Lunar Laser Ranging

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University of Colorado
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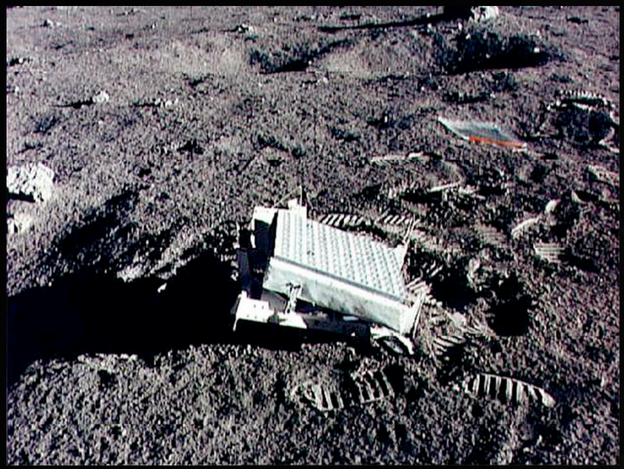
Outline

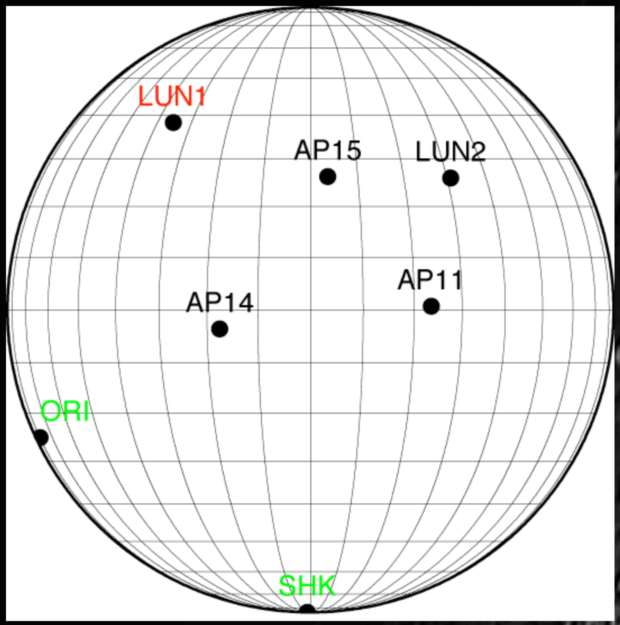
- History of LLR
- Measurements & Detectors
- Science enabled by LLR
- Summary

History

- First retroreflector array positioned on lunar surface by crew of Apollo 11, July 1969
- 4 more positioned by Apollo 14,15, and French built arrays on Soviet Luna missions



Apollo 14 retroreflector



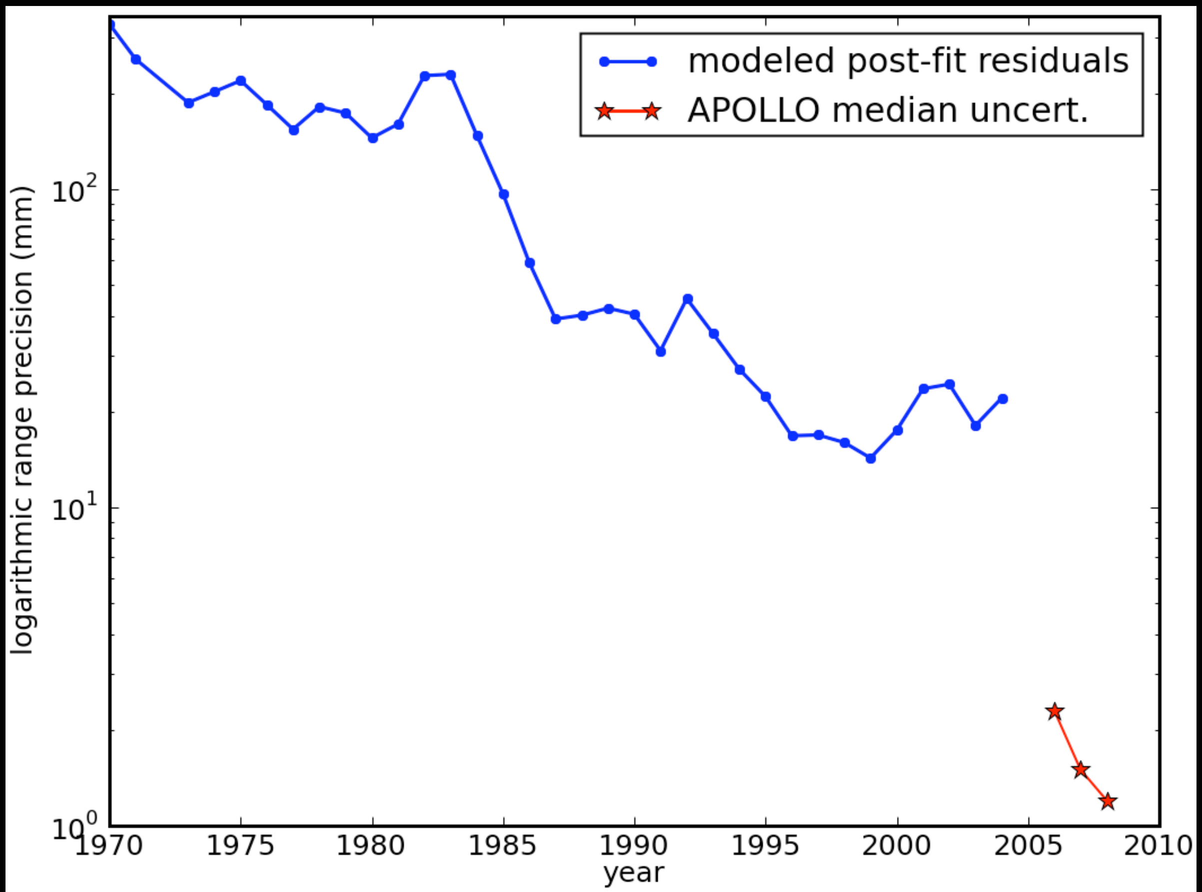
Distribution of arrays on lunar surface

History

- Early ranging measurements at Lick, McDonald (right), CERGA (France)
- Now, APOLLO (Apache Point Observatory Lunar Laser-ranging Operation)

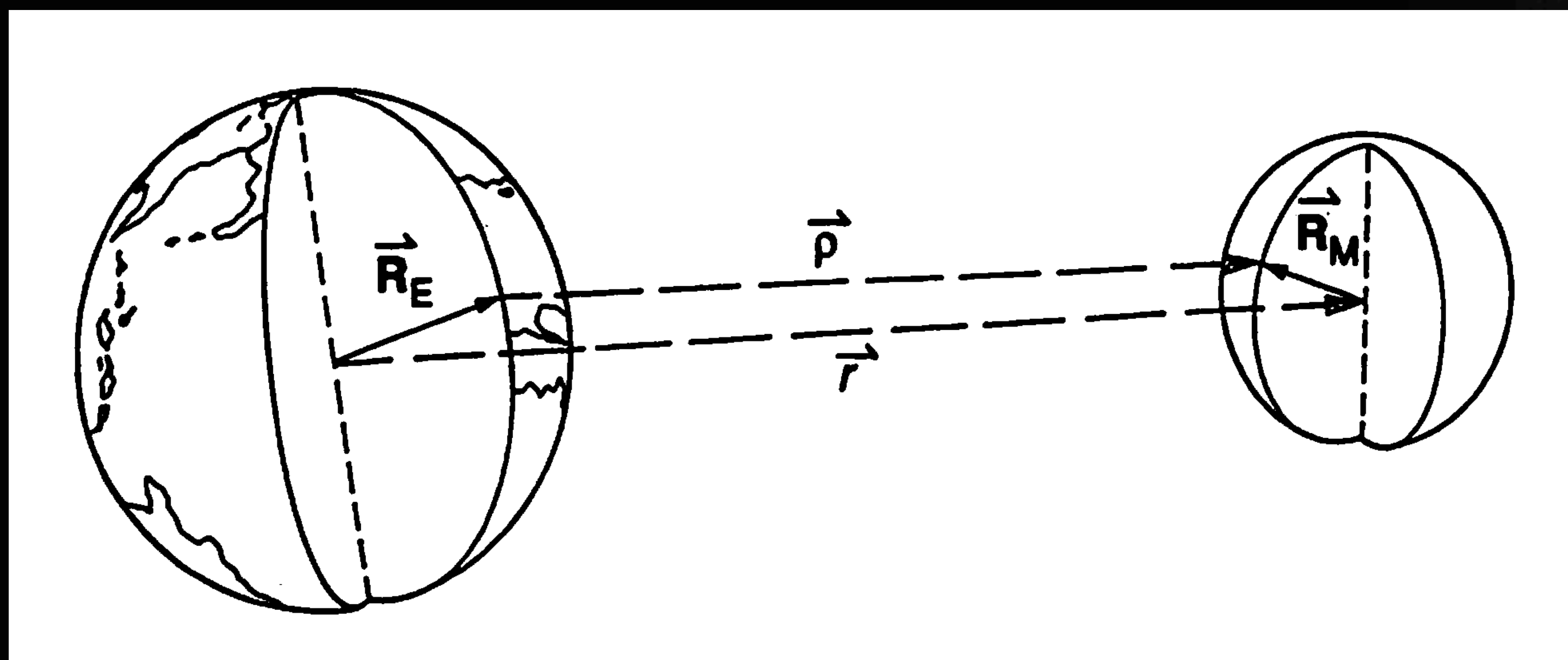
History

- First measurements good to ~20cm



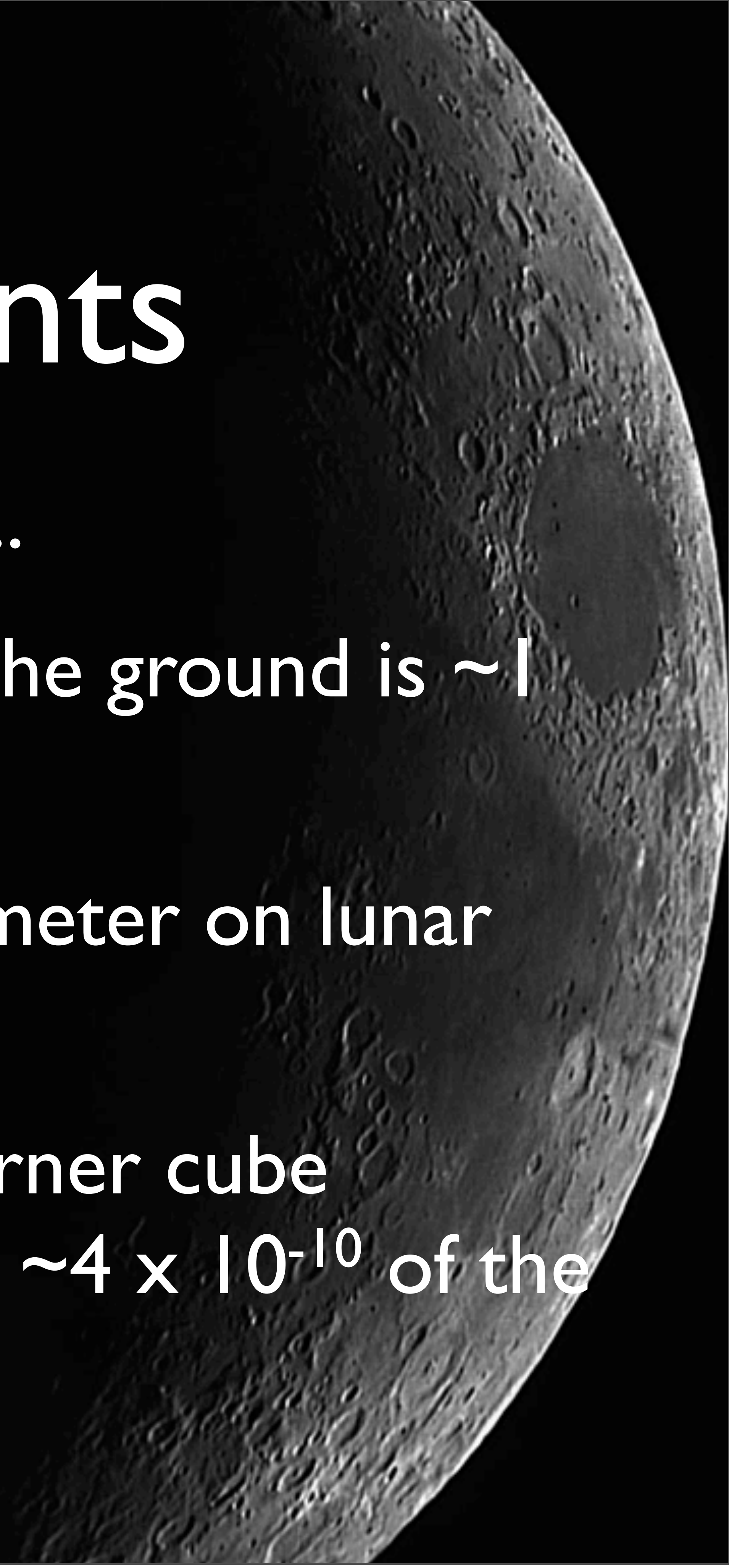
- Ground station changes get this down to ~2cm in the 1980's (even with a smaller scope!)
- Early data still vital for studying effects with long characteristic timescales

Measurements



$$\vec{\rho} = |\vec{r}| + \vec{R}_M \cdot \hat{r} - \vec{R}_E \cdot \hat{r}$$

Measurements



- Light leaves laser on the ground...
  - Best atmospheric seeing from the ground is ~1 arcsecond
    - Beam diverges to 1.8 km diameter on lunar surface
      - Apollo 3.8 cm diameter corner cube retroreflector only catches $\sim 4 \times 10^{-10}$ of the incoming light

Measurements

- Spread of Apollo retroreflector ~ 10 arcseconds
  - Beam diverges to 20 km diameter area on Earth's surface
    - A 1m telescope on Earth receives only 2×10^{-9} of returning photons
- Total losses: $\sim 10^{-20}$! (not including additional problems like detector QE, mirror reflectance, etc. on ground)

The APOLLO Laser

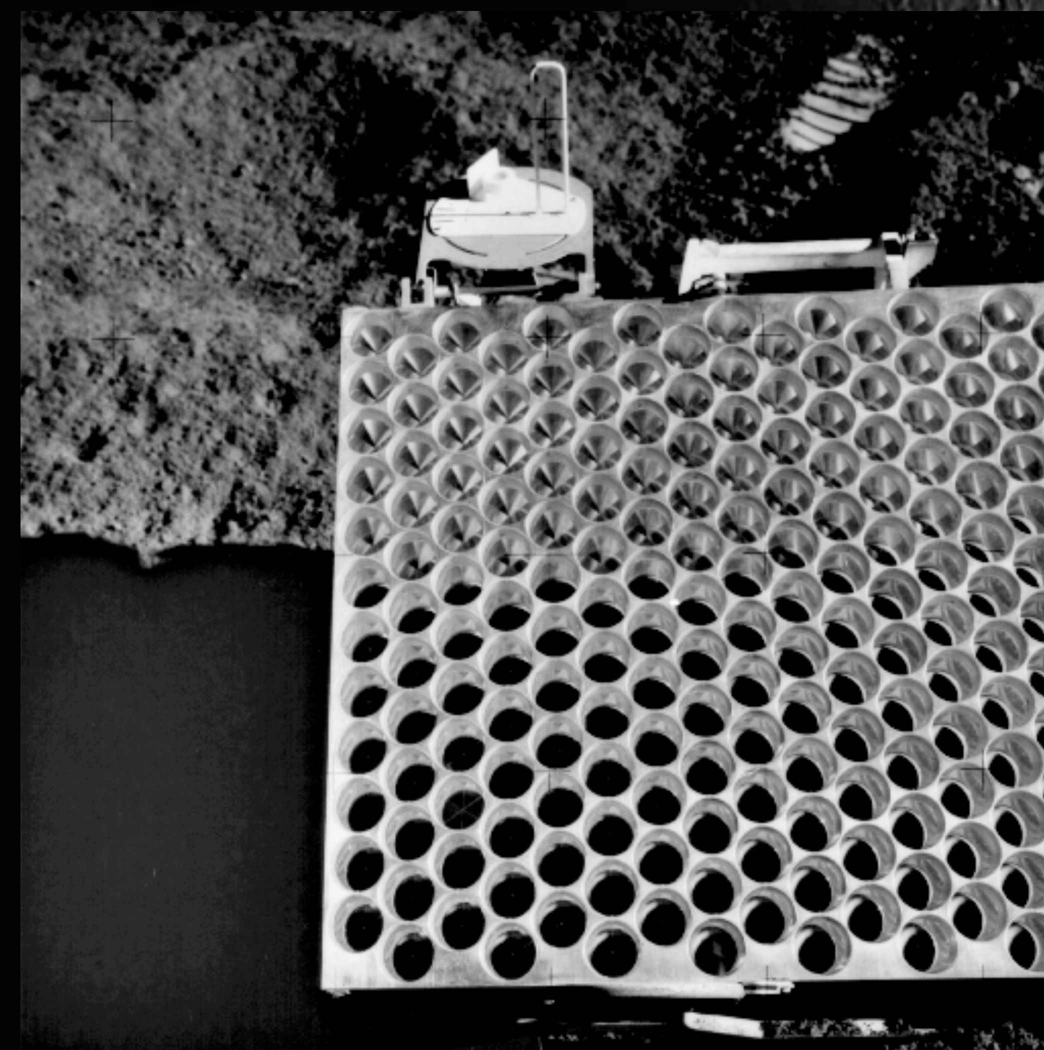
$$\lambda = 532\ nm$$
$$E_{pulse} = 115\ mJ$$
$$\nu_{pulse} = 20\ Hz$$
$$\sigma < 100\ ps$$

$$\Rightarrow \quad 6 \times 10^{18} photons/sec$$

- Need many pulses for multiple detections!

Detectors

Apollo 3.8cm retroreflector (right), and a 10cm retroreflector just qualified for lunar environment (left)


Apollo 15 retroreflector (300 3.8cm corner cube retroreflectors)

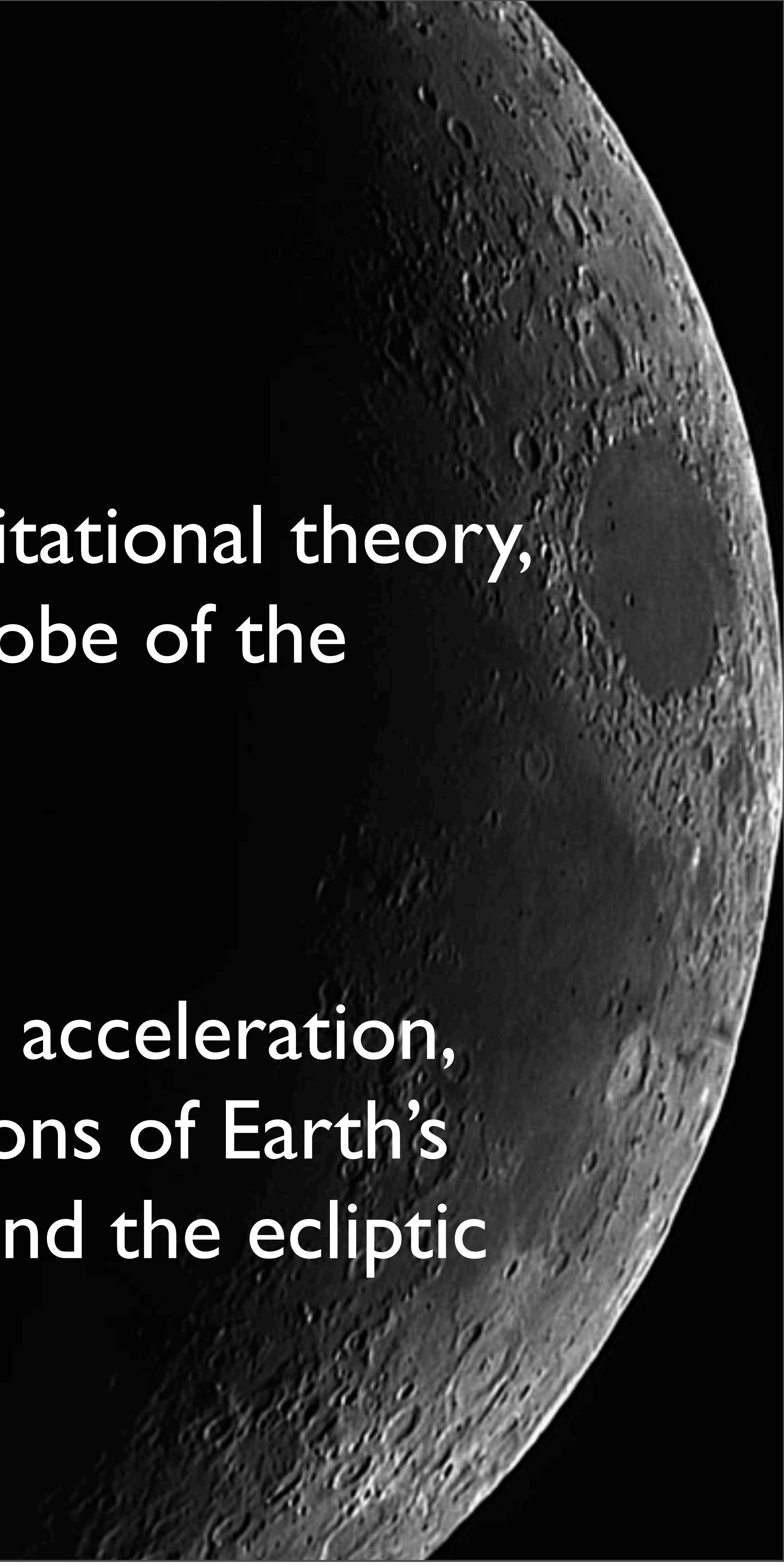
Detectors

Lunar Libration

- Physical size of Apollo arrays is now the limiting factor
- Changing orientation due to lunar libration causes spread in return times

Future Detectors

- Retroreflectors > 10cm could provide returns as good as the Apollo arrays
- However, they are more susceptible to thermal expansion, which becomes significant systematic error around ~1mm



Science

- LLR can be used to test gravitational theory, in addition to serving as a probe of the Moon's interior
  - First, must correct for:
    - Precession, nutation, tidal acceleration, and the relative orientations of Earth's equator, the lunar orbit, and the ecliptic

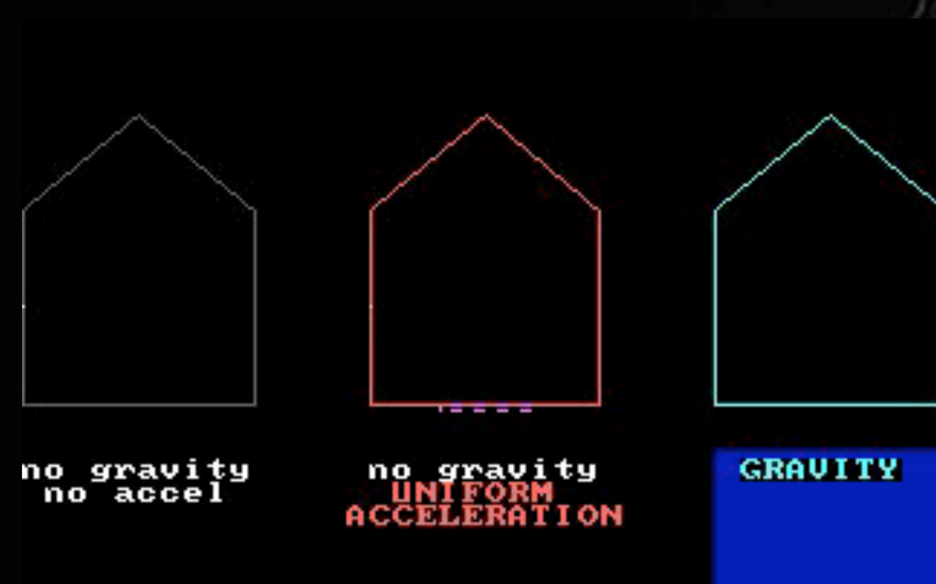
Testing GR with LLR

1. Is the Equivalence Principle exact?

- Equality of gravitational and inertial masses

$$M_{inertial} \times a = M_{gravitational} \times g$$

- Nearly all alternate theories of gravity predict EP violations

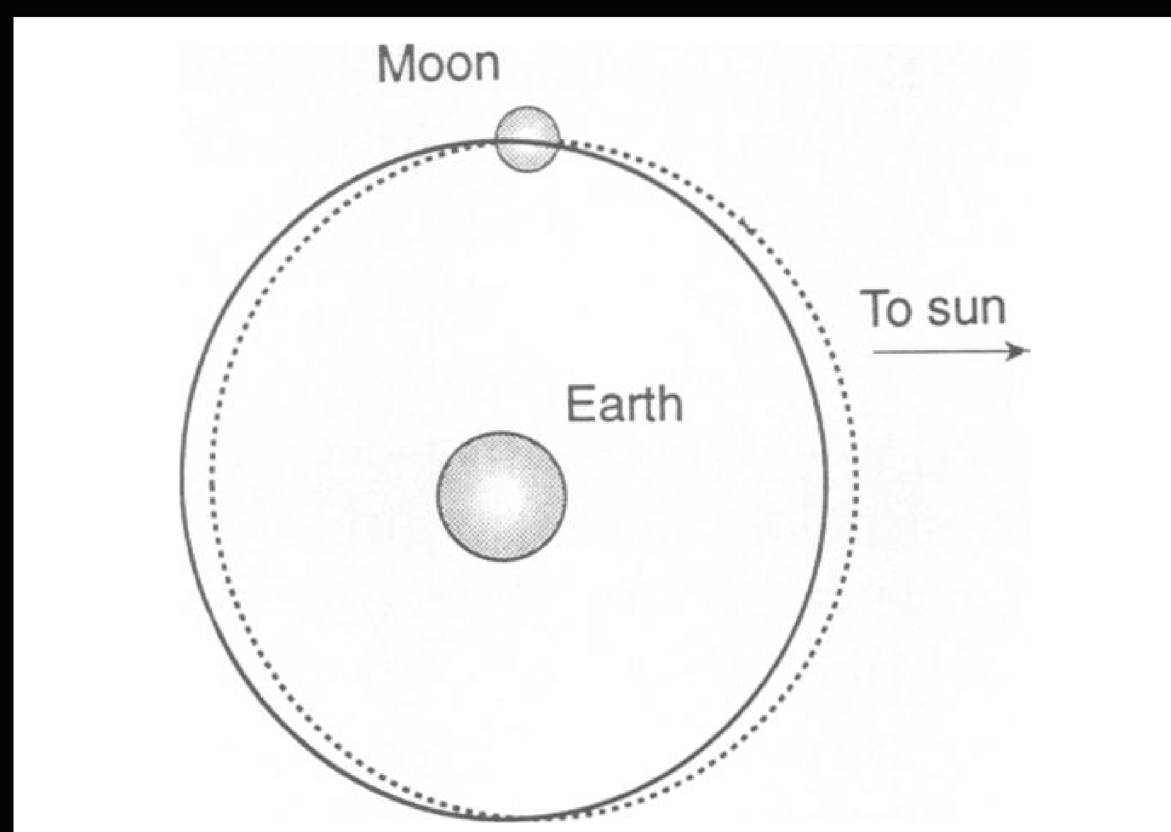


Testing GR with LLR

- Weak Equivalence Principle:
  - Laws of *motion* are the same for freely falling bodies and bodies in inertial reference frames
- Strong Equivalence Principle:
  - Laws of *nature* are the same in uniform static gravitational fields and non-inertial reference frames

Testing GR with LLR

How does gravity pull on itself?



Testing GR with LLR

2. Does the strength of gravity vary with time?

$$F = G\frac{m_1 m_2}{r^2}$$

Current LLR constraint:

$$\frac{\dot{G}}{G} < (4 \pm 9) \times 10^{-13}/yr$$

Testing GR with LLR

3. Do extra dimensions/new physics alter the inverse square law?

- Modifying gravity to explain dark energy has repercussions for lunar orbit
- Accuracy needed to falsify/confirm such theories is within a factor of 10 of current LLR

Testing GR with LLR

4. What is the nature of space-time?

- GR predicts that a gyroscope moving through curved space-time will precess
  - "Geodetic precession" of 19.2 ms/yr
- Earth-Moon system = gyroscope (essentially)
- LLR Constraint:

$$K_{gp} = (-1.9 \pm 6.4) \times 10^{-3}$$

Testing GR with LLR

- Parameterized Post-Newtonian Formalism

  $\gamma = \text{space-time curvature produced/unit mass}$

  $\beta = \text{measure of gravity's non-linearity}$

- In GR, $\gamma = \beta = 1$
- Current Constraints:

  $(\gamma - 1) = (2.1 \pm 2.3) \times 10^{-5}$ (Shapiro Delay)

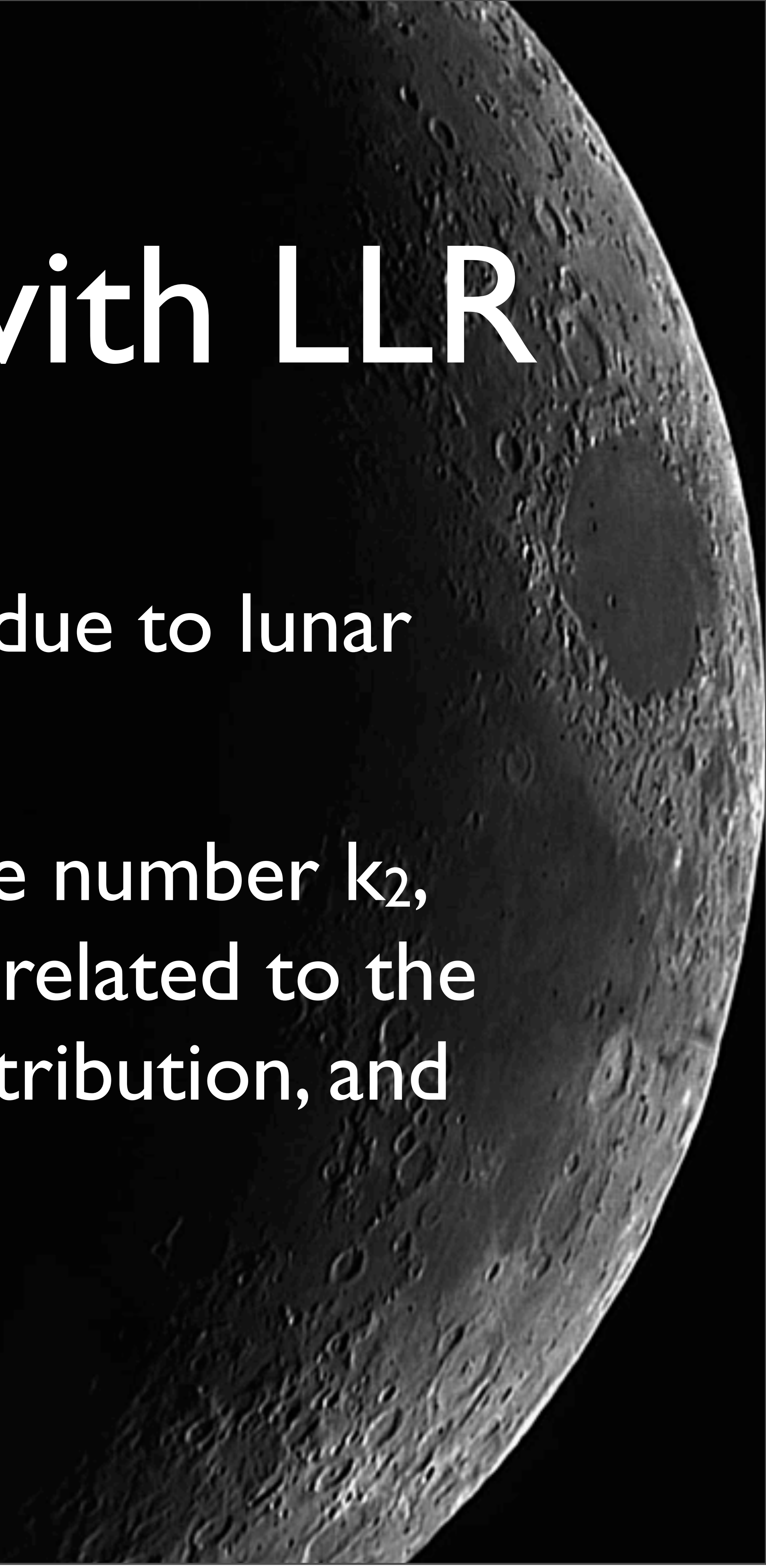
  $(\beta - 1) = (1.2 \pm 1.1) \times 10^{-4}$ (LLR)

Testing GR with LLR

Science	Timescale	Current (cm)	1 mm	0.1 mm
Weak Equivalence Principle	Few years	$\|\Delta a/a\| < 1.3\times10^{-13}$	10^{-14}	10^{-15}
Strong Equivalence Principle	Few years	$\|\eta\| < 4.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
Time variation of G	~10 years	9×10^{-13} yr^{-1}	5×10^{-14}	5×10^{-15}
Inverse Square Law	~10 years	$\|\alpha\| < 3\times10^{-11}$	10^{-12}	10^{-13}
PPN β	Few years	$\|\beta-1\| < 1.1\times10^{-4}$	10^{-5}	10^{-6}

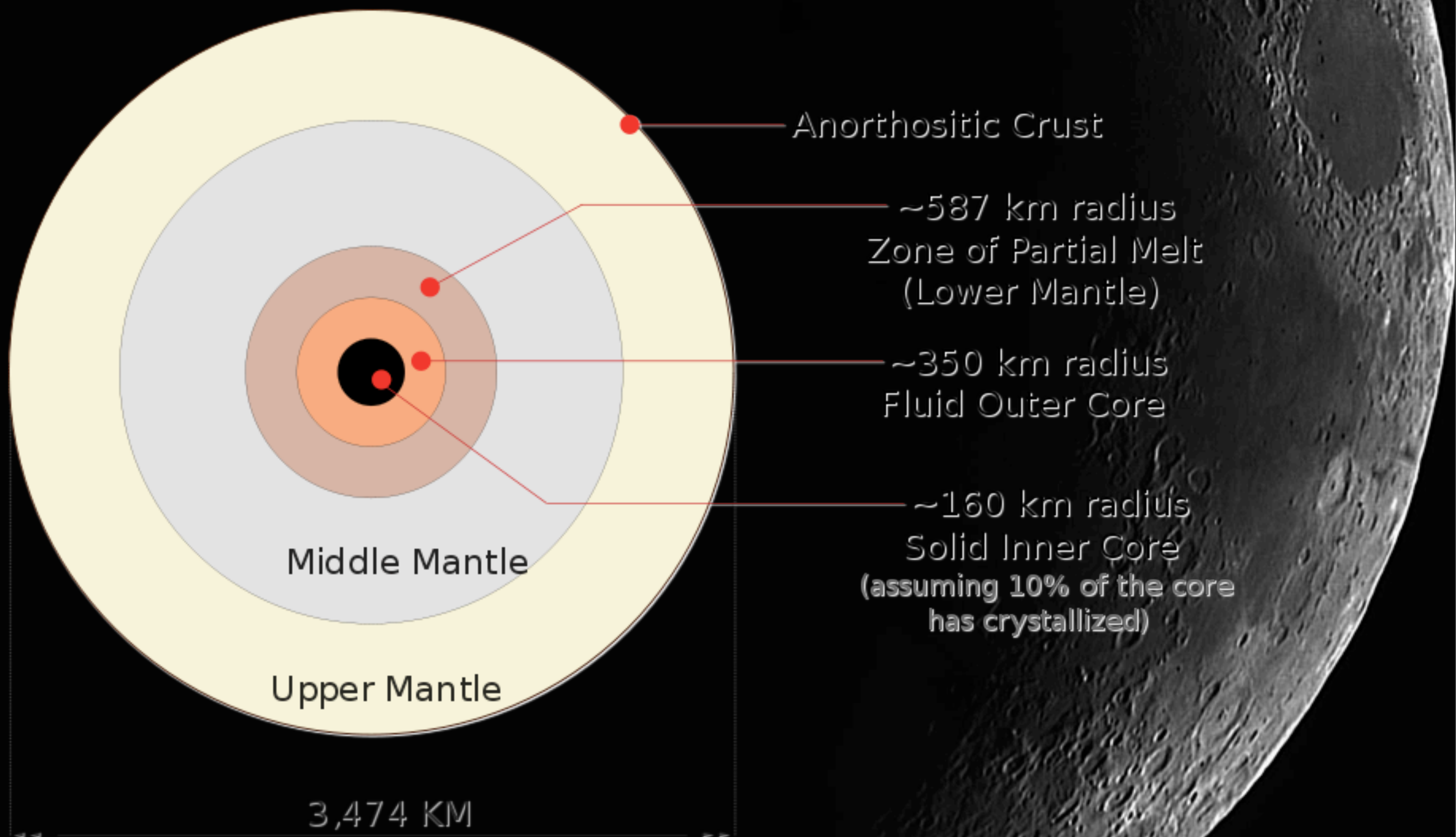
Current and future science deliverables from LLR. LLR is the best test for all but WEP.

Lunar Science with LLR



- Range measurements change due to lunar libration and tides
- Moments of inertia, lunar Love number k_2, and variations in libration are related to the Moon’s composition, mass distribution, and internal dynamics

Lunar Science with LLR



Lunar Science with LLR

1. Core Mantle Boundary (CMB) Dissipation

- Fluid core first proven by LLR through energy dissipation by flow of fluid along CMB
- Depends on fluid core size, viscosity, CMB roughness

2. Free Physical Librations

- Could be stimulated by eddies at CMB, LLR would see as irregularities in polar wobble

Lunar Science with LLR

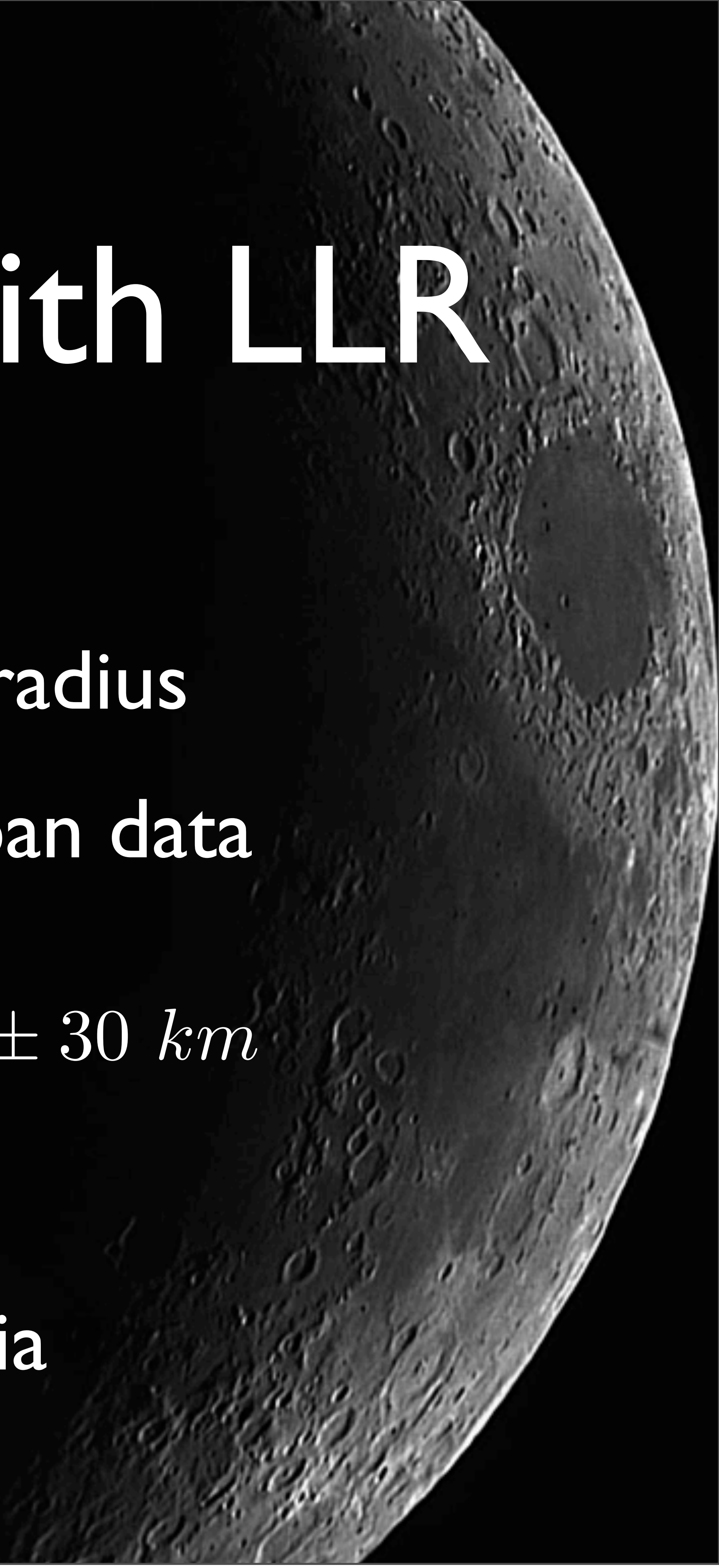
3. Fluid Core Moment of Inertia

- Depends on core density and radius
- Requires accurate long time span data

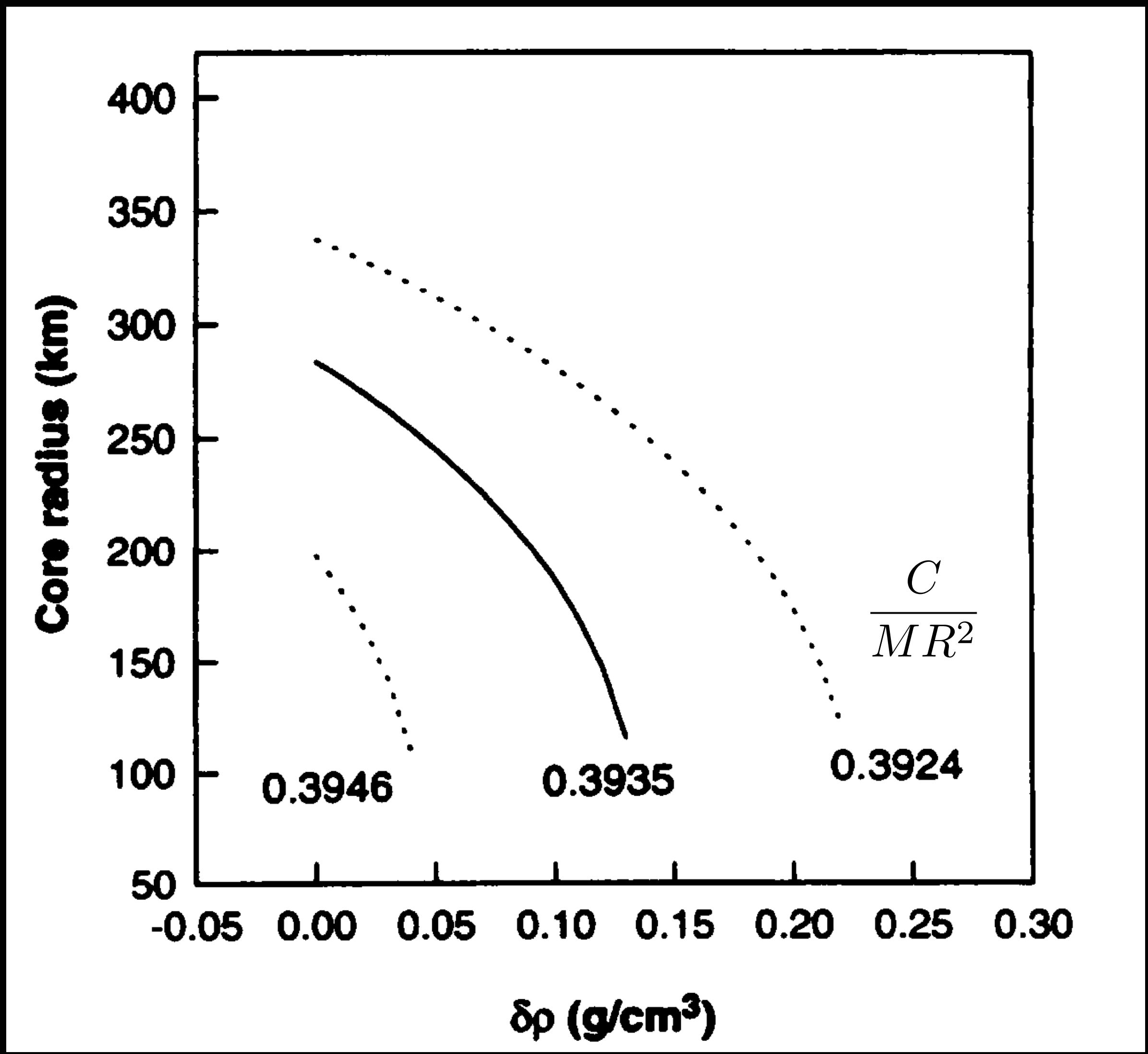
$$\frac{C_f}{C} = (12 \pm 4) \times 10^{-4} \sim 390 \pm 30\ km$$

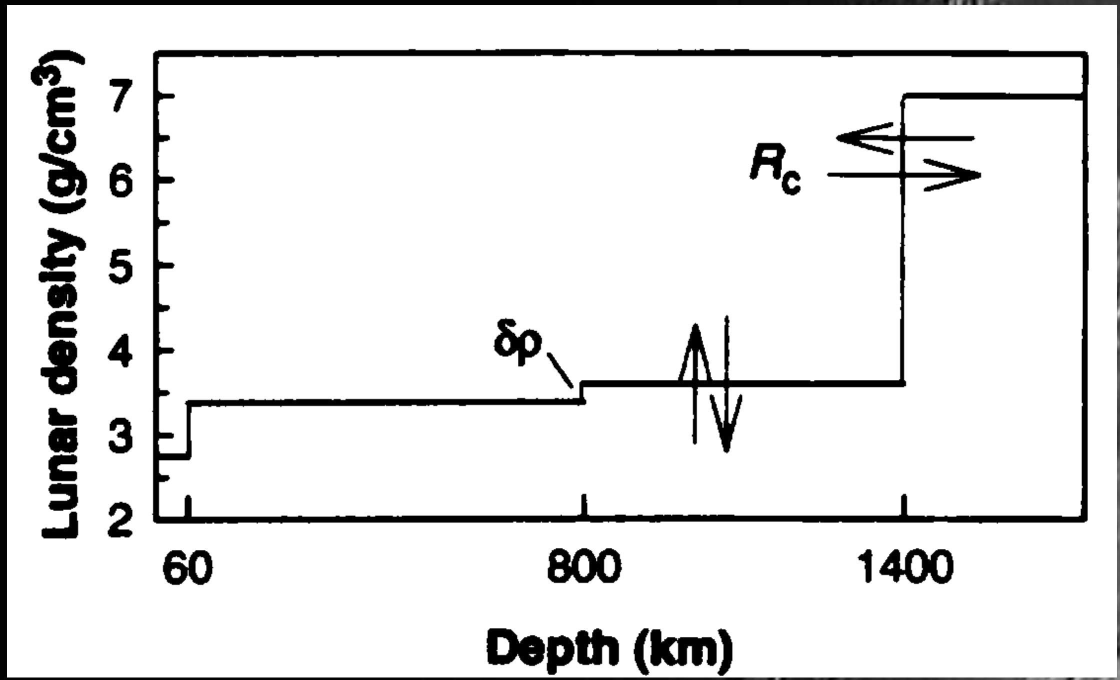
(uniform iron core)

4. Whole Moon Moment of Inertia



Lunar Science with LLR





Constraints on core radius from moment of inertia and lower mantle density contrast

$\delta\rho =$ Lower Mantle Density Contrast

Summary

- LLR provides best constraints for GR (other than WEP) to date
- Also can provide valuable information of lunar interior
- However, now limited by size of Apollo arrays
- A wider distribution of larger retroreflectors would enhance sensitivity and maintain returns

Questions?

Sources

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