

# Celebrating 50 years of Satellite and Lunar Laser Ranging



Dell'Agnello S (INFN-LNF & ASI-CTS), Bianco G (ASI-CGS & INFN-LNF)  
for the SCF Lab Team, INFN - Laboratori Nazionali di Frascati (Rome), Italy

In collaboration with: *International Laser Ranging Service (ILRS)*

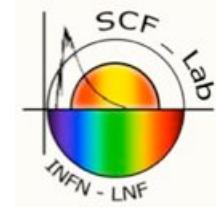
**Workshop on “Fundamental and Quantum Physics with Lasers”**

INFN-LNF, Frascati (RM), Italy

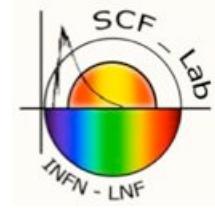
October 23, 2014

# Outline and science

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- Laser invention - **1960**
- First free-space Satellite Laser Ranging - **1964**
- Lunar Laser Ranging – **1969**, test of fundamental gravity, **Apollo and Lunokhod reflectors**
- Space Geodesy applications – **1974/92, LAGEOS I/II**
- Global Navigation Satellite System (GNSS) – late 80s, **Galileo now**
- New enabling technology for gravity, planetary exploration/geodesy – next: **Mars and beyond**
- International Year of Light **2015** (IYL-2015)



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# Satellite Laser Ranging (SLR) & Lunar Laser Ranging (LLR)

are Time of Flight (ToF) measurements

1<sup>st</sup> SLR to cube corner retroreflector (CCR):  
October 31, 1964 from NASA-GSFC,  
by Plotkin et al



## 19th International Workshop on Laser Ranging

Celebrating 50 Years of SLR: Remembering the Past and Planning for the Future

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# 19th **Celebrating 50 Years of SLR** Remembering the Past and Planning for the Future International Workshop on Laser Ranging

Annapolis, MD   October 27-31, 2014

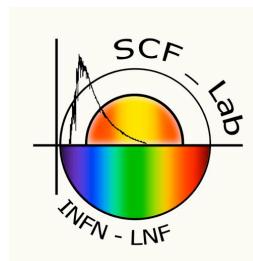


International Technical Laser Workshop 2012 (ITLW-12)

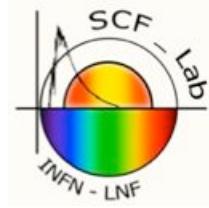
11/19/2012

The ILRS held an International Technical Laser Workshop 2012 (ITLW-12) on "Satellite, Lunar and Planetary Laser Ranging: characterizing the space segment" at the Frascati National Laboratories of the INFN-LNF, Frascati (Rome), Italy on November 5-9, 2012, in conjunction with a one-day Workshop on "ASI-INFN ETRUSCO-2 Project of Technological Development and Test of SLR Payloads for GNSS Satellites". The meeting focused on the laser ranging space segment including retroreflector arrays for Earth orbiting satellites and the moon, with special attention to the expanding role of ranging to GNSS and geosynchronous satellites. Topics also included receivers in space for time transfer experiments (T2L2), one-way ranging to lunar orbiters (LRO) and interplanetary spacecraft (MLA, MOLA), and data relay systems.

# INFN-NASA “Affiliation” Partnership on Laser Ranging and Laser Retroreflectors

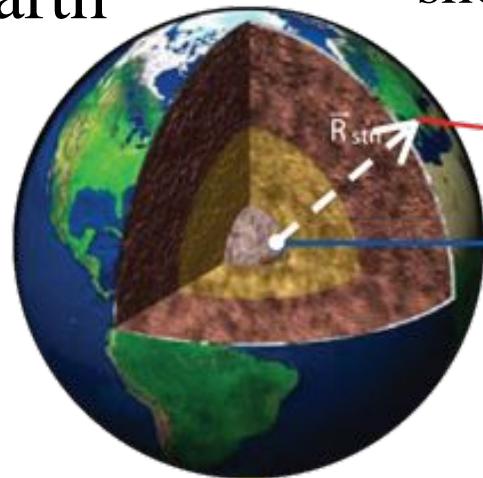


# Satellite/Lunar Laser Ranging (SLR/LRR)



- GeoMetroDynamics (GMD) in space
- Unambiguous position/distance measurement (so-called ‘laser range’) to cube corner retroreflectors (CCRs) with short laser pulses and a time-of-flight technique
  - Time-tagging with H-maser clocks

Earth

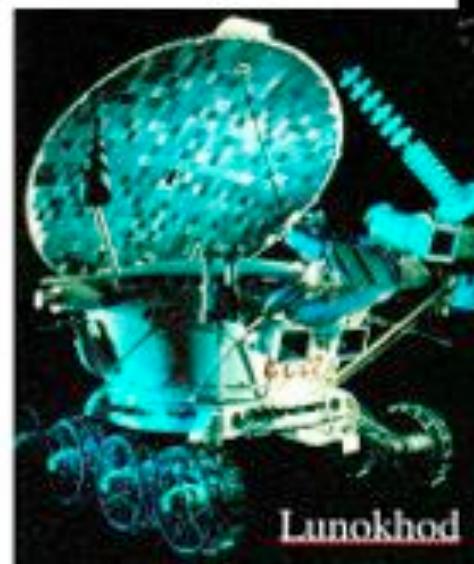
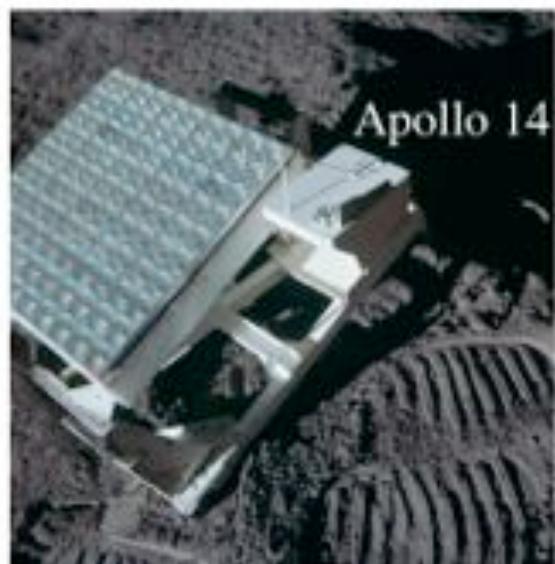
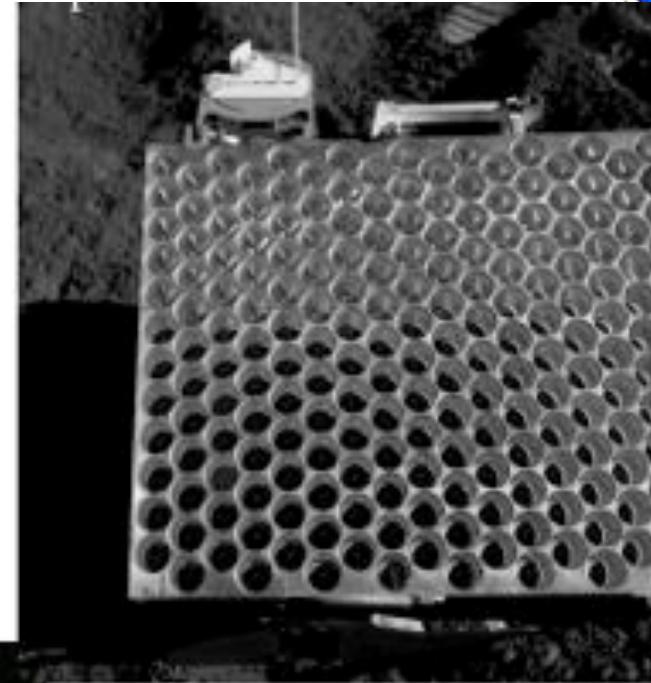
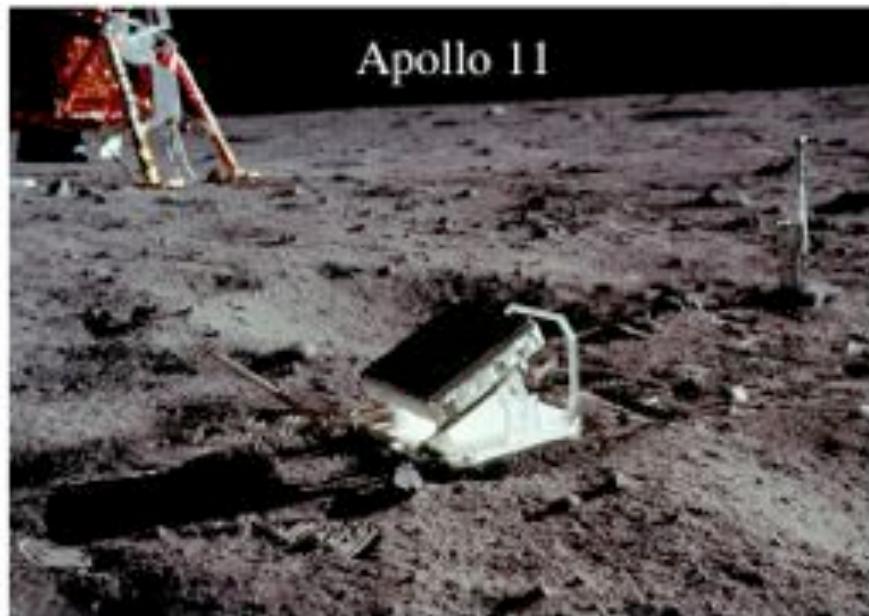
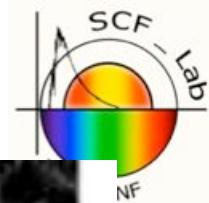


Moon

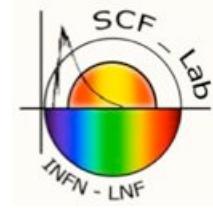
- Precise positioning (normal points at mm level, orbits at cm level)
- Absolute accuracy (used to define Earth center of mass, geocenter, and scale of length)
- Passive, maintenance-free Laser Retroreflector Arrays (LRAs)



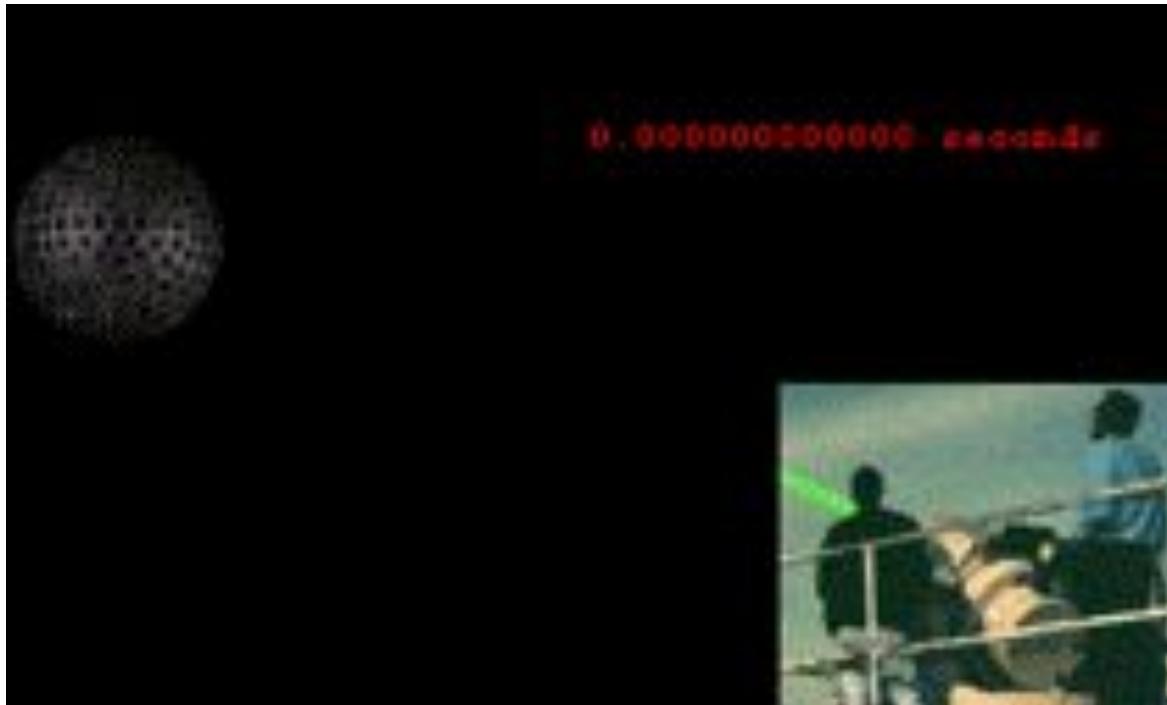
# Lunar reflectors: Apollo & Lunokhod



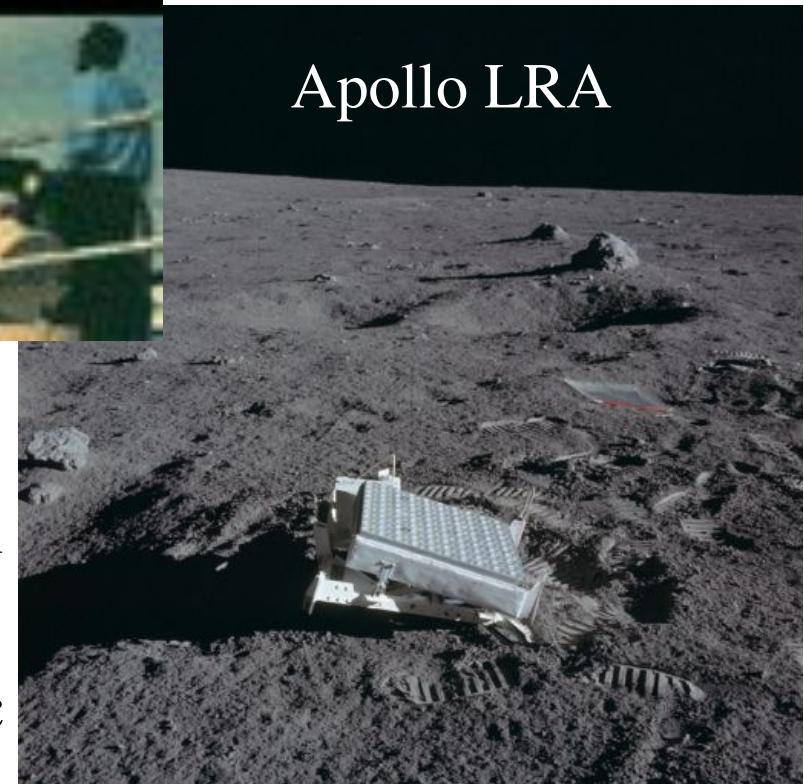
# SLR/LLR examples



S  
L  
R



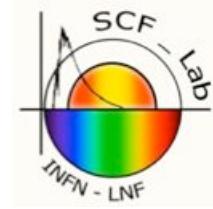
Moon  
( $d \sim 380000$  km):  
ToF  $\sim 2.5$  sec



LAGEOS  
( $h \sim 6000$  km):  
ToF  $\sim 0.05$  sec

Apollo LRA

# Space geodesy, GNSS, Gravitation



## Intern. Terrestrial Reference System:

- **Geocenter** from SLR/LAGEOS
  - **Scale** from SLR/LAGEOS & Very long Baseline Interferometry (VLBI)
  - **Orientation** from VLBI
  - **Distribution** w/GNSS
  - DORIS ...



# SLR CONSTELLATION: low orbits to the Moon



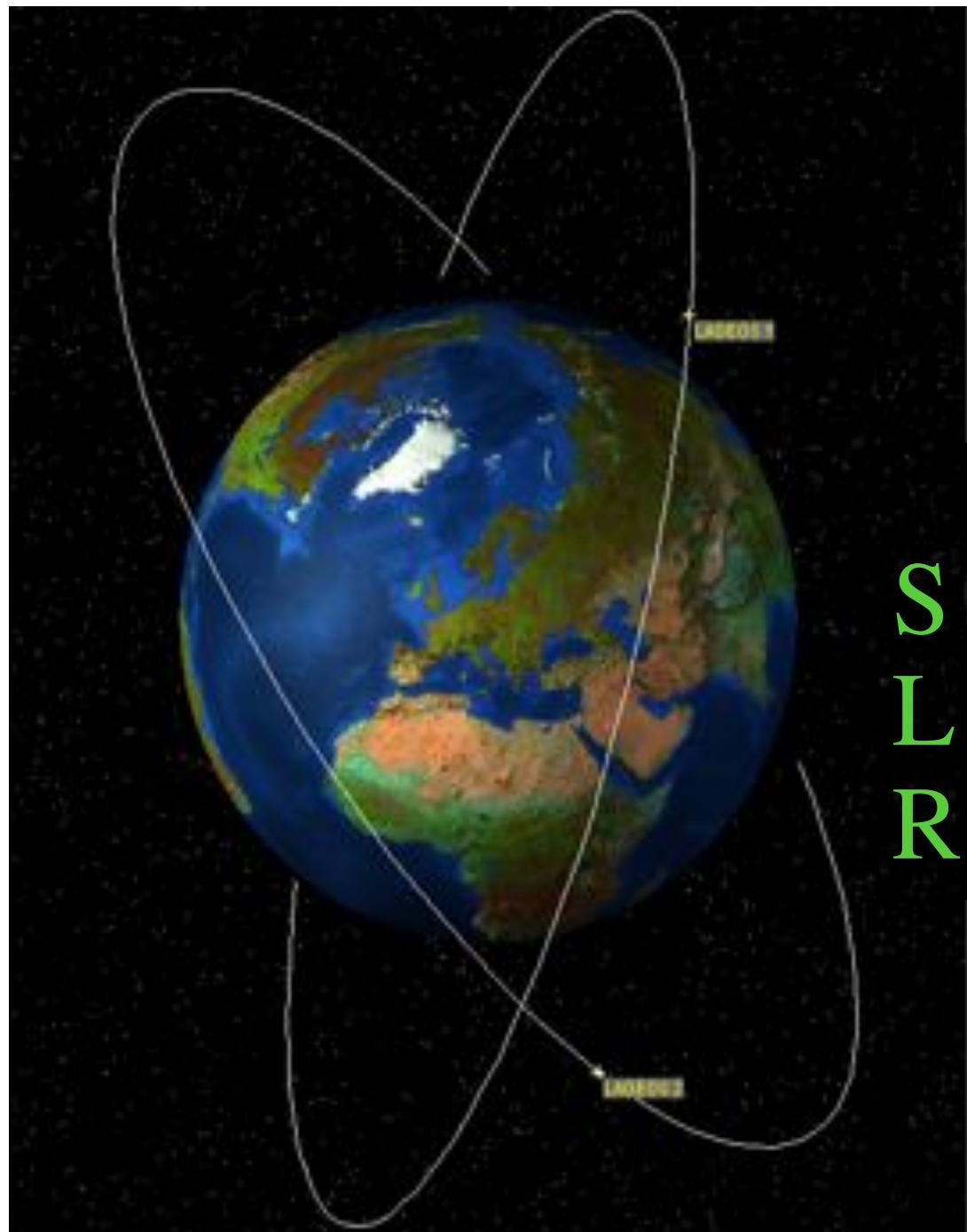
# Int. Terrestrial Reference System (ITRS)



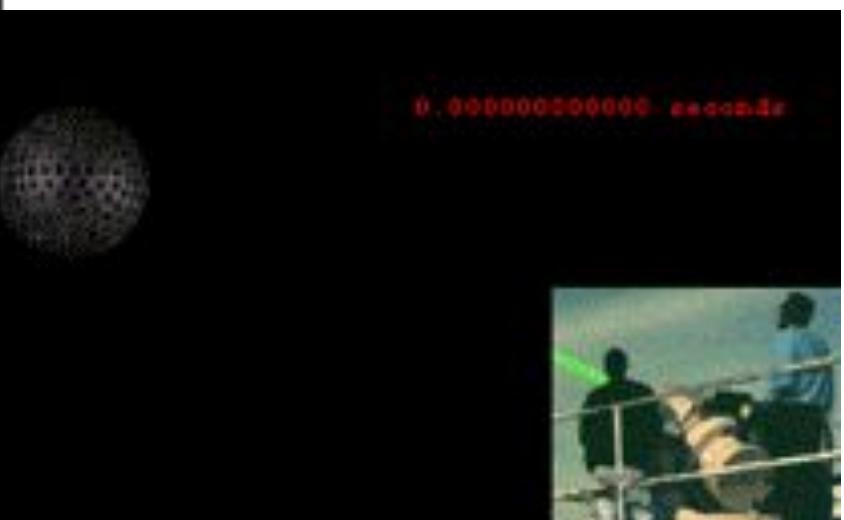
Space geodesy long-term goal: SLR CONSTELLATION

- Define and maintain an ITRS with an accuracy of 1 mm and a stability of 0.1 mm/year over a 10-year period
- Now ITRS is about a factor (few to) 10 less accurate/stable





# Test of General Relativity: Lageos measurement of Lense-Thirring effect (frame-dragging) with 10% relative accuracy (Ciufolini & Pavlis 2004)



# “Centro di Geodesia Spaziale (CGS) *Giuseppe Colombo*”

Matera, Italy

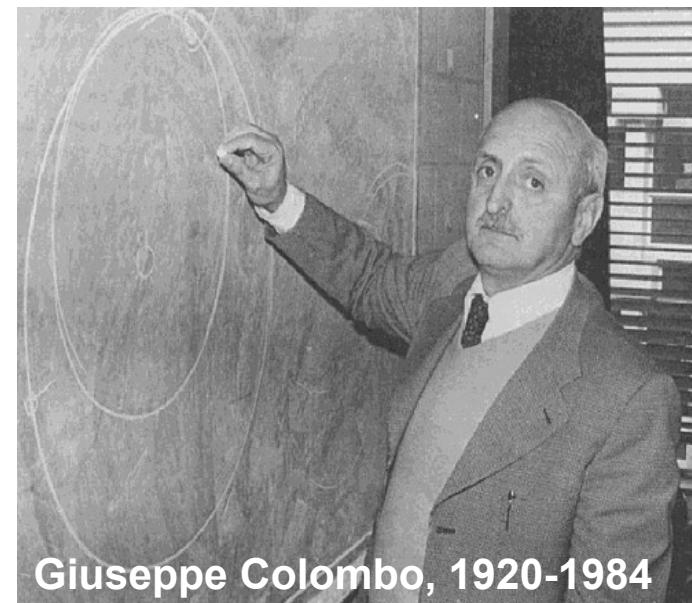
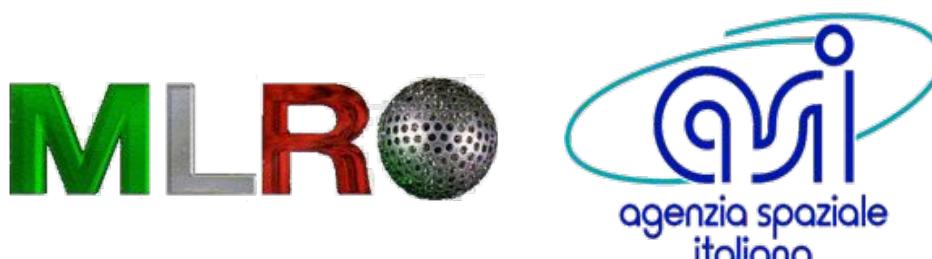
Tri-colocated within ITRF by SLR, VLBI, GNSS

Slide courtesy of G. Bianco



MLRO,  
Matera Laser Ranging Observatory

LLR since March 2010  
Led by G. Bianco, since 2014 also  
Chairman of ILRS Governing Board



Giuseppe Colombo, 1920-1984

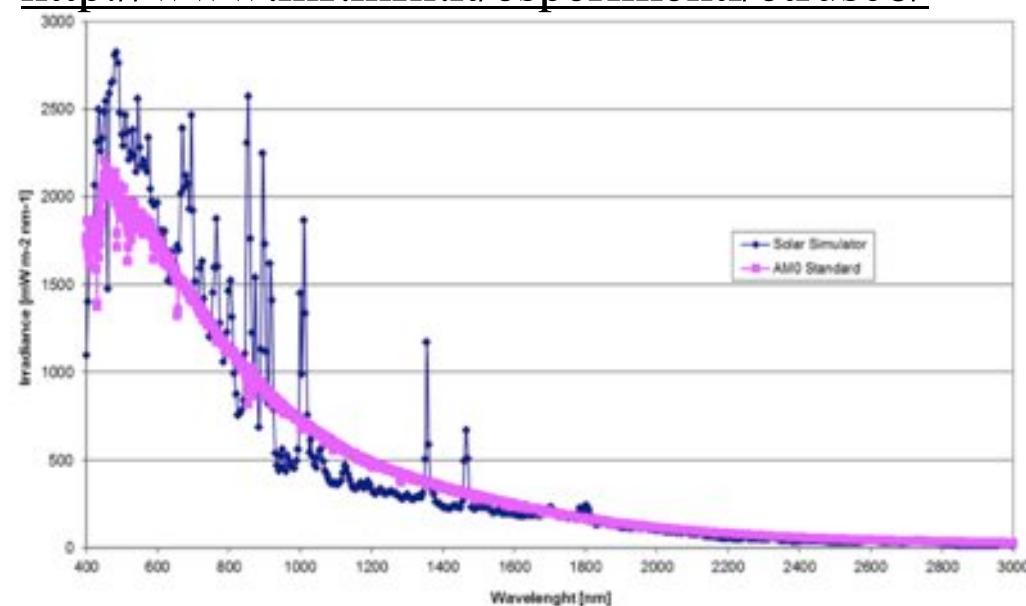
**3-station colocation, OCA-CERGA, Obs. du Calern, France**  
**(courtesy of)**

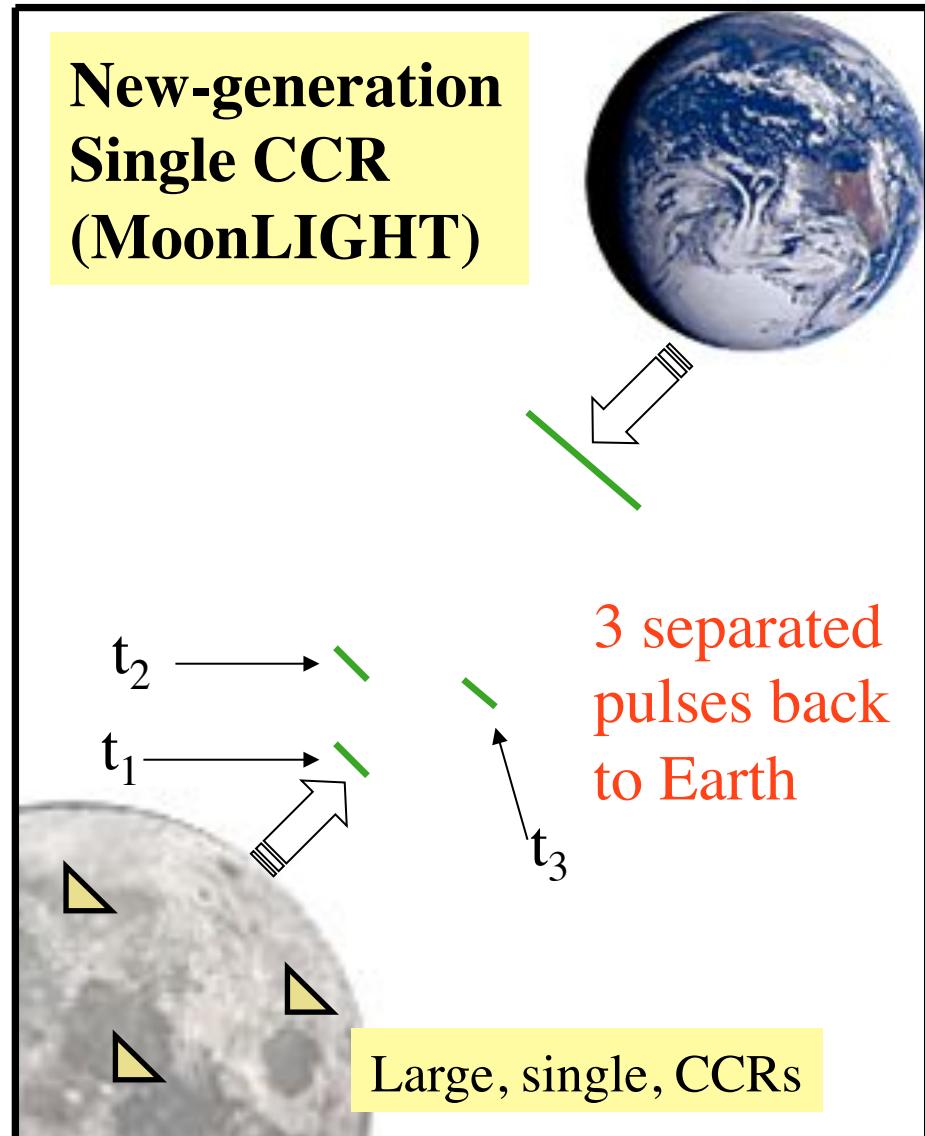
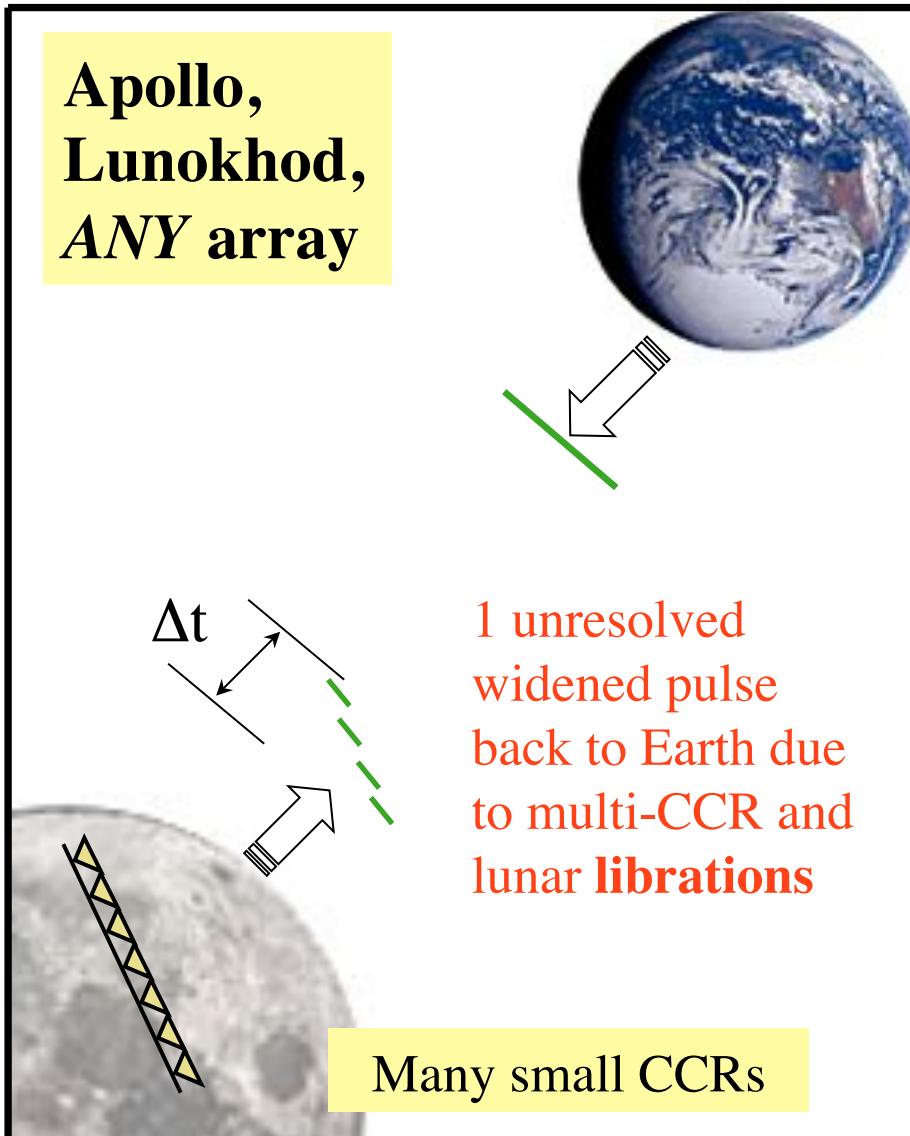
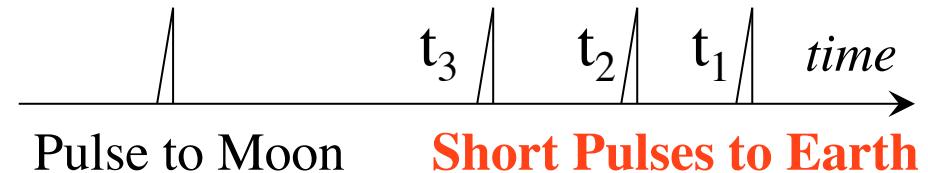
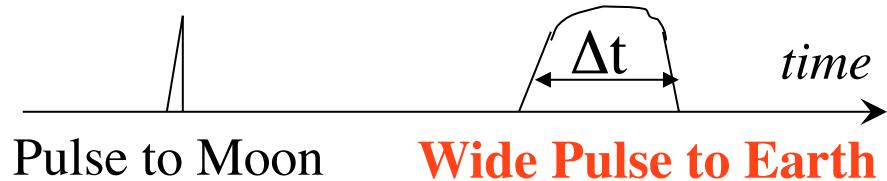


# SCF\_Lab: two OGSEs, 2 AM0 sun simulators



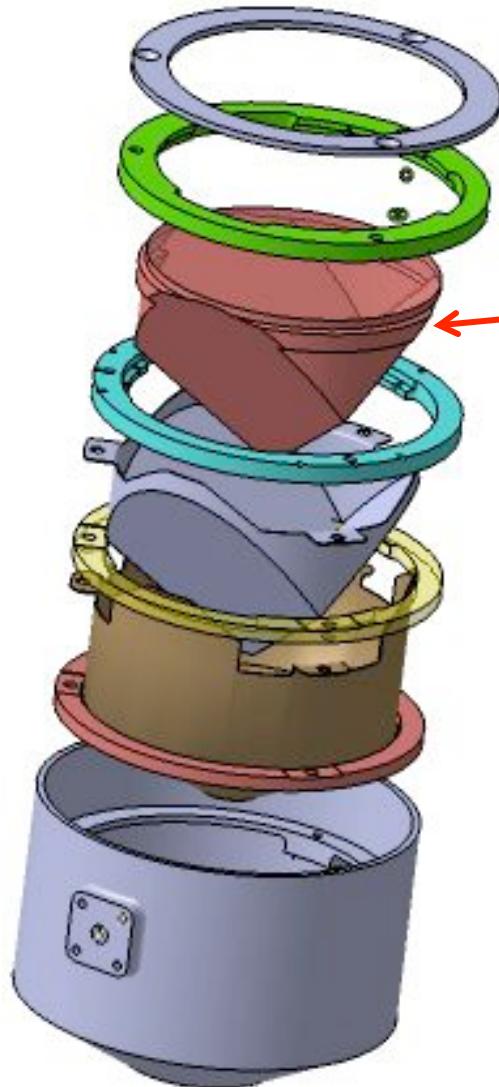
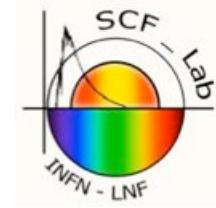
- 2 AM0 simulators, IR thermometry, diffraction pattern, Fizeau interferometry
- SCF (top right) with GNSS Retroreflector Array of Hollow technology. IR port with Ge window
- SCF-G (bottom right) cryostat with the GNSS Retroreflector Array of fused silica technology. IR port at right with black cover on
- J. Adv. Space Res. 47 (2011) 822–842
- <http://www.lnf.infn.it/esperimenti/etrusco/>





# MoonLIGHT Cube Corner Retroreflector

(Moon Laser Instrumentation for General relativity High accuracy Tests)

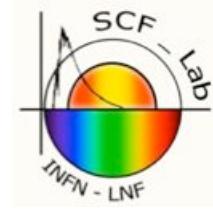


## MoonLIGHT-2 INFN-CSN2 experiment

### **MoonLIGHT vs. Apollo:**

- Passive. Both uncoated
- Suprasil 311 vs. Suprasil 1
- Single reflector 100 mm vs. array of 100-300 reflectors of 38 mm
- Laser return better than Apollo 15, ‘brightest’ of Apollo arrays

**MoonLIGHT: 1kg, 130 mm × 100 mm**



# LLR tests of General Relativity

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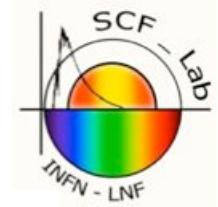
## & current prospects of up to $\times 100$ improvement (see dedicated poster by E. Ciocci)

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

Science measurement / Precision test of violation of General Relativity	Time scale	Apollo/Lunokhod few cm accuracy*	MoonLIGHTs	
			1 mm	0.1 mm
Parameterized Post-Newtonian (PPN) $\beta$	Few years	$ \beta-1  < 1.1 \times 10^{-4}$	$10^{-5}$	$10^{-6}$
Weak Equivalence Principle (WEP)	Few years	$ \Delta a/a  < 1.4 \times 10^{-13}$	$10^{-14}$	$10^{-15}$
Strong Equivalence Principle (SEP)	Few years	$ \eta  < 4.4 \times 10^{-4}$	$3 \times 10^{-5}$	$3 \times 10^{-6}$
Time Variation of the Gravitational Constant	$\sim 5$ years	$ \dot{G}/G  < 9 \times 10^{-13} \text{ yr}^{-1}$	$5 \times 10^{-14}$	$5 \times 10^{-15}$
Inverse Square Law (ISL)	$\sim 10$ years	$ a  < 3 \times 10^{-11}$	$10^{-12}$	$10^{-13}$
Geodetic Precession	Few years	$ K_{gp}  < 6.4 \times 10^{-3}$	$6.4 \times 10^{-4}$	$6.4 \times 10^{-5}$

Also:

- **Selenodesy**: measurement of deep interior, complementary to GRAIL
- **Exploration**: precise positioning of landing site, hopping and roving



# Lunar Laser Ranging stations

"old stations" (McDonald, Grasse, MLR2)

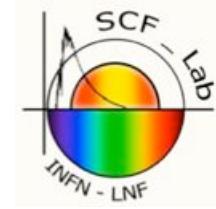


Apache Point station

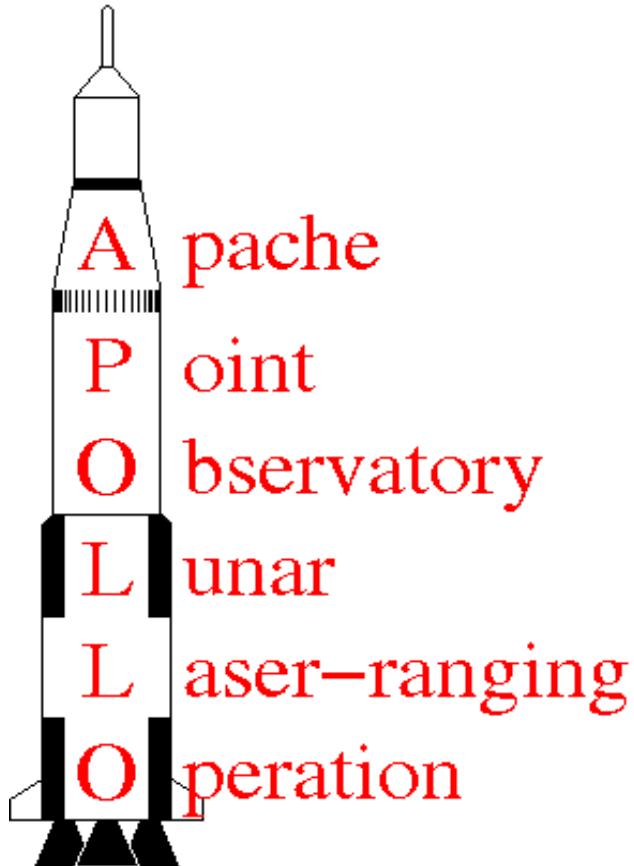


# New ‘APOLLO’ laser station (**since 2007**):

## Achieving the 1 mm ToF



Leader: Tom Murphy, UCSD



- APOLLO offers order-of-magnitude improvements to LLR by:
  - Using a **3.5 m telescope** at a high elevation site
  - Using a **16-element APD array**
  - Operating at **20 Hz** pulse rate
  - Multiplexed timing capable of detecting **multiple photons** per shot
  - Tight integration of experiment with analysis
  - Having a fund-grabbing acronym
    - APOLLO is jointly funded by the NSF and by NASA
- Started operations in 2007

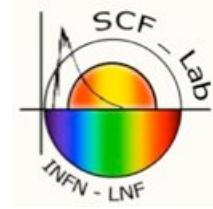


Telescope diameter = 1.5 m  
**LLR since 2010**



# SLR/LLR test of fundamental gravity

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- LLR test of General Relativity
  - Planet and Space Sci 74 (2012), *Martini, Dell'Agnello et al*
  - Nucl Phys B 243–244 (2013) 218–228, *Currie, Dell'Agnello et al*
- LLR and SLR constraints to General Relativity with Spacetime Torsion
  - PRD 83, 104008 (2011), *March, Bellettini, Tauraso, Dell'Agnello*
  - GERG (2011) 43:3099–3126, *March, Bellettini, Tauraso, Dell'Agnello*
- Solar System constraints to Non-Minimally Coupled Gravity, “ $f_1(R)+f_2(R)$ ” theories
  - PRD 88, 064019 (2013), *Bertolami, March, Páramos*
  - Physics Letters B 735 (2014) 25–32, *Castel-Branco, Páramos, March*

# Measurement of the relativistic precessions of the pericenter of LAGEOS II

Lucchesi, Peron, Phys. Rev. Lett., 105, 2010

PRL 105, 211101 (2010)

Selected for a Viewpoint in Physics  
PHYSICAL REVIEW LETTERS

2010 issue  
13 DECEMBER 2010

## Accurate Measurement in the Field of the Earth of the General-Relativistic Precession of the LAGEOS II Pericenter and New Constraints on Non-Newtonian Gravity

David M. Lucchesi<sup>1,2</sup> and Roberto Peron<sup>1</sup>

<sup>1</sup>Istituto di Fisica dello Spazio Interplanetario, Istituto Nazionale di Astrofisica, IFSI-INAF,  
Via del Fosso del Cavaliere 100, 00133 Roma, Italy

<sup>2</sup>Istituto di Scienze e Tecnologie dell'Informazione, Consiglio Nazionale delle Ricerche, ISTC-CNR,  
Via G. Moruzzi 1, 56124 Pisa, Italy  
(Received 18 July 2010; published 29 November 2010)

## Measurement of LAGEOS II pericenter advance

Lucchesi, Peron, Phys. Rev. D, 89, 2014

PHYSICAL REVIEW D 89, 062002 (2014)

## LAGEOS II pericenter general relativistic precession (1993–2005): Error budget and constraints on gravitational physics

David M. Lucchesi<sup>1</sup>

Istituto di Astrofisica e Planetologia Spaziali, Istituto Nazionale di Astrofisica, (IAPS/INAF),  
Via del Fosso del Cavaliere 100, 00133 Roma, Italy;  
Istituto di Scienze e Tecnologie dell'Informazione, Consiglio Nazionale delle Ricerche, ISTC-CNR,  
Via G. Moruzzi 1, 56124 Pisa, Italy; and  
Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Pisa, Largo E. Fermi corso 2, 56127 Pisa, Italy

Roberto Peron<sup>1</sup>

Istituto di Astrofisica e Planetologia Spaziali, Istituto Nazionale di Astrofisica, (IAPS/INAF), Via del Fosso  
del Cavaliere 100, 00133 Roma, Italy; and  
Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Roma Tor Vergata,  
Via della Ricerca Scientifica 1, 00133 Roma, Italy  
(Received 16 April 2013; published 7 April 2014)

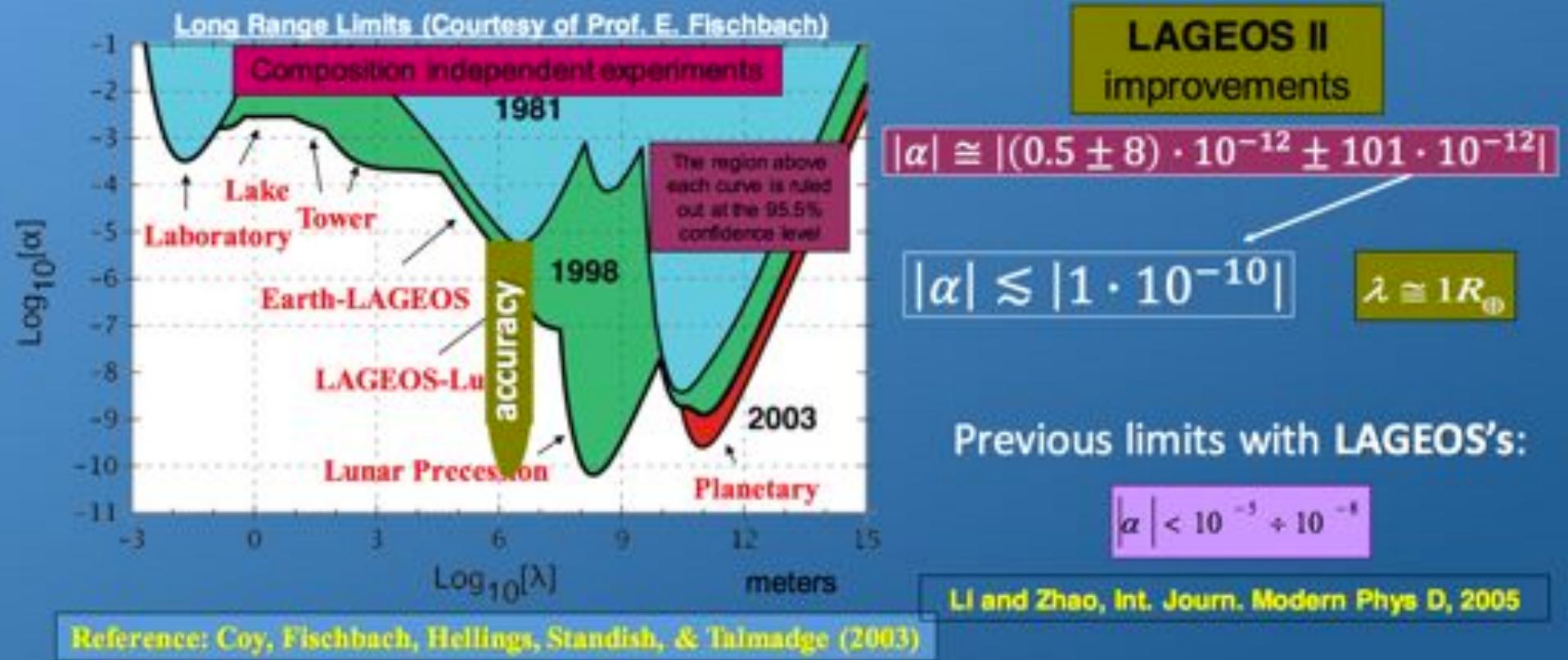
## New measurement of LAGEOS II pericenter advance and Error Budget

Lucchesi, Peron et al,  
INFN-CSN2 LARASE experiment

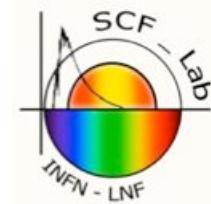


## Constraints in gravitational theories

- Constraints on a long-range force: Yukawa-like interaction



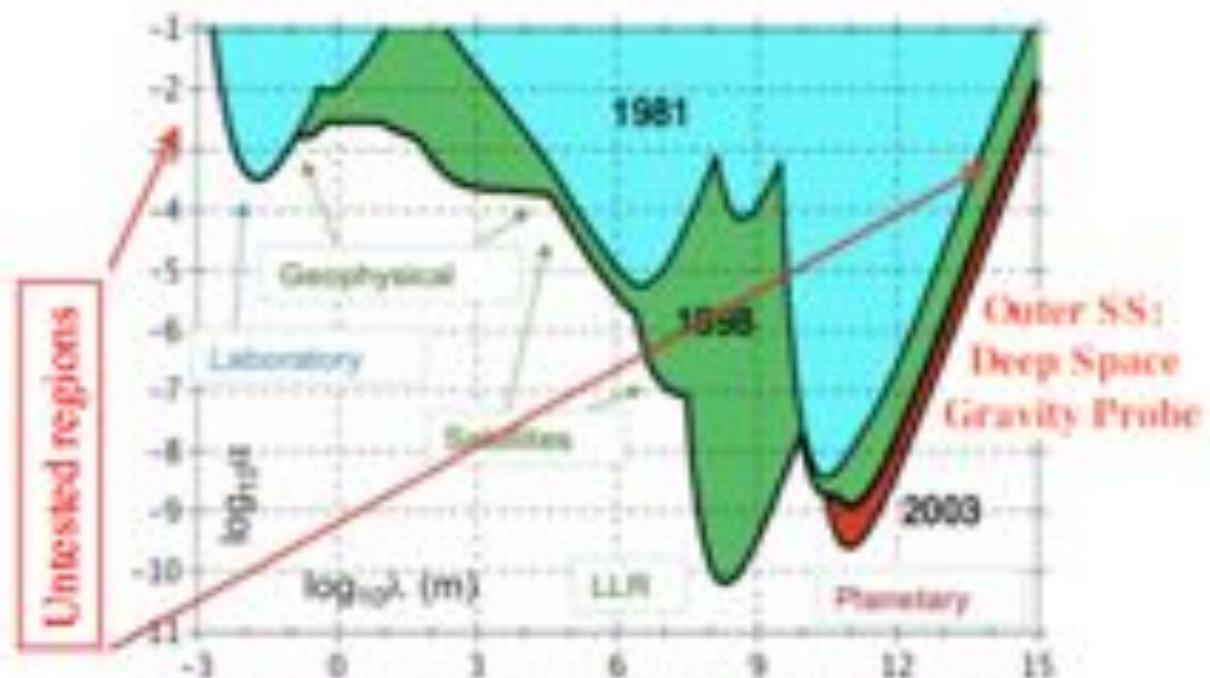
# Limits on $1/r^2$ deviations with LLR: up to $\alpha < 10^{-12}$



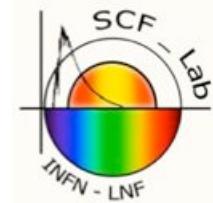
MoonLIGHT designed to provide accuracy of  $100\mu\text{m}$  or better on tspace segment (the CCR), if deployed by drilling the regolith (Lunar Google X Prize, Astrobotic mission)

If other error sources on LLR will improve with time at the same level, then MoonLIGHT CCRs will improve limits on  $\alpha$  from  $\sim 10^{-10}$  to  $\sim 10^{-12}$  at scales  $\lambda$  of  $\sim 10^6$  meters

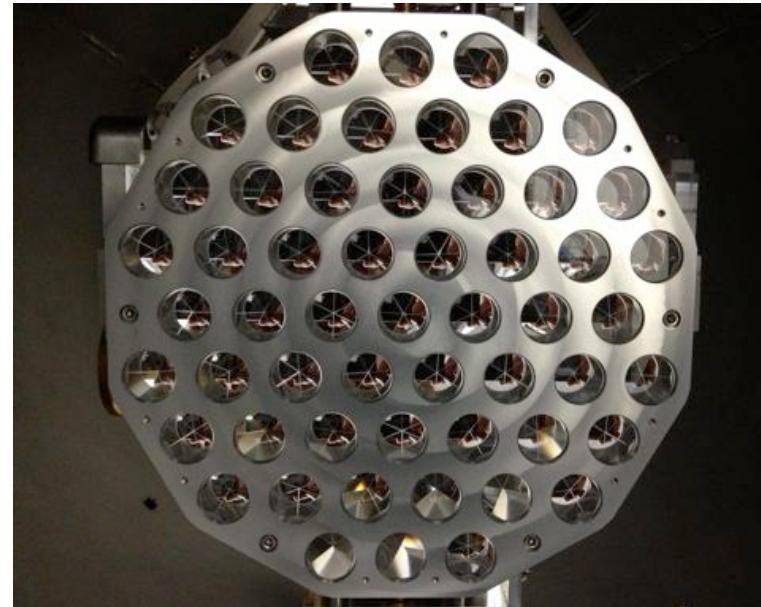
Limits on additional Yukawa potential:  
 $\alpha \propto (\text{Newtonian-gravity}) \times e^{-r/\lambda}$



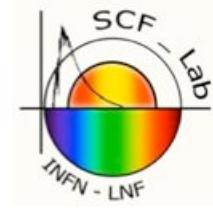
# Laser Ranging to GNSS Constellations



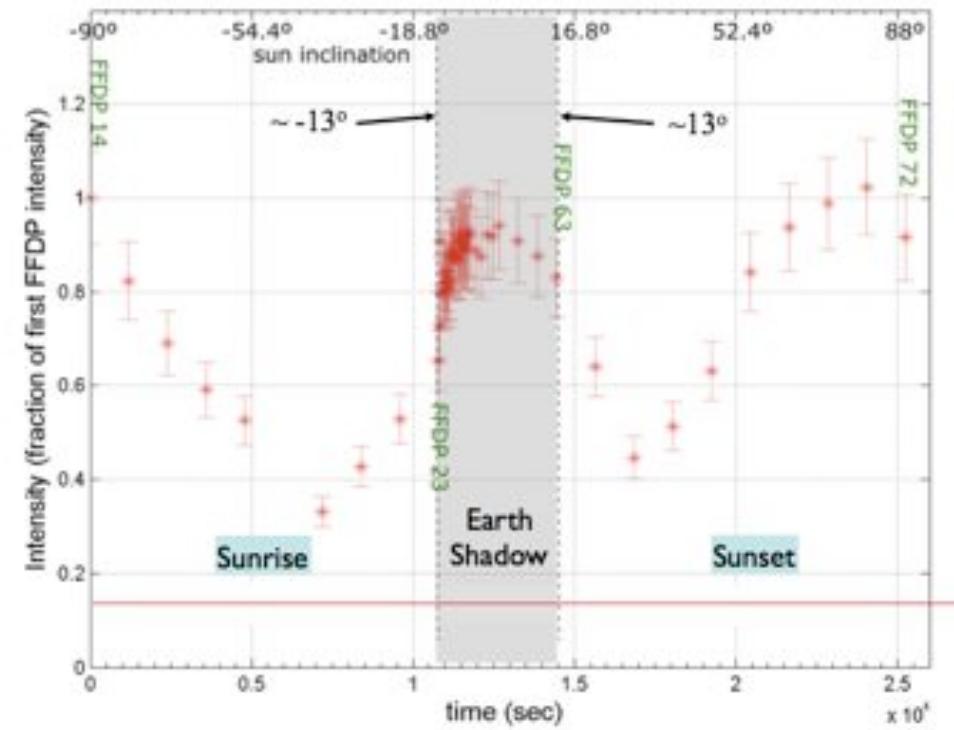
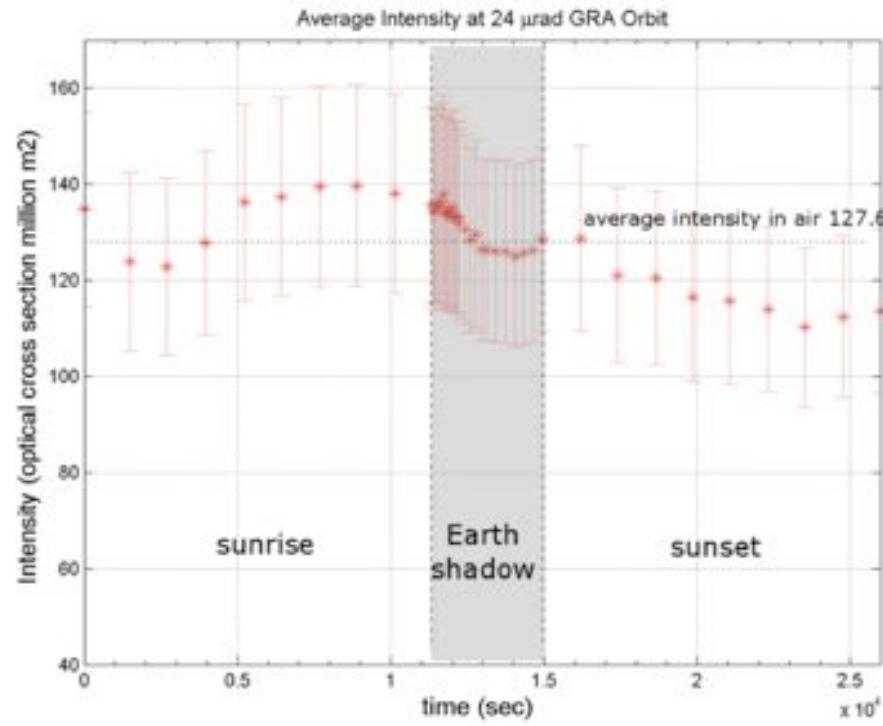
- Improve positioning accuracy of navigation satellites: GLONASS (Russia), GPS (USA)
- In turn, improve positioning accuracy of end-users on ground, road, rail, ship, flight, etc.
- Augment and improve ITRS determination
- Improve and stabilize space geodesy
- We built a GNSS Retroreflector Array (GRA) with specs according to ILRS & SCF\_Lab recommendations
  - ASI-INFN Project for Galileo/GPS (ETRUSCO-2)
- We characterize performance of Laser Retroreflector Array of Galileo IOV (bottom)



# GRA and Galileo IOV reflector performance

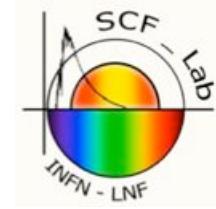


- GRA by INFN-ASI: 3.5 kg, 400 mm diameter; lighter/smaller than Galileo IOV. No degradations within  $\pm 15\%$  errors (left)
- Galileo IOV: in 2010 for ESA we measured one IOV reflector, which showed performance degradations (right)

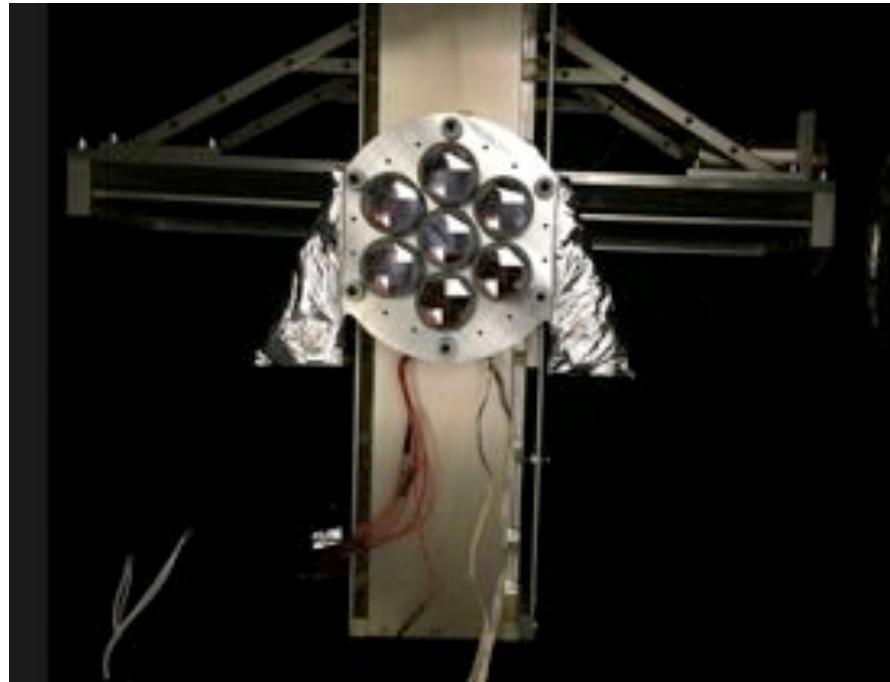


# NEXT: More SCF-Testing of Galileo IOV

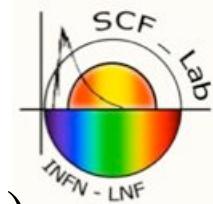
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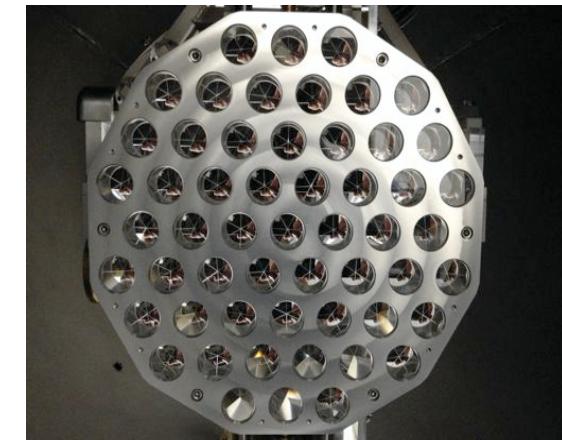
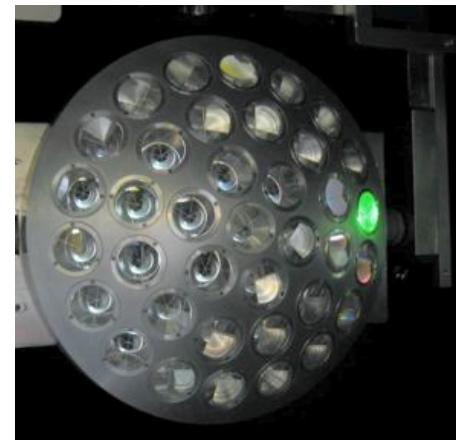
- ESA-INFN contract on model of reduced size, 7 flight reflectors
  - Tests complete, results to be delivered soon to ESA



# MIUR Project “Laser Ranging to Galileo”



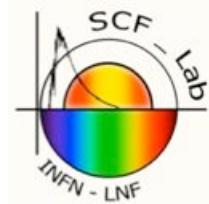
- ASI & INFN instrumentation upgrades (MLRO & SCF\_Lab)
- ASI Laser ranging and SCF-Test of Galileo, GRA and LAGEOS



Macro-Activity 1 Year 1 and 2	Macro-Activ. 2 Year 1	Macro-Activ. 3 Year 1	Macro-Activity 4 Year 2	Macro-Activity 5 Year 2	Macro-Activity 6 Year 2	Macro-Activity 7 Year 2
<b>MLRO-SCF_LAB Harmonization:</b> Harmonization of MLRO and SCF_LAB upgrades and integration of the results of the upgraded MLRO and SCF_LAB (includes Management)	MLRO@CGS: Equipment Upgrade	SCF_LAB@LNF: Infrastructure Upgrade	Upgraded MLRO: Laser Ranging to LRAs onboard Galileo satellites	Upgraded SCF_LAB: Lab Characterization of Galileo LRA Flight Model (on loan to LNF from ESA)	Upgraded MLRO: Laser Ranging to LAGEOS	Upgraded SCF_LAB: Lab Characterization of LAGEOS Engineering Model (on loan to LNF from NASA)

LRA = Laser Retroreflector Array

# Conclusions: towards IYL-2015



 United Nations  
Educational, Scientific and  
Cultural Organization



- International
- Year of Light
- 2015

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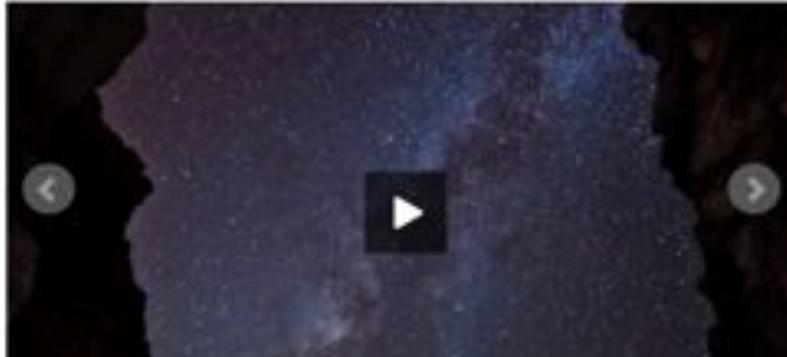
## 2015 INTERNATIONAL YEAR OF LIGHT AND LIGHT-BASED TECHNOLOGIES

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International  
Year of Light  
2015

HOME | ABOUT THE YEAR OF LIGHT | EVENT PROGRAMME | WHY LIGHT MATTERS | LEARN ABOUT LIGHT | HANDS ON INVOLVEMENT | COSMIC LIGHT | LIGHT FOR DEVELOPMENT | SCIENCE STORIES



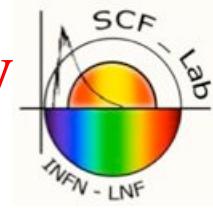
Opening Ceremony - 19-20 January 2015 | Women in Science | Cosmic Light 2015 Video Trailer | Light 2015 Blog



EVENT CALENDAR

Oct 23.	Optics and Education - 2014
Oct 26.	Symposium of 'Light' during TWAS 25th Annual Meeting, Bangalore, India
Oct 27.	The Reliability of Advanced Light Sources 2014 (RALS 2014), Novosibirsk, Russia

# Microreflector for Exploration, Geodesy, Gravity

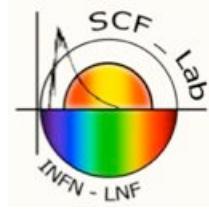


## INRRI: INstrument for landing-Roving laser Retroreflector Investigations

- Laser ranging/altimetry, lasercomm check/calibration, lidar atmosphere investigations by ORBITERS to INRRI on rovers
  - Accurate positioning of landing site
  - Accurate positioning of roving exploration activity
  - Multiple INRRIs: establish planetary geodesy reference frame
- INRRI is:
  - Passive
  - Compact (~5 cm x 2 cm)
  - Very lightweight ~30 gr
  - No pointing required

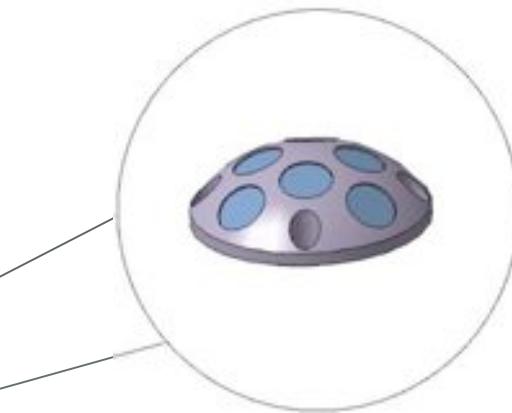
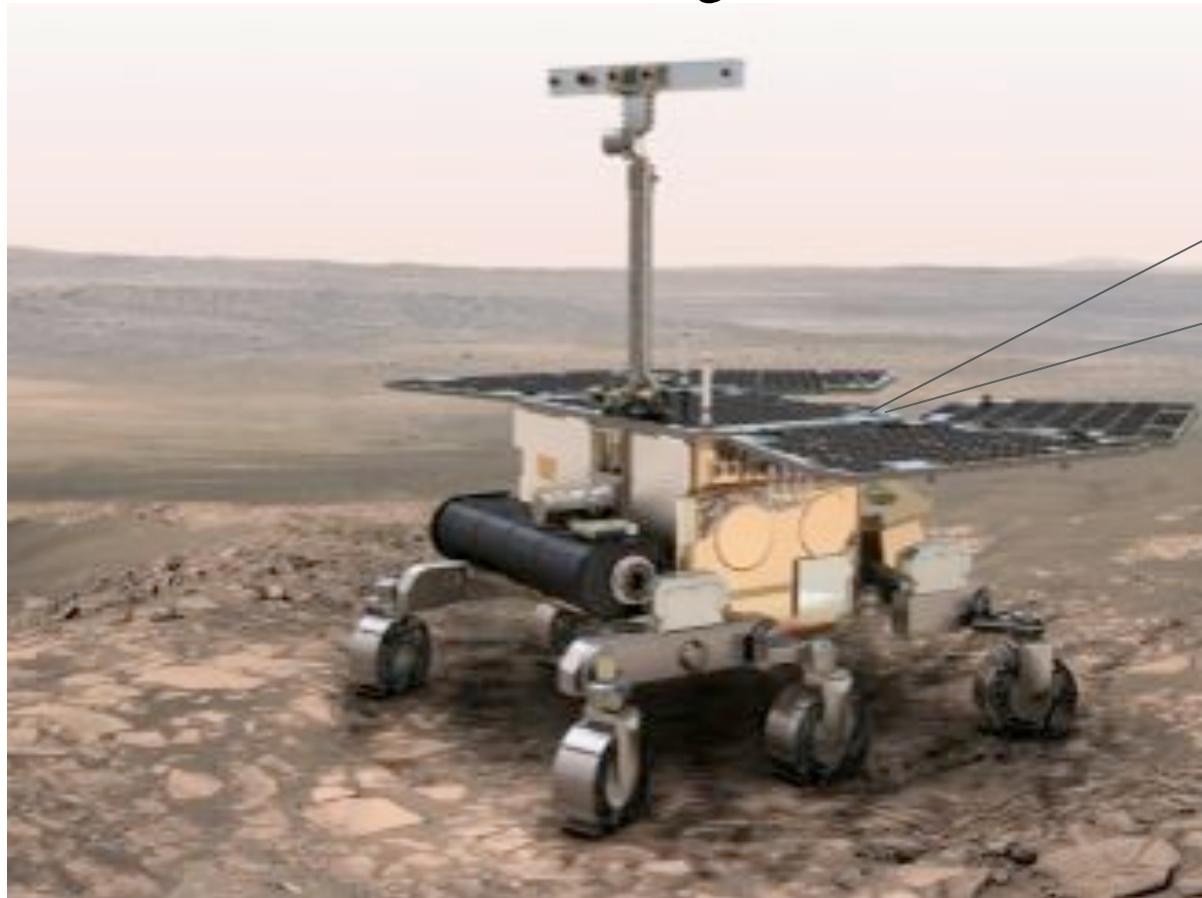


# INRRI also for Mars Rovers

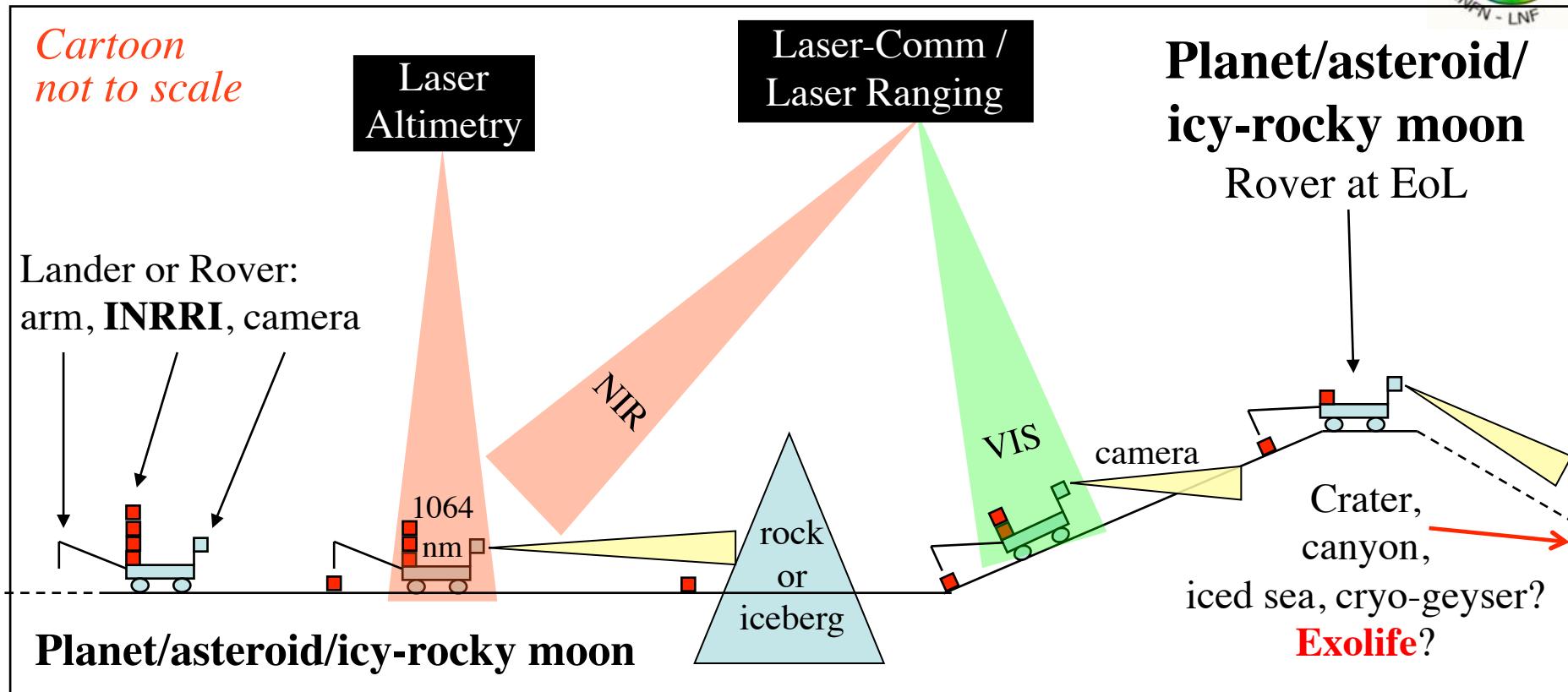
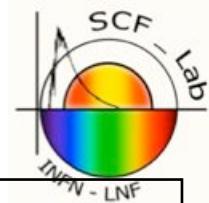


Extend work from Moon to Mars:

- Geodesy, Georeferencing of Exploration activity
- Lidar atmosphere trace species detection
- Lasercomm test & diagnostics



# INRRI<sup>s</sup> on Moon, Mars, Jupiter/Saturn moons



- Selenolocate Lander/Rover with laser retroreflector:
  - Laser Altimetry at nadir (LRO-like) to rovers/landers at poles of moon(s)
  - Laser Ranging (Comm) to reflectors anywhere (LADEE / iROC / OPALS-like)
- **Deploy INRRI networks.** Also on far side of Earth's Moon