Fundamental Physics for and in space

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Center for Applied Space Technology and Microgravity (ZARM)
University of Bremen

UN/Malaysia Expert Meeting on Human Space Technology

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Bremen: where we are

Bremen: where we are

Bremen: where we are

Bremen: where we are

Bremen: largest aerospace location in Germany

- Companies
  - Astrium (Columbus module, thruster of Ariane, cryogenic upper stage of Ariane)
  - OHB – Systems (Galeileo, ...)
  - Airbus
- New DLR–Institute for Space Systems
- University: ZARM
  - participation in many space projects (MICROSCOPE, LPT, LISA, ...)
  - many microgravity–activities (drop tower, ESA TT, cold atoms, ...)
  - cooperations with DLR, PTB, CNES, ONERA, NASA, JPL, ...
  - education
- Space Conferences
  - IAC 2003
  - Quantum to Cosmos 2007 & 2009
  - COSPAR 2010

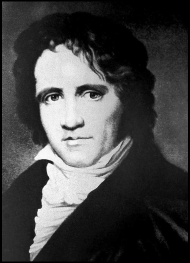
Bremen science history related to space

Johann Hieronymus Schröter 1745 — 1816

- largest observatory in Europe
- founded Astronomical Society

Wilhelm Heinrich Olbers 1758 — 1840

- founder of modern cosmology



Friedrich Wilhelm Bessel 1784 — 1846

- Bessel ellipsoid
- flattening of Earth
- test of Equivalence Principle

Outline

1. Introduction

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2. Fundamental physics under microgravity conditions
   - Main physical quests
   - Space conditions
   - Technologies

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   - Testing the UFF
   - Clocks: Testing the UGR
   - Cold atoms in space
   - Condensed matter phenomena

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What we are talking about?

We talk

- about physics – not medicine, biology, chemistry, geology, engineering, ...
- about fundamental physics – not material sciences, electronics, environmentel physics, or other applied physics areas
- about gravitational physics, quantum mechanics, particle physics, statistical physics, quantum optics,

under the condition of

- free fall = microgravity

why?

- in microgravity one can perform experiments which are not possible on ground
- this opens up a new experimental parameter space

for many fundamental physics questions microgravity offers
a unique experimental environment

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- Physical and technological revolutions are beyond criteria like "return of investment". Such requirements will kill substantial developments.
  Example: At the development of General Relativity applications like GPS and TAI could not be foreseen.

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- Physical and technological revolutions are beyond criteria like "return of investment". Such requirements will kill substantial developments. Example: At the development of General Relativity applications like GPS and TAI could not be foreseen.

discussion partially based on an ESA TT *Fundamental Physics on the ISS* chaired by H. Dittus & C.L.

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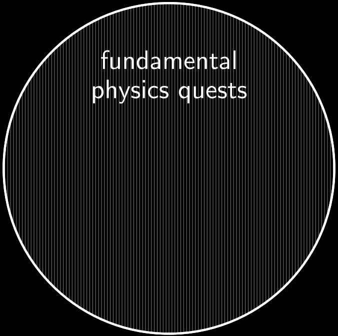
Systematics: How to choose space projects



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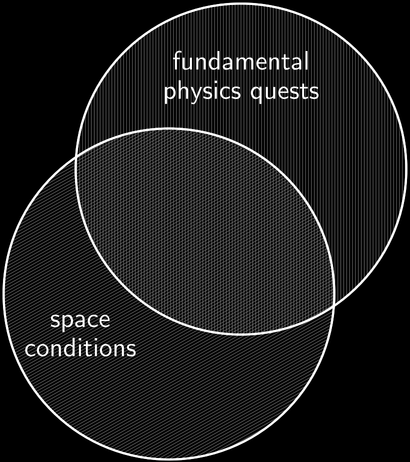

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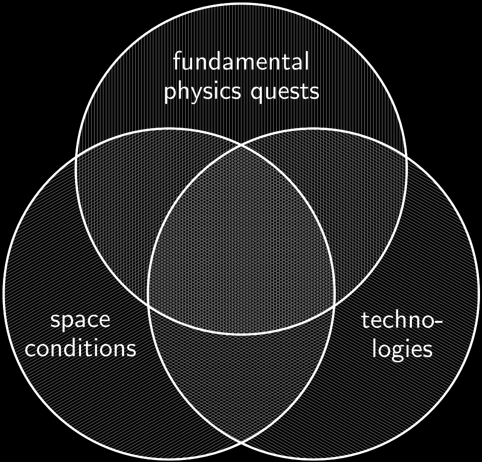

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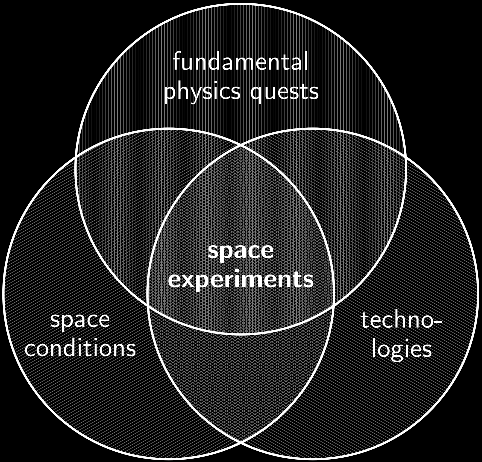

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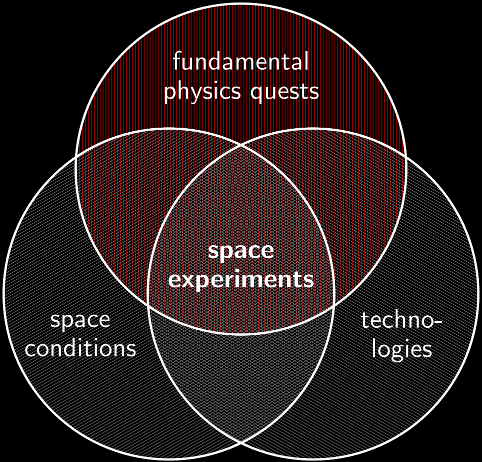

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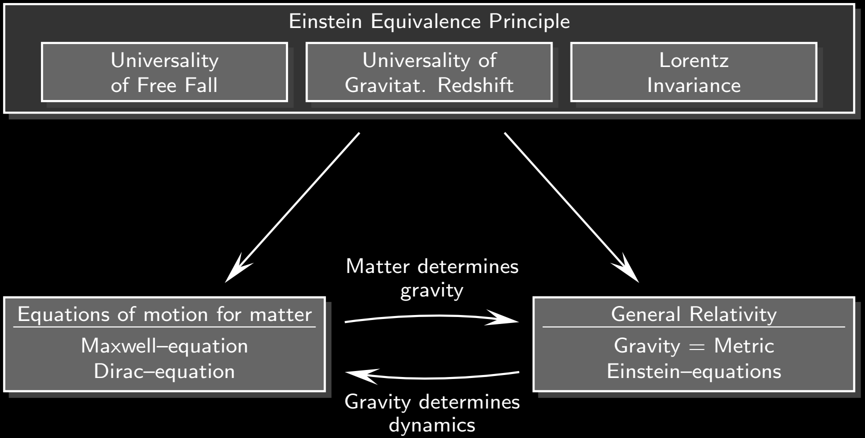
Structure of standard physics



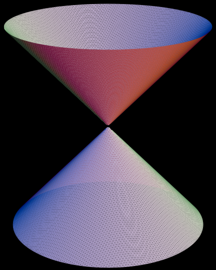
The present situation

All aspects of Lorentz invariance are experimentally well tested and confirmed

Foundations

Postulates

- $c = const$
- Principle of Relativity



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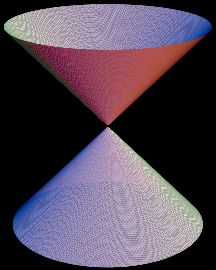


Tests

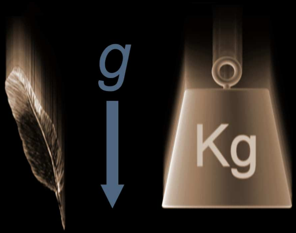
- Independence of c from velocity of the source
- Universality of c
- Isotropy of c
- Independence of c from velocity of the laboratory
- Time dilation
- Isotropy of physics (Hughes–Drever experiments)
- Independence of physics from the velocity of the laboratory

The present situation

Many aspects of the Universality of Free Fall are experimentally well tested and confirmed

Postulate

In a gravitational field all structureless test particles fall in the same way



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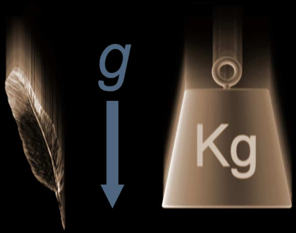


Tests

UFF for

- Neutral bulk matter
- Charged particles
- Particles with spin

No test so far for

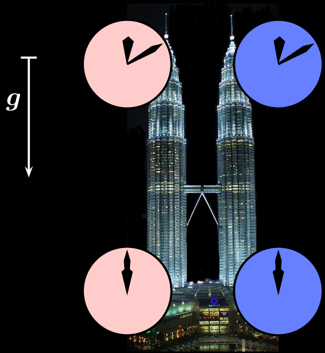
- Anti particles

The present situation

Many aspects of the Universality of the Gravitational Redshift are experimentally well tested and confirmed

Postulate

In a gravitational field all clocks behave in the same way



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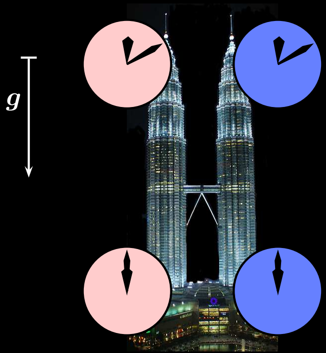

Tests

UGR for

- Atomic clocks: electronic
- Atomic clocks: hyperfine
- Molecular clocks: vibrational
- Molecular clocks: rotational
- Resonators
- Nuclear transitions

No test so far for

- Anti clocks

Science: The present situation

All predictions of General Relativity are experimentally well tested and confirmed

Foundations

The Einstein Equivalence Principle

- Universality of Free Fall
- Universality of Gravitational Redshift
- Local Lorentz Invariance

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$\Downarrow$

Implication

Gravity is a metrical theory

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Implication

Gravity is a metrical theory

$\Rightarrow$

Predictions for metrical theory

- Solar system effects
  - Perihelion shift
  - Gravitational redshift
  - Deflection of light
  - Gravitational time delay
  - Lense–Thirring effect
  - Schiff effect
- Strong gravitational fields
  - Binary systems
  - Black holes
- Gravitational waves

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General Relativity

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⇓

General Relativity

⇐

Consequences

BH, binary systems, lensing, ...

The present situation

Today's standard theories

Frame theories	Interactions
Quantum theory	Electrodynamics
Special Relativity	Gravity
General Relativity	Weak interaction
Statistical mechanics	Strong interaction
Problems	**Wish**
• Incompatibility of quantum theory and General Relativity • Problem of time • Occurrence of singularities	Unification of all interactions

Need of modifications of standard theories, but standard theories derived from observations
$\Rightarrow$ need for larger domain of experience = larger parameter space, other observations, more precise measurements

Search for new physics

- standard theories are derived from validity of Einstein Equivalence Principle
- due to unresolved fundamental inconsistencies standard physics cannot be completely correct

⇒ There have to be modifications to standard physics

Most important possible modifications

- Modifications in Maxwell, Dirac, Einstein equations
  ⇒ Violation of Einstein Equivalence Principle
  ⇒ Search for violations of the Einstein Equivalence Principle
- Space–time fluctuations – space–time foam
  ⇒ Violation of Einstein Equivalence Principle
  ⇒ Decoherence, spreading of wave packets, higher order derivatives, ... ⇒ Fundamental noise (holographic noise)
- Time–dependence of constants

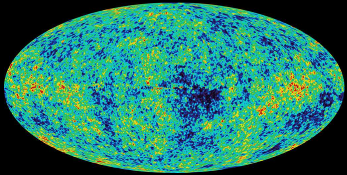
Other modifications can also be well justified

Summary: Main quests

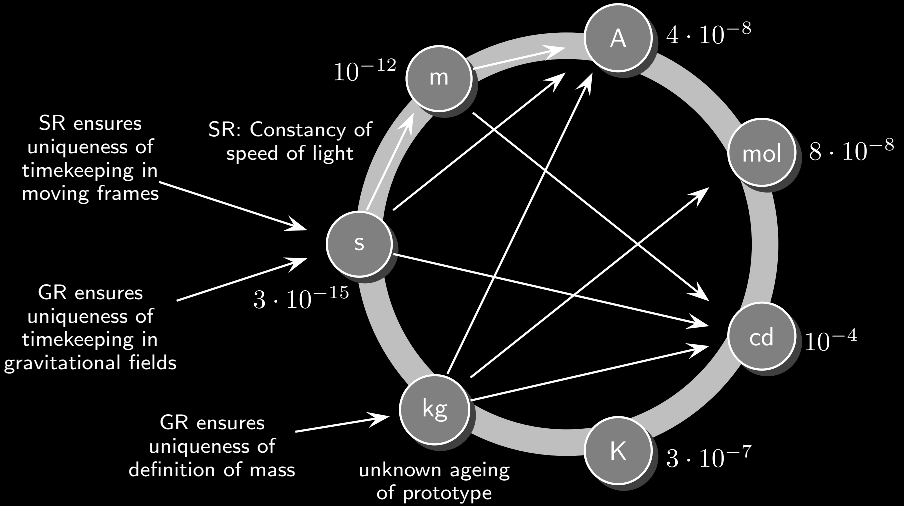
Most hot topics in Fundamental Physics

- Laboratory physics
  - Universality of Free Fall
  - Universality of the Gravitational Redshift
  - Local Lorentz Invariance
  - time dependence of constants
  - Newton at small scales
- Astrophysics/cosmology
  - Dark Matter
  - Dark Energy

all has to do with gravity



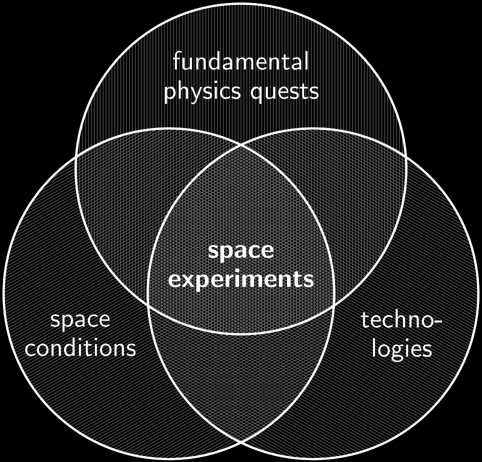
One application: Metrology



SR & GR = Physics of space and time ≡ fundamental metrology

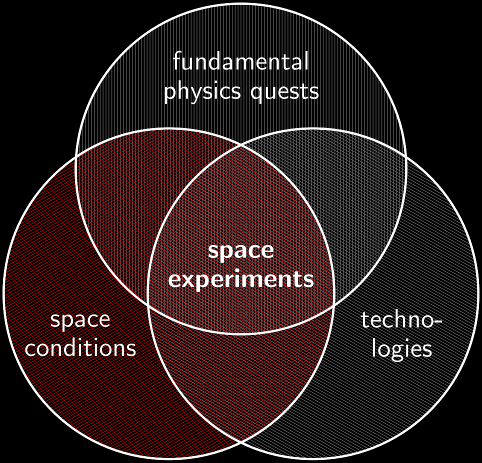
Metrology

Systematics: How to choose space projects



The conditions for space projects

Systematics: How to choose space projects



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Space conditions

- Large differences in the gravitational potential
- Large velocities
- Large distances
- Free fall
- Quiet environment

Space conditions

- Large differences in the gravitational potential
  - Necessary for testing UGR
  - Necessary for measurement of absolute gravitational redshift with clocks
- Large velocities
  - Necessary for testing Doppler effect
- Large distances
  - Necessary for gravitational wave detection (LISA)
  - Necessary for measuring gravitat. potential at large distances or weak gravity (Pioneer, MOND, dark matter vs modified gravity)
- Free fall
  - Long exposure to small forces: tests of UFF and tests of non–Newtonian gravity at short distances
  - Good environment to make ultracold BECs
  - Long free evolution time of quantum systems
  - Necessary to test Newton's law for small accelerations
- Quiet environment
  - Disentanglement from seismic noise
  - More flexibility to vary experimental parameters

Microgravity environments

platform	μg–**quality**	μg–**duration**
drop tower	$\geq 10^{-6}$	4.7 d for drops
		9.2 s for catapult mode
parabolic flights	$\geq 10^{-2}$	20 s
ballistic rockets	$\geq 10^{-5}$	6 min
ISS	$\geq 10^{-3}$	days to months
satellite	$\geq 10^{-6}$	days to years

Bremen Drop Tower of ZARM

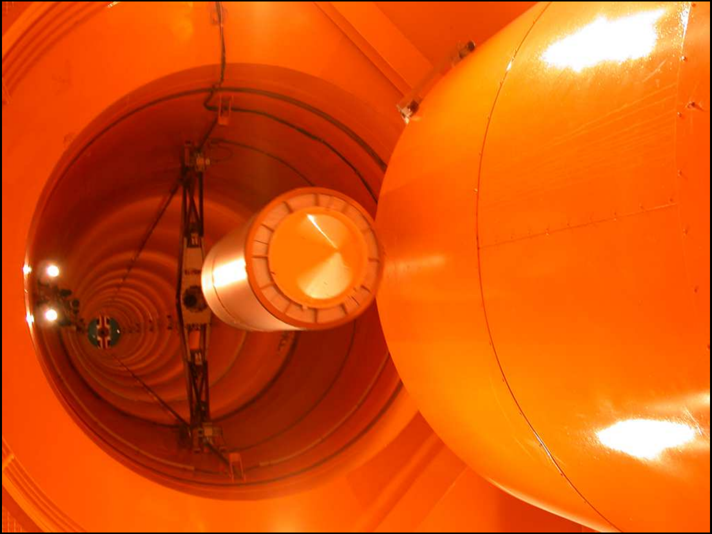
Tower 146 m

drop tube
110 m

free fall time
$= 4.7$ s

deceleration
$\sim 30\ g$

Bremen Drop Tower of ZARM



⟹ Talk of Dr. Thorben Koenemann, Thursday 2 p.m.

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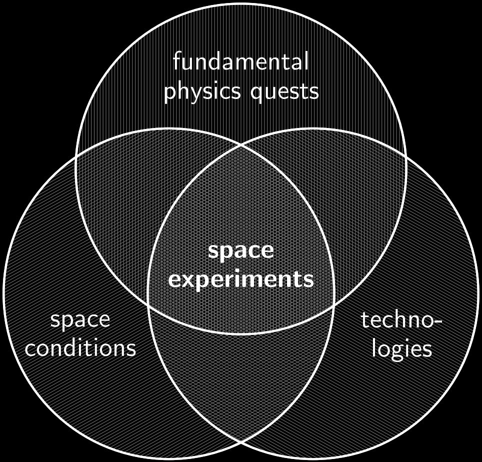

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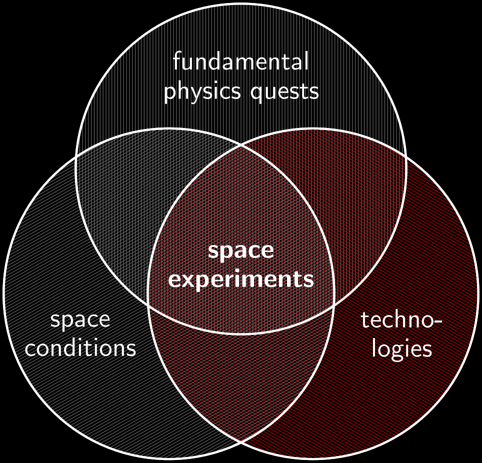

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Experimental / technological quests

In order improve the experiments one needs in general (for space as well as for laboratory experiments)

- very precise clocks, optical clocks with accuracy of 10^{-18}
- very precise length standards
- new definition of mass
- detection of tiny forces, tiny interactions
- Satellite attitude and orbit control

high precision needs
– quantum mechanics
– quantum optics

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  - SQUIDS
  - matter wave interferometry (atom, molecule, BEC)
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  - microthrusters
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Clocks in space

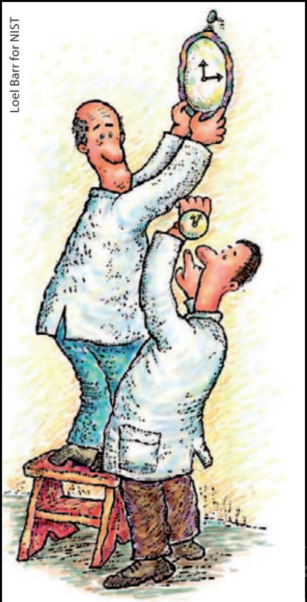
Positioning

- special relativistic time dilation ~ 4 km/day
- gravitationl redshift ~ 10 km/day

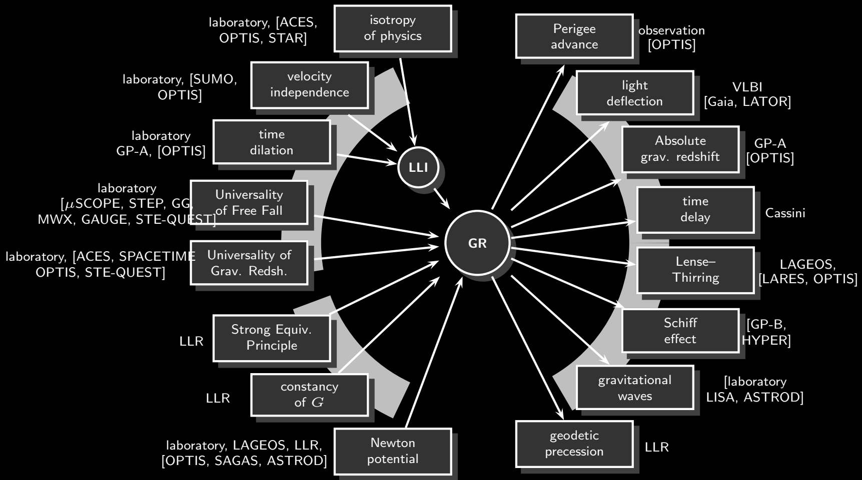
today's clocks are such precise so that they can "see" 30 cm height difference (later they will "see" 1 cm height difference)

relativistic gravitation = General Relativity is applied science

in order to have a well defined Temps Atomique International TAI one needs clocks in space



Science and missions



Mission aiming at testing GR

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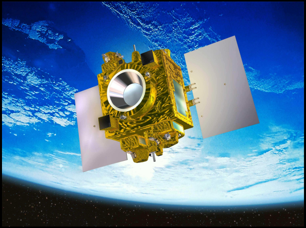
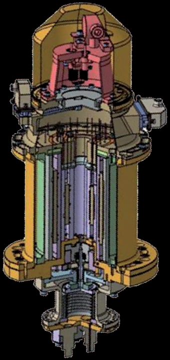
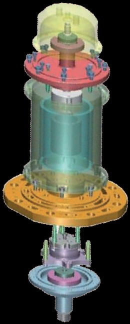
MICROSCOPE: The Mission

- French space mission with participation of CNES, ESA, ZARM and PTB
- Mission goal: Test of Equivalence Principle with an accurary of $\eta = 10^{-15}$
- Mission overview:
  - Micro-satellite of CNES Myriade series
  - Drag–free satellite
  - Sun–synchronous orbit
  - Altitude about 800 km
  - Mission lifetime of 1 year
- Payload:
  - Two high–precision capacitive differential accelerometers
  - Science sensor: Ti and Pt test mass
  - Reference sensor: two Pt test masses
- Test of accelerometers at ZARM drop tower



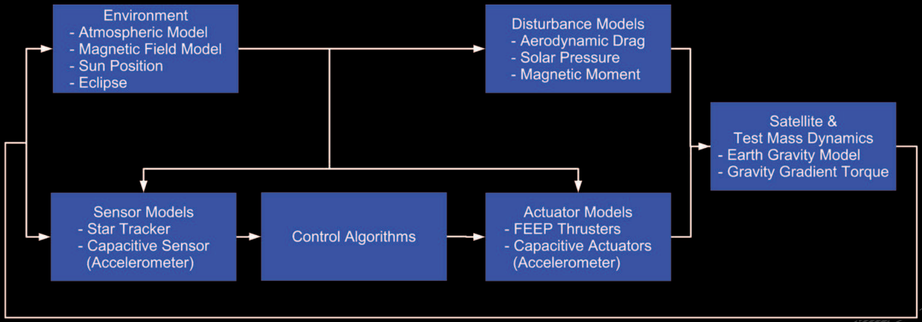




MICROSCOPE: Mission Modeling

Simulation tool HPS (High Performance Satellite Dynamics Simulator)

- Cooperation project of ZARM and the DLR Institute of Space Systems
- Modular design with user interface Matlab/Simulink
- Feature: Modeling of disturbances due to surface forces by means of finite elements



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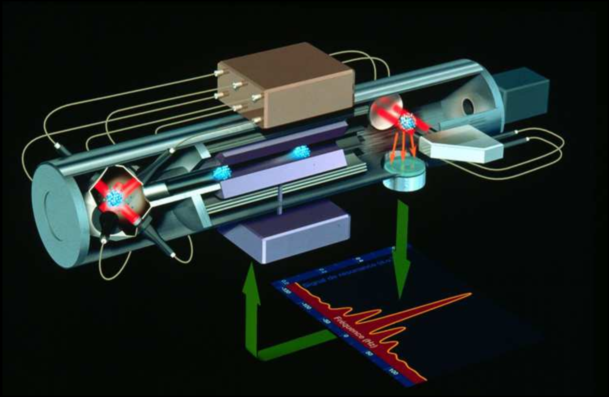
Clocks: Pharao



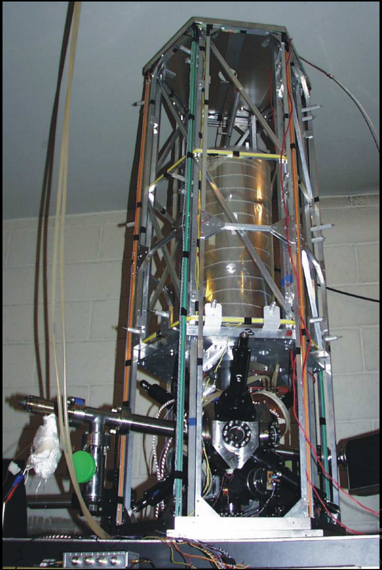
Based on Ramsey scheme with very slow atoms: interrogation of atoms after a long free evolution time

only possible in space

Clocks: Pharao

Science objectives

- Stability 10^{-16}
- Measuring gravitational redshift
- Clock – clock comparison: universality of gravitational redshift
- Time–dependence of fine structure constant α
- Clock synchronization – definition of TAI



Outline

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2. Fundamental physics under microgravity conditions
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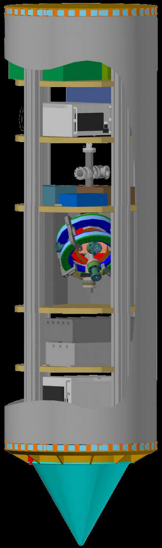
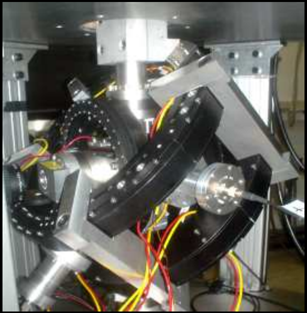
ATKAT (ATom–KATapult)

- first experimental demonstration of magneto-optical trap (MOT) with Rb atoms in microgravity at Bremen Drop Tower
- preliminary part of the QUANTUS project pursuing a Bose–Einstein–condensate (BEC) of Rb atoms in microgravity at the drop tower
- investigates feasibility of ultracold atoms in drop tower conditions
- probes frequency and power stability of laser system during capsule acceleration phase in the catapult system of the drop tower

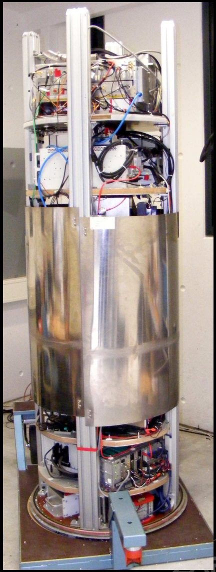
QUANTUS: BEC in microgravity



design of capsule



vacuum chamber

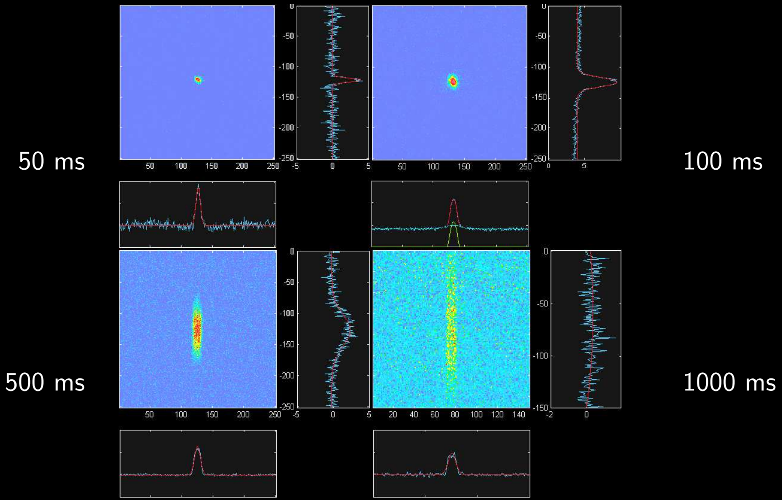


capsule

First BEC in microgravity / extended free fall

LU Hannover, ZARM, MPQ Munich, U Hamburg, HU Berlin, U Ulm

BEC in microgravity – long free evolution



10^4 atoms, 1 s free evolution time (not possible on ground)

van Zoest et al, Science 2010

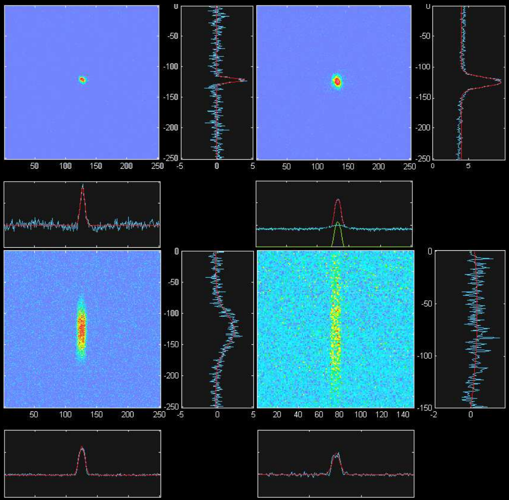
BEC in microgravity – long free evolution

50 ms

100 ms

500 ms

1000 ms



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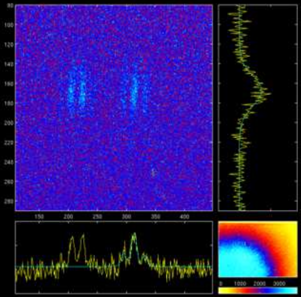
Interference

Interference for long time of flight (at the moment > 0.6 s)



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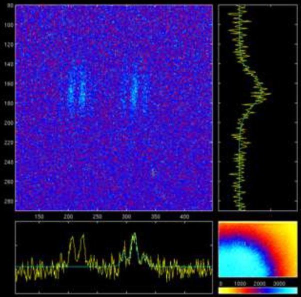


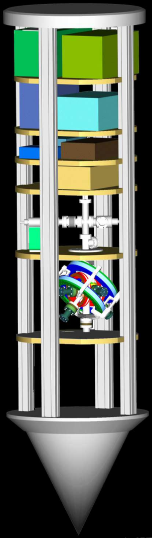
Capability for long time observations of ultracold atoms

- BEC
- Phase shift
- Probability distribution

BEC in free fall

- Status
  - until now more than 300 drops
  - BEC is created regularly
  - extremely robust (survives $\sim 50\,g$)

  Worldwide most advanced technology towards space application and fundamental quantum physics in μg
- Ongoing work
  - PRIMUS (PRäzisions–Interferometrie mit Materiewellen Unter Schwerelosigkeit)
  - FOKUS (FaserOptischer FrequenzKamm Unter Schwerelosigkeit)
  - ATUS (Atom Interferometer Modeling)
  - Fluctuations in Quantum Systems
- In future
  - Fundamental Physics experiments
  - Drop tower — Texus — ISS
  - Inertial sensors
  - High precision clocks



FOKUS: Frequency Comb

New: Frequency comb in the Drop Tower (with MenloSystems)

- Atom interferometry with two atomic species to test the Equivalence Principle in the Quantum Domain

$$\delta\phi = \quad \boldsymbol{k} \cdot \boldsymbol{g}\, T^2$$

- Frequency comb is used for high precision frequency comparison $\sim 10^{-18}$ with frequencies of ratios up to 10^5. Here
  - phaselinking two Raman laser systems
  - optical generation of highly stable microwave frequency
- First application of frequency comb in microgravity $\Rightarrow$ pathfinder for future space based applications
  - optical clocks
  - cold atoms (interferometry)
  - interaction–free detection

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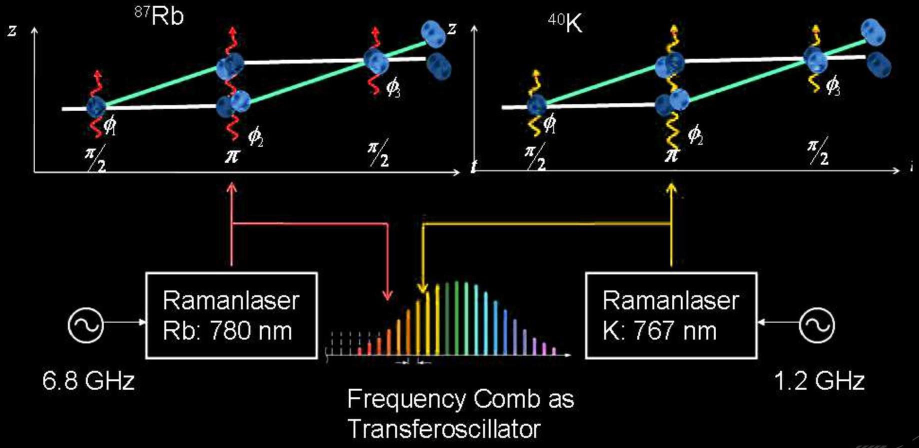
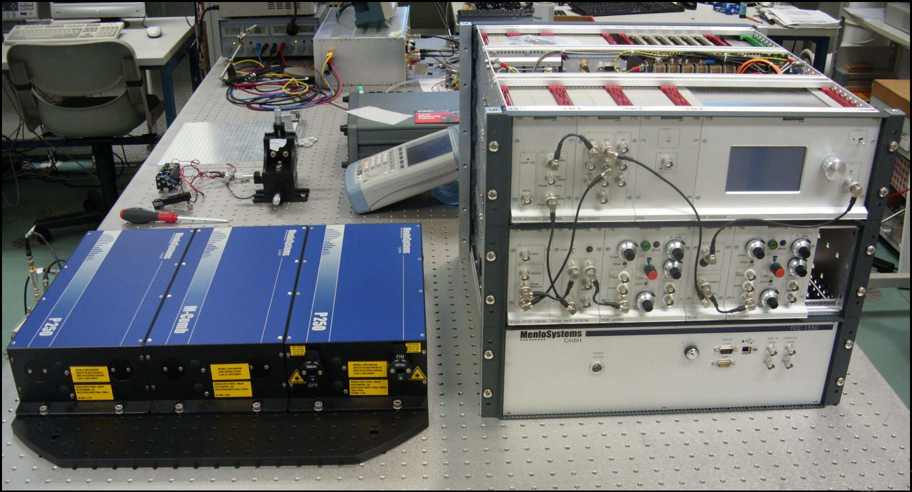
Frequency Comb

Phaselink of beam splitting lasers
QUANTUS + PRIMUS : 2 species atom interferometer



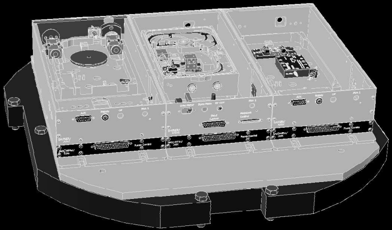
Frequency Comb

The frequency comb in the lab

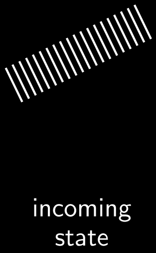


Frequency Comb

- Fiberlaser frequency comb (MenloSystems)
- Remote operation via WLAN
- Battery powered (24V / 8 A)
- Compact and robust design, to withstand 50 g acceleration
- First drop 4.3.2010



PRIMUS: Concept of interferometry



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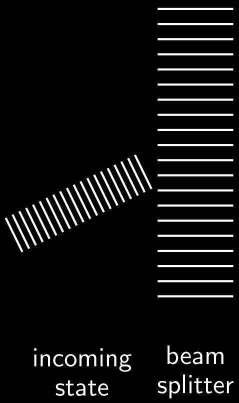

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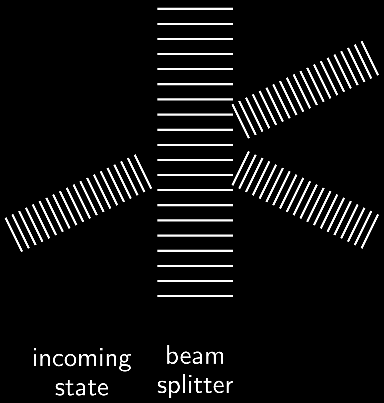

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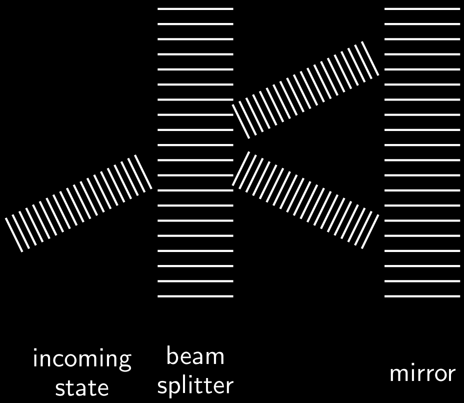

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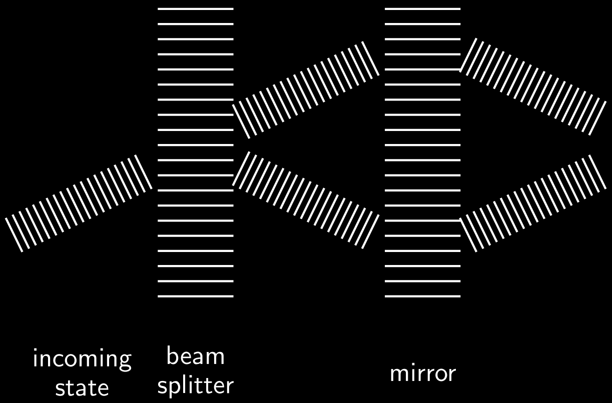

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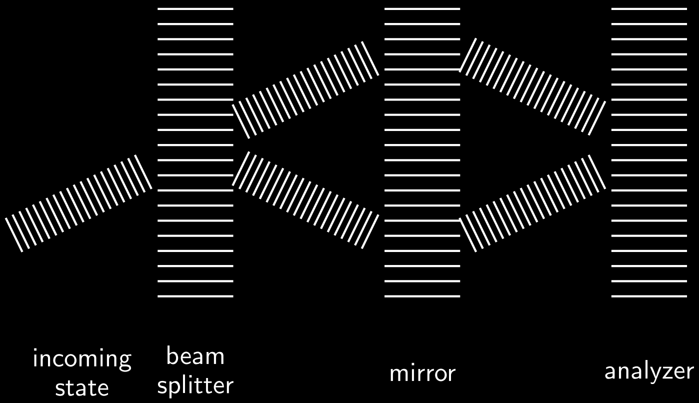

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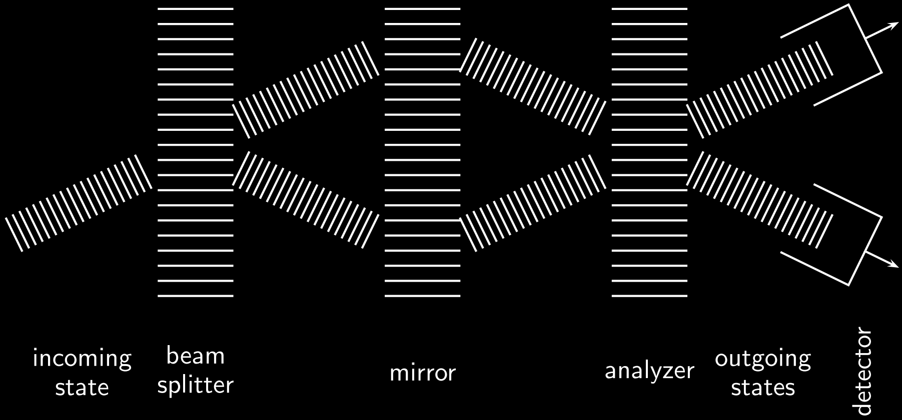

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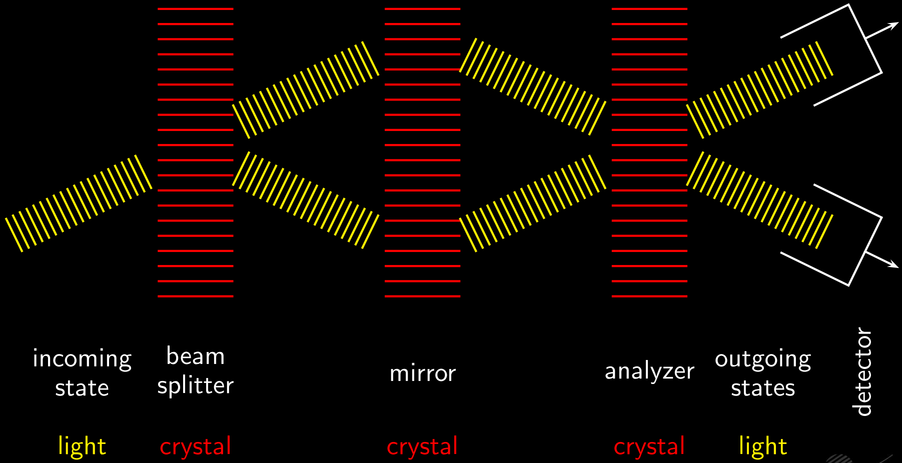

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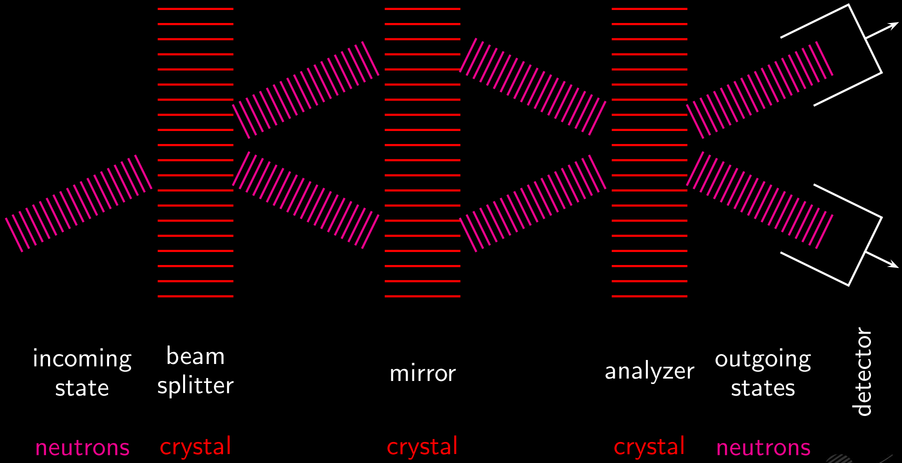

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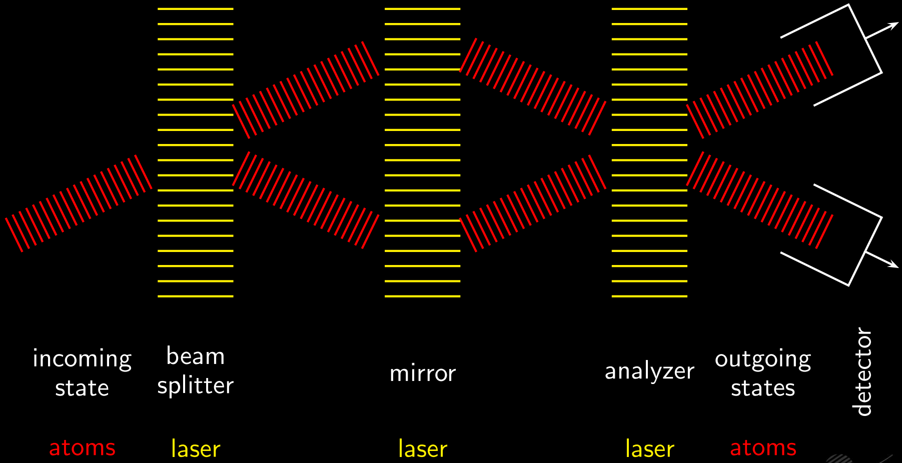
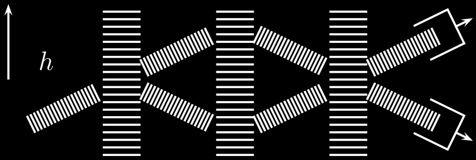


Atomic interferometry

- one of the most fundamental concepts in physics
- compares two identical systems with different history
- Interferometry in
  - configuration space
  - momentum space
  - spin space
  - energy space



Phase shift

$$\delta\phi = \int_{\text{upper}} V(h(t))dt - \int_{\text{lower}} V(h(t))dt \approx \left(V(h_{\text{upper}}) - V(h_{\text{lower}})\right)T \approx \frac{dV}{dh}hT$$
$$= \frac{dV}{dh}\,\Delta v_h\,T^2$$

$h \sim T$, $T =$ propagation time

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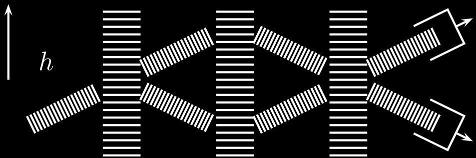

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Atomic interferometry

Phase shift

$$\delta\phi = \frac{dV}{dh}\,\Delta v_h\, T^2$$

Can manipulate velocity of atoms:

- can make Δv_h large (multiple π–pulses)
- can make T large (more efficient)
  - possible only for atoms (atoms have to be sufficiently coherent)
  - possible only in space

Neutron interferometry and atom interferometry

$$\begin{aligned} \delta\phi_{\text{acceleration}} &= -\boldsymbol{k}\cdot\boldsymbol{g}\,T^2 \\ \delta\phi_{\text{rotation}} &= -\boldsymbol{k}\cdot(\boldsymbol{\Omega}\times\boldsymbol{v})\,T^2 \end{aligned}$$

For neutrons $T \sim 10^{-5}$ s
For atoms T may be many seconds

Possible experiments with cold atoms

This opens up a new physical regime with new improved tests in microgravity: Application of cold atoms for fudamental physics research

- **Test of quantum principles**
  - Testing linearity of quantum mechanics
  - Search for fundamental decoherence, quantum to classical transition
  - Measuring wave packet spreading
  - Quantum reflection and diffraction
  - Study of the measurement process
- **Test of gravity principles**
  - Quantum test of UFF
  - Quantum test of UFF with atoms with spin
  - Newton potential at small distances
  - Testing relativistic effects
  - Giant hydrogen atom
  - Gravity trampoline
- **Combined tests (towards quantum gravity)**
  - Investigation of self gravity
  - Test of semiclassical Einstein equations
  - Search for modified dispersion relation

Possible experiments with cold atoms

Application of cold atoms for fudamental physics research

- **Further issues**
  - measuring atom–atom interactions
  - Influence of fluctuations
  - Neutrality of atoms
  - Modified dispersion relation
    - Atom recoil effects
    - BECs
  - Test of Newton's axioms
    - Test of Newton's first axiom (there are force–free motions, inertial system)
    - Test of Newton's second axiom (force $=$ mass $\times$ acceleration)
    - Test of Newton's third axiom (*actio* $=$ *reactio*, active vs. passive mass or charge)
  - BEC as boson star
  - Analogue gravity: simulation of black holes

Cold atoms in microgravity: Technology

Technological applications of cold atoms

- accelerometers
- gyroscopes
- gradiometers
- high precision atomic clocks

used for

- measuring the gravitational field of the Earth (geodesy, climate research, ocean warming, ice melting, ...)
- establishing improved TAI from space

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Condensed matter – emergent phenomena

- superfluidity
- measurement of critical points
- universality aspects of phase transitions
- scaling effects
- boundary effects
- renormalization group theory

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Atomic interferometry: Test of Equivalence Principle

Phase shift

$$\delta\phi = \qquad kgT^2$$

Atomic interferometry: Test of Equivalence Principle

Phase shift with different inertial and gravitational masses

$$\delta\phi = \frac{m_{\mathrm{g}}}{m_{\mathrm{i}}} k g T^2$$

Atomic interferometry: Test of Equivalence Principle

Phase shift with different inertial and gravitational masses

$$\delta\phi = \frac{m_{\rm g}}{m_{\rm i}} k g T^2$$

For two different atomic species $\Rightarrow$ access to Eötvös parameter

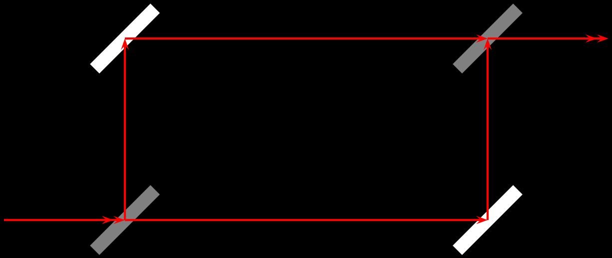
$$\eta \sim \left(\frac{m_{\rm g}}{m_{\rm i}}\right)_2 - \left(\frac{m_{\rm g}}{m_{\rm i}}\right)_1$$

presently $\eta \leq 10^{-10}$ (Chu & Peters 1999)

Superposition principle

Model non–linear Schödinger equation (Bialnicky–Birula PRL 1977, Shimony, PRA 1978)

$$i\frac{\partial\psi}{\partial t} = -\frac{1}{2m}\Delta\psi + a\left[\ln\left(b\psi^*\psi\right)\right]\psi$$



$$\delta\phi = 2\,\frac{d}{\hbar}\,a\,\sqrt{\frac{m}{2E}}\,\ln\alpha\,, \qquad \alpha = \text{ attenuation}$$

Test with neutron interferometry $a \leq 3.4\cdot 10^{-13}\ \mathrm{eV}$ (Shull et al, PRL 1980)
atomic interferometry should lead to orders of magnitude improvement

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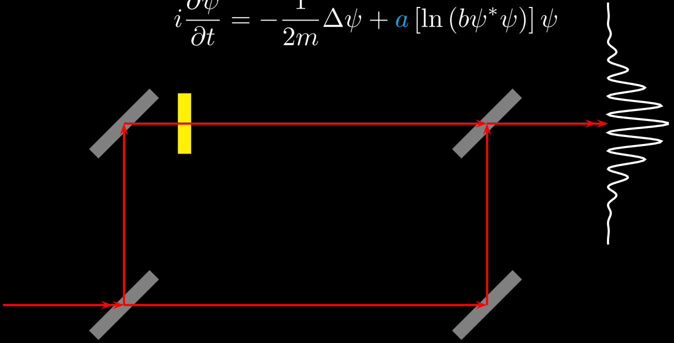

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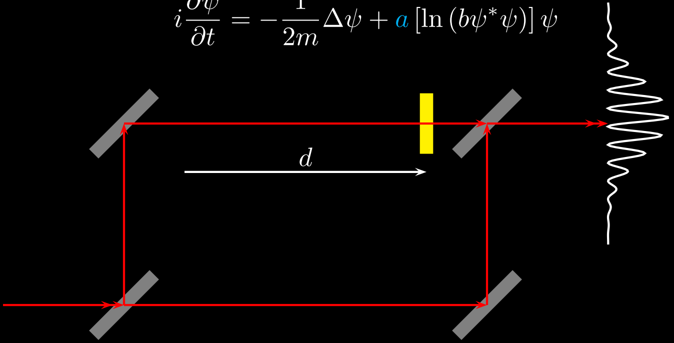

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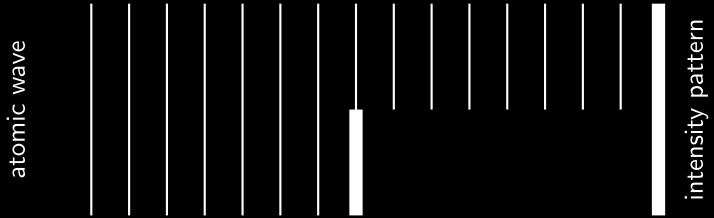
Superposition principle

Alternative measurement: Scattering at edges



- yields best estimates for neutrons: $a \leq 3 \cdot 10^{-15}$ eV
- depends on velocity of particles $\rightarrow$ should be better by many orders of magnitude for cold atoms
- quantum reflection
- quantum diffraction

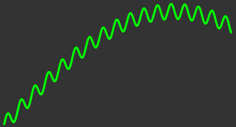
Atomic interferometry: Test of Newton's second axion

Question

Why equations of motion are of second order?

Model

most simple model: motion in constant electric field



$$\epsilon \ddddot{\boldsymbol{x}} + m\ddot{\boldsymbol{x}} = q\boldsymbol{E}_0$$

leads to ordinary motion + high frequency *zitterbewegung*

Ion interferometric measurement of acceleration

phase shift

$$\Delta\phi = A(\omega)\boldsymbol{k} \cdot \ddot{\boldsymbol{x}}(\omega)\, T^2$$

with transfer function $A(\omega)$

If nothing will be seen → estimate $\epsilon \leq 10^{-50}\,\mathrm{kg\,s^2}$
(C.L. & Rademaker 2009)

Atomic interferometry: Search for fundamental noise

The model

Fluctuations of space–time metric

$$i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\left(\delta^{ij}+h^{ij}\right)\partial_i\partial_j\psi + V\psi\,, \qquad h^{ij}, V \text{ fluctuating}$$

Consequences

- Leads to master equation of Lindblad form for density operator
- Leads to decoherence of quantum system (washing out of interference fringes)
- decoherence time

$$\tau_{\rm D} = \frac{2\hbar^2}{(\Delta E)^2\tau_{\rm c}} = 2\left(\frac{\hbar}{\Delta E\tau_{\rm c}}\right)^2\tau_{\rm c}$$

- for $\tau_{\rm c} = t_{\rm Planck}$

$$\tau_{\rm D} = \frac{10^{13}\ {\rm s}}{(\Delta E/{\rm eV})^2}$$

too large. Will be better for BECs. (Breuer, Göklü, C.L. 2009)

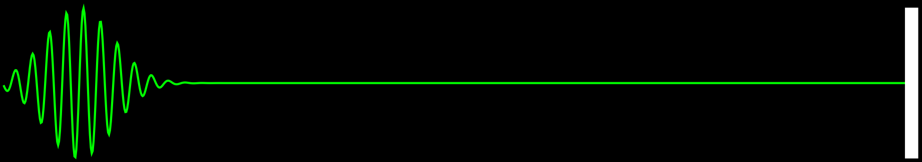
Cold atoms

Further consequence of space–time fluctuations

Spreading of wave functions

For Gaussian correlation and Gaussian initial wave packet

$$\langle x^2(t)\rangle = \underbrace{\sigma^2 + \frac{\hbar^2}{4m^2\sigma^2}t^2}_{\text{free evolution}} + \underbrace{\frac{\sigma_{px}}{m}t}_{\text{diffusion}} + \underbrace{\frac{V_0}{3\sqrt{2\pi}m^2a^3}t^3}_{\text{superdiffusion}}$$



Time–of–flight measurement: t^3 — advantage of long flight times

Advantage for cold (slow) atoms

(Göklü, C.L. Camacho & Macias 2009)

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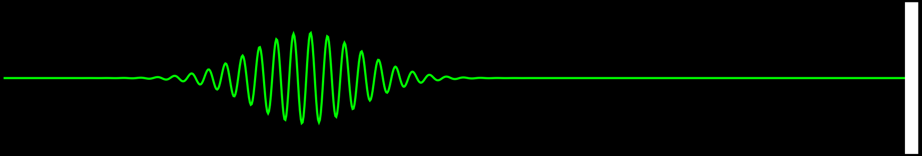

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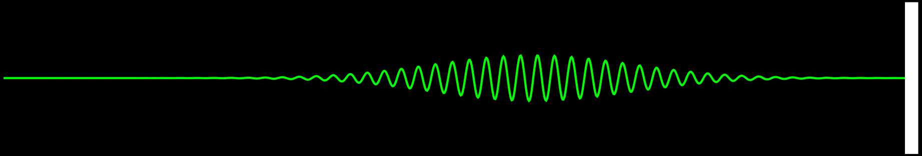

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Advantage for cold (slow) atoms

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Cold atoms & atomic interferometry: Further science

- Measuring Lense–Thirring on small time scales (HYPER mission)
- space–time fluctuations
  - Decoherence of higher order
  - Influence of space–time fluctuation on atoms with spin (enhancement of effect)
- Non–abelian optics
- Structure of gravity
  - Testing non–local gravity (vgl. Hehl & Mashhoon 2009)

$$F = -\frac{GM}{r^2} - \frac{GM}{\lambda r} = -\frac{GM}{r^2}\left(1 + \frac{r}{\lambda}\right)$$

  - Gravitational SME–effects (Kostelecky et al 2008)

$$U(\boldsymbol{x}) = \frac{GM}{r}\left(1 + \frac{x^i a_{ij} x^j}{r^2}\right)$$

  - Finsler–geometry (C.L., Lorek & Dittus, GRG 2009, C.L. & Perlick 2009)

$$\frac{r^3}{T^2} = (1 + A(r))\frac{GM}{4\pi^2} \qquad \ddot{r} = (1 + B(r))\frac{GM}{r^2}$$

Cold atoms & atomic interferometry: Further science

- Anomalous dispersion relations for atoms (Amelino–Camelia & C.L. 2004, 2009)

$$E^2 - \boldsymbol{p}^2 = m^2 c^4 + \eta_1 \frac{E^3}{E_{\mathrm{QG}}} + \ldots$$

- Linearity between force and acceleration $\leftrightarrow$ Newtons axioms for small acceleration (related to dark matter, Milgrom 1983, Ignatiev 2006)
- Gravitational waves
- Test of Local Lorentz Invariance
- Test of Newtonian potential on large scales (SAGAS mission)
- Test of Newtonian potential on small scales

Outline

1 Introduction

2 Fundamental physics under microgravity conditions
- Main physical quests
- Space conditions
- Technologies

3 Selection of projects and proposals
- Testing the UFF
- Clocks: Testing the UGR
- Cold atoms in space
- Condensed matter phenomena

4 More science with benefit from microgravity

5 Further applications

6 Summary and Outlook

Applications

Practical applications

- Geodesy with short time resolution, Grace follow–on porposal
- Gradiometer
- Clock synchronization — TAI

Outline

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Steps to ISS

Example QUANTUS

1. first realization in drop tower
   - proof of principle
   - miniaturization of apparatus
   - robustness of apparatus
2. realization in drop tower with catapult
   - further miniaturization of apparatus
3. rocket
   - construction of autonomous system
   - relyability
4. ISS / satellite
   - relyability
   - safety

Thanks and Literature

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