GEOREFERENCING OF LANDERS/ROVERS, TEST OF GENERAL RELATIVITY, METRICS OF LUNAR INTERIOR

WITH LASER RETROREFLECTORS

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NASA-Ames, Mountain View CA, Jan 12, 2018

SCF_Lab
Satellite/Lunar/GNSS
laser ranging/altimetry and Cube/microsat
Characterization Facilities Laboratory

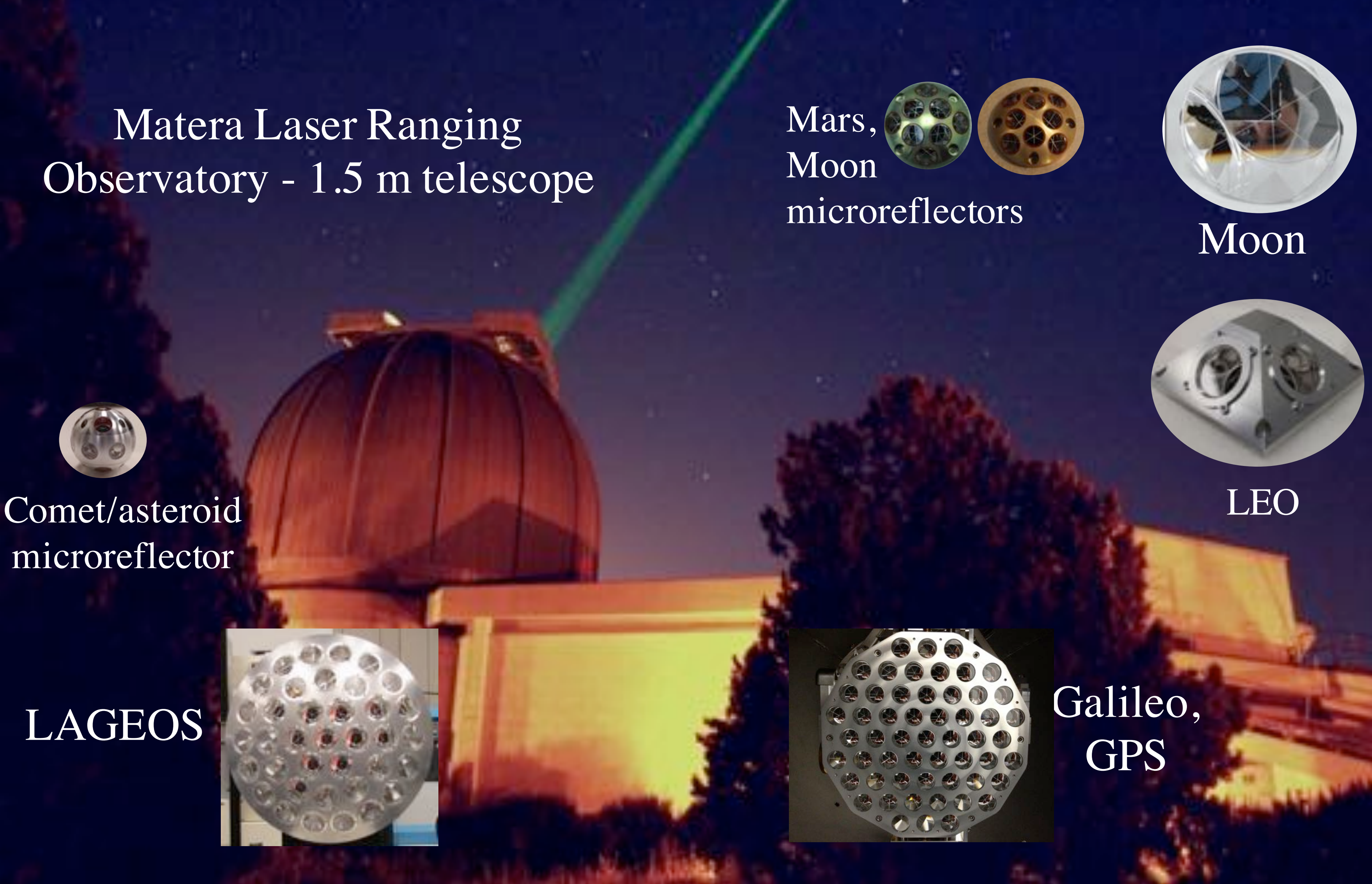
INFN Affiliation to NASA-SSERVI

Signed in Rome on Sep 15, 2014

INFN proposal to NASA:
laser retroreflectors for the whole solar system

Right: SSERVI news, visit by C. Elachi (JPL) & E. Flamini (ASI Chief Scientist)

INFN – ASI JOINT LABORATORY on Laser Retroreflectors & Laser Ranging



Lunar science & exploration assets

- MoonLIGHT, the single *big* Lunar laser retroreflector
  - MoonLIGHT: Moon Laser Instrumentation for General relativity High accuracy Tests. **4 inch diameter reflector**
  - Observed from Earth (532 nm)
- INRRI, the Solar System & Mars *micro*reflector array
  - INRRI: Instrument for landing-Roving laser Retroreflector Investigations. **½ inch diameter reflectors**
  - Observed, for example from LRO (Lunar Reconnaissance Orbiter) with LOLA = Lunar Orbiter Laser Altimeter (1064 nm)
- Big reflector is a Italy-USA collaboration, m-reflector Italy only
- PEP, the Planetary Ephemeris Program *orbital SW*
  - Lunar/Martian positioning data. Developed at the Harvard-Smithsonian Center for Astrophysics **(CfA)**, USA, by Shapiro, Reasenberg, Chandler since 1960s
- Frontiers of new Physics
  - Lunar positioning data matched with cosmological constraints
  - New insights toward a determination of extensions of GR

Lunar Laser Ranging (LLR) test of General Relativity

- Improvements of space segment up to × 100 with MoonLIGHTs plus current LGN of Apollo/Lunokhods

Science measurement / Precision test of violation of General Relativity	Apollo/Lunokhod * few cm accuracy	MoonLIGHTs** mm
Parameterized Post-Newtonian (PPN) β	$\lvert\beta-1\rvert < 1.1\times10^{-4}$	10^{-5}
Weak Equivalence Principle (WEP)	$\lvert\Delta a/a\rvert < 1.4\times10^{-13}$	10^{-14}
Strong Equivalence Principle (SEP)	$\lvert\eta\rvert < 4.4\times10^{-4}$	3×10^{-5}
Time Variation of Gravitational Constant	$\lvert\dot{G}/G\rvert < 9\times10^{-13}yr^{-1}$	5×10^{-14}
Inverse Square Law (ISL) - Yukawa	$\lvert\alpha\rvert < 3\times10^{-11}$	10^{-12}
Geodetic Precession	$\lvert K_{gp}\rvert < 6.4\times10^{-3}$	6.4×10^{-4}

* J. G. Williams et al PRL 93, 261101, (2004)

** M. Martini et al Plan. & Space Sci., 74, 276, (2012)

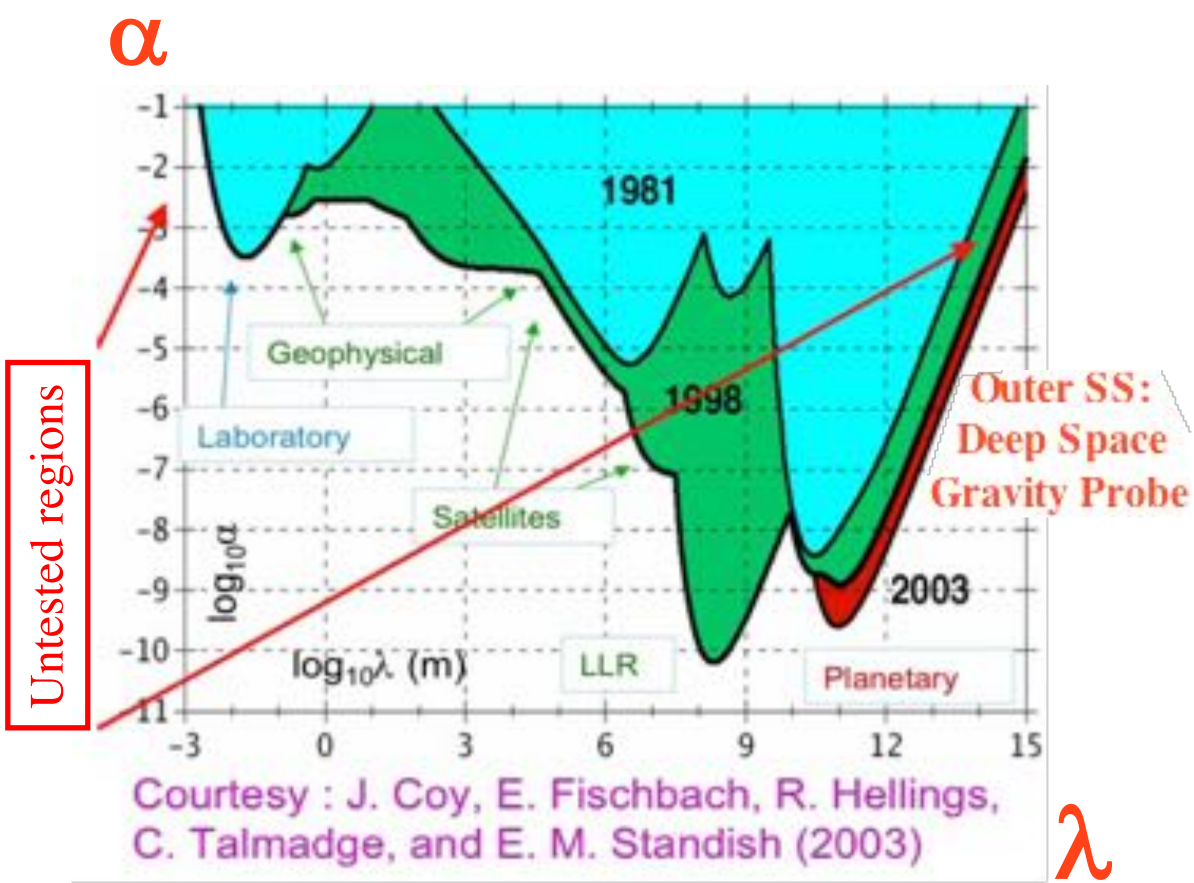
** E. Ciocci et al, Adv. Space Res. Vol. 6, Issue 5, 1115-1129, (2017)

** O. Luongo, S. Dell'Agnello, S. Capozziello, in preparation, (2018)

Limits on Yukawa potential: **(Newtonian potential)** $\times\, \alpha \times e^{-r/\lambda}$

MoonLIGHT provides accuracy 100 times better on the space segment (the reflectors)

When other LLR error sources will have improved up the same level, MoonLIGHT-2 will improve limits from **$\alpha \sim 3\text{x}10^{-11}$ down to $<10^{-12}$ at scales $\lambda \sim$ million km**



Lunar Laser Ranging for Selenodesy

- Lunar Laser Ranging provided the best data for the deep interior of the moon. This analysis has been used to supplement the data from the GRAIL mission analysis
  - ✓ In 1998, analysis of the LLR data discovered and measured the size, shape and dissipation of the liquid core of the Moon (Williams et al)
  - ✓ Confirmed by a re-analysis of Apollo Seismometry data (Weber et al 2011)
- Our next-gen retroreflectors will strengthen the collaboration with GRAIL (Gravity Recovery and Interior Laboratory) data analysis on inner moon structure
- NASA "Resource Prospector" Rover mission:
  - ✓ Our reflectors proposed as payloads – *see next slide*
- What Next: New Frontiers AO on the Moon (LGN) expected
  - ✓ With Clive Neal (U. Notre Dame et al)

NASA lunar Resource Prospector

INFN AOO_PRESIDENZA-2016-0001253 del 12/10/2016

INFN

IL PRESIDENTE

Roma, 12th October 2016

Yvonne Pendleton
Director
NASA-SSERVI
Greg Schmidt,
Deputy Director, International Partnerships
NASA-SSERVI

Cc: **Doug Currie**
University of Maryland

Dear Mrs. Pendleton,
Dear Mr. Schmidt,

As discussed in a recent programmatic meeting on the INFN Affiliation to SSERVI, we provide this letter to express the INFN specific interest in the Resource Prospector mission (RPM) to the Moon, which is in formulation within NASA. In the framework of the INFN Affiliation to NASA-SSERVI signed in Sep. 15, 2014, we collaborate on laser retroreflector array (LRA) applications to exploration and research for a variety of solar system destinations. In fact, an LRA provided by ASI-INFN is onboard ESA's ExoMars 2016 "Schiaparelli" lander and we are developing LRA models for asteroids/comets and for Phobos/Deimos.

Next-generation lunar LRAs and Lunar Laser Ranging (LLR) data analysis remain one of the main pillars of the Affiliation, coordinated by Simone Dell'Agnello for INFN. RPM aims to be the first mining expedition on another world. We believe that RPM, in which NASA-Ames has a prominent role, will be a stepping stone achievement not only for lunar, but for the whole solar system science, exploration and colonization. As such, we also believe that RPM will greatly benefit from being equipped with the next generation LRAs developed jointly by INFN and Doug Currie of the University of Maryland (formerly Principal Investigator of the Apollo LRAs). For these reasons, I would like to express our interest in participating in RPM as one of the main goals of the INFN Affiliation.

INFN President's formal letter to NASA-SSERVI

INFN AOO_PRESIDENZA-2016-0001253 del 12/10/2016

In the remainder, I wish to remind some items of fruitful past collaboration. INFN is active in the development of next-generation lunar laser retroreflector arrays (LRAs), as well as lunar laser ranging (LLR) data analysis. We carry out the hardware work in close collaboration with D. Currie of the University of Maryland. In Frascati, Italy, INFN built and operates the SCF_Lab, a unique space test facility for LRA characterization. The SCF_Lab is an LLR analysis center of the International Laser Ranging Service (ILRS) and forms a "Joint Lab" with the Matera Laser Ranging Observatory (MLRO) operated by ASI in southern Italy. We collaborated (upon nomination by ASI) in the Core Instrument working group of the International Lunar Network (ILN) heralded by NASA, ASI and other space agencies and within the NLSI community coordinated by NASA-Ames, which finally evolved into SSERVI.

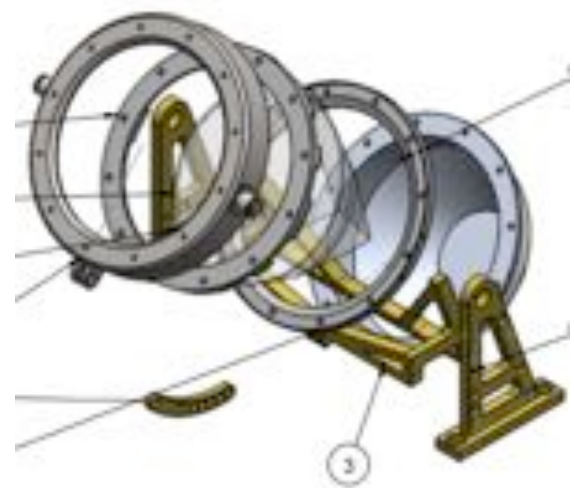
We are looking forward to further collaboration with SSERVI.

Best regards,

ISTITUTO NAZIONALE DI FISICA NUCLEARE
IL PRESIDENTE
(Prof. Fernando Ferroni)

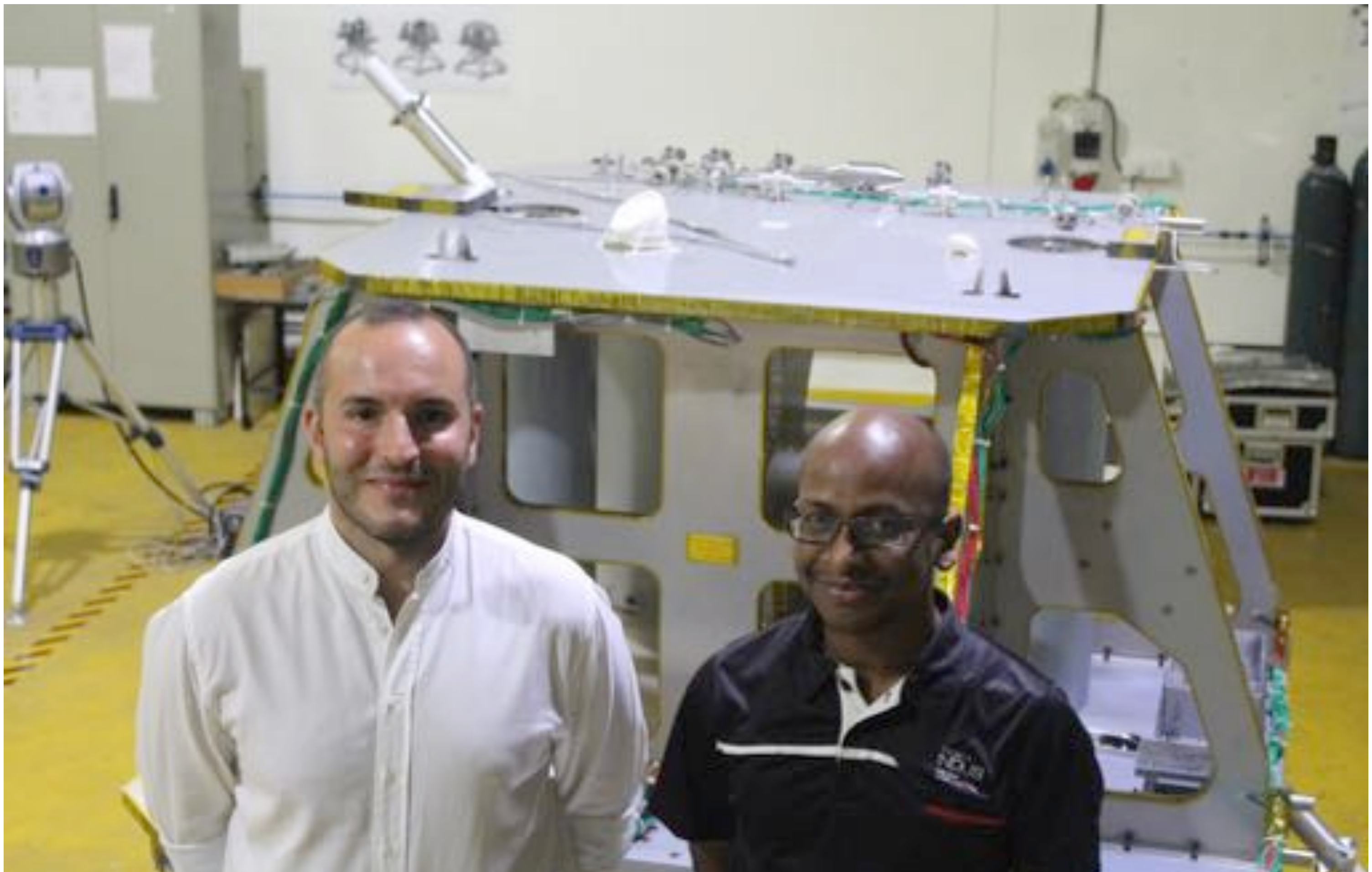
Lunar landing/roving opportunities

- **TeamIndus** (India, commercial)
- **Moon Express 1** (USA, commercial)
- **NASA Resource Prospector** (USA, NASA)
- **CNSA Chang'E program** (China, CNSA)
- **New Frontiers AO** (USA, NASA)?

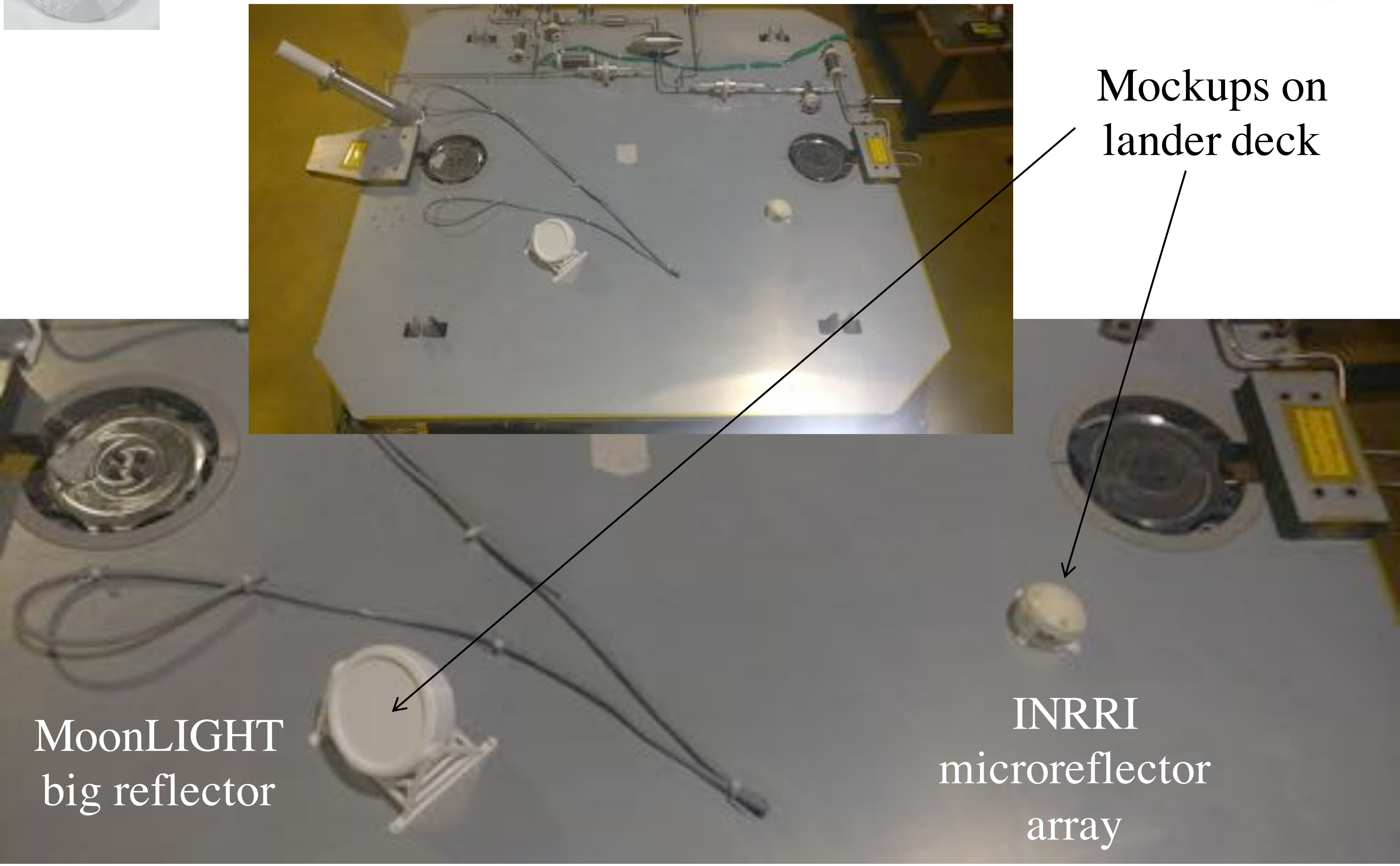


TeamIndus lander/minirover mission

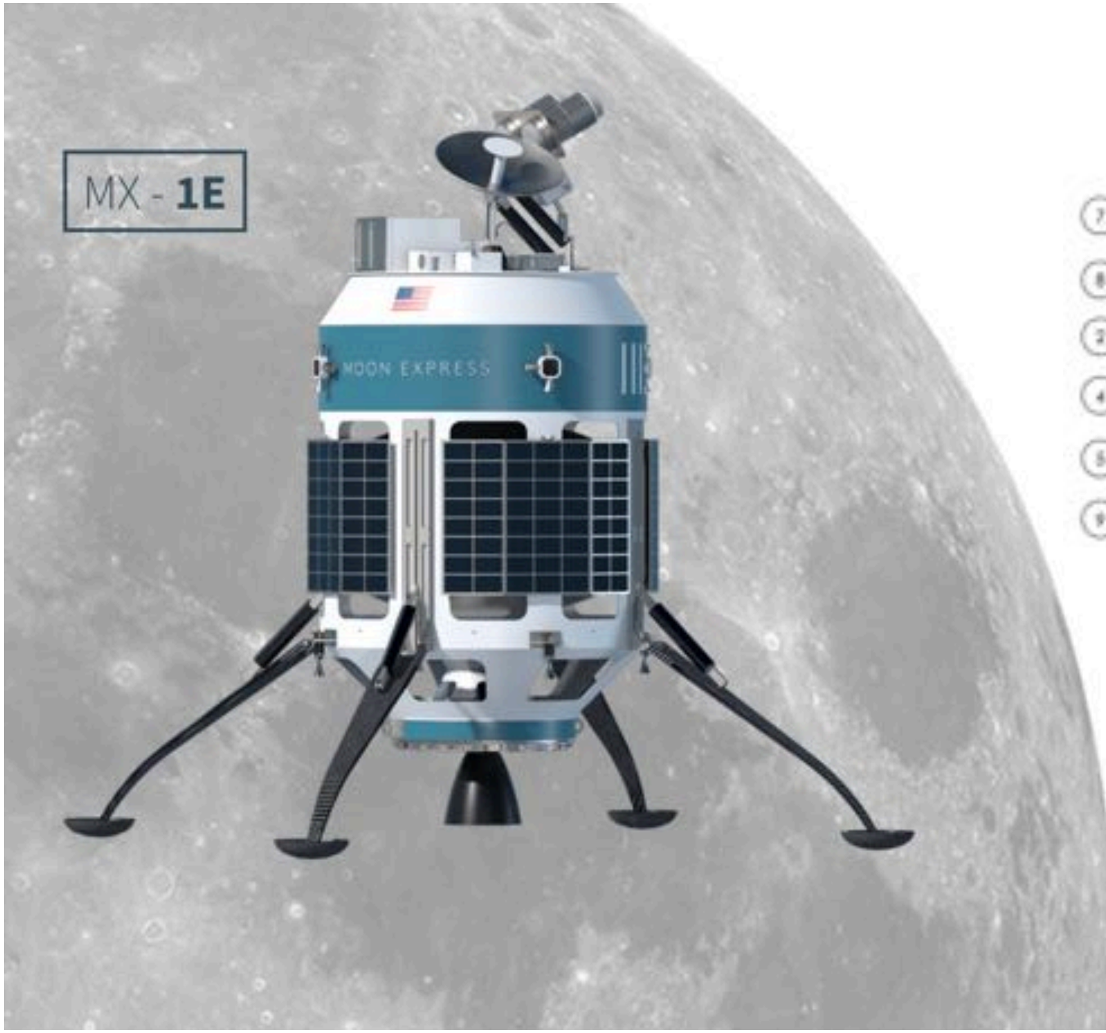
MoonLIGHT & INRRI mockups delivered to Bangalore in Aug 2017 (picture below). Now doing qualifications for delivery of Flight Models

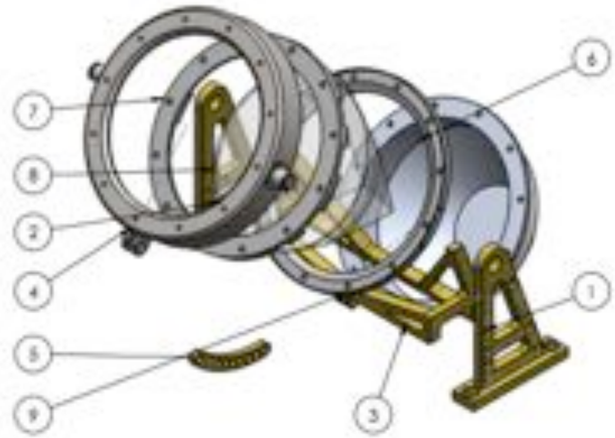


TeamIndus 2018 mission



Moon Express mission MX-1E



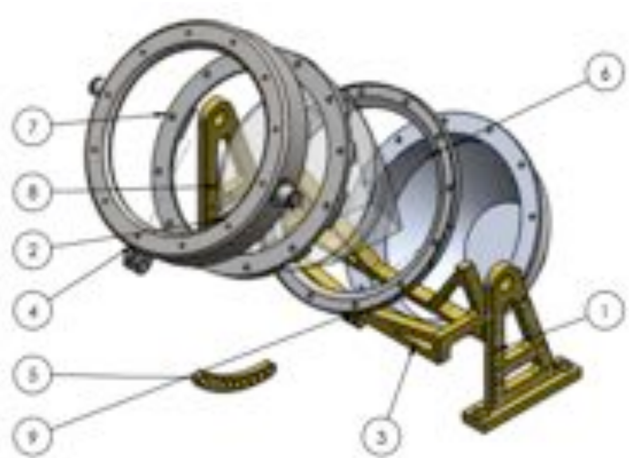


Moon Express mission MX-1E

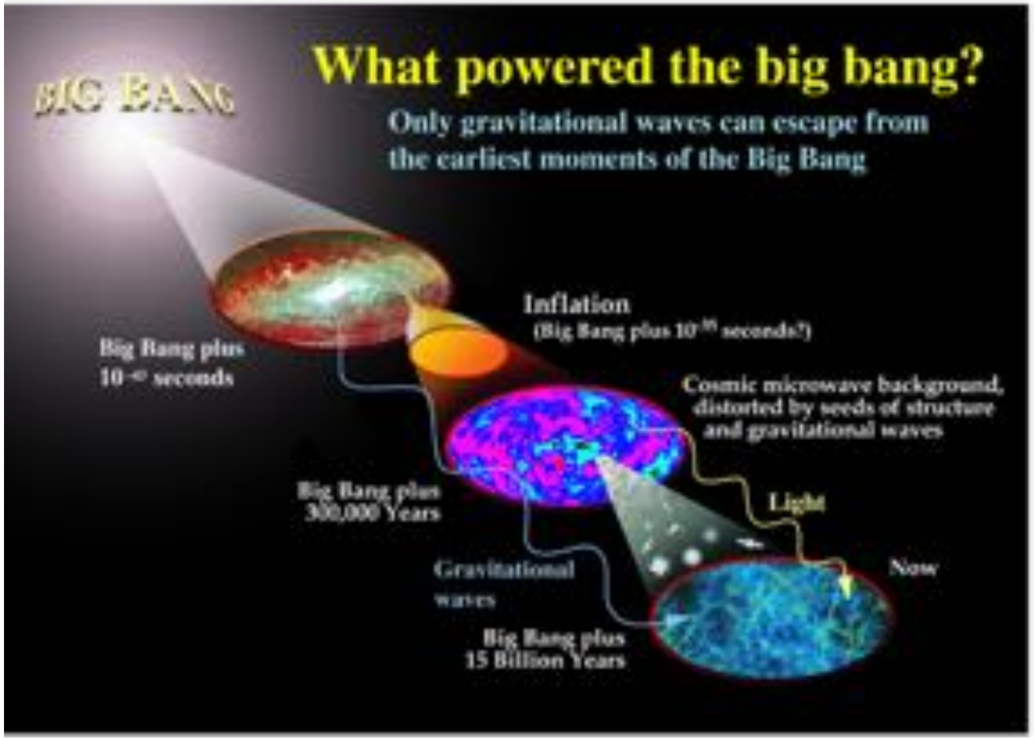
EXPEDITION ONE: LUNAR SCOUT

THE 1ST COMMERCIAL VOYAGE TO THE MOON

The ***Lunar Scout*** expedition will be the first commercial voyage to the Moon. This historic expedition will demonstrate the cost effectiveness of entrepreneurial approaches to space exploration, carrying a diverse manifest of payloads including the International Lunar Observatory, "MoonLight" by the INFN National Laboratories of Frascati and the University of Maryland, and a Celestis memorial flight. Following



New Physics with LLR



To address the evidence of possible departures from General Relativity at the level of Solar System and to motivate the use of retroreflectors on the Moon and Mars we need a theory which extends gravity having the following "requirements":

A – highly motivated from a geometrical point of view

B – widely-accepted by the community

C – predictive on departures at the Solar System regime

D – comparable with cosmic data

A particular family of NLTG is f(R)-gravity in metric formalism, in which the Hilbert Lagrangian is replaced by any non-linear density depending on R. GR is retrieved in (and only in) the particular case f (R)=R.

In these theories there is a second order part that resembles Einstein tensor (and reduces to it if and only if f(R) = R) and a fourth order "curvature part" (that reduces to zero if and only if f (R) = R):

$$f'(R(g))\,R_{\mu\nu}(g) - \frac{1}{2}f(R(g))g_{\mu\nu} - \nabla_\mu\nabla_\nu f'(R(g)) + g_{\mu\nu}\Box f'(R(g)) = \kappa T_{\mu\nu}$$

New Physics with LLR

$$G_{\alpha\beta} = \frac{1}{f'(R)}\left\{\frac{1}{2}g_{\alpha\beta}\left[f(R) - Rf'(R)\right] + f'(R)_{;\alpha\beta} - g_{\alpha\beta}\Box f'(R)\right\} + \frac{\kappa T^{(m)}_{\alpha\beta}}{f'(R)} = T^{(\mathrm{curv})}_{\alpha\beta} + \frac{T^{(m)}_{\alpha\beta}}{f'(R)}$$

$$\gamma - 1 = -\frac{F''(R)^2}{F'(R) + 2F''(R)^2}, \qquad G_{eff} = \frac{G_{Newton}}{f'(R)}$$

$$\beta - 1 = \frac{1}{4}\left[\frac{F'(R)\cdot F''(R)}{2F'(R) + 3F''(R)^2}\right]\frac{d\gamma}{dR}.$$

1) First, we fix by Gdot/G the value of f'
2) Second, we fix with gamma the value of f''
3) Third, we use beta to fix the variation of gamma, having f'''
4) Fourth, we compare those results with cosmology at our time to see if f',f'',f''' are compatible with cosmic observations
5) Fifth, we can fix the free parameters of a model which may be particularly relevant in the literature

From FRW metric we take the expansion series of the scale factor a(t), having:

$$q(t) = -\frac{1}{a}\frac{d^2a}{dt^2}\frac{1}{H^2} \qquad j(t) = \frac{1}{a}\frac{d^3a}{dt^3}\frac{1}{H^3}$$

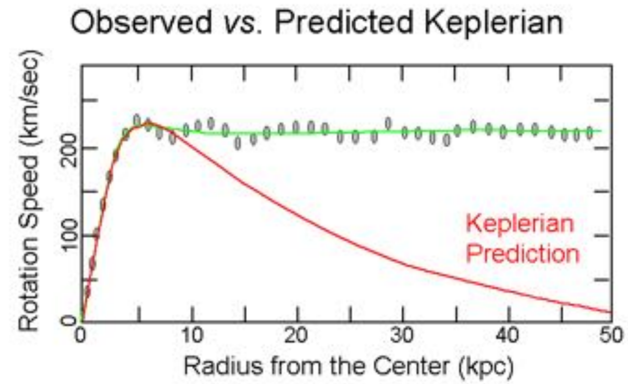
And then measuring q0, j0 by cosmology we compare our bounds in the Solar System also with cosmology

$$f(R) = \sum_n \frac{f^n(R_0)}{n!}(R - R_0)^n \simeq f_0 + f_1 R + f_2 R^2 + f_3 R^3 + \ldots.$$

A prototype: Taylor expansion

New Physics with LLR

Providing a solution to **Dark Matter**



Finally in the weak field limit of modified gravity…

$$\begin{cases} g_{tt}(t,r) \simeq 1 + g_{tt}^{(2)}(t,r) + g_{tt}^{(4)}(t,r) \\ g_{rr}(t,r) \simeq -1 + g_{rr}^{(2)}(t,r) \\ g_{\theta\theta}(t,r) = -r^2 \\ g_{\phi\phi}(t,r) = -r^2 \sin^2\theta \end{cases},$$

$$\Phi_{grav} = -\left(\frac{GM}{f_1 r} + \frac{\delta_1(t) e^{-r\sqrt{-\xi}}}{6\xi r}\right)$$

1) **Sixth, we can compare the modified potential with data**
2) **Seventh, we can get constraints over KGP in the field of f(R) gravity**
3) **FUTURE DEVELOPMENTS: we can match recent results over GRB170817A/GW170817 Neutron Star merging with our results**

Conclusions

- MoonLIGHT, the single *big* Lunar laser retroreflector and INRRI, the Solar System *micro*reflector array soon to be deployed on the Moon
  - ✓ *Microreflectors already on ESA & NASA Mars landers*
- Enhancing PEP, the Planetary Ephemeris Program orbital SW with General Relativity
- Available data for testing *new physics models, i.e. F(R)*
- Matching between cosmology and local tests in the Solar System *through experimental constraints set with MoonLIGHTs*

Thanks!