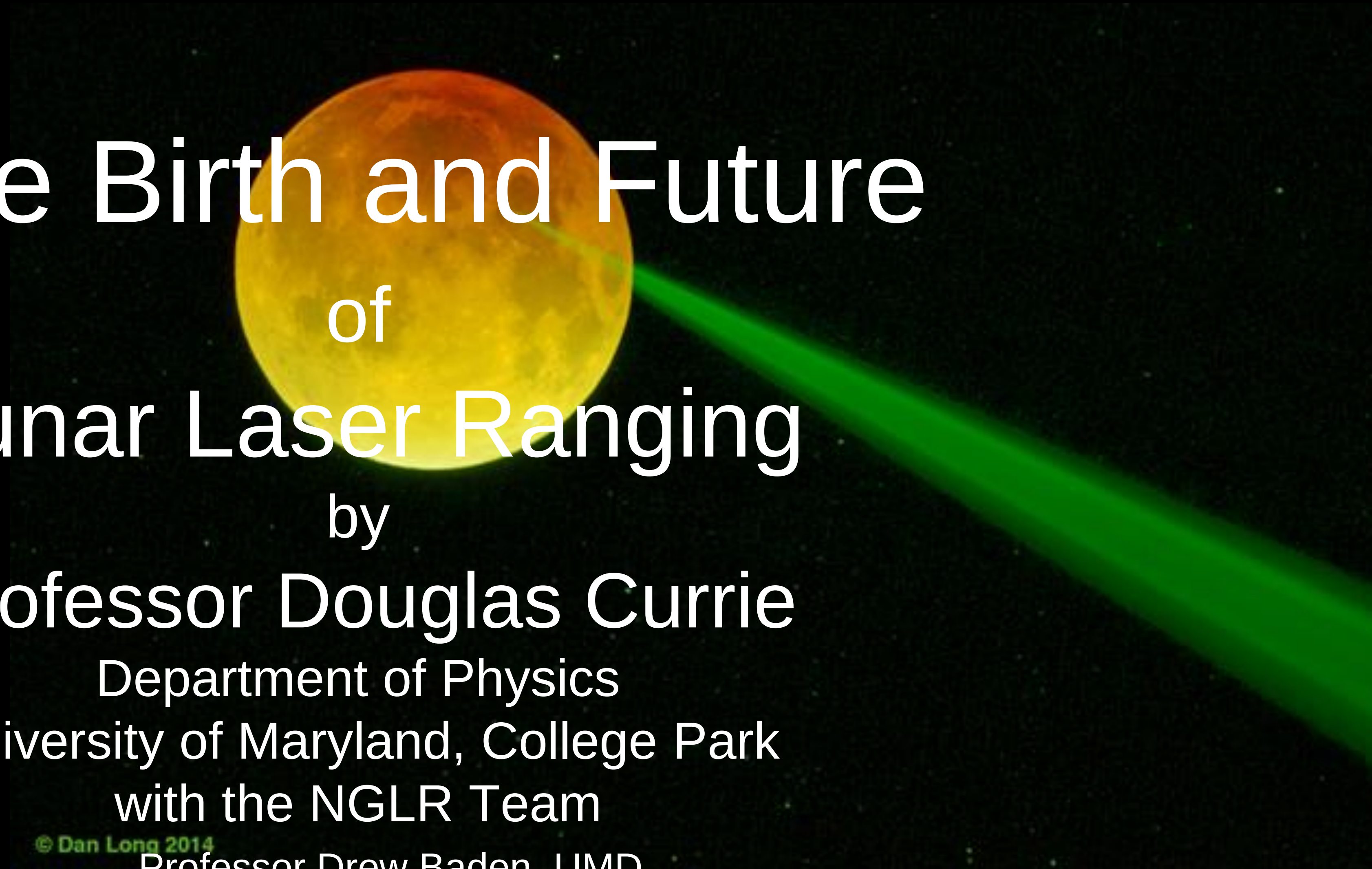


The Birth and Future

of

Lunar Laser Ranging

by

Professor Douglas Currie

Department of Physics

University of Maryland, College Park

with the NGLR Team

Professor Drew Baden, UMD

Dr. Dennis Wellnitz, UMD

Dr. Jim Williams, JPL

Dr. Giovanni Delle Monache, INFN-LNF

Dr. Bradford Behr, UMD

Dr. Simone Dell’Agnello, INFN-LNF

Lester Putnam, UMD

Dr. Chensheng Wu, UMD

William Kleyman, UMD

Ruth Carter, UMD

Naomi Russo, UMD

SPACE AND COSMIC RAY PHYSICS SEMINAR

Outline

- Overview of Why We Want to do Lunar Laser Ranging
- Pre-History of Professor Bob Dicke's Group at Princeton
- Preparation for Science on Apollo 11 by NASA
- Preparation and Development of Retroreflector Array for Apollo 11
- Development of Lunar Laser Ranging Observatories
- Science Results from Our LLR Observations
- Current Limitations to the Ranging Accuracy
- Advantages and Design of NGLR formerly LLRRA-21
- Fabrication, Deployments and Flights for NGLR
- Science for NGLR

First Why

Should We Embark
Such a Complicated and Risky Journey

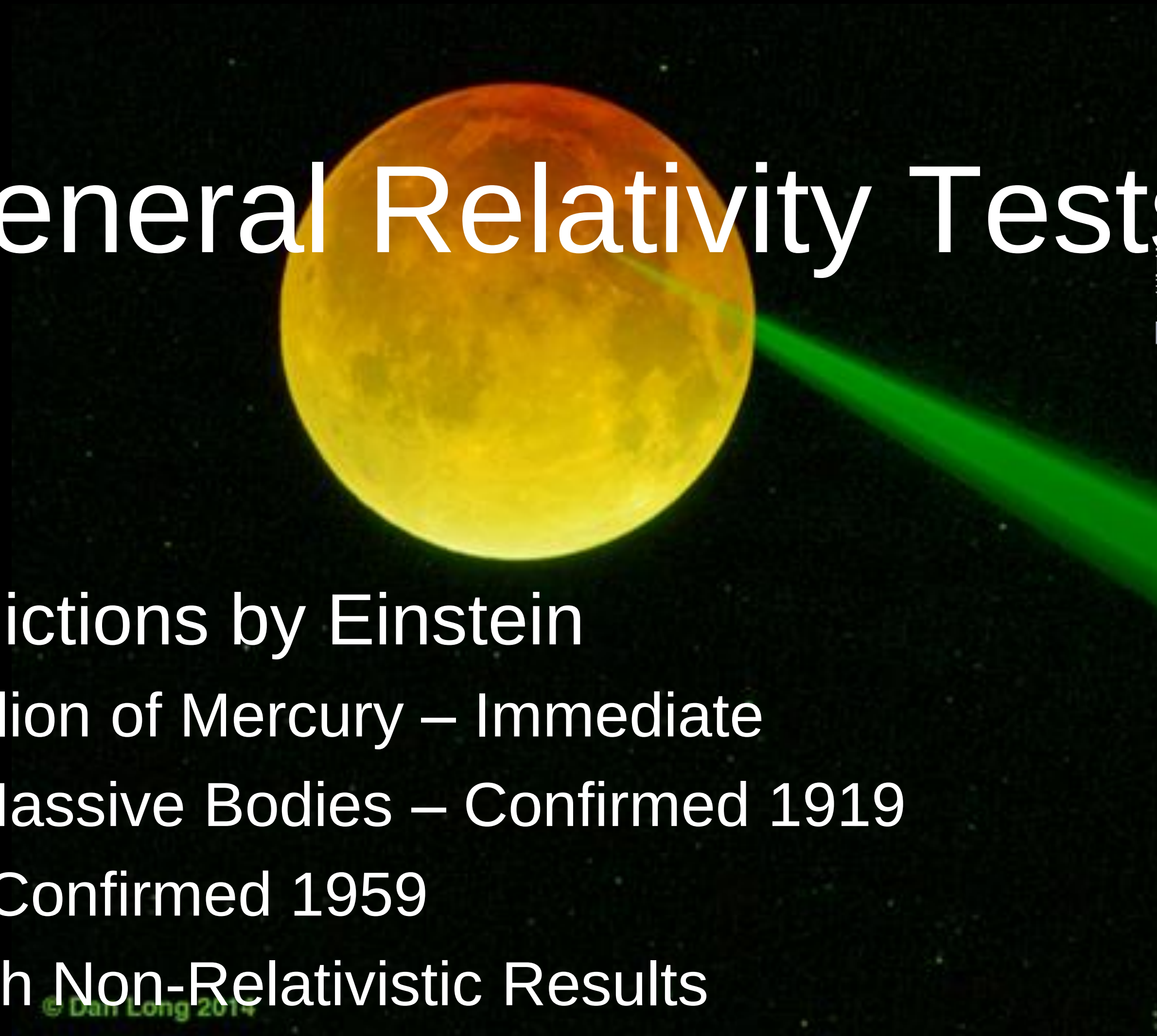
Early Aspects & Motivations

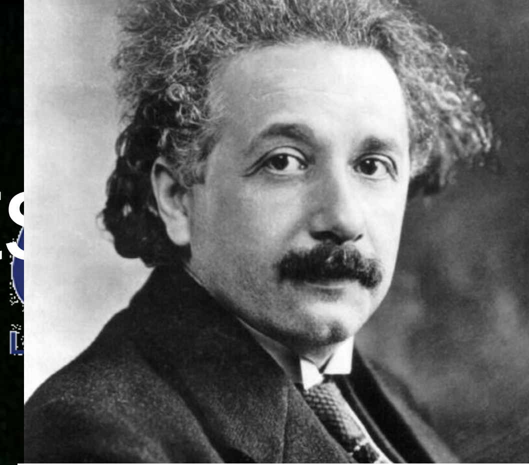
- Historically, the Orbit of the Moon and Its Distance from Earth
  - Has Been Studied for Millennia, Because of Its Importance for:
    - Navigation
    - Eclipse Prediction
    - Tidal Tables for Ocean Navigation
    - Understanding the Formation of the Earth-Moon System
- Early in the Last Millennium
  - General Relativity and Tests Thereof Became an Important Field in Physics
  - Quantum Mechanics Has Been Discovered and Has Been Very Well Tested
  - Fundamental Incompatibility of QM and GR Continue to This Day
- Later, Issues of the Internal Structure of the Moon Became of Interest
  - Again, This Relates to the Solar System Formation Questions
    - Of the Moon, the Earth And Other Planets, Both Solar System Planets and Exo-Planets

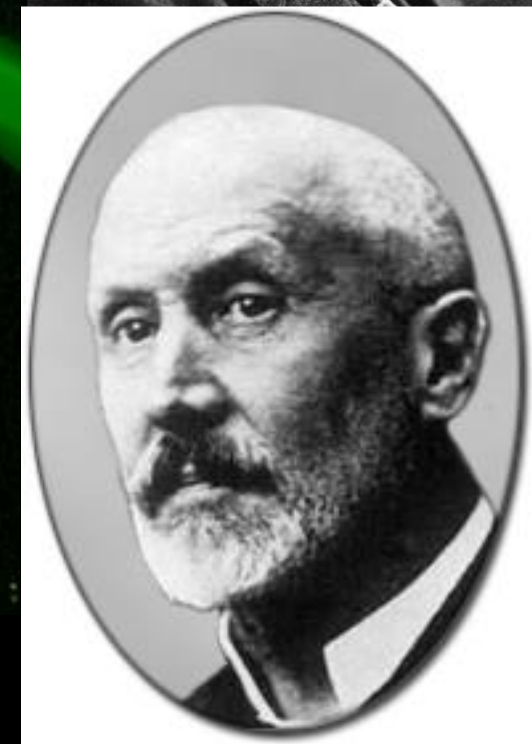
Lunar Distance - PreHistory

- Astronomical Determinations
  - Early Greek Estimates of:
    - Earth Radius 0.6%
    - Distance to the Moon 4%
- Radar Ranging to the Lunar Surface
  - By USNO With an Accuracy of ~150 m
- Space Craft Orbiting the Moon
  - Detected the Distance to the Center of Mass
- Optical Ranging Using a Laser without Retroreflector
  - By MIT/LL to the Lunar Surface
- Problem of Above Methods for the Determinations of the Distance
  - Determinations of Distance to Surface Area Rather Than Fixed Point
  - Thus Not Accurate Enough to Test General Relativity Or Gravitation
  - Thus Not Accurate Enough to Investigate Lunar Interior

Early General Relativity Tests







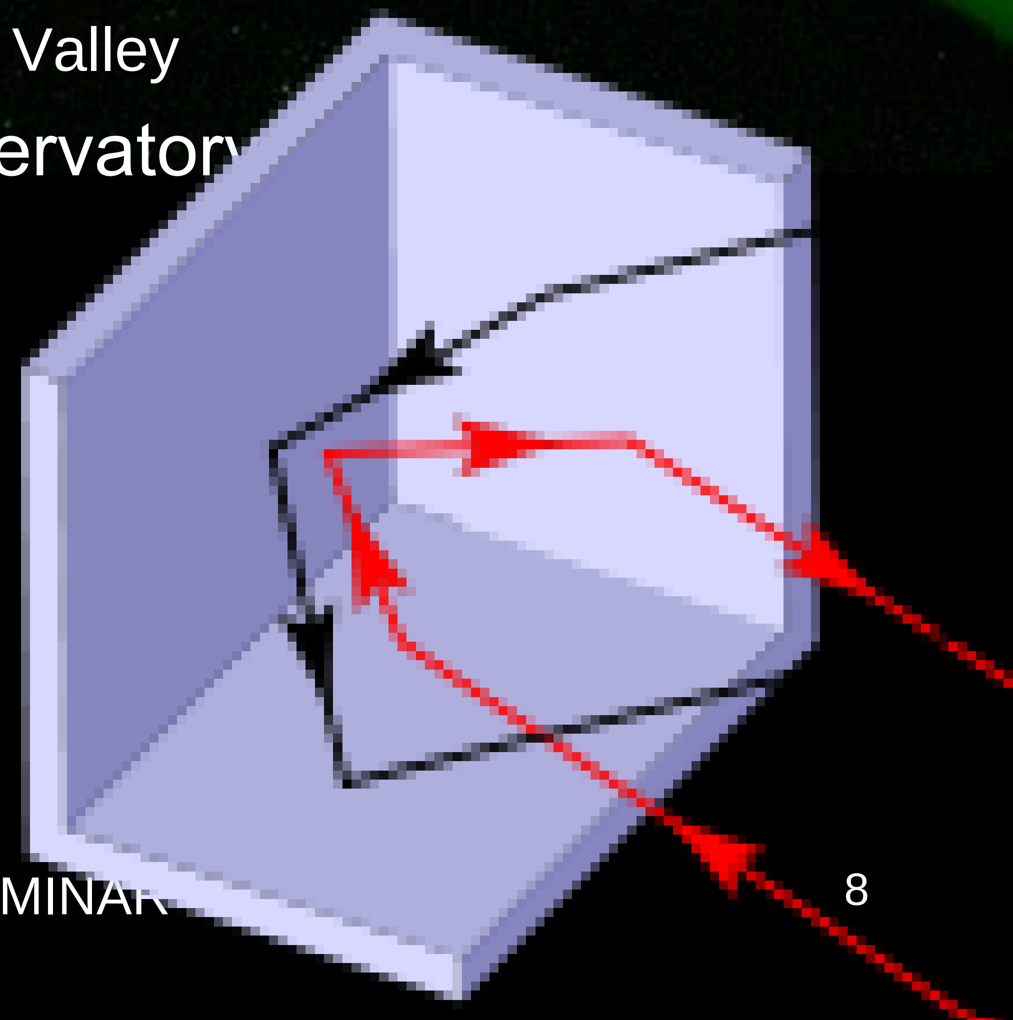
- Initial Experimental Predictions by Einstein
  - Precession of the Perihelion of Mercury – Immediate
  - Bending of Light about Massive Bodies – Confirmed 1919
  - Gravitational Redshift - Confirmed 1959
  - Required Agreement With Non-Relativistic Results
- Loránd Eötvös/Dicke – Laboratory Experiments
  - Weak Equivalence Principle (WEP)
- Joe Weber at the University of Maryland
  - Conceptualization of Gravity Wave Measurements
    - Defined Methods of Observations
  - Early GW Observations with Bar Antennae

Pre-History of Dicke Group

- Professor Robert Dicke of Princeton University
  - Early Interest in Tests of General Relativity
    - Measured the Gravitational Red Shift
    - Investigated the Precession of Mercury
    - Developed the Scalar-Tensor – Brans-Dicke – As an Alternative to General Relativity
- Considered Ranging to the Lunar Surface with Spotlight
  - Insufficient Accuracy – Ranging from the Surface – Variable Topology
  - Insufficient Return Signal – Outgoing Beam Was Too Broad
- In the 1960's – Two Great Leaps Forward
  - Ted Maiman Demonstrated the Laser with High Pulse Energy and Narrow Beam
  - John Kennedy said "We are Going to Put a Man on the Moon"
- Finally, Measurements of Sufficient Accuracy for Science in Many Fields
  - Could, in Principle, Be Accomplished!!!

Laser Ranging & Retroreflectors

- Illuminate Moon With a Short Laser Pulses Like Nano-seconds
- “Normal” Diffuse Reflection from Lunar Surface
  - Radiation Goes Into 2 Pi Steradians
  - Great Loss of Signal
  - Successive Reflection from Mountain And Then Valley
- Need a “Directed” Return Back to the Observatory
- Could Use a Flat Mirror
  - Needs to Be Actively Very Precisely Pointed
  - To Only One LLR Observatory at One Time
  - Required Mechanical/Electrical Components
    - Cannot Last 50 years
- Solution Is to Use a Retroreflector
  - Solid “Cube Corner” of Glass



Preparation For Apollo 11 Science

- ALSEP – Apollo Lunar Surface Experiments Package
- Major NASA Science Project for the Manned Landing
  - Starting Several Years Before Launch
  - A Major Suite of Scientific Instruments Was Defined And Developed
  - Scheduled for Use During All Apollo Missions Through Apollo 16
- Astronauts Began to Practice for Apollo 11 EVA
  - Using the ALSEP 11 Scientific Suite of Experiments
  - Astronauts Would Have Only a Short Time on the Lunar Surface
  - There Was Not Enough Time to Deploy All of the Experiments
  - In Addition, the Lunar Surface Conditions Were Unknown
    - Tommy Gold Said That the Astronauts Would Sink 30 Feet Into the Lunar Dust
- NASA Must Look for a Replacement Suite of Experiments

From ALSEP To ELSEP

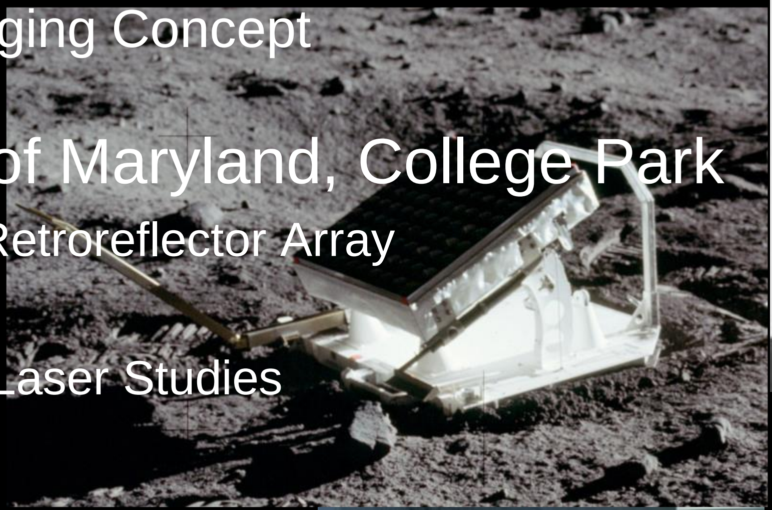
- NASA Solicits a New Set of Experiments
  - Early Apollo Scientific Experiments Payload (ELSEP)
  - Experiments Must Be Easy to Deploy
  - Experiments Must Have Light Or No Power Requirements
  - Experiments Must Have Light Or No Communication Requirements
- The Initial Feasibility Calculations for Lunar Laser Ranging
  - Performed By Bob Dicke’s Group at Princeton University
  - They Had Been Considering the Possibilities for Some Time
- Final Proposal for the Apollo 11 LLRRA for the ELSEP
  - Was Created And Submitted to NASA
  - ~12 Months Before Launch
- NASA Accepted Our Proposal for Retroreflector Array for Apollo 11

Bob Dicke

Carroll Alley

Apollo 11 Team

- Original Team for Our Apollo 11 Retroreflector Array
- Robert H. Dicke – Princeton University
  - GR Tests, Microwave Technology,
  - Cosmic Microwave Background Radiation (CMBR)
  - Originator of Lunar Laser Ranging Concept
- Carroll O. Alley – University of Maryland, College Park
  - Principal Investigator, Apollo 11 Retroreflector Array
  - General Relativity Tests
  - Optical And Atomic Physics And Laser Studies



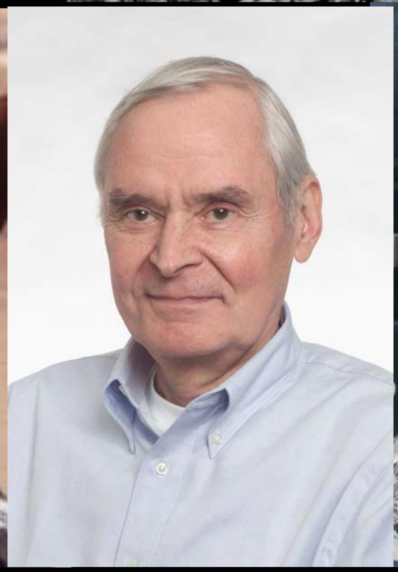
Jim Faller

Bill Kaula

Pete Bender

Jim Williams

Derral Mulholland

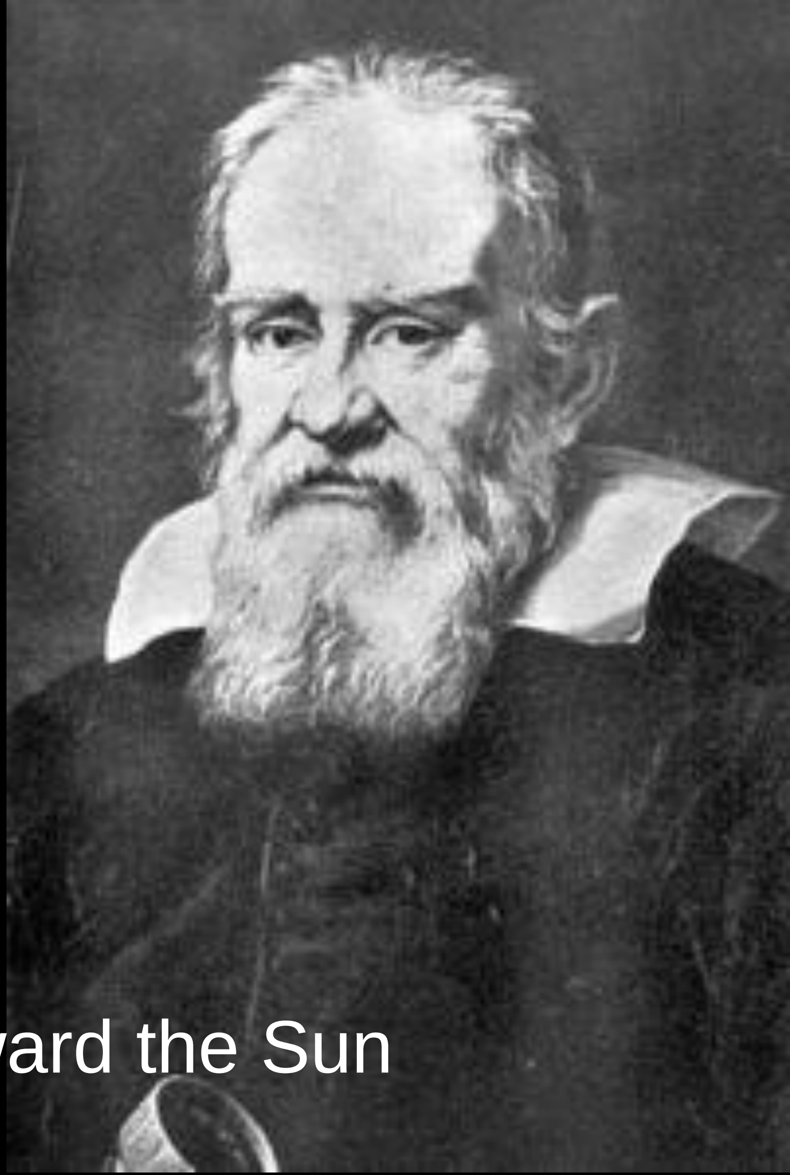


Dave Wilkinrson

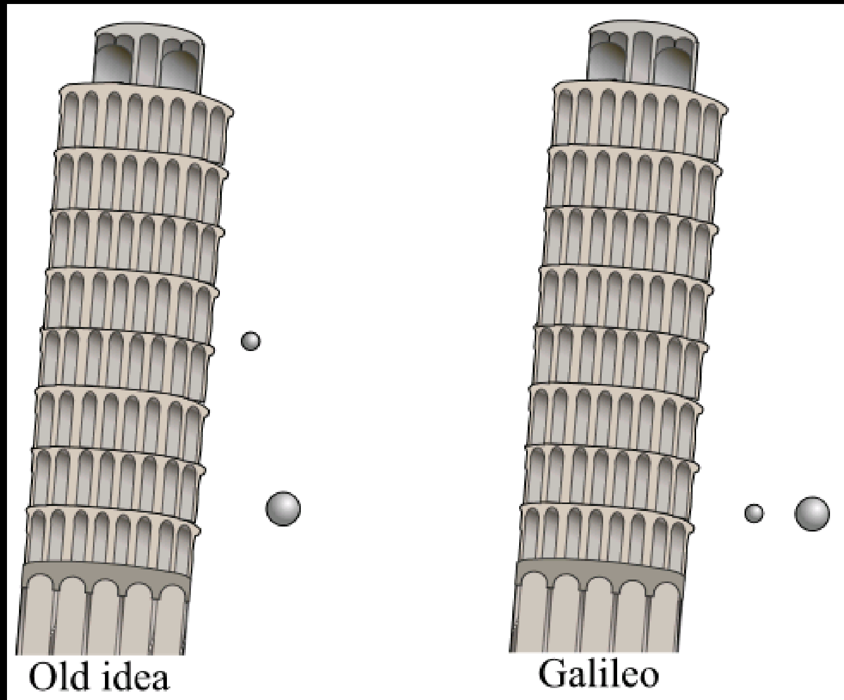
Henry Plotkin

Doug Currie

Science Objectives



- Many Science Objectives in Proposal
  - Too Many for My Allocated Time
- Galileo’s Apocryphal Experiment
  - Weak Equivalence Principle (WEP)
  - Rates at Which the Earth And Moon Fall Toward the Sun
- Structure of the Lunar Interior
  - Crustal Response to Tidal Stresses
  - Internal Structure from Crust to Core
- Testing of General Relativity
  - Comparison With the Brans-Dicke Theory

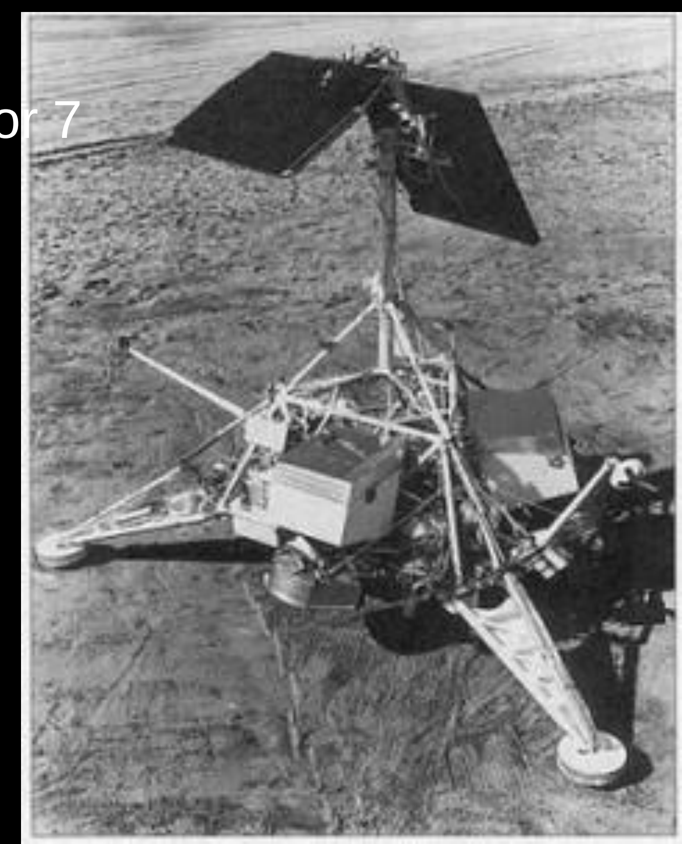


LLR/Retroreflector Proposal

- Final Proposal to NASA for Apollo 11 Retroreflector Array
  - Final Proposal Delivered ~12 months Before Launch
  - Very Short Time for Final Design and Fabrication
- Issues Raised in the Review of Our Final Proposal
  - Cannot Perform Single Photoelectron Detection
    - We Had Been Doing SPD for Years So This Was Not an Issue
  - Cannot Point a Laser to the Required 1 Arc-Second Accuracy
    - Our Team Had Laser Pointing Experience – Henry Plotkin Was Already Laser Ranging to Satellites
    - But Plotkin Used Much Wider Laser Beams
      - To Range to LEO Satellites Which Are Much Closer Than the Moon
  - Coincidently I Had Been Calculating Whether the Astronauts Could See Our Laser
    - Answer Was No – Due to Anomalies of the Way the Human Eye Detects Faint Point Pulses of Light
    - But Surveyor 7 Spacecraft Was About to Be Launched to Land on the Moon
    - This Would Provide a Camera that Was Located on the Lunar Surface
    - Perhaps the Surveyor Camera Could See a Laser That We Transmit from Earth
      - Detailed Analysis Determined That the Surveyor 7 Camera Should Be Able to See a Laser Beam Transmitted from Earth

Validation of Pointing Ability

- Surveyor 7 As a Possible Vehicle for the Validation
- Surveyor 7 Was to Be Launched in Only a Few Days
  - This Was to Be the Last Surveyor Lunar Landing
- Revision of My Calculation Indicate Surveyor Could See a Laser
  - A CW Argon Ion Laser Was Needed Instead of the Pulsed Ruby Laser
- Carroll Alley And I Went to the Surveyor Science Team Meeting
  - To Get Permission to Point a Laser at Surveyor 7
  - Their Meeting Took Place at the Cape During the Launch of Surveyor 7
  - The Surveyor 7/Laser Illumination Experiment Was Approved
- We Quickly Assembled a Set of Collaborators
  - Jim Brault at the McMath Telescope at the Kitt Peak Observatory
  - Jim Faller at the Wesleyan University
  - Mike Shumate at the Table Mountain Observatory of JPL



McMath Telescope Operation

Surveyor 7 is Launched

Jim Brault And I Meet at Kitt Peak

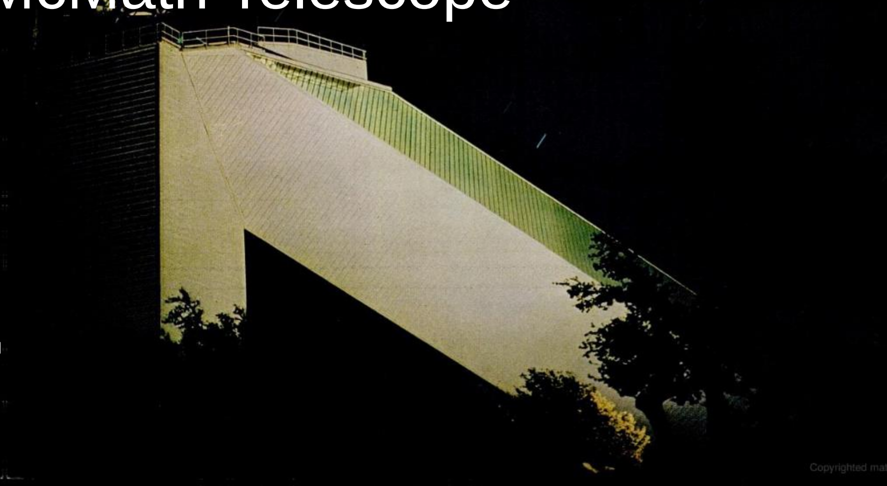
- Crawled Over the McMath Telescope
- To Determine Experiment Requirements

Back at UMCP

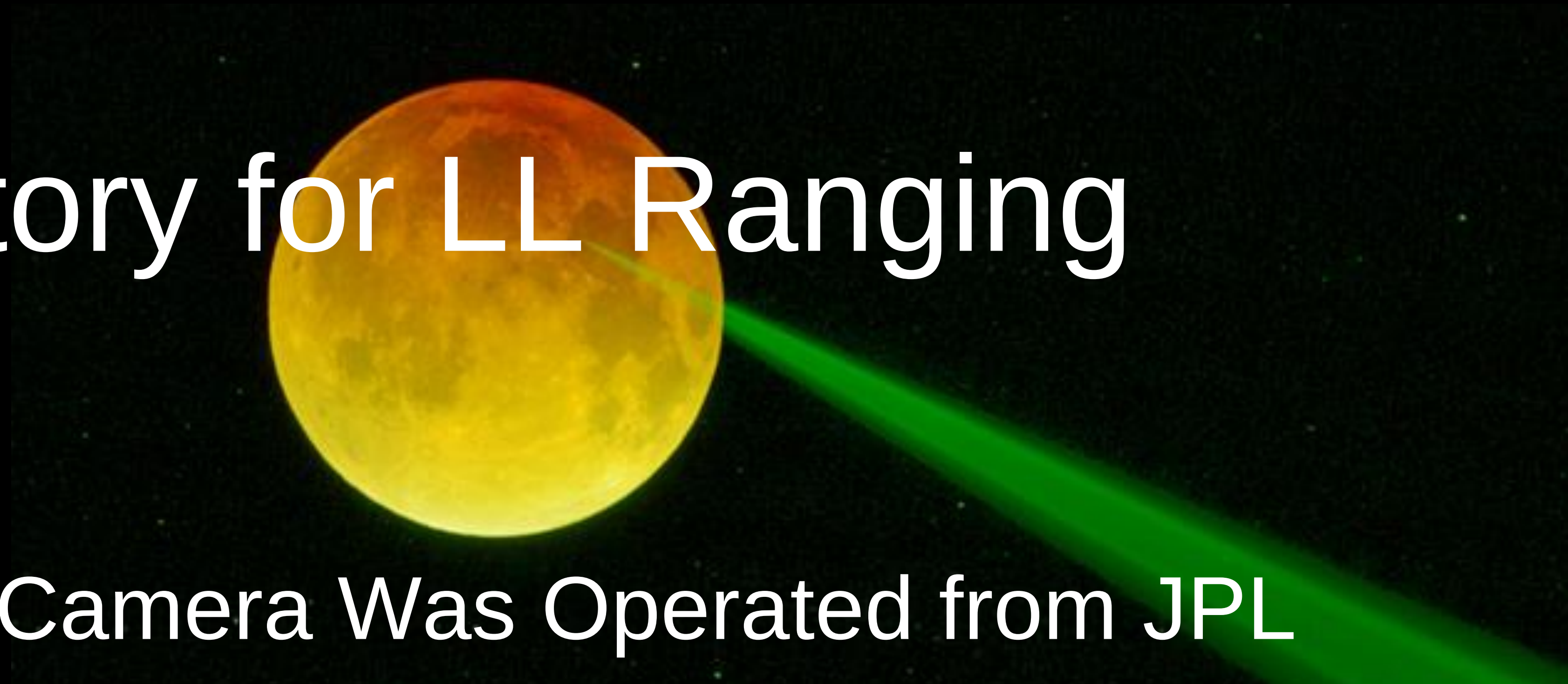
- We Built the Required Hardware in 36 hours
- Shipped the Hardware to McMath
- The Hardware was Installed in the Telescope
- All Was Ready When the Surveyor Arrived at the Moon

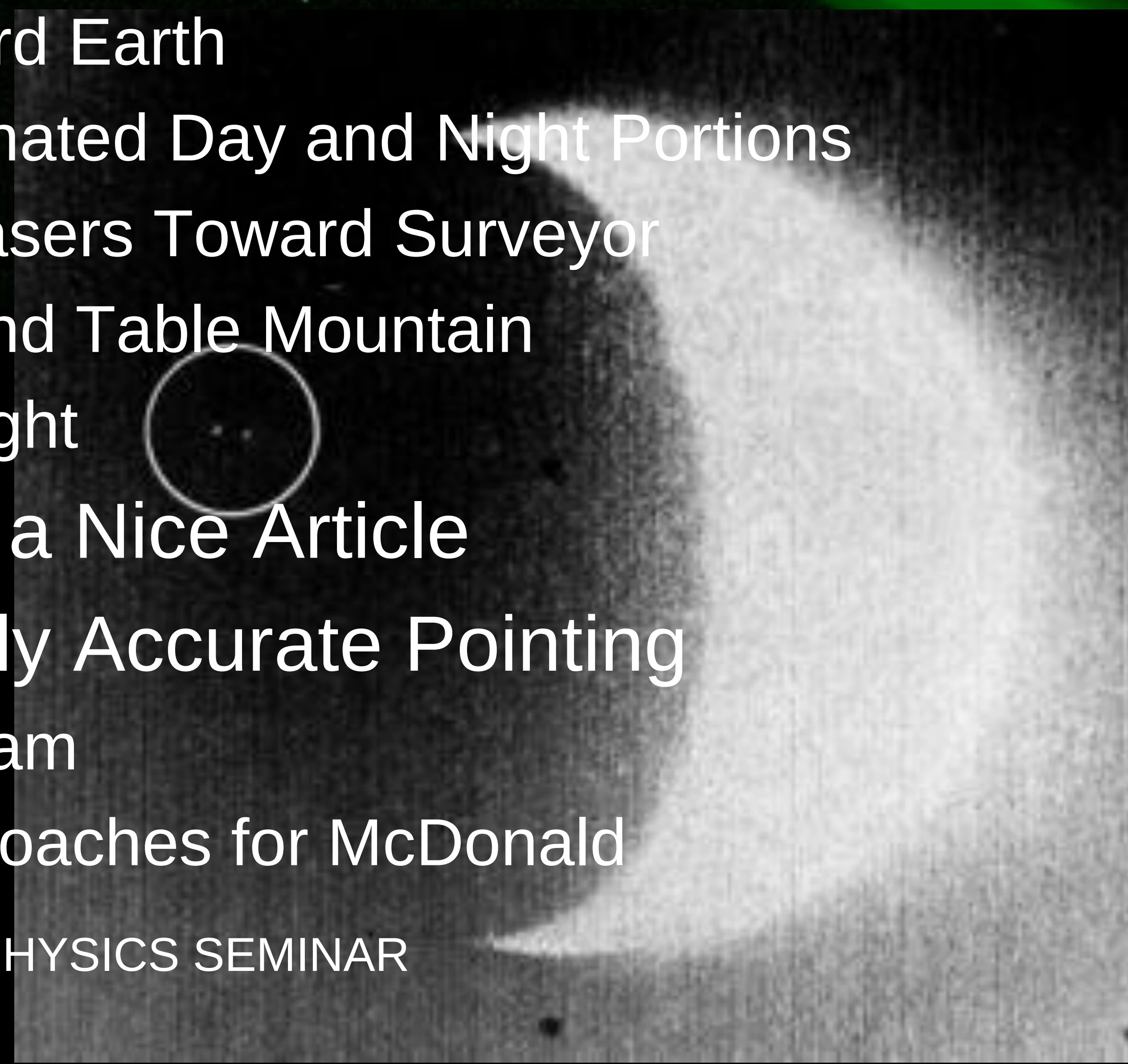
McMath Personnel Shown in the Image

- Jim Brault – Responsible for McMath Telescope
- Sherman Poultney – UMCP
- Eric Silverberg - – UMCP



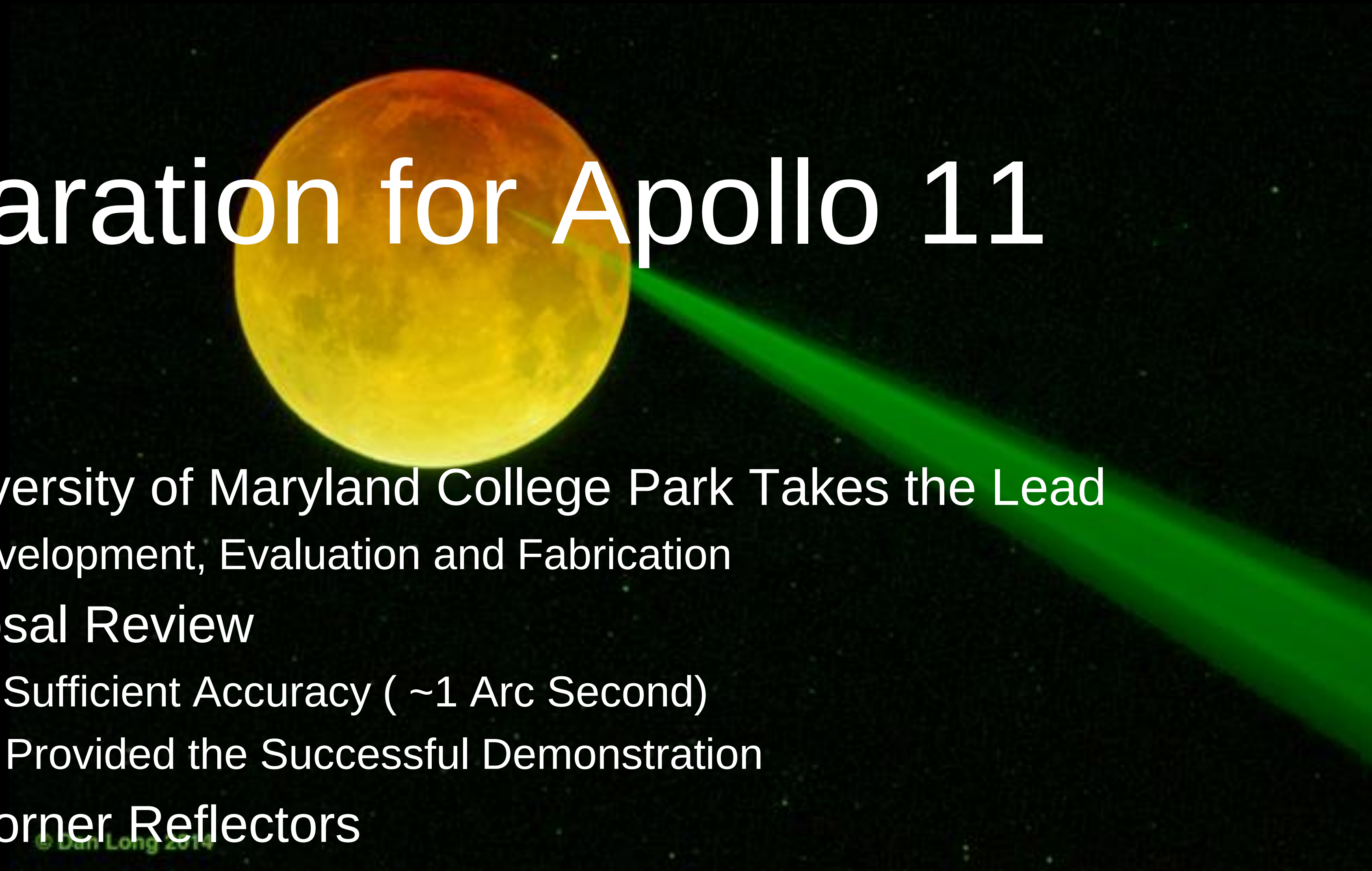
Preparatory for LL Ranging





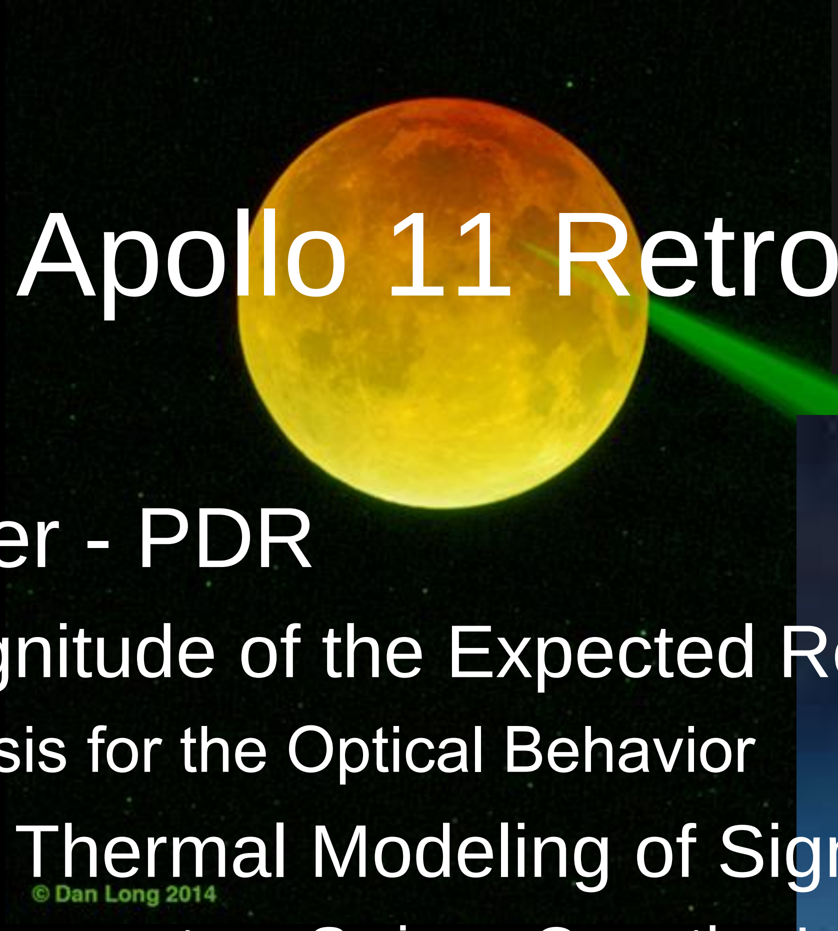
- The Surveyor 7 Camera Was Operated from JPL
  - We Pointed the Camera Toward Earth
  - Image of Earth Showing Illuminated Day and Night Portions
  - Four Earth Stations Pointed Lasers Toward Surveyor
  - Laser Detections of McMath and Table Mountain
  - Eastern Stations Were in Twilight
- Life Magazine Provided with a Nice Article
- Demonstrated that Sufficiently Accurate Pointing
  - Could Be Achieved By Our Team
  - Useful Definition of Good Approaches for McDonald

Preparation for Apollo 11



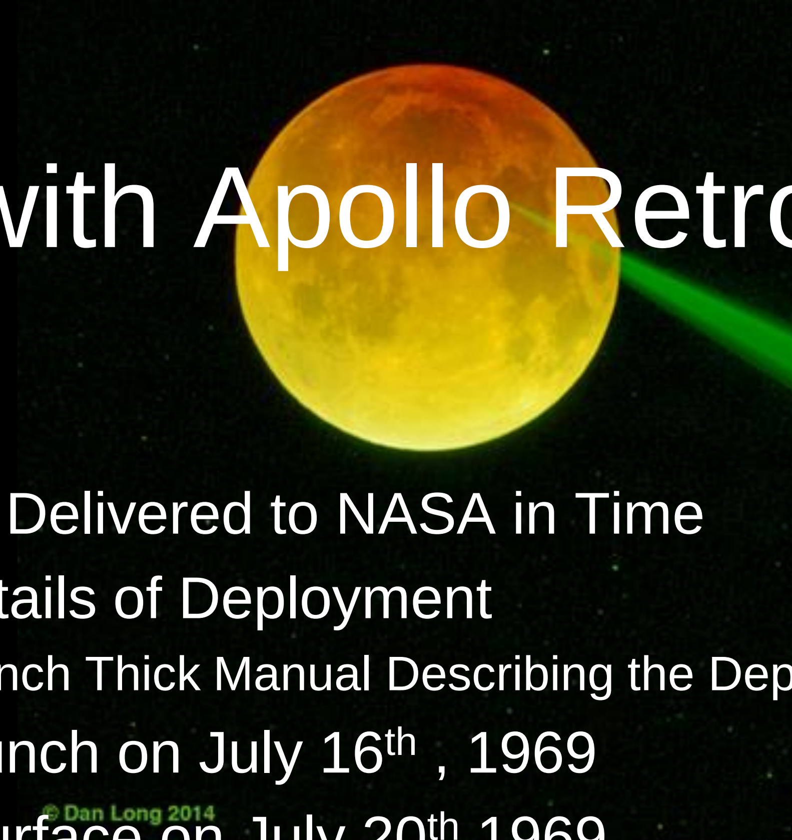
- Carroll Alley at the University of Maryland College Park Takes the Lead
  - Very Short Time for Development, Evaluation and Fabrication
- Issues Raised in Proposal Review
  - Pointing the Laser with Sufficient Accuracy (~1 Arc Second)
  - Surveyor 7 Experiment Provided the Successful Demonstration
- Selected Solid Cube Corner Reflectors
  - Uncoated (TIR) CCRs to Survive the Solar Heat Load Effects
  - With Ren-Fang Chang, We Analyzed a CCR Using Total Internal Reflection (TIR)
- Arthur D. Little Participated in Analysis for PDR
- Bendix Corporation was Prime Contractor for CDR
- We Gave Deployment Instructions to Buzz Aldrin,
  - But, of Course, He Had a Thick Book on How to Do It.

Contractors for Apollo 11 Retroreflector

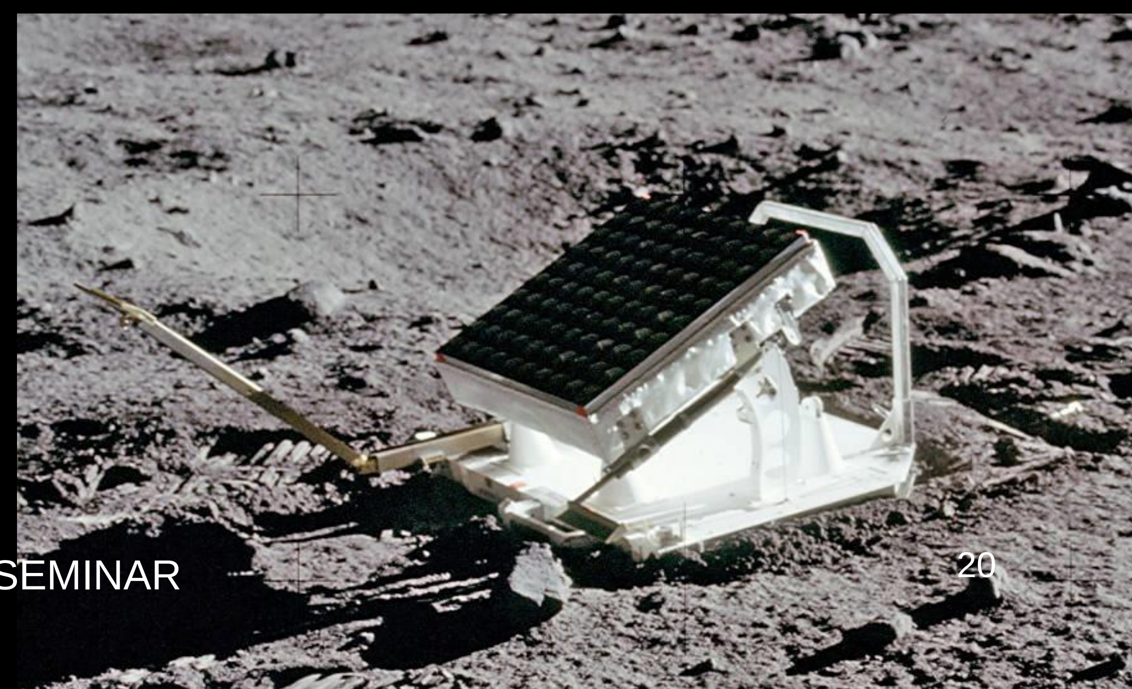


- Arthur D. Little – Peter Glaser - PDR
  - – Provided Analysis of the Magnitude of the Expected Returns
    - Confirming Our Team's Analysis for the Optical Behavior
  - – Provided Confirmation of the Thermal Modeling of Signal Return
    - Addressed Impact of 300K Temperature Swings Over the Lunar Cycle
  - – Preliminary Detailed Hardware Designs
- Perkin Elmer – Paul Forman - Zygo
  - – Provided the Fabrication of the Cube Corner Retroreflectors
- Bendix - CDR
  - – Responsible for the Fabrication of the Flight Hardware
  - – Responsible for the Interfaces With NASA

LLR History with Apollo Retroreflectors



- Apollo 11 Retroreflector Array Delivered to NASA in Time
- We Briefed Buzz Aldrin on Details of Deployment
  - Of Course, He Already Had a 1-inch Thick Manual Describing the Deployment
- We Attended the Saturn 5 Launch on July 16th , 1969
- Eagle Landed on the Lunar Surface on July 20th 1969
- Buzz Deployed the Retroreflector Array
- Later, Buzz Told Me that It Was the Easiest Experiment Deployment



The Preparation Of the Lunar Package Is in Process

But We Need Ground Stations To Perform the Ranging

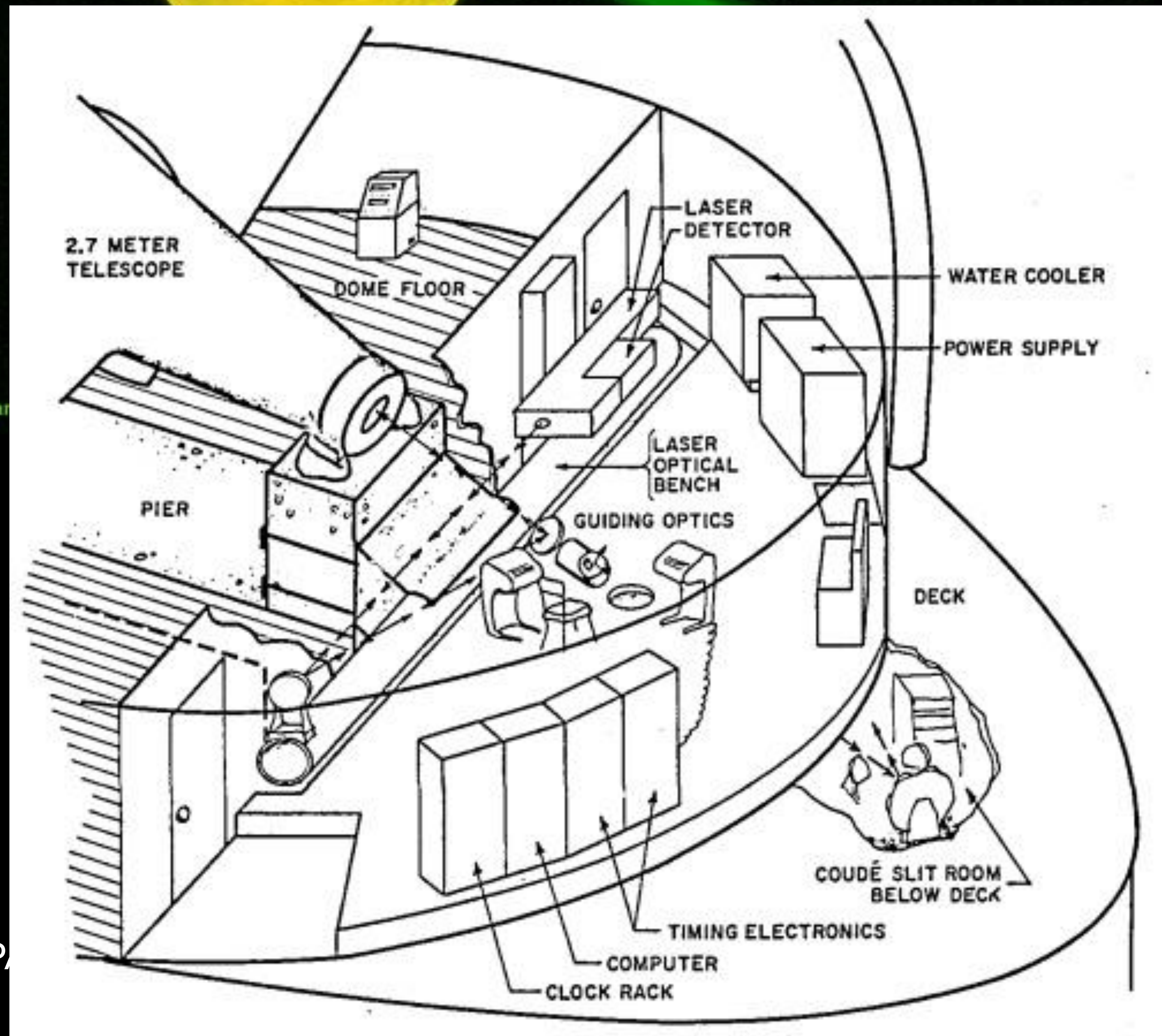
LLR Observatories

- We Need Lunar Laser Ranging Observatories (LLROs)
  - Carroll and I Made Visits to Several Candidate Observatories
    - The 60-inch Telescope at AMOS on Maui, Hawaii – Scheduling Problems
    - The 120-inch Telescope at Lick Observatory on Hamilton Mountain, California - Backup
    - The 107-inch Telescope at McDonald Observatory at Fort Davis, Texas - Primary
- Developing & Deploying Hardware for the LLR Observatory
  - Goddard Space Flight Center Provided the Laser And Other Systems
    - Henry Plotkin And His Crew Operated the Laser System for Years
  - University of Maryland, College Park
    - Doug Currie, with Carroll Alley, Sherman Poultney, And Others
- Installation at Observatory Was Completed
  - And Initial Ranging Operation Proceeded
- Lick and McDonald Achieved Successful Initial Ranging

LLR at McDonald Observatory

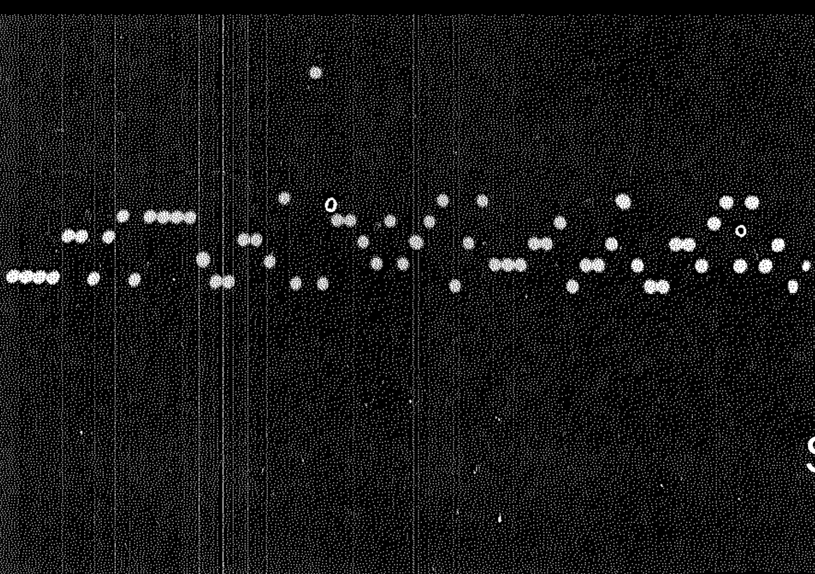
- McDonald Observatory
  - Mt. Locke, Fort Davis, Texas
- LLRO Created for Regular Operation
  - Configured for Operation Over the Next Decade
- Other Stations Active in First Few Years
  - Lick Observative – For the Initial Acquisition
  - French MeO at Côte d' Azur – Long Term Operation
  - Crimea, Soviet Union – Initial Ranging
  - APOLLO at Apache Point, NM
    - Developed Much Later By Tom Murphy of UCSD
    - Currently Operated by GSFC - Best Current Precision

McDonald LLR Observatory



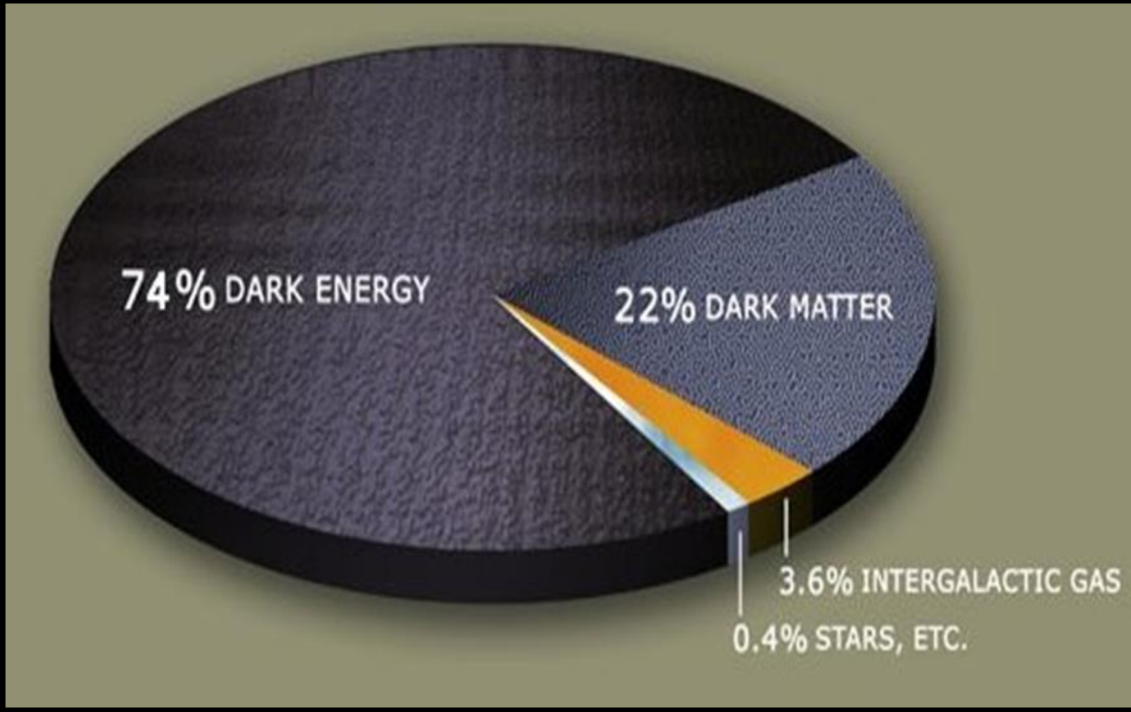
Operating Personnel

- University of Maryland
  - Doug Currie
  - Eric Silverberg
  - Sherman Poultney
  - Charlie Steggerda
  - John Mullendore
  - John Raynor
- University of Texas
  - Brian Warner
  - Wayne van Citters
  - Bernie Bopp
  - Don Wells
  - Mike McCants
- GSFC
  - Windell Williams
  - Robert Gonzales



So Much for Getting LLR Started
But Why Do This
and
Has There Been Anything to Show for All This Effort?

Questions in



- Thirty Years Ago
  - We Knew All About the Universe
- Vera Rubin Studied Motion of Stars
  - Stars Do Not Rotate "Properly" About the Galactic Center
  - Do Not Know Why, But We Call the Phenomenon Dark Matter
- Perlmutter, Schmidt & Riess Looking at Super Nova
  - Distant Galaxies Are Moving Too Fast
  - Do Not Know Why, But We Call the Phenomenon Dark Energy
- Something Strange Seems to Be Going on With Gravity
- Cannot Fit General Relativity Into Quantum Mechanics

CURRENT ISSUES

- Open Questions in Cosmology and Fundamental Physics
  - Nature of Dark Matter
    - Gravitational Observations Are the Only Clue to Date
    - Other Possibilities Addressed By the MOND Theories
    - However, I Will Leave the Alternative to the Particle Physics Analyses
  - Nature of Dark Energy
    - Supernova Discoveries of Acceleration of Distant Galaxies
    - Einstein’ Lambda Constant
    - Quintessence – That Is Issues of General Relativity
  - Relation Between GR And Quantum Mechanics
    - Attempts toward the Quantization of Gravity
    - String Theory Implies Variation of Fundamental Constants
- Must Test GR to the Limit of the Available Technologies

Current Relativity Science

- **A List of Some Relativity Results Determined with 50 Years of LLR Data**

Equivalence principle parameter	η	(6 ± 7) . 10−4
Metric parameter	γ − 1	(4 ± 5) . 10−3
Metric parameter	β − 1: direct measurement	(−2 ± 4) . 10−3
Time-varying gravitational constant	˙G/G (year−1)	(6 ± 8) . 10−13
Differential geodetic precession	ΩGP -ΩdeSit (per century)	(6 ± 10) . 10−3
Yukawa coupling constant	α (for λ =4 · 105 km)	(3 ± 2) . 10−11
“Preferred-frame” parameter	α1	(−7 ± 9) . 10−5
“Preferred-frame” parameter	α2	(1.8 ± 2.5) . 10−5
Special relativistic parameters	ζ1 − ζ0 − 1	(−5 ± 12) . 10−5
Influence of dark matter	δggalactic (cm s−2)	(4 ± 4) . 10−14

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- From Juergen Mueller and Franz Hofmann
- Of the Leibniz Universität Hannover

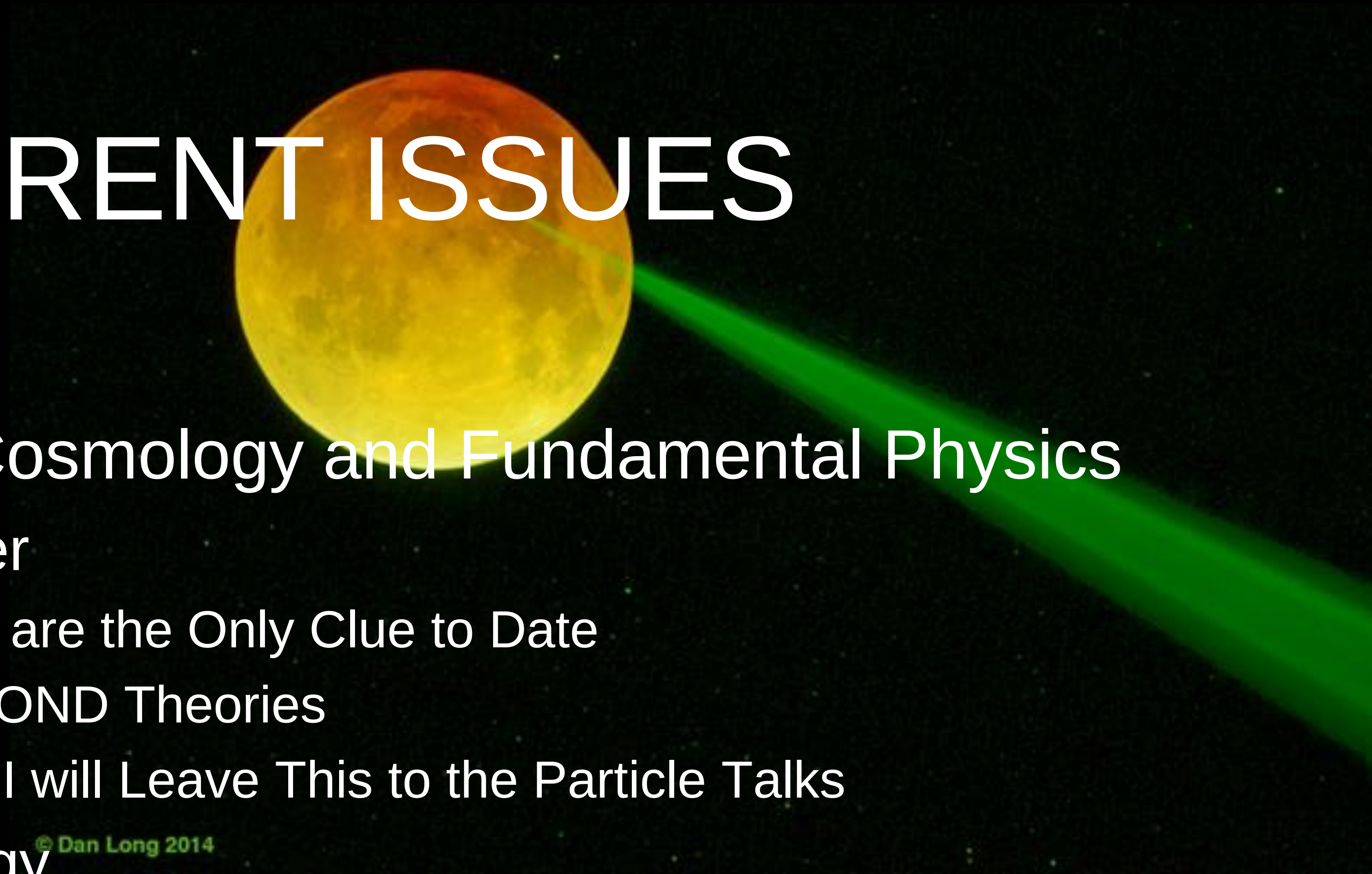
GRAVITATIONAL & GR SCIENCE

- LLR Currently Provides our Best Tests of:
  - The Strong Equivalence Principle (SEP)
  - **Time Rate-of-Change of G**
  - Inverse Square Law, Deviation of 1/r
  - Gravito-Magnetism
  - **Weak Equivalence Principle (WEP)**

MOND Theories

- What Explains the “Dark Matter” Observations?
  - – Modification of the Newtonian Dynamical Theories
    - MOND Theories
  - – As Yet Unknown Particles
- Brans-Dicke Theory
  - – LLR Pushed the Parameter to Unphysical Value of 79
- MOND Theories
  - – Initial Version – LLR Values of G-dot Disconfirmed Theory
  - – Current Version – Difficult but NOT Investigated

CURRENT ISSUES



- Open Questions in Cosmology and Fundamental Physics
  - Nature of Dark Matter
    - Gravitational Effects are the Only Clue to Date
    - Addressed by the MOND Theories
    - However, for Now – I will Leave This to the Particle Talks
  - Nature of Dark Energy
    - Supernova Discoveries of Acceleration of Distant Galaxies
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    - Quintessence
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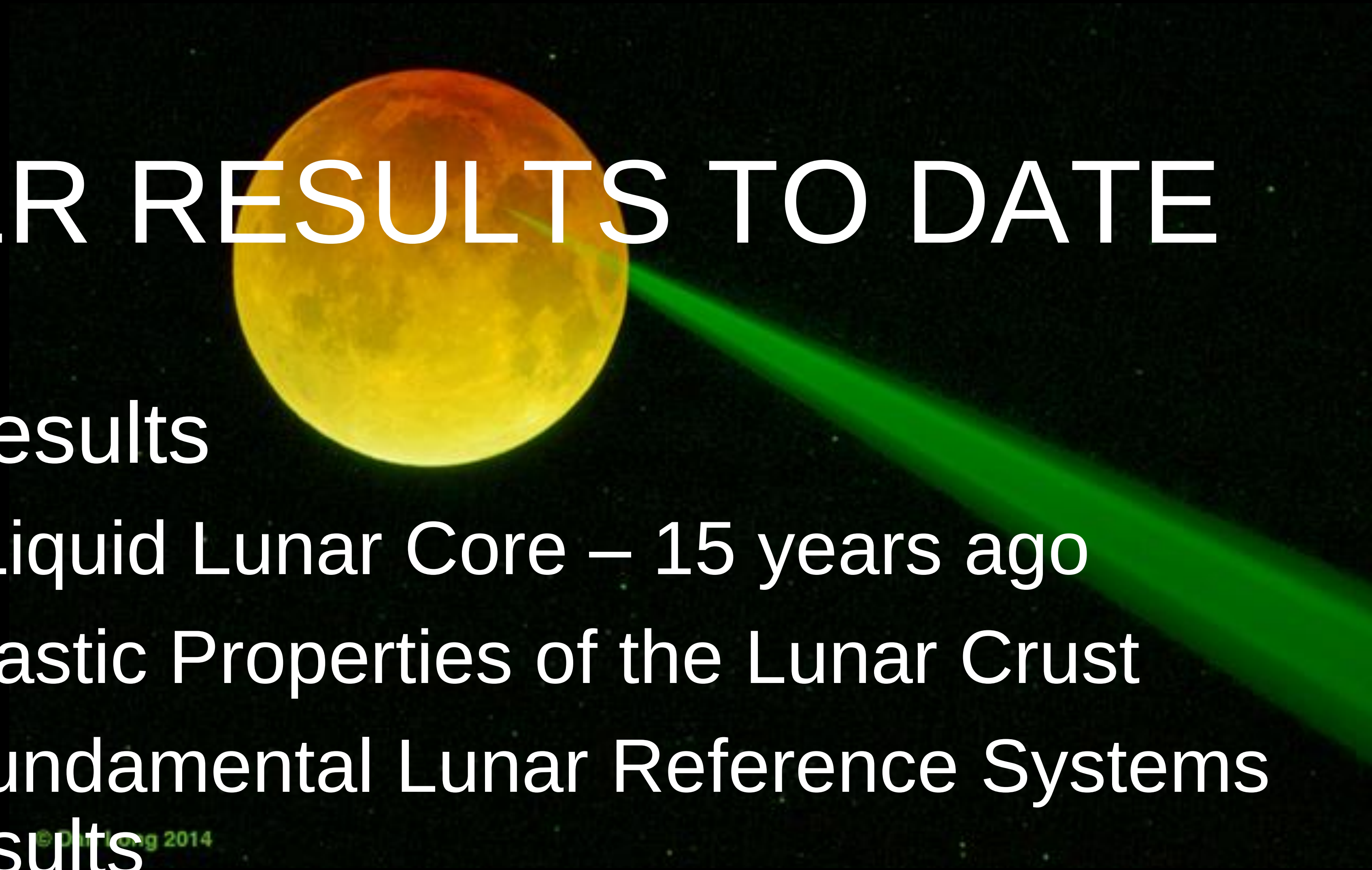


OTHER RESULTS TO DATE

- Lunar Physics Results
  - – Discovered the Liquid Lunar Core – 15 years ago
  - – Evaluated the Elastic Properties of the Lunar Crust
  - – Basis for Both Fundamental Lunar Reference Systems

Earth Science Results

Plate Tectonics Or the Motion of the Continents

Addressed Question of Historical vs. Current Motion

LLRP Has Been Measuring the Current Motion

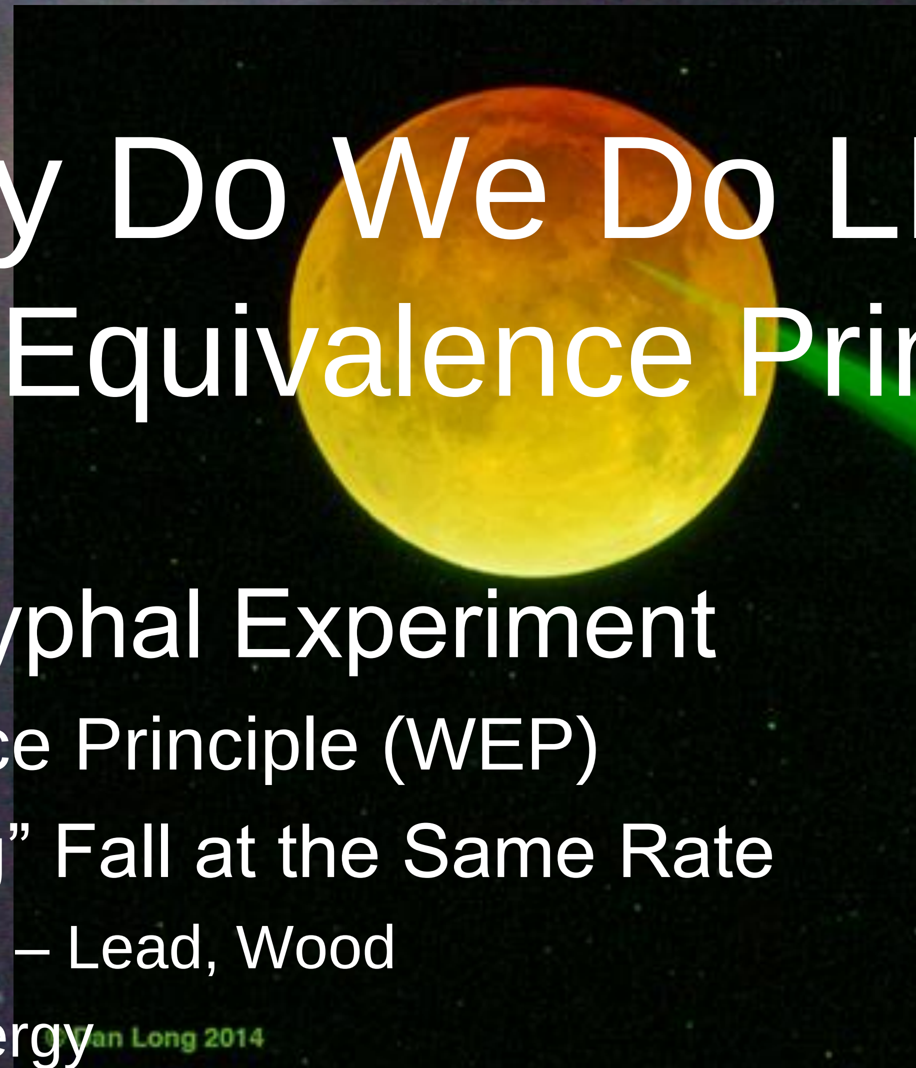
Earth Rotation

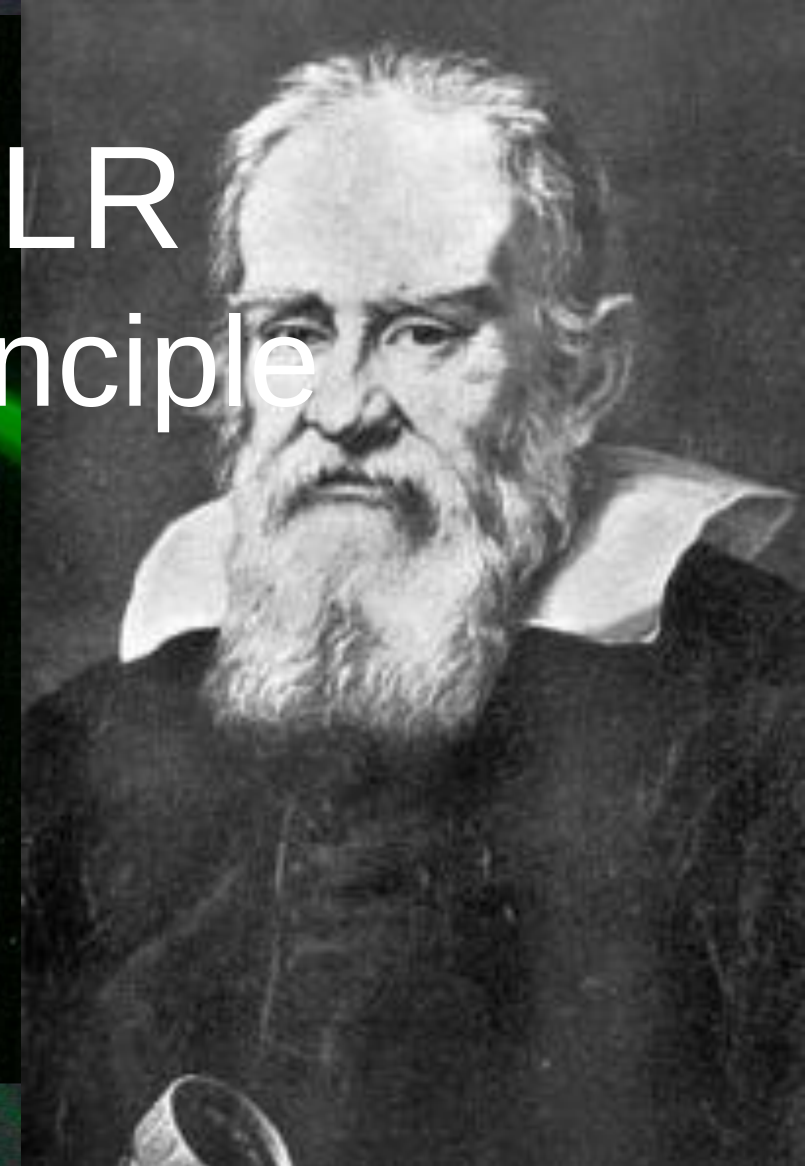
Evaluated the Changes in the Length of the Day

Measurement of Polar Wander

Chandler Wobble to High Accuracy

Why Do We Do LLR
Weak Equivalence Principle

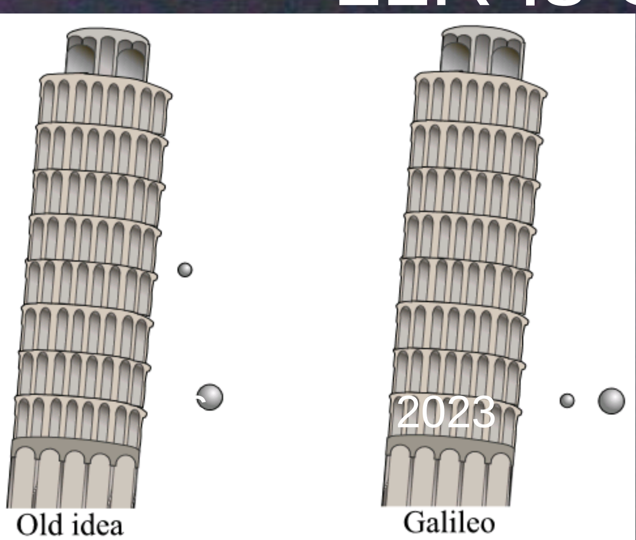


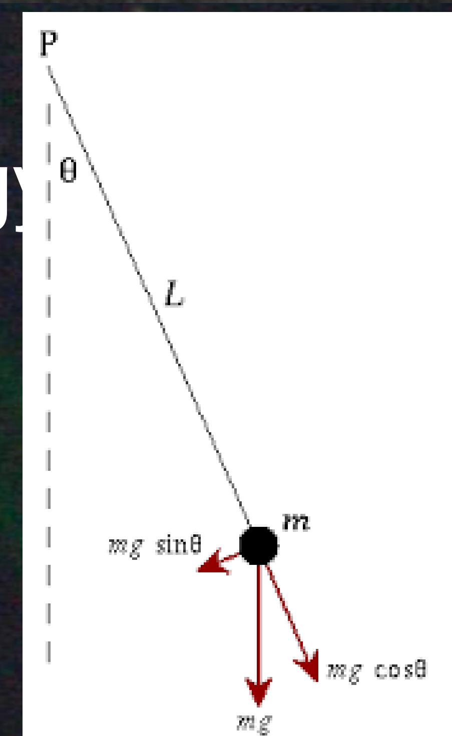


- Galileo’s Apocryphal Experiment
  - Weak Equivalence Principle (WEP)
  - Does “Everything” Fall at the Same Rate
    - Different Masses – Lead, Wood
    - Gravitational Energy
  - LLR Measures the Differential Acceleration
    - Of the Rate That Earth And Moon Fall Toward the Sun
- LLR Is Only Determination For Gravitation Energy

Also Laboratory Measurenmts of WEP

Eötvös and followers

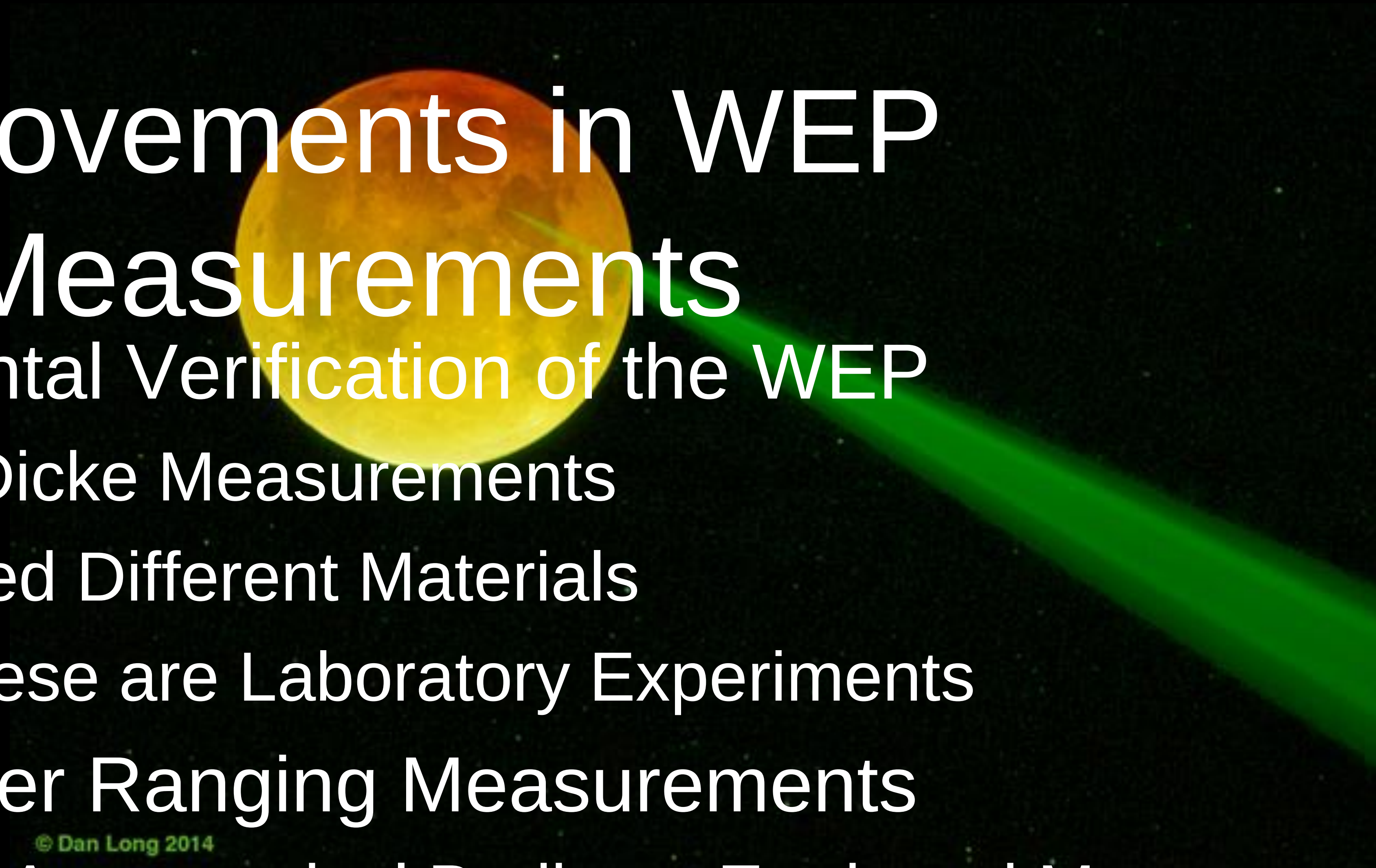




2023

SPACE AND COSMIC RAY PHYSICS SEMINAR

Improvements in WEP Measurements

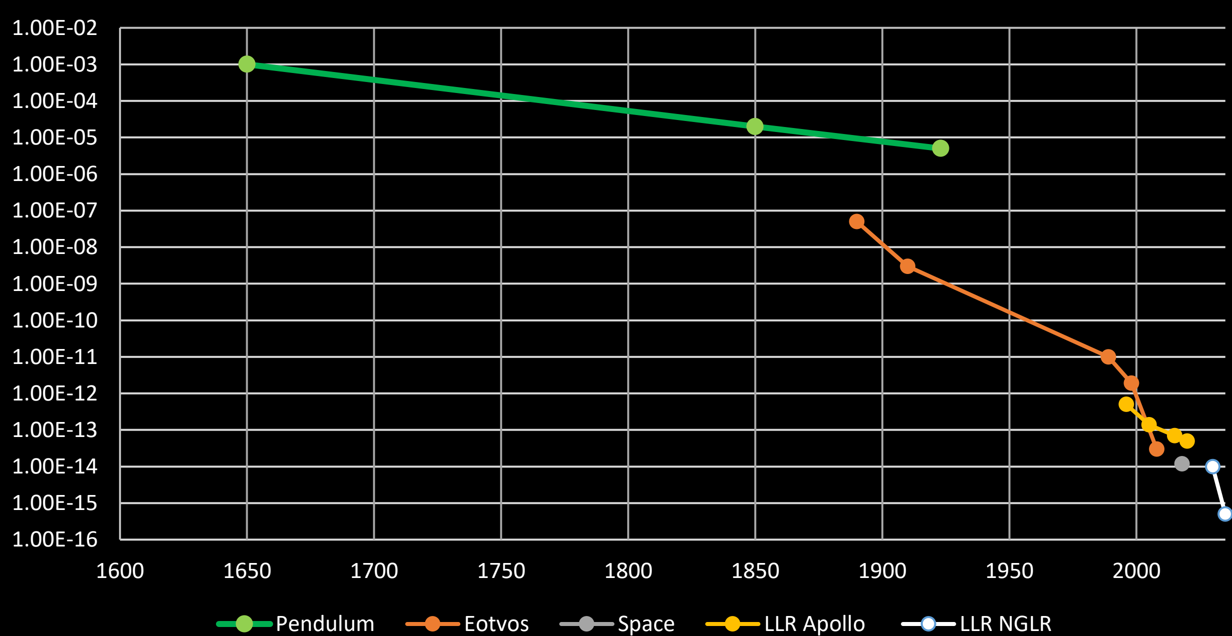


- Experimental Verification of the WEP
  - – Eötvös/Dicke Measurements
  - – Compared Different Materials
  - – All of These are Laboratory Experiments
- Lunar Laser Ranging Measurements
  - – Massive Astronomical Bodies – Earth and Moon
  - – They Move on “Geodesics”
    - Force Free Paths in Curved Space Time
    - Acceleration Toward the Sun and/or the Moon
- LLR Accuracy Addresses Gravitational Energy
  - Gravitational Energy Falls at the Same Rate as a Mass

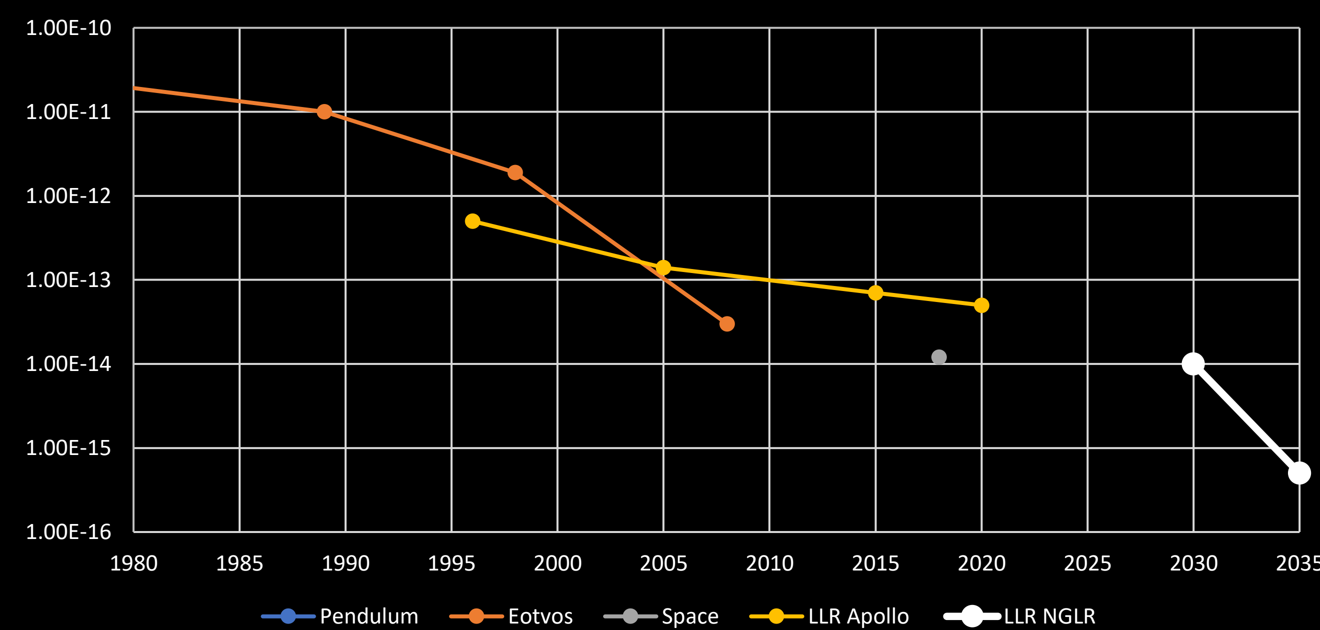
History of WEP Accuracy

- WEP Measurenmts Started with Galileo’s Pendulum Measurements
- Eotvos Followed with Laboratory Torsion Balance Approach
- LLR/Apollo Retroreflector Arrays Started in 1969
- MICROSCOPE Space Experiment
- LLR/NGLR with Existing/Improved LLRO Capabilities
- **Four NGLRs & Upgraded LLROs Provides 2 Decades Improvement**

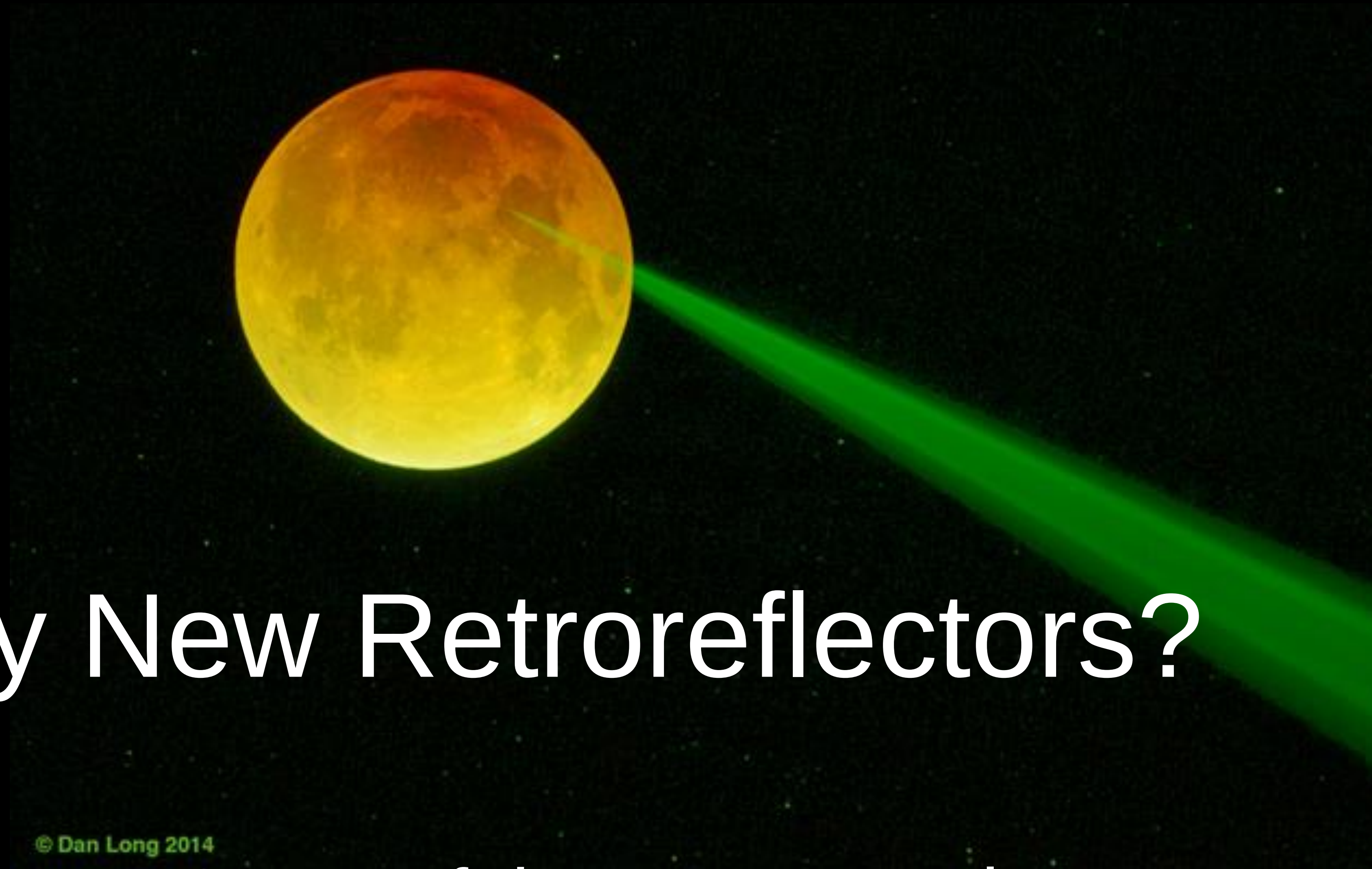
Full History of WEP



Recent History of WEP



Why Deploy New Retroreflectors?

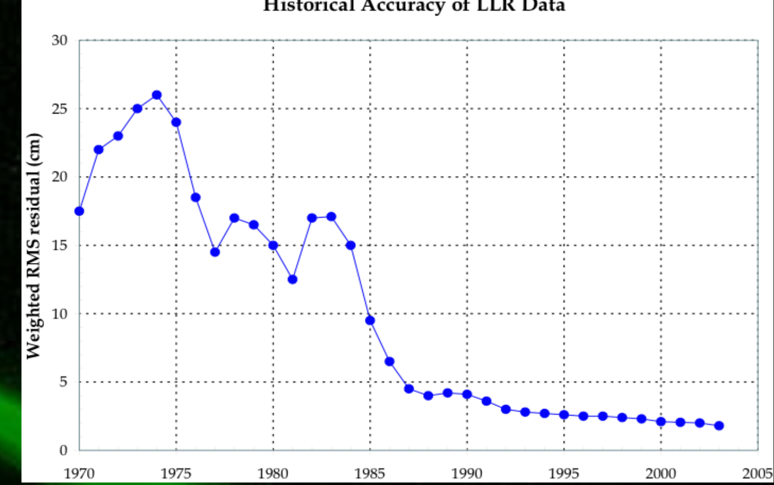


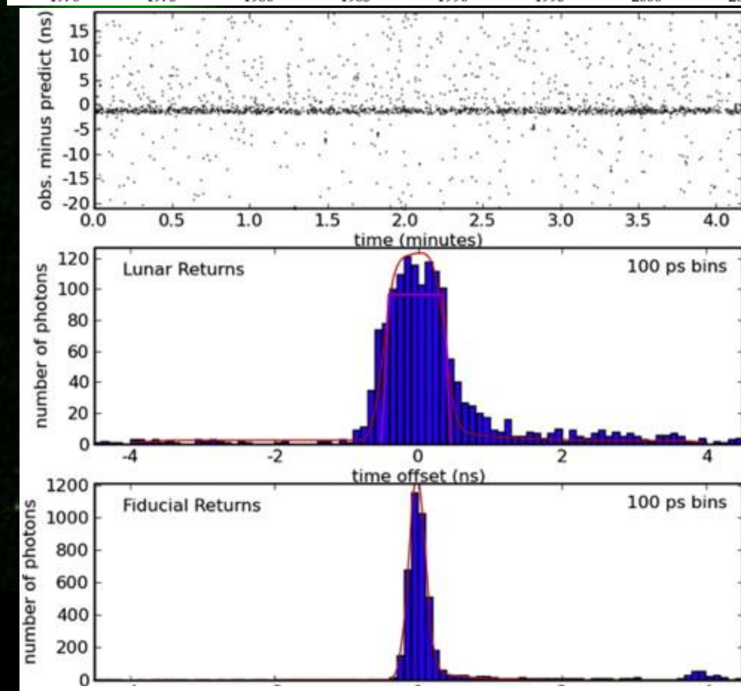
We Already Have Some of the Best Results

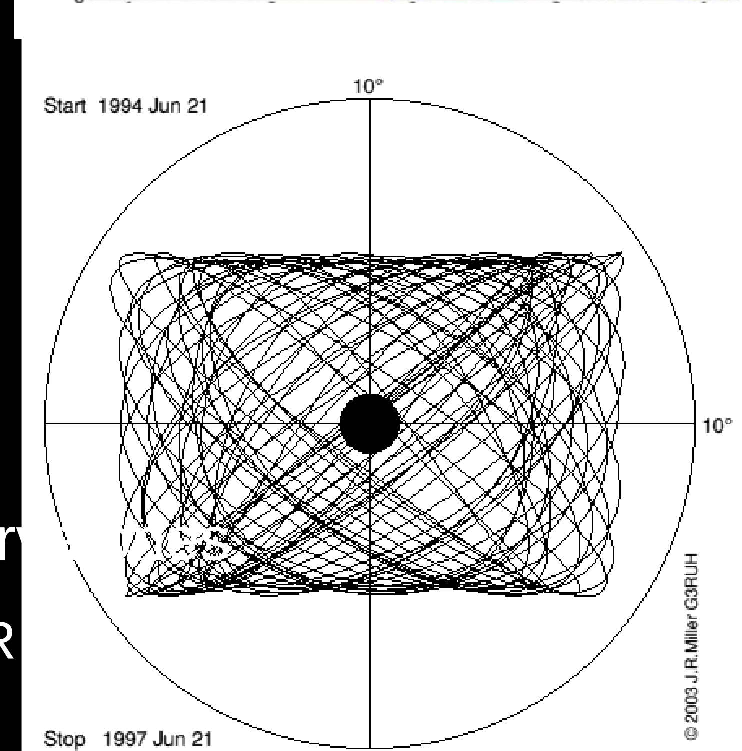
In Many Fields

Why Make a New Retroreflector

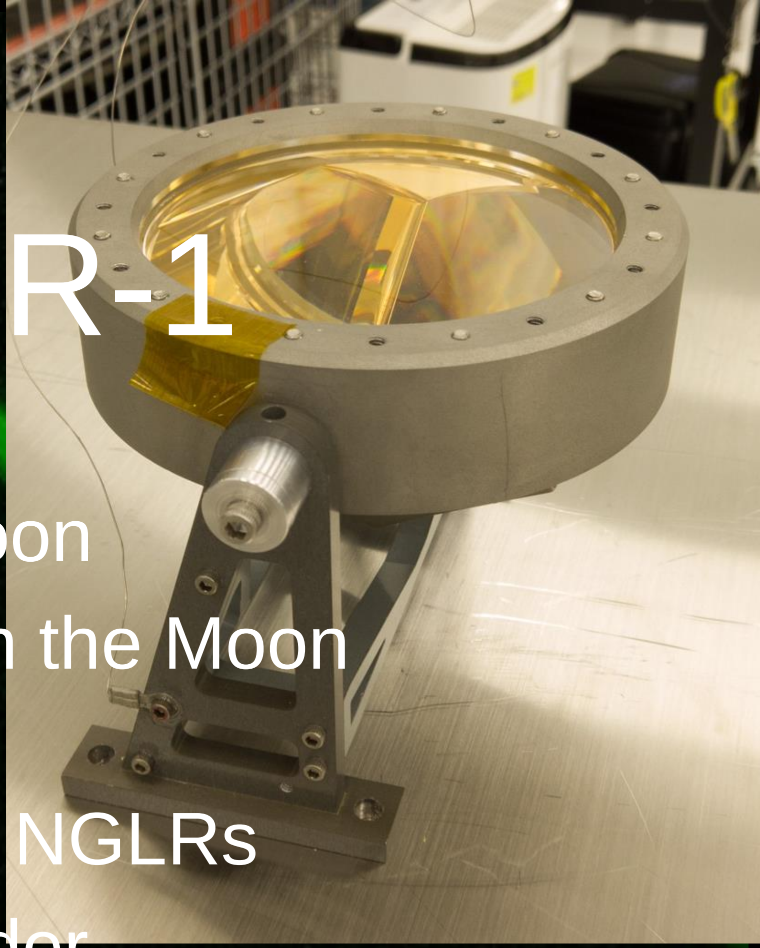
- Accuracy of LLR Lunar Ephemeris Has Stabilized
- Lunar Librations are a Problem
  - Moon Appears to Rotate Over a Month Up to 10º
- Apollo 11 Retroreflector Array of 100 Small CCRs
  - The Apollo 11 Array Is 0.825 × 0.686 meters
  - Tilted By Up to 10º by the Lunar Librations
- The Laser Photons Could Be Reflected
  - From Far Corner Or Near Corner of the Tilted Array
  - ~ 75 mm Spread in Measured Ranges (r.m.s.)
- In 2004, NASA Announced a Return to the Moon
- Our Objective Is to Eliminate This Error Source
  - Now Feasible to Support Ranging at Sub-Millimeter Level
  - This Will Allow Additional Lunar Laser Retroreflector Obser







Flight Status of NGLR-1

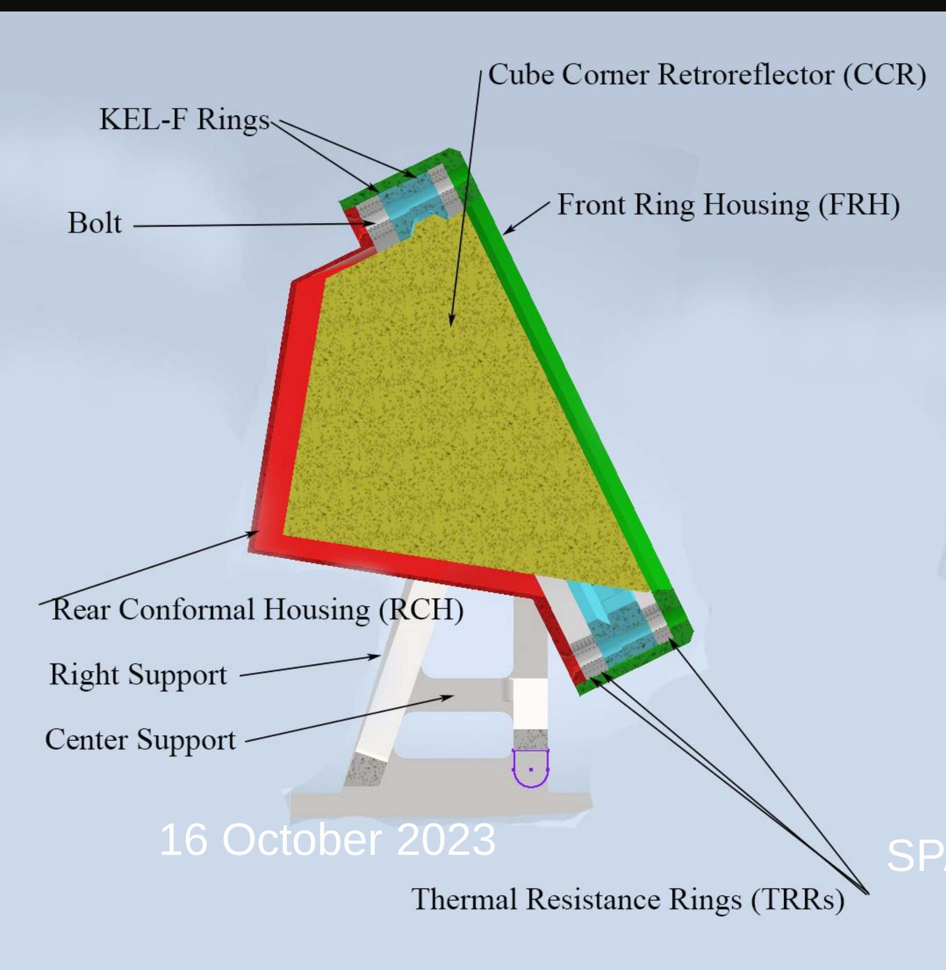


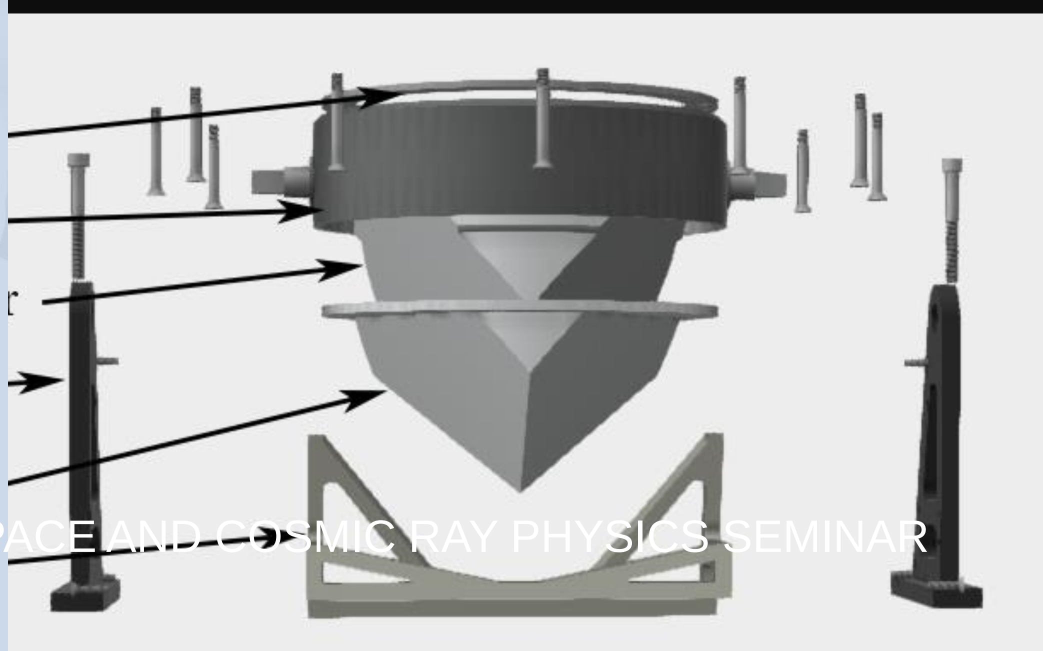
- In 2004. NASA Announced Plans to Return to the Moon
- We Prepared Proposal to NASA to Deploy NGLRs on the Moon
  - In Response to a NASA Solicitation - LSITP
- In 2019, NASA Selected Our Proposal to Fabricate 3 NGLRs
- To Be Carried to the Moon By a Robotic CLPS Provider
  - Commercial Lunar Payload Services
- NGLR-1 Is to Be Deployed on the Moon By Firefly Aerospace
  - During the Summer/Fall of 2024
  - In Mare Crisium,
    - a Crater in the North-East Quadrant of the Moon
- NGLR-2 to Planned to Be Deployed
  - Near the South Pole

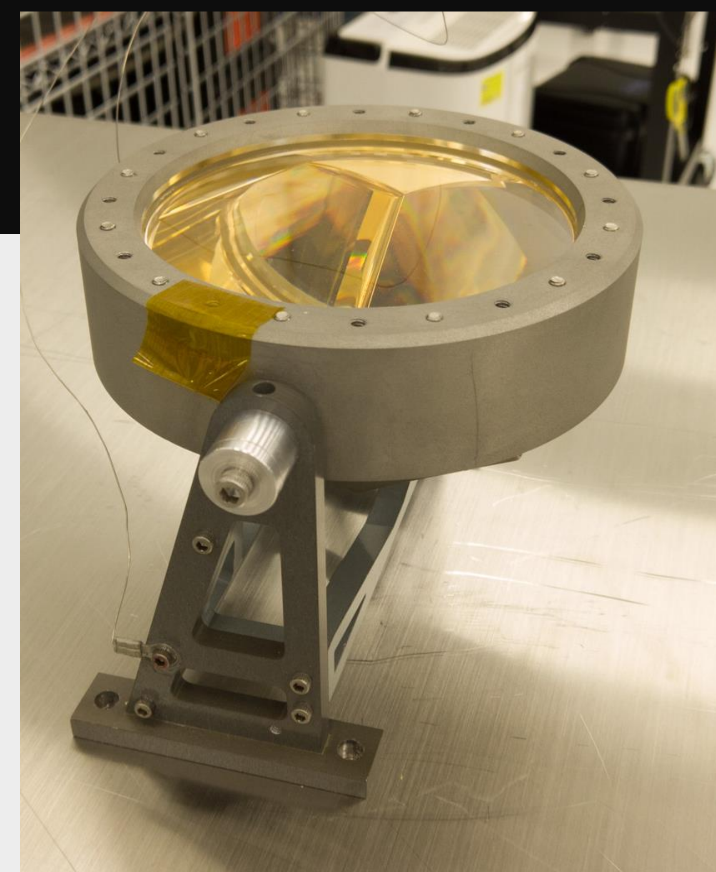
SUMMARY of THE NGLR

- No Power Is Required
- No Data Stream Is Required
- No Electronics Is Required
- No Software Is Required

- 1.6 kilograms
- 15 by 15 by 13 cm
- NGLR-1 Passed
  - Shock and Vibration for 19D
- NGLR-1 Was Delivered in March

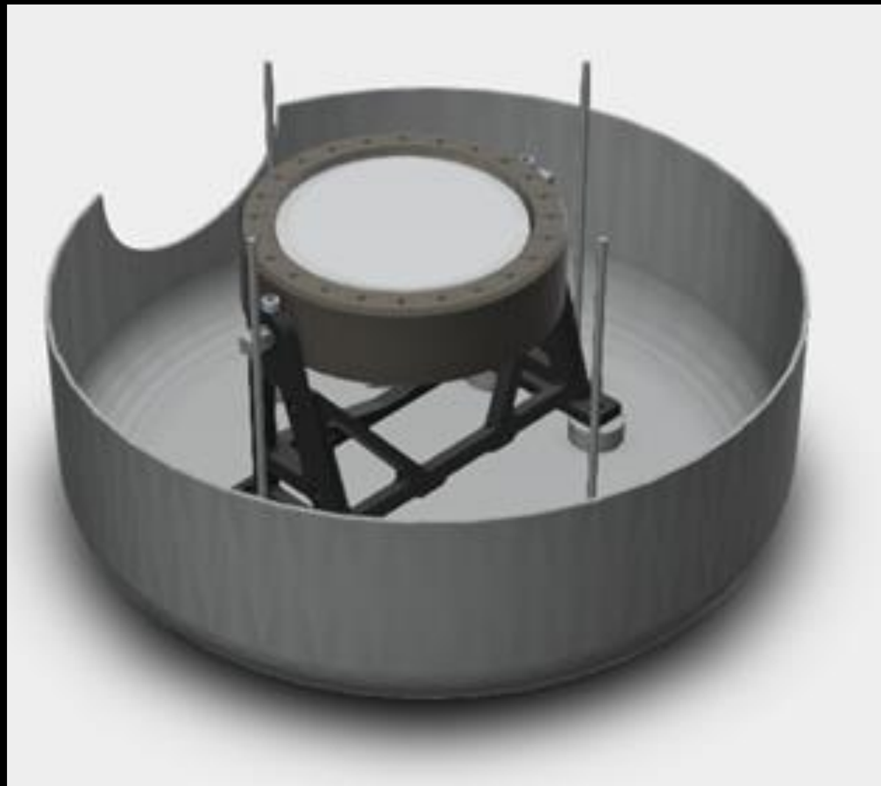




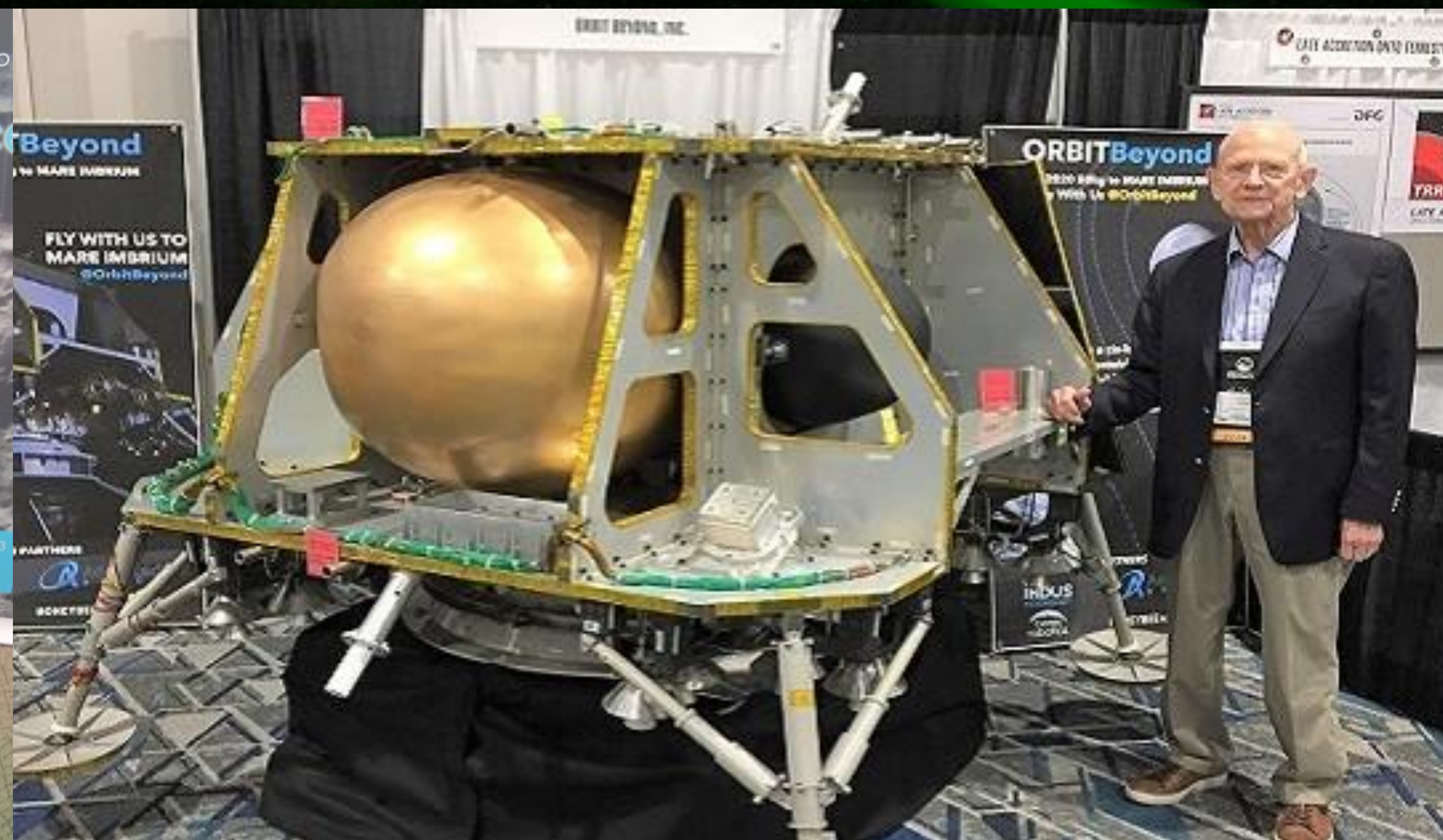


Reviewing the Upcoming NGLR Missions

- Deployment of NGLR-1 on the Moon By the Blue Ghost Lander
  - Developed By Firefly Aerospace via the Commercial Lunar Payloads Service (CLPS)
- This NASA Task Order 19D Mission Incorporates NGLR-1
  - TO 19D Lasts 2 Weeks Plus Perhaps 2 Days After Sunset
  - Firefly Is Investigating Re-Wakening on the Next Lunar Day
- Regarding NGLR-1 During this TO 19D Mission
  - Pointing Back Toward Earth
    - NGLR-1 is Mounted on the Antennae Support Panel (ASP)
      - Earth pointing Accuracy Provided By Firefly is Sufficiently Accurate
      - Correct Final Pointing is Critical For the Future LLR Science and Currently in Negotiation
  - Range Gate Issues at the LLROs
  - Thermal Issues
    - NGLR-1 is Mounted on the Antennae Support Panel
    - No Effective Thermal Isolation from Hot ASP
    - Reduced Magnitude of Return Signal Level to the LLROs
  - NGLR-2 and NGLR-3 to Be Deployed on the Lunar Surface
    - NGLR-2 Will Be Deployed Near the South Pole
    - Deployed on the Lunar Surface



Flight by Commercial Carrier



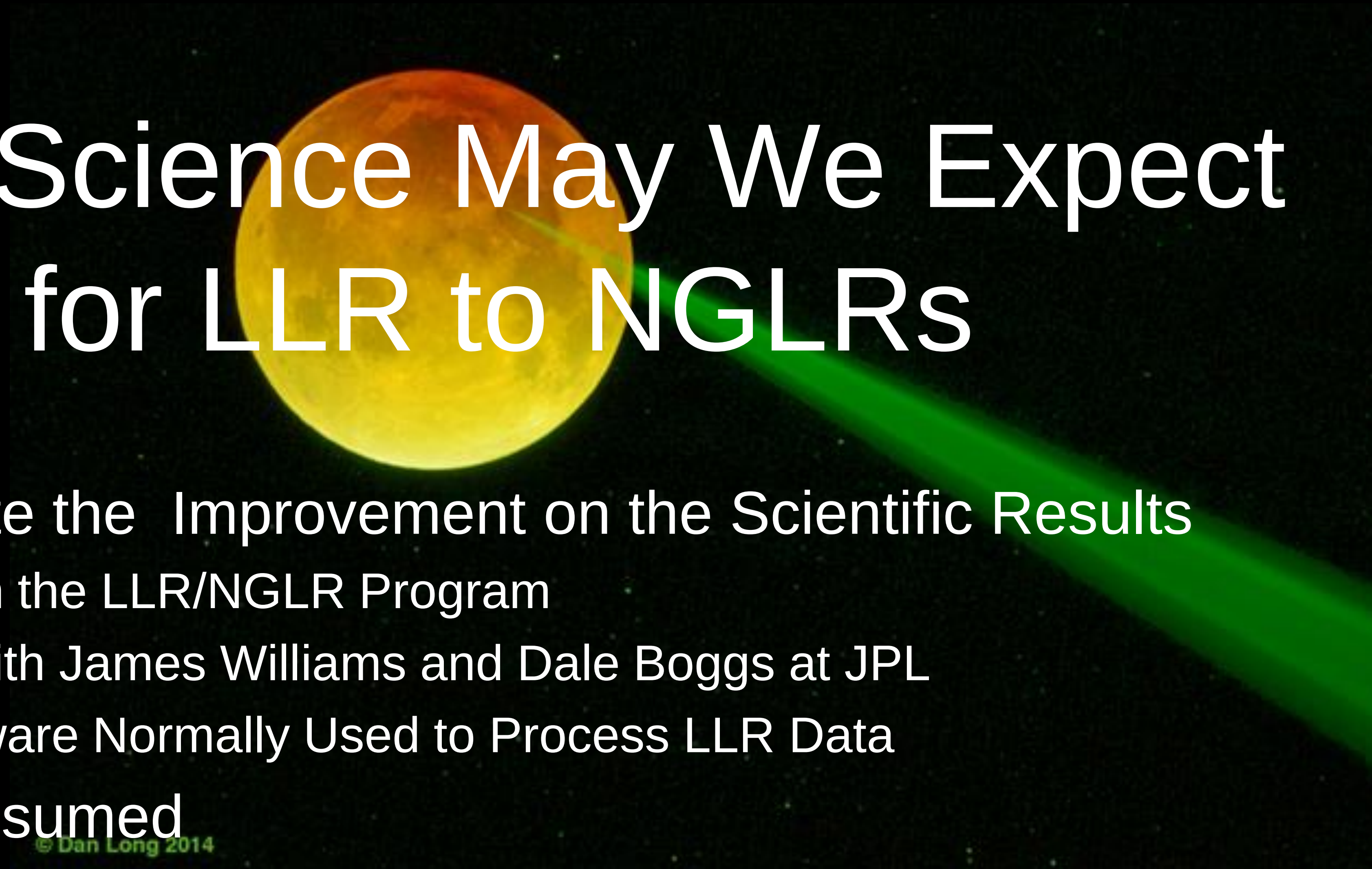
Future Progress

What Is Required
To Realize the Greater Accuracy

Future Science

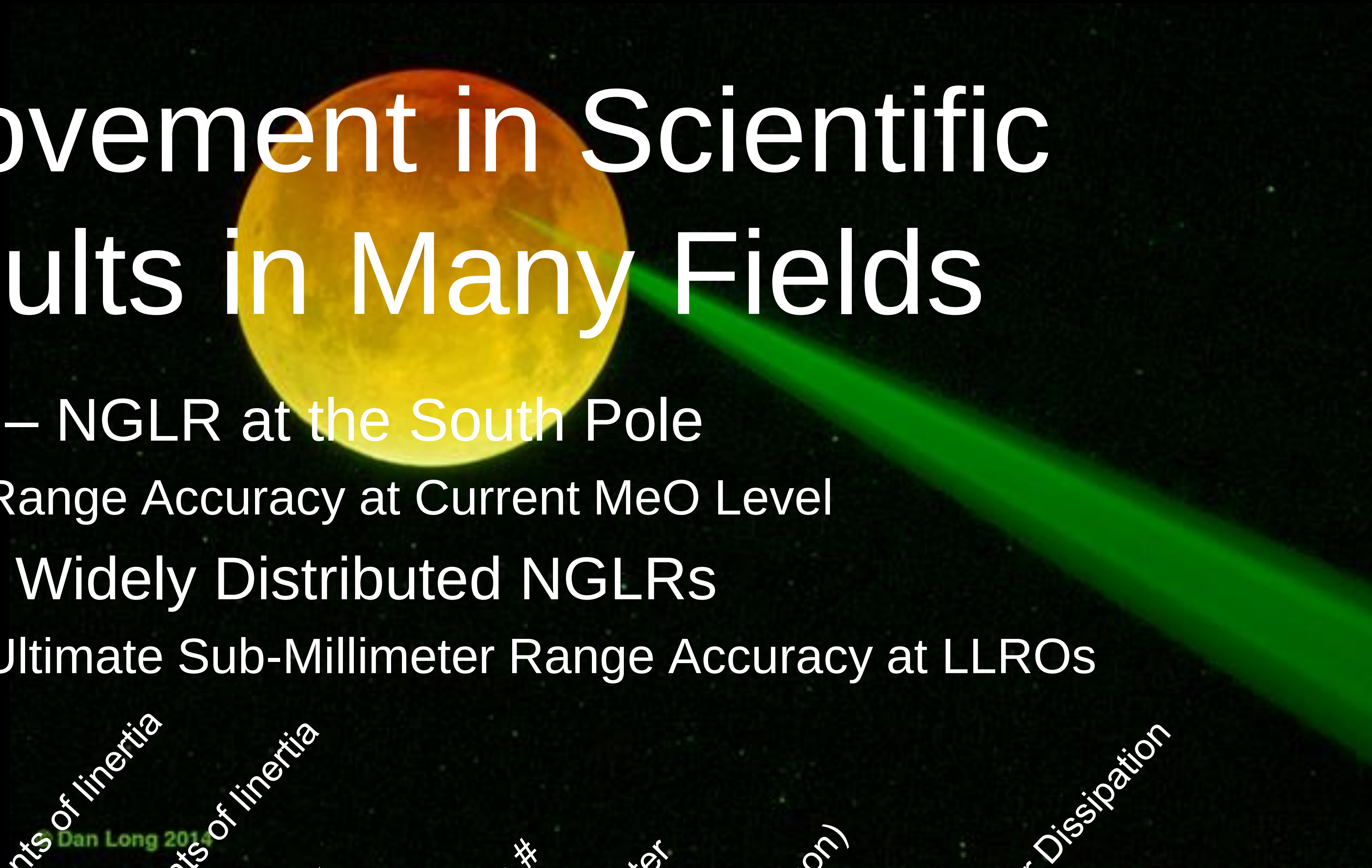
- What Explains the “Dark Matter” Observations?
  - Modification of the Gravitational Theory
    - Address MOND Theories – Which Ones Are Compatible
  - As Yet Unknown Particles
- Internal Lunar Structure
  - Continued Collaboration With GRAIL
    - Addressing the Moon from Crust to Core
- Further Tests of General Relativity
  - Addressing Conflict of Quantum Mechanics And GR
  - Evaluate GR to the Limit of Available Technologies

What Science May We Expect for LLR to NGLRs



- A Simulation to Evaluate the Improvement on the Scientific Results
  - That Are Possible Within the LLR/NGLR Program
  - Has Been Conducted With James Williams and Dale Boggs at JPL
  - Using the Analysis Software Normally Used to Process LLR Data
- 6 Year Mission Was Assumed
  - Investigated Many Different Parameters in Addressing For LLRO Acracy
  - Investigated Many Different Configurations of NGLR Deployment
- Addressed a Limited Number of Science Parameters
- Sample For Two NGLR Configurations And Different LLRO Accuracies
  - Improvement Over Current Accuracies Obtained With Apollo and Lunokhod RAs

Improvement in Scientific Results in Many Fields

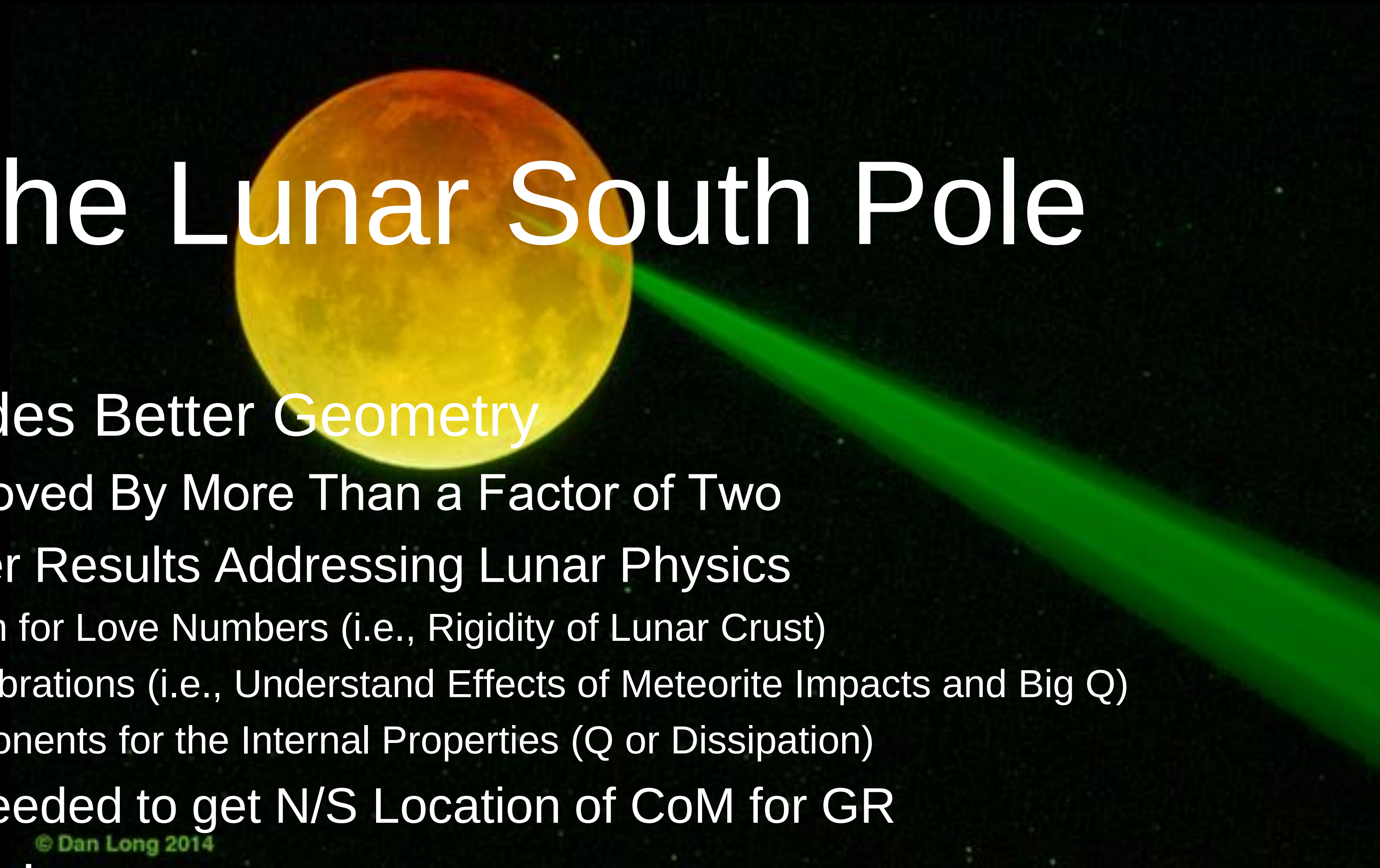


- Case 1 SPL – NGLR at the South Pole
  - Assuming Range Accuracy at Current MeO Level
- Case 2 Four Widely Distributed NGLRs
  - Assuming Ultimate Sub-Millimeter Range Accuracy at LLROs

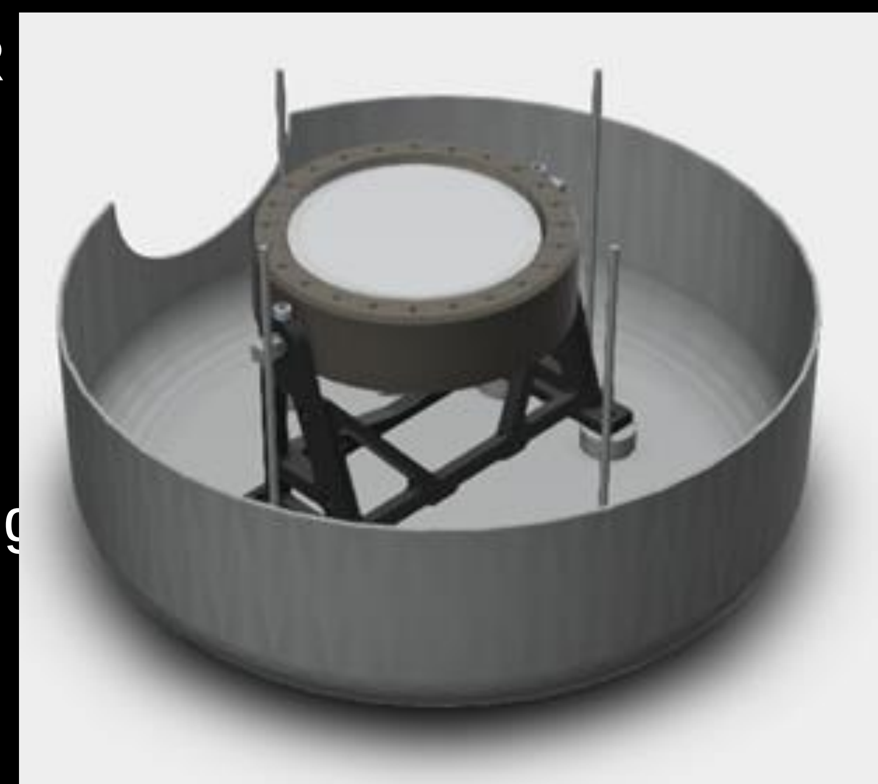
	Ratio of Moments of Iinertia	Ratio of Moments of Iinertia	Vertical Love #	Horizontal Love #	WEP Parameter	GM(Earth+Moon)	Internal Lunar Dissipation
Case	Beta	Gam	h_2	l_2	cos D	<a>	Tau S 815 d
SPL	92% 13x	74% 3.9x	87% 7.9x	70% 3.3x	98% 56x	98% 50x	7% 40x
CRS WST SW SPL	99% 111x	99.8% 420x	99.5% 212x	99.8% 570x	99.4% 162x	99.3% 147x	99.7% 330x

Table 2 Factors and percentages of improvement with the Artemis III mission and the assumption that ranging by the LLROs is performed at the ultimate levels of accuracy supported by the basic SBR package.

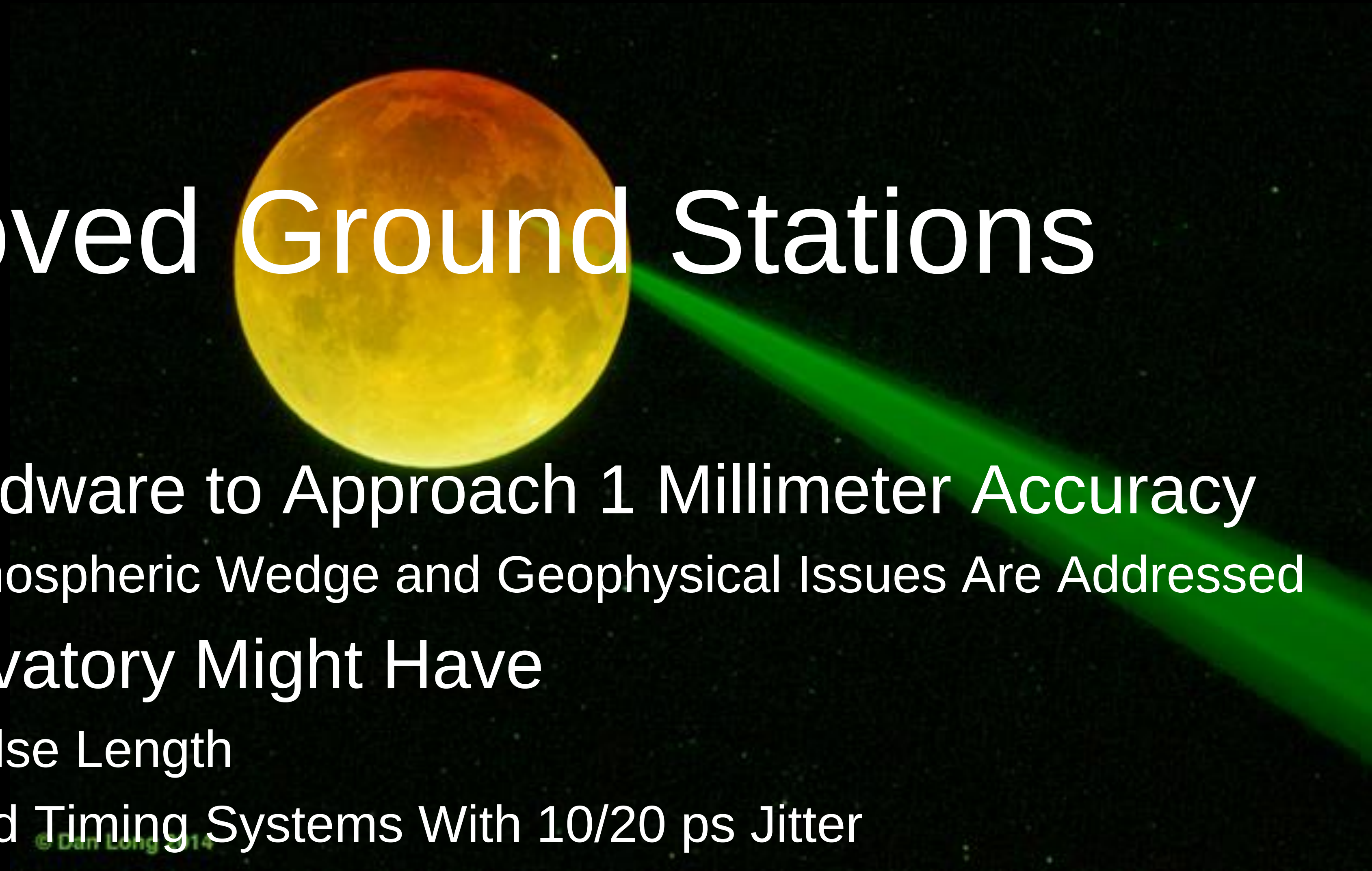
Why the Lunar South Pole



- South Pole Provides Better Geometry
  - "Lever Arm" Improved By More Than a Factor of Two
  - Will Provide Better Results Addressing Lunar Physics
    - Longer Lever Arm for Love Numbers (i.e., Rigidity of Lunar Crust)
    - Better Physical Librations (i.e., Understand Effects of Meteorite Impacts and Big Q)
    - Better N/S Components for the Internal Properties (Q or Dissipation)
  - Better Rotation needed to get N/S Location of CoM for GR
- Better thermal environment
  - Low sun angle – No Direct Illumination of NGLR
  - Lower Regolith Temperature
  - Only illumination is on Side of NGLR-A
  - Therefore, Better Signal During Lunar Day
- Issues
  - Need Mountain Peak for Continual Earth Viewing
  - Preservation of Bare Silver Needs Analysis



Improved Ground Stations



- Need Advanced Hardware to Approach 1 Millimeter Accuracy
  - Further Accuracy If Atmospheric Wedge and Geophysical Issues Are Addressed
- Ideally a LLR Observatory Might Have
  - 20 ps or Less Laser Pulse Length
  - Detector, Electronic And Timing Systems With 10/20 ps Jitter
  - Meteorological And Geophysical Systems For Atmospheric Delay Calibrations
  - Better Local Range Predictions to Set Range Gate
  - Faster Recovery After Noise Detection– to Control of Full Moon Noise
- For Example – At the Wettzell SLR Station
  - 10 ps Laser and Appropriate Electronics Implies Theoretical <1 mm/shot
  - Single Shot Precision Improved by a Factor of ~30 for High Libration Angles
  - Even Better Normal Point Accuracy If the Atmospheric Wedge Angle Is Known

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Better Atmospheric Modeling

- Horizontal Density Gradients in Earth's Atmosphere
  - Currently We Measure Local Pressure, Temperature and Humidity
  - Acceptable Atmospheric Delay Correction If Moon Is Directly Overhead
  - However, This Never Happens – Normally at Approximately 40^{o} Elevation
  - Thus, We Are Sensitive to Density Variations Over ~7 Kilometers (Horizontal)
  - This Results in Range Measurement Offsets of 1 Or 2 Millimeters
    - Evaluated Using Satellite Observations By E. Pavlis And G. Hulley
    - Typical Observations at 40^{o} Due to Latitude of LLR Observatories
  - Possible Use Global Weather Maps And Local Met Data to Model
    - Various Studies of This Are in Progress
  - Possible Direct Instrumental Measurements of Zenith Wedge
    - Two Color Refractometer at UMCP
  - Better Knowledge of the Wedge is Even More Important
    - For Low Elevation SLR Observations

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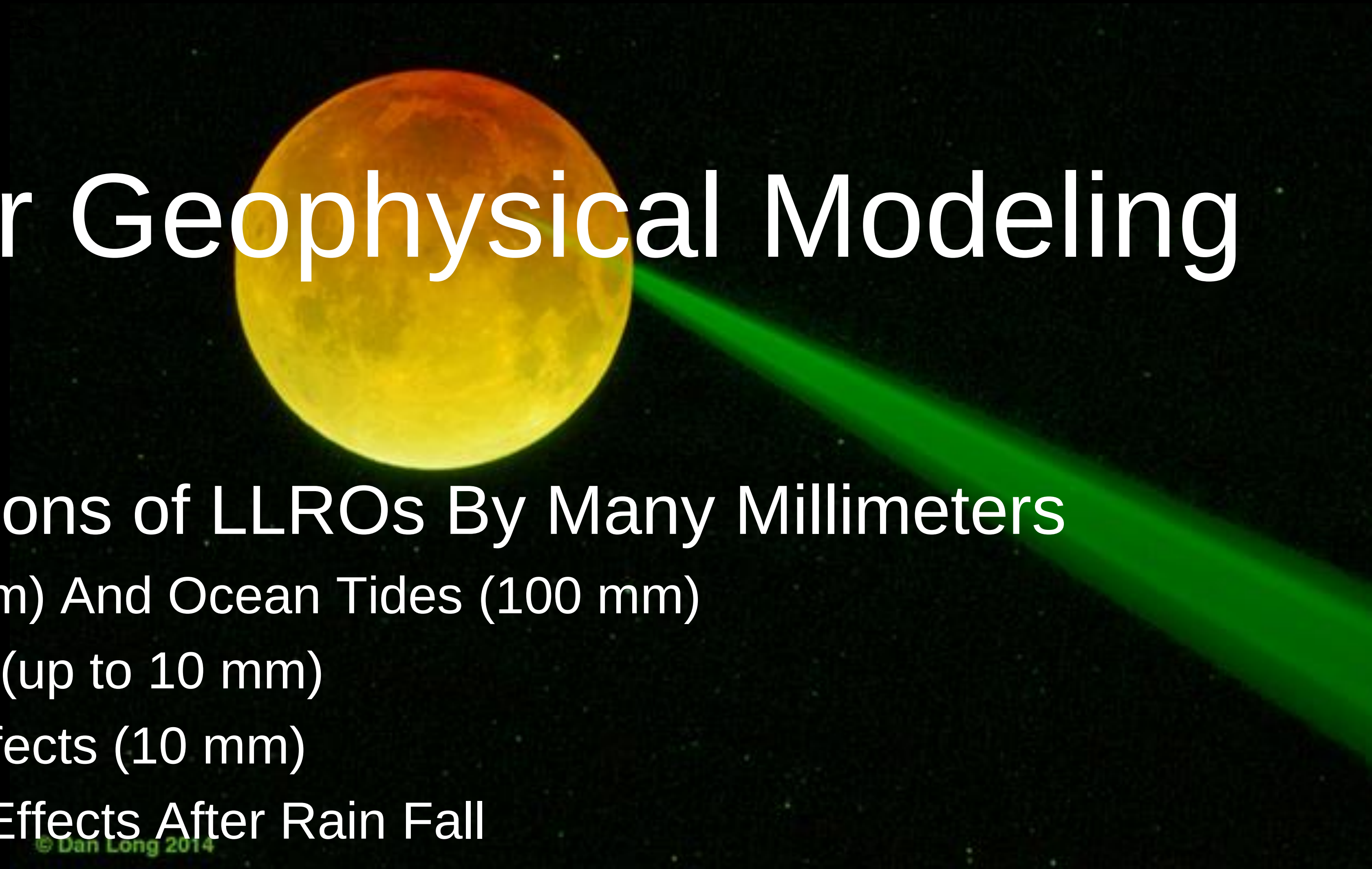
Better Geophysical Modeling



- Geophysical Motions of LLROs By Many Millimeters
  - Solid Earth (300 mm) And Ocean Tides (100 mm)
  - Atmospheric Tides (up to 10 mm)
  - Seasonal Water Effects (10 mm)
  - Short Term Water Effects After Rain Fall
- Currently Addressed in ILRS SLR Community at the mm Level
  - Modeling of Solid Earth And Ocean Tides
  - Gravimeters Located at the LLROs
  - Satellite Measurenmts to Surface Retroreflectors
- Need More Analysis
  - To Reliably Achieve Range Accuracies at Sub-Millimeter Level

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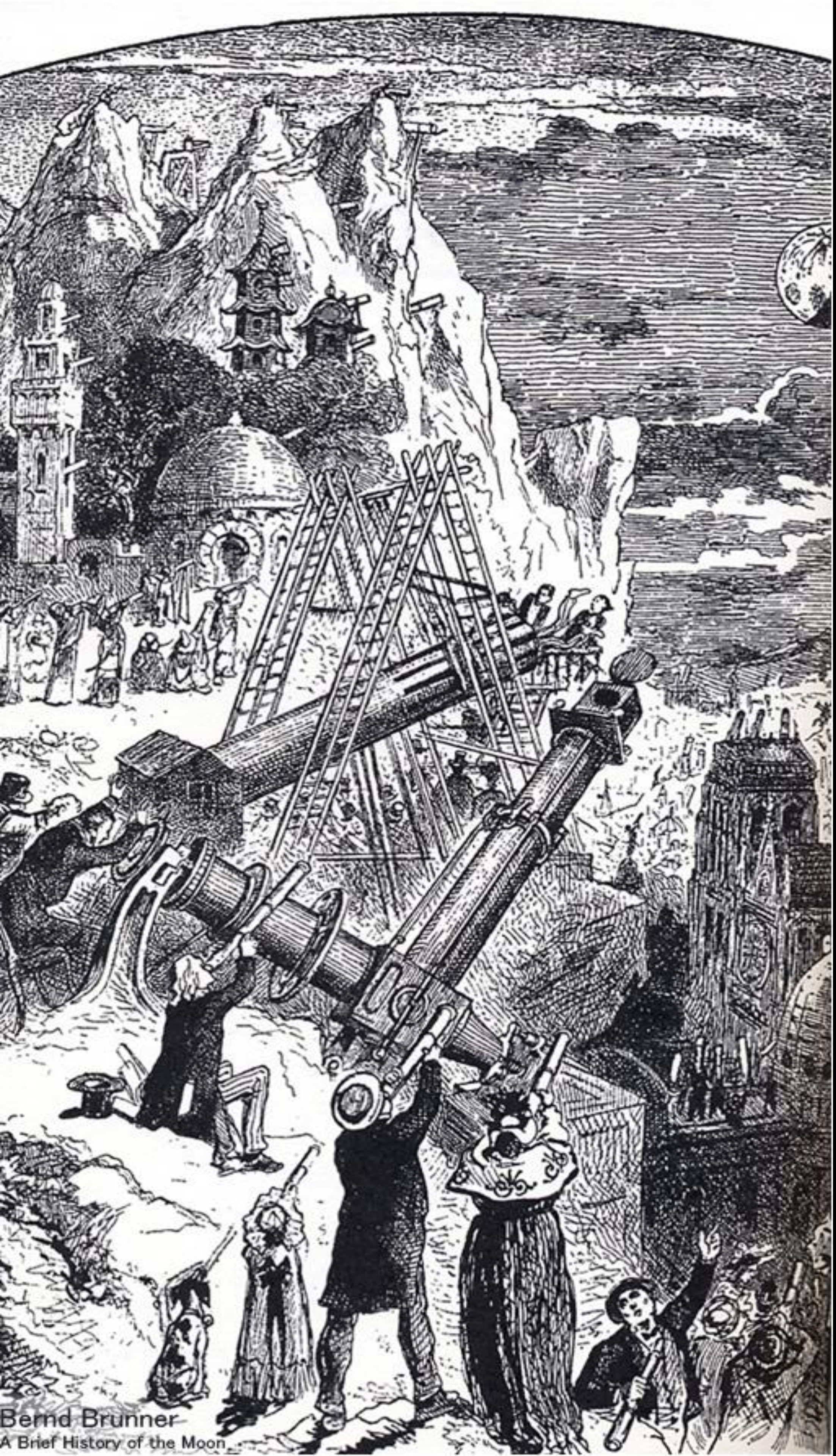
Conclusions:
Technical and Scientific Heritage

- Results of Our Lunar Laser Ranging Program to Date
  - Demonstrated the Highly Successful LLR Technology
  - Obtained Many of the Most Accurate Scientific Values in the Fields of:
    - Understanding the Physics of the Moon (Discovered the Liquid Core, Evaluated the Love Numbers, etc.)
    - Established Fundamental Lunar Reference Systems (For Cislunar Navigation And For Lunar Mapping)
    - Tests of General Relativity (Determined the Accuracy of WEP, etc.)
    - Cosmology (Demonstrated the Constancy of Big G in Time and Space, etc.)
- Next Generation Lunar Retroreflectors (NGLRs) Project
  - Completed Successful Fabrication of NGLR-1
  - First NGLR Has Been Delivered to Firefly Aerospace
  - Deployment on the Moon Expected in the Fall of 2024
- Expected NGLR Science Return Looks Extremely Interesting
  - Orders of Magnitude Improvement in the Accuracy of Our Scientific Results
    - Beyond the Current Accuracy Obtained By Ranging to Apollo Retroreflector Arrays
    - Many of Which Are Already the Most Accuracy Currently Available
- NGLRs Will Allow Some SLR Stations to Join Our LLRO Network
  - To Better Detect Systematic Biases



Thank You!
Any
Questions?
Or
Comments?

with
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LSSO Team
LUNAR Team
&
NGLR Team

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