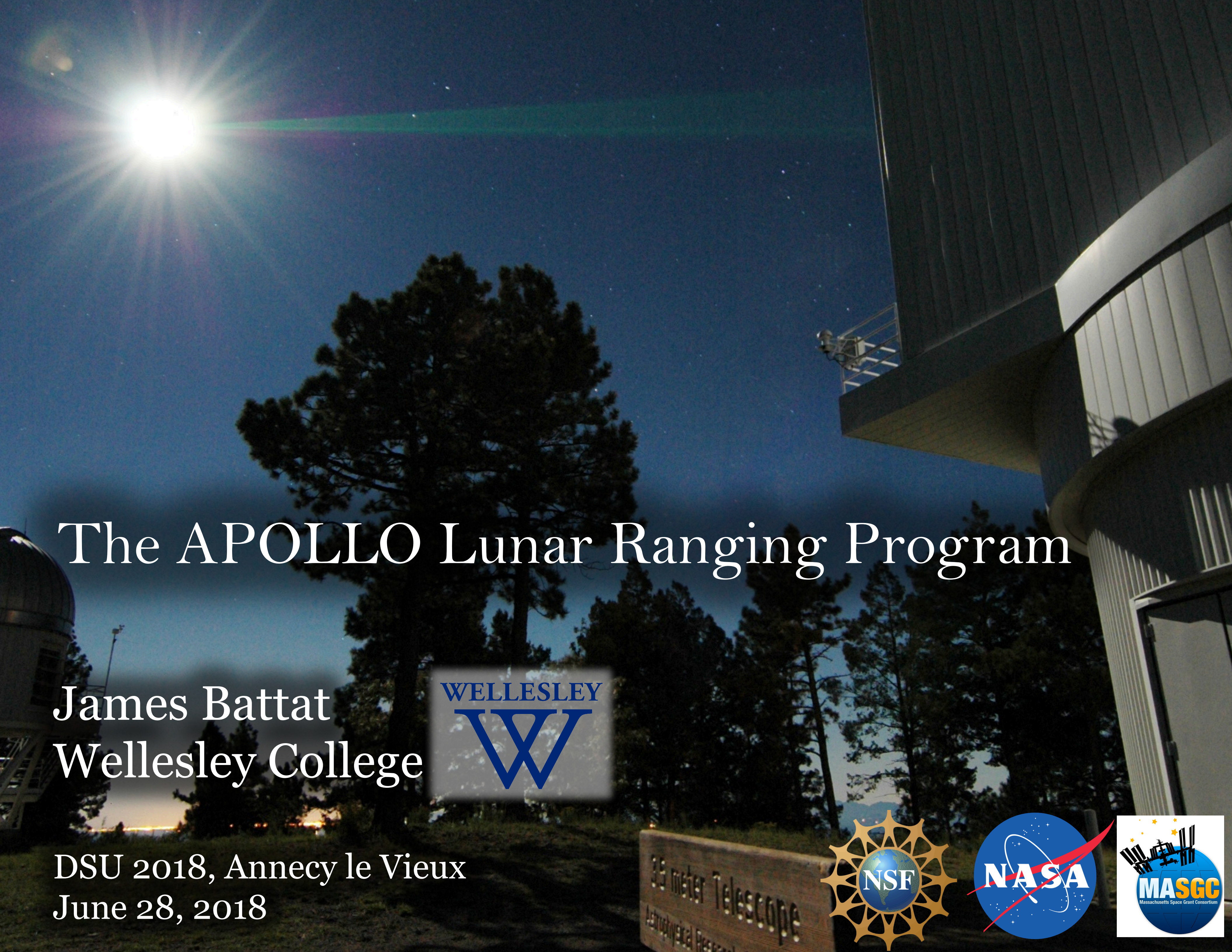


The APOLLO Lunar Ranging Program

James Battat
Wellesley College

WELLESLEY

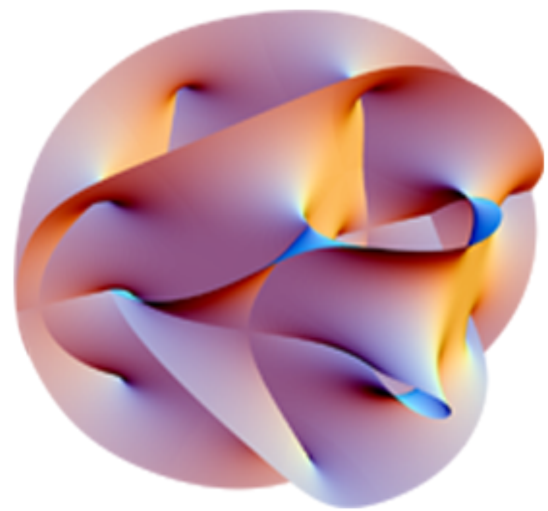
DSU 2018, Annecy le Vieux
June 28, 2018

Outline

- Motivation & science capability of LLR
- Historical LLR performance
- APOLLO system and status
  < 1-2 mm range ~~precision~~ accuracy
- Computational model improvements underway to extract gravitational physics constraints

The motivation to search

- All fundamental forces deserve experimental scrutiny
- General Relativity and Quantum Mechanics are fundamentally incompatible. Gravity is relatively *poorly tested*
- Scalar fields from string-inspired models can produce measurable effects:
  - Violation of equivalence principle
  - Time variation of fundamental constants
- Precision tests of gravity provide incisive tests of post-Einstein theories



LLR: a precision probe of gravity

these are existing constraints – expect 10x improvement with APOLLO

• Weak EP	$\Delta a/a$	10^{-13}
• Strong EP	η	10^{-4}
• $1/r^2$ deviations		$10^{-10}\ F_G$
• $(dG/dt)/G$		$10^{-12}\ yr^{-1}$ (1% over the age of the Universe)
• Gravitomagnetism		0.1%
• Geodetic precession		0.5%

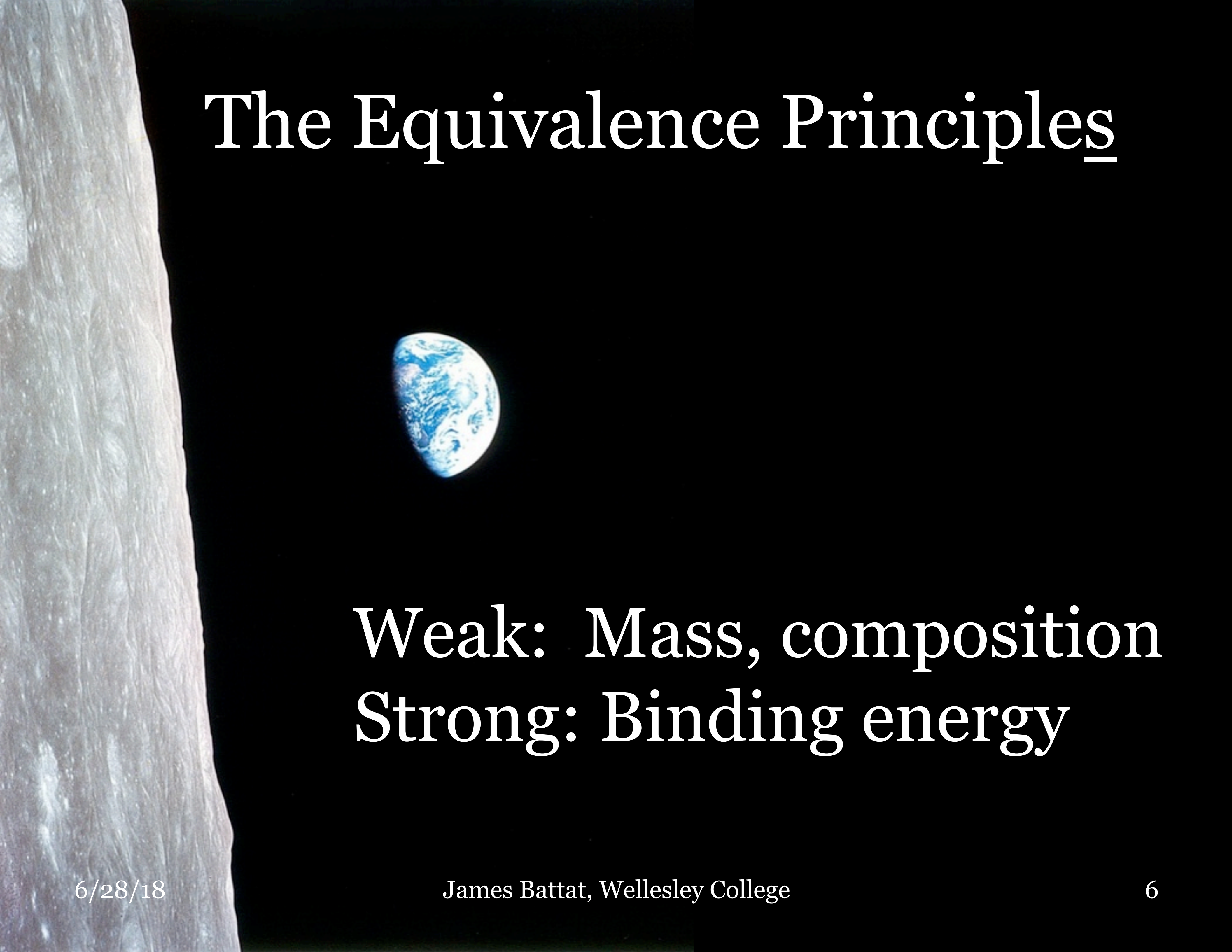
Earth-Moon has $v^2/c^2 \sim 10^{-8}$ in the Solar System frame
Expect relativistic phenomena of order $(10^{-8})(4e8)$ m ~ 4 m

LLR: a precision probe of gravity

these are existing constraints – expect 10x improvement with APOLLO

• Weak EP	$\Delta a/a$	10^{-13}	⟵	MICROSCOPE 10^{-14} Touboul et al., PRL 2017 (arXiv:1712.01176)
• Strong EP	η	10^{-4}	⟵	Pulsar triple system J0337+1715 Gusinskaia et al., J. Phys. Conf. (2017) but no limits published yet...
• $1/r^2$ deviations		10^{-10} F_G		
• $(dG/dt)/G$		10^{-12} yr^{-1}		
• Gravitomagnetism		0.1%		
• Geodetic precession		0.5%		

The Equivalence Principles



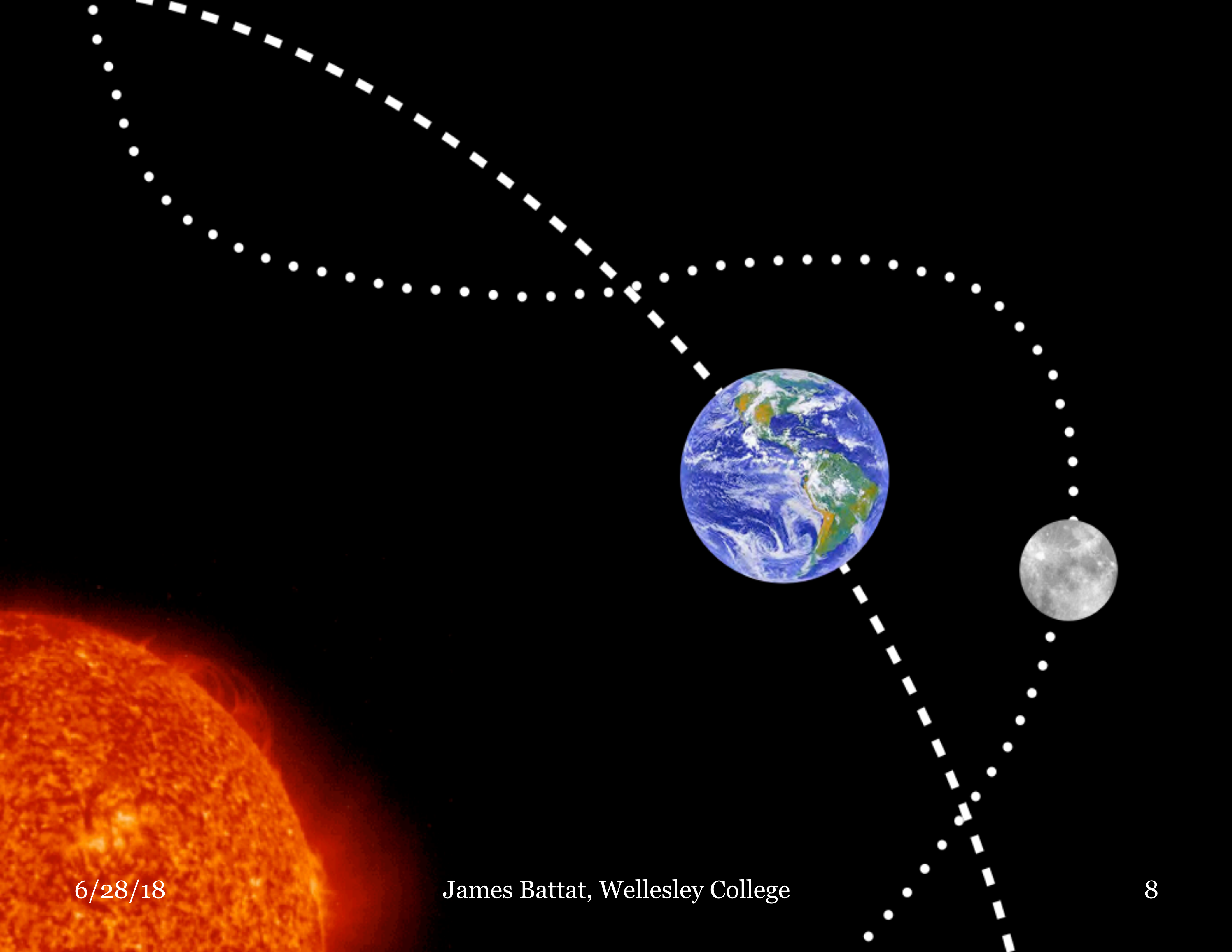
Weak: Mass, composition
Strong: Binding energy

Strong Equivalence Principle

Sky & Telescope

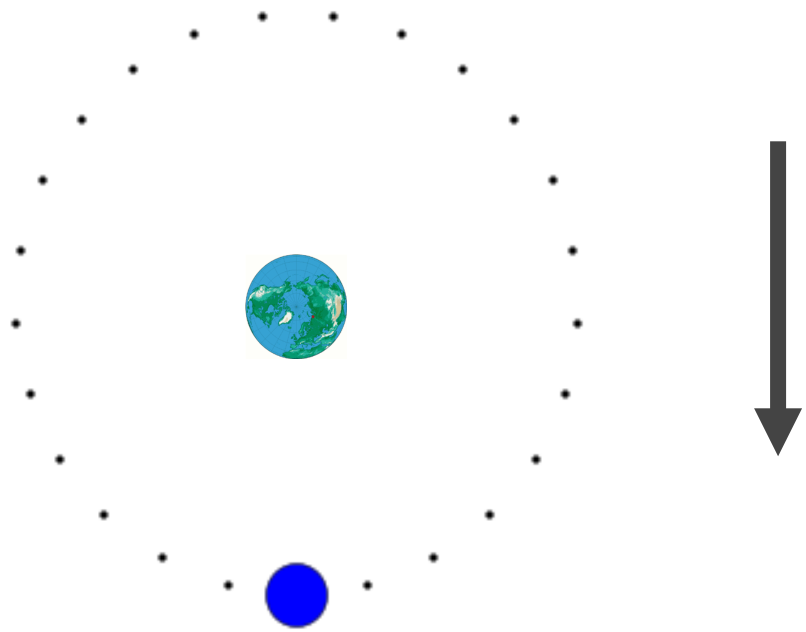
$$E_{B.E.} = -\frac{GM_1M_2}{R}$$

$$M_{B.E.} = \frac{E_{B.E.}}{c^2}$$



EP Violation in the Lunar Orbit

"Nominal" Lunar orbit

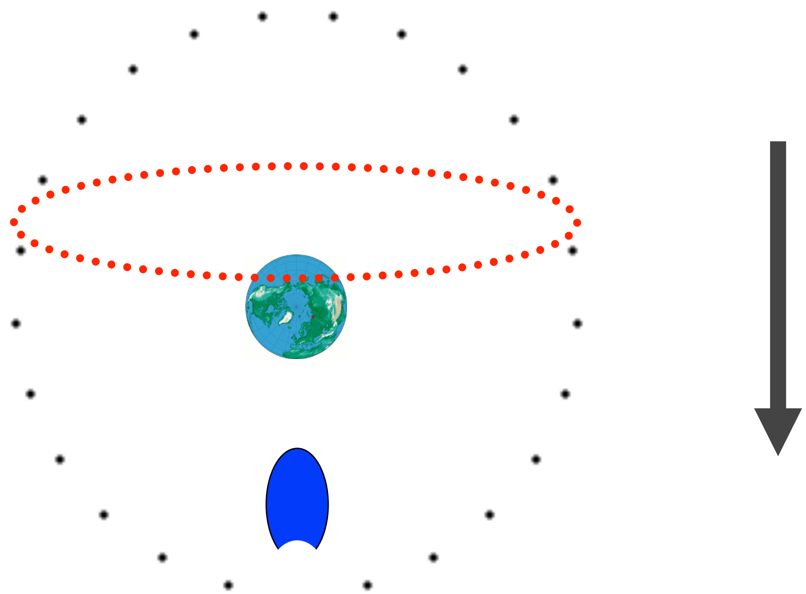


to the Sun

EP Violation in the Lunar Orbit

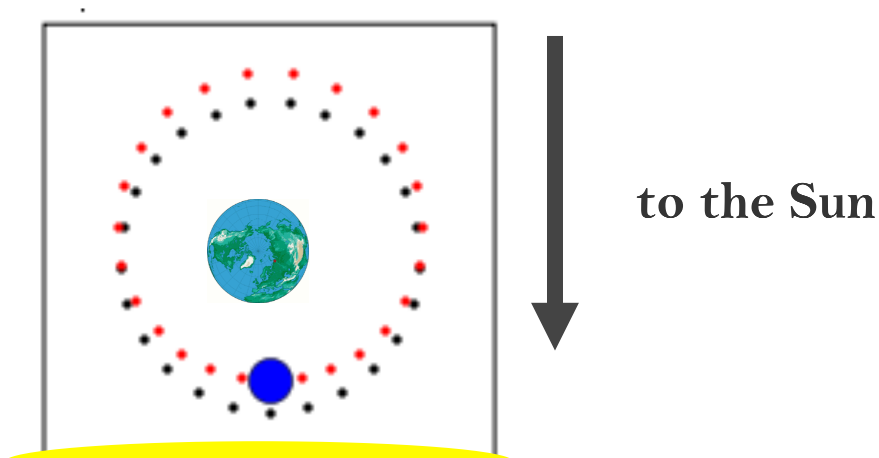
"Nominal" Lunar orbit

Orbit under EP violation (polarized)

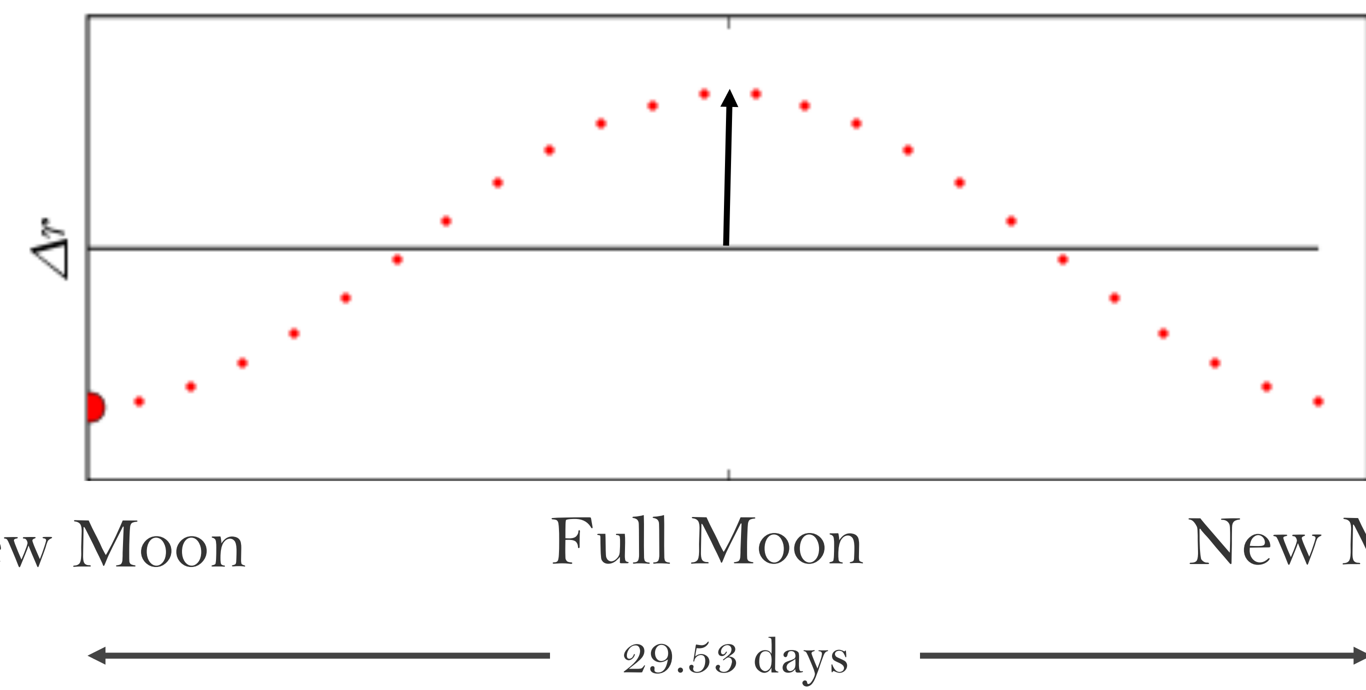


to the Sun

SEP Violation in the Lunar Orbit



$$\Delta r = 13.1\eta \cos D \quad \text{meters}$$



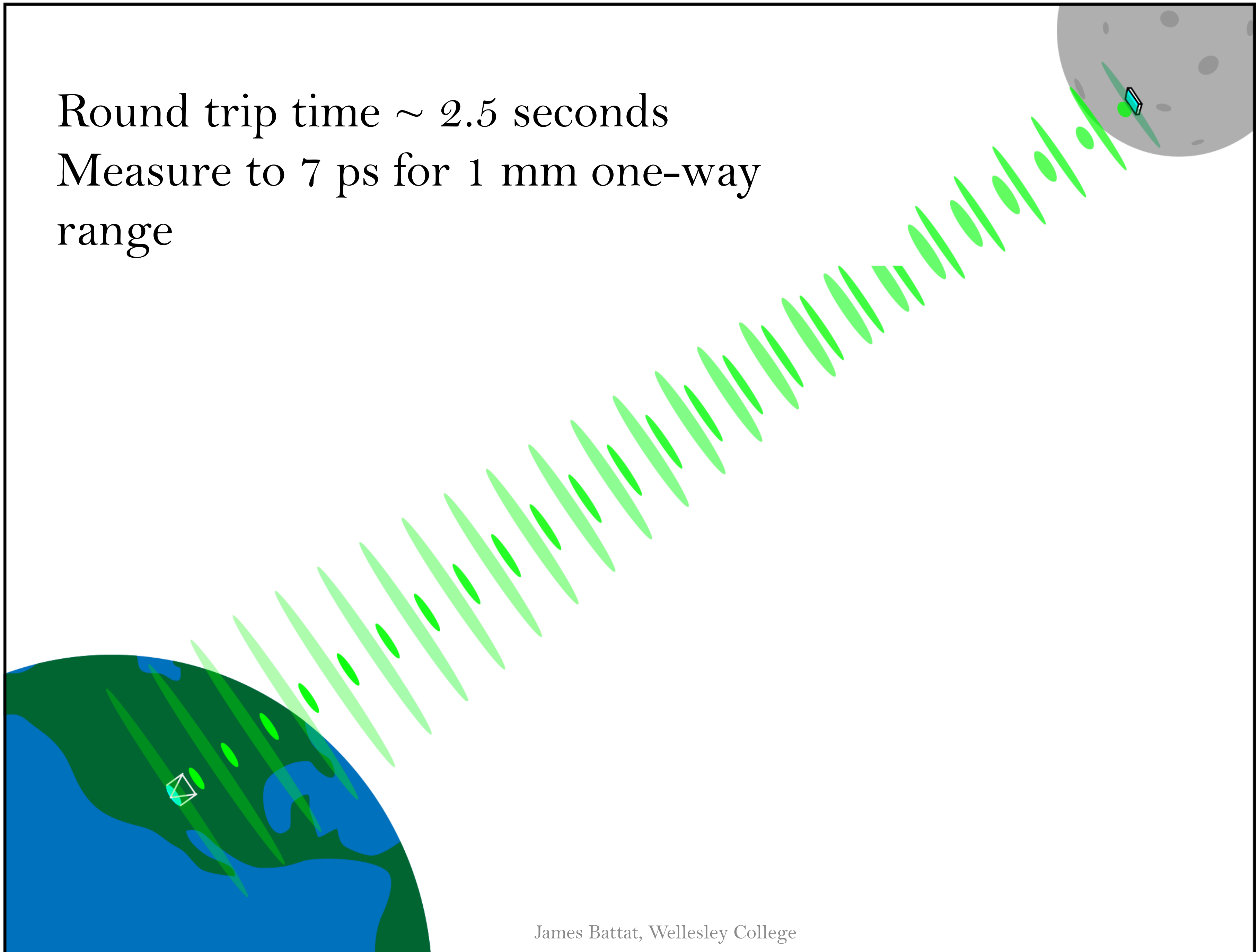
$$\eta \leq 5 \times 10^{-4}$$

by LLR

Lunar Laser Ranging 101

Round trip time ~ 2.5 seconds

Measure to 7 ps for 1 mm one-way range



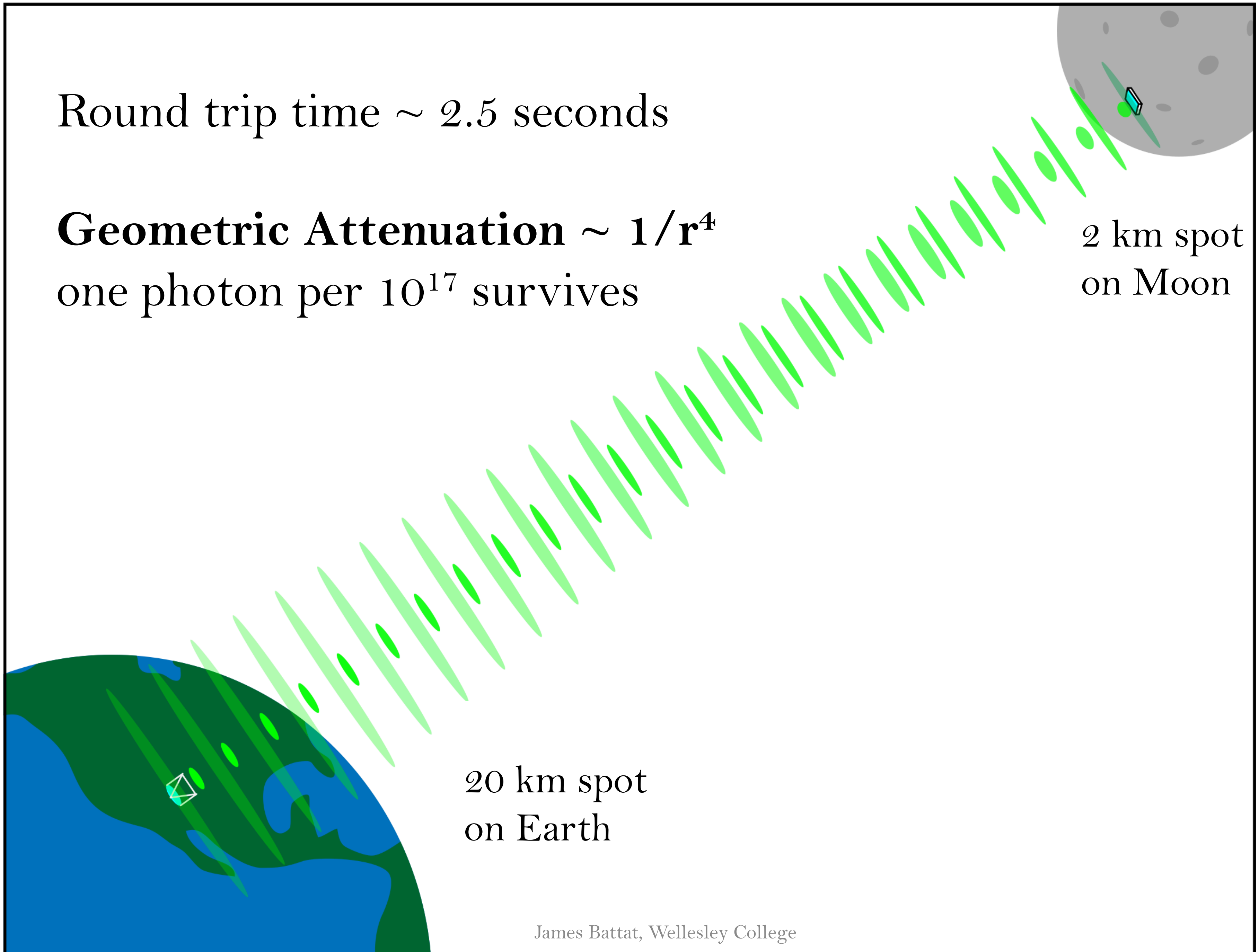
Big Bang Theory: making it look easy!

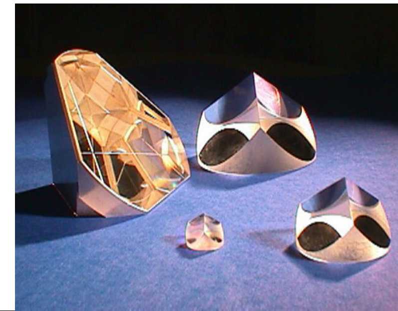
Lunar Laser Ranging 102

Round trip time ~ 2.5 seconds

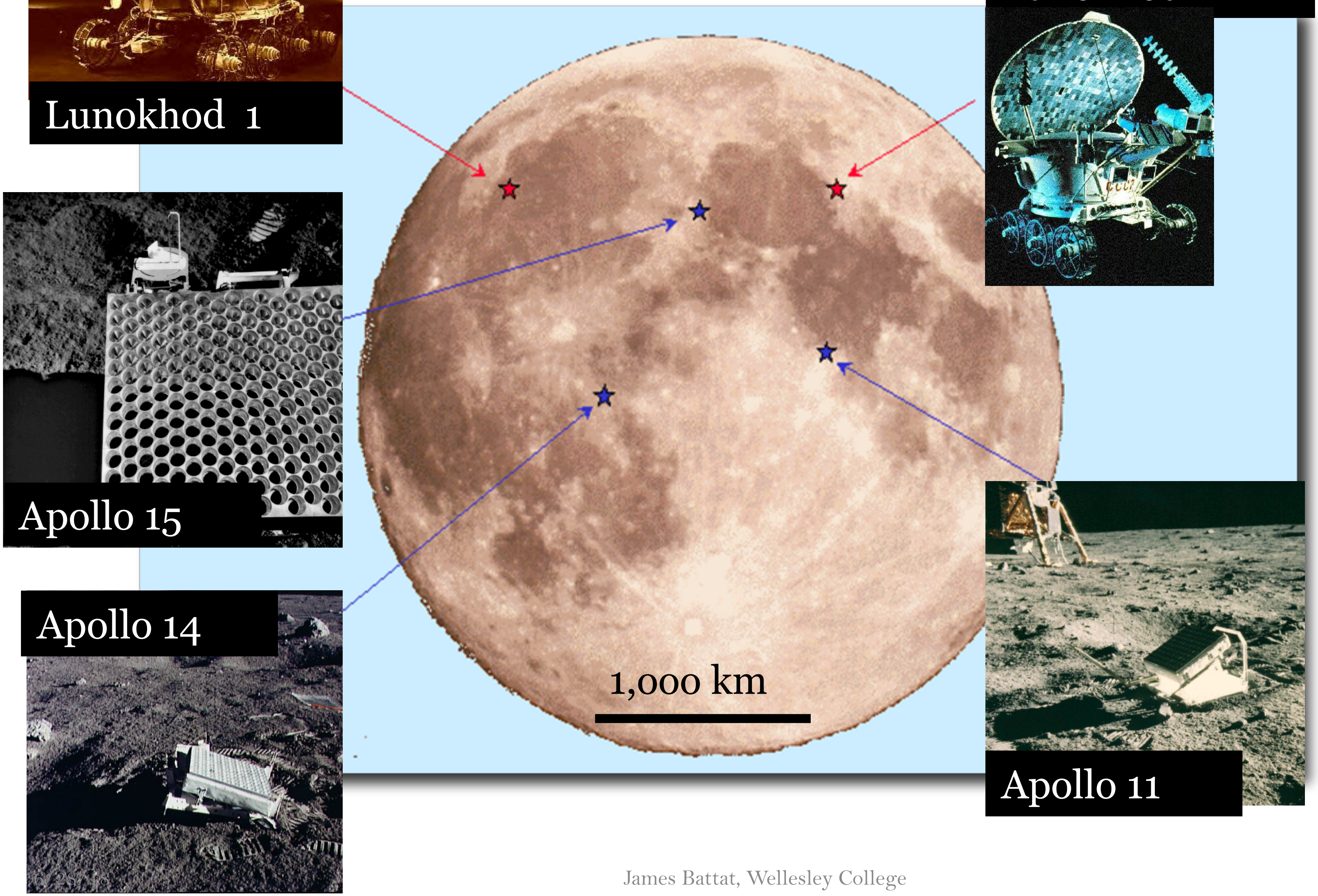
Geometric Attenuation ~ 1/r⁴

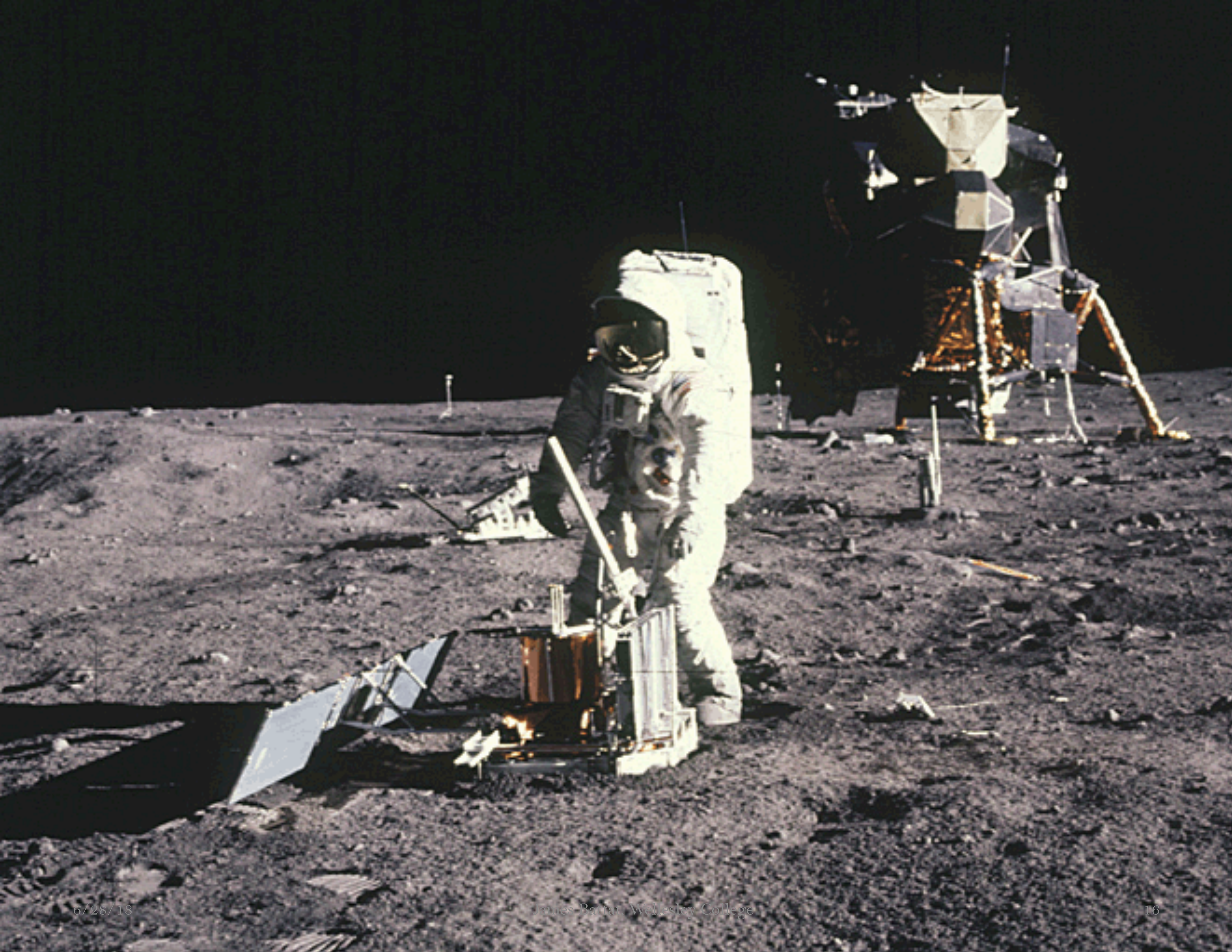
one photon per 10^{17} survives

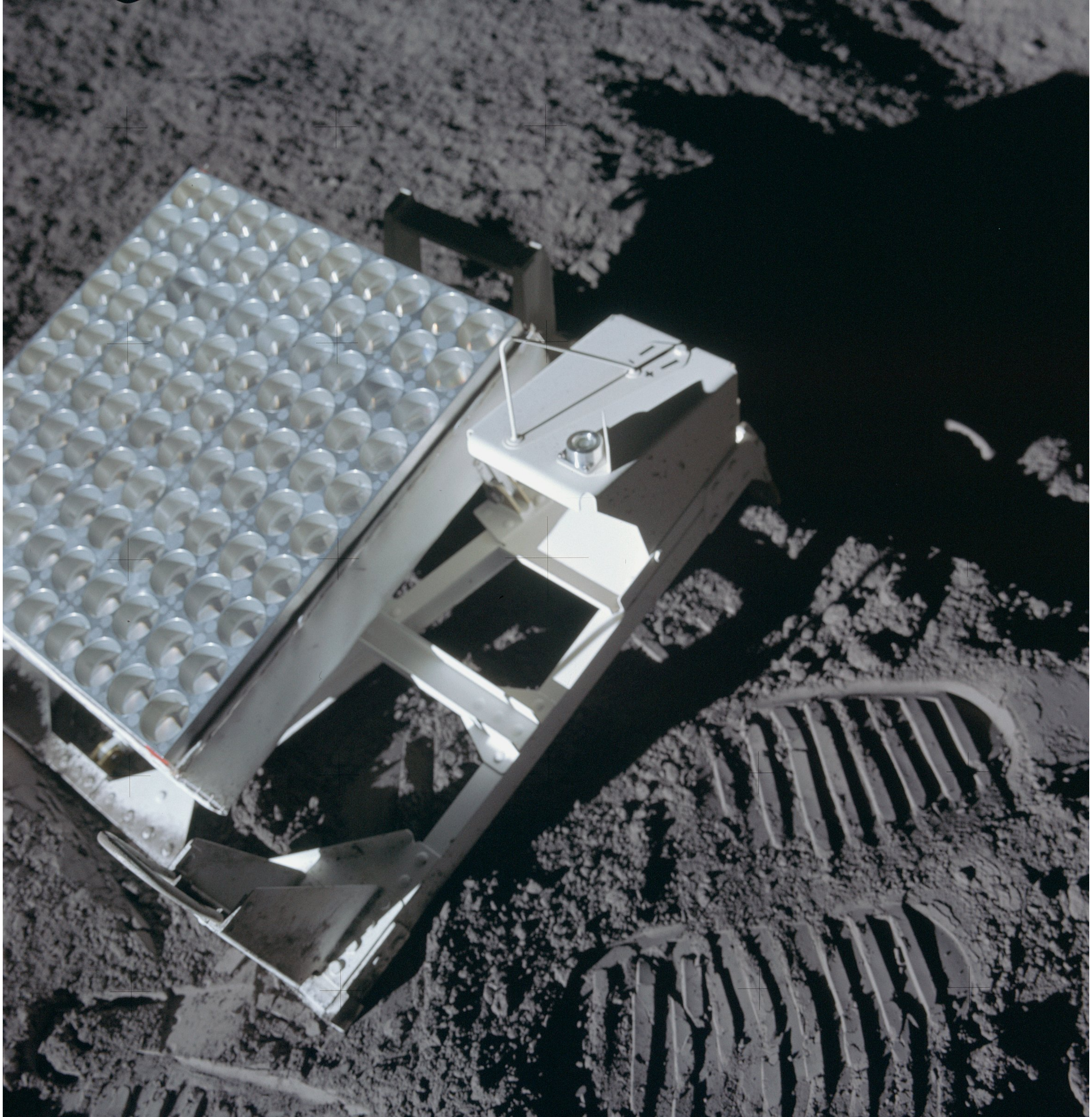


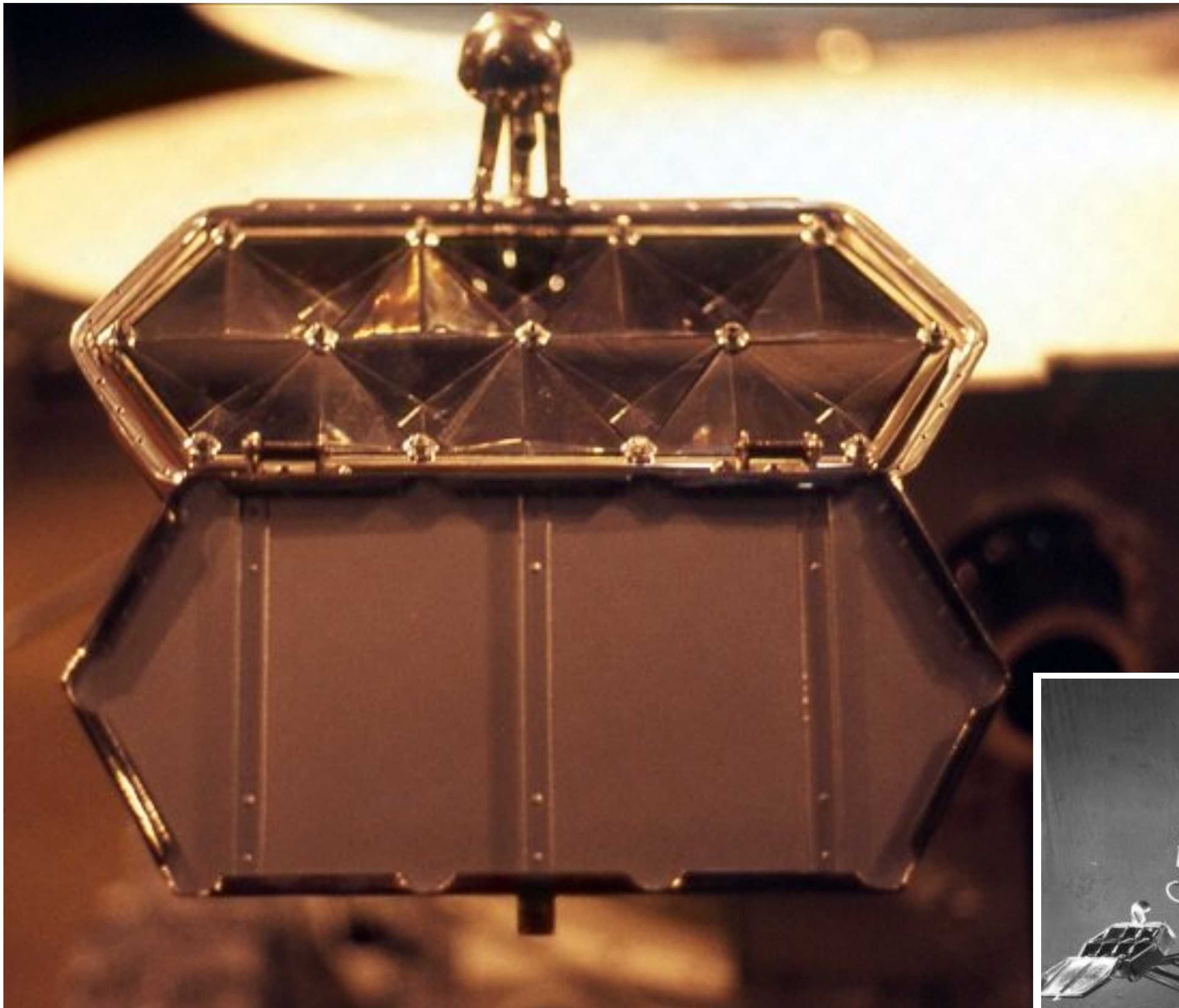


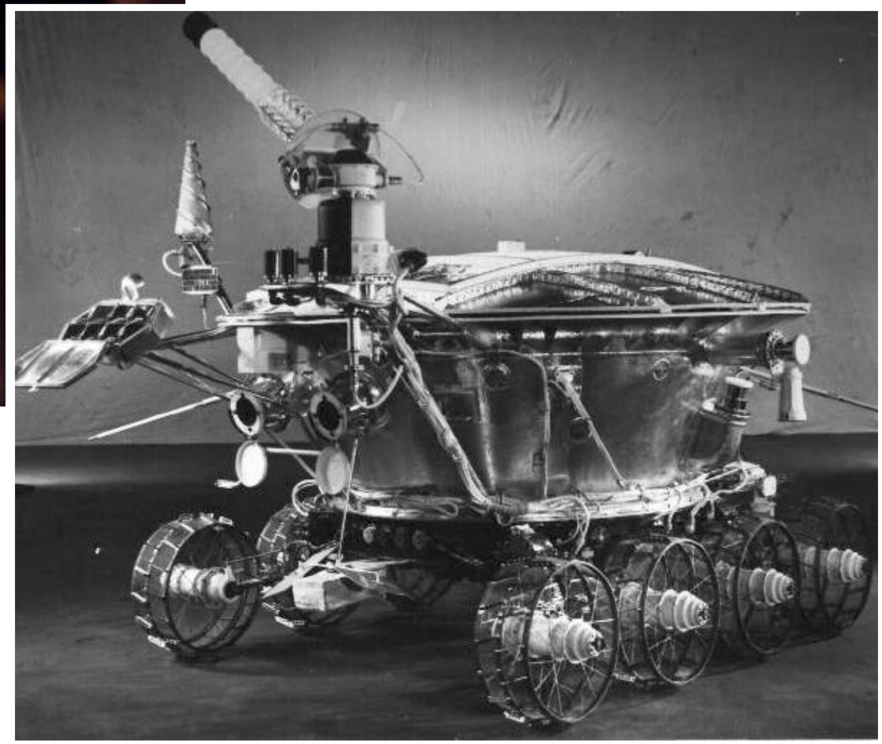
LLR Targets

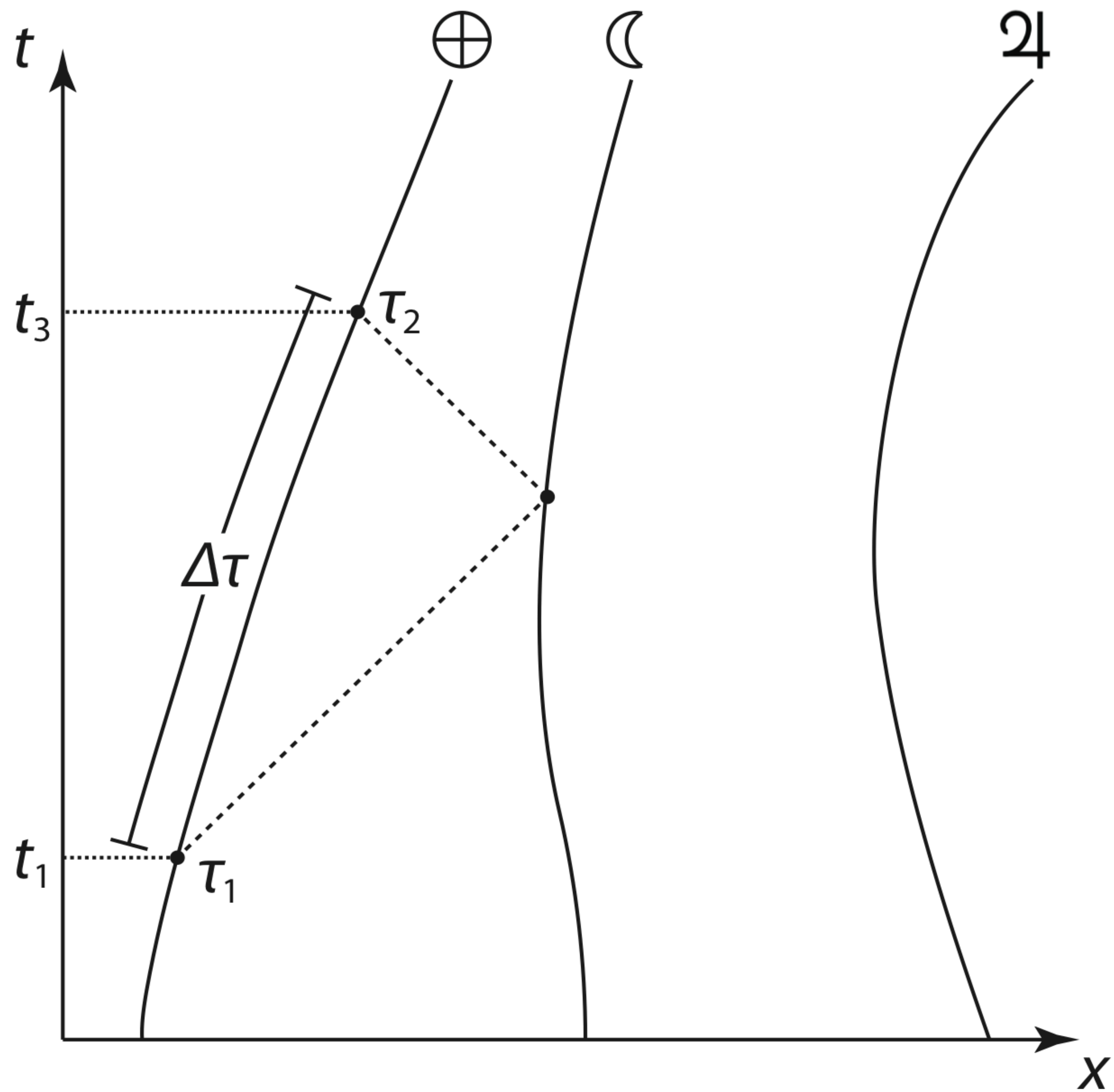


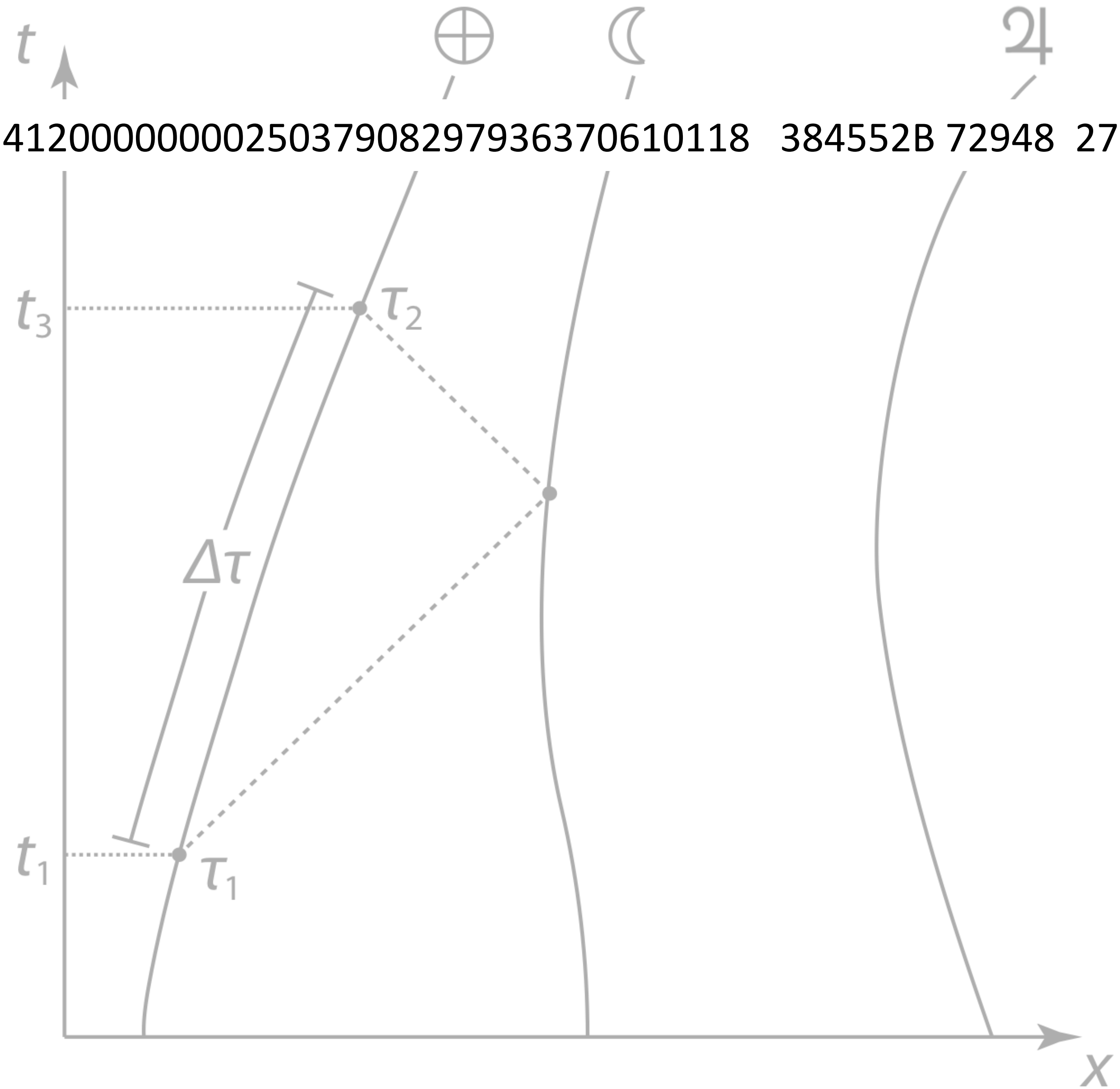









t
⊕
☾
♃
t_3
τ_2
$\Delta\tau$
t_1
τ_1
x



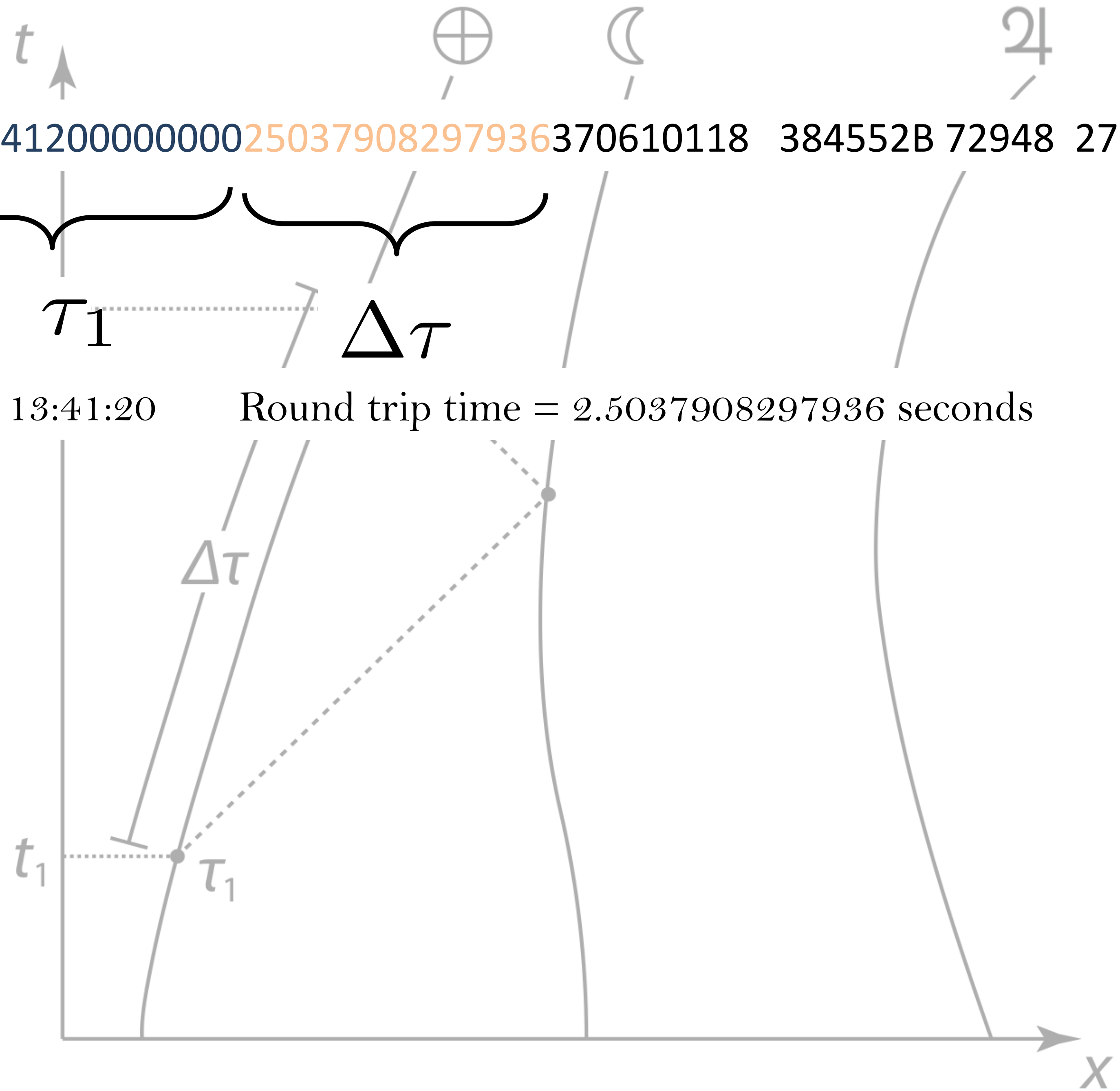
5120150116134120000000025037908297936370610118   384552B 72948 2713 5320A 477A

51201501161341200000000250379082979363706101118   384552B 72948 2713 5320A 477A

τ_1 $\Delta\tau$

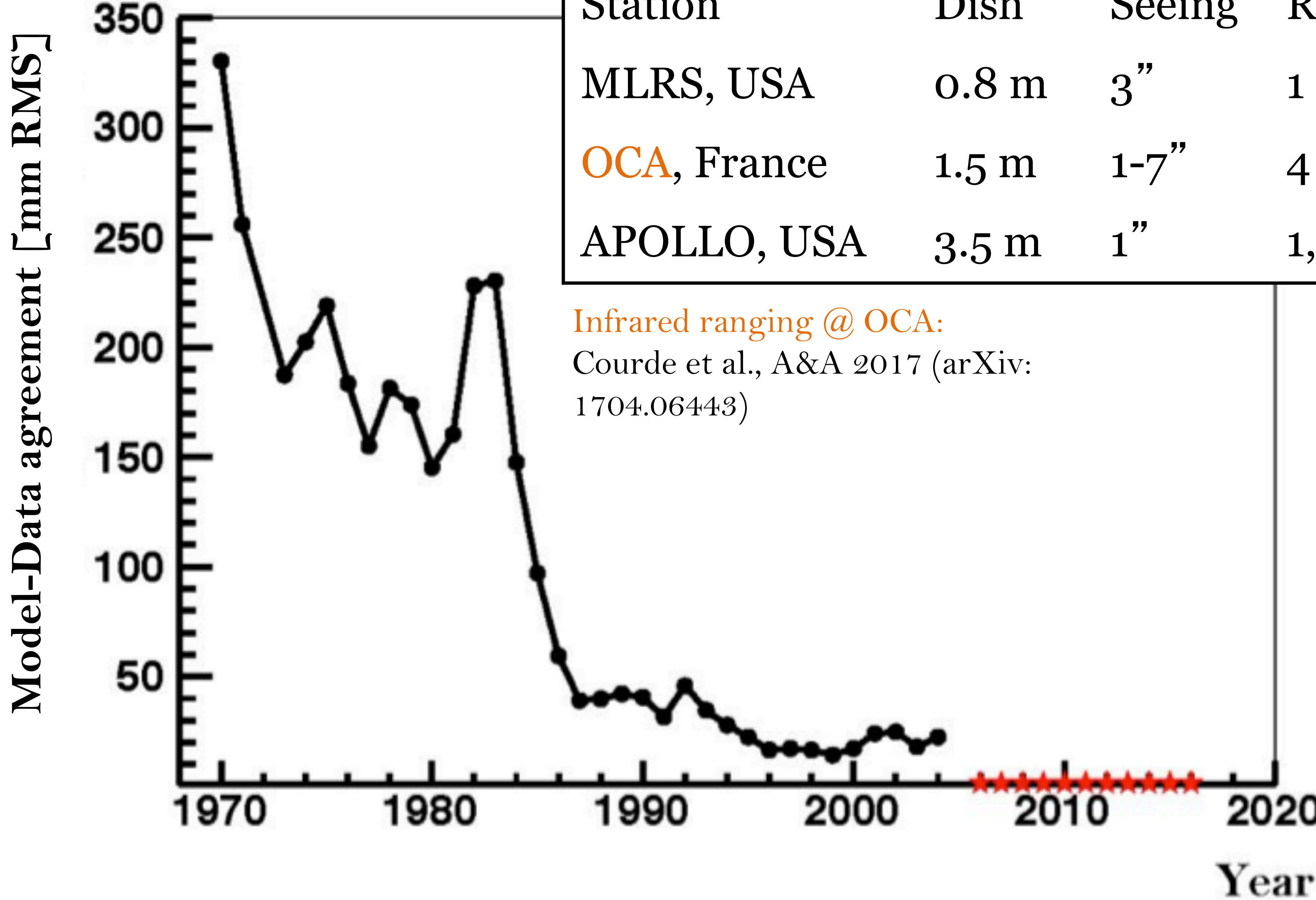
2015 Jan 16 13:41:20

Round trip time = 2.5037908297936 seconds



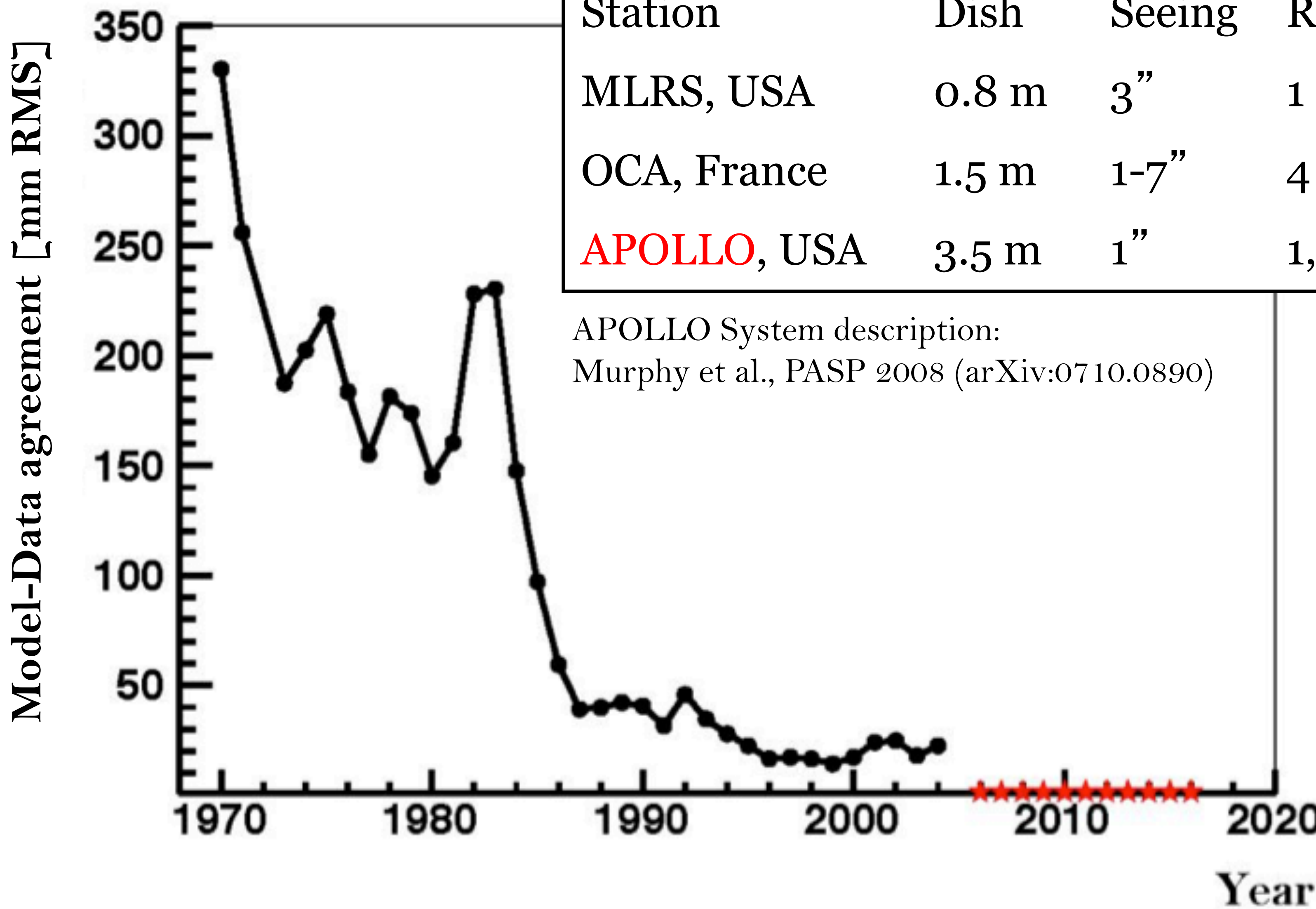
Historical Laser Ranging Performance

Station	Dish	Seeing	Rate (γ/min)
MLRS, USA	0.8 m	3”	1
OCA, France	1.5 m	1-7”	4
APOLLO, USA	3.5 m	1”	1,000



Infrared ranging @ OCA:
Courde et al., A&A 2017 (arXiv: 1704.06443)

Historical Laser Ranging Performance



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APOLLO System description:
Murphy et al., PASP 2008 (arXiv:0710.0890)

Historical Laser Ranging Performance

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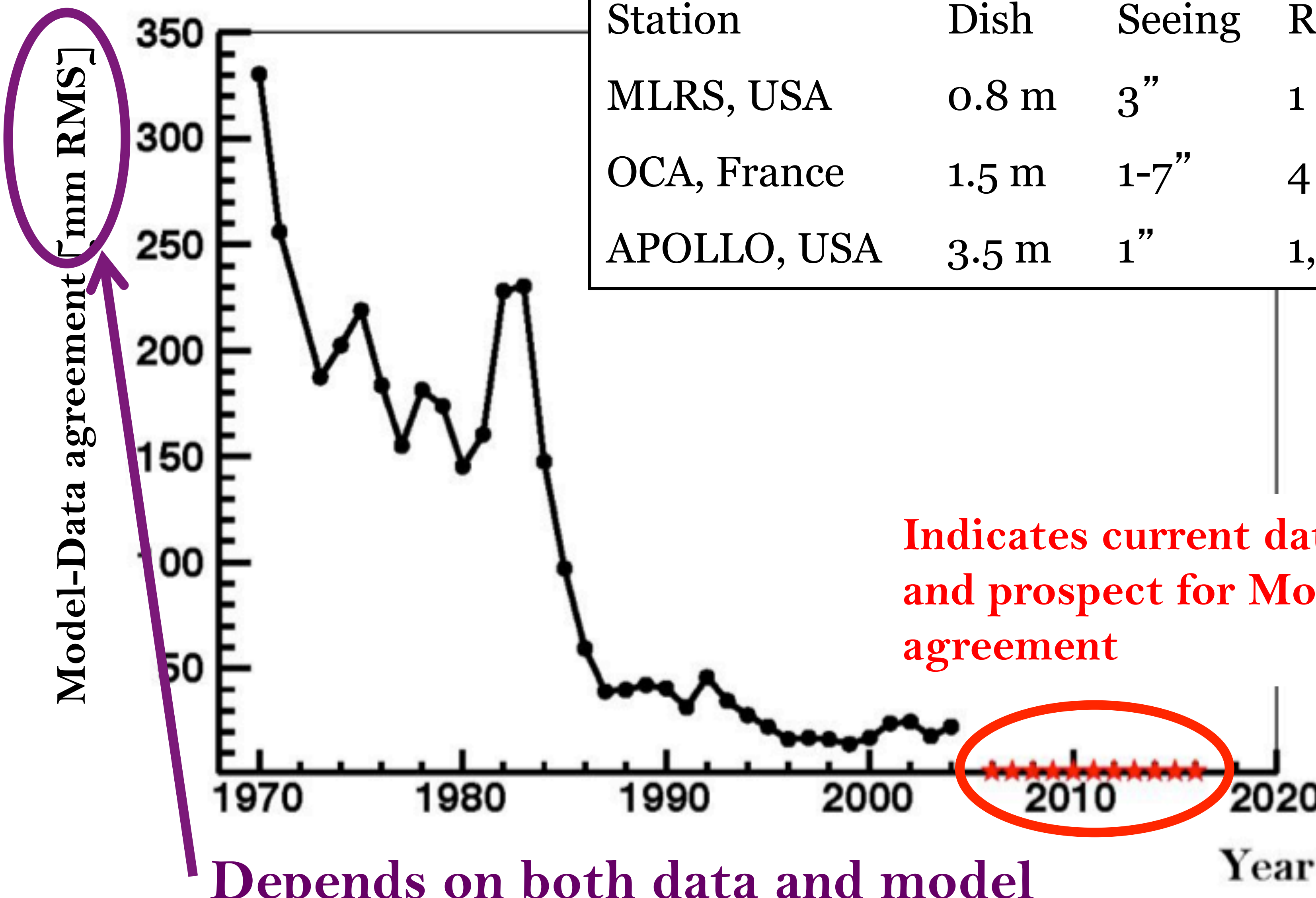
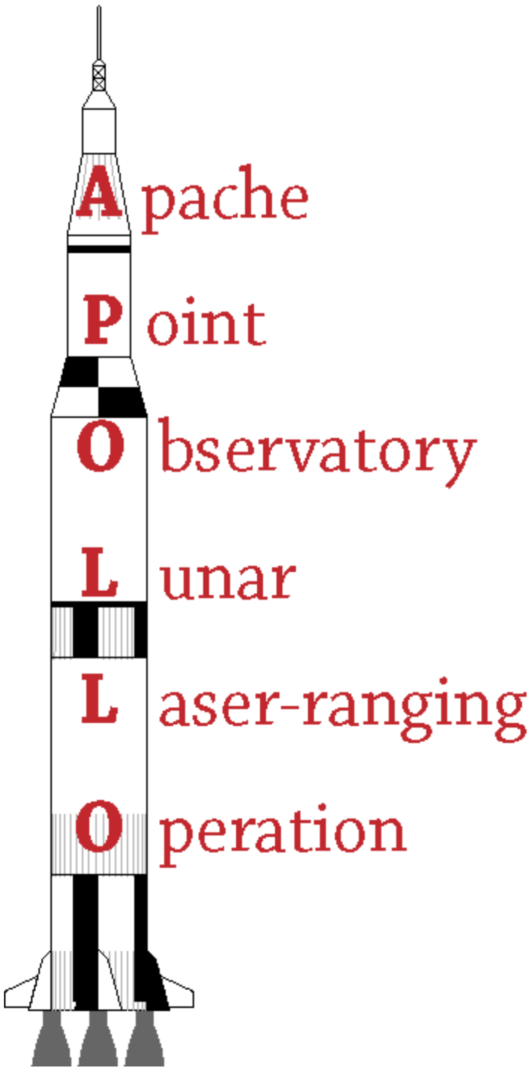


APOLLO Collaboration



U.C. San Diego
Tom Murphy (PI)
Bob Reasenberg
Nick Colmenares
Sanchit Sabhlok

Wellesley College
James Battat

U. Washington
Eric Adelberger
Erik Swanson

Harvard University
Christopher Stubbs
John Chandler
Irwin Shapiro

Humboldt State U.
C. D. Hoyle

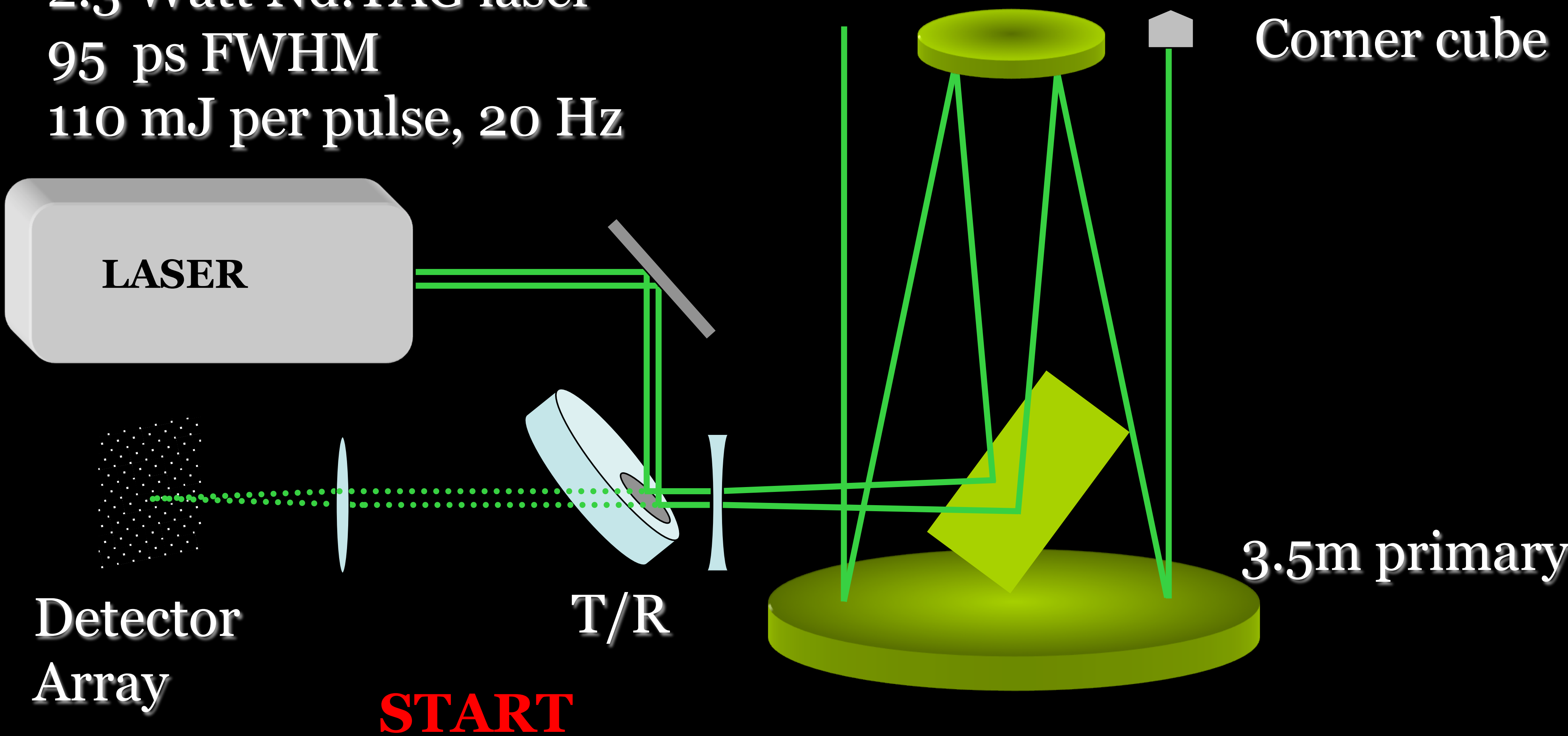
Northwest Analysis
Ken Nordtvedt

Apache Point Observatory
Russet McMillan

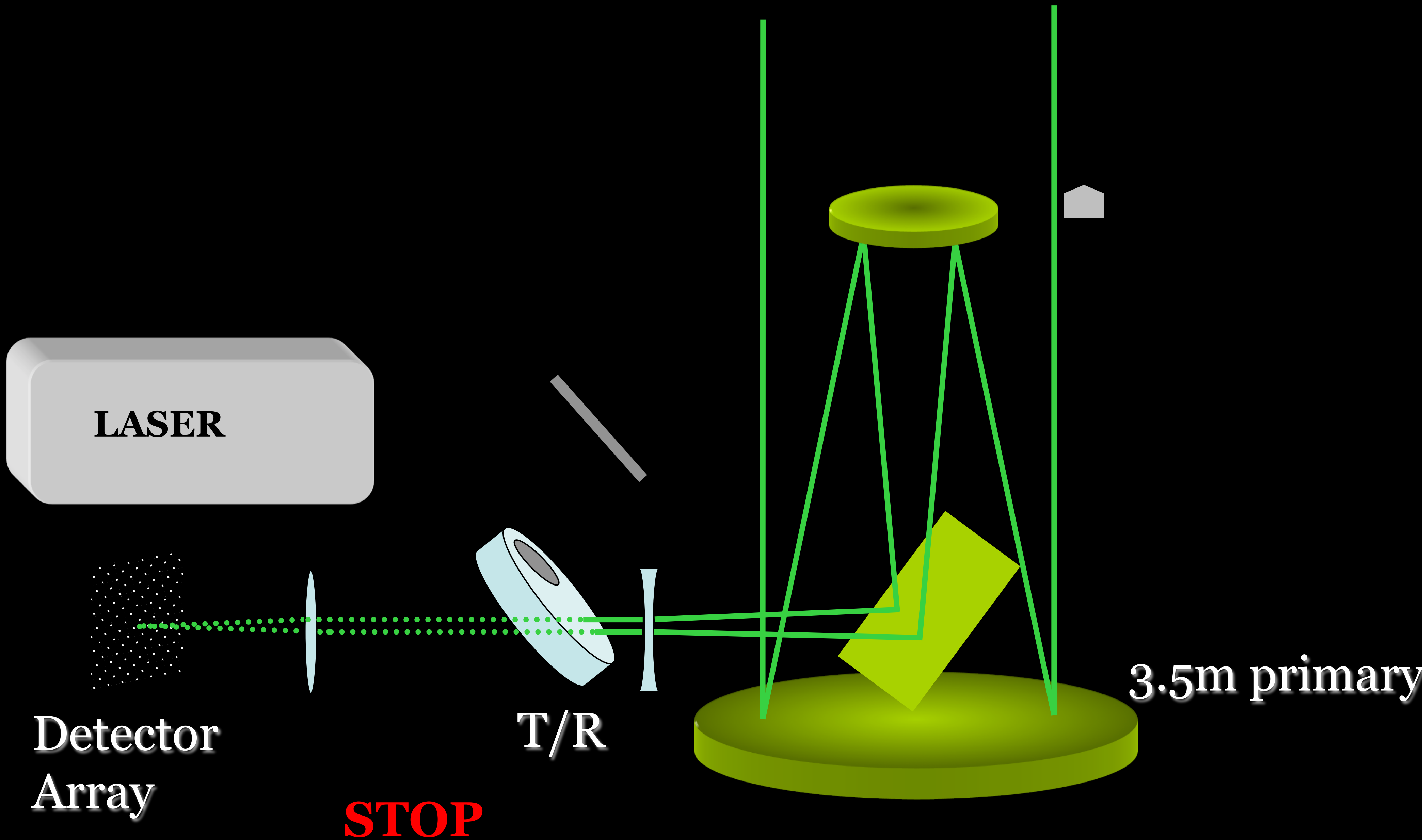
APOLLO: The Earth-End

Laser Ranging Apparatus: Transmit

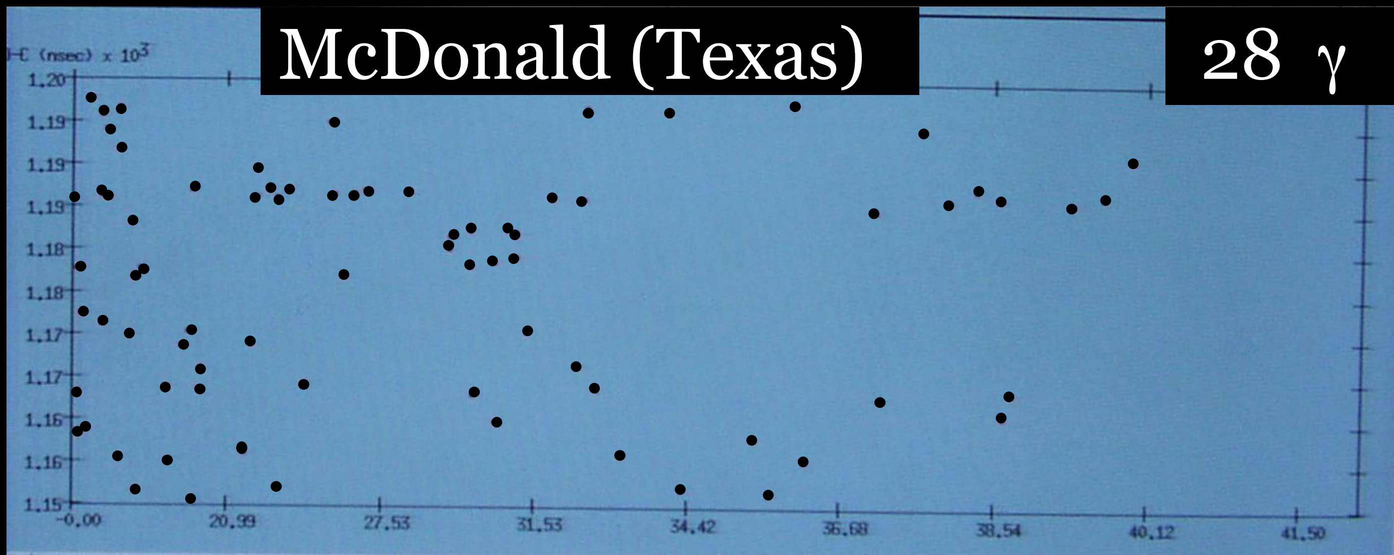
2.3 Watt Nd:YAG laser
95 ps FWHM
110 mJ per pulse, 20 Hz



Laser Ranging Apparatus: Receive



Then

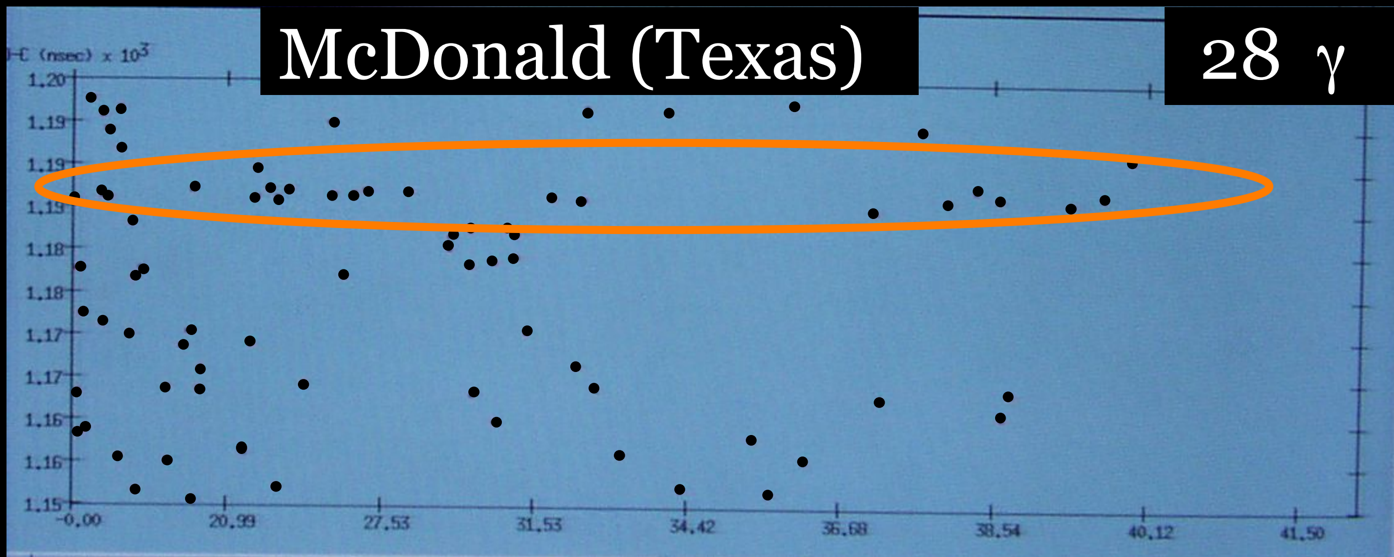


Observed Minus Theory

40 minutes

Then

Observed Minus Theory

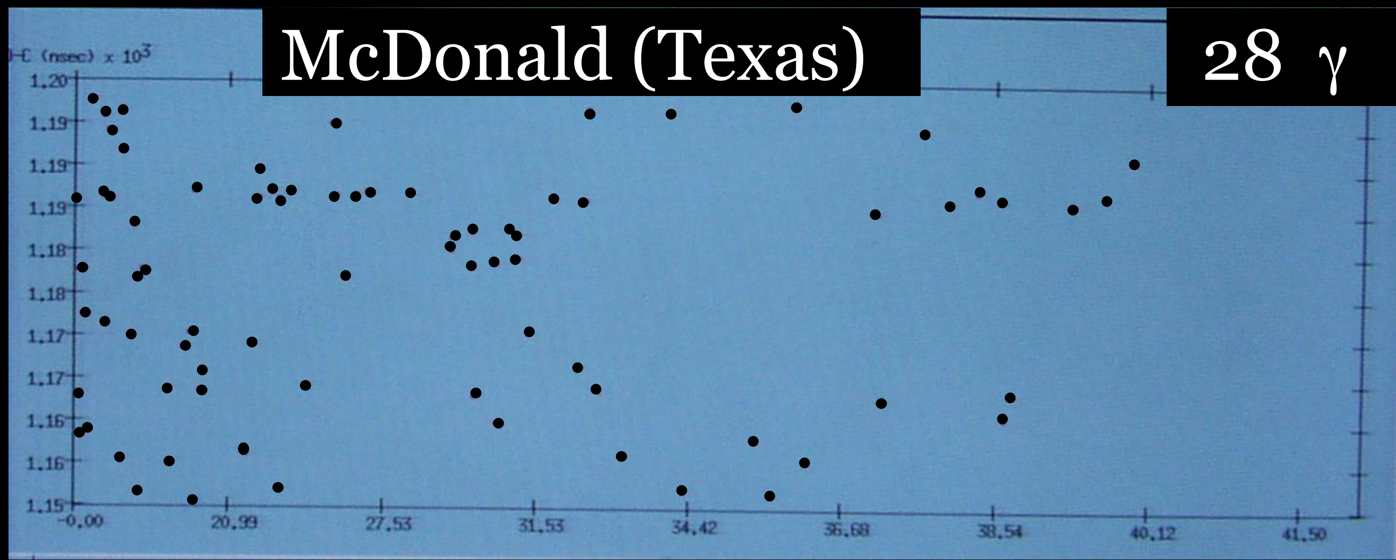


peut-être?

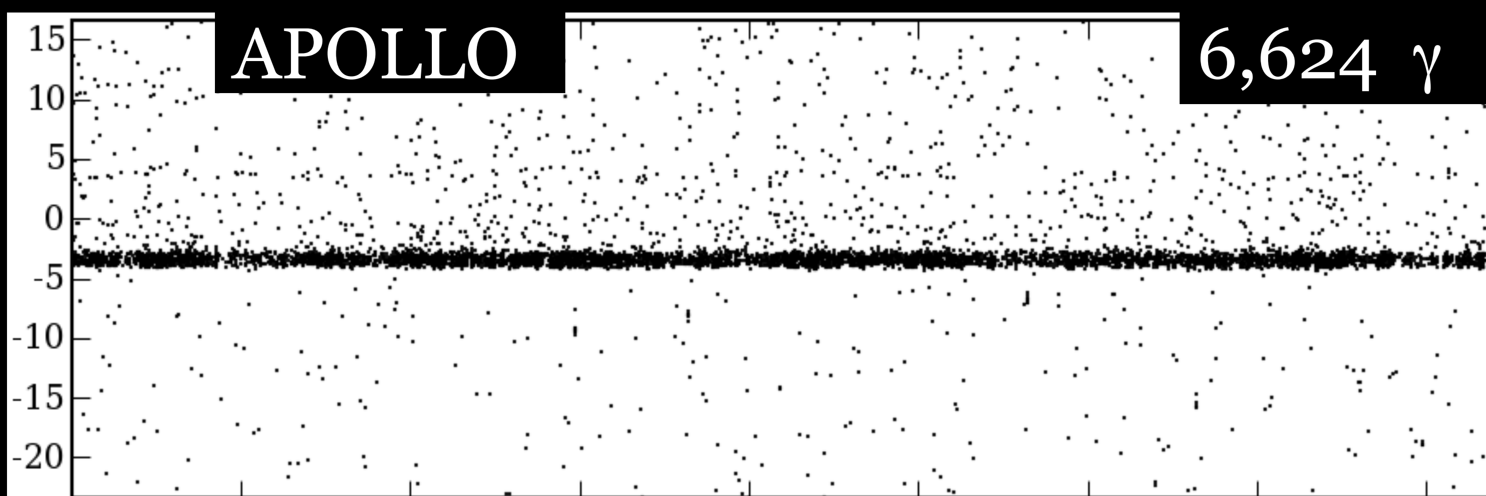
40 minutes

Now

Observed Minus Theory



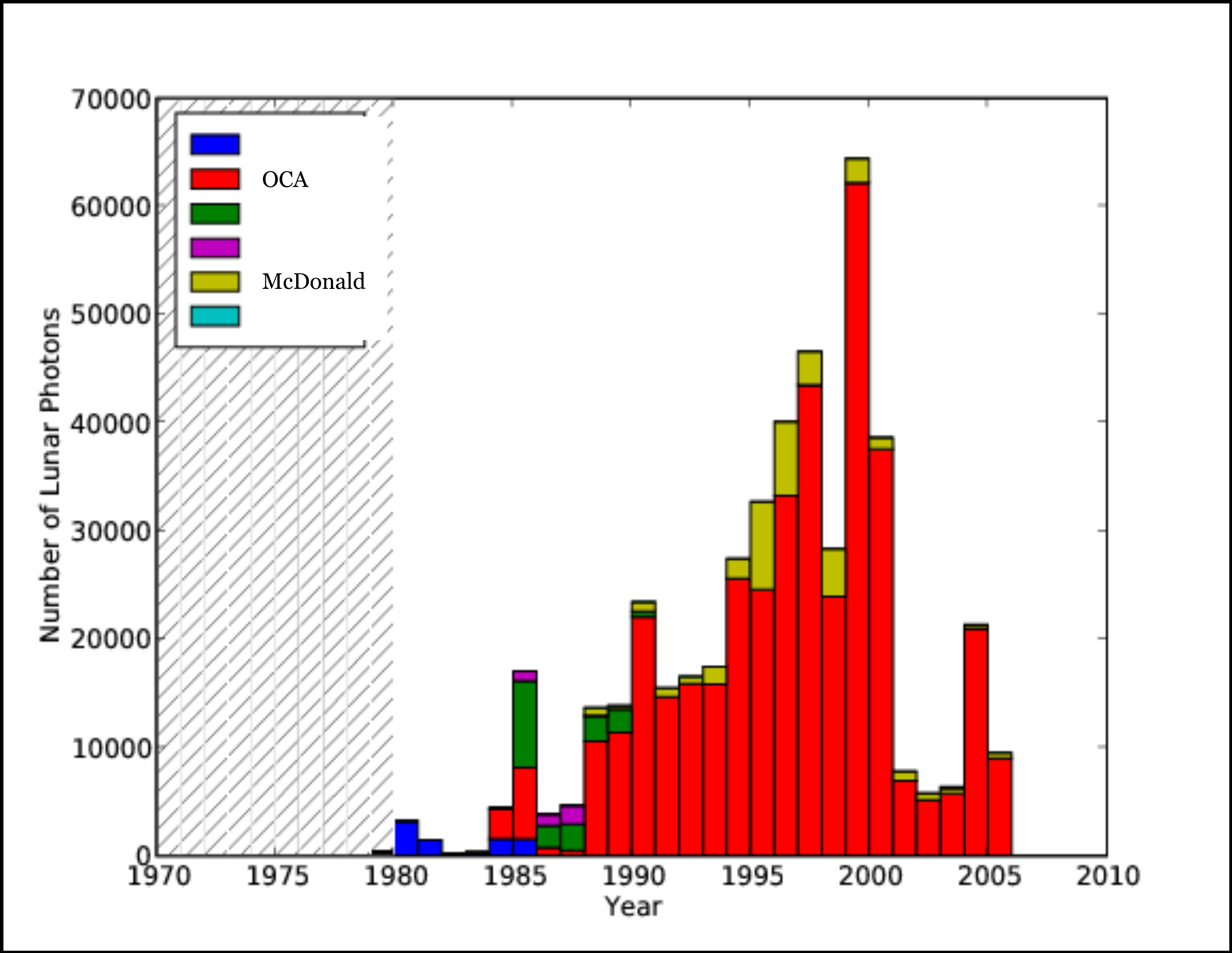
40 minutes



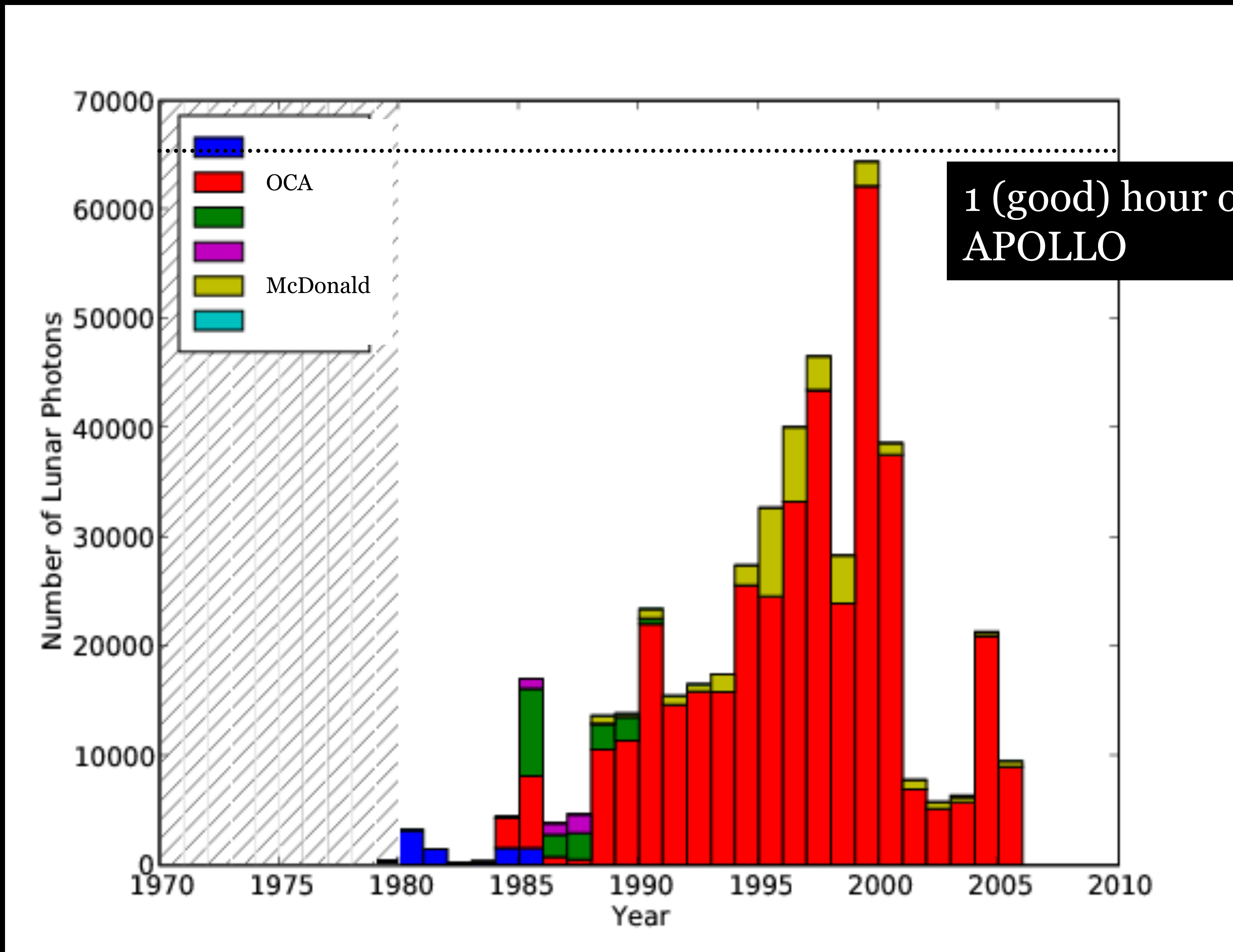
40 ns

4 minutes

Yearly Photon Yield

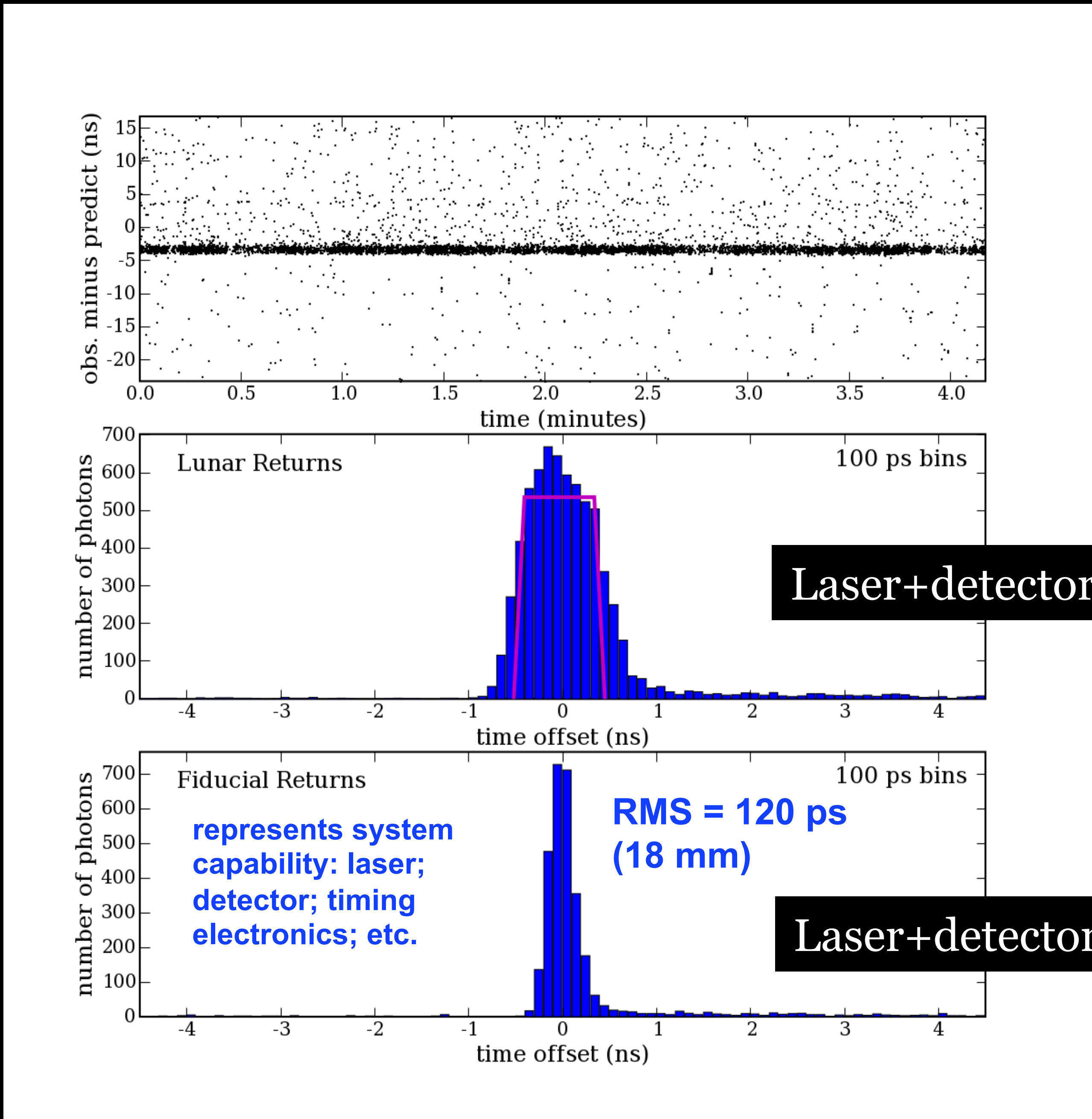


Yearly Photon Yield



1 (good) hour on APOLLO

Sub-mm precision ranging demonstrated



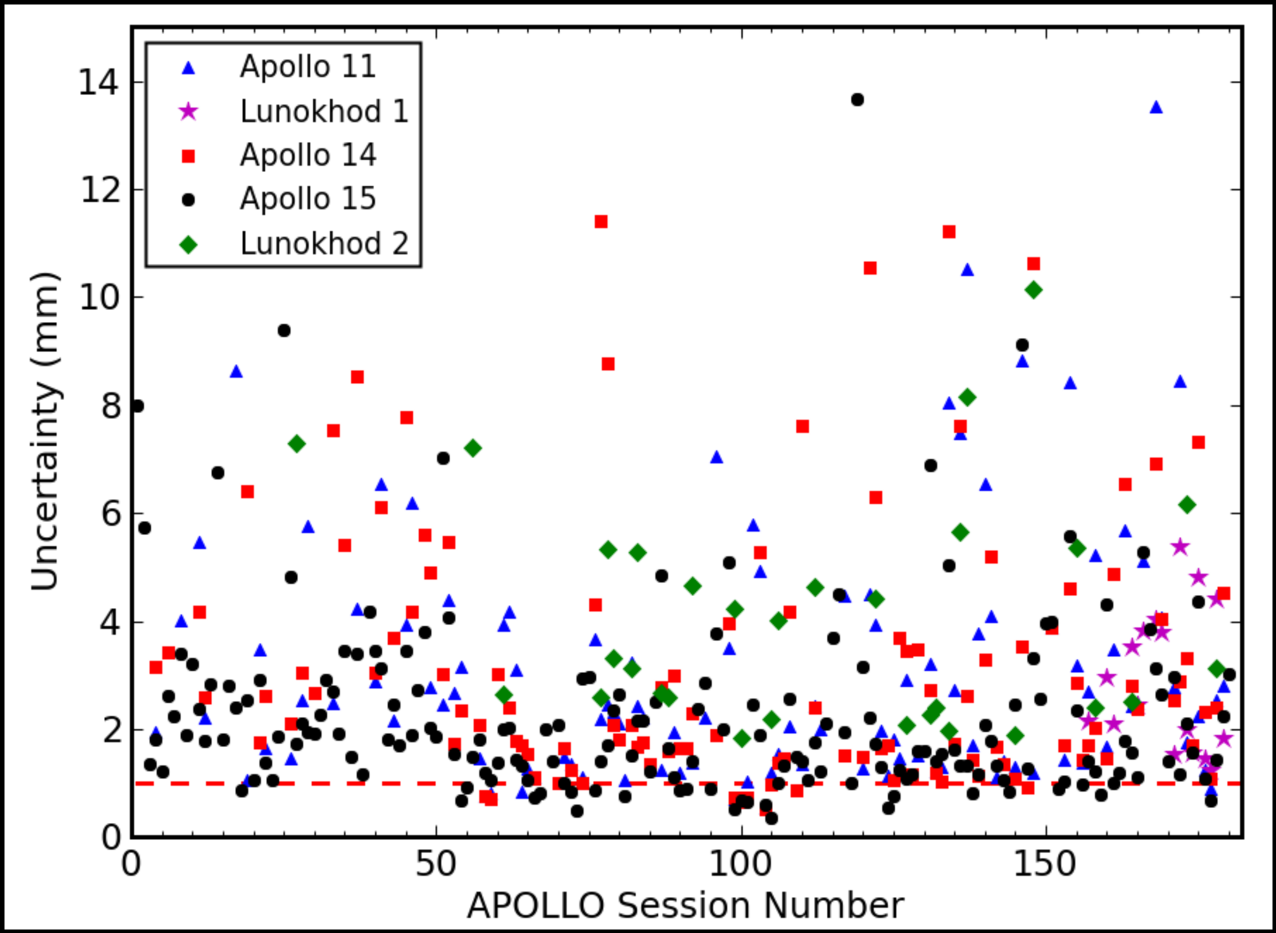
Apollo 15 **2007.11.19**

- 6624 photons in 5000 shots
- 369,840,578,287.4 ± 0.8 mm
- 4 detections with 10 photons

Limitation: lunar libration & size of reflector array

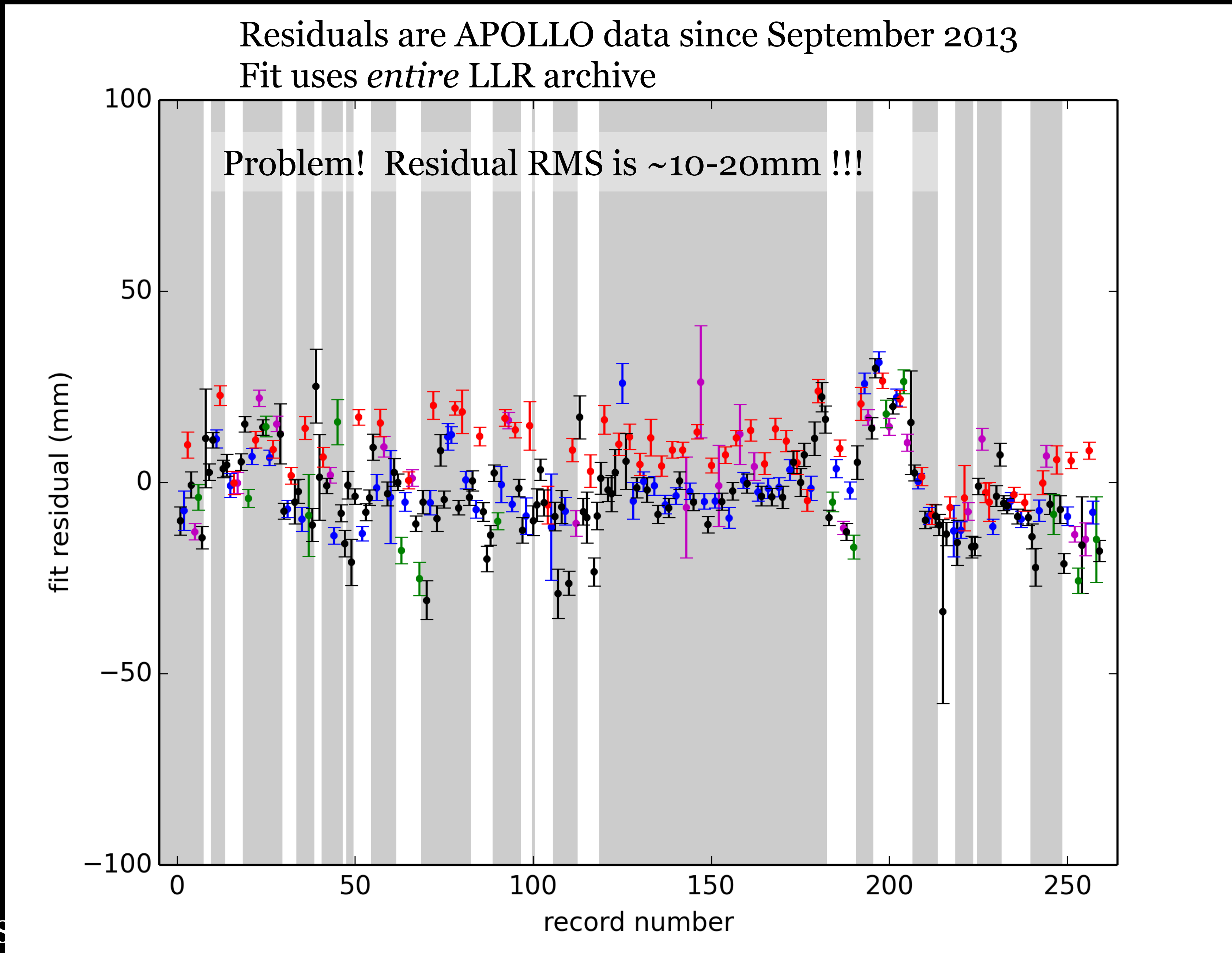
We cannot resolve individual corner cubes within an array

APOLLO Data Precision

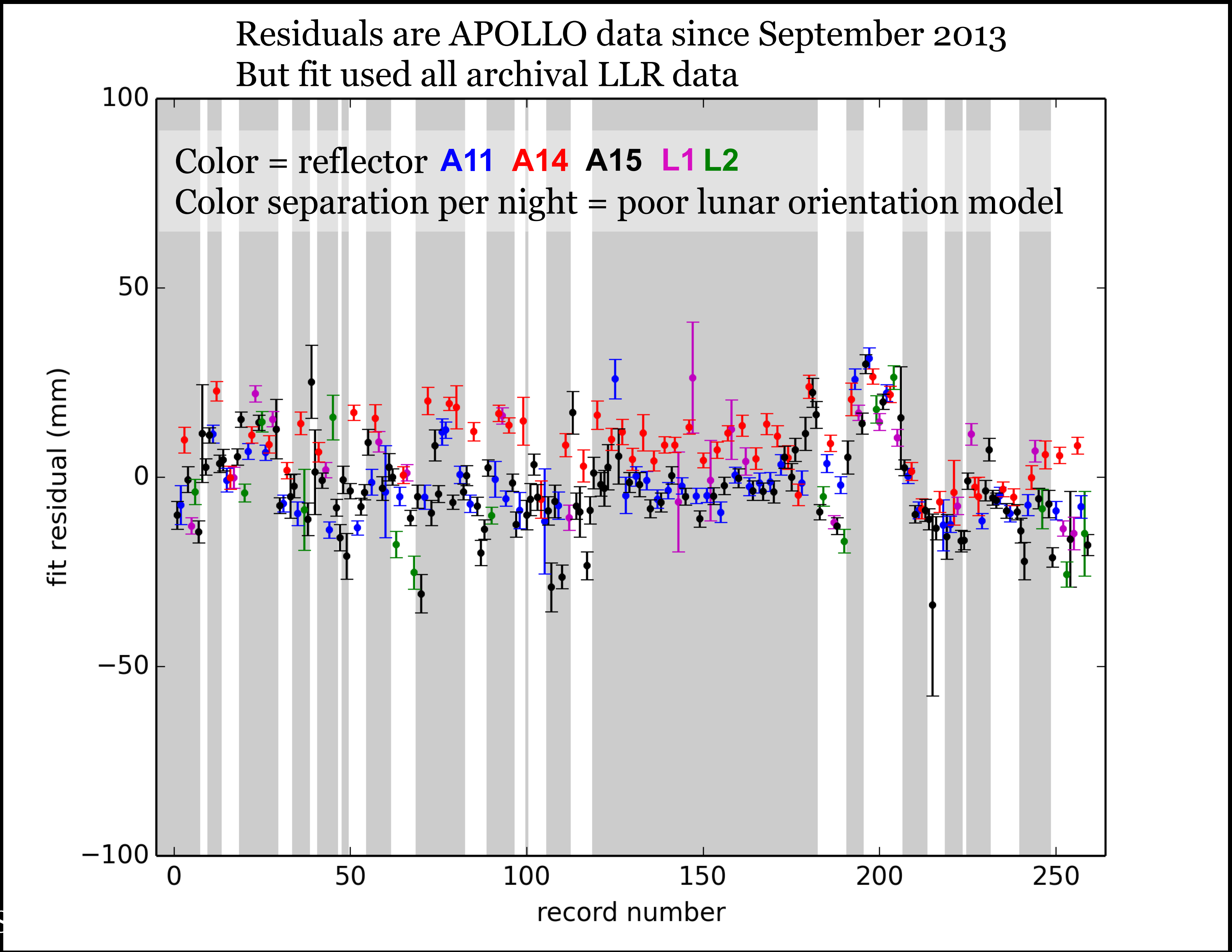


- Uncertainties are per night, per reflector; pre-APOLLO sub-centimeter rare
- Medians are 2.4, 2.7, 2.4, 1.8, 3.3 mm for A11, L1, A14, A15, L2, respectively
- Combined nightly median range error is 1.4 mm

Model vs. Data comparison



Model vs. Data comparison



Absolute Calibration System

Adelberger et al. CQG, 2017 arXiv:1706.09550

- Calibration laser pulses inserted at a known rate
- Simultaneous with lunar ranging

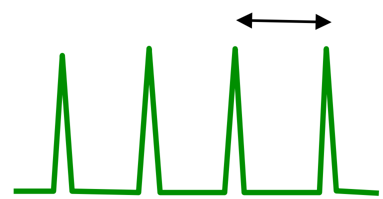
An "optical ruler" overlaid on data.

Cesium frequency standard
Microsemi 5071A
df/f ~ 10^{-12}

Fiber Laser
Toptica
PicoFYb
80 MHz

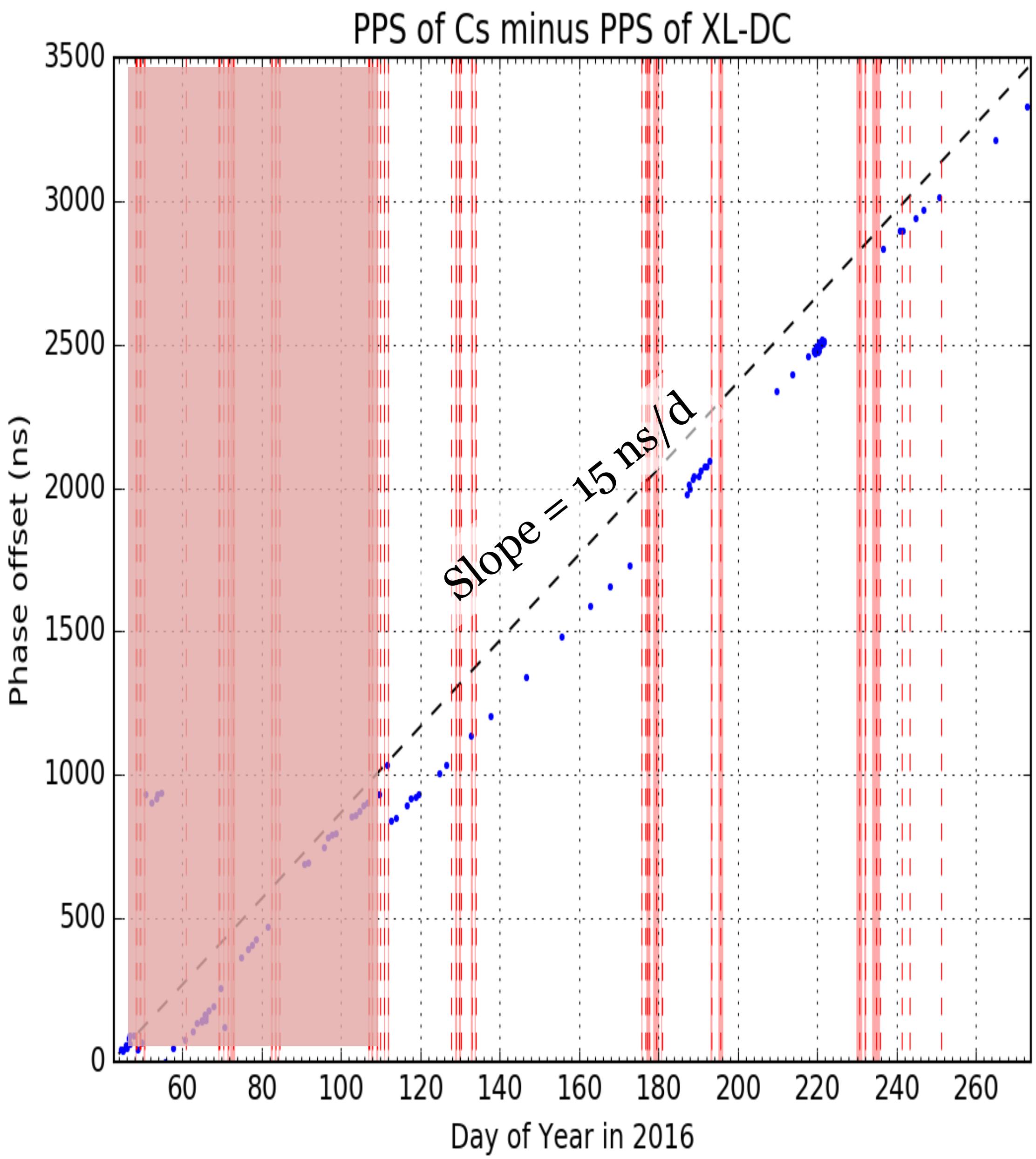
Laser locked to Cs standard

12.5000 ns



< 10ps pulse width
< 1 ps jitter

Aside: Gravitational Redshift



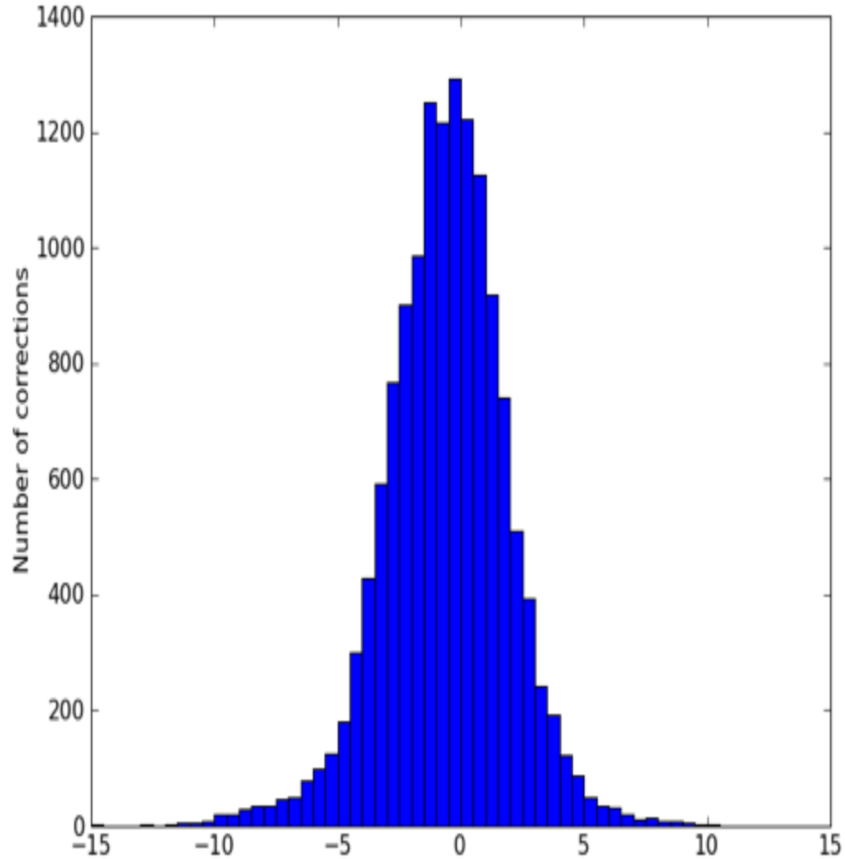
Atomic clock at 2.8 km
vs.
GPS clock "at" sea level

$$\Delta f / f$$

Gravitational Redshift:	3.0×10^{-13}
Cs clock intrinsic:	-1.3×10^{-13}
Net:	1.7×10^{-13}

Predict: 15 ns/day phase accumulation

Measure GPS-Cs clock offset



GPS clock offset [mm one-way lunar range]

vs.

GPS has excellent long-term stability, but worse short-term stability than Cs.

GPS clock offsets equivalent to ~2.5 mm added in quadrature to the raw range precision.

Now use the Cs clock (sub-mm)

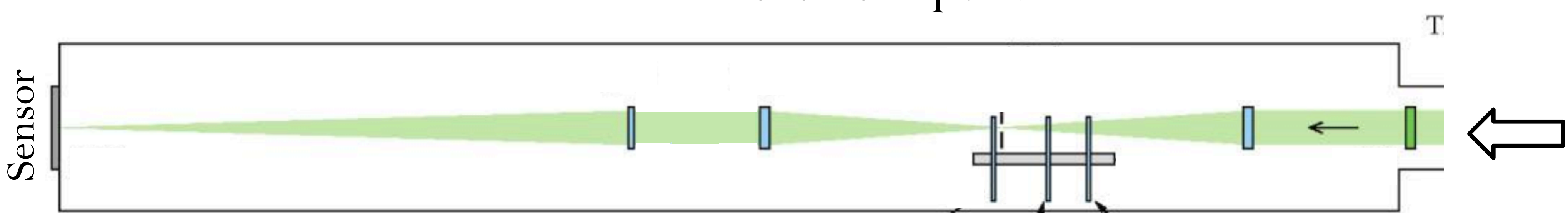
Have back-corrected our 10-year data archive as well!

Laser ranging with ACS overlay

No lunar photons in center of collimated beam because of shadow of telescope secondary mirror.

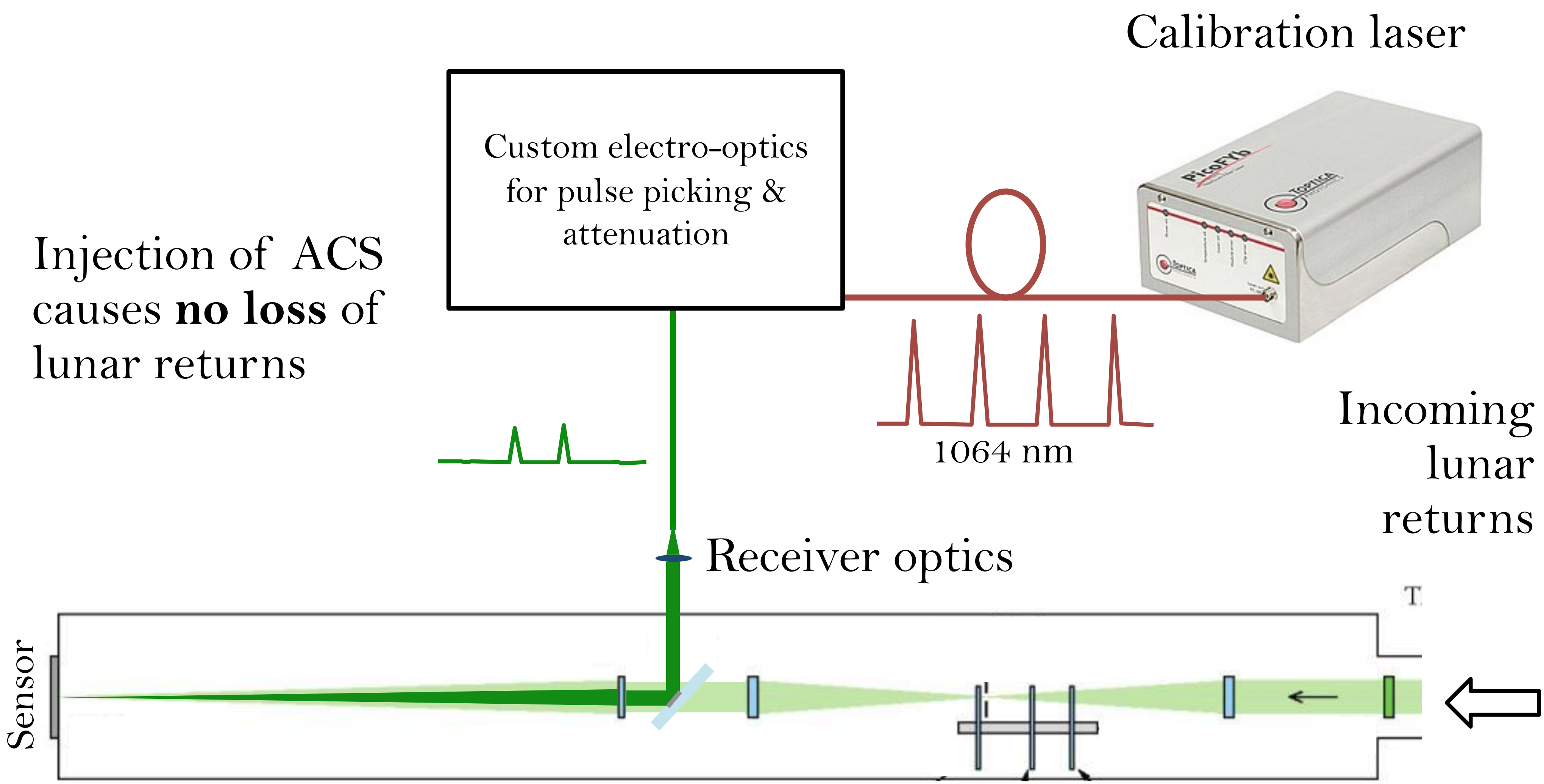
Incoming lunar returns

Receiver optics

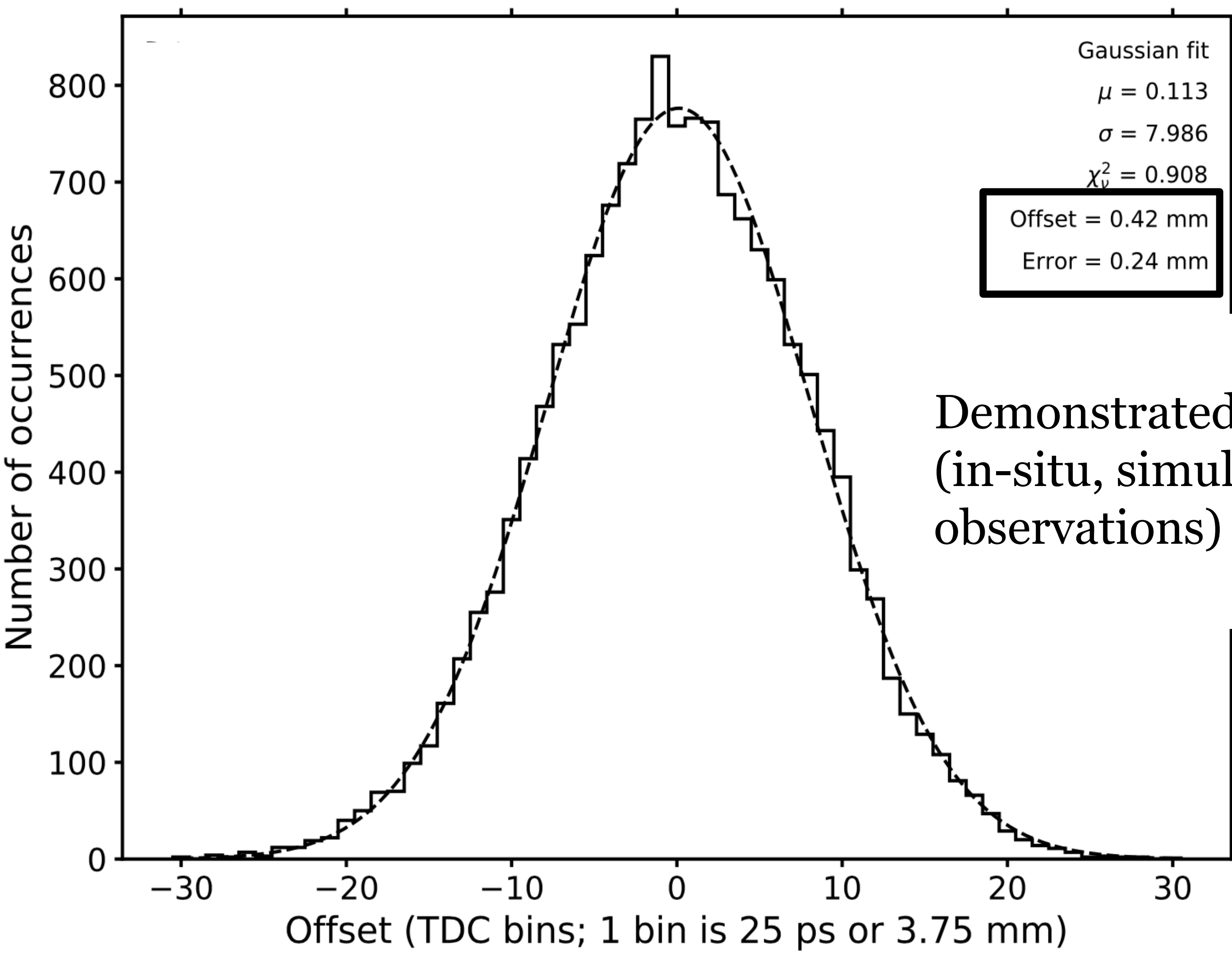


Laser ranging with ACS overlay

Injection of ACS causes **no loss** of lunar returns



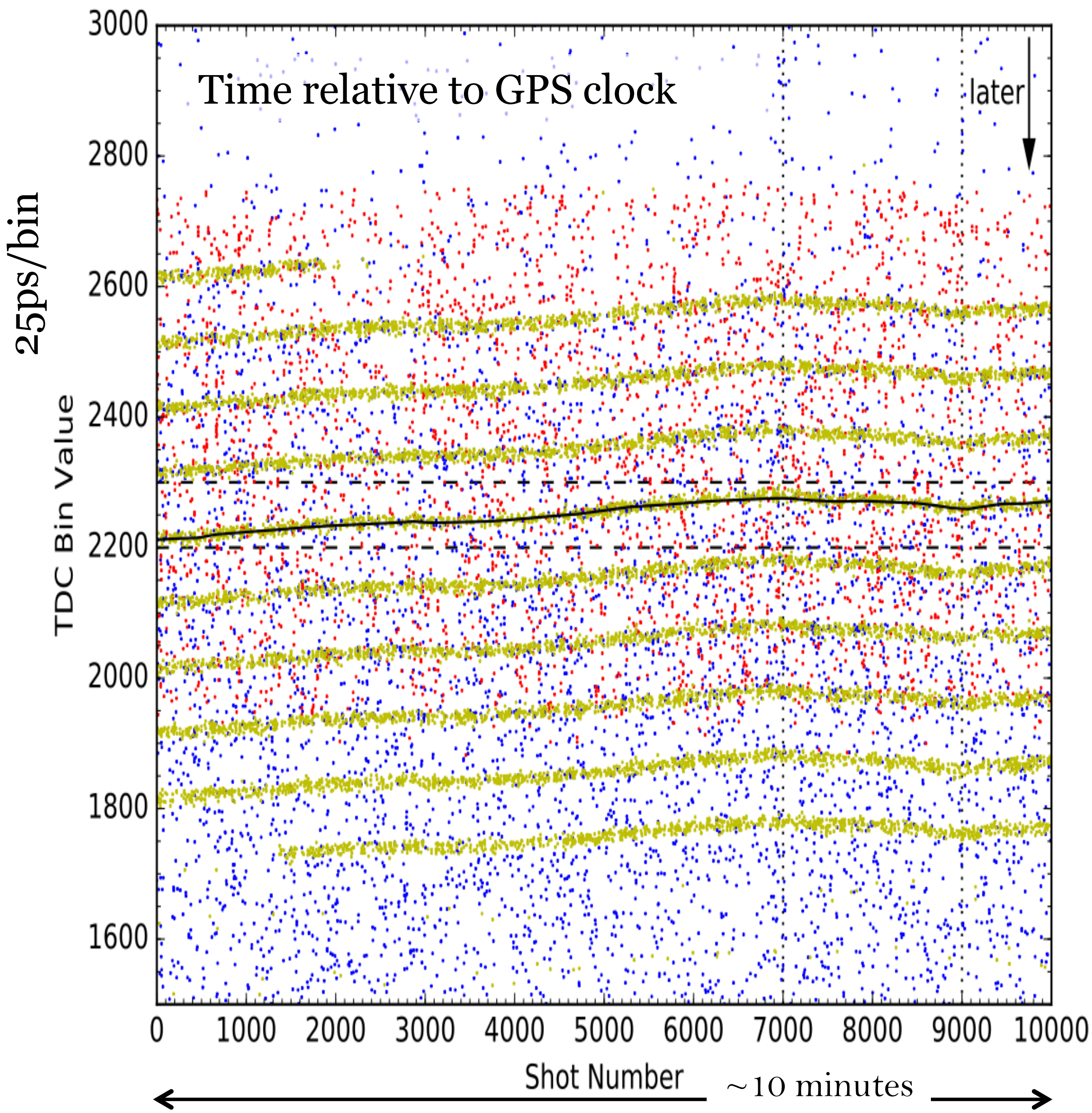
Compare APOLLO measurements of Δt of ACS pulse pairs with N*12.500000 ns



Demonstrated sub-mm timing accuracy (in-situ, simultaneous with LLR observations)

Adelberger et al. CQG, 2017 arXiv:1706.09550

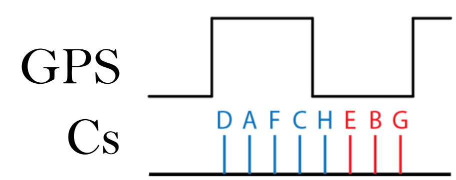
ACS calibration atop Lunar Returns 2016.09.12



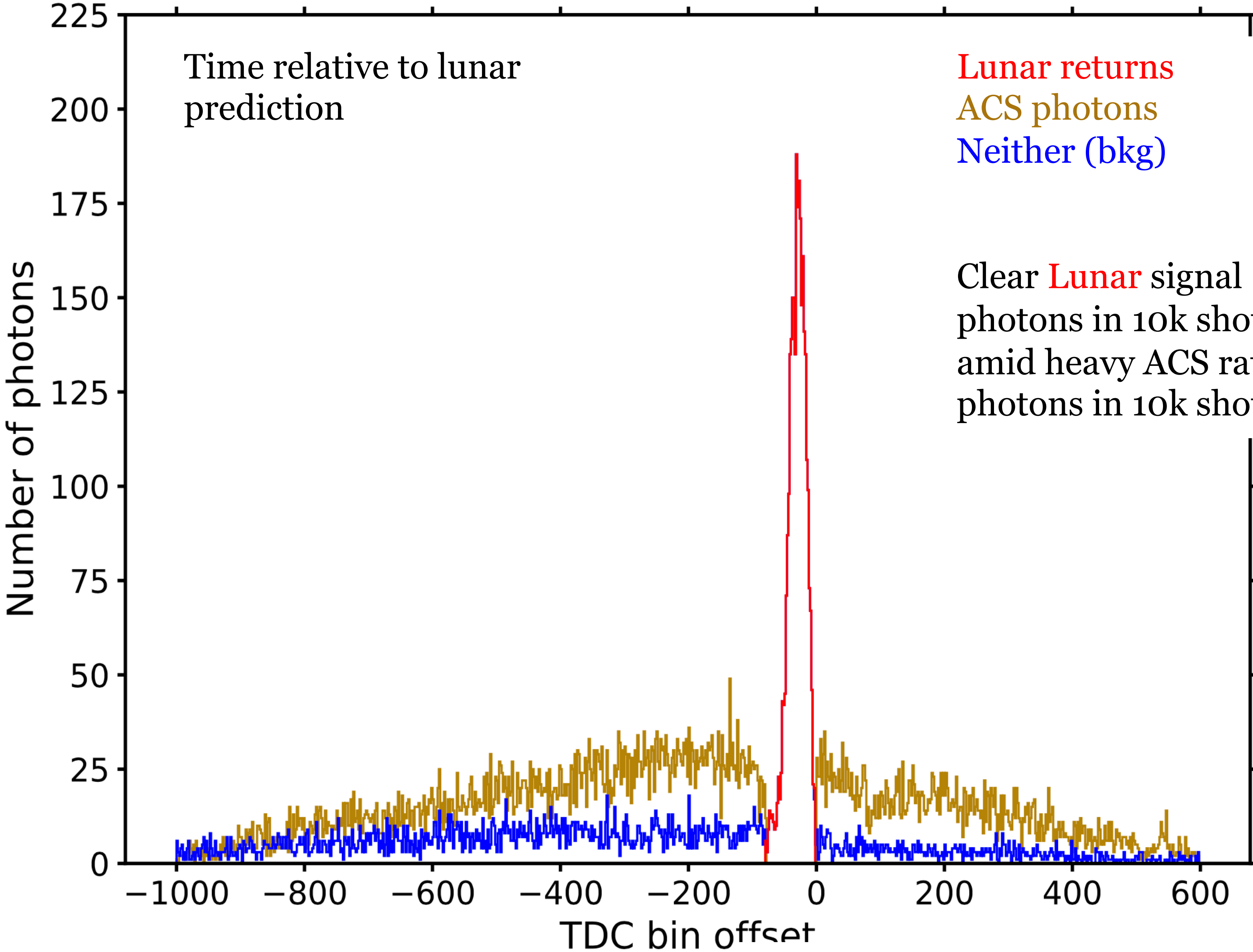
Total shots (10k)
ACS photons (11k)
Lunar returns (3k)
Neither (bkg)
– clock comparison

Can tag ACS photons very efficiently even when overlaid with Lunar returns.

Use knowledge of ACS clock phase relative to GPS clock



ACS calibration atop Lunar returns 2016.09.12



Clear Lunar signal (3k photons in 10k shots), even amid heavy ACS rate (11k photons in 10k shots)

Adelberger et al. CQG, 2017 arXiv:1706.09550

The Absolute Calibration System shows that:

- APOLLO **accuracy is 1–2 mm,** characterized at the sub-mm level
  Confident that **range model deficiencies** cause the ~10 mm residuals
- GPS clock offsets caused ~2.5 mm range error (correctable)
  Back-correction applied to the entire 10-year APOLLO data archive (clock logs) **reduces typical archival range error from 2.5 mm to 1.6 mm**
- Cs clock now in use & on-demand calibration now standard
  Enables routine monitoring of system stability
- The ball is squarely in the modeling community's court now.

Adelberger et al., CQG (2017) arXiv:1706.09550
Liang et al., CQG (2017) arXiv:1706.09421

Ongoing: Solar System model upgrades

- Very few capable models

APOLLO residuals (rms)

France, Russia, Germany, USA (JPL and **Harvard**)

Some groups are in communication to share ideas

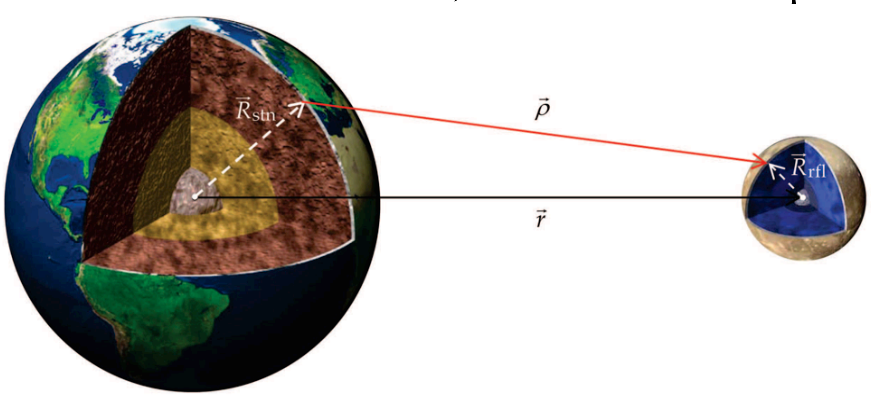
JPL: ~15 mm

PEP: ~30 mm

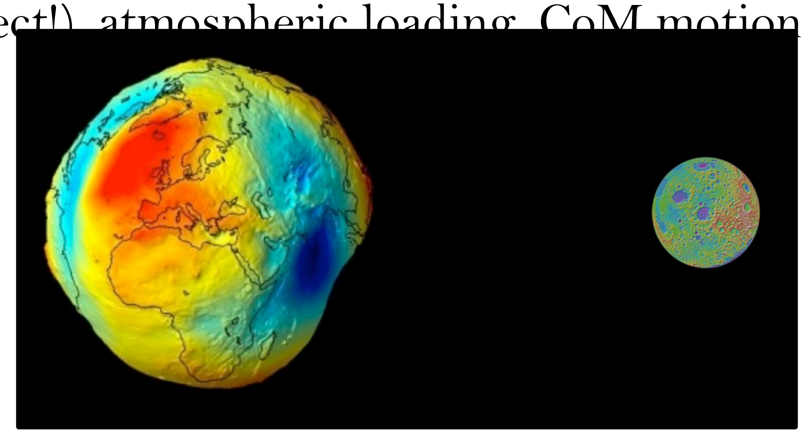
Planetary Ephemeris Program

- Current focus of model development
  - Find bugs/limitations (e.g. some series truncated for cm accuracy)
  - Improve/expand models

    Lunar interior, solar radiation pressure (4 mm effect!), atmospheric loading, CoM motion



vs.



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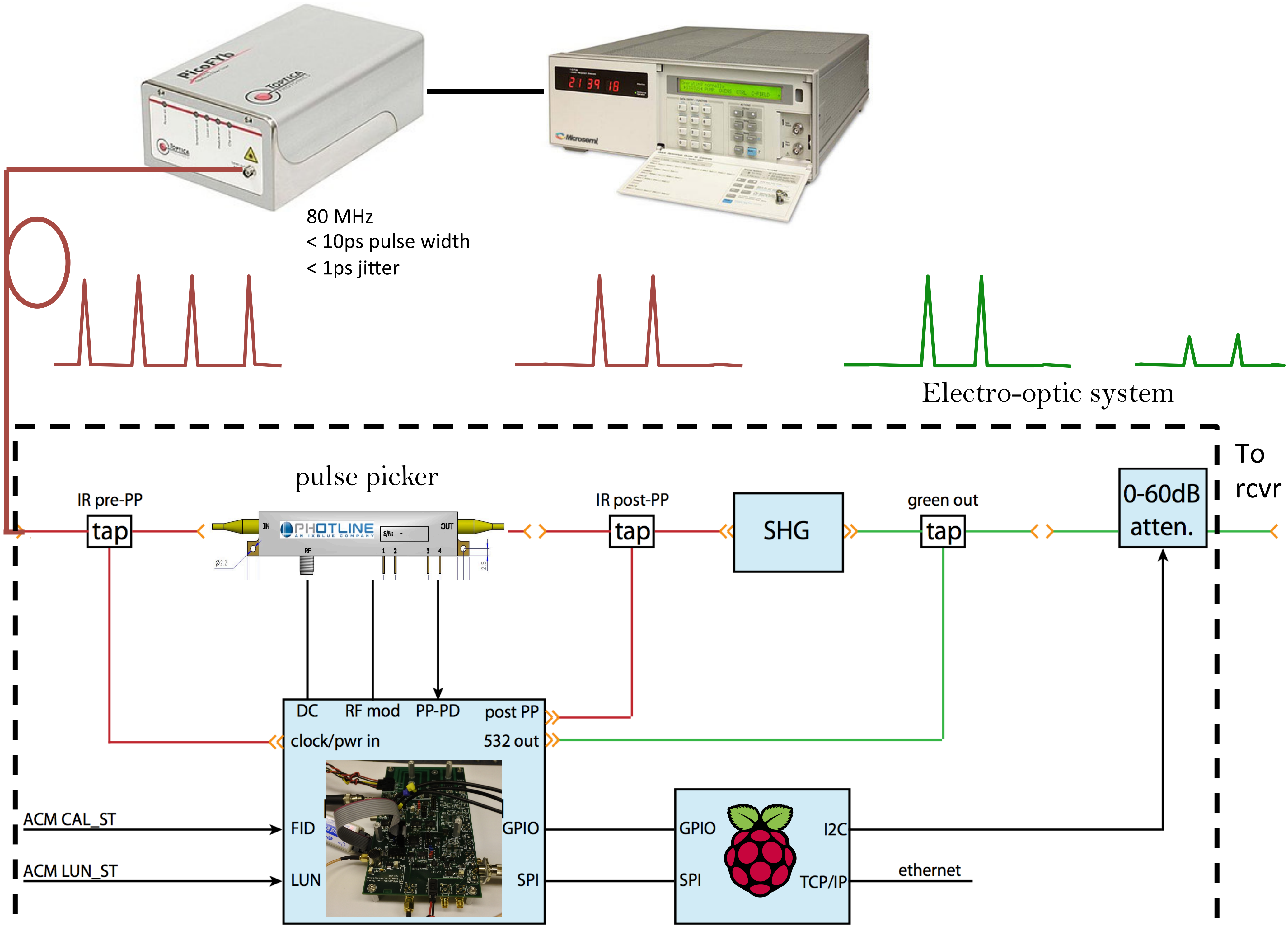
    Lunar interior, solar radiation pressure (4 mm effect!), atmospheric loading, CoM motion

- **PEP** advantages
  - Full monolithic integration of Solar System + Moon
  - Broad datasets (radar, doppler, planetary fly-bys, pulsar timing)
  - **Tight coupling between APOLLO & PEP: ~real-time testing**

Conclusion

- LLR provides frontier constraints on gravity
- APOLLO delivers millimeter-accurate LLR data
- Model improvements are required for improved gravitational constraints
- A close and productive APOLLO-PEP collaboration is underway

EXTRAS



80 MHz
< 10ps pulse width
< 1ps jitter
Electro-optic system
pulse picker
IR pre-PP
tap
IR post-PP
tap
SHG
green out
tap
0-60dB atten.
To rcvr
DC
RF mod
PP-PD
post PP
clock/pwr in
532 out
ACM CAL_ST
ACM LUN_ST
FID
LUN
GPIO
SPI
GPIO
SPI
I2C
TCP/IP
ethernet

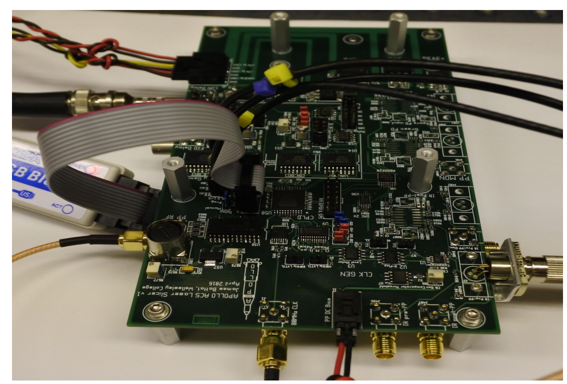
Absolute Calibration System

- Part 1: Clock: Cs vs. GPS

  Installed February 2016

- Part 2: Laser, pulse selection and overlay with LLR observations

  Installed August 2016



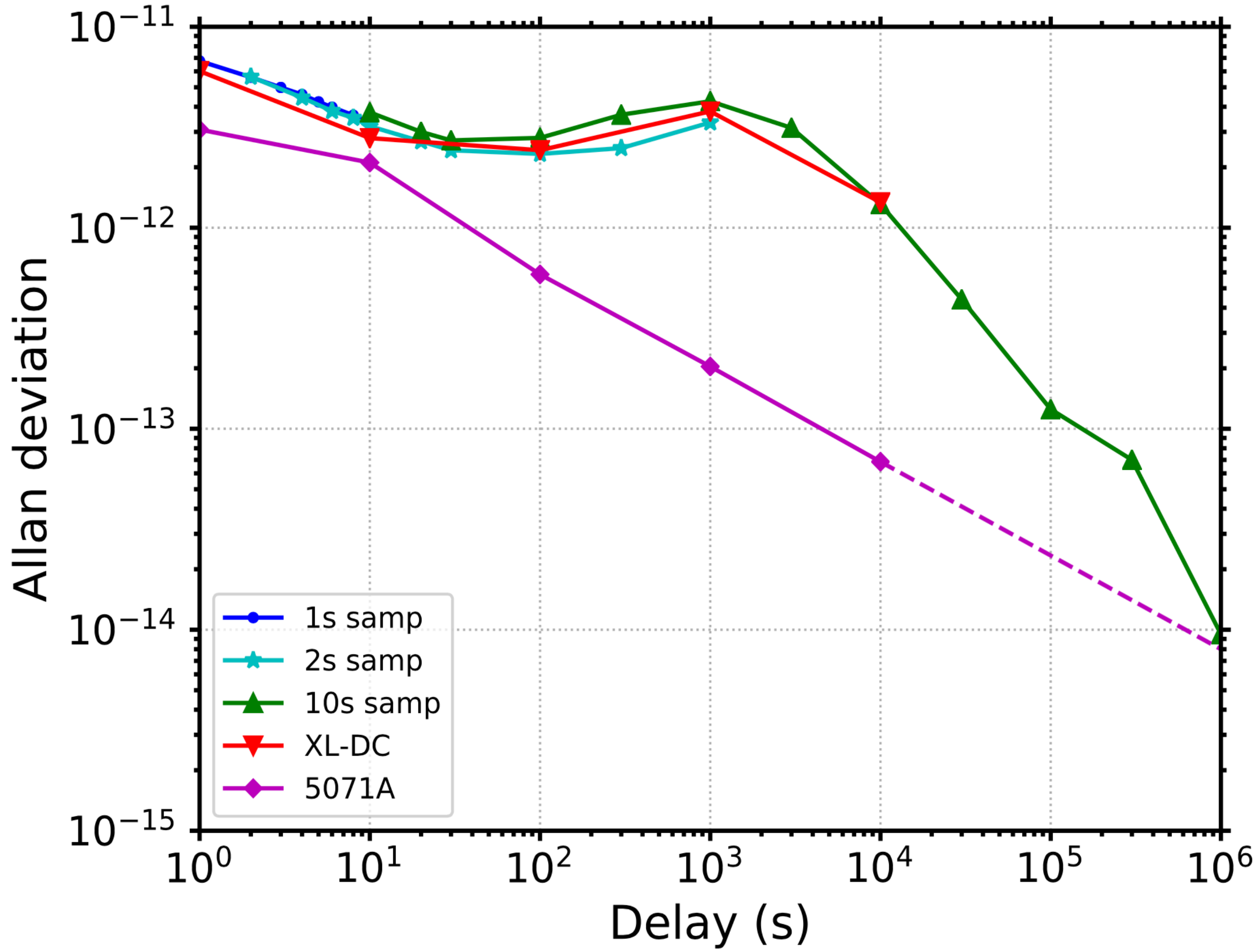
Phase 1: Clock installation (Feb. 2016)

GPS clock

Universal Counter
(Clock comparison)

Cs clock

Allan Deviation of Cs and XL-DC clocks



Uses Cs clock as the reference for XL-DC measurements.

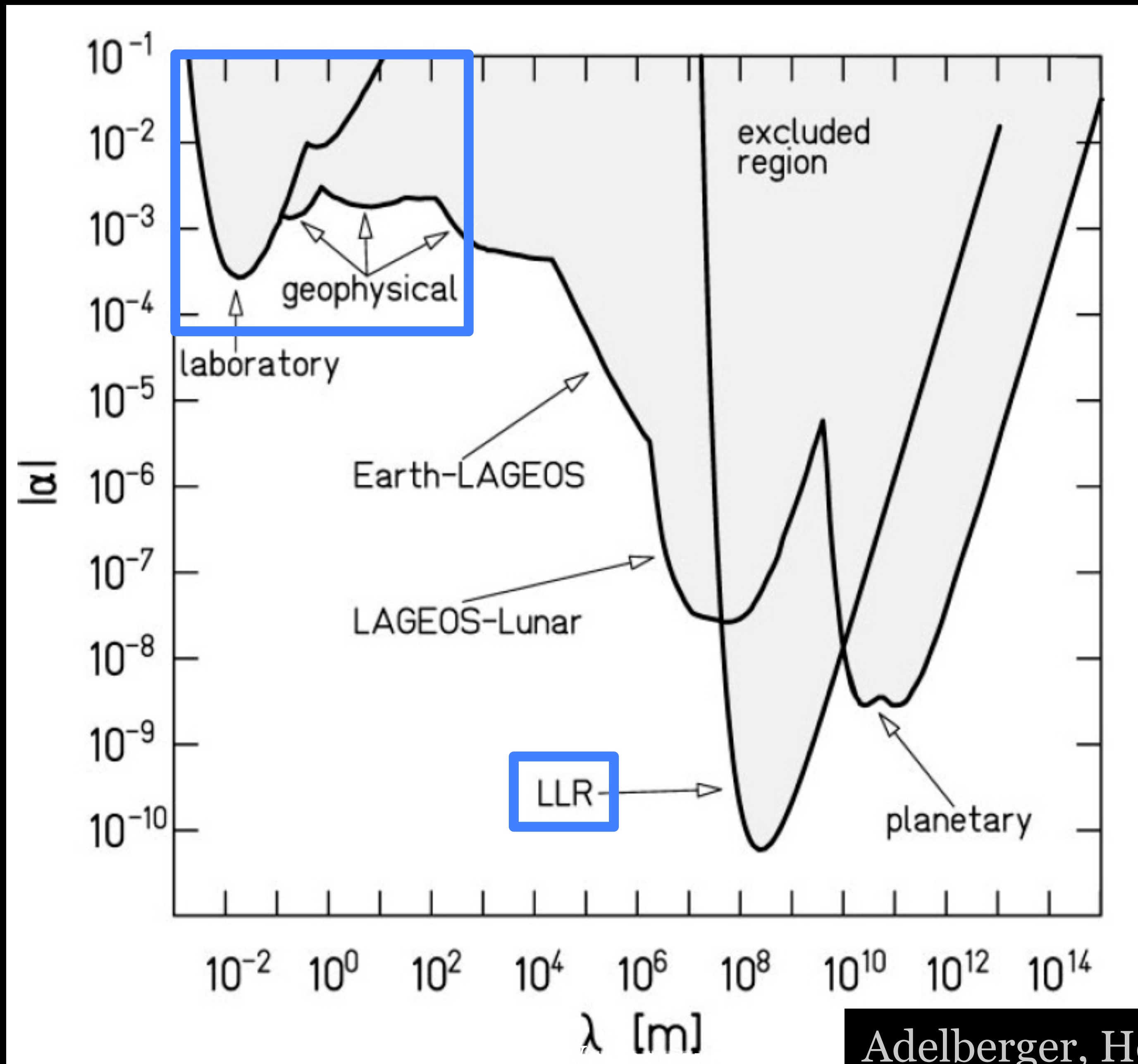
Cs Allen deviation measured by manufacturer relative to a hydrogen maser

Cs has better short-term stability

XL-DC does better at >1e6 seconds due to GPS tie-in

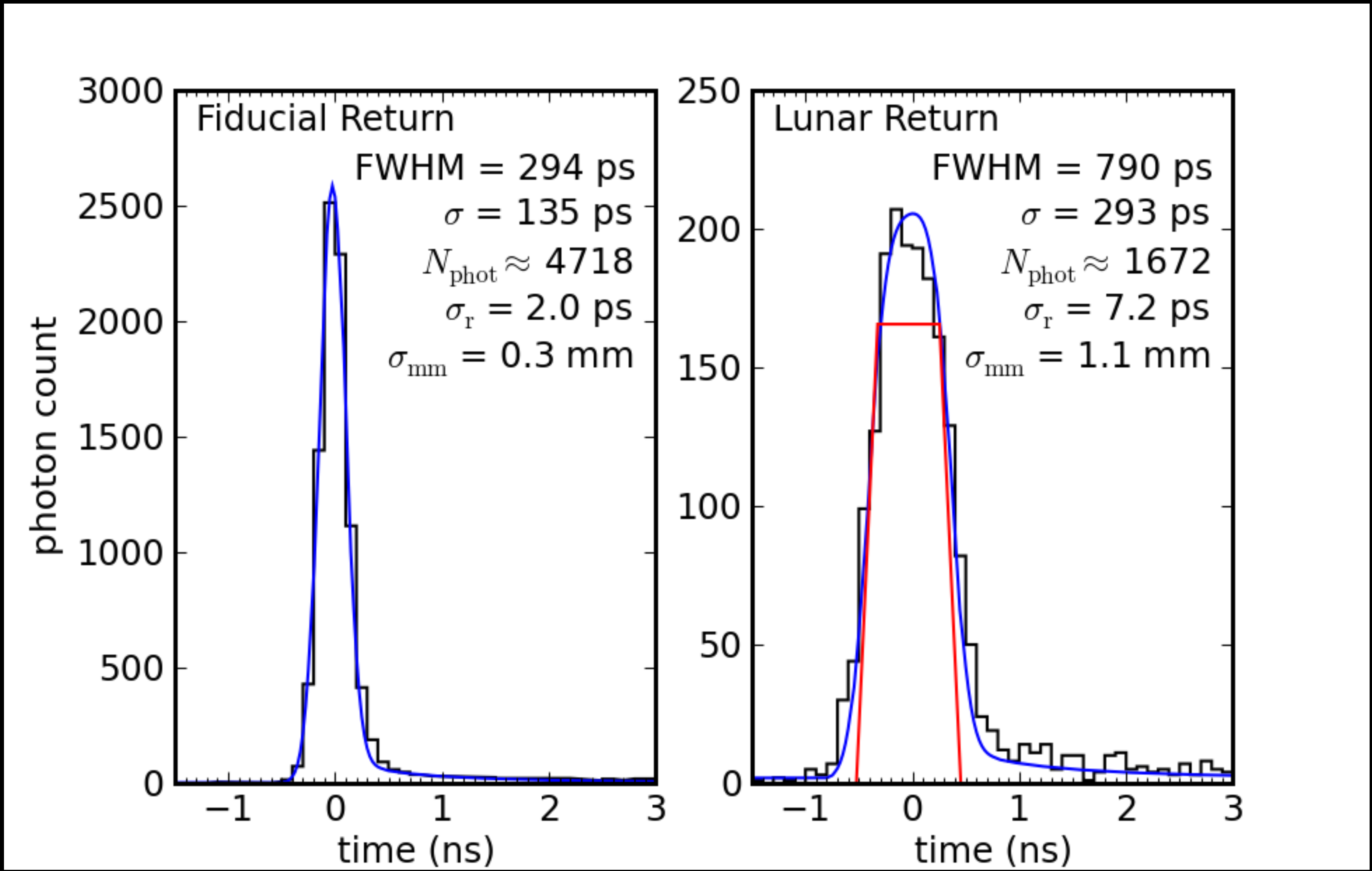
Note difficulty of GPS solution at 1e3 second timescale (atmospheric effects)

Yukawa Interaction Constraints

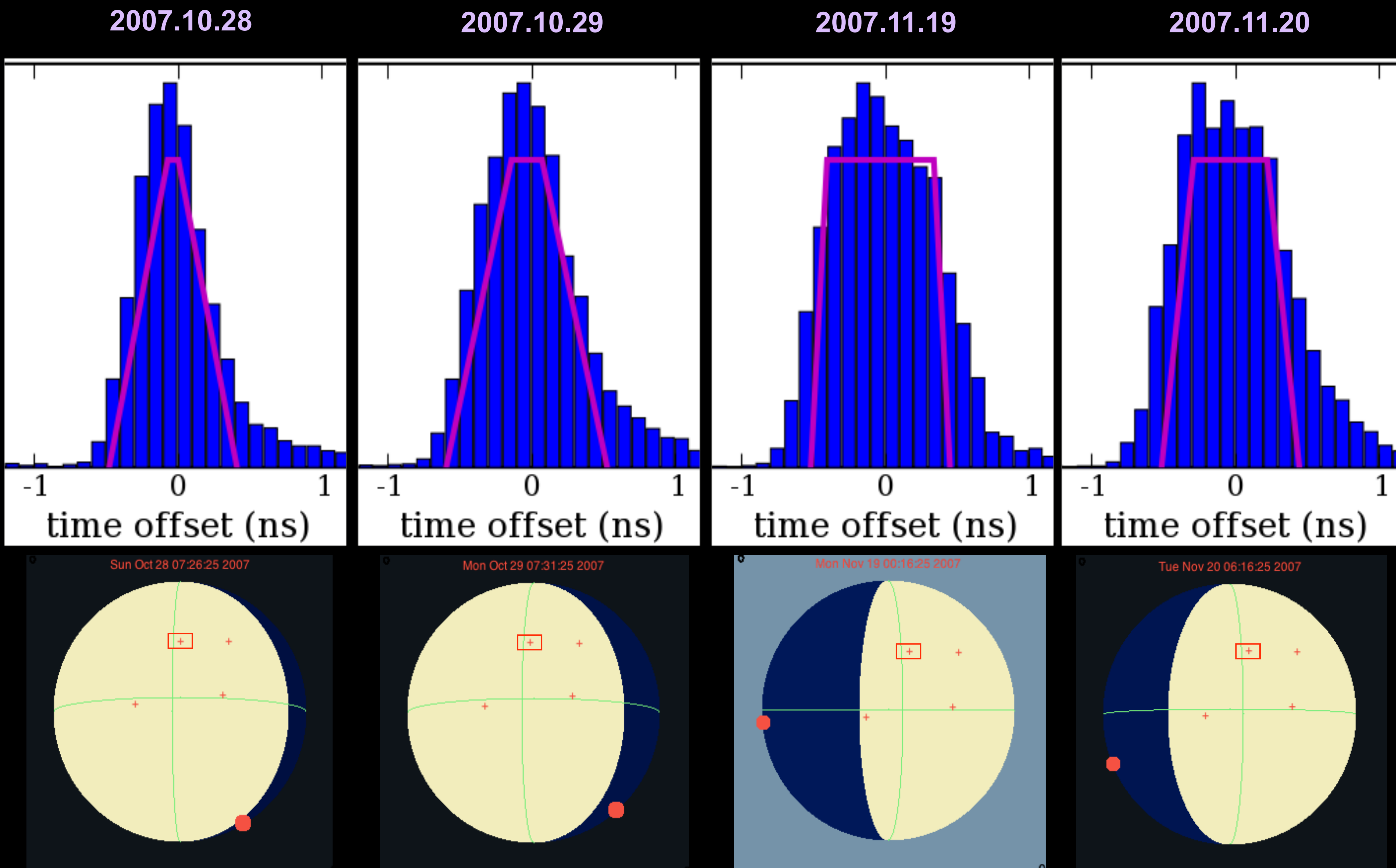


Adelberger, Heckel, Nelson
hep-ph/0307284

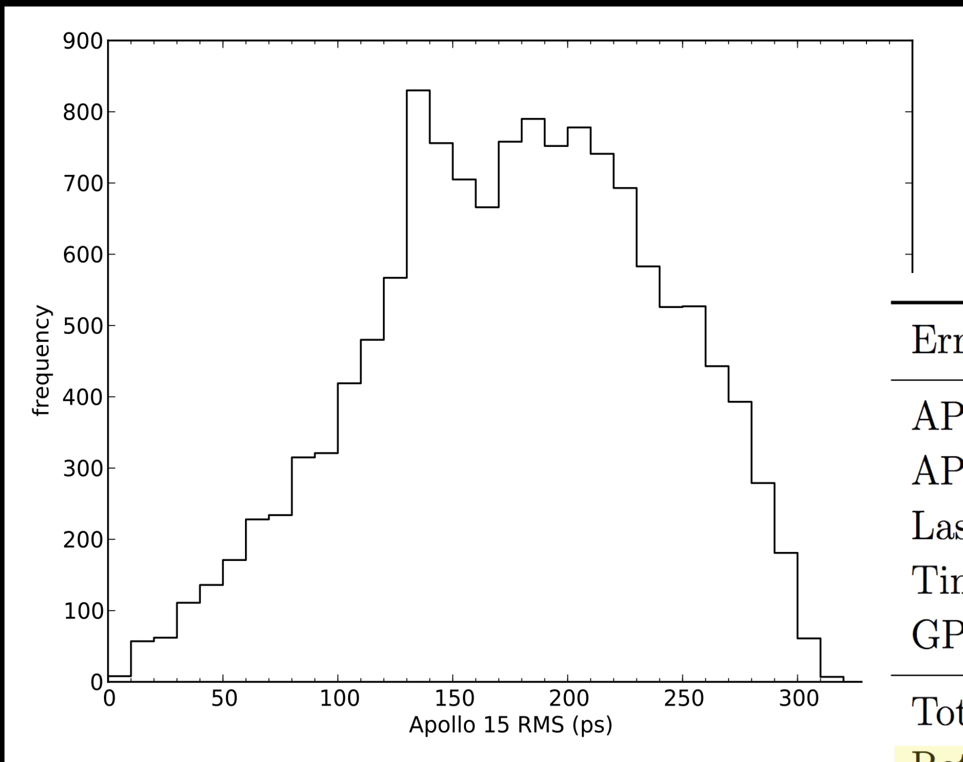
Fitting the Return & Reflector Trapezoid



Sensing the Array Size & Orientation



Libration dominates the error budget



Error Source	RMS Error (ps)	RMS Error (mm)
APD illumination	60	9
APD intrinsic	< 50	< 7.5
Laser pulse	45	7
Timing electronics	20	3
GPS clock	7	1
Total APOLLO	93	14
Retroreflector array	100–300	15–45
Total random uncertainty	136–314	20–47