Lunar and Interplanetary Laser Ranging

2nd EPS Conference on Gravitation – 5-7 July 2021

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

International Collaborators & Agency PMs/PoCs

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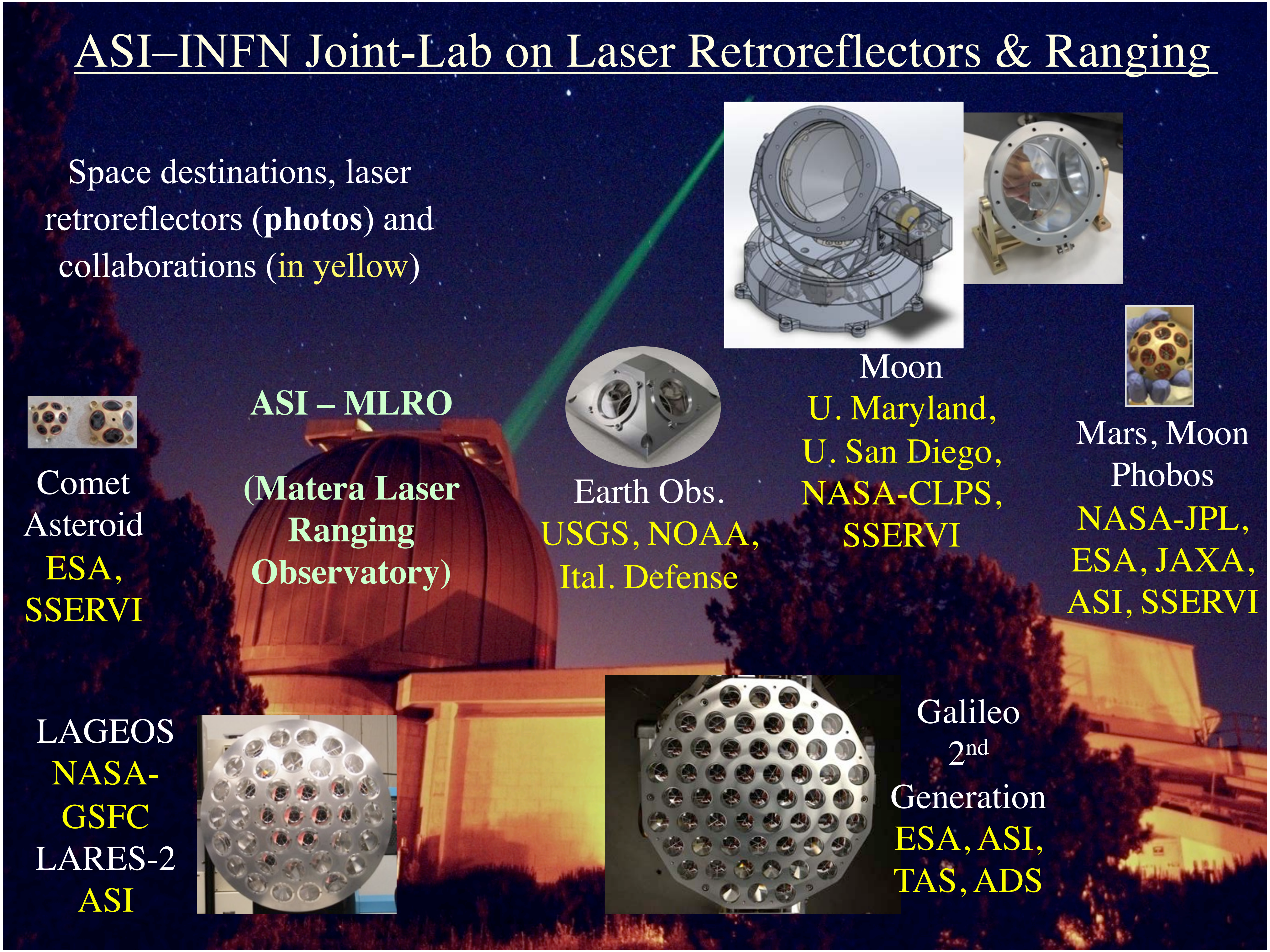
Outline

- Lunar Laser Ranging/Retroreflectors & gravitational physics
  - ✓ First lunar missions: to Reiner Gamma (ESA reflector & to Mare Crisium (NASA reflector) in 2023/2024
- Mars microreflectors' network
  - ✓ InSight 2018, Perseverance 2020, ExoMars 2022
- Other Mars system missions
  - ✓ Mars Moons eXplorer to Phobos, 2024
  - ✓ Mars Sample Return, 2026+
- Conclusions

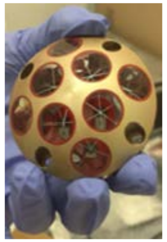

ASI–INFN Joint-Lab on Laser Retroreflectors & Ranging
Space destinations, laser retroreflectors (photos) and collaborations (in yellow)
ASI – MLRO
(Matera Laser Ranging Observatory)
Comet
Asteroid
ESA,
SSERVI
Earth Obs.
USGS, NOAA,
Ital. Defense
Moon
U. Maryland,
U. San Diego,
NASA-CLPS,
SSERVI
Mars, Moon
Phobos
NASA-JPL,
ESA, JAXA,
ASI, SSERVI
LAGEOS
NASA-
GSFC
LARES-2
ASI
Galileo
2nd
Generation
ESA, ASI,
TAS, ADS

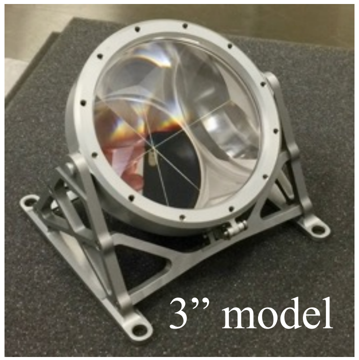
Joint-Lab of INFN–Frascati and ASI–Matera

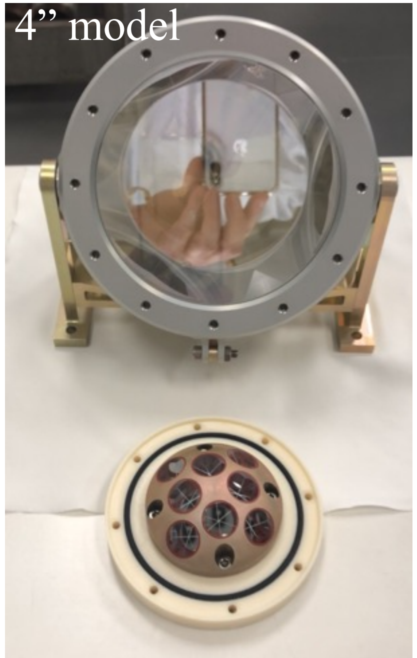
- **WP 2000 INFN-LNF Operations**
  - WP 2100 SCF_Lab Internal Special Facility
  - WP 2200 SCF_Lab2 Internal Special Facility
  - WP 2300 Project of Future Range Corrections
- **WP 3000 Advanced Laser Payloads and Systems**
  - WP 3100 Moon, Cislunar Space and LOP-DSG
  - WP 3200 Mars System
  - WP 3300 Galileo and EGNOS
  - WP 3400 Earth Observation & Space Geodesy
  - WP 3500 Studies for New Applications and Destinations
- **WP 4000 Testing of Gravity in the Solar System**
- **WP 5000 Theories of Gravity for the Solar System**

WBS of ASI-INFN Joint-Lab (2021-2026)

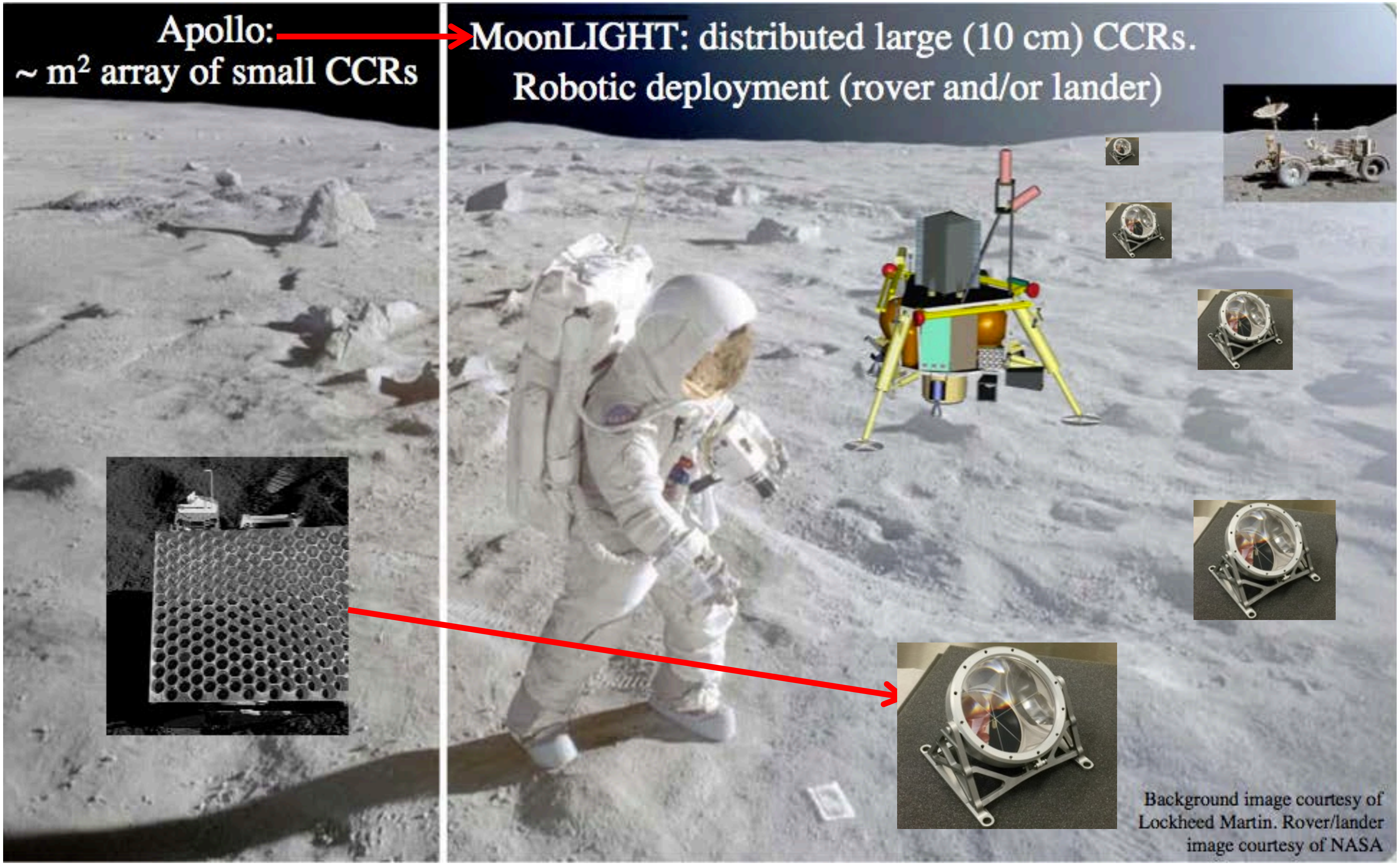
Moon (**large**) & Mars (**micro**) reflectors



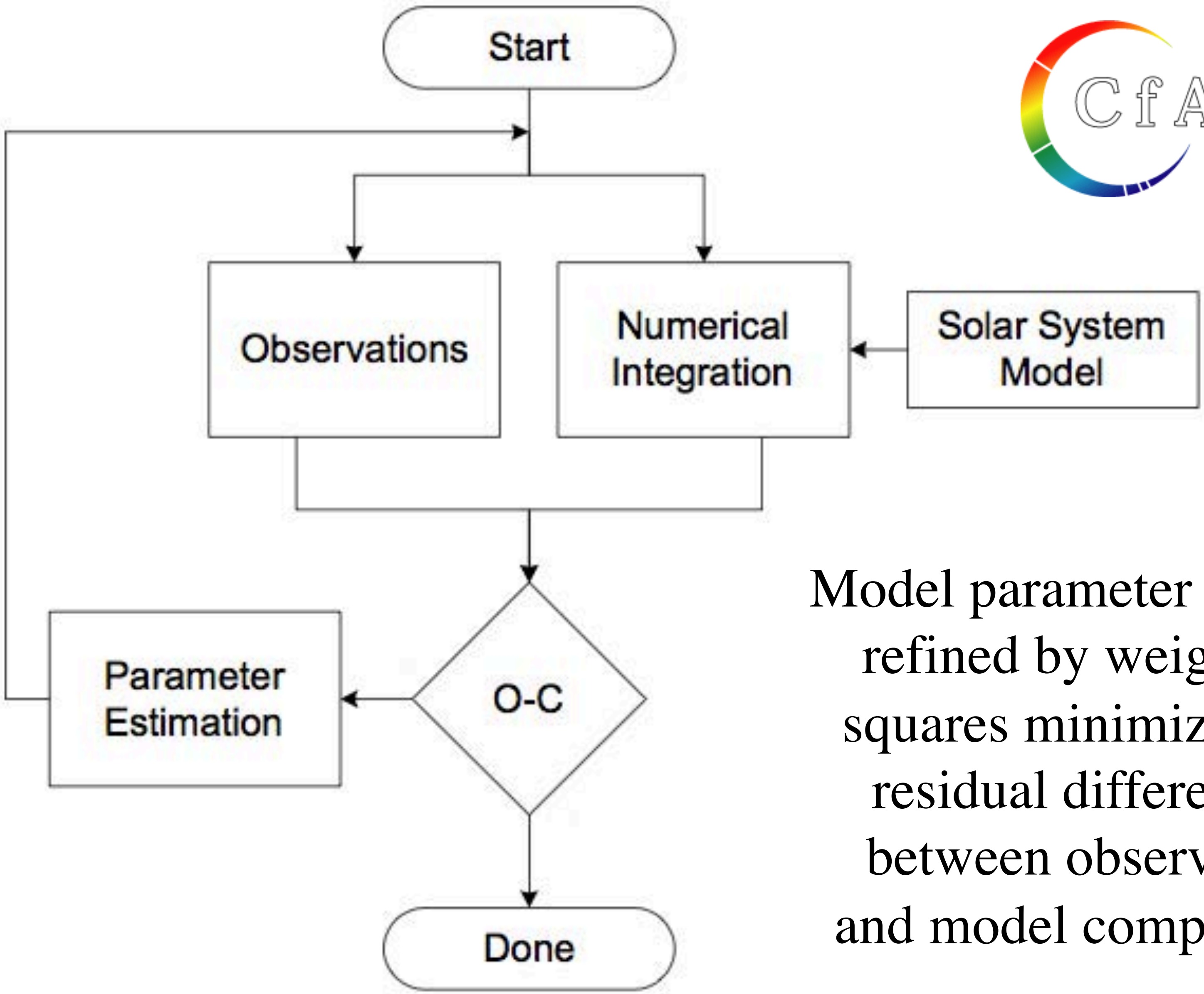




Replace arrays with single/large retroreflectors



PEP (Planetary Ephemeris Program by CfA)



Model parameter estimates are refined by weighted least-squares minimization of the residual differences O-C, between observations (O) and model computations (C)

Example of Lunar Test of General Relativity

- Lunar Laser Ranging (**LLR**), analysis by INFN using the Planetary Ephemeris Program (PEP) software by the Harvard-Smithsonian CfA
- LLR data by APOLLO (USA), Grasse (France), ASI-Matera (Italy) ...
- LLR measures pure $\mathbf{\dot{G}_N/G_N}$, Mars retroflectors sensitive to $\dot{G}_N/G_N$ & $\mathbf{\dot{M}_{SUN}/M_{SUN}}$
- Moon & Mars retroreflectors together can separate $\dot{G}_N/G_N$ & $\dot{M}_{SUN}/M_{SUN}$

Gravitational measurement	Apollo/Lunokhod LLR accuracy (~ few cm)	Next generation LLR accuracy (~1 mm)	Time scale	Ultimate goal LLR accuracy (~0.1 mm)
WEP	$\left\|\frac{\Delta a}{a}\right\| < 1.4 \times 10^{-13}$	10^{-14}	Few years	10^{-15}
SEP	$\|\eta\| < 4.4 \times 10^{-4}$	3×10^{-5}	Few years	3×10^{-6}
β	$\|\beta - 1\| < 1.1 \times 10^{-4}$	10^{-5}	Few years	10^{-6}
$\frac{\dot{G}}{G}$	$\left\|\frac{\dot{G}}{G}\right\| < 9 \times 10^{-13} yr^{-1}$	5×10^{-14}	$\sim$ 5 years	5×10^{-15}
Geodetic precession	6.4×10^{-3}	6.4×10^{-4}	Few years	6.4×10^{-5}
$1/r^2$ deviation	$\|\alpha\| < 3 \times 10^{-11}$	10^{-12}	$\sim$ 10 years	10^{-13}

* J. G. Williams et al. Phys. Rev. Lett. 93, 261101 (2004)
** M. Martini, S. Dell'Agnello, Springer DOI 10.1007/978-3-319-20224-2_5 (2016)
Currie, D. G. et al. (2013), Acta Astronautica 68, 667–680.

Theory and combined experimental limits on spacetime torsion + GR

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

Constraining spacetime torsion with the Moon and Mercury

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(Received 13 December 2010; published 4 May 2011)

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.

Theory and experimental limits on spacetime torsion extension of GR

Gen Relativ Gravit (2011) 43:3099–3126
DOI 10.1007/s10714-011-1226-2

RESEARCH ARTICLE

Constraining spacetime torsion with LAGEOS

Riccardo March · Giovanni Bellettini ·
Roberto Tauraso · Simone Dell'Agnello

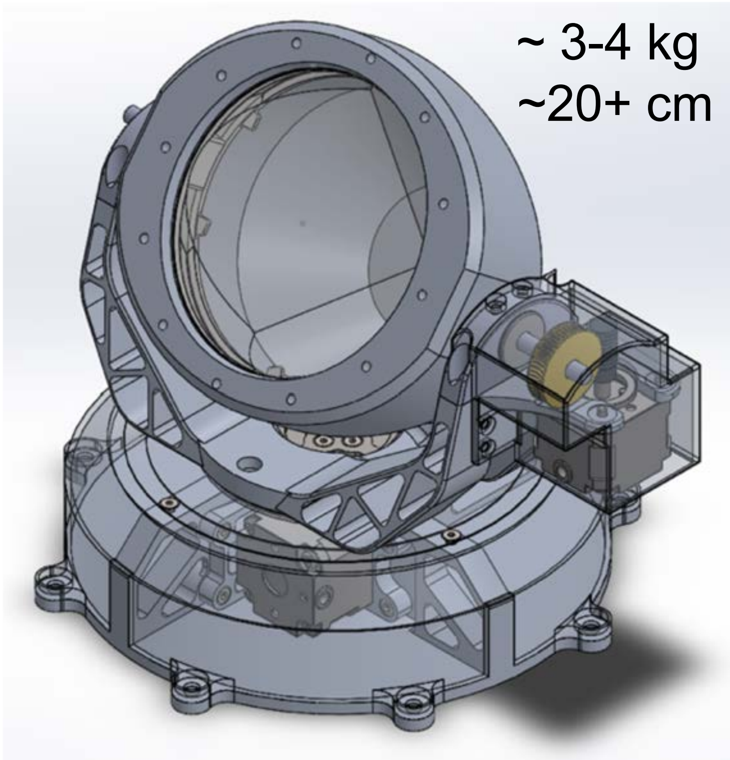
Received: 15 December 2010 / Accepted: 10 July 2011 / Published online: 24 July 2011

Abstract We compute the corrections to the orbital Lense-Thirring effect (or frame-dragging) in the presence of spacetime torsion. We analyze the motion of a test body in the gravitational field of a rotating axisymmetric massive body, using the parametrized framework of Mao, Tegmark, Guth and Cabi. In the cases of autoparallel and extremal trajectories, 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. We also show how the LAser GEOdynamics Satellites (LAGEOS) can be used to constrain torsion parameters. We report the experimental constraints obtained using both the nodes and perigee measurements of the orbital Lense-Thirring effect. This makes LAGEOS and Gravity Probe B complementary frame-dragging and torsion experiments, since they constrain three different combinations of torsion parameters.

INFN – ESA Contract for a next-gen lunar laser retroreflector with an Earth pointing actuator

- Selected by ESA with Earth pointing actuator (dual gimbal)
  Within the European Exploration Envelope Program (E3P)

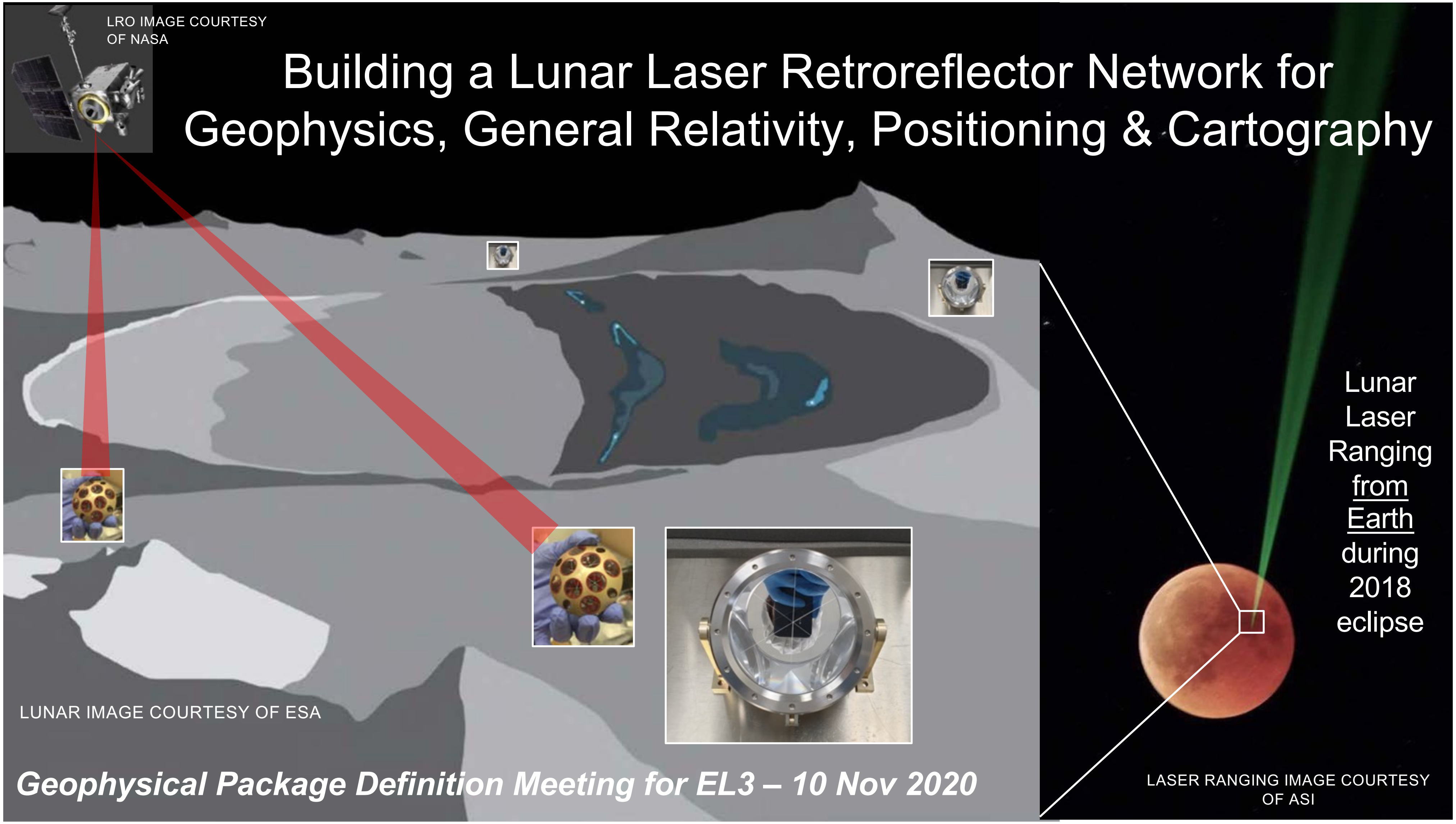
- NASA-ESA agreement for a NASA-CLPS (2021 PRISM AO)
- Lunar landing to the Reiner-Gamma crater (7N, 59W) in 2023/2024



ESA Call for Ideas for European Large Logistics Lander,EL3:

>300 ideas

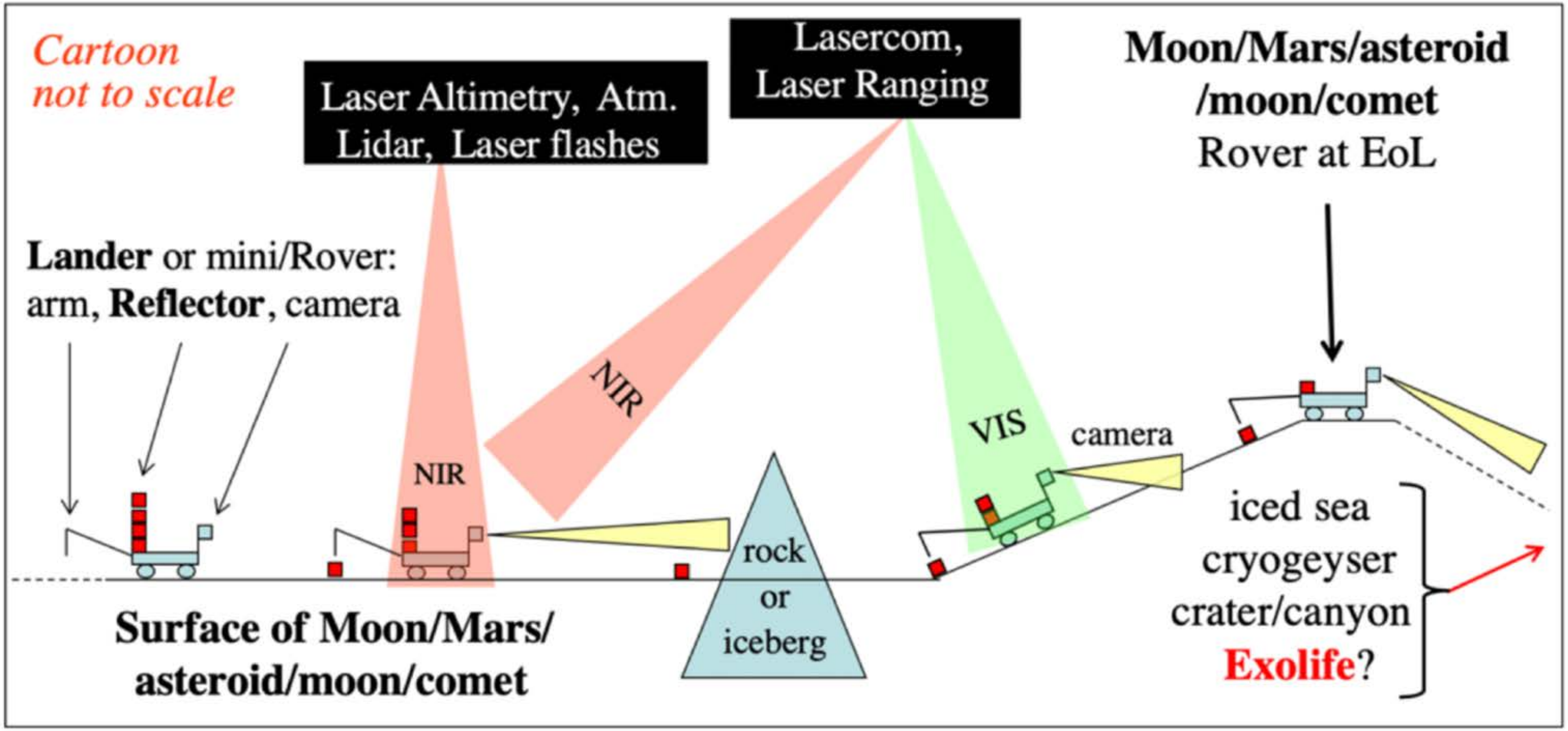
Reflectors part ESA Topical Team on lunar Geo/Physics



ESA “European Large Logistics Lander (EL3)”

Single, large reflector (bottom left) for lunar missions

Miniaturized reflectors enable laser positioning of Landers, Rovers, Mobility Elements all over the solar system (also Moon far side)



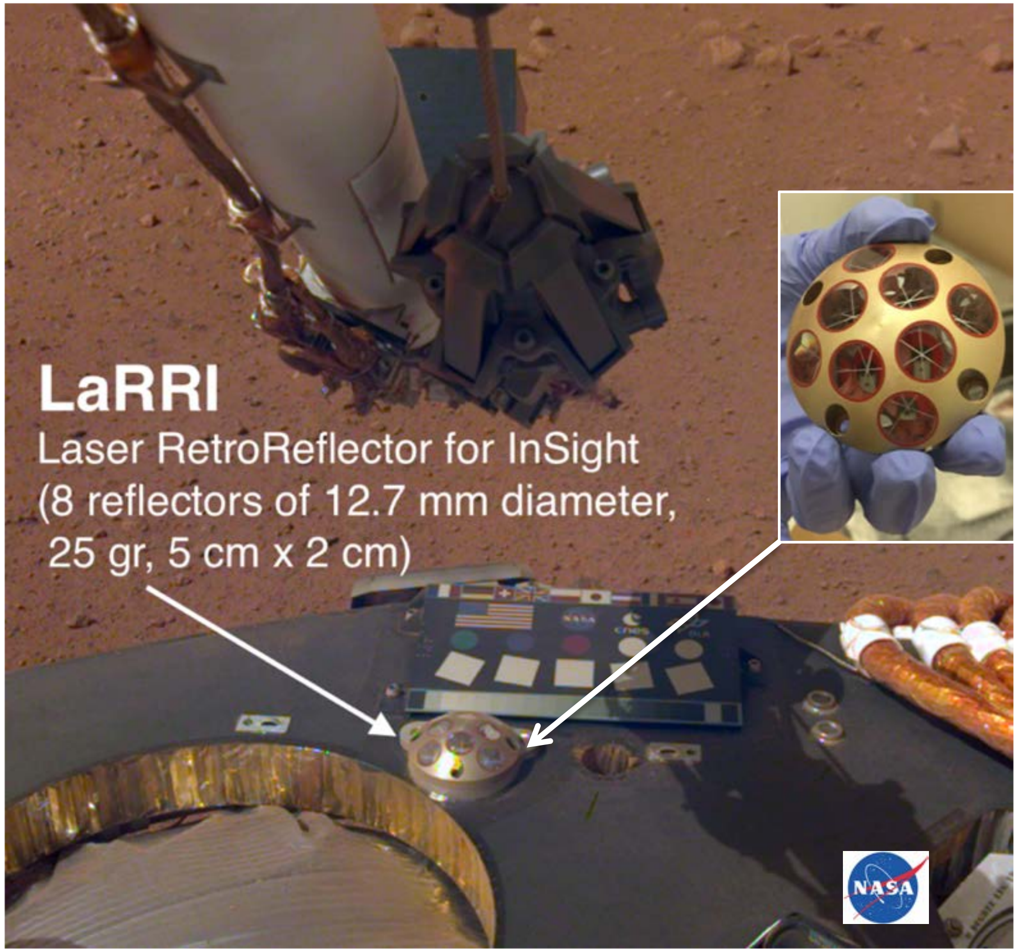
Mars

- Microreflectors (miniaturized laser retroreflectors) for
  - NASA InSight 2018, NASA Perseverance 2020, ESA ExoMars 2022
  - INFN microreflectors & ASI Agreements with NASA/ESA
- Lasers in Mars orbit
  - ASPEN lidar (proposed for the Planetary Science Decadal Survey)
  - Future infrastructure of (classical) lasercom terminals
  - Mars Ice Mapper (NASA, CSA, JAXA, ASI)
- Mars Sample Return program (MSR)
  - NASA Sample Retrieval Lander (SRL) and Perseverance
  - ESA Sample Fetch Rover (SFR)
  - ASI-INFN now proposing retroreflectors for SRL & SFR

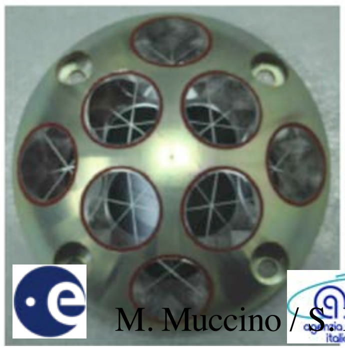
Heritage: laser *microreflectors* by INFN-ASI for Mars

- Accuracy dominated by orbiting laser
- Additional crust tie points on orbiter maps
- Good performance in space conditions:
  L. Porcelli et al. Space Sci Rev, 215 (2019), Iss. 1
- PFM space qualifications (for InSight)
  - Bakeout: T = 97°C ± 1°C for > 48 hr
  - Contamin. Control & Planet. Protection
  - TVT: 3 cycles, max = +110°C ± 1°C, min = -135°C ± 1°C, w/2-hr dwell time
  - Random vibration & pyroshock (table)

Frequency (Hz)	PFM (g)
100	42
2000	2121
10000	2121

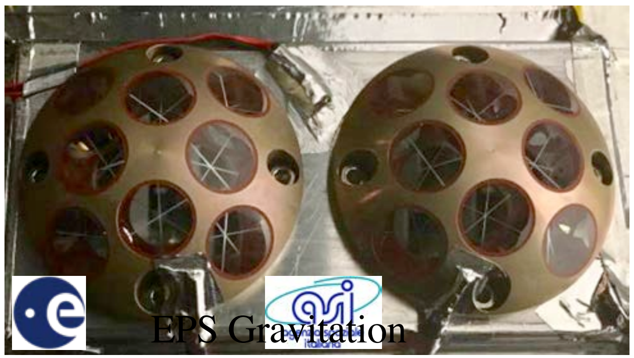


EXOMARS 2016



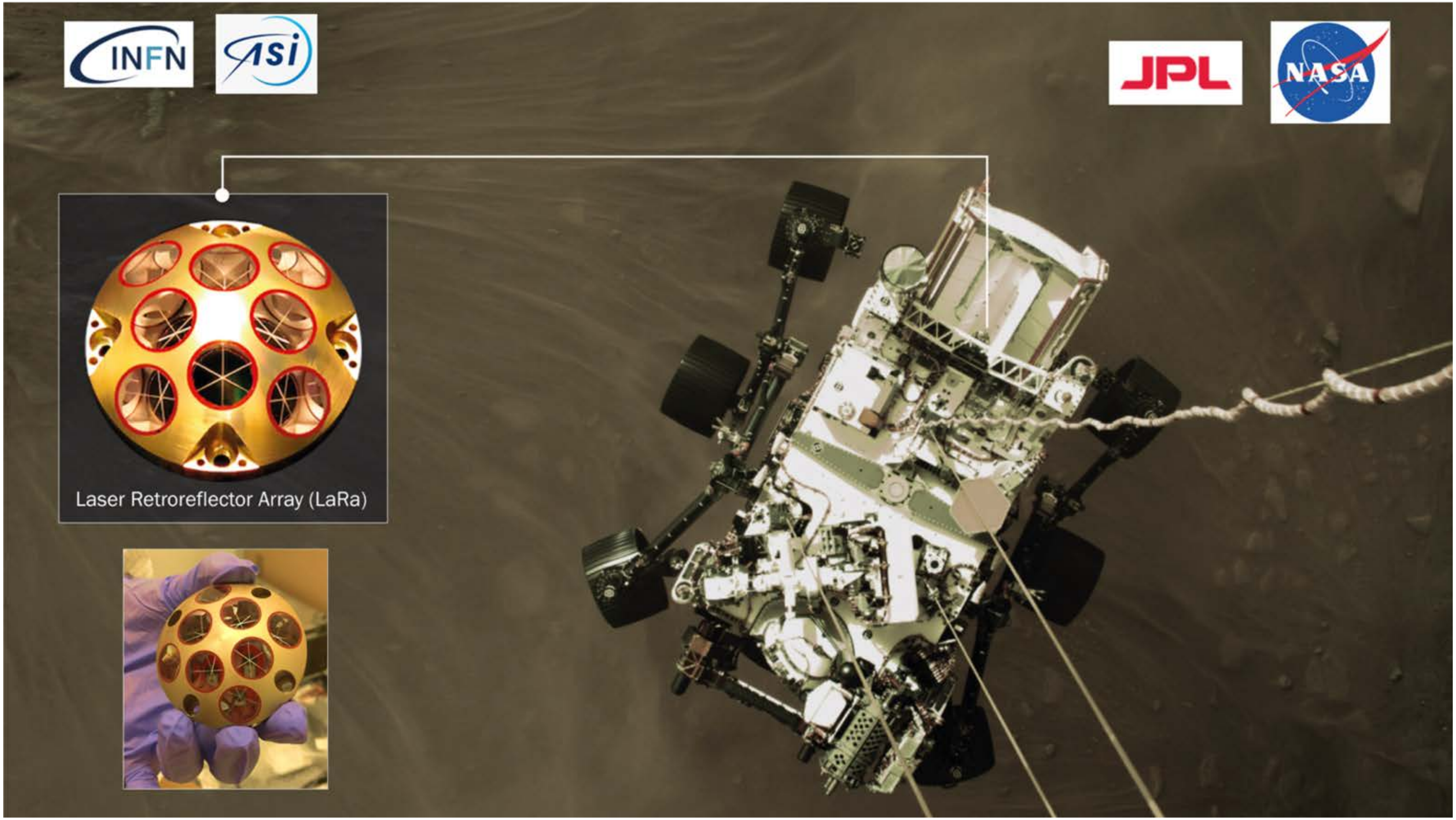
INSIGHT 2018

EXOMARS 2022 (SPARE)

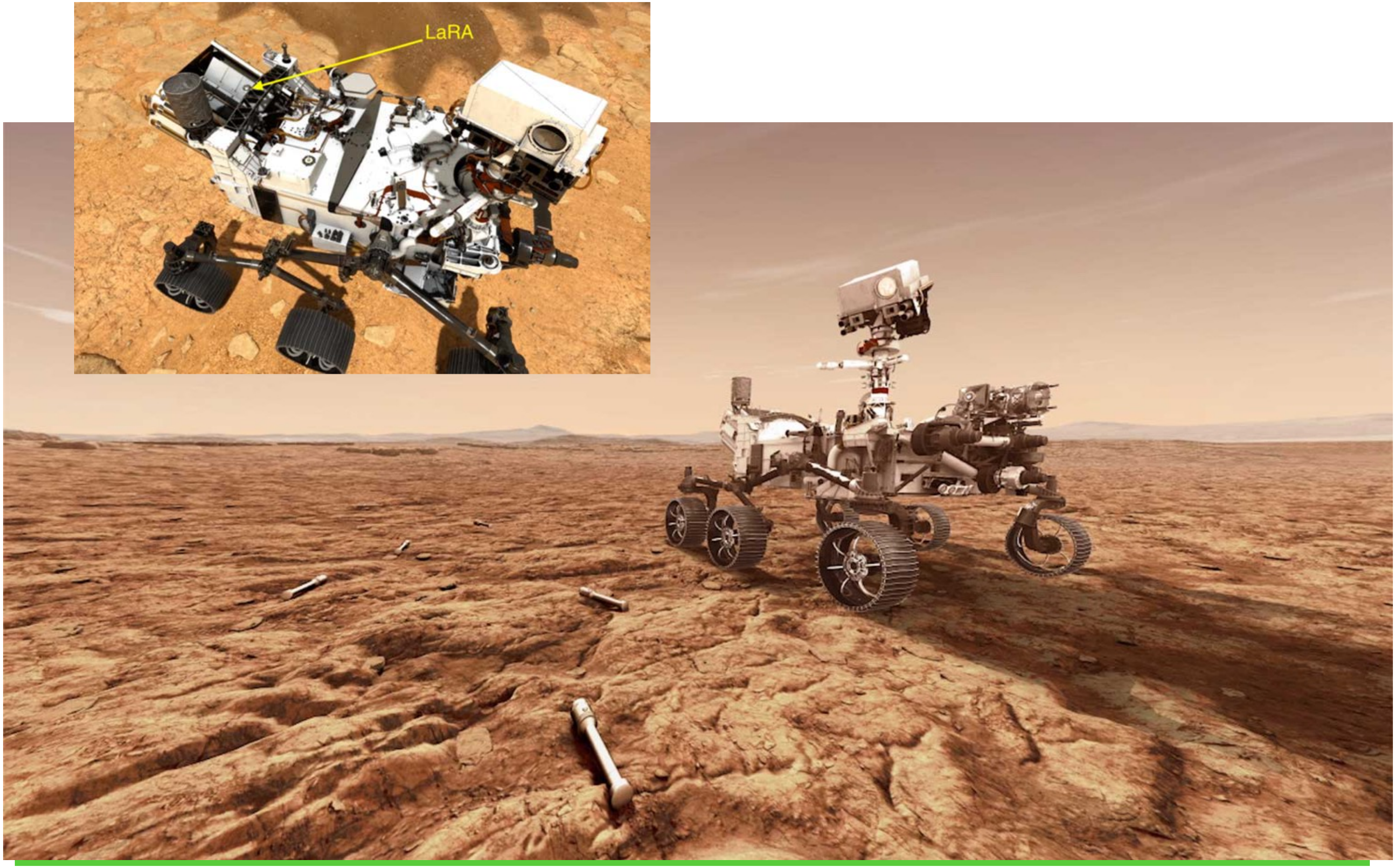


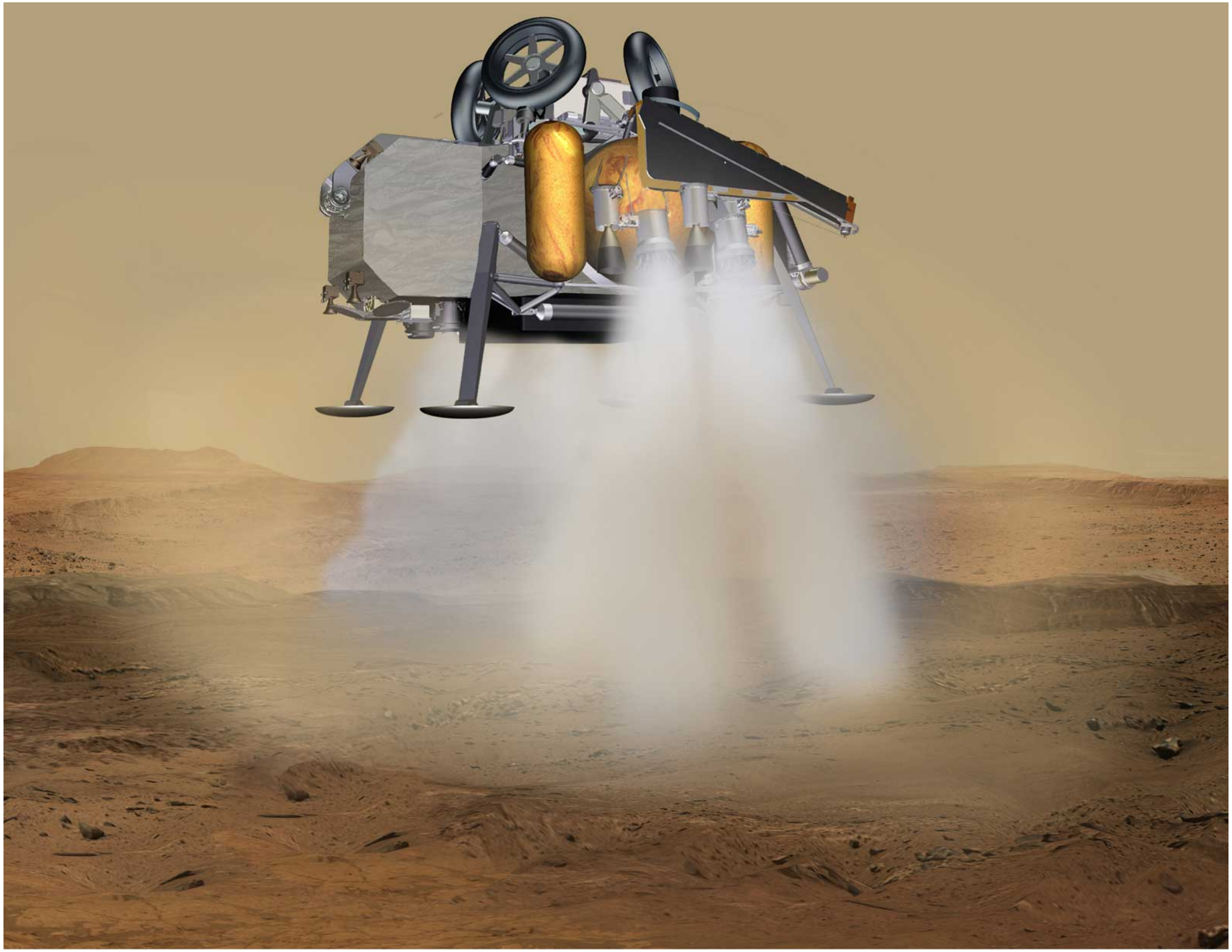
PERSEVERANCE 2020 (SPARE)

NASA Perseverance with LaRA microreflector during successful landing in Feb 2021

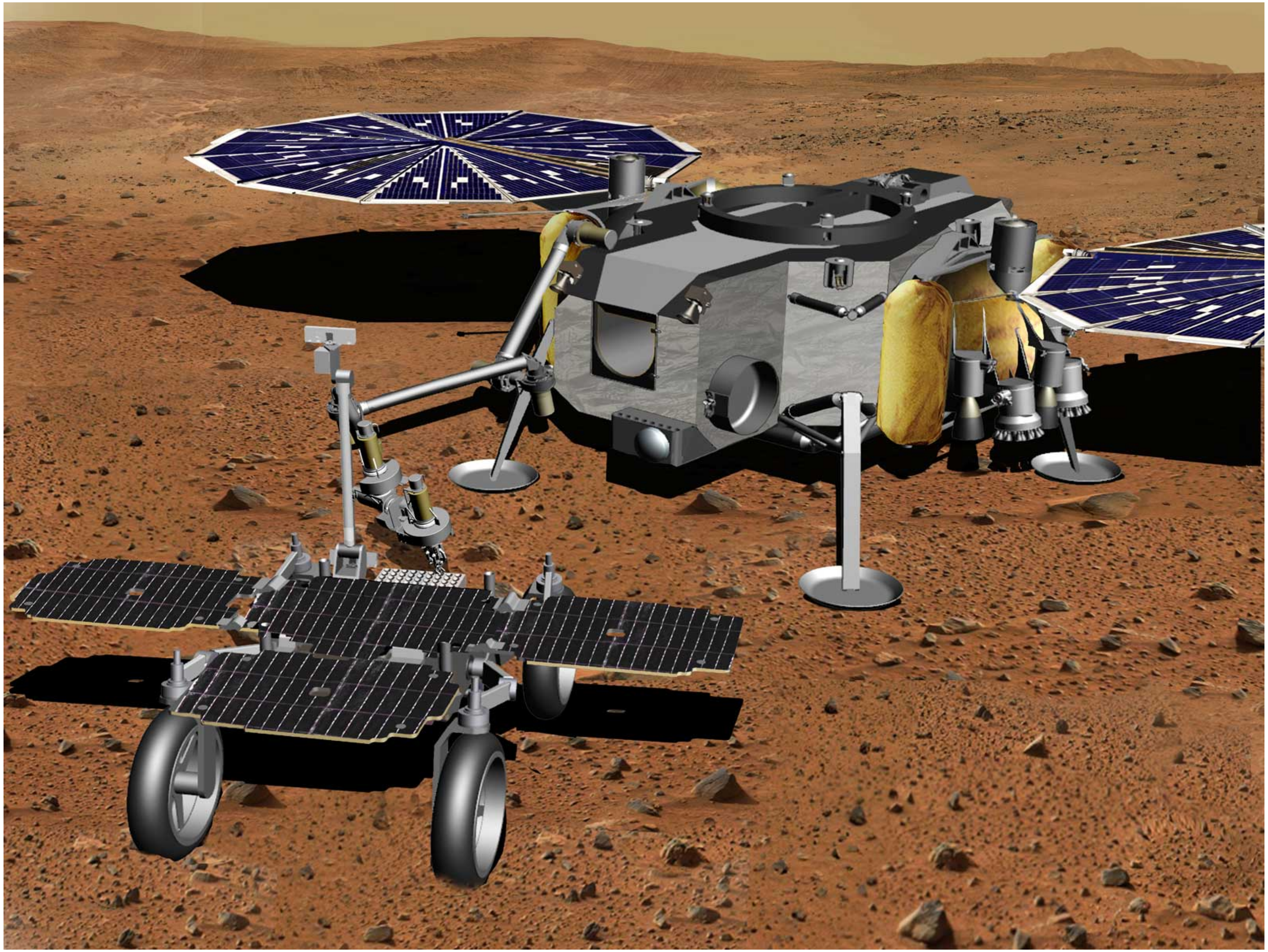


NASA Perseverance 2020 Rover with LaRA

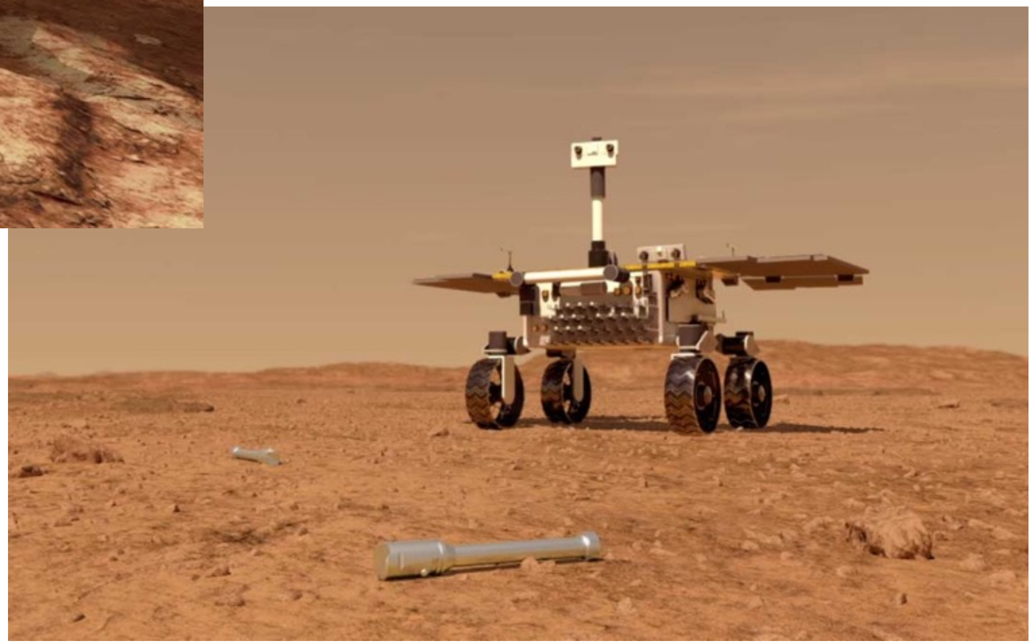




NASA Sample Return Lander & ESA Sample Fetch Rover



Sample Fetch Rover (bottom right) will get Perseverance samples (top left)



Test General Relativity w/Mars retroreflectors

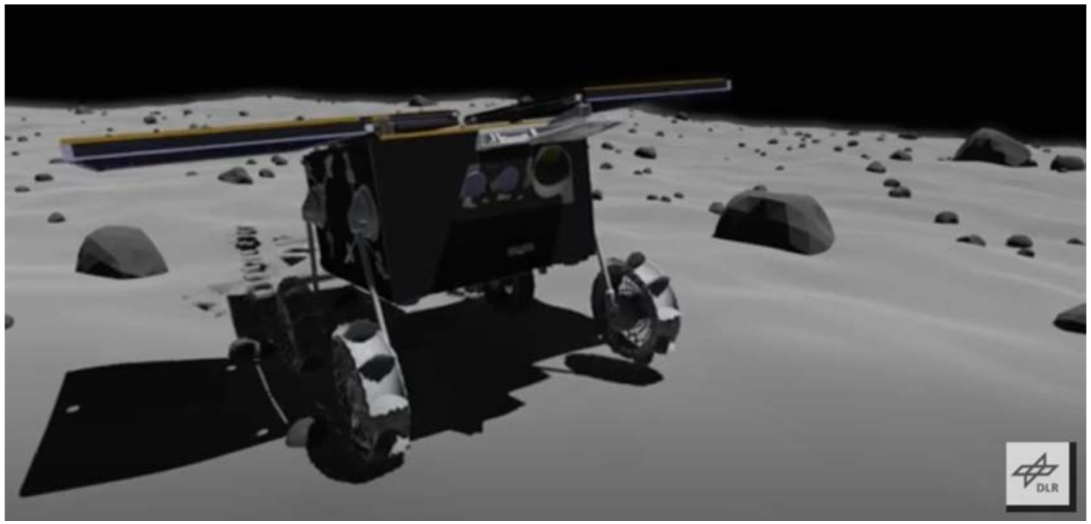
- Network of passive microreflectors on Mars surface
- Test of General Relativity at 1.5 AU
  - Estimate Mars center of mass, like Selenocenter with lunar reflectors
  - PPN b (strong equivalence principle) (Sun-Earth-Mars-Jupiter)
  - Gdot/G (gravitational constant) (Sun-Mars)
  - $1/r^2$ force law (Yukawa potential) (Sun-Mars)
  - PPN g (spacetime curvature) (Sun-Mars)
- Analysis with PEP (Planetary Ephemeris Program) by CfA
- Literature & physics discussion (a few picks):
  - 'Historic' Shapiro time delay with Vikings, 1970s
  - J. Anderson, J. Williams, Class. Q. Grav. 18 (2001) 2447
  - S. Turyshev et al, arxiv:1003.4961v2, 3 Sep 2010 & its many refs.
- Same program possible with reflectors on Phobos & Deimos

Mars test of General Relativity (PEP simulations)

- Assume network of microreflectors (non-ideal, ~all North)
  - Phoenix (68N, 234E), Viking1 (22N, 50W), Viking 2 (48N, 258W)
  - Curiosity (4S, 137E), Opportunity (2S, 354E)
- Assume data rate: 1 laser normal point (NP) every 7 Sols
  - Weather/ops limitations; visibility from orbiter like MRO is once/Sol
- Accuracy: 10 cm-10 m (Mars ephemeris ~100-50 m)
  - Earth-orbiter: radio ranging; or laser (à la LLCD) or laser transponder experiments (MLA/MOLA). Orbiter-surface: laser ranging/altimetry

Time / NP 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
Comparative Accuracy With data/mission	**<1 x E-04** Lunar Laser Ranging MESSENGER/Mercury	**2.3 x E-05** Cassini/Saturn	**9 x E-13** Lunar Laser Ranging

- Mission to Phobos, launch in 2024
- Spacecraft & lidar by JAXA, rover by CNES/DLR
- ASI microreflector(s) by INFN on the rover
- Other future lasers @Mars?
  - Mars Ice Mapper mission (NASA, JAXA, CSA, ASI)
  - ASPEN atmospheric lidar proposed for USA Decadal Survey



Conclusions & outlook

- Lunar Retroreflectors back to the Moon after 50+ years
- 3rd Mars microreflector with ExoMars 2022
- Mars Moons eXplorer to Phobos in 2024
- Mars Sample Return lander (NASA) & rover (ESA), 2026+
- ESA – Hera: lidar, 2 cubesats (w/reflectors) to Didymos, 2024+
- (Far?) future:
  - ✓ NASA - Europa Lander (long study) & lasercom @Jupiter
  - ✓ Other Deep Space Quantum/Classical Links
    - ✓ USA Decadal Survey white papers underway