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**SELECT EXPERIMENTAL TRENDS IN ASTRO-PARTICLE
PHYSICS IN SPACE**

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Abstract

This report is in part based on the contribution to the Detector Working Group presented at the meeting on *LNF long term planning*, held on May 7, 2004, at INFN-LNF (Frascati, Italy). The initial work has been expanded, in some case evolving into experimental R&D work on new activities (LAZIO-SiRad and LARES).

We will describe: (i) satellites with magnetic spectrometers for particle physics in low earth orbits (LEO, ~ 400 Km), (ii) the idea of networks of μ -satellites (for example to monitor the short term instability of the Van Allen belts); (iii) stratospheric balloon-based experiments; (iv) satellite laser-ranging experiments for testing the frame-dragging effects predicted by general relativity (GR), the equivalence principle and, possibly, for setting bounds on string-inspired brane theoretical models.

We think that this document can be the starting point for future and further work in astro-particle physics in space at LNF.

1 Introduction

The report is organized as follows: the second section describes the experimentally mature field of magnetic spectrometers in space while the third contains a discussion on micro-satellites. This is followed by general considerations about strategic choices to do physics in low Earth orbits by the ESA astronaut Roberto Vittori. Balloon-based experiments are mentioned in section five as an interesting research approach alternative to satellites and to the International Space Station (ISS). Precision tests of general relativity and, possibly, for new physics with the Satellite Laser Ranging technique are reported in the section before conclusions.

2 Magnetic spectrometers in LEO

Two major astroparticle physics experiments in space using magnetic spectrometers have been funded and built in recent years with a highly prominent participation by INFN:

- PAMELA [1]: this satellite, which is nearing completion, adopts a permanent magnet (0.48 T at the center) and will be placed in an elliptical orbit at an altitude between 350 and 610 Km on board of the Russian Resurs-DK1 satellite in 2005. PAMELA weights about 0.5 Ton and has a geometric factor $GF=20.5 \text{ cm}^2 \text{ sr}$. LNF has a long-time involvement in the WIZARD program [2] and in PAMELA.
- AMS-02 [3]: this satellite will employ for the first time a large superconducting magnet (6 T) and will be installed on the ISS (altitude $\sim 400 \text{ Km}$) in 2008 by a Space Shuttle flight. AMS-02 will weigh about 6.5 Ton and have a $GF \sim 5000 \text{ cm}^2 \text{ sr}$. Detector integration is foreseen for 2007.

These experiments are similar to a typical particle physics experiment capable of measuring γ , e^\pm , p/\bar{p} and nuclei in LEO between 50-100 MeV and 1 TeV. Among the primary goals of AMS-02 and PAMELA we cite:

- Measurement of the spectra of Solar and Galactic cosmic rays outside the atmosphere at intermediate energies (up to TeV).
- Search for a Neutralino signal in a possible bump structure in the positron momentum spectrum or in a deviation of the anti-proton spectrum with respect to the expected behavior.
- Search for anti-Helium. The AMS-01 experiment, which was flown inside the Shuttle *Discovery* for about ten days in June 1998 (STS-19), was equipped with a permanent magnet and did not have an e.m. calorimeter. AMS-01 published an upper

limit on the value of the flux ratio of anti-He/He of 1.1×10^{-6} [4]. For comparison, PAMELA is expected to have a sensitivity to this ratio of about 7×10^{-8} .

The operation in space requires a design and construction of detectors, mechanics, cryogenics and magnets which is completely different from the standards of ground-based particle physics experiments. Space qualification (SQ) is mostly performed by national space agencies (NASA, ESA, ASI) and by very specialized international companies, like for example: Space Cryomagnetics Ltd, UK (ex “Oxford Instruments; this firm produced the KLOE superconducting solenoid magnet in 1997 and is now manufacturing the AMS-02 solenoid); Lockheed Martin Space Operations, US (for AMS-02 it is in charge of the support structure on the ISS, the avionics on the Shuttle and all related safety issues); CSIST, Taiwan (SQ electronics; significant commitments in AMS-02); Carlo Gavazzi Spazio, Italy (mechanics, avionics and integrated systems). Basic SQ requirements are: (i) very high ratio of stiffness/mass, stress_resistance/mass; (ii) stringent temperature cycle tests (up to ± 70 degC), thermo-vacuum tests (TVTs), vibration tests.

3 μ -satellites

The space qualification, the cost of launches for satellite weights above a few hundred Kg and the associated long time schedule represents an obstacle, which is out of the control of HEP funding agencies, like DOE and INFN, which in many cases pay and build half (or more) of the experiments. This difficulty has recently led to the consideration of an additional and complementary approach, based on the deployment of small and light (1-100 Kg) satellites (μ -satellites) with commercial launchers, where the acceptance is recovered by making a **network** of them. A discussion about this option was initiated at an internal meeting about the on-going and future INFN initiatives in astro-particle physics in space held at LNGS on May 5, 2004 [5].

This “modular” approach is scientifically sound provided that the physics case can be pursued by segmenting the detector acceptance (GF) into a network. It also allows a low cost feasibility test, like test-beam experiments in HEP. The approach seems also financially affordable for INFN, given that typical costs are few million euro for the first μ -satellite, decreasing with multiplicity. Note that at the Surrey Space Center [6], located south of London, a University has been able to launch and operate about 1 μ -satellite/yr since the mid '80s. This modular approach could be strategically convenient, since one would not rely completely on national space agencies: μ -satellites can be launched commercially within months. When possible and strategically convenient, select INFN sites could acquire partial certification for SQ.

One example of μ -satellite network is the monitoring of the activity and composition of the Van Allen belts of charged particles (e^\pm , p/\bar{p} and nuclei), which are trapped into the e.m. field around the Earth. Relatively simple detectors equipped with Si layers, plastic scintillators and magnetometers could measure the pitch angle and bouncing altitude of charged particles in the belts (together with the e.m. field). Russian researchers during the past two decades have reported possible evidence that short term instabilities in the pitch angle distribution and in the number of escaping particles occurs around a typical time of a few hours (~ 3.4 hr) before intense earthquakes. A working hypothesis is that particle losses in the belts are due to seismic-induced ionospheric perturbations. Such a study of the Van Allen belts has, potentially, a significant social interest.

3.1 The Italian Soyuz Mission 2 (by R. Vittori)

The Italian Soyuz Mission 2 (ISM2) is an initiative planned and realized with minimum support from the Space Agencies. It concentrates on the usage and potential of the ISS as test bed mostly for technology development and verification, for aerospace medicine research, and for astro-particle physics. Most of the technologies and sciences on board of ISM2 are the result of converging interests and efforts of universities, laboratories, and industries. The Regione Lazio, with the newly created Aerospace District, provided the institutional frame and financial support in which to develop new ideas, new technologies and new science. Specifically, the LAZIO-Sirad experiment (see next subsection) maybe the prototype for a network of μ -satellites in LEO to further investigate the possible correlation between earthquakes and the variation of the electromagnetic field. At the same time, once upgraded with a graphical interface, LAZIO-Sirad could offer astronauts real time monitoring of the radiation conditions on board the ISS. The overall mission is financed and supported by FILAS spa (Finanziaria LAziale di Sviluppo), ESA, ASI, the Russian space agency for what concerns the launch and NASA for what concerns the use of the ISS.

3.2 The LAZIO-SiRad project

An R&D experiment called LAZIO-SiRad (Low Altitude Zone Ionization Observatory [7]) is in preparation as part of ISM2. LAZIO-Sirad will be launched with a Progress spacecraft (unmanned Soyuz) from the Baikonur cosmodrome at the end of February 2005 and will be operated by the crew of the Soyuz flight of April 2005. This crew will include an Italian ESA astronaut, Roberto Vittori. This Soyuz will be docked with the ISS for about 10 days. The experiment is being built by a collaboration of several universities and laboratories, led by INFN within the GR V activities. A group from LNF has built

two structural mechanical parts.

- 1) The LAZIO-SiRad Main Electronics Box (MEB), which is the overall mechanical enclosure (both the *qualification* model, QM, and the *flight* model, FM).
- 2) The EGLE MB box (both QM and FM versions), which is external to the LAZIO-SiRad MEB. LAZIO is equipped with the high precision low frequency magnetometer EGLE (Esperia's Geomagnetometer for a Low frequency wave Experiment [8]). Magnetic field signals detected by the EGLE magnetic head probe are amplified, filtered and acquired by the EGLE acquisition and data handling board located into the EGLE MB box.

Although LAZIO-SiRad is not a large project, it is a very integrated space mission, since it involves several space agencies and has to be launched with a tight time schedule (in practice less than 6 months).

The goal of LAZIO-SiRad (see fig. 1) will be to monitor the real-time variations of the radiation environment in the ISS and to measure the activity of the Van Allen belts in LEO. Scintillators are used to trigger on the passage of charged particles and silicon detectors will measure their charge up to $Z=25$ (Iron nuclei) in the range ~ 10 to ~ 100 MeV, with a large geometric aperture ($GF \sim 60 \text{ cm}^2\text{sr}$). Together, they will record particle arrival times, their line of arrival (pitch angle), their direction of arrival. This will provide measurements of the pitch angle distribution within short time intervals (from few seconds to few minutes depending on the position on the orbit). EGLE will measure the magnetic environment inside the ISS concurrently to the measurement of charged particle fluxes and will examine potential pre- and post-seismic effects.

LAZIO-SiRad integration will be done in Rome Tor Vergata, where a first acceptance test will be performed by ESA in December 2004. Afterwards, SQ tests will be done at the INFN-Perugia SERMS SQ facility [9]. Another acceptance test for outgassing will occur at the ESA ESTEC site (Holland) and the final one in Russia (either in Moscow or in Baikonur).

4 Access to the International Space Station and low Earth orbits (by R. Vittori)

High energy and astro-particle physics can find new perspectives in LEO, either with networks of satellites or with the ISS as laboratory for science and as micro-gravity test bed for the preparation of experiments. Interesting possibilities are provided by the Russian Space Agency, that is progressively offering important resources and capabilities for commercial and private applications, thus allowing an increased flexibility also to research and science. Moreover, the new interest and investments of China in space may increase even

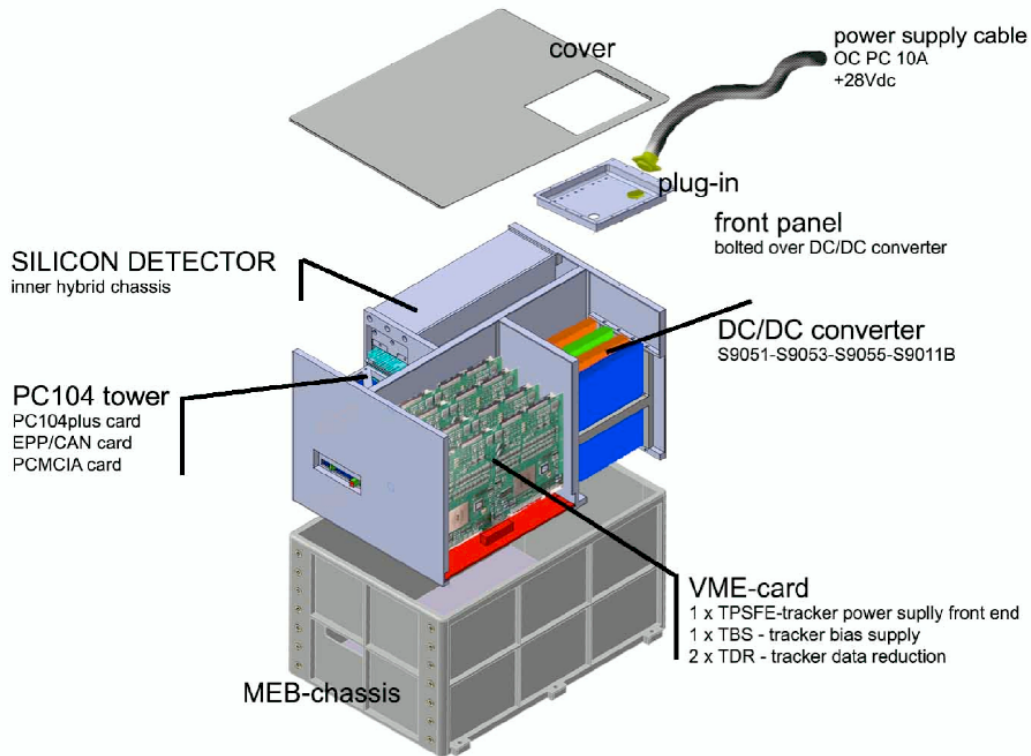


Figure 1: Exploded view of the LAZIO-SiRad experiment.

further the options to plan and perform science outside our atmosphere. The role and contribution of the Space Agencies, instead, will gradually leave the LEO in direction of farther exploration destinations (Moon and Mars). As a natural consequence, the effort of universities and laboratories will have to rely on autonomous capacities and planning capabilities. Specifically, INFN could take in the future a more independent capability to perform science in outer space, including possible participation of its scientists to missions on board of the ISS. In general, ideas coming from the intersection of experimental particle physics and relativistic astrophysics can rinvigorate the use and scope of the ISS in the next ten years.

5 Balloon-based astro-particle experiments

The satellite and ISS-based program is complementary to the cosmic ray searches with atmospheric balloons, which have been successfully carried out for more than 20 years up to altitudes of 40 Km. These balloon experiments did not find so far any evidence

for anti-matter of primary origin. Spectra of secondary e^+ and \bar{p} have been measured, with increasing statistics and precision, extending the energy range up to 50 GeV ([2] and references therein). LNF personnel from the WIZARD collaboration has carried out balloon experiments from 1989 up to 1998 (the last CAPRICE [15] launch). Details of this work can be found in the 1998 and earlier LNF Annual Activity Reports and in [15].

A milestone experiment, for its high scientific return and relatively low cost is BOOMERANG. The data from the 1998 flight of the BOOMERANG balloon provided a measurement the anisotropy of the Cosmic Microwave Background (CMB), which was superseded only in 2003 by the more precise data of the WMAP satellite. The evolution of BOOMERANG is B2K: “B2K is a new experiment which inherits the technologies of BOOMERANG, and uses a microwave telescope on board of a stratospheric balloon to map the intensity and polarization of the CMB” [10]. “The measurements of CMB anisotropy show that the quadrupole component is small, but non vanishing, so we expect a small degree of linear polarization in the CMB, about 5-10% of the anisotropy” [11]. B2K shares the same goal with a major ESA satellite mission, called PLANCK [12]. Planck is foreseen to be launched in 2007. The first B2K flight occurred on January 6, 2003 from the Antarctic plateau.

An interesting evolution of this type of experiments are ultra long duration balloon (ULDB) flights, up to 100 days. An example of ULDB experiments is CREAM [13], which attempts to measure the hadronic cosmic ray spectrum around 10^{14} - 10^{15} eV, where there is a significant change of slope. “This *knee* has caused much speculation since its discovery over 40 years ago. The origin of this feature remains unknown, but it may suggest that more than one astrophysical process is responsible for cosmic ray acceleration. The bulk of CR are thought to be accelerated in galactic supernovae shocks. A class of models (e.g.: Lagage & Cesarsky, 1983) predict both a cutoff at an approximate maximum energy of $Z \times 10^{14}$ eV, where Z is the particle charge, and an elemental composition of primary cosmic rays shifting towards heavier elements at high energy” [13]. Note that it has been recently proposed [14] that the knee might be explained by the interaction of protons and nuclei with very non-relativistic relic Big Bang anti-neutrinos with mass around $0.5 \text{ eV}/c^2$.

6 Satellite laser-ranging (SLR) experiments

This category of satellites carry on board numerous Corner Cube Reflectors (CCRs), which are used for tracking (“ranging”) their positions along their orbits. CCRs are special mirrors which always reflect an incoming light beam back in the direction it came from. The satellite ranging is achieved by shining from Earth multiple laser beams (each

associated with a telescope for aiming at the satellite) managed by the International Laser Ranging Service (ILRS). The reflected laser beam is also observed with the telescope, providing a measurement of the round-trip distance between Earth and the satellite. A number of ranging experiments during the past three decades have provided important geodesy measurements, including the Earth Gravity Model (EGM) and its time variations.

The ancestor of the SLR technique was the Lunar Ranging RetroReflector (LRRR) Experiment deployed by the Apollo 11, 14 and 15 missions to the Moon (a similar device was on board of the Soviet Union *Lunakhod 2*). This is the only Apollo experiment that is still returning data from the Moon [16]. The laser beam has a 7 Km diameter when it reaches the Moon and about 20 Km back to Earth. The Moon distance has been determined with an accuracy of 3 cm (the average distance from the Earth to the Moon is 384,400 kilometers). The LRRR experiment improved the knowledge of [16]: 1) the Moon's orbit; 2) the rate at which the Moon is receding from Earth (currently 3.8 cm/yr); 3) variations in the rotation of the Moon; 4) changes of the Earth's rotation rate; 5) the precession of the Earth spin axis (18.6-yr "nutation"). In addition, the LRRR data have been used to measure the De Sitter or "geodetic precession" [17] predicted by GR to an accuracy of 0.35%. This shift arises from the effect of the gravitational field on the velocity of an orbiting gyroscope [18].

GR also predicts that a rotating central body like Earth will drag the local space-time around it (*frame dragging*). This effect, predicted by Lense and Thirring (LT) in 1918, will cause the precession of the *node* of an artificial satellite of the Earth (the node, or nodal line, is the intersection of the Earth equatorial plane with the satellite orbit; see fig 2). Note that the LT precession is fundamentally different from the De Sitter precession: while the latter is basically due to the mass of the central non-rotating body, the former is a genuine rotation effect: currents of mass generate additional space-time curvature. This phenomenon is called gravitomagnetism for its close formal analogy with magnetism in electrodynamics [18] [19].

The LT effect has been measured for the first time in 1998 [20] using two laser-ranged satellites: LAGEOS¹ (NASA), launched in 1976 with a Delta-2 rocket and LAGEOS II (NASA-ASI) launched in 1992 with the Space Shuttle. The LAGEOS orbits have a semi-major axis of about 12,000 Km and their LT node shift is just 33 mas/yr (mas = millisecond of arc), that is, 1.9 meter/yr ! With laser-ranging the LAGEOS position can be tracked with a mm-level accuracy and their orbits reconstructed with cm-level instrumental uncertainty. The measured value is in agreement with GR, with an error much larger than the ranging resolution, due to two non-gravitational perturbations (NGP): (1) the de-

¹Laser GEOdynamics Satellite

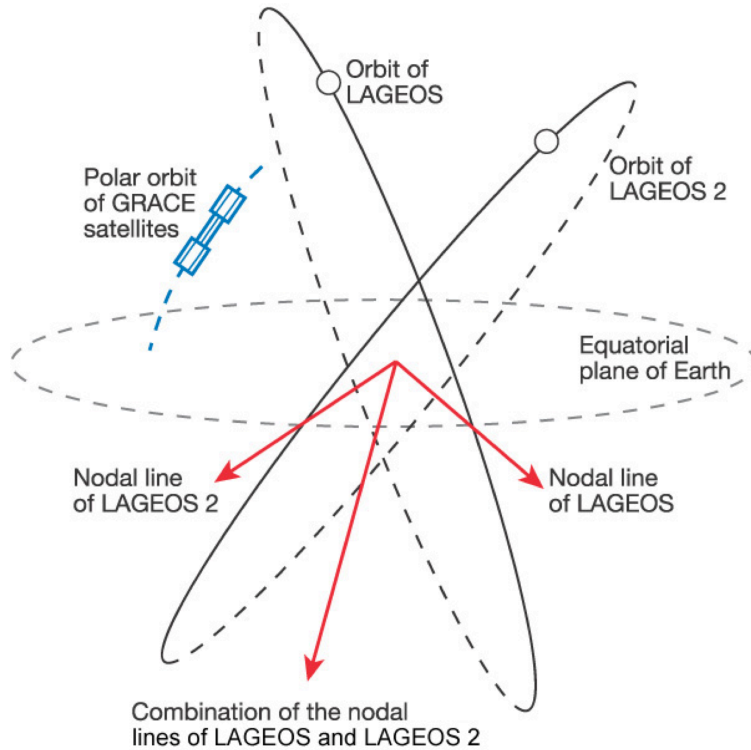


Figure 2: The LAGEOS orbits and nodal lines. The orbit of the two GRACE satellites.

viation of the EGM from the perfect $1/r$ behavior and (2) the thermal thrusts (TTs) that the satellites receive along their orbits. TTs have three basic sources: (i) the direct solar radiation pressure, (ii) the pressure from the solar radiation reflected by Earth (Earth UV albedo) and (iii) the IR radiation from Earth (Yarkovski-Rubincam effect, which dominates the error on LT).

The preliminary 2002 EGM from GRACE data (see following subsection) and a re-analysys of the LAGEOS and LAGEOS II data, allowed a decrease of the LT uncertainty to 10% [18] (see also fig. 2). This is to be compared to the uncertainty of the 1998 result, based on older EMGs (JGM-3 and EGM96), which is generally considered to be in the range 20-40% and “not easy to be confidently assessed” [18].

The Gravity Probe B (GPB) experiment [21], lauched in April 2004 by NASA, is now taking data to measure the LT effect at the 1% level using orbiting gyroscopes (GPB is based on a different and complementary concept to the LAGEOS).

A modern and improved version of the LAGEOS, called LARES/Weber-Sat, is being designed by a Collaboration of Italian and US Universities, the ILRS, INFN-LNF and INFN-Lecce. LARES² will measure LT at 1% or better, taking advantage of the re-

²LASer RELativity experimentS

cent high-accuracy EGMs and exploiting a thorough geometrical, mechanical and thermal characterization and, possibly, a new satellite design to reduce and control TTs. The LNF group has been funded by INFN GR II to perform an R&D work to find a suited satellite structure to strongly suppress TTs and to estimate the residual TTs accurately. An additional physics goal of LARES is the improvement of the limits on the violation of the Einstein Equivalence Principle.

A strong suppressions of the TTs, which are nowadays the limiting NGP, opens the way to studying effects due to new physics on the orbital elements of LARES. For this purpose, perigee shifts are among the most sensitive observables. For example, a recent string-inspired brane model [22] might imply perigee shifts observable after 5 years of ranging data with LARES, with TTs kept under control. This possibility is currently under study. Measuring such an effect for the Moon with Lunar ranging data requires at least a 20-fold improvement of ranging resolution [22] and is complicated by the difficulty of knowing the Moon center of mass, while knowledge of the center of mass is extremely simplified for an spherical artificial satellite like LARES. Models like [22] are on a less firm theoretical ground than GR, but they are still very interesting, also because superstring theories are hoped to offer a way to the quantization of gravity.

6.1 Global Positioning System (GPS)

Currently, two very sophisticated missions, DLR's CHAMP (Challenging Minisatellite Payload [23]), launched in 2000, and the two NASA satellites called GRACE (Gravity Recovery And Climate Experiment), launched in March 2002, are mapping the EGM to unprecedented accuracy.

CHAMP is a small German satellite mission for geoscientific and atmospheric research and applications, managed by GFZ Potsdam. Using an advanced GPS receiver, magnetometer, accelerometer, star sensor, laser retro-reflector, ion drift meter, CHAMP measures how its orbit changes in response to Earth gravitational pull, enabling researchers to map indirectly the density of Earth crust. By mapping the density to a high precision over many years, scientists can detect changes in variables such as seawater level, the thickness of the polar ice caps, and even the density of the atmosphere [23].

The two GRACE satellites are identical spacecrafts, orbiting in the same polar orbit some 200-250 Km apart. They range each other via a K-band radar, they are both equipped with precise accelerometers and both can be tracked by GPS.

In addition to Geodesy and to its use for many astro-particle physics experiments in space, GPS techniques have other applications of outstanding social interest. For example, one of ESA's leading projects in this decade, GALILEO [24], is the large-scale

deployment of GPS info for civil use throughout Europe.

7 Conclusions

Building an astro-particle experiment or satellite for outer space or a balloon for the stratosphere requires on behalf of INFN (and LNF) a significant synergy between resources and personnel which are spread across all scientific groups (GR I to V). In order for this activity to be efficient and strategically convenient for LNF, it must be a project-driven process, with focussed participation. The will of investing into experimental astro-particle physics is justified by the open issues of major and fundamental scientific interest in this field.

- The nature and origin of the unobserved dark energy and dark matter density apparently implied by several current measurements (CMB, large scale structures, Supernove Type Ia) and by the cosmological “Standard Model” of the universe. The SNAP satellite [25] by DOE and NASA (as part of their Joint Dark Energy Mission, JDEM) to be launched around 2012 will improve significantly the accuracy of the measurement of the supernovae acceleration. FERMILAB and especially SLAC, two laboratories with a long HEP tradition are significantly involved in the SNAP project.
- The changes of the slope of the cosmic ray flux spectra around 10^{15} eV (the “knee”), around 3×10^{18} eV (the “ankle”) and the apparent presence of cosmic rays beyond the so-called GZK cutoff at 10^{20} eV. This extreme end of the spectrum is being measured by the ground experiment AUGER [26]. A clear evidence for events beyond 10^{20} eV by AUGER, will help the approval of the EUSO observatory [27] (ESA and the EUSO Consortium), which is designed to measure ultra high energy cosmic rays (UHECR) viewing downward the Earth’s atmosphere from the ISS.
- Currently, the most important test of GR is the on-going direct search for gravitational waves by several existing and proposed experiments, on Earth and in outer space. An additional precision experimental test of GR is the measurement of the frame-dragging effect by GP-B (total cost ~ 700 M\$) and by the proposed precision LARES satellite (estimated cost ~ 1 Meuro). In general, a potential window for new physics and for gravitation theories alternative to GR is the measurement of anomalous perihelion and perigee shifts.

New interest for astro-particle physics in space is emerging at LNF and we hope that the select topics and activities described in this document will be the starting point for future and further work in this field.

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