



GEFÖRDERT VOM



Bundesministerium
für Bildung
und Forschung



Leibniz
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Hannover

The Hannover VLBAI Atom Interferometer

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K. Zipfel, C. Schubert, E. M. Rasel, DS
Institut für Quantenoptik



The VLBAI facility

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

Drop mode – 1st generation source

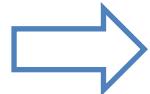
2×10^5 at, 2 photons, $2T = 800$ ms, $T_{\text{prep}} = 3$ s

$\rightarrow 1.7 \times 10^{-9}$ m/s² @1s

Launch mode – 2nd generation source

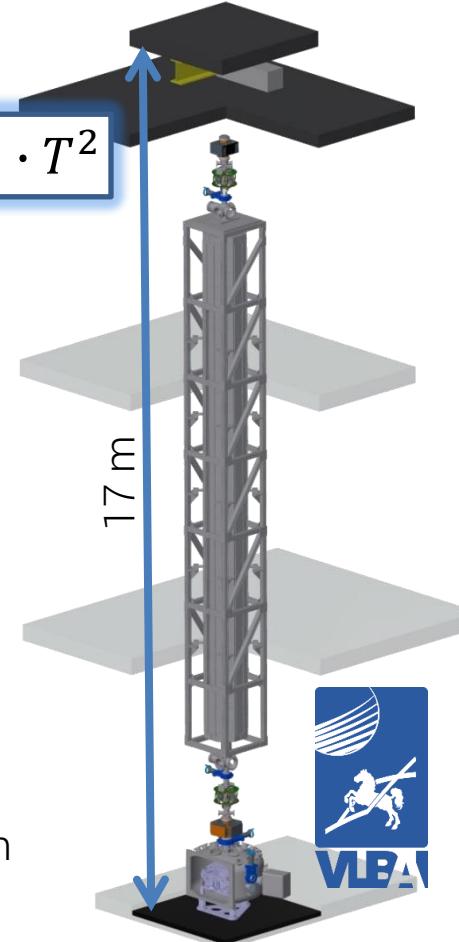
1×10^6 at, 4 photons, $2T = 2.8$ s, $T_{\text{prep}} = 3$ s

$\rightarrow 4 \times 10^{-11}$ m/s² @1s



$\sim 10^{-13}$ g after O(1 day) of integration

[DS et al., arXiv:1909.08524]



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

Wuhan (China)



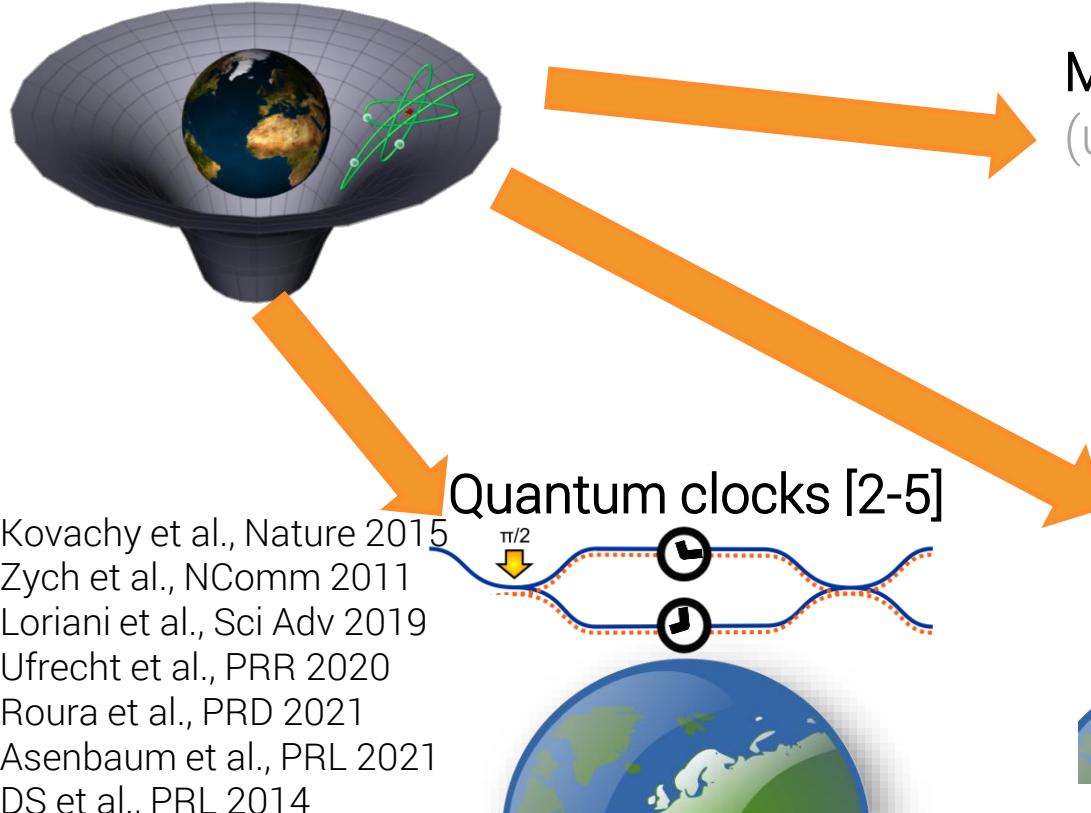
J. Hogan, PhD thesis, Stanford U.
(2010)



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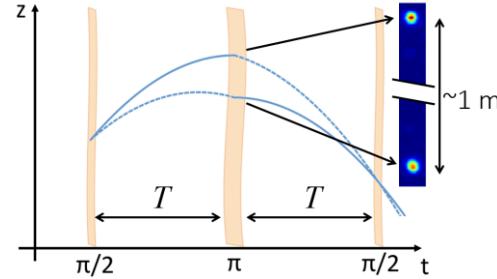
Matter waves in gravity

also: Earth
observation &
geodesy

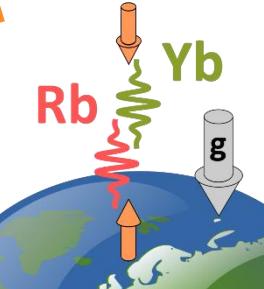
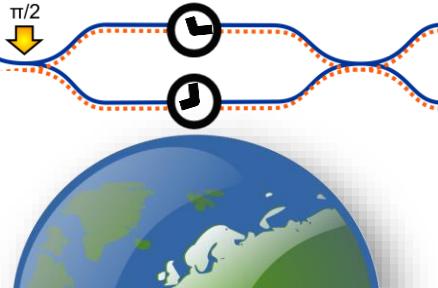


- [1] Kovachy et al., Nature 2015
- [2] Zych et al., NComm 2011
- [3] Loriani et al., Sci Adv 2019
- [4] Ufrecht et al., PRR 2020
- [5] Roura et al., PRD 2021
- [6] Asenbaum et al., PRL 2021
- [7] DS et al., PRL 2014

Macroscopic delocalization [1]
(using non-classical states)



Quantum clocks [2-5]



Testing the
Universality of
Free Fall [6,7]

Global VLBAI network



[1]

- Improved hydrology
- Volcanology [2]
- Earthquake warning [3]
- Model Earth's elastic response
- Measurement of gravity variations as part of the height changes deduced from VLBI, SLR, GNSS

- Detection of the proper modes of the Earth nucleus
- Research on the deformation of the Earth crust due to the ocean and atmospheric load
- Measurement of geocenter variations [4]

[1] Hinderer et al., 2007

[2] Carbone et al., Earth Sci Rev (2017)

[3] Montagner et al., Nat. Comm. (2016)

[4] Männel & Rothacher, J Geod (2017) 91:933–944

The VLBAI facility

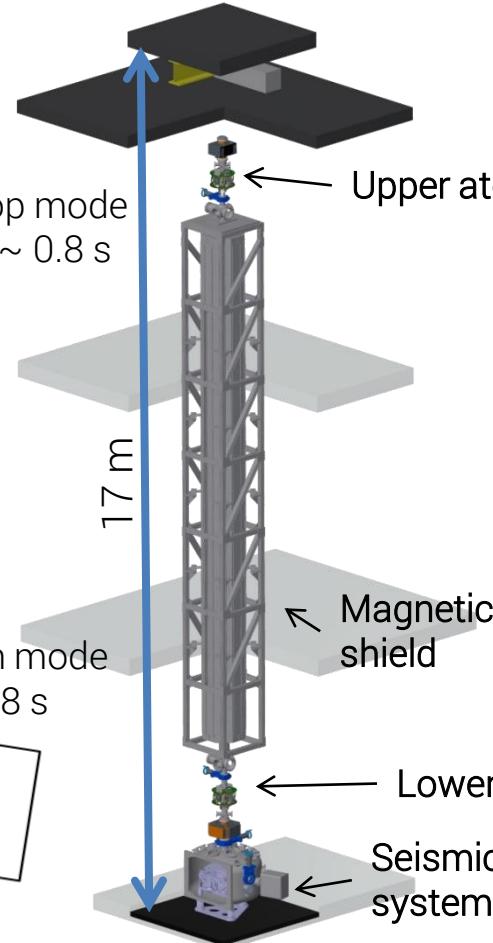
Atomic sources

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



Inertial reference

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



Al-zone & magnetic shield

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



[DS et al., arXiv:1909.08524]

The VLBAI facility

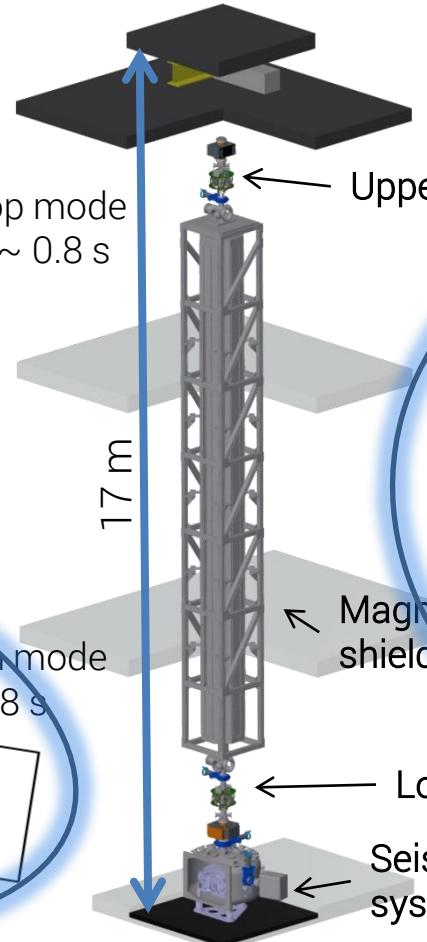
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[DS et al., arXiv:1909.08524]

Winding a 10m solenoid (by hand)



2017-11-09
2017-11-10



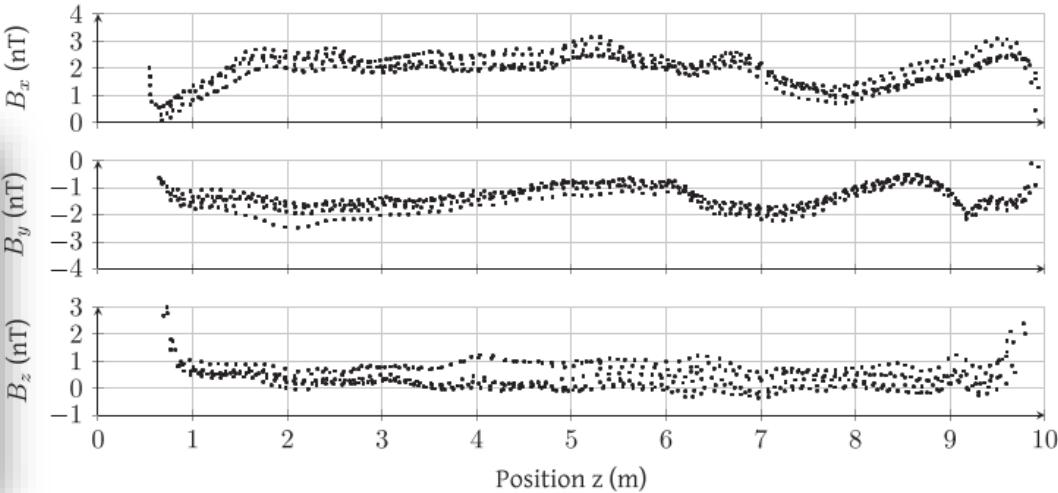
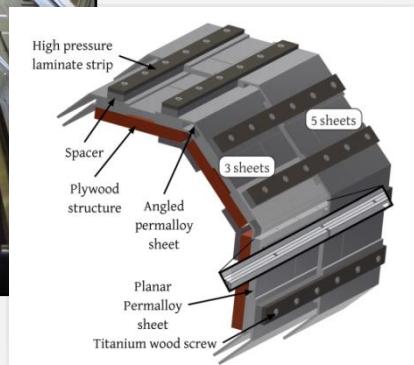
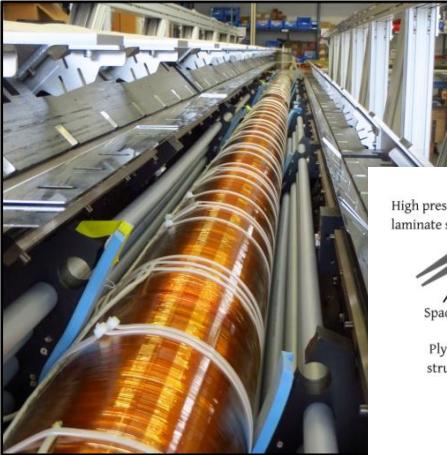
Solenoid

- Ca. 2km Cu wire
- $\sim 7\Omega$ resistance
- $<0.1 \text{ mW}/\mu\text{T}^2$ dissipation

Winding a 10m solenoid (by hand)



High-performance magnetic shield



- Octagonal dual layer ~10m shield
- Increasing thickness towards center
 - Prevent saturation & field bump
- No global annealing, no welds
- Scalable design
- Perturbation theory: <3 nT/m gradient
 $\rightarrow \sim 10^{-13}$ m/s² @ 1.5 μT bias

[Wodey et al., RSI (2020)] 

[Lezeik et al., arXiv:2209.08886 (2022)]

7t baseline on the road

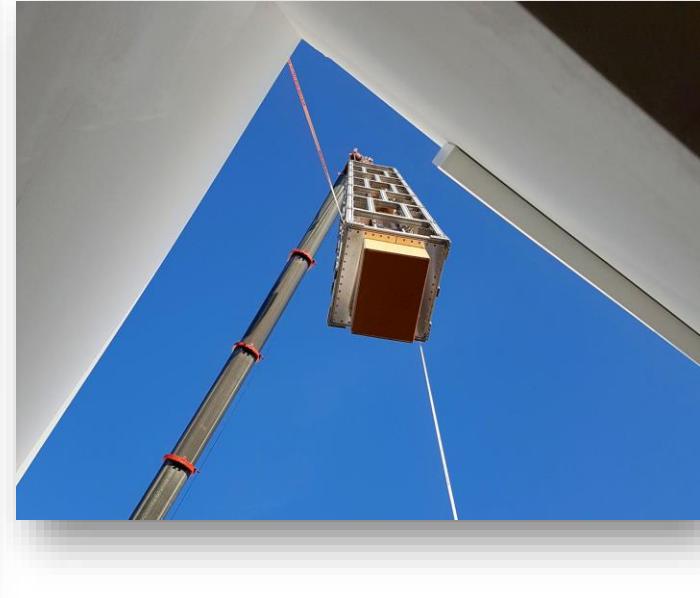


Dennis Schlippert
schlippert@iqo.uni-hannover.de

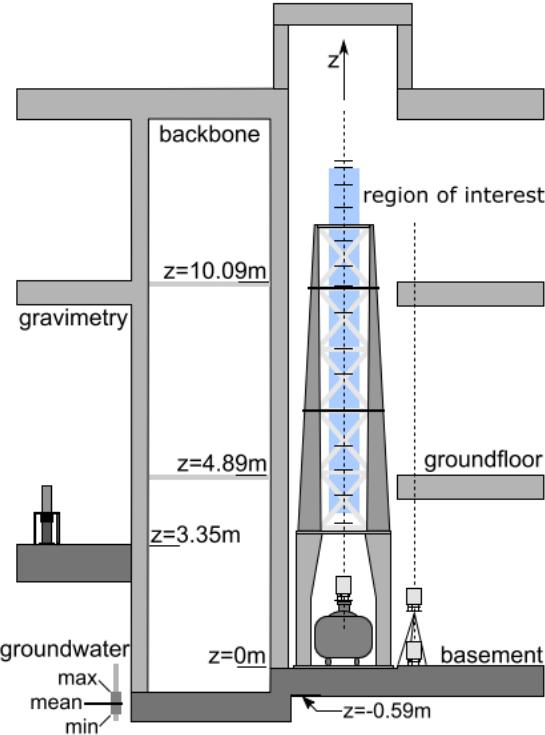
13.03.2023

VLBAI baseline installation

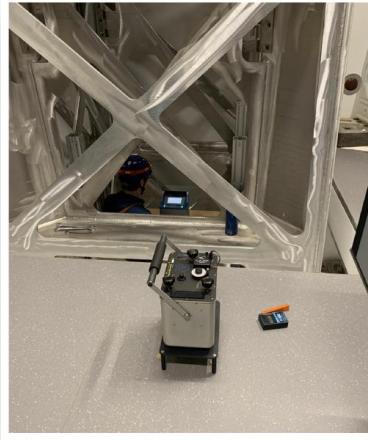
December 2019



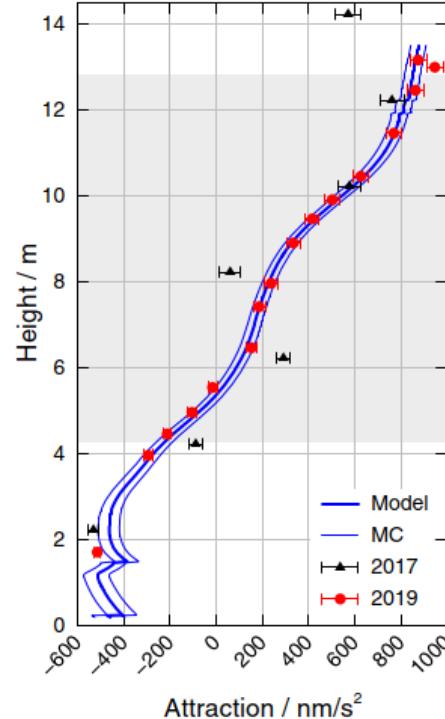
Gravity field modelling for VLBAI



$$g_0 - \gamma z_{\text{eff}} = \frac{\Delta\phi_{\text{tot}}}{k_{\text{eff}} T^2}$$

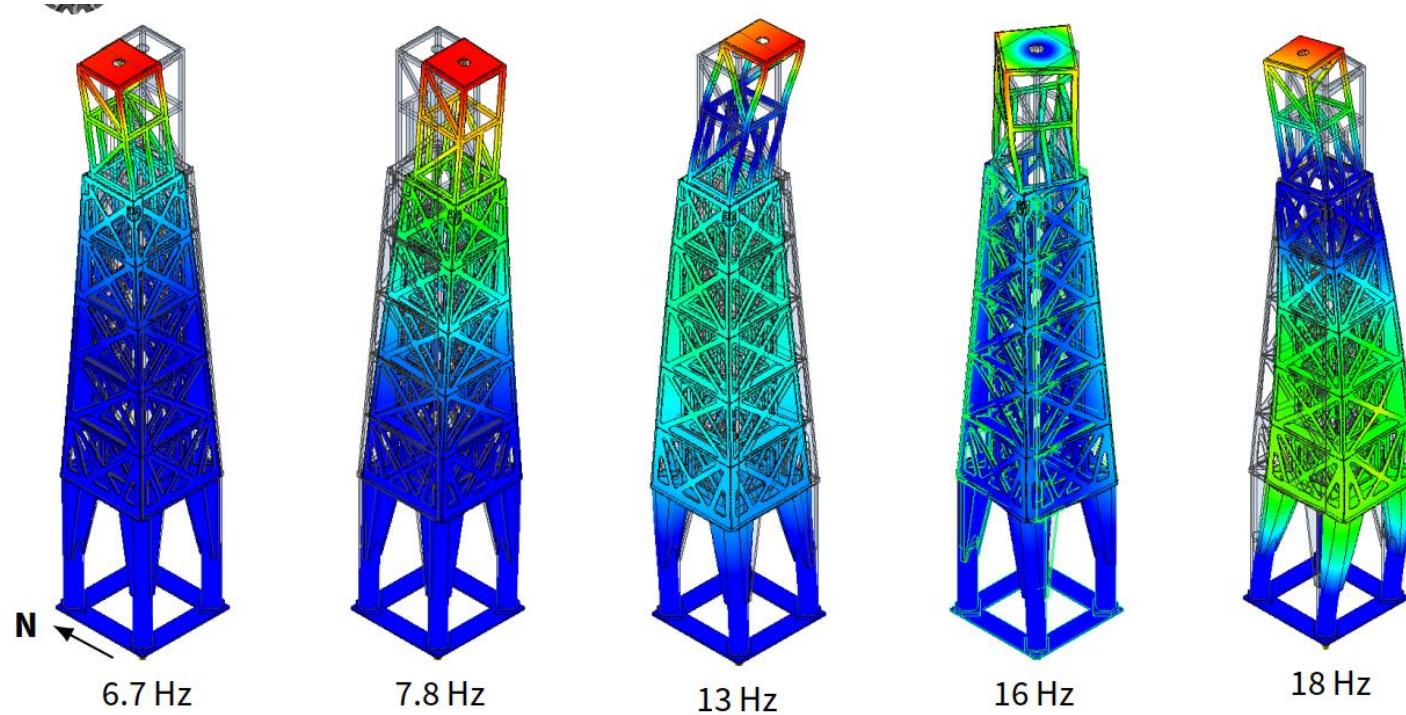


- Bias: 2.6 nm/s^2
- Standard uncertainty of gravity network $< 9 \text{ nm/s}^2$

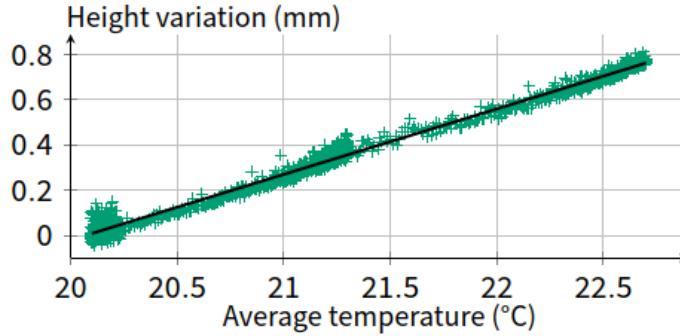


[Schilling et al., J. Geod. 2020] 
 [Lezeik et al., arXiv:2209.08886 (2022)]

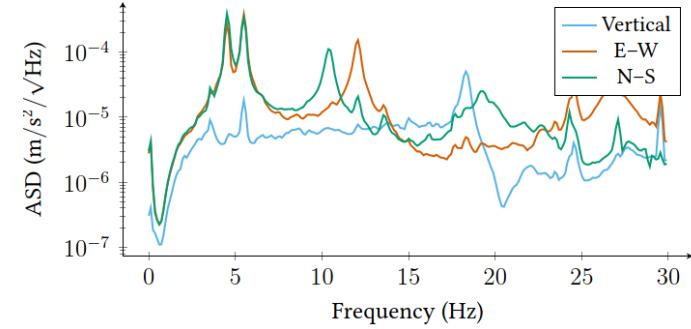
Vibration modes of the 10m tower



Support structure – stability & thermal expansion



- Track tower height through laser ranging while changing A/C setpoints
- Fitted expansion coefficient: $2.4 \times 10^{-5} /m$
- Tabulated value for Al: $2.31 \times 10^{-5} /m$



- Effective height: $3 \text{ nm/s}^2 \text{ per mm}$
- Influence of tower oscillations
 - Horizontal motion of $50 \mu\text{m}$ at 5 Hz
 - $<1 \text{ nm}$ vertical
 - Transverse gradients → $<3 \text{ pm/s}^2$

[Wodey, PhD defense 2021]

BBR force & temperature monitoring

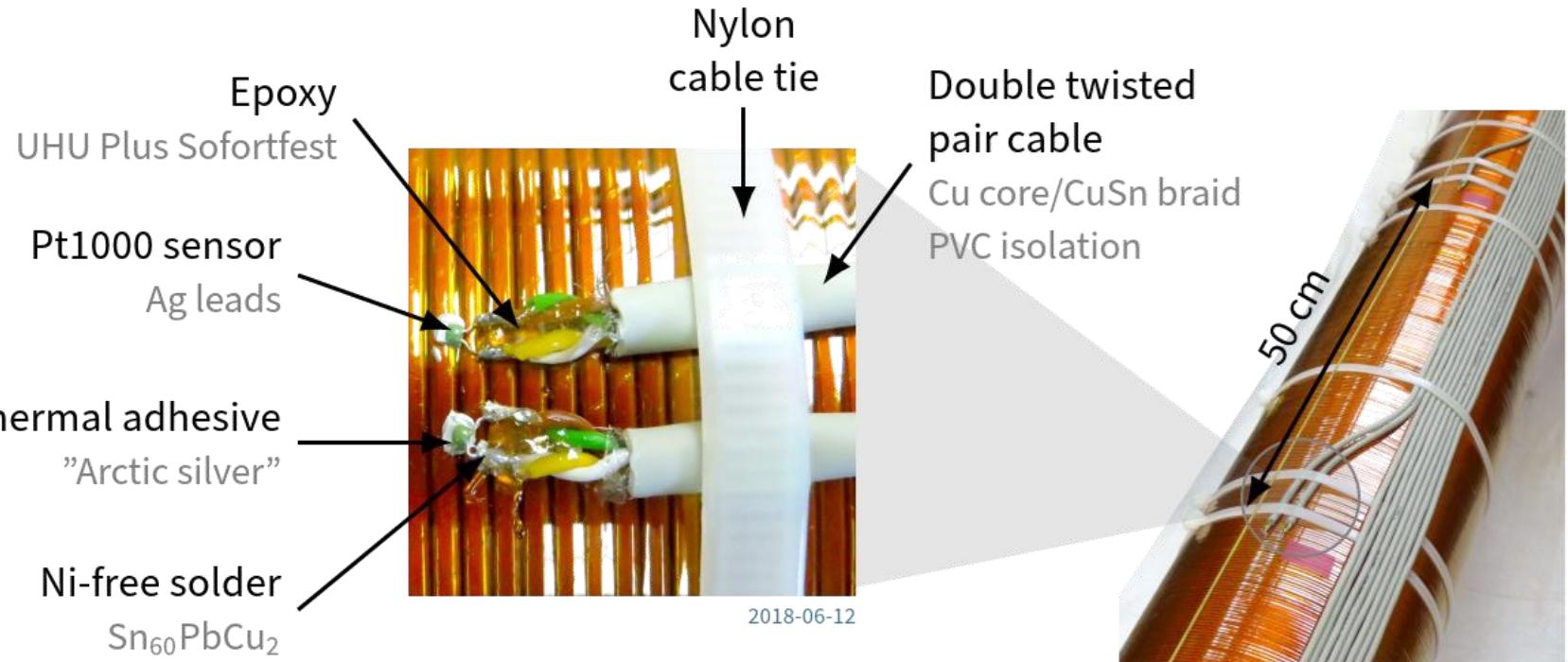
Black-body radiation acts as a dipole potential – bias acceleration
[Haslinger et al., Nat. Phys 2018]

$$\delta a(z) = -8 \frac{a_x \sigma}{mc\varepsilon_0} \cdot T^3(z) \partial_z T(z)$$

At $T=300\text{K}$, $|\partial_z T| < 5\text{K/m}$ yield $|\delta a| < 1\text{nm/s}^2$



Temperature sensing

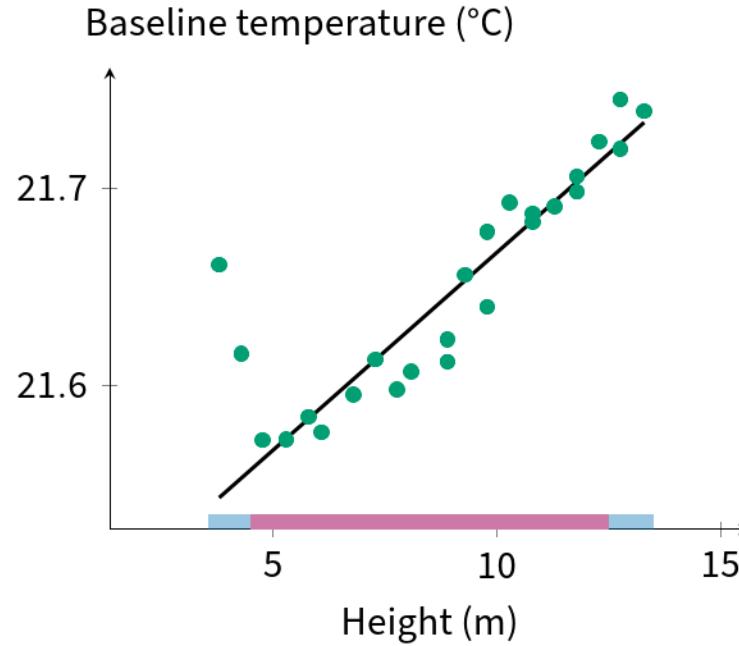


All materials tested at PTB Berlin / BMSR-2: < 50 pT remanence at 4 cm

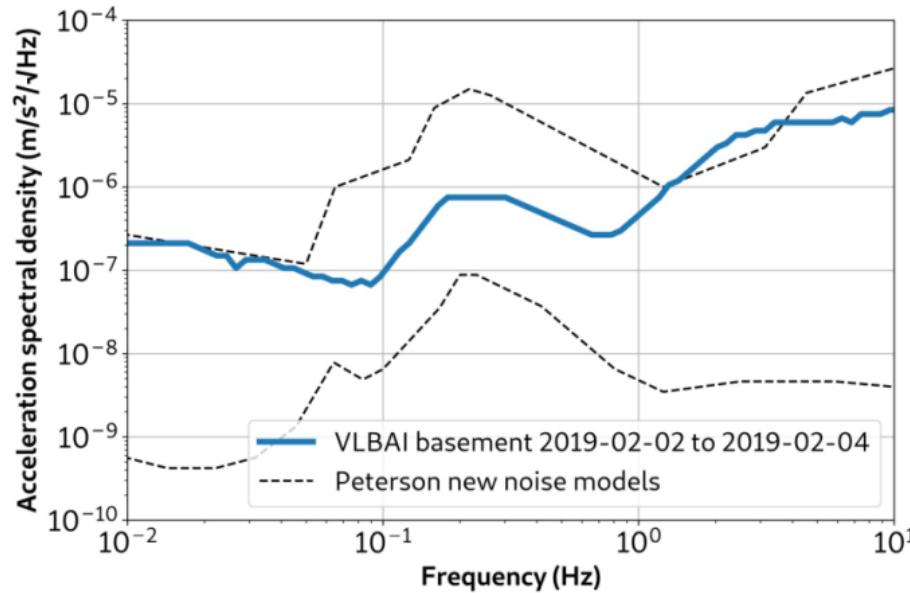
[Wodey, PhD defense 2021]

Anticipated bias acceleration through BBR force

- ▶ RTDs rated to ± 30 mK between 25 °C and 55 °C (1/10 DIN EN 60751)
- ▶ Iterative readout, least-squares network adjustment. Adjusted uncertainty: 14 mK
- ▶ Discrepancy between redundant sensors: 4 mK to 38 mK
- ▶ Adjusted overall gradient: 20 mK/m around 21.65 °C (over interferometry region)
- ▶ Corresponding acceleration bias for ^{87}Rb : 3 pm/s 2 .



Seismic noise in the VLBAI facility



The VLBAI seismic attenuation system

VLBAI-SAS key features

- Vacuum-compatible to $<10^{-7}$ mbar
- 6 DOF sensing and actuation
- Passive suspension through 3 geometric anti-spring (GAS) filters
 - Artificially aged maraging steel with nickel coating
 - 260 mHz vert. resonance per individual GAS filter
 - 320 mHz combined vert. resonance
- Digital feedback loops

Actuators

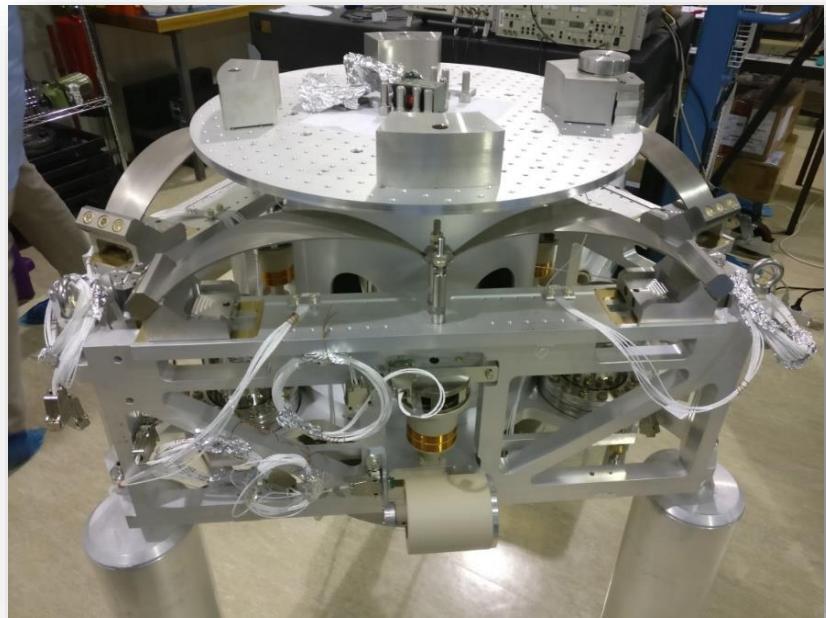
- 3x vertical voice coil
- 3x horizontal voice coil
- 3x vertical DC correction springs

Positioning sensors

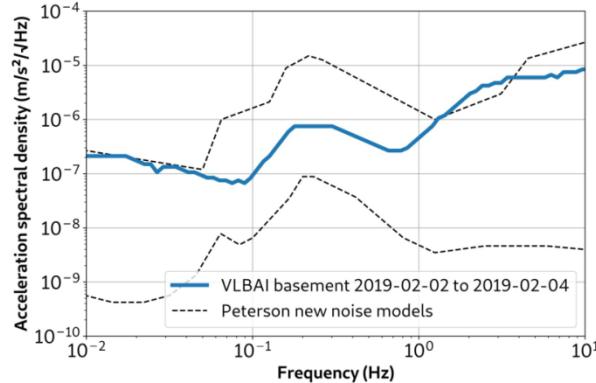
- 3x vertical LVDTs

Inertial sensors

- 3x Trillium T120 triaxial seismometer
- 1x Trillium T240 triaxial seismometer
- 1x 2-axis tilt meter

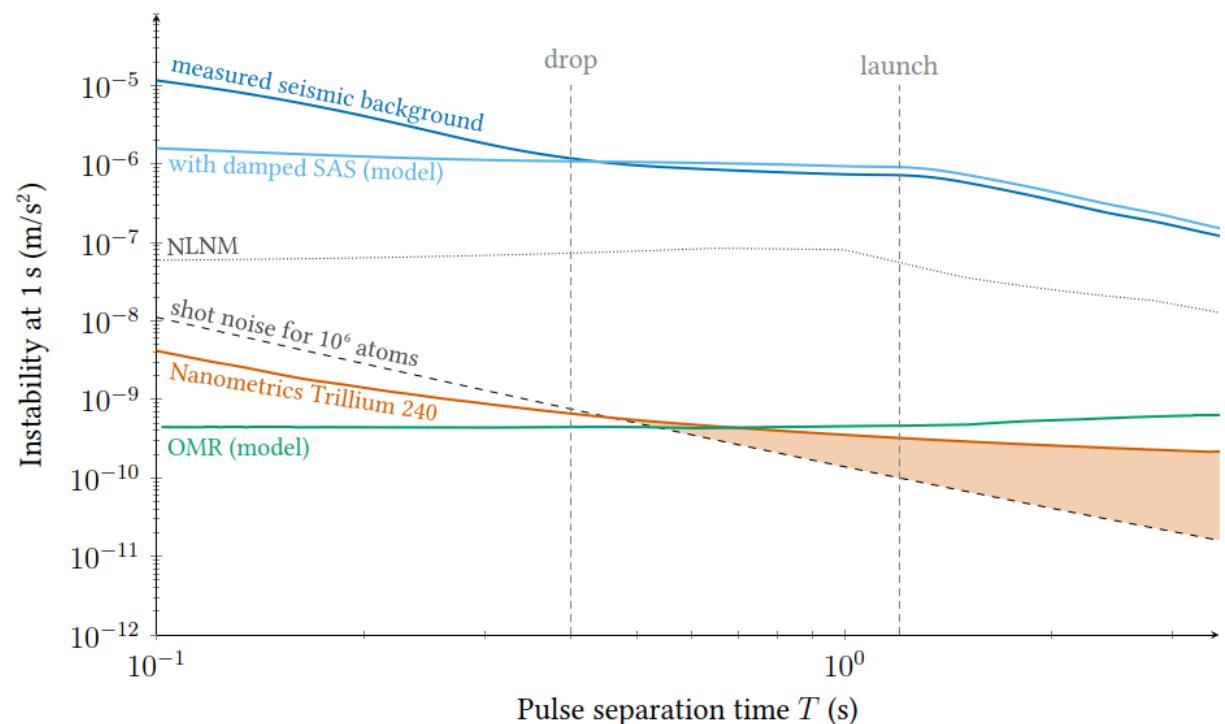


Seismic noise in the VLBAI facility



What's to expect?

- Correlation with motion sensors is a key ingredient to performance beyond state-of-the-art!



[Wodey, PhD thesis LUH, 2021] 

The VLBAI facility

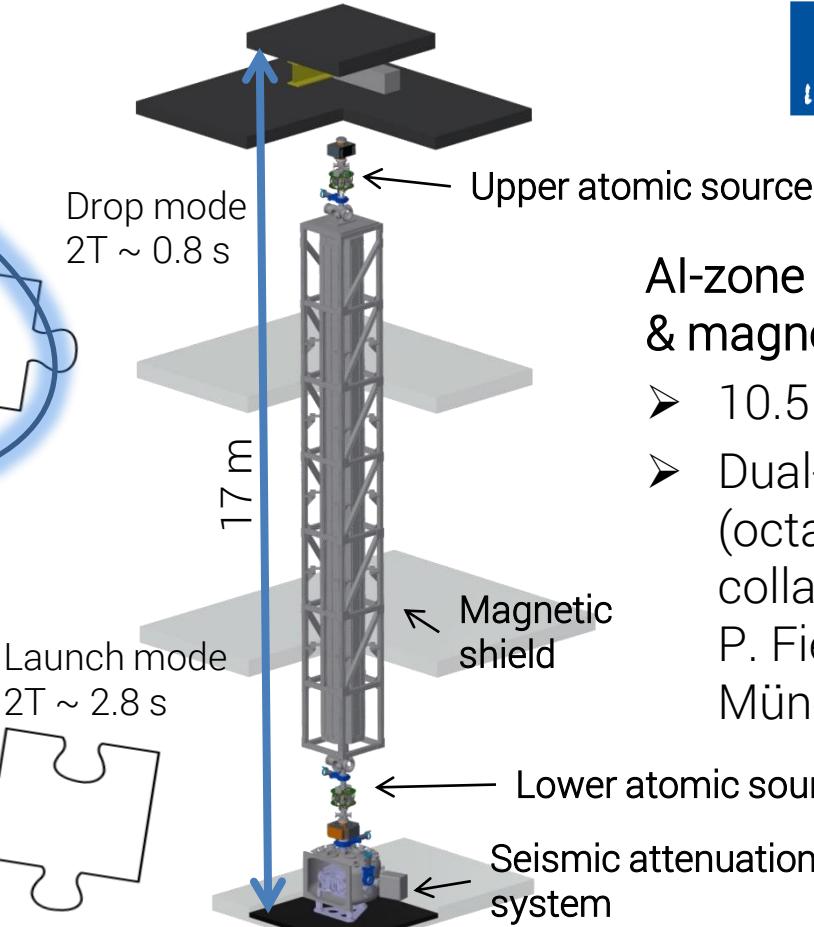
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[DS et al., arXiv:1909.08524]

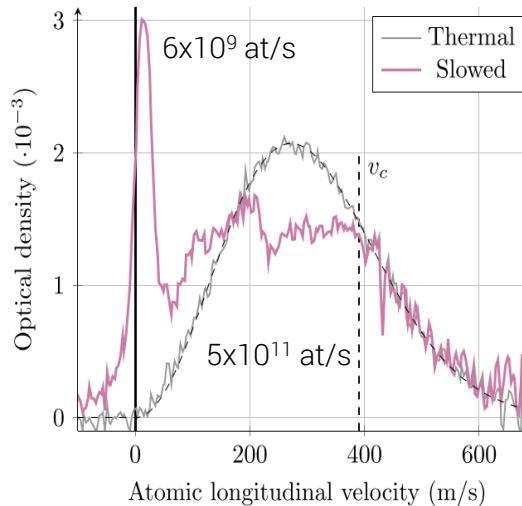
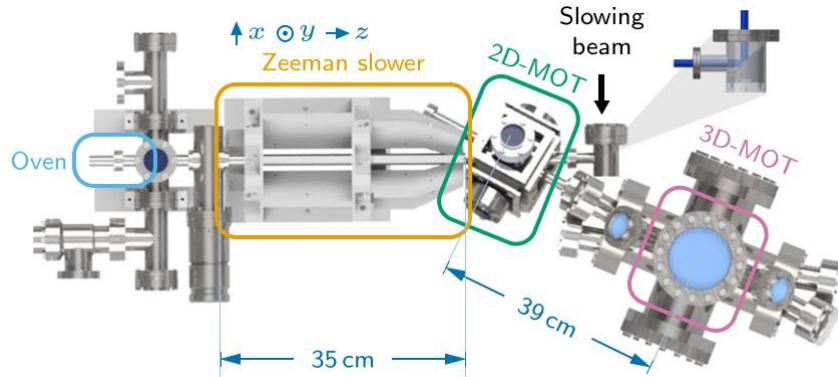


Al-zone & magnetic shield

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High-flux Yb source

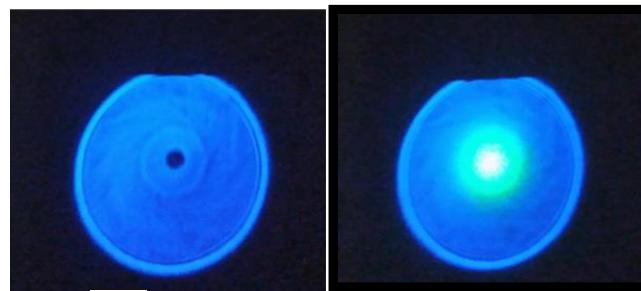


Previous results

- 1×10^9 at/s captured by blue MOT [1]

Next steps

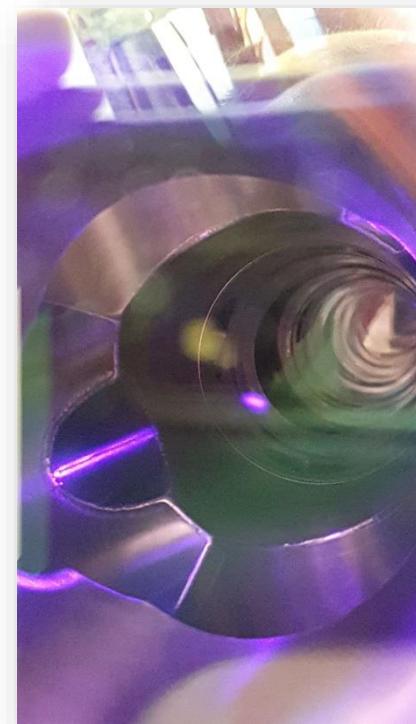
- Two-color core shell MOT
- BEC in painted optical trap [2]
- AI on ALL the lines



[1] Wodey et al. J. Phys. B: At. Mol. Opt. Phys. 54 (2021) 035301



[2] Roy et al., PRA (2016)



Why all-optical? Why matter-wave lensing?

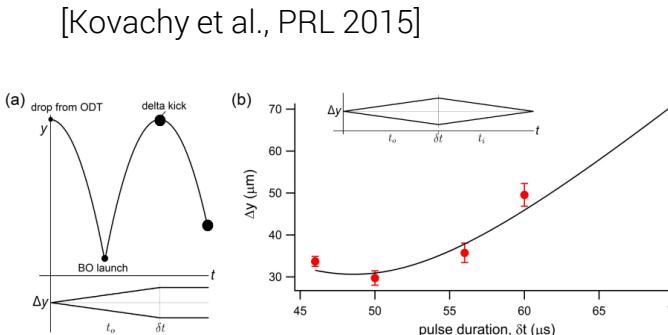


Long baselines usually demand large free apertures in-line (~10 cm)

- Challenging circumstances for strongly confining magnetic traps
- Solution: all-optical setups
 - Also applicable to non-magnetic species

Matter-wave lensing enables

- Access to lowest kinetic energies
- Shortcuts of evaporation trajectories → higher flux



[Gochnauer et al., atoms 2021]

[Deppner et al., PRL 2021]

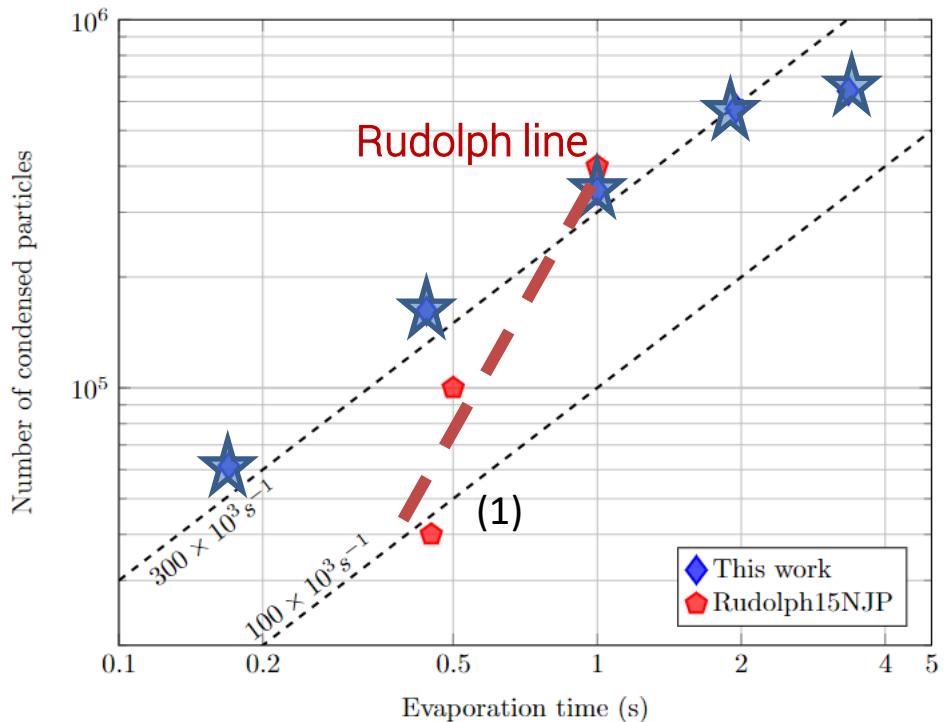
Rapid sources for long baselines

Prototype experiment using ^{39}K [1]

- State-of-the-art all-optical flux
 $\geq 2 \times 10^5$ atoms/s
- Competitive with best chip sources
- Methods applicable to VLBAI

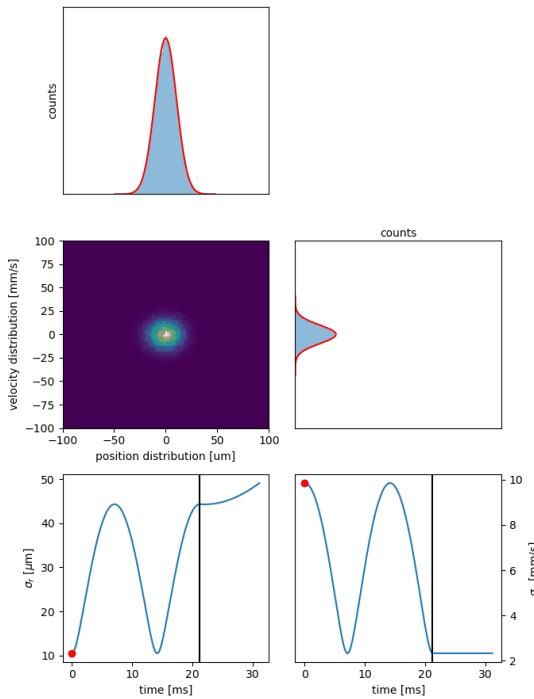
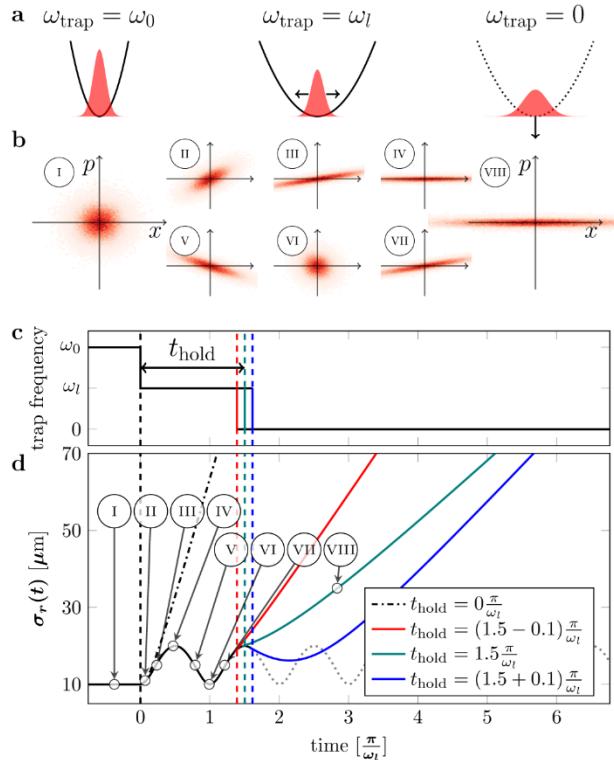
Other setups:

- (1) **All-optical:** G. Salomon et al *Phys. Rev. A* **90**, 033405 (2014)
 Atom number: 2×10^4 ; evaporation time: ~ 2 s
- (2) **Hybrid trap:** M. Landini et al *Phys. Rev. A* **86**, 033421 (2012)
 Atom number: 8×10^5 ; evaporation time: 3.5 s
- (3) **Chip trap:** J. Rudolph et al *New J. Phys.* **17** 065001 (2015)
 - Largest BEC:
 Atom number: 4×10^5 ; evaporation time: 1.1 s
 - Fastest BEC:
 Atom number: 4×10^4 ; evaporation time: 450 ms



[Herbst et al., arXiv:2201.04544 (2022)] (accepted in PRA)

All-optical matter-wave lens



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

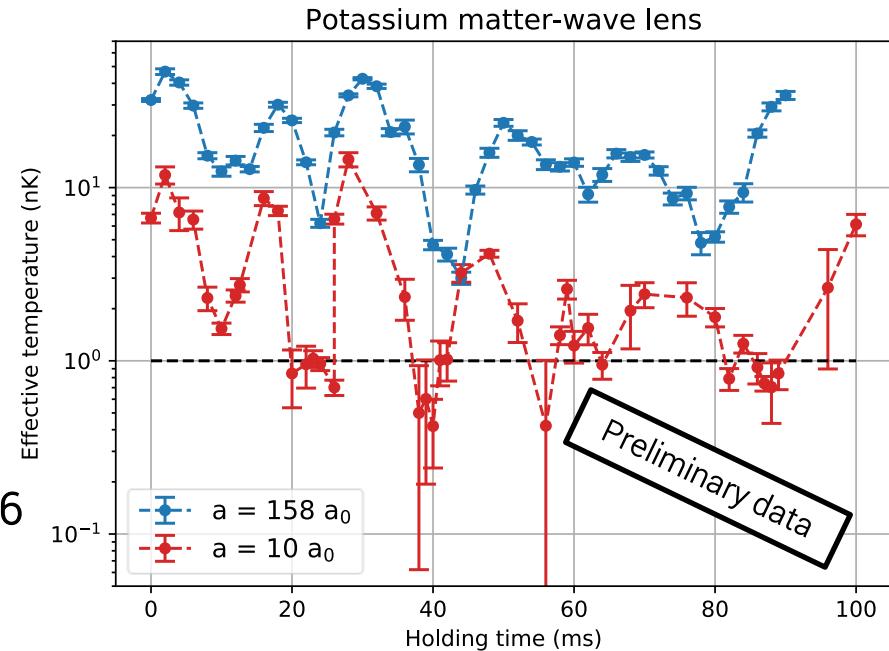
Potassium matter-wave lens

Method

- Rapid decompression in horizontal direction induce size oscillations
- Release at turning point maximizes size while minimizes the expansion rate

Results for ^{39}K

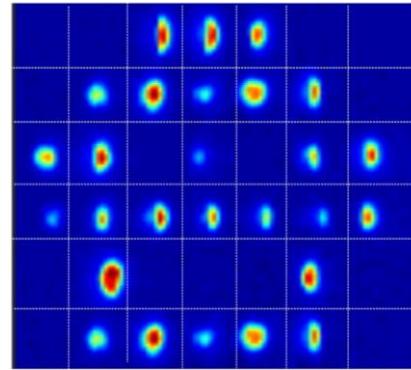
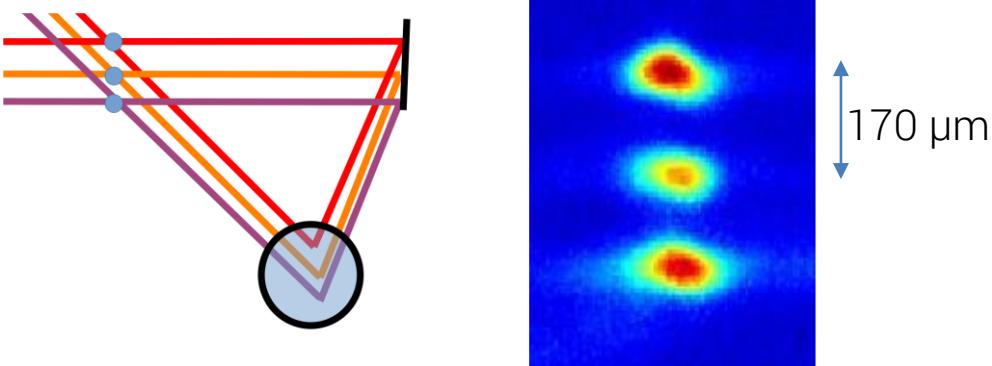
- Lens with $a = 158 a_0$: $32 \text{ nK} \rightarrow 3 \text{ nK}$
→ Reduction by a factor of 10.6
- Lens with $a = 10 a_0$: $6.7 \text{ nK} \rightarrow < 1 \text{ nK}$
→ Reduction from lensing by a factor of ~ 9.6
→ Global reduction by a factor of 4.8
- Current limitation: Magnification of the detection system and drop distance



Arbitrary control using painted potentials

2D-AOD proof-of-principle experiments

- Up to 7-fold split of BECs
- Simultaneous generation of multiple BECs
- Demonstration of vertical stack in a recycled crossed trap



Applications

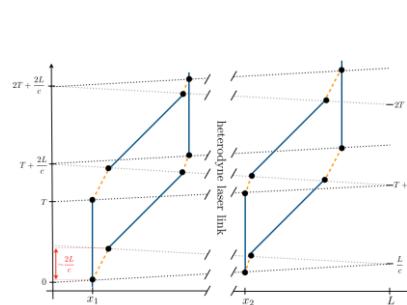
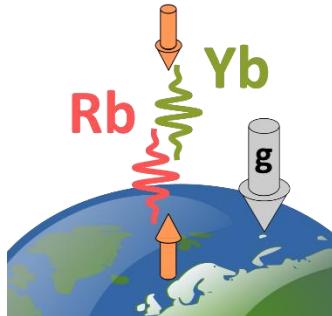
- Guided interferometry
- Wave front analysis
- Multiple sources
→ Increased duty cycle

Outlook



VLBAI offers

- Unique species combination
- Unique high-flux BEC sources
- Access to studies of decoherence mechanisms
 - High-sensitivity absolute measurements
 - Advanced differential capabilities
- Unique platform capable of quantum clock interferometry
- Studies of concatenated interferometry
 - Fast source and extended delay line



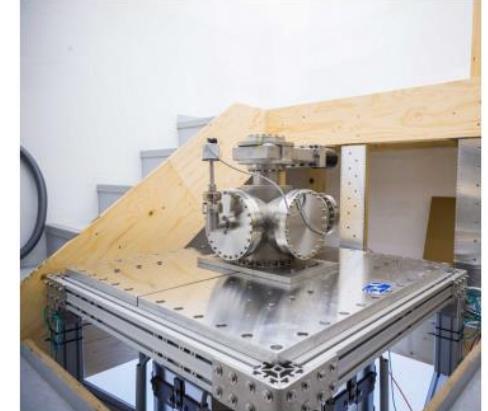
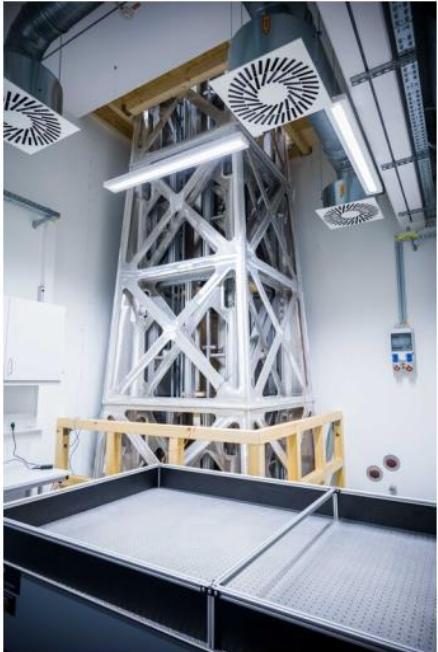
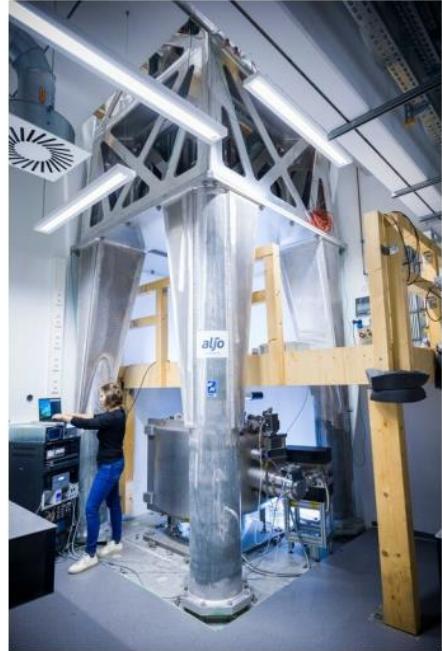
VLBAI as a pathfinder for vertical GWD

- Atoms
 - High-flux source concepts
 - Painted atom optics
 - Capability of 0(10m) single photon interferometry
- Infrastructure
 - Statics, verticality, scalability
 - Magnetic shielding
 - Seismic attenuation
 - Gravity gradients
 - Correlation & rotation compensation

[Loriani et al., New J. Phys. 21 063030 (2019)]



Labs are ready – atoms about to move



Thanks for your attention!



@quantumsensing

111
102
1004

Leibniz
Universität
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Christian
Schubert



Naceur
Gaaloul



Ernst
Rasel



Terrestrial VLBAI workshop

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13.03.2023

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Alexander
Herbst



Henning
Albers



Ashwin
Rajagopalan