Constraining Spacetime Torsion with Lunar Laser Ranging, Mercury Radar Ranging, LAGEOS, next lunar surface missions and BepiColombo

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17th International Laser Workshop on Laser Ranging - Bad Koetzting, Germany, May 16-20, 2011

* Presented by S. Dell'Agnello

Outline

- Introduction
- Spacetime torsion predictions
- Constraints with Moon and Mercury
- Constraints with the LAser GEOdynamics Satellite (LAGEOS)
- LLR prospects and opportunities
- Conclusions

- In the spare slides: further reference material
- See also talk of Claudio Cantone (ETRUSCO-2), talk and poster by Alessandro Boni (LAGEOS Sector, Hollow reflector) and, especially, the talk of Doug Currie (LLR for the 21st century)

INFN (brief and partial overview)

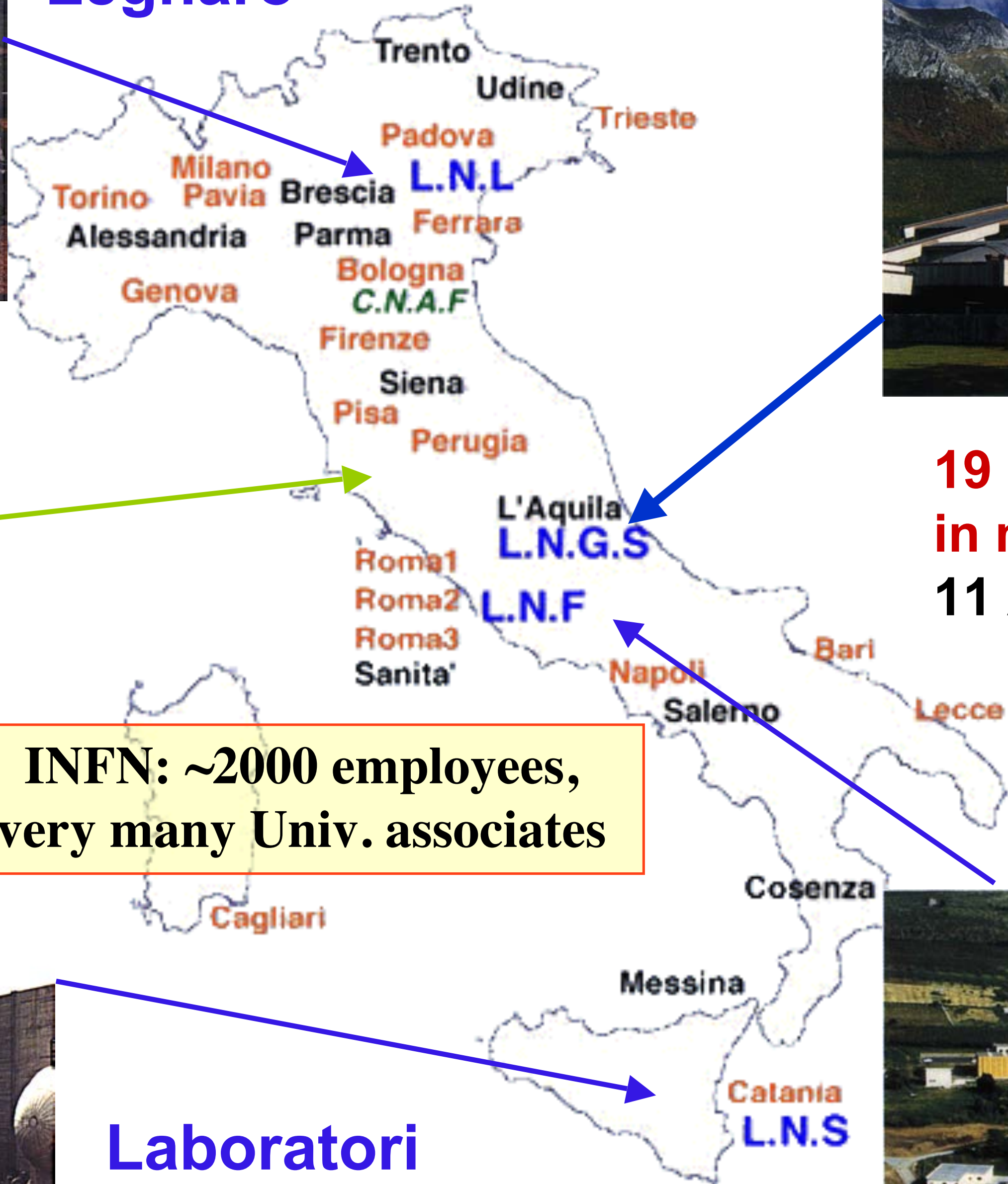
- INFN; public research institute
  - Main mission: study of fundamental forces (including gravity), particle, nuclear and astroparticle physics and of its technological and industrial applications (SLR, LLR, GNSS, space geodesy…)
- Prominent participation in major astroparticle physics missions:
  - FERMI, PAMELA, AGILE (all launched)
  - **AMS-02**, to be launched by **STS-134 Endeavor to the International Space Station (ISS)** on May 16, 2011
- **VIRGO**, gravitational wave interferometer (teamed up with LIGO)
- …. More, see http://www.infn.it

INFN-LNF (brief and partial overview)

- Located in Frascati, near Rome, next to ESA-ESRIN (which includes the ASI Science Data Center, ASDC), and to INAF-IFSI. Well connected to Rome airports and train stations
- Large-scale Infrastructure of the "European Research Framework Programme (FP)"
- Largest physics national lab in Italy
  – Several particle accelerator facilities and experiments
  – Gravitational bar antenna
  – Space facility **SCF: SLR/LLR Characterization Facility**
  – … More, see http://www.lnf.infn.it

Legnaro

Gran Sasso (underground lab)



19 Sites ("Sezioni") in major cities

11 Associated sites

4 National Labs

VIRGO-EGO

European
Gravitational
Observatory

INFN: ~2000 employees, very many Univ. associates

Laboratori del Sud (Catania)

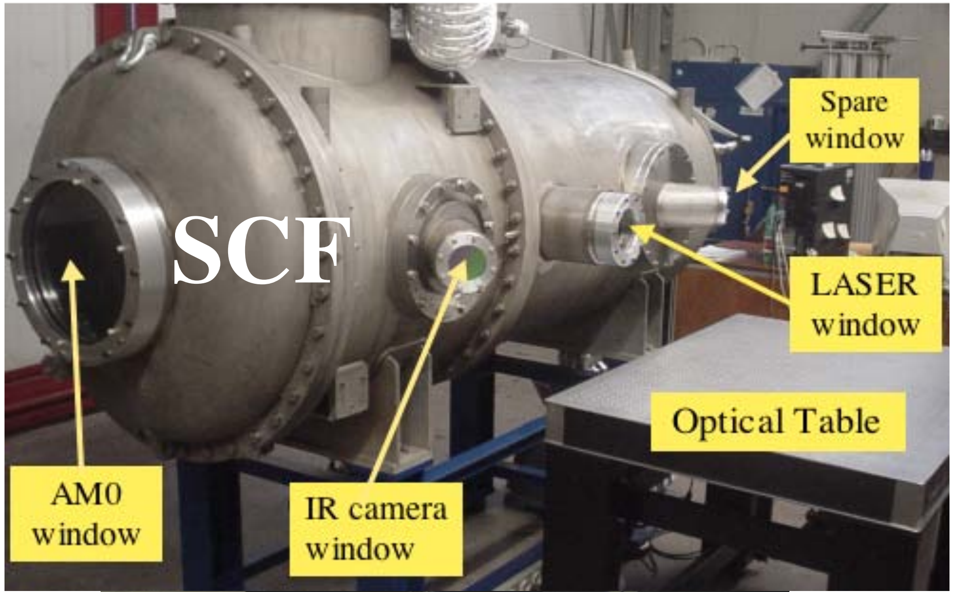
Current SCF research activities

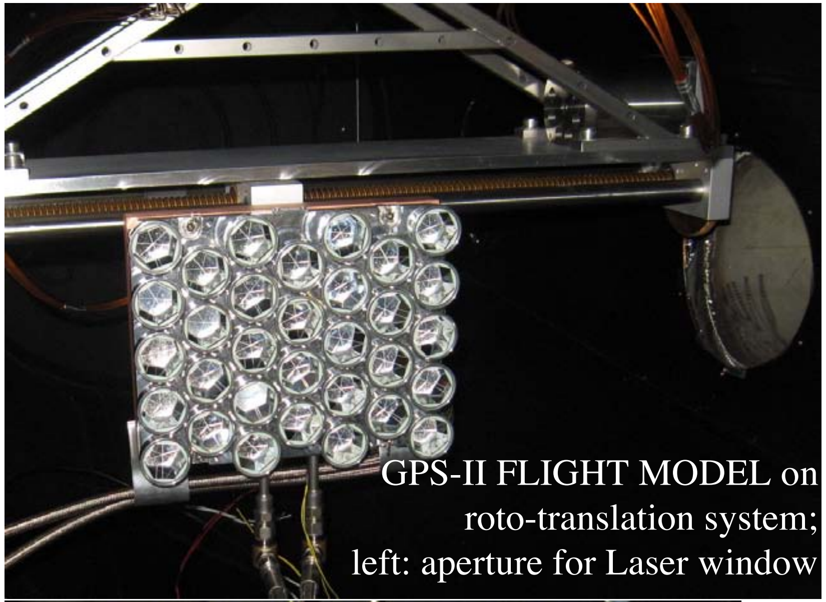
- Our approved projects:
  - **MoonLIGHT-ILN** (LLR) ==> See talk by Doug Currie
    - LLR analysis effort using CfA's Planetary Ephemeris Program (PEP)
  - **ETRUSCO-2** (SLR of GNSS and LAGEOS) ==> See talks and poster by Claudio Cantone, Alessandro Boni

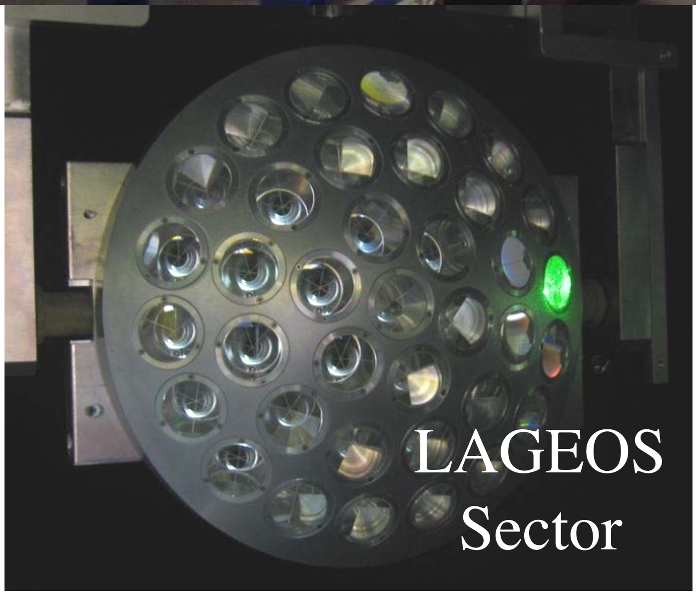
- Study of new gravitational physics theories: theoretical predictions and experimental test

- We collaborate with:
  - Italian Air Force, ASI-CGS@Matera, University of Maryland, Harvard-Smithsonian Center for Astrophysics (CfA), NASA-GSFC, NASA Lunar Science Institute (NLSI), UCSD, International Lunar Network (ILN) …

SLR/LLR Characterization Facility (SCF)







Constraining spacetime torsion with the Moon and Mercury

Theoretical predictions and experimental limits on new gravitational physics

Extension of work by *Y. Mao, M. Tegmark, A. H. Guth and S. Cabi*, PRD 76, 1550 (2007)
[indicated ad **MTGC**]

PHYSICAL REVIEW D **83,** 104008 (2011)

Constraining spacetime torsion with the Moon and Mercury

We report a search for new gravitational physics phenomena based on Riemann-Cartan theory of general relativity including spacetime torsion. Starting from the parametrized torsion framework of Mao, Tegmark, Guth, and Cabi, we analyze the motion of test bodies in the presence of torsion, and, in particular, we compute the corrections to the perihelion advance and to the orbital geodetic precession of a satellite. We consider the motion of a test body in a spherically symmetric field, and the motion of a satellite in the gravitational field of the Sun and the Earth. We describe the torsion field by means of three parameters, and we make use of the autoparallel trajectories, which in general differ from geodesics when torsion is present. We derive the specific approximate expression of the corresponding system of ordinary differential equations, which are then solved with methods of celestial mechanics. We calculate the secular variations of the longitudes of the node and of the pericenter of the satellite. The computed secular variations show how the corrections to the perihelion advance and to the orbital de Sitter effect depend on the torsion parameters. All computations are performed under the assumptions of weak field and slow motion. To test our predictions, we use the measurements of the Moon's geodetic precession from lunar laser ranging data, and the measurements of Mercury's perihelion advance from planetary radar ranging data. These measurements are then used to constrain suitable linear combinations of the torsion parameters.

Constraining spacetime torsion with the Moon and Mercury

Theoretical predictions and experimental limits on new gravitational physics

Spacetime torsion described at order higher than MTGC, by three dimensionless torsion parameters, $\mathbf{t_1}$, $\mathbf{t_2}$, $\mathbf{t_3}$ (we added t_3 compared to MTGC). General approach, no specific model assumed

These 3 parameters (and the other, frame draging parameters, described in the next slides) combine with the PPN to determine the gravitational physics of several types of solar system natural bodies and artificial satellites.

Therefore, we used data from past and present space missions to test (to limit, to constraint) the torsion parameters. We also showed how future mission will improve this search

Value of t_1 fixed by imposing validity of newtonian limit of the theory

We demonstrated that Mercury's perihelion precession depends on torsion, unlike in the MTGC paper

Constraining spacetime torsion with the Moon and Mercury

Theoretical predictions and experimental limits on new gravitational physics

Extension of work by *Y. Mao, M. Tegmark, A. H. Guth and S. Cabi*, PRD 76, 1550 (2007) [indicated ad **MTGC**] and correction of their error on Mercury's perihelion advance

LLR measurement of the lunar geodetic precession (deviation from general relativity):

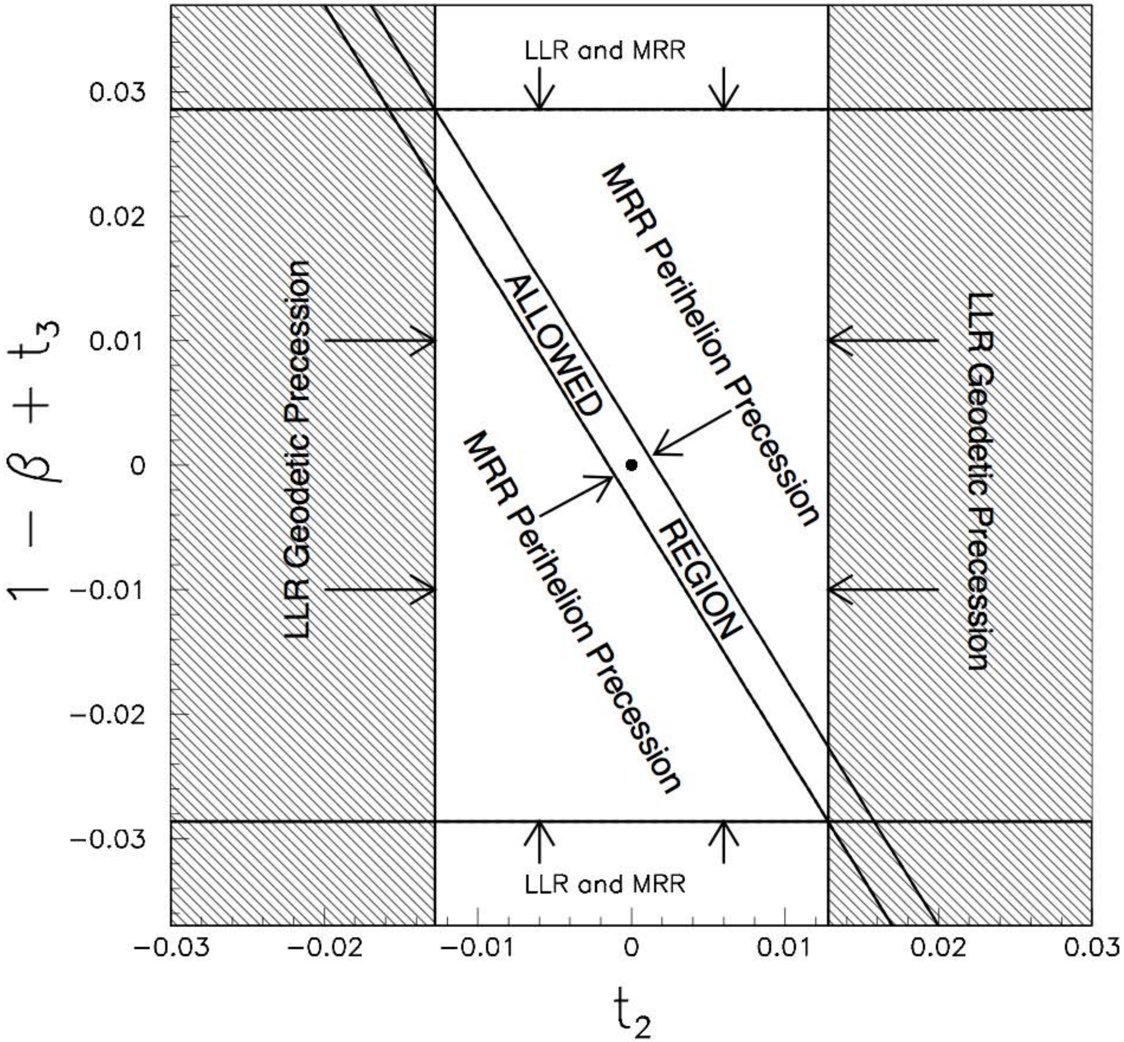
K_{gp} = -0.0019+/- 0.0064

J. G. Williams, S. G. Turyshev, and D. H. Boggs, PRL 93, 261101 (2004)

MRR measurement of Mercury perihelion precession (deviation from general relativity):

0.1% accuracy on (β-1)

I. I. Shapiro, Gravitation and Relativity 1989, edited by N. Ashby, D. F. Bartlett, and W. Wyss (Cambridge University Press, Cambridge, England, 1990), p. 313.



Constraining spacetime torsion with the Moon, Mercury, Gravity Probe B, more MRR data and BepiColombo

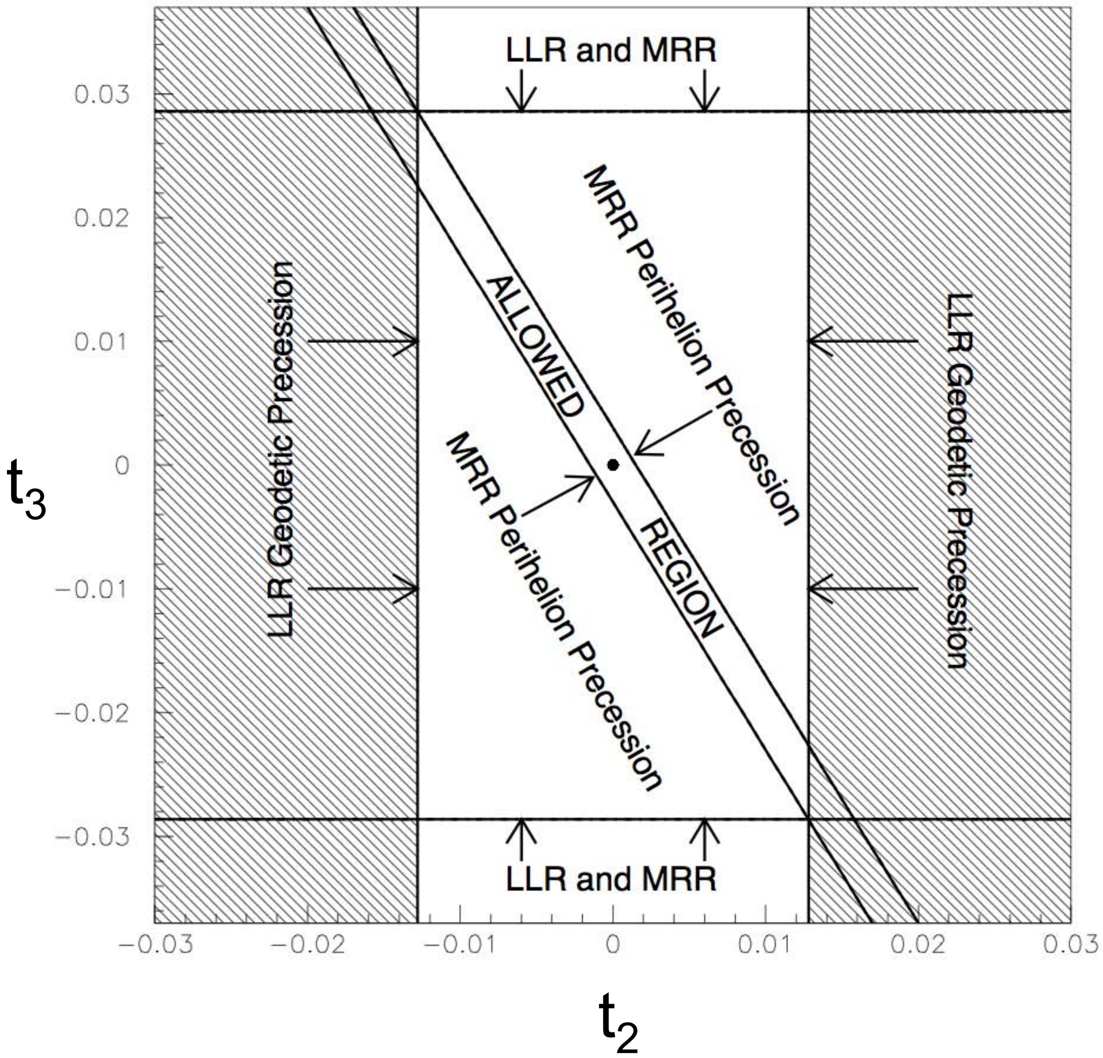
If Nordtvedt effect assumed: with LLR $|\beta\text{-}1| < 1.1\times10^{-4}$ (PRL 93, 261101 (2004)) **==> direct limit on t_3 +2 t_2**

Geodetic precession (GP) plays special role, because measured with very different techniques:

- Continuing LLR of Apollo/Lunokhod and by high accuracy APOLLO
- Next lunar surface missions
- New, better LLR payloads
- GPB
- BepiColombo (ESA, JAXA …)

<u>Further improvements</u>:

- 10 years of MRR data taken after 1990 and so far not analyzed



Constraining spacetime torsion with BepiColombo

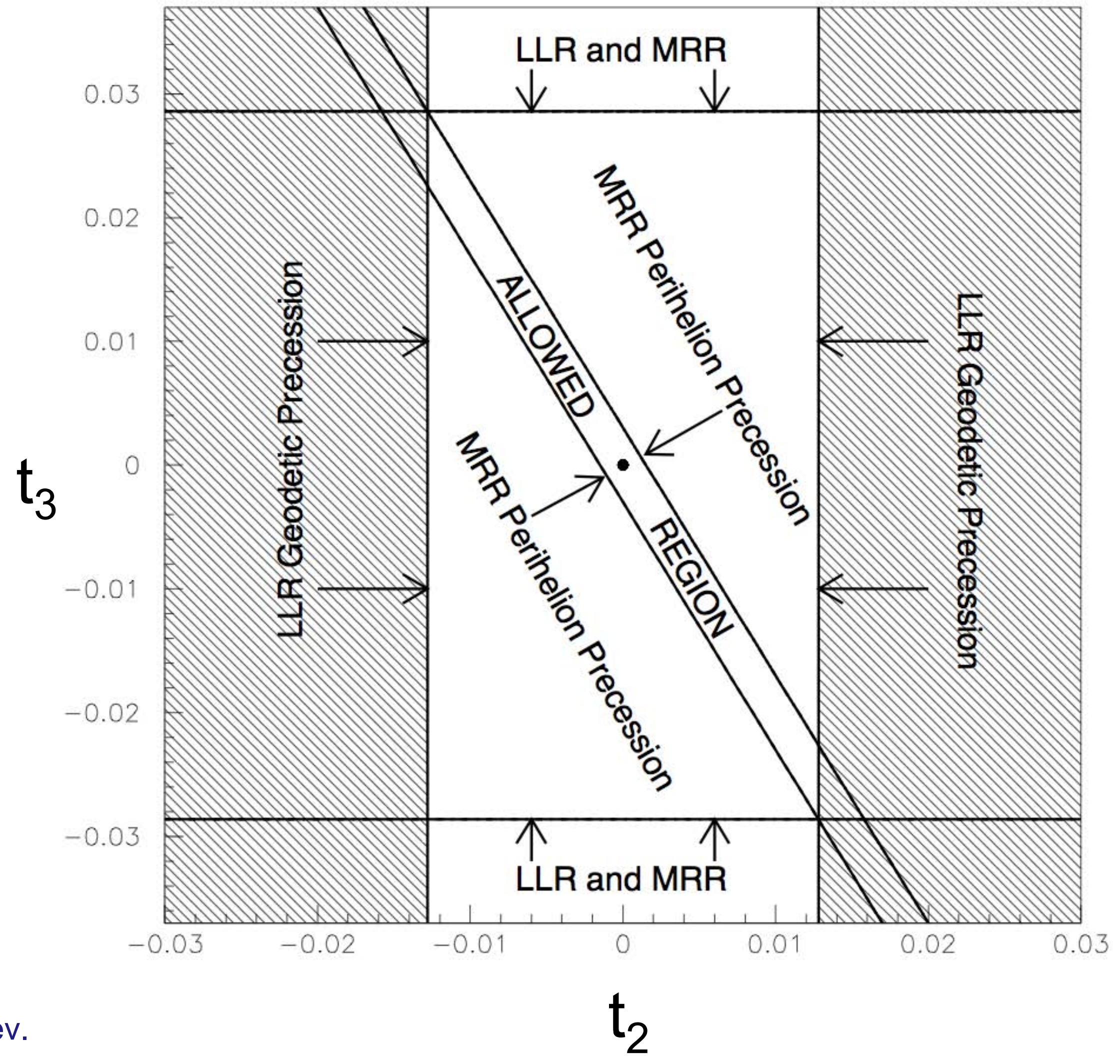
Further improvements with BepiColombo:

- GP for Mercury is larger, ~20”/cy compared to ~2”/cy for the Moon

- Two orbiters very precisely tracked by radio science (RS, @cm level)

- Several years of mission

- New MRR, simultaneous with BepiColombo, would greatly protect from systematic effects from the two techniques (MRR, RS), whose space segment, at least, is dramatically different (orbiters and planet itself)



<u>Physics papers on BepiColombo</u>:

A. Milani et al., Phys. Rev. D 66, 082001 (2002)

N. Ashby, P. L. Bender, and J. M. Warh, Phys. Rev. D 75, 022001 (2007)

Constraining spacetime torsion with LLR, Gravity Probe B and LAGEOS nodal rate

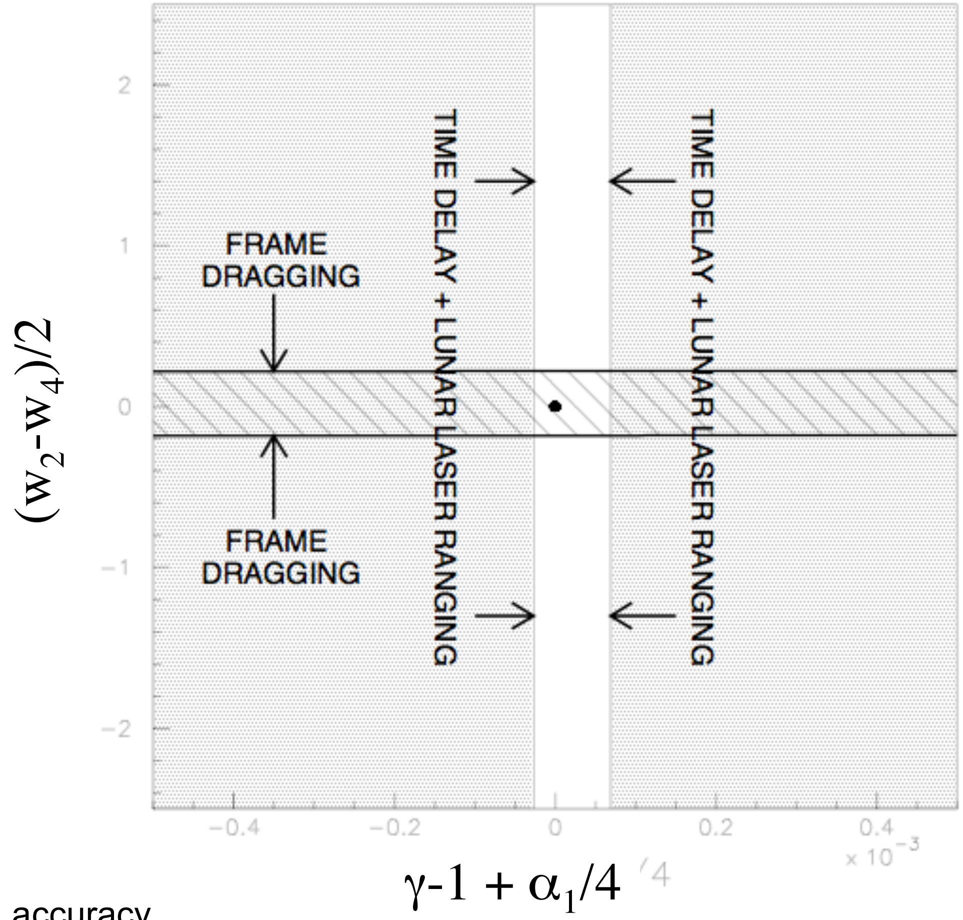
arxiv:1101.2791v2 [gr-qc]

Gedetic Precession needs to be subtracted to measure both Lense-Thirring (LT) effect and to set torsion limits with LAGEOS. GPB, instead, has measured separately GP & LT

GPB and LAGEOS are complementary LT and torsion experiments. They constrain different linear combinations of 5 additional parameter of the theory, which describe additional FRAME DRAGGING due to SPACETIME TORSION:

$w_1+w_2+w_3-2w_4+w5$ (GPB)

$(w_2-w_4)/2$ (LAGEOS, node)



Using published 10% accuracy on LT (Ciufolini, Pavlis 2004)

Constraining spacetime torsion with LLR, Gravity Probe B and LAGEOS nodal & perigee rates

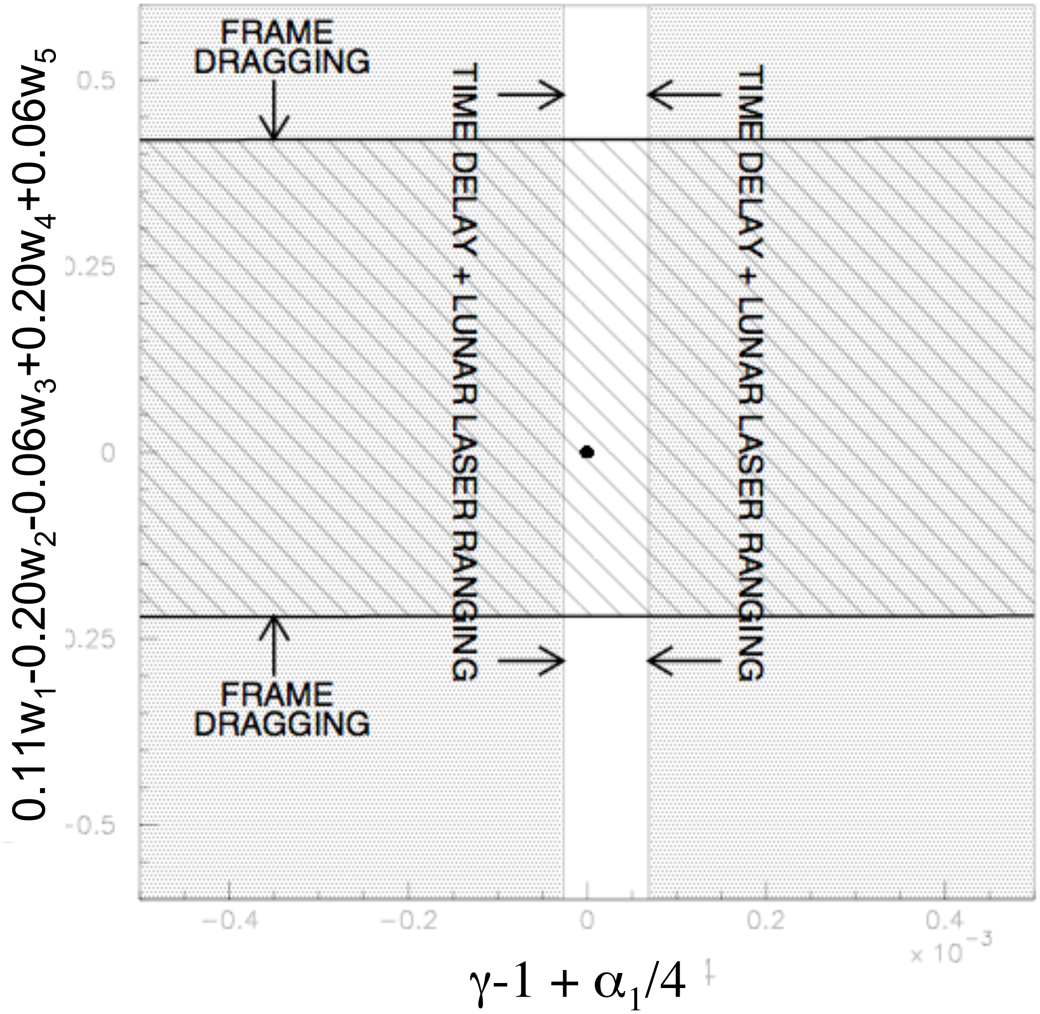
arxiv:1101.2791v2 [gr-qc]

Using published 32% accuracy on LT (D. Lucchesi), and 1998 measurement of LT (Ciufolini et al)

GPB and LAGEOS constrain different linear combinations of the 5 FRAME DRAGGING TORSION PARAMETERS:

$w_1+w_2+w_3-2w_4+w5$ (GPB)

$0.11w_1-0.20w_2-0.06w_3+0.20w_4+0.06w_5$ (LAGEOS, node+perigee)



International Lunar Network (ILN) concept

http://iln.arc.nasa.gov/ Nine Countries

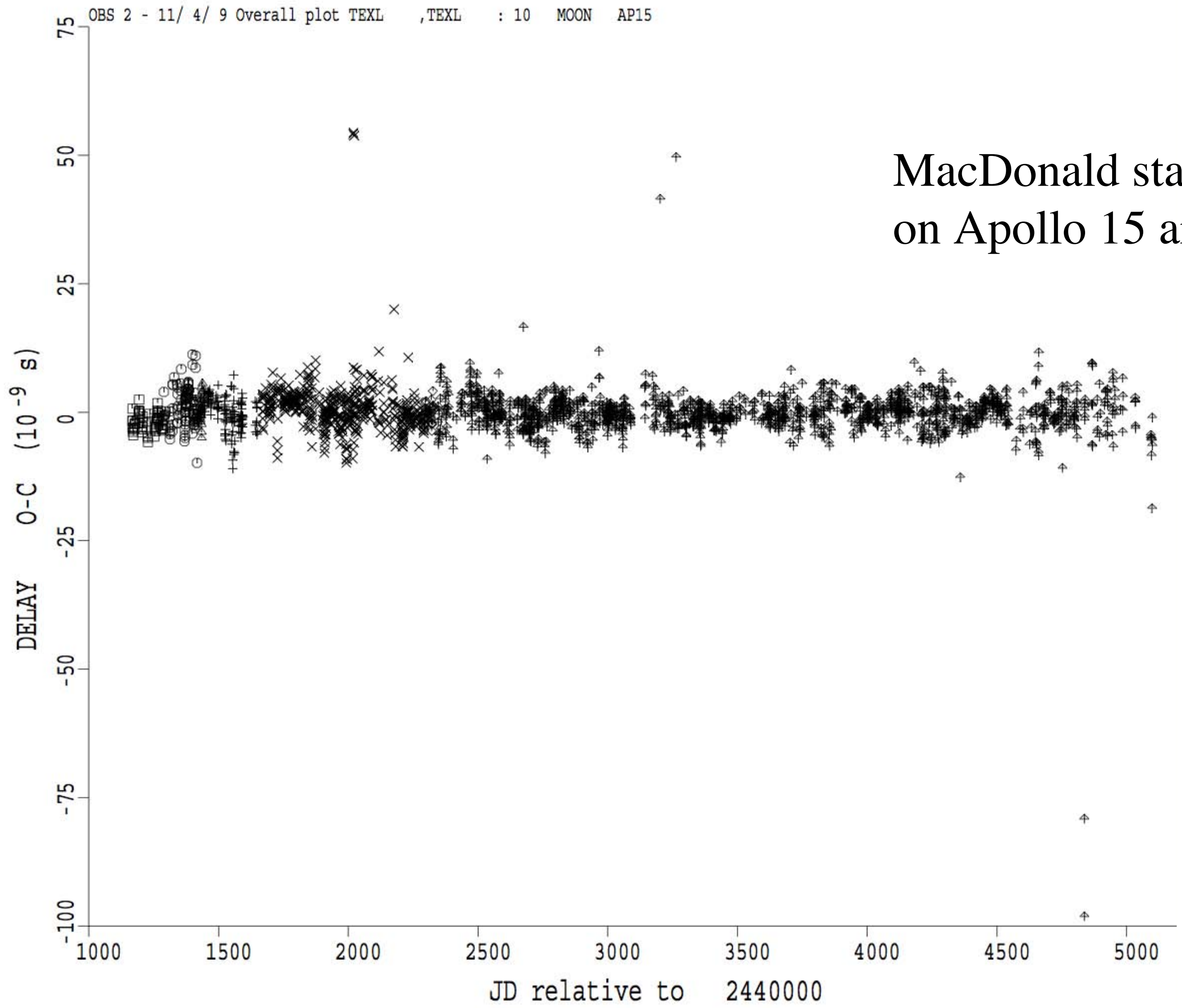
40 years of 'LLR' test of General Relativity

(Logo by NASA)

Lunar Geophysics Network (LGN) of multi-site simultaneously operating instruments:

- –Seismometer
- –Thermal heat flow probe
- –E&M Sounder
- –**Lunar Laser Ranging payload**

LLR O-C residuals' analysis with PEP

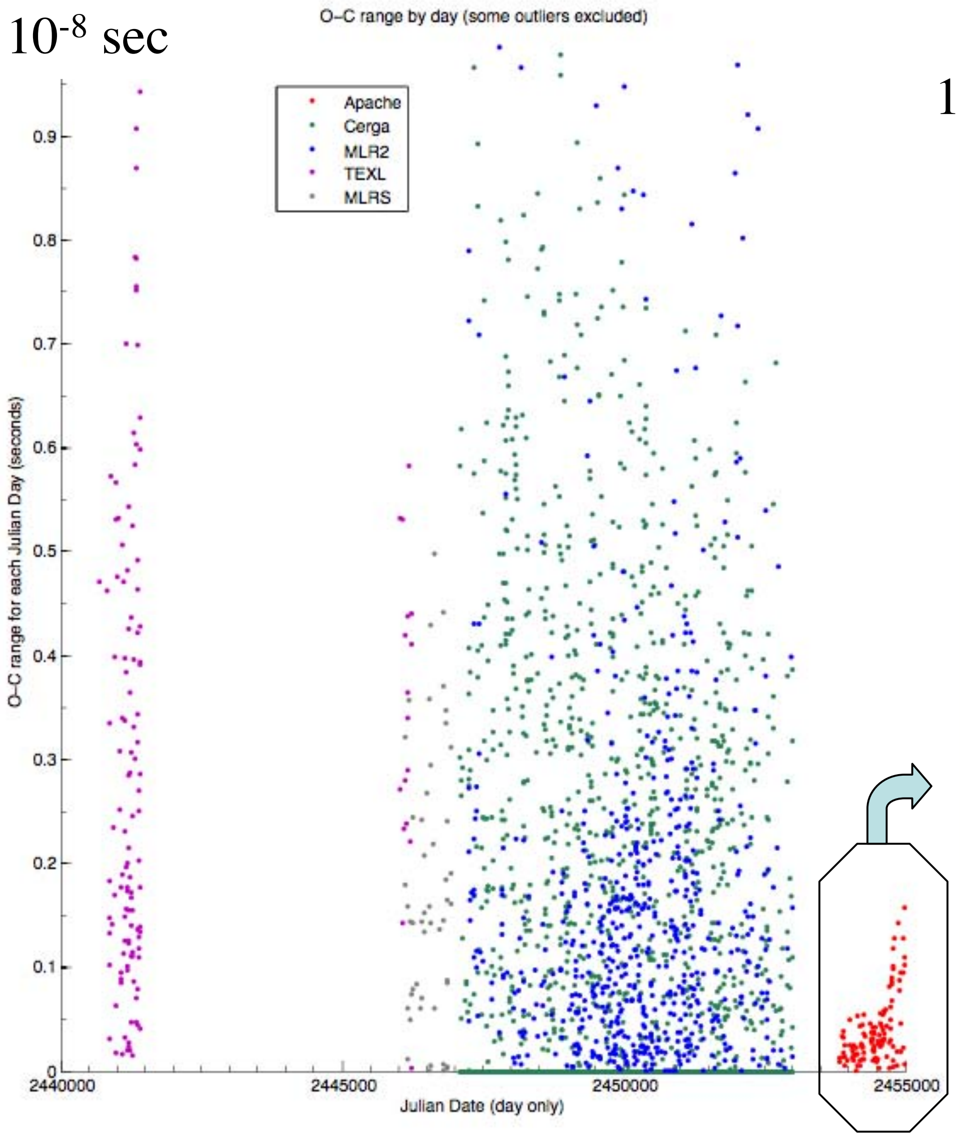


MacDonald station
on Apollo 15 array

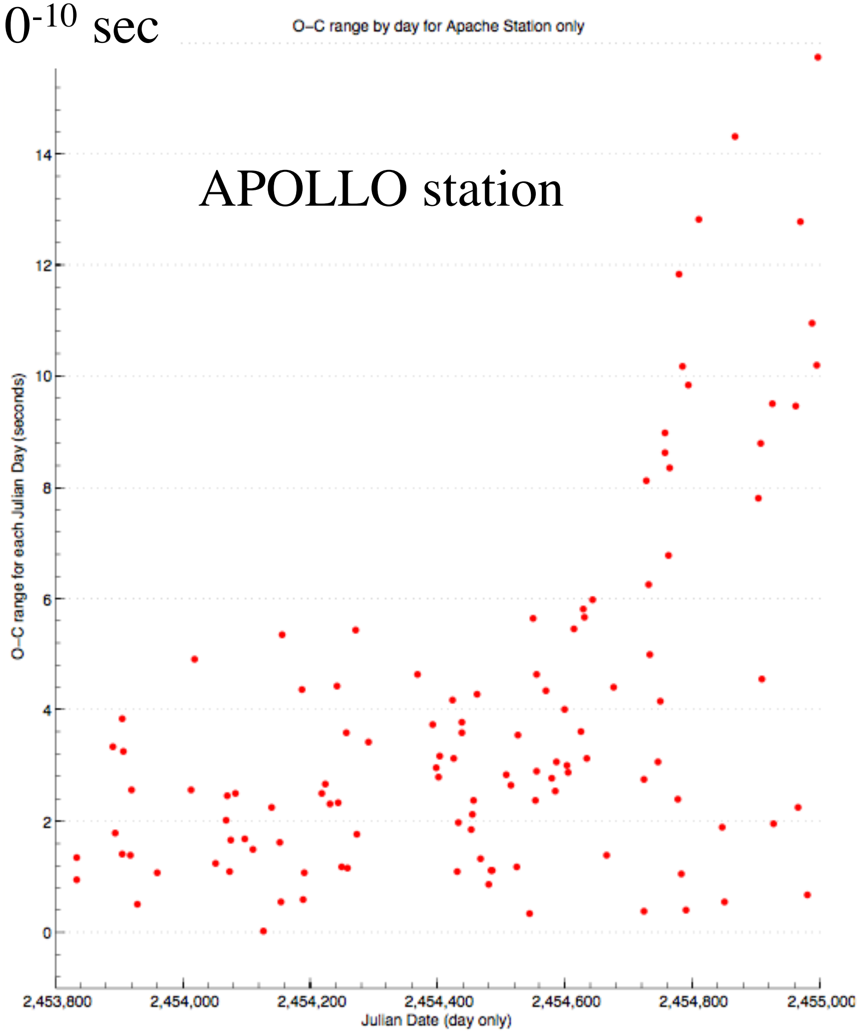
|(O-C)$_i$-(O-C)$_j$| for all arrays i,j with PEP

Sensitive to station accuracy, Earth rotations and Lunar librations

10^{-8} sec



10^{-10} sec



LLR prospects and opportunities

- **NASA PSD** (Planetary Science Division) plan to respond to Decadal Survey, recommendations for the Moon:
  - Lunar Geophysics Network (LGN), following the ILN concept, identified as one of the two priorities for a 'New Frontier' mission
- Other lunar landing missions, like JAXA's Selene-2
- New experimental frontier:
  - Univ. of Maryland (PI) and INFN-LNF are developing a new generation LLR uncoated payload since several years, LLRRA21/MoonLIGHT, see talk by D. Currie
  - INFN-LNF is **DOUBLING the SCF** (= SCF + SCF-G) and **EXTENDING the power of the SCF-Test** significantly

Frascati Mini-Workshop on 2nd Generation Lunar Laser Ranging

INFN-LNF, March 25, 2010

Highlights

Talks were held while, at the same time, 24x7 shifts were done in Frascati by the LNF group to SCF-Test the "MoonLIGHT/LLRRA21" cube corner retroreflector (solid, Suprasil 1, 100 mm diameter)!!

On that same night, in Matera, MLRO observed 6 LLR Normal Points!! Analysis is in progress in the US and Italy…

Program

10:00 Introduction and goals of the "MoonLIGHT-ILN" INFN Experiment
Simone Dell'Agnello (LNF)

10:15 MoonLIGHT/LLRRA21: payload design and SCF-Test
Doug Currie (Univ. of Maryland), Giovanni Delle Monache (LNF)

10:45 APOLLO: operation, timing, lunar dust
Tom Murphy (Univ. of California at San Diego)

12:00 First look at LLR residuals with PEP at LNF
Manuele Martini (LNF)

12:30 Lunch at the Cafeteria

13:30 Photo at the SCF and tour of DAFNE/KLOE

14:00 Search for new physics with CfA's PEP software
James Battat (MIT, representing also CfA)

15:15 LLR and Gravitomagnetism
Tom Murphy (Univ. of California at San Diego)

16:00 Coffee break

16:30 General discussion on status and new opportunities
All

Frascati 2nd Generation LLR Mini-workshop photo

March 25, 2010, outside the SCF lab, during 24x7 shifts for the SCF-Test of the "MoonLIGHT/LLRRA21" CCR

Small photos: people absent, on SCF night shifts or training for flight STS-134, May 16, 2011

Conclusions
Spacetime torsion: a practical example of search for new physics with solar system experiments

In conclusion, our two papers and MTGC's show that a new gravitational model described by several parameters can be tested by a combination of different solar system experiments and experimental techniques, like:

LLR
MRR
GPB gyros
LAGEOS
Lunar Geophysics Network (realization of the **ILN** concept)
BepiColombo mercury orbiters.

We do not know where new (gravitational) physics will manifest itself and how. This study, continuing the work by MTGC and extending the PPN formalism, shows a practical example to tackle this challenging, but important tasks, even in the difficult case of several parameters.

Main Reference Documents

- [RD-1] Dell'Agnello, S., et al, Creation of the new industry-standard space test of laser retroreflectors for the GNSS and LAGEOS, J. Adv. Space Res. **47** (2011) 822–842.
- [RD-2] P. Willis, Preface, Scientific applications of Galileo and other Global Navigation Satellite Systems (II), J. Adv. Space Res., **47** (2011) 769.
- [RD-3] D. Currie, S. Dell'Agnello, G. Delle Monache, A Lunar Laser Ranging Array for the 21st Century, Acta Astron. **68** (2011) 667-680.
- [RD-4] Dell'Agnello, S., et al, Fundamental physics and absolute positioning metrology with the MAGIA lunar orbiter, Exp Astron DOI 10.1007/s10686-010-9195-0. ASI Phase A study. Work under Contract INAF-RHI n. 20080508-1 for the Phase A Study of the ASI Small Mission MAGIA
- [RD-5] Dell'Agnello, S. et al, A Lunar Laser Ranging Retro-Reflector Array for NASA's Manned Landings, the International Lunar Network and the Proposed ASI Lunar Mission MAGIA, Proceedings of the 16th International Workshop on Laser Ranging, Space Research Centre, Polish Academy of Sciences Warsaw, Poland, 2008.
- [RD-5] March, R., Bellettini, G., Tauraso, R., Dell'Agnello, S., Constraining spacetime torsion with the Moon and Mercury, Physical Review D **83**, 104008 (2011)
- [RD-7] March, R., Bellettini, G., Tauraso, R., Dell'Agnello, S., Constraining spacetime torsion with LAGEOS, arxiv:1101.2791v2 [gr-qc], 24 Feb 2011.
- [RD-8] International Lunar Network (http://iln.arc.nasa.gov/), Core Instrument and Communications Working Group Final Reports:

  http://iln.arc.nasa.gov/sites/iln.arc.nasa.gov/files/ILN_Core_Instruments_WG_v6.pdf

  http://iln.arc.nasa.gov/sites/iln.arc.nasa.gov/files/WorkingGroups/WorkingGroups2.pdf

LLR: Precision Tests of General Relativity

Best test with a single experiment

- Best measurement of relativistic geodetic precession of lunar orbit, a true three-body effect (3m ± 1.9 cm)/orbit (0.64% error)
- Violation of: Weak (composition dependent) and, through the Nordtvedt effect, Strong Equivalence Principle (related to gravitational self-energy)
- Parametrized Post-Newtonian (PPN) parameter β, measures the non-linearity of gravity. In RG β=1
- Time variation of universal gravitational constant G
- Best tests inverse square law ($1/r^2$)

J. G. Williams, S. G. Turyshev, and D. H. Boggs, PRL 93, 261101 (2004)

Science measurement	Time scale	1st Generation accuracy (cm)	2nd Gen 1 mm	2nd G. 0.1 mm
Parameterized Post-Newtonian (PPN) β	Few years	$\lvert\beta-1\rvert<1.1\times10^{-4}$	10^{-5}	10^{-6}
Weak Equivalence Principle (WEP)	Few years	$\lvert\Delta a/a\rvert<1.4\times10^{-13}$	10^{-14}	10^{-15}
Strong Equivalence Principle (SEP)	Few years	$\lvert\eta\rvert<4.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
Time Variation of the Gravitational Constant	~5 years	$\lvert\dot{G}/G\rvert<9\times10^{-13}yr^{-1}$	5×10^{-14}	5×10^{-15}
Inverse Square Law (ISL)	~10 years	$\lvert\alpha\rvert<3\times10^{-11}$	10^{-12}	10^{-13}

SLR/LLR work by the SCF Team

- **First-ever** SCF-Test of:
  - GPS-II retroreflector array **flight model** property of UMD
  - GLONASS and Galileo's GIOVE-A and -B retroreflector prototype by V. Vasiliev
  - LAGEOS Sector **engineering model** property of NASA-GSFC
  - **Hollow** retroreflector prototype provided by GSFC
  - **Galileo IOV** retroreflector prototype property of ESA
  - New generation LLR retroreflector, for:
    - First manned landing - 2006 NASA LSSO Program (the beginning of U. of Maryland and INFN-LNF collaboration LLRRA21/MoonLIGHT)
    - Two ASI studies, including MAGIA for Phase A
    - NLSI "CAN" Project (LUNAR, Directed by J. Burns)
- Response to NASA's ILN anchor nodes Request For Info (RFI)
- Response to ESA's RFI for lunar lander

ET-2 Poster.

Intl. team:
ILRS,
UMD,
CfA,
GSFC,
UCSD,
....

Activity for NASA/ASI: LLRRA21/MoonLIGHT

Lunar Laser Ranging Retroreflector Array for the 21st century (US) /
Moon Laser Instrumentation for General relativity High-accuracy Tests (It)

The US-Italy LLRRA21/MoonLIGHT Team

D. G. Currie (US PI) ***University of Maryland at College Park, MD, USA***

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J. Battat ***MIT, USA***

J. Chandler ***CfA, USA***

R. Vittori ***ESA-EAC and Aeronautica Militare Italiana, Rome, Italy***

D. Carrier ***Lunar GeoTechnical Institute, Lakeland, Florida, USA***

APOLLO Lunar Laser-Ranging Observatory (T. Murphy et al), UCSD, USA

ASI-CGS, Matera Laser-Ranging Observatory (G. Bianco et al), ASI, ITALY

R&D supported by INFN, by NASA contracts and ASI MAGIA phase A study

One past activity for ASI by INFN-LNF (not an SCF-Test)

- Industrial optical FFDP acceptance test, in-air and isothermal conditions, of 110 flight reflectors manufactured by Zeiss for the LARES mission
  - Accomplished by INFN-LNF in 3 working weeks before Christmas 2008:
    - At the optics lab with 633 nm wavelength
    - 15 days, enormous amount of retroreflector handling by LNF team, no casualty, completely successful
  - 110 retroreflectors accepted and paid by ASI, on the basis of this test activity by INFN-LNF
  - THIS WAS ONLY AN FFDP TEST IN AIR AND ISOTHERMAL CONDITIONS; NOT AN SCF-TEST
  - <u>ASI reference document: DC-OSU-2009-012</u>