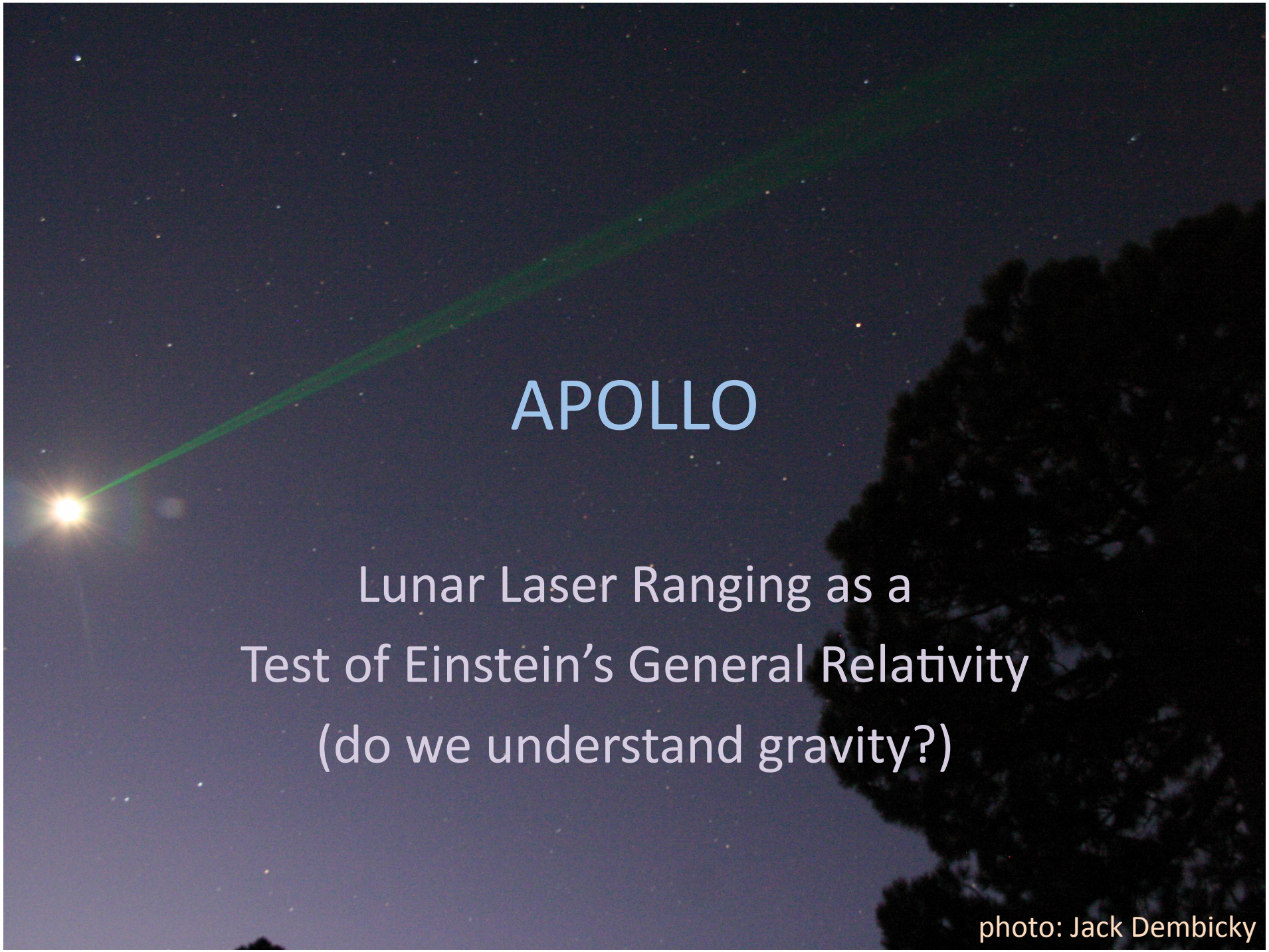
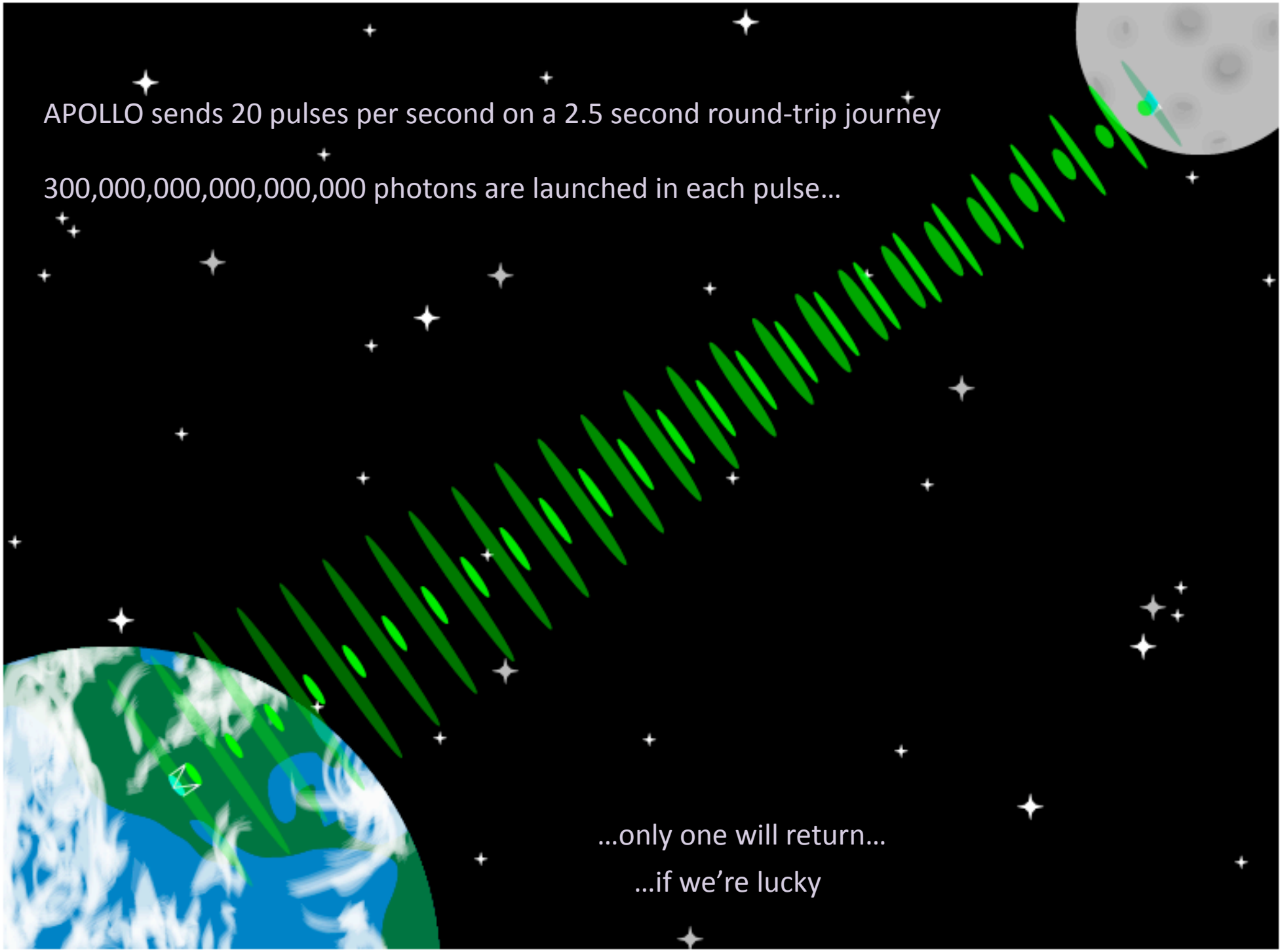
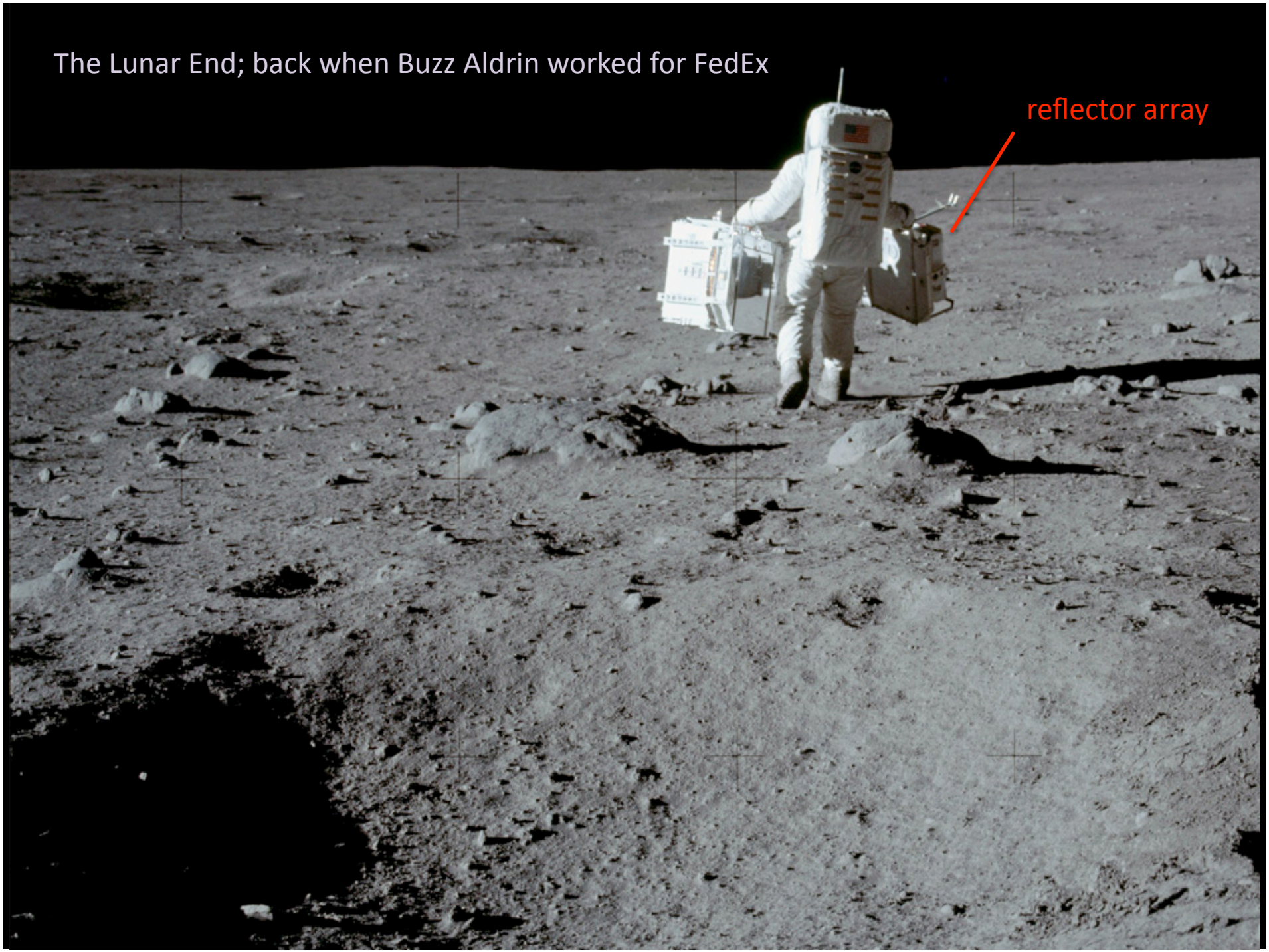

APOLLO
Lunar Laser Ranging as a
Test of Einstein's General Relativity
(do we understand gravity?)
photo: Jack Dembicky


APOLLO sends 20 pulses per second on a 2.5 second round-trip journey
300,000,000,000,000,000 photons are launched in each pulse…
…only one will return…
…if we're lucky

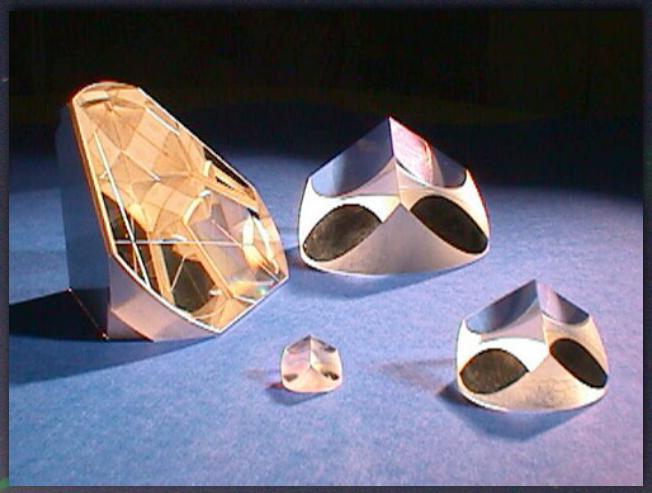
Big Bang Theory: Making it Look Easy

flexibly scheduled, high-performance, 3.5 meter telescope

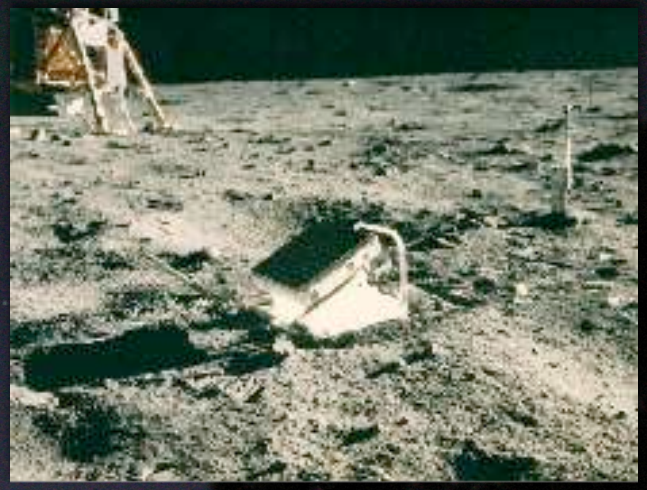
Laser Mounted on Telescope


The Lunar End; back when Buzz Aldrin worked for FedEx
reflector array

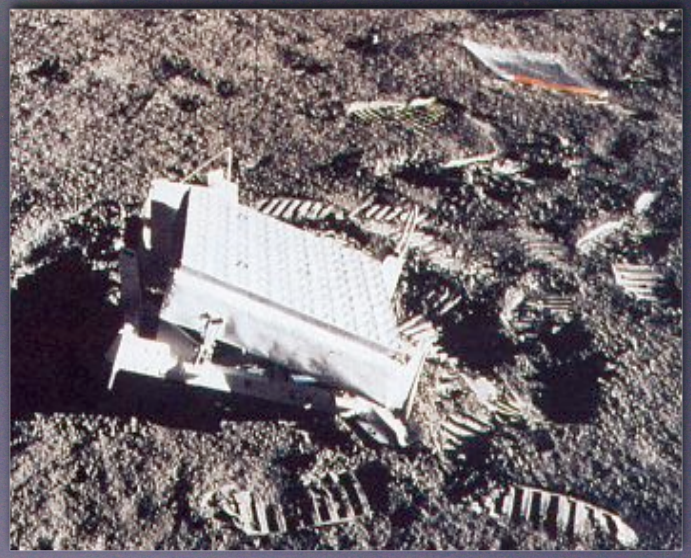
Lunar Reflectors



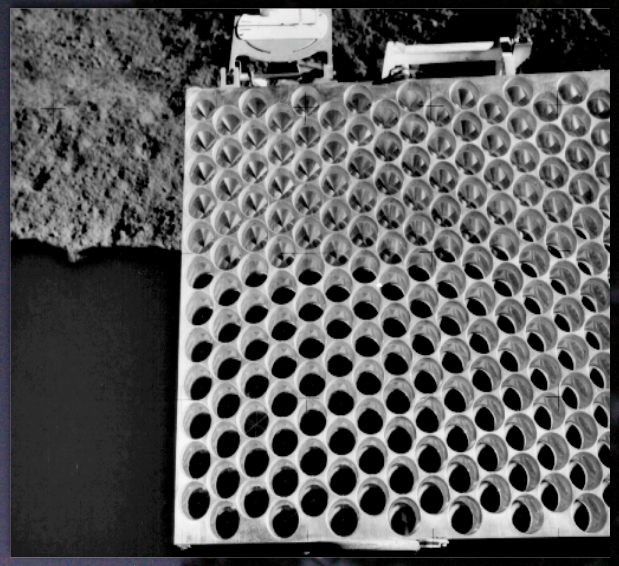
Corner cubes



Apollo 11 retroreflector array



Apollo 14 retroreflector array

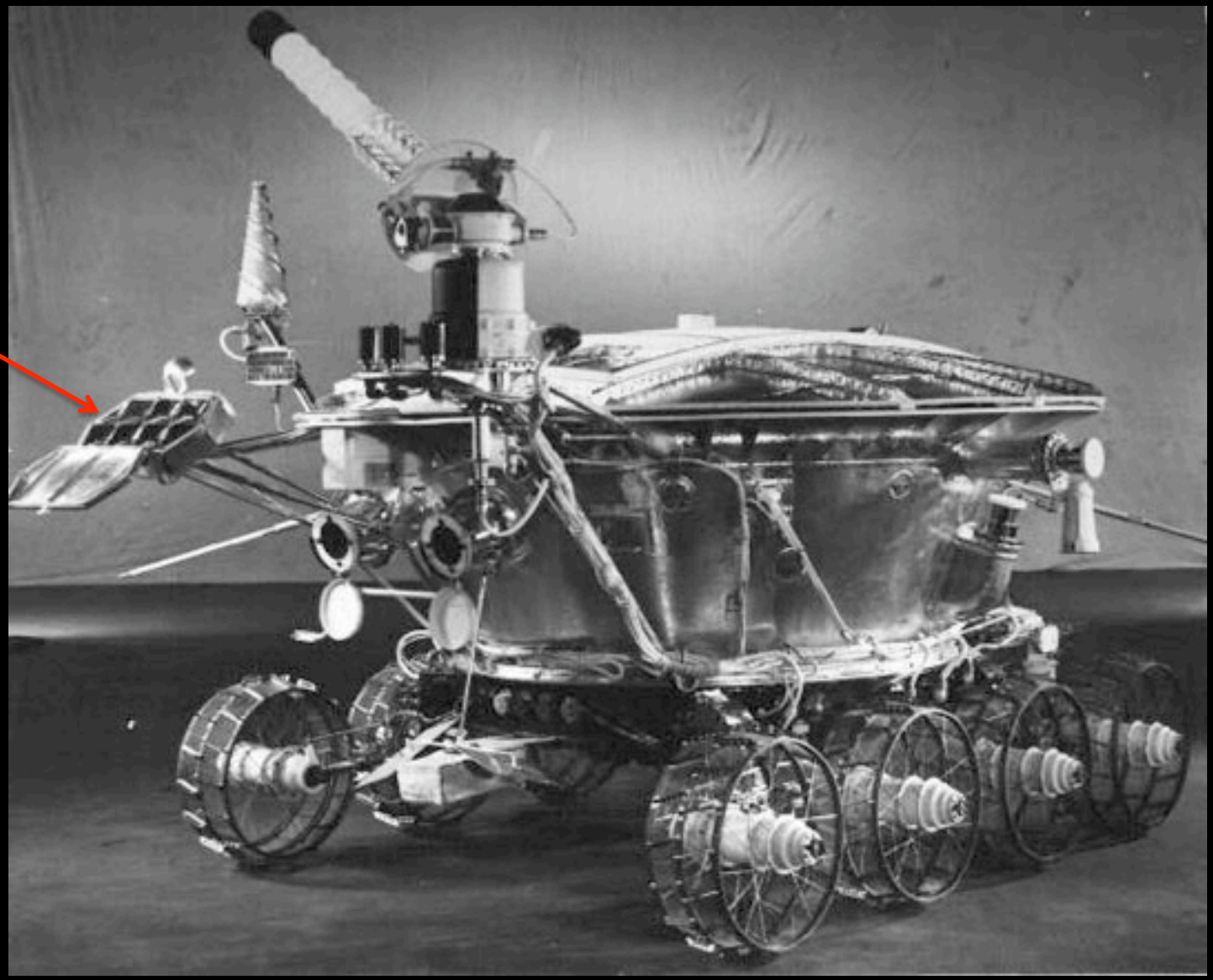


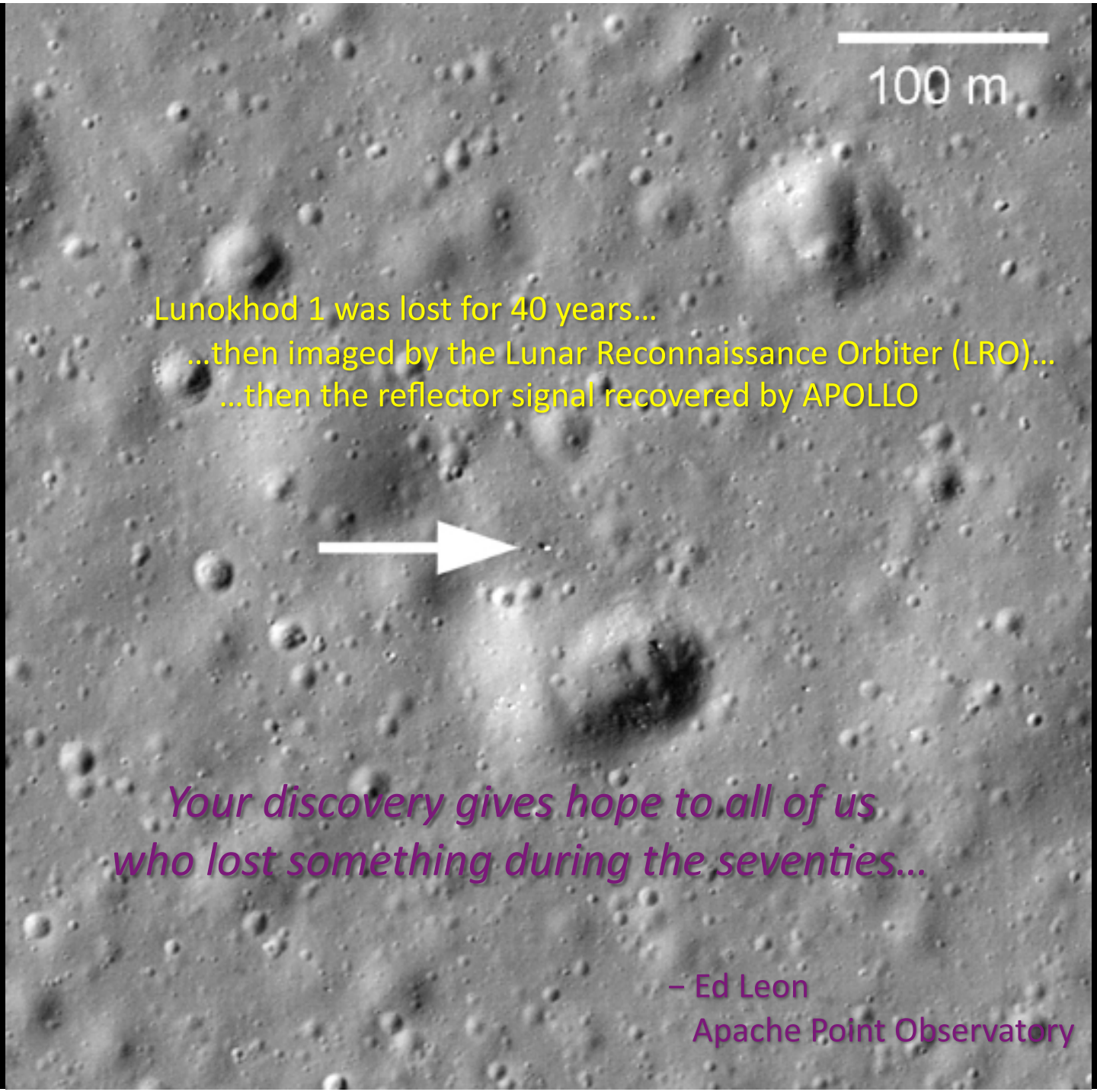
Apollo 15 retroreflector array

Reflector Positions

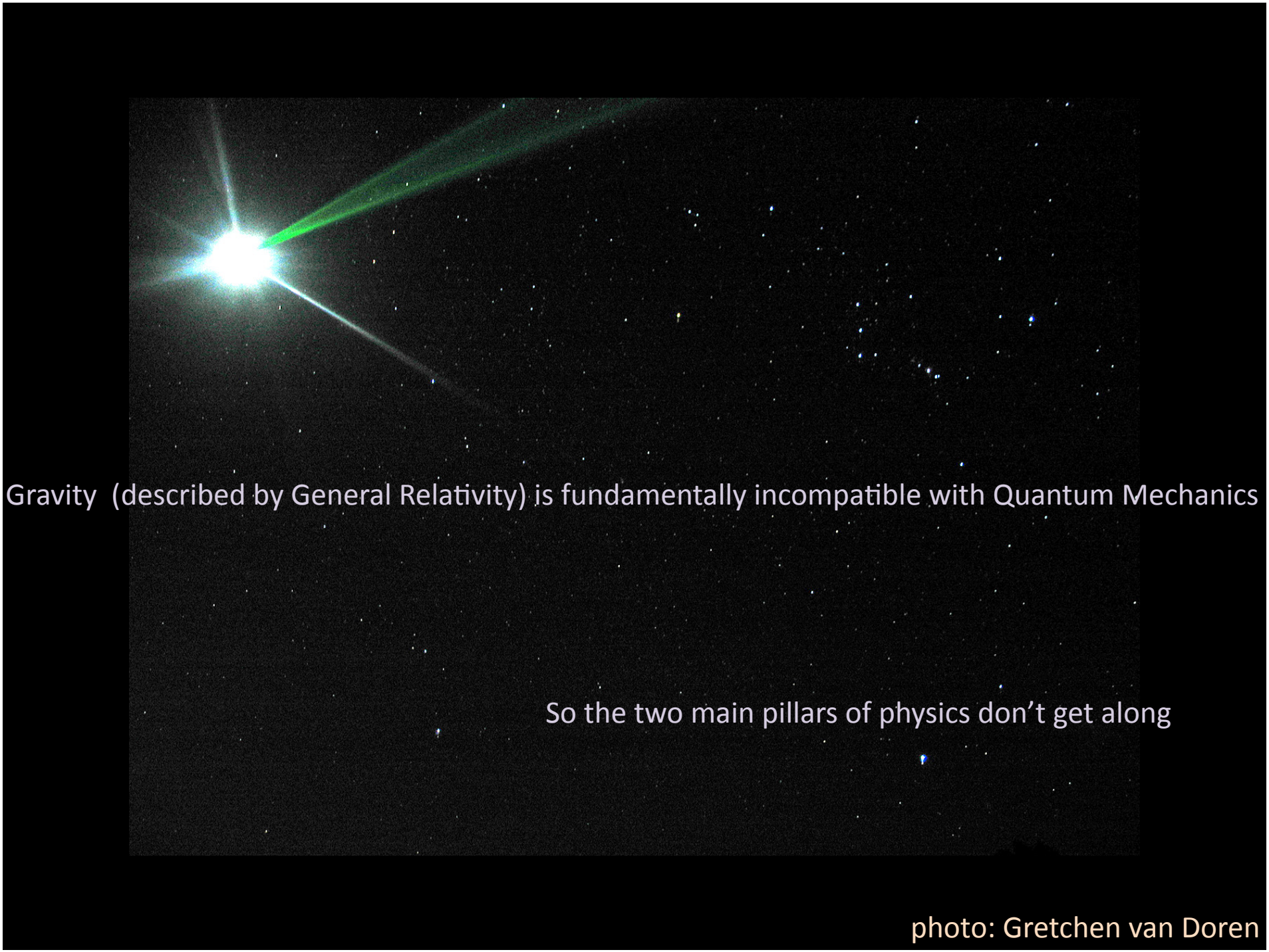
- The Apollo missions left:
  - Apollo 11: 100 corner cubes
  - Apollo 14: 100 corner cubes
  - Apollo 15: 300 corner cubes
- The Soviets landed:
  - Luna 17; Lunokhod 1 rover
  - Luna 21; Lunokhod 2 rover
  - each with 14-cube array, comparable in response to Apollo arrays

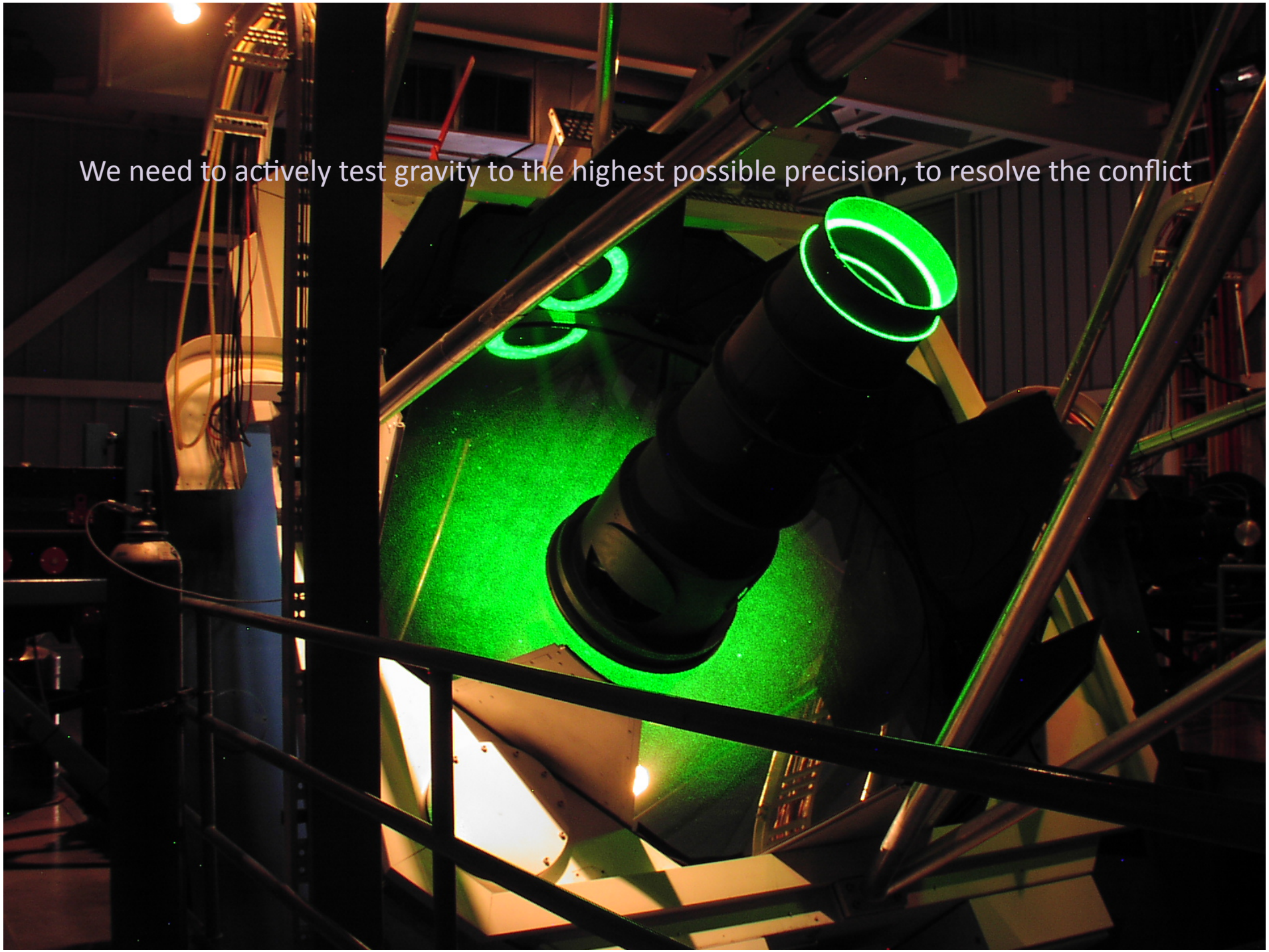
Lunokhod Rover



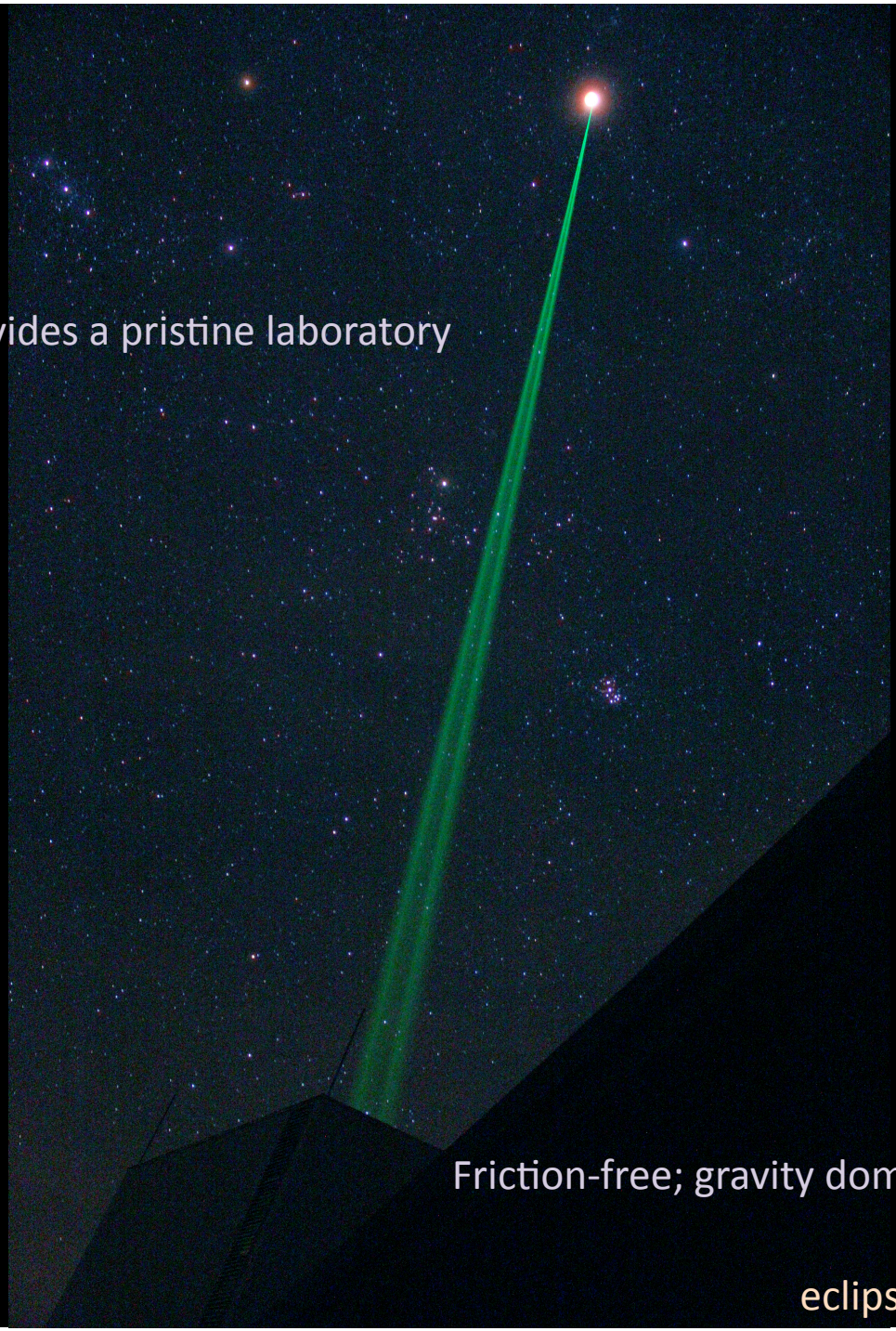

100 m
Lunokhod 1 was lost for 40 years…
…then imaged by the Lunar Reconnaissance Orbiter (LRO)…
…then the reflector signal recovered by APOLLO
Your discovery gives hope to all of us who lost something during the seventies…
– Ed Leon
Apache Point Observatory


Why do we do this? Besides the fact that it's cool?
meter Telescope
photo: Dan Long


Gravity (described by General Relativity) is fundamentally incompatible with Quantum Mechanics
So the two main pillars of physics don’t get along
photo: Gretchen van Doren


We need to actively test gravity to the highest possible precision, to resolve the conflict

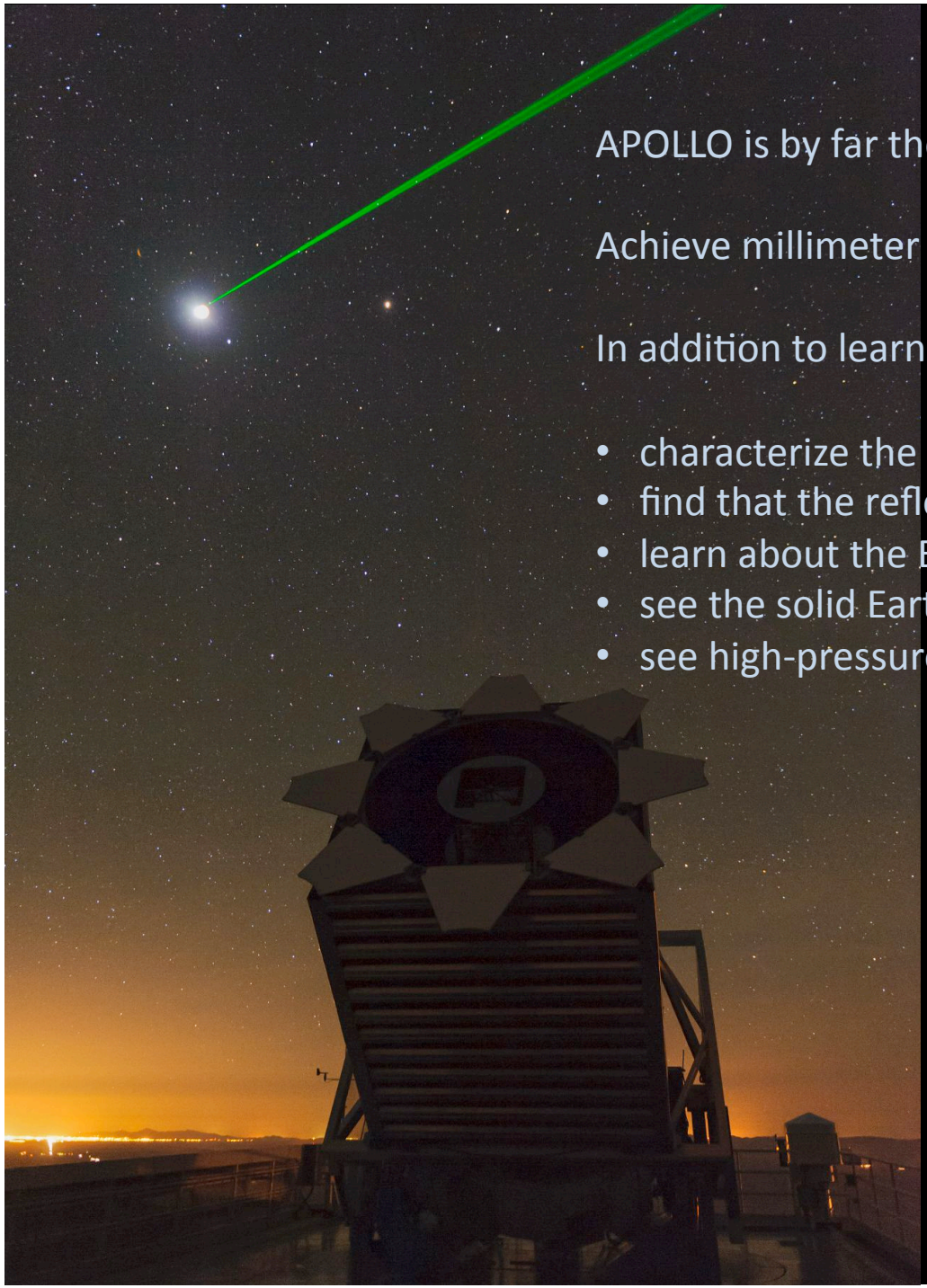
The solar system provides a pristine laboratory



Friction-free; gravity dominates; big test masses

eclipse photo: Jack Dembicky


Einstein's gravity (general relativity) imposes ~10 meter departures of the Moon's orbit compared to Newton's gravity
Testing to millimeter precision answers: was Einstein right?
eclipse photo: Dan Long



APOLLO is by far the premier lunar ranging facility in the world

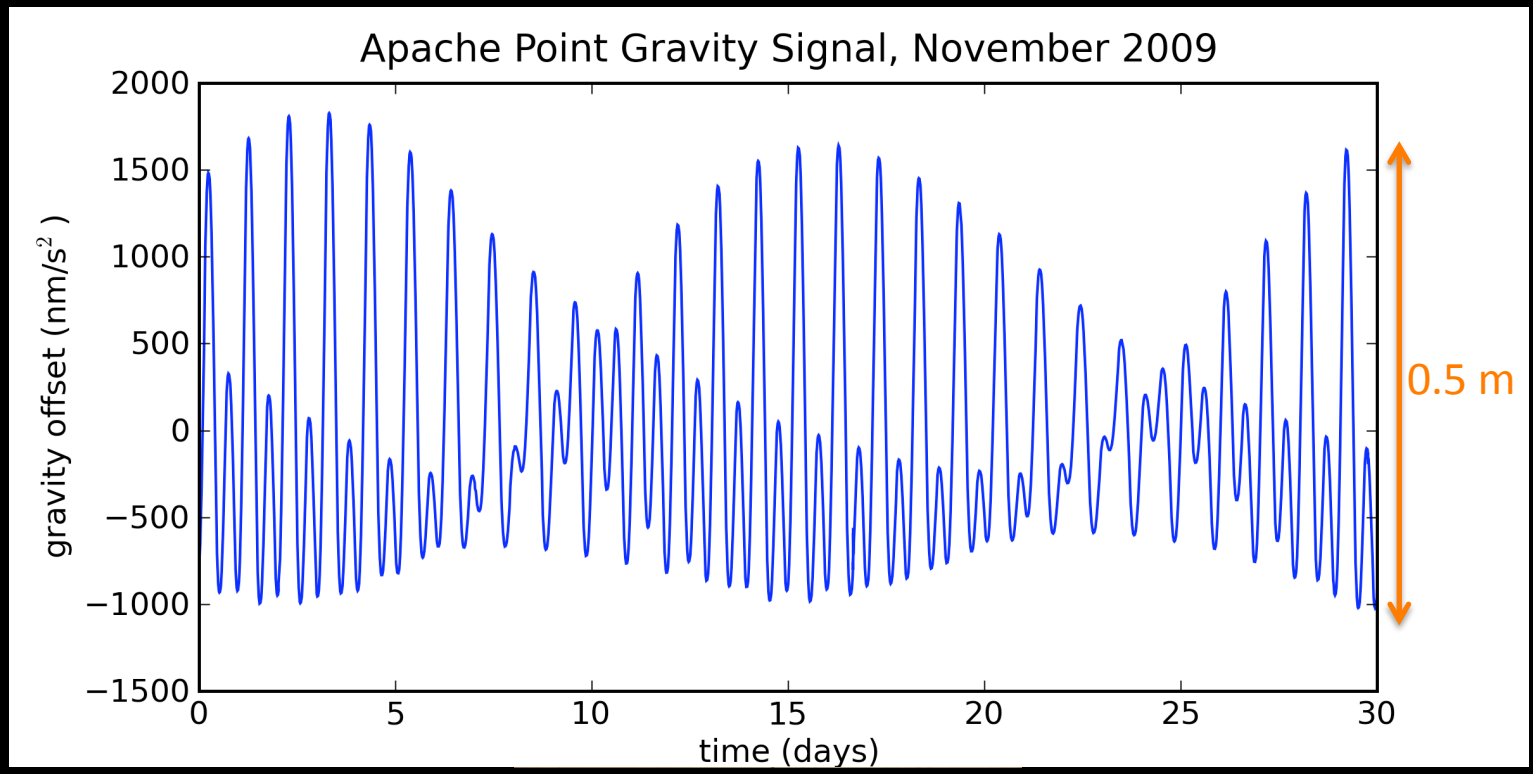
Achieve millimeter range precision, challenge to model

In addition to learning about gravity, we:

- characterize the Moon's liquid core
- find that the reflectors are half-covered by dust
- learn about the Earth's floppy crust (at mm level)
- see the solid Earth rising and falling two feet due to tides
- see high-pressure weather systems pushing down on NM

photo: Dan Long

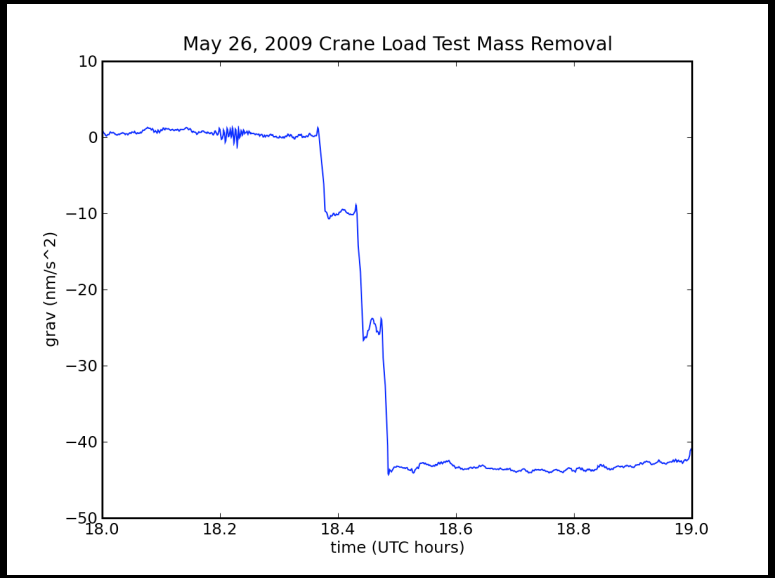
Superconducting Gravimeter Sees All



  - gravimeter has sub-millimeter height sensitivity
- Helps us characterize tides, measure loading of crust
  - *fight gravity with gravity!*

Fun with Gravimetry

- One day saw three steps in gravity record
  - unequal, within 10 minutes
- Turns out to have been giant concrete blocks used to load-test the observatory crane being moved away
  - can tell which was moved first, second, third
- Also see telescope dome rotation as up to 5 nm/s^2 offset
- See Earth ringing for a month after Chilean earthquake Feb. 2010 and Sendai in March 2011
  - 20 minute period “breathing”



2014.04.15 Eclipse: Test Reflector Health

Astronomy Picture of the Day, 2014.04.18: Dan Long