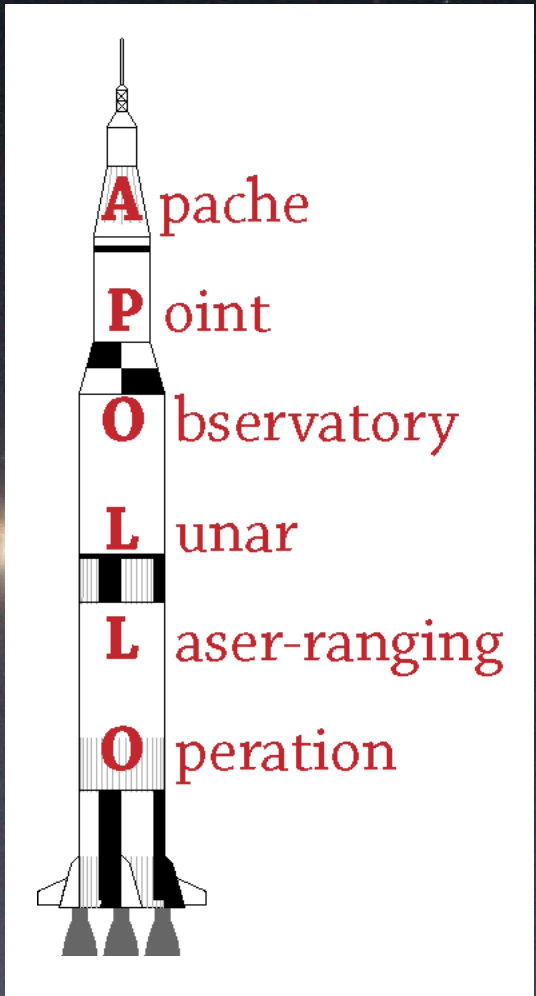
APOLLO

Status Update
Dusty Reflectors
Lunokhod 1 Found

Tom Murphy (UCSD)

photo credit: Jack Dembicky

APOLLO: One small step for science… …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
  - Team includes T. Murphy, E. Adelberger, J. Battat, C.D. Hoyle, N. Johnson, R. McMillan, E. Michelsen, K. Nordtvedt, C. Stubbs, E. Swanson

APO 3.5 m, New Mexico, 2800 m elevation

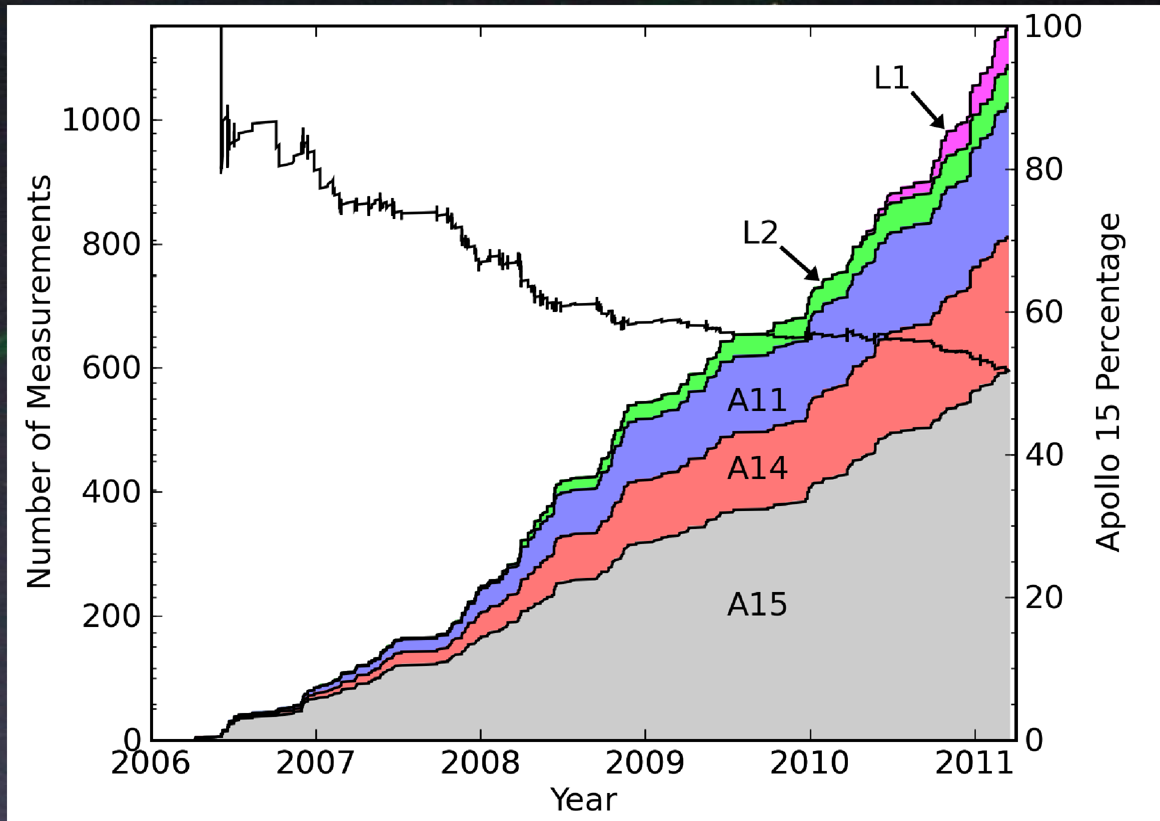
Breaking All Records

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)

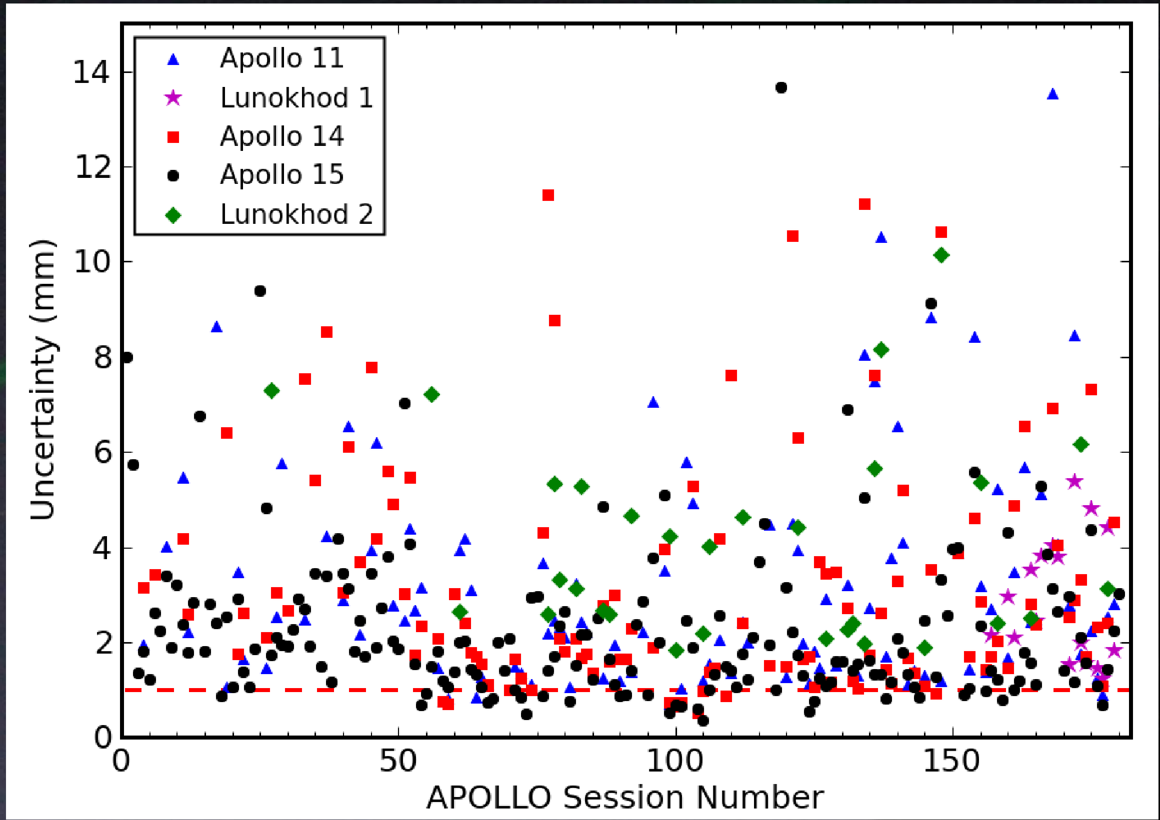
- APOLLO has greatly surpassed previous records
  - roughly 70 times OCA rate on Apollo reflectors
- APOLLO can operate at full moon
- Often a majority of APOLLO returns are multiple-photon events
  - record is 12 photons in one shot (out of 12 functioning APD elements)
  - APD array (many buckets) is crucial

APOLLO Data Campaign



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

APOLLO Data Quality

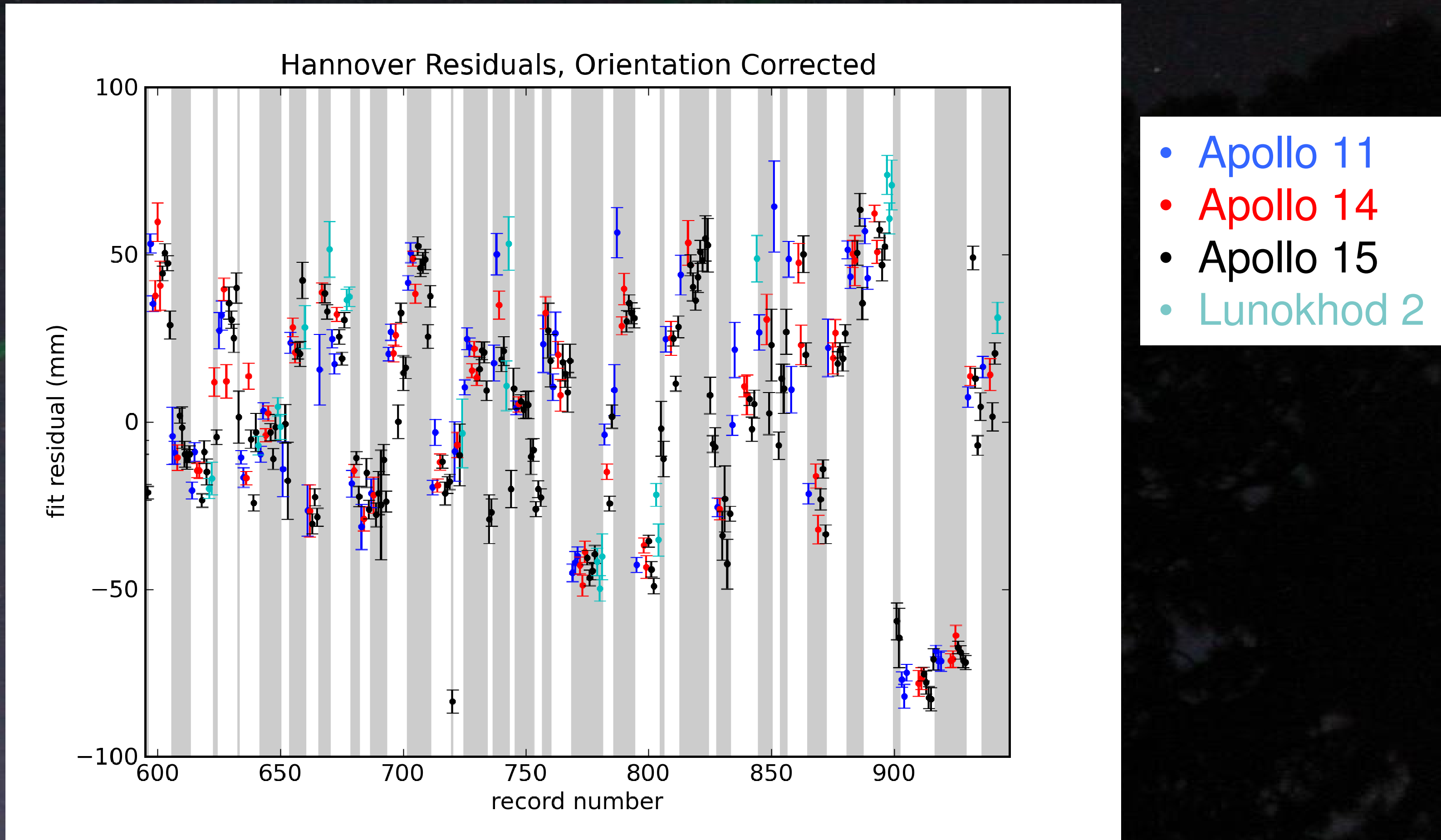


- Uncertainties are per night, per reflector; pre-APOLLO sub-centimeter rare
- Medians are 2.4, 2.7, 2.4, 1.8, 3.3 mm for A11, L1, A14, A15, L2, resp.
- Combined nightly median range error is 1.4 mm

Next Step: Model Development

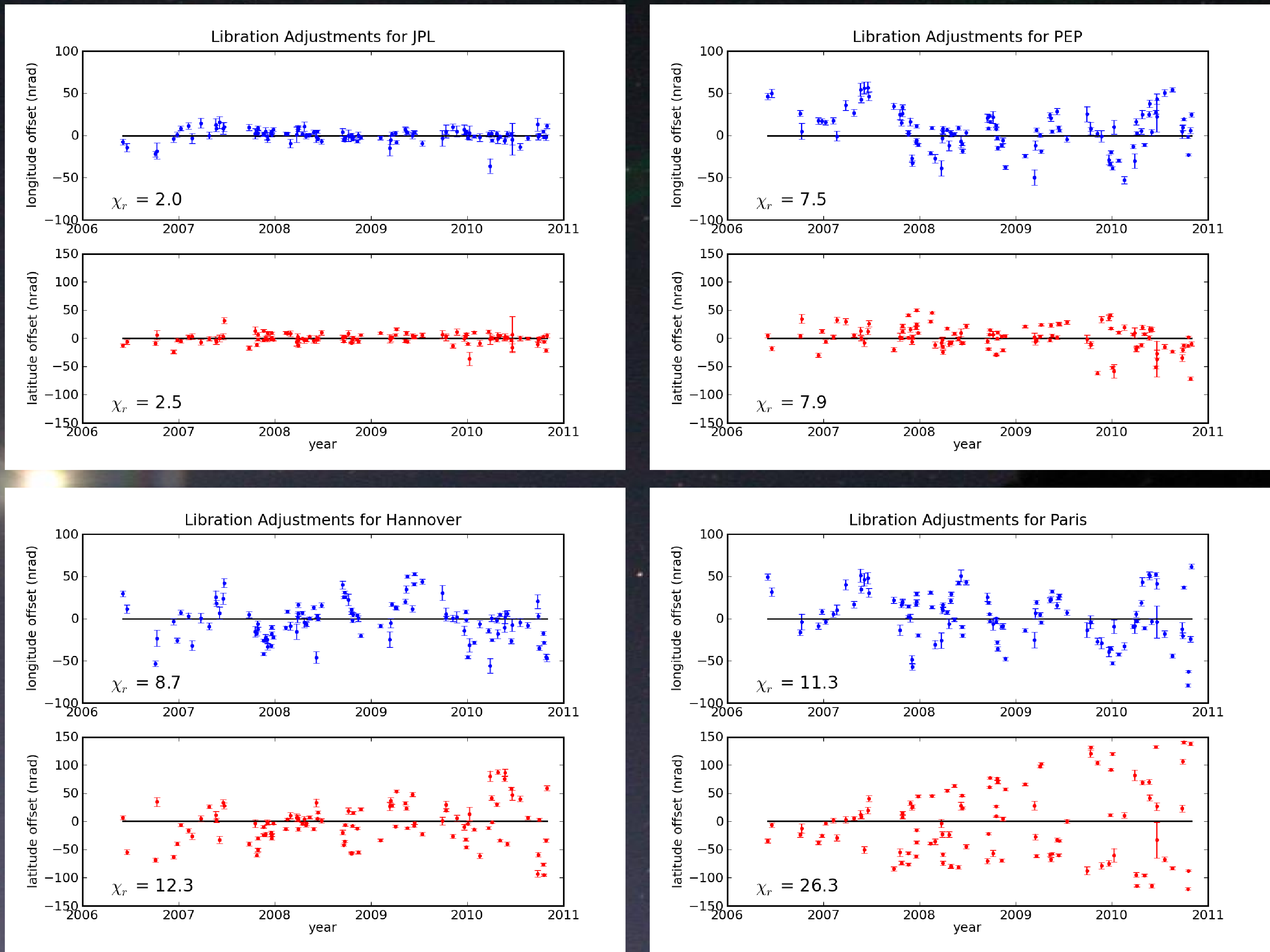
- Extracting science from LLR data requires a model that includes *all the physics* that can influence the Earth-Moon range
  - N-body relativistic gravity in solar system
  - body figure torques
  - site displacement phenomena
- The best LLR models currently produce > 15 mm residuals
- Many few-millimeter effects are not yet included
  - crustal loading phenomena from atmosphere, ocean, hydrology
  - geocenter motion (center of mass with respect to geometry)
  - tidal model needs improvement
  - atmospheric propagation delay model needs updating
  - Earth orientation models could better incorporate LLR data
  - multipole representations of Earth and Moon mass distributions need improvement

Example: Adjusting Lunar Orientation



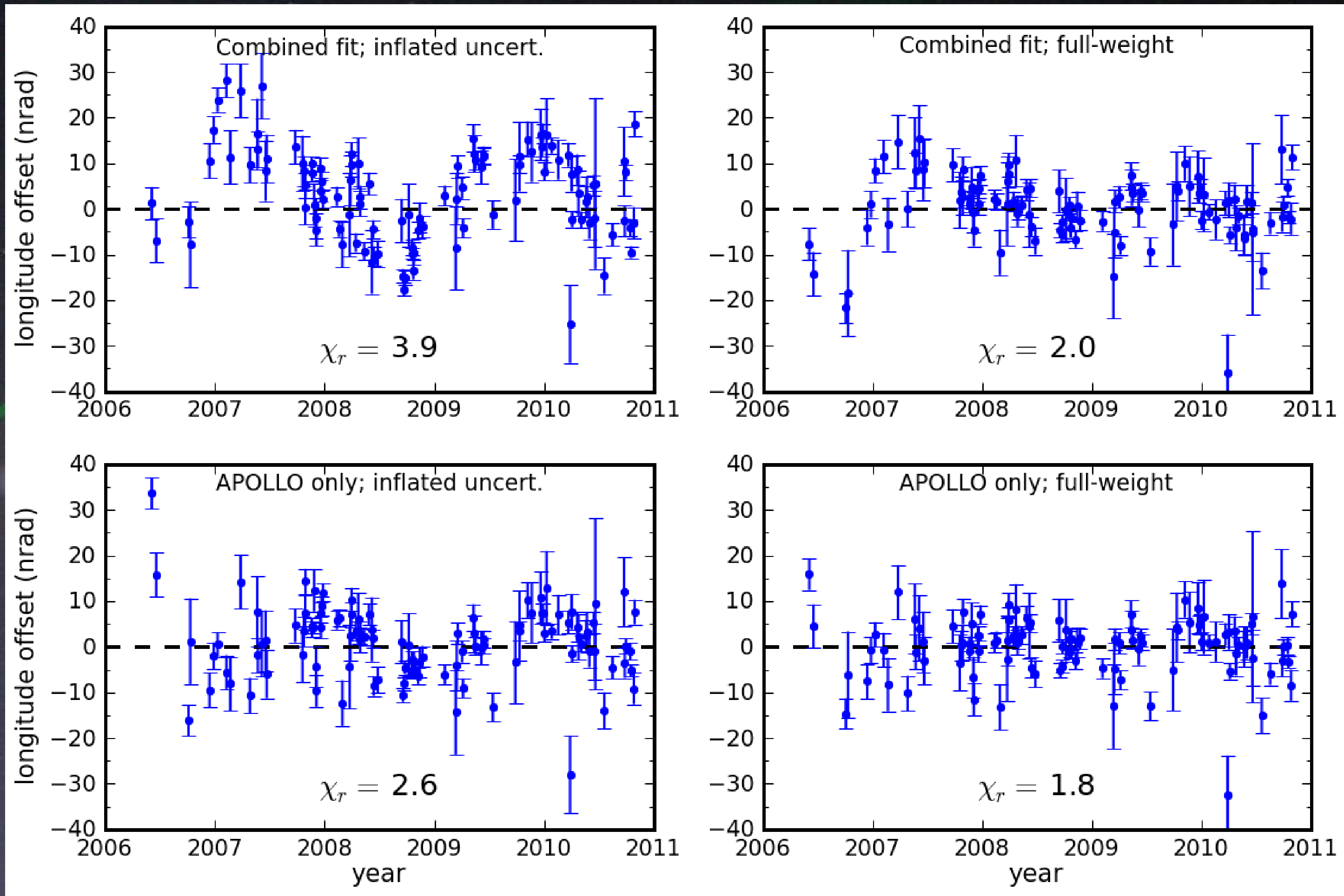
APOLLO data clearly call for orientation adjustments each night (vertical bands)

Re-orienting all the models



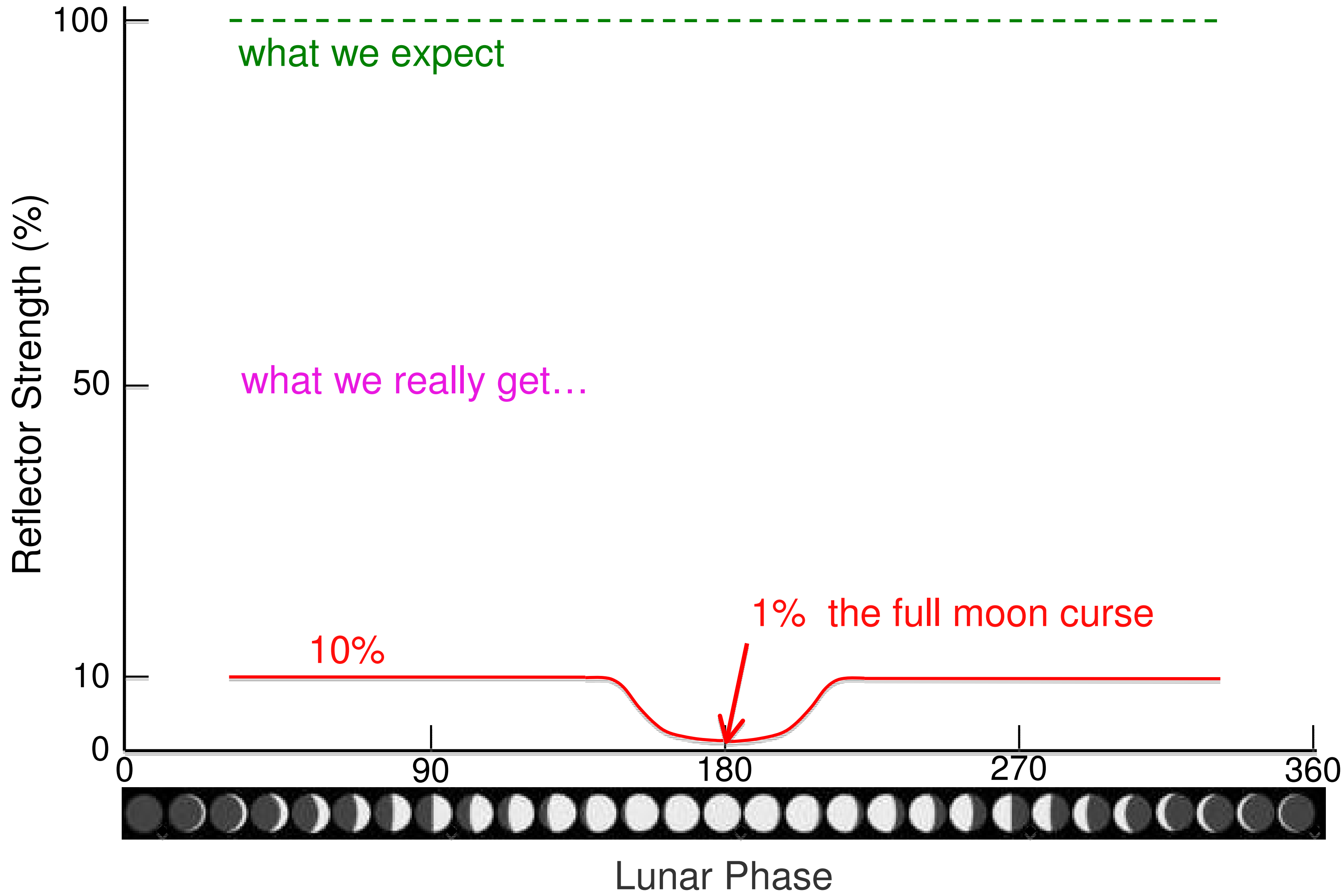
10 nrad
is 17 mm
at the Moon's
surface

A closer look at the best model (JPL)

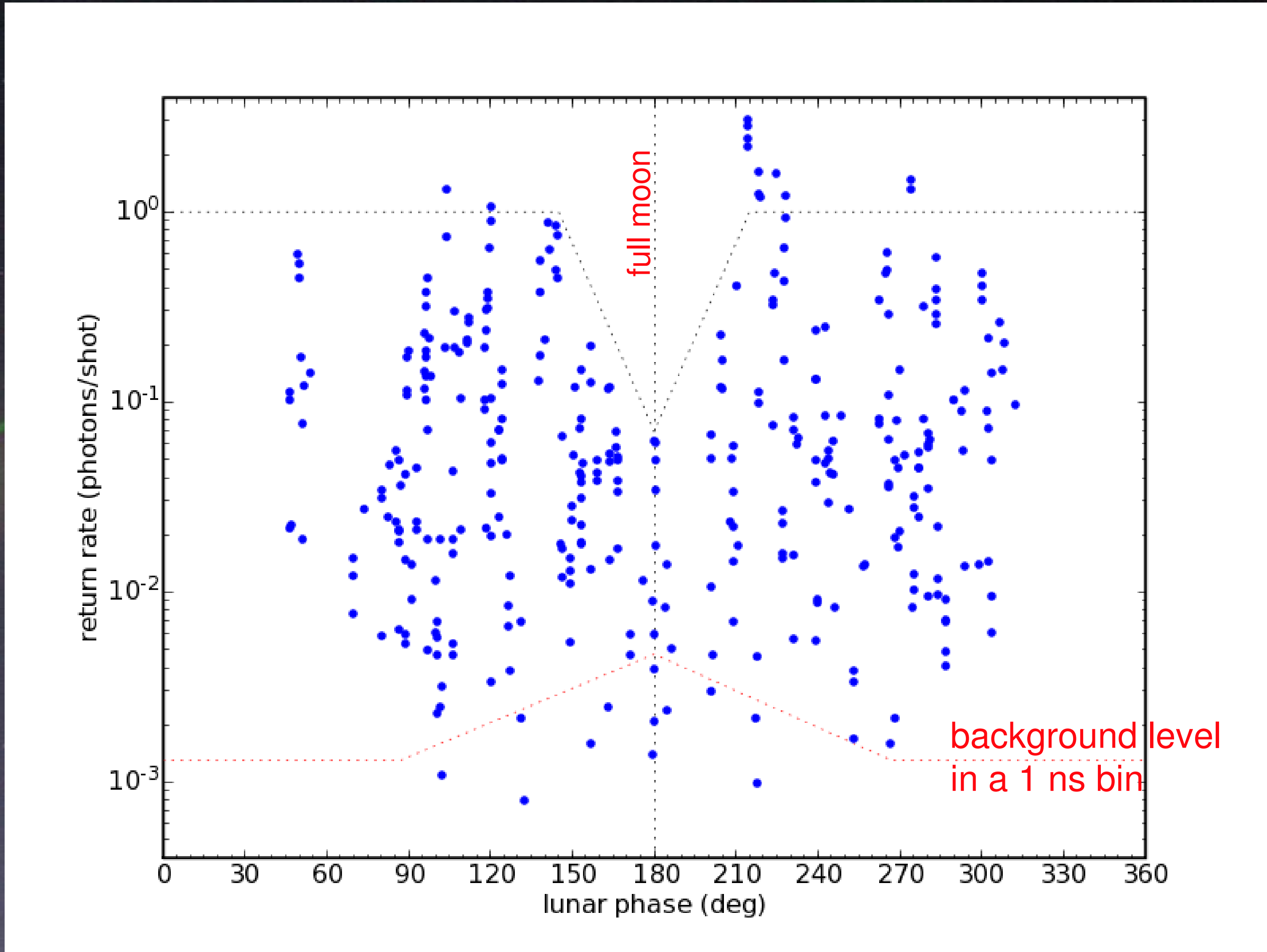


More weight to APOLLO data ➔ model does better on orientation

Reflector Degradation

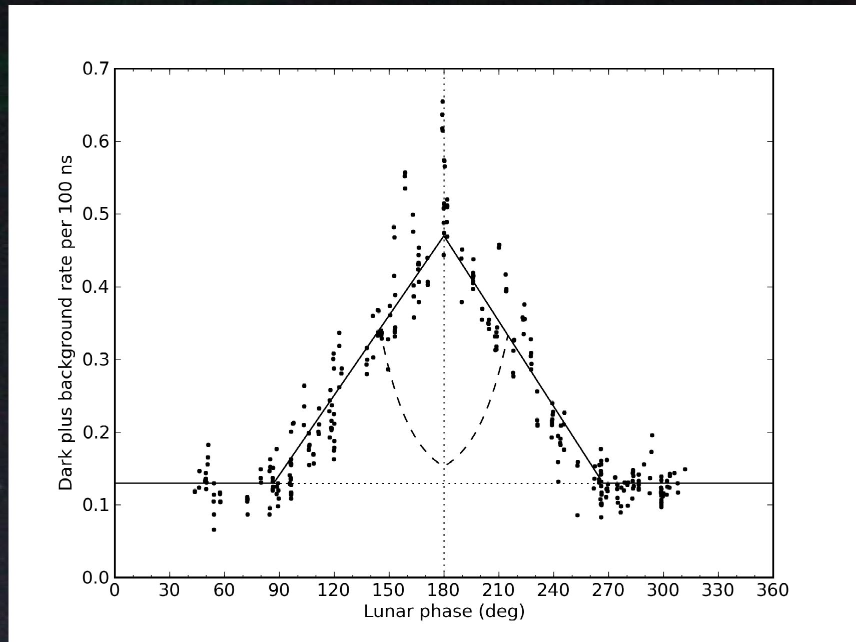


APOLLO rates on Apollo 15 reflector

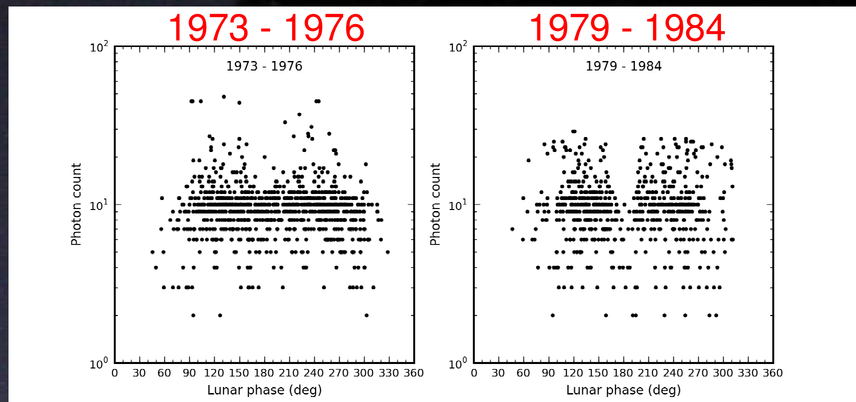


More on the deficit

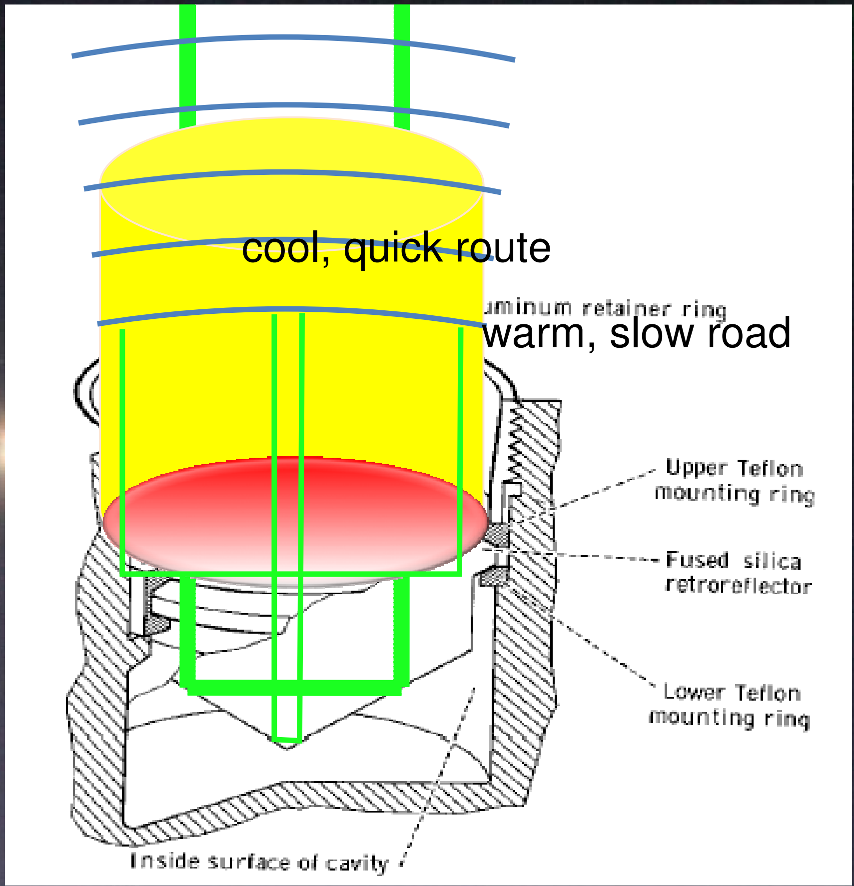
- APOLLO system sensitivity is not to blame for full-moon deficit
  - background is not impacted



- 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

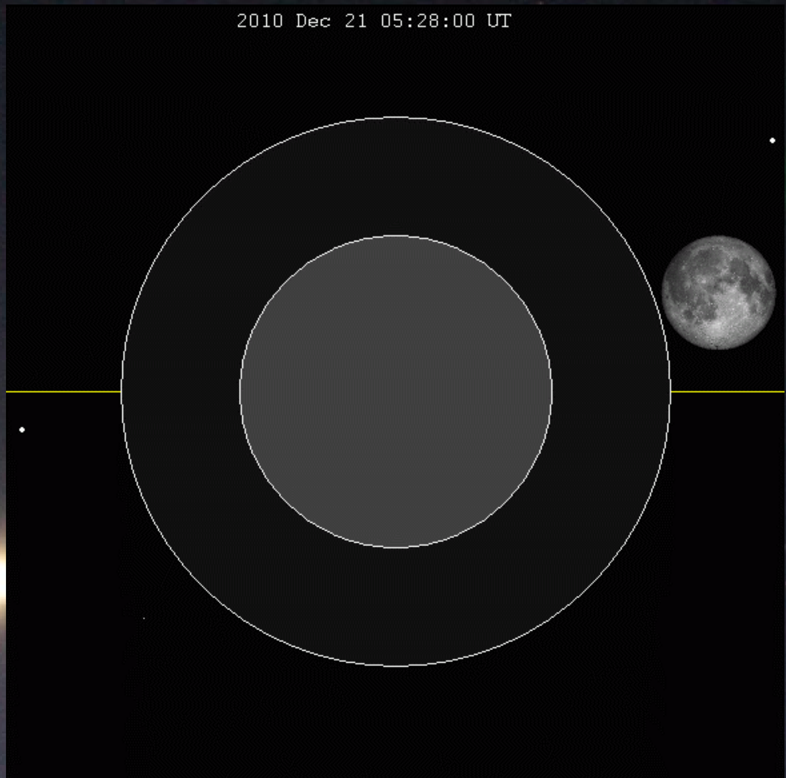


What’s Wrong?

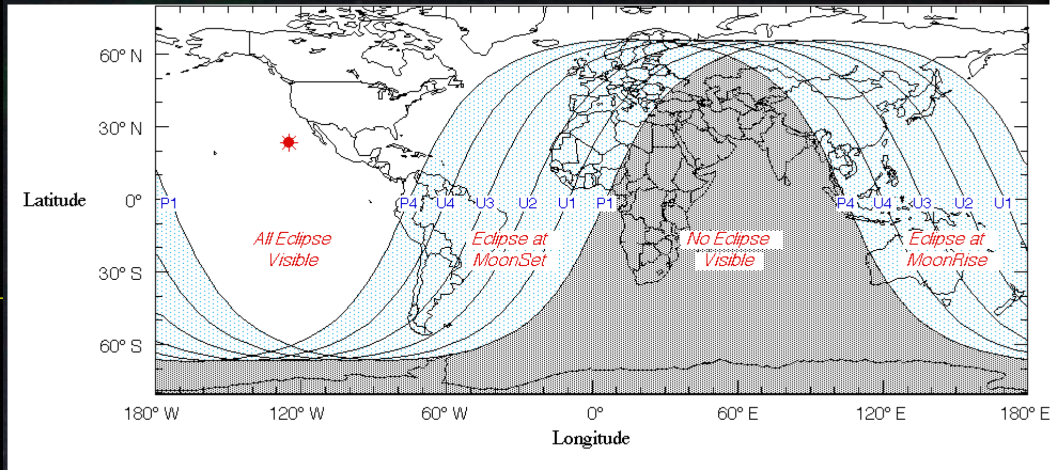


- The full-moon deficit, together with normal eclipse behavior, gives us the best clues:
  - thermal nature
  - absorbing solar flux
- Most likely: dust
  - Obviously could explain overall deficit (10%)
- Full moon effect then due to solar heating of dust
  - sun comes straight down tube at full moon
  - 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

Eclipse Opportunity



perfect eclipse for North America



- On December 21, 2010 (UTC), a perfectly-positioned eclipse gave us a celestial light switch
  - verified that sunlight is responsible for full moon curse
  - examine response time: is it thermal effect in corner cubes?

Eclipse Pics

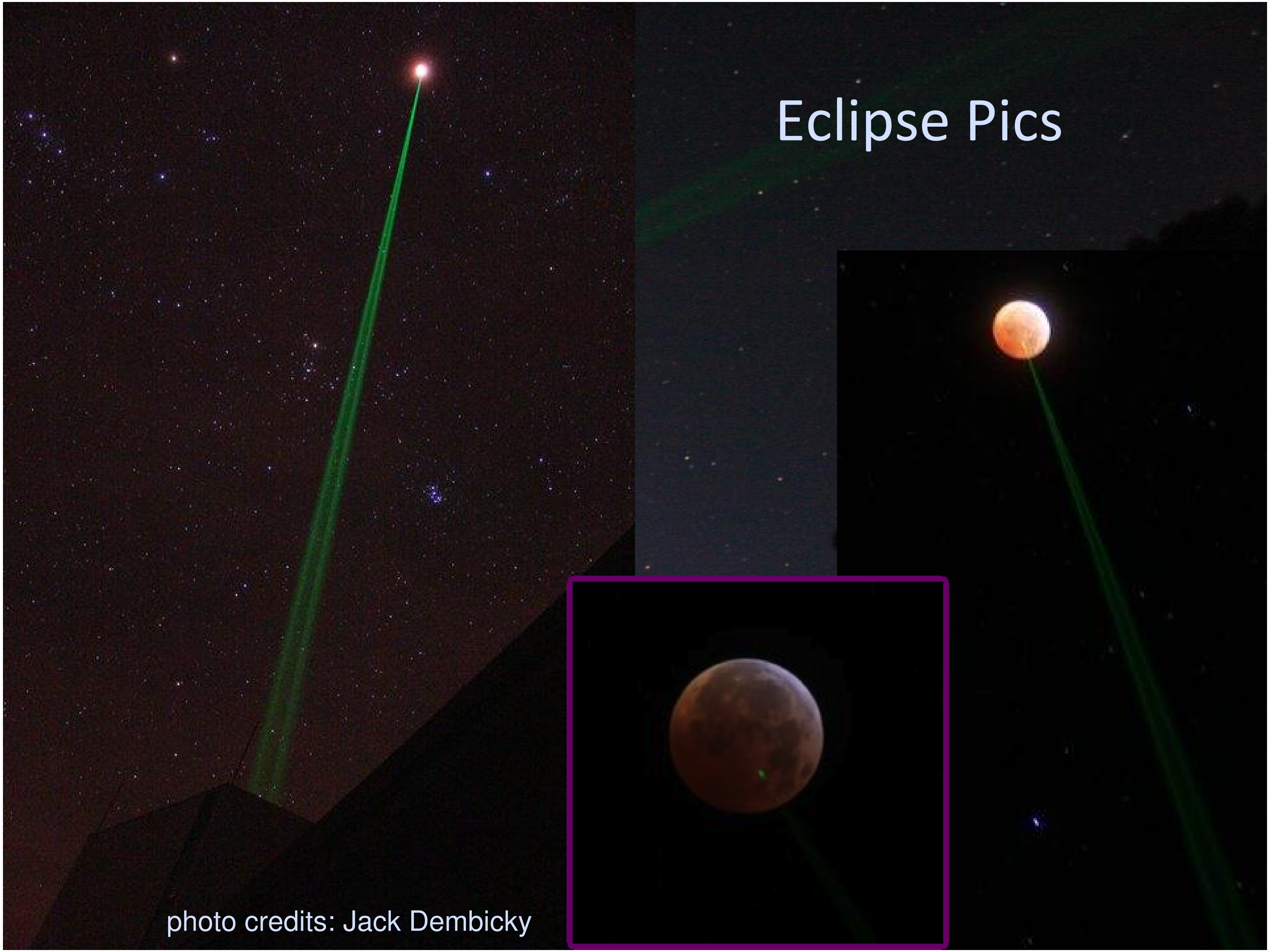
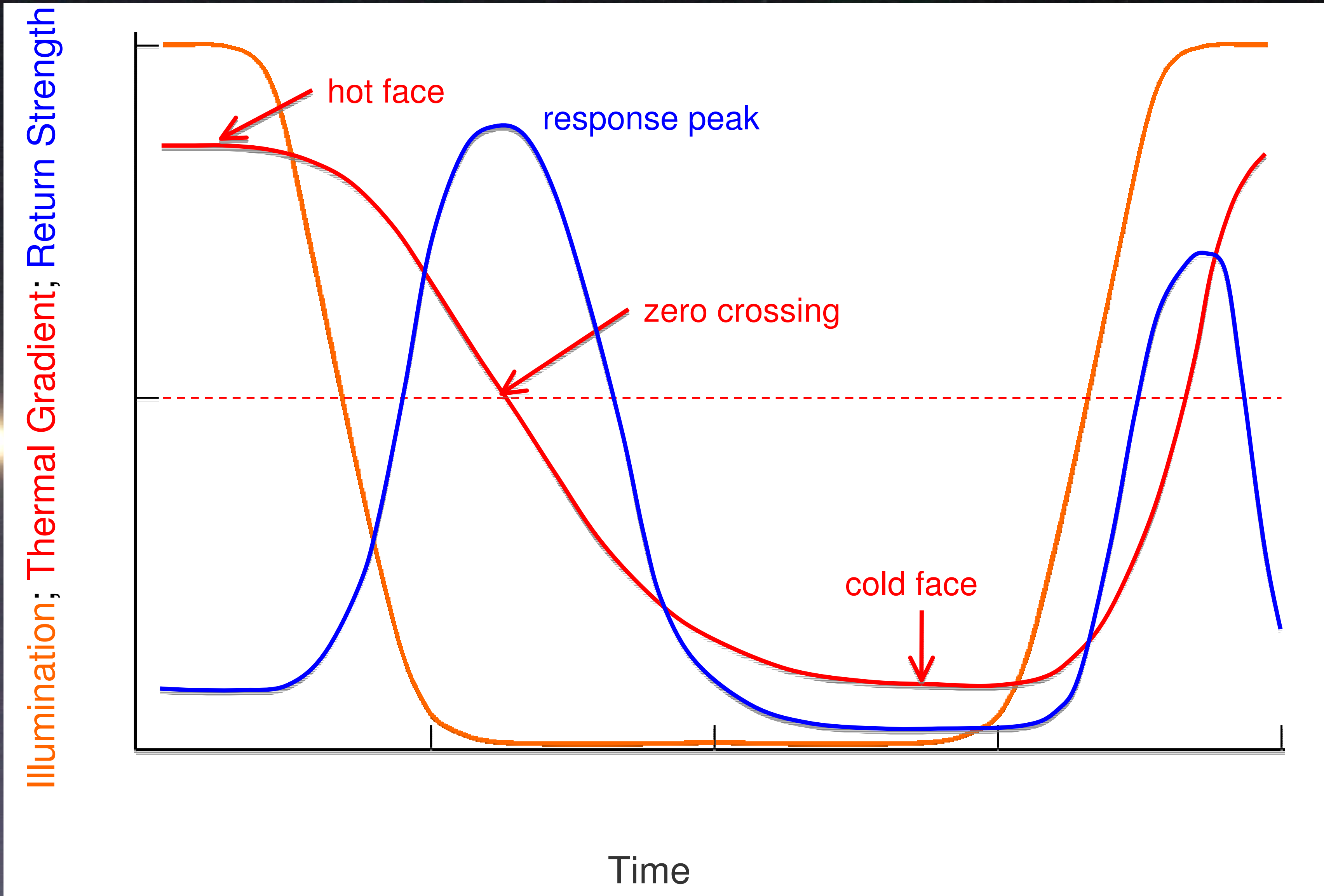
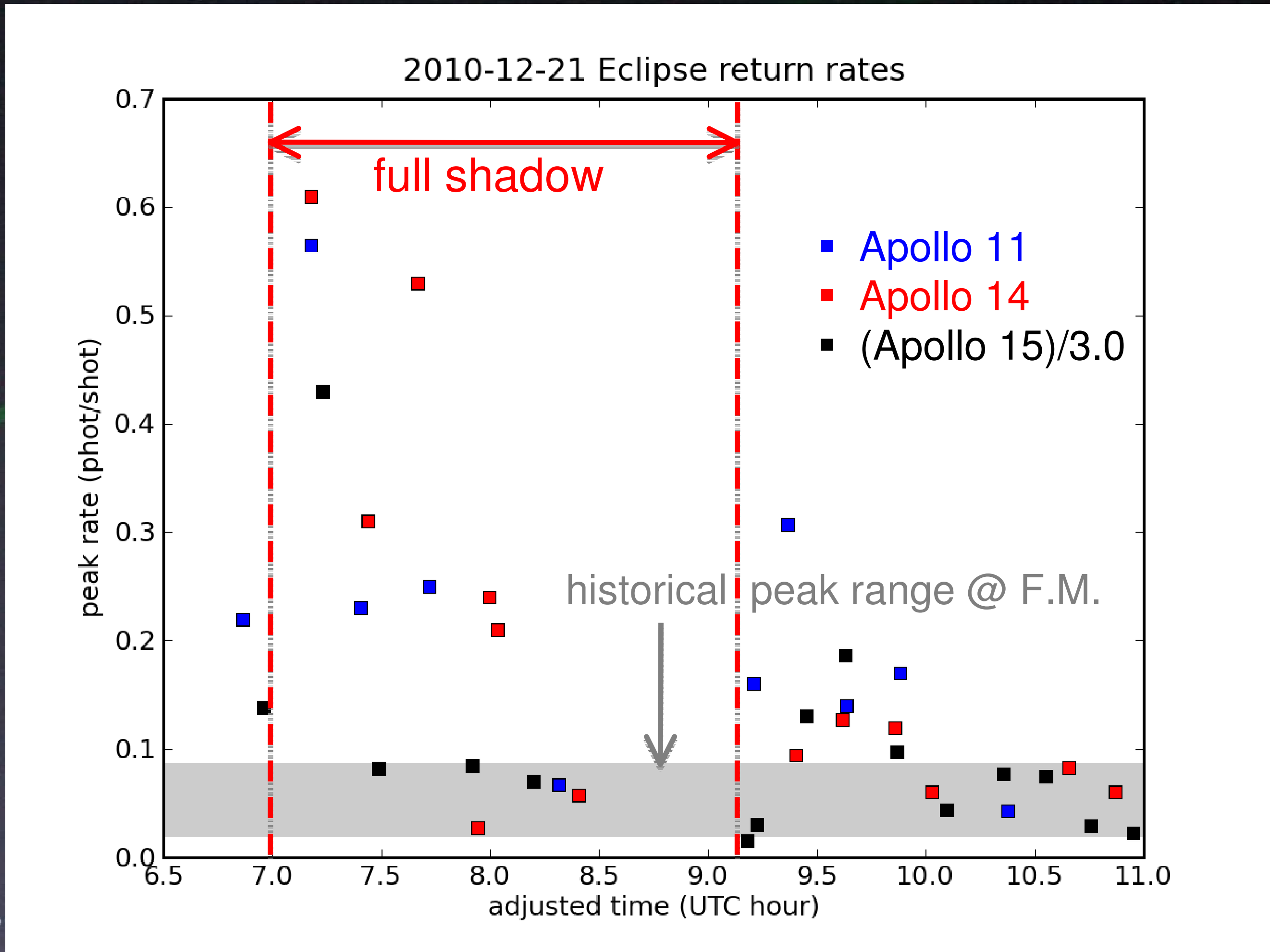


photo credits: Jack Dembicky

Cartoon of Expectations



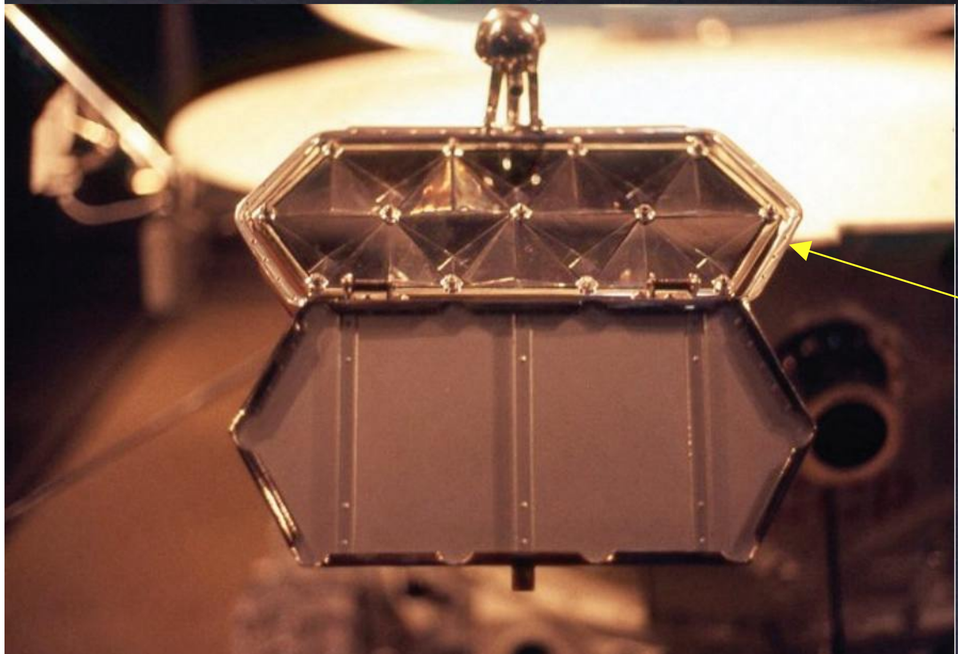
Preliminary Eclipse Results

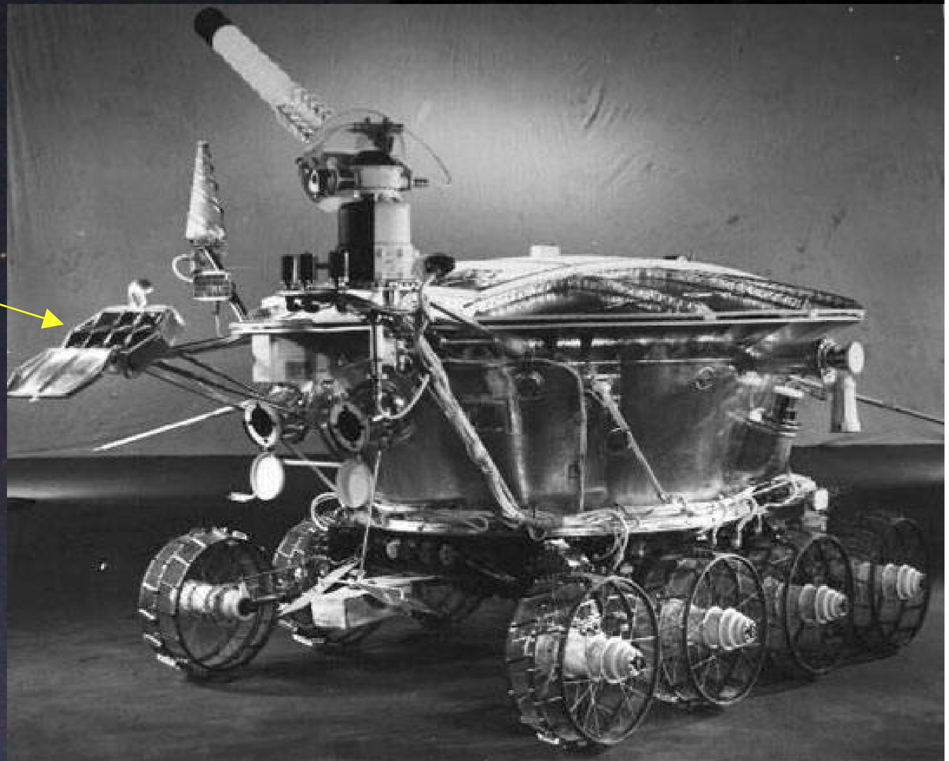


robust recovery initially, then down, and brief resurgence once light returns

The Lunokhod 1 Reflector

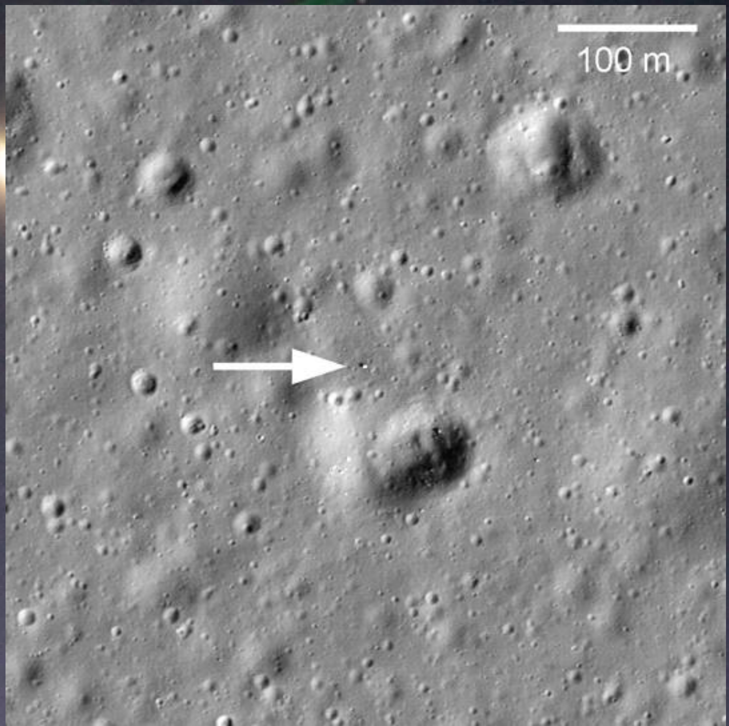
- **14** triangular CCRs, 11 cm side length
- Landed November 1970
- Sporadic early reports of Soviet and French ranging; no records persist
- Identical design to later Lunokhod 2 reflector
  - would expect L1 to be weak, like L2…or worse

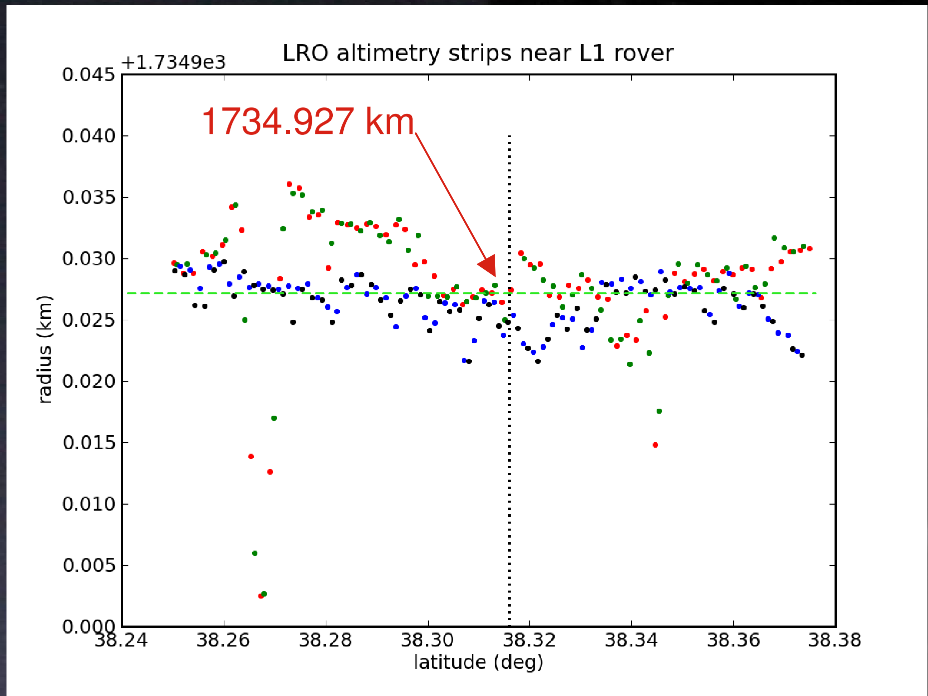




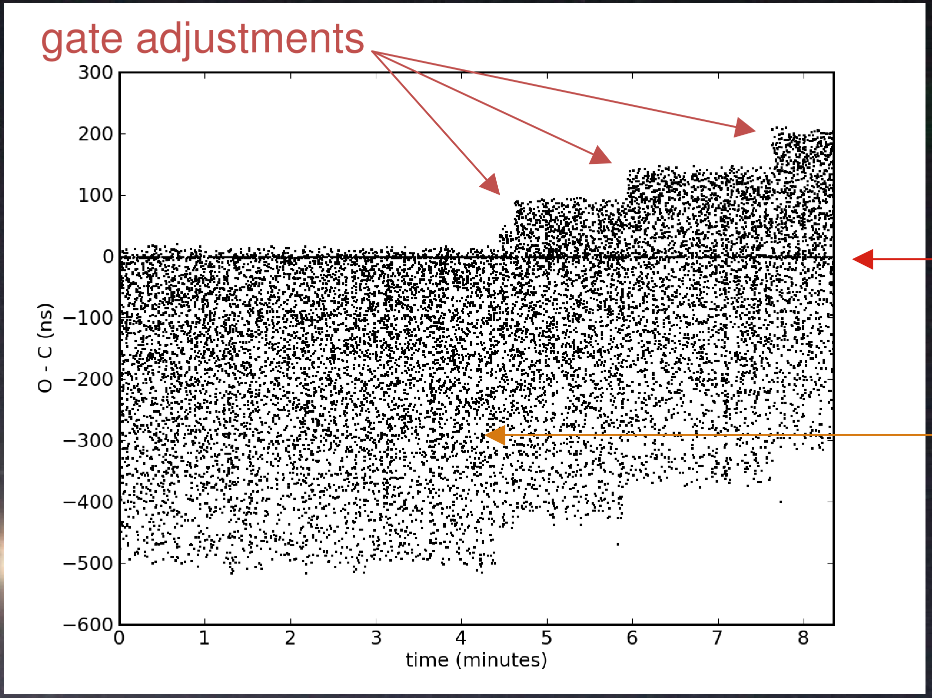
Enter LRO

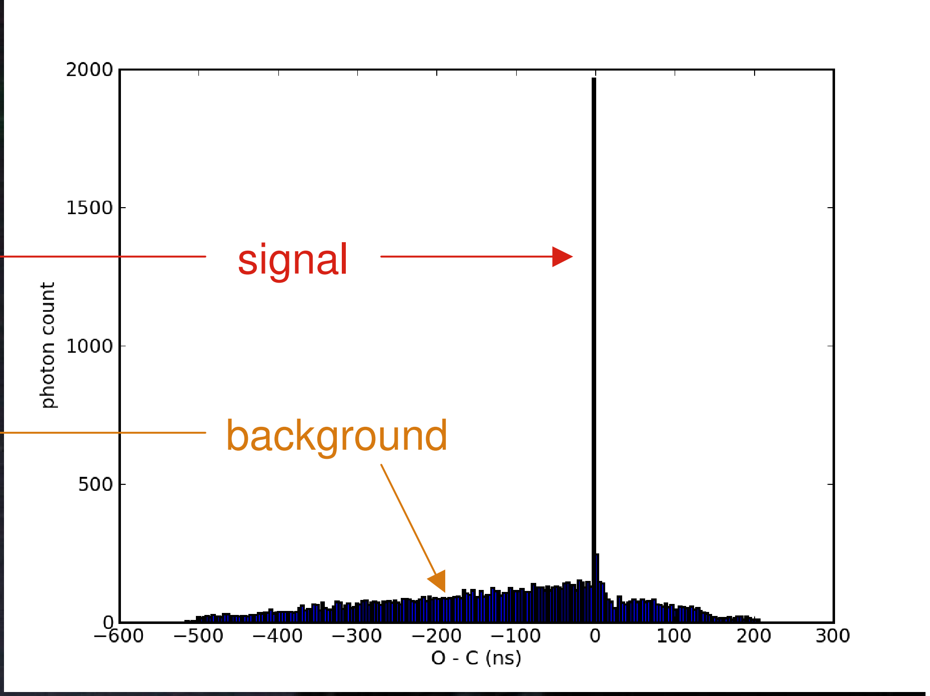
- The Lunar Reconnaissance Orbiter (LRO) paved the way:
  - LROC imaging (March 2010) found the rover and provided coordinates
  - LOLA altimetry fixed the site radius
  - LRO corner cube array prompted APOLLO to develop wide gate



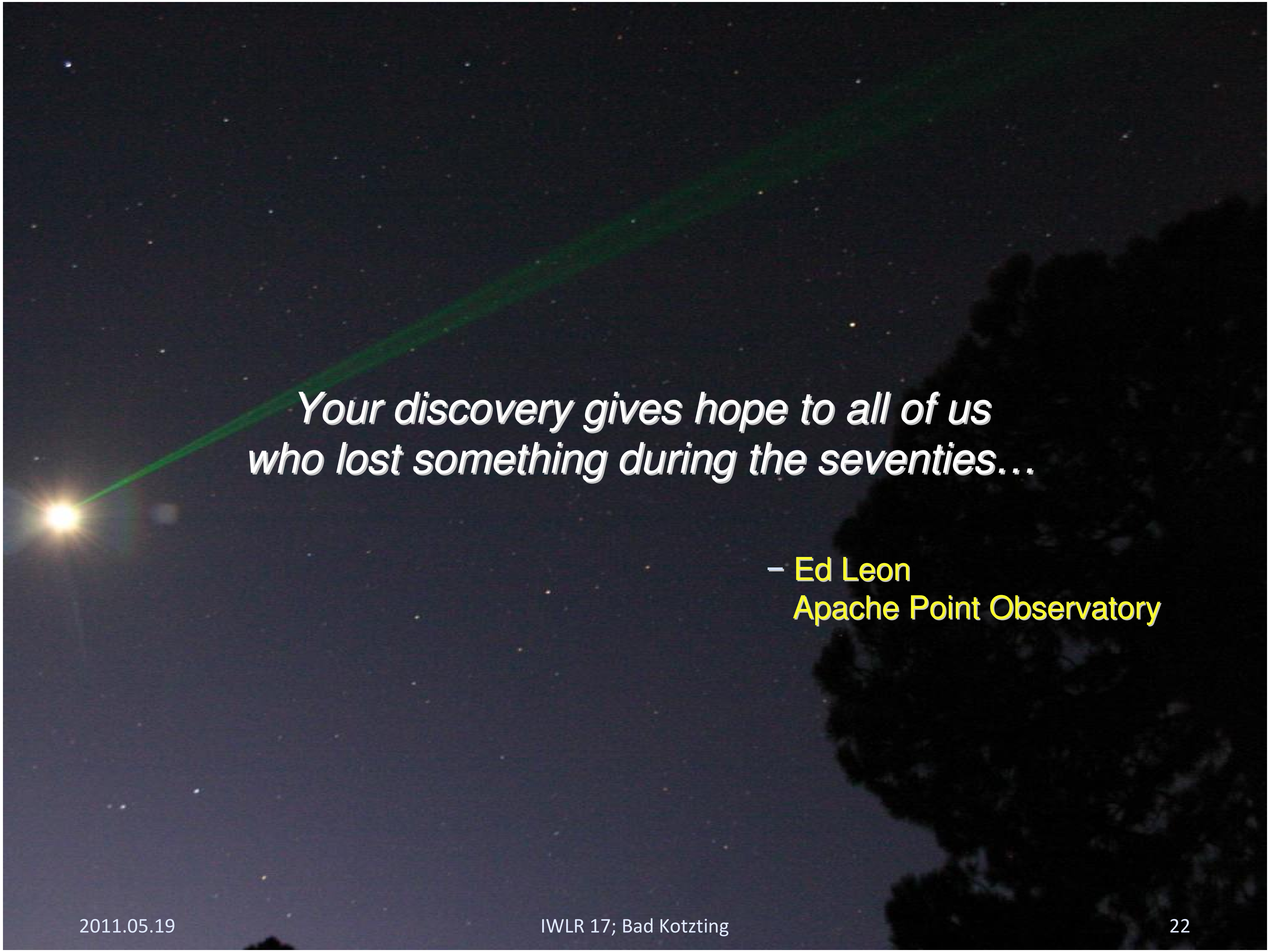


APOLLO Find, 22 April, 2010





- Armed with 100 meter accurate coordinates, APOLLO's first favorable telescope time produced stunning results
- Offset was 40 m (270 ns) in projected range (100 m lateral), putting signal at edge of gate
- Gate adjustments in first run confirmed reality
- Almost 2000 photons in first try: so bright we thought we were being fooled

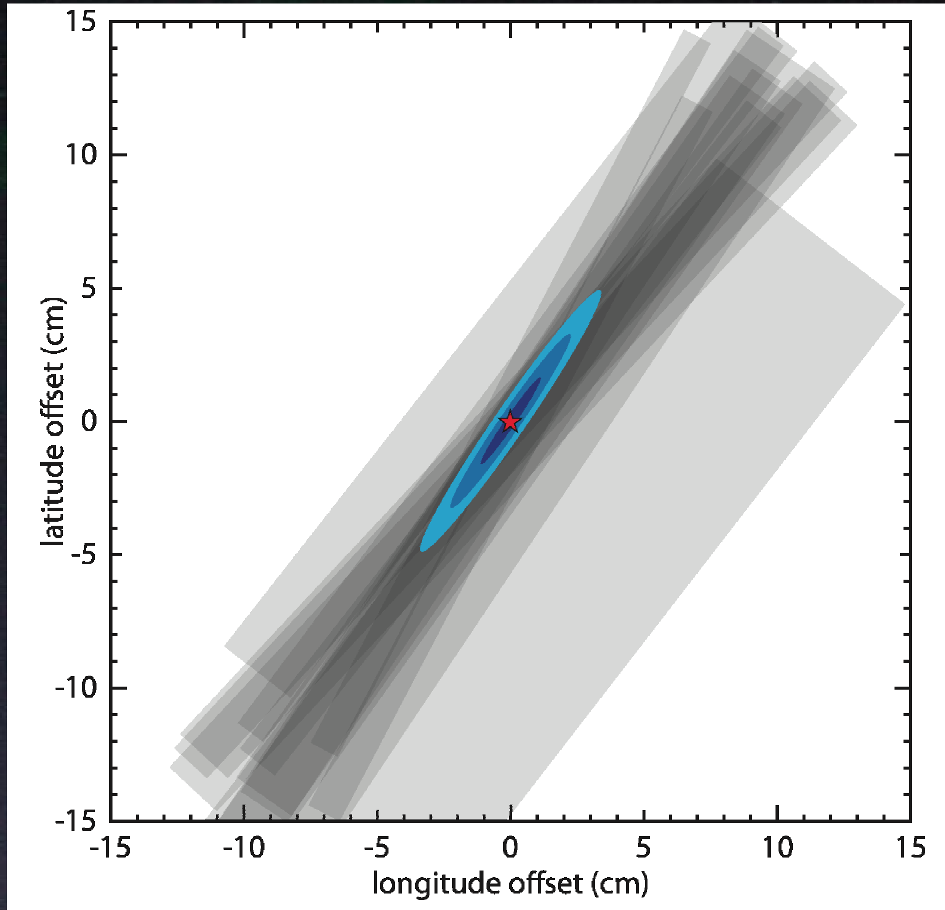


Your discovery gives hope to all of us
who lost something during the seventies…

– Ed Leon
Apache Point Observatory

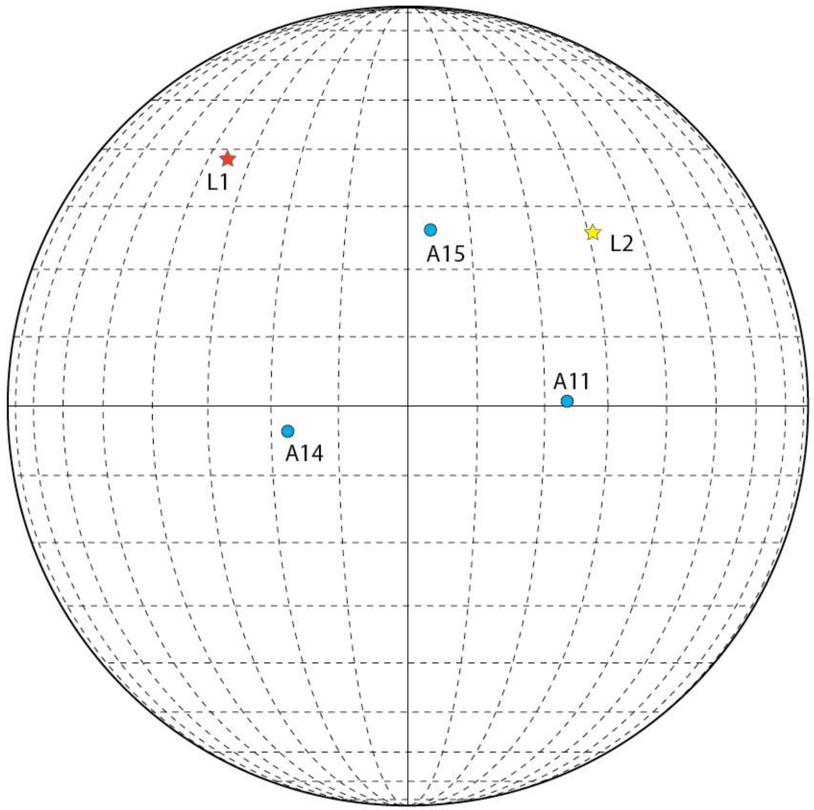
Current Error Ellipse

- Based on a few months of observation at a limited sampling of librations, we have a centimeter-level position determination
- Error ellipses are 1σ, 2σ, 3σ
- Best-fit position, in DE421 Principal-Axis coordinates:
  - r = 1734928.72
  - lat = 38.3330784°
  - lon = -35.036674°
- Location of L1 makes it especially valuable for science



Potential Impact on Science

- L1 is the farthest reflector from the apparent lunar center
- Offers best leverage on libration determination
  - key for C.o.M. motion → gravity
  - also for lunar interior study
- Unlike Apollo reflectors, L1 (and L2) offer *both* latitude and longitude libration sensitivity
- More reflectors probe tidal deformation



Reflector	θ from center	libration sensitiv.	longitude sensitiv.	latitude sensitiv.
A11	23.5°	0.40	0.40	0.01
A14	17.9°	0.31	0.30	0.06
A15	26.4°	0.44	0.06	0.44
L1	50.0°	0.77	0.45	0.51
L2	39.5°	0.63	0.46	0.37

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
- Our steady-state campaign is now 4.5 years old
  - began October 2006, one year after first light
- Now grappling with analysis in the face of vastly better data
  - much new stuff to learn, with concomitant refinements to data reduction and to the analytical model
  - plans to develop open source LLR/planetary analysis code
- Some surprises along the way
  - degradation of reflectors
  - found lost Lunokhod 1 reflector; now have 5