

# Nordita Winter School 2017

## The SOLAR SYSTEM



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.



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, Mardi, Mercredi, Thursday, Friday, Saturday, Sunday**

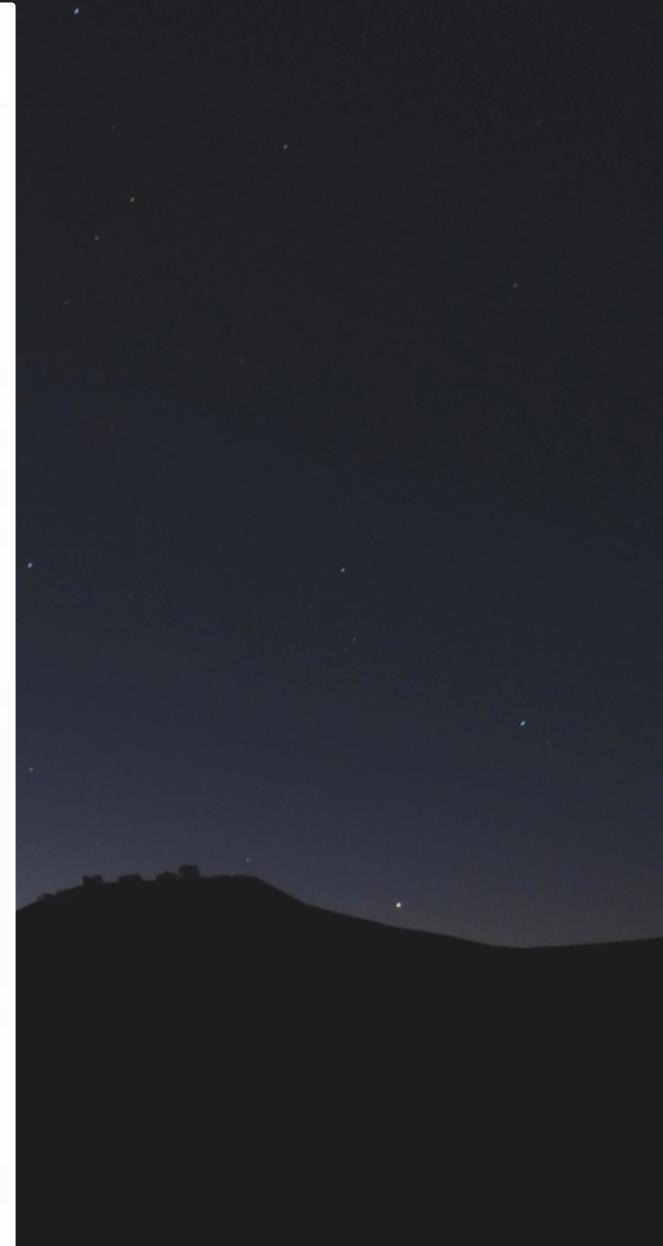
Måndag, tisdag, onsdag, torsdag, fredag, lördag, söndag.

Moving astres, called in greek  $\pi\lambda\alpha\nu\eta\tau\eta\zeta$ , planets.

Venus

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

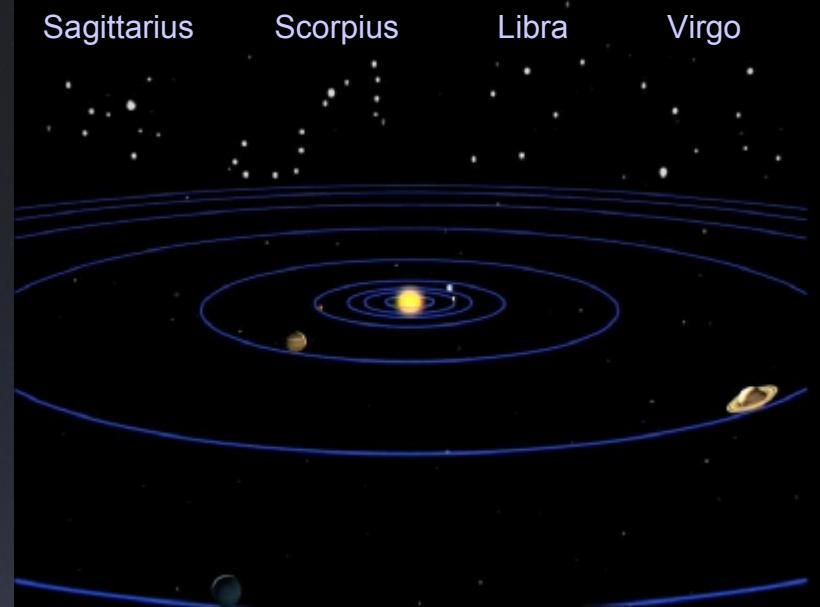
# L'ÉTOILE MYSTÉRIEUSE



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 !



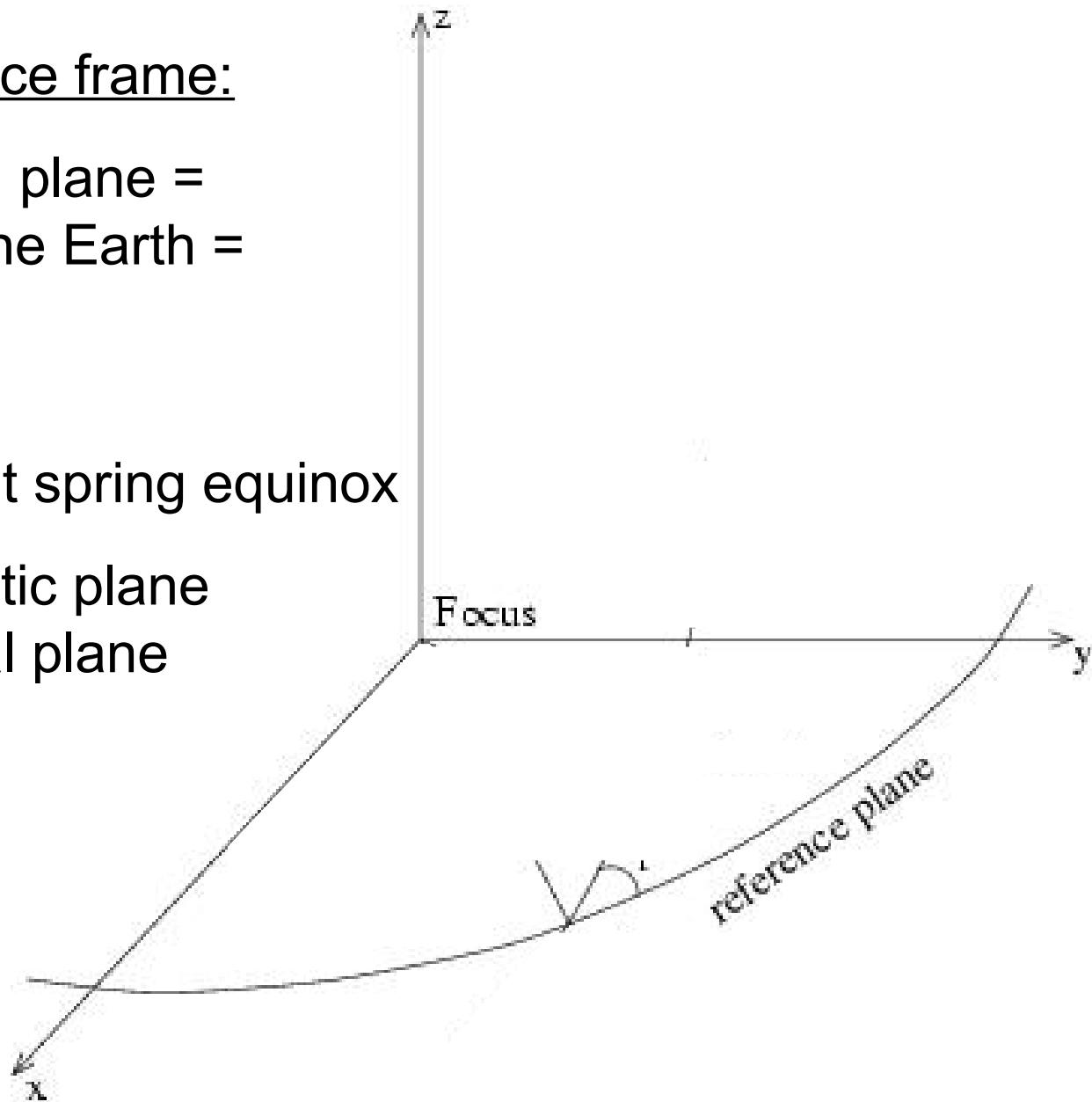
# REFERENCE FRAME

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

$\Omega$  = longitude of the (ascending) node

$\omega$  = argument of the pericenter

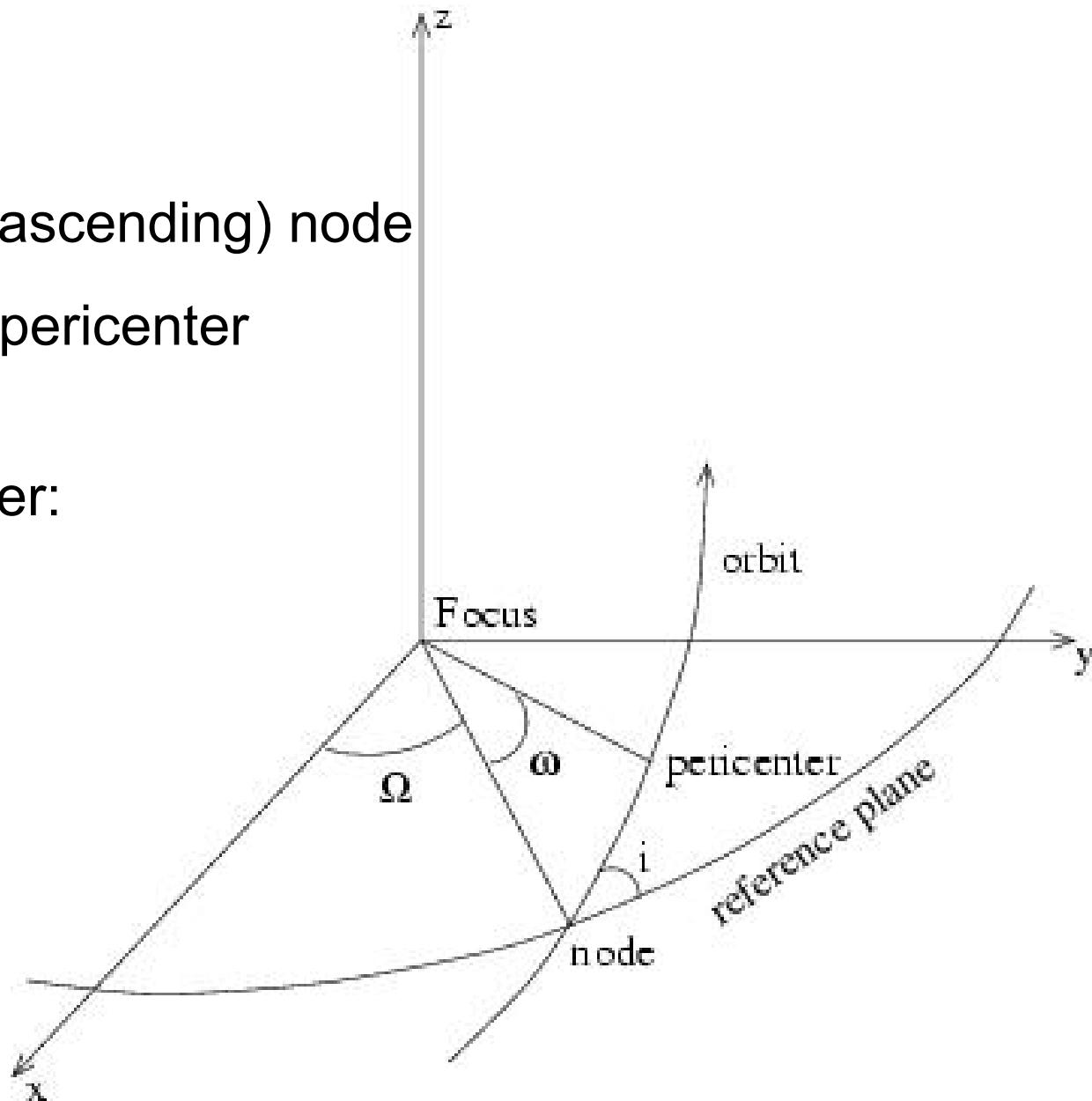
Longitude of pericenter:

$$\varpi = \omega + \Omega$$

Mean longitude:

$$\lambda = M + \varpi$$

Longitude :  
angle / frame



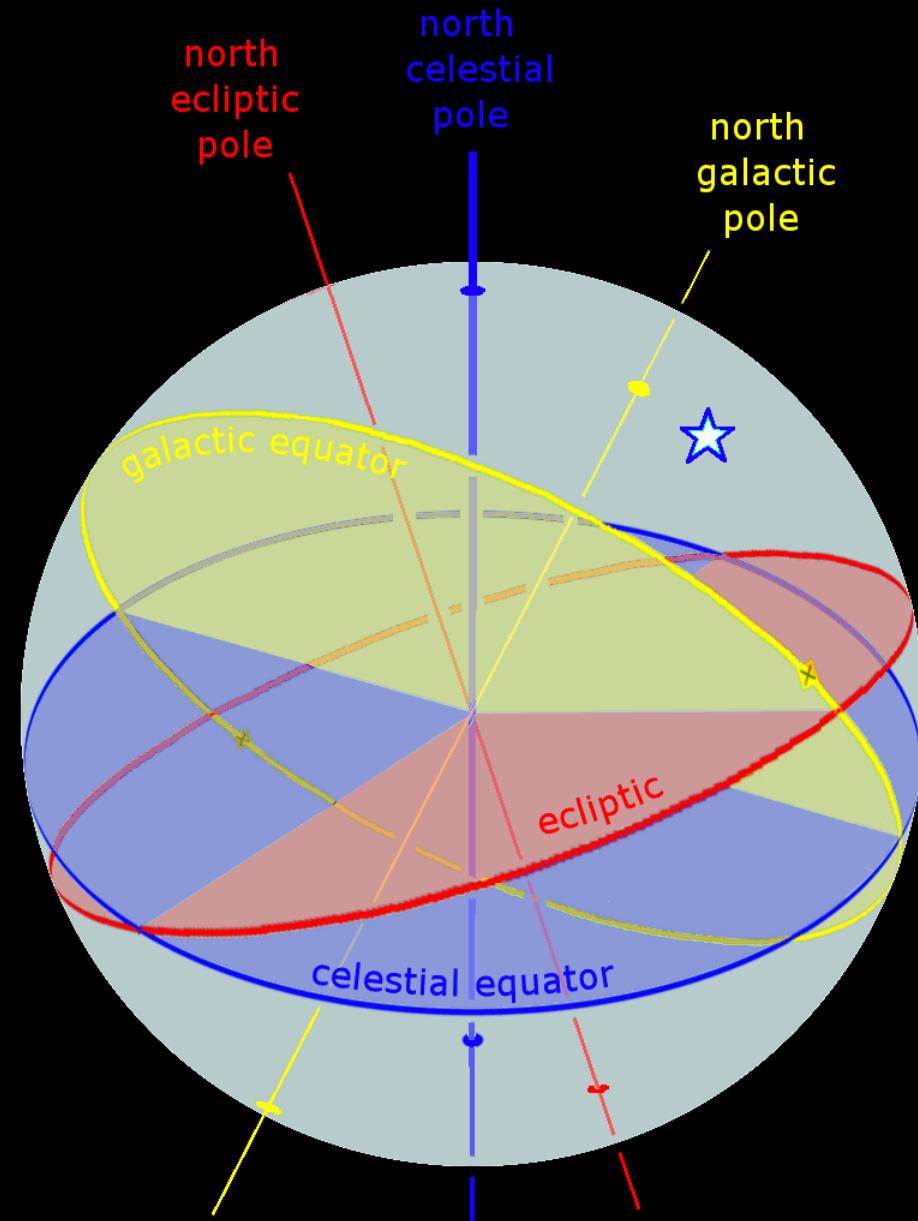
# CELESTIAL COORDINATES

Sky coordinates :

Latitude =  
declination,  $\delta$ .  
 $\delta=+90^\circ$  above  
Earth's north pole.

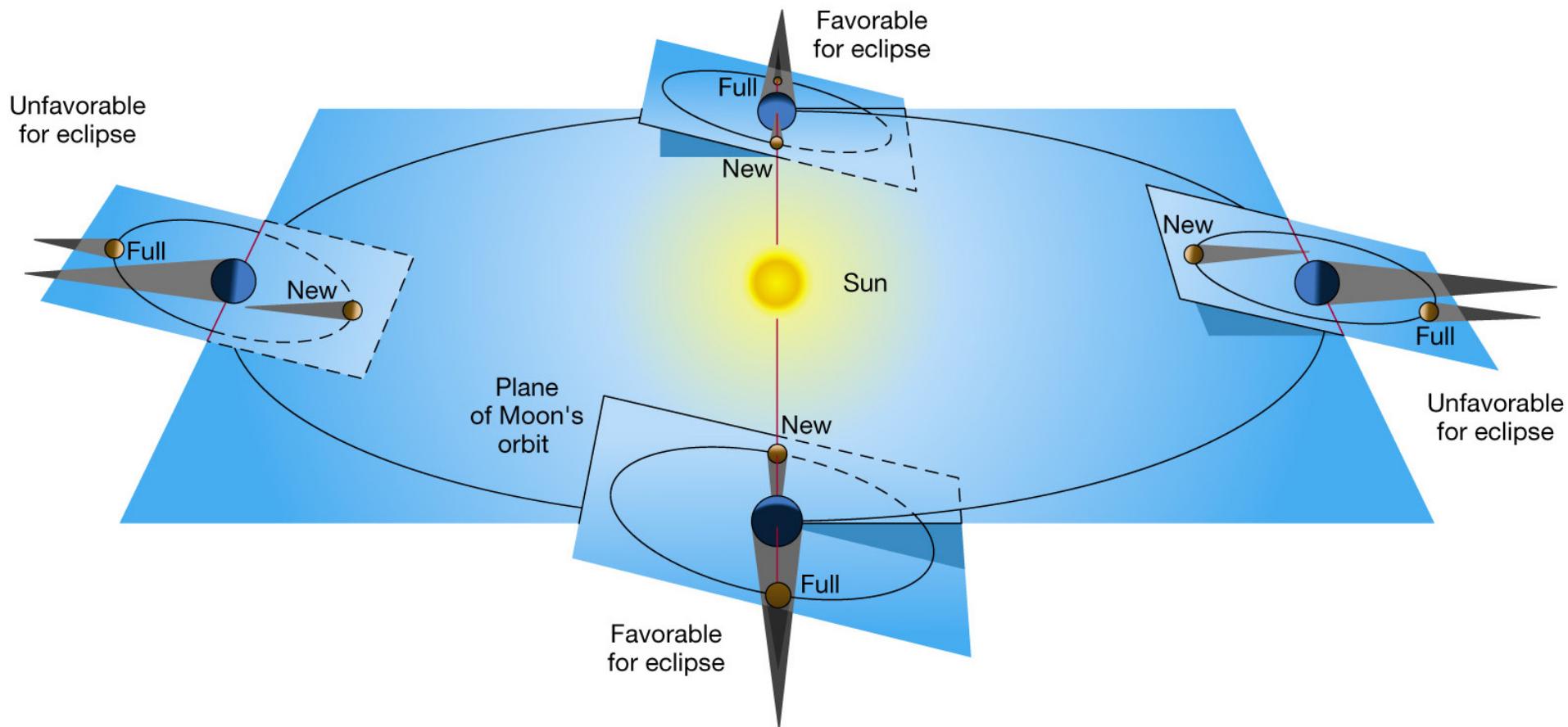
Longitude =  
right ascension,  $\alpha$   
from vernal point.  
Given in hours :  
24h =  $360^\circ$ .

Other coordinates  
are possible...



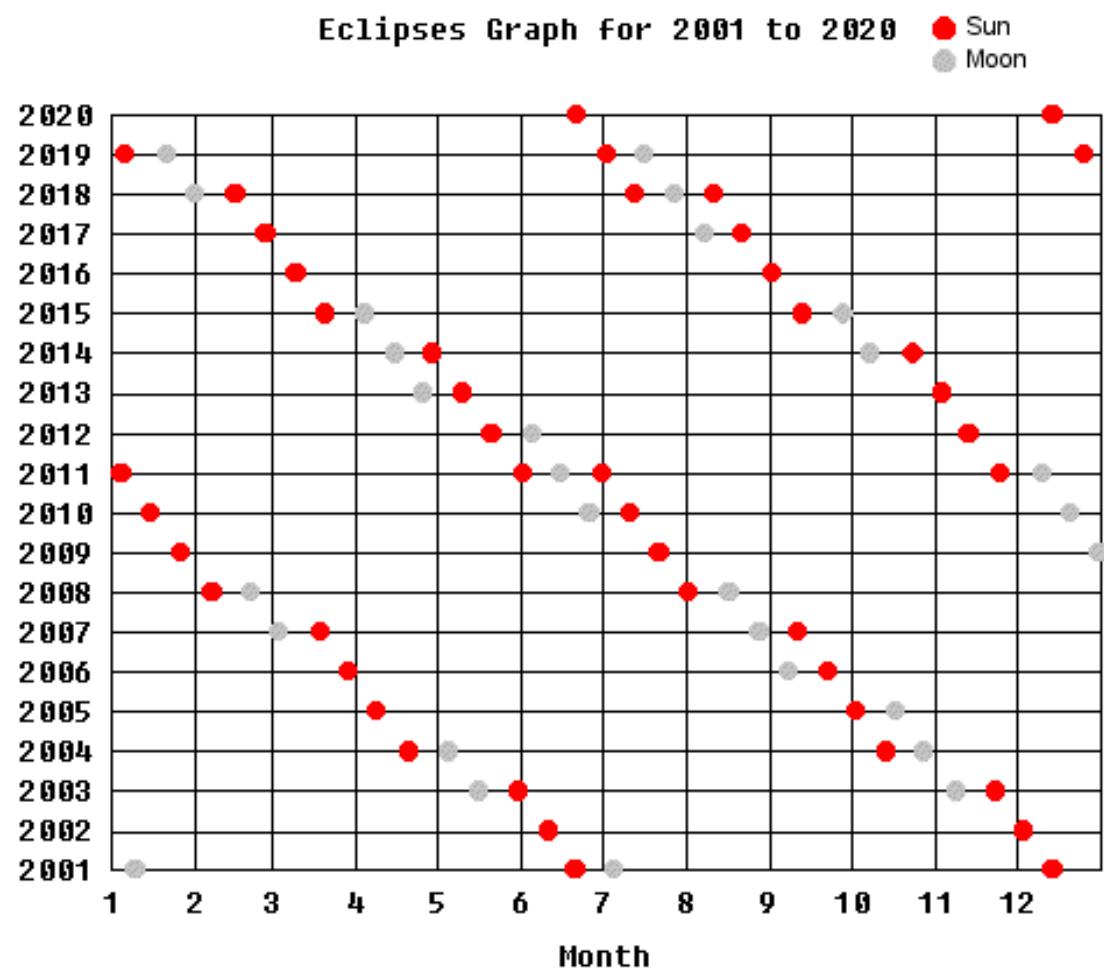
Application : the Moon has  $5^\circ$  inclination with respect to the ecliptic plane. It passes « above » or « below » the Sun, except when the Sun is in the line of node => eclipses !

→ 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, 2<sup>nd</sup> 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 hits the bottom of water wells in Asswan, but is  $8^\circ$  from the vertical direction in Alexandria.

→ 3<sup>rd</sup> proof that the Earth is round !

Given  $\alpha = 8^\circ$ ,

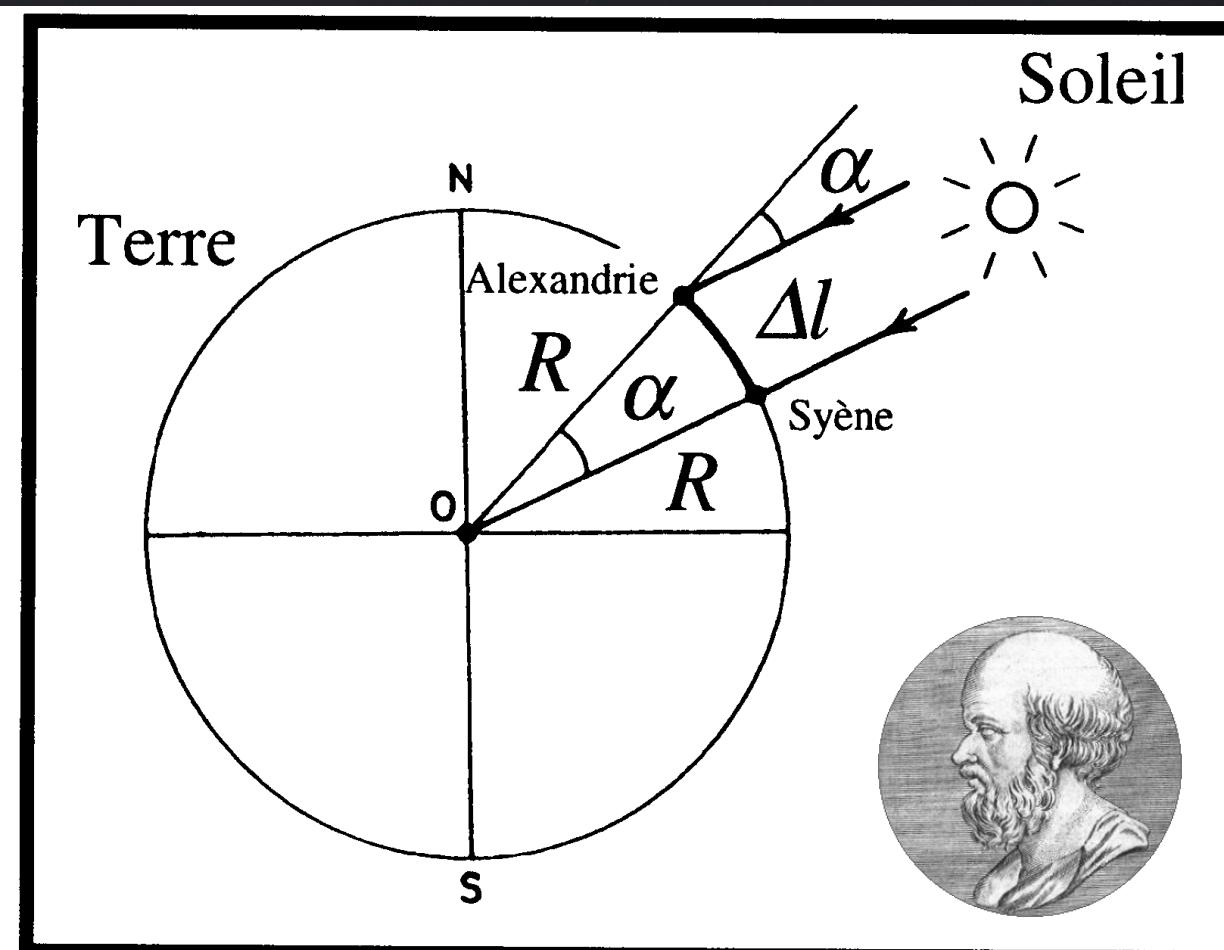
$\Delta l = 889\text{km}$ ,

What is the Earth's circumference ?

→ 40 000 km

Its radius ?

→ 6 400 km

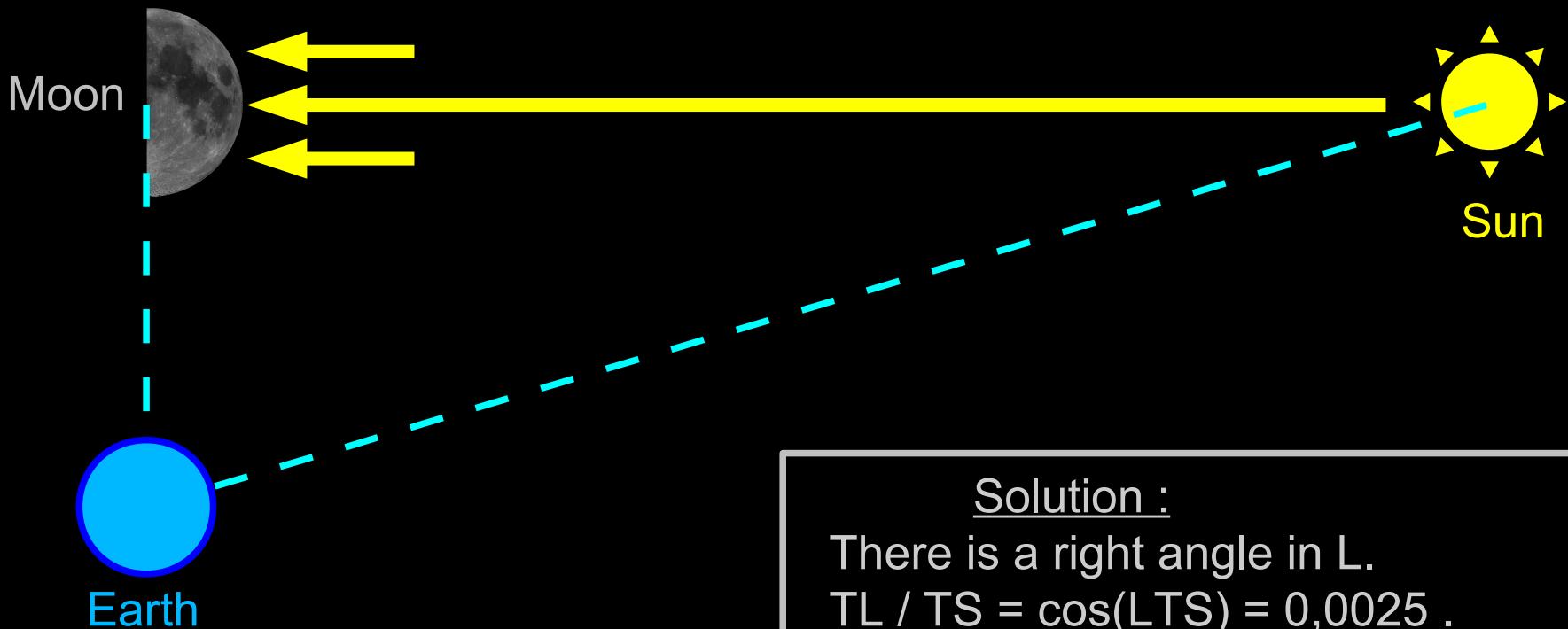


At first Quarter, what can we say about the triangle TLS ?

If the angle MSE is  $0.15^\circ$ , how far/big is the Sun ?

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

If the angle MES is  $89.85^\circ$ , how far/big is the Sun ?



Solution :

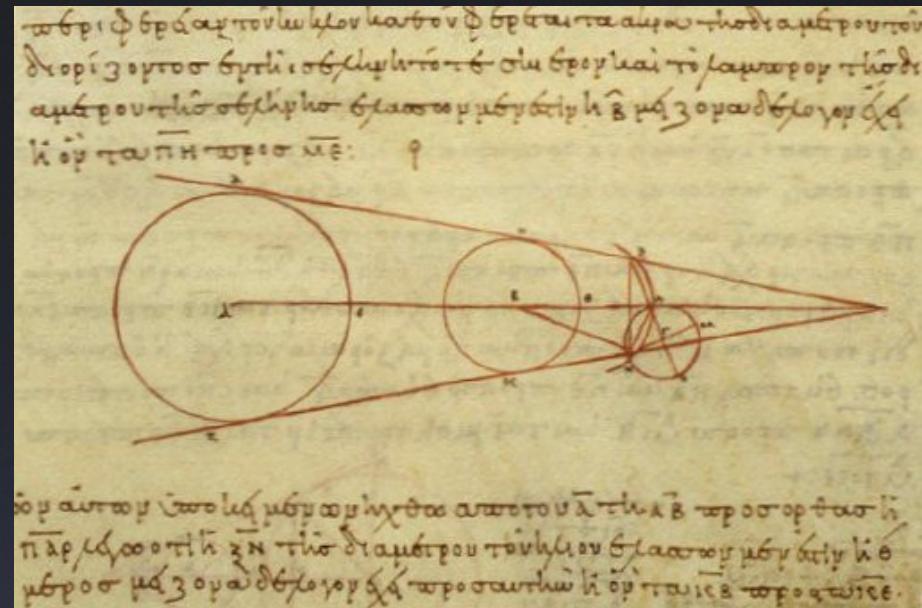
There is a right angle in L.  
 $TL / TS = \cos(LTS) = 0,0025$  .  
Thus  $TS = 400 \times TL$ .

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 ?

Teide National Parc, saturday 12, 6pm.

Deduce the Earth – Moon distance



	rock	Moon
width	4,5 m	3476 km
distance	500 m	X ?

$$X = 3476 \text{ km} \times (500 \text{ m} / 4,5 \text{ m}) = 386\,000 \text{ km}$$

# What's the distance of the Moon and Sun ?

## Aristarchus again :

The Moon appears as large as 90cm stick placed 100m away (angular diameter =  $0,5^\circ$ ).

It is 4 times smaller than the Earth (3476 km diametre), hence, according to Thales' theorem, the Earth-Moon distance is :  $3476 \times 100 / 0,9 = 384\,000$  km.

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

**1 A.U. = 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 40000 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

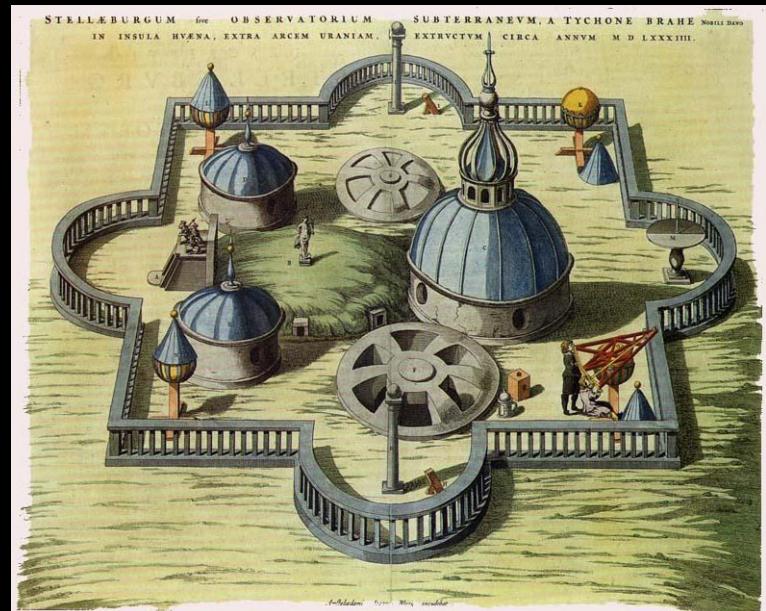
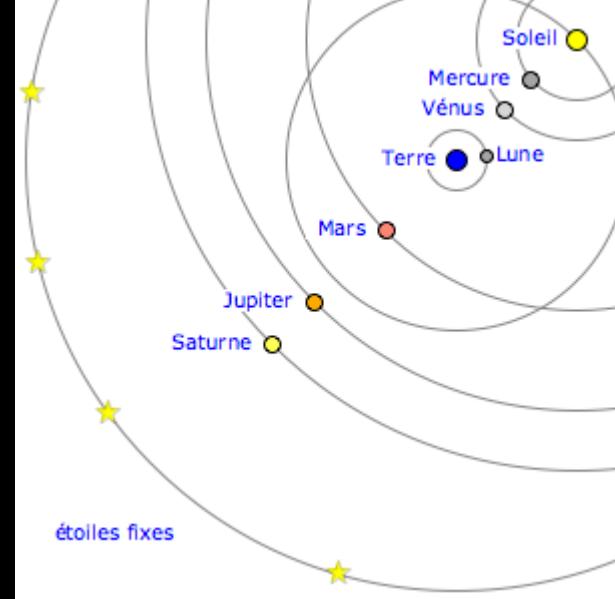
# Tycho Brahe (late XVI<sup>o</sup>)

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) :

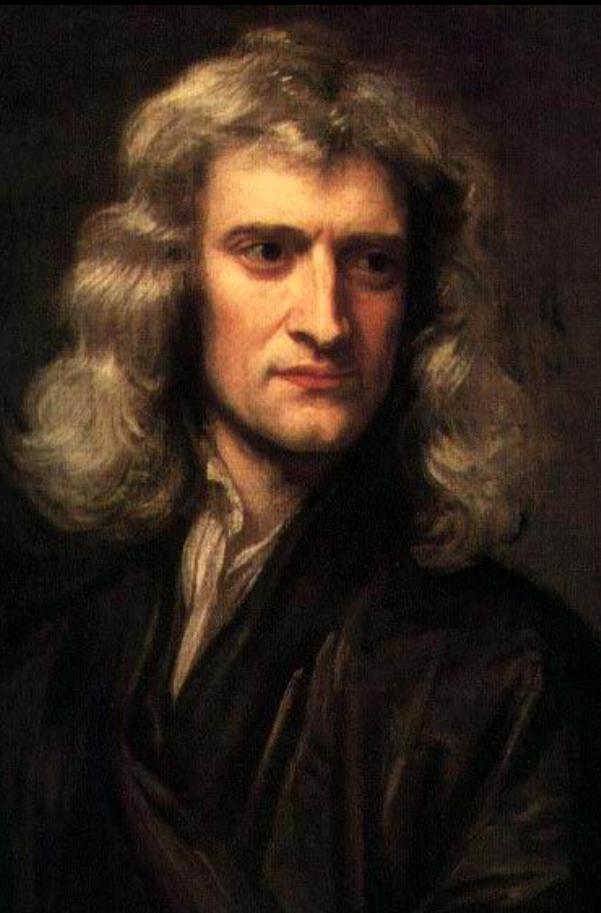
- 1) The planetary orbits are ellipses, with the Sun in a focus, not at the centre.
- 2) A line segment joining a planet and the Sun sweeps out equal areas during equal time intervals (conservation of angular momentum)
- 3) The square of the orbital period is proportionnal to the cube of the semi-major axis (the further, the slower)



# Universal gravitation (XVII°)

Isaac Newton's law of **universal gravitation** explains 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 → 9<sup>th</sup> 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

## Some other basic definitions :

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

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

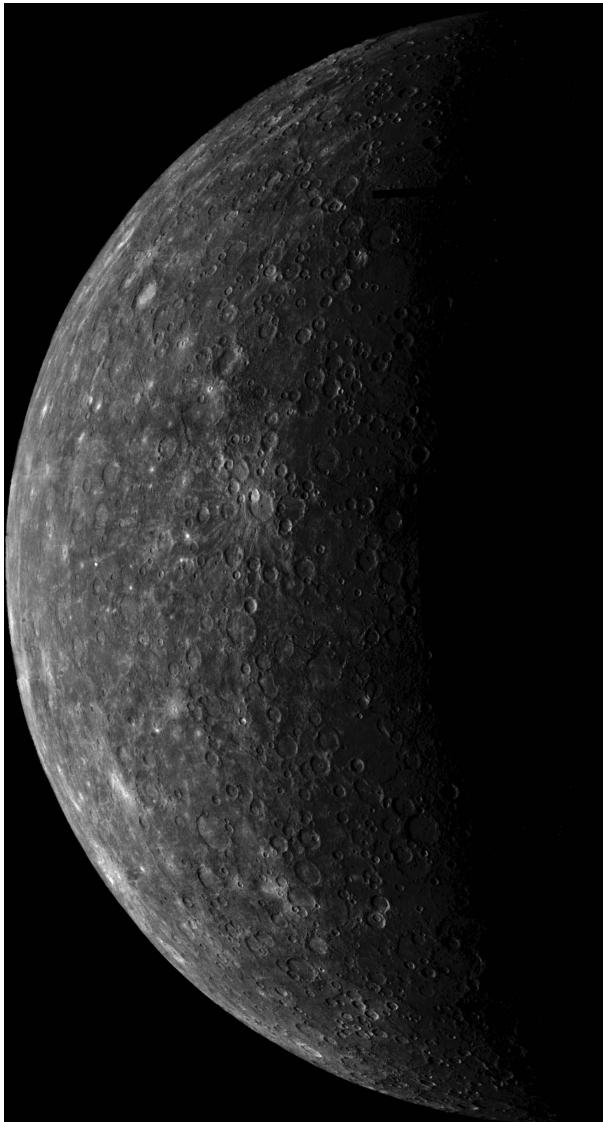
**Milky Way** = **The Galaxy** = all the stars we see in the sky,  
including the white band famous as the milky way.  
Size :  $\sim 100\,000$  light-years.

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

**The Universe** = everything we can see with any instrument.  
Size :  $\sim 14$  billion light-years.

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

# MERCURY



Semi major axis : 0.387 AU.

Eccentricity : 0,2

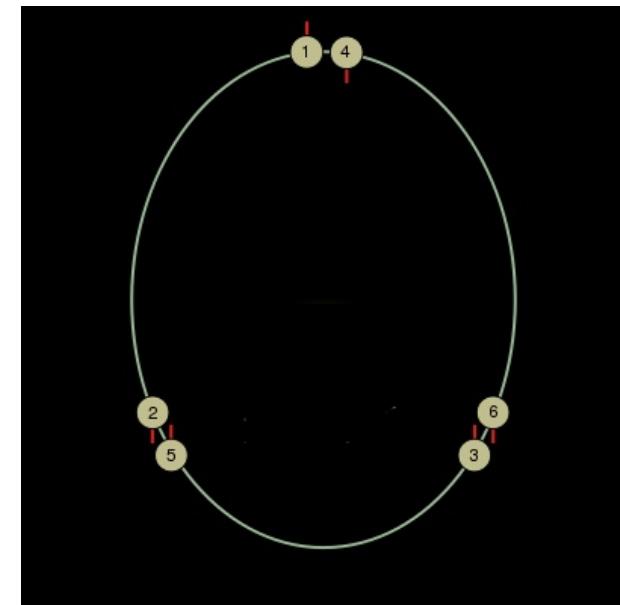
Mass :  $3.3 \times 10^{23}$  kg = 0.055 of Earth

Radius : 2440 km = 38% of Earth

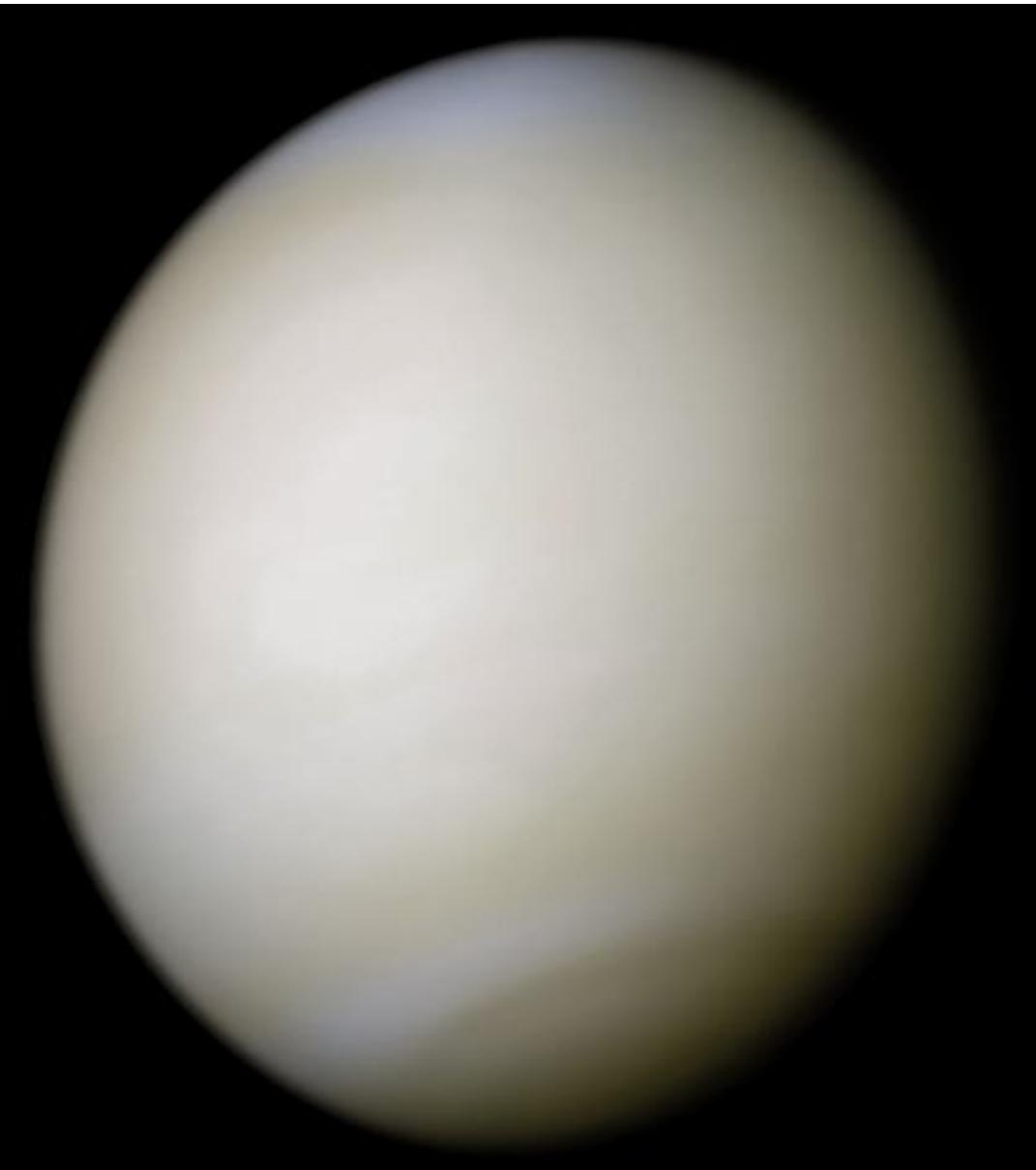
Density : 5 340 kg.m<sup>-3</sup>.

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

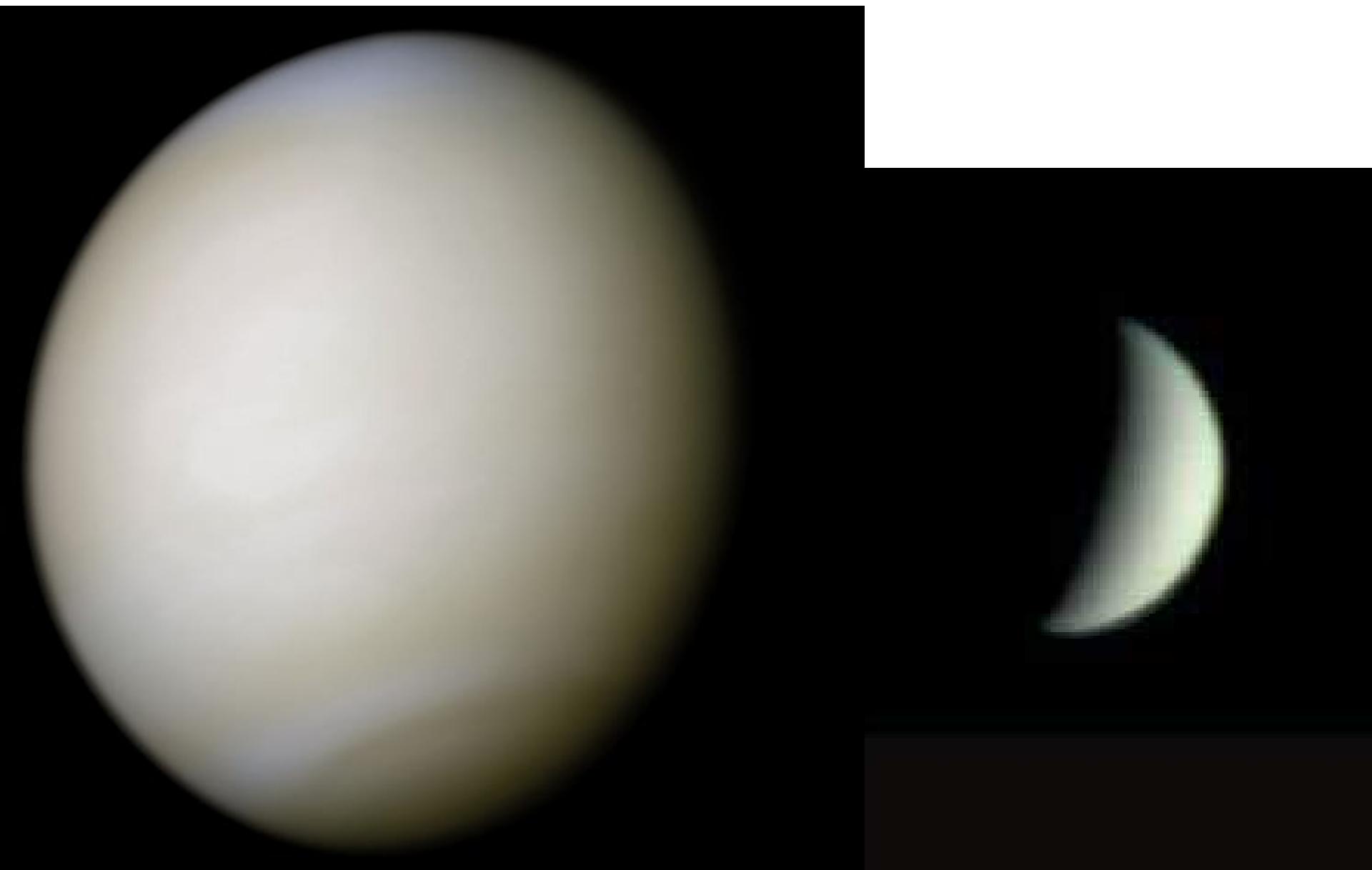
Radius : 0.95% of Earth

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

Atmosphere : 95 Bars on  
the ground.

Rotation : slow (243 days)  
and retrograde (or inclined  
by  $177^\circ$ )

# VENUS



# EARTH



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

Eccentricity : 0,016.

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

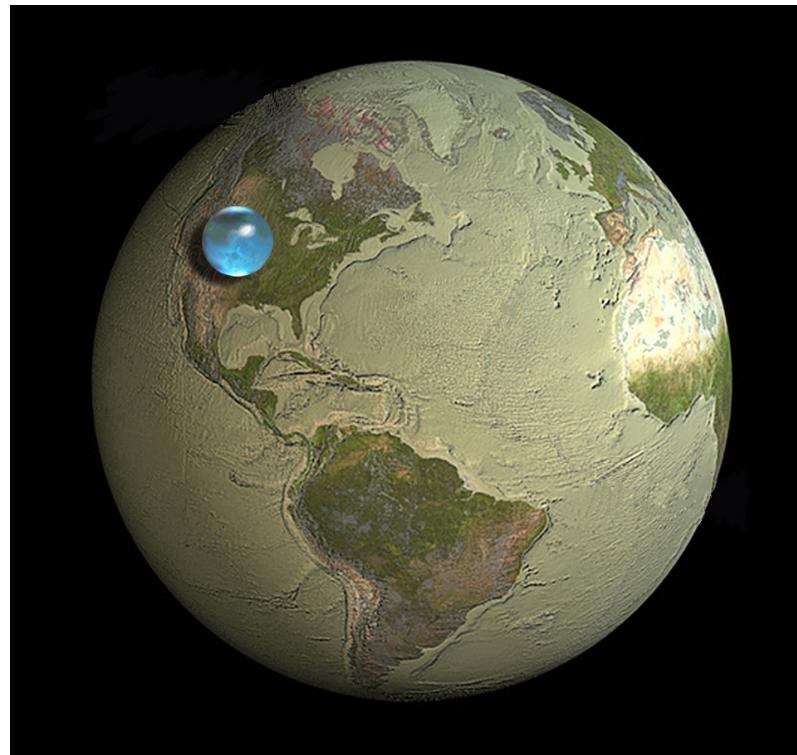
? A day = 24h ?

Mass :  $6 \times 10^{24}$  kg =  $3 \times 10^{-6} M_{\text{sun}}$ .

(0.025% of which is water)

Radius : 6371 km

Density : 5 515 kg.m<sup>-3</sup>.



# MOON



Semi major axis : 384 400 km

Eccentricity : 0.055

Mass :  $\sim 1/80 M_{\text{earth}}$

Radius :  $\sim 1/4 R_{\text{earth}}$

Density : 3 344 kg.m<sup>-3</sup>.

→ 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 :  $6.4 \times 10^{23}$  kg = 0,1  $M_{\text{Earth}}$ .

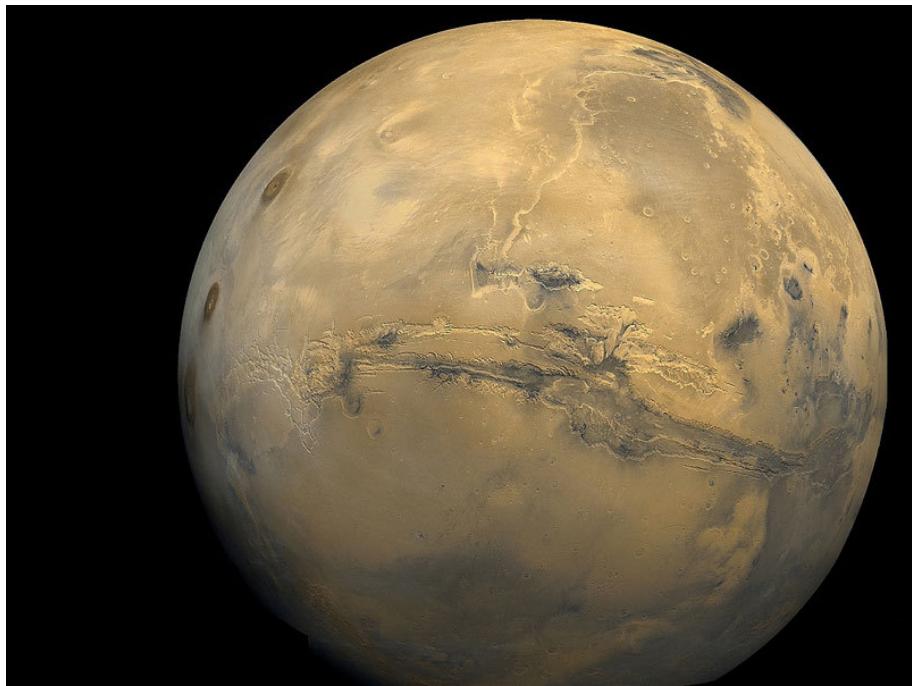
Radius : 3 390 km = 0.53  $R_{\text{Earth}}$ .

Density : 3 934 kg.m<sup>-3</sup>.

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

Proofs of past water presence : hydrated minerals, chenals...

Essentially lost with the atmosphere.



# JUPITER

24

Semi major axis : 5,2 AU.

Eccentricity : 0,048.

Mass :  $1.9 \times 10^{27}$  kg = 0,001  $M_{\text{Sun}}$ .

Radius : 70 000 km.

Density : 1 327 kg.m<sup>-3</sup>.

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.

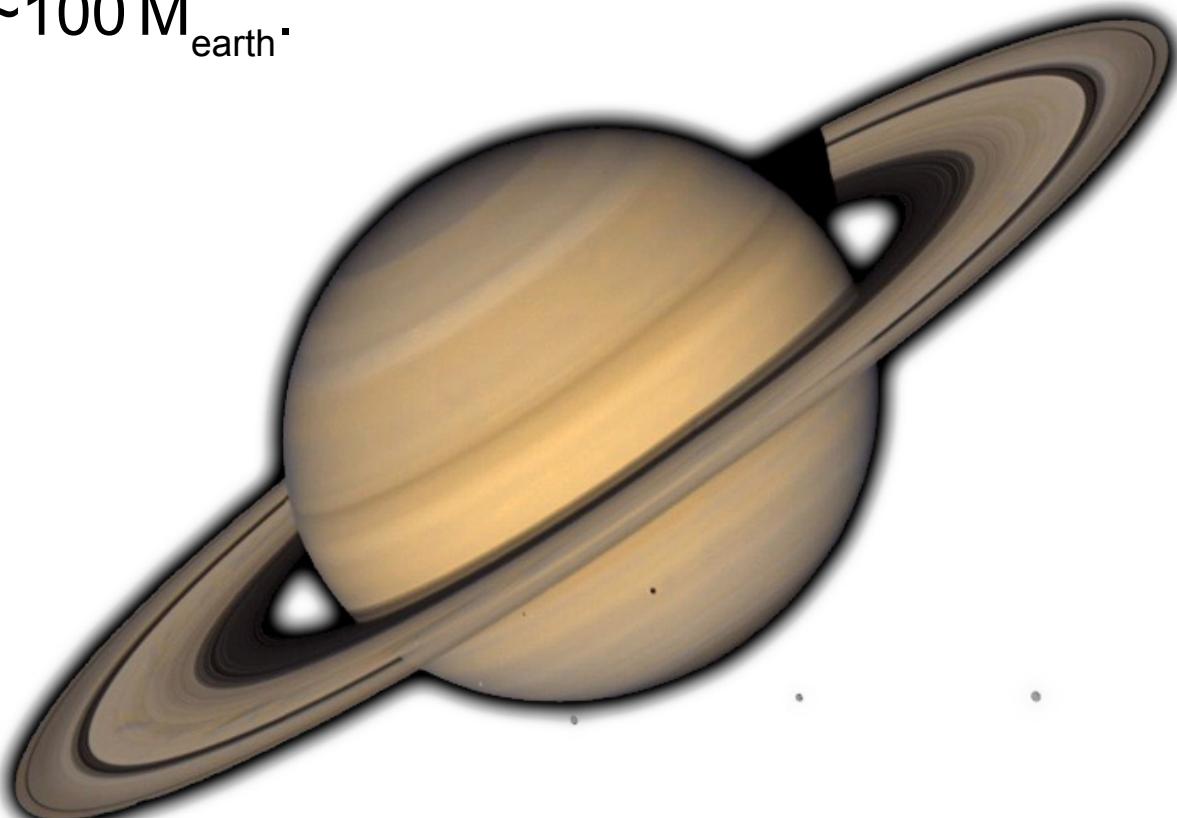
Mass :  $5.68 \times 10^{26}$  kg =  $\sim 100 M_{\text{earth}}$ .

Radius : 60 000 km.

Density : 700 kg.m<sup>-3</sup>.

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

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





# URANUS

Semi major axis : 19,2 AU.

Eccentricity : 0,047.

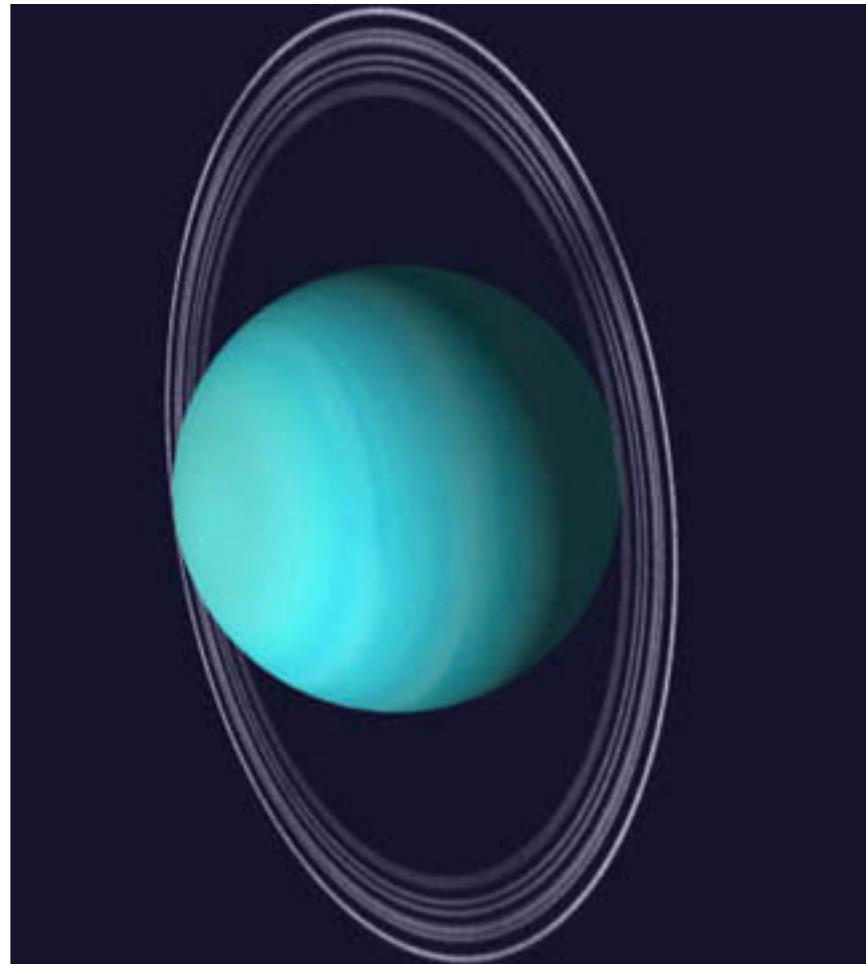
Mass :  $8.68 \times 10^{25}$  kg = 14.5 M<sub>earth</sub>.

Radius : 25 500 km = 4 R<sub>earth</sub>.

Density : 1270 kg.m<sup>-3</sup>.

Rotation : 17h, tilted at 98°.

Discovered by Herschell in 1781,  
by chance.





# NEPTUNE

Semi major axis : 30.1 AU.

Eccentricity : 0,0086.

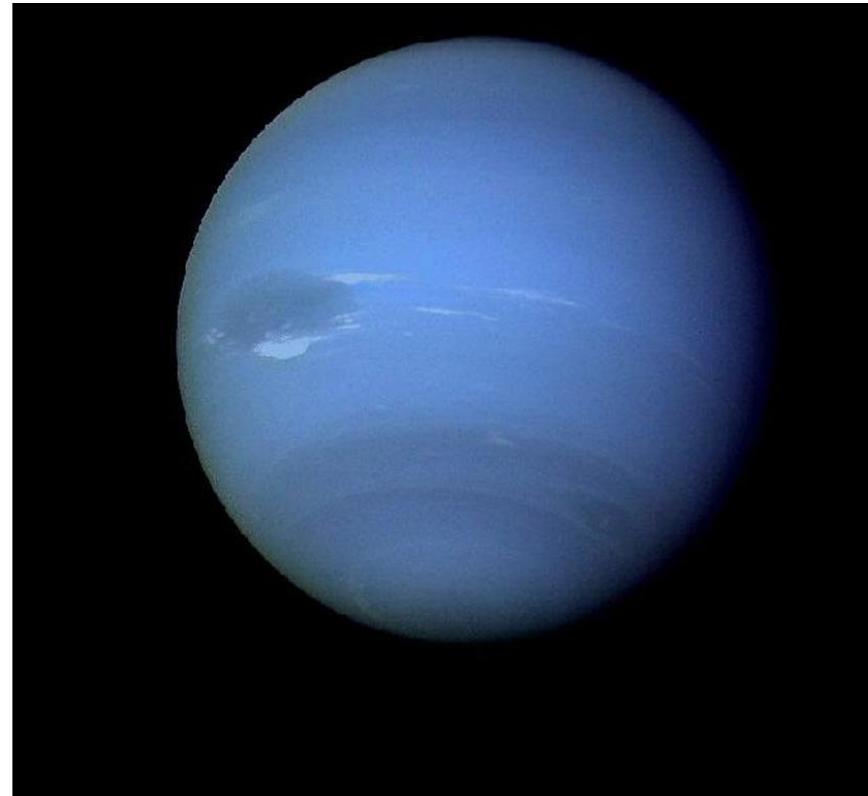
Mass :  $10,2 \times 10^{25}$  kg = 17.2 M<sub>earth</sub>.

Radius : 24 600 km.

Density : 1640 kg.m<sup>-3</sup>.

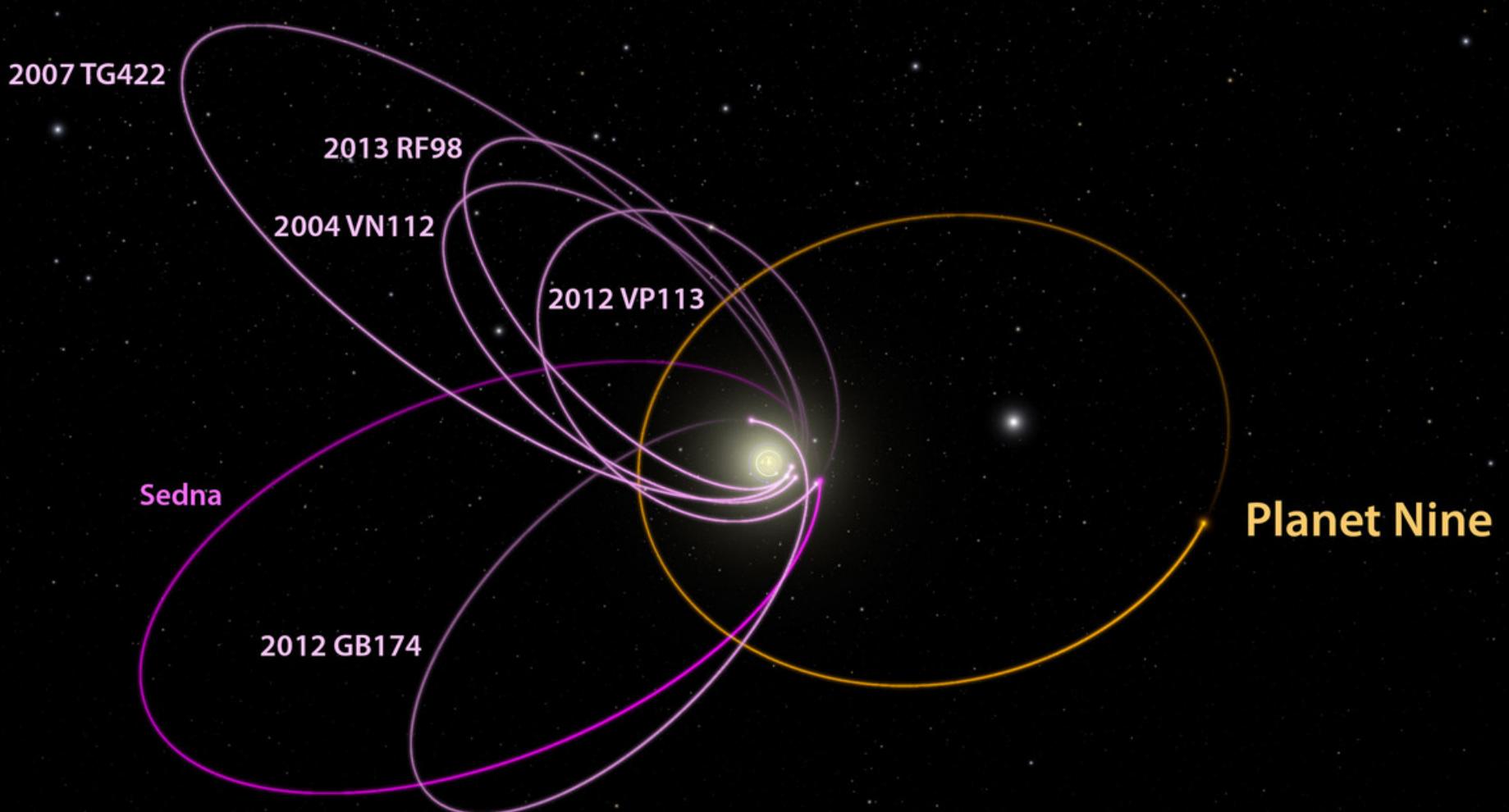
Rotation : 16h, tilted at 30°.

Discovered by Le Verrier in 1846,  
by calulations.



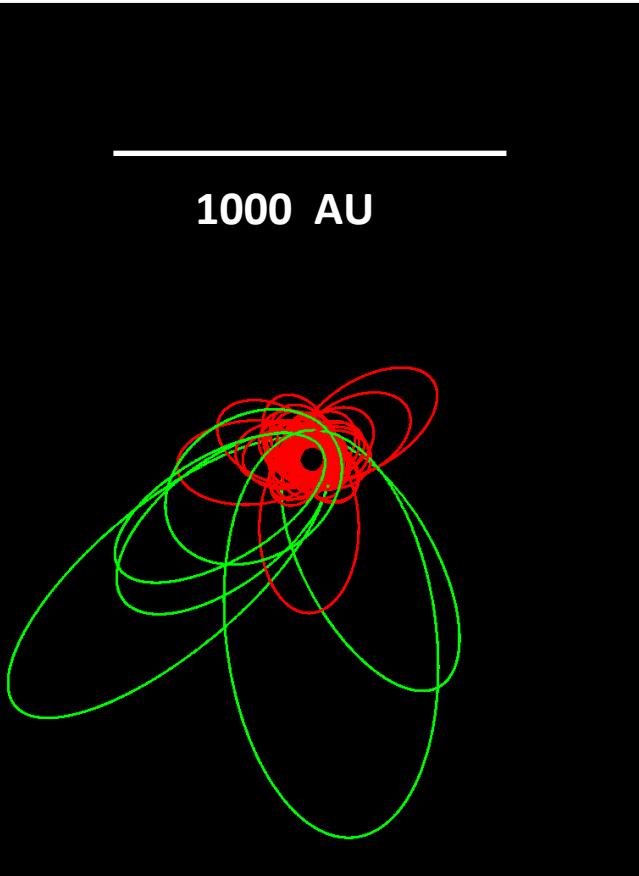
# PLANET IX ?

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



# PLANET IX ?

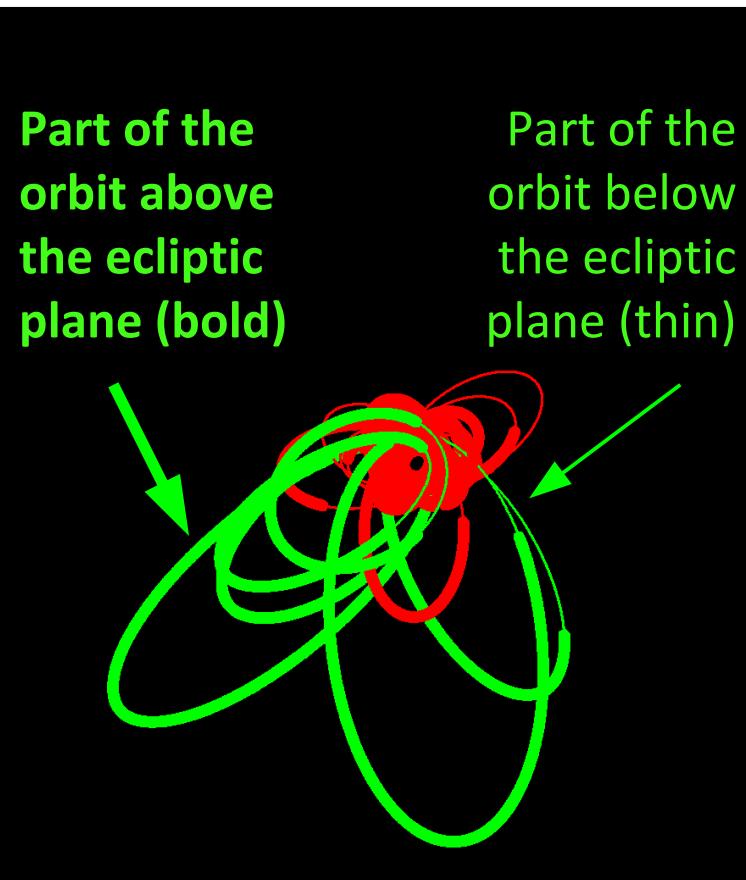
Ever since Neptune was discovered, there has been a few claims of a 9<sup>th</sup> planet. Is this one the good one ?



Claim based on the observation that the most elongated orbits of the Kuiper belt (green) show a preferred orientation, while the others (in red) don't.

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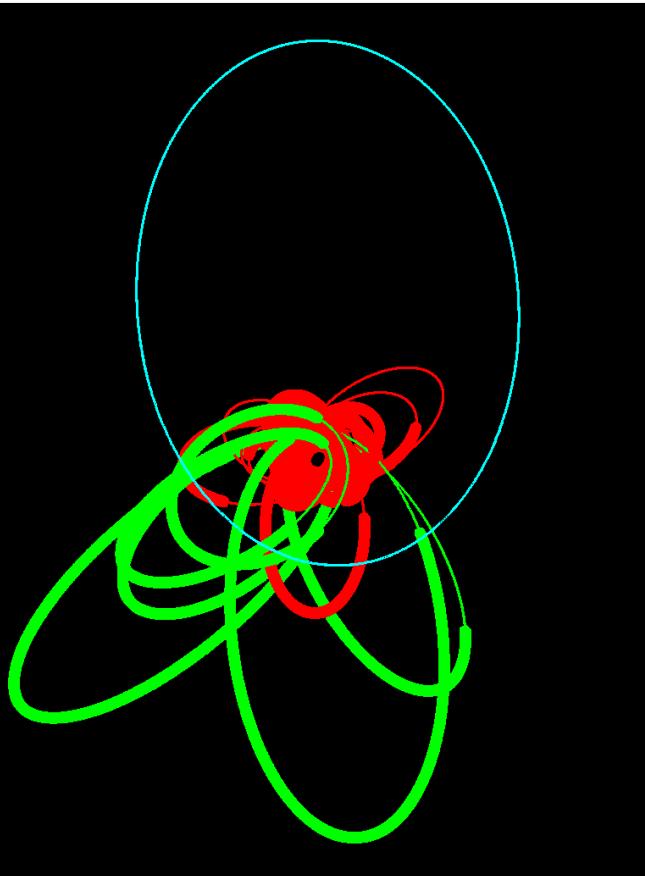
Also, the orientation of these orbits is peculiar: their ascending nodes are grouped.

Probability for this clustering to be random luck : 0.007%.

Precession at various rates should disperse this concentration.

# PLANET IX ?

Batygin & Brown show that a planet on an anti-aligned orbit can maintain the observed orbital confinement.



Characteristics of Planet IX :

Mass :

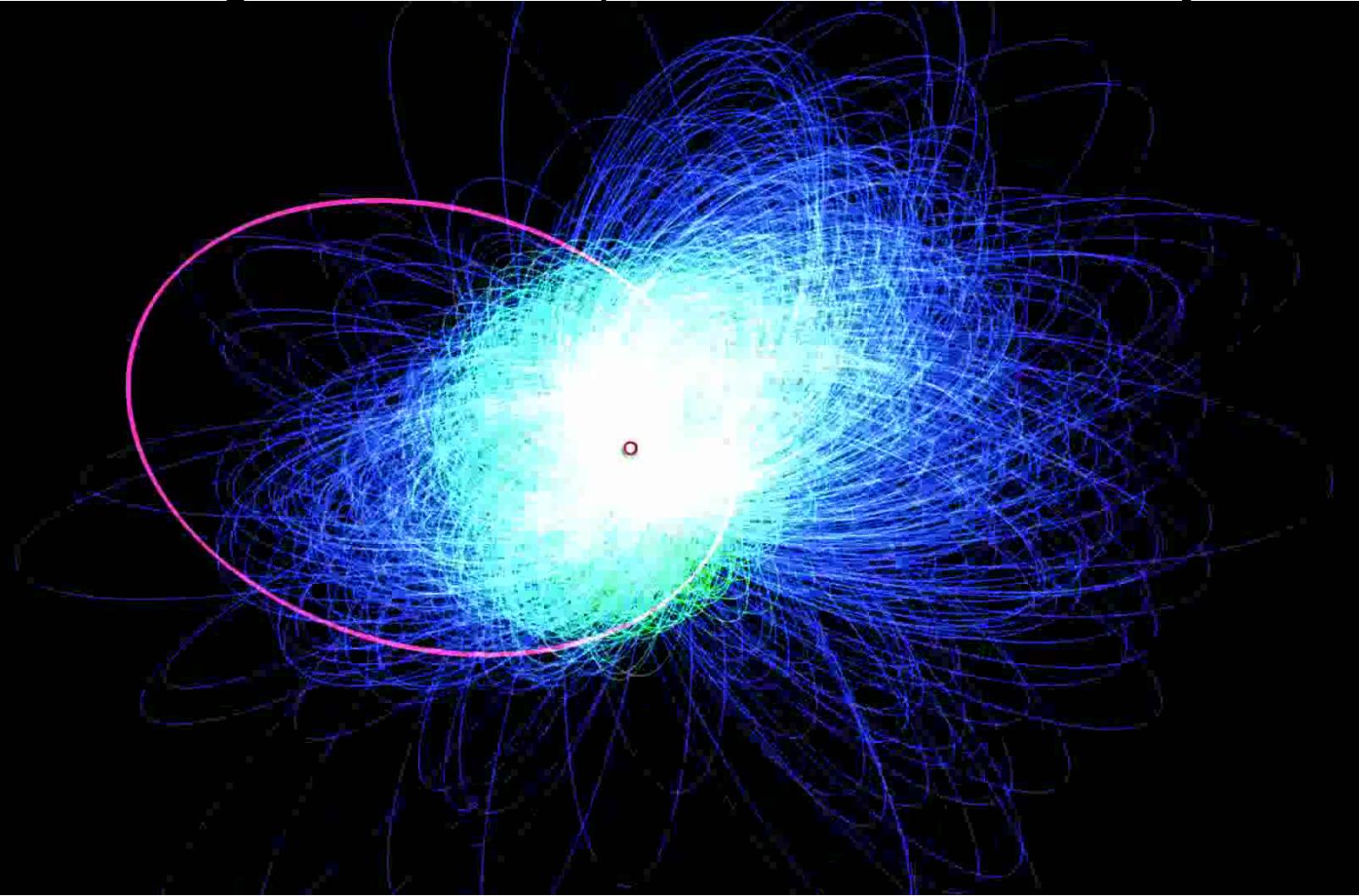
~10-15 Earth masses  
(half to one Neptune)

Orbital period :

~15000 – 20000 years

# PLANET IX ?

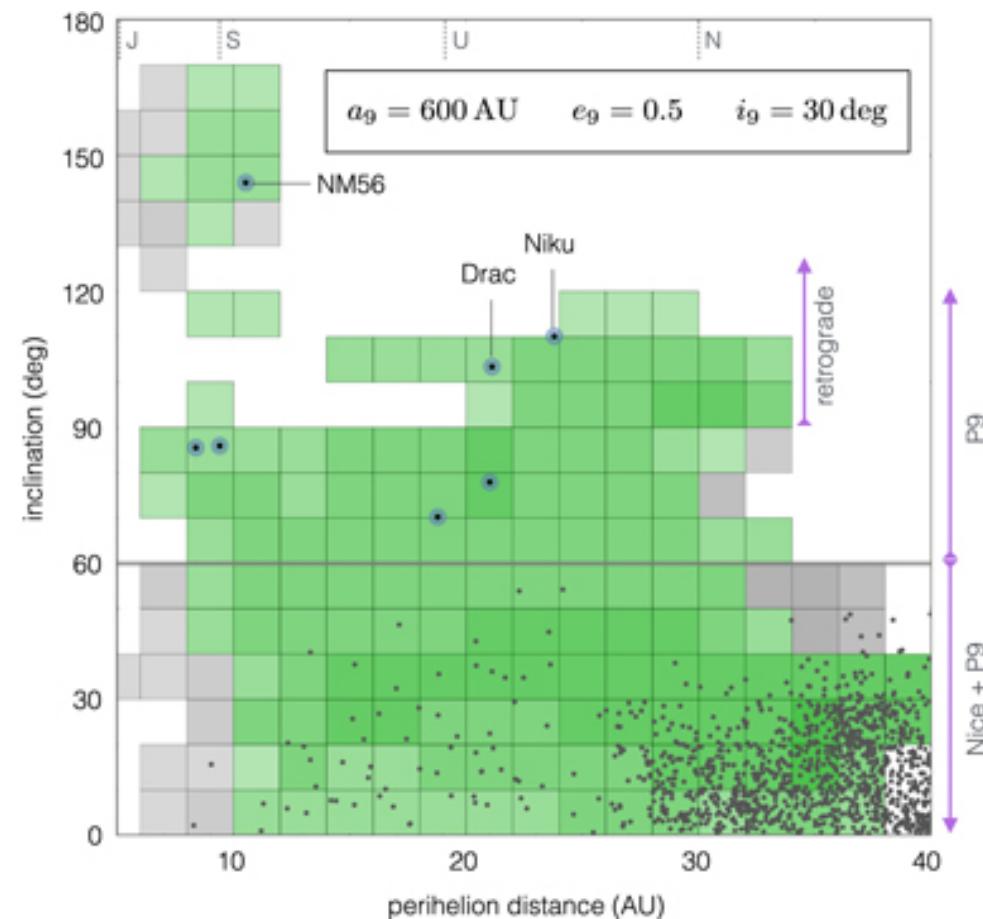
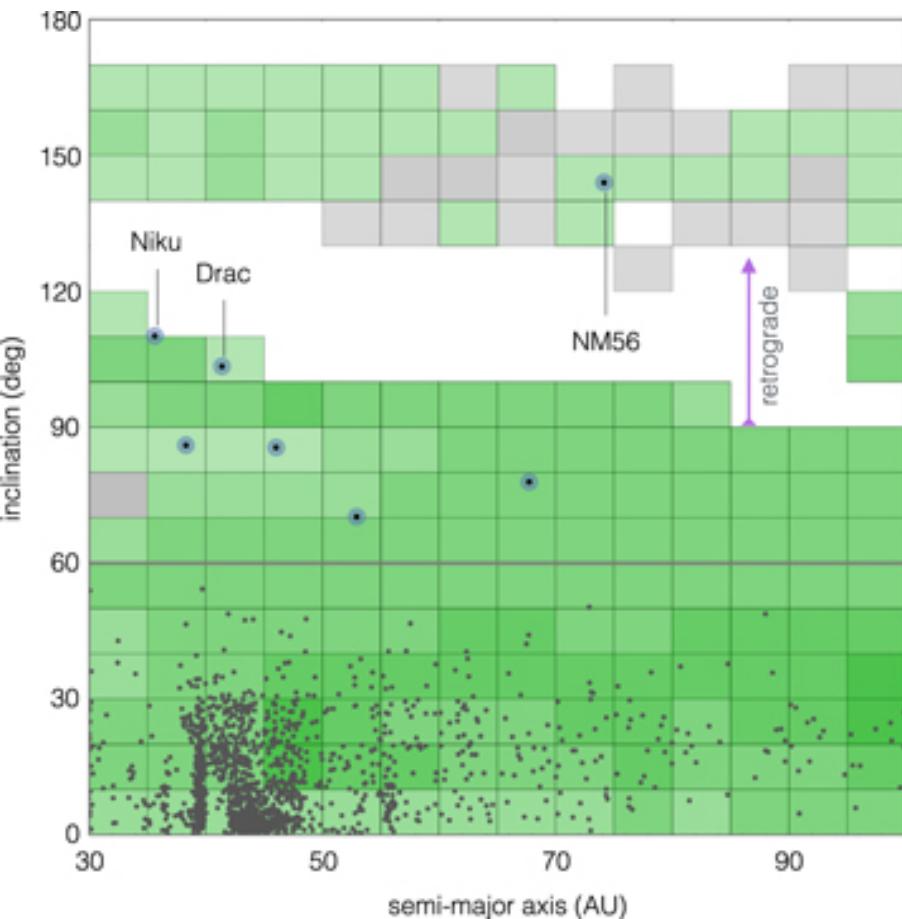
Batygin & Brown further show that such a planet allows **only** anti-aligned orbits to survive through the age of the Solar System, starting from an isotropic cloud of scattered objects.



# PLANET IX ?

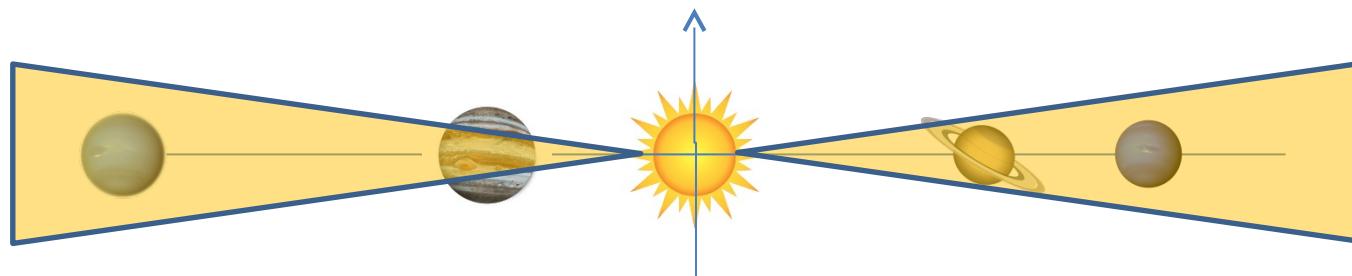
Batygin & Brown show that a planet on an anti-aligned orbit can maintain the observed orbital confinement.

They also show that a planet IX could explain the presence of highly inclined (even retrograde) Kuiper Belt objects.



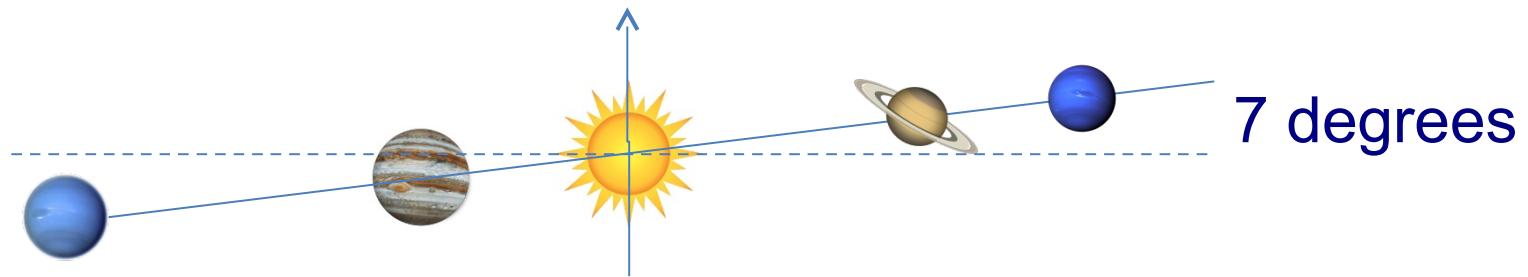
# PLANET IX and the MISALIGNMENT

Such a planet could explain the mysterious misalignment between the reference plane of the Solar System and the Sun's equator.



# PLANET IX and the MISALIGNMENT

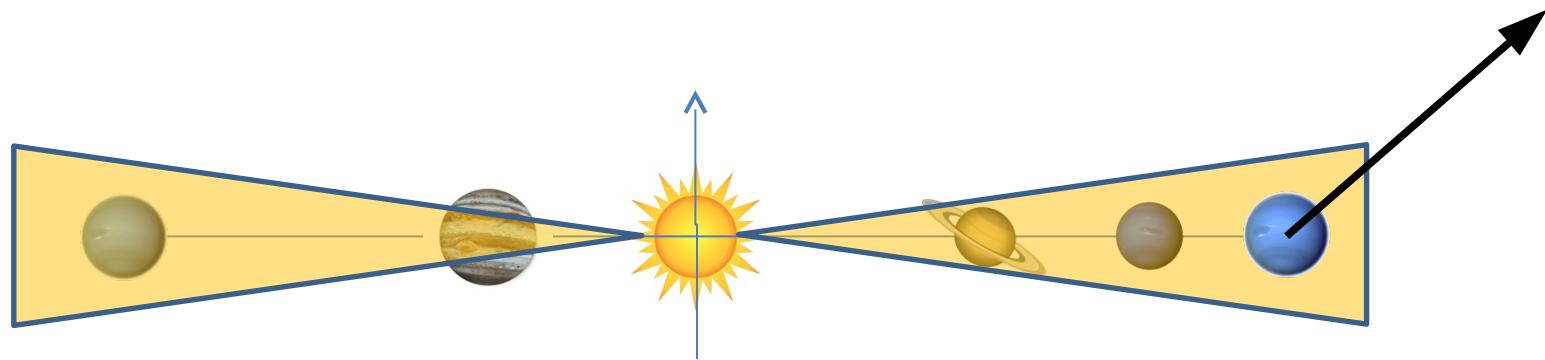
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# PLANET IX and the MISALIGNMENT

Gomes, Deienno, Morbidelli (2016)

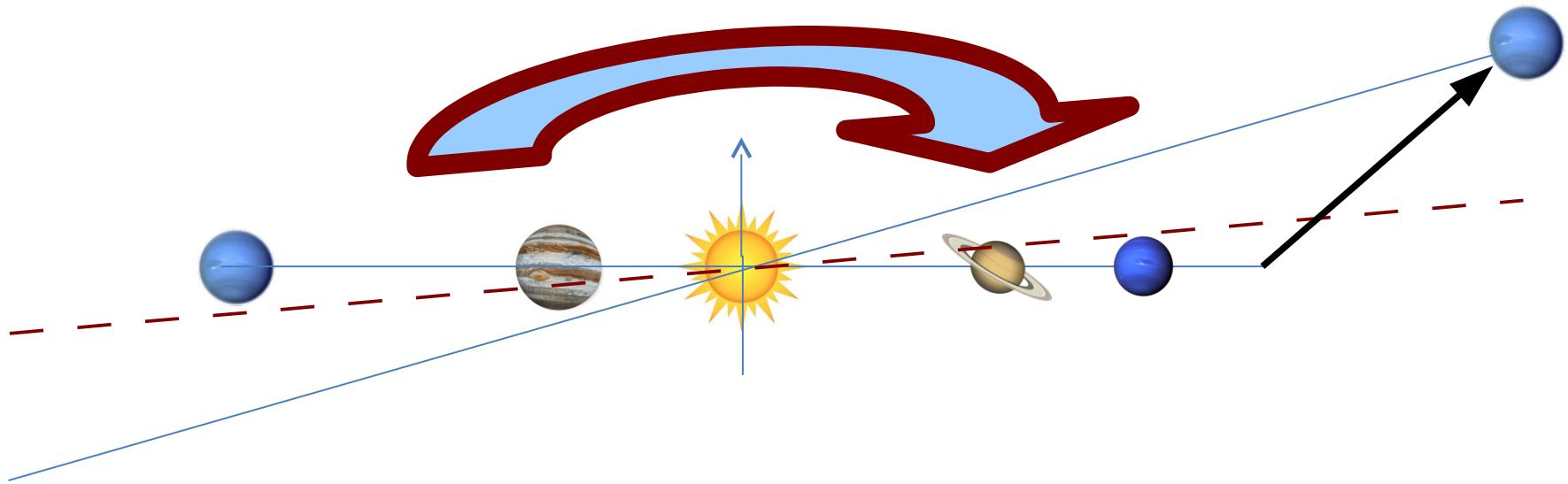
Bayley, Batygin, Brown (2016)



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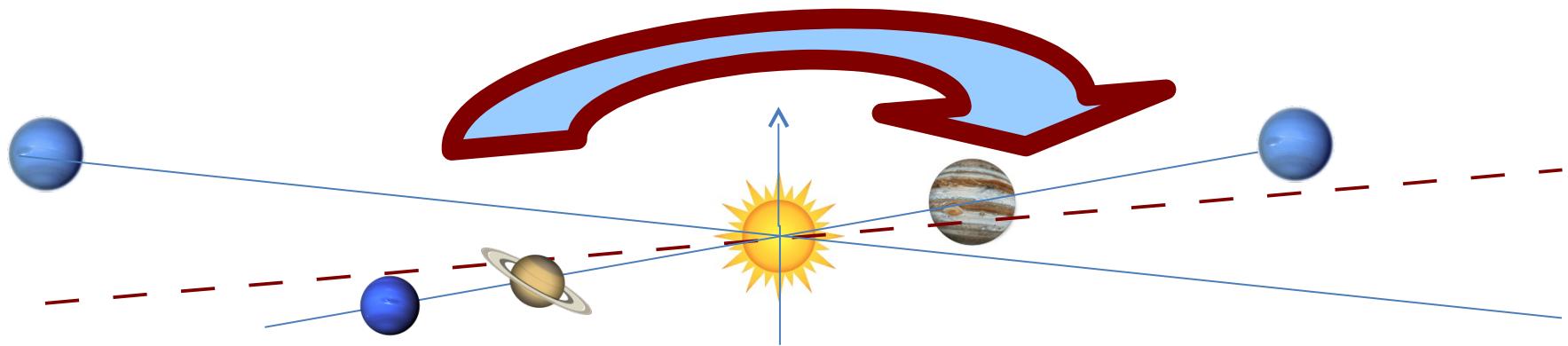


| New invariable plane, around |  
| which the others precess. |

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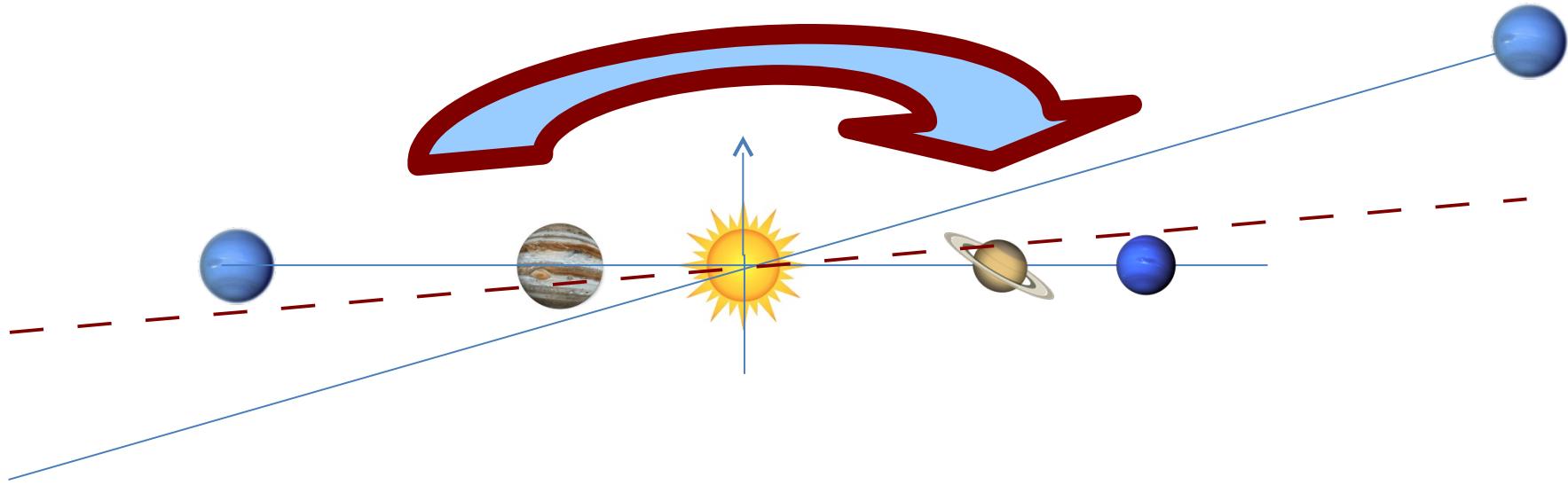


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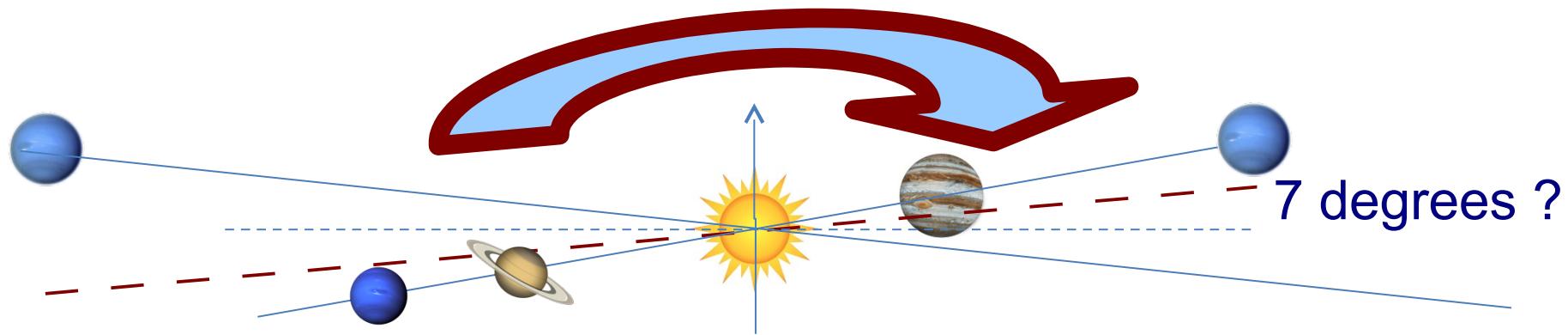


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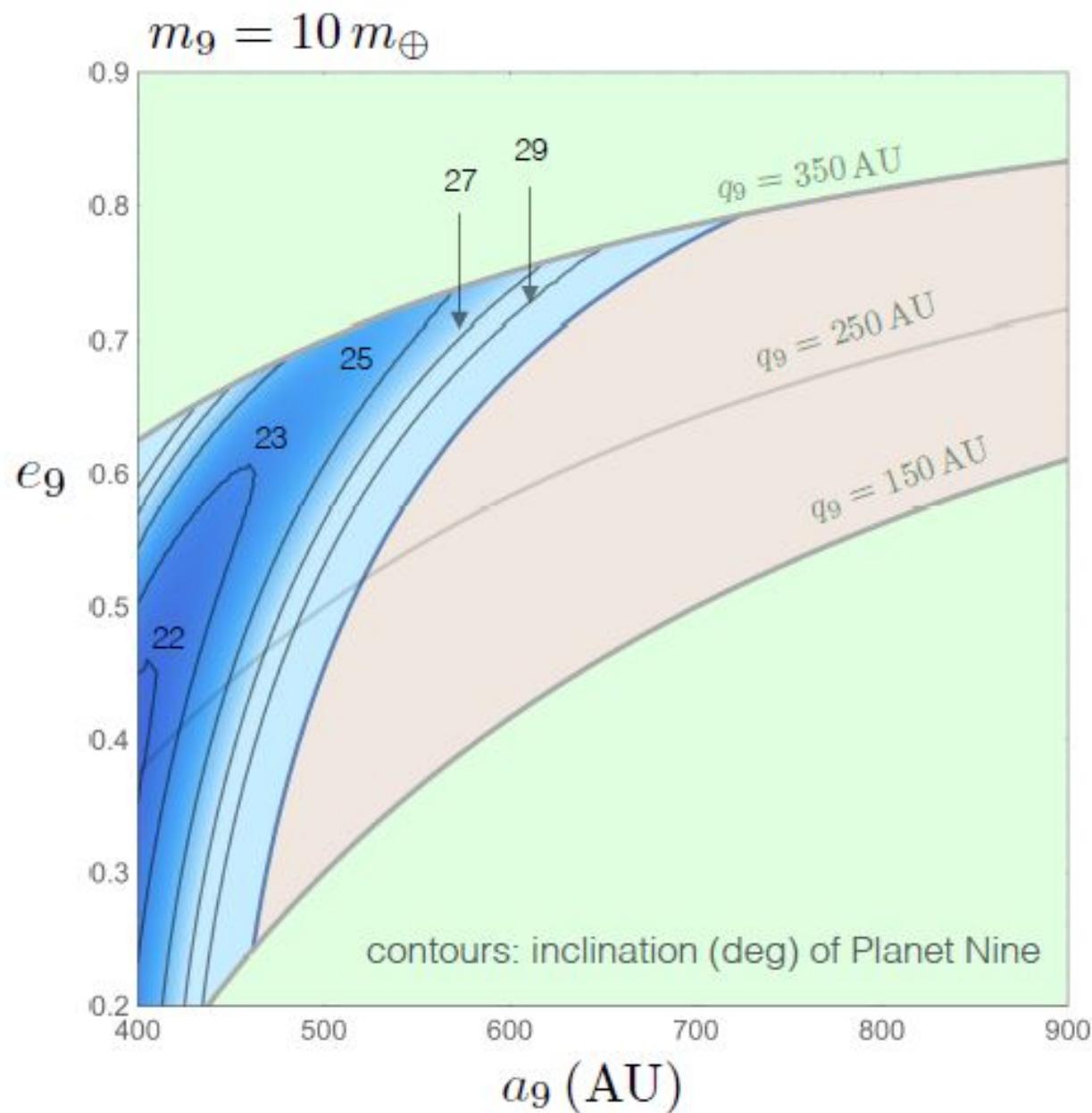
Gomes, Deienno, Morbidelli (2016)

Bayley, Batygin, Brown (2016)



# PLANET IX and the MISALIGNMENT

Bayley, Batygin,  
Brown (2016)



# PLANET IX : where is it now ?

Since the 60s, we can measure with tremendous precision the distances between Earth and spacecrafts around other planets, and compare these distances with ephemerids predictions.

Difference = residues.

Best constraint : Cassini @ Saturn ( $\sim 100m$ ) !

# PLANET IX : where is it now ?

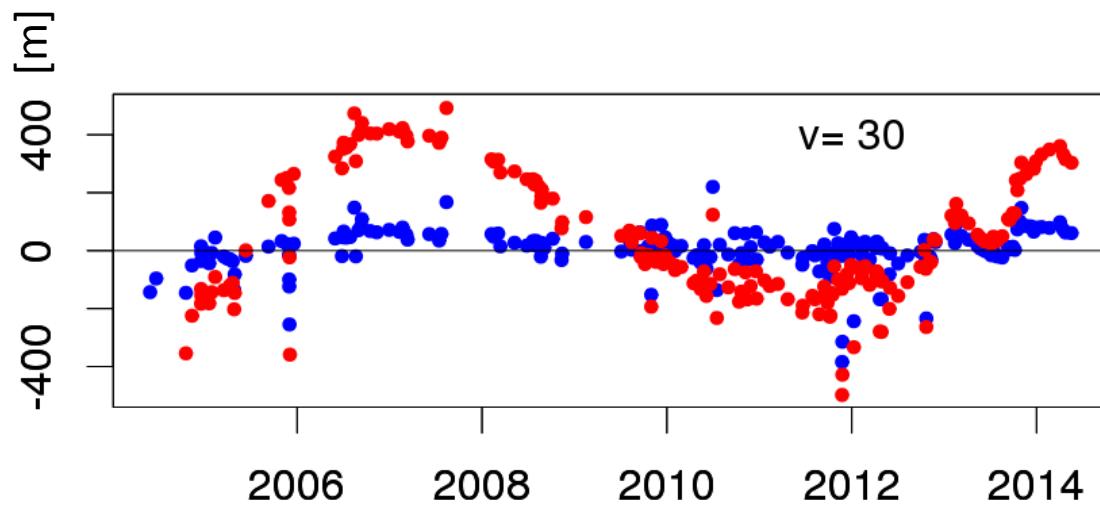
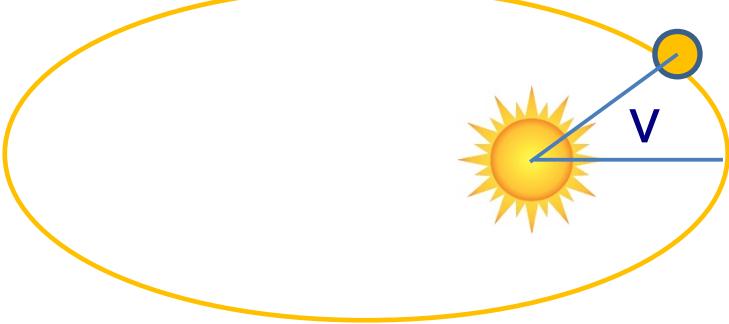
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Fienga & Laskar (2016) :

Compare residues **without P9**, and **with a P9** at different places on its orbit (true anomaly  $v$ ).  $v = 30^\circ$ : excluded !



# PLANET IX : where is it now ?

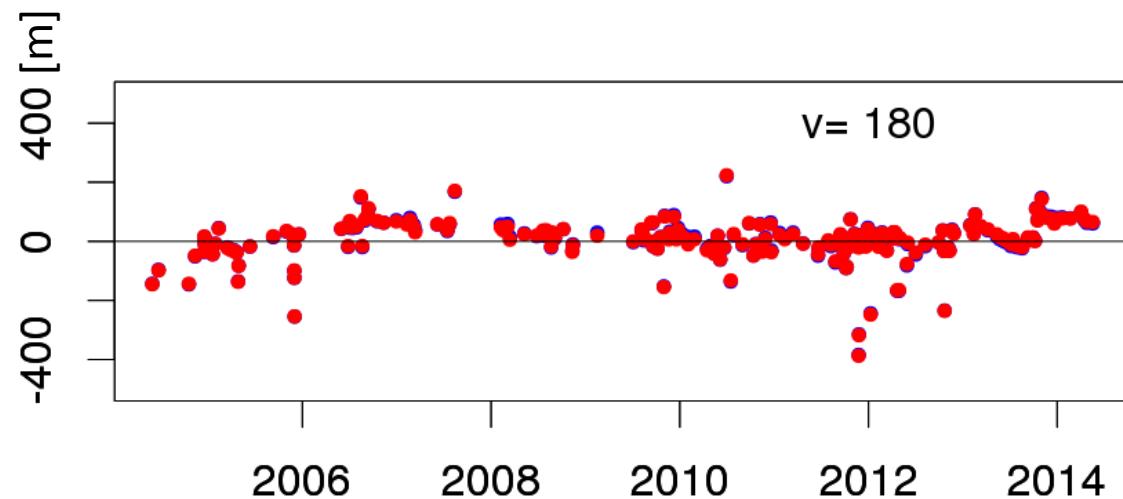
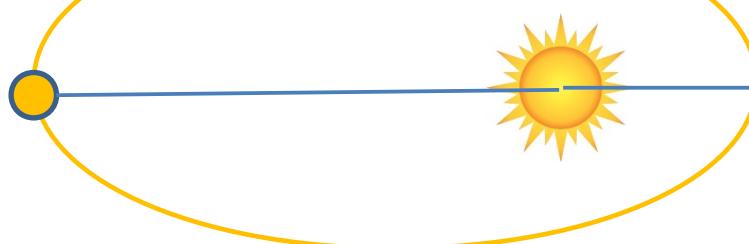
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Difference = residues.

Best constraint : Cassini @ Saturn ( $\sim 100m$ ) !

Fienga & Laskar (2016) :

Compare residues **without P9**, and **with a P9** at different places on its orbit (true anomaly  $v$ ).  $v = 180^\circ$  : no significant effect.



# PLANET IX : where is it now ?

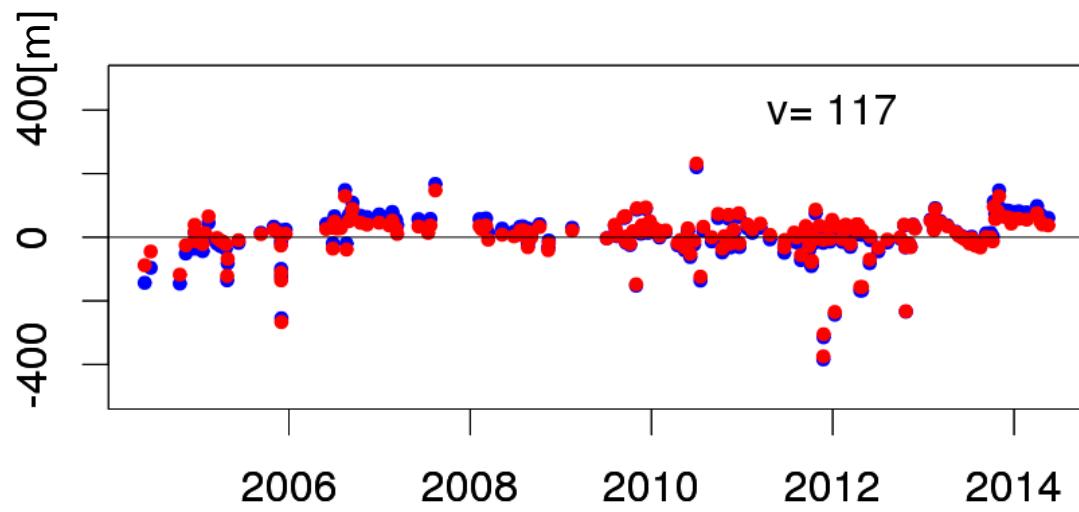
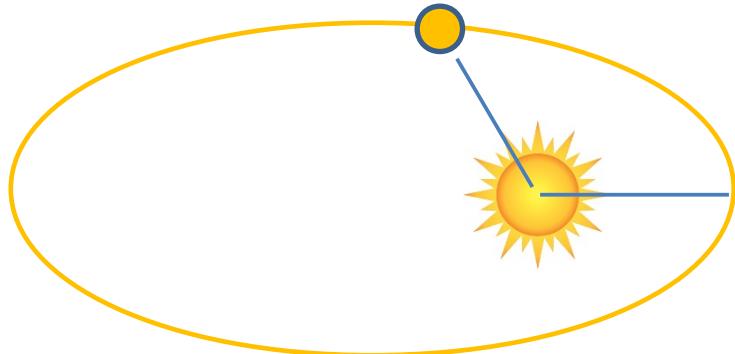
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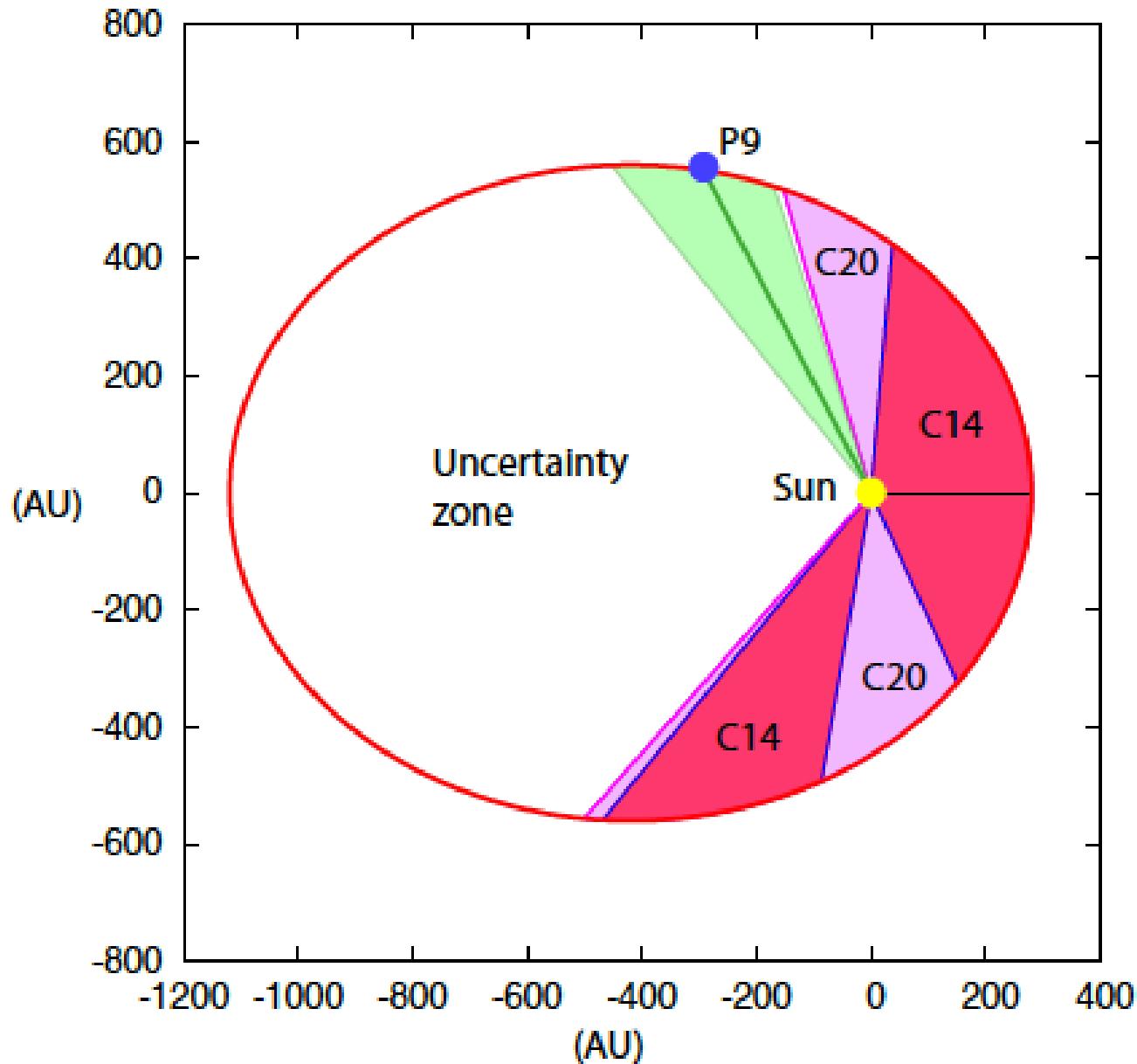
Fienga & Laskar (2016) :

Compare residues **without P9**, and **with a P9** at different places on its orbit (true anomaly  $v$ ).  $v = 117^\circ$  : slightly better !



# PLANET IX : where is it now ?

Fienga & Laskar  
(2016) :



# PLANET IX : conclusion

Planet 9 is NOT (yet) discovered.

However, the evidences in favor of its presence are rather serious. Residues in Saturn's position may give a hint to where it is now, but if not, the whole orbit will have to be scanned (observing programmes dedicated to this hunt are starting). Stay tuned...

# Solar System Model

Largest representation to scale:  
the Swedish Solar System !

Scale : 1/20000000.

Sun : Ericsson Globe (110m)

Venus : Here ! In front of the  
Vestenskapens Hus.

Planet 9 ? If at 455 AU now,  
at the North Pole !



# Solar System Model

Possible future representation to scale : The Côte d'Azur model

Scale : 1/60000000.

Sun : Big dome of the Nice observatory  
(built by Eiffel & Garnier) (23m)



Planets : In remarkable sites seen from the Observatory.

