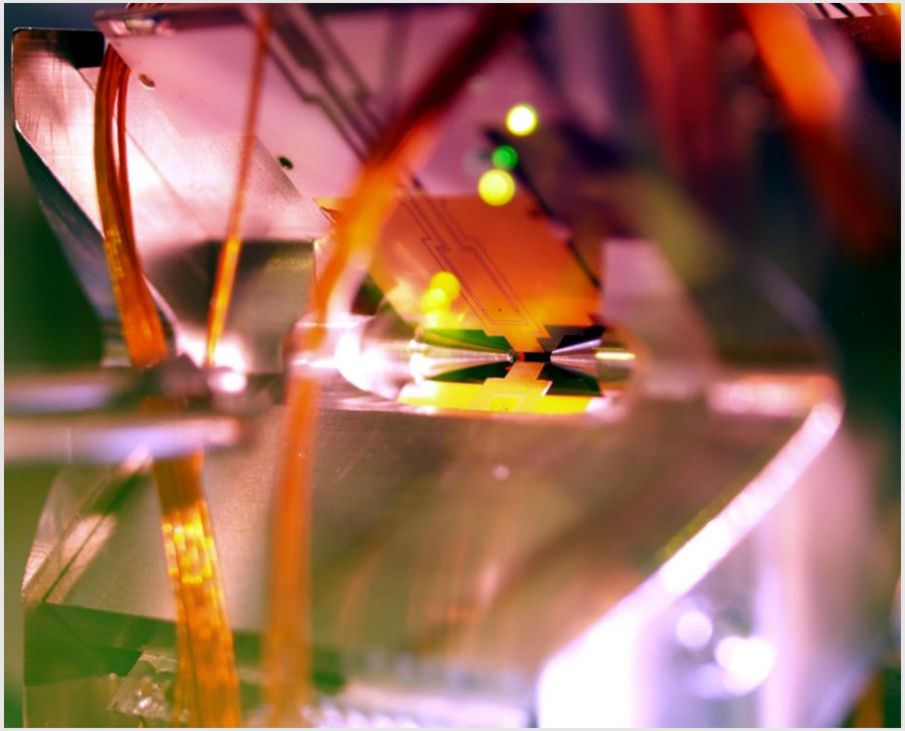
http://www.quantenbit.de/

https://gbar.web.cern.ch/GBAR/index.php

Techniques for Ground state cooling of anti-Hydrogen-ions



Principle of GBAR experiment

Sympathetic ground state cooling

New trap production procedure

Challenges of wavepacket expansion

Temperature measurement via Young interferences

Requirements and planing for the cryo trap

Sebastian Wolf, Andreas Koglbauer and Ferdinand Schmidt-Kaler, Johannes Gutenberg-University Mainz

financial support

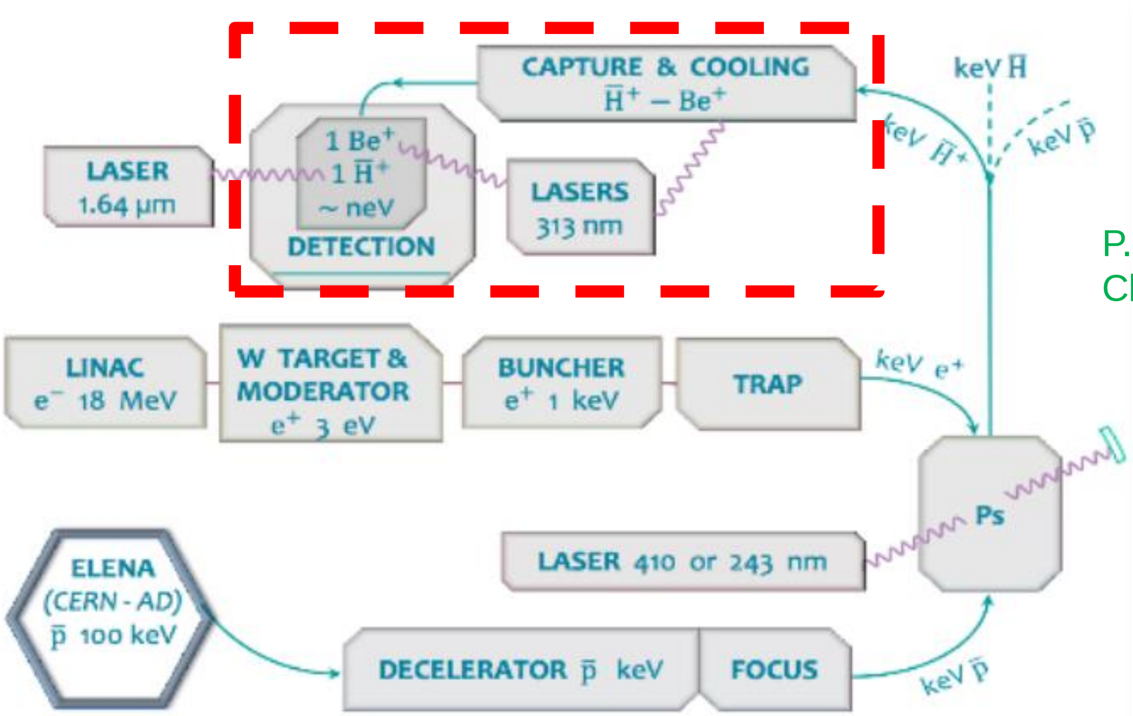
DFG Deutsche Forschungsgemeinschaft

PRISMA

ANR

5th of August 2015, 3rd International Workshop on Antimatter and Gravity | London

GBAR experimental scheme



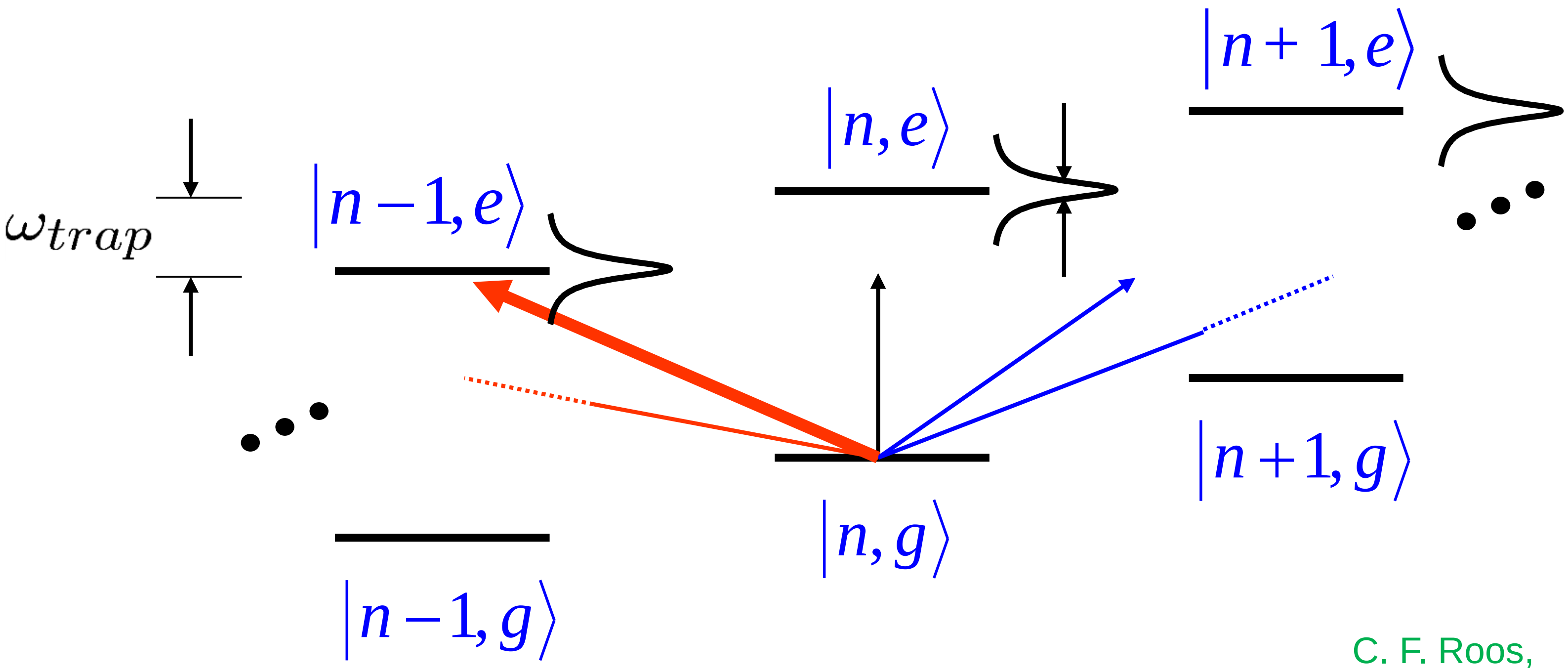
P. Perez and Y. Sacquin,
Class. Quantum Grav. **29**, 184008 (2012)

Doppler cooled ions T ~ 1mK
Rising height h ~ 5 m

→ Ground State cooling
→ (T~10 µK, h ~ 10 cm)

„Strong confinement“

$$\omega_{trap} >> \gamma$$



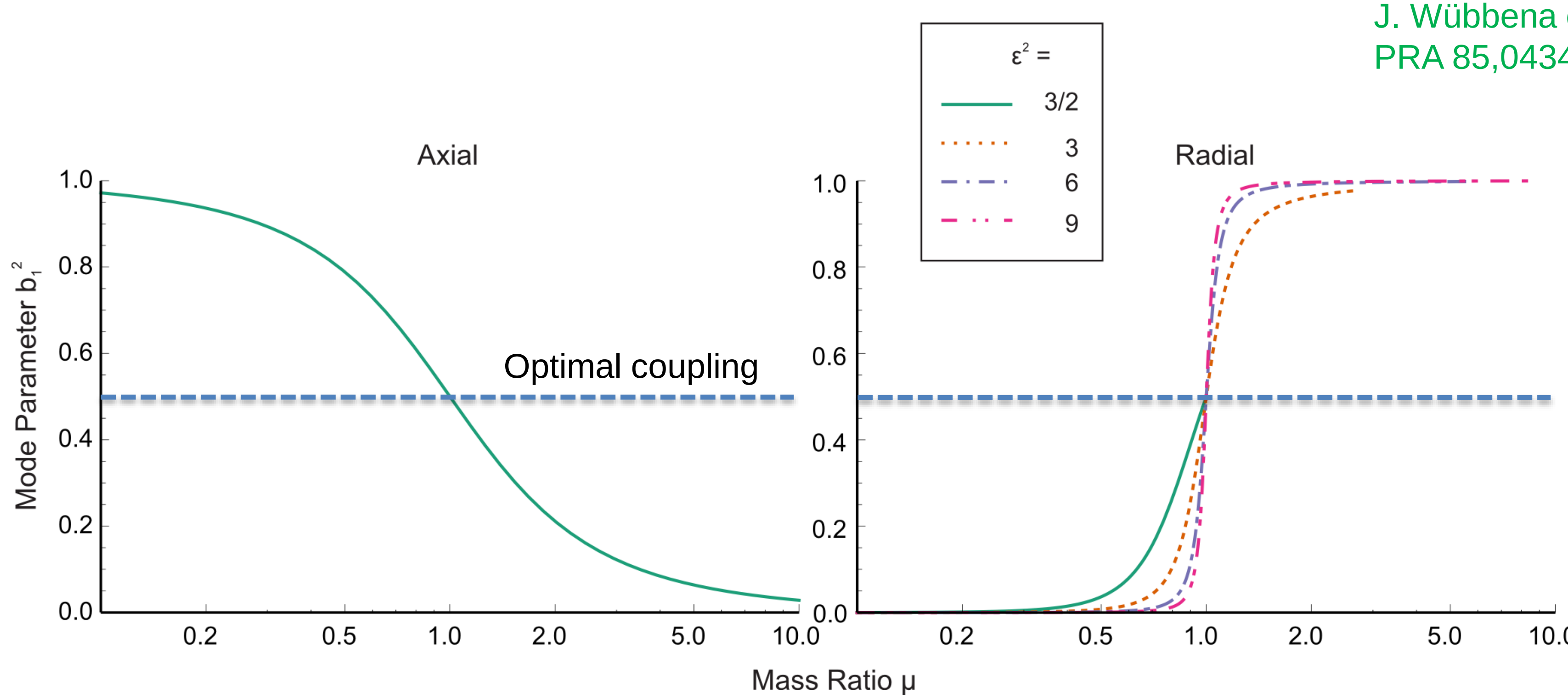
C. F. Roos,
Phys. Rev. Lett. **85**, 5547 (2000)

strong confinement – well resolved sidebands:
Selective excitation of a single sideband only,
e.g. here the red SB

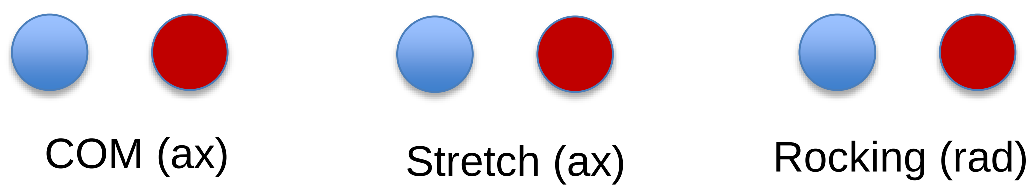
Problem in high mass ratio

$$\varepsilon \sim {}^{\omega_{rad}}/_{\omega_{ax}}$$

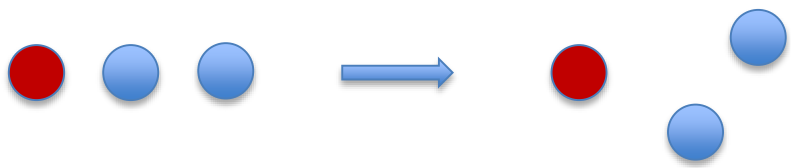
J. Wübbena et al.,
PRA 85,043412 (2012)



Be:H = 9:1
Ca:Be = 4.4:1



Increased coupling near ZigZag transitions



$$\alpha = \left(\frac{\omega_{ax}}{\omega_{rad}}\right)^2$$

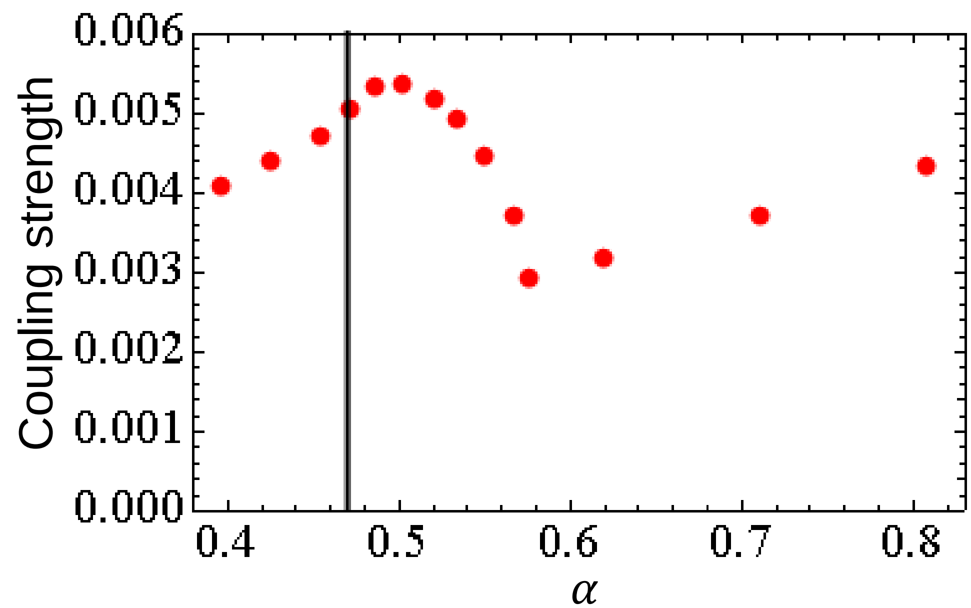
$$\alpha_{\text{krit}} \approx 0.47$$

Calculation of oscillation modes and frequencies
equilibrium positions

oscillation modes and frequencies

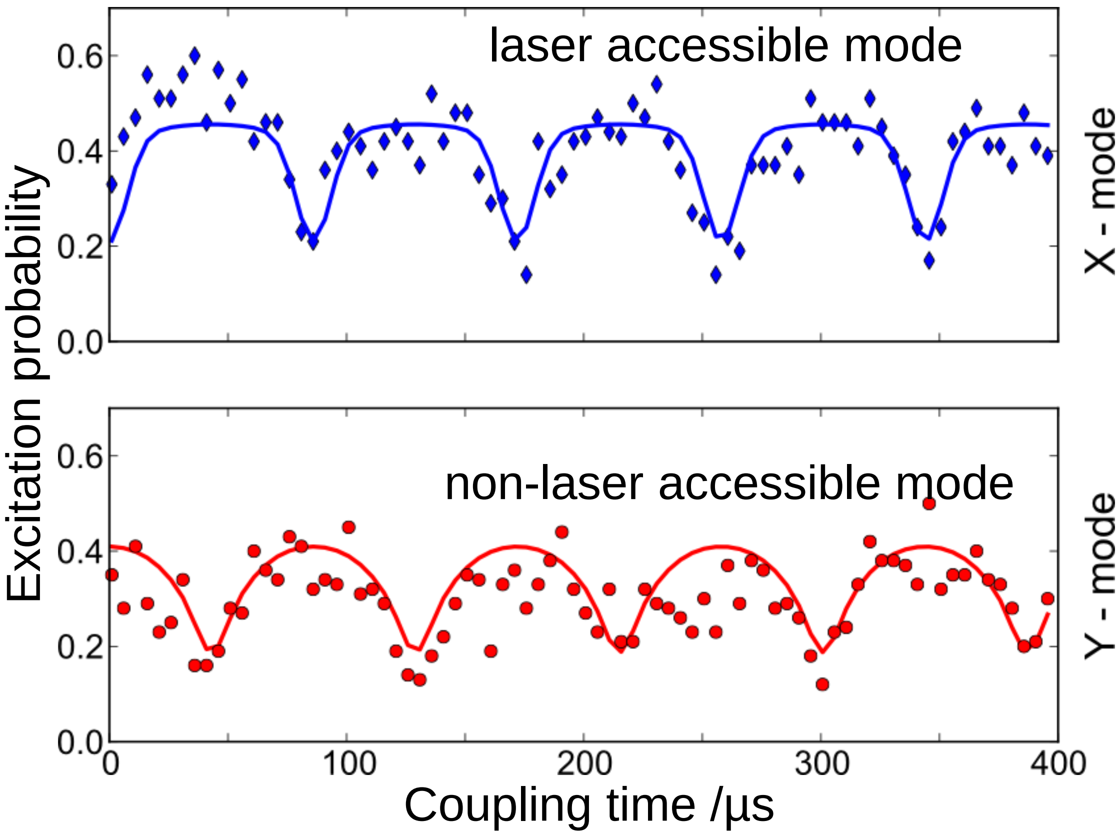
$$H_{i,j} = \frac{\partial}{\partial x_i}\frac{\partial}{\partial x_j}V.$$

$$\{\tilde{\omega}_j/\omega_z\} = \{\lambda \geq 0 |\, \det(M^{-1}H - \lambda^2 I) = 0\}$$



H. Kaufmann et al.,
Phys. Rev. Lett. 109, 263003 (2012)

Mode coupling by irridation of difference frequencies



In this setup:

Not accessible due to geometric reasons

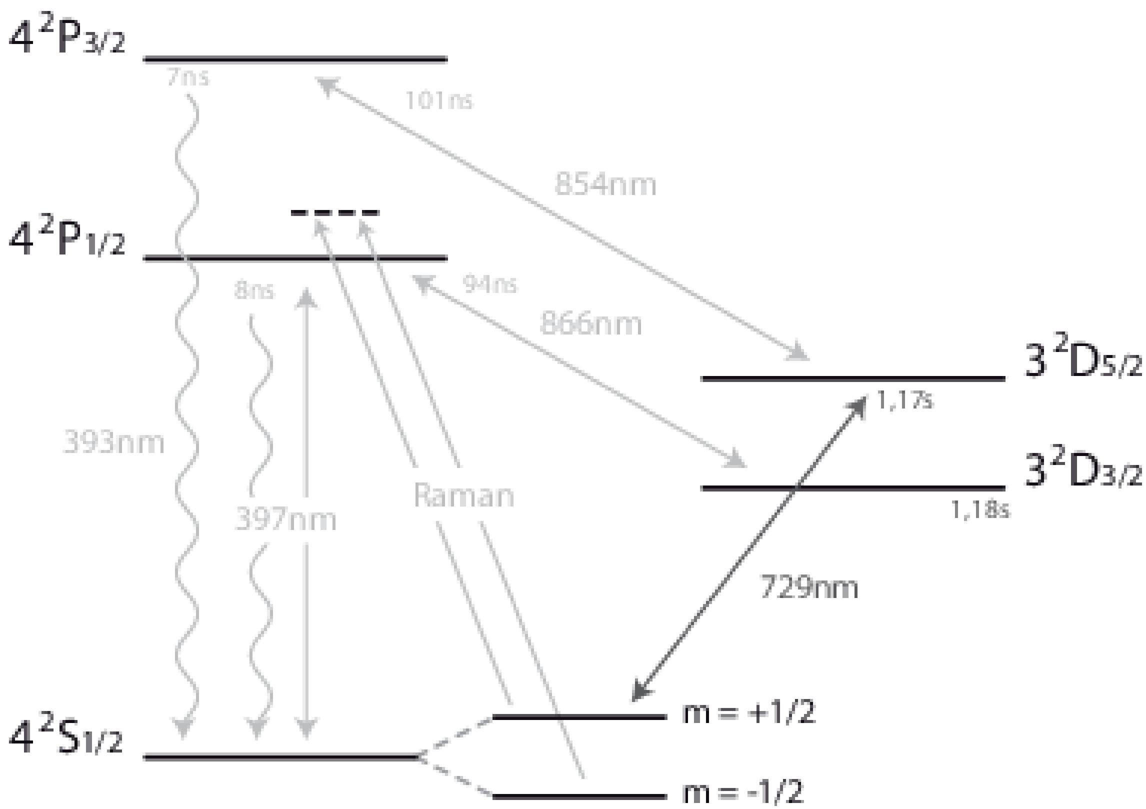
In Gbar:

Huge mass ratio results in low coupling

→ Ground state cooling despite low coupling

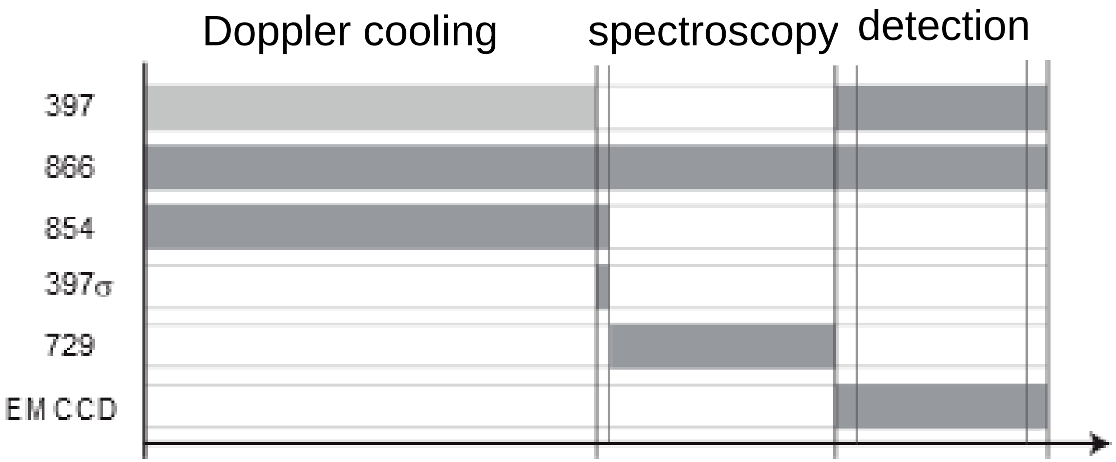
D. J. Gorman et al.,
Phys. Rev. A **89**, 062332 (2014)

Level scheme of $^{40}Ca^{+}$ ions

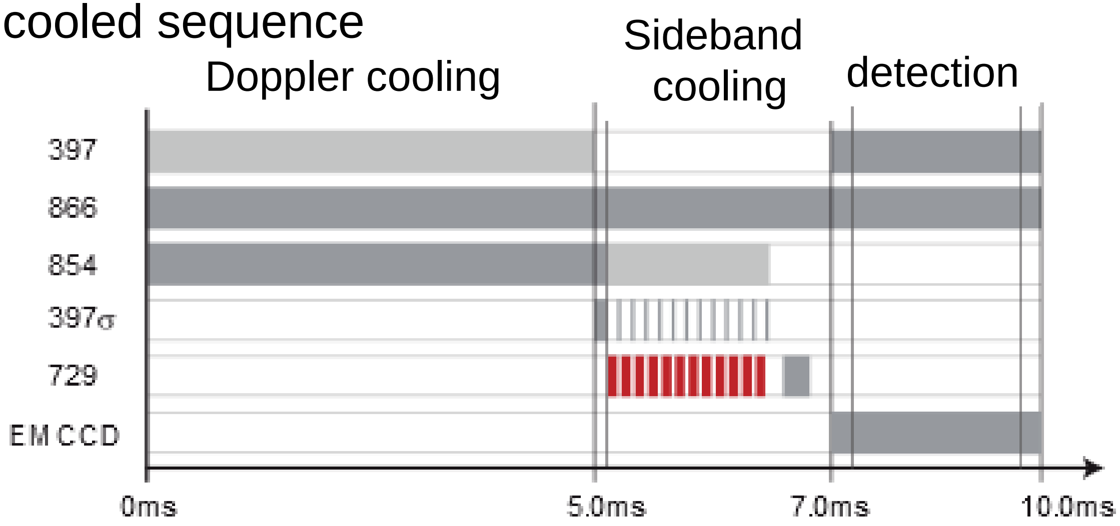


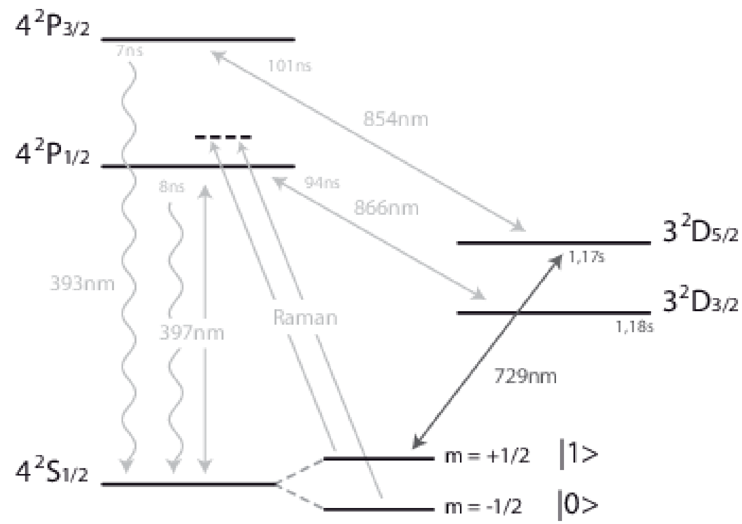
Sideband spectroscopy and cooling sequence

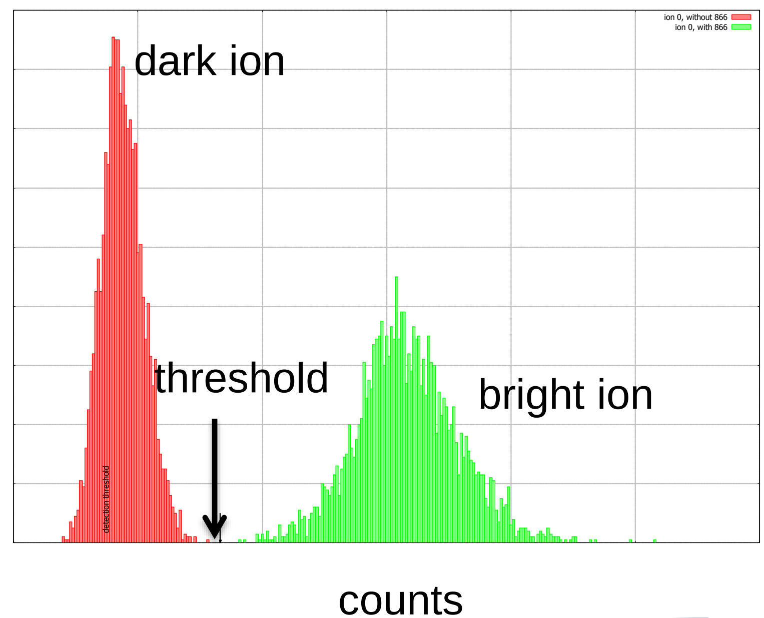
Doppler cooled sequence



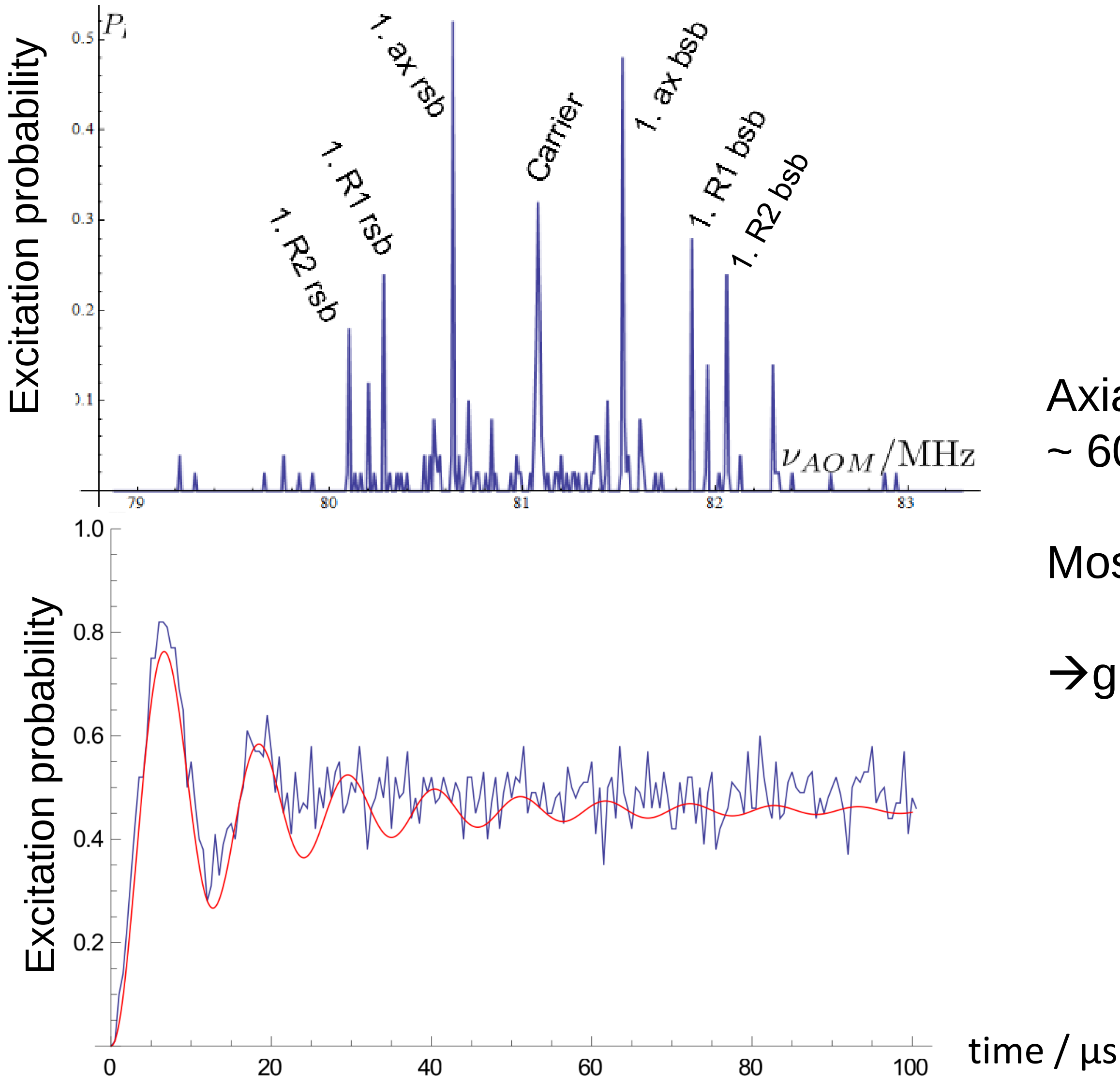
Ground state cooled sequence







Sideband spectrum of single Ca^+ ion



Axial heating rate in precision trap
~ 60 phonons/ms

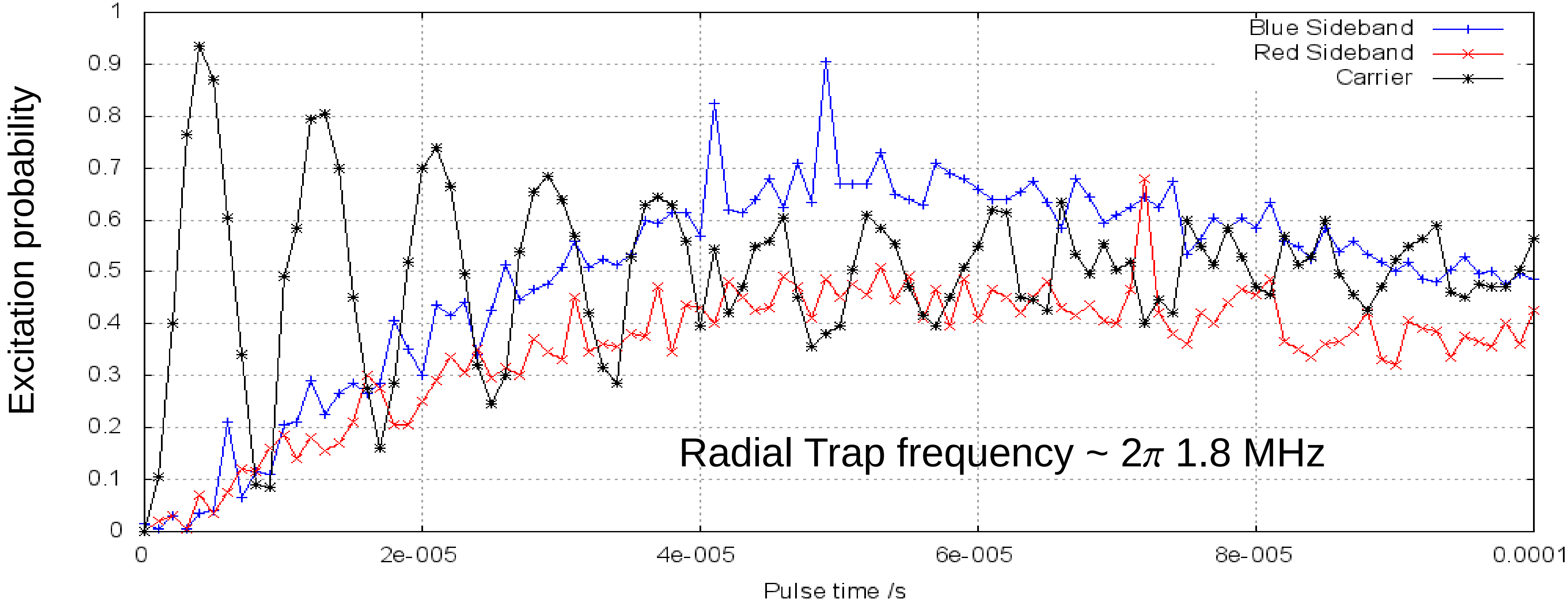
Most probable due to floating electrode

→ground state cooling not possible

Sideband cooling to low phonon numbers

Results in identical trap in radial mode
(Implantation trap, Gerorg Jacob and Karin Groot-Berning)

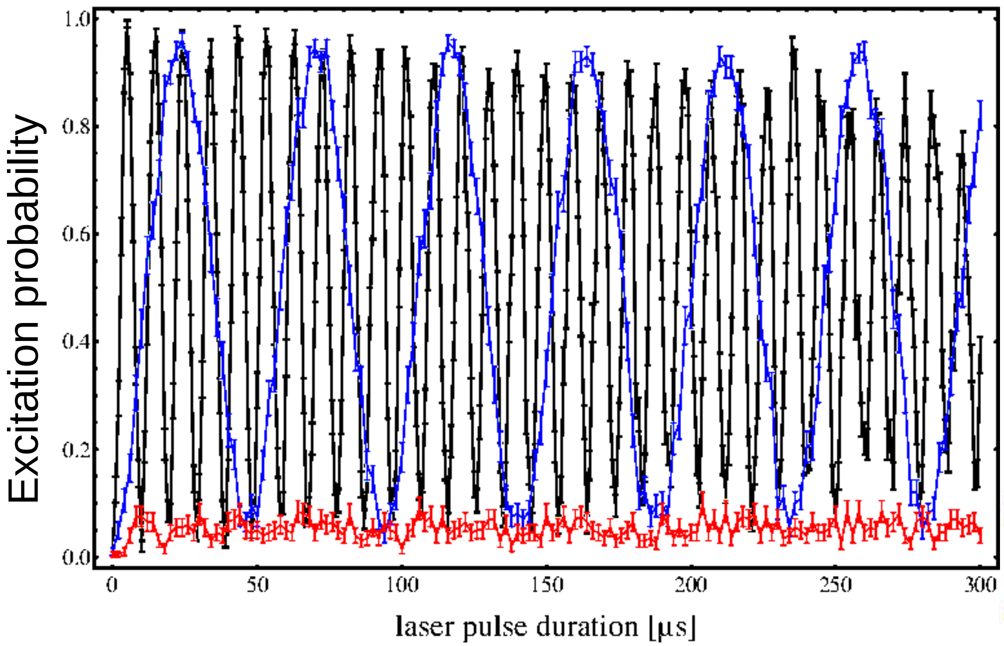
$$\Omega_{car} \sim (1-\eta^2\bar{n})\,\Omega_0$$
$$\Omega_{rsb} \sim \eta\,\sqrt{\bar{n}}\,\Omega_0$$
$$\Omega_{bsb} \sim \eta\,\sqrt{\bar{n}+1}\,\Omega_0$$

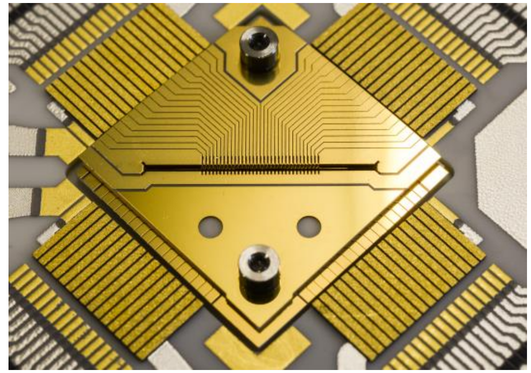


$$\bar{n} \sim 1.9$$

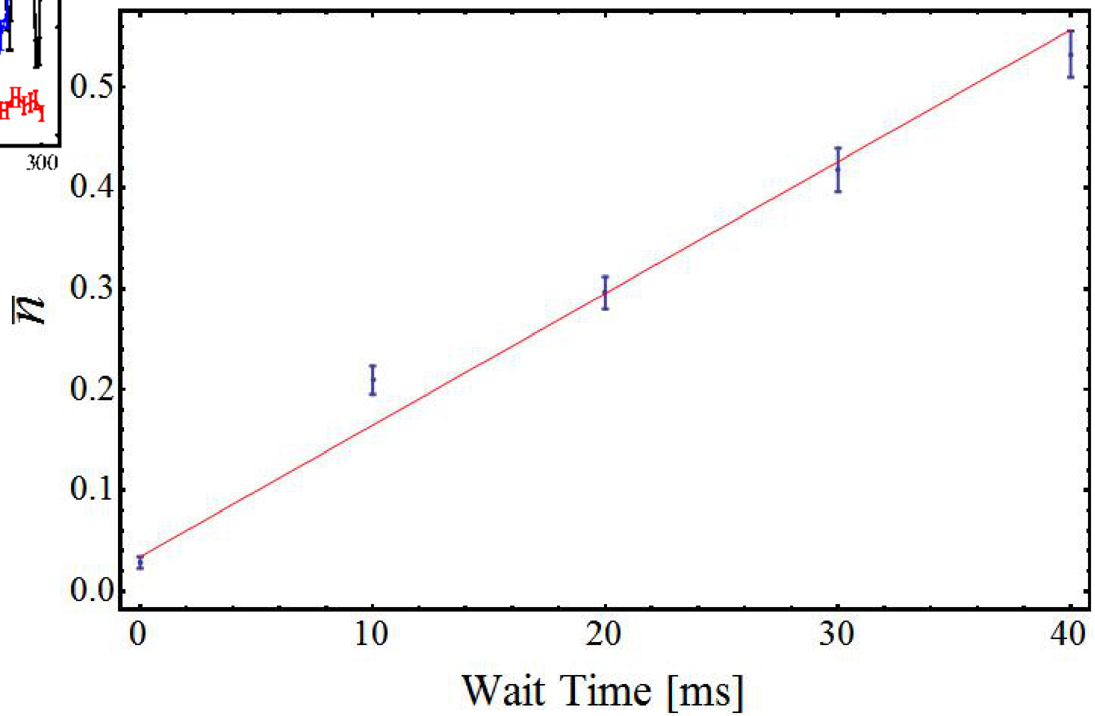
$$0.8\,phonons/ms < \dot{n} < 10 phonons/ms$$

New trap design with electroplated electrodes





MicroTrap design with electroplating



$\overline{n} \sim 0.033$

$\dot{n} \sim 13\ phonons/s$

@ trap frequency $2\pi\ 1.7\ MHz$

Distance ion ↔ electrodes: $d = 225\mu m$

In GBAR trap $d = 475\ \mu m$

$\dot{n}\ \propto d^{-4}$

$\Rightarrow\ \dot{n}_{GBAR} \sim 0.7\ phonons/s$

Adiabatic wavepacket expansion

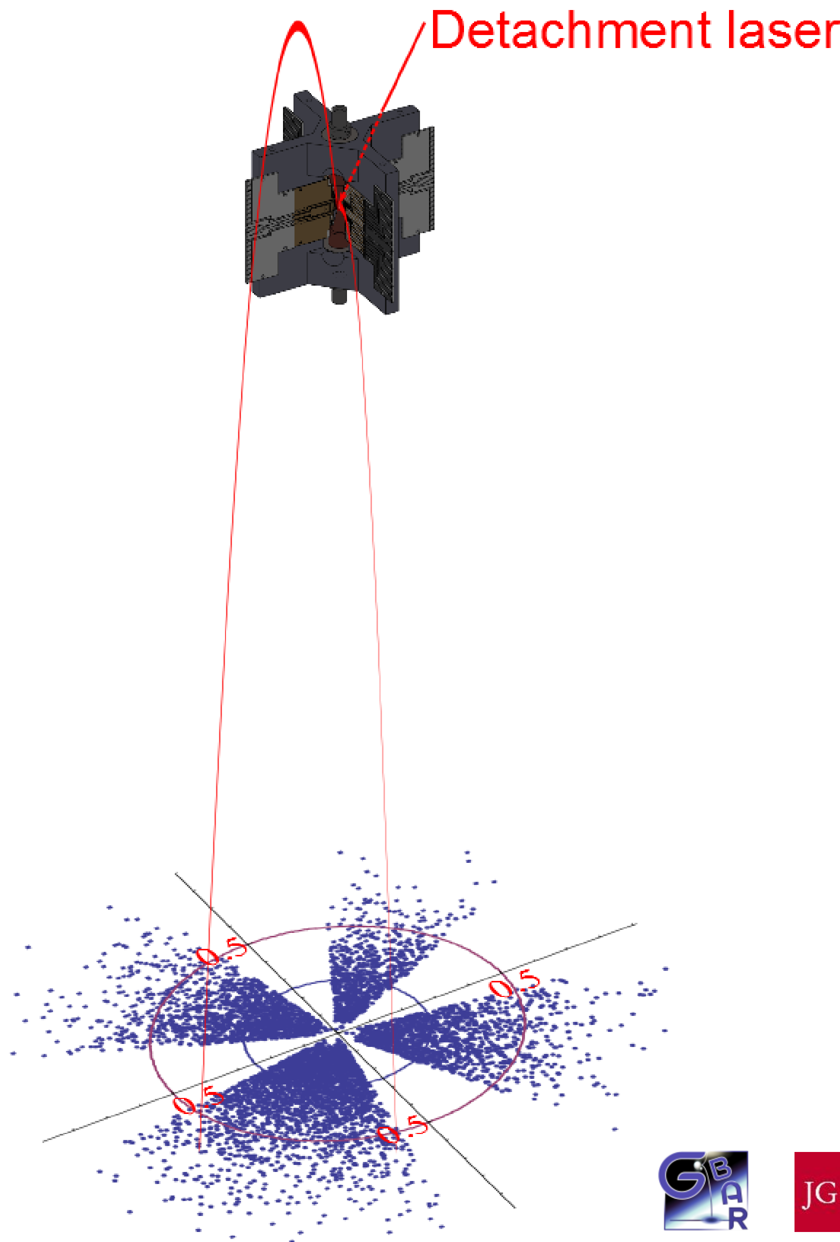
Heisenberg limited ground state

$$\frac{\Delta \bar{g}}{\bar{g}} = \sqrt{\left(\frac{\Delta x}{2\,h}\right)^2 + \left(\frac{\hbar}{2\,m\sqrt{2\bar{g}\,h\,\Delta x}}\right)^2}$$

Optimal position spread for g determination
→ $\omega_{ax} = 2\pi\ 1\ Hz;\ \Delta x_{min} = 88\mu m$

Main error from velocity spread

Solution:
Vertical trap and adiabatic opening of axial potential



G. Dufour et al.,
Eur. Phys. J. C, **74** 2731 (2014)

Adiabaticity vs. Heating rate

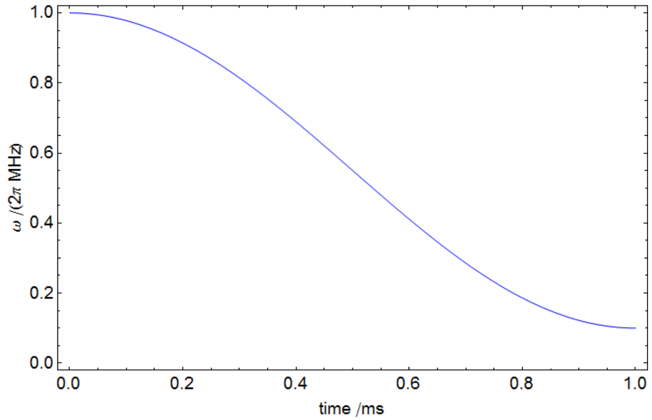
Axial adiabatic expansion $\omega_{ax} = 2\pi\ 1\ MHz \ \rightarrow 2\pi\ 0.1\ MHz$

Sin²-ramp

$$\frac{dn}{dt} \propto \ \omega^{-1}$$

Adiabaticity criterium

$$\frac{\dot{\omega}(t)}{\omega(t)^2} \ll 1, \forall t$$

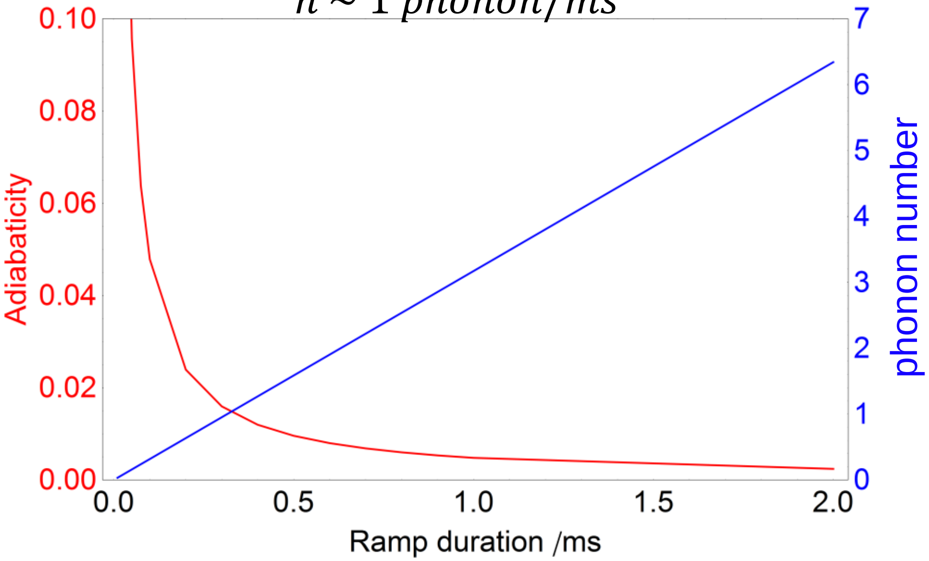


S. Schulz et al.,
Progress of Physics **54**, 648 (2006)

G. Poulsen et al.,
Phys. Rev. A **86**, 051402(R) (2012)

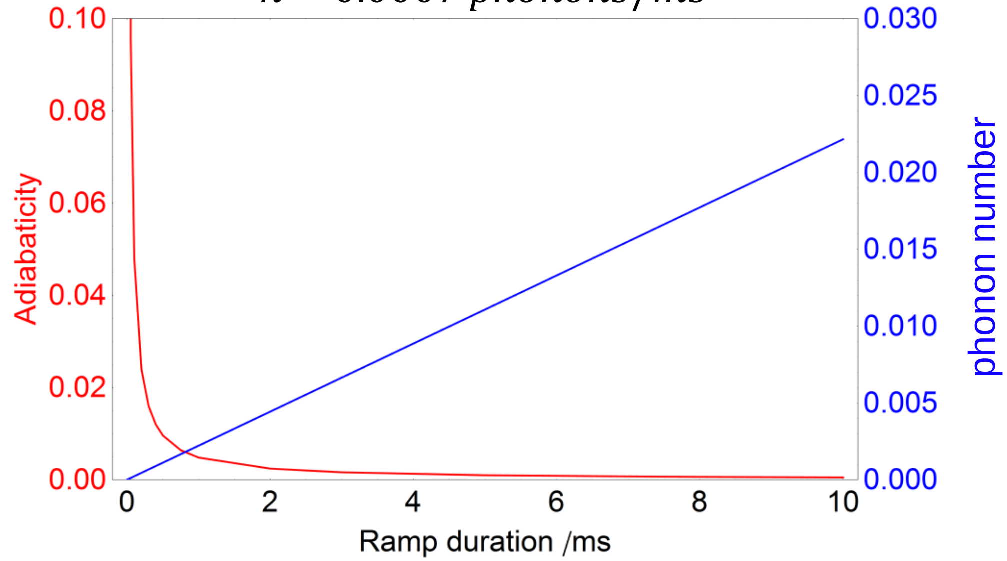
„old“ trap

$\dot{n} \sim 1\ phonon/ms$



„new“ trap

$\dot{n} \sim 0.0007\ phonons/ms$



Adiabaticity vs. Heating rate

Axial adiabatic expansion $\omega_{ax} = 2\pi\ 1\ MHz\ \rightarrow 2\pi\ 0.1\ MHz$

Sin²-ramp

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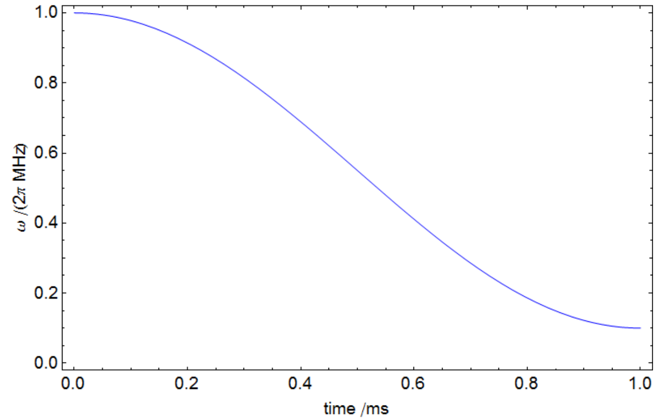

S. Schulz et al.,
Progress of Physics **54**, 648 (2006)

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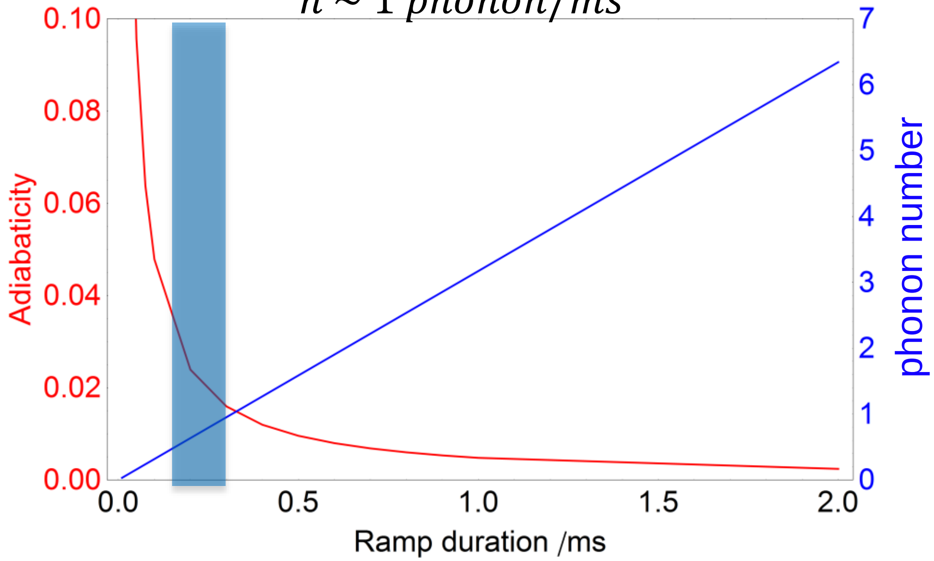

„new“ trap

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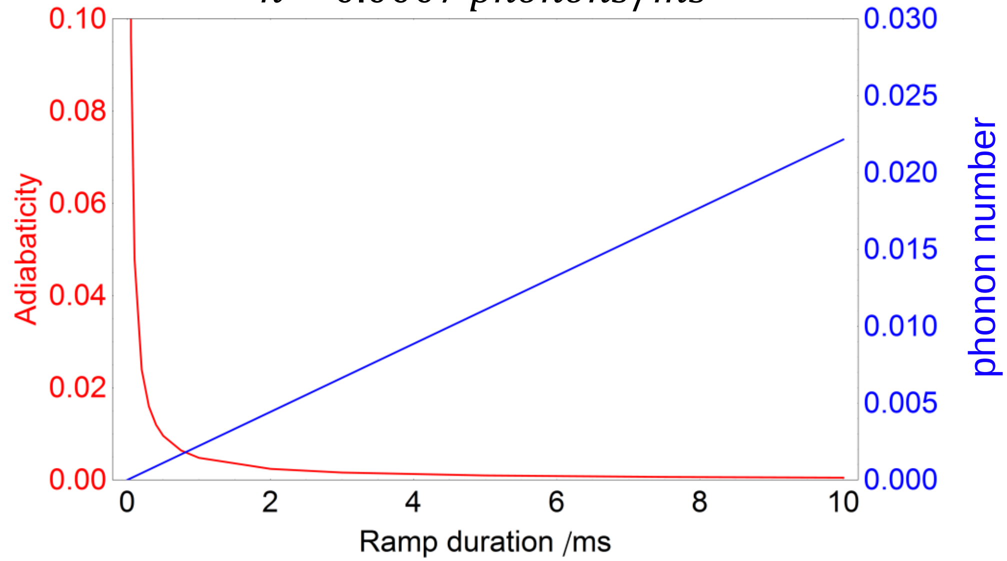

Adiabaticity vs. Heating rate

Axial adiabatic expansion $\omega_{ax} = 2\pi\ 1\ MHz\ \rightarrow 2\pi\ 0.1\ MHz$

Sin²-ramp

$$\frac{dn}{dt} \propto \omega^{-1}$$

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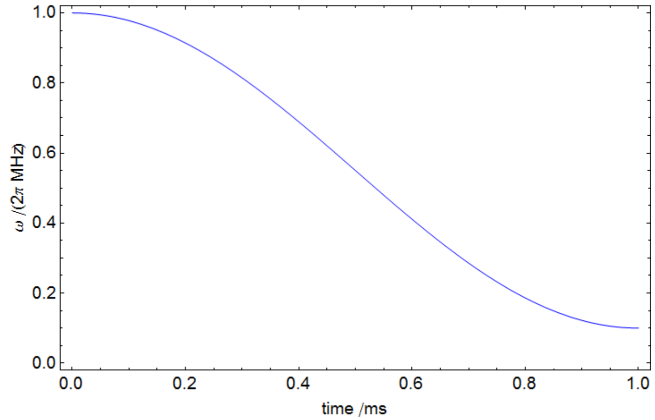
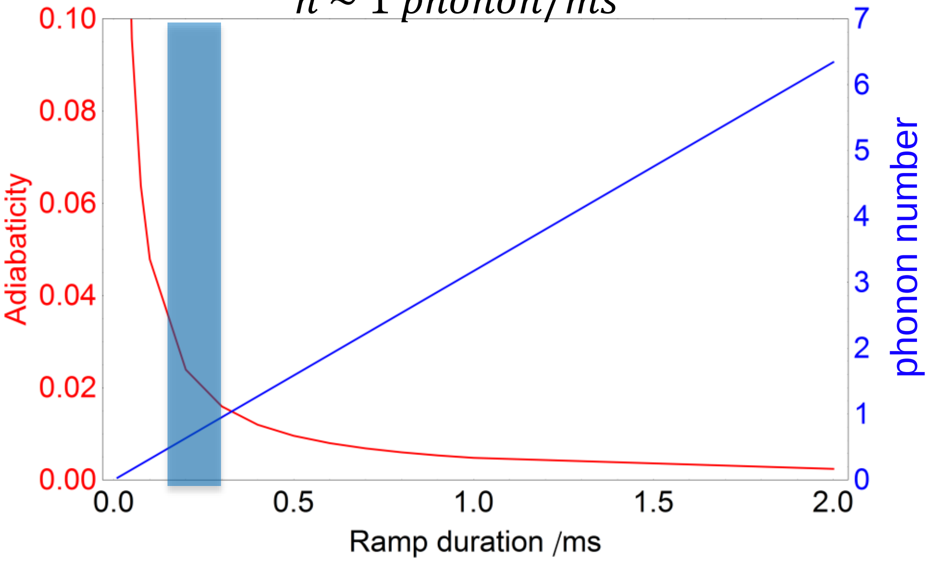


S. Schulz et al.,
Progress of Physics **54**, 648 (2006)

G. Poulsen et al.,
Phys. Rev. A **86**, 051402(R) (2012)

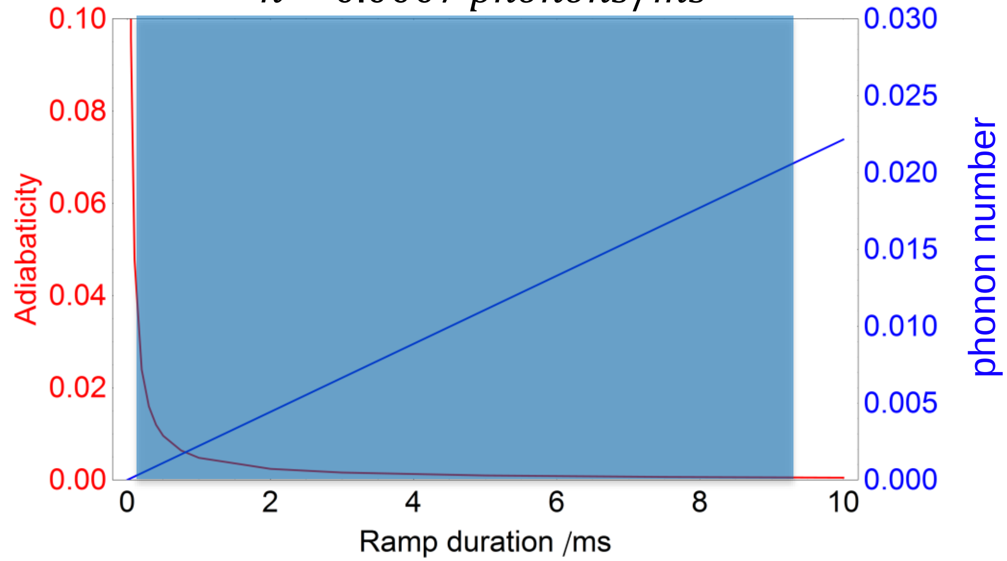
„old“ trap

$\dot{n} \sim 1\ phonon/ms$



„new“ trap

$\dot{n} \sim 0.0007\ phonons/ms$

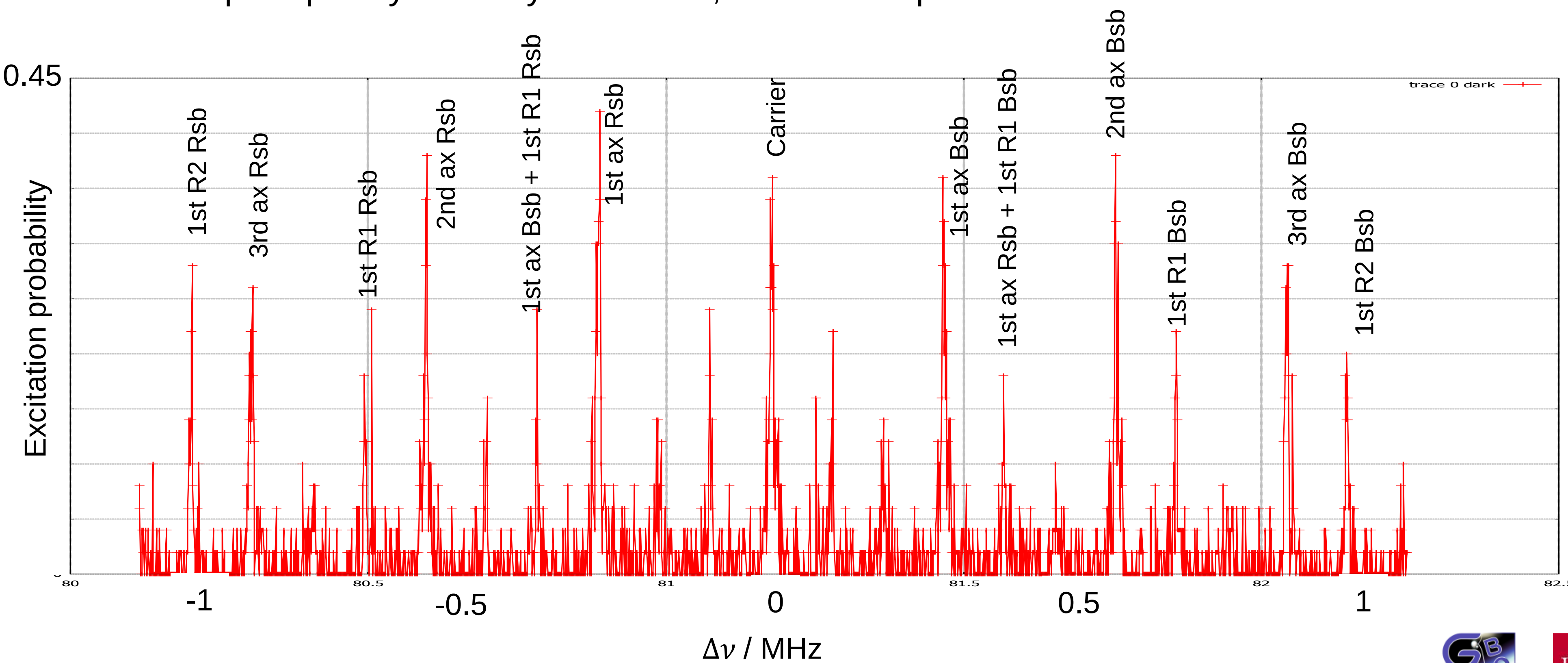


Temperature measurement after expansion

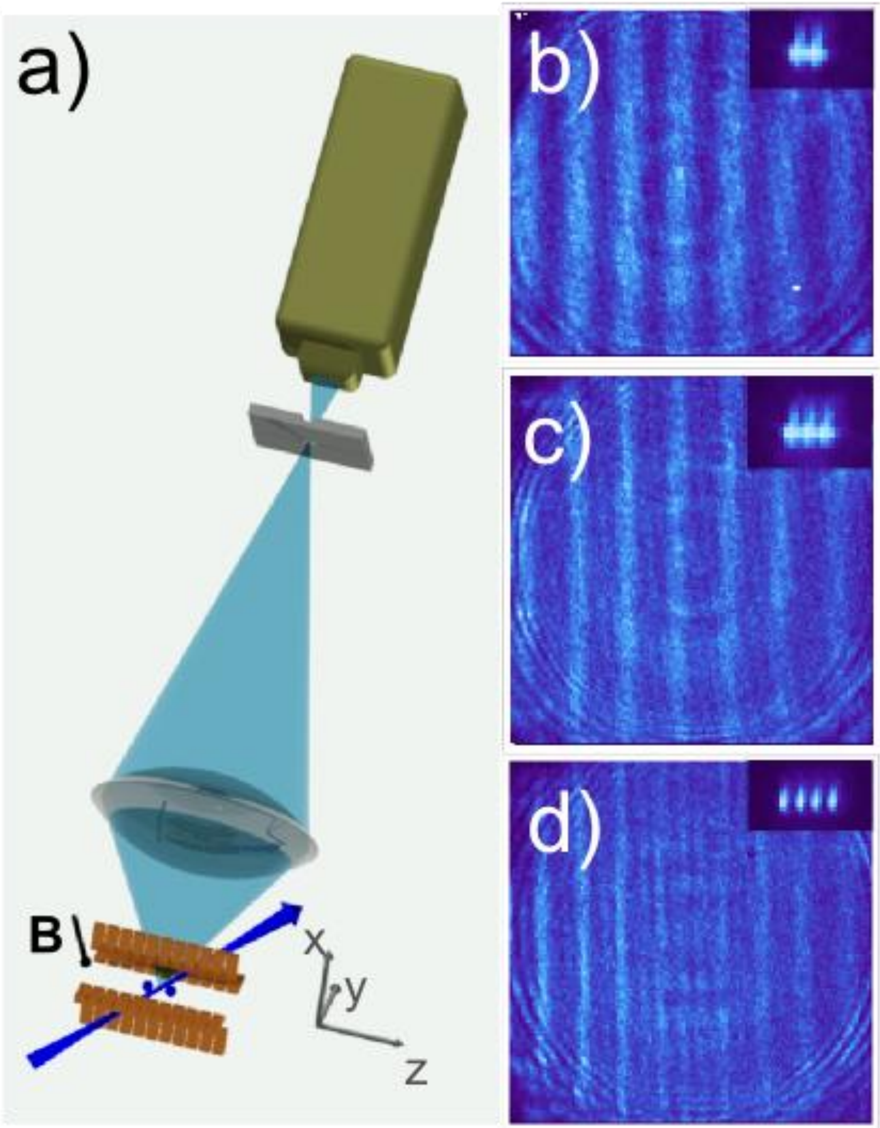
$$\eta = k \cos\phi \sqrt{\frac{\hbar}{2\, m\, \omega}}$$ Lamb-Dicke parameter

$$\Omega_{n+m,n} = \Omega_0 e^{-\frac{\eta^2}{2}} \eta^{|m|} L^{|m|}_{\min(n,n+m)}(\eta^2) \frac{(\min(n,n+m))!}{(\max(n,n+m))!}$$ Rabi frequency of sidebands

small trap frequency → many sidebands, hard to interprete/adress



Young-interference of ions in far-field



Debye-Waller factor

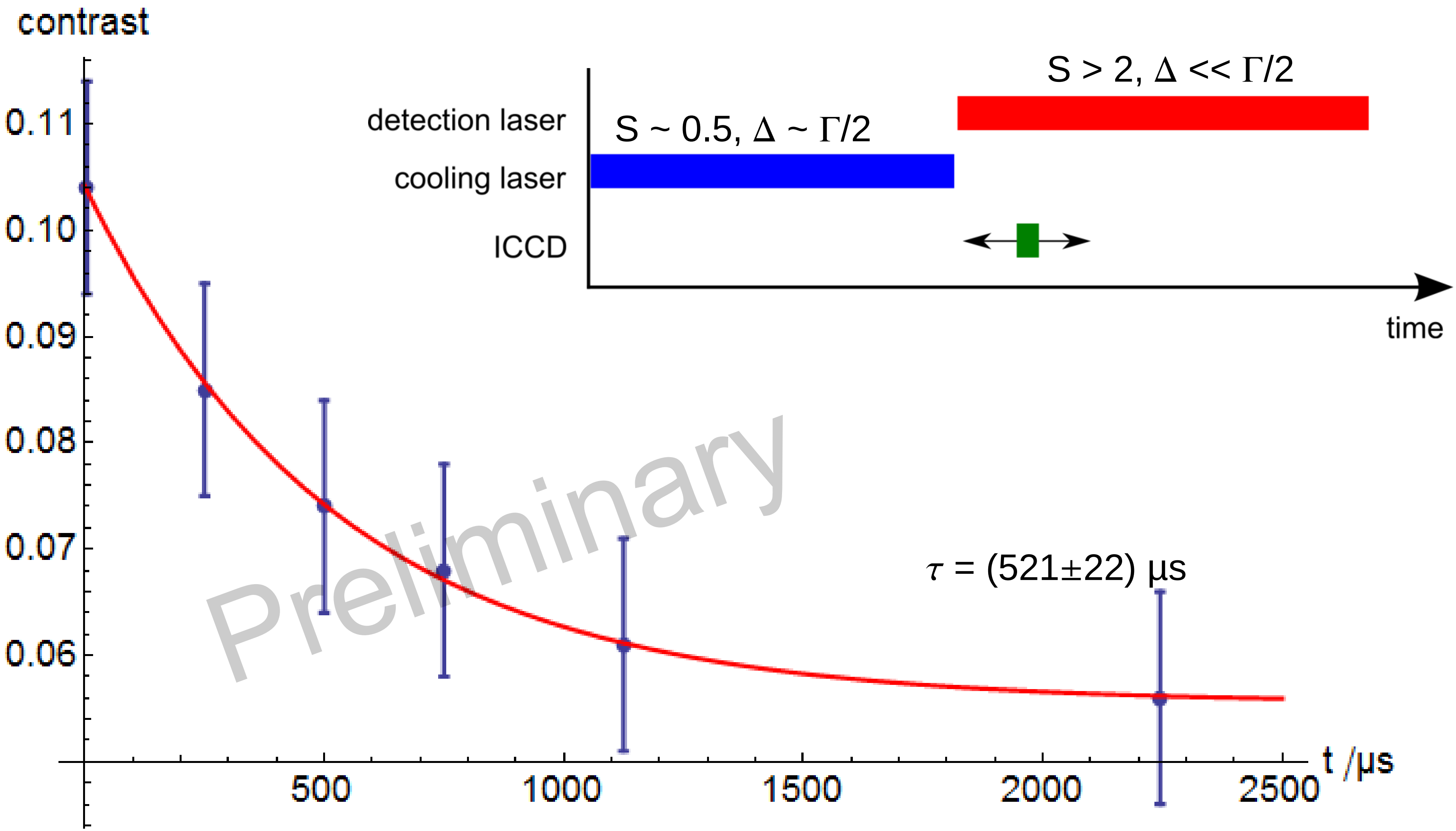
$$I(\boldsymbol{q}) = 2I_0(1 + \cos(q_z d)\exp\{-\langle[\boldsymbol{q}\cdot(\boldsymbol{u_1} - \boldsymbol{u_2})]^2\rangle/2\})$$

$$\boldsymbol{q} = \boldsymbol{k}_{out} - \boldsymbol{k}_{in}$$

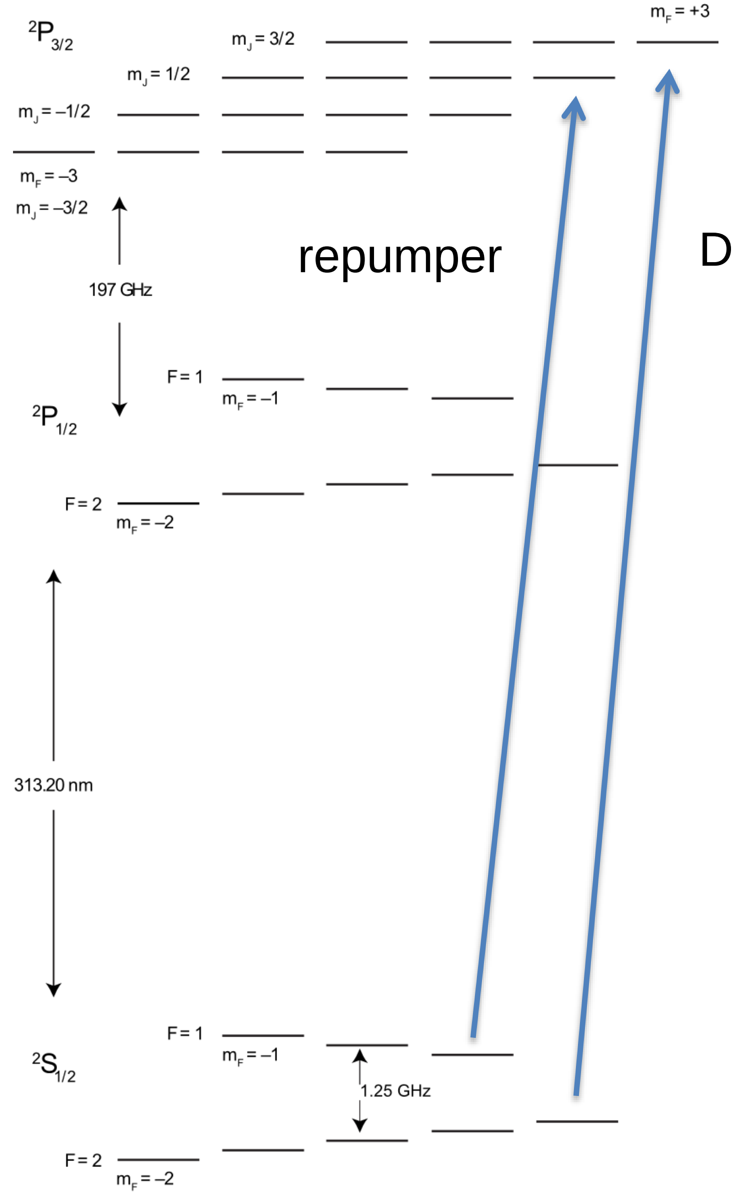
→ Contrast is temperature dependant

U. Eichmann et al.,
Phys. Rev. Lett. **70**, 2359 (1993)

Thermometry with two ion crystals



Level scheme of $^9Be^+$ ions



I=3/2

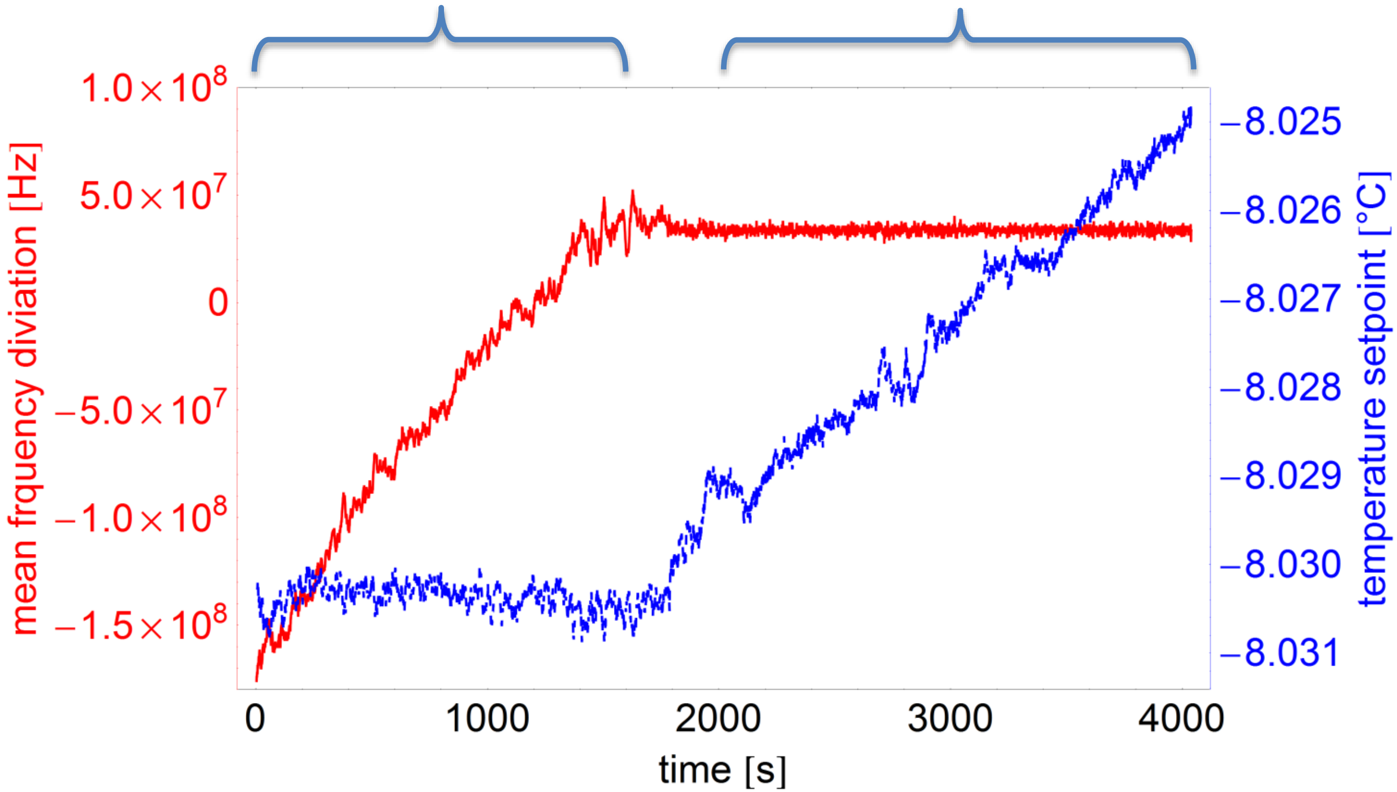
D. J. Wineland et al.,
Phys. Rev. Lett. **50**, 628 (1983)

Distributed **B**ragg **R**eflector diode

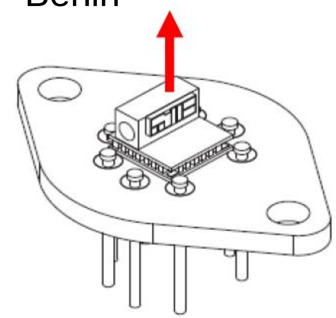
λ = 626 nm

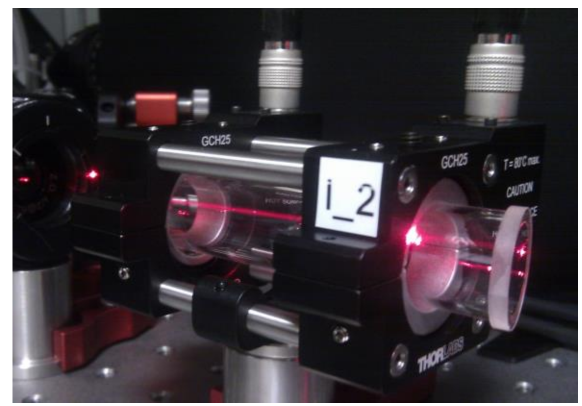
Only temperature stabilzed

Locked on wavemeter
Frequency variation < 1.6 MHz



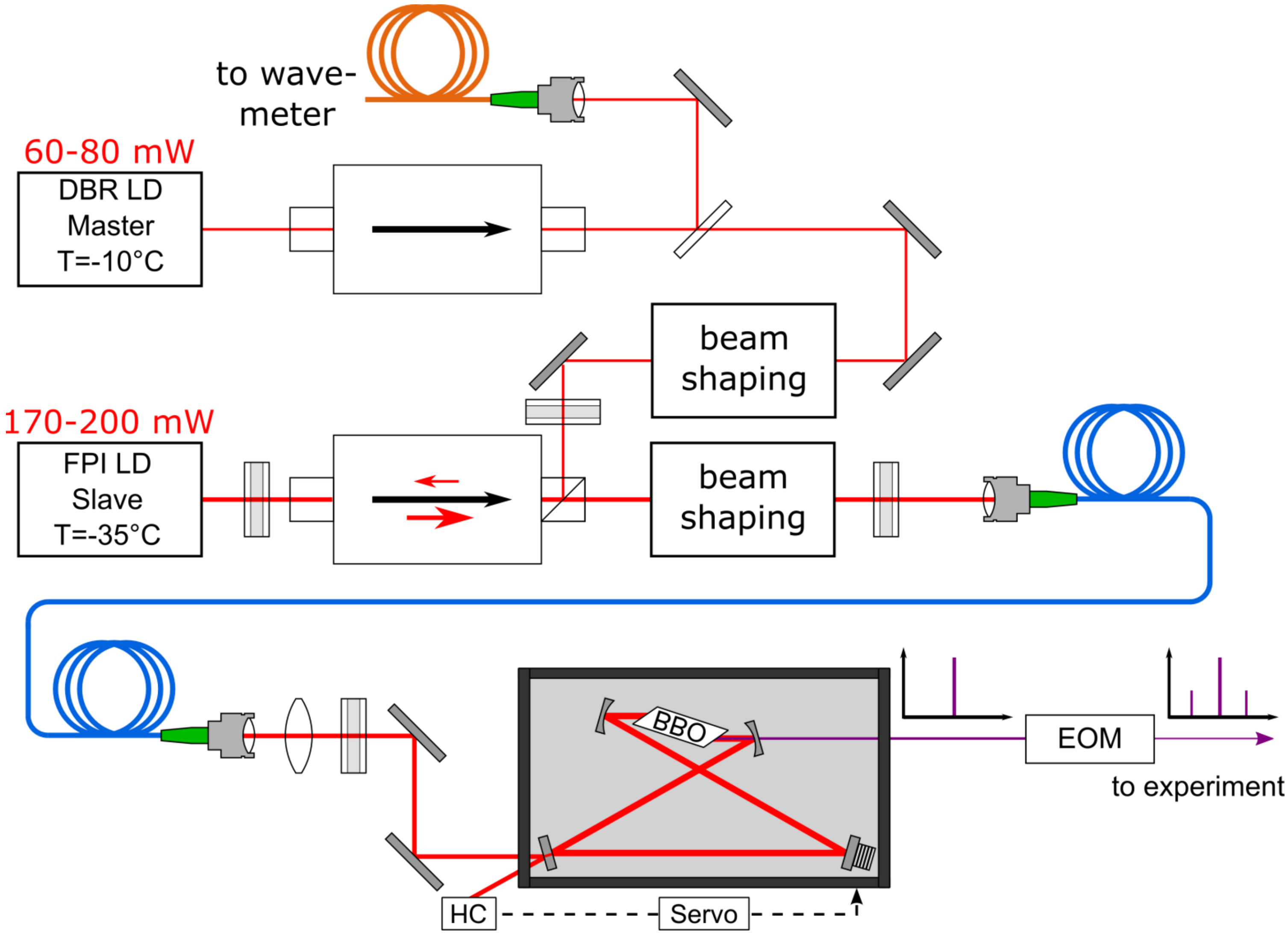
from Ferdinand-Braun-Institute Berlin



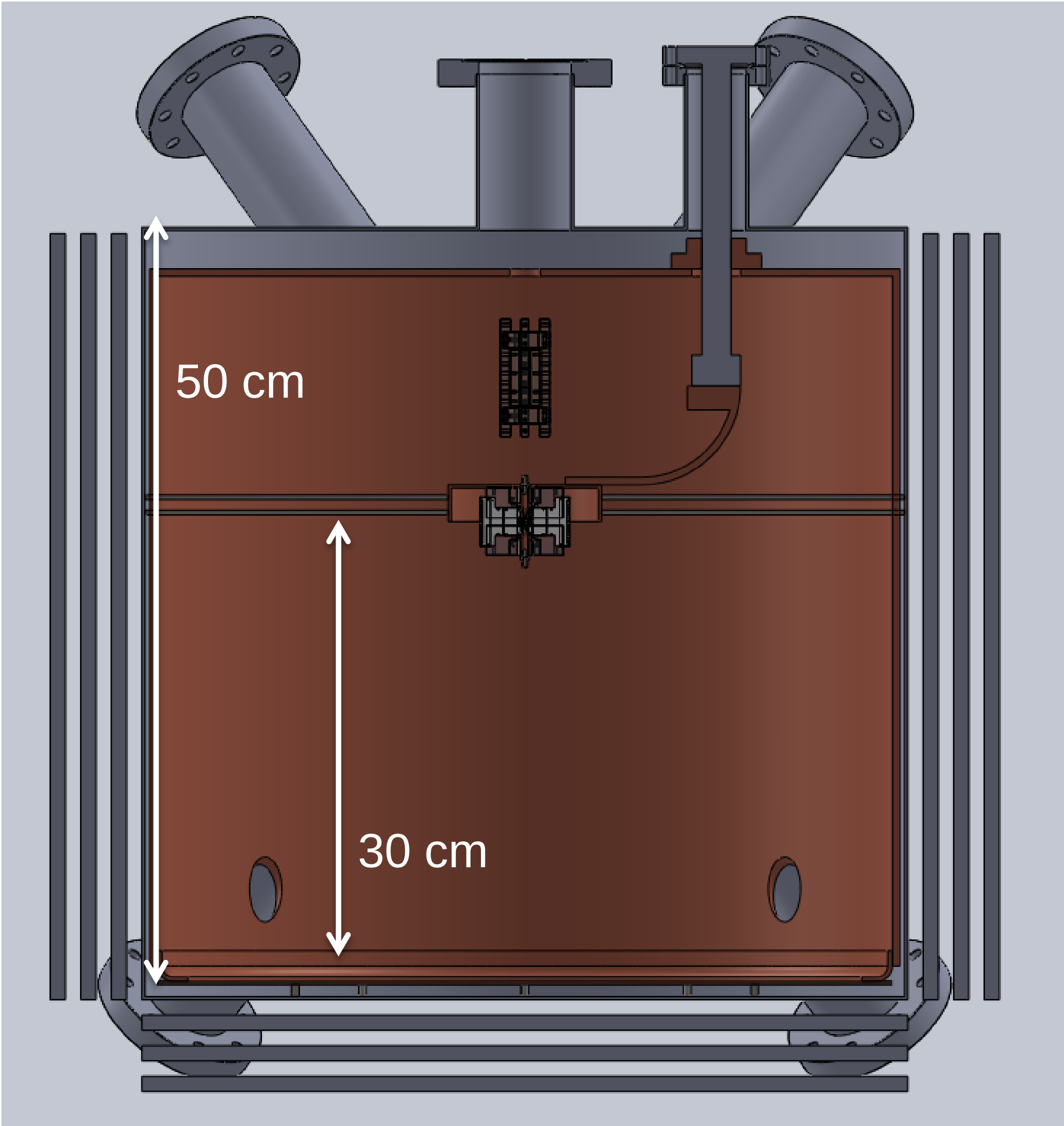


Currently setting up an Iodine spectroscopy cell

313nm Laser setup for Beryllium cooling

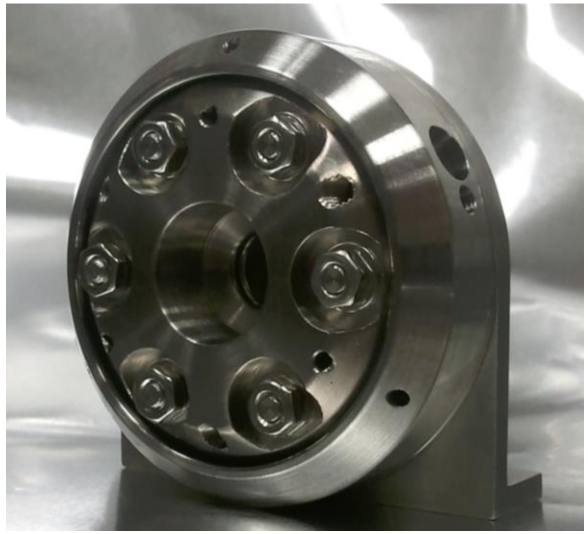


Cryogenic UHV setup

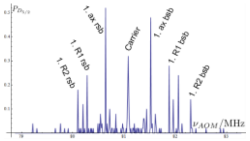


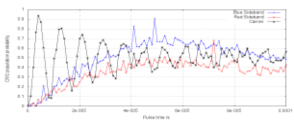
Design constraints

- Cryo (heating rate, pressure)
- Optical access (lasers, CCD)
- Thin walls (pion detection)
- Ion optics ($\overline{H}^+$ transport)
- Capture trap
- Velocity shaper

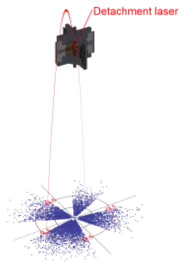


Conclusion and Outlook

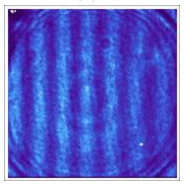




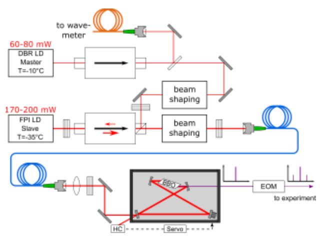
Sideband spectroscopy and cooling
Increased mode coupling required — **2015**



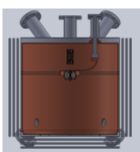
Adiabatic expansion for decreased momentum distribution — **2016**



Interference contrast for temperature measurements — **done**



construction of Beryllium laser setup — **2015**



Cryo setup design — **2016**