APOLLO

Testing Gravity and Geodesy via Laser Ranging to the Moon

Tom Murphy (UCSD)

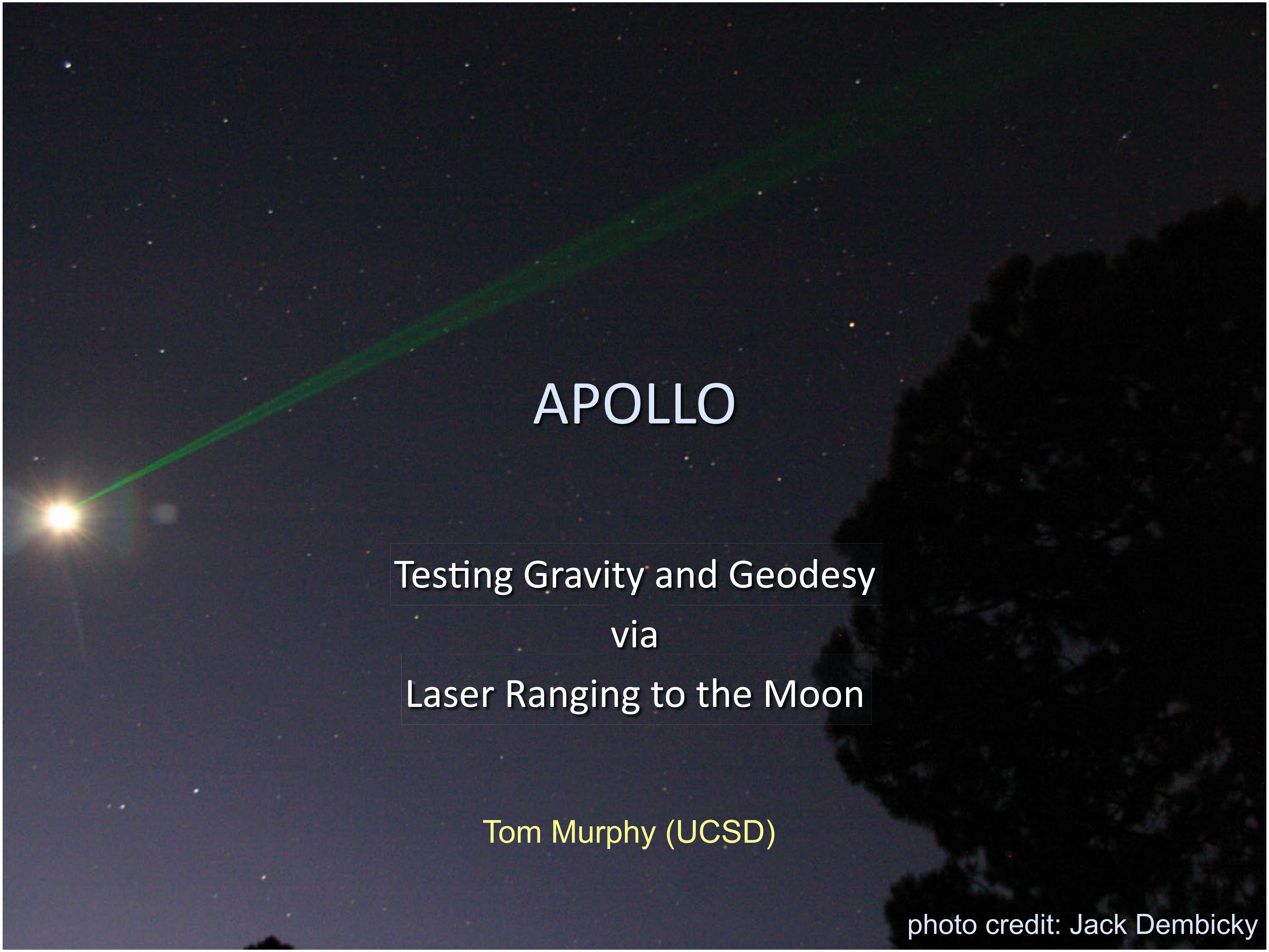


photo credit: Jack Dembicky

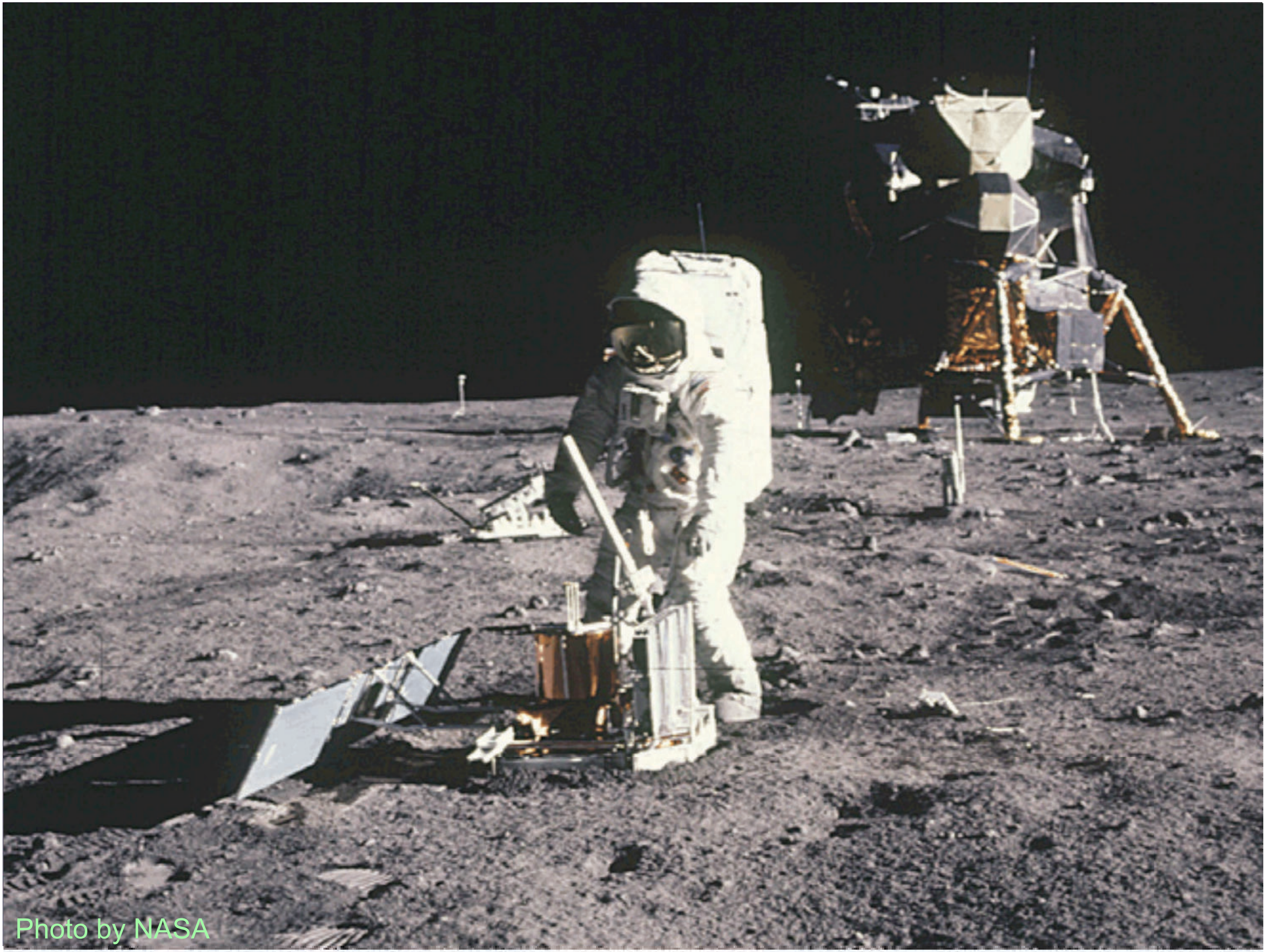
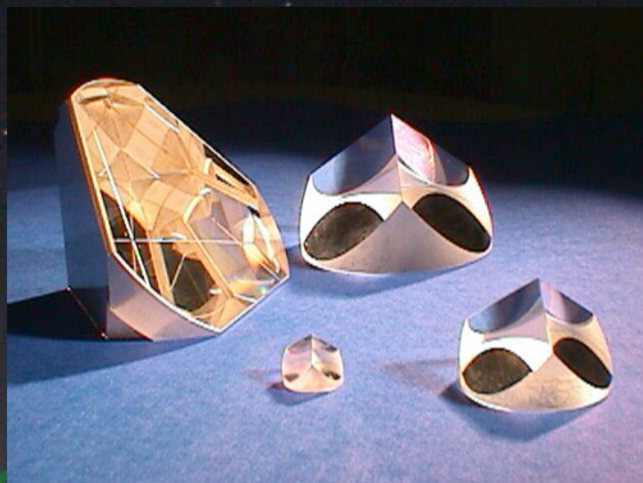
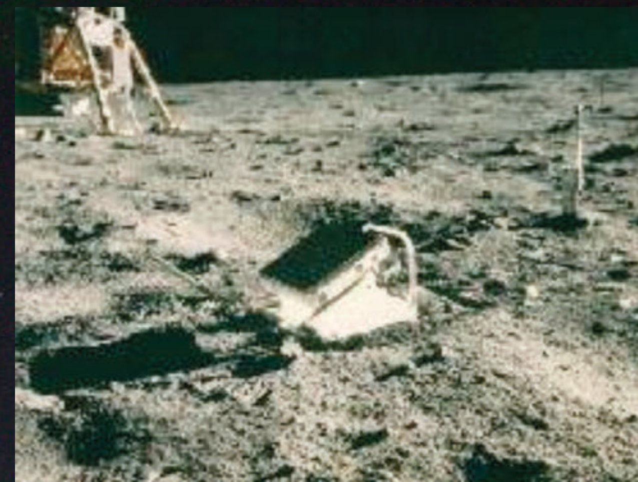


Photo by NASA

Lunar Retroreflector Arrays

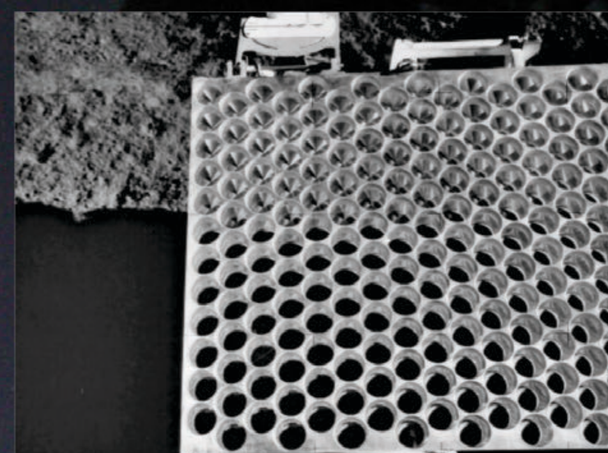


Corner cubes



Apollo 11 retroreflector array

Apollo 14 retroreflector array



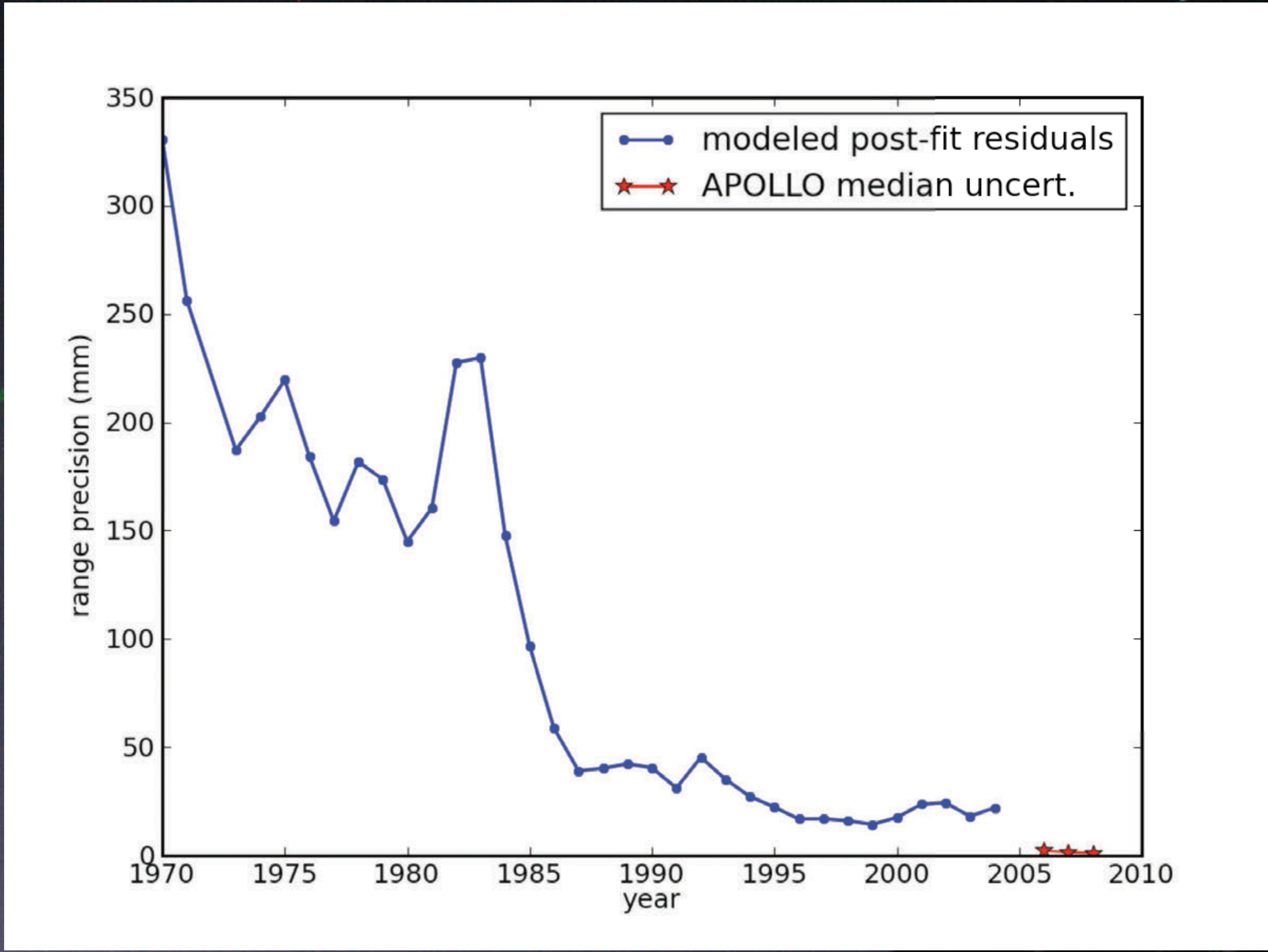
Apollo 15 retroreflector array

The Reflector Positions

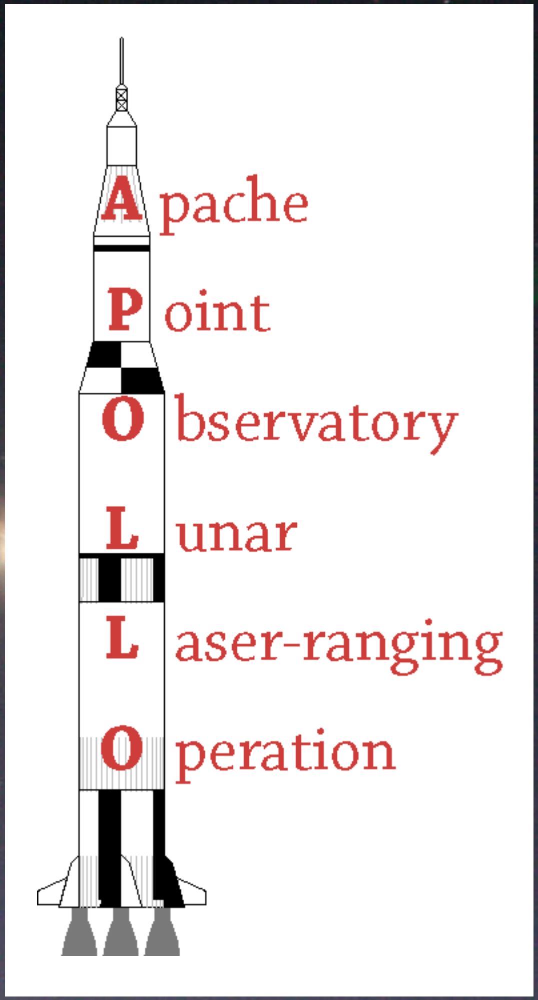
- Three Apollo missions left reflectors
  - Apollo 11: 100-element
  - Apollo 14: 100-element
  - Apollo 15: 300-element
- Two French-built, Soviet-landed reflectors were placed on rovers
  - Luna 17: Lunokhod 1 rover
  - Luna 21: Lunokhod 2 rover
  - similar in size to A11, A14
- Signal loss is huge:
  - $\approx 10^{-8}$ of photons launched find reflector (atmospheric seeing)
  - $\approx 10^{-8}$ of returned photons find telescope (corner cube diffraction)
  - $>10^{17}$ loss considering other optical/detection losses

LLR through the decades

Previously
200 meters



APOLLO: one giant leap for LLR



- APOLLO offers order-of-magnitude improvements to LLR by:
  - Using a 3.5 meter telescope
  - Operating at 20 pulses/sec
  - Using advanced detector technology
  - Gathering multiple photons/shot
    - Achieving millimeter range precision
  - Tightly integrating experiment and analysis
  - Having the best acronym
    - funded by NASA & NSF

The APOLLO Collaboration

UCSD:
Tom Murphy (PI)
Eric Michelsen
Nathan Johnson

Harvard:
Chris Stubbs
John Chandler

U Washington:
Eric Adelberger
Erik Swanson

Bryn Mawr:
James Battat

Humboldt State:
C. D. Hoyle

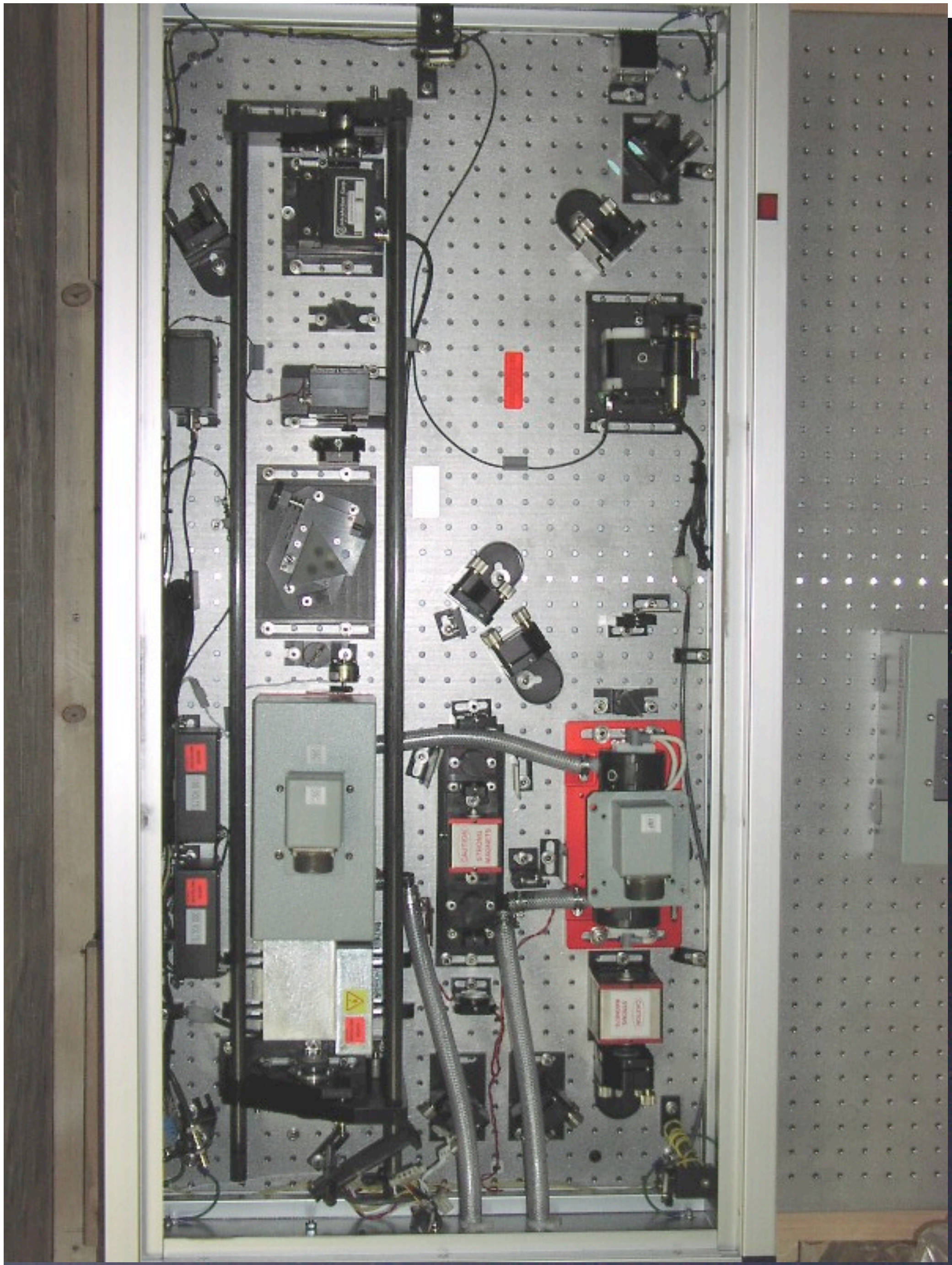
Apache Point Obs.
Russet McMillan

Northwest Analysis:
Ken Nordtvedt

The Earth-End

APOLLO’s Secret Weapon: Aperture

- The Apache Point Observatory’s 3.5 meter telescope
  - Southern NM (Sunspot)
  - 9,200 ft (2800 m) elevation
  - Great “seeing”: 1 arcsec
  - Flexibly scheduled, high-class research telescope
    - APOLLO gets 8–10 < 1 hour sessions per lunar month
  - 7-university consortium (UW NMSU, U Chicago, Princeton, Johns Hopkins, Colorado, Virginia)

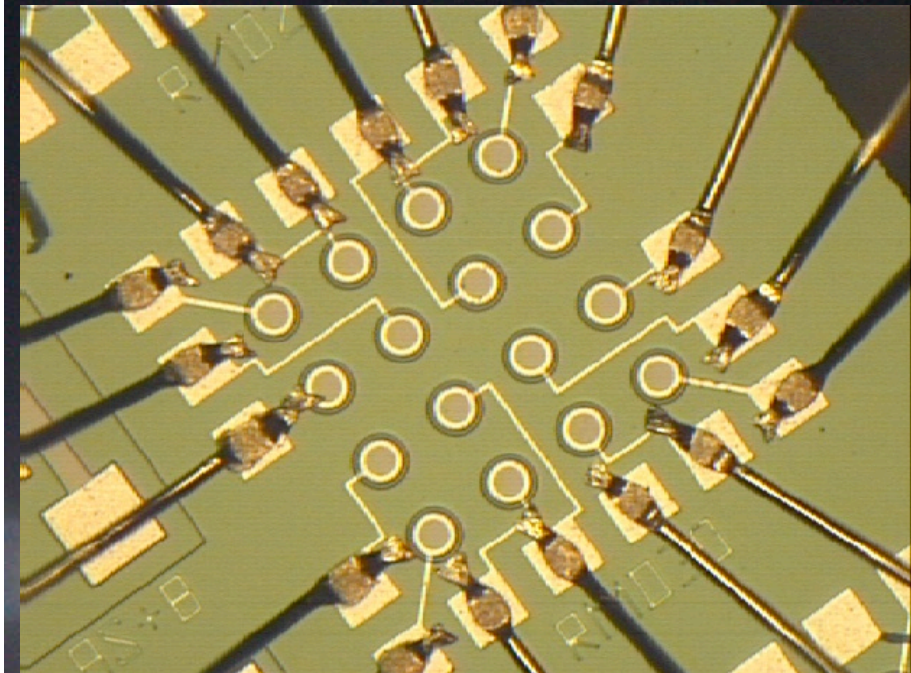


APOLLO Laser

- Nd:YAG; flashlamp-pumped; mode-locked; cavity-dumped
- Frequency-doubled to 532 nm
  - 57% conversion efficiency
- 90 ps pulse width (FWHM)
- 115 mJ (green) per pulse
  - after double-pass amplifier
- 20 Hz pulse repetition rate
- 2.3 Watt average power
- GW peak power!!

- Beam is expanded to 3.5 meter aperture
  - Less of an eye hazard
  - Less damaging to optics

Catching All the Photons

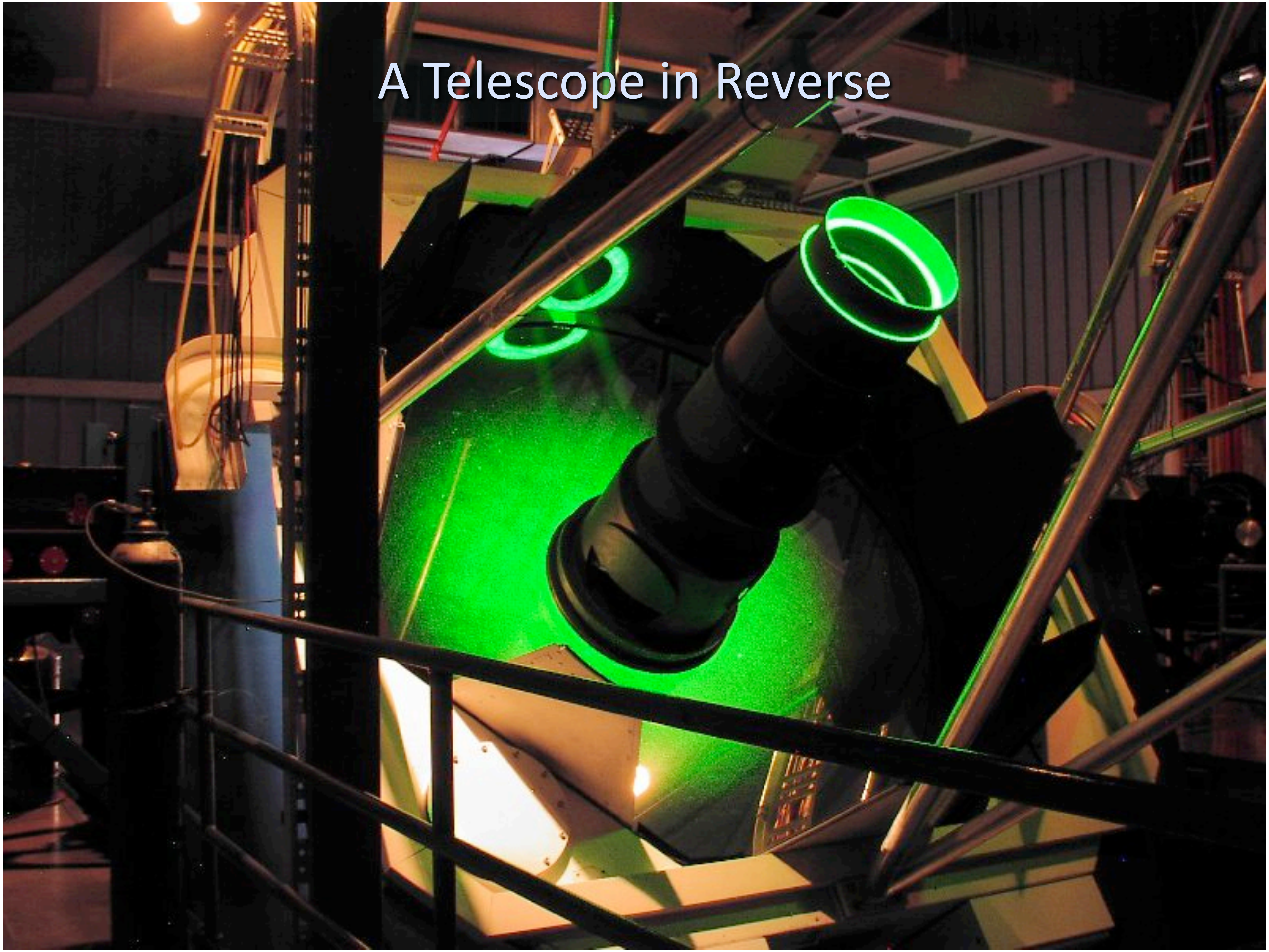


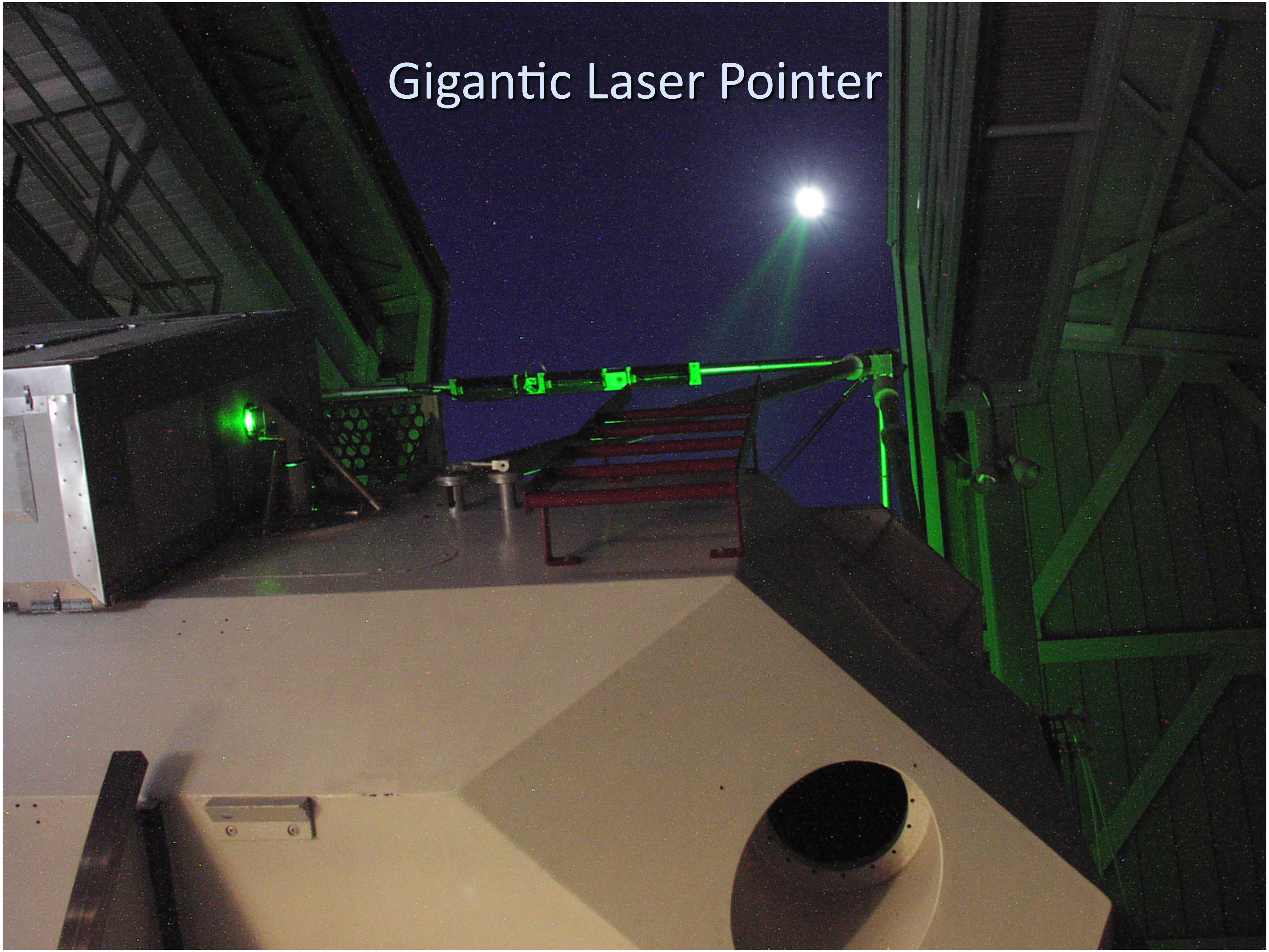
- Several photons per pulse necessitates multiple "buckets" to time-tag each one
  - Avalanche Photodiodes (APDs) respond only to *first* photon
- Lincoln Lab prototype APD arrays are perfect for APOLLO
  - 4×4 array of 30 μm elements on 100 μm centers
- Lenslet array in front recovers full fill factor
  - Resultant field is 1.4 arcsec on a side
  - Focused image is formed at lenslet
  - 2-D tracking capability facilitates optimal efficiency

Timing System

- XL-DC (Truetime/Symmetricomm)
  - GPS-disciplined ovenized quartz
  - low phase noise (-155 dBc/Hz)
  - multiplied to 5× for 50 MHz ECL clock "backbone"
- 16-channel CAMAC Time-to-Digital Converter
  - 13 ps jitter
  - measures from photon START to clock-derived STOP
- Error budget dominated by finite reflector, tilted by libration
  - could certainly do better timing, but would wash out anyway

Laser Mounted on Telescope

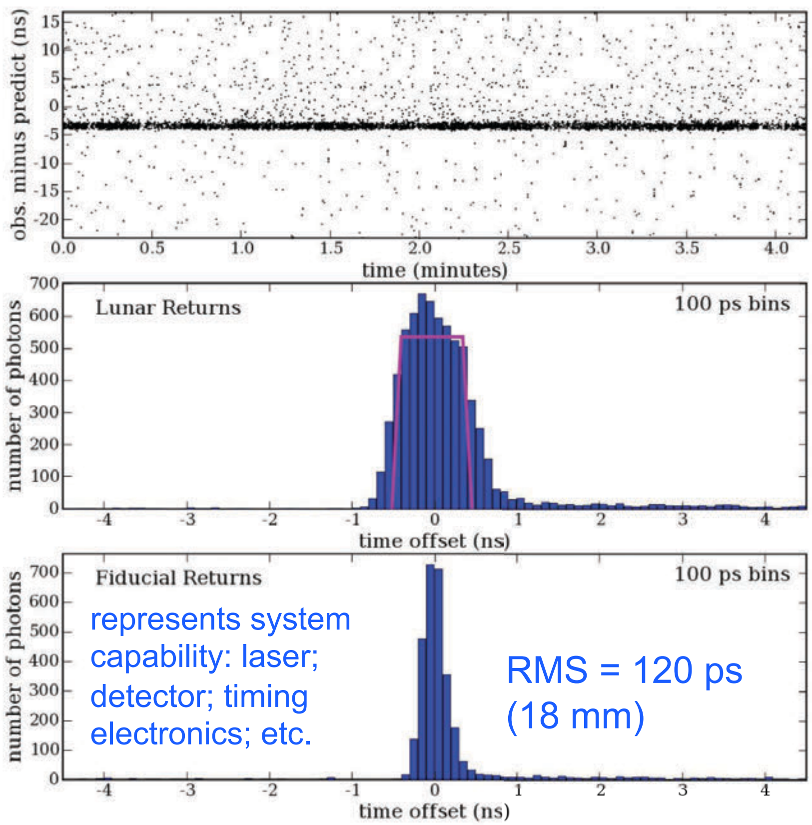

A Telescope in Reverse

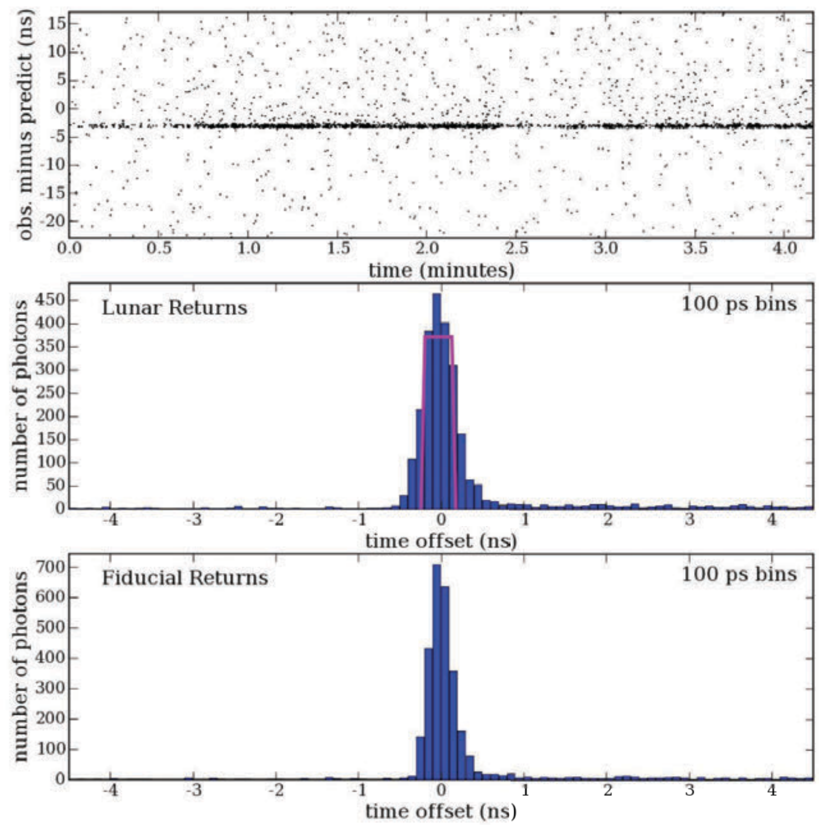

Gigantic Laser Pointer

Killer Returns

Apollo 15 2007.11.19 Apollo 11

red curves are theoretical profiles: get convolved with fiducial to make lunar return

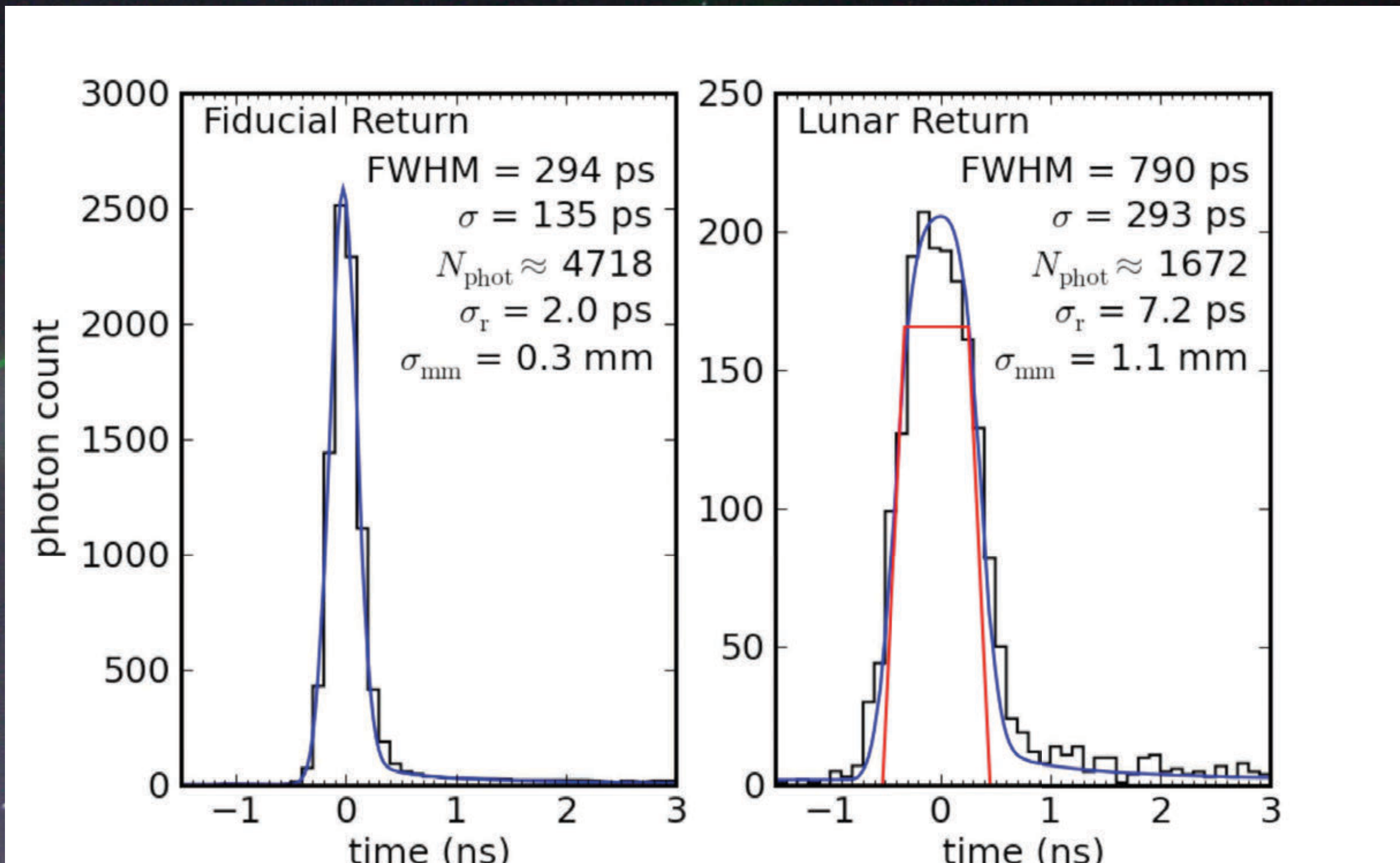




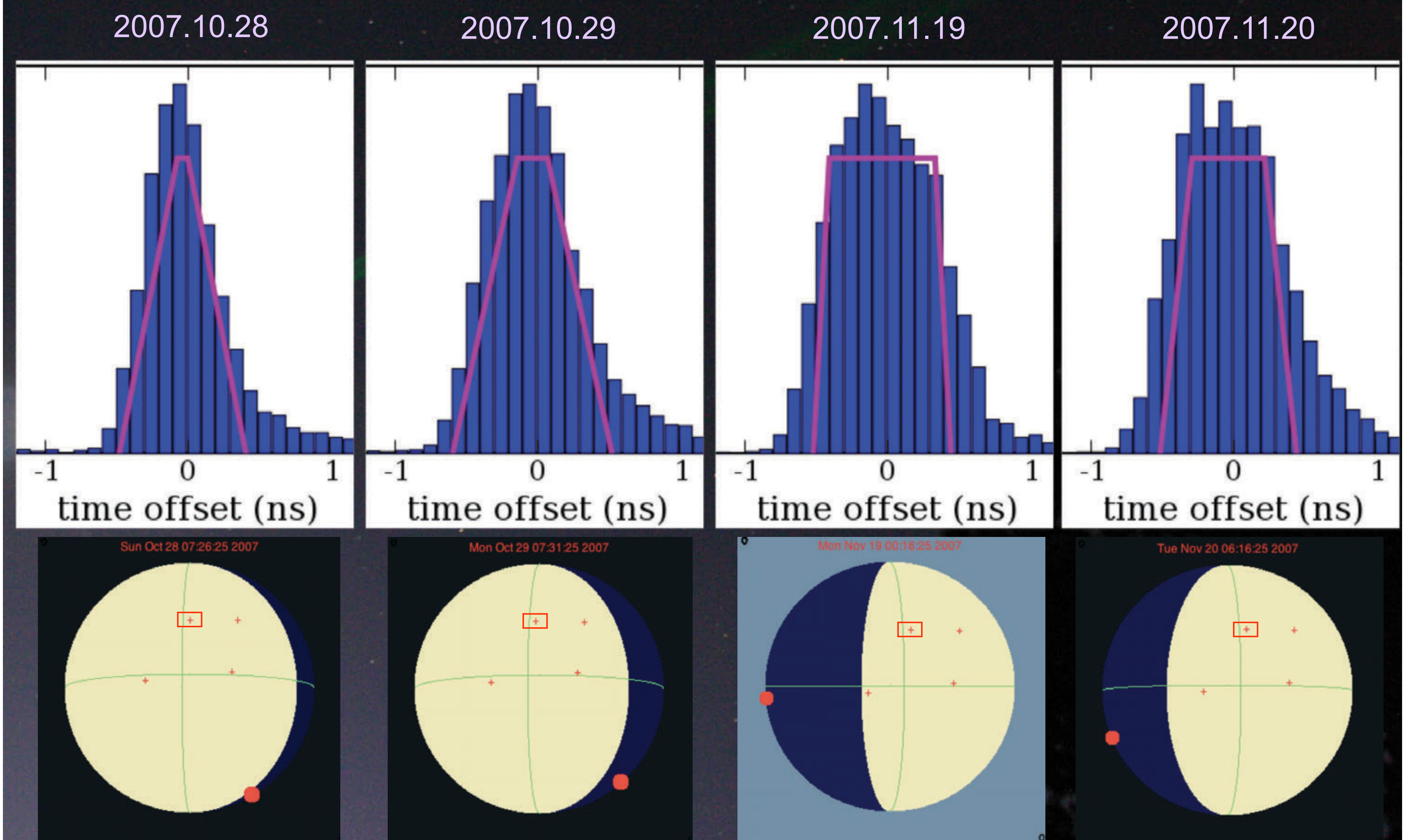
- 6624 photons in 5000 shots
- 369,840,578,287.4 ± 0.8 mm
- 4 detections with 10 photons

- 2344 photons in 5000 shots
- 369,817,674,951.1 ± 0.7 mm
- 1 detection with 8 photons

Fitting the Return & Reflector Trapezoid



Sensing the Array Size & Orientation



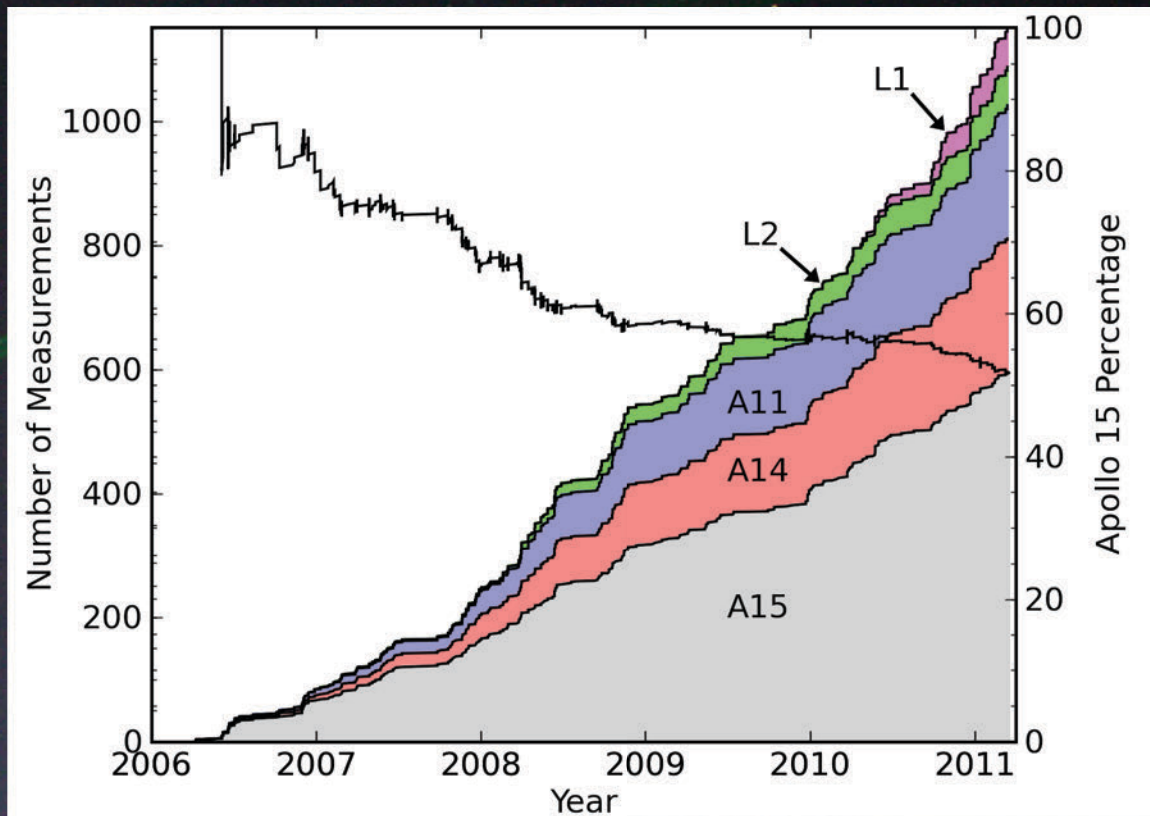
Breaking All Records

Reflector	APOLLO max photons/5-min	APOLLO max photons/shot (5 min avg)
Apollo 11	5395 (65×)	0.90
Apollo 14	9125 (69×)	1.52
Apollo 15	18875 (67×)	3.15
Lunokhod 2	900 (31×)	0.15

(relative to pre-APOLLO record)

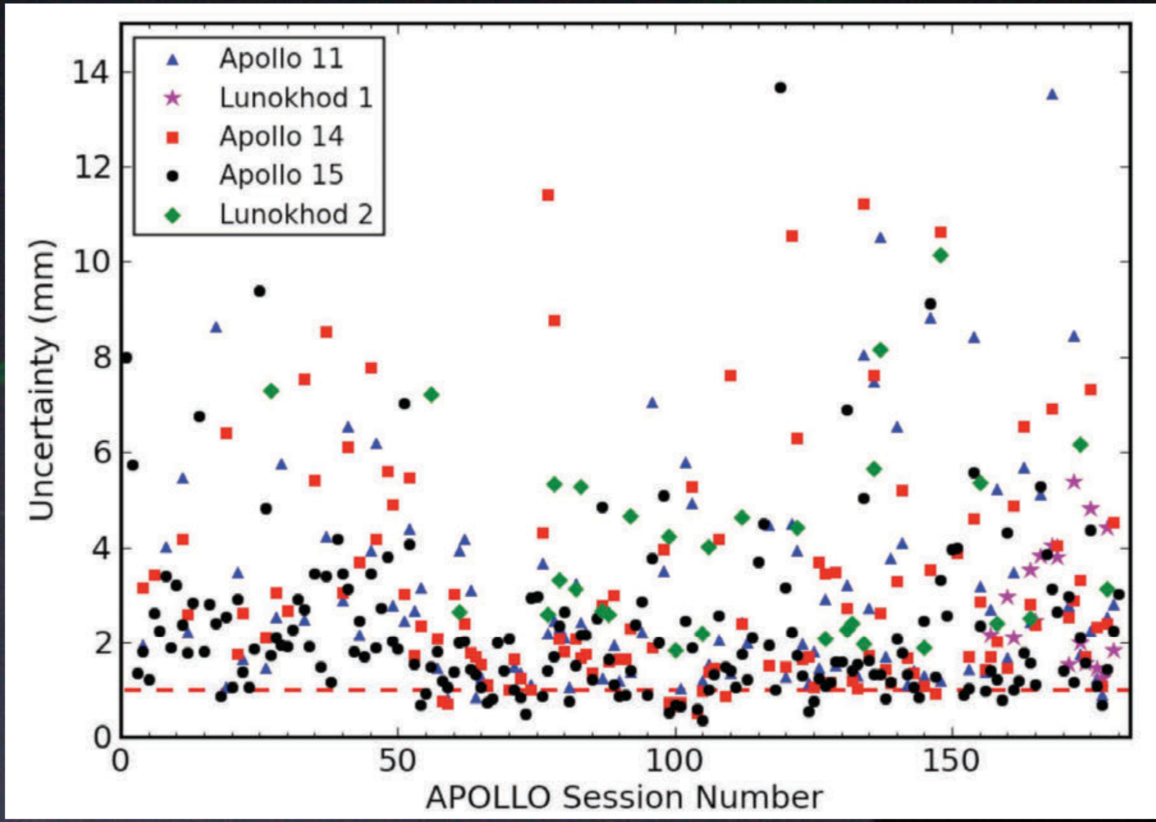
- APOLLO has greatly surpassed previous records
  - max rates for French and Texas stations about 0.1 and 0.02, respectively
- APOLLO can operate at full moon
  - other stations can't (except during eclipse), though EP signal is max at full moon!
- Often a majority of APOLLO returns are multiple-photon events
  - record is 12 photons in one shot (out of 12 functioning APD elements)
  - APD array (many buckets) is crucial

APOLLO Data Campaign



- Steady accumulation of data; less reliance on Apollo 15 over time
- Found Lunokhod 1 in 2010

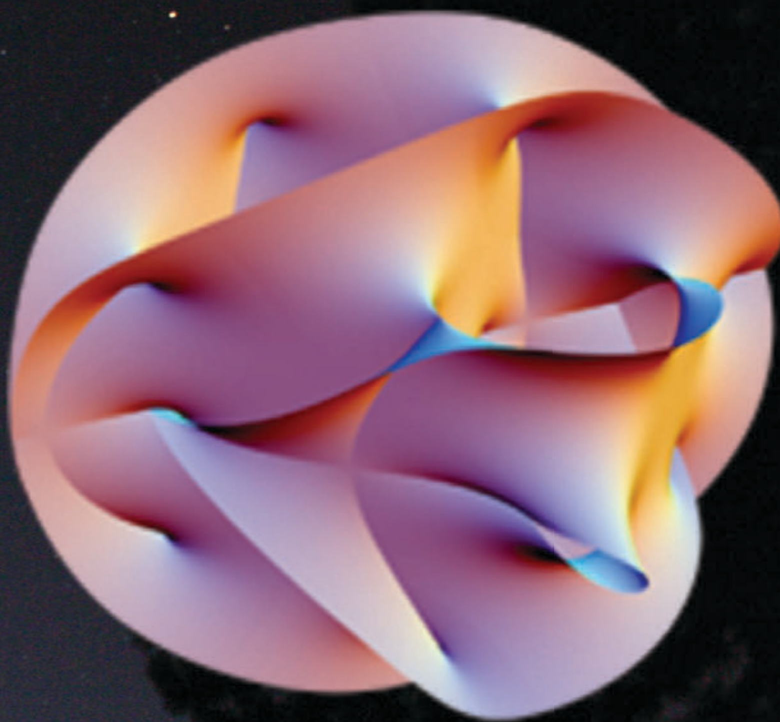
APOLLO Data Quality



- Uncertainties are per night, per reflector; pre-APOLLO sub-centimeter rare
- Medians are 2.4, 2.7, 2.4, 1.8, 3.3 mm for A11, L1, A14, A15, L2, resp.
- Combined nightly median range error is 1.4 mm

Gravity Cries for Help

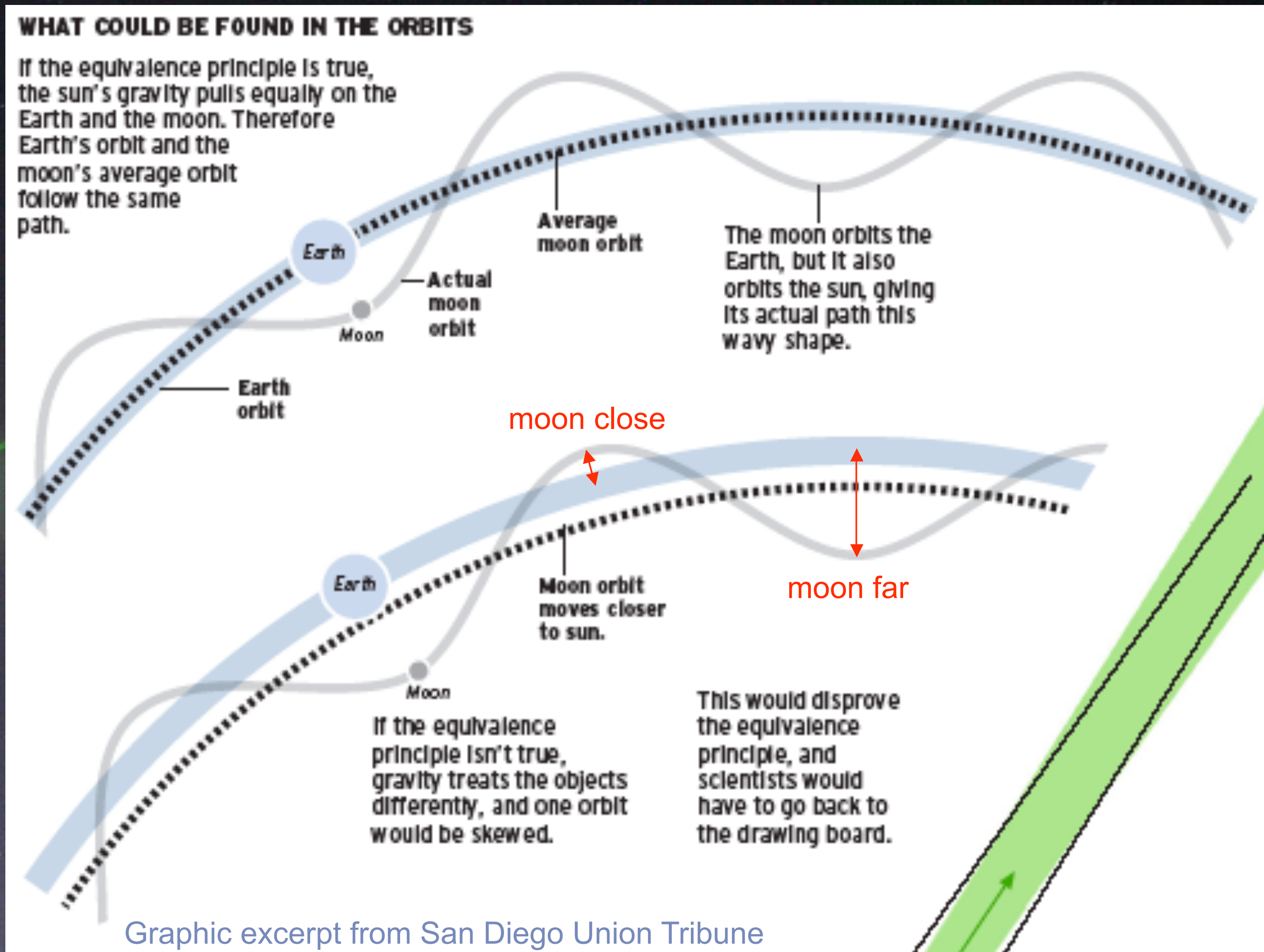
- General Relativity (GR) and Quantum Mechanics are fundamentally incompatible
  - gravity relatively poorly tested
- New physics of the dark sector could be misunderstanding of large-scale gravity
  - GR used as metric backdrop for cosmic expansion
- Scalar fields introduced by string-inspired and other modifications to GR produce potentially measurable effects
  - violation of the equivalence principle
  - time variation of fund. “constants”



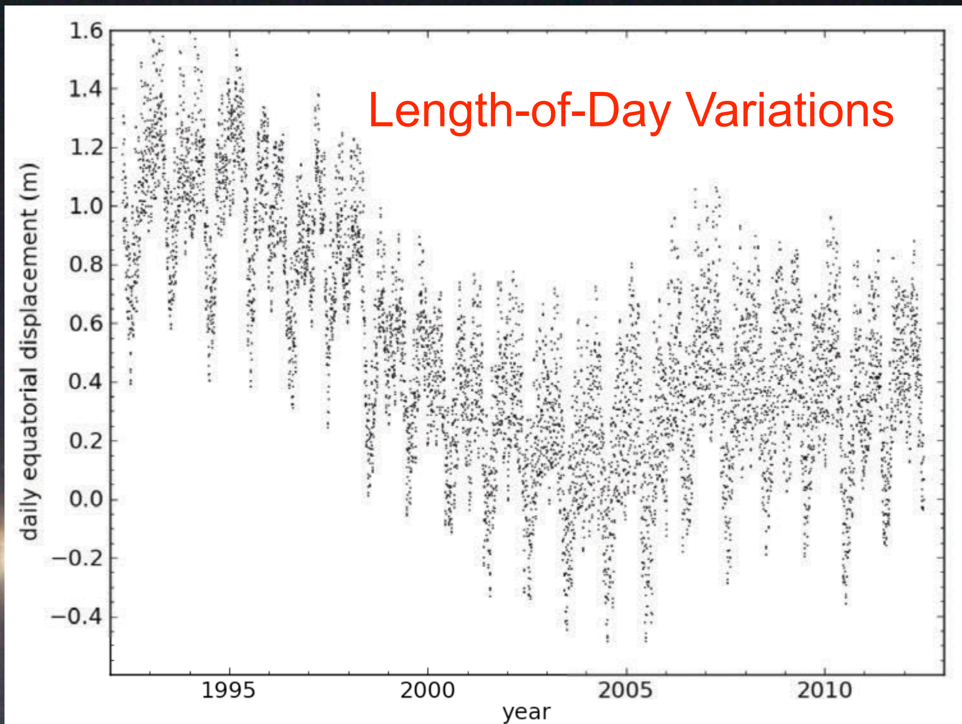
Equivalence Principle Flavors

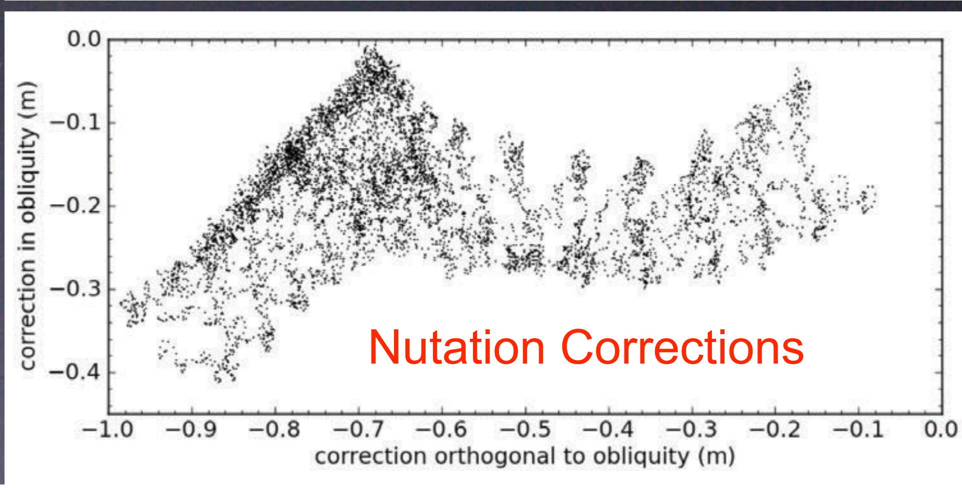
- Weak EP
  - Composition difference: e.g., iron in earth vs. silicates in moon
  - Probes all interactions but gravity itself
    - Currently tested by LLR to $\Delta a/a < 10^{-13}$
    - Comparable to best lab tests by Eöt-Wash group at UW
      - but better choices of mass pairs offer stronger WEP test than LLR
- Strong EP
  - Applies to gravitational "energy" itself
    - Earth self-energy has equivalent mass ($E = mc^2$)
      - Amounts to 4.6×10^{-10} of earth's total mass-energy
    - Does this mass have $M_G/M_I = 1.00000$?
  - Another way to look at it: gravity pulls on gravity
    - This gets at *nonlinear* aspect of gravity (PPN β)
  - LLR provides the best way to test the SEP
    - pulsar timing is closest competitor

EP Signal, Illustrated

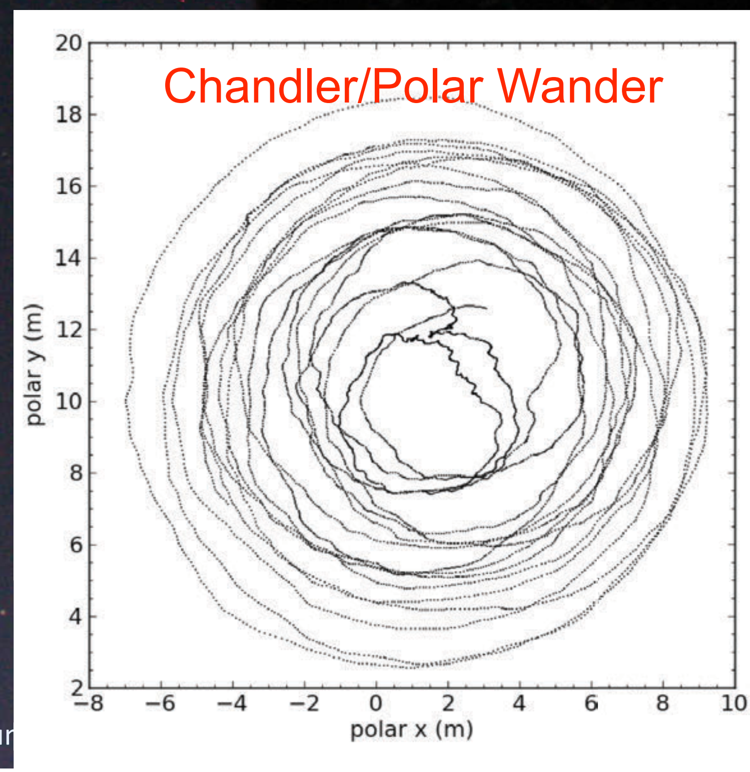


Earth Orientation





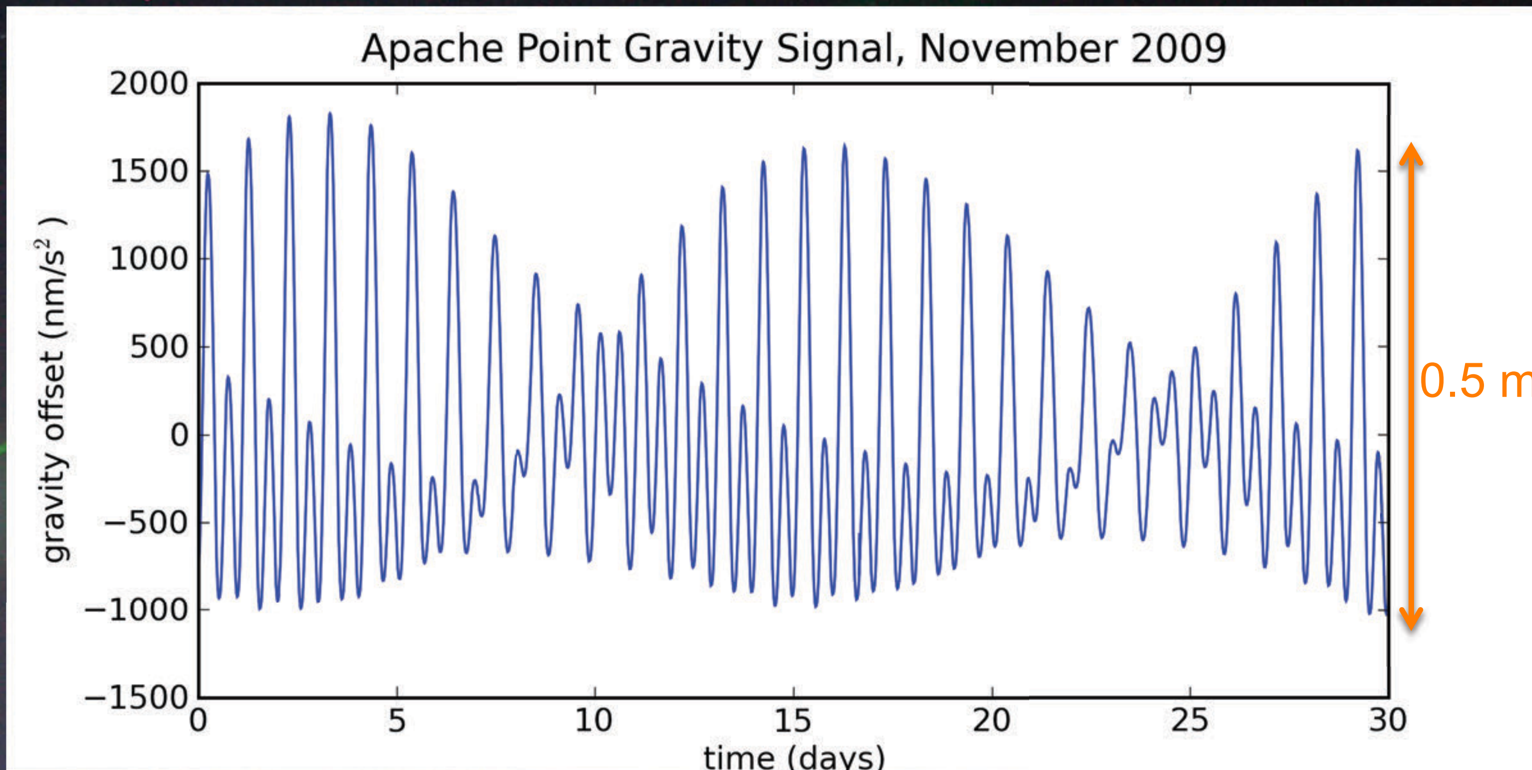
- Millimeter LLR easily picks up Earth orientation vagaries
- But sampling unimpressive



Better Sampling: Transponder on Moon

- A laser transponder on the Moon solves many problems
  - devastating $1/r^4$ link becomes vastly more forgiving $1/r^2$
  - opens up LLR to global network of SLR stations
  - results in vastly improved data volume and sampling
  - global distribution averages out local variation
- Also good stepping stone to interplanetary ranging; optical communications

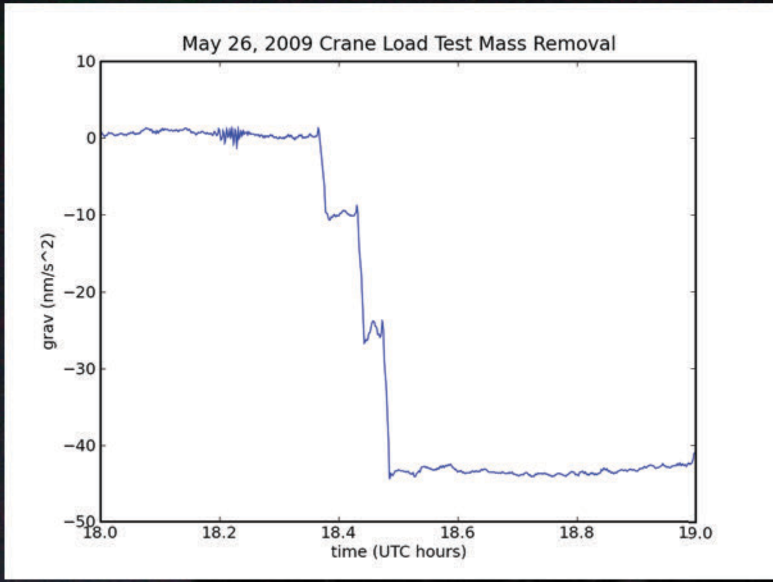
Superconducting Gravimeter Installed



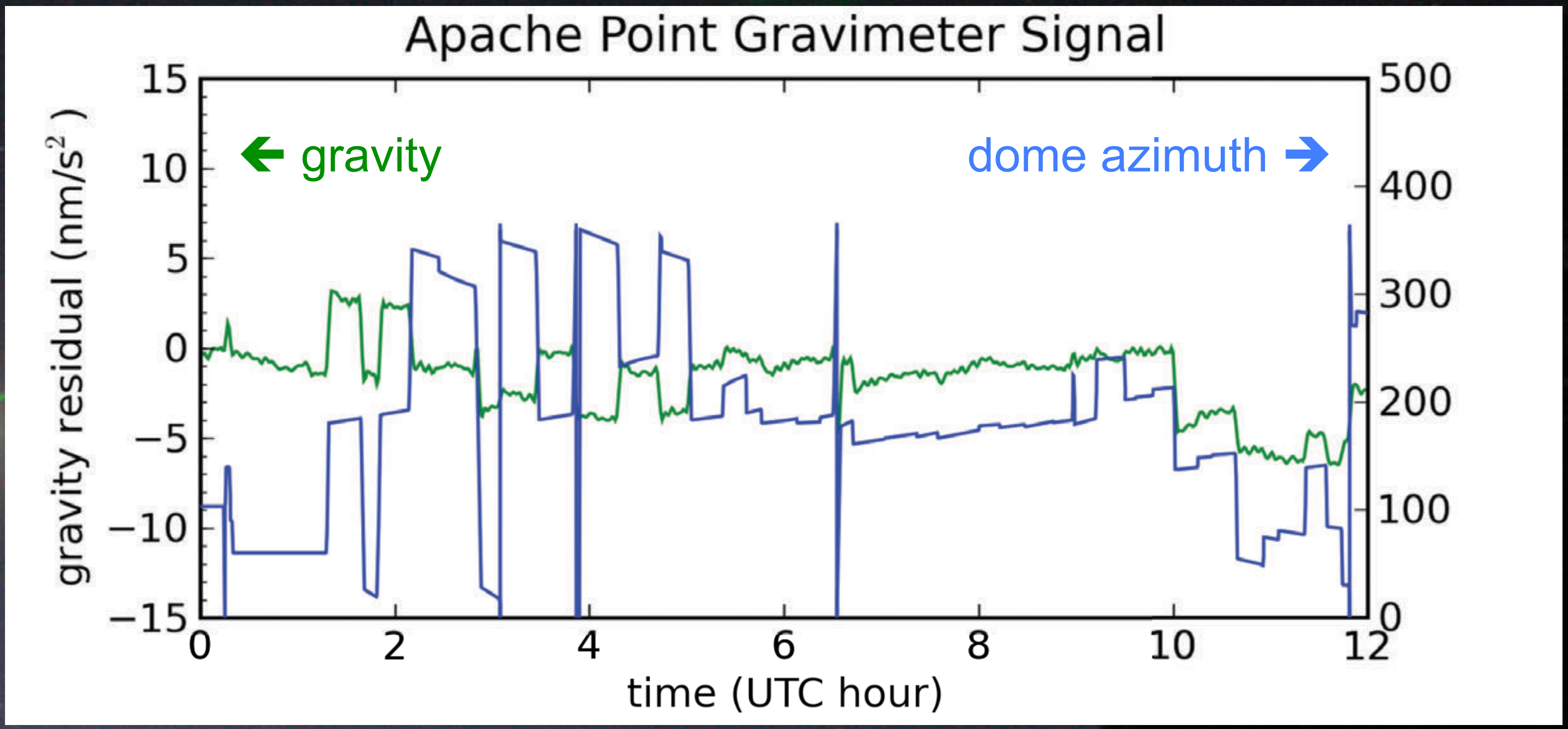
- We care about millimeter displacements of floppy Earth crust
  - gravimeter has sub-millimeter height sensitivity
- Will help us characterize tides, measure loading of crust
  - *fight gravity with gravity!*

Fun with gravimetry

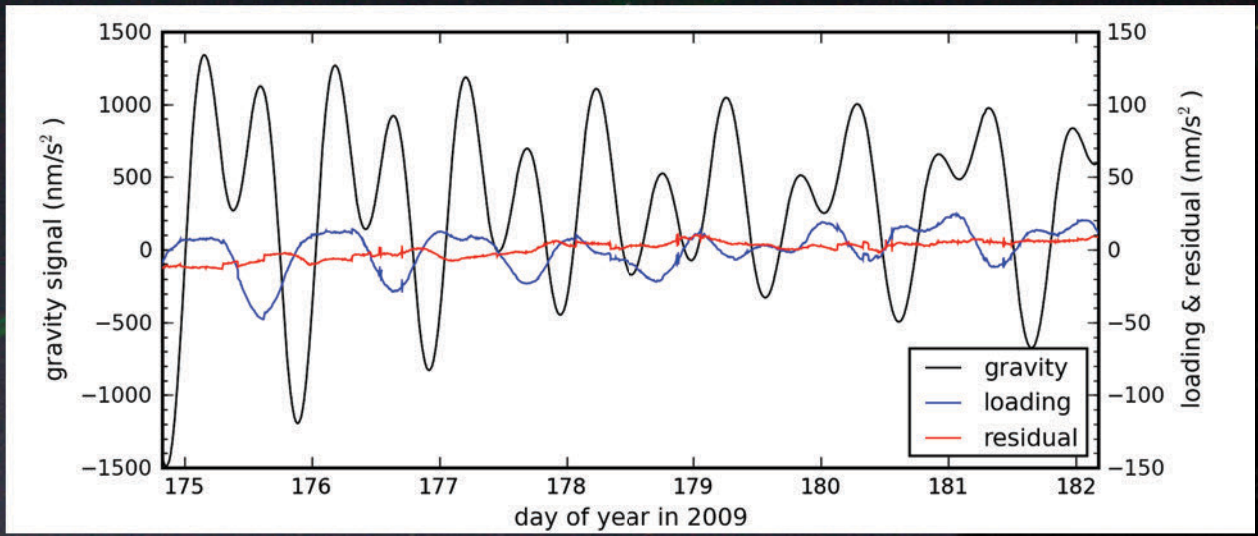
- One day saw three steps in gravity record
  - unequal, within 10 minutes
- Turns out to have been giant concrete blocks used to load-test the observatory crane being moved away
  - can tell which was moved first, second, third
- Also see telescope dome rotation as up to 5 nm/s^2 offset
- See Earth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



Gravity Signal from Dome

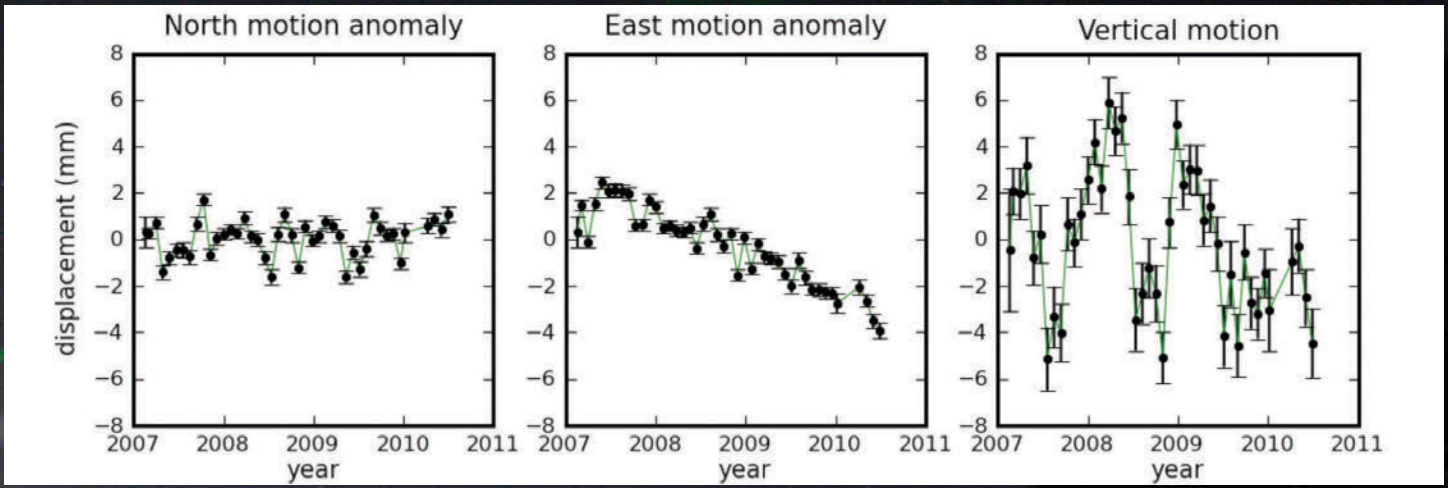


Superconducting Gravimeter Benefits



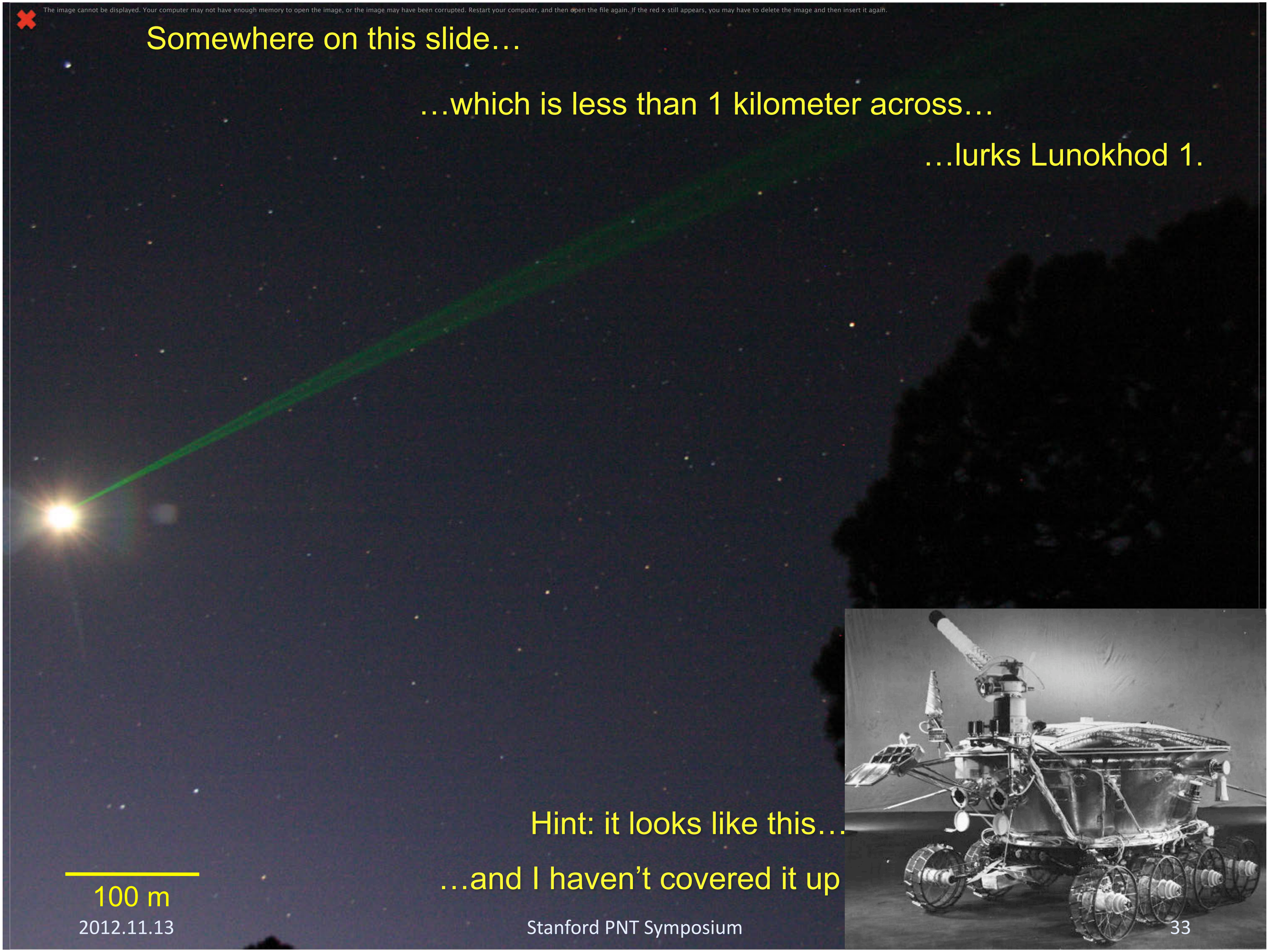
- SG is a great way to measure tides at site
- Gravity is a proxy to site displacement
- Probes ocean loading, ground water loading, atmospheric loading

EarthScope GPS Pitching In



- The NSF-funded Plate Boundary Observatory (part of EarthScope) installed a GPS station 2.5 km away from APOLLO
- Resolution in monthly interval is 0.3 mm horizontal, 1.2 mm vertical
- Will help constrain crust motion, loading phenomena

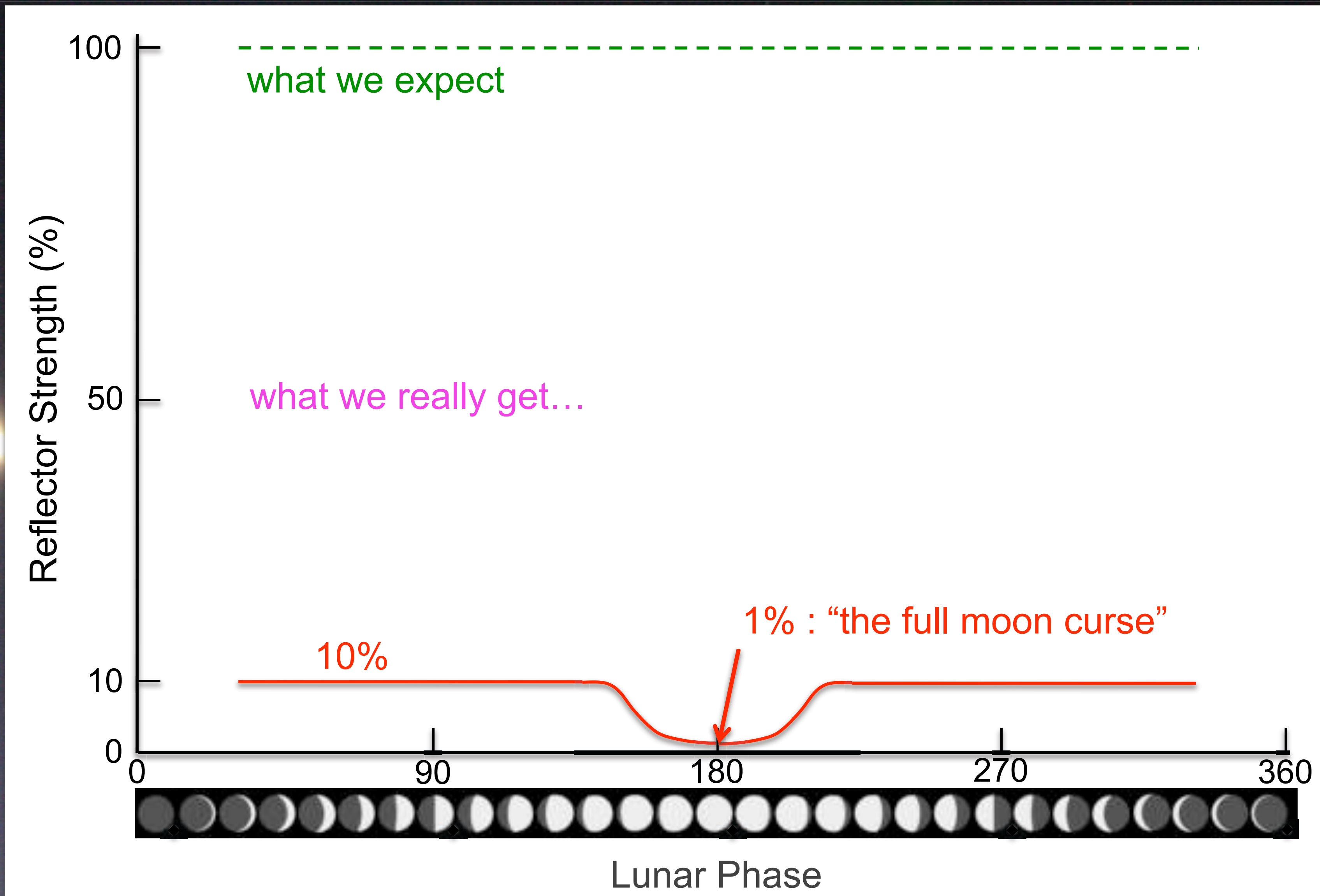
Surprises


The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.
Somewhere on this slide…
…which is less than 1 kilometer across…
…lurks Lunokhod 1.
Hint: it looks like this…
…and I haven’t covered it up
100 m

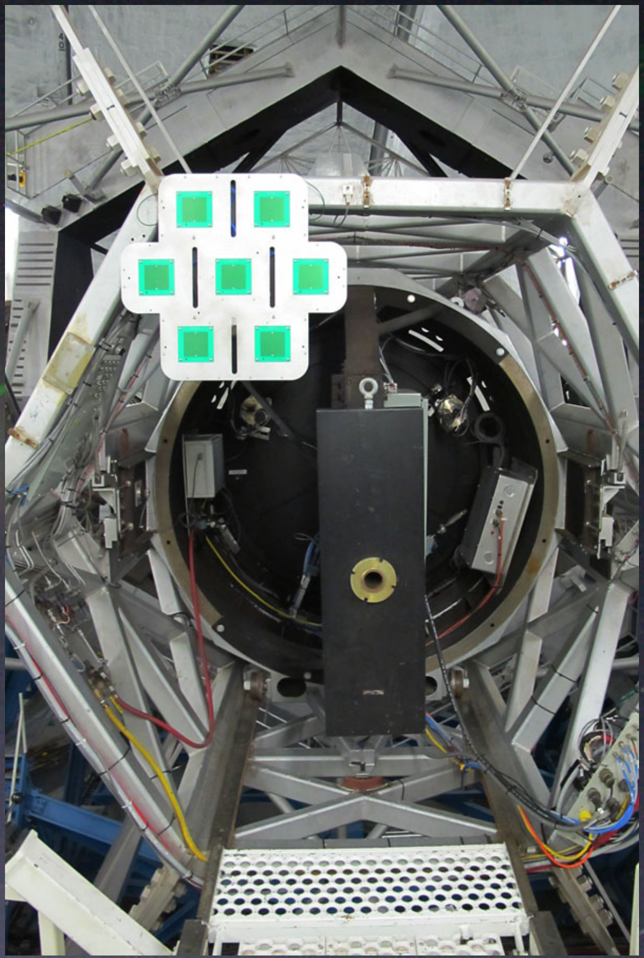
Your discovery gives hope to all of us
who lost something during the seventies…

– Ed Leon
Apache Point Observatory

Reflector Degradation



Transponder Detector



- Phased array passively listening to 1090 MHz transponder chatter
- Ratio of directional to omni-directional reliably determines if aircraft is near boresight
  - indep. of xmit power, distance, etc.
- Installed on APO and Keck, others interested

Summary & Next Steps

- APOLLO is a millimeter-capable lunar ranging station with unprecedented performance
- Given the order-of-magnitude gains in range precision, we expect order-of-magnitude gains in a variety of tests of fundamental gravity
- Besides gravity, LLR is sensitive to Earth orientation, the lunar interior, and coordinate frames
- Some surprises along the way
  - degradation of reflectors
  - found lost Lunokhod 1 reflector; now have 5
  - also developed aircraft transponder detector for illumination avoidance
- Trying 2-way ranging to corner cube array on LRO (1-way works…)