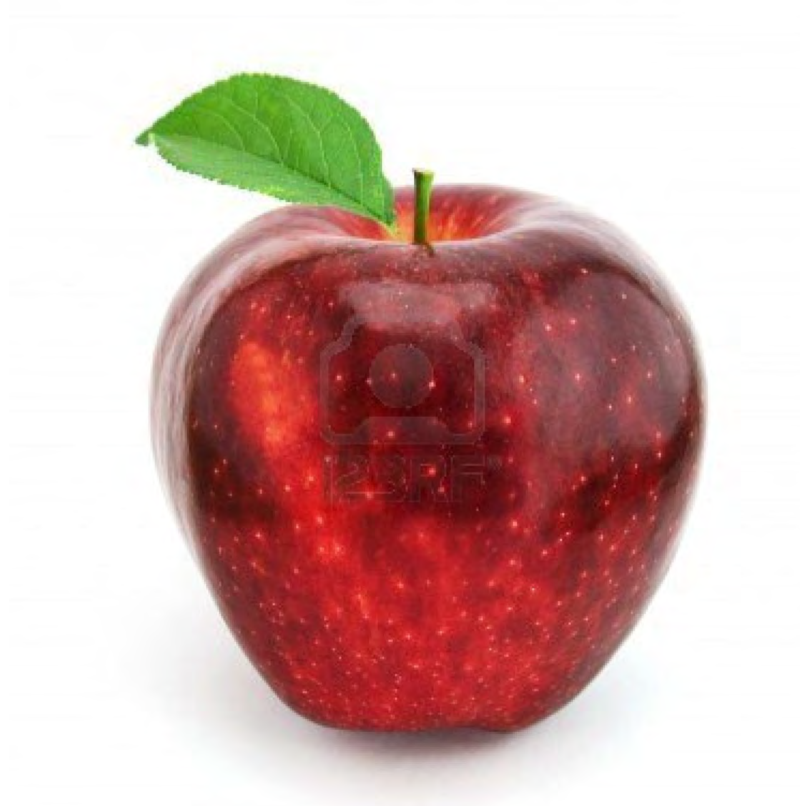
atom interferometry



exploiting the superposition principle
foundations and applications

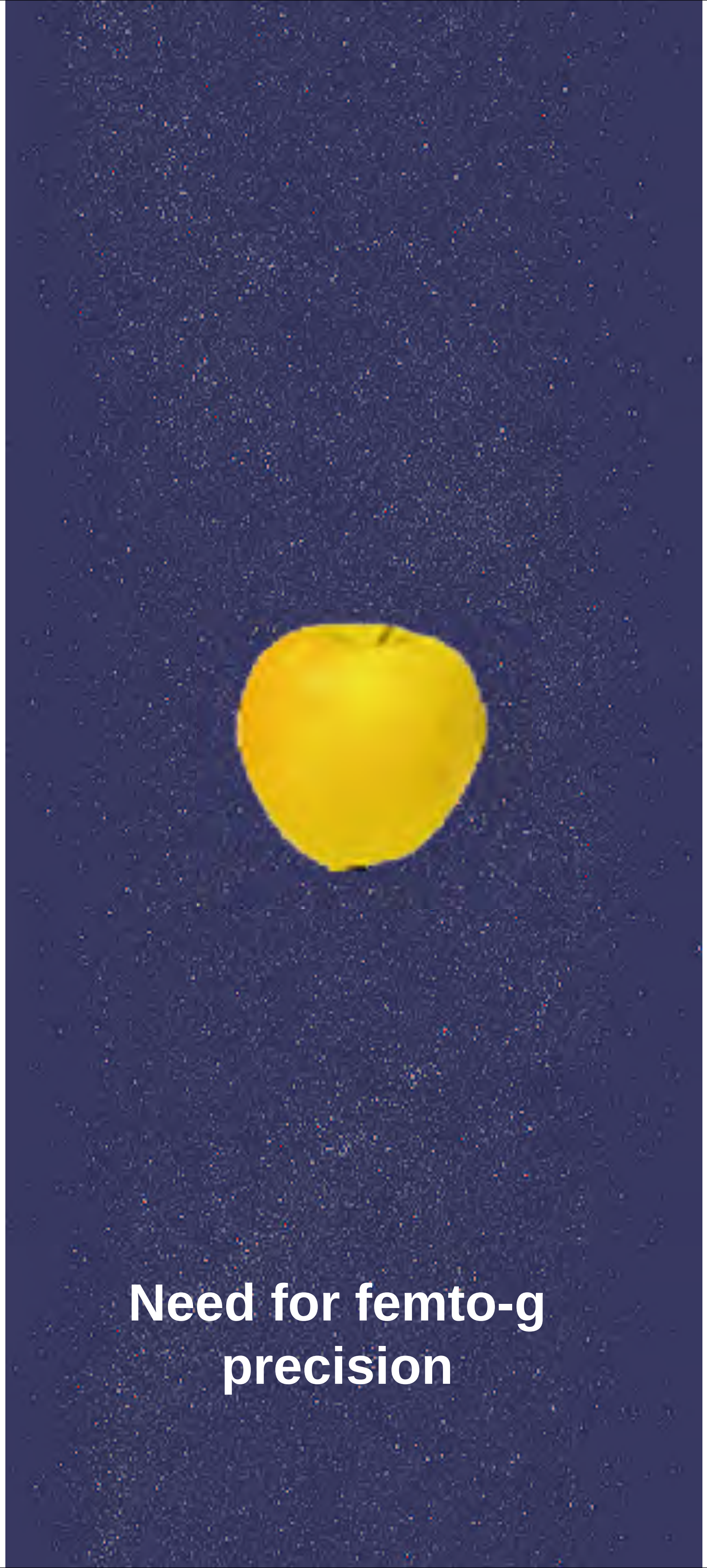
Lecture on
Atomic Quantum Sensors
-
State of the art and perspectives

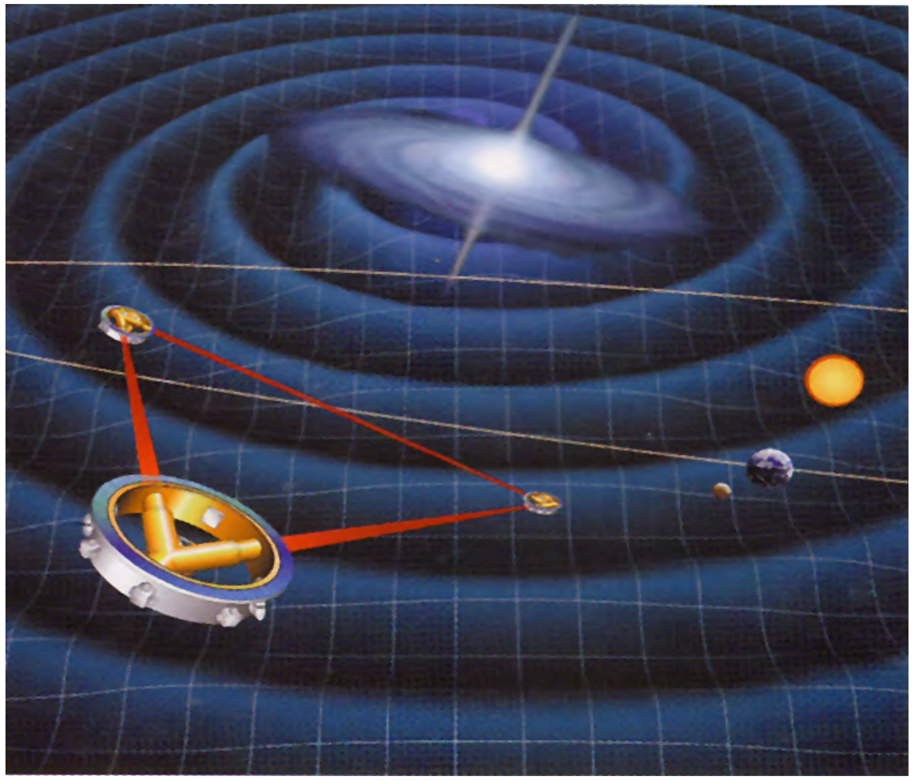
What is an inertial sensor?

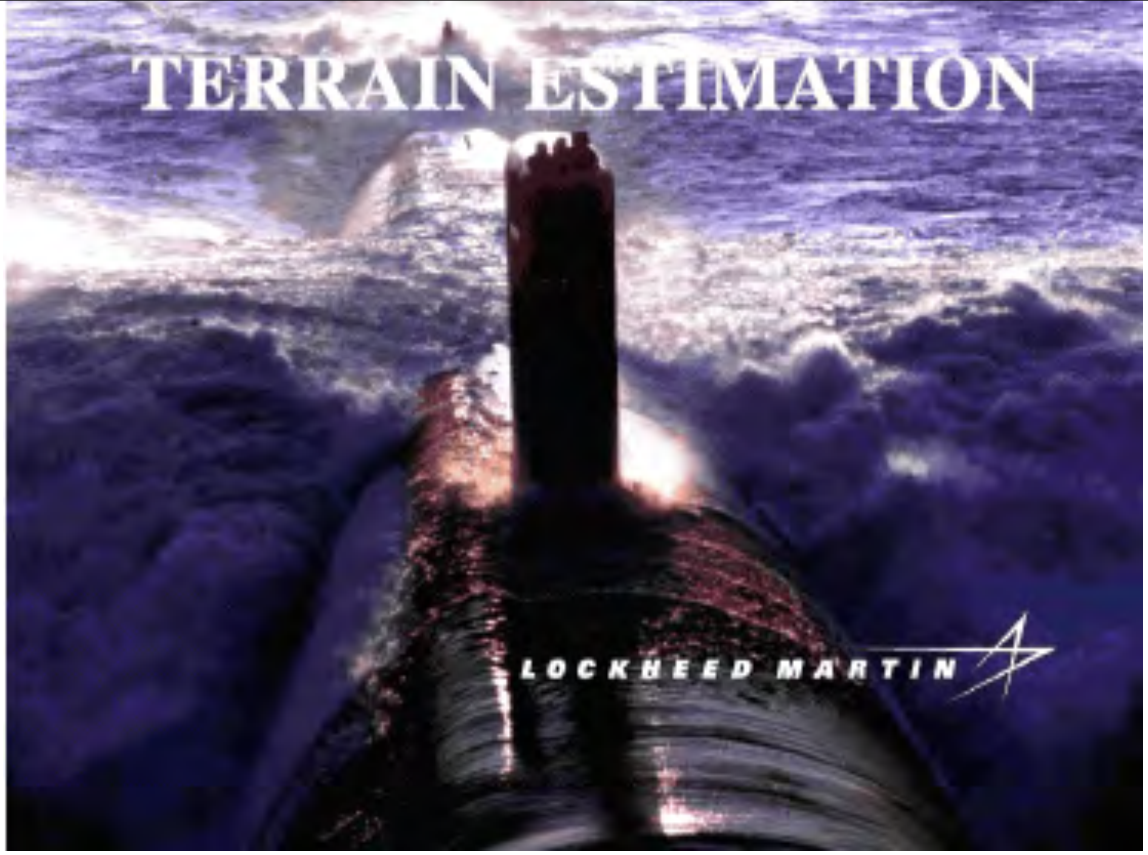
"Best-possible experimental realisation of the free fall"

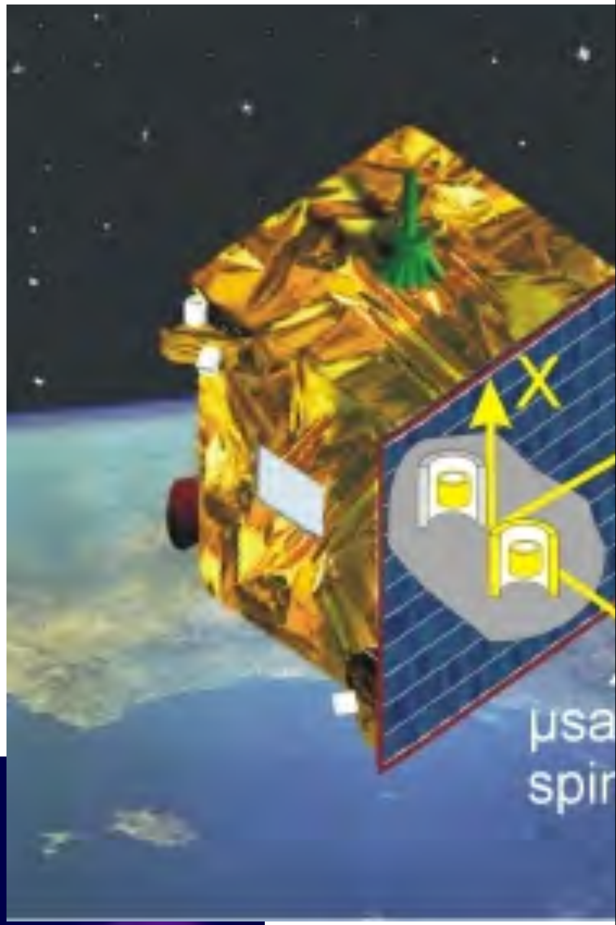
Purely gravitational coupling

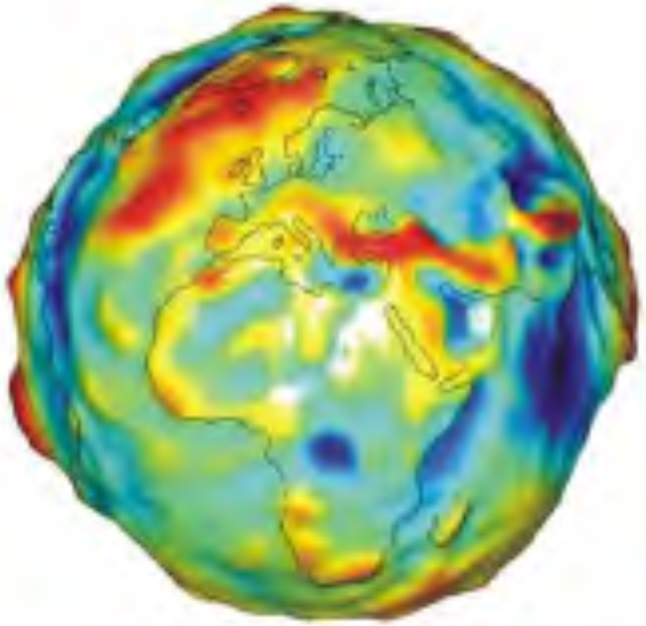
Non-magnetic and neutral,
no geometry dependence,
no ionisation, no aging
(patch effects)

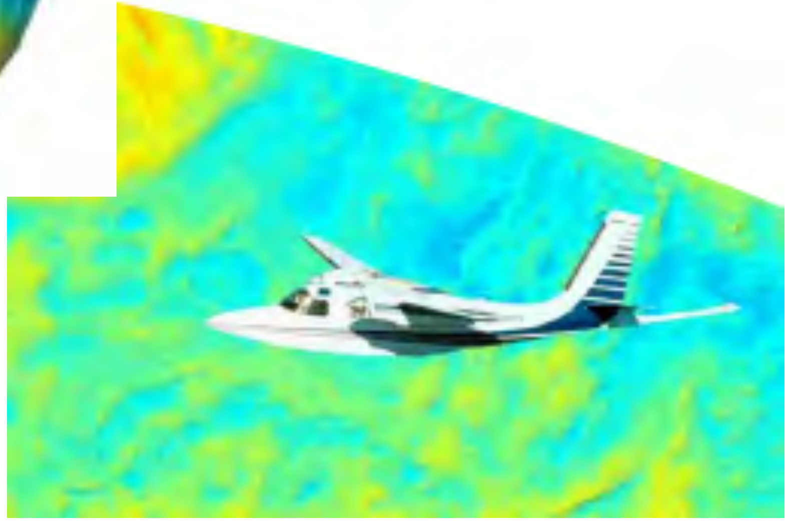


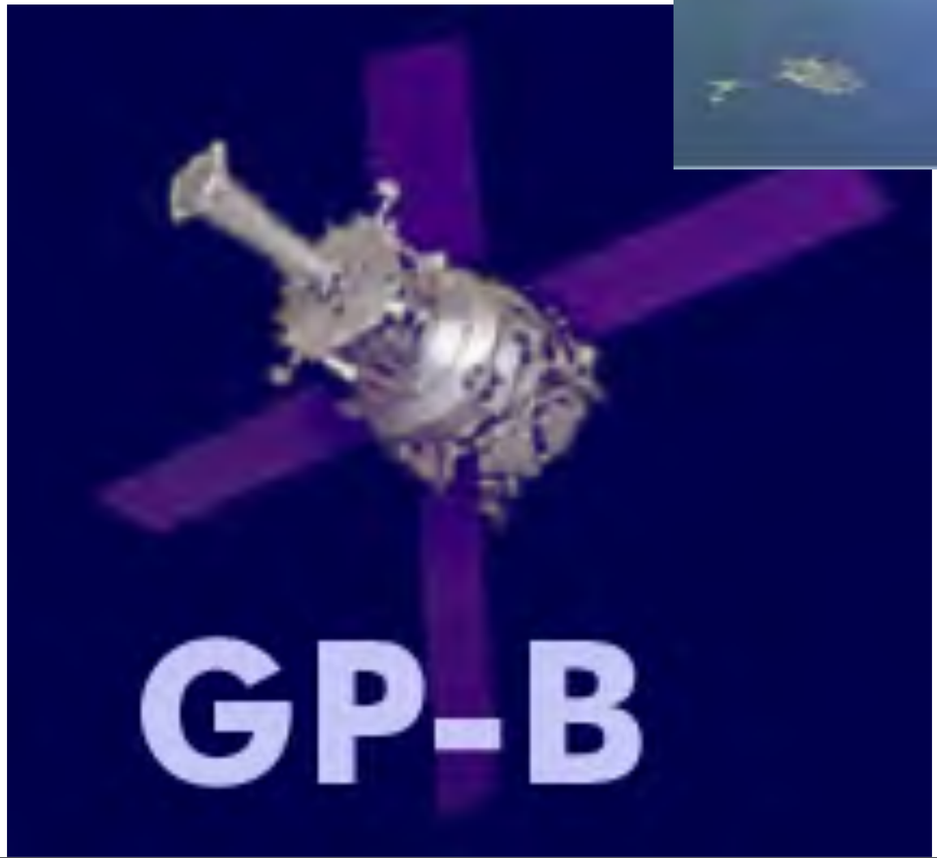


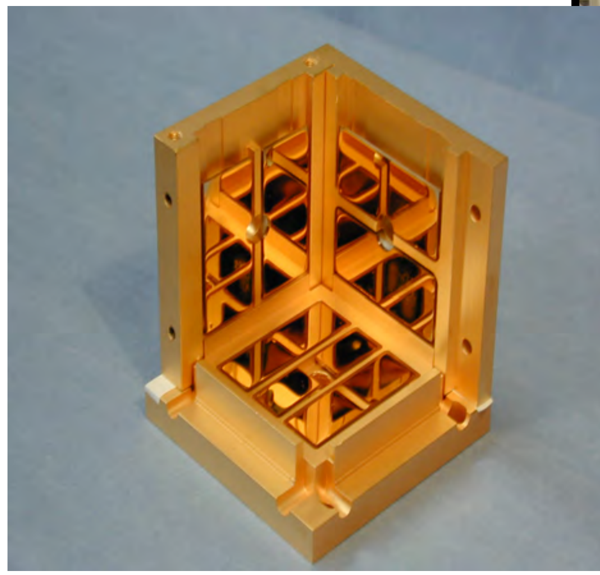

TERRAIN ESTIMATION
LOCKHEED MARTIN


X






GP-B



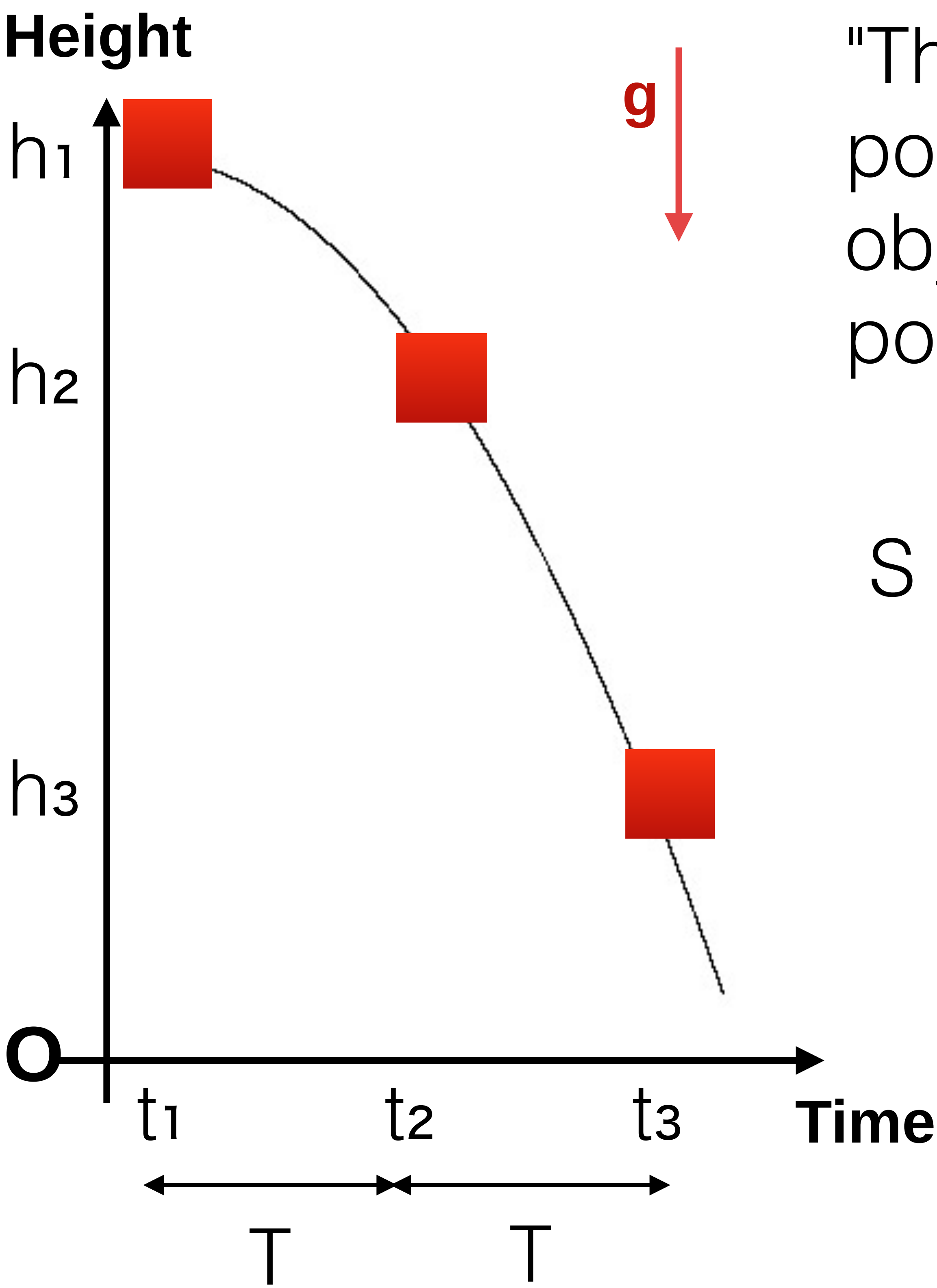
Atomic Sensors

-a future technique for geodesy

Outline: Atomic Quantum Sensor

- What does it measure ?
- How does it work ?
- Why Quantum ?
- Typical features
- Quantum Gravimeters (and Gyroscopes)
- Fundamental physics with matter waves
- Perspectives

What does it measure ?



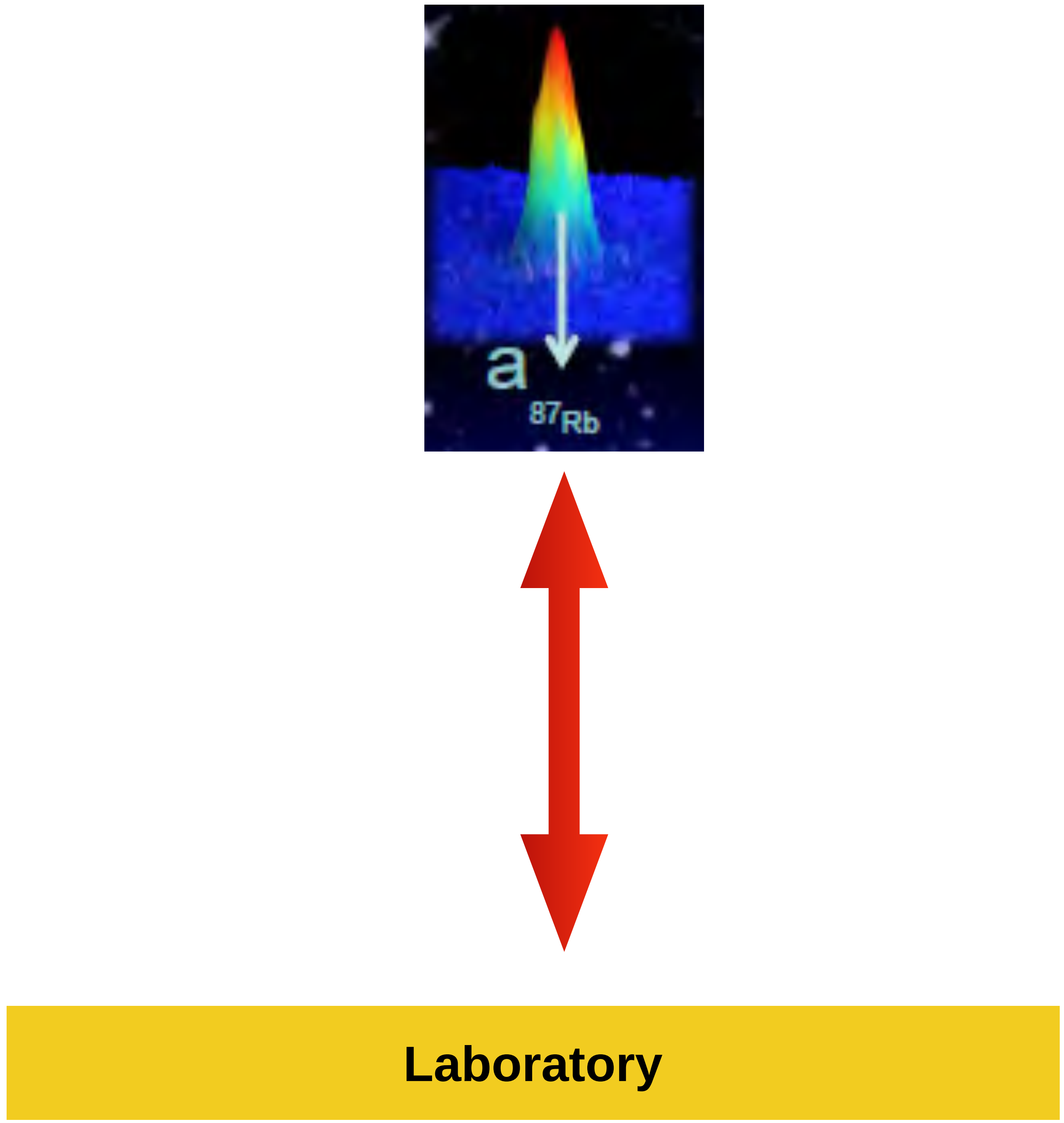
"The double increment of the position at different times of an object with respect to a reference point (**O**) of the laboratory system"

$$S = (h_3 - h_2) - (h_2 - h_1)$$

$$= [h(t+2T) - h(t+T)] - [h(t+T) - h(t)]$$

What does it measure ?

Using atoms as objects ...



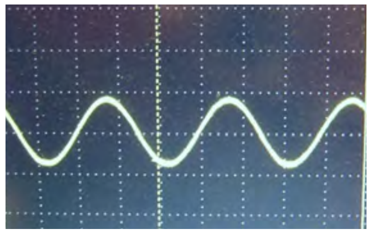
What does it measure ?

How does it work ?

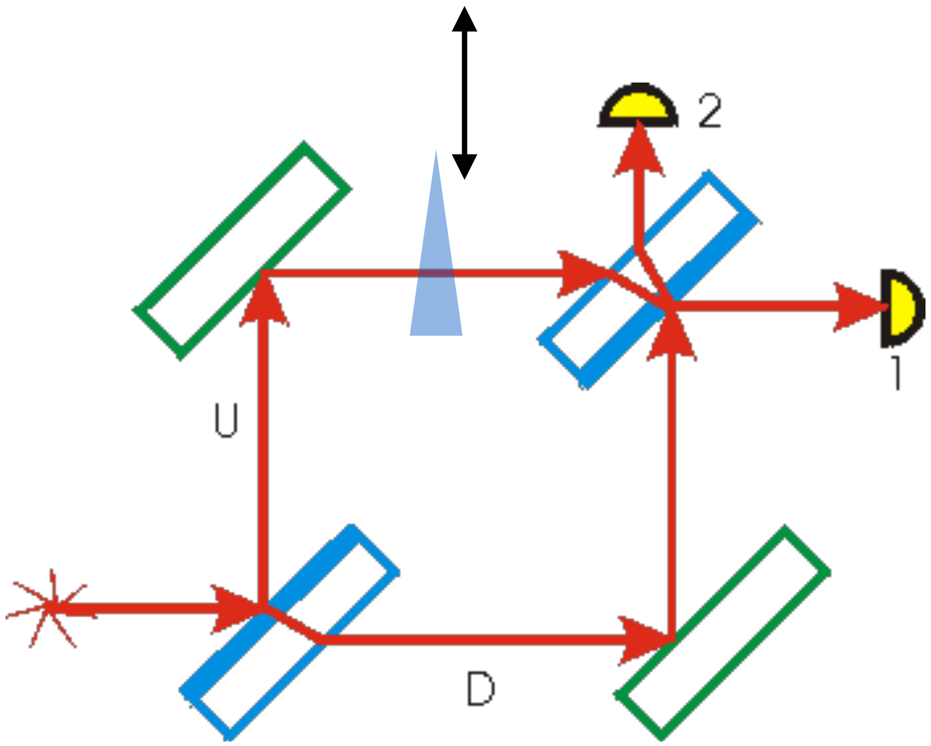
**"The double difference
is measured with
an (matter wave) interferometer "**

Example for a Mach-Zehnder type interferometer with **light**

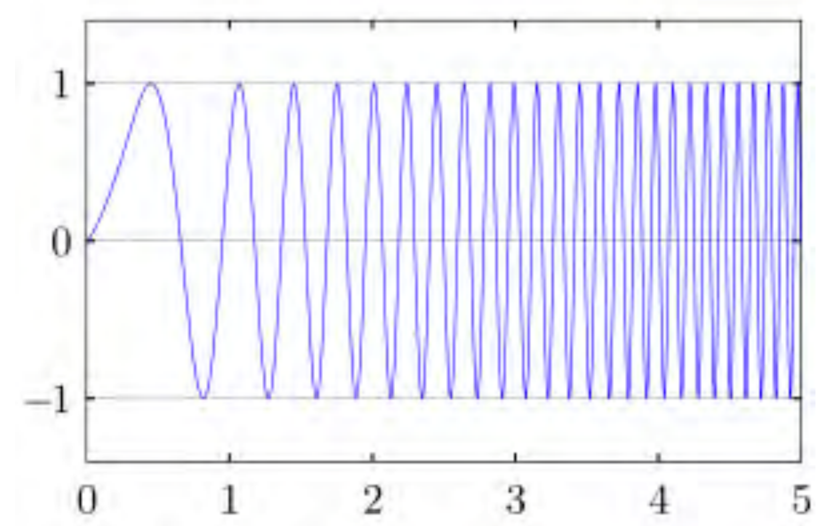
$$S = I * (1 + cos[\frac{2\pi}{\lambda}(L_D - L_U)])$$



S: Signal at detector 1
I: Source intensity
L: path length
λ: wavelength of light



Mach-Zehnder type interferometer with light using a falling corner cube

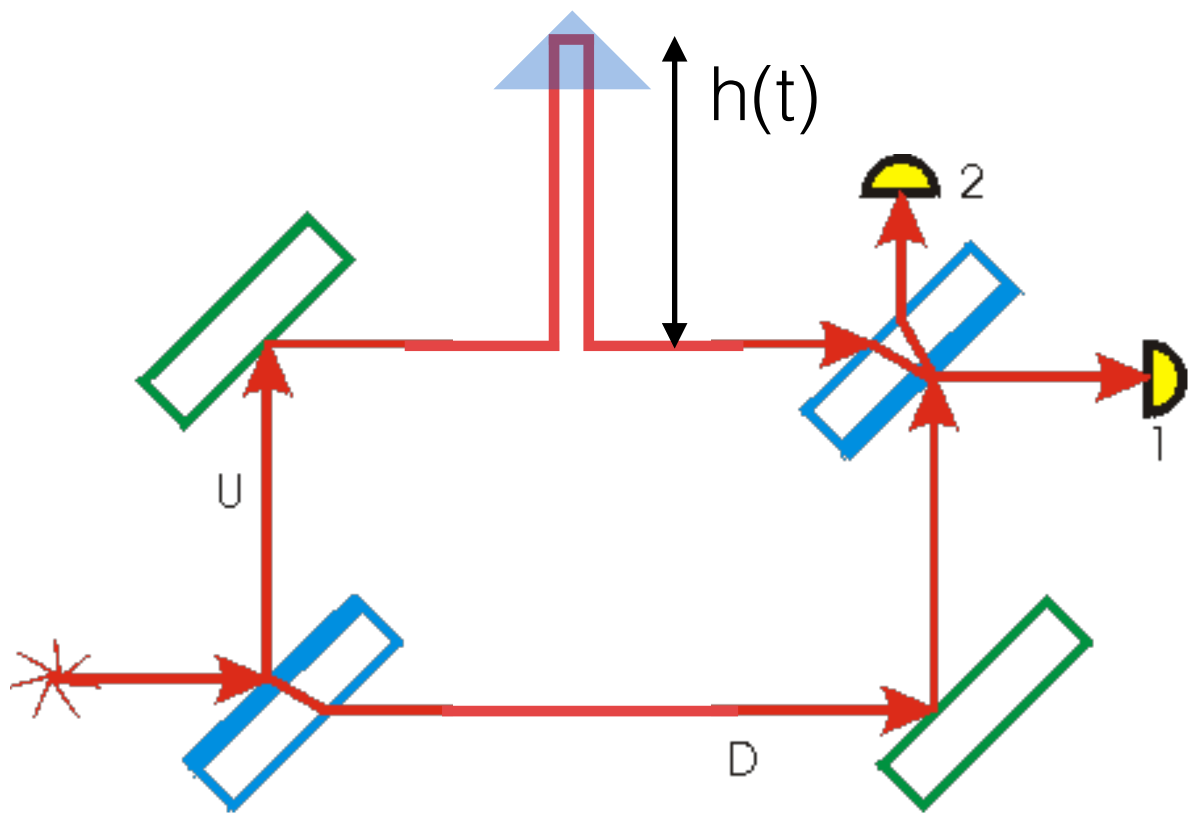


$$S(t) = I * (1 + cos[\frac{2\pi}{\lambda}(L_D(t) - L_U)])$$

$$L_D(t) = L_{D_0} + 2h(t)$$

S: Signal at detector 1
I: Source intensity
L: path length
λ: wavelength of light

Falling corner cube



How does it work

How does an interferometer work for matter?

"Matter has wave features"

"Matter has wave features"

Planck constant

Momentum → $$p = m \cdot v = \frac{h}{\lambda}$$

de Broglie wavelength

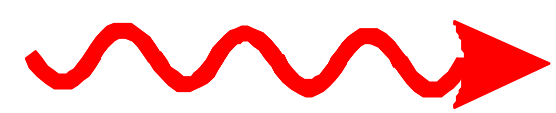
Louis Victor de Broglie
Nobel prize 1929

classical world

Momentum of the particle

quantum world

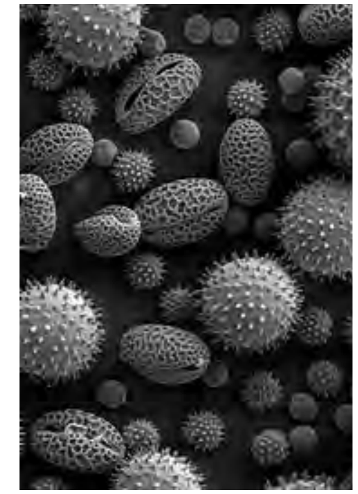
De-Broglie wave



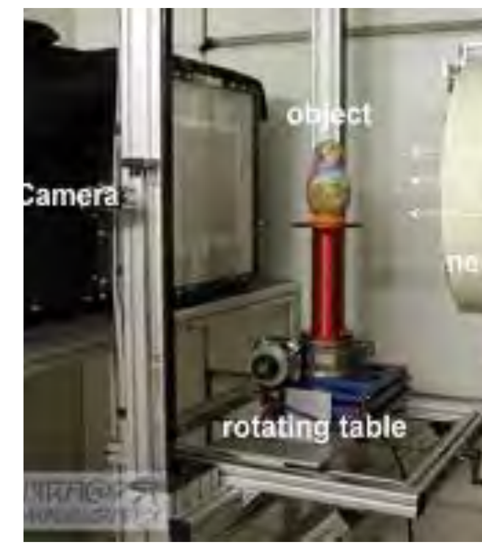
Matter waves

Matter wave optics at work:

- Electron microscopy

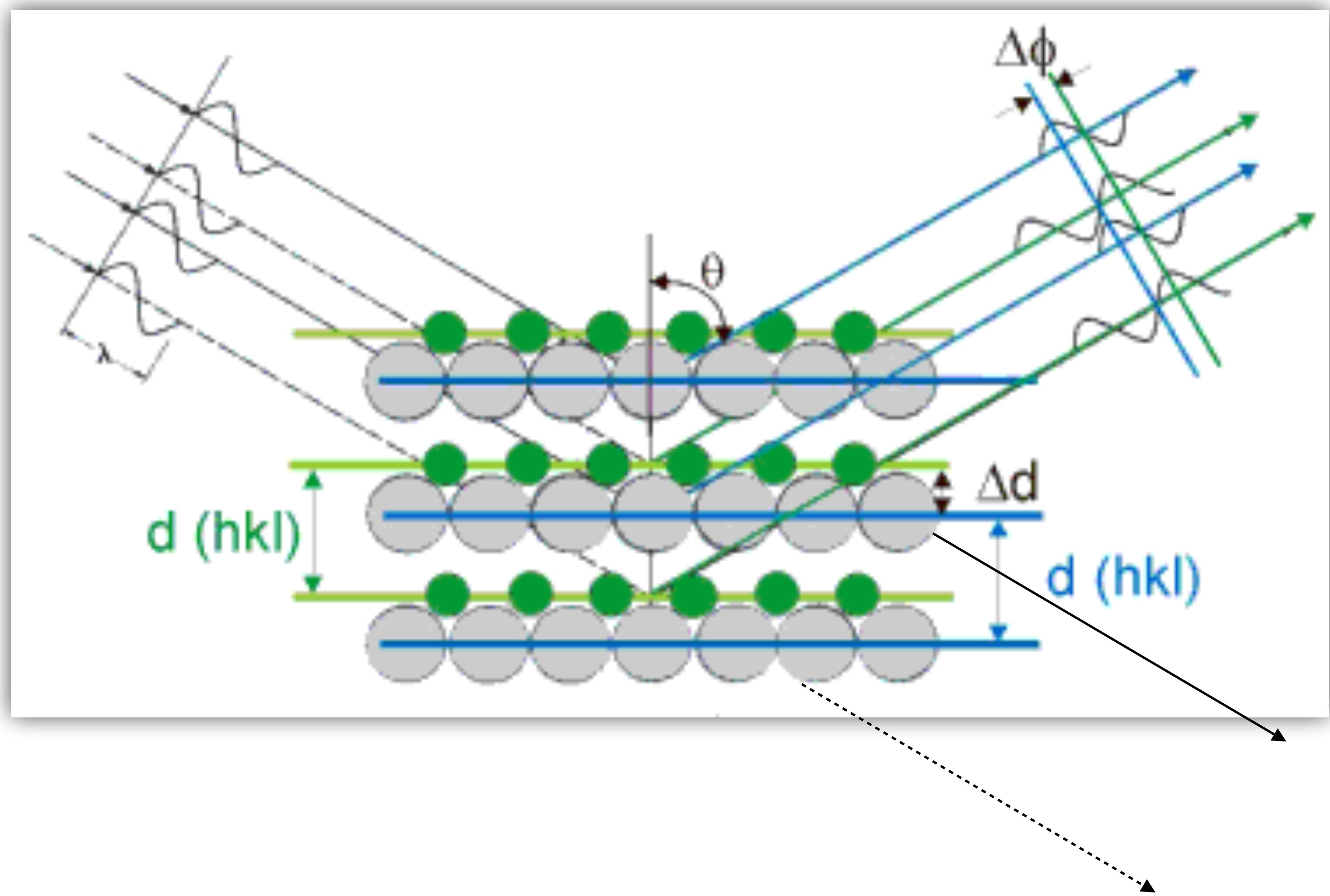


- Neutron tomography



- Crystal structure analysis

Bragg scattering



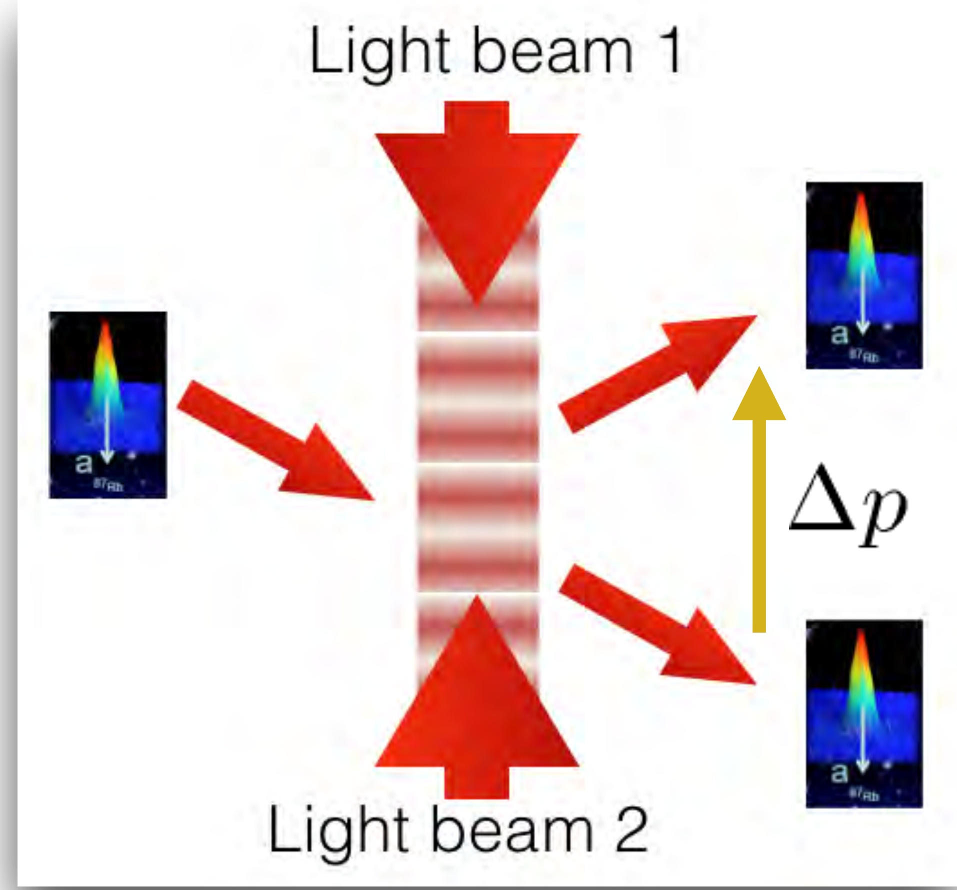
How to "split" matter/atoms ?

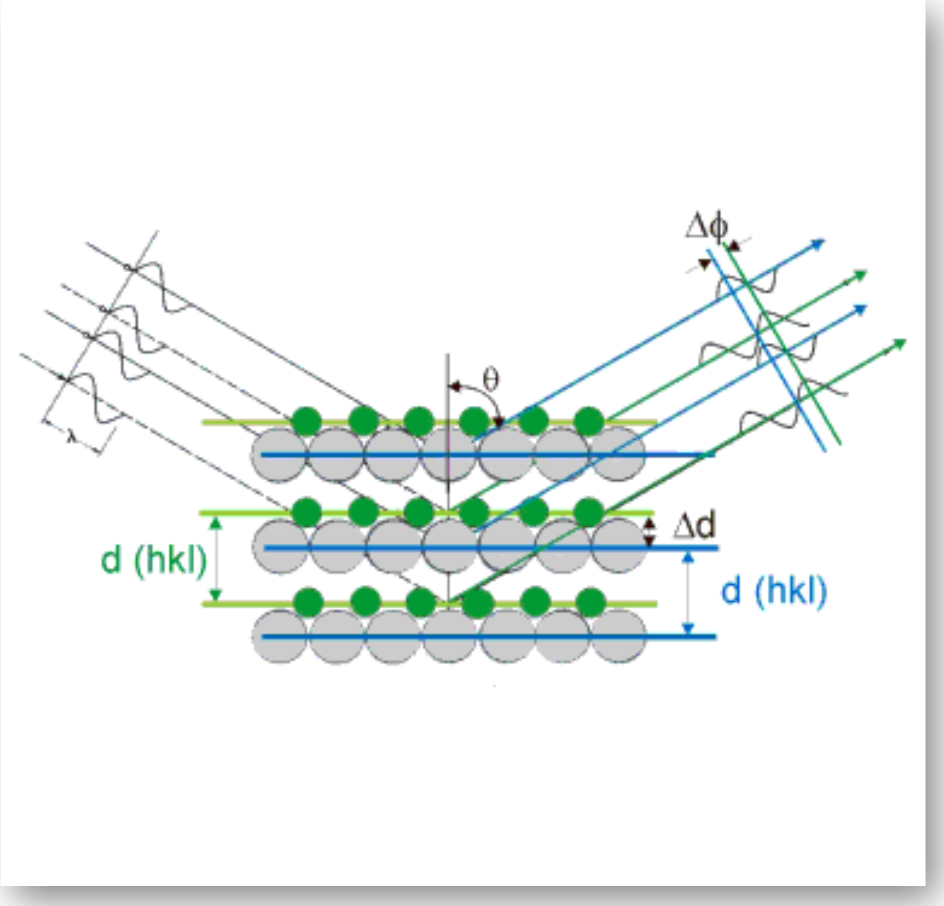
How to "split" matter/atoms ?

With light !

Bragg scattering crystals of "light" vs. real crystals

interference pattern of light versus crystal planes

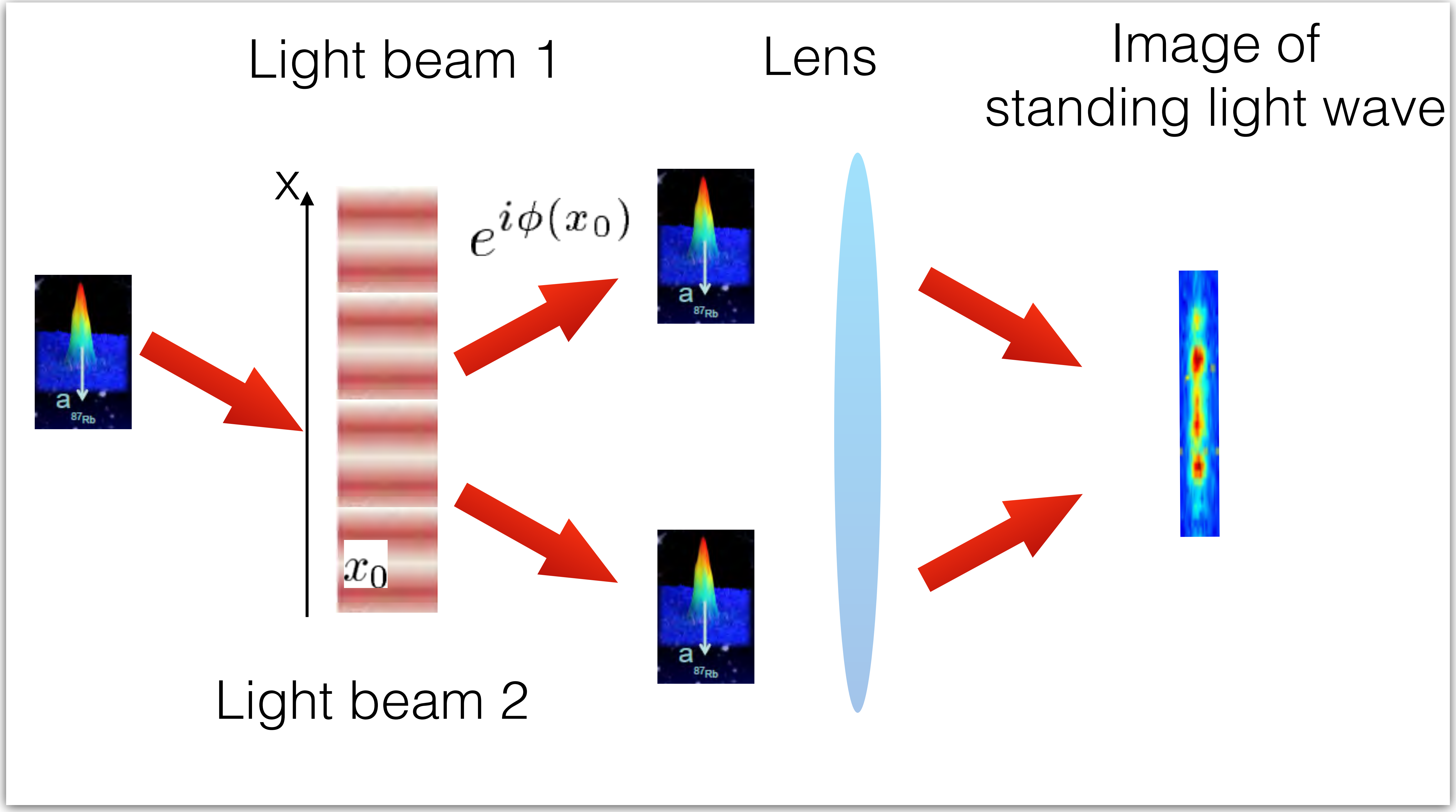




Momentum transfer $$\Delta p = \frac{2\pi}{d} = k_{eff}$$ Effective photon recoil

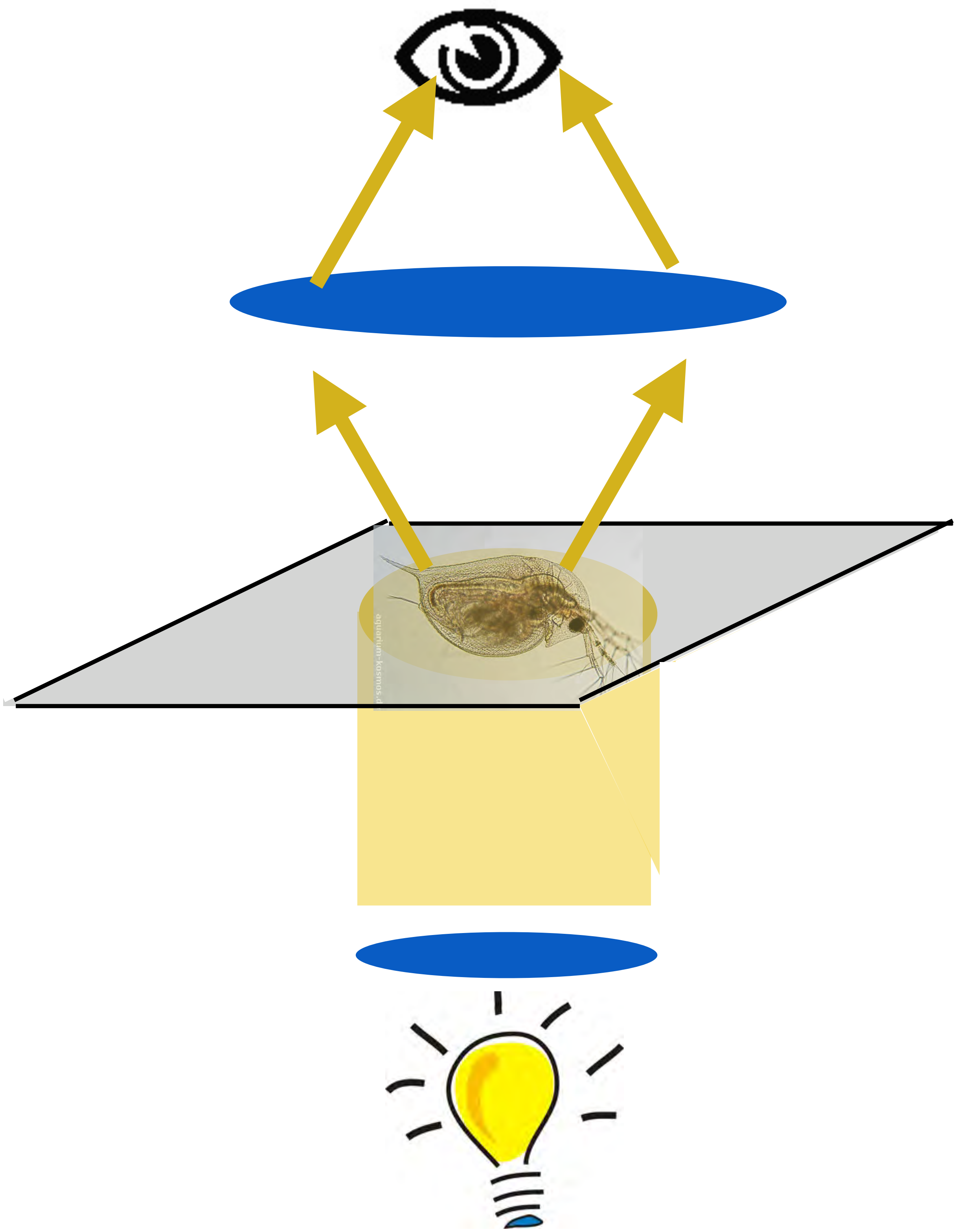
d: grating constant / periodicity

Bragg scattering for "light" crystals



Coherent beam splitting

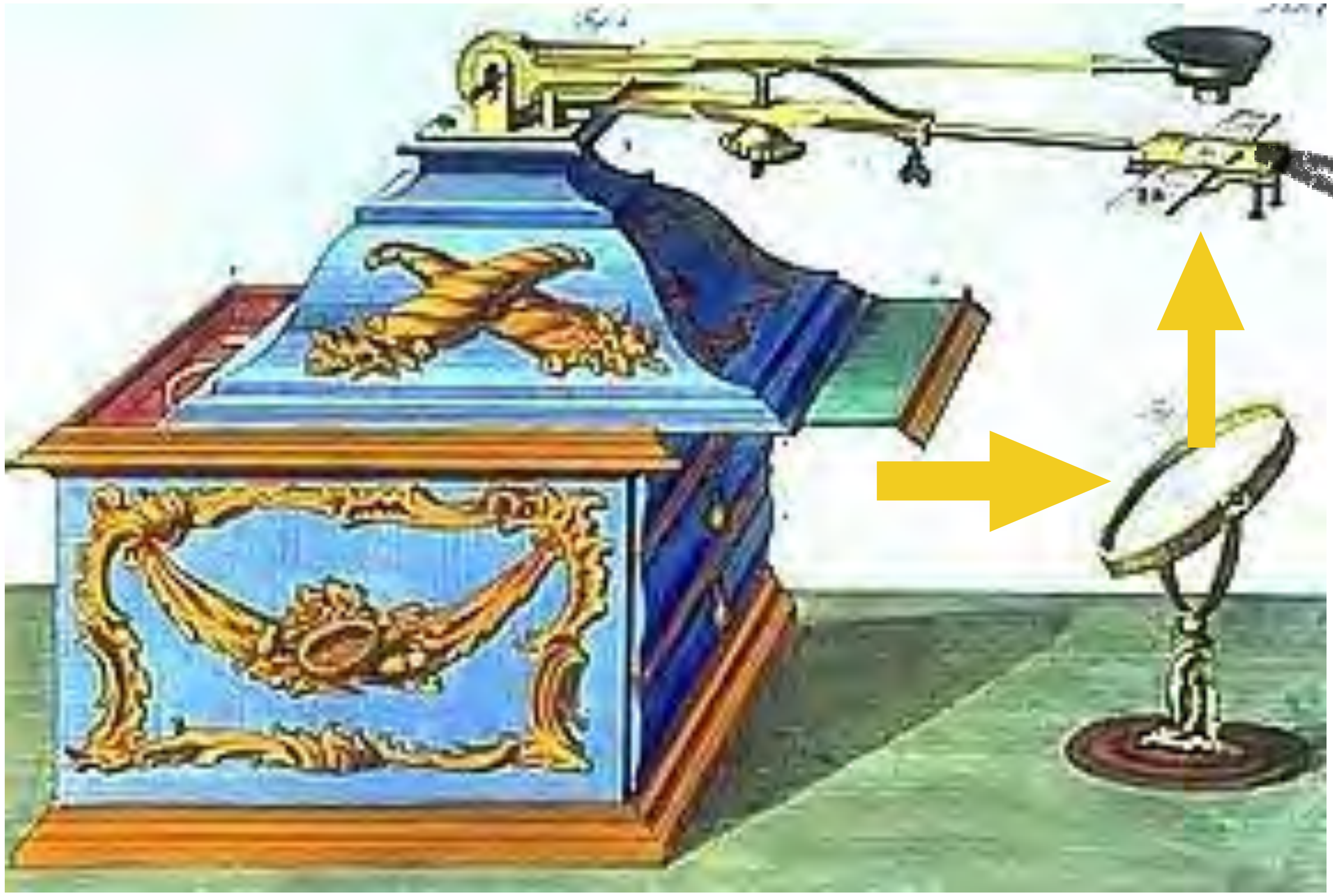
Theory about image formation

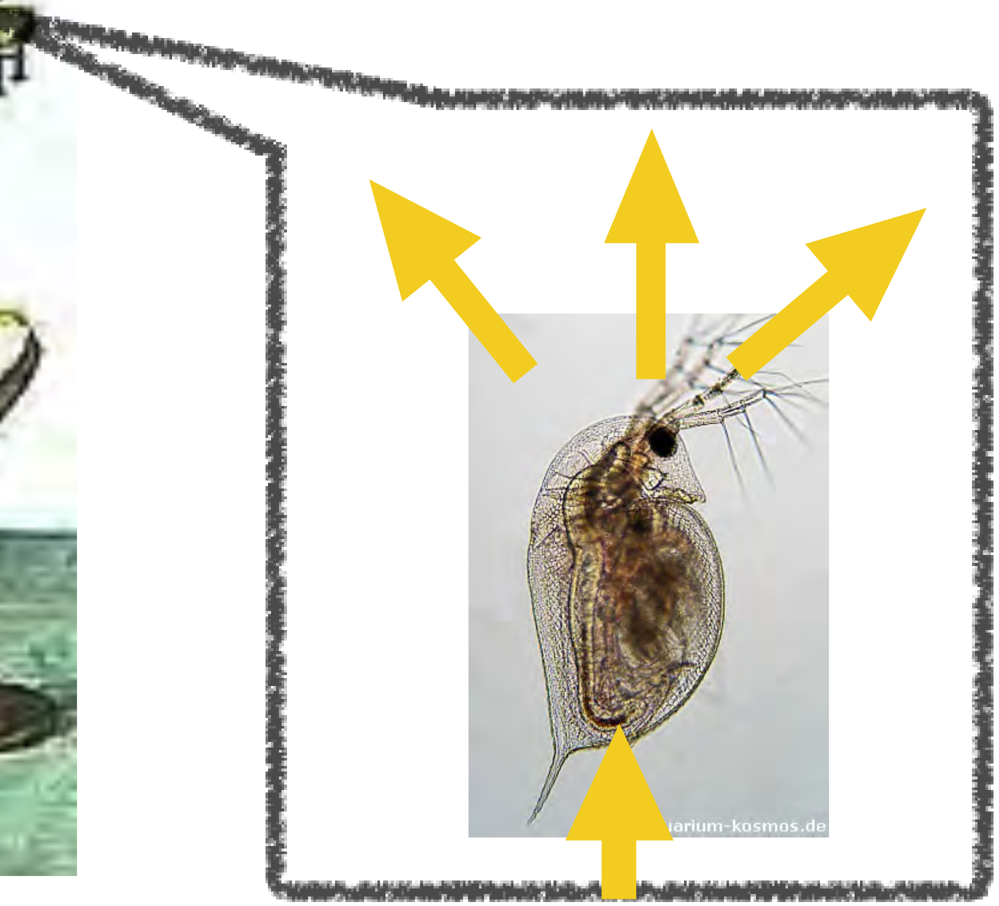


Ernst Abbe

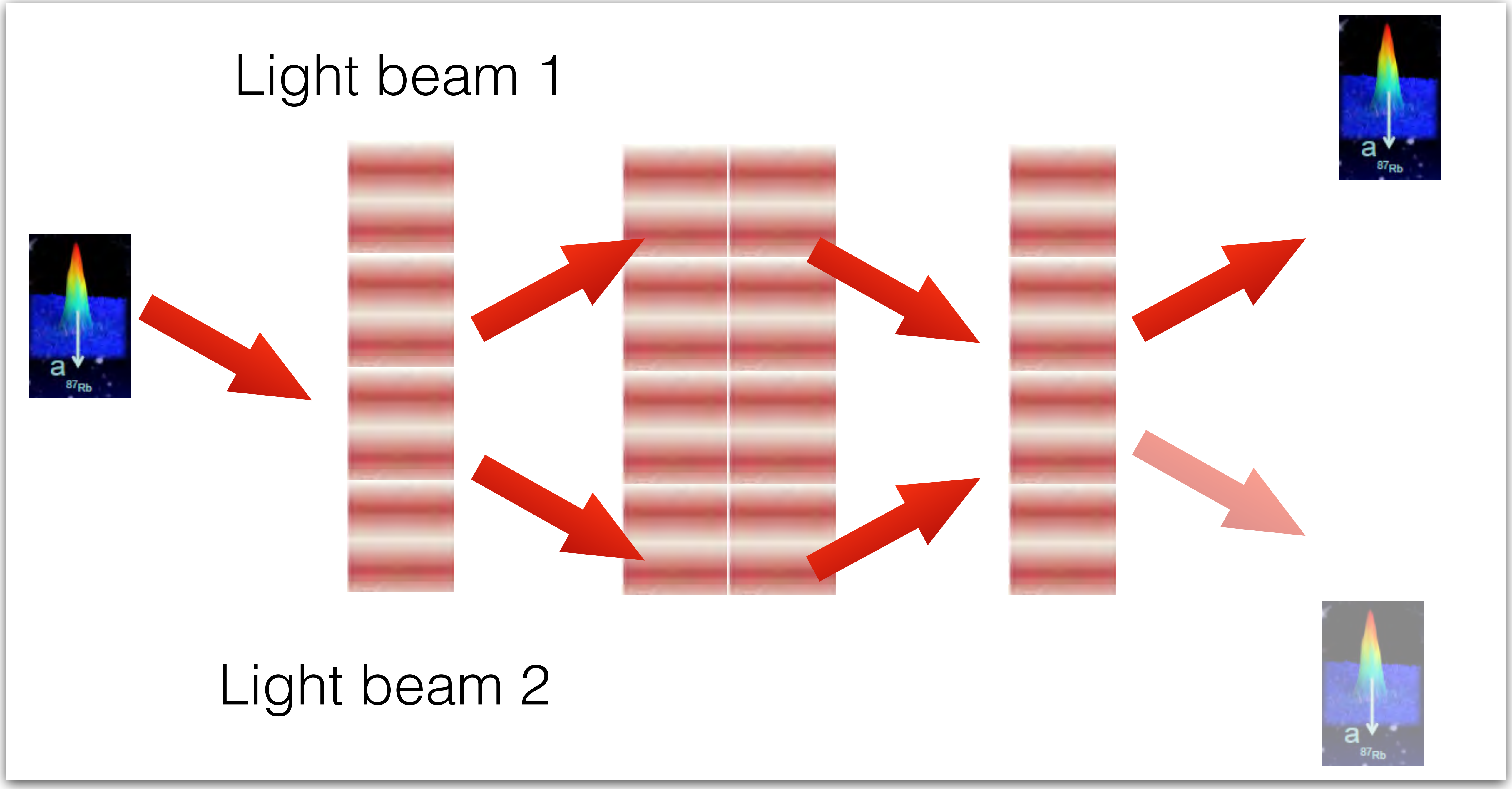
Light microscopy

Ernst Abbe

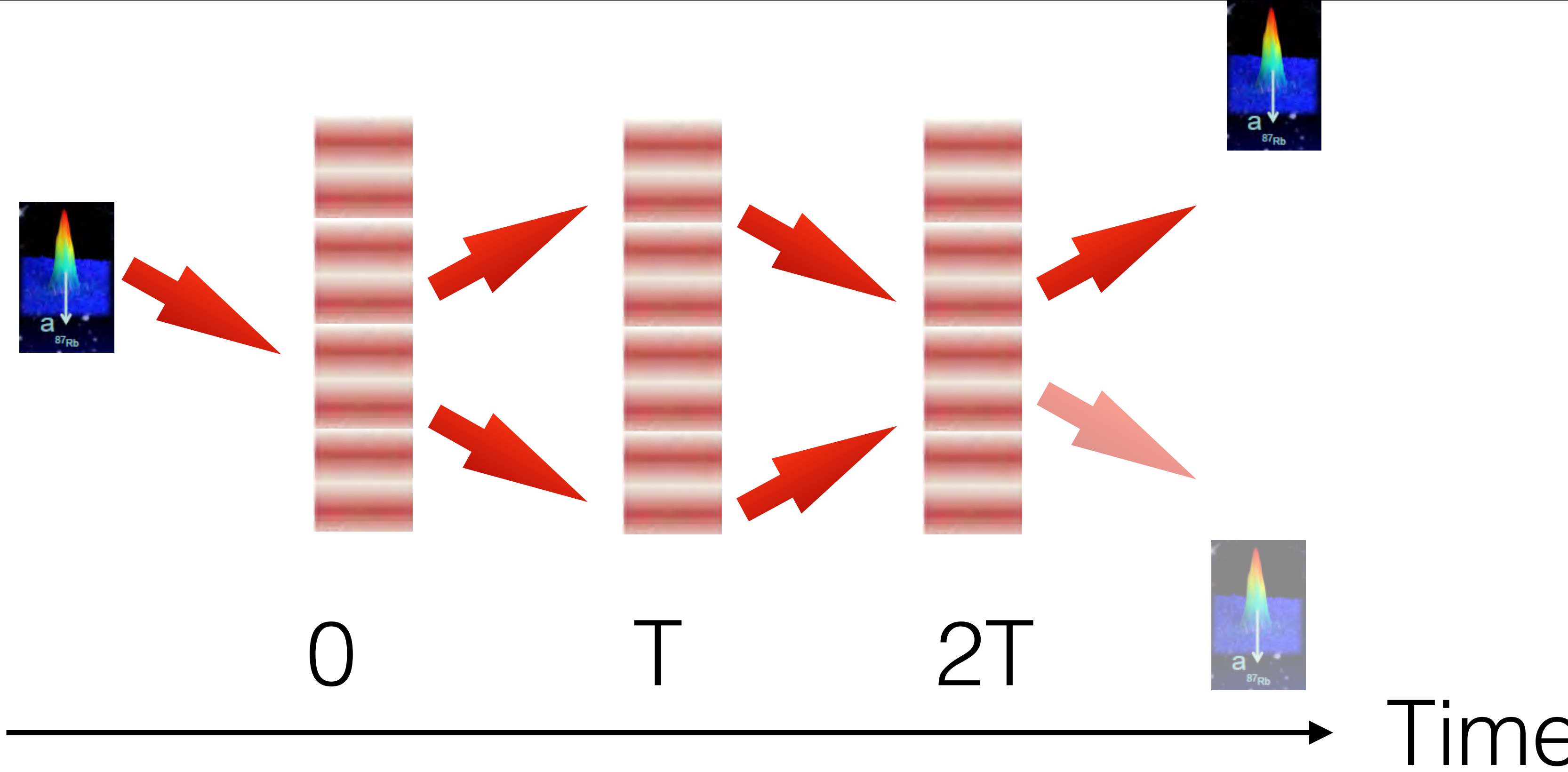




Interferometric Phase Read out



$$S \propto e^{i[(\varphi_3 - \varphi_2) - (\varphi_2 - \varphi_1)]}$$



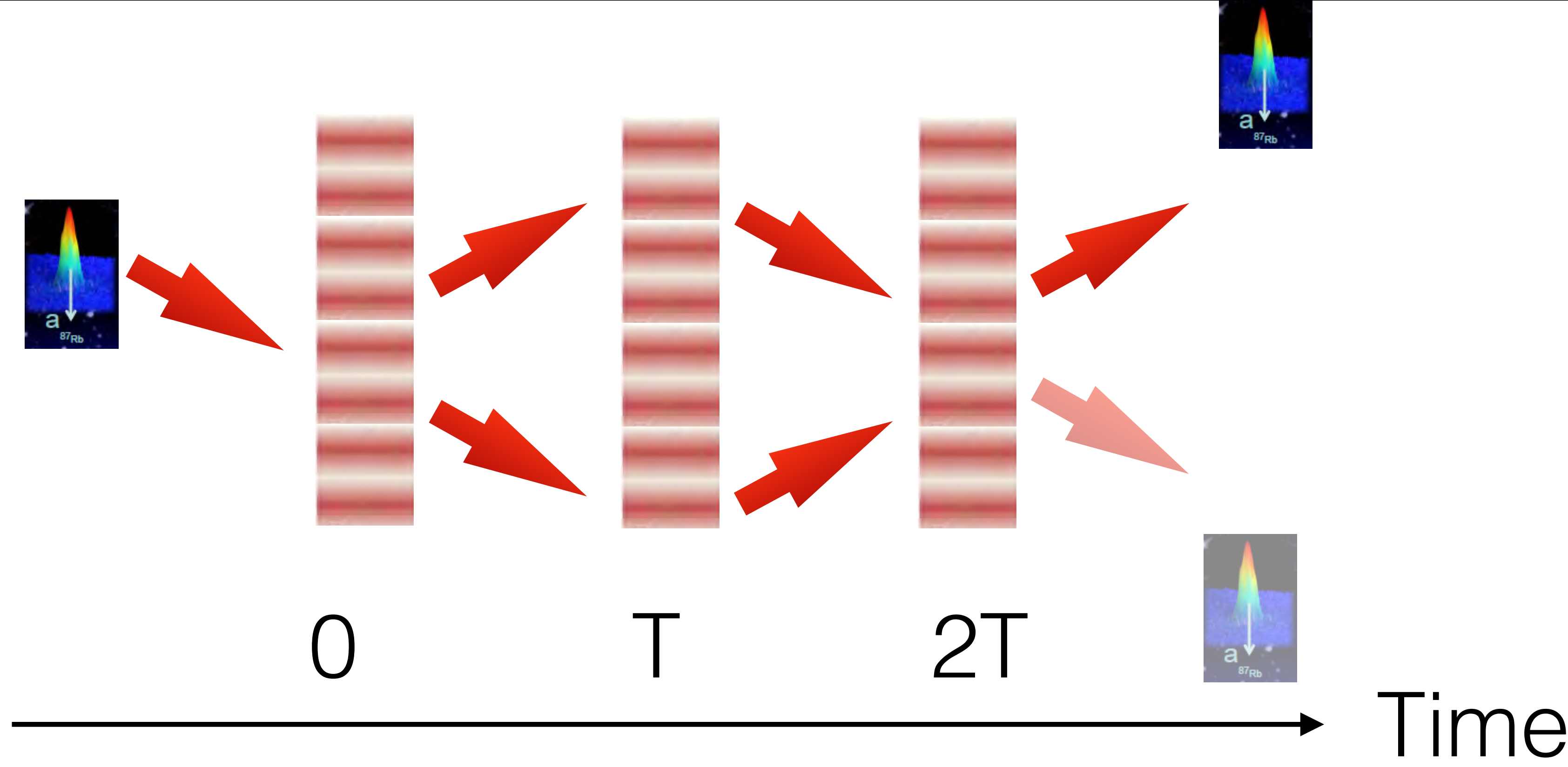
$$e^{i[(\varphi(2T)-\varphi(T))-(\varphi(T)-\varphi(0))]} = e^{i[\Delta(2T)-\Delta(T)]k_{eff}}$$

Double increment of change in position during 2T

$$\Delta(2T) - \Delta(T) = \int_T^{2T} v(t)dt - \int_0^T v(t)dt = a(T)T^2$$

$$\Delta\phi = \vec{k}_{eff} \cdot \vec{a} * T^2$$

Accelerational Phase shift



$$e^{i[(\varphi(2T) - \varphi(T)) - (\varphi(T) - \varphi(0))]} = e^{i[\Delta(2T) - \Delta(T)]\,k_{eff}}$$

Double increment of change in position during 2T

Daniel M. Greenberger, Wolfgang P. Schleich, and Ernst M. Rasel
Relativistic effects in atom and neutron interferometry and the differences between them
Phys. Rev. A 86, 063622 (2012)

Wolfgang P. Schleich, Daniel M. Greenberger and Ernst M. Rasel
A representation-free description of the Kasevich–Chu interferometer: A resolution of the redshift controversy
New J. Phys. 15 (2013) 013007 (48pp)

Wolfgang P. Schleich, Daniel M. Greenberger, and Ernst M. Rasel
The redshift controversy in atom interferometry: Representation dependence of origin of phase shift
Phys. Rev. Lett. 110, 010401 (2013)

Accelerational Phase shift

VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

Observation of Gravitationally Induced Quantum Interference*

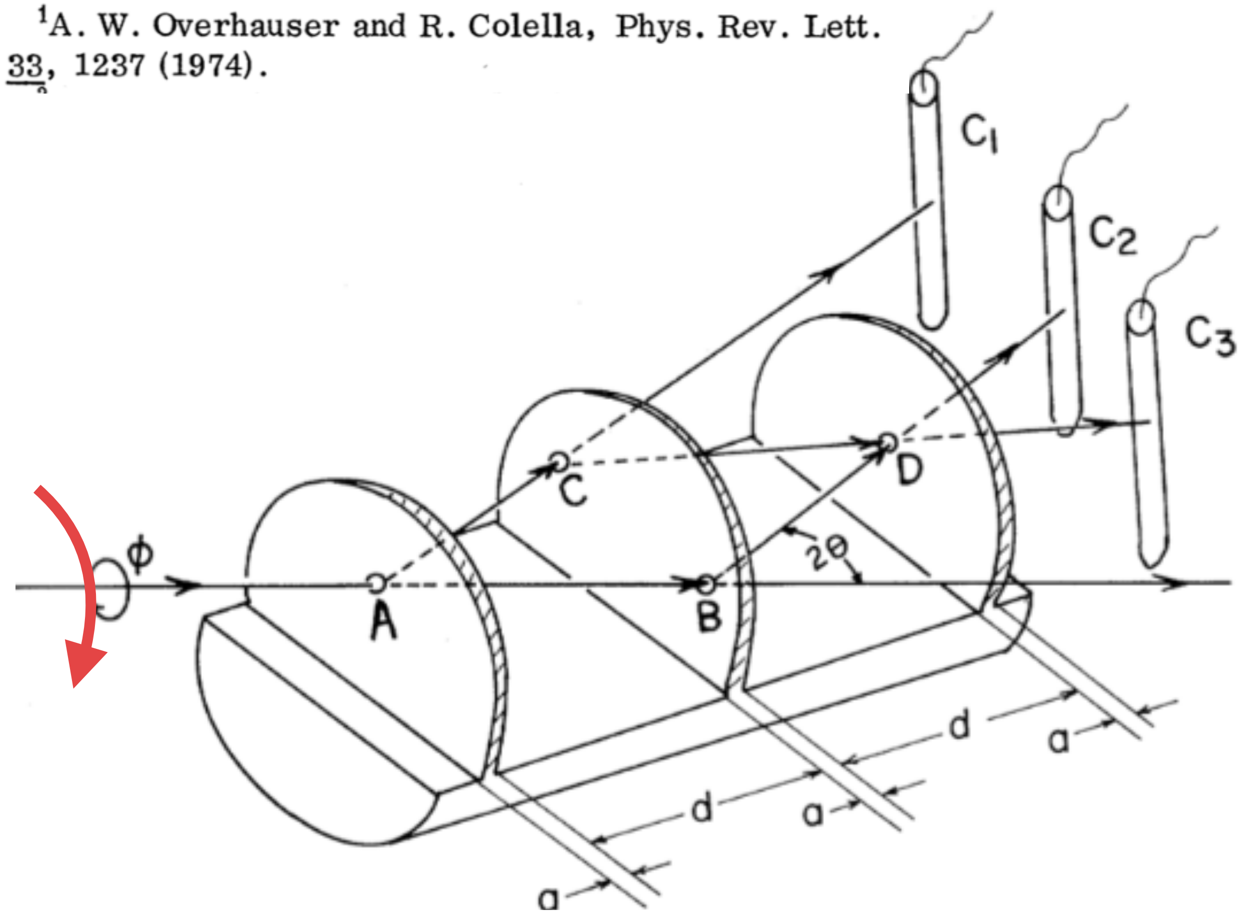
R. Colella and A. W. Overhauser
Department of Physics, Purdue University, West Lafayette, Indiana 47907

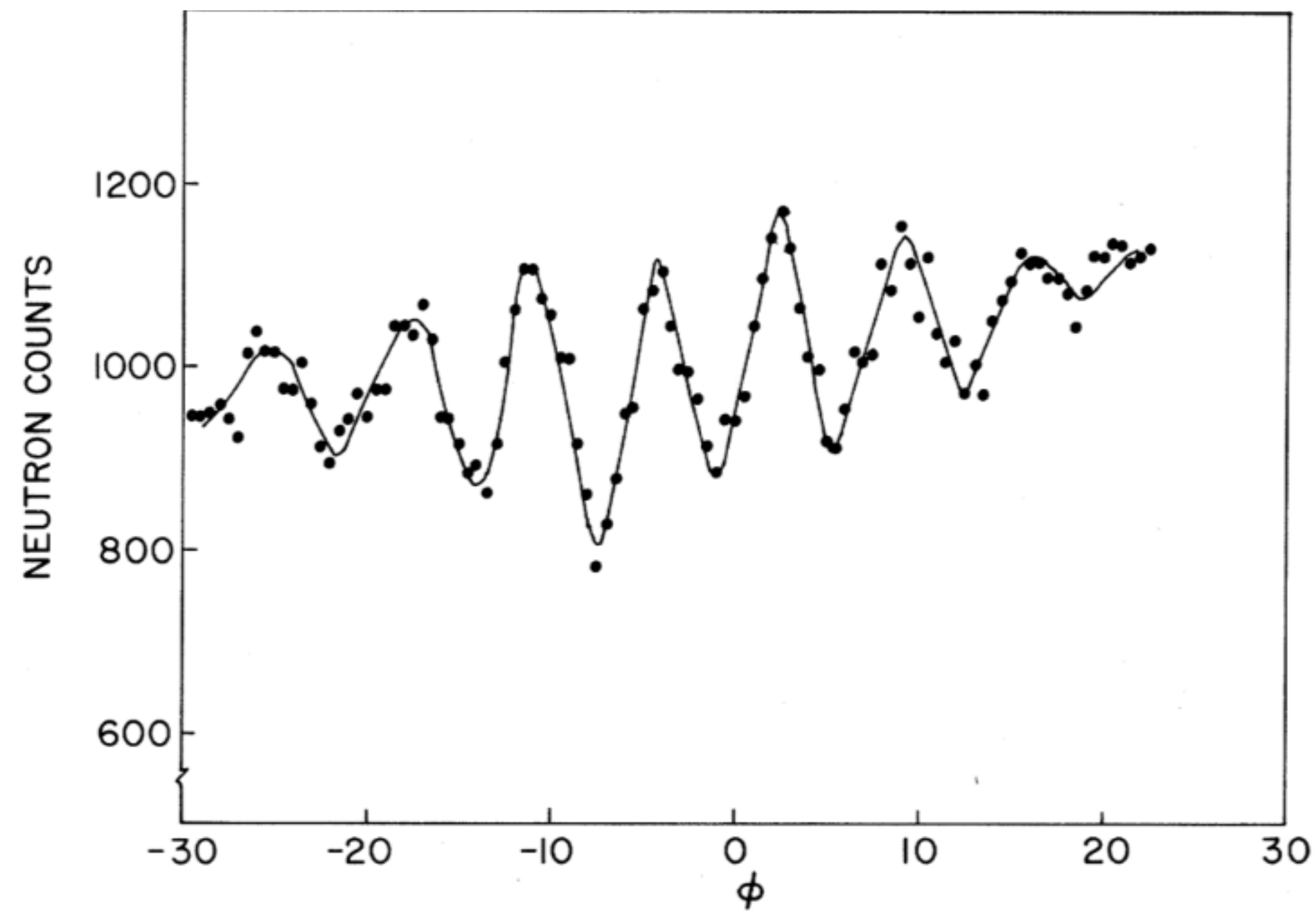
and

S. A. Werner
Scientific Research Staff, Ford Motor Company, Dearborn, Michigan 48121
(Received 14 April 1975)

We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.

[1]A. W. Overhauser and R. Colella, Phys. Rev. Lett. 33, 1237 (1974).



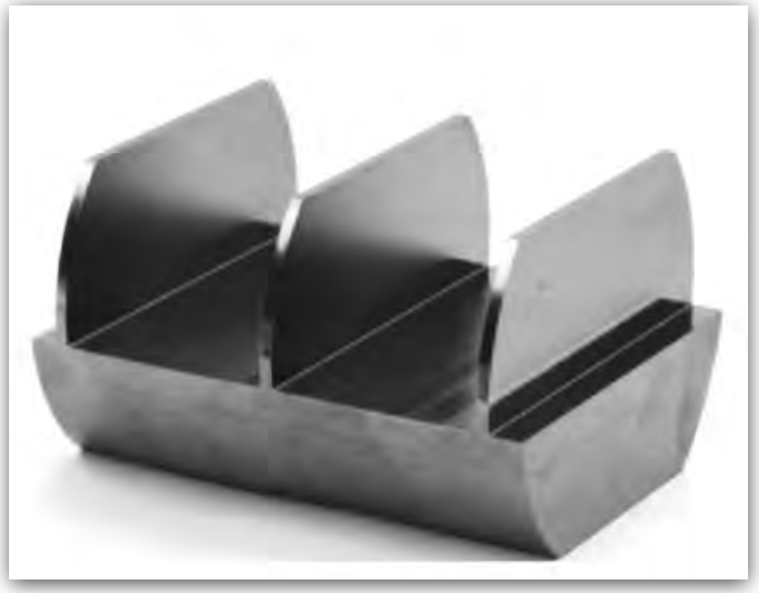


New generation of experiments: J.F. Clauser in the 80s

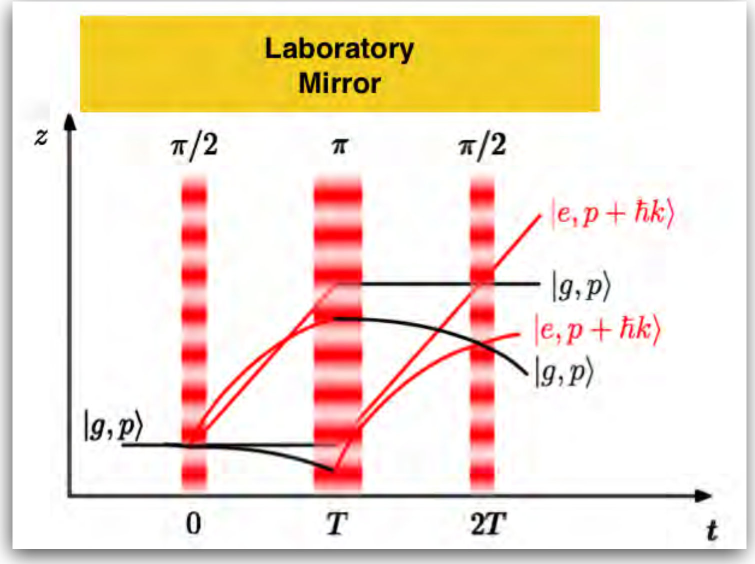
Analogies

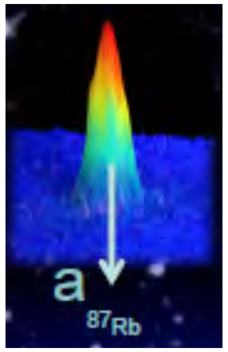
Modern COWG-type Experiments

Bragg scattering of neutron waves at silicon crystals



Bragg scattering of atom waves at crystals made out of light





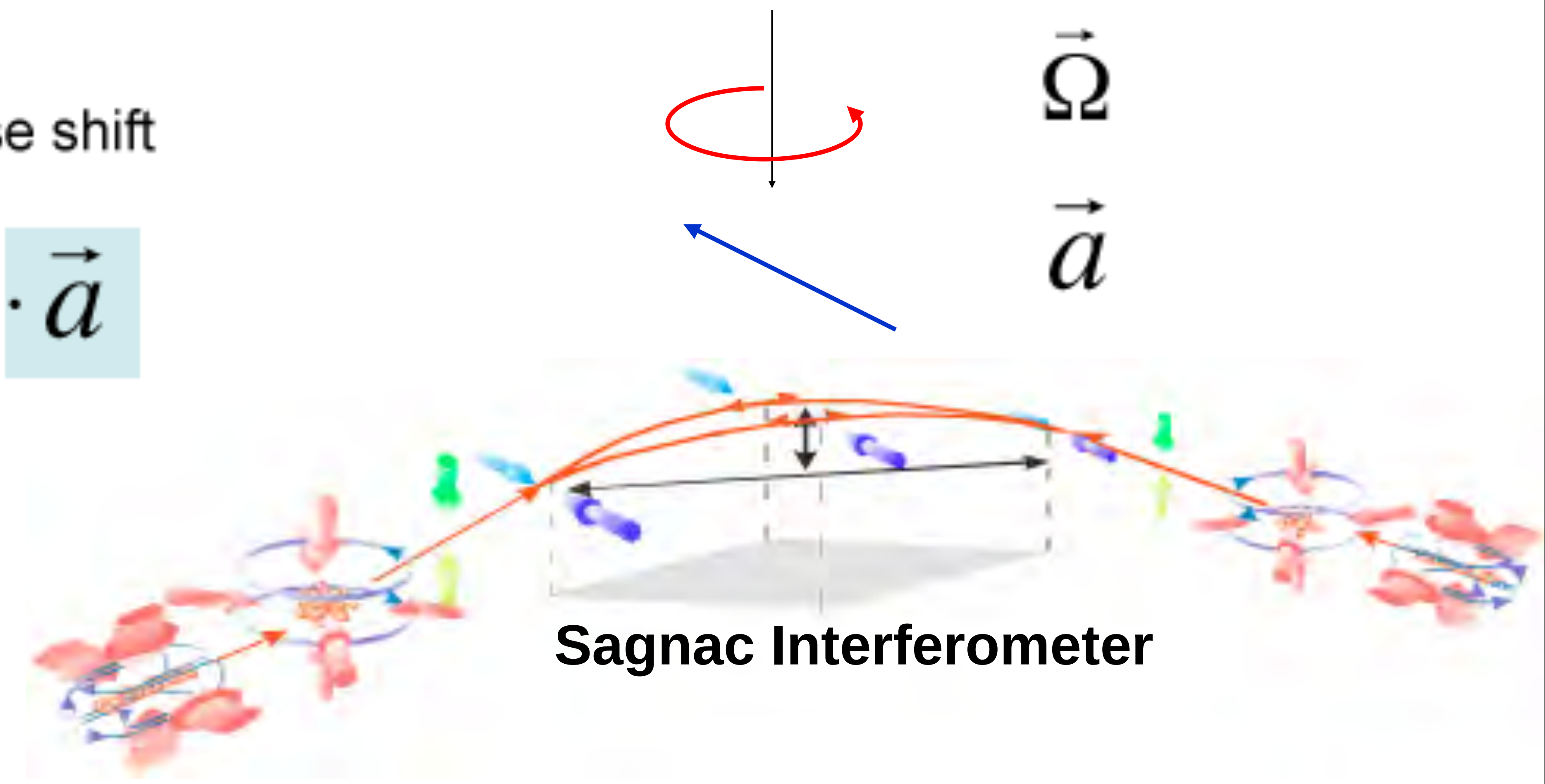
Measuring inertial forces

Rotational Phase shift

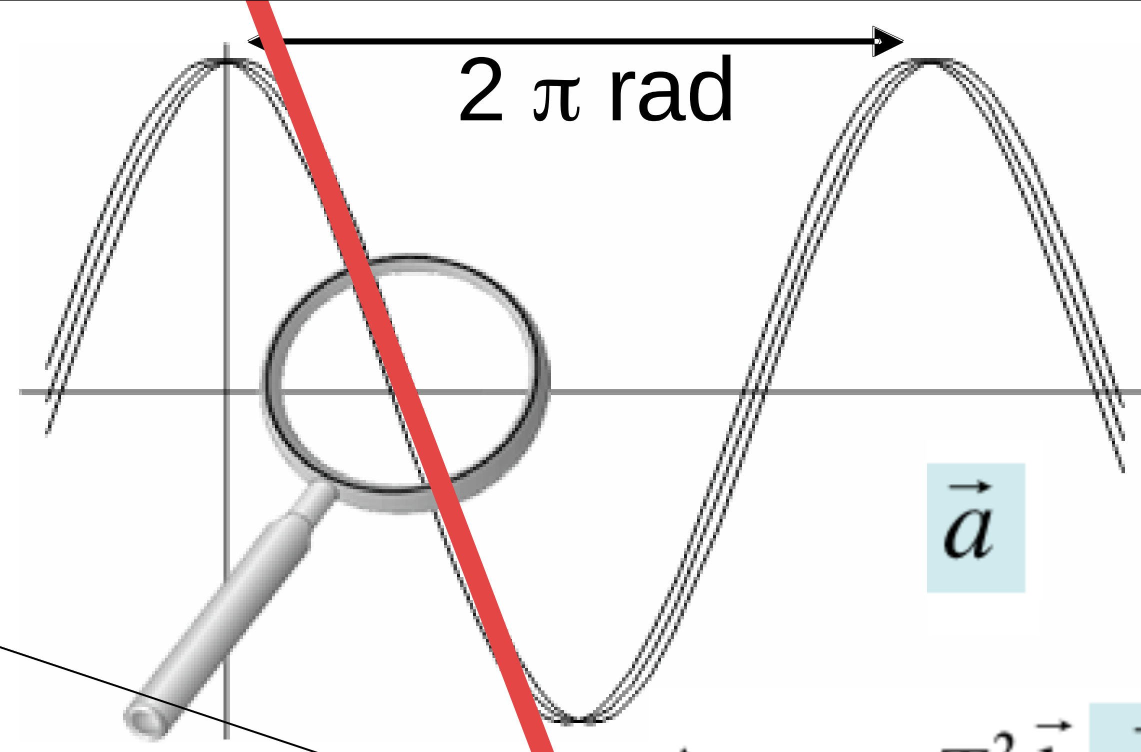
$$\Delta\varphi_{rot} = \frac{2m_{Atom}}{\hbar}\vec{A}\cdot\vec{\Omega} \propto T^2$$

Accellerational Phase shift

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



$$(\Delta\Omega)^2 = (\Delta\varphi)^2 / \left(\frac{\partial\varphi}{\partial\Omega}\right)^2$$



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

Minimising phase noise

- Increasing number of atoms
- Beating the shot noise
- Environmental control
  → Space / Underground laboratory
- Ultrastable lasers (frequency, intensity)

Increasing sensitivity

- Long interaction times
  → large atomic mass
  → space / fountains
- Ultra cold atoms
- Coherence
- Large momentum transfer

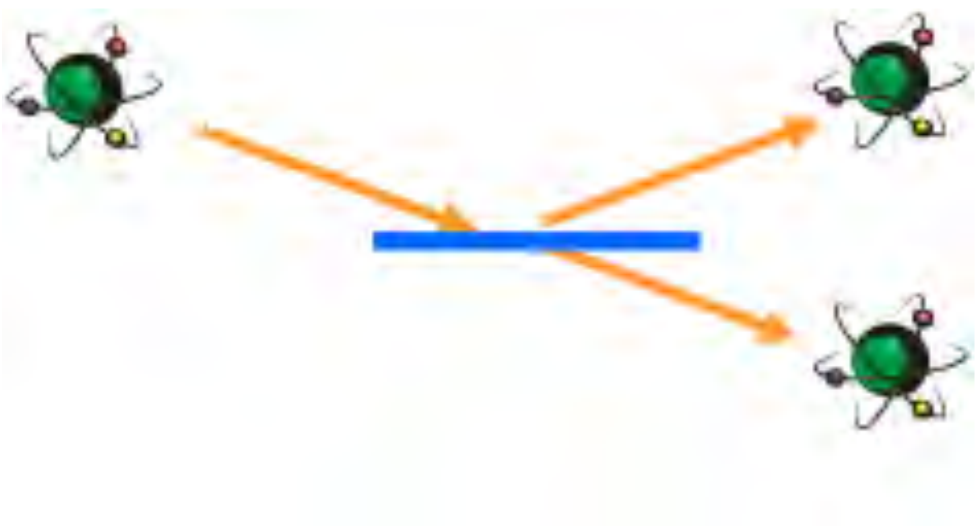
"The double difference of the height is measured during free fall with an atom-light interferometer"

"Atomic waves are coherently split, redirected and combined with the atom-light interaction: 2-photon process"

Why quantum ?

Why calling it a "Quantum Sensor"?

Superposition Principle ⟷ Wave-particle dualism

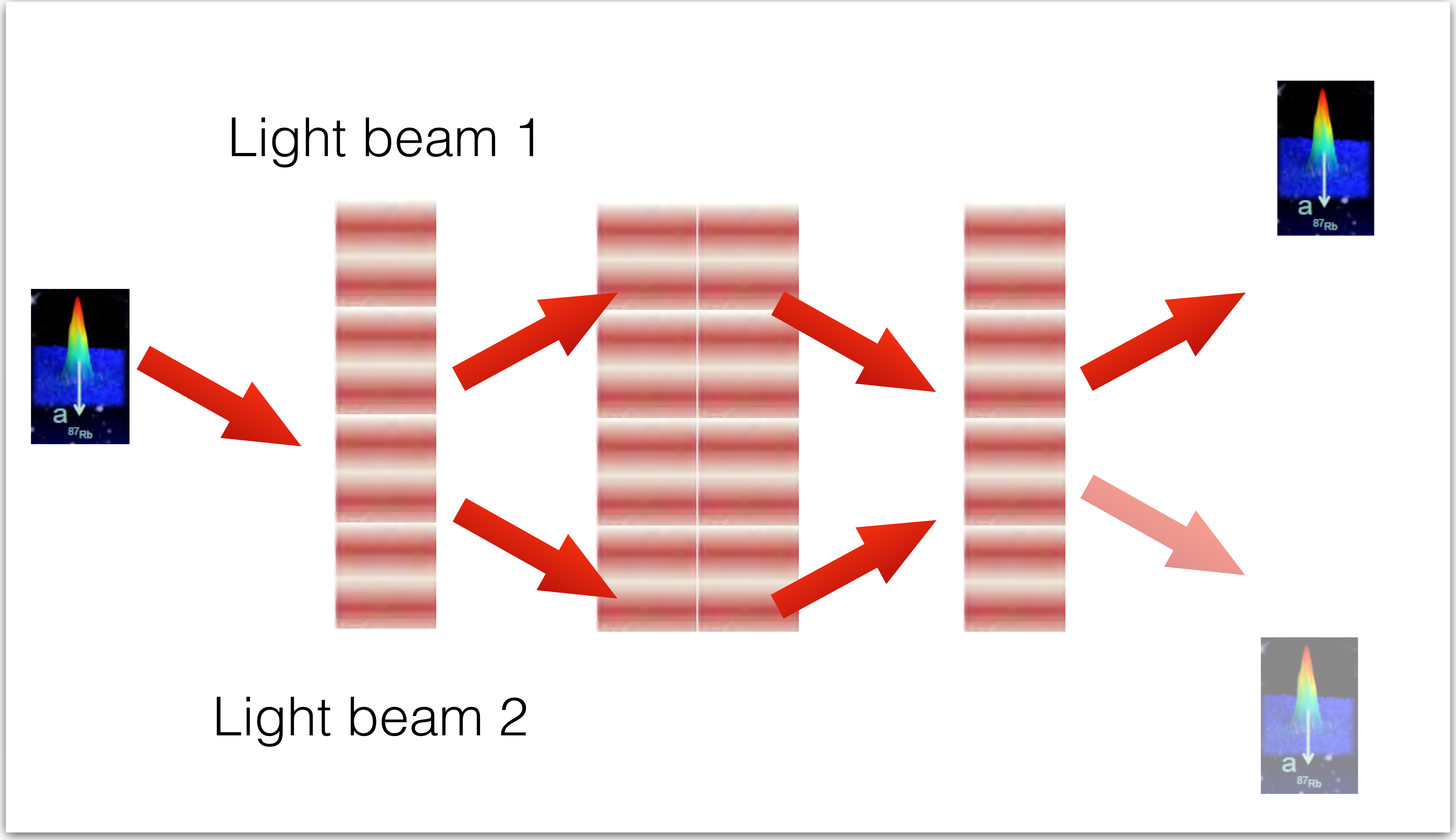


Atom moves up

+

Atom moves down

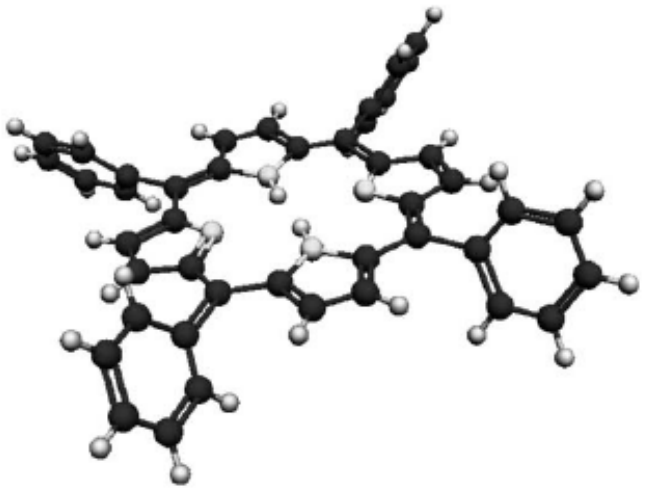
Atom Interferometer

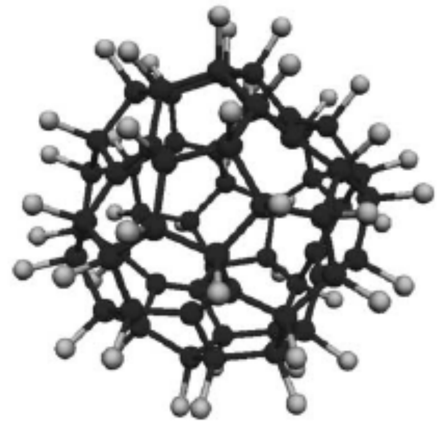


Quantenslalom

Courtesy by H. Rauch, TU Wien

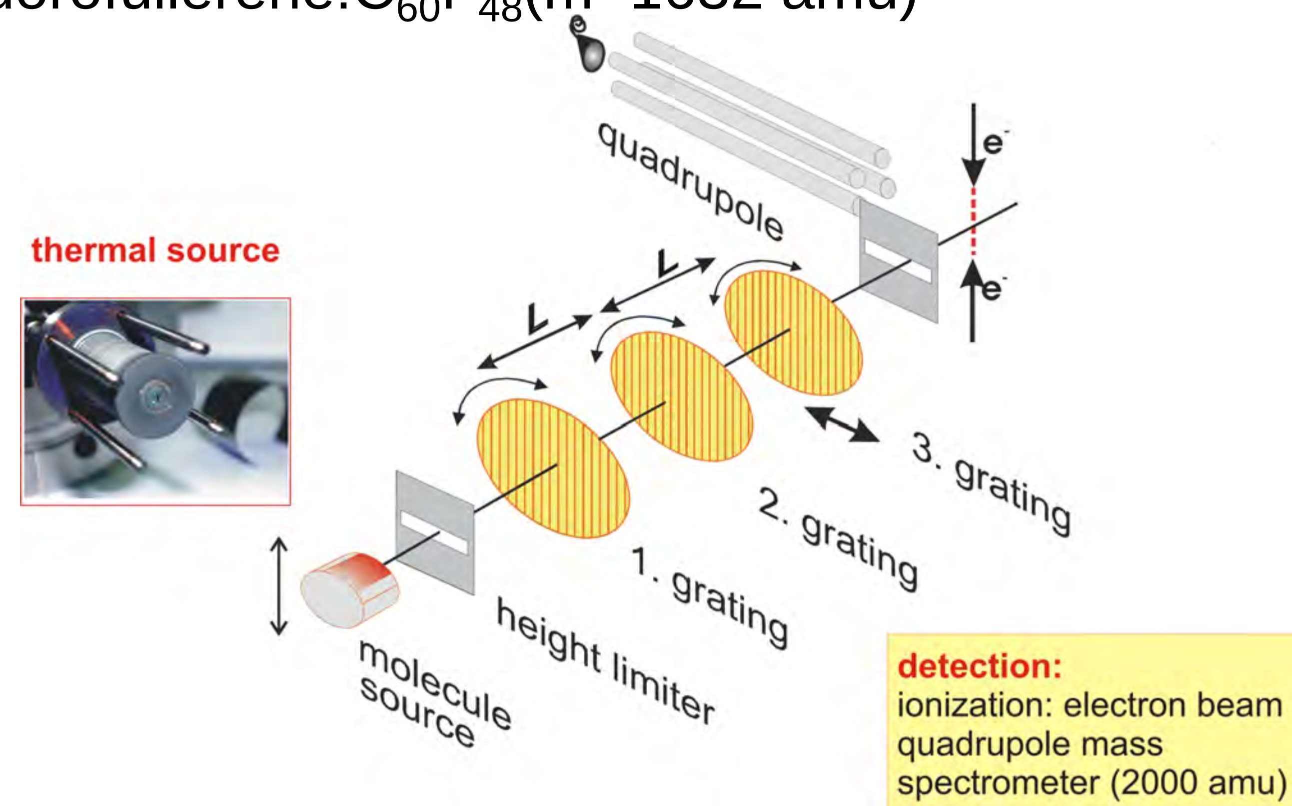
Matter waves - a macroscopic phenomenon ?

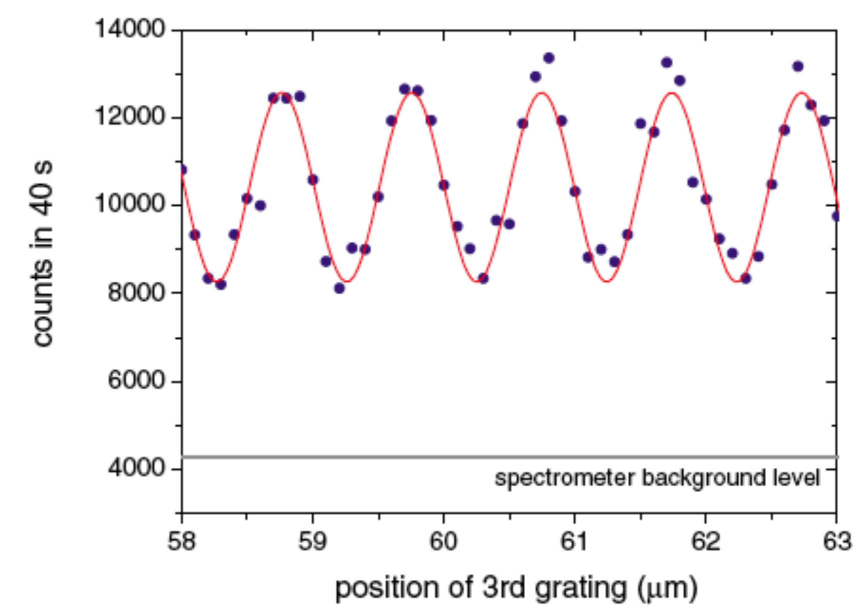




Tetraphenylporphyrin: $C_{44}H_{30}N_4$ (m=614amu)

Fluorofullerene:$C_{60}F_{48}$(m=1632 amu)





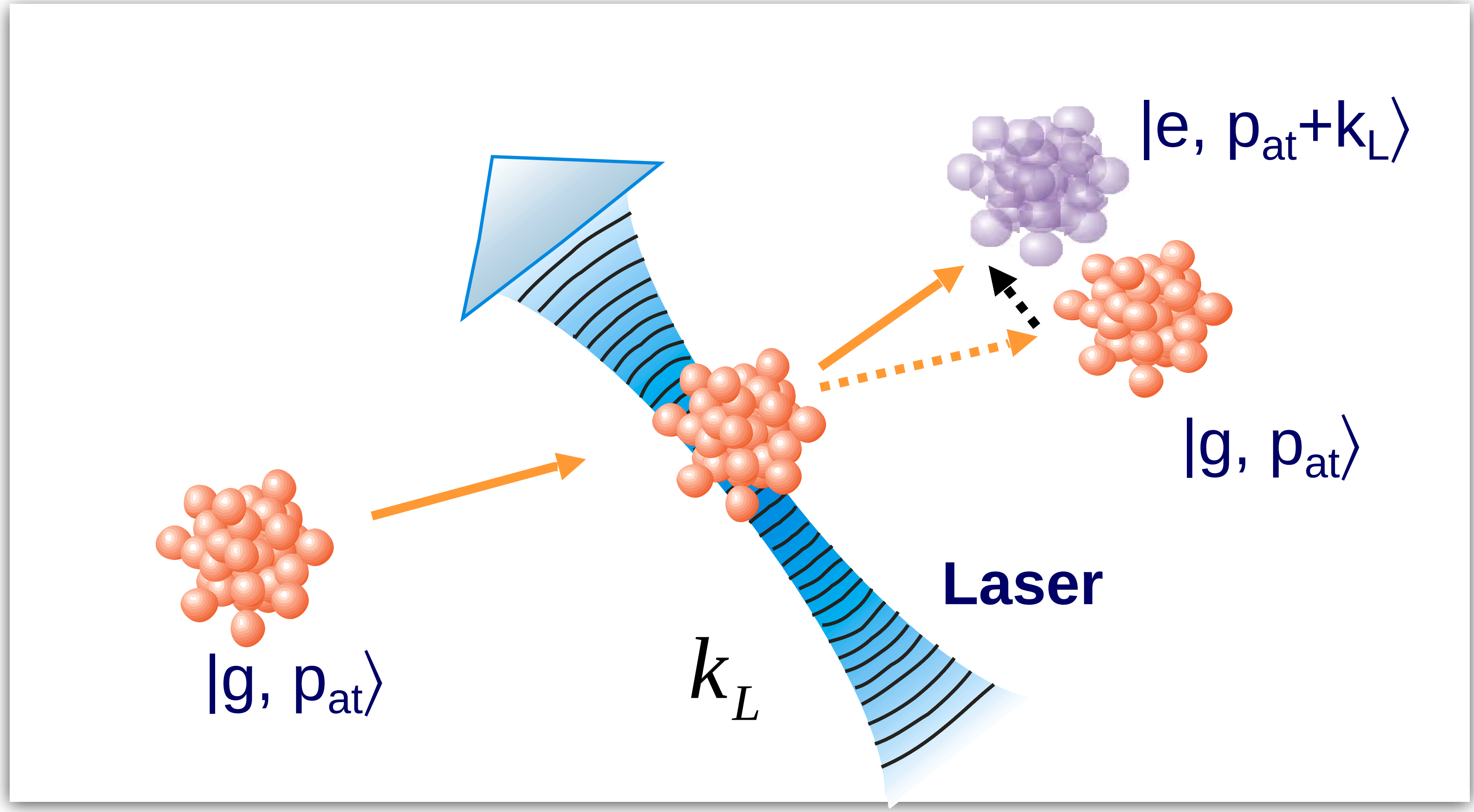
Why quantum ?

Each atom is moving up *and* down at the same time

Wave vs. particle nature

Typical features

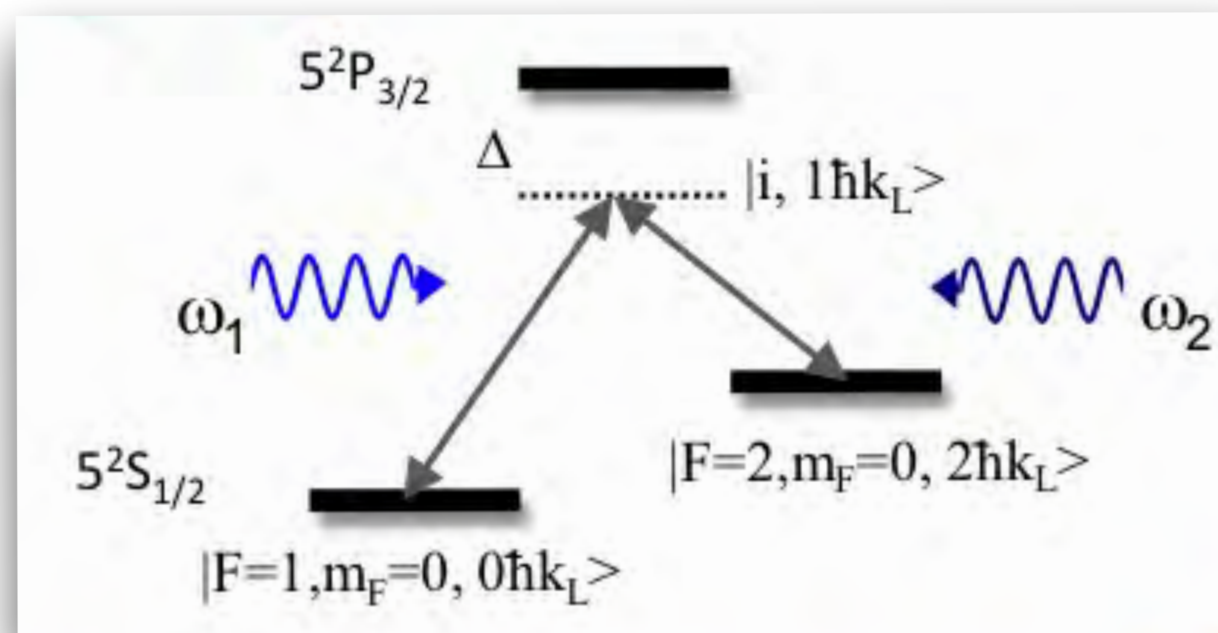
The mechanical effect of light



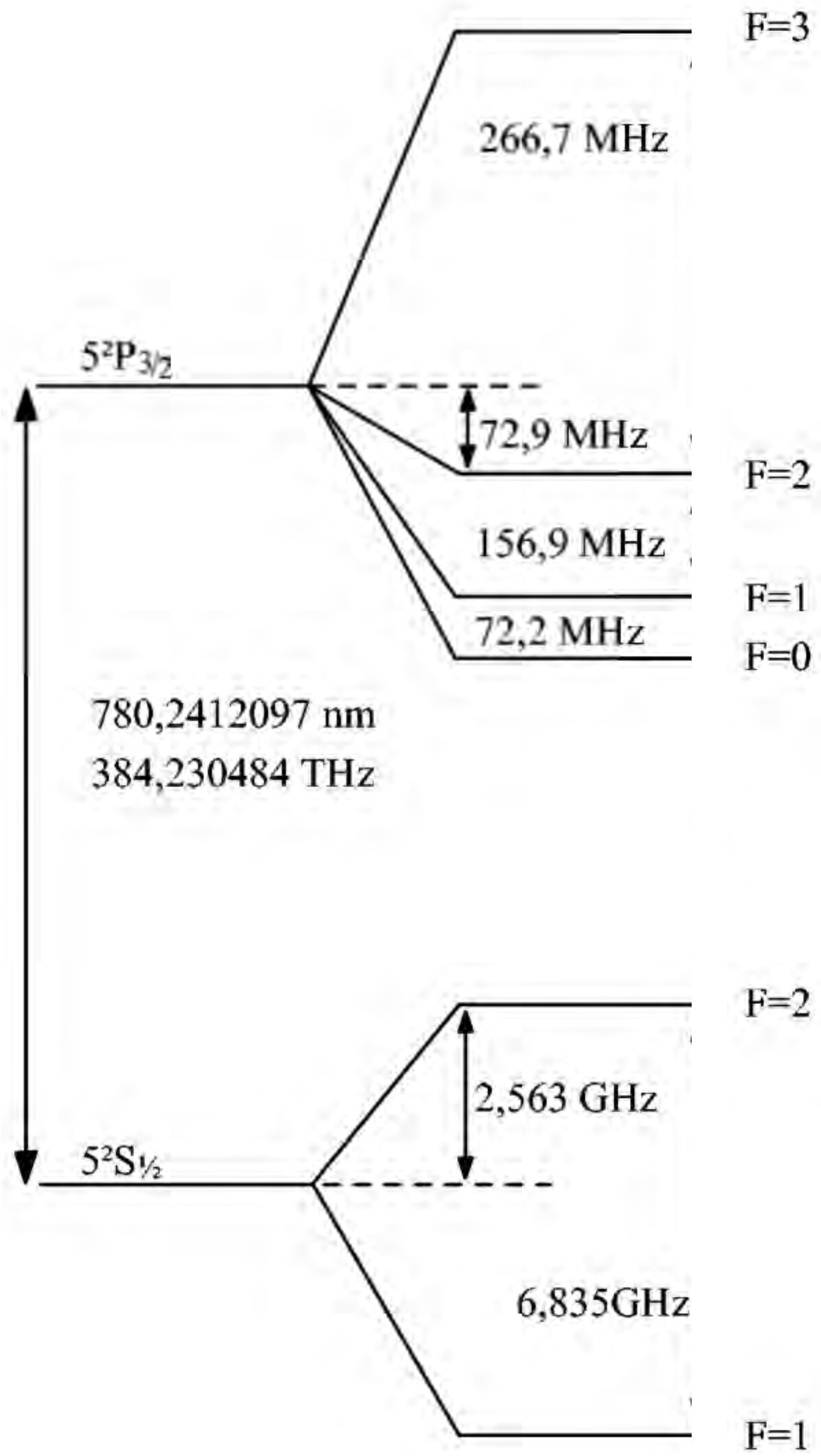
Photon recoil velocity

$$\vec{v}_{rec} = \frac{1}{m_{atom}} \hbar \vec{k}_L$$

Rubidium 87

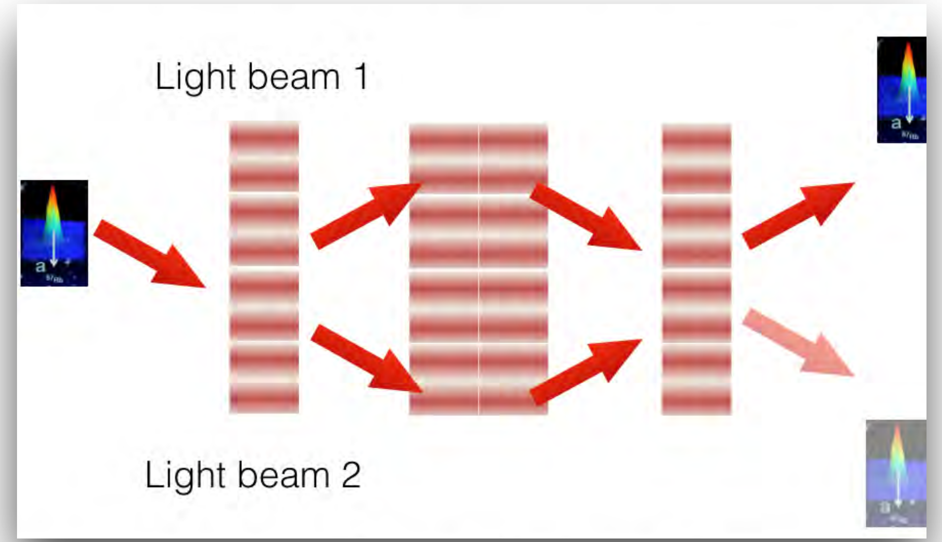


Typical features


F=3
266,7 MHz
5²P3/2
72,9 MHz
F=2
156,9 MHz
F=1
72,2 MHz
F=0
780,2412097 nm
384,230484 THz
F=2
2,563 GHz
5²S½
6,835GHz
F=1

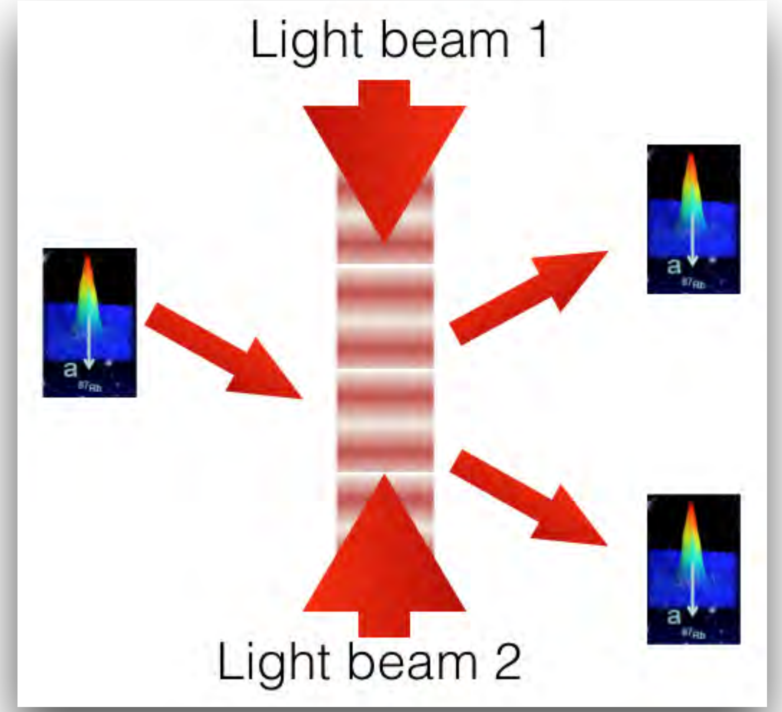
Rubidium

Typical features



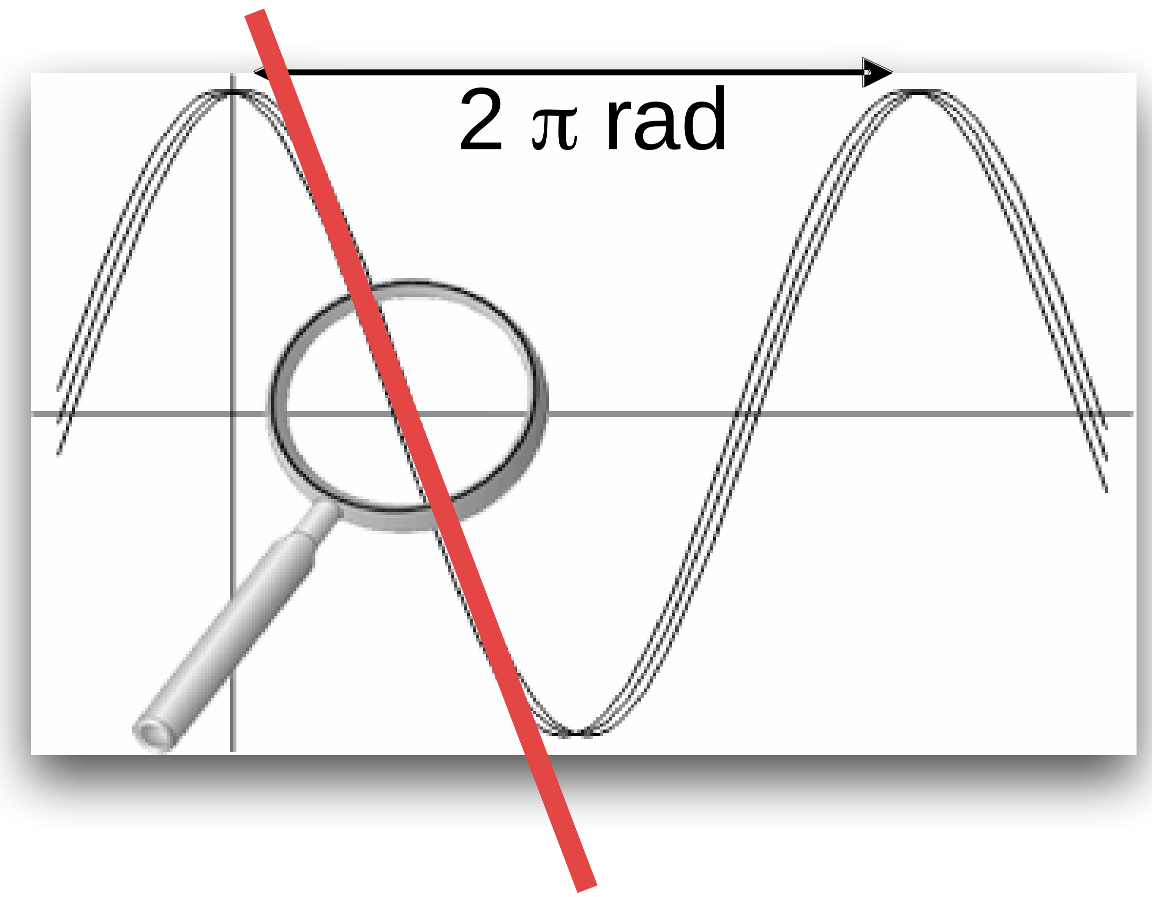
- Rubidium isotope 87 - 1 000 000 atoms
- Typical wavelength: 780 nm
- Splitting velocity:
  scales with twice the photon recoil ~ 1cm/s
- Sensitivity for accelerations

$$\Delta\phi = \vec{k}_{eff} \cdot \vec{a} * T^2 = 1.6 * 10^7 a_k T^2$$



- Mean velocity at room temperature several 100 m/s
- Width of the Bragg resonance is very narrow

Slowing down the atoms by laser cooling



$$\phi_a = \vec{k}_{eff} \cdot \vec{a} * T^2 = 1.6 * 10^7 a_k T^2$$

$$(\Delta a)^2 = (\Delta\varphi)^2 \,/\, \left(\frac{\partial \phi_a}{\partial a}\right)^2$$

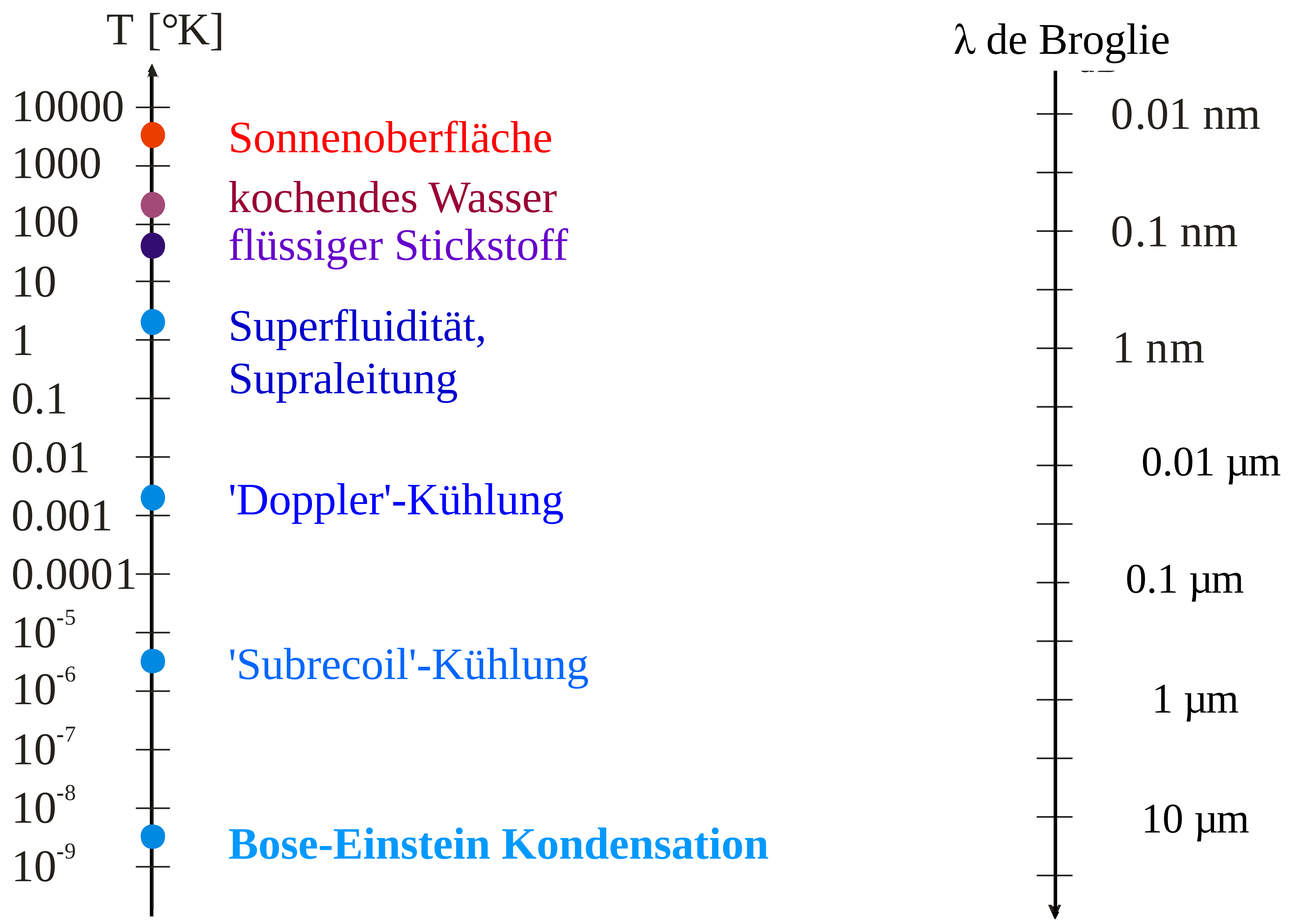
Noise

Temperature versus atomic speed

Temperature		Speed
4000°C - 1 Mio. °C	sun surface	5000 - 100.000 m/s
100 °C	boiling water	700 m/s
-196 °C	liquid nitrogen	240 m/s
-260 °C	Supraconduction	90 m/s
100 millionth Kelvin	'Doppler' Temperature	30 cm/s
1 millionth Kelvin	'recoil' Temperature	3 cm/s
10 billionth Kelvin	‘Bose-Einstein Condensation’	3 mm/s

T = 0 Kelvin ≈ - 273 °C

Temperaturen versus Wellenlänge



Today atom interferometer work with laser cooled ensembles

Lower temperatures (sub recoil) are desired

Sensitivity scales

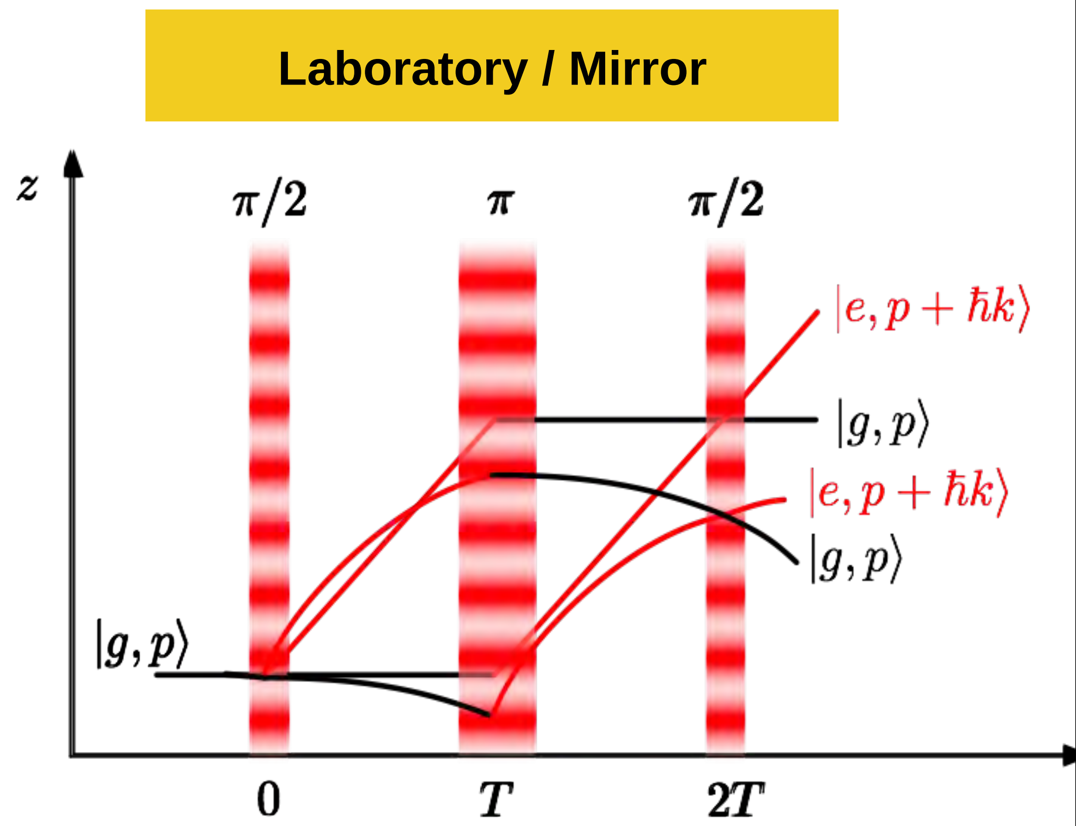
- with the square of the free fall duration
- linearly with the splitting

Instrument Noise 1-10 mrad

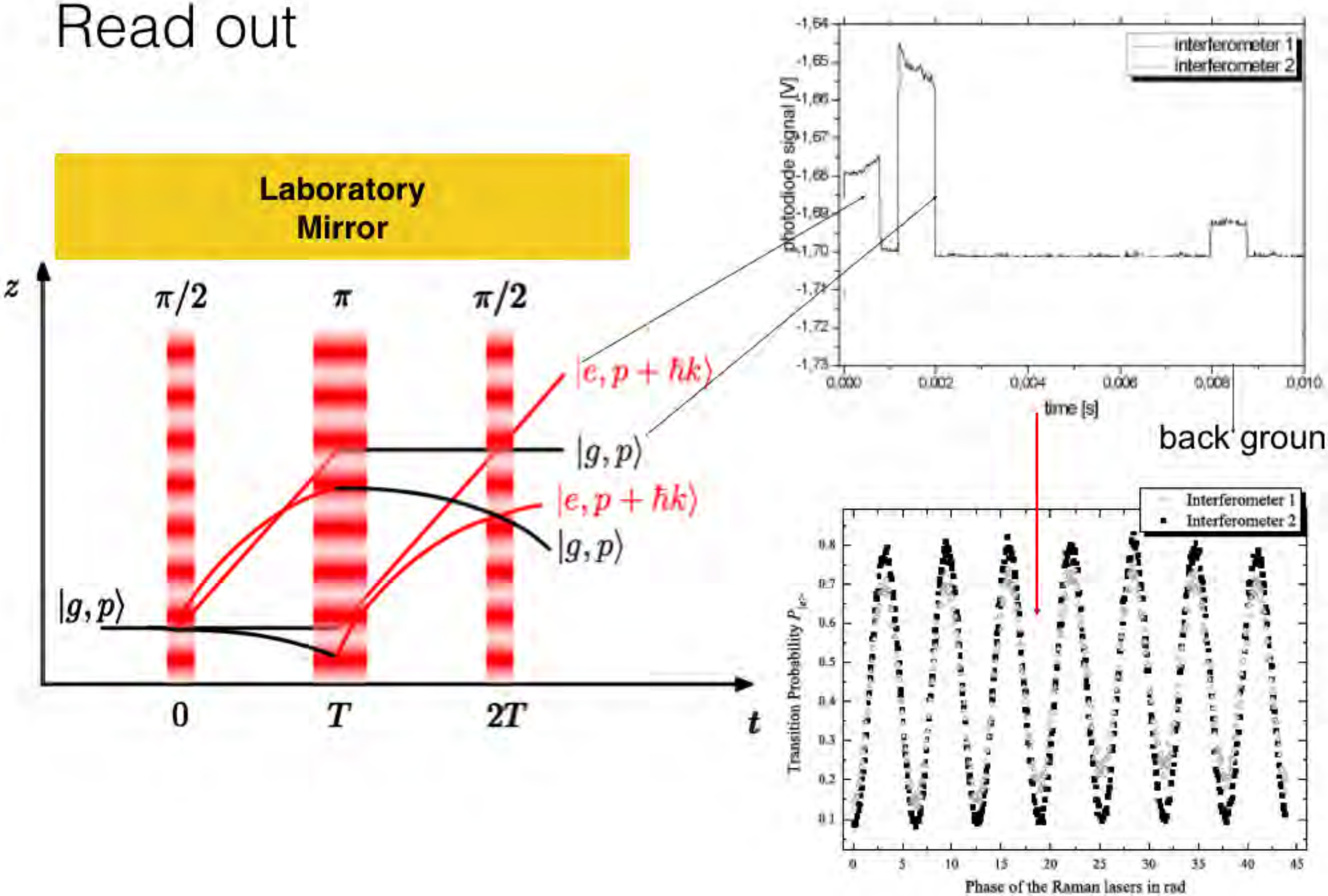
The Quantum Gravimeter

Sequence for an atom interferometer

Prepare atoms	Laser cooling Select the non-magnetic Zeeman state Launch or drop atoms	0.1-1 s
Perform Interferometry	Raman or Bragg type process	0.1 - ? s
Detect atoms	Fluorescence / absorption Detection	0.01 s
Check systematics	Change parameters	



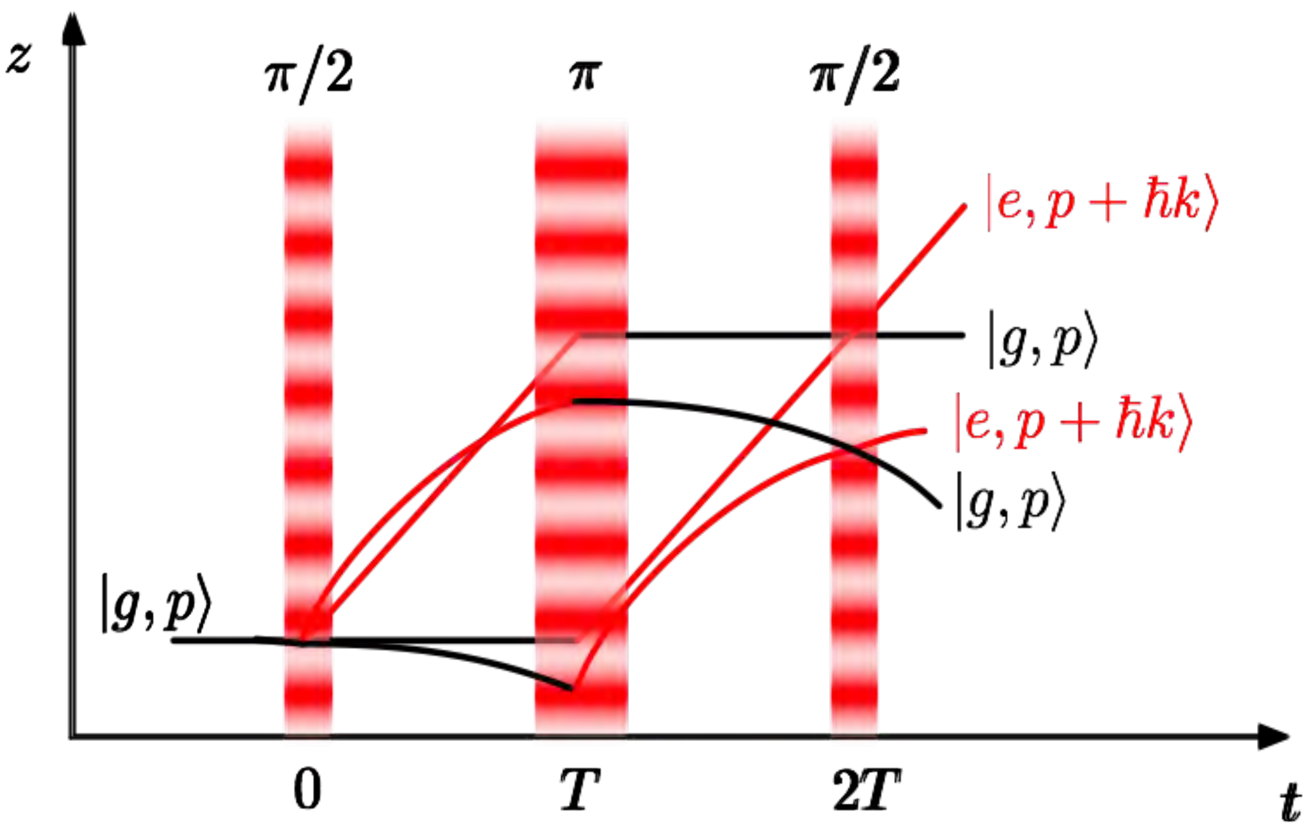
Read out

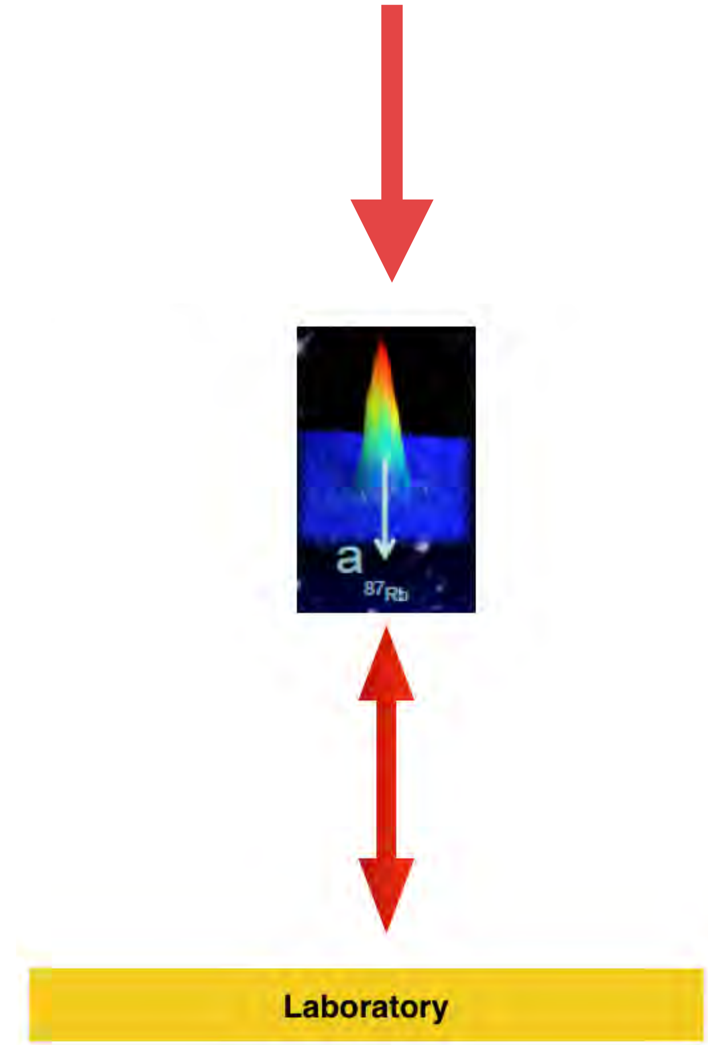


Laboratory Mirror
z
$\pi/2$
π
$\pi/2$
$|e, p + \hbar k\rangle$
$|g, p\rangle$
$|e, p + \hbar k\rangle$
$|g, p\rangle$
$|g, p\rangle$
0
T
$2T$
t
interferometer 1
interferometer 2
photodiode signal [V]
time [s]
back ground
Interferometer 1
Interferometer 2
Transition Probability $P_{|e\rangle}$
Phase of the Raman lasers in rad

Temporal atom interferometer

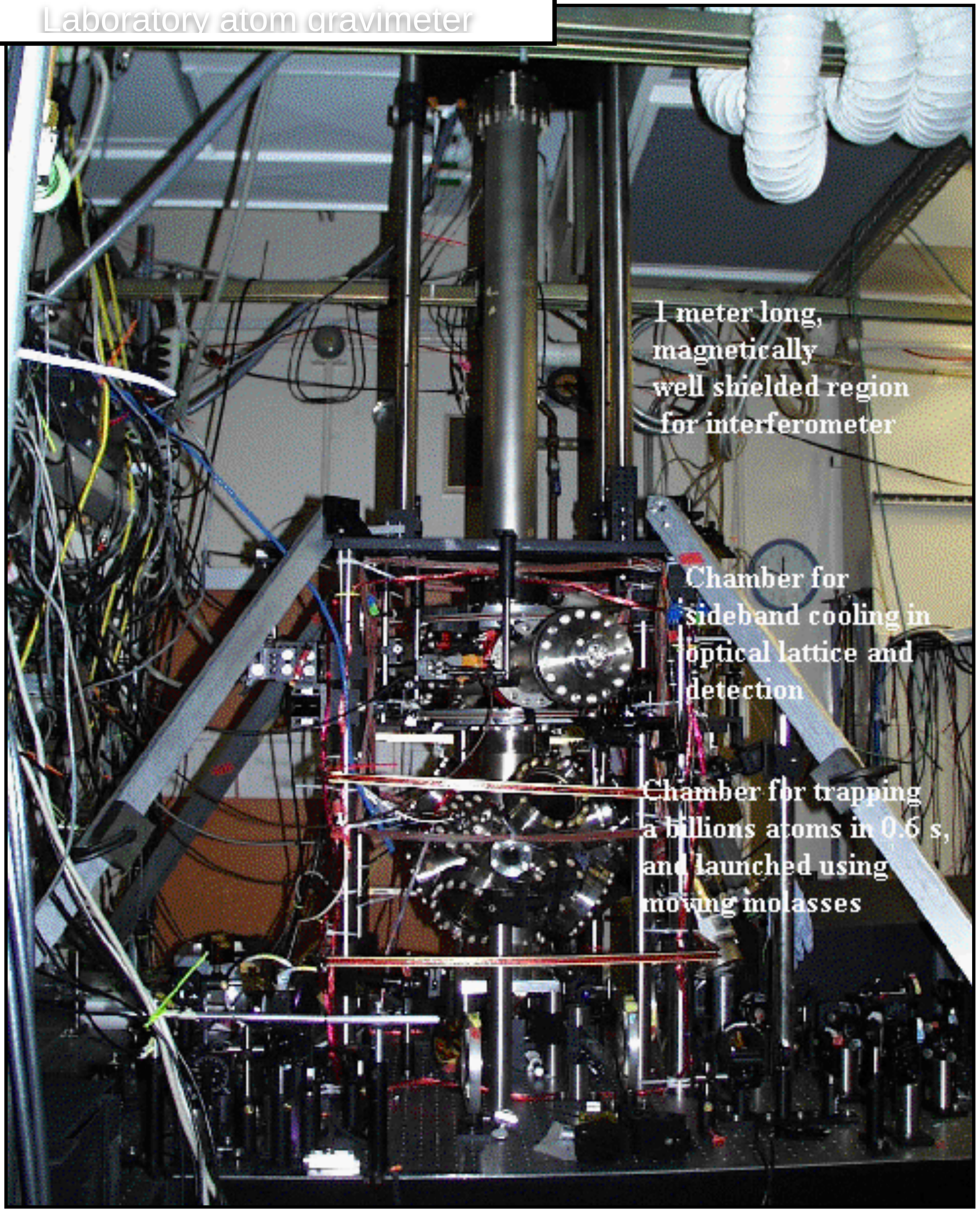
Laboratory / Mirror

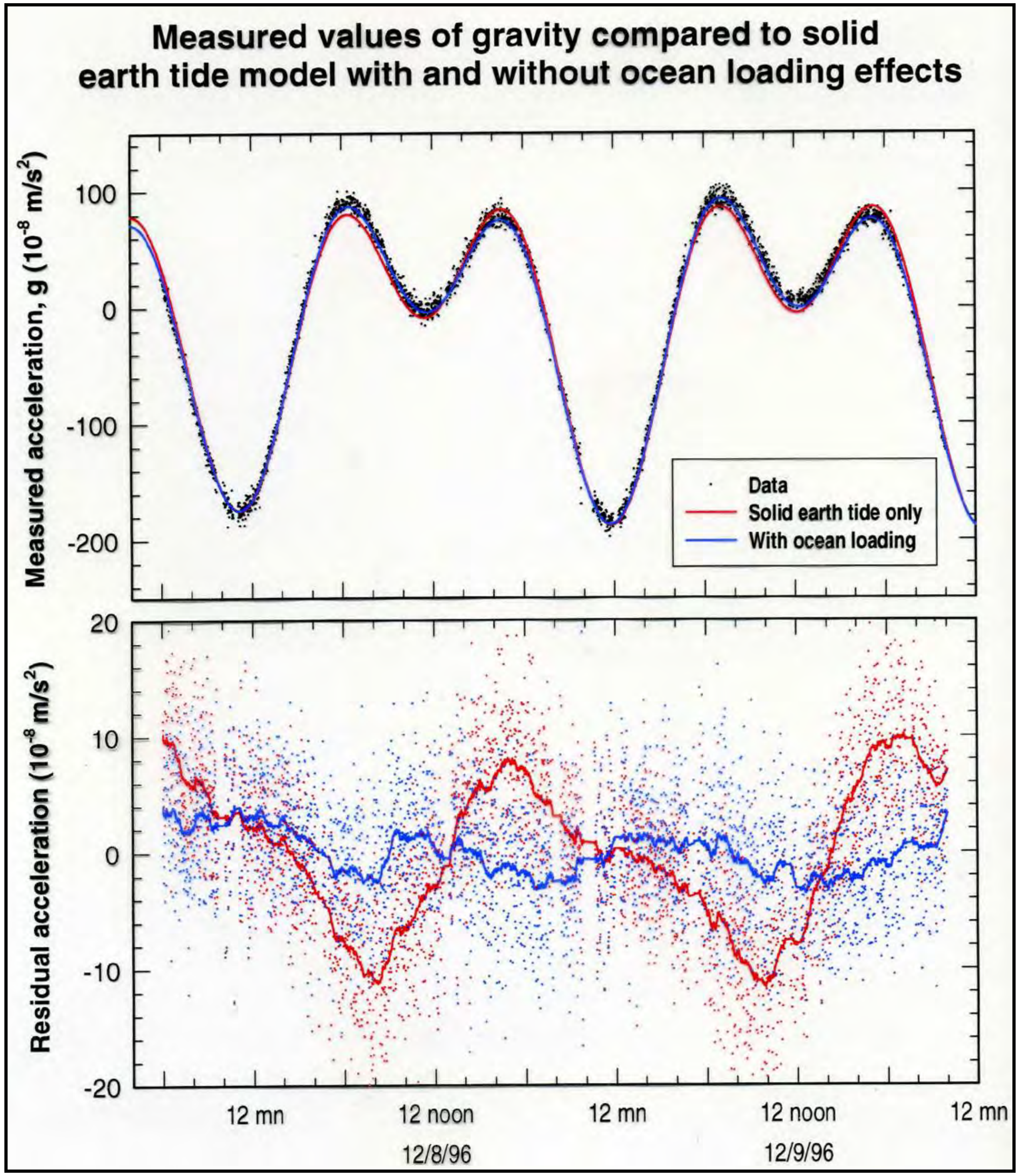




- temporal sequence of laser pulses
- in direction of free fall

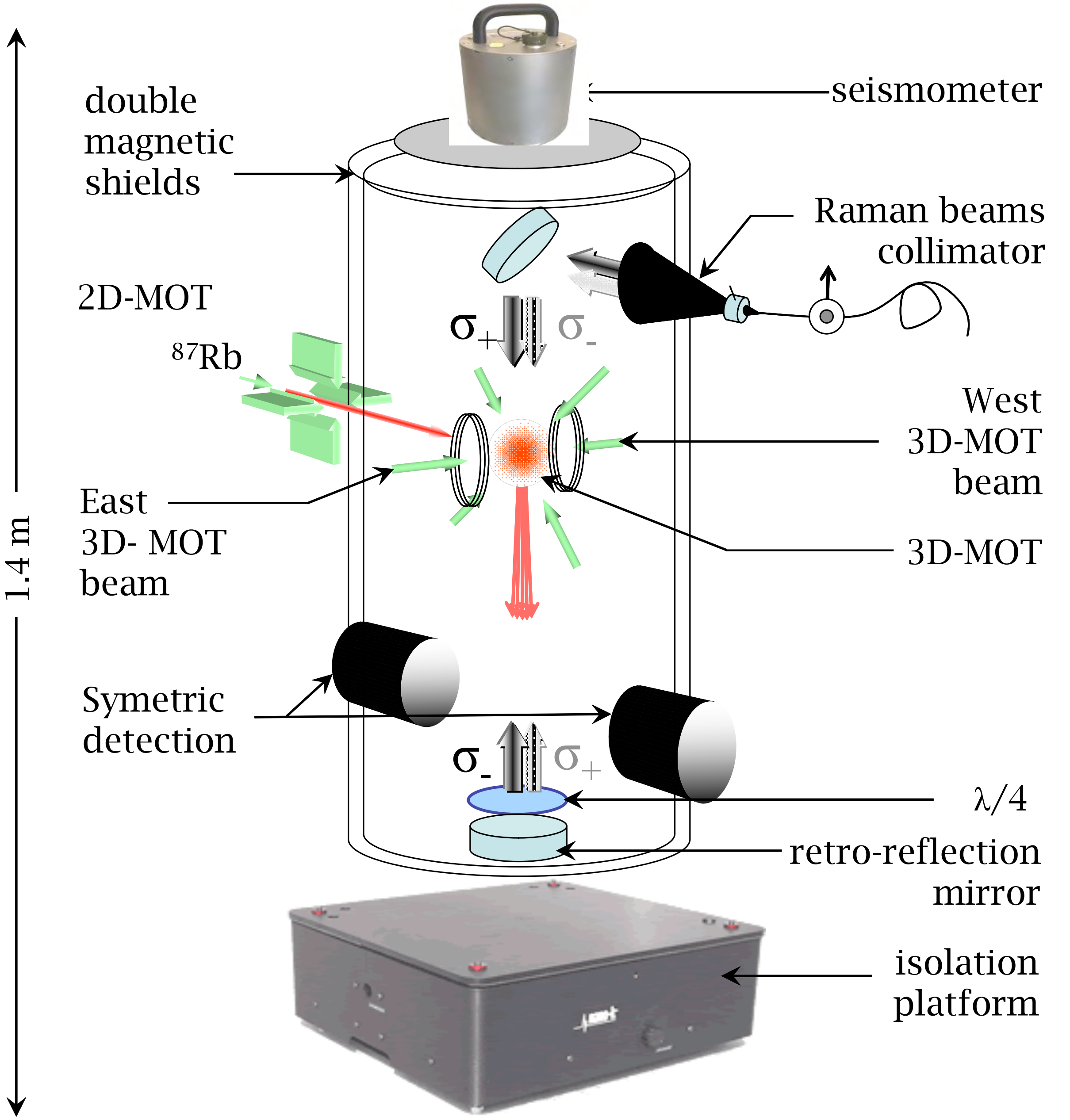
First atomic gravimeter



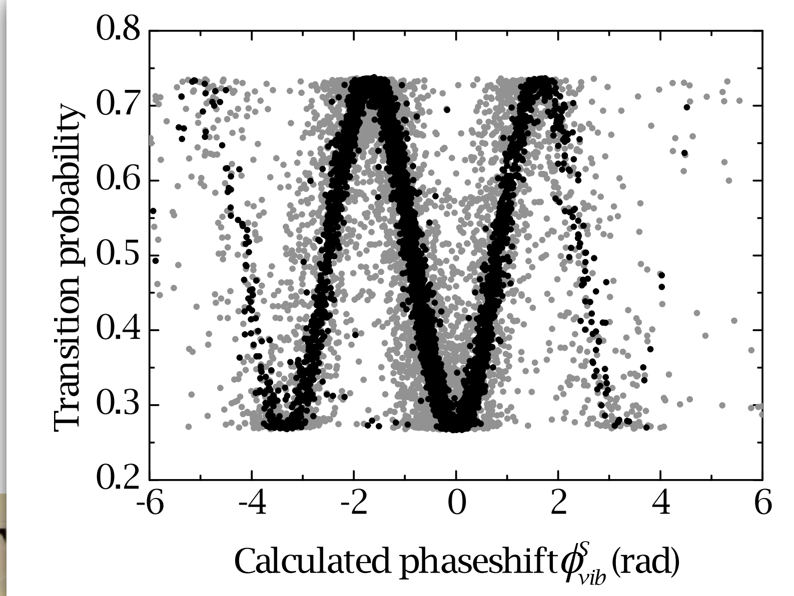


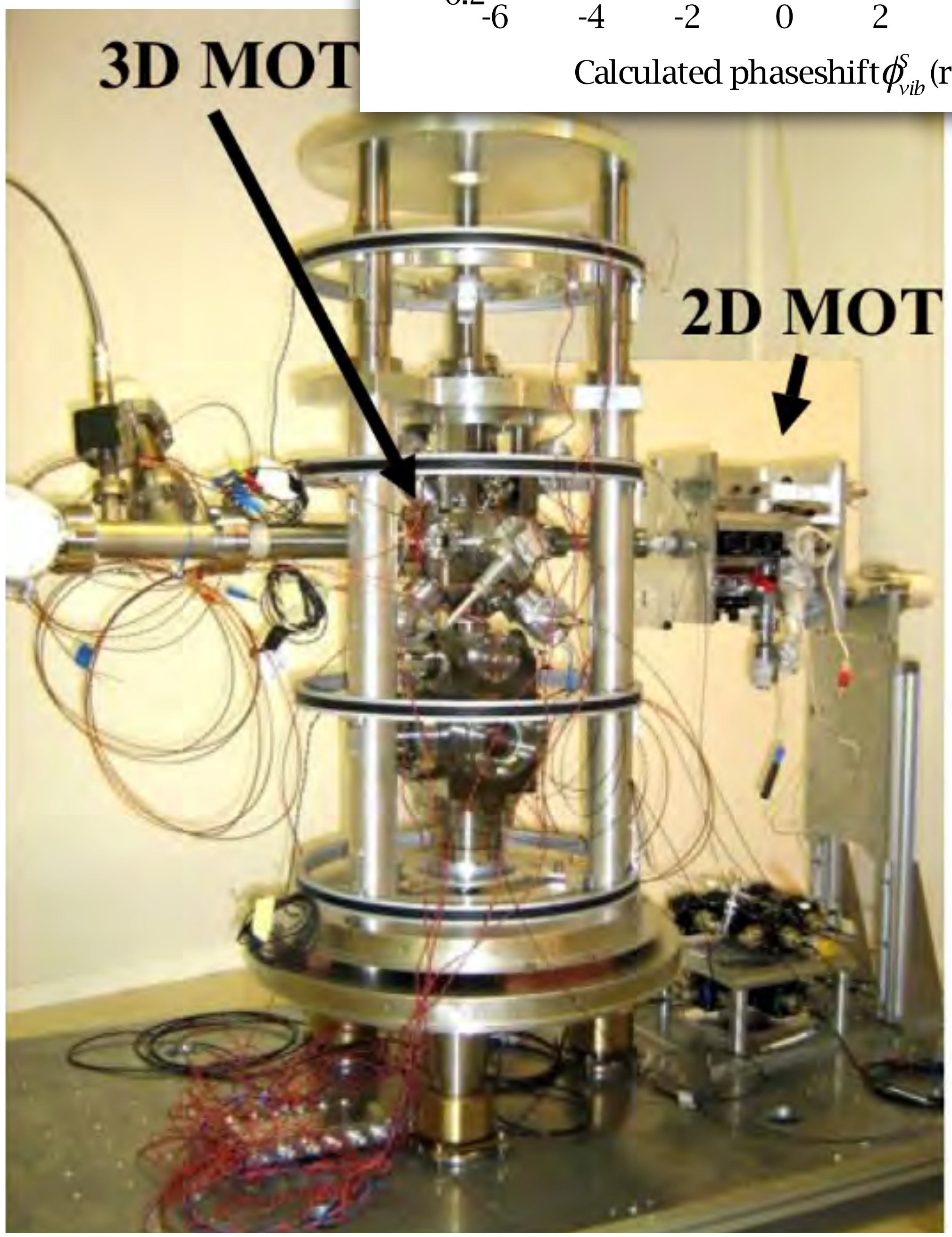
A. Peters, S. Chu Stanford University

Absolute gravimetry with cold atoms



Sensor : free fall atoms, g deduced from frequency measurement
Vibration rejection with a seismometer and an isolation plateform,
Repetition rate : 2.8 Hz

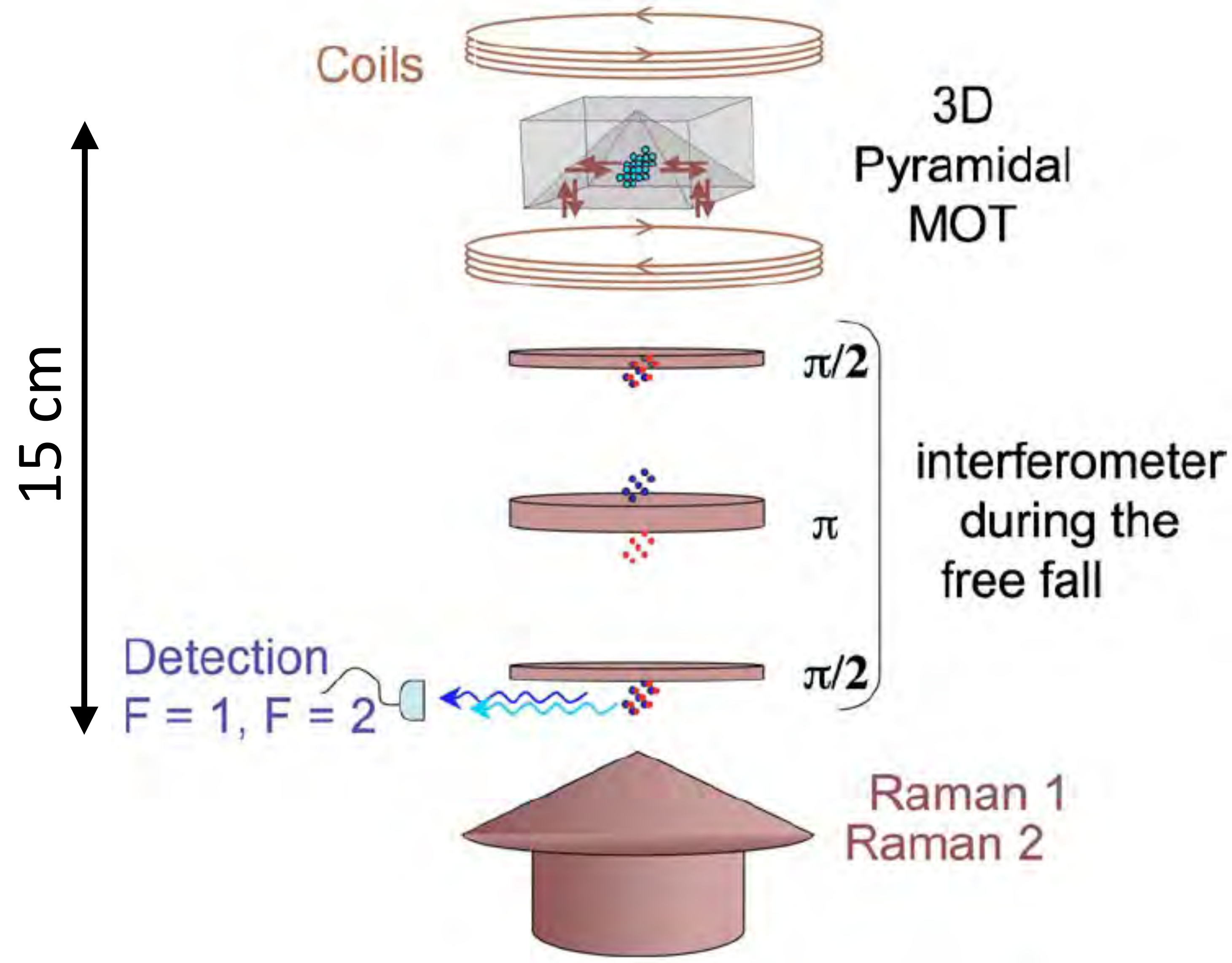




Compact Gravimeter at SYRTE - Paris

Application:

- Field sensor for local gravity measurements
- Commercial alternative to FG 5 light gravimeter

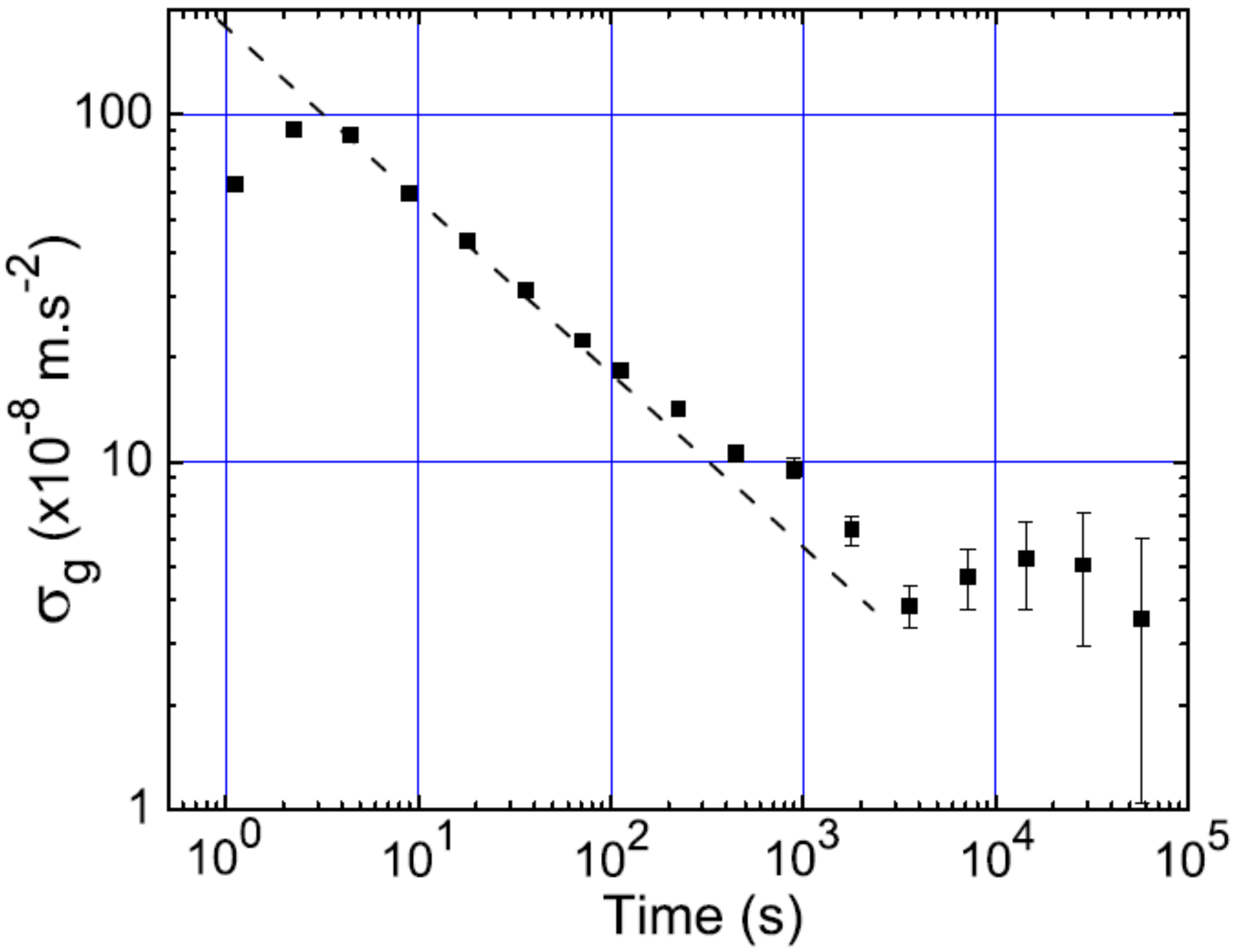


[Q. Bodart, et al. Appl. Phys. Lett. **96**, 134101 (2010)]

Features:

- Pyramidal MOT
- 1 laser with 50 mW for source, beam splitting and detection

Compact Gravimeter at SYRTE - Paris



Features:

- Pyramidal MOT
- 1 laser with 50 mW for source, beam splitting and detection

[Q. Bodart, et al. Appl. Phys. Lett. **96**, 134101 (2010)]

Sensitivity:

- Short term: $1{,}7\times10^{-7}$ g/Hz$^{1/2}$
- Long term: 5×10^{-9} g @ 10^3s

Fundamental physics with matter waves

The (weak) Principle of Equivalence

- Are inertial and gravitational mass really equivalent?
- Do all bodies fall equally?

$m_{inertial} = m_{gravitational}$

$$m_{A,i}\,\vec{a} = \vec{F} = G\,\frac{M_{E,G}\,m_{A,G}}{r^2}$$

Heinrich Hertz: *Die Constitution der Materie* (1884):

“And yet, in reality, we are dealing with two properties, two essential properties, of matter which may be contemplated quite independent of one another and which prove by experience, and only by it, to be completely equivalent.

This coincidence is rather to be considered a most wonderful mystery which requires an explanation”.

The (weak) Principle of Equivalence

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$$\vec{F} = m_i \cdot \vec{a} = m_g \vec{g}$$

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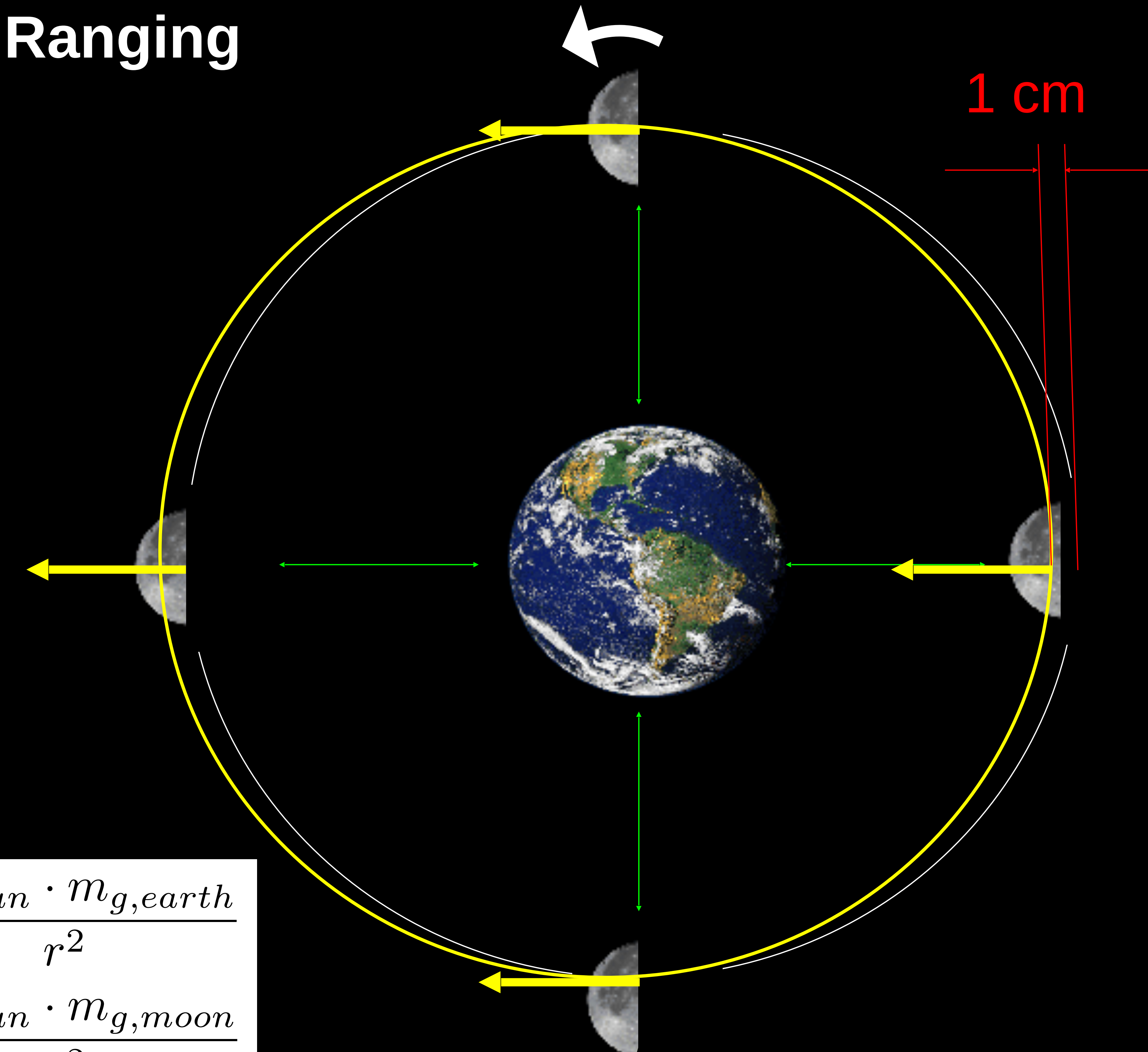
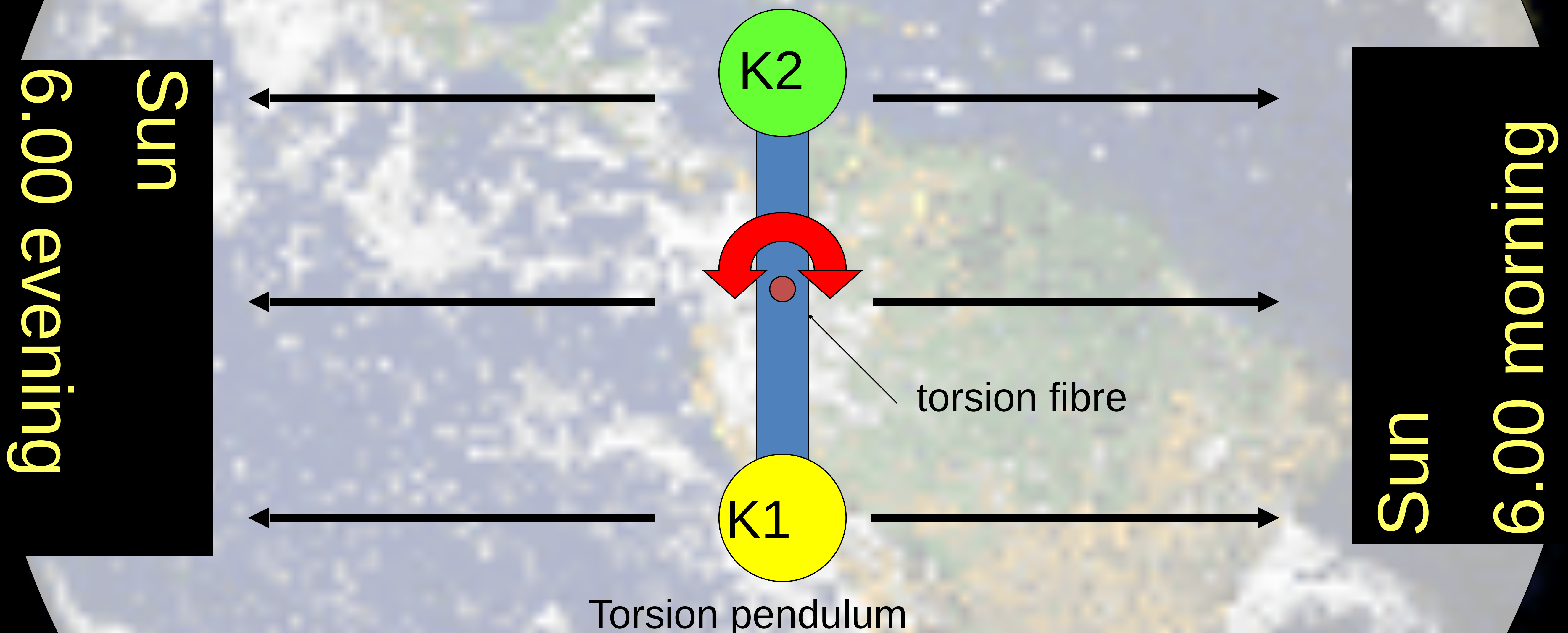
Lunar Laser Ranging



$$m_{i,earth}\vec{a} = G\frac{m_{g,sun} \cdot m_{g,earth}}{r^2}$$

$$m_{i,moon}\vec{a} = G\frac{m_{g,sun} \cdot m_{g,moon}}{r^2}$$

Torsion pendulum experiments

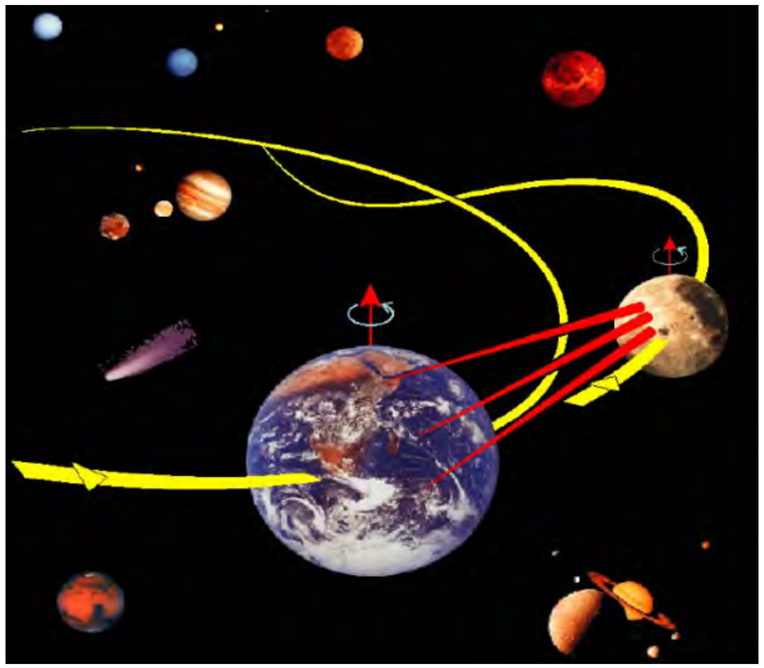


K1 Chemical composition of the earth

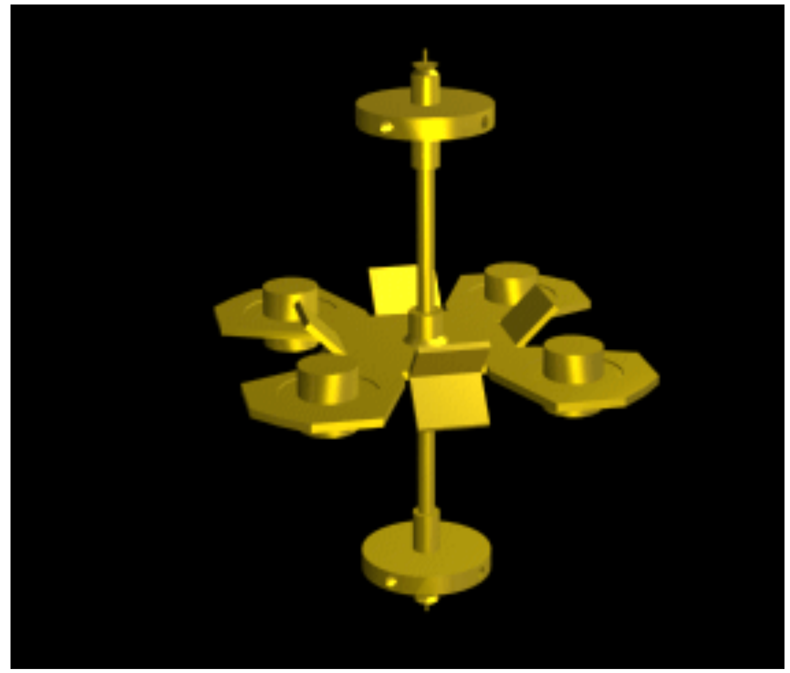
K2 Chemical composition of the moon

Tests with classical matter

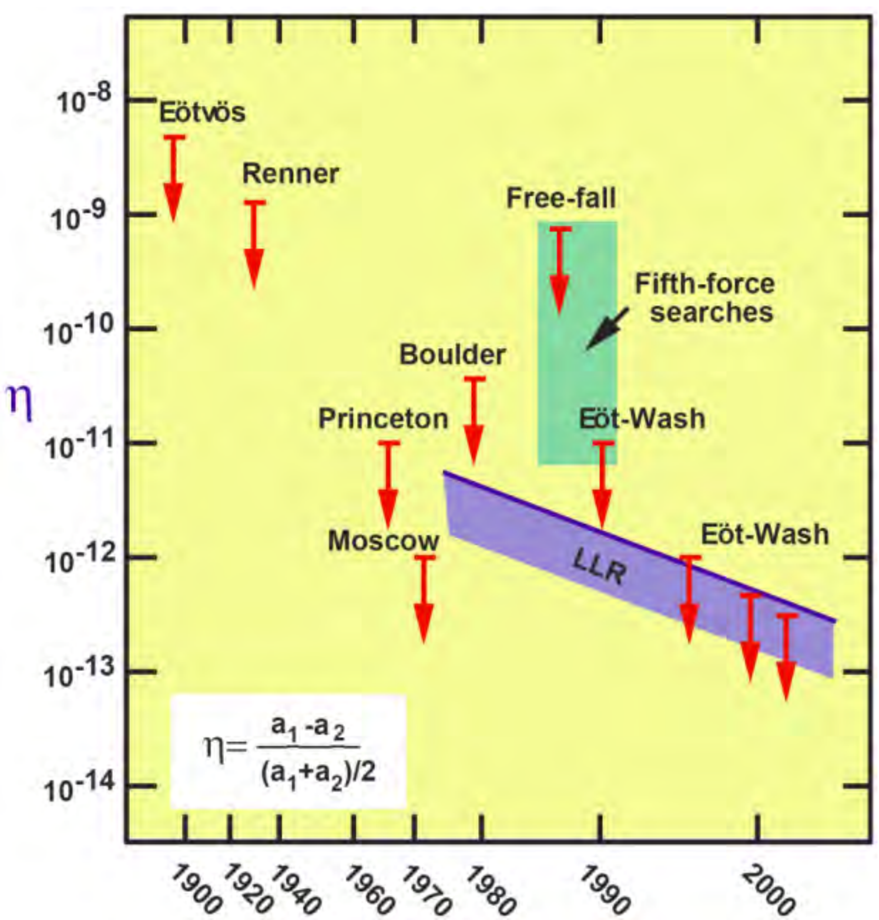
Lunar Laser Ranging



Pendulum experiments



MICROSCOPE



$$\eta = \frac{a_1 - a_2}{(a_1 + a_2)/2}$$

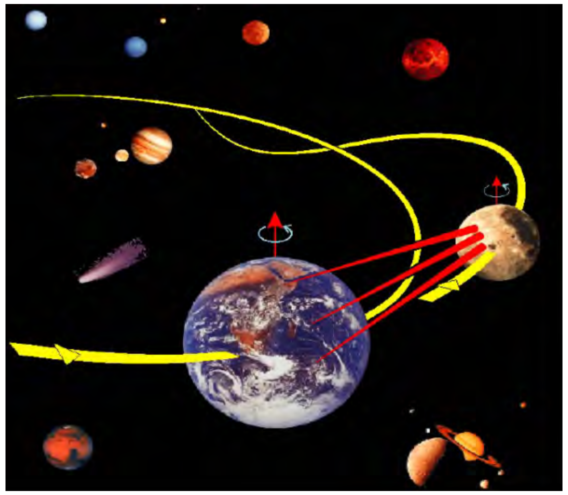
- **Lunar laser ranging**
  $\eta \leq 1.3 \cdot 10^{-13}$ (J.G. Williams *et al.*, PRL 93, 261101 (2004))
- **Torsion balance**
  $\eta \leq 1.3 \cdot 10^{-13}$ (Schlamminger *et al.*, PRL 100, 041101 (2008))

Tests with different de Broglie wavelengths

$$p = m \cdot v = \frac{h}{\lambda}$$

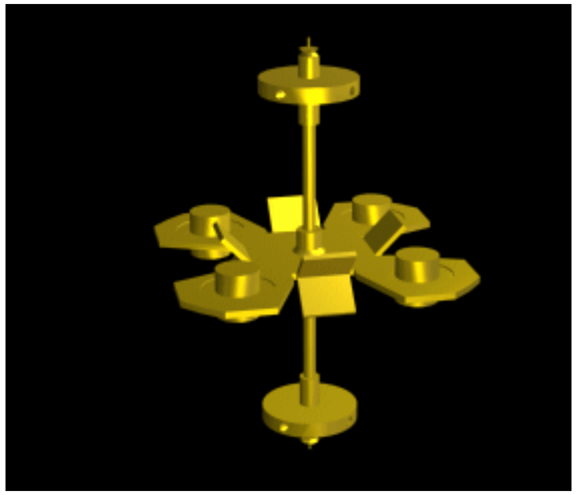
Lunar Laser Ranging

$<< 10^{-50}$ m



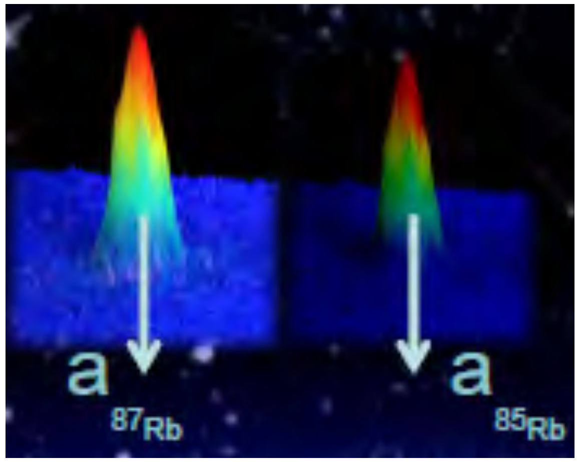
Pendulum experiments

$<< 10^{-23}$ m



Bose-Einstein Condensate

~ 0,01mm



IOP PUBLISHING — CLASSICAL AND QUANTUM GRAVITY
Class. Quantum Grav. **25** (2008) 105012 (10pp) doi:10.1088/0264-9381/25/10/105012

Metric fluctuations and the weak equivalence principle

Ertan Göklü and Claus Lämmerzahl

depends on the type of particle and the fluctuation scenario. The scenario considered in this paper is a most simple picture of spacetime fluctuations and gives an existence proof for an apparent violation of the weak equivalence principle and, in general, for a violation of Lorentz invariance.

$$\left(\frac{m_{\mathrm{g}}}{m_{\mathrm{i}}}\right)^i_p = 1 + \alpha^i_p.$$

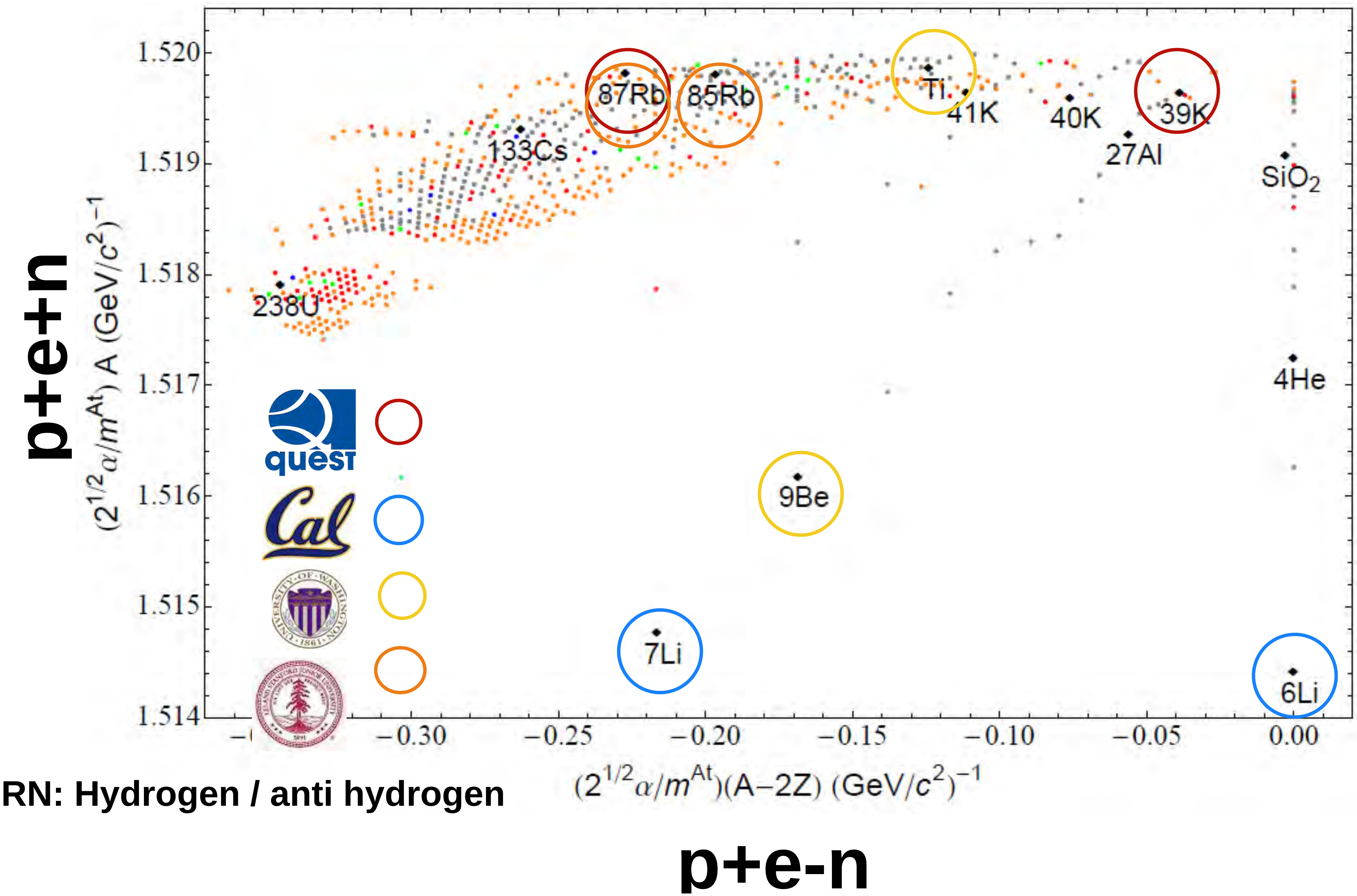
$$\alpha^i_p = \left(\frac{l_{\mathrm{Pl}}}{\lambda_p}\right)^\beta a^{ii}.$$

Quantum tests are
complementary to classical tests

extended parameter range of test theories

$$g^{\mathrm{T}} = g(1+\beta^{\mathrm{T}}), \quad \beta^{\mathrm{T}} \equiv \frac{2\alpha}{m^{\mathrm{T}}}\left(\bar{a}^{\mathrm{T}}_{\mathrm{eff}}\right)_0 - \frac{2}{3}(\bar{c}^{\mathrm{T}})_{00}$$

Hohensee et al., arXiv:1106.2241v1 (2011)



CERN: Hydrogen / anti hydrogen

Many experiments worldwide

– ^{85}Rb vs. ^{87}Rb
  $\eta \leq 1.8 \cdot 10^{-7}$ (S. Fray *et al.*, PRL 93, 240404 (2004))
– ^{133}Cs atom interferometer vs. falling corner cube (FG5)
  $\eta \leq 7 \cdot 10^{-9}$ (A. Peters *et al.*, Nature 400 (1999))

*)See poster by Alexis Bonnin

Group	Species
CERN	Hydrogen / Antihydrogen
	^{6}Li / ^{7}Li
/ ONERA*)	^{85}Rb/ ^{87}Rb
/ U. Bordeaux	$^{(85)/87}$Rb $^{39(40/41)}$K
	Ti/Be

There is also a Kasevich-style fountain experiment constructed in China

Quantum tests with matter waves

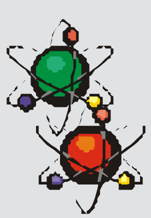
Verifying two pillars of Einsteins Theory

Einstein Equivalence Principle

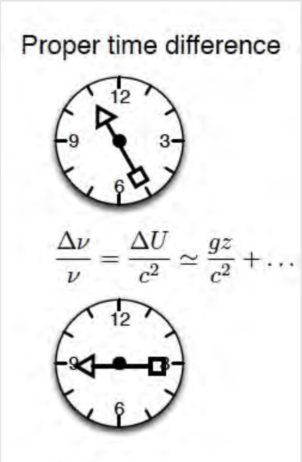
Universality of free fall

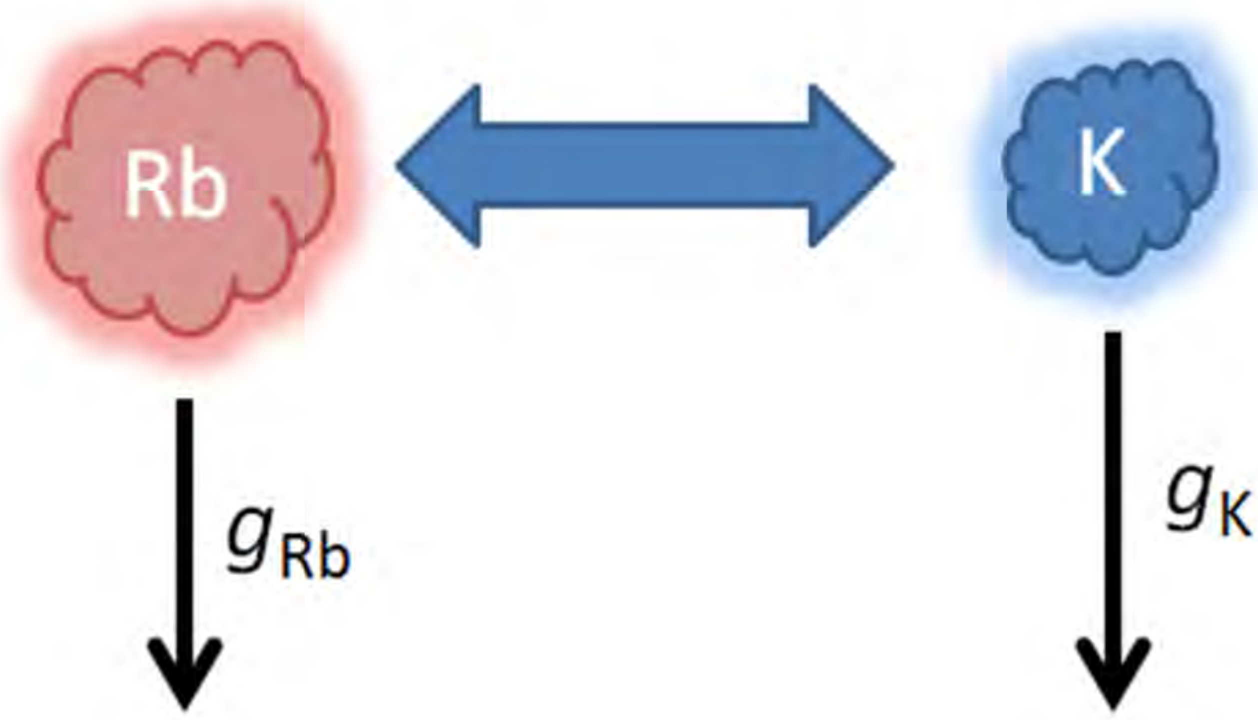
?

Universality of redshift

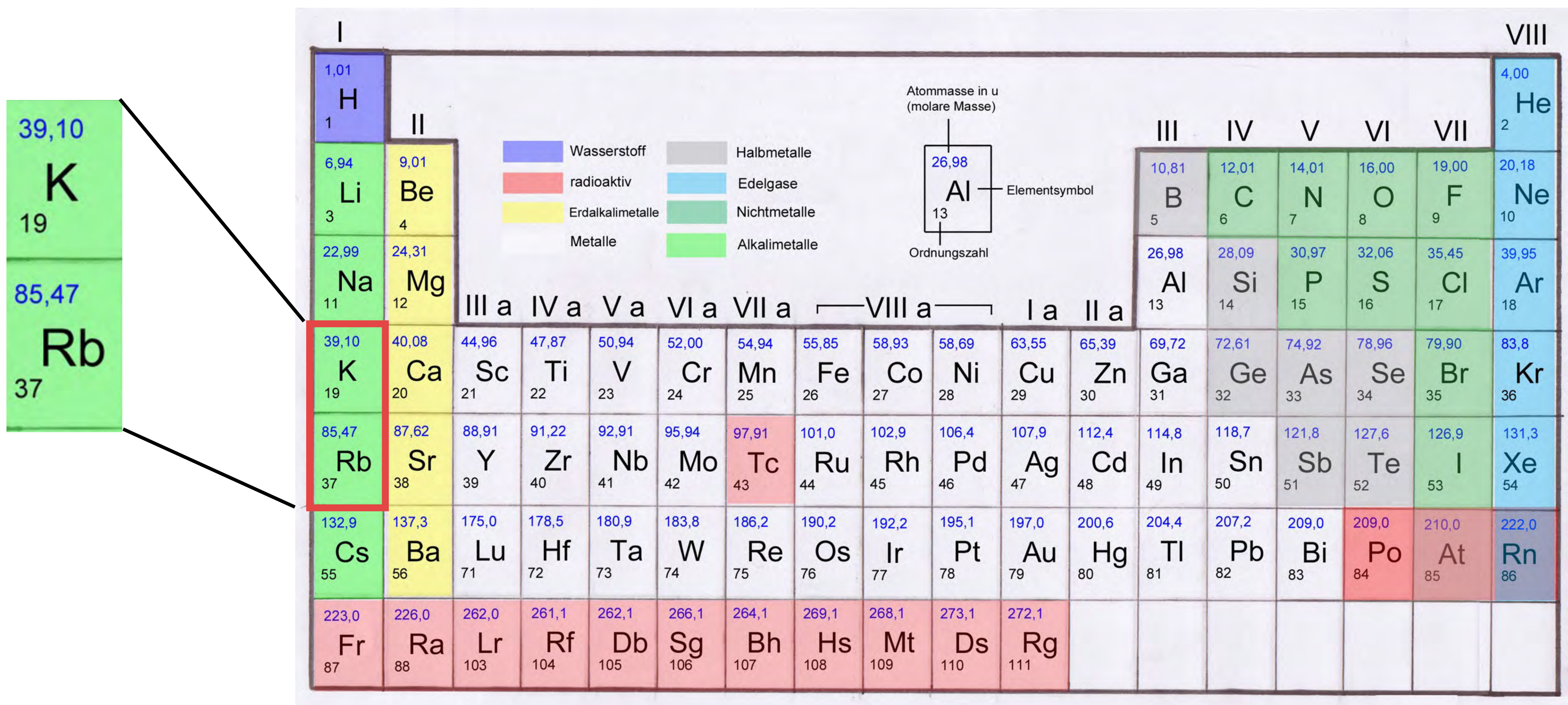


Energy conservation

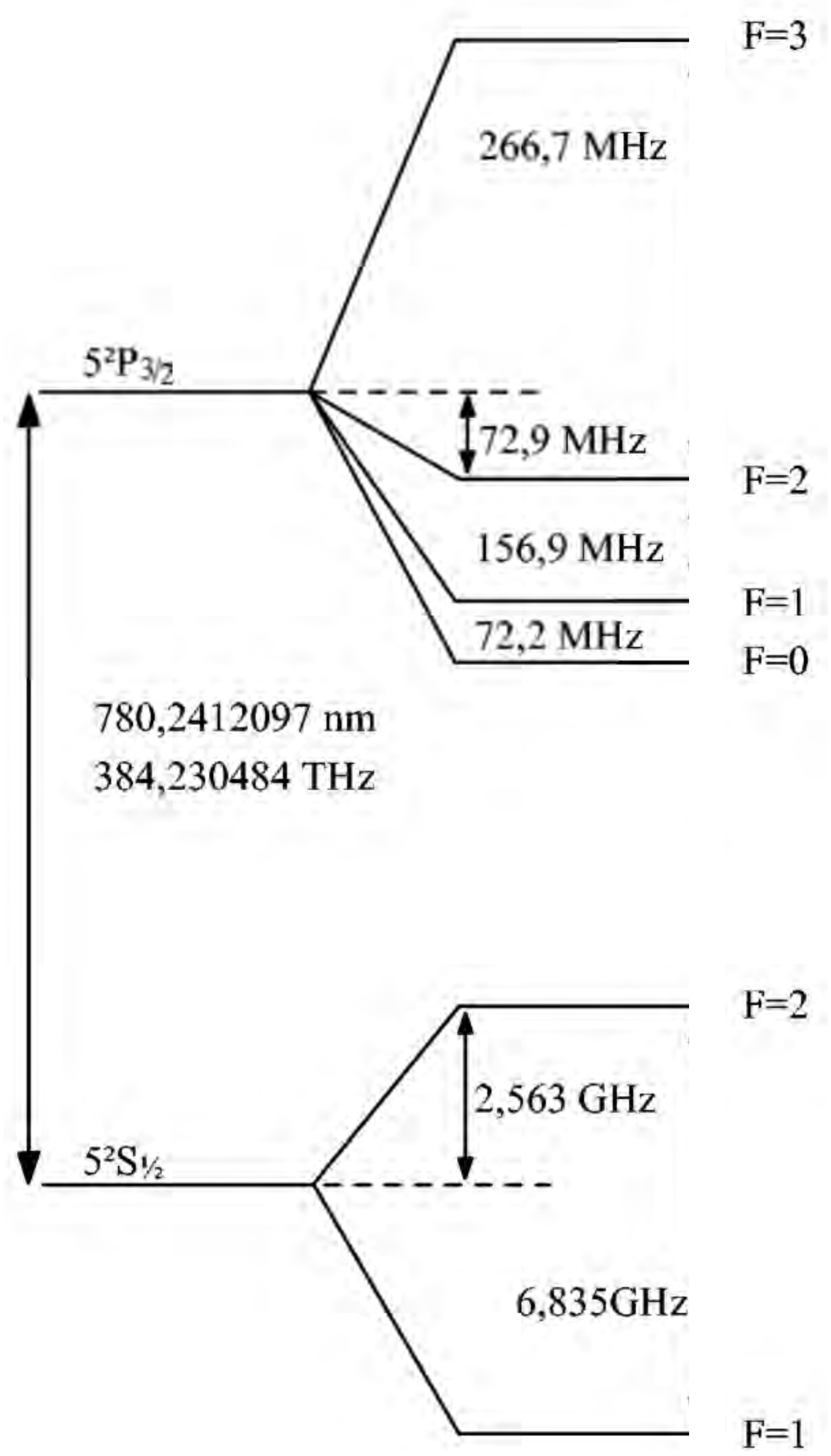




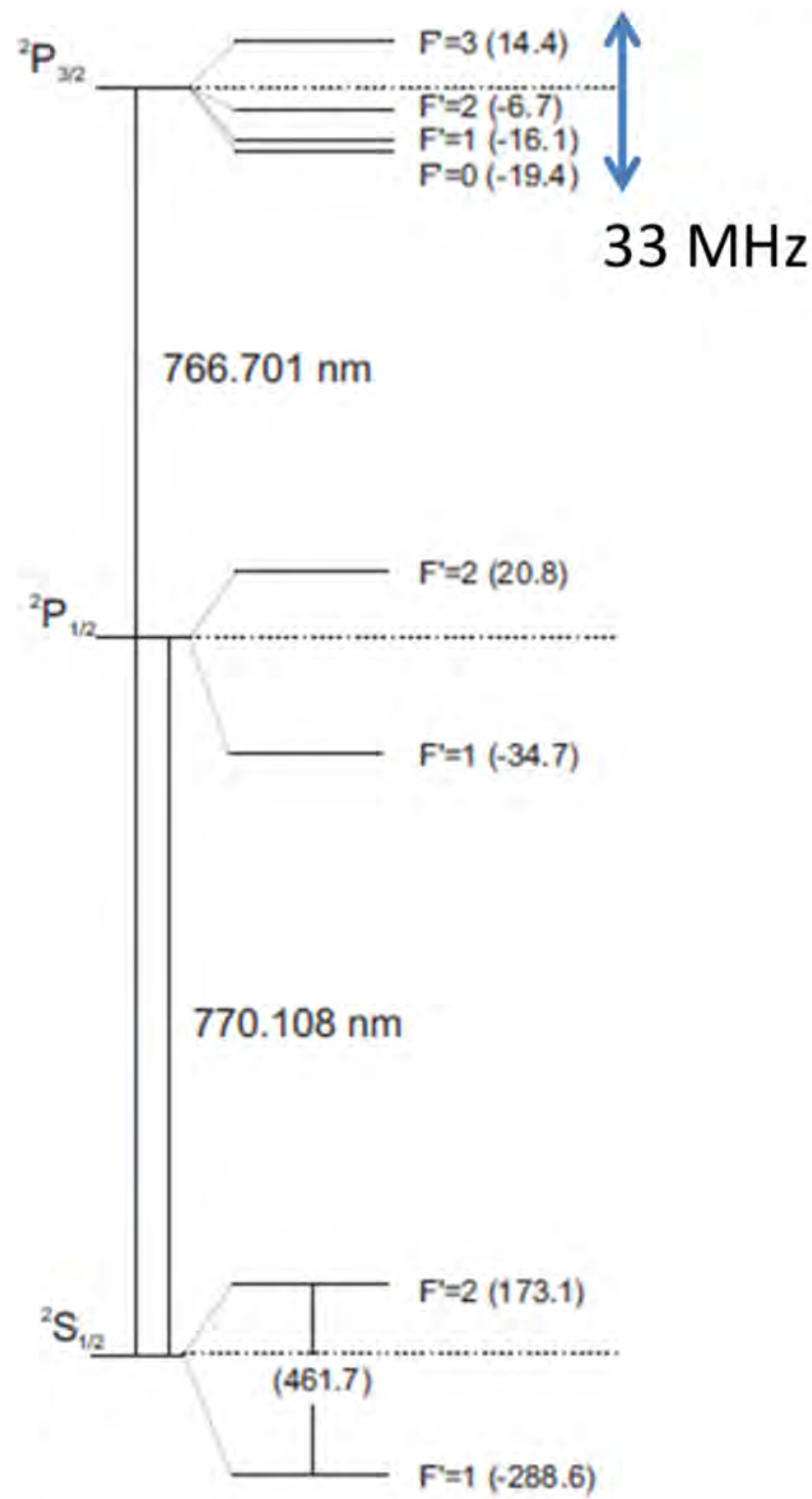
Rb
K
g_{Rb}
g_K



39,10
K
19
85,47
Rb
37
Wasserstoff
radioaktiv
Erdalkalimetalle
Metalle
Halbmetalle
Edelgase
Nichtmetalle
Alkalimetalle
Atommasse in u
(molare Masse)
26,98
Al
13
Elementsymbol
Ordnungszahl
I
II
III
IV
V
VI
VII
VIII
III a
IV a
V a
VI a
VII a
VIII a
I a
II a

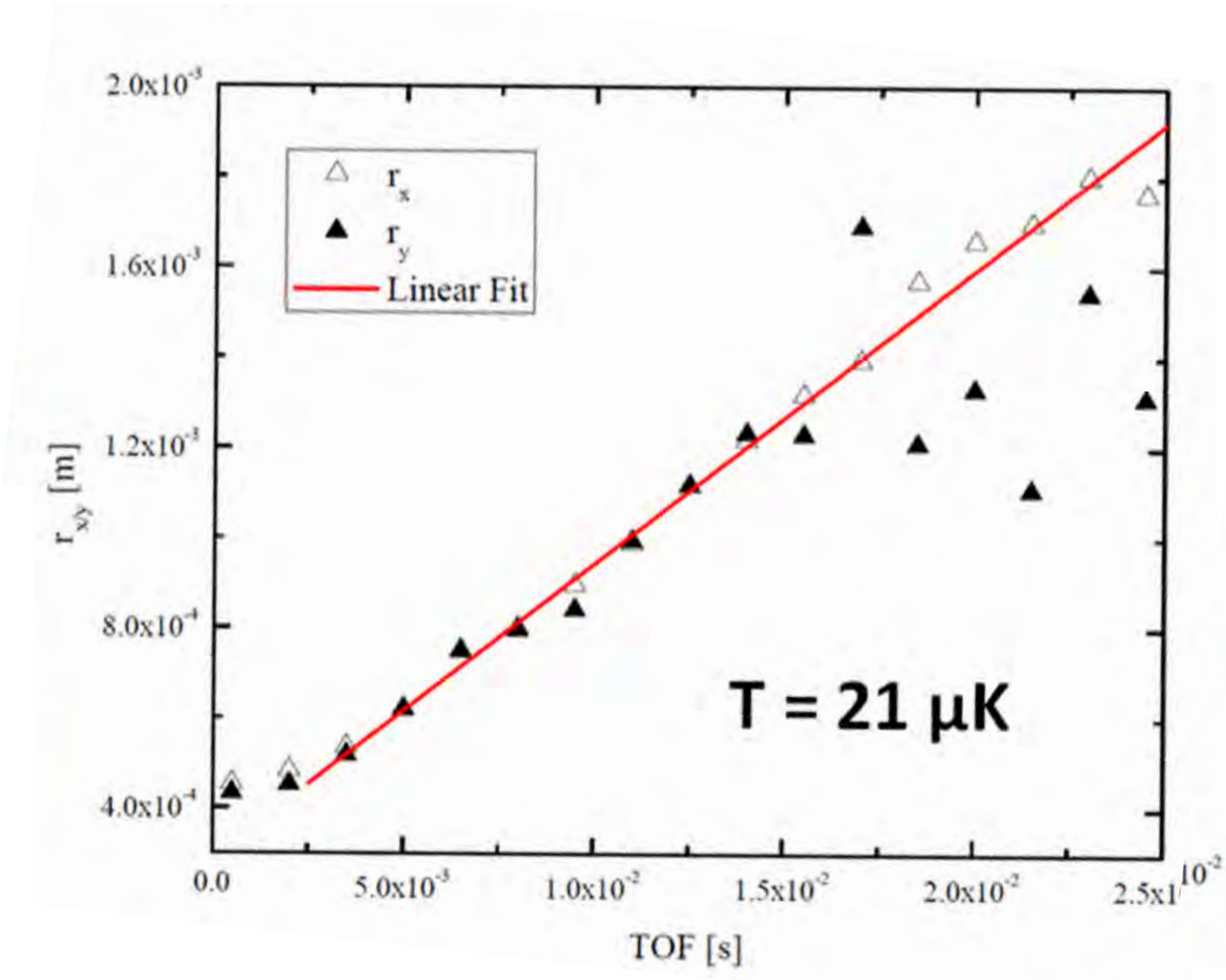


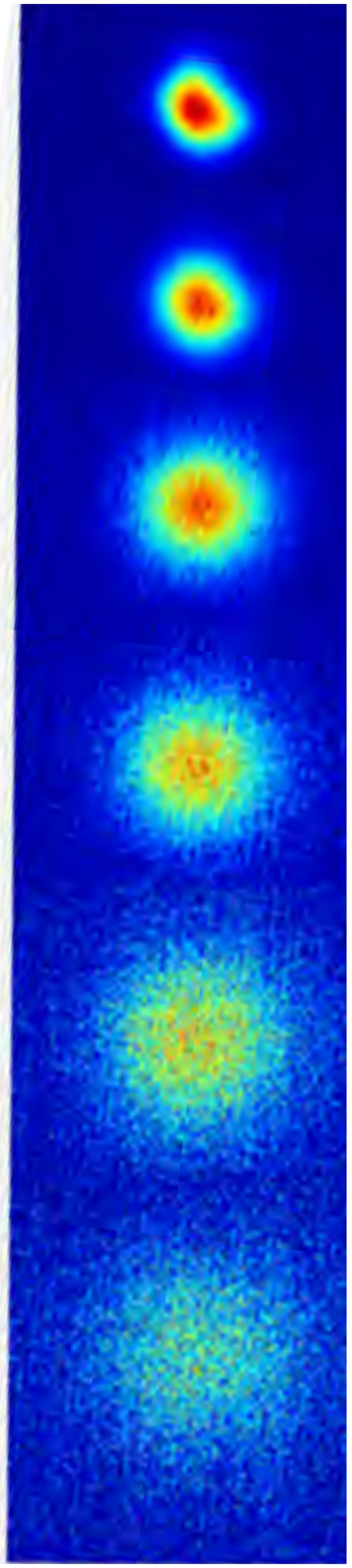
Rubidium



Potassium

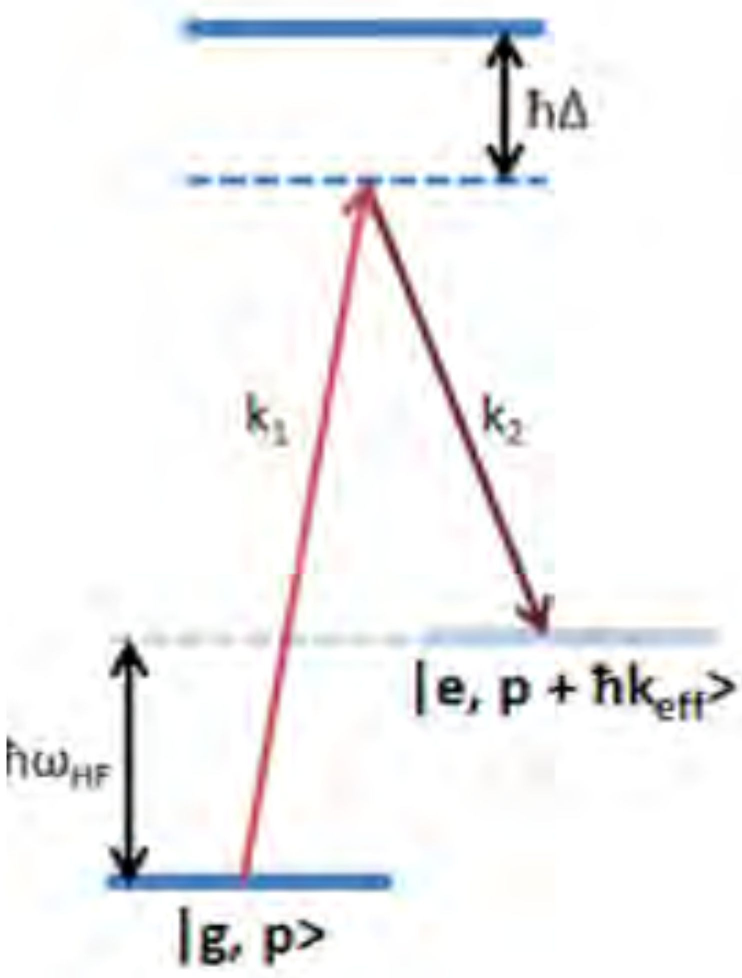
Cooling potassium

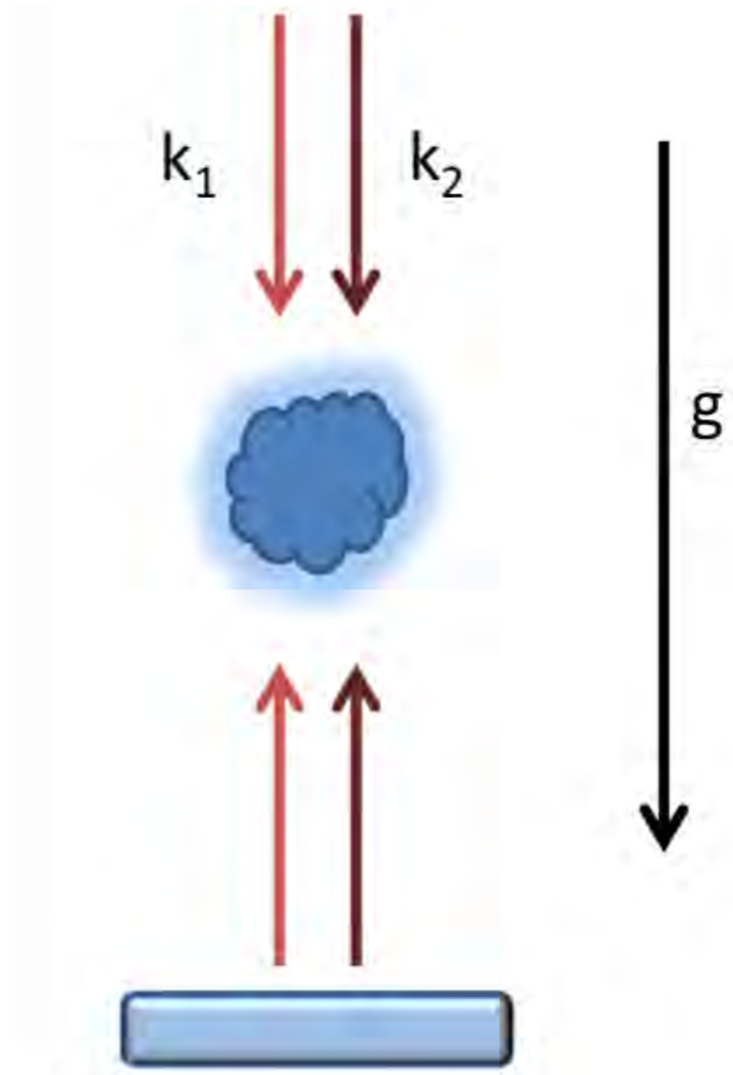




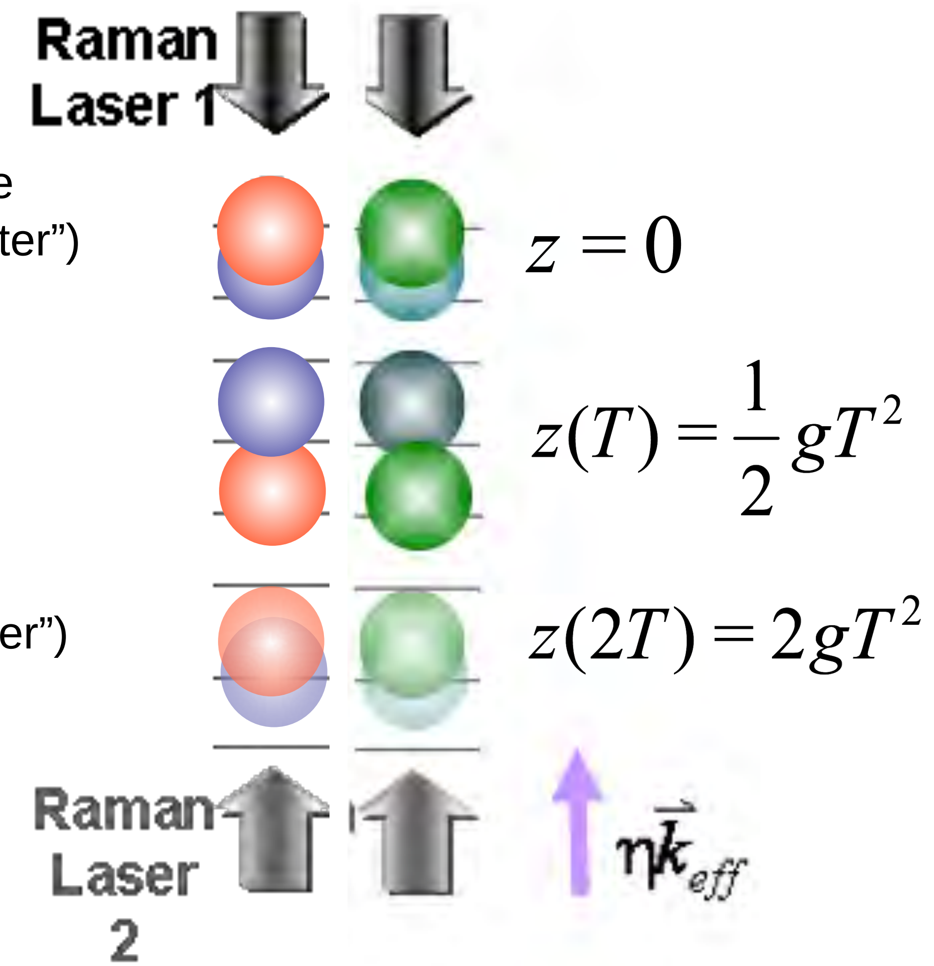
Sub-Doppler cooling: M. Landini, Phys. Rev. A 84, 043432 (2011)

Raman-type beam splitter





Dual atom species interferometer for the EP test with quantum matter (Rb and/or K isotopes)



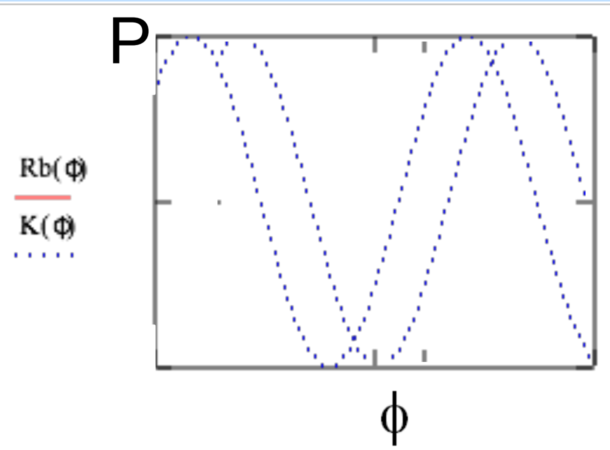
Gravity induced phase shift

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

$$\varphi = k_{eff} g T^2$$

$$P_{Rb} = A \sin(\varphi) + B$$

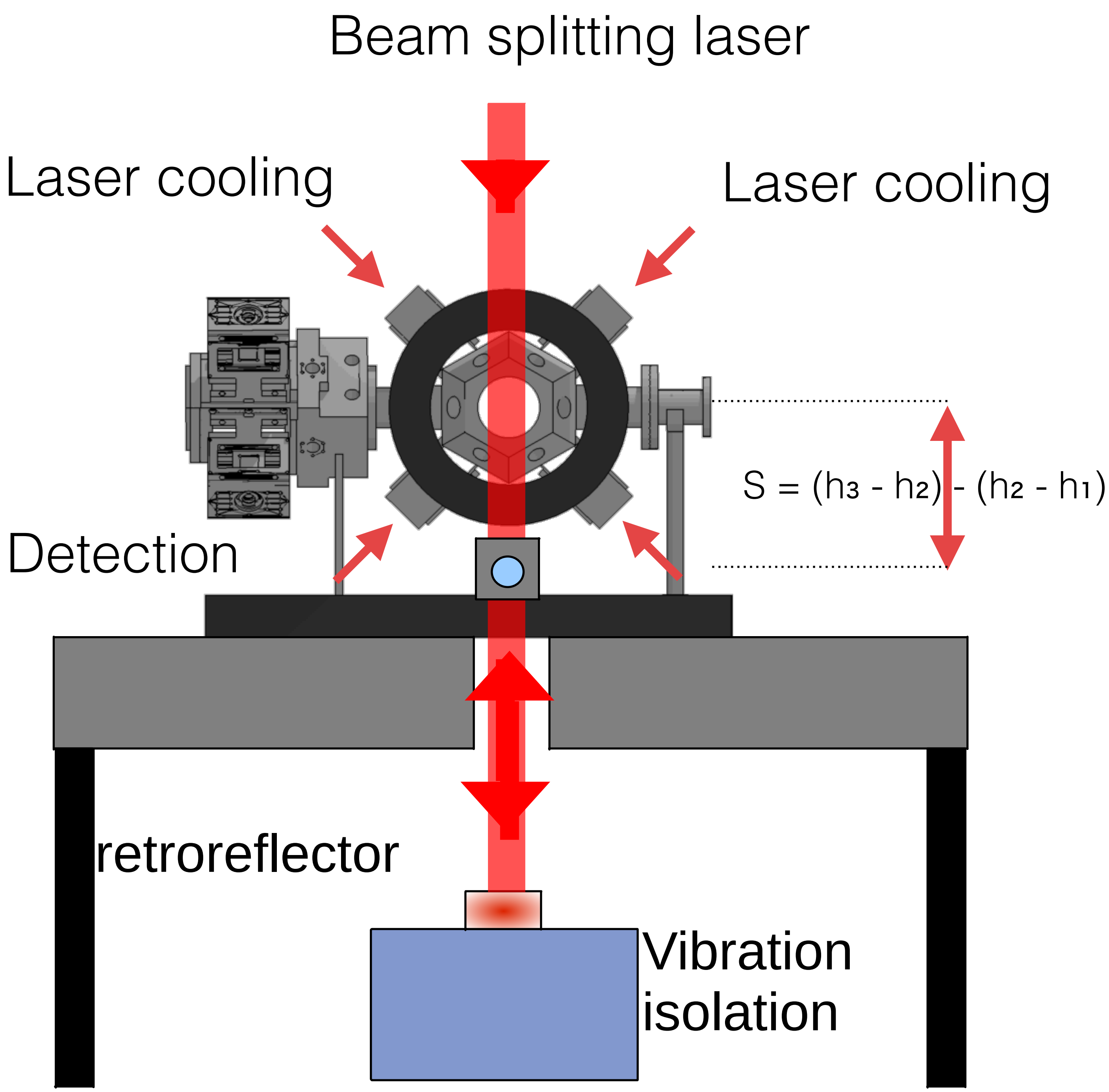
$$P_K = C \sin(\varphi + \Delta\varphi) + D$$



$$\Delta\varphi \neq 0$$

<u>If EEP is violated</u>

Set-up of an dual atom interferometer at IQ to test the Einstein principle of equivalence



Noisy and unstable environment

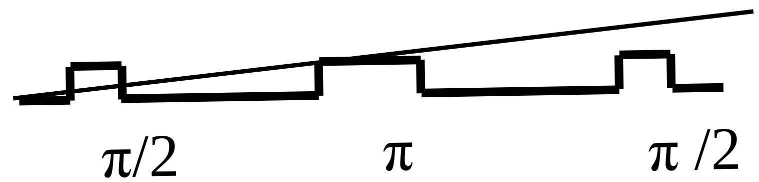
Frequency chirp to simulate free fall

- Free fall → Doppler shift of the resonance

condition of the Raman transition

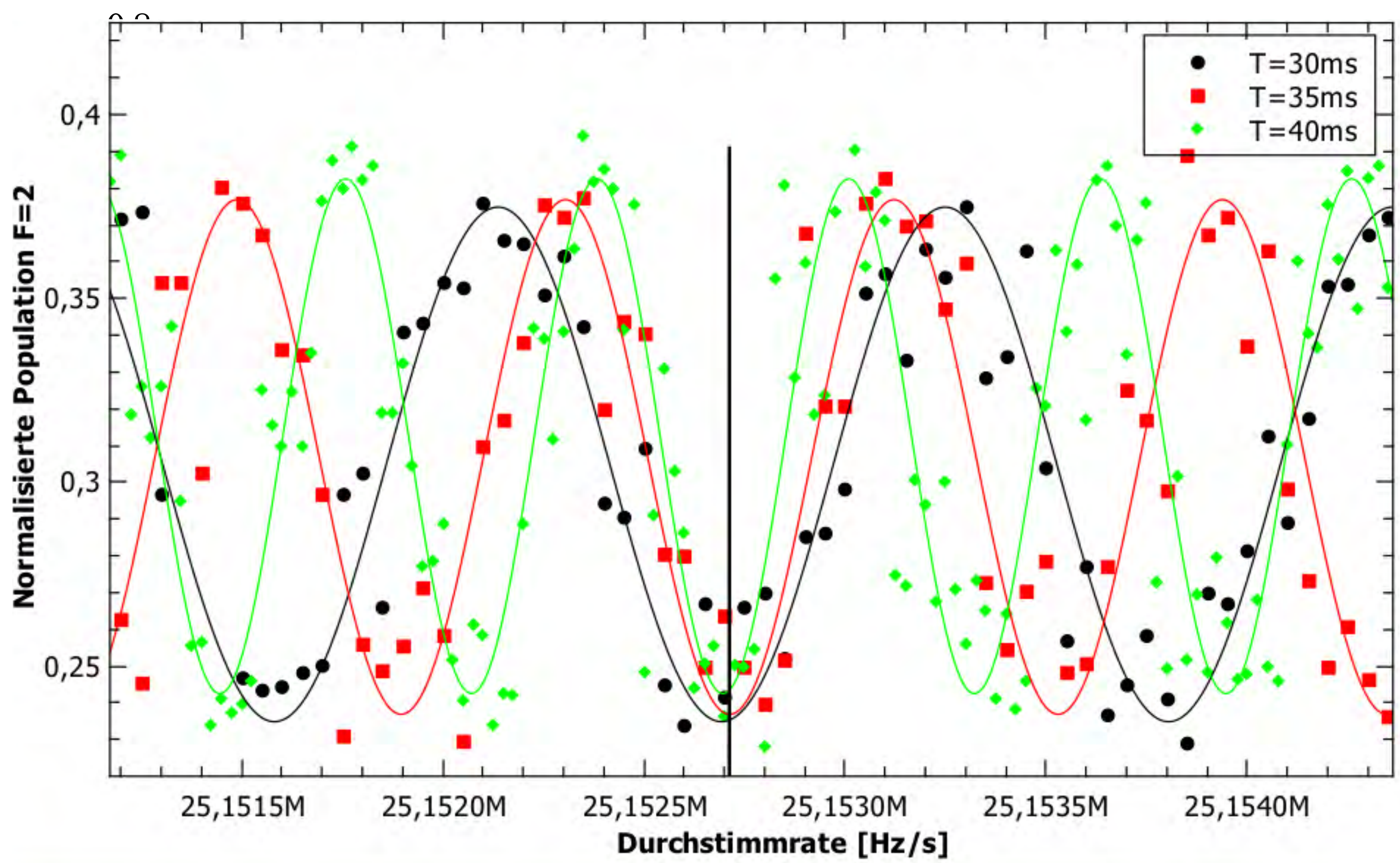
$$\delta(\vec{v}) = \overrightarrow{k_{eff}}.\vec{v} = \overrightarrow{k_{eff}}.(\vec{g}\,t + \vec{v_0})$$

$$\Rightarrow \Delta\Phi = k_{eff}.g.T^2 - \alpha T^2$$

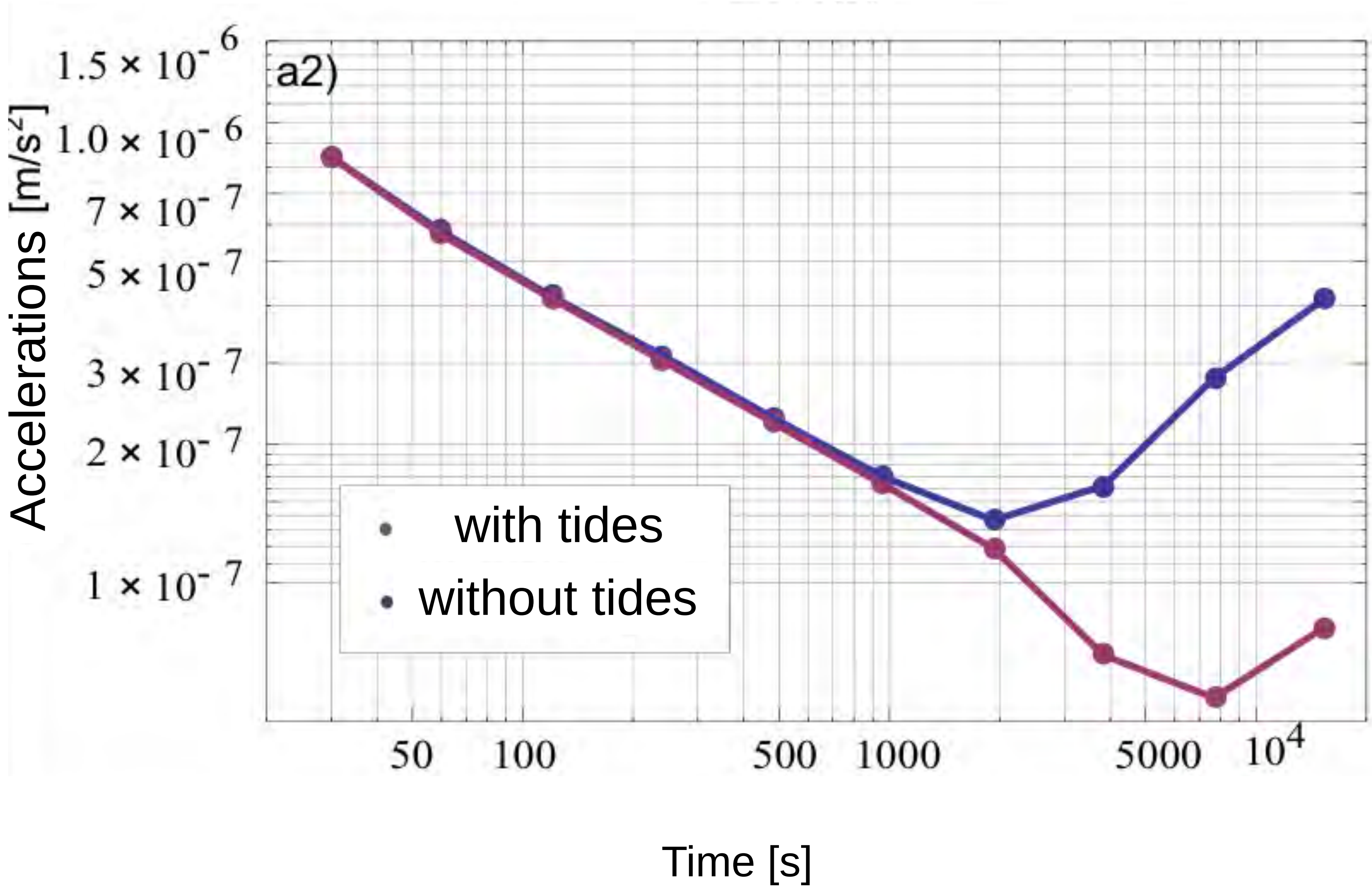


- Dark fringe : independent of T

$$g = \frac{\alpha_0}{k_{eff}}$$



Rb gravimeter operated during weekends



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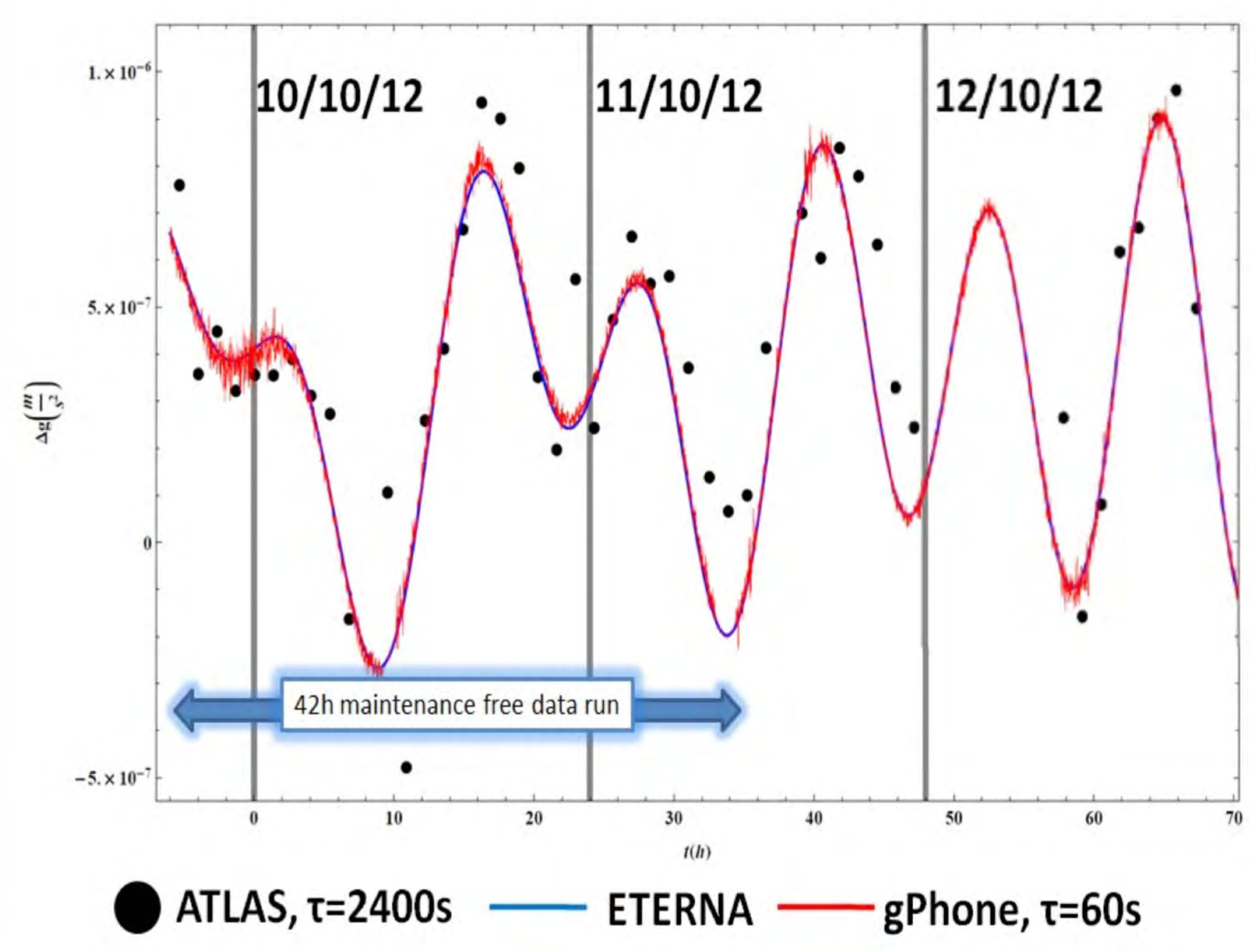
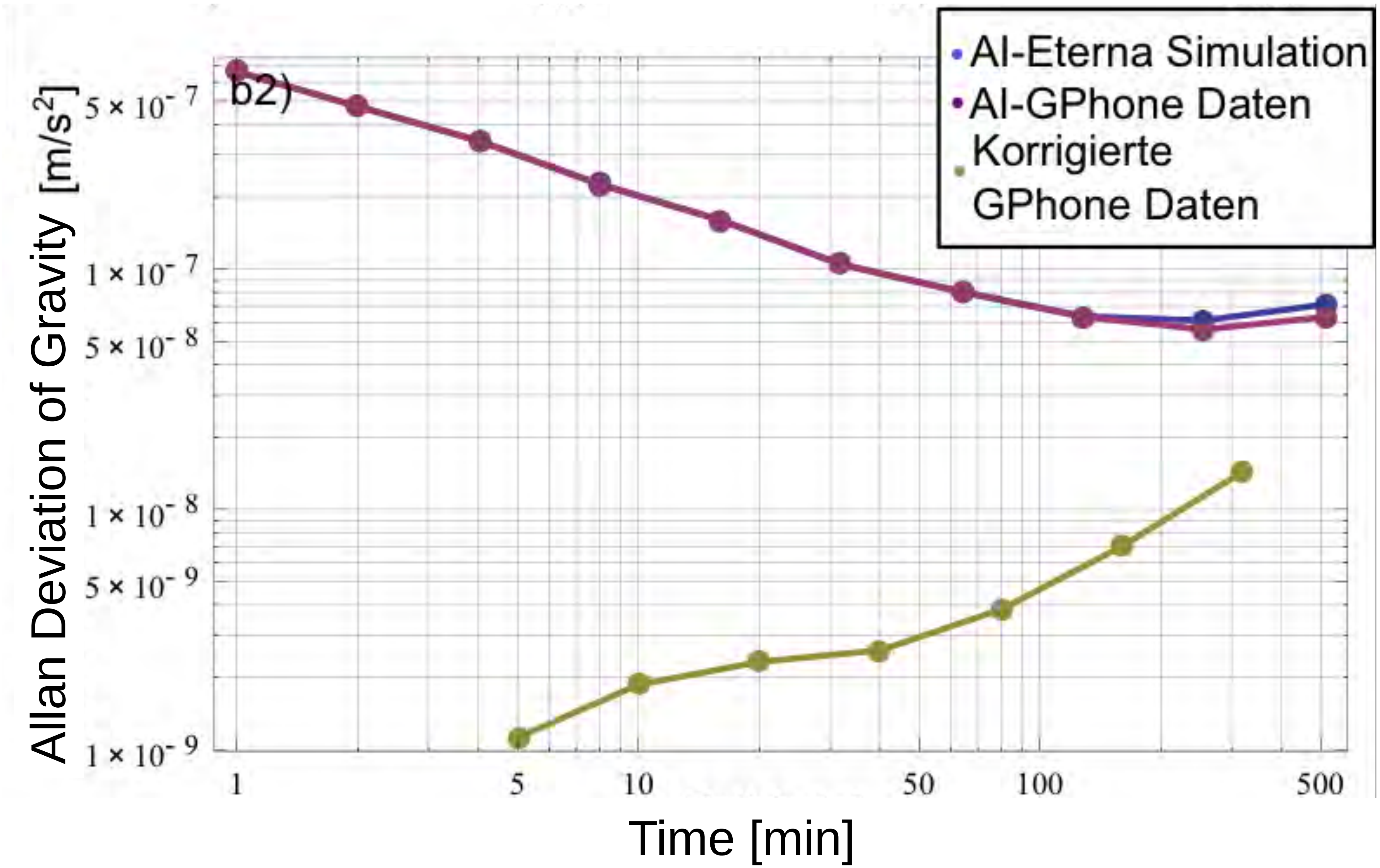
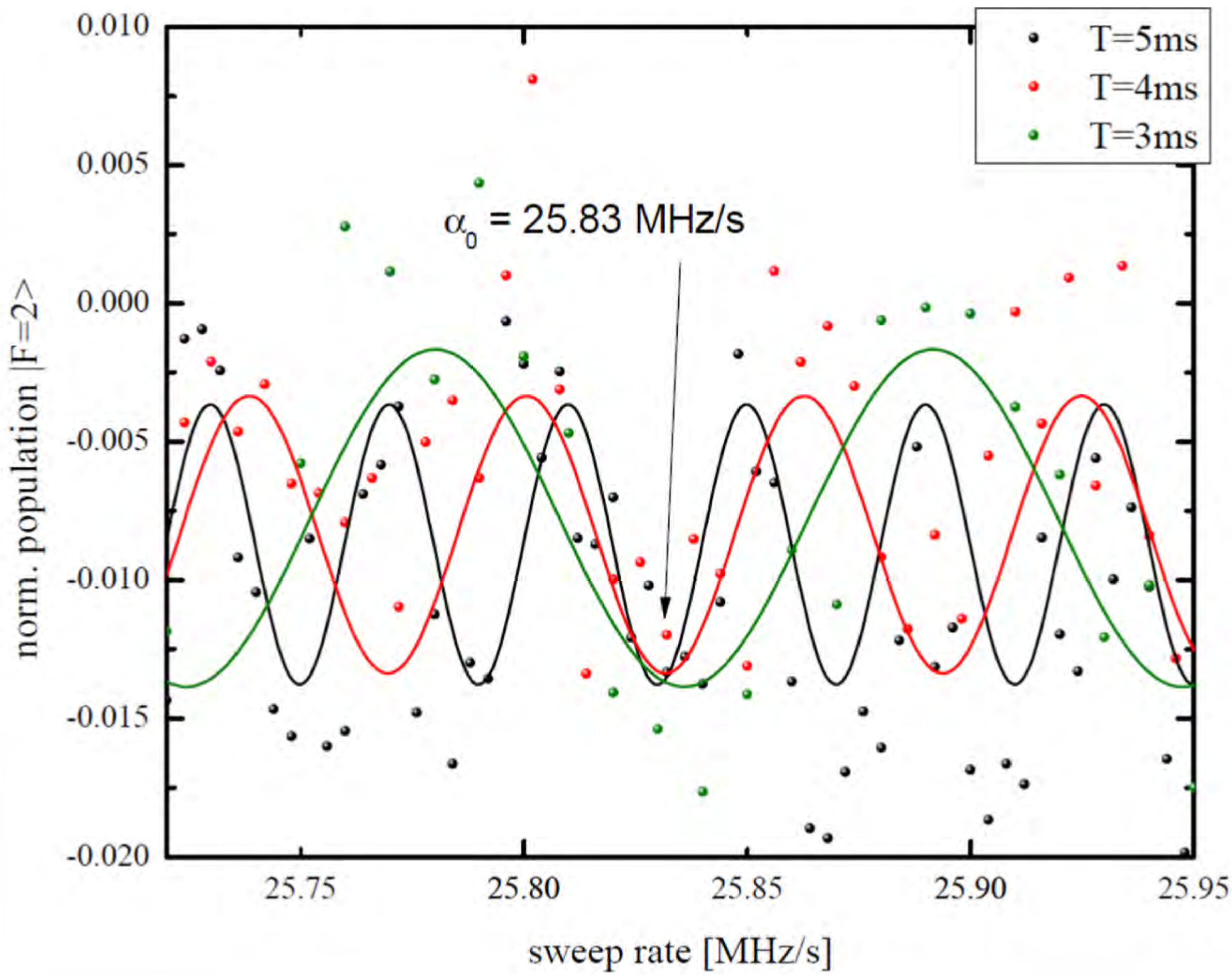


Rb gravimeter compared with GPhone



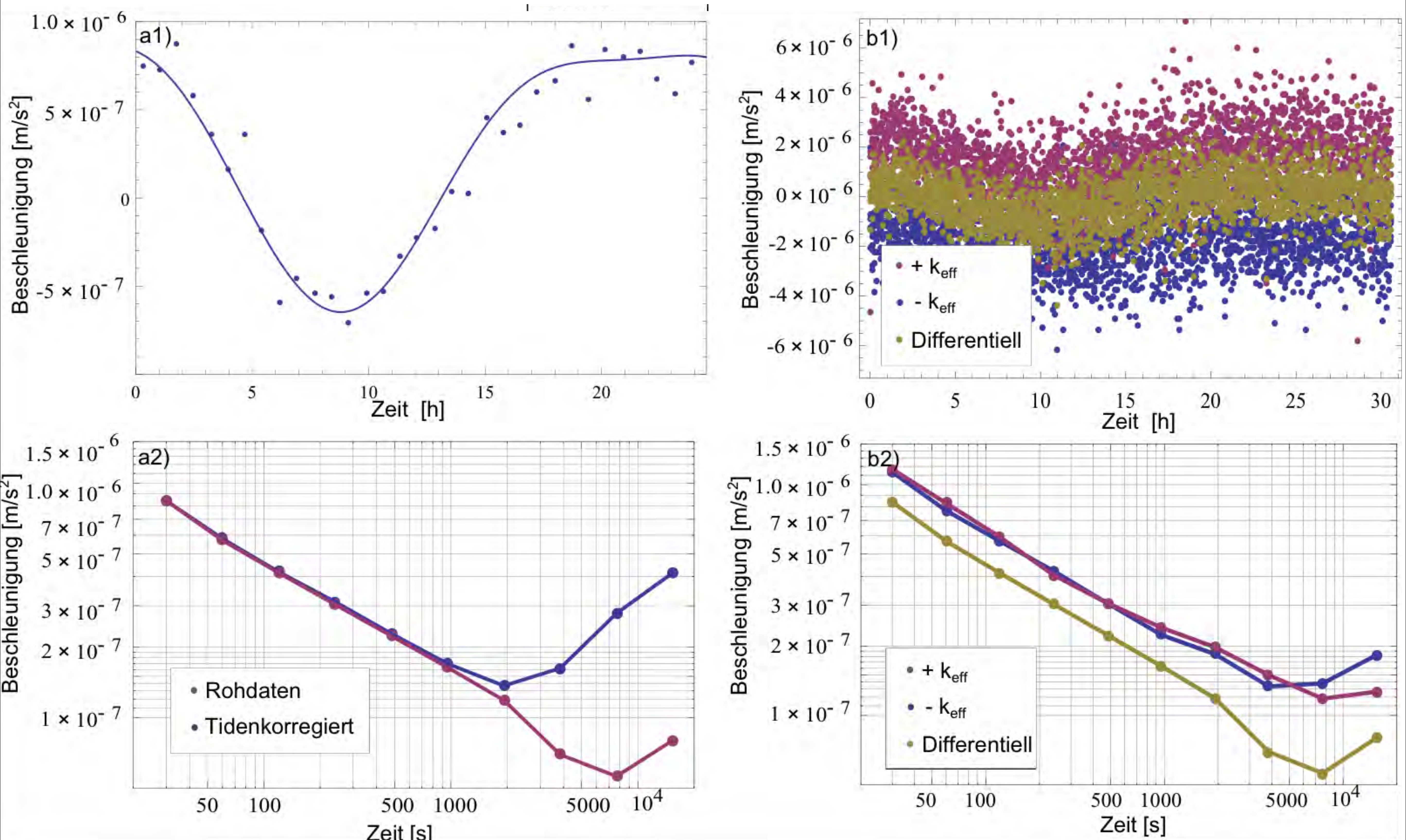
- Comparisons with GPhone provided by J. Flury (IfE)
- Short term stability limited by environmental noise

First inertial sensitive AI using ^{39}K



First steps to test the weak equivalence principle.
Targeted sensitivity $\leq 10^{-9}$

Rb gravimeter operated during weekends



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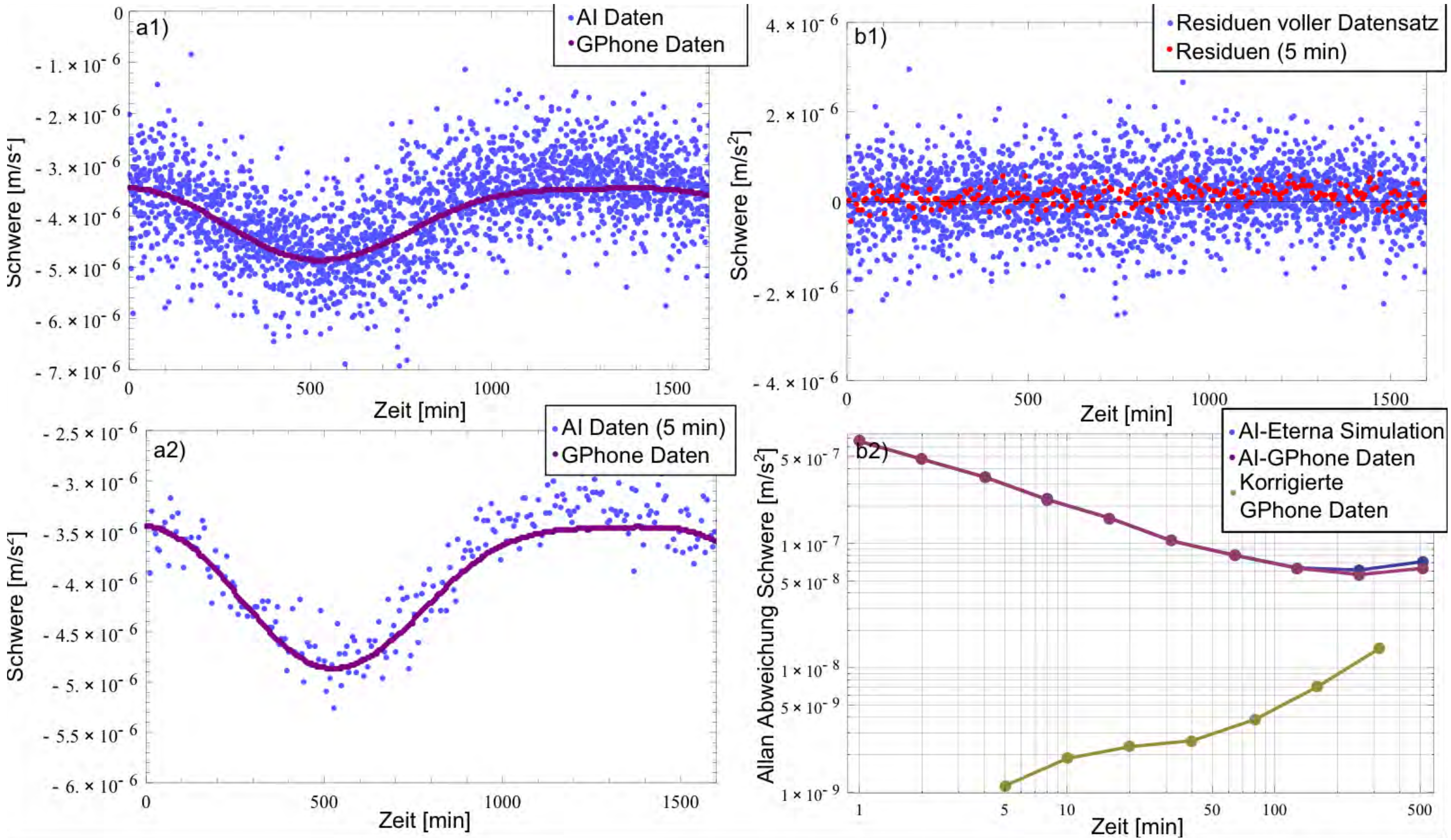


- Comparisons with GPhone provided by J. Flury (IfE)
- Short term stability limited by environmental noise

Take home messages

- Clocks and matter wave interferometer test two aspects of the Einstein principle of equivalence:

  "2 sides of the same medal"

- Matter wave interferometry extend the range of test parameters (Holger Müller and Mike Hohensee)
- Matter-wave tests are yet orders of magnitude off from classical tests
- New devices will enhance the sensitivity by extending free fall: J. Hogan / M. Kasevich, ICE, QUANTUS experiment at the drop tower

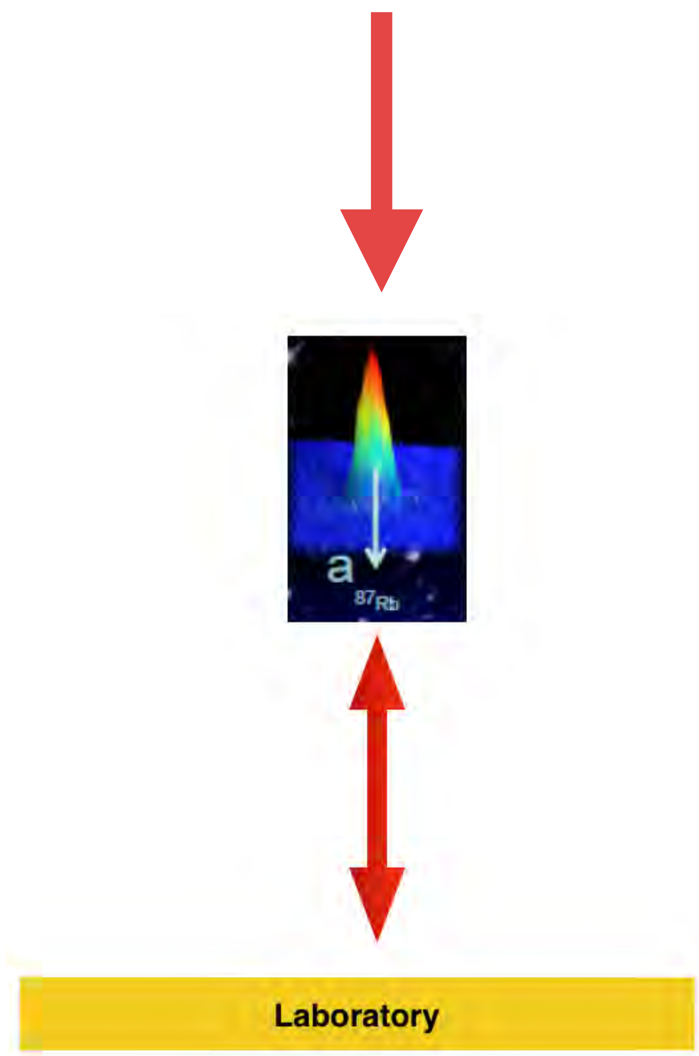
Perspectives

Very Long Baseline Atom Interferometry

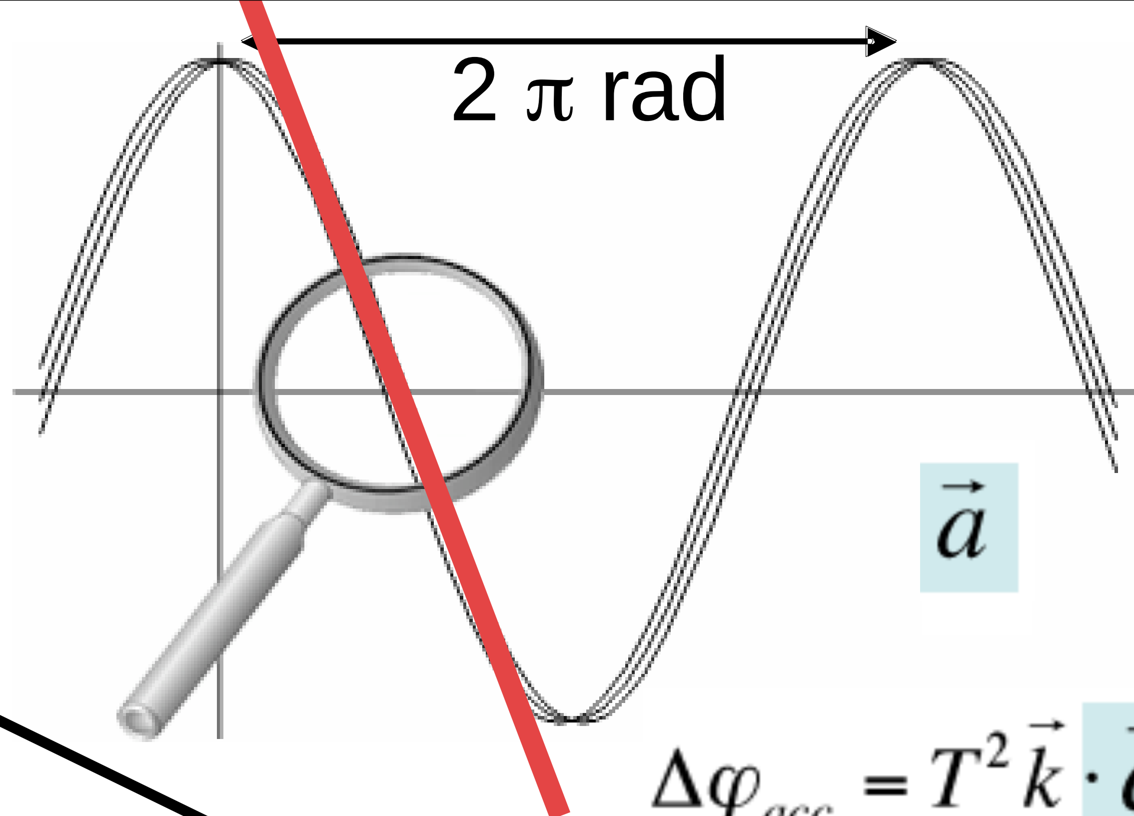
On Ground and in Microgravity

Sequence for an atom interferometer

Prepare atoms	Laser cooling Select the non-magnetic Zeeman state Launch or drop atoms	0.1-1 s
Perform Interferometry	Raman or Bragg type process	0.1 - ? s
Detect atoms	Fluorescence / absorption Detection	0.01 s
Check systematics	Change parameters	



$$(\Delta\Omega)^2 = (\Delta\varphi)^2 / (\frac{\partial\varphi}{\partial\Omega})^2$$



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

Minimising phase noise

- Increasing number of atoms
- Beating the shot noise
- Environmental control
- Ultrastable lasers (frequency, intensity)

Increasing sensitivity

- Long interaction times
  → large atomic mass
- ultra cold atoms
- Coherence
- Large momentum transfer

The importance of sub-recoil energies & spatial mode features

Systematics - inhomogeneities

- Gravity gradients and rotations
- Convolution of the matter wave and light mode
- Wave curvature
- Control of the centre-of-mass motion
- Detection

Signal to noise

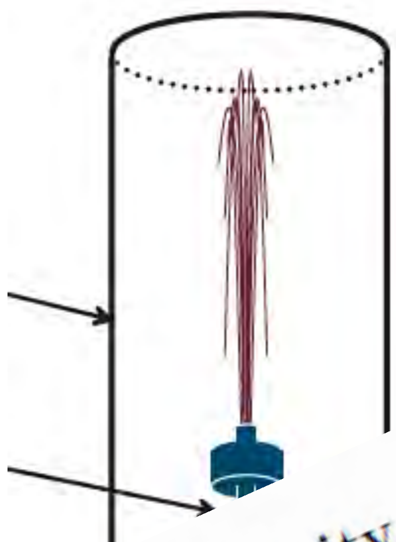
- Efficiency of large momentum beam splitter
- Beating the shot noise

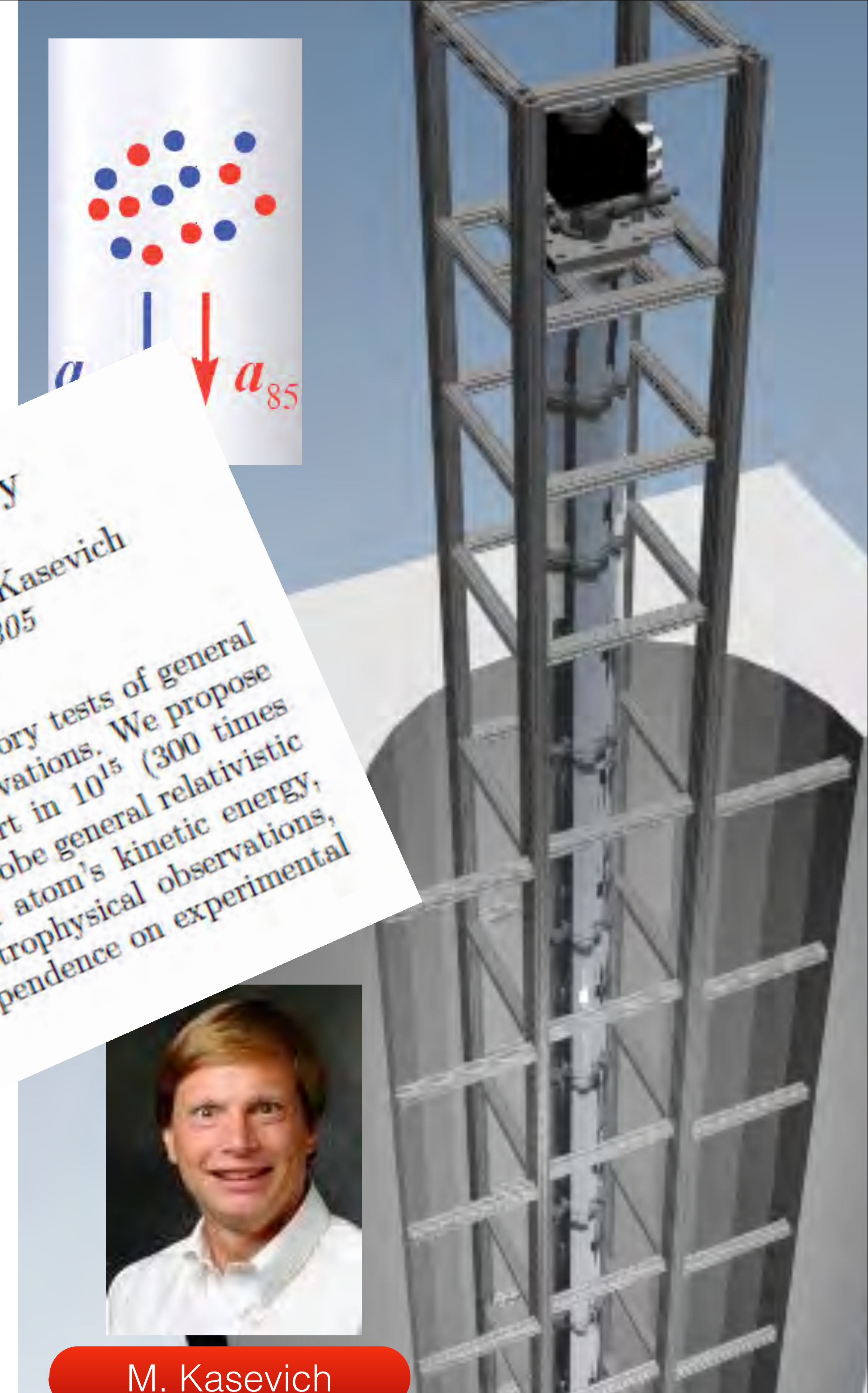
} **Ultracold (nK, pK) atoms**

Coherent optics

Fountains & Drop facilities

From 1 to 10 m high atom drop tower





Testing General Relativity with Atom Interferometry

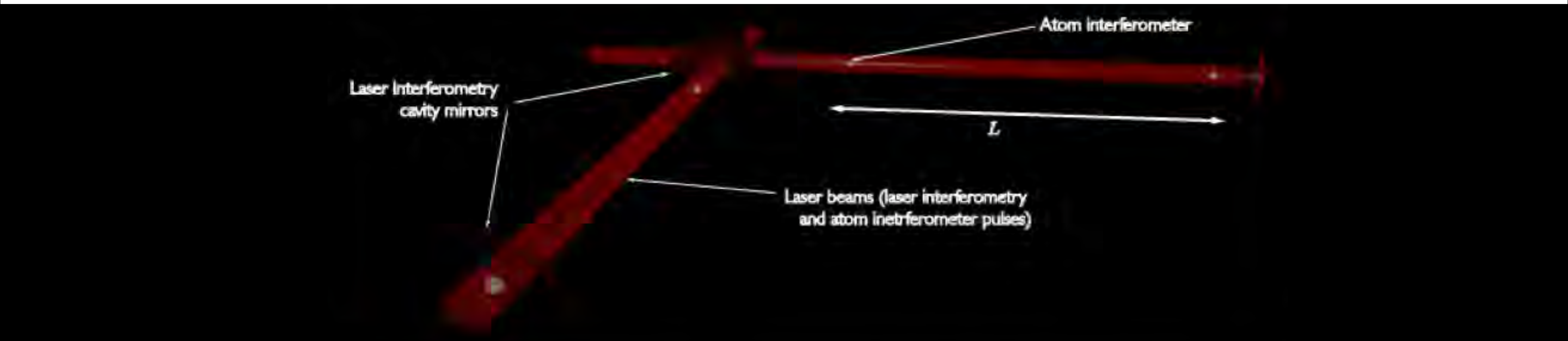
Savas Dimopoulos, Peter W. Graham, Jason M. Hogan, and Mark A. Kasevich
Department of Physics, Stanford University, Stanford, California 94305

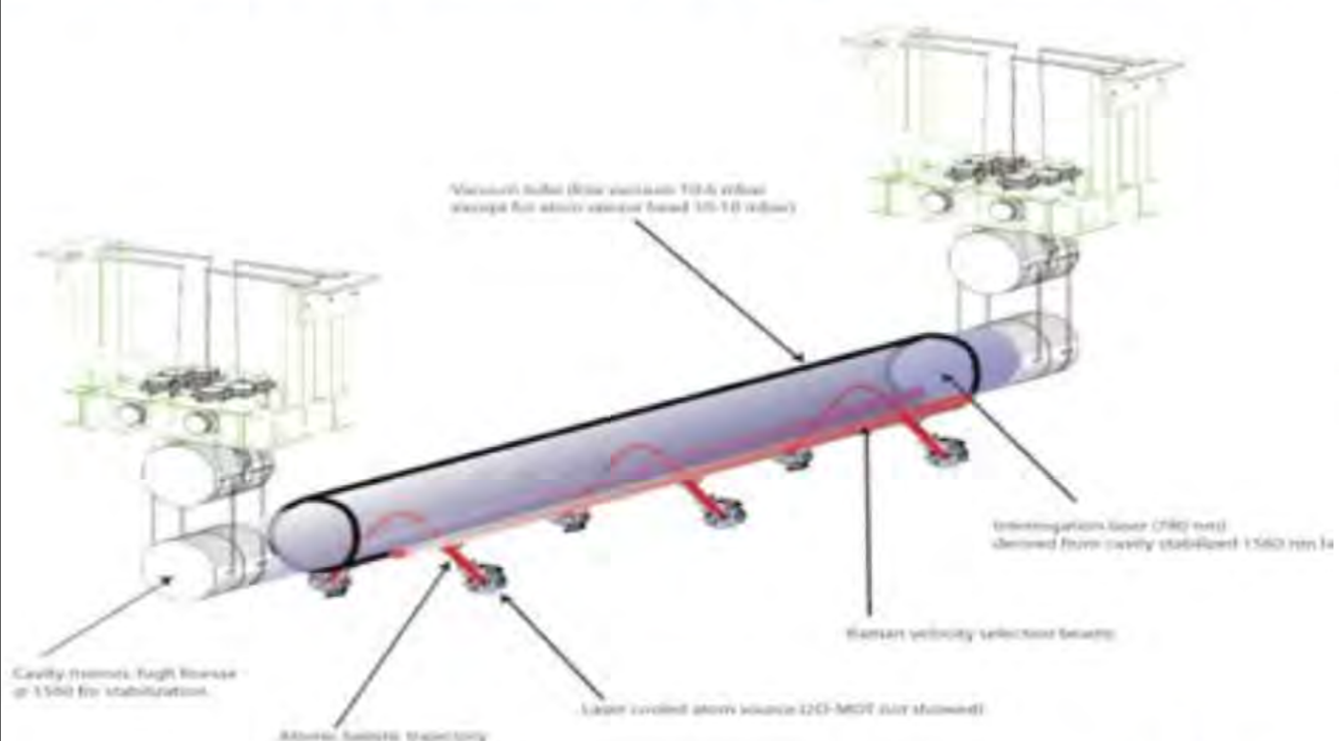
(Dated: October 11, 2006)

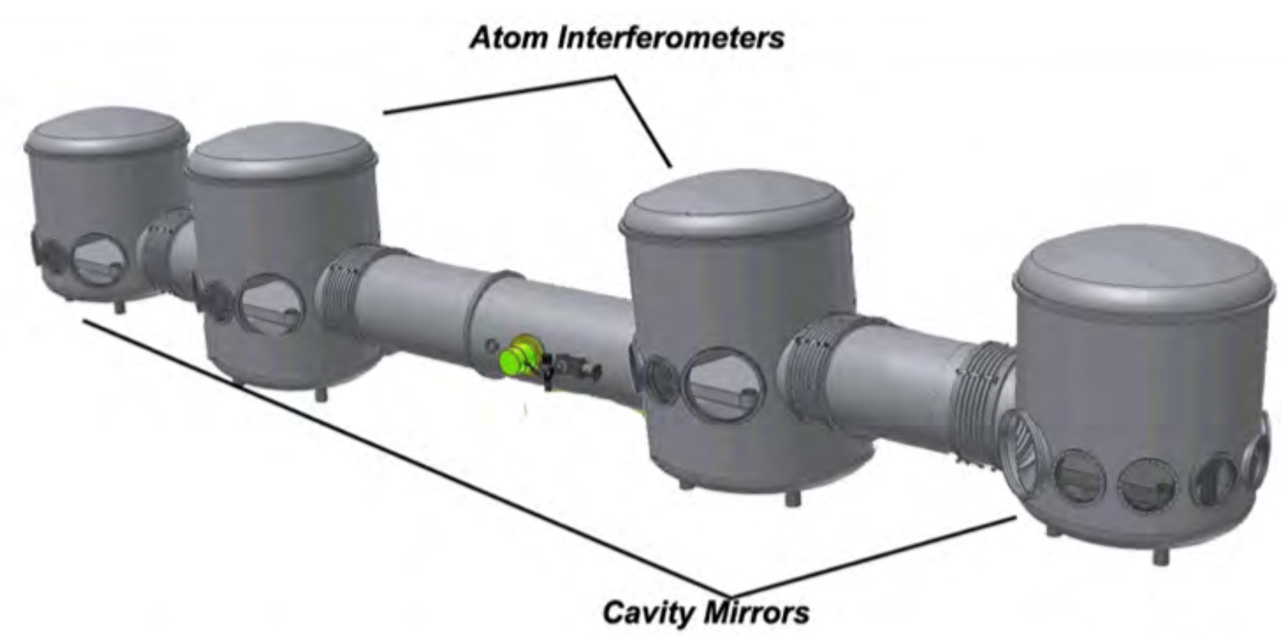
The unprecedented precision of atom interferometry will soon lead to laboratory tests of general relativity to levels that will rival or exceed those reached by astrophysical observations. We propose such an experiment that will initially test the equivalence principle to 1 part in 10^{15} (300 times 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, laboratory tests can isolate these effects via their different functional dependence on experimental variables.

M. Kasevich

MIGA France (PI P. Bouyer, U. Bordeaux)







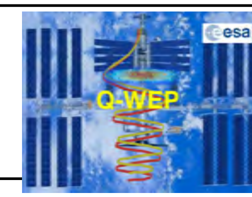
Perspectives

VLBAI in Microgravity

Platforms for experiments in extended free fall

platform	µg-quality [g]	µg-duration
High Fountaines	-	-
droptower Einstein elevator	10^{-6}	4.8 s, 9s with catapult
ISS	10^{-4}	days to months
space carrier	10^{-6}	3 days
airplanes	10^{-2}	20 seconds
ballistic rockets	10^{-5}	up to 6 minutes
satellite	10^{-6}	2-5 years





INSTITUT d'OPTIQUE GRADUATE SCHOOL

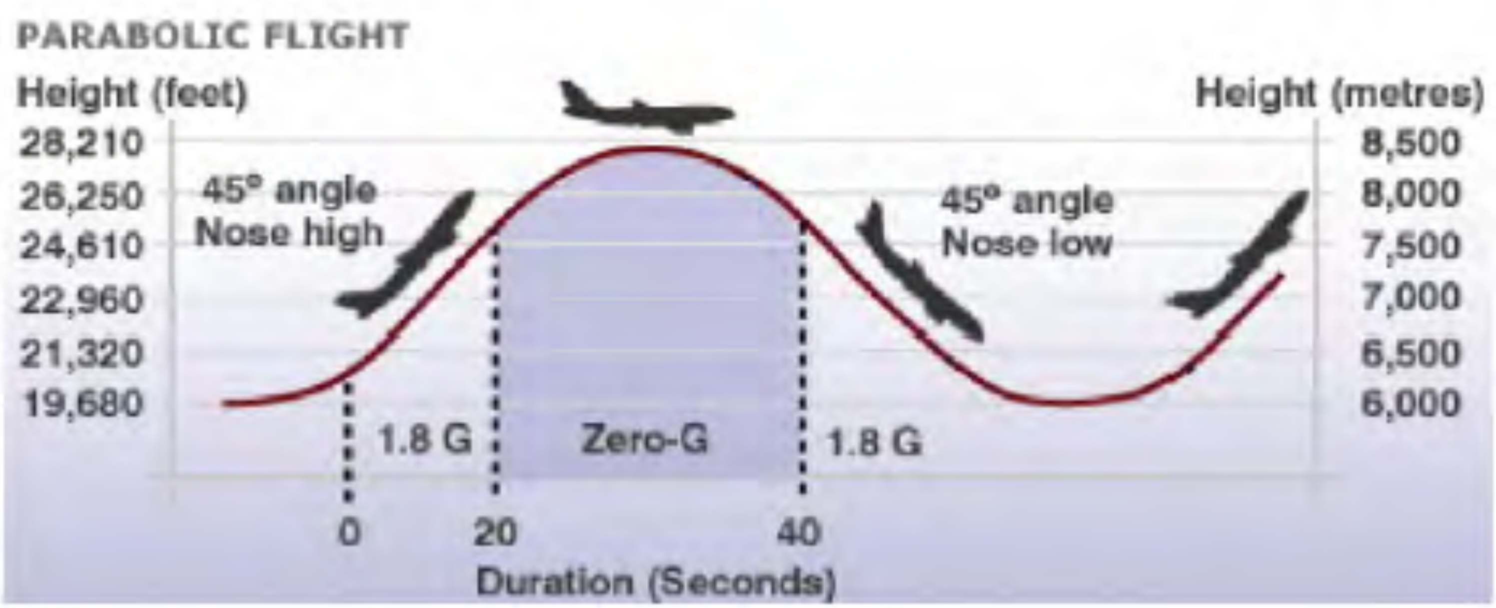
AIRBORNE ATOM SENSORS : FROM GROUND TO SPACE

P. BOUYER

Laboratoire Charles Fabry de l'Institut d'Optique, Palaiseau, France

UNIVERSITÉ PARIS-SUD 11

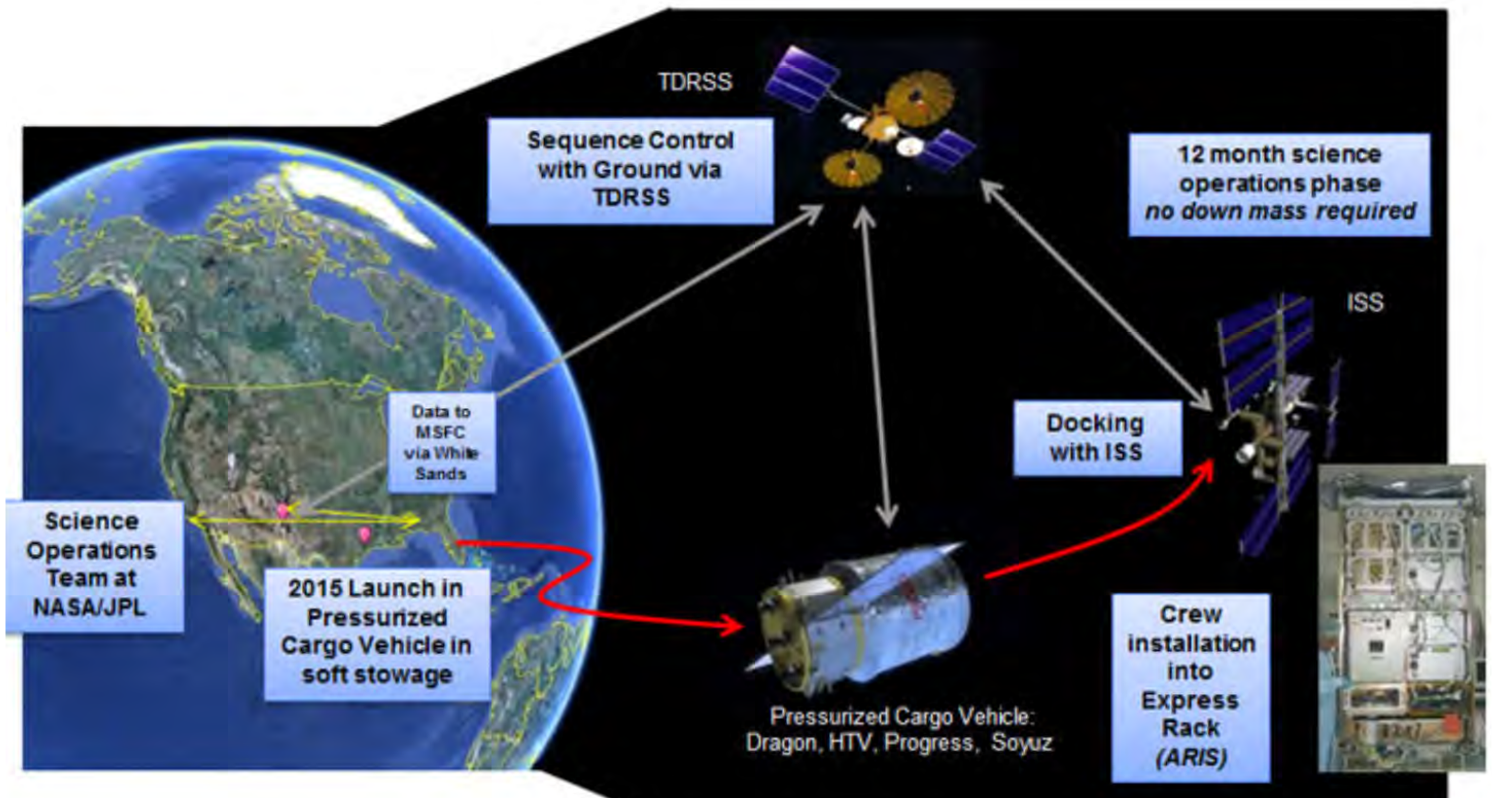
First tests in March 2007 : 500 parabolas since then

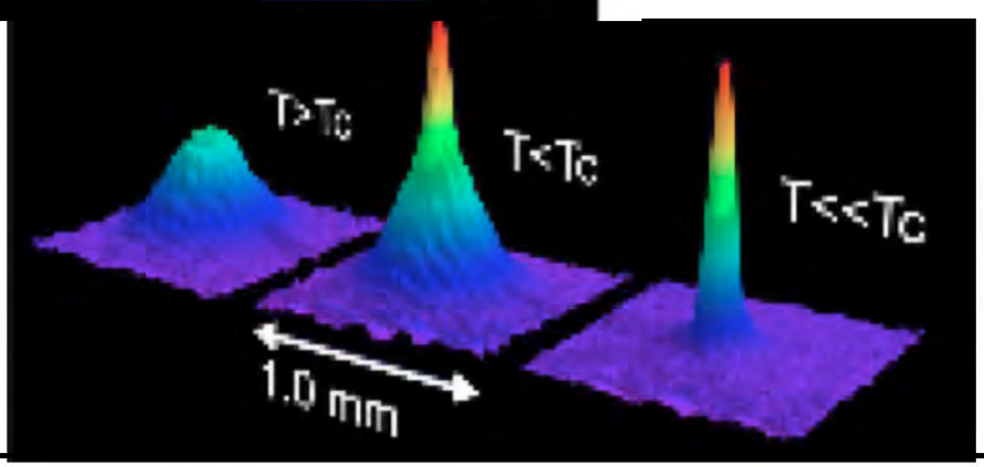


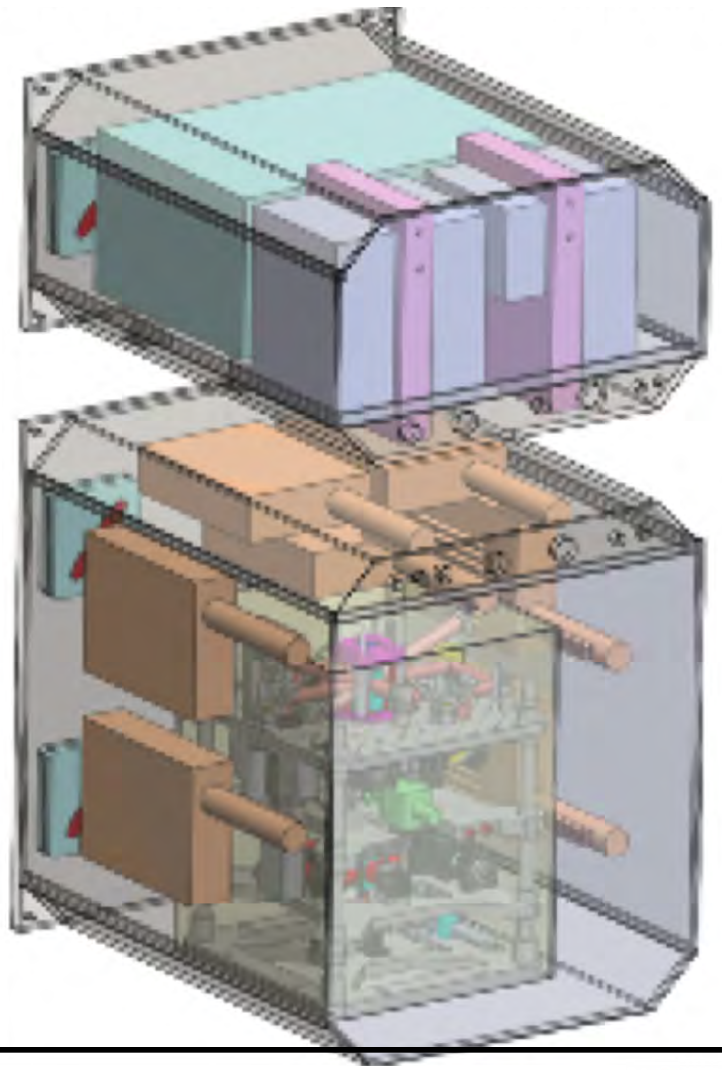
Perspectives

Jet Propulsion Laboratory
California Institute of Technology

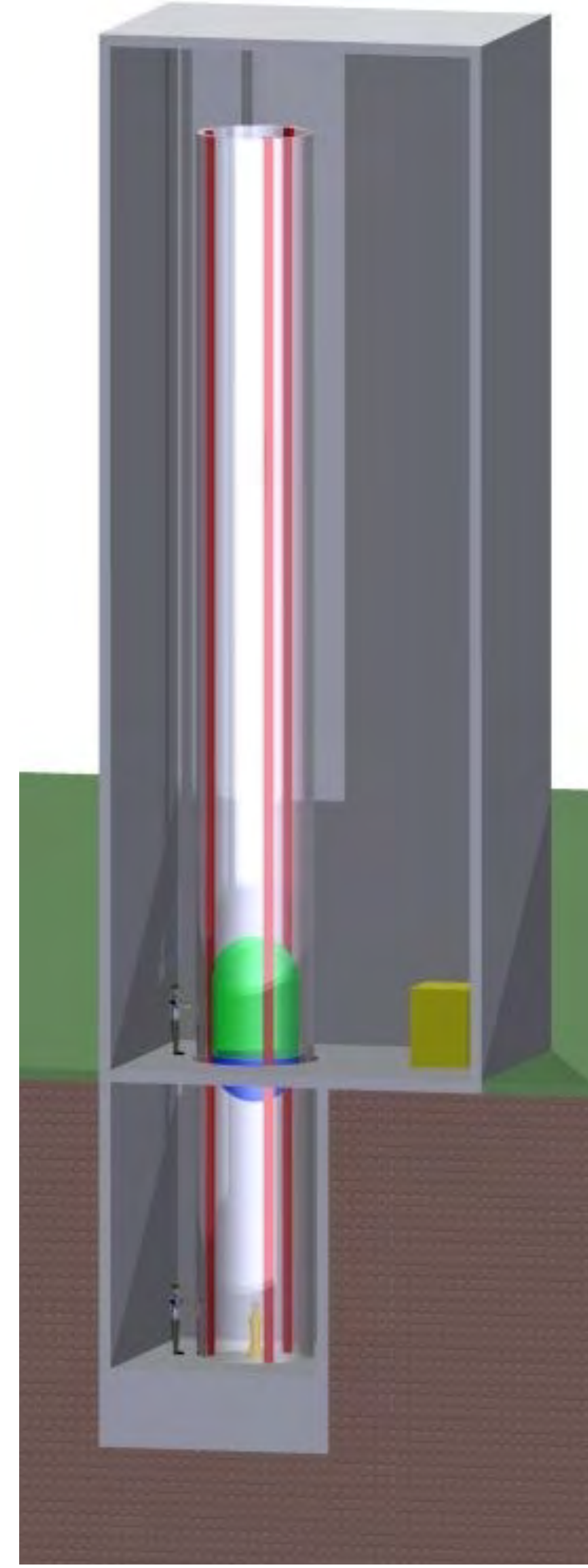
CAL EXPRESS rack implementation







Free fall Simulator:
Living Einsteins dreams



very long baseline atom interferometry

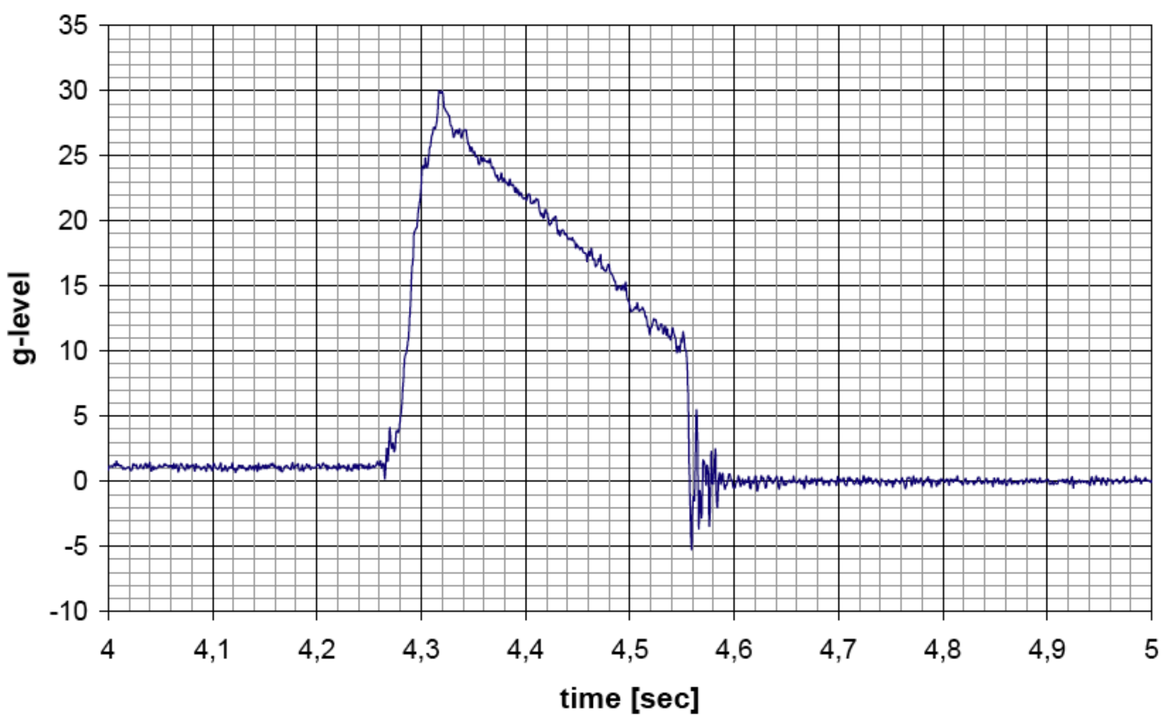
The Bremen Drop Tower at ZARM: A low energy/low noise lab for matter waves

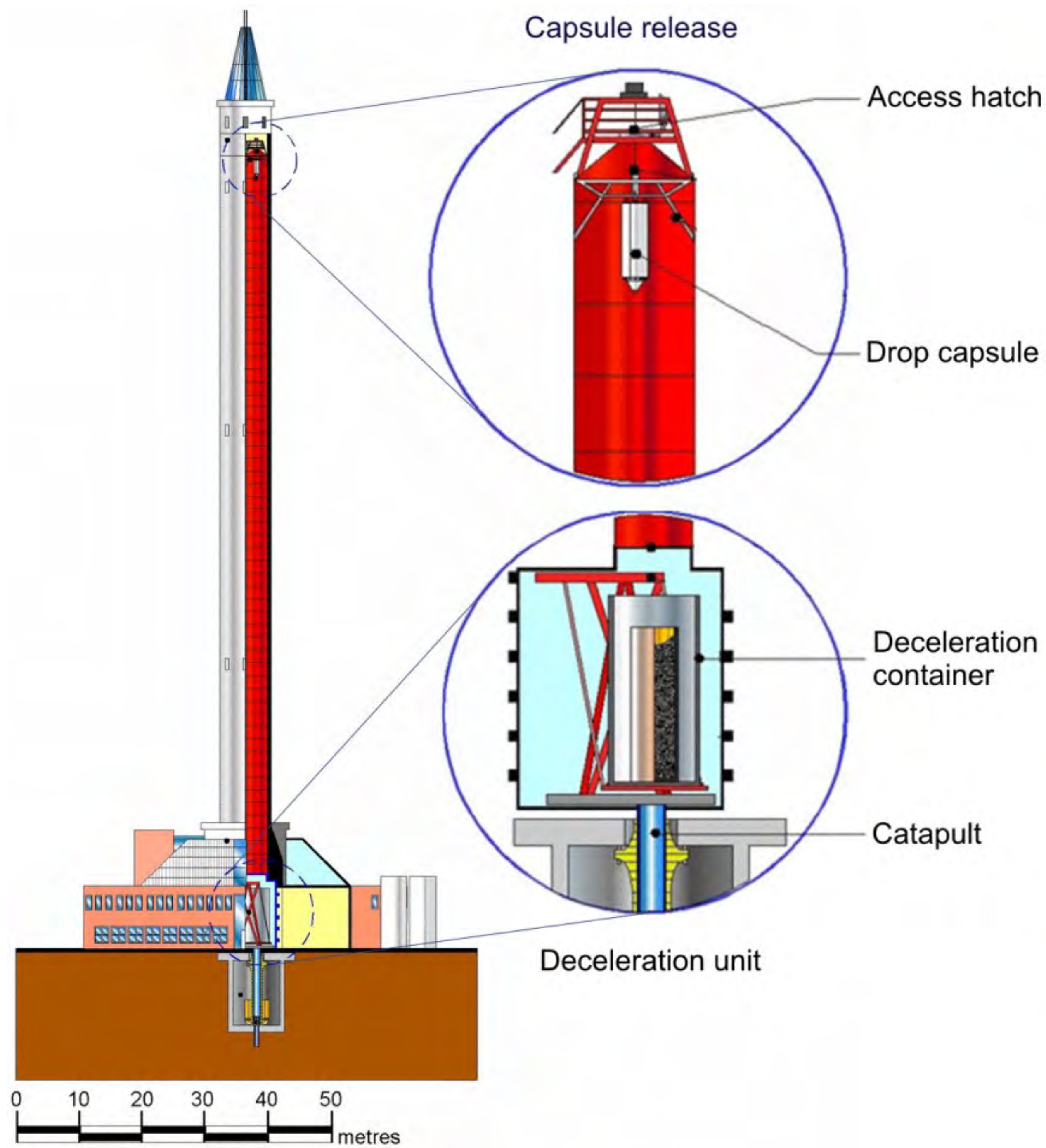
Duration of experiments

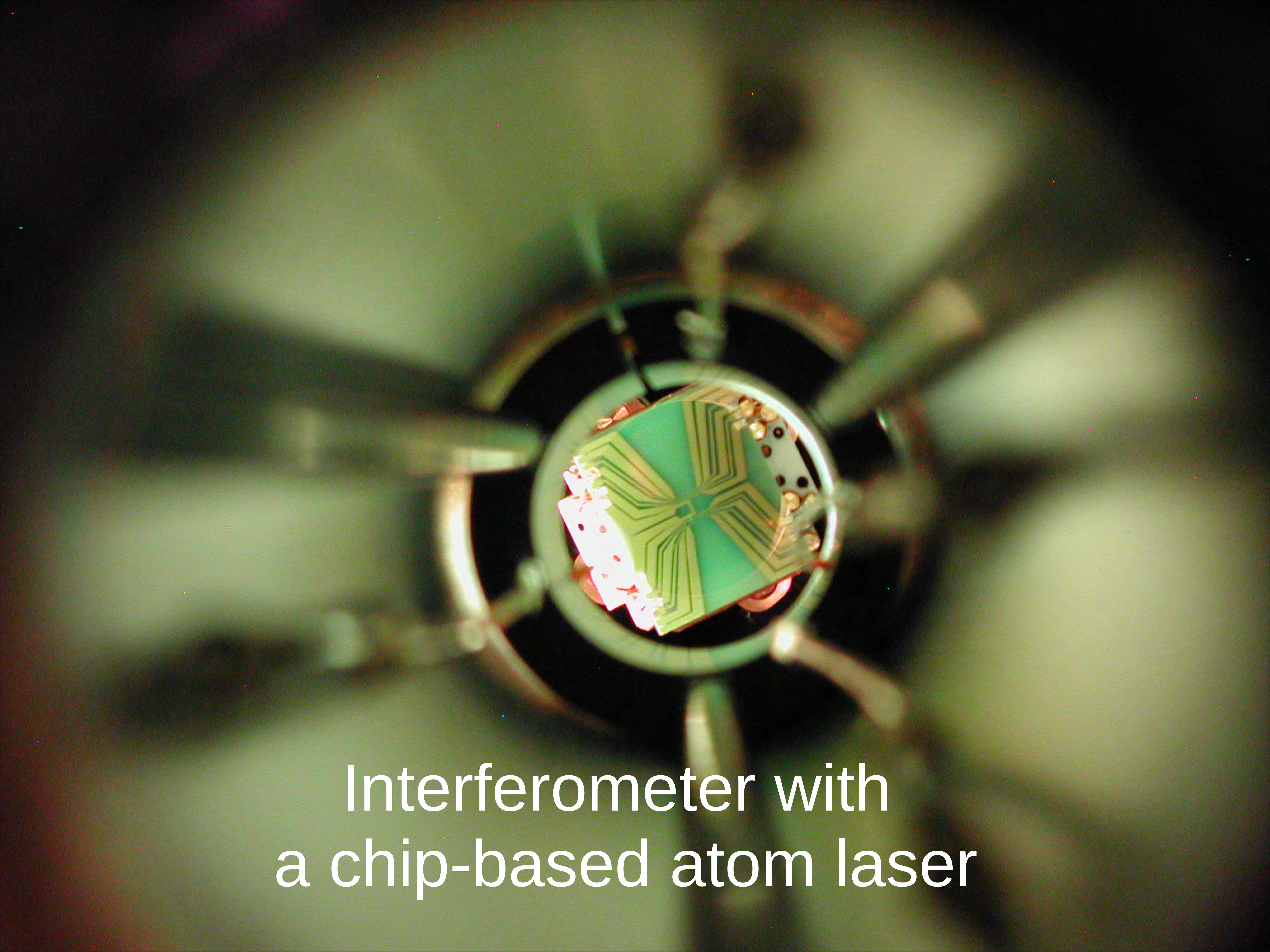
Drop from 100m: 4 seconds

Catapult: 9 seconds

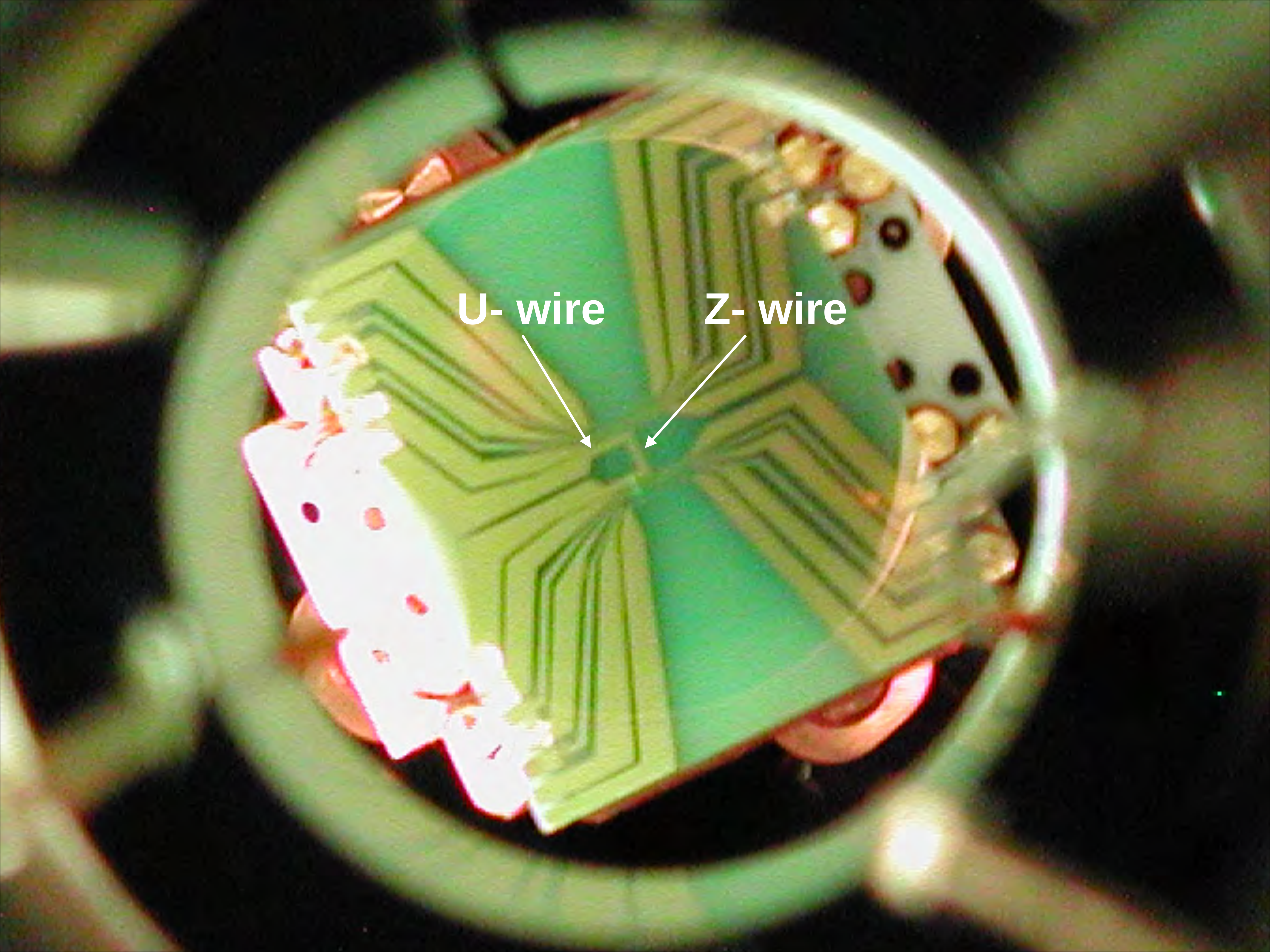
QUANTUS laser system was the first scientific equipment flown in the catapult

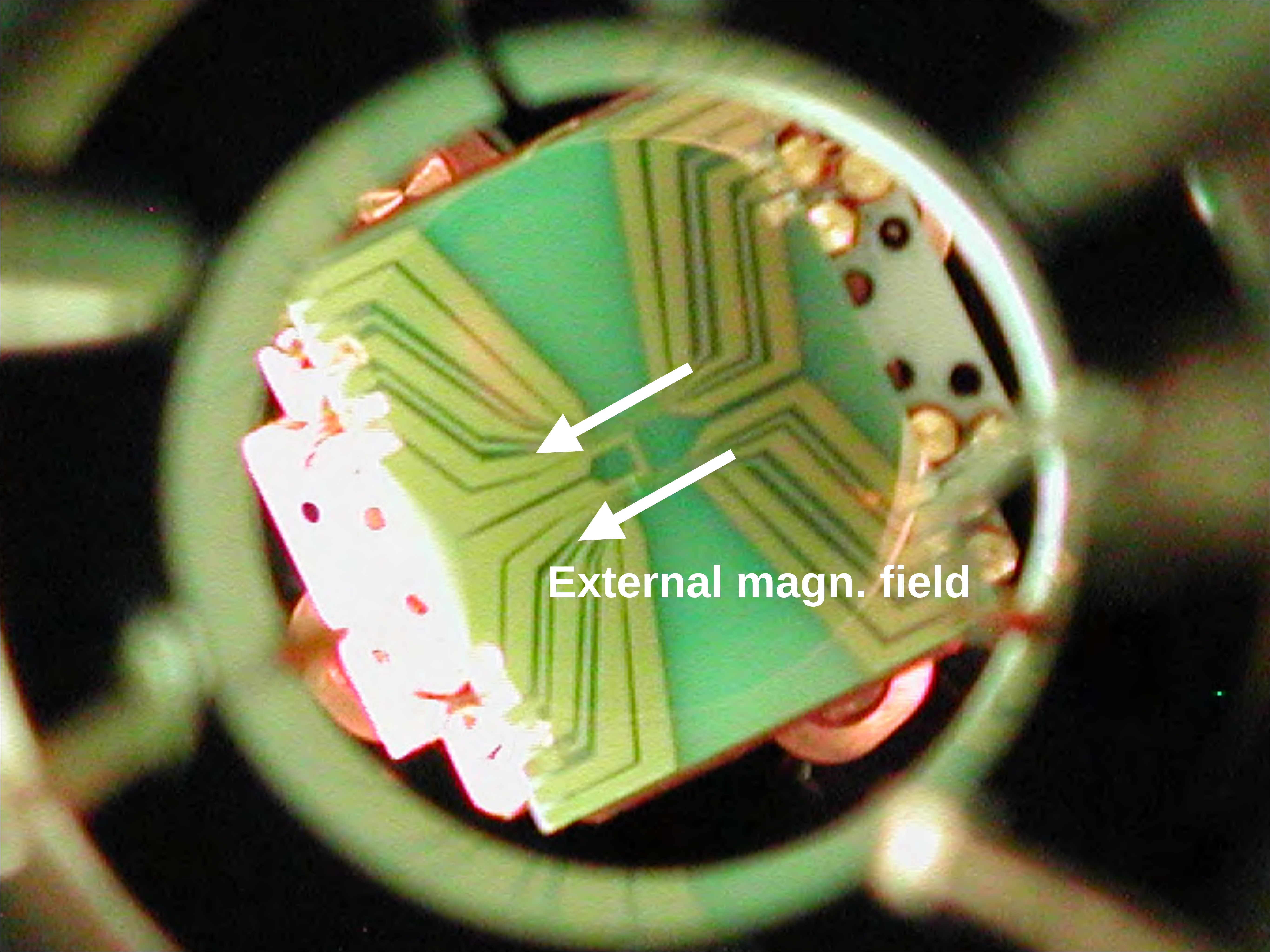


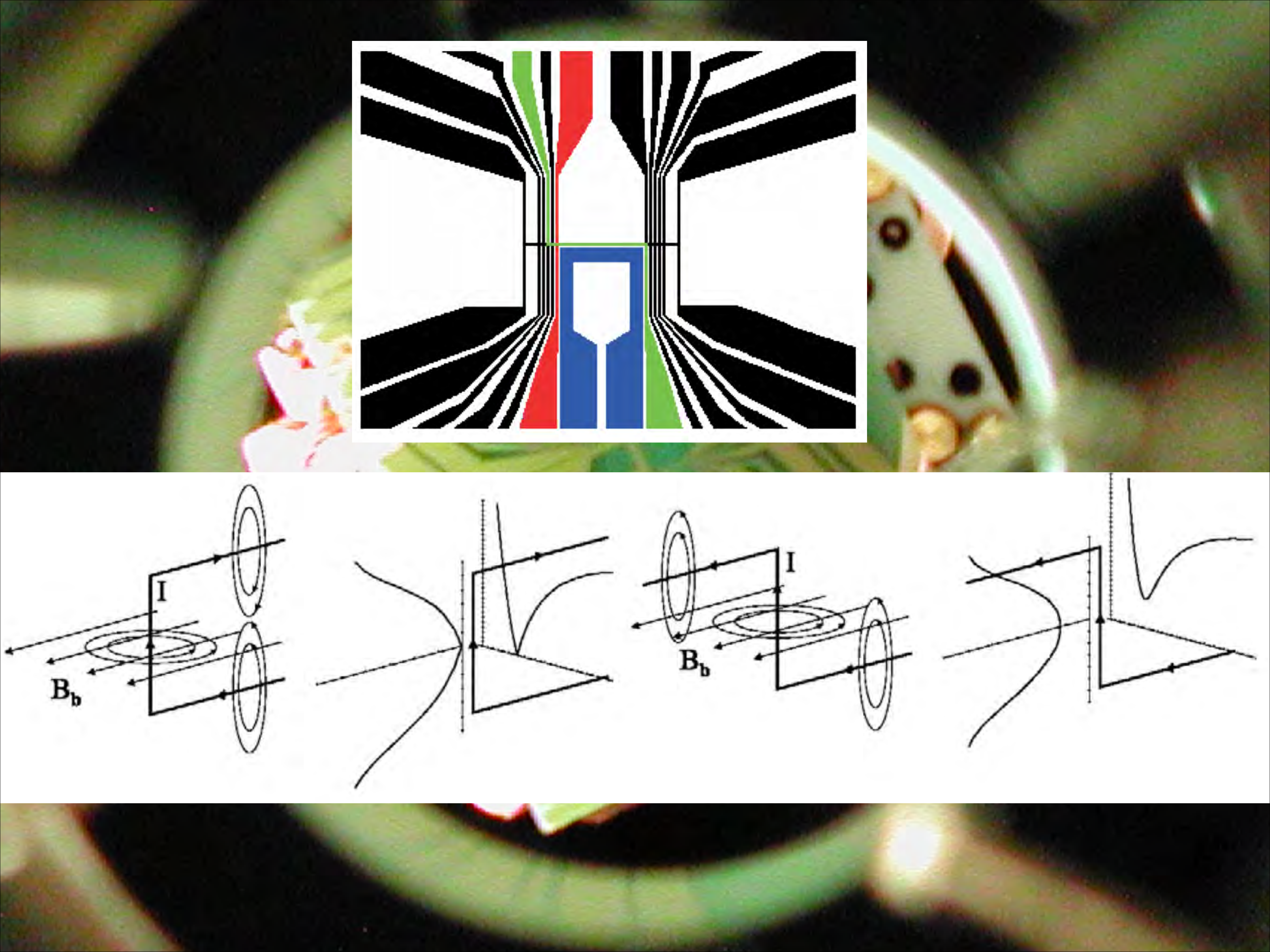


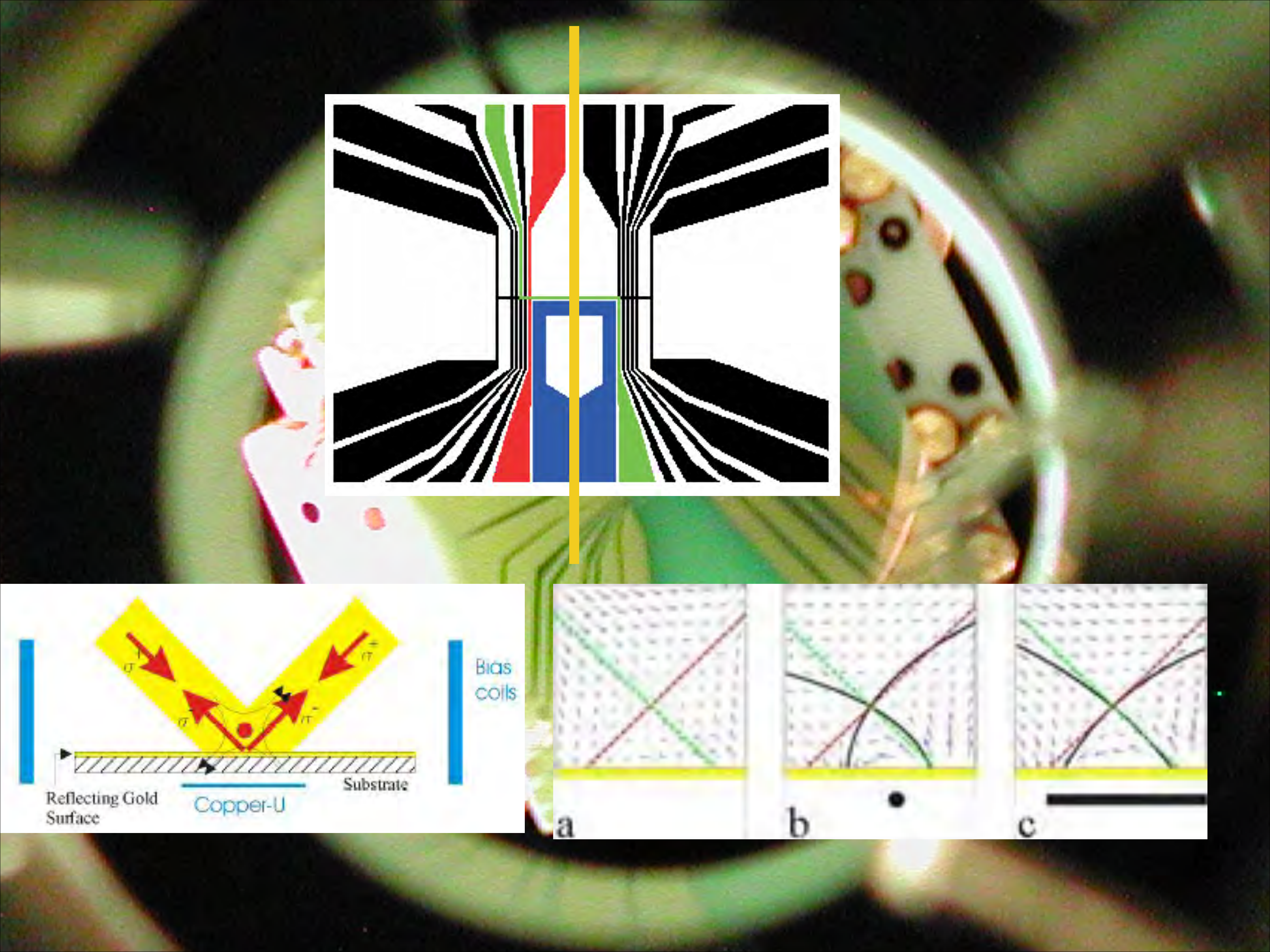


Interferometer with
a chip-based atom laser

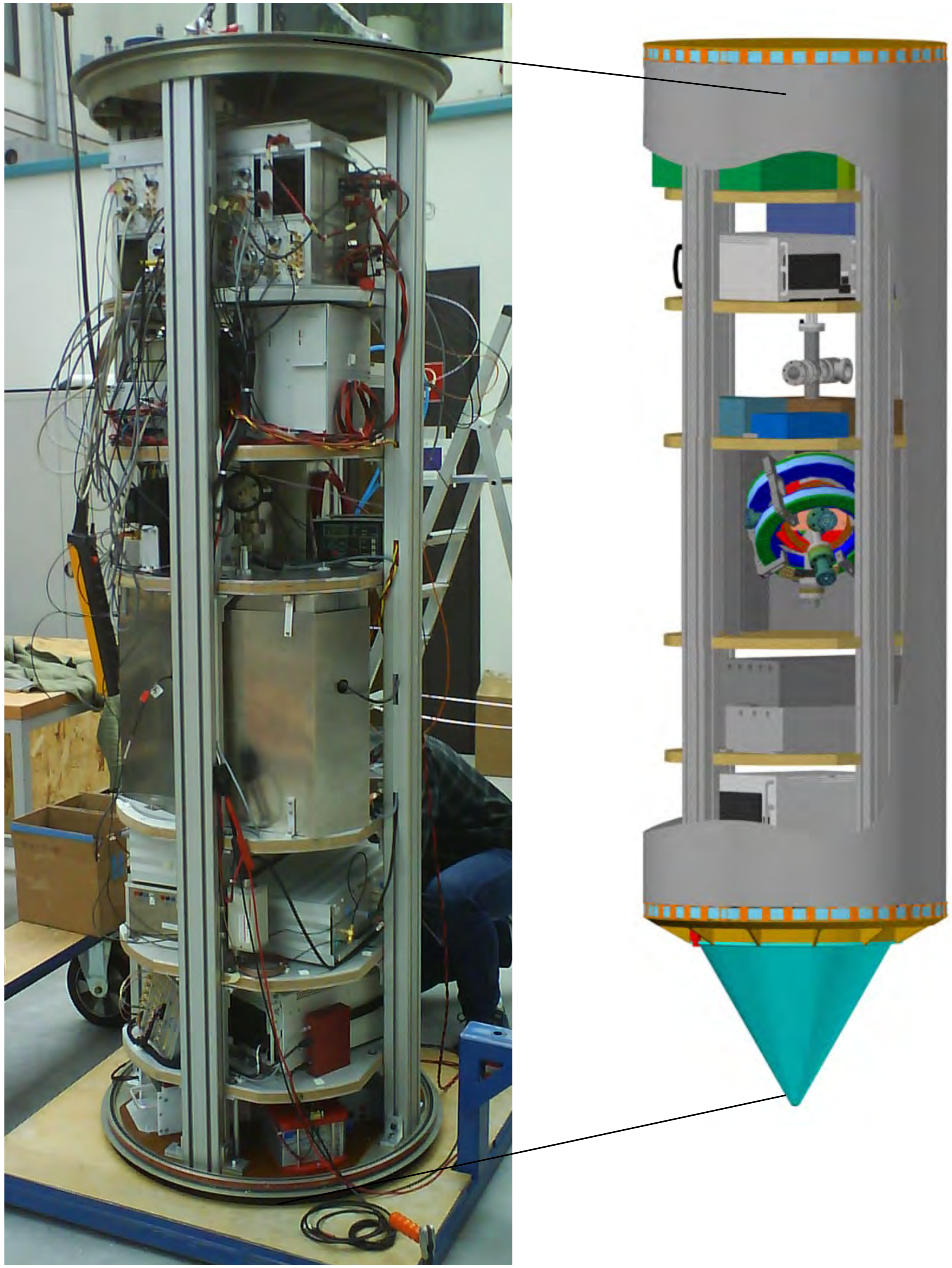

U- wire
Z- wire

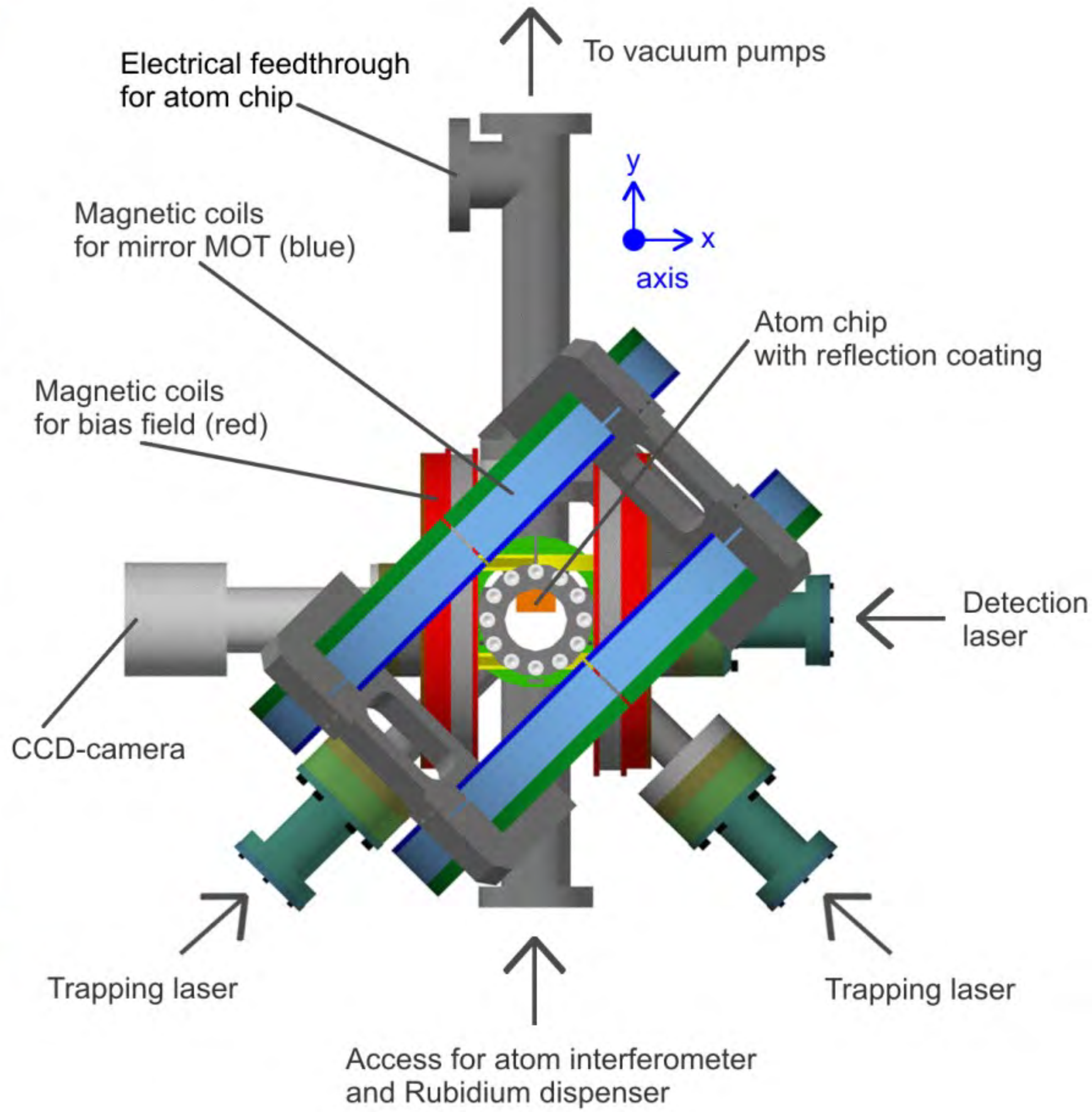

External magn. field


I
B_b
I
B_b


Bias
coils
Reflecting Gold
Surface
Copper-U
Substrate
a
b
c

QUANTUS I





To vacuum pumps
Electrical feedthrough
for atom chip
y
x
axis
Magnetic coils
for mirror MOT (blue)
Atom chip
with reflection coating
Magnetic coils
for bias field (red)
Detection
laser
CCD-camera
Trapping laser
Trapping laser
Access for atom interferometer
and Rubidium dispenser

Status

- more than 400 drops
- Robust alignment
- 3 drops per day
- High complexity

Study of Evolution & control of condensates

Test of chip-based atom lasers for precision inertial sensing

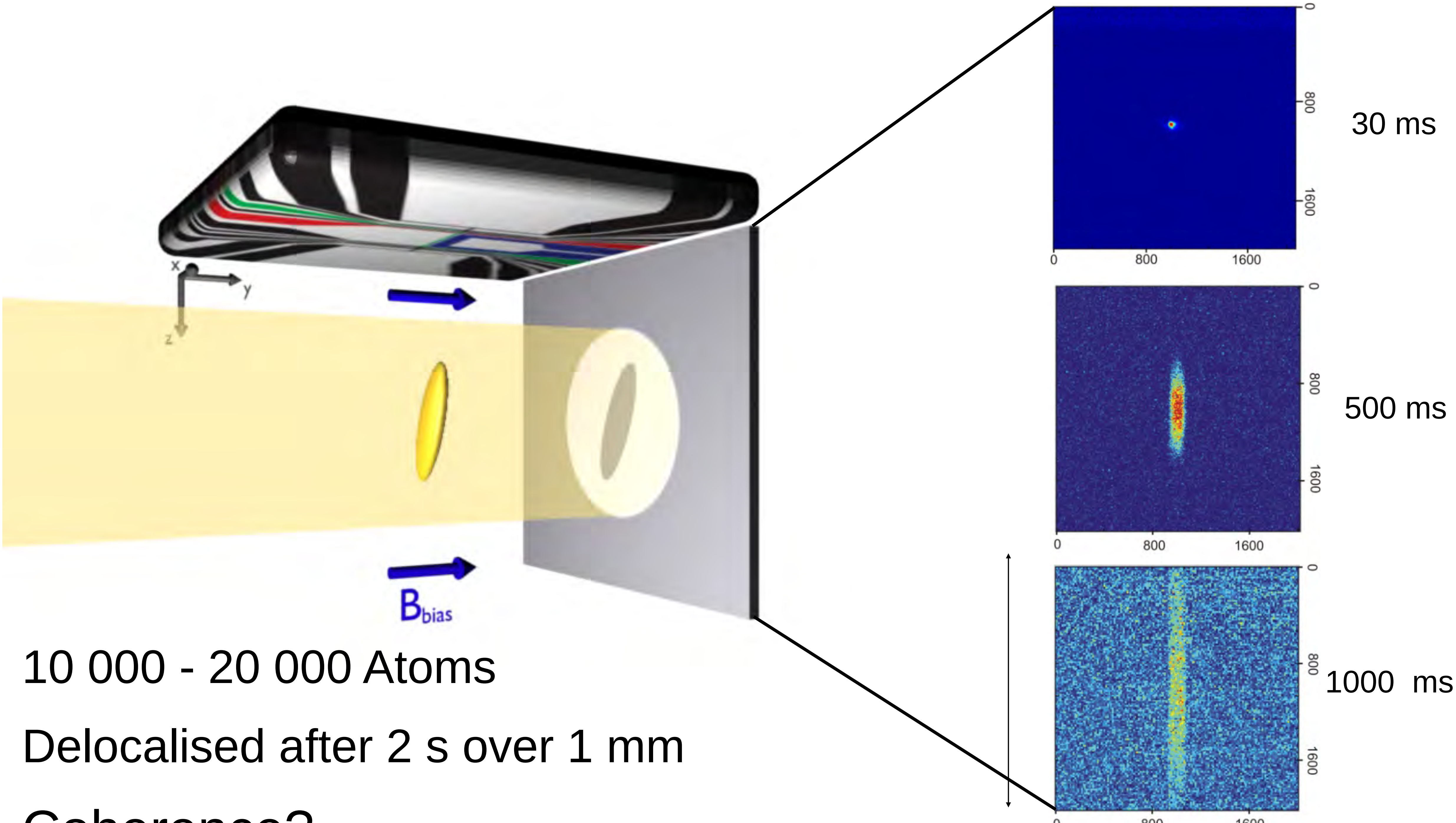
In future:

Test of free fall of isotopes of potassium and rubidium

Evolution of an atomic wave packet

during the free fall of up to 1000 ms duration

van Zoest *et al.* *Science* **328**, 1540 (2010)



10 000 - 20 000 Atoms

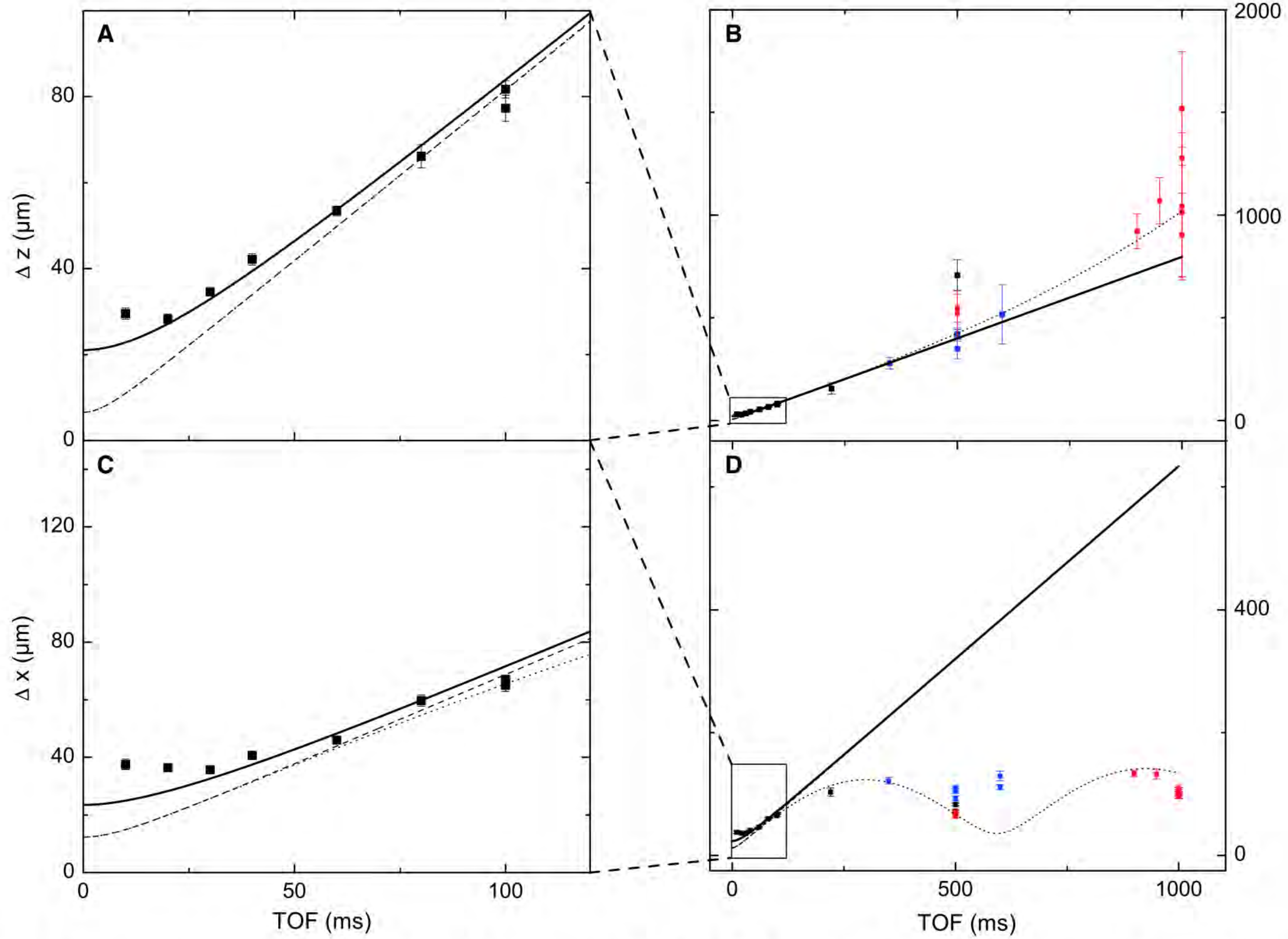
Delocalised after 2 s over 1 mm

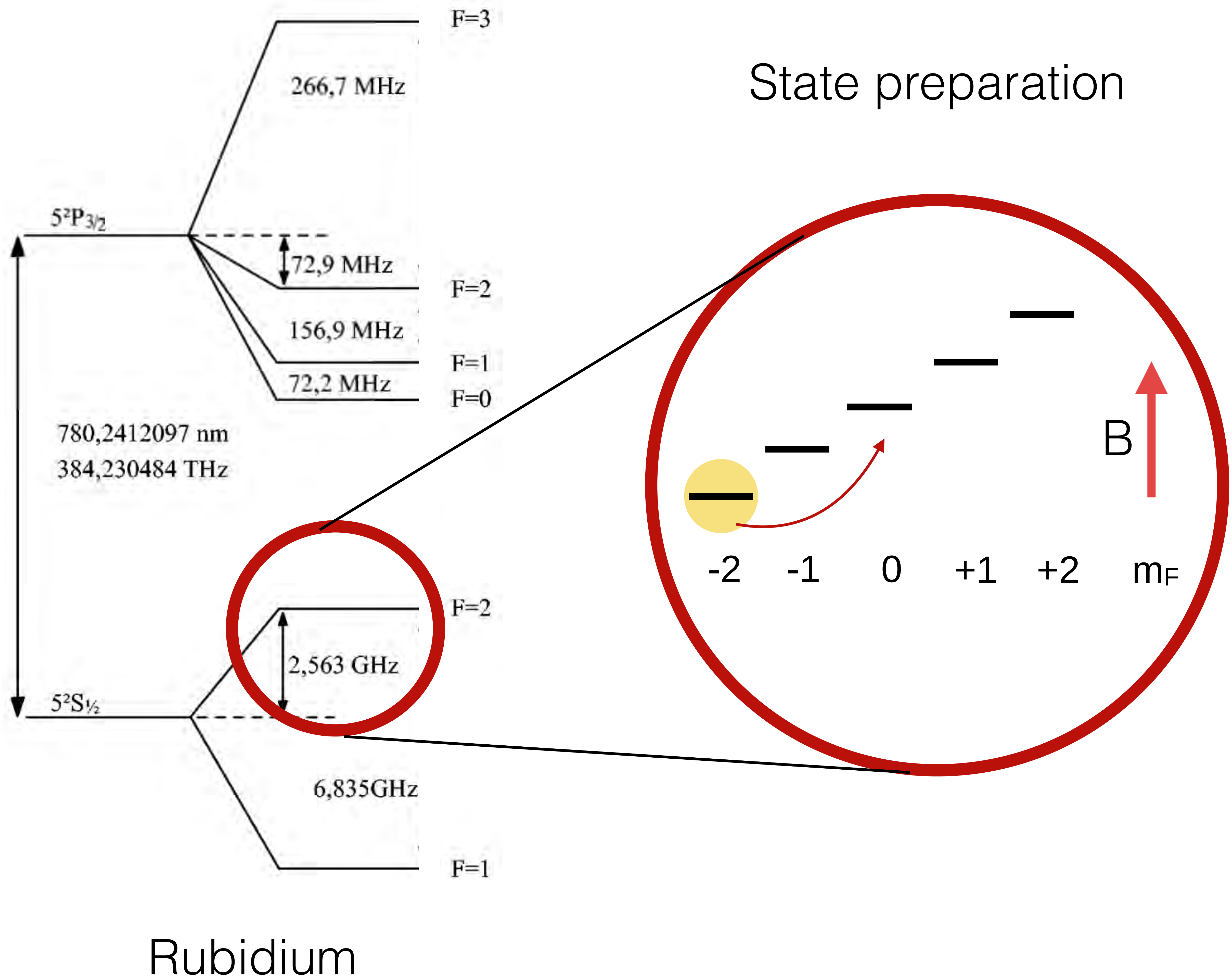
Coherence?

Evolution of an atomic wave packet

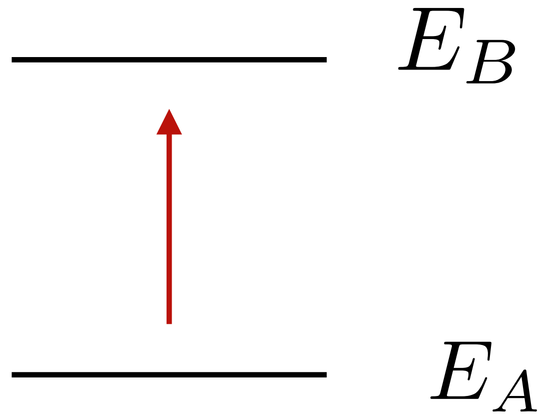
during the free fall of up to 1000 ms duration

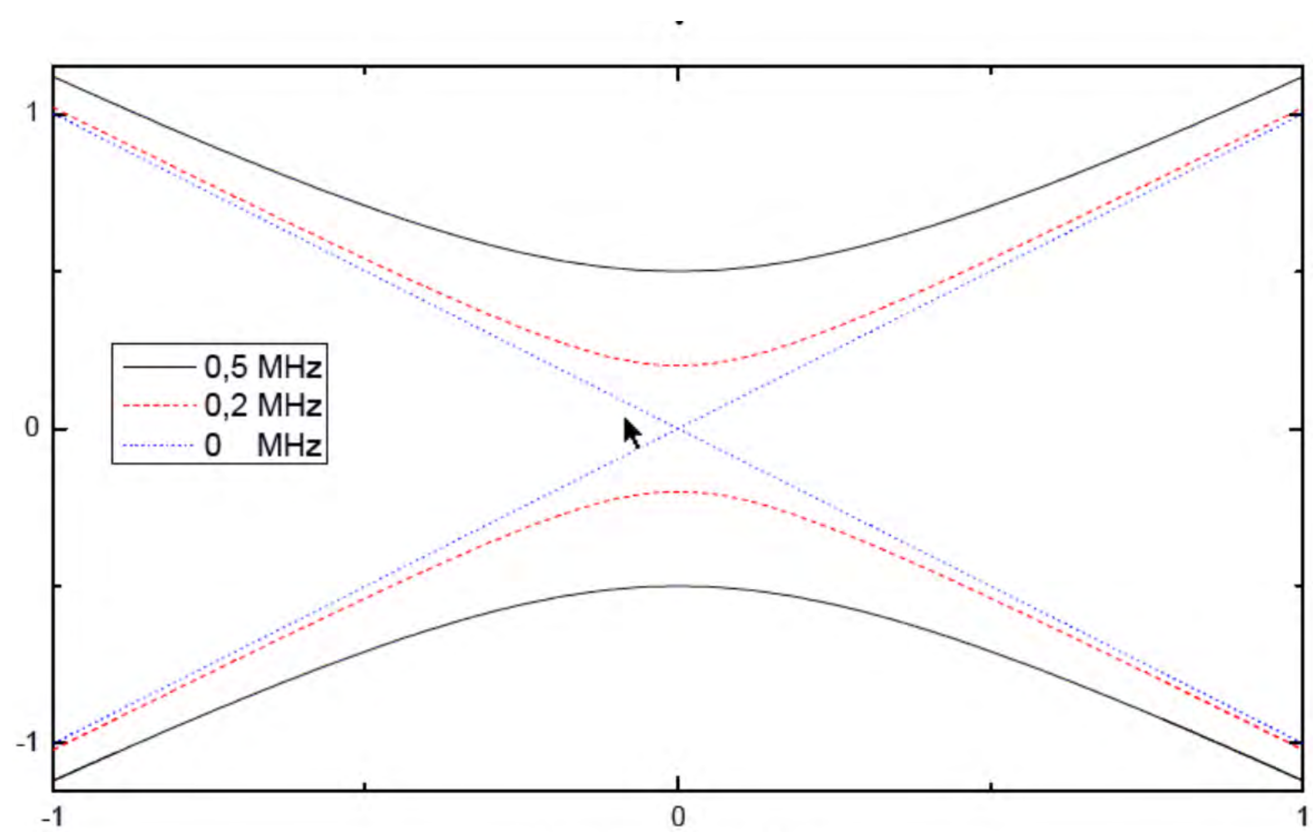
van Zoest *et al.* *Science* **328**, 1540 (2010)



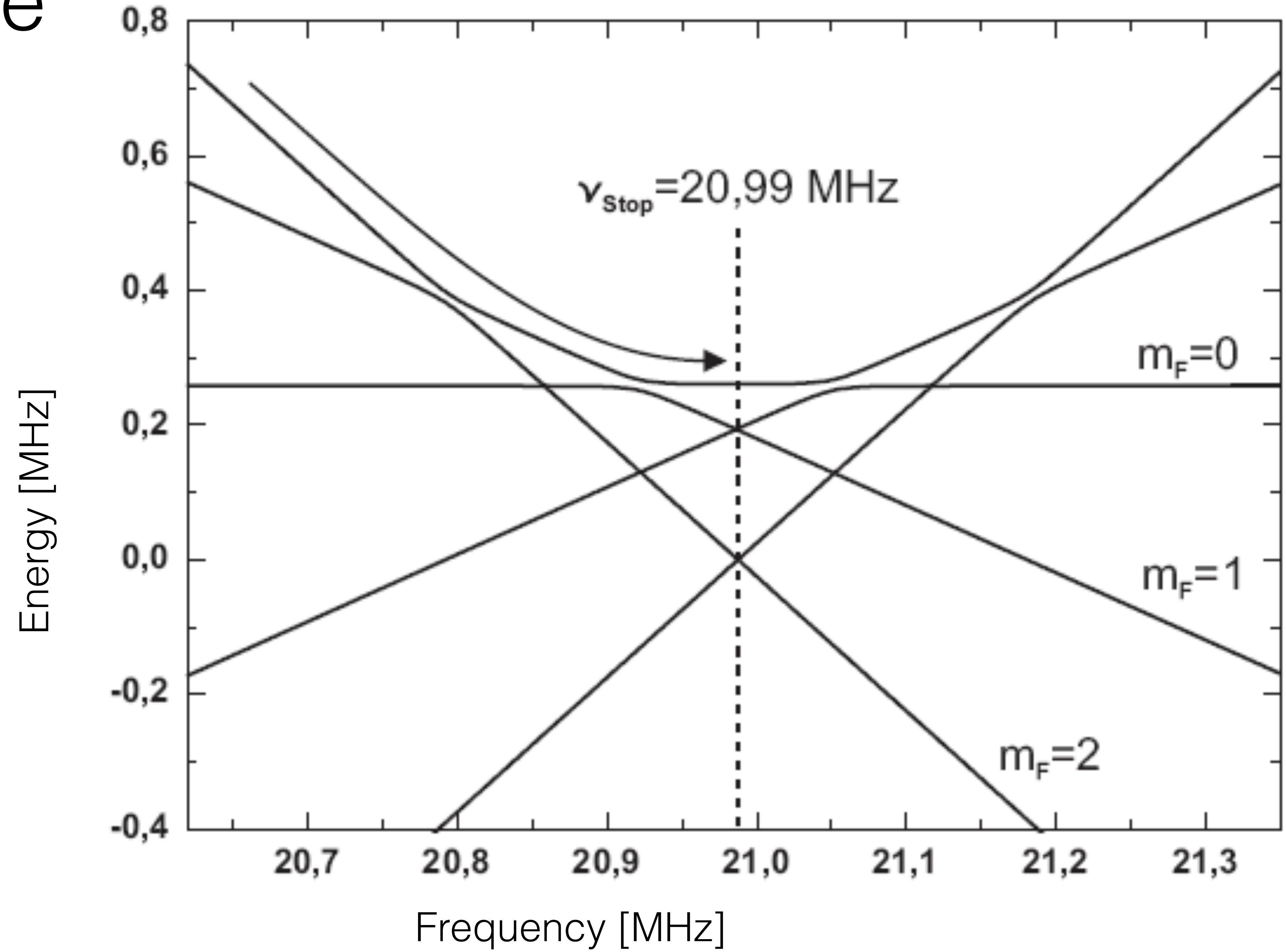


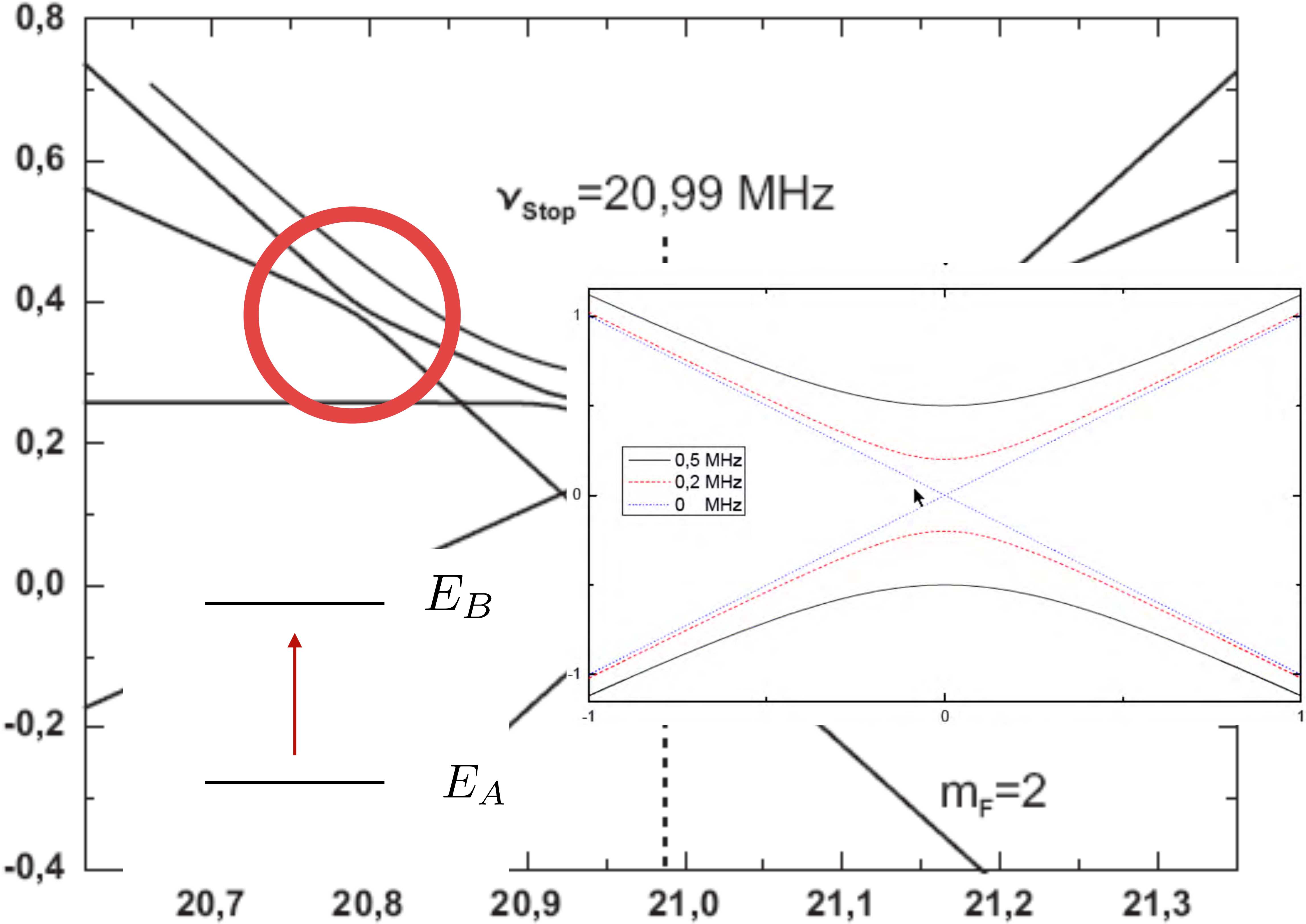
State preparation
F=3
266,7 MHz
5²P3/2
72,9 MHz
F=2
156,9 MHz
F=1
72,2 MHz
F=0
780,2412097 nm
384,230484 THz
F=2
2,563 GHz
5²S½
6,835GHz
F=1
B
-2
-1
0
+1
+2
mF
Rubidium


E_B
E_A


0,5 MHz
0,2 MHz
0 MHz
1
0
-1
-1
0
1

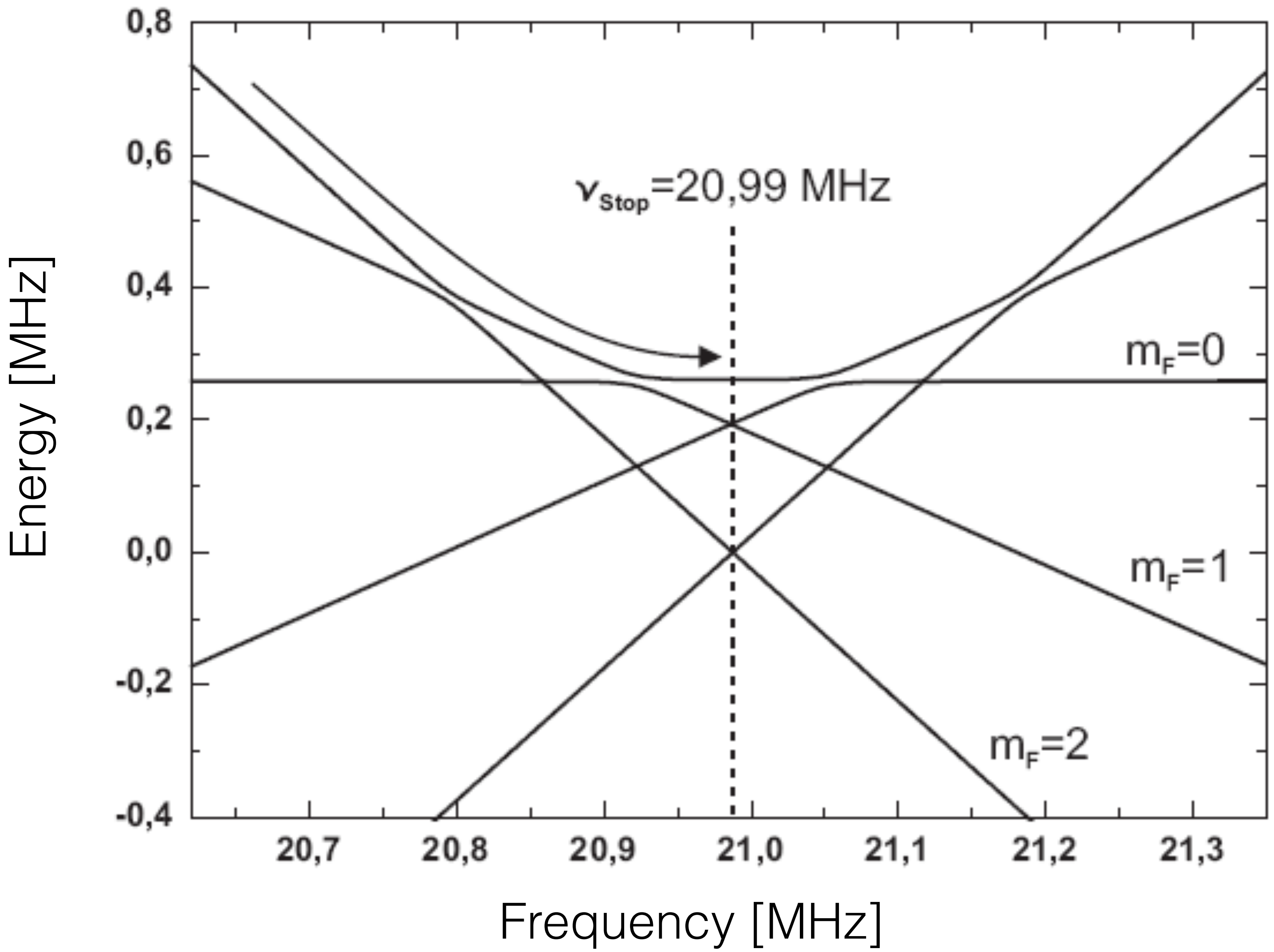
Preparation of atomic wave packet in the non-magnetic state via rapid adiabatic passage

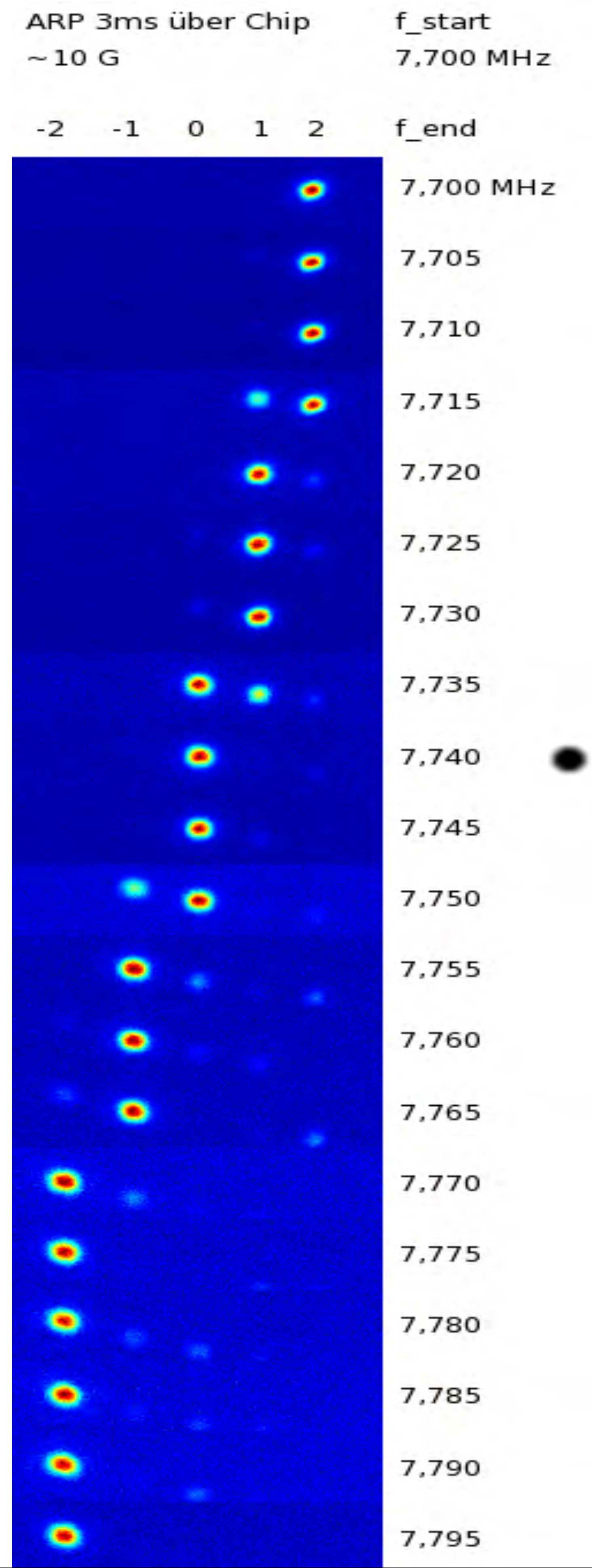




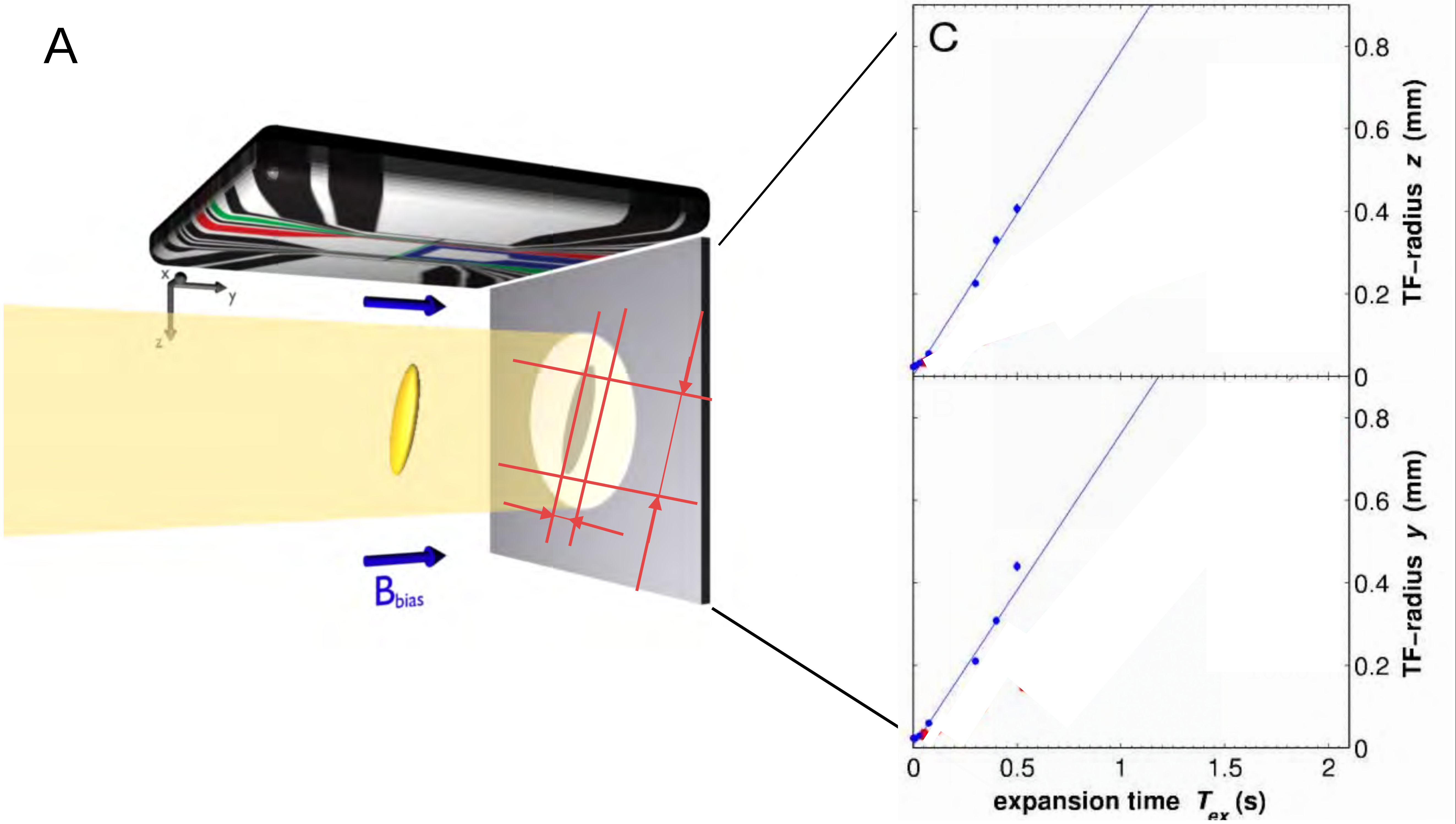
0,8
0,6
0,4
0,2
0,0
-0,2
-0,4
20,7
20,8
20,9
21,0
21,1
21,2
21,3
ν_{Stop}=20,99 MHz
m_F=2
E_B
E_A
0,5 MHz
0,2 MHz
0 MHz
1
0
-1
-1
0
1

Preparation of atomic wave packet in the non-magnetic state via rapid adiabatic passage





Longest free fall of a quantum object 2 s obtained with Delta kick cooling



Delta-Kick "Cooling"

The name "cooling" is misleading as there no gain in phase space density

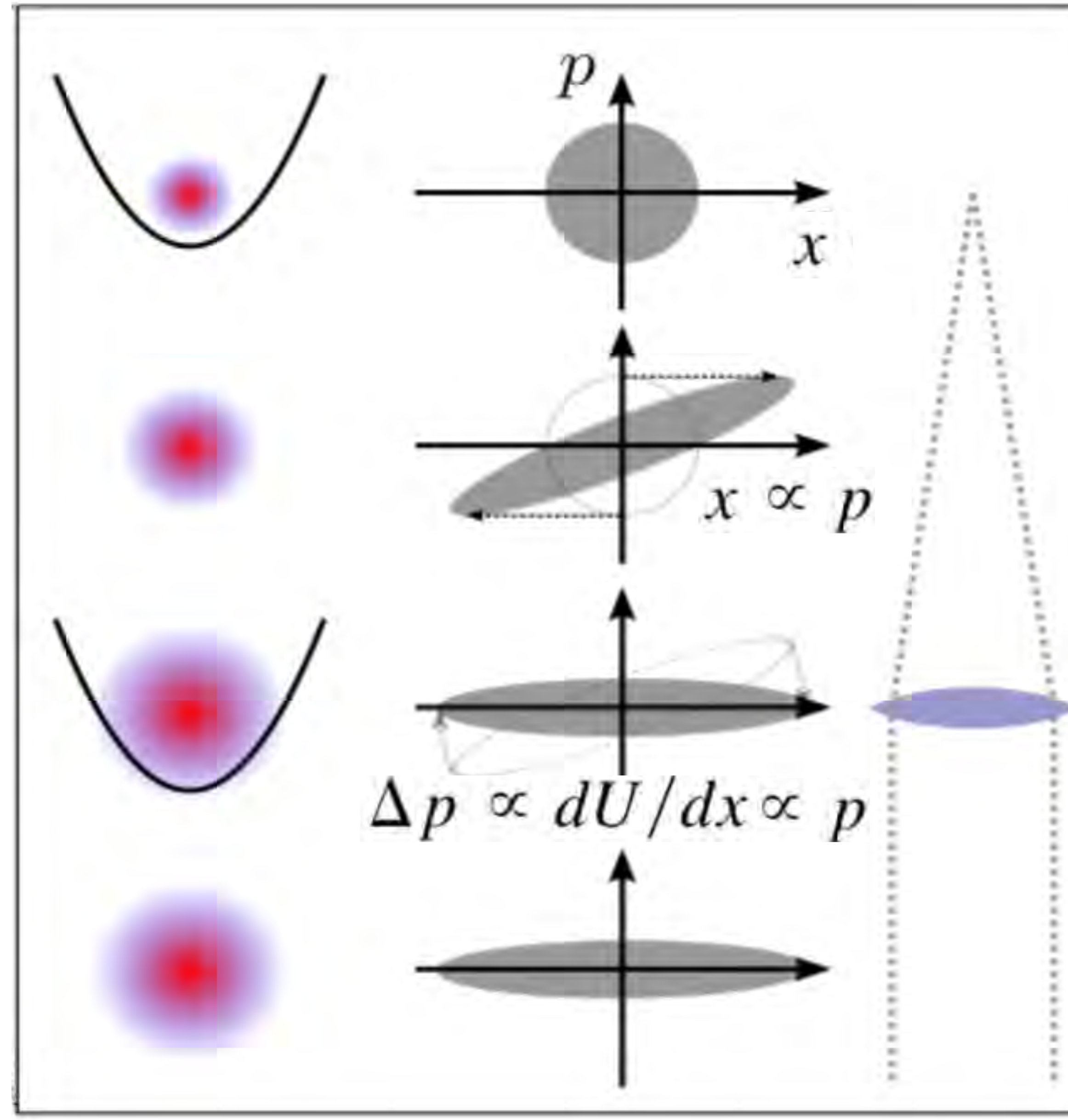
$$H_k = \frac{p^2}{2m} + V(x)\delta(t - T)$$

$$V(x) = \sqrt{2\pi}\,\tau_p U(x)$$

$$U(x) \approx m\omega^2 x^2/2$$

After the free expansion after the release position and momentum of the atoms have a linear relation ship

$$\Delta p \propto dU/dx \propto x \propto p$$



VOLUME 78, NUMBER 11 PHYSICAL REVIEW LETTERS 17 MARCH 1997

Delta Kick Cooling: A New Method for Cooling Atoms

Hubert Ammann and Nelson Christensen
Department of Physics, University of Auckland, Private Bag 92019, Auckland, New Zealand
(Received 11 November 1996)

We present a new technique for cooling atoms below the photon recoil temperature. Free expansion and a subsequent application of a pulsed potential narrows the momentum distribution provided the atoms were initially well localized. Time scales for this cooling mechanism are shorter than those for other techniques. We give the one dimensional results for quantum and classical distributions of atoms initially held in an optical lattice or a dipole trap. The pulsed lattice potential is the same as that used in the recent atom optics realization of the quantum delta kicked rotor. [S0031-9007(97)02699-9]

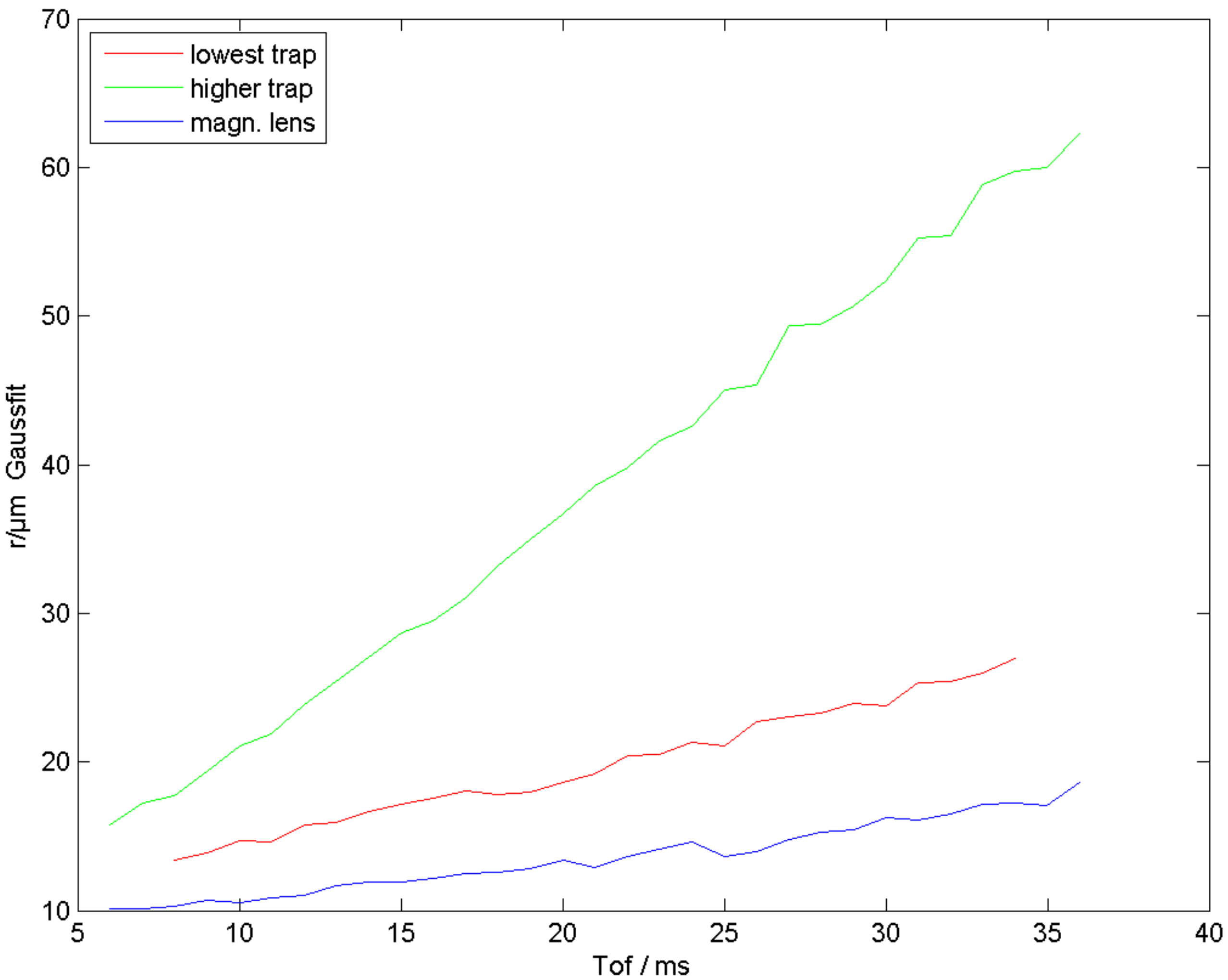
February 1986 / Vol. 11, No. 2 / OPTICS LETTERS 73

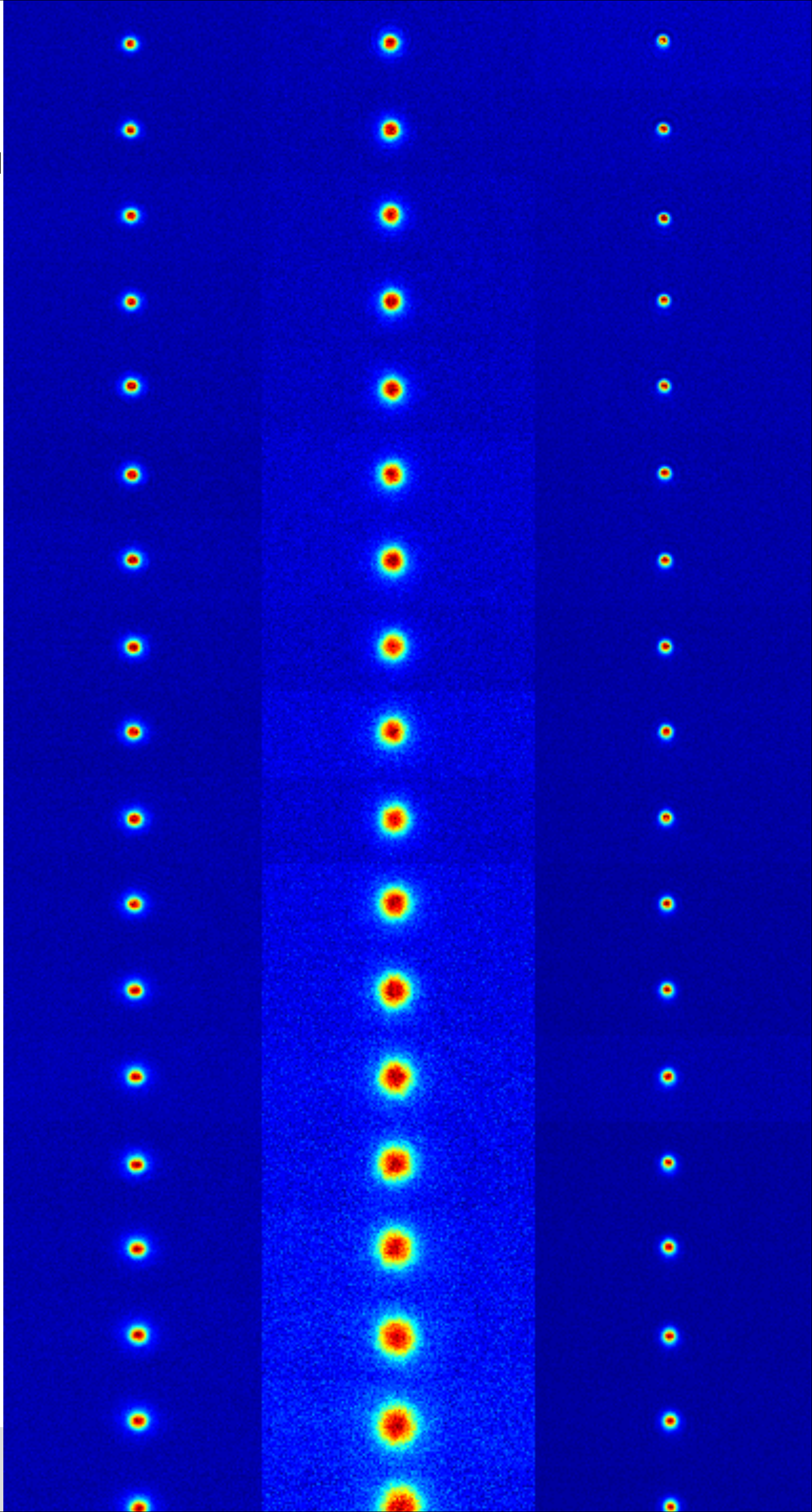
Proposal for optically cooling atoms to temperatures of the order of 10^{-6} K

S. Chu, J. E. Bjorkholm, A. Ashkin, J. P. Gordon, and L. W. Hollberg
AT&T Bell Laboratories, Holmdel, New Jersey 07733

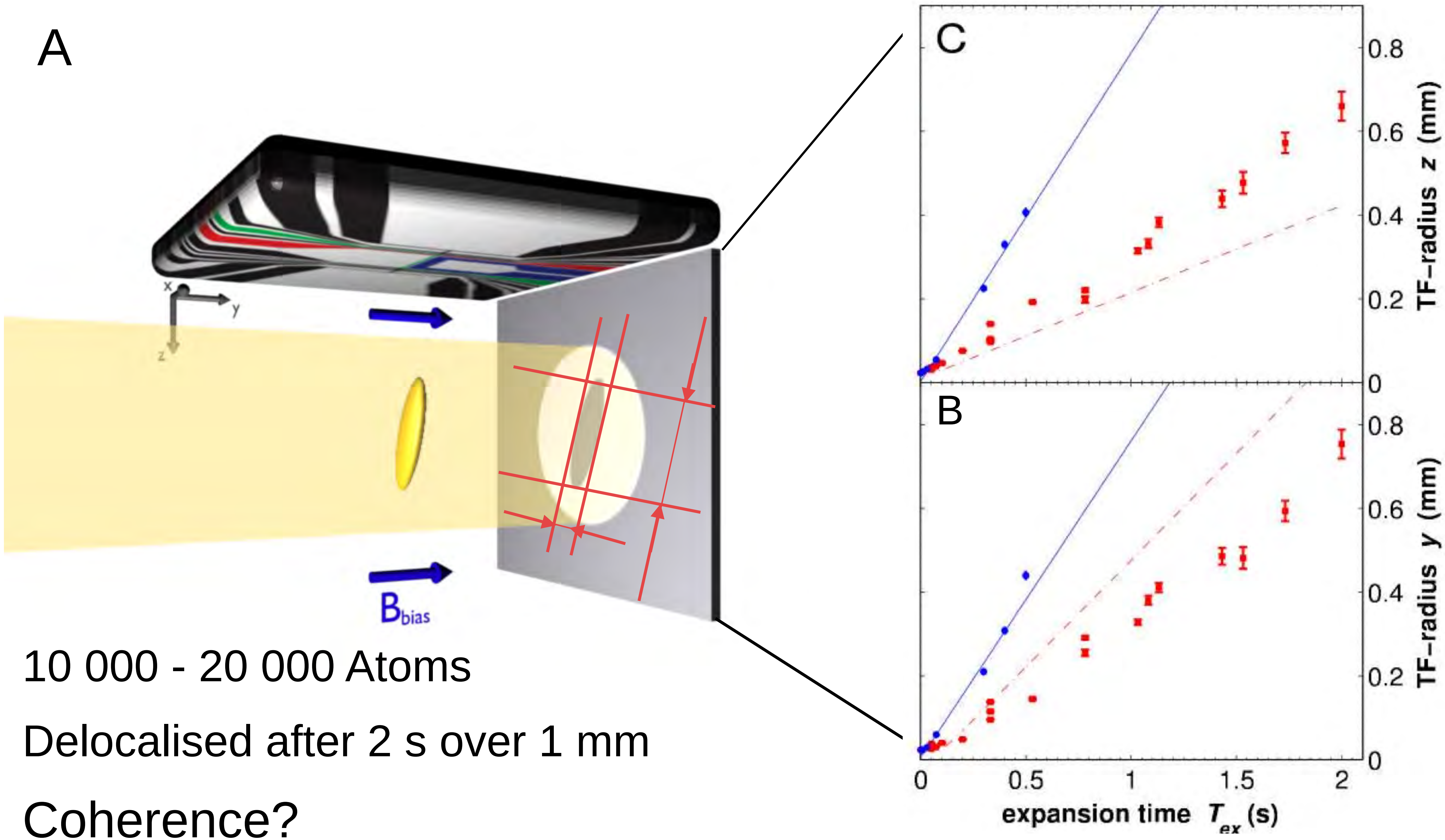
Reduction of the expansion rate by a "3D magnetic lens"

- Lowest trap freq. on ground
- tighter trap
- applied magnetic lense 2ms after release for 300µs





Longest free fall of a quantum object 2 s obtained with Delta kick cooling



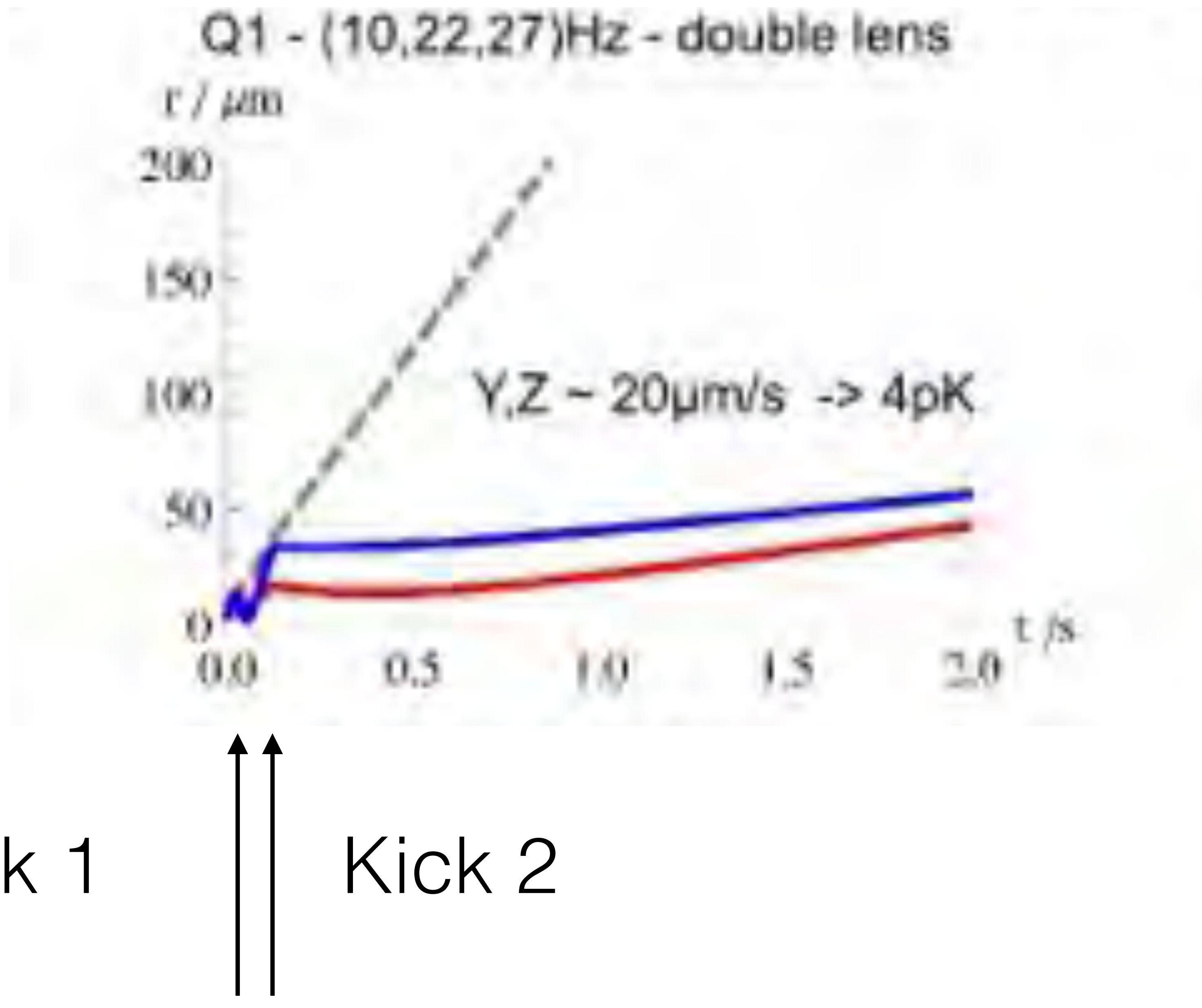
10 000 - 20 000 Atoms

Delocalised after 2 s over 1 mm

Coherence?

DKC - achieving energies in the pK range ?

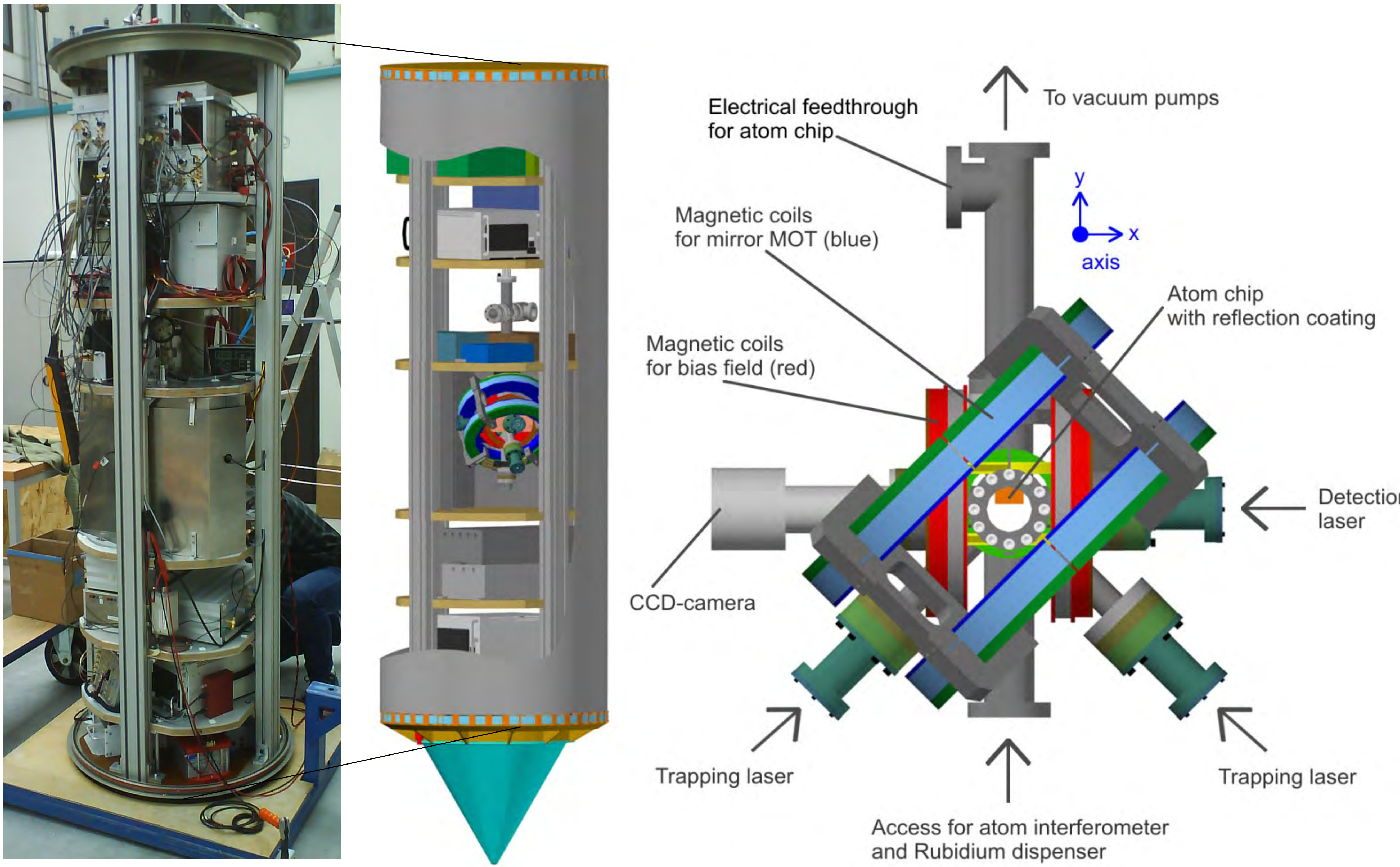
- Employing DKC twice - a matter-wave telescope



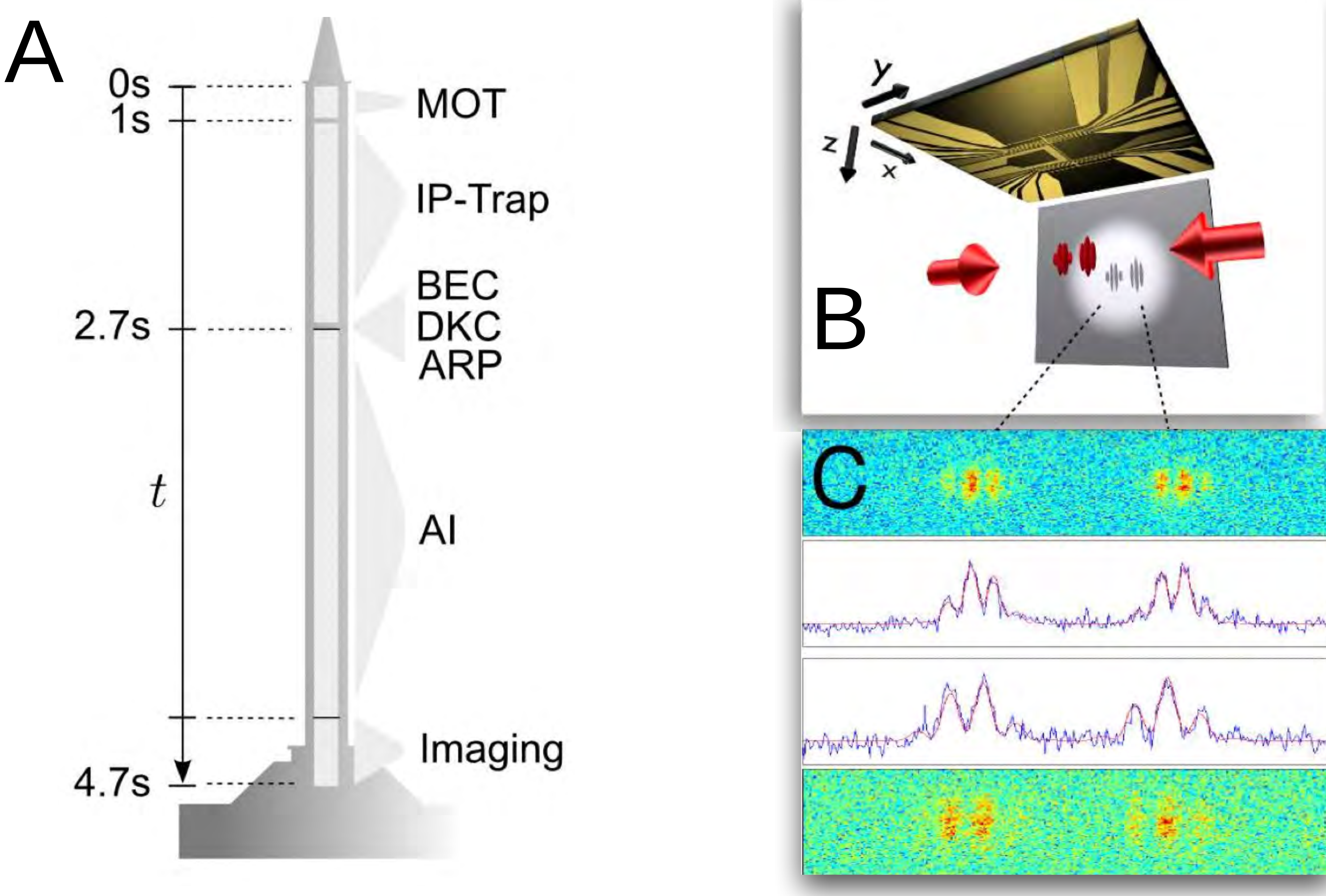
Kick 1

Kick 2

Upgrade of QUANTUS I

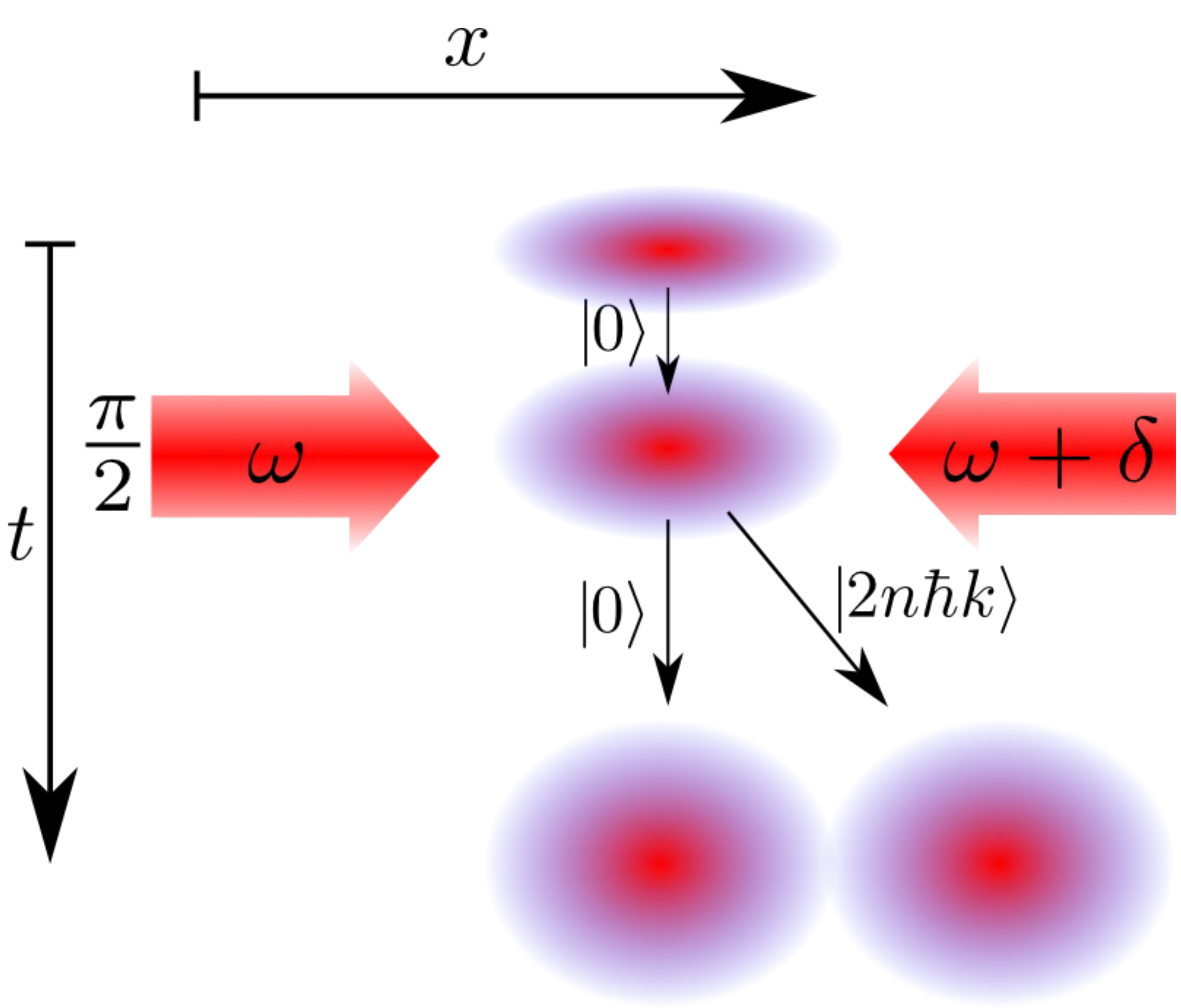


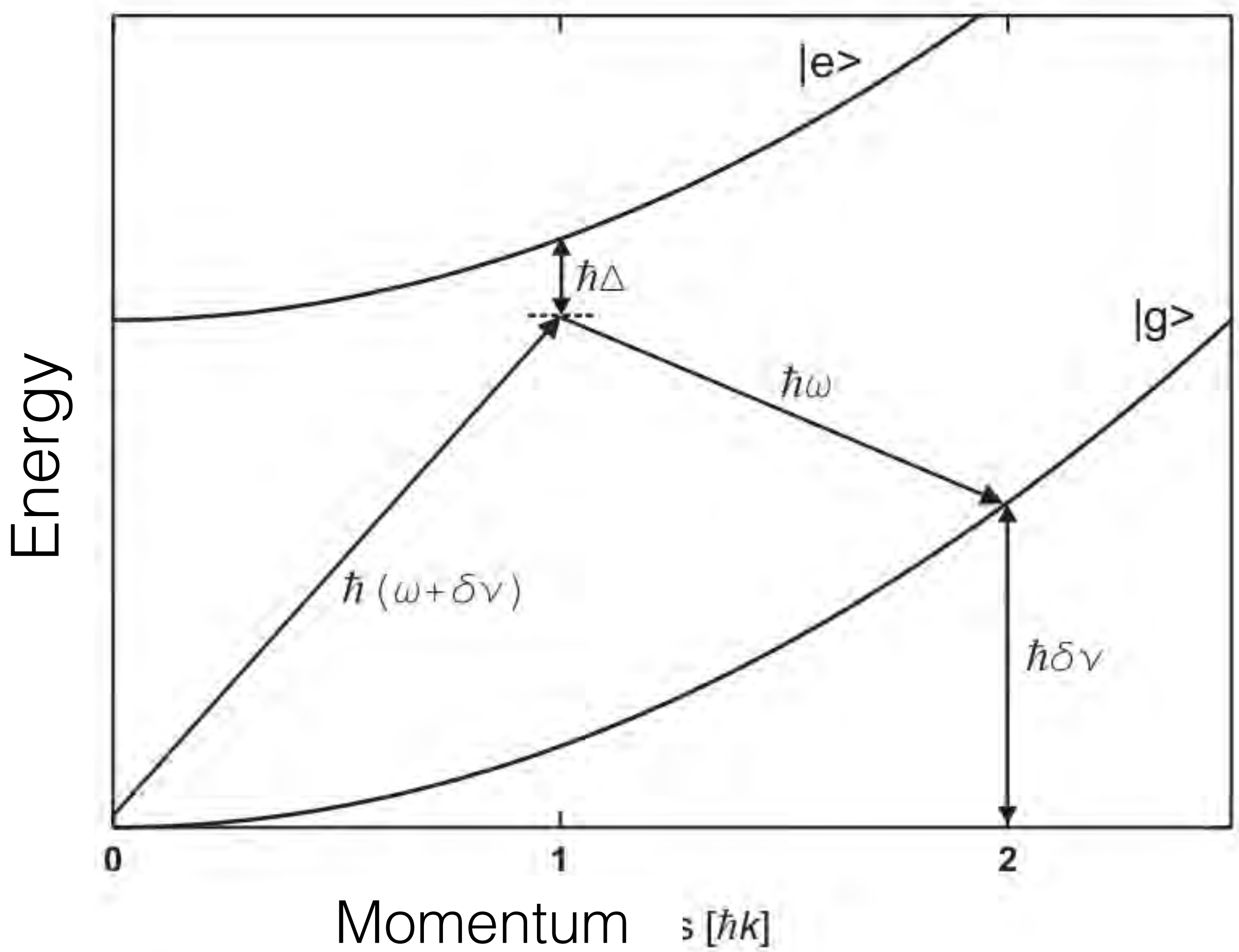
Interferometry (MZI) with BEC in microgravity



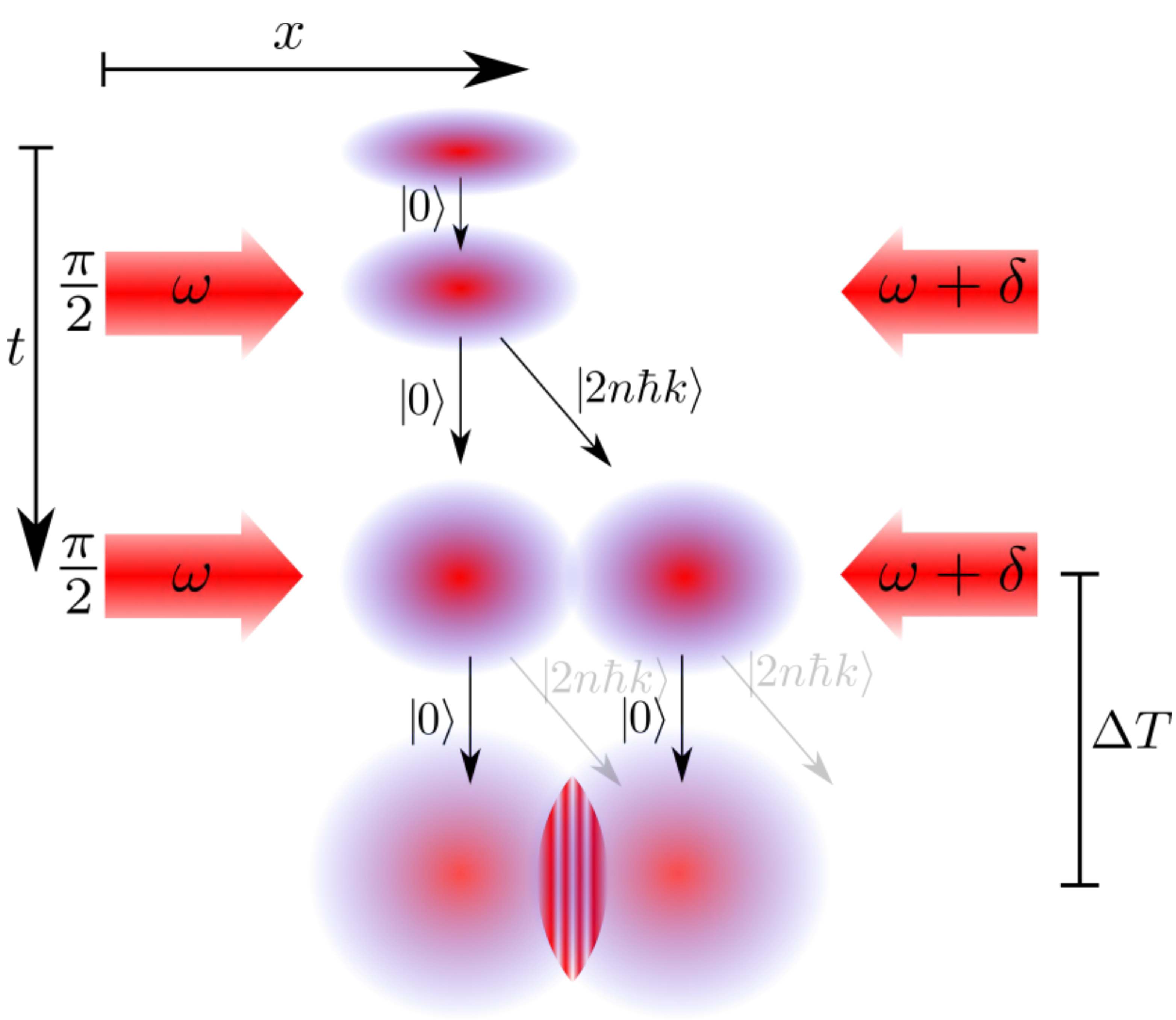
Interferometry (MZI) with BEC in microgravity

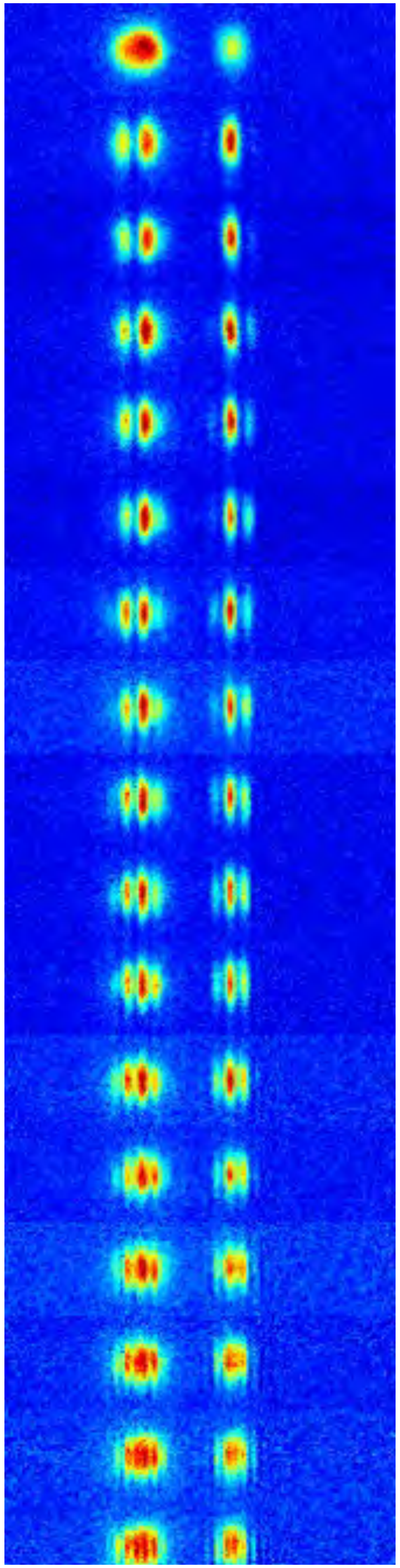
- Coherent manipulation with a moving light grating



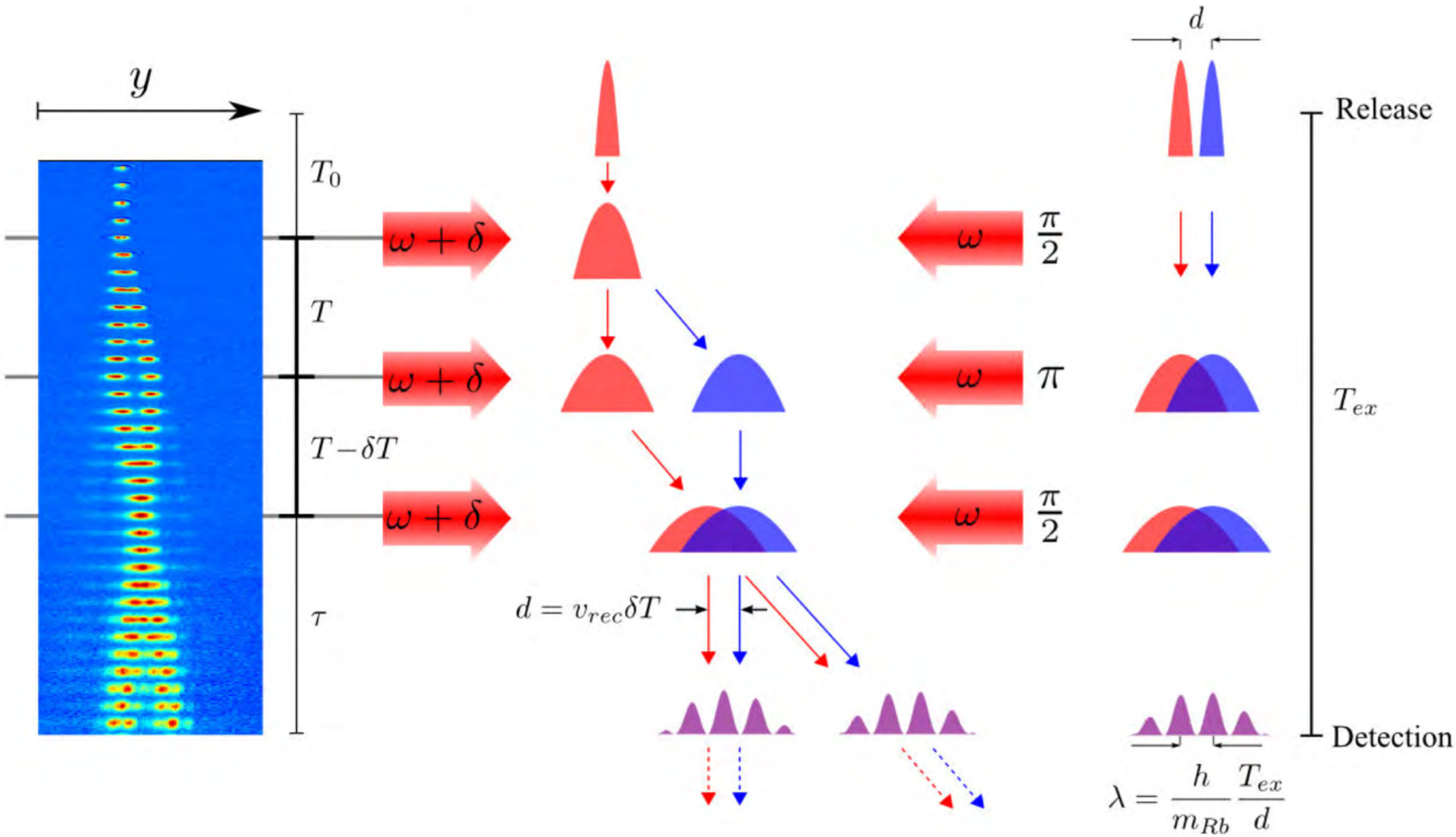


Shear interferometer

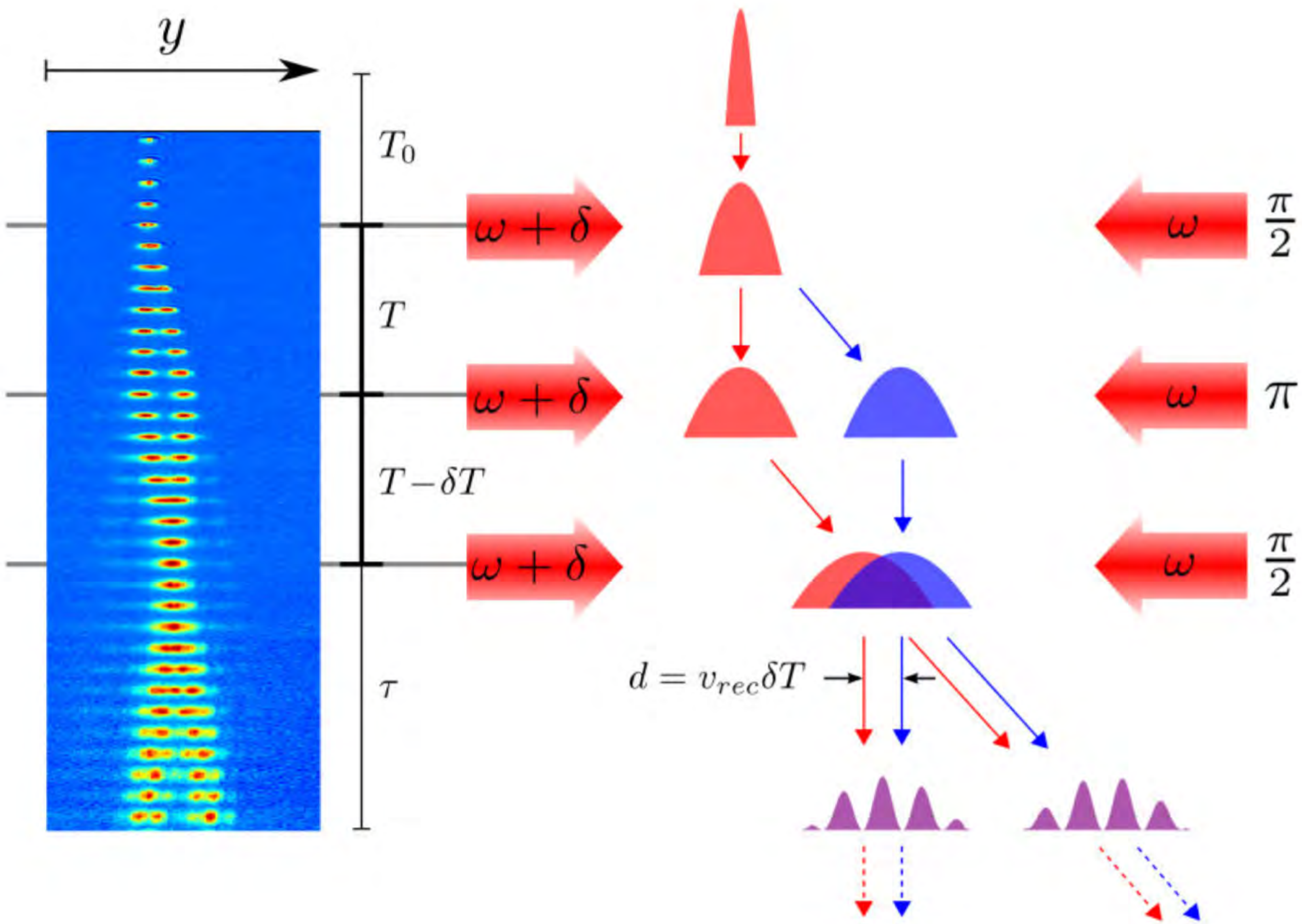


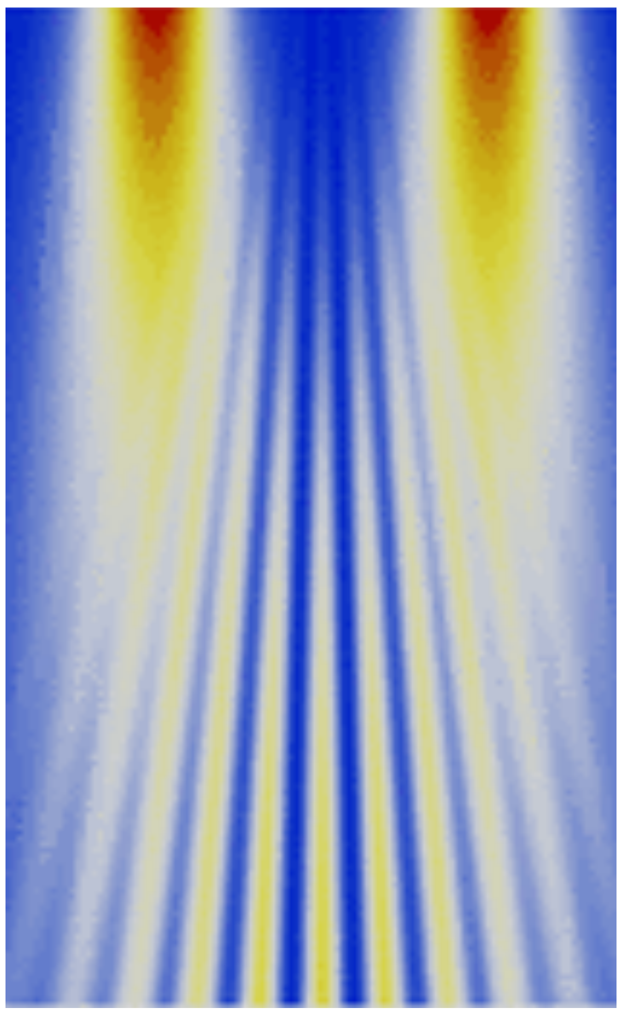


Asymmetric Interferometer (MZI)

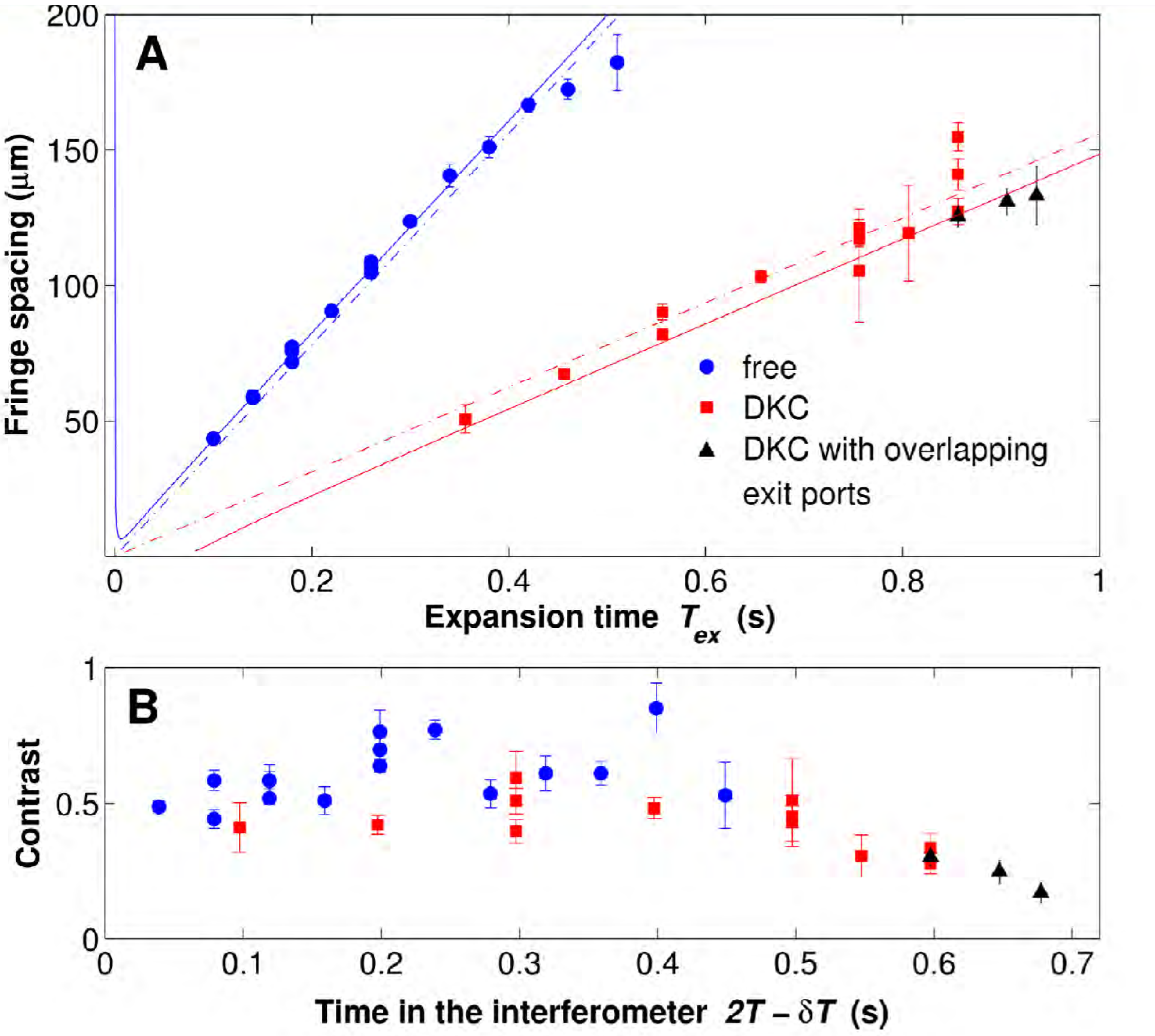


A gigantic meter-length double slit experiment



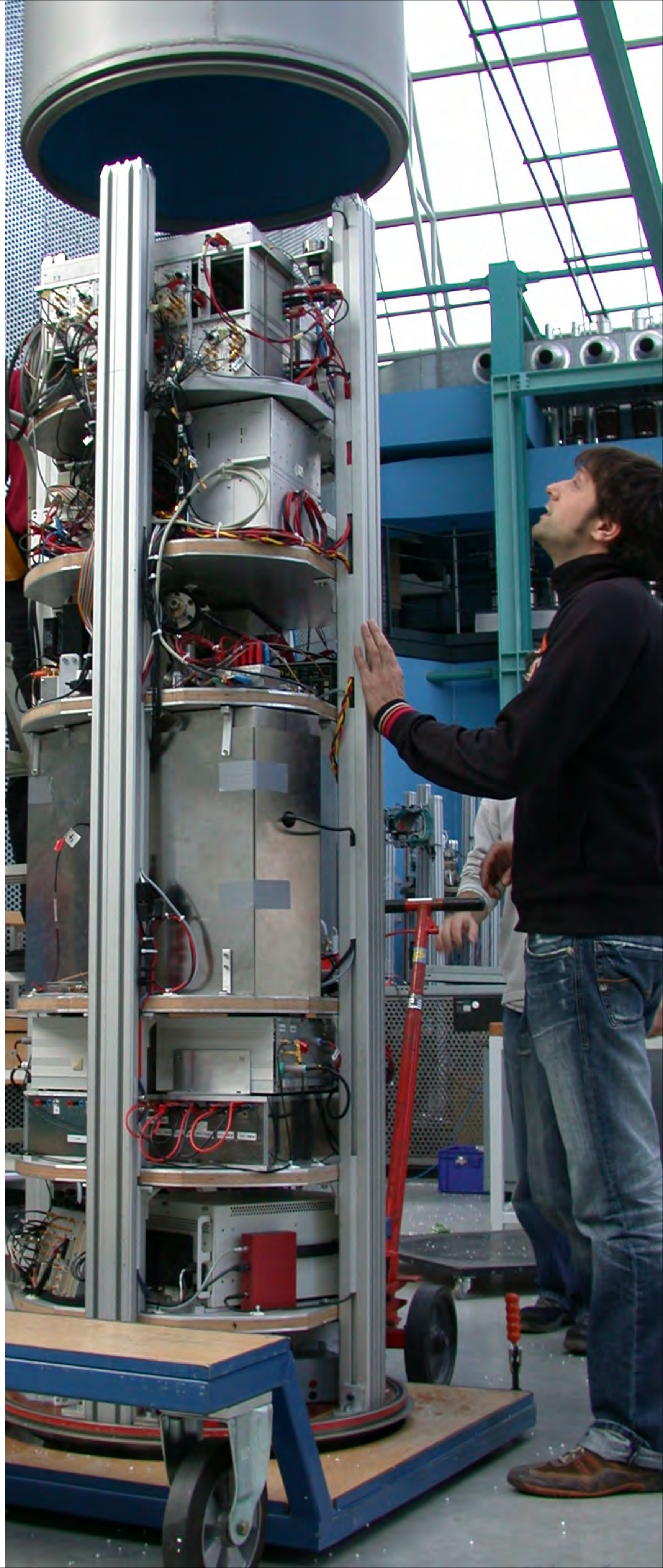


Coherence of BEC w/wo DKC in microgravity



The achievements of QUANTUS I

- Demonstration of technological feasibility of Bose Einstein Condensation in microgravity
- Interferometer based on BEC in microgravity
- Longest observed BEC in free fall
- Longest matter wave Interferometer time demonstrated in microgravity (2T=600 ms)
- Biggest spatial (with respect to actual size) and temporal separation of a macroscopic wave packet
- Laboratory for testing the necessary tools for high resolution atom interferometry in microgravity / extended free fall
- nK/pK laboratory



Advantages

- Robust
- Low power, atoms are "close" to wires
- Large gradients, high trap frequencies

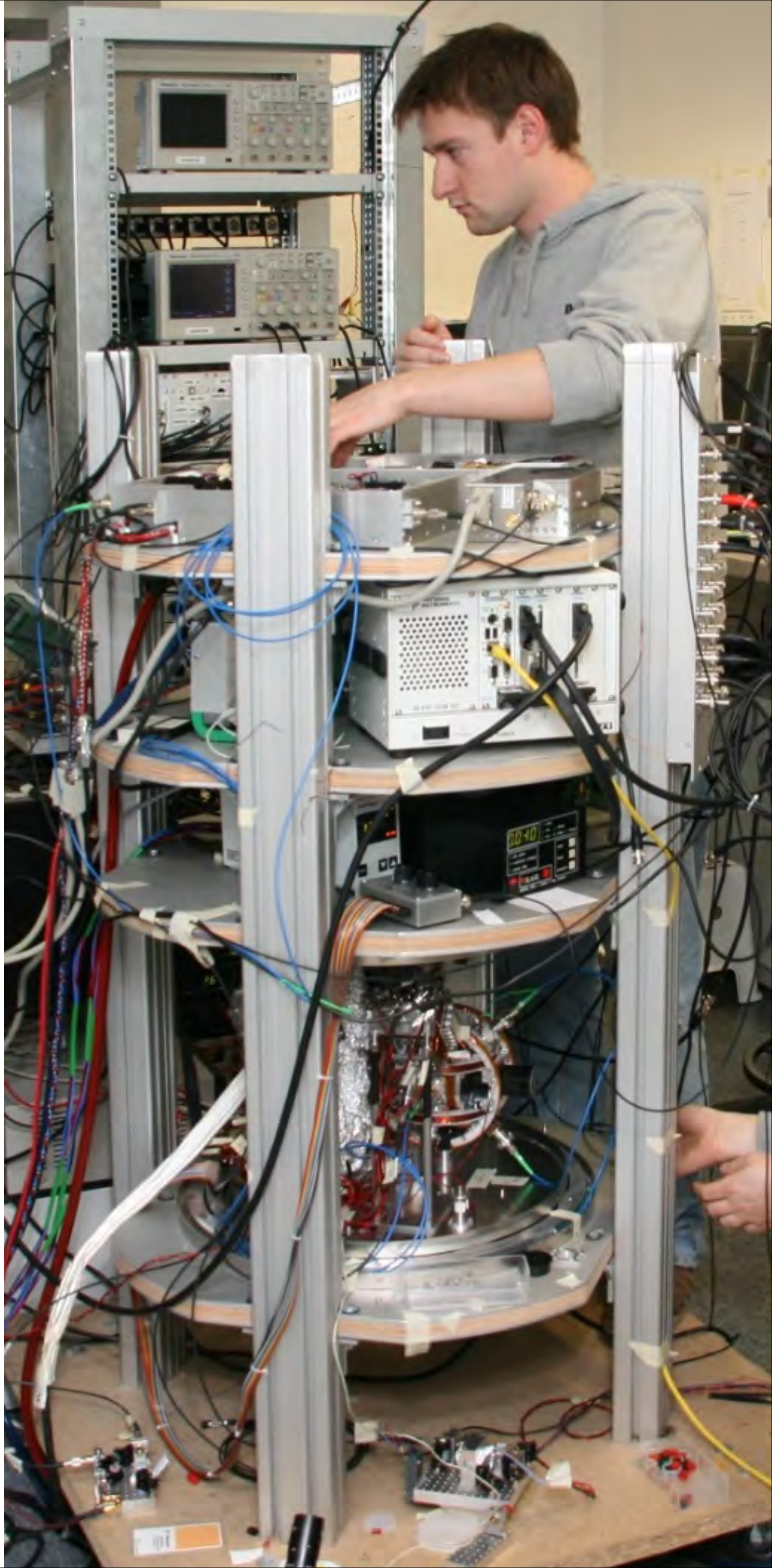
Challenges

- Small volumes
- Small atom numbers
- Background loading, slow loading times

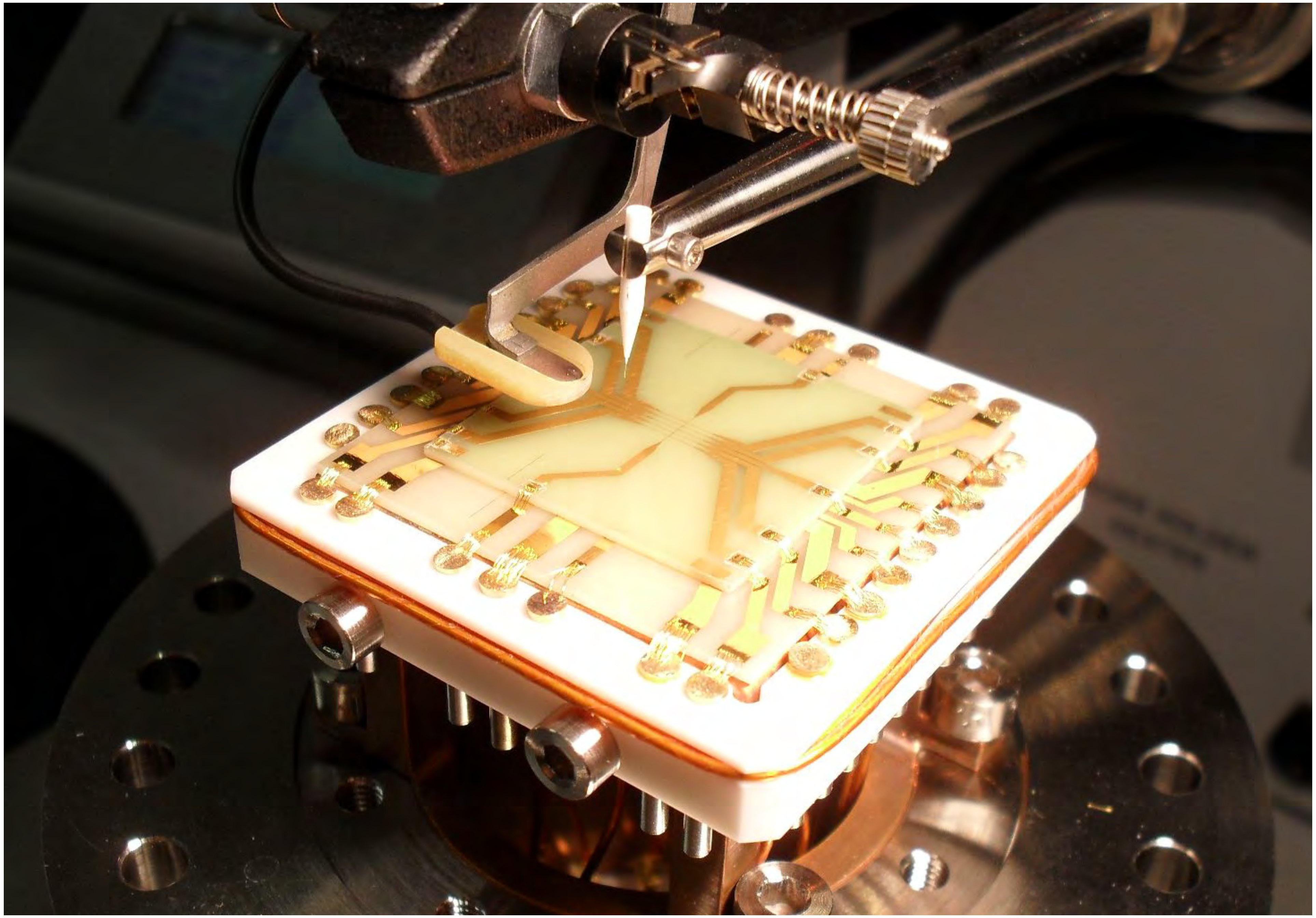
QUANTUS-1

versus

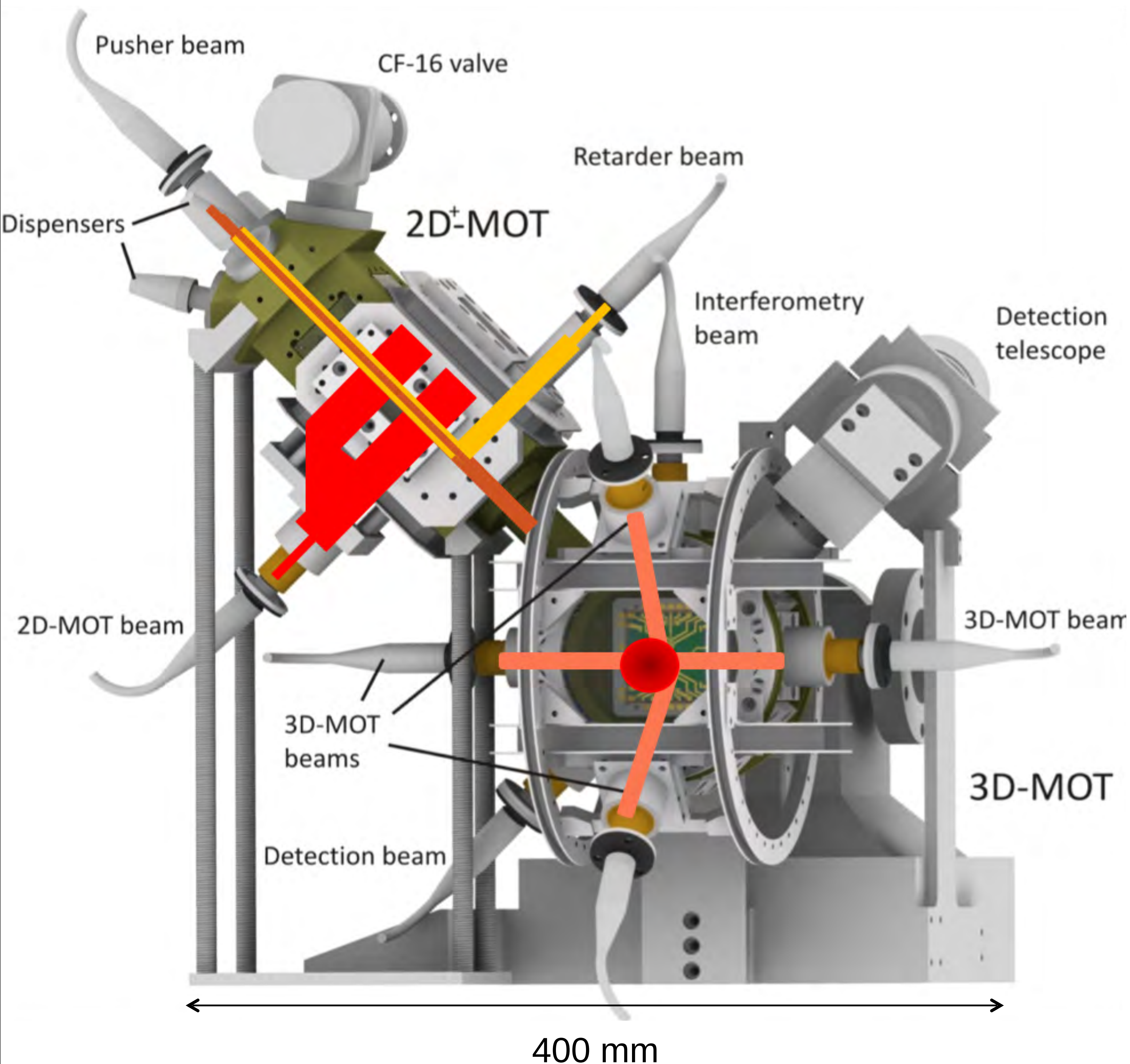
QUANTUS-2

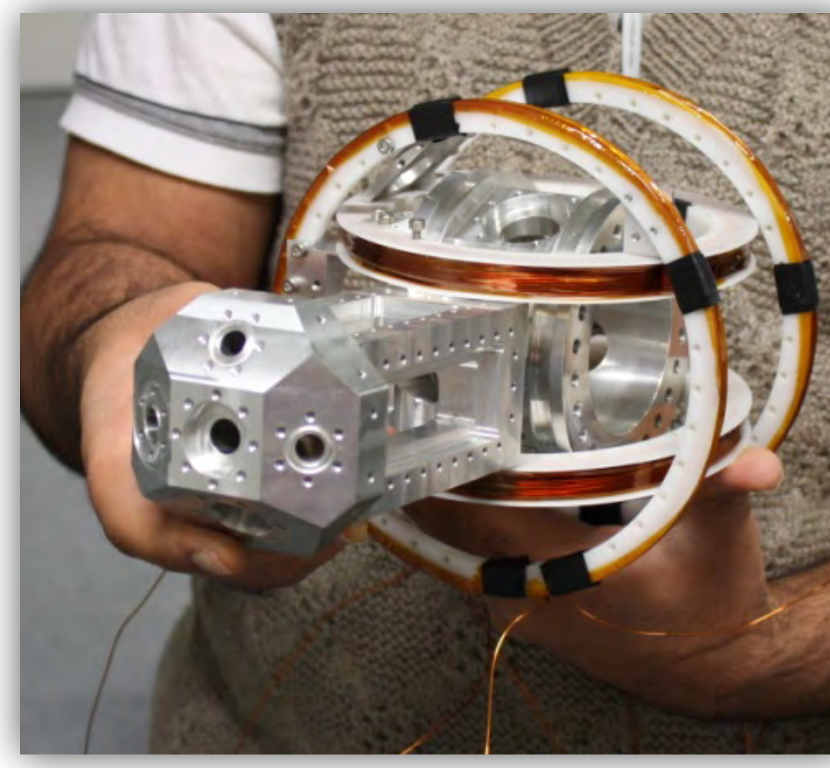


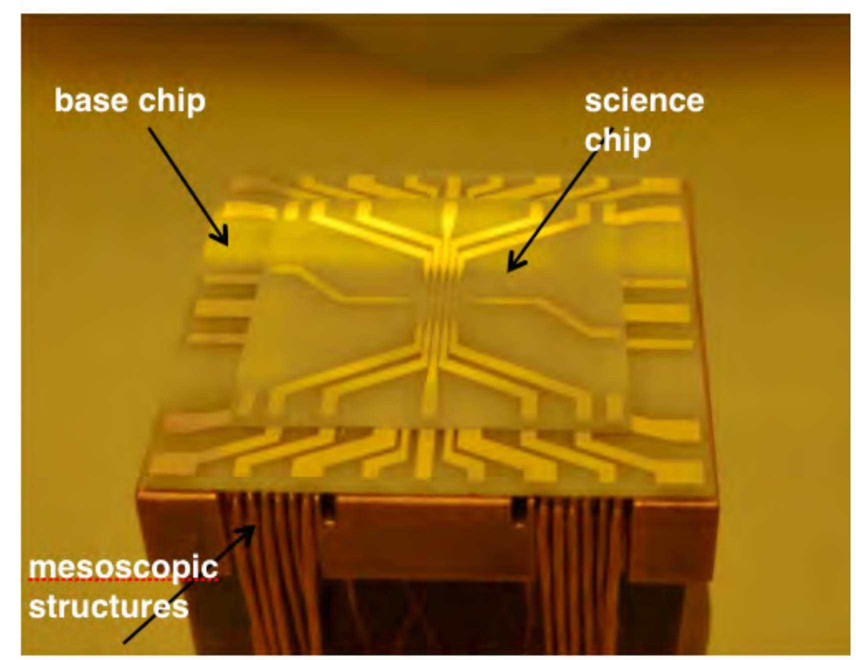
Advanced atom chips (QUANTUS 2)



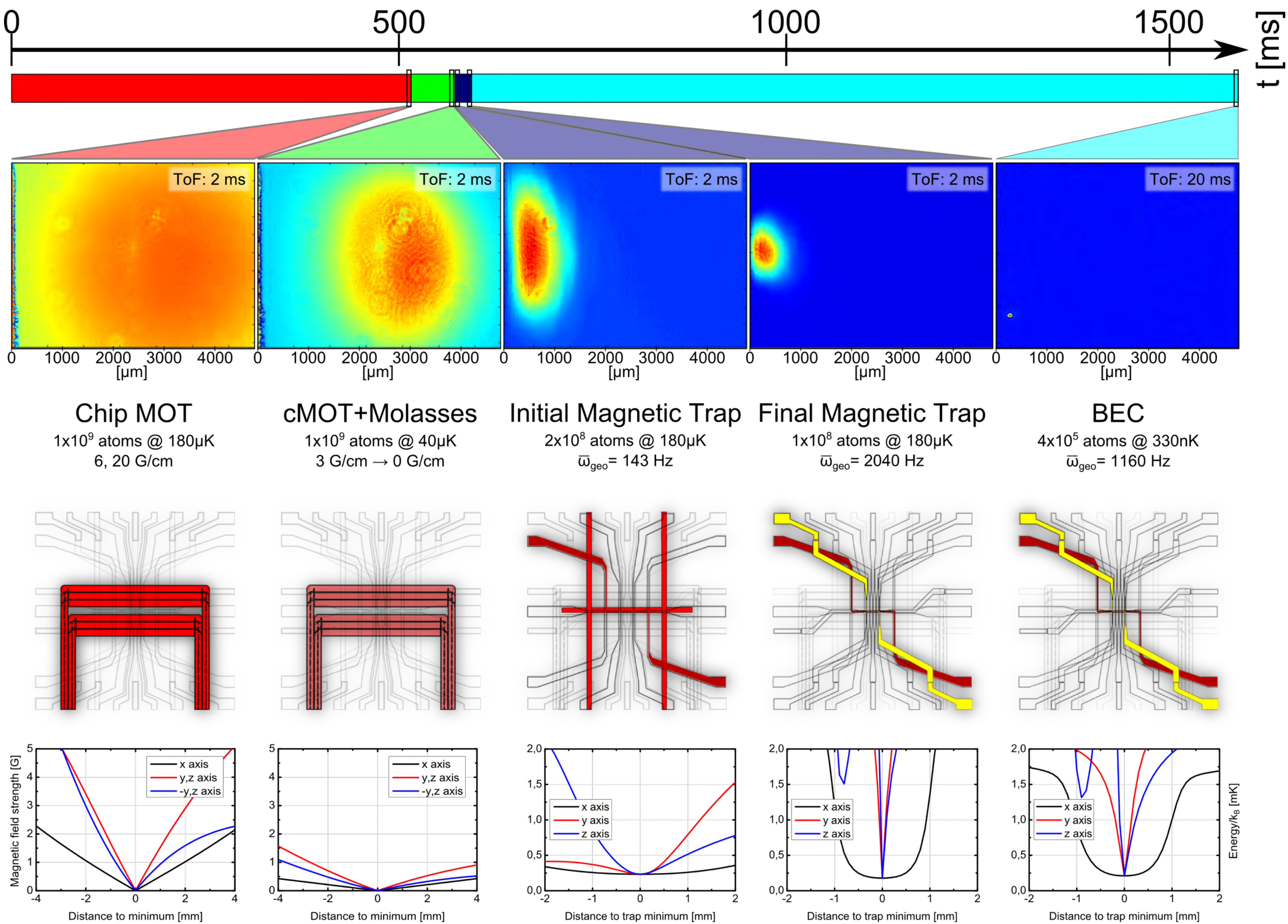
QUANTUS-2: setup







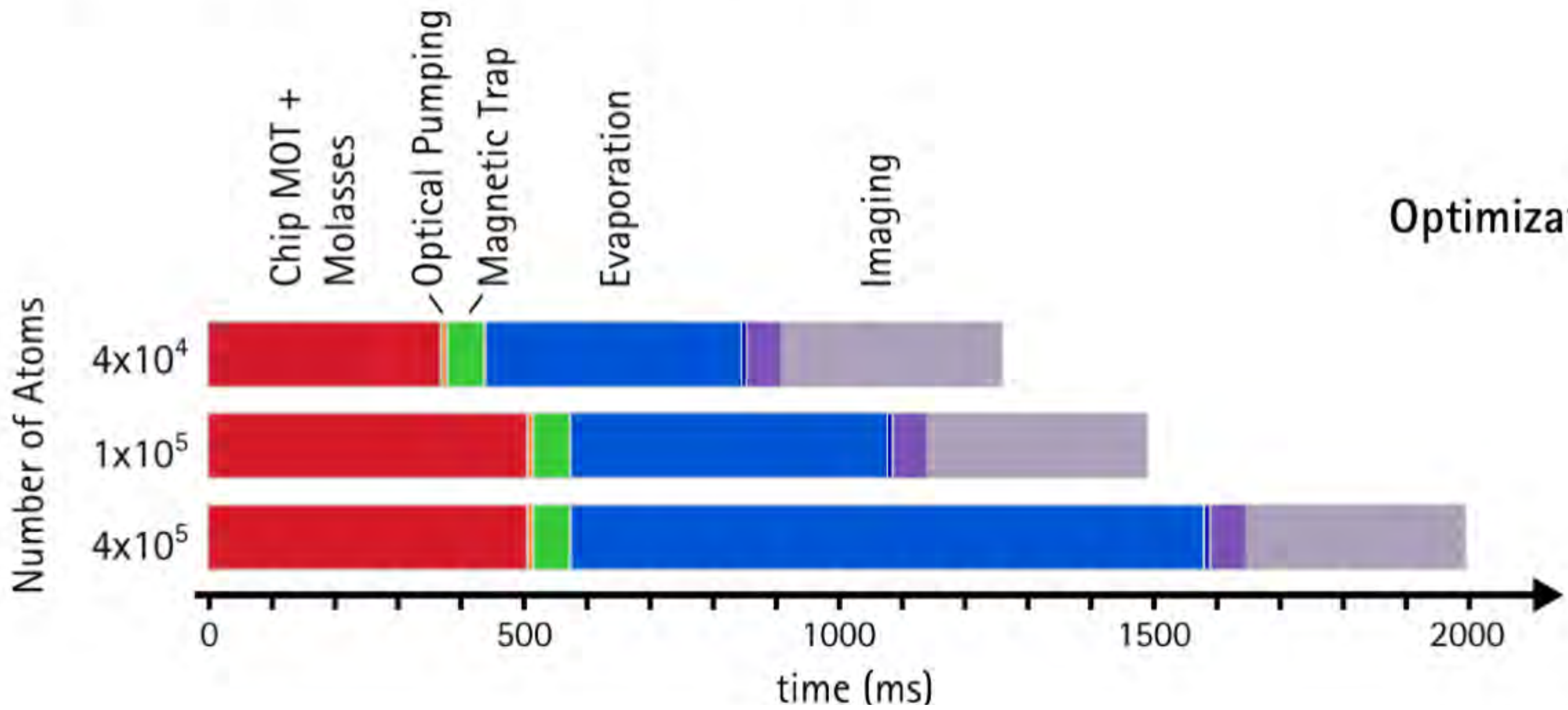
QUANTUS-2: experimental sequence



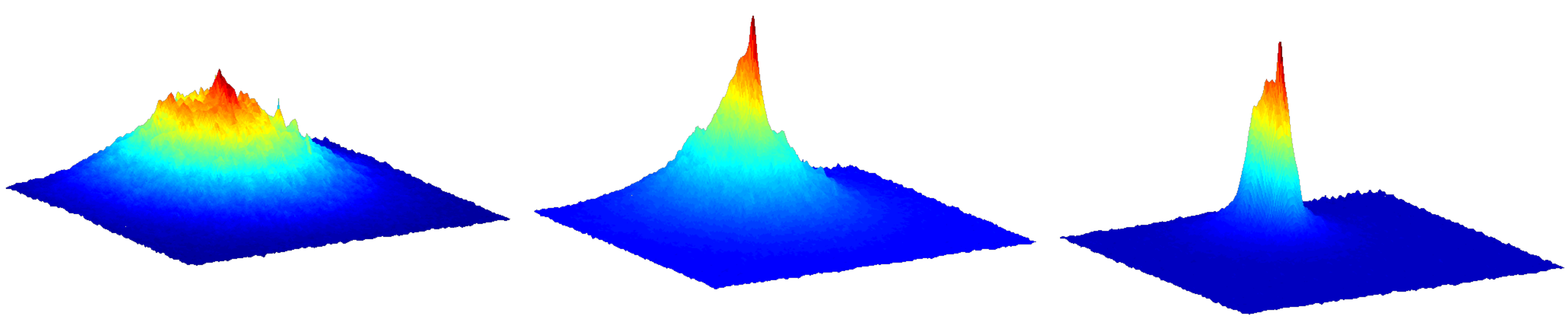
QUANTUS-2: performance

Particle number in dependence of BEC creation time:

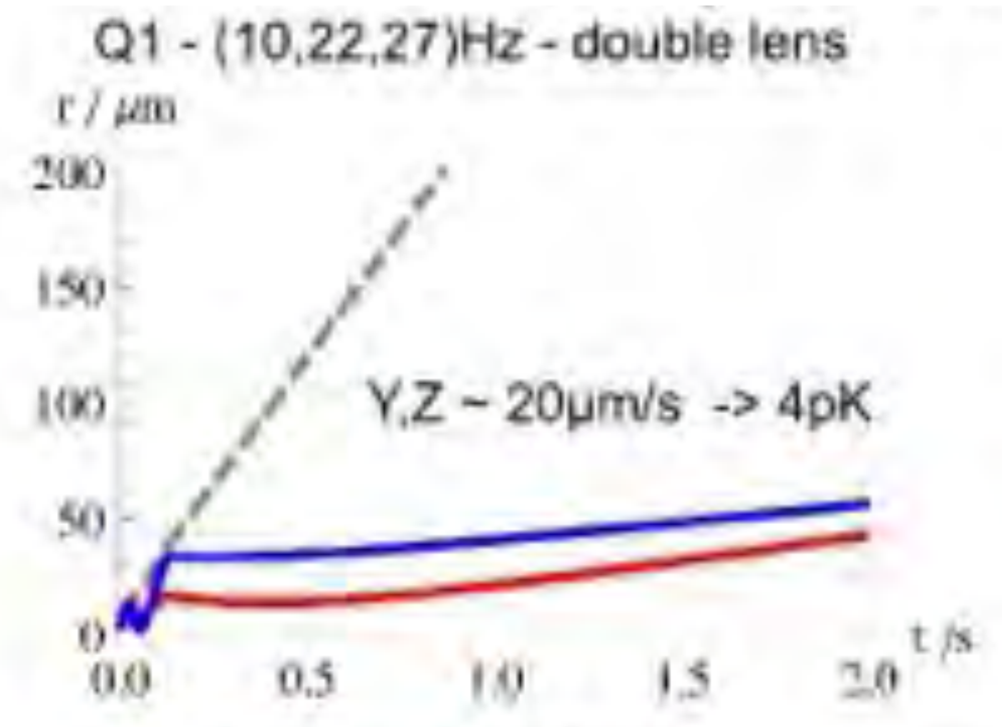
- Largest BEC: 4×10^5 atoms in 1.6s
- Typical BEC: 1×10^5 atoms in 1.1s
- Fastest BEC: 4×10^4 atoms in 0.85s

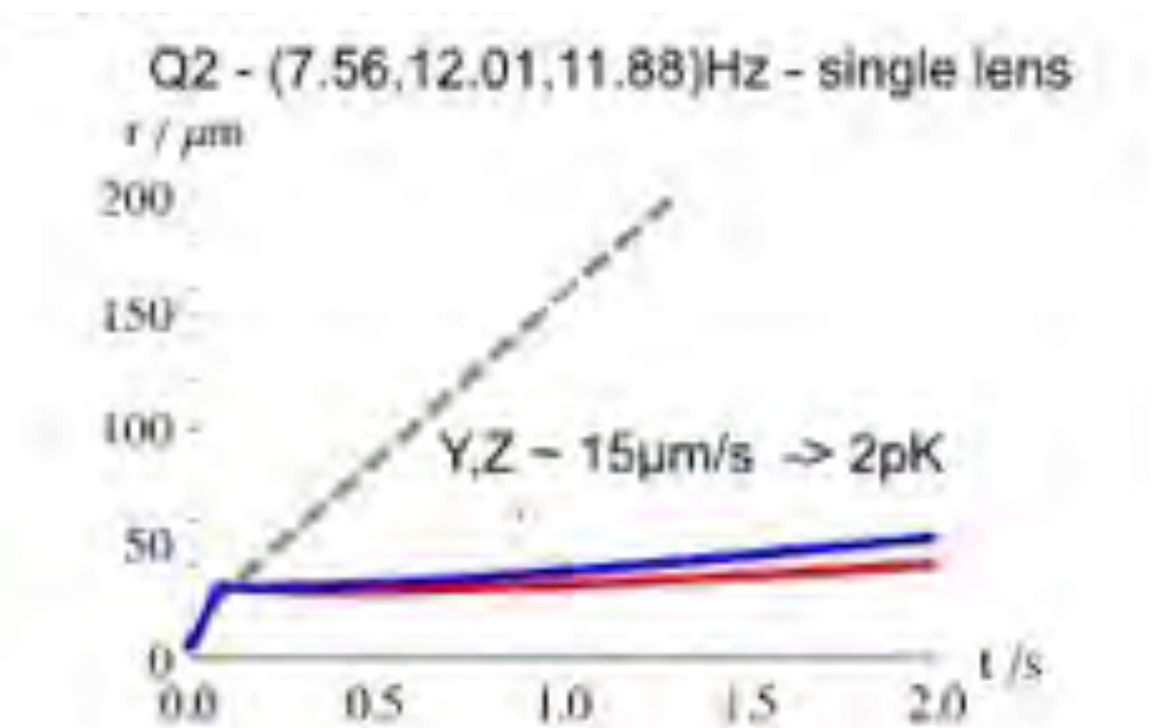


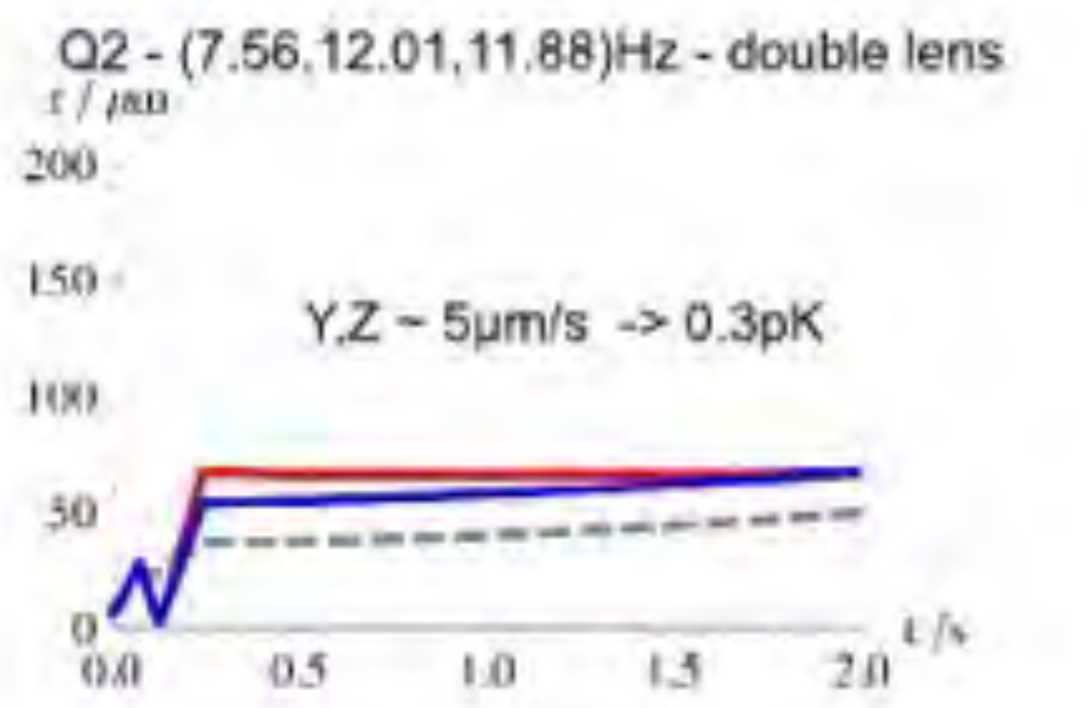
Optimization ongoing!



QUANTUS-2: DKC performance







Advantages

- Robust
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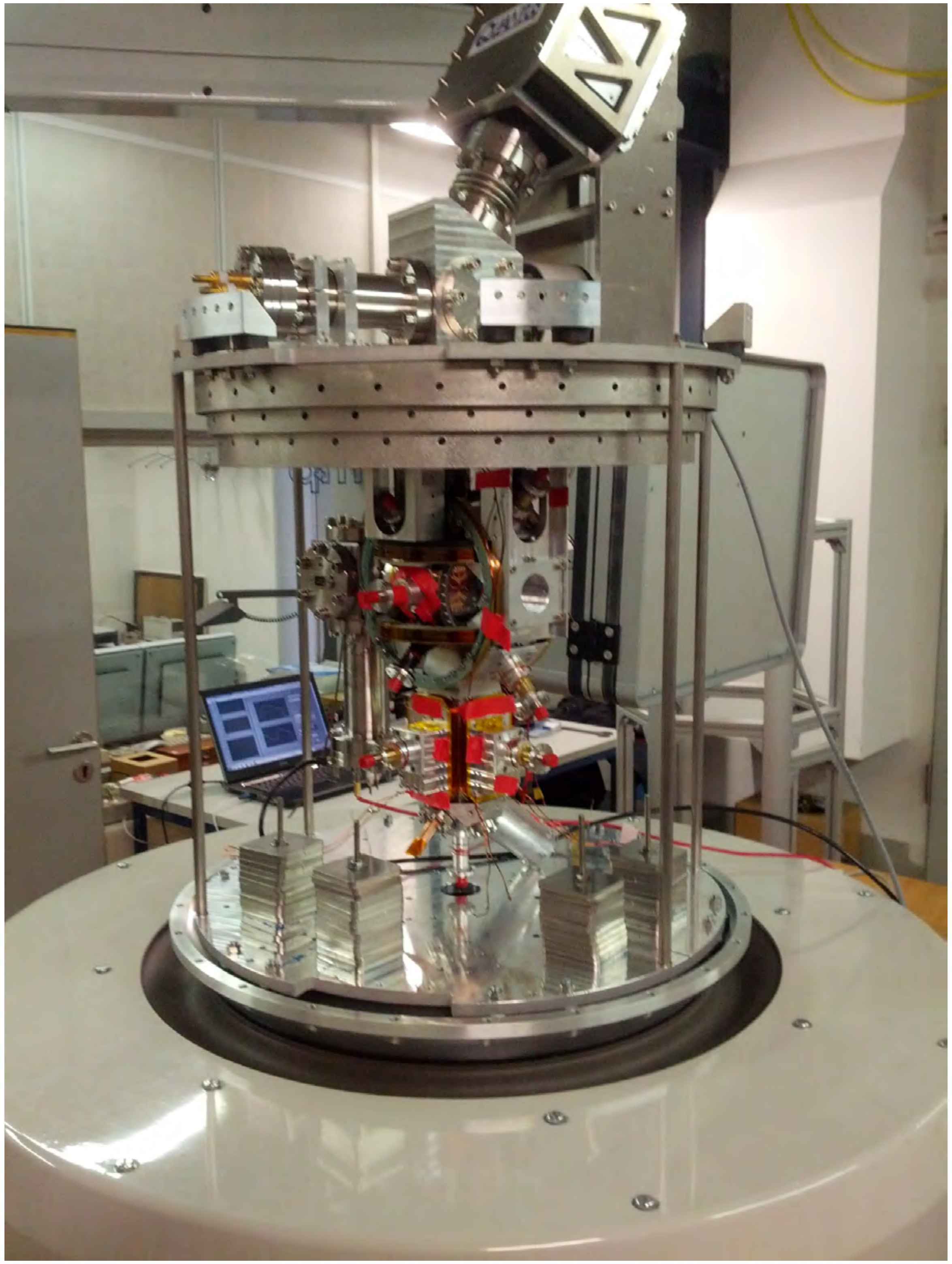
- Large gradients, high trap frequencies

Challenges

- Small volumes
- Small atom numbers
- Background loading, slow loading times

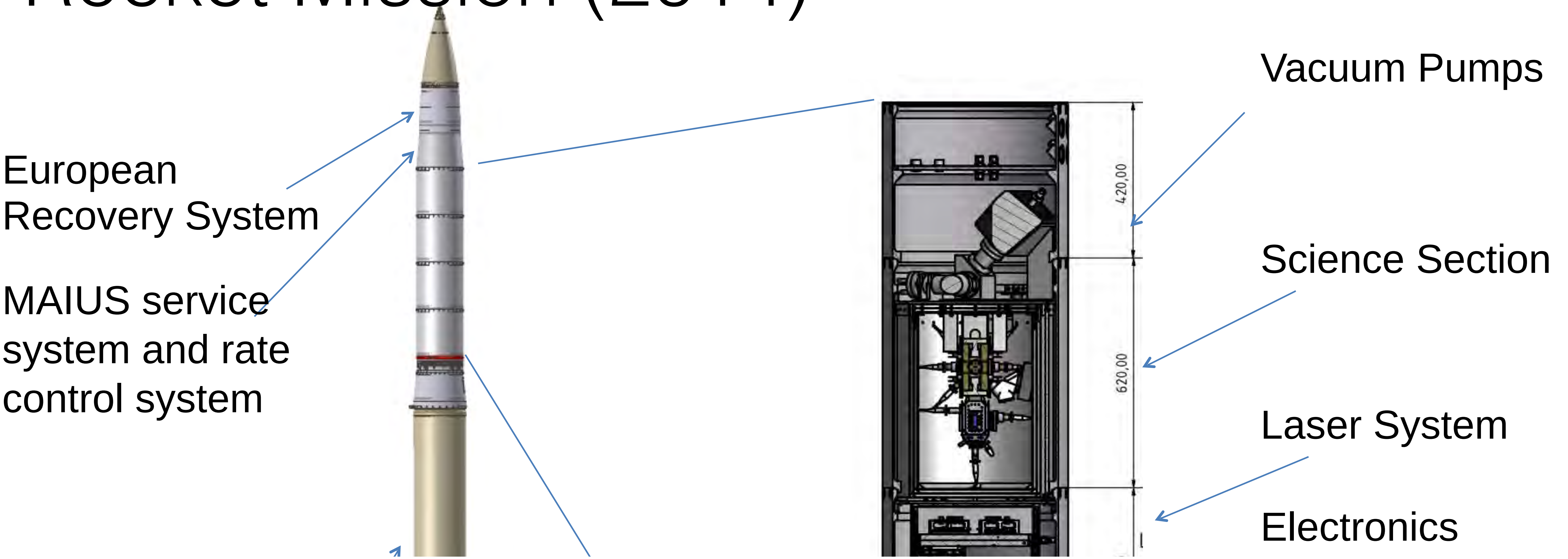
Chip based atom interferometers



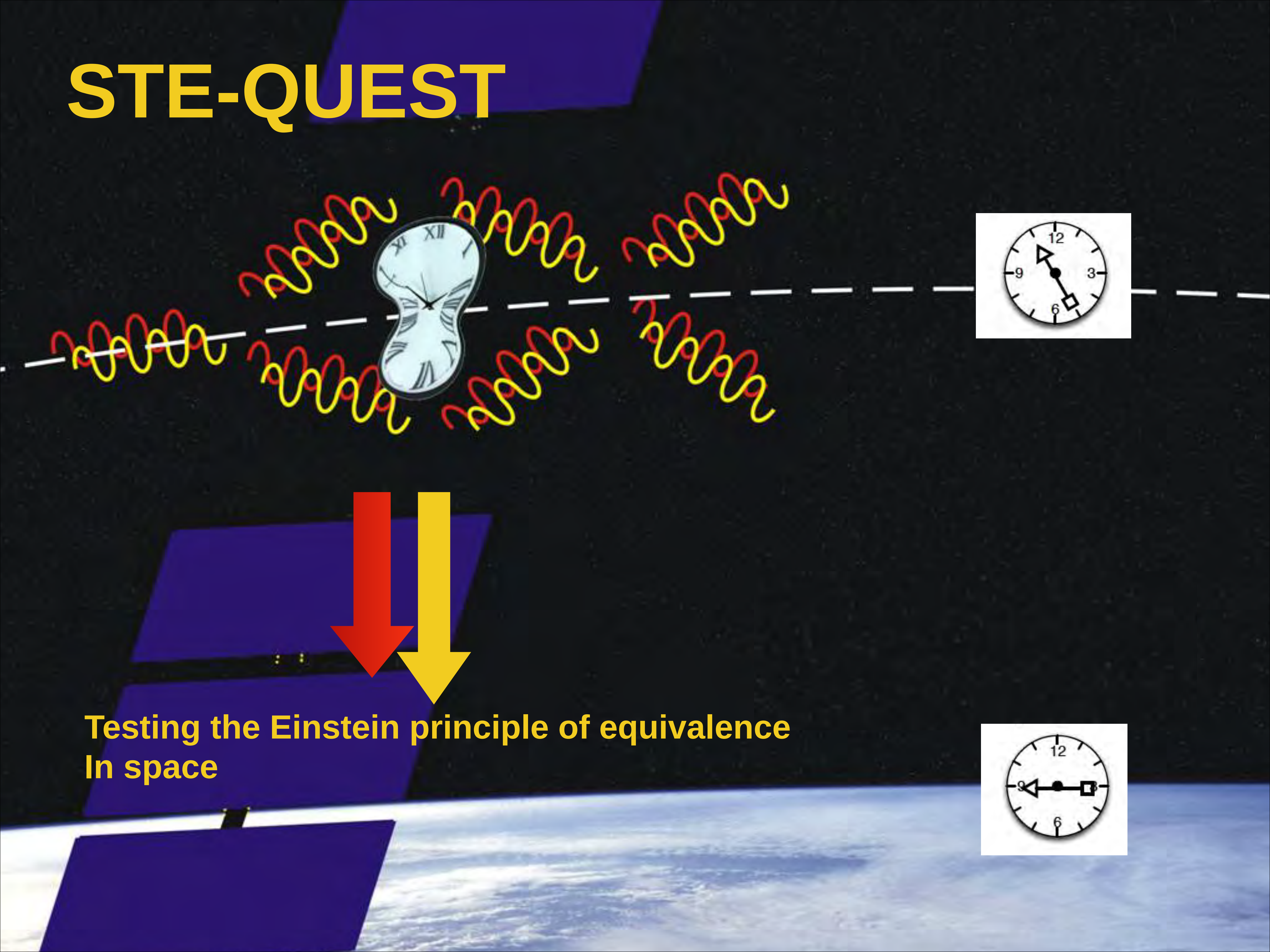
Shaker test of a chip-based atom interferometer

- New window for accuracy for gravimetry thanks to ultra cold matter
- High flux, fast, compact
- New concepts for interferometry
- Robust devices without mechanical parts (5.4 g RMS 60s)
- Autonomous operation

MAIUS: An Atom-Interferometry Sounding Rocket Mission (2014)

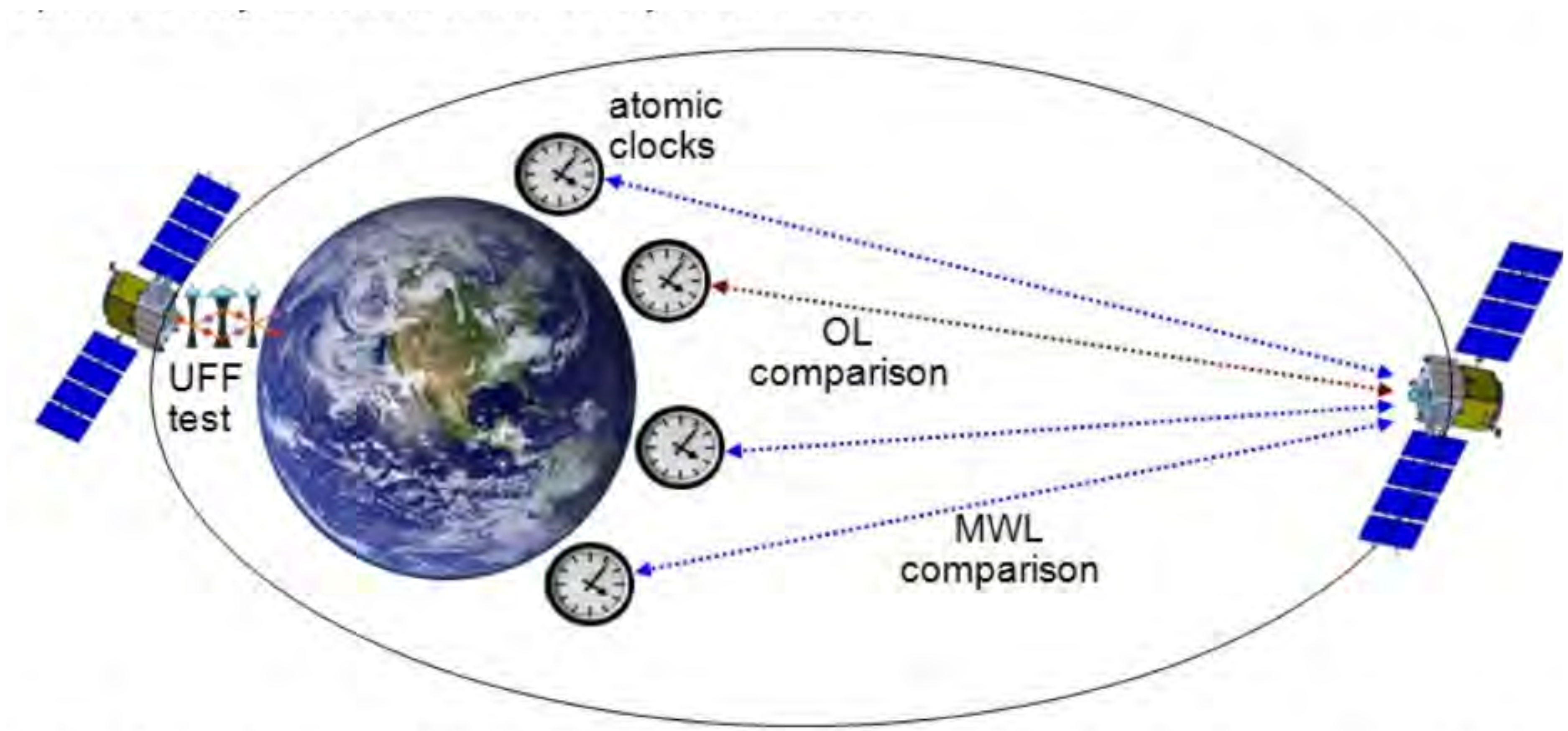


- Goals
  - First demonstration of a BEC-based atom interferometer on a sounding rocket
  - Testing interferometry and probing quantum mechanics at unprecedented times scales
  - Achieving ultra low energy ensembles


STE-QUEST
Testing the Einstein principle of equivalence
In space

Science Objective of the STE-QUEST ATom Interferometers (ATI)

- Comparison of the propagation of matter waves (85/87 Rb) in the Earths gravitational field to parts in 10^{15}

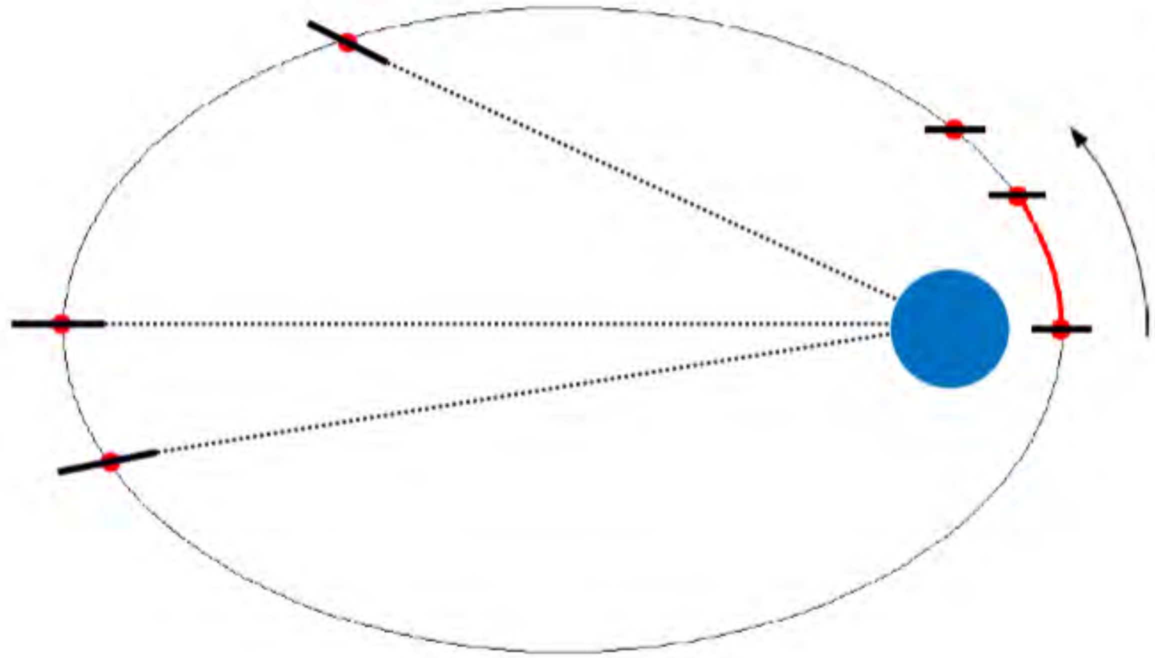


Measurement & Characterisation

Characterisation

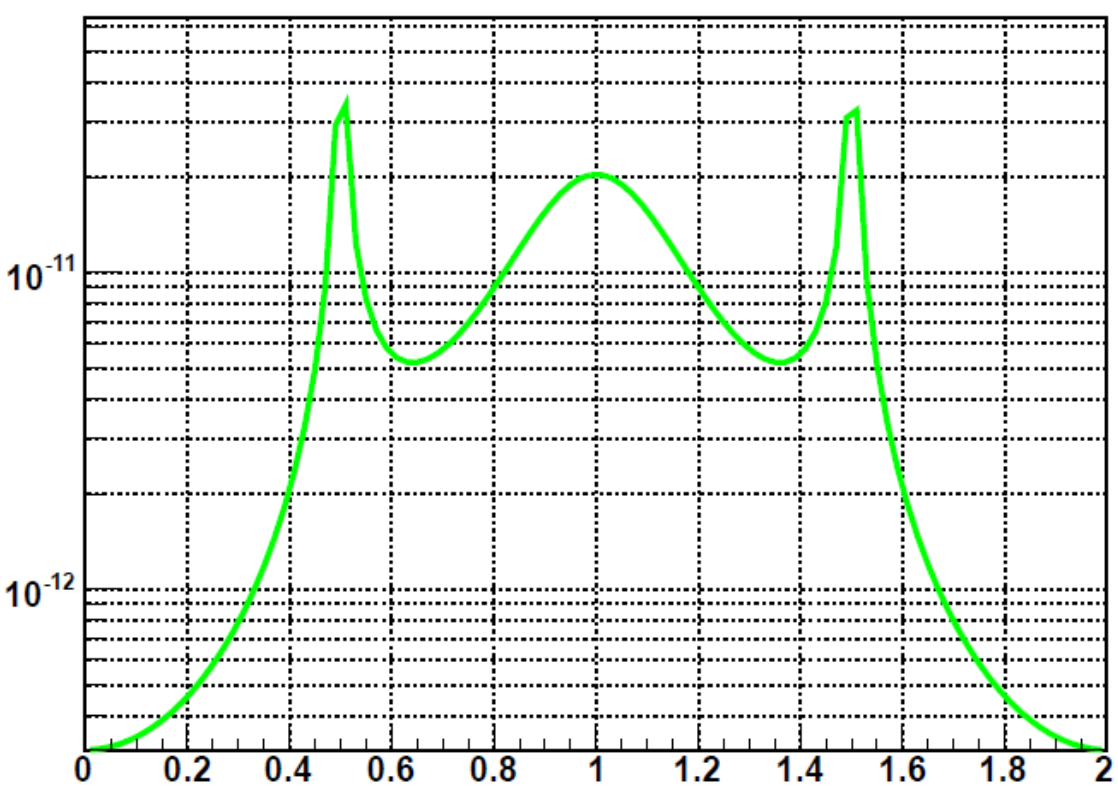
Eötvös ratio: $\eta(87,85) = \frac{|a_{87} - a_{85}|}{g(r)} = \frac{|\Delta a|}{g(r)}$

Apogee:
- g << 3 m/s²
- rotation rate $2.2 \cdot 10^{-5}$ rad/s
- Contrast < 0.007 with T = 5 s



Perigee:
- g > 3 m/s²
- rotation rate $1 \cdot 10^{-6}$ rad/s
- Contrast > 0.6 with T = 5 s

non-rotating satellite



Sensitivity: $\sigma_{\Delta a} = 2.92 \cdot 10^{-12}\ \mathrm{m/s^2}$

(single shot, differential, 60 % contrast at 700 km altitude)

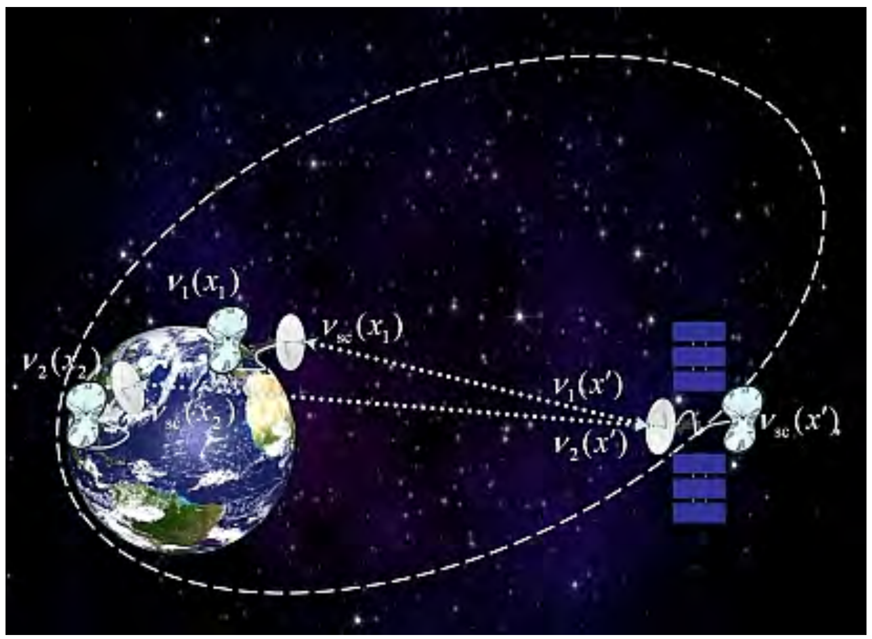
↓ integration to reach $\eta = 10^{-15}$

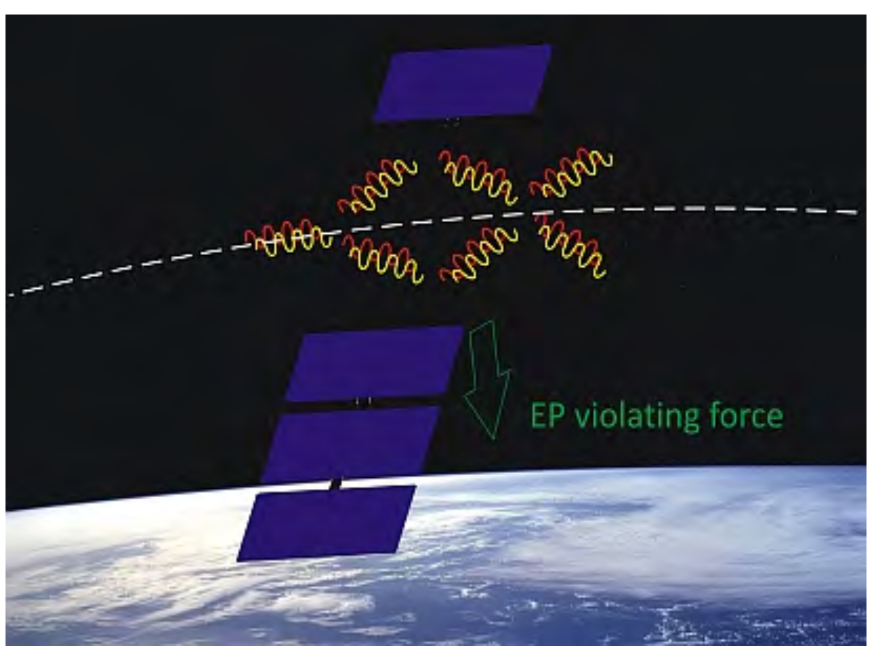
$\sigma_{\eta,1orbit,700} = 4.65 \cdot 10^{-14}$ → 2163 orbits

$\sigma_{\eta,1orbit,1900} = 4.85 \cdot 10^{-14}$ → 2353 orbits = 4.3 years

Space-Time Explorer and QUantum Equivalence principle Space Test (STE-QUEST)

Atom interferometer part: test of the weak equivalence principle to one part in 10^{15}





Dual species atom interferometer

- 0.07 nK ^{87}Rb / ^{85}Rb ensembles
- 10^6 atoms each
- scaling factor kT^2, $\mathrm{k} = 8\pi/(780\ \mathrm{nm})$, T = 5 s
- cycle time 20 s

Eötvös ratio: $\eta(87{,}85) = \frac{|a_{87} - a_{85}|}{g(r)} = \frac{|\Delta a|}{g(r)}$

Sensitivity: $\sigma_{\Delta a} = 2.92 \cdot 10^{-12}\ \mathrm{m/s^2}$

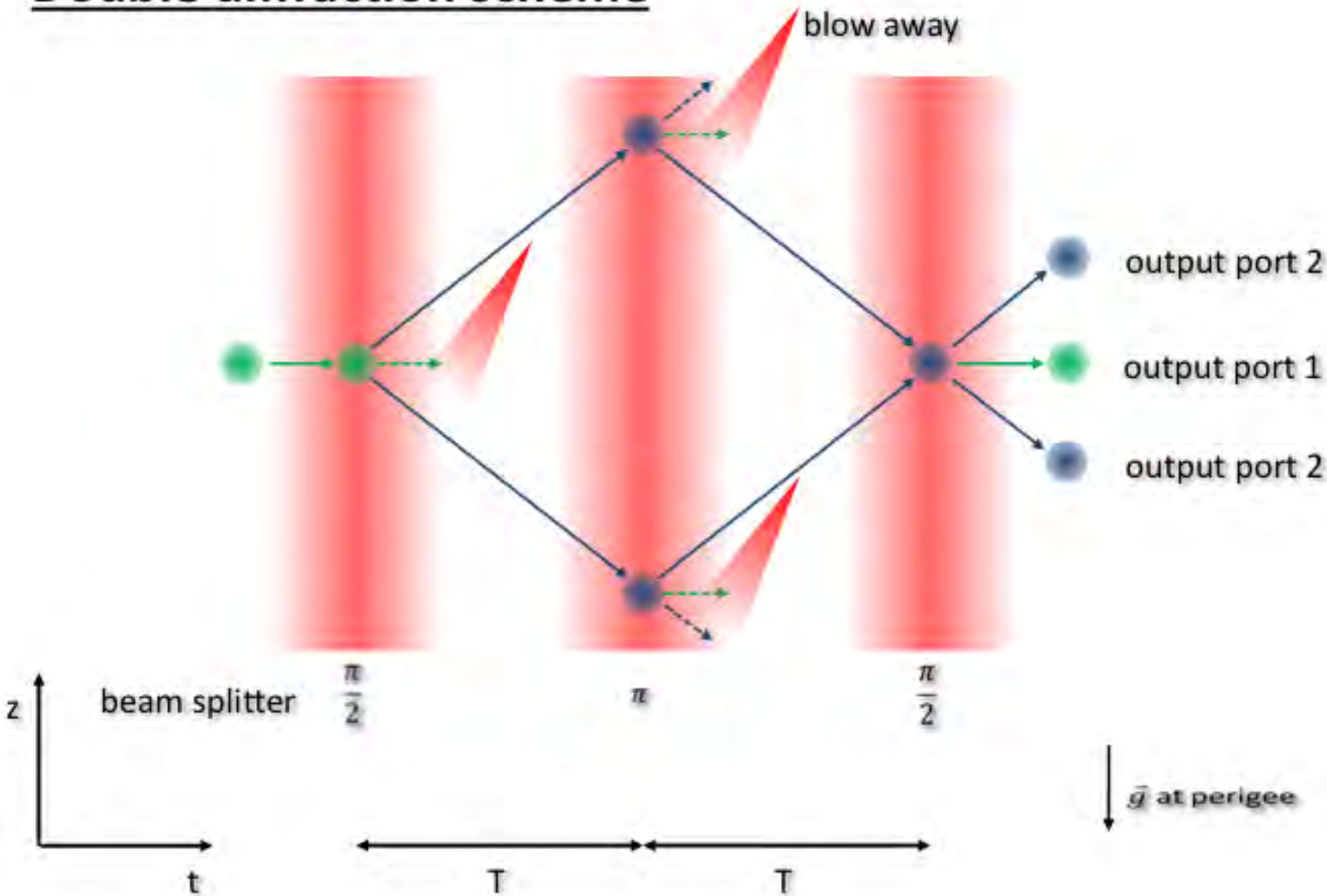
(single shot, differential, 60 % contrast at 700 km altitude)

integration to reach $\eta = 10^{-15}$

$\sigma_{\eta,1orbit,700} = 4.65 \cdot 10^{-14}$ → 2163 orbits

$\sigma_{\eta,1orbit,1900} = 4.85 \cdot 10^{-14}$ → 2353 orbits = 4.3 years

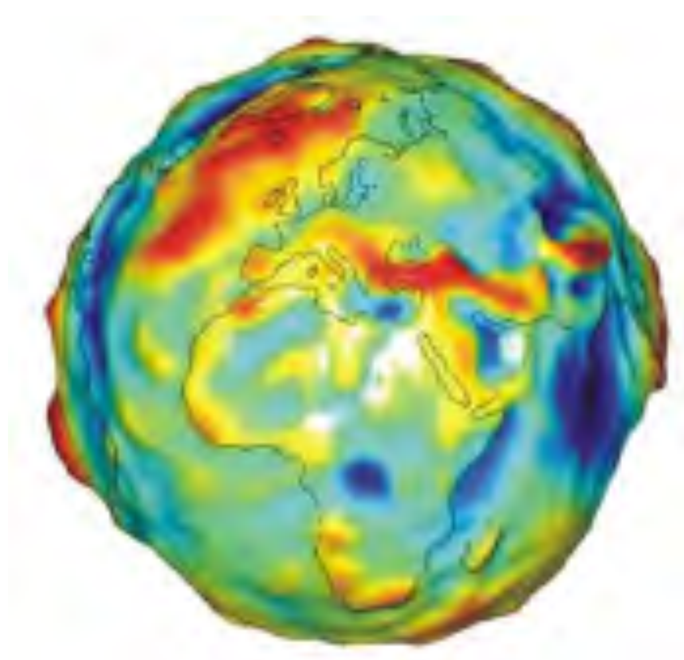
Double diffraction scheme



Motivations

Earth observation

- Precision gravimetry
- Rotation sensing



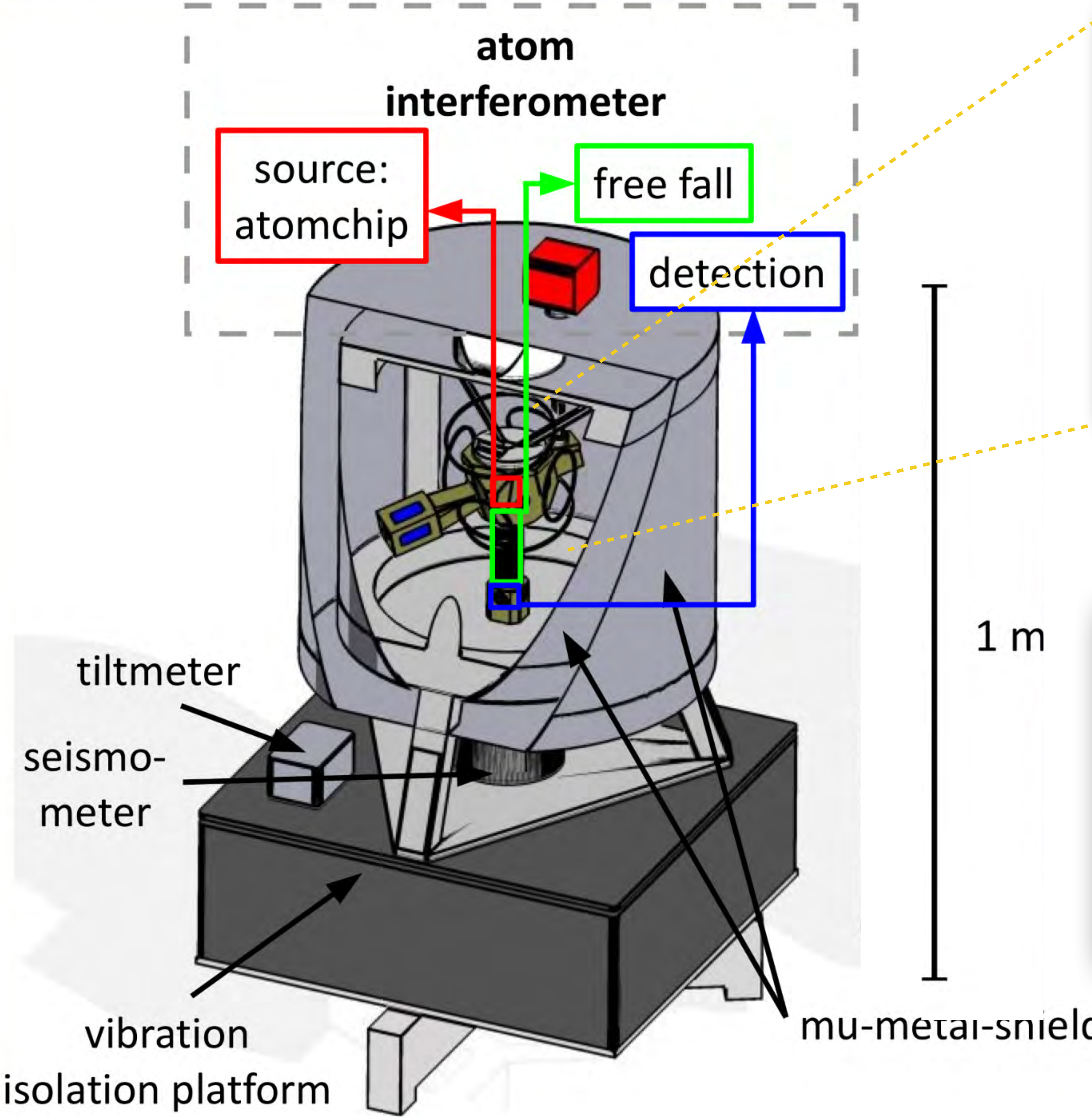
Fundamental physics

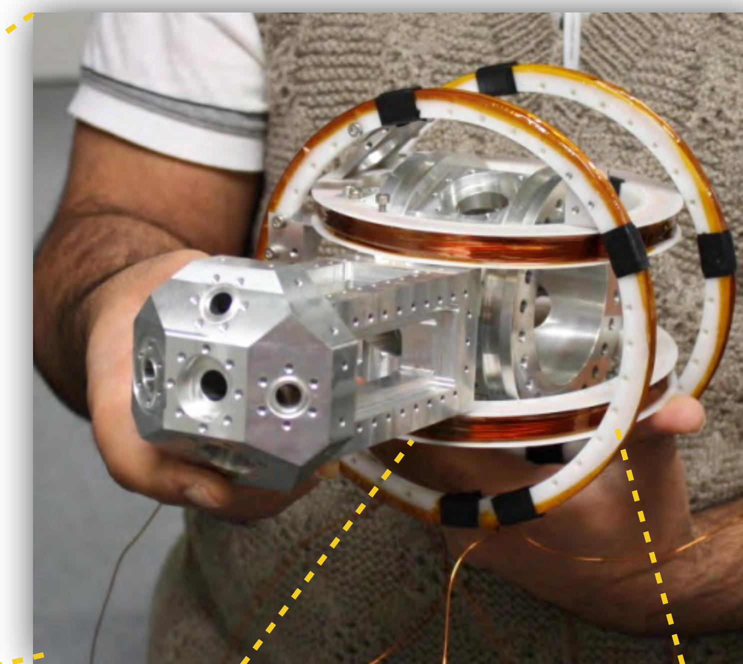
- Are inertial and gravitational mass really equivalent?
- Do all bodies fall equally?
- (De-)coherence

Perspectives

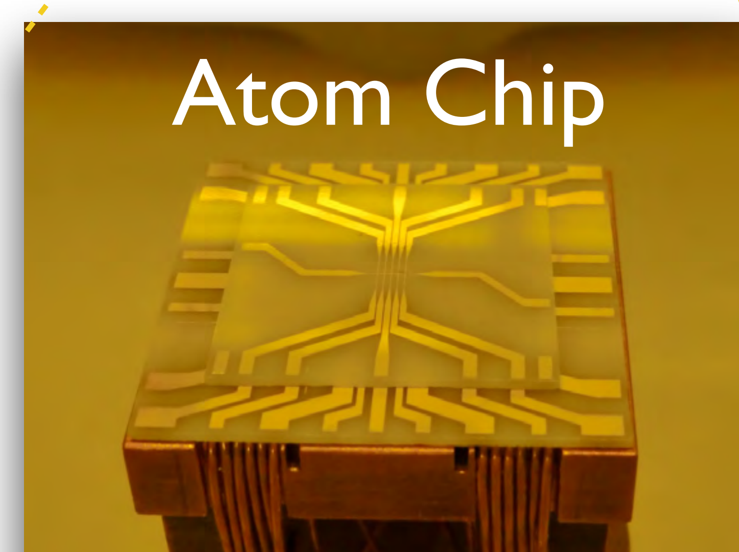
Spin-off: Quantum Gravimeter

Chip based quantum gravimeter





Cooperation with J. Müller, IfE

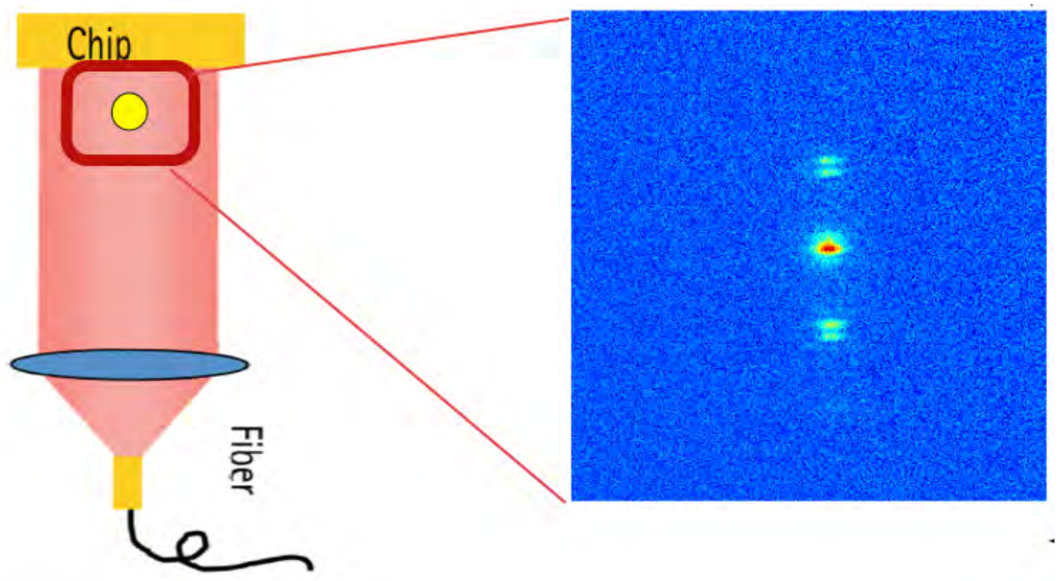


Particle number in dependence of BEC creation time:

- Largest BEC: $4x10^5$ atoms in 1.6s
- Typical BEC: $1x10^5$ atoms in 1.1s
- Fastest BEC: $4x10^4$ atoms in 0.85s

Chip-based quantum gravimeter

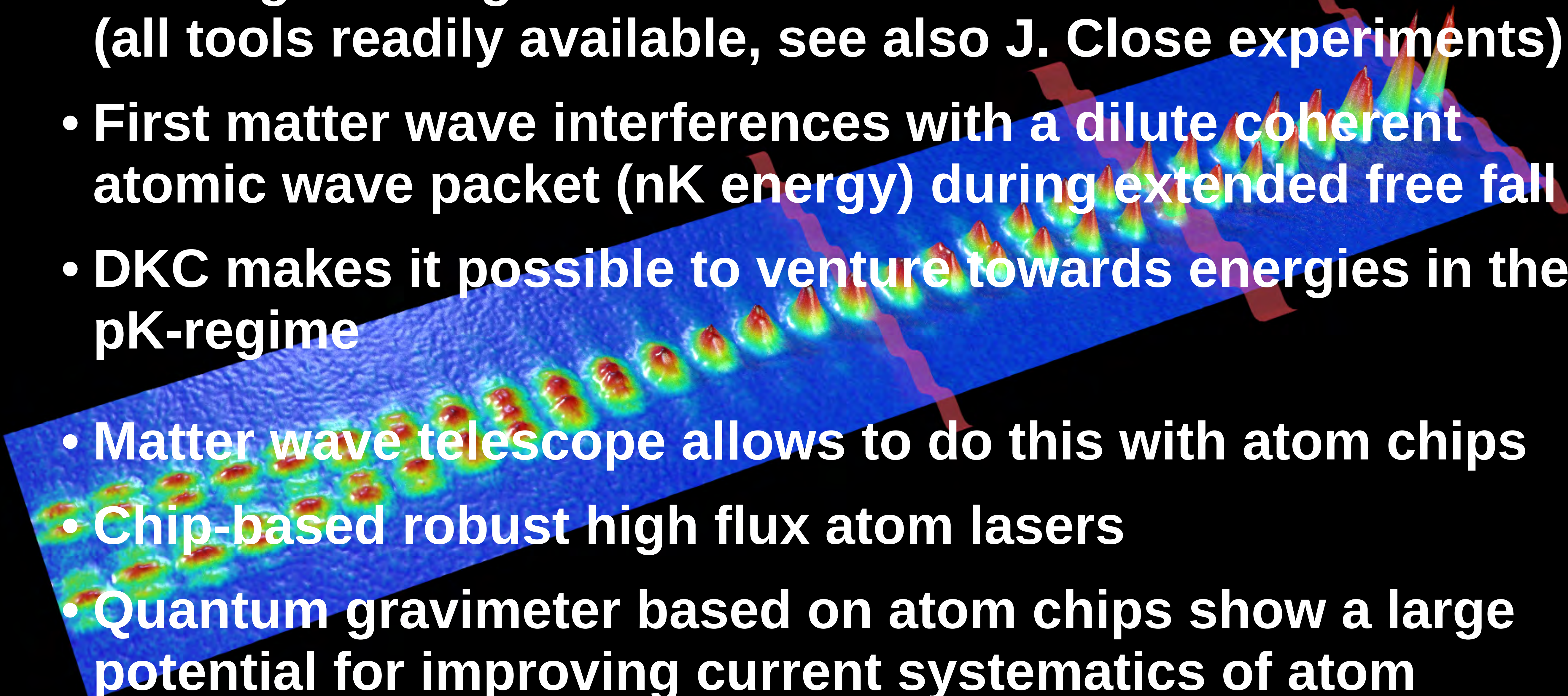
- High atom number
- Important functions can be made by atom chip
  - Trapping and evaporative cooling
  - Delta-kick cooling
  - Transfer into non-magnetic state
  - Reference mirror
- Sub recoil cold atoms
- Bragg interferometry



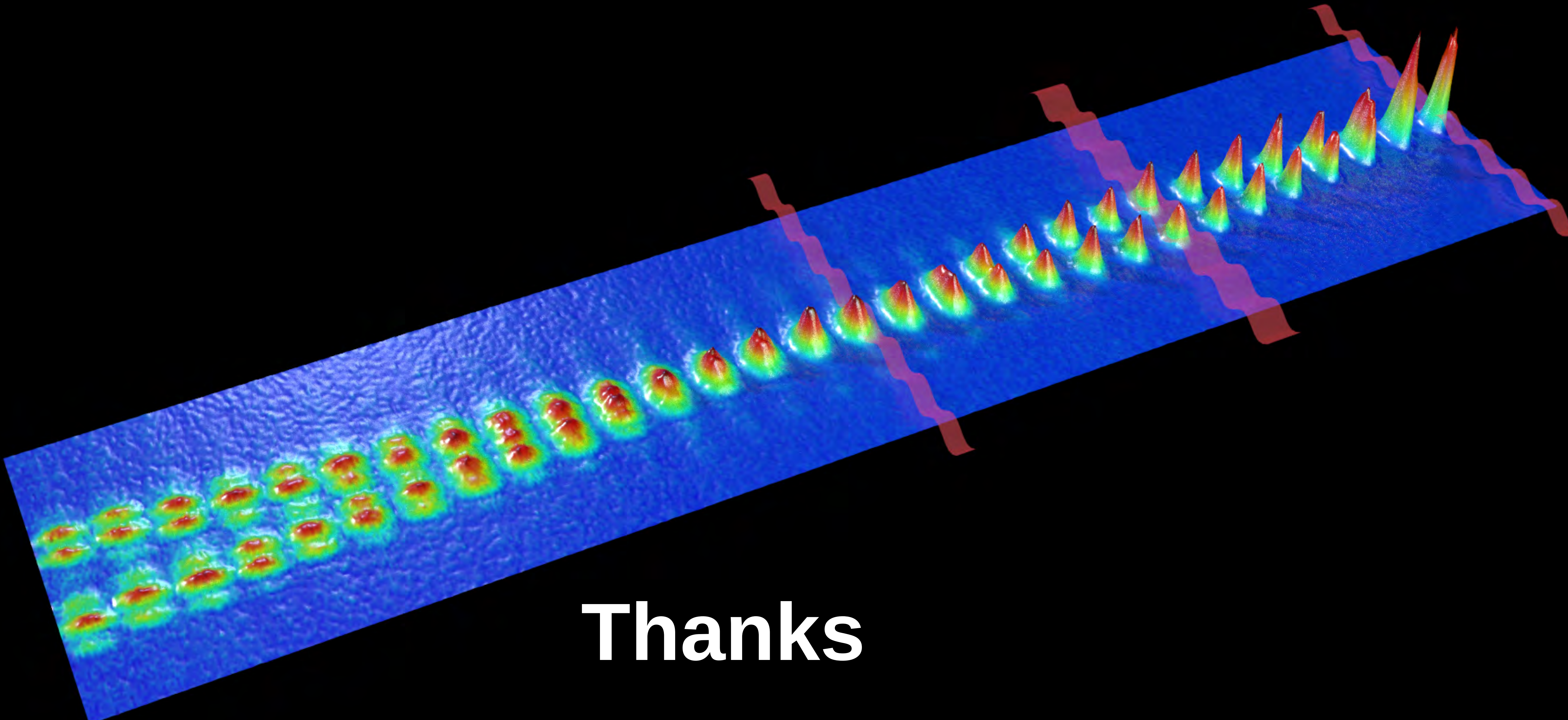
Summary

- Atom interferometer are promising tools for monitoring gravity over long time scales with high precision (absolute gravimetry)
- Instruments develop from laboratory devices to robust sensors
- Large potential for future improvements, large operational range
- New era of sub recoil cooled atoms will revolutionize high precision sensing
- Stationary facilities with unprecedented sensitivity are a new focus of research

Take home messages



- Paradigm change from laser cooled to ultra cold atoms (all tools readily available, see also J. Close experiments)
- First matter wave interferences with a dilute coherent atomic wave packet (nK energy) during extended free fall
- DKC makes it possible to venture towards energies in the pK-regime
- Matter wave telescope allows to do this with atom chips
- Chip-based robust high flux atom lasers
- Quantum gravimeter based on atom chips show a large potential for improving current systematics of atom interferometers
- Rocket capable atom interferometers test scheduled for 2014 to investigate matter waves at extended times of free fall

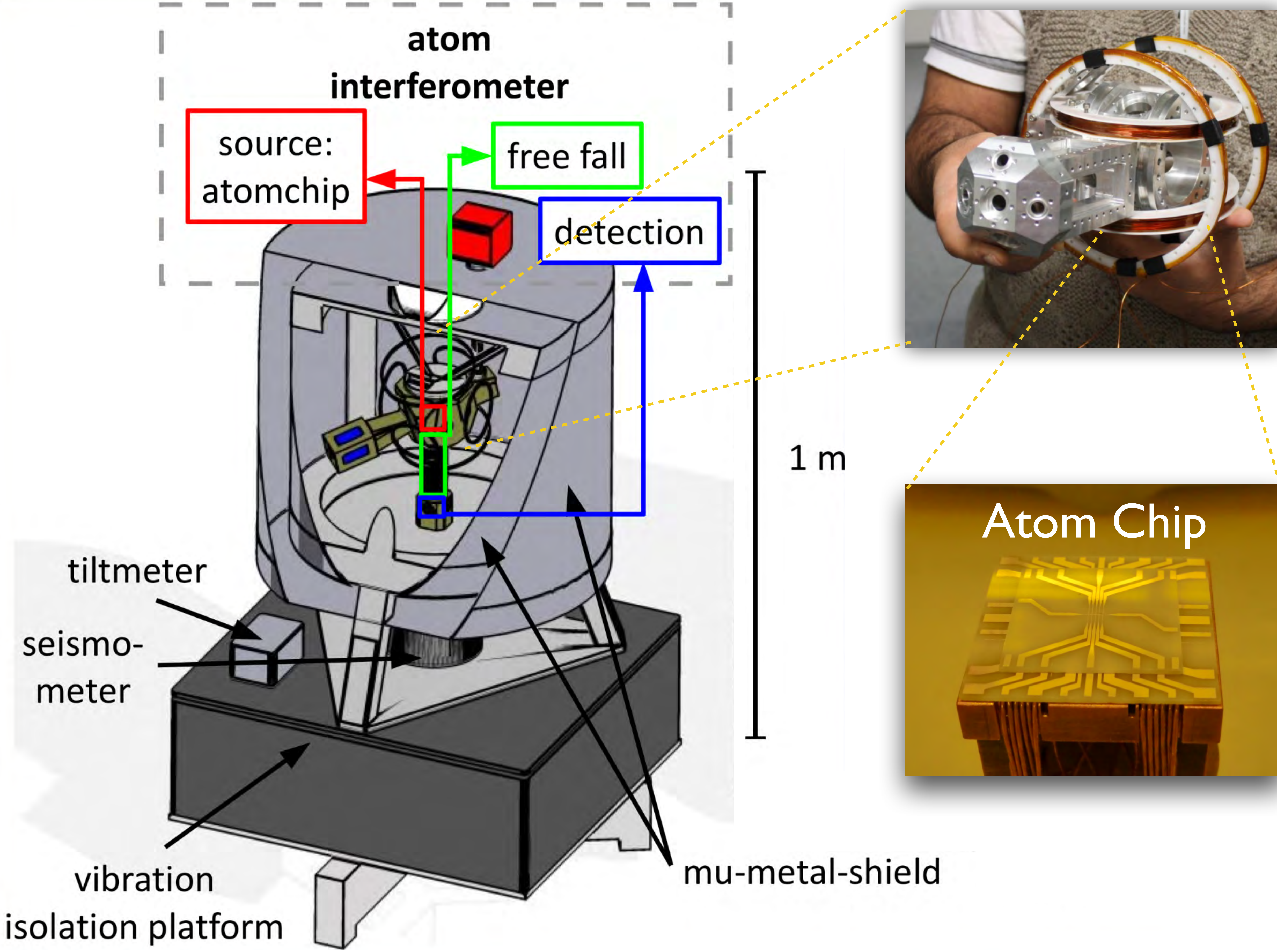


Thanks

atom interferometry

from small to tall

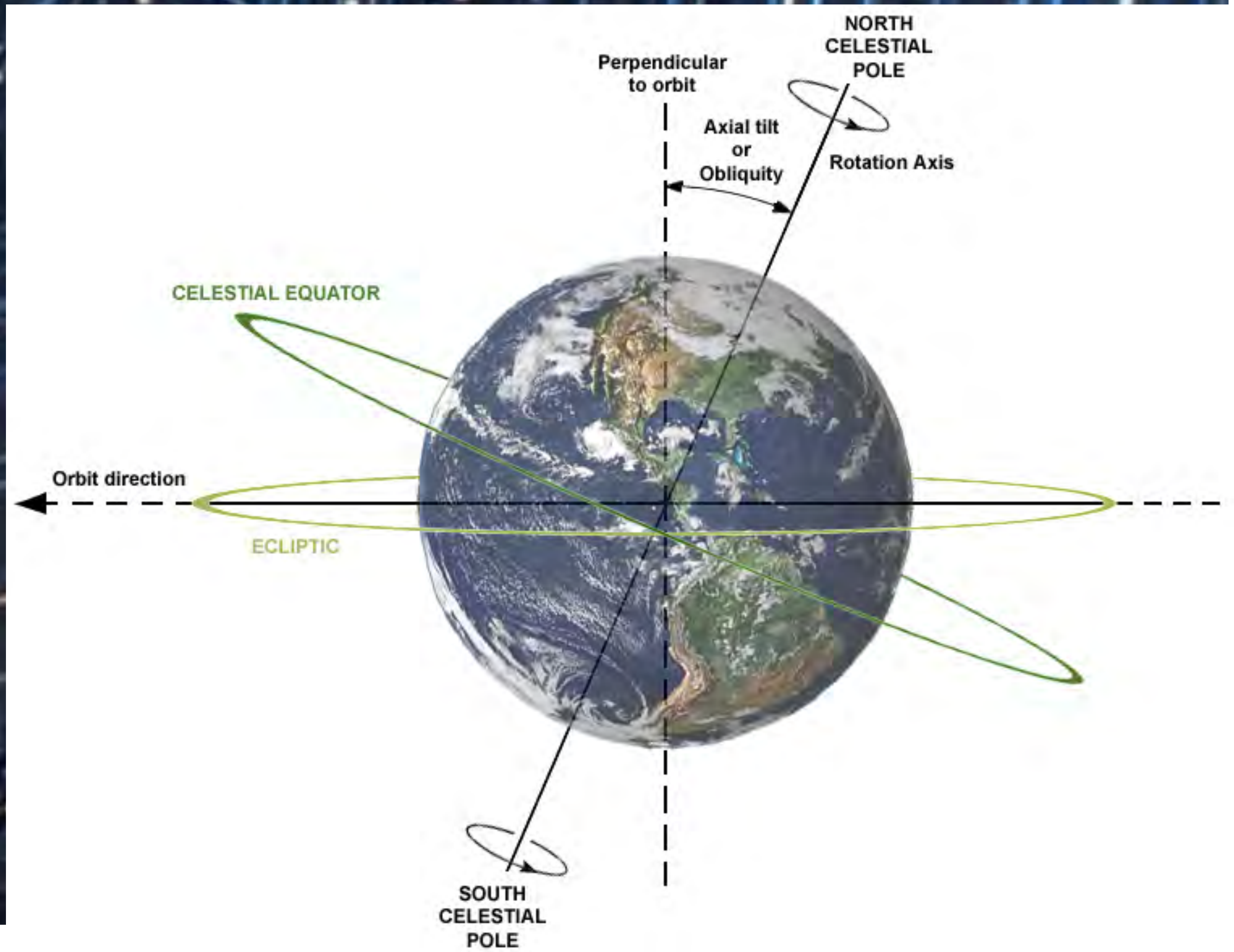
Lecture on
Inertial Atomic Quantum Sensors
-
State of the art and perspectives



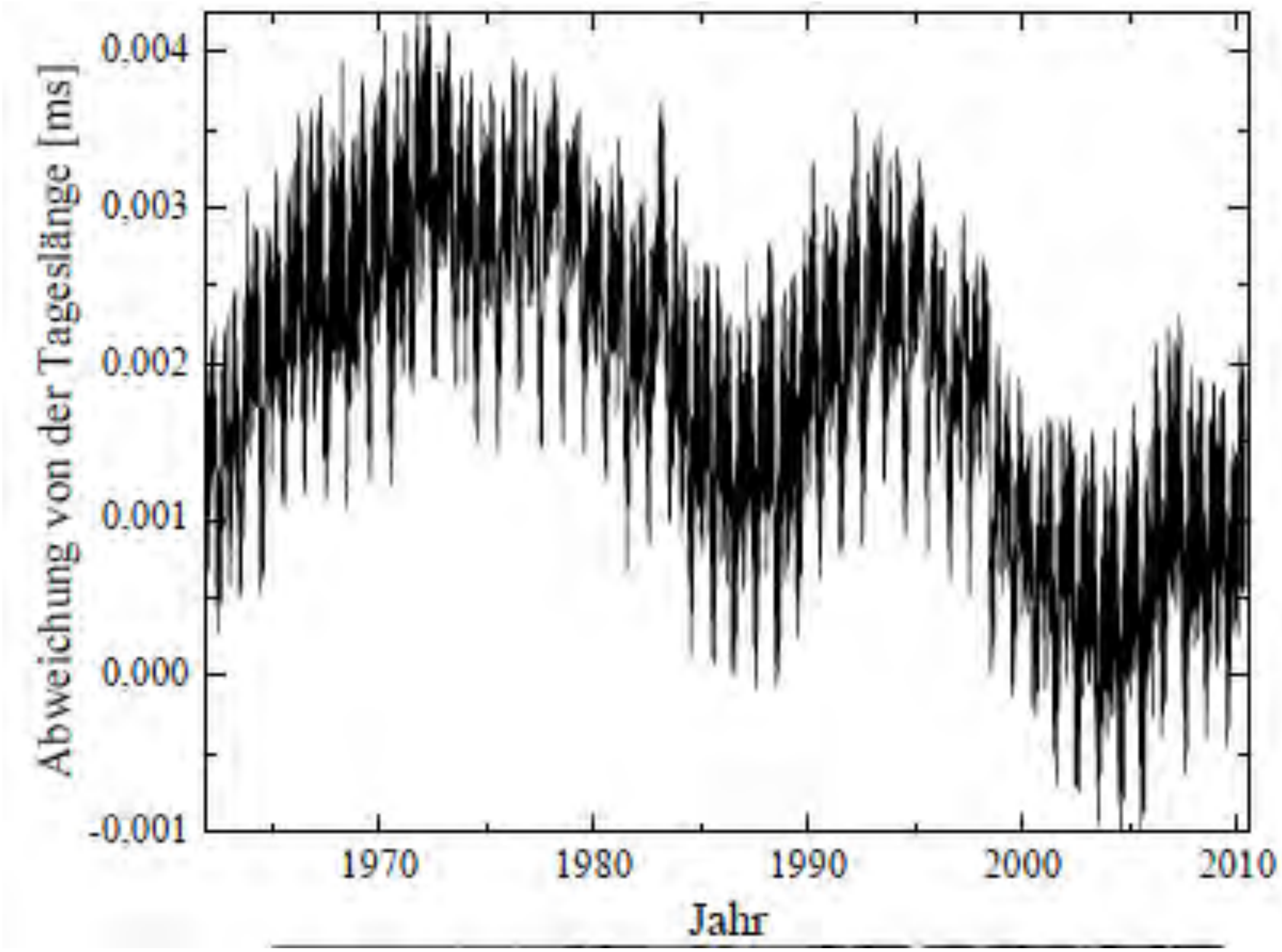
Chip based quantum gravimeter

The Quantum Gyroscope

Gyroscopes

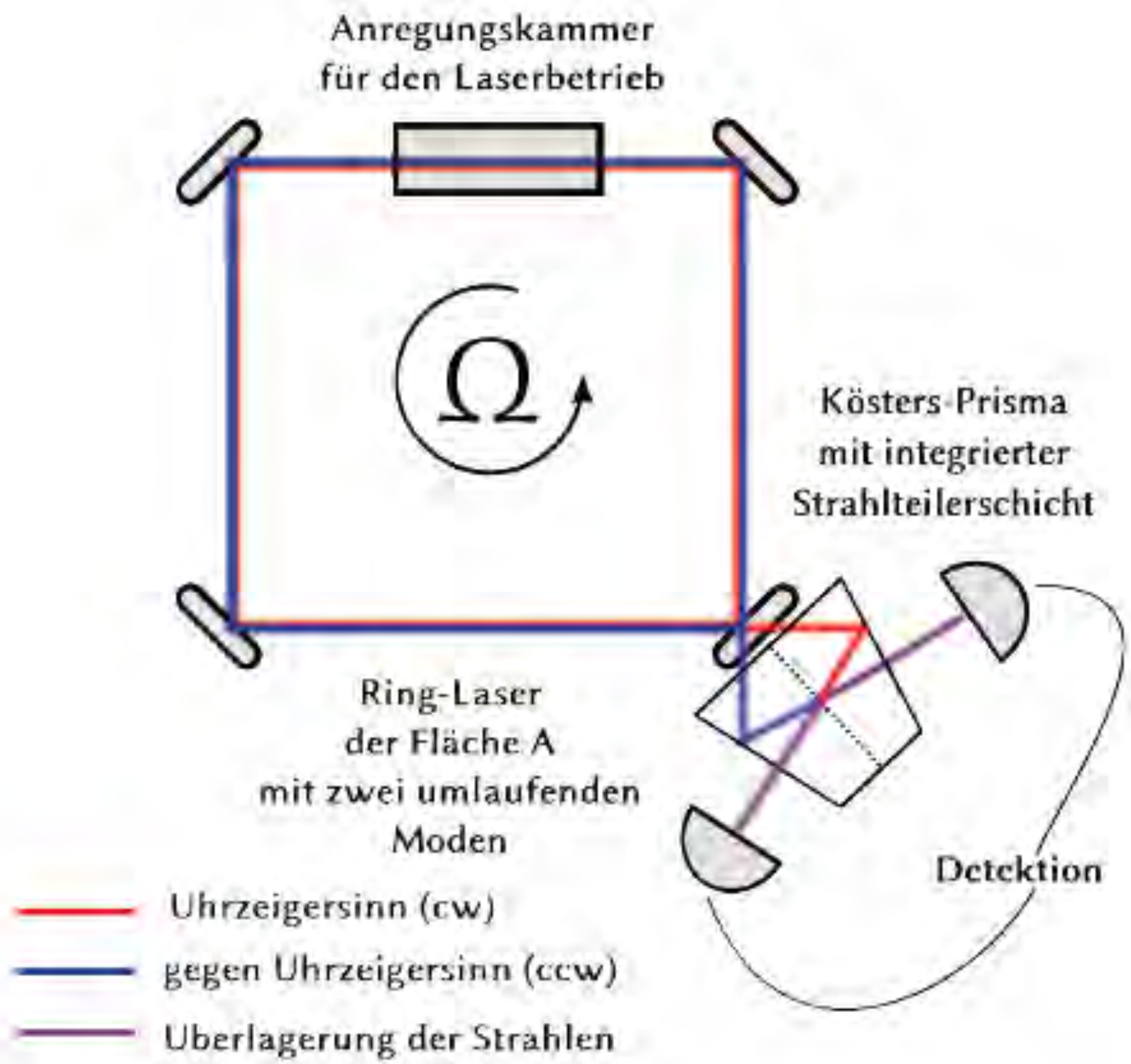

NORTH
CELESTIAL
POLE
Perpendicular
to orbit
Axial tilt
or
Obliquity
Rotation Axis
CELESTIAL EQUATOR
Orbit direction
ECLIPTIC
SOUTH
CELESTIAL
POLE

Gyroscopes


0,004
0,003
0,002
0,001
0,000
-0,001
Abweichung von der Tageslänge [ms]
1970
1980
1990
2000
2010
Jahr

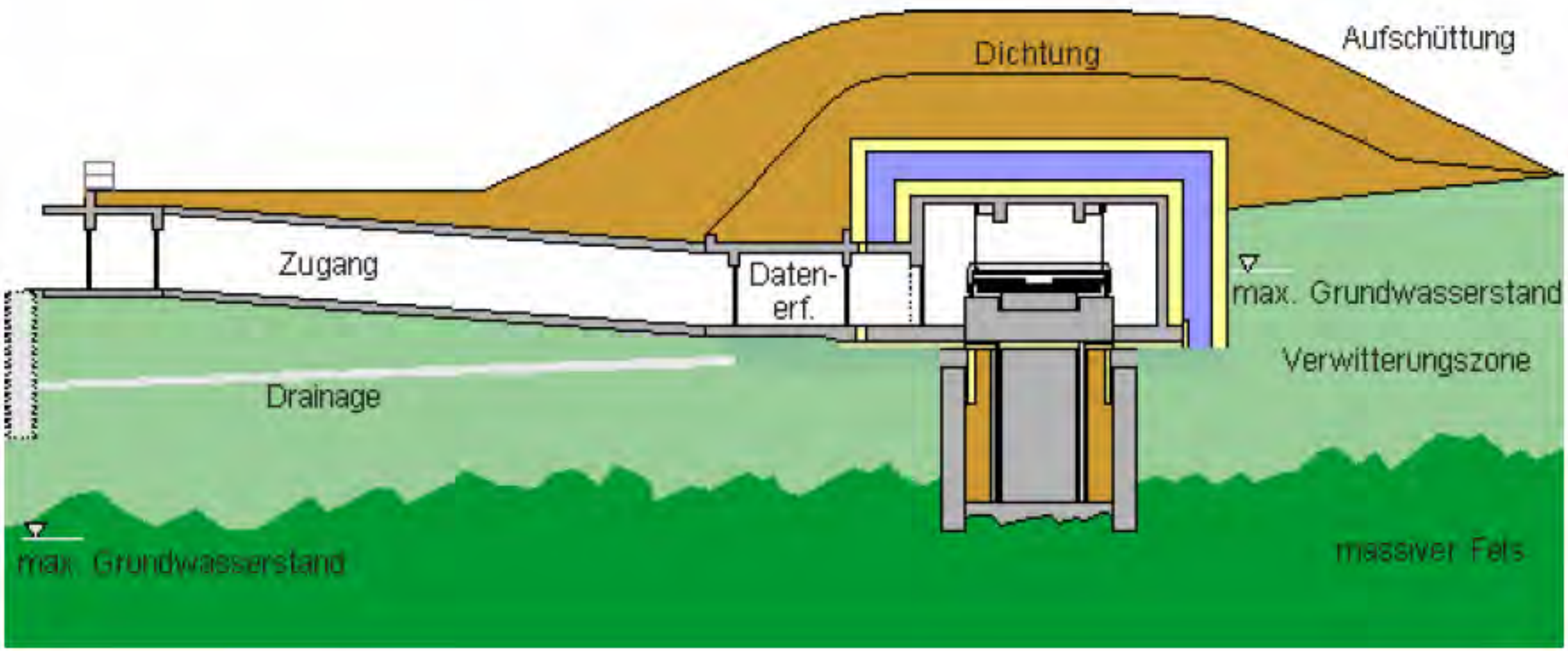

QUASAR
c·τ
BASELINE
400 km - 12000 km

Gyroscopes



$$\Delta f = f_{Sagnac} = \frac{4A\Omega}{\lambda P}$$

Gyroscopes



…at Fundamentalstation Wettzell

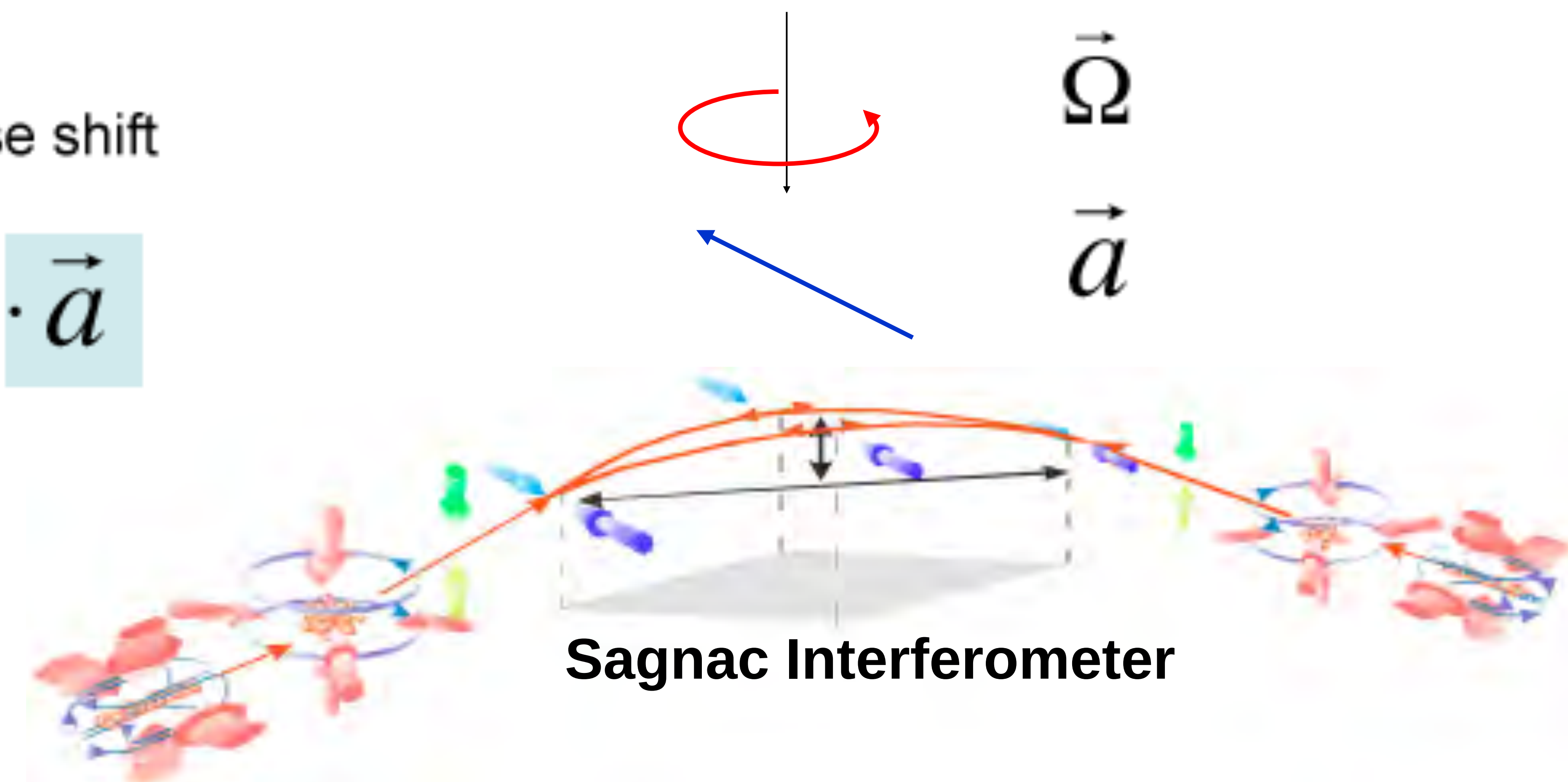
Different Topologies for measuring inertial forces

Rotational Phase shift

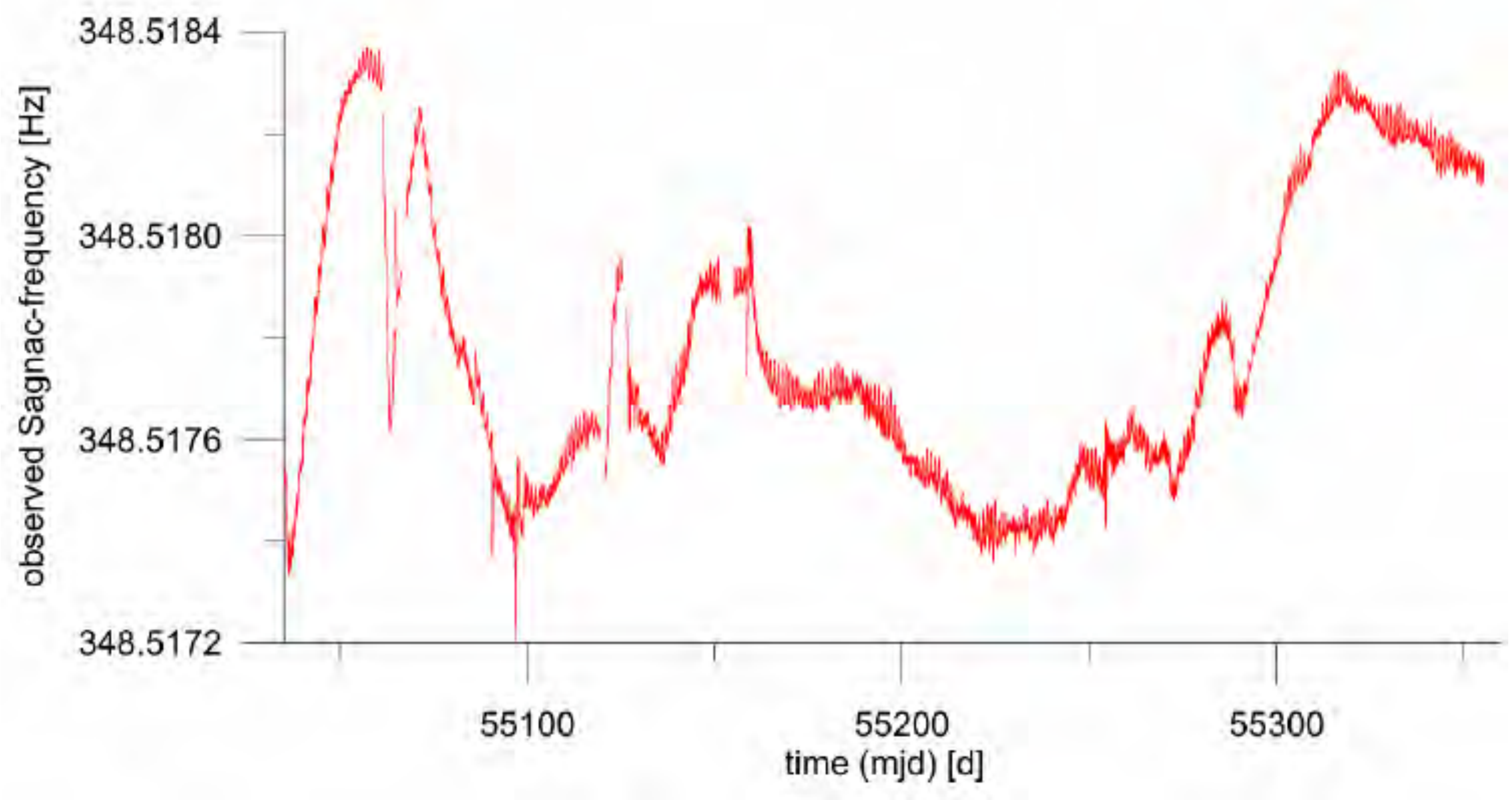
$$\Delta\varphi_{rot} = \frac{2m_{Atom}}{\hbar}\vec{A}\cdot\vec{\Omega} \propto T^2$$

Accellerational Phase shift

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

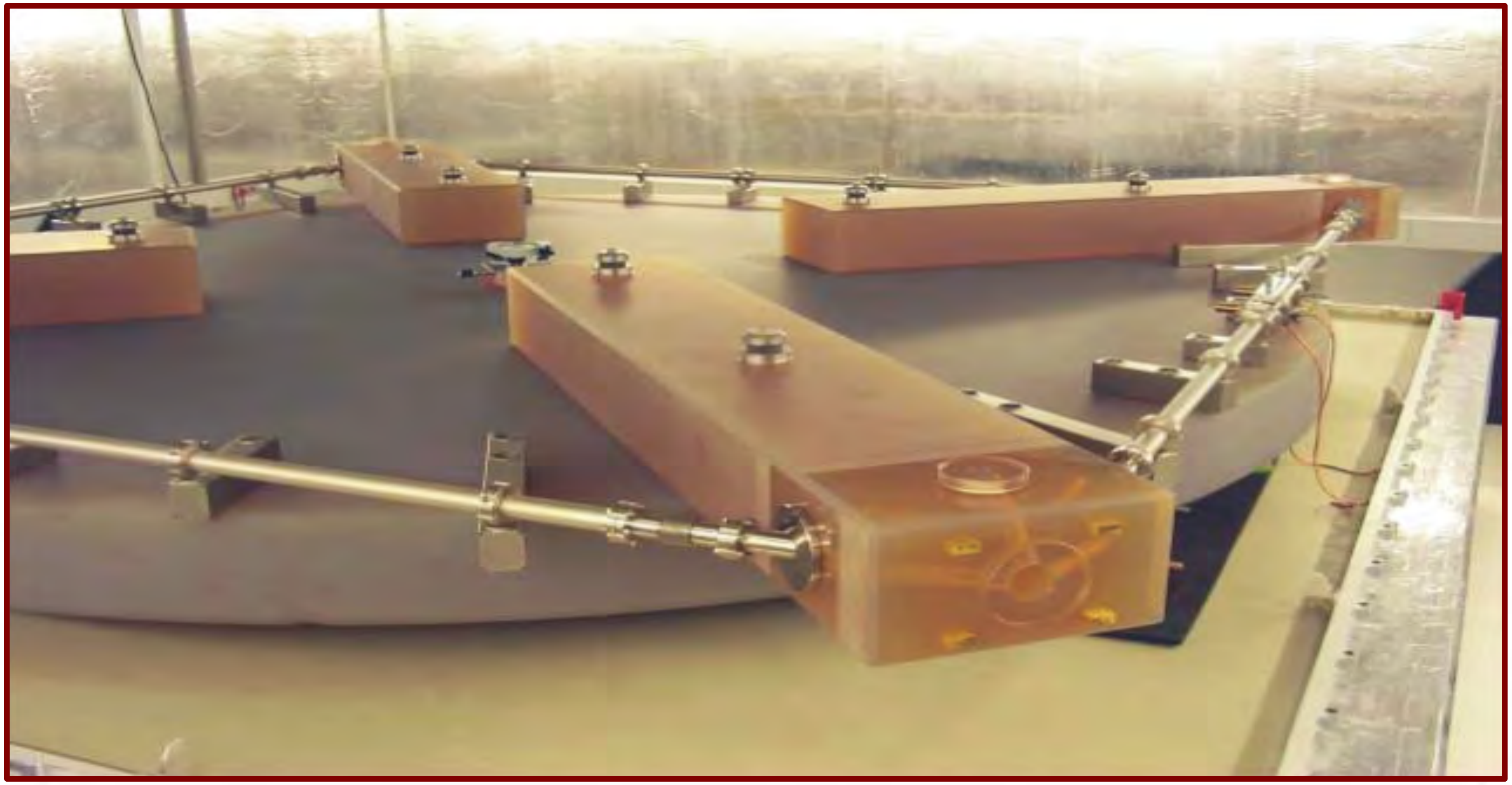


Gyroscopes



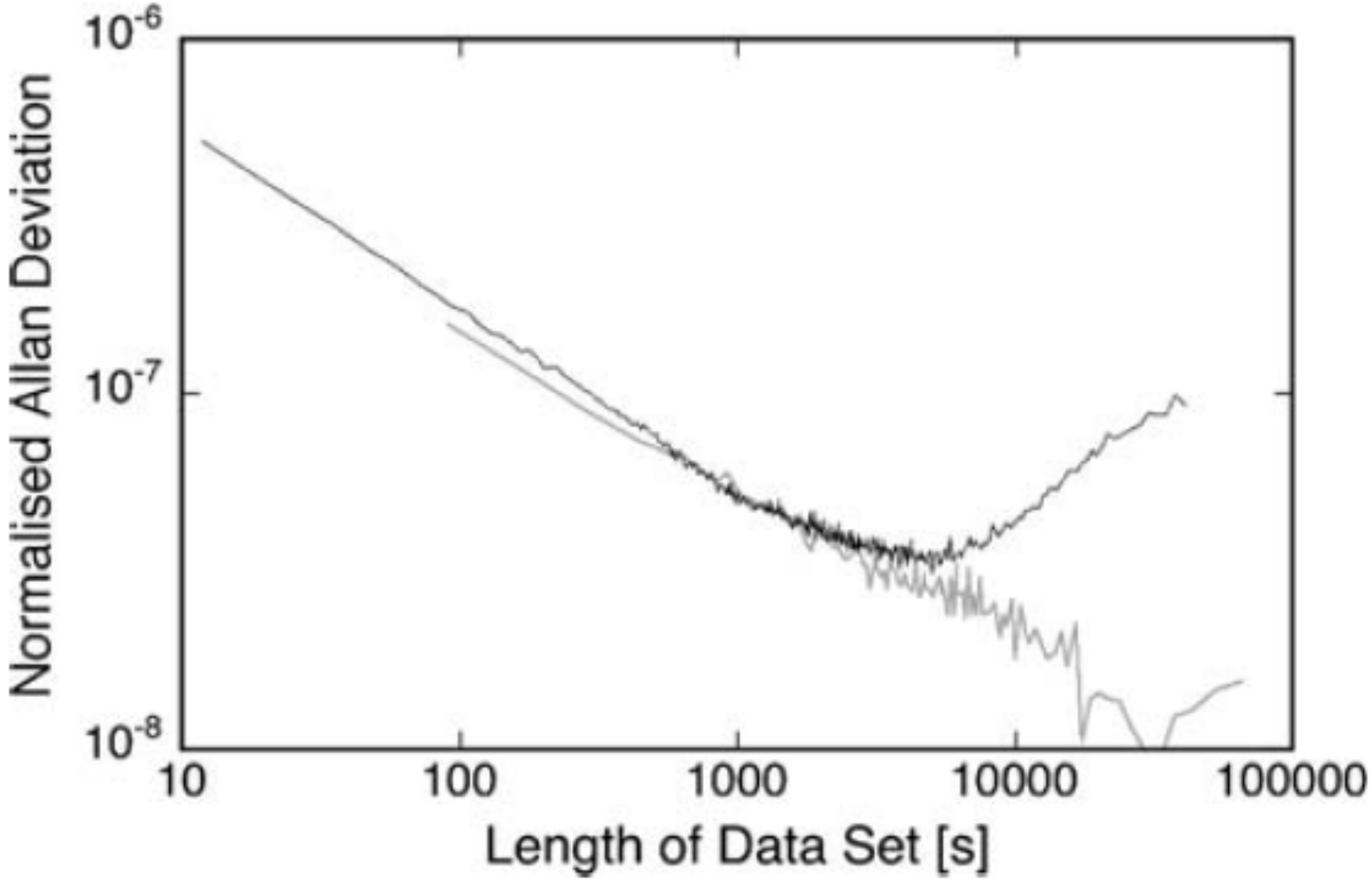
348.5184
348.5180
348.5176
348.5172
observed Sagnac-frequency [Hz]
55100
55200
55300
time (mjd) [d]

Gyroscopes

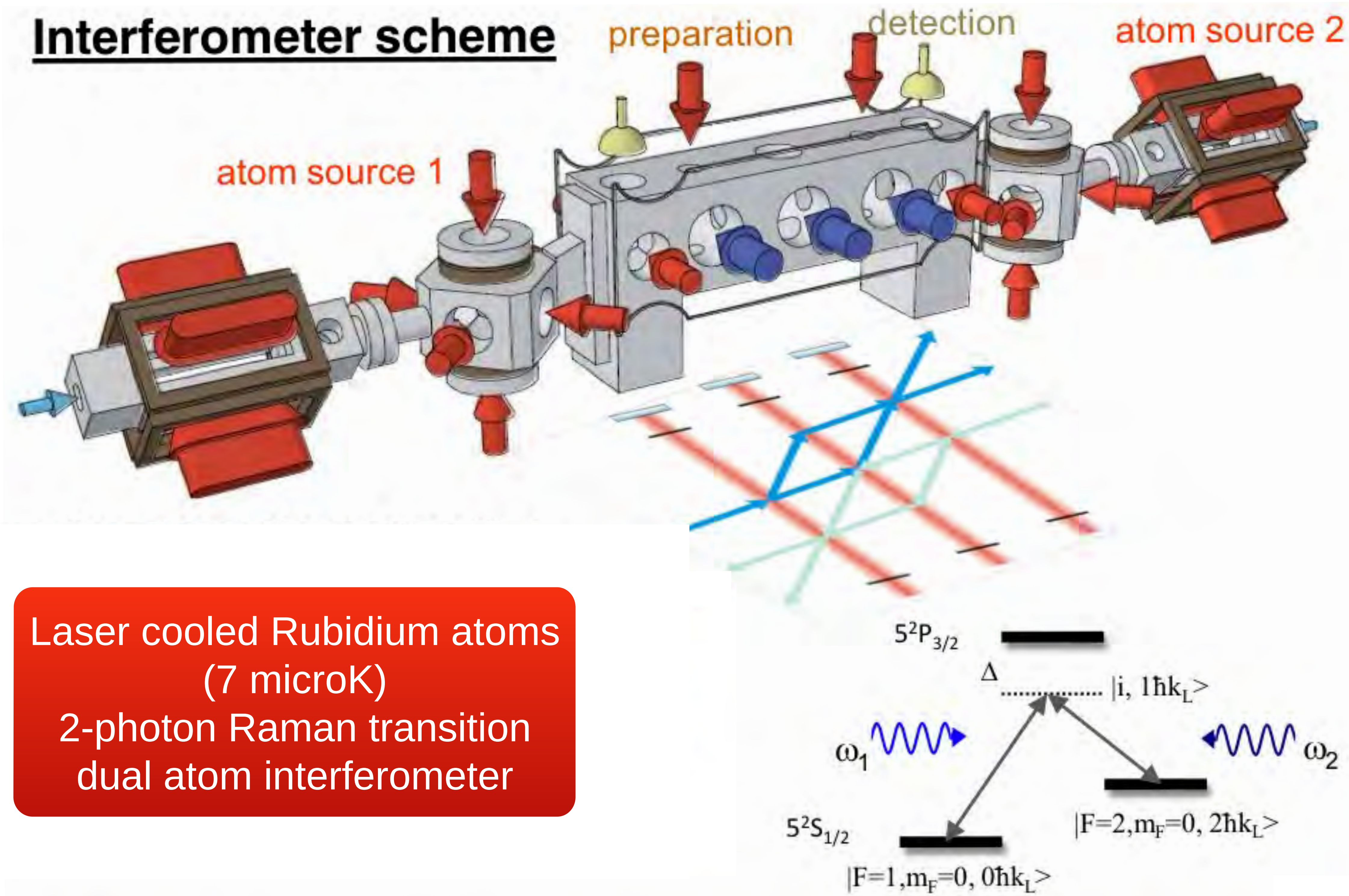


…at Fundamentalstation Wettzell

Gyroscopes



…at Fundamentalstation Wettzell

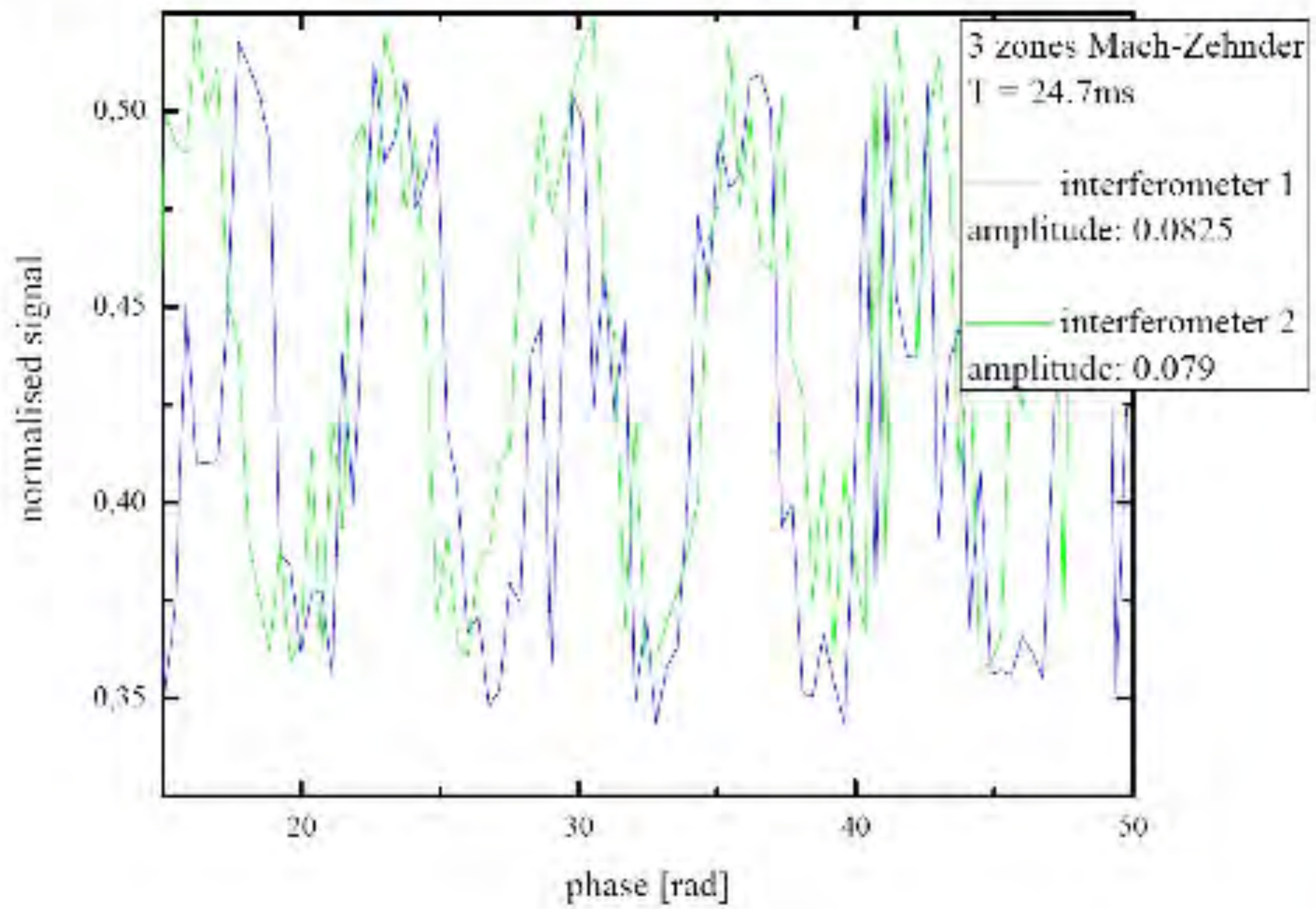


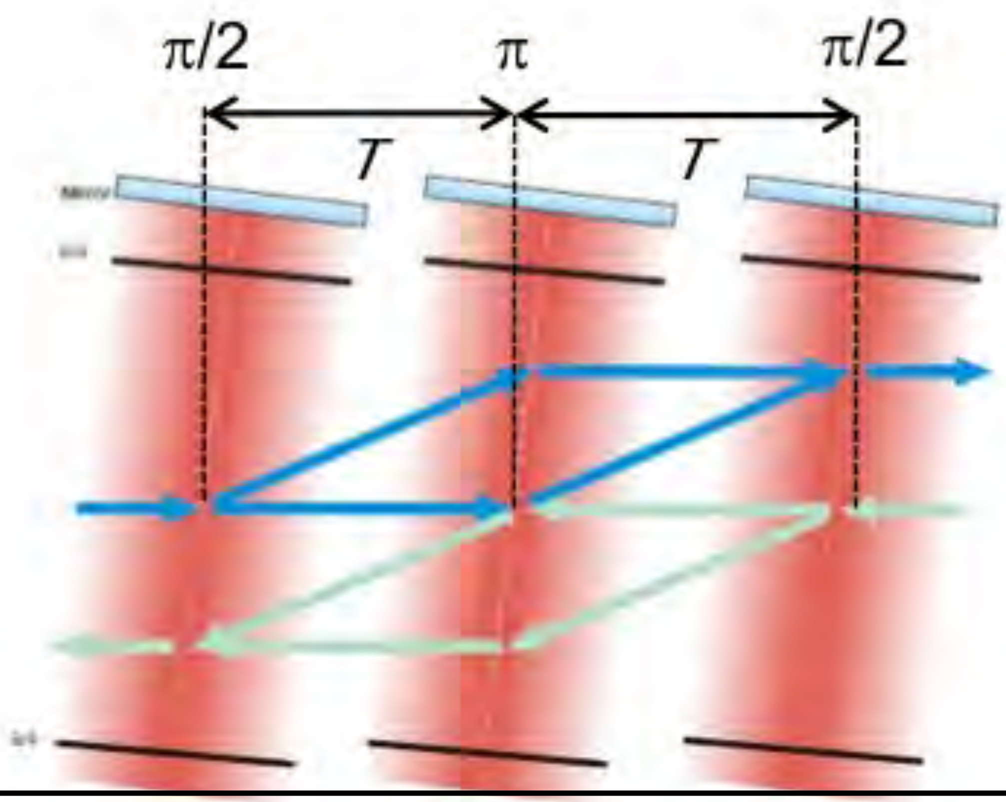
Laser cooled Rubidium atoms
(7 microK)
2-photon Raman transition
dual atom interferometer

[T. Müller, M. Gilowski, M. Zaiser, T. Wendrich, E.M. Rasel and W. Ertmer, Eur. Phys. J. D 53, 273–281 (2009)]

Mach-Zehnder type interferometer

- Enclosed area **A = 19 mm²**
- Total int. time: 2T= 49 ms
- Cycle time ~ 0.5 s
- Contrast: 20 %

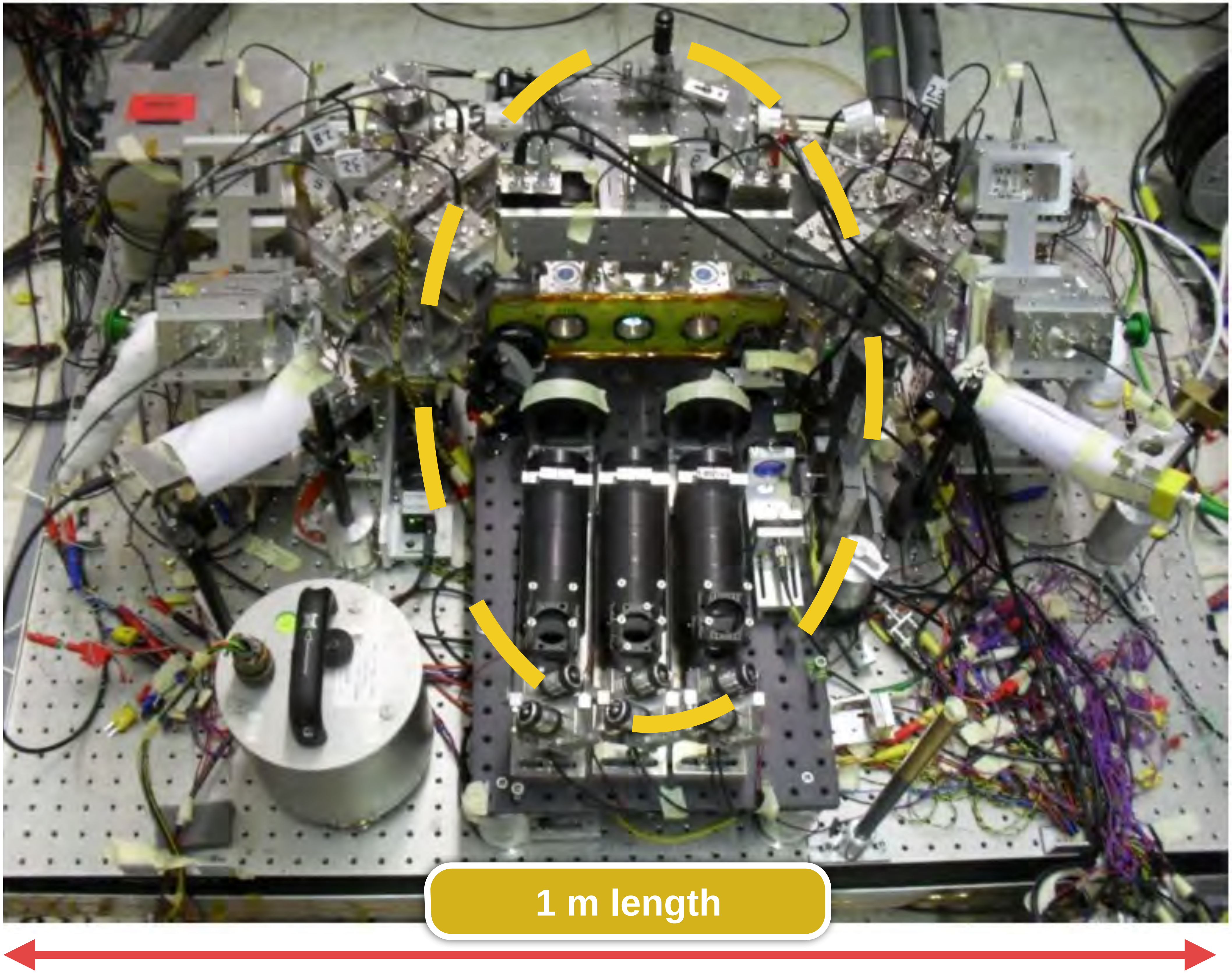




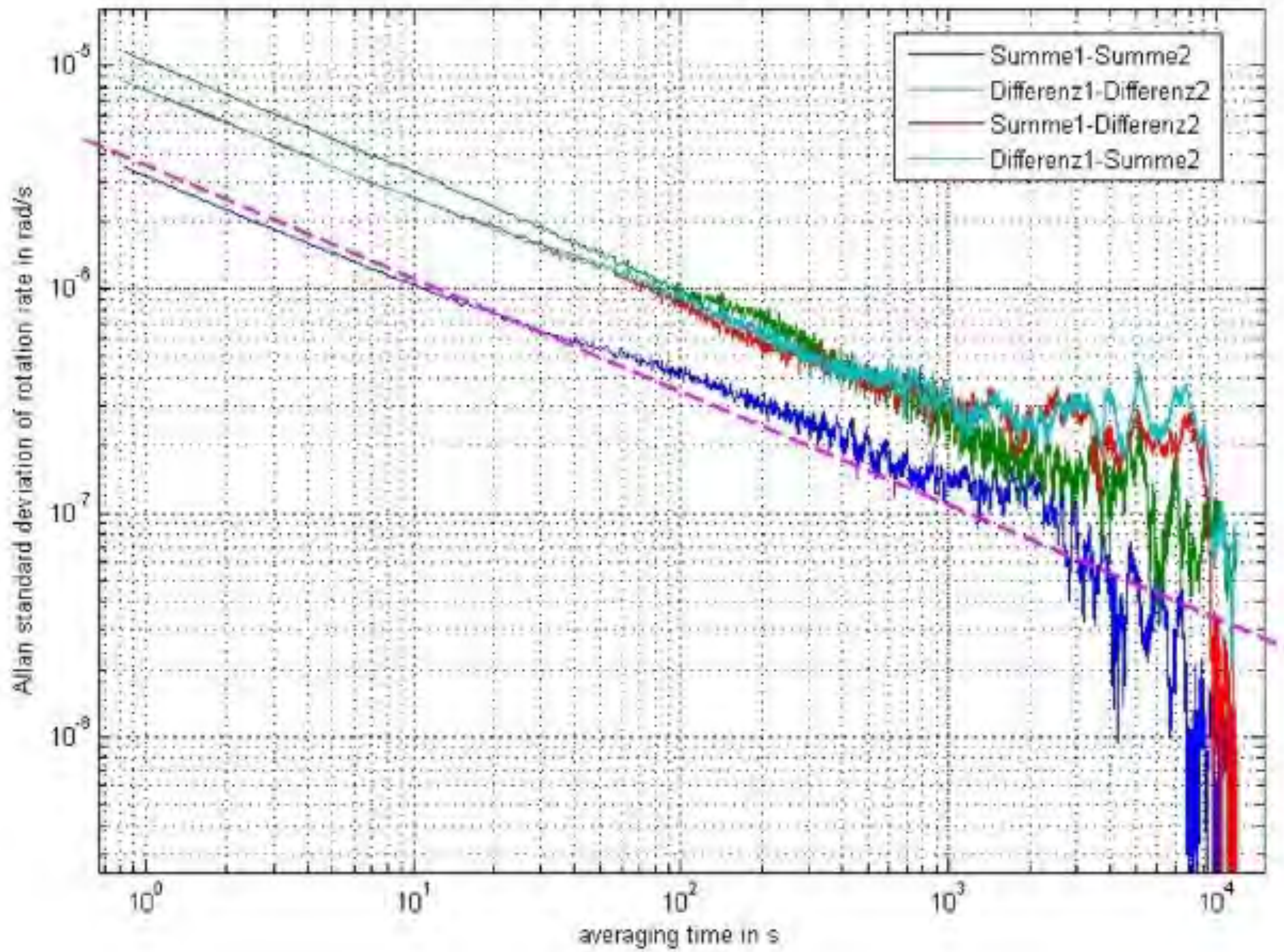
Current resolution

→ 6.1·10⁻⁷ rad/s @ 1s

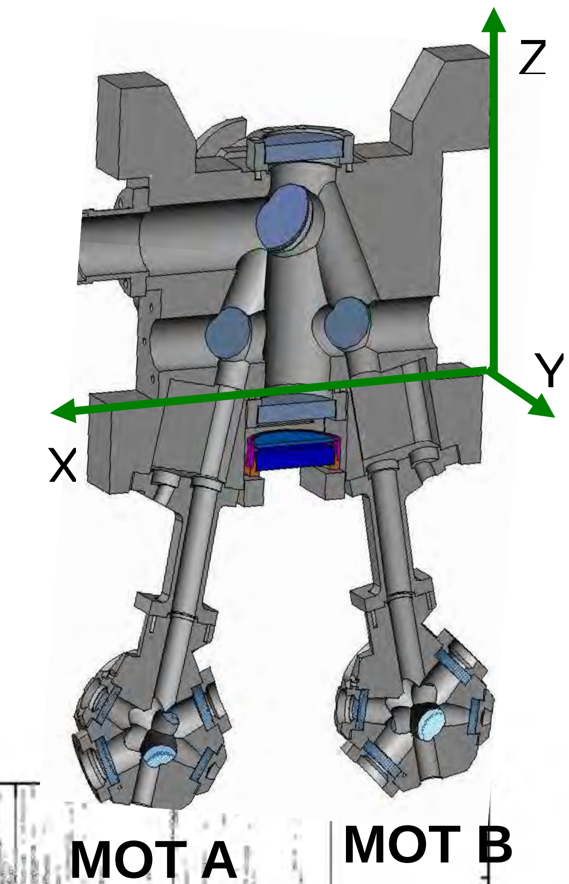
Differential Cold Atom Sagnac Interferometer



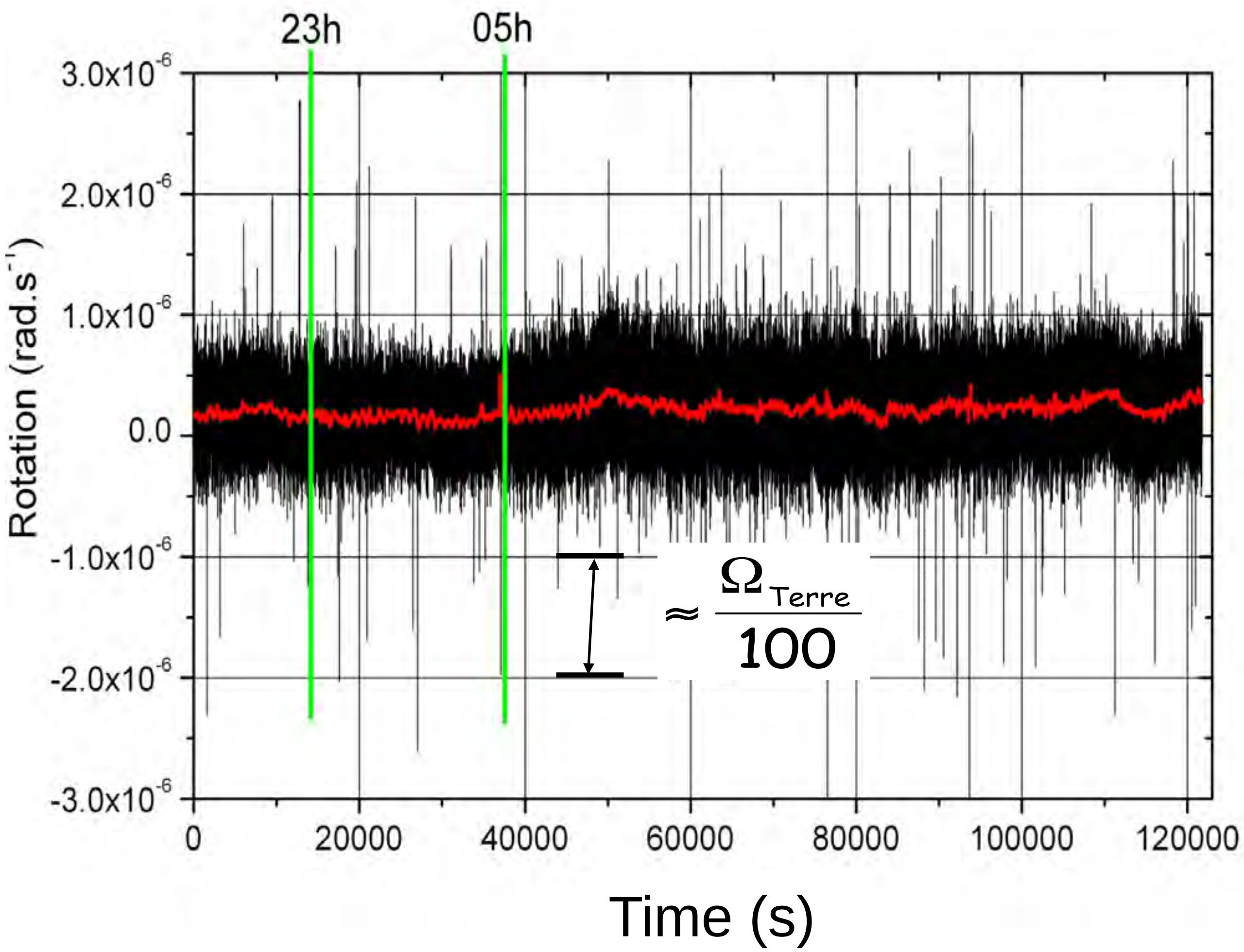
Differential Cold Atom Sagnac Interferometer

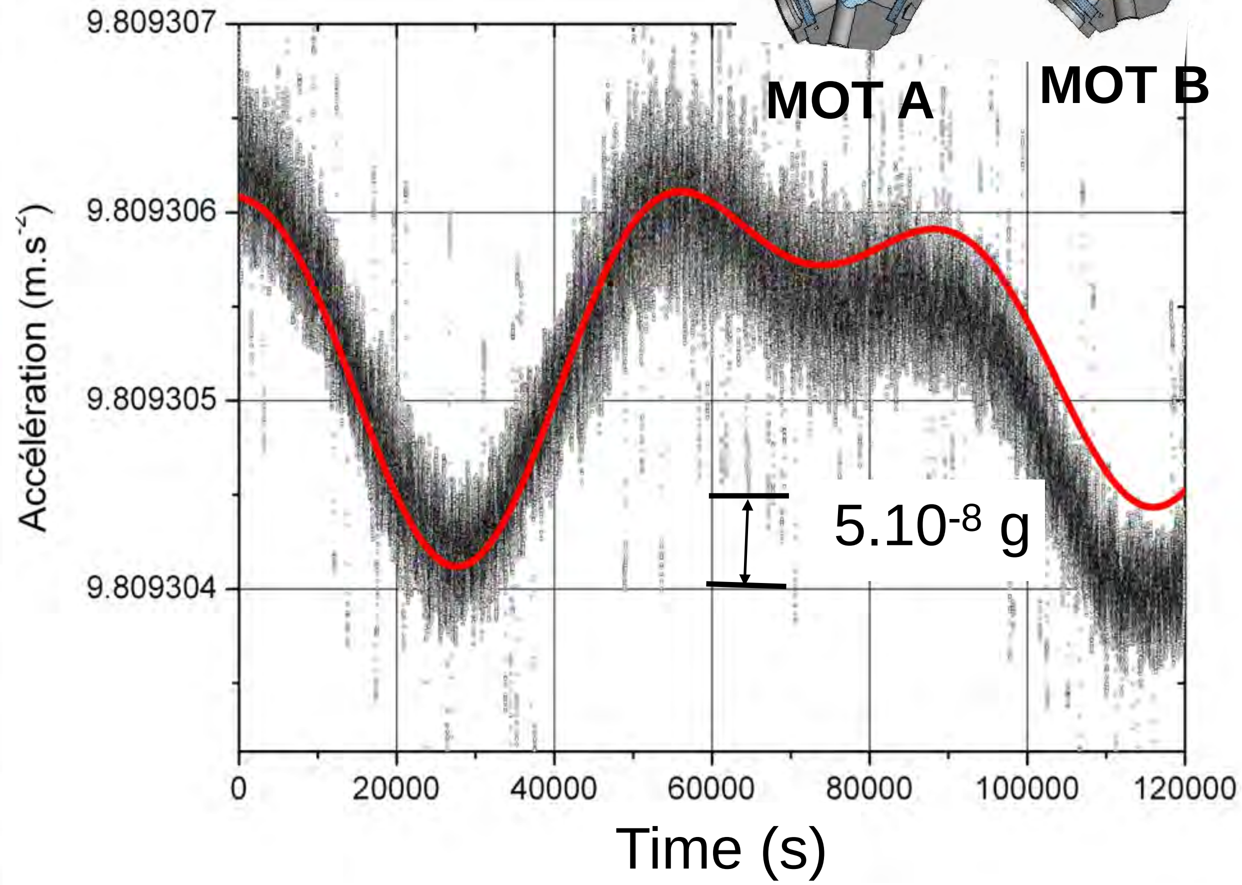


Gyroscopes

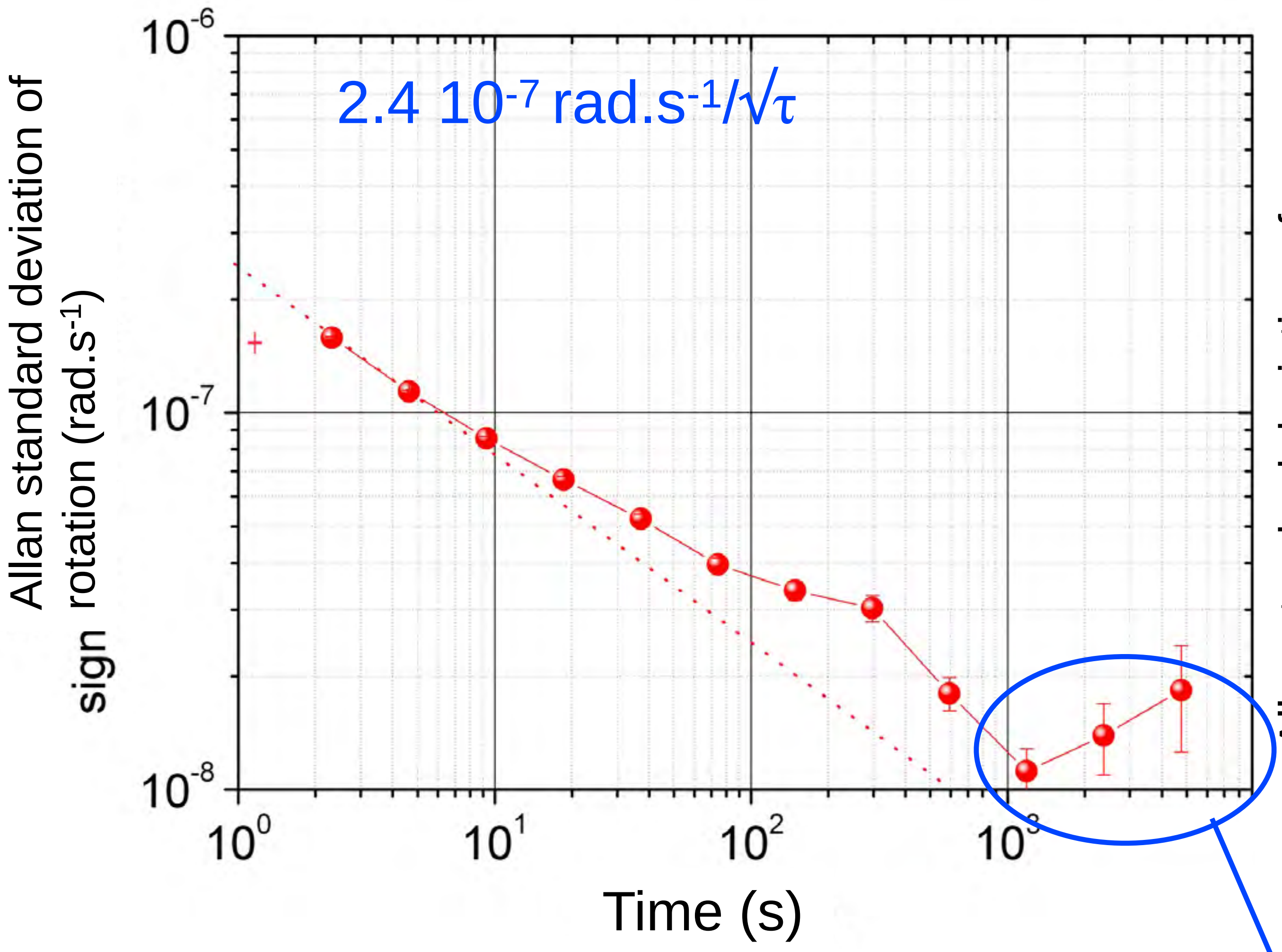


34 hours

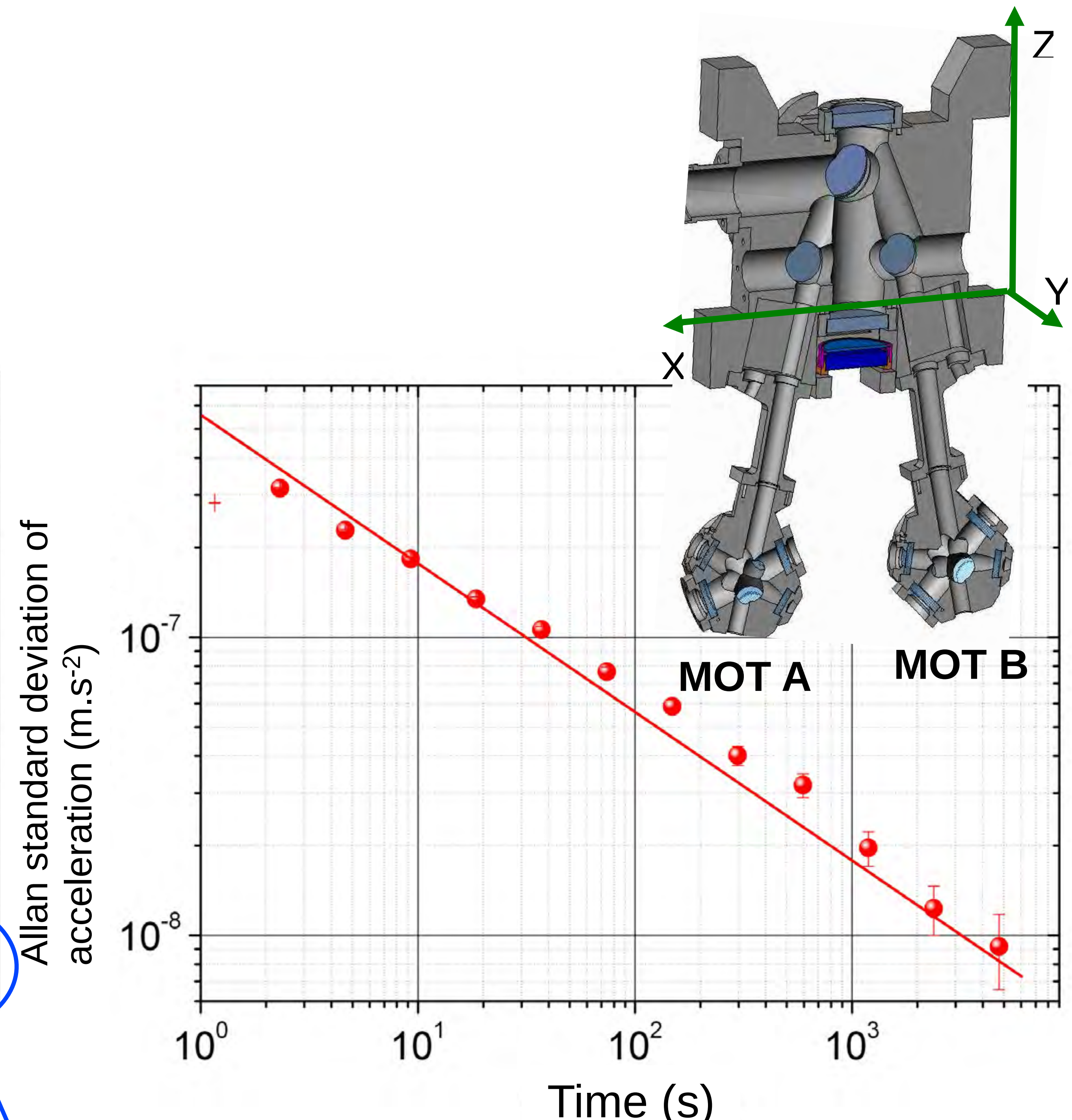




Gyroscopes



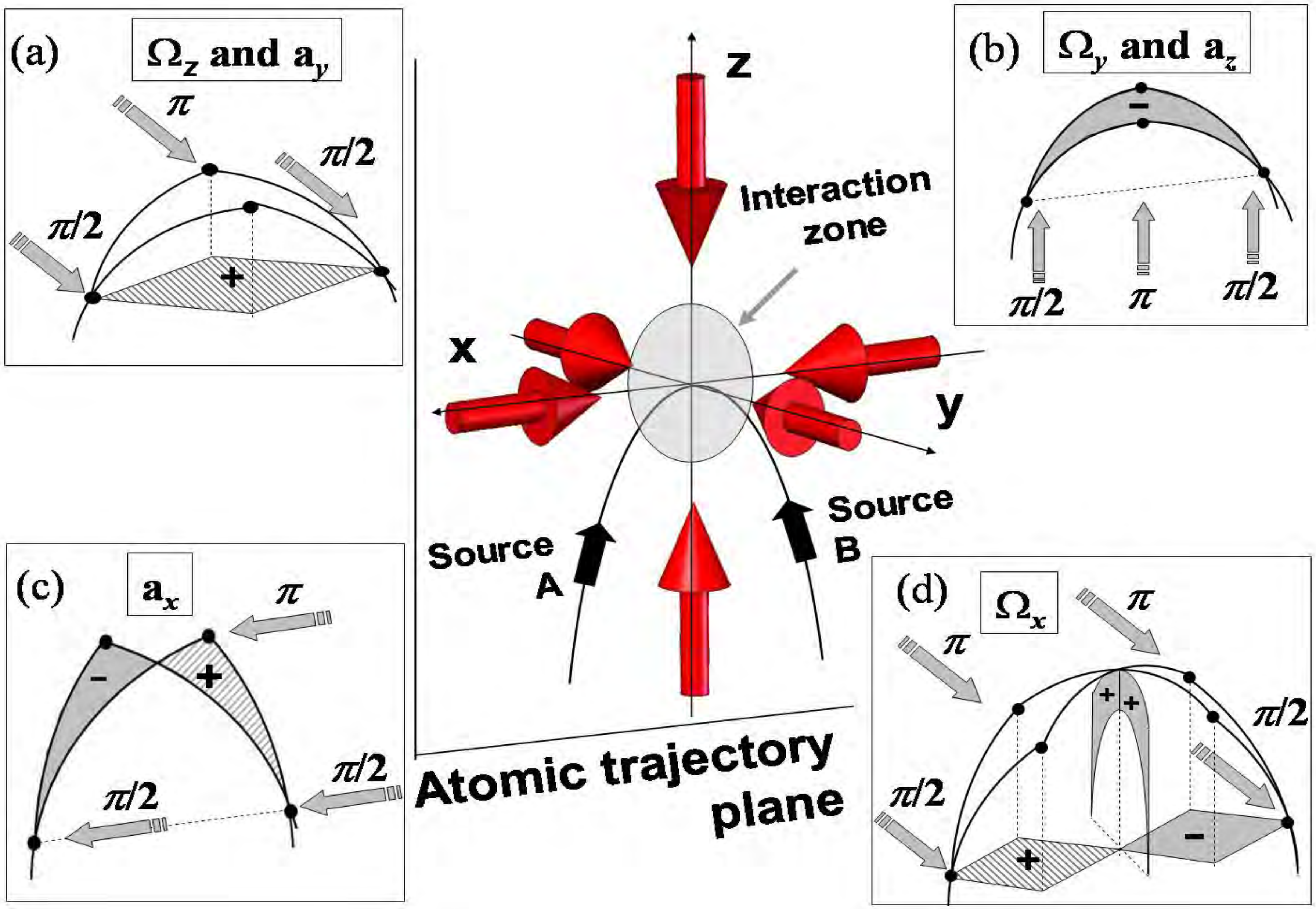
Rotation limited by Quantum Projection Noise



Acceleration limited by vibrations

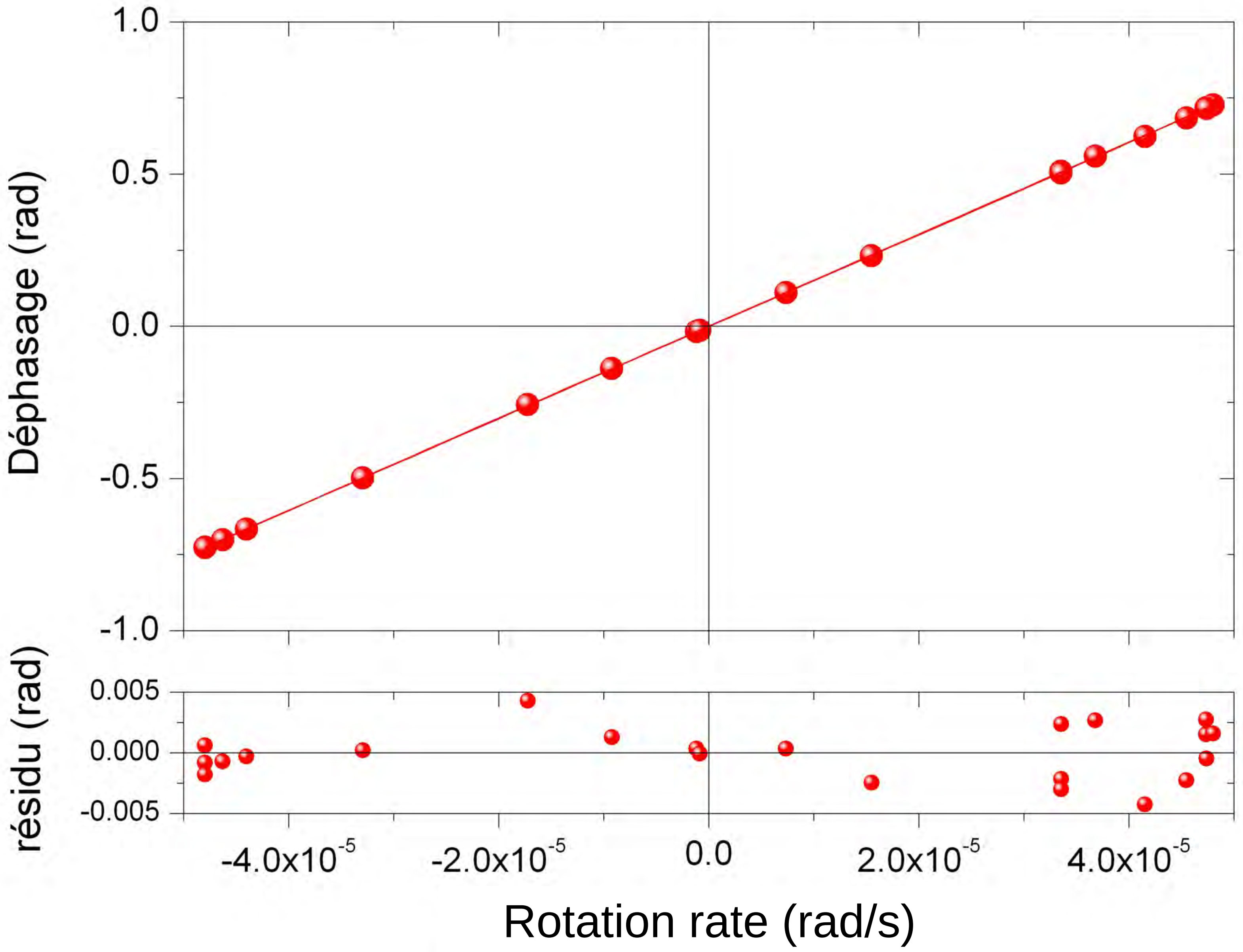
temperature fluctuations

Measurement of the 6 axes of inertia



B. Canuel *et al.*, PRL **97,** 010402 (2006)

Linearity of the scale factor



Measure of the scale factor

15124 ± 12 rad /(rad.s^{-1})

Gyroscope linearity :

quadratic $< 10^{-5}$

cubic $< 10^{-4}$