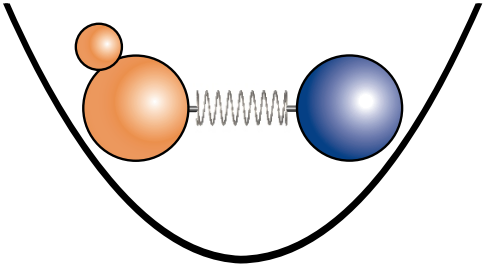
DIFCOS Experiment

Doing **I**nteresting, **F**earless, **C**ool and **O**riginal **S**tuff

Fabian Wolf
QUEST Institute,
PTB Braunschweig



September 24, 2024

QUEST Group Retreat, Warberg

The Team

DIFCOS Team 2024/2025

- Max graduated December 2024 (now at DLR)

The Team

DIFCOS Team 2024/2025

New Season

Till Rehmert
(Senior PhD)

Gabriele Gatta
(Guest researcher,
Sias group, Firenze)

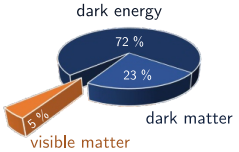
2013 Fabian
(dependent group leader)

Sylvain Noël
(Junior PhD)

Johannes Mertens
(Student assistant)

- Max graduated December 2024 (now at DLR)

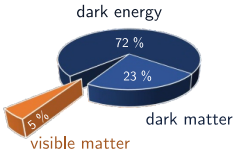
The dark sector



- Standard model describes only $\sim$ 5 % of the universe

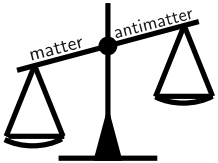
Beyond the standard model of physics

The dark sector



- Standard model describes only ~ 5 % of the universe

Baryon asymmetry



- Standard model CP violation to weak to account for matter anti-matter imbalance

Beyond the standard model of physics

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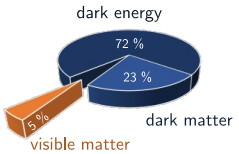

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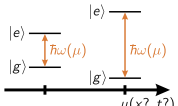
Variation of fundamental constants



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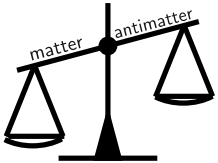

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Beyond the standard model of physics

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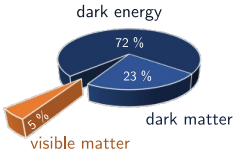

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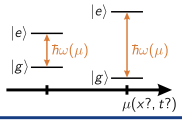

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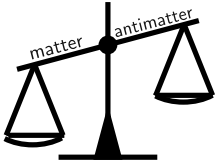

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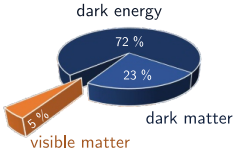
electron electric dipole moment (eEDM)

Beyond the standard model of physics

The dark sector



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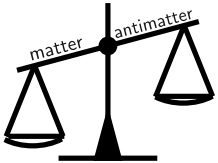

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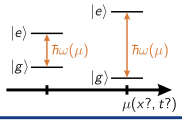
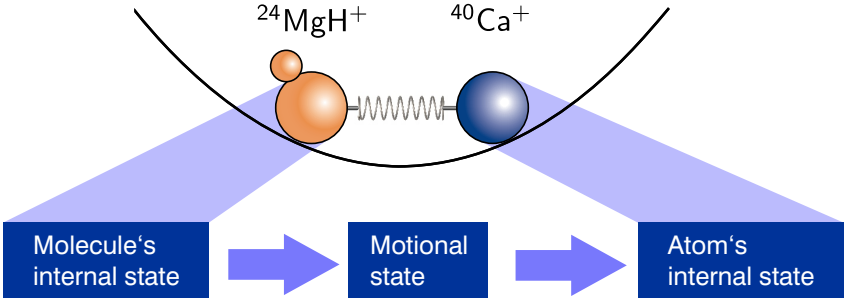


electron electric dipole moment (eEDM)

Precision spectroscopy of molecular ions

› vibrational spacing scales with m_p/m_e

› internal electric fields of GV/cm possible

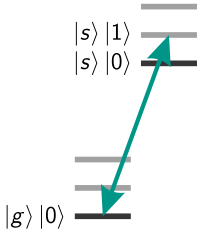


Molecule is trapped simultaneously with an atomic ion

- Laser cooling via the atomic ion
- Read out the molecule's state via the atomic ion

Motional state serves as transfer bus

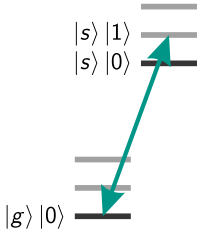
Traditional quantum logic spectroscopy



- Adress sideband on optical transition
  - e.g. Aluminum clock, highly charged ions
- Dedicated laser for each species
- Difficult for complex groundstates

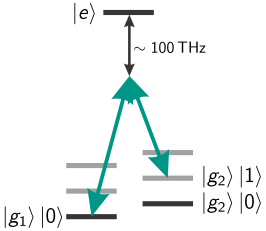
Different flavours of quantum logic spectroscopy

Traditional quantum logic spectroscopy



- Adress sideband on optical transition
  - e.g. Aluminum clock, highly charged ions
- Dedicated laser for each species
- Difficult for complex groundstates

Far-detuned Raman quantum logic spectroscopy (FaDeRaQuLoS)

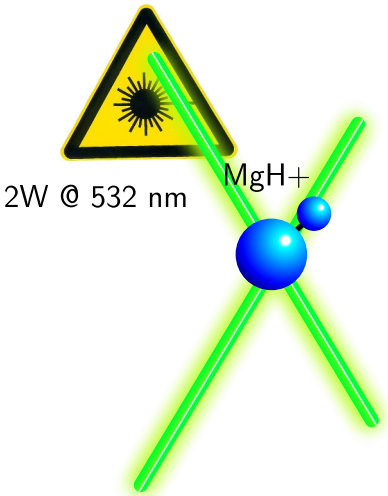


- pioneered by NIST group for CaH^+
- Does not require excited metastable state
- One laser rules them all
- Required energy gap can be produced by AOMs
  - Frequency comb allows bridging THz gaps

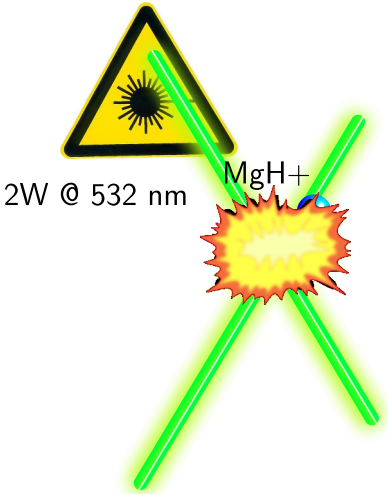
Dissociation

$MgH+$

Dissociation



Dissociation



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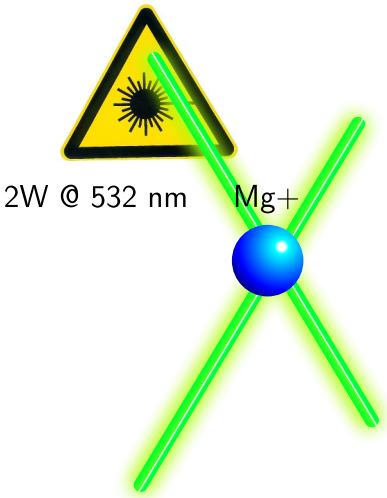

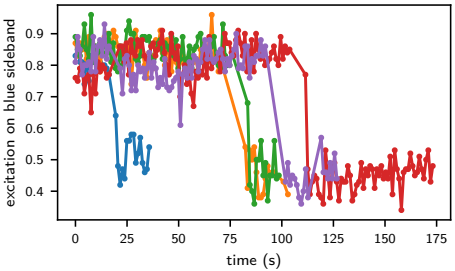

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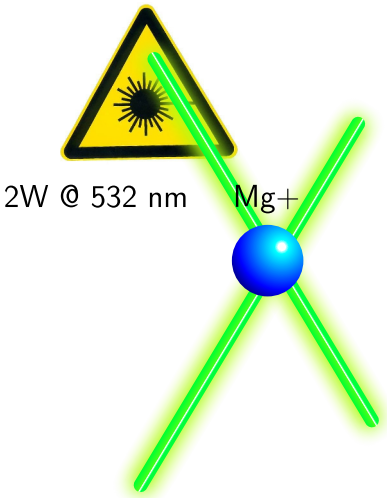

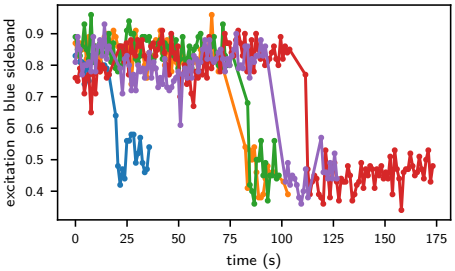

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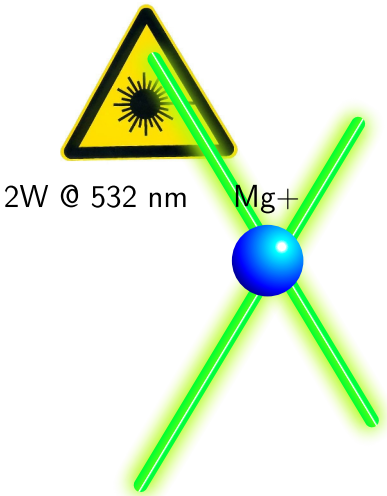
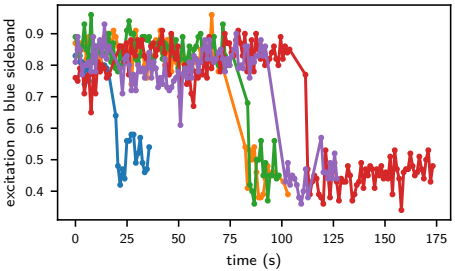
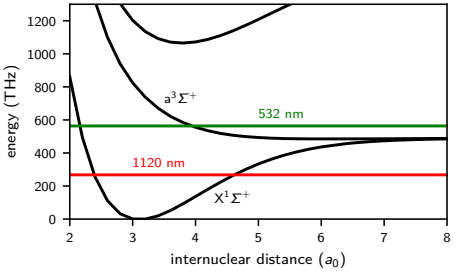






What happened then?

- New laser had to be set up
- What to do in the mean time with nicely working setup?

We decided to investigate Ti^+ in the mean time

- Last year we reported Ti^+ quantum logic spectroscopy
  published:
  T. Rehmert et al. Quantum logic control of a transition metal ion, Physical Review Letters **134**, 113201 (2025)

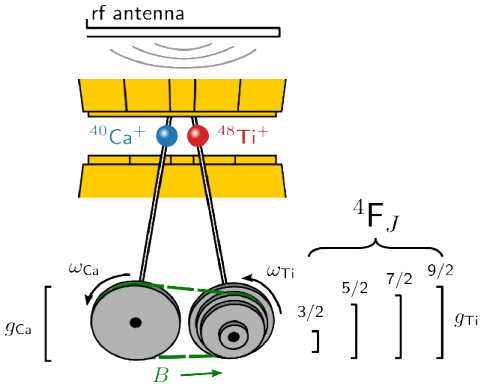
g factor measurements using quantum logic and simultaneous co-magnetometry

The grand finale of our unintended excursion into titanium quantum logic spectroscopy

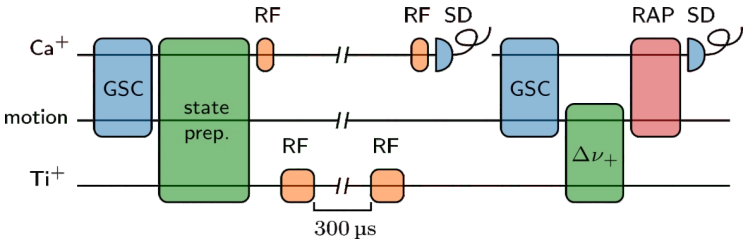
- submitted (T. Rehmert et al. arXiv:2508.15488 (2025)

T. Rehmert et al. arXiv:2508.15488 (2025)

- $^{40}Ca^{+}$ $^{2}S_{1/2}$ state as **co-magnetometer**
  - well-known from Penning trap experiments
    (Tommaseo et al EPJ D 25, 113 (2003))
  - suppresses effects from magnetic field fluctuations
- Collaboration with M. Safronova group

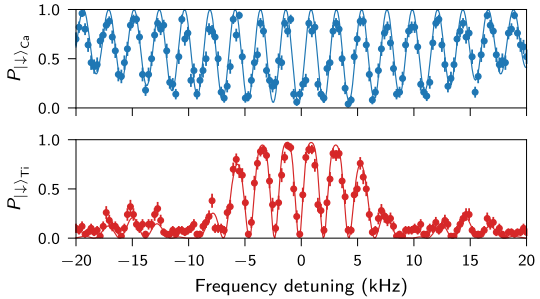


Experimental Scheme



- Simultaneous Ramsey interrogation
- Sequential readout (Ca: direct, Ti: quantum-logic)

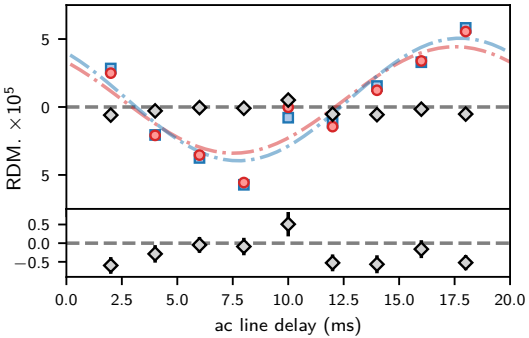
(T. Rehmert et al. arXiv:2508.15488 (2025))



50Hz noise suppression

50 Hz magnetic field noise from AC-line

- **Individual frequencies** affected by magnetic field changes
- **g factor** not affected
  - suppression by simultaneous co-magnetometry



(T. Rehmert et al. arXiv:2508.15488 (2025))

In case you forgot: This project is about molecules

Let's get back to molecular ions

"Beware that, when fighting monsters, you yourself do not become a monster...

for when you gaze long into the molecule. The molecule gazes also into you."

Back to molecular ions

- New laser a 1120nm does not dissociate MgH^+

Challenges

	MgH^+	Ti^+
dwell time in state	seconds	tens of minutes
occupied states @300K	~ 10	4
Zeeman splittings	$\sim$ kHz	$\sim$ MHz

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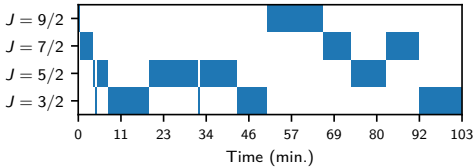

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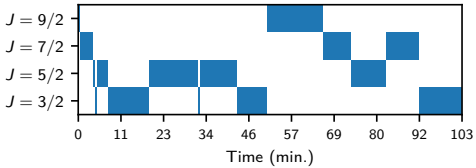

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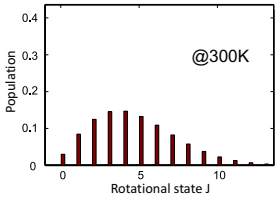
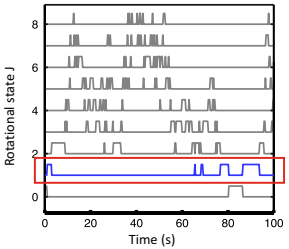
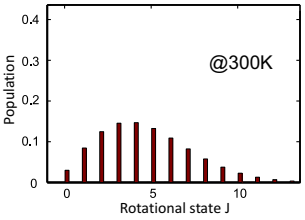
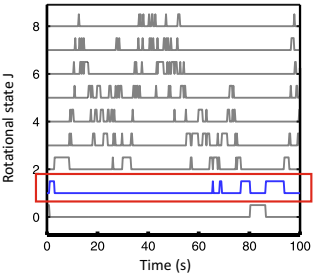
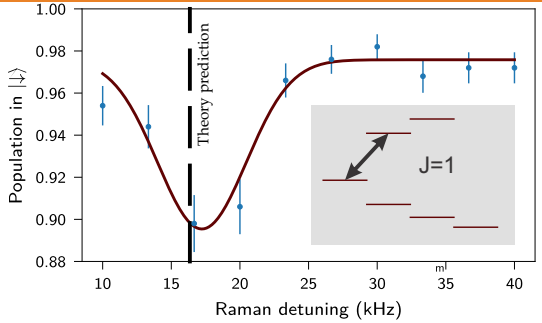


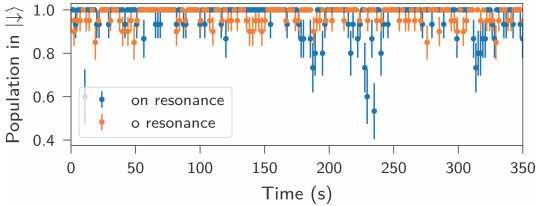


Preliminary quantum logic signal





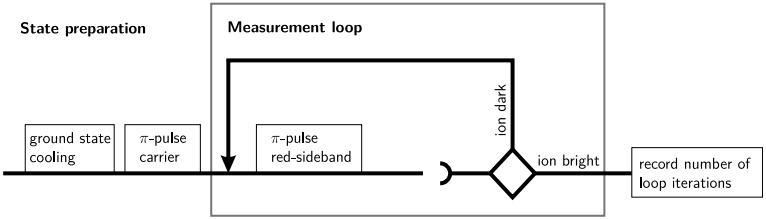




A new method for measuring heating rates

Not really related to the previous topic

Heating rate measurements



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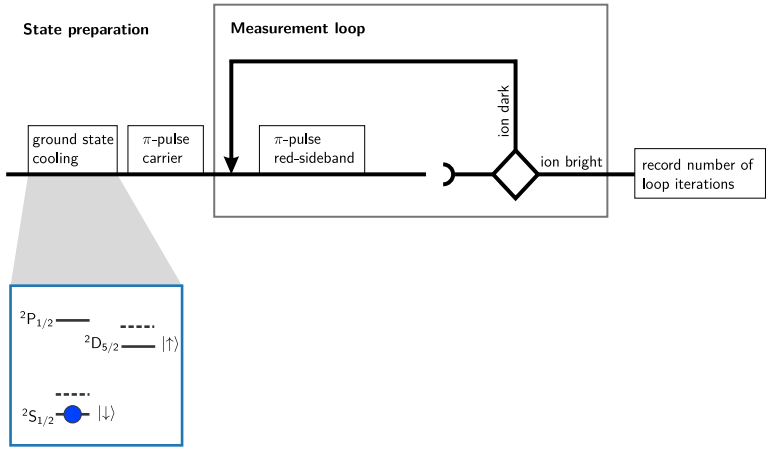

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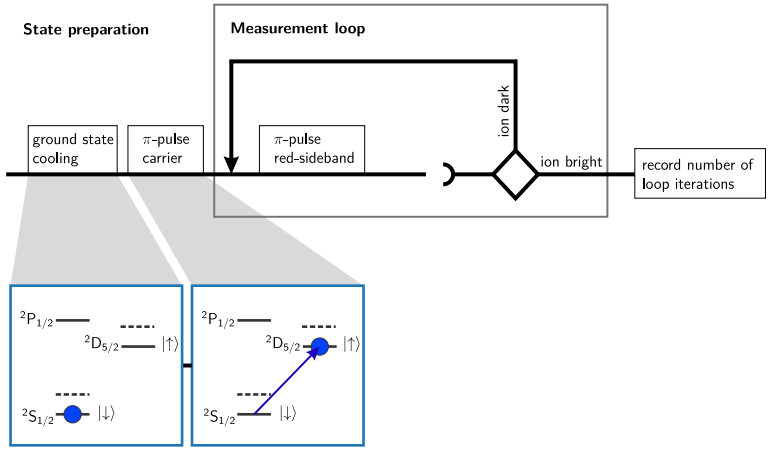

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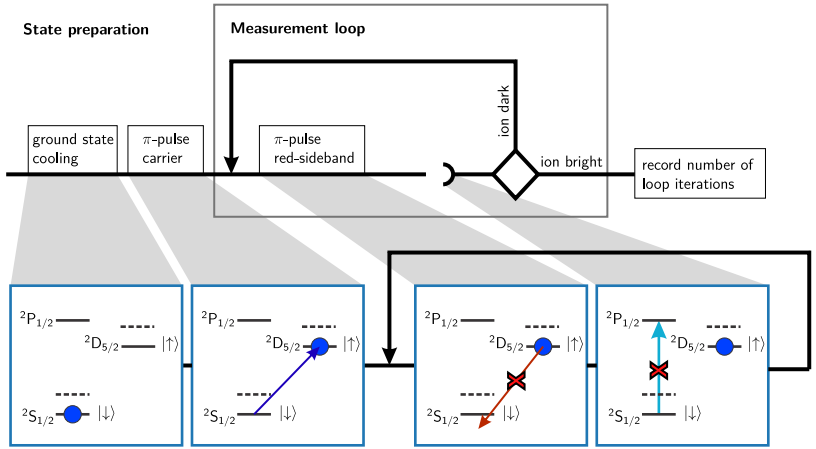

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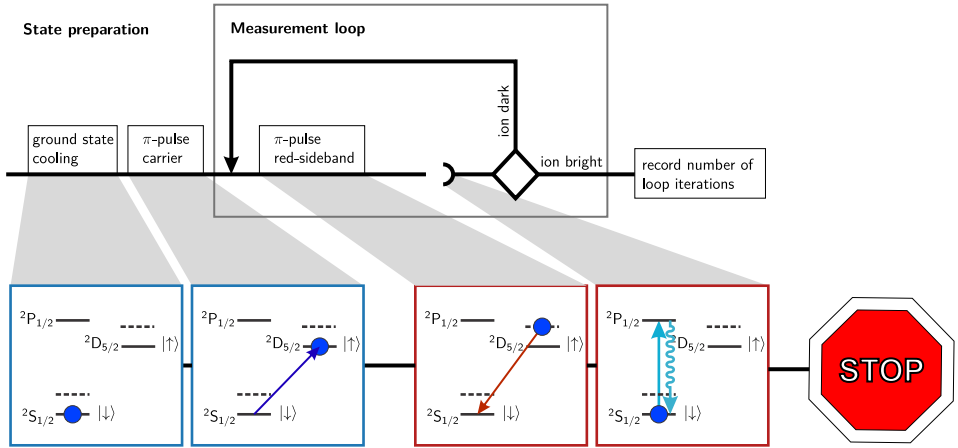
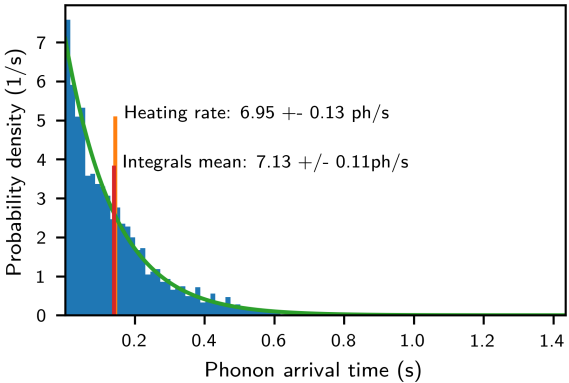


Heating rate measurement

- Phonon arrival time follows **exponential distribution**
- Inverse of mean is heating rate

$$\Gamma_{\mathrm{h}} = \frac{1}{\langle T \rangle} \qquad (1)$$

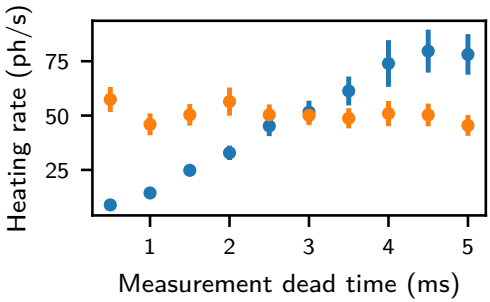
  - directly extracted from histogram
  - for time-restricted measurements from fit



Coherent and incoherent heating

- Measurement strength can be tuned by introducing additional deadtime
- **Incoherent heating** will not be affected
- **Coherent heating** is suppressed by stronger measurement
  - Quantum Zeno suppression

SIMULATION NOT MEASURED!

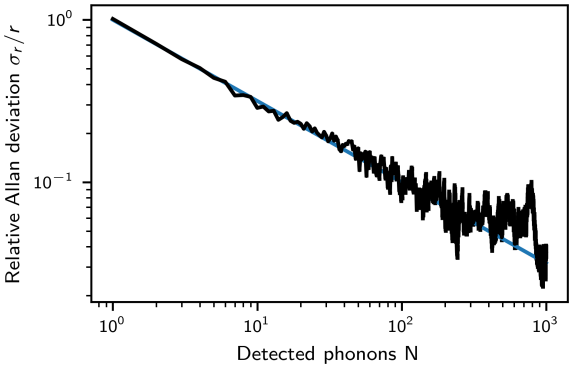


Statistical uncertainty

Standard deviation of the mean

- $\sigma_r = \frac{\Gamma_h}{\sqrt{N}}$
  N : number of detected phonons
- $\sigma_r = \sqrt{\frac{\Gamma_h}{\tau}}$
  τ : measurement time

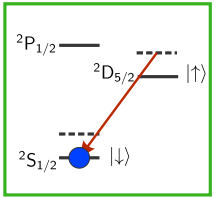
Standard quantum limit of heating rate measurements



Systematic errors

Ideal Scenario

- State change only after phonon excitation
- State change after each phonon excitation



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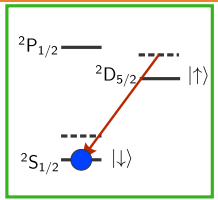
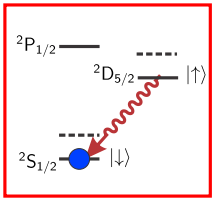


Spontaneous decay

- Without heating ion goes into bright state
- Overestimation of heating rates



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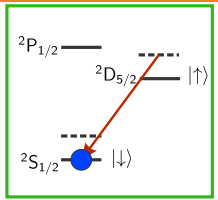

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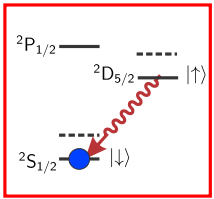
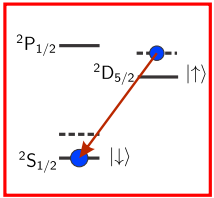


Sideband infidelities

- Despite heating population remains in dark state
- Underestimation of heating rates



Comparison to other methods

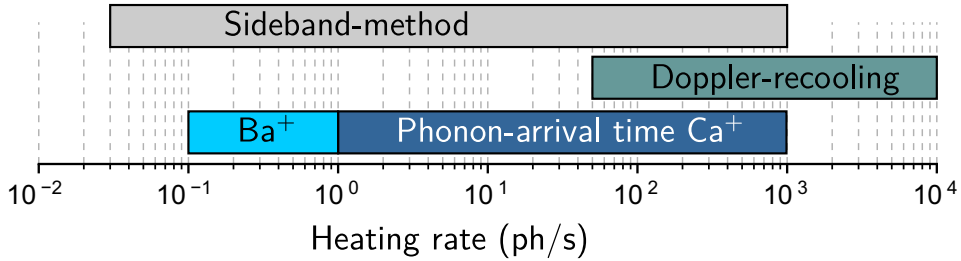
Auto-calibrating

- No initial guess of heating rate requires
- Measurement time is automatically adapted

Broad range

- Covers typical heating rates
- Depends on ion species

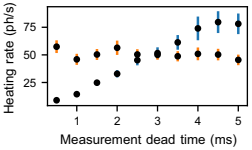
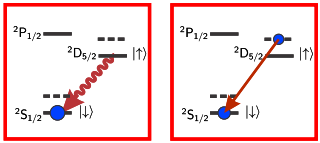
Metrologically clean



Plans for the near future

Todo list

- Measure Quantum Zeno suppression for coherent heating
- Investigate correlation of heating with 50Hz noise
  - similar to photon-correlation for micro-motion measurements
- Model systematic uncertainties



Ground loops?