APOLLO

Overview

Performance

Findings

Tom Murphy (UCSD)

photo credit: Jack Dembicky

The APOLLO Collaboration

UCSD:
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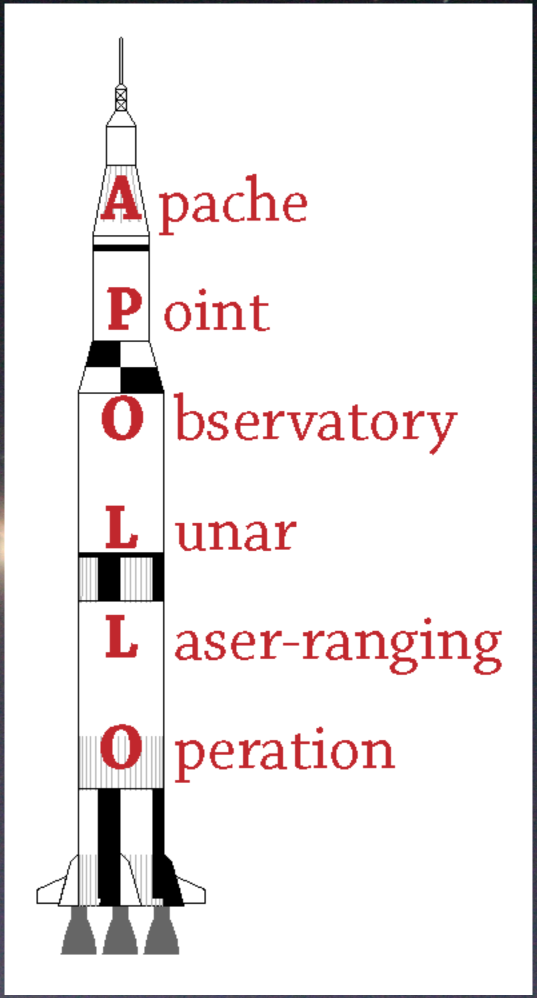
Wellesley:
James Battat

Humboldt State:
C. D. Hoyle

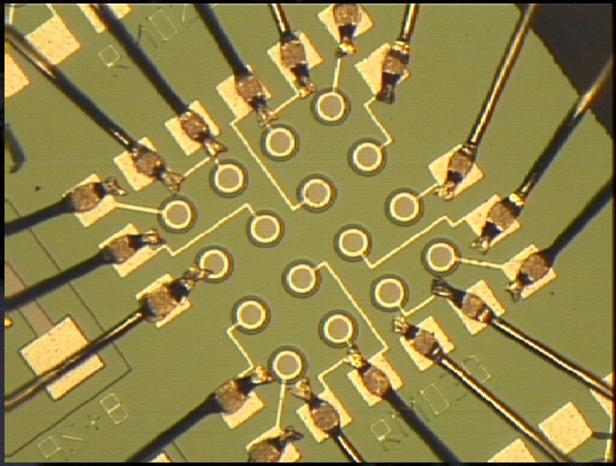
Apache Point Obs.
Russet McMillan

Northwest Analysis:
Ken Nordtvedt

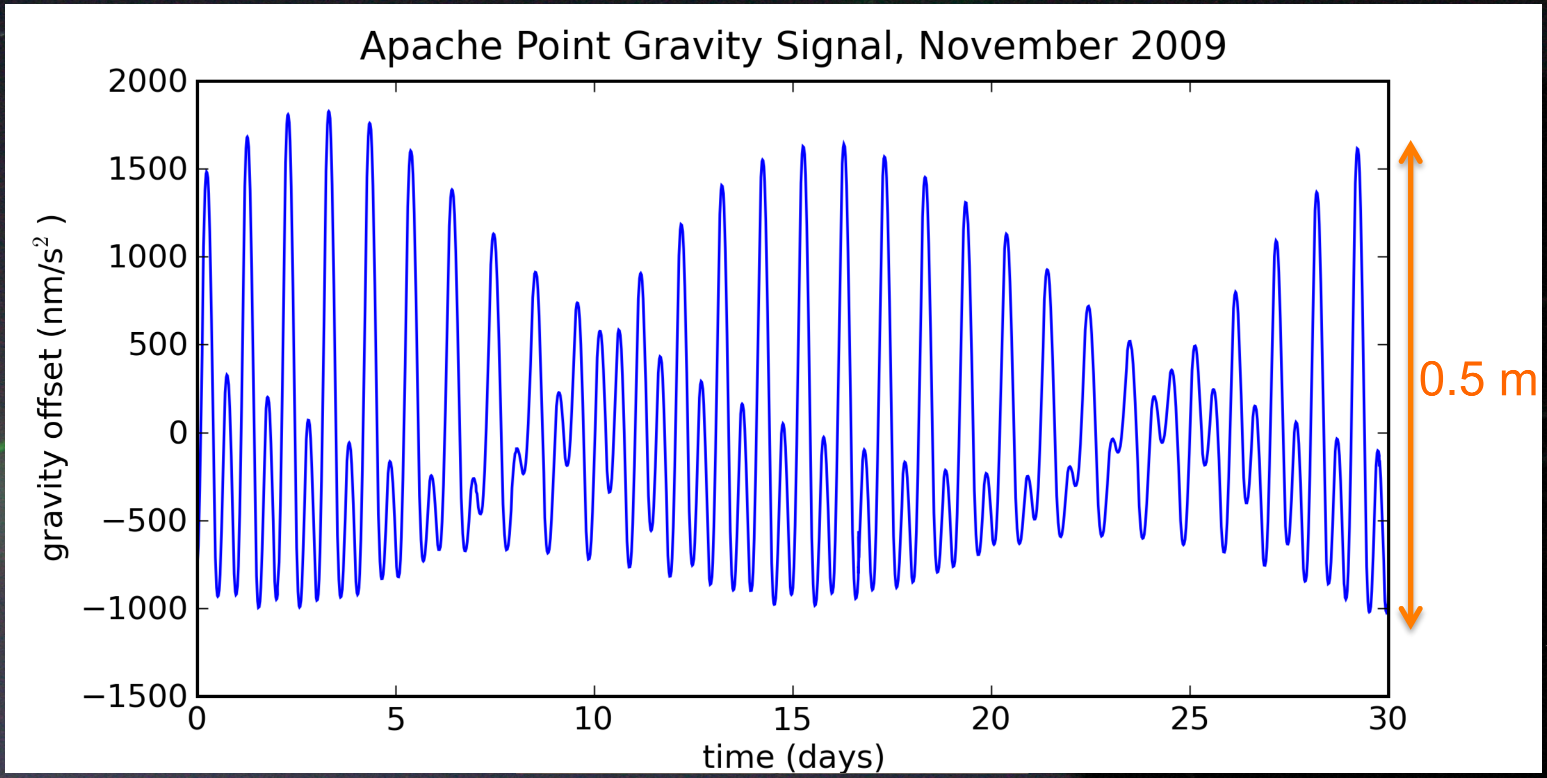
APOLLO At a Glance



- 3.5 m telescope at 2800 m (9200 ft)
  - 1 arcsec (5 μrad) seeing common
  - competitively scheduled
  - 2% of time: 8–10 < 1 hr spots per month
- 20 Hz, 100 mJ, 100 ps, 532 nm laser
- 4×4 APD array (1.4 arcsec field of view)
  - 100 μm center spacing; 40 μm elements
  - lenslet array
- Fiducial CCR
  - on secondary
- ~50 shot juggle

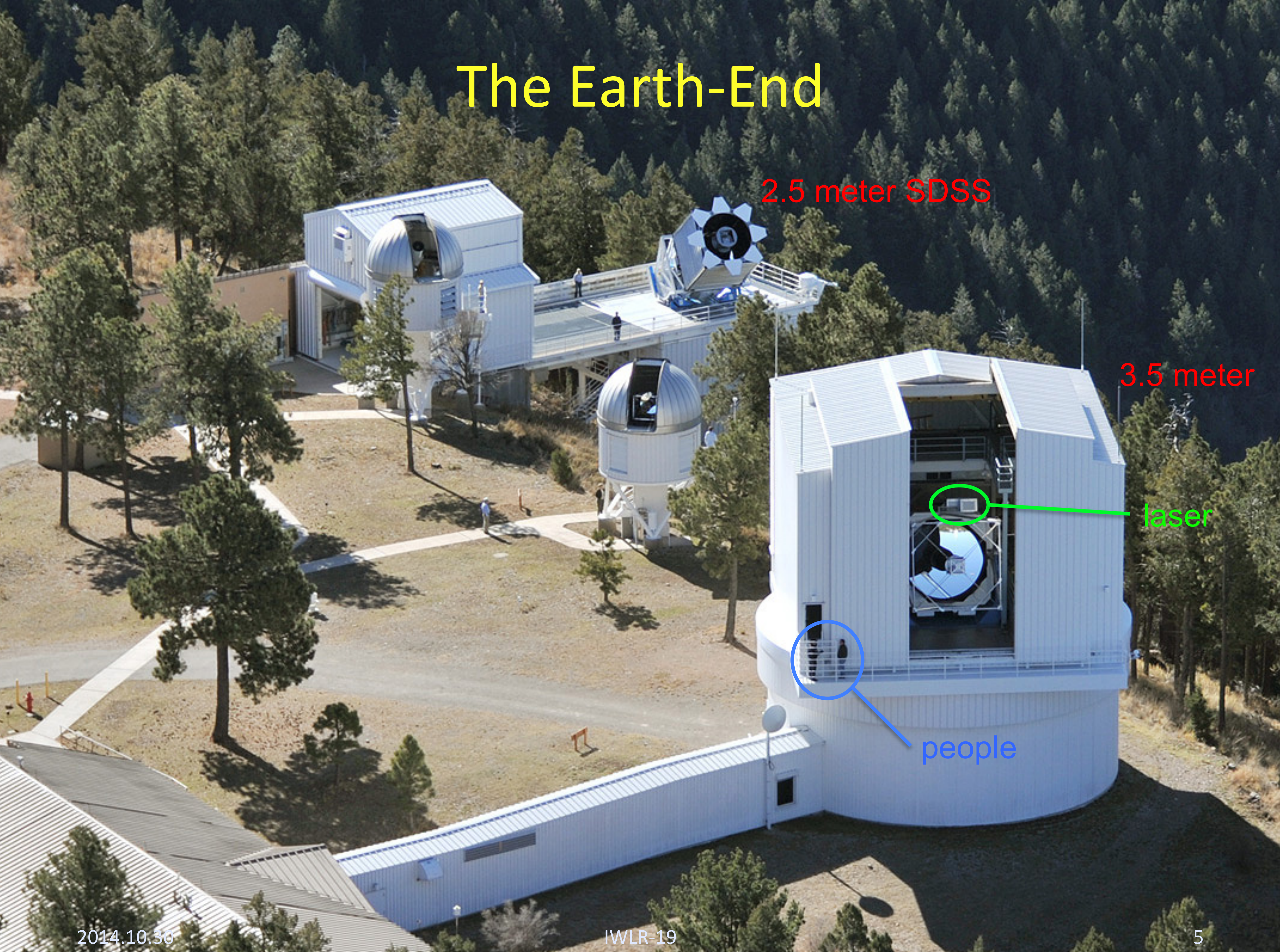


Superconducting Gravimeter Installed



- 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!*

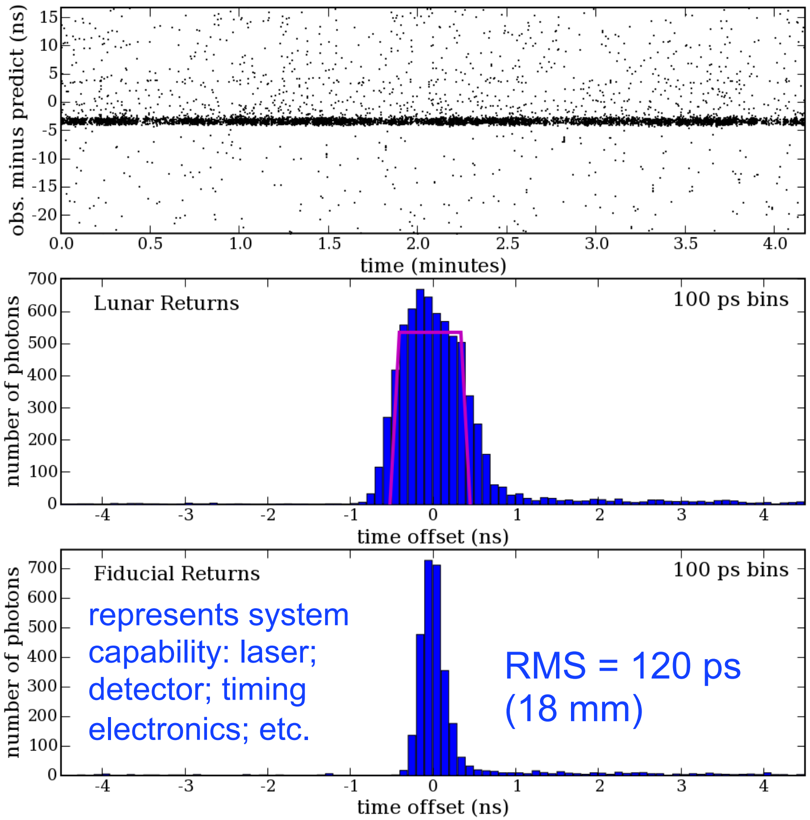
The Earth-End

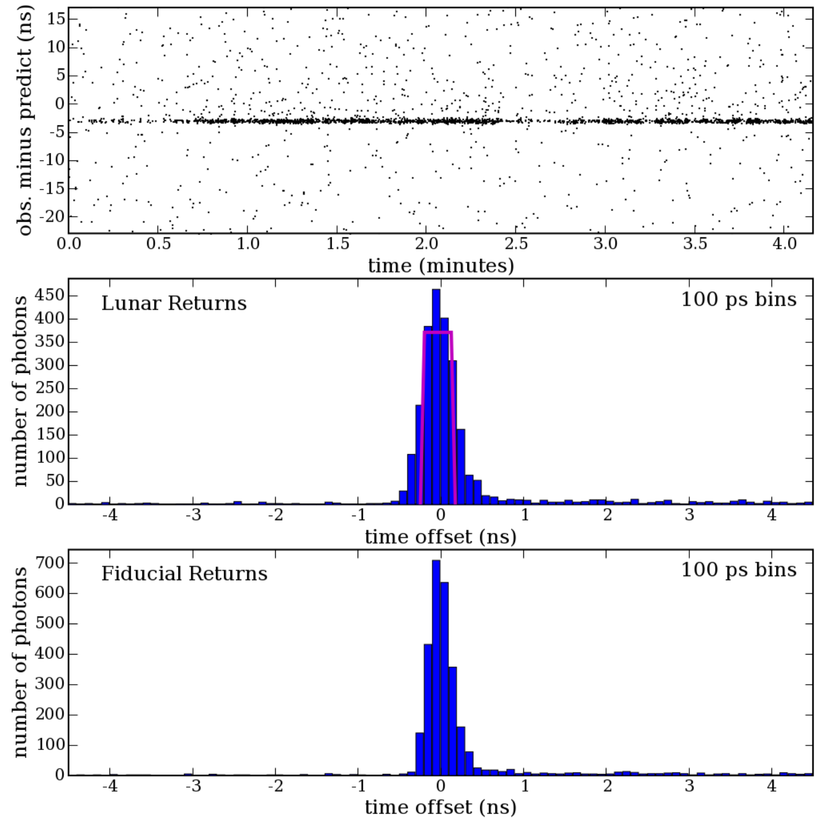


Strong Returns

Apollo 15 2007.11.19 **Apollo 11**

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

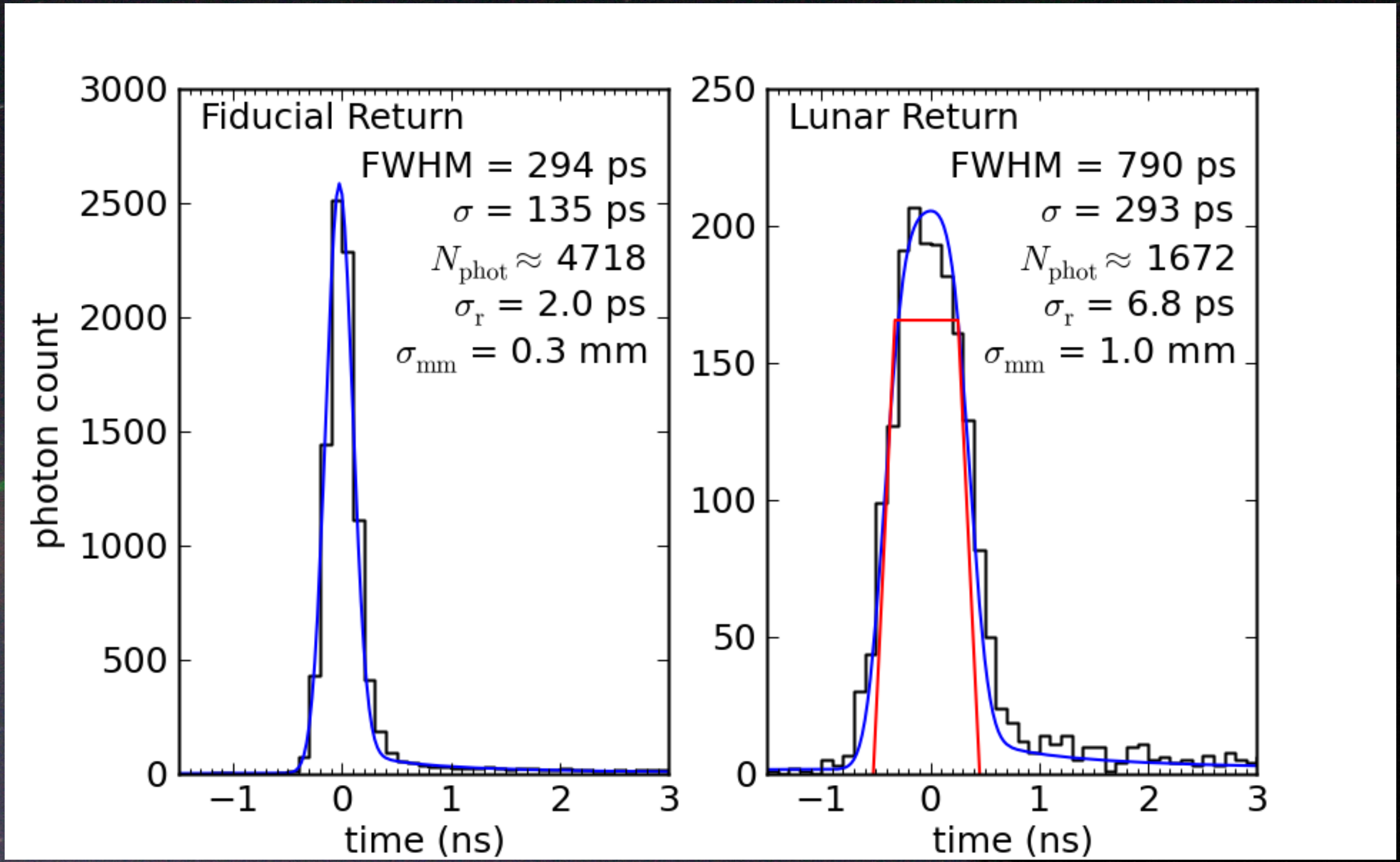




- 6624 photons in 5000 shots
- 369,840,578,287.4 ± 0.8 mm
- 4 detections with 10 photons

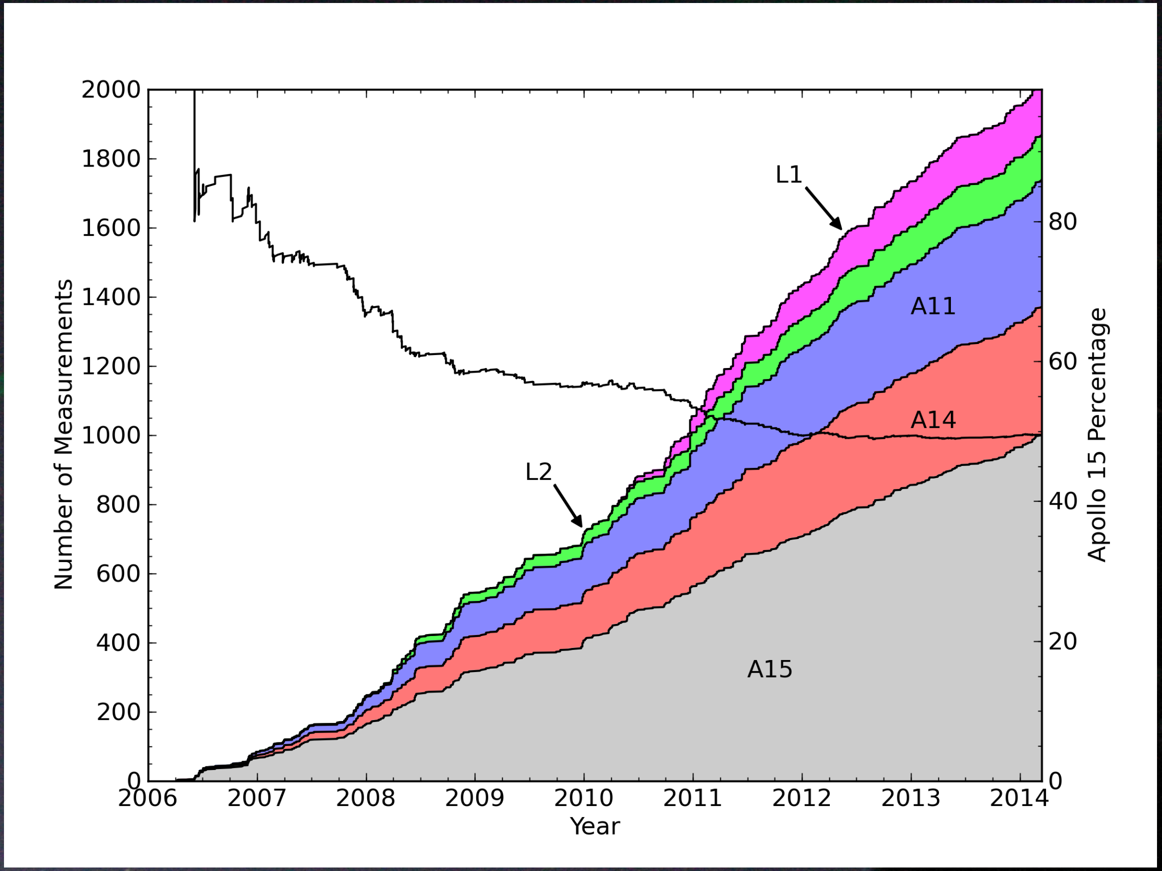
- 2344 photons in 5000 shots
- 369,817,674,951.1 ± 0.7 mm
- 1 detection with 8 photons

Fitting the Return & Reflector Trapezoid



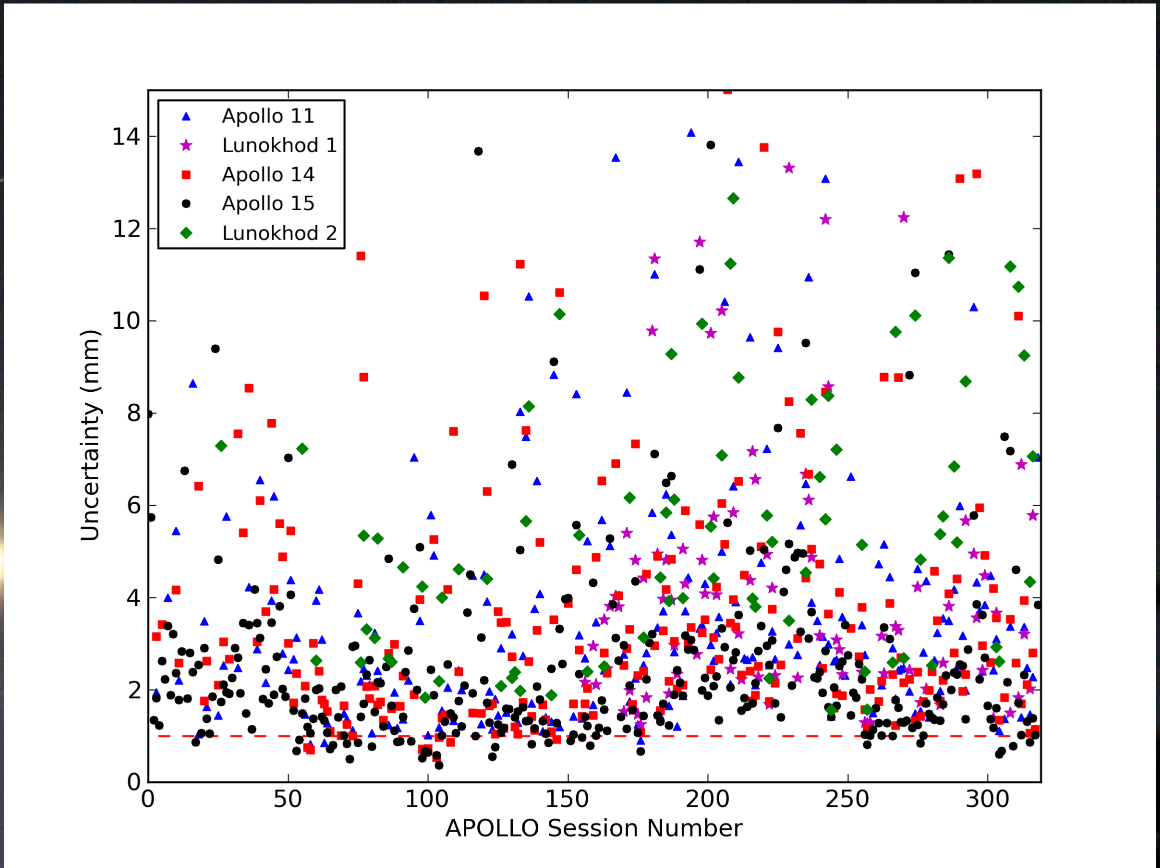
Functional fit to fiducial (local corner cube), including APD diffusion tail.
Convolve with known trapezoid reflector function & slide for best fit.
Fit parameter uncertainty similar to Poisson expectation.

APOLLO Data Campaign



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

APOLLO Estimated (Random) Uncertainty

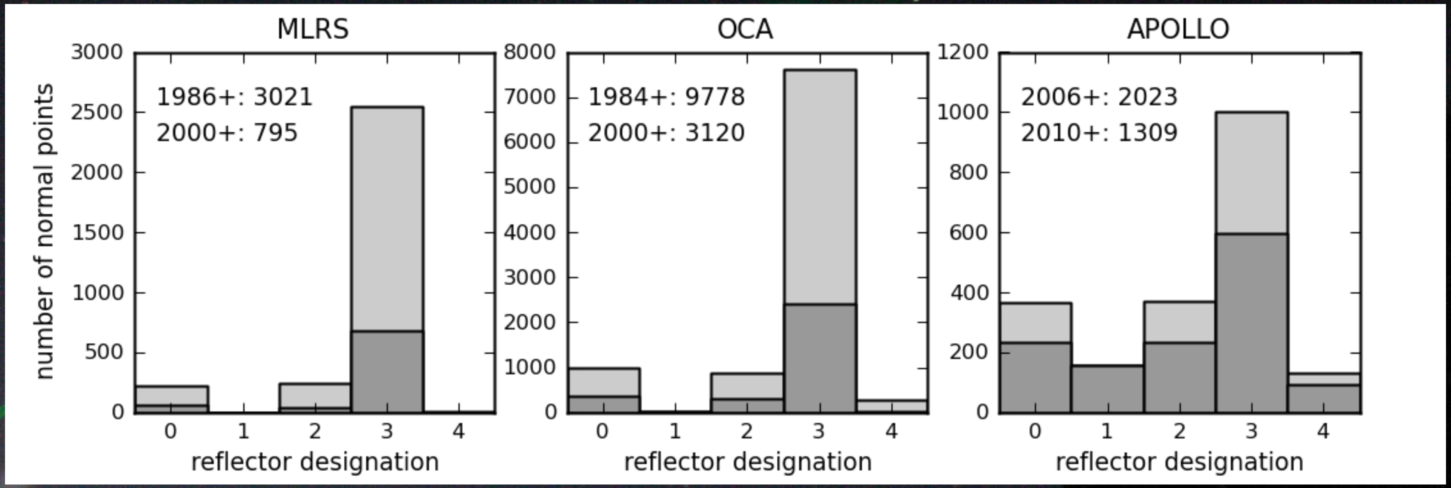


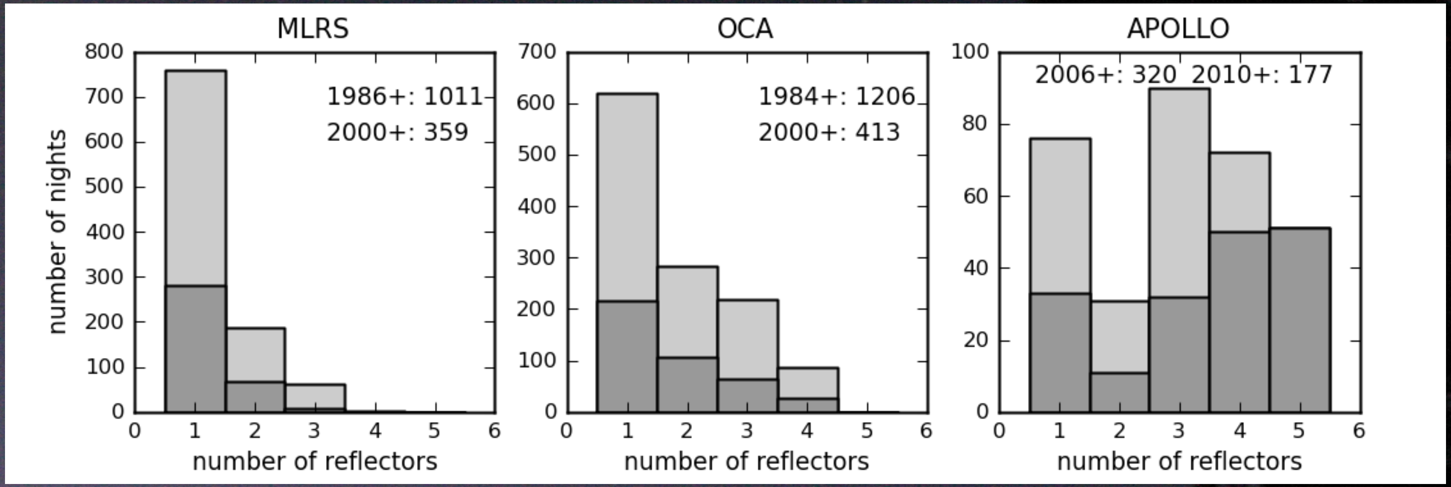
Note: realistic uncert. may be factor of 2 larger (or convolve with 20 ps)

Note: 1.5 yr @ poorer quality 2010.12.01 to 2012.04.06: 6× scale or 60 ps convolve

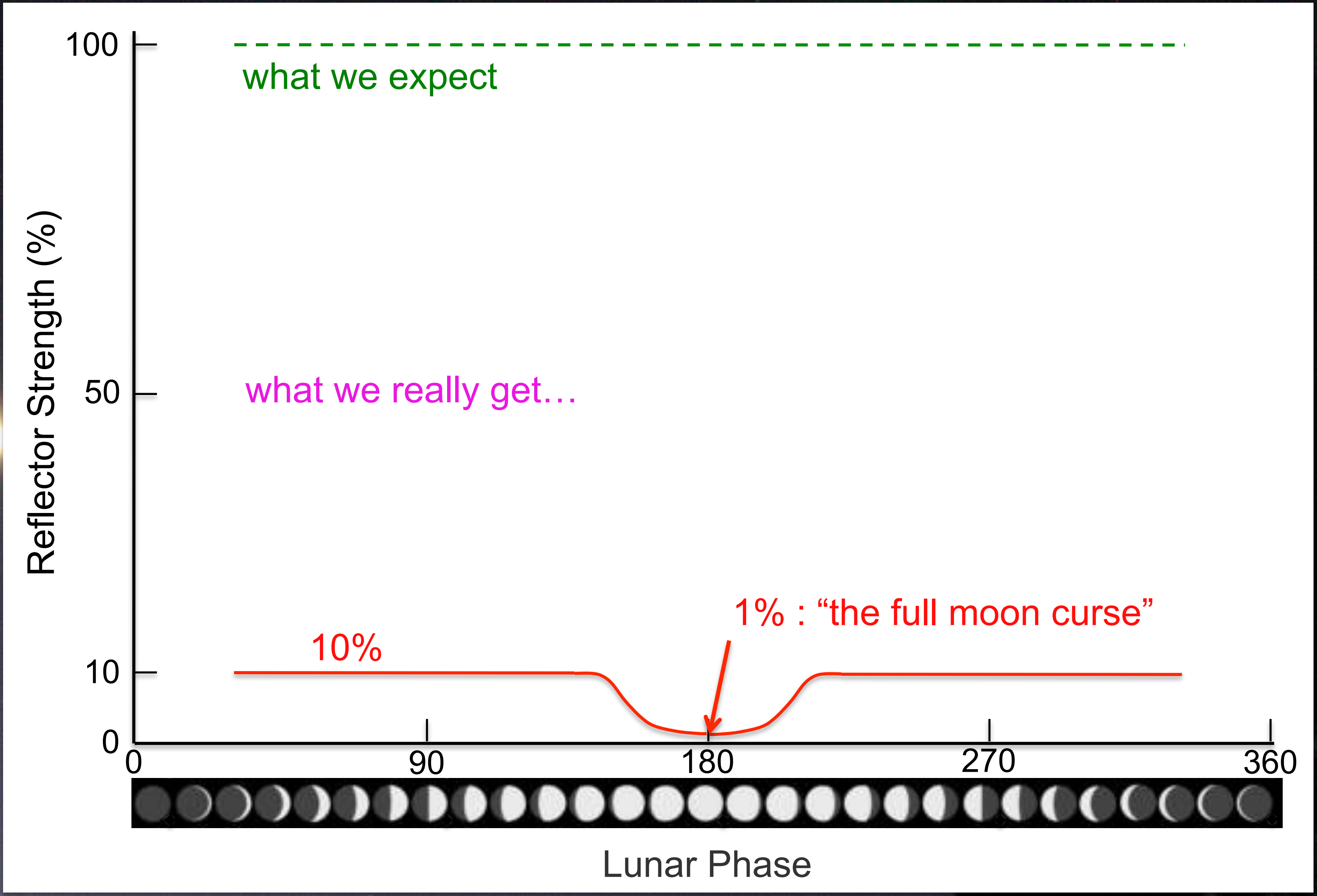
- Uncertainties are per night, per reflector
- Medians are 2.7, 3.6, 2.7, 1.9, 5.2 mm for A11, L1, A14, A15, L2, respectively
- Combined nightly median range error is 1.45 mm

Branching Out to Other Reflectors

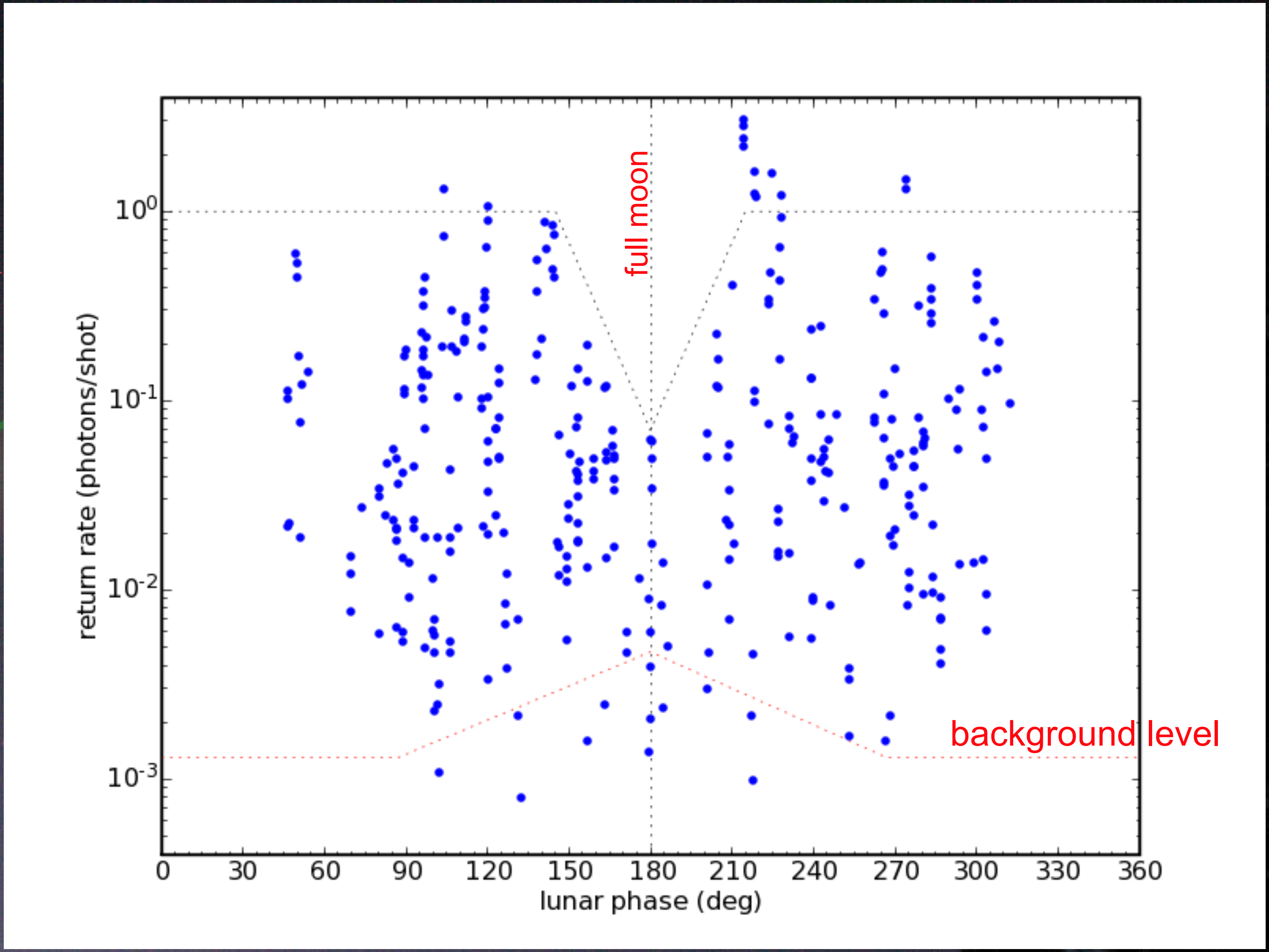




Reflector Degradation

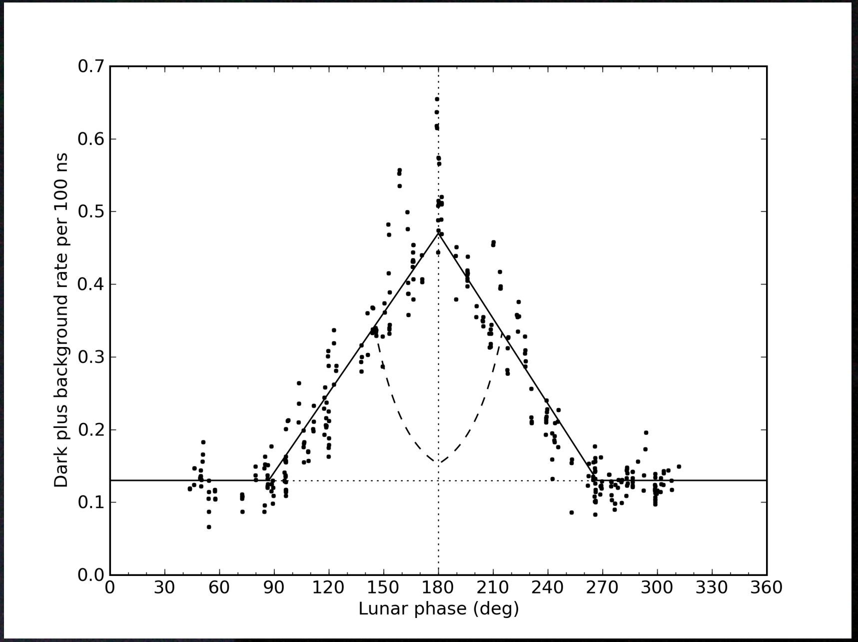


APOLLO rates on Apollo 15 reflector

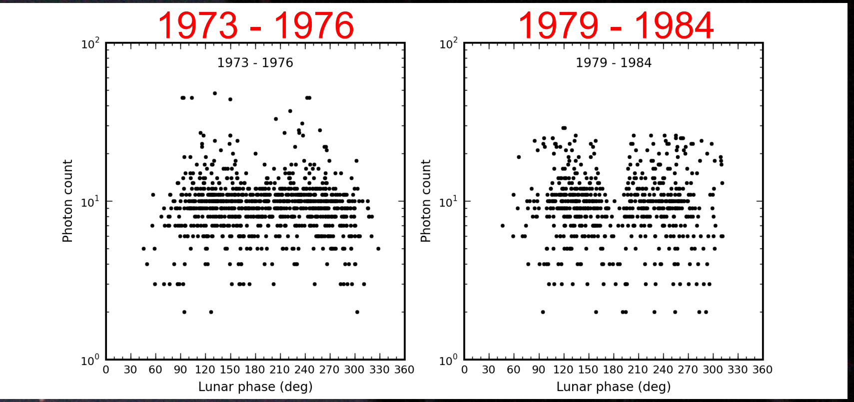


More on the deficit

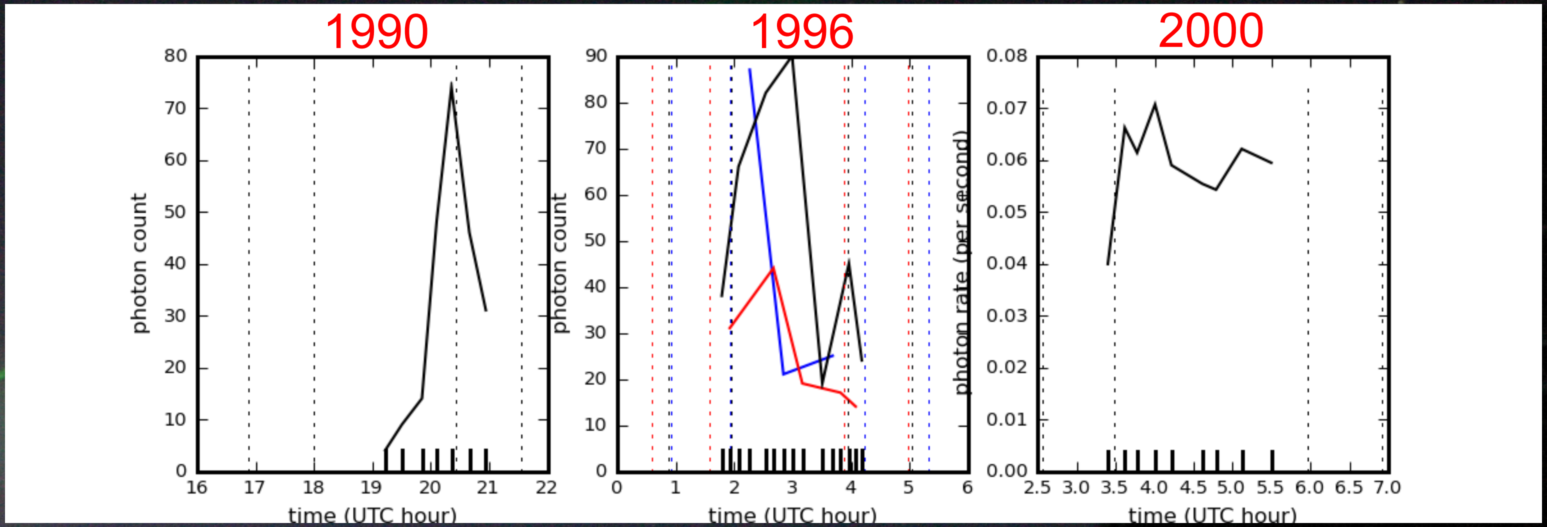
- APOLLO system sensitivity is not to blame for full-moon deficit
  - background is not impacted



- 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

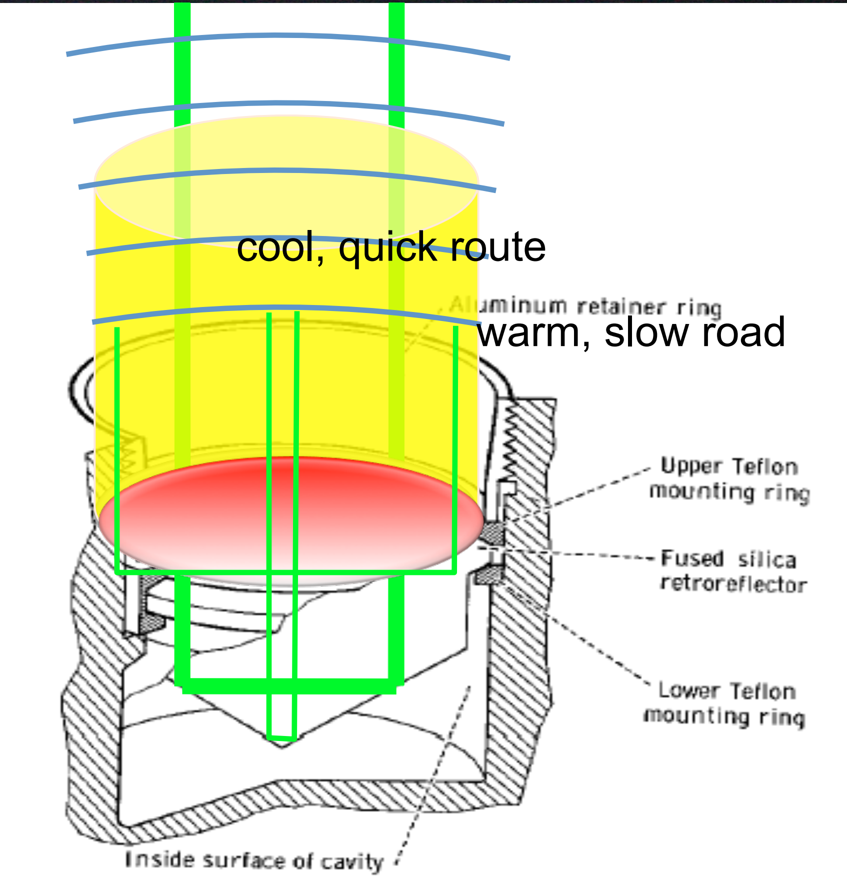


Past Eclipses, OCA Observations



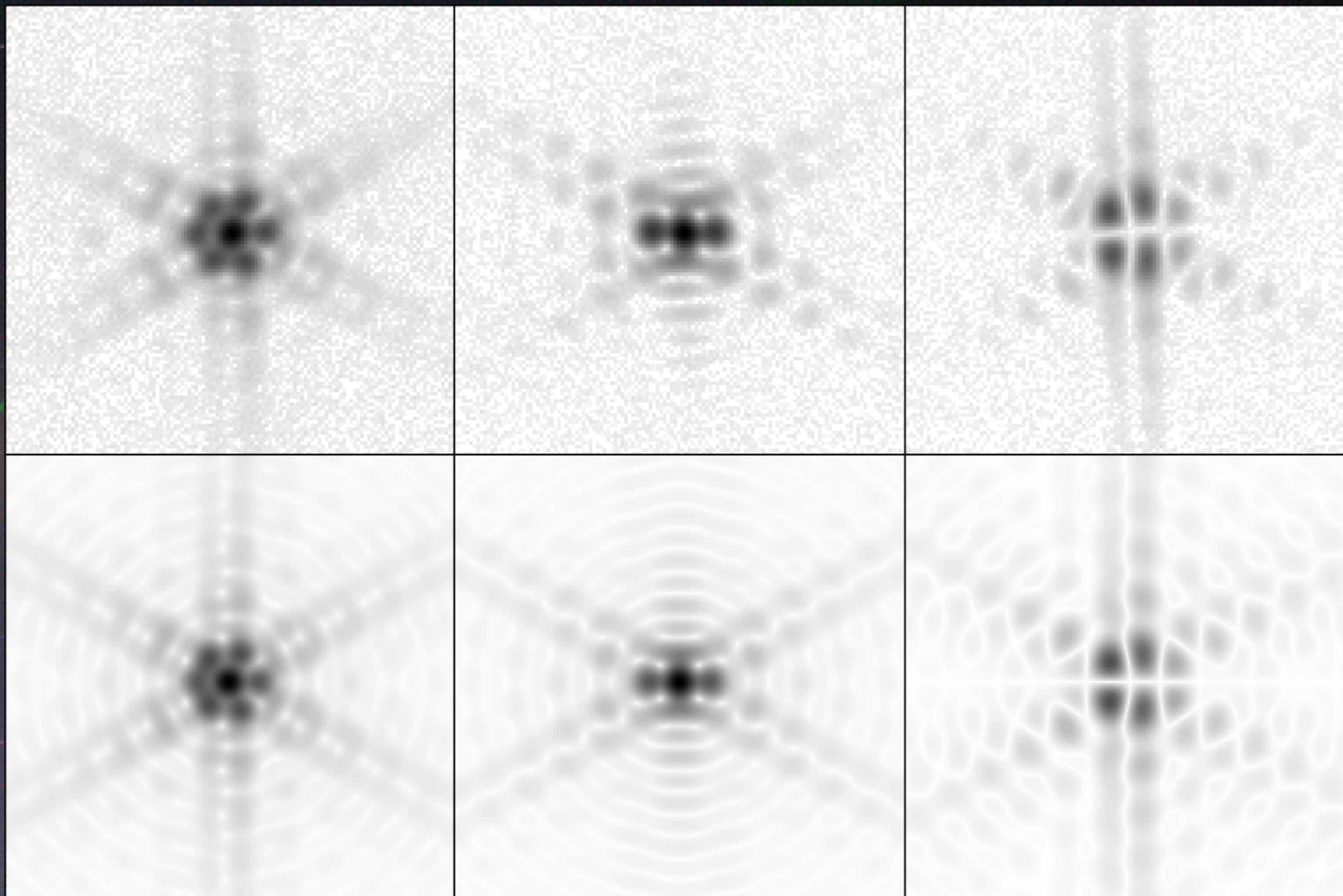
- Strong signal during eclipse
  - Apollo 11 (blue) was about as strong as this station saw in decades of ranging: definitely a special night
- Take your pick: late peak; early peak; no peak
- LLR is hard: ups and downs can be acquisition difficulty

What's Wrong?

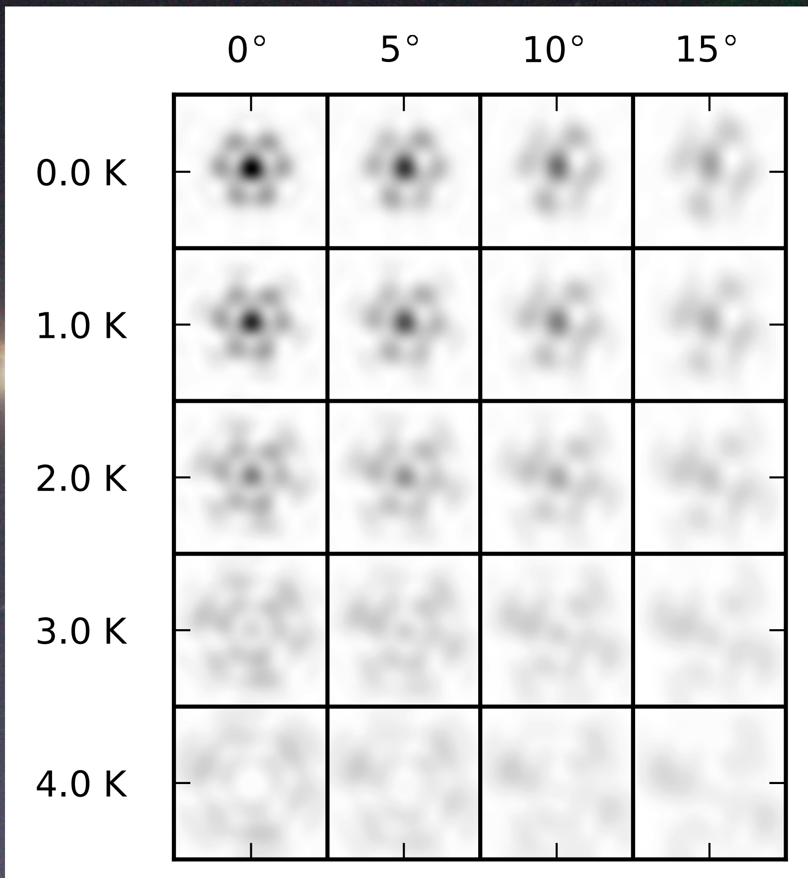


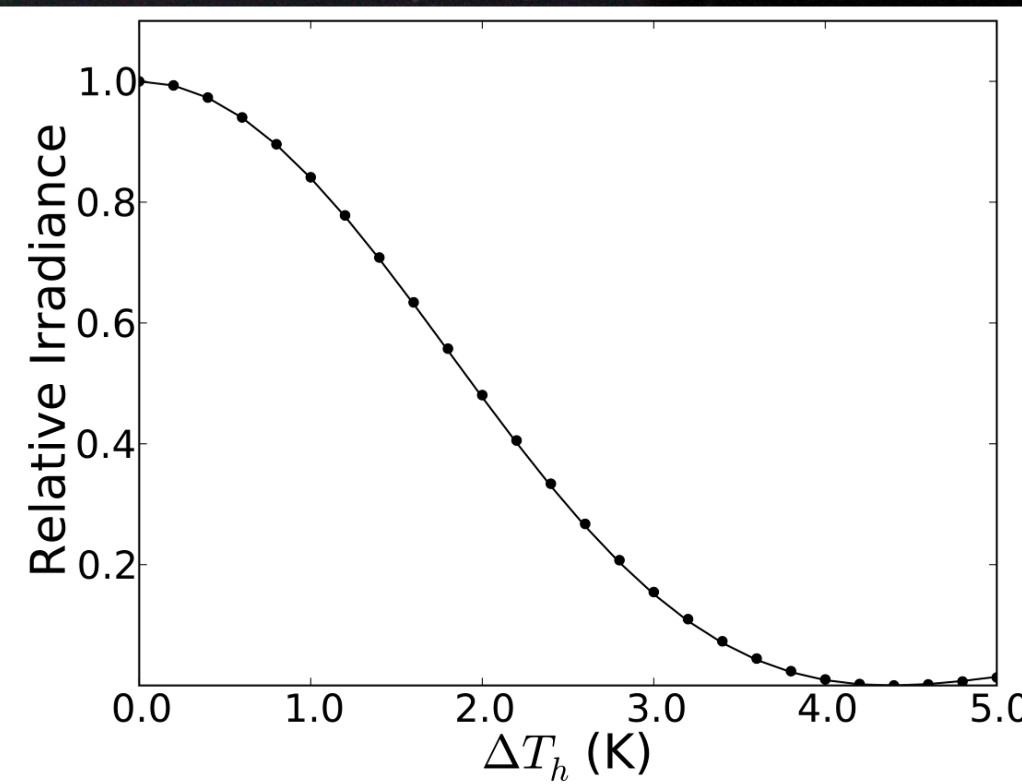
- The full-moon deficit, together with normal eclipse behavior, gives us the best clues:
  - thermal nature
  - absorbing solar flux
- Most likely: dust
  - Obviously could explain overall deficit (10%)
- Full moon effect then due to solar heating of dust
  - sun comes straight down tube at full moon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

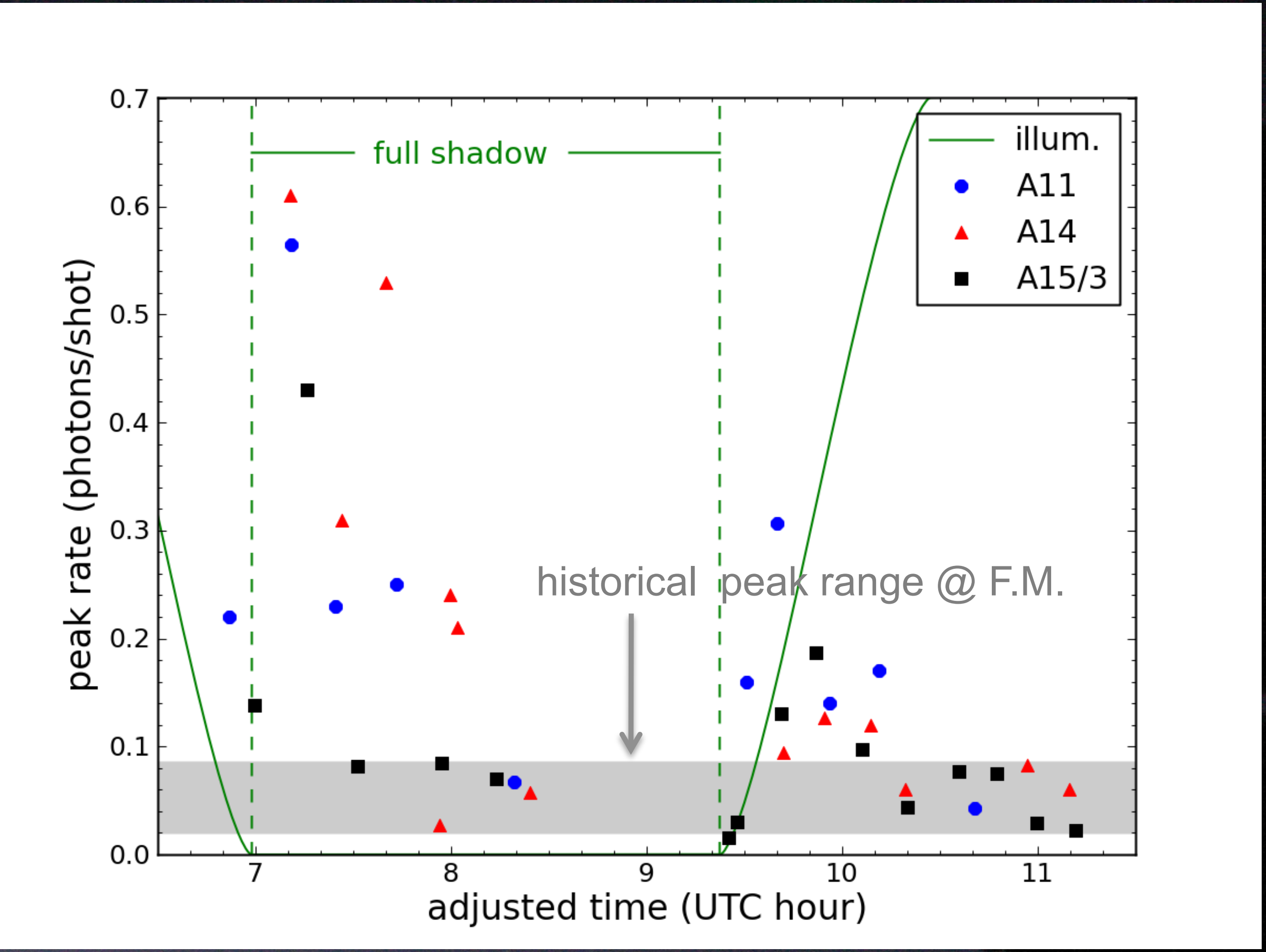


Exploring Orientation & Thermal Gradients



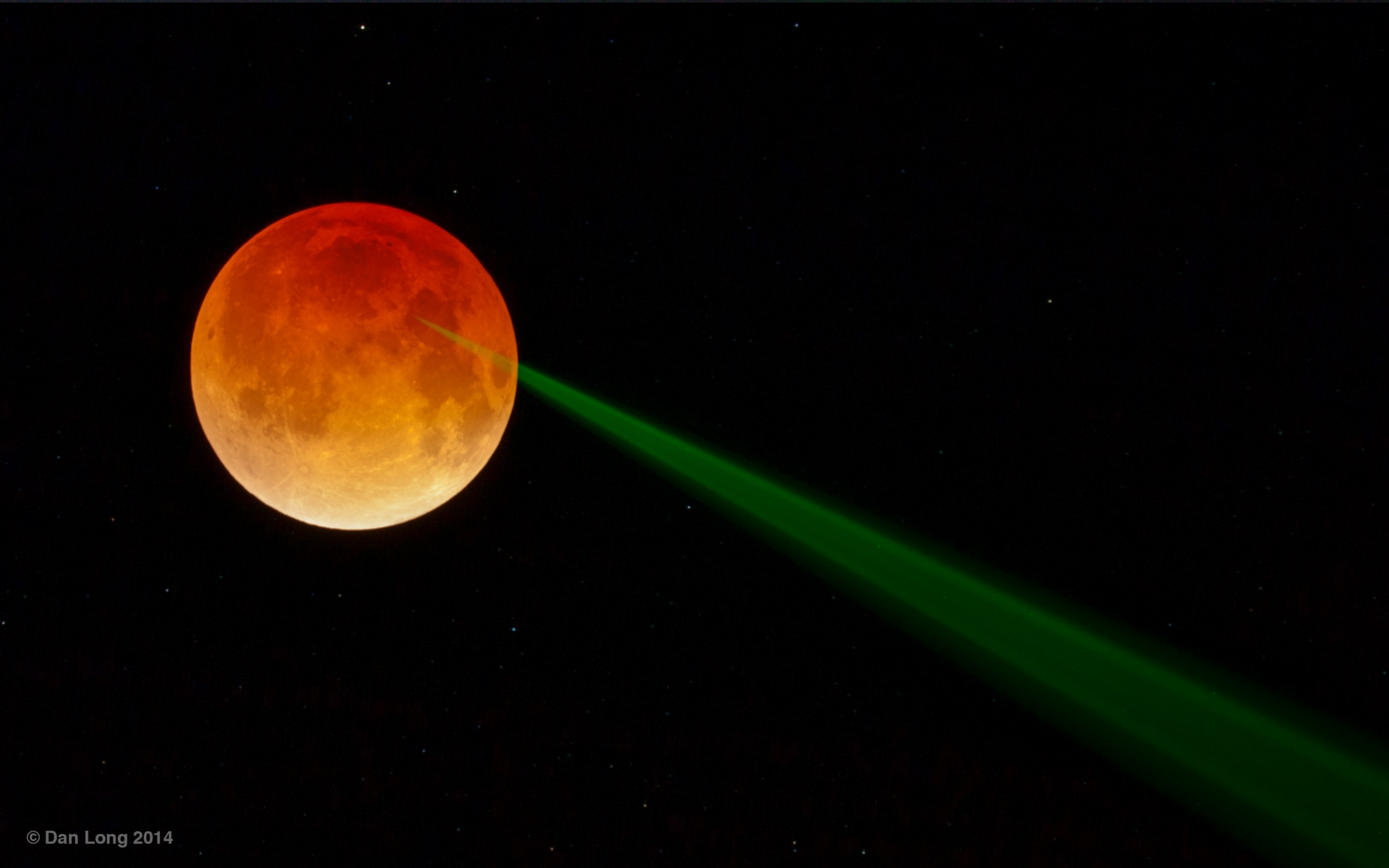


2010 Eclipse Results

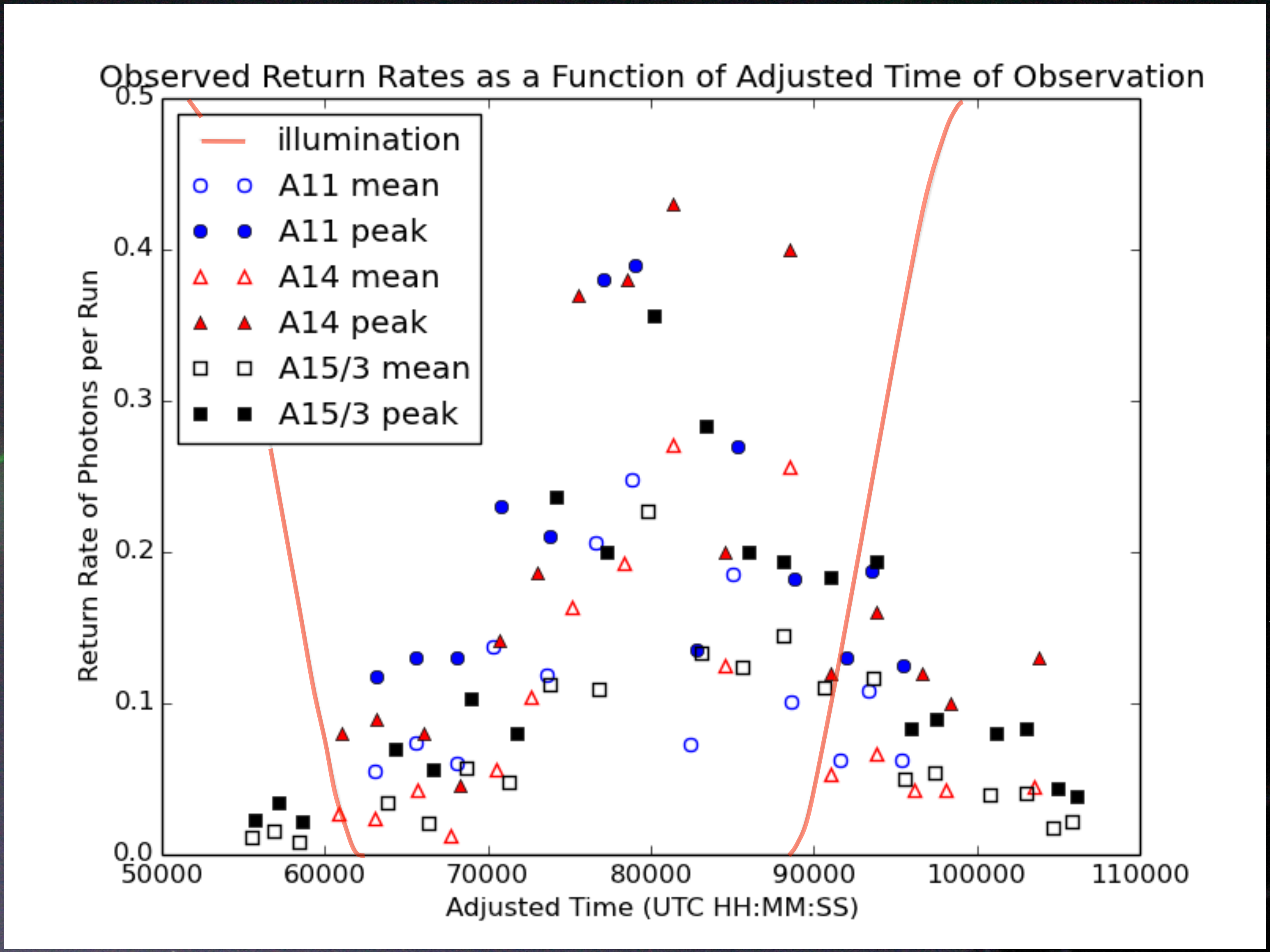


robust recovery initially, then down, and brief resurgence once light returns

2014.04.15 Eclipse



Dramatic Effect, Again



What Can We Say?

- Thermal effect real: solar absorption happening
  - likely dust coating; *could* be bulk absorption, but not expected
- 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

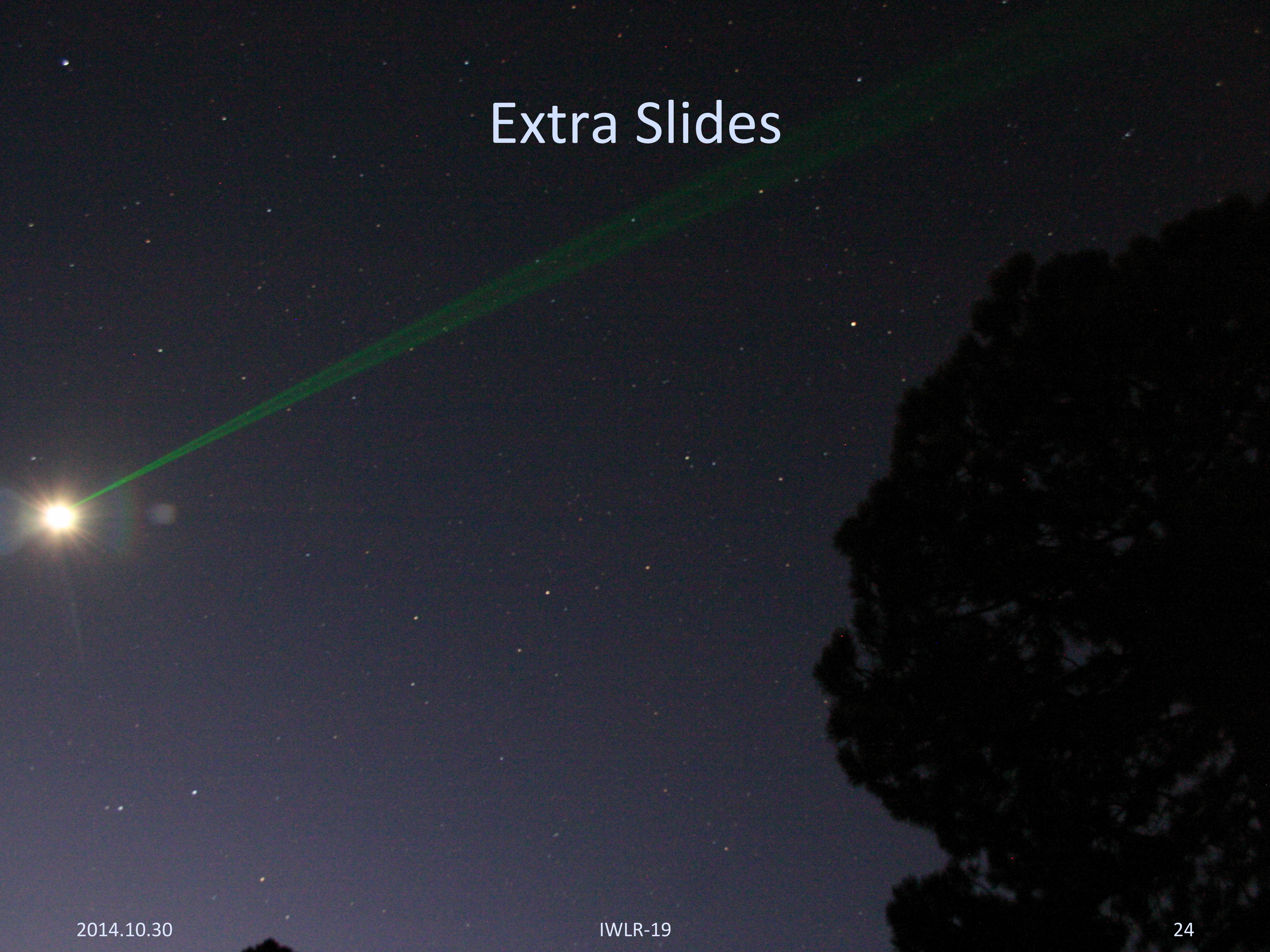
Other News

- LRO 1-way attempts successful 9/10 times
  - confirmed one-arcsec (5 μrad) beam/tracking
- LRO 2-way to corner cubes unsuccessful
  - 10 attempts, only 2 in decent conditions
- Embarking on Absolute Calibration System
  - verify clock, end-to-end detection/timing performance
  - note distinction between "calibration" and "fiducial"
- New detector/electronics installed Sept. 2013
  - baseline established; reducing past year; release very soon
- Continue working with Planetary Ephemeris Program
  - productive intercomparison with Paris and Hannover
  - formalizing procedure for assessing realistic parameter uncertainties

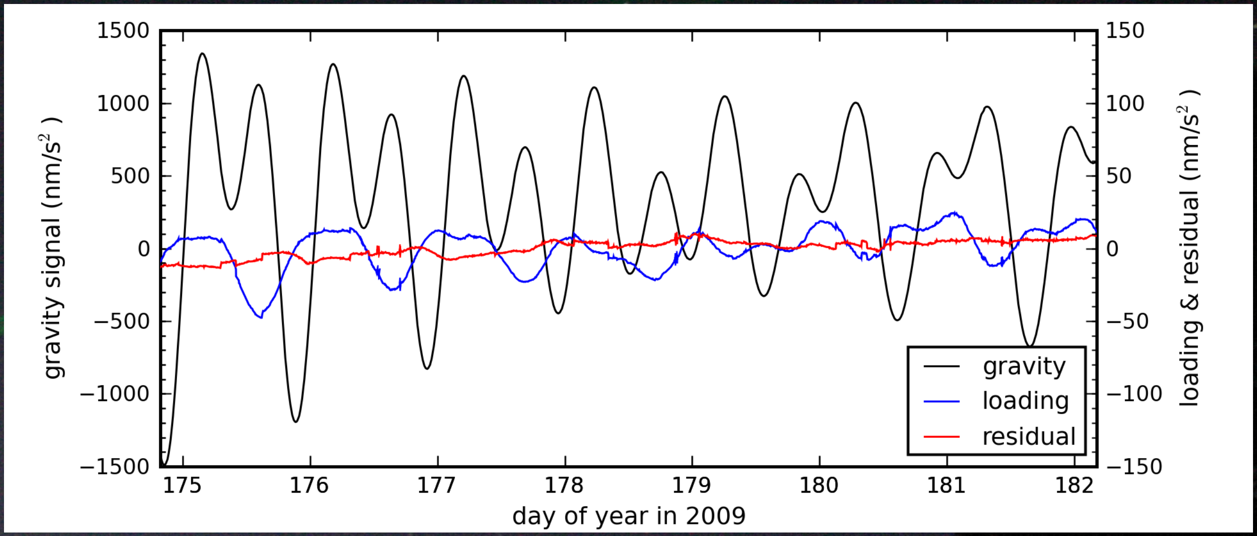
Reprints on Hand

- 2× Review Article on LLR
- 2× results from 2010 eclipse
- 1× polarization & diffraction patterns from TIR CCRs
- 1× thermal gradient impacts on CCR diffraction patterns
- 1× recovery of Lunokhod 1 reflector
- 1× TBAD concept
- 1× report on TBAD performance at APO

Extra Slides

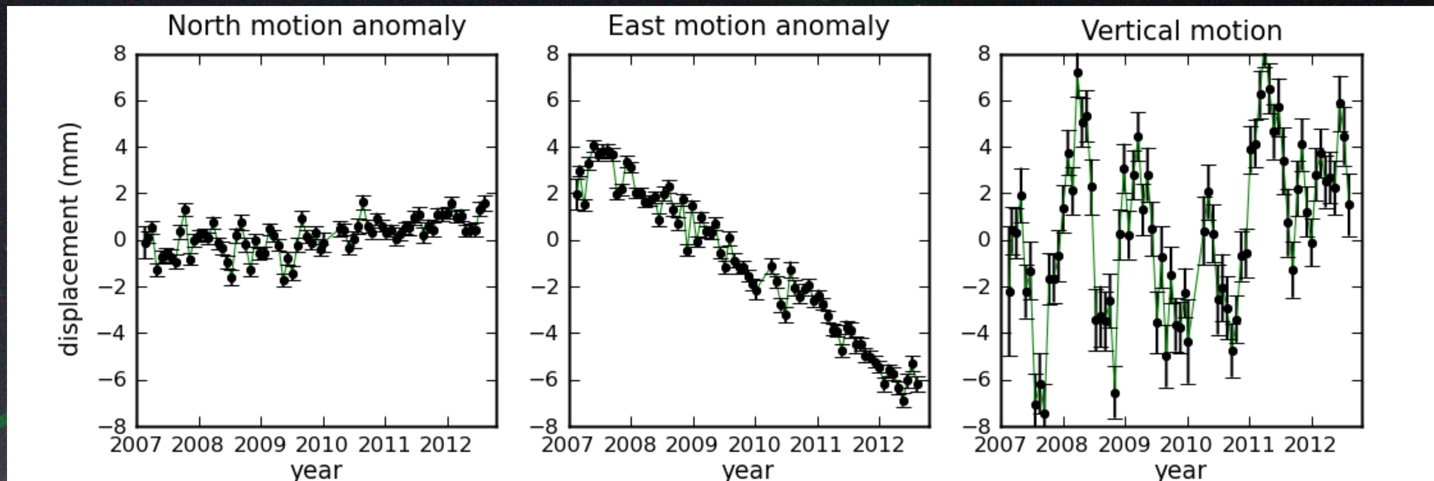


Superconducting Gravimeter Benefits



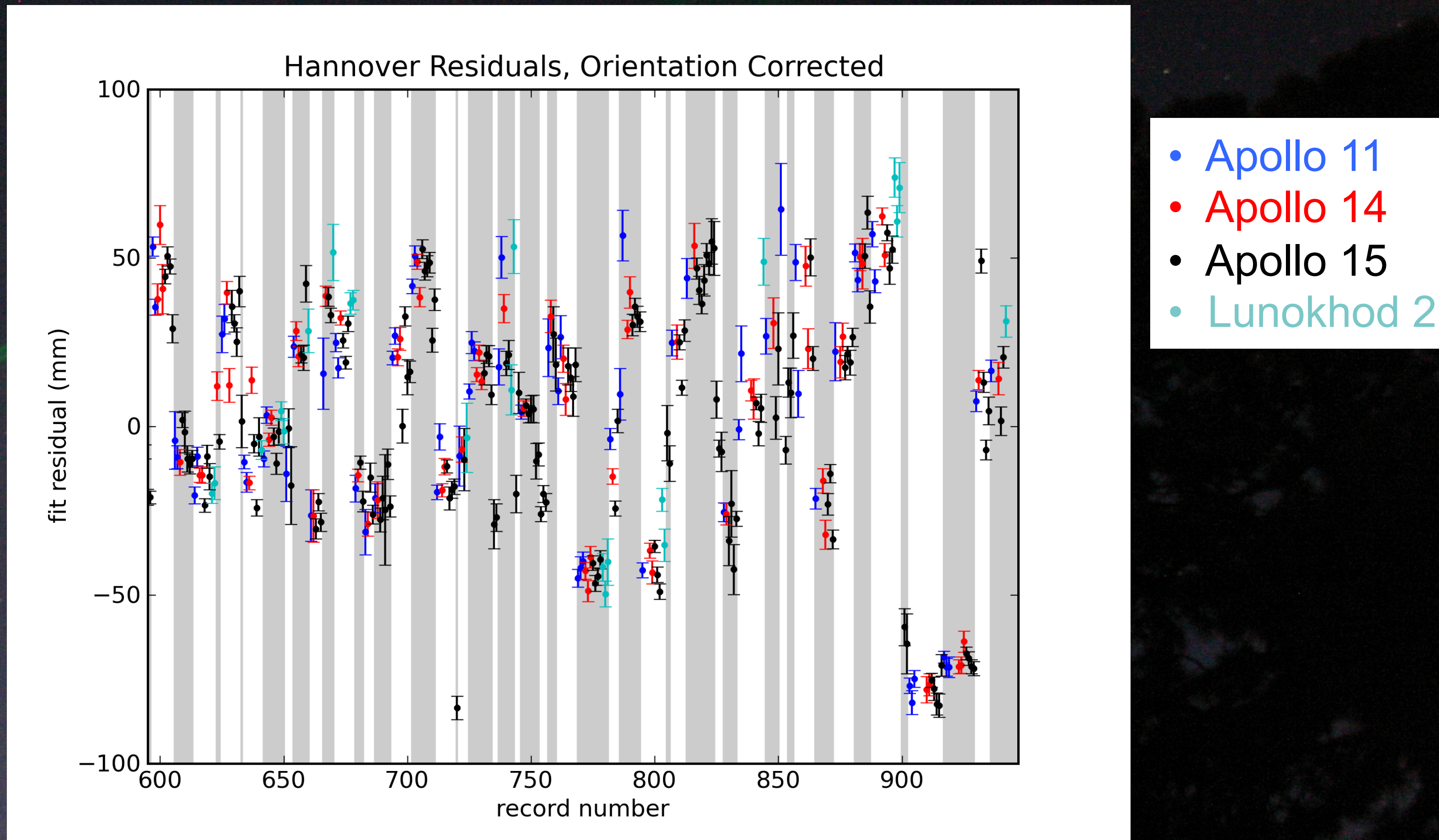
- SG is a great way to measure tides at site
- Gravity is a proxy to site displacement
- Probes ocean loading, ground water loading, atmospheric loading

EarthScope GPS Pitching In



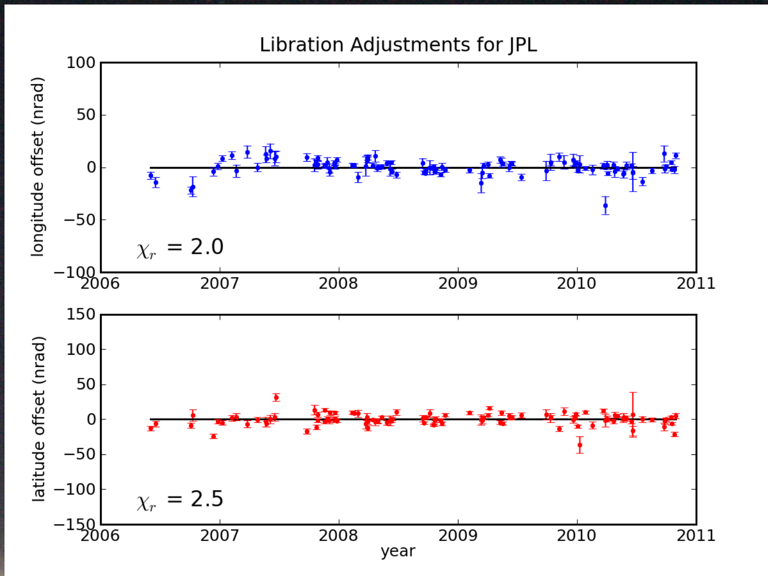
- The NSF-funded Plate Boundary Observatory (part of EarthScope) installed a GPS station 2.5 km away from APOLLO
- Resolution in monthly interval is 0.3 mm horizontal, 1.2 mm vertical
- Will help constrain crust motion, loading phenomena

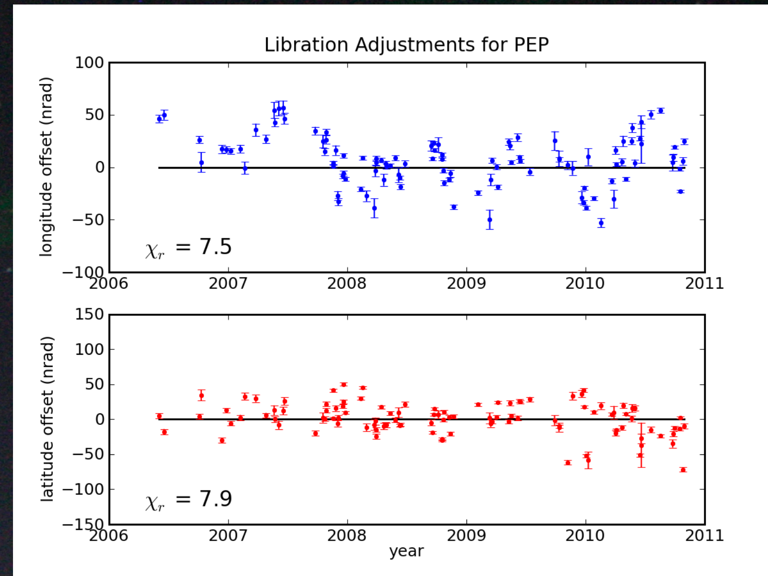
Example: Fixing Lunar Orientation

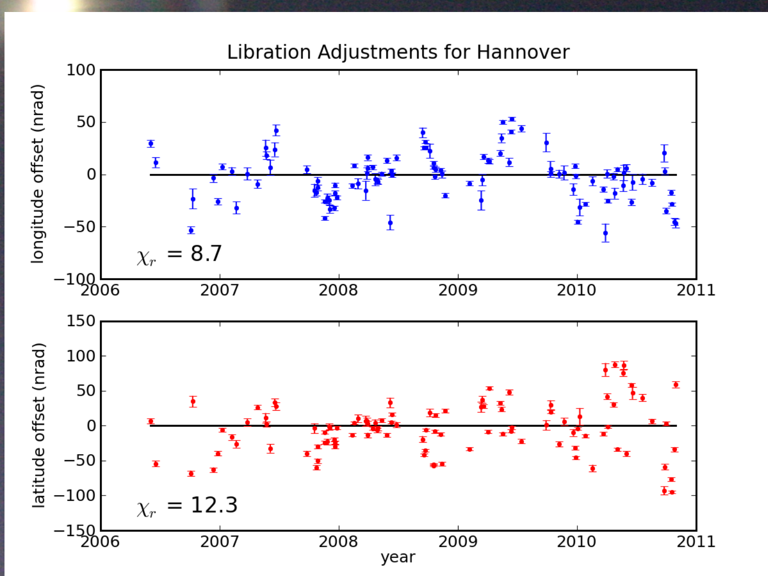


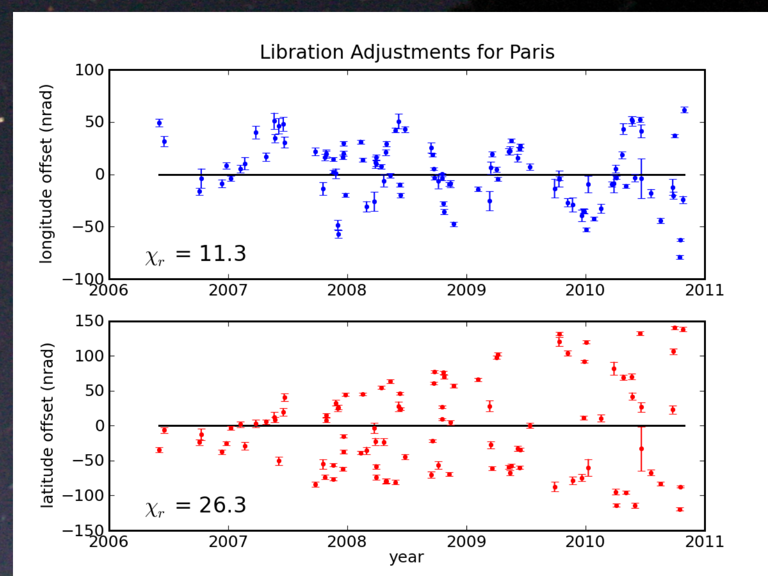
APOLLO data clearly call for orientation adjustments each night (vertical bands)

Re-orienting all the models



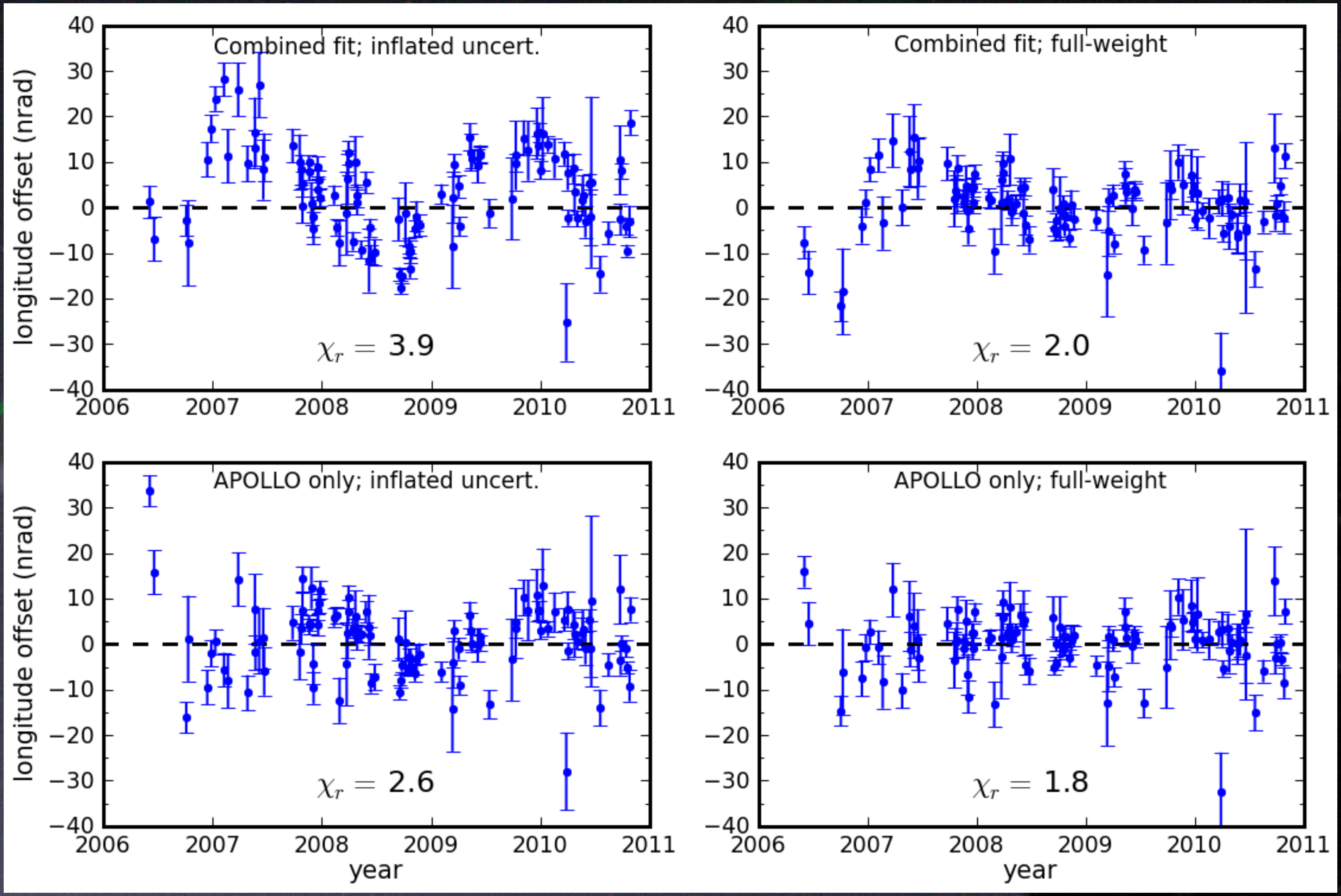






10 nrad
is 17 mm
at the Moon's
surface

A closer look at the best model (JPL)



More weight to APOLLO data ➔ model does better on orientation