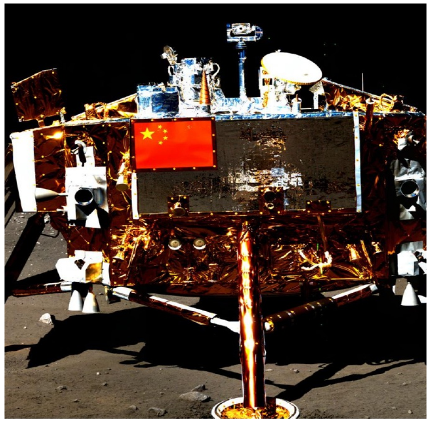
Proposed INFN Contribution to the Chinese Lunar Exploration Program

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

IHEP-INFN Meeting, May 27, 2016 - Rome, Italy

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



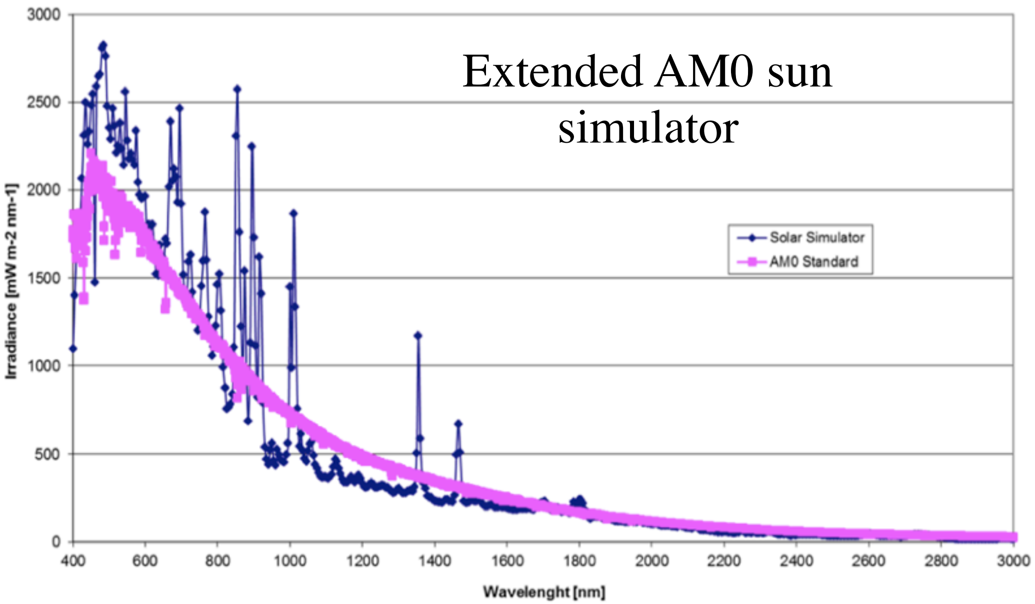
Outline

- Key partnerships with ASI and NASA. Now also China
- Moon: a laser-ranged test mass for General Relativity and new physics
- Support to Lunar (Martian) geodesy and exploration for Space Agencies
- What Next: extend program to Mars

(*Within INFN these are INFN - CSN2 / CSN5 activities*)

Joint Lab on laser retroreflectors & ranging

- **MLRO** = Matera Laser Ranging Observatory @ ASI-CGS
  - For data sharing also **ASDC** = ASI Science Data Center @ ASI-HQ
- **SCF_Lab** @ INFN-Frascati: unique reflector expertise
  - Two Optical Ground Support Equipment (OGSE), SCF and SCF-G
  - Two AM0 sun simulators, IR thermometry
  - Optical testing: Far Field Diffraction Patters, Fizeau Interferometry



Space Geodesy Center
Giuseppe Colombo
Matera, Italy

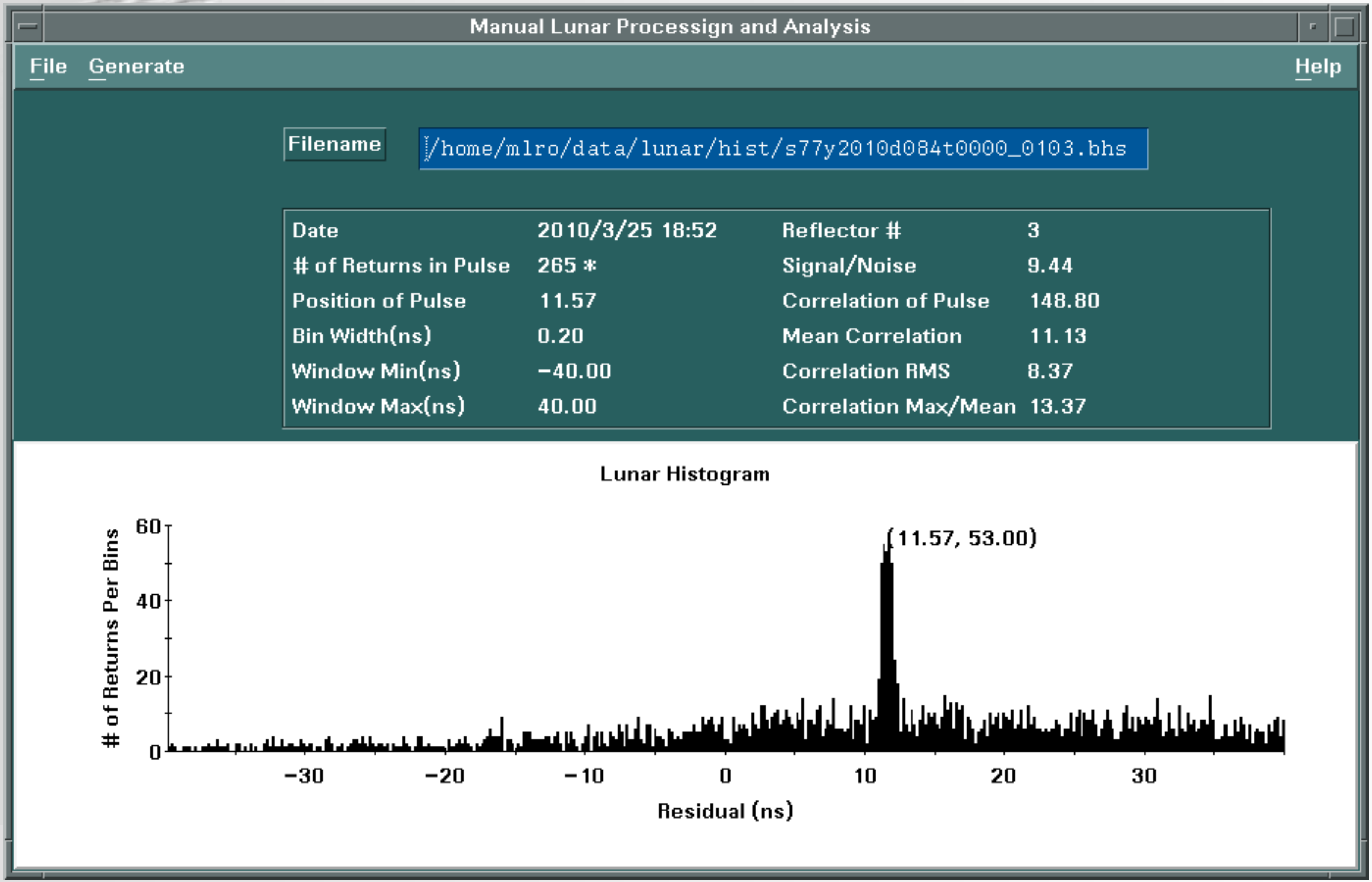
Satellite / Lunar Laser Ranging (SLR / LLR), GNSS, VLBI stations

(slides courtesy of Pippo Bianco)

agenzia spaziale italiana


MLRO
1.5 m telescope

MLRO LLR ToF on Apollo 15 reflectors



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, visiting GSFC after meeting with John Grunsfeld at NASA-HQ.
Discussed partnership and Mars laser retroreflectors

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

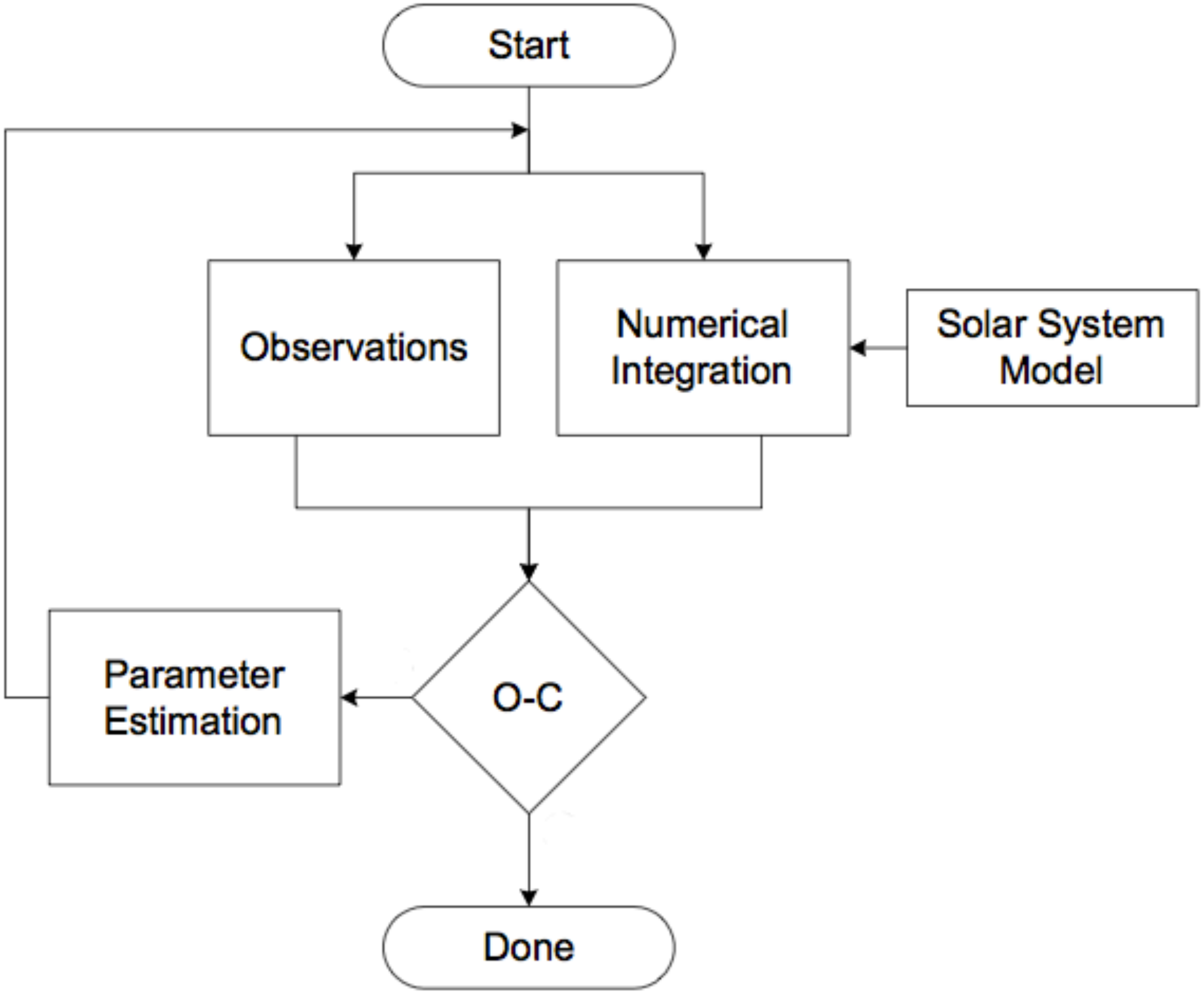
Our Moon-Mars assets

- **MoonLIGHT, the *big* Lunar laser retroreflector**
- **INRRI, the Martian laser *micro*reflector**
- **Planetary Ephemeris Program (PEP) *orbital SW***

Lunar/Martian positioning data: we use PEP, developed in USA at the Harvard-Smithsonian Center for Astrophysics (CfA) by Shapiro, Reasenberg, Chandler since 60/70s

Weighted least-squares minimization of residuals “O-C”, that is, Observations minus Computations

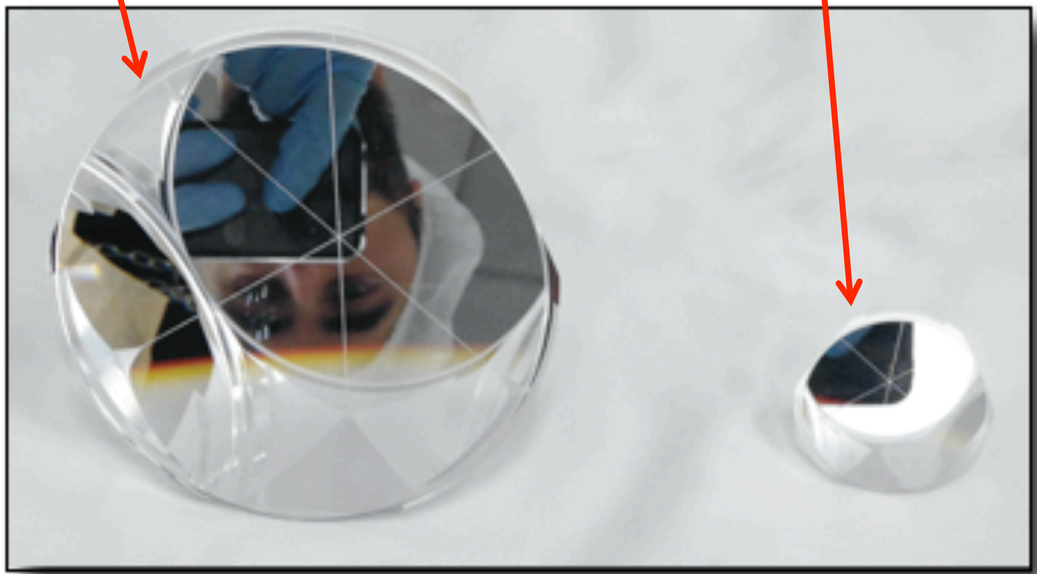
PEP (analysis of Moon-Mars orbits)

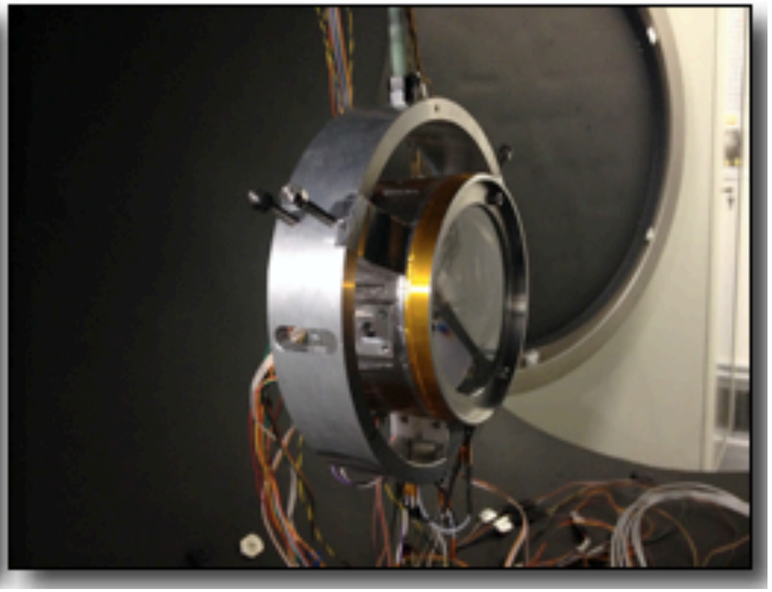


MoonLIGHT-2: Next Generation Lunar Laser Retroreflector

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

MoonLIGHT (10 cm) **Apollo (3.8 cm)** **MoonLIGHT package**

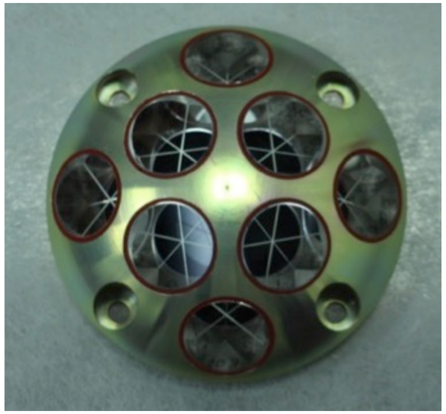




Microreflector for the Moon and beyond

INRRI = INstrument for landing-Roving laser Retroreflectors Investigations

- Laser-located by planetary/moon orbiters, not by Earth
  - Laser altimetry (LOLA on LRO), Laser ranging, Lasercom
    - NASA LADEE: lasercom ToF with ~100 psec accuracy
  - Laser flashes + cameras (LROC on LRO)

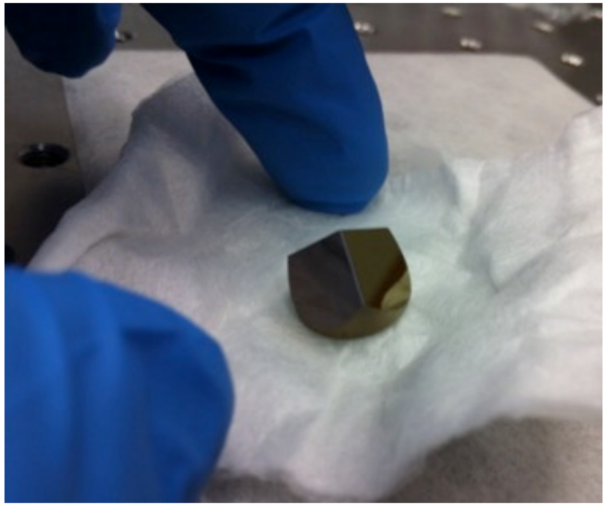


INRRI beyond the Moon

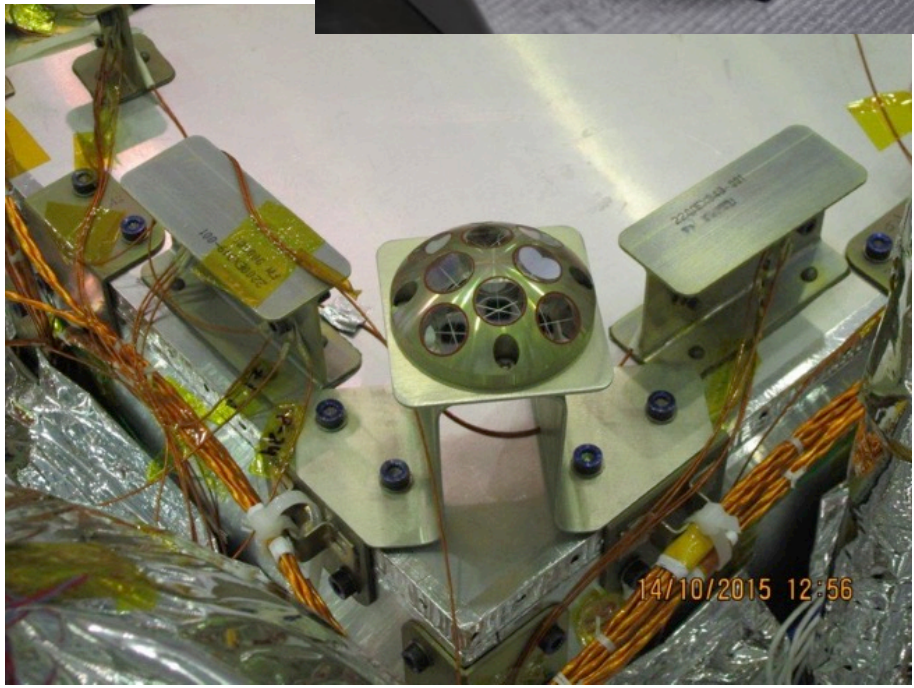
INRRI = INstrument for landing-Roving laser Retroreflectors Investigations

- 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
- Lidar-based/aided landing (return to lander/rover)
- Lasercomm test & diagnostics

INRRI (Mars) qualification & integration

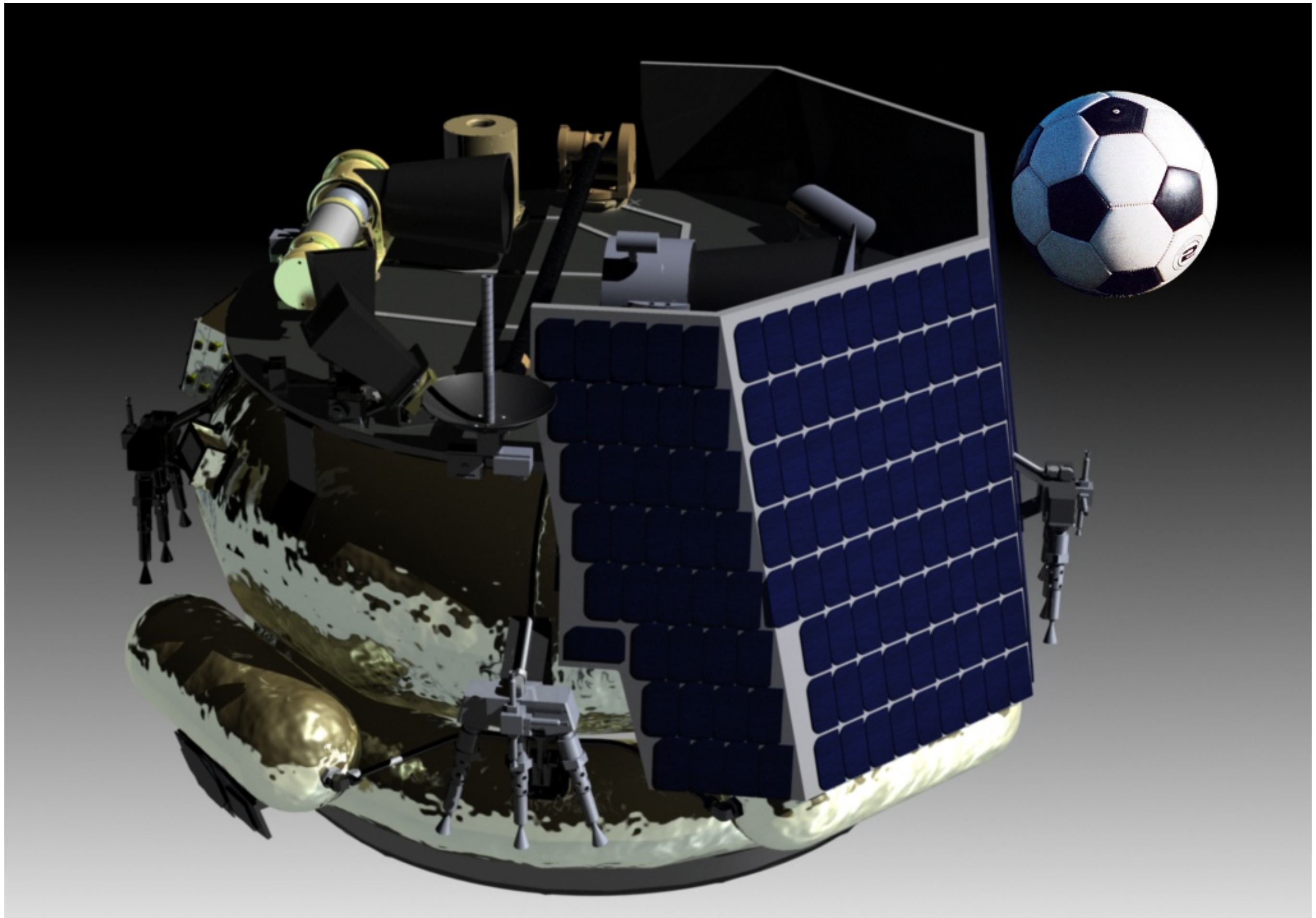


Reflector load/peel test.
TVT (158-328 K).
Vibe/shock (proton)
@SERMS.
Load/peel test.
Mass loss check.



MoonLIGHT-2 missions

Moon Express 1 (US, 2017-18), agreement on May 15, 2015
Competing also for Google Lunar X Prize



Lunar missions

Chang'E,
Chinese Moon Goddess

Chang'E-4 (China, 2018)

Far side lander + rover, two INRRI microreflectors, to be laser-located by NASA's orbiter LRO

Agreement in preparation

Chang'E-5 (China, ≥2020)

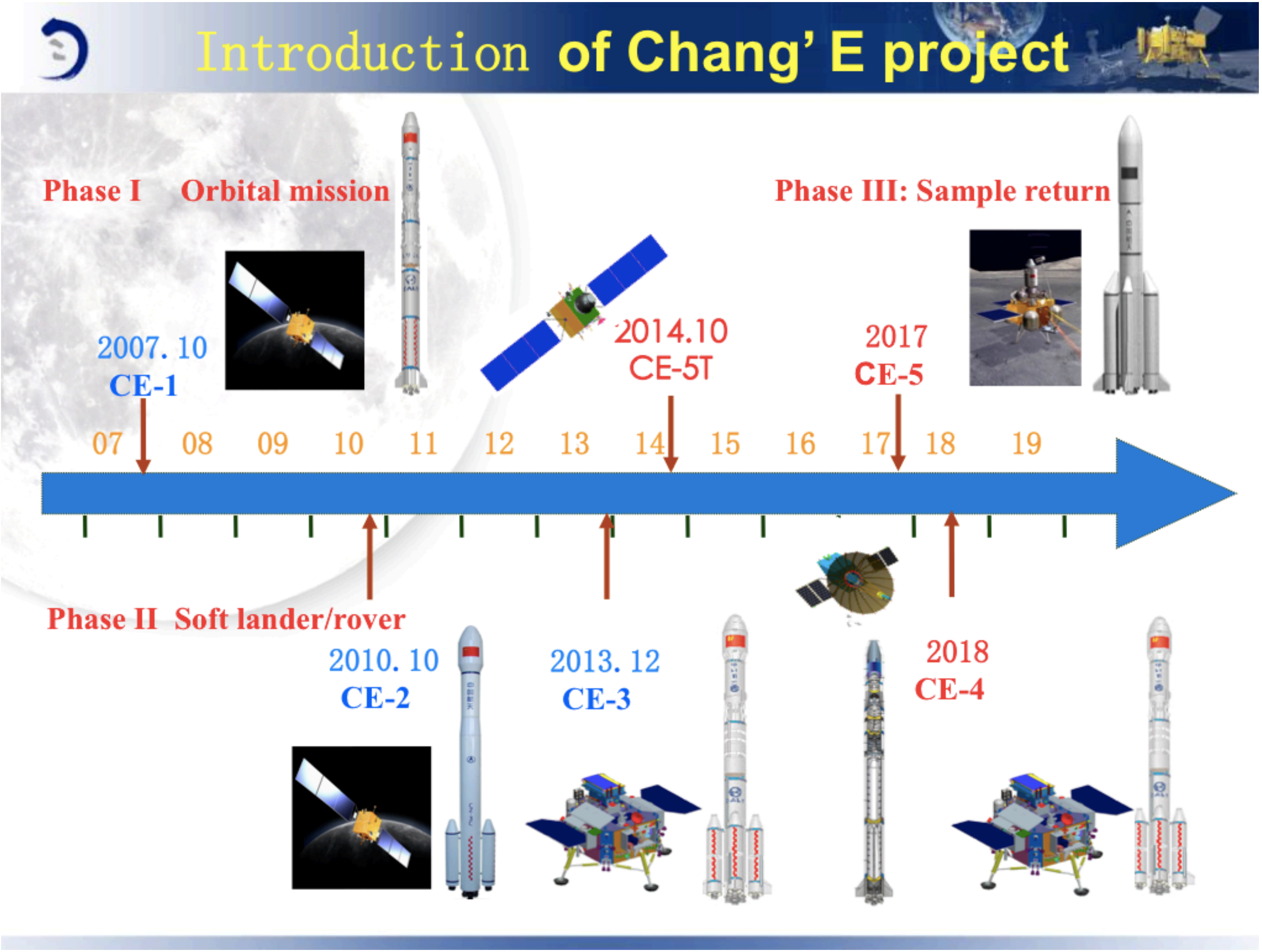
Near side, MoonLIGHTs + INRRIs

After Chang'E-4:

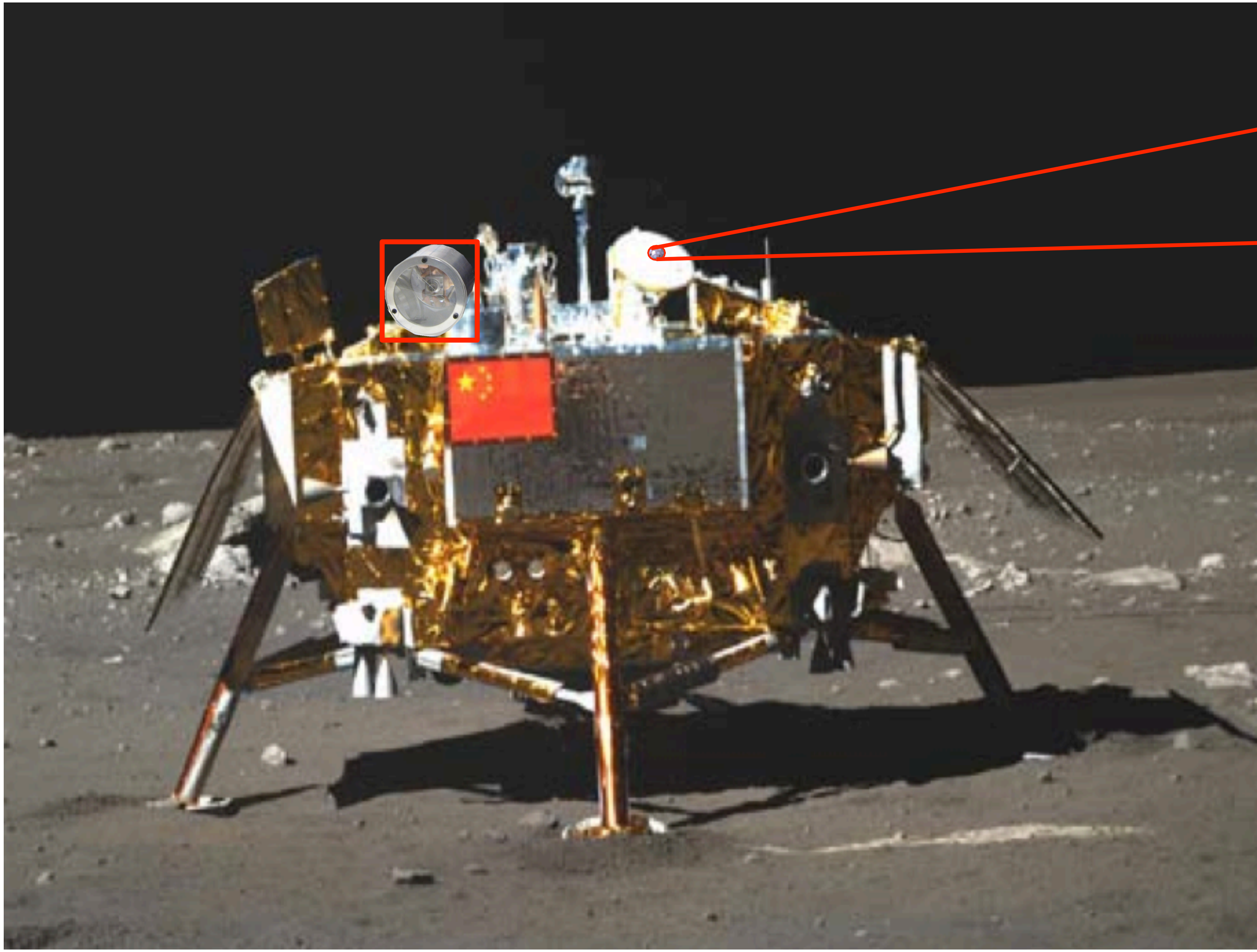
- New ESA DG (Wörner): far side long-term *Moon Village*
- Russian lander: "Luna 27", near side (2021)

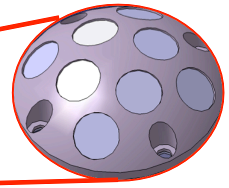
→ Several laser retroreflector milestones for colonization

Slide courtesy of Wang Qian (CNSA)



MoonLIGHT/INRRI *imagined* on Chang'E lander

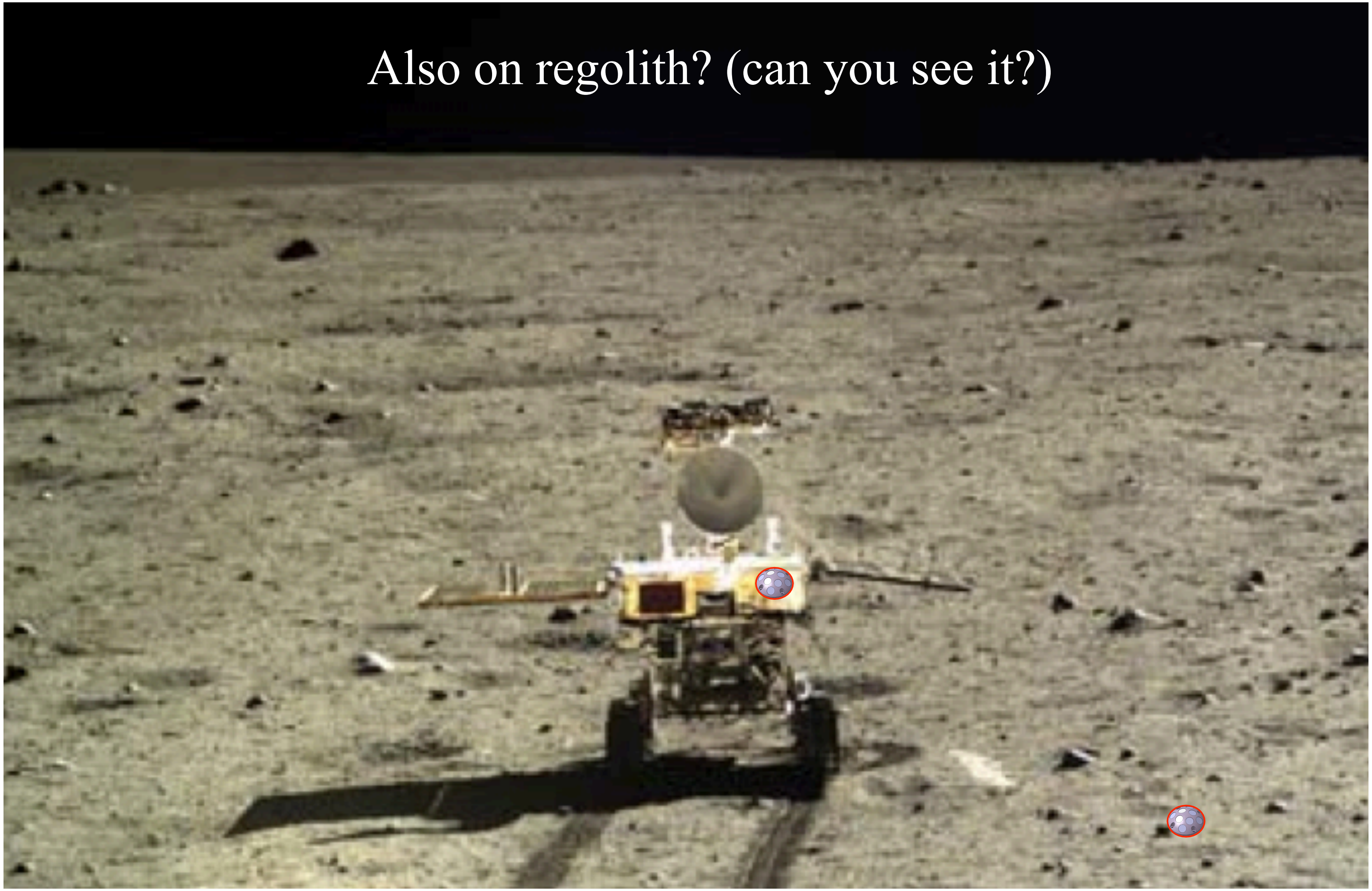




Compact
Light
Passive
INRRI is
~54 mm diam.
~20 mm high
25 grams

Drawing
not to scale

INRRI *imagined* on Yutu minirover



Lunar Laser Ranging test of gravity

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

Note: table does not include INRRI on Chang-E-4 on far side

INRRI on far side will improve geometric lever arm to estimate Selenocenter

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

* 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

LLR test of the Equivalence Principle

If EP is violated:

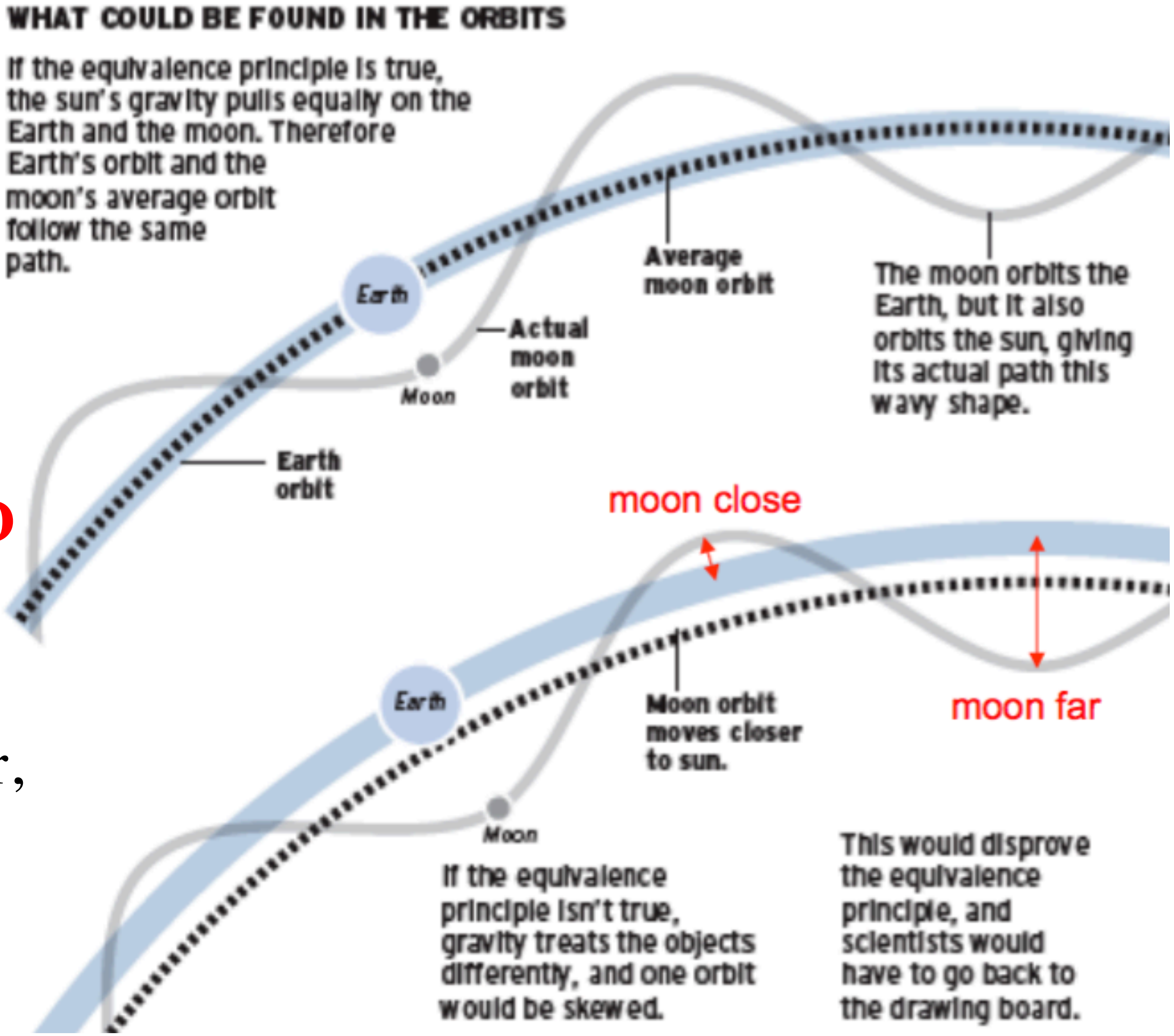
lunar orbit displaced along Earth-Sun line;

periodic variation of Earth-Moon distance

Δr (m) = 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 $\propto$ 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 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 law is broken
- Test of temporal variation of G from LLR data

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

- **Best limit to date** (to my knowledge)

  Less than 1% change over age of Universe

Non-Minimally Coupled gravity (NMC)

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

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.

f(R) & f^1(R)+f^2(R) theories ➔ provide 'weak' gravity & alternatives to dark energy/matter scenario

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*

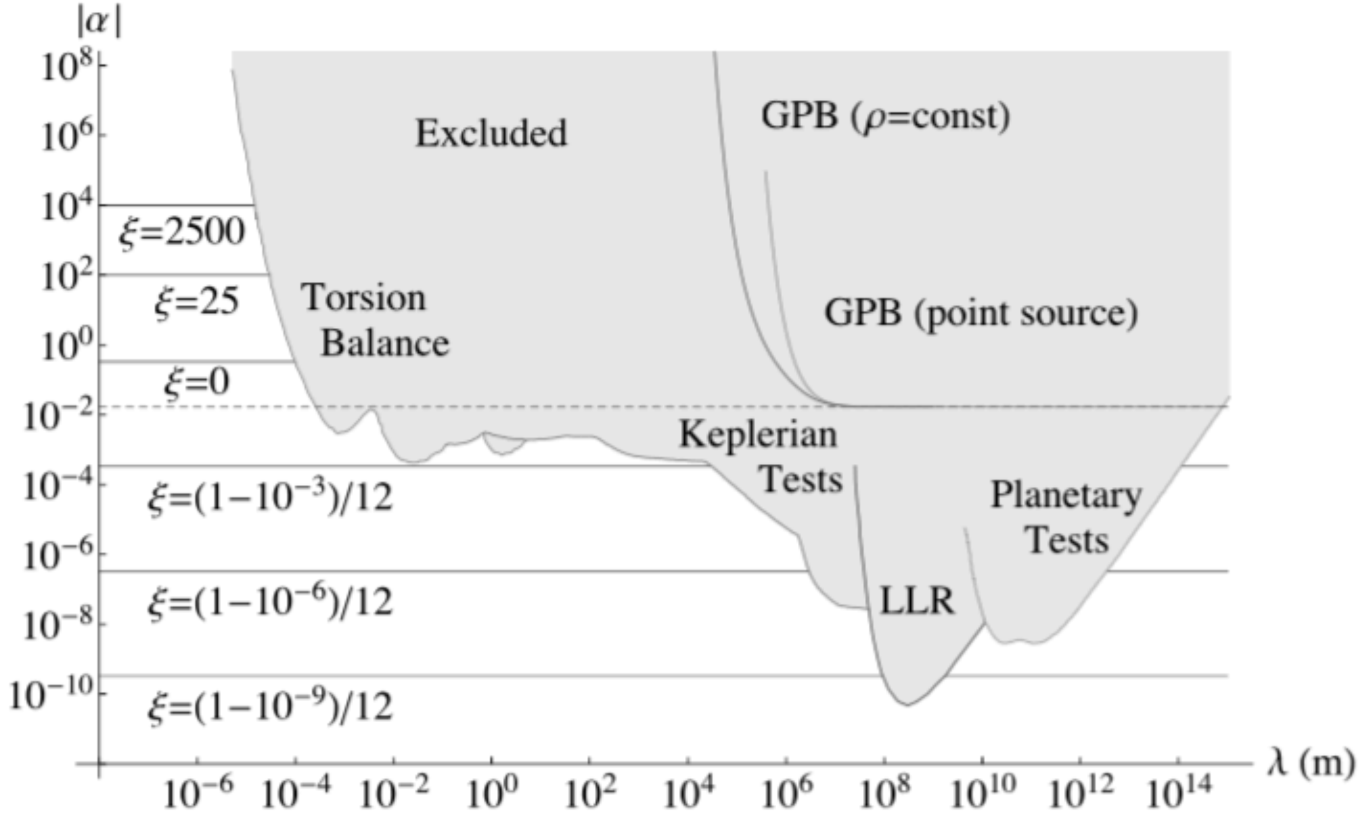
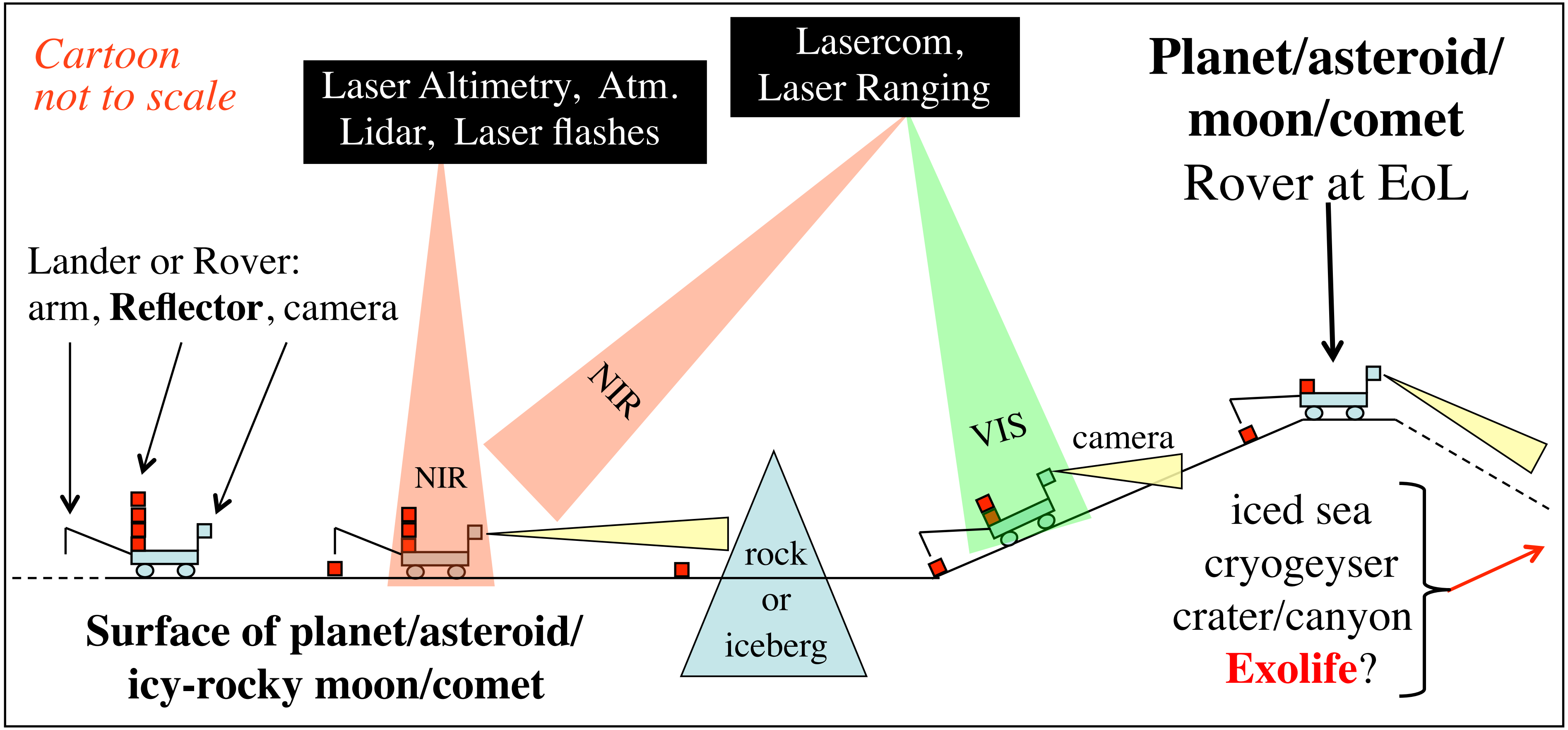


Fig. 2. Yukawa exclusion plot for α and λ. Adapted from Refs. [41,46].

INRRI microreflector on Mars

- Accurate positioning of landing-roving
- Definition of *Mars Greenwich*
- Test of General Relativity and its extensions
- Lidar-based/aided landing (return to lander/rover)
- Atmospheric trace species detection by lidar on orbiter
- Lasercomm test & diagnostics

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

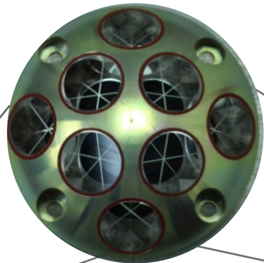
Italian microreflector INRRI on ExoMars

First laser retroreflector on the surface of Mars & beyond the Moon

Passive, long lifetime; light: 25 gr; compact: ~5cm×2cm

Launched on March 14, 2016, with ExoMars EDM

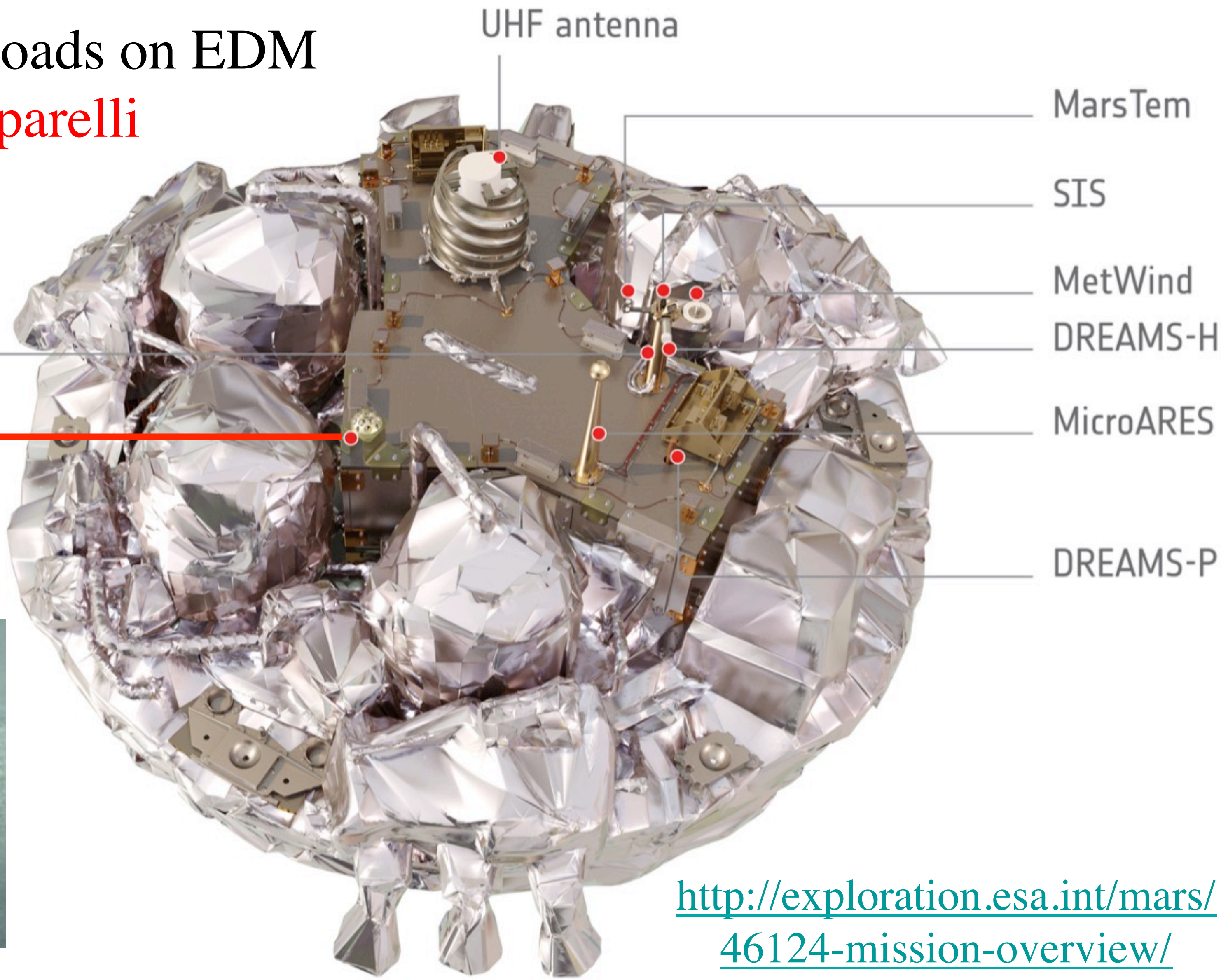
TGO (Trace Gas Orbiter)



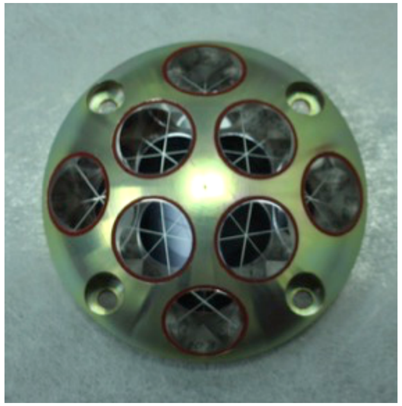
EDM
2016

INRRI on ExoMars EDM 2016 of ESA-ASI

Science payloads on EDM lander Schiaparelli



INRRI
25 gr
~5cm×2cm

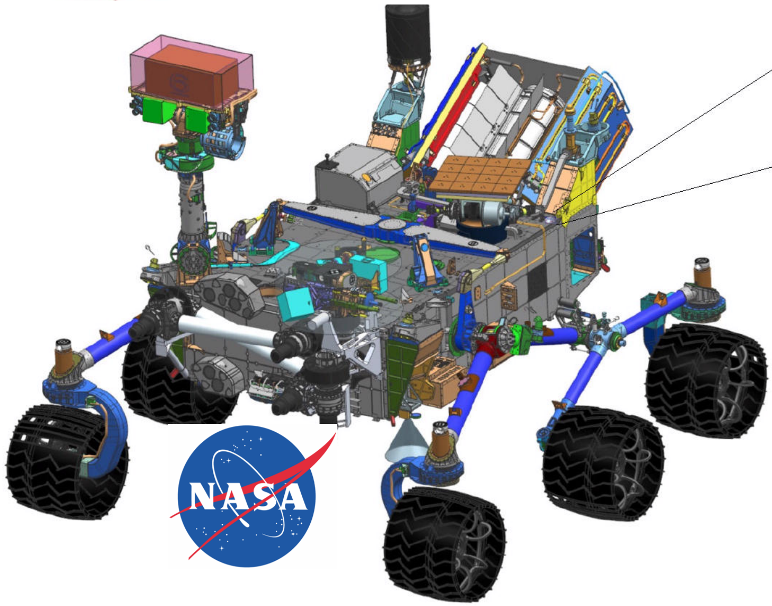


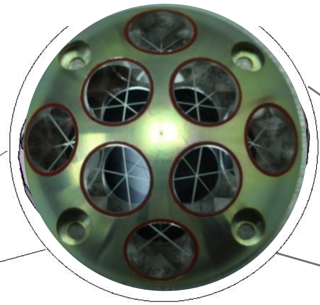
http://exploration.esa.int/mars/46124-mission-overview/

Testing Mars gravity: INRRI microreflectors

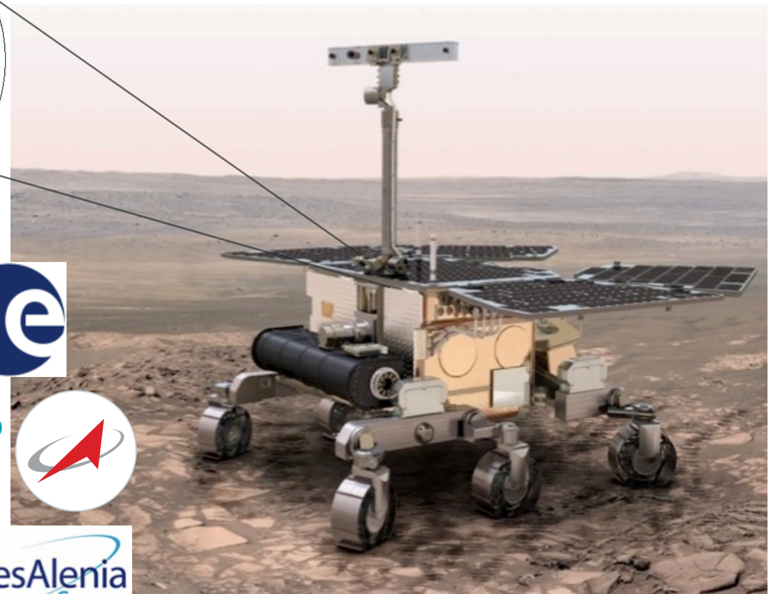
- INRI is in ASI 3-year Plan 2016-18. Opportunities:
  - NASA/ASI: Mars 2020 (×1), Insight 2018 (×1)?
  - ESA/ASI: ExoMars 2016 (×1), ExoMars 2020 (×2)
  - SpaceX: Falcon Heavy, Dragon Capsule, launch in 2018 (×1)
- China recently announced it will land on Mars (2020)

Mars 2020 (NASA)





ExoMars 2020



Mars surface rovers/landers physics

- 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
- MGN of INRRIs at 'symbolic' locations (~all north)
  - 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 – 10 m

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)*

Outlook

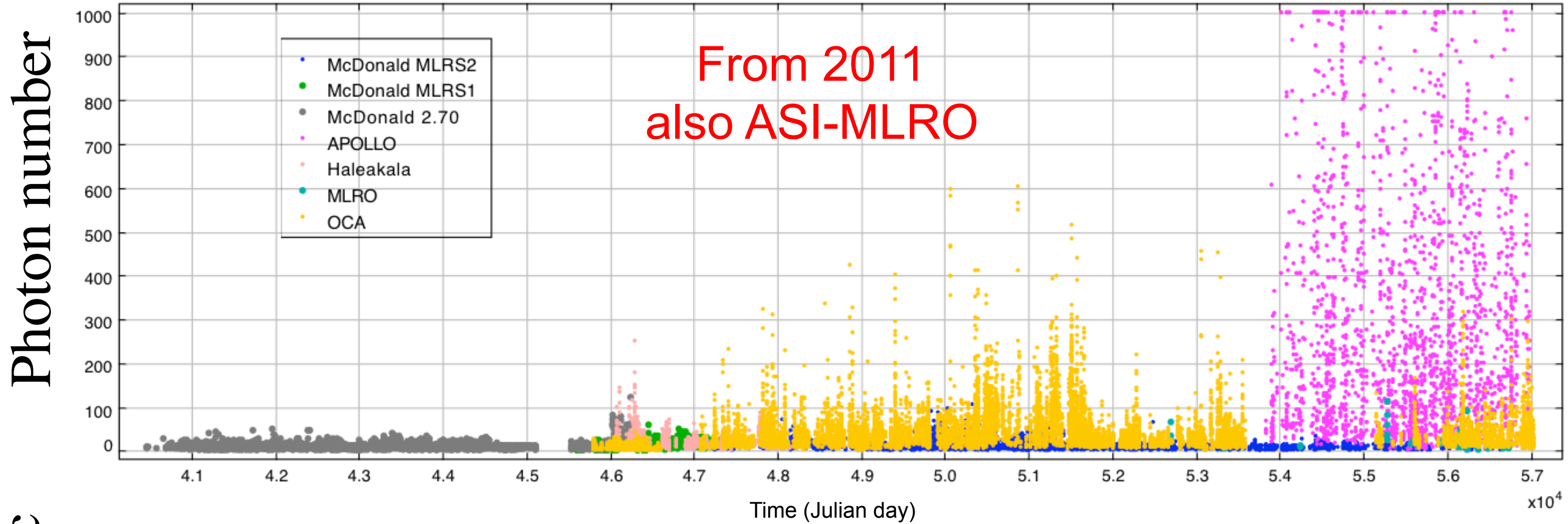
- Key partnerships with ASI and NASA. Now also China
- Moon: a laser-ranged test mass for General Relativity and new gravitation physics
- Support to Lunar (Martian) geodesy and exploration for Space Agencies
- What Next: extend program to Mars

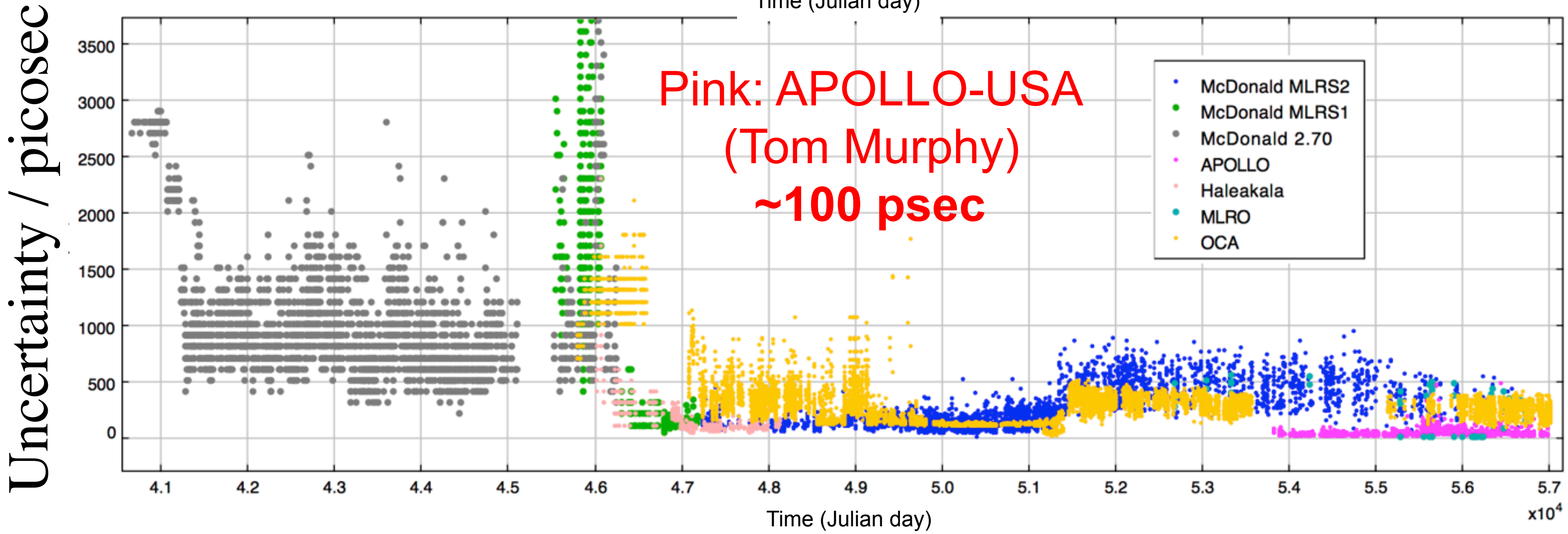
Spares

Outlook: Solar System lab, up to 2030

- Test GR in 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
- What Next: Asteroids/Comets; Europa/Encelado lander/ rover: further extend lever arm

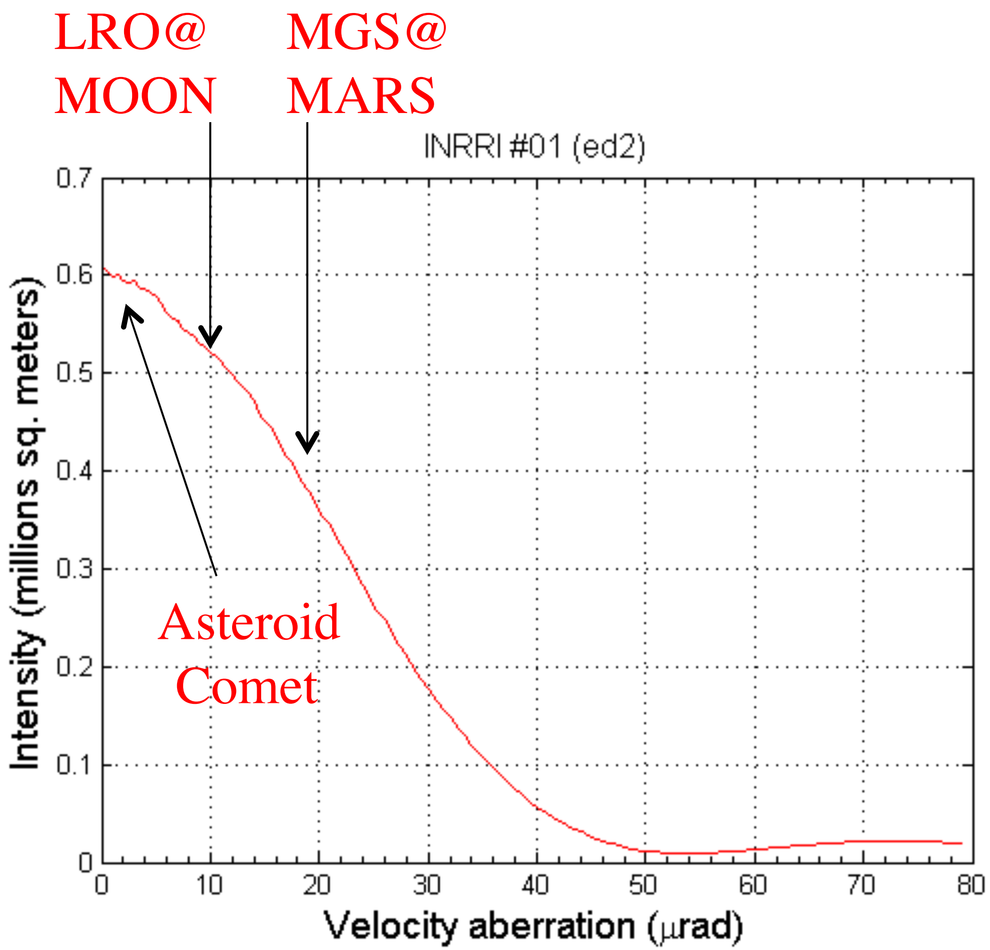
Lunar O-C residual analysis with PEP

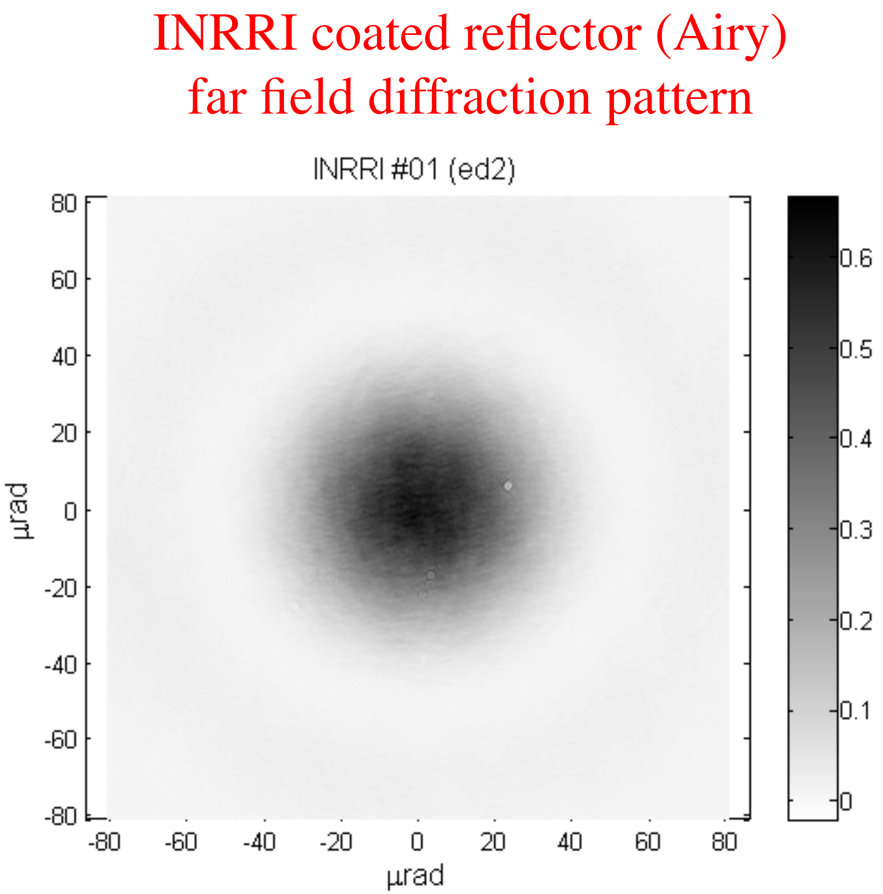




INRRI laser location by orbiters

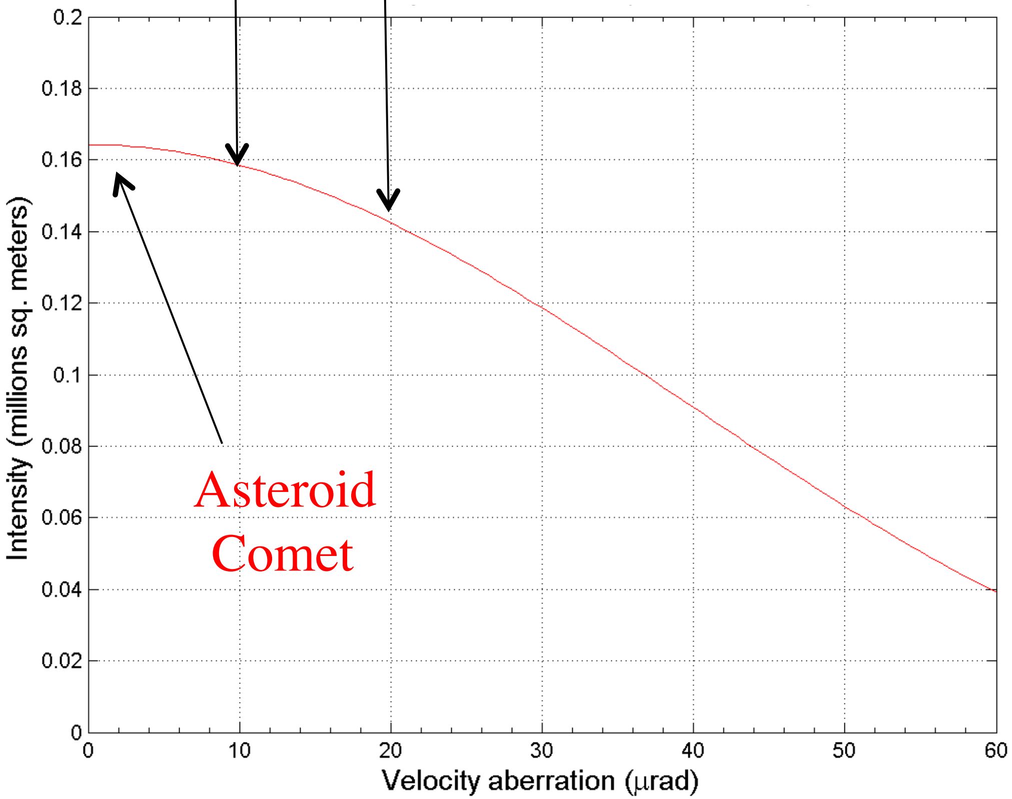
INRRI **measured** laser return, or *lidar optical cross section*, in units (msqm, μrad) at <u>532 nm.</u> It is adequate to observe INRRI



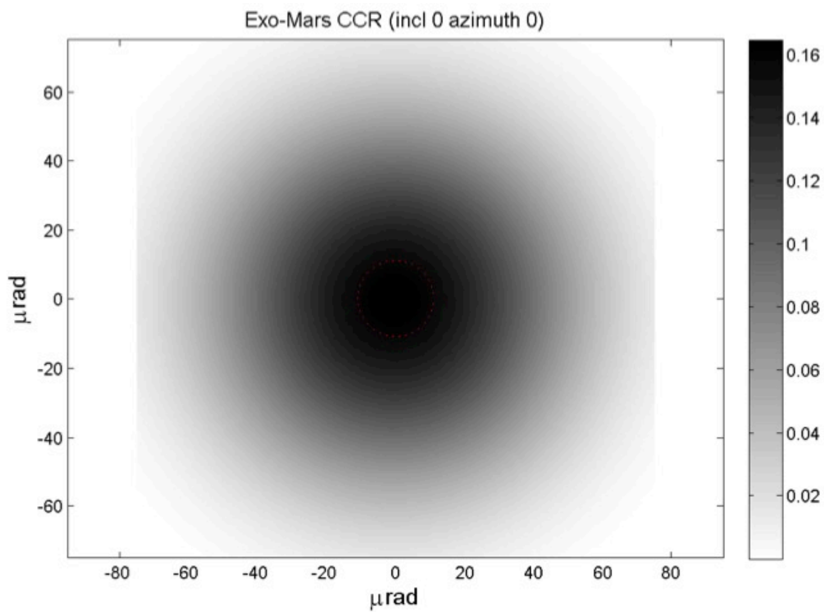


INRRI laser location by orbiters

INRRI simulated laser return (CodeV), or *lidar optical cross section*, in units (msqm, μrad) at 1064 nm (LOLA, MOLA). Airy peak even wider at 1550 nm (LLCD). It is adequate to observe INRRI



INRRI coated reflector (Airy) far field diffraction pattern



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

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:

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

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

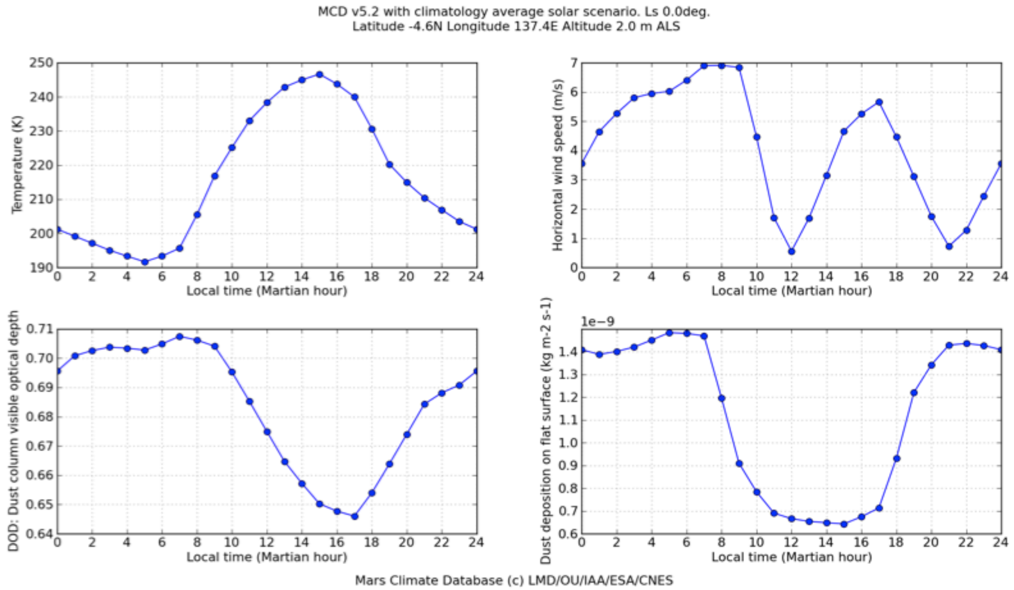
- Subtracting UW from LLR results one gets the SEP test:

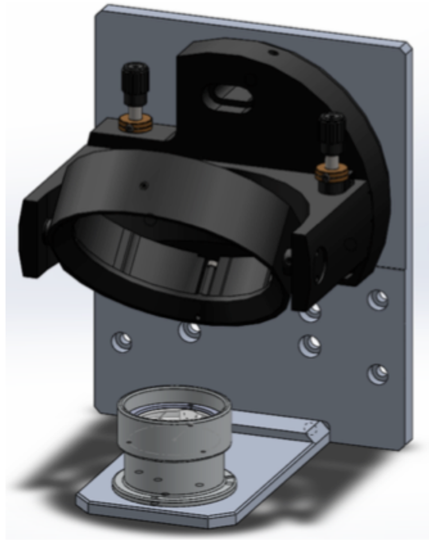
$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{SEP} = (-2.0 \pm 2.0) \times 10^{-13}$$

SEP can only be tested LLR

Mars weather

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





NMC gravity: PPNY = PPN + Yukawa

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

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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