A LUNAR LASER RANGING RETRO-REFLECTOR ARRAY for the 21st CENTURY

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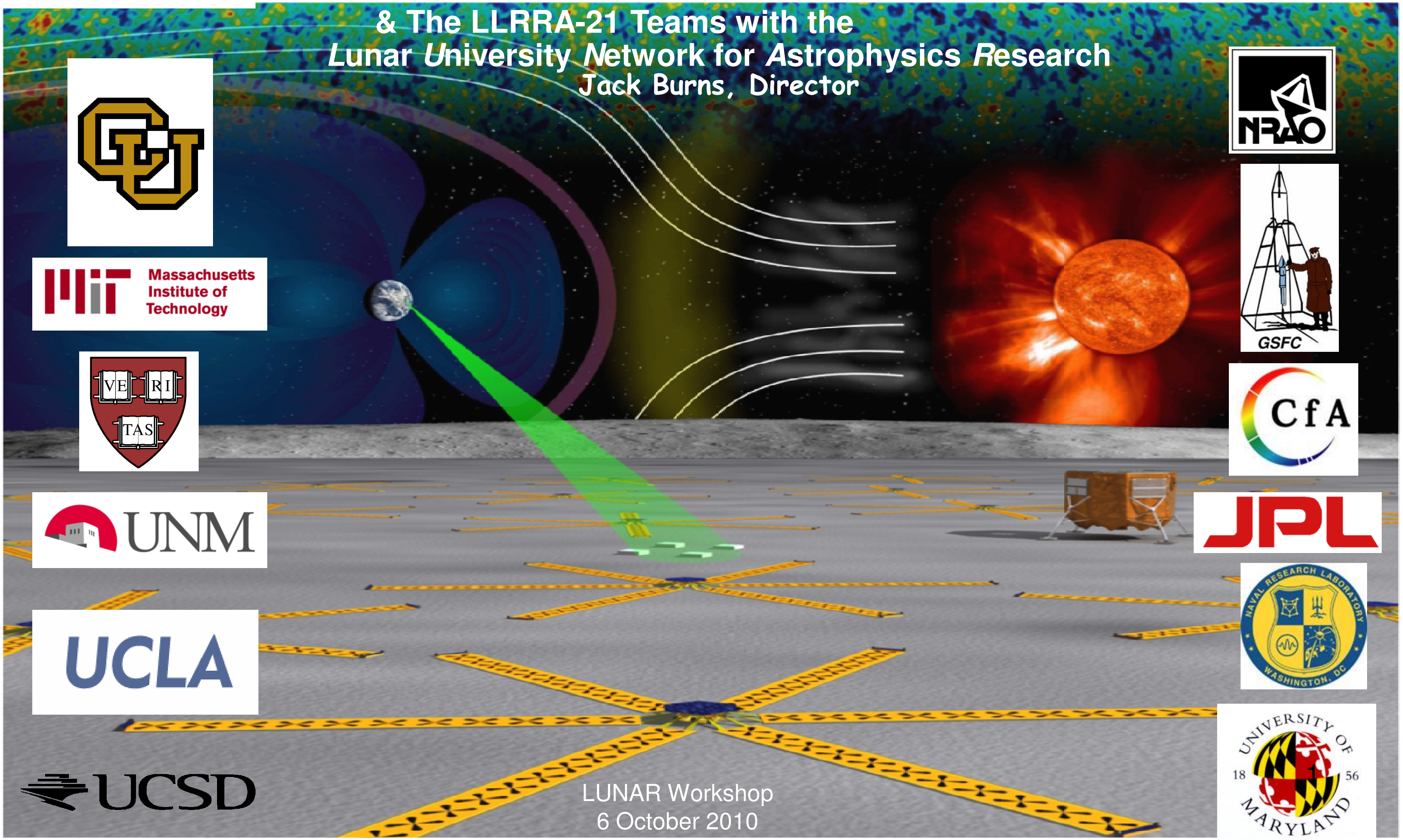

Role of LLRRA-21

- Future Goal
  - Much Greater Accuracy for Better Science by 200
- Immediate Problem
  - Today, for 1 mm, only APOLLO Can Reach This
  - Only A Few Observations / month
- Immediate Goal
  - ~ 1 mm Precision with a Few Returns
  - With a Return ~ like Apollo 15
  - Multiple Stations, Similar in Capability to McDonald

Why Laser Ranging to the Moon

- Lunar Science - Only Way to Study Lunar Interior
  - Discovery of the Liquid Core
  - Measure the Size and Shape of Liquid Core
  - Many other Properties – Tidal Dissipation, Inner Core, etc.
- General Relativity
  - Negligible Effect of Non-Gravitational Forces
  - Many of the Best GR Tests to Date
  - Sufficient Mass
    - Measurement of Inertial Properties of Grav.Energy
  - Variation of Fundamental Constants – Big G
    - No Temporal Variation
    - No Spatial Variation

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Gravitational and Particle Physics Panel

Much is unknown about fundamental theory: Modifications of general relativity *on* accessible scales are not ruled out by today's fundamental theories and observations. It makes sense to look for them by testing general relativity as accurately as possible. Cost-effective experiments that increase the precision of measurement of PPN parameters, and test the strong and weak equivalence principles, should be carried out. For example, improvements in **Lunar Laser Ranging** promise to advance this area.

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- The direct detection of gravitomagnetic effects (the Lense-Thirring precession) from Lageos/Grace, Gravity Probe B, and **lunar laser ranging**.
- The lunar laser ranging verification of the strong equivalence principle to 10-4, meaning that the triple graviton vertex is now known to a better accuracy than the triple gluon vertex.
- Limits on the fractional rate of change of the gravitational constant
- G (< 10-12) Limits on the fractional rate of change of the gravitational constant G (< 10-12/yr) from **lunar laser ranging**. Atomic experiments limiting time variation of the fine structure constant to 10-16/yr over periods of several years.
- Experiments that are in progress include the Microscope equivalence principle experiment, the **APOLLO lunar laser ranging** observations, and tests of general relativity using torsion balances and atom interferometry.
- Improved strong and weak equivalence principle limits. Better determination of PPN parameters and and $\dot{G}/G$ from next generation **Lunar laser ranging**

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Gravitational and Particle Physics Panel

- A new **Lunar Laser Ranging (LLR)** program, if conducted as a low cost robotic mission or an add-on to a manned mission to the Moon, offers a promising and cost-effective way to test general relativity and other theories of gravity (Figure 8.12). So far, LLR has provided the most accurate tests of the weak equivalence principle, the strong equivalence principle and the constancy in time of Newton's gravitational constant. These are tests of the core foundational principles of general relativity. Any detected violation would require a major revision of current theoretical understanding. As of yet, there are no reliable predictions of violations. However, because of their importance, the panel favors pushing the limits on these principles when it can be done at a reasonable cost. The installation of **new LLR retroreflectors** to replace the 40 year old ones might provide such an opportunity. The panel emphasizes again that its opinion that experiments improving the measurements of basic parameters of gravitation theory are justified only if they are of moderate cost. Therefore, it recommends that NASA's existing program of small- and medium-scale astrophysics missions address this science area by considering, through peer review, experiments to test general relativity and other theories of gravity. **The panel notes that a robotic placement of improved reflectors for LLR** is likely to be consistent with the constraints of such a program. It returns to this recommendation below in the context of a recommendation to augment the Explorer program.

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Cosmology and Fundamental Physics Panel

These complex spin-induced orbital effects are the consequences of “frame dragging,” a fundamental prediction of Einstein’s theory that has been probed in the Solar System using Gravity Probe B, LAGEOS satellites, and **Lunar laser ranging**, and has been hinted at in observations of accretion onto neutron stars and black holes.

LLRRA-21 Teams

- **LSSO Team – NASA**

- Douglas Currie   Principal Investigator
  - University of Maryland, College Park, College Park m MD, USA
  - NLSI, Moffett Field, CA, USA &
  - INFN-LNF Frascati, Italy
- Bradford Behr
  - University of Maryland, College Park, MD, USA
- Tom Murphy
  - University of California at San Diego, San Diego, CA , USA
- Simone Dell'Agnello
  - INFN/LNF Frascati, Italy
- Giovanni Delle Monache
  - INFN/LNF Frascati, Italy
- W. David Carrier
  - Lunar Geotechnical Institute, Lakeland, FL, USA
- Roberto Vittori
  - Italian Air Force, ESA Astronaut Corps
- Ken Nordtveldt
  - Northwest Analysis, Bozeman, MT, USA
- Gia Dvali
  - New York University, New York, NY and CERN, Geneva, CH
- David Rubincam
  - GSFC/NASA, Greenbelt, MD, USA
- Arsen Hajian
  - University of Waterloo, ON, Canada

- **INFN-LNF Frascati Team**

- Simone Dell'Agnello   PI   INFN-LNF, Frascati, Italy
- Giovanni Delle Monache   INFN-LNF, Frascati, Italy
- Douglas Currie   U. of Maryland, College Park, MD, USA
-    NLSI, Moffett Field, CA, USA &
-    INFN-LNF, Frascati, Italy
- Roberto Vittori   Italian Air Force & ESA Astronaut Corps
- Claudio Cantone   INFN-LNF, Frascati, Italy
- Marco Garattini   INFN-LNF, Frascati, Italy
- Alessandro Boni   INFN-LNF, Frascati, Italy
- Manuele Martini   INFN-LNF, Frascati, Italy
- Nicola Intaglietta   INFN-LNF, Frascati, Italy
- Caterina Lops   INFN-LNF, Frascati, Italy
- Riccardo March   CNR-IAC & INFN-LNF, Rome, Italy
- Roberto Tauraso   U. of Rome Tor Vergata & INFN-LNF
- Giovanni Bellettini   U. of Rome Tor Vergata & INFN-LNF
- Mauro Maiello   INFN-LNF, Frascati, Italy
- Simone Berardi   INFN-LNF, Frascati, Italy
- Luca Porcelli   INFN-LNF, Frascati, Italy
- Giuseppe Bianco   ASI Centro di Geodesia Spaziale
-    "G. Colombo", Matera,

What have the Apollo Arrays Done

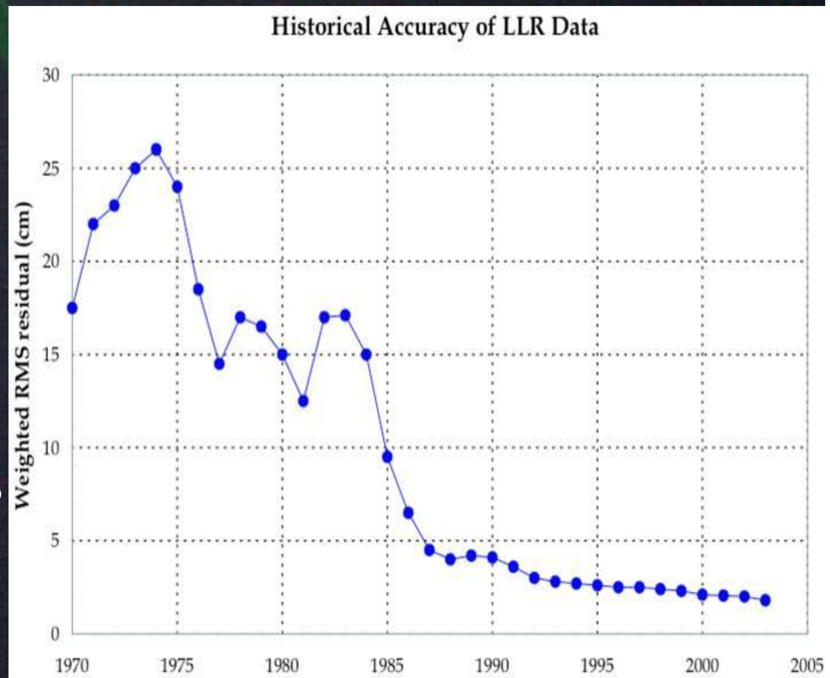
- The Earth-Moon System Provides an Ideal System
  - To Evaluate Relativity and Einstein's Theory
  - To Understand the Interior of the Moon
- Moon is Massive enough to Resist Drag/Pressure
- Moon is Far Enough to be in a Solar Orbit (Weakly Bound)
- LLR Currently Provides our Tests of:
  - The Weak Equivalence Principle (WEP)*: Δ a / a < 1.3×10-13
  - The Strong Equivalence Principle (SEP): $\eta = 4\beta - \gamma - 1$ < 4×10^{-4}
  - Time-Rate-of-Change of G to < 7×10^{-13} per year
  - Inverse Square Law to 3×10^{-11} at 10^{8} m scales
  - Geodetic Precession to 0.6 %
  - Gravitomagnetism to 0.1 %
  - Initial Definition of Liquid Lunar Core
  - Love Numbers of the Crust
  - Free Librations and Q of the Moon

LLRRA-21 Motivations

- Astrophysical Science Motivations
  - Fundamental Incompatibility Between
    - Quantum Mechanics and General Relativity
  - Dark Energy may be Aspect of Large-Scale Gravity
    - Dvali Idea Replaces Normal GR with Leaky Gravity
    - Can be Seen in Precession of Lunar Orbit
  - Dark Matter inspires Alternative Gravity Models (MOND)
    - Further Tests of Inverse Square Law could Confirm or Deny
- Lunar Science Motivations
  - Liquid Core – Dimensions, Shape, Rotation
  - Inner Solid Core – Existence, Size, Rotation
  - Rotational Dynamics – Q, External Impacts

SHORT HISTORY

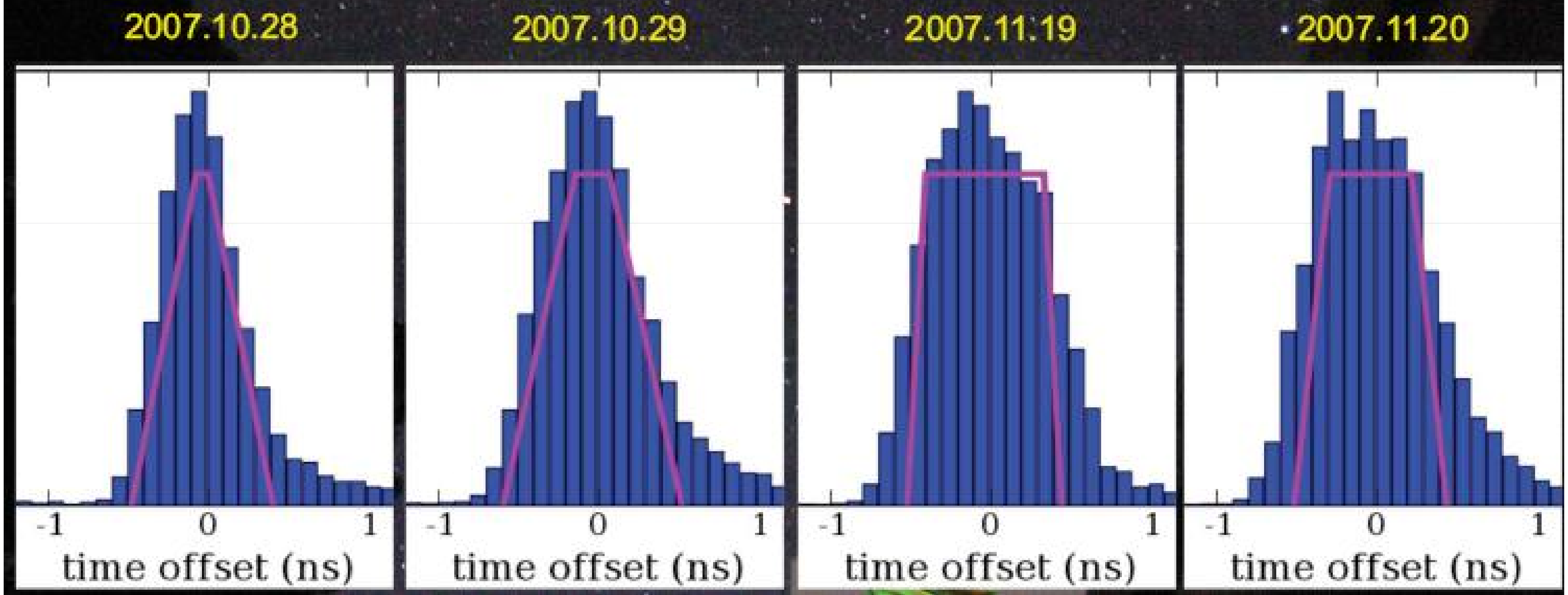
- Apollo Lunar Laser Ranging Arrays 1969
  - Thermal and Optical Analysis and Testing
  - McDonald LLR Station
- 2006
  - Return to the Moon
  - Could Address Accuracy Limit
- 2007
  - LSSO for 100 mm CCR
  - Lunar Science Sortie Opportunities
- 2009
  - NLSI > LUNAR at University of Colorado



LIBRATION PROBLEMS

- Why is there a Problem with the Apollo Arrays
  - Libration in Both Axis of 8 degrees
  - Apollo Arrays are Tilted by the Lunar Librations
  - CCR in Corner is Further Away by Several Centimeters
  - Even Short Laser Pulse is Spread
  - Results in a Range Uncertainty by ~2 cm
  - APOLLO Station of Tom Murphy UCSD
    - Thousands of Returns per Normal Point
    - Root N to Get Range to 1 – 2 millimeters
    - Needs Large Telescope
    - Hard to get Daily Coverage

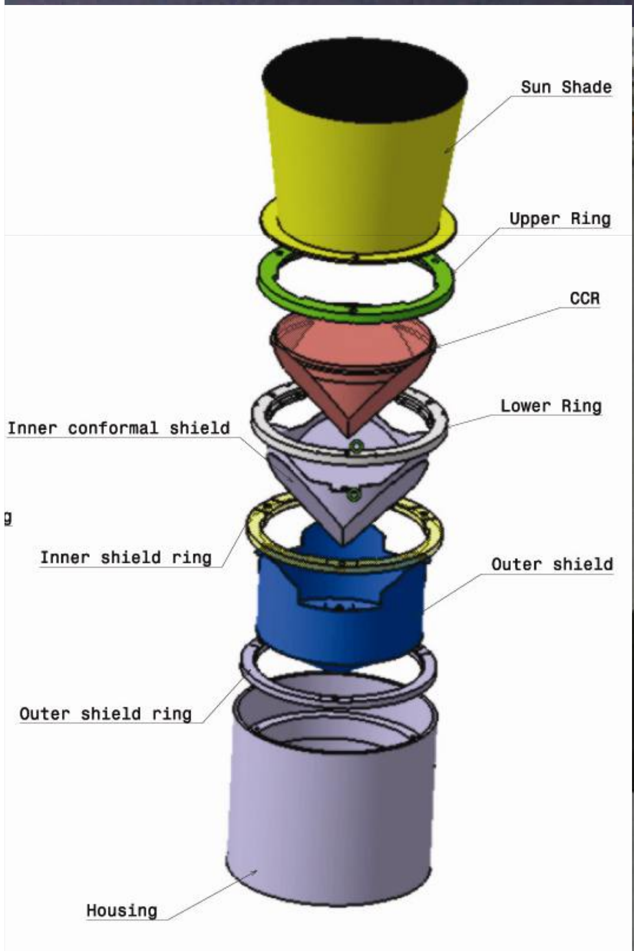
Sensing Array Size and Orientation



University of Maryland, College Park

Lunar Laser Ranging Array for the 21st Century

Nominal Package



CHALLENGES for SOLID CCR

- Fabrication of the CCR to Required Tolerances
- Sufficient Return for Reasonable Operation
  – Ideal Case for Link Equation
- Thermal Distortion of Optical Performance
  – Absorption of Solar Radiation within the CCR
  – Mount Conductance - Between Housing and CCR Tab
  – Pocket Radiation - IR Heat Exchange with Housing
  – Solar Breakthrough - Due to Failure of TIR
- Stability of Lunar Surface Emplacement
  – Problem of Regolith Heating and Expansion
  – Drilling to Stable Layer for CCR Support
  – Thermal Blanket to Isolate Support
  – Housing Design to Minimize Thermal Expansion

CCR FABRICATION CHALLENGE

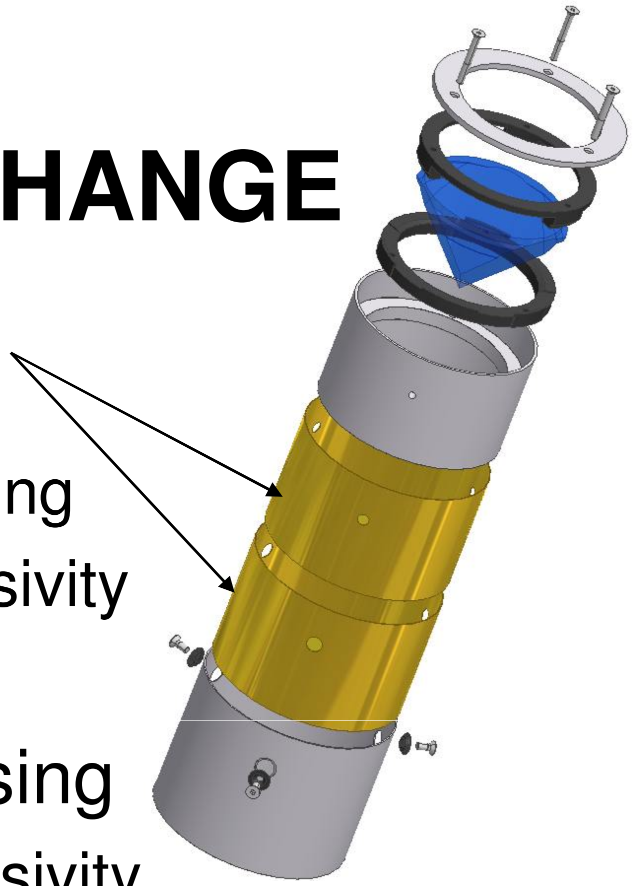
- CCR Fabrication Using SupraSil 1 Completed
- Specifications / Actual
  - Clear Aperture Diameter - 100 mm / 100 mm
  - Mechanical Configuration - Expansion of Our APOLLO
  - Wave Front Error - 0.25 / 0.15 [λ/6.7]
  - Offset Angles
    - Specification
      - **0.00”, 0.00”, 0.00” +/-0.20”**
    - Fabricated
      - **0.18”, 0.15”, 0.07”**
- Flight Qualified
  - with Certification

THERMAL/SOLAR ANALYSIS THEORETICAL

Solar Absorption within CCR

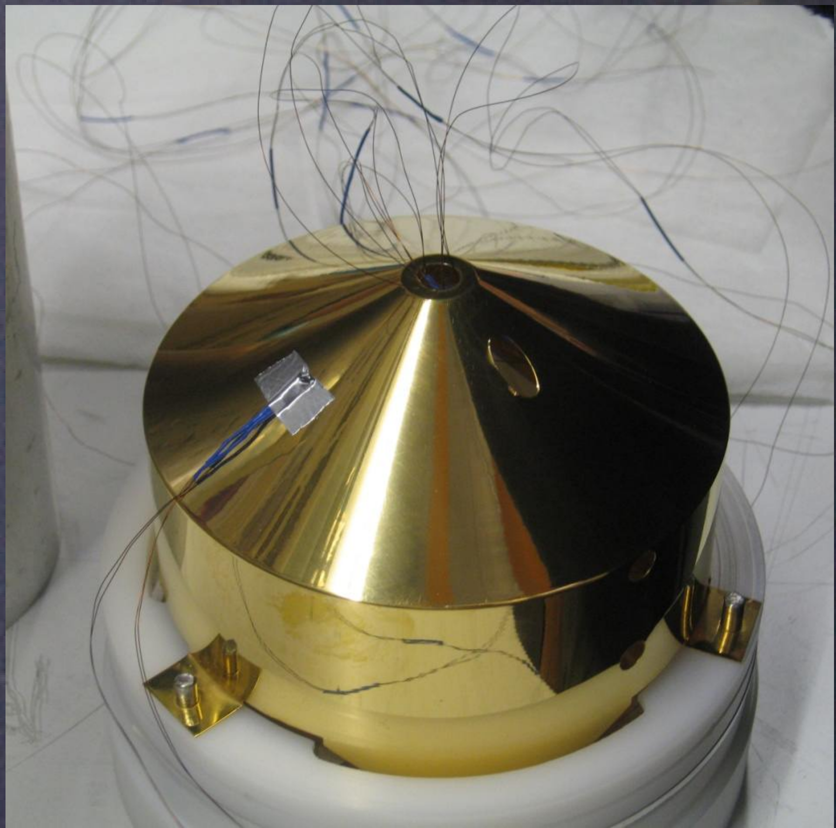
- Solar Heat Deposition in Fused Silica
  - Solar Spectrum – AMO-2
  - Absorption Data for SupraSil 1/311
  - Compute Decay Distance for Each Wavelength
  - Compute Heat Deposition at Each Point
    - Beer’s Law
  - Thermal Modeling Addresses:
    - Internal Heat Transport and Fluxes
    - Radiation from CCR to Space
    - Radiation Exchange with Internal Pocket Surroundings
    - Mount Conduction into the Support Tabs

POCKET RADIATION EXCHANGE

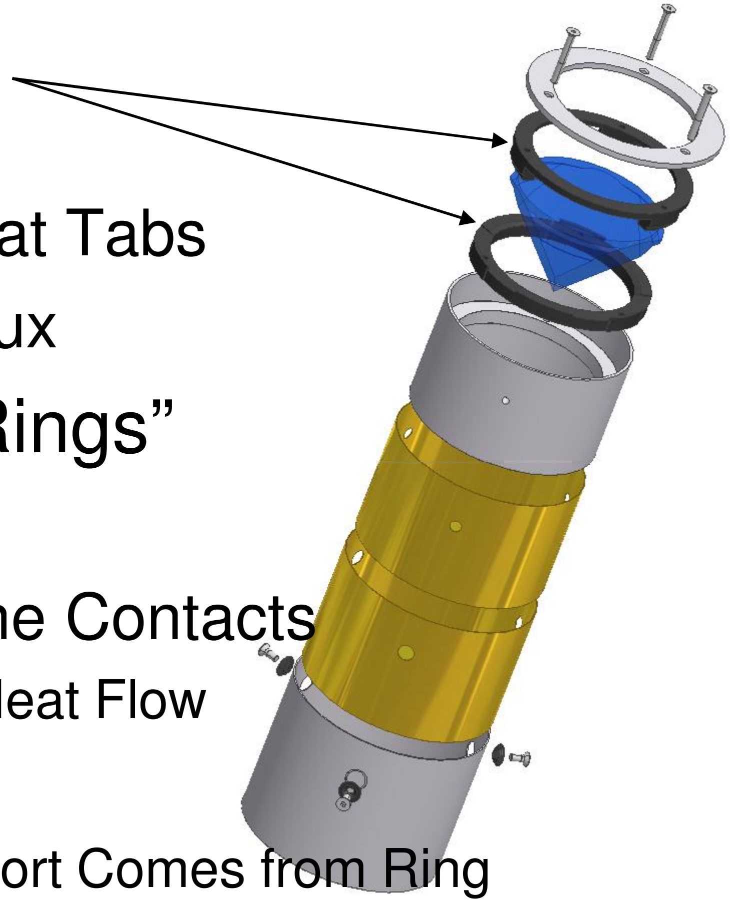


- Challenge:
  - IR Radiation Between CCR & Housing
  - SiO_2 Has High IR Absorptivity/Emissivity
  - Heat Flux Causes Optical Distortion
- Isolation Between CCR and Housing
  - Low Emissivity Coatings – 2% Emissivity
  - Successive Cans or Multiple Layers
- Simulation Indicates Isolation is Effective
- Thermal Vacuum Chamber Validation
  - In April 2009 at SCF at INFN/LNF at Frascati

INNER & OUTER THERMAL SHIELDS

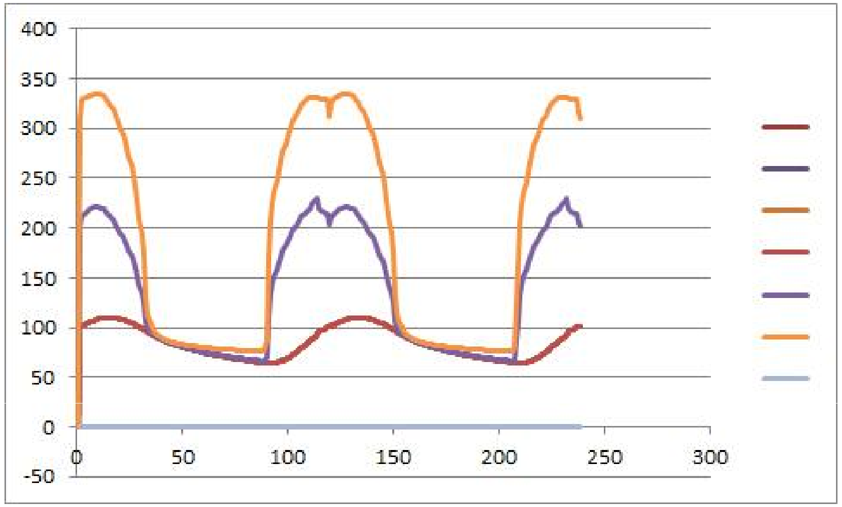


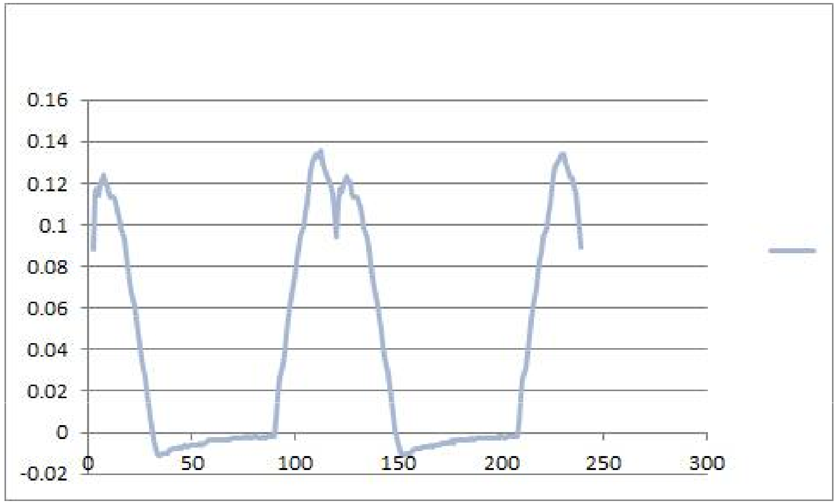
MOUNT CONDUCTANCE

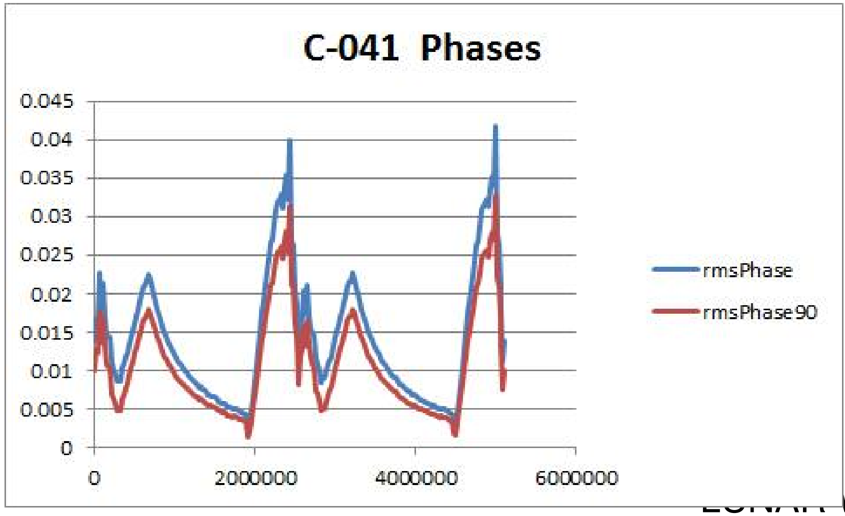


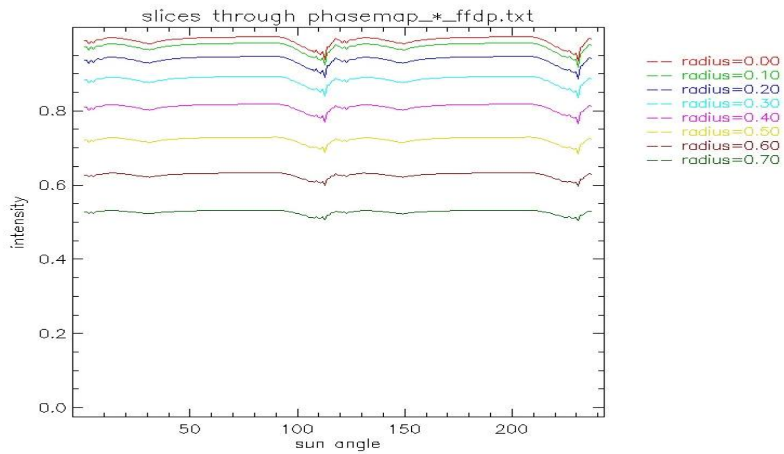
- Challenge:
  - Heat flow from Housing to CCR at Tabs
  - Optical Distortion due to Heat Flux
- Support of CCR with KEL-F “Rings”
  - Intrinsic Low Conductivity
  - Use of Wire Inserts with Only Line Contacts
    - Line Contact of Support Reduces Heat Flow
  - Supports Launch Environment
    - KEL-F Wire Compresses and Support Comes from Ring
- Estimated (to be Validated in SCF) 1 Milli-W/^{o}K

Thermal Analysis





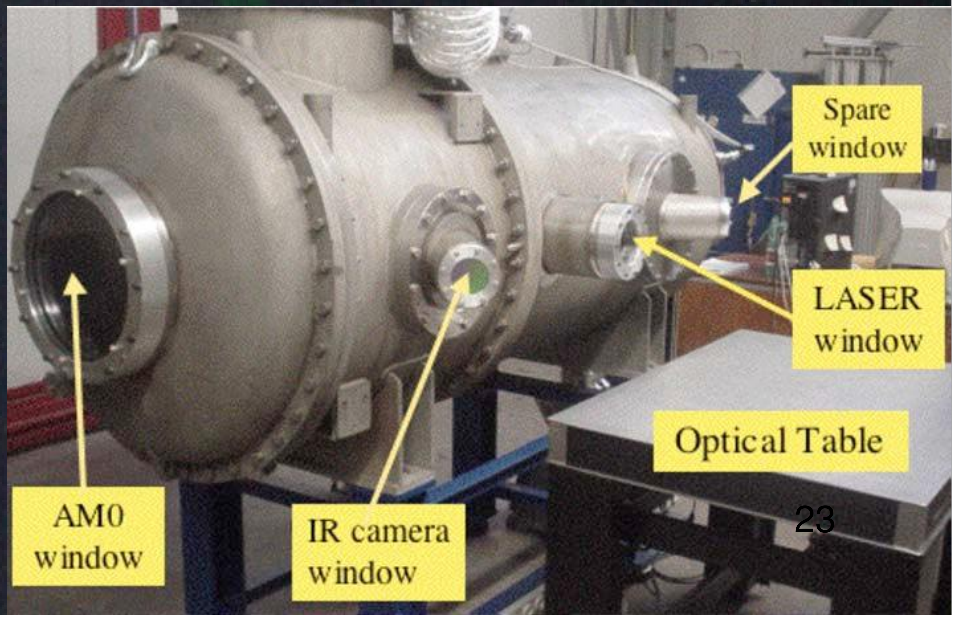




LLRRA-21 PACKAGE

CURRENT STATUS

- Preliminary Definition of Overall Package
- Completed Preliminary Simulations
  - LSSO – Lunar Science Surface Opportunities
  - Thermal (CCR, Regolith, Housing), Optical
- Completed Phase I Thermal Vacuum Tests
  - Solar Absorption Effects on CCR
  - CCR Time Constants –
    - IR Camera – Front Face
    - Thermocouples – Volume
    - Preliminary Optical FFDP

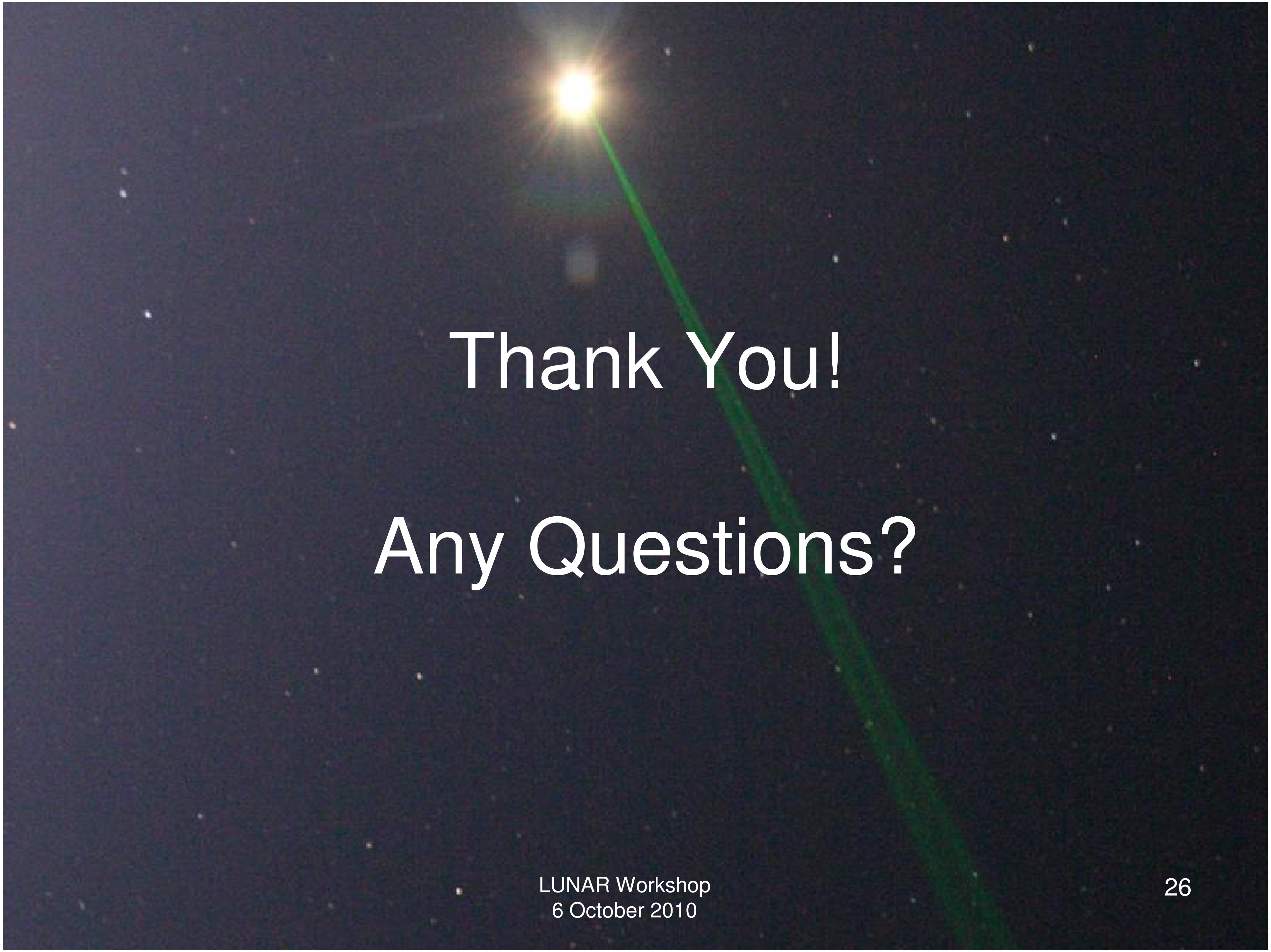


MISSION OPPORTUNITES
&
Acknowledgements

- Possible Roles for 100 mm Solid CCR Retroreflector
  - NASA
    - Google Lunar X Prize - 2013
    - International Lunar Network (ILN) Anchor Nodes
    - Lunar Express – Lockheed Martin
    - Manned Landing - LSSO / NASA Program
  - Italian Space Agency & INFN
    - MAGIA – ASI & INFN
      - Proposed ASI Lunar Orbiter to Carry a 100 mm Solid CCR
    - Italian ILN Retroreflector Instrument
      - MoonLIGHT-ILN INFN Experiment – Just Approved

Google Lunar X Prize

- Prize by Google Corporation for 30 M$
  - Only Private Funds to Accomplish GLXP Objectives
- Government Money is Acceptable for Non-GLXP Goals
  - For Other Objectives – Like LLRRA-21
- Currently I am Working with:
  - Lunar Express, LM — Hai Li
  - Astrobotics — David Gump
  - Moon Express — Bob Richards
  - NextGreatLeap — Michael Joyce
  - Penn State University — Miles Smith
  - FREDNET — Sean Casey
- Multiple Missions that May Be Successful
  - Achieve an Array of Retroreflectors

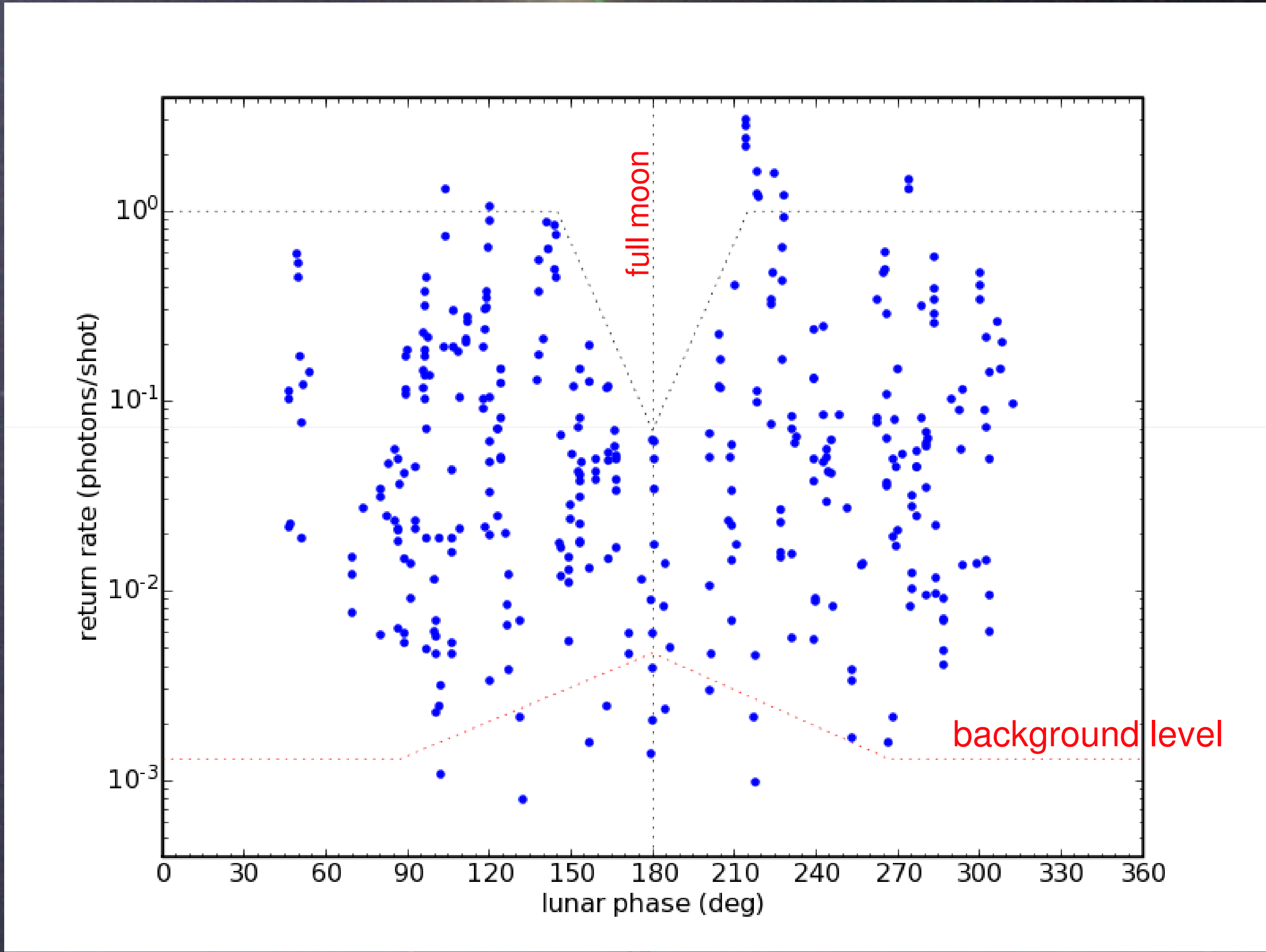


Thank You!

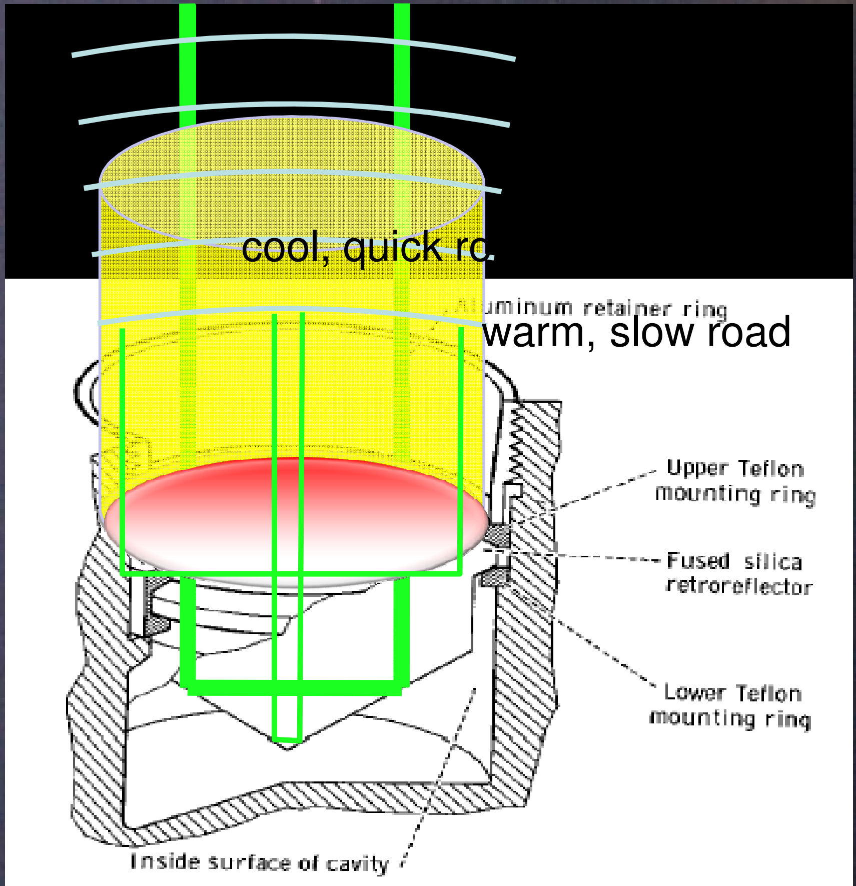
Any Questions?

- Paper on LLR for Decadal Survey
  - http://www.lpi.usra.edu/decadal/leag/StephenMMerkowitz.pdf
- Sept 2007 - Google Lunar X- Prize
- http://commercialspace.pbworks.com/f/Public+Background.pdf
- http://commercialspace.pbworks.com/f/Public+ILN.pdf

APOLLO rates on Apollo 15 reflector

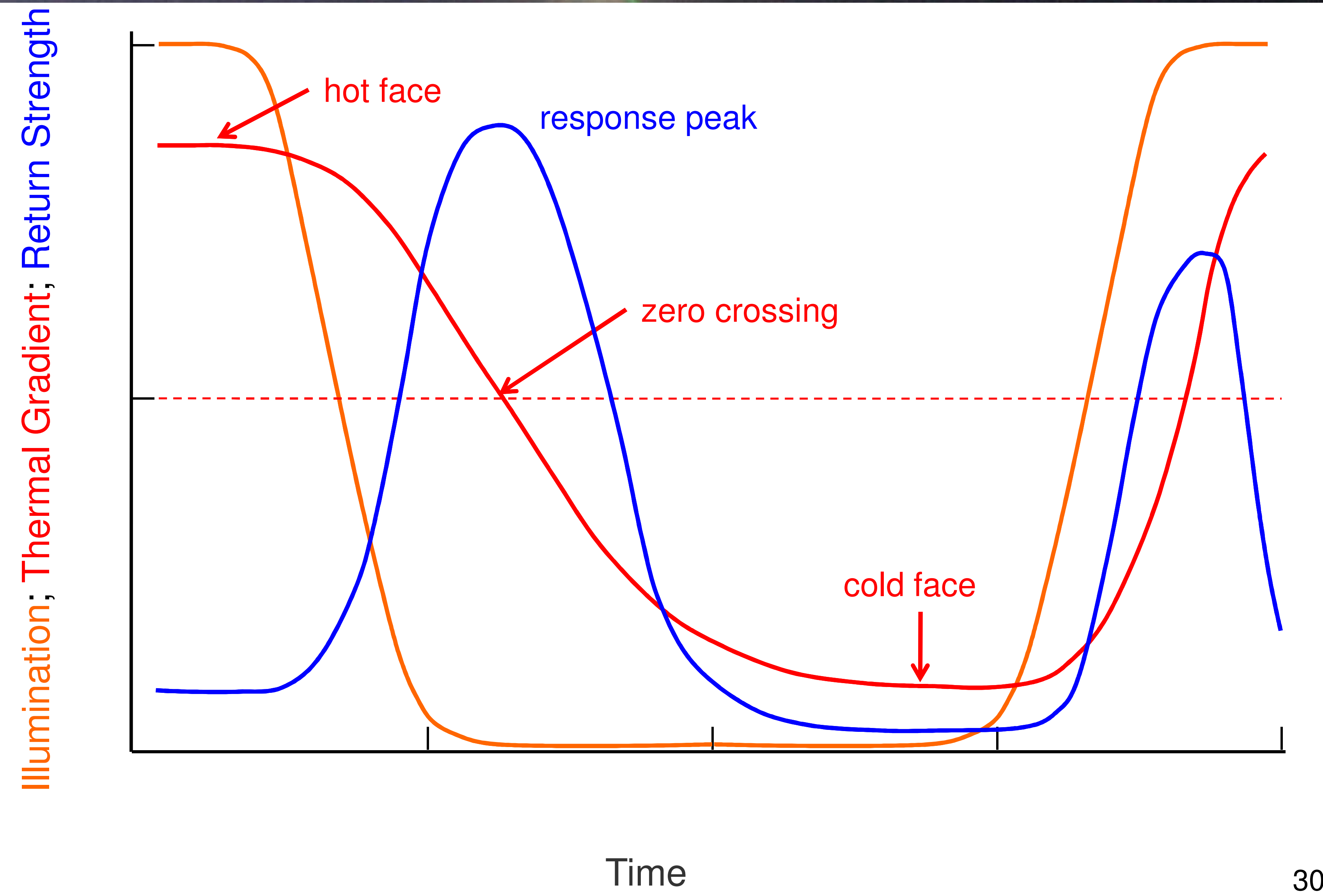


What’s Wrong?

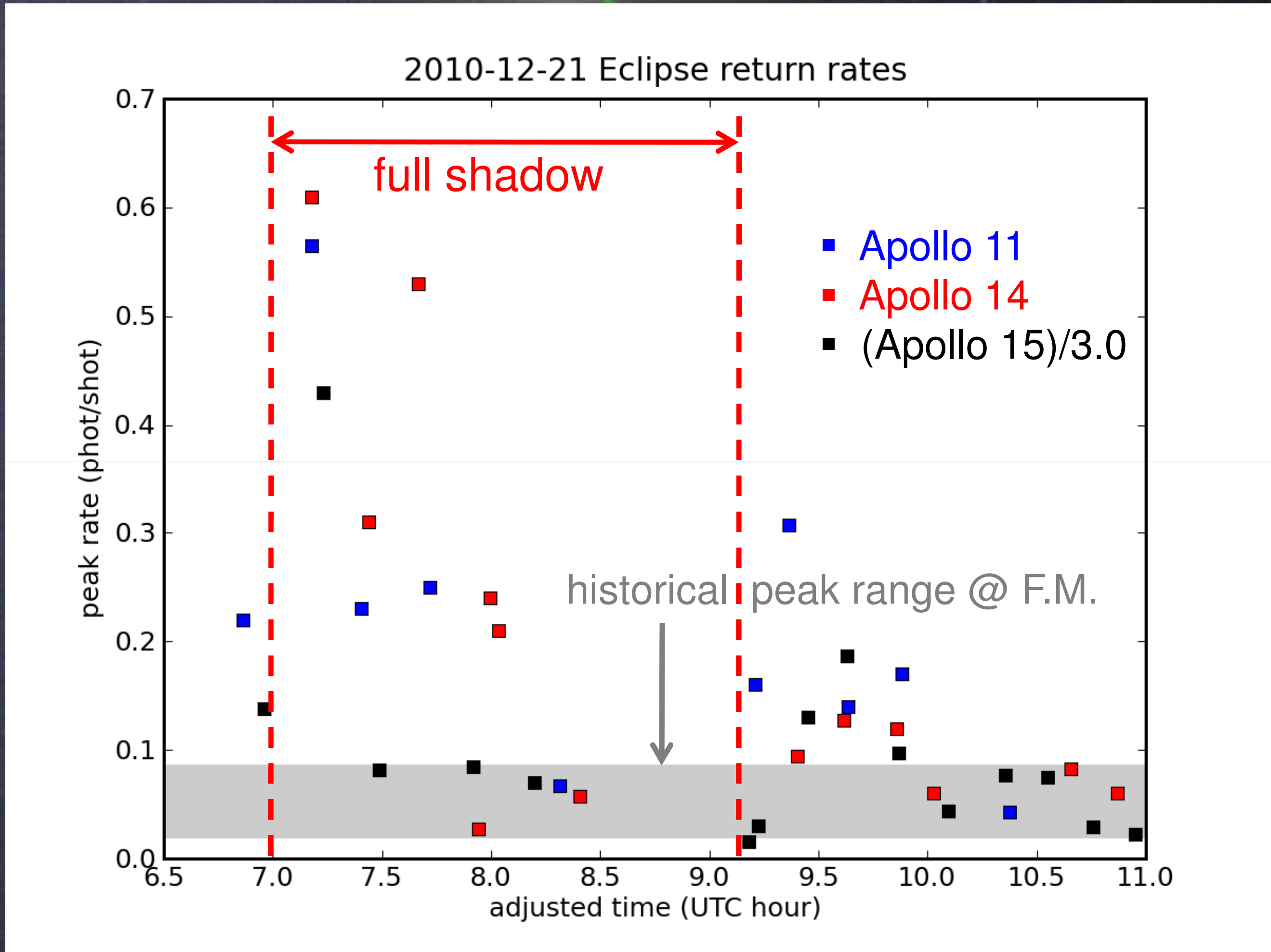


- The full-moon deficit, together with normal eclipse behavior, gives us the best clues:
  - thermal nature
  - absorbing solar flux
- Most likely: dust
  - Obviously could explain overall deficit (10%)
- Full moon effect then due to solar heating of dust
  - sun comes straight down tube at full moon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

Cartoon of Expectations



Preliminary Eclipse Results



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