SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

l'Observatoire de Paris | IMCCE
Institut de Mécanique Céleste et de Calcul des Éphémérides

Dynamical model of lunar core and observational constraint by LLR

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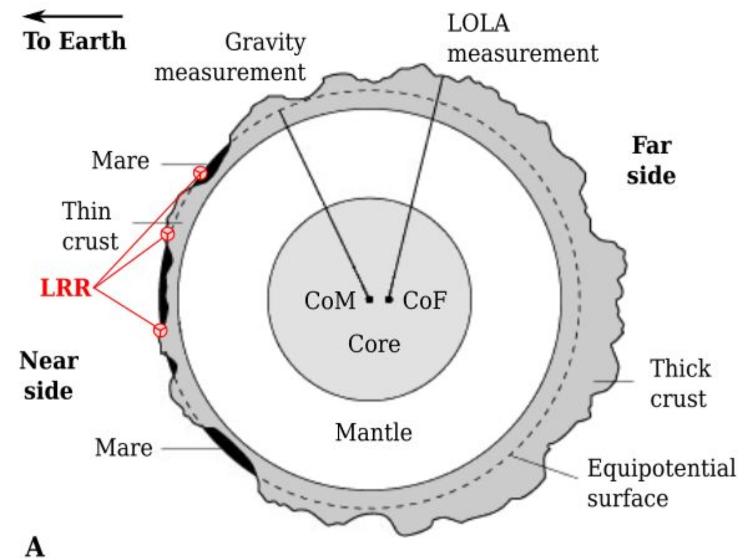
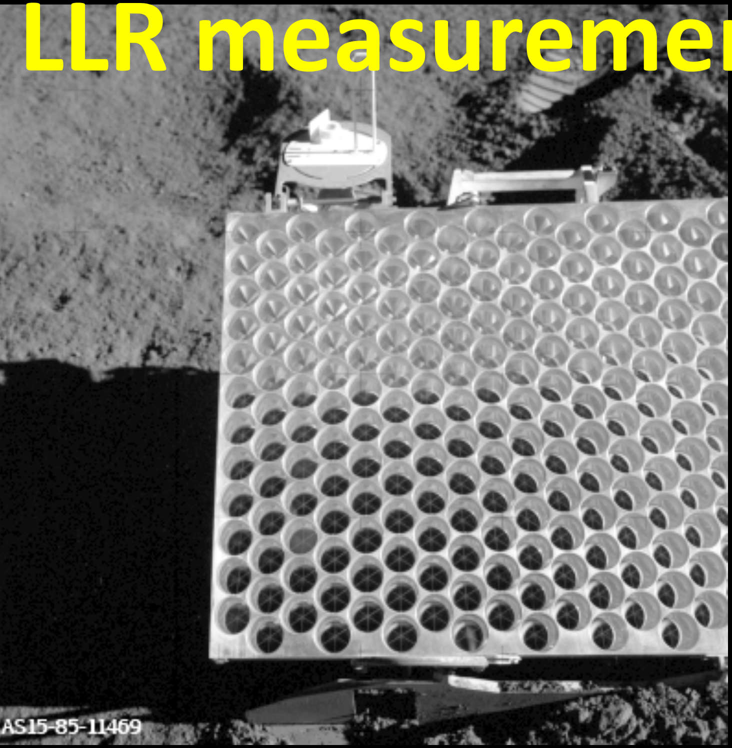
Open questions

- The presence of a lunar fluid core has been revealed by **dynamical,** magnetic, and seismic data (e.g. Yoder 1981, Hood et al. 1999, Williams et al. 2001, Weber et al. 2011, Garcia et al. 2011)

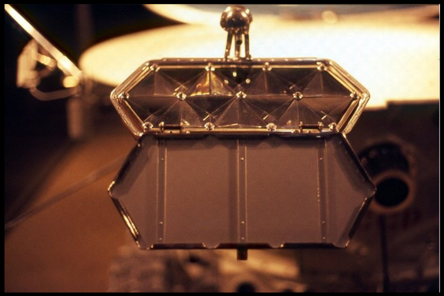


- However, the knowledge of its interior properties is still challenging:
  - Size/density of the fluid core
  - Presence of an inner core?
  - Presence of a Low Viscosity Zone?
- How the rotational dynamics and LLR experiment can access to the lunar interior properties?

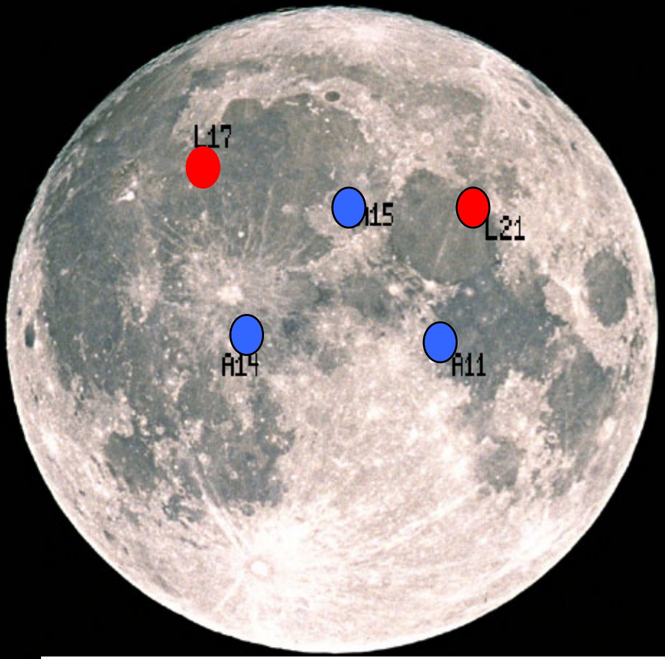
LLR measurements

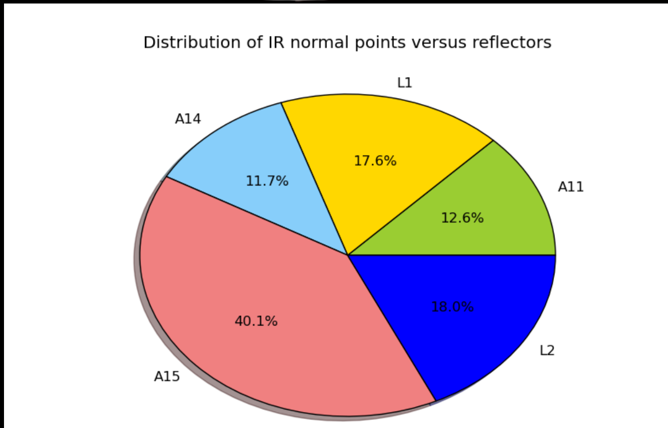


Retroreflector A15



Lunakhod



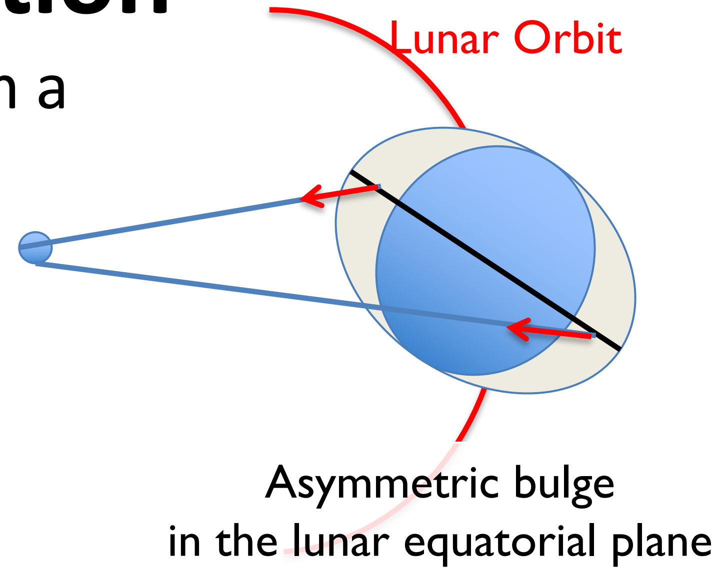


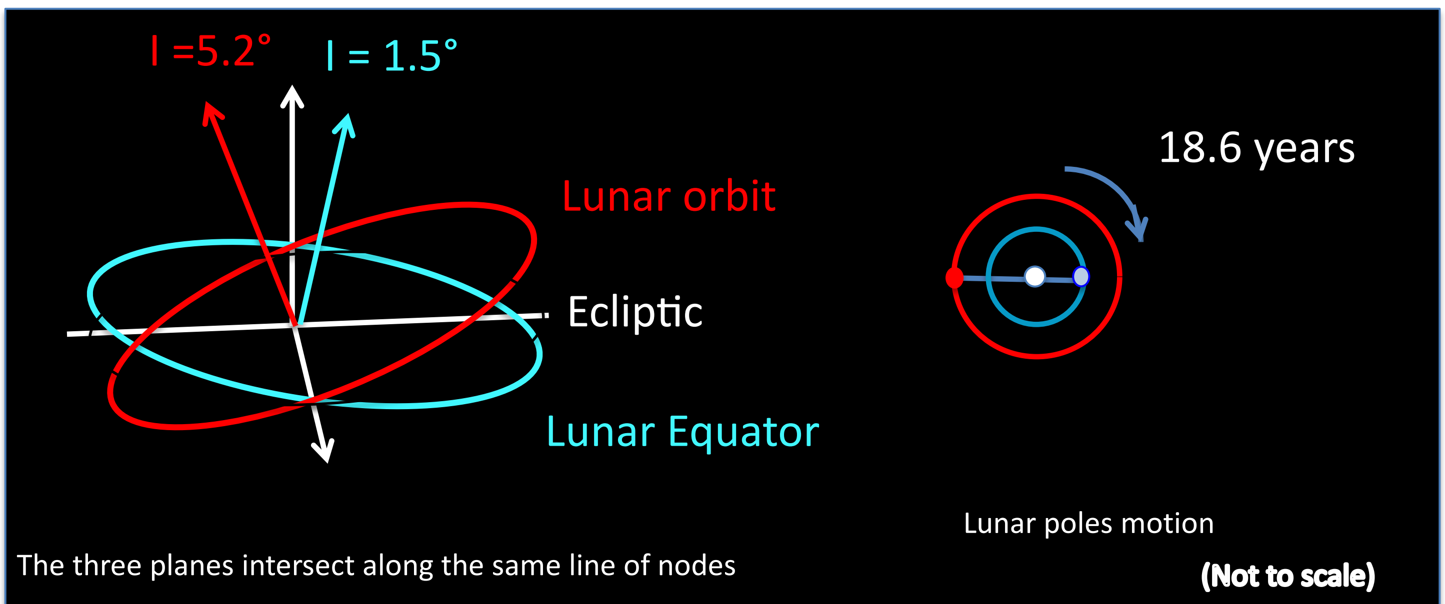
Statistics 2015-2018, IR at OCA

- Time span : 1969-today
- Number of NP : ~ 26000
- Apollo station telescope of 3.5 meters
- Grasse-OCA laser : green and IR
- Earth-Moon distance accuracy of ~ cm
- Theoretical accuracy : few mm

Moon's rotation

- **Physical librations** are departure from a uniform rotational motion
- **Cassini state** is an **equilibrium** state where the spin axis, normal to the orbital plane and the normal to the ecliptic plane are aligned
- The obliquity is **constant**.

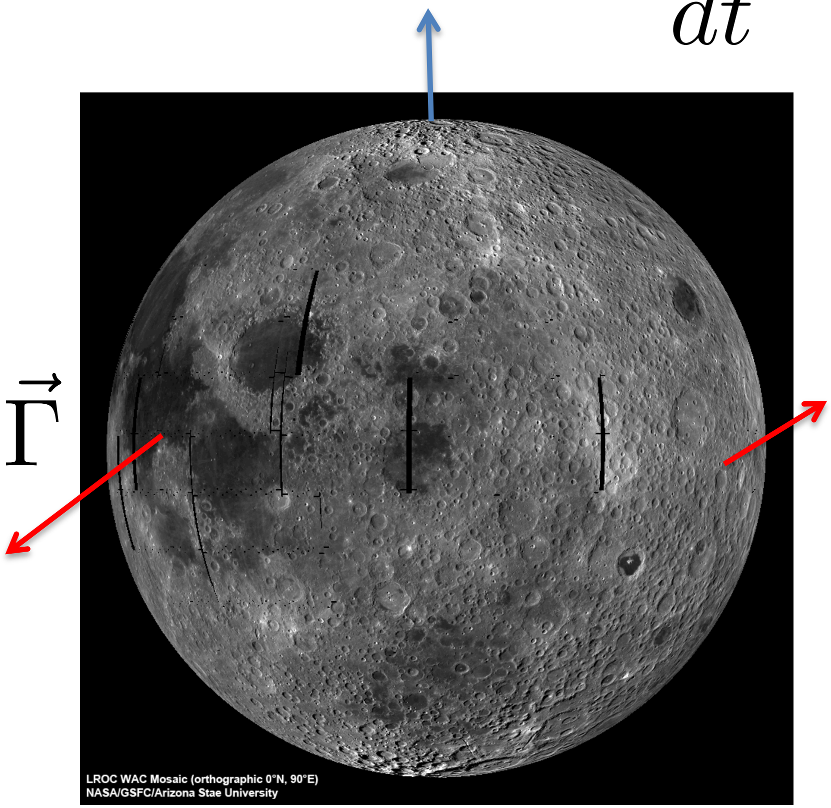


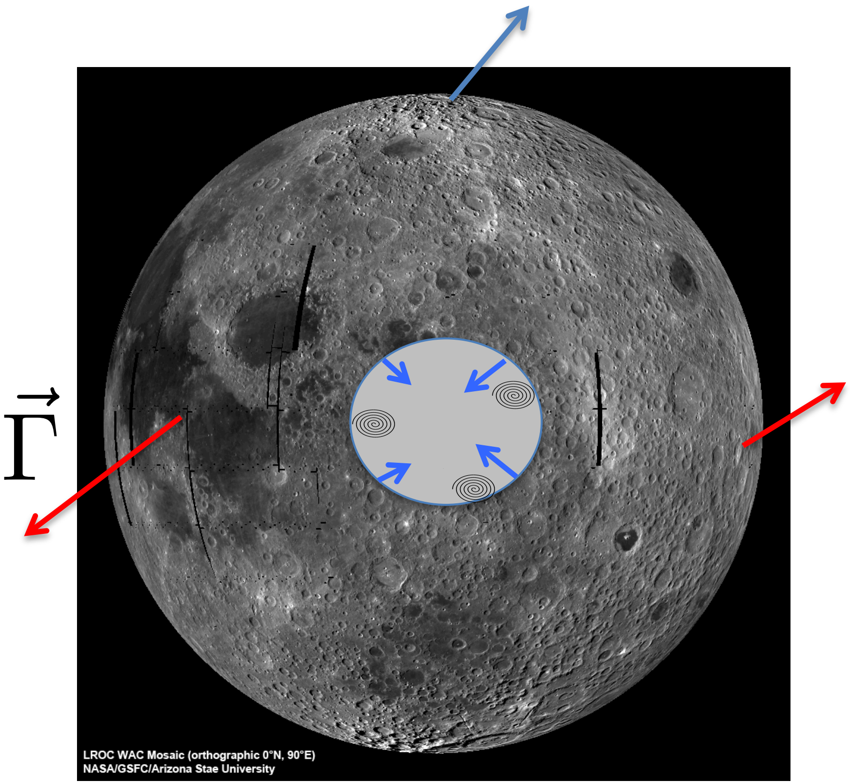


(e.g. Colombo 1966, Peale 1969, Henrard and Murigande 1986, Bouquillon et al 2003).

Influence of the fluid core

$$\frac{d\vec{H}}{dt} = \vec{\Gamma}$$ Angular momentum equation





$$\vec{H} = I\vec{\omega}$$

With a fluid core

$$\vec{H} = \vec{H}_c + I_m\vec{\omega}$$

(e.g. Williams et al 2001, Richard, Rambaux, Charnay 2014 (extension), Dumberry and Wieczorek 2016….)

Lunar-Laser Ranging Experiment and ephemerides

- Numerical planetary and lunar ephemerides DE, EPM, IfE and INPOP (e.g. Williams *etal., Pavlov etal., Hoffman etal. Fienga etal.)*
  - Lunar accuracy ~ ***2 cm*** and ***1 mas*** in rotation over **50 years**.
  - Fundamental physics, geophysics, selenophysics and **interior** of the Moon.

- These models (DE, EPM, INPOP) are joint numerical integration of the orbits of the Moon, the Earth, the planets and asteroids, and of the lunar rotation

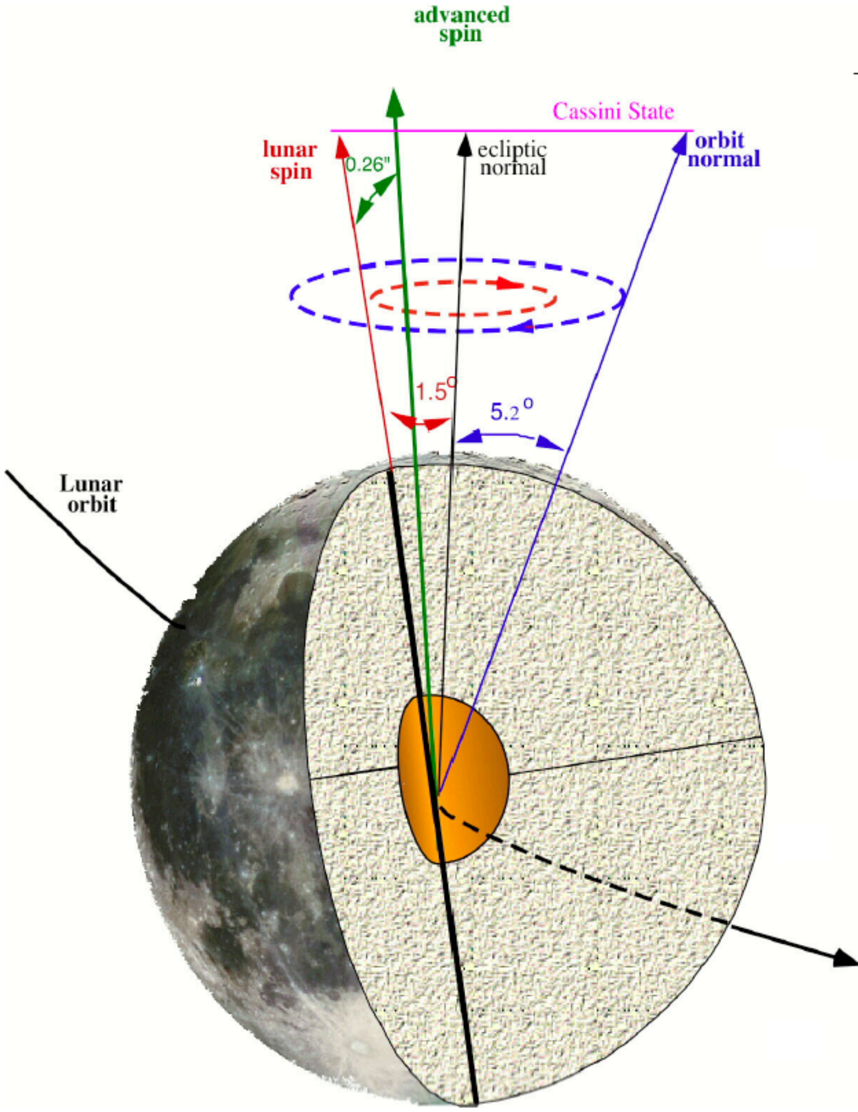
- Dynamical partial derivatives of the orbits and lunar Euler angles with respect to solution parameters such as moment of inertia, gravity field, tides, dissipation, CMB flattening, and initial conditions.

Dynamical signature of the lunar core

- Departure of the spin of the Moon to the Cassini state of ~260 mas.
- Attributed to the fluid core dissipation (Yoder 1981)
- Tidal dissipation and core-mantle friction (Williams et al. 2001)

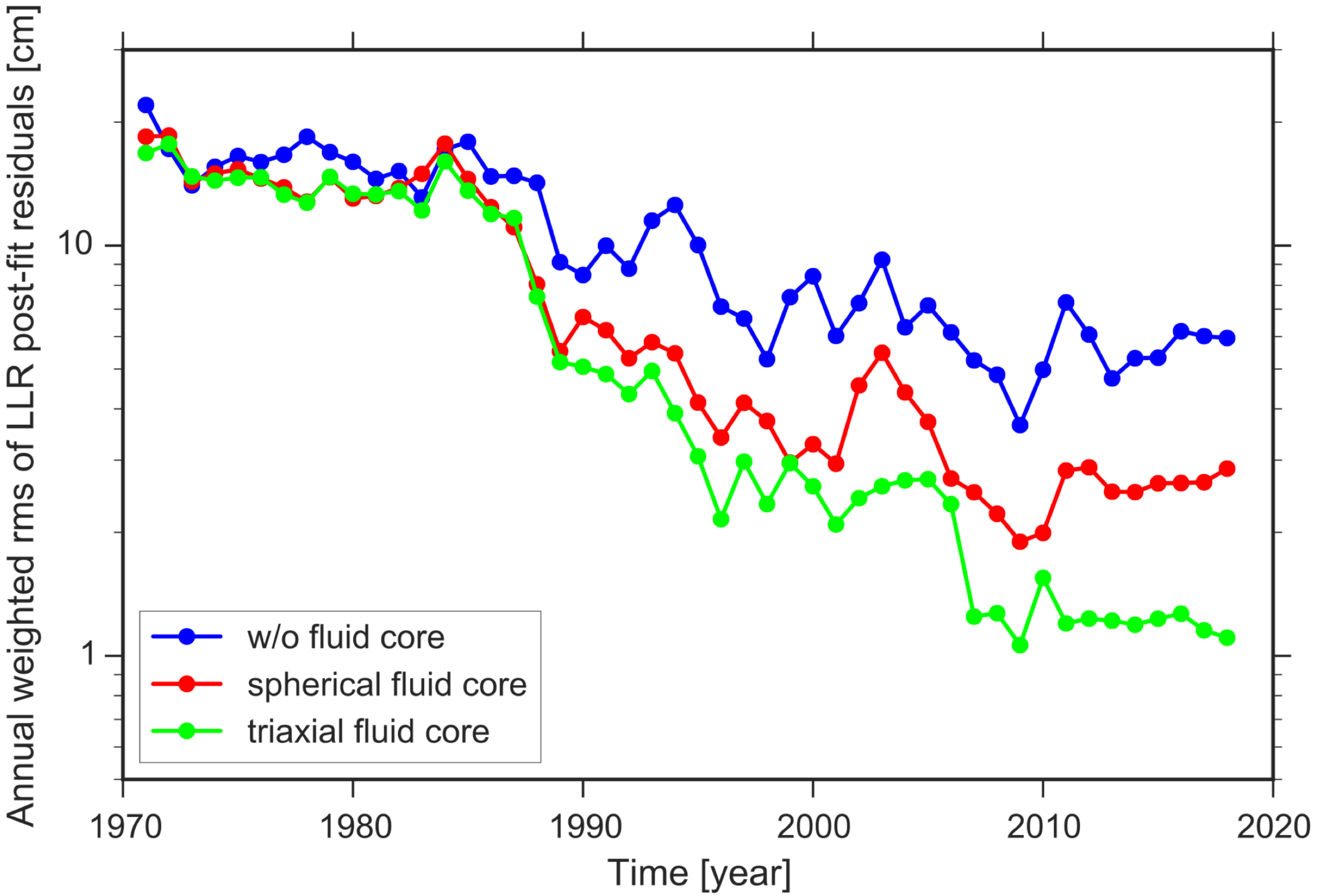
$$\vec{N^c} = K(\vec{\omega} - \vec{\omega^c})$$

- CMB flattening (axi-symetric) estimation (Williams et al. 2008, Williams et al. 2014)



(Williams et al 2001)

Weighted root-mean-square of LLR post-fit residuals w/o and with fluid core

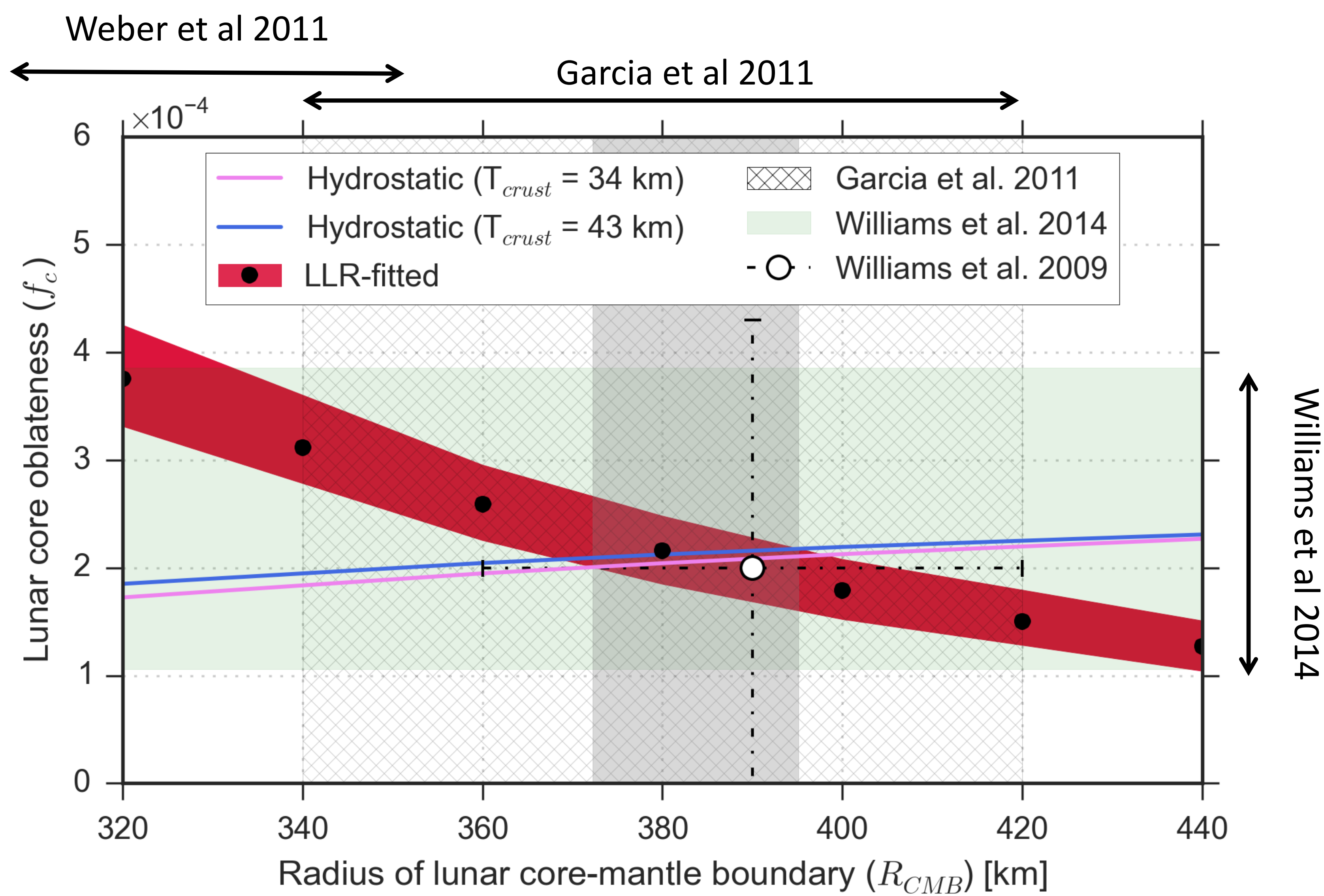


Direct approach

1. Fixed a value of R_{CMB}
2. From INPOP17a geophysical parameters built a new reference lunar interior (density profile)
3. Fit the polar flattening with LLR data
4. Iteration to step (2) with the new set of parameters to converge towards a solution at the fixed R_{CMB}

Full dynamical equations with the triaxiality and here the inner core is neglected.

LLR-fitted values of the lunar core oblateness

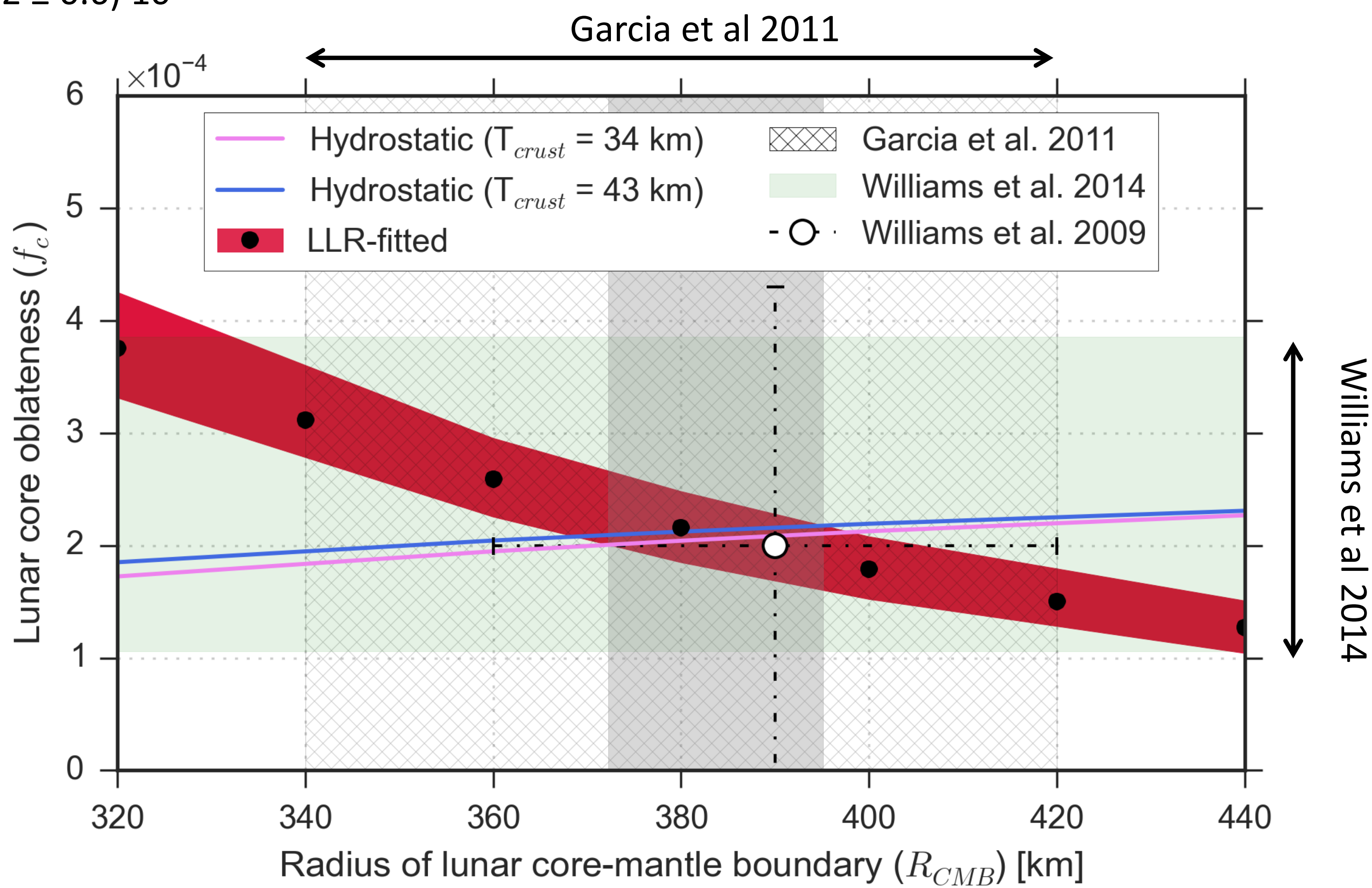


$$f_c = \frac{C_c - \frac{A_c+B_c}{2}}{C_c}$$

(Viswanathan et al. 2019)

LLR-fitted values of the lunar core oblateness

$f_c = (2.2 \pm 0.6)\ 10^{-4}$

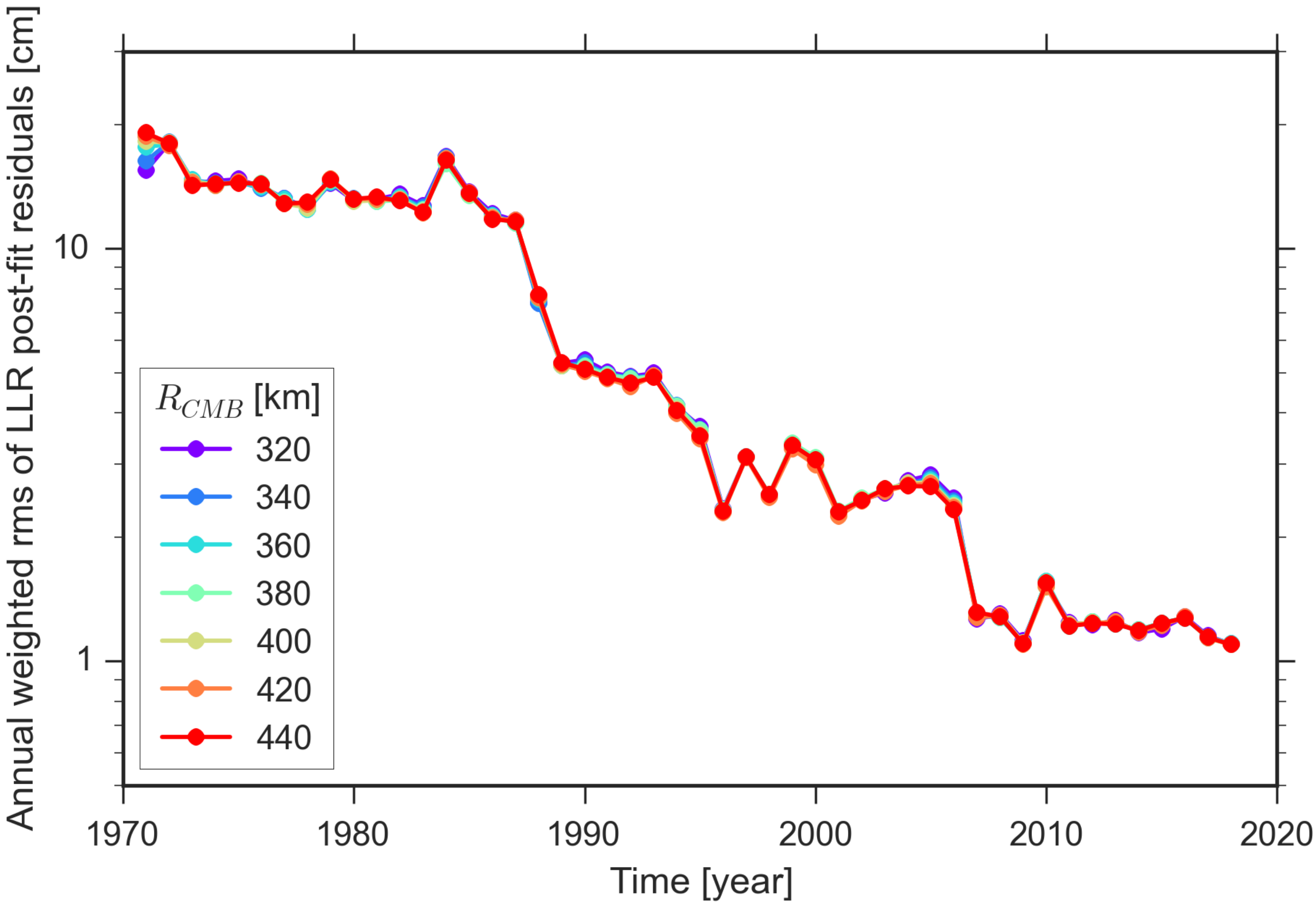


$R_{CMB} = 381 \pm 12$ km

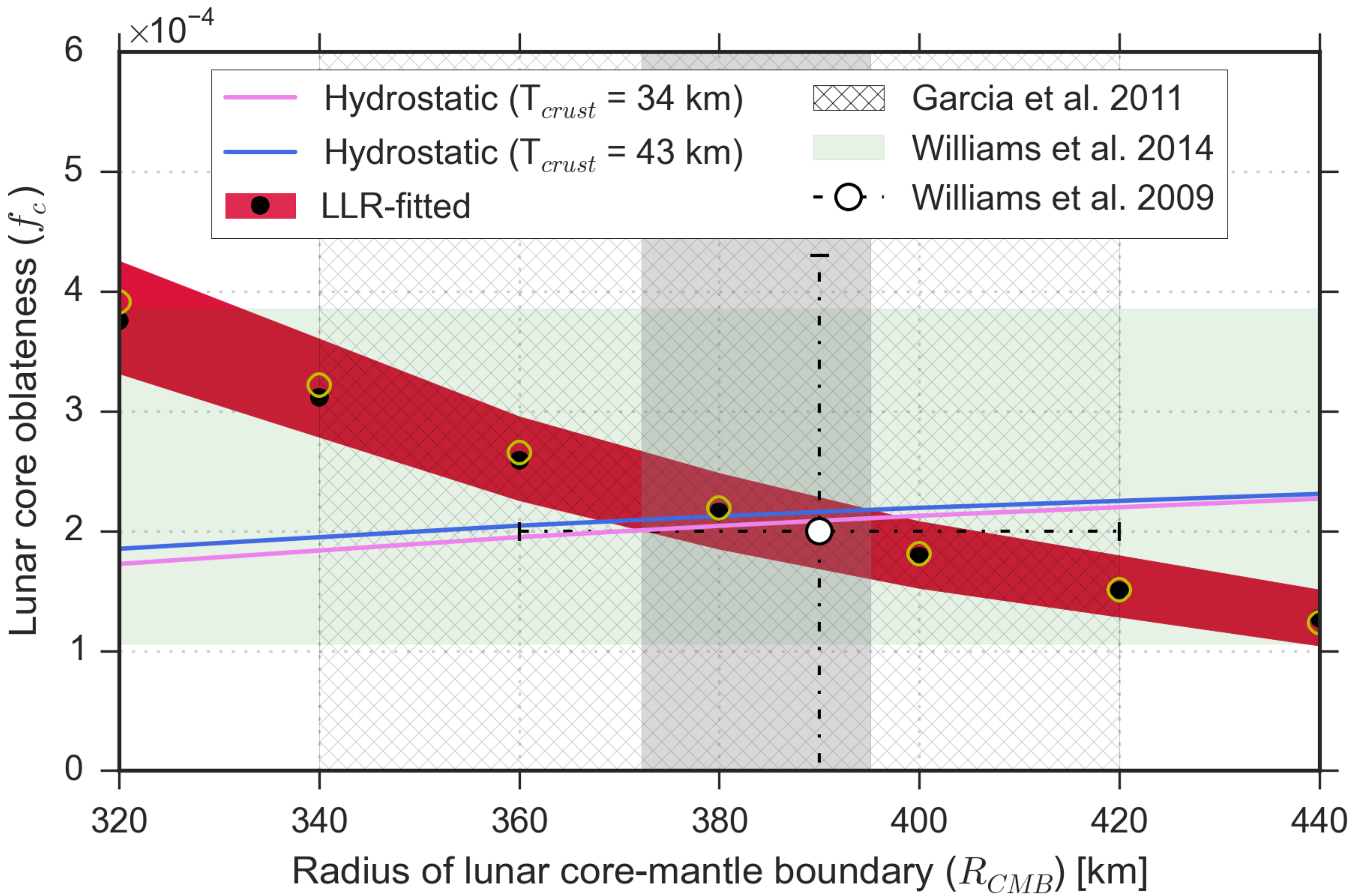
(Consistent with Wieczorek et al. 2019)

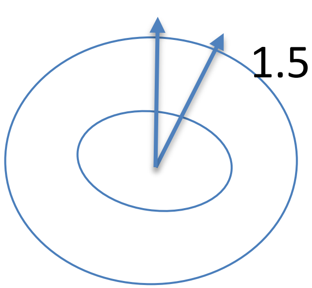
(Viswanathan et al. 2019)

Weighted root-mean-square of LLR post-fit residuals with fluid core



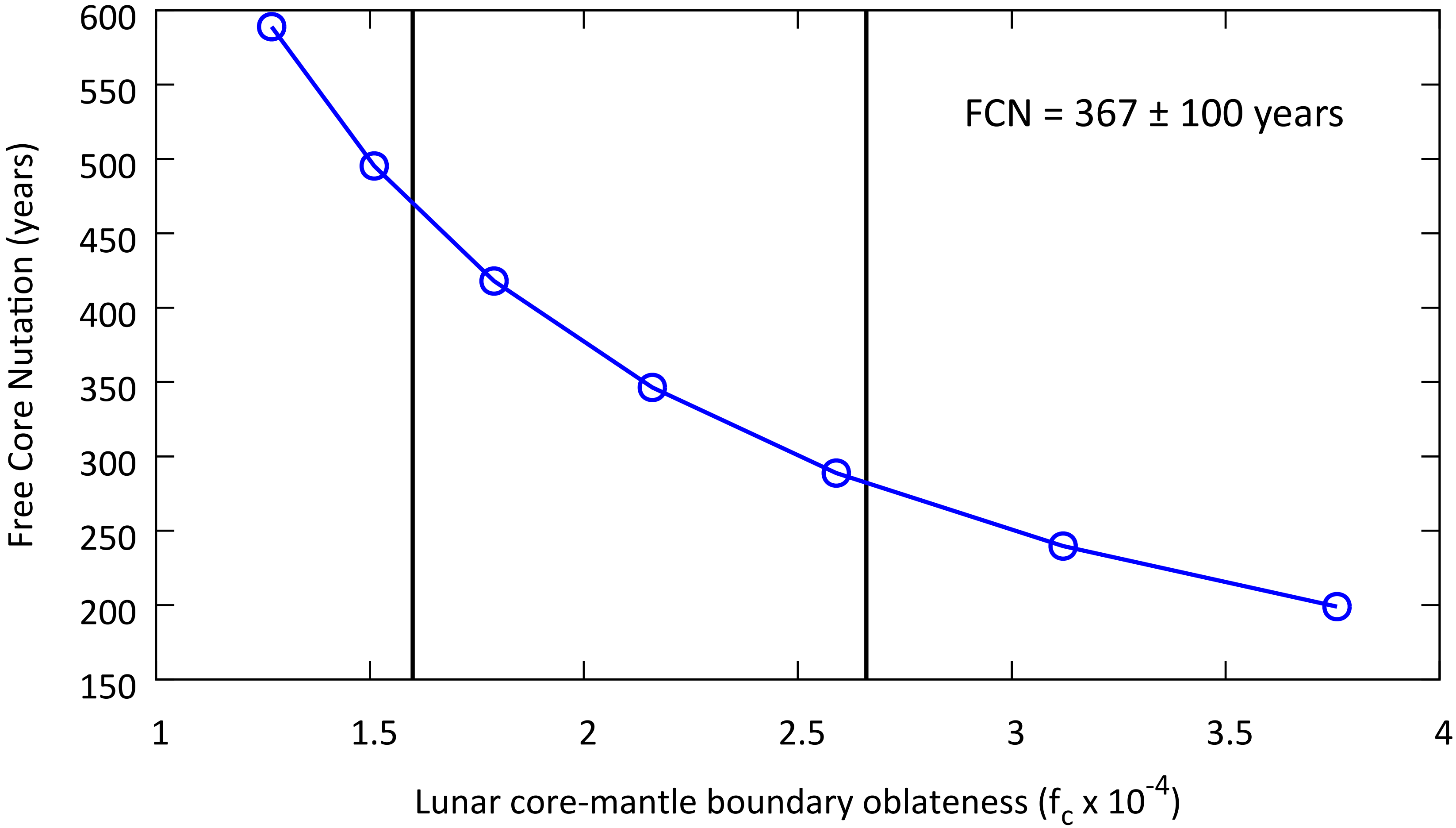
Inclination of the lunar core





(Goldreich 1983
Meyer and Wisdom 2011)

Estimation of the FCN



Period FCN ~ 27.32 / fc (Rambaux and Williams 2011)

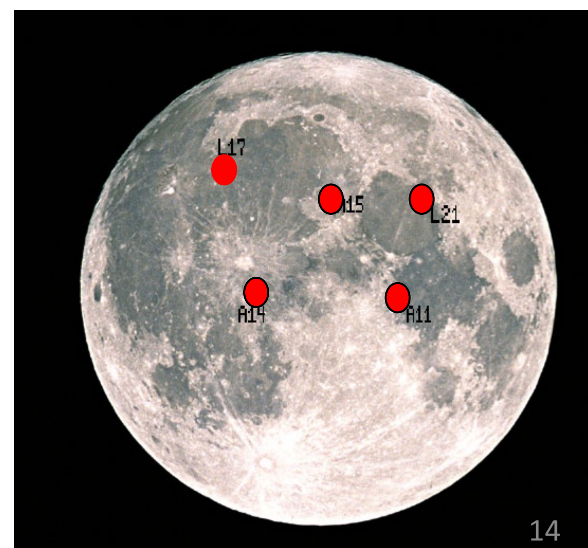
Conclusion

o Lunar Laser Ranging continues to provide new results because of improving range with station (APOLLO, New Mexico, USA), updated station (Grasse, OCA, France), new stations, data analysis accuracies (DE430, EPM, IfE, INPOP), and echoes from the lost retroreflector!

o The fluid core friction controls (1/3) the departure of the Cassini state;
o The oblateness of the core has been determined in the LLR fit =(2.2 $\pm$ 0.6) 10^{-4};
o Constrain on the size of the core (381 $\pm$ 12 km) assuming that the CMB is at the hydrostatic equilibrium

o Estimation of the FCN period (367 $\pm$ 100 years) and its detection in libration series is still in progress.
o The core mass fraction is in the range of 1.63-2.06%
o Signature of an inner core is not yet observed.

o New retroreflectors or active laser transponders settled to the surface of the Moon will offer improved accuracies to mm and new results…



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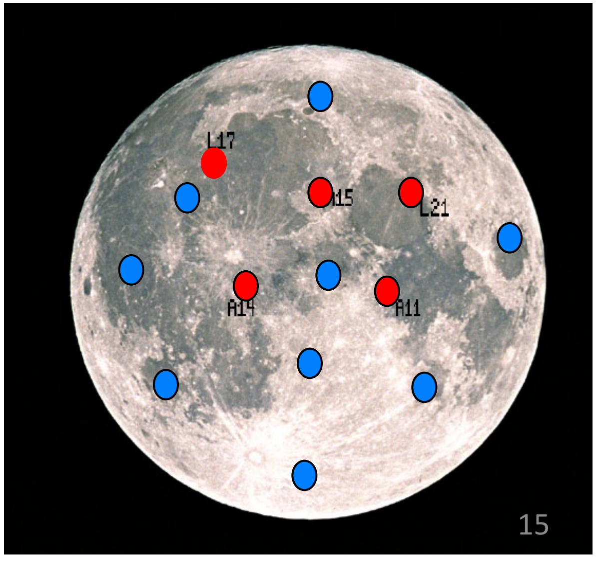
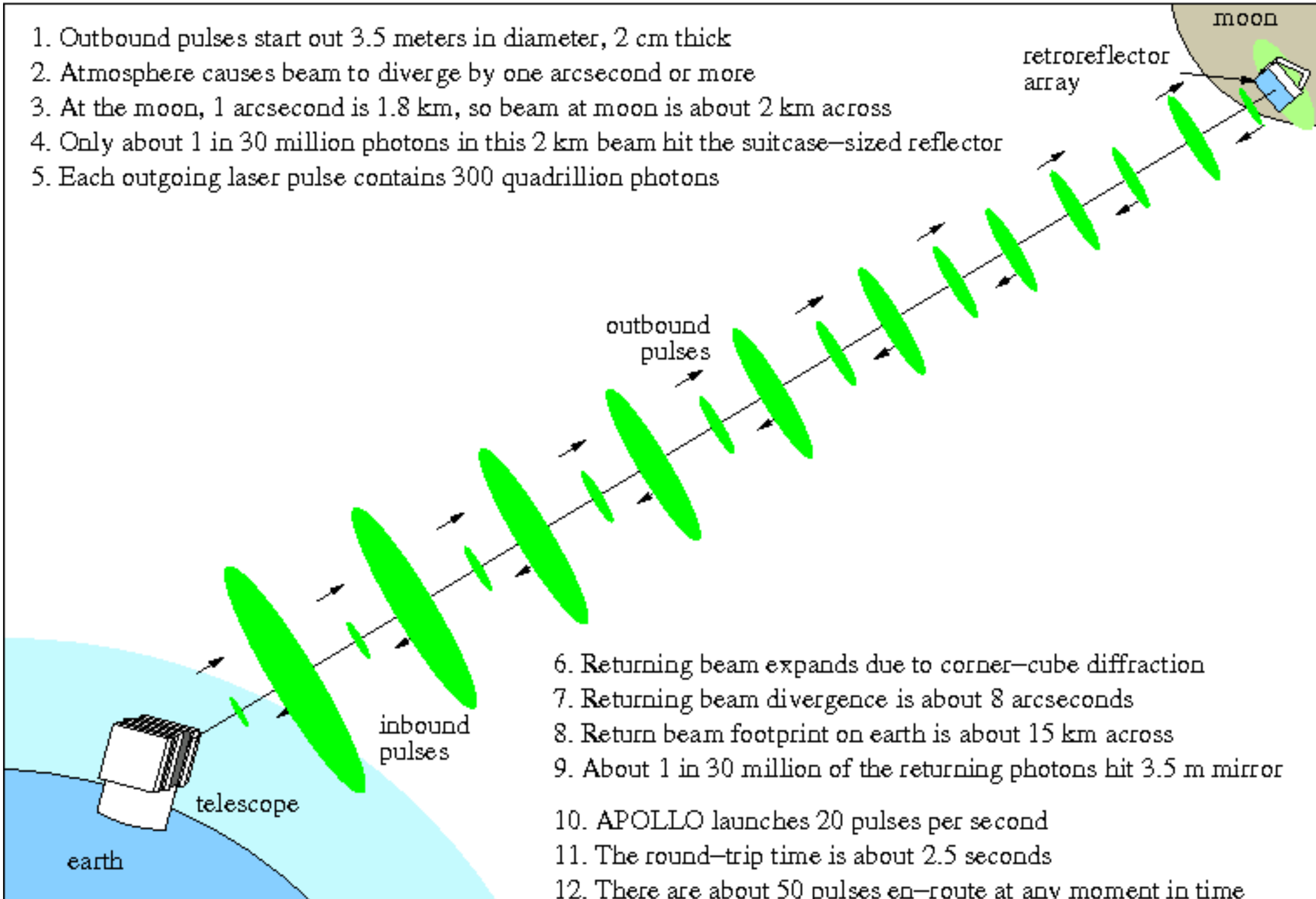
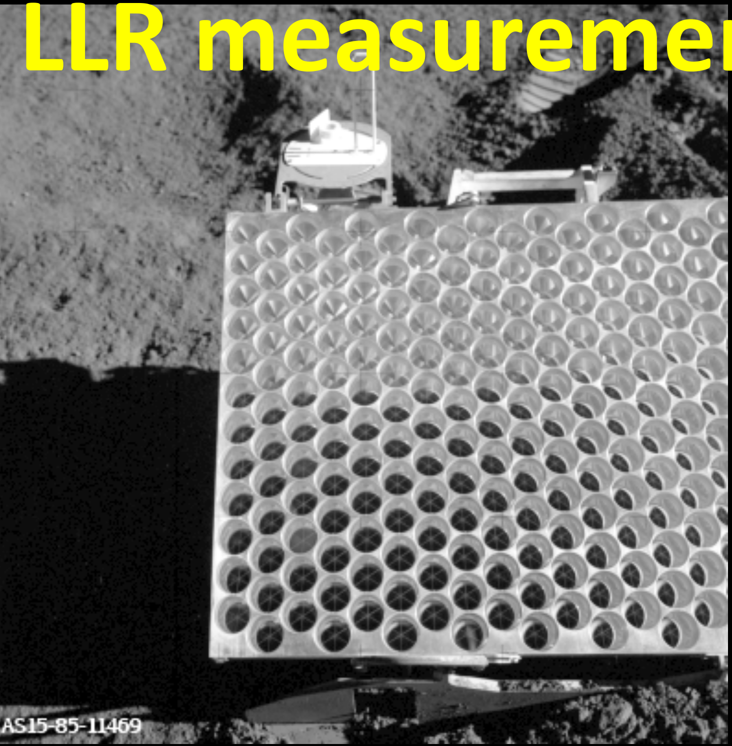


Lunar Laser Ranging principle



(T. Murphy)

LLR measurements



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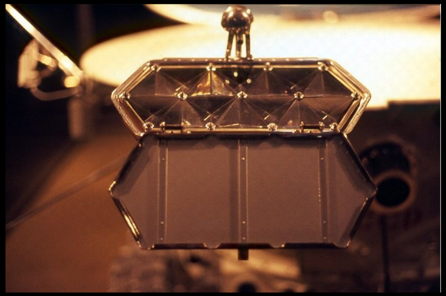

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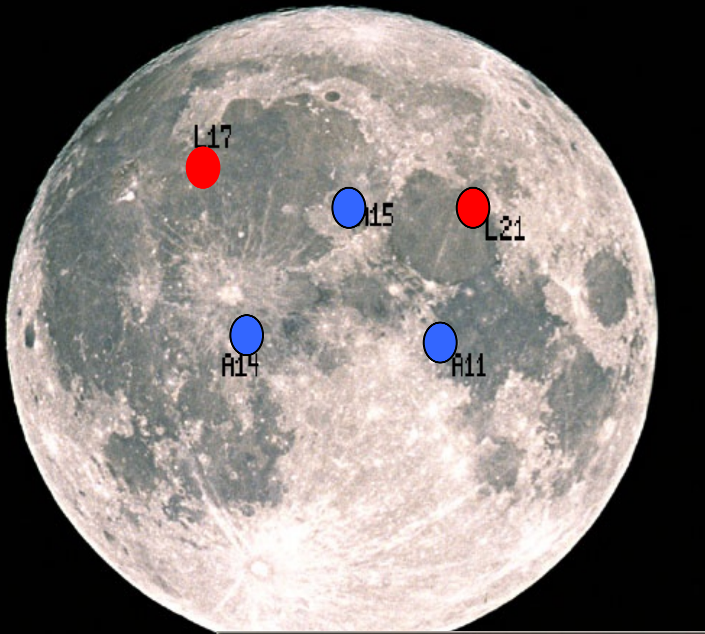


Station Laser-Lune Grasse, OCA

Reference lunar interior model

Three layer model :
crust, mantle and fluid core

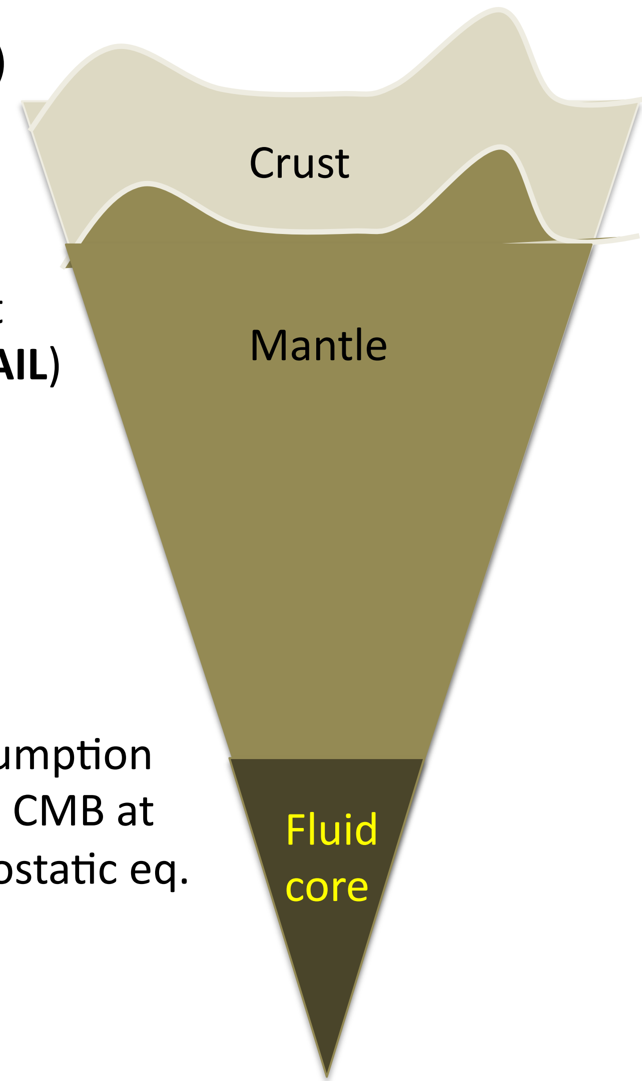
Constrained from INPOP17a
(radius, mass, moment of inertia)

$$U(r_j) = W_j(r_j) + W_{cent}(r_j) + W_{tidal}(r_j).$$

Non-hydrostatic
(measured by **LRO**)

Gravity coefficient
(measured by **GRAIL**)

Assumption
that CMB at
Hydrostatic eq.



(method as Meyer and Wisdom 2011, Dumberry and Wieczoreck 2016;
agreement with Wieczoreck et al. 2019)