Within the next two years, two more retroreflectors were brought to the Moon by astronauts from Apollo 14 and Apollo 15 (see Fig. 3). A fourth one came in 1973 with the Soviet Lunakhod II spacecraft. Since then, laser stations on the ground can fire to these reflectors and get enough photons back (in spite of an overall signal loss of about 10^{-21} !) to be able to measure the separation distance from measurement of the round–trip travel times (photons are received about 2.6 *s* after they are sent). The accuracy currently achieved for a range measurement observing session (corresponding to tens of minutes of photon returns) is of 2–3 cm. After almost 30 years of ever–improving quality of data and data analysis, the amplitude of the parallactic inequality relevant for testing the Equivalence Principle is measured to a precision of 1.3 cm, allowing scientists to conclude that any deviation of the Earth and the Moon from the Universality of Free Fall (i.e. any fractional difference of their accelerations toward the Sun) must be less than $5\cdot10^{-13}$ [16, 17].

If one could rule out any composition–dependent violation of Equivalence for the Earth and the Moon, then this result could only be interpreted as proving that the gravitational binding energies of the Earth and the Moon contribute equally to their gravitational and inertial masses to about 1 part in 10^3. However, the Earth and the Moon do have different composition. The average composition of the Earth is dominated by its iron–nickel core, while the composition of the Moon is closer to that of the (less dense) Earth mantle, primarily made of silicates. Unless iron–nickel on one side and silicates on the other do accelerate the same in the gravitational field of the Sun (and to an accuracy comparable to that of the laser ranging test), Lunar Laser Ranging data cannot be interpreted without ambiguity as a test of how equally gravitational binding energies of the Earth and the Moon contribute to their gravitational and inertial masses

This ambiguity has recently been removed thanks to experiments carried out at the University of Washington, in Seattle, with "miniature" earths and moons placed on a continuously rotating torsion balance whose twist data have been analyzed for any deviations from the Universality of Free Fall with respect to the Sun [5]. The composition of the test bodies was chosen for them to resemble, to the best of current knowledge, the core of the Earth and its mantle. Improvements in the apparatus have allowed a sensitivity of a few 10^{-13} in the measurement of fractional differences in the acceleration of the test bodies toward the Sun, which is good enough for the ambiguity of Lunar Laser Ranging data to be resolved

5 Recent and ongoing laboratory experiments

A re–analysis of the Eötvös experiments carried out by [18] in 1986 has had the merit to draw the attention of a large number of scientists from all over the world to the Equivalence Principle and to the measurement of the universal constant of gravity. In relation to the Equivalence Principle the authors made the point that the most accurate tests available at the time –those carried out in Princeton [12] and in Moscow [13]– had checked for violation of Equivalence in the gravitational field of the Sun, thus over a range of 1 *AU*, while the old Eötvös tests at the turn of the century were still the most accurate ones as far as tests in the gravitational field of the Earth are concerned.

Since then, the most systematic and successful experiments on the Equivalence Principle are the so called "Eöt–Wash" experiments carried out by the group of E. Adelberger at the University of Washington in Seattle. The *Eöt–Wash* apparatus is a torsion balance operated at room temperature with small test cylinders (10 *g* each) placed on a turntable whose rotation provides a modulation of the expected signal with the period of about 1*hr*. Frequency modulation is crucial in order to check for violation in the field of the Earth (or of a local mass nearby), otherwise the signal would be DC and therefore very hard to detect, like in the Eötvös experiments. Moreover, the turntable can rotate quite fast, thus increasing the modulation frequency of the signal by about 24 times with respect to [12, 13]. However, should any local mass anomaly couple differently with the test bodies (i.e. because of their different multipole mass moments), the corresponding differential acceleration will also be modulated at the rotation frequency of the turntable. This would obviously not happen in the experiments [12, 13], where the modulation of the signal (in the field of the Sun) is provided by the rotation of Earth itself and the effect of any local mass anomaly is DC. The procedure set up by the *Eöt−Wash* group to deal with this issue is to first use *ad-hoc* test cylinders in which the various multipole moments (starting from those of lower degree) have been amplified in order to amplify the corresponding effects caused by mass anomalies close by (but also in the region around the laboratory). Then, a variable distribution of masses is set up around the torsion balance to be adjusted (on the basis of numerical calculations as well as of direct measurements) until those effects are canceled. By a careful procedure of successive iterations it is possible to select an appropriate mass distribution that minimizes the perturbations from local mass anomalies on the torsion balance, and the instrument is ready to mount the cylinders devoted to testing the Equivalence Principle. Helmholtz coils and μ−metal shielding are needed in order to reduce the torque caused by the magnetic field of the Earth interacting with the residual magnetic moment of the tray. This is a typical need of torsion balance experiments because they are based on the measurement of a torque.

No violation has been detected, and the sensitivity of the experiments has steadily improved: from 1 part in 10^{11} in 1990 [3] to about 1 part in 10^{12} in 1994 [4], to about 1 part in 10^{13} in 1999 [5]. In [3, 4] data were checked for violation of Equivalence in the field of the Earth with test bodies made of Be/Al and Be/Cu. In [5] the source mass was the Sun and the test bodies were manufactured to simulate the difference in composition between the Earth and the Moon, in order to remove the ambiguity of Lunar Laser Ranging tests of the Equivalence Principle, as discussed in the previous Section.

Other research groups are carrying out torsion balance experiments to test the Equivalence Principle. In India [19] the apparatus is located underground at a remote site characterized by a very low level of seismic noise; the torsion balance has the shape of a ring, with two halves of different materials, much more massive than in the *Eöt−Wash* balance (1.5 *kg* each). The balance does not rotate and data (measurements of the deflection angle) are checked for violation of Equivalence in the gravitational field of the Sun, as in [12, 13]. The instrument is very sensitive and the laboratory itself has been very carefully constructed for such sensitive measurements. However, systematic effects apparently related to daily variation of atmospheric pressure still need to be taken care of.

R. Newman [20], from the University of California at Irvine, leads the only group that is attempting to set up a cryogenic torsion pendulum for gravitational experiments, the expected advantages being: reduced thermal noise, reduced temperature sensitivity, improved temperature control and possibly also improved characteristics of the suspension fibre. In addition, the experiment is operated at a very remote site, in a former missile bunker where the microseismic noise power spectrum is about two orders of magnitude less than that at Irvine.

At the University of Washington, Seattle, P. Boynton [21] is working on a torsion pendulum for testing Newtonian gravity at room temperature. The accent in this case is on the use of a new observable (the second harmonic amplitude of the pendulum motion) that provides measurement of extremely small torques with significant freedom from effects that may limit the traditional, non-cryogenic applications of the torsion pendulum.

A new version [22] of the classical mass dropping Galileo–type experiment has been initiated by Italian scientists from the University of Pisa after the publication of [18]. Rather than dropping separate masses of different composition, the authors drop a (vertical) disk whose two halves are made of Al and Cu respectively (350 *g* each, with a drop height of about 4 *m*): any deviation from the Universality of Free Fall would cause an angular acceleration of the free falling disk around its axis and such a motion can be accurately measured by means of a modified Michelson interferometer in which the two arms terminate at two corner–cube reflectors mounted on the rim of the disk. The original goal of the experiment was to test for any composition dependent effect in the range between 10 *km* and the radius of the Earth. The experiment reached the sensitivity $\Delta g/g=7.2\cdot 10^{-10}$ finding no deviation from the Universality of Free Fall. It is interesting to note that the same experiment has been performed also with a homogeneous disk, which should obviously result in a zero signal.

A short distance test of the Equivalence Principle based on the torsion balance has been performed more recently [23] by the *Eöt–Wash* group using a large rotating source mass (3 *ton* of ^{238}U) and checking for its effect on a torsion balance with test cylinders in Cu/Pb. The balance was sensitive to a relative differential acceleration $\Delta a/a \cong 10^{-9}$ from the rotating source mass and the result helped to set better limits on new composition-dependent interactions in the distance range from 10 to 10000 *km*.

6 Advantages of an Equivalence Principle experiment in low Earth orbit

The advantage of performing an Equivalence Principle test in low Earth orbit is a *driving signal* about *3* orders of magnitude bigger than in ground laboratories. If test bodies of different composition orbit around the Earth at an altitude *h,* a violation of Equivalence η would make them fall differently toward the Earth, with a differential acceleration (one with respect to the other):

$$a_{EP} = \eta \cdot \frac{GM_\oplus}{(R_\oplus + h)^2} \qquad (a_{EP} \cong \eta \cdot 840\ cm \cdot s^{-2} \quad for \quad h \cong 500\,km) \tag{19}$$

By comparison with Equivalence Principle experiments in which the test bodies are suspended against local gravity on the surface of the Earth this effect is –for the same value of the Eötvös parameter η – 500 or 1400 times bigger, depending on whether ground experiments consider the Earth or the Sun as the source mass (see (5) and (10)).

Another advantage of a space experiment is the absence of weight in orbit. The largest acceleration inside the orbiting laboratory (the spacecraft) is about 100 *million* times smaller than the local acceleration of gravity on the surface of the Earth. The goal of the experiment being the detection of an extremely small acceleration (η << 1 in (19)), this is obviously an advantage. In addition, in a space experiment the only nearby mass that can disturb the experiment is the mass of the spacecraft itself, which can be better controlled.