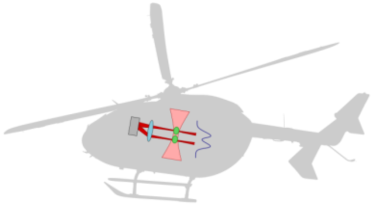
Matter-wave collimation to picokelvin energies with scattering length and potential shape control

Alexander Herbst

Leibniz University Hannover



Guided matter-wave interferometry group

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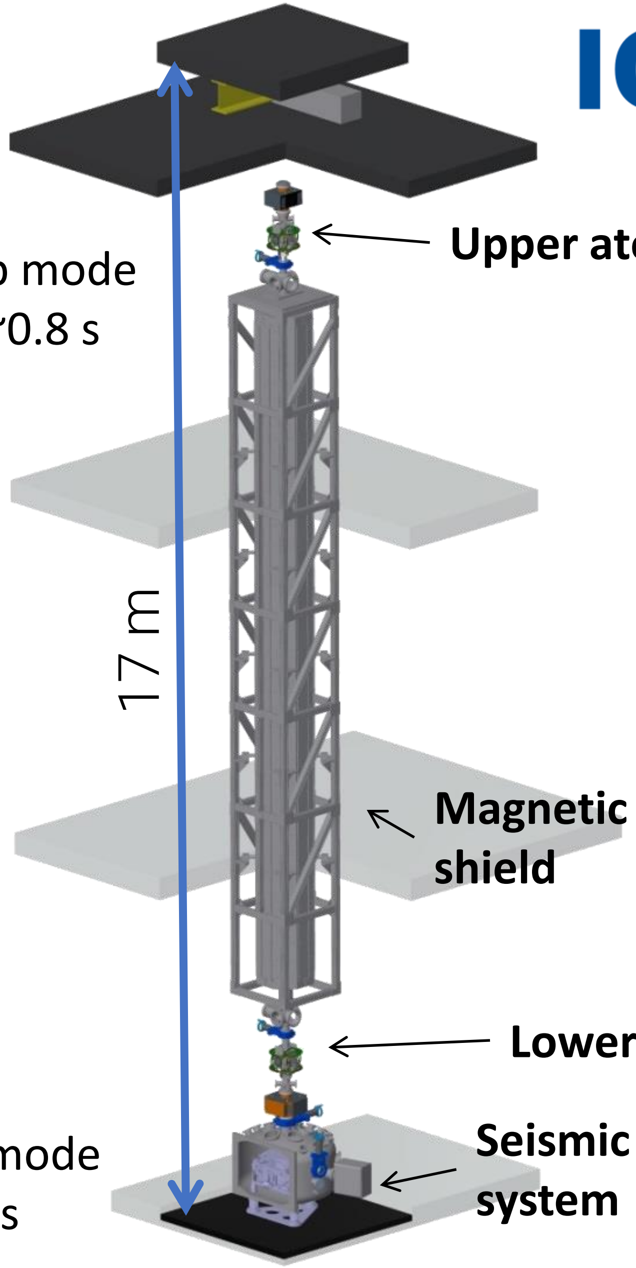
The VLBAI facility

Atomic sources

- Rubidium & ytterbium (quantum-degenerate)
- Drop/launch mode

Inertial reference

- Geometric anti-spring system (f_0 ~ 320 mHz) with active stabilization
- Rotation compensation system (cf. Kasevich, Müller groups)



Drop mode
2T ~0.8 s

17 m

Upper atomic source

Magnetic shield

Lower atomic source

Seismic attenuation system

Launch mode
2T ~ 2.8 s

AI-zone & magnetic shield

- 10.5 m CF 200 Al tube
- Dual-layer mu-metal (octagonal geometry; collaboration with P. Fierlinger, TU München)

[Schlippert et al., arXiv:1909.08524]

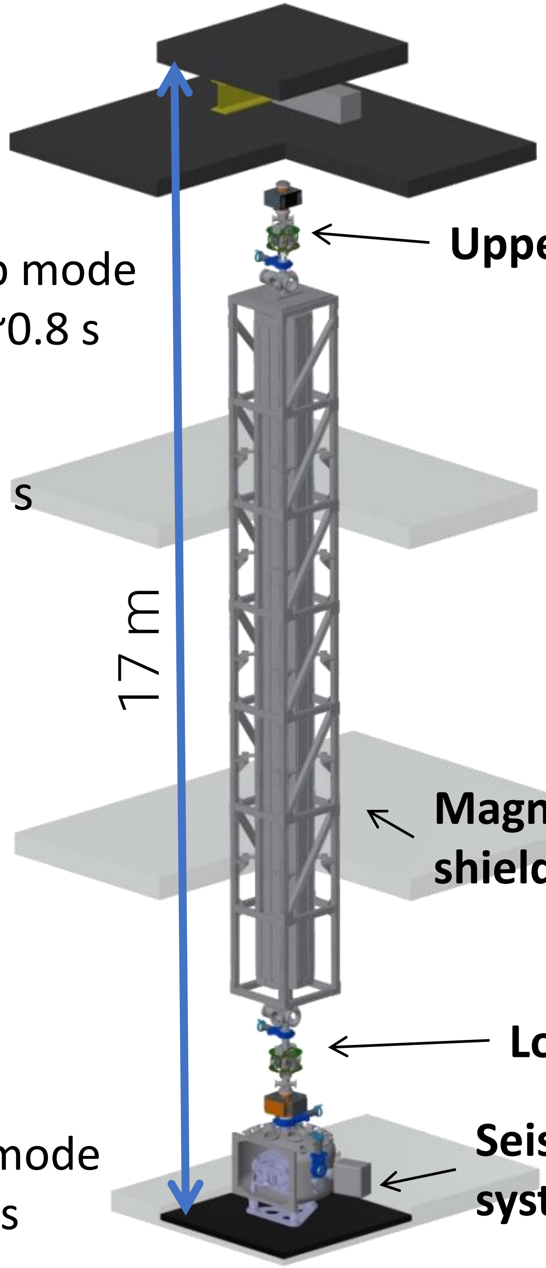
The VLBAI facility

$$\boxed{\Delta\phi = k_{\text{eff}} \cdot g \cdot T^2}$$

Drop mode – 1st generation source
2×10^5 at, 2 photons, 2T = 800 ms, T_{prep} = 3 s
→1.7×10^{-9} m/s² @1s

Launch mode – 2nd generation source
1×10^6 at, 4 photons, 2T = 2.8 s, T_{prep} = 3 s
→4×10^{-11} m/s² @1s

→ ~10^{-13} g after O(1 day) of integration



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Launch mode
2T ~ 2.8 s

[Schlippert et al., arXiv:1909.08524]

Gen. Rel. Grav. 43(7) 1931 (2011)

Wuhan (China)

J. Hogan, PhD thesis, Stanford U. (2010)

Stanford (USA)
+ ANU, Firenze, Berkeley,
Stanford (II), UK, …

Long baseline challenges

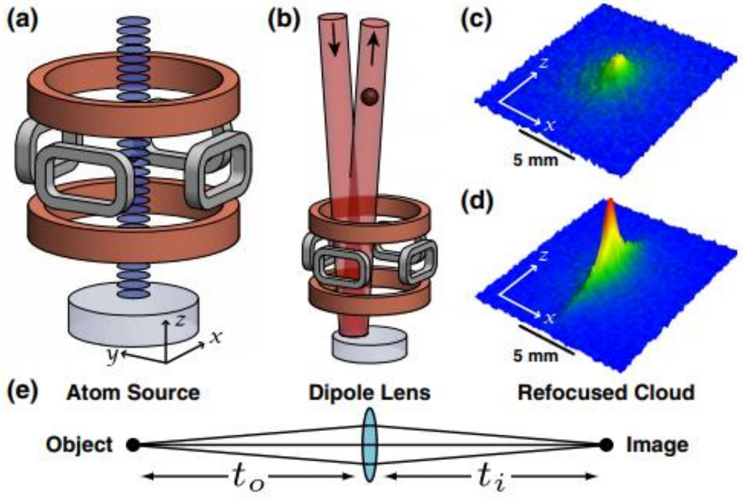
Long baselines usually demand large free apertures in-line (~10 cm or more)

- Challenging circumstances for strongly confining magnetic traps (large distance or beam clipping)
- Yb and Sr are non-magnetic

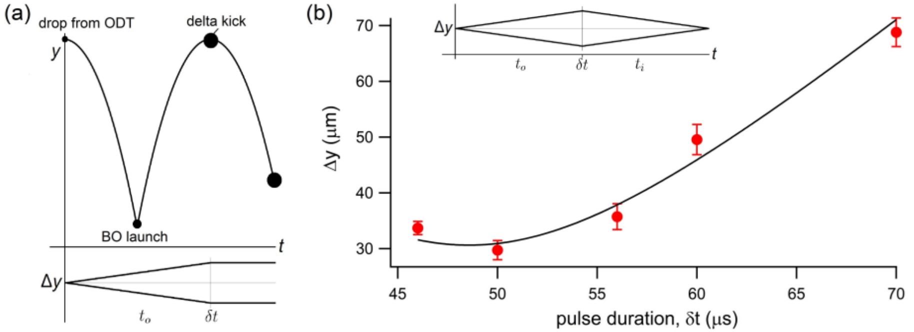
➢ Solution: All-optical setups

Matter-wave lensing

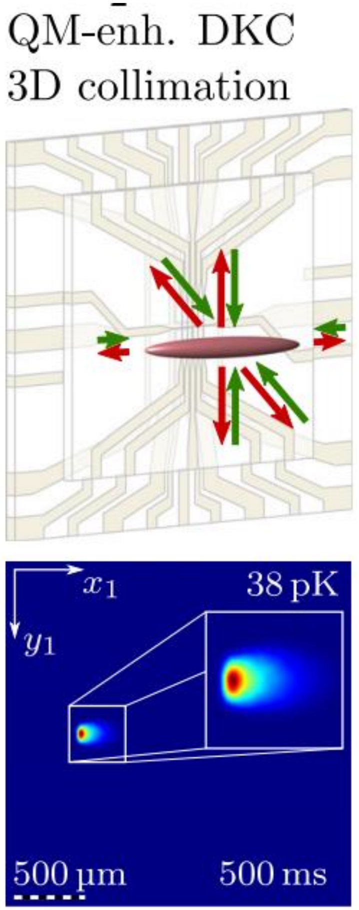
- Access to lowest kinetic energies
- Shortcuts of evaporation trajectories → higher flux
- Long initial time-of-flight can be experimentally challenging w/o micro-gravity



[Kovachy et al., PRL 2015]

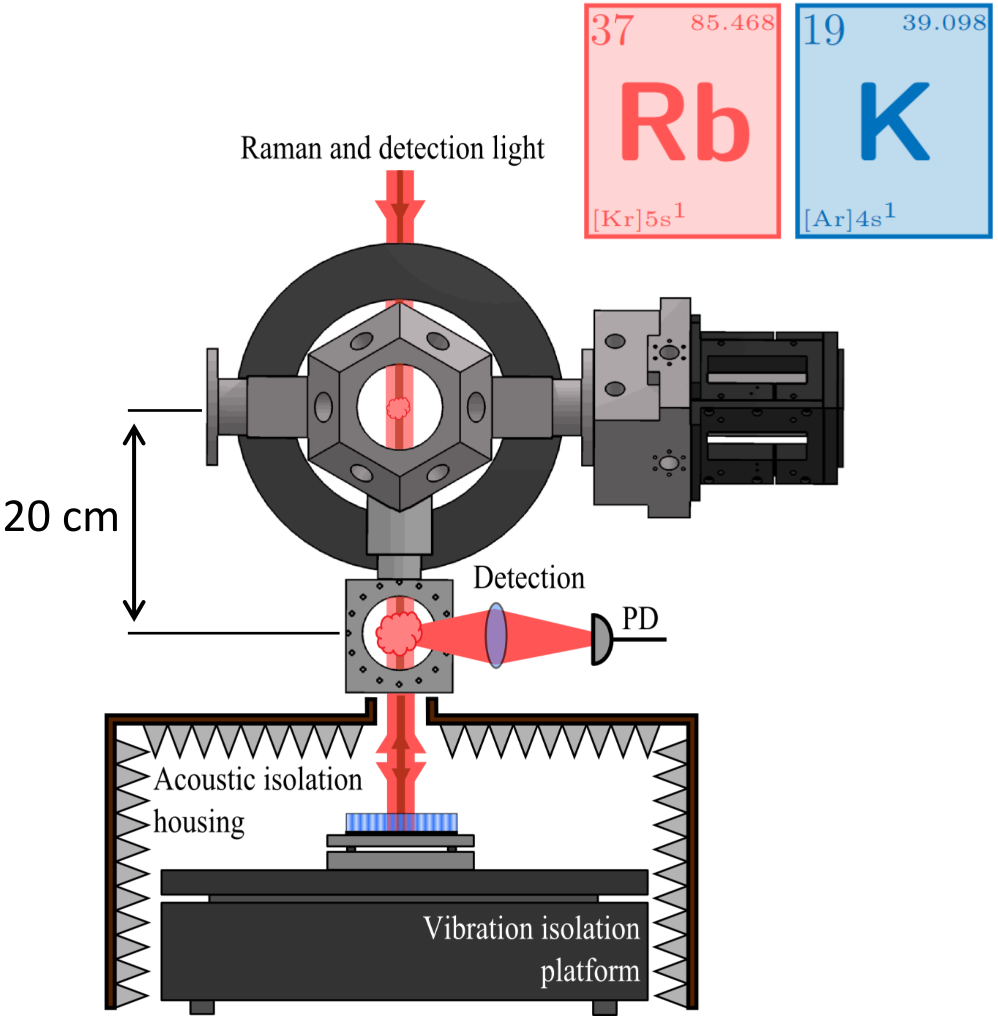


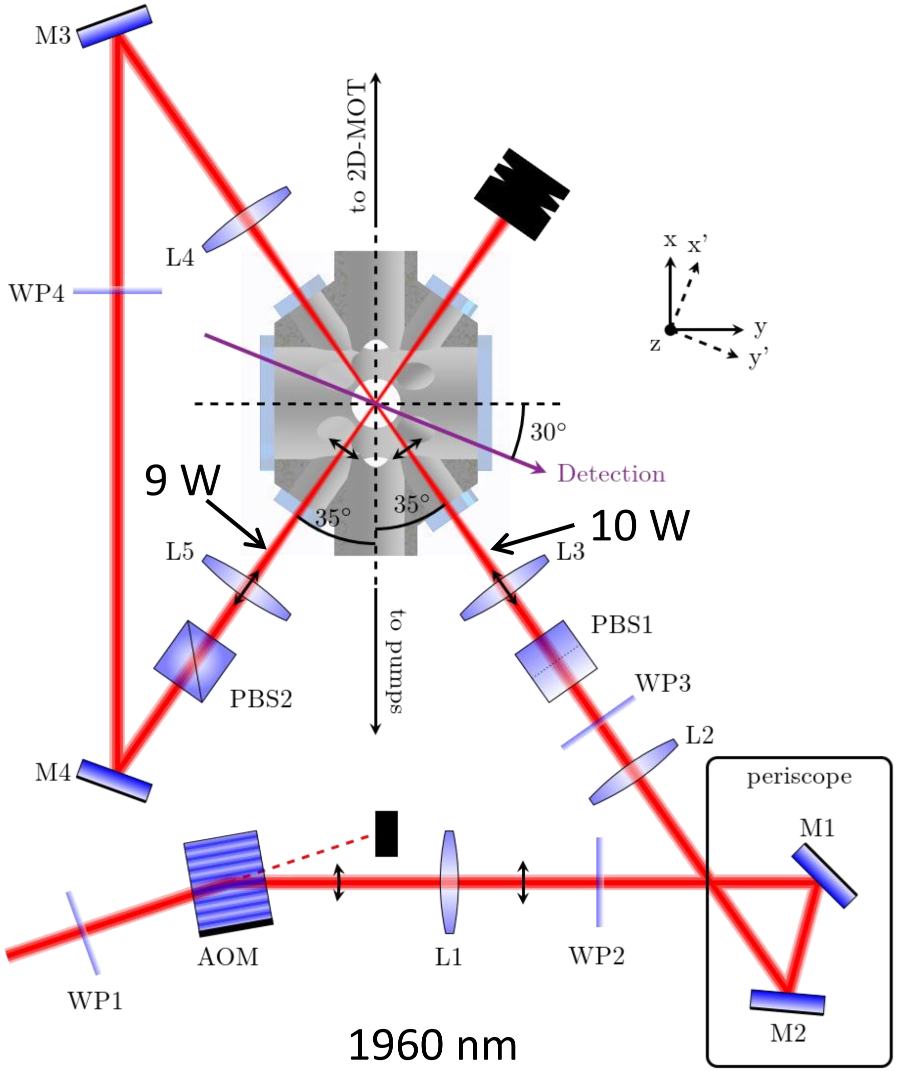
[Gochnauer et al., atoms 2021] ©



[Deppner et al., PRL 2021]

Experimental setup





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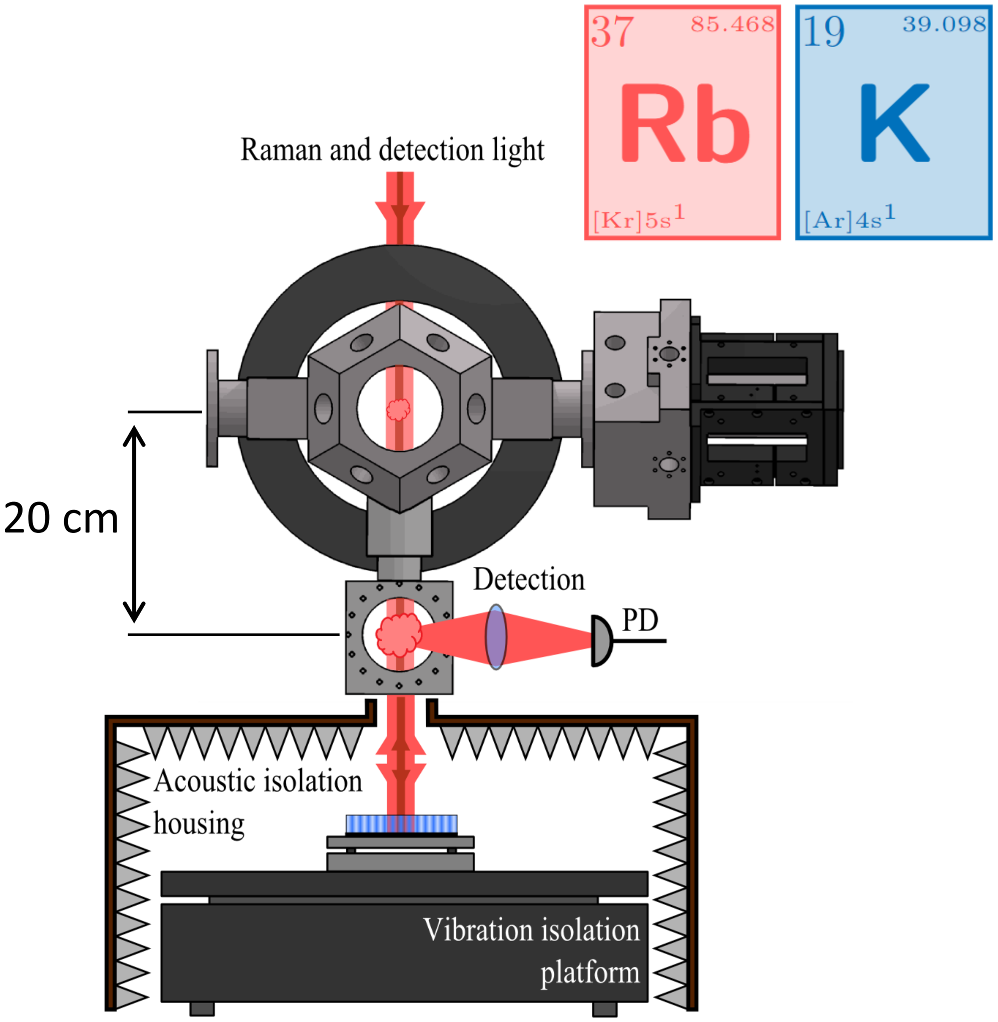

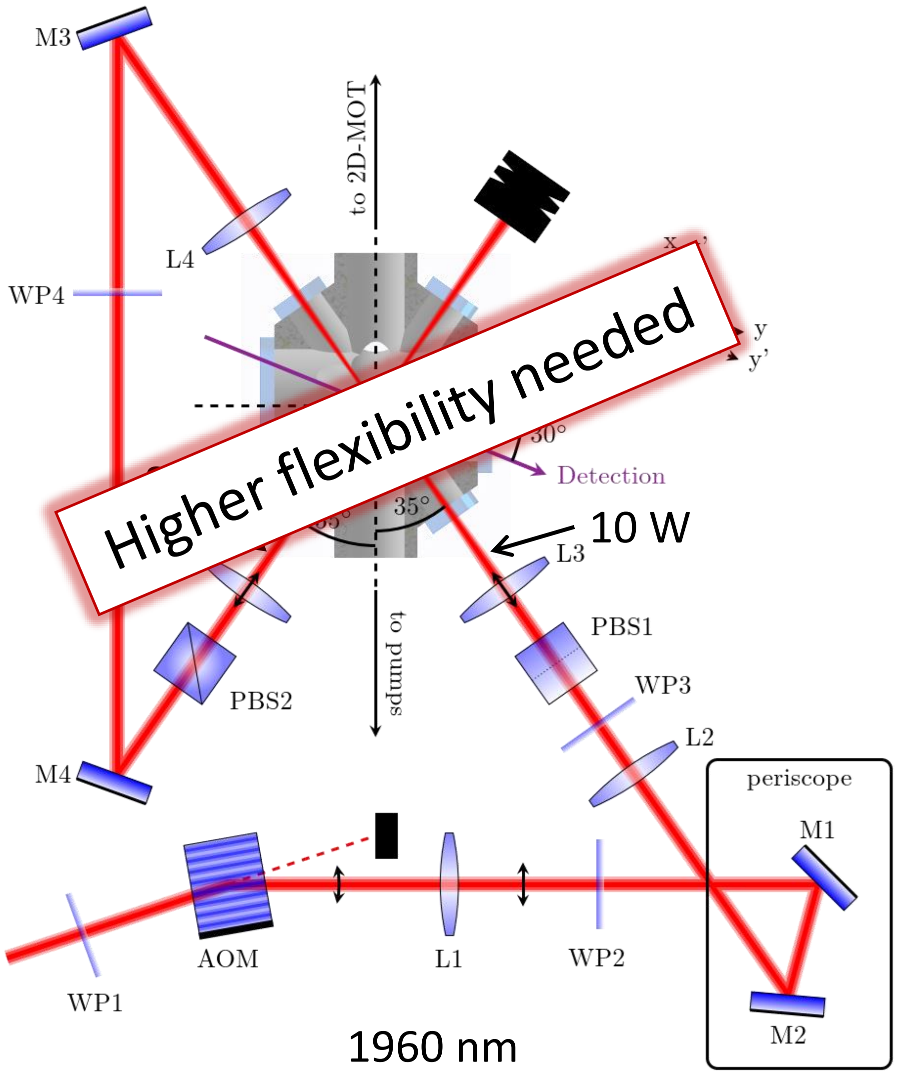

Higher flexibility needed

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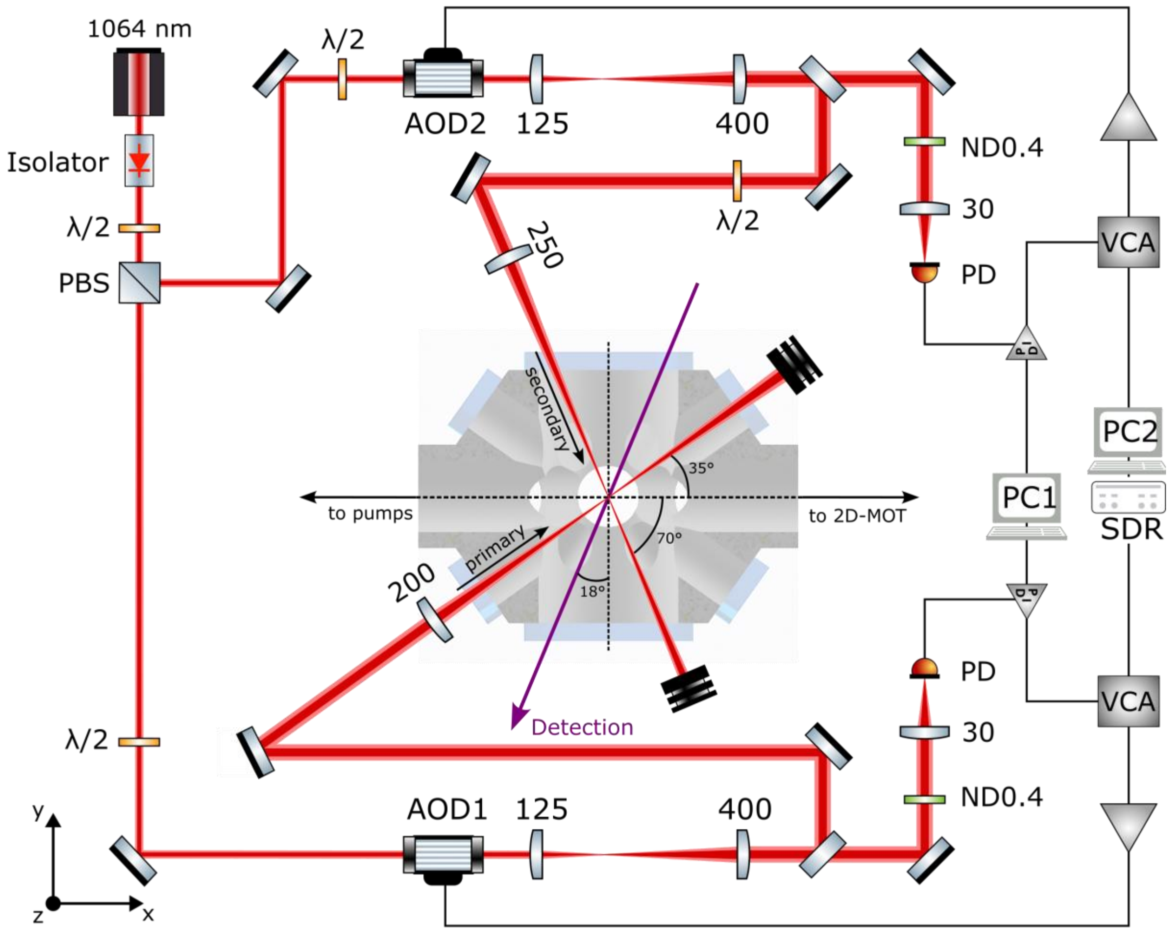
Experimental setup

- Source systems for molasses cooled ^{39}K, ^{87}Rb
- Independent control of ODT beams:
  - Primary beam: 16 W with w_0 = 24 µm waist
  - Secondary beam: 16 W with w_0 = 30 µm waist
- 2D-AOD: 1.5 mm horizontal and vertical modulation stroke



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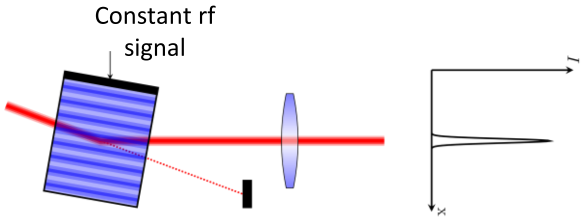
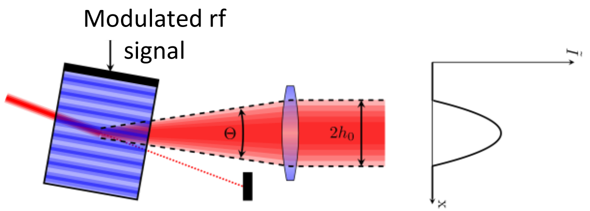
Time-averaged optical potentials

Without center-position modulation:



$$\omega_x = \sqrt{-\frac{2U_0}{m\boldsymbol{w_{0,x}^2}}}$$

With center-position modulation:



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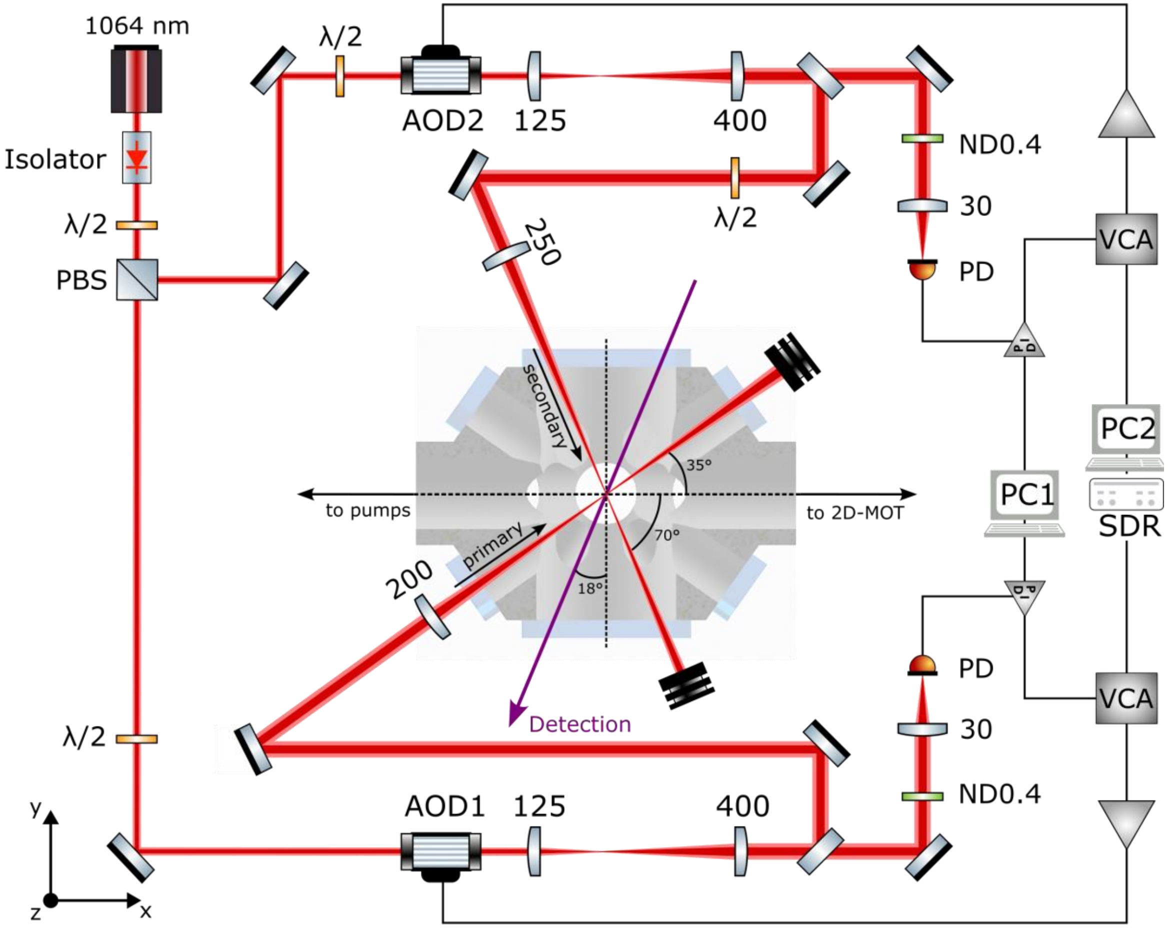

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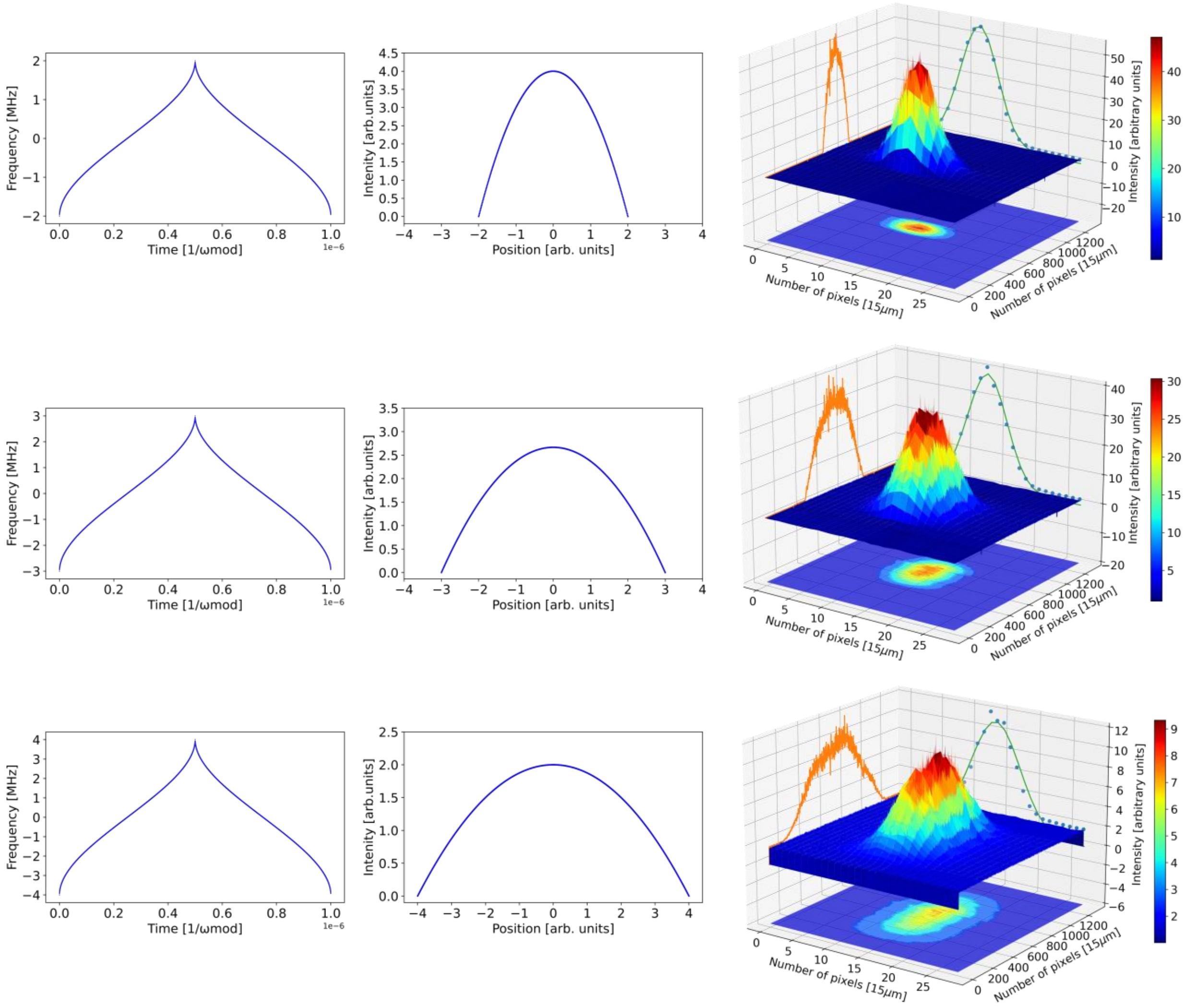

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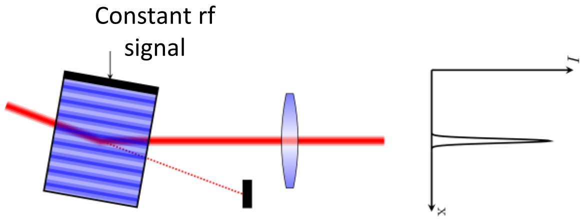

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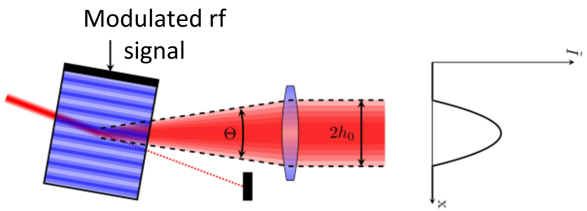

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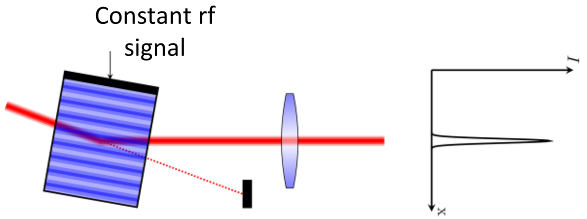

$$\omega_x = \sqrt{-\frac{2U_0}{m\boldsymbol{w}_{\mathbf{0,x}}^{\mathbf{2}}}}$$

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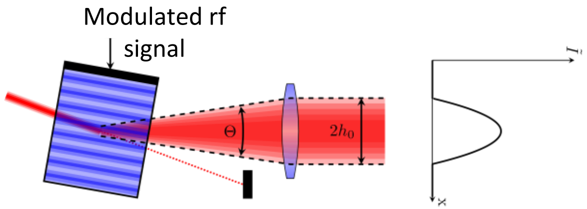
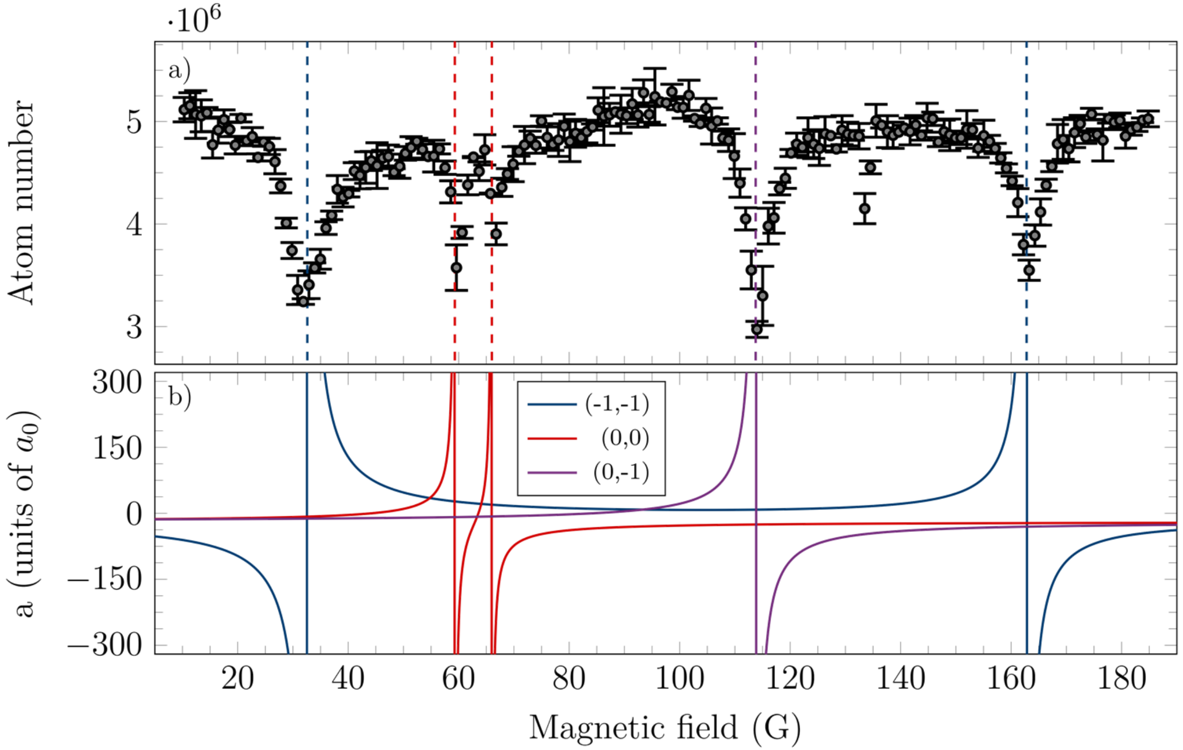


$$\omega_x = \sqrt{-\frac{2U_0}{m\boldsymbol{h}_{\mathbf{0}}^{\mathbf{2}}}}$$

Feshbach resonances

19 39.098
K
[Ar]4s^1

$$a(B) = a_{\mathrm{bg}}\left(1 - \sum_i \frac{\Delta B_i}{B - B_{0i}}\right)$$



Evaporation optimization

Evaporative cooling dynamics:

background gas collisions

$$\frac{dN}{dt} = -\left(\boxed{\Gamma_{\mathrm{ev}}} + \boxed{\Gamma_{\mathrm{3b}}} + \Gamma_{\mathrm{bg}}\right) N$$

compression

$$\frac{dT}{dt} = -\left(\frac{\boxed{\Gamma_{\mathrm{ev}}}}{3}(\eta + \alpha - 3) - \frac{\boxed{\Gamma_{\mathrm{3b}}}}{3} - \boxed{\frac{\dot{\bar{\omega}}}{\bar{\omega}}}\right) T + \frac{\Gamma_{\mathrm{sc}} E_r}{3 k_b}$$

off-resonant scattering

Evaporation rate: $\Gamma_{\mathrm{ev}} \propto \frac{N \bar{\omega}^3 a^2}{T}$

Three-body loss rate: $\Gamma_{\mathrm{3B}} \propto \frac{N^2 \bar{\omega}^6 a^4}{T^3}$

Evaporation efficiency:

$$R \propto \frac{T^2}{N \bar{\omega}^3 a^2}$$

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Evaporation optimization

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Evaporation efficiency:

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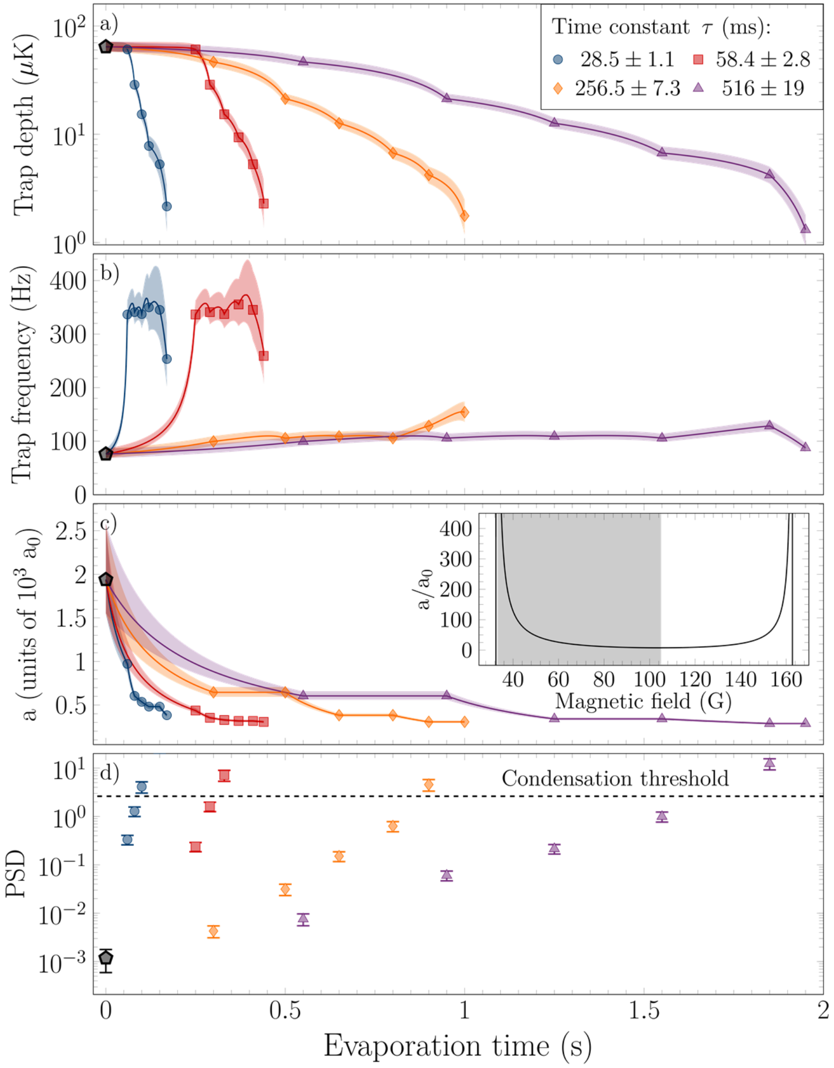
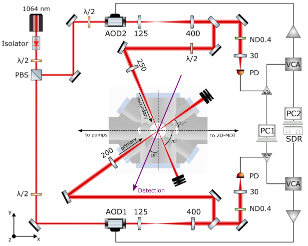
- ➢ **6×10^4 condensed particles after 170 ms**
- ➢ **6×10^5 condensed particles after 2 s**





[Herbst et al., Phys. Rev. Research 6, 013139 (2024)]

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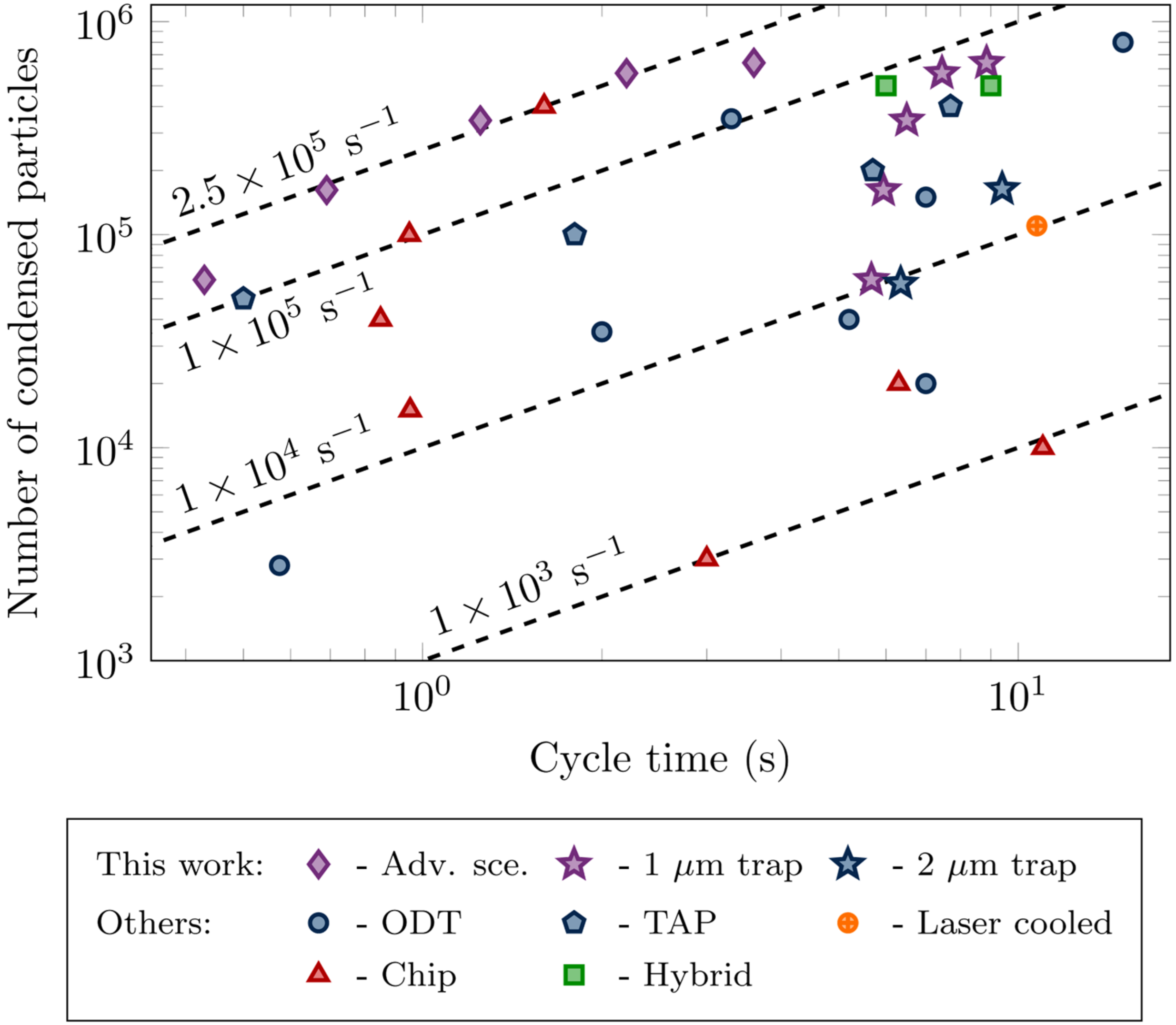
Performance comparison

Current setup limited by MOT loading time

- Combination of ODTs with TAPs and tunable interactions allows to match the performance of chip traps



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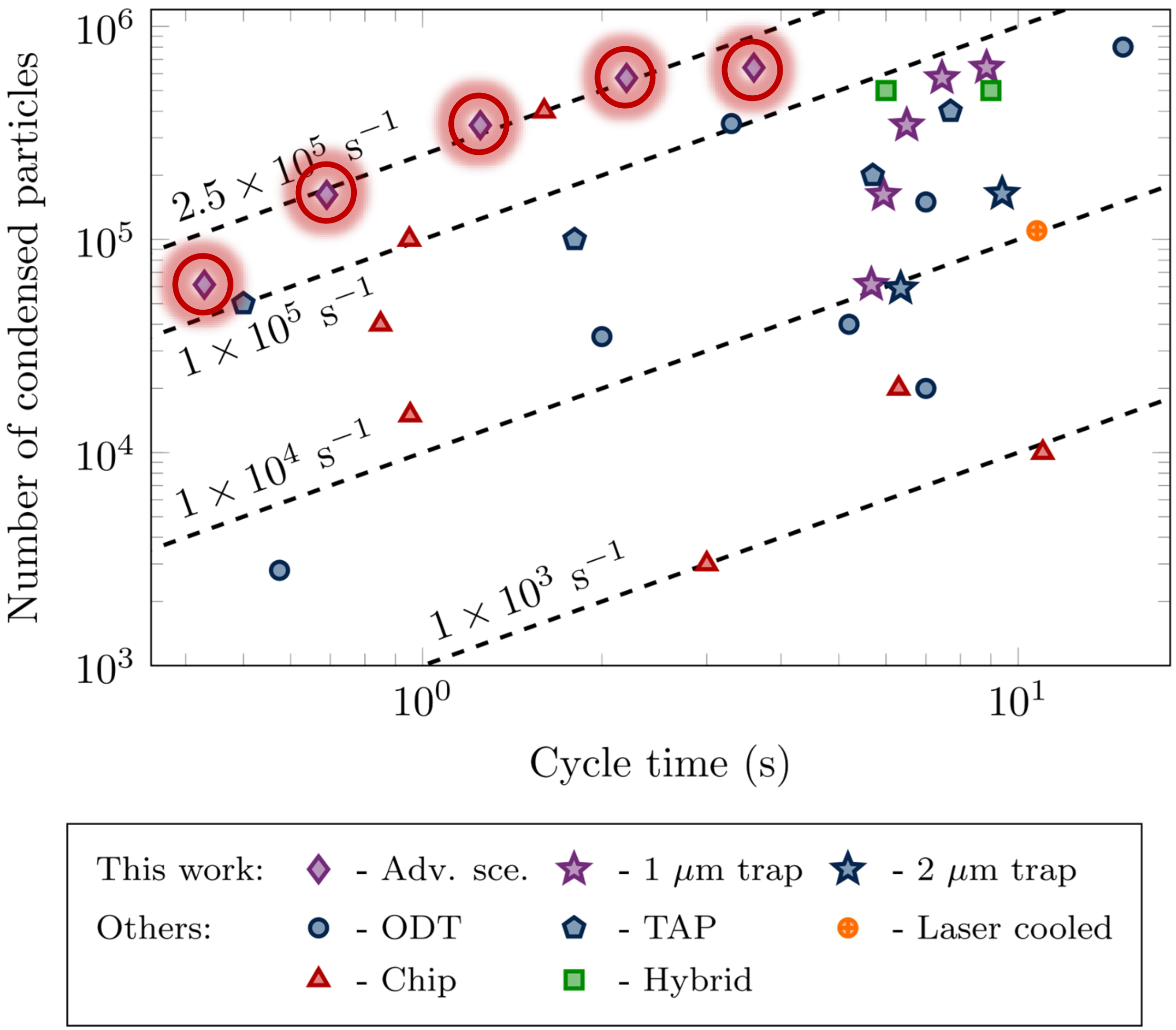

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Performance comparison

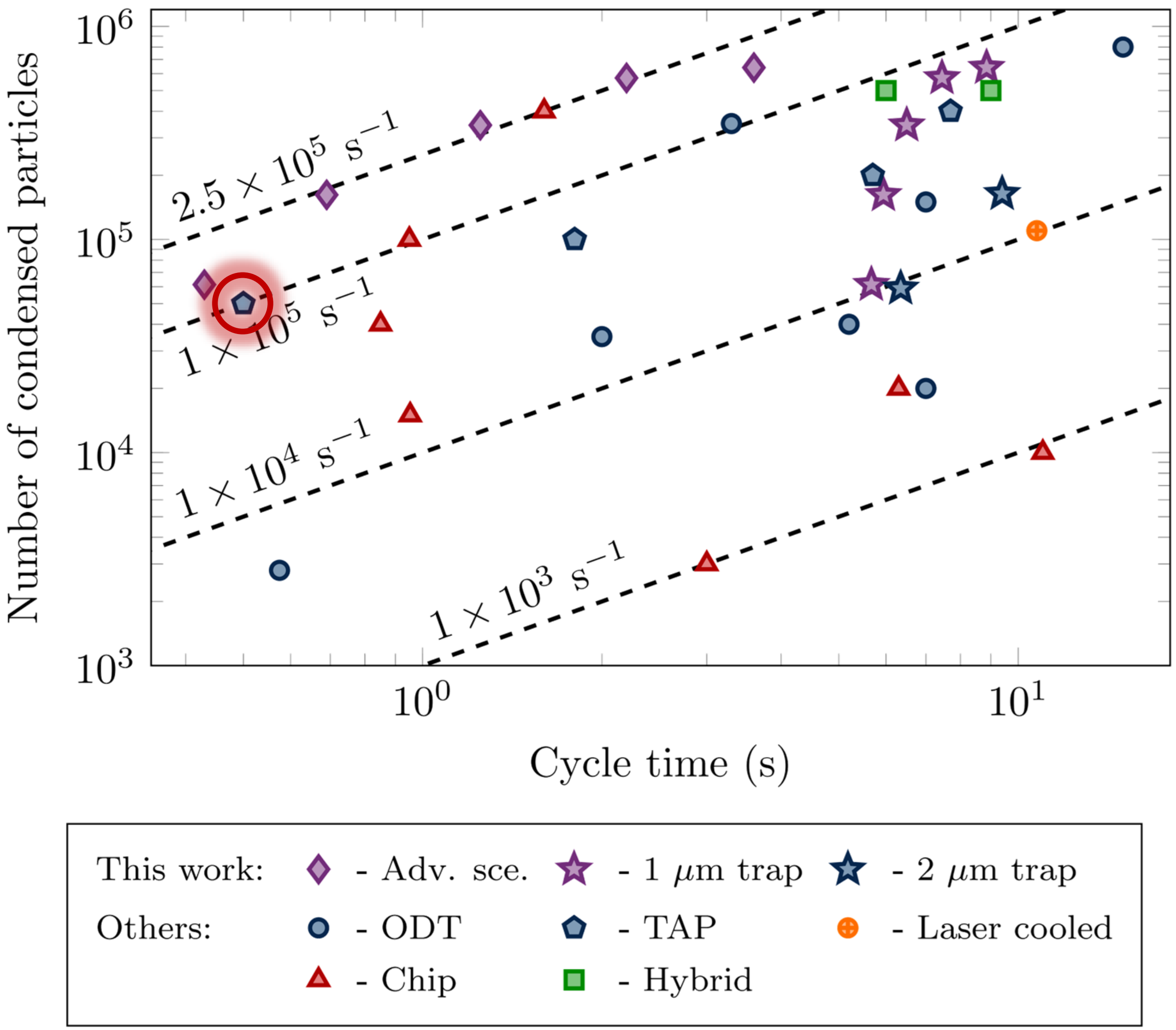
Current setup limited by MOT loading time

- Combination of ODTs with TAPs and tunable interactions allows to match the performance of chip traps

Similar results achieved with ^{87}Rb by further increasing the trap frequencies, using smaller beam waists:

$$\Gamma_{\mathrm{ev}} \propto \frac{N\bar{\omega}^3}{T} \qquad R \propto \frac{T^2}{N\bar{\omega}^3}$$

[Hetzel, Dissertation, 2023, Leibniz University Hannover]



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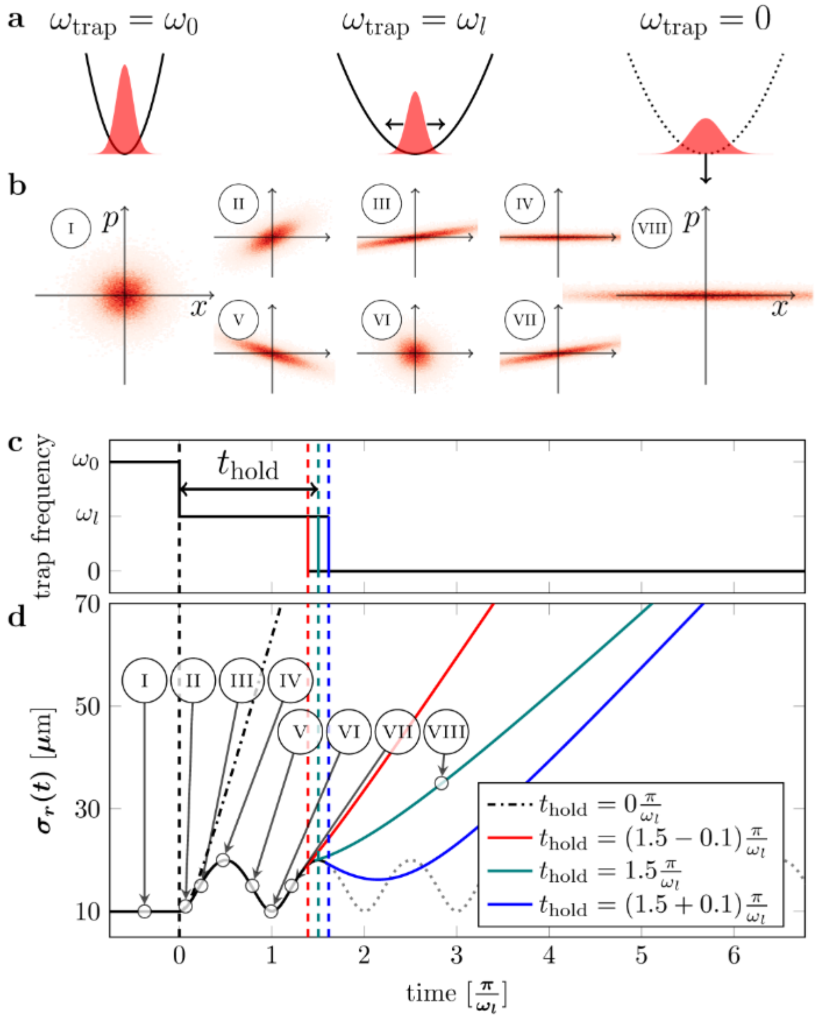
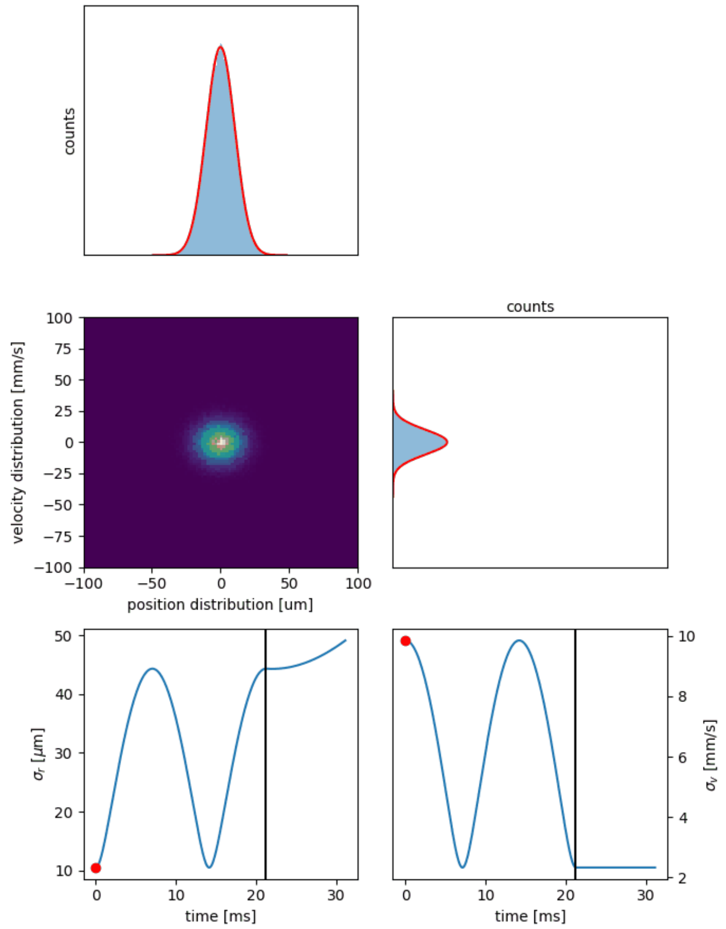
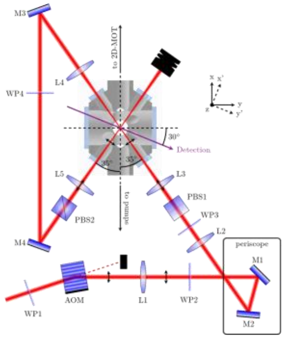
All-optical matter-wave lens

37 85.468
Rb
[Kr]5s^1







[Albers et al., Commun. Phys. 5, 60 (2022)] 🅭

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All-optical matter-wave lens

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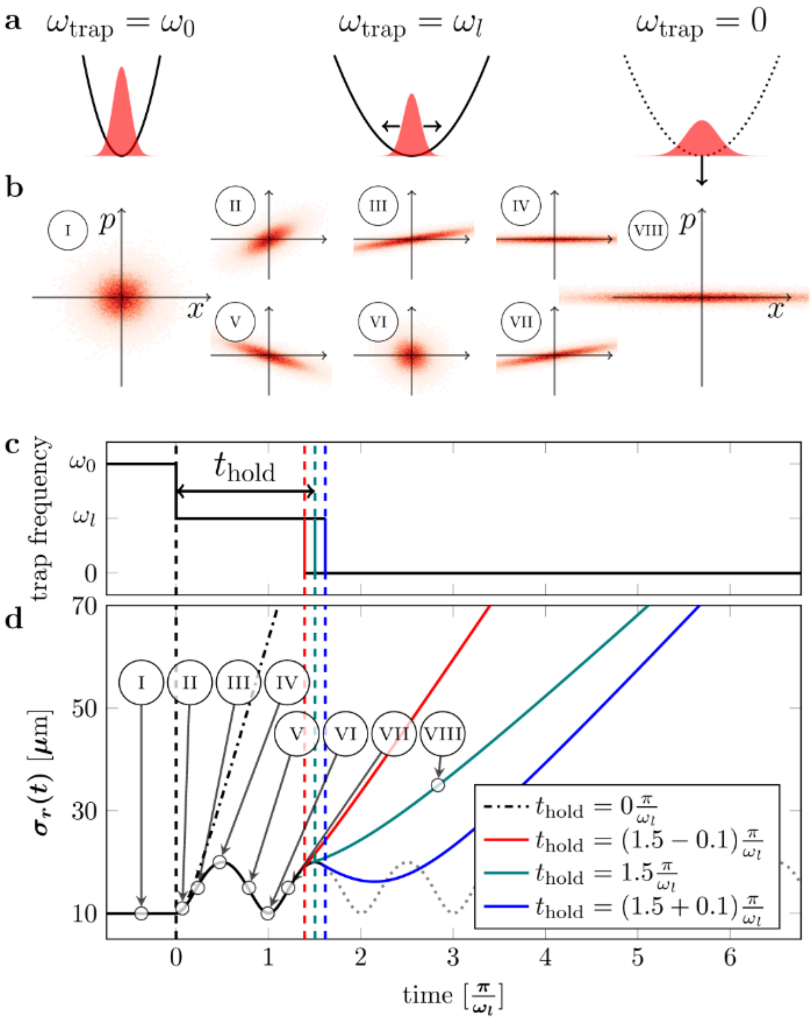

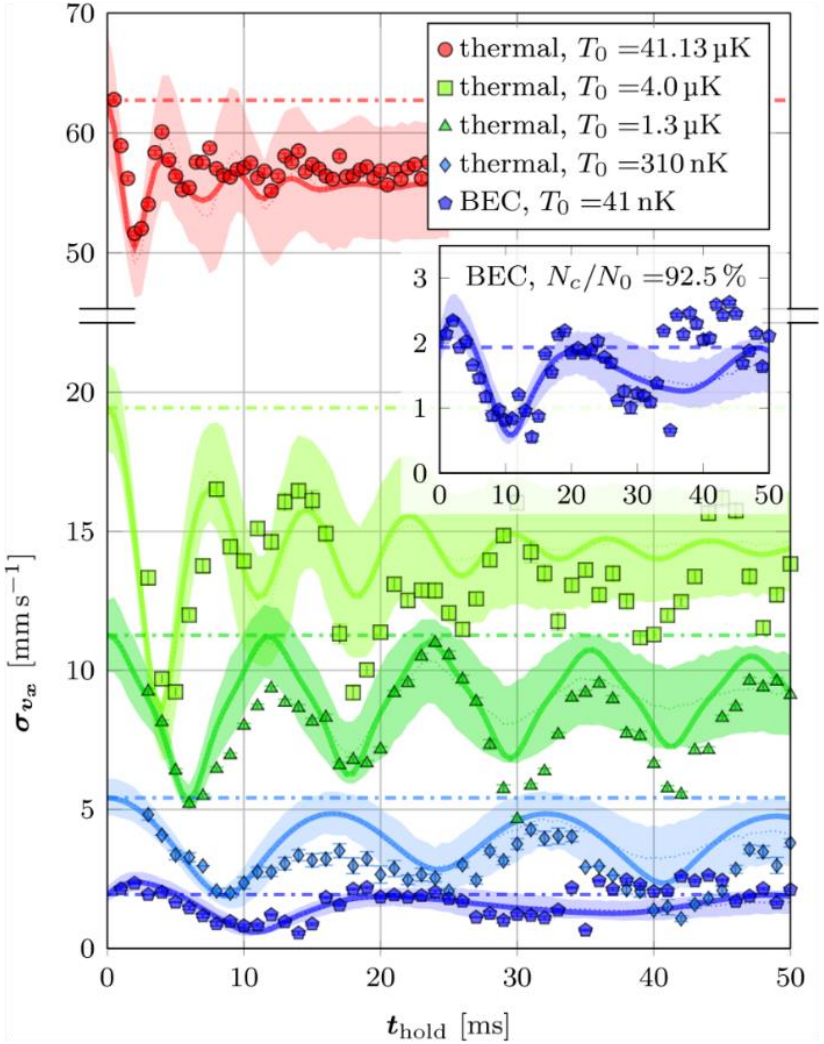

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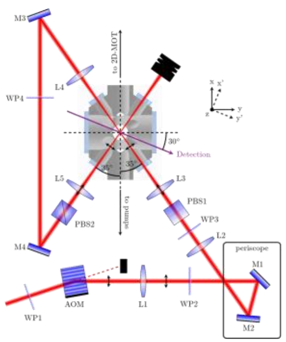

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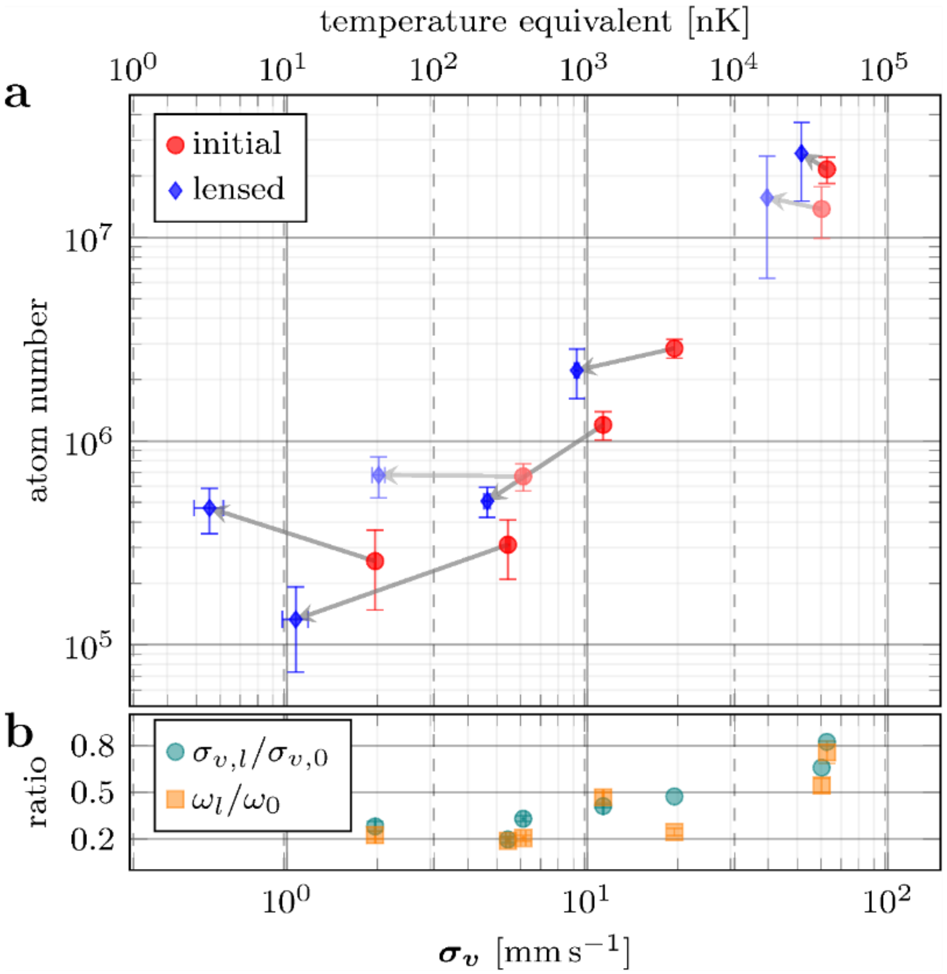

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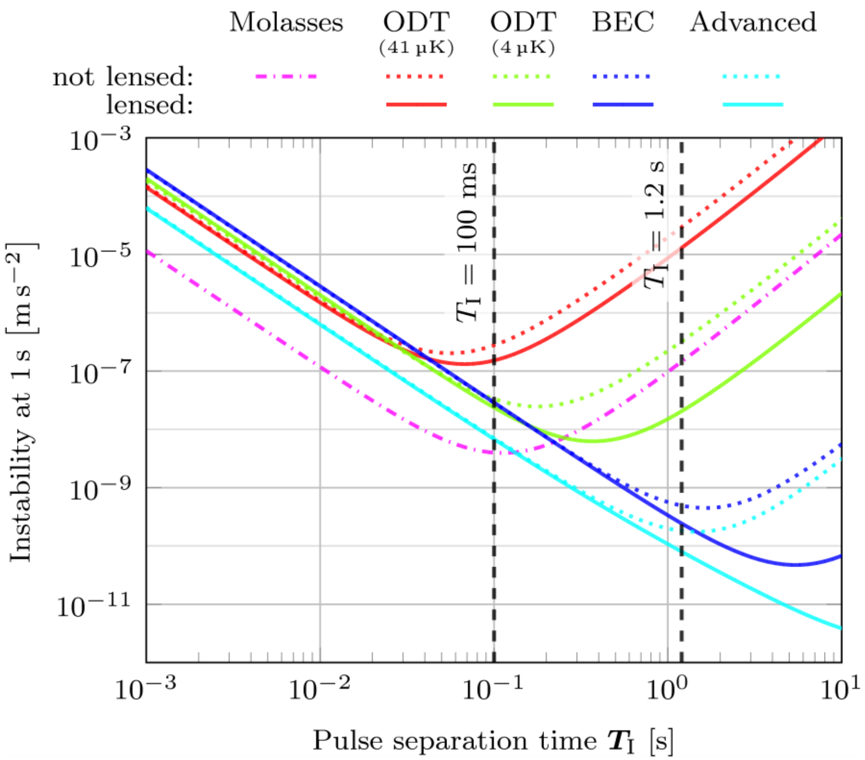
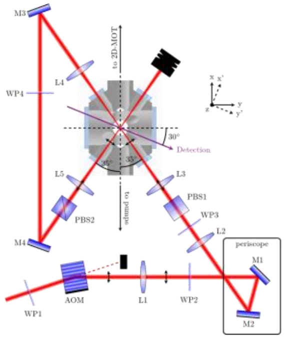
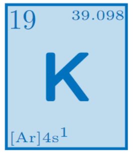


$$\sigma_a(\tau) = \frac{1}{C\sqrt{N} n k_{\mathrm{eff}} T_{\mathrm{I}}^2} \cdot \sqrt{\frac{t_{\mathrm{cycle}}}{\tau}}$$

Shortcuts of evaporative cooling possible



Matter-wave lens with ^{39}K



- Expansion fundamentally bound by uncertainty principle:

$$\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$$

- Initial Δx depends on trap geometry/frequencies

- Repulsive interactions increase momentum:

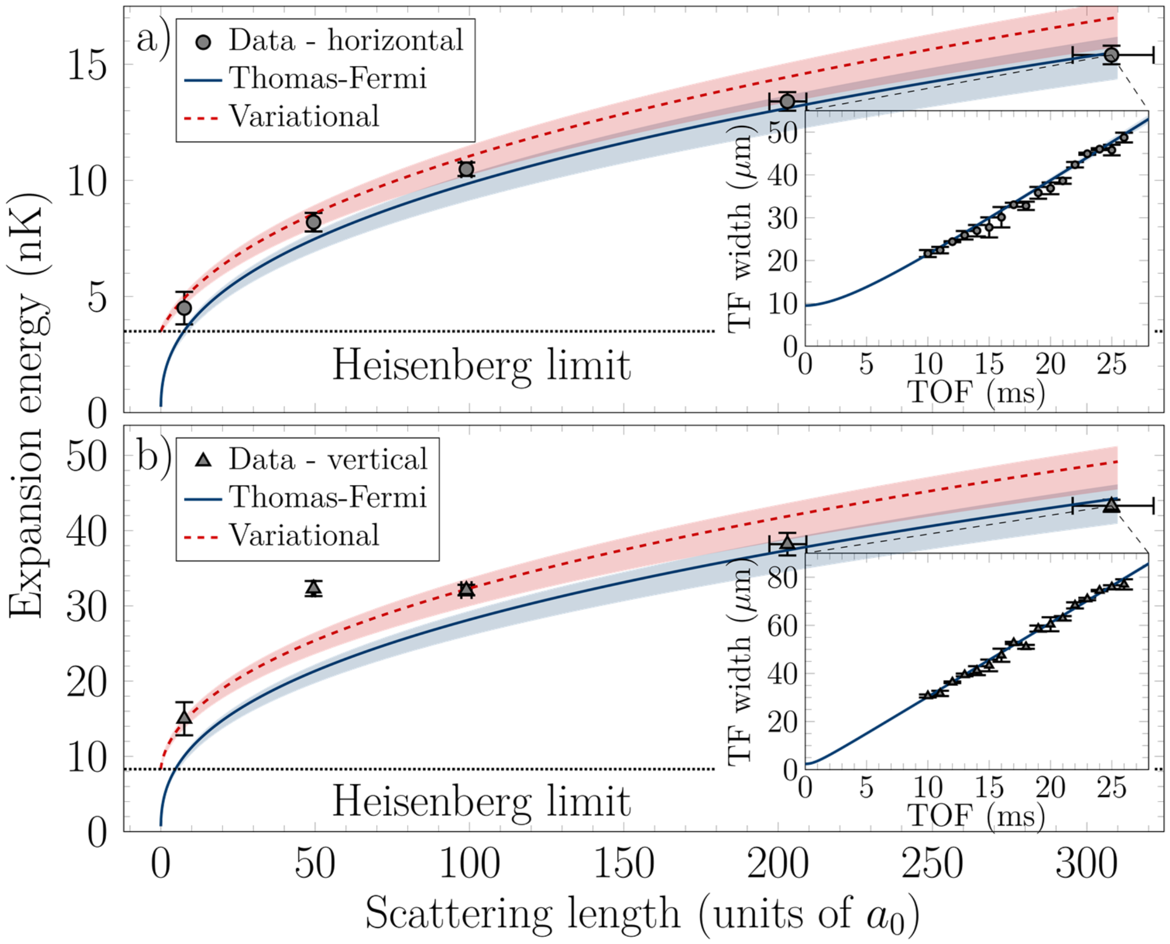
$$i\hbar \frac{\partial \Psi(\vec{r},t)}{\partial t} = \left(-\frac{\hbar^2}{2m}\Delta + V(\vec{r}) + g|\Psi(\vec{r},t)|^2 \right) \Psi(\vec{r},t)$$

Thomas-Fermi approximation (a ≥ 50 - 150 a_0):

- neglects kinetic energy term
- Thomas-Fermi distribution

Variational approach (a < 50 - 150 a_0):

- includes kinetic energy term
- Gaussian distribution



Matter-wave lens with ^{39}K

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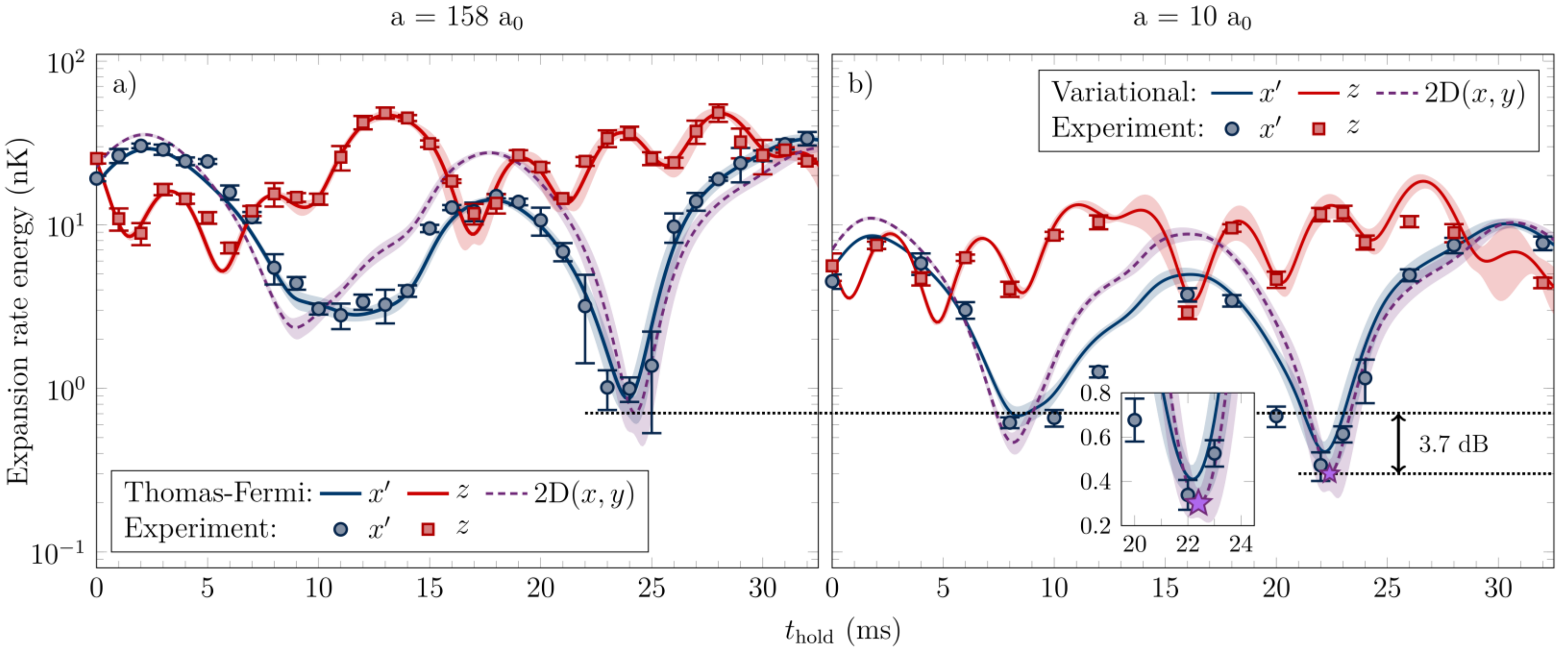
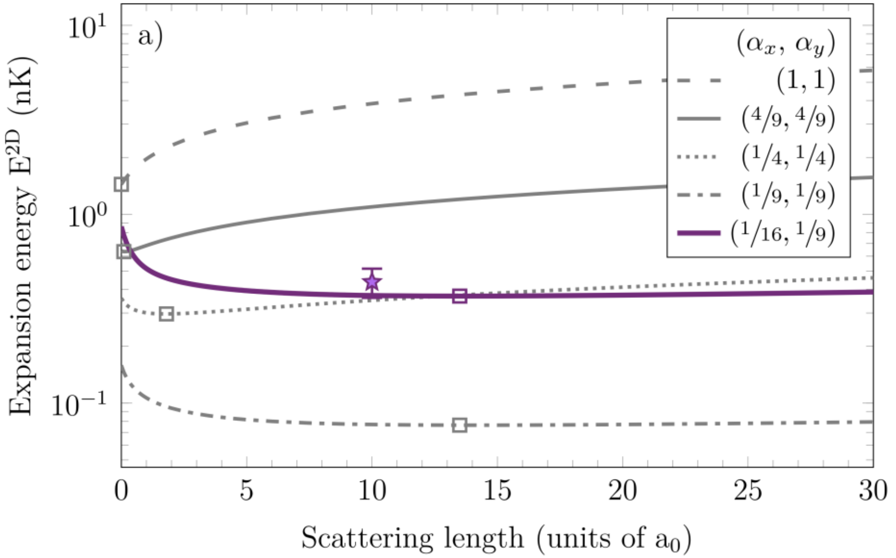
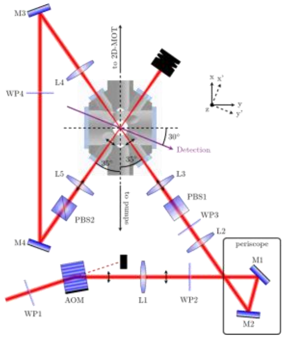
K
[Ar]4s^1

- Application of same lensing scheme with ^{39}K
- Dedicated tuning of scattering length allows to reduce mean-field energy prior to release





Results at 10 a$_0$:
1D: 340 ± 12 pK
2D: 438 ± 77 pK



[Herbst et al., arXiv:2310.04383 (2024)]

Outlook

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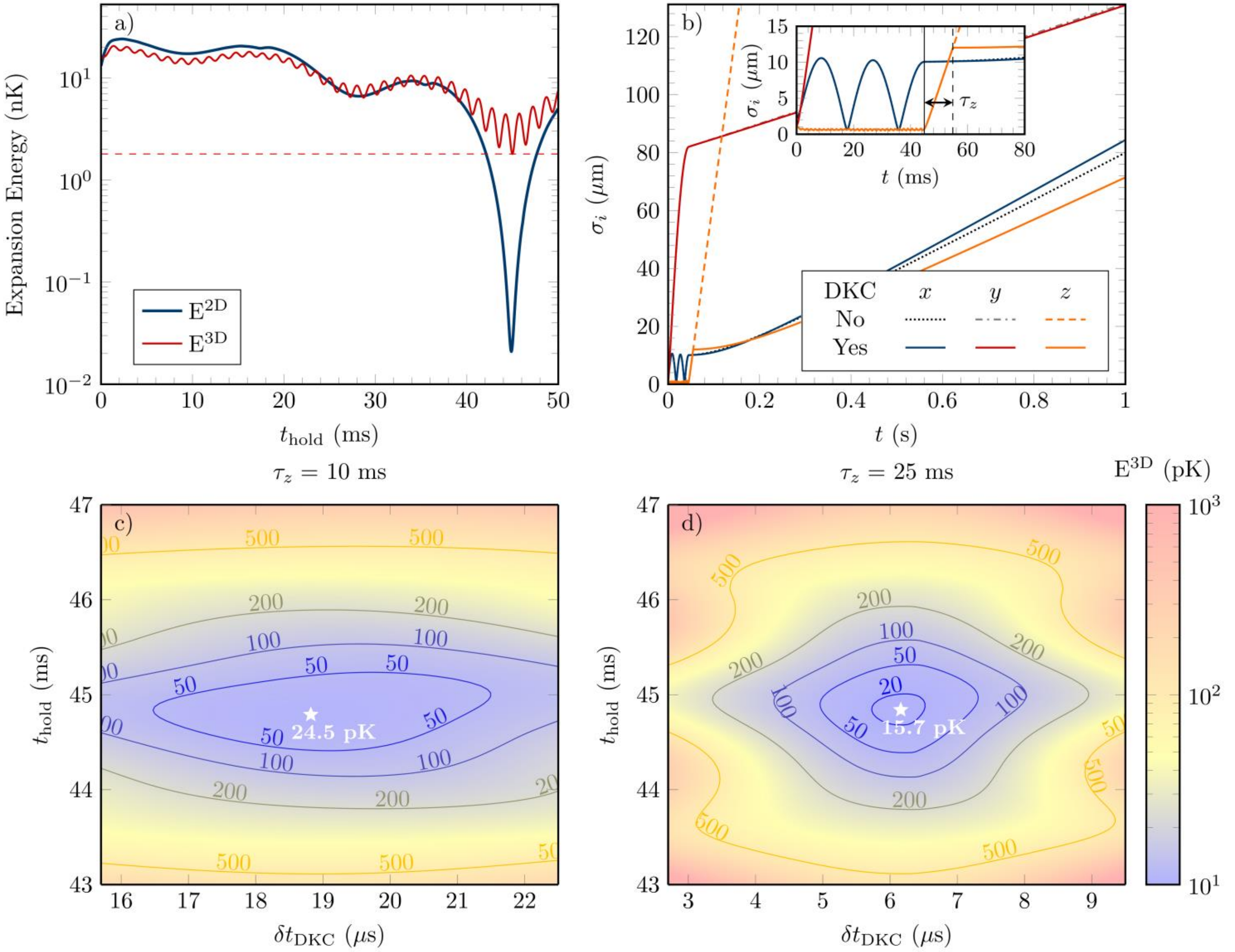
K
[Ar]4s^1

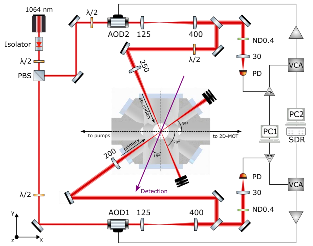
- Combination of continuous matter-wave lens with pulsed delta-kick collimation after release
- Co-moving ODT (via AOD) allows for up to 30 ms of free-fall



3D simulations:

- For ^{39}K below 20 pK with tunable interactions
- For ^{87}Rb below 100 pK w/o tunable interactions
- Directly applicable to Sr and Yb

[Herbst et al., arXiv:2310.04383 (2024)]



Thank you for your attention!

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Wei Liu


Knut Stolzenberg


Sebastian Bode


Robin Corgier


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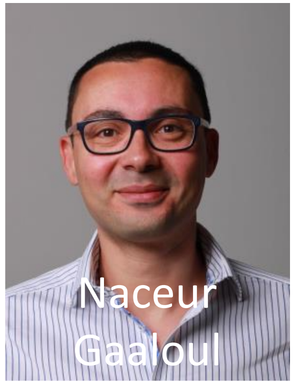
Naceur Gaaloul


Ernst Rasel


Dennis Schlippert

PRIMUS

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

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