Quantum tests

Claus Lämmerzahl
July 17, 2018

1st EPS Meeting on Gravitation
Rome, 19 - 21 February 2019

DFG
Research Training Group
Graduiertenkolleg
Models of Gravity

Universität Bremen*
*EXZELLENT.
Gewinnerin in der
Exzellenzinitiative

CENTER OF
APPLIED SPACE TECHNOLOGY
AND MICROGRAVITY
ZARM

Outline

Quantum mechanics

- The foundations
- Main features
- Open problems

Outline

Quantum mechanics

- The foundations
- Main features
- Open problems

Gravitation

- The foundations
- The gravitational field equations
- Main features
- Open problems

Outline

Quantum mechanics

- The foundations
- Main features
- Open problems

Gravitation

- The foundations
- The gravitational field equations
- Main features
- Open problems

Quantum devices

Outline

Quantum mechanics

- The foundations
- Main features
- Open problems

Gravitation

- The foundations
- The gravitational field equations
- Main features
- Open problems

Quantum devices

Quantum tests

- Two generic tests
- General quests and approaches
- Test of Gravitational redshift
- Atom interferometry
- Quantum-to-classical transition
- Towards tests of the quantum gravity domain

Outline

Abstract

Quantum mechanics is at the basis of our understanding of all matter and - since with the behavior of matter we explore space and time - also of our understanding of space-time. In the recent years, also quantum technologies became more and more important for practical purposes. This includes quantum sensors, quantum metrology, quantum information, quantum cryptography, quantum computing, etc. Of particular importance is the coupling of quantum matter to gravity. In this talk we collect the foundations of quantum mechanics, the foundations of relativistic gravity, and corresponding tests, in particular tests exploring the quantum-gravity interaction. Also the relevance of this research for practical purposes is described.

Outline

Outline

Quantum mechanics: the postulates

- the physical system: quantum object $| \psi \rangle \in \mathscr{H}$

Quantum mechanics: the postulates

- the physical system: quantum object
- quantization

$$\begin{aligned} x &\rightarrow \hat{x} \\ p &\rightarrow \hat{p} \end{aligned}$$

Quantum mechanics: the postulates

- the physical system: quantum object
- quantization
- measurement process

$$| \, \psi \, \rangle \quad \xrightarrow{\hat{A}} \quad \{a, | \, a \, \rangle, |\langle a \mid \psi \, \rangle|^2\}$$

Quantum mechanics: the postulates

- the physical system: quantum object
- quantization
- measurement process
- dynamics: Schrödinger equation

$$i\hbar\partial_t \mid \psi \rangle = \hat{H}(\hat{x}, \hat{p}) \mid \psi \rangle$$

Quantum mechanics: the postulates

- the physical system: quantum object
- quantization
- measurement process
- dynamics: Schrödinger equation

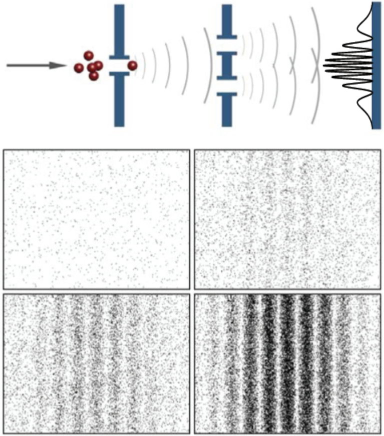
$$i\hbar\partial_t \mid \psi \rangle = \hat{H}(\hat{x}, \hat{p}) \mid \psi \rangle$$

everything works extremely well: all experiments can be completely understood in terms of their calculation

Outline

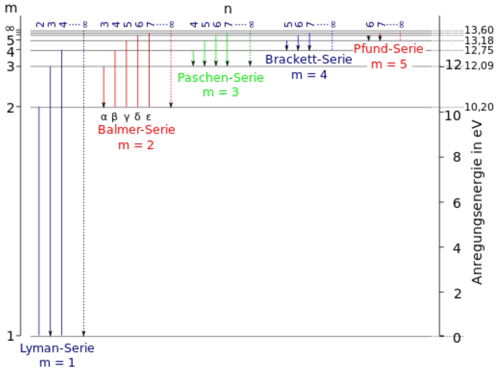
Quantum mechanics: Main phenomena

- for all physical systems: interference, diffraction, ..., impossibility to get which-way information, delayed-choice experiment, action-at-a-distance a la Aharonov-Bohm, ...



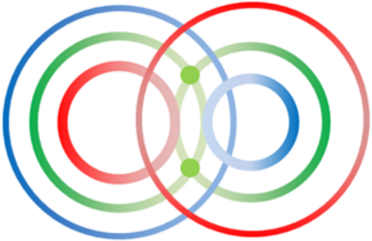
Quantum mechanics: Main phenomena

- for all physical systems: interference, diffraction, ..., impossibility to get which-way information, delayed-choice experiment, action-at-a-distance a la Aharonov-Bohm, ...
- energy levels: quantum systems are characterized by a finite number of numbers



Quantum mechanics: Main phenomena

- for all physical systems: interference, diffraction, ..., impossibility to get which-way information, delayed-choice experiment, action-at-a-distance a la Aharonov-Bohm, ...
- energy levels: quantum systems are characterized by a finite number of numbers
- entanglement



"Biphoton symbolic representation" by Neolexx/Wikimedia

$$\frac{1}{\sqrt{2}} (| \, 0 \, \rangle_A \otimes | \, 1 \, \rangle_B - | \, 1 \, \rangle_A \otimes | \, 0 \, \rangle_B)$$

Quantum mechanics: Main phenomena

- for all physical systems: interference, diffraction, ..., impossibility to get which-way information, delayed-choice experiment, action-at-a-distance a la Aharonov-Bohm, ...
- energy levels: quantum systems are characterized by a finite number of numbers
- entanglement
- no cloning - no broadcasting

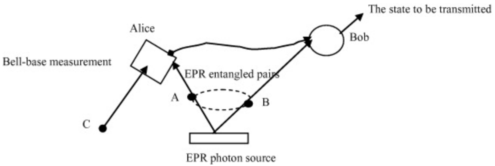
no unitary operation U with

$$U \mid \psi \rangle \otimes \mid 0 \rangle \quad = \quad \mid \psi \rangle \otimes \mid \psi \rangle$$

ZARM

Quantum mechanics: Main phenomena

- for all physical systems: interference, diffraction, ..., impossibility to get which-way information, delayed-choice experiment, action-at-a-distance a la Aharonov-Bohm, ...
- energy levels: quantum systems are characterized by a finite number of numbers
- entanglement
- no cloning - no broadcasting
- quantum teleportation



Wen, Tian, Niu, Phys. Scr. 2010

Quantum mechanics: Uniqueness

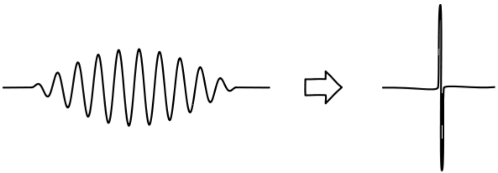
- standard model of elementary particles: unique description of electrons, quarks, neutrons, protons, ...
- atoms are the same everywhere in the universe
- quantum phenomena are the same everywhere in the universe
- allows, e.g., perfect dissemination of physical units since quantum states are uniquely defined through a finite number of numbers (no machining necessary, no prototype, ...)
- beyond classical physics: spin degree of freedom

- technological aspect: huge potential for miniaturization

Outline

Quantum mechanics: Open problems

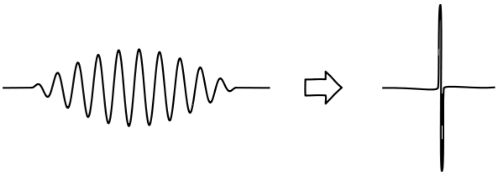
- big interpretational problem: collapse of wave function



J. Norton

Quantum mechanics: Open problems

- big interpretational problem: collapse of wave function



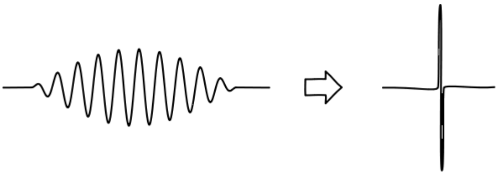
J. Norton

- classical limit

quantum mechanics "as well as" $\rightarrow$ classical mechanics "either or"

Quantum mechanics: Open problems

- big interpretational problem: collapse of wave function



J. Norton

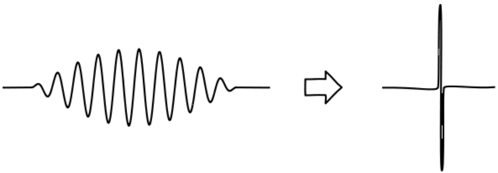
- classical limit

quantum mechanics "as well as" → classical mechanics "either or"

- zero point energy and gravity

Quantum mechanics: Open problems

- big interpretational problem: collapse of wave function



J. Norton

- classical limit

quantum mechanics "as well as" $\rightarrow$ classical mechanics "either or"

- zero point energy and gravity

however: we can work very well without solving these problems, for practical work no solution is needed $\rightarrow$ purely interpretational problems

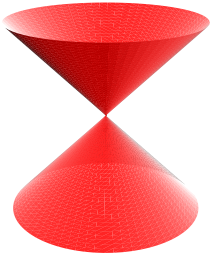
Outline

Outline

Gravitation

Basic principles of gravity (Ehlers, Pirani, Schild 1972; Will 1993)

- **Conformal structure** behavior of light rays $\rightarrow$ metric structure, locally Special Relativity



$c = const$
Minkowski metric η_{ab}
many tests $10^{-15} - 10^{-30}$

Gravitation

Basic principles of gravity (Ehlers, Pirani, Schild 1972; Will 1993)

- **Conformal structure** behavior of light rays $\rightarrow$ metric structure, locally Special Relativity

- independence of c from velocity of source: $\leq 10^{-11}$
- isotropy of c: $\leq 10^{-17}$
- Kennedy-Thorndike: $\leq 10^{-17}$
- time dilation: $\leq 10^{-8}$

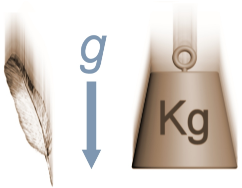
Gravitation

Basic principles of gravity (Ehlers, Pirani, Schild 1972; Will 1993)

- **Conformal structure** behavior of light rays $\rightarrow$ metric structure, locally Special Relativity
- **Universality of Free Fall**

there exists a coordinate system so that for all particles

$$\frac{d^2x^\mu}{dt^2} \overset{*}{=} 0$$

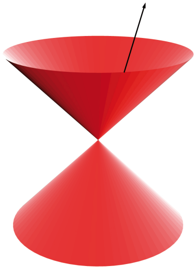


- bulk matter, MICROSCOPE $\eta \leq 10^{-15}$ (Touboul et al, PRL 2017)
- spin matter
- charged matter
- anti-matter $\rightarrow$ Michael Doser, next talk

Gravitation

Basic principles of gravity (Ehlers, Pirani, Schild 1972; Will 1993)

- **Conformal structure** behavior of light rays $\rightarrow$ metric structure, locally Special Relativity
- **Universality of Free Fall**
- **Compatibility** no superluminal velocity



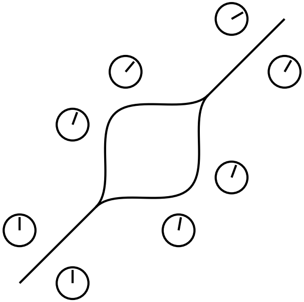
$v < c$

- laboratory: $\leq 10^{-6}$
- astroparticle tests: $\leq 10^{-21}$

Gravitation

Basic principles of gravity (Ehlers, Pirani, Schild 1972; Will 1993)

- **Conformal structure** behavior of light rays $\rightarrow$ metric structure, locally Special Relativity
- **Universality of Free Fall**
- **Compatibility** no superluminal velocity
- **Uniqueness of time-keeping** or uniqueness of quantum mechanics or **Local Position Invariance**



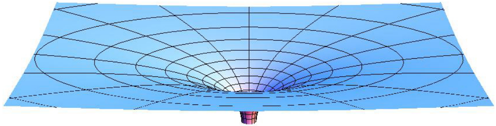
clocks may show different time (twin paradox), but same ticking rates required

many different clock tests $\alpha \leq 10^{-4}$
anti clocks, Galileo

Gravitation

Basic principles of gravity (Ehlers, Pirani, Schild 1972; Will 1993)

- **Conformal structure** behavior of light rays $\rightarrow$ metric structure, locally Special Relativity
- **Universality of Free Fall**
- **Compatibility** no superluminal velocity
- **Uniqueness of time-keeping** or uniqueness of quantum mechanics or **Local Position Invariance**

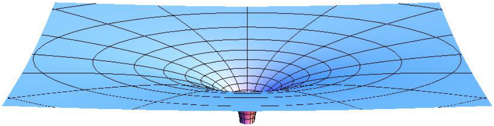


Einstein Equivalence Principle

Gravitation

Basic principles of gravity (Ehlers, Pirani, Schild 1972; Will 1993)

- **Conformal structure** behavior of light rays $\rightarrow$ metric structure, locally Special Relativity
- **Universality of Free Fall**
- **Compatibility** no superluminal velocity
- **Uniqueness of time-keeping** or uniqueness of quantum mechanics or **Local Position Invariance**



Einstein Equivalence Principle

Result: Gravity can be described by a pseudo-Riemannian manifold $g_{\mu\nu}$

applies also to fields: Maxwell, Dirac, ...

ZARM

Outline

The field equations

- There is no unique physical way to derive the Einstein field equations
- Attempts: PPN formalism
  still loopholes: torsion, Finsler geometry, non-Newtonian gravity, anisotropy on the Newtonian level (SME), ...
- Guiding principle: action principle

$$S = \int R\sqrt{-g}\, d^4x + \int \mathcal{L}_{\text{matter}}\, d^4x$$

  extremalization

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}\,, \qquad T_{\mu\nu} = \frac{1}{\sqrt{-g}} \frac{\delta \mathcal{L}_{\text{matter}}}{\delta g^{\mu\nu}}$$

- One major consequence: Black Holes

ZARM

Outline

Predictions, consequences

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

Predictions, consequences

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

$\Downarrow$

Implication

Gravity is a metrical theory

Ehlers, Pirani & Schild 1972

Predictions, consequences

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

$\Downarrow$

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

Predictions, consequences

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

$\Downarrow$

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

$\Leftarrow$

General Relativity

ZARM

Outline

Open problems

observational

- Dark Matter

Open problems

observational

- Dark Matter
  - some kind of matter?
  - modified gravity?

Open problems

observational

- Dark Matter
- Dark Energy

- some kind of matter?/energy?
- modified gravity?

Open problems

observational

- Dark Matter
- Dark Energy

- some kind of matter?/energy?
- modified gravity?

structural

- singularities

Open problems

observational

- Dark Matter
- Dark Energy

- some kind of matter?/energy?
- modified gravity?

structural

- singularities

- hidden behind the horizon
- singularities not present for quantum systems

Open problems

observational

- Dark Matter
- Dark Energy

- some kind of matter?/energy?
- modified gravity?

structural

- singularities
- cosmic censorship

- hidden behind the horizon
- singularities not present for quantum systems

Open problems

observational

- Dark Matter
- Dark Energy

- some kind of matter?/energy?
- modified gravity?

structural

- singularities
- cosmic censorship

- hidden behind the horizon
- singularities not present for quantum systems
- collapse model

Open problems

observational

- Dark Matter
- Dark Energy

- some kind of matter?/energy?
- modified gravity?

structural

- singularities
- cosmic censorship

- hidden behind the horizon
- singularities not present for quantum systems
- collapse model

quantization of gravity

Open problems

observational

- Dark Matter
- Dark Energy

- some kind of matter?/energy?
- modified gravity?

structural

- singularities
- cosmic censorship

- hidden behind the horizon
- singularities not present for quantum systems
- collapse model

quantization of gravity

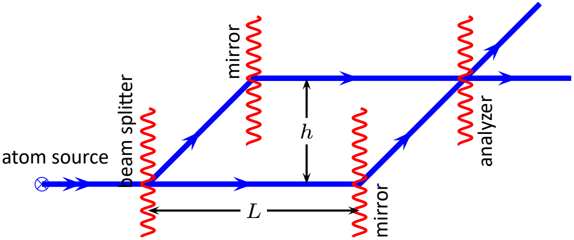
- singularities
- Hawking radiation
- information paradox

ZARM

Outline

Quantum devices / Quantum technologies

- quantum sensors - atom interferometers,



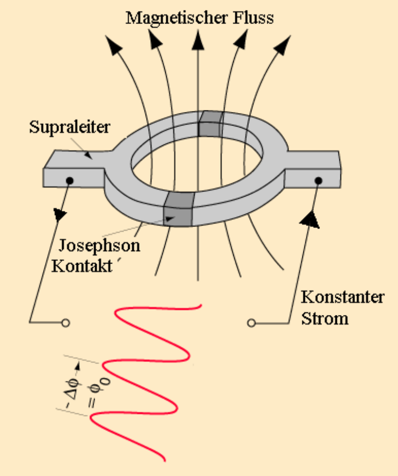
Quantum devices / Quantum technologies

- quantum sensors - atom interferometers, clocks

PTB

Quantum devices / Quantum technologies

- quantum sensors - atom interferometers, clocks, SQUIDS, ...



Wikipedia

Quantum devices / Quantum technologies

- quantum sensors - atom interferometers, clocks, SQUIDS, ...
- quantum metrology - new definition of physical units, realization via quantum systems (uniqueness)
  - clocks
  - quantum Hall effect, Josephson effect: new definition of kg
  - quantum dots for the Ampere

old definition of units:

- 1 s are 9 192 631 770 periods of the radi- ation of the transition between the two hyperfine levels of the ^{133}Cs ground state.
- 1 m is the length traveled by light in vacuum during 1/299 792 458 of a s.
- 1 kg is equal to the mass of the prototype.
- 1 A is that current through two long thin parallel conductors 1 metre apart, which produces a force of $2 \cdot 10^{-7}$ N/m.
- 1 K is 1/273.16 of the thermodynamic temperature of the triple point of water.
- 1 mol is the amount of substance of a sys- tem which contains as many elementary entities as there are atoms in 12 g of ^{12}C.

Quantum devices / Quantum technologies

- quantum sensors - atom interferometers, clocks, SQUIDS, ...
- quantum metrology - new definition of physical units, realization via quantum systems (uniqueness)
  - clocks
  - quantum Hall effect, Josephson effect: new definition of kg
  - quantum dots for the Ampere

new definition of units

- 1 s are 9 192 631 770 periods of the radi- ation of the transition between the two hyperfine levels of the ^{133}Cs ground state.
- 1 m is the length traveled by light in vacuum during 1/299 792 458 of a s.
- kg from definition of $\hbar$
- A from definition of e
- K from definition of k_B
- mol from definition of N_A
- 1 cd is the luminous intensity of a source that emits monochromatic radiation of frequency $540 \cdot 10^{12}$ hertz and that has a radiant intensity in that direction of 1/683 W/steradian.

Quantum devices / Quantum technologies

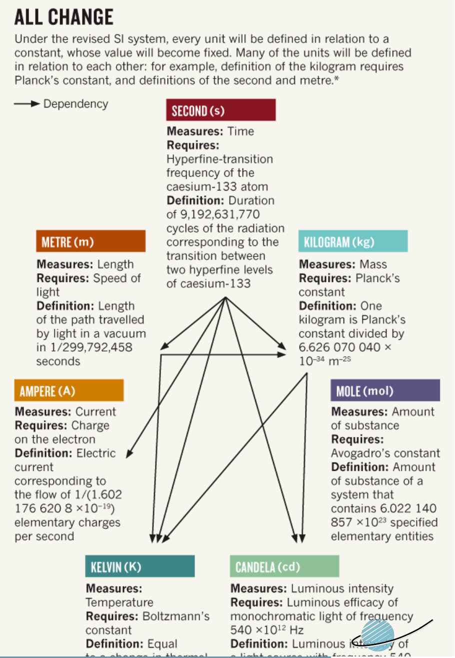
- quantum sensors - atom interferometers, clocks, SQUIDS, ...
- quantum metrology - new definition of physical units, realization via quantum systems (uniqueness)
  - clocks
  - quantum Hall effect, Josephson effect: new definition of kg
  - quantum dots for the Ampere

realization of units

- s through atomic clock
- m through light
- kg through Watt balance (QHE and Josephson effect)
- A through quantum dots
- K through energy comparison
- mol through silicon sphere
- cd

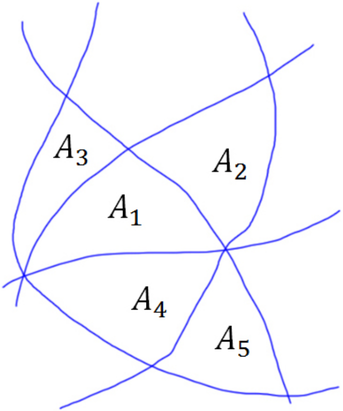
Quantum devices / Quantum technolog

- quantum sensors - atom interferometers, clocks, SQUIDS, ...
- quantum metrology - new definition of physical units, realization via quantum systems (uniqueness)
  - clocks
  - quantum Hall effect, Josephson effect: new definition of kg
  - quantum dots for the Ampere



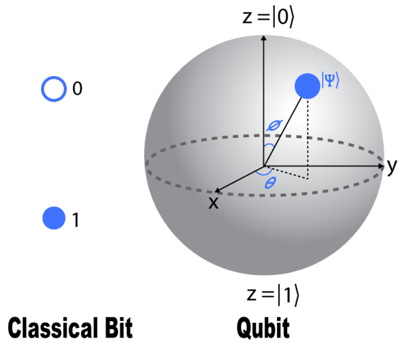
Quantum devices / Quantum technologies

- quantum sensors - atom interferometers, clocks, SQUIDS, ...
- quantum metrology - new definition of physical units, realization via quantum systems (uniqueness)
  - clocks
  - quantum Hall effect, Josephson effect: new definition of kg
  - quantum dots for the Ampere
- quantum networks - networks of entangled clocks for geodesy, quantum internet, ...



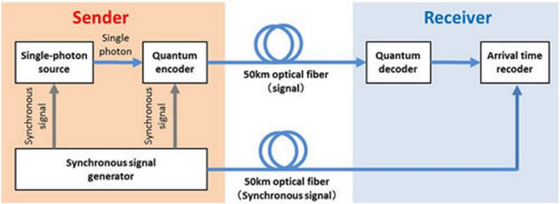
Quantum devices / Quantum technologies

- quantum sensors - atom interferometers, clocks, SQUIDS, ...
- quantum metrology - new definition of physical units, realization via quantum systems (uniqueness)
  - clocks
  - quantum Hall effect, Josephson effect: new definition of kg
  - quantum dots for the Ampere
- quantum networks - networks of entangled clocks for geodesy, quantum internet, ...
- quantum computing



Quantum devices / Quantum technologies

- quantum sensors - atom interferometers, clocks, SQUIDS, ...
- quantum metrology - new definition of physical units, realization via quantum systems (uniqueness)
  - clocks
  - quantum Hall effect, Josephson effect: new definition of kg
  - quantum dots for the Ampere
- quantum networks - networks of entangled clocks for geodesy, quantum internet, ...
- quantum computing
- quantum cryptography

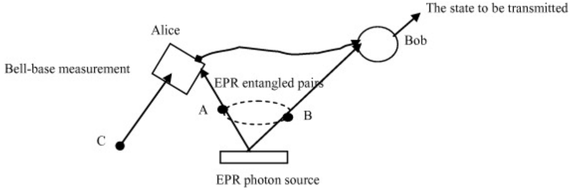


from phys.org

ZARM

Quantum devices / Quantum technologies

- quantum sensors - atom interferometers, clocks, SQUIDS, ...
- quantum metrology - new definition of physical units, realization via quantum systems (uniqueness)
  - clocks
  - quantum Hall effect, Josephson effect: new definition of kg
  - quantum dots for the Ampere
- quantum networks - networks of entangled clocks for geodesy, quantum internet, ...
- quantum computing
- quantum cryptography
- teleportation



Wen, Tian, Niu, Phys. Scr. 2010

Outline

Outline

Quantum test of the Equivalence Principle

Model

Schrödinger equation in gravitational field

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\Delta\phi + m\ U\psi$$

Phase shift

For pure gravitational acceleration

- atom interferom. (Bordé 1989)

$$\delta\phi = \quad k \cdot g\ T^2$$

- neutron interference (CL, GRG 1996)

$$\delta\phi = C \cdot g\ T^2$$

Discussion

- Exact quantum result
- UFF exactly fulfilled
- Does not depend on $\hbar$
- $\hbar$ comes in by introducing classical notions
  - height = $h = v_z T = \frac{\hbar k}{m} T$
  - length = $l = v_0 T$

  then

$$\delta\phi = k_z g T^2 = \frac{mghl}{\hbar v_0}$$

- classical notions are operationally not realized
- $\delta\phi = k_z g T^2$ contains experimentally given quantities only

ZARM

Quantum test of the Equivalence Principle

Model

Schrödinger equation in gravitational field

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m_i}\Delta\phi + m_g U\psi$$

Phase shift

For pure gravitational acceleration

- atom interferom. (Bordé 1989)

$$\delta\phi = \frac{m_g}{m_i}\,k\cdot g\,T^2$$

- neutron interference (CL, GRG 1996)

$$\delta\phi = C\cdot g\,T^2$$

Discussion

- Exact quantum result
- UFF exactly fulfilled
- Does not depend on $\hbar$
- $\hbar$ comes in by introducing classical notions
  - height = $h = v_z T = \frac{\hbar k}{m} T$
  - length = $l = v_0 T$

  then

$$\delta\phi = k_z g T^2 = \frac{mghl}{\hbar v_0}$$

- classical notions are operationally not realized
- $\delta\phi = k_z g T^2$ contains experimentally given quantities only

ZARM

Quantum test of the Equivalence Principle

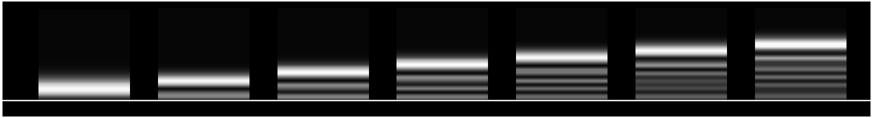
Peters, Chung & Chu, Nature 2000: quantum matter vs. classical matter, $\eta \lesssim 10^{-9}$
Fray et al, PRL 2004: different rubidium isotopes, $\eta \lesssim 10^{-7}$
Schlippert et al, PRL 2014: rubidium and potassium, $\eta \lesssim 10^{-7}$

drop tower: expected $\eta \lesssim 10^{-11}$
space: expected $\eta \lesssim 10^{-15}$

- can be used for an operational definition of the equivalence principle in the quantum domain, even in curved space–time (C.L., GRG 1996)
- it can be shown that this operational definition is equivalent to the minimal coupling procedure (C.L., APP 1997)

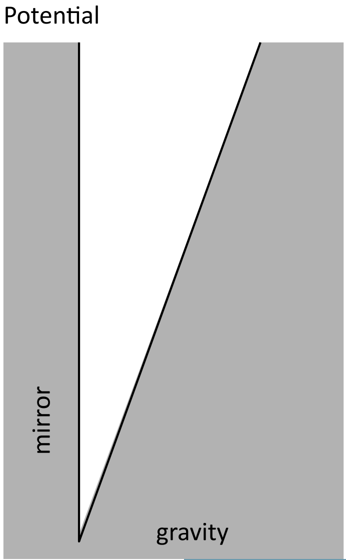
BEC in GOST

- BEC in gravito-optical surface trap (GOST)
- boundary conditions $\psi = 0$ for $z = 0$
- spacing between nodes depends on gravitational acceleration



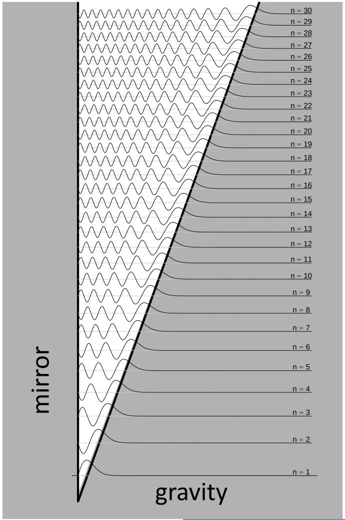
$n = 1$ $n = 2$ $n = 3$ $n = 4$ $n = 5$ $n = 6$ $n = 7$

Neutron eigenstates in gravitational field



Neutron eigenstates in gravitational field

Potential

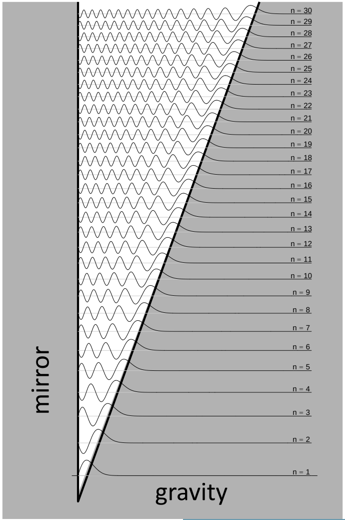


Süßmann 1965, LL

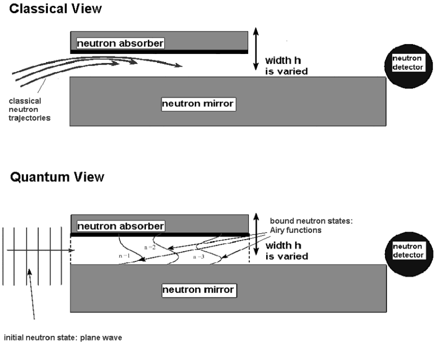
ZARM

Neutron eigenstates in gravitational field

Potential



experimental setup

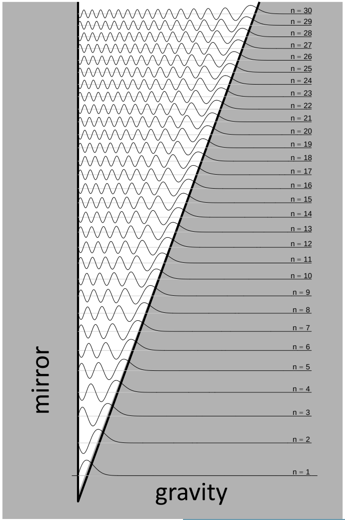


Süßmann 1965, LL

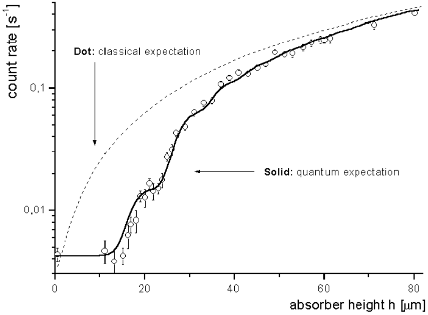
ZARM

Neutron eigenstates in gravitational field

Potential



measurement



Süßmann 1965, LL
Nesvizhevsky et al 2002

ZARM

Outline

General quests related to the quantum – gravity regime

- **Test of quantum principles**
  - study of the measurement process
  - testing linearity of quantum mechanics
  - search for fundamental decoherence
  - measuring wave packet spreading
  - exploring the quantum degrees of freedom (spin)
- **Quantum test of gravity principles**
  - quantum test of UFF
  - quantum test of UFF with atoms with spin
  - test of UGR
  - test of UFF and UGR for gravitomagnetism
  - testing all GR effects
- **Combined tests (towards quantum gravity)**
  - entanglement in gravitational fields
  - investigation of self gravity
  - test of semiclassical Einstein equations
  - search for modified dispersion relation

General quests related to the quantum – gravity regime

- **Test of quantum principles**
  - study of the measurement process
  - testing linearity of quantum mechanics
  - search for fundamental decoherence
  - measuring wave packet spreading
  - exploring the quantum degrees of freedom (spin)
- **Quantum test of gravity principles**
  - quantum test of UFF
  - quantum test of UFF with atoms with spin
  - test of UGR
  - test of UFF and UGR for gravitomagnetism
  - testing all GR effects
- **Combined tests (towards quantum gravity)**
  - entanglement in gravitational fields
  - investigation of self gravity
  - test of semiclassical Einstein equations
  - search for modified dispersion relation

most of the tests profit from

- large potential differences
- long distances
- long free fall time – long integration/accumulation time
- quiet environment

General quests related to the quantum – gravity regime

- **Test of quantum principles**
  - study of the measurement process
  - testing linearity of quantum mechanics
  - search for fundamental decoherence
  - measuring wave packet spreading
  - exploring the quantum degrees of freedom (spin)
- **Quantum test of gravity principles**
  - quantum test of UFF
  - quantum test of UFF with atoms with spin
  - test of UGR
  - test of UFF and UGR for gravitomagnetism
  - testing all GR effects
- **Combined tests (towards quantum gravity)**
  - entanglement in gravitational fields
  - investigation of self gravity
  - test of semiclassical Einstein equations
  - search for modified dispersion relation

most of the tests profit from

- large potential differences
- long distances
- long free fall time – long integration/accumulation time
- quiet environment

$\rightarrow$ space conditions

ZARM

Quantum Tests in space

benefit from space conditions

- atom interferometers:
  sensitivity $\sim T^2$
- clocks:
  gravitational potential
- laser interferometry:
  long distances
- entanglement over large distances:
  quantum key distribution from space
- quantum metrology:
  definition of kg via Watt balance with inertial force in space

Quantum Tests in space

benefit from space conditions

- atom interferometers: sensitivity $\sim T^2$
- clocks: gravitational potential
- laser interferometry: long distances
- entanglement over large distances: quantum key distribution from space
- quantum metrology: definition of kg via Watt balance with inertial force in space

space missions

- GP-A (test of GR) completed
- LLR (test of GR, Earth science) running
- GP-B (test of GR) completed
- LARES (test of GR) running
- LISA Pathfinder (gw astronomy, test of GR) completed
- MAIUS / QUANTUS (test of QM and GR) completed/running
- Galileo (test of GR) completed
- QUESS, QKD (Quantum Key Distribution, test of QM) completed
- ACES / PHARAO (metrology, test of GR) launch 2020
- LISA (gravitational waves) launch 2028+

Quantum Tests in space

benefit from space conditions

- atom interferometers:
  sensitivity $\sim T^2$
- clocks:
  gravitational potential
- laser interferometry:
  long distances
- entanglement over large distances:
  quantum key distribution from space
- quantum metrology:
  definition of kg via Watt balance with inertial force in space

planned projects

- BECCAL launch 2024
- MAQRO (test of quantum-to-classical transition)
- BOOST (optical tests of SR)
- STE-QUEST (atom interferometry and clocks, tests of GR)
- ...

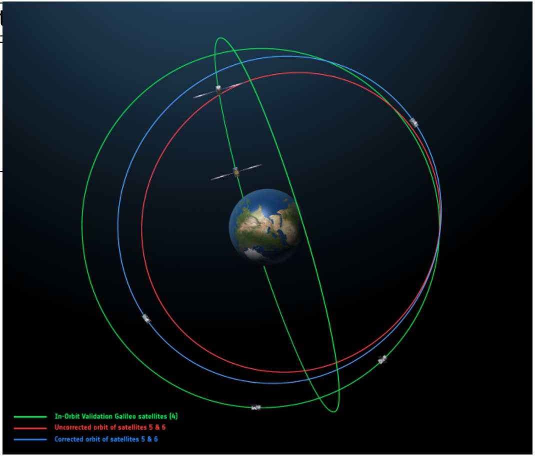
Outline

Galileo 5 and 6

	after launch	after correction	target orbit
e	0.233	0.1561	~ 0
a [km]	26,192	27,977	29,900
i	49.774	49.7212	55
$r_a - r_p$ [km]	11,681	8,730	~ 0

Galileo 5 and 6

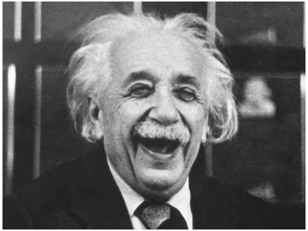
	after launch	after correction	t
e	0.233	0.1561	
a [km]	26,192	27,977	
i	49.774	49.7212	
$r_a - r_p$ [km]	11,681	8,730	

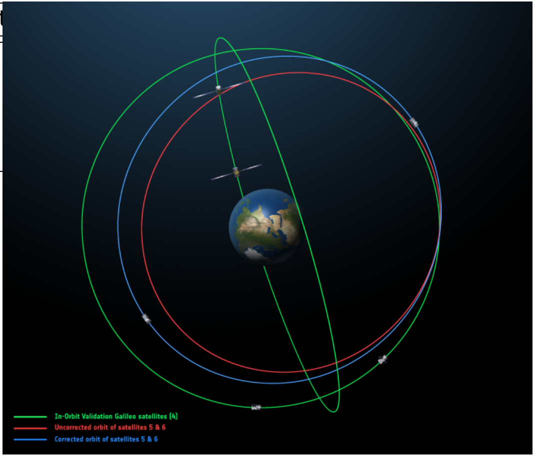


ZARM

Galileo 5 and 6

	after launch	after correction	t
e	0.233	0.1561	
a [km]	26,192	27,977	
i	49.774	49.7212	
$r_a - r_p$ [km]	11,681	8,730	





Galileo clocks and redshift

Galileo clocks

- passive Hydrogen maser PHM and Rubidium clock RAFS
- stability: $\sigma_{\mathsf{HM}} = 3 \cdot 10^{-15}$ and $\sigma_{\mathsf{RAFS}} = 2 \cdot 10^{-14}$ at time scale of one orbit

Redshift

- redshift between perigeum and apogeum

$$\frac{\Delta\nu}{\nu} = (1+\alpha)\frac{GM}{c^2}\left(\frac{1}{r_{\mathsf{p}}} - \frac{1}{r_{\mathsf{a}}}\right) \quad \Rightarrow \quad \Delta t = 2(1+\alpha)\frac{\vec{r}\cdot\vec{v}}{c^2}$$

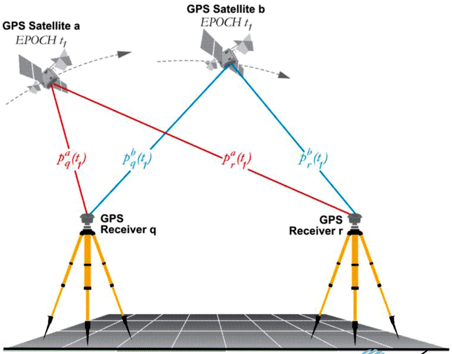
- experimental parameter: α
- with the maximum difference of radius of ~ 8730 km one gets the maximum redshift $\frac{\Delta\nu}{\nu} \approx 5 \cdot 10^{-11}$
- corresponds to 370 ns time gain per revolution (nominal ~ 0.5 ns)

Clock data

Pseudo range for measured times

$$P^s_{r,f}(t) = \|\vec{r}_r(t) - \vec{r}^s(t-T)\| + c\left(\Delta t_r(t) - \Delta t^s(t-T)\right) + c\left(d_{r,f}(t) - d^s_r(t-T)\right) + I^s_{r,f} + T^s_{r,f} - m^s_{r,P,f}(t) + \epsilon^s_{r,P,f}(t)$$

- Measurement of signal travel times = pseudo range
- one has to determine satellite clock corrections Δt^s
- clock corrections depend, among others, on orbit information: 30 cm $\rightarrow$ 1 ns

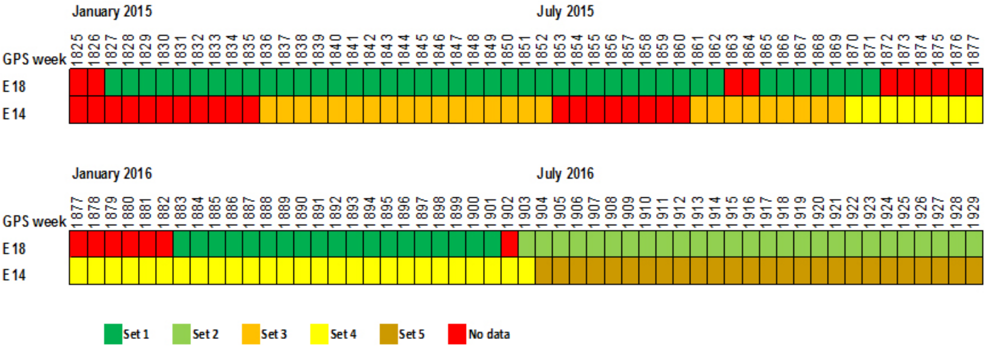


ZARM

Clock data

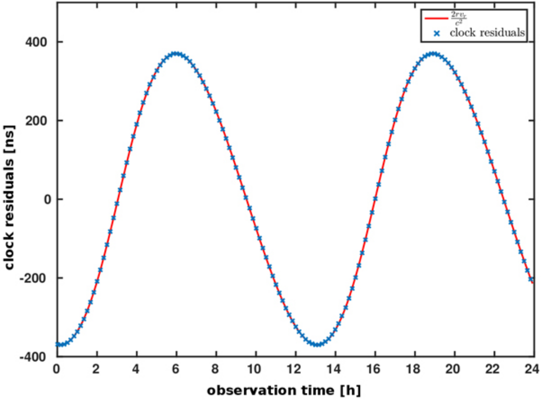
Clock and orbit products are made available to us by ESOC

- 30 s sampling on clock $\leftrightarrow i$ / 300 s sampling on orbit
- Customized reprocessing to needs of data analysis (E. Schönemann, F. Dillsner, T. Springer from ESOC)



Data without relativistic correction

GPS week 1870; day 0



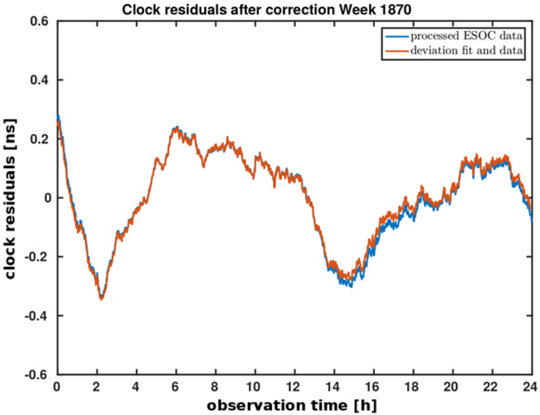
- relativistic effects included
- gravitational redshift + Doppler

$$\Delta t = 2\frac{\vec{r}\cdot\vec{v}}{c^2}$$

- $\sim$ 370 ns modulation amplitude

Data without relativistic “correction”

GPS week 1870; day 0



- relativistic effects modeled and removed by ZARM
- comparison to final ESOC products
- provides a check of basic common understanding
- variations of ~ 0.5 ns due to systematic effects

Least squares fit model

$$S = \sum_{i=1}^{n} \left(\epsilon_i - \alpha \left(\int_{\text{path}} \left(\frac{GM_\oplus}{rc^2} \left(1 - \frac{J_2 a_\oplus^2}{2r^2} \left(\frac{3z^2}{r^2} - 1 \right) \right) + \frac{v^2}{2c^2} \right) dt_i \right) - a_0 - a_1 t_i \right)$$

with

ϵ_i clock residuals

J_2 axially symmetric quadruple moment of Earth (flattening)

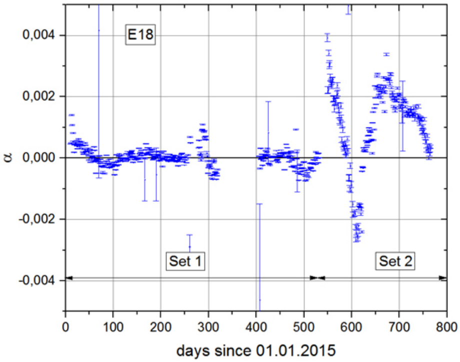
a_0 clock offset parameter

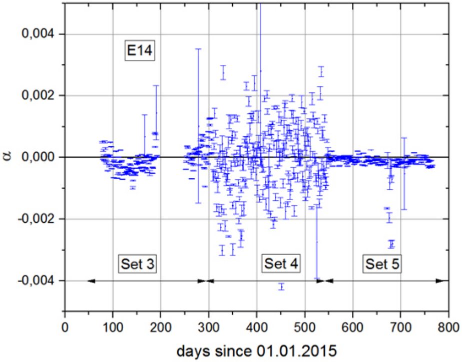
a_1 clock drift parameter

to be determined α

working on Bayesian data analysis

Preliminary statistics on all α results





- two years of data: 585 days, resp. 610 days
- evaluation ongoing ...

Partial results

set	$\alpha \cdot 10^{-4}$	$\sigma \cdot 10^{-4}$	n	outliers	gap days	span [days]
set 1	0.14	2.89	405	15	101	521
set 2	11.20	13.27	205	2	11	218
set 3	-0.75	3.92	163	9	59	231
set 4	-0.43	10.75	232	9	0	241
set 5	-0.97	1.12	190	12	15	217

Systematics: approach

- Temperature, magnetic fields, attitude as discussed in TN1 not yet considered due to lack of data
- Focus on solar radiation pressure
  - correlate with sun elevation, derive model
  - model SRP a priori from geometric satellite model
  - use SLR data from ILRS campaign and reprocess products
- Look for other correlations with readily accessible data (orbit parameters, eclipse phases,...)

Result

Improvement of GP-A result by a factor of 4 (Herrmann et al, PRL 2018)

conservative assumptions - colleagues from SYRTE get an improvement by a factor of 5 (Delva et al, PRL 2018) - ongoing discussion

Systematics: approach

- Temperature, magnetic fields, attitude as discussed in TN1 not yet considered due to lack of data
- Focus on solar radiation pressure
  - correlate with sun elevation, derive model
  - model SRP a priori from geometric satellite model
  - use SLR data from ILRS campaign and reprocess products
- Look for other correlations with readily accessible data (orbit parameters, eclipse phases,...)

Result

Improvement of GP-A result by a factor of 4 (Herrmann et al, PRL 2018)

conservative assumptions - colleagues from SYRTE get an improvement by a factor of 5 (Delva et al, PRL 2018) - ongoing discussion

Galileo satellites are not designed for such kind of test: dedicated satellite might give further substantial improvements

Outline

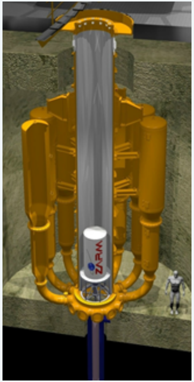
QUANTUS facilities

QUANTUS I

4.7 s

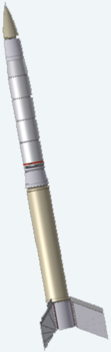
QUANTUS II

9.3 s



MAIUS

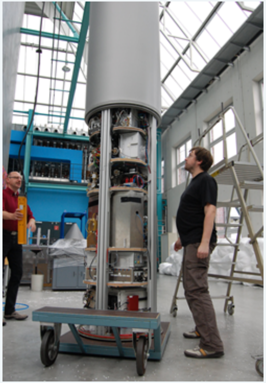
$\sim$ 5 min



QUANTUS apparatuses

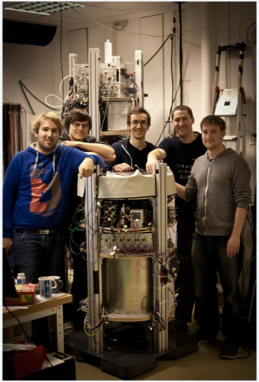
QUANTUS I

4.7 s



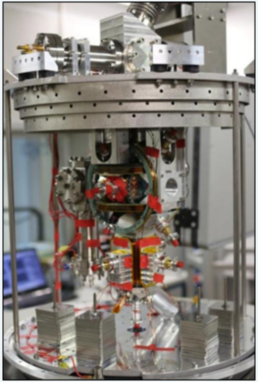
QUANTUS II

9.3 s



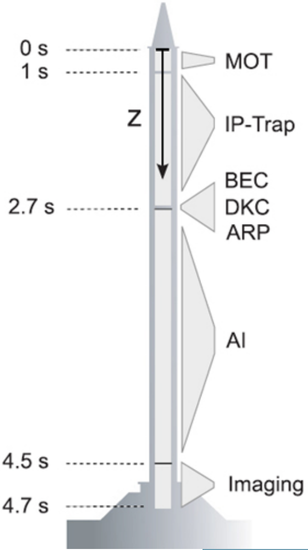
MAIUS

$\sim$ 5 s



ZARM

Preparation of BEC in the drop tower

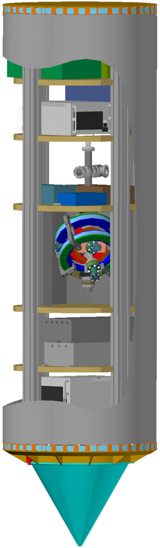


- 10^7 atoms in MOT
- $5 \cdot 10^6$ atoms in magnetic trap
- ~ 1.5 s evaporation cooling
- 10^4 atoms in BEC
- 10 – 30 Hz trap frequency
- T = 9 nK (kinetic energy)
- $F = 2, m_F = 0$ state

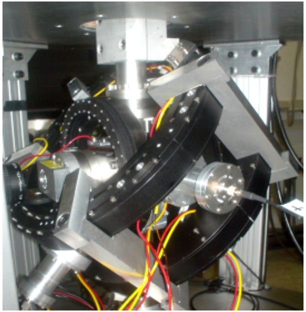
- until now more than 450 drops

- DCK = Delta Kick Cooling
- ARP = Adiabatic Rapid Passage (transfer from $m_F = 2$ to a non-magnetic $m_F = 0$ state)

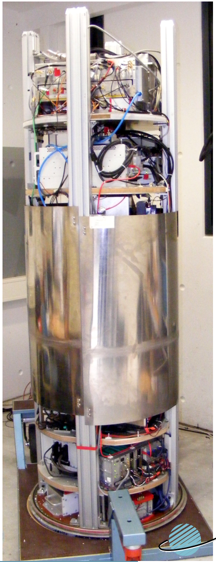
BEC in microgravity



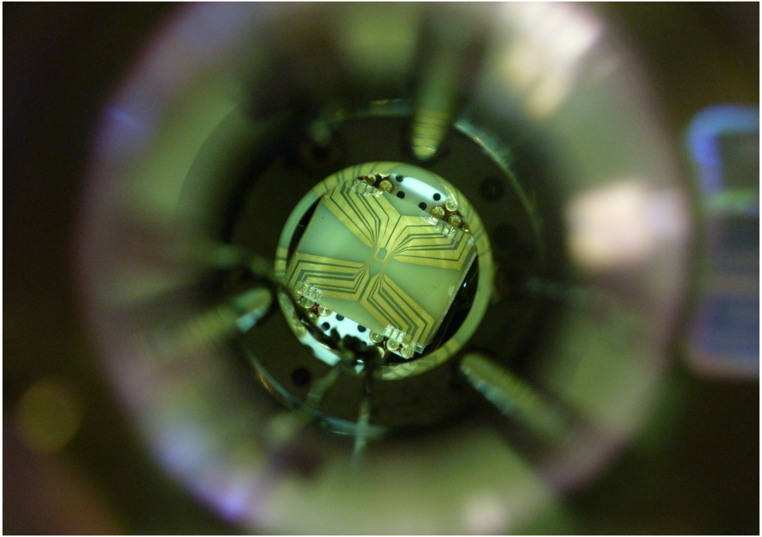
design of capsule



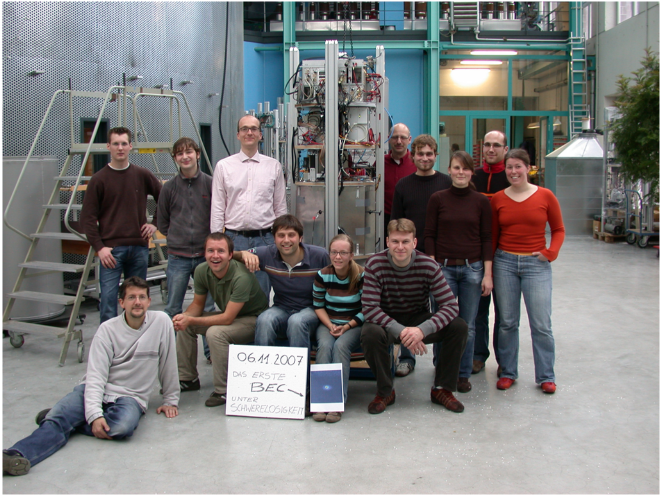
vacuum chamber



QUANTUS I: Atom chip technology



First BEC in microgravity / extended free fall



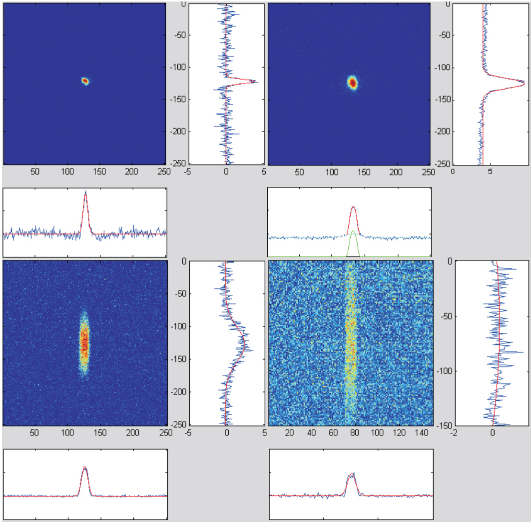
LU Hannover, ZARM, MPQ Munich, U Hamburg, HU Berlin, U Ulm

ZARM

BEC in microgravity – long free evolution

50 ms

100 ms



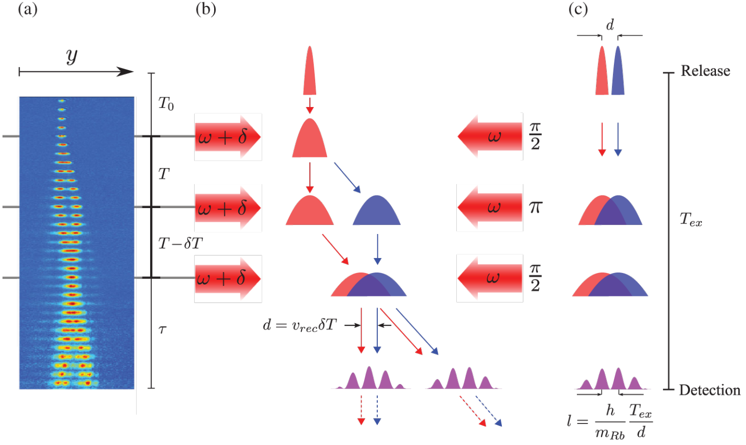
500 ms

1000 ms

ZARM

Interference

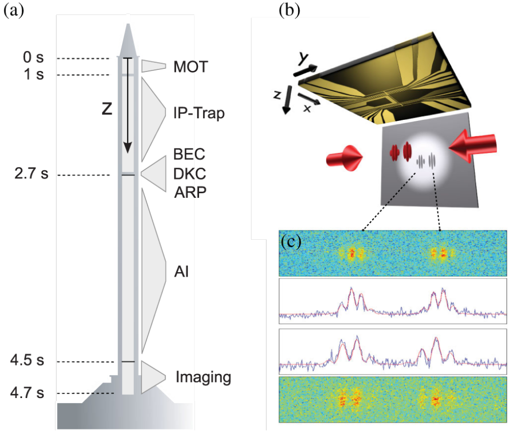
Interference for long time of flight (at the moment $>$ 0.6 s)



Müntinga et al, PRL 2013

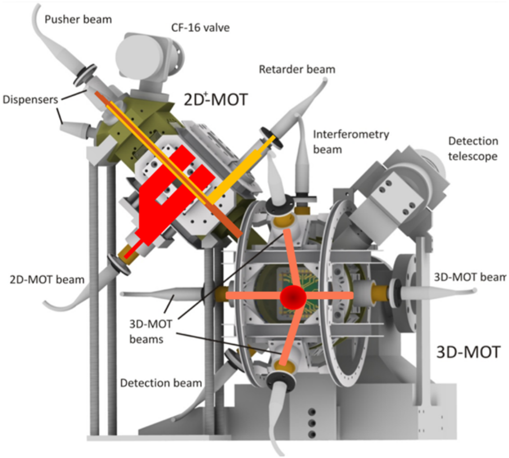
Interference

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



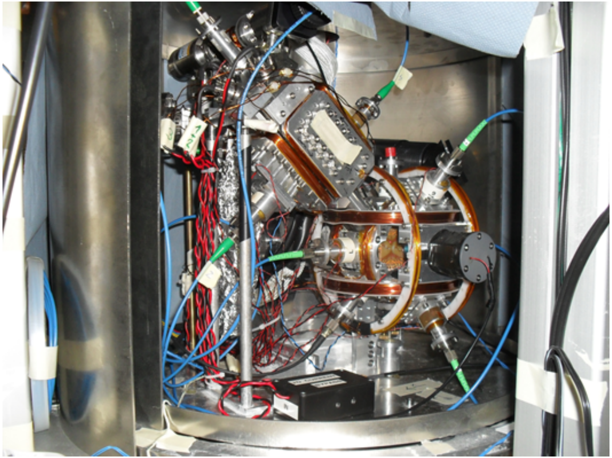
Müntinga et al, PRL 2013

QUANTUS II



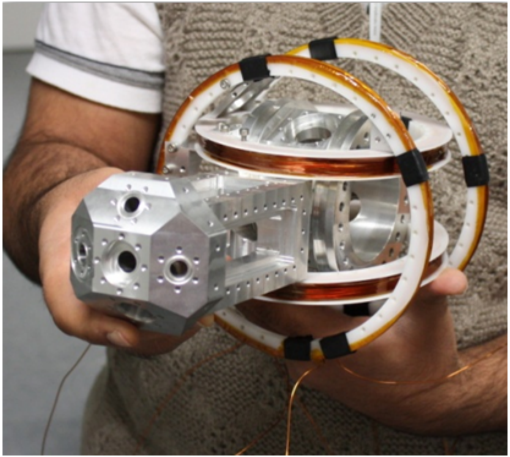
QUANTUS II: further miniaturization

QUANTUS II



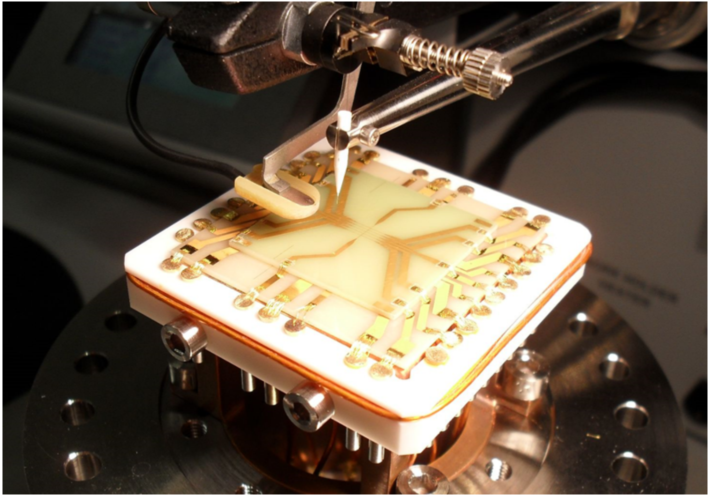
QUANTUS II: further miniaturization

QUANTUS II



QUANTUS II: further miniaturization

QUANTUS II



QUANTUS II: further miniaturization — new generation multilayer atomic chip

QUANTUS II

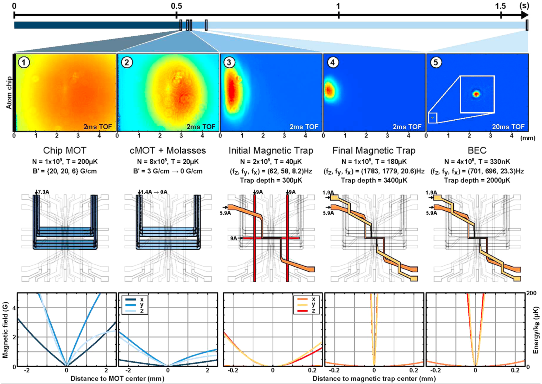
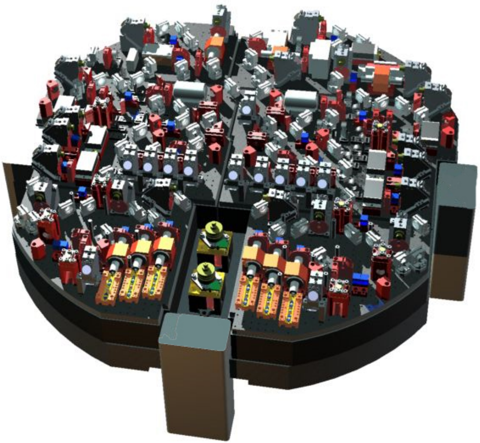


Figure 3. Source scheme to prepare 4×10^5 quantum degenerate atoms in 1.6 s. Five absorption images of the atoms illustrate the steps involved (①–⑤). The chip structures used as well as the magnetic field calculated with a model of the wire structures are shown below the images. (The trap bottom has been substracted for the magnetic traps.) All chip configurations are used in conjunction with external bias fields. ① After 500 ms 1×10^9 atoms are loaded into a MOT generated by the mesoscopic U structure. ② The atoms are compressed and molasses cooled to 20 μK. ③ 2×10^8 atoms can be captured in the initial magnetic trap, formed by the mesoscopic H and a base chip Z structure. ④To improve the evaporation efficiency, the trap is compressed by switching from the mesoscopic H structure to a science chip Z structure, while keeping the base chip Z switched on. ⑤During evaporation to BEC the trap is decompressed once to avoid three-body collisions.

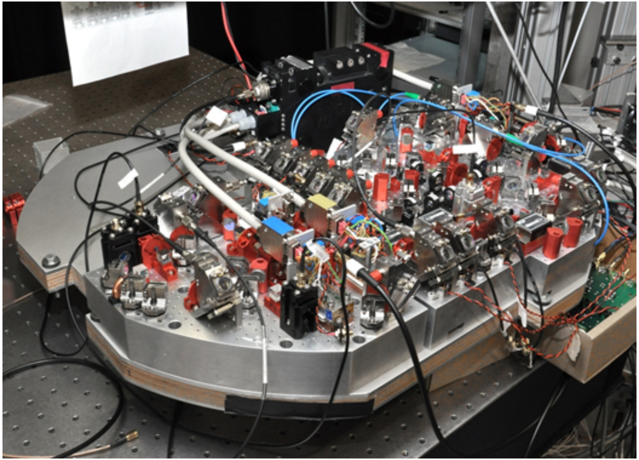
QUANTUS II: further miniaturization — new generation multilayer atomic chip

QUANTUS II



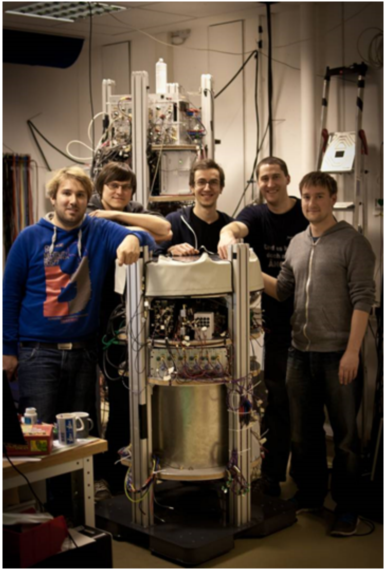
QUANTUS II: further miniaturization — technical scetch

QUANTUS II



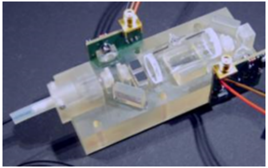
QUANTUS II: further miniaturization — diode laser

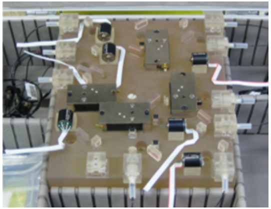
QUANTUS II

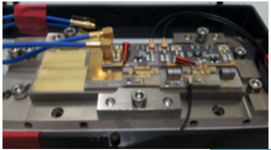


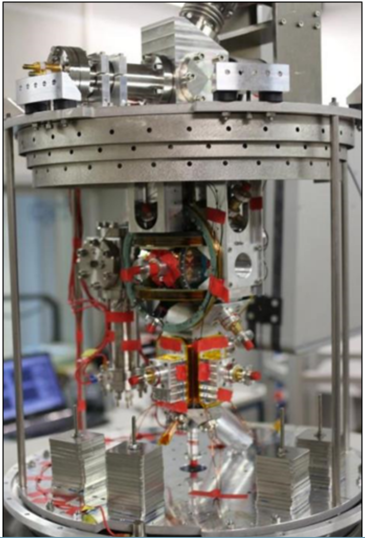
QUANTUS-II = worldwide fastest and largest chip-based BEC

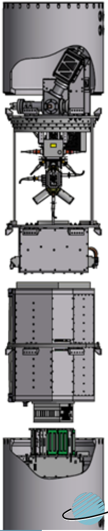
Sounding rocket MAIUS









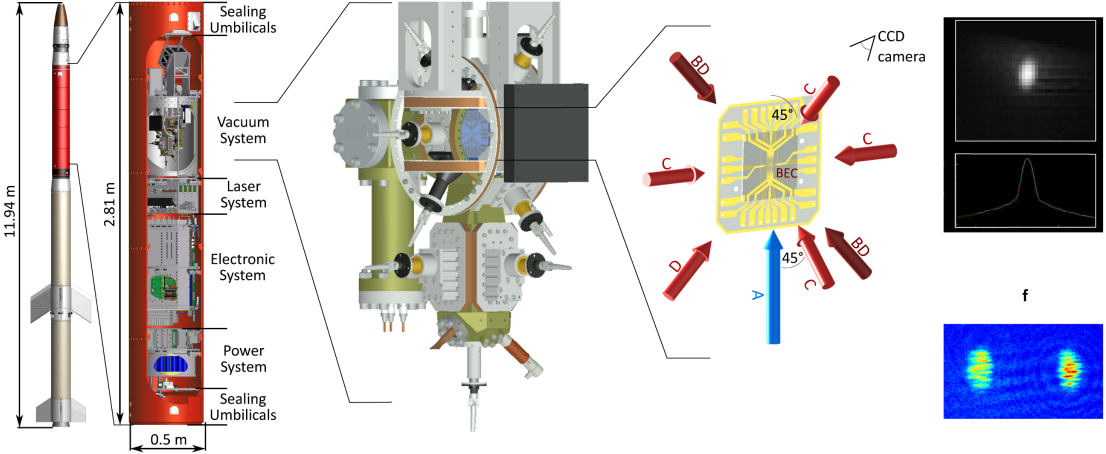


ZARM

Sounding rocket MAIUS

ZARM

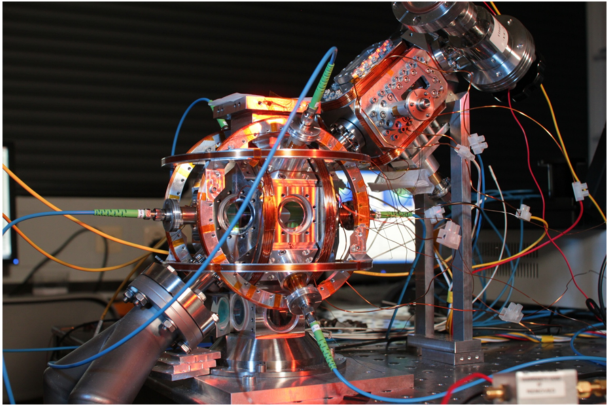
Sounding rocket MAIUS



Becker et al, Nature 2018

The goal: ISS

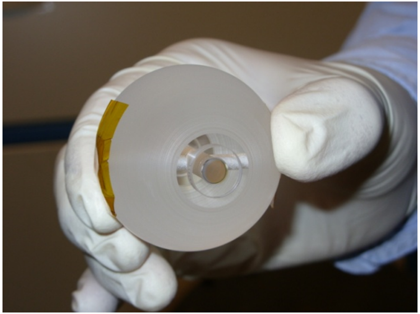
PRIMUS



dipole trap (instead of chip)

PRIMUS metrology

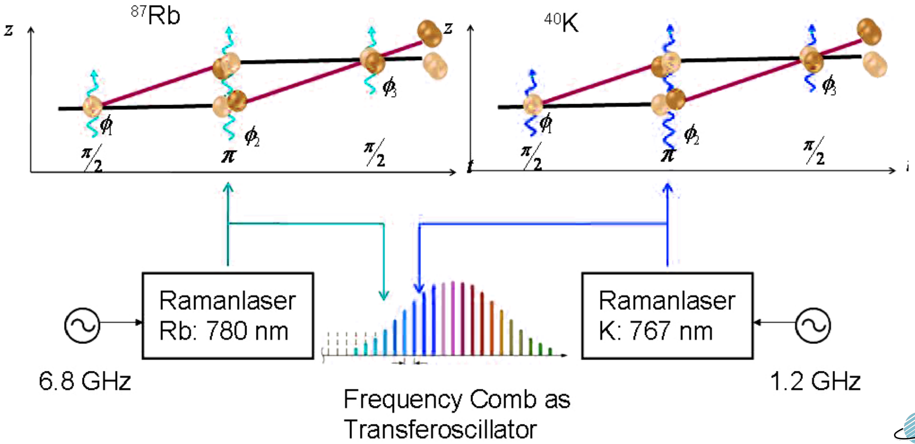
- Frequency comb
  - Remote operation via WLAN
  - Battery powered (24V / 8 A)
  - First drop 4.3.2010
- high finesse optical resonators



ZARM

PRIMUS

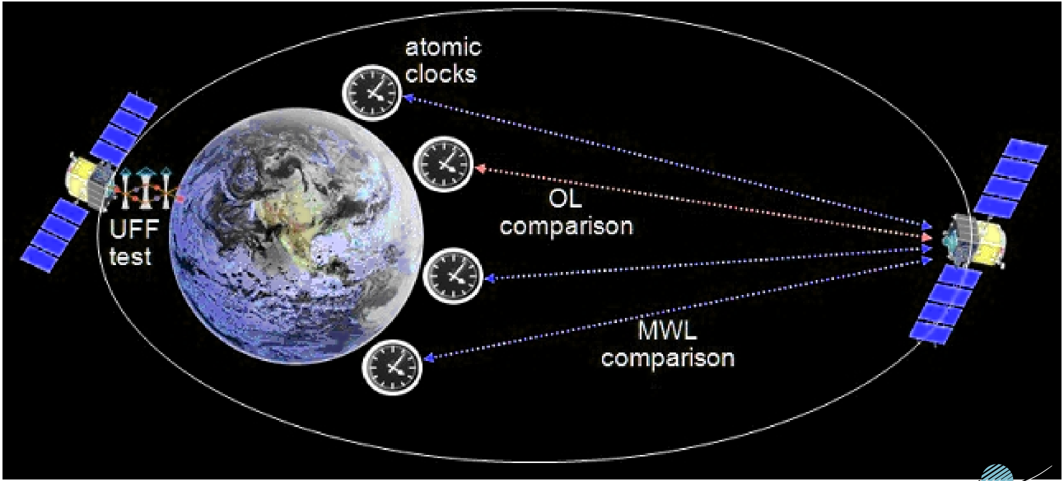
Test of Equivalence Principle with atom interferometry
Phase link between lasers
2–species atom interferometer



ZARM

STE–QUEST

mission scenario



Outline

Summary MAQRO

MAQRO	=	Macroscopic Quantum Resonators
	=	WAX + DECIDE + CASE

WAX	=	Wave function Expansion
DECIDE	=	Decoherence Interference Experiment
CASE	=	Comparative Acceleration Sensing Experiment

Science cases

WAX: searches for fundamental decoherence by means of wave packet spreading

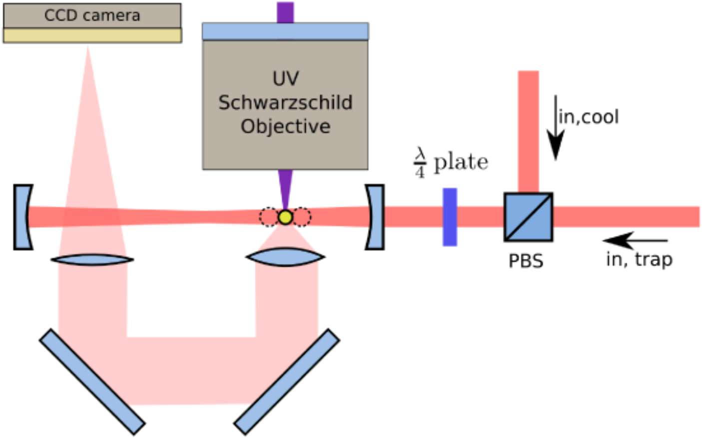
DECIDE: test the predictions of quantum theory for quantum superpositions of macroscopic objects containing more than 10^8 atoms

CASE: demonstrate the performance of a novel type of inertial sensor based on optically trapped microspheres

MAQRO Science cases

- will gravitation lead to modfications of quantum physics for very massive objects? [self gravity at quantum level?]
- are macroscopic quantum superpositions at all possible or are there yet unknown decoherence mechanisms? [quantum to classical tramsition]
- the short de-Broglie wavelength of massive particles can be used for high sensitivity matter wave interferometry with practical applications [practical application]

Setup of MAQRO/DECIDE



ZARM

Outline

ZARM

Decoherence

The model

- model

$$H = \frac{1}{2m}\left(\delta^{ij} + \tilde{\alpha}^{ij} + \gamma^{ij}(t)\right) p_i p_j$$

- discuss now the influence of γ^{ij} and neglect $\tilde{\alpha}^{ij}$
- neglect small x–dependence

Noise model

- isotropic fluctuations $\gamma^{ij}(t) = \sigma\delta^{ij}\xi(t)$
- white noise $\langle\xi(t)\rangle = 0$, $\langle\xi(t)\xi(t')\rangle = \delta(t - t')$
- dimσ^2 = time = τ_c

- practically no influence from colored noise
- $\gamma^{ij}(t)$ random process

Decoherence

Master equation

- stochastic Schrödinger equation in interaction picture

$$i\hbar\frac{d}{dt}\mid\tilde{\psi}\rangle = \tilde{H}_\gamma\mid\tilde{\psi}\rangle\,, \qquad \tilde{H} = e^{\frac{i}{\hbar}H_0 t}H_\gamma e^{-\frac{i}{\hbar}H_0 t}$$

  with random Hamiltonian $\tilde{H}_\gamma$ with $\langle\tilde{H}_\gamma\rangle_t = 0$
- averaging over fluctuations $\Rightarrow$ averaged density matrix

$$\tilde{\rho}(t) = \langle\mid\tilde{\psi}\rangle\langle\tilde{\psi}\mid\rangle$$

- master equation for averaged density matrix to second order in the fluctuations

$$i\hbar\frac{d}{dt}\tilde{\rho} = -\frac{i}{\hbar}\int_0^t\langle[\tilde{H}_\gamma(t),[\tilde{H}_\gamma(t'),\tilde{\rho}(t)]]\rangle dt'$$

ZARM

Decoherence

Markovian master equation

- in Schrödinger picture

$$i\hbar \frac{d}{dt}\rho(t) = [H_0, \rho(t)] + i\hbar(\mathscr{D}\rho)(t)$$

  with

$$(\mathcal{D}\rho)(t) = -\frac{1}{2}[V,[V,\rho(t)]] \qquad \text{with} \qquad V = \frac{\sqrt{\tau_c}}{\hbar}\frac{p^2}{2m}$$

- master equation is in Lindblad form $\Rightarrow$ defines a completey positive quantum–dynamical semigroup
- energy is conserved

- $\mathcal{D}$ is the dissipator

Decoherence

Decoherence time

- solution of master equation in momentum space

$$\rho(p,p',t) = \exp\left(-\frac{i}{\hbar}\Delta E t - \frac{(\Delta E)^2 \tau_c}{2\hbar^2} t\right) \rho(p,p',0)$$

decoherence time

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

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

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

- too large for being observable
- may change for BECs

(Breuer, Göklü & C.L. 2009)

Spreading of wave packets

Model

- dynamics: same model as above

$$H = H_0 + V(x)\,, \qquad V(x) = \mathscr{O}(h\partial\partial h, \partial h \partial h)$$

- V is Gaussian random function

$$\langle V(x)\rangle = 0\,, \qquad \langle V(x), V(x')\rangle = V_0^2 \delta(t-t')g(x-x')$$

The spreading

for Gaussian correlation and Gaussian initial wave packet

$$\langle x^2(t)\rangle = \underbrace{\sigma^2 + \frac{\hbar^2}{4m^2\sigma^2(0)}t^2}_{\text{free evolution}} + \underbrace{\frac{5V_0^2}{\sqrt{2\pi}m^2a^7}t^3}_{\text{superdiffusion}}$$

Self gravity

Non-relativistic self gravity (e.g. Giulini & Grossardt)

$$i\hbar\dot{\psi} = -\frac{\hbar^2}{2m}\Delta\phi + mU\psi\,, \qquad \Delta U = 4\pi G\bar{\psi}\psi$$

Relativistic self gravity (Boson stars, Kunz et al)

$$0 = \psi + m^2\psi + V(\psi)\,, \qquad R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \kappa T_{\mu\nu}(\psi)$$

- Experimental realization of Boson stars (needs high density)
  - Spherically symmetric configurations
  - Rotating configurations
- Interference of two self-gravitating objects

ZARM

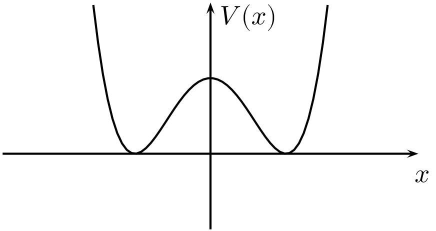
Semiclassical Einstein equations

Semiclassical Einstein equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \kappa \langle \psi \mid \widehat{T}_{\mu\nu} \mid \psi \rangle$$

Symmetrized and antisymmetrized states in double-well potential

$$\mid \psi_\pm \rangle = \frac{1}{\sqrt{2}} \left(\mid \psi_1 \rangle \pm \mid \psi_2 \rangle \right)$$



- Symmetrized and antisymmetrized states have same spatial density $\| \mid \psi_+ \rangle \| = \| \mid \psi_- \rangle \|$
- Symetrized and antisymmetrized states create different gravitational field: $\langle \psi_+ \mid \widehat{T}_{\mu\nu} \mid \psi_+ \rangle \neq \langle \psi_- \mid \widehat{T}_{\mu\nu} \mid \psi_- \rangle$
- Gravitational field can be probed by slow atoms ($v \sim 1\ mm/s$)

(Peres & Lindner, PRA 2004)

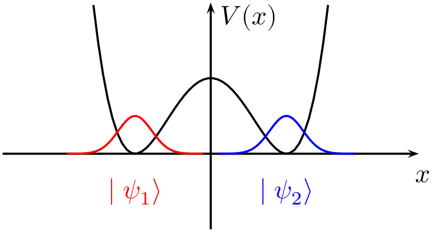
Semiclassical Einstein equations

Semiclassical Einstein equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \kappa \langle \psi \mid \widehat{T}_{\mu\nu} \mid \psi \rangle$$

Symmetrized and antisymmetrized states in double-well potential

$$\mid \psi_\pm \rangle = \frac{1}{\sqrt{2}} \left(\mid \psi_1 \rangle \pm \mid \psi_2 \rangle \right)$$



- Symmetrized and antisymmetrized states have same spatial density $\| \mid \psi_+ \rangle \| = \| \mid \psi_- \rangle \|$
- Symetrized and antisymmetrized states create different gravitational field: $\langle \psi_+ \mid \widehat{T}_{\mu\nu} \mid \psi_+ \rangle \neq \langle \psi_- \mid \widehat{T}_{\mu\nu} \mid \psi_- \rangle$
- Gravitational field can be probed by slow atoms ($v \sim 1\ mm/s$)

(Peres & Lindner, PRA 2004)

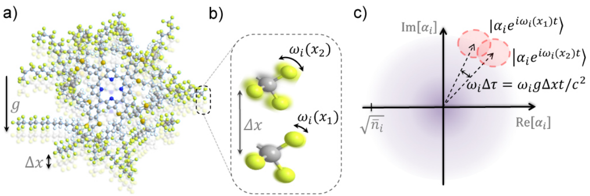
Outlook - further issues

Quantum time

- Is the Compton frequency of an atom a clock? “A rock as a clock” (Müller, Peters, Chu, Nature 2010)

Decoherence

- decoherence of extended quantum states through position-dependent time dilation (Pikovski et al., Nat.Phys. 15. June (2015))



Outline

ZARM

Summary

What is special of quantum mechanics and gravity?

- uniqueness of quantum matter – no need for prototypes
- uniqueness of coupling (passive and active)

Practical applications of quantum devices, some with huge impact on the society

- geodesy, reference frames ($\rightarrow$ talk of Jürgen Müller)
- positioning
- metrology, TAI
- quantum cryptography (quantum internet)
- quantum computing
- wide range of quantum sensors

Advantage of space for

- quantum sensors
- quantum metrology

Summary

What is special of quantum mechanics and gravity?

- uniqueness of quantum matter – no need for prototypes
- uniqueness of coupling (passive and active)

Practical applications of quantum devices, some with huge impact on the society

- geodesy, reference frames ($\rightarrow$ talk of Jürgen Müller)
- positioning
- metrology, TAI
- quantum cryptography (quantum internet)
- quantum computing
- wide range of quantum sensors

Advantage of space for

- quantum sensors
- quantum metrology

Quantum devices provide the technology of the 21st century

ZARM

Thank you for your attention

Thanks to

- Hansjörg Dittus
- Christoph Günther
- Eva Hackmann
- Sven Herrmann
- Meike List
- Fritz Merkle
- Jürgen Müller
- Hauke Müntinga
- Volker Perlick
- Ernst Rasel
- Benny Rievers
- Piet Schmidt

- Center of Excellence “Quantum Frontiers”
- DFG Research Training Group ”Models of Gravity”
- DFG Collaborative Research Center ”Relativistic Geodesy” *geo*-Q
- DFG Collaborative Research Center ”Designed Quantum States of Matter” DQ-*mat*
- German Research Foundation DFG
- German Space Agency DLR
- European Space Agency ESA
- Center of Excellence QUEST
- ERASMUS MUNDUS
- IRAP-PhD
- German Israeli Foundation

ZARM