Gravity subject to closer scrutiny: New experimental tests

Claus Lämmerzahl
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DFG
Research Training Group
Graduiertenkolleg
Models of Gravity

Universität Bremen*
*EXZELLENT.
Gewinnerin in der
Exzellenzinitiative

CENTER OF
APPLIED SPACE TECHNOLOGY
AND MICROGRAVITY
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Outline

General Relativity

- The geometrical structure
- The gravitational field equations

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Consequences and tests

- Weak field consequences
- The strong gravity regime
- Further consequences

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- MICROSCOPE: Universality of Free Fall
- Quantum tests: QUANTUS, PRIMUS, MAIUS, STE-QUEST, MAQRO, ...
- Galileo: Gravitational redshift
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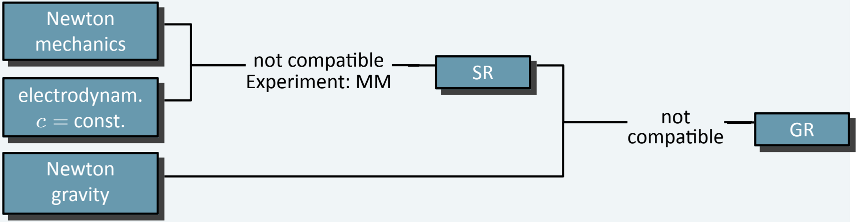
Summary and outlook

On the development of General Relativity

Historical embedding / development of relativistic theories



Meaning of GR

- very small effects on Solar system scale: perihelion shift, light deflection, redshift, gravitational time delay, Schiff effect, Lense-Thirring effect, ...
- if one takes serious the equation for GR: Black Holes – now convincing evidence for their existence $\rightarrow$ triumph of theory !!!
- then perhaps also time travel, worm holes, ... ?

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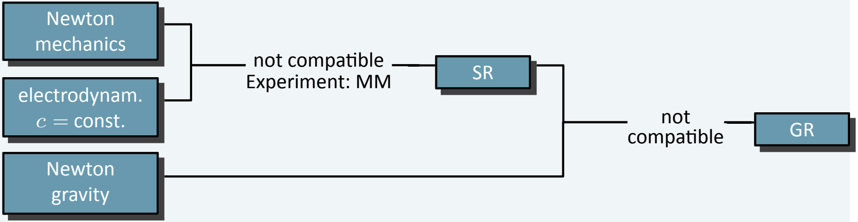

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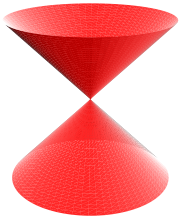
Gravitation

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 $\to$ metric structure, locally Special Relativity
- **Universality of Free Fall**

there exists a coordinate system so that for all particles

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

- bulk matter, Schlamminger et al, 2003: $\eta \leq 10^{-13}$, MICROSCOPE $\eta \leq 10^{-15}$
- spin matter
- charged matter
- anti-matter

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Gravitation

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

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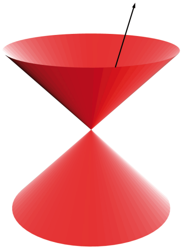
- **Universality of Free Fall**
- **Compatibility** no superluminal velocity



$v < c$

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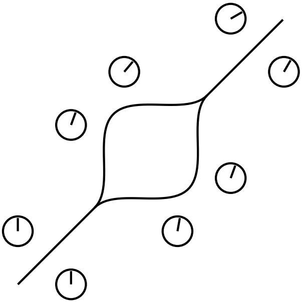
- **Uniqueness of time-keeping** or uniqueness of quantum mechanics or **Local Position Invariance**



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

many different clock tests $\alpha \leq 10^{-4}$

anti clocks, Galileo

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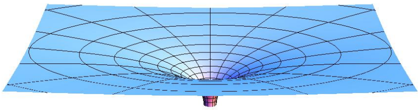

Einstein Equivalence Principle

Gravitation

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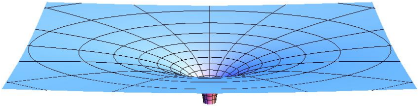

Einstein Equivalence Principle

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

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

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Summary and outlook

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

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

variation

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

- One major consequence: Black Holes

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Formalism

- equation for the **gravitational field**: Einstein equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- **equation of motion** of a pointlike particle moving in the gravitational field: geodesic equation

$$0 = \frac{d^2 x^\mu}{ds^2} + \left\{ {}^{\,\mu}_{\rho\sigma} \right\} \frac{dx^\rho}{ds} \frac{dx^\sigma}{ds}$$

  $\left\{ {}^{\,\mu}_{\rho\sigma} \right\}$ is the Christoffel symbol, and $ds = \sqrt{g_{\mu\nu} dx^\mu dx^\nu}$
  extended particles: Mathisson-Papapetrou-Dixon equations
- **clock reading** = proper time

$$s = \int ds$$

  operationally defined through standard clocks (Perlick, GRG 1987), approximately realized by atomic clocks

Tests of consequences

- effect on light rays
  - light deflection (VLBI, Gaia) Eddington
  - lensing Twin Quasar Q0957+561
  - shadows of black holes (EHT)
- orbital effects
  - perihelion shift (Mercury) Le Verrier
  - Lense-Thirring effect: spin-orbit coupling (LAGEOS) Ciufolini
  - back reaction effects (binary systems) Hulse-Taylor, grav. waves
- effects on extended bodies
  - Schiff effect: spin-spin coupling (GP-B) Everitt
- clock effects / effects on frequency
  - gravitational redshift Pound-Rebka, GP-A
  - gravitational time delay Cassini

+ all special relativistic effects: time dilation, Doppler effect, Sagnac effect, length contraction, aberration, ...

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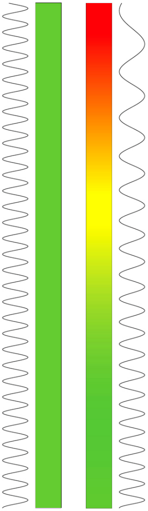
Consequences for gravitation

light effects

- gravitational redshift
  Pound & Rebka, GP A



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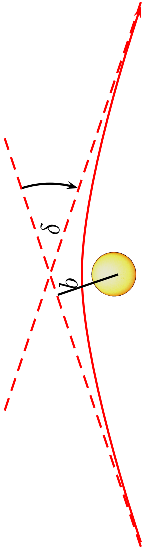

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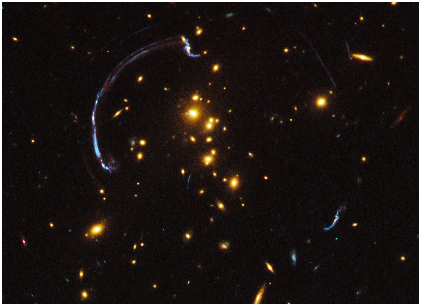

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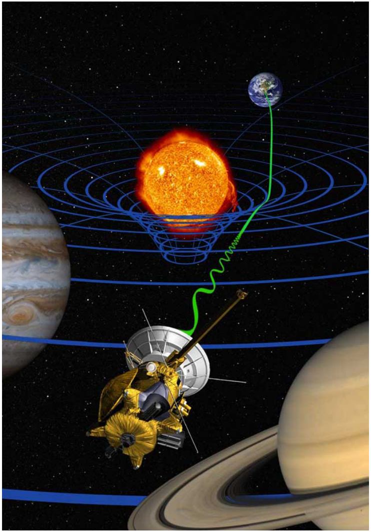

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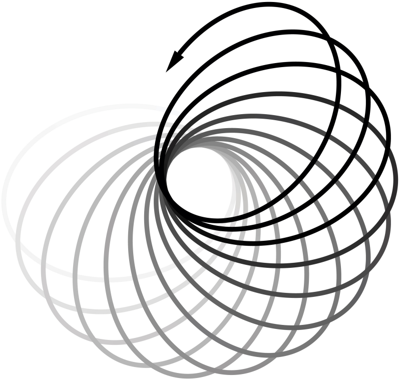
orbital effects for particles

- perihelion shift
  le Verrier



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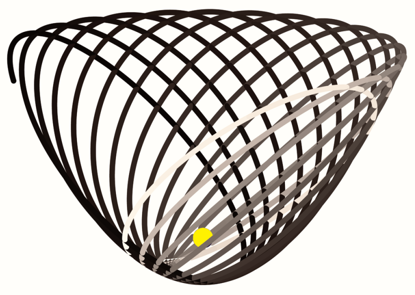

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extended objects, continua

- Schiff effect
  Everitt et al 2012

Mathisson-Papapetrou-Dixon

$$\begin{aligned} D_v p^\mu &= R^\mu{}_{\nu\rho\sigma} v^\nu S^{\rho\sigma} \\ &\qquad + D_\mu R_{\rho\sigma\tau\kappa} J^{\rho\sigma\tau\kappa} \\ D_v S^{\mu\nu} &= v^\mu p^\nu - v^\nu p^\mu \end{aligned}$$

supplementary condition

$$p(S) = 0 \qquad \text{or} \qquad g(S, v) = 0$$

or others

extremely complicated to solve
one example Hackmann, C.L., Obukhov, Puetzfeld, Schaffer, PRD 2015

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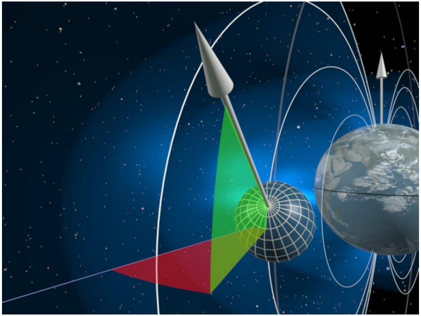

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all tests are confirming GR to the order of $10^{-4} - 10^{-5}$

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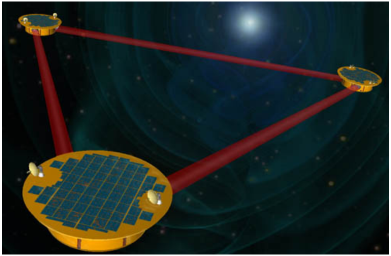
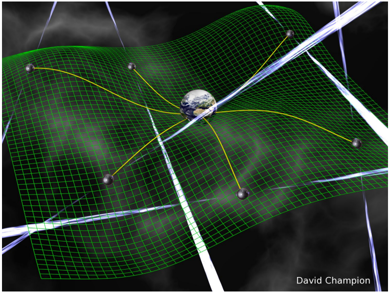
Black Hole observations

- gravitational wave interferometers or PTA: merger of BHs
  gravitational wave detection





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- gravitational wave interferometers or PTA: merger of BHs
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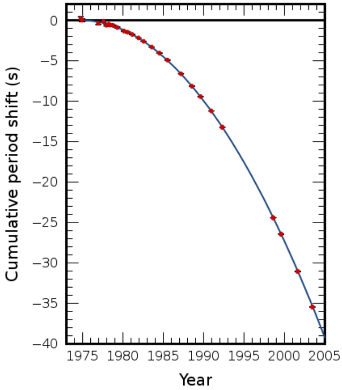
- backreaction – indirect proof of existence of gravitational waves
  Hulse & Taylor

increase of orbiral frequency of binaries



Hulse-Taylor binary

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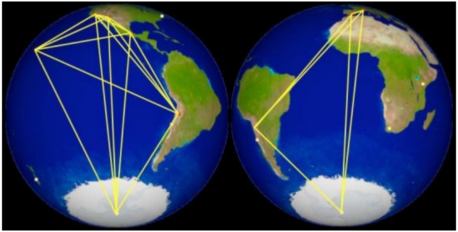

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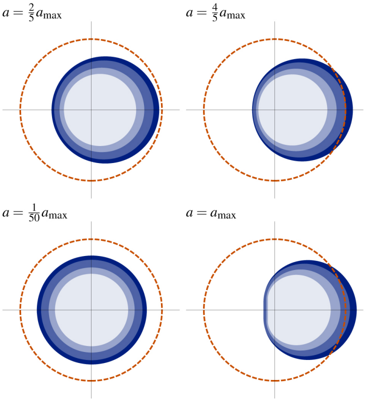

Grenzebach, Perlick, C.L., PRD 2014

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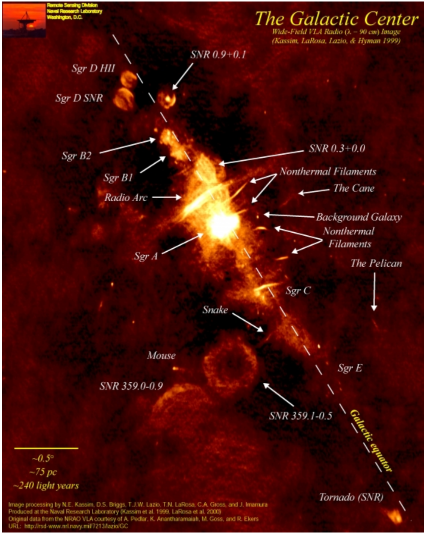

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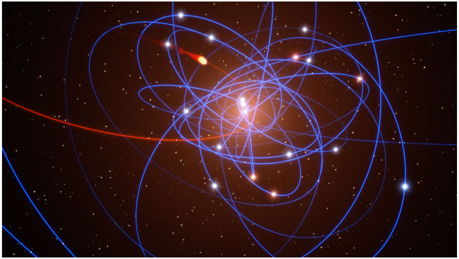

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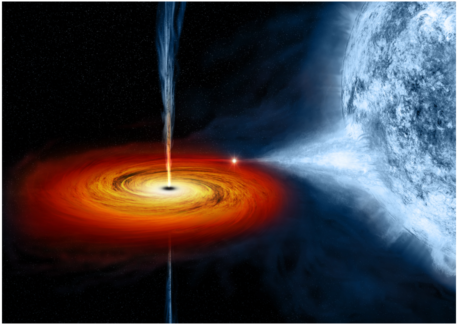

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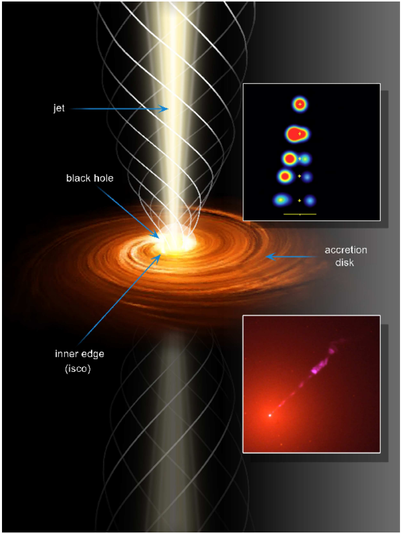

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Physics of Black Holes

Questions, what can one do with the observations?

- spin of Black Holes

in standard theory: maximum spin of Black Hole

$$S_{\text{max}} = \frac{GM^2}{c}$$

then spin parameter should obey

$$\chi = \frac{cS}{GM^2} \leq 1$$

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Physics of Black Holes

Questions, what can one do with the observations?

- spin of Black Holes
- no-hair theorem

- in GR Black Holes are characterized by mass M, spin a, and charge Q only
- violations are possible in generalized theories of gravity

Physics of Black Holes

Questions, what can one do with the observations?

- spin of Black Holes
- no-hair theorem
- alternative gravity theories

e.g. Gauss-Bonnet, based on Lagrangian

$$
\begin{aligned}
L &= R - \tfrac{1}{2}\partial_\mu \phi \partial^\mu \phi + \alpha e^{-\gamma\phi} R_{\text{GB}} \\
R_{\text{GB}} &= R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} - 4 R_{\mu\nu} R^{\mu\nu} + R^2
\end{aligned}
$$

α Gauss-Bonnet, γ dilaton
Comparison with Kerr:

- EGBd BHs have $\chi > 1$
- EGBd BHs have smaller horizon area than Einstein BHs (except for large J/M^2)
- EGBd BHs have larger temperature than Einstein BHs
- test particles have larger ISCOs
- test particles have smaller orbital frequency

Physics of Black Holes

Questions, what can one do with the observations?

- spin of Black Holes
- no-hair theorem
- alternative gravity theories
- alternative matter models
  - Boson stars
  - neutrino balls
  - gravastars
  - Planck stars
  - regular Black Holes, e.g. from nonlinear electrodynamics

Boson stars (Kunz, Kleihaus, List, C.L., Schroven)

$$L = R + \partial_\mu \phi \partial^\mu \phi + V(\phi)$$

e.g. Ayon-Beato-Garcia regular Black Hole

$$g_{00} = 1 - \frac{2Mr^2}{(r^2 + Q^2)^{\frac{3}{2}}} + \frac{Q^2 r^2}{(r^2 + Q^2)^2}$$

explored through geodesics Garcia, Hackmann, Kunz, C.L., Macias 2015

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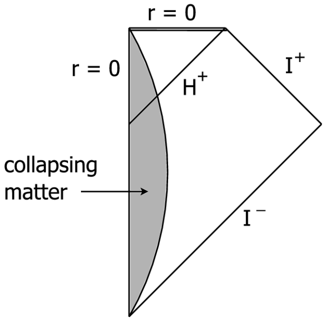

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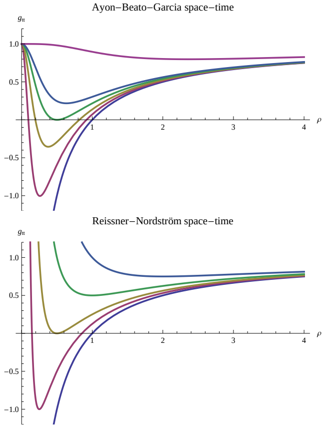
- role of singularity (BH without singularity)

Ayon-Beato & Garcia PRL 1998



other approach Klinkhamer 2013

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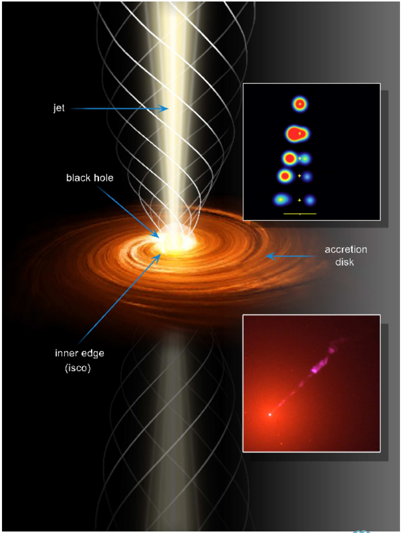
- Black Holes in nontrivial environment



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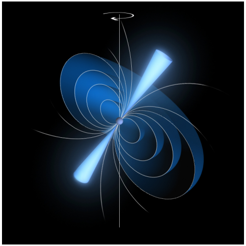
Physics of Neutron Stars

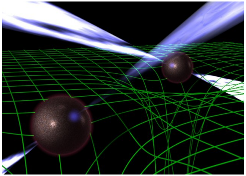
gravitational properties

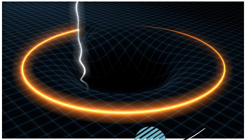
- gravitational field of a neutron star
- deformation in external gravitational field
- influences motion through Mathisson-Papapetrou-Dixon equations
- influences creation of gravitational waves

properties of neutron stars

- cooling
- maximum mass
- quasi-periodic oscillations
- glitches
- creation of X-ray and Gamma Ray Bursts







ZARM

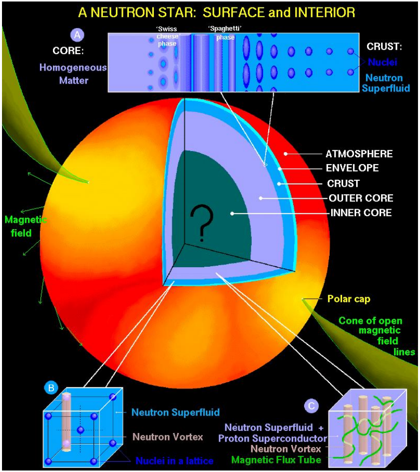
Physics of Neutron Stars

all depends on

- structure
- elasticity moduli
- specific heat
- thermal conductivity
- neutrino emissivity
- equation of state

this depends on **matter model**

all this can be explored through the motion of the neutron stars and the emitted gravitational waves



Outline

General Relativity

- The geometrical structure
- The gravitational field equations

Consequences and tests

- Weak field consequences
- The strong gravity regime
- Further consequences

Big open questions

New tests

- MICROSCOPE: Universality of Free Fall
- Quantum tests: QUANTUS, PRIMUS, MAIUS, STE-QUEST, MAQRO, ...
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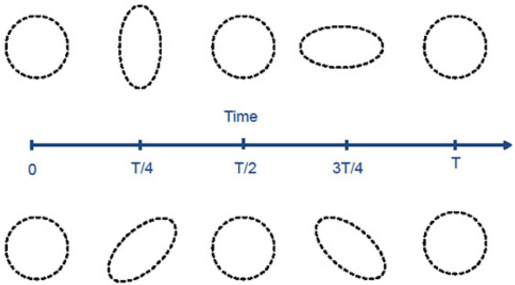
Summary and outlook

Further consequences for gravitation

gravitational waves

- from BH-BH binaries (clean test of BH physics)
- from BH-NS binaries (clean test of NS physics)
- from NS-NS binaries



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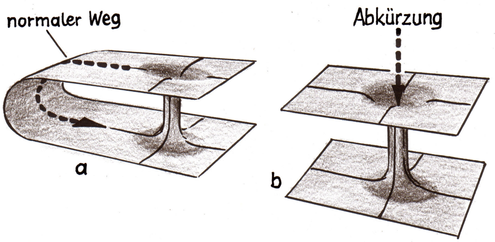
local solutions

- wormholes



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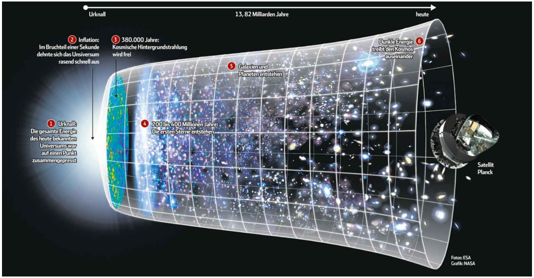
- wormholes

global solutions

- cosmology



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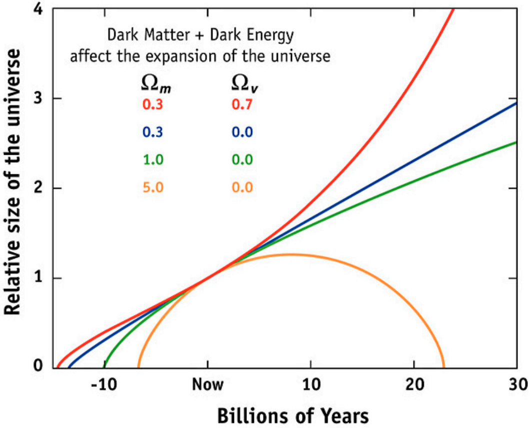
- wormholes

global solutions

- cosmology
- big bang



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Summary and outlook

Inconsistencies between GR and quantum mechanics

singularities: general prediction of GR – singularity theorems

- GR: pointlike singularities – black holes, big bang
- QM: uncertainty relation forbids point-like phenomena

notion of time

- QM: time is external parameter
- GR: time is dynamical

information paradox

- objects disappear in black hole
- Hawking radiation thermal

zero point energy

- QM: zero point energy (Casimir effect)
- GR: all sorts of energy are source of the gravitational field
- problem of cosmological constant

structural inconsistency

- GR is local
- QM is global

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structural inconsistency

- GR is local – nonlocal generalization? Mashhoon, Hehl
- QM is global

Open problems

general fundamental problems

- quantum to classical transition
- fundamental decoherence, measurement process
- equivalence principle (inertia = weight = gravitating mass)
- constancy of constants

“technical” problems

- renormalization
- self force
- QFT in curved space-time

“smoking guns”

- Dark Matter
- Dark Energy

still to understand completely

- Black Holes
- Neutron stars
- Cosmic rays

ZARM

Outline

ZARM

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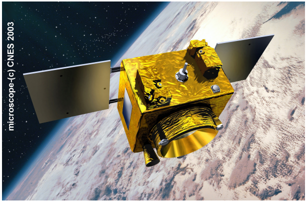
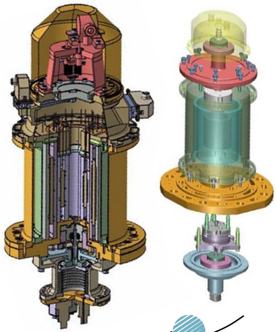
Summary and outlook

MICROSCOPE: The Mission

- French space mission with participation of CNES, ESA, ZARM and PTB
- Mission goal: Test of Equivalence Principle with an accurary of $\eta = 5 \cdot 10^{-16}$
- 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
- modeling





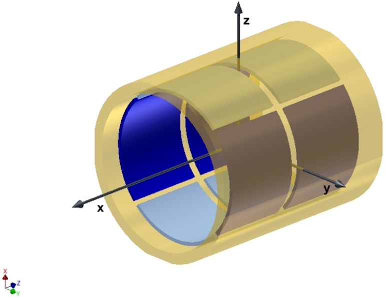
Universality of Free Fall in space

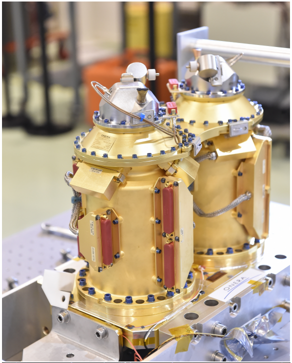
First data evaluation as SWG member

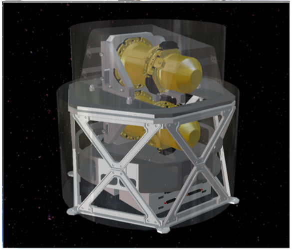
video

Main payload T-SAGE

- developed and built by ONERA
- two differential acceleromters, each containing two test masses
- test mass made by PTP
- each test mass is controlled by 18 electroides







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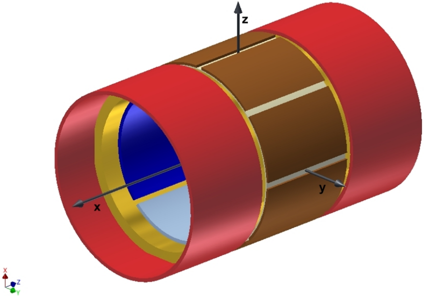
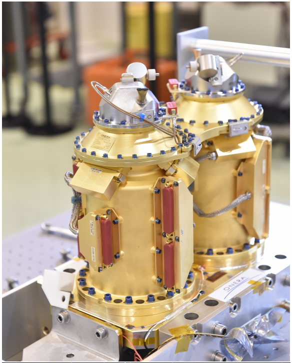
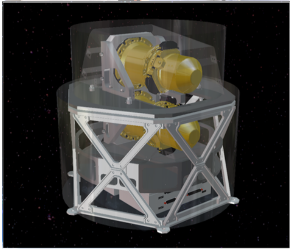


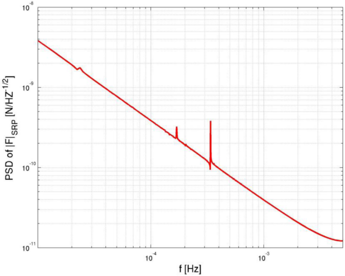


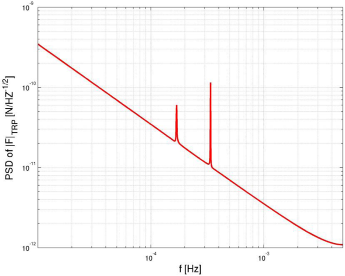


ZARM

Disturbances

- Solar radiation pressure
- thermal radiation pressure





through the rotation the UFF-violating signal can be shifted in frequency space

MICROSCOPE Group:
Stefanie Bremer, Meike List, Benny Rievers, Hanns Selig, C.L.

Disturbances

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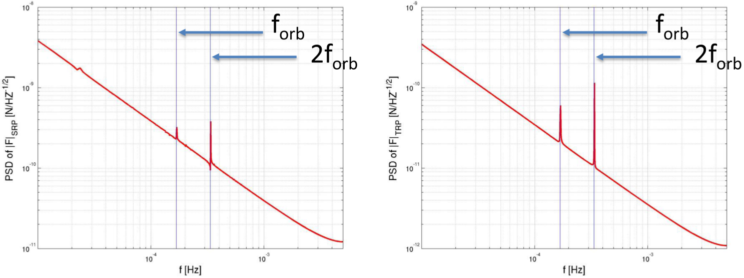

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Summary and outlook

Theory

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)

$$\boxed{\delta\phi = \qquad k \cdot g\ T^2}$$

- neutron interf. (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

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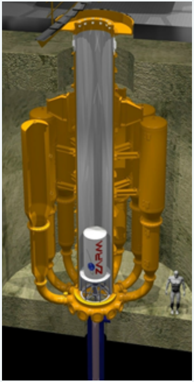
QUANTUS facilities

QUANTUS I

4.7 s

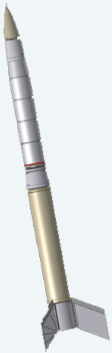
QUANTUS II

9.3 s



MAIUS

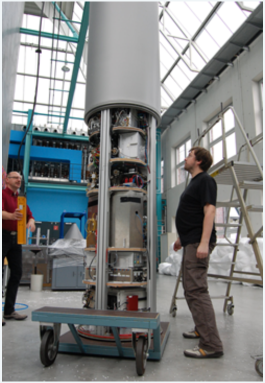
$\sim$ 5 min



QUANTUS apparatuses

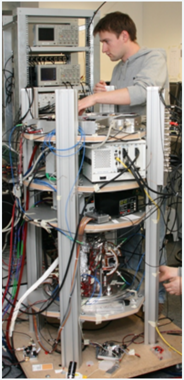
QUANTUS I

4.7 s



QUANTUS II

9.3 s



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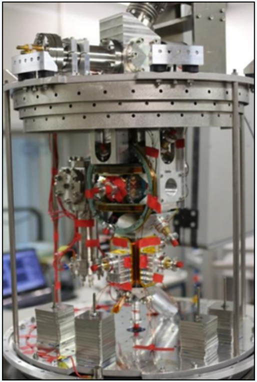
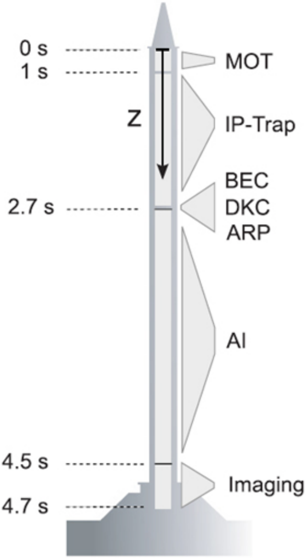


Preparation of BEC in the drop tower



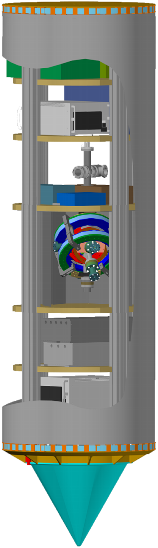
- 10^7 atoms in MOT
- $5 \cdot 10^6$ atoms in magnetic trap
- ~ 1.5 s evaporation cooling
- 10^4 atoms in BEC
- 10 – 30 Hz trap frequency
- T = 9 nK (kinetic energy)
- $F = 2, m_F = 0$ state

- until now more than 450 drops

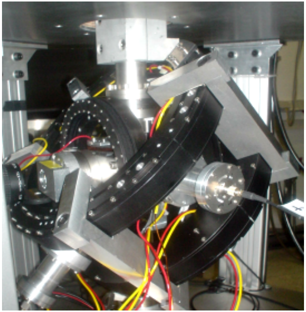
- DCK = Delta Kick Cooling
- ARP = Adiabatic Rapid Passage (transfer from $m_F = 2$ to a non-magnetic $m_F = 0$ state)

ZARM

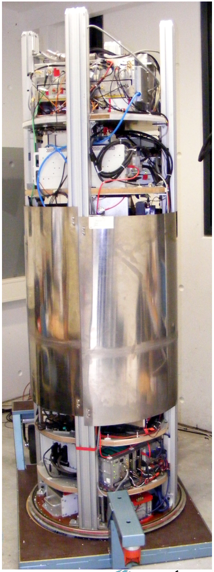
BEC in microgravity



design of capsule

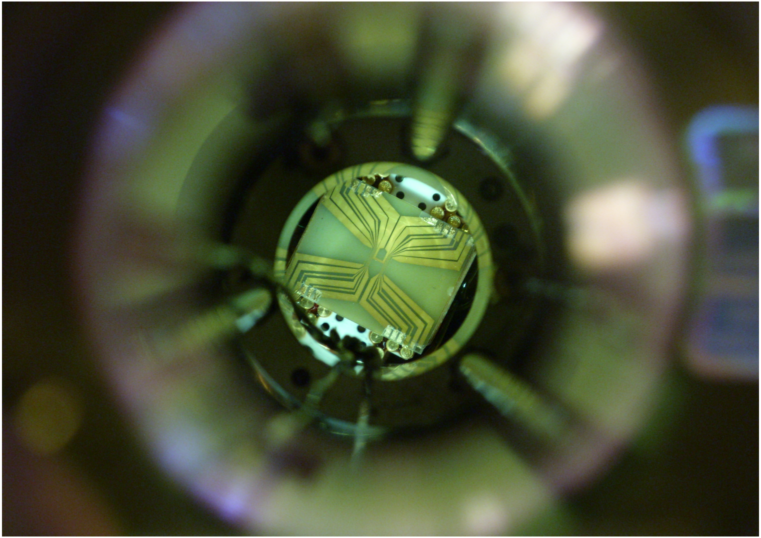


vacuum chamber



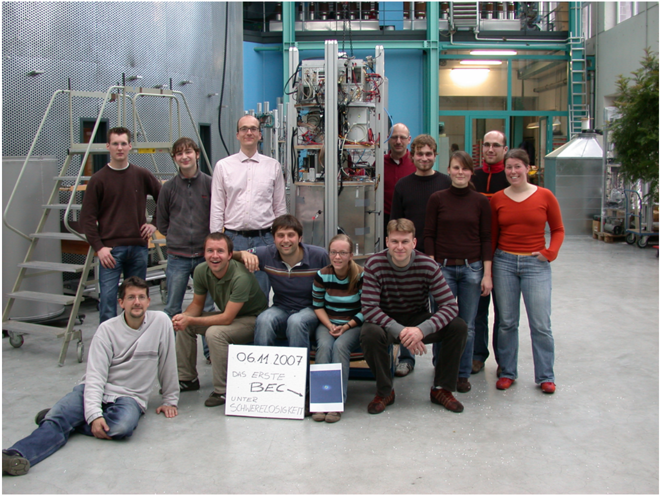
capsule

QUANTUS I: Atom chip technology



ZARM

First BEC in microgravity / extended free fall

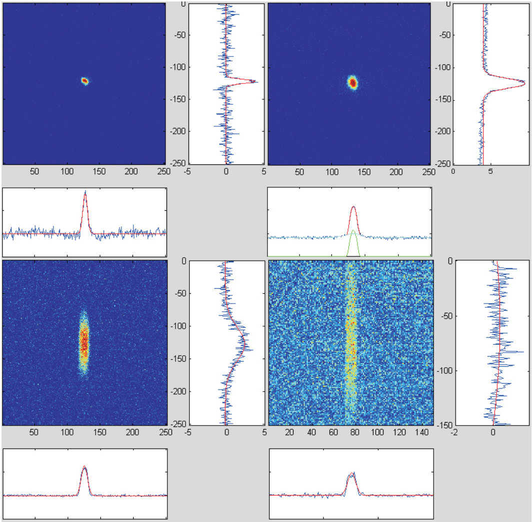


LU Hannover, ZARM, MPQ Munich, U Hamburg, HU Berlin, U Ulm

BEC in microgravity – long free evolution

50 ms

100 ms



500 ms

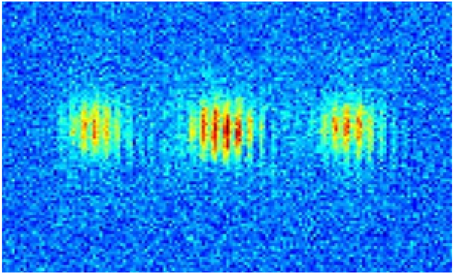
1000 ms

10^4 atoms, 1 s free evolution time, van Zoest et al, Science 2010

ZARM

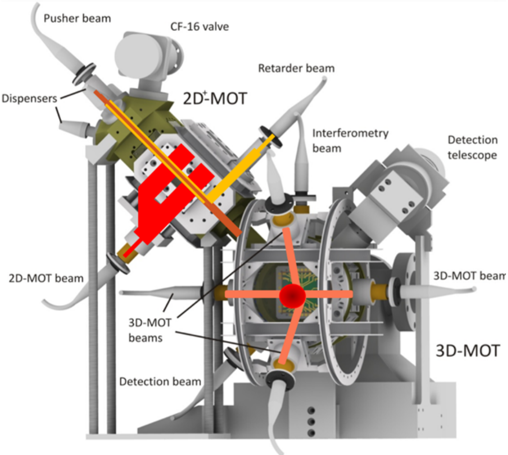
Interference

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



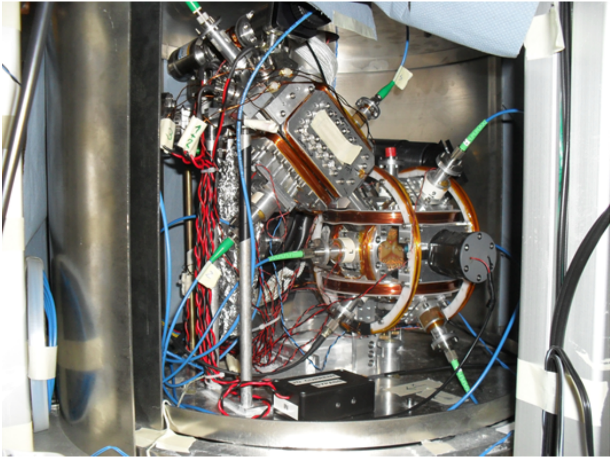
Müntinga et al, PRL 2013

QUANTUS II



QUANTUS II: further miniaturization

QUANTUS II



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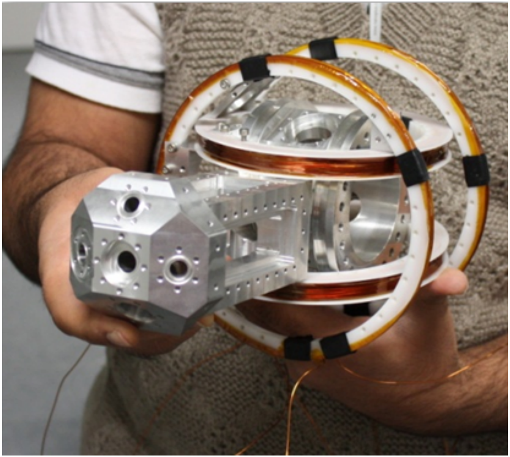

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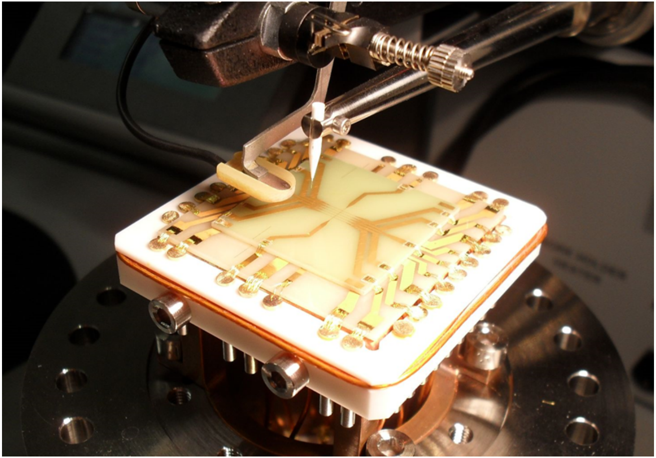
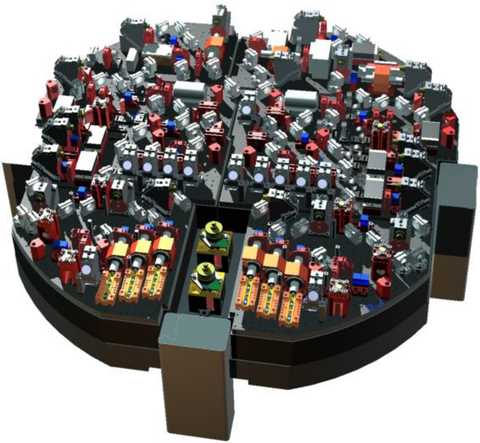


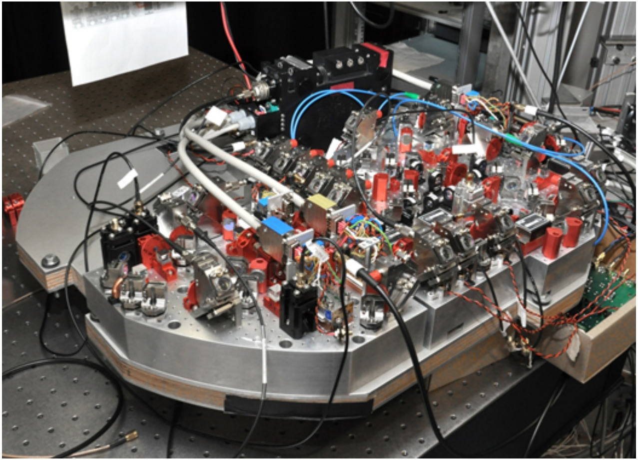
QUANTUS II: further miniaturization — new generation multilayer atomic chip

QUANTUS II



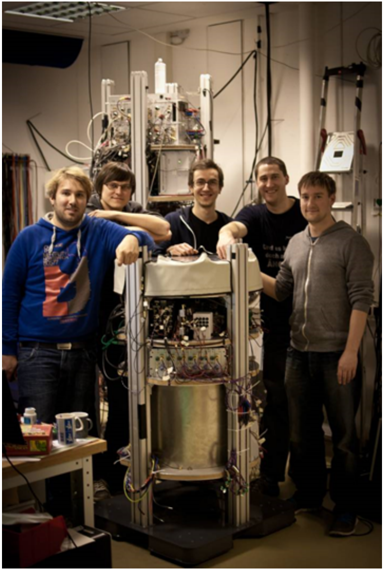
QUANTUS II: further miniaturization — technical scetch

QUANTUS II



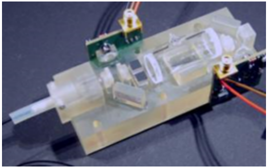
QUANTUS II: further miniaturization — diode laser

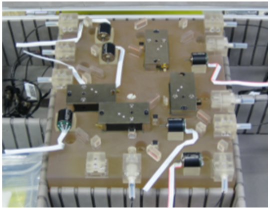
QUANTUS II

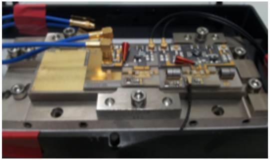


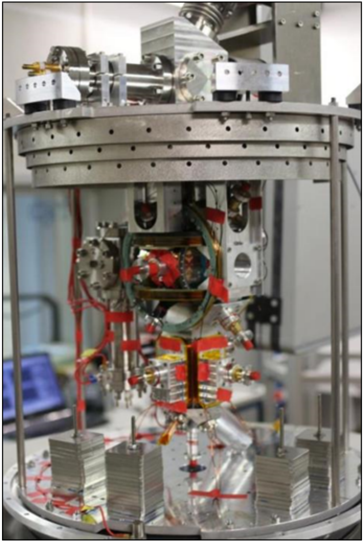
QUANTUS-II = worldwide fastest and largest chip-based BEC

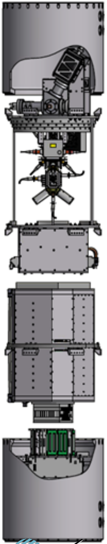
Sounding rocket MAIUS







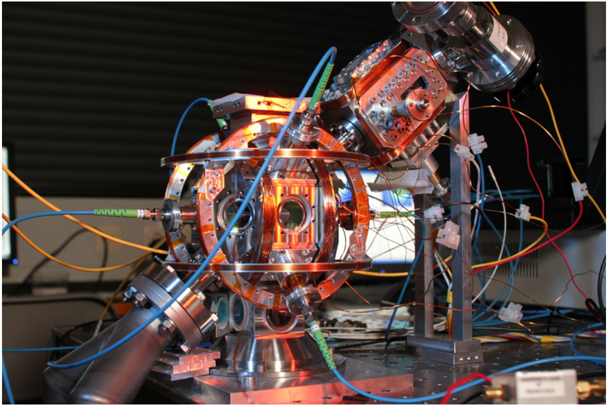




Sounding rocket MAIUS

The goal: ISS

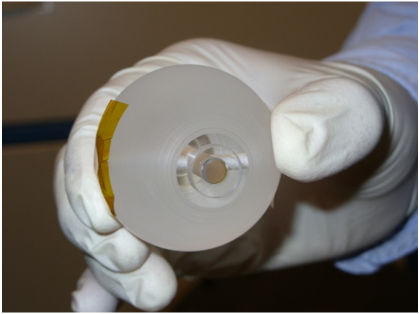
PRIMUS



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



Possible experiments with cold atoms

fundamental research

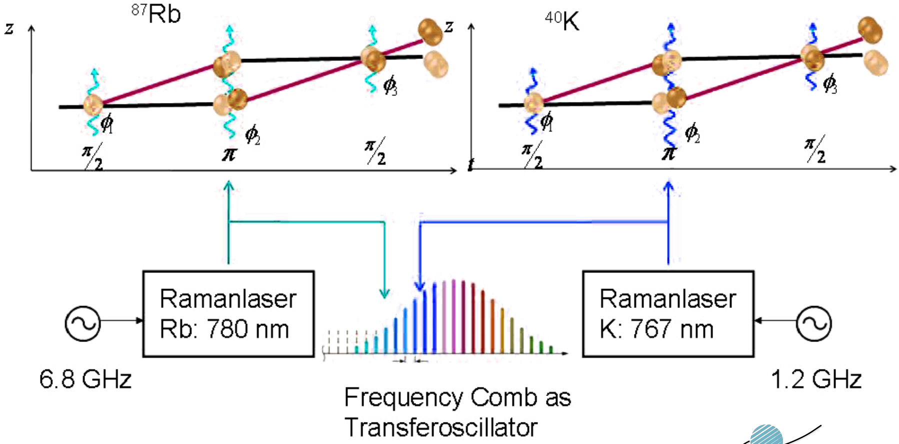
- test of quantum principles
- quantum tests of gravity
- search for quantum gravity effects

applications

- geodesy
- inertial sensors

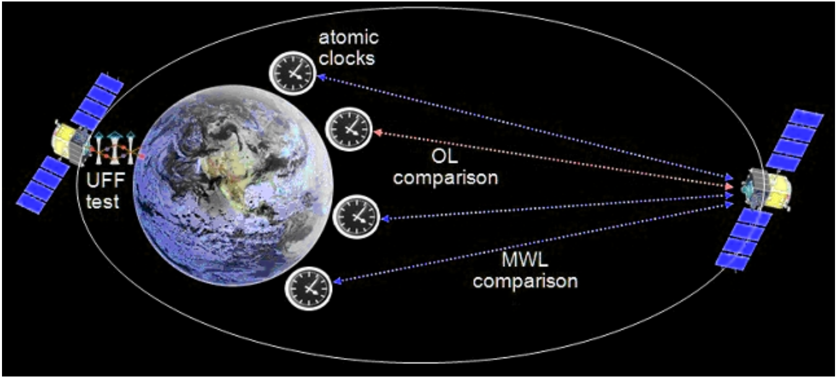
STE–QUEST

Test des Äquivalenzprinzips mit Atominterferometrie
Phasenlink zwischen Laser
2–Spezies Atominterferometer



STE–QUEST

mission scenario



Summary MAQRO

MAQRO	=	Macroscopic Quantum Resonators
	=	WAX + DECIDE + CASE

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

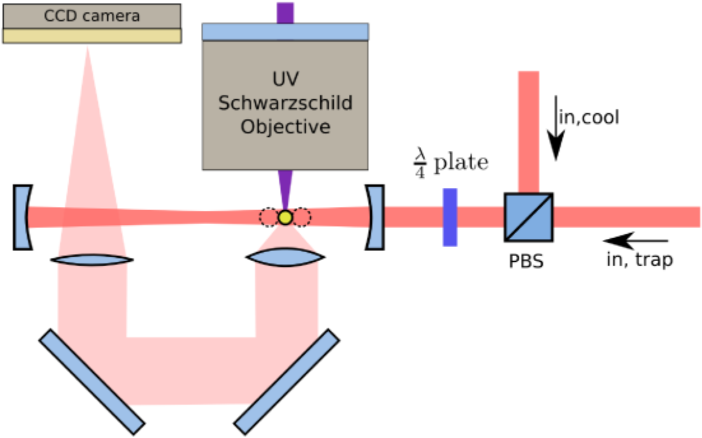
Science cases

- 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?
- are macroscopic quantum superpositions at all possible or are there yet unknown decoherence mechanisms?
- the short de-Broglie wavelength of massive particles can be used for high sensitivity matter wave interferometry with practical applications

Setup of MAQRO/DECIDE



Outline

Galileo

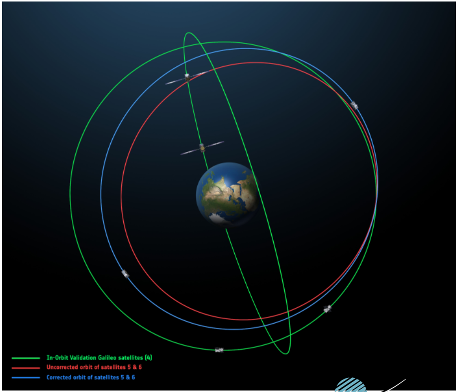
	after launch	after correction	target orbit
e	0.233	0.1561	~ 0
a [km]	26,192	27,977	29,900
i	49.774	49.7212	55
$r_a - r_p$ [km]	11,681	8,730	~ 0

Galileo-group

- Daniela Kunst
- Felix Finke
- Meike List
- Benny Rievers
- Volker Perlick, Sven Herrmann, Dirk Puetzfeld, Eva Hackmann, C.L.

Funding

- RelaGal (DLR)
- GREAT (ESA)



Galileo clocks and redshift

Galileo clocks

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

Redshift

- redshift between perigaeum and apogaeum

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

- experimental parameter: α
- wth 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)

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Clock data

data analysis centers correct the received clock data from G 5 + 6 for

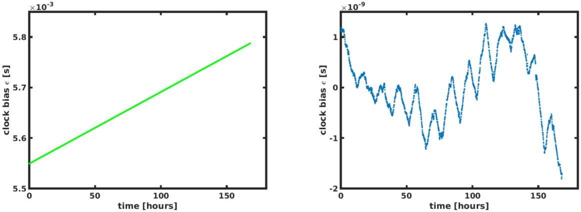
- atmospheric delays
- relativistic delays
- ...

unmodeled and sytematic effects remain: clock bias ϵ

Pseudo range for measured times

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

substract linear and quadratic drift



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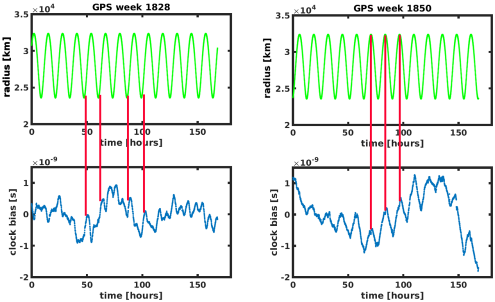
Analyzation of residual error

- Indication for systematics related to effects induced by the sun
- Apply sophisticated model for solar radiation pressure for orbit propagation
- Fit clock residuals to



$$\epsilon = 2\alpha \frac{\vec{r} \cdot \vec{v}}{c^2} \approx A_\alpha \sin\left(\omega_{\mathsf{sat}} t + \varphi\right)$$

where we fix the frequency and the phase shift using information from the orbit products (fit parameter A_α). Here $\alpha = \alpha_{\mathsf{grav}} + \alpha_{\mathsf{systematic}}$

- The values of A_α will oscillate over one year due to sun induced effects $\rightarrow$ statistical analysis will help to reduce the error in the measurement

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Outline

General Relativity

- The geometrical structure
- The gravitational field equations

Consequences and tests

- Weak field consequences
- The strong gravity regime
- Further consequences

Big open questions

New tests

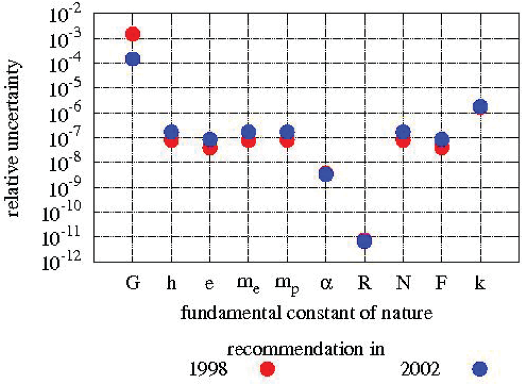
- MICROSCOPE: Universality of Free Fall
- Quantum tests: QUANTUS, PRIMUS, MAIUS, STE-QUEST, MAQRO, ...
- Galileo: Gravitational redshift
- The gravitational constant

Summary and outlook

Introduction

G is the most interesting of all constants

- Gravitation very weak, therefore G difficult to measure; G known with least precision
- measurement of G can also be interreted as search for Quantum Gravity
- G essential for Planck units; meaning?
- $G = 1$ possible per definitionem; (Theory: $c = \hbar = G = 1$) Consequences?



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Which constants are around?

Types of constants

- kinematical constants: $\hbar$, k_B, ...
  conversion quantities (energy $\leftrightarrow$ frequency, energy $\leftrightarrow$ temperature, ...)
- dynamical/geometrical constant: c (without interaction)
  conversion quantity (distance $\leftrightarrow$ time)
- dynamical constants: G, e, ... (interactions)
  coupling constants (G universal, e universal through charge quantization, ...)
- Particle parameters: particle masses, Weinberg angle, CKM angle, ...

- fundamental constants: c, $\hbar$, G, (e)
- natural constants: particle parameters, angles, ...,

Questions

- How are these constants defined?
- What is the meaning of these constants?

The velocity of light and Planck constant

Velocity of light c

- c is constant (equivalent to validity of SR)
- alternative: fixing c ($c = 299.792.458\ m/s$) gives conversion factor between s and m.

The Planck constant $\hbar$

- Conversion factor between frequency and energy : $E = \hbar\nu$
- can be determined by means of Watt balance assuming validity of UFF

$$h = \frac{4}{K_J^2 R_K}$$

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Conversion of units

- da c konstant, kann man s in m umrechnen: $x = ct$
- da $\hbar$ konstant, kann man s oder m in kg umrechnen $E = \hbar\nu$
- da G konstant, kann man eine Skala festlegen (z.B. Planck–Skala)

- $\hbar$ reine Umrechengröße, da nicht in Dynamik involviert
- c dynamisch begründete (ohne Wechselwirkung – Kausalität) Umrechengröße
- G eine Kopplungskonstante

man kann konsistent $G = 1$ setzen

- kann damit Masse definieren: 1 kg ist die Masse von Kugeln, die im Abstand von 1 m die Kraft 1 N aufeinander ausüben
- dann Masse experimentell nur mit ca. 10^{-4} genau definierbar $\Rightarrow$ Verschlechterung der Situation
- nicht praktikabel: jede neue Messung von m würde potentiell eine Neubewertung der Goldreserven nach sich ziehen ...

Planck units

Planck 1899: With the constants $\hbar$, c and G we can build time, length and mass

Planck–Zeit	$t_{\text{Planck}} = \sqrt{\frac{\hbar G}{c^5}} = 5.39106 \cdot 10^{-44}$ s
Planck–Länge	$l_{\text{Planck}} = \sqrt{\frac{\hbar G}{c^3}} = 1.616199 \cdot 10^{-35}$ m
Planck–Masse	$m_{\text{Planck}} = \sqrt{\frac{\hbar c}{G}} = 2.1765 \cdot 10^{-8}$ kg

- m_{Planck} aus

Schwarzschild radius $\frac{Gm}{c^2} = \frac{\hbar}{mc}$ Compton wave length

- characterizes quantum gravity scale
- for two particles with mass m_{Planck} and charge e we have $F_{\text{grav}} > F_{\text{el}}$

there are other natural units before Planck ...

Stoney units

Stoney 1874: With the constants e, c and G we can build time, length and mass

Stoney–Zeit	$t_{\text{Stoney}} = \sqrt{\frac{e^2 G}{4\pi\epsilon_0 c^6}} = 3 \cdot 10^{-46}$ s
Stoney–Länge	$l_{\text{Stoney}} = \sqrt{\frac{e^2 G}{4\pi\epsilon_0 c^4}} = 1 \cdot 10^{-37}$ m
Stoney–Masse	$m_{\text{Stoney}} = \sqrt{\frac{e^2}{4\pi\epsilon_0 G}} = 2 \cdot 10^{-10}$ kg

- for two particles with mass m_{Stoney} and charge e: $F_{\text{grav}} = F_{\text{el}}$ kann damit m_{Stoney} definieren
- characterizes scale of gravito–electromagnetic effects (Reissner-Nordström solution)

Stoney units

m_{Stoney} is the mass of a particle with charge e, so that the classical electron radius equals the Schwarzschild radius

$$\text{class. electron radius} \quad r_e = \frac{e^2}{4\pi\epsilon_0 mc^2} = \frac{Gm}{c^2} = \frac{1}{2} r_S \quad \text{Schwarzschild radius}$$

with class. electron radius r_e from

$$\text{rest energy} \quad mc^2 = \frac{e^2}{4\pi\epsilon_0 r_e} \quad \text{self energy}$$

perhaps more meaningful natural systems: much more easy to realize

Measurements of G

- Weakness of gravity $\Rightarrow$ measurement of G very difficult $\Rightarrow$ large uncertainties
- Error sources (one needs large masses)
  - inhomogeneity of the masses
  - determination of the vcenter of mass
- Traditional procedures
  - torsion balance
    - active motion
    - compensated motion
  - weighting of masses
  - pendulum
- new procedure: atomic interferometry

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Measurements of G

TABLE XVII. Summary of the results of measurements of the Newtonian constant of gravitation G relevant to the 2010 adjustment.

Source	Identification[a]	Method	Value (10^{-11} m^3 kg^{-1} s^{-2})	Rel. stand. uncert. u_r
Luther and Towler (1982)	NIST-82	Fiber torsion balance, dynamic mode	6.672 48(43)	6.4×10^{-5}
Karagioz and Izmailov (1996)	TR&D-96	Fiber torsion balance, dynamic mode	6.672 9(5)	7.5×10^{-5}
Bagley and Luther (1997)	LANL-97	Fiber torsion balance, dynamic mode	6.673 98(70)	1.0×10^{-4}
Gundlach and Merkowitz (2000, 2002)	UWash-00	Fiber torsion balance, dynamic compensation	6.674 255(92)	1.4×10^{-5}
Quinn *et al.* (2001)	BIPM-01	Strip torsion balance, compensation mode, static deflection	6.675 59(27)	4.0×10^{-5}
Kleinevoß (2002); Kleinvoß *et al.* (2002)	UWup-02	Suspended body, displacement	6.674 22(98)	1.5×10^{-4}
Armstrong and Fitzgerald (2003)	MSL-03	Strip torsion balance, compensation mode	6.673 87(27)	4.0×10^{-5}
Hu, Guo, and Luo (2005)	HUST-05	Fiber torsion balance, dynamic mode	6.672 28(87)	1.3×10^{-4}
Schlamminger *et al.* (2006)	UZur-06	Stationary body, weight change	6.674 25(12)	1.9×10^{-5}
Luo *et al.* (2009); Tu *et al.* (2010)	HUST-09	Fiber torsion balance, dynamic mode	6.673 49(18)	2.7×10^{-5}
Parks and Faller (2010)	JILA-10	Suspended body, displacement	6.672 34(14)	2.1×10^{-5}

[a]NIST: National Institute of Standards and Technology, Gaithersburg, MD, USA; TR&D: Tribotech Research and Development Company, Moscow, Russian Federation; LANL: Los Alamos National Laboratory, Los Alamos, New Mexico, USA; UWash: University of Washington, Seattle, Washington, USA; BIPM: International Bureau of Weights and Measures, Sèvres, France; UWup: University of Wuppertal, Wuppertal, Germany; MSL: Measurement Standards Laboratory, Lower Hutt, New Zealand; HUST: Huazhong University of Science and Technology, Wuhan, PRC; UZur: University of Zurich, Zurich, Switzerland; JILA: a joint institute of the University of Colorado and NIST, Boulder, Colorado, USA.

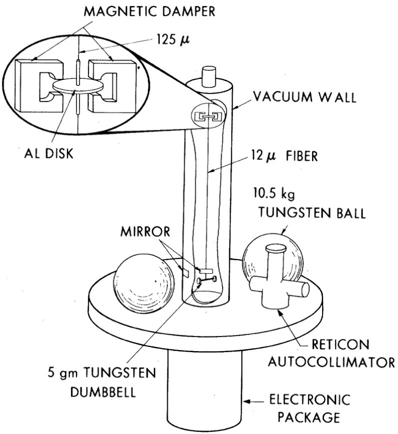
measurement always means

- measurememt of G
- verification of $1/r^2$–law

Torsion balance: active motion

Luther & Towler, PRL 1982

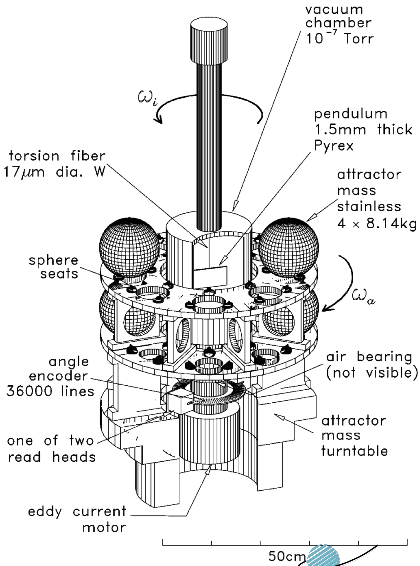
- Measurement principle: gravitating masses rotate around test masses, frequency of torsion pendlum is modified through presence of gravitating masses, choice of a particular frequency suppresses noises
- Error sources:
  - center of mass of gravitating masses
  - position and geometry of small masses
  - inertial moments of the mirror
  - non-linear behavior of torsion pendulum



Torsion balance: compensated motion

Gundlach & Merkowitz, PRL 2000

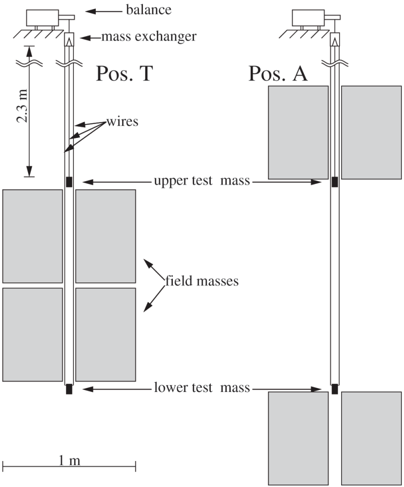
- Messprinzip: Torsionpendel rotiert $\Rightarrow$ kann Frequenz bestimmen, was Umwelteinflüsse reduziert, Feedback reguliert Rotation so, dass Torsionsfaden nicht verdrillt (Vermeidung des Kuroda–Effekts), Messung von G aus Winkelbeschleunigung des Torsionspendels
- dominante Fehlerquellen:
  - Position der gravitierende Massen
  - Pendelgemetrie
  - Temperaturschwankungen



Measuring the weight

Schlamminger, Holzschuh, Kündig, Nolting, Pixley, Schurr & Straumann, PRD 2006

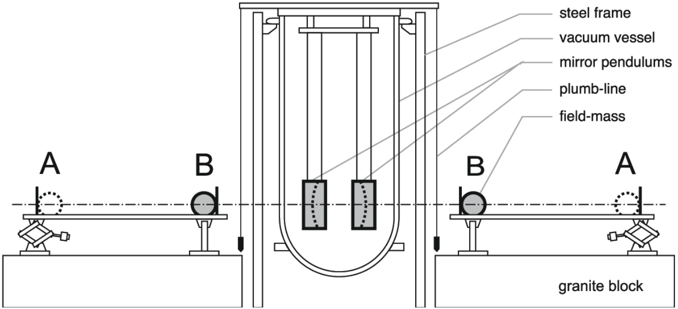
- measurement principle: measurement of the weight for different positions of the gravitating masses by means of a balance
- gravitating masses: Mercury in a container $\Rightarrow$ very homogeneous mass
- error source: determination of the mass



Pendulum

Kleinevoss, thesis 2002, Mayer et al, GRG 2012

- Measurement principle: Fabry–Perot gravimeter: Abstandsmessung zwischen Pendel mittels Mikrowellenresonator, Abstandsänderung ergibt Frequenzänderung
- Error sources: positioning, homogeneity of graviting masses



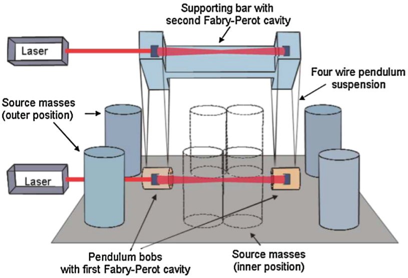
Pendulum

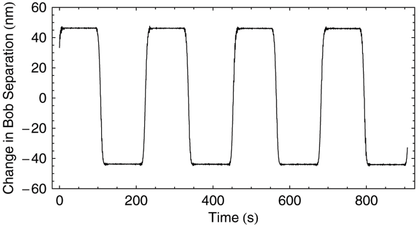
Parks & Faller, PRL 2010

- Measurement principle: distance between pendula measured by means of a Fabry-Perot interferometer
- Test masses positioned at saddle point of the gravitating masses $\Rightarrow$ insensitive w.r.t. uncertainty of positiong
- most precise measurememt of G

$$G = (6.67234 \pm 0.00014) \cdot 10^{-11} \frac{m^3}{kg^2\ s}$$

$$\frac{\Delta G}{G} = 2.1 \cdot 10^{-5}$$





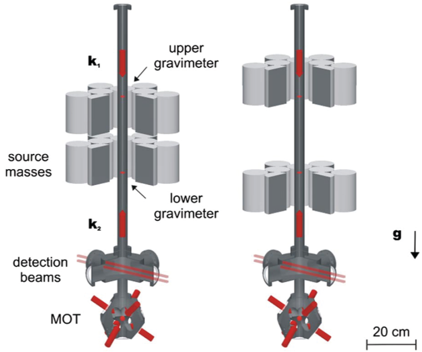
Atom interferometry

Lamporesi, Bertoldi, Cacciapuoti, Prevedelli & Tino, PRL 2008

- Measurement principle: measuremet of the gravitational acceleration for different positions of the gravitating masses
- Measurement: phase shift

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

- uncertainty approx. 1 order of magnitude larger than Parks & Faller
- uncertainty mainly through uncertainty of the position of the gravitating masses



Outline

General Relativity
- The geometrical structure
- The gravitational field equations

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- Weak field consequences
- The strong gravity regime
- Further consequences

Big open questions

New tests
- MICROSCOPE: Universality of Free Fall
- Quantum tests: QUANTUS, PRIMUS, MAIUS, STE-QUEST, MAQRO, ...
- Galileo: Gravitational redshift
- The gravitational constant

Summary and outlook

Summary and outlook

Astrophysical tests

- strong gravity regime
- limits of our experence: Black Holes
- test of matter models (neutron stars)
- high energy particles
- gravitational waves

Laboratory tests

- tests of fundamental principles (UFF, UGR, LLI)
- search for quantum gravity effects

Summary and outlook

Open issues

- Dark Matter
- Dark Energy
- Black Holes and neutron stars
- Quantum Gravity

New experimental devices

- squeezing
- large quantum systems
- entangled systems
- ...

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Thank you for your attention

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