Fundamental Physics in Space

The Advantages of Space for Fundamental Physics

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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

Introduction

Systematic approach

Discussion

Status of Fundamental physics in space

just completed, running, and just starting projects

- LLR (test of GR, Earth science)
- GP-B (test of GR)
- Cassini (test of GR, planetary science)
- LARES (test of GR)
- AMS (particle physics)
- LISA Pathfinder (gw astronomy, test of GR)
- Gaia (astrometry, test of GR)
- MICROSCOPE (test of GR)
- MAIUS / QUANTUS (test of QM and GR)
- Galileo (test of GR)
- QKD (Quantum Key Distribution, test of QM)
- GRACE-FO (geodesy, test of GR)
- ACES / PHARAO (metrology, test of GR)
- James Webb ST

Status of Fundamental physics in space

upcoming and planned projects

- LISA (gravitational waves)
- STEP, GG (test of GR)
- MAQRO (test of quantum-to-classical transition)
- BOOST (optical tests of SR)
- STE-QUEST (atom interferometry and clocks, tests of GR)
- ...

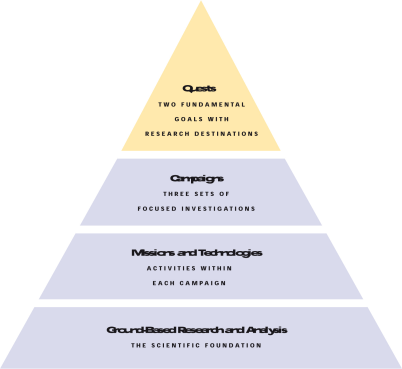
questions / tasks of this meeting

- what did we reach?
- what should be next? ... depends on
  - main science questions (may have changed)
  - technological readiness (new developments?)

Earlier roadmaps

NASA Roadmap for *Fundamental Physics in Space*, 2000

Research and analysis form the foundation, missions and technologies implement the campaigns, and the campaigns — the sets of focused investigations — are designed to satisfy our two quests.



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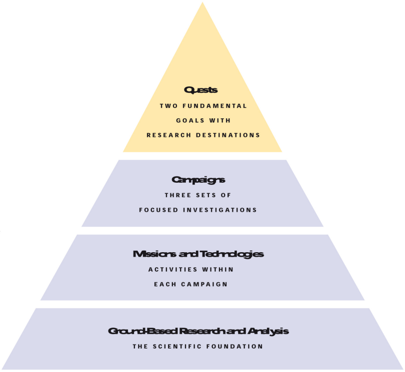

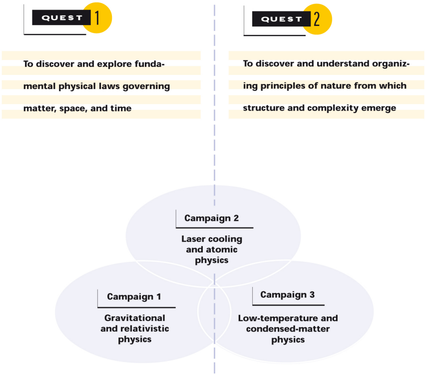

Earlier roadmaps

NASA Roadmap for *Fundamental Physics in Space*, 2000

Campaign 1 — Gravitational and Relativistic Physics

- Satellite Test of the Equivalence Principle (STEP)
- Gravity Probe-B (GP-B) (Code S)
- Superconducting Microwave Oscillator (SUMO)
- Gravitational Wave Missions (Code S and ESA)
- Spacetime Mission (STM)
- Laser Interplanetary Ranging Experiment (LIRE)
- Alpha Magnetic Spectrometer (AMS) (NASA/DOE)

Campaign 2 — Laser Cooling and Atomic Physics

- Laser-Cooled Clock Experiments (LACE)
- Electron Dipole Moment Experiment (EDM-X)
- Bose–Einstein Condensation (BEC)
- Space Atom Laser (SAL)
- Space Matter-Wave Gyroscope (SMW-G)

Campaign 3 — Low-Temperature and Condensed-Matter Physics

- Critical Dynamics in Microgravity Experiment (DYNAMX)
- Microgravity Scaling Theory Experiment (MISTE)
- Superfluid Universality Experiment (SUE)
- Experiments Along Coexistence Near Tricriticality (EXACT)
- Boundary Effects on the Superfluid Transition (BEST)
- Superfluid Hydrodynamics Experiment (SHE)
- Kinetics of the Superfluid Helium Phase Transition (KISHT)

Earlier roadmaps

A Roadmap for *Fundamental Physics in Space*, Prepared by the ESA-appointed *Fundamental Physics Roadmap Advisory Team* (FPR-AT), 2010

Fundamental Physics Roadmap

The Fundamental Physics Roadmap Advisory Team (FPR-AT) has been convened by ESA in order to draw up recommendations on the scientific and technological roadmap necessary to lead Europe toward the realization of future space missions in the framework of the Cosmic Vision 2015-2025 plan in the field of fundamental physics. The scientific fields covered are:

- Tests of fundamental laws and principles;
- Detection and study of gravitational waves;
- Quantum mechanics in a clean environment;
- Cold atom physics, new frequency standards and quantum technologies;
- The fundamental physics of dark energy and dark matter;
- Space-based efforts in astroparticle physics.

Earlier roadmap

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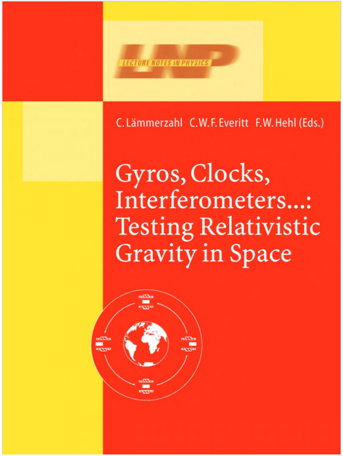
Members of the Fundamental Physics Roadmap Advisory Team
Pierre Binétruy, APC, Paris (F) [*chair*]
Philippe Bouyer, Institut d'Optique, Palaiseau (F)
Mike Cruise, University of Birmingham (UK)
Luciano Iess, Universita La Sapienza, Rome (I)
Gijs Nelemans, Radboud University Nijmegen (NL)
Ernst Rasel, University of Hannover (D)
Stephan Schiller, Heinrich-Heine-Universität Düsseldorf (D)
Alicia Sintes Olives, Universitat de les Illes Balears (E)
Wolfgang Schleich, Ulm University (D)
Alan Watson, Leeds (UK)
Bill Weber, Universita di Trento (I)
Peter Wolf, LNE-SYRTE, Paris (F)

Further publications



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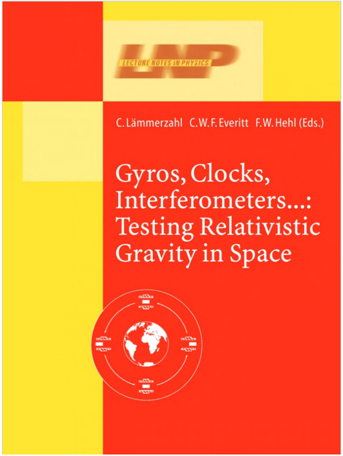

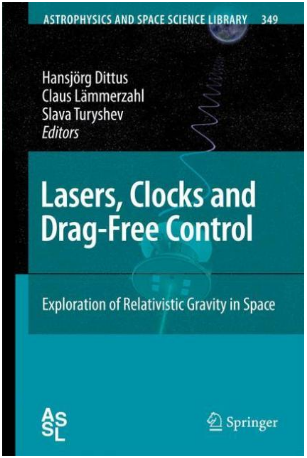

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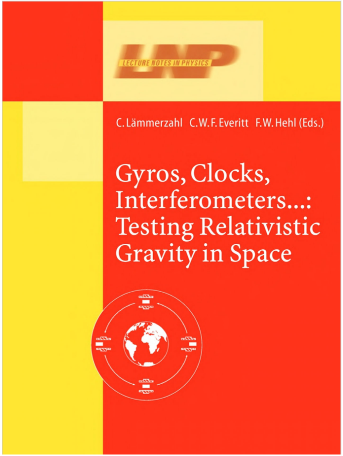

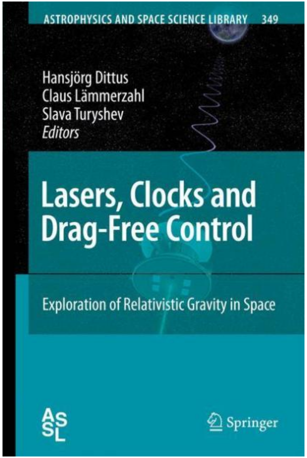

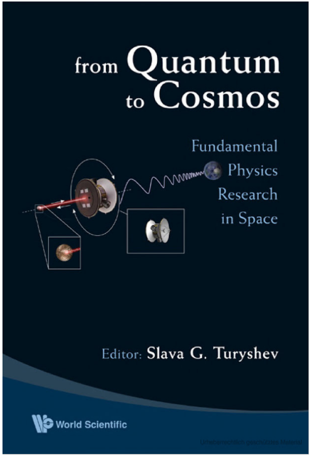

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Outline

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Systematic approach

Discussion

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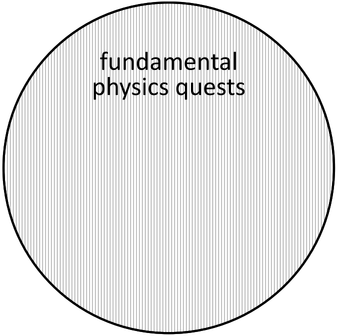

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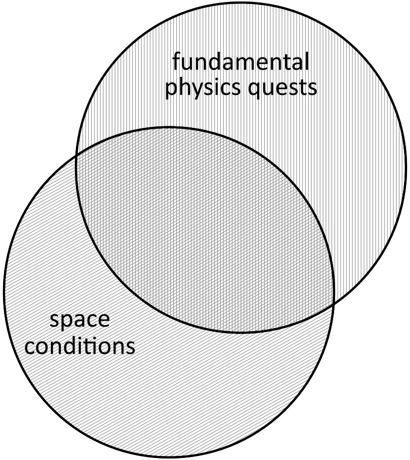

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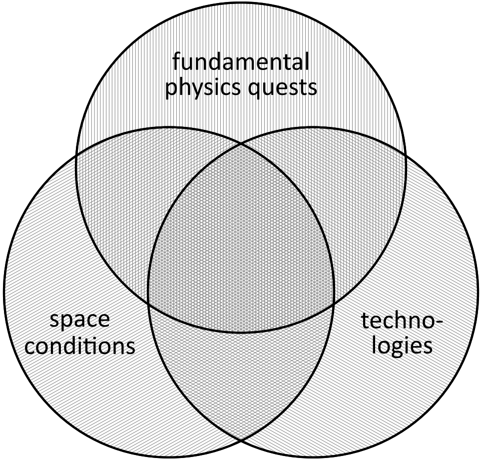

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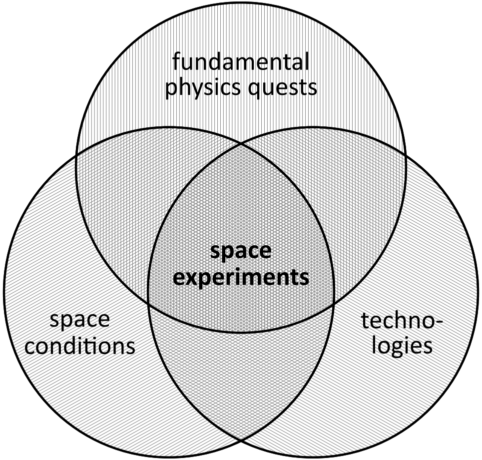

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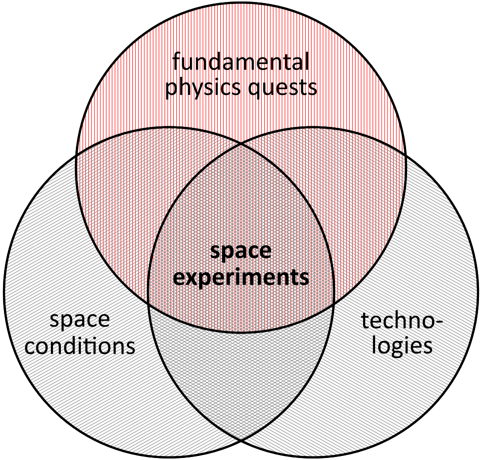

Fundamental questions

Structure of fundamental theories

- Quantum mechanics
- General Relativity
- Electrodynamics
- Standard model of particle physics

Structure of fundamental principles

- The measurement process
- Statistics
- Chaos
- Turbulence

Important issues

- Einsteins Equivalence principle
- Black Holes
- Decoherence
- The quantum–to–classical transition
- Scaling laws
- Phase transitions, structure formation

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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- GR is local – nonlocal generalization?
- QM is global

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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, in particular in BH space-times

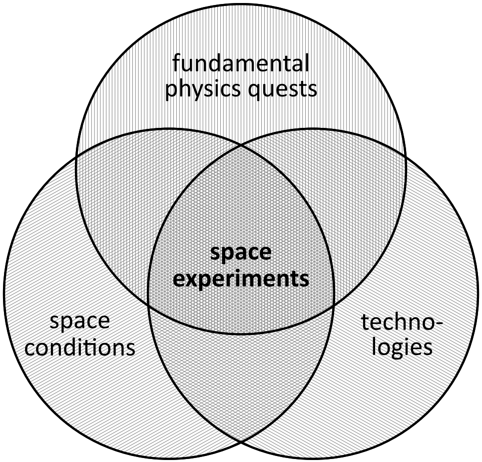
“smoking guns”

- Dark Matter
- Dark Energy

still to understand completely

- Black Holes
- Neutron stars
- Cosmic rays

Systematics: How to choose space projects



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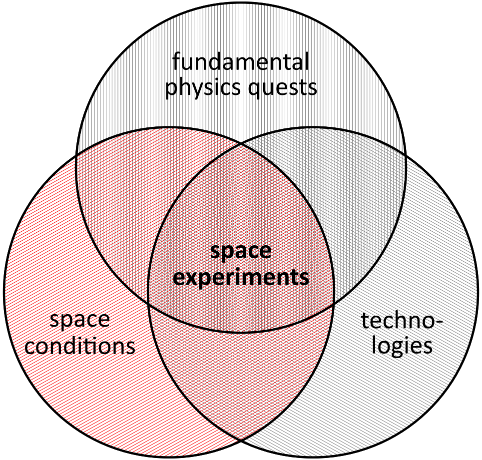


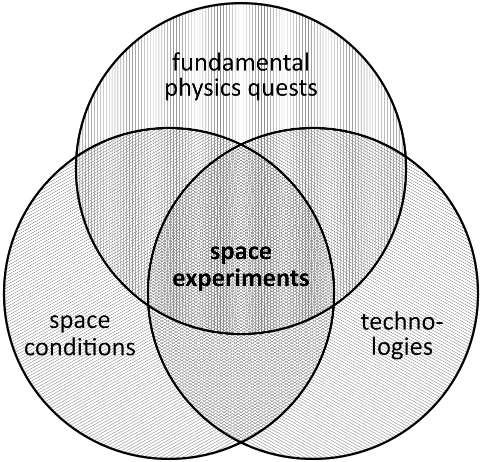
Tests in space: Advantages

- large potential differences
- high velocities
- big distances
  - astrophysics (large baselines, e.g. EHI)
- free fall
- quiet environment

Tests in space: Advantages

- large potential differences
  - necessary for testing UGR
  - necessary for measurement of absolute gravitational redshift with clocks
- high velocities
  - necessary for testing Doppler effect / time dilation / independence of c from v
- big distances
  - necessary for gravitational wave detection (LISA)
  - necessary for measuring gravitat. potential at large distances or weak gravity (MOND, dark matter, ...)
  - astrophysics (large baselines, e.g. EHI)
- free fall
  - long exposure to small forces: tests of UFF and tests of non–Newtonian gravity at short distances and small acceleration
  - good environment to make ultracold BECs
  - long free evolution time of quantum systems (needed for heavy quantum systems)
  - principal behavior of ordinary and quantum fluids
- quiet environment
  - disentanglement from seismic noise
  - more flexibility to vary experimental parameters

Systematics: How to choose space projects



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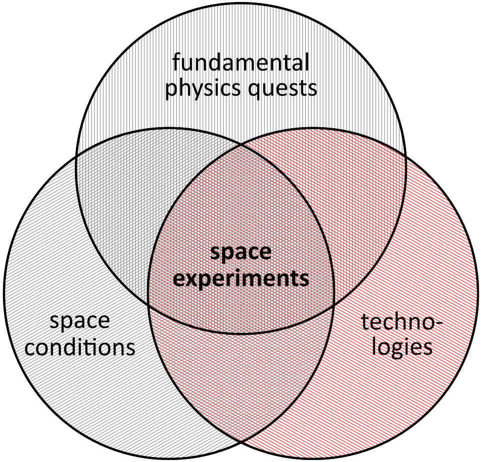

Experimental and technological challenge

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

- **very precise clocks**, optical clocks with accuracy of 10^{-18}
- **very precise length standards**
- **detection of tiny forces, tiny interactions**
- **Satellite attitude and orbit control** for force-free environment, geodesy, atrophysics, ...

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  - lasers, links, fibers
  - optical resonators
  - frequency comb
- **very precise length standards**
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  - SQUIDS
  - matter wave interferometry (atom, molecule, BEC)
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  - drag free control
  - microthrusters

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high precision, metrology needs
– quantum mechanics
– quantum optics

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What is special with quantum mechanics?

quantum mechanics is universal

- atoms are the same everywhere
- quantum phenomena are everywhere the same
- perfect dissemination of standards

quantum mechanics offers its high potential under microgravity

- effects scale with square of free fall time

that means:

- we need quantum technologies
- quantum technologies show best performance in microgravity

The use of quantum techniques

metrology – quantum metrology

- time – time in space, synchronization from space
- length, distance

application in geodesy and Earth sciences

- gravimetry – satellite geodesy
- leveling

new definition of mass

- Avogadro
- Watt balance in space

quantum techniques for fundamental physics

- Einstein Equivalence Principle – search for small forces, anisotropies

Possible experiments with cold atoms

fundamental research

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

applications

- geodesy
- inertial sensors

Cold atoms in microgravity: Technology

Technological applications of cold atoms

- accelerometers
- gyroscopes
- gradiometers
- high precision atomic clocks

used for

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

Examples

space and microgravity experiments (most with quantum systems)

- clocks: GP A [clocks]
- ACES – PHARAO [clocks]
- dynamics of bodies: GP B [SQUID]
- MICROSCOPE (GG, POEM, STEP...)
- Equivalence Principle in the quantum domain: PRIMUS, QUANTUS, STE-QUEST [clocks, atom interferometry]
- LISA [lasers]
- MAQRO [quantum]
- entanglement on large distances [quantum technology]
- cryogenic fluids on the ISS

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Criteria for future science, technologies, missions, ...

what should be the next Fundamental Physics missions?

your ideas ....