Quantum Physics:
Perspectives of Future Microgravity Research

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Overview

- Achievements, new approaches, open questions, future perspectives in: „Quantum Physics“

- Quantum physics in microgravity environment

Achievements, new approaches, open questions, future perspectives in: „Quantum Physics“

- Understanding the concepts of the quantum world (**Quests**)
- Quantum engineering
- Degenerate quantum gases
- Quantum techniques
- Fundamental tests

Quests

- Non-locality, quantum realism, Copenhagen interpretation (Niels Bohr)
- Entanglement
- Superposition, decoherence
- Plural universes (*string theory*)
- Big bang, dark matter and energy, ...
- Quantum ... Gravity

More specific quests

- Gravitational wave astronomy
- Nanoscopic quantum world
- Mesoscopic quantum world
- Macroscopic quantum to classical world
- Equivalence principle
- Constancy of physical constants
- Preferred frame research

Achievements, new approaches, open questions, future perspectives in: „Quantum Physics“

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Quantum Engineering

- Quantum & atom optics
  - Non-classical light and mater wave fields or modes
  - Quantum non-demolition measurements
  - Squeezing, down to low frequencies
  - Light & matter wave interferometry “beyond all limits”
  - Entanglement & Quantum correlation of light fields, atoms, molecules, ions, and macroscopic bodies
  - Laser cooling and trapping of atoms, molecules, ions, and macroscopic bodies

Achievements, new approaches, open questions, future perspectives in: „Quantum Physics“

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Degenerate quantum gases

- Bose Einstein Condensates (BEC)
  - *Coldest matter in the universe*
- Degenerate ultra-cold Fermi gases
  - *"Collision-less"*
- Degenerate mixtures, spinor gases
- Atom lasers
  - *Brilliant matter wave sources*
- Atom chips
  - *Integrated atom optics*

Achievements, new approaches, open questions, future perspectives in: „Quantum Physics“

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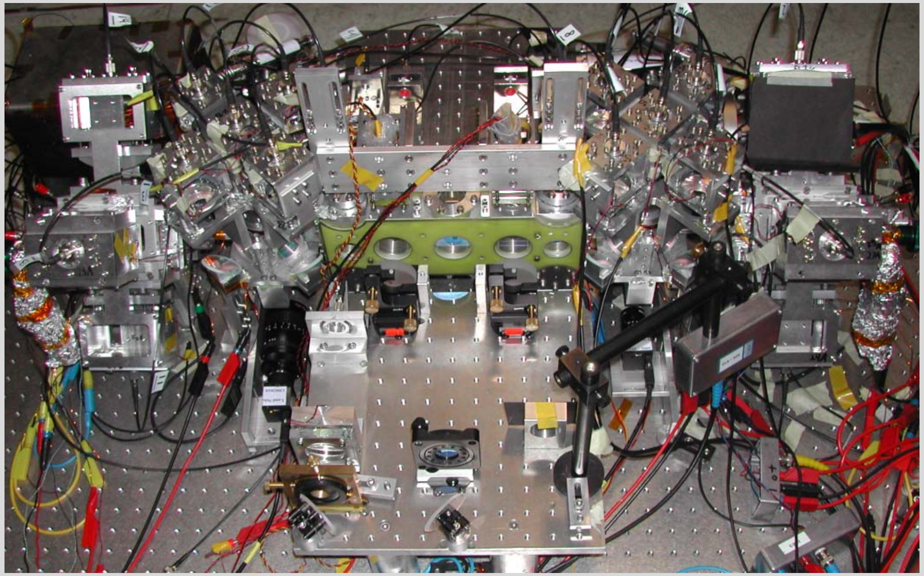
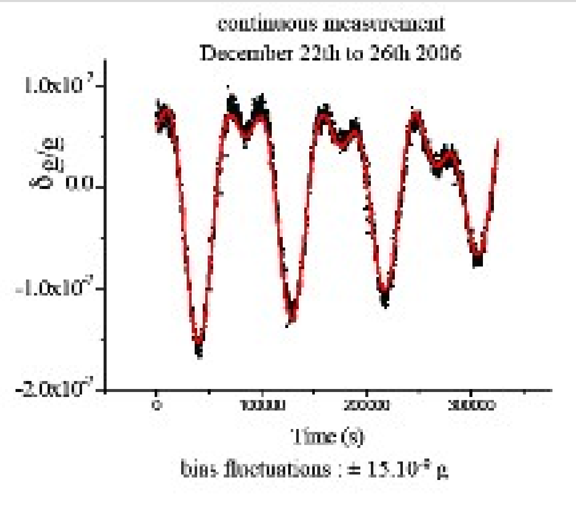
Quantum techniques

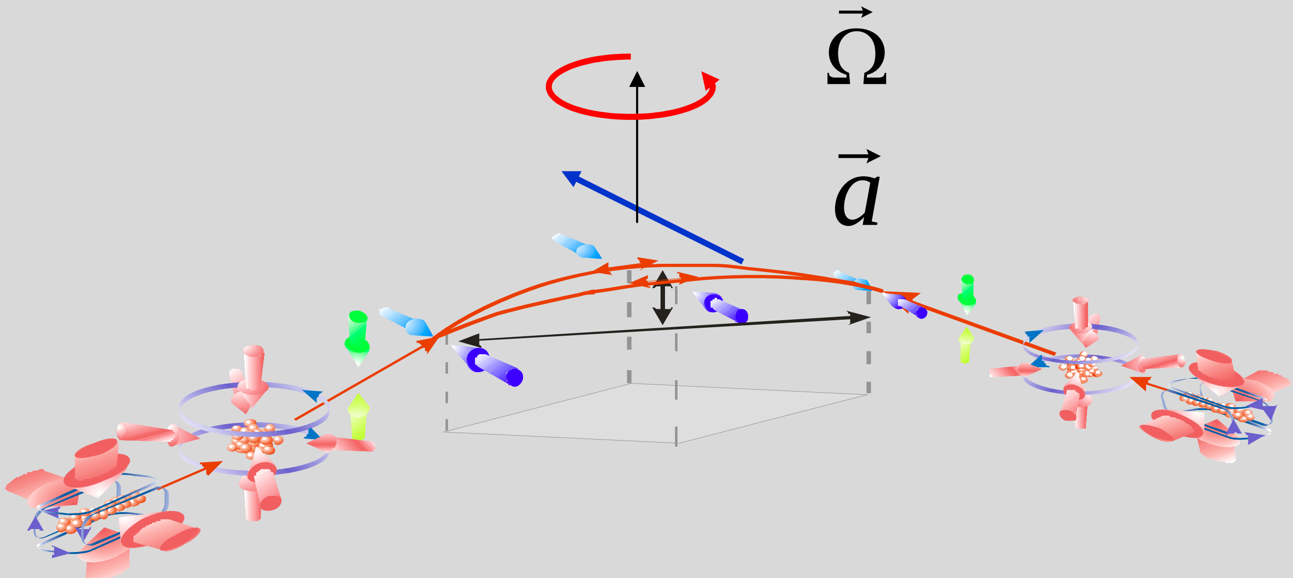
- Quantum information
  - Quantum cryptography, teleportation, computing
- Quantum metrology
- Non-classical light and matter wave sources
- (Light and) Matter wave interferometry
  - Interferometry at the quantum limit and beyond
    - e.g. inertial sensing
    - Gravitational wave detection

Quantum Sensors



Gravimeter (SYRTE)

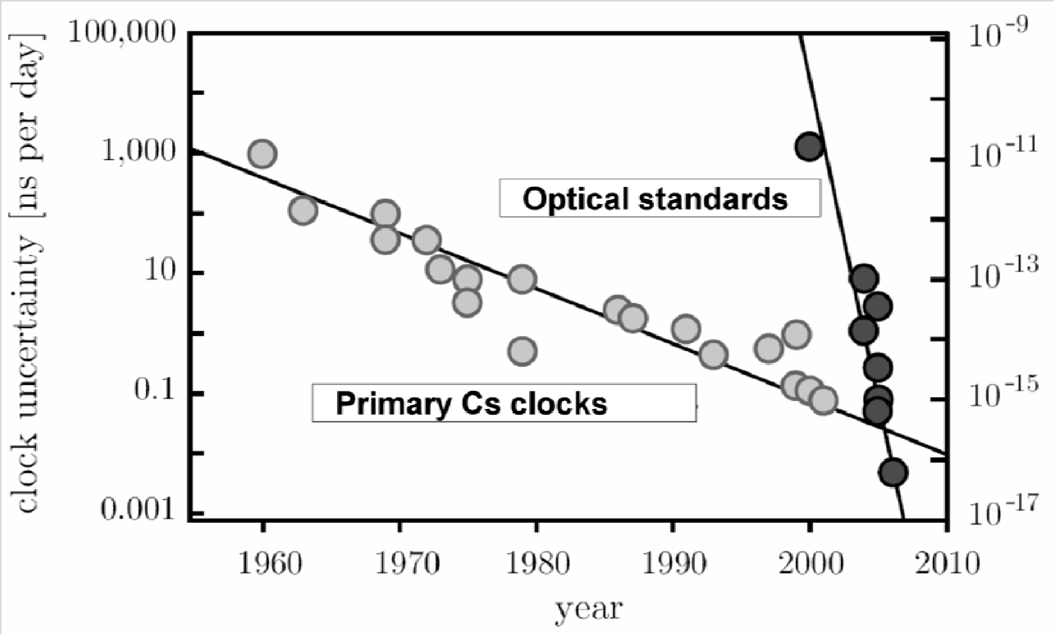




Transportable Cold Rubidium Sagnac Interferometer

Optical Atomic Clocks

- Now better than primary Caesium standard
- Promise 10^{-18} ...
- Pre-stabilise laser to cavity



- Post-stabilise to cold atomic reference

Achievements, new approaches, open questions, future perspectives in: „Quantum Physics“

- Understanding the concepts of the quantum world (**Quests**)
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Fundamental Physics Tests

- Space-Time (GR) (see S. Schiller, Hj. Dittus)
- Gravitational waves (see B. Schutz, K. Danzmann)
- Foundation of quantum mechanics
  - Matter-wave interferometry on the crossover between the classical and quantum world (see M. Arndt)
  - EPR-type experiments over long distances and unperturbed by environmental and gravitational disturbances (see H. Weinfurter)
  - Vision: Testing entanglement over very long distances and with macroscopic bodies

Fundamental Physics Tests

- Quantum gravity
  - Exploration of matter wave decoherence by space-time fluctuations
  - Testing the equivalence principle by free falling quantum probes (distinct atomic species)

    (Proposed < ... 10^{-17}, tested @ 10^{-13})
  - Investigation the time variance of fundamental constants
    - Fine structure α (drift (tested) < 10^{-17} /a)
    - Gravitation G (drift (tested) < 10^{-13} /a)

Overview

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Benefits of extended free fall & µ-gravity

For inertial atomic quantum sensors and atomic clocks, ... :

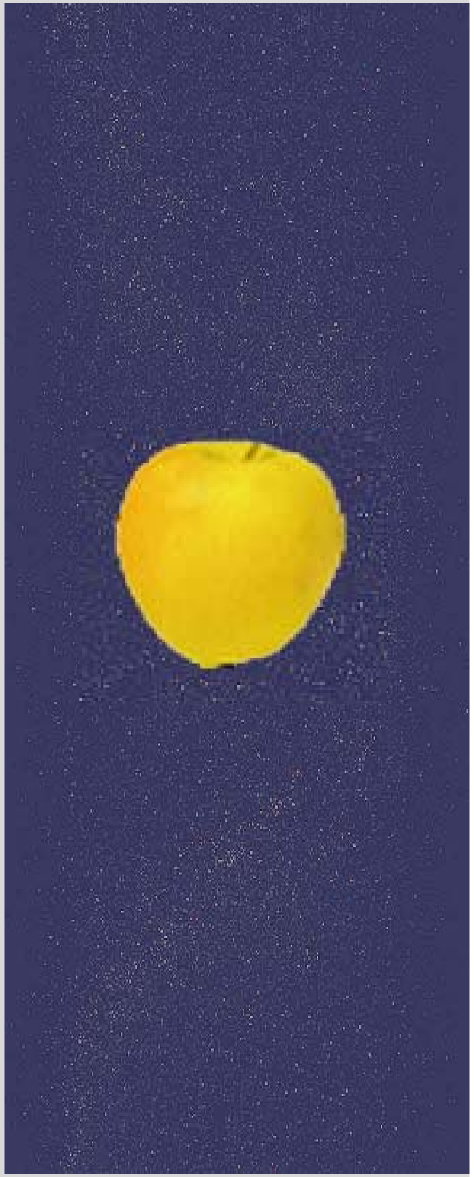
- Extended Time of Evolution

+

- Perturbation-free Evolution

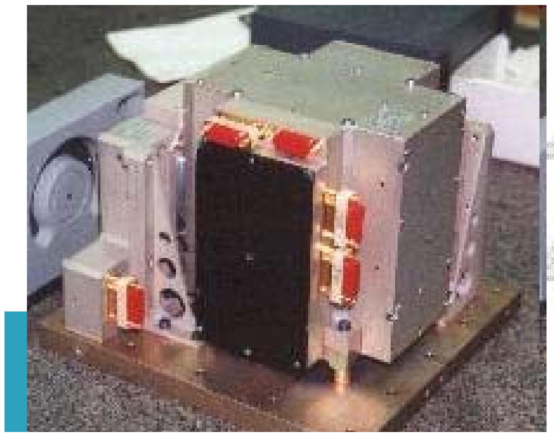
+

- Must not compensate gravity / levitate the atoms

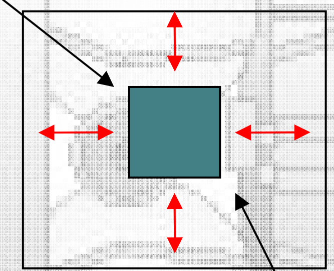


Concepts for the perfect implementation of the free fall

ONERA



free falling proof masses



… guiding the satellite

(laboratory system)

$$3\cdot 10^{-10}\,\frac{g}{\sqrt{\mathrm{Hz}}}\,@\,10^{-2}/10^{-1}\,\mathrm{Hz}$$

$$3\cdot 10^{-11}\,\frac{g}{\sqrt{\mathrm{Hz}}}\,@\,10^{-4}-10^{-1}\,\mathrm{Hz}$$

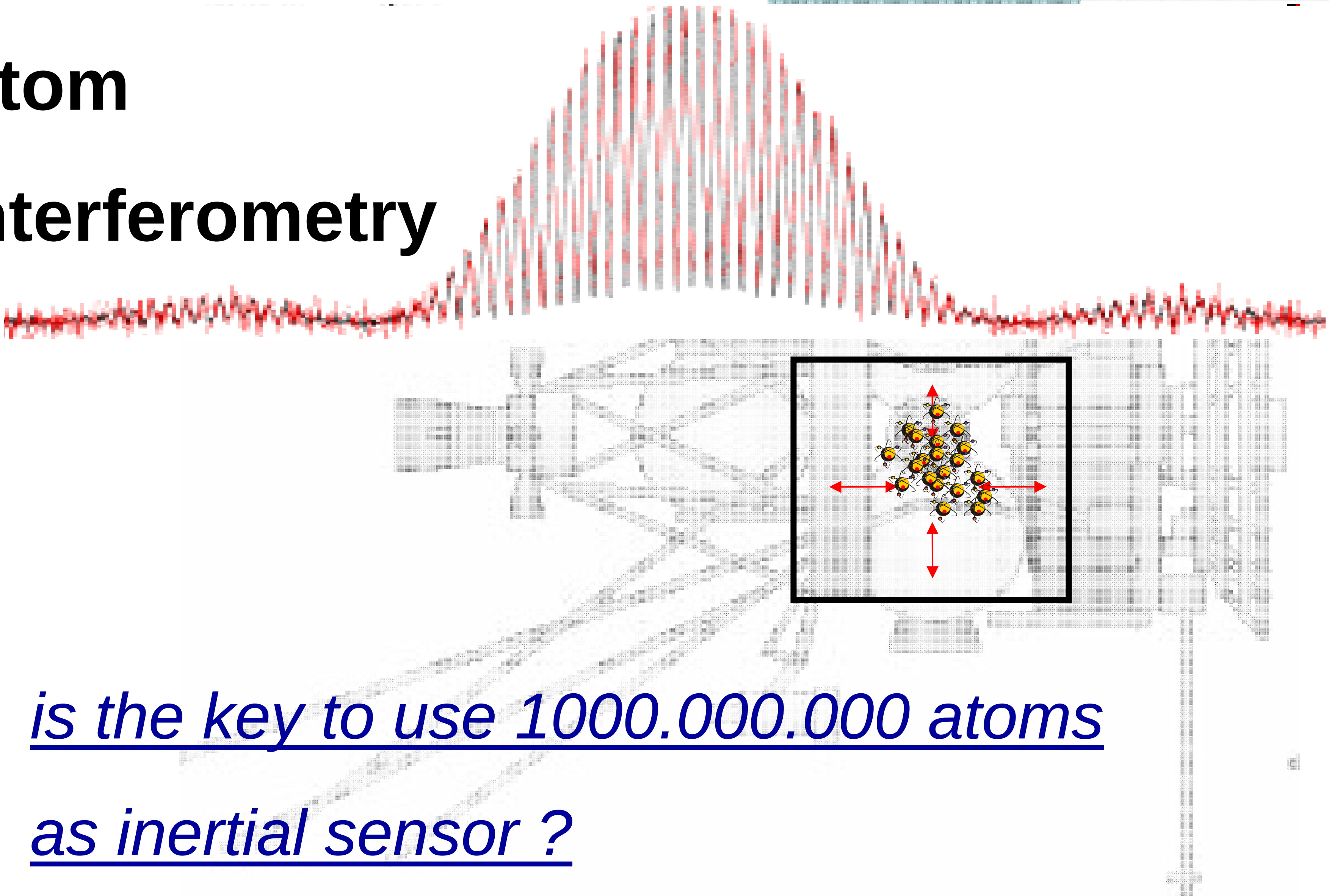
Read out of

distance or relative motion by

- **optical means,**
- **capacitive measurements, or**
- **magnetometers**

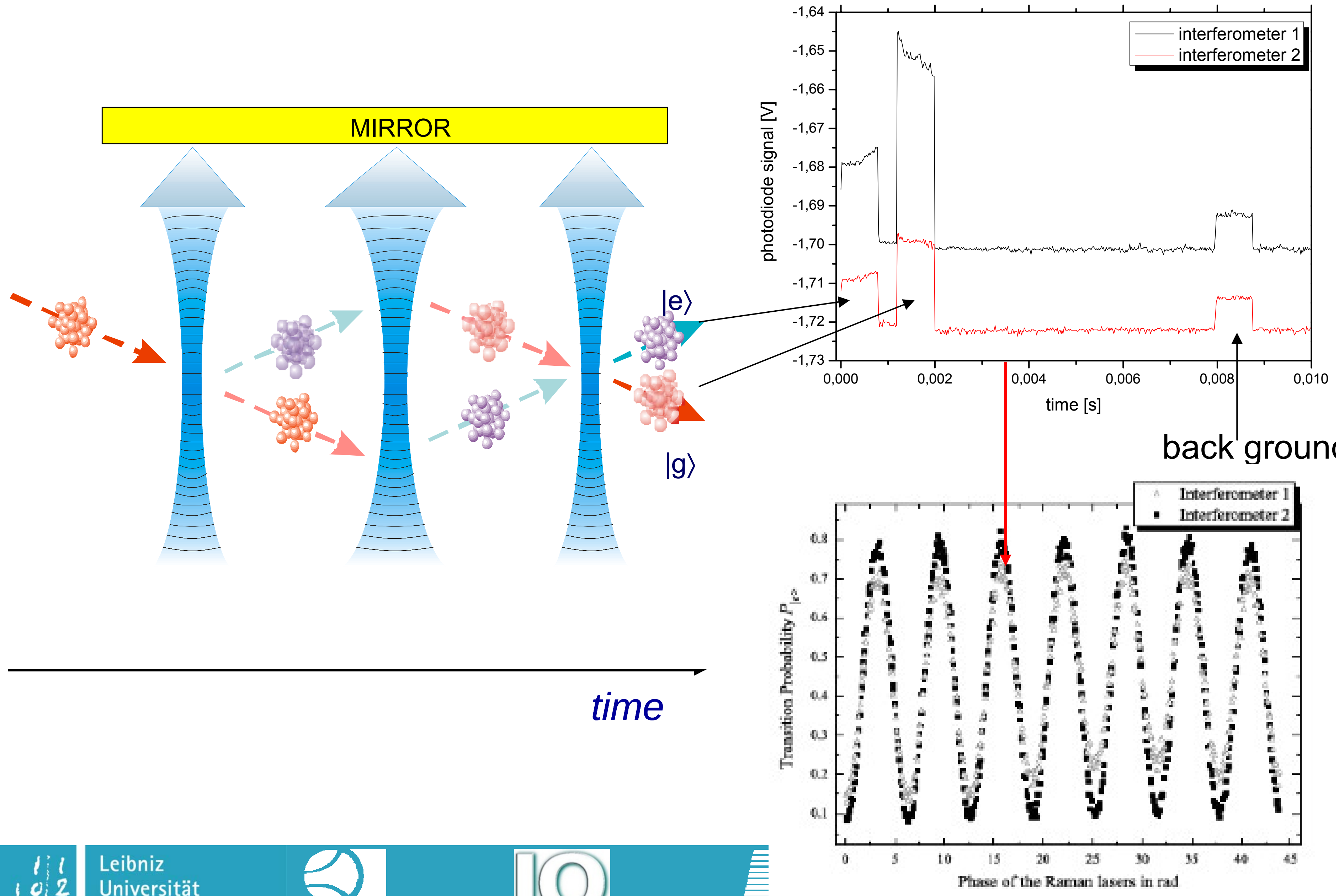
Atom

interferometry



is the key to use 1000.000.000 atoms

as inertial sensor ?



MIRROR
|e⟩
|g⟩
time
photodiode signal [V]
time [s]
interferometer 1
interferometer 2
-1,64
-1,65
-1,66
-1,67
-1,68
-1,69
-1,70
-1,71
-1,72
-1,73
0,000
0,002
0,004
0,006
0,008
0,010
back groun
Interferometer 1
Interferometer 2
Transition Probability
Phase of the Raman lasers in rad
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
5
10
15
20
25
30
35
40
45

Extended Time of Evolution

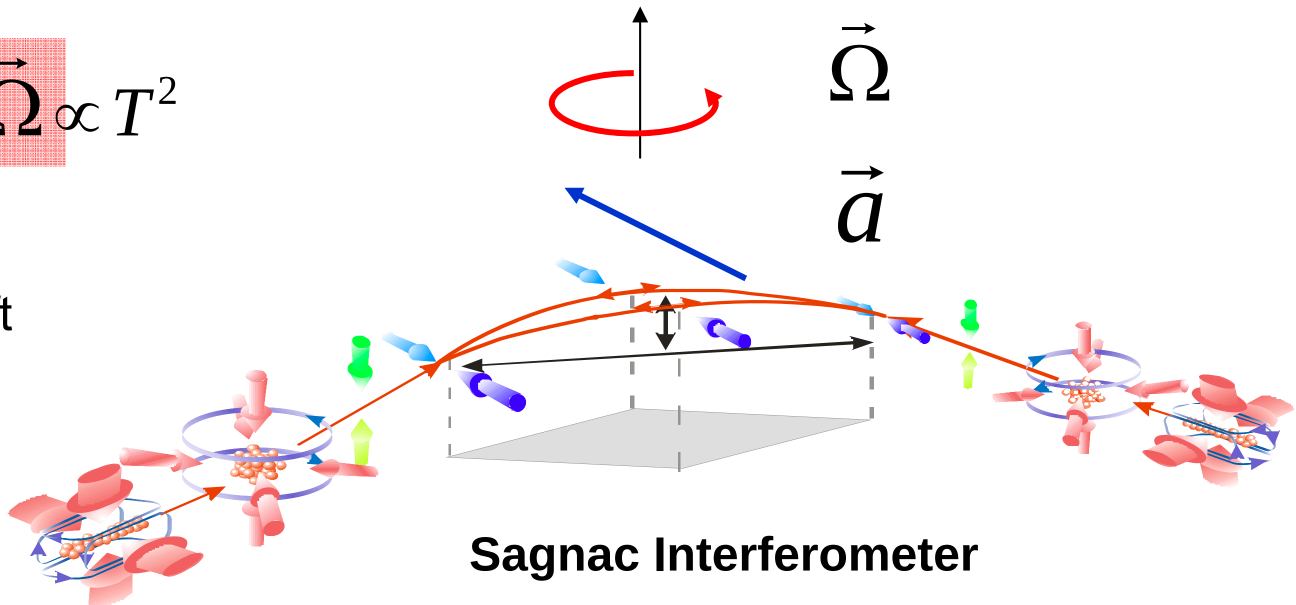
Inertial Quantum Sensors

Rotational Phase shift

$$\Delta\varphi_{rot} = \frac{2m_{Atom}}{\hbar}\vec{A}\cdot\vec{\Omega} \propto T^2$$

Accellerational Phase shift

$$\Delta\varphi_{acc} = T^2\vec{k}\cdot\vec{a}$$



Sagnac Interferometer

Extended Time of Evolution

Inertial Quantum Sensors

Rotational Phase shift

$$\Delta\varphi_{rot} = \frac{2m_{Atom}}{\hbar}\vec{A}\cdot\vec{\Omega} \propto T^2$$

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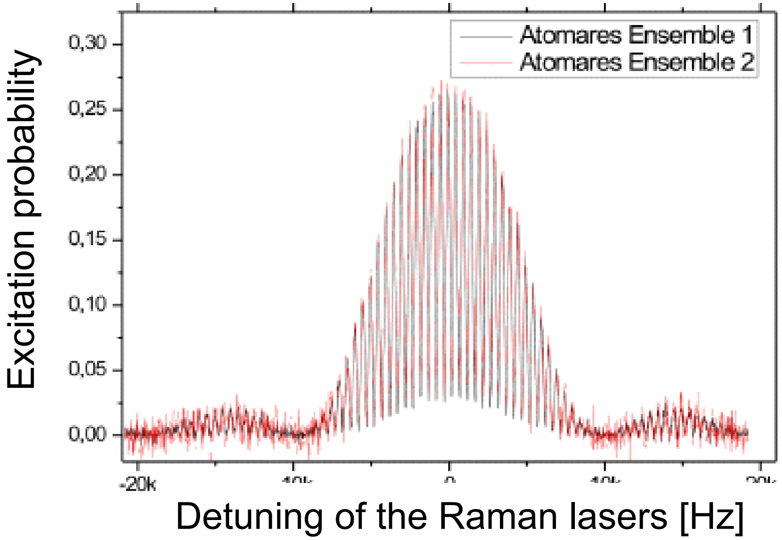
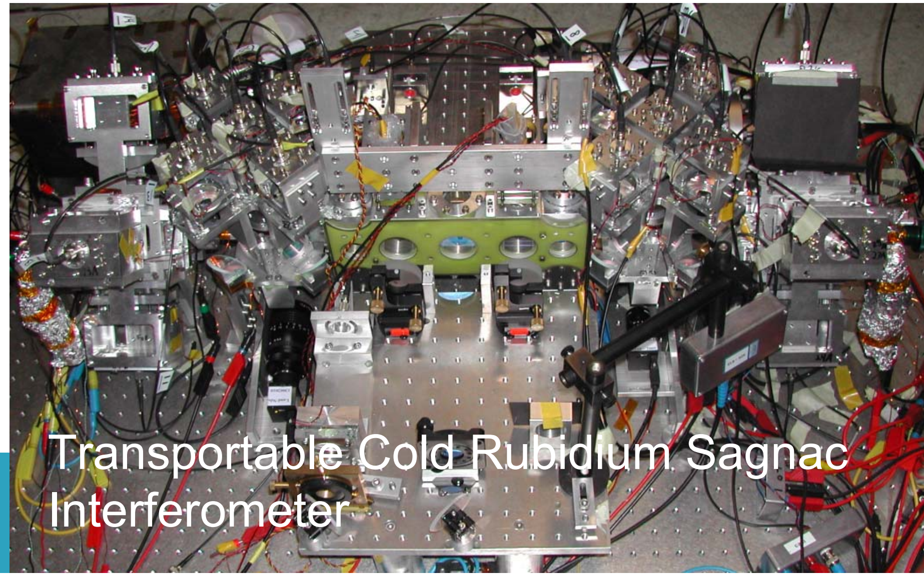
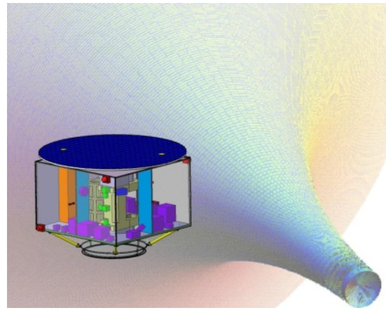
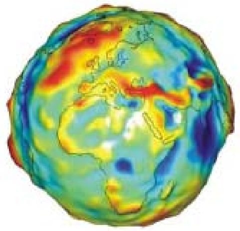



Transportable Cold Rubidium Sagnac Interferometer

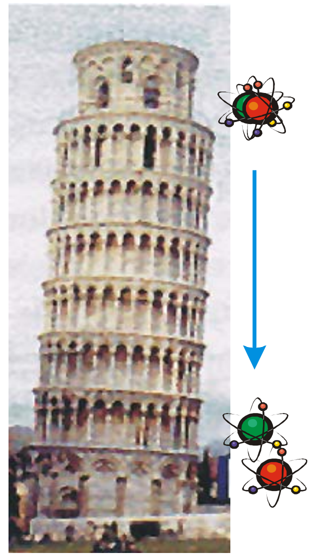
Application of quantum techniques

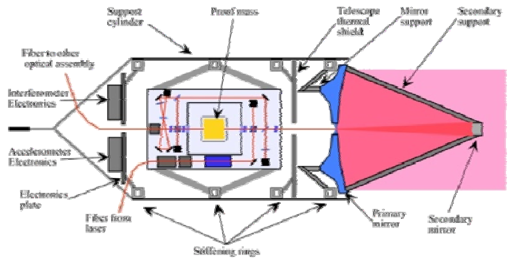
Inertial sensors, Exploring gravity & fundamental physics





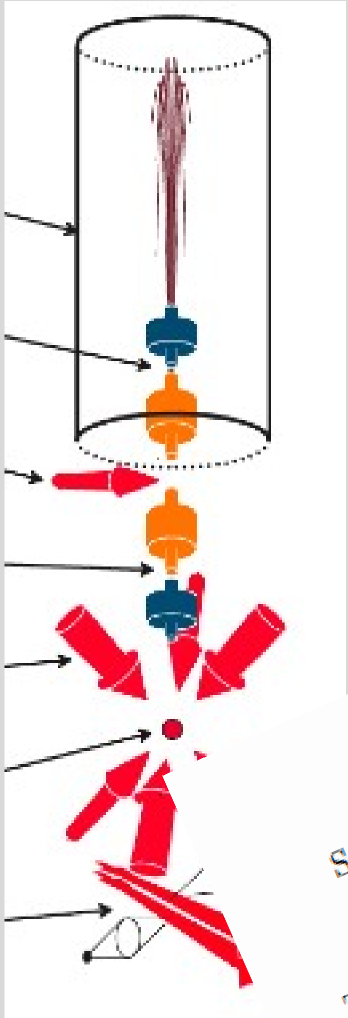
- Earth Observation
- Measurement of relativistic effects & gravity
- Pioneer anomaly
- Testing the Weak Equivalence Principle
- Drag-free sensors perhaps in gravitational wave detectors ?

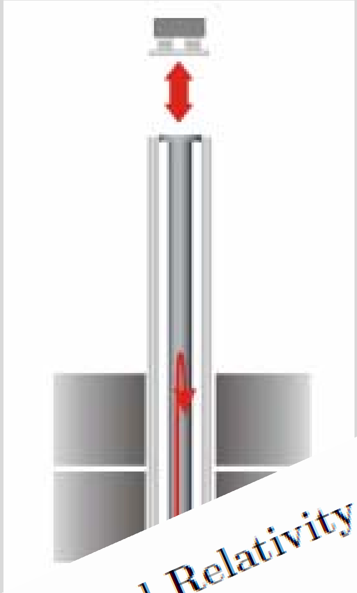


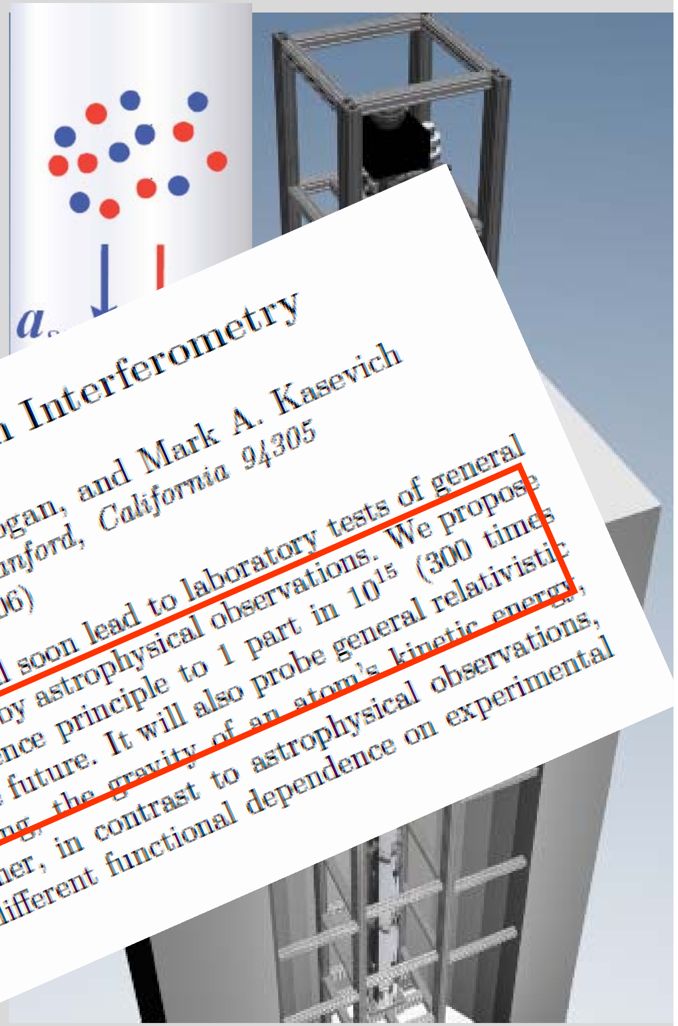


Fountains & Drop facilities

10 m atom drop tower





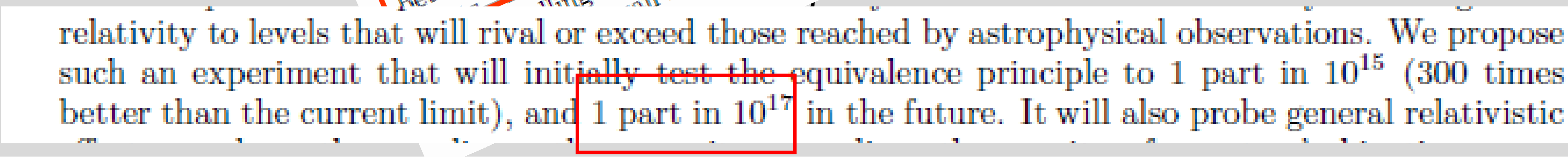


Testing General Relativity with Atom Interferometry

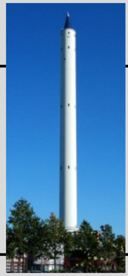
Savas Dimopoulos, Peter W. Graham, Jason M. Hogan, and Mark A. Kasevich
Department of Physics, Stanford University, Stanford, California 94305
(Dated: October 11, 2006)

The unprecedented precision of atom interferometry will soon lead to laboratory tests of general relativity to levels that will rival or exceed those reached by astrophysical observations. We propose such an experiment that will initially test the equivalence principle to 1 part in 10^{15} (300 times better than the current limit), and 1 part in 10^{17} in the future. It will also probe general relativistic effects—such as the non-linear three-graviton coupling, the gravity of an atom's kinetic energy, and the falling of light—to several decimals. Further, in contrast to astrophysical observations, ... isolate these effects via their different functional dependence on experimental

Picture by courtesy of.
Y. Sortais (PhD-Thesis)

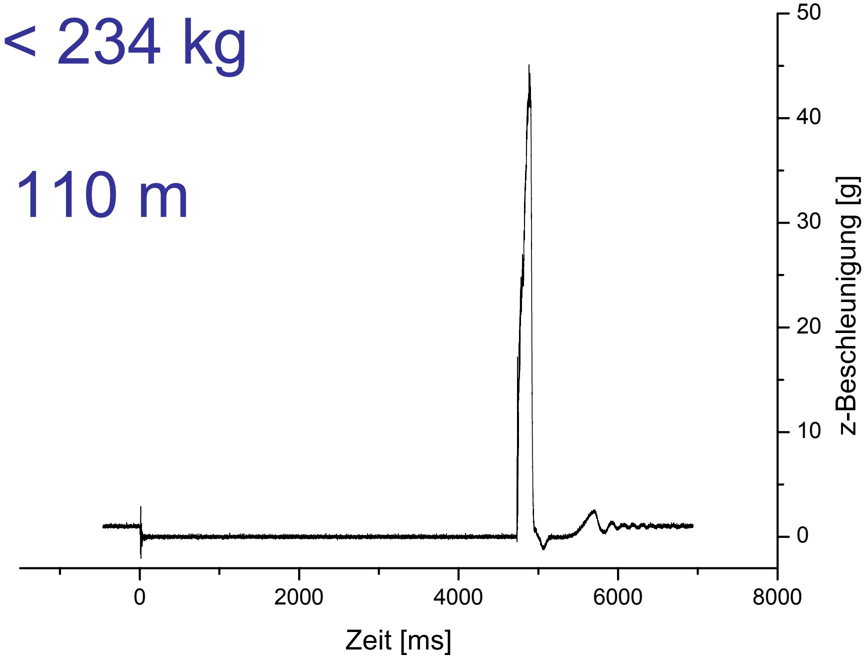

relativity to levels that will rival or exceed those reached by astrophysical observations. We propose such an experiment that will initially test the equivalence principle to 1 part in 10^{15} (300 times better than the current limit), and 1 part in 10^{17} in the future. It will also probe general relativistic

Carrier for experiments during extended free fall

platform	μg-quality [g]	μg-duration
droptower 	10^{-6}	4.8 s, x 2 with catapult
ISS	10^{-4}	days to months
space carrier	 10^{-6}	3 days
parabola flights	10^{-2} 	20 seconds
ballistic rockets	 10^{-5}	6 minutes

Conditions & Requirements

- Free Fall: up to 4.5 s
- Duration > 1 BEC-Experiment
- 3 flights per day
- Test of a robust BEC Facilities
  Dimensions < 0.6 ∅ x 1.5 m
  < 234 kg
- Height 110 m



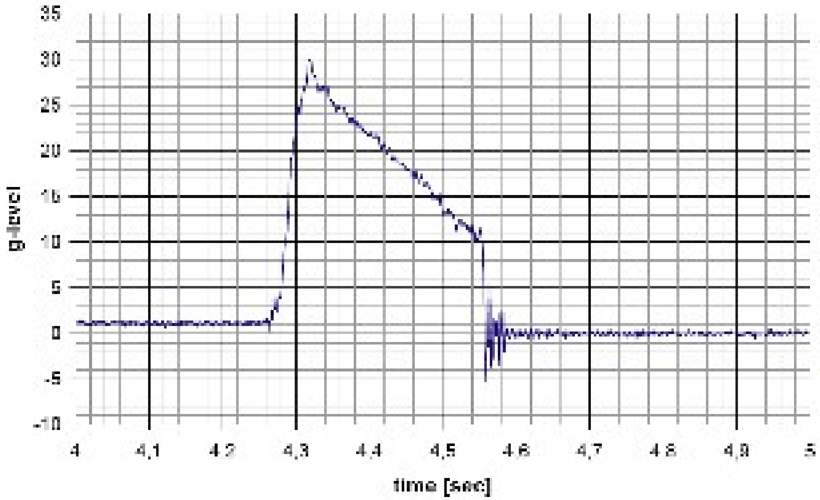
The Bremen Drop Tower at ZARM

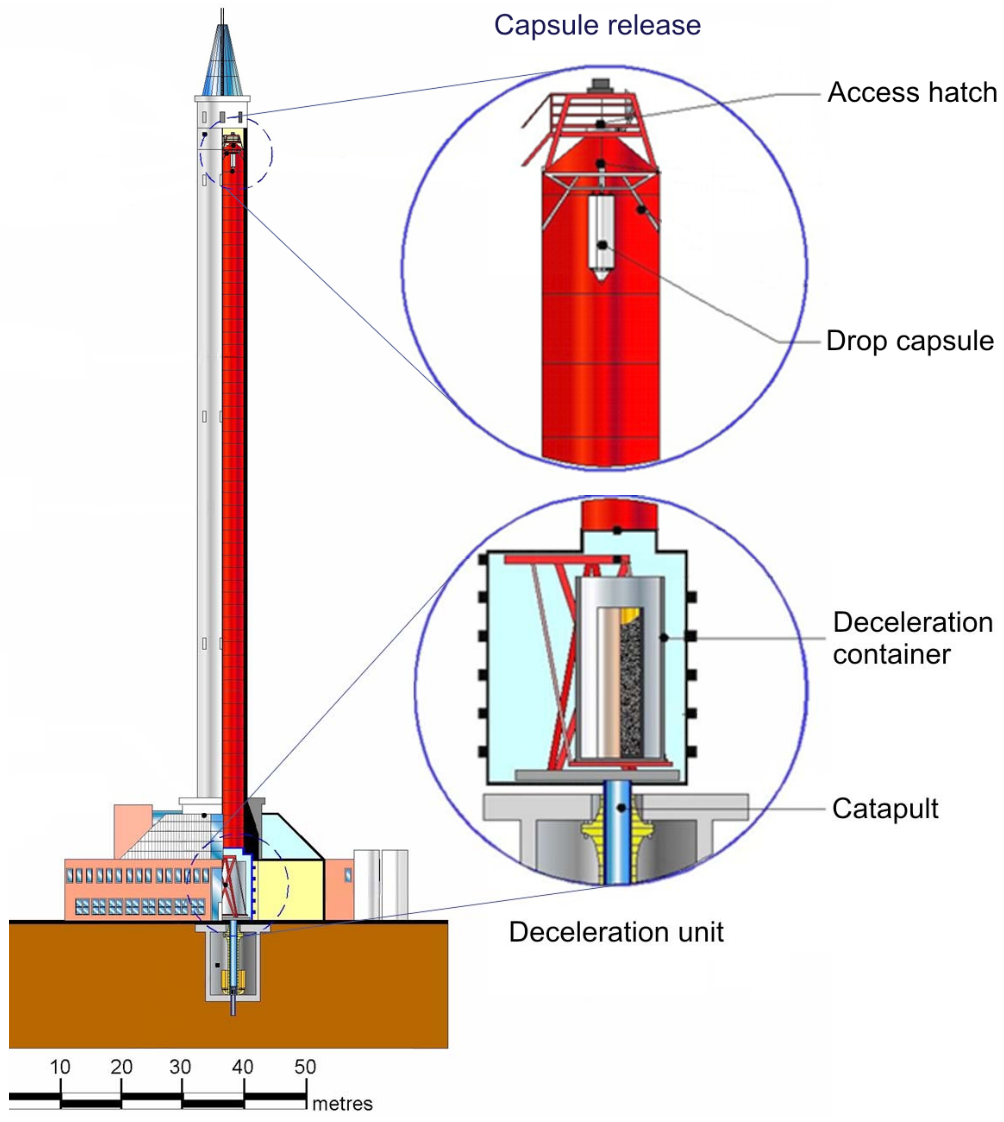
Duration of experiments

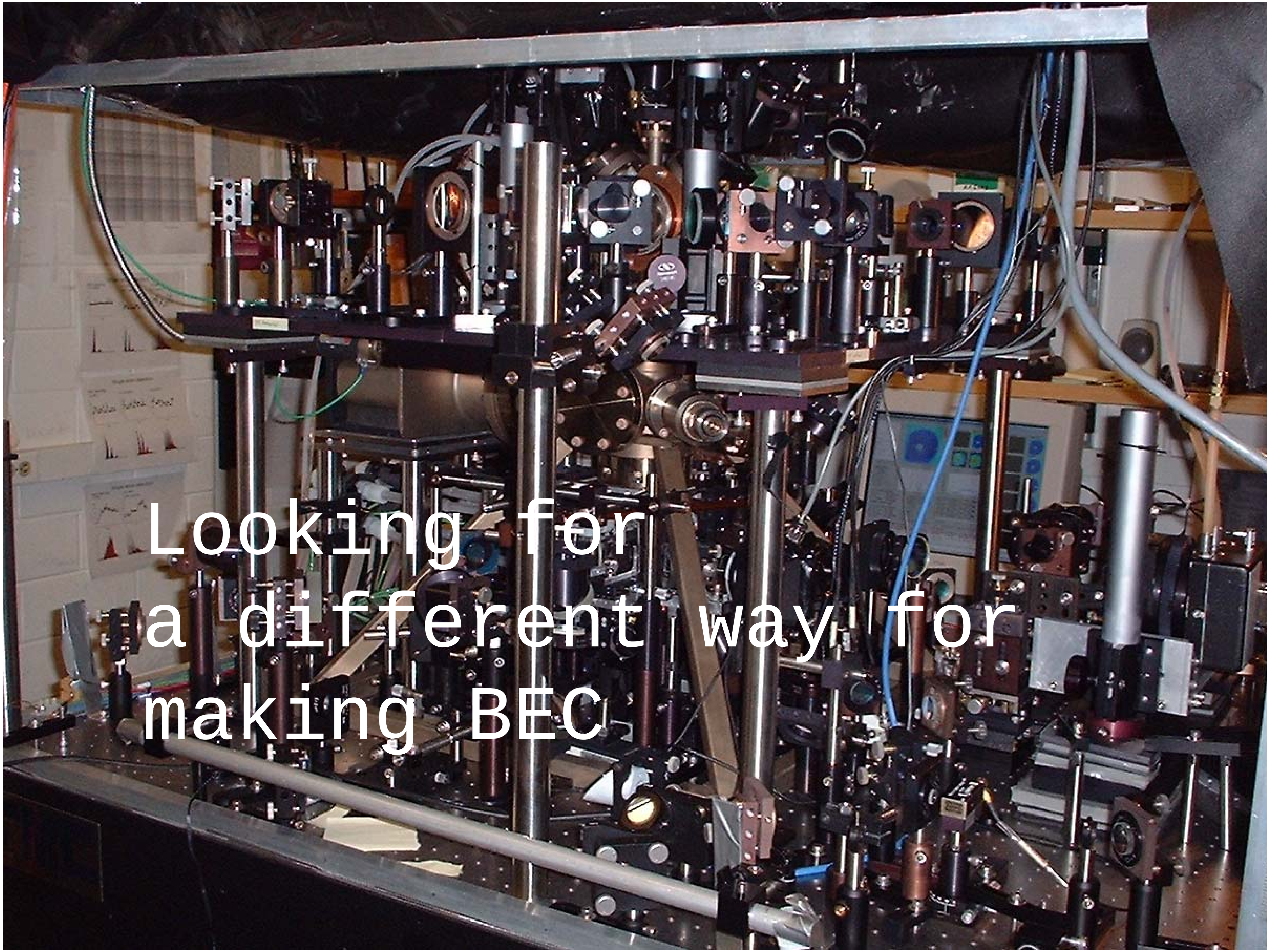
Drop from 100m: 4 seconds

Catapult: 9 seconds

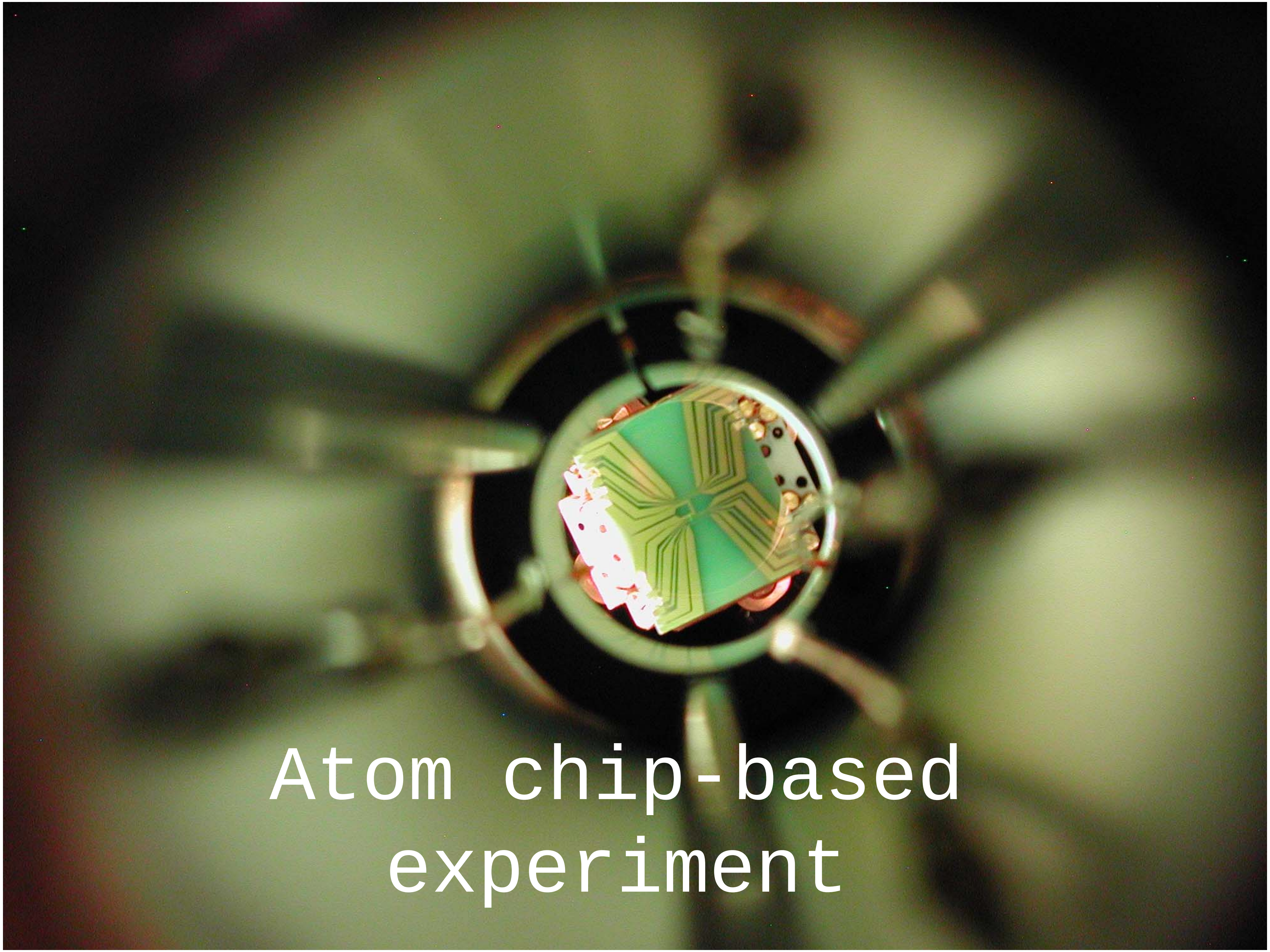
Laser system was first scientific equipment flown in the catapult







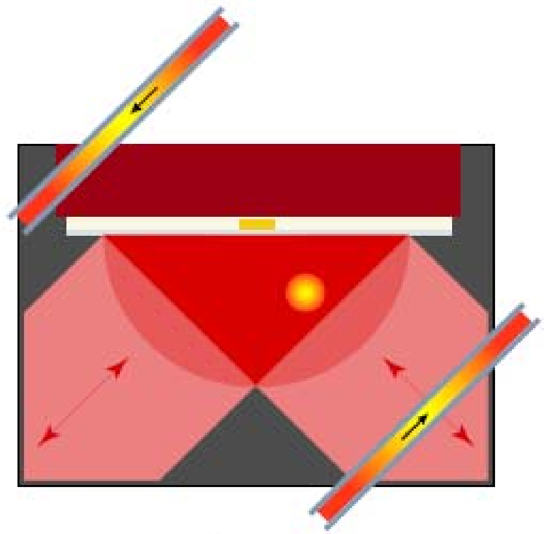
Looking for
a different way for
making BEC


Atom chip-based
experiment

Steps to BEC

- External MOT
- Chip-MOT
- Moving MOT
- Molasses
- State transfer
- Storage in magn. trap
- Evaporation
- Analysis of BEC

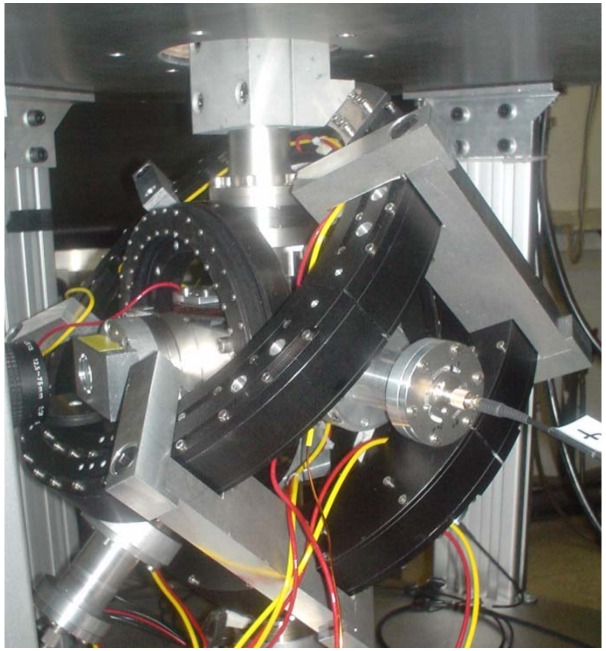
Mirror MOT

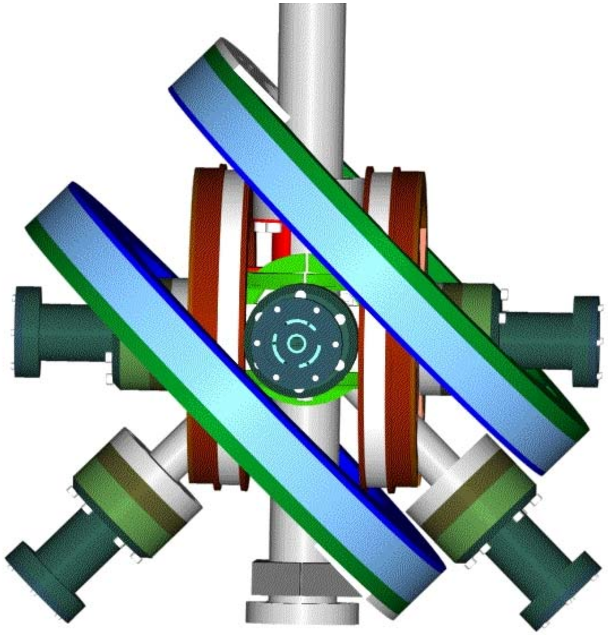


Number: 1,3 x 10^7

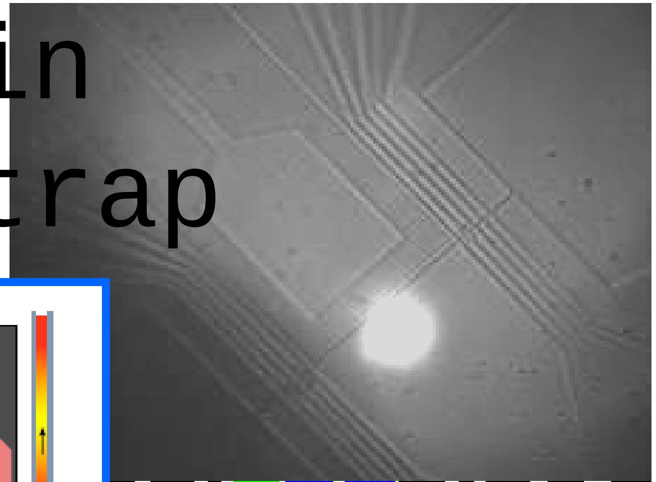
Temperature: 220 µK

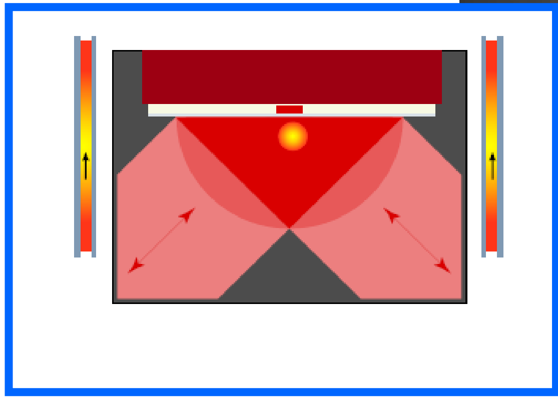
MOT- Loading: 10 s





Transferring atoms in the magneto-static trap

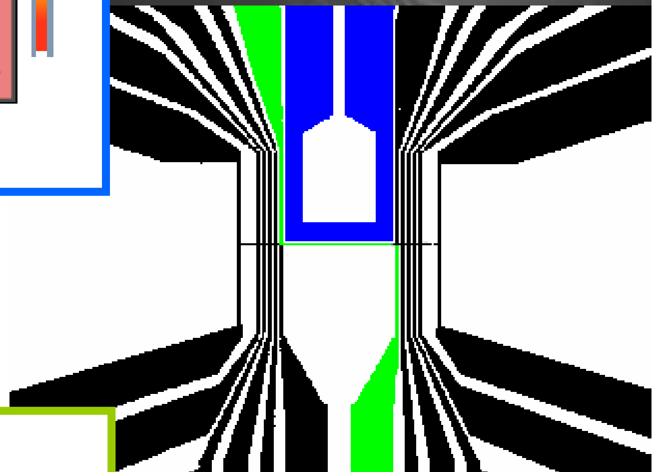


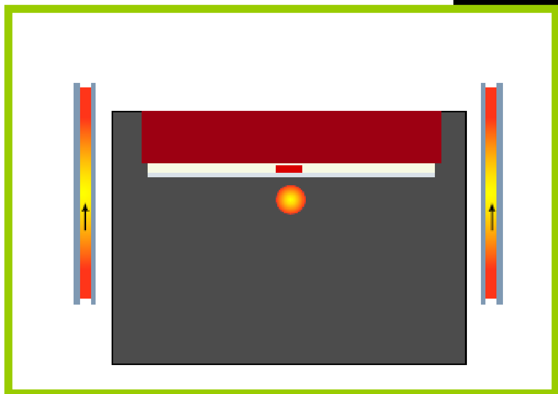


Atom number: 6,0 x 10^6

Molasses

Temperature: ~ 23 µK

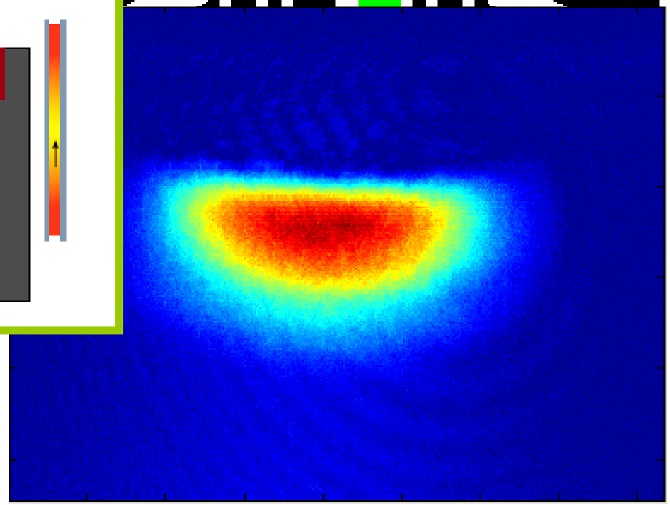


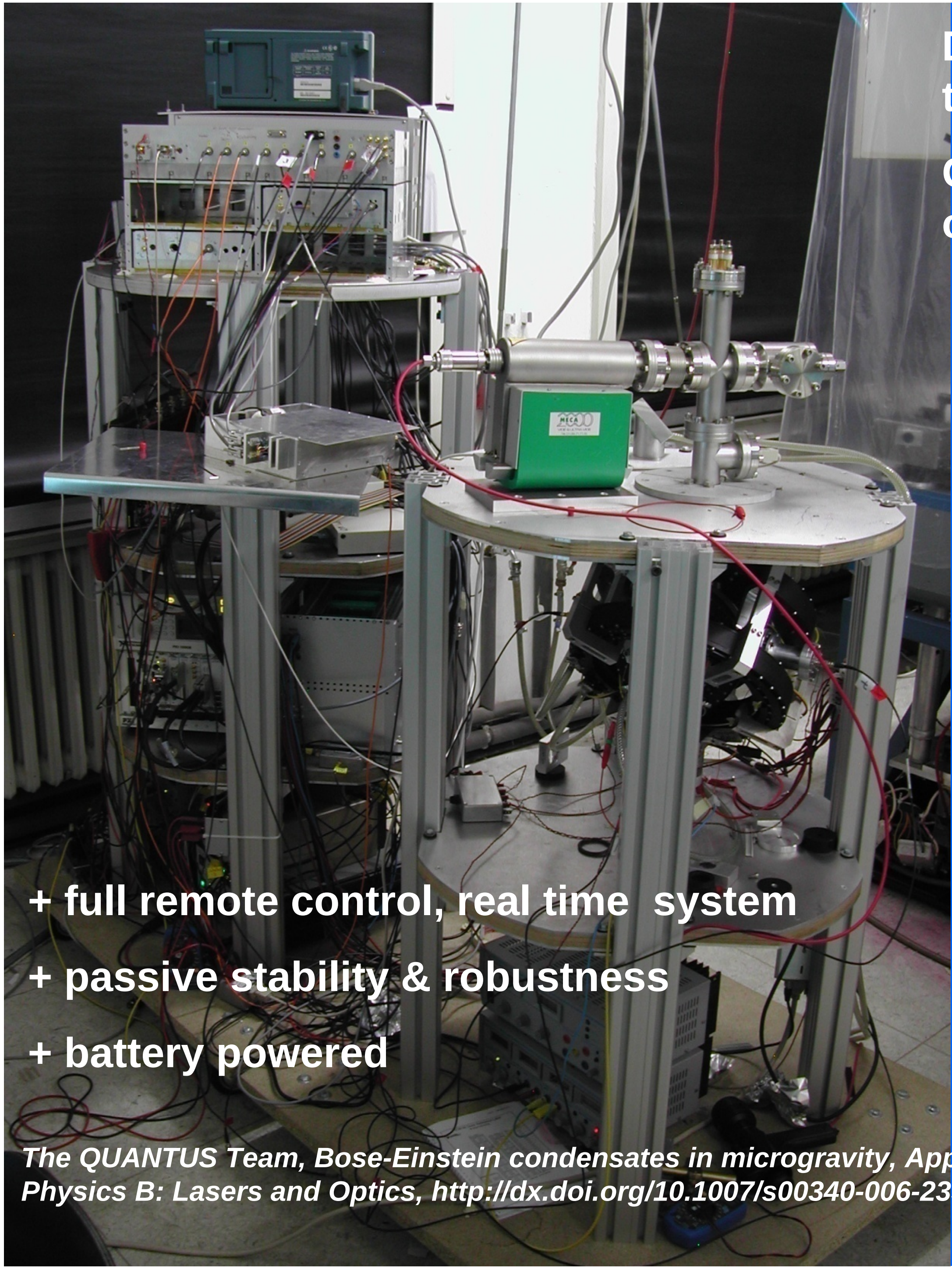


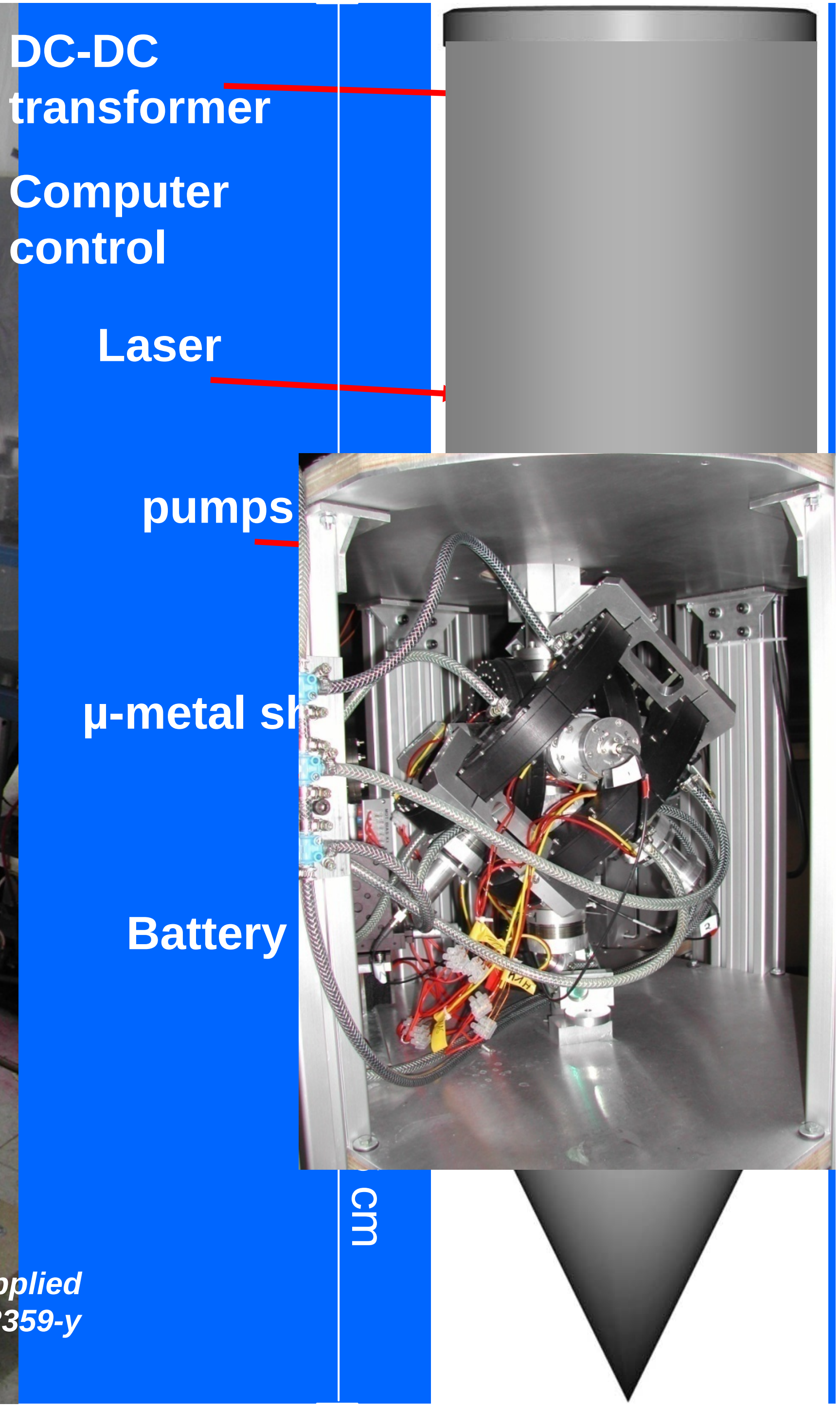
Atom number: 3 x 10^6

Temperature: >40 µK after transfer

Compression in 200 ms





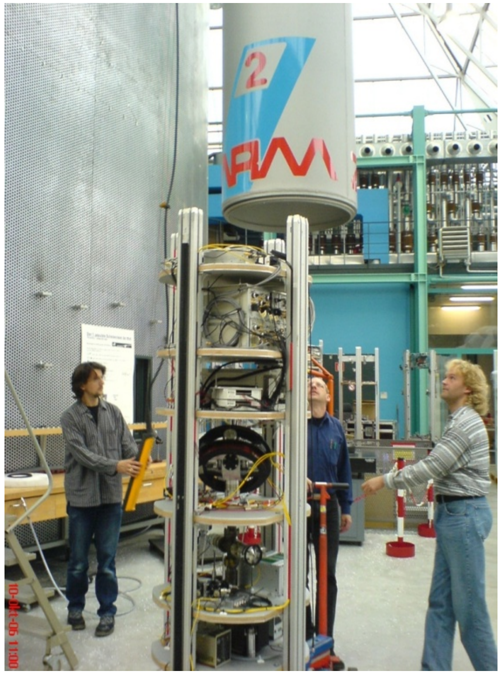


+ full remote control, real time system

+ passive stability & robustness

+ battery powered

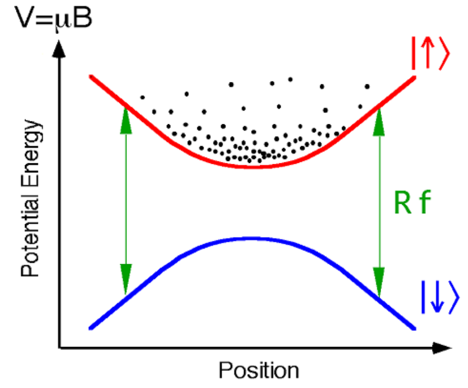
The QUANTUS Team, Bose-Einstein condensates in microgravity, Applied Physics B: Lasers and Optics, http://dx.doi.org/10.1007/s00340-006-2359-y

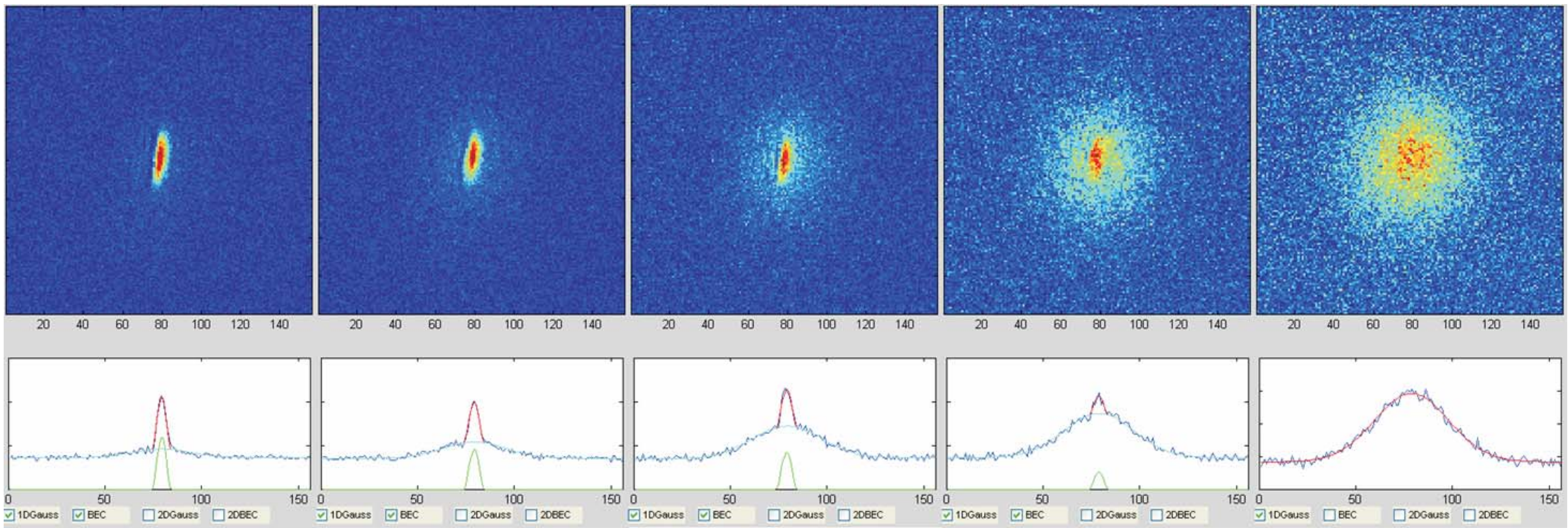

2


2


Bimodal distribution

Duration of evaporation ~ 1.2 s
after TOF 16 ms
number of condensed atoms ~5000

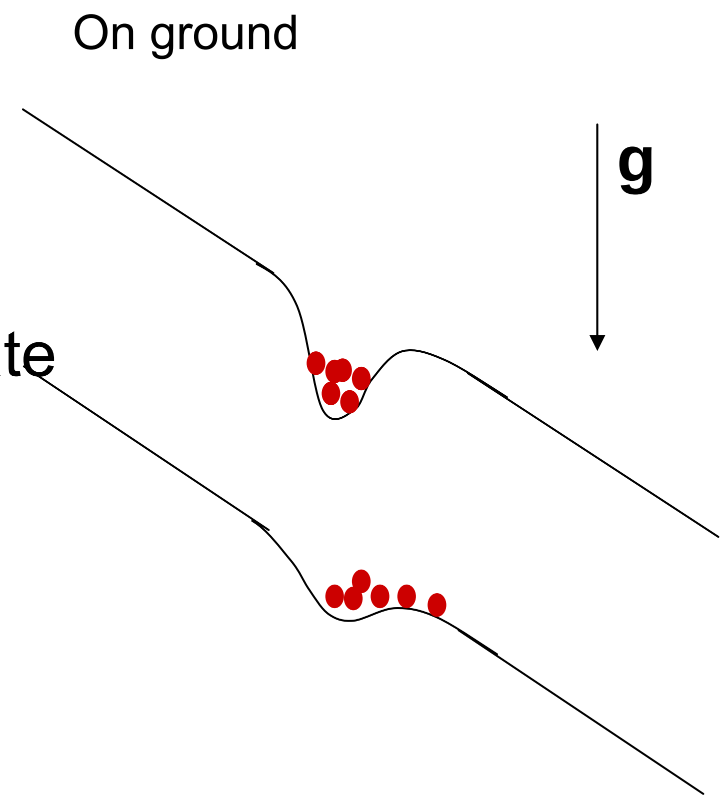


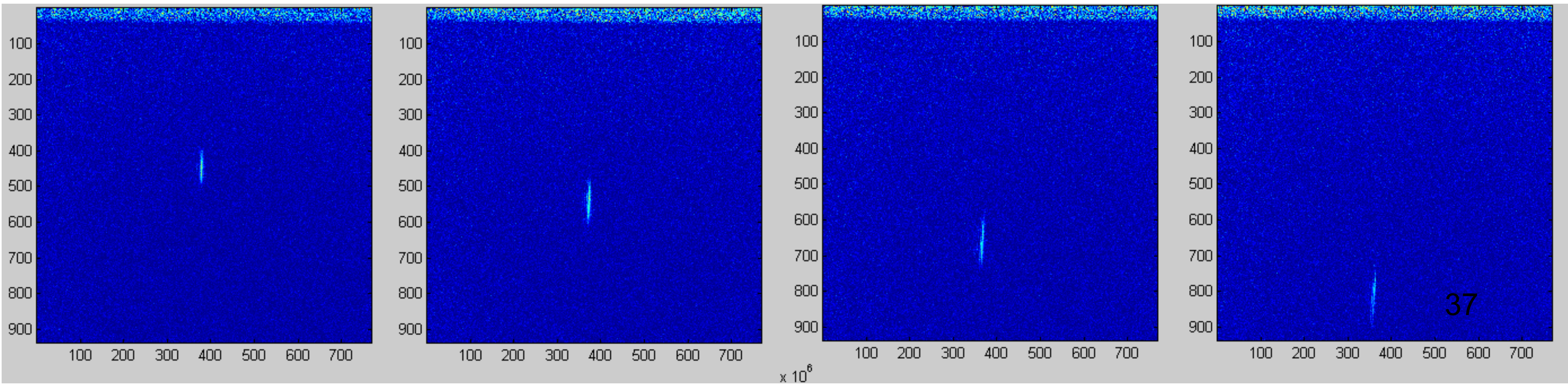


Final frequency of evaporation ramp [MHz]
1,88 1,90 1,92 1,94 1,96

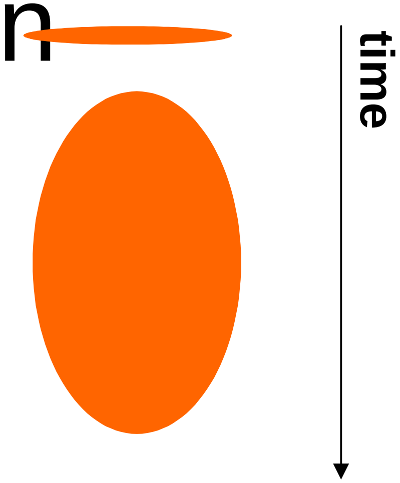
Shallow traps

- Requires low trap frequencies
- On ground: Trap too shallow to levitate atoms (trap frequ. < 30 Hz)
- Control of trap dynamics & release





Slowing free expansion

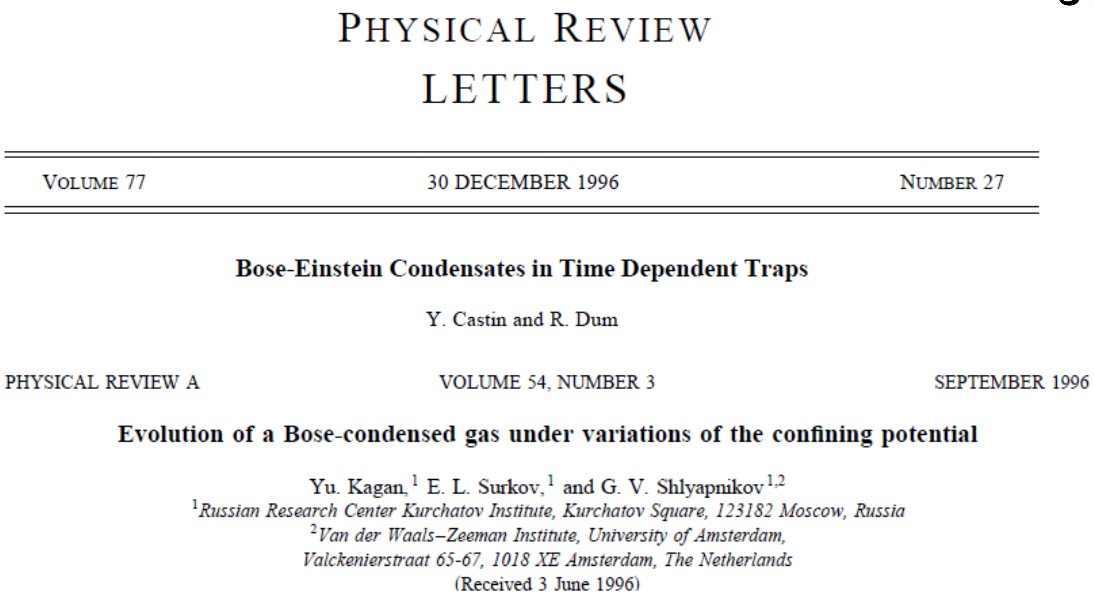


- Conversion of interaction energy to kinetic energy

- Reducing density before release

  by lowering trap depth (frequency)

- Regime of asymptotic aspect



PHYSICAL REVIEW LETTERS

VOLUME 77 | 30 DECEMBER 1996 | NUMBER 27

Bose-Einstein Condensates in Time Dependent Traps

Y. Castin and R. Dum

PHYSICAL REVIEW A | VOLUME 54, NUMBER 3 | SEPTEMBER 1996

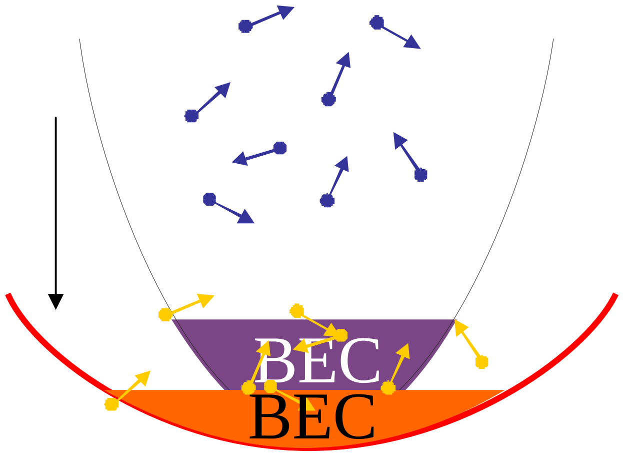
Evolution of a Bose-condensed gas under variations of the confining potential

Yu. Kagan,[1] E. L. Surkov,[1] and G. V. Shlyapnikov[1,2]

[1]*Russian Research Center Kurchatov Institute, Kurchatov Square, 123182 Moscow, Russia*

[2]*Van der Waals–Zeeman Institute, University of Amsterdam, Valckenierstraat 65-67, 1018 XE Amsterdam, The Netherlands*

(Received 3 June 1996)



Status

- > 130 drops
- rare alignments
- 3 drops per day

Ongoing work

Studying the evolution of the outcoupled condensate

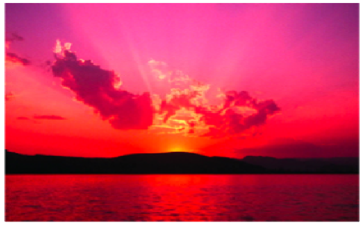
Control of the condensate

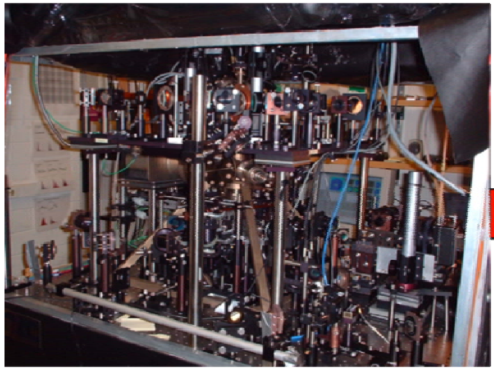
Probing the residual magnetic fields F=2, m_F=2

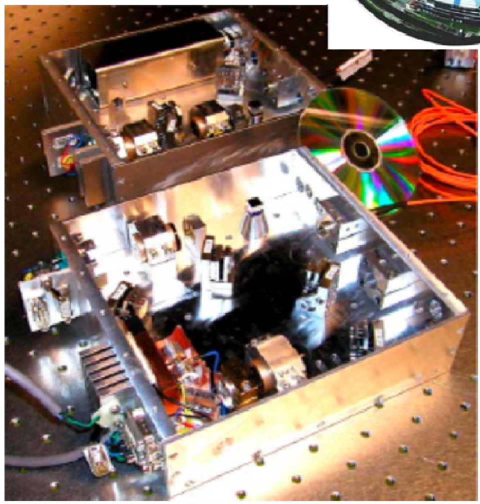
Short & Mid Term at the Drop Tower

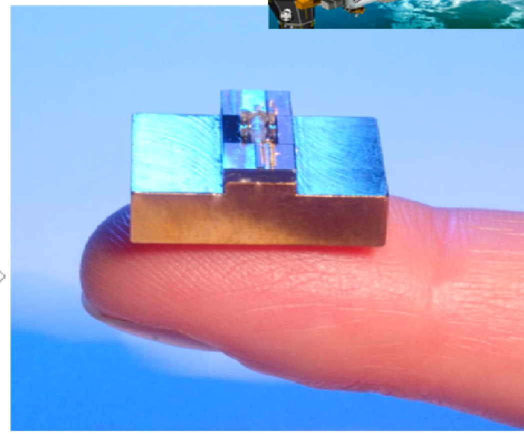
- Extending the interaction time
- Study optical & magnetic atomic sources for quantum matter in µ-g environment
- Evaporation
- Atom-Atom Interaction
- Temporal Coherence Properties (4 - 9 s)
- Chip-based Clock
- Atom Interferometry
- Dual Species Source
- Drop tower for atoms

BEC in Microgravity
- shrinking the facility components -









Equipment for terrestrial BEC generation …

Laser system for a BEC in the QUANTUS facility (cf. CD size)

Laser system based on chip technology

First successful BEC experiments in 1995

First successful drop in 2007

The future

Future needs for space applications?

- Learning from the Cosmic Vision call!
- programmes and studies for improved technology readiness
- Forming excellent international teams
- Mission opportunities on ISS or “suited” platforms


My Thanks to the QUANTUS
Team and DLR

Thank you for your attention