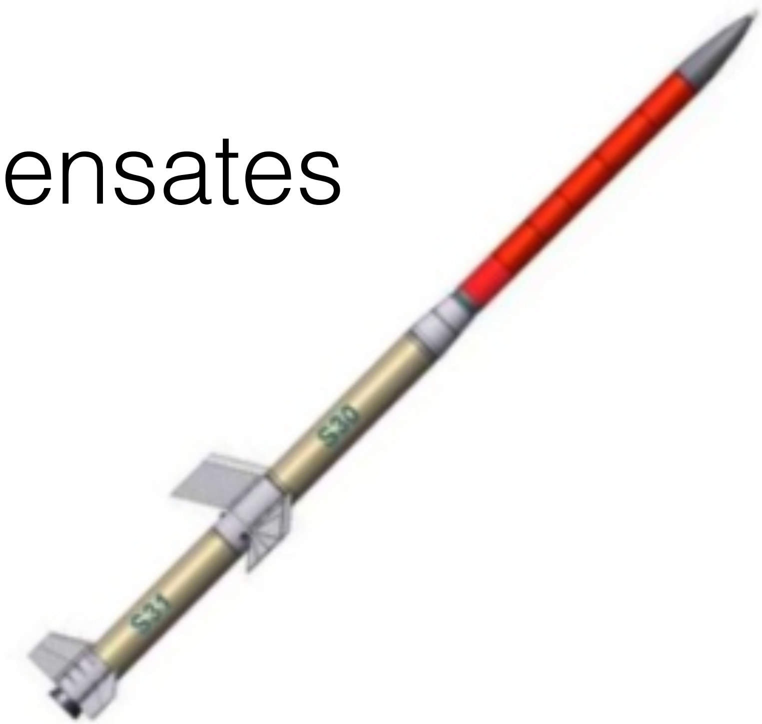
Interferometry with Bose-Einstein condensates in space: MAIUS

-

November 14th 2014

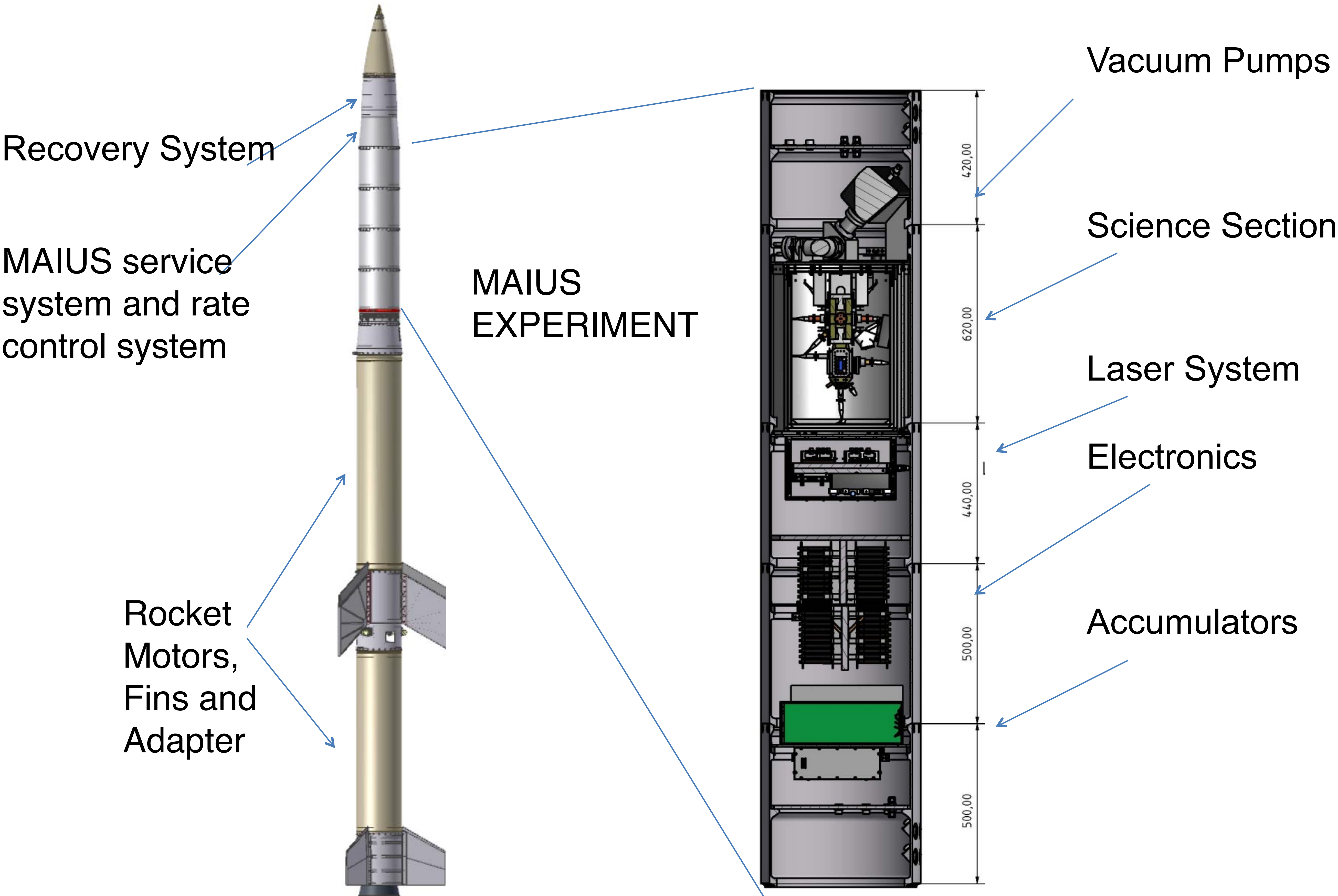


Fundamental physics with matter waves

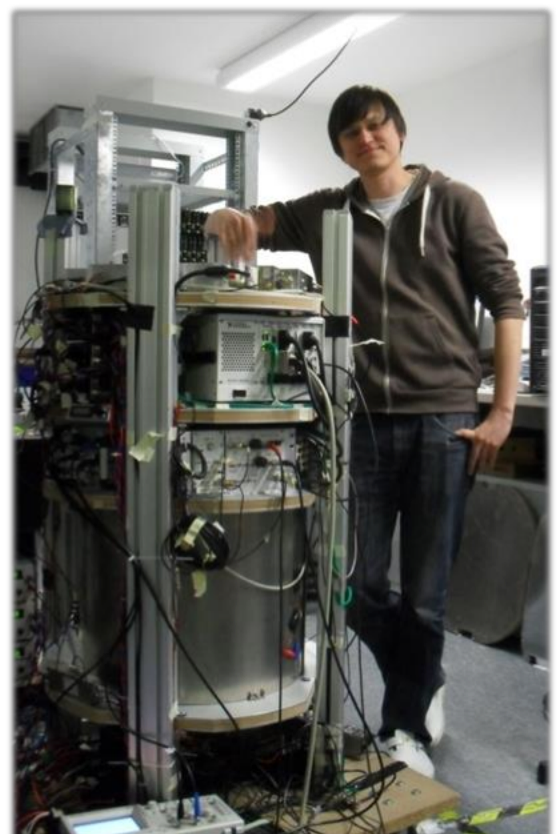
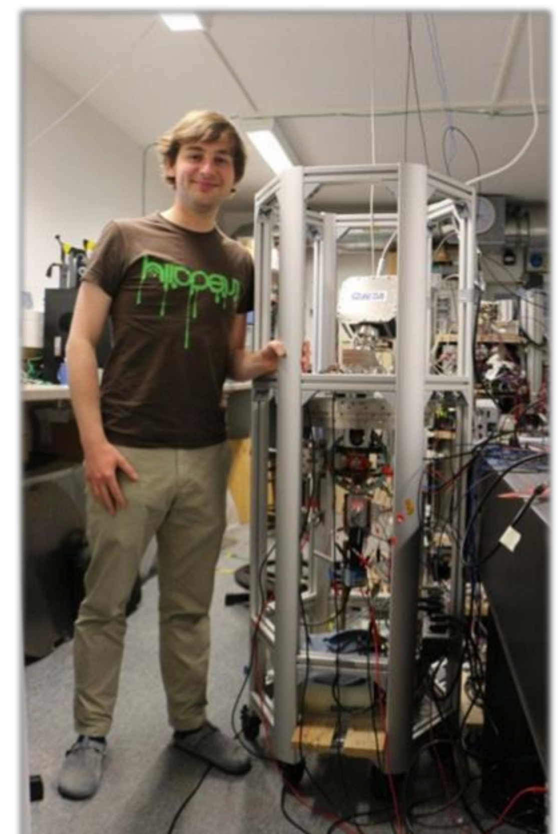
MAIUS:
An Atom-Interferometry Sounding Rocket Mission

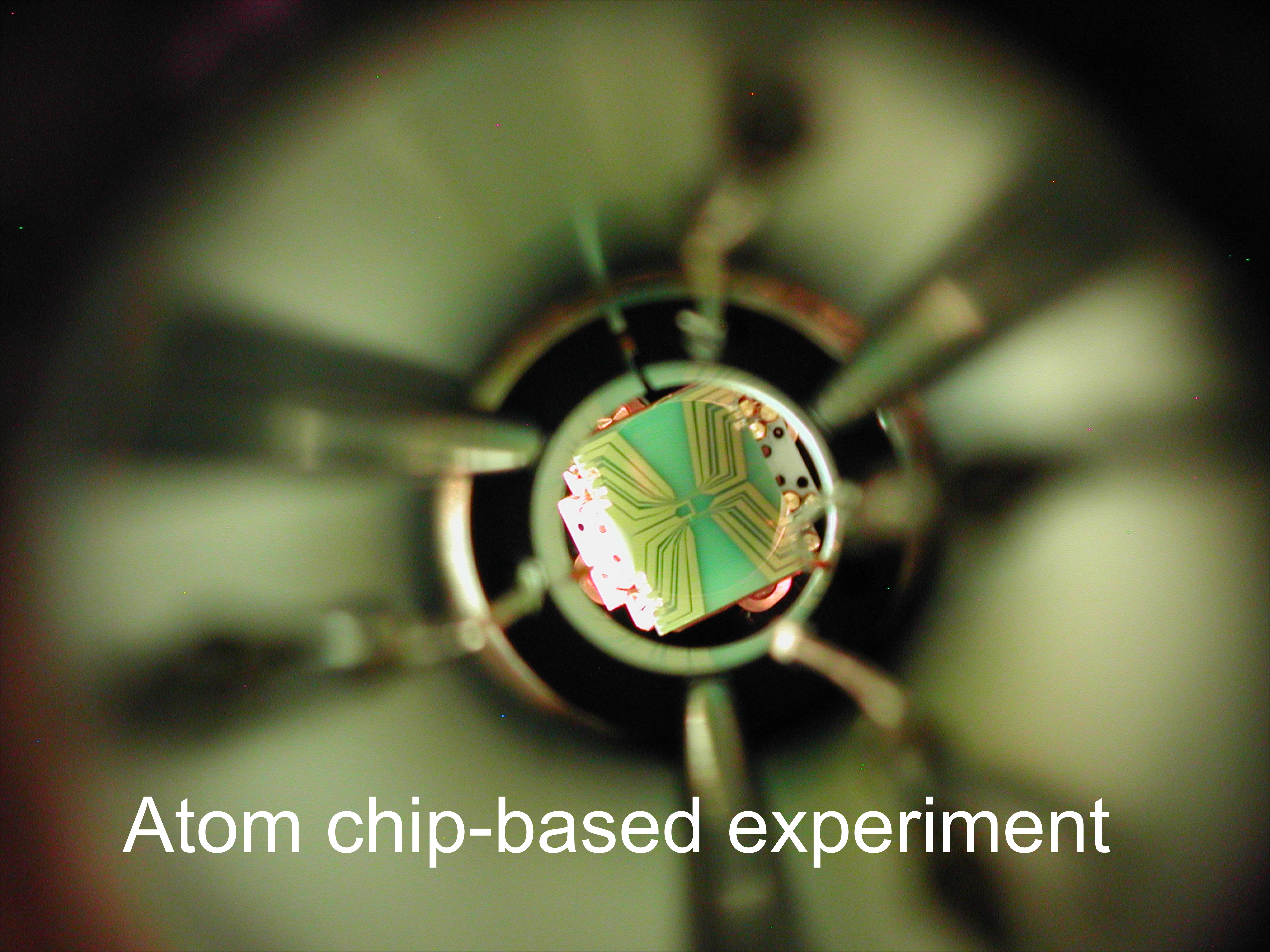
- Goals
  - Achieving ultra low energy ensembles
  - μ-gravity enhanced BEC of 10^6 ^{87}Rb-atoms
  - First demonstration of a BEC-based atom interferometer on a sounding rocket / in space
  - First creation of a BEC on a sounding rocket / in space
- Mission Outline
  - Initialization of the experiment in very little time
  - 6 min of free fall
  - Improved design based on predecessor experiments QUANTUS 1+2
  - Interferometer using Bragg-type beam splitters
  - 350 s of weightlessness – usage of VSB-30 rocket

MAIUS: Payload outline

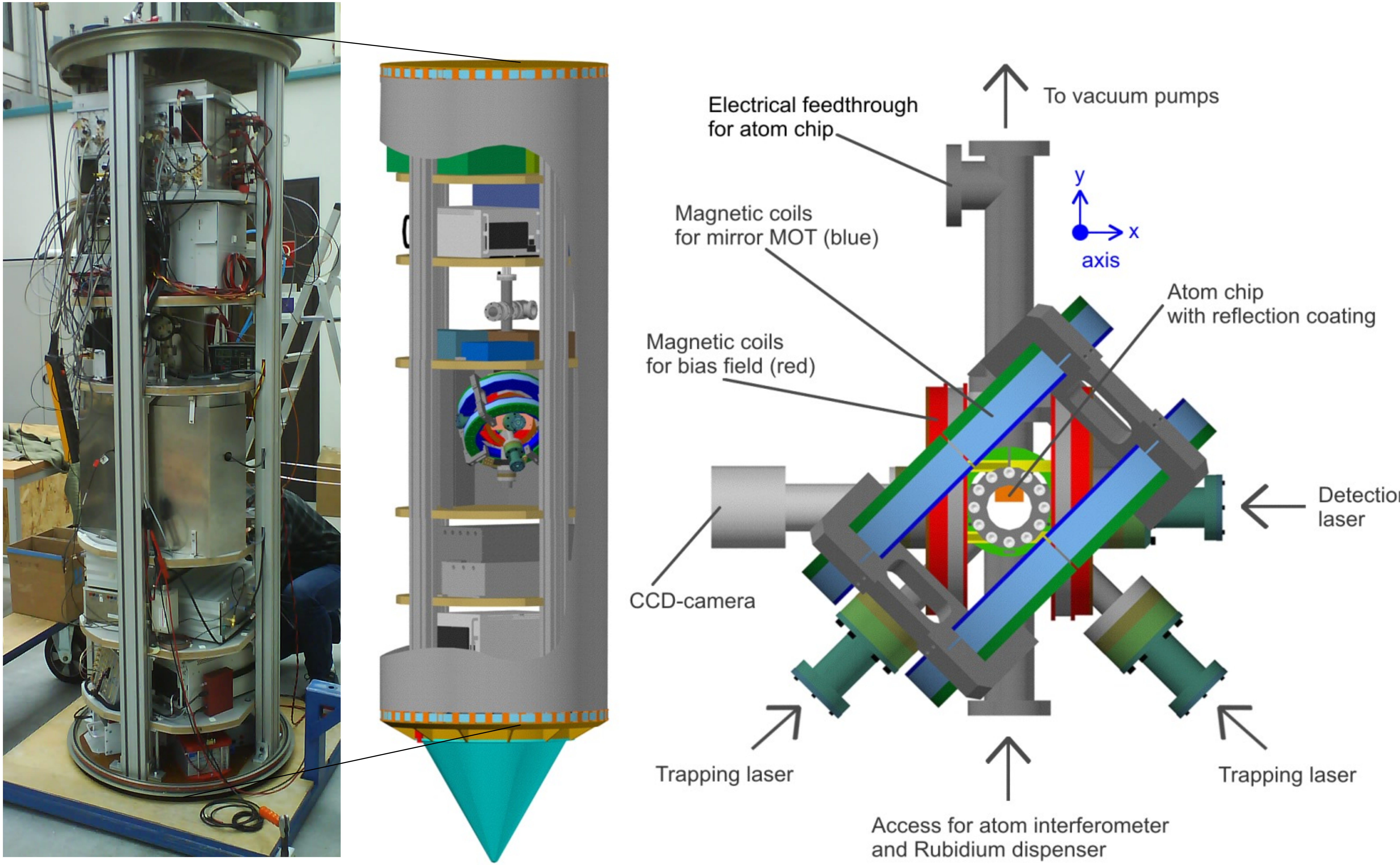


Miniaturisation efforts

Drop tower experiments		Space mission
QUANTUS-I	QUANTUS-II	MAIUS
		


Atom chip-based experiment

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

Drop studies

Status

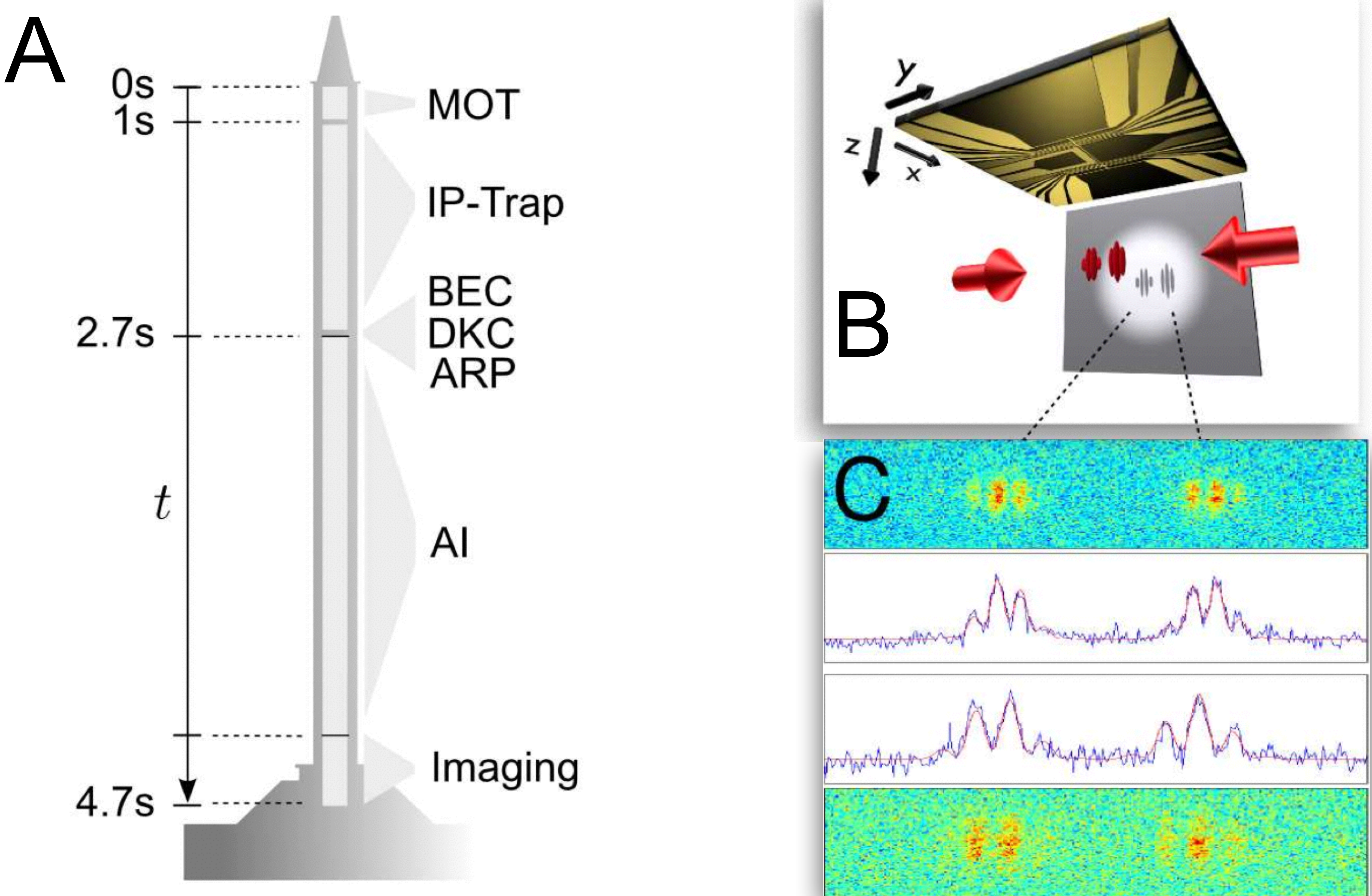
- more than 400 drops
- Robust alignment
- 3 drops per day
- High complexity

Study of Evolution & control of condensates

Test of chip-based atom lasers for precision inertial sensing

QUANTUS

Interferometry (MZI) with BEC in microgravity



Delta-Kick "Cooling"

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

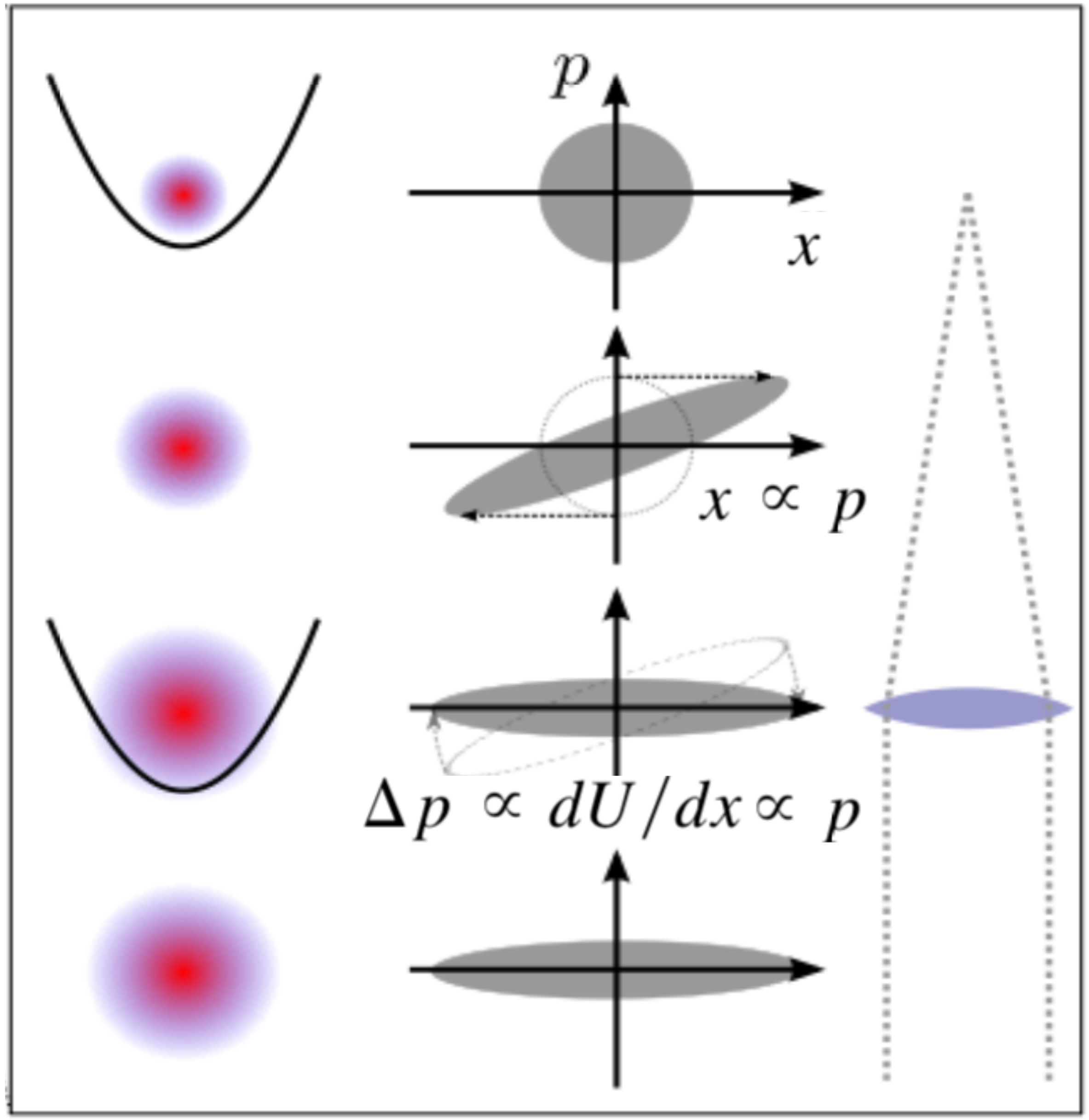
$$H_k = \frac{p^2}{2m} + V(x)\delta(t-T)$$

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

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

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]

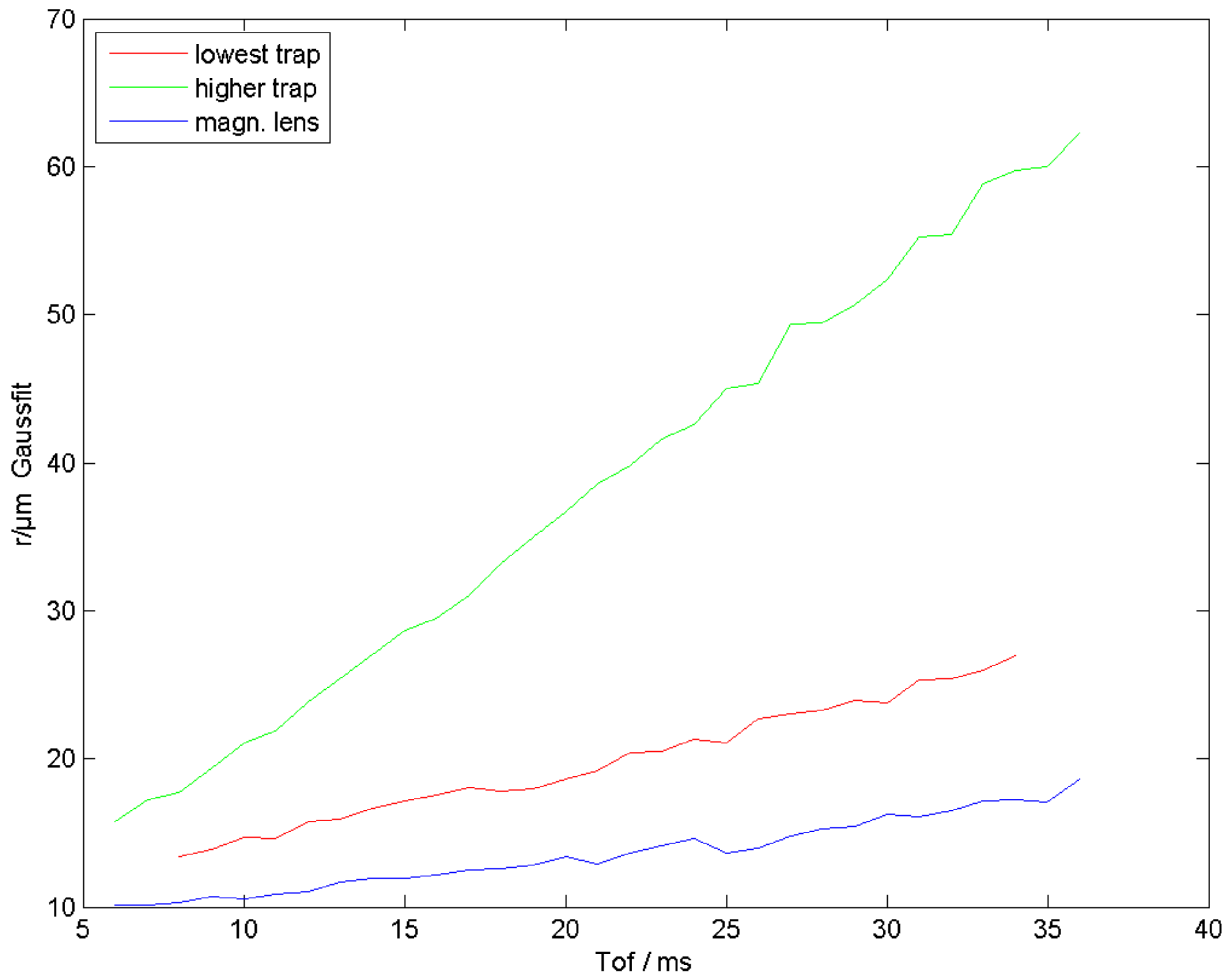
February 1986 / Vol. 11, No. 2 / OPTICS LETTERS 73

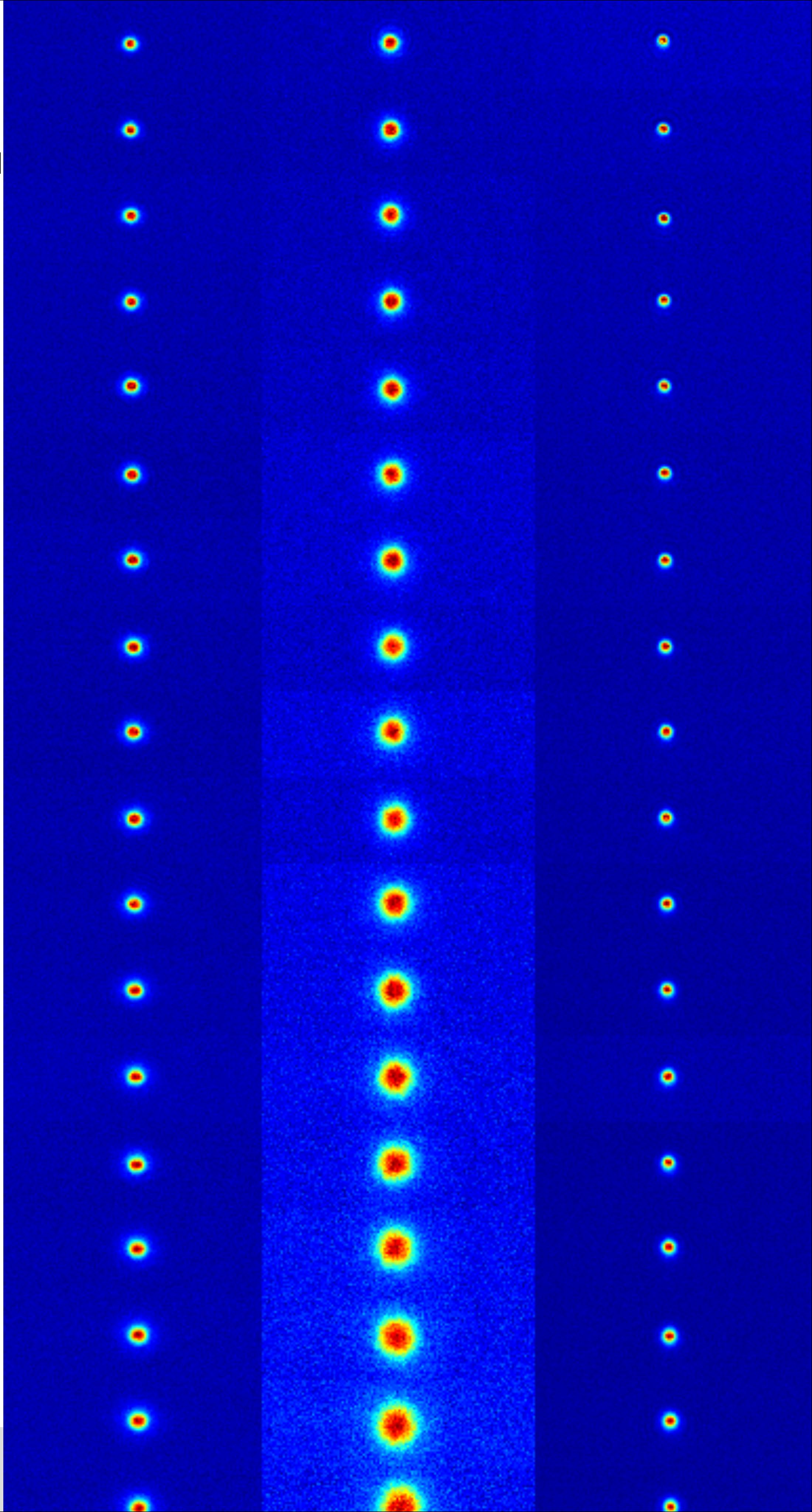
Proposal for optically cooling atoms to temperatures of the order of 10^{-6} K

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

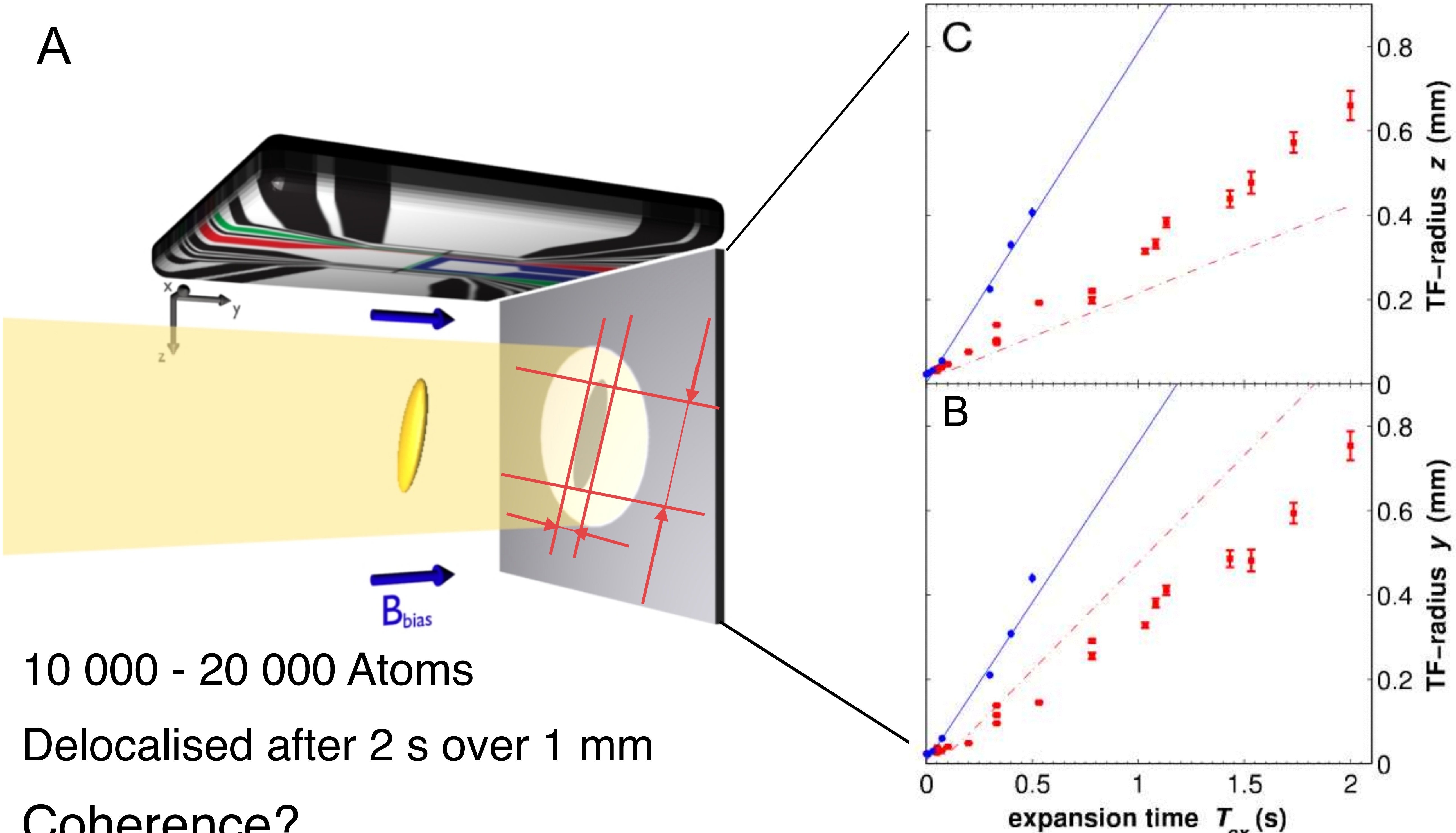
Reduction of the expansion rate by a "3D magnetic lens"

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





Delta kick cooling of BEC



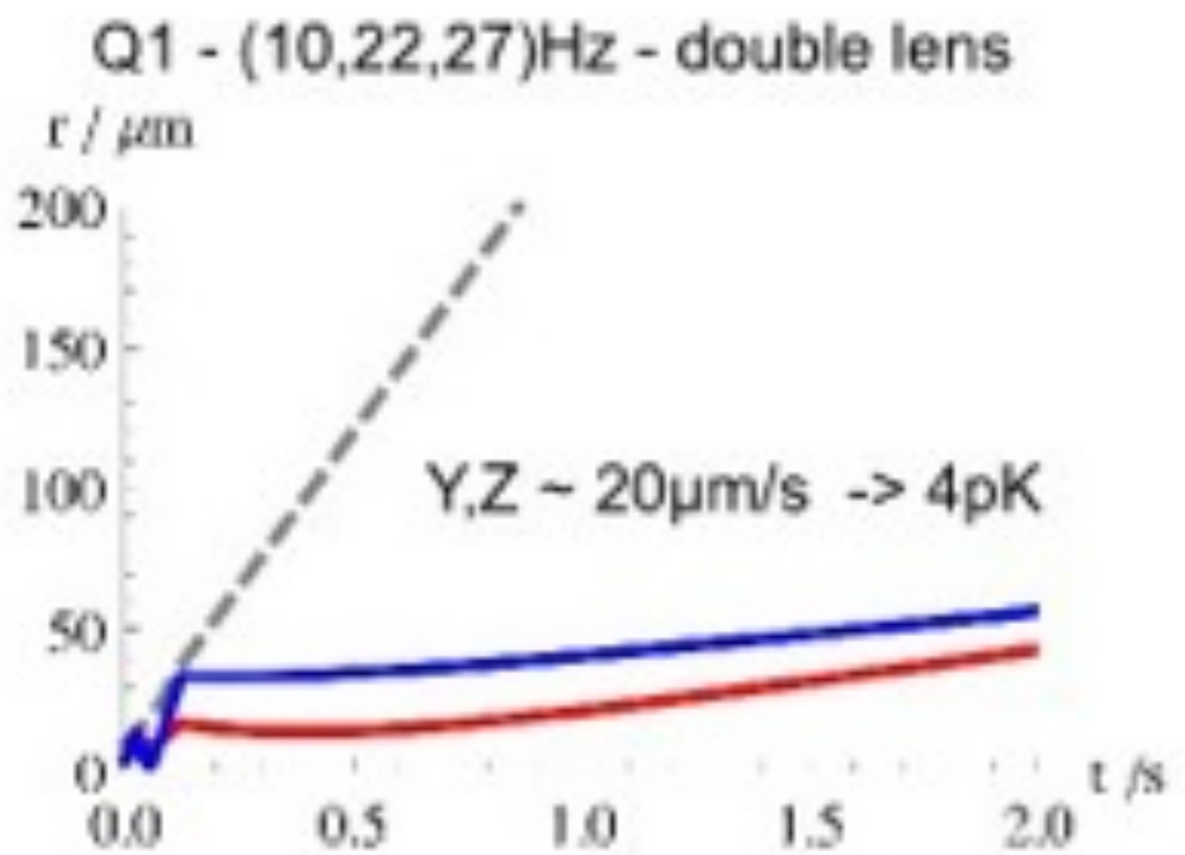
10 000 - 20 000 Atoms

Delocalised after 2 s over 1 mm

Coherence?

DKC - achieving energies in the pK range ?

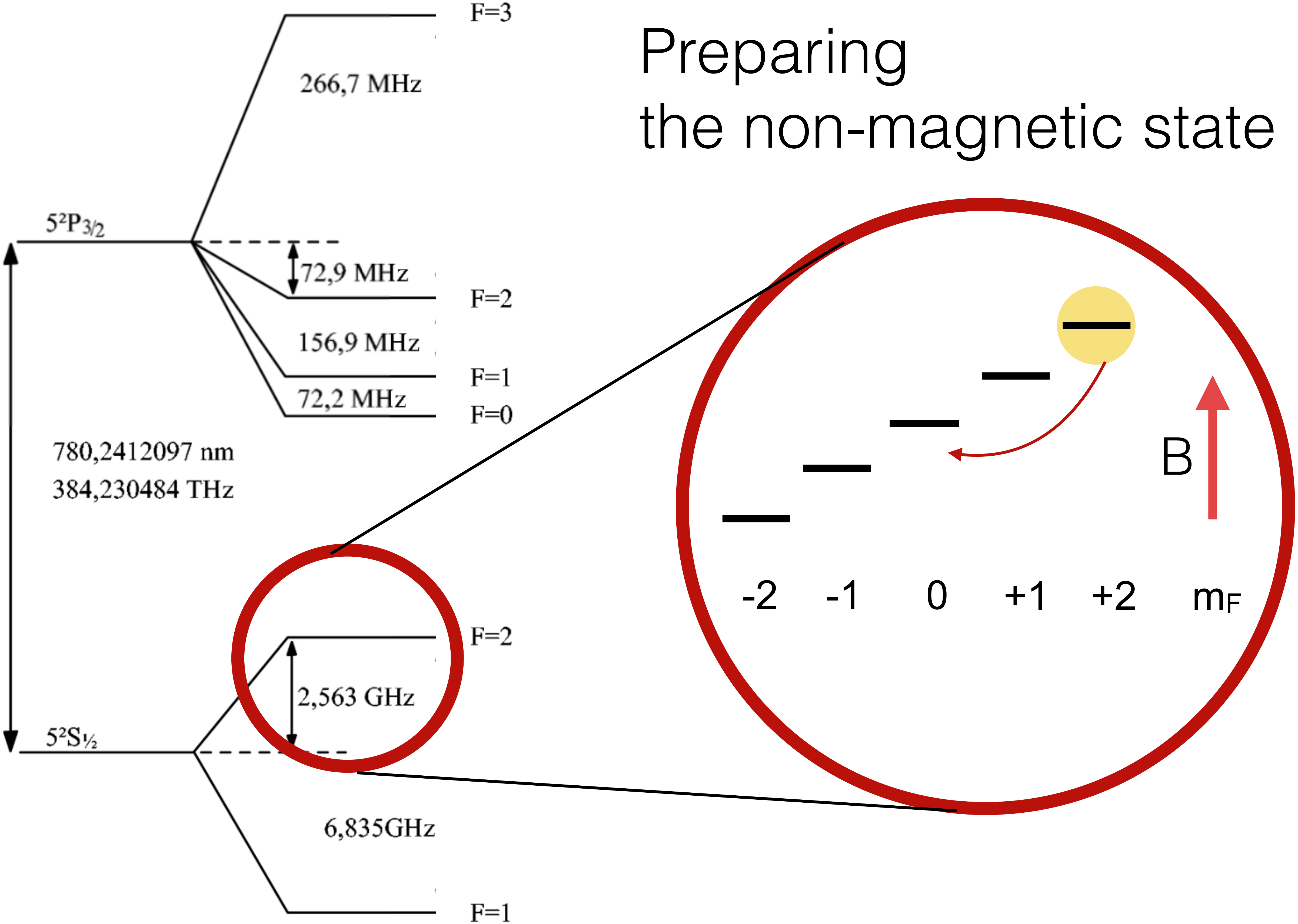
- Employing DKC twice - a matter-wave telescope



Kick 1

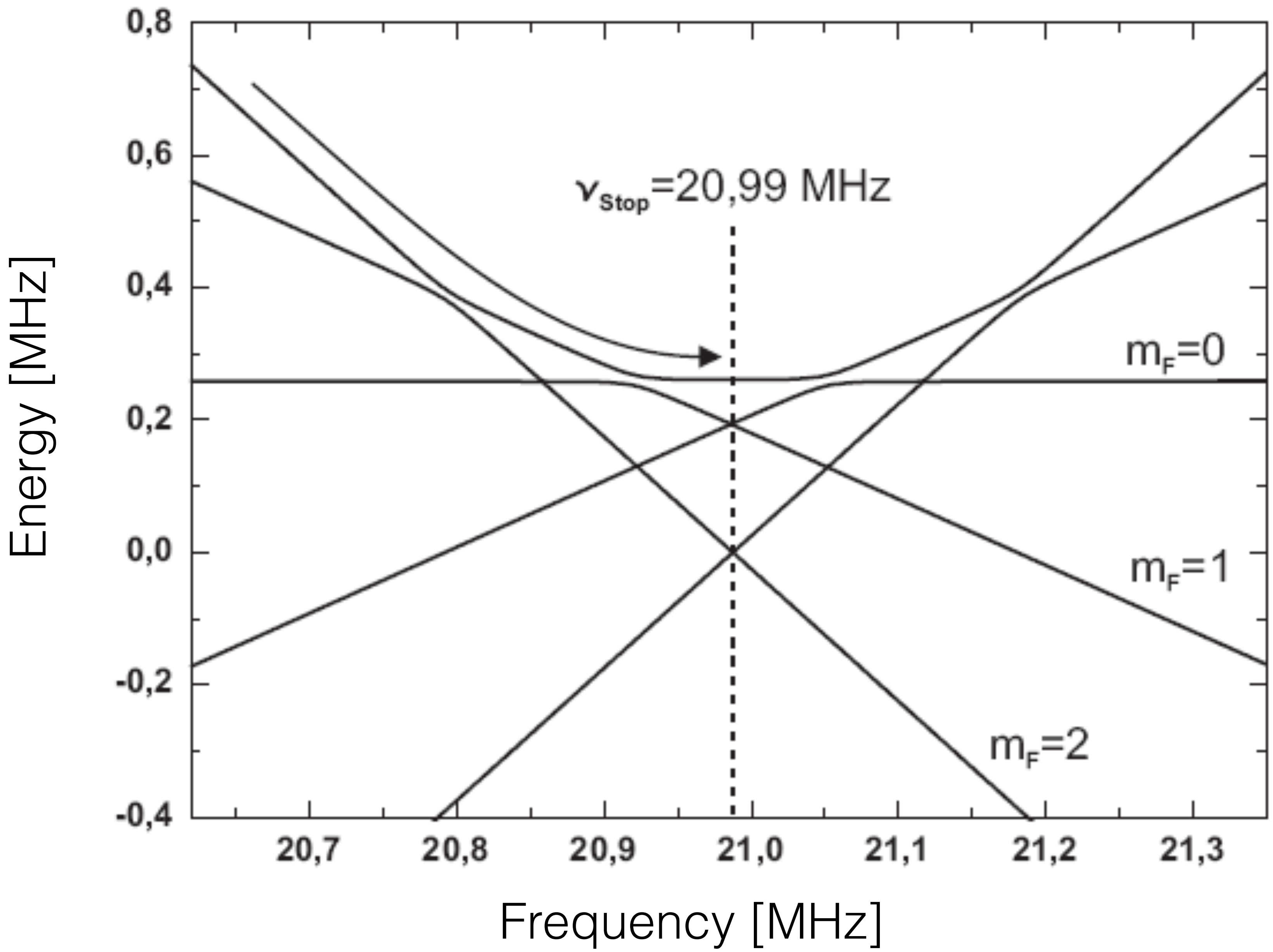
Kick 2

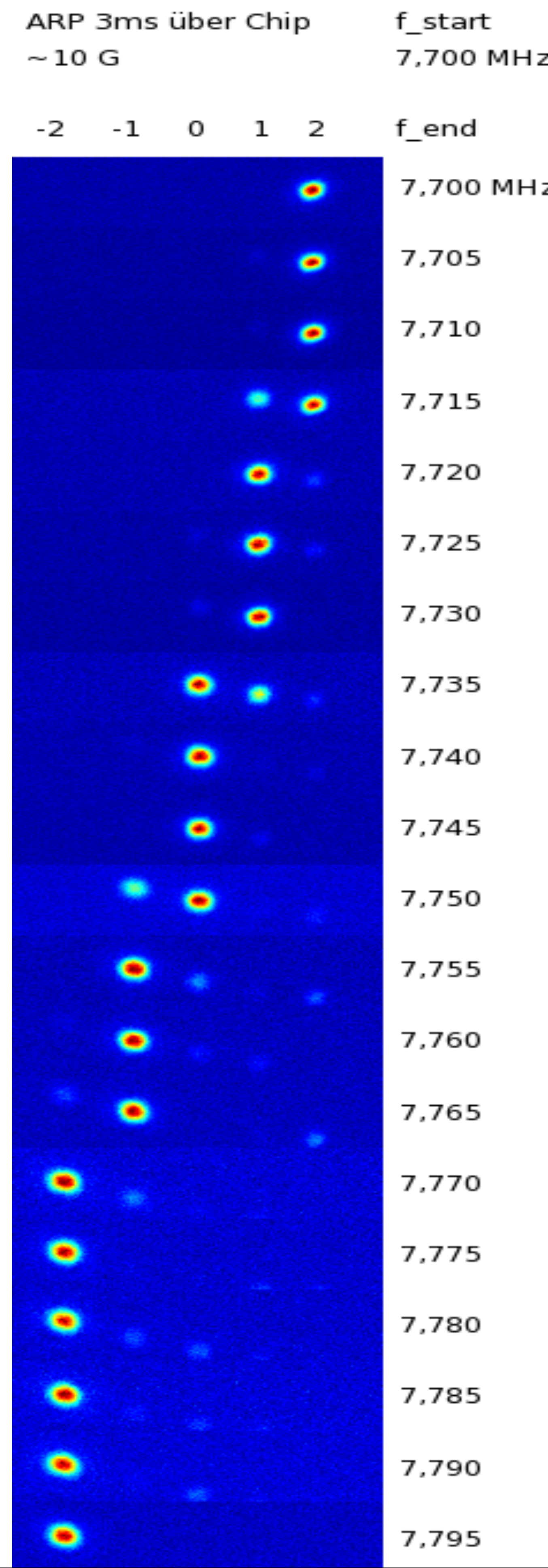
Preparing the non-magnetic state



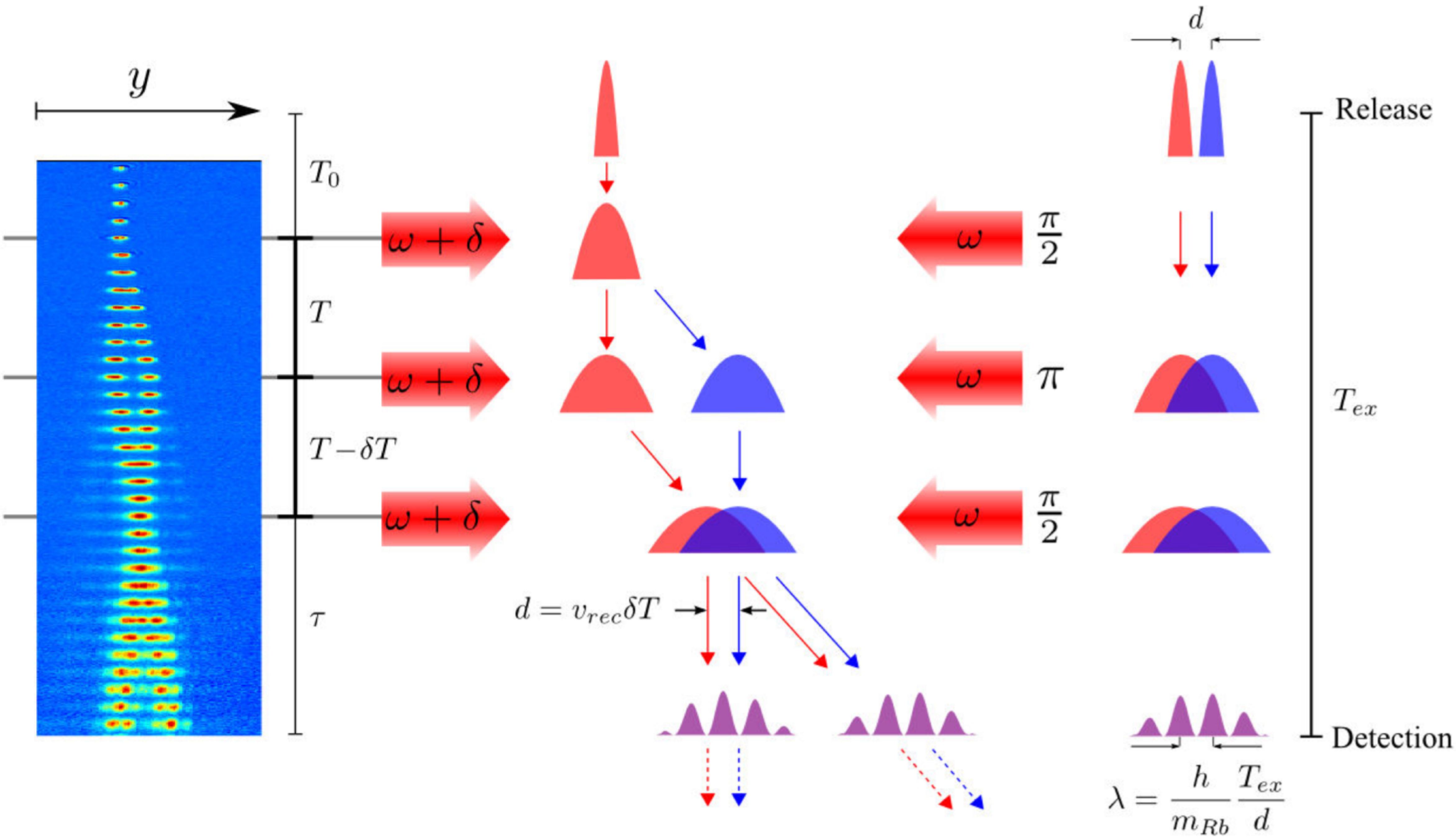
Rubidium

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

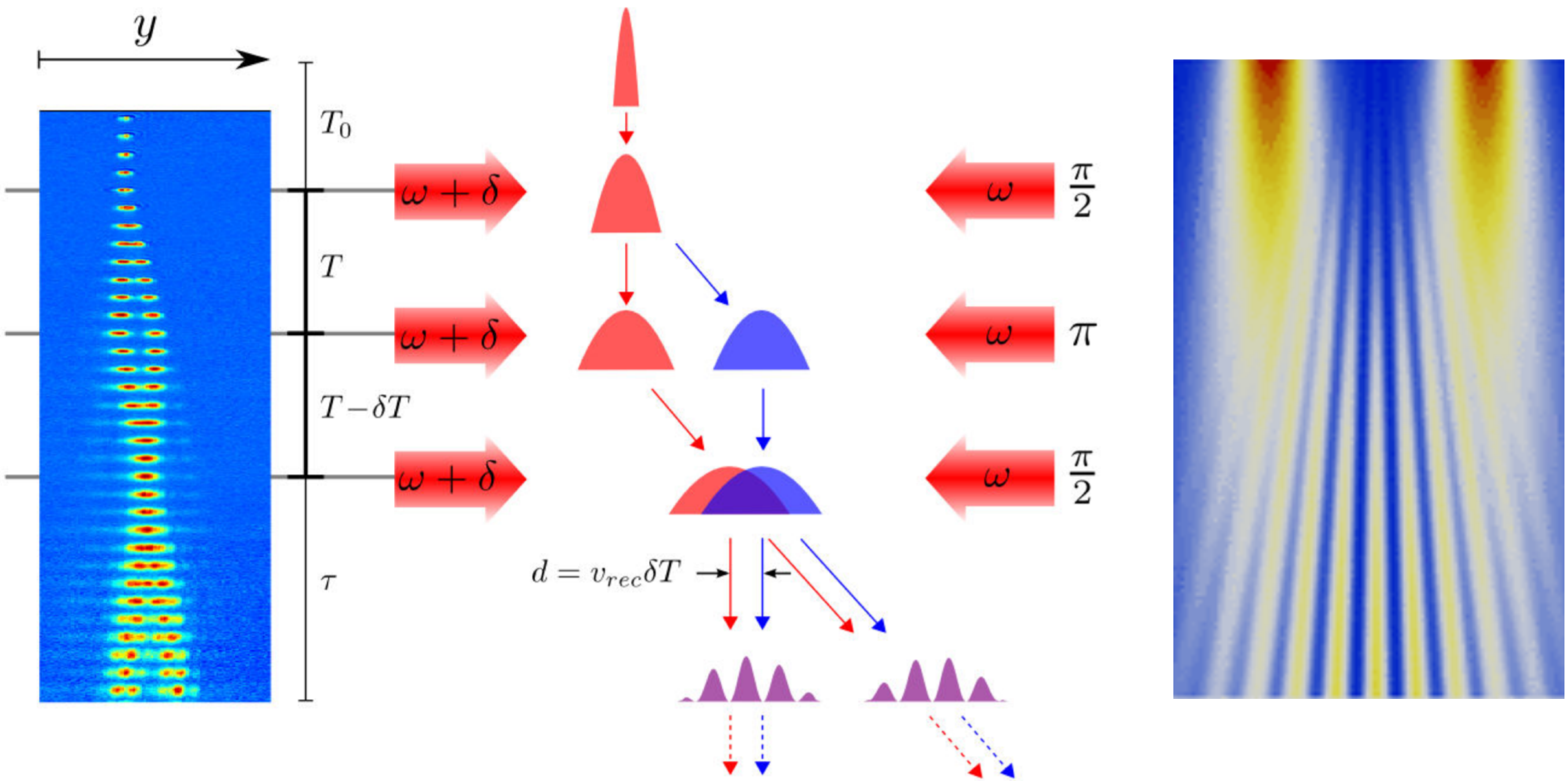




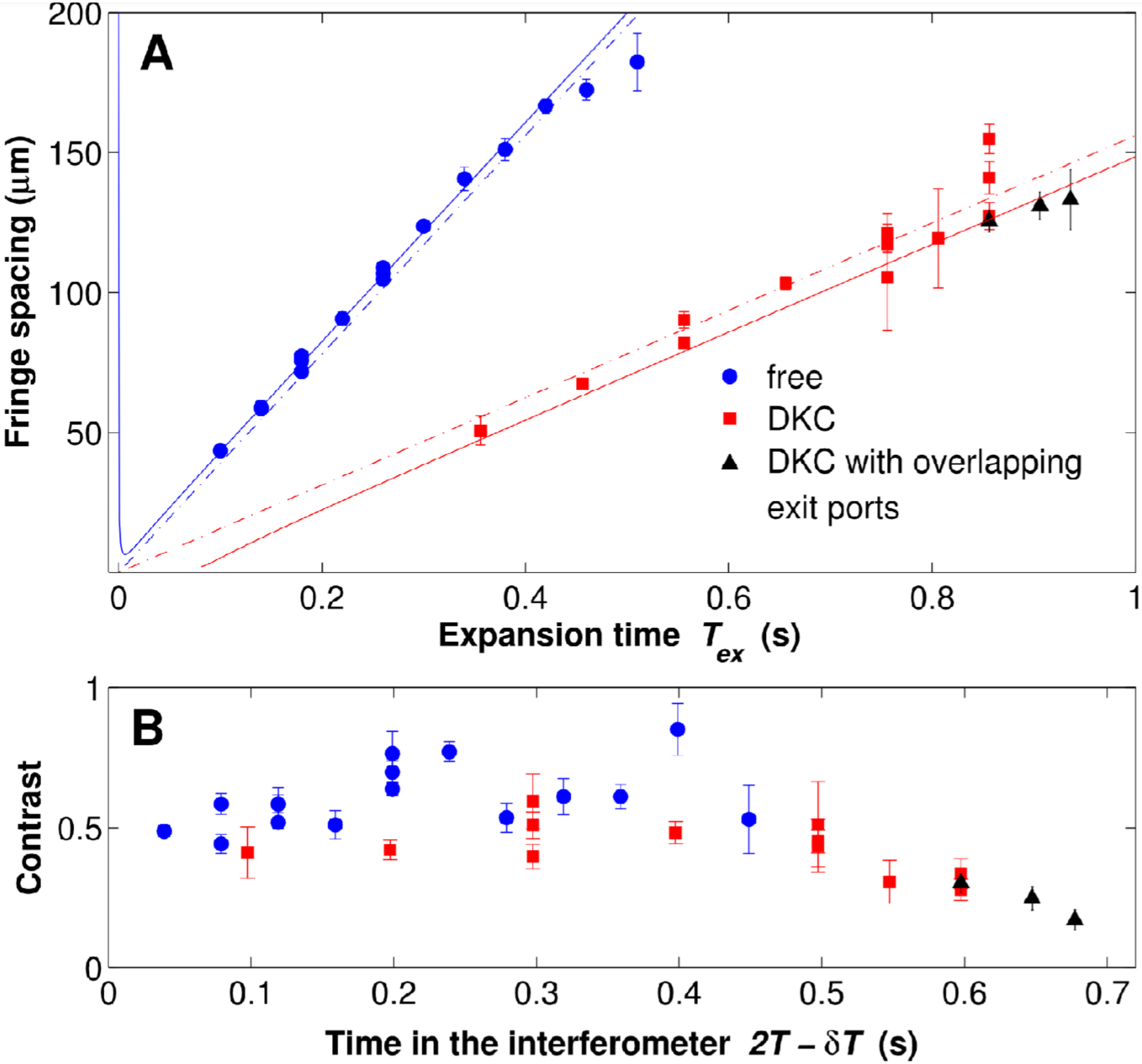
Asymmetric Interferometer (MZI)



A gigantic meter-length double slit experiment



Coherence of BEC w/wo DKC in microgravity



The achievements of QUANTUS 1

- Demonstration of technological feasibility of Bose Einstein Condensation in microgravity
- Interferometer based on BEC in microgravity
- 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

Atom Chip-based experiments

Advantages

- Robust
- Low power, atoms are located near the surface
- Large gradients, high trap frequencies

Challenges

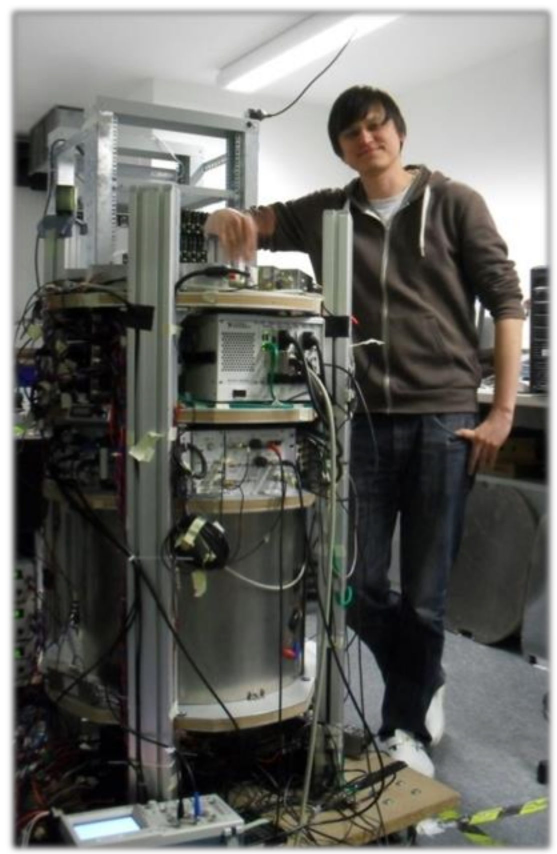
- Small volumes
- Small atom numbers
- Background loading, slow loading times

Next generation atom chips

Drop tower experiments

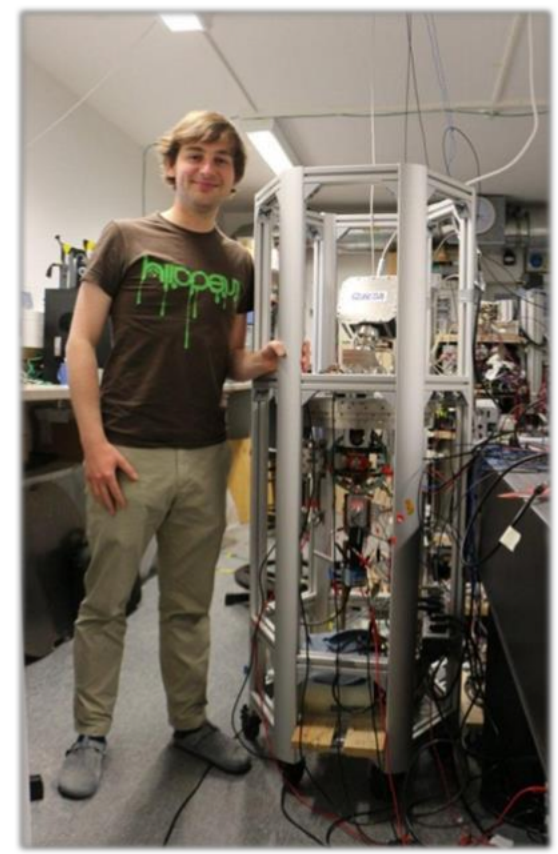
QUANTUS-I

QUANTUS-II



Space mission

MAIUS



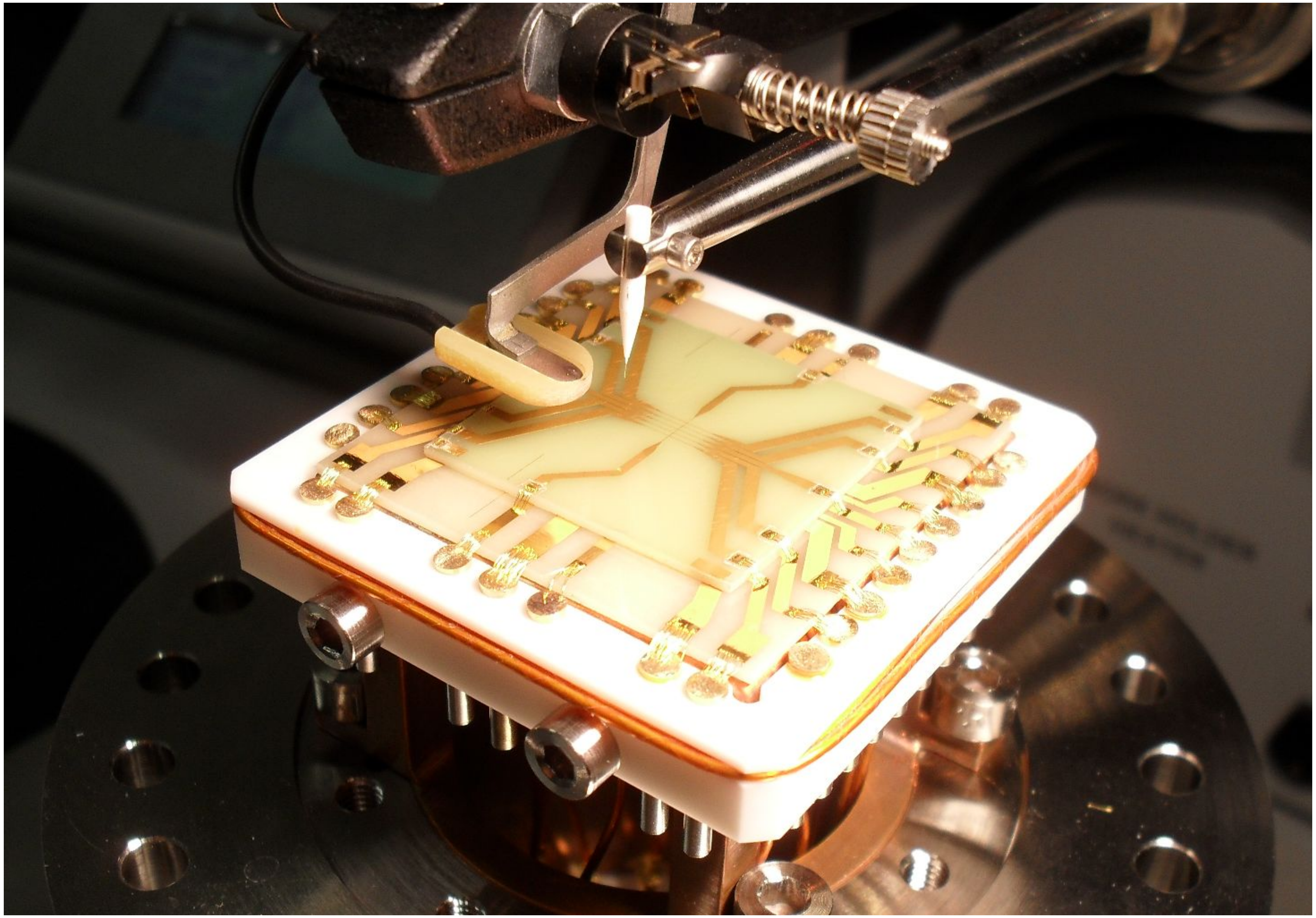
QUANTUS-2

A catapult capable multi species interferometer operated with chip based atom lasers

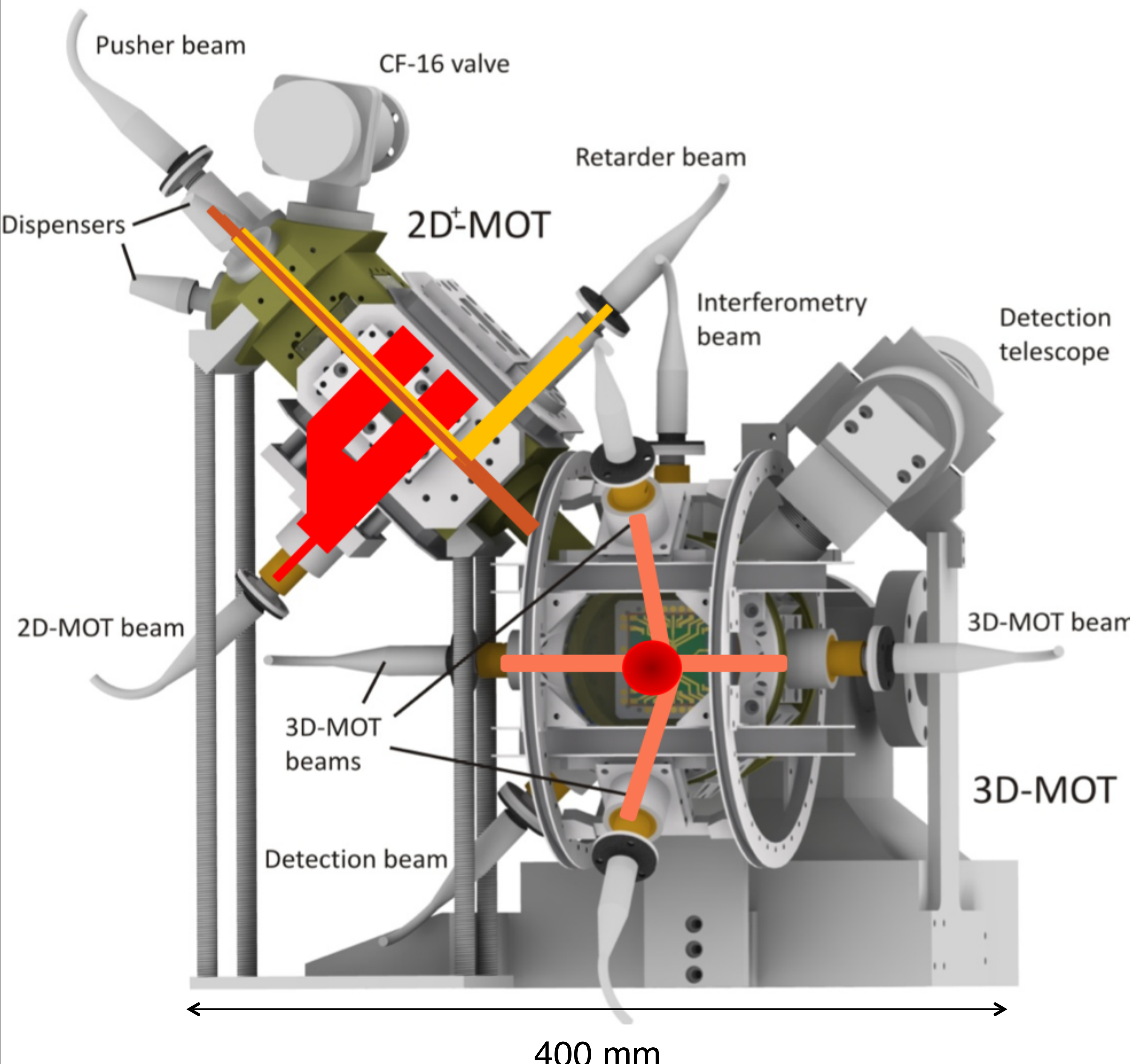
Dual species atom interferometer:

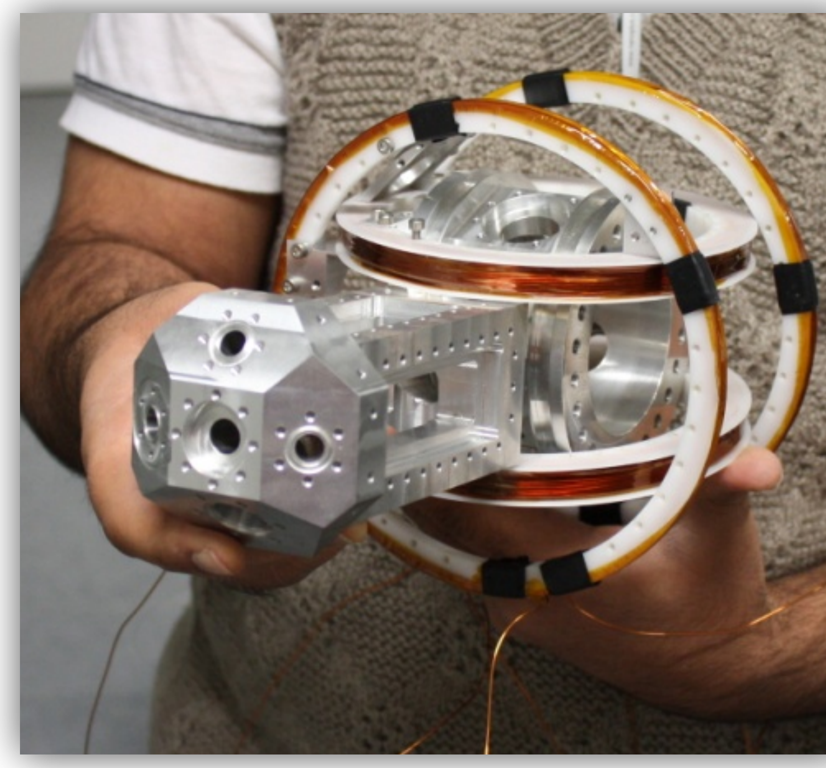
- $^{39,40,41}K/^{87}Rb$ interferometer in the drop tower
- 4.7s µg in drop mode, 8 s µg in catapult mode
- Interferometry time 2T = 6s

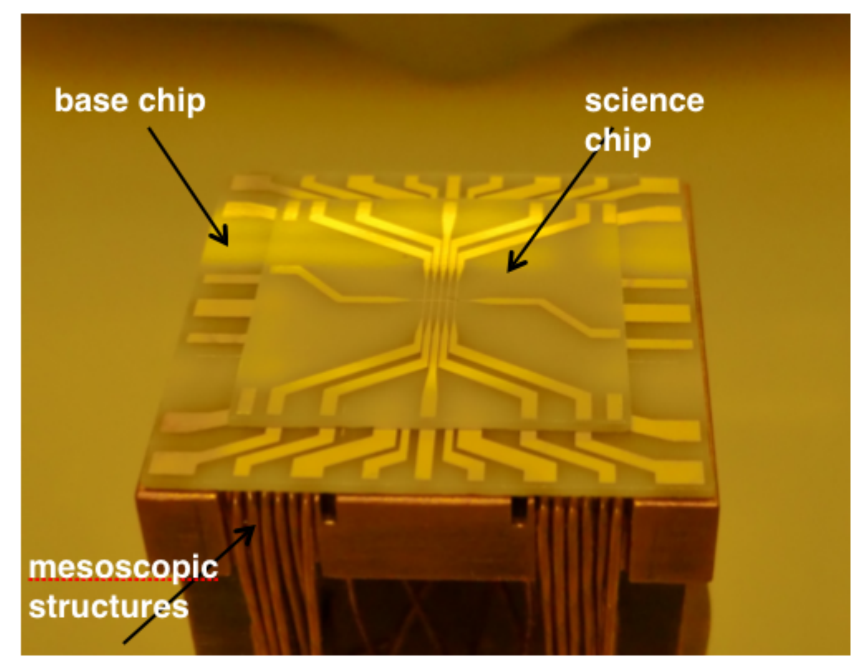
Advanced atom chips (QUANTUS 2)



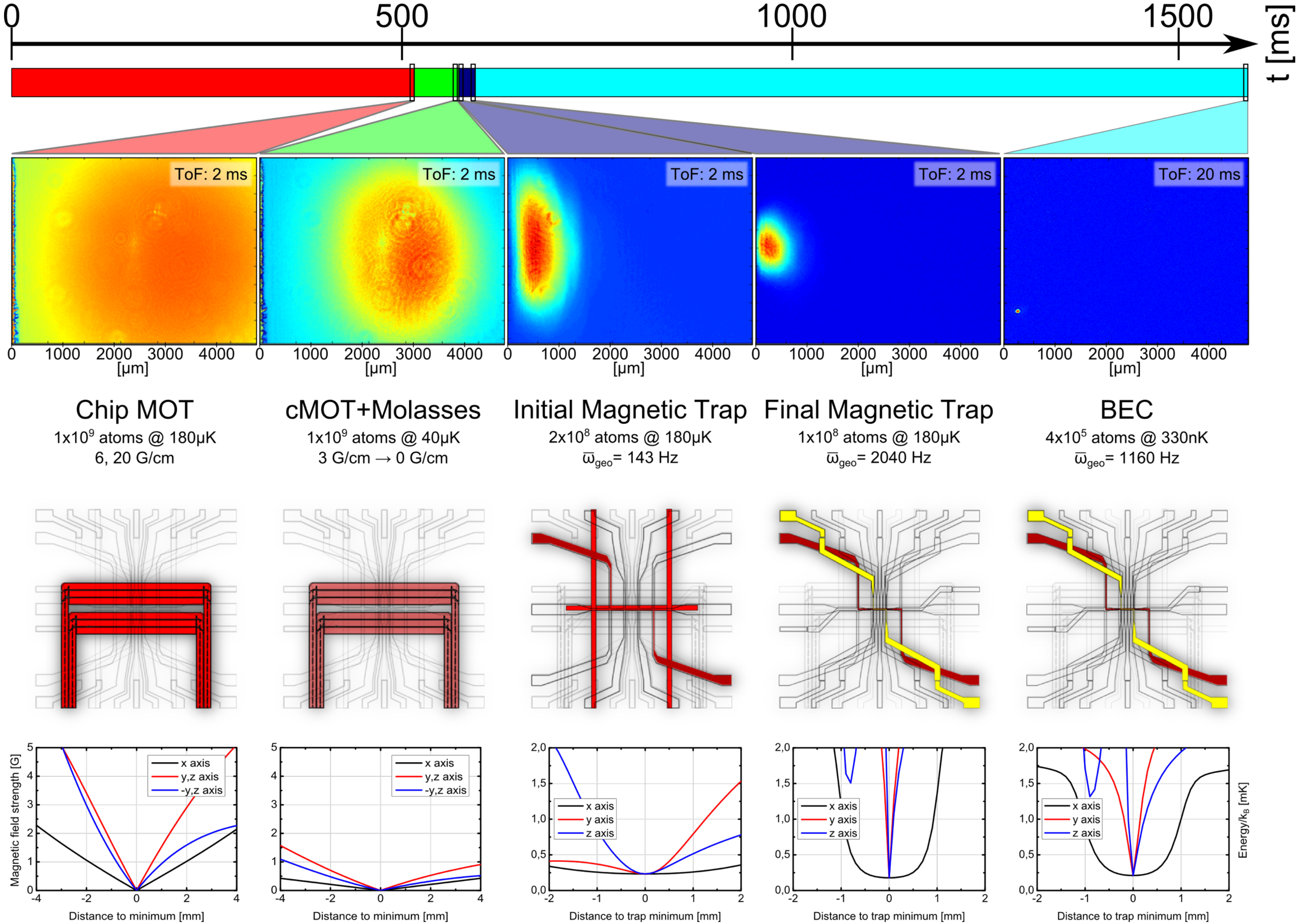
QUANTUS-2: setup







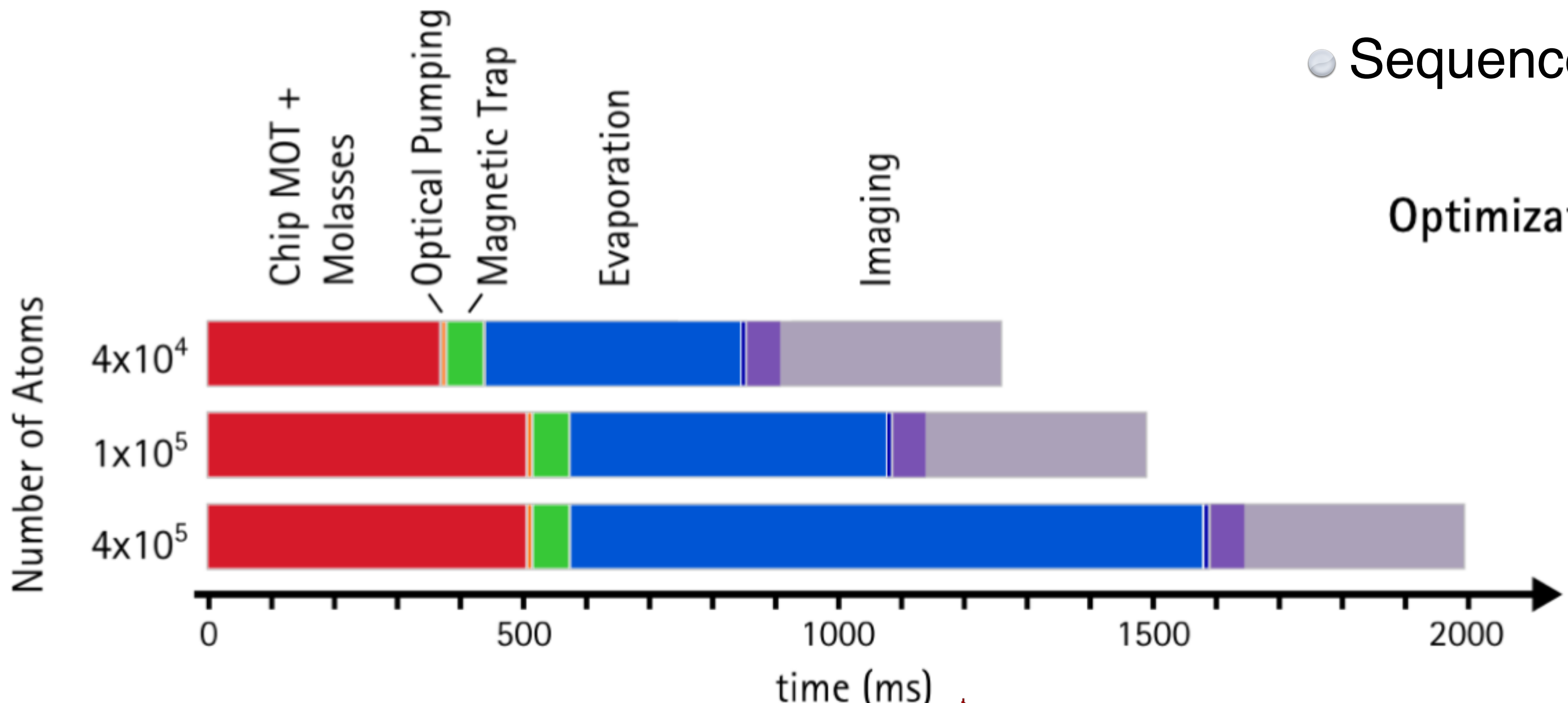
QUANTUS-2: experimental sequence

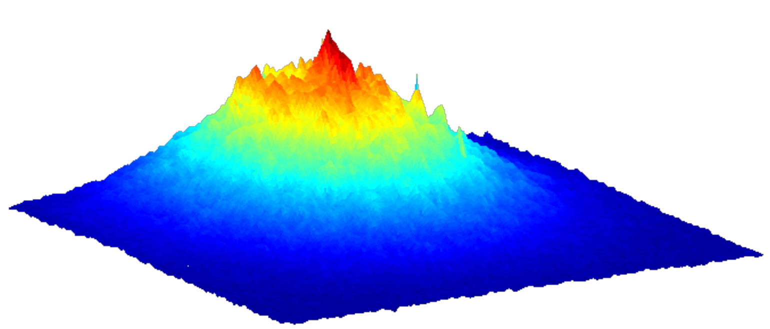


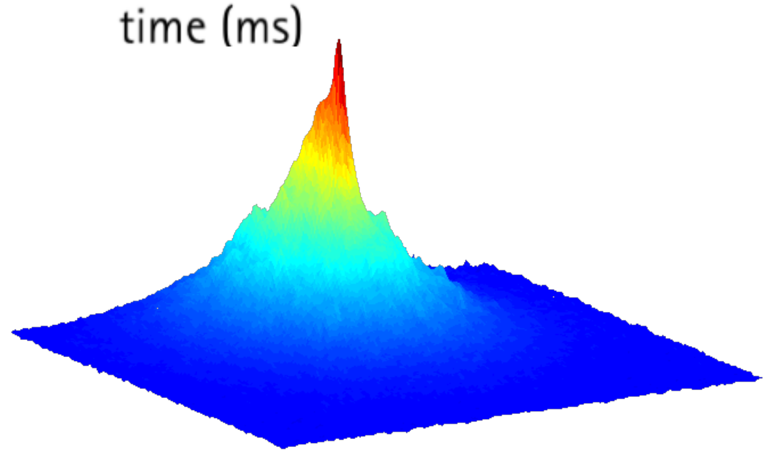
QUANTUS-2: performance

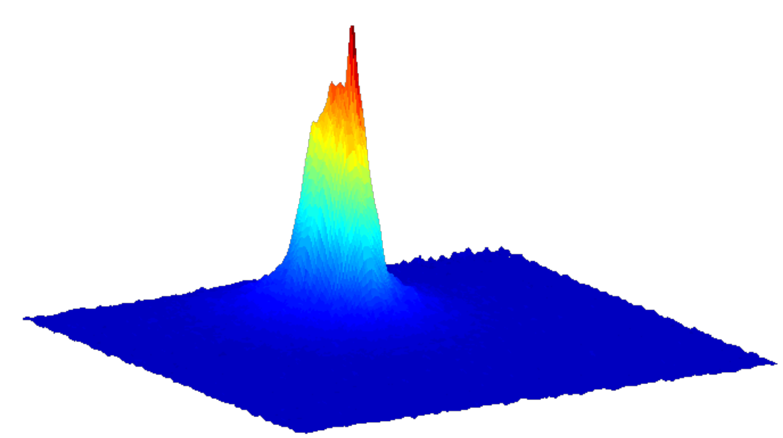
Particle number in dependence of BEC creation time:

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









- Particle Number (BEC):

  $\geq 5\cdot10^5$ (QU-1: $8\cdot10^{3}$- 10^4)

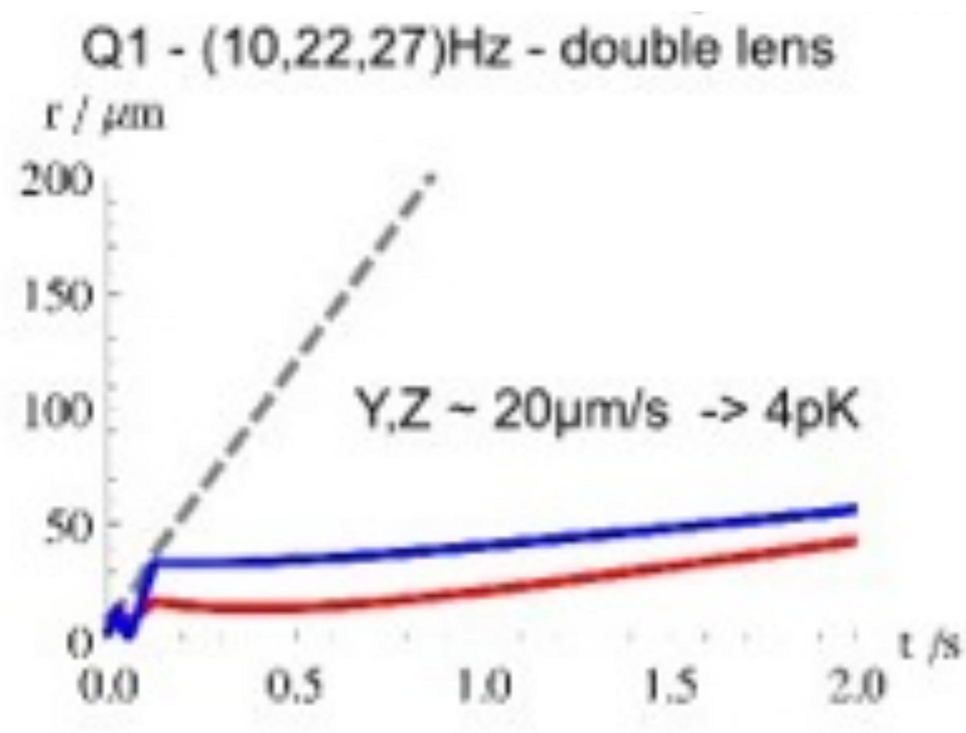
- Duration of Preparation:

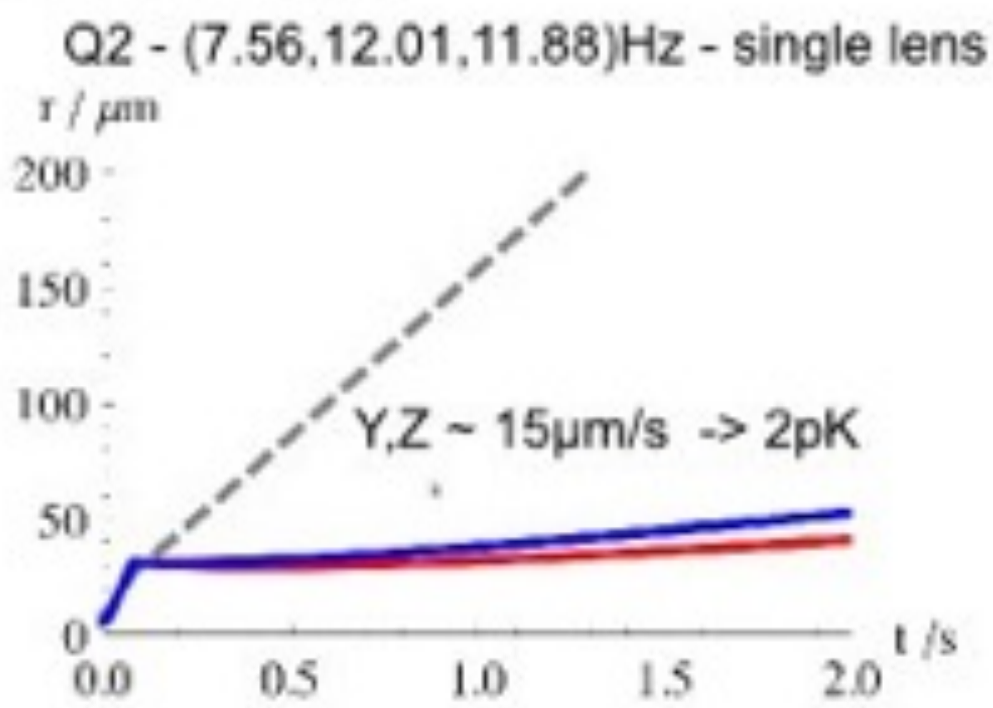
  <1- 3 s (Q-I:11s)

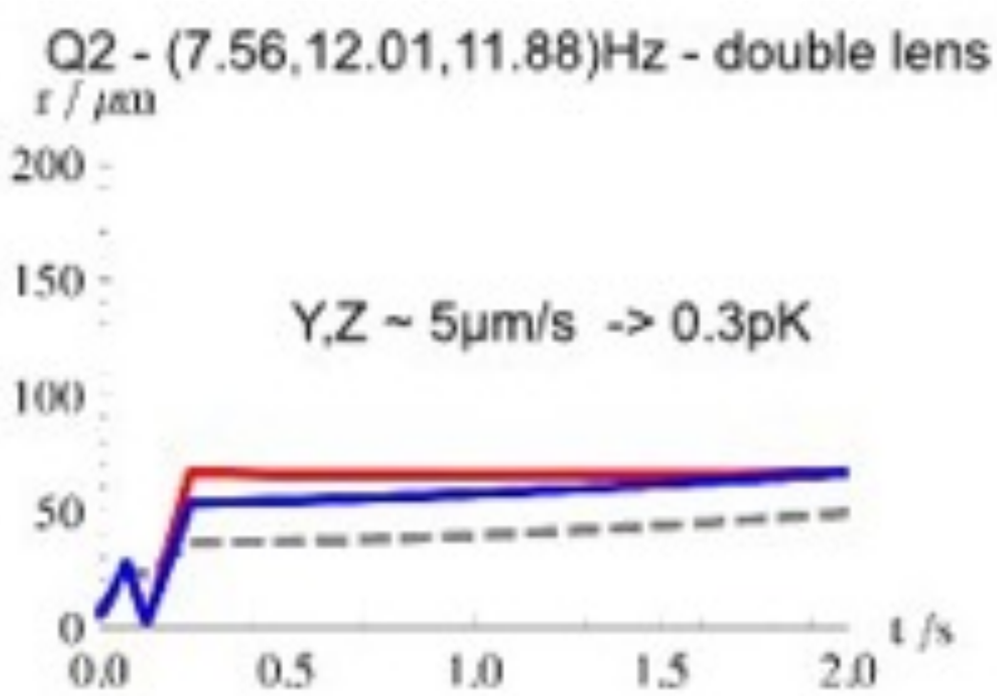
- Sequence Cycle Time: < 2s

Optimization ongoing!

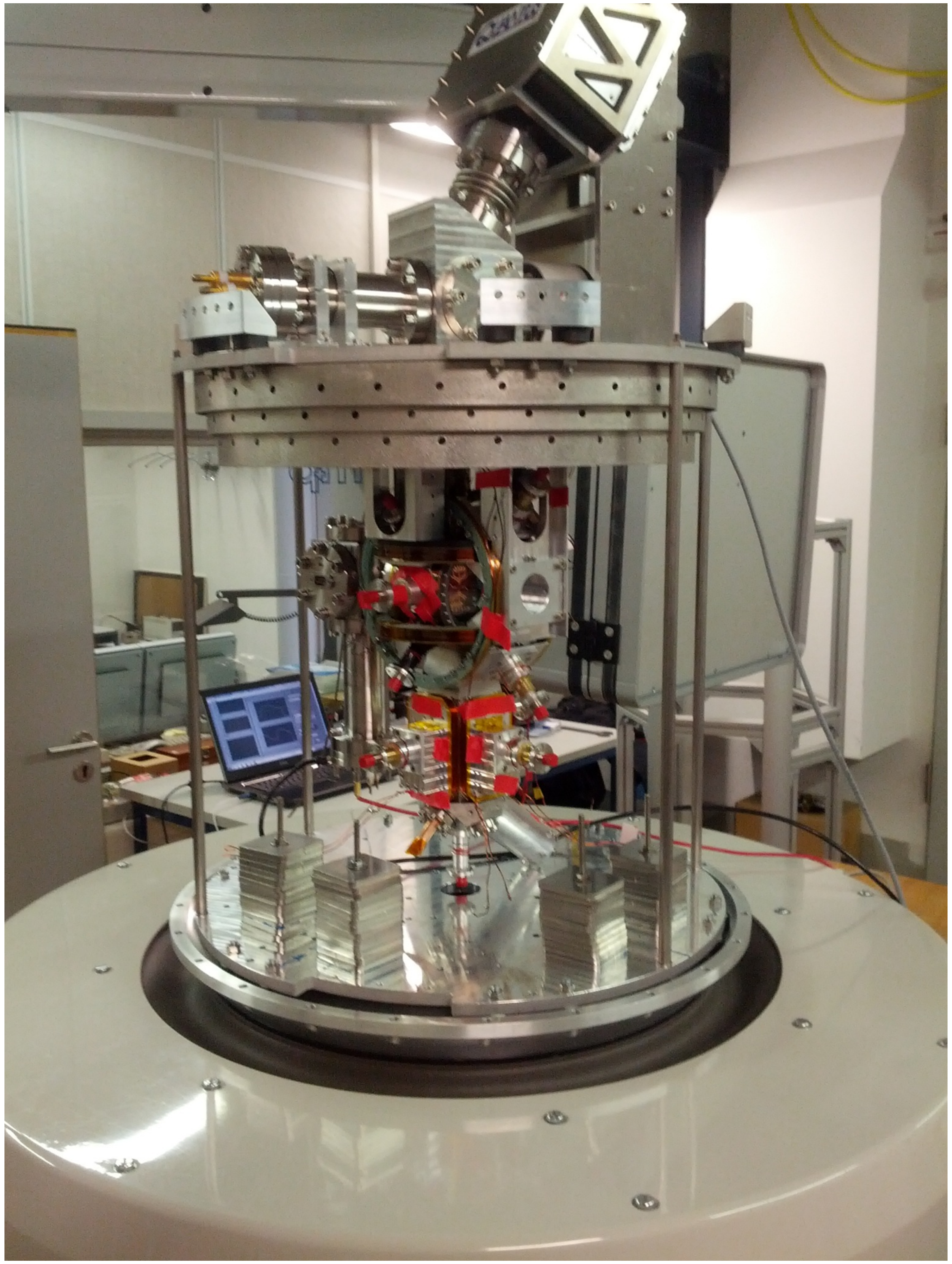
QUANTUS-2: DKC performance







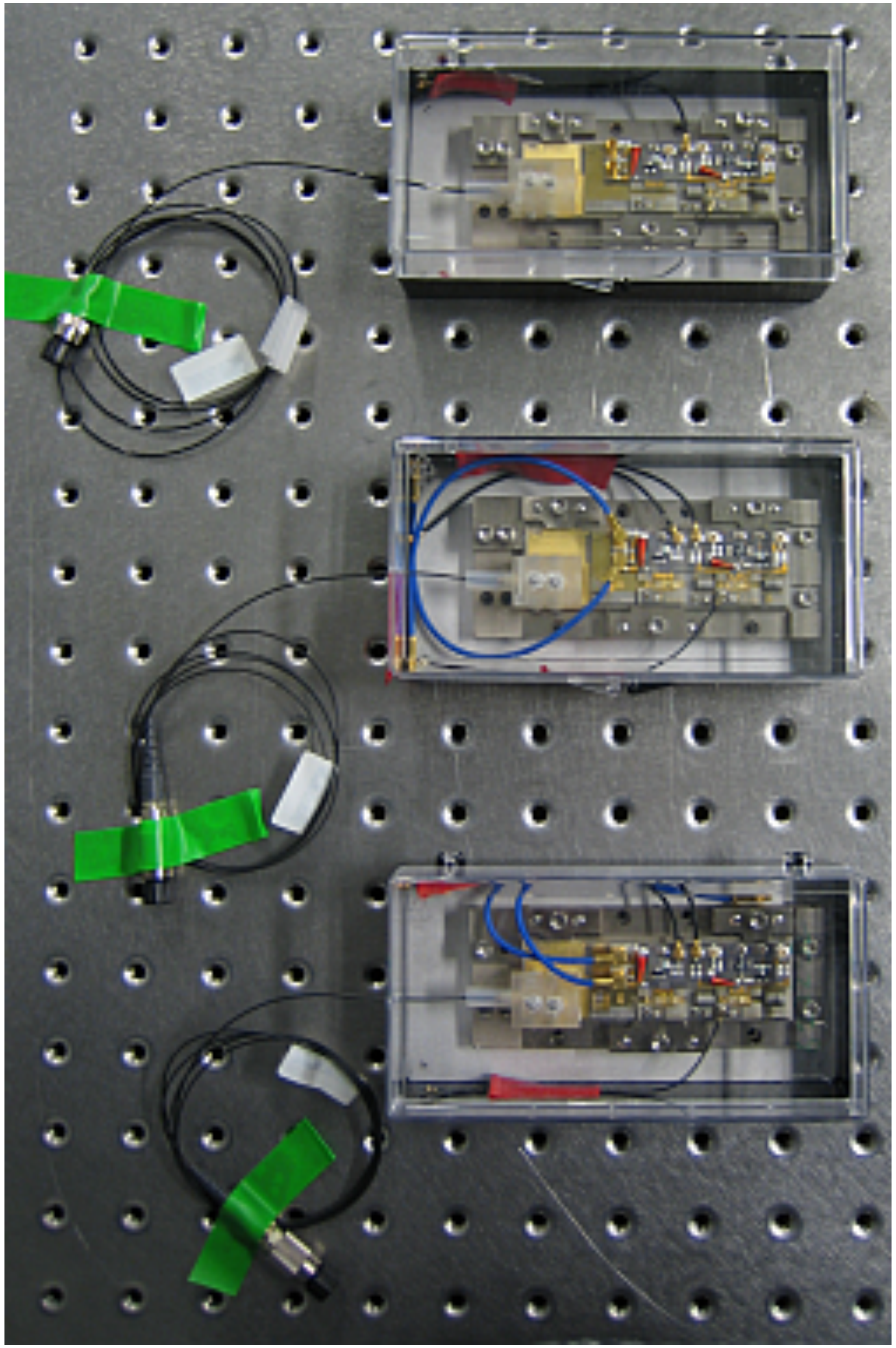
Chip based atom interferometers

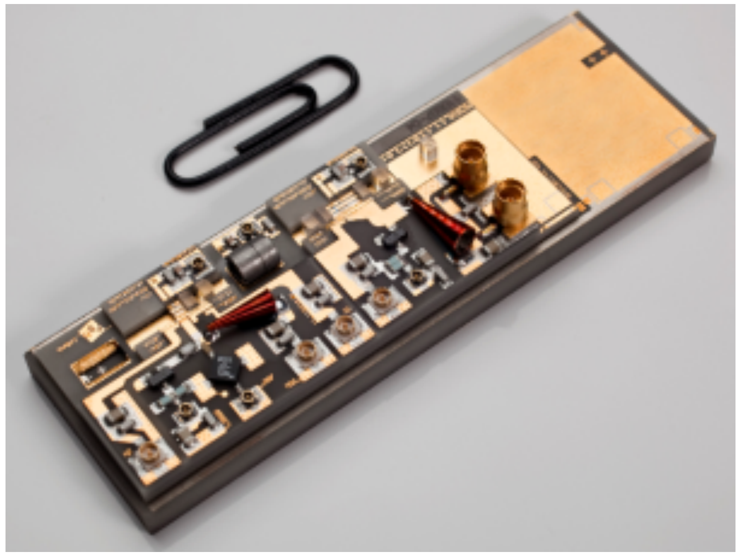


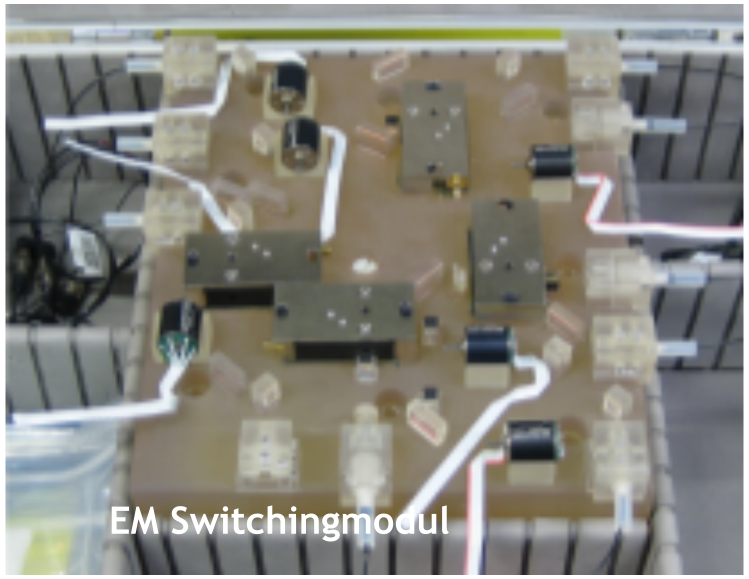
Shaker test of a chip-based atom interferometer

- 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

Light generation and manipulation (FBH, HUB, Hamburg)



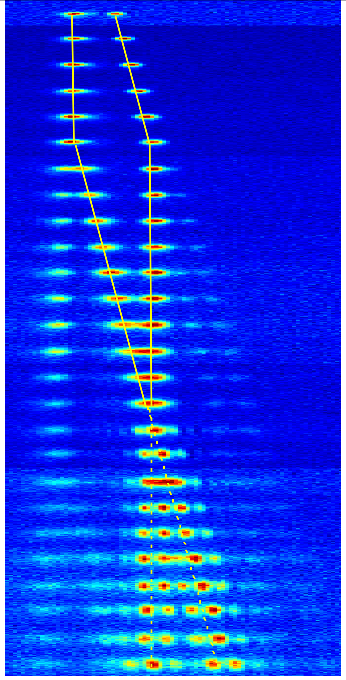




Experiments at the drop tower and catapult

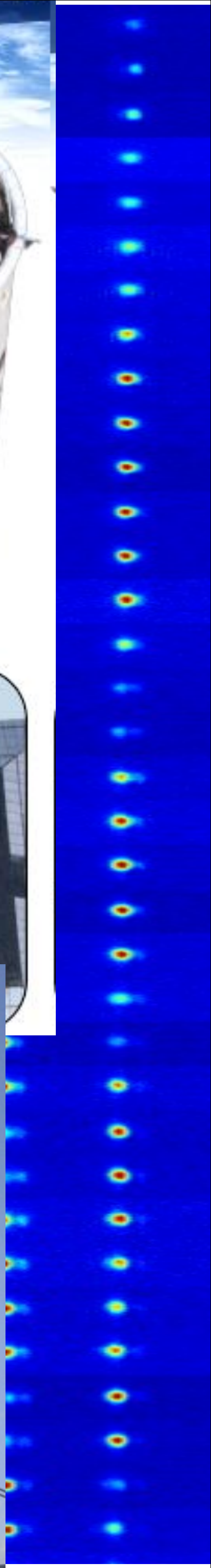
QUANTUS I:

- Demonstrating multiple delta-kick cooling
- Investigating dephasing mechanisms
- Demonstrating Bragg type double diffraction with BEC



QUANTUS II

- Ultra long interferometry, improved delta- kick-cooling, µgravity enhanced atom laser
- Dephasing by the gravity gradient
- Drop & catapult experiments on dual species sources and interferometry

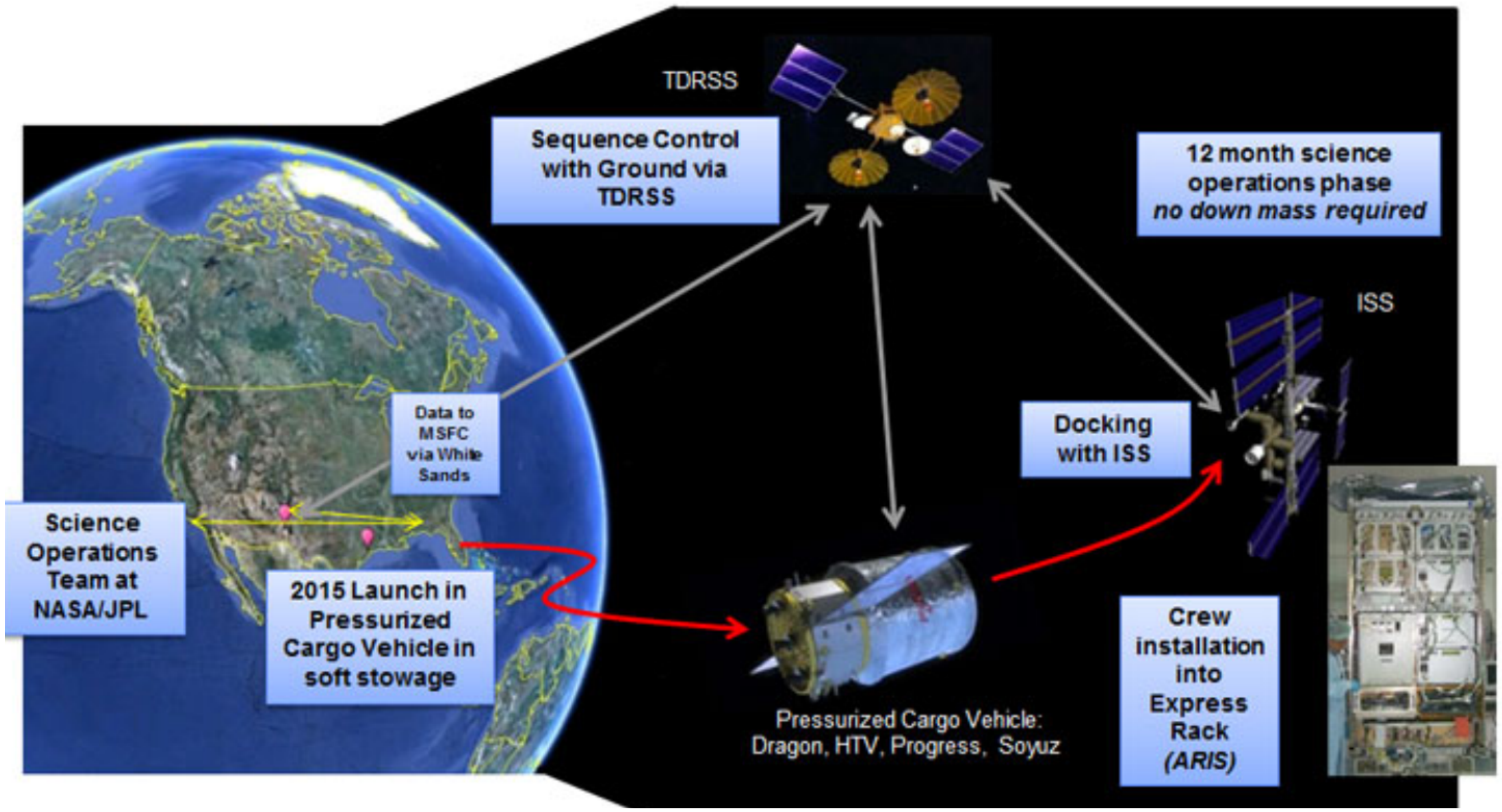


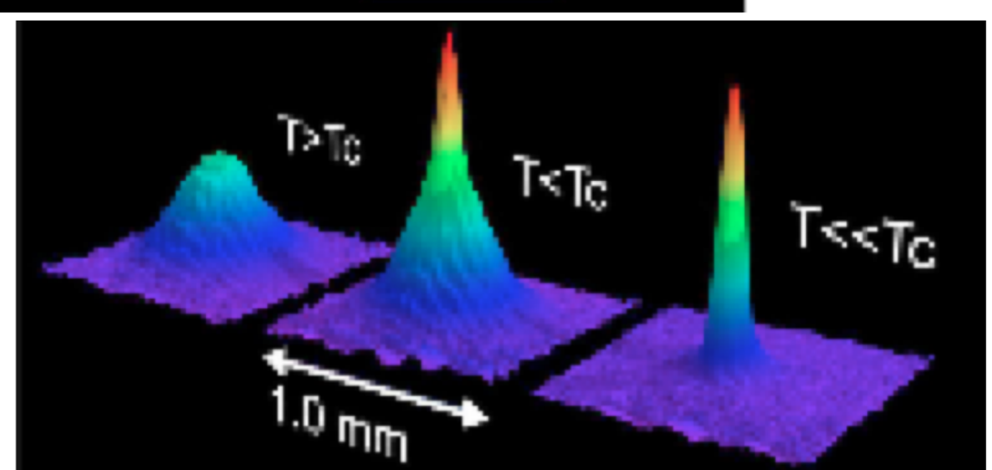
MAIUS

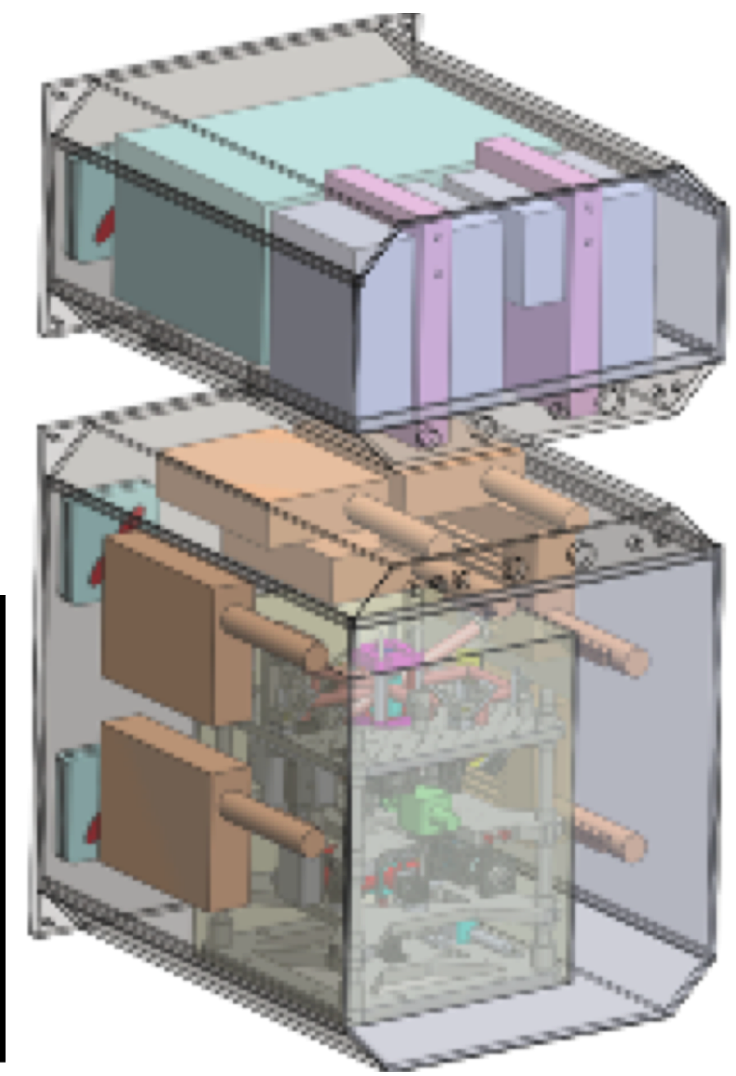
- Atom interferometer hosted on a rocket 2014

Jet Propulsion Laboratory
California Institute of Technology

CAL EXPRESS rack implementation







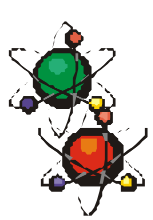
Quantum tests

Einsteins Equivalence Principle

Universality of free fall

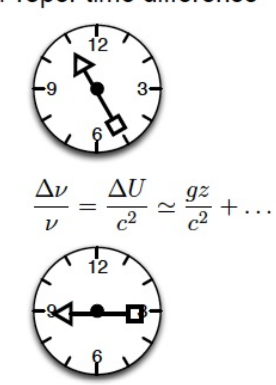
?

Universality of redshift



Schiffs Conjecture

Proper time difference



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.

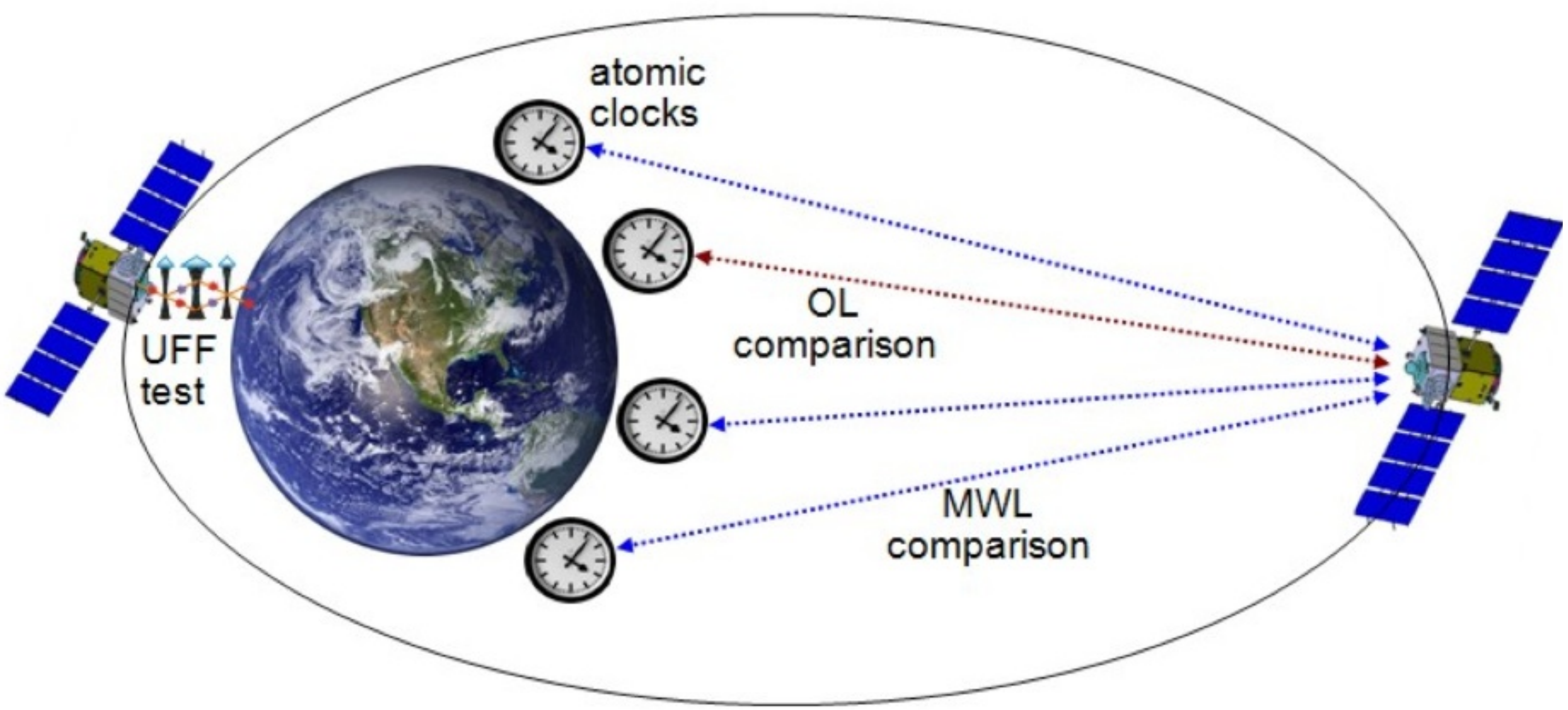
$$\left(\frac{m_{\mathrm{g}}}{m_{\mathrm{i}}}\right)_p^i = 1 + \alpha_p^i.$$

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

STE-QUEST

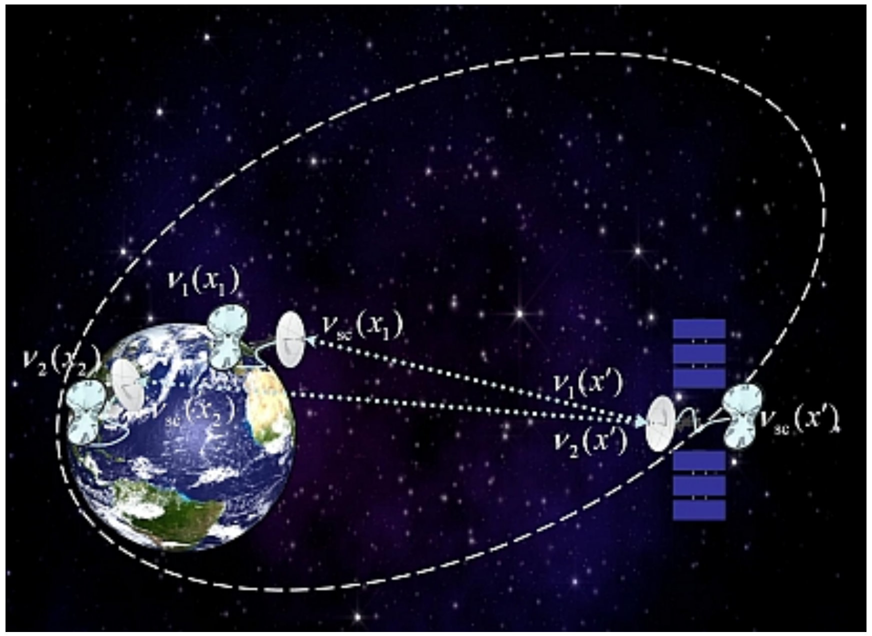
Science Objectives

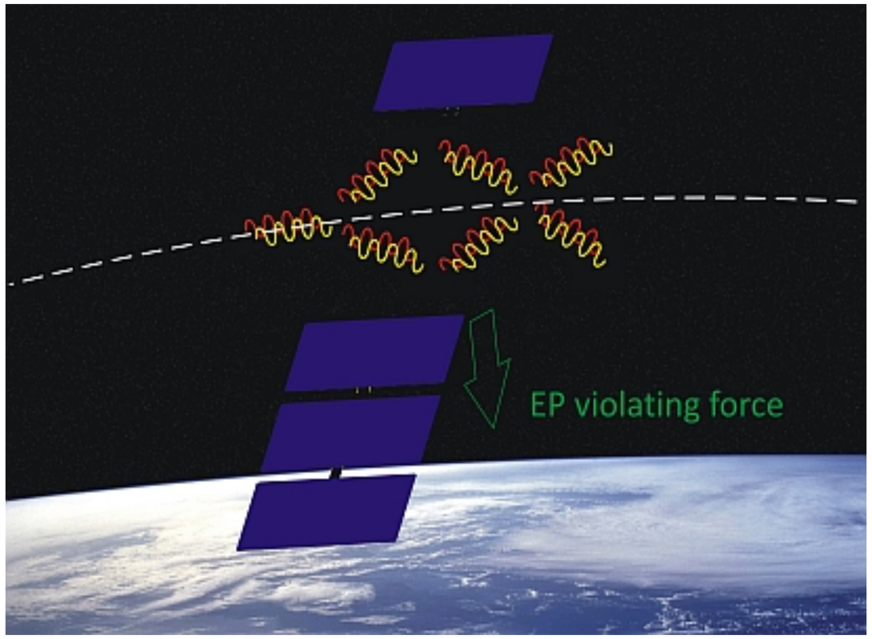
- Measurement of the time dilation in the vicinity of the Earth to parts in 10^7
- Comparison of the propagation of matter waves (85/87 Rb) in the Earths gravitational field to parts in 10^{15}



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, $k = 8\pi/(780\ \mathrm{nm})$, 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 $\eta = 10^{-15}$

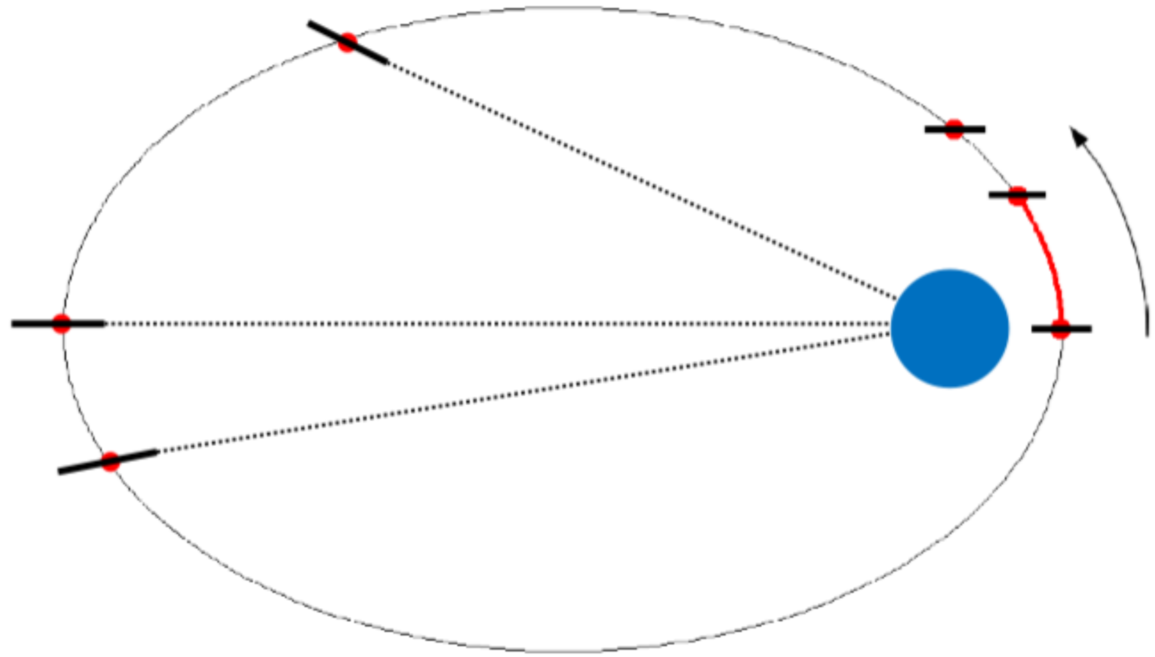
$\sigma_{\eta,1orbit,700} = 4.65 \cdot 10^{-14}$ → 2163 orbits

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

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

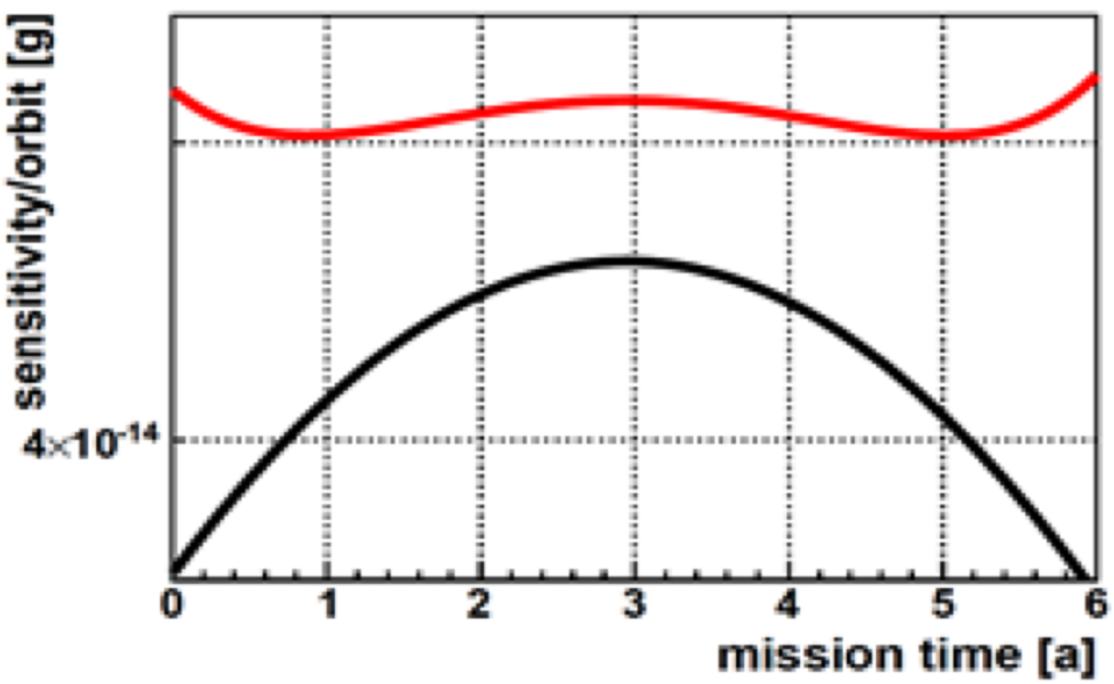
Apogee:

- 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



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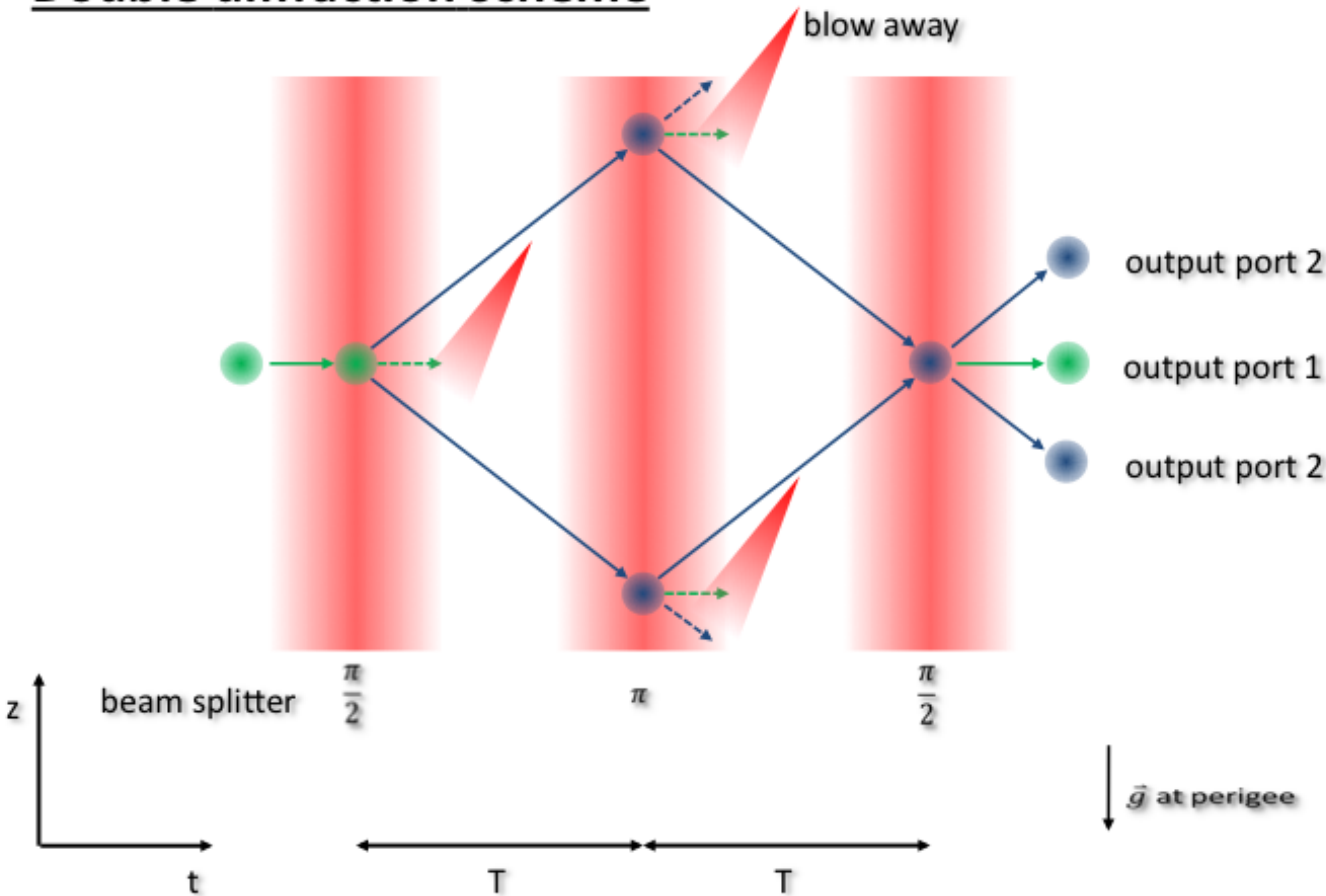
$\sigma_{\eta,1orbit,1900} = 4.85 \cdot 10^{-14}$ → 2353 orbits = 4.3 years

STE-QUEST Error Budget & Requirements

Error source	**Error term $\Delta a = \Phi_{\Delta a}/(kT^2)$**	**Conditions**	**Bias in 10^{-15} m/s^2**
Gravity gradient	$-T_{zz}\,\Delta z$ $-TT_{zz}\,\Delta v_z$	$\Delta z = 1.1\cdot10^{-9}$ m $\Delta v_z = 3.1\cdot10^{-10}$ m/s	2.6 3.5
Coriolis acceleration	$-2\Omega_y\,\Delta v_x$ $-2\Omega_x\,\Delta v_y$	$\Delta v_x = 3.1\cdot10^{-10}$ m/s $\Delta v_y = 3.1\cdot10^{-10}$ m/s	$-6.3\cdot10^{-1}$ $-6.3\cdot10^{-1}$
Other terms (rotations / gradients)	$-(\Omega_{orb}^2-\Omega_c^2)\,\Delta z$ $-T(6\Omega_c\Omega_{orb}-3\Omega_{orb}^2-3\Omega_c^2)\,\Delta v_z$ $T(2\Omega_{orb}^3+\Omega_c^3)\,\Delta x$ $TT_{xx}\Omega_{orb}\,\Delta x$ $-7/6\cdot T^2T_{zz}\Omega_{orb}\,\Delta v_x$ $-7/6\cdot T^2T_{xx}\Omega_{orb}\,\Delta v_x$ $-\Omega_{orb}\Omega_z\,\Delta y$	$\Delta x = 1.1\cdot10^{-9}$ m $\Delta y = 1.1\cdot10^{-9}$ m $T_{zz} = -2GM_e/R^3 = -2.26\cdot10^{-6}$ s^{-2} $\Omega_c \approx \Omega_{orb} = 1.4$ mrad/s, $\Omega_c - \Omega_{orb} \approx \Omega_x = \Omega_y = 1$ μrad/s $T_{xx} = T_{yy} = -T_{zz}/2$	$-3.2\cdot10^{-3}$ $< 10^{-3}$ $4.9\cdot10^{-2}$ $9.1\cdot10^{-3}$ $2.9\cdot10^{-2}$ $-1.5\cdot10^{-2}$ $-1.6\cdot10^{-3}$
Photon recoil	$T^4T_{zzz}\hbar^2k^2/16\,(m_{87}^{-2} - m_{85}^{-2})$	$T_{zzz} = 6GM_e/R^4 = -9.57\cdot10^{-13}$ m^{-1}s^{-2}	$3.9\cdot10^{-2}$
Self-gravity		Apogee measurement - subtraction	1
Magnetic field gradients	$B_0\,\delta B\,\hbar\,(K_{87}/m_{87} - K_{85}/m_{85})$	$B_0 = 100$ nT, $\delta B < 0.1$ nT/m, $K_{87} = 575.15$ Hz/G^2, $K_{85} = 1293.98$ Hz/G^2	1
Effective wave front (beam splitter lasers)	$(T_{at,87}/m_{87} - T_{at,85}/m_{85})\,k_B/R_e$	$\lambda/300$ mirror → $R_e = 250$ km, $T_{at} = 0.07$ nK Collimation $R_i \sim 400$ m → $R_e > 250$ km, $T_{at} = 0.07$ nK	$6.3\cdot10^{-1}$ $2.8\cdot10^{-1}$
Mean field	$\int_0^{2T} dt\,[\mu V(0) / (\hbar V(t)N^{-1/2})]$	BEC radius at first beam splitter 300 μm, expansion rate 82 μm/s, tuned atom numbers uncertainty of 1000	$2\cdot10^{-5}$
Spurious accelerations	$CMRR \cdot a_{spur}$	$CMRR = 2.5\cdot10^{-9}$, $a_{spur} = 4\cdot10^{-7}$ m/s^2	1

Double diffraction scheme



Take home messages

- Robust chip based atom laser
- First BEC in microgravity
- First matter wave interferences with BEC (nK energy) in microgravity
- Detailed understanding and control of the BEC evolution
- Atom Interferometry at unprecedented evolution times for coherence studies & new interferometers
- New record breaking generation of atom chips for 2 species: QUANTUS II
- Rocket capable atom interferometer, launch 2014
- Technological spin-off for geodesy

Atomic Quantum Sensors

Atom-Chip

Robust & Compact Laser

Fermionic Source

50 WM 0346

Theory

Drop Tower & Space Integration

Thank you