• The Birth and Future

of

Lunar Laser Ranging

by

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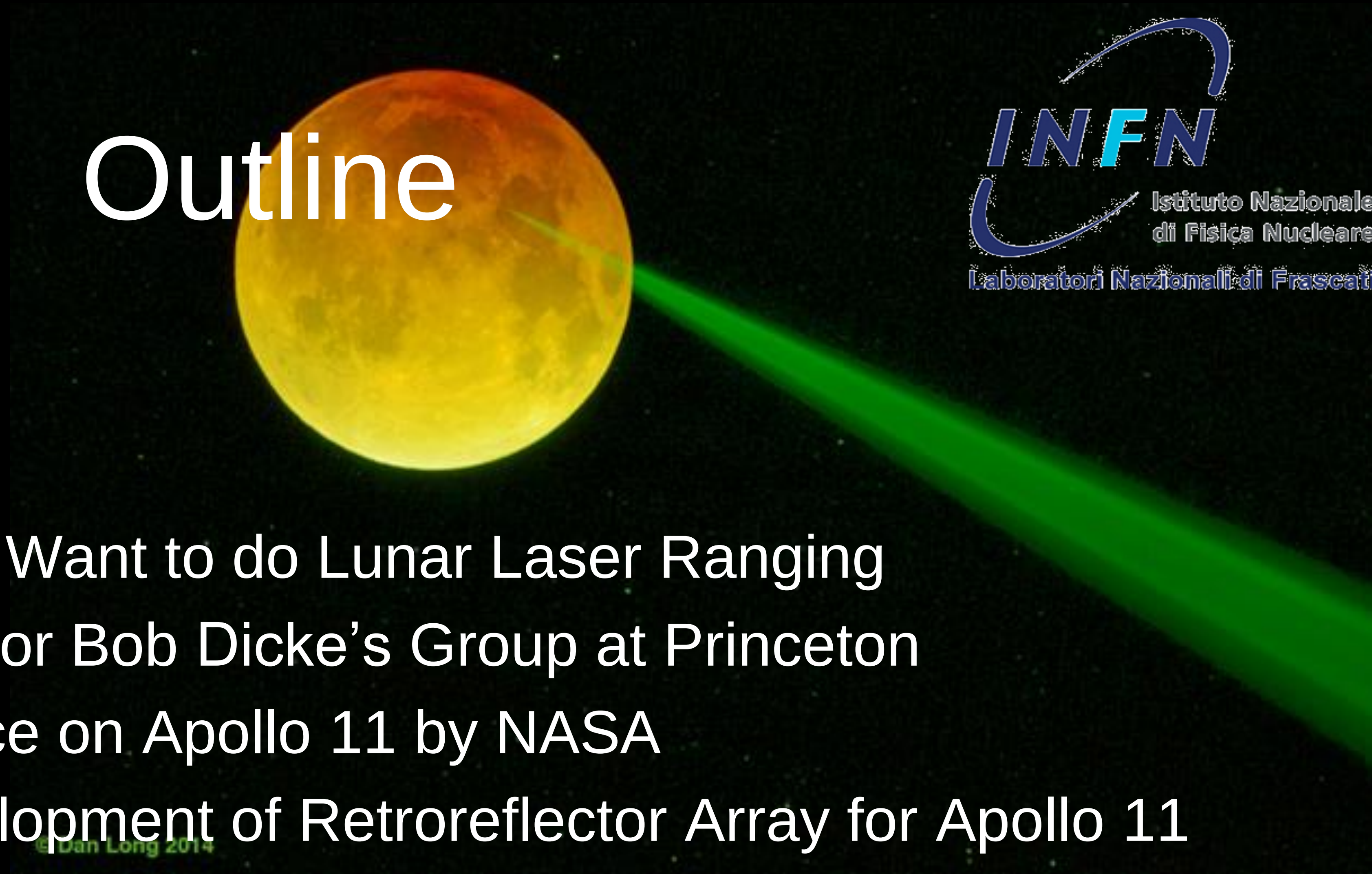
Outline

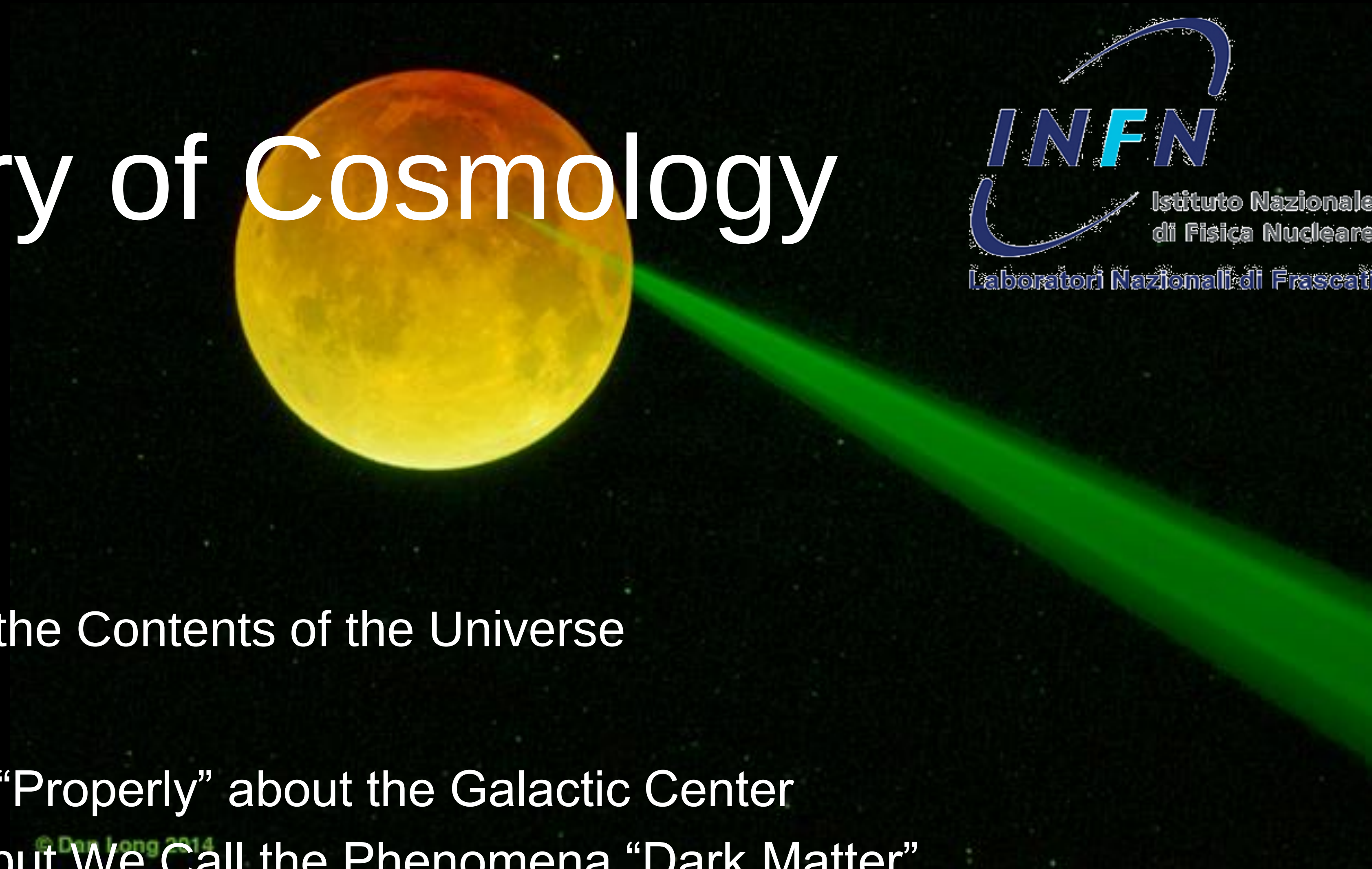


- Overview of Why We Want to do Lunar Laser Ranging
- Pre-History of Professor Bob Dicke's Group at Princeton
- Preparation for Science on Apollo 11 by NASA
- Preparation and Development of Retroreflector Array for Apollo 11
- Development of Lunar Laser Ranging Observatories
- Science Results from Our 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

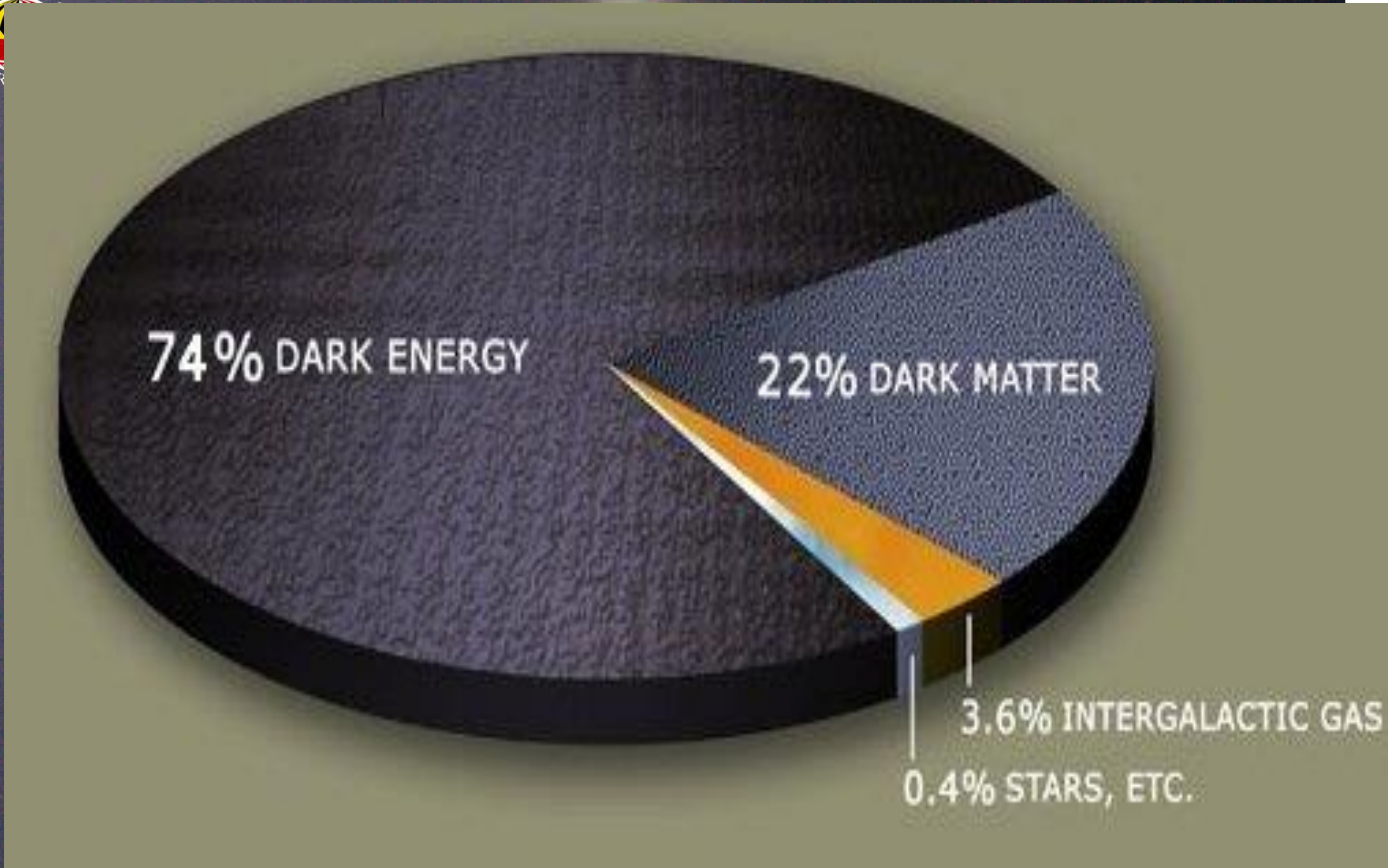
First Why

Should We Embark
Such A Complicated and Risky Journey

History of Cosmology

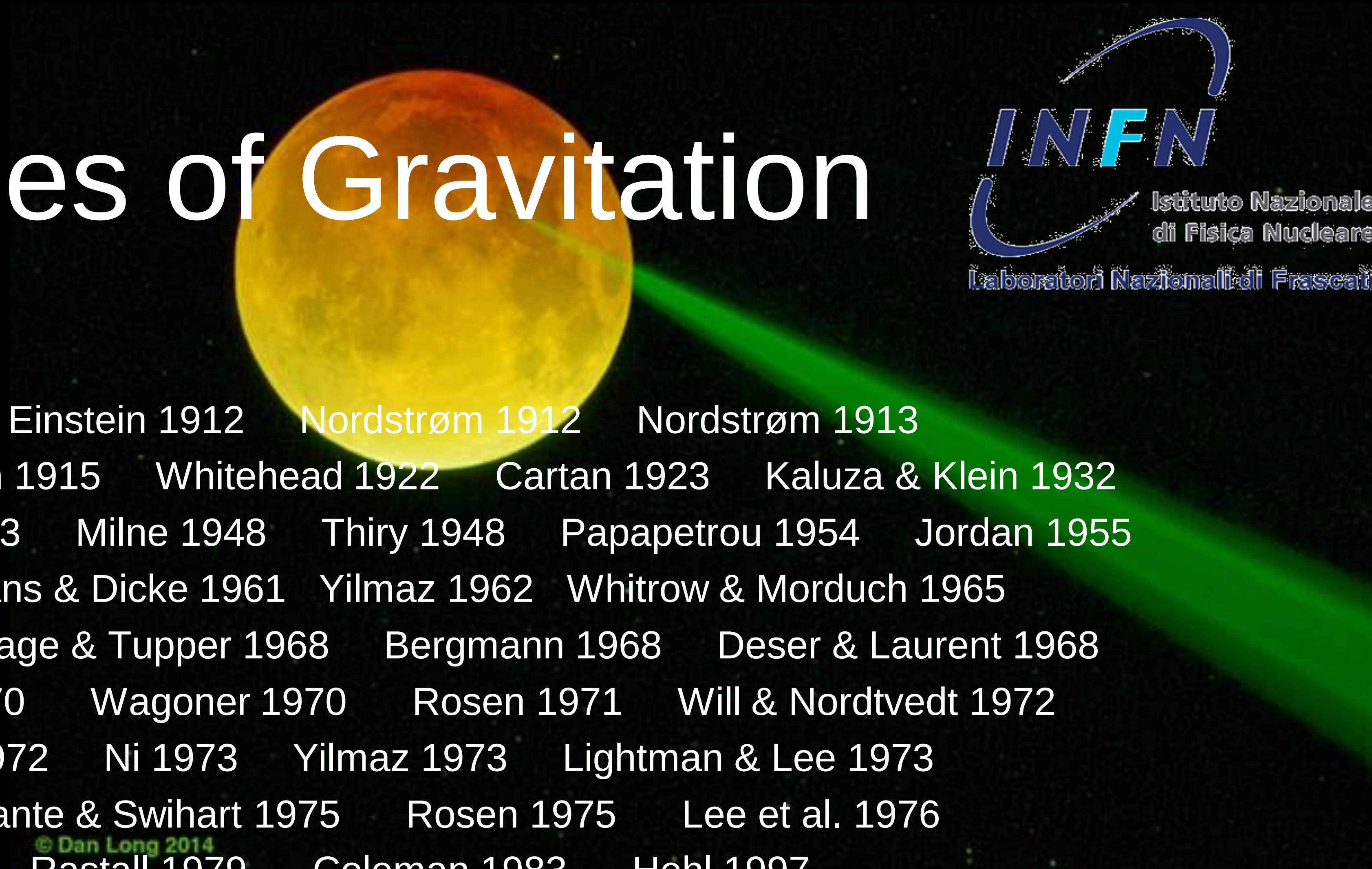


- Twenty Years Ago
  - We Knew All About the Contents of the Universe
- Vera Rubin
  - Stars do not Rotate “Properly” about the Galactic Center
  - Do Not Know Why, but We Call the Phenomena “Dark Matter”
- Perlmutter, Schmidt & Riess
  - Distant Galaxies Were Moving Away from Us Too Fast
  - Do Not Know Why, But We Call that Phenomena “Dark Energy”
- Something Strange Seems to be Going on With Gravity
- Cannot Fit General Relativity into Quantum Mechanics



General Relativity vs. Quantum Mechanics

Theories of Gravitation

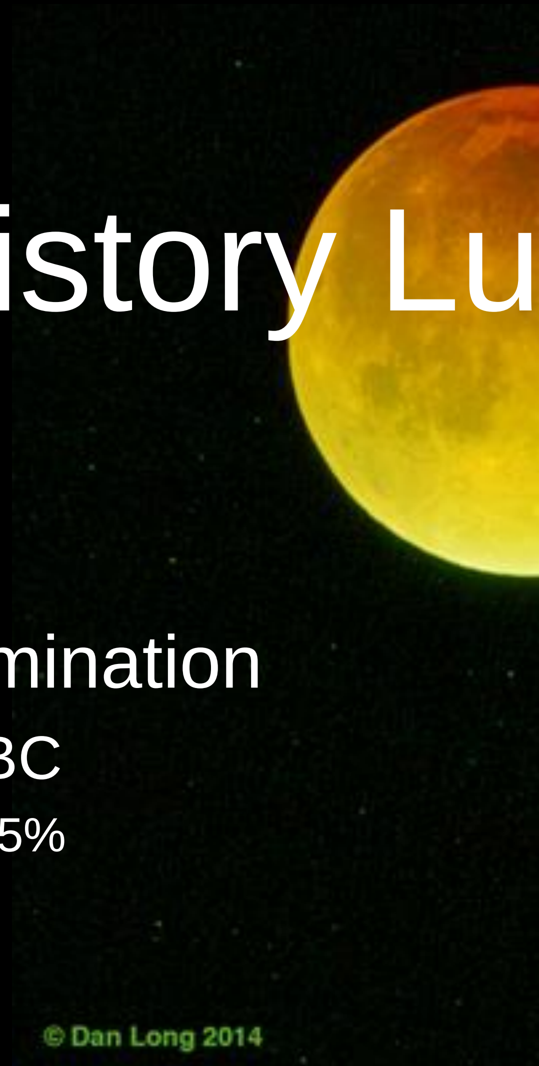


- Newton 1686 Poincaré 1890 Einstein 1912 Nordstrøm 1912 Nordstrøm 1913
- Einstein & Fokker 1914 Einstein 1915 Whitehead 1922 Cartan 1923 Kaluza & Klein 1932
- Fierz & Pauli 1939 Birkhoff 1943 Milne 1948 Thiry 1948 Papapetrou 1954 Jordan 1955
- Littlewood & Bergmann 1956 Brans & Dicke 1961 Yilmaz 1962 Whitrow & Morduch 1965
- Kustaanheimo & Nuotio 1967 Page & Tupper 1968 Bergmann 1968 Deser & Laurent 1968
- Nordtvedt 1970 Bollini et al. 1970 Wagoner 1970 Rosen 1971 Will & Nordtvedt 1972
- Ni 1972 Hellings & Nordtvedt 1972 Ni 1973 Yilmaz 1973 Lightman & Lee 1973
- Lee, Lightman & Ni 1974 Belinfante & Swihart 1975 Rosen 1975 Lee et al. 1976
- Bekenstein 1977 Barker 1978 Rastall 1979 Coleman 1983 Hehl 1997
- — Some authors proposed more than one theory, e.g. Einstein, Ni, Lee, Nordtvedt, Yilmaz,
- — Some theories are just variations of others
- — Some theories were proposed in the 1910s/20s; many theories in the 1960s/70s
- — Overlooked: this is not a complete list! Essentially, this ends before Dark Matter and Dark Energy
- Theory must be:
- — Complete: not a law, but a theory. Derive experimental results from first principles
- — Self-consistent: get same results no matter which mathematics or models are used
- — Relativistic: Non-gravitational laws are those of Special Relativity
- — Newtonian: Reduces to Newton's equation in the limit of low gravity and low velocities

Early Aspects & Motivation

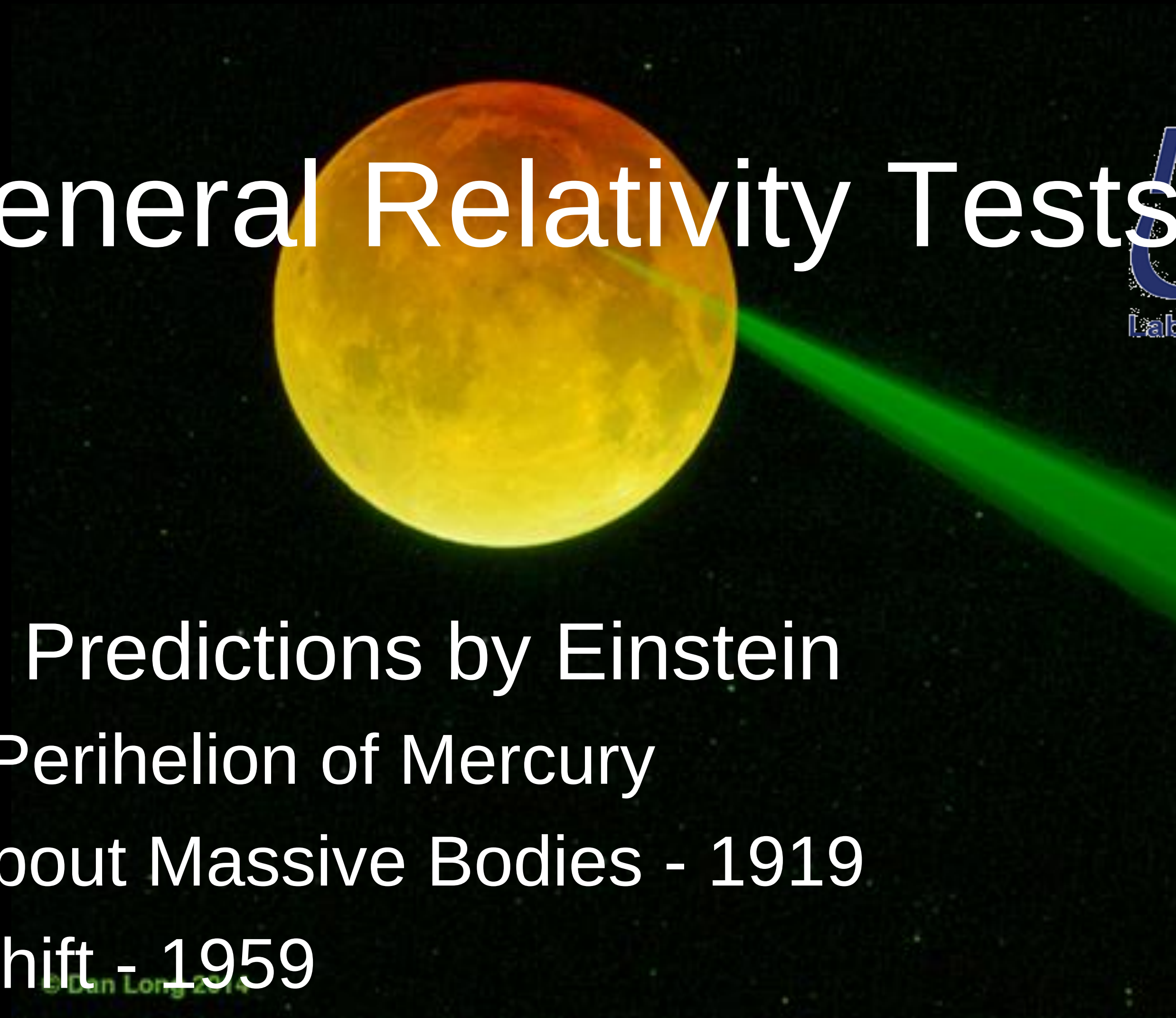
- Historically, the Orbit of the Moon and Its Distance
  - Has Been Studied for Millennia
    - Navigation
    - Eclipse Prediction
    - Tidal Tables
- During the Last Millennium
  - GR Tests have Become an Important Part of Physics
  - Fundamental Incompatibility of QM and GR
- Later, Issues of the Internal Structure of the Moon
  - Again as It Relates to the Lunar Formation Question
  - Hints for the Physics of Planetary Formation

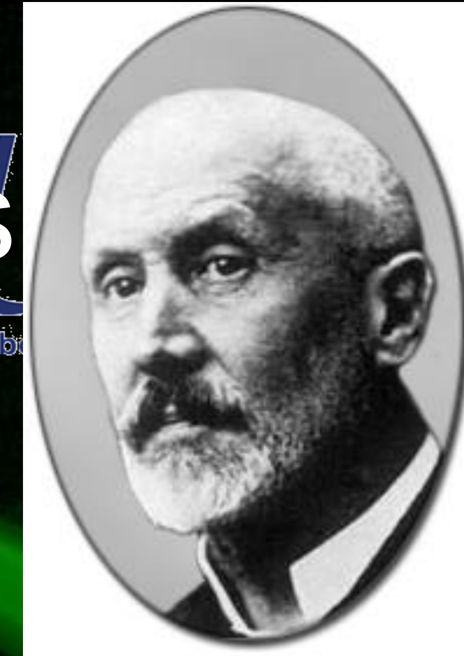
Pre-History Lunar Distance



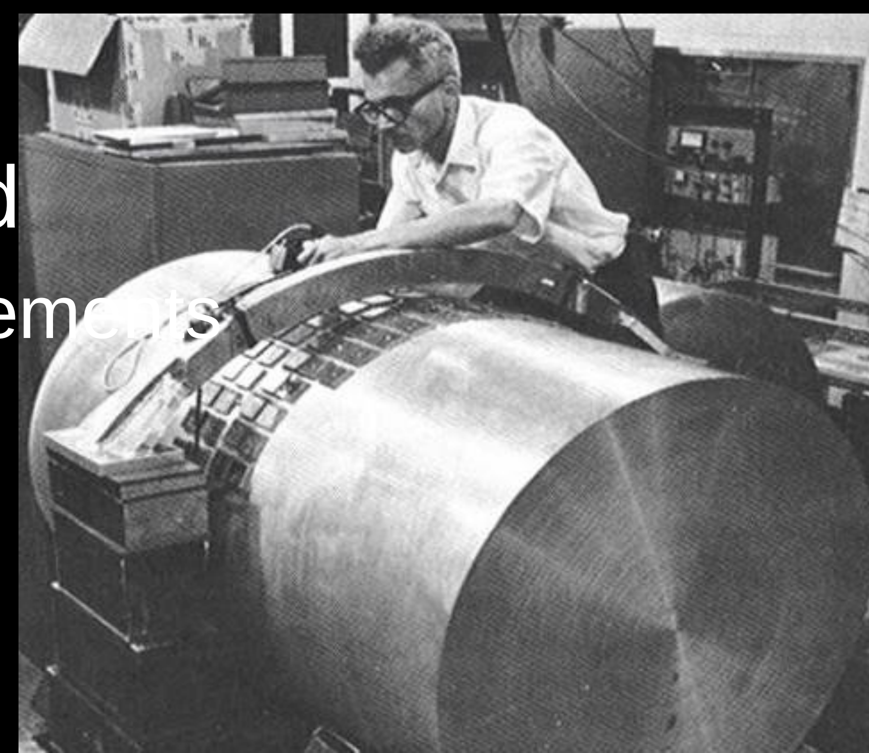
- Astronomical Determination
  - Early Greek – 270 BC
    - About 386,243 km – 5%
- Radar Ranging
  - 1959 USNO 150 m
- Optical Ranging
  - 1962 - MIT – 1 ms – Few Kilometers
- Lunar Orbiting Space Craft
- Problem:
  - Not Accurate Enough for General Relativity Test
  - Not Accurate Enough to Quantify the Structure of the Lunar Interior

Early General Relativity Tests





- Initial Experimental Predictions by Einstein
  - Precession of the Perihelion of Mercury
  - Bending of Light about Massive Bodies - 1919
  - Gravitational Redshift - 1959
- Loránd Eötvös – Laboratory Experiments
  - Weak Equivalence Principle (WEP)
- Joe Weber at the University of Maryland
  - Conceptualization of Gravity Wave Measurements
  - Early GW Observations with Bar Antennae

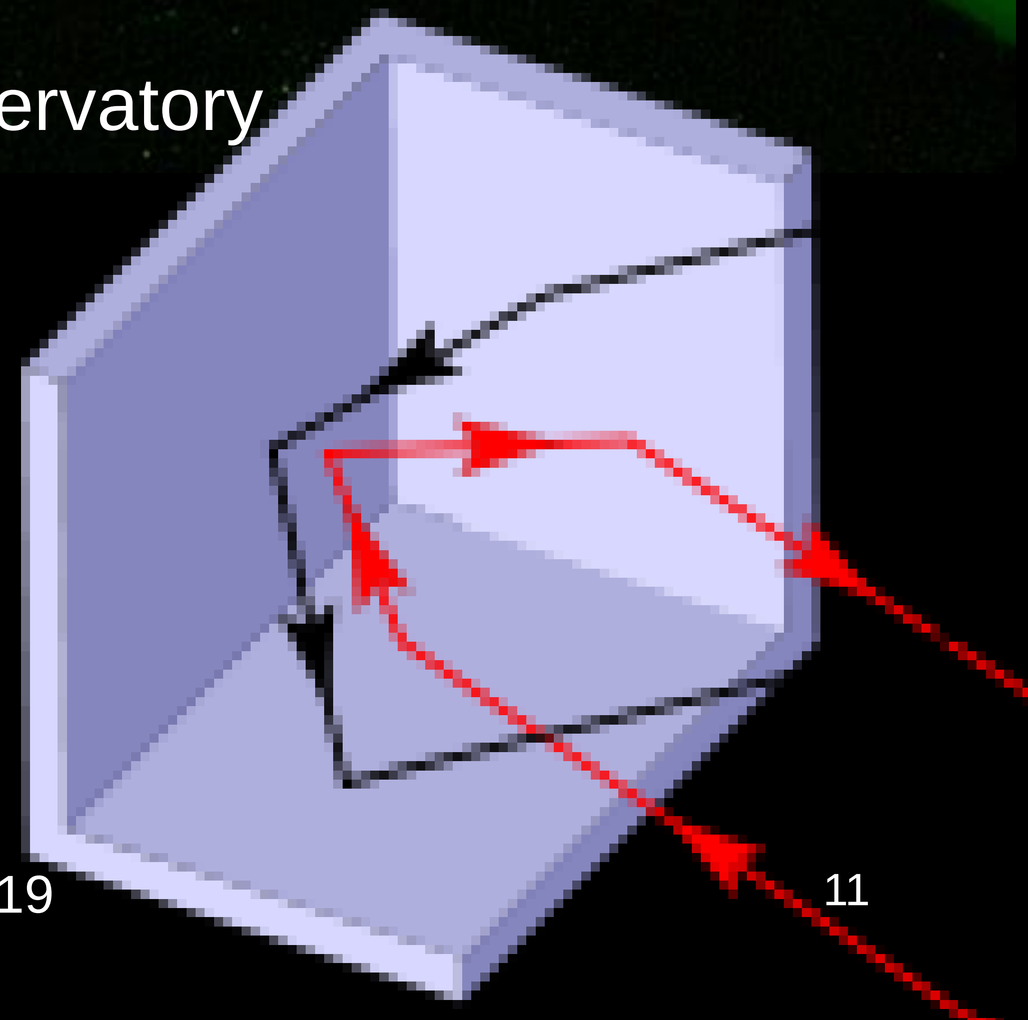


Pre-History of Dicke Group

- Professor Robert Dicke of Princeton University
  - Early Interest in Tests of General Relativity
    - Measured the Gravitational Red Shift
    - Investigated the Precession of Mercury
    - Scalar-Tensor – Brans-Dicke – Alternative to General Relativity
- Considered Ranging to the Surface with Spotlight
  - Insufficient Accuracy – Ranging from the Surface
  - Insufficient Signal – Outgoing Beam was too Broad
- In the 1960’s – Two Great Leaps Forward
  - Ted Maiman Invented and Demonstrated the Laser
  - John Kennedy said “We are Going to put a Man on the Moon”
- Finally, Measurements of Sufficient Accuracy
  - Could Finally, In Principle, be Accomplished!!!

Laser Ranging & Retroreflectors

- Illuminate Moon with a Short Coherent, Narrow Laser Pulses
- “Normal” Diffuse Reflection from Lunar Surface
  - Radiation Goes into 2 Pi Steradians
  - Great Loss of Signal
- 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
  - Mechanical/Electrical Components
    - Cannot Last 50 years
- Retroreflector
  - Solid “Cube Corner” of Glass



Preparation for Apollo 11 Science

- ALSEP – Major NASA Science Project for the Manned Landing
  - Starting About Two Years Before Launch
  - Major Suite of Scientific Instruments
  - Defined For All Apollo Missions Through Apollo 16
- Astronauts Began To Practice for Apollo 11 EVA
  - Using the ALSEP 11 Scientific Suite of Experiments
  - Only Short Time on the Surface
  - Not Enough Time to Deploy All Experiments
  - Surface Conditions Unknown
    - Tommy Gold Had Said That We Would Sink 30’ in the Lunar Dust
- NASA Looks for Replacement Suite of Experiments

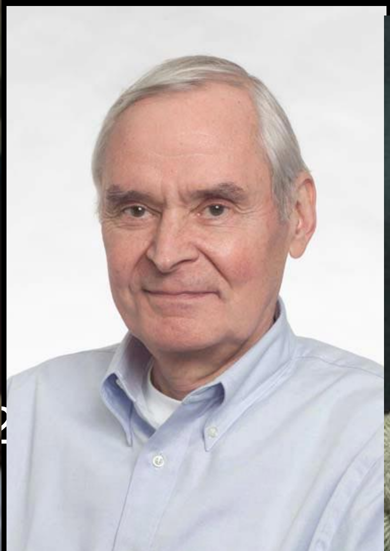
ALSEP to ELSEP

- NASA Requests Experiments for ELSEP
  - Early Apollo Scientific Experiments Payload
  - Easy to Deploy
  - Light or No Power Requirements
  - Light or No Communication Requirements
- Initial Feasibility Calculations for Lunar Laser Ranging
  - Performed by Bob Dicke’s Group at Princeton
  - Had Been Considering Possibilities for Some Time
- Proposal for Apollo 11 LLR in the ELSEP Submitted to NASA
  - 9 Months before Launch
- NASA Accepted Our Proposal for Retroreflector Arrays for Apollo 11

Proposal and LURE Group

- Robert H. Dicke – Princeton University
  - GR Tests, Microwave Technology, Cosmic Microwave Background Radiation (CMBR)
- Carroll O. Alley – University of Maryland, College Park
  - Principal Investigator, Atomic Physics, General Relativity Tests
- Peter L Bender – JILA - University of Colorado Boulder
  - Detection of Gravity Waves in Space - LISA
- David T. Wilkinson - Physics - Princeton University
  - The Leader in the Cosmic Microwave Background Radiation (CMBR)
- James E. Faller – Physics - Wesleyan University
  - Cube Corner Retroreflectors, Absolute Gravimeters

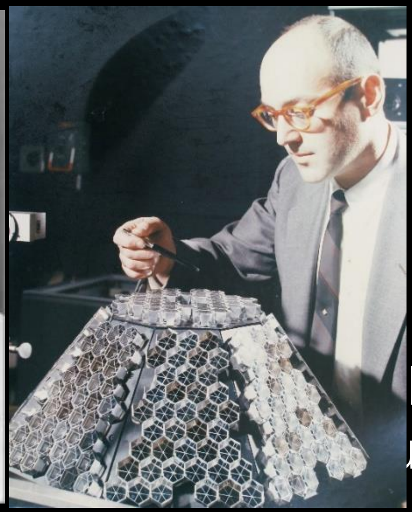


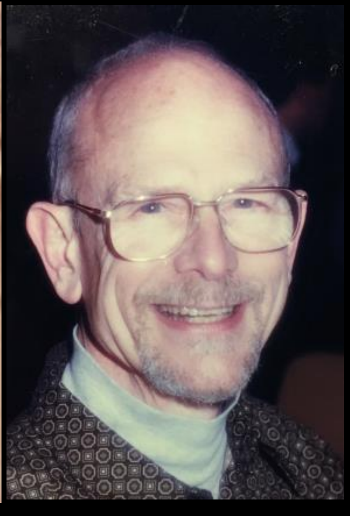




Proposal and LURE Group

- William M. Kaula - IGPP - University of California, Los Angeles
  - Space-Based Geodesy using Satellite Orbits
- Gordon J. F. MacDonald – MIT, UCLA, UCSB, Dartmouth and UCSD
  - Geophysicist, Environmental Scientist, Continental Drift
- Henry H. Plotkin – GSFC – UMBC
  - Started the Field of Satellite Laser Ranging
- James G. Williams – JPL
  - Expert on Processing Ephemris Data and Extracting The Science
- J. Derral Mulhollond – JPL
  - Lunar Ephemeris
- Douglas G. Currie – Physics – University of Maryland, College Park
  - Lunar Laser Ranging, Hubble Space Telescope, Stellar Interferometry

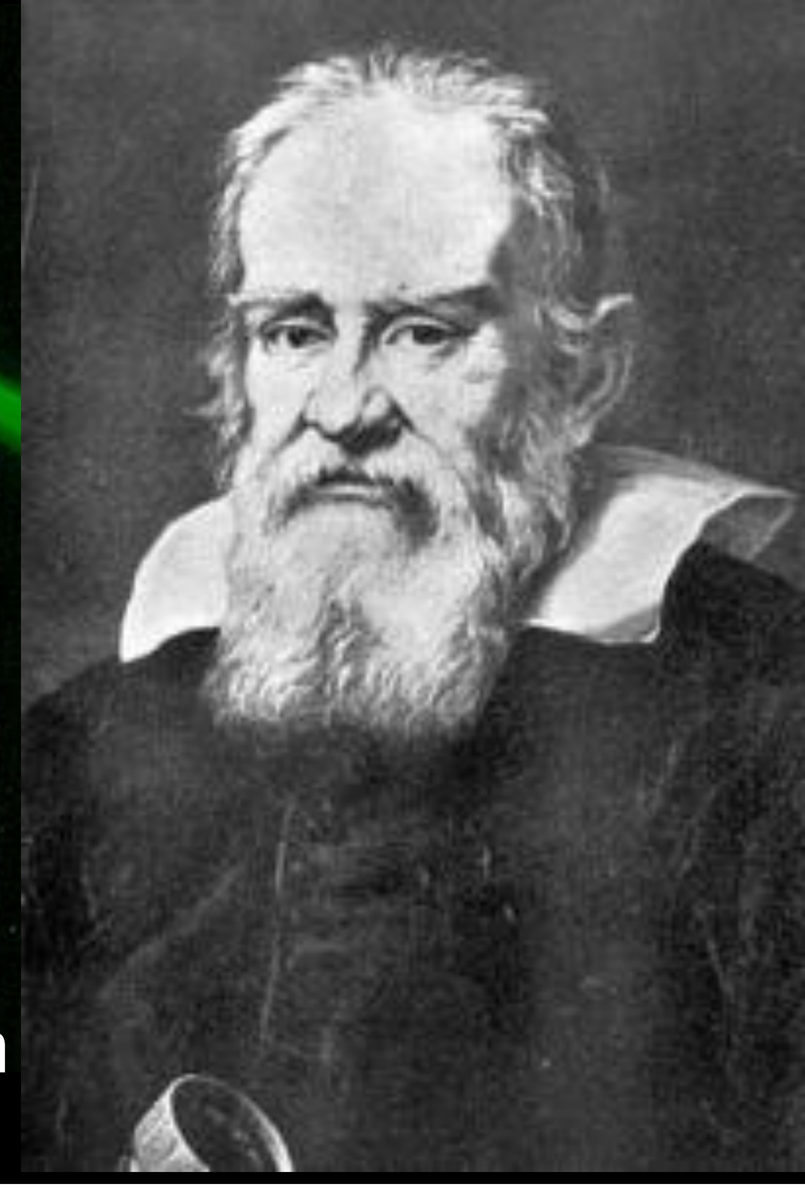


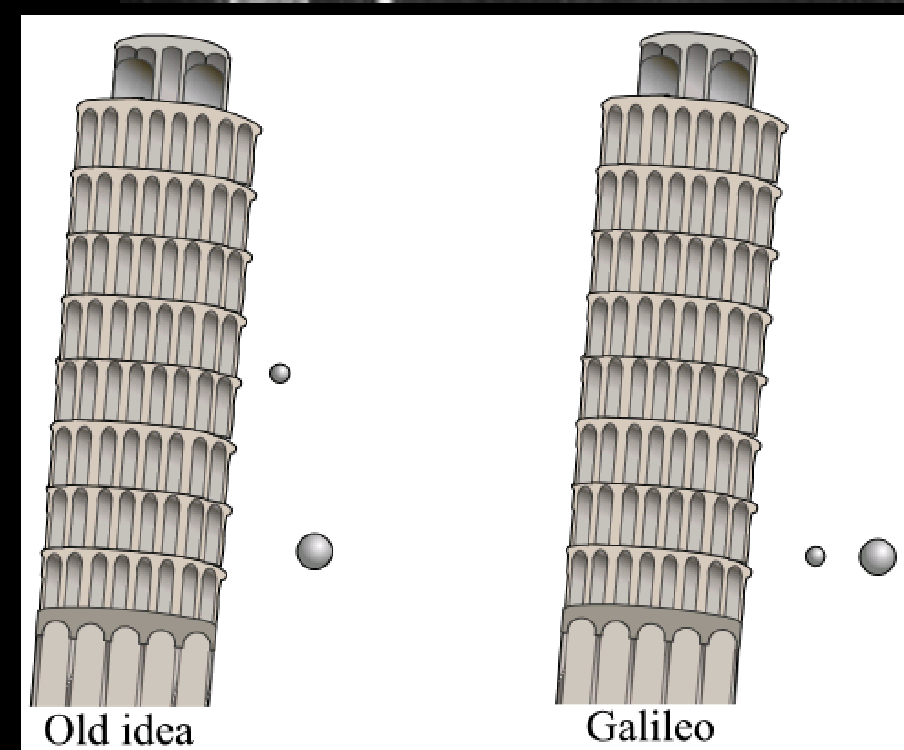


Science Objectives

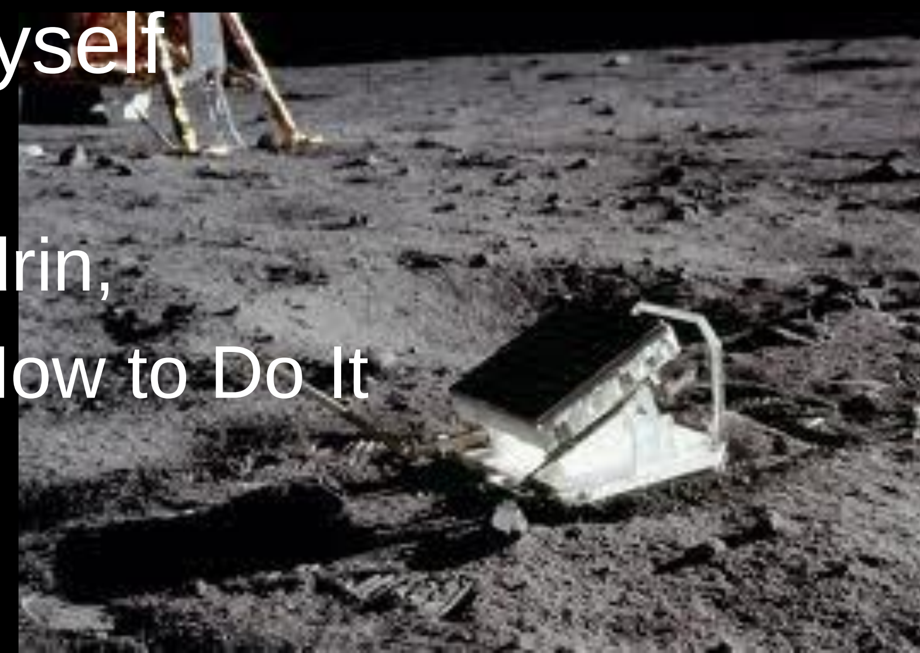
- Many Science Objectives
  - Too Many for My Allocated Time
- Galileo’s Apocryphal Experiment
  - Weak Equivalence Principle (WEP)
  - Rate that the Earth and Moon Fall to the Sun
- Structure of the Lunar Interior
  - Crustal Response to Tide
  - Internal Structure from the Crust to Core
- Testing of General Relativity
  - Brans-Dicke Theory





Preparation for Apollo 11

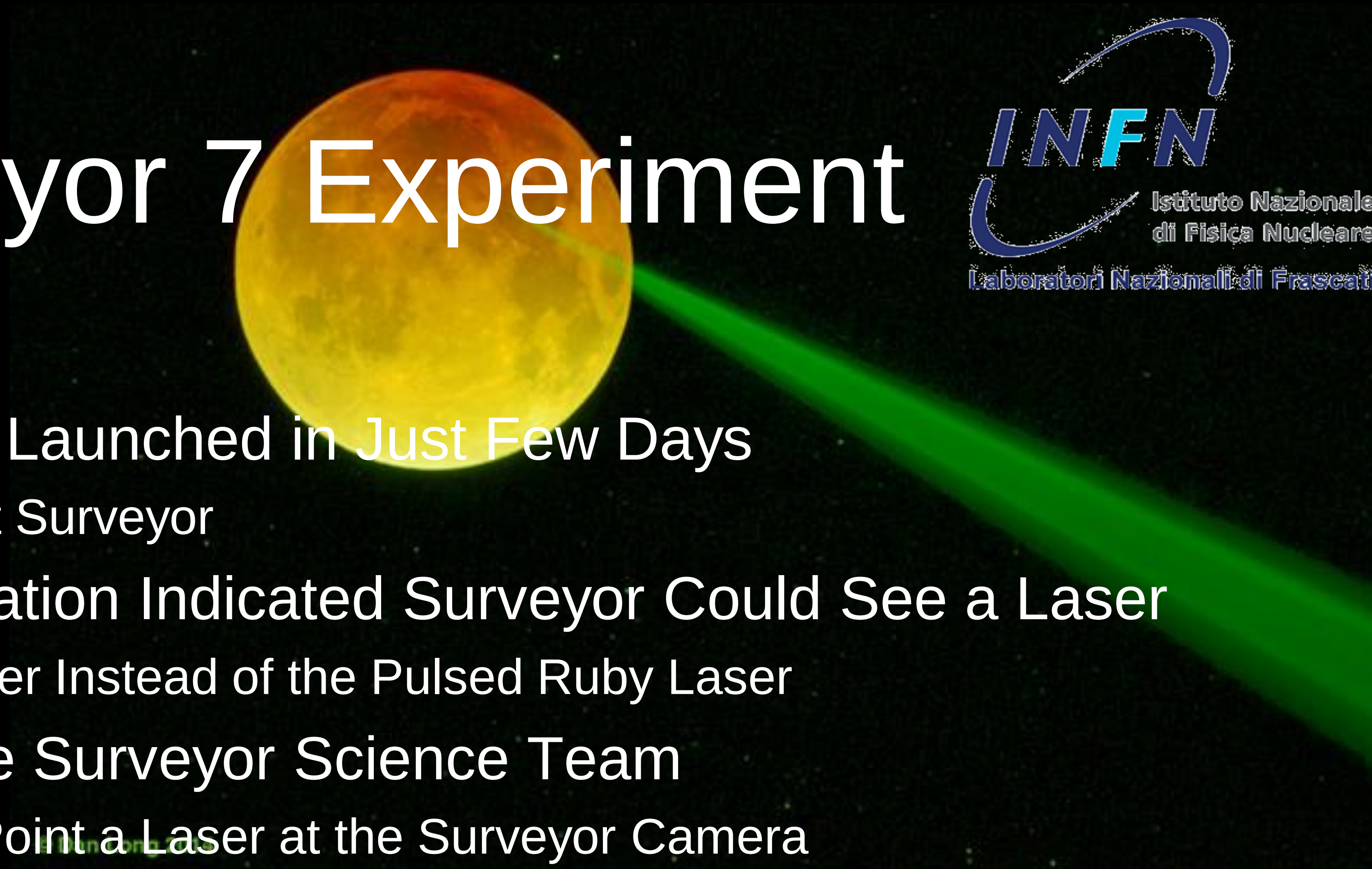
- Carroll Alley at the University of Maryland Takes the Lead
  - We at UMCP were Close to NASA Hdqrs and GSFC
  - Very Short Time for Development, Evaluation, Fabrication and Blessing
- Selected an Array of 38 mm Solid Cube Corner Reflectors
  - To Survive the Solar Heat Load Effects We Chose Uncoated (TIR) CCRs
  - With Ren-Fang Chang, We Made the First Analysis of a CCR Using TIR
- Carroll, Harry Krielmeyer, Jim Faller and Myself
  - Were Called Down to the Cape
  - To Give “Deployment Instructions” to Buzz Aldrin,
  - Of Course, He Had a Book an Inch Thick on How to Do It



LLR/Retroreflector Proposal

- Final Proposal to NASA for Apollo 11 Retroreflector Array
  - Proposal Delivered ~ 9 months Before Launch
  - Very Short Time for Preparation
- Proposal Reviews
  - Cannot Perform Single Photoelectron Detection
    - We Had Been Doing It for Years So This Was Not an Issue
  - Cannot Point a Laser to the Required 1 arc-second Accuracy
    - We 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 Far Closer Than the Moon
  - Coincidently I Had Been Calculating Whether the Astronauts Could See Our Laser
    - No – Due to Anomalies of the Way the Human Eye Detects Faint Point Pulses of Light
    - But Surveyor 7 Was About to be Launched to the Moon
    - This Would Be a Camera on the Lunar Surface
    - Perhaps It Could See a Laser Transmitted from Earth

Surveyor 7 Experiment



- Surveyor 7 Was to be Launched in Just Few Days
  - This was to be the Last Surveyor
- Revision of My Calculation Indicated Surveyor Could See a Laser
  - Using a CW Argon Laser Instead of the Pulsed Ruby Laser
- COA and I Went to the Surveyor Science Team
  - To Get Permission to Point a Laser at the Surveyor Camera
  - They Were Assembled for Meeting at the Cape for the Launch
  - After Our Presentation, They Oked the Experiment
- Assembled Collaborators to Project the Lasers
  - McMath Telescope at Kitt Peak – Jim Brault
  - Wesleyan University – Jim Faller
  - Table Mountain Observatory of JPL – Mike Shumate
  - Another Group in New England

McMath Telescope Operation

- Surveyor 7 is Launched While We Are at the Cape
- Jim Brault and I Met at Kitt Peak
  - We Crawled Over the McMath Telesclope
  - To Determine What Hardware Would be Required
- Flying Back to UMCP
  - We Built the Hardware in 36 hours
  - Shipped the Hardware to McMath
  - Installed Hardware in the Telescope
  - Ready on Arrival of Surveyor 7 at the Moon
- McMath Personnel for Operations
  - Jim Brault – Responsible for McMath
  - 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 Day and Night Portions
  - Four Stations Pointed Lasers Toward Surveyor
  - Laser Detections of McMath and Table Mountain
  - Eastern Stations Were in Twilight
- Life Magazine Covered with a Nice Article
- Demonstrated that Sufficiently Accurate Pointing
  - Could Be Achieved
  - Useful Definition of Good Approaches for McDonald

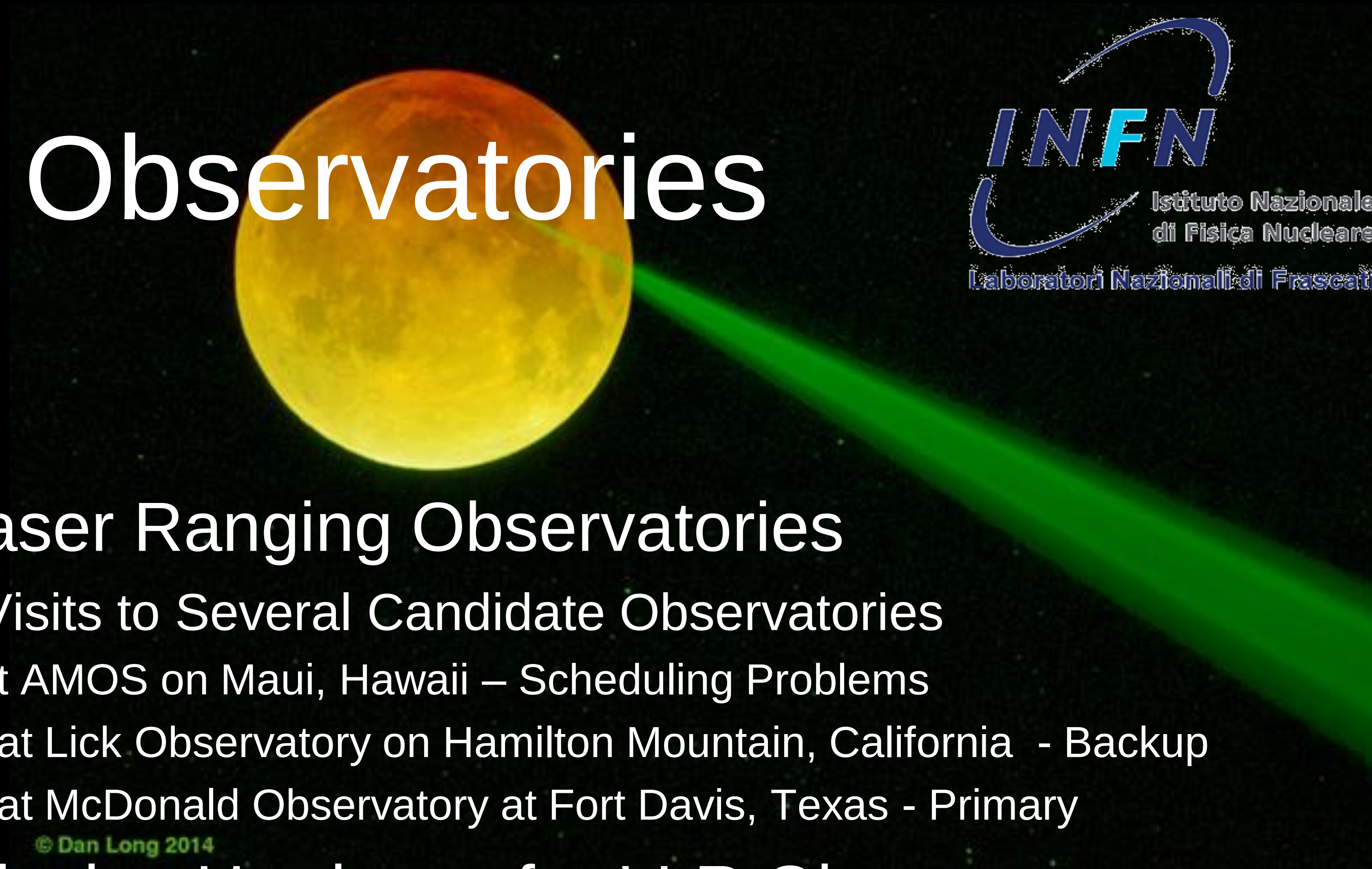
Contractors for Apollo 11 Retroreflectors

- Arthur D. Little – Peter Glaser - PDR
  - Analysis of Expected Returns
    - Confirming LURE Analysis for Optical Behavior
  - Thermal Modeling of Signal Return
    - Impact of 250K Temperature Swings Over the Lunar Cycle
  - Preliminary Detailed Hardware Designs
- Perkin Elmer – Paul Forman - Zygo
  - Fabrication of Cube Corner Retroreflectors
- Bendix - CDR
  - Responsible for Fabrication of Flight Hardware
  - Responsible for the Interfaces with NASA
- Apollo 11 Movie

The Preparation of the Lunar Package Is On the Way

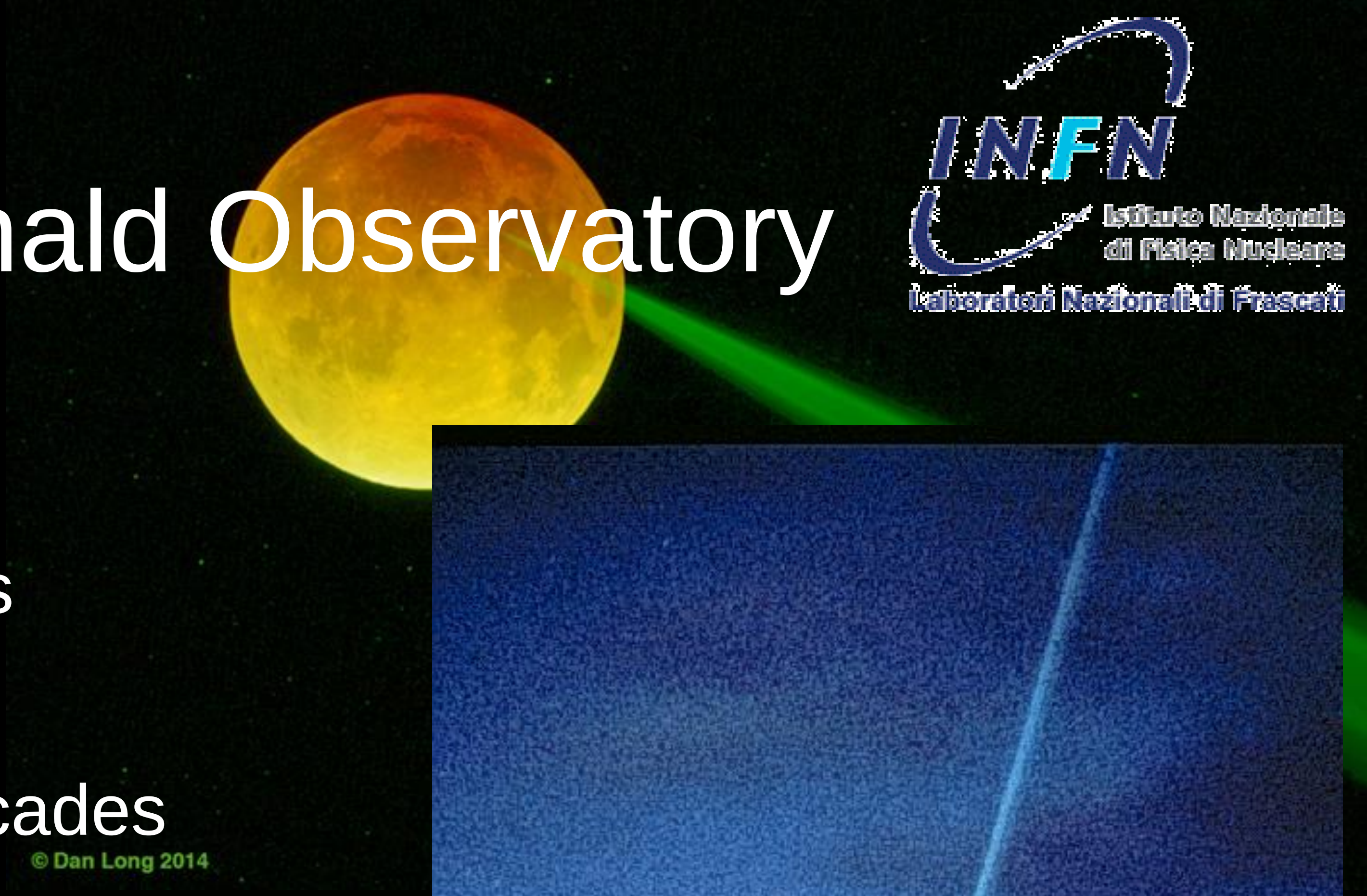
But We Need Ground Stations To Perform the Ranging

LLR Observatories



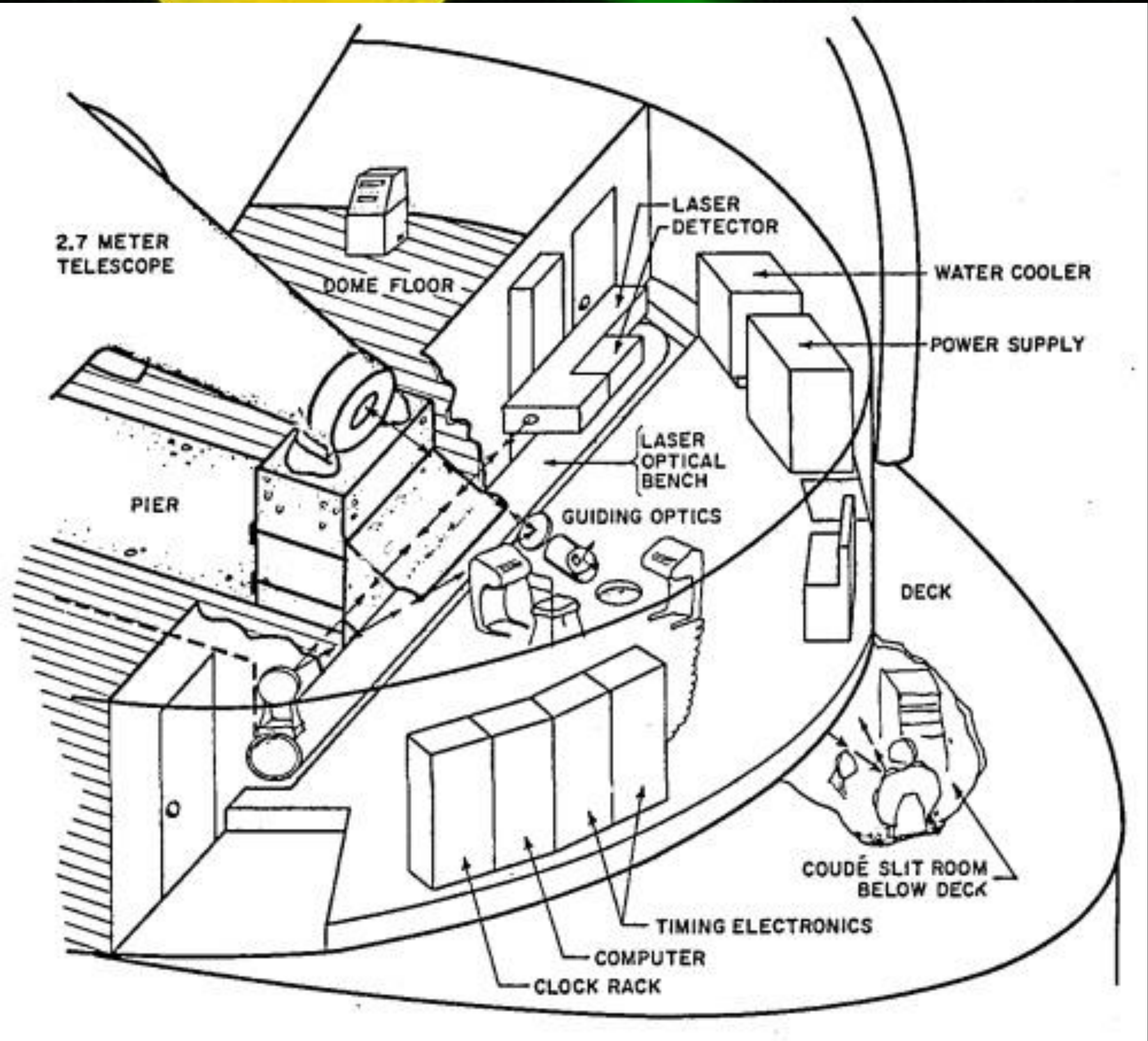
- We Need Lunar Laser Ranging Observatories
  - Carroll and I Made Visits to Several Candidate Observatories
    - 60-inch Telescope at AMOS on Maui, Hawaii – Scheduling Problems
    - 120-inch Telescope at Lick Observatory on Hamilton Mountain, California - Backup
    - 107-inch Telescope at McDonald Observatory at Fort Davis, Texas - Primary
- Developing & Deploying Hardware for LLR Observatory
  - Goddard Space Flight Center Provided the Laser
    - Henry Plotkin
  - University of Maryland, College Park
    - Carroll Alley, Doug Currie, Sherman Poultney etc.
- Installation at Observatory and Initial Operation

LLR at McDonald Observatory



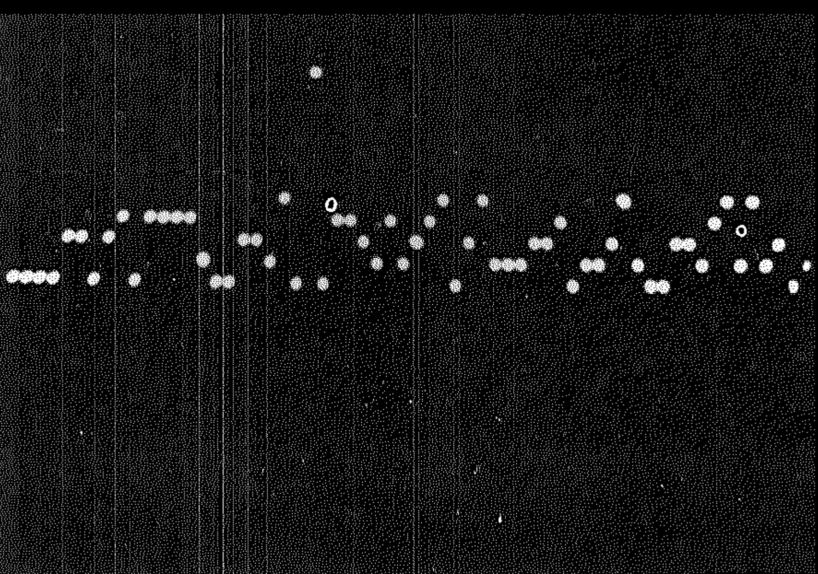
- McDonald Observatory
  - Mt. Locke, Fort Davis Texas
- Regular Operation
  - Configured for the Next Decades
- Other Stations
  - Lick Observatory, Mt. Hamilton, CA – Initial Acquisition
  - Crimea, Soviet Union – Initial
  - French MeO at Côte d' Azur, France – Long Term
  - APOLLO at Apache Point, NM
  - MLRO Station in Matera, Italy
  - Wettzell SLR Station in Bad Koetzting , Germany

McDonald LLR Observatory



Operating Personnel

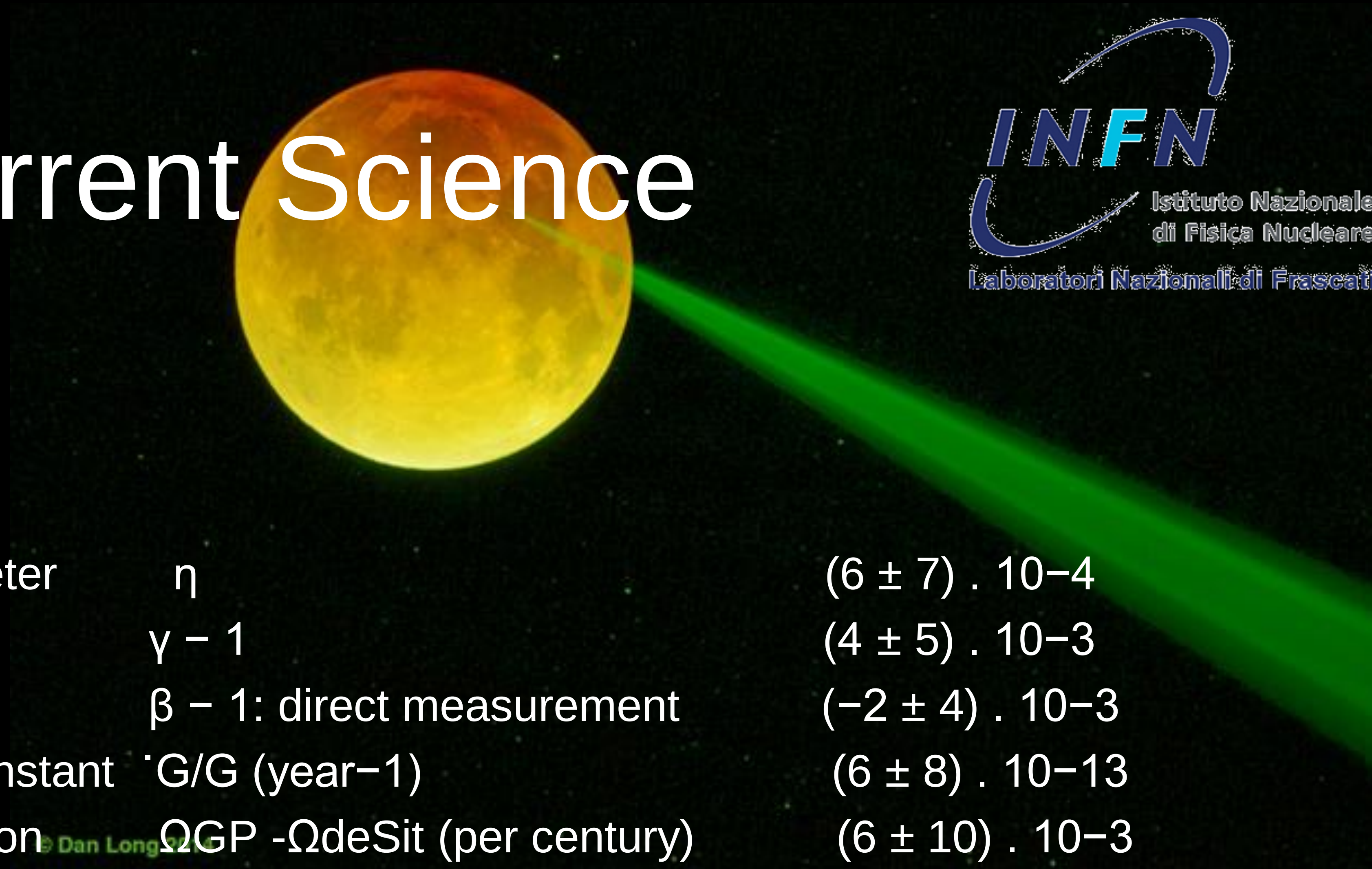
- University of Maryland
  - Doug Currie
  - Eric Silverberg
  - Sherman Poultney
  - Charlie Steggerda
  - John Mullendore
  - John Raynor
- University of Texas
  - Brian Warner
  - Wayne van Citters
  - Bernie Bopp
  - Don Wells
  - Mike McCants
- GSFC
  - Windell Williams
  - Robert Gonzales



So Much for Getting LLR Started

Has There Been Anything to Show for All This Effort?

Current Science



- 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

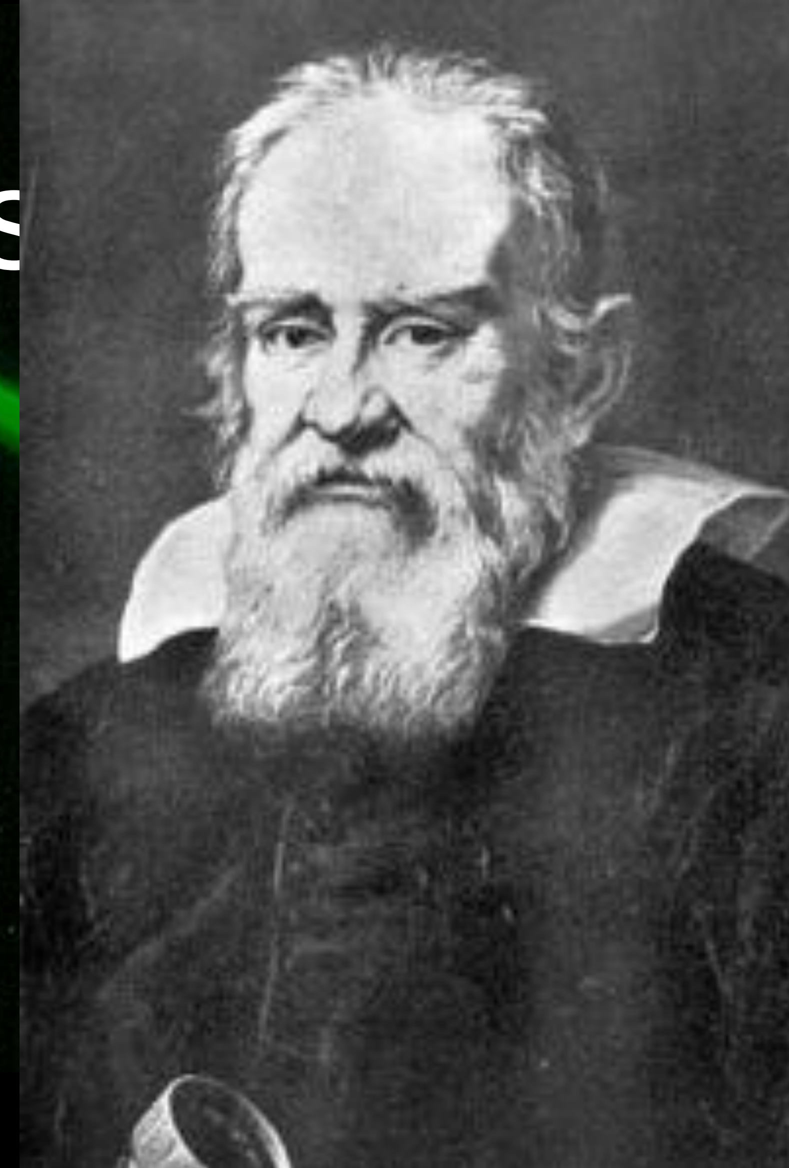
- from Juergen Mueller and Franz Hofmann

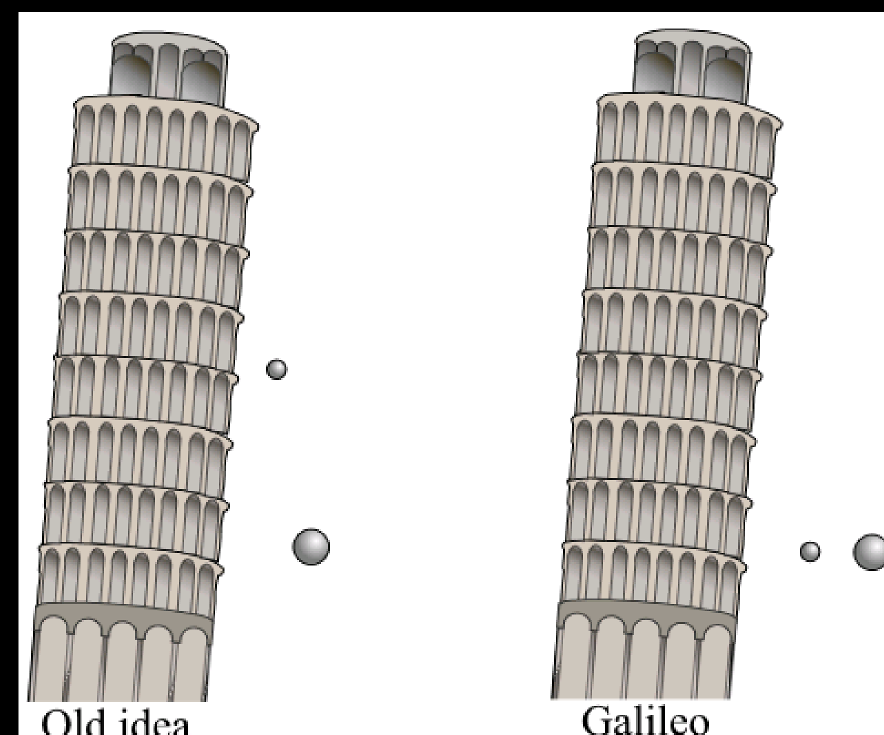
GRAVITATIONAL & GR SCIENCE

- 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)**

Science Objectives

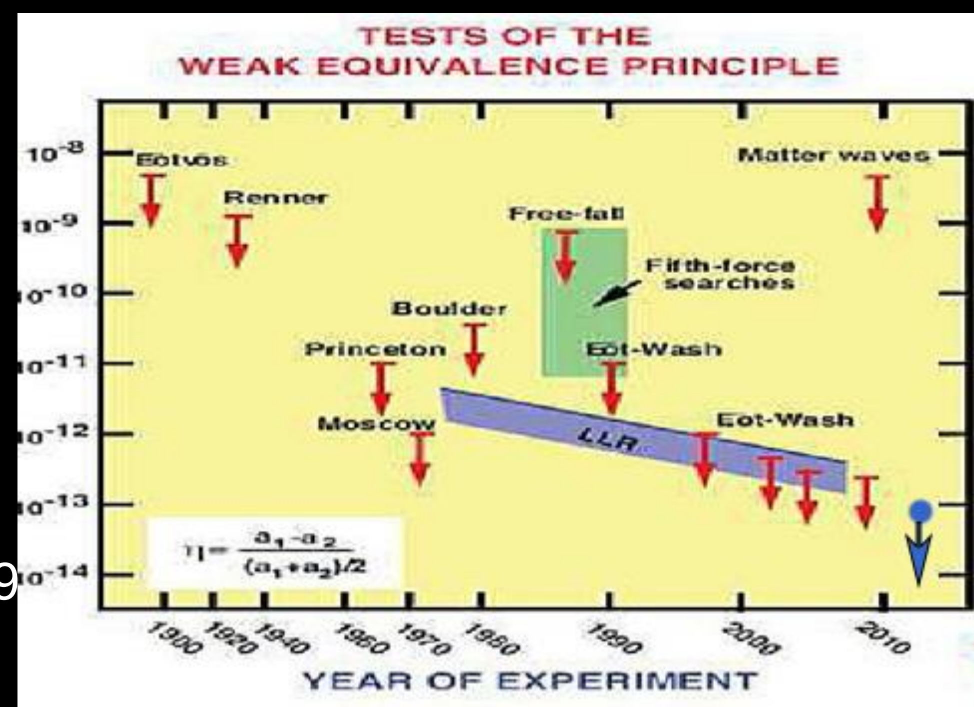
- Galileo’s Apocryphal Experiment
  – With the Leaning Tower of Pisa
  – Rate that the Earth and Moon Fall to the Sun
- Structure of the Lunar Interior
  – Crustal Response to Tide
  – Interior Structure from Crust to Core
- Testing of General Relativity
  – Brans-Dicke Theory
- Earth Science
  – Continental Drift
  – Length of the Day





Improvements in WEP Measurements

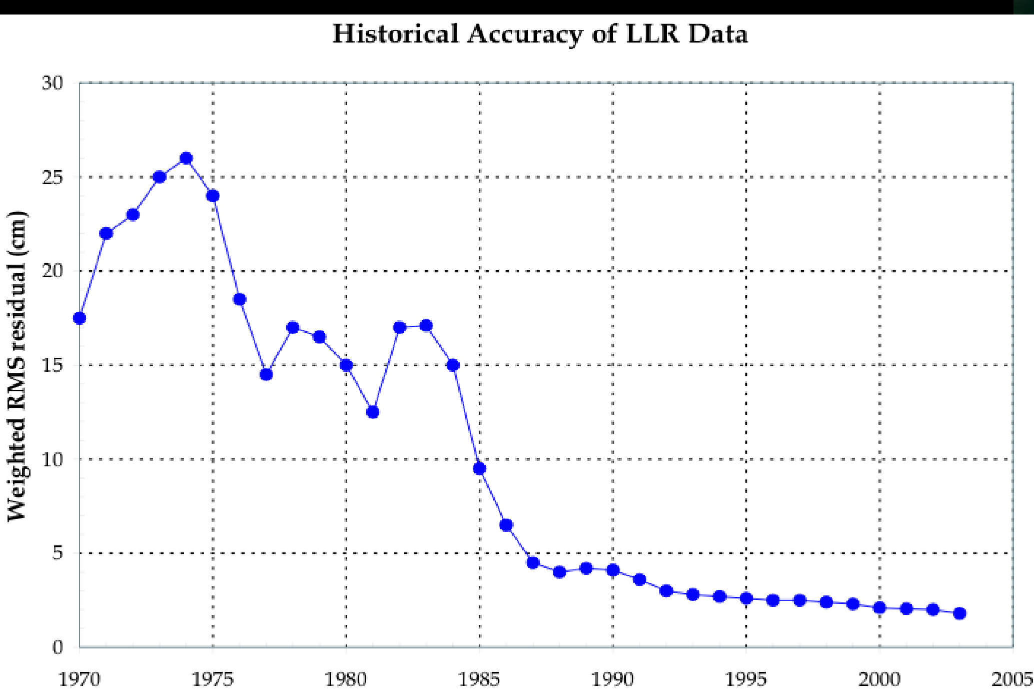
- Experimental Verification of the WEP
  - Eötvös/Dicke Measurements
  - Compared the Acceleration of Different Materials
  - All Laboratory Experiments
- Lunar Laser Ranging Measurements
  - Massive Astronomical Bodies – Earth and Moon
- LLR Measures Inertial Properties
  - Of Gravitational Energy
  - Unique

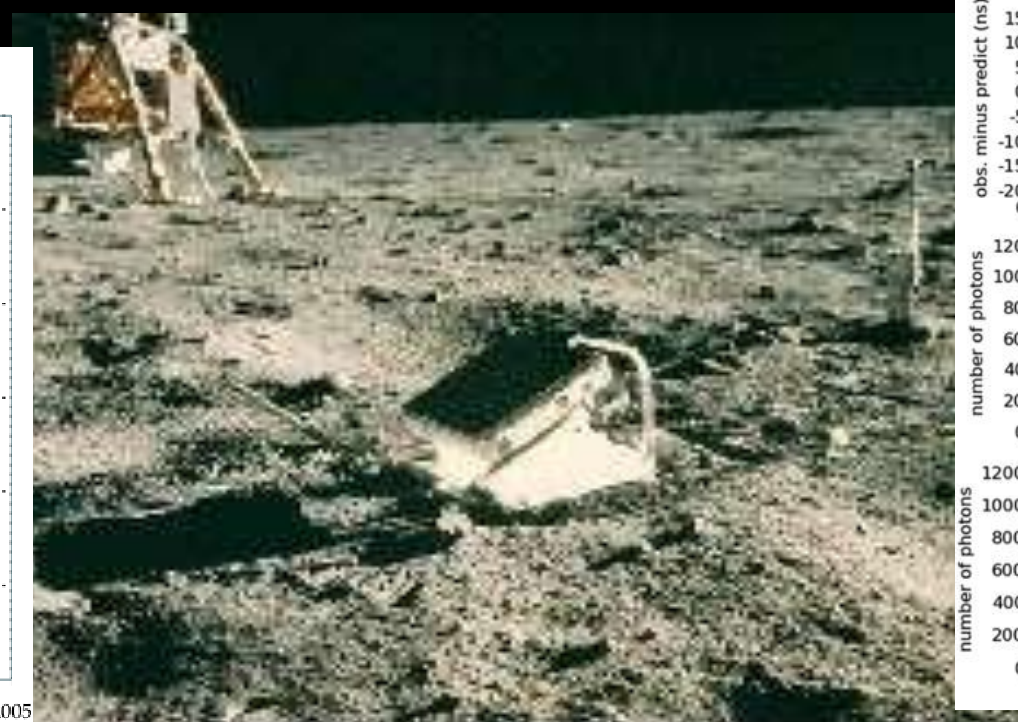


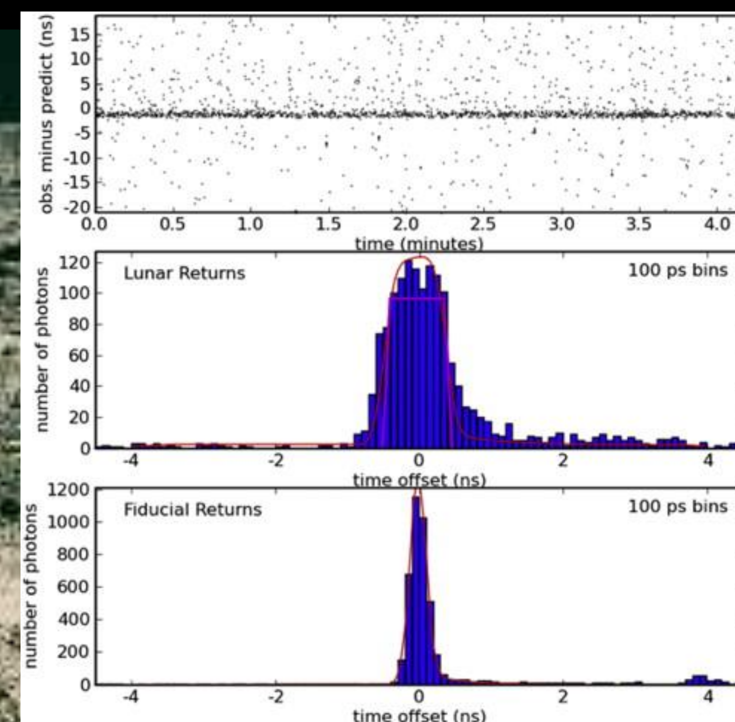
Why Deploy New Retroreflectors?

LIBRATION PROBLEM

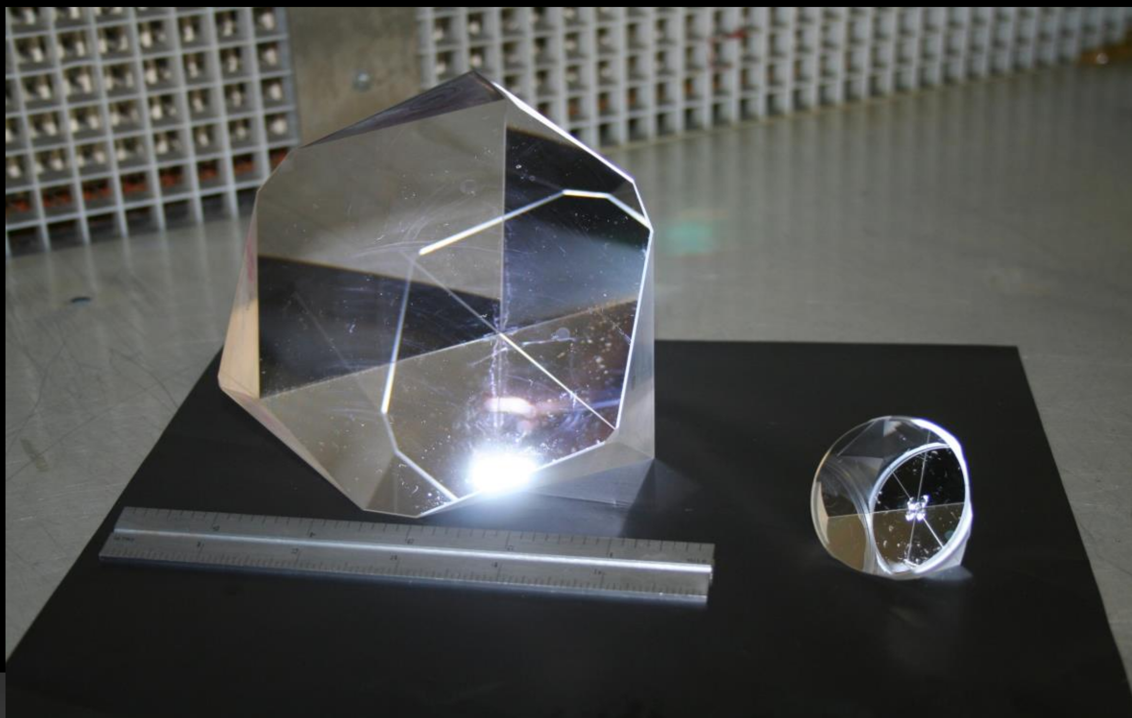
- Why is There a Problem with the Apollo Arrays
  - Lunar Librations in Tilt Both Axis by 8/10
  - Apollo Arrays are Tilted by the Lunar Librations
  - Corner CCRs can have Different Ranges
    - As large as 200 mm for the Apollo 15 array







Next Generation Lunar Retroreflector



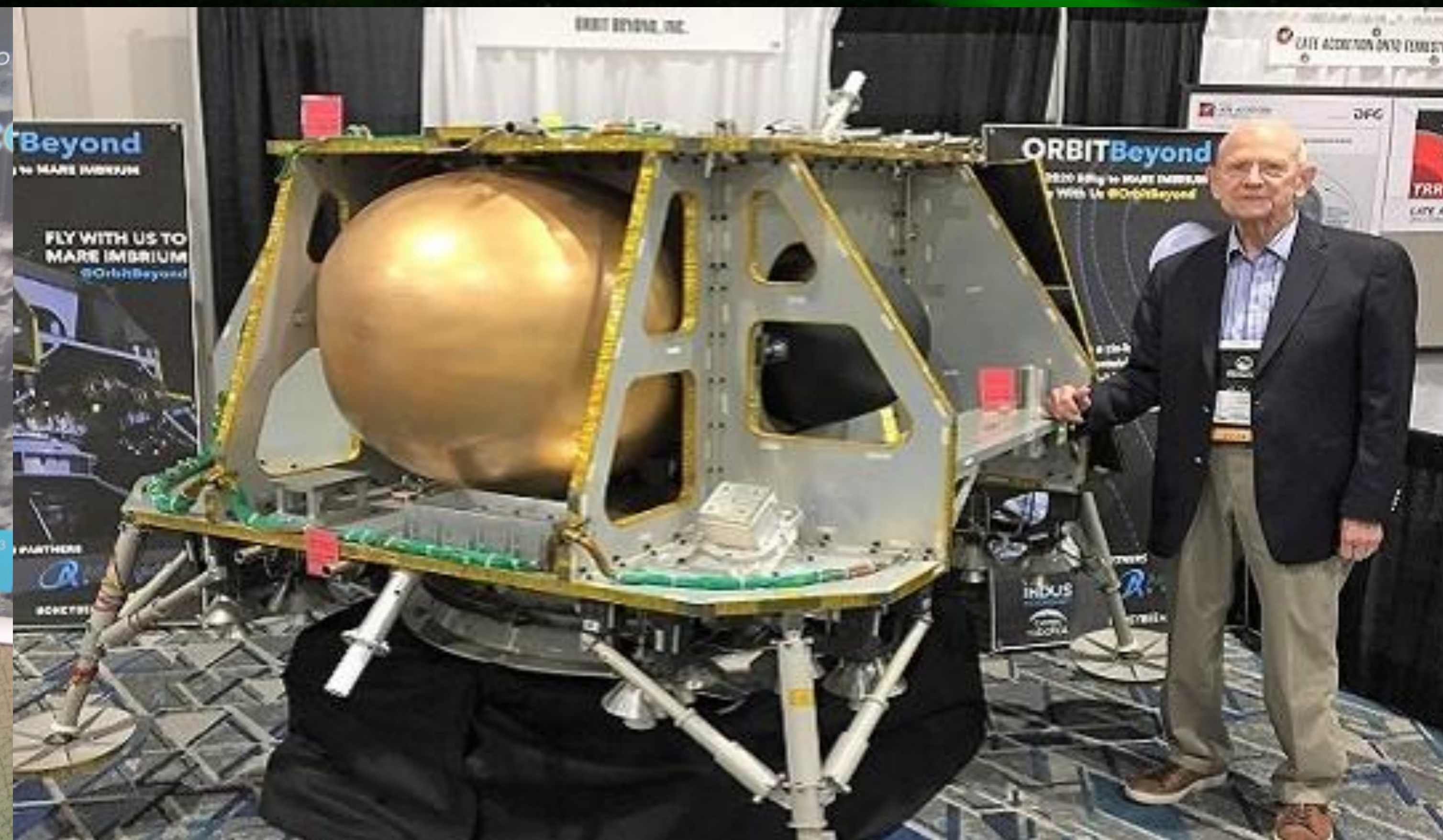
24 October 2019

ILRS Technical Workshop 2019
Stuttgart, Germany

Current Status of Our NGLR

- NASA Has Selected the UMCP to Create 3 NGLRs
- To Be Deployed On the Lunar Surface in 2021
  - By Un-Mannered Commercial Carriers
- NGLR Eliminates Libration Problem
- Supports Improved Ranging Accuracy
  - By Up to a Factor of 100 for Each Shot
  - Depends Upon the LLR Observatory Hardware
  - Better Understanding of the Earth's Atmosphere

Flight by Copmmercial Carrier



Future Progress

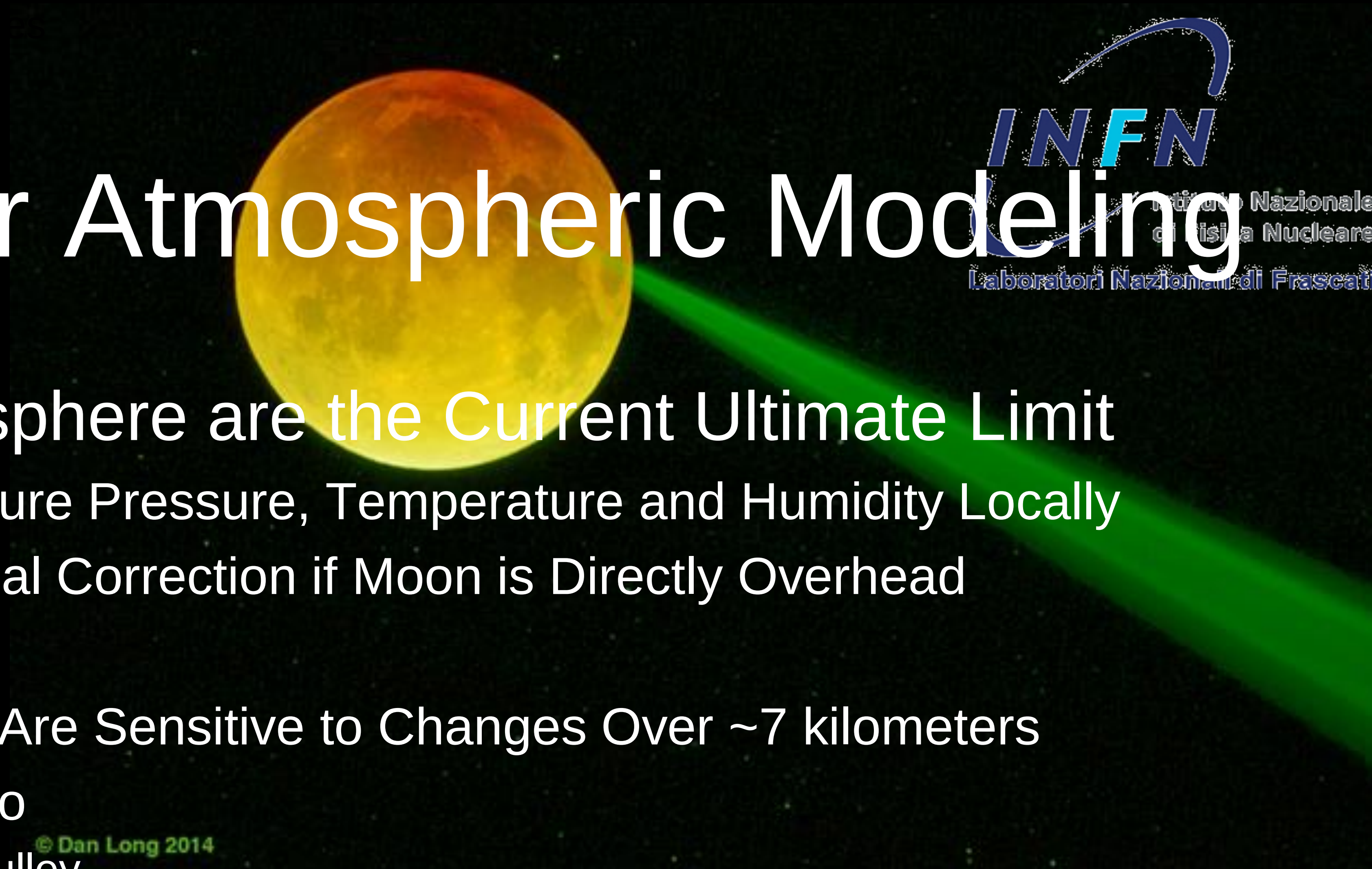
What is Needed
To Achieve the Greater Accuracy

Improved Ground Stations

- Need Advanced Hardware to Reach 1 mm per Shot
  - And Beyond If We Can Conquer the Atmospheric Wedge Problem
- Ideally a LLR Observatory Might Have
  - 20 ps laser
  - Electronic and Timing System with 10 ps jitter
  - Meteorological and Geophysical Stations for Calibrations
  - Better Local Range Predictions to Set Range Gate
  - Tight Range Gate – To Control of Full Moon and Day Sky Noise
- For Example – At the Wettzell SLR Station
  - Currently ~150 mm Single Shot Offsets at High Libration Angles
  - 10 ps Laser and Appropriate Electronics Implies <1 mm/shot
  - Single Shot Precision Improved by a Factor of ~100 for High Libration Angles
  - Even Better Normal Point Accuracy if the Atmospheric Wedge Angle is Known

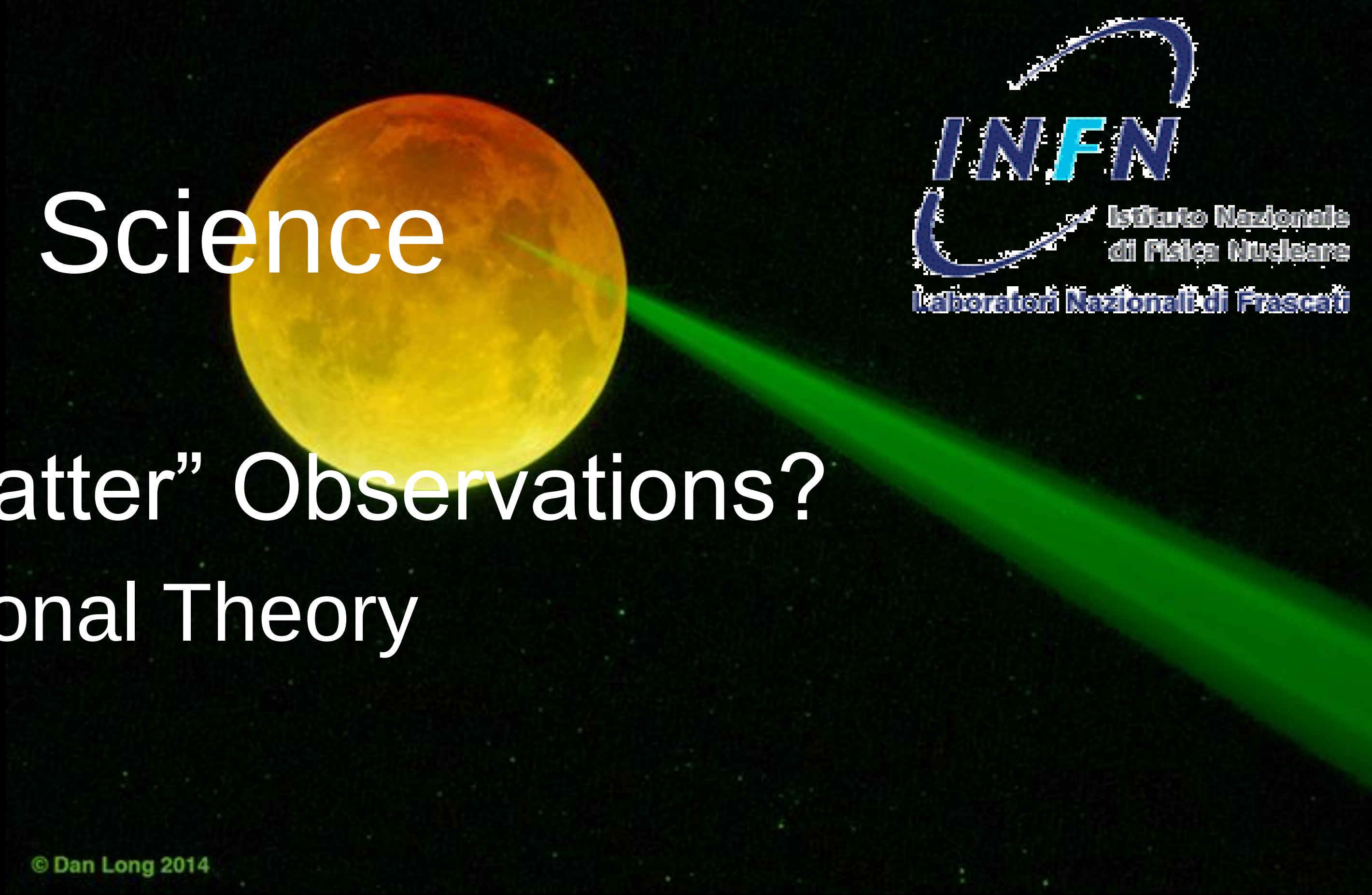
G. C. Hulley
Erricos C. Pavlis

Better Atmospheric Modeling

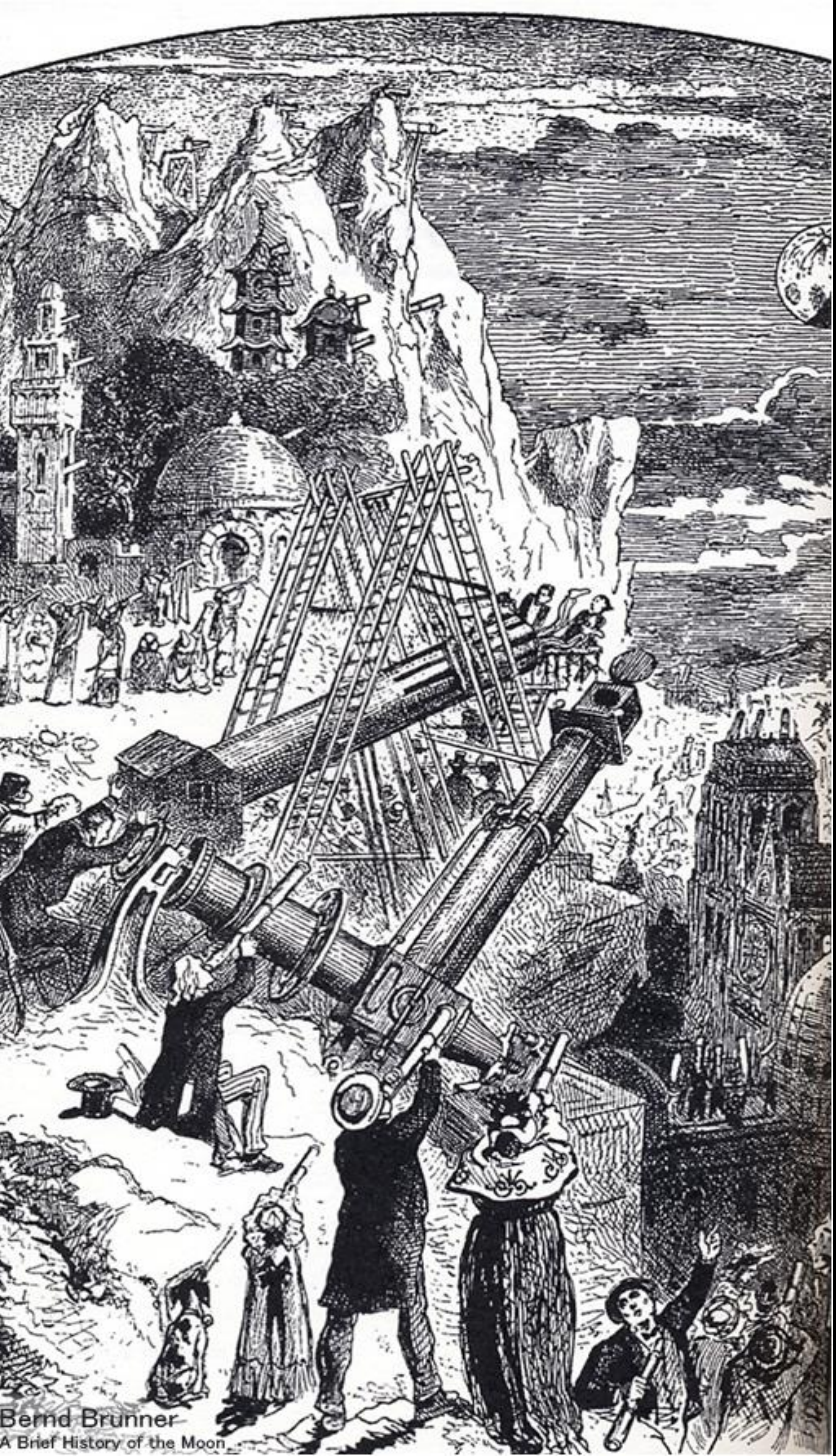


- Wedges in Atmosphere are the Current Ultimate Limit
  - Currently We Measure Pressure, Temperature and Humidity Locally
  - Acceptable Spherical Correction if Moon is Directly Overhead
  - Never Happens
  - At 40 degrees, We Are Sensitive to Changes Over ~7 kilometers
  - Errors of a mm or so
    - E. Pavlis and G. Hulley
    - Typical Observations at 40 degrees Due to Latitude of LLR Observatories
  - Possible Use Local Met Data to Model the Wedge
    - 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

Future Science



- What Explains the “Dark Matter” Observations?
  - Modification of the Gravitational Theory
    - MOND Theories
  - As Yet Unknown Particles
- Internal Lunar Structure
  - Support of Our Proposed Lunar Geophysical Network Program
  - We Have Just Received the Award of a Study Contract
- Further Tests of General Relativity
  - Conflict of Quantum Mechanics and GR



Thank You!
any
Questions?
or
Comments?

with
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