A transportable absolute Quantum Gravimeter employing collimated Bose-Einstein condensates

Waldemar Herr
for the Institute of Quantum Optics team

Picture from wikipedia by Andree Stephan

DLR Institut für Satellitengeodäsie und Inertialsensorik

Leibniz Universität Hannover

State of the art atom gravimeters

CAG @ Paris [1]

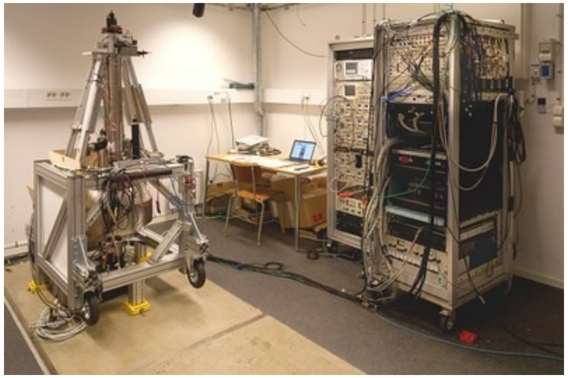
Picture form: arXiv:1404.6722

Systematic effect	Correction μGal	U μGal
Alignement	1.2	0.5
Frequency reference	3.2	0.1
RF phase shifts	0	< 0.1
Gravity gradient	-13	< 0.1
Self gravity effect	-2.1	0.1
Coriolis	-5.3	1
Wavefront distortions	0	4 (1)*
…		
TOTAL	-23.2	4.3

* Karcher, et al., NJP **20**, 2018

GAIN @ Berlin [2]

Picture from: https://www.physics.hu-berlin.de/en/qom/research/ai



Systematic effect	Offset	Error (nm/s^2)
Raman Wavefronts	28	± 22
Coriolis Effect	0	± 15
Magnetic Field Effects	0	± 10
RF Group delay	0	± 10
Self Gravitation	-19	± 5
Reference Laser Freq.	12(10)	± 5
Synchronous Vibrations	0(-92)	$\pm 5(50)$
AC Stark Shift (1PLS)	0	± 5
Rb background vapour	-5	± 3
AC Stark Shift (2PLS)	0	± 2
vertical alignment	0(1)	± 1
Total	**16(-77)**	**$\pm$32(59)**

AQG from Muquans [3]

Sensitivity:	50 µGal/√Hz at a quiet place
Measurement frequency:	2 Hz
Long-term stability:	< 1 µGal
Accuracy:	under evaluation

[1] B. Fang et al., "Metrology with Atom Interferometry: Inertial Sensors from Laboratory to Field Applications", J. Phys. Conf. Ser. **723**, (2016)

[2] C. Freier et al., "Mobile quantum gravity sensor with unprecedented Stability", J. Phys. Conf. Ser. **723**, (2016)

[3] www.https://www.muquans.com/product/absolute-quantum-gravimeter/

Today’s most accurate atom gravimeters

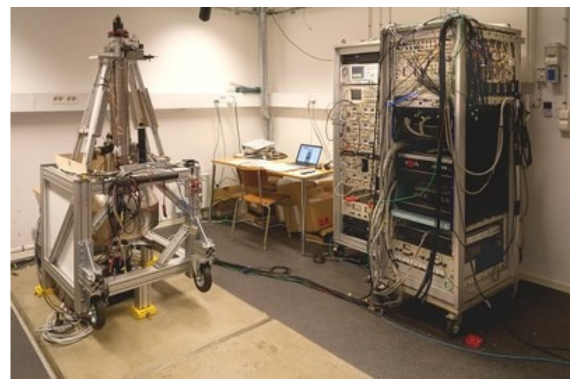
CAG @ Paris [1]

Picture form: arXiv:1404.6722

Systematic effect	Correction μGal	U μGal
Alignement	1.2	0.5
Frequency reference	3.2	0.1
RF phase shifts	0	< 0.1
Gravity gradient	-13	< 0.1
Self gravity effect	-2.1	0.1
Coriolis	-5.3	1
Wavefront distortions	0	4 (1)*
...		
TOTAL	-23.2	4.3

* Karcher, et al., NJP **20**, 2018

GAIN @ Berlin [2]



Picture from: https://www.physics.hu-berlin.de/en/qom/research/ai

Systematic effect	Offset ($\mathrm{nm/s^2}$)	Error
Raman Wavefronts	28	± 22
Coriolis Effect	0	± 15
Magnetic Field Effects	0	± 10
RF Group delay	0	± 10
Self Gravitation	-19	± 5
Reference Laser Freq.	12(10)	± 5
Synchronous Vibrations	0(-92)	$\pm 5(50)$
AC Stark Shift (1PLS)	0	± 5
Rb background vapour	-5	± 3
AC Stark Shift (2PLS)	0	± 2
vertical alignment	0(1)	± 1
Total	**16(-77)**	**$\pm 32(59)$**

As of today, all atom gravimeters use **thermal clouds** and are limited in their accuracy due to the **Coriolis** and the **Wavefront** distortion effects.

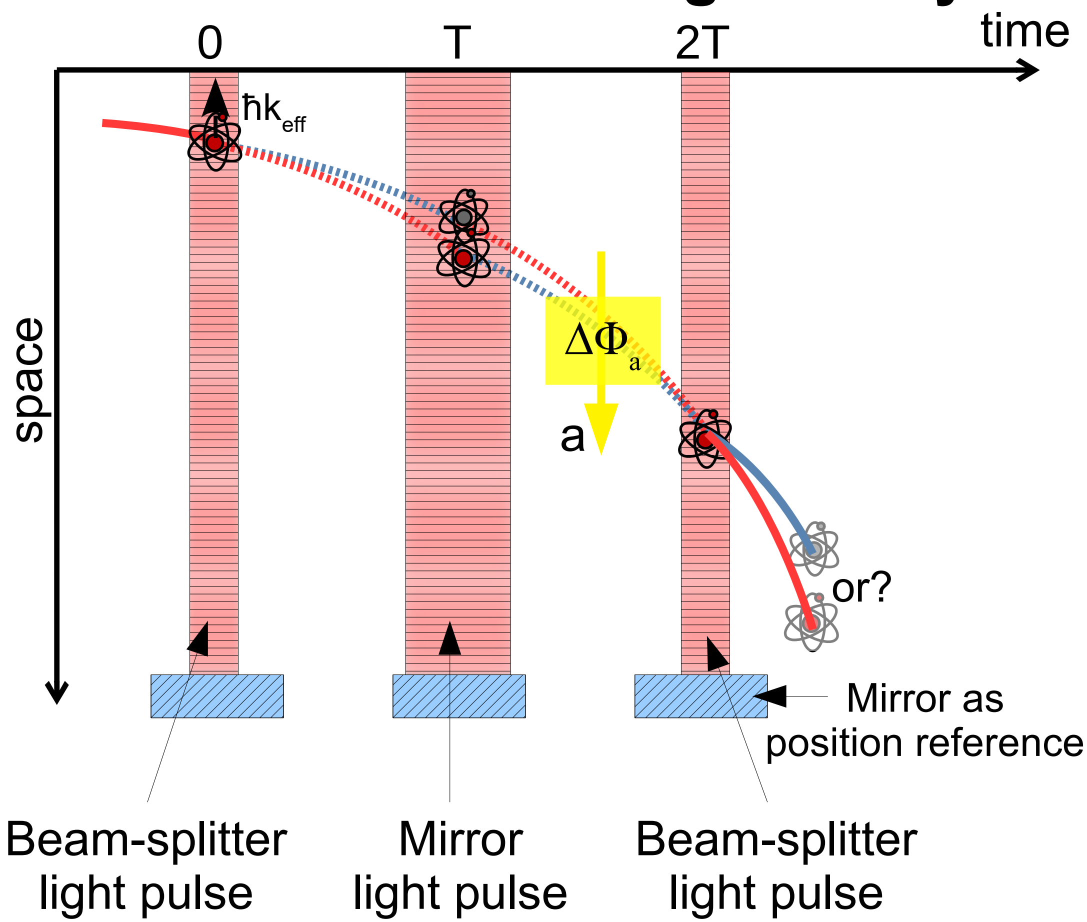
Our Quantum Gravimeter-1 (QG-1) will mitigate these limitations by employing **collimated Bose-Einstein Condensates (BEC)** as probes for atom gravimetry.

[1] B. Fang et al., “Metrology with Atom Interferometry: Inertial Sensors from Laboratory to Field Applications”, J. Phys. Conf. Ser. **723**, (2016)

[2] C. Freier et al., “Mobile quantum gravity sensor with unprecedented Stability”, J. Phys. Conf. Ser. **723**, (2016)

Principle of an atom gravimeter

Mach-Zehder like geometry



The position wave-function of each single atom within an ensemble is split into two trajectories, mirrored after a time T and recombined at 2T by a last beam-splitter. The gravitationally induced phase difference ΔΦa governs the output of the matter-wave interferometer.

Acquired phase difference due to acceleration a:

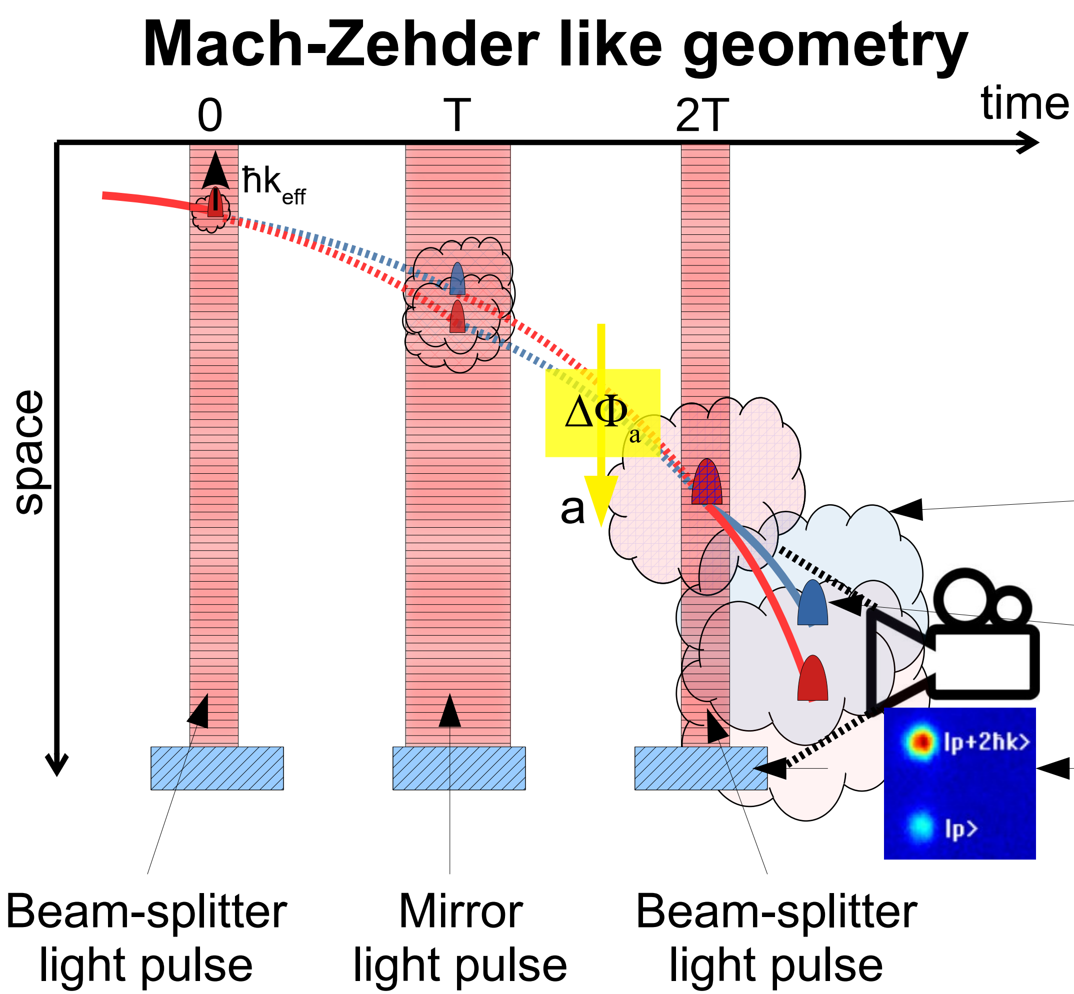
$$\Delta\Phi_a = a \cdot \underbrace{\mathbf{k_{eff}} \cdot \mathbf{T^2}}_{\text{Huge magnification factor solely dependent on a measurement of frequency}}$$

Huge magnification factor solely dependent on a measurement of frequency

→ **perfect for high bias stability and absolute measurements**

a: acceleration
k_{eff}: eff. wave vector (**n**·2π/λ)
T: time between pulses

BEC interferometer vs. thermal AI



The measurement is performed with atomic ensembles of high atom number. The better the control over these ensembles, the higher the accuracy of the gravimetric measurement.

Thermal atoms versus BEC:

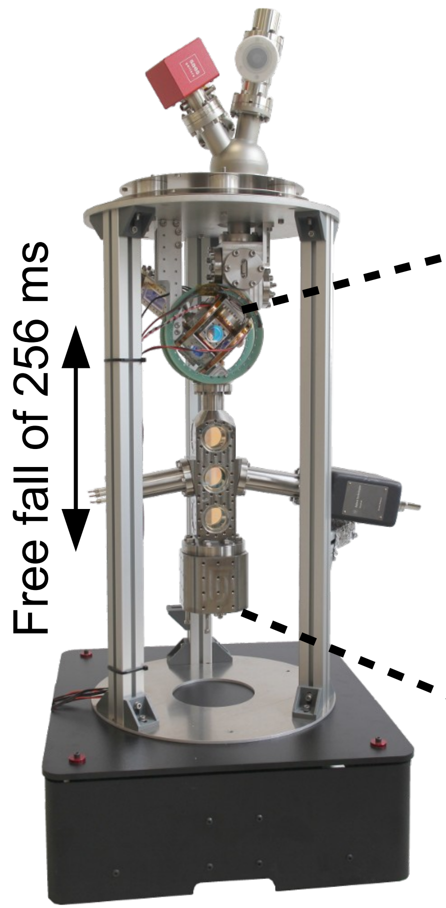
- **Thermal clouds** at few µK show unfavourable large expansion rate
- **BECs** can be collimated in 3D to drastically reduce expansion rate
- Sub-recoil **BECs** can be detected spatially separated within one image giving 3D position information and reducing detection noise

a: acceleration
k_{eff}: eff. wave vector ($\mathbf{n}\cdot 2\pi/\lambda$)
T: time between pulses

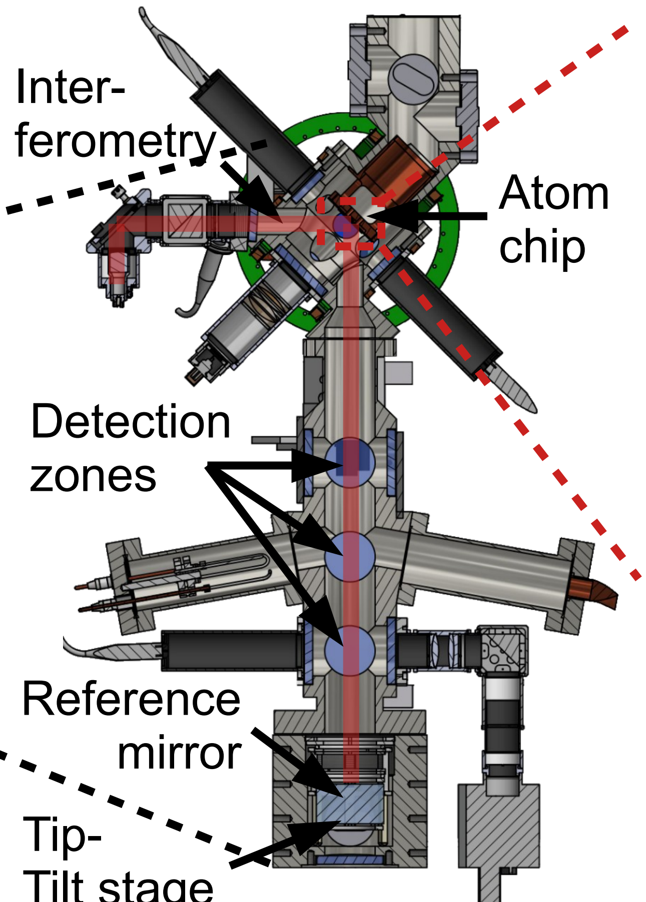
BEC interferometer QG-1

Transportable Quantum Gravimeter-1 (QG-1)

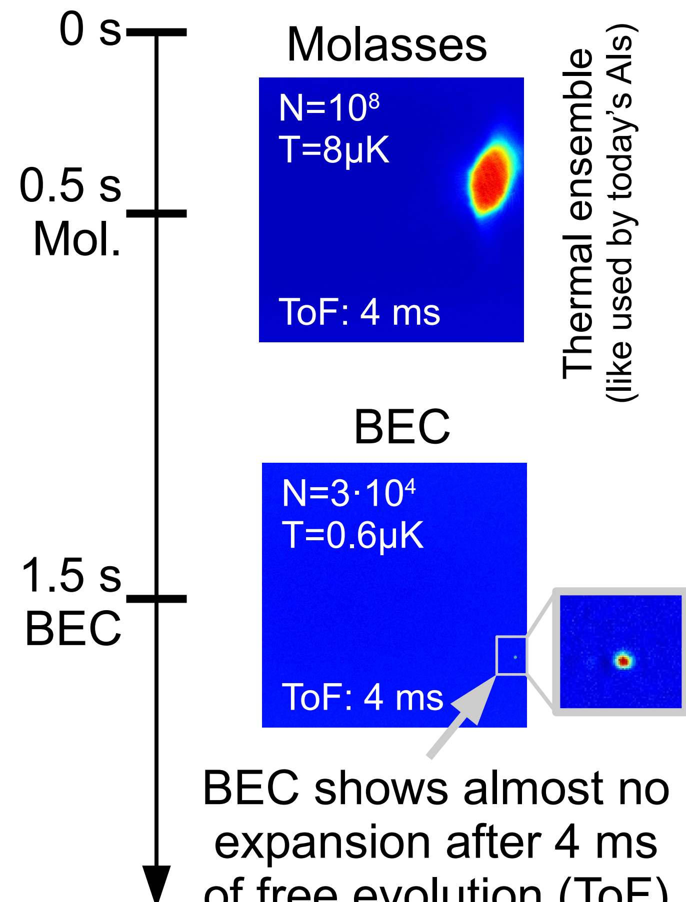
Sensor head of QG-1
(without magn. shield)



Interferometry section
of QG-1



Source performance
of QG-1 (prelim.)

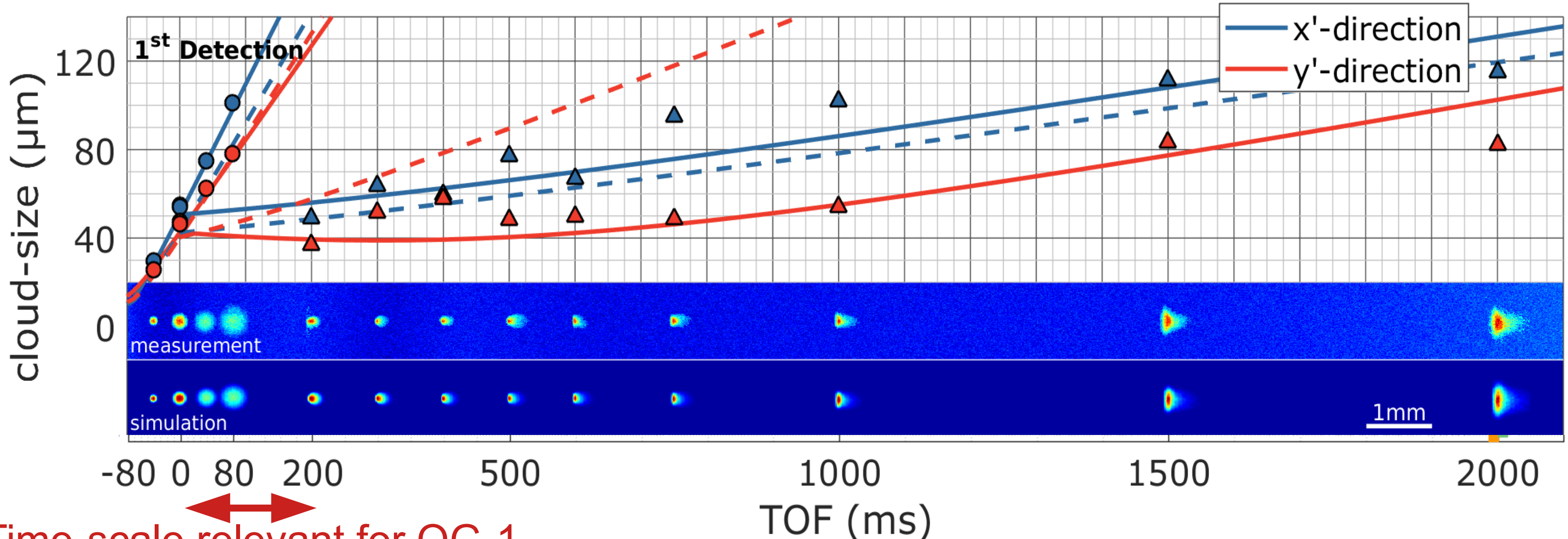


BEC shows almost no expansion after 4 ms of free evolution (ToF)

Method now in implementation in QG-1

Collimating a BEC in 3D to 38 pK using an atom chip

The expansion rate of a BEC has been strongly reduced at a TF-radius of 50 µm (t=0) by the magnetic lensing technique and reached a final TF-radius of only <120 µm after t=2000 ms of free propagation.
The same technique will be employed in QG-1 to freeze-out the expansion rate of the BEC for the interferometer time of 2T=200 ms.



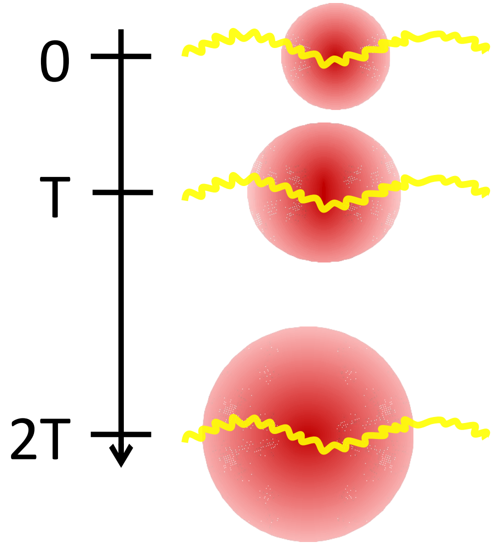
Time-scale relevant for QG-1

Experiment performed by QUANTUS-2 in the Drop Tower Bremen (Publication in preparation)

Conclusion and accuracy estimation

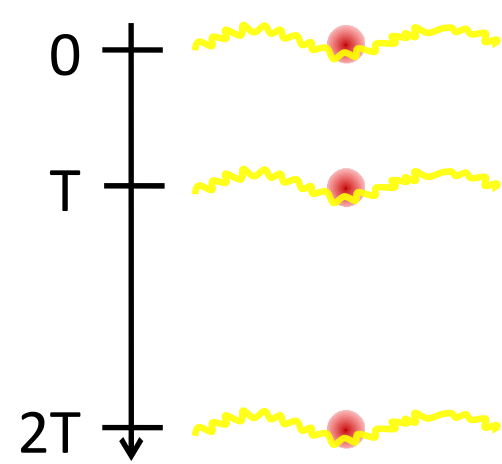
Atom Gravimeter

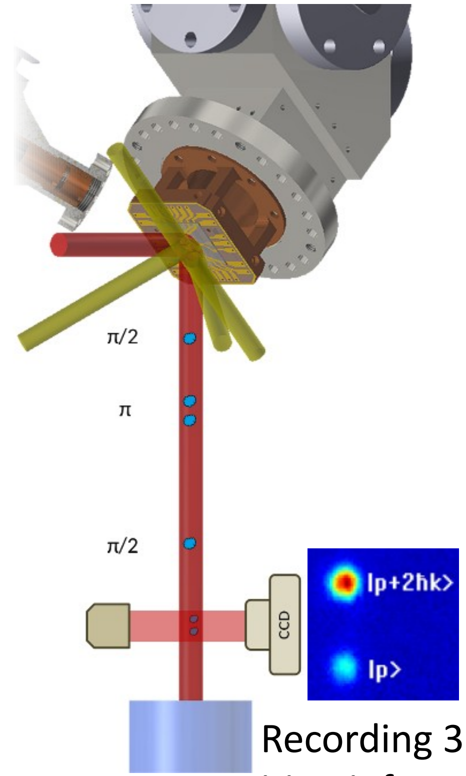
Laser cooled atoms
show large expansion rates
and a horizontal initial velocity



Quantum Gravimeter-1

Magnetically collimated BECs
do almost not expand and
drop controllable downwards





Recording 3D
position information
to mitigate Coriolis effect

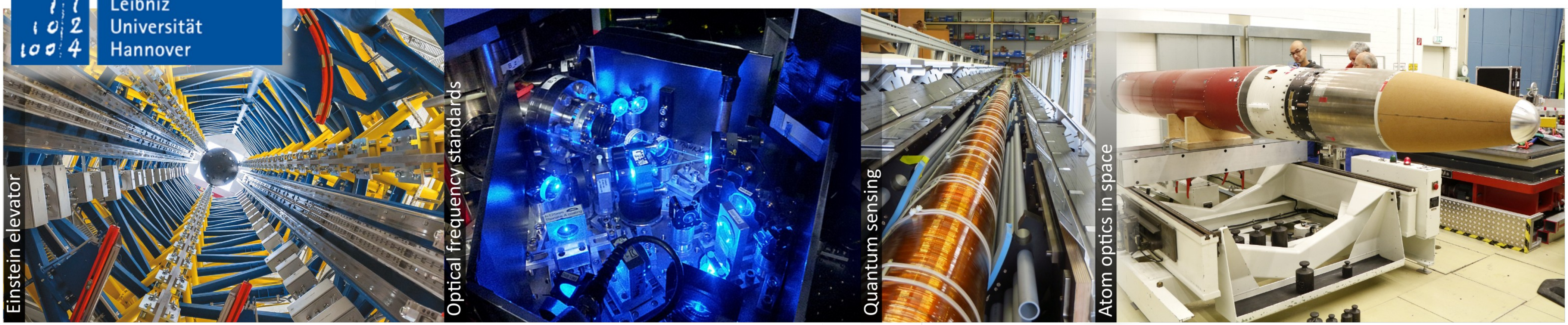
Systematic effect (in nm/s²)	**CAG** [1]	**GAIN** [2]	**QG-1** [3] (projected)
Wavefront distorsion	40	22	< 0.4
Coriolis effect	10	15	< 0.3
Total	**43**	**32**	**< 1**

[3] N. Heine et al., “A transportable quantum gravimeter employing delta-kick collimated Bose-Einstein condensates”, Under revision.

DLR Institut für Satellitengeodäsie und Inertialsensorik

Leibniz Universität Hannover

Thank you for your attention



Institut für Quantenoptik

Hannover Institute of Technology

Exzellenzcluster QuantumFrontiers

DLR Institut für Satellitengeodäsie und Inertialsensorik

Sonderforschungsbereich

Förderprogramm des DLR Raumfahrtmanagements

join us!