SCF_Lab:
Fundamental/Applied Physics in Space

S. Dell'Agnello for the SCF_Lab Team (INFN-LNF)
http://www.lnf.infn.it/esperimenti/etrusco/

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

SCF_Lab

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

Outline

(*These are INFN-CSN2/CSN5 research activities*)

- Key partnerships with ASI and NASA
- Moon: a laser-ranged test mass for General Relativity and new gravitational physics
- New INFN-ASI (non-ballistic) frontier: Mars as a laser-ranged test mass for General Relativity and new physics
- Phobos/Deimos, Asteroids/Comets
- Outlook: now to 2030

Joint Lab on laser retroreflectors & ranging

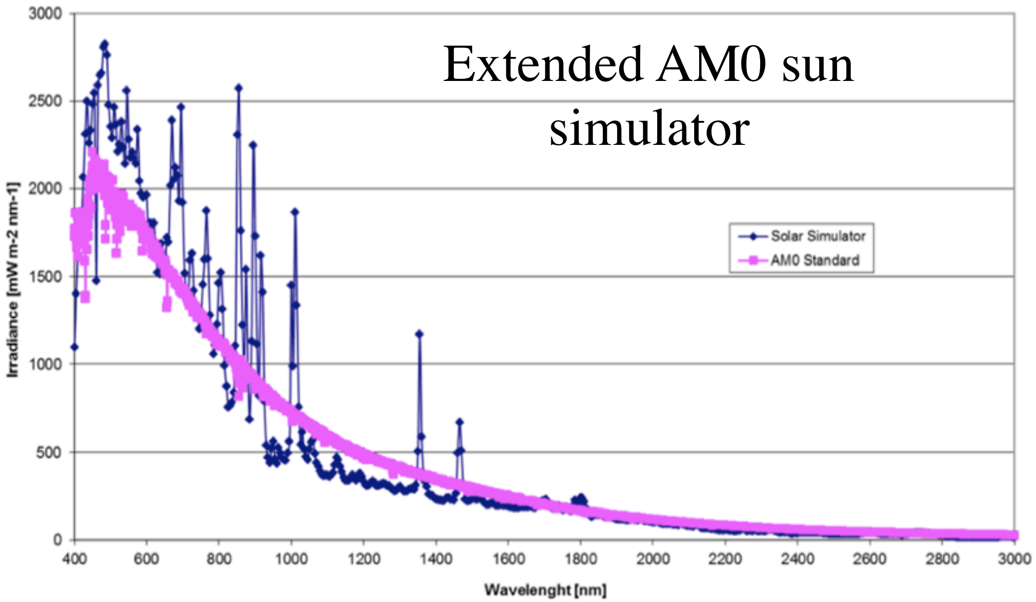
Matera Laser Ranging Observatory @ ASI-CGS

SCF_Lab @ INFN-Frascati: Optical Ground Support Equipment (OGSE) SCF, SCF-G

Two AM0 sun simulators, IR thermometry

Optical testing: Far Field, Fizeau interferometry

Space Geodesy Center
Giuseppe Colombo
Matera, Italy



Space Geodesy Center
Giuseppe Colombo
Matera, Italy

(slides courtesy of Pippo Bianco)

agenzia spaziale
italiana


MLRO

INFN Affiliation to NASA-SSERVI

Signed in Rome on Sep. 15, 2014

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

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

May 19, 2015: INFN visit to NASA-HQ/GSFC

INFN President, Ferroni (center) visiting GSFC after meeting with John Grunsfeld at HQ. Discussed SSERVI Affiliation and Mars applications.

May 19, 2016: visit of ASI President, Battiston to NASA-JPL. Confirmed joint interest ASI-NASA-INFN for Mars missions.

<u>Late-breaking news</u>:
Italian microreflector for SpaceX mission with the **Falcon Heavy** rocket and **Dragon** Capsule (unmanned) to land on Mars on 2018 !!

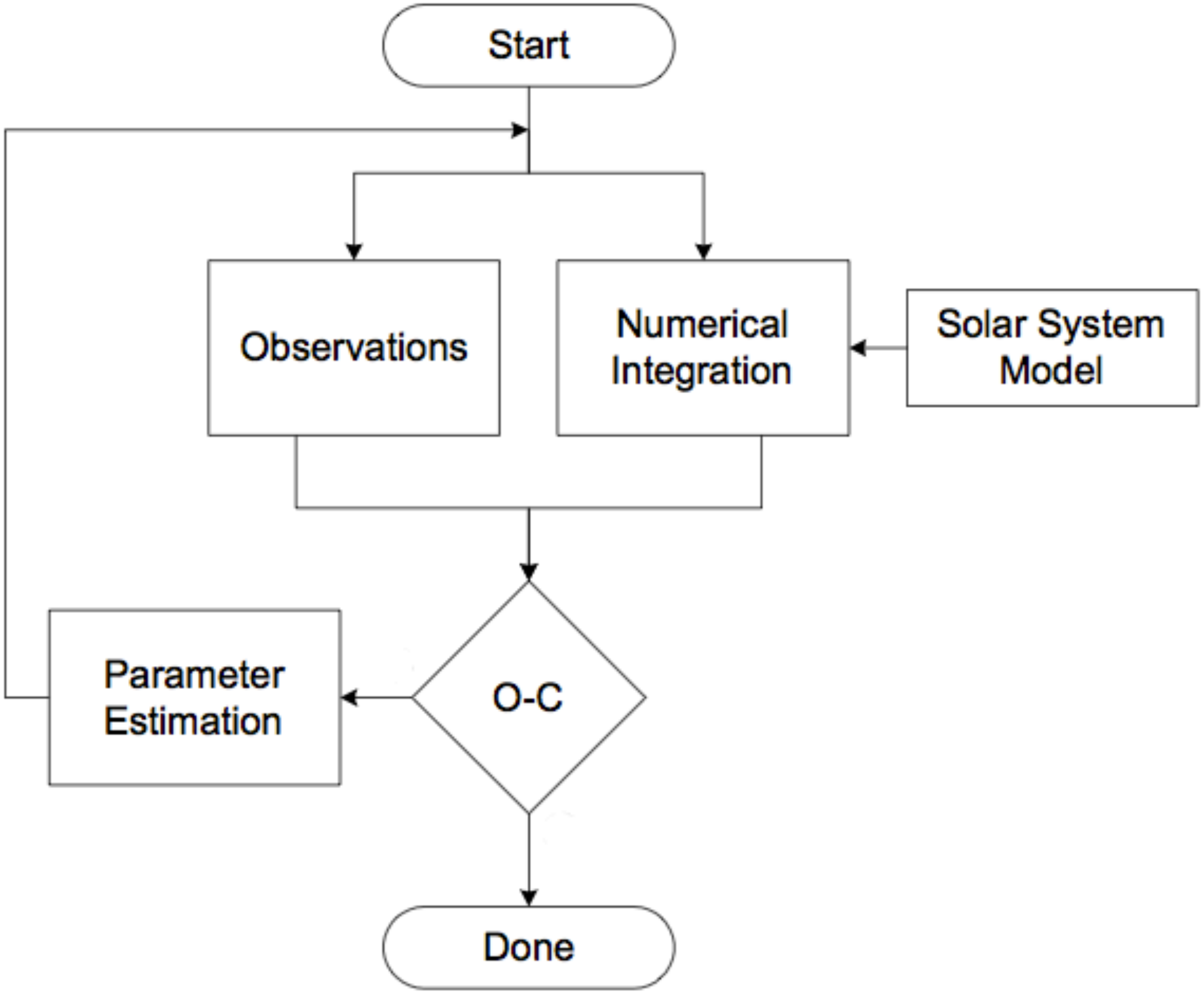
The ‘family jewels’

MoonLIGHT, the *big* Lunar laser retroreflector
INRRI, the Martian laser *micro*reflector
PEP, the orbital SW

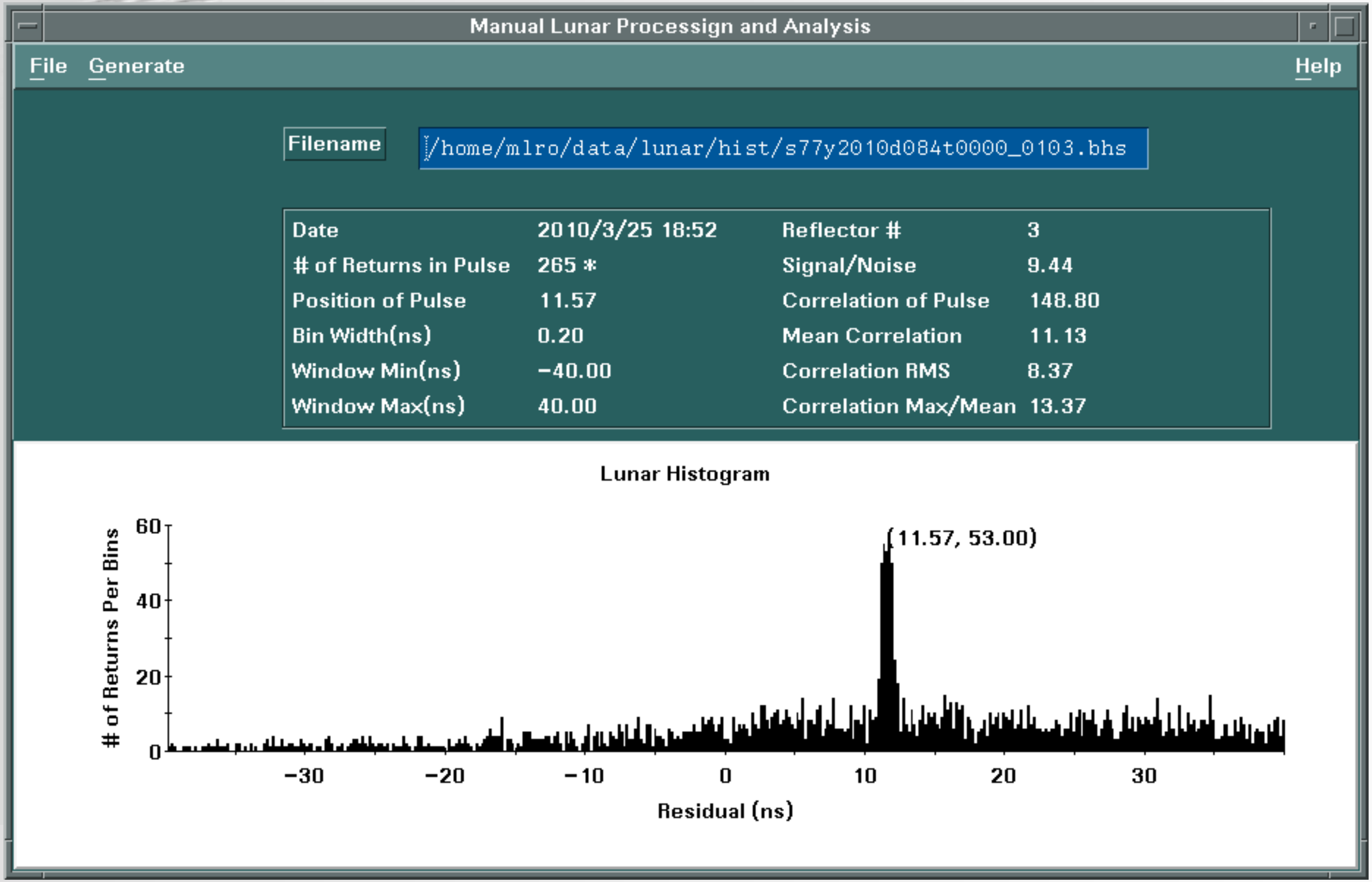
To analyze Lunar/Martian data we used the sw package Planetary Ephemeris Program (PEP) developed at CfA by I. Shapiro, Reasenberg, Chandler since 1960/70s.

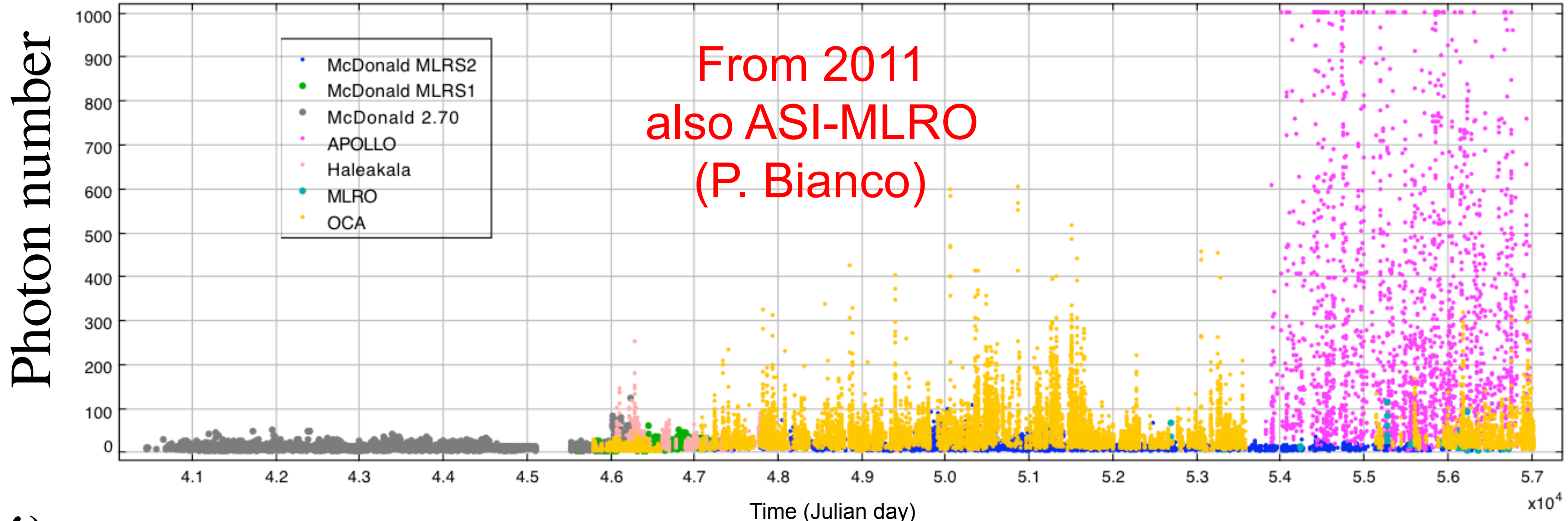
The model parameter estimates are refined by minimizing the residual differences, in a weighted least-squares sense, between observations (O) and model predictions (C, stands for ”Computation”), O-C.

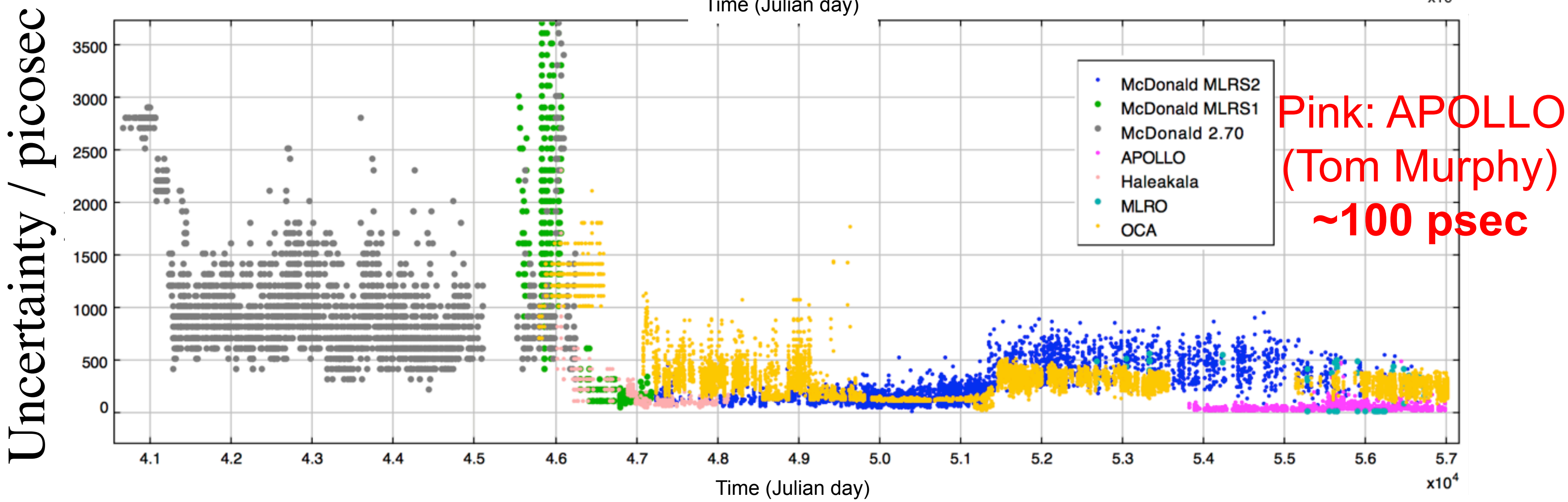
PEP (analysis of Moon & Mars data)



LLR ToF (by ASI-MLRO on Apollo 15)



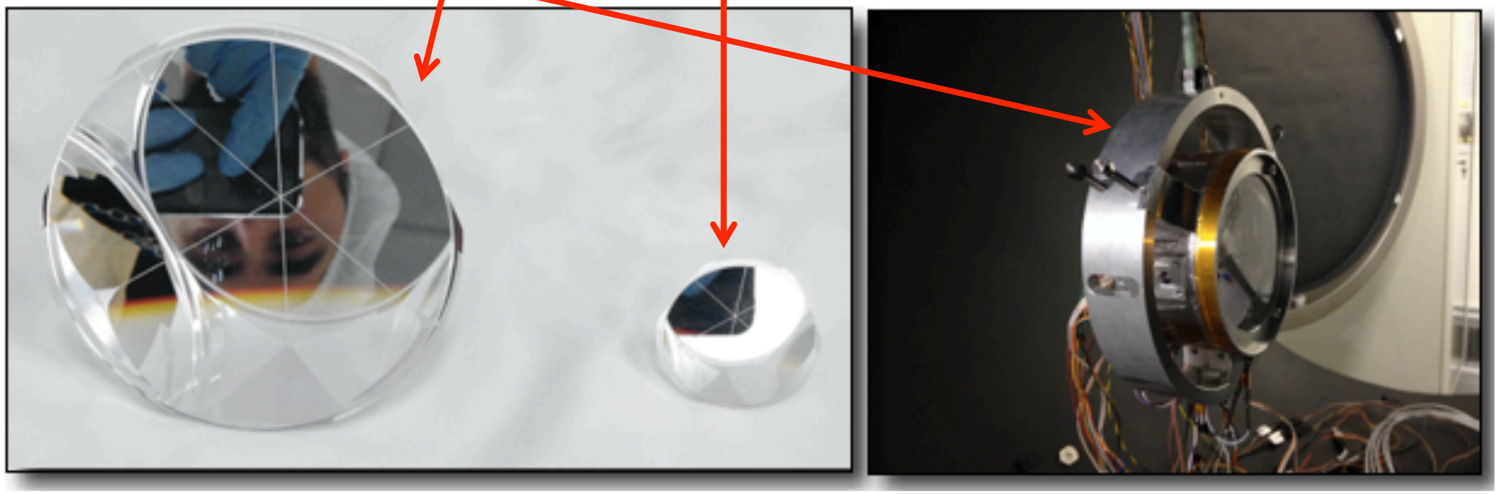

Photon number
1000
900
800
700
600
500
400
300
200
100
0
McDonald MLRS2
McDonald MLRS1
McDonald 2.70
APOLLO
Haleakala
MLRO
OCA
From 2011
also ASI-MLRO
(P. Bianco)
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8
4.9
5.0
5.1
5.2
5.3
5.4
5.5
5.6
5.7
x10^4
Time (Julian day)


Uncertainty / picosec
3500
3000
2500
2000
1500
1000
500
0
McDonald MLRS2
McDonald MLRS1
McDonald 2.70
APOLLO
Haleakala
MLRO
OCA
Pink: APOLLO
(Tom Murphy)
~100 psec
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8
4.9
5.0
5.1
5.2
5.3
5.4
5.5
5.6
5.7
x10^4
Time (Julian day)

MoonLIGHT-2: Next Generation Lunar Laser Retroreflector

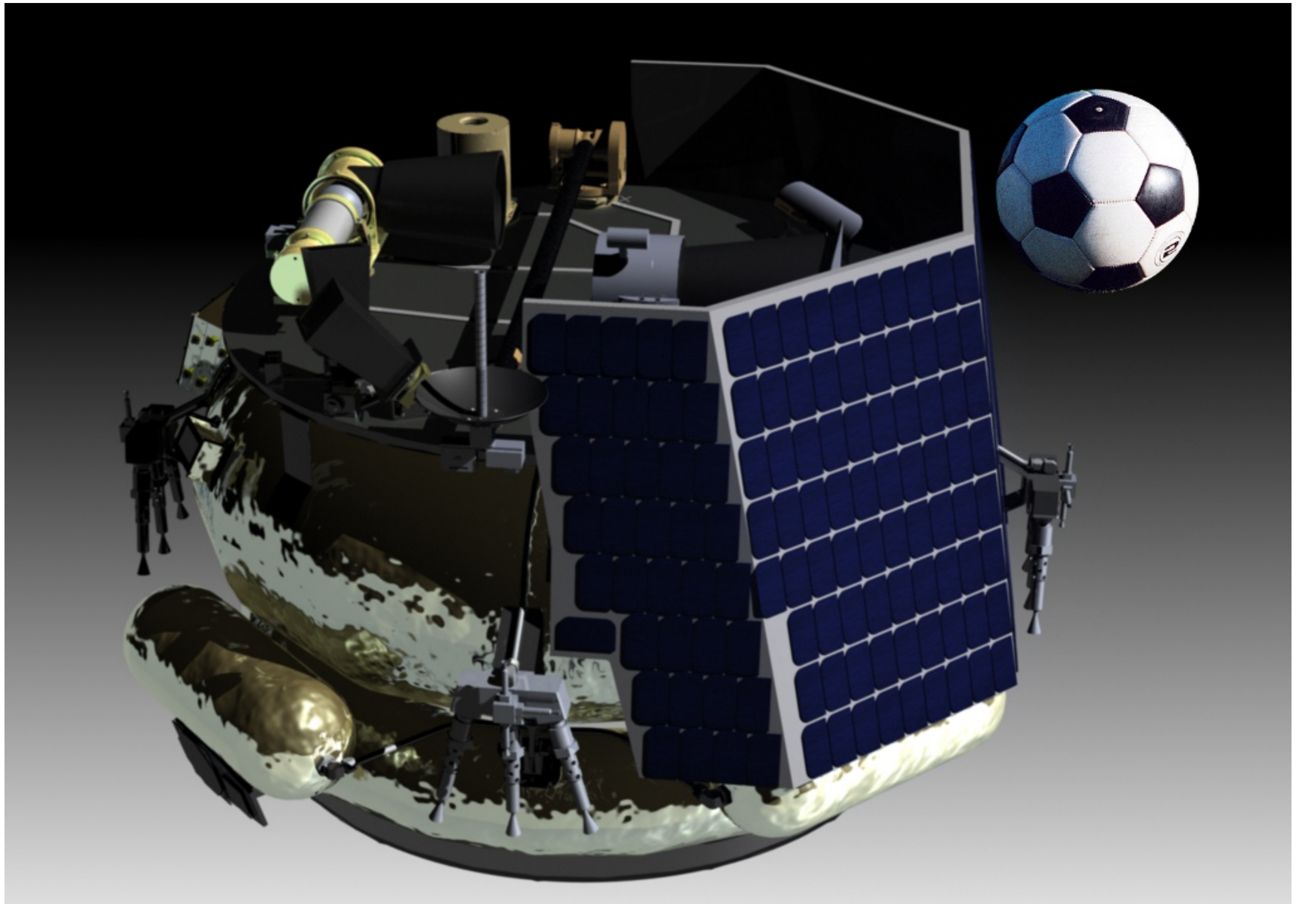
- Collaboration
  - LNF, Padova, U. Maryland (formerly PI of Apollo reflectors)
  - Lunar stations: ASI-MLRO (Italy), APOLLO (US, the best)

MoonLIGHT, Apollo reflector



MoonLIGHT-2 missions

Moon Express 1 (US, $\geq$ 2017)   agreement signed on May 15, 2015



Lunar missions

- Chang'E-4 (China, 2018-2019)
  - Far side lander + rover, two INRRI microreflectors, to be laser-located by NASA's orbiter LRO
    - Negotiations between INFN-CNSA-ASI-NASA/SSERVI
- Chang'E-5 and 6 (China, ≥2020)
  - Near side, MoonLIGHTs + INRRIs

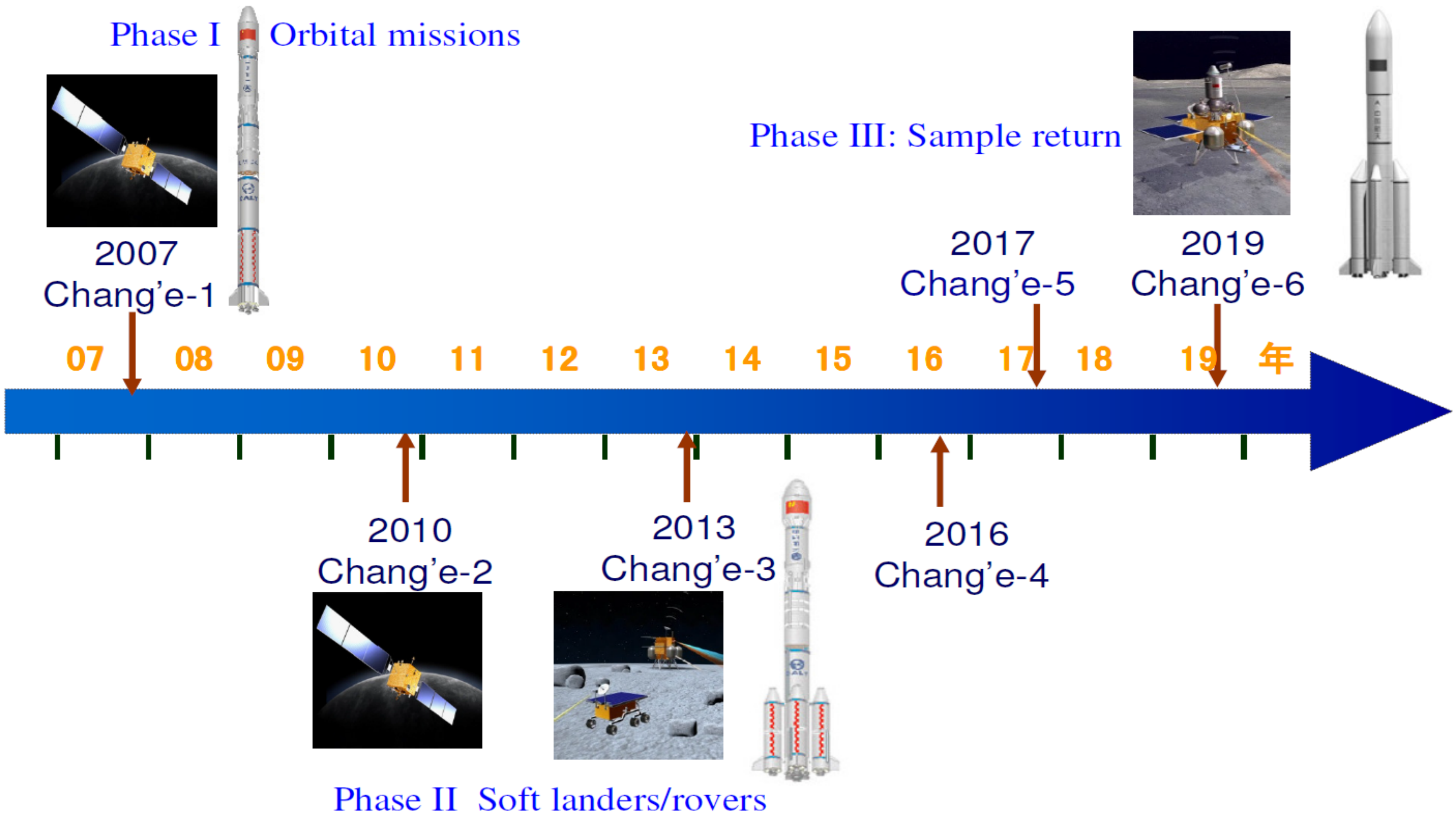
Chang'E,
Chinese Moon Goddess

Plus:

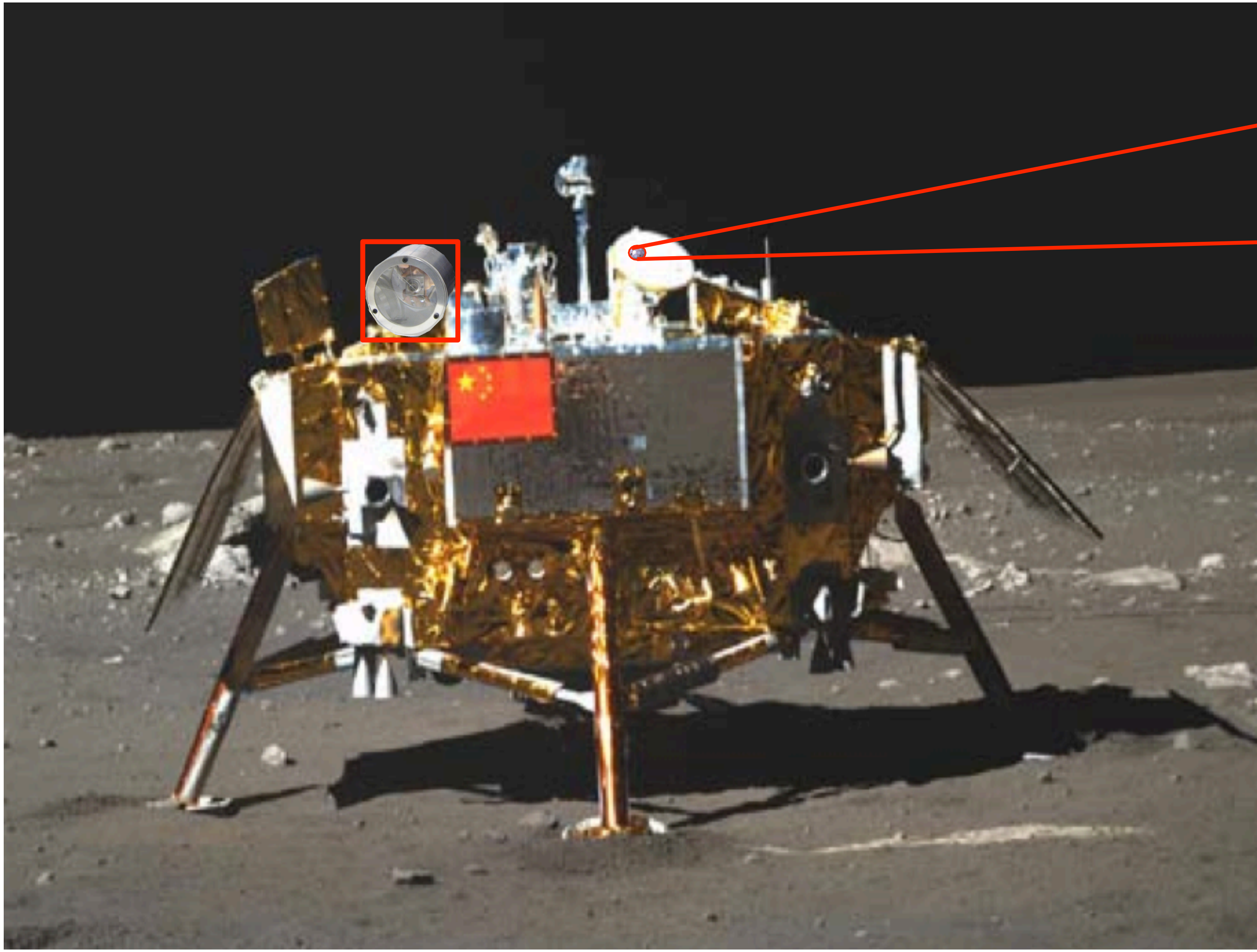
New ESA DG: long-term *Moon Village*

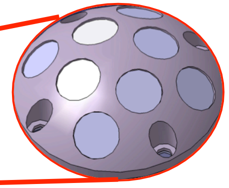
→ Several laser retroreflector milestones for colonization

Chinese Lunar Exploration Program



MoonLIGHT-INRRI *imagined* on Chang'E lander



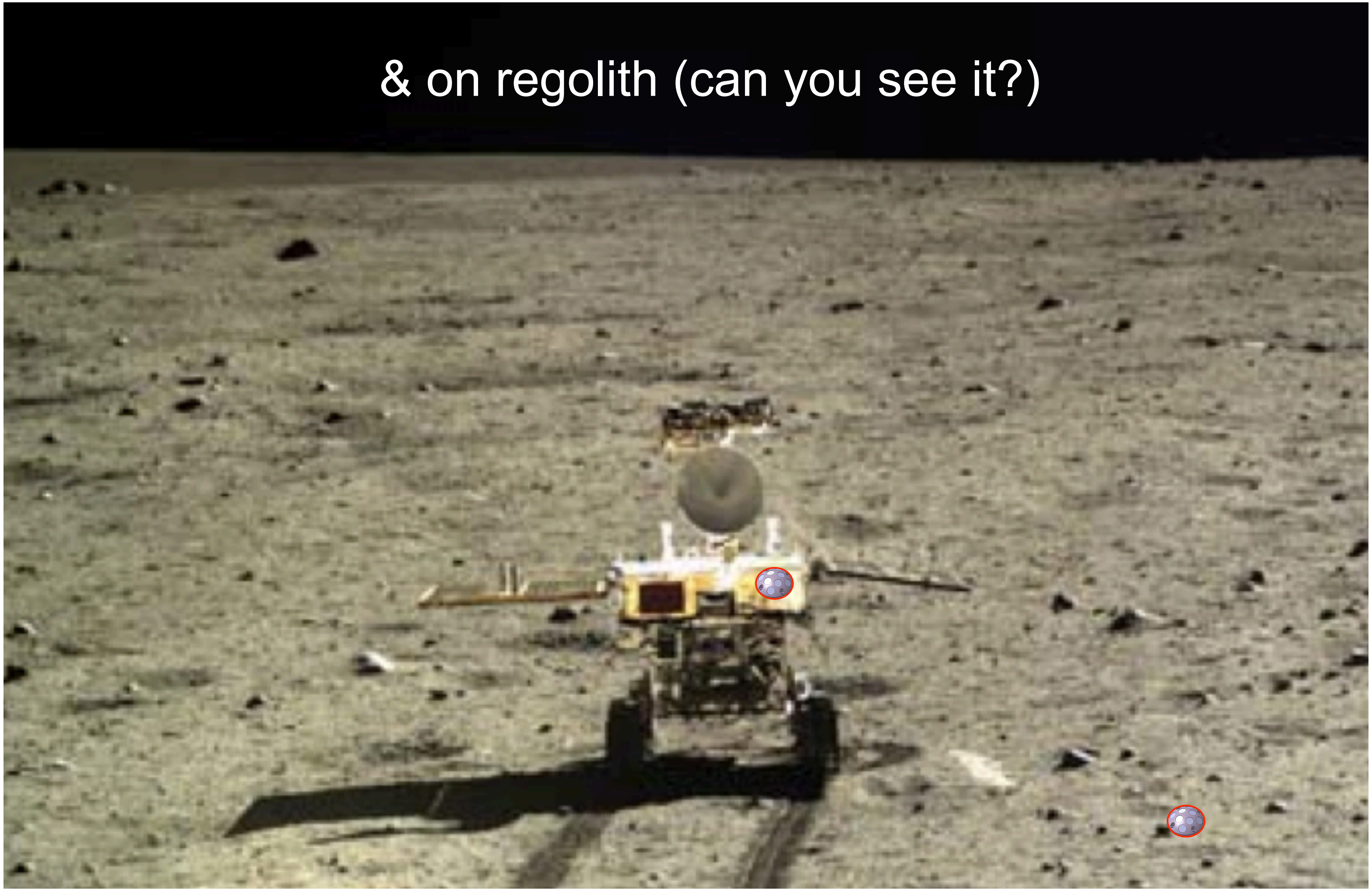


Compact,
light,
Passive

(drawing
not to scale!

INRRI is
~54 mm diam.
~20 mm high)

INRRI *imagined* on Yutu minirover



Lunar Laser Ranging (LLR) test of gravity

General Relativity: precisions tests, improvements up to ×100 with MoonLIGHT, next-generation laser retroreflectors

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

** M. Martini et al Plan. & Space Sci. 74 (2012) 276–282; M. Martini PhD thesis 2016

Science measurement / Precision test of violation of General Relativity	Apollo/Lunokhod * few cm accuracy	MoonLIGHTs ** mm	sub-mm
Parameterized Post-Newtonian (PPN) β	$\|\beta-1\| < 1.1\times10^{-4}$	10^{-5}	10^{-6}
Weak Equivalence Principle (WEP)	$\|\Delta a/a\| < 1.4\times10^{-13}$	10^{-14}	10^{-15}
Strong Equivalence Principle (SEP)	$\|\eta\| < 4.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
Time Variation of the Gravitational Constant	$\|\dot{G}/G\| < 9\times10^{-13}yr^{-1}$	5×10^{-14}	5×10^{-15}
Inverse Square Law (ISL) - Yukawa	$\|\alpha\| < 3\times10^{-11}$	10^{-12}	10^{-13}
Geodetic Precession	$\|K_{gp}\| < 6.4\times10^{-3}$	6.4×10^{-4}	6.4×10^{-5}

Test of Equivalence Principle (EP)

- Weak EP (*feather vs. hammer*)
  - Composition difference: iron in Earth vs. silicates in Moon
  - Probes all interactions but gravity itself. Tested by LLR to $\Delta a/a < 10^{-13}$
- Strong EP (*small hammer vs. big hammer*)
  - Applies to gravitational "self-energy"
  - Earth self-energy has equivalent mass ($E = mc^2$)
    - 4.6×10^{-10} of Earth's total mass-energy
  - Does this mass have $M_G/M_I = 1.00000\ldots$?
  - Gravity pulls on gravity. *Nonlinear* aspect of gravity => **PPN β**
  - LLR provides the best way to test the SEP
- WEP contribution measured in the lab with torsion pairs (miniature Earth and Moon) by EotWash group
- WEP effects subtracted in LLR analysis => access to SEP

LLR test of the Strong Equivalence Principle

- LLR test of EP sensitive to *both* composition-dependent (CD) and self-energy violations

UW: Baessler et al, PRL **83**, 3585 (1999);
Adelberger et al Cl. Q. Gravity **12**, 2397 (2001)

- University of Washington (UW) laboratory EP experiment with "miniature" Earth and Moon, measures *only* CD contribution:

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{WEP,UW} = (1.0 \pm 1.4) \times 10^{-13}$$

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{WEP,LLR} = (-1.0 \pm 1.4) \times 10^{-13}$$

- Subtracting UW from LLR results one gets the SEP test:

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{SEP} = (-2.0 \pm 2.0) \times 10^{-13}$$

SEP can only be tested LLR

LLR test of the Equivalence Principle

If EP is violated:

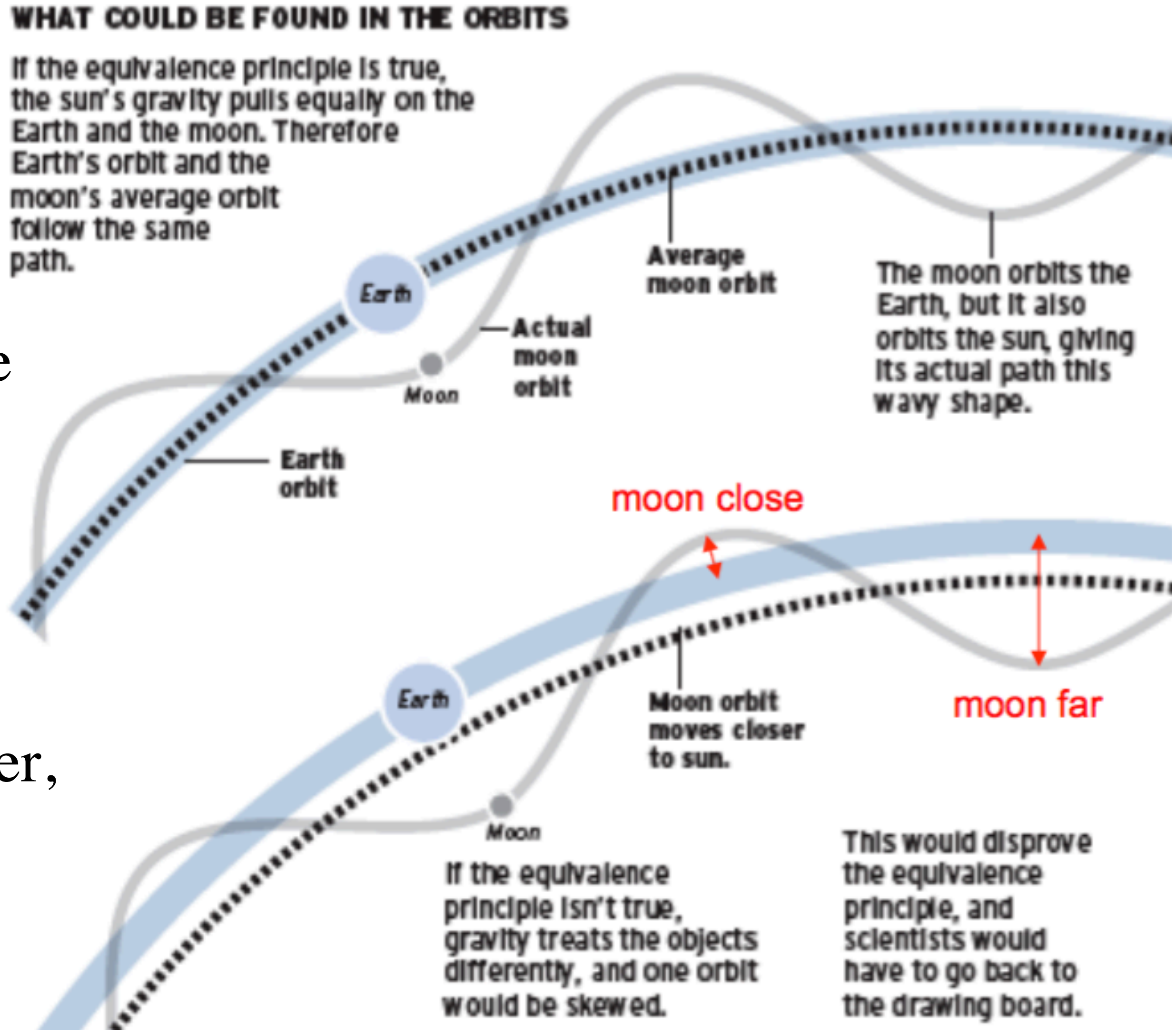
lunar orbit displaced along Earth-Sun line;

periodic variation of Earth-Moon distance

$\Delta r = 13.1\ \eta \times \cos D$

D = lunar phase angle

η = Nordtvedt parameter, describes gravitational self-energy



Graphic excerpt from San Diego Union Tribune

LLR SEP test: implications on η and PPN β

- SEP violation is due to self-energy (U) contribution only

$$[(M_G/M_I)]_{SEP} = 1 + \eta\,(U/Mc^2)$$

U/M ∝ M => to test SEP need astronomical bodies => only LLR

- Theory prediction

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{SEP} = [U_e/Mc^2 - U_m/Mc^2] \times \eta$$
$$= -\,4.45 \times 10^{-10} \times \eta$$

- Considering in η only PPN β and γ

$$\boldsymbol{\eta = 4\beta - \gamma - 3 = (4.4 \pm 4.5) \times 10^{-4}}$$

- β describes non linearity of gravity associated to a SEP violation
- Using Cassini's value of γ:

$$\boldsymbol{\beta - 1 = (1.2 \pm 1.1) \times 10^{-4}}$$

Best η and β measurement to date

LLR test of Gdot/G

- G variation may be related to expansion of the Universe, in which case Gdot/G = $\sigma \times$ (Hubble constant)

  σ: dimensionless parameter depending on G & cosmological model allowing for G evolution

- If *G* changes with time, Kepler's law is broken
- Test of temporal variation of G from fit of LLR data gives

$$Gdot/G = (4 \pm 9) \times 10^{-13}/\text{year}$$

  - ✓ **Best limit to date** (to my knowledge)
  - ✓ Less than 1% change over age of Universe

- Error on Gdot/G depends on
  - ✓ Accuracy of LLR measurements
  - ✓ Square of time span of LLR data

Non-Minimally Coupled gravity (NMC)

f(R) & $f_1(R)+f_2(R)$ theories ➔ provide 'weak' gravity & alternatives to dark energy/matter scenario

The action functional of nonminimally coupled (NMC) gravity is of the form [8]

$$S = \int \left[\frac{1}{2} f^1(R) + [1 + f^2(R)]\mathcal{L} \right] \sqrt{-g} d^4x, \quad (1)$$

where $f^i(R)$ (with $i = 1, 2$) are functions of the Ricci scalar curvature R, $\mathcal{L}$ is the Lagrangian density of matter, and g is the metric determinant. The Einstein-Hilbert action is recovered by taking

$$f^1(R) = 2\kappa(R - 2\Lambda), \qquad f^2(R) = 0, \qquad (2)$$

where $\kappa \equiv c^4/16\pi G$, G is Newton's gravitational constant and Λ the cosmological constant.

Yukawa limits (α vs. λ) on NMC gravity

O. Bertolami, R. March (INFN-LNF) et al, **Solar System constraints to nonminimally coupled gravity**, *PRD 88, 064019 (2013)*

R. March (INFN-LNF) et al, **Perturbation of the metric around a spherical body from a nonminimal coupling between matter and curvature**, *PL B 735 (2014) 25–32*

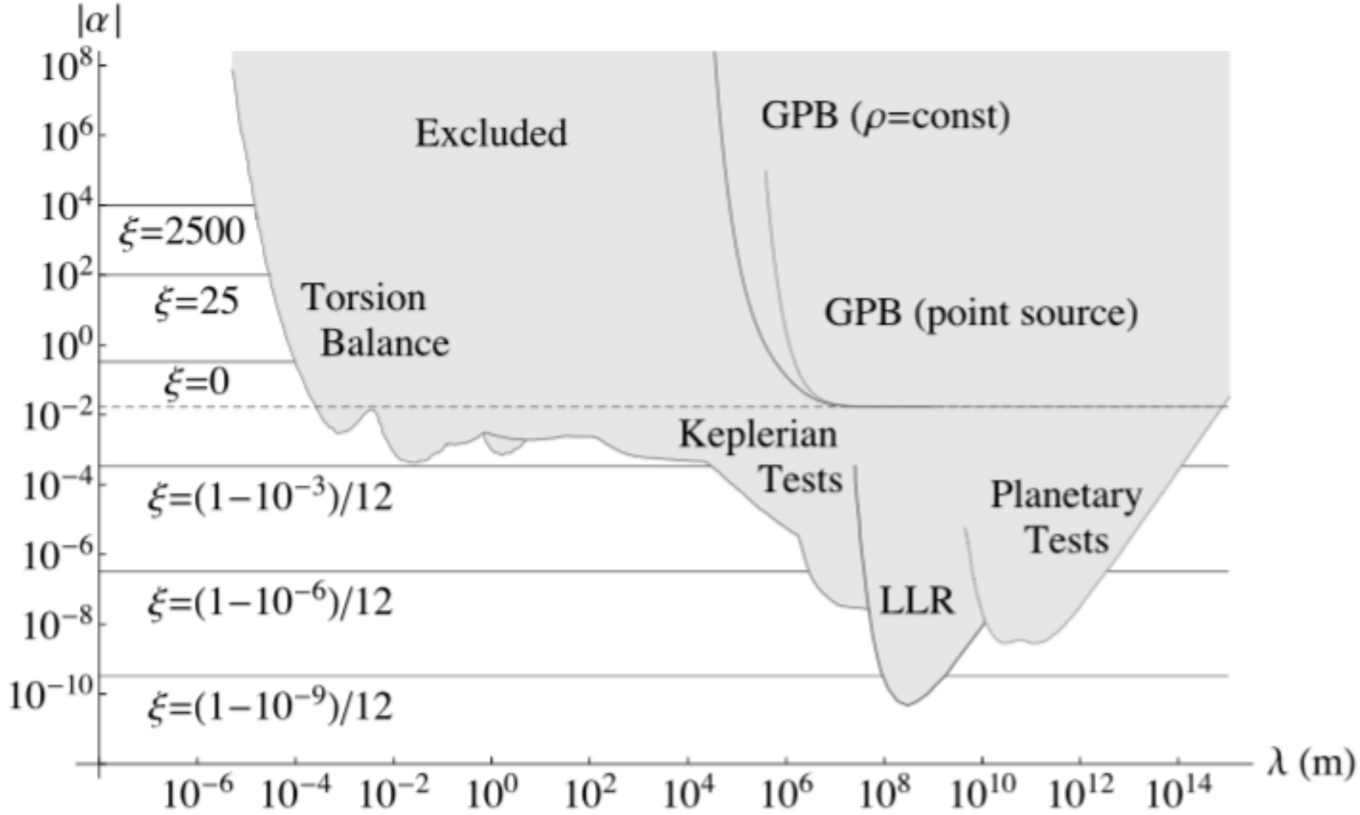


Fig. 2. Yukawa exclusion plot for α and λ. Adapted from Refs. [41,46].

NMC gravity: PPNY = PPN + Yukawa

The $1/c$ expansion of nonminimally coupled curvature-matter gravity model and Solar System experiments

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Istituto per le Applicazioni del Calcolo, CNR, Via dei Taurini 19, 00185 Roma, Italy and INFN - Laboratori Nazionali di Frascati (LNF), Via E. Fermi 40, Frascati 00044 Roma, Italy

Orfeu Bertolami‡ and Jorge Páramos§
Departamento de Física e Astronomia and Centro de Física do Porto, Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre 687, 4169-007 , Porto, Portugal

(Dated: July 27, 2015)

The effects of a nonminimally coupled curvature-matter model of gravity on a perturbed Minkowski metric are presented. The action functional of the model involves two functions $f^1(R)$ and $f^2(R)$ of the Ricci scalar curvature R. This work expands upon the results previously reported in Ref. [1], extending the framework developed there to compute corrections up to order $O(1/c^4)$ of the metric. It is shown that additional contributions arise due to both the non-linear form $f^1(R)$ and the nonminimal coupling $f^2(R)$, including exponential contributions that cannot be expressed as an expansion in powers of $1/r$. Some possible experimental implications are assessed.

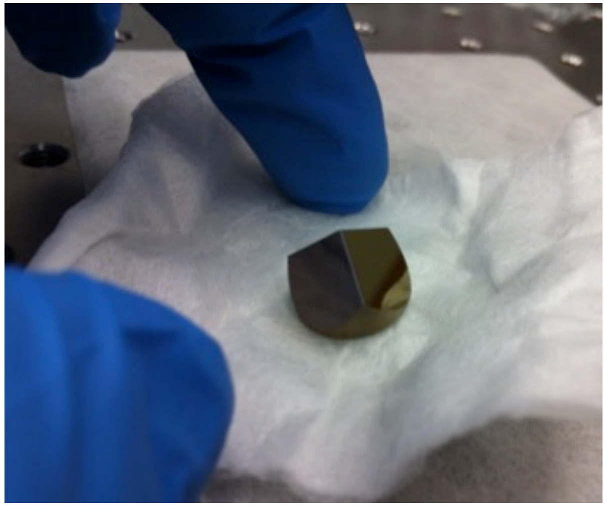
Extra perihelion precession to be constrained w/Mercury-Mars

Beyond the Moon

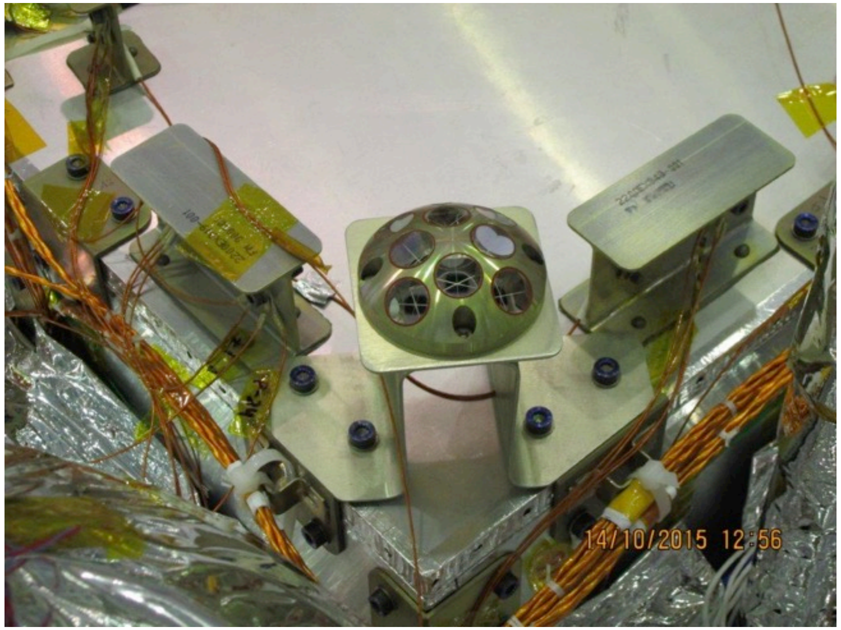
INRRI = INstrument for landing-Roving laser Retroreflectors Investigations

- Laser-located by planetary/moon orbiters, not by Earth
  - Laser altimetry, Laser ranging, Lasercom
    - NASA LADEE: lasercom ToF with ~100 psec accuracy
  - Topography by laser flashes + cameras (like LROC)
- Accurate positioning of landing-roving
- Test of General Relativity and its extensions
- Lasercomm test & diagnostics
- Atmospheric trace species detection by space-borne lidar
- Lidar-based/aided landing (return to lander/rover)
- …

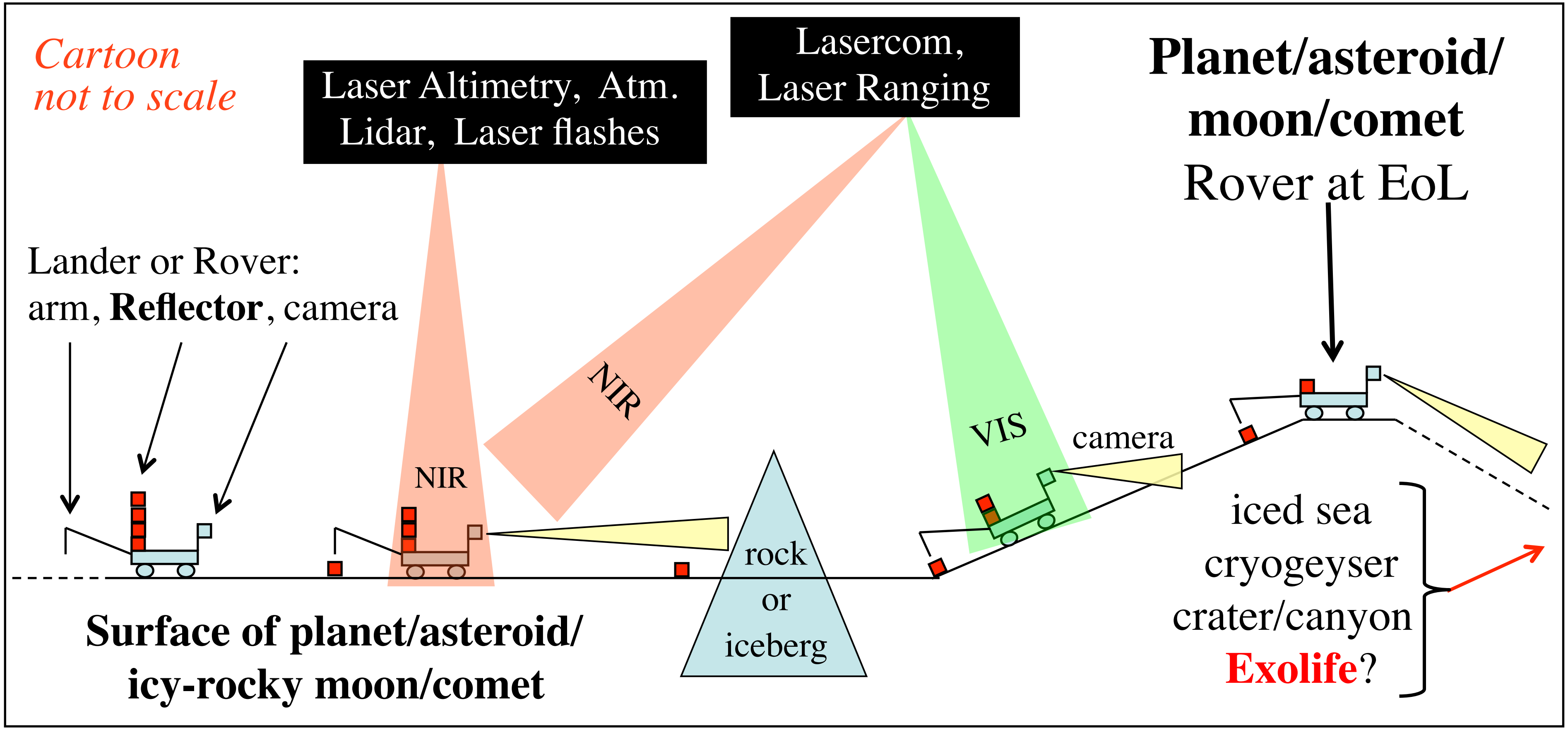
INRRI space qualification & integration



Reflector load/peel test.
TVT (158-328 K).
Vibe/shock (proton) @SERMS.
Load/peel test.
Mass loss check.



Reflectors on Moon/Mars, asteroids/comets, icy/moons

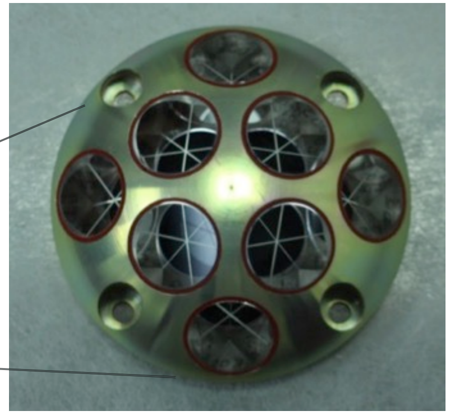


Laser-locate Rover/Lander w/reflector from orbiters. Moon far side

Global and local reflector networks to serve Exploration, Planetary Science, Geodesy and test Fundamental Gravity

Italian microreflector on ExoMars EDM

First laser retroreflector on the surface of Mars & beyond the Moon
Launched on March 14, 2016



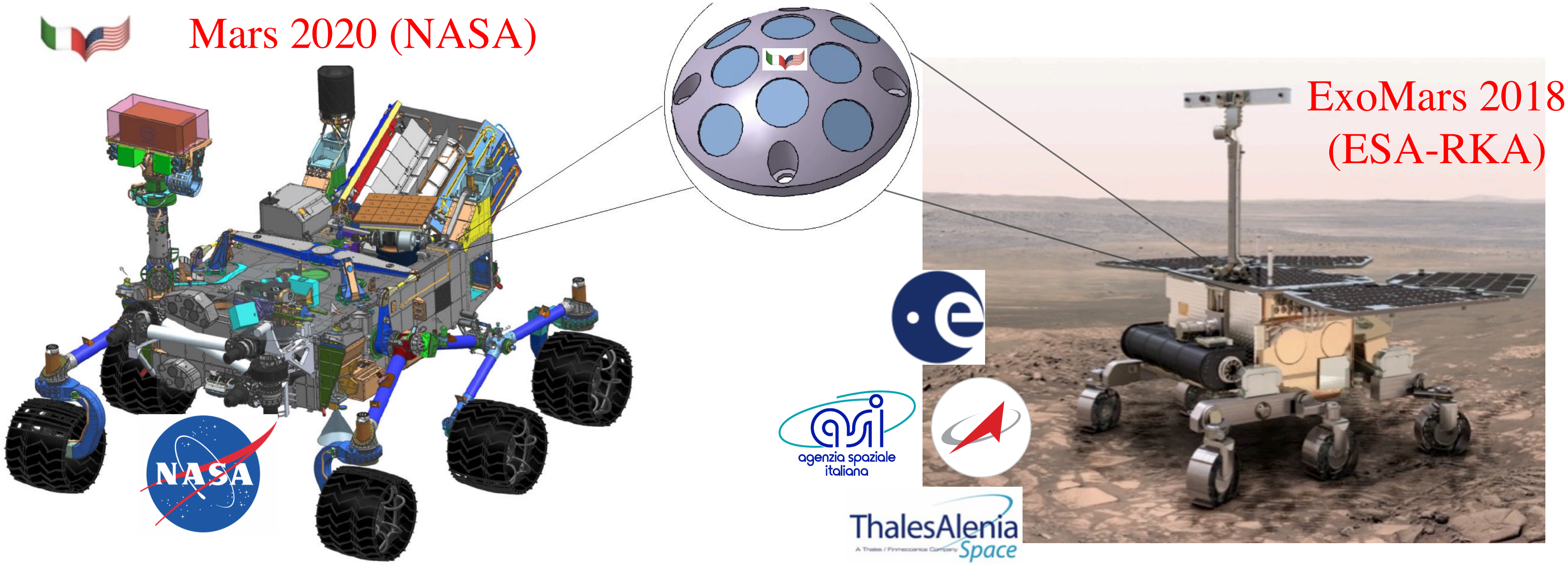
Passive, long lifetime
Lightweight: 25 gr
Compact: ~5cm×2cm

INRRI

INstrument for landing-**R**oving **R**etroreflector **I**nvestigations

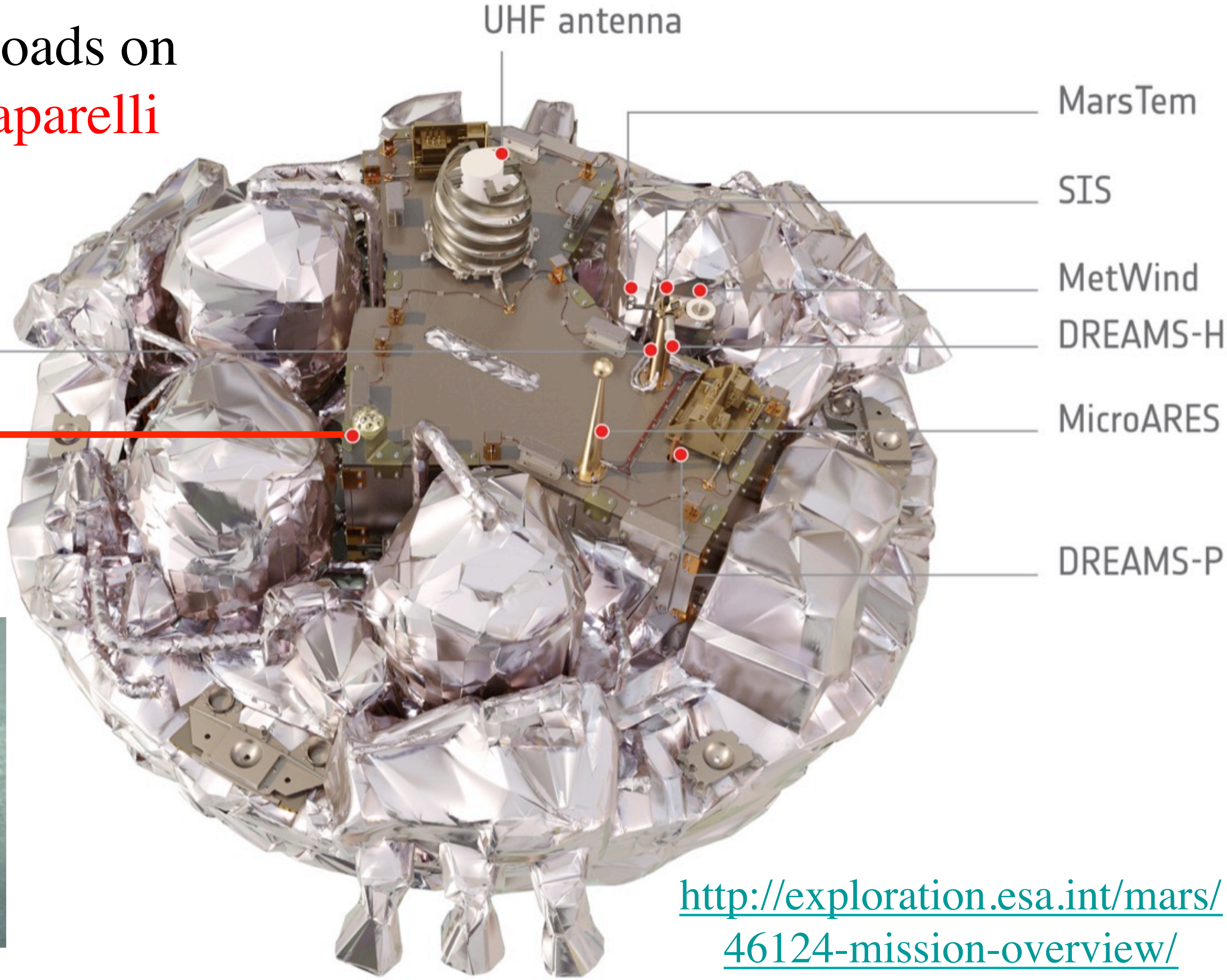
Testing Mars gravity: INRRI microreflectors

- INRI is in ASI 3-year Plan 2016-18
  - NASA/ASI: Mars 2020 (×1), Insight 2018 (×1)?
  - ESA/ASI: ExoMars 2016 (×1), ExoMars 2020 (×2)
  - SpaceX: Falcon Heavy, Dragon Capsule, launch in 2018 (×1)

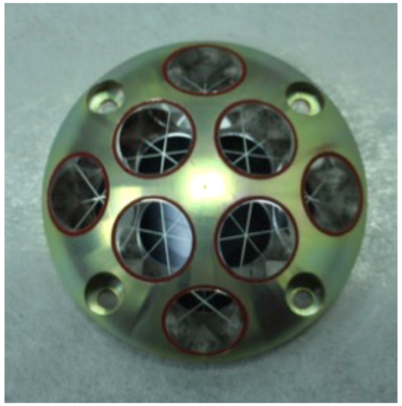


INRRI on ExoMars EDM 2016 of ESA-ASI

Science payloads on Lander Schiaparelli



INRRI
25 gr
~5cm×2cm



http://exploration.esa.int/mars/46124-mission-overview/

Mars surface (rovers/landers) physics goals

- Multiple INRRIs: **Mars Geo/physics Network (MGN)**
- Test of General Relativity (GR) at 1.5 AU
  - Mars center of mass estimated with INRRIs like Selenocenter with Lunar Geophysical Network (LGN)
  - PPN gamma (Sun-Mars)
  - PPN beta (Sun-Mars-Jupiter)
  - Gdot/G, $1/r^2$ law
- PEP (Planetary Ephemeris Program) analysis
- Next: constrain Non-Minimally Coupled gravity (NMC)

GR tests with Mars – PEP simulations

- Extend work done with Mars Viking landers & Moon reflectors
- Assume MGN of INRRIs at 'symbolic' locations
  - 68N, 234E = Phoenix Lander
  - 4S, 137E = Curiosity Rover; 2S, 354E = Opportunity Rover
  - 22N, 50W = Viking 1 lander; 48N, 258W = Viking 2 lander
- Due to weather effects: 1 laser PEP normal point every 7 Sols
- Preliminary results for: 10 years of data, accuracy ≥10 cm, MGN basically all north hemisphere

INRRI: Time/Accuracy	Accuracy on β-1	Accuracy on γ-1	Accuracy on $\dot{G}/G$
10 years / 10 m	1.7 x E-04	7.2 x E-04	3.8 x E-14
10 years / 1 m	3.7 x E-05	1.6 x E-05	1.4 x E-14
10 years / 10 cm	7.4 x E-07	3.2 x E-06	2.9 x E-15
Accuracy now	**1 x E-04** Lunar Laser Ranging, *JPL, PEP(CfA/INFN)*	**2.3 x E-05** Cassini, *JPL ODP, Bertotti et al*	**9 x E-13** Lunar Laser Ranging, *JPL, PEP(CfA/INFN)*

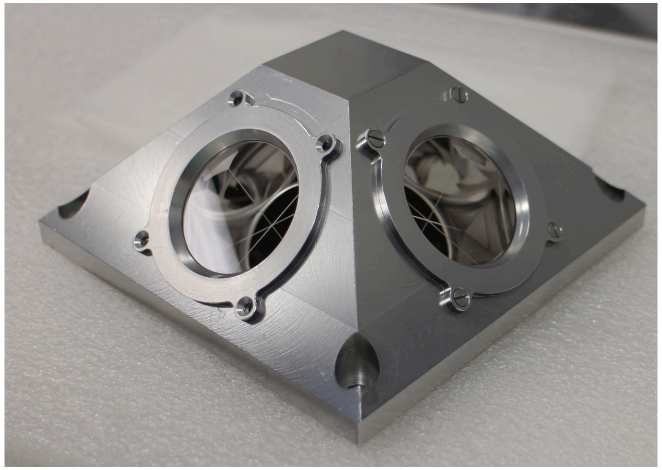
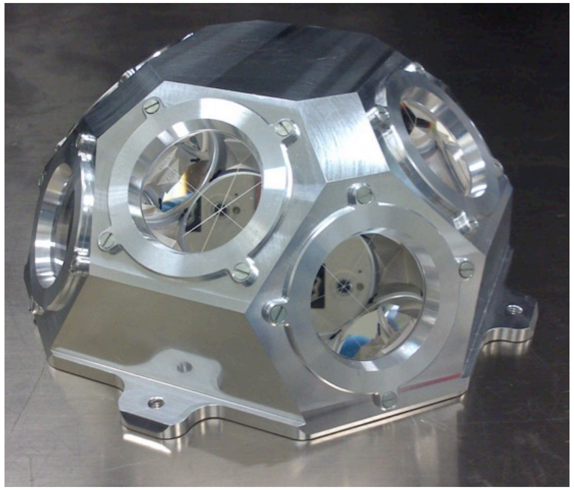
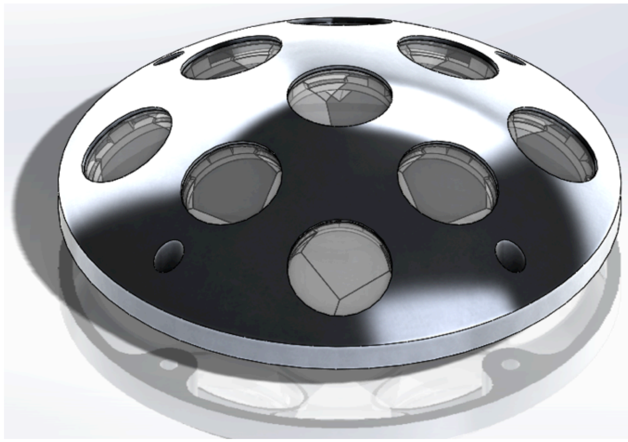
Phobos/Deimos surface reflectors

- **PANDORA**: Phobos ANd DeimOs laser Retreflector Array

- Reconstruct Phobos-Deimos orbits → focii of orbits is the Mars center of mass → additional test of General Relativity at 1.5 AU
  - PPN g (spacetime curvature), PPN beta
  - Gdot/G (gravitational constant), $1/r^2$ force law at 1.5 AU
- PEP (Planetary Ephemeris Program)
- Physics reach: similar to INRRIs on Mars
- Next: constrain Non-Minimally Coupled gravity (NMC)

Phobos/Deimos surface reflectors

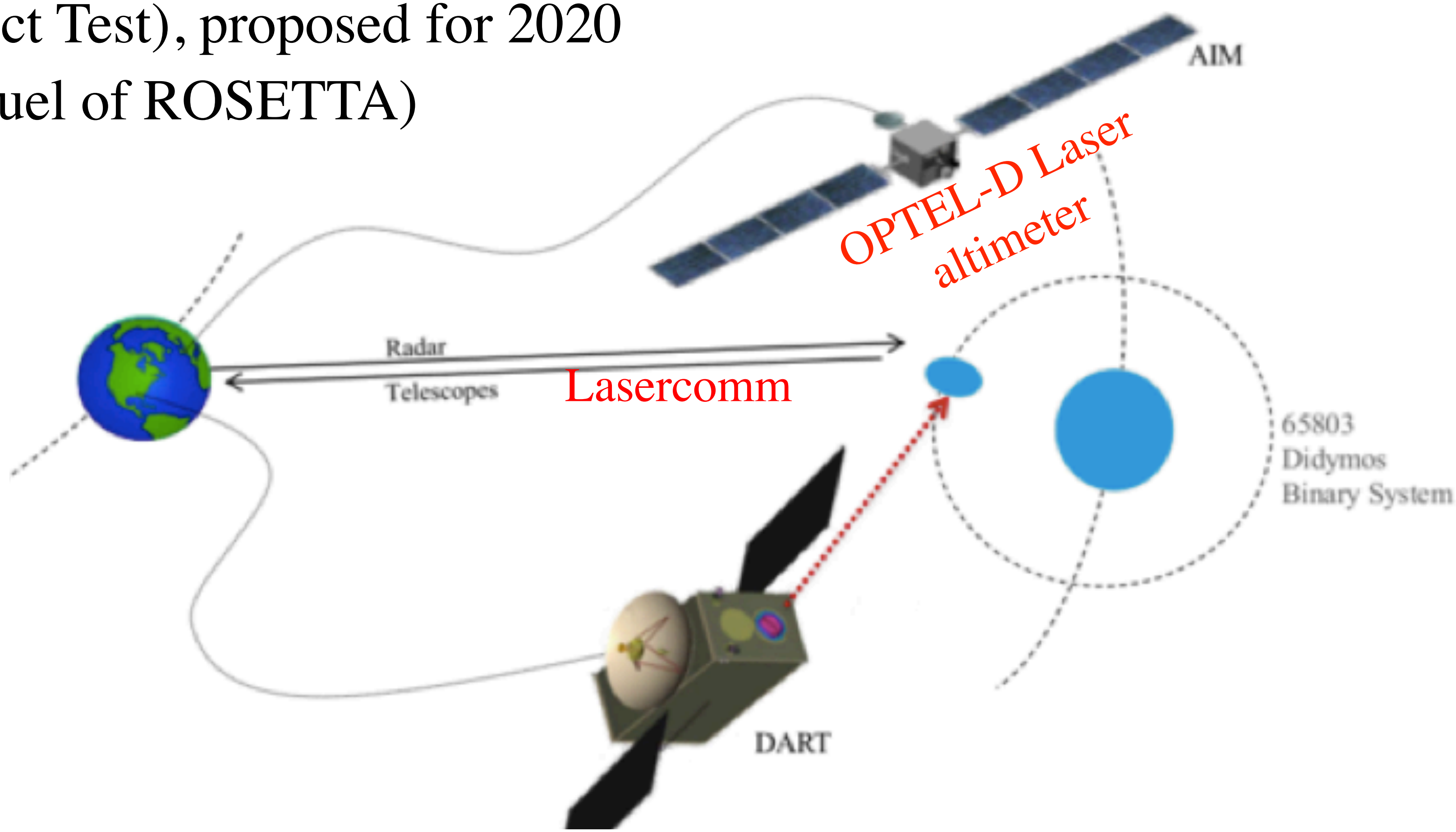
- R&D within INFN Scientific Committee n. 5 (CSN5)
  - Synergism with Earth Observation: Italian Ministry of Defense/Foreign Affairs for COSMO-SkyMed and Copernicus (EU Flagship)
  - Part of SSERVI Affiliation
- Possible PANDORA designs for Mars orbiters
  - Note: INRRI and/or COSPHERA for Phobos/Deimos orbiters

Laser Microreflectors for AIM-DART

R&D on proposed microreflectors support goals of ESA-NASA mission AIM-DART (Asteroid Impact Mission – Double Asteroid Redirect Test), proposed for 2020

(Sequel of ROSETTA)



Laser positioning of Didymoon before/after DART

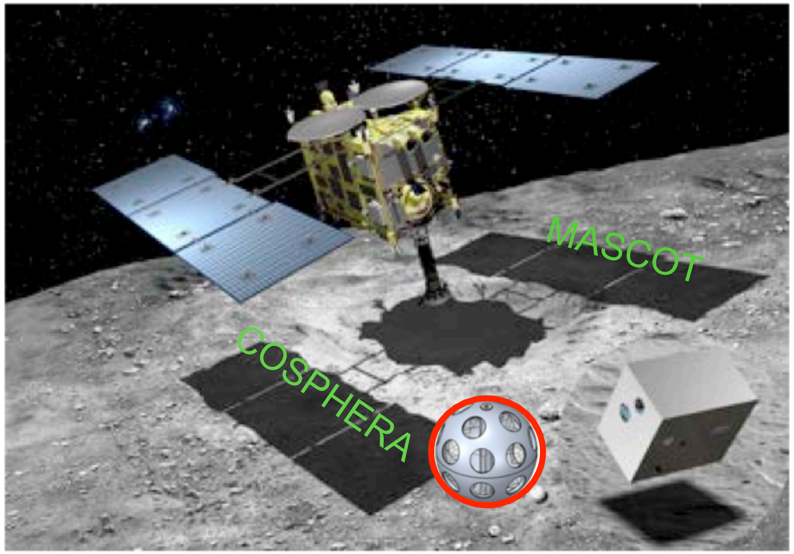
- ExoMars microreflector on MASCOT-2
  - ✓ Weight < 2×10^{-3} of MASCOT-2 mass
- COSPHERA, landed/dropped separately

ExoMars Microreflector

Laser altimeter/lasercomm

OPTEL-D; MASCOT by DLR

COSPHERA by INFN



Artist's conception of HY-2 during sampling, also showing MASCOT landed on the surface. CREDIT:JAXA/Akihiro Ikeshita.

(COSPHERA size no to scale)

COSPHERA

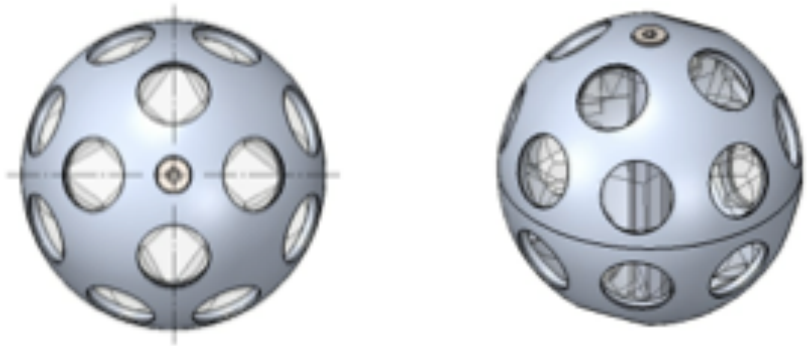
COmet/asteroid SPHErical micro-Reflector Array

Passive, very small/light, omnidirectional, lifetime of decades

HERITAGE: ExoMars, 1/2”, microreflectors, ~5 cm size, ~ 75 gr

To adjust (reduce) laser return: optical coatings; nanoreflectors?

To be first-ever laser retroreflector on an asteroid or comet



INFN Istituto Nazionale di Fisica Nucleare

Outlook: Solar System lab, up to 2030

- Test GR & New Physics, weak-field/slow-motion
- Improve up to x100: SEP, β, G*dot*, γ, ISL, K_{GP}…
- Moon: excellent test body, legacy & new missions
- Mars: other excellent test body, thanks to MGN by ESA-NASA-ASI by ~2020
  - Reflectors on Phobos & Deimos: enhance Mars physics
- NMC gravity: Mercury/Mars: promising test bodies
  - BepiColombo radar ranging data, Mars INRRI network
- Asteroids/Comets; Europa/Encelado lander/rover: further extend lever arm

Spares

Positioning with lasercom

Data & ToF/navigation in the solar system

- Lasercom on deep space orbiters very powerful, designed to transfer PetaBytes of data from space to Earth
- Lasercom orbiters can do laser ranging ToF
- One-way ToF demonstrated from/to Moon by LADEE !!
- This allows in principle for laser positioning/navigation
- Ultimate example: lasercom bridges from Jupiter orbits, to the Martian system, to the Earth-Moon system
- Also far side of the Moon, for ex. with Chang'E-4 (2018)
  - Can exploit LRO and its laser altimeter LOLA !!

Linking ITRF with ICRF

(RF = Reference Frame)

- Laser retros as permanent, passive *milestones*
- ITRF = International **Terrestrial** Reference Frame = stations of ILRS (International Laser Ranging Service)
- IMRF = I. Moon RF = Apollo/Lunokhod laser reflectors
- IARF = Int. Ares (Mars in Greek) RF = microreflectors on Mars landers, rovers, …
- ICRF: Int. **Celestial** RF = I*RF, Quasars (Very Long Baseline Interferometry), …

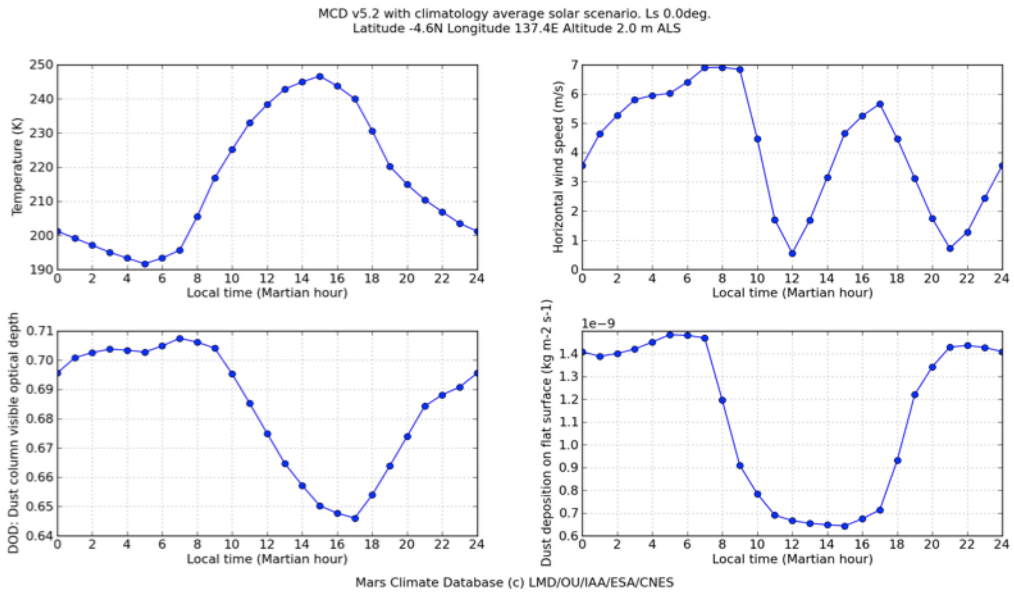
Linking ITRF with ICRF and more

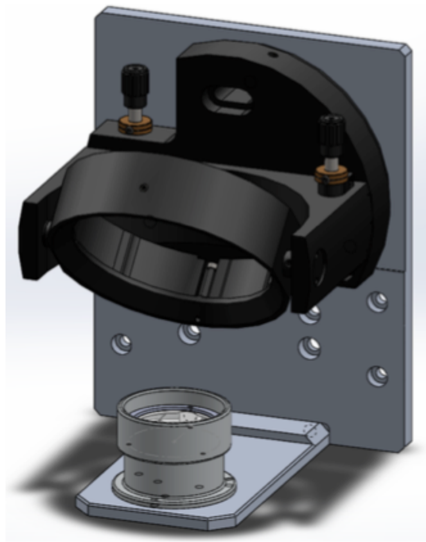
- Networks of laser retros on planetary systems: E-Moon far side, Mars/P/D, Jupiter, Saturn, Didymos
- Service to solar system exploration and science, and to planetary defense (from asteroids)

- **Example**: ExoMars “Schiaparelli” lander: 1st reflector on Mars
- Request by DLR PI of the Ganymede Laser Altimeter (GALA), a payload on ESA’s JUpiter ICy moons Explorer (JUICE) L Class mission:
  - “*the ExoMars retroreflector would provide an excellent opportunity for us to establish a link from GALA during a Mars flyby foreseen in the nominal cruse trajectory. We could use this link for verification of our pointing*“
- We see this as just the beginning

Weather studies: Mars Climate Database

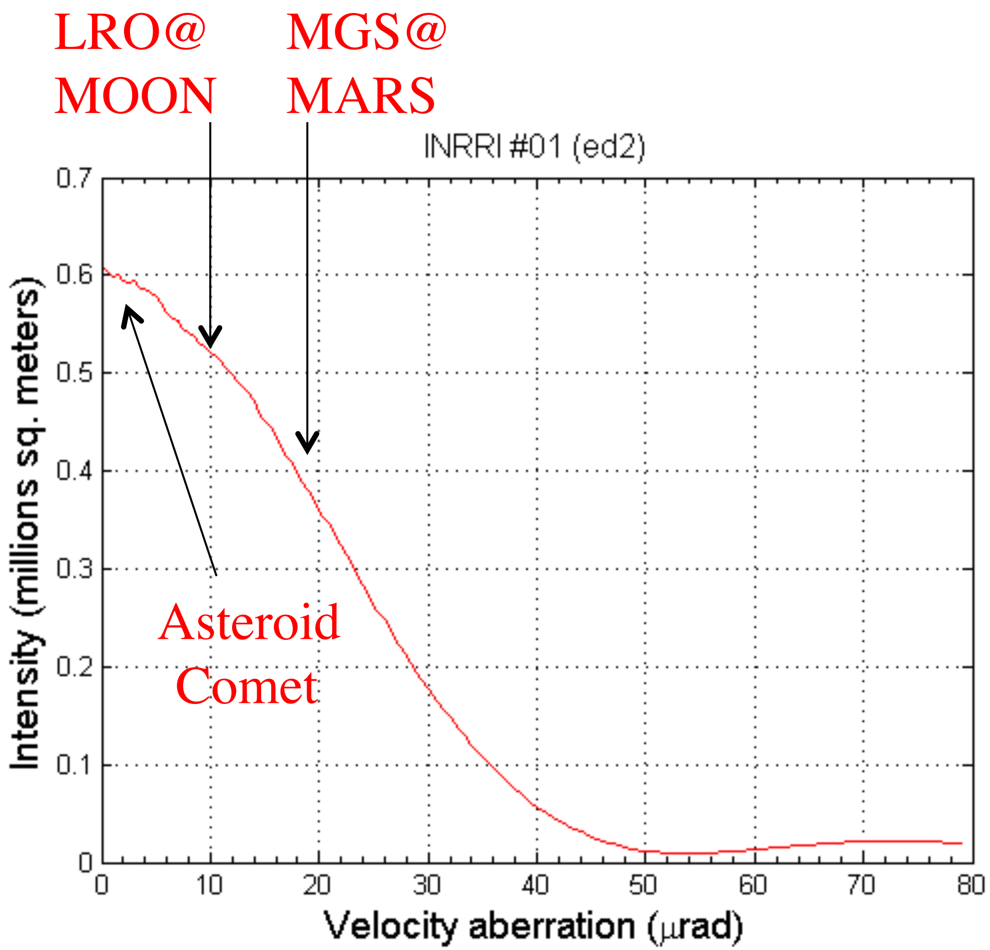
- Unlike Moon, Mars has severe sand storms, which cyclically cover/ clean optics (solar panels of MERs and INRRI reflectors)
- INRRIs dome shape and very compact size ease dust slipping
- Mars electrically neutral, dust blown away by winds, Van der Waals forces lower than on Moon (Vikings observations)
- Mars Climate DB: www-mars.lmd.jussieu.fr/mcd_python/
- Left: conditions seen by Curiosity rover on 10/10/2015
- Right: setup to measure effect of dust on reflector optical performance



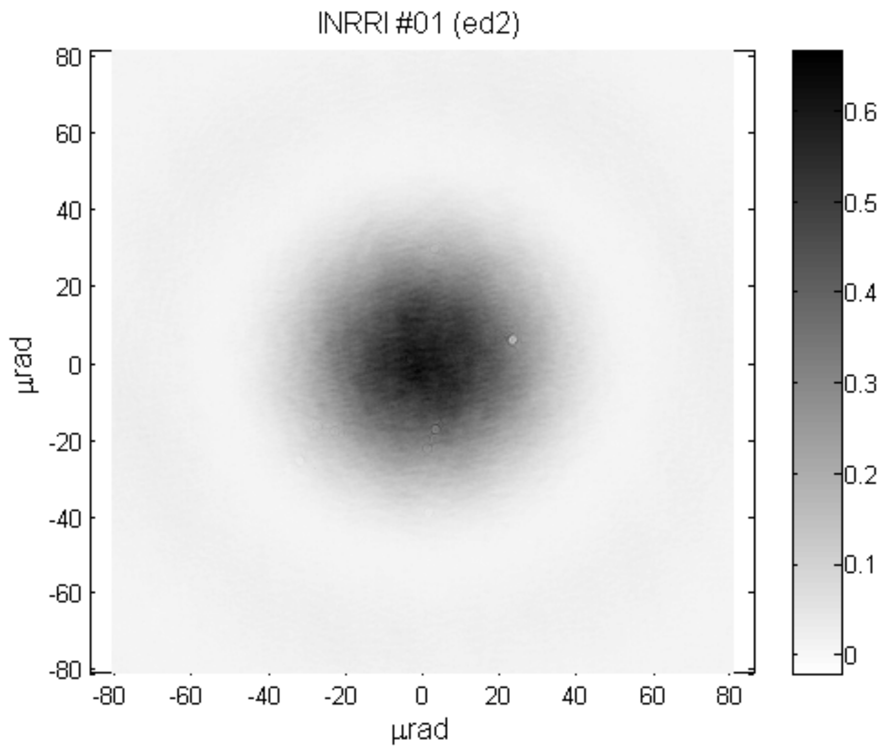


INRRI laser location by orbiters

INRRI **measured** laser return, or *lidar optical cross section*, in absolute units (msqm, μrad) at 532 nm



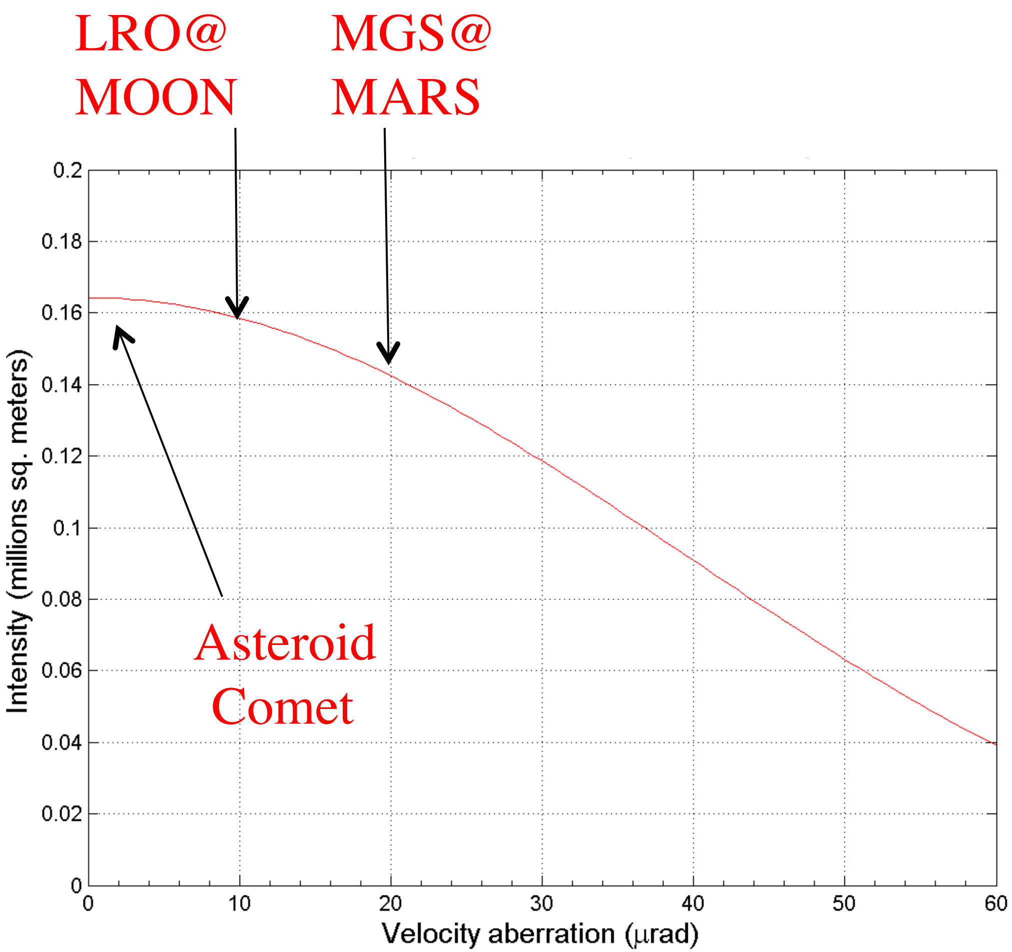
INRRI coated reflector (Airy) far field diffraction pattern



INRRI laser location by orbiters

INRRI simulated laser return (CodeV), or *lidar optical cross section*, in absolute units (msqm, μrad) at 1064 nm (LOLA, MOLA)

Airy peak even wider at 1550 nm (LLCD)



INRRI coated reflector (Airy) far field diffraction pattern