Introductory and Refresher Course on Satellite and Lunar Laser Ranging

Lunar Laser Ranging

History of LLR

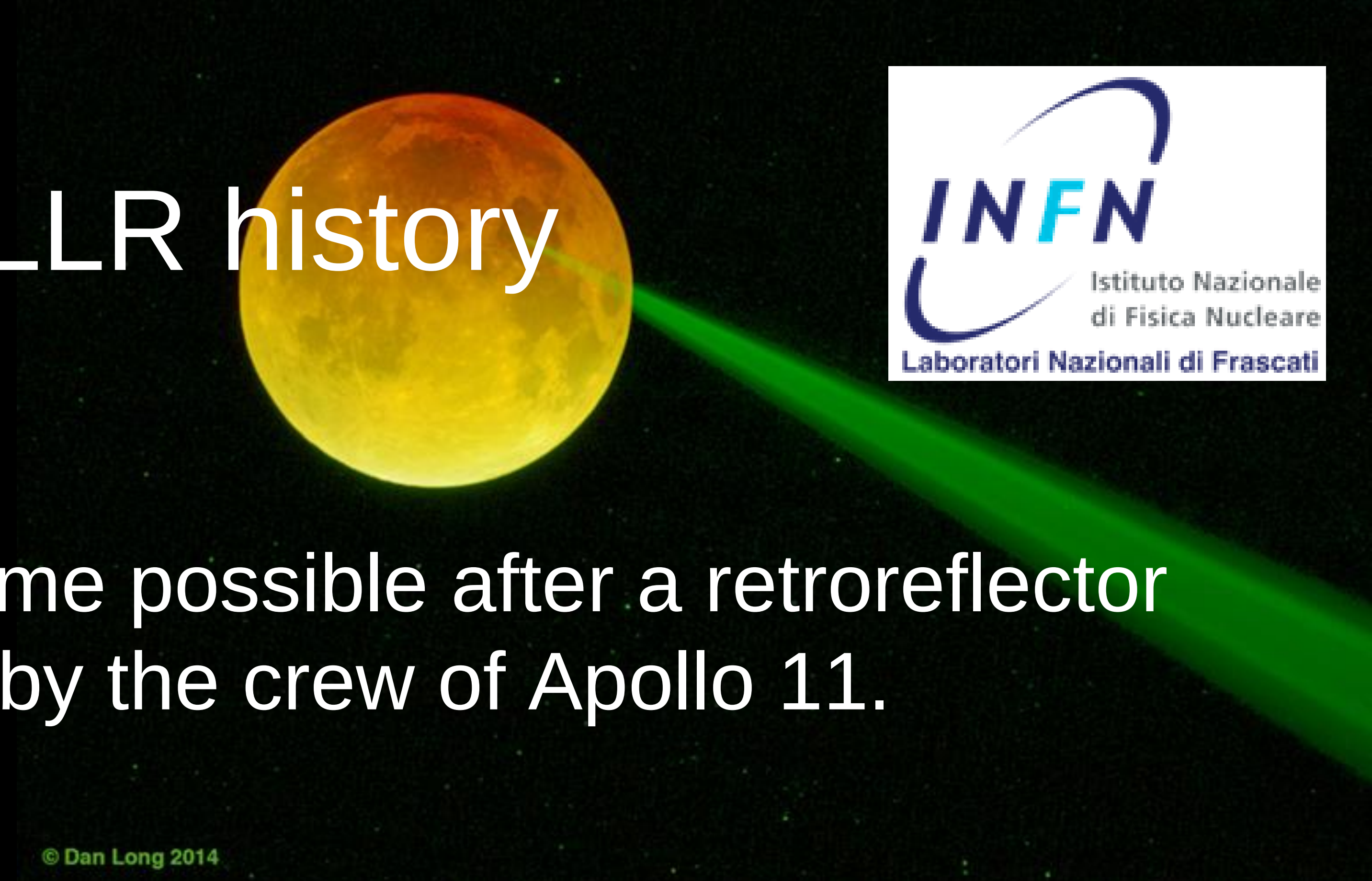
How is LLR different from SLR

LLR network

LLR contribution to science

Challenges of LLR: next retroreflector’s generation

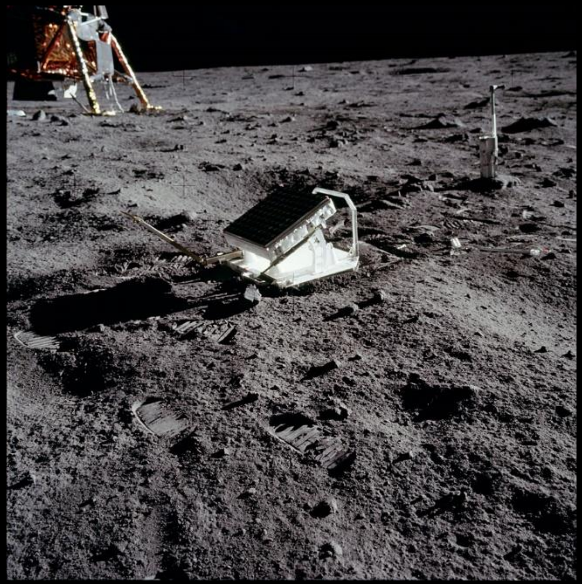
LLR history



- Lunar laser ranging became possible after a retroreflector was placed on the Moon by the crew of Apollo 11.

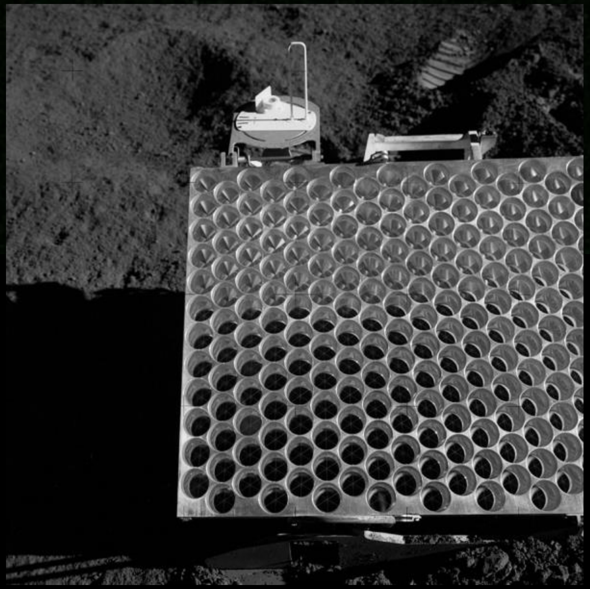
- Five retroreflectors were placed on the Moon during the Apollo and Luna programs:
  – Apollo 11 in July 1969
  – Luna 17 (Lunokhod 1) in November 1970
  – Apollo 14 in February1971
  – Apollo 15 in July 1971
  – Luna 21 (Lunokhod 2) in January 1973

LLR history APOLLO retroreflectors



APOLLO 11
(07/1969)
Square 46 X 46 cm
100 corner cubes

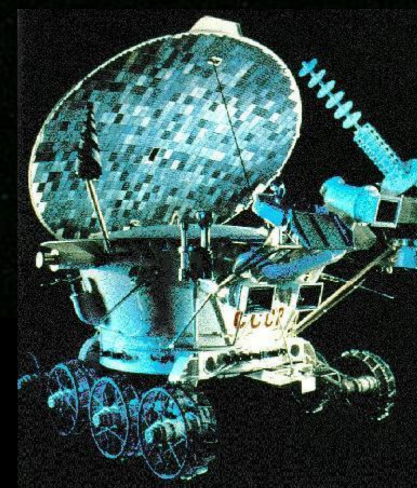
APOLLO 14
(02/1971)
Square 46 X 46 cm
100 corner cubes



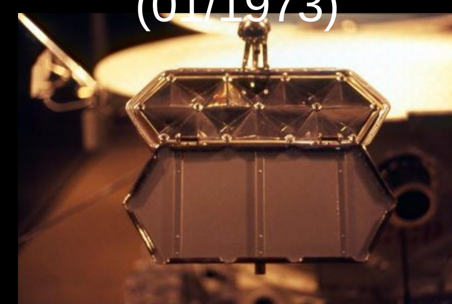
APOLLO 15
(07/1971)
Rectangle 104 X 61 cm
300 corner cubes

LLR history
Lunokhod
retroreflectors

Lunokhod 1
(11/1970)



Lunokhod 2
(01/1973)



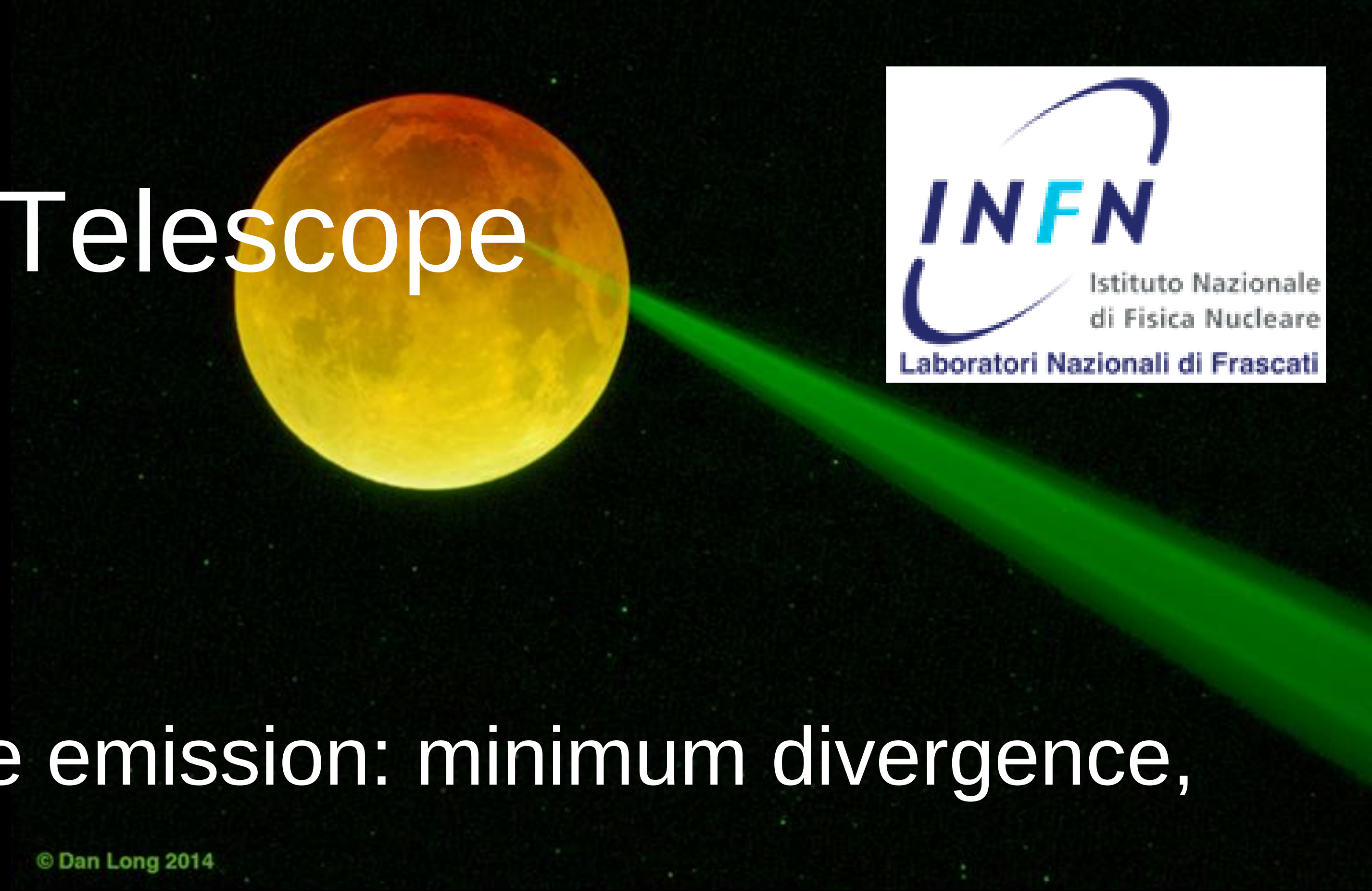
Rectangle 44 X 19 cm
14 corner cubes

How is LLR different from SLR

- The link budget is function of power 4 of the distance:
  - SLR tracking: from 300km to 36 000km
  - LLR tracking: around 400 000km

- LLR requires more efficient equipment:
  - Larger telescope
  - More powerful laser
  - Better pointing and the tracking quality
  - Single photon detection

Telescope

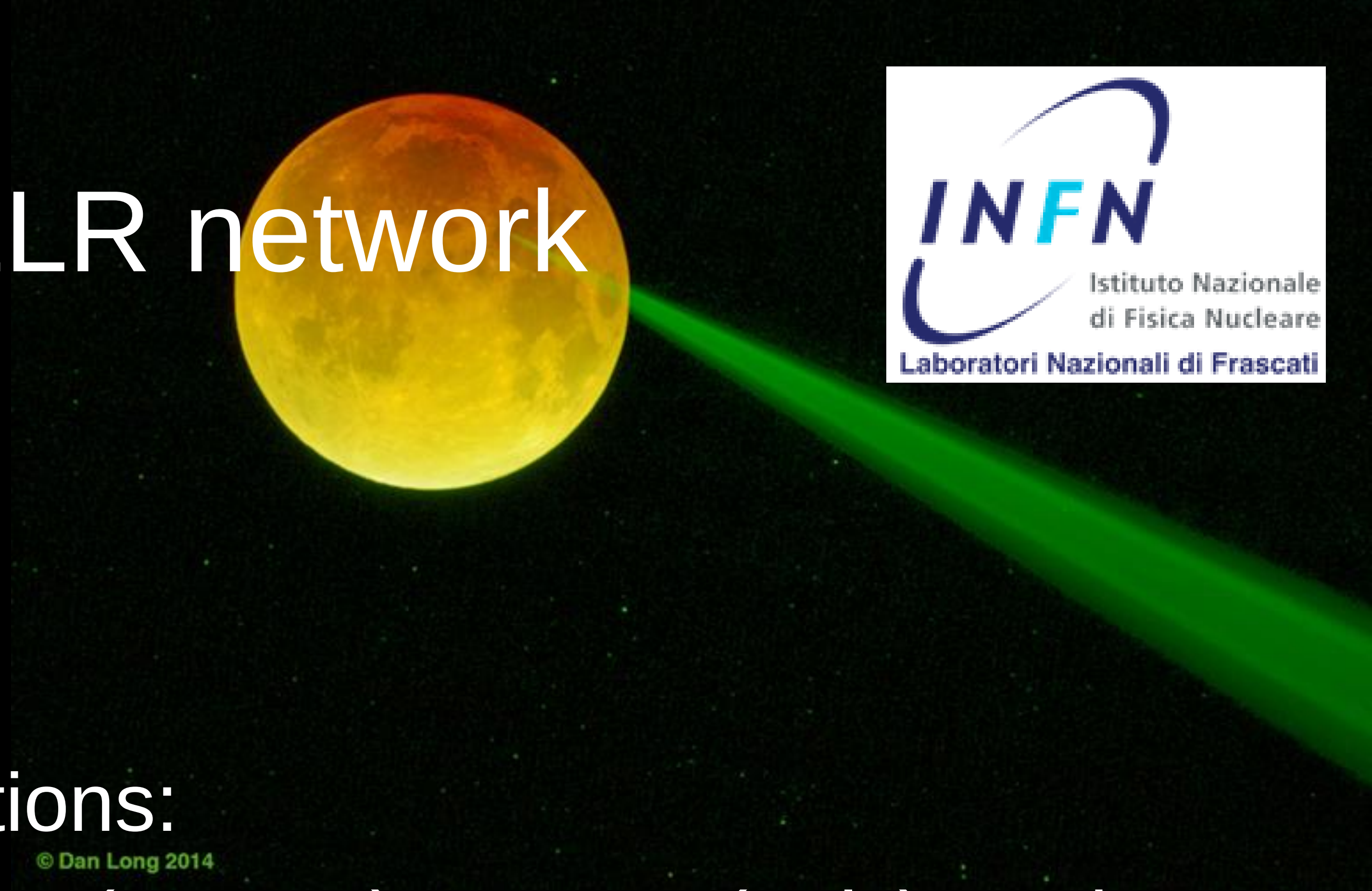


- The largest diameter at the emission: minimum divergence, small spot on the Moon.
- The largest diameter at the reception: maximum number of photons.
- Good pointing: better than 1 arcsecond, but reference stars or craters can be used to correct the errors of the mount.
- Good tracking: better than 1 arcsecond for 10 minutes.

Laser

- The most powerful laser possible
  - The more narrow the pulsewidth, the less energy there is at the output.
- Due to the limited accuracy of the retroreflectors, and the weak link budget, short pulsewidth is not necessary (100ps).
- Ranging in infrared:
  - More energy
  - Less noise

LLR network



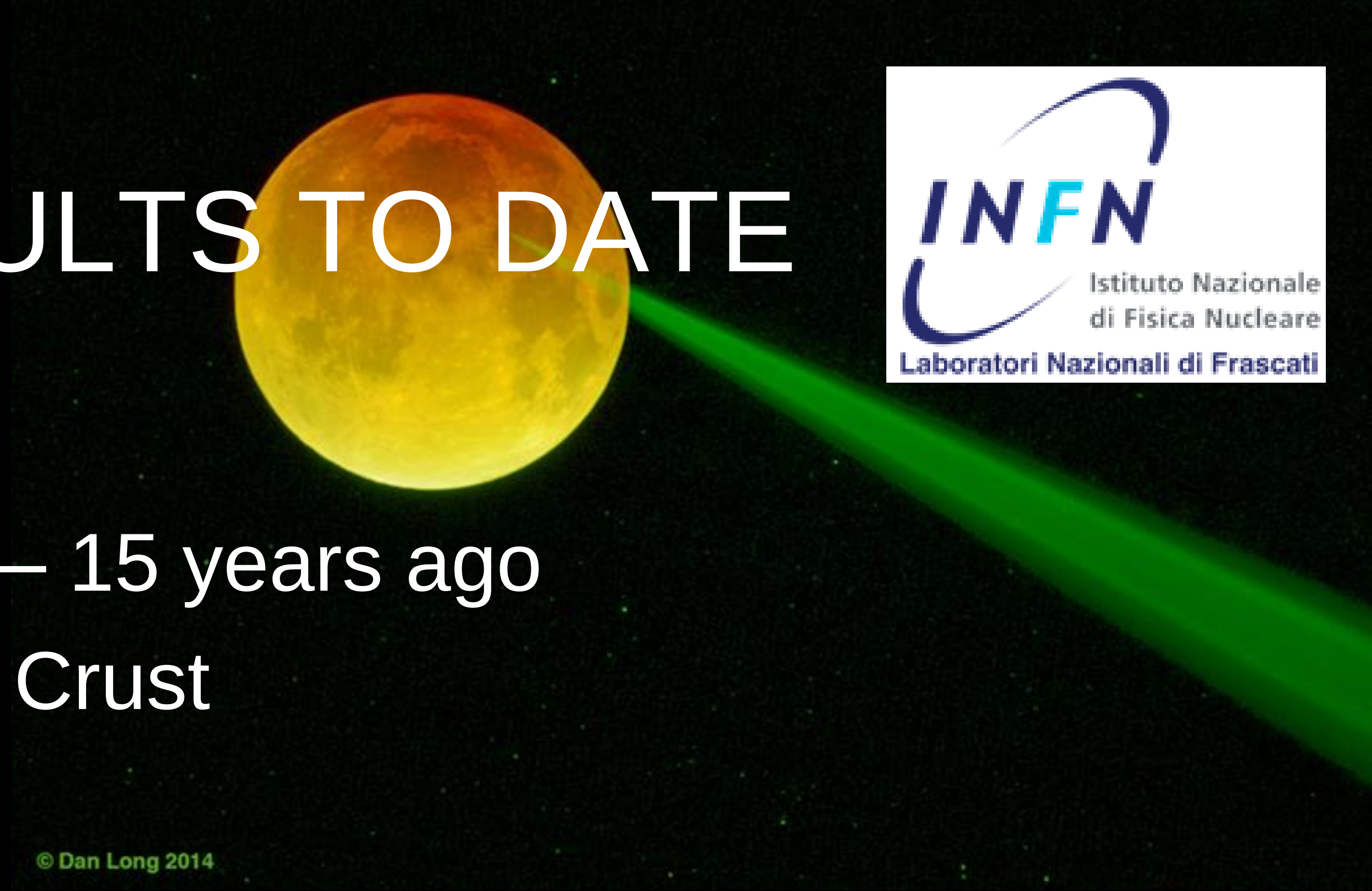
- Four operational LLR stations:
  – APOLLO (USA), Grasse (France), Matera (Italy), and Wettzell (Germany).

- Stations in development:
  – In China, Russia, and South-Africa

LLR contribution to science

- Five Retroreflectors Deployed
  - Apollo11, Luna17, Apollo14 and Apollo15 & Luna21 Missions
- Still Working
- Almost Daily Ranging Continues
- Analysis of Long Data History
- Evacuated Many Science Areas
  - Earth Science
  - Lunar Physics
  - Tests of General Relativity
  - Gravitation
  - Cosmology

RESULTS TO DATE



- Lunar Physics
  - – Discover of Liquid Core – 15 years ago
  - – Elastic Properties of the Crust

Earth Science Results

Plate Tectonics

Question of Historical vs. Current Motion

LLRP has been Measuring the Current Motion

Earth Rotation

Evaluated the Changes in the Length of Day

Measurement of Polar Wander

Chandler Wobble to High Accuracy

EARTH SCIENCE RESULTS

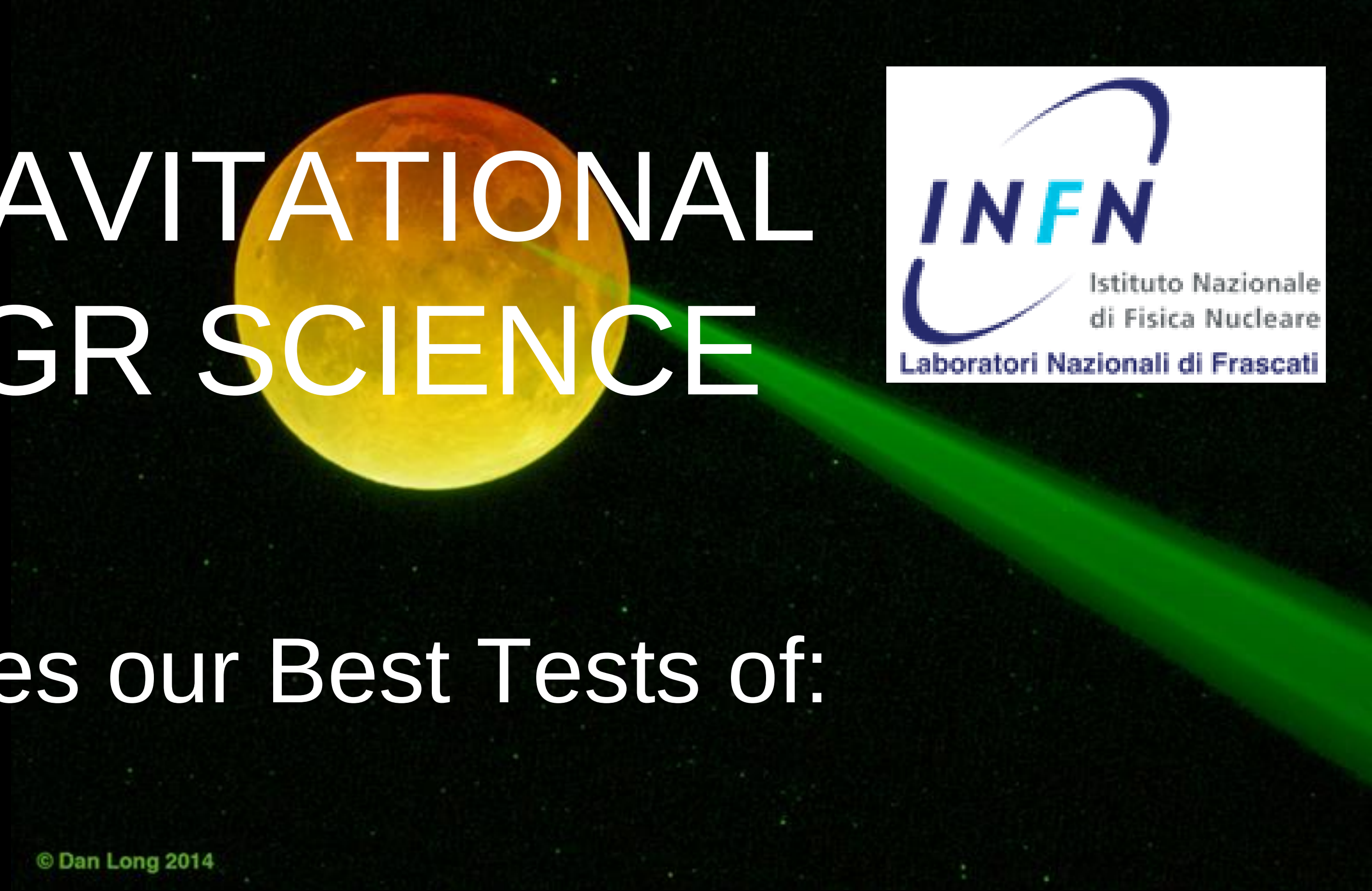
- Plate Tectonics
  - Question of Historical vs. Current Motion
  - We Measured Current Motion
- Earth Rotation
  - Evaluated the Changes in the Length of Day
- Measurement of Polar Wander
  - Chandler Wobble to High Accuracy

LLR GR RESULTS TO DATE

Equivalence principle parameter	η	(6 ± 7) . 10−4
Metric parameter	γ − 1	(4 ± 5) . 10−3
Metric parameter	β − 1: direct measurement	(−2 ± 4) . 10−3
Time-varying gravitational constant	˙G/G (year−1)	(6 ± 8) . 10−13
Differential geodetic precession	ΩGP -ΩdeSit (per century)	(6 ± 10) . 10−3
Yukawa coupling constant	α (for λ =4 · 105 km)	(3 ± 2) . 10−11
“Preferred-frame” parameter	α1	(−7 ± 9) . 10−5
“Preferred-frame” parameter	α2	(1.8 ± 2.5) . 10−5
Special relativistic parameters	ζ1 − ζ0 − 1	(−5 ± 12) . 10−5
Influence of dark matter	δggalactic (cm s−2)	4 ± 4) . 10−14

from Juergen Mueller and Franz Hofmann

GRAVITATIONAL & GR SCIENCE



- LLR Currently Provides our Best Tests of:
  - The Strong Equivalence Principle (SEP)
  - Time Rate-of-Change of *G*
  - Inverse Square Law, Deviation of 1/r
  - Weak Equivalence Principle (WEP)
  - Gravito-Magnetism

Weak Equivalence Principle

- Galileo's Apocryphal Experiment
  - Weak Equivalence Principle
  - Rate that the Earth and Moon Fall to the Sun
- Einstein is Correct
  - In Absence of Air
  - All bodies Fall at Same Rate
  - Best Measurements to Date
- Even Gravity Energy is Hard to Push
  - Only Experiment to Measure This

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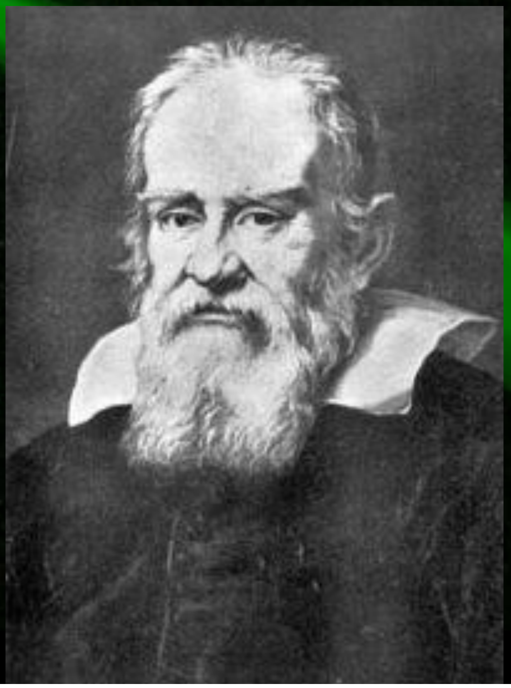
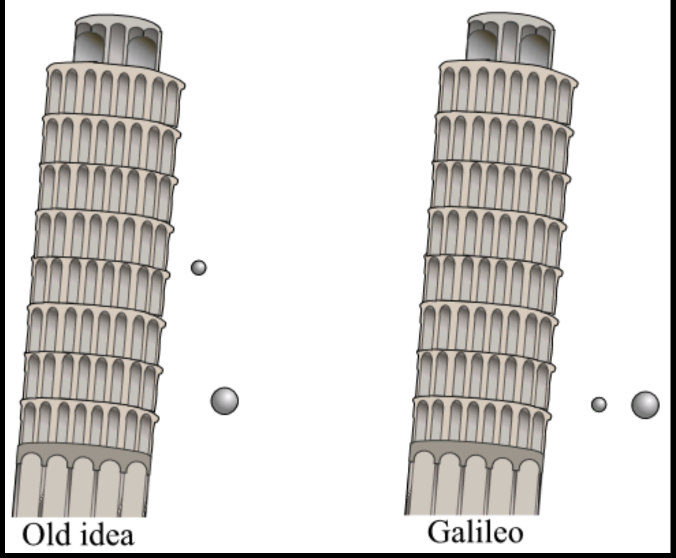
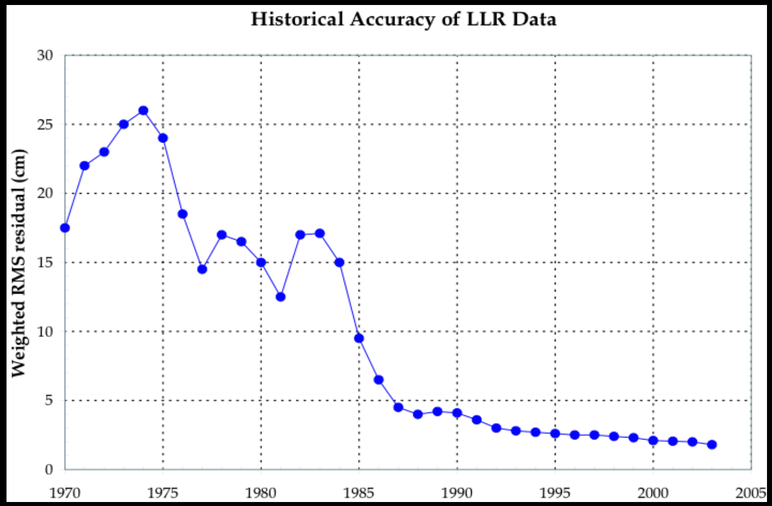




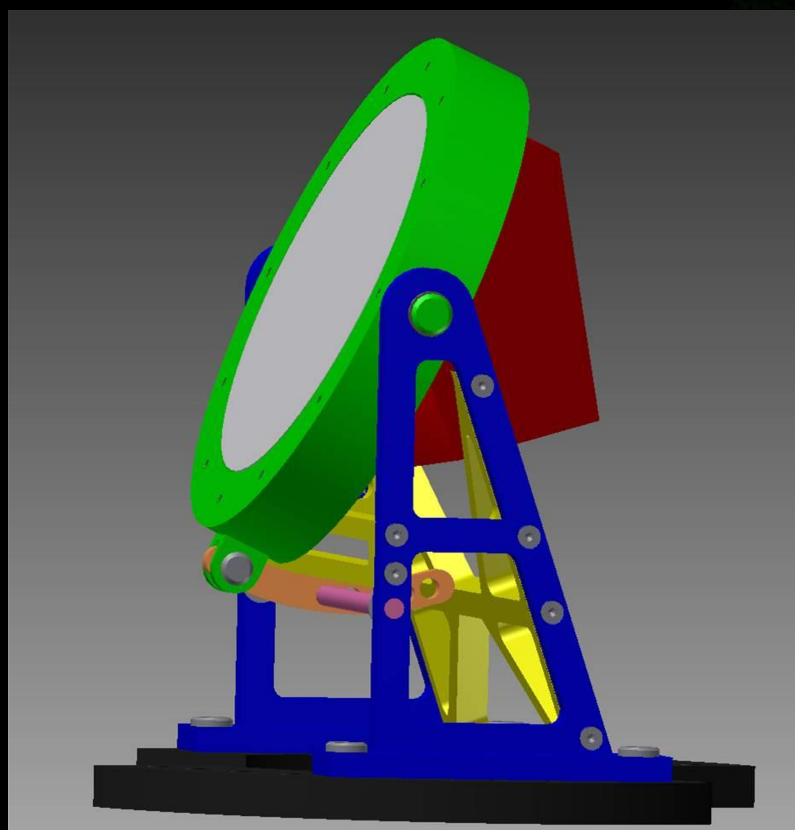
LIBRATION PROBLEM

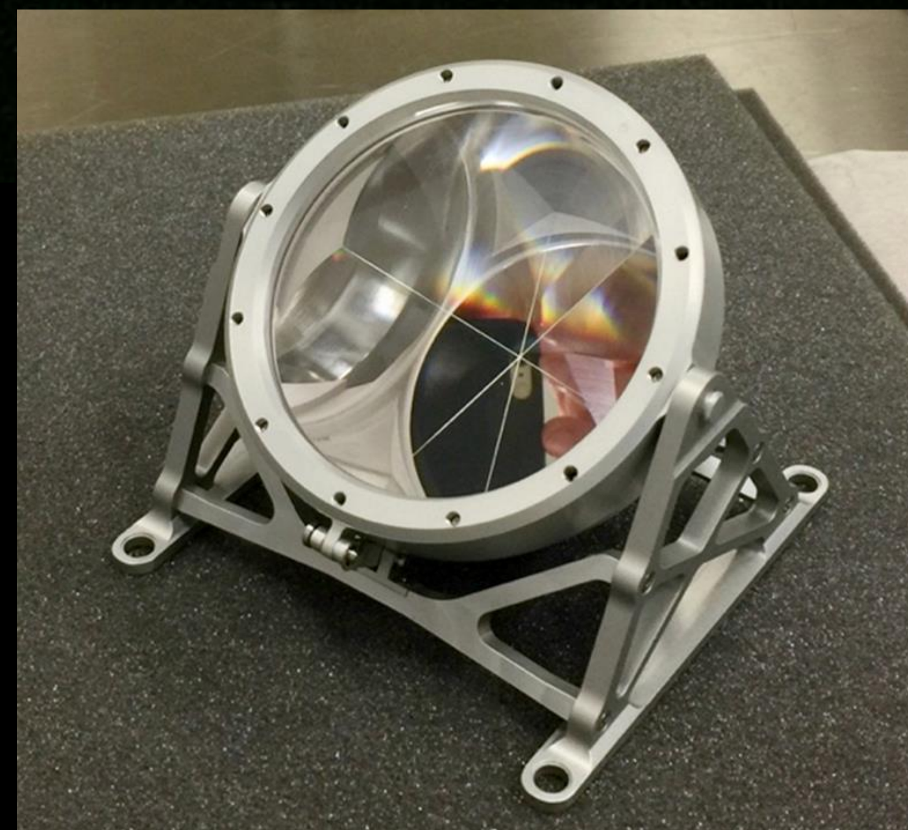
- Why is there a Problem with the Apollo Arrays
  - Lunar Librations in Tilt Both Axis by 8/10
  - Apollo Arrays are Tilted by the Lunar Librations
  - Corner CCRs can have Different Ranges
    - As large as 100 mm for the Apollo 15 array
- Solution is One Large Retroreflector



Current Next Generation RetroReflector

- Ranging Accuracy Improved by Up to a Factor of 100
- Limits to the Science Improvement
  - Ground Station Hardware and Procedures
  - Modeling of Horizontal Gradients in the Earth’s Atmosphere





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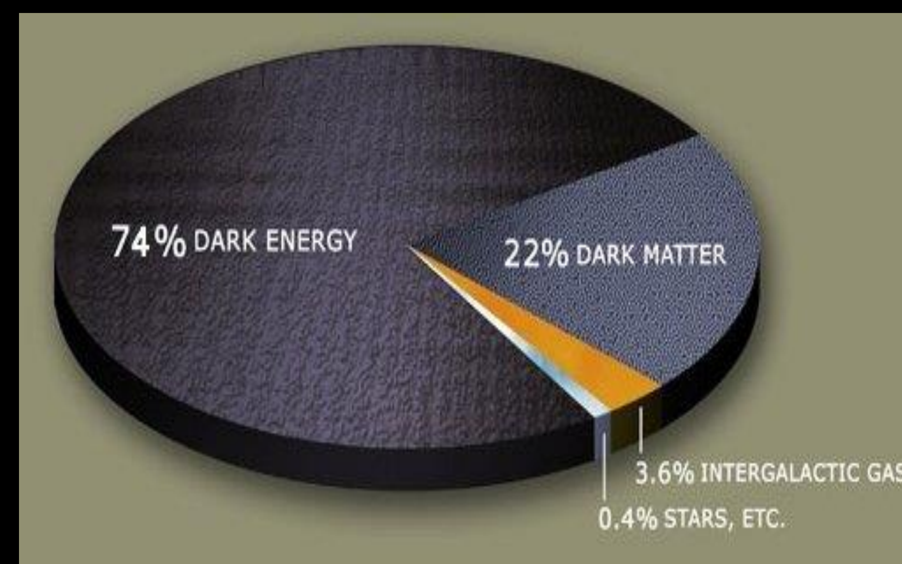
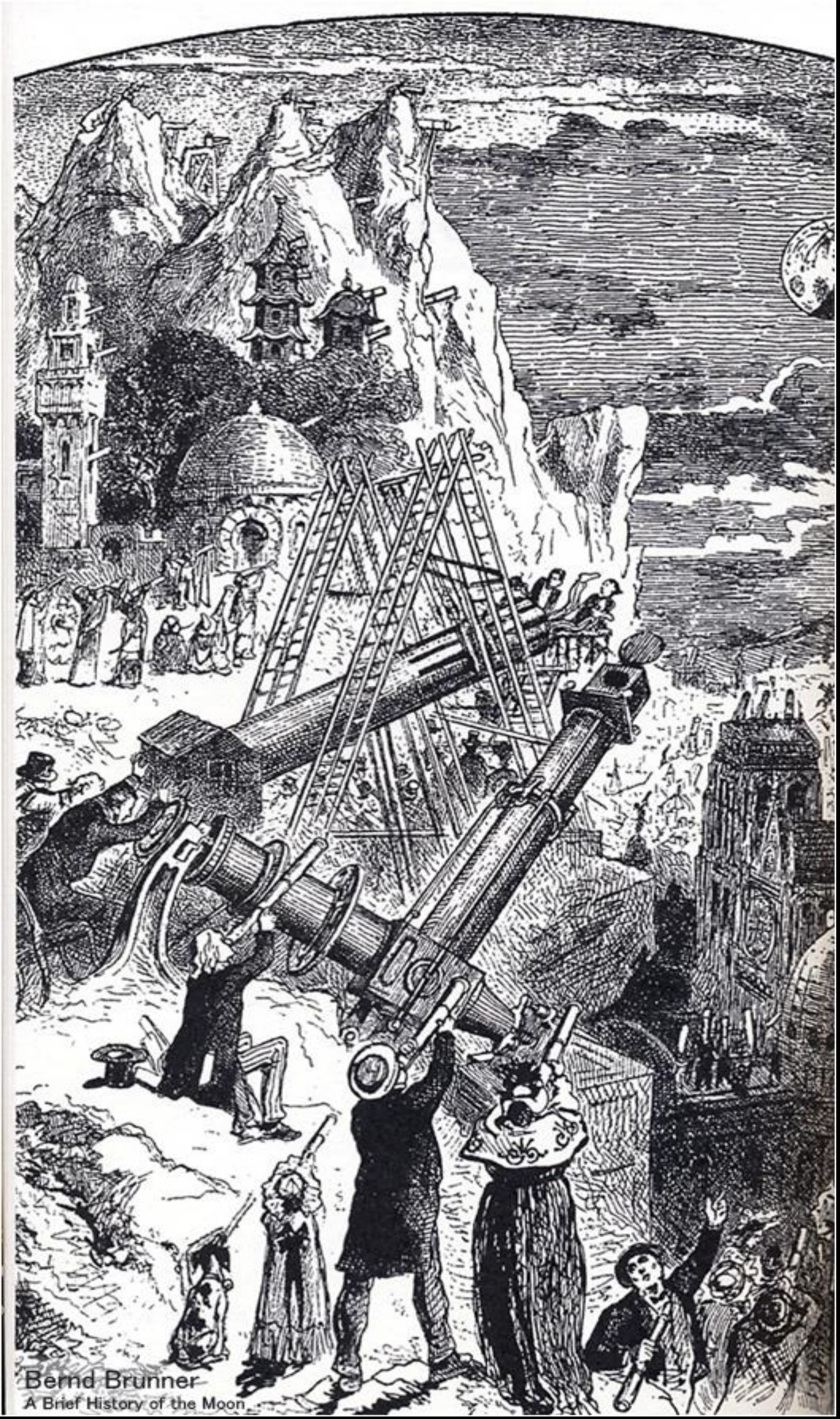
Conclusions

- Retroreflector Arrays Still Working after 50 years
- They Continue to Produce New Science
  - Lunar Science
  - Gravitational Physics and Tests of General Relativity
- NGLRs Will Improve Ranging Accuracy by up to 100
  - Limited only by Ground Stations and Atmospheric Modeling
- NASA Has Selected UMCP
  - To Deliver Three NGLRs
  - For Lunar Surface Deployment in 2021
- Why Push
  - 95% of Content of Universe is Unknown
  - GR and Quantum Mechanics in Conflict





Thank You!

any

Questions?

or

Comments?

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