Critical Thermal Control Issues

for

Gravitation and General Relativity Tests

by

Professor Douglas Currie

Department of Physics

University of Maryland, College Park

with

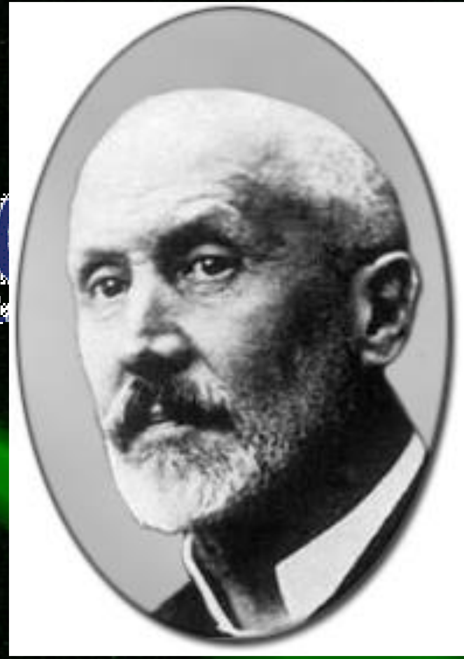
MEng. Giovanni Delle Monache INFN-LNF

Dr. Bradford Behr UMCP

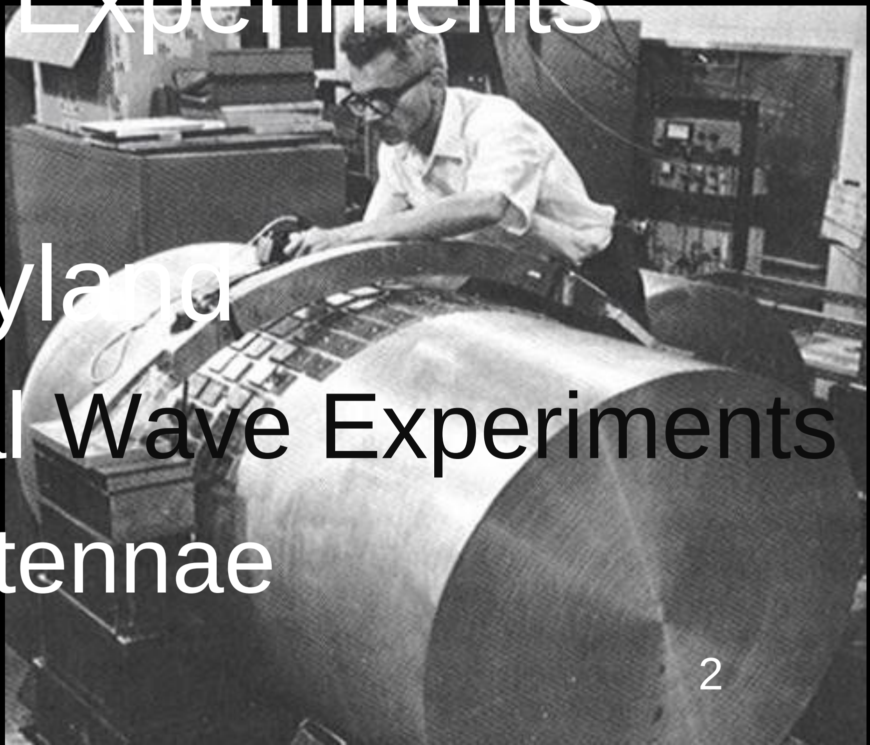
Dr. Simone Dell'Agnello INFN-LNF

Dr. Chensheng Wu UMCP

Early Testing of General Relativity



- Initial Experimental Predictions by Einstein
  - Precession of the Perihelion of Mercury
  - Bending of Light about Massive Bodies - 1919
  - Gravitational Redshift - 1959
  - Agreement with Non-Relativistic Results
- Loránd Eötvös/Dicke – Laboratory Experiments
  - Weak Equivalence Principle
- Joe Weber at the University of Maryland
  - Conceptual Exposition of Gravitational Wave Experiments
  - Early GW Measurements with Bar Antennae



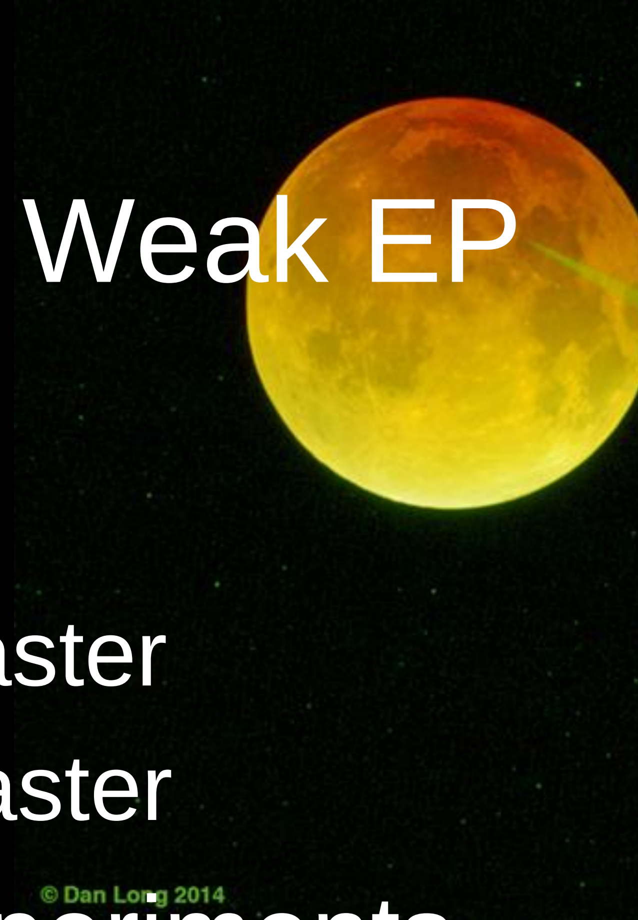
PreHistory of Dicke Group

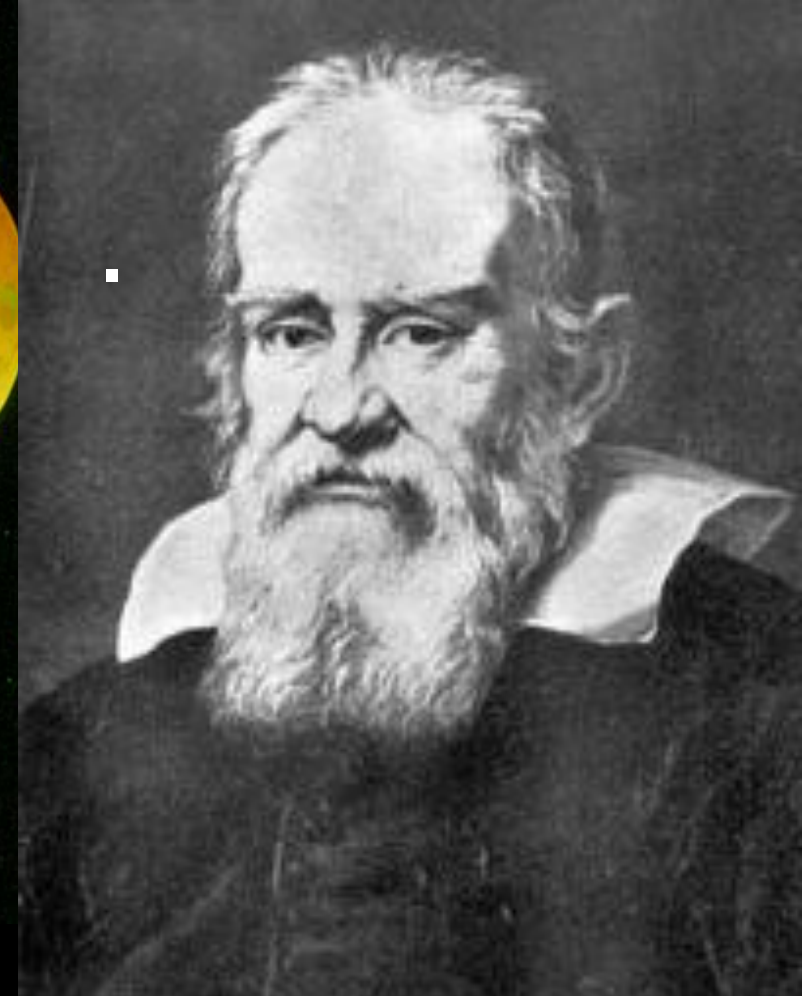
- Professor Robert Dicke of Princeton
  - Early Interest in Tests of General Relativity
    - Measured the Gravitational Red Shift
    - Investigated the Precession of Mercury
    - Developed the Scalar-Tensor Theory
      - Alternative to General Releativty
  - Considered Ranging to the Lunar Surface with a Spotlight
    - Insufficient Accuracy – Variations from the Surface Topography
    - Insufficient Signal – Outgoing Beam was Too Broad
  - In the 1960's – Two Great Leaps Forward
    - Ted Maiman Demonstrated the Laser
    - President Kennedy said "We are Going to put a Man on the Moon"
  - Measurements of Sufficient Accuracy
    - Could Finally be Accomplished!!!

Preparatory for LL Ranging

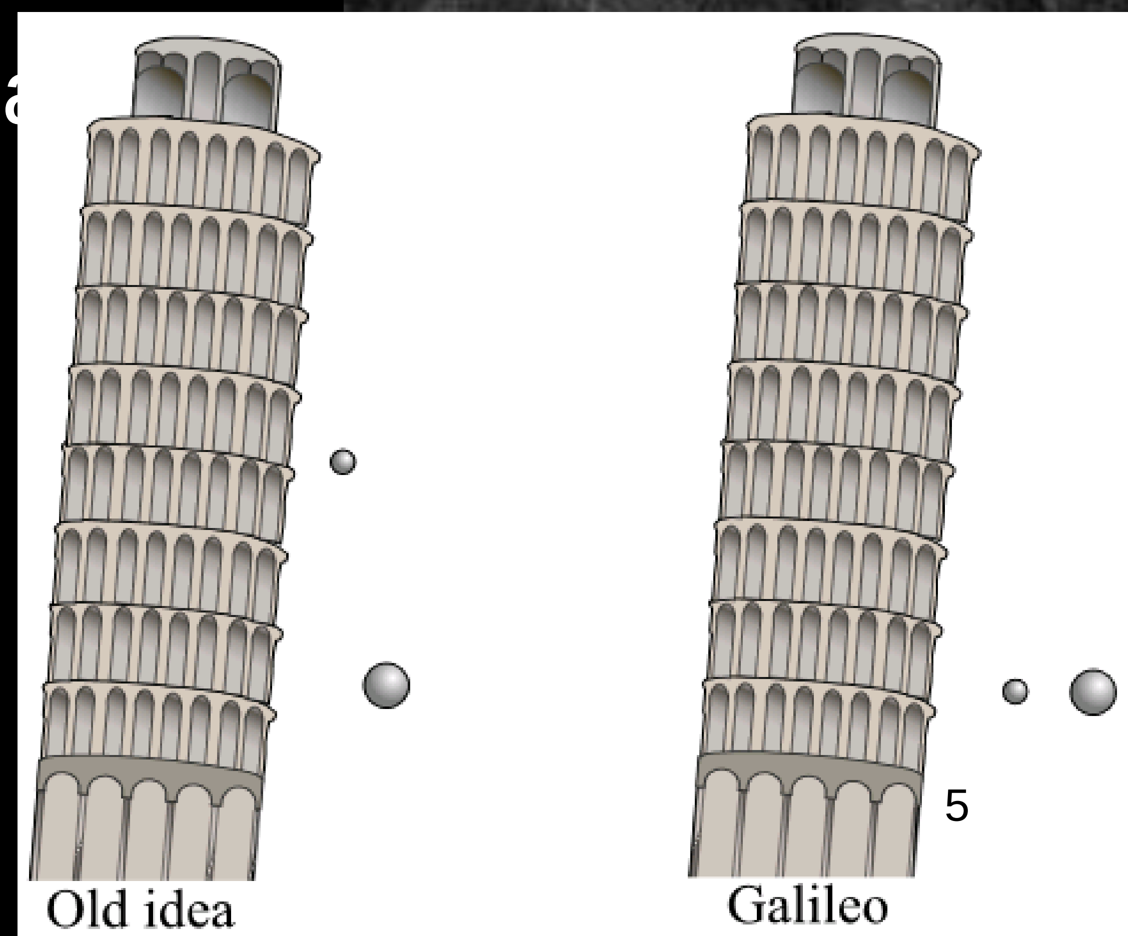
- Can One Point a Laser with Sufficient Accuracy
  - Could An Astronaut on the Moon See Our Laser
  - Last Surveyor Might be Able to See the Laser
  - Image of Earth Showing Laser Transmissions
  - Surveyor Image
  - Life Magazine
- Selection of Permanent Station
  - MacDonald Observatory
  - AMOS 60 Inch

Galileo and Weak EP

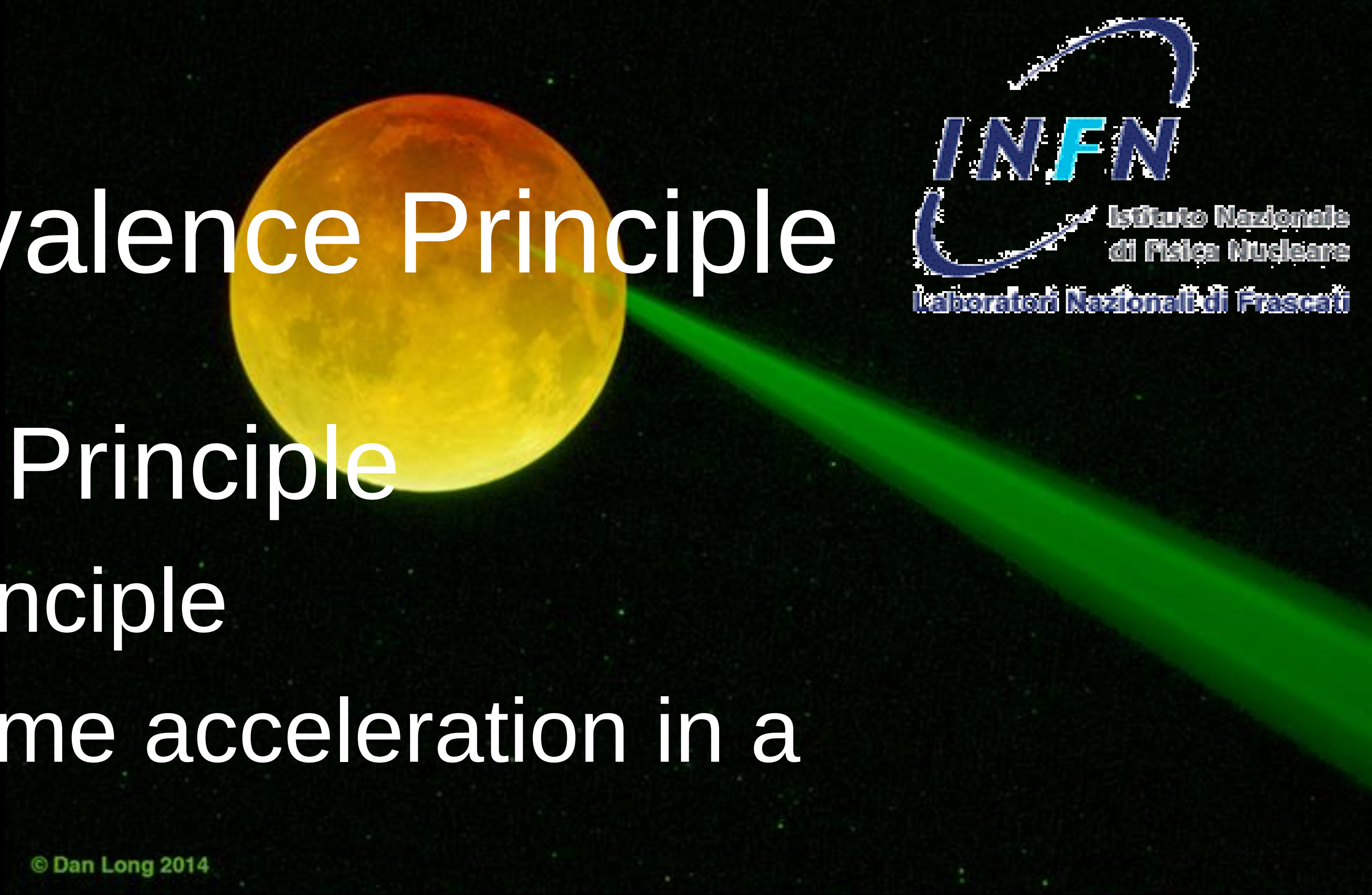




- Aristotle
  - – Heavy Objects Fall Faster
  - – Dense Objects Fall Faster
- Galileo – Thought Experiments
  - – Big and Small – Same Materia
  - – Different Material
- Galileo – Experiments
  - – Inclined Planes
  - – Tower of Pisa ???



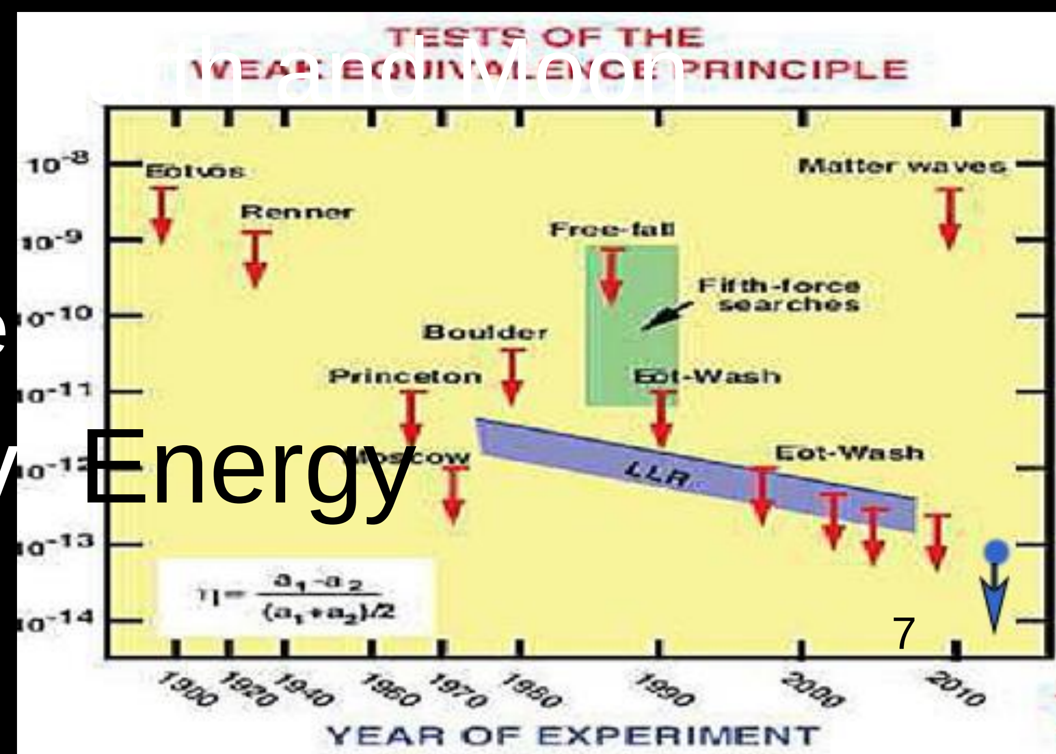
Galilean Equivalence Principle



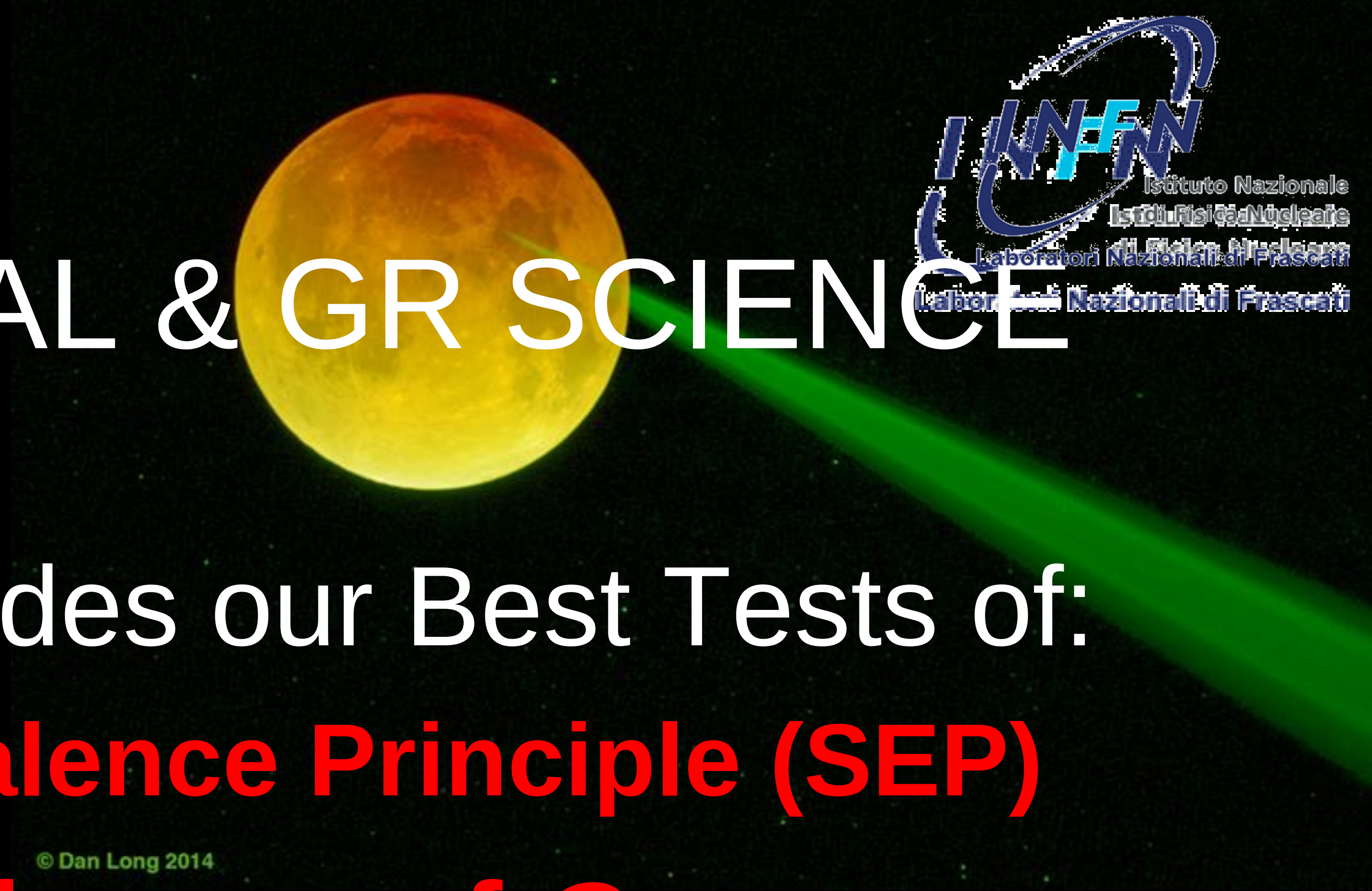
- Galilean Equivalence Principle
  - Weak Equivalence Principle
  - All bodies have the same acceleration in a
    - Gravitational Field
      - Lead, Feather, Gravitational Energy
    - Magnetic Field
      - Iron, Wood,
    - Electric Field
      - Positively Charged Body, Neutral Body
  - Galilean Equivalence Principle
    - Gravitational Force is Unique even in Daily Life

Improvements in WEP Measurements

- Experimental Verification of the WEP
  - Eötvös/Dicke Measurements
  - Compared Different Materials
  - All Laboratory Experiments
- Lunar Laser Ranging Measurements
  - Massive Astronomical Bodies –
  - They Move on “Geodesics”
    - Force free Paths in Curved Space
- LLR Accuracy Measures Grav Energy



GRAVITATIONAL & GR SCIENCE

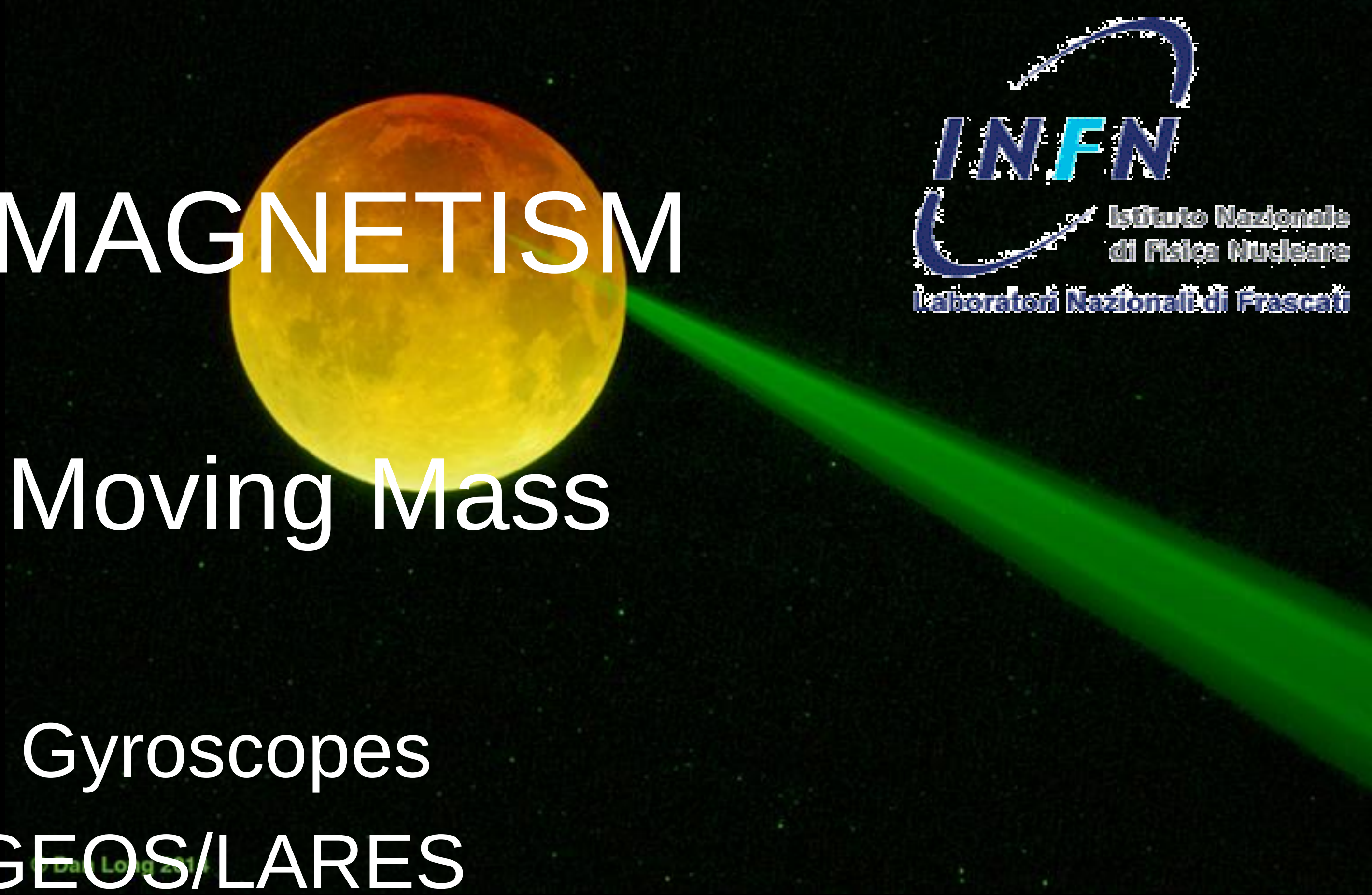


- LLR Currently Provides our Best Tests of:
  - **The Strong Equivalence Principle (SEP)**
  - **Time Rate-of-Change of *G***
  - **Inverse Square Law, Deviation of 1/r**
  - **Weak Equivalence Principle (WEP)**
  - **Gravito-Magnetism**

MOND Theories

- What Explains the "Dark Matter" Observations?
  - Modification of the Gravitational Theory
    - MOND Theories
  - As Yet Unknown Particles
- Brans-Dicke Theory
  - Parameter Pushed to 79
- MOND Theories
  - Initial Version – LLR G-dot Disconfirmed
  - Current Version – Difficult but NOT Investigated

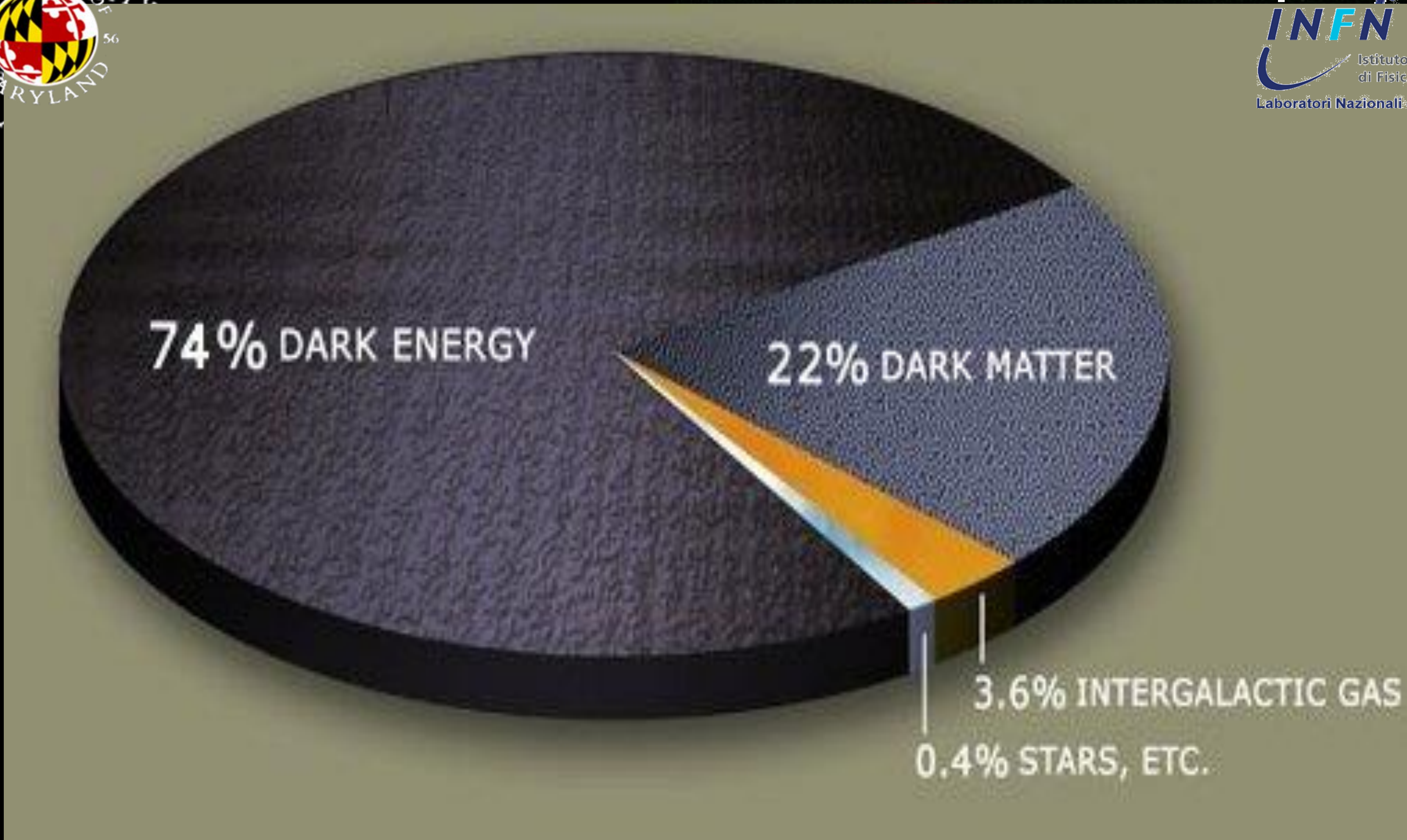
GRAVITO-MAGNETISM



- Effects of Rotation or Moving Mass
  - Earth Rotation
    - Twists Space – Affects Gyroscopes
    - GP-B and Cuifolini LAGEOS/LARES
    - ~ 1% Measurements
- Like Electro-Magnetism
  - Spin and Currents
    - Motion of Earth and Moon in Sun's Gravitational Field
    - Causes Polarization of Lunar Orbit
    - 0.1 % Measurement

Questions in Cosmology

- Twenty Years Ago
  - We knew All about the Universe
- Vera Rubin
  - Stars do not Rotate “Properly” about the Galactic Center
  - Do not know why, but we call it Dark Matter
- Perlmutter, Schmidt & Riess
  - Distant Galaxies were Moving too Fast
  - Do not know why, but we call it Dark Energy
- Something Strange Seems to be Going on with Gravity
- Cannot fit General Relativity into Quantum Mechanics

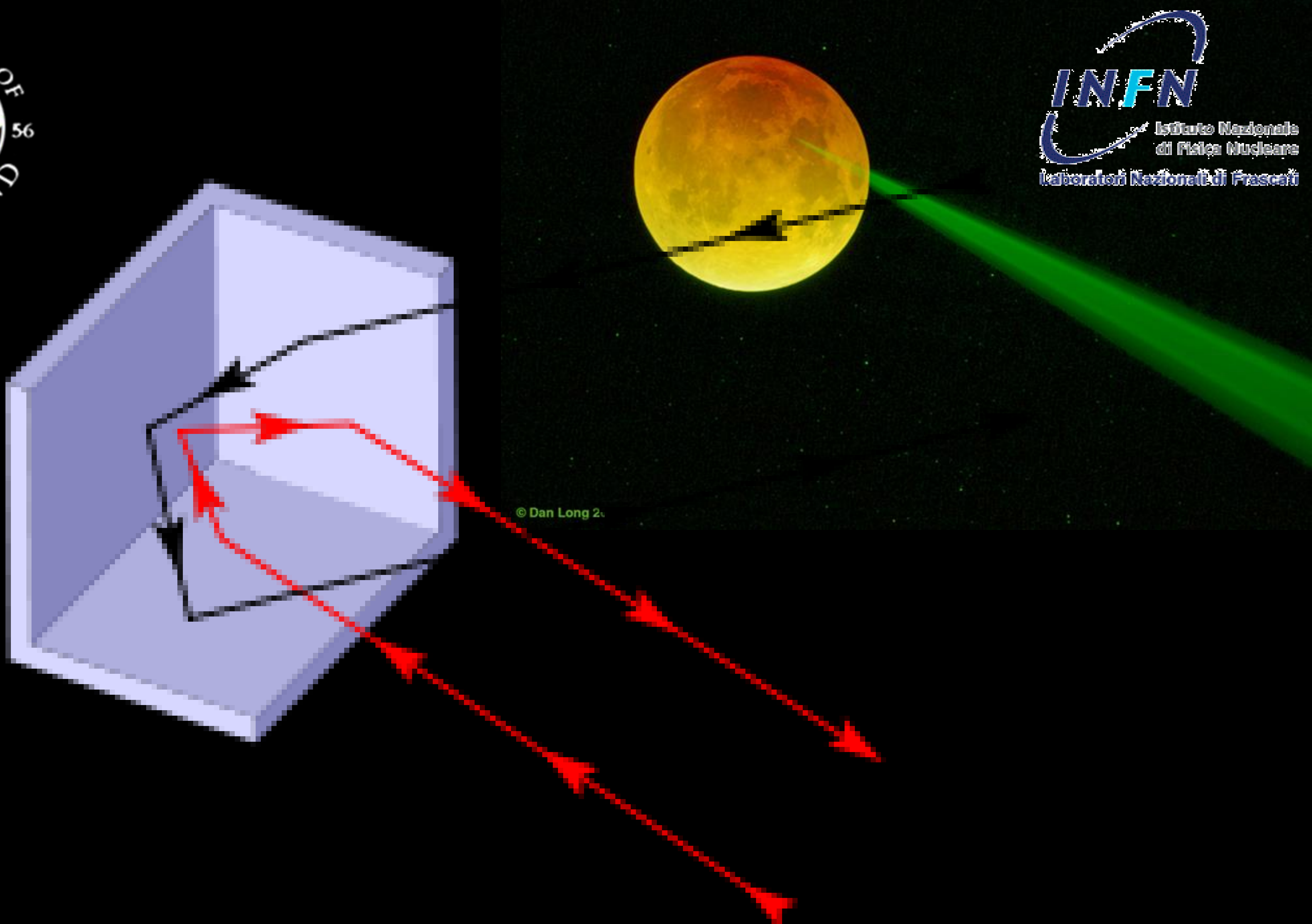


and the problem with

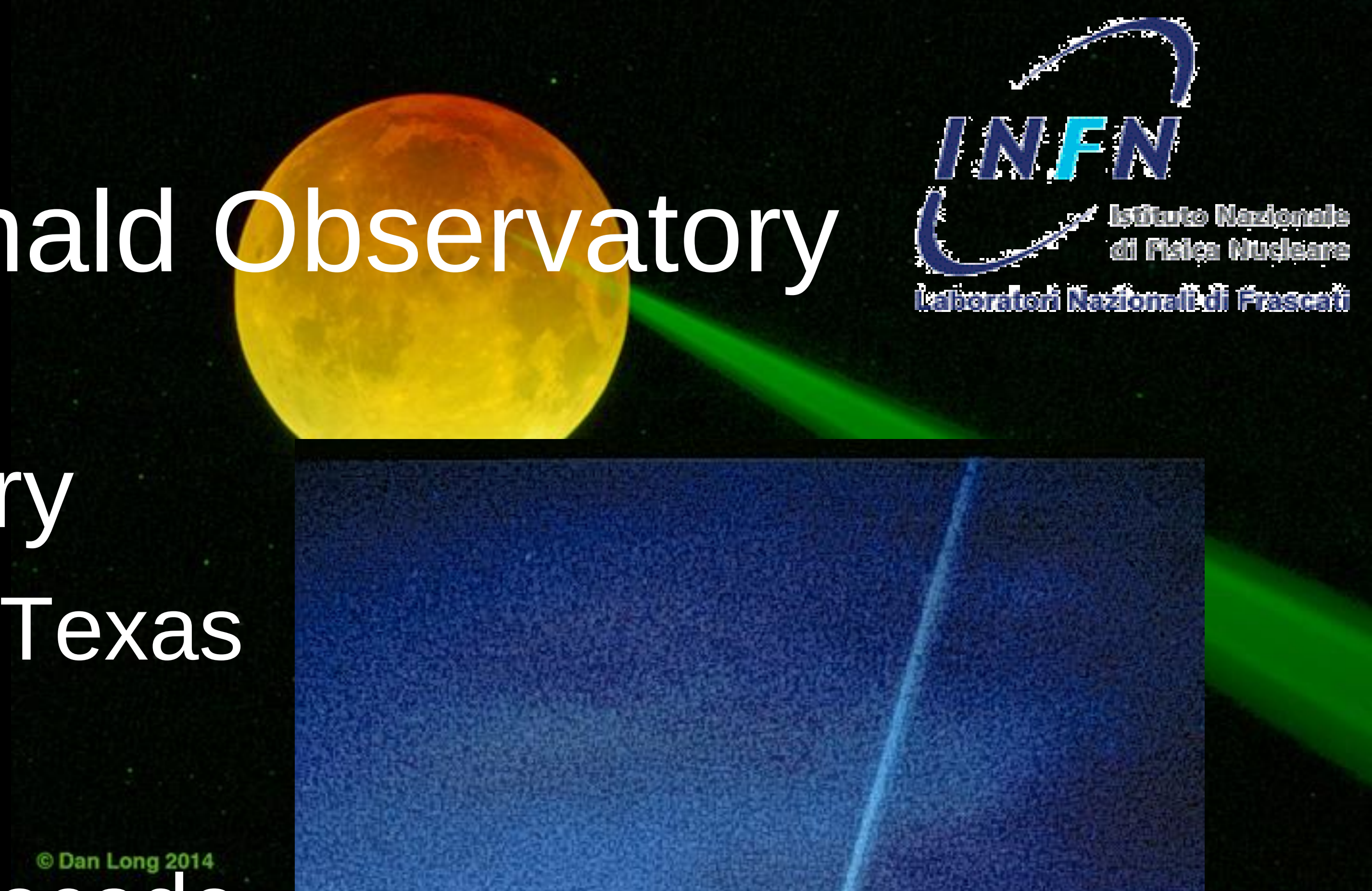
General Relativity vs. Quantum Mechanics

Overview of Lunar Laser Ranging

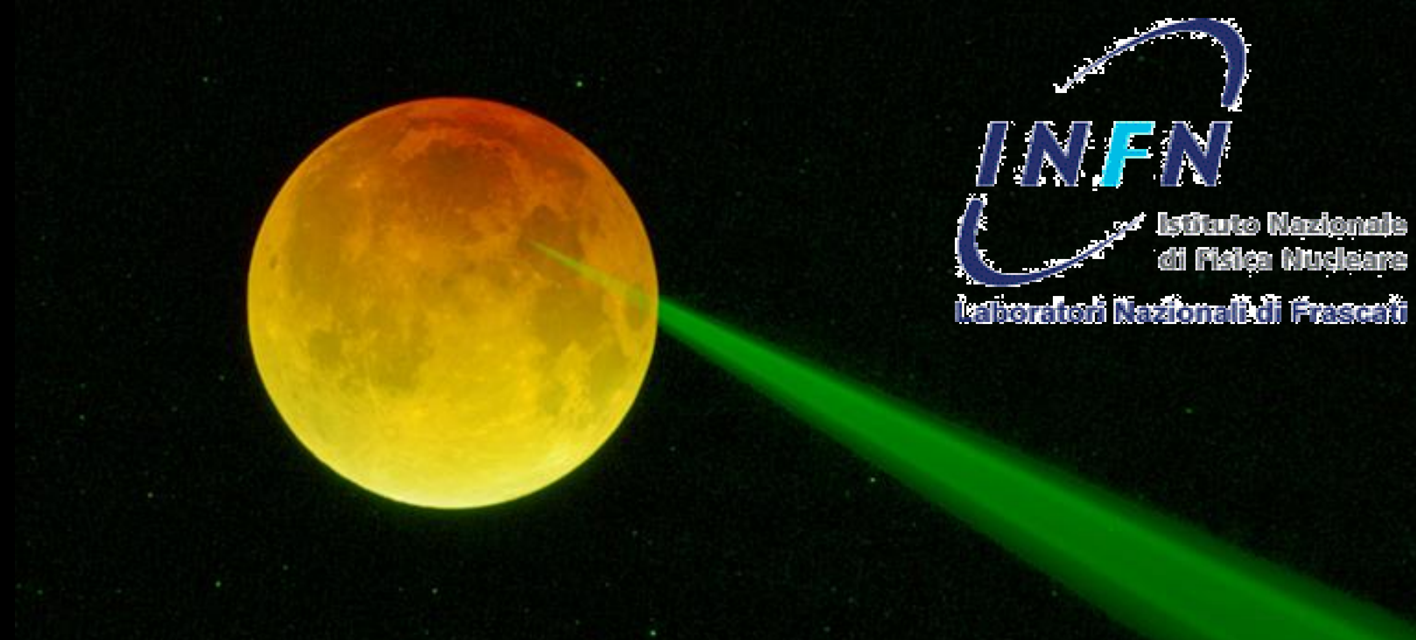
- Operational Procedure
  - Narrow Laser Pulses Transmitted
  - Reflected from Fixed Point on the Moon
  - Light Travel Time is Precisely Measured
  - Make Many Repeated Measurements over years
  - Analyze Time Series of Measurements for Frequencies
- Apollo Range Improvements
  - Kilometers (Radar) to ~300 mm
- Continue for Long Time Series
  - Originally 3 Ranges per Day
- Problem with the Mirrors

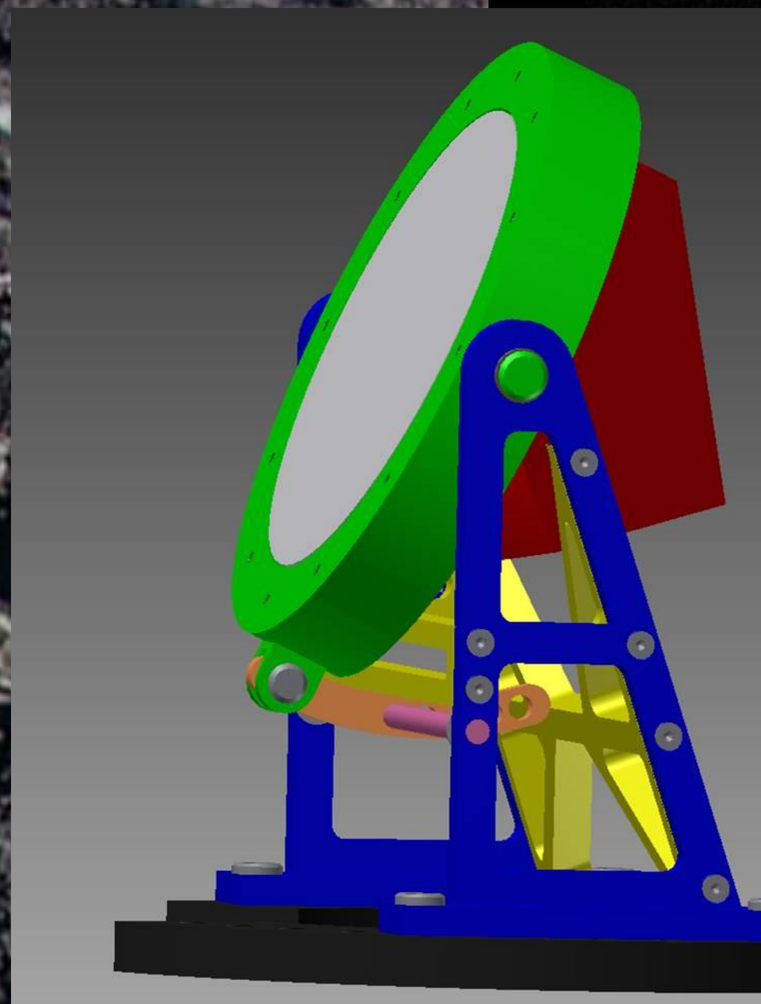


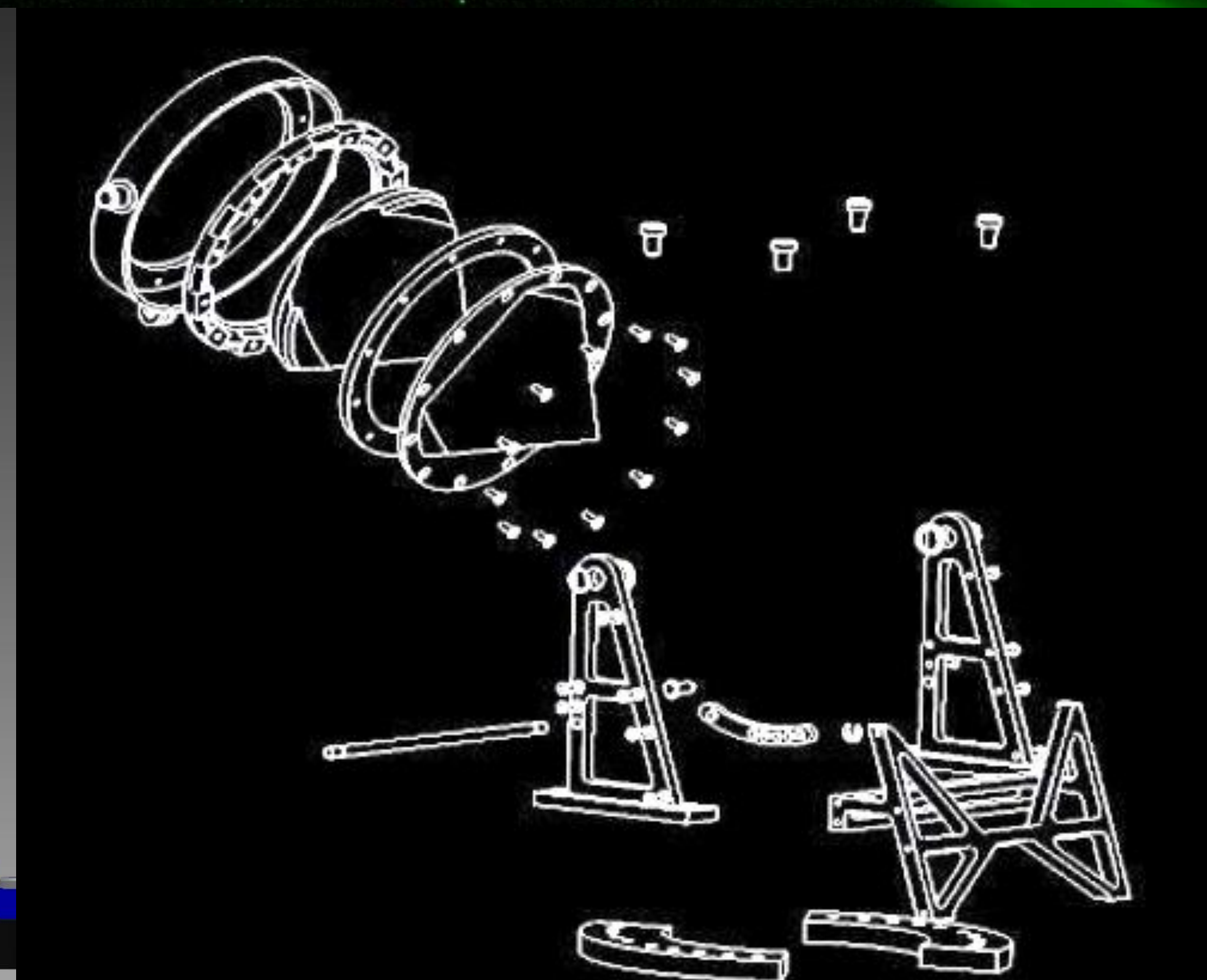
LLR at McDonald Observatory



- McDonald Observatory
  - Mt. Locke, Fort Davis Texas
- Regular Operation
  - Configured for Next Decade
- Other Stations
  - Lick – Initial Acquisition
  - French Côte d' Azur – Long Term
  - Crimea, Soviet Union - Initial
  - APOLLO Tom Murphy Best Current





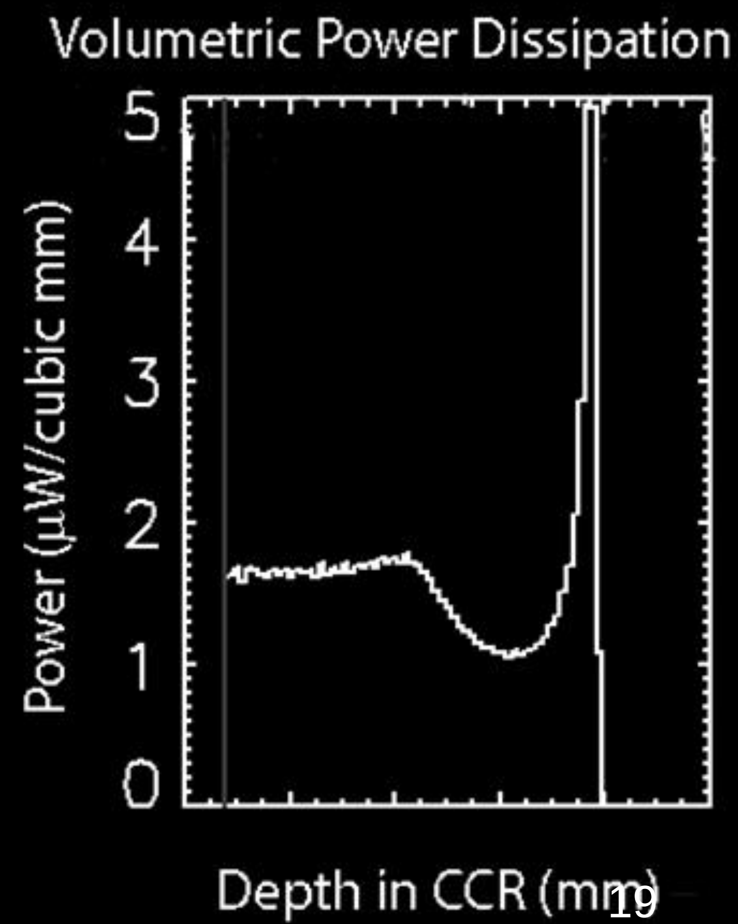


THERMAL CHALLENGES

- Index of Refraction Depends on Temperature
  - That is, the Optical Properties of the CCR Prism
- Degradation of Optical; Properties
  - Light Leaving the CCR is then not “Perfect”
- As a Result, the Return is Spread over Large Area
  - Signal at the Telescope will be Very Small or None
- In the Early Lunar Morning
  - Housing is at 300 K (~Room temperature)
  - CCR is at 70K (~! 200C Below Room Temperature)
  - Gradients in Temperature Must be Less than 0.3K

THERMAL 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
    - Mount Conduction into the Support Tabs



SOOTO Simulation Program

- Solar/Optical/Orbital/Thermal/Optical (SOOTO)
- Two Branches – Design and Operational
- Three Sub-Programs
  - Heatload 3D (HL3D)
    - IDL UMCP INFN-LNF
  - Thermal Desktop
    - C&R Technologies
  - Thermal/Phase/Slice (TPS)
    - IDL UMCP INFN-LNF

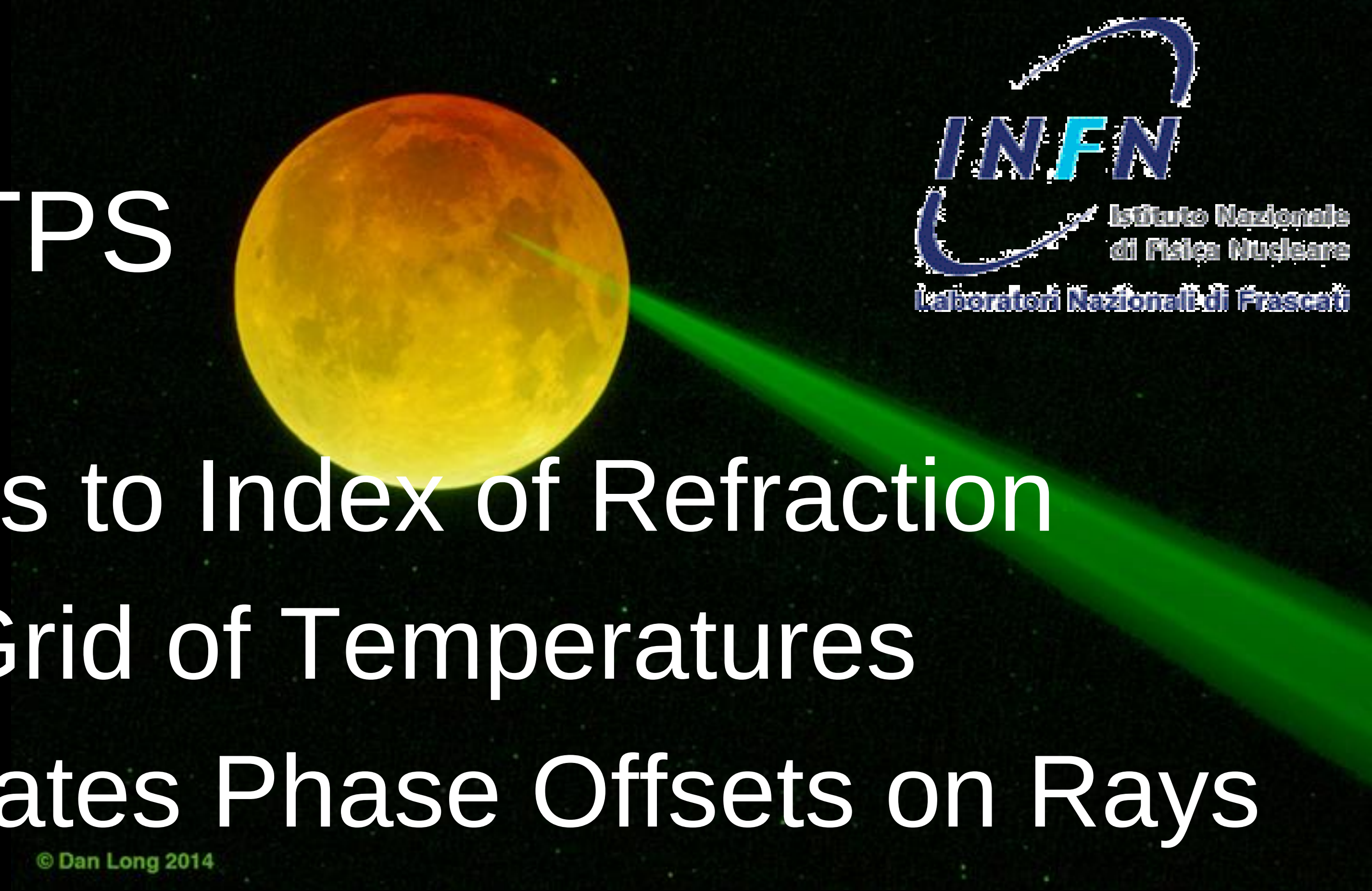
Heat Load 3D

- Effects of Solar Input to CCR
- Changes in Angles over a Lunation
- Different Effects on Different Parts of CCR
- Trace N (typically 1000) Rays through CCR
- Wavelength (Color) Dependent Absorption
  – 1000 Color Bands – 1 Nanometer in Width
- Compute Absorption in Each mm Cube
  – For Each Wavelength Band
- Result – Heat Load in Each Cubic mm

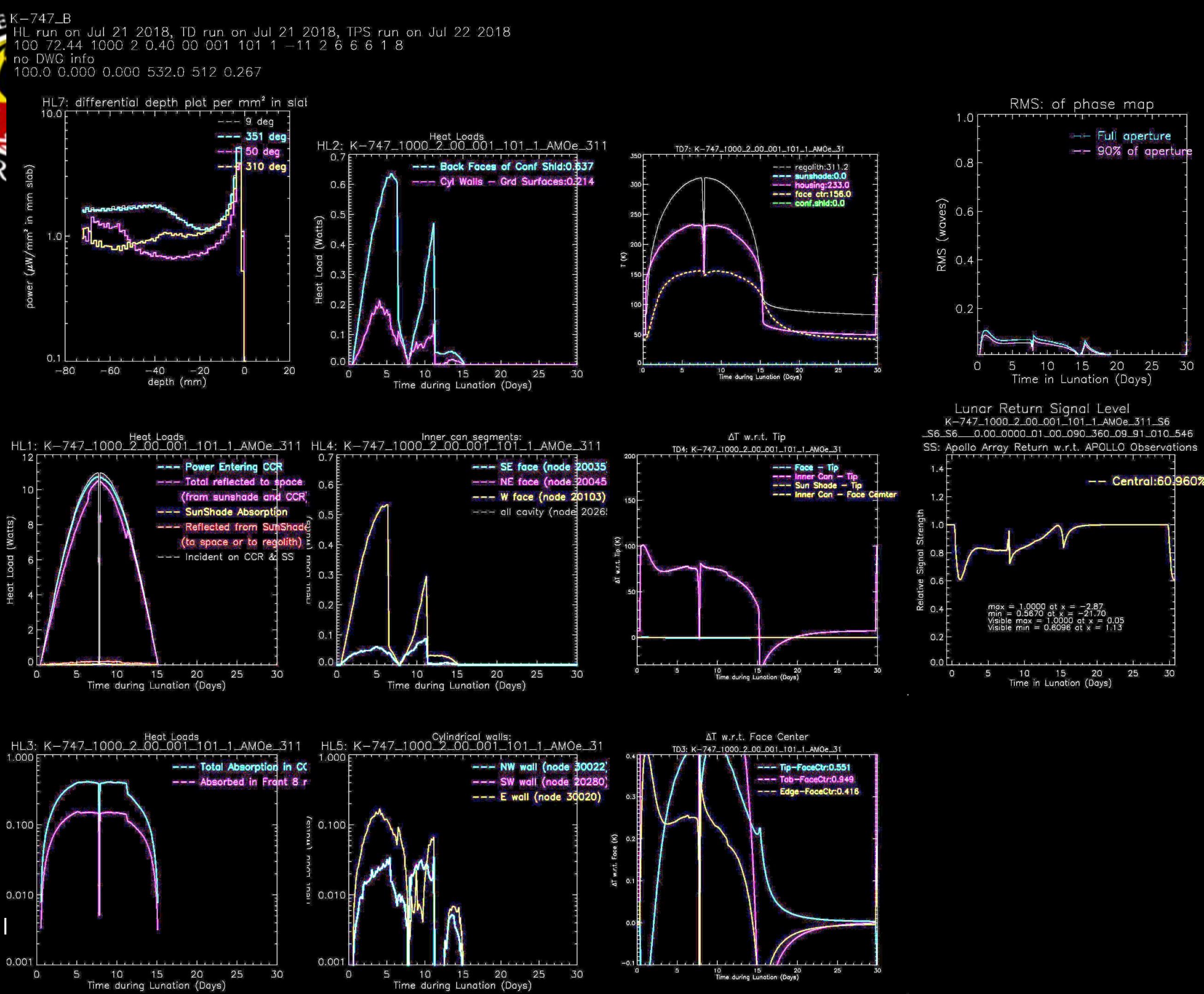
Thermal Desktop

- Provides Changing Illumination in Time
  - – Absorption on Housing
    - Regolith and Instrument Deck Temperatures
- Converts Energy Inputs to Temperatures in CCR
- Address Radiation between Hosing and CCR
- Addresses Radiation Exchanges
  - – between Housing and Regolith and Instrument Deck
- Addresses internal Conduction in Housing

TPS



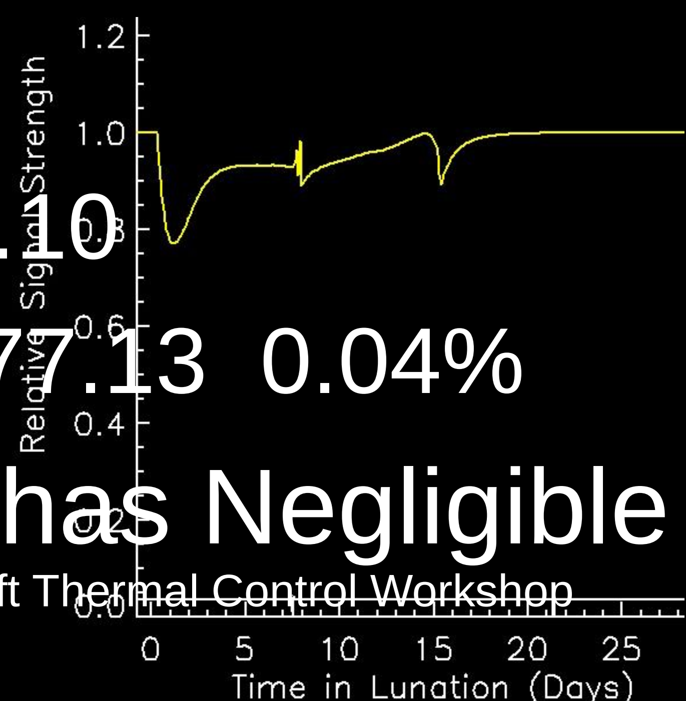
- Converts Temperatures to Index of Refraction
- Traces Rays thru 3D Grid of Temperatures
- Determines and Integrates Phase Offsets on Rays
- Produces an Output Phase Map for Each Time
- In Operational Mode
  - Addresses Phases Shifts due to TIR
  - Phase Shifts due to Back Angle Offsets
- Provides Signal Returns with Velocity Aberration

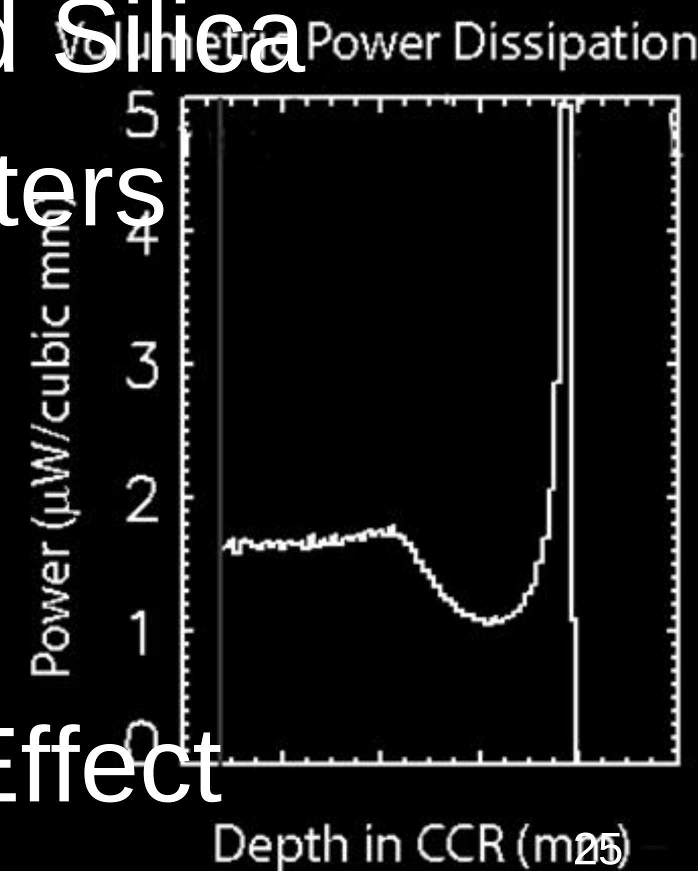


K-747_B
HL run on Jul 21 2018, TD run on Jul 21 2018, TPS run on Jul 22 2018
100 72.44 1000 2 0.40 00 001 101 1 -11 2 6 6 6 1 8
no DWG info
100.0 0.000 0.000 532.0 512 0.267
HL7: differential depth plot per mm² in slab
9 deg
351 deg
50 deg
310 deg
power (μW/mm² in mm slab)
depth (mm)
Heat Loads
HL2: K-747_1000_2_00_001_101_1_AMOe_311
Back Faces of Conf Shld:0.637
Cyl Walls - Grd Surfaces:0.214
Heat Load (Watts)
Time during Lunation (Days)
TD7: K-747_1000_2_00_001_101_1_AMOe_31
regolith:311.2
sunshade:0.0
housing:233.0
face ctr:156.0
conf.shld:0.0
T (K)
Time during Lunation (Days)
RMS: of phase map
Full aperture
90% of aperture
RMS (waves)
Time in Lunation (Days)
Heat Loads
HL1: K-747_1000_2_00_001_101_1_AMOe_311
Power Entering CCR
Total reflected to space
(from sunshade and CCR)
SunShade Absorption
Reflected from SunShade
(to space or to regolith)
Incident on CCR & SS
Heat Load (Watts)
Time during Lunation (Days)
Inner can segments:
HL4: K-747_1000_2_00_001_101_1_AMOe_311
SE face (node 20035)
NE face (node 20045)
W face (node 20103)
all cavity (node 2026
Heat Load (Watts)
Time during Lunation (Days)
ΔT w.r.t. Tip
TD4: K-747_1000_2_00_001_101_1_AMOe_31
Face - Tip
Inner Can - Tip
Sun Shade - Tip
Inner Can - Face Center
ΔT w.r.t. Tip (K)
Time during Lunation (Days)
Lunar Return Signal Level
K-747_1000_2_00_001_101_1_AMOe_311_S6
_S6_S6___0.00_0000_01_00_090_360_09_91_010_546
SS: Apollo Array Return w.r.t. APOLLO Observations
Central:60.960%
Relative Signal Strength
max = 1.0000 at x = -2.87
min = 0.5670 at x = -21.70
Visible max = 1.0000 at x = 0.05
Visible min = 0.6096 at x = 1.13
Time in Lunation (Days)
Heat Loads
HL3: K-747_1000_2_00_001_101_1_AMOe_311
Total Absorption in CC
Absorbed in Front 8 r
Time during Lunation (Days)
Cylindrical walls:
HL5: K-747_1000_2_00_001_101_1_AMOe_31
NW wall (node 30022)
SW wall (node 20280)
E wall (node 30020)
Heat Load (Watts)
Time during Lunation (Days)
ΔT w.r.t. Face Center
TD3: K-747_1000_2_00_001_101_1_AMOe_31
Tip-FaceCtr:0.551
Tab-FaceCtr:0.949
Edge-FaceCtr:0.416
ΔT w.r.t. Face (K)
Time during Lunation (Days)

Volumetric Absorption in CCR

- Historically Believed to be the Worst Problem
- Wavelength Dependent
- Geometrically Complicated
- Need Absorption Info on 311 Fused Silica
- Run SOOTO with Nominal Parameters
- Max Loss at Dawn
  - Signal Return of 77.10
  - For No Absorption 77.13 0.04%
- Absorption in CCR has Negligible Effect





Housing Radiation to CCR

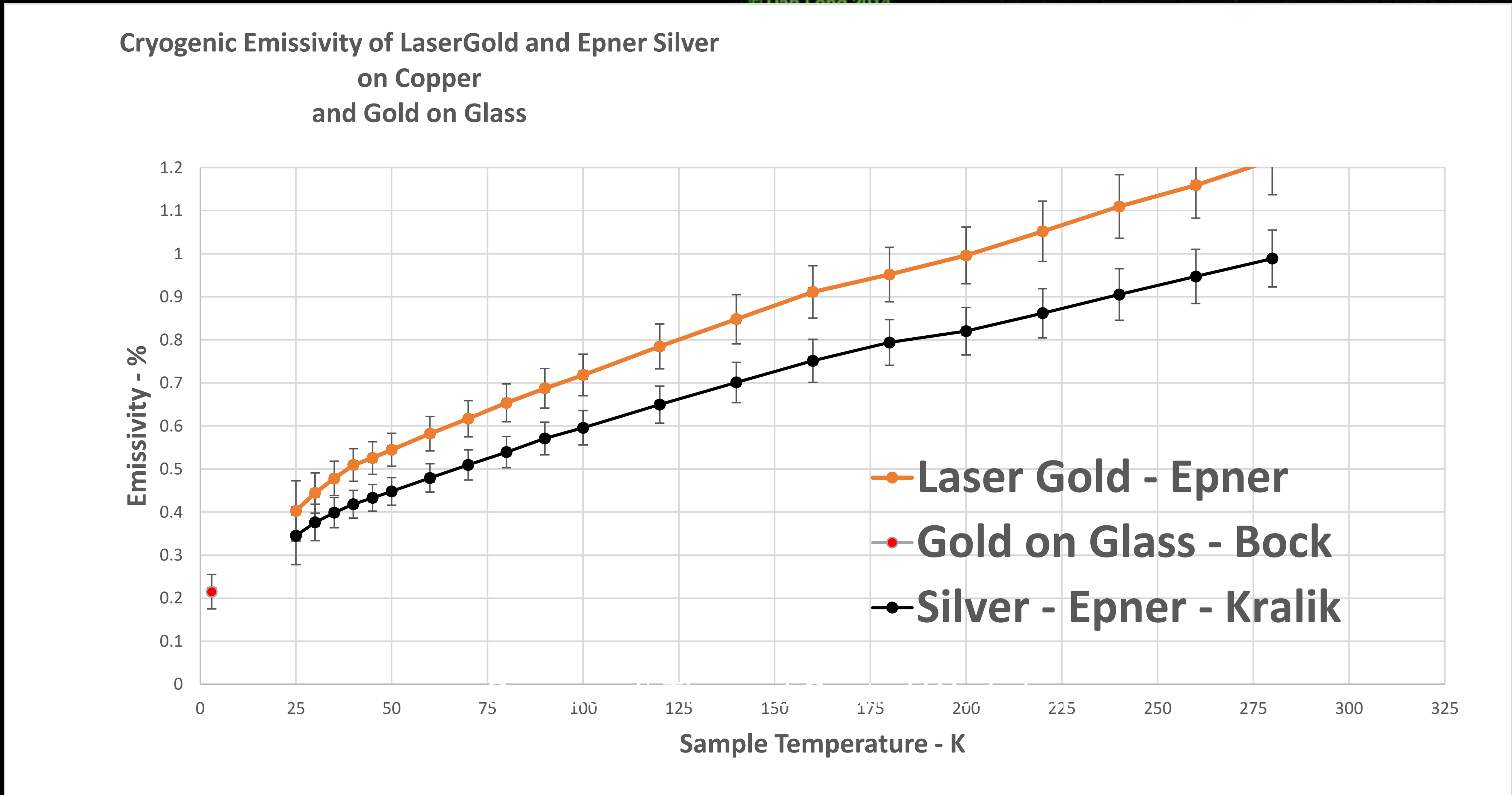
- Internal Radiation from Housing to Back of CCR
- Apollo Approach would have Totally Lost Signal
- Radiation from Internal Housing of Aluminum
- Gold has Low Emissivity - ~2% in Literature
- Cryogenic Electrical Behavior Implies Better
- Investigated “Laser Gold” by Epner Technology
- Still Only Measured Values of 2%

Need Low Emissivity Coating

- Needed Measurements of Cryogenic Emissivity
- High Purity but Knoop Hardness of 160
  - Compactness Might Increase Electrical Resistance
  - Therefore Increase Emissivity
- Tomáš Králík of Czech Technical University
  - Prague, The Czech Republic
- Sent Him Samples of Laser Gold and Silver
  - To Measure Cryogenic Emissivity

Need Low Emissivity Coating

- Needed Measurements of Cryogenic Emissivity
- High Purity but Problem - Knoop Hardness of 160
- Tomáš Králík of Czech Technical University

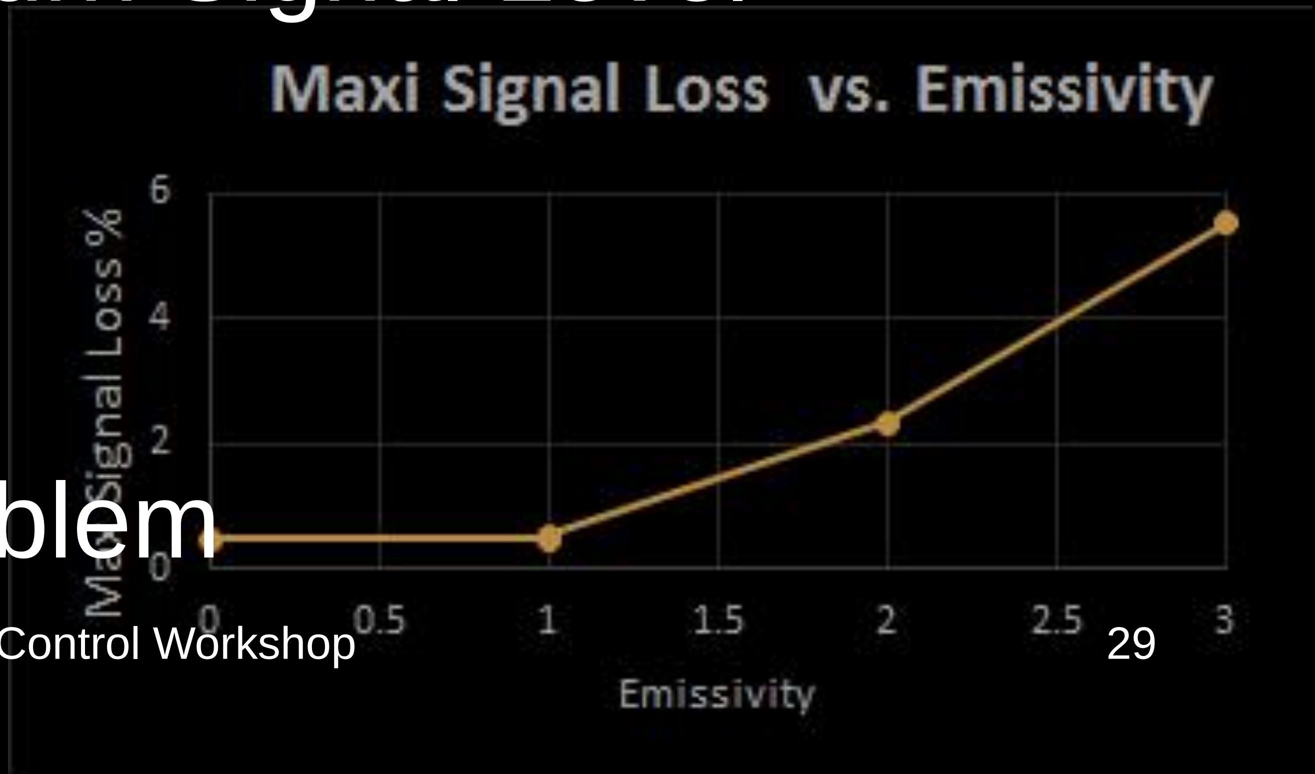


Does Use of Gold Work

- Is This Sufficient to Provide Acceptable Signal
- Again, “Nominal” Parameters
  - Except No Conductivity via Tabs (Pure RCH Emis.)

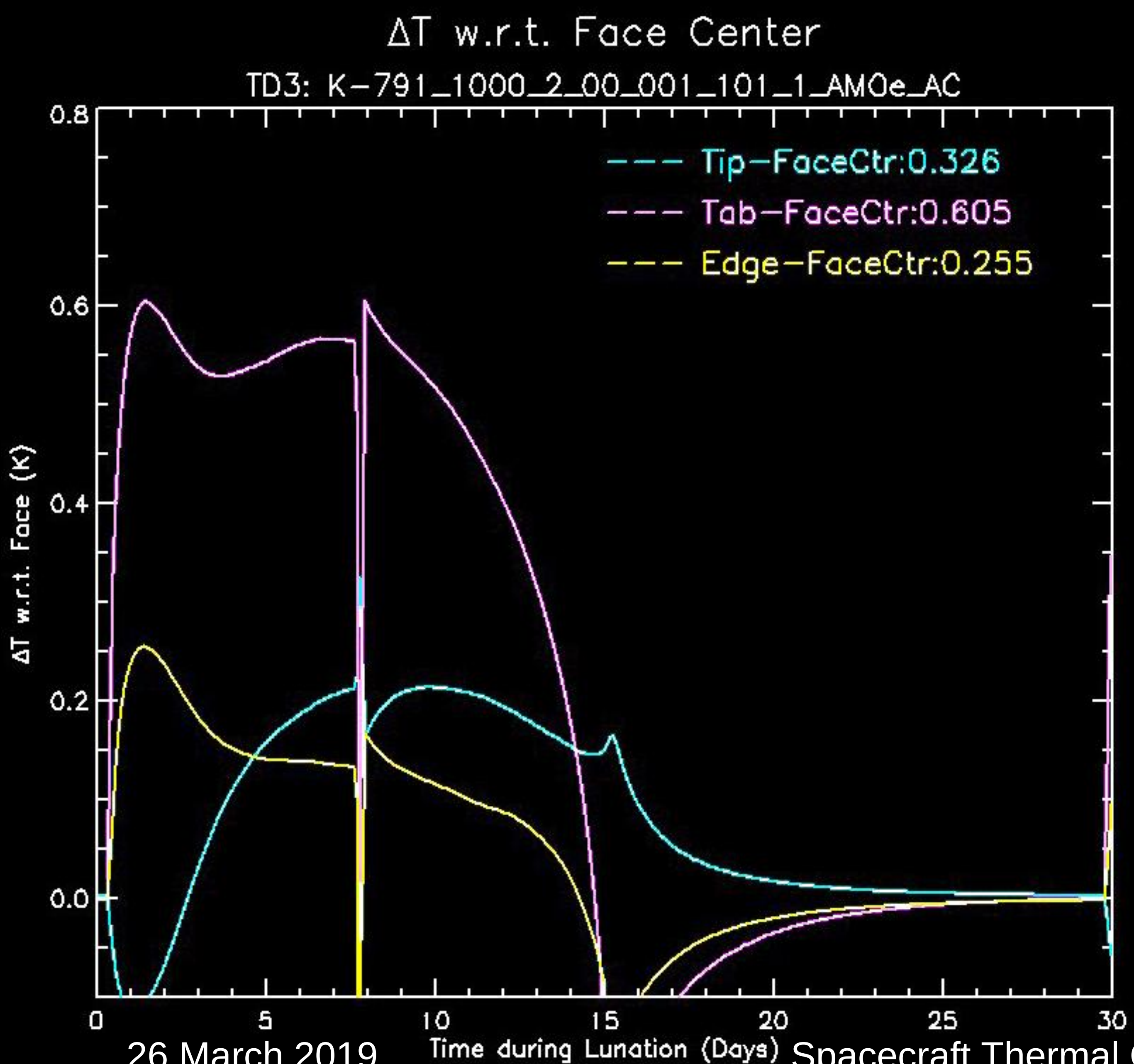
© Dan Long 2014

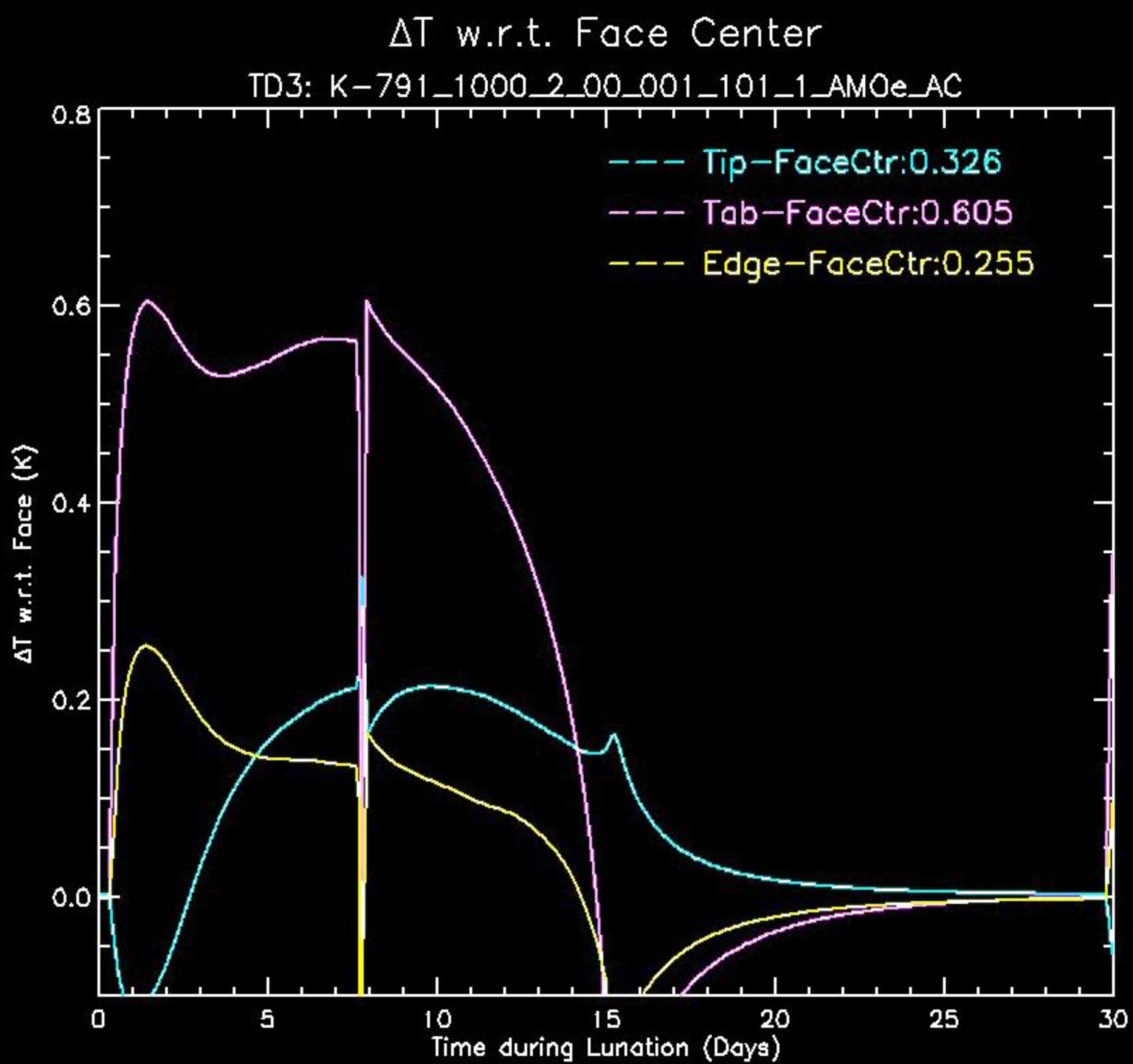
- Focus on Dependence on Low Emissivity
- Percentage Loss of Return Signal Level
  - Aluminum 82%
  - 2% Gold 2.34%
  - Measured Gold <0.47%
- Gold Eliminates the Problem

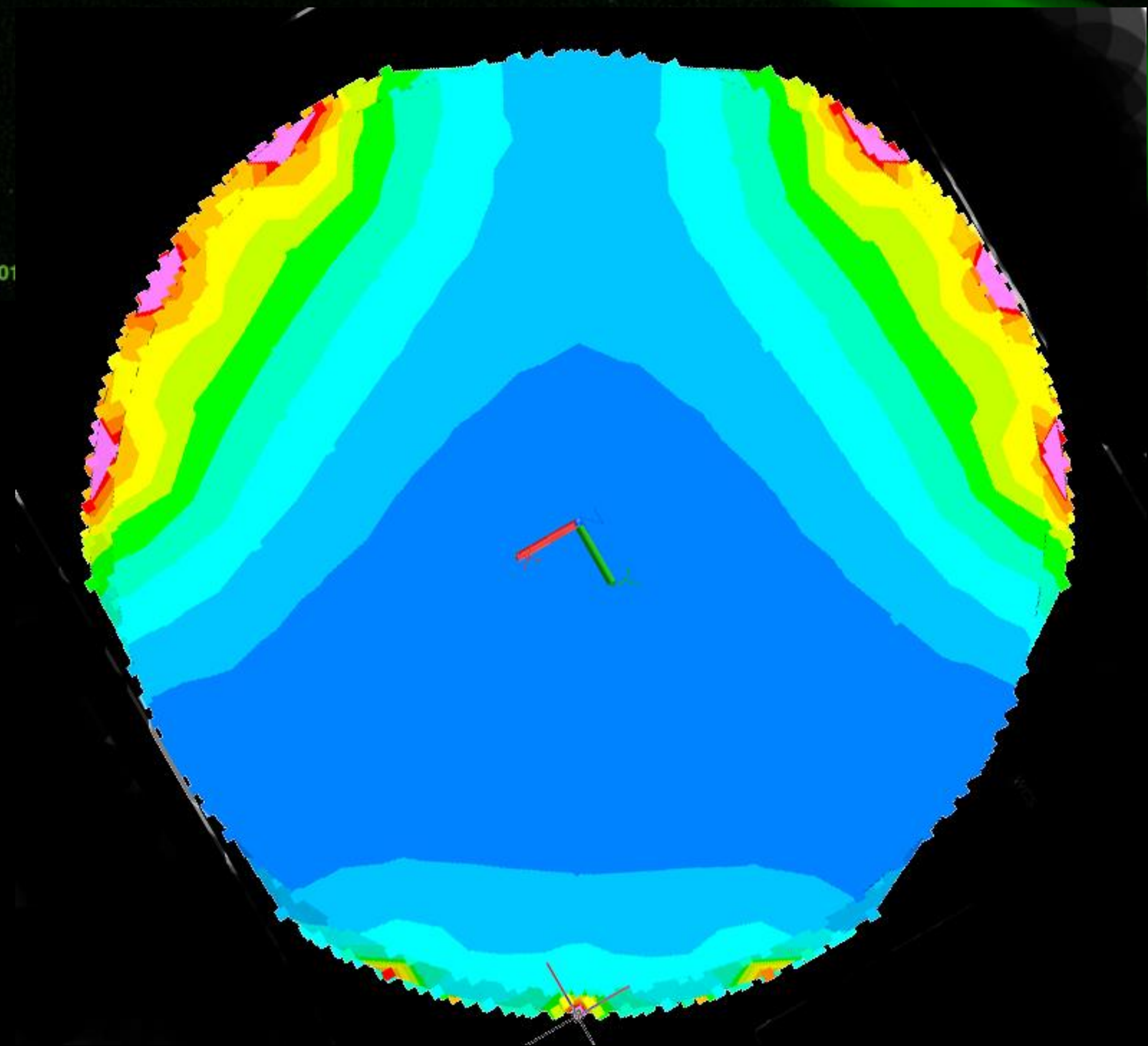


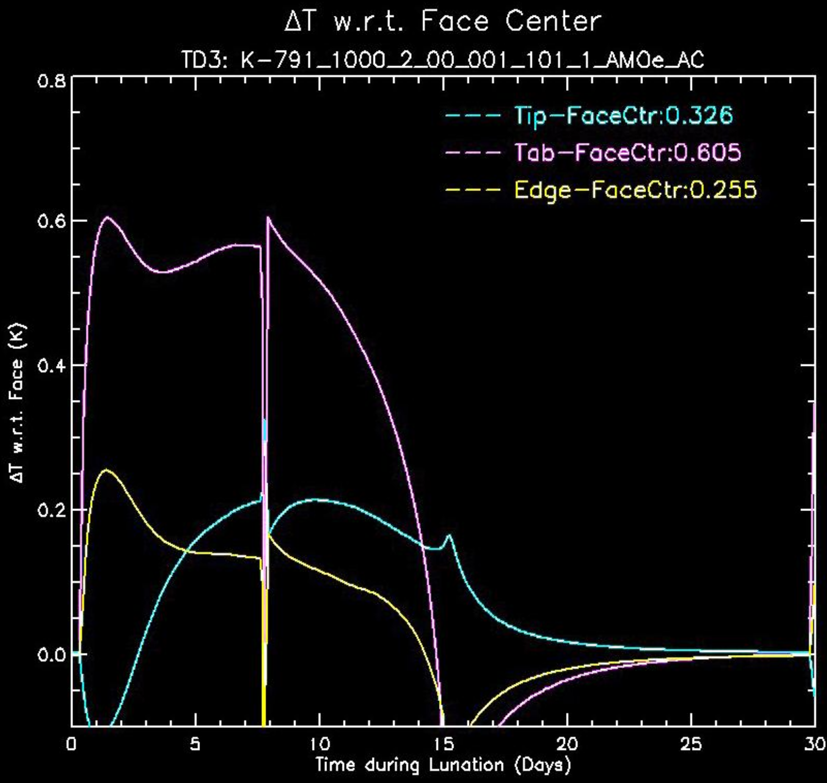
Mount Conductance

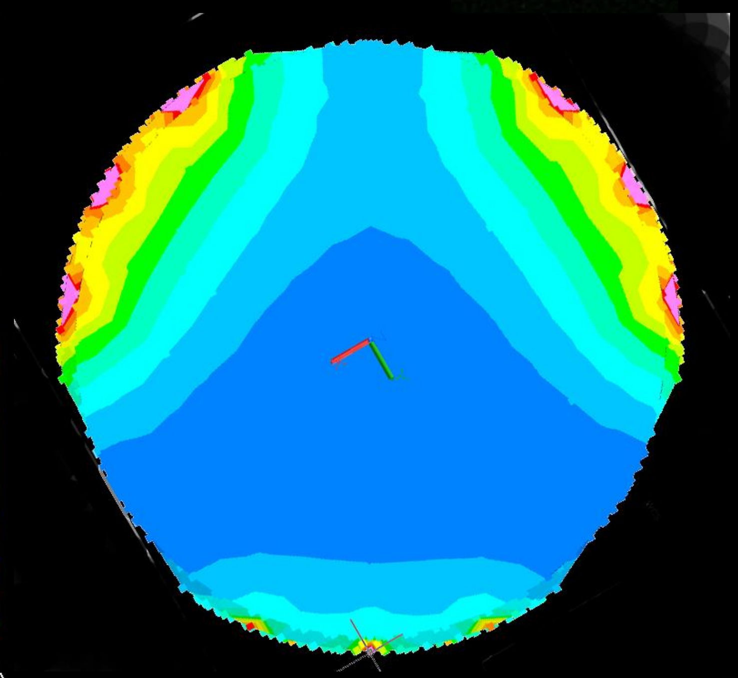
- Having Defeated the “Folk Lore” Problems
  - Arrive at the Real Problem
- CCR Does Not Float in Suspension
- Our (Very Successful) Apollo Design
  - KEL-F Rings Against Tabs
  - Support During Launch Environment
- For Our Next Generation Lunar RR
- Added 2 mm “Wires” Between Tab & KEL-F
  - For Very Low Contact Area

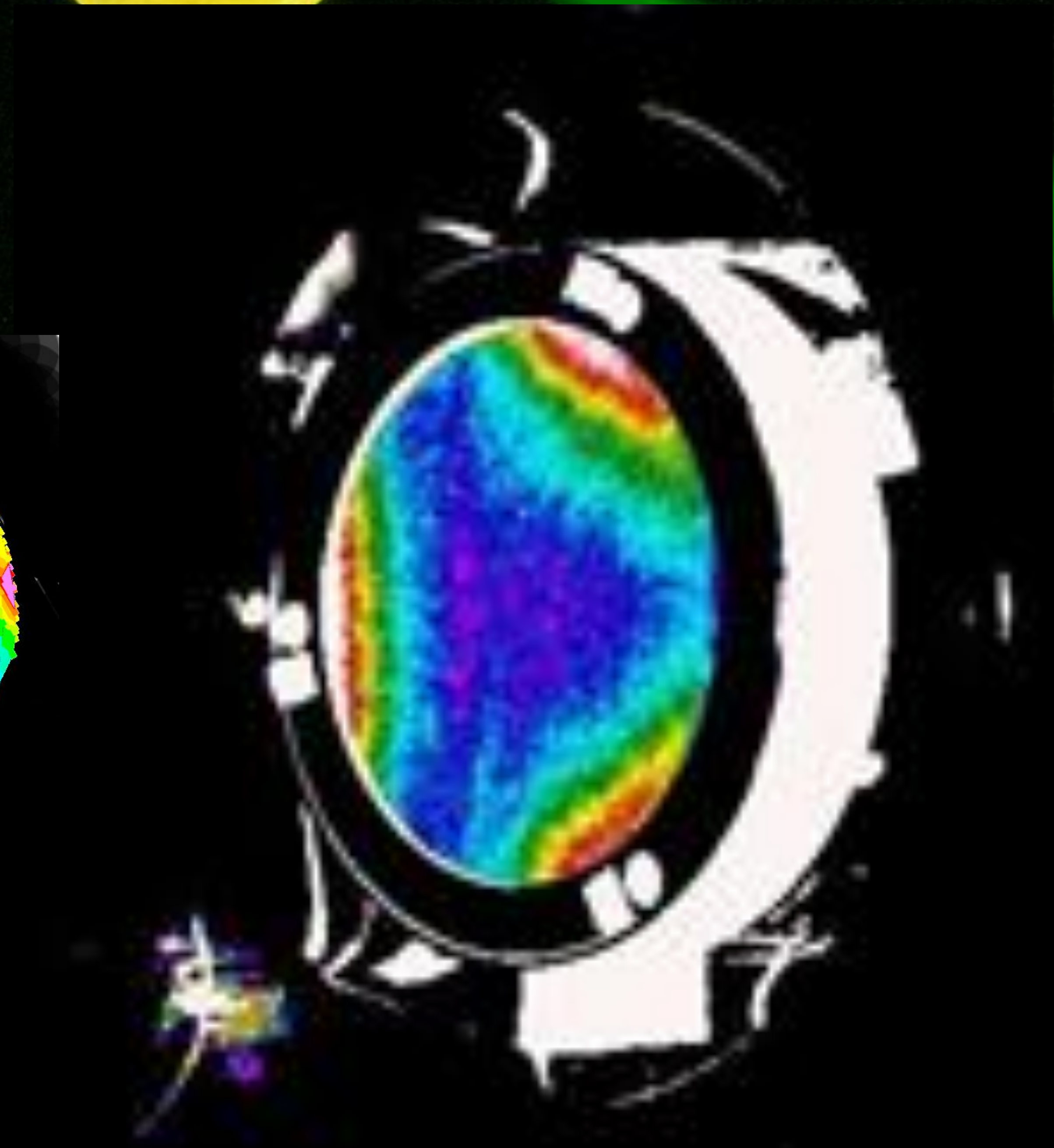

ΔT w.r.t. Face Center
TD3: K-791_1000_2_00_001_101_1_AMOe_AC
Tip-FaceCtr:0.326
Tab-FaceCtr:0.605
Edge-FaceCtr:0.255
ΔT w.r.t. Face (K)
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
Time during Lunation (Days)


ΔT w.r.t. Face Center
TD3: K-791_1000_2_00_001_101_1_AMOe_AC
Tip−FaceCtr:0.326
Tab−FaceCtr:0.605
Edge−FaceCtr:0.255
ΔT w.r.t. Face (K)
Time during Lunation (Days)
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30




ΔT w.r.t. Face Center
TD3: K-791_1000_2_00_001_101_1_AM0e_AC
Tip-FaceCtr:0.326
Tab-FaceCtr:0.605
Edge-FaceCtr:0.255
ΔT w.r.t. Face (K)
Time during Lunation (Days)





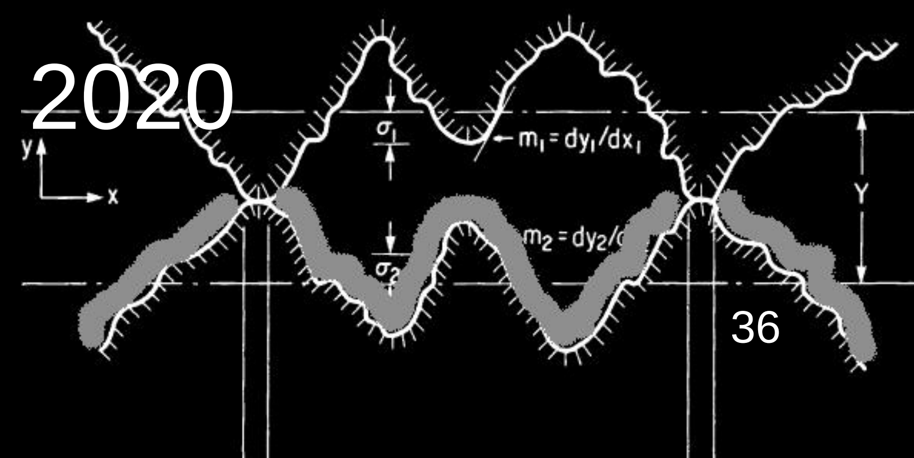
- So we see that the dominant challenge
  - Conduction in the Tab/KEL-F Supports
  - Between the CCR and the Housing
  - Assuming Low Emissivity Gold
  - Assuming Literature Values for Absorption of SiO_2
- Assumes Our Calculation of Conduction
  - And Our Wire Configuration for Supports
- Implies Loss of ~20% at Lunar Dawn
- Problem with the Launch Environment

- Addressing the Launch Environment Challenge
- Conduction is Roughly Independent of Area
  - – Assuming the Same Weight
- Therefore Could Remove Wires and
  - – Rest the CCR Tab on the KEL-F Ring
- Calculation of This is Significantly Different
  - – From Our Calculation of the Wire Conduction

© Dan Long 2014

Future Plans

- Further Validation of SOOTO Simulation Program
- Address Conduction for Greater Contact Area
  - Weak dependence of Conductivity on Area of Contact
    - Analytic Investigation
    - T/V Tests to Evaluate Effect
    - Investigate Stainless Steel Ring with Thin Gold Coating
- Proposal to NASA for 3 NGLR Submitted
- Flight to Moon on Lander of Commercial Carrier
  - Program to Deliver to CC by March 2020



- Thanks
- Any Questions
- or Comments