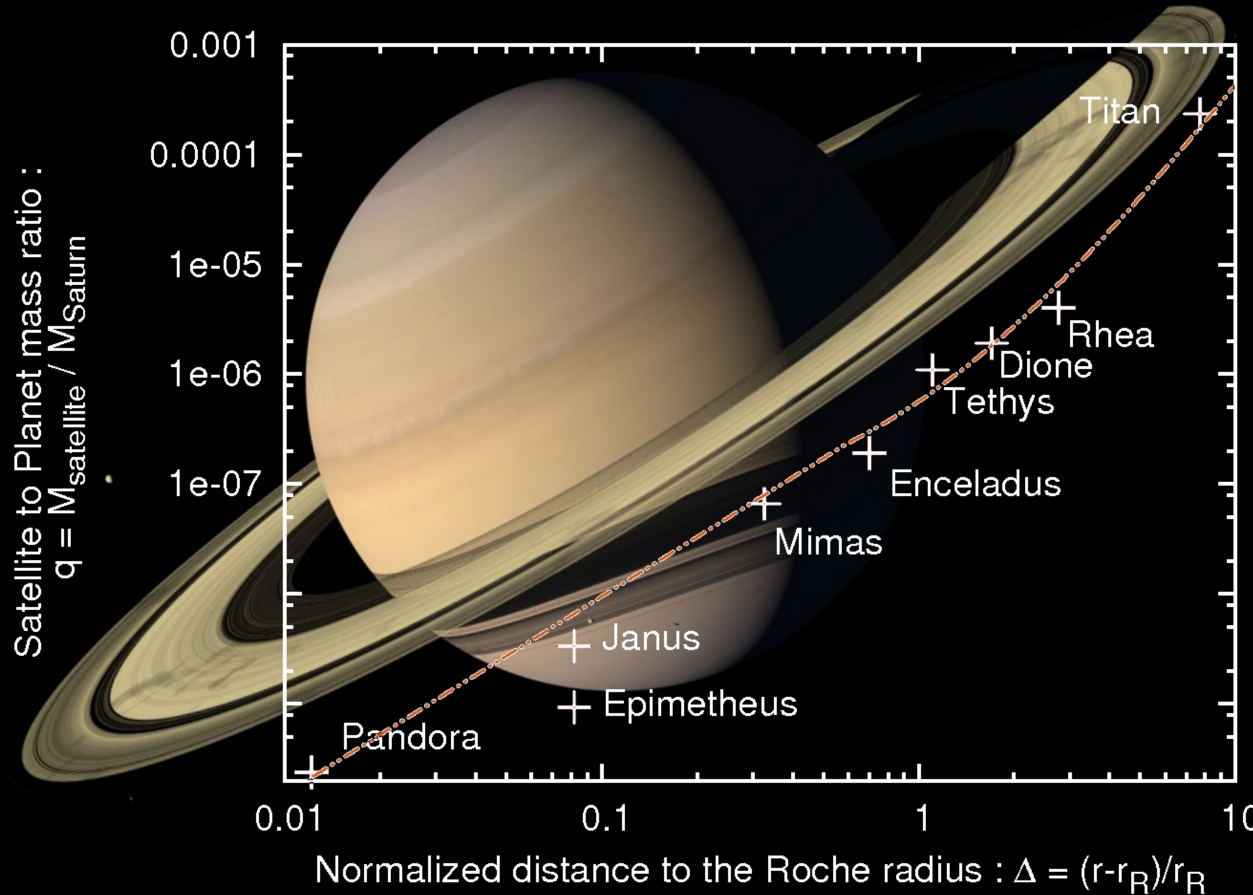
INTERNAL STRUCTURE and MOONS EVOLUTION



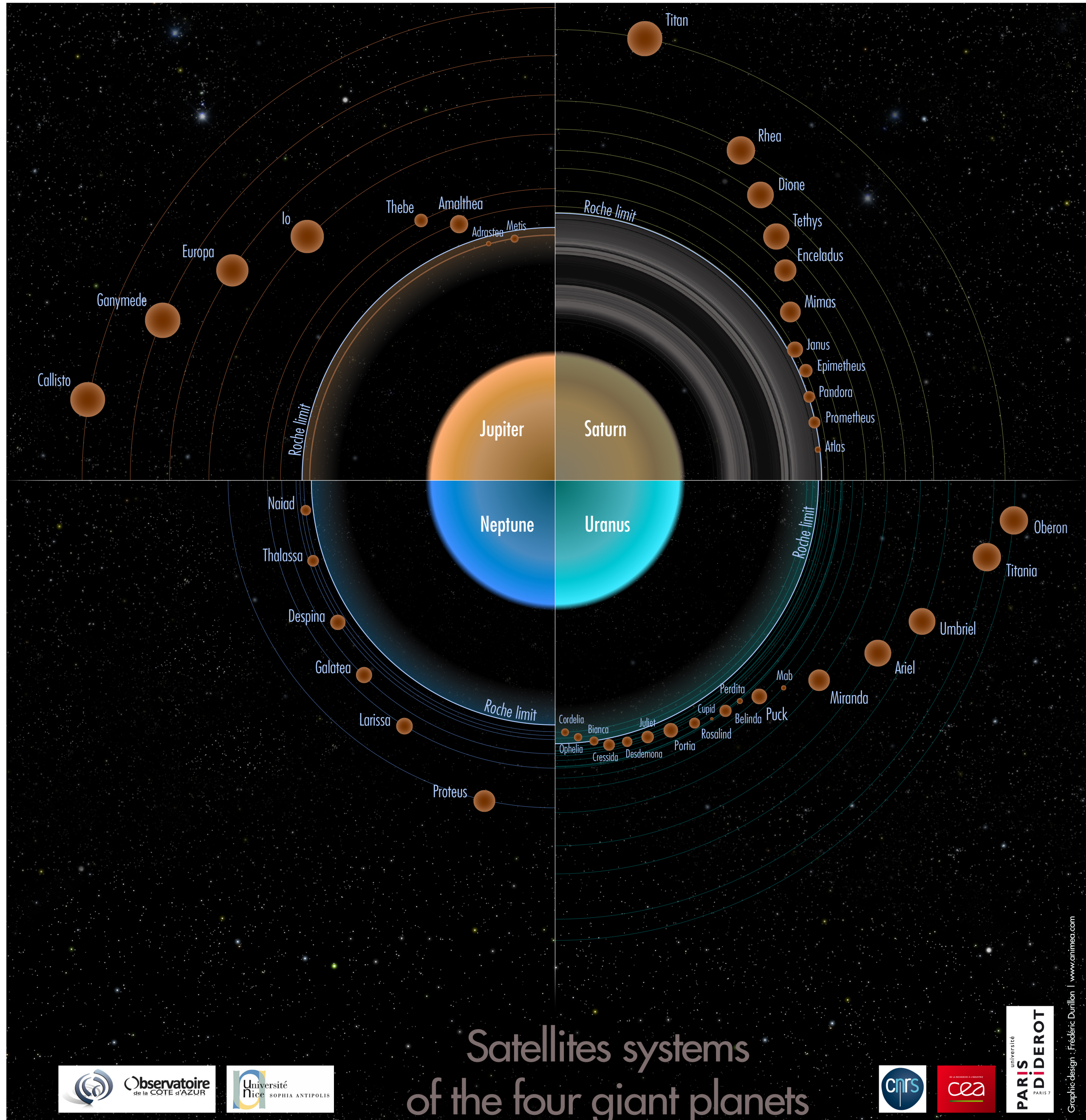
Aurélien CRIDA, with Sébastien CHARNOZ

REGULAR SATELLITES

Distributions of giant planets' regular satellites :

- don't reach the planet
- ranked by mass
- pile-up at a few planetary radii (small bodies)

Why ?



EVOLUTION of the SATELLITES

Planetary tides make satellites migrate **outwards** (ex : the Moon, Deimos) or inwards (ex : Phobos), if they are **outside** / inside the synchronous orbit.

Synchronous orbit :
Orbital period = spin period of the planet
Saturn : ~10h30 → r = 111 000 km (in the rings).

$$\frac{dr}{dt} = \frac{3\, k_{2p}\, M_{satellite} \sqrt{G}\, R_p^5}{Q_p \sqrt{M_p}\, r^{11/2}}$$

k2 = Love number.
Q = dissipation factor. Depends on internal structure !

Little migration in 4.5 Gyrs => large Q .
Goldreich & Soter (1968) : Q=18 000.
NB : Lainey et al. (2012, 2015) : Q=1700 !

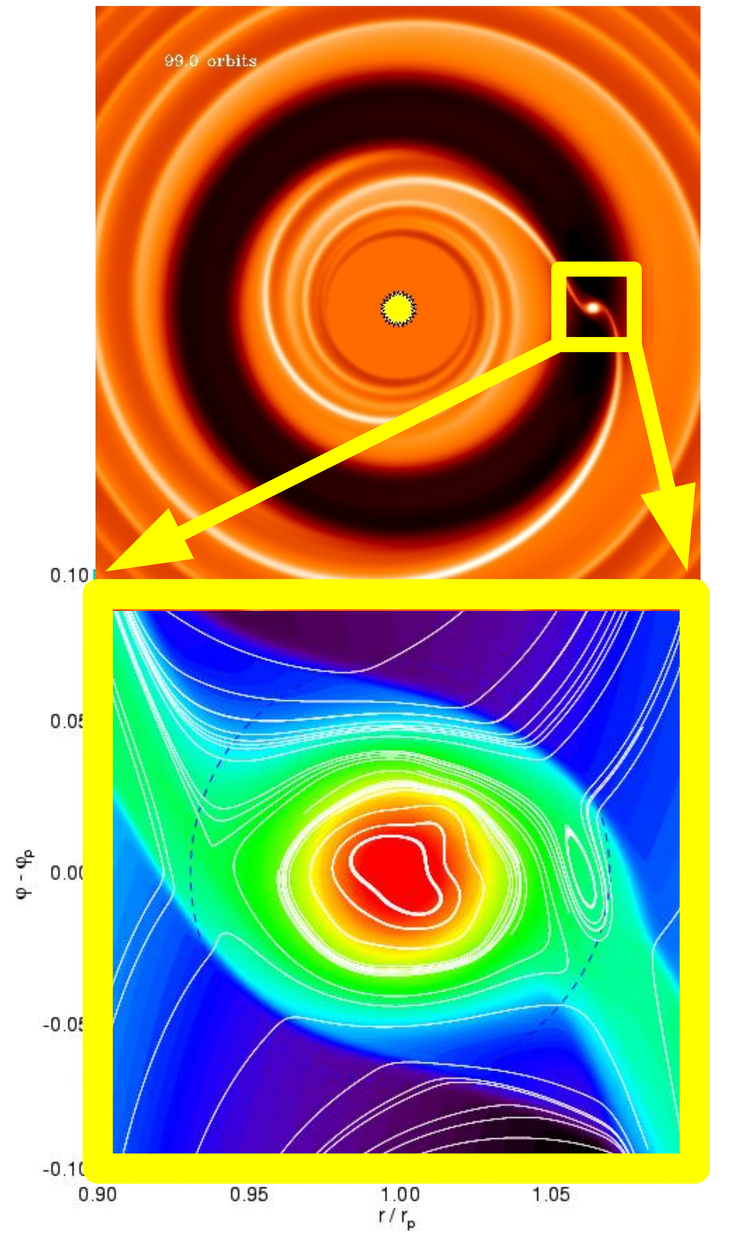
ORIGIN of the SATELLITES ?

Planets form in a gas/dust disk around the Sun.

A giant planet carves a gap in the disk, and has its own circum-planetary disk.

A mini-planetary system would then form around the planet.

(Canup & Ward 2002, 2006 ;
Sasaki et al. 2010 ;
Mosqueira & Estrada 2003a,b...)



This model can't explain the mass-distance feature.

Reminder 1: the Roche Radius

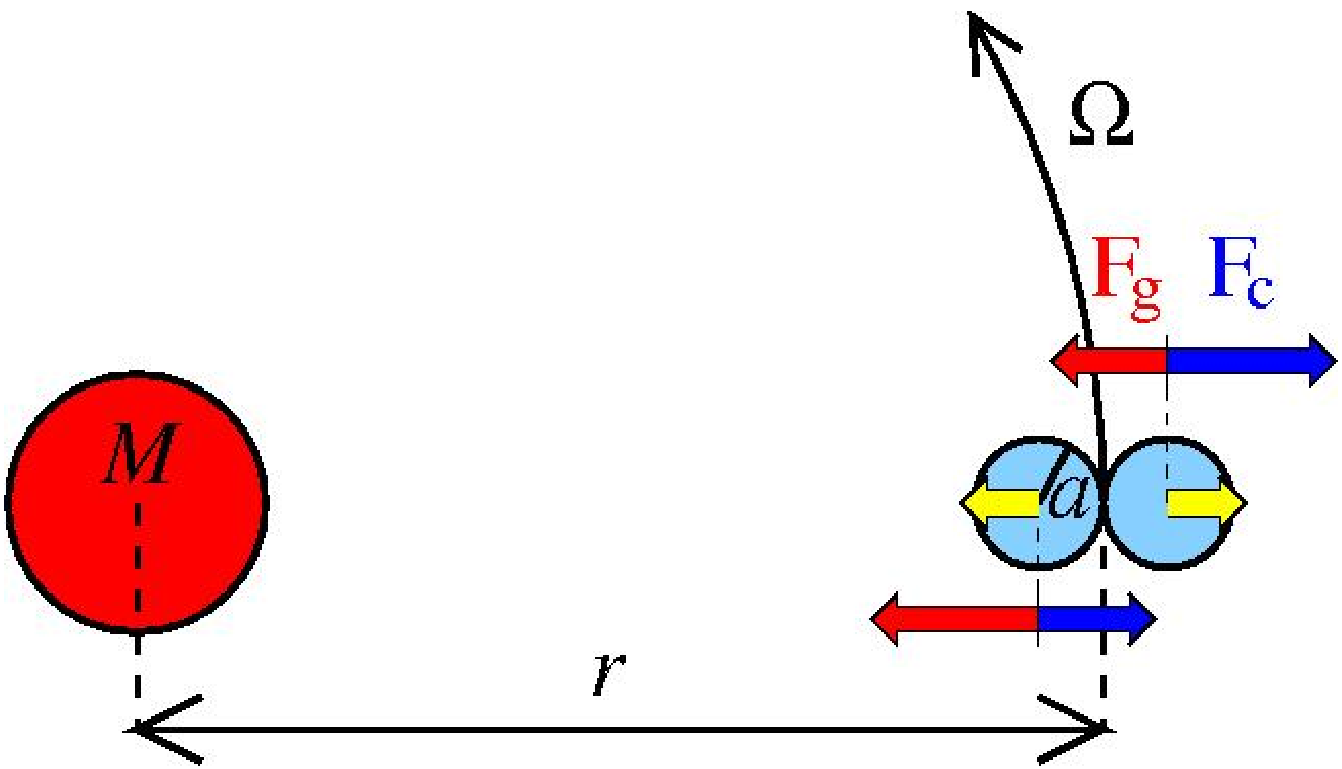
Reminder : Tidal forces (per mass unit) :

$\Omega = (GM/r^3)^{1/2}$

$F_g = GM / (r+/-a)^2$

$F_c = \Omega^2(r+/-a)$

$F_{tide} = 3\Omega^2 a$



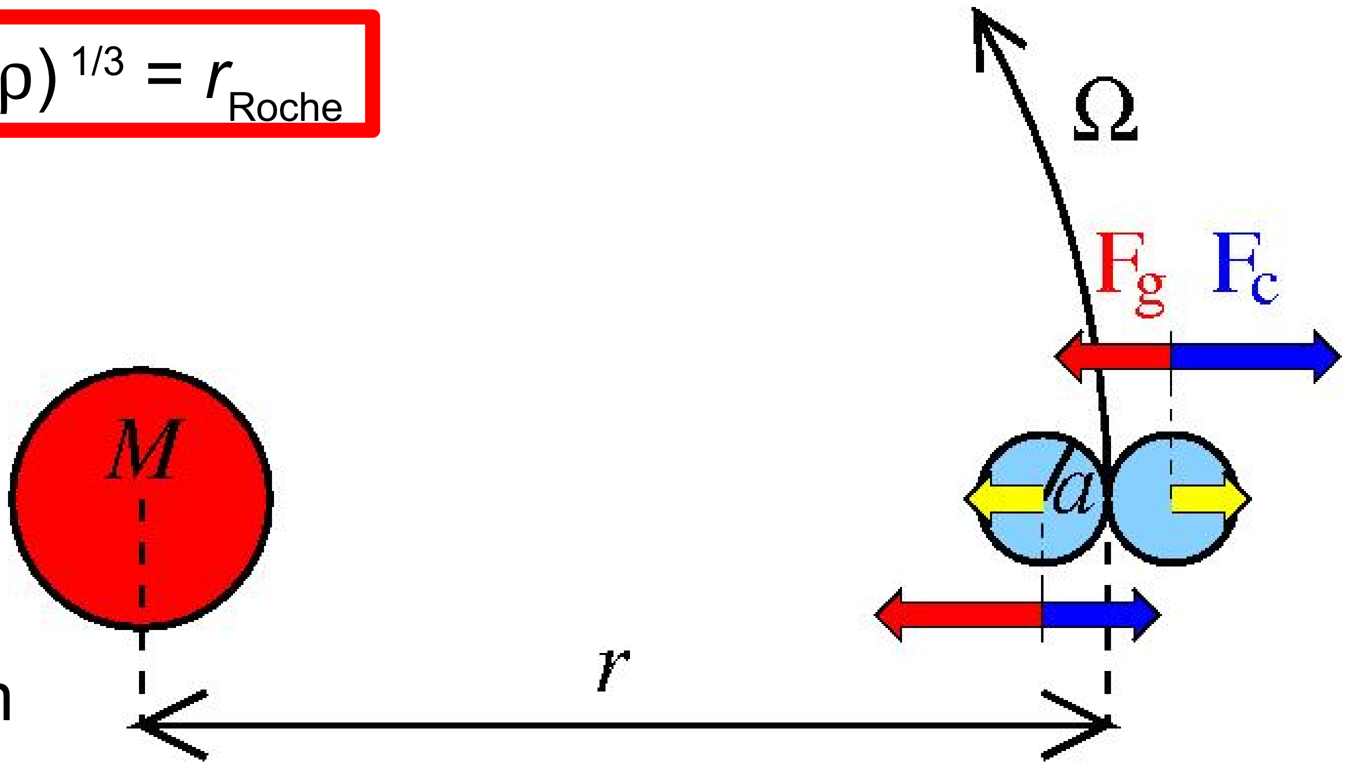
Reminder 1: the Roche Radius

Self-gravity force of the two bodies (per mass unit) :

$F_{sg} = G^*(4/3)\pi\rho a^3 / (2a)^2$

Condition for stability of the aggregate : $F_{sg} > F_{tide}$,

or : $r > (9M/\pi\rho)^{1/3} = r_{Roche}$



<u>Application:</u>

$M = M_{Saturn}$,

$\rho = 600\ kg.m^{-3}$

$r_{Roche} = 1,4\ 10^8\ m$

Reminder 2: Kepler's law

The *cube of the radius of an orbit is proportionnal to the square of the period.*

$$P^2 = (4\pi^2/GM_*) r^3$$

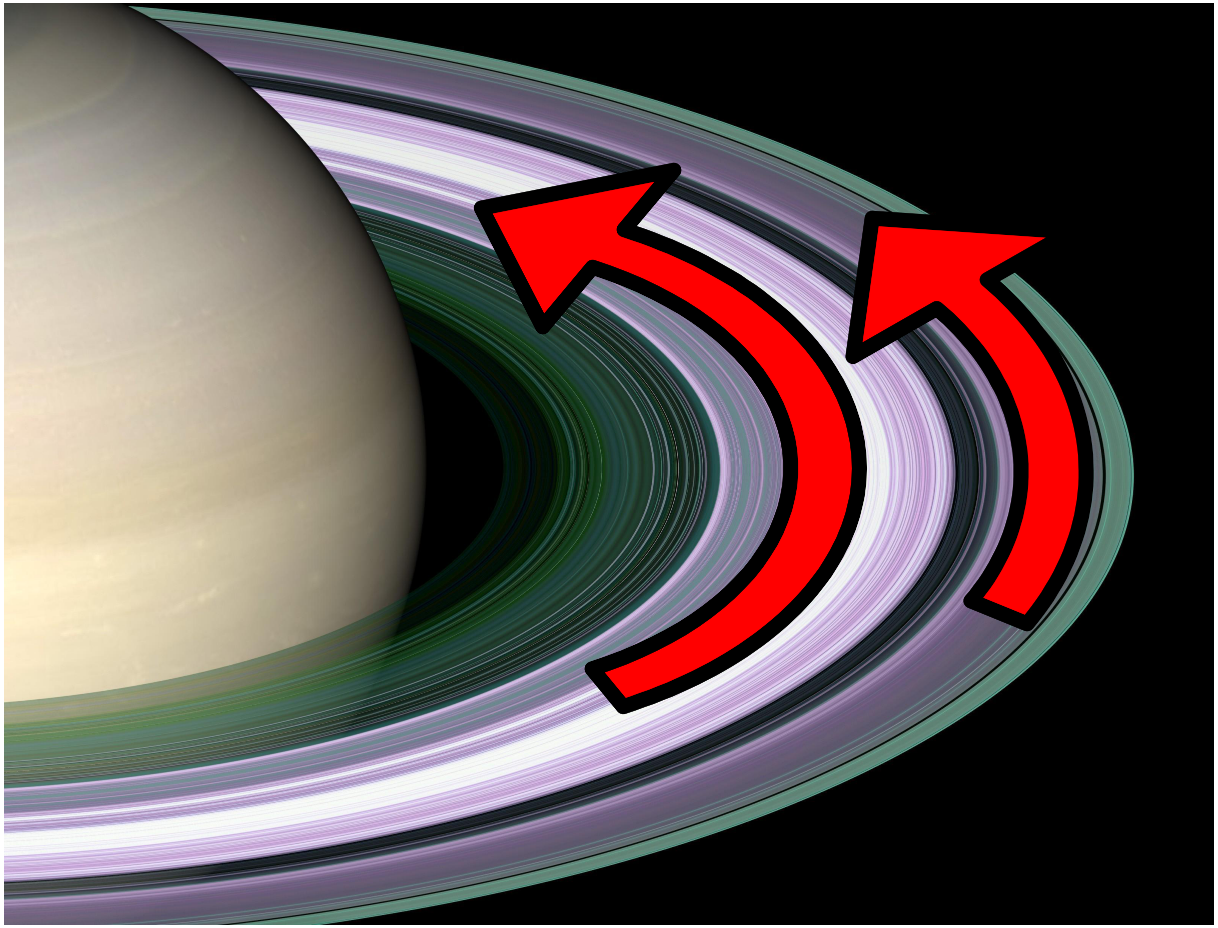
angular velocity : $\Omega=(GM_* / r^3)^{1/2}$

decreases with r .

specific orbital
angular momentum : $j=(G M_* r)^{1/2}$

increases with r !

1) Evolution of Saturn's rings



The inside rotates faster than the outside,

so friction accele-rates the outside (positive torque, increase of j thus r),

and slows down the inside (negative torque, r decrease).

Total: spreading.

Any astrophysical disk in Keplerian rotation spreads by viscous friction (eg. Lynden-Bell & Pringle 1974).

1) Evolution of Saturn's rings

Viscous spreading : $dM_{rings}/dt = - M_{rings} / t_\nu$, with $t_\nu = r_R^2 / \nu$.

Note $M_{rings} = \pi r_R^2 \Sigma$, $D = M_{rings} / M_{saturn}$, and $\bar{t} = t / T_R$. ($T_R = 2\pi/\Omega_R$.)

Daisaka et al. (2001)'s prescription for the viscosity :

$\nu_{grav} = \sim 46\, G^2 \Sigma^2 / \Omega^3$ at r_R , the ring's radius.

Analytics :

$r_R^2/\nu = r_R^6 \pi^2 \Omega_R^3 / (46\, G^2 M_{rings}^2)$

$r_R^2/\nu = (\pi^2 / 46\, \Omega_R)\, (M_p/M_{rings})^2$

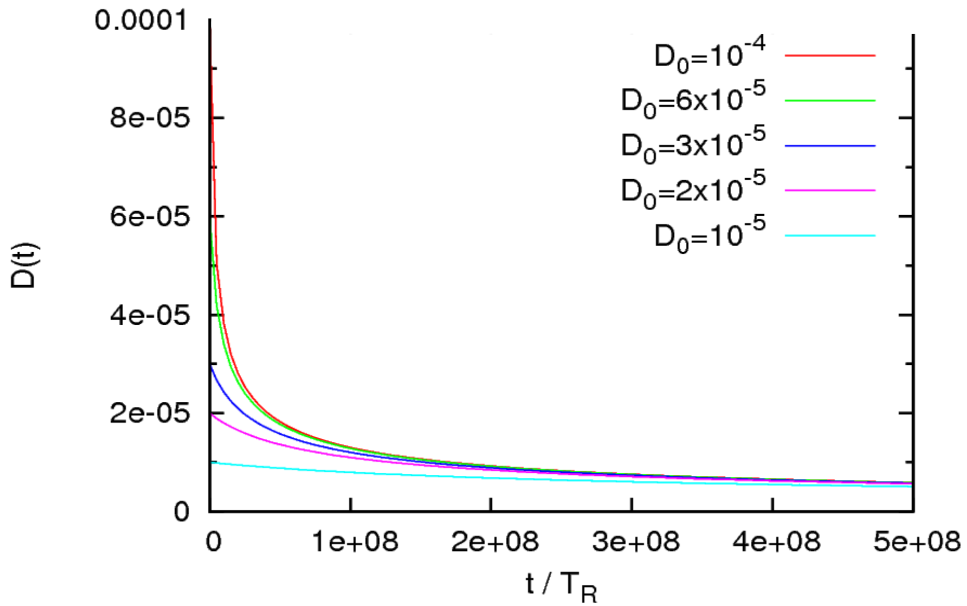
$(dD / d\bar{t}\,) =\sim - 30\, D^3$

$$D(\bar{t}) = 1 / \sqrt{(60\, \bar{t} + D_0^{-2})}$$

If $\bar{t} >> 1/60D_0^2$, $D(\bar{t}) = (1/60\bar{t})^{1/2}$, indep of D_0 !

$\bar{t}$ = 4.5 Gyr → $D < \sim 10^{-7}$.

Now, $D = 8 \times 10^{-8}$...



2) Satellites children of the rings

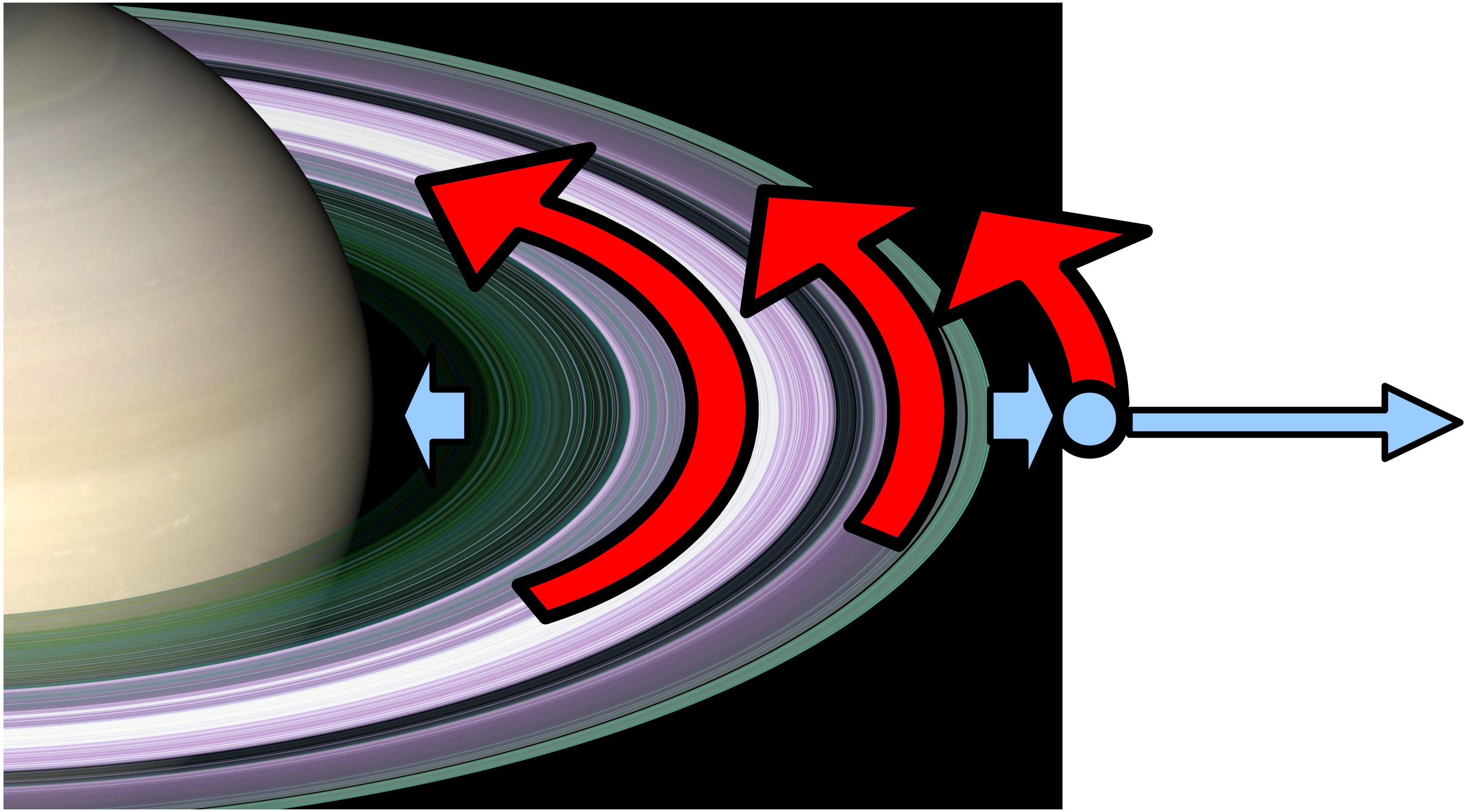
We have seen that the rings spread...

On the inside, the ice falls into Saturn.

On on the outside ?

After crossing the Roche limit, the ice boulders agglomerate, accrete, coallesce, and form new small satellites !

2) Satellites children of the rings



The new satellites have a smaller angular velocity than the rings particles. Therefore, they are accelerated and repeled outwards...

2) Satellites children of the rings

Total torque : $$\Gamma = \frac{8}{27}\left(\frac{M_{satellite}}{M_{Saturne}}\right)^2 \Sigma\, r^4 \Omega^2 \Delta^{-3}$$

proportionnal to $M_{\text{satellite}}^2$ and to Δ^{-3}, where $\Delta=(r-r_R)/r_R$.
(Lin & Papaloizou 1979)

The bigger satellites migrate outwards faster,
the further you are, the more slowly you move.

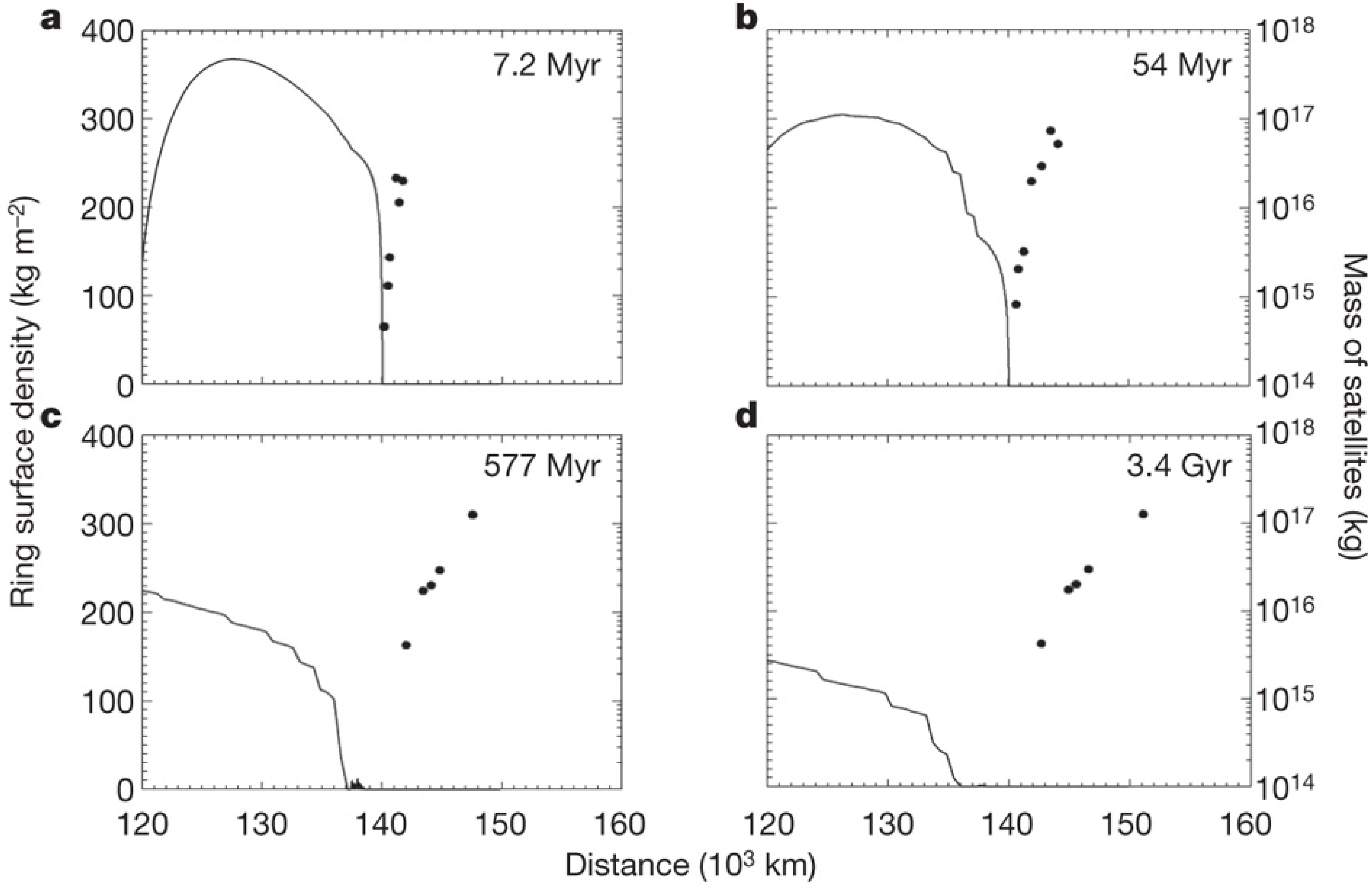
Numerical application :

~10^8 years ago, Janus was in the rings !

2) Satellites children of the rings
2.1) The small moons

Numerical simulation of **present day Saturn's rings**, with satellite formation beyond r_{Roche} :

Formation of Prometheus, Pandora, Epimetheus, Janus.

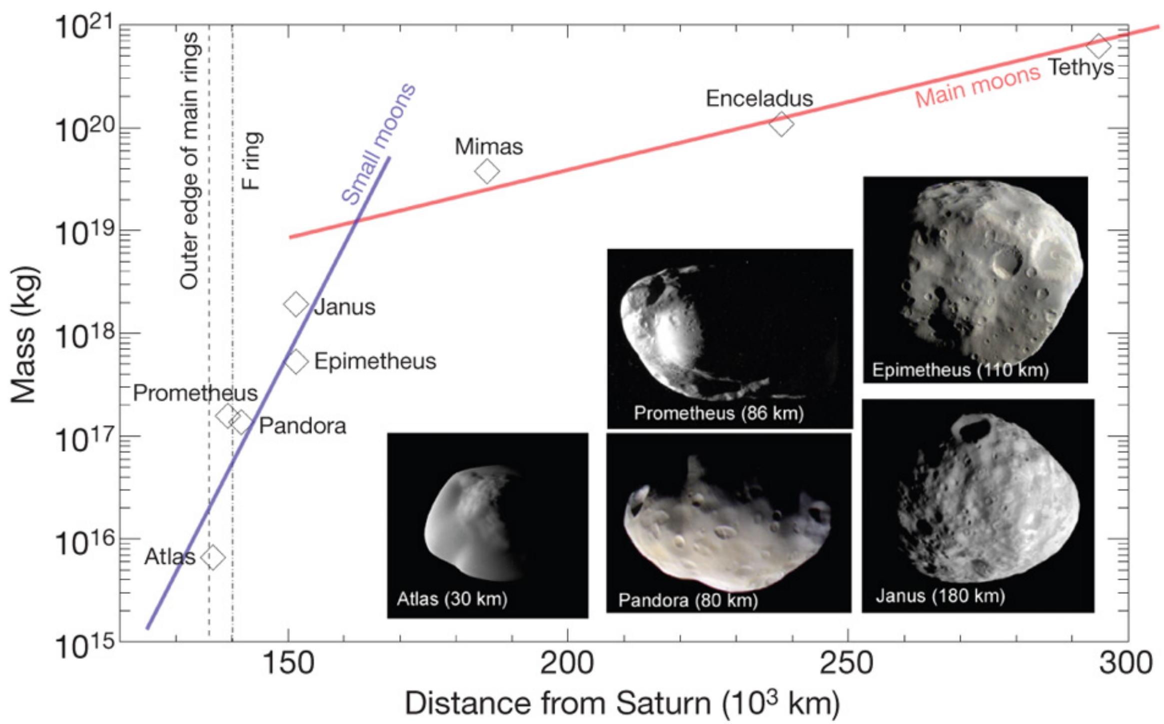


2) Satellites children of the rings
2.1) The small moons

This explains surprising properties of the small moons :

- underdense (~600 kg.m-3)
- same spectrum as the rings
- dynamically young
- young surfaces

(Charnoz, Salmon, & Crida, 2010)



2) Satellites children of the rings
2.2) The mid-sized moons

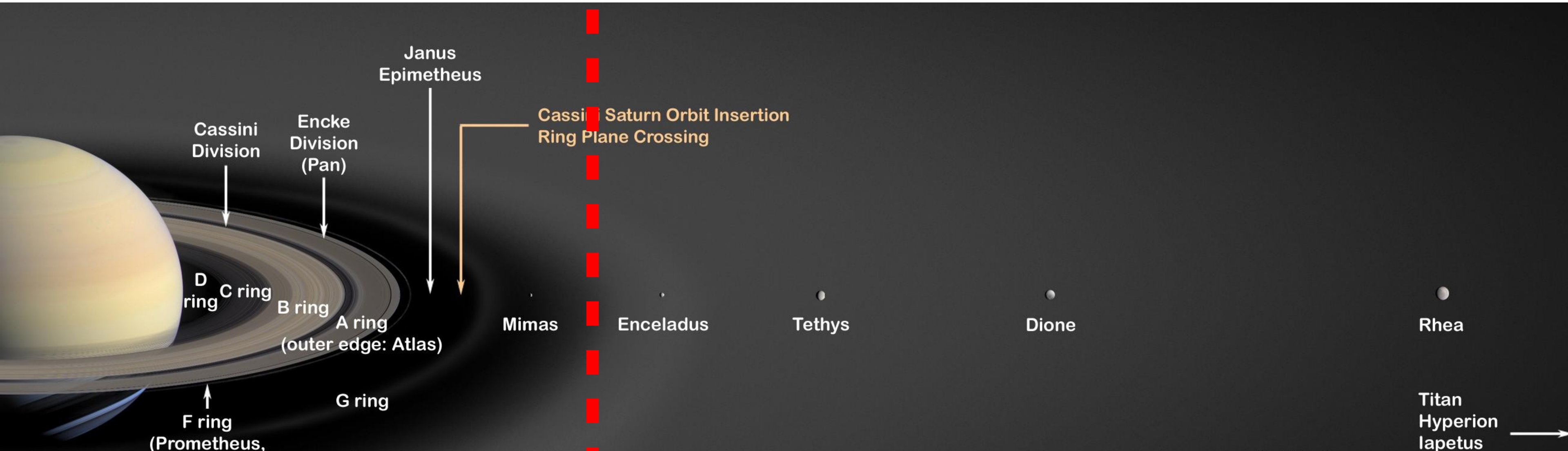
Add in the simulations :

1) Very massive rings initially (Canup 2010 ; Salmon et al 2010)

2) Saturnian tides beyond 222000 km: with Q=1700 (Lainey et al. 2012)

$$\frac{dr}{dt} = \frac{3\, k_{2p}\, M_{satellite} \sqrt{G}\, R^5_{Saturne}}{Q_{Saturne} \sqrt{M_{Saturne}}\, r^{11/2}}$$

We reproduce well the whole system up to Rhea !
(Charnoz, Crida, Castillo-Rogez, et al. 2011)



2) Satellites children of the rings

Movie :

Numerical simulation of Saturn's moon formation from an initial massive rings

In illustration of

Crida A., Charnoz S., 2012. « Formation of regular satellites from ancient massive rings in the Solar System ». Science, November 30th 2012

Discussion

Arguments in favor of this model :

✔ Ages are ranked by distance : the further, the older.
→ formation of one after the other, in logical order.
(see further)

✔ The mid-sized moons have irregular cores, and irregular global composition : stochastic formation of silicate aggregates in the rings, coated with ice.
→ at least for Dione & Rhea's core.

✔ The mid sized moons have young cratering ages, and couldn't survive the Late Heavy Bombardment, hence must have formed less than 4 Gyrs ago.
→ to be checked carefully + study of debris impacts

(Charnoz, Crida, Castillo-Rogez, et al. 2011)

Discussion

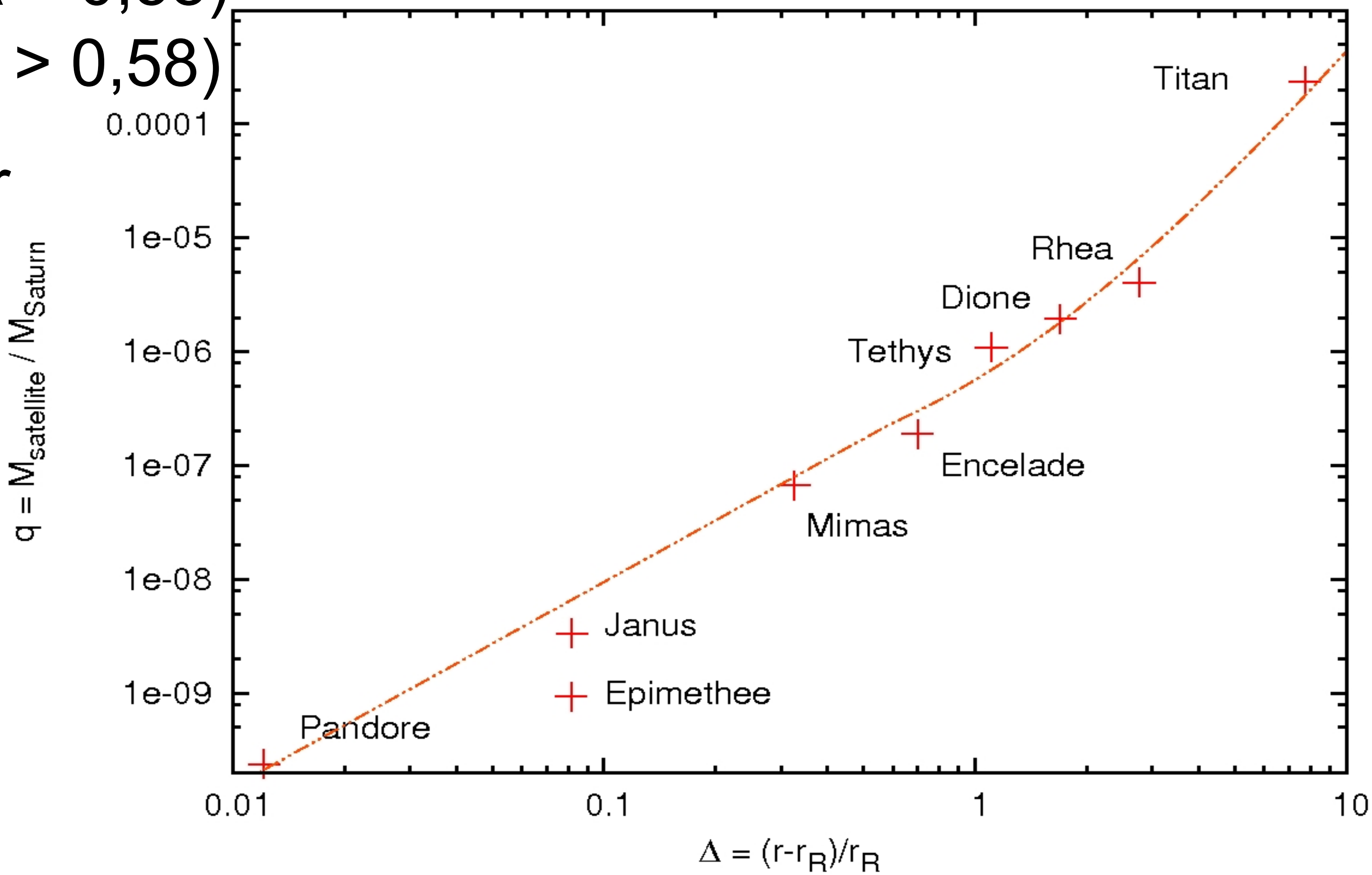
Arguments in favor of this model :

✔ Analytic calculations show that the spreading of rings produces a system of satellites with (Crida & Charnoz 2012) :

$M \alpha \Delta^{9/5}$ ($\Delta < 0{,}58$)

$M \alpha r^{3{,}8}$ ($\Delta > 0{,}58$)

Spectacular agreement, indep. of Q



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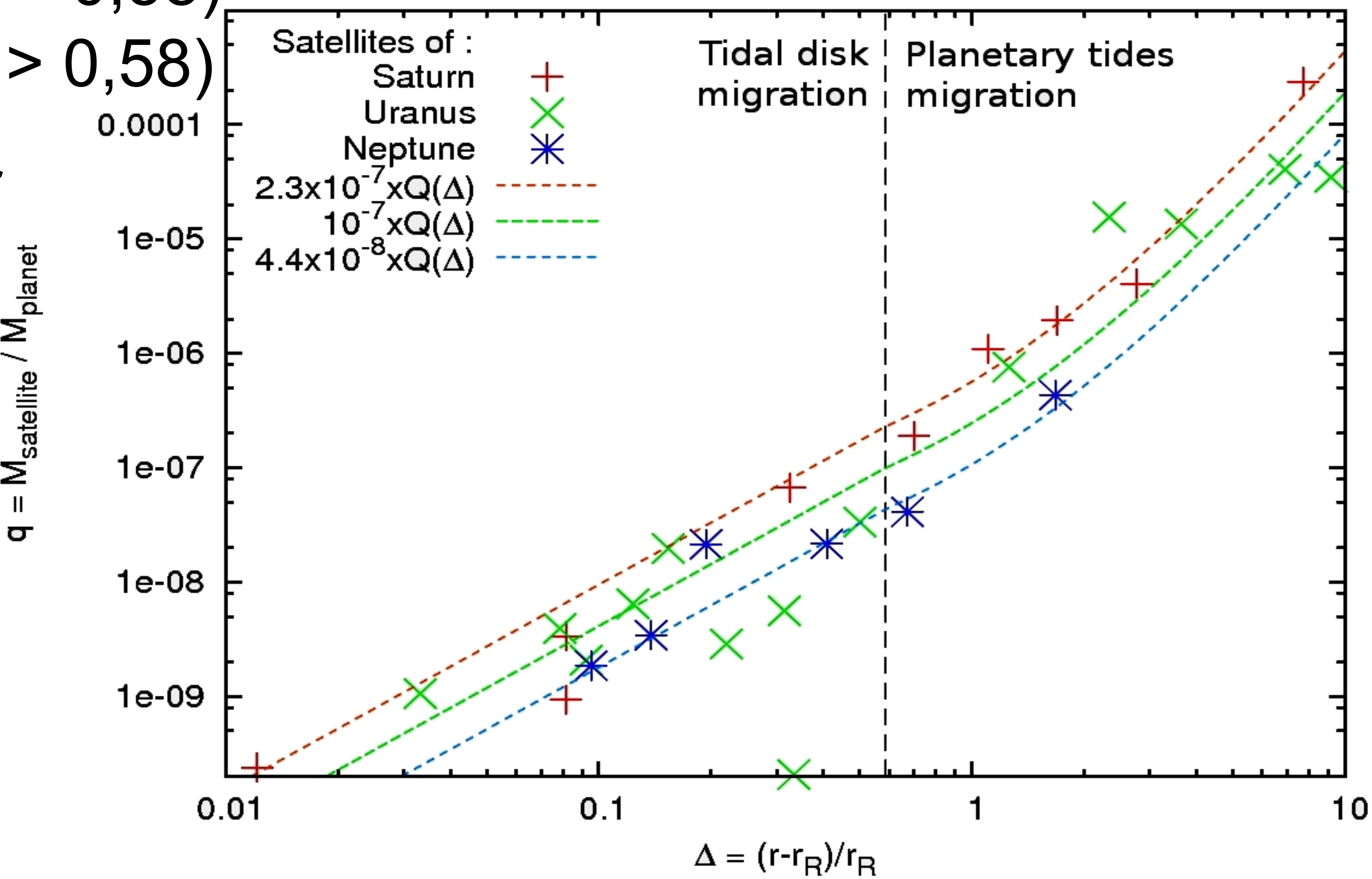
Also for Uranus & Neptune !



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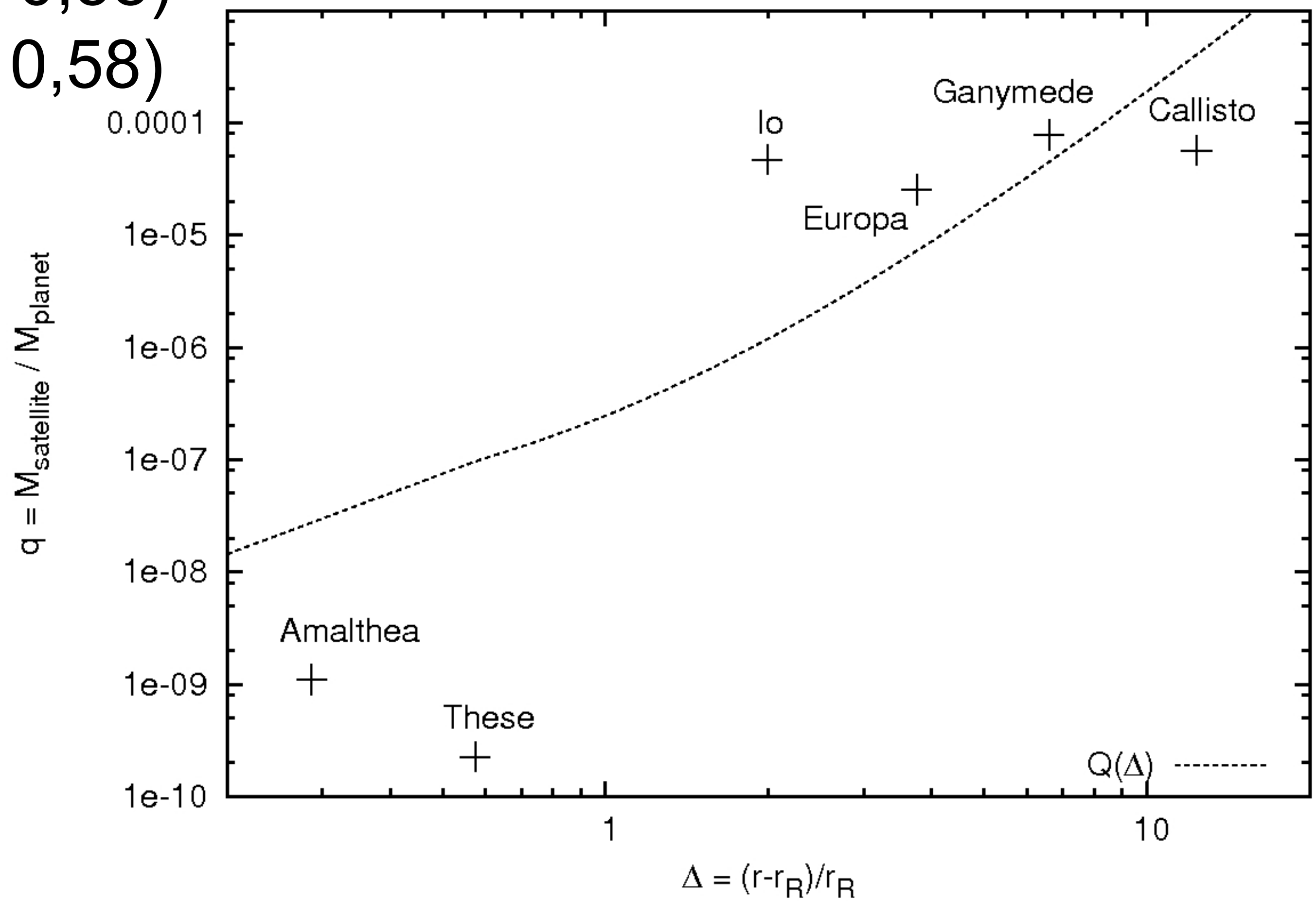
Also for Uranus & Neptune !

Not for Jupiter :-(



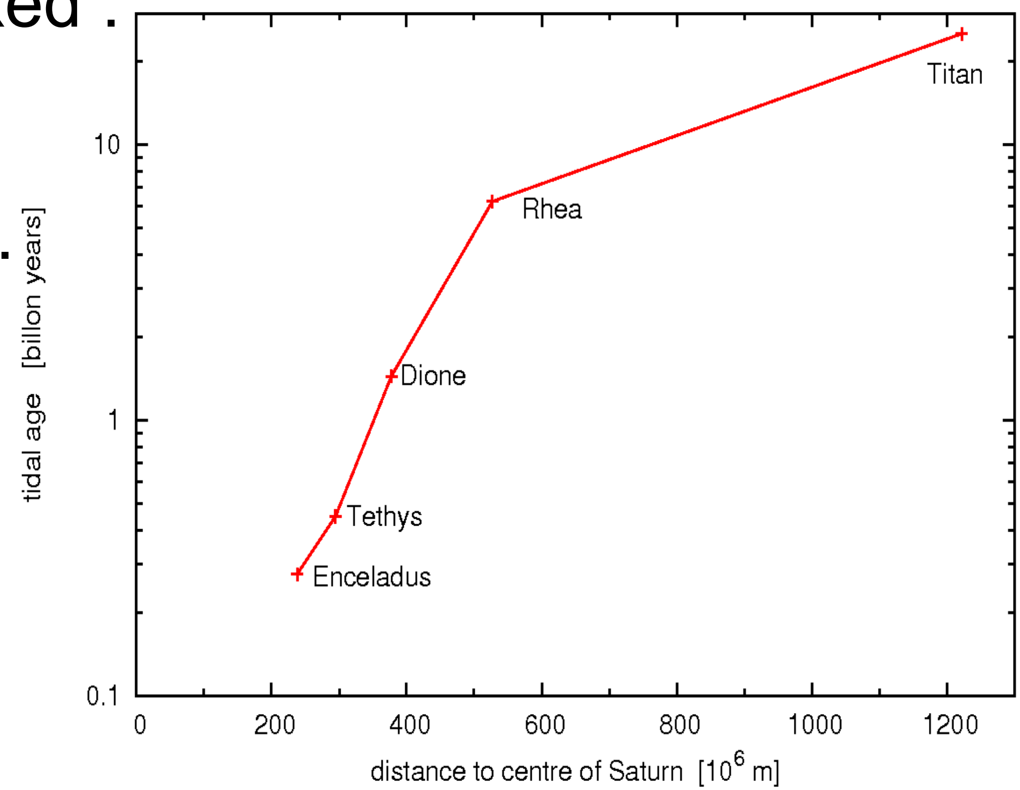
Discussion

Timing :

How long does it takes to bring the satellites at their present position with Saturn's tides ?

$$\frac{dr}{dt} = \frac{3\,k_{2p}\,M_{satellite}\,\sqrt{G}\,R^5_{Saturne}}{Q_{Saturne}\sqrt{M_{Saturne}}\;r^{11/2}}$$

✓***Tidal ages*** are well ranked : the further, the older.
→ formation of one after the other, in logical order.



With Q_{saturn} = 18000, several Gyrs.

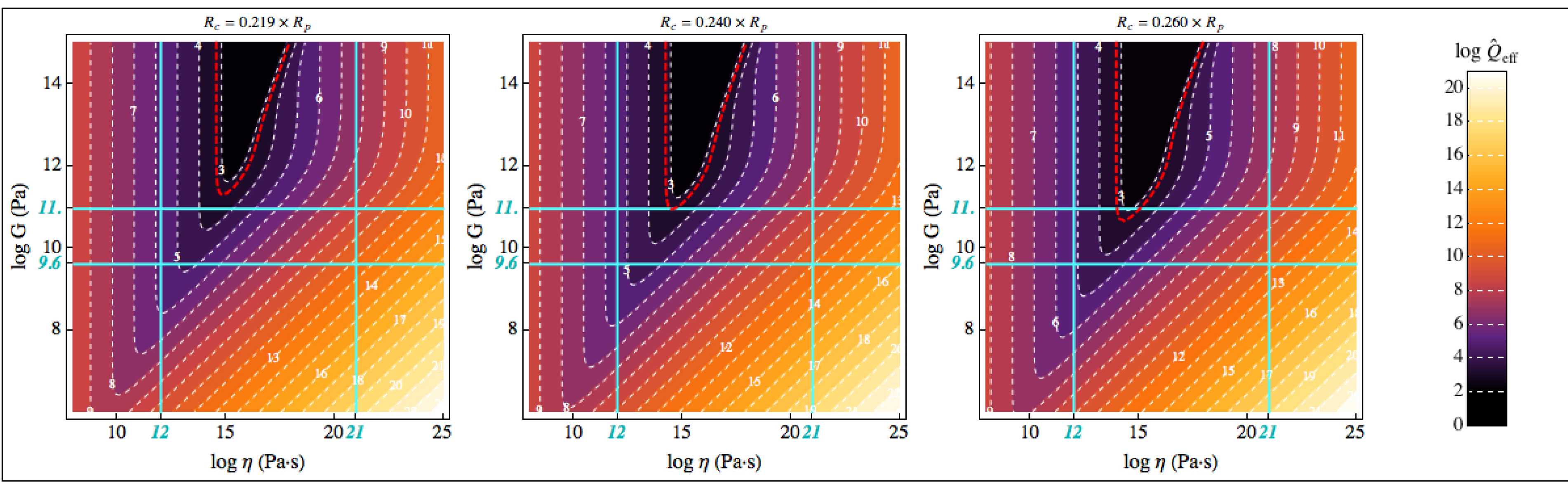
With Q_{saturn} = 1700, even Rhea is younger than the Solar System !

Discussion

Dissipation inside Saturn ?

Remus et al. (2012) computed the dissipation factor Q as a function of the viscoelastic parameters G and η, for a Saturn-like planet with an ice-silicate core and a gas envelope, perturbed at Enceladus' frequency :

TIDAL EFFECTIVE DISSIPATION FACTOR $\hat{Q}_{eff}$ OF A SATURN-LIKE PLANET (M_c = 18.65 × $M_p^{\oplus}$) AT THE TIDAL FREQUENCY OF ENCELADUS (ω = 2.25×10^{-4} rad·s^{-1})



The size and nature of the core matter a lot !

CONCLUSION

The rings spread over the age of the Solar System which gives birth to the satellites inside (upto?) Titan.

Saturn's system is a living system, still evolving !

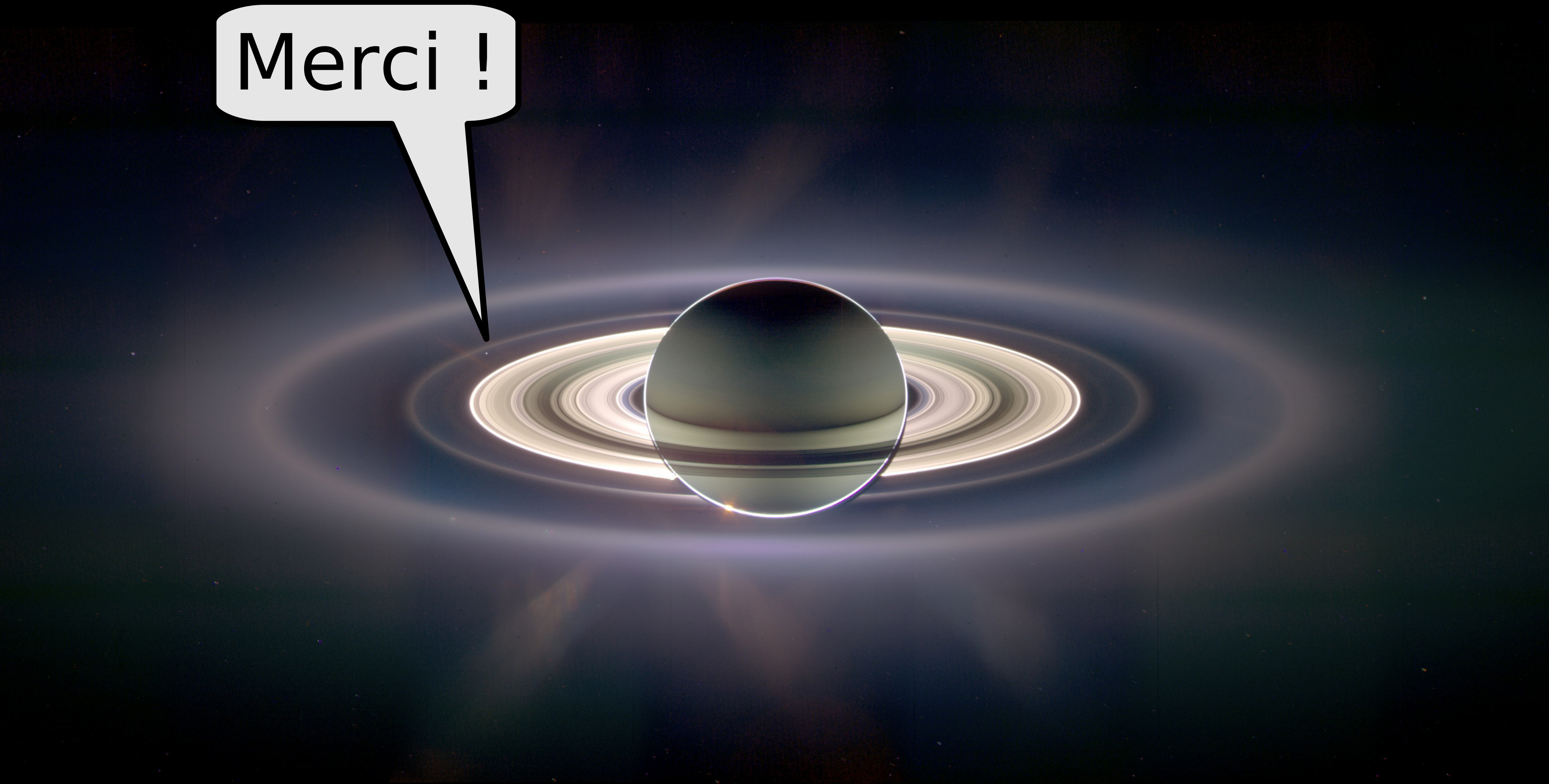
How fast ? It depends on Saturn's interior...

References :

Charnoz, Salmon, Crida (2010), *Nature*

Charnoz et al. (2011), *Icarus*

Crida & Charnoz (2012), *Science*



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