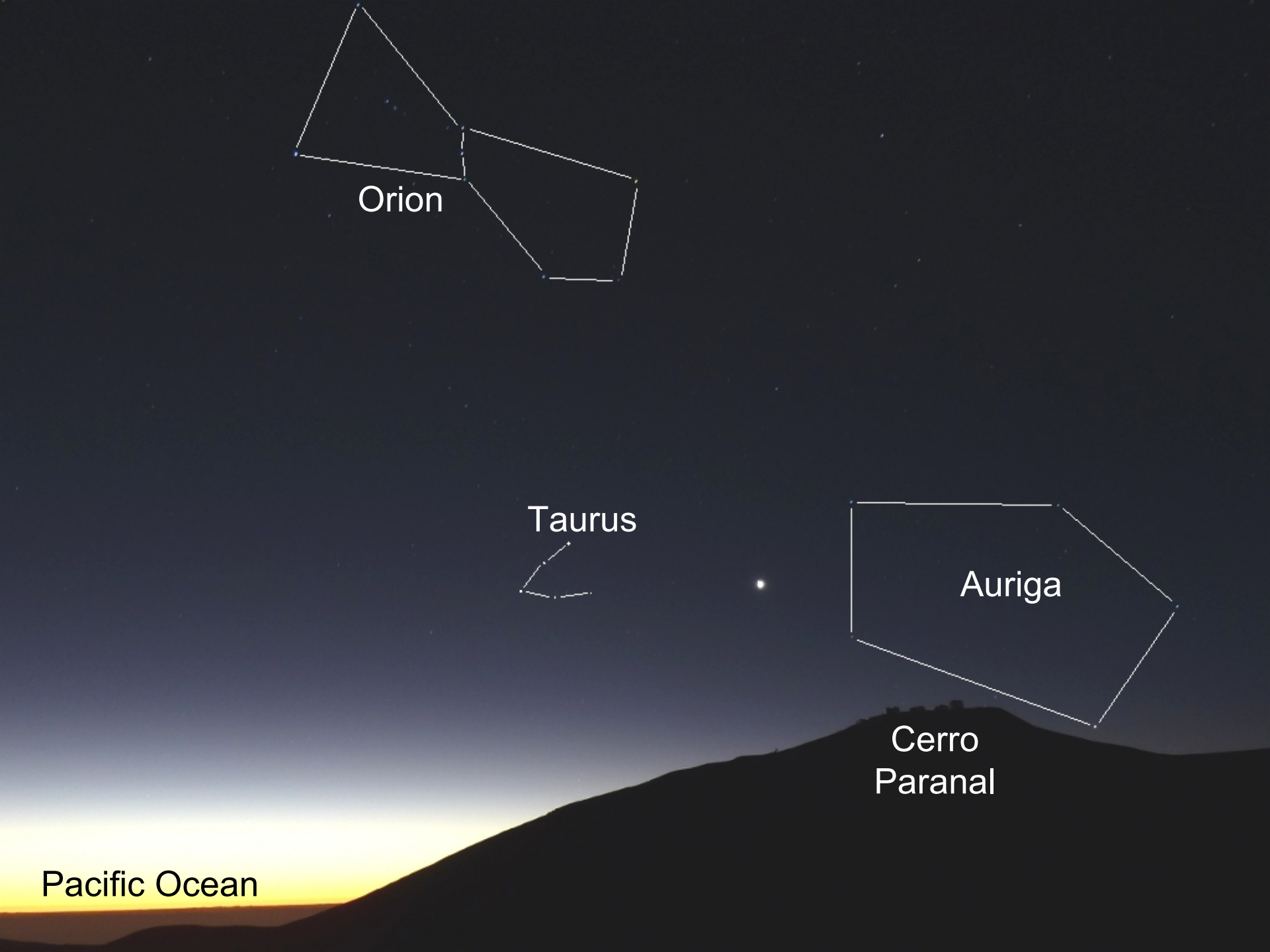
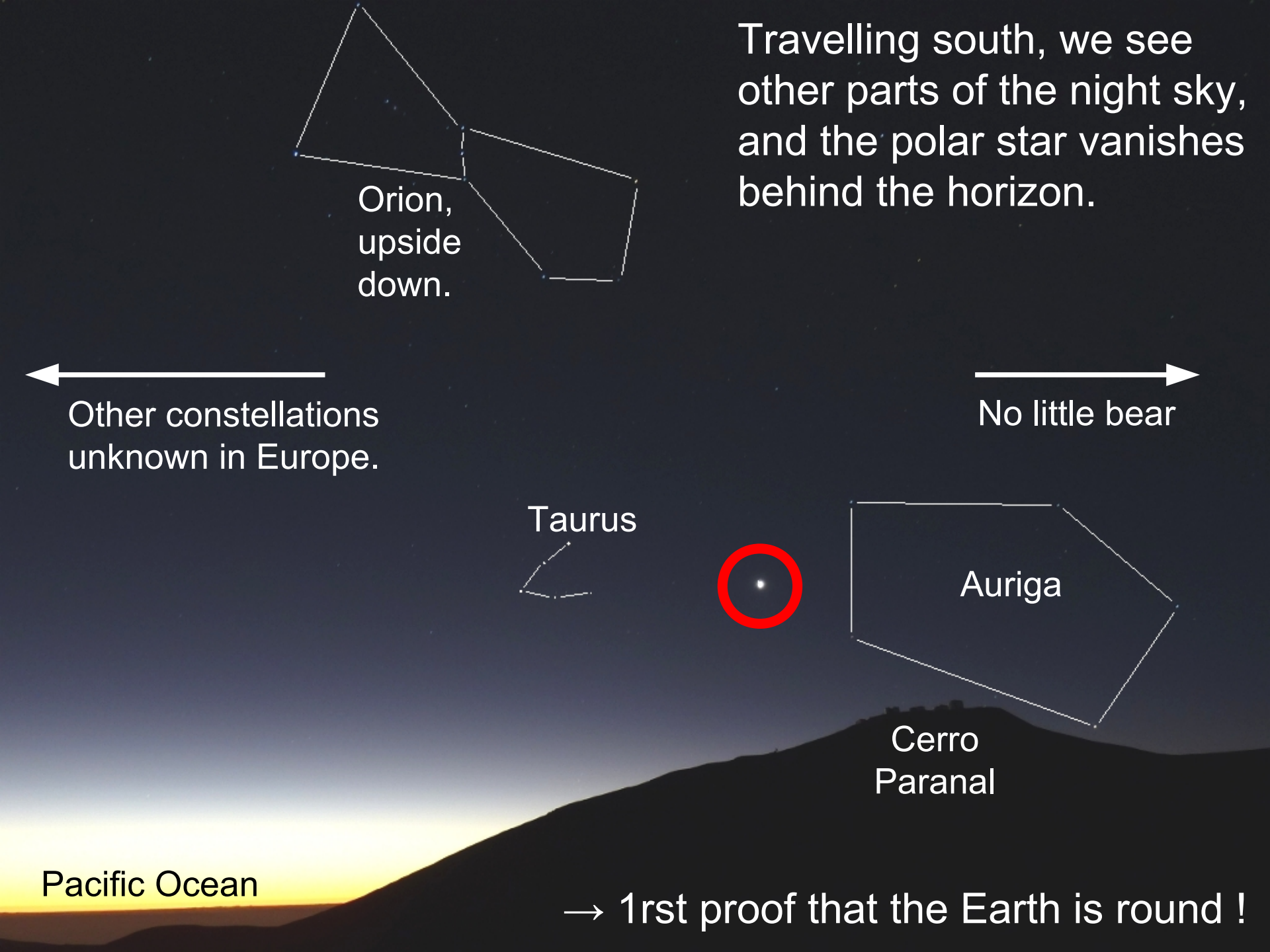
IAC Winter School 2016

The SOLAR SYSTEM

Observatoire de la CÔTE d'AZUR

Aurélien CRIDA


Orion
Taurus
Auriga
Cerro
Paranal
Pacific Ocean


Travelling south, we see other parts of the night sky, and the polar star vanishes behind the horizon.
Orion, upside down.
Other constellations unknown in Europe.
No little bear
Taurus
Auriga
Cerro Paranal
Pacific Ocean
→ 1rst proof that the Earth is round !

7 anomalies in the sphere of the fixed stars
→ 7 days of the week :

Moon, Mars, Mercury, Jupiter, Venus, Saturn, Sun
Monday, **Mar**di, **Mercre**di, Thursday, Friday, **Satur**day, **Sun**day

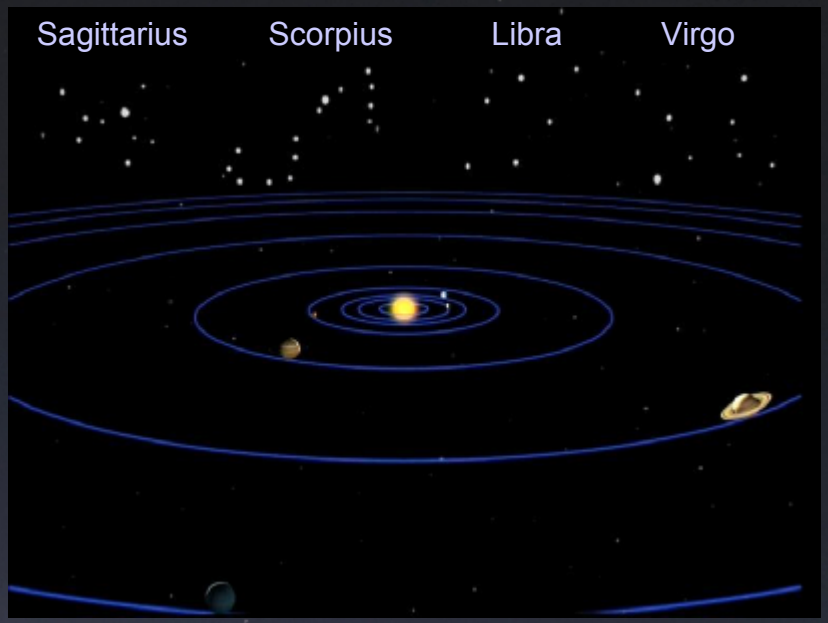
Luna, Marte, Mercurio, Jupiter, Venus, Saturno, Sole
lunes, martes, miércoles, jueves, viernes, sábado, domingo.

Moving astres, called in greek πλανητης , planets.

These celestial bodies move, but not anywhere...
One has never seen a planet in the Big Bear :

Planets belong to the ecliptic plane, whose intersection with the celestial sphere marks the Zodiac.

The sky in May 2007



The Solar System is flat.

The Solar System is flat, and one can see it !

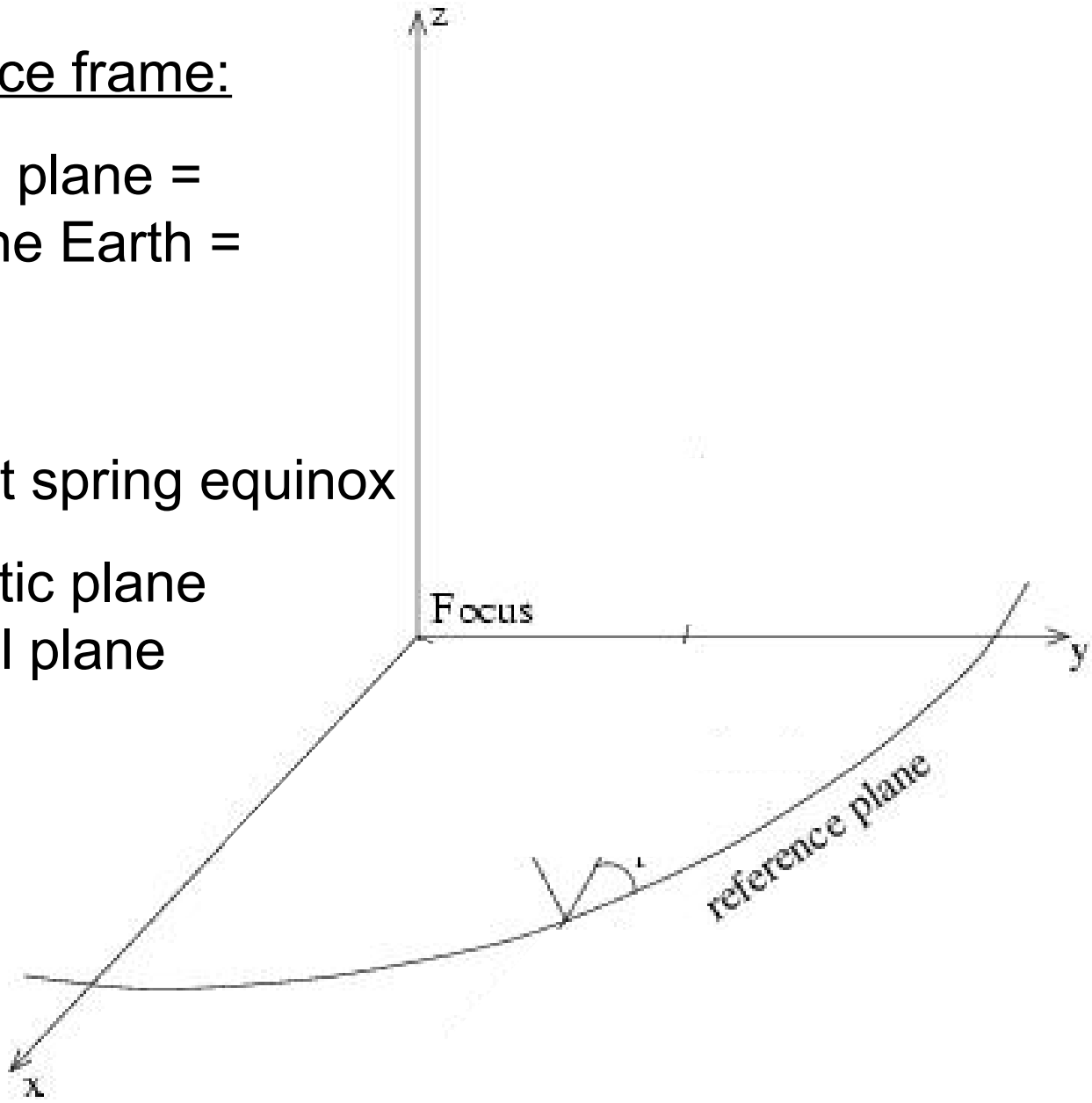
REFERENCE FRAME

Solar System reference frame:

(x,y) plane = zodiacal plane =
plane of the orbit of the Earth =
ecliptic plane

x = vernal point =
direction of the Sun at spring equinox

= intersection of ecliptic plane
and Earth's equatorial plane



ORBITAL ELEMENTS

i = inclination

Ω = longitude of the (ascending) node

ω = argument of the pericenter

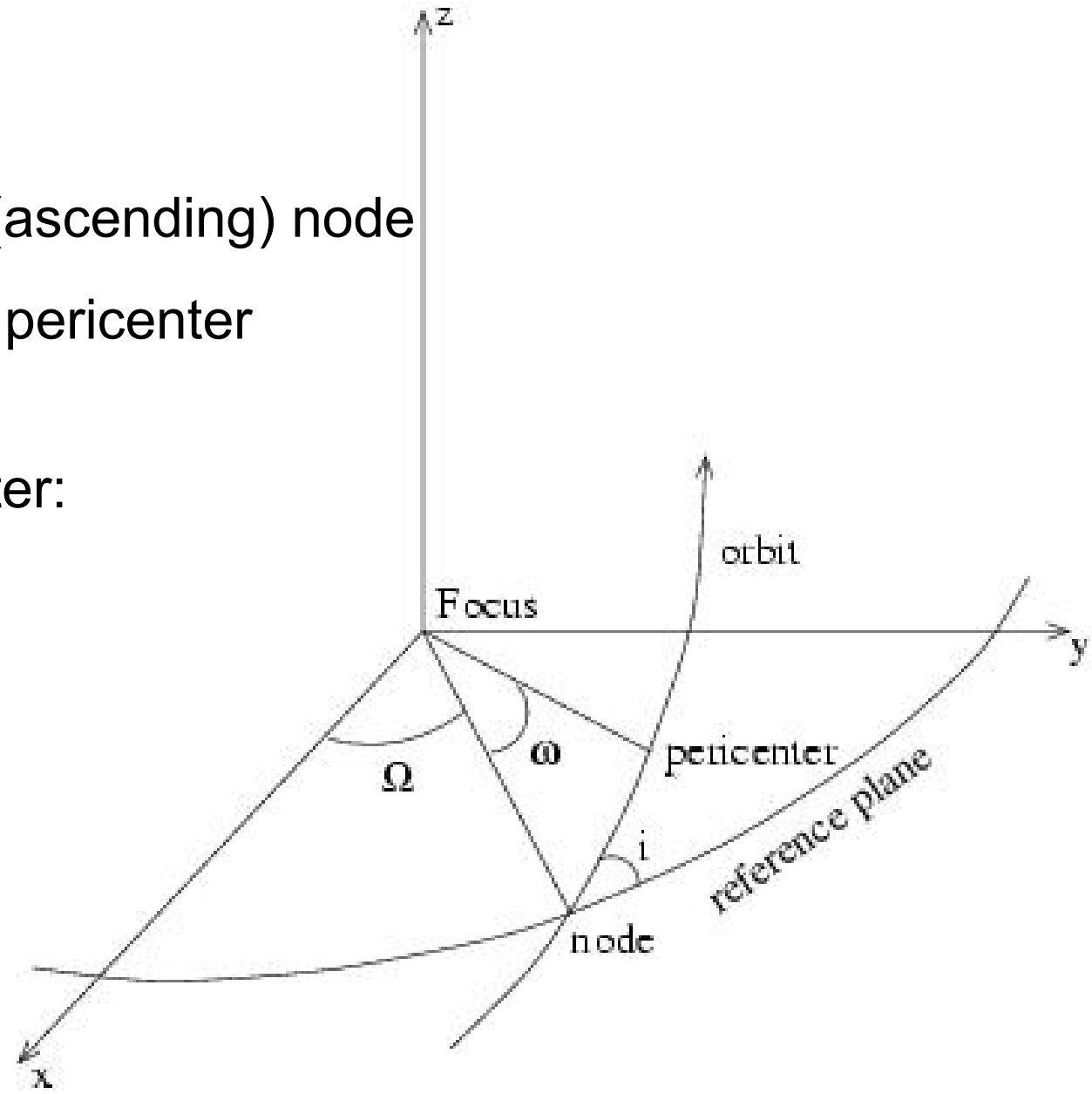
Longitude of pericenter:

$\varpi = \omega + \Omega$

Mean longitude:

$\lambda = M + \varpi$

Longitude :
angle / frame



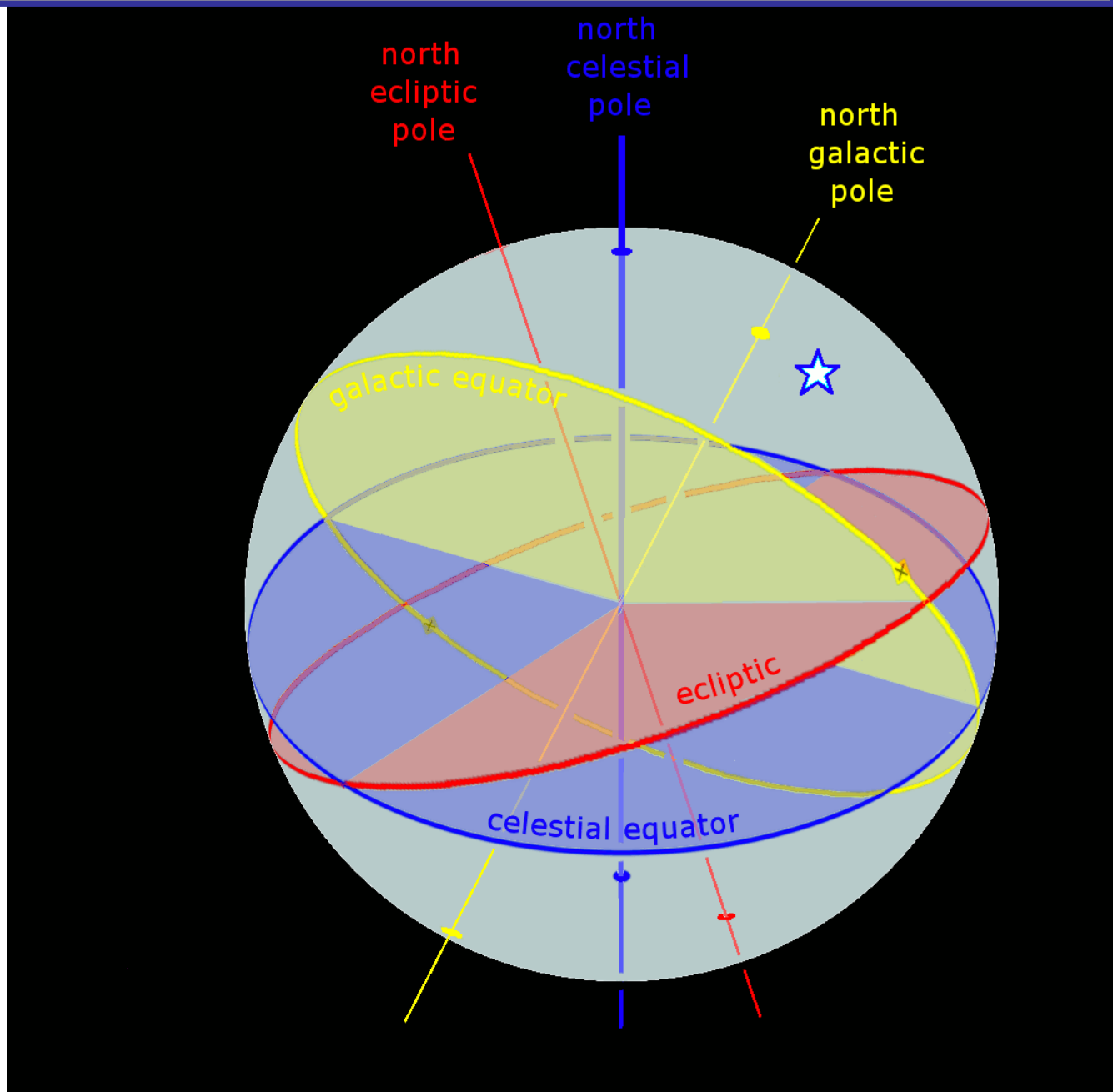
CELESTIAL COORDINATES

Sky coordinates :

Latitude = declination, δ. δ=+90° above Earth's north pole.

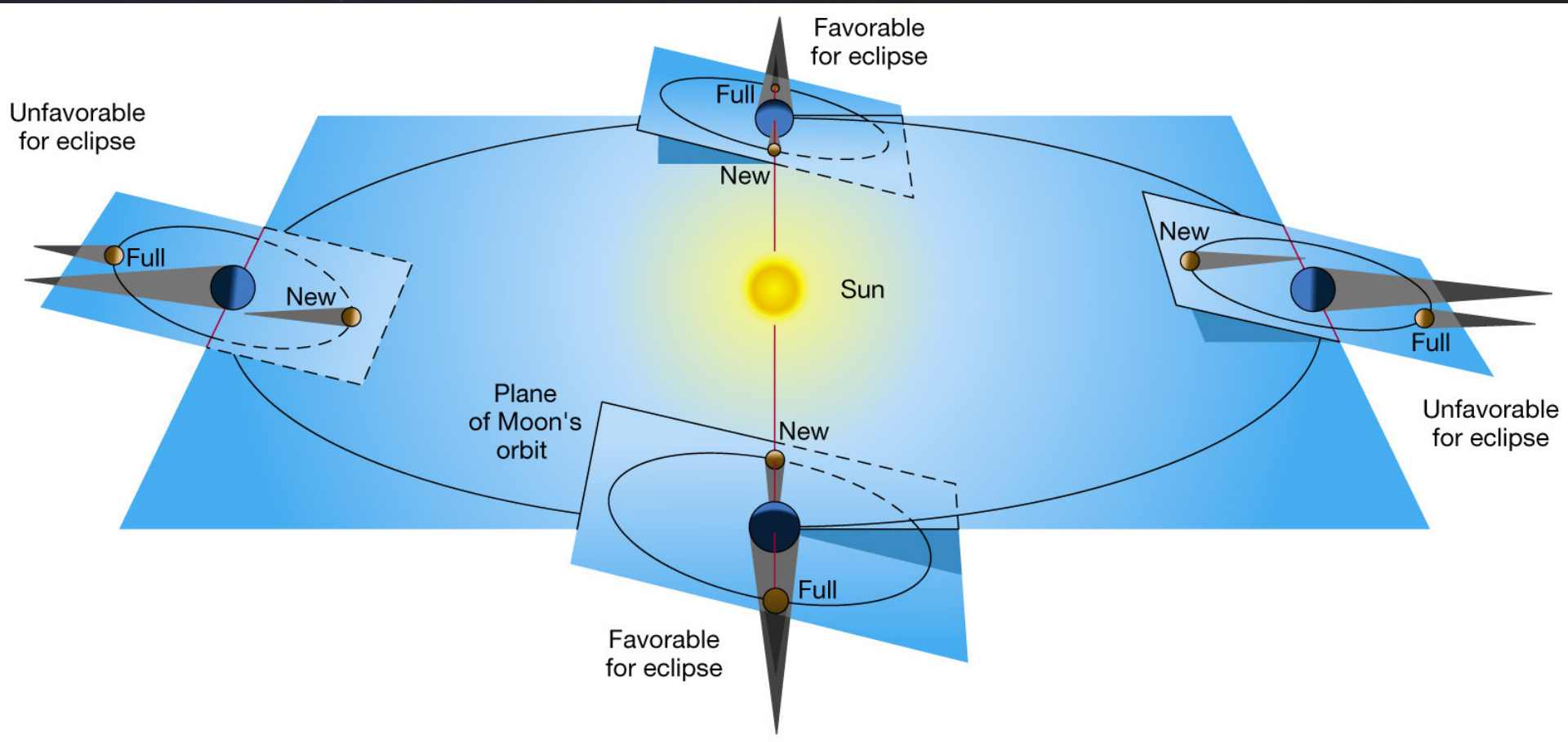
Longitude = right ascension, α from vernal point. Given in hours : 24h = 360° .

Other coordinates are possible...



Application : the Moon has 5° inclination with respect to the ecliptic plane. It passes « above » or « below » the Sun, except when the Sun is in the line of node => eclipses !

→ Twice a year, there is a Moon eclipse, and possibly a Sun eclipse 2 weeks apart.



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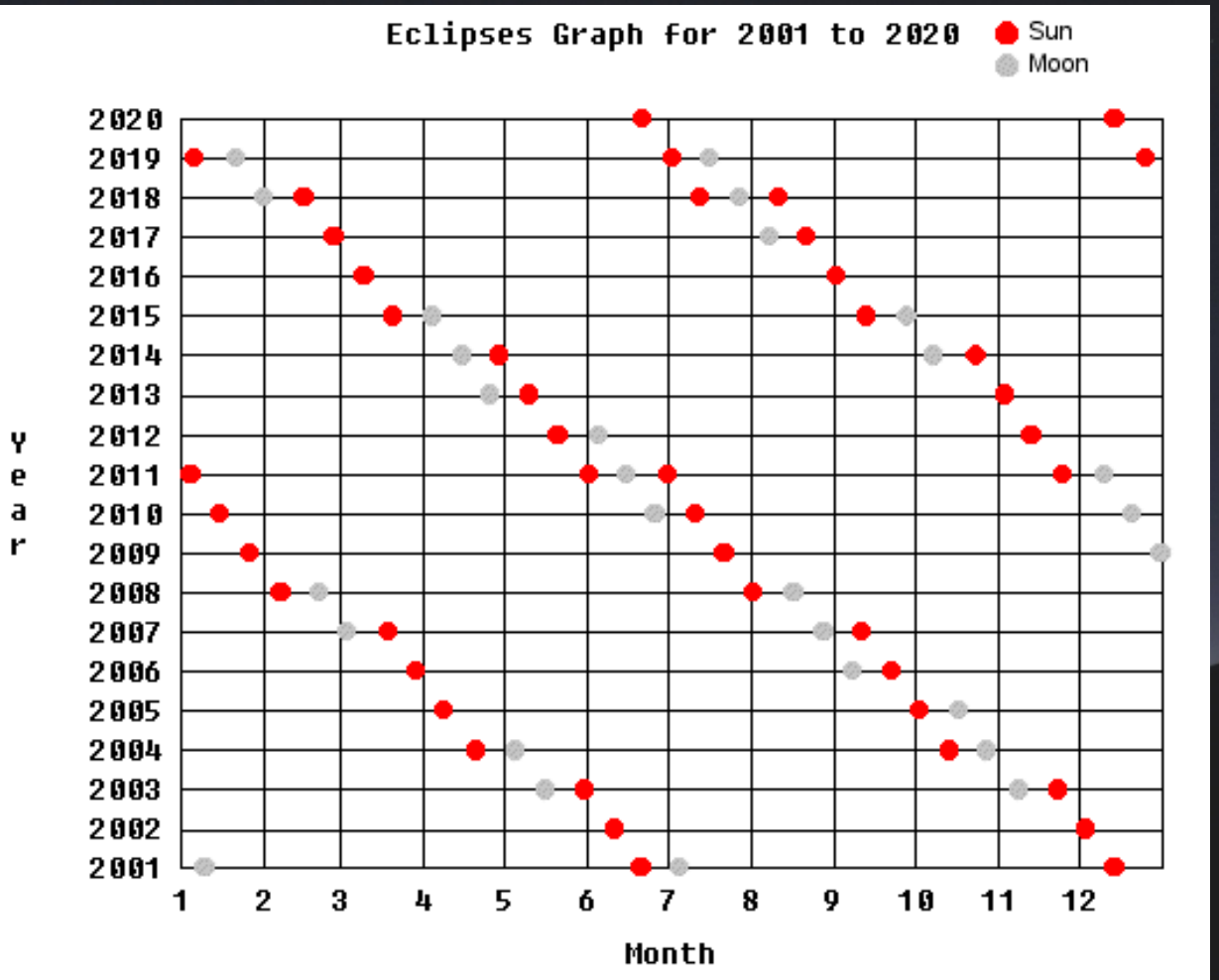


The Moon's orbital plane slowly precesses → shift of the dates year after year...

All the planes in the solar system precess :
- Earth's equator
- planet's orbits around the Sun...

The Sun has the same angular diameter as the Moon.

(Épernay, 11 / 8 / 1999)

(Sahara, Libya, 26 / 3 / 2006)

The Moon fits **3** times in the Earth's shadow (round, 2nd proof).

Exercise :

Draw the Earth, its shadow, the Moon, its shadow, respecting the relative sizes.

→ The Moon is **4** times smaller than the Earth.

What's the size of the Earth ?

Eratosthenes :

At the summer solstice, the Sun lits the bottom of water wells in Asswan, but is 8° from the vertical direction in Alexandria.

→ 3rd proof that the Earth is round !

Given α = 8° ,

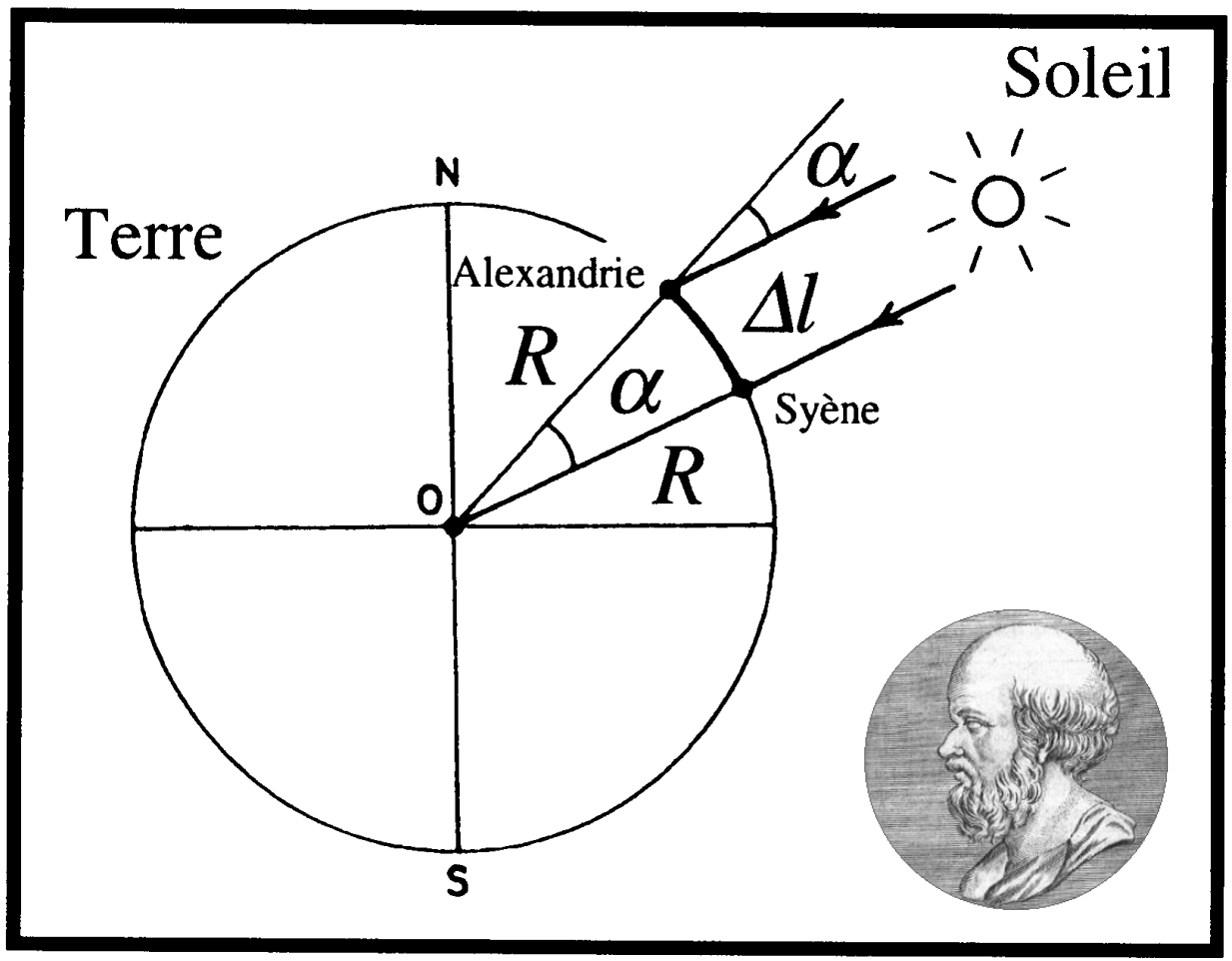
Δl = 889km,

What is the Earth's circumference ?

→ 40 000 km

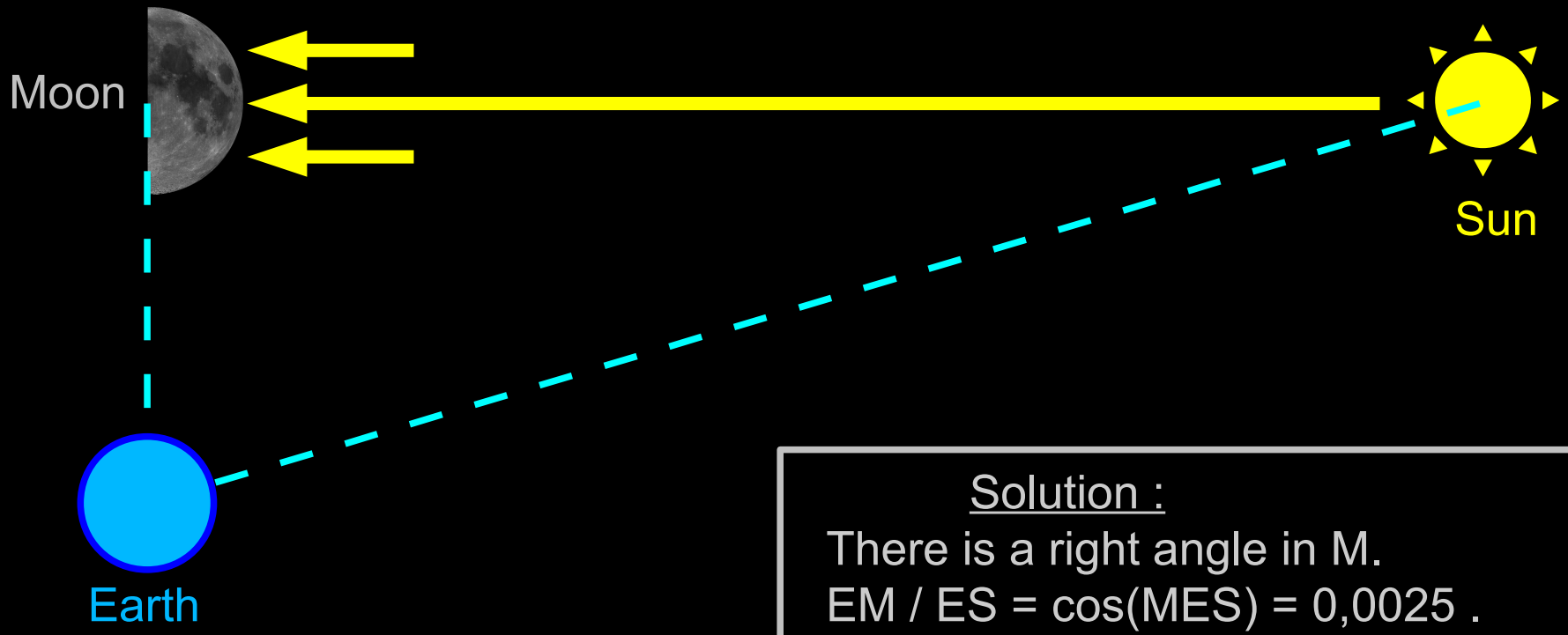
Its radius ?

→ 6 400 km



At first Quarter, what can we say about the triangle EMS ?

If the angle MES is 89.85°, how far/big is the Sun ?



Solution :

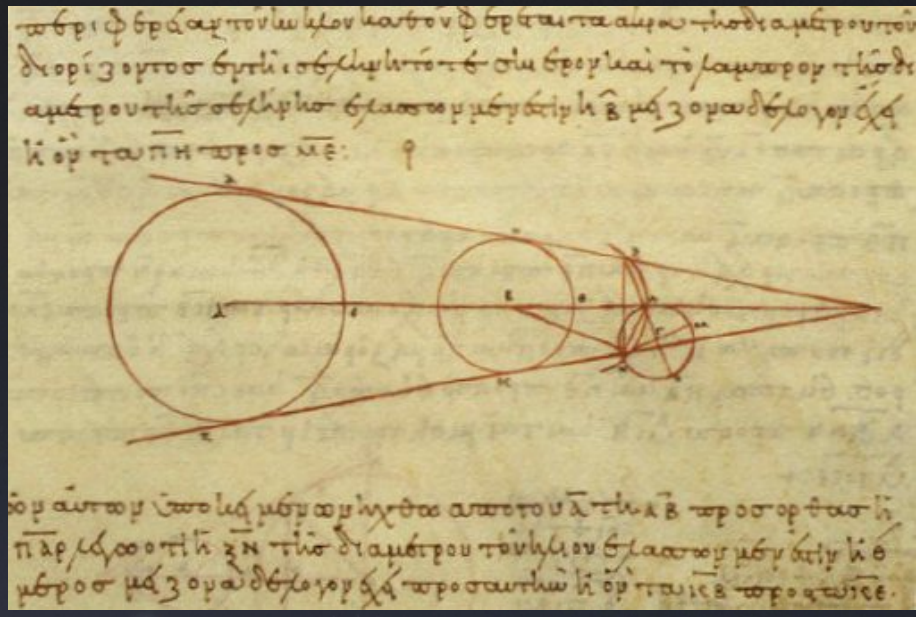
There is a right angle in M.
EM / ES = cos(MES) = 0,0025 .
Thus ES = 400 x EM.

The Sun is 400 times further, thus larger than the Moon (as they have the same angular diameter).
Hence 100 times larger than the Earth.

The Sun is 100 times larger than the Earth,

so, the Earth should rotate around the Sun...

Alexandra Tavernier
(junior world champion, senior bronze medal)



Aristarchus of Samos
(-310 -230)

What's the distance of the Moon and Sun ?

Aristarchus again :

The Moon appears as large as 90cm stick placed 100m away (angular diameter = 0,5°).
It is 4 times smaller than the Earth (3476 km diametre), hence, according to Thales' theorem,
the Earth-Moon distance is : 3476*100/0,9 = **384 000 km**.

From this, one derives the Earth-Sun distance, called the *Astronomical Unit* (reminder: TS = 390 TL) :

1 U.A. = 150 millions kilometres.

Summary :

With simple observations, a stick and a camel, we find that :

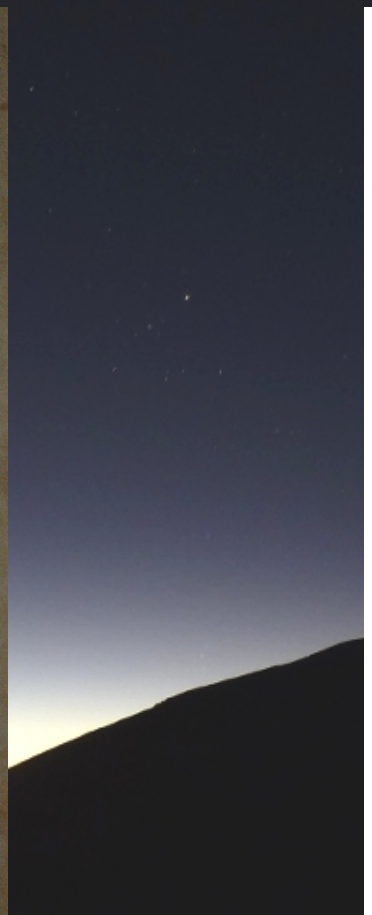
- the Solar System is flat
- the Earth is round, with a circumference of 40 000 km,
- the Moon is 4 times smaller than the Earth,
- the Sun is 100 times larger than the Earth,

→ the Moon orbits around the Earth, & the Earth around the Sun.

- the Earth – Moon and Earth – Sun distances.

In spite of these obvious facts, people still ~~voted for Donald Trump~~ adopted Ptolemeus' geocentric model of the Universe, based on ~~Fox News~~ Aristoteles' ideas that the skies are perfect, with only circular motion, and the Earth is not pure...

Earth at the centre was also promoted by the monotheisms.



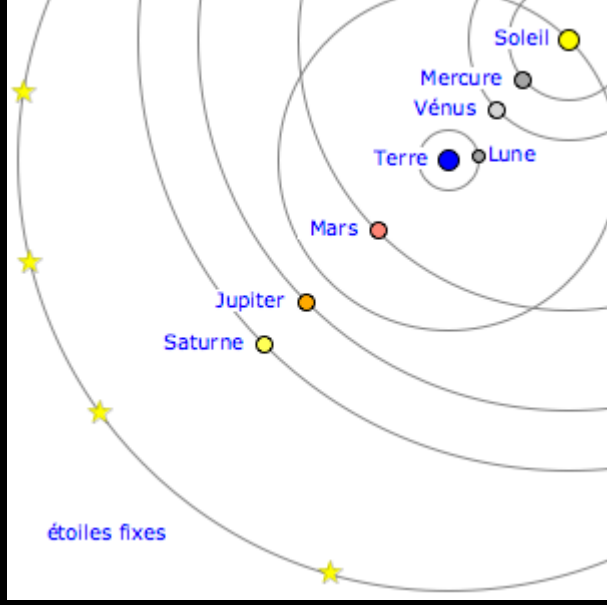
Copernicus (1473-1543), conversation with God

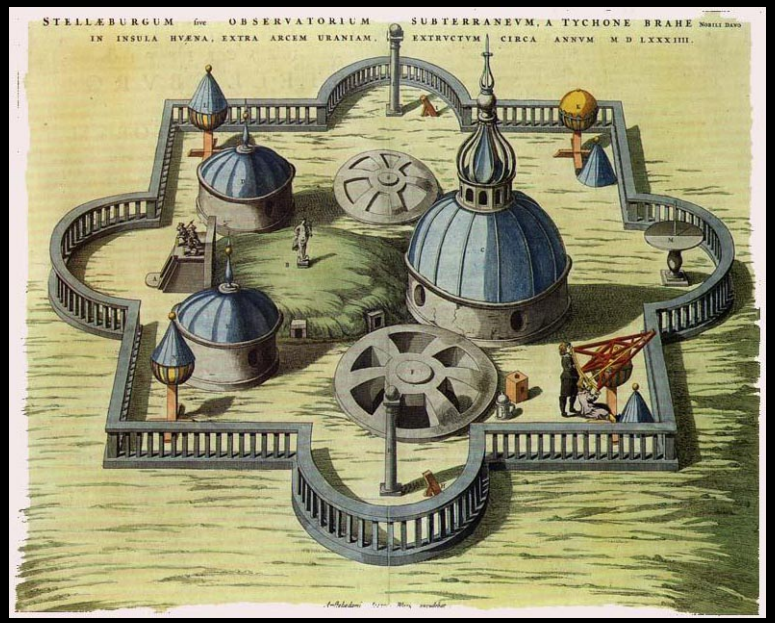
Tycho Brahe (late XVI°)

Danish astronomer.

His precise observations confirm that the planets orbit around the Sun.

But he suggests that the latter still orbits around a fixed Earth.





Kepler (~1600)

Deduces 3 properties of the orbits of the planets from Tycho's observations :

Three laws of Kepler (1609) :

1) The planetary orbits are ellipses, with the Sun in a focus, not at the centre.

2) A line segment joining a planet and the Sun sweeps out equal areas during equal time intervals (conservation of angular momentum)

3) The square of the orbital period is proportionnal to the cube of the semi-major axis (the further, the slower)

Universal gravitation (XVII°)

Isaac Newton's law of **universal gravitation** expains mathematicaly Kepler's 3 laws.

$$F = G M_1 M_2 / d^2$$

1781 : Discovery of Uranus, in the ecliptic plane, by chance.

1801: Discovery of Ceres → a new planet !

Then, discovery of other asteroids → asteroid belt.

1846 : Discovery of Neptune, by calculation !

1930 : Discovery of Pluto → 9th planet !

Then, discovery of other trans-neptunian objects, a few being even larger → Kuiper belt.

We need a clear definition of a planet.

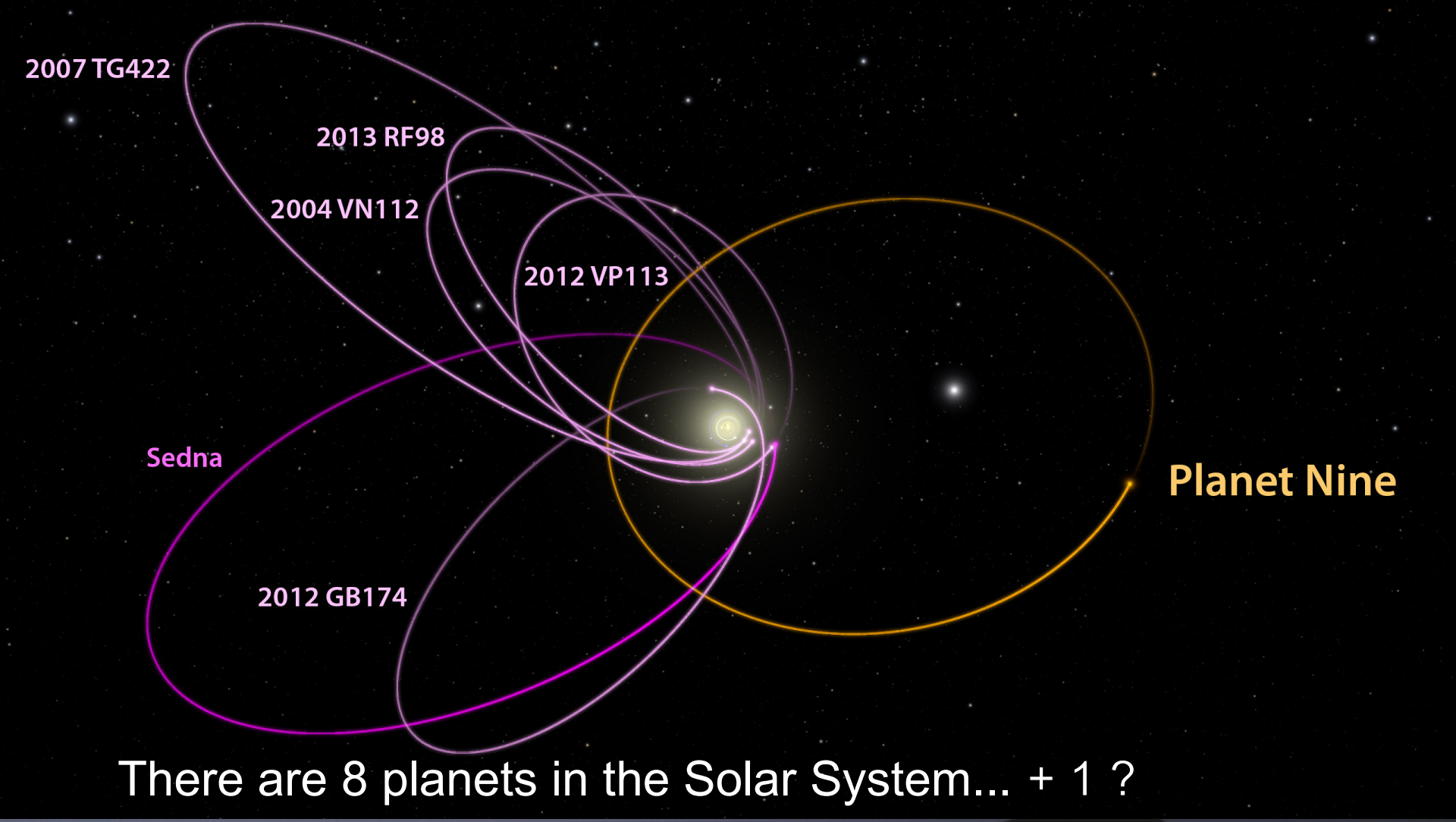
Official definition (IAU, 2006) :

A planet is a celestial body that
- orbits around the Sun,
- has a large enough mass so that its own gravity gives it a spherical shape (hydrostatic equilibrium),
- dominates the local dynamics, has eliminated any other body on a nearby orbit.

There are 8 planets in the Solar System.

If the third condition is not met : *dwarf planet*

There are 3 dwarf planets in the Solar System :
Eris, Pluto, Ceres



There are 8 planets in the Solar System... + 1 ?

Some other basic definitions :

Solar System = the Sun + bodies gravitationally bound to it (planets & their satellites, asteroids, comets, dust).
Size : ~ 1 light-year.

Star = a celestial body massive enough to make nuclear fusion, and produce its own visible light (planets don't).

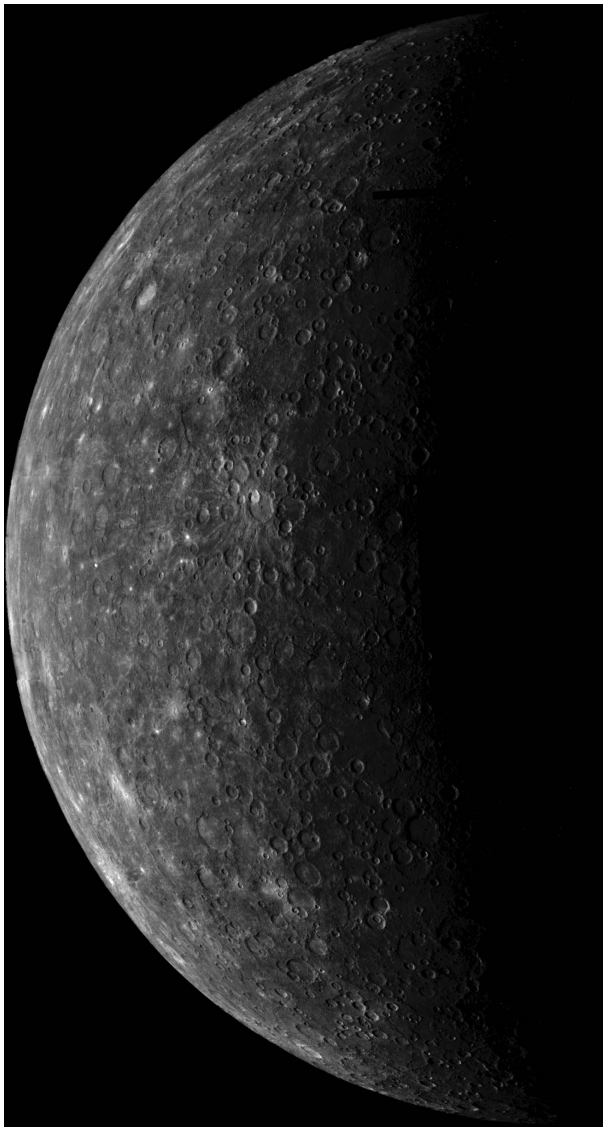
Milky Way = The Galaxy = all the stars we see in the sky, including the white band famous as the milky way.
Size : ~ 100 000 light-years.

A galaxy = a group of billions of stars, an « island universe ».

The Universe = everything we can see with any instrument.
Size : ~ 14 billion light-years.

Light-year = distance light travels in 1 year = 10^{16} m.

MERCURY



Semi major axis : 0.387 AU.

Eccentricity : 0,2

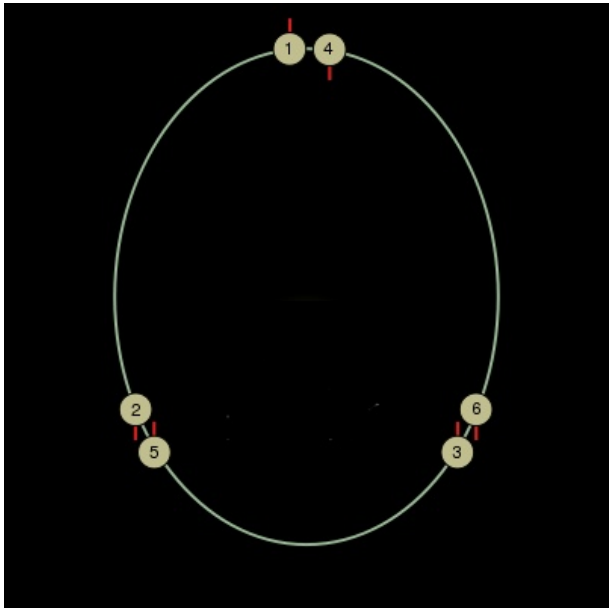
Mass : 3.3 x 10^{23} kg = 0.055 of Earth

Radius : 2440 km = 38% of Earth

Density : 5 340 kg.m^{-3}.

Mag field : ~Earth's field / 60.

Rotation :
spins 3 times
in 2 orbits
around the Sun.
(*resonance*)



VENUS

Semi major axis : 0.72 AU.

Eccentricity : 0,2.

Mass : 5/6 of Earth

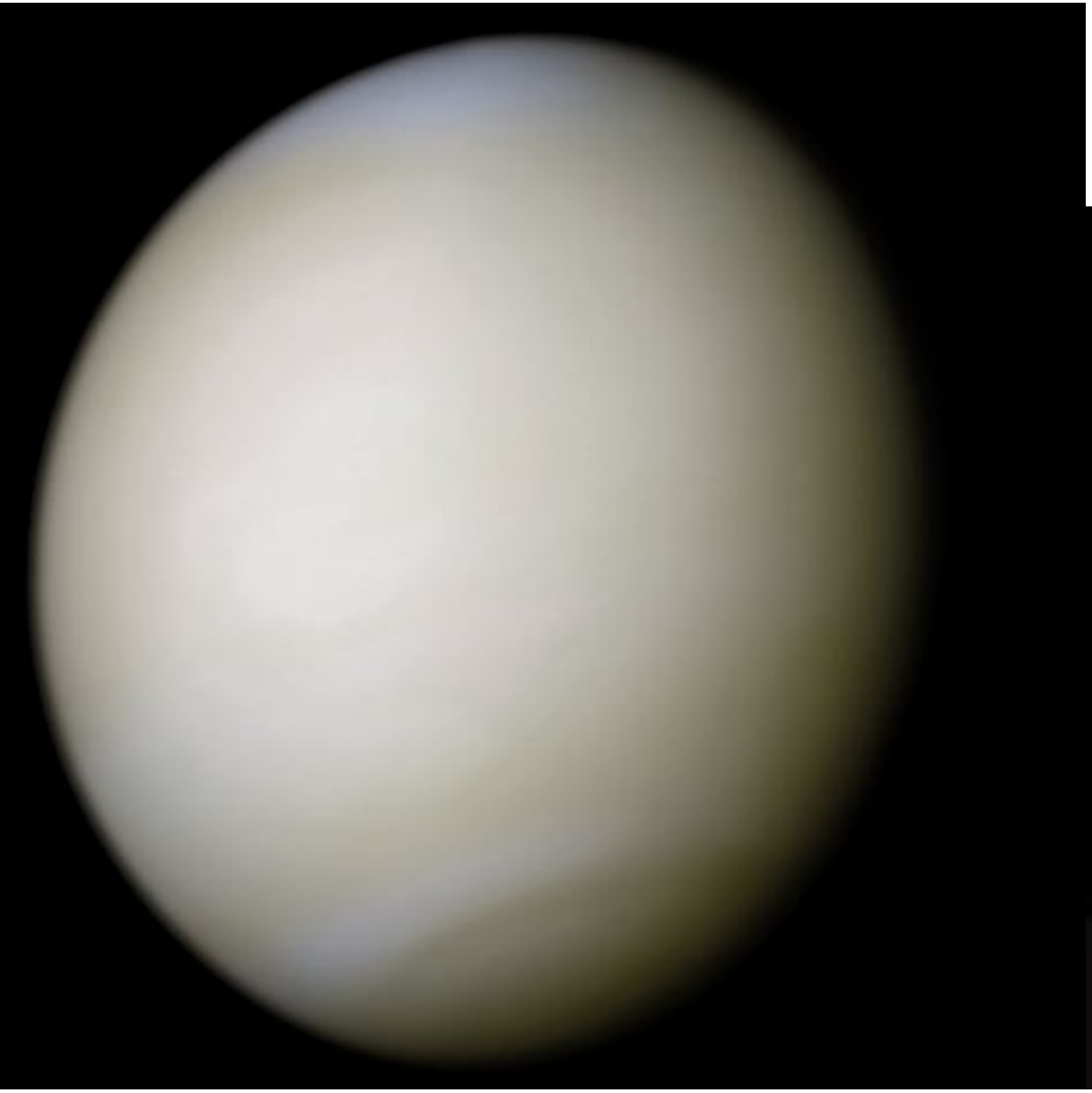
Radius : 0.95% of Earth

Density : 5 340 $kg.m^{-3}$.

Atmosphere : 95 Bars on the ground.

Rotation : slow (243 days) and retrograde (or inclined by 177°)

VENUS



EARTH

Semi major axis : 1 AU = 149 597 887 km.

Eccentricity : 0,016.

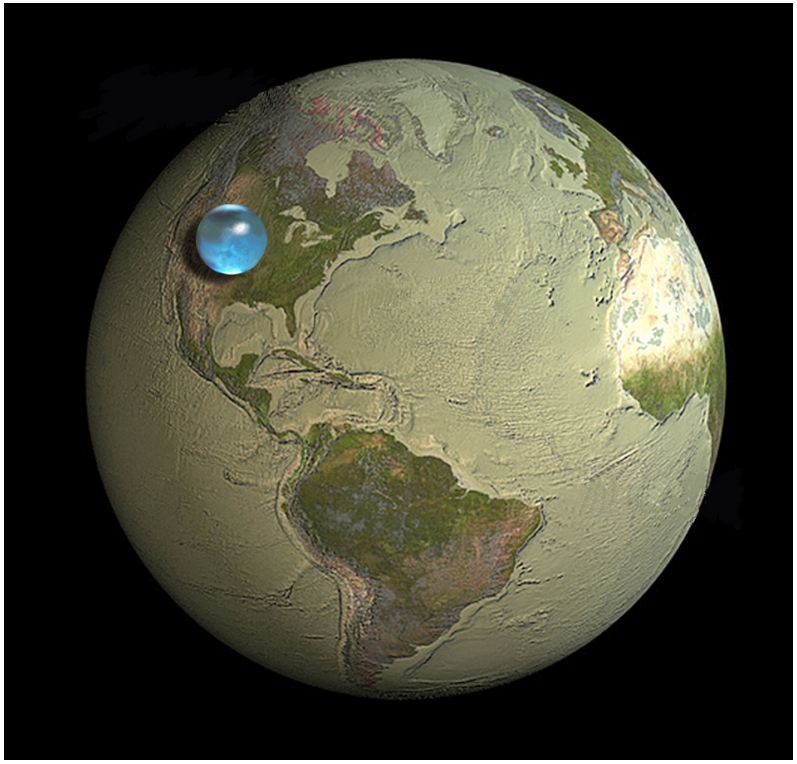
Rotation : sideral period = 23h56min, inclinaison = 23,4°.

? A day = 24h ?

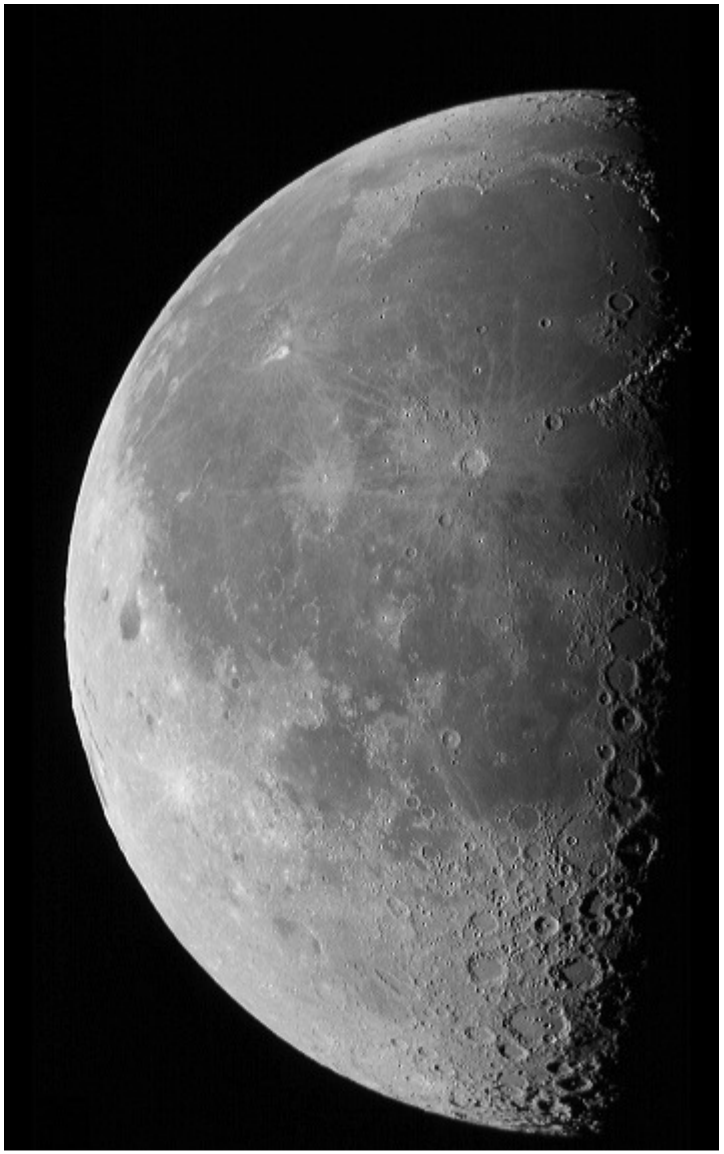
Mass : 6 x 10^{24} kg = 3 x 10^{-6} M_{sun}.
(0.025% of which is water)

Radius : 6371 km

Density : 5 515 kg.m^{-3}.



MOON



Semi major axis : 384 400 km
Eccentricity : 0.055

Mass : ~ 1/80 M_{earth}

Radius : ~1/4 R_{earth}

Density : 3 344 $kg.m^{-3}$.

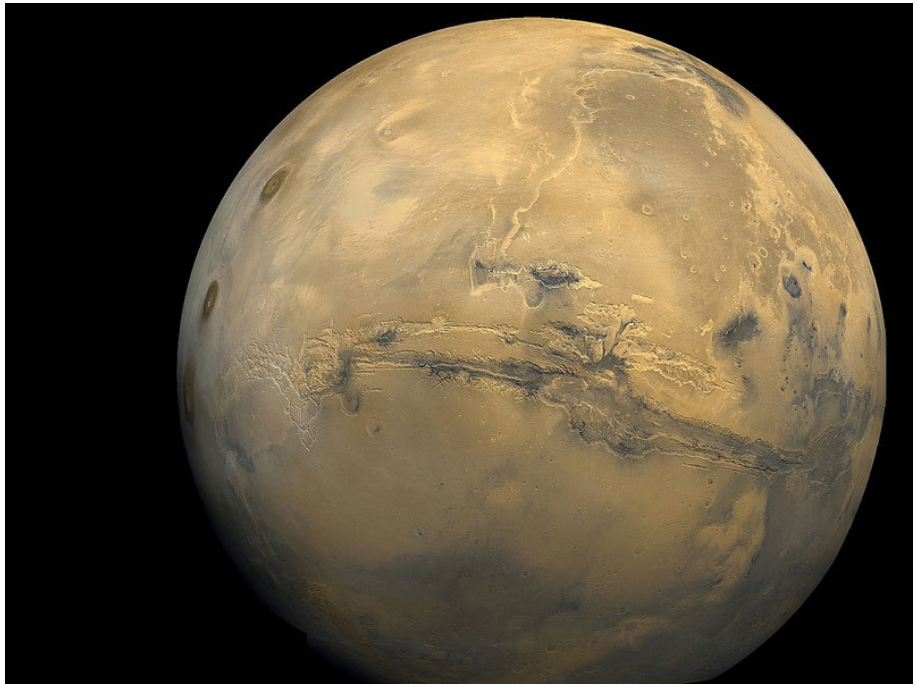
→ very small core < 4% mass

Chemically very close to Earth's mantle (drier).

Orbital period = Rotation period = 27d 7h 43m

Time between 2 new moons (synodic period) : 29d 12h 44m

MARS ♂



Semi major axis : 1,52 AU.

Eccentricity : 0,09.

Rotation : period = 24h37min
inclination = 25,2°.

Mass : 6.4×10^{23} kg = 0,1 M_{earth}.

Radius : 3 390 km = 0.53 R_{earth}.

Density : 3 934 $kg.m^{-3}$.

Water : in the polar caps + ice in the ground (permafrost).

Proofs of past water presence : hydrated minerals, chenals...
Essentially lost with the atmosphere.

JUPITER

Semi major axis : 5,2 AU.

Eccentricity : 0,048.

Mass : 1.9×10^{27} kg = 0,001 M_{sun}.

Radius : 70 000 km.

Density : 1 327 $kg.m^{-3}$.

Rotation : 10h,
axial tilt : 3°.

Satellites : many,
including the 4 galilean moons
Io, europa, Ganymede, Callisto.

SATURN

Semi major axis : 9,6 AU.

Eccentricity : 0,054.

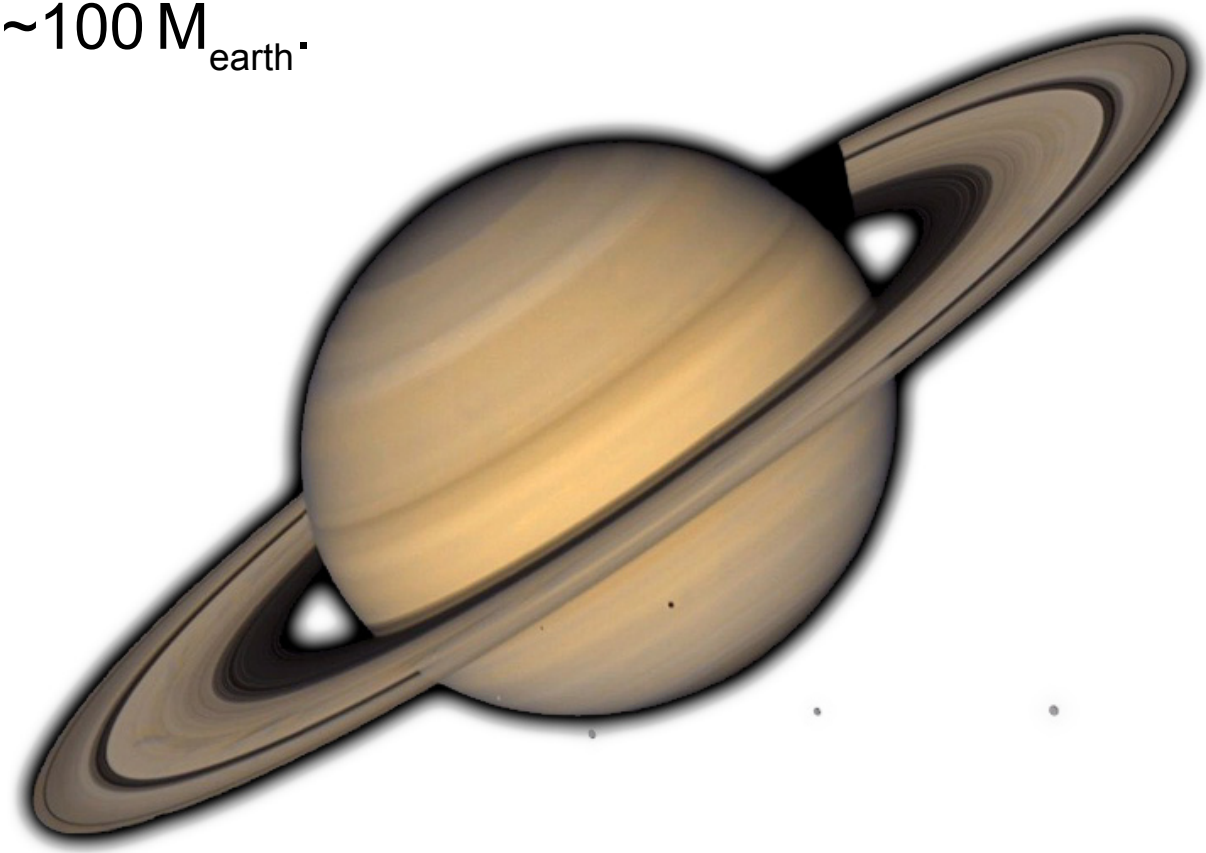
Satellites : many, including Titan, the only satellite with an atmosphere.

Mass : 5.68×10^{26} kg = ~100 M_{earth}.

Radius : 60 000 km.

Density : 700 $kg.m^{-3}$.

Rotation : 10 à 11 h,
axial tilt : 26°.



URANUS

Semi major axis : 19,2 AU.

Eccentricity : 0,047.

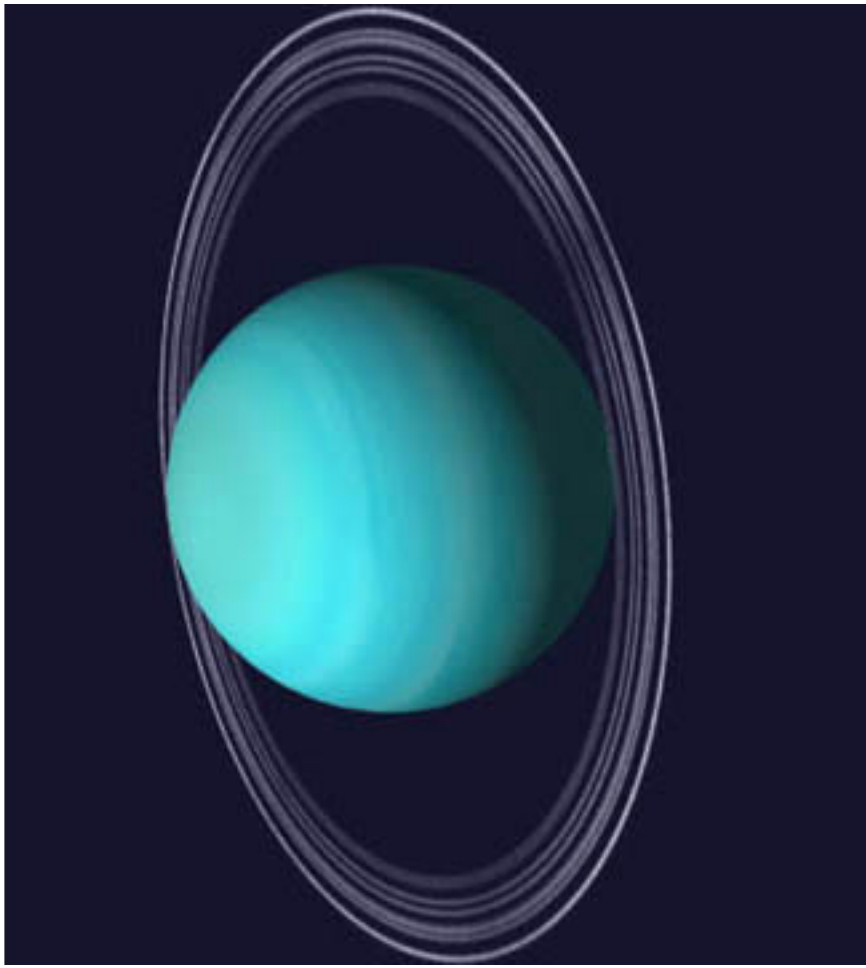
Mass : 8.68×10^{25} kg = 14.5 M_{earth}.

Radius : 25 500 km = 4 R_{earth}.

Density : 1270 $kg.m^{-3}$.

Rotation : 17h, tilted at 98°.

Discovered by Hershell in 1781, by chance.



NEPTUNE

Semi major axis : 30.1 AU.

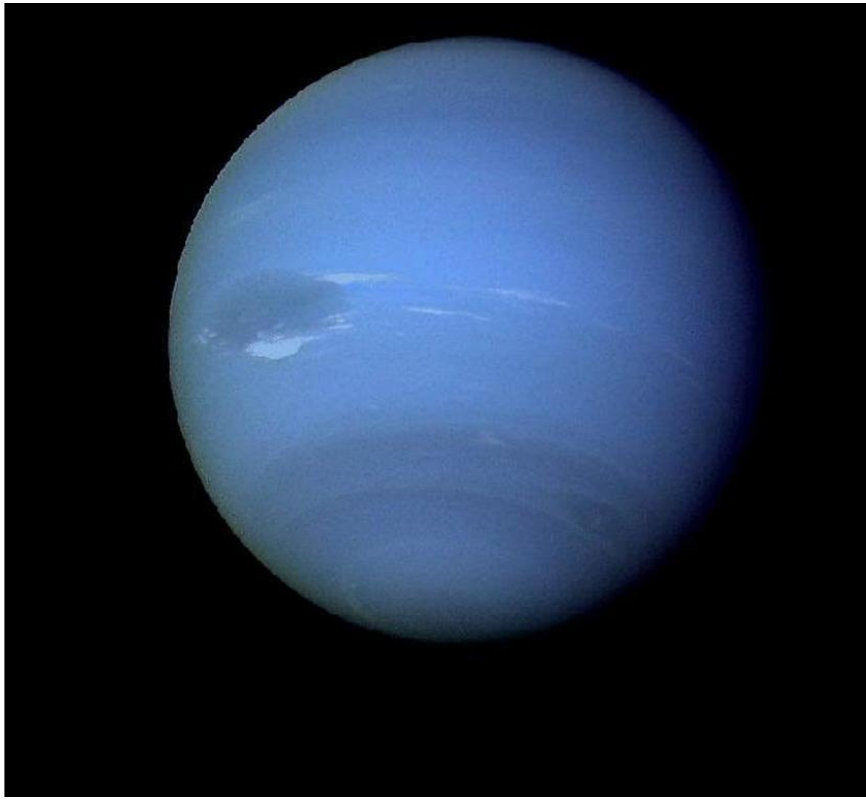
Eccentricity : 0,0086.

Mass : $10{,}2 \times 10^{25}$ kg = 17.2 M_{earth}.

Radius : 24 600 km.

Density : 1640 $kg.m^{-3}$.

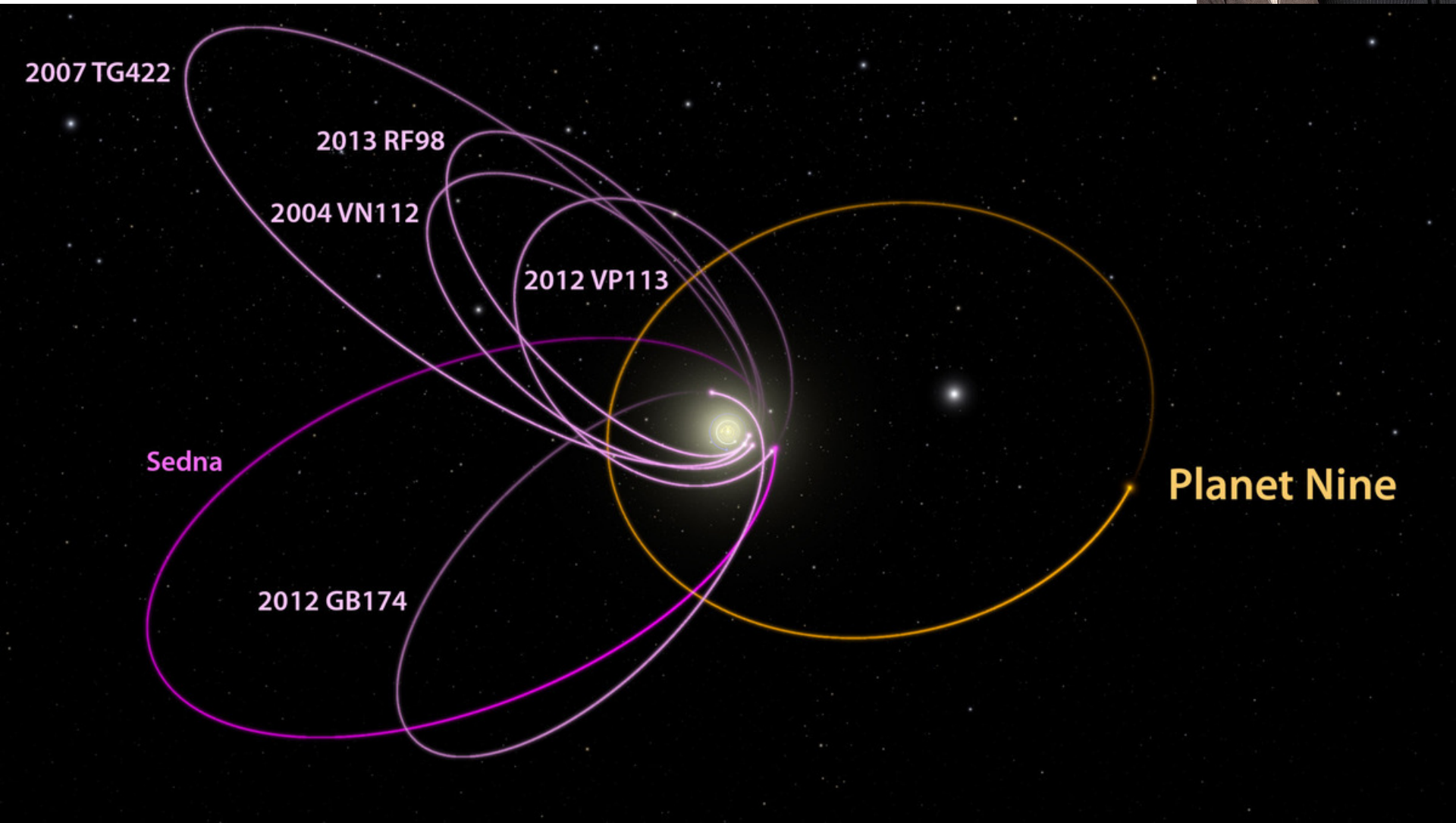
Rotation : 16h, tilted at 30°.

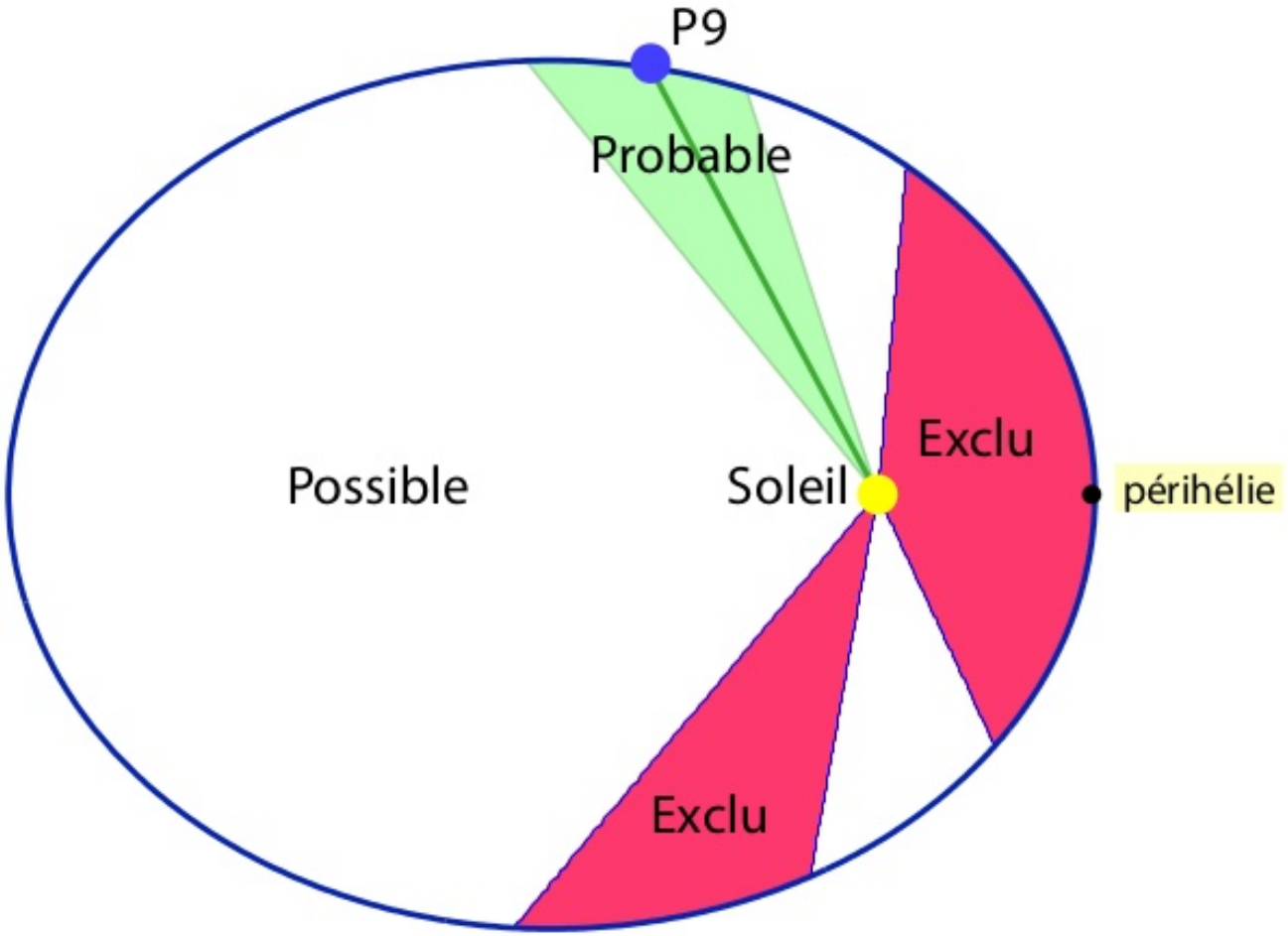


Discovered by Le Verrier in 1846, by calulations.

PLANET IX ?

Suggested by Konstantin BATYGIN & Mike BROWN, from the strange alignment of the orbits of KBOs.



PLANET IX ?

Tested by Agnes FIENGA & Jacques LASKAR,
from the ephemerids of Saturn.