The ESA Fundamental Physics Roadmap (FPR)

Pierre Binétruy, APC, Paris
chair of FPR - Advisory Team

FPR workshop, ESTEC, 21-22 January 2010

Mandate of the Fundamental Physics Roadmap Advisory Team (FPR-AT)

« The FPR-AT has been assembled by ESA in order to draw a recommendation 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 FPR-AT has the task of consulting the broad scientific community* on this issue and of preparing a recommendation to ESA on the best scientific and technological roadmap to lead Europe toward these goals. »

« The FPR-AT will focus on space-based applications but will also take into account current and future progress being made or likely to be made from ground-based installations and instruments. »

What is fundamental physics in this context?

- Tests of fundamental laws and principles e.g. equivalence principle, constancy of constants, inverse square gravitational law
- 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: high energy cosmic particles, antimatter,…

The brief of the FPR-AT is to deliver a report covering the following points:

1) long-term scientific goal(s) for fundamental physics;
2) intermediate scientific goal(s) toward the same long-term goals;
3) a survey of the extant and planned facilities useful to achieve the scientific goals mentioned above, both space- and ground-based;
4) scientific goals among the ones mentioned above likely to be achieved with extant or planned facilities;
5) future facilities (not covered under point 3) needed to achieve the goals listed under points 1) and 2);
6) technologies needed for the establishment of the future facilities under point 5) The roadmap should consider and include among the intermediate scientific and technological goals the relevant "milestones" where applicable, i.e. intermediate goals which must be achieved before the longer-term goals can be considered feasible.

The context

Present status of Cosmic Vision :

• M1 (2017)-M2 (2018)

Euclid, Cross Scale, Marco Polo
Plato, Solar Orbiter, SPICA

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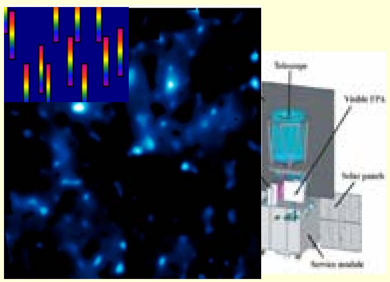
Downselection to 3 (or 4) missions in February 2010



EUCLID
(Dark Energy)
Deep space survey

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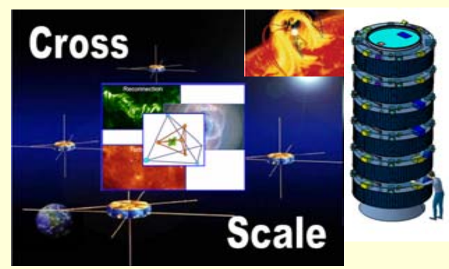
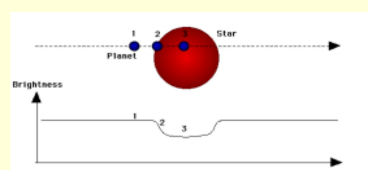
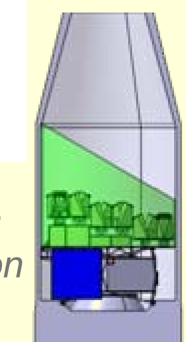
SOLAR Orbiter



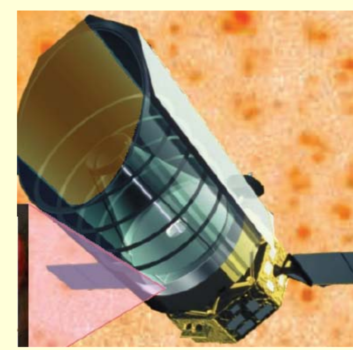
Cross-Scale
Plasma physics

Marco-Polo
NEO sample return
in collab. with JAXA





PLATO
Exoplanet detection
& star characterization



SPICA
3.5 m IR
observatory
in collab. with JAXA

No Fundamental Physics mission selected in the first call

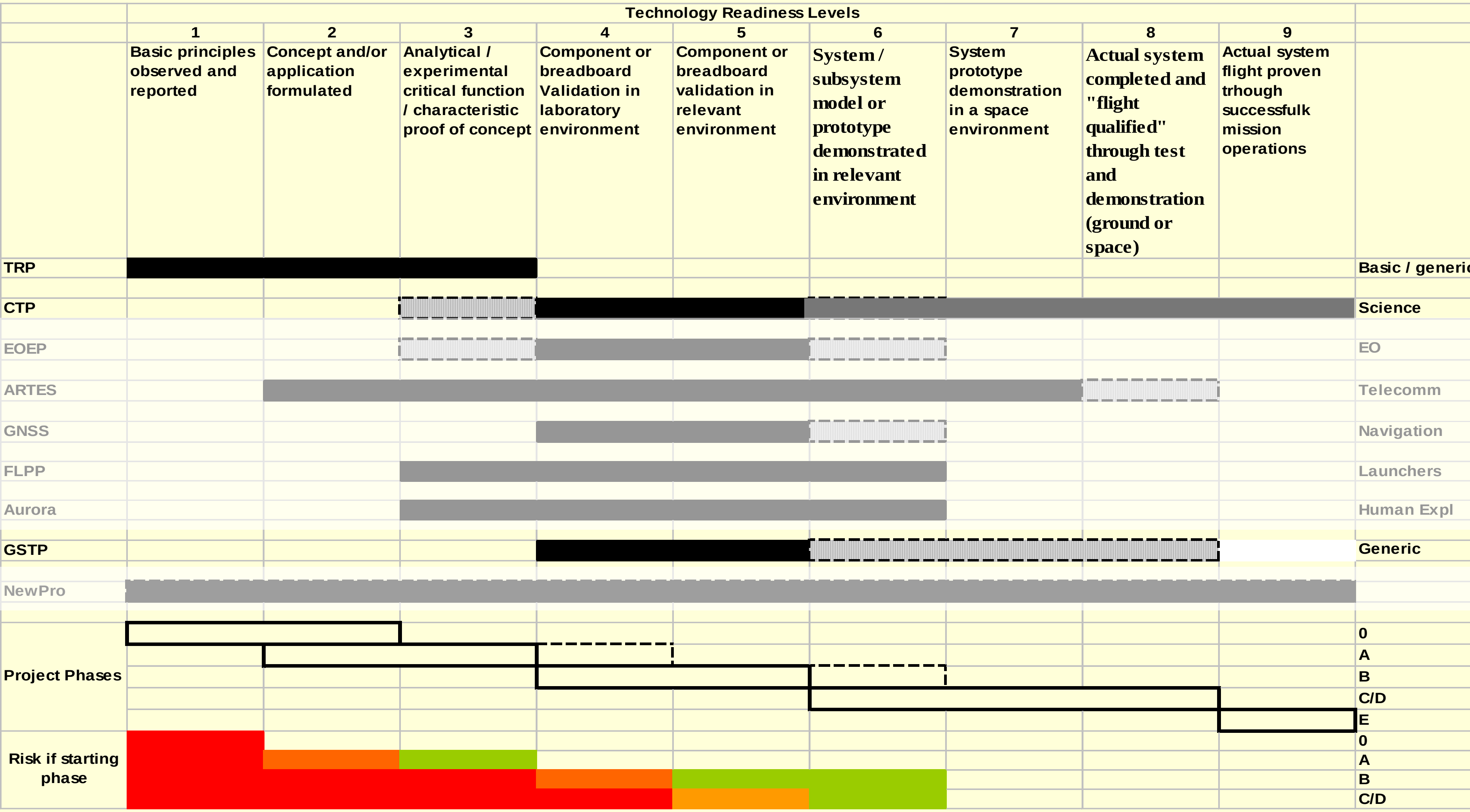
(except a recommendation to host a bias-reduced accelerometer on a planetary mission: GAP for Gravity Advanced Package)

Has led to a certain number of questions within and without ESA:

- What is the role of FPAG?
- Which directions for fundamental physics (SPC)? What are the scientific motivations?
- Are new technologies treated properly in the technical evaluation?
- On which of these technologies should one focus the effort?

Important, even vital for the field, to have missions selected in the next calls

The dictatureship of TRL



Present status of Cosmic Vision :

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Solar Orbiter, Marco Polo, Cross Scale,
Plato, Euclid, SPICA

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Downselection to 3 (or 4) missions in February 2010

• L1 (2020)

LISA, IXO, EJSM (Laplace)

Gravity Advanced Package?

Downselection to 2 in 2011

• M3 (2021)

Call in 2011

• L2 (2025?)

Present status of Cosmic Vision :

- M1 (2017)-M2 (2018)

Solar Orbiter, Marco Polo, Cross Scale,
Plato, Euclid, SPICA

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Downselection to 3 (or 4) missions in February 2010

- L1 (2020)

LISA, IXO, EJSM (Laplace)

Gravity Acceleration Package?

Downselection to 2 in 2011

- M3 (2021)

Call in 2011

- L2 (2025?)

short-term : 2010-2011 (getting ready for M3 call)
mid-term : 2015 (getting ready for L2 call)
long-term : 2020 (preparing the post-CV era)

Members of FPR-AT

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« The FPR-AT has the task of consulting the broad scientific community on this issue and of preparing a recommendation to ESA on the best scientific and technological roadmap to lead Europe toward these goals. »

- call for white papers issued on 6 April 2009 (deadline 28 May)
- presentations at conferences : Q2C4 (Sept.), 11th ICATPP (Oct.)
- public release of a draft of the roadmap in January 2010
- workshop at ESTEC : 21-22 January 2010

Some 100 participants!

• call for white papers issued in April 2009:

Gravitational wave and dark energy not included because existing proposals already in the selection process of Cosmic Vision 1

some 20 white papers received, most of them gathering the answers of a large community

Optical clocks *(3)*
Atom interferometers *(1)*
Deep space gravity *(4)*
Tests of quantum physics *(2)*
Equivalence principle *(1)*
Ultra-high energy cosmic rays *(5)*
Cosmology *(2)*
Industrial partner viewpoint *(1)*

<u>Meetings of FPR-AT</u>

2-3 June 2009 : screening of the white papers, general discussion

23 October 2009 : including gravitational waves and dark energy, first outlay of the roadmap and distribution of homework to FPR-AT members

26-27 November 2009 : first draft of the roadmap to be discussed

December 2009-January 2010 : numerous teleconferences

January 2010 : distribution of a draft of the roadmap to the community

21-22 January 2010 : workshop at ESTEC

March 2010 : deadline for the final version of the roadmap

Numerous existing roadmap documents, more or less specialized

- ESA Cosmic Vision : space science for Europe 2015-2025, October 2005
- The need for space flight opportunities in fundamental physics, EPS position paper, 2005
- A science vision for European astronomy, ASTRONET, 2007
- Status and perspective of astroparticle physics in Europe, ASPERA, 2008
- ESA Space Atomic Clocks (SOC) mid-term report (September 2008)
- ESA Space Atom Interferometers (SAI) mid-term report (June 2009)
- Gravitational Waves International Committee Roadmap (June 2009)
- Space-based research in fundamental physics and quantum technologies, S.G. Turyshev et al., arXiv 0711.0150
- Controlling the quantum world: the science of atoms, molecules and photons, committe on AMO2010, NRC, US Physics 2010 decadal survey

+ national roadmaps …

The draft of the roadmap

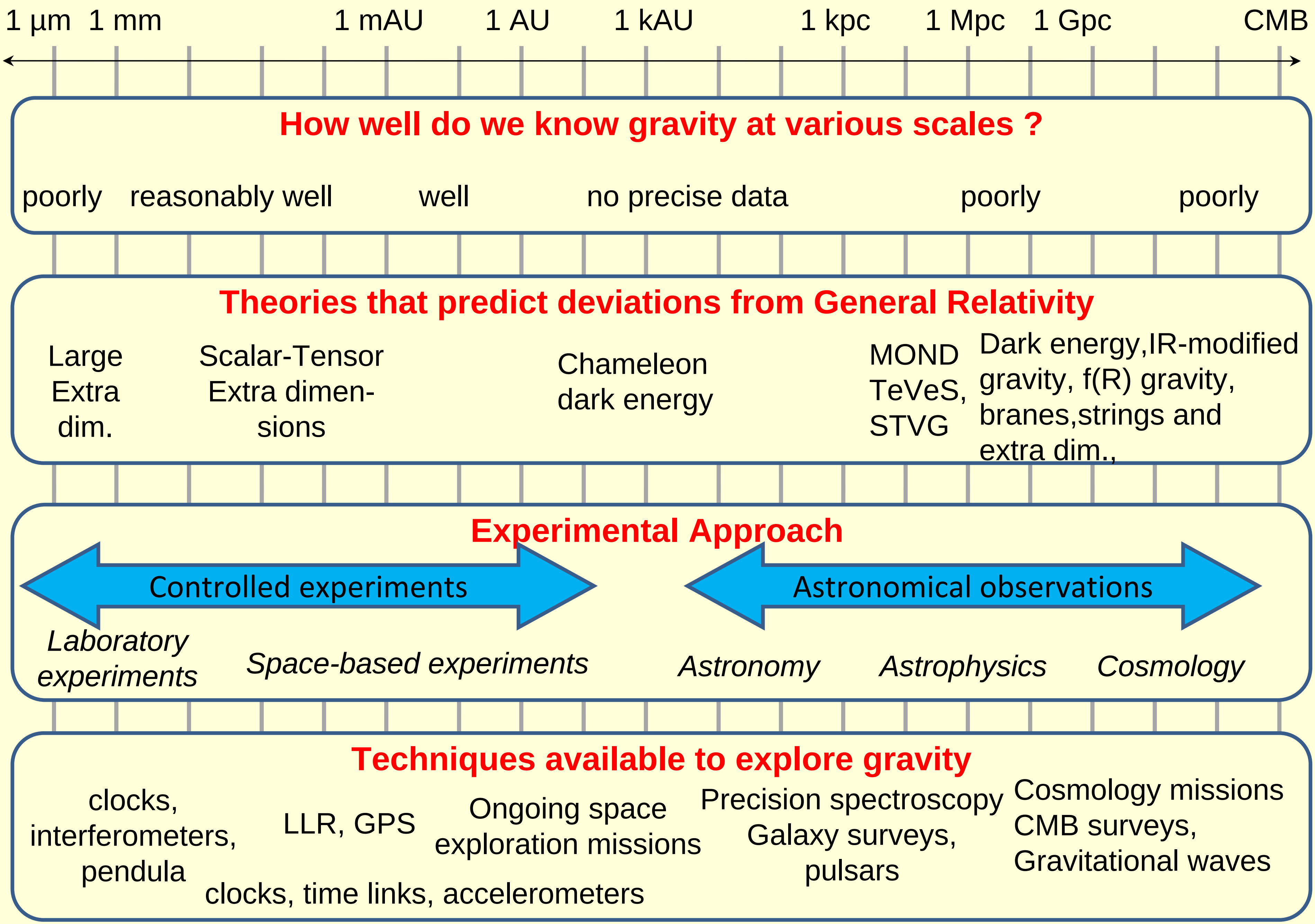
Contents

The scientific field covered by this roadmap: present status

Tests of fundamental laws: tests of fundamental principles, in particular the equivalence principle (weak equivalence principle, local Lorentz invariance and local position invariance including constancy of constants), tests of the law of gravity at all length scales, as well as in its weak or strong regime, structure and dimensionality of spacetime, tests of the foundation of quantum mechanics, tests of the Standard Model

Search for fundamental constituents: scalar fields for dark energy, dark matter particles, antimatter, graviton, fundamental strings, etc.

A field more unified than it may seem at first sight!


1 µm
1 mm
1 mAU
1 AU
1 kAU
1 kpc
1 Mpc
1 Gpc
CMB
How well do we know gravity at various scales ?
poorly
reasonably well
well
no precise data
poorly
poorly
Theories that predict deviations from General Relativity
Large Extra dim.
Scalar-Tensor Extra dimen-sions
Chameleon dark energy
MOND TeVeS, STVG
Dark energy,IR-modified gravity, f(R) gravity, branes,strings and extra dim.,
Experimental Approach
Controlled experiments
Astronomical observations
Laboratory experiments
Space-based experiments
Astronomy
Astrophysics
Cosmology
Techniques available to explore gravity
clocks, interferometers, pendula
LLR, GPS
Ongoing space exploration missions
clocks, time links, accelerometers
Precision spectroscopy Galaxy surveys, pulsars
Cosmology missions CMB surveys, Gravitational waves

A field with multiple connections

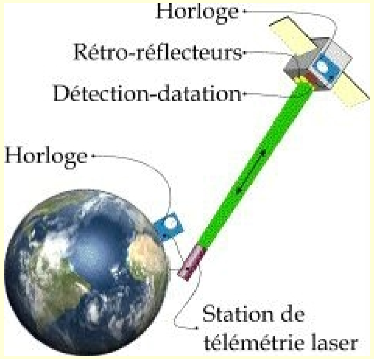
Astrophysics e.g. LISA is a FP-astrophysics mission
use of pulsars as cosmic clocks
dark energy
indirect search for dark matter vs astrophysical sources
use of UHECR for astronomy

Solar system science e.g. lunar laser ranging
radio ranging to Cassini
precise orbit determination of interplanetary spacecrafts or landers

Wide array of applications in geodesy, planetary gravity, global positioning, altimetry, telecommunications…

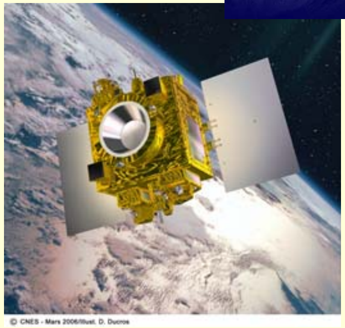
New technologies… but a rich space experience!

PAMELA
2006



T2L2
2008

FERMI
2008



Microscope

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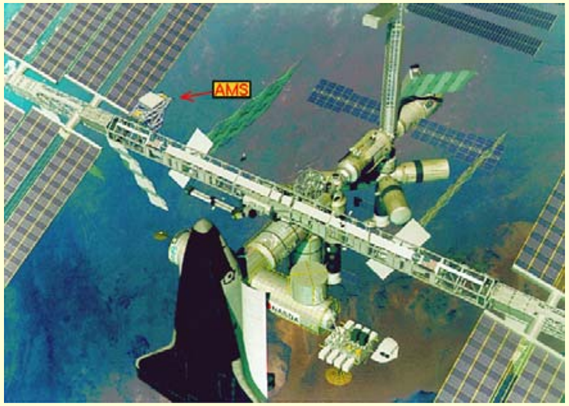
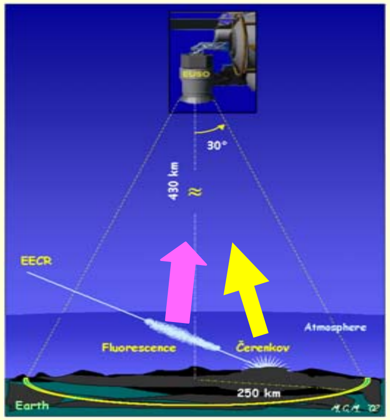
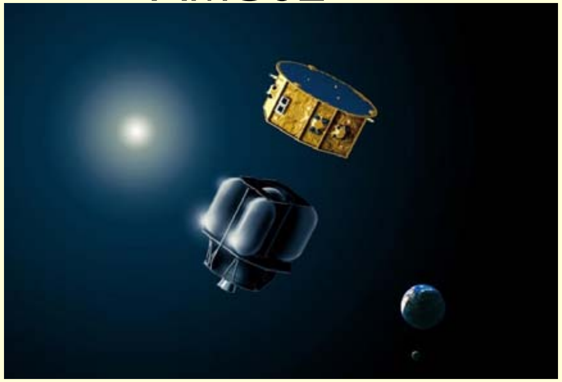
ACES



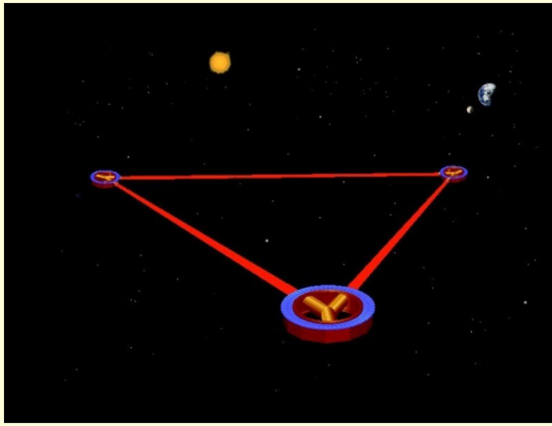
AMS02



JEM-EUSO



LISA Pathfinder



LISA

Ground vs space: future prospects on grounds vs prospective missions

A question often asked to the field of fundamental physics, e.g.:

- development of clocks on ground vs clocks in space
- Auger vs EUSO

Clocks on ground vs clocks in space

Mission type **Relevant gravitational potential difference**	Ground	ISS or low altitude orbit	Highly elliptic high-altitude Earth orbit	Inner solar system (Mercury)	Close fly-by of Sun (6 Solar radii)	Outer solar system
in Earth field	4×10^{-13} (c)	4×10^{-11}	5×10^{-10}	-	-	-
in Sun field	3×10^{-10} (f)	4×10^{-13} (d,e)	4×10^{-13} (d,e)	2×10^{-8}	4×10^{-7}	9×10^{-9}
Type of test	**Ground improvement in 10 years., incl. ACES**	**Improvement with next-generation space optical clocks**				
Time invariance of fundamental constants	40 (a,b)	-	-	-	-	-
Local Position Invariance I: Coupling of Earth gravity to fundamental constants	35 (c)	300	40 000 (k)	-	-	-
Local Position Invariance II: Coupling of Sun gravity to fundamental constants	10 (a,b)			70 (m)	1000 (m)	-
Redshift measurement in Earth field	35 (i)	350	40 000 (k)	-		-
Redshift measurement in Sun field	10 000 (e,g)	100 000 (e,k)	100 000 (e,k)	4×10^{7}	7×10^{6} (h)	2×10^{7}
Other science opportunities	Local mapping of Earth gravitational field at 10 cm level	Local and real-time mapping of Earth gravitational field at 1 cm level Lorentz Invariance	Local and real-time mapping of Earth gravitational field at 1 cm level Lorentz Inv.	2nd order redshift test, Shapiro time delay x 100 Lorentz invariance	2nd order redshift test Combine with Shapiro Time delay?	Probe gravity on large scale; Combine with Shapiro Time delay?

Table 1: Potential improvement of tests performed with 10^{-17} clocks in space, in comparison to those in principle feasible over the next 10 years on the ground and with the ACES mission, where the (transportable) ground clocks gradually improve to 1×10^{-18} level. Values are approximate improvement factors.

Auger vs EUSO

Complementary:

- Auger: well-established technique, good precision on energy and angle
- JEM-EUSO: less-established technique, precision increasing with energy, huge aperture allowing larger fluxes (and study of potential sources)

Ground vs space interferometers for gravitational waves

LISA frequency window $[10^{-4},10^{-1}]$Hz only reached in space
Corresponding sources are massive compact objects (often extragalactic)

Ground vs space for atom interferometers

Space increases the measurement time from about 100 ms to 10s or more

Sensitivity of matter wave interferometers for rotations and accelerations increases with the square of measurement time.

A roadmap for fundamental physics

Key science objectives

- Can we make new tests of the fundamental principles of GR?

(**properties of gravitational waves in the 10^{-4}, 10^{-1} Hz range, test of equivalence principle, measurement of PPN coefficients, clock redshift**)

- What is the law of gravity at all scales?

(**motion of massive bodies, propagation of light, clock redshifts**, galactic and cosmological observations)

- How does gravity behave in the strong field regime (close to black holes, neutron stars)?

(**gravitational waves in the subHz range**, X-ray missions,É)

- Is Lorentz invariance a symmetry of our Universe?

(**test of local Lorentz invariance, test of the equivalence principle, study of distant sources of energetic particles and photons**)

- Can we make new tests of the laws of quantum mechanics?

(**entangled photons, matter interferometry**)

- Can we get insight into the possible unification of gravity and the quantum theory (Standard Model)?

(**test of equivalence principle, nonconstancy of constants, test of Lorentz invariance, neutrino cross section at high energies, detection of superheavy particles**)

- If dark energy exists, what is its nature?

(**test of equivalence principle, tests of nonconstancy of constants, test of long range forces,** gravitational lensing, standardizable candles/rulersÉ)

- If dark matter exists, what is its nature?

(**detection of high energy cosmic particles**, **test of long range forces,** lensing)

- What are the mechanisms of the acceleration of cosmic particles?

(**detection of high energy cosmic particles of various kinds**)

Priorities

- Approved missions

"It is of vital importance to the field of fundamental physics that the missions presently approved (LISA Pathfinder, ACES and MICROSCOPE) are launched with no further delay."

- Candidate missions of CV1

EUCLID: "the issue of dark energy has far reaching consequences in fundamental physics."

"The LISA mission is central to fundamental physics, both through its scientific program and the technologies developed for its completion."

• “Regarding the forthcoming M3 call, it is felt by the Advisory Team that it is important to provide guidelines for a mission that would improve by some two orders of magnitude the precision of key parameters testing the laws of gravity, especially general relativity.”

M-mission with an optical clock

Assuming an uncertainty of the onboard clock of 1×10^{-17}, and an optical link allowing the comparison of such a clock to ground optical clocks at the same level of uncertainty, one can envisage two scenarios:

- high Earth orbit
- inner solar system orbit

• Equivalence principle and accelerometers

"A test of the weak equivalence principle, at the level of 10^{-17} or better, would provide an important test for many theories proposed beyond the Standard Model and General Relativity."

"For candidate mission concepts, using macroscopic test masses, to be successful in the M3 call, it is important that they be able to demonstrate on ground that their sensitivity goals are compatible with possible performance. This includes pushing measurements of systematic error sources and stray force noise, in addition to readout noise, near to the levels needed in space."

"Matter wave interferometry could represent a very interesting alternative, especially if a violation is observed by MICROSCOPE or other experiments."

• Missions to the outer solar system

> "Despite the strong interest in testing gravity at all length scales, the Advisory Team thinks that fundamental physics alone does not provide a broad enough scientific motivation to justify a dedicated fundamental physics L-mission in the outer solar system, but that such a mission needs to be combined with substantial planetary science objectives."

> "When combined with a planetary mission the fundamental physics instruments are likely to impose stringent constraints and need to be included in the mission design at an early stage. The Advisory Team recommends that a genuinely mixed fundamental physics and planetary mission be considered."

- High energy missions

> "When combined with a planetary mission the fundamental physics instruments are likely to impose stringent constraints and need to be included in the mission design at an early stage. The Advisory Team recommends that a genuinely mixed fundamental physics and planetary mission be considered."

- Mission of opportunity: JEM-EUSO

> "The Advisory Team supports the active participation of the European community in ultra-high energy cosmic rays in the Japanese mission JEM-EUSO on the Japanese module of the ISS. This is an excellent opportunity to test the possibility of detecting such cosmic rays from space. If successful, this would open the road to an even higher statistics of cosmic rays of the highest energy."

ISS recommendations

"The Advisory Team supports the continuation of the development of the ISS mission "SOC" with lattice optical clocks, that aims at improving the Earth gravitational redshift measurement, Local Position Invariance test, and ground clock comparison accuracy by one order compared to ACES. The technology developments required for this mission and for a M3 clock mission will have significant overlap."

"The strong technology development program on atom interferometry sensors, presently undertaken in drop towers, parabolic flights, sounding rockets and in the ISS should be vigorously pursued.[…]. The outcome of tests on the Space Station or an other adequate platform are considered as milestones for missions beyond 2020 targeting tests of the principle of equivalence better than 1 part in 10^{17}. From this point of view, the Advisory Team supports the continuation of the "Space Atom Interferometer" (SAI) project."

Technology

Detailed technology development plans are proposed in section C.3 for:

- free-falling test masses, accelerometers and drag-free satellites
- optical clocks
- optical links
- matter-wave interferometers
- ultra-high energy cosmic ray detection

Short-term technology developments:

"A strong technology program should be continued in order to bring the LISA mission closer to its completion."

"The required technology development (clock and link) necessary for the M3 mission proposed above should be implemented in an efficient manner, building on existing know-how in European research labs and industry, in particular on the ACES heritage. We recommend concentrating on the most promising and realistic clock […]."

"We recommend advancing the technology of inertial sensors with a high bias stability at the lowest Fourier frequencies and a sensitivity better than 10^{-11} m/s^2/√Hz (atom interferometry sensors or other). »

The community and its organization

Census of the community through a message sent broadly to Fundamental physics groups throughout Europe.

Results to be included in the final document.

Some communities may not have received this message (e.g. astroparticle physics)

Recommendations:

"Close cooperation and interchange between research institutes, space agencies, and space industries becomes of key importance for accelerating the necessary transfer of know-how, vital for any successful space project. In particular,

- Space agencies and industries need to acquire know-how in cutting edge research, technology, and measurement methodology, based on the expertise of scientific institutes across Europe. This includes the understanding of the physical processes at the basis of precision measurements and precision instruments.
- Research institutes need to develop expertise in space missions and space technologies. This includes a profound understanding of all the challenges and the limitations that a space project brings along.

Given the technological challenges of the field of fundamental physics, it is important that, very early in the projects, industry and academic labs be closely associated."

Discussion groups

Participants randomly distributed among the 4 working groups

All 4 working groups discuss in parallel *the same questions*

Report of the working groups will show where there is consensus and where there is debate.

Questions

1. In the overview (section B.1), the scientific field covered by fundamental physics in space is described. Do you agree with this description ? Did we miss anything ?

2. How can we better exploit progress in theoretical physics to promote the science case for fundamental gravitational physics missions (for instance equivalence principle, tests of general relativity and PPN, links with cosmology)?

3. How would you rate the importance of probing gravity at all scales (see Figure p. 8). How important is it to probe gravity at the scale of the solar system ?

4. Should the roadmap be more explicit about potential applications in geodesy, global positioning, navigation, telecommunication… ? Are there specific technological developments in this direction that would benefit the field of fundamental physics ?

5. Table 1 summarizes the expected improvement of tests with clocks on ground vs clocks in space. Any comment on this Table ?

6. Is the list of key science objectives given in Section C.1 complete ?

7. It has been proposed to provide a « gravity exploration toolbox » that could be attached to any deep space missions. We think that this puts some stringent constraint on such a mission and recommend on the contrary (p. 30) that a common FP-planetary mission be developped from the beginning. What is your opinion ?

8. What are the prospects for a combined planetary – fundamental physics mission to the outer solar system : which measurement and instruments will be of most interest for fundamental physics?

9. Does an optical clock mission in high Earth orbit or inner solar system orbit provide sufficient science gain for an M3 candidate (see p. 27,28)? Which scenario is preferable? What instruments onboard are required/desirable?

10. How realistic is the present technology, and the presented technology development plan (p. 37) for such a mission? Does the recommended technology development need to be more specific at this stage (eg. recommending a particular atom or ion?).

11. In the roadmap, tests of the equivalence principle are singled out as being at the heart of fundamental physics (p. 28). Do you agree with this status ? Which level of accuracy do you think we should reach in order to constrain models ?

12. It is recommended (p. 29) that ground-based studies should aim to narrow down the gap towards reaching sensitivities in space compatible with a test of the equivalence principle in the 10^{-17} range. To what extent, do we need to be realistic? Do we need to be more quantitative in the roadmap ?

13. What do you think of the recommendations regarding the gravitational wave program ? Should we discuss the post-LISA projects (Big Bang Observer, DECIGO) ?

14. What do you think of the development plan proposed for clocks in space (p. 35 ff)? Is it too narrow or too broad ? Is it realistic in terms of time and goals ?

15. What do you think of the development plan proposed for matter wave interferometers (p. 39ff)? Is it too narrow or too broad ? Is it realistic in terms of time and goals ?

16. What do you think of the development plan proposed for links (p. 38ff)?

17. Is it reasonable, as stated p. 31, to wait for the result of present and near future high energy particle missions and experiments before designing a mission concept for the next generation space experiments in that field?

18. Do you agree with the recommendation p. 31 of supporting European participation to JEM-EUSO as a mission of opportunity ?

19. Are the recommendations in Section C.4 sufficiently prioritized to allow the community to focus its effort and money on a few fully identified goals ?

20. Do the recommendations of the roadmap fully capitalize upon the investment of technology development and flight heritage of the current generation of fundamental physics missions (ACES, MICROSCOPE, LISAPathfinder) and missions with fundamental physics elements (Bepi-Colombo and GAIA, for instance)?

21. Do you think that the fundamental physics community should be better organized and, if so, how (FP7, advisory committee,..) ?

22. In fundamental physics, the specific need for a close collaboration between industry and research laboratories very early in the projects is stressed in the roadmap. How to achieve this ?

23. How to help research institutes to develop expertise in space technologies (qualityinsurance, test facilities,…)?
Is it the role of national space agencies ?

24. The roadmap has focused on the situation in Europe. Is it too Eurocentric ?