Atomic Quantum sensors in space

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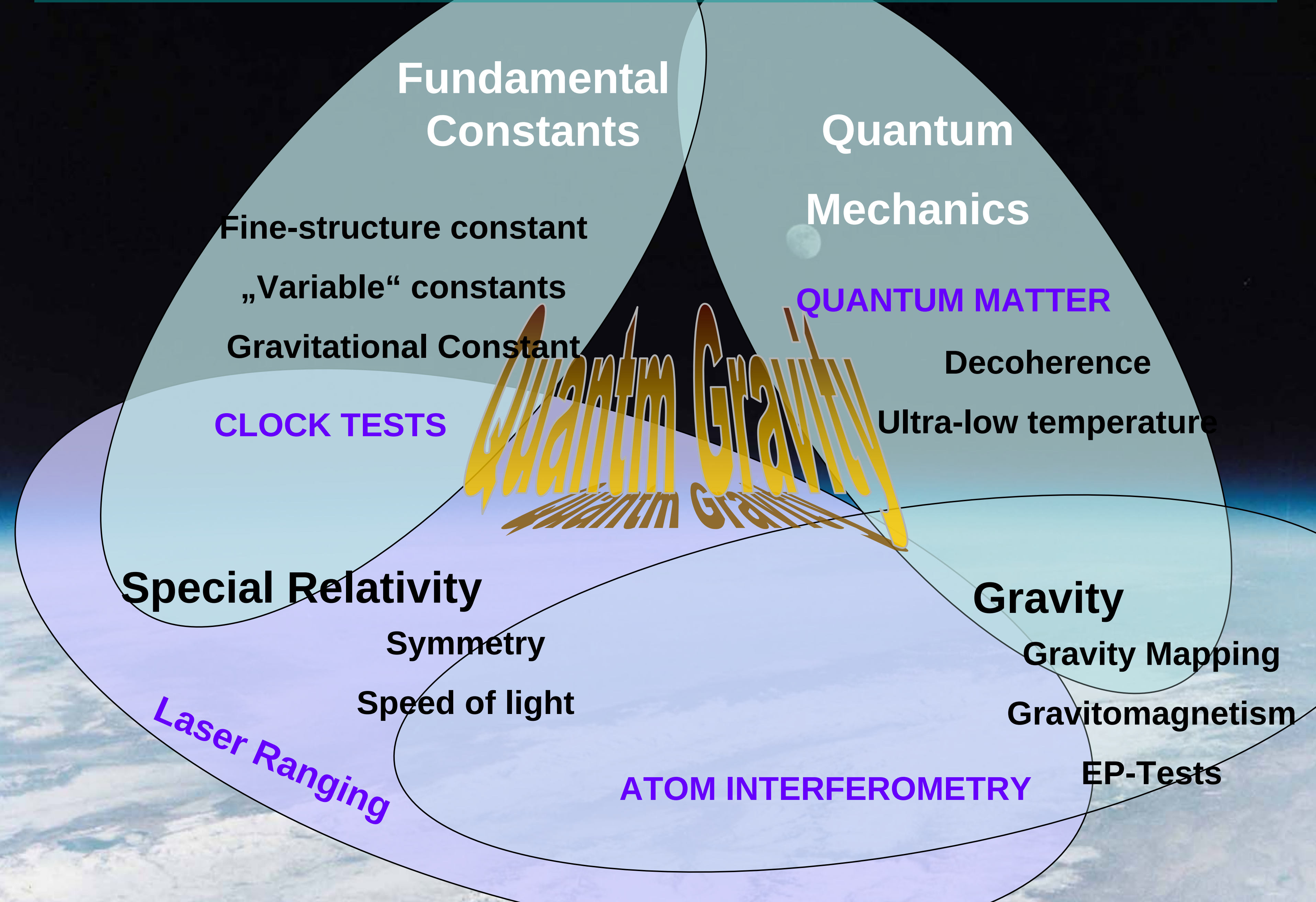
University of Hannover, Germany

From Quantum to Cosmos

Airlie Center, May 22-24, 2006

Fundamental Physics Research in Space

Fundamental Physics in Space



Atom Interferometry

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CASI
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HYPER
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•Drop tower
•Exp. Setup
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FINAQS
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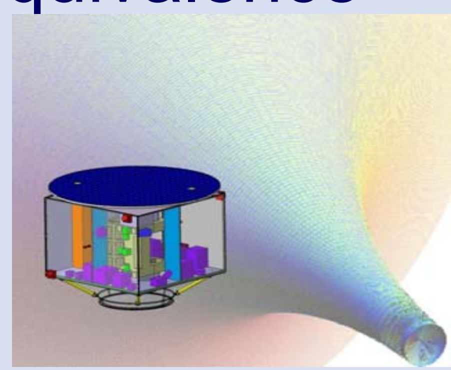
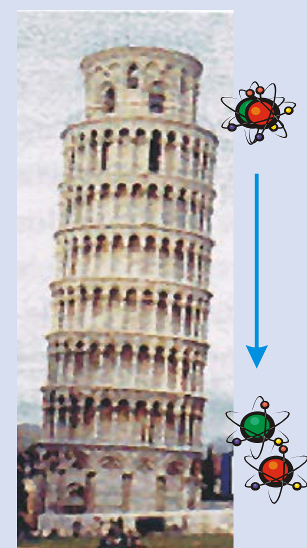
Conclusion

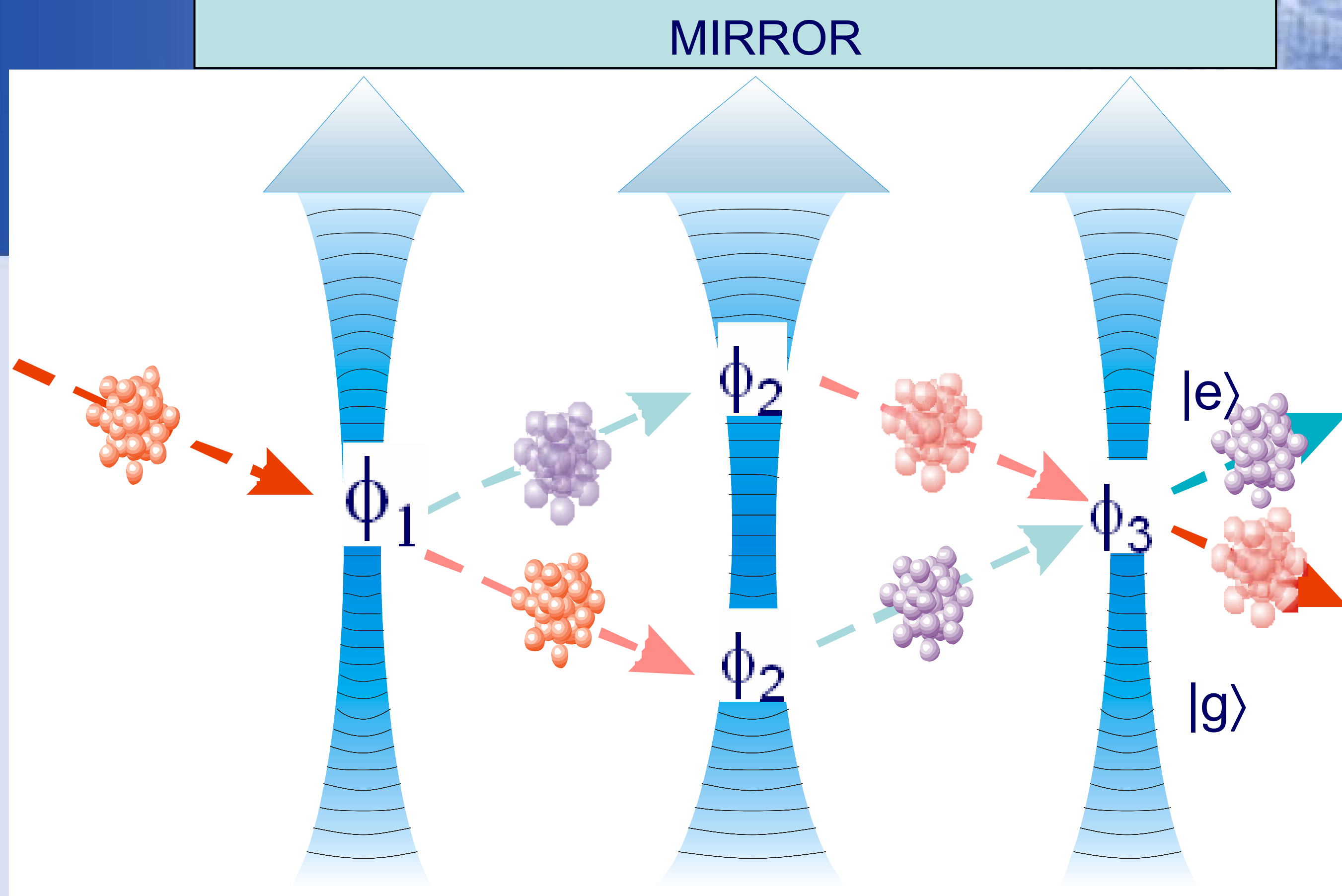
Fields of interest:

- Inertial standards and references
- Gravimeters
  - earth observation
- testing of relativistic effects and gravity
  - Testing the weak equivalence principle
- Drag-free sensors





Atom-Light Interferometer



position

Signal at the output ports

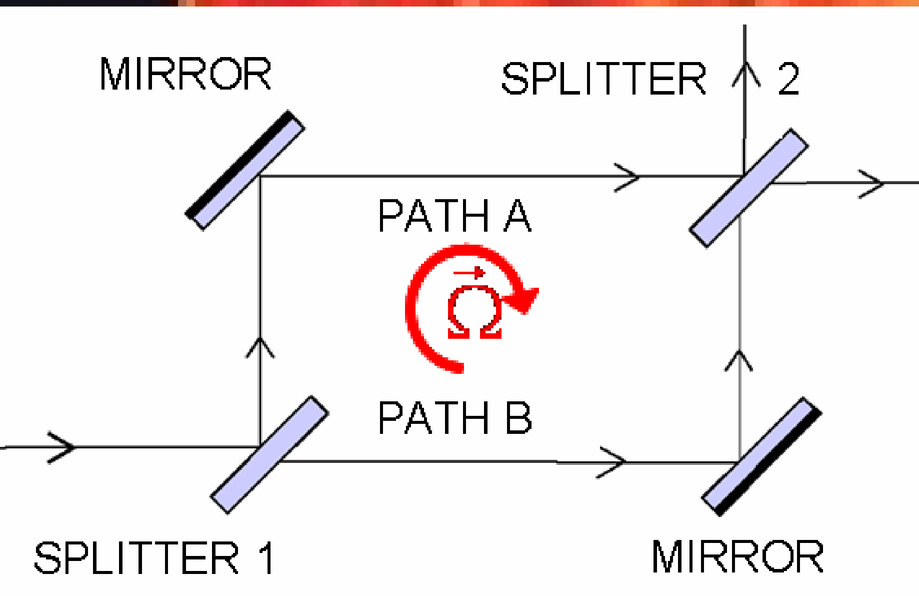
time

$$S \sim \cos[(\phi_3 - \phi_2)-(\phi_2 - \phi_1)]$$

See e.g. : Ch. J. Bordé, Gen. Rel. Grav. **36**, (2004), 475

Sagnac-Effekt

Rotational induced Phase shift:



for Light :

$$\Delta\varphi_{rot} = \frac{4\pi}{\lambda c}\vec{A}\cdot\vec{\Omega}$$

for Atoms :

$$\Delta\varphi_{rot} = \frac{4\pi}{h} m_{at}\,\vec{A}\cdot\vec{\Omega}$$

→ Gain by de Broglie-waves : $\sim 10^{11}$

Rotation sensing

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$\Omega_E \approx 7{,}2 \cdot 10^{-5}$ rad/s

$\Delta\Omega_E / \Omega_E$

- 10^{-0} - Earth rotation
- 10^{-1}
- 10^{-2}
- 10^{-3}
- 10^{-4} - Seismic
- 10^{-5}
- 10^{-6}
- 10^{-7} - Tidal forces
- 10^{-8} - Variation of earth rotation
- 10^{-9} our goal (single shot)
- 10^{-10} - Relativistic effects
- 10^{-11} - Galactic rotation
- 10^{-12}

Different Methods:

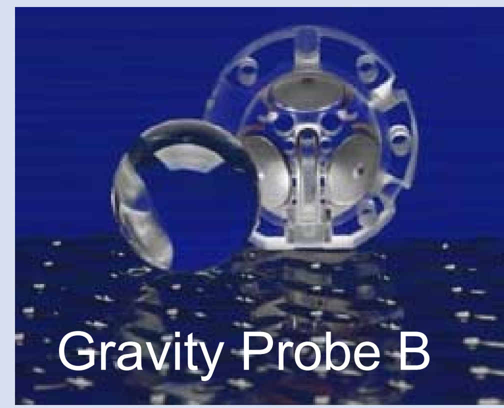
Resolution:

$10^{-8} – 10^{-9}$ rad

in 24 h

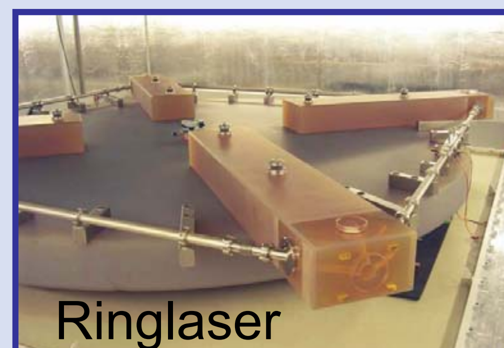
Resolution:

10^{-9} rad in 1 year



Resolution:

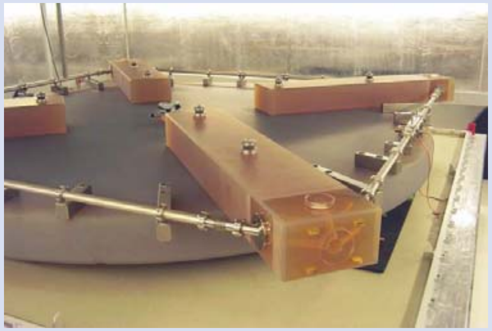
$10^{-10} – 10^{-11}$ rad/s $\sqrt{Hz}^{-1}$



Atom Interferometry

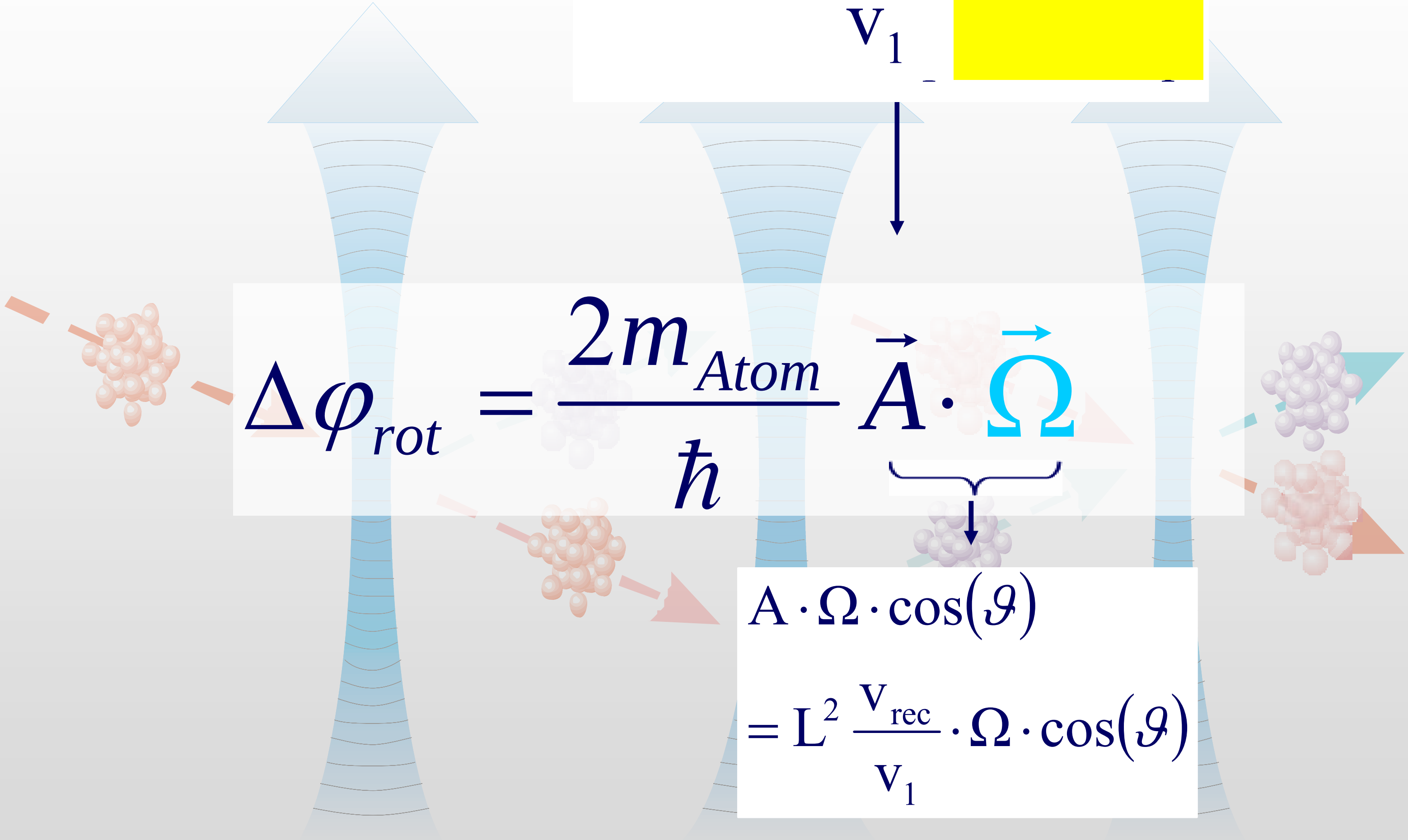
Benefits of atoms:

- quantum standards
- intrinsic gain by matter wave of 10^{10} compared to light
- ideal microscopic test masses
- Alternative and complementary technique



Ring Laser Gyroscope

Cold Atoms!



$$A = L^2 \frac{v_{rec}}{v_1} \ll 1$$

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

$$A \cdot \Omega \cdot \cos(\vartheta)$$

$$= L^2 \frac{v_{rec}}{v_1} \cdot \Omega \cdot \cos(\vartheta)$$

Quantum Sensors

CASI

Atomic Sagnac Interferometer

IQ activities

QUANTUS

BEC in microgravity

ATLAS

Coherent source for atom interferometry

Cold Atom Sagnac Interferometer

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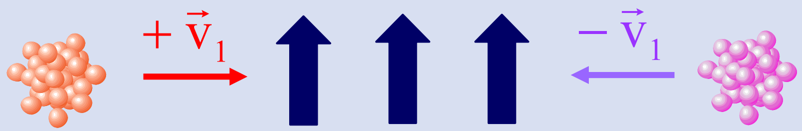
- double interferometer for differential measurement
    - discrimination of rotation and acceleration



$$S_1 \sim \cos(\varphi_{rot} + \varphi_{acc})$$

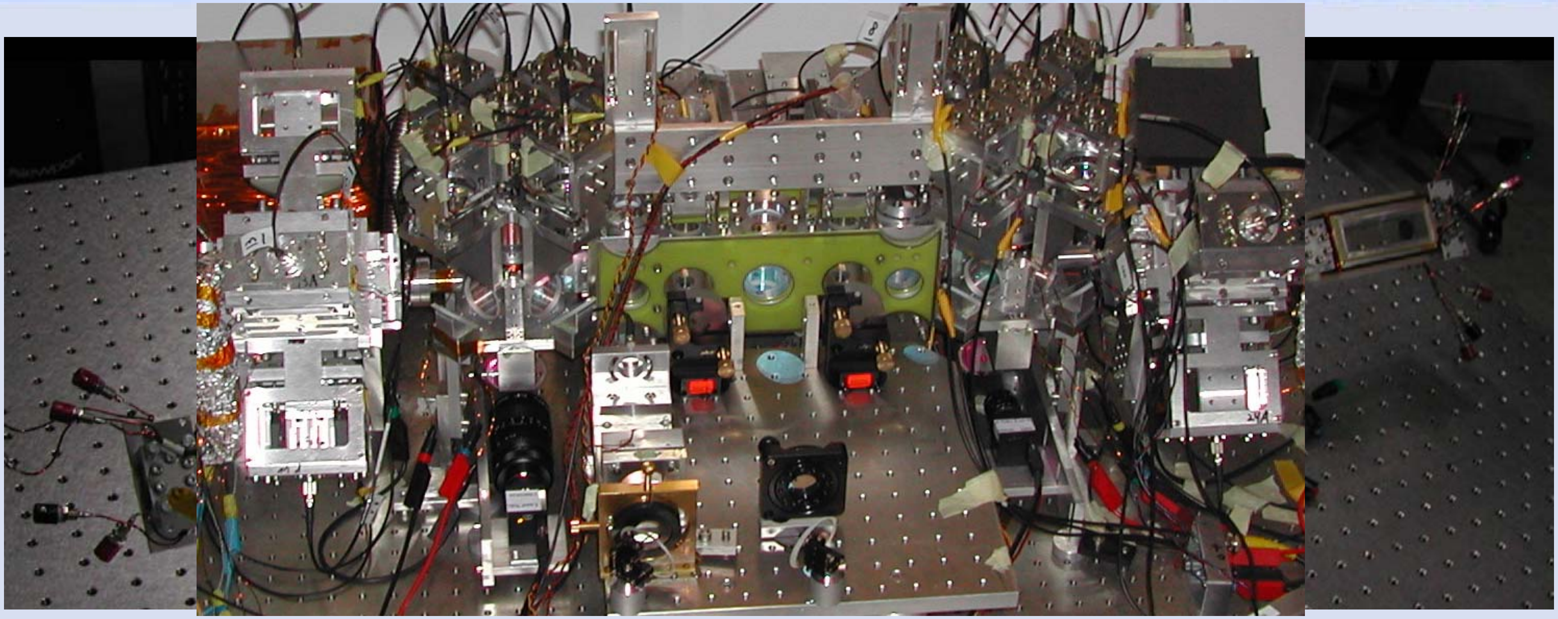
$$S_2 \sim \cos(-\varphi_{rot} + \varphi_{acc})$$

- transportable setup
- stability and control
- big enclosed area

} ⟶ Cold atoms

- Investigation of different measurement strategies and
- interferometer topologies
- flexible configuration (online switching)

CASI: concept



- Interferometer in Mach-Zehnder-type topology
- (spatial and/or temporal domain possible)
- Two photon Raman transitions as beam splitters
- intense and flexible sources of cold ^{87}Rb atoms
- sensitivity: 10^{-9} rad/s $Hz^{-1/2}$

*C. Jentsch, T. Müller, E. Rasel, and W. Ertmer, Gen. Rel. Grav, **36**, 2197 (2004)*

Experimental details: Atomic source

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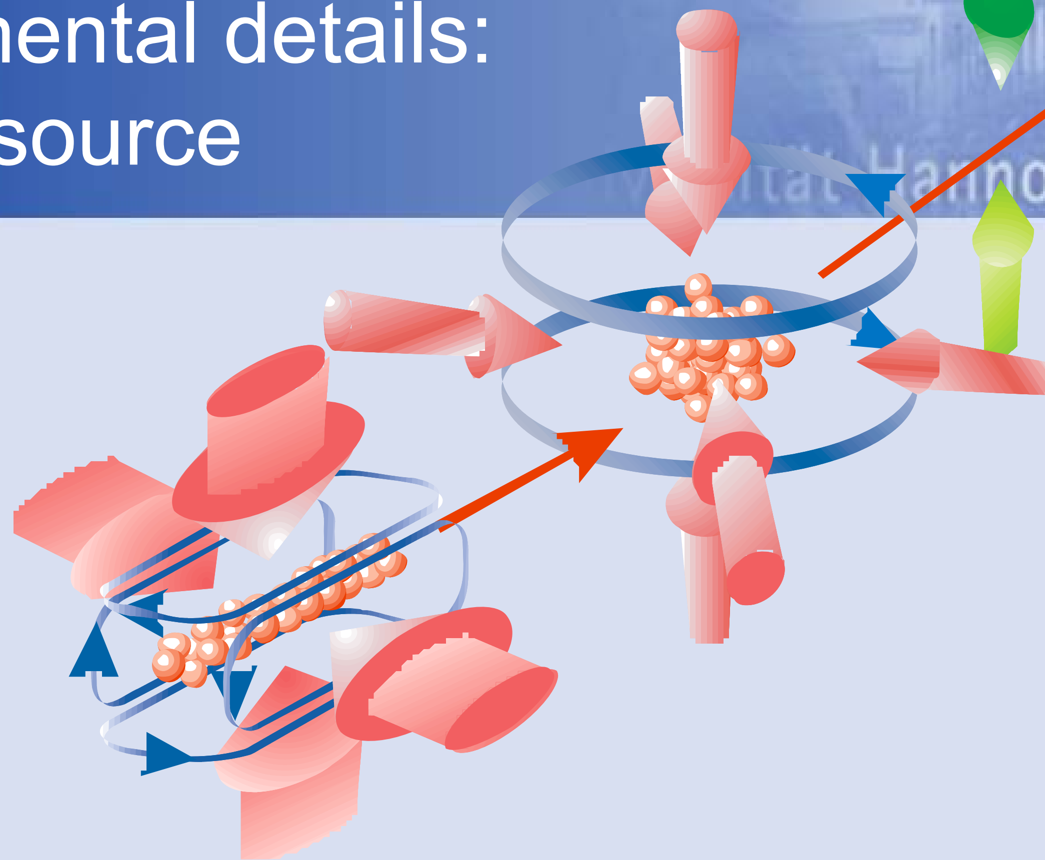

- Two-stage concept:
  - 2D-MOT delivering high flux (4×10^{10} at/s) of cold atoms
  - flux enhancement by additional pushing beam
- 3D-MOT/molasses as second cooling stage
  - flexible molasses configuration for systematic studies

Experimental details: Raman laser system

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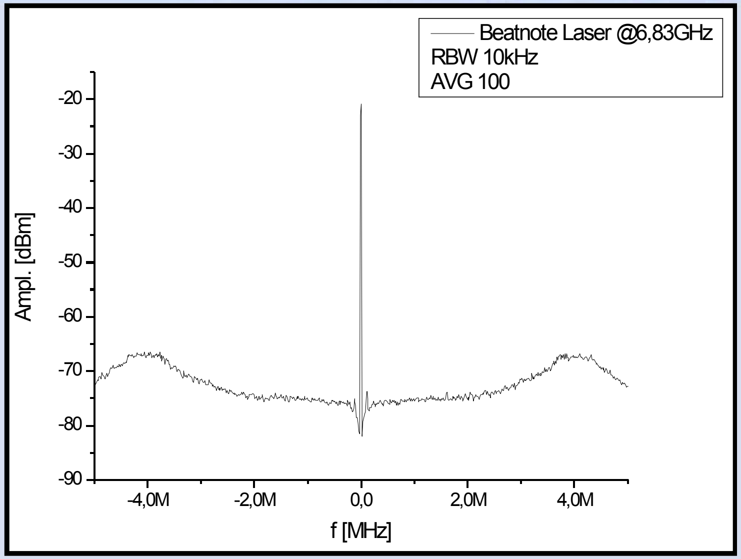
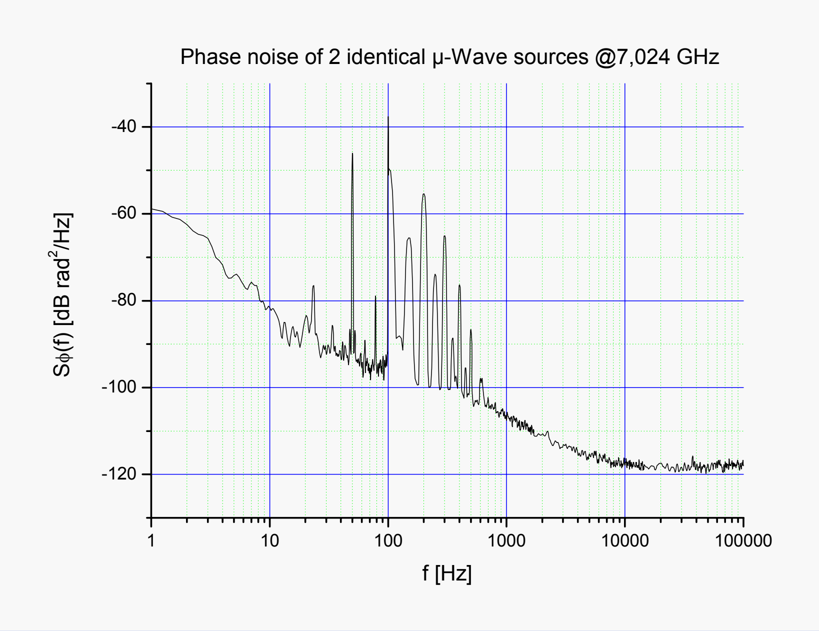
- Optical PLL of two high power diode-laser-systems (>0,5 W each ⟶ short pulses)





- Minimal phase error with ultra stable µ-wave reference (collaboration with LNM-SYRTE)

Current status

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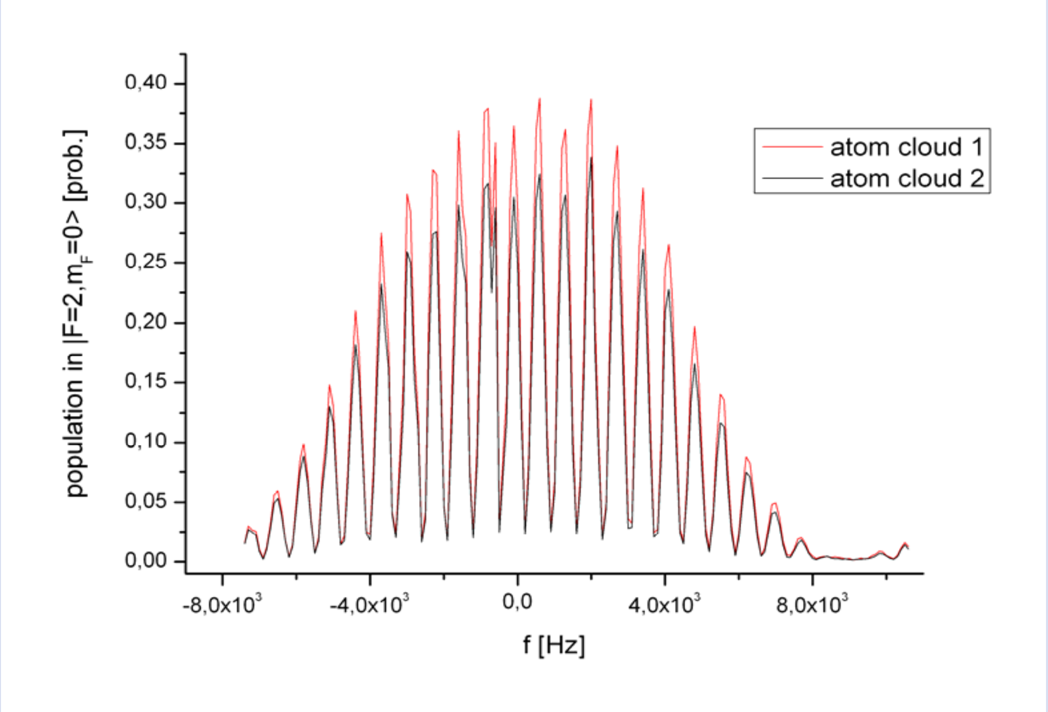
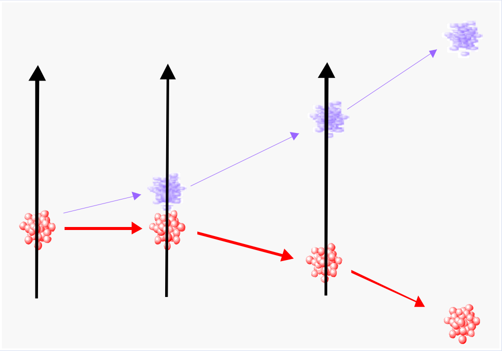
- double interferometer in time domain
- Currently improving dominant noise sources (preparation, detection)

Ramsey-type experiment for evaluating frequency dependent shifts



CASI next steps

- Rotation sensing (time domain interferometry, summer 2006) ~ (10^{-7} rad/s $Hz^{-1/2}$)
- Stepwise enhancement of resolution to final sensitivity
  → signal integration
- Characterization of different measurement types & topologies
- New types/additional beam splitters for further resolution increasing



CASI future plans

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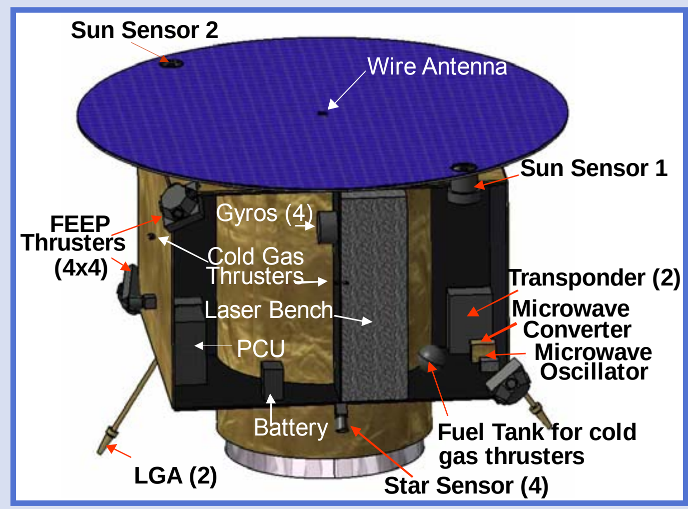
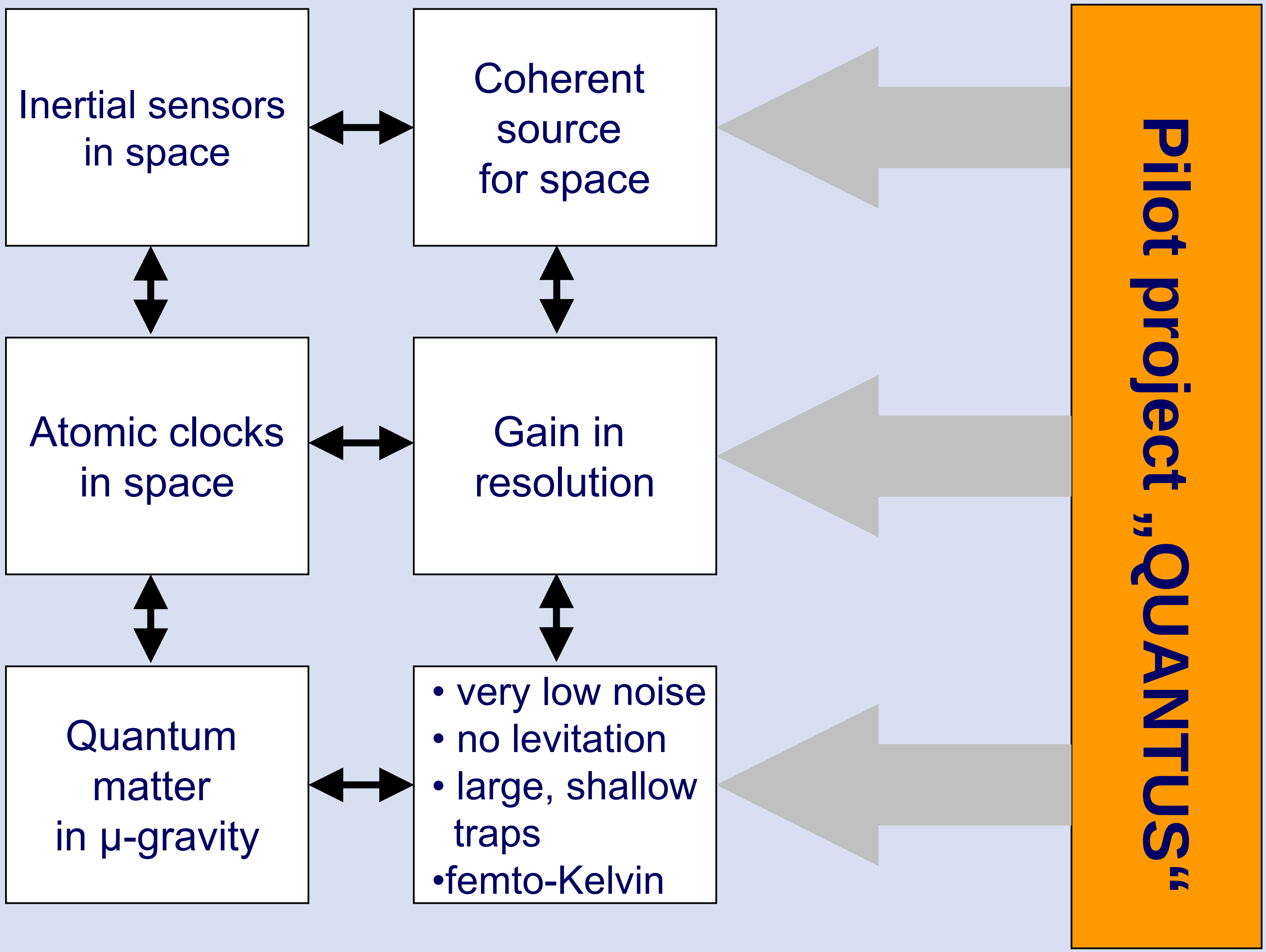
- Exploring the quantum (and technical) limits
  → microgravity
- HYPER mission: ESA assessment study performed
- Technical feasibility confirmed *(ESA assessment study report, ESA-SCI (2000), 10)*
- Ultimate limitation: atomic temperature

→ Need for ultracold atoms !!



Benefits of microgravity

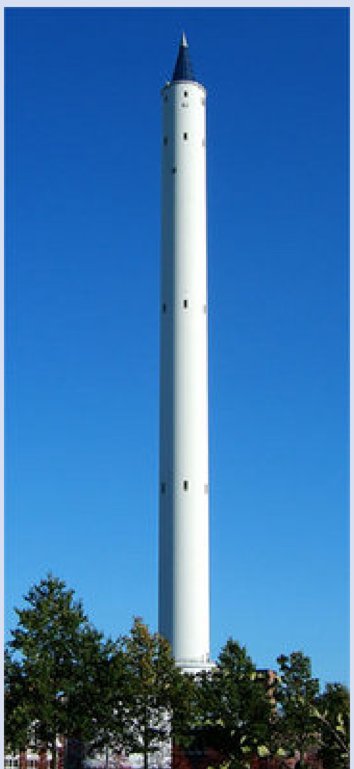


QUANTUS

Quantum Matter in Microgravity

(Quantensysteme unter Schwerelosigkeit)

Quantus



The QUANTUS Team

IQO-Teams

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QUANTUS

- **Team**
- Drop tower
- Exp. Setup
- Lasers
- Status & Next steps
- Perspectives

FINAQS

- Atlas

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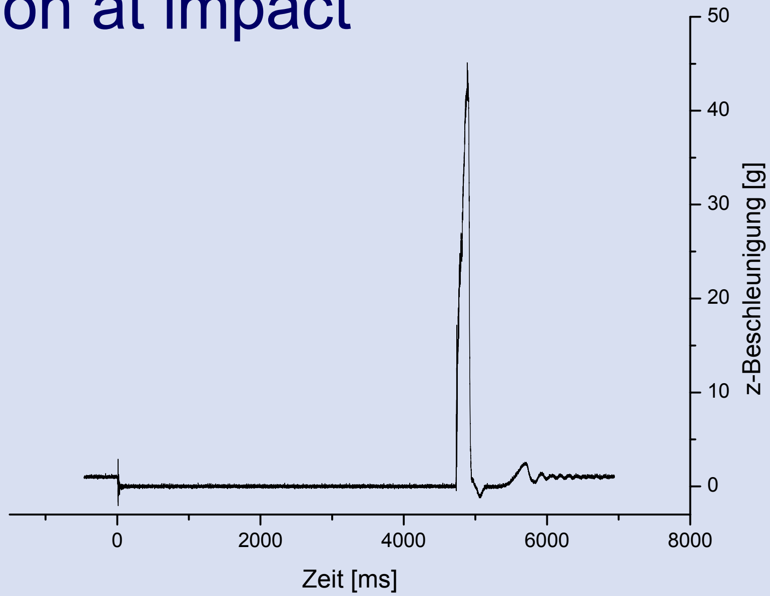
German aerospace center

University of Hannover	University of Berlin	University of Hamburg	MPQ Munich	MPQ Munich	ZARM Bremen
W. Ertmer E. M. Rasel T. v. Zoest	A. Peters W.Lewoczko	K. Sengstock K. Bongs A. Vogel S. Wildfang	T. Hänsch J. Reichel T. Steinmetz	T. Hänsch J. Reichel T. Steinmetz	H.-J. Dittus C. Lämmerzahl T. Könemann W. Brinkmann

The drop tower facility Bremen

- 4 to 9 seconds free fall
- 110 meters height
- 3 drops per day
- 10^{-6} g residual acceleration
- 50 g deceleration at impact



Boundary conditions for droptower experiments

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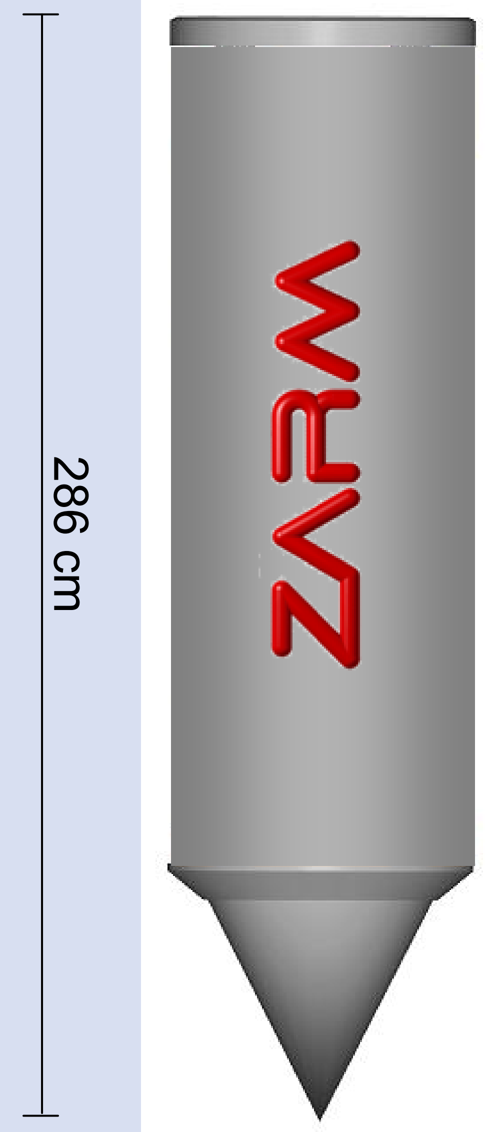
Payload area:
173 cm height, 60 cm diameter

Maximum weight:
500 kg, thereof 234 kg for payload

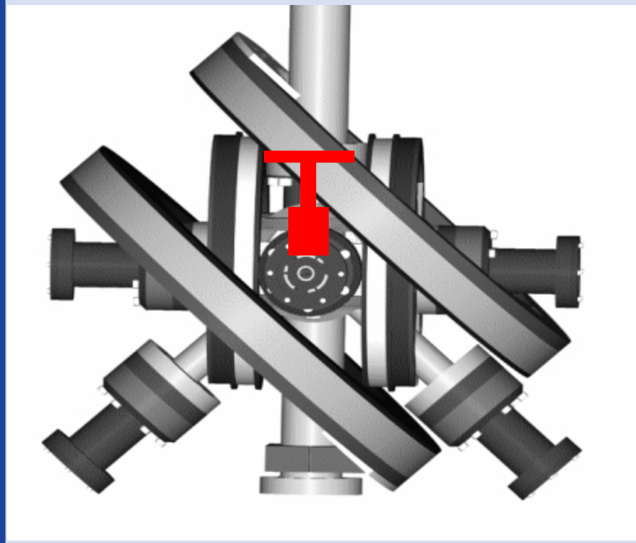
Capacity of the onboard battery pack: 25 Ah

Cooling power: 2.3 kW

Remote controlled experiment



Experimental setup I



- Small and robust design for applications under microgravity/space conditions
- One chamber design due to space limitations
- BEC will be realized on a micro trap-Chip

LIAD with selective short wavelength (395 nm) for effective desorbing

C. Klempt, T. van Zoest, T. Henninger, O. Topic, E. Rasel, W. Ertmer, and J. Arlt; Phys Rev A ***73****, 013410, (2006)*

Loading procedure

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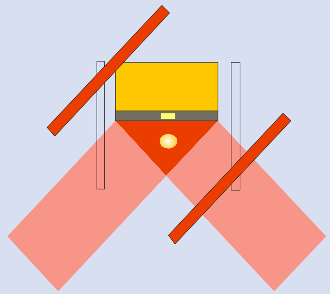
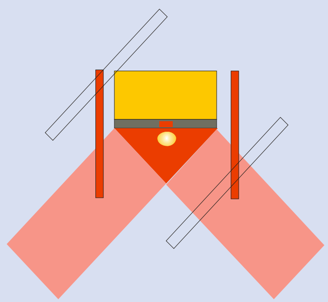
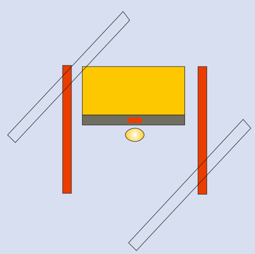


Loading atoms into „external“ MOT with bigger trapping volume (2-3 mm away from chip surface)



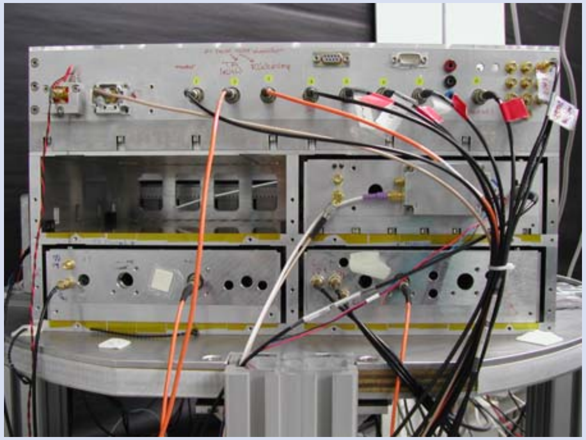
Transfer into „Chip-MOT“, BIAS coils generate together with chip wire quadrupole-field at position of magnetic trap (300 µm away from chip surface)



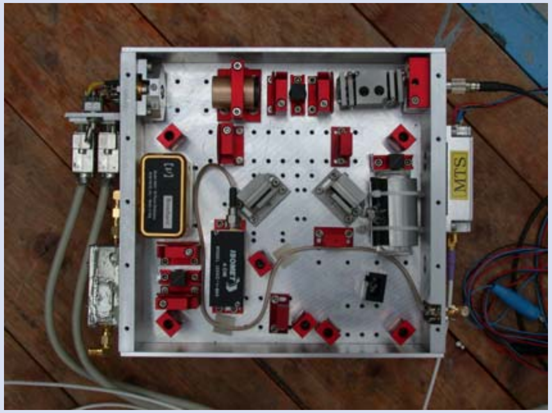
After molasses cooling, atoms are transferred into magnetic trap.

Laser setup

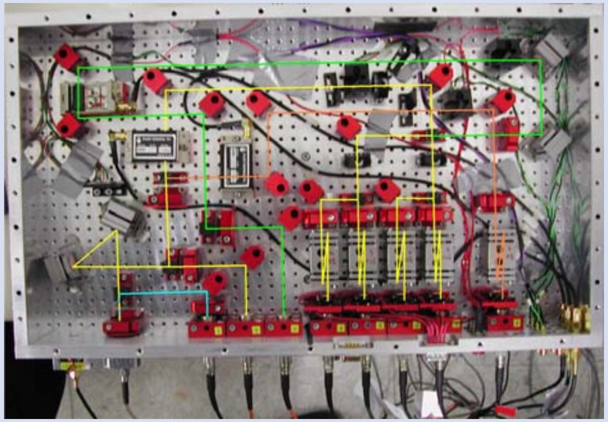
- Robust laser design for implementation in drop capsule
- Modular design guarantees flexible setup
- Connection between modules via polarization maintaining fibers



20 cm



45 cm



Laser component drop test

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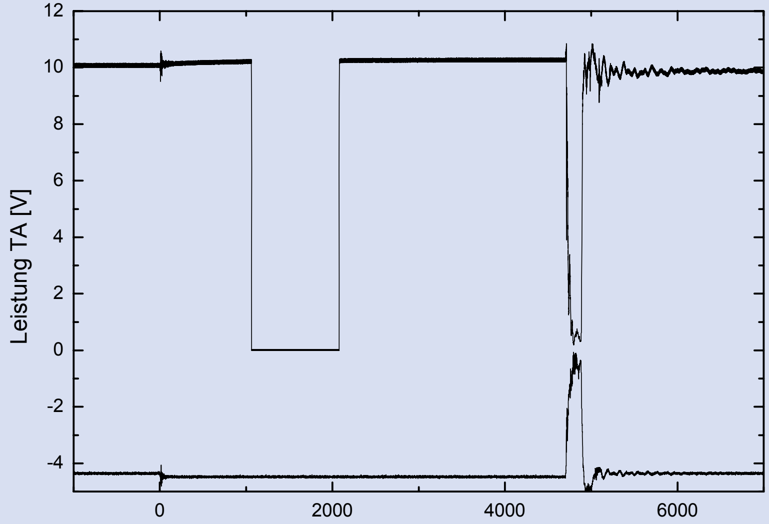
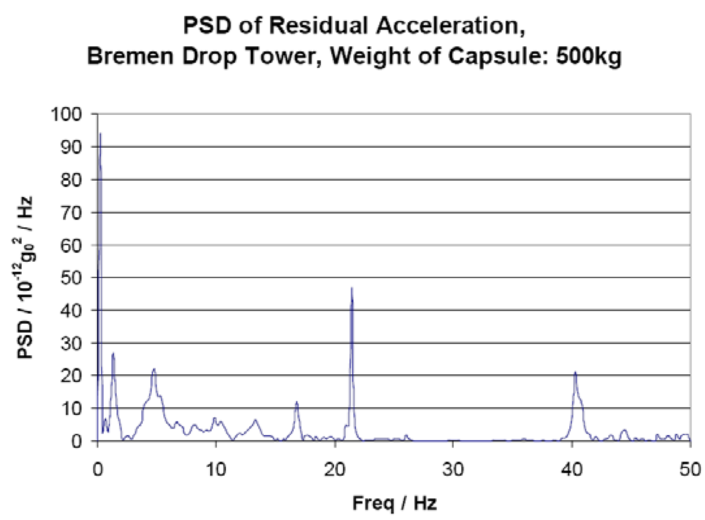
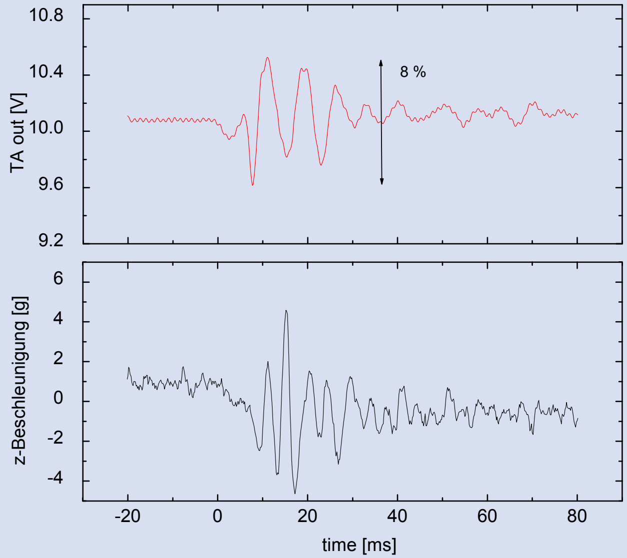




- Intensity more than 95% after impact
- Small intensity fluctuations during release



Status & next steps

- 1,2 x 10^7 atoms loaded into Mirror-MOT
- 1,0 x 10^7 atoms loaded into Chip-MOT
- Currently loading magnetic trap and test of evaporation ramp
- Assembled all subsystems into the drop capsule

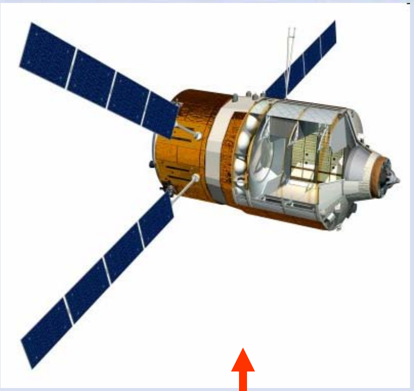
Next steps

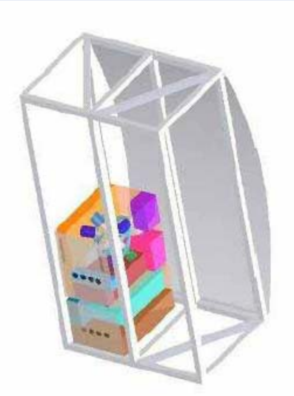
- First launch in September 2006
- Analysis of first BEC under µ-gravity conditions
- Investigation of other chip structures

avenue to space experiments

Perspectives: ATV

- Maiden Flight: 2007- annual flights
- BEC apparatus 25% of 1 ATV rack
- µg-quality $<10^{-6}$g
- Weight < 200 kg / power << 1000 W
- Drop tower experiment is a big step in space qualification (eventually parabolic flights)
- Flight opportunity before 2010?





FINAQS
Future Inertial Quantum Sensors

„Harnessing atoms at their quantum limit“

EU – project

Involved Institutes:

- University of Hannover, Germany
- Humboldt-University of Berlin, Germany
- IOTA, Paris, France
- LENS, Florence, Italy
- SYRTE, Paris, France

FINAQS: scientific goals

- Explore quantum limits of inertial sensors
- Investigate potential of atom lasers and degenerate quantum gases for use in inertial quantum sensors
- Study and development of new concepts for coherent matter wave optics
- Implement new sensors as test beds

Hannover University: (ATLAS)

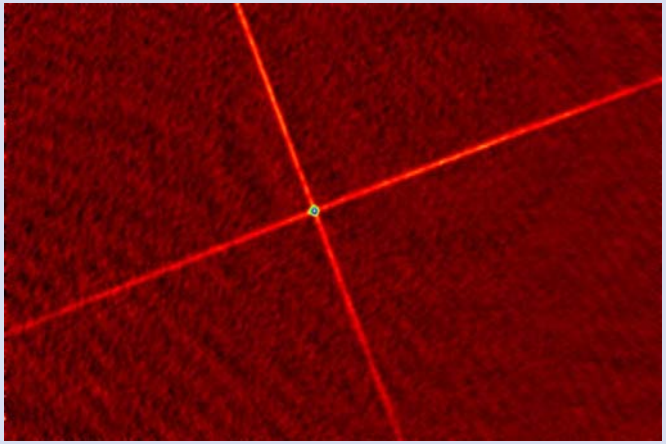
design of a compact atom laser source

ATLAS

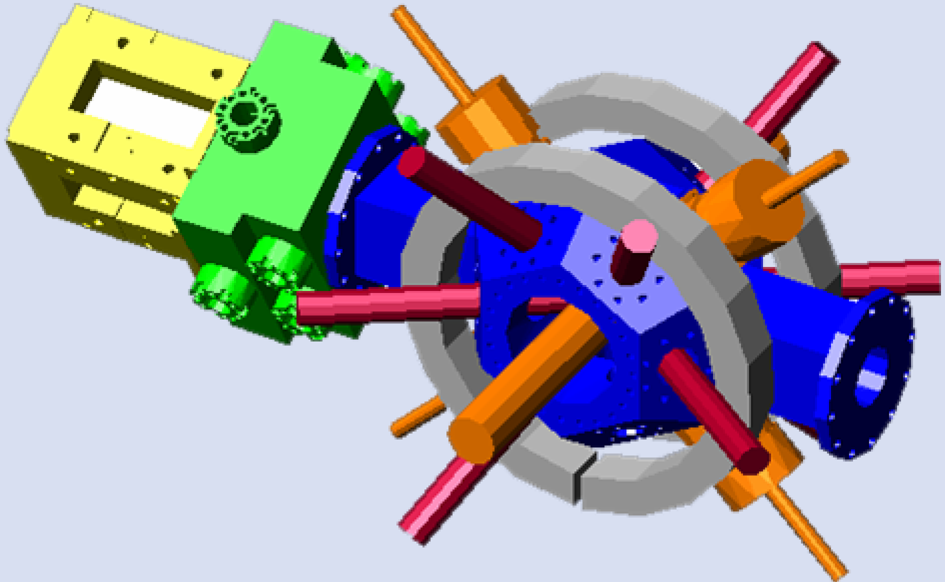
Atom laser by all-optical means

Advantages:

- Trapping of all m_F-sub-states
- Production of different species
- Fast production of BEC
- No magnetic fields



Picture: J. Nes et al., IQ, ATOMICS



Conclusion

- Atomic quantum sensors represent a rapidly growing field for research in general physics.
- Different complementary projects ongoing at IQ.
- Growing networks and collaborations for a full exploration of the high potential of this field.

The teams

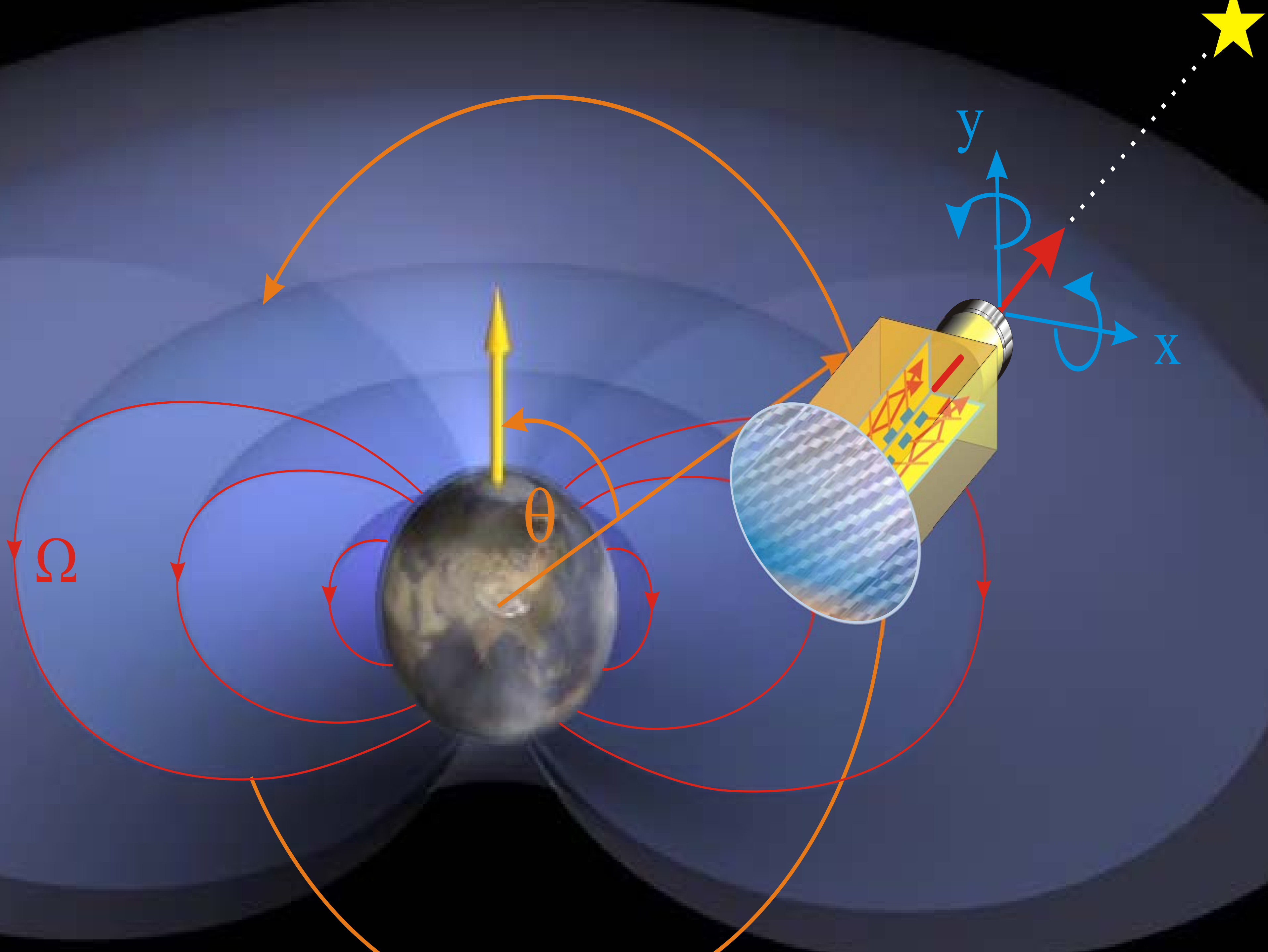
E.M. Rasel
W. E.

- CASI:
  T. Müller
  T. Wendrich
  M. Gilowski
  (C. Jentsch)
  SYRTE, Paris

- ATLAS:
  M. Zaiser
  SYRTE, Paris
  IOTA, Paris
  LENS, Florence
  HU, Berlin

- QUANTUS:
  T. van Zoest
  ZARM, Bremen
  HU, Berlin
  University of Hamburg
  MPQ, Munich
  University of Ulm


ENOUGH SPACE FOR
EXCITING EXPERIMENTS



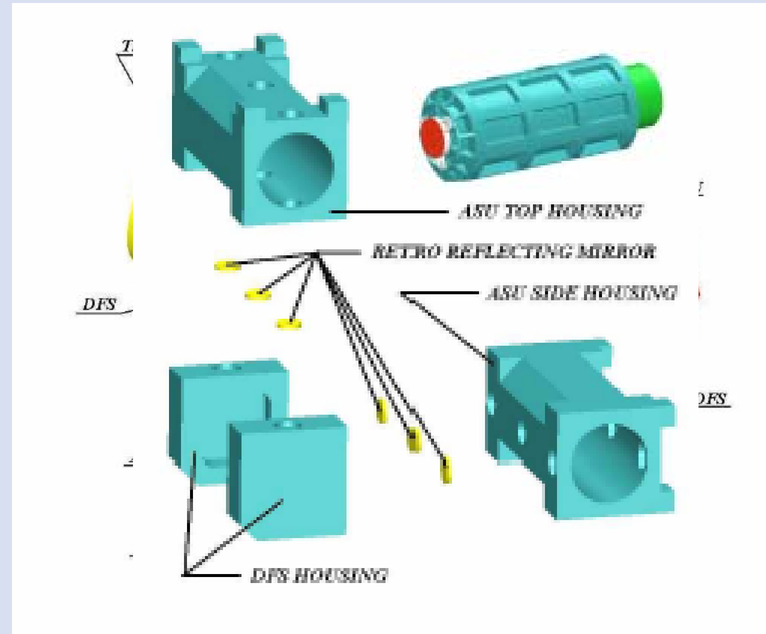
y
x
θ
Ω

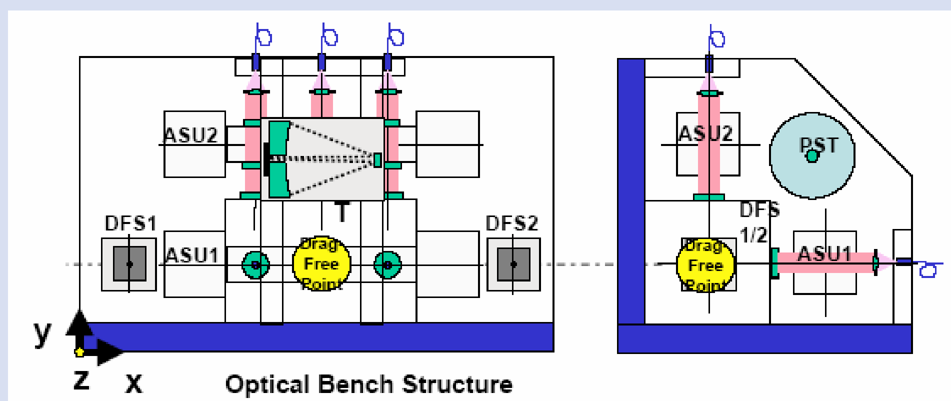
Hyper

…performance

- 2 atomic MOTs
- Launch of 10^9 at @ 2µK
- with 20 cm/s, $2T_{Drift}$ = 3 s
- Length: 60 cm

- Ω_{SNL}=4·10^{-12} rad/s/√Hz
- A_{SNL} = 10^{-12} g/√Hz
- per shot, 0.3 Hz





Optical Bench Structure

Fundamental Physics in Space