Fundamental Physics in Space
The Advantages of Space for Fundamental Physics

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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.
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.

**QUEST 1**
- To discover and explore fundamental physical laws governing matter, space, and time

**QUEST 2**
- To discover and understand organizing principles of nature from which structure and complexity emerge

**Campaign 1**
- Gravitational and relativistic physics

**Campaign 2**
- Laser cooling and atomic physics

**Campaign 3**
- Low-temperature and condensed-matter physics
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 (KSFHT)
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)
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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

Gyros, Clocks, Interferometers...: Testing Relativistic Gravity in Space

C. Lämmerzahl, C.W.F. Everitt, F.W. Hehl (Eds.)
Further publications
Further publications
Outline

Introduction

Systematic approach

Discussion
Systematics: How to choose space projects

fundamental physics quests
Systematics: How to choose space projects

fundamental physics quests

space conditions
Systematics: How to choose space projects

fundamental physics quests

space conditions

technologies
Systematics: How to choose space projects

- Fundamental physics quests
- Space experiments
- Space conditions
- Technologies
Systematics: How to choose space projects

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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

Important issues
- Turbulence
- 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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**structural inconsistency**
- GR is local – nonlocal generalization?
- 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, 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

- Fundamental physics quests
- Space experiments
- Space conditions
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Systematics: How to choose space projects
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 gravitational 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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- Technologies
- Space conditions
Systematics: How to choose space projects
Experimental and technological challenge

In order to 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, astrophysics, ...
Experimental and technological challenge

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

- **very precise clocks**, optical clocks with accuracy of $10^{-18}$
  - lasers, links, fibers
  - optical resonators
  - frequency comb

- **very precise length standards**
  - lasers, laser interferometry

- **detection of tiny forces, tiny interactions**
  - SQUIDS
  - matter wave interferometry (atom, molecule, BEC)

- **Satellite attitude and orbit control** for force-free environment, geodesy, atrophysics, ...
  - drag free control
  - microthrusters
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high precision, metrology needs
  – quantum mechanics
  – quantum optics
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
Outline

Introduction

Systematic approach

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

what should be the next Fundamental Physics missions?

your ideas ....