# Shining Dark on Dust

Using Total Lunar Eclipses
to expose
Dust Accumulation on Apollo Reflectors

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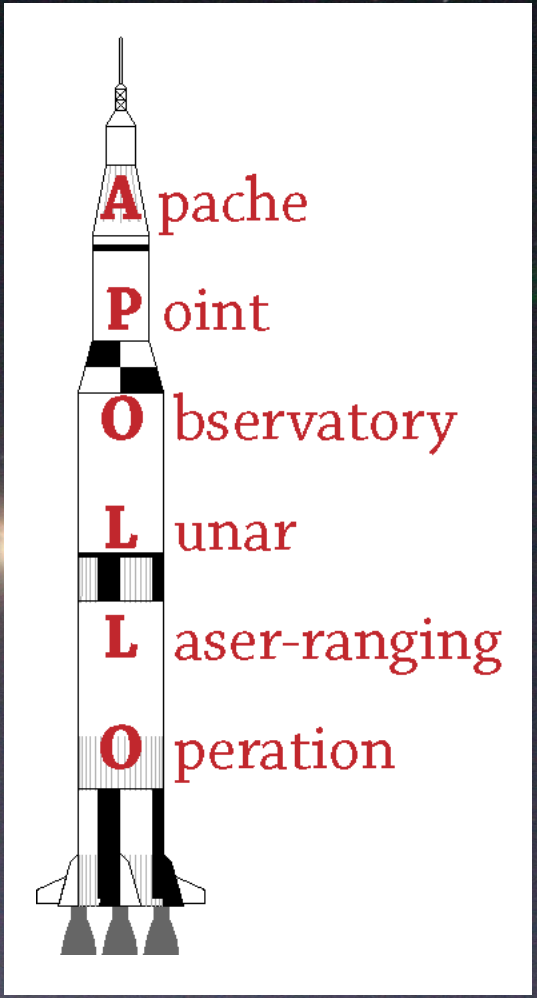
# APOLLO: one giant leap for LLR




- APOLLO performs lunar laser ranging (LLR) to test the foundations of gravity
  - Is General Relativity (GR) correct?
  - Equivalence Principle violation?
  - Time variation of gravitational strength?
  - Departure from $1/r^2$ force law?
  - Gravitomagnetism (GR effect)
  - Geodetic Precession
- APOLLO gets millimeter range precision
  - GR departures from Newton ~10 m level
- Acronym assures funding by NASA
  - ~50/50 NASA/NSF

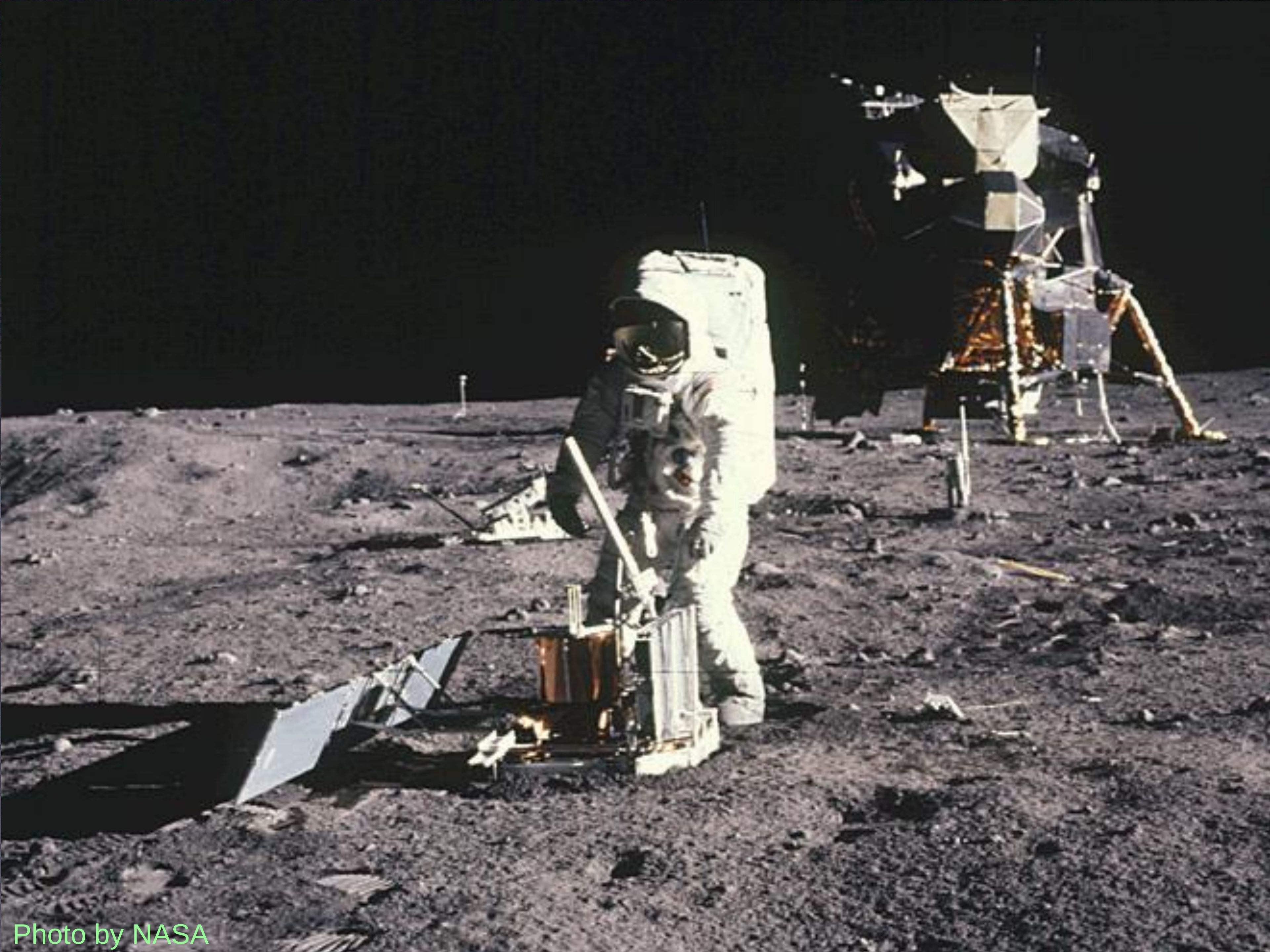
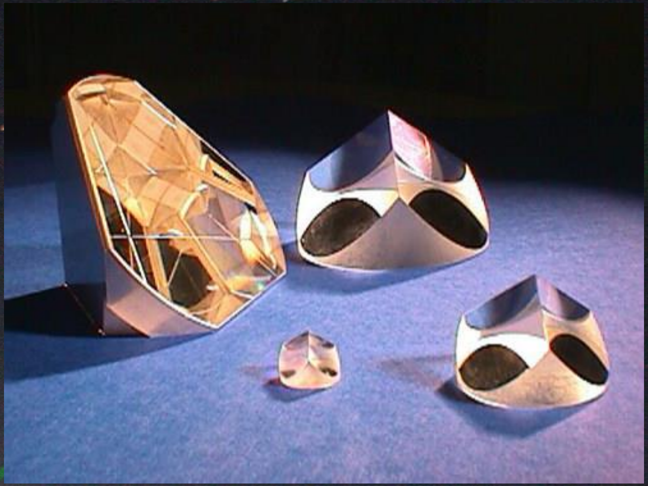


Photo by NASA

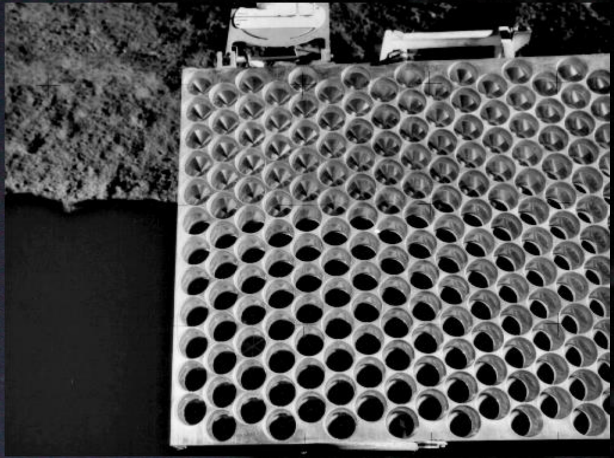
# Lunar Retroreflector Arrays



Corner cubes

Apollo 11 retroreflector array

Apollo 14 retroreflector array

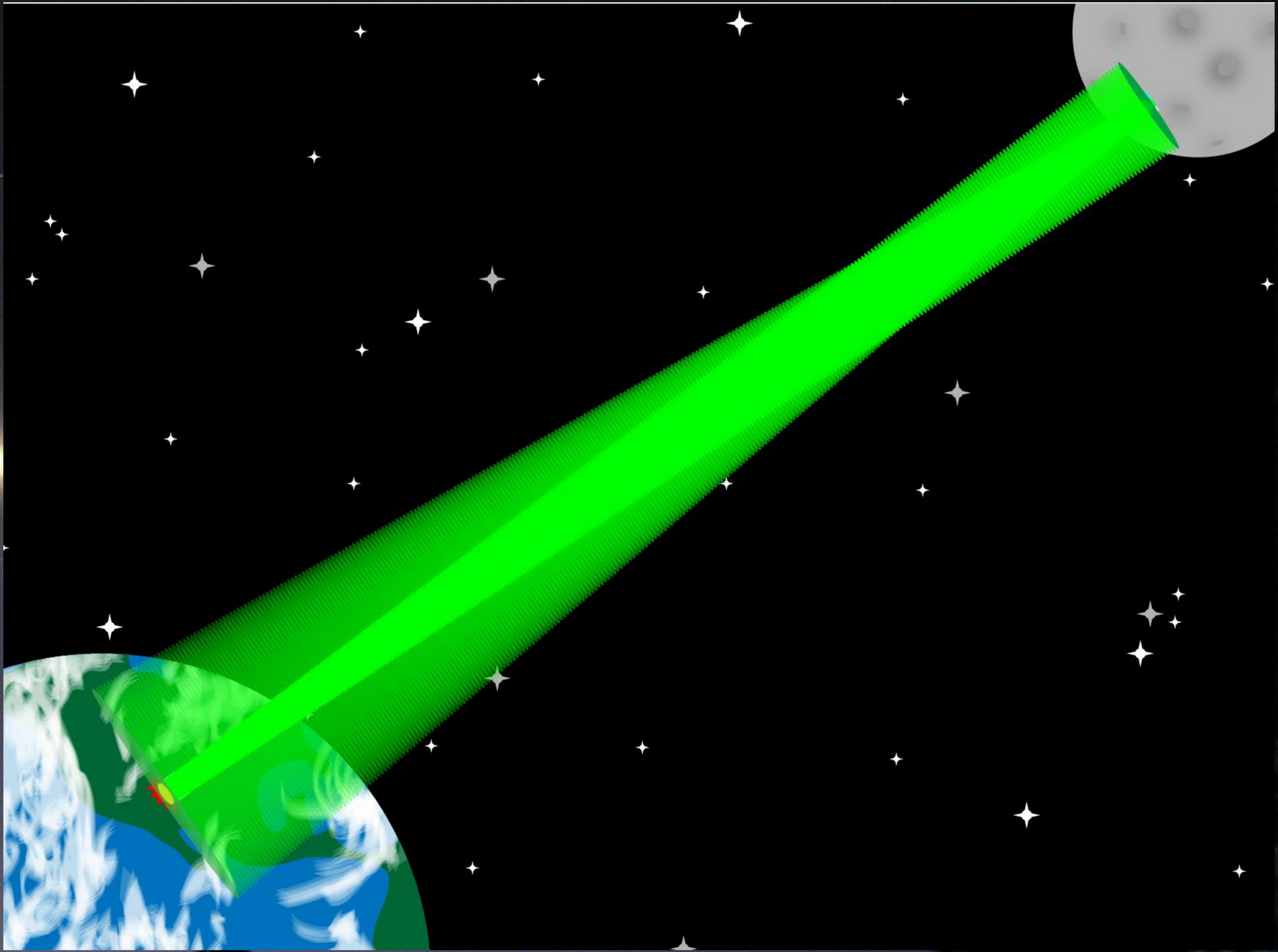


Apollo 15 retroreflector array

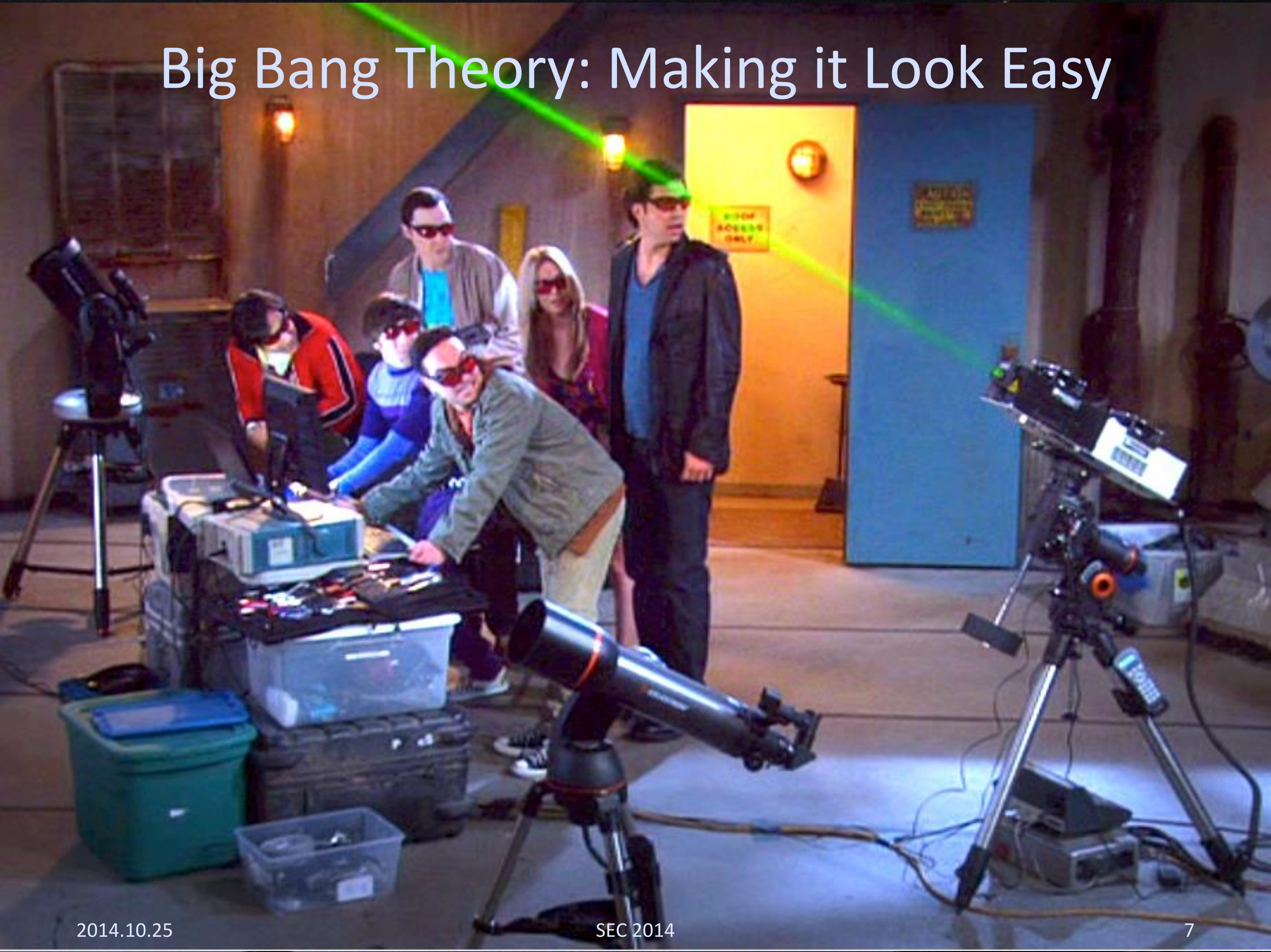
# The Reflector Positions


- 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

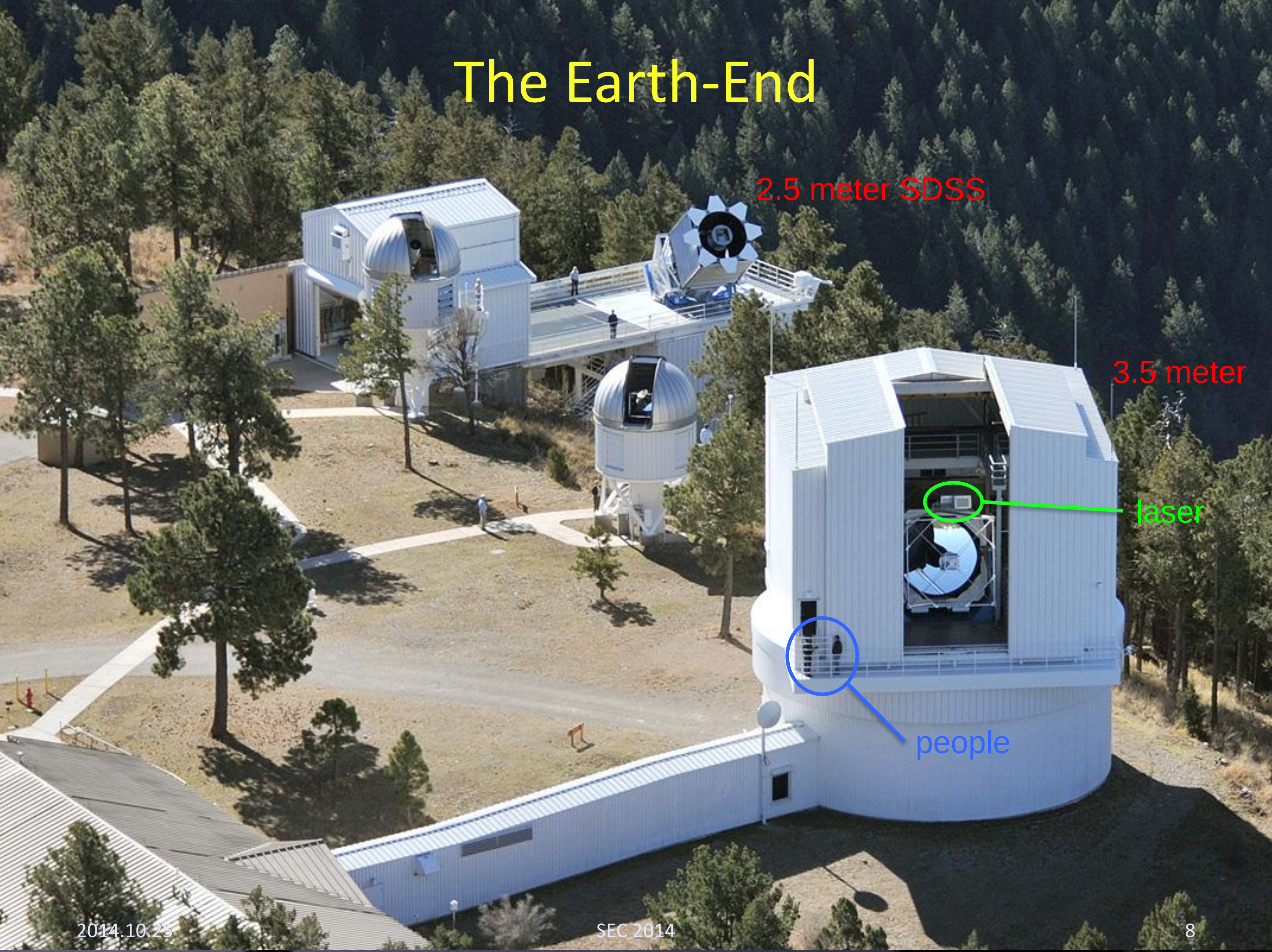
# How Does it Work?



# Big Bang Theory: Making it Look Easy

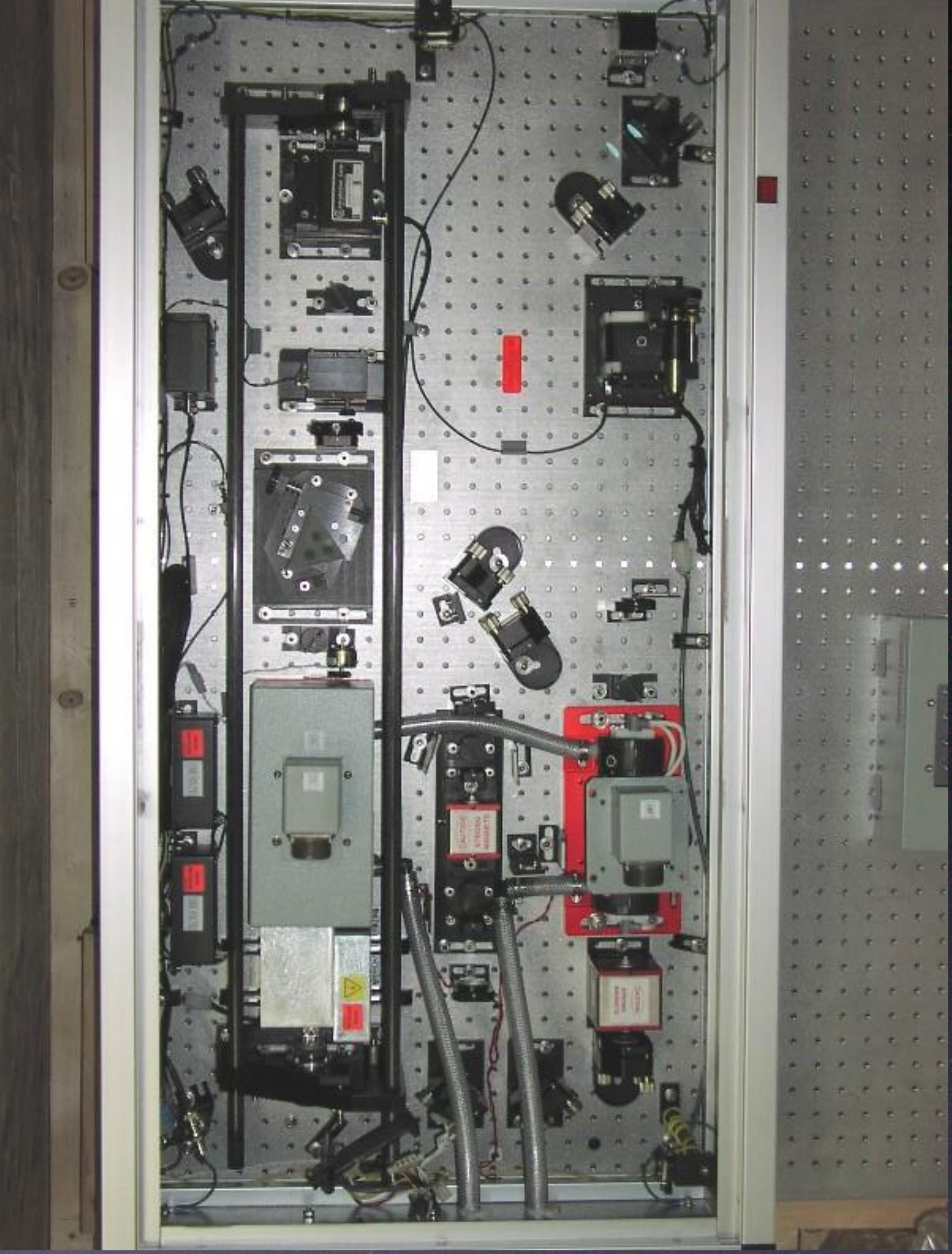


# The Earth-End



# 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

# Laser Mounted on Telescope

# A Telescope in Reverse

# Gigantic Laser Pointer

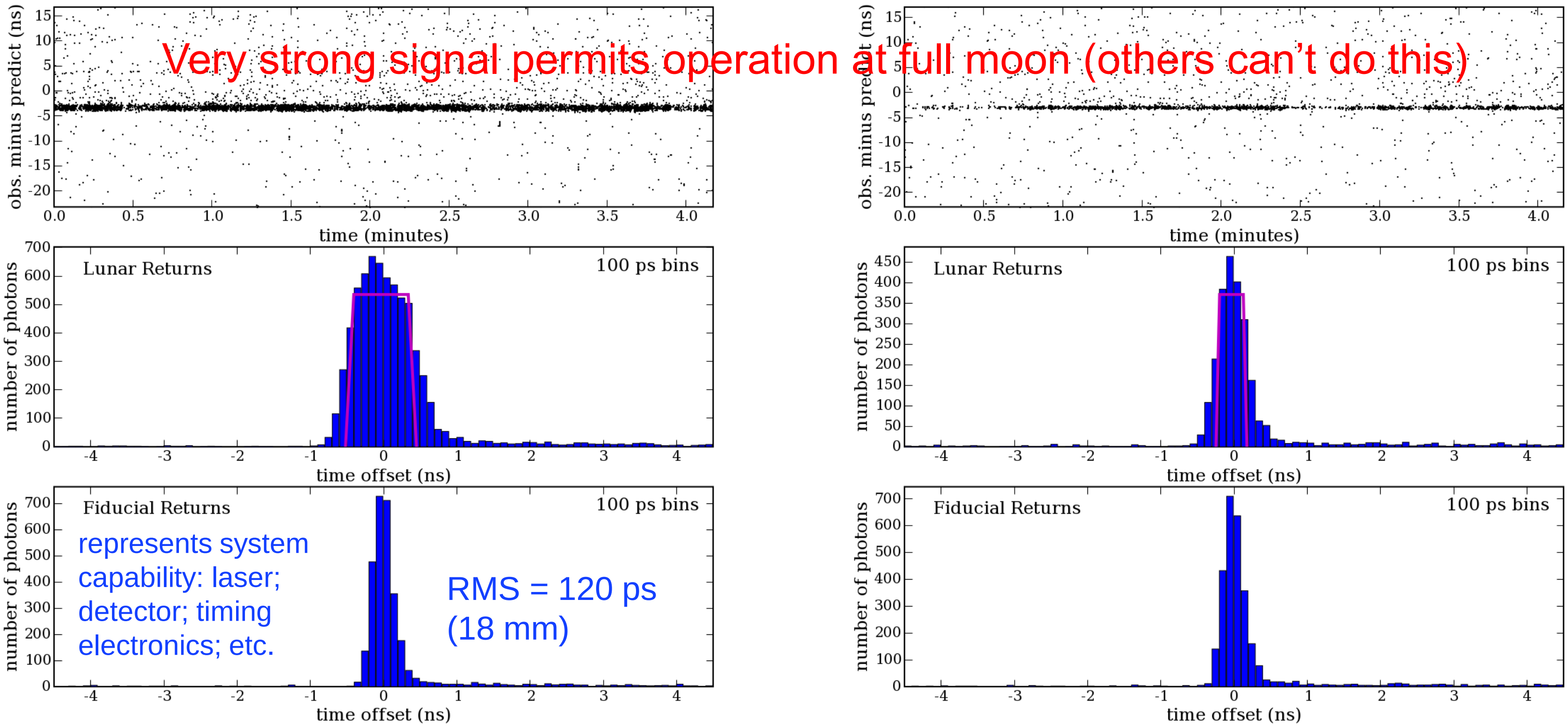
photo by Dan Long

# Killer Returns

Apollo 15 2007.11.19 Apollo 11

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

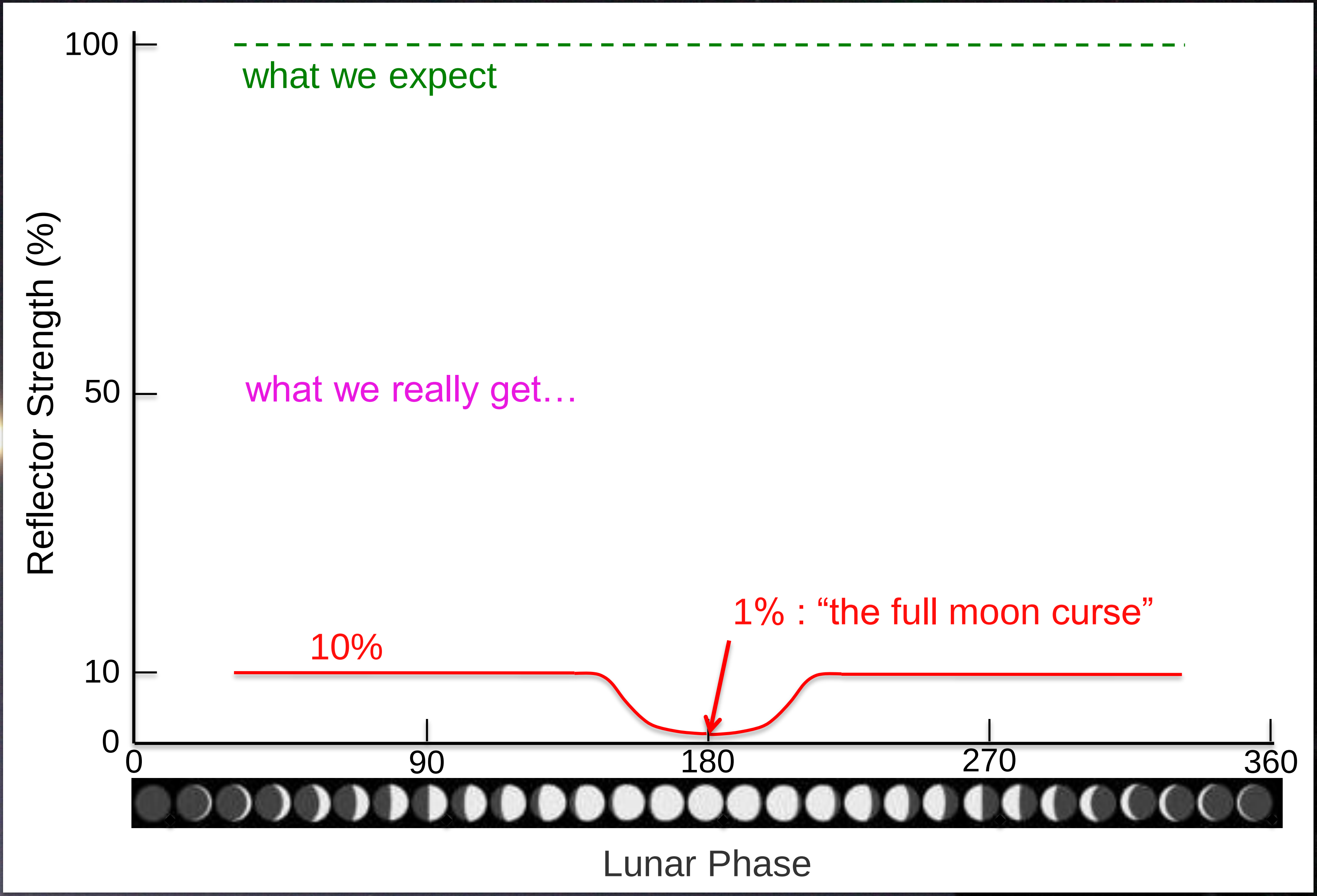
Very strong signal permits operation at full moon (others can't do this)



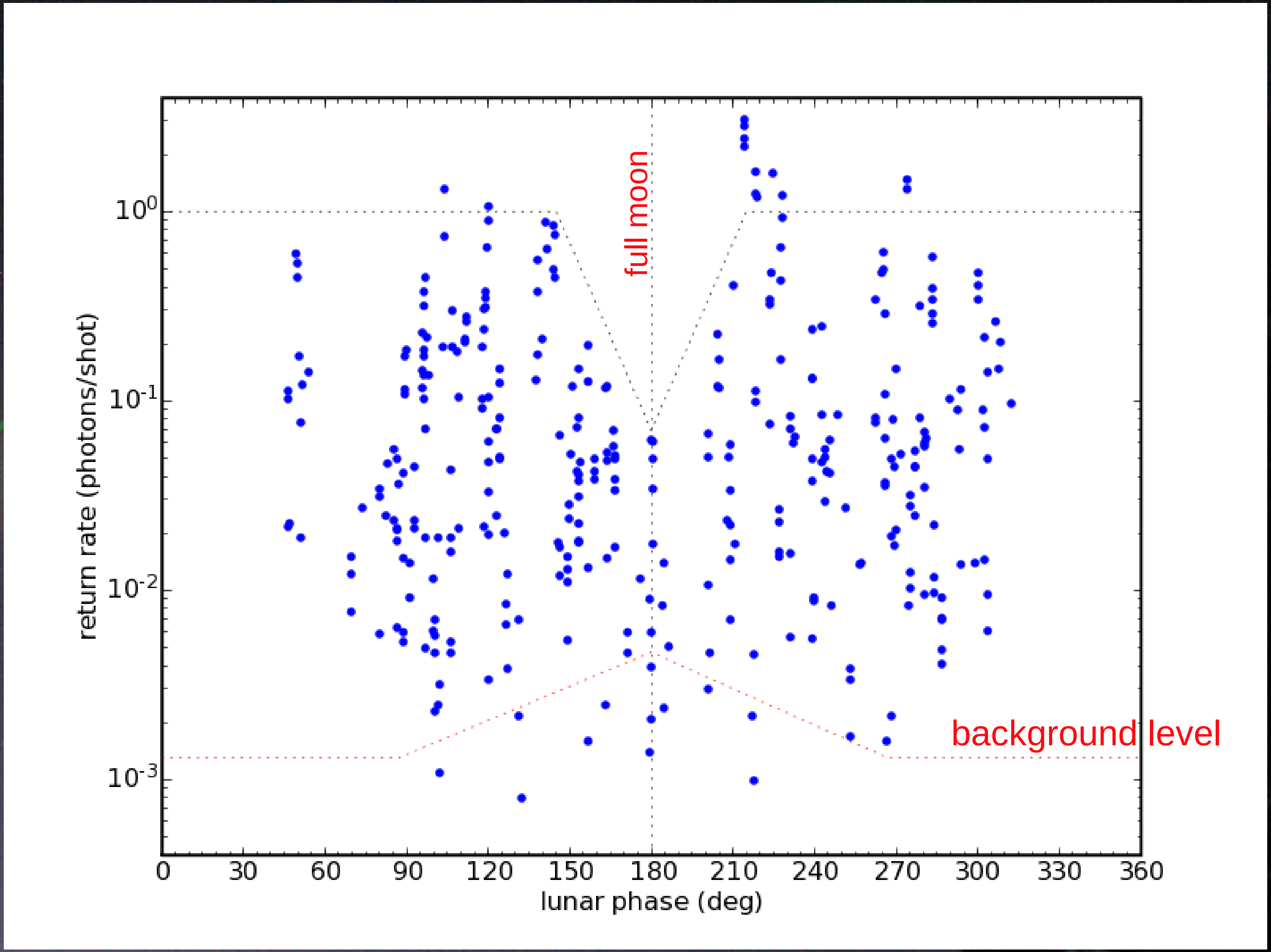

- 6624 photons in 5000 shots
- 369,840,578,287.4 ± 0.8 mm
- 4 detections with 10 photons

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

# Not All is Rosy in LLR-Land

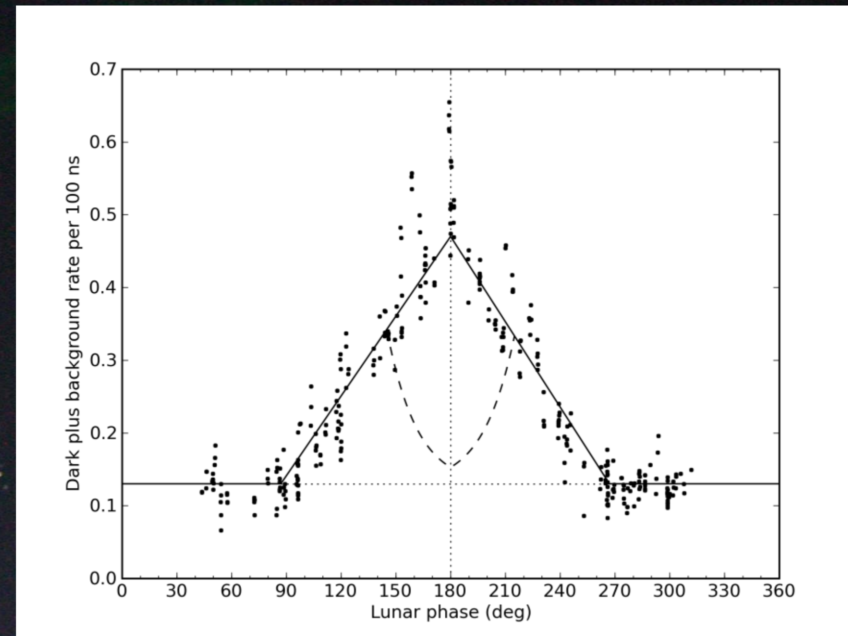


# APOLLO rates on Apollo 15 reflector

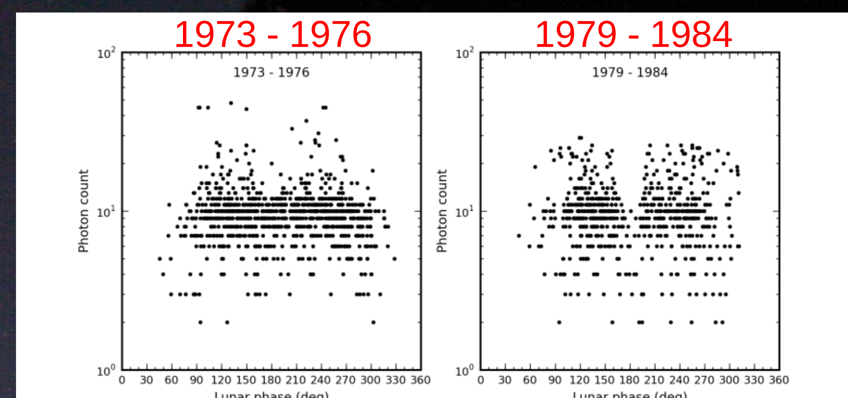


# More on the deficit

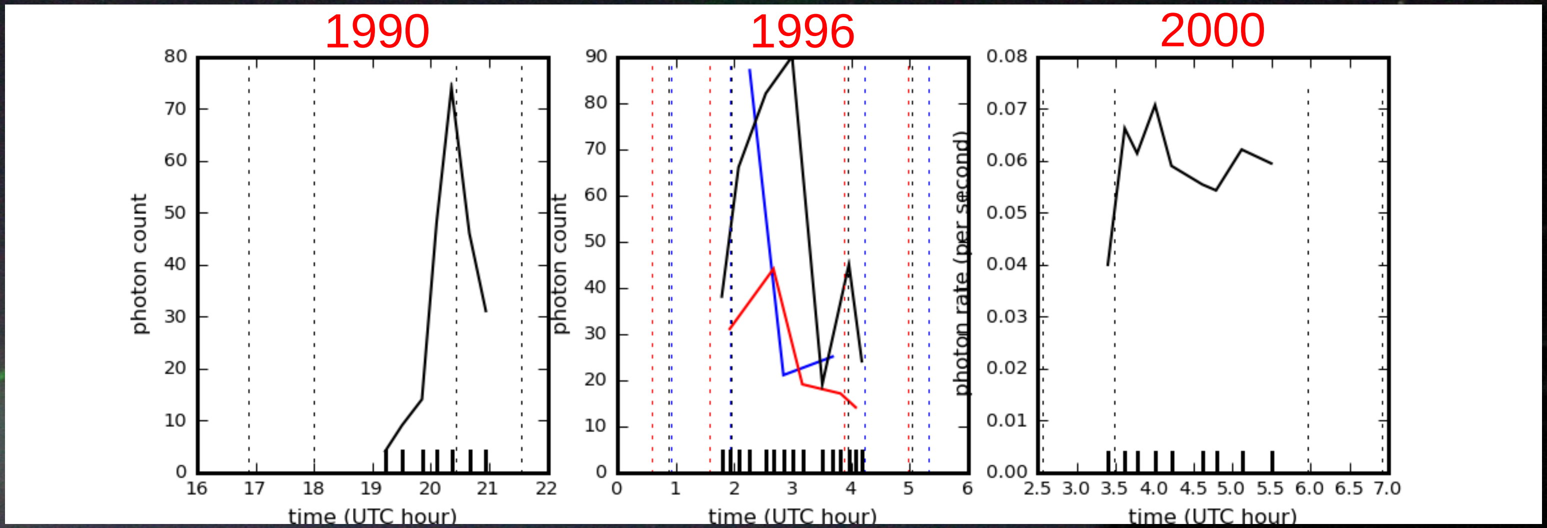
- APOLLO system sensitivity is not to blame for full-moon deficit
  - background is not impacted




- Early LLR data trucked right through full-moon with no problem
- The deficit began to appear around 1979
- No full-moon ranges from 1985 until 2006, except during eclipse

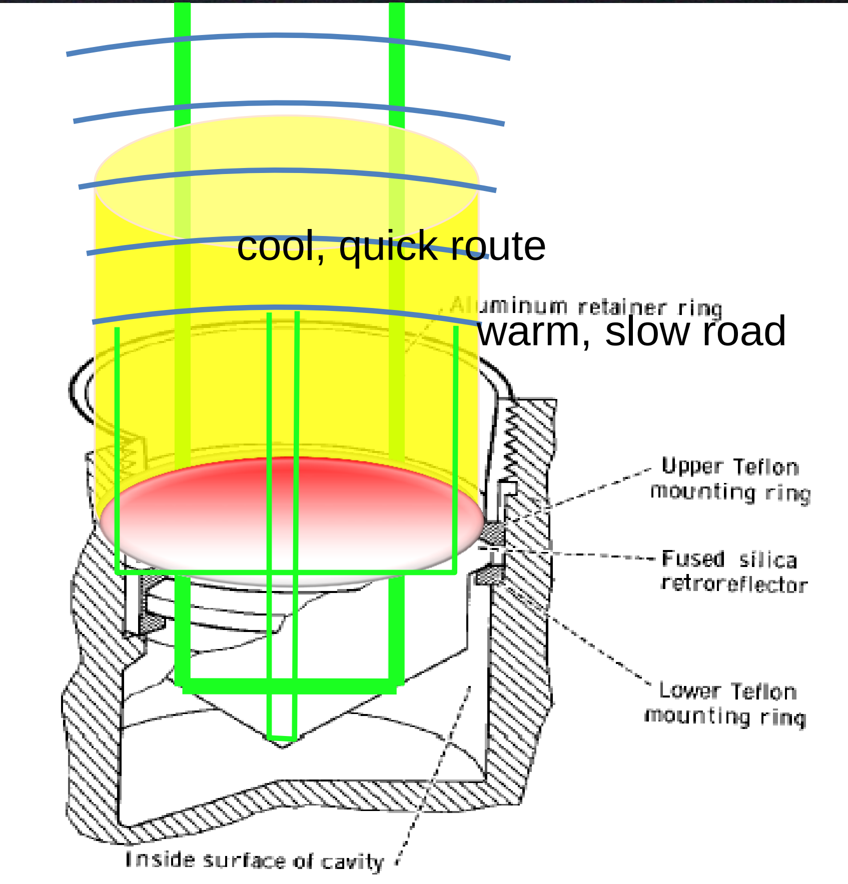


# Past Eclipses, French Observations



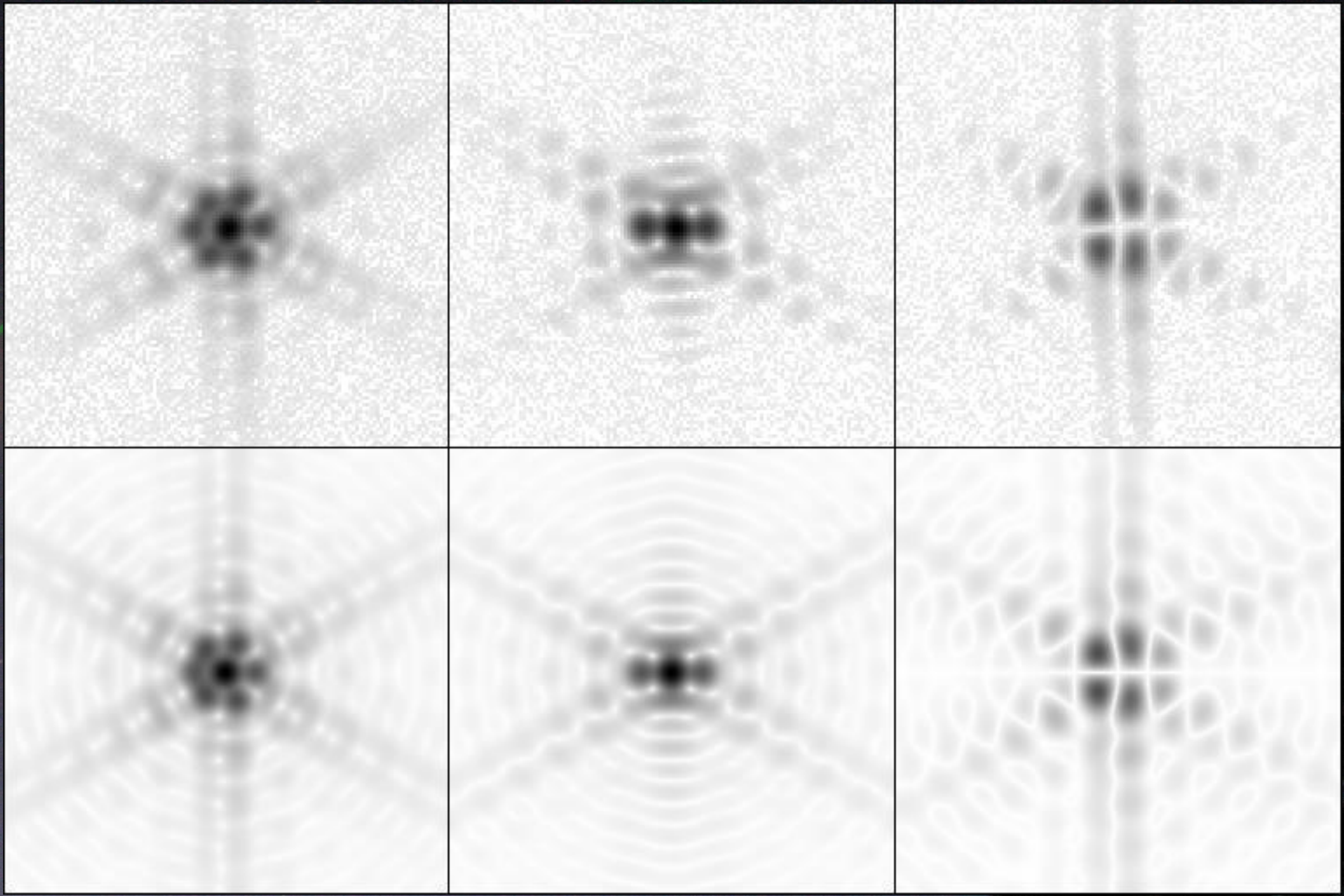

- Strong signal during eclipse
  - Apollo 11 (blue) was about as strong as this station saw in decades of ranging: definitely a special night
- Take your pick: late peak; early peak; no peak
- LLR is hard: ups and downs can be acquisition difficulty

# What's Wrong?

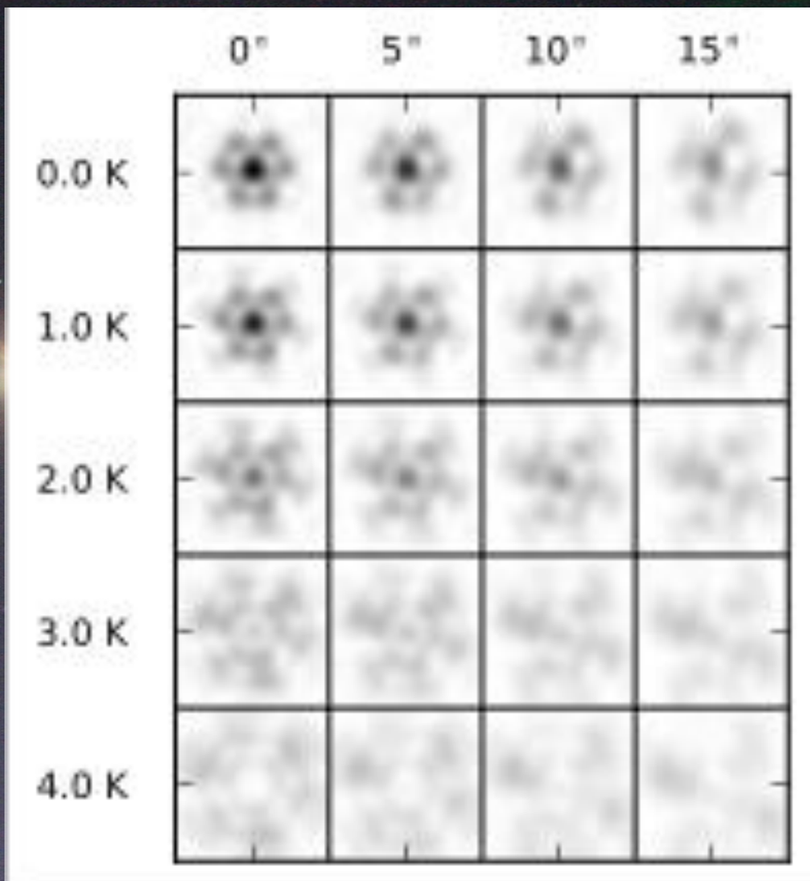


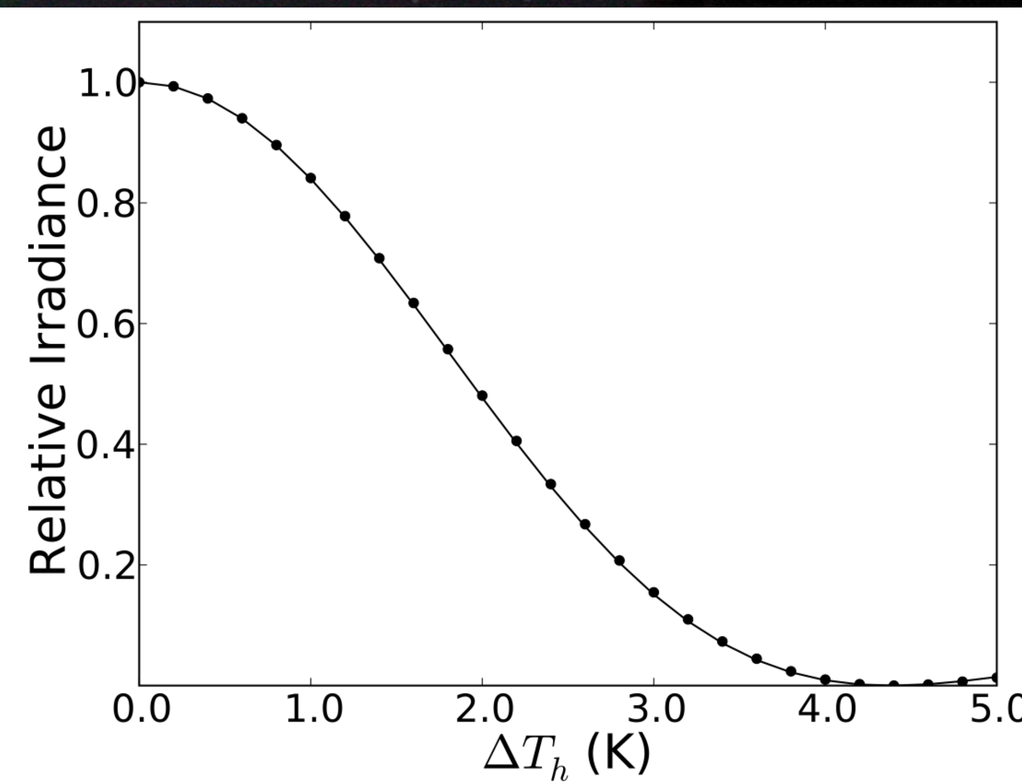

- The full-moon deficit, together with normal eclipse behavior, gives us the best clues:
  - thermal nature
  - absorbing solar flux
- Most likely: dust
  - Obviously could explain overall deficit (10%)
- Full moon effect then due to solar heating of dust
  - sun comes straight down tube at full moon
  - makes front hotter than vertex of corner cube, leading to divergence of exit beam
  - only takes 4° C (7° F) gradient to introduce 10× reduction

# Modeling CCR Diffraction Patterns



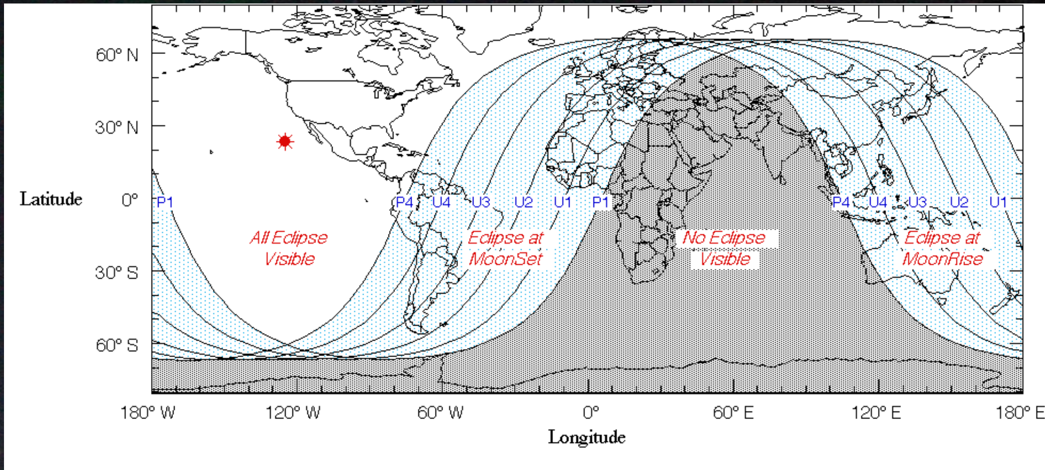
# Exploring Orientation & Thermal Gradients



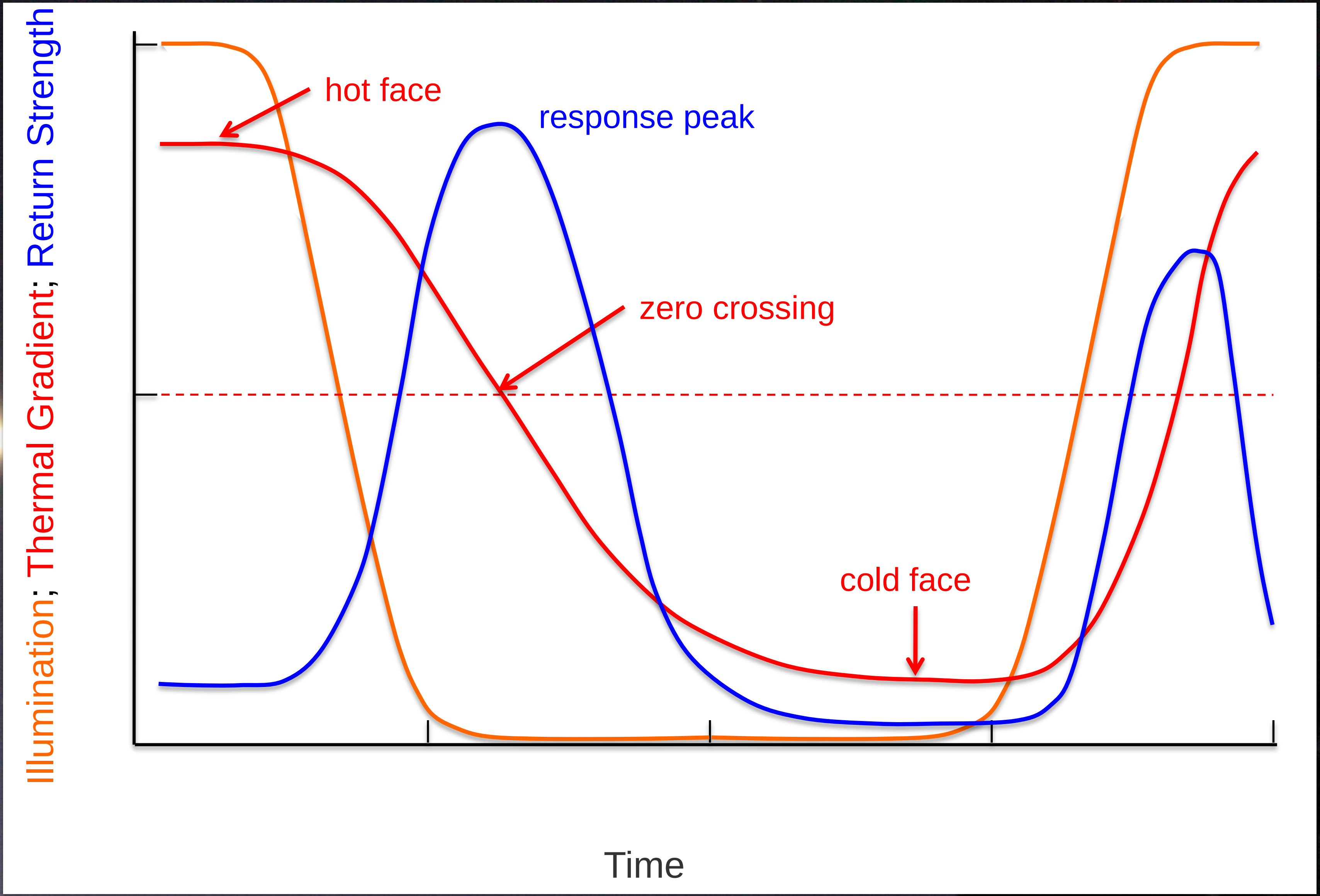
# Eclipse as Light Switch


Dec. 2010: perfect eclipse for North America




- If sunlight is to blame, let's shut it off at full moon!
  – need to intercede with massive body: move heaven and earth?
  – examine response time: is it a thermal effect in corner cubes?

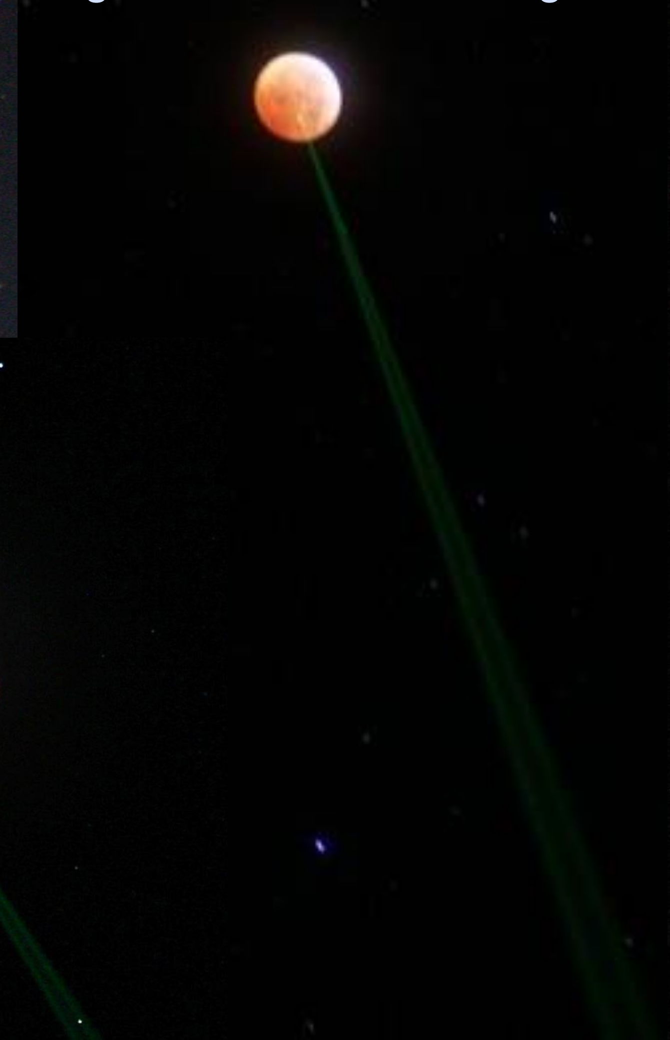
# Cartoon of Expectations

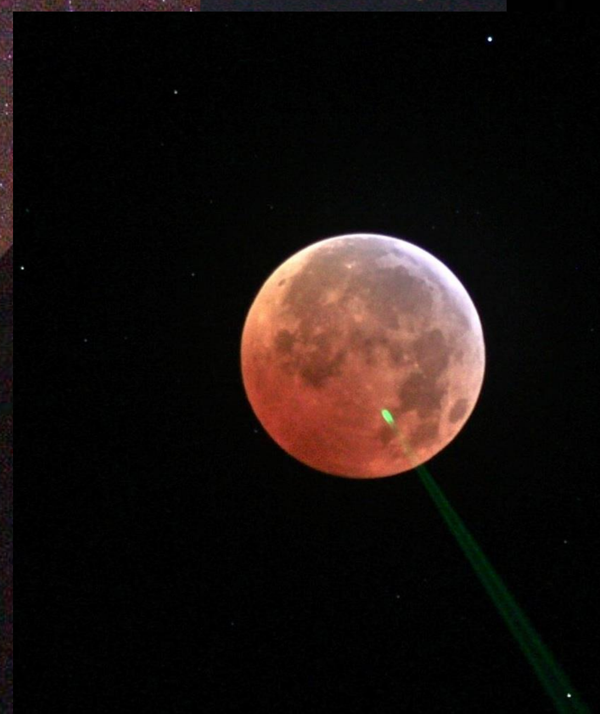


# December 21, 2010

Near-zenith at mid eclipse for APOLLO

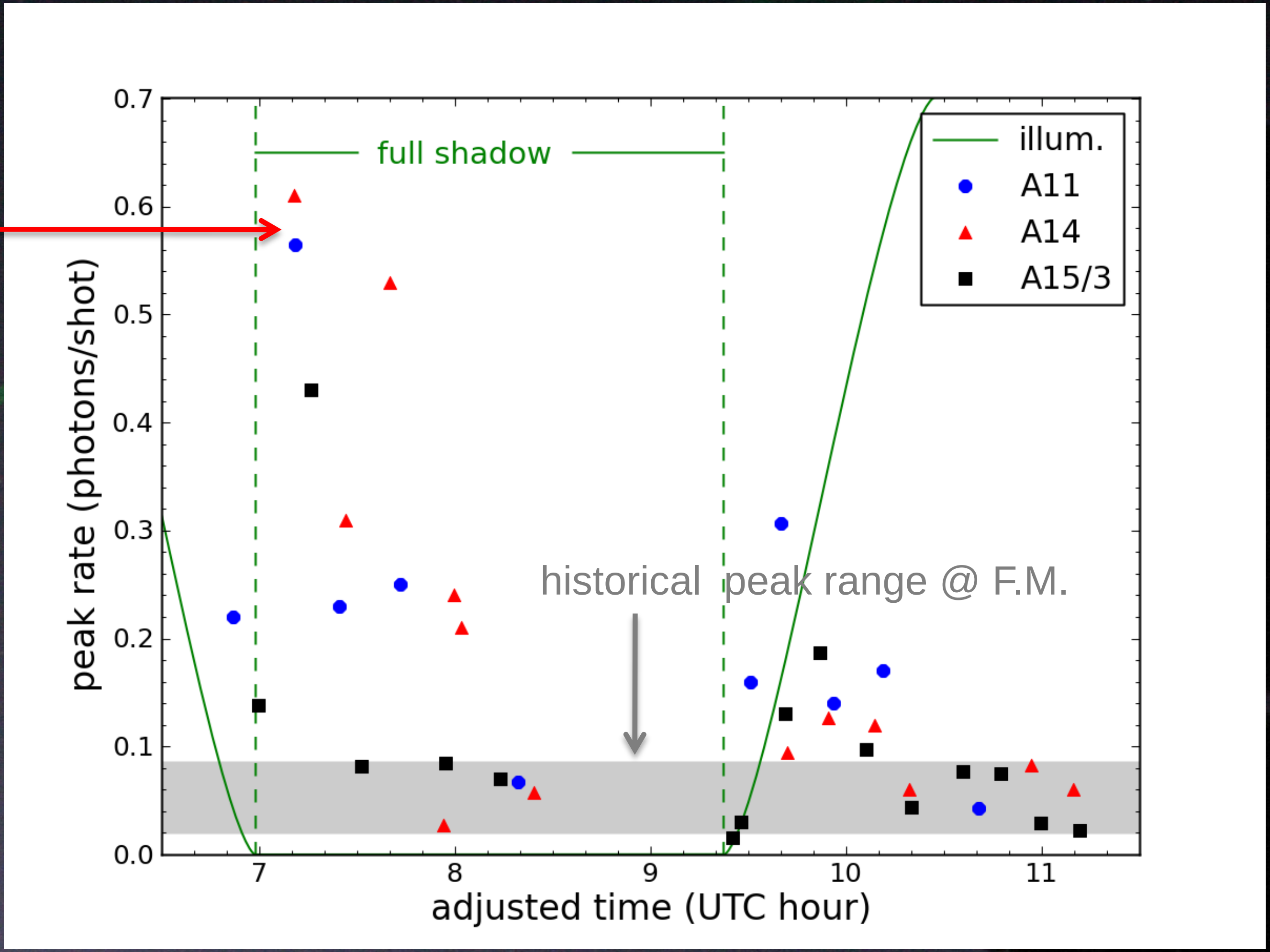
but variable, high, thin clouds that night





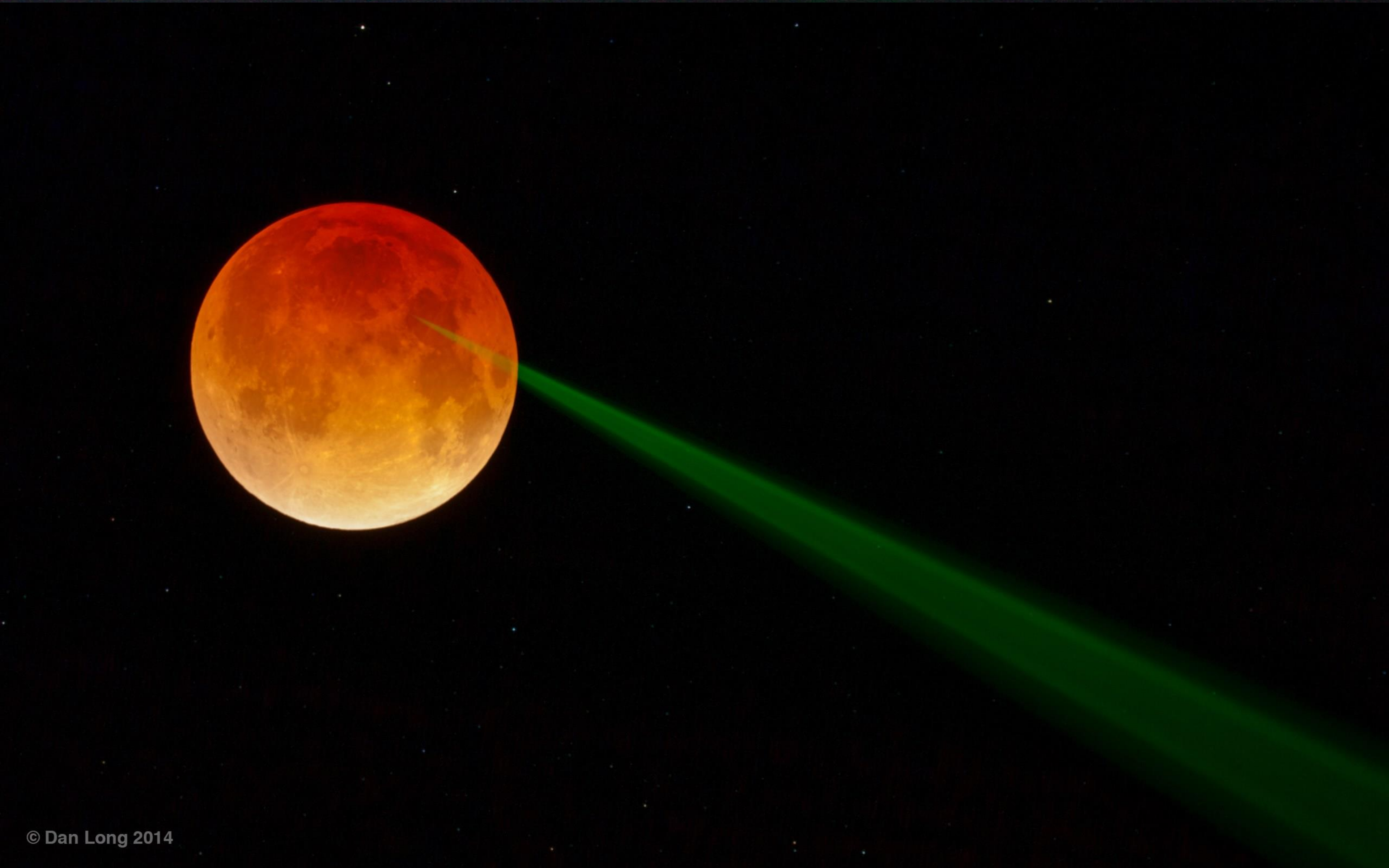
# 2010 APOLLO Eclipse Results

~10× better than ever at full moon!

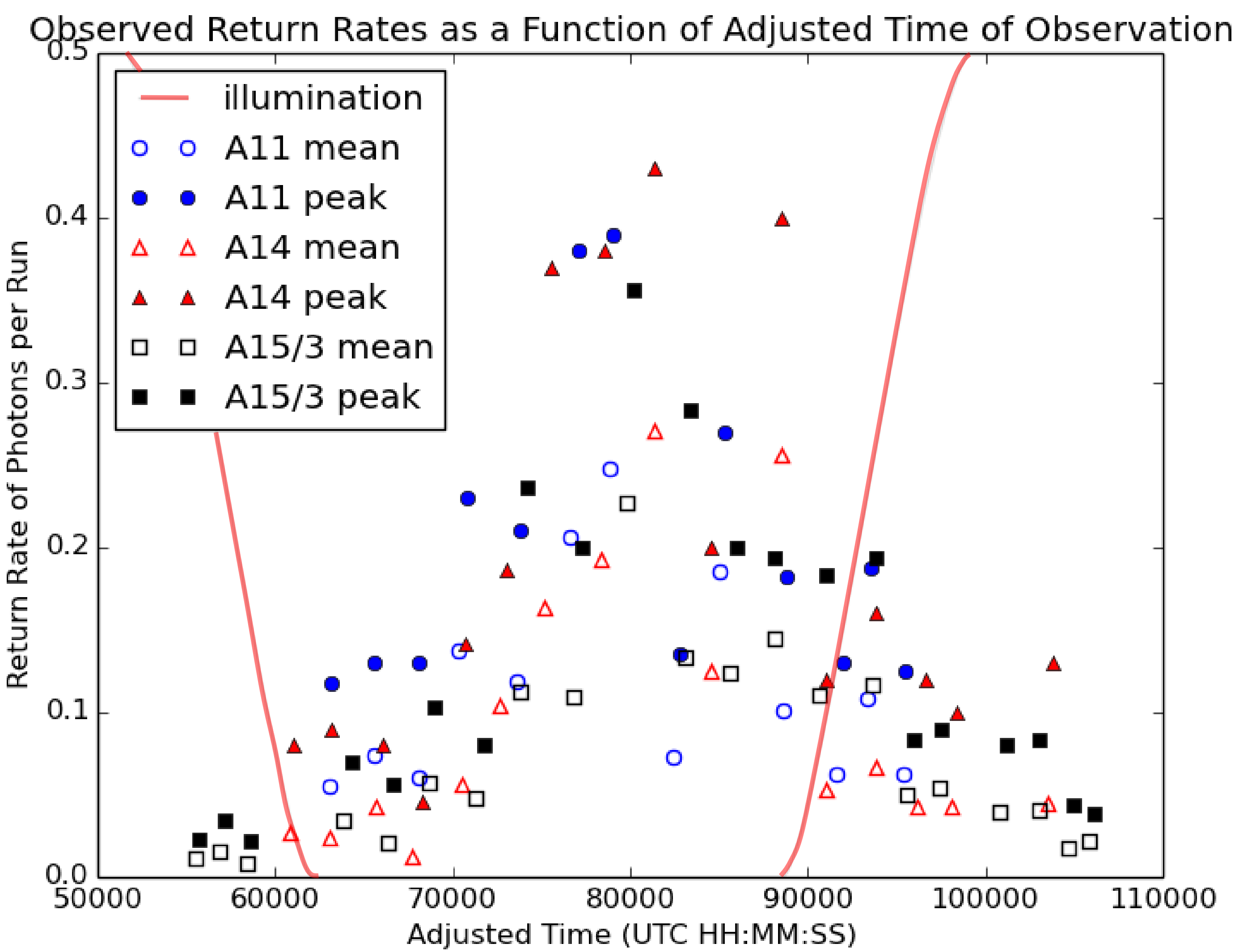



robust recovery initially, then down, and brief resurgence once light returns

# 2014.04.15 Eclipse



# Still See Dramatic Effect, but Single-Peak



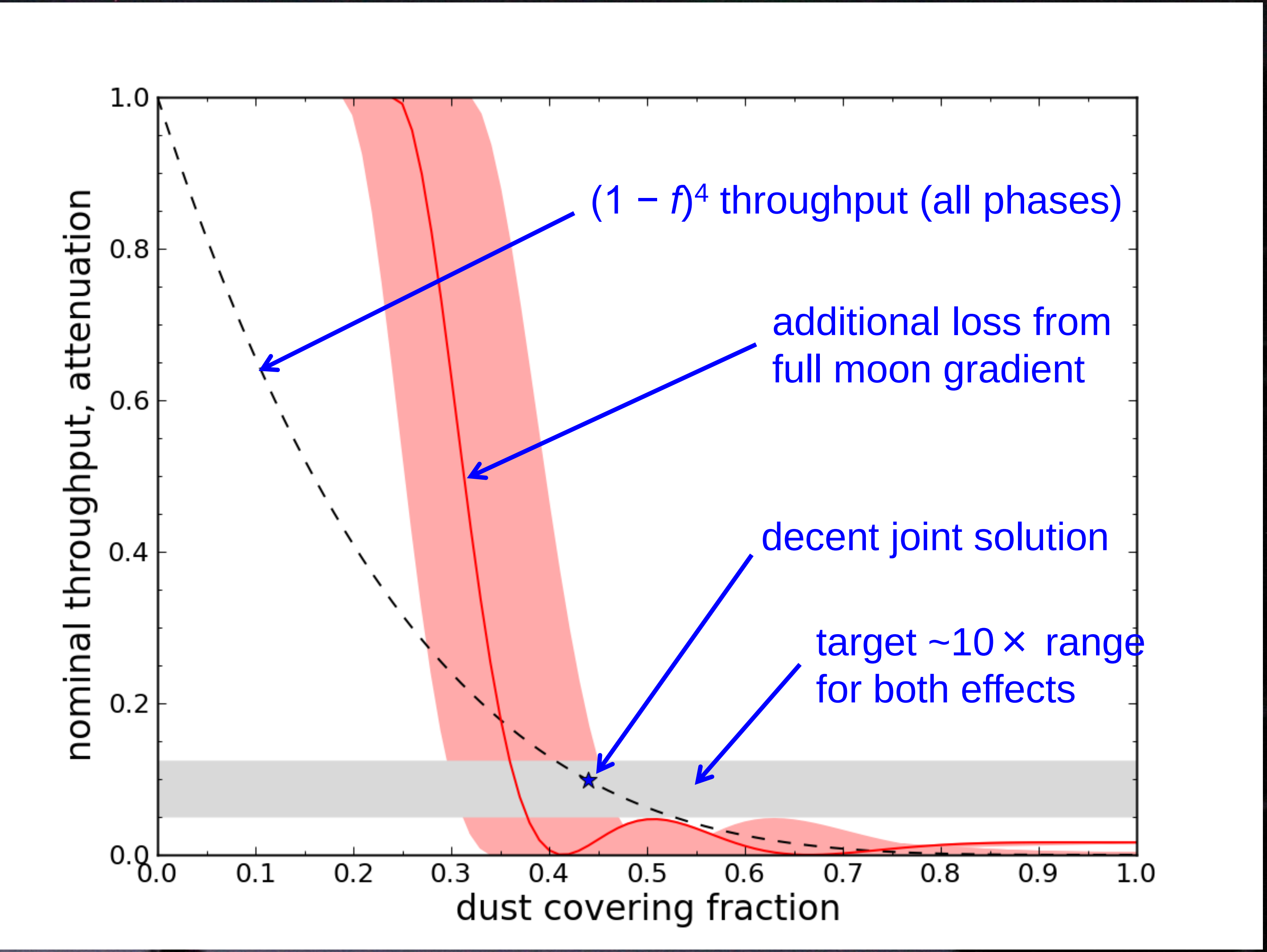
# Reconciliation?

- Thicker set of clouds during 2010 eclipse coincide with dip
  - analysis of opacity suggested this wasn't responsible
- Conditions in 2014 eclipse pristine
  - and signal was acquired well before umbral stage commenced
- Must conclude that single peak is correct
  - cartoon predicting double peak got "lucky!"
  - time constant is longer: thermal coupling to aluminum pallet

# What *CAN* We Say?

- Thermal effect real: solar absorption happening
  - likely dust coating
- Roughly 10 × signal loss over expectations, at all phases
- Factor of 10−15 additional signal loss at full moon
  - recovering to admirably strong levels during both eclipses
  - consistent with thermal gradients in 3−4 K range at full moon
- Putting together: 10 × attenuation plus large gradient
  - suggests dust covering fraction is $f \approx 0.4$−$0.5\%$
  - double-pass and diffraction result in far-field intensity $(1 - f)^4$
  - similar fraction computed from radiative balance to get gradient

# Covering Fraction



# Summary

- APOLLO is a millimeter-capable lunar ranging station testing gravity
- Strong signal allows LLR operation at full-moon
- Found that reflectors were “sick” near full moon; suspected thermal/solar issue
- Eclipse provides celestial light switch to test idea
- CONFIRMED: definite solar/thermal effect, likely due to dust deposition (signal levels outstanding during eclipse)
- ESTIMATE: dust covering fraction of nearly 50%
  – roughly a mono-layer per century