PRECISION TESTS OF GENERAL RELATIVITY AND GRAVITATION by LUNAR LASER RANGING

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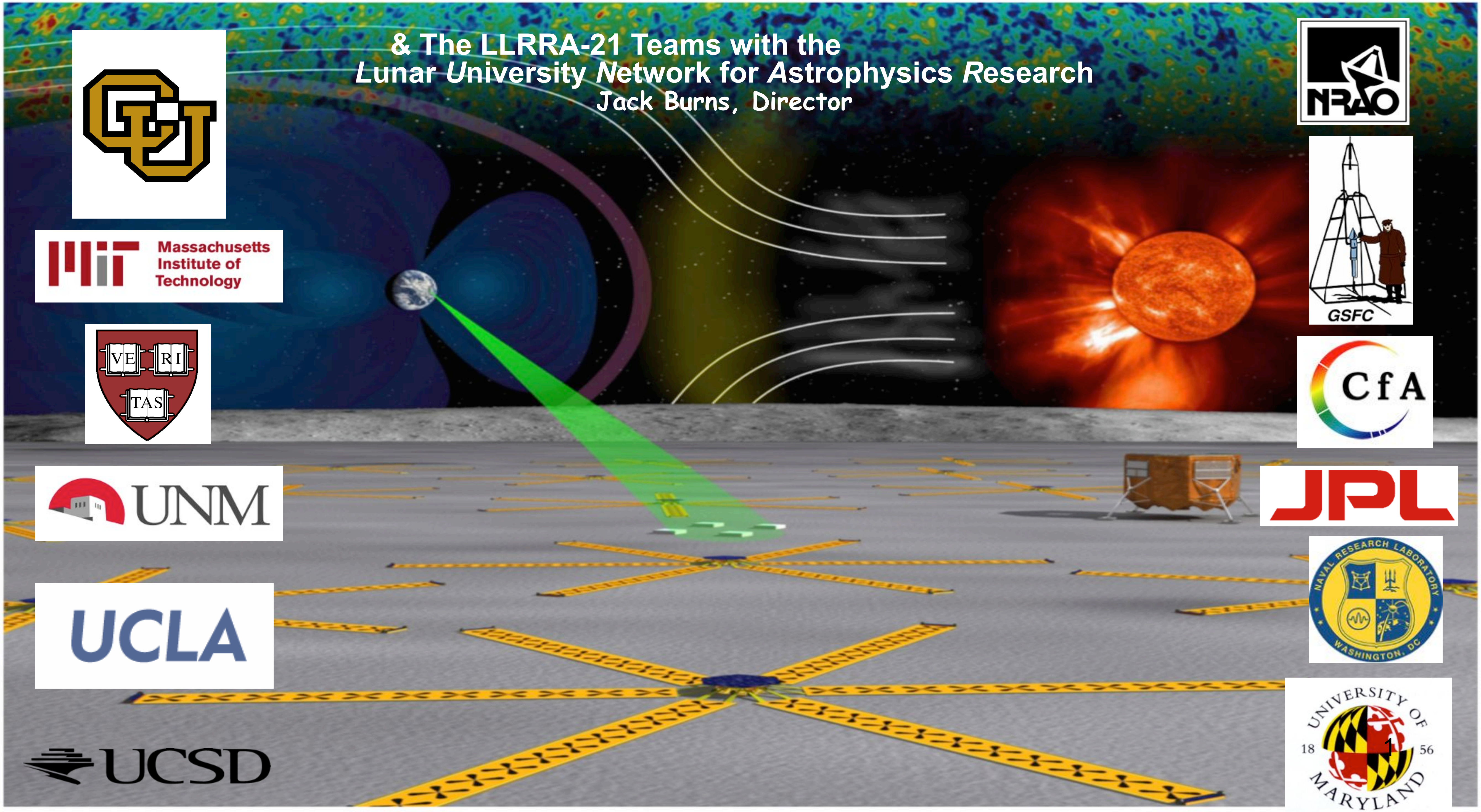
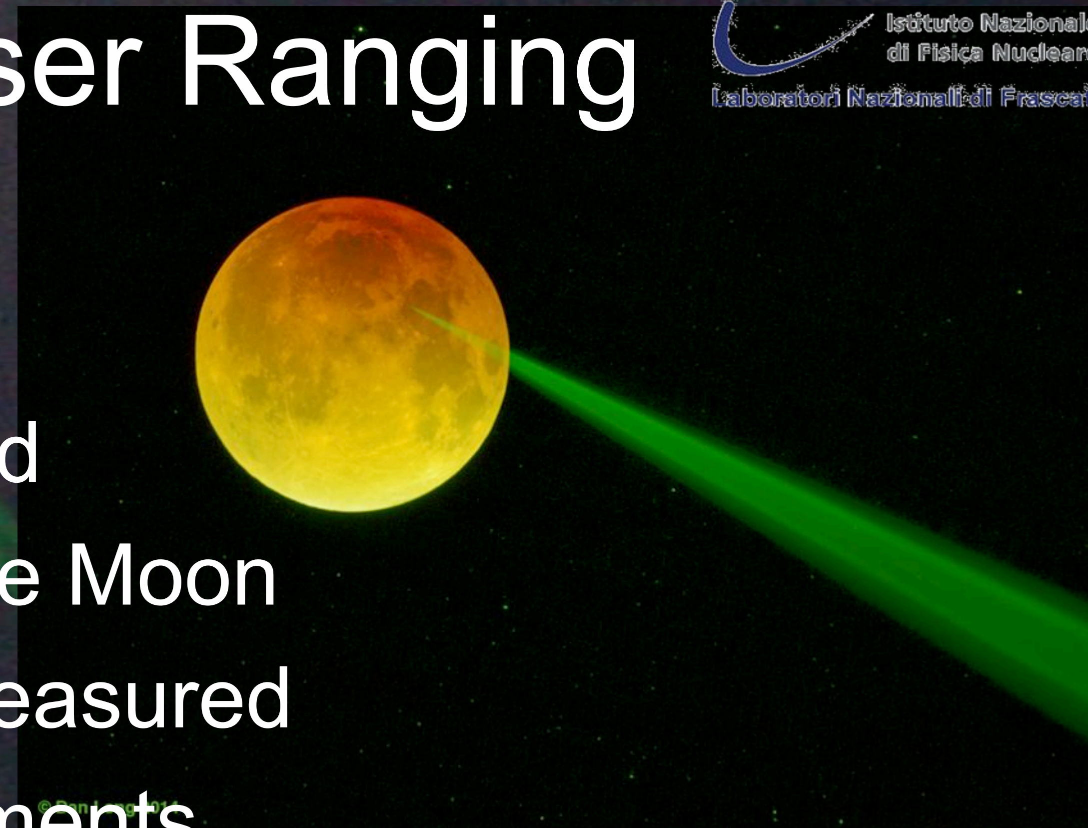


& The LLRRA-21 Teams with the
***L**unar **U**niversity **N**etwork for **A**strophysics **R**esearch*
Jack Burns, Director

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
    - 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!!!

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
  - 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

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**
  - **Geodetic Precession**
  - **The Weak Equivalence Principle (WEP)**
  - **Gravitomagnetism**

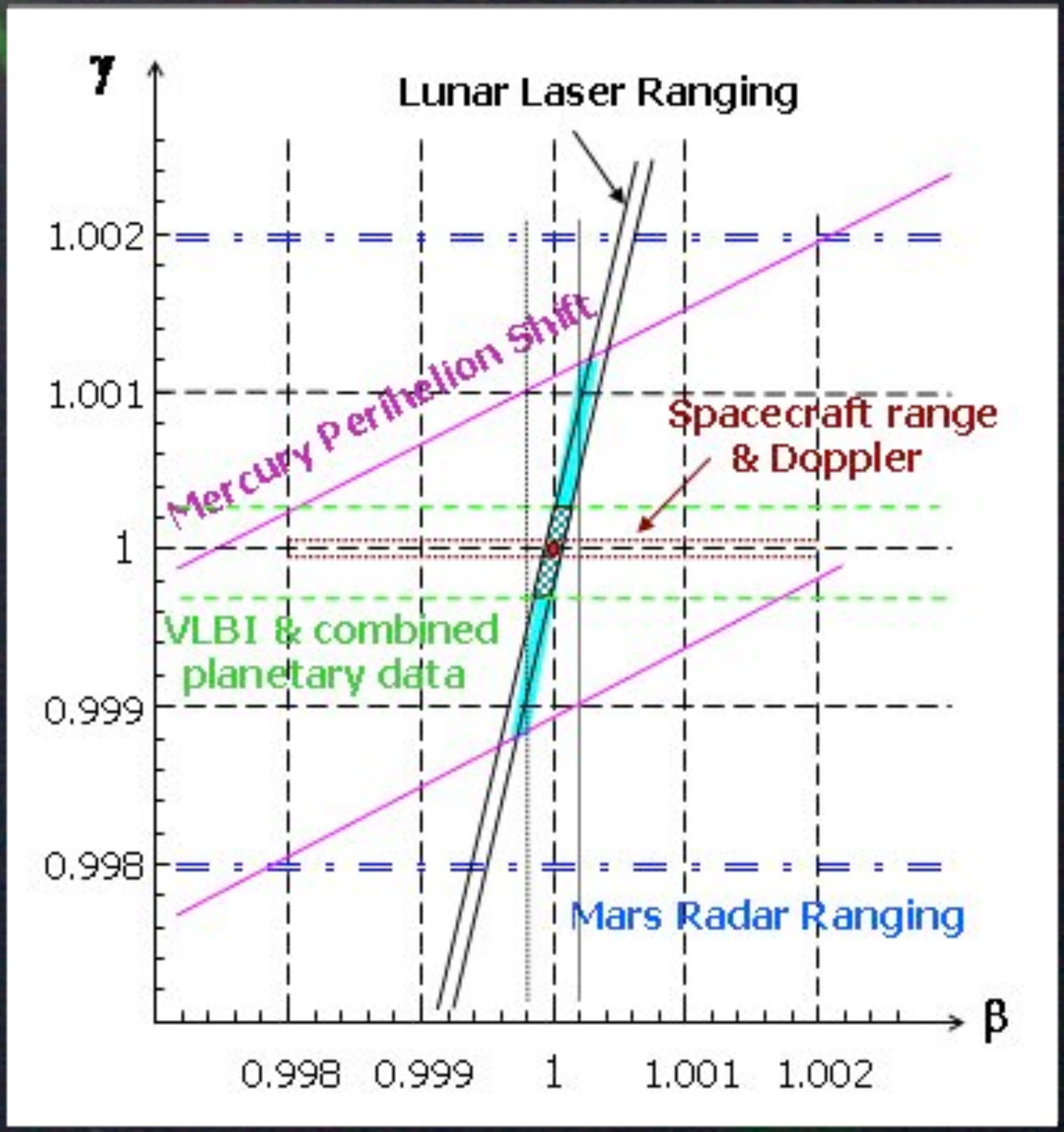
LLR GR RESULTS TO DATE

Equivalence principle parameter	η	(6 ± 7) . 10−4
Metric parameter	$\gamma - 1$	(4 ± 5) . 10−3
Metric parameter	$\beta - 1$: 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

JOINT PARAMETER ANALYSIS

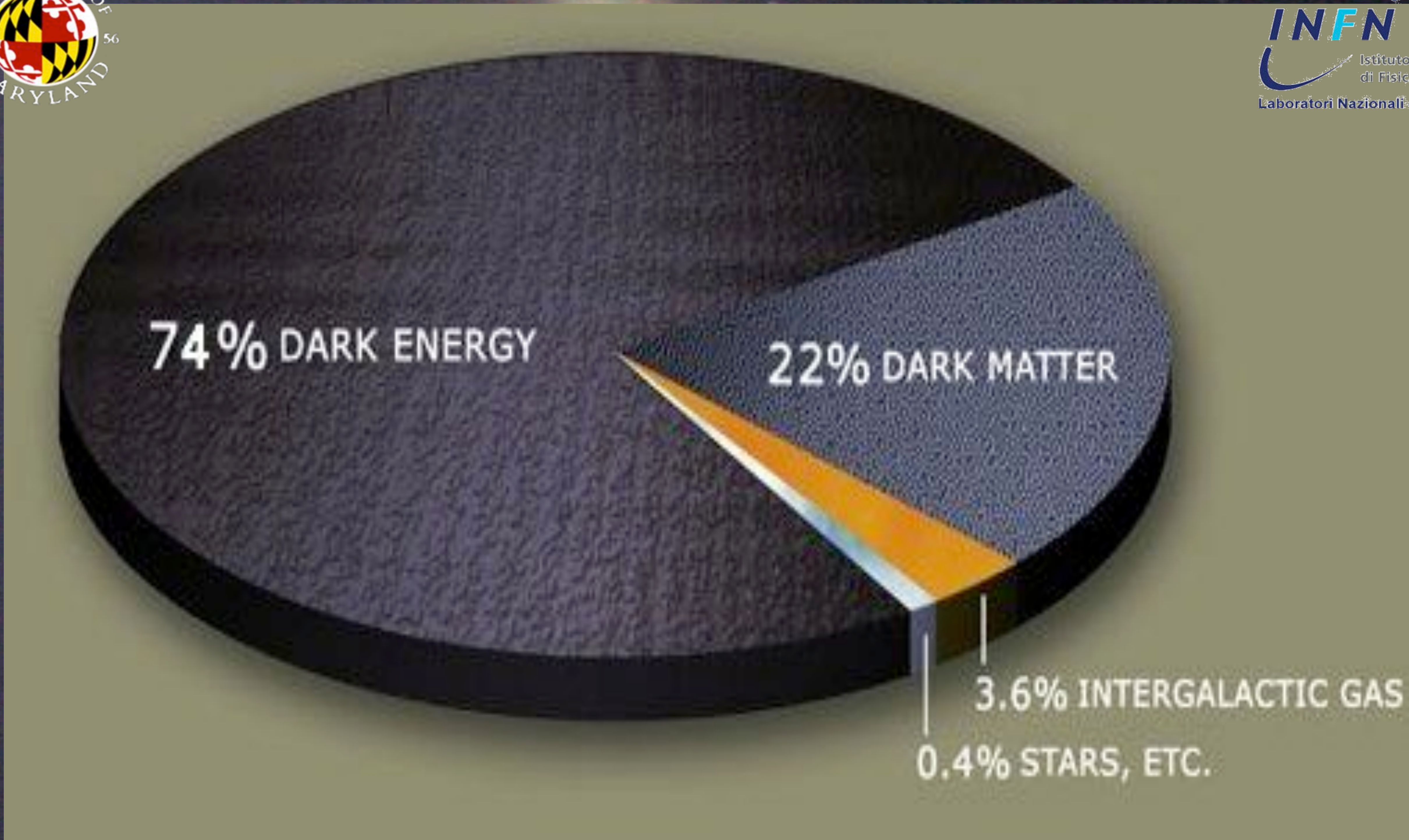
- The Post-Newtonian Parameterization (PPN) describes deviations from GR
- The main parameters are γ and β
  - γ tells us how much spacetime curvature is produced per unit mass
  - β tells us how nonlinear gravity is (self-interaction)
  - γ and β are identically 1.00 in GR
- Current limits have:
  - $(\gamma - 1) < 2.5\times10^{-5}$ (Cassini)
  - $(\beta - 1) < 1.1\times10^{-4}$ (LLR)



Tom Murphy

CURRENT ISSUES

- Open Questions in Cosmology and Fundamental Physics
  - Nature of Dark Matter
    - Gravitational Observations 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
    - Einstein' Lambda Constant
    - Quintessence
  - Relation between GR and Quantum Mechanics
    - Attempts toward the Quantization of Gravity
    - String Theory implies Variation of Fundamental Constants



and the problem with

General Relativity vs. Quantum Mechanics

PURPOSE of LLR

- Many Theories Proposed to Address Current Issues
  - Need to Select Those Consistent with the Real World
  - Requires Pushing Observations to Constrain Theories
- This will Lead Theories with Physical Consistency
- LLR Provides Broadest Range of Measurements
  - Addressing Many Aspects of Gravitation and GR
- Combines with Many Individual Classes of Obs.
  - SpaceCraft Radar, SN, WMAP, Balloon & Local Exper.

Theoretical Landscape of the 20th Century:
Competing Theories of Gravity

- **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 listing ends before Discovery of 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
-
- Slava G. Turyshev

FUTURE OF LLR

- Need to Push Experiments to Greater Accuracy
  - To Vector in on Understanding Current Challenges
- Continue to Use the 3 Apollo Arrays and
  - the two French/Russian Arrays
  - Continued Slow Improvements in Limits
- Next Generation of Accuracy
  - Next Generation of RetroReflectors – LLRRA-21
  - Enhanced Observing Program
  - Upgrade of Analysis and Science Software

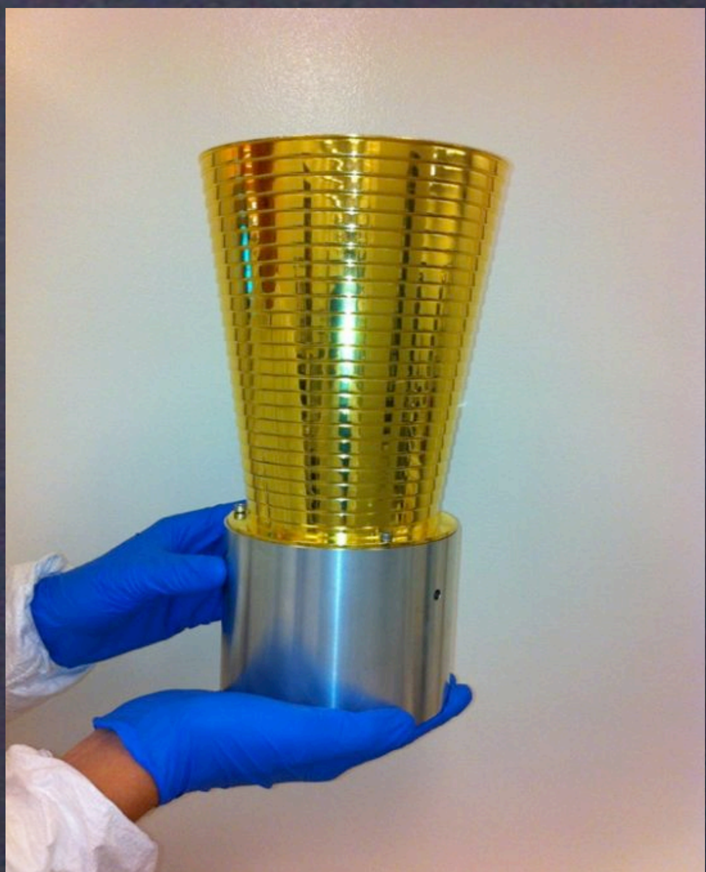
LIBRATION PROBLEM

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

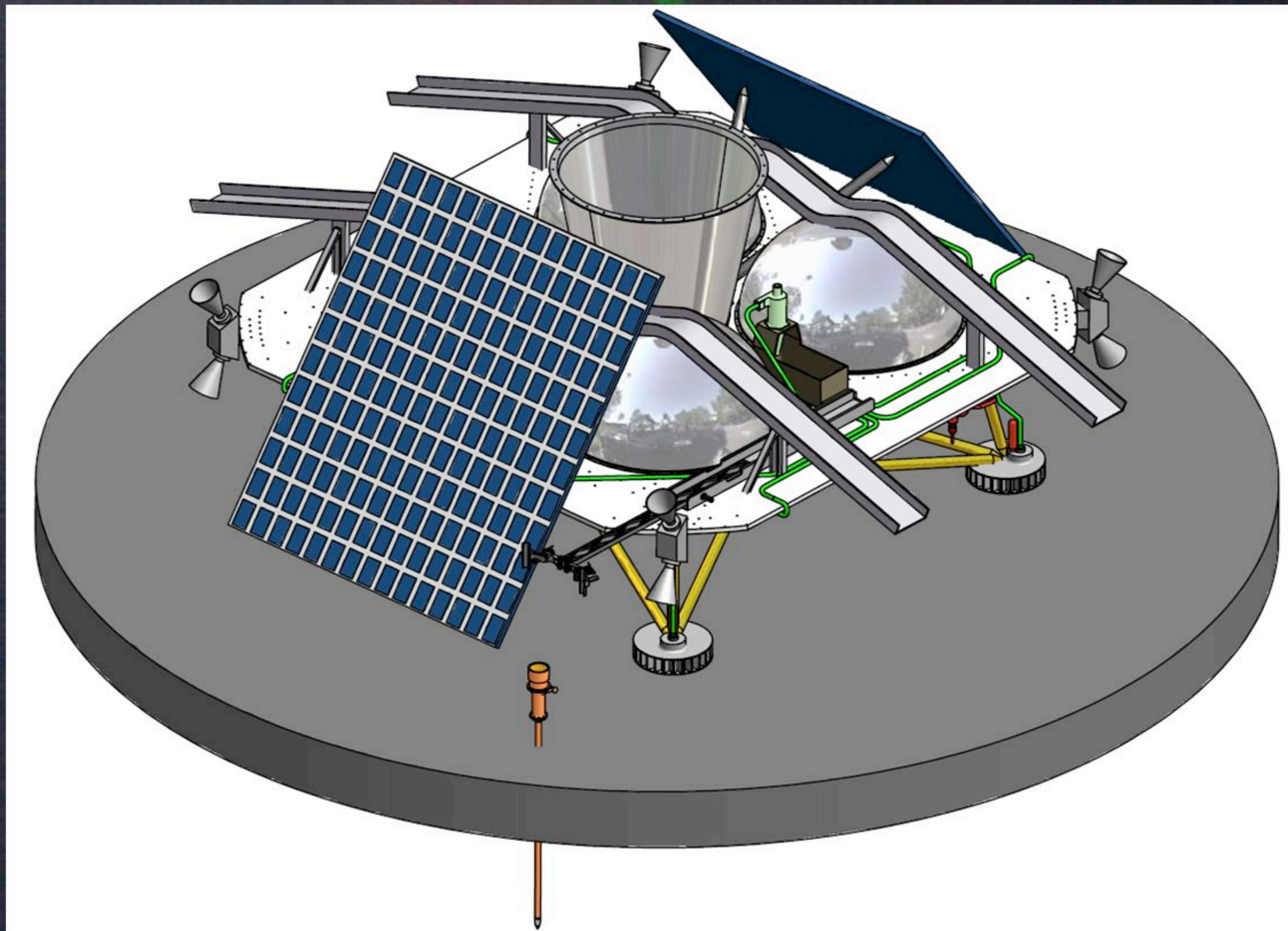
LARGE SOLID CCR CHALLENGES

- CCR Fabrication to New Tight Requirements
  - Demonstrated
- Thermal Distortion of CCR
  - Simulation Program – See ILRS Paper
  - Thermal Vacuum Tests at INFN-LNF
- Stability of Emplacement on Lunar Surface
  - Mounted on Lander - < 2 mm Motion
  - Anchored Deep in Regolith - < 0.1 mm

LLRRA-21 & MoonEx1

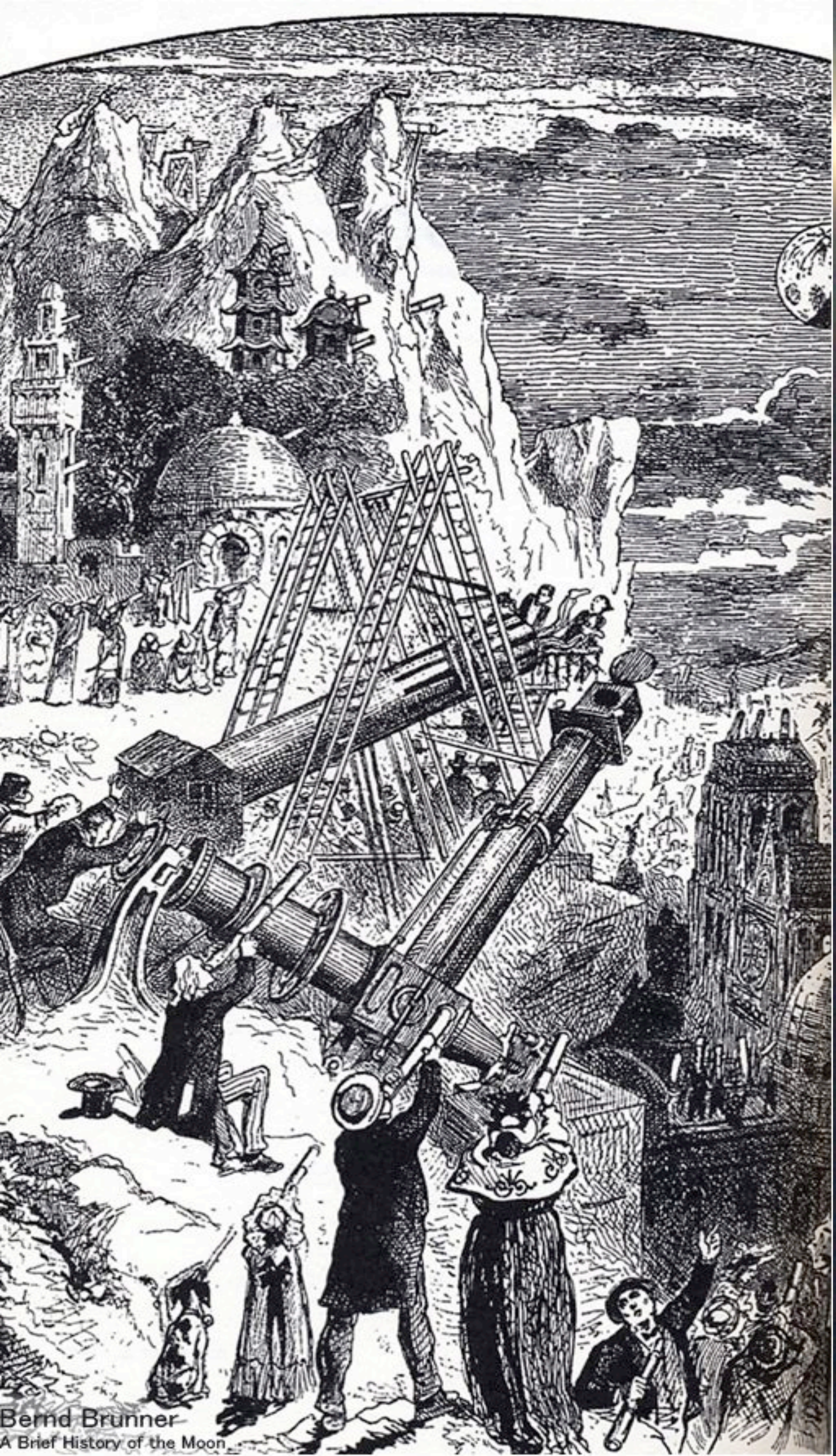


Anchored Deployment Astrobotics & Honeybee



GRAVITATIONAL & GR SCIENCE
Hannover Simulation

- Future LLR Science Parameters in 2030:
  - Each Improved by a factor **XX** over Current
  - **The SEP** 15
  - **Time Change of *G*** 47
  - **Inverse Square Law, Yakawa** 56
  - **Geodetic Precession** 45
  - The Weak Equivalence Principle (WEP)
  - Gravitomagnetism



Thank You!

any

Questions?

or

Comments?

.

with

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Italian Space Agency
INFN-LNF, Frascati
LSSO Team
&
LUNAR Team

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SUNSHADE REQUIREMENTS

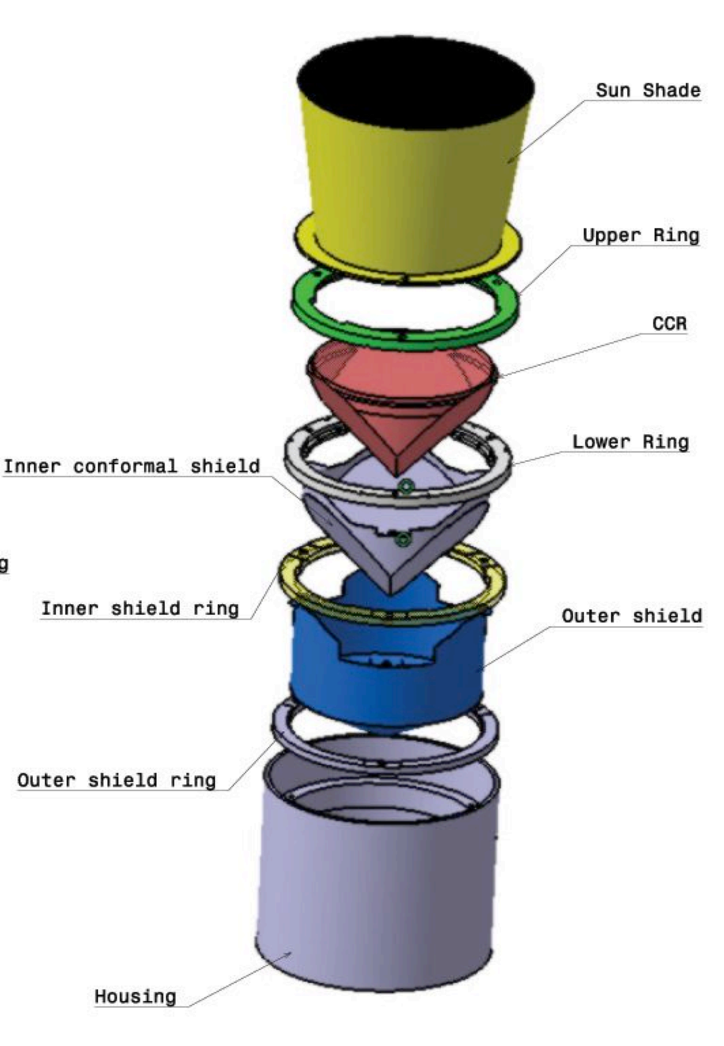
- Philosophically
  - Need Sunshade and Pointing
- Possible Rejection of Rides
  - Need Numerical Evaluation of Loss
- Need Detailed Simulations
  - Muller & Hoffman – IfE – Hannover
  - Chandler – CfA – Cambridge
- New Reflectors, Enhanced Observations
  - 2030, Additional Ground Stations

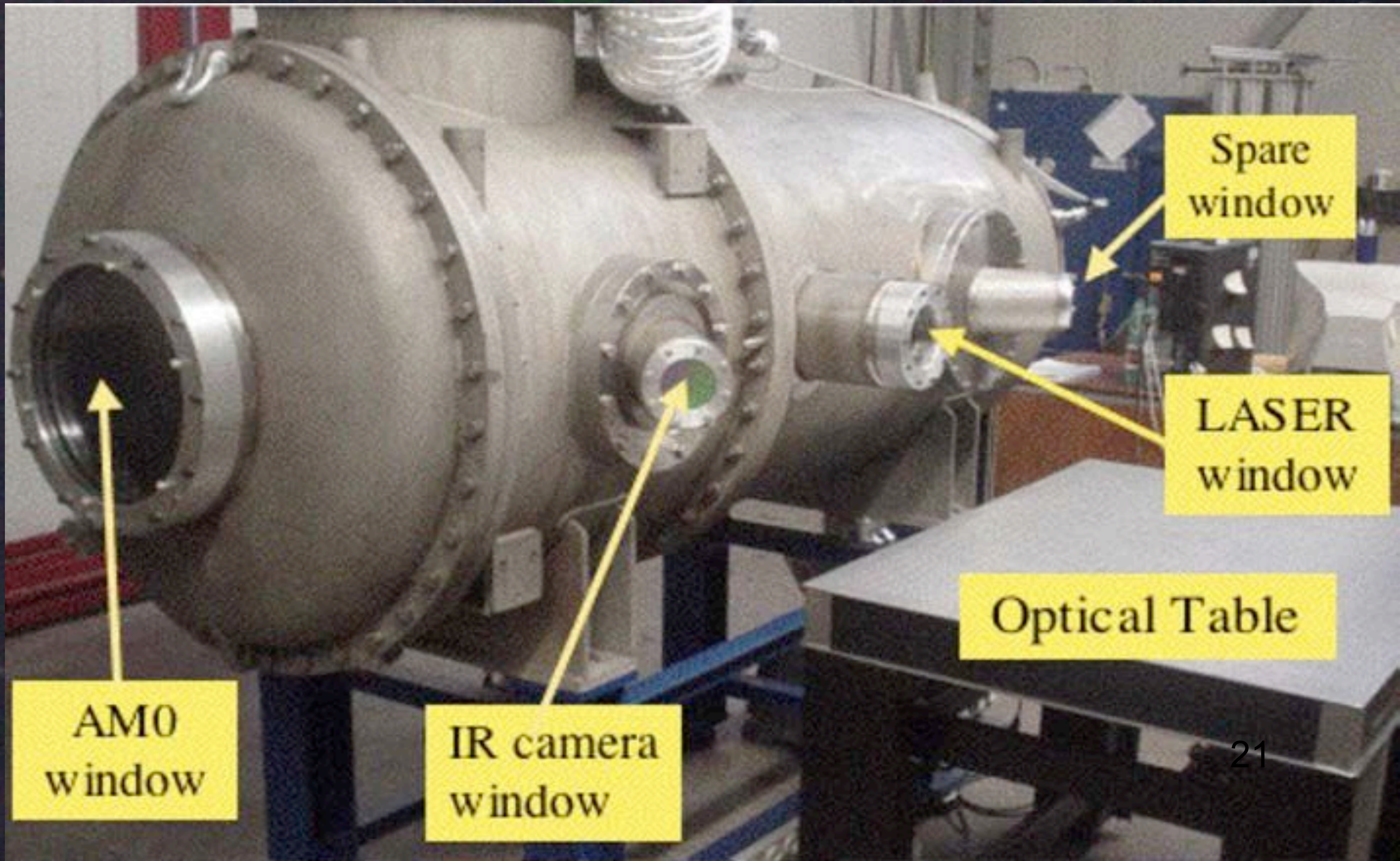
LARGE SOLID CCR CHALLENGES

- CCR Fabrication to New Requirements
  – Demonstrated
- Thermal Distortion of CCR
  – Simulation Program – See ILRS Paper
  – Thermal Vacuum Tests at INFN
- Stability of Emplacement on Lunar Surface
  – Mounted on Lander - ~ 10 mm Motion
  – Anchored Deep in Regolith - < 0.1 mm

CURRENT STATUS

- Preliminary Definition of Overall Package
- Completed Preliminary Simulations
- Completed Phase I Thermal Vacuum Tests





OVERALL LLR PROGRAM

- Candidate Flight Opportunities
  - Google Lunar X Prize Teams
    - Moon Express - 2015
    - Astrobotics - 2015
  - Russia/ESA – Luna-27 - 2019
- Participating Ranging Stations
  - Lunar Laser Ranging Station – e.g. APOLLO in New Mexico
    - Large Telescope Aperture
    - Needs Laser and Electronics Upgrade
  - Satellite Laser Ranging Stations – e. g. Matera in Italy
    - Good Lasers , Good Timing
    - Smaller Apertures
    - Needs Capability Analysis

OVERALL LLR PROGRAM

- Evaluate Expected Science by Improved Ranging Accuracy
  - Accuracy of Various Science Objectives
  - Time Scales to Obtain the Improved Science Objectives
  - Mueller at University of Hannover & CfA-INFN-LNF at Frascati
- Upgrade Data Processing of Ranging Observations
  - Conversion of the Observed Ranges to Residuals
  - Conversion of the Residuals to Frequencies
  - Conversion of the Frequencies to Science Objectives
- Lunar Data Analysis Locations
  - USA - JPL – Jim Williams
  - Germany – University of Hannover – Juergen Mueller
  - France - Observatoire de Paris, Paris - Jacques Laskar
  - Italy – INFN-LNF in Frascati/Center for Astrophysics – Chambers/Dell'Agnello

CONCLUSIONS

- LLRRA-21 Will Support Improved Ranging Accuracy
  - By a Factor of 10 to 100
  - Depending Upon Deployment Method
- LLRRA-21 Provides a High Signal Return
  - Equal to Current Signal Return from Apollo 15 Array
  - Supports Many More Observations/Month
  - Supports Many More Lunar Capable Ground Stations
- LLRRA-21 Ready for Flight by End of 2015
  - Package Weighs Less than 1.7 kilogram + Pointing Mechanism
  - No Power or Communication Required
- Extremely Cost Effective for the Quality of Science
  - Excellent Technical Heritage – Thousands of CCRs in Orbit
  - Excellent Scientific Heritage – Widely Recognized Science

EARTH SCIENCE RESULTS

- Plate Tectonics
  - Question of Historical vs. Current Motion
  - We Measured Current Motion
- Earth Rotation
  - Evaluated the Changes in the Length of Day
- Measurement of Polar Wander
  - Chandler Wobble to High Accuracy

LUNAR SCIENCE RESULTS

- Discovery of the Inner Liquid Core
- Dissipation at Liquid-Core/Mantle Interface
- Physical Librations in Longitude
- Lunar Moment of Inertia
- Free Librations – in Crustal Frame
- Love Numbers of the Crust

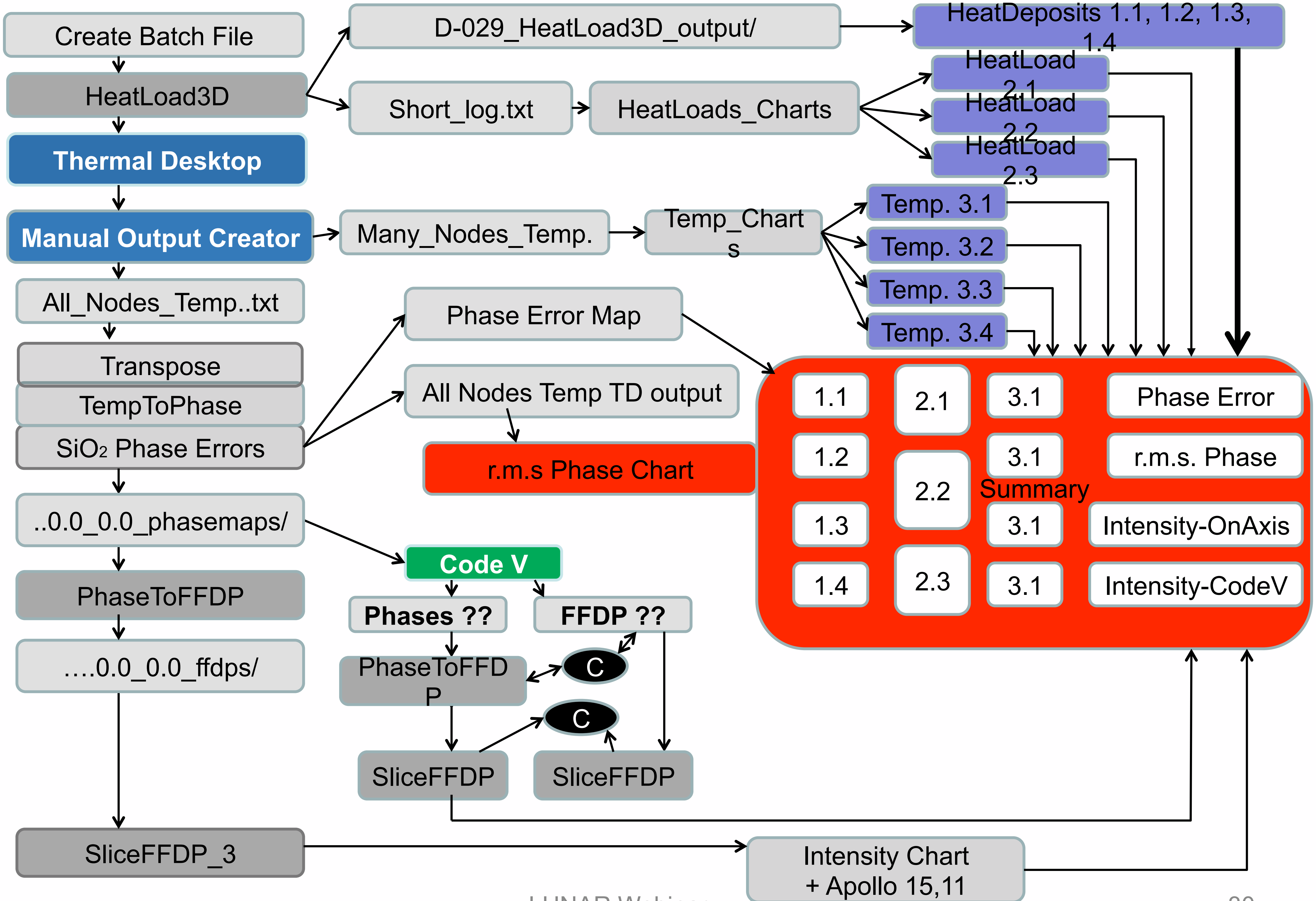
Decadal Remarks w.r.t. Lunar Laser Ranging

- 2010 Planetary Decadal Survey
  - Recommended NGL as Discovery Mission
  - Including **Lunar Laser Retroreflectors**
- Astro2010 Gravitational and Astrophysics Panel
  - Specifically Recommended LLRs
  - "improvements in **Lunar Laser Ranging** promise to advance this area"
  - "G ($< 10^{-12}$/yr) from **lunar laser ranging"**
  - "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"
  - "recommendation below in the context of a recommendation to augment the Explorer program"
- NRC Report
  - The Scientific Context for the Exploration of the Moon
  - *Emplace a geophysical network to include … the* ***new laser ranging retroreflectors***

Regolith Drilling in Apollo

Kriz Zacny at HoneyBee

LLRRA-21 Thermal/Optical Simulation



DARK ENERGY

- Some Implications of Theories Violating GR
  - Violation of Equivalence Principle
  - Values
- Current Measurements
- Future Measurements

GR and Quantum Mechanics

- Some Implications of Theories
  - Violations of Equivalence Principle
    - SEP – Modern Theories with Scaler Contriution
    - WEP String Theories,
  - Values
    - SEP $|\eta| \leq 4\times10^{-4}$
    - Aaa   -1.8 +/- 1.9)x10^-13
    - WEP 3x10^14$\Delta a/a \approx 10^{-13}$
- Current Measurements

- Future Measurements