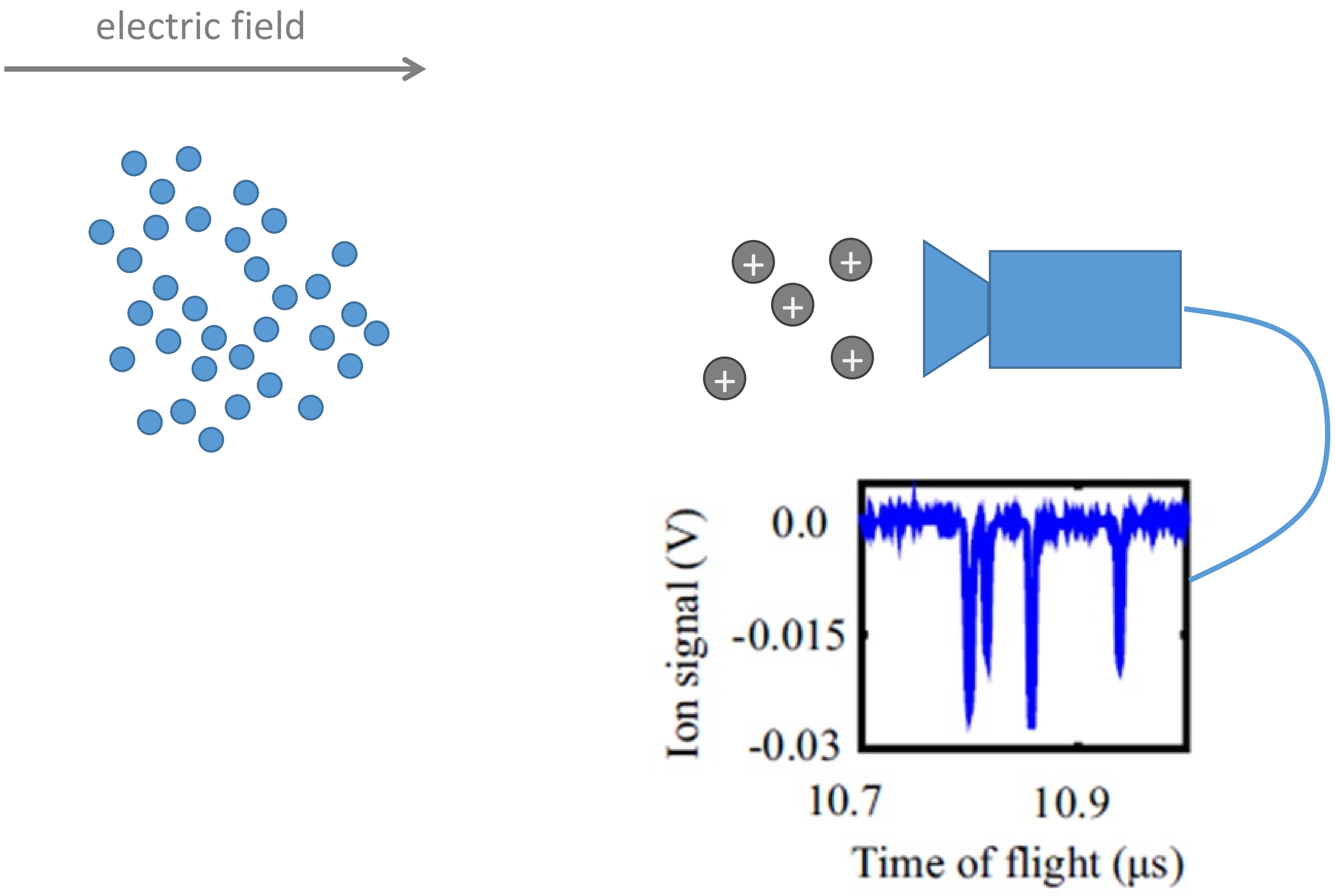


Field ionization

Exciting and detecting Rydberg atoms

Field ionization



Characterizing the dipole trap using Rydberg excitations

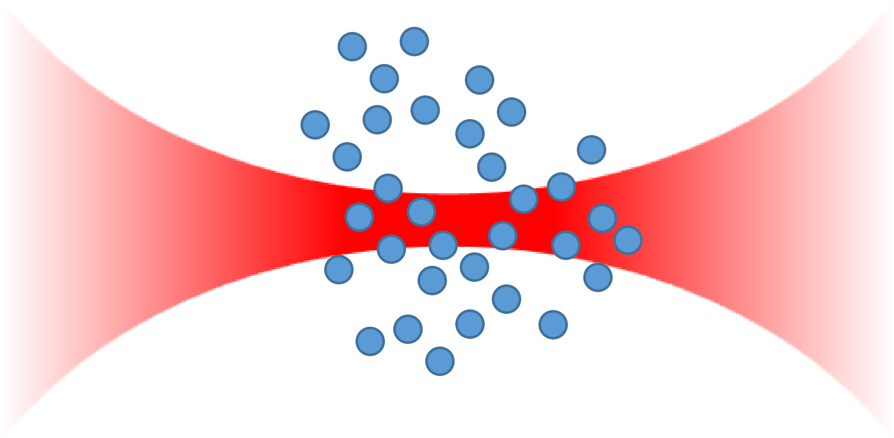
$$I(\vec{r}) = I(r,z) = \frac{2P}{\pi w^2(z)} e^{-2\frac{r^2}{w^2(z)}}$$

$$\Downarrow$$

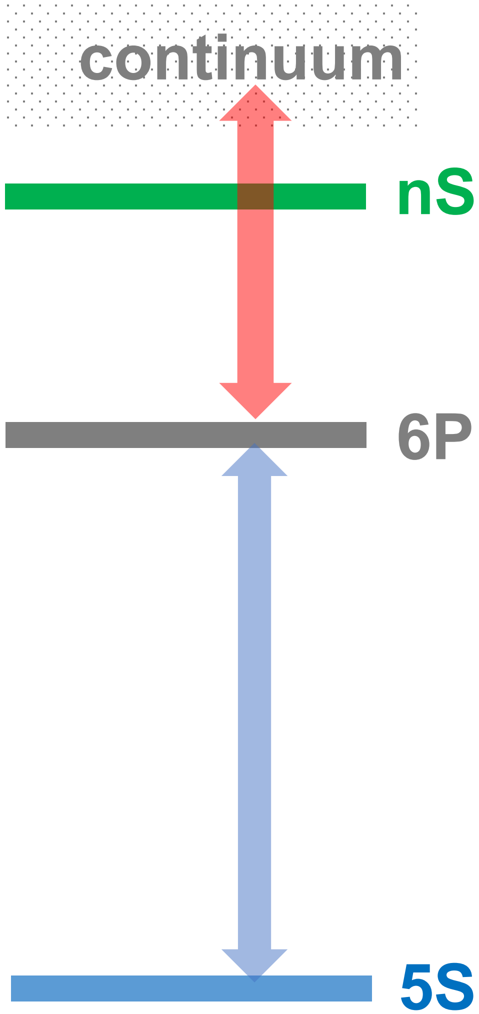
light shift $$U(\vec{r}) \simeq \frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\Delta} I(\vec{r})$$

trap frequency $$\omega_r = \sqrt{\frac{4U_0}{Mw_0^2}}$$

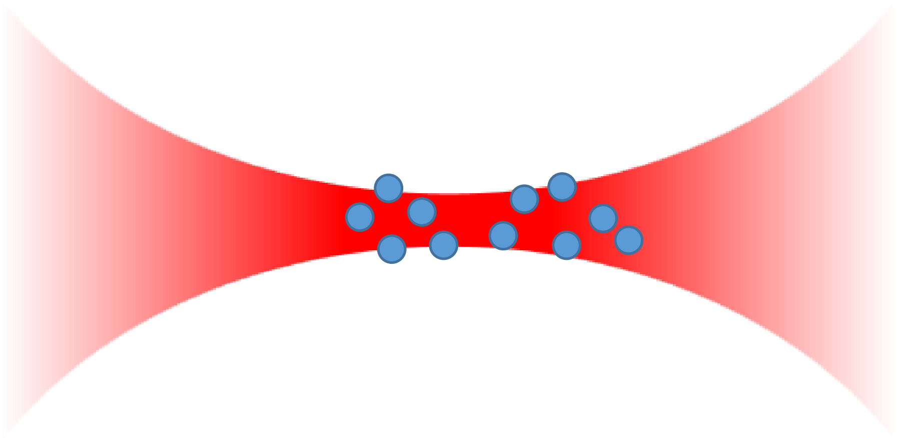
840 nm



Characterizing the dipole trap using Rydberg excitations

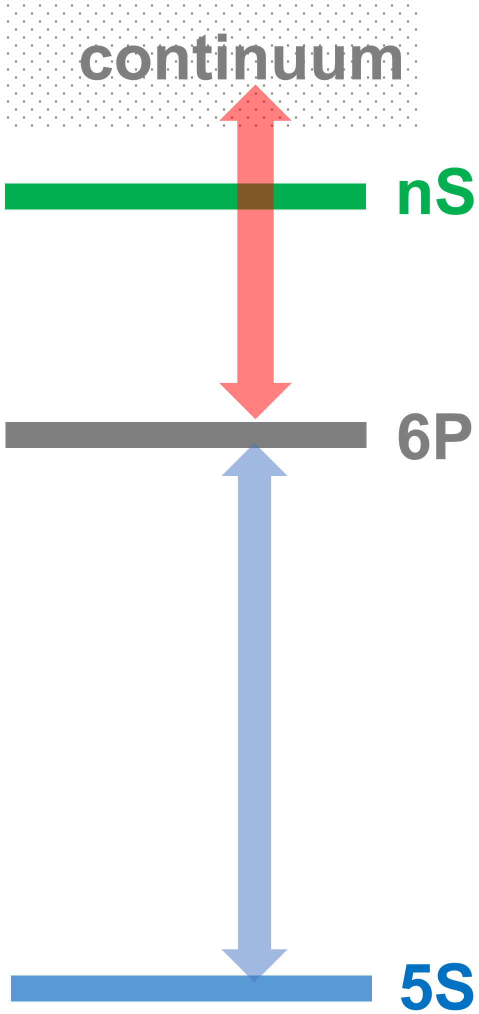


photoionization



- measure number of atoms in dipole trap using photoionization
- measure trap frequency via parametric heating / loss

Characterizing the dipole trap using Rydberg excitations



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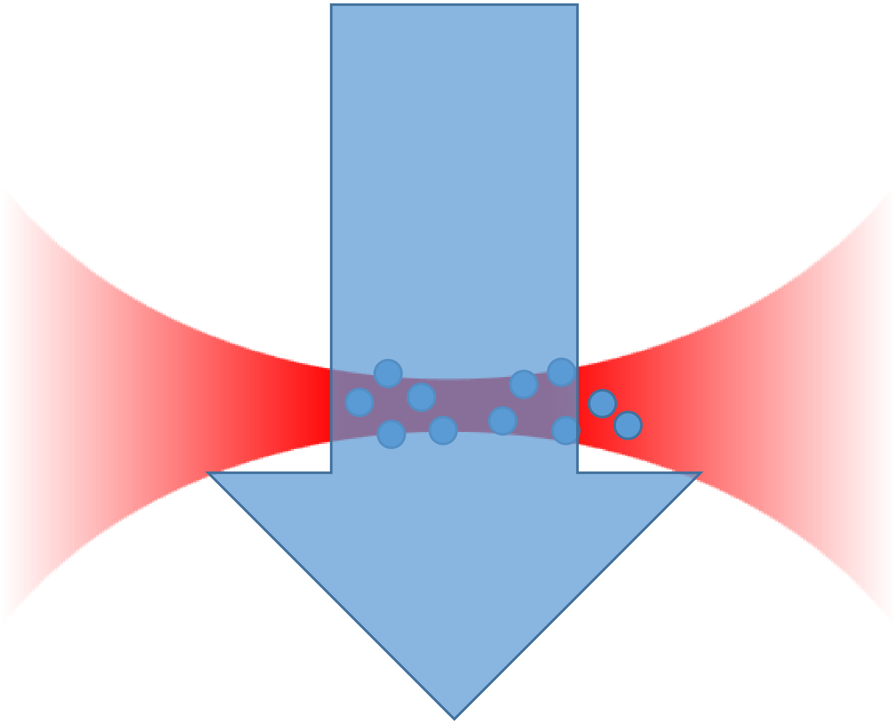

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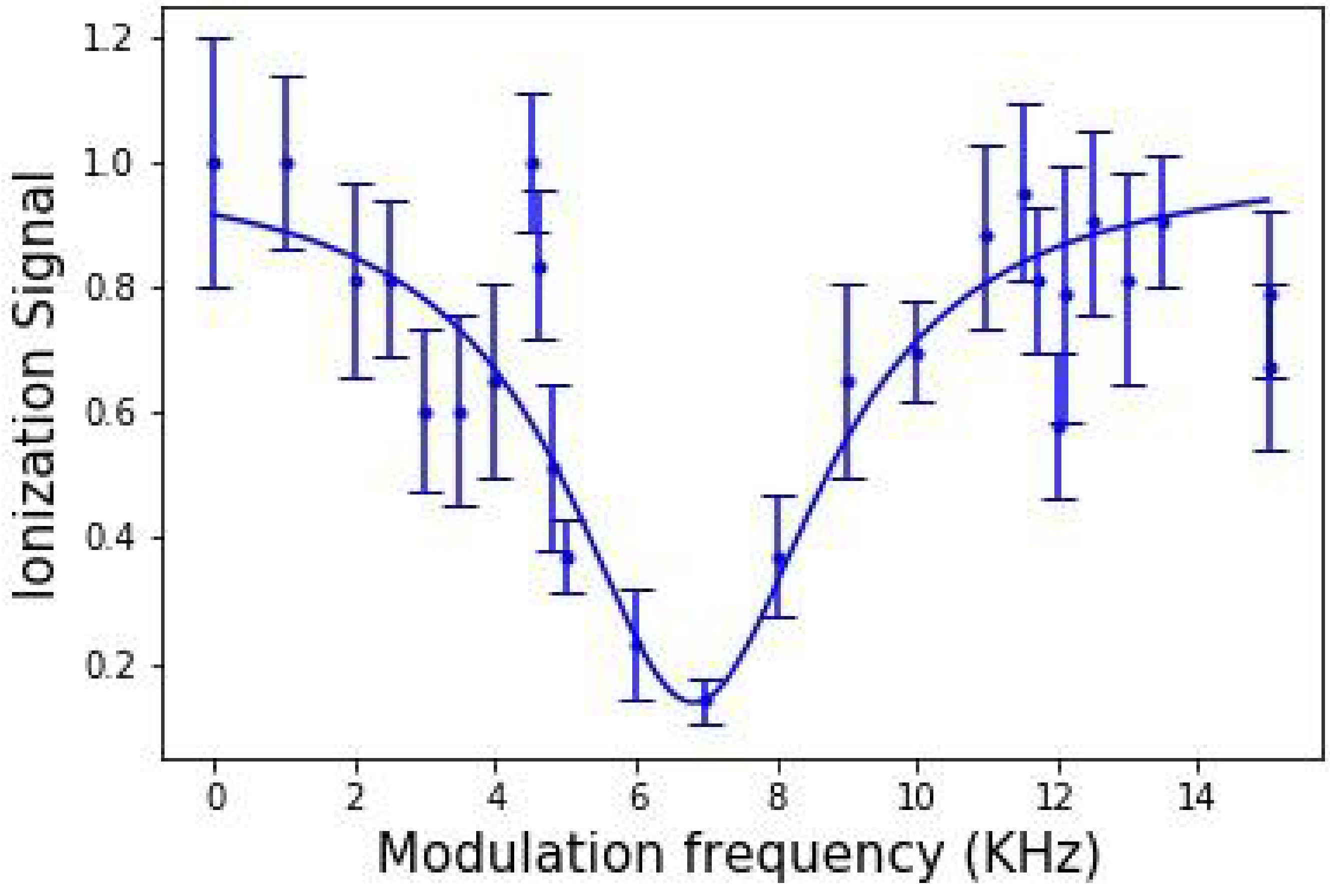

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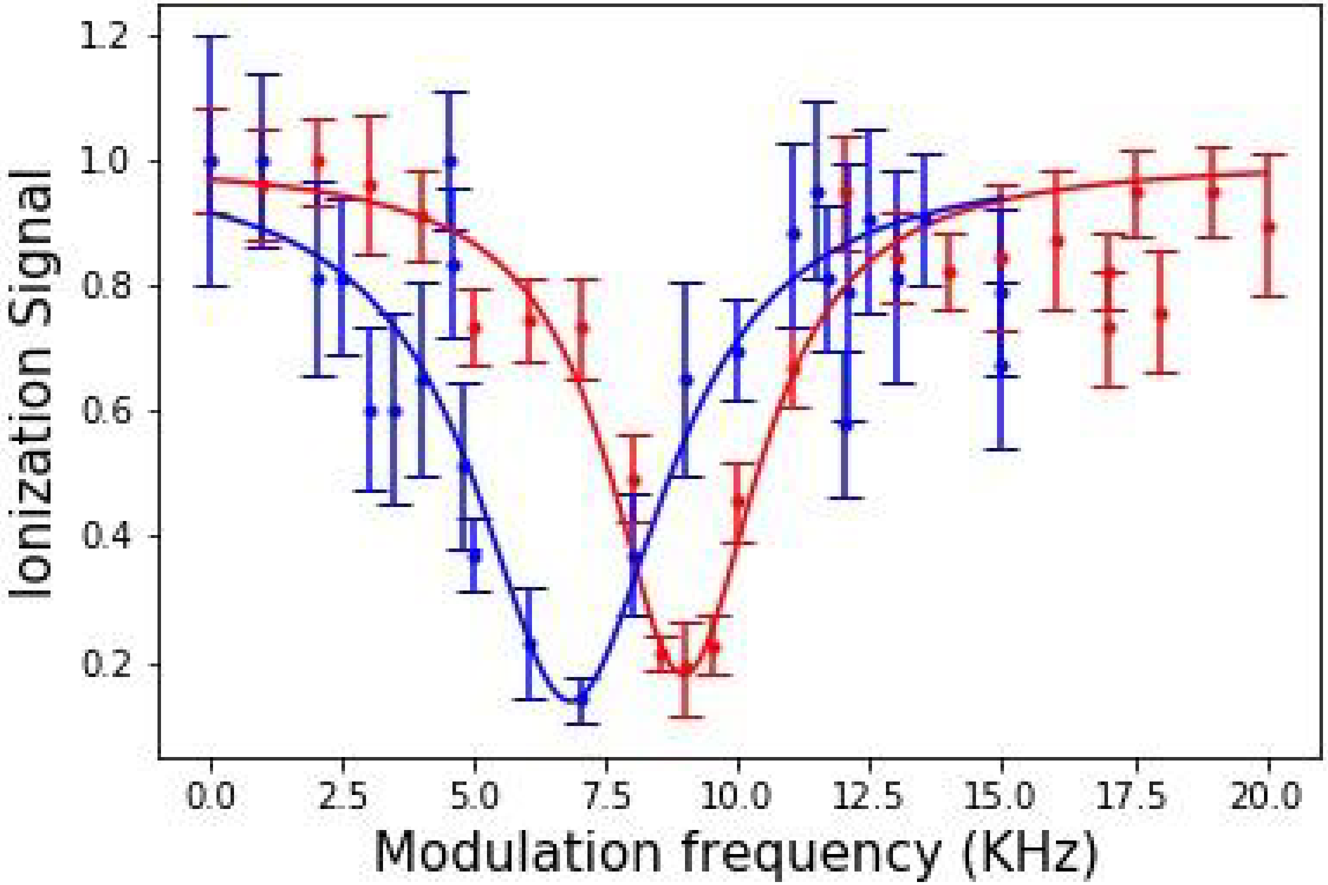
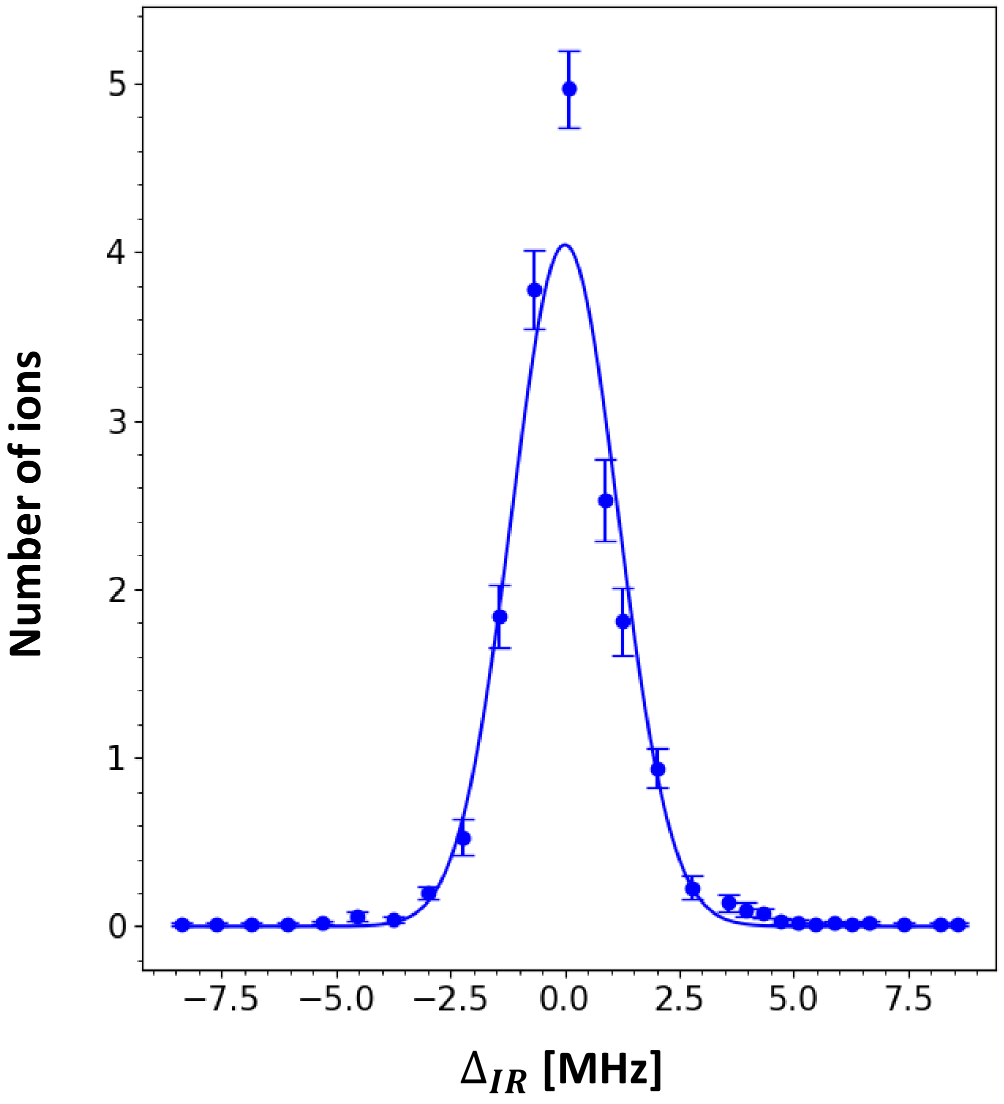
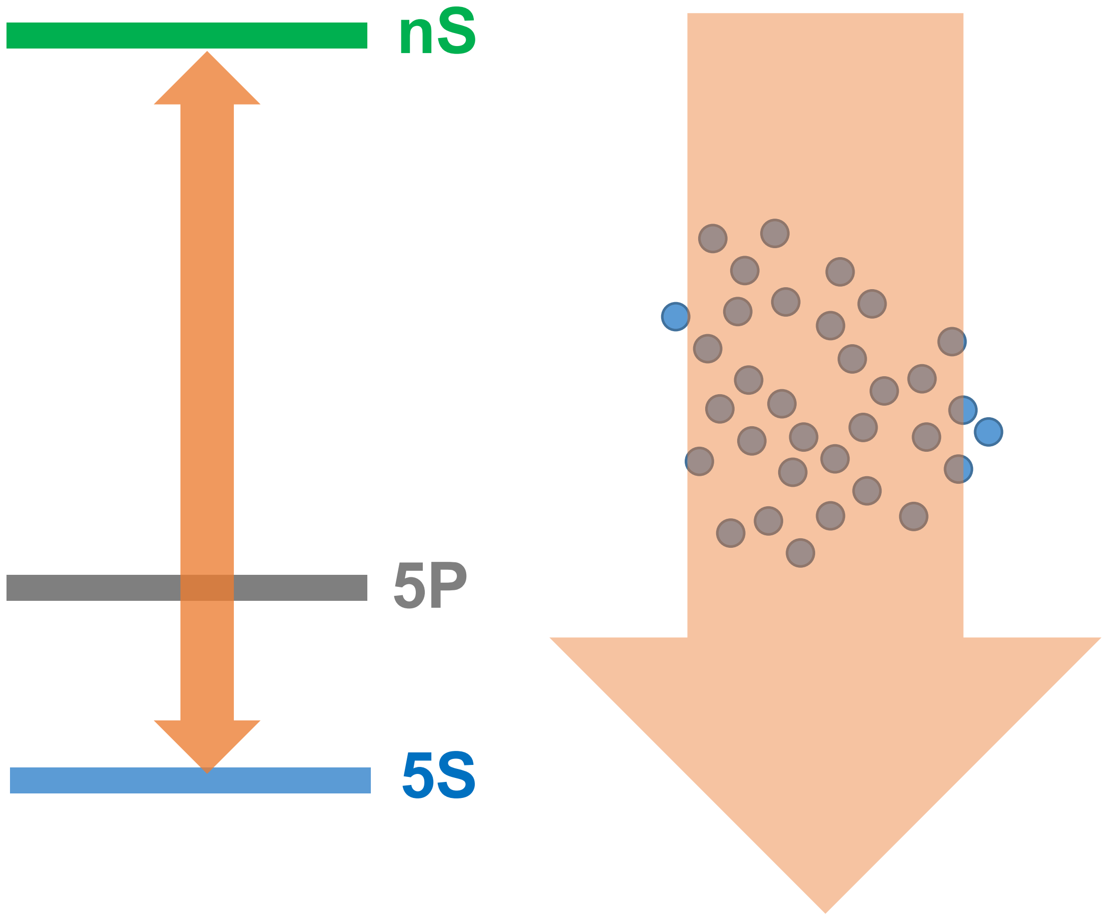


- Can realiably detect very small numbers of atoms due to high ion detection efficiency

Characterizing the dipole trap using Rydberg excitations





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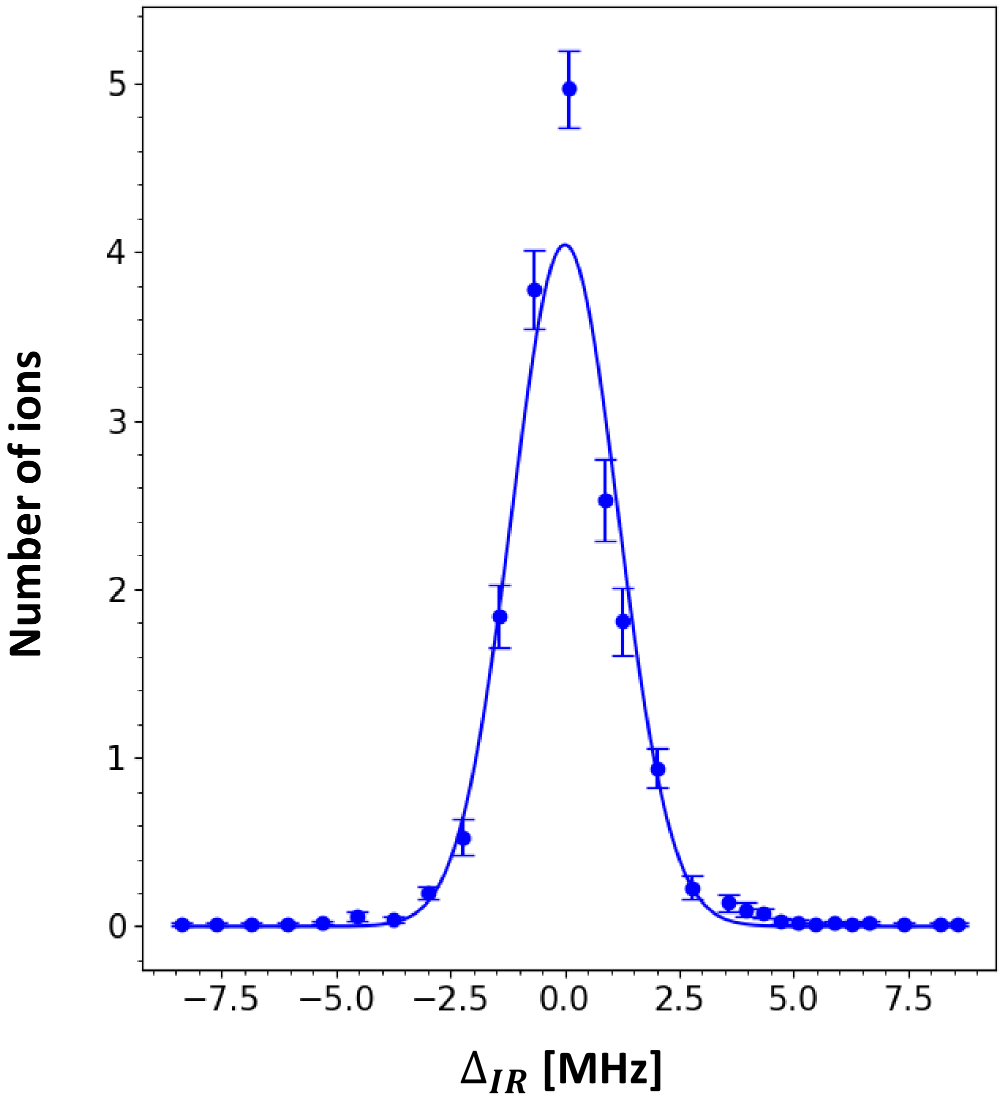

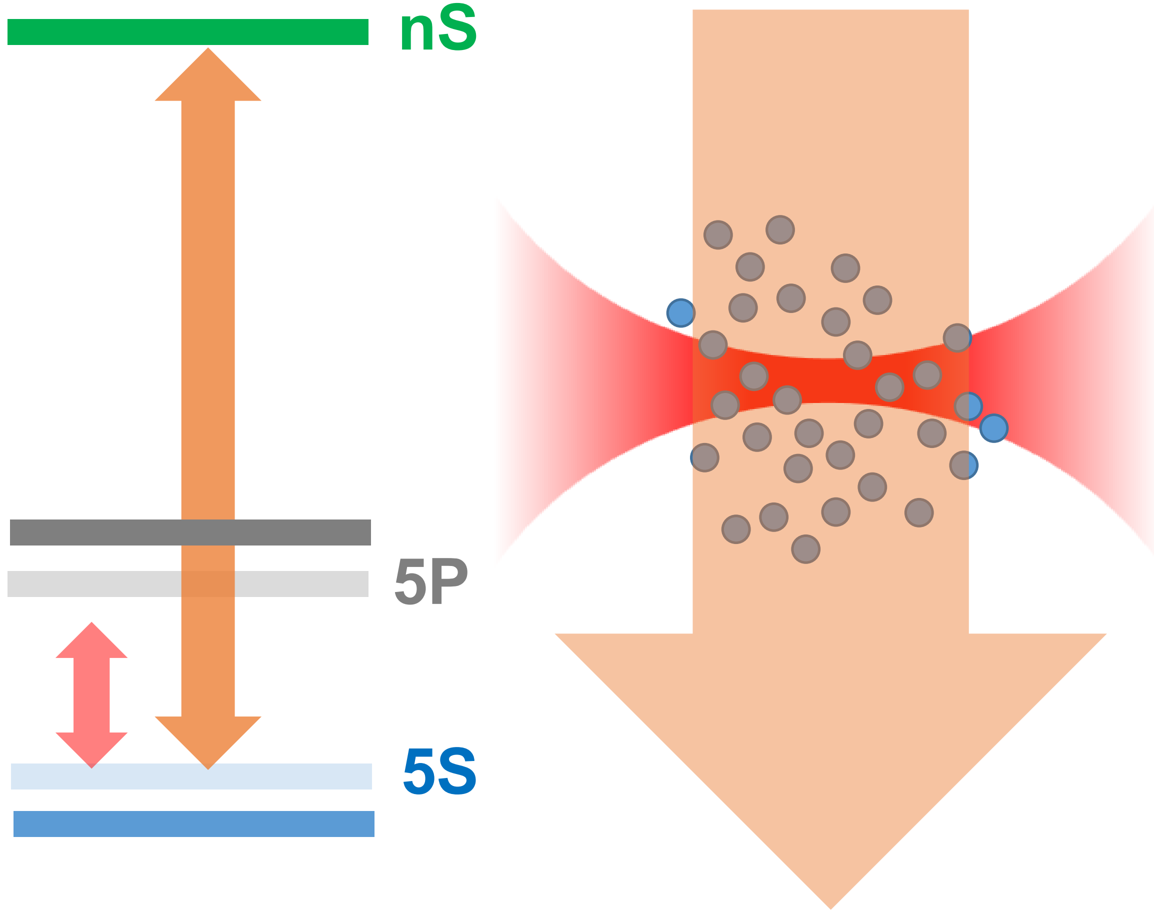

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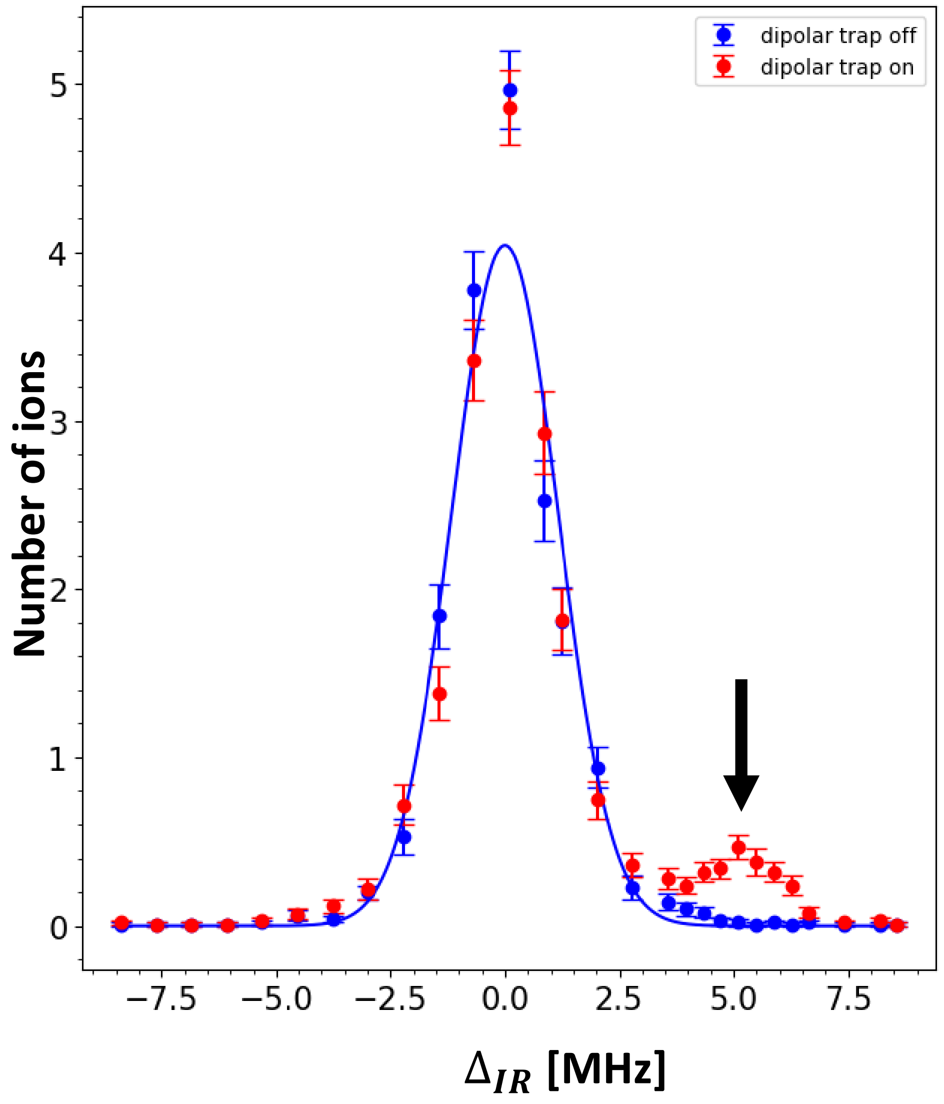

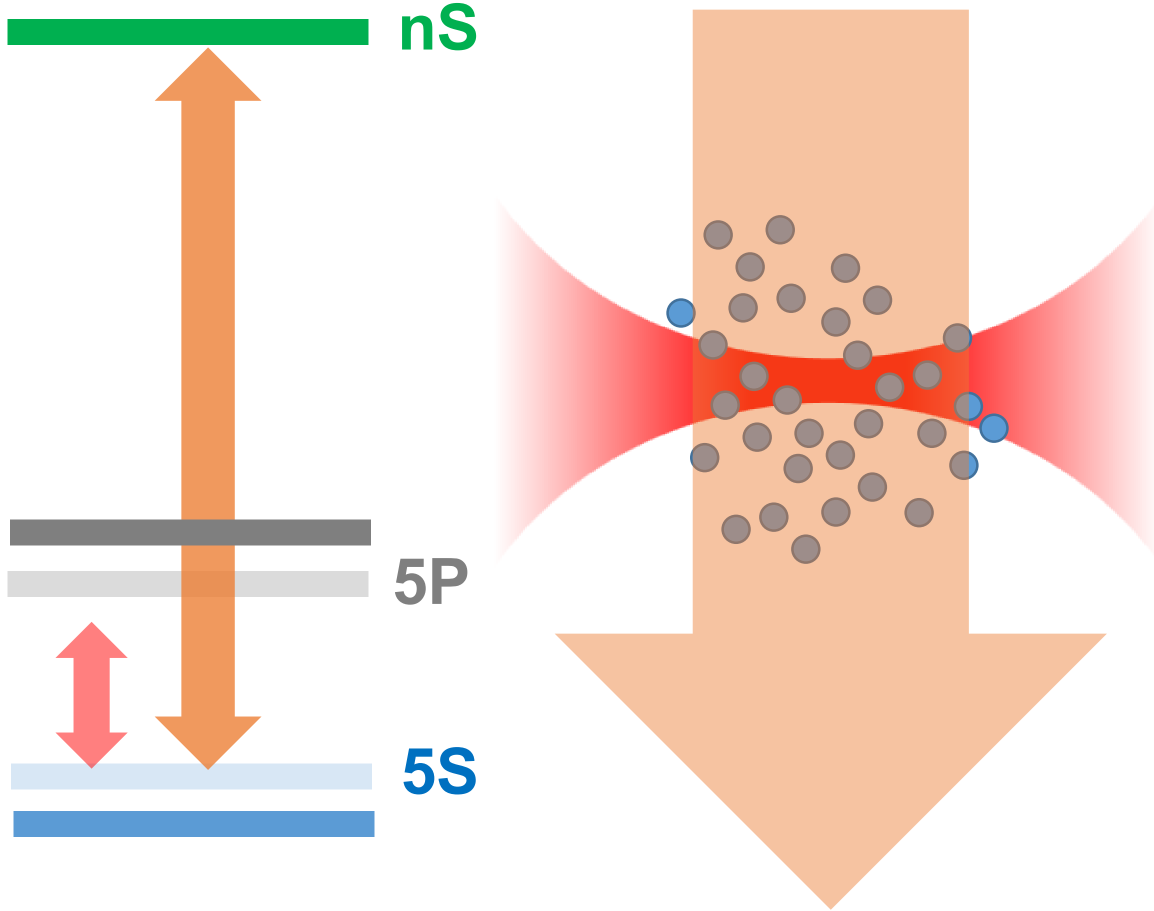

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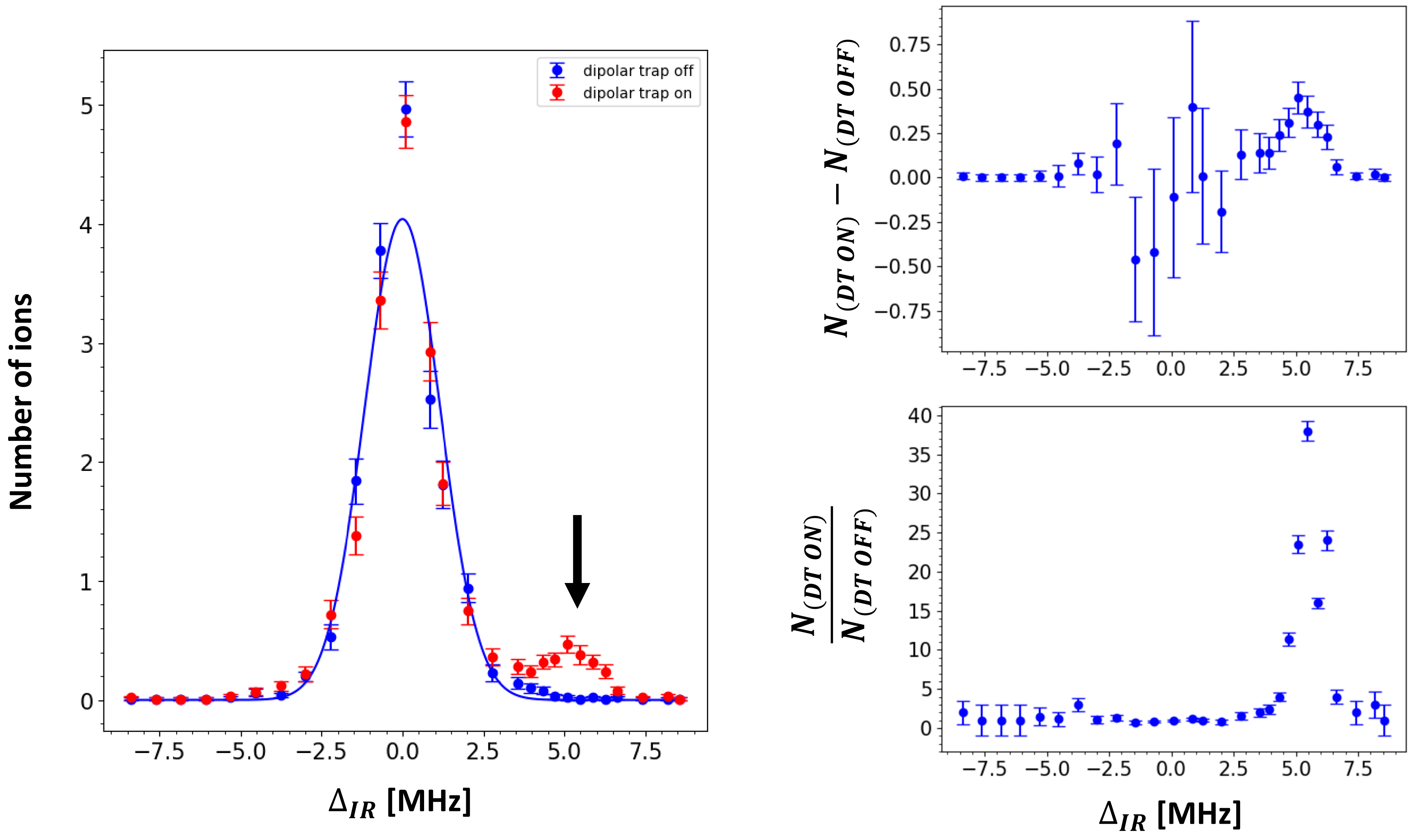
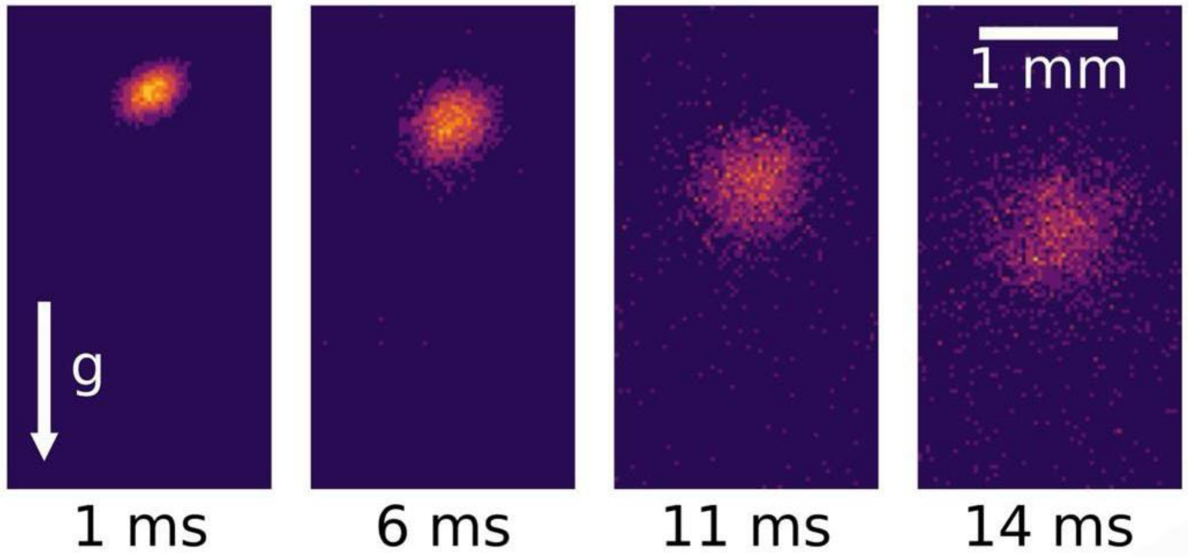


Measuring atom temperature using Rydberg excitation



R. Hobson et al, Rev. A**101**, 013420 (2020)

standard method: time-of-flight $\rightarrow$ map momentum distribution to spatial distribution

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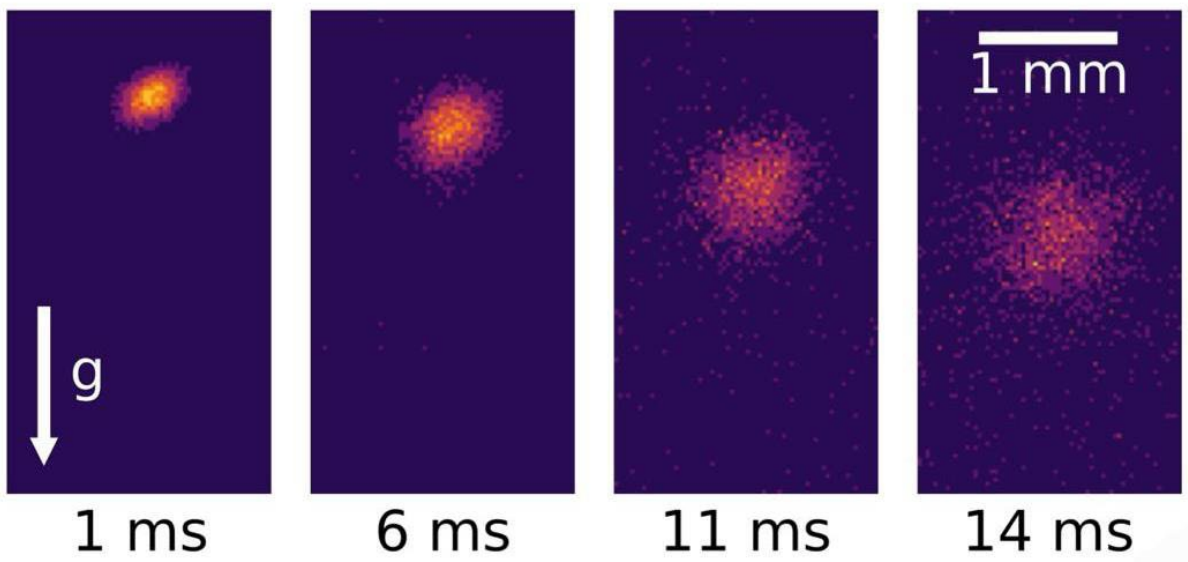


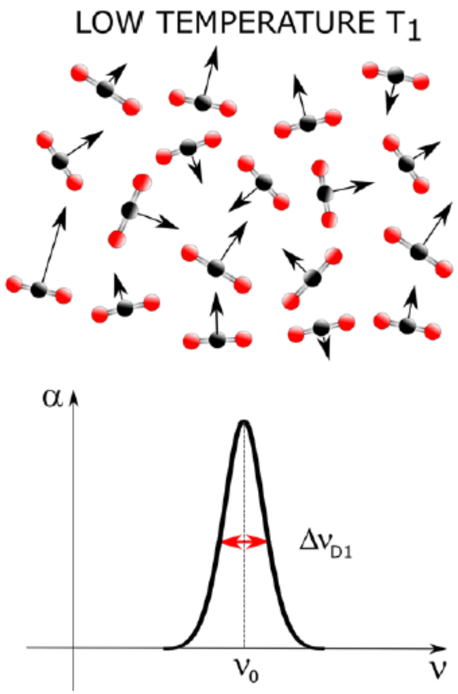
R. Hobson et al, Rev. A**101**, 013420 (2020)

standard method: time-of-flight $\rightarrow$ map momentum distribution to spatial distribution

drawbacks: need to know initial spatial distribution; assumes uniform temperature in sample; doesn't work well for small atom numbers

Measuring atom temperature using Rydberg excitation

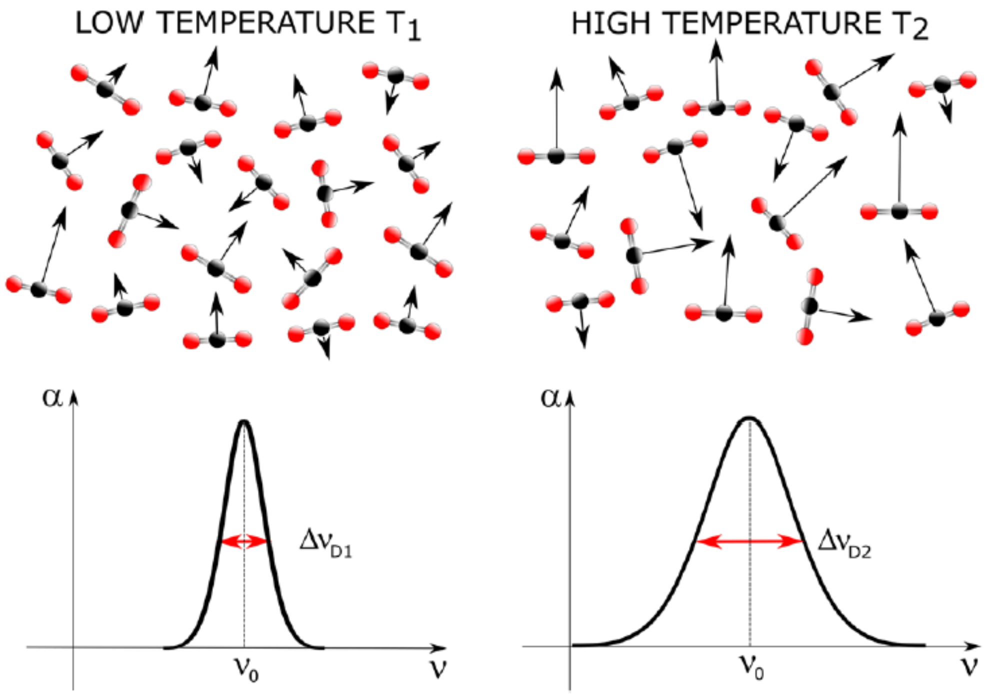
Doppler broadening



$$\Delta \nu_D = \frac{\nu_0}{c}\sqrt{\frac{2kT}{m}}$$

Measuring atom temperature using Rydberg excitation

Doppler broadening



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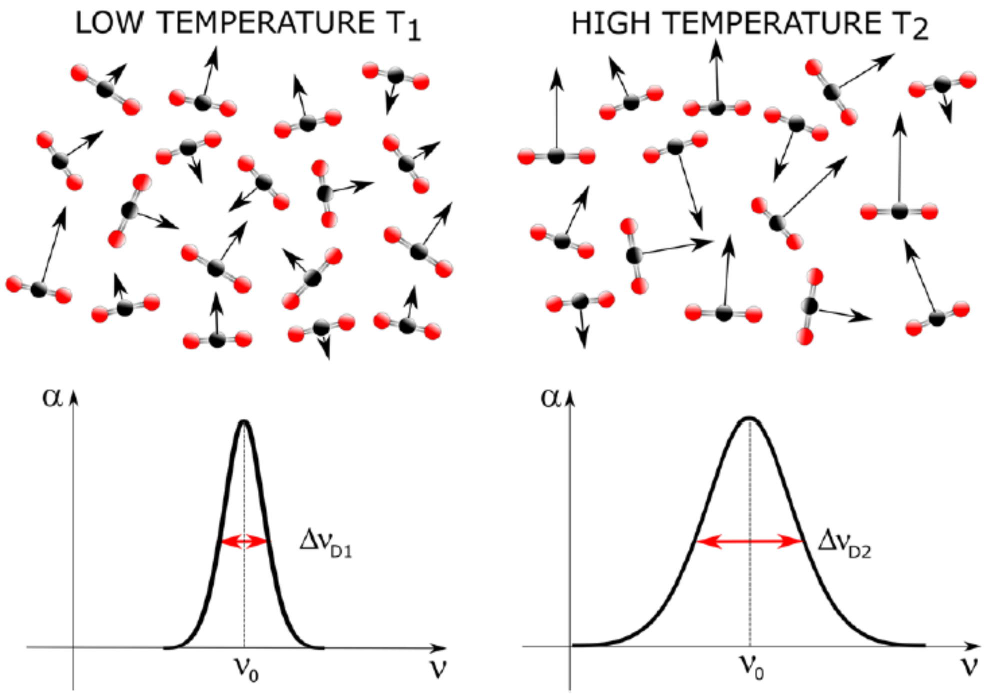

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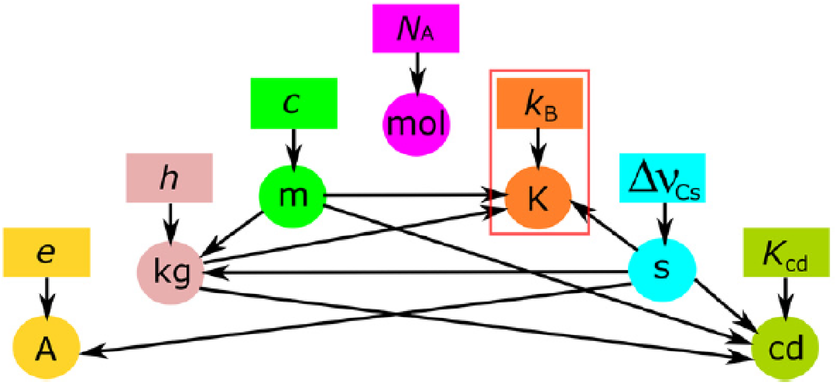


1. Introduction

1.1. The *Mise en pratique* of the new kelvin and the ITS-90 temperature scale

On November 16, 2018, the *Conférence générale des poids et mesures* (CGPM) approved the revision of the International System of Units (SI), shifting the definition of SI units from a particular property of matter of a primary sample to a direct link with a fundamental constant. Such a paradigmatic shift affected the definition of the ampere, the kilogram, the mole, and the kelvin starting from May 20, 2019.

As highlighted in Fig. 1, the kelvin, the SI unit for the absolute temperature, has been redefined in terms of a fixed value of the Boltzmann constant $k_B = 1.380\,649 \times 10^{-23}$ J K^{-1},[1] rather than as a fraction of the temperature of the triple point of water (TPW). Since

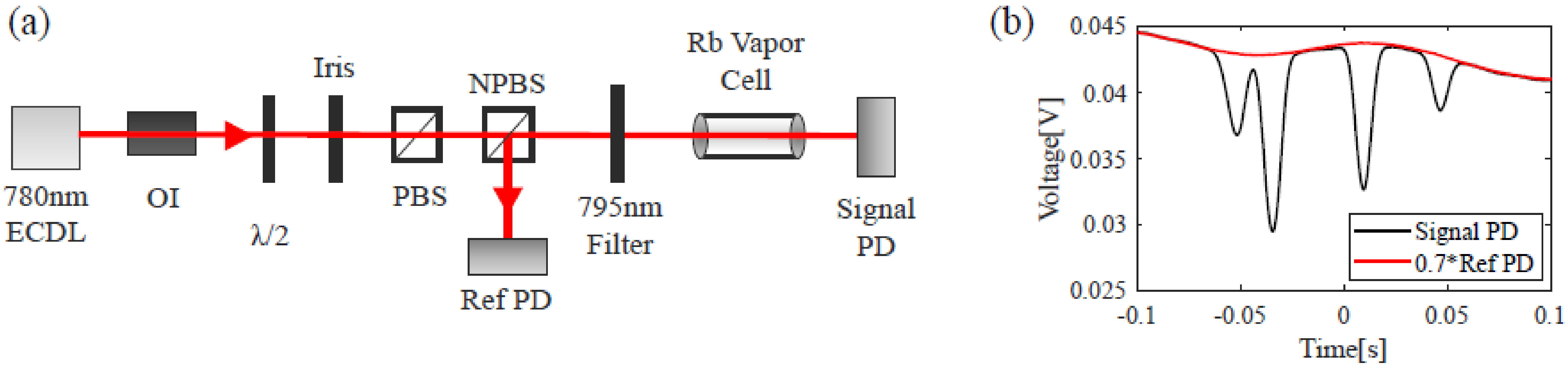
Journal of Physical and Chemical Reference Data ARTICLE scitation.org/journal/jpr

Laser-Based Primary Thermometry: A Review

Cite as: J. Phys. Chem. Ref. Data 50, 031501 (2021); doi: 10.1063/5.0055297
Submitted: 27 April 2021 • Accepted: 3 August 2021 •
Published Online: 7 September 2021

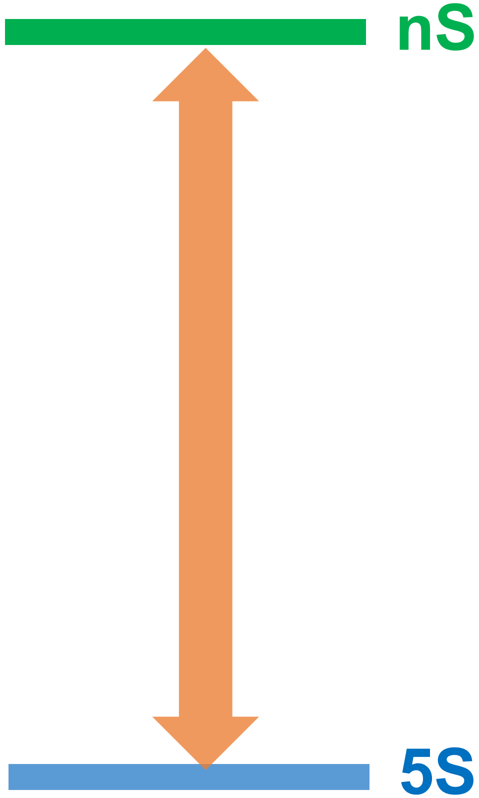
R. Gotti,[a] M. Lamperti, D. Gatti, and M. Marangoni[a]

Measuring atom temperature using Rydberg excitation



measurement of Doppler broadening at room temperature ↔ measurement of temperature

Measuring atom temperature using Rydberg excitation



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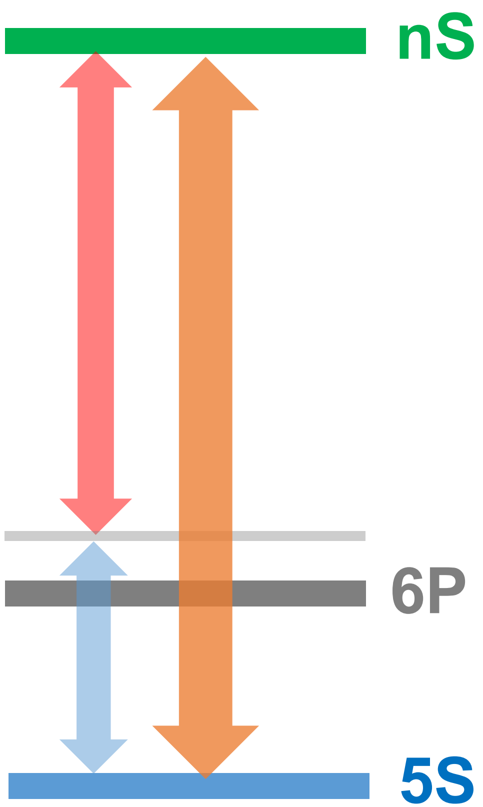
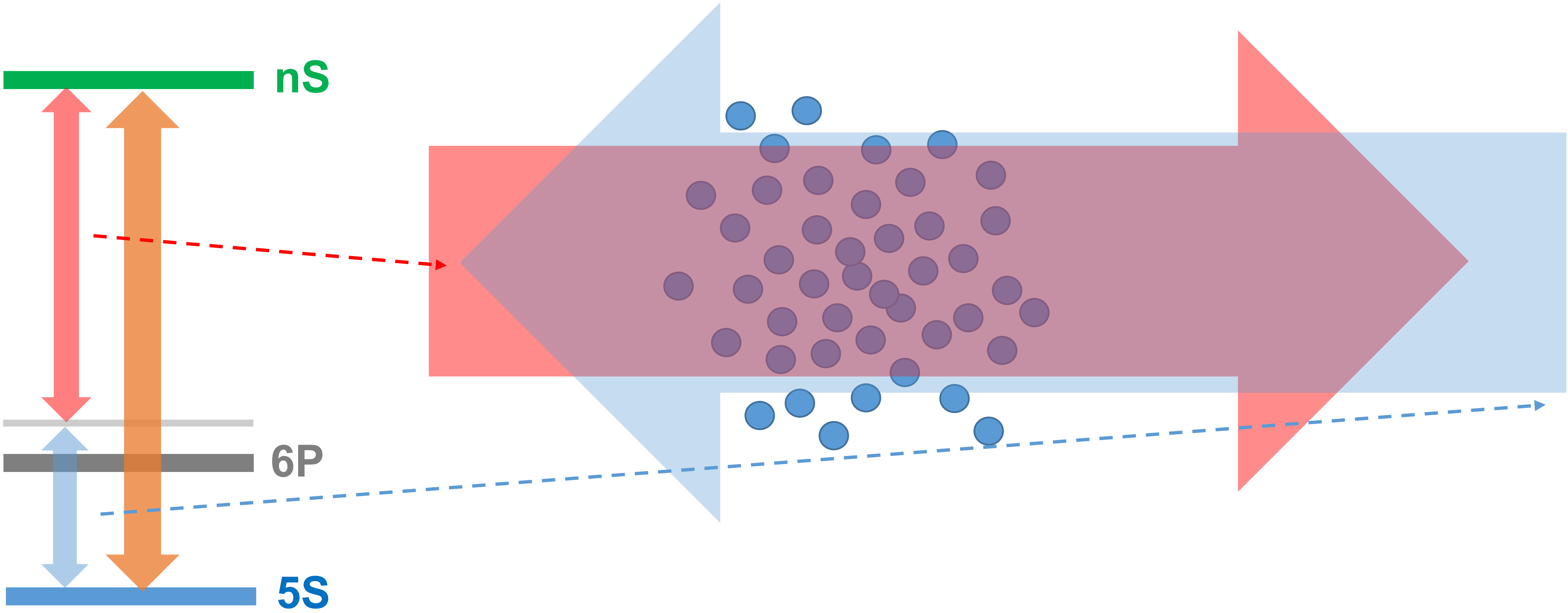


Two-photon Rydberg excitation

Measuring atom temperature using Rydberg excitation



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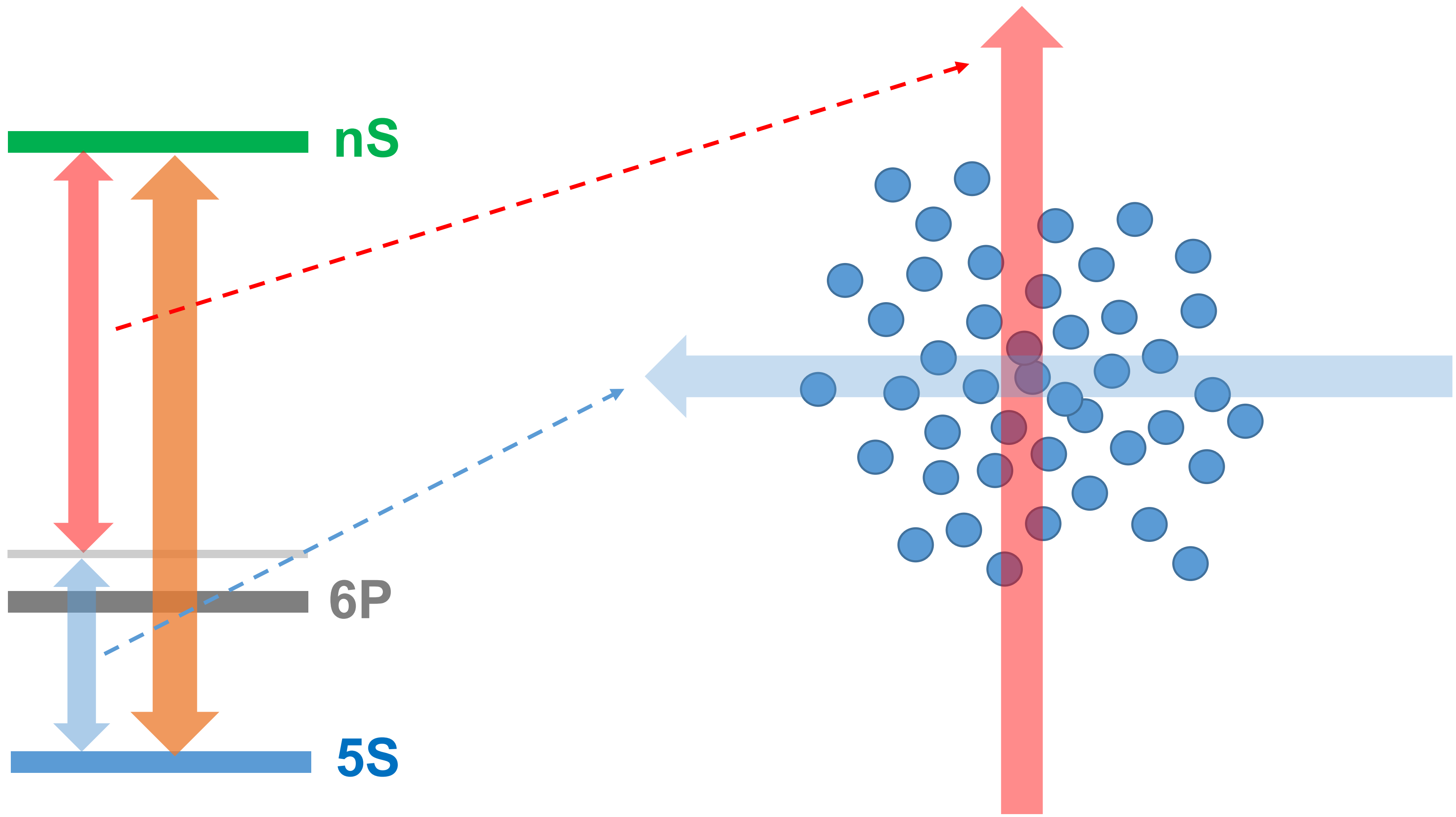
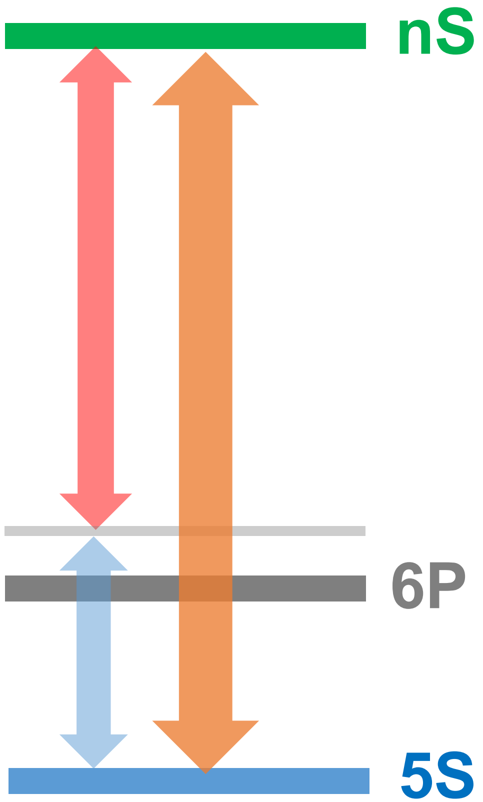


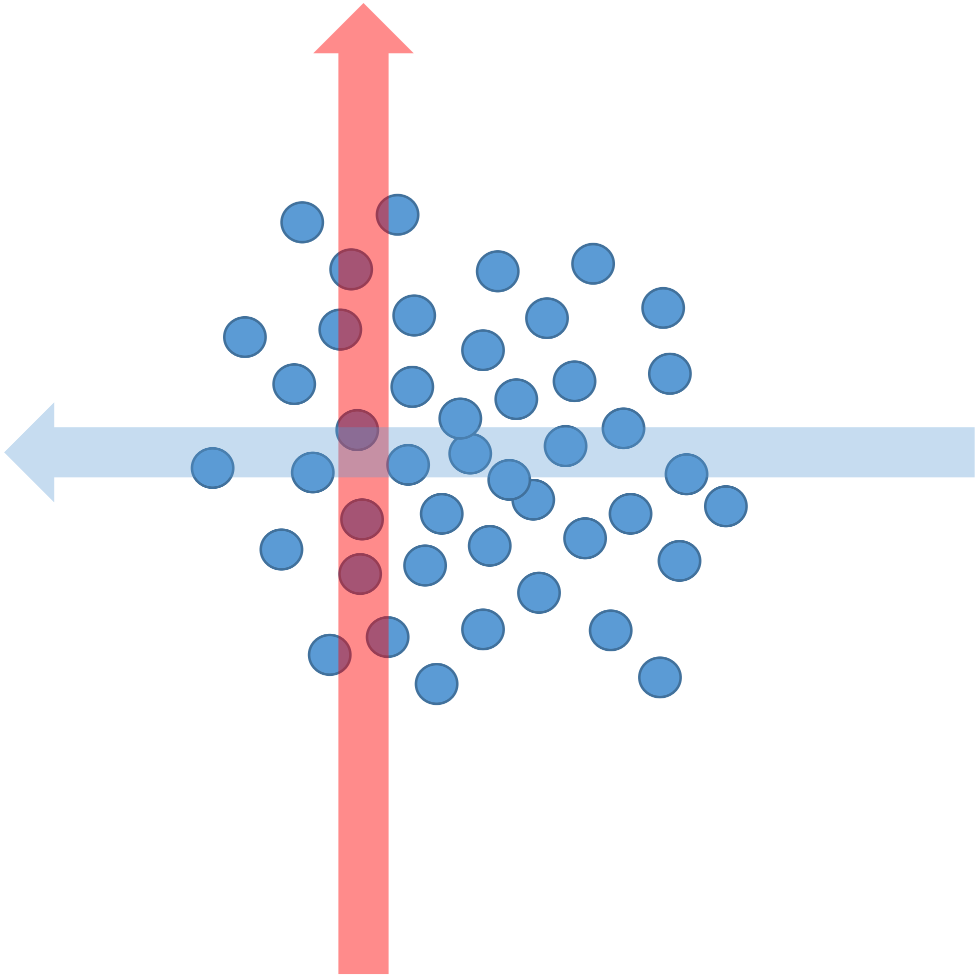
Two-photon Rydberg excitation

spatially selective excitation (30 microns)

Measuring atom temperature using Rydberg excitation

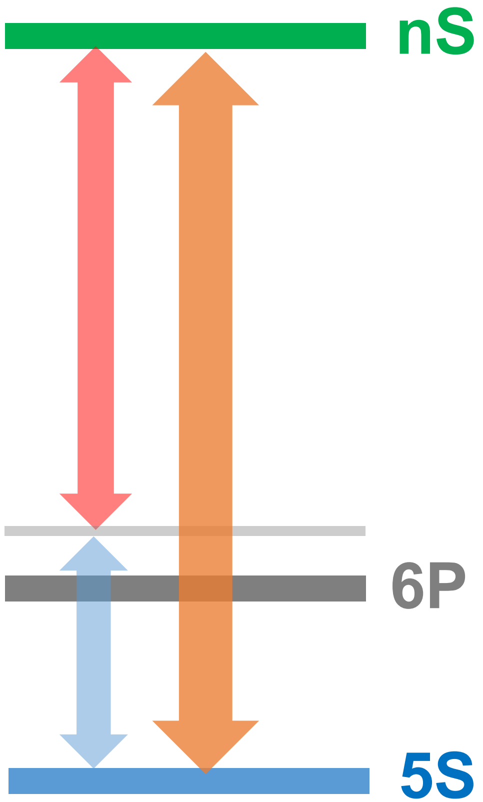


Two-photon Rydberg excitation

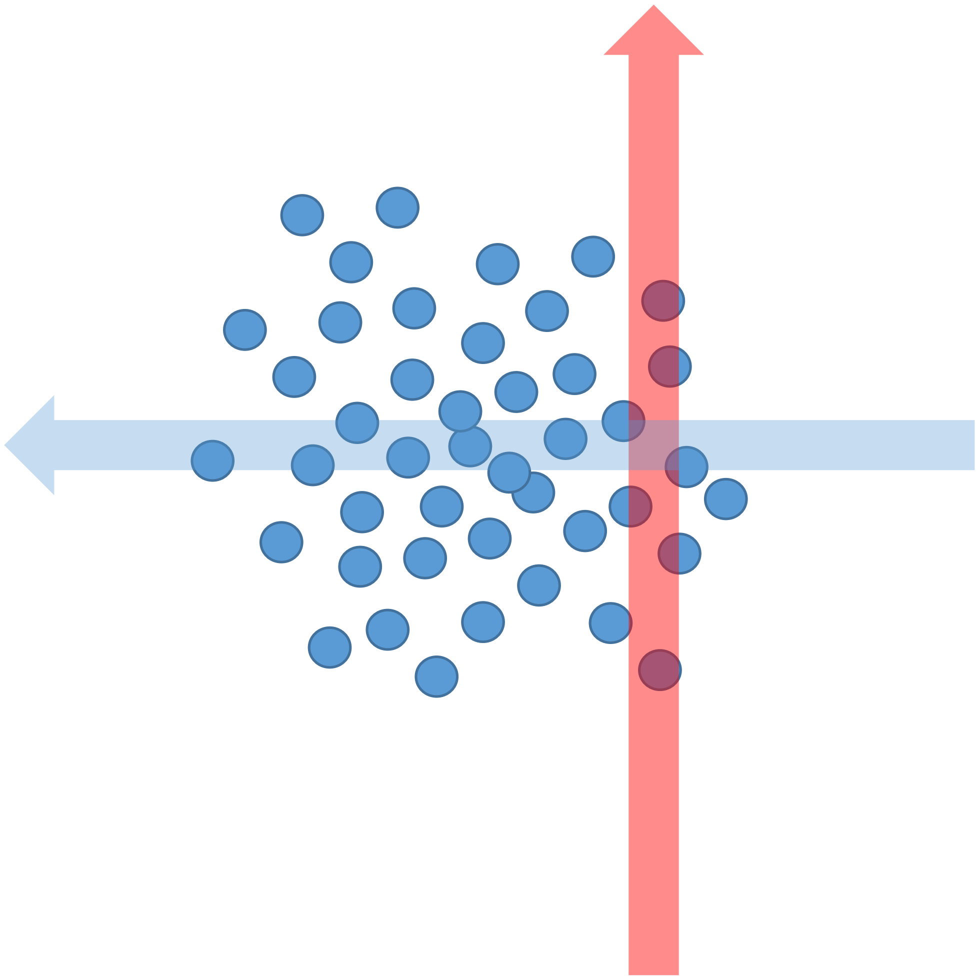


spatially selective excitation (20 microns)

Measuring atom temperature using Rydberg excitation

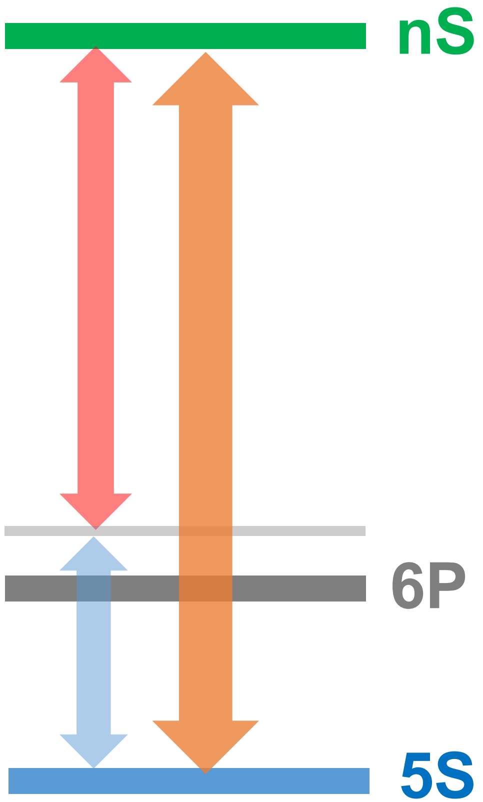


Two-photon Rydberg excitation

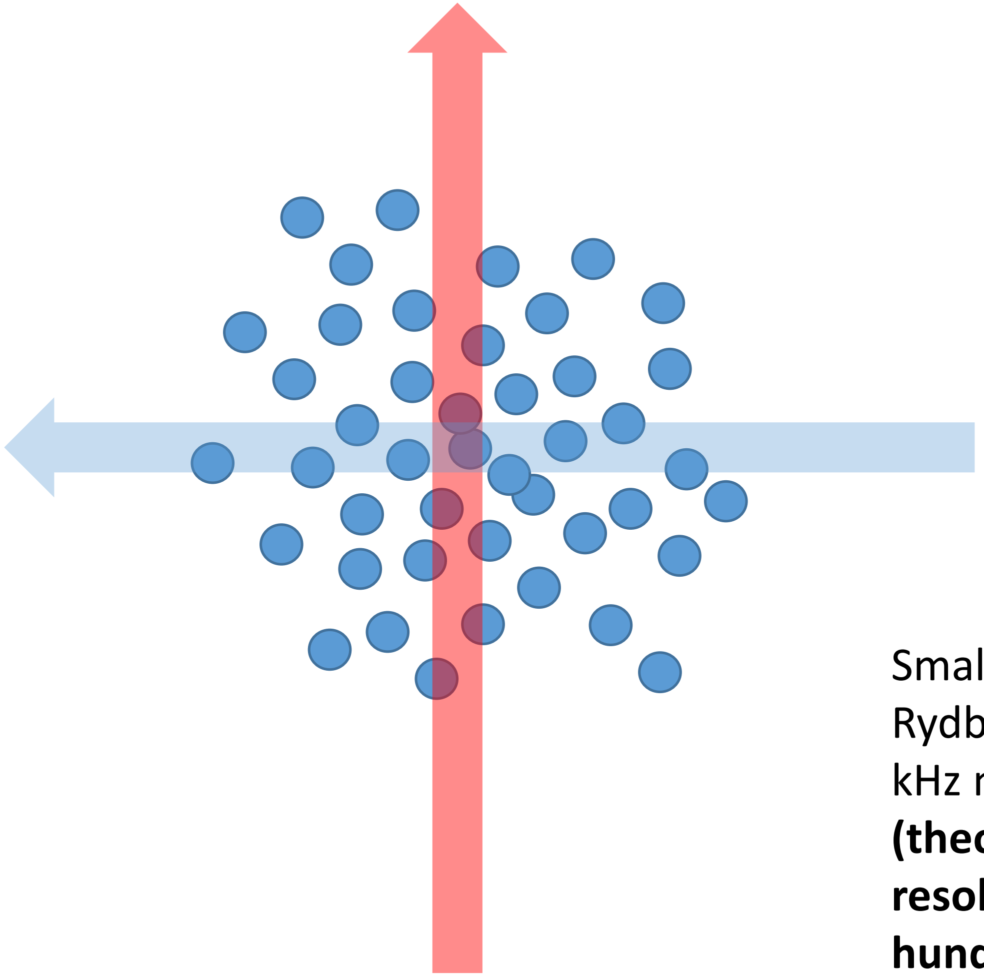


spatially selective excitation (30 microns)

Measuring atom temperature using Rydberg excitation



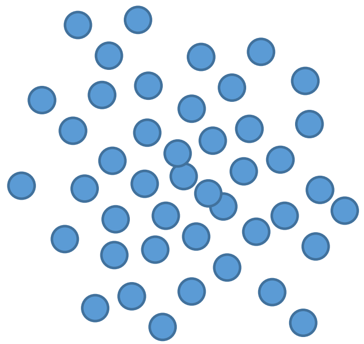
Two-photon Rydberg excitation



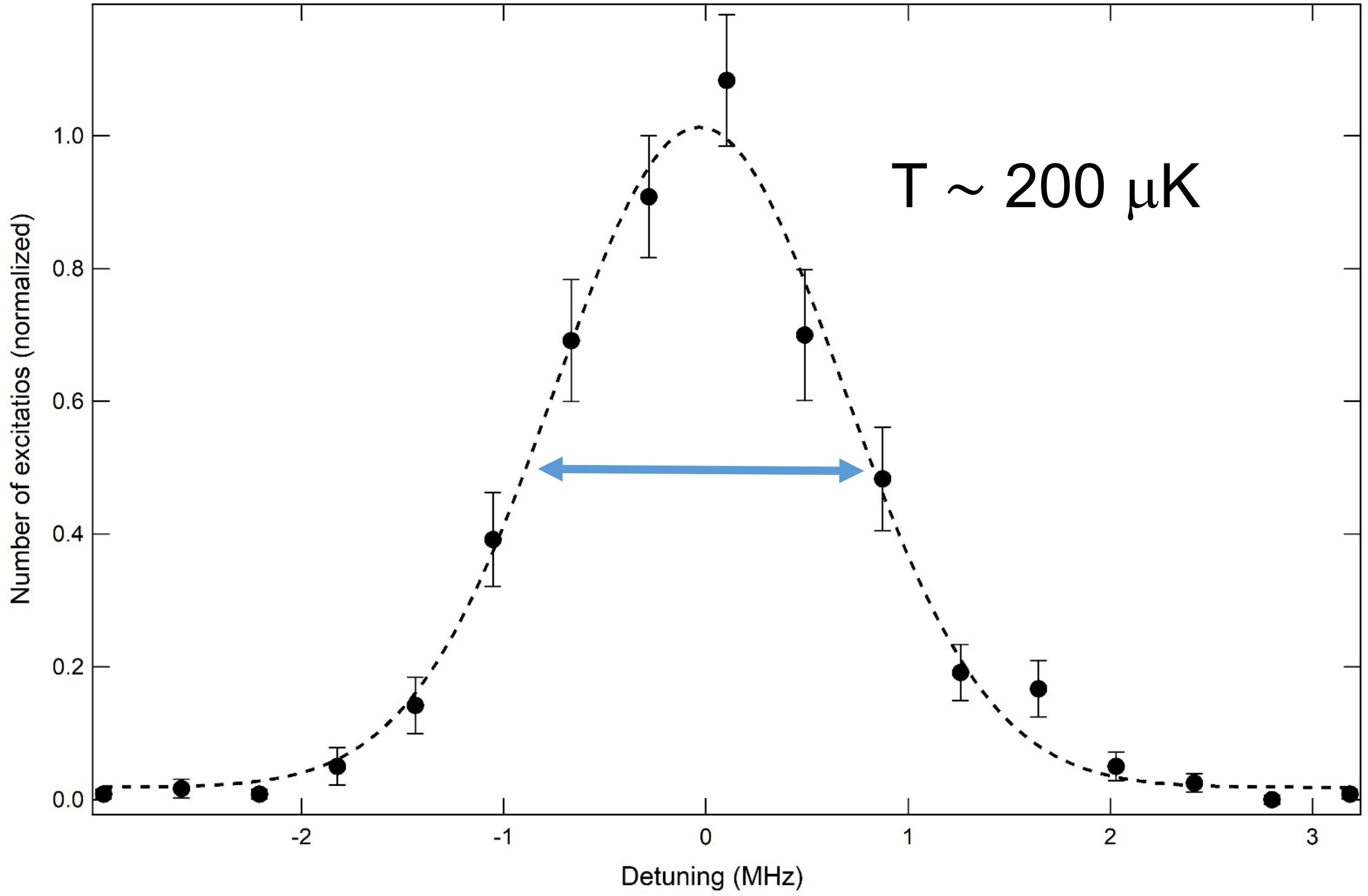
spatially selective excitation (30 microns)

Small intrinsic linewidth of Rydberg transition of a few kHz means **good (theoretical) temperature resolution down to a few hundred nK!**

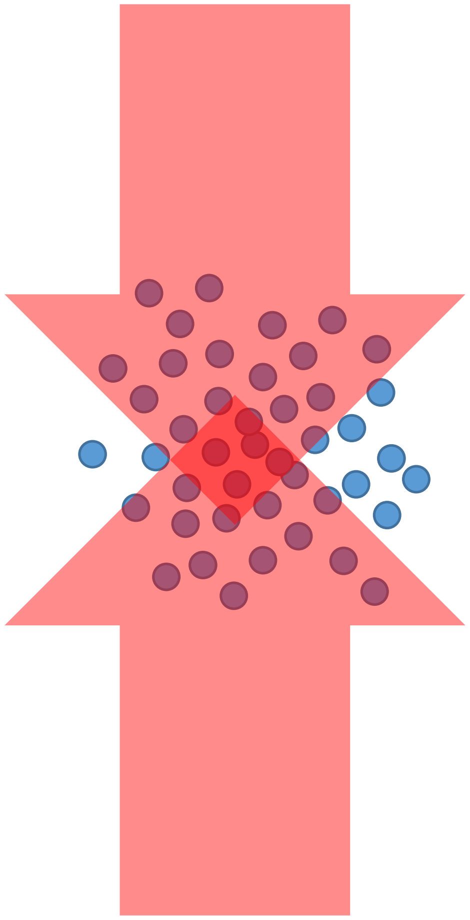
Measuring atom temperature using Rydberg excitation

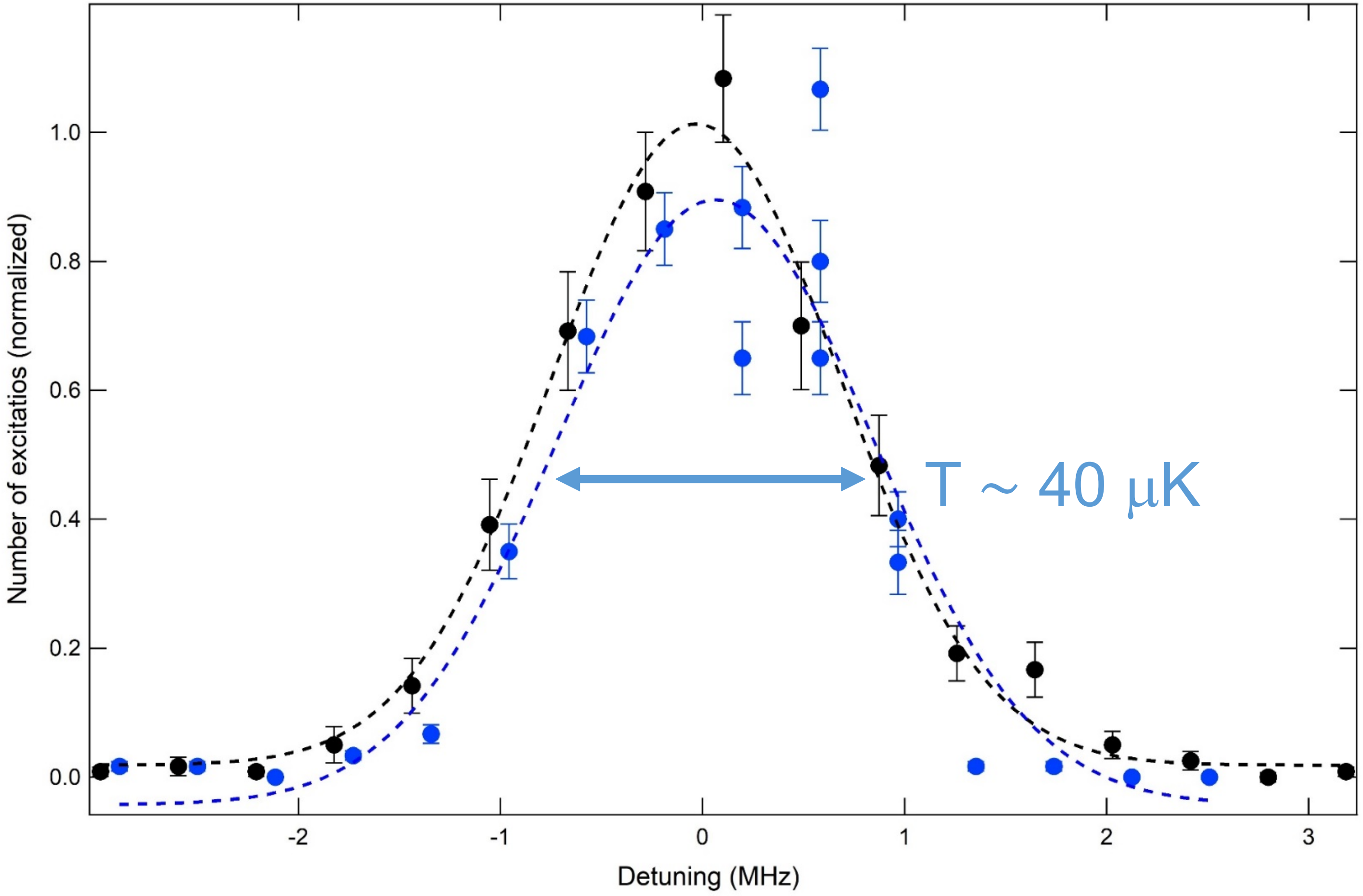


atoms in MOT



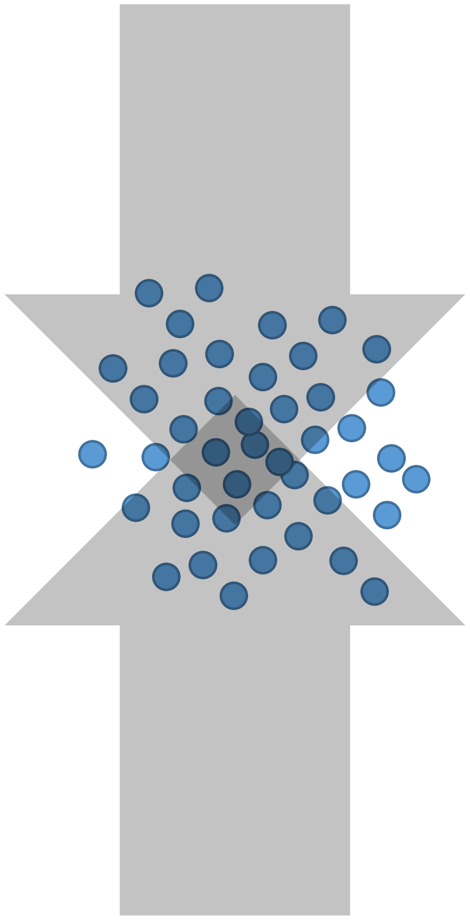
Measuring atom temperature using Rydberg excitation



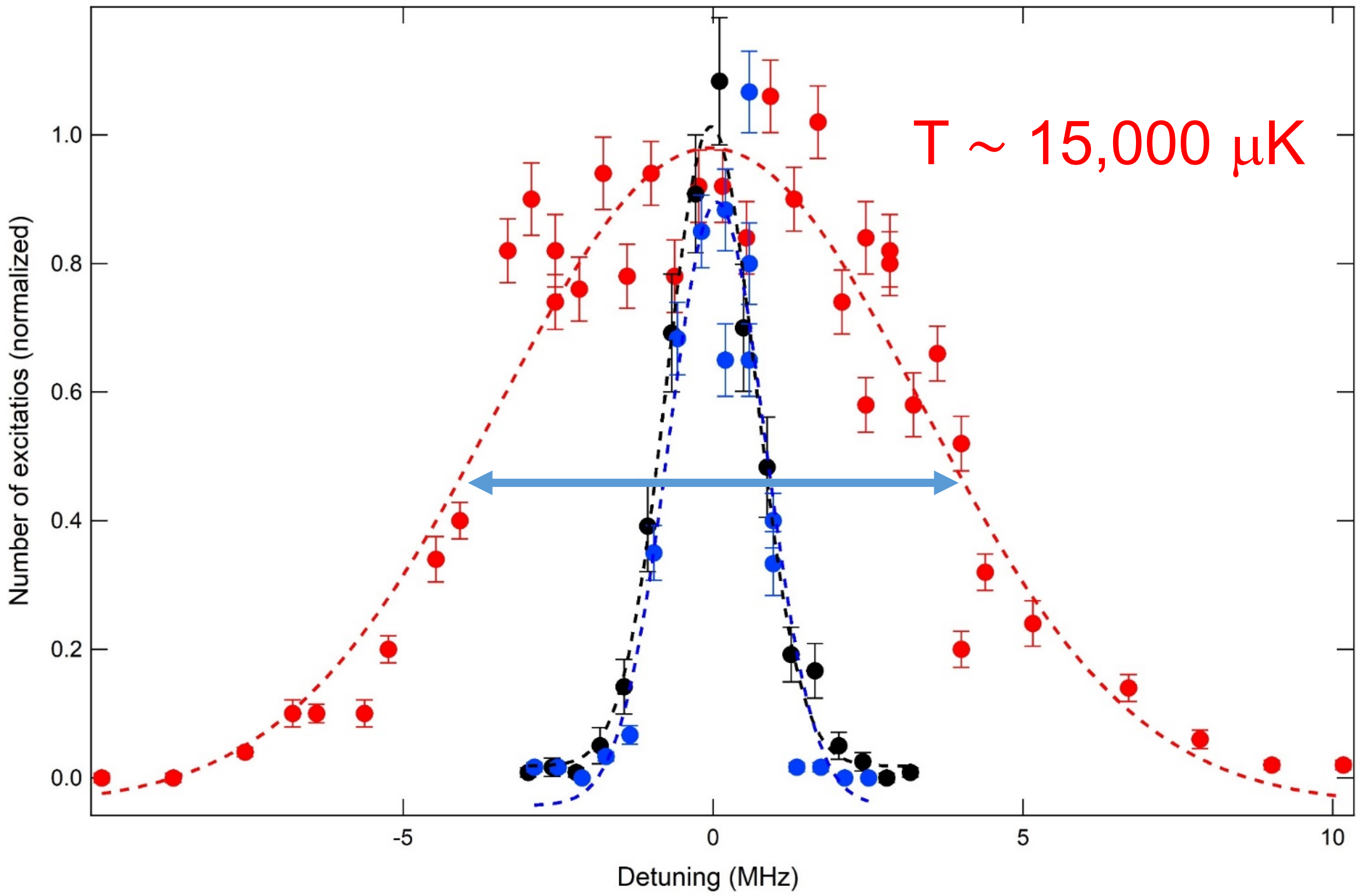


optical molasses cooling

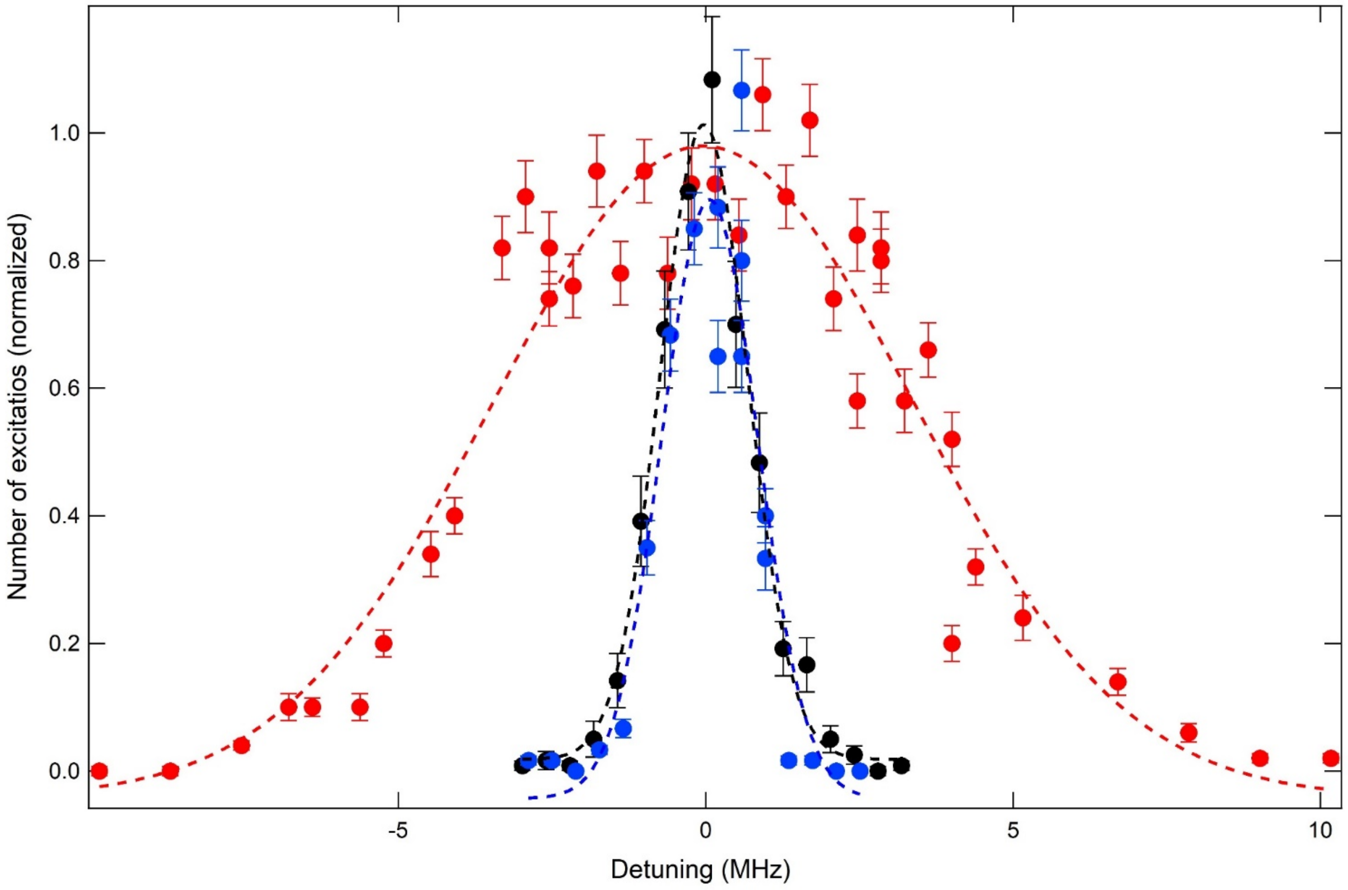
Measuring atom temperature using Rydberg excitation

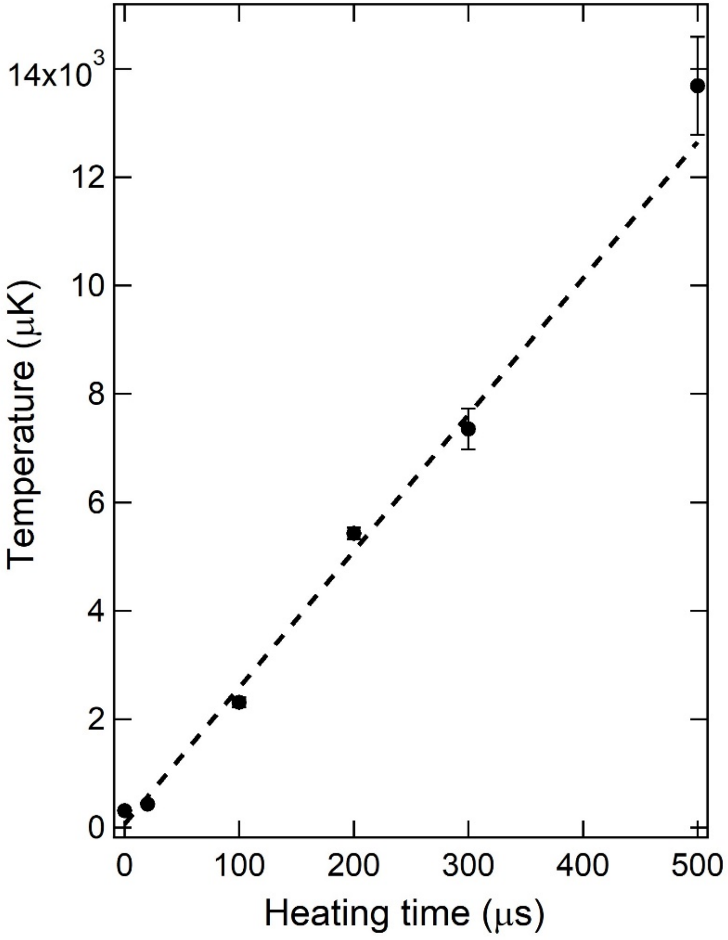


resonant heating

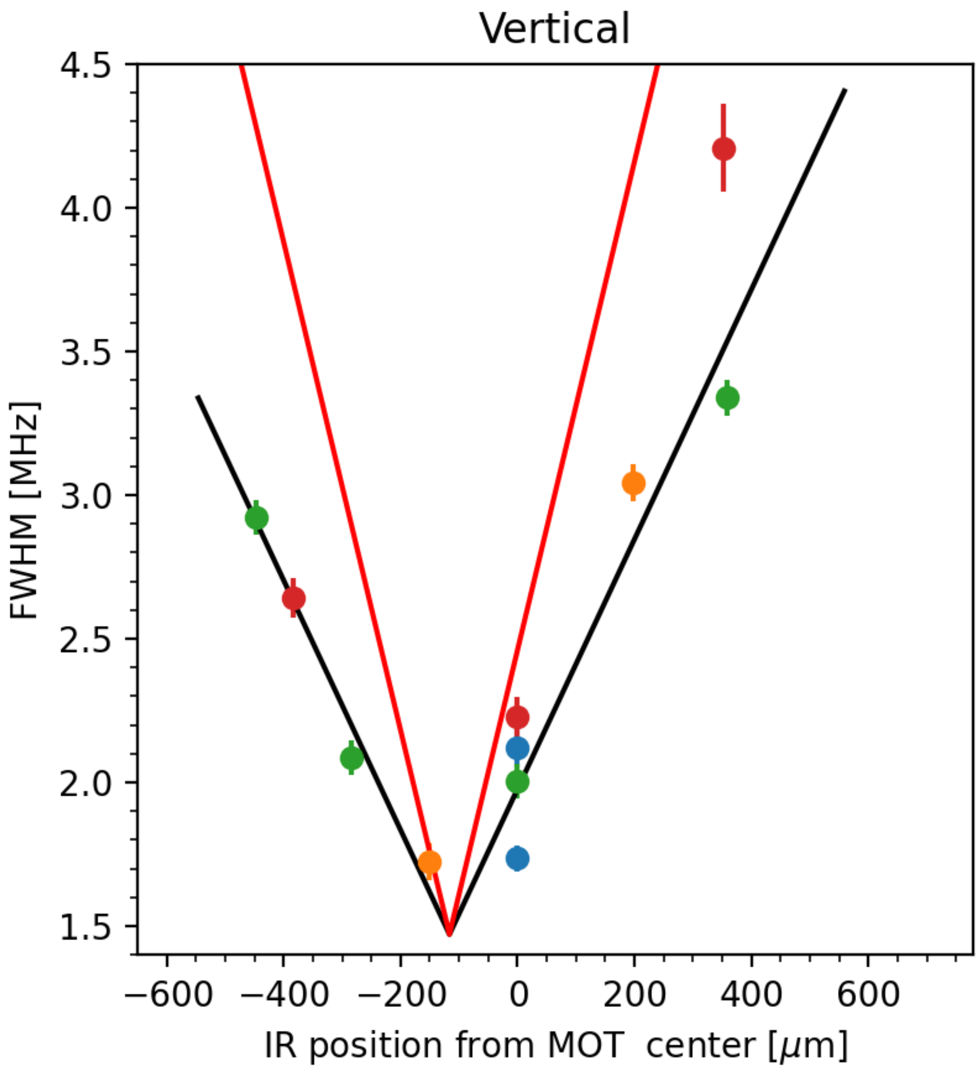


Measuring atom temperature using Rydberg excitation





How do we know that we are measuring local temperature?



- Leave magnetic field switched on and measure total broadening, including Zeeman shift due to locally varying magnetic field (linear gradient)

- centre of MOT does not coincide with zero of magnetic field (probably due to imbalanced MOT beams)

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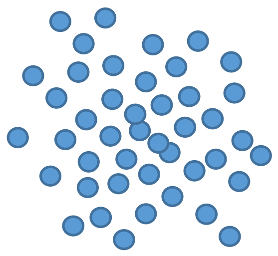

atoms in MOT or optical molasses

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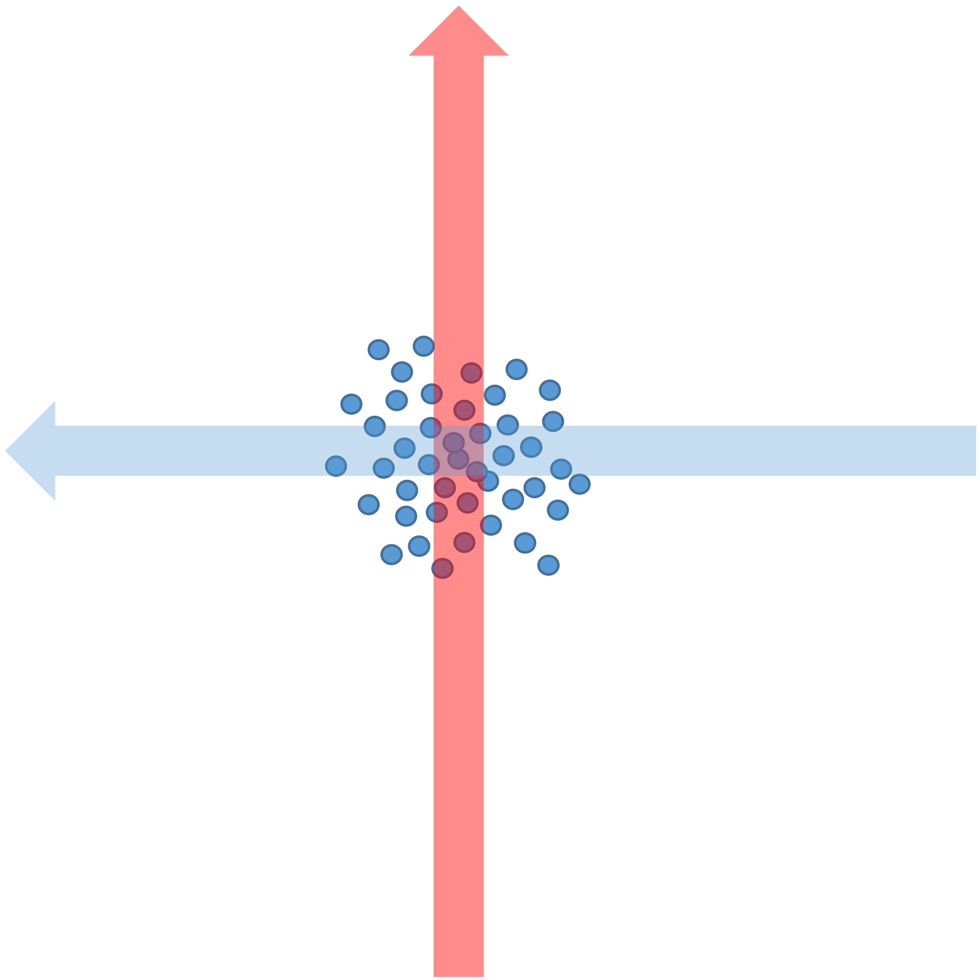

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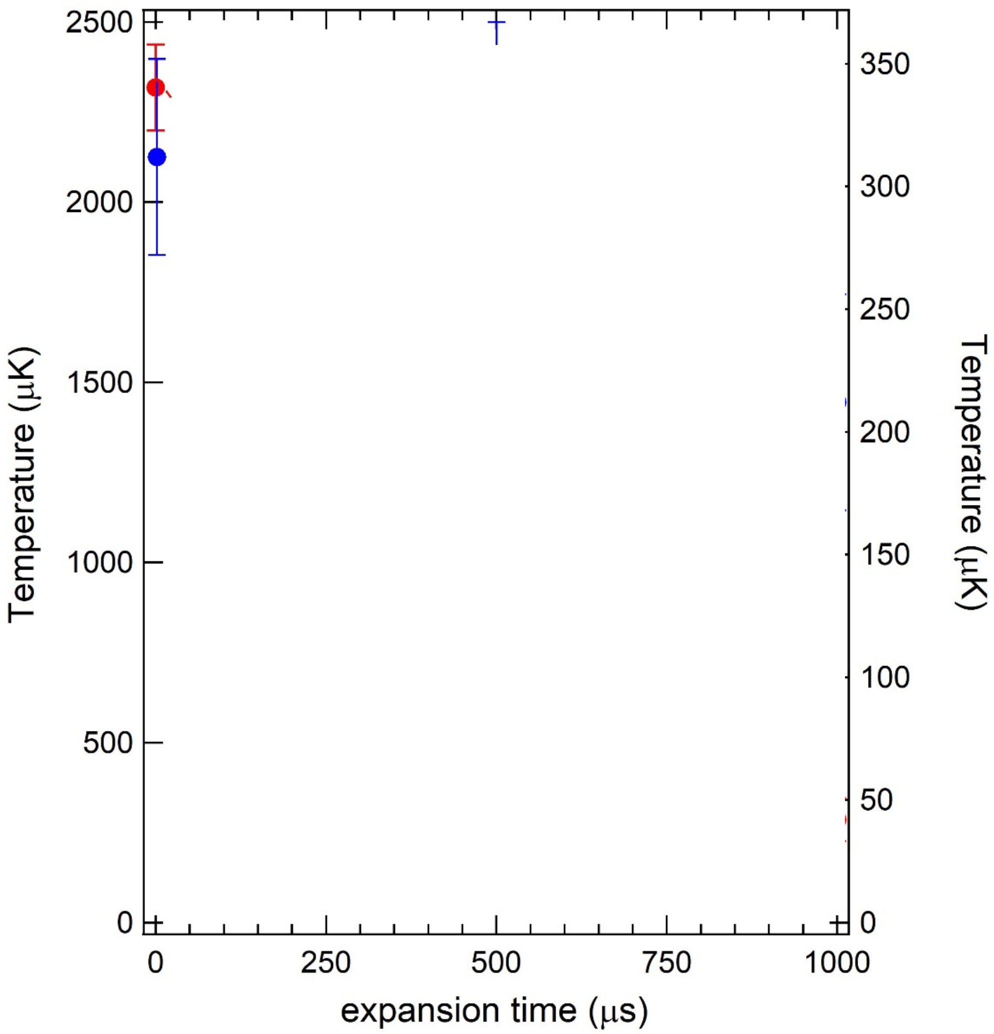

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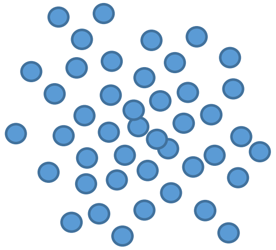
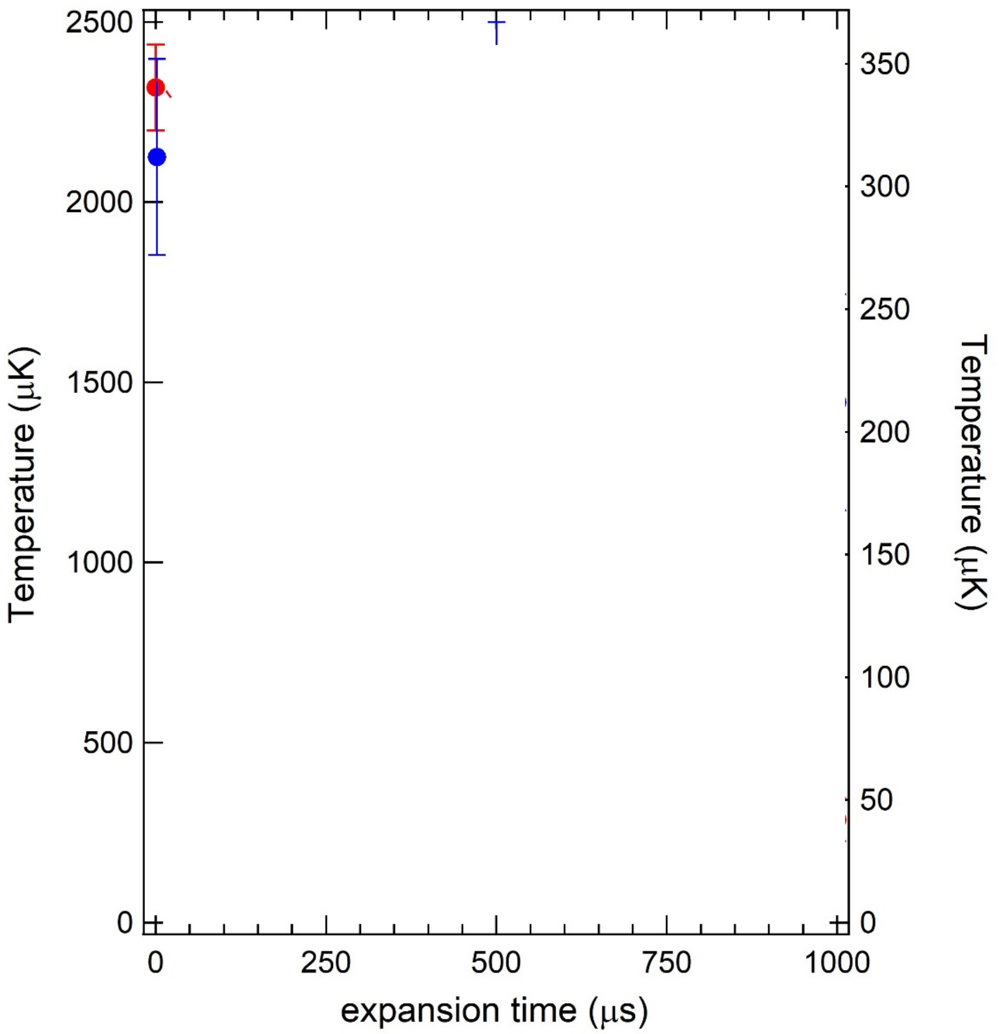


ballistic expansion



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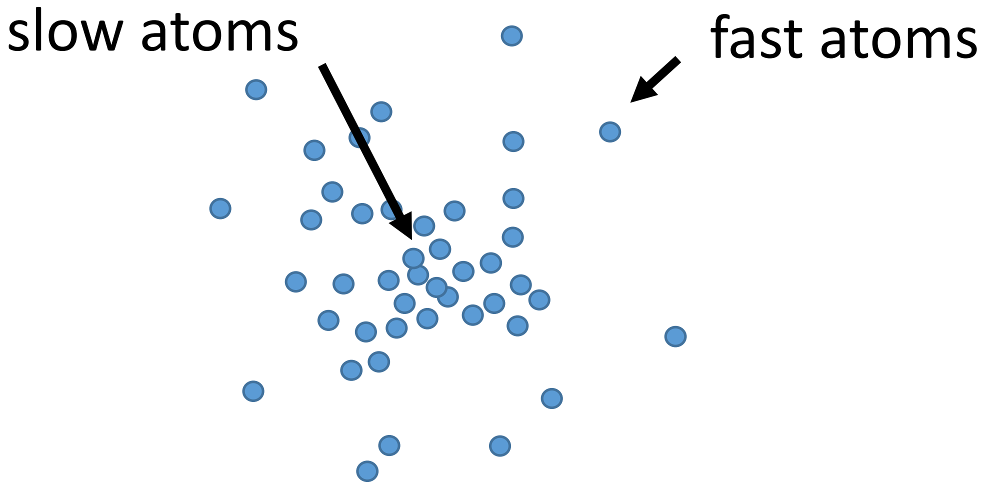

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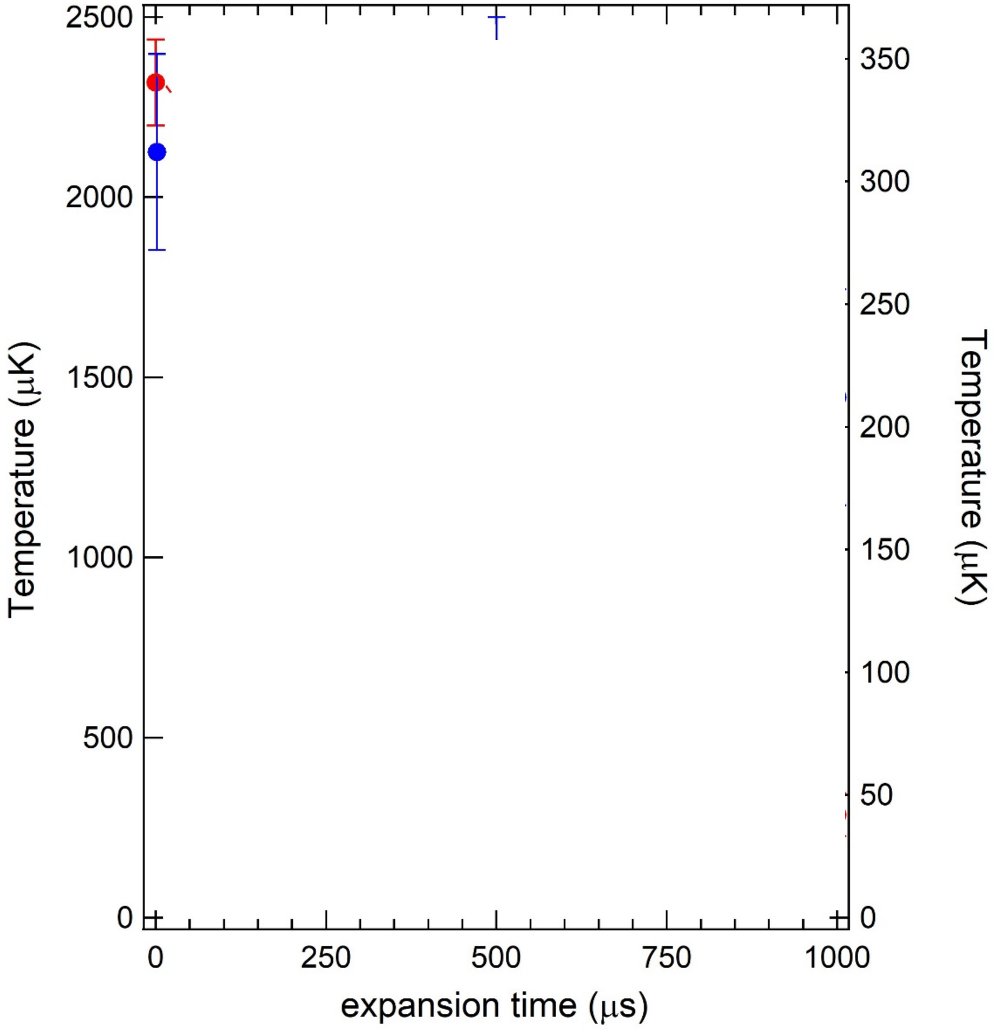

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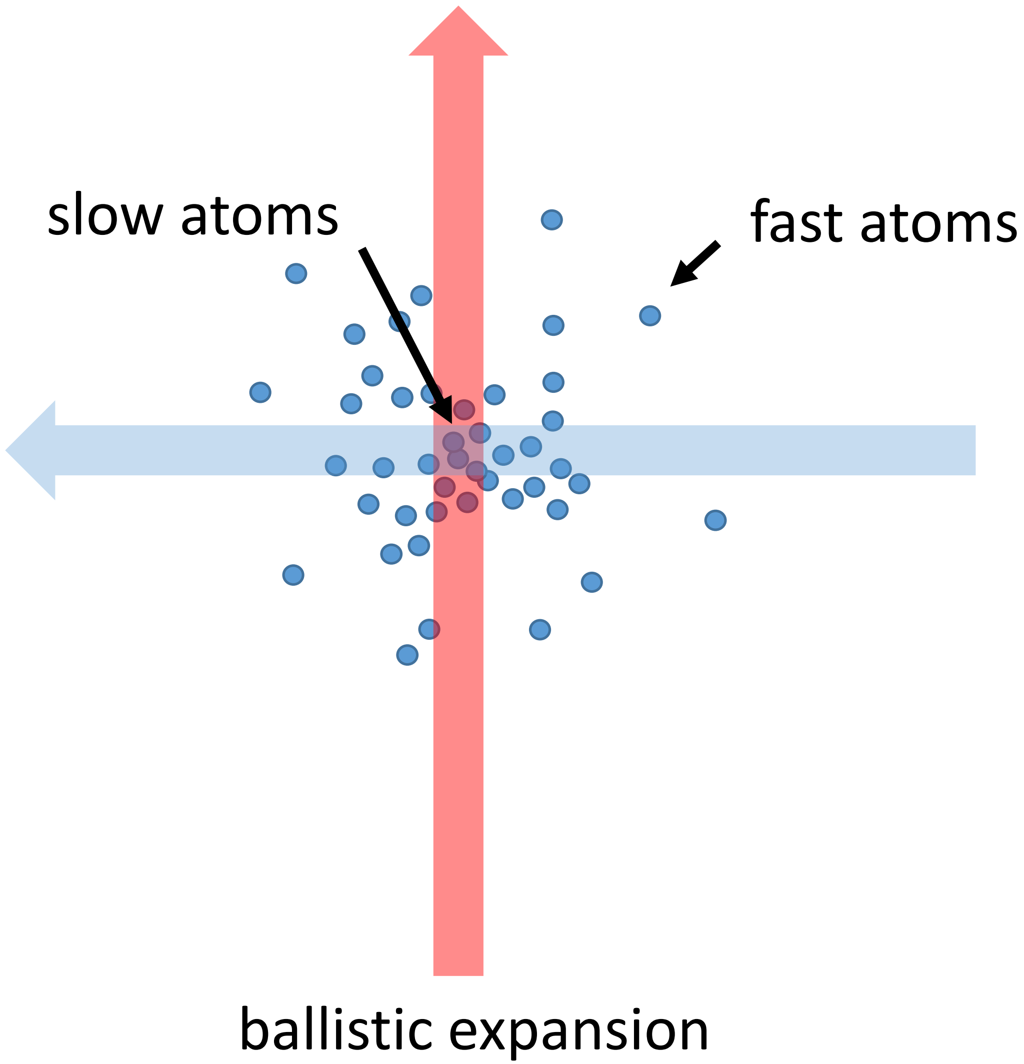

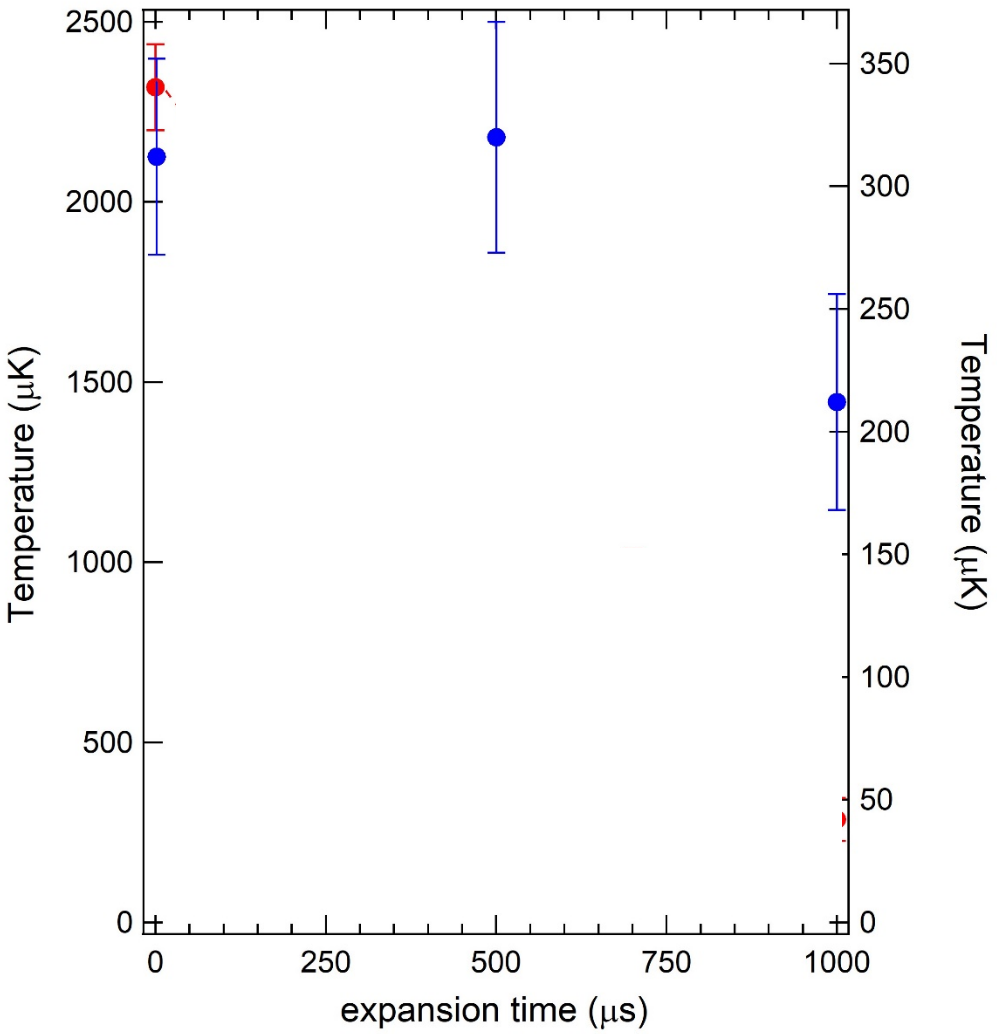

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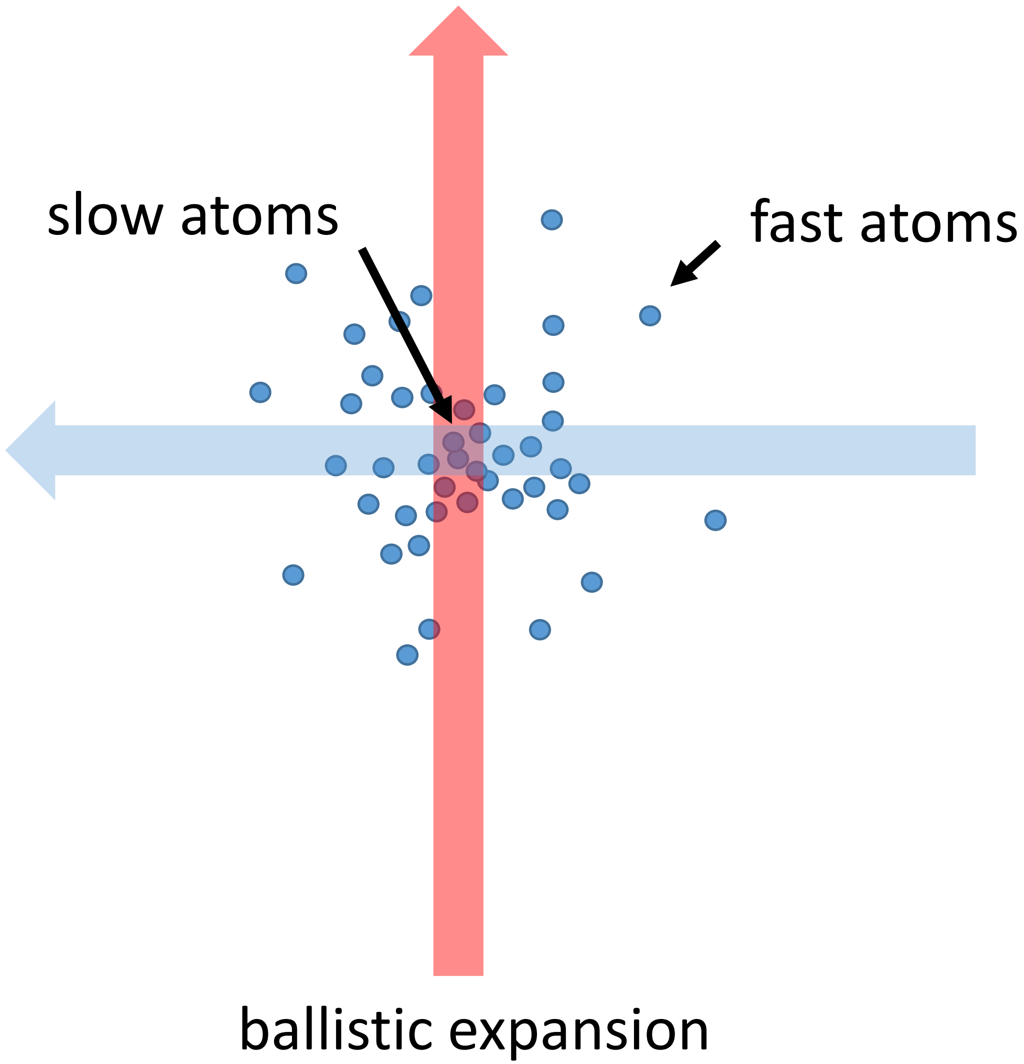
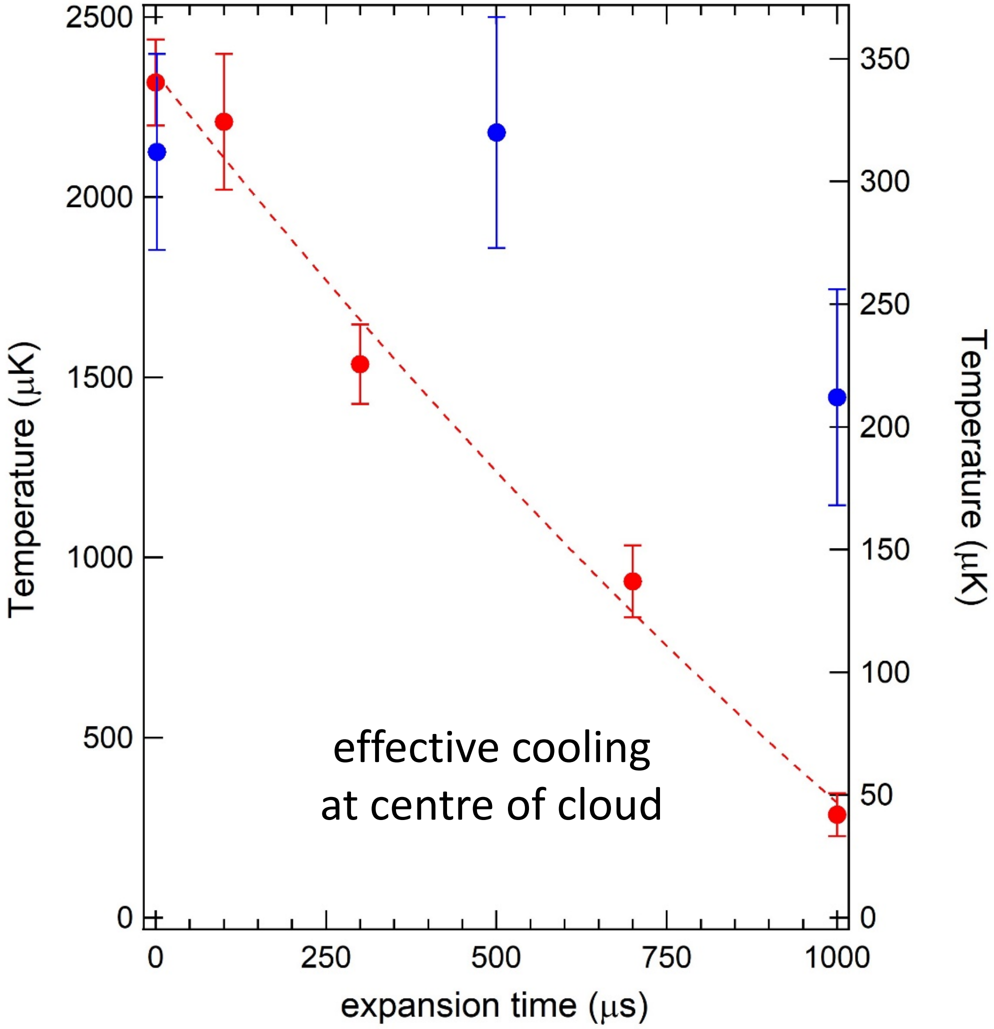
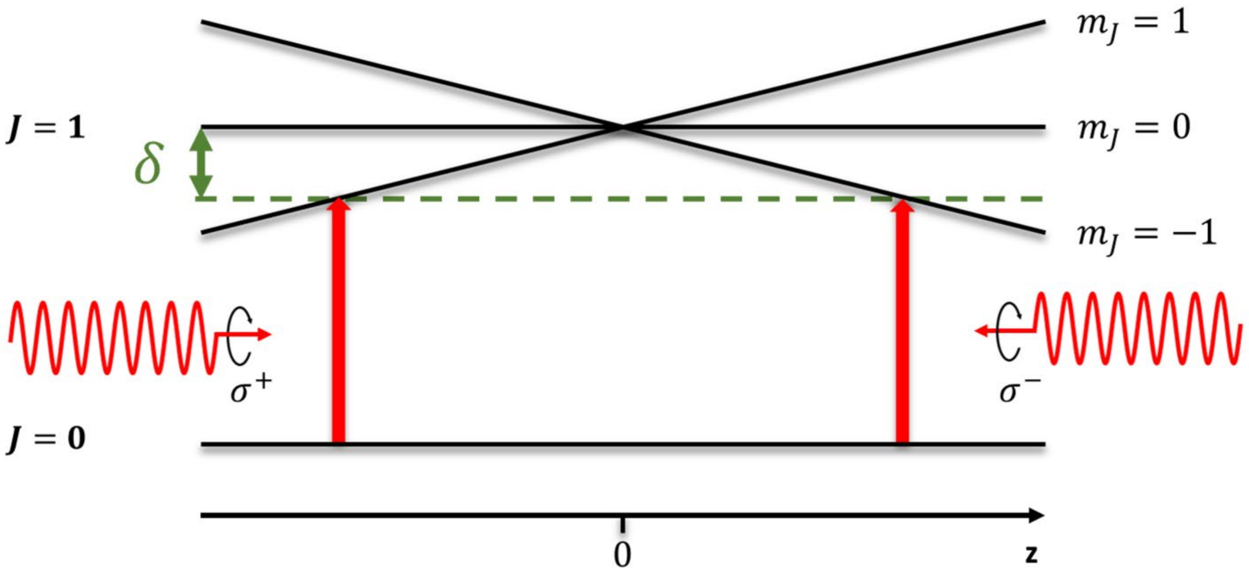


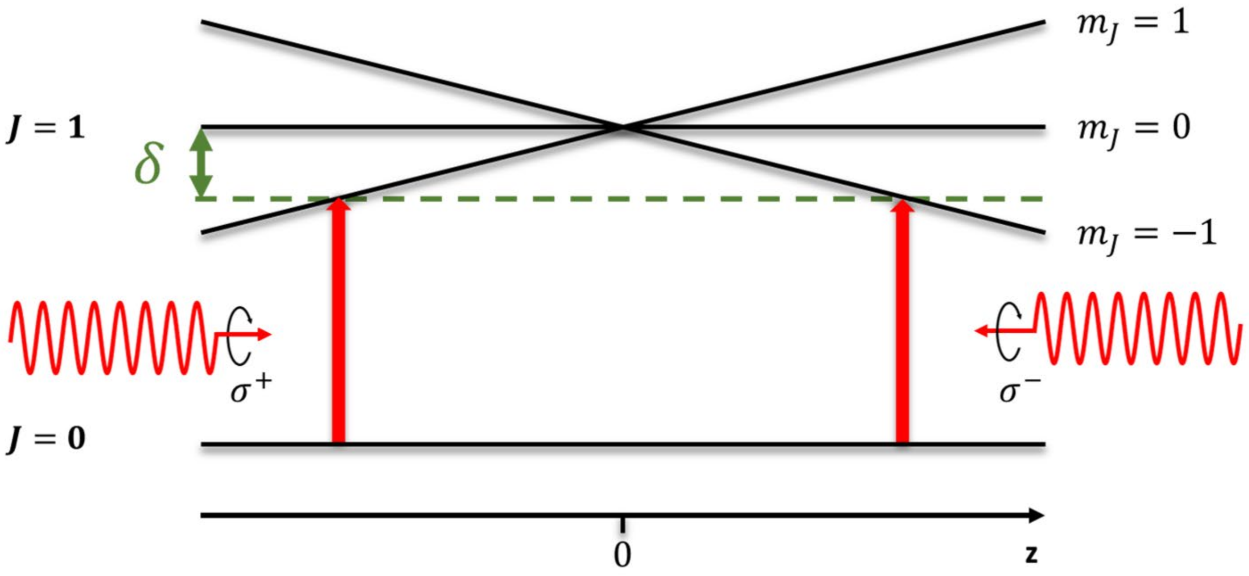


Question: is the temperature in a MOT uniform?



$$\boldsymbol{F}_{tot} = \boldsymbol{F}_{spring} + \boldsymbol{F}_{abs}$$

Question: is the temperature in a MOT uniform?



$$\boldsymbol{F}_{tot} = \boldsymbol{F}_{spring} + \boldsymbol{F}_{abs} + \boldsymbol{F}_{rerad}$$

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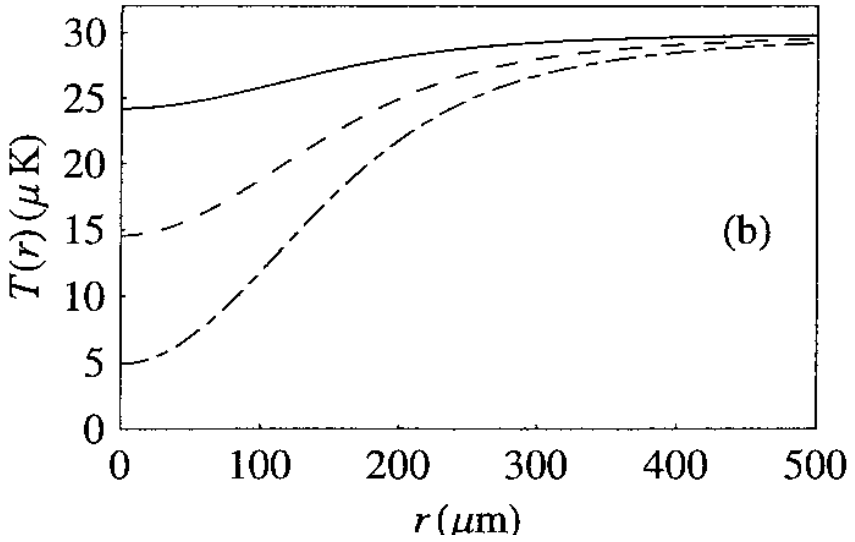

A. S. Arnold and P. J. Manson Vol. 17, No. 4/April 2000/J. Opt. Soc. Am. B 497

Atomic density and temperature distributions in magneto-optical traps

A. S. Arnold* and P. J. Manson

Department of Physics, University of Otago, P.O. Box 56, Dunedin, New Zealand

$$\boldsymbol{F}_{tot} = \boldsymbol{F}_{spring} + \boldsymbol{F}_{abs} + \boldsymbol{F}_{rerad}$$

$$\nabla \boldsymbol{P}(\boldsymbol{r}) = \boldsymbol{F}_{tot}\, n(\boldsymbol{r})$$

$$\nabla \boldsymbol{P}(\boldsymbol{r}) = k_B[T(\boldsymbol{r})\boldsymbol{\nabla} \mathrm{n}(\mathbf{r}) + \mathrm{n}(\mathbf{r})\boldsymbol{\nabla}\mathrm{T}(\mathbf{r})] = \mathbf{F}_{\mathrm{tot}}\mathrm{n}(\mathbf{r})$$

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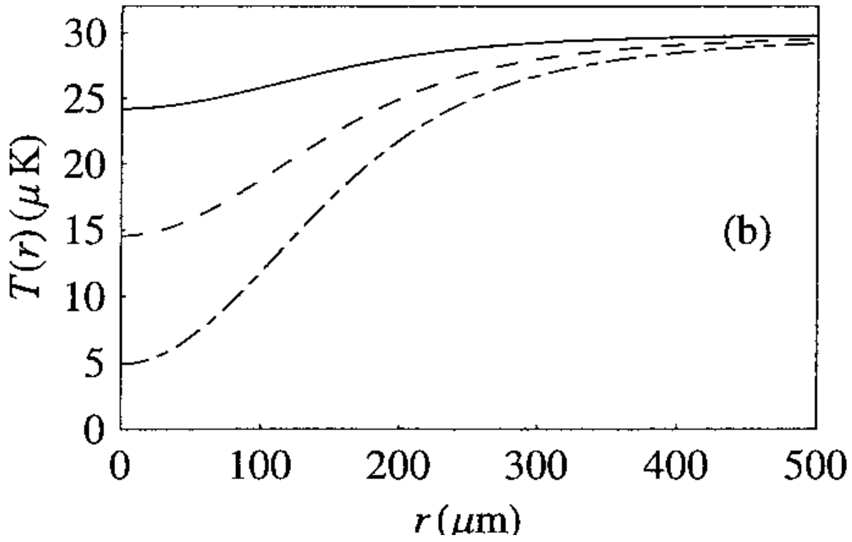

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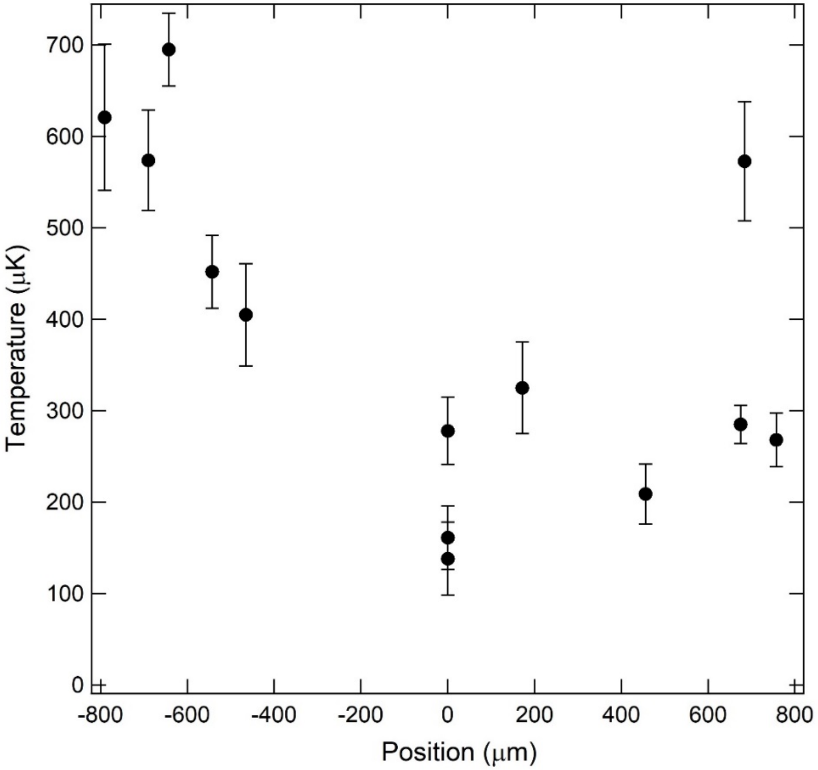

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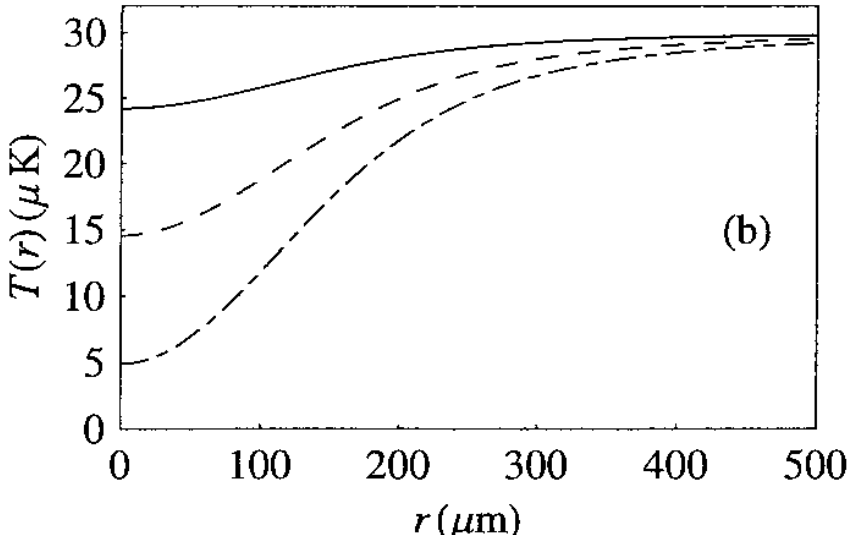

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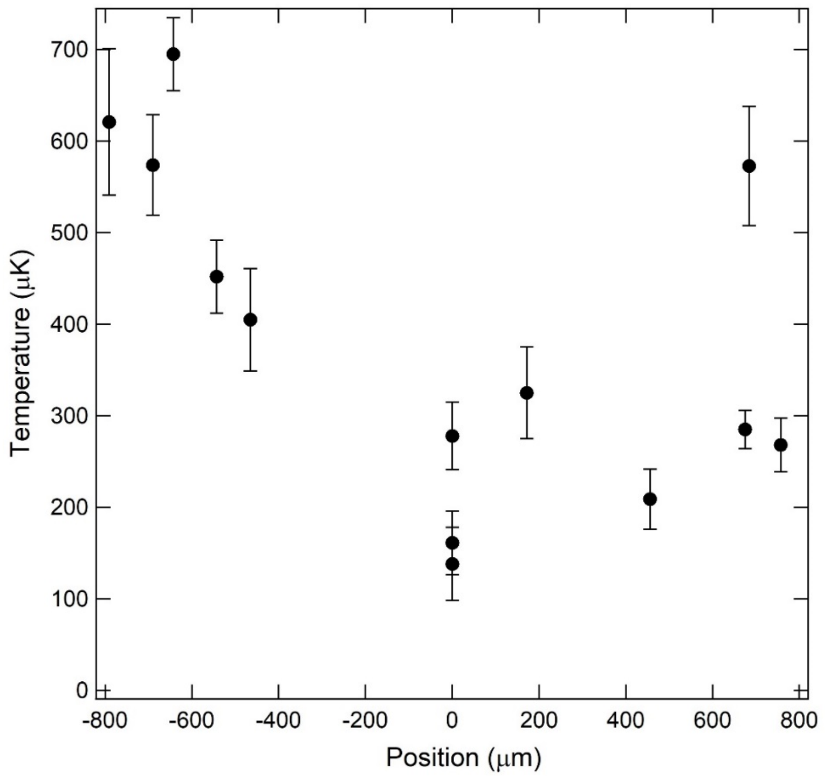
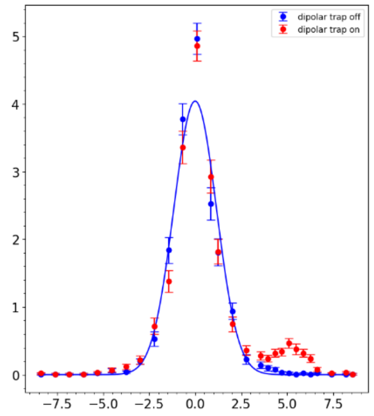


Other applications: measurement of energy transport; link between high-temperature and ultra-low-temperature measurements

Conclusions

- Rydberg excitations are useful for characterizing cold atom systems

- Dipole traps can be characterized using photoionization and Rydberg excitation to measure the trap frequency and light shift



- Temperature can be measured with spatial resolution using Rydberg Doppler broadening thermometry