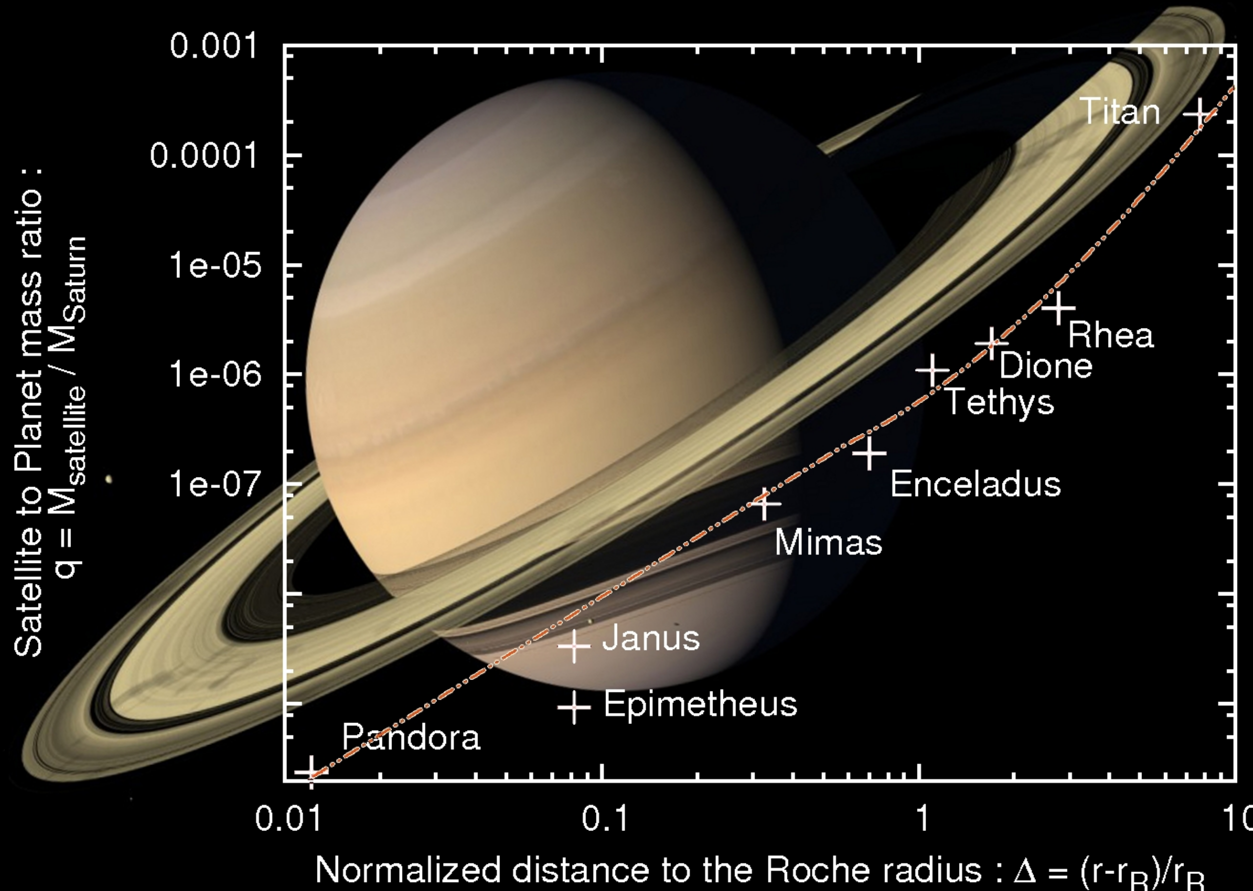
Formation of Satellites from Rings



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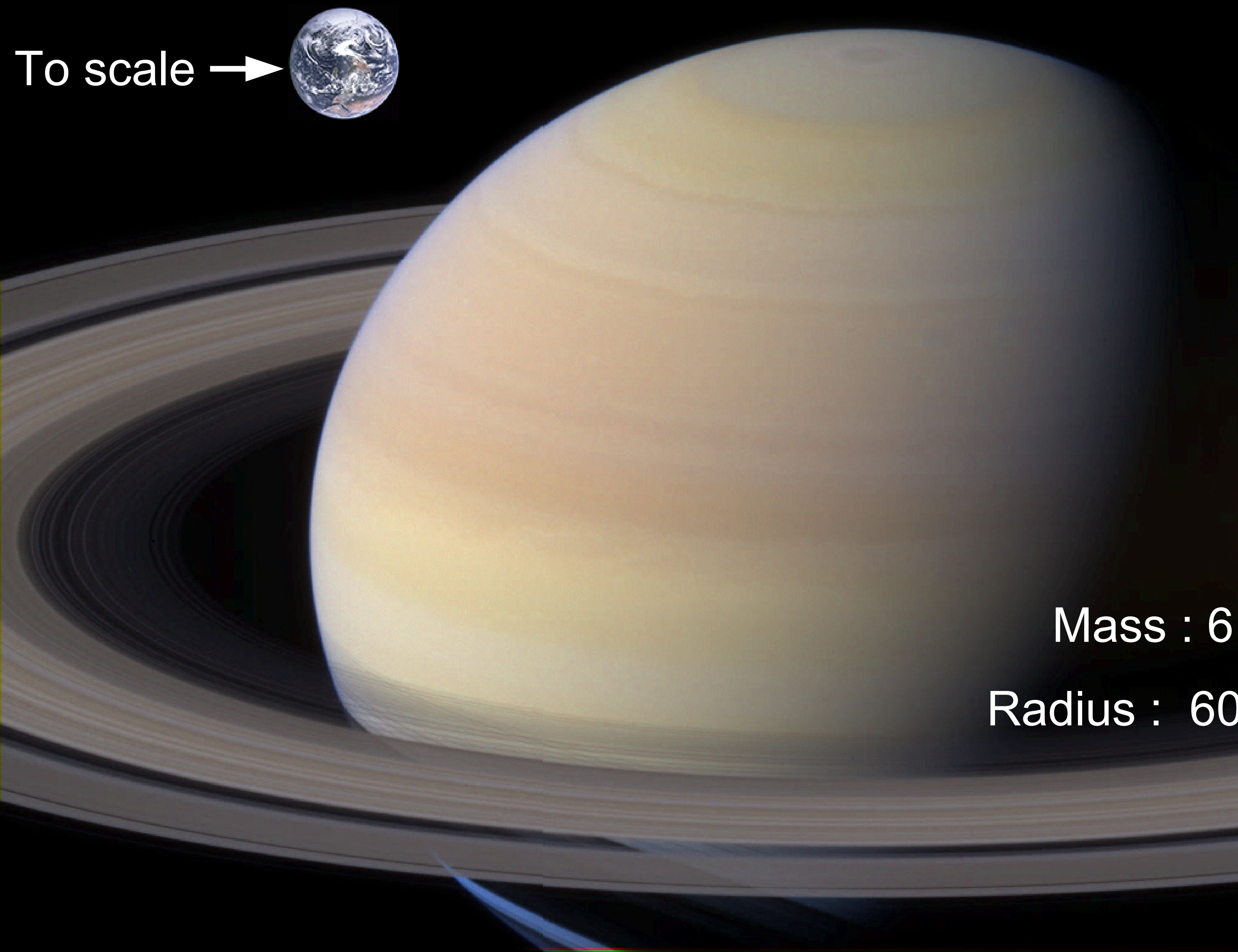
IUF

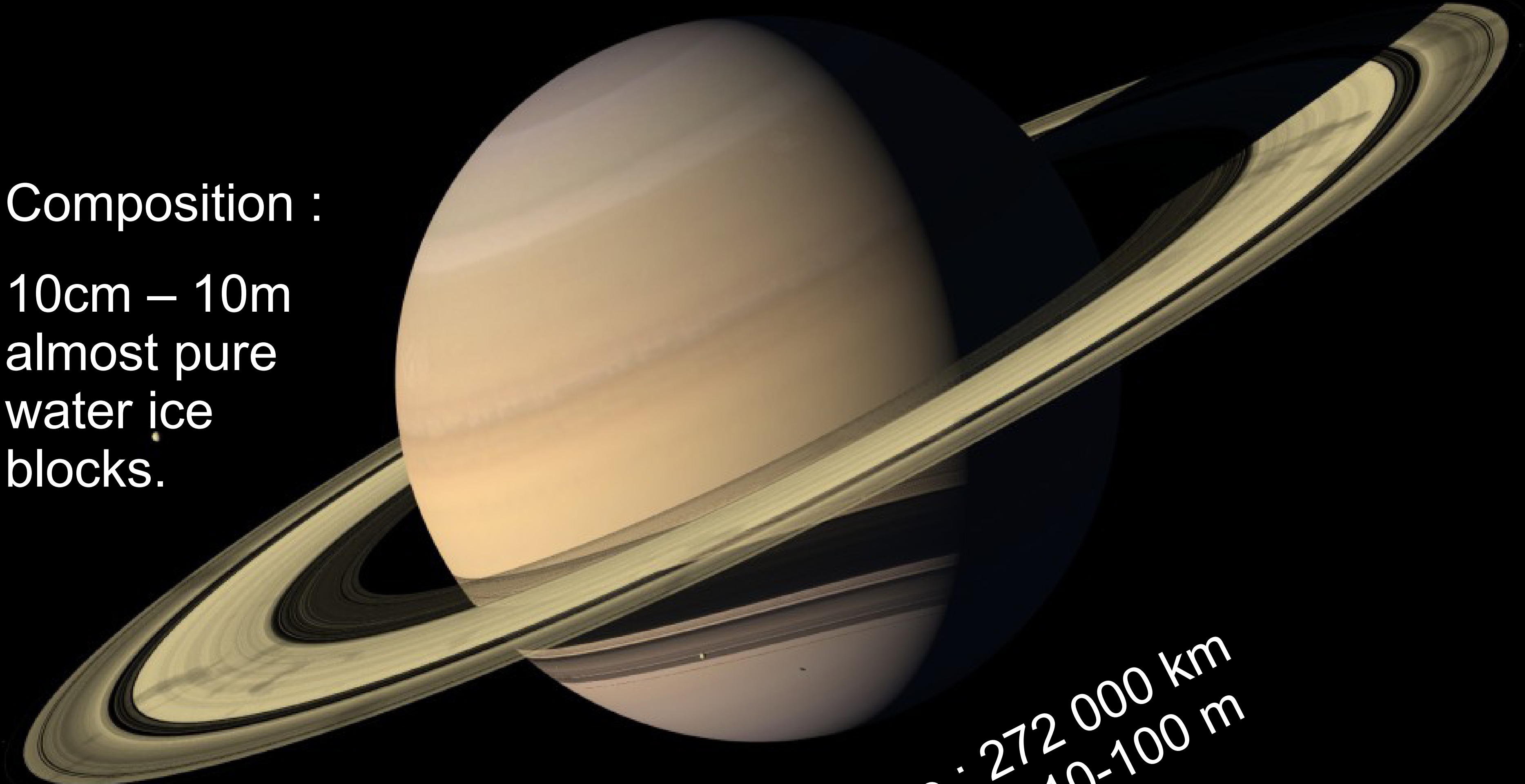
SATURN



Mass : 6×10^{26} kg

Radius : 60 000 km.

RINGS

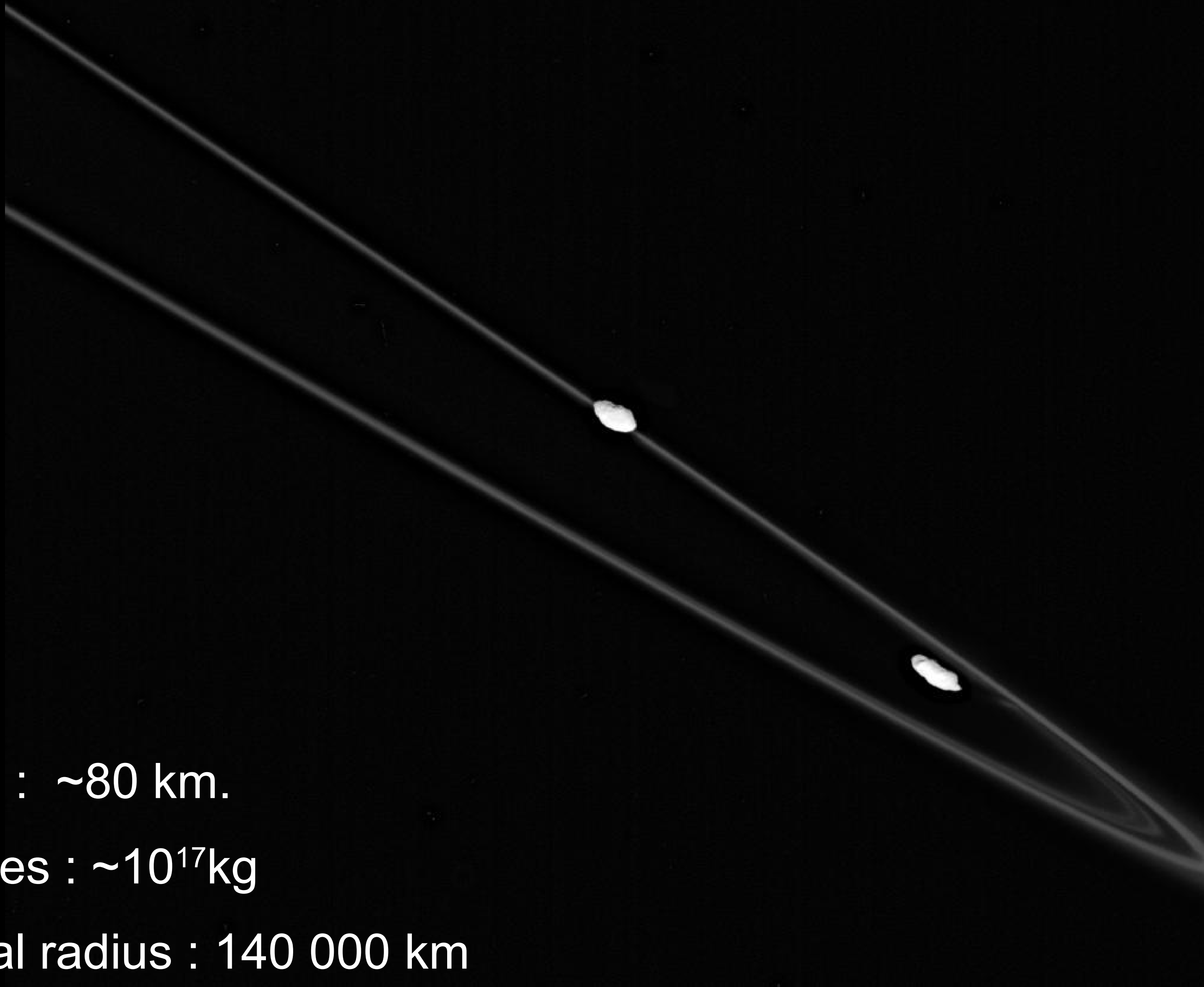


Composition :

10cm – 10m almost pure water ice blocks.

Diametre : 272 000 km
Thickness : 10-100 m

PROMETHEUS & PANDORA



Sizes : ~80 km.

Masses : ~10^{17}kg

Orbital radius : 140 000 km

JANUS & EPIMETHEUS

Sizes : 180 & 110 km.

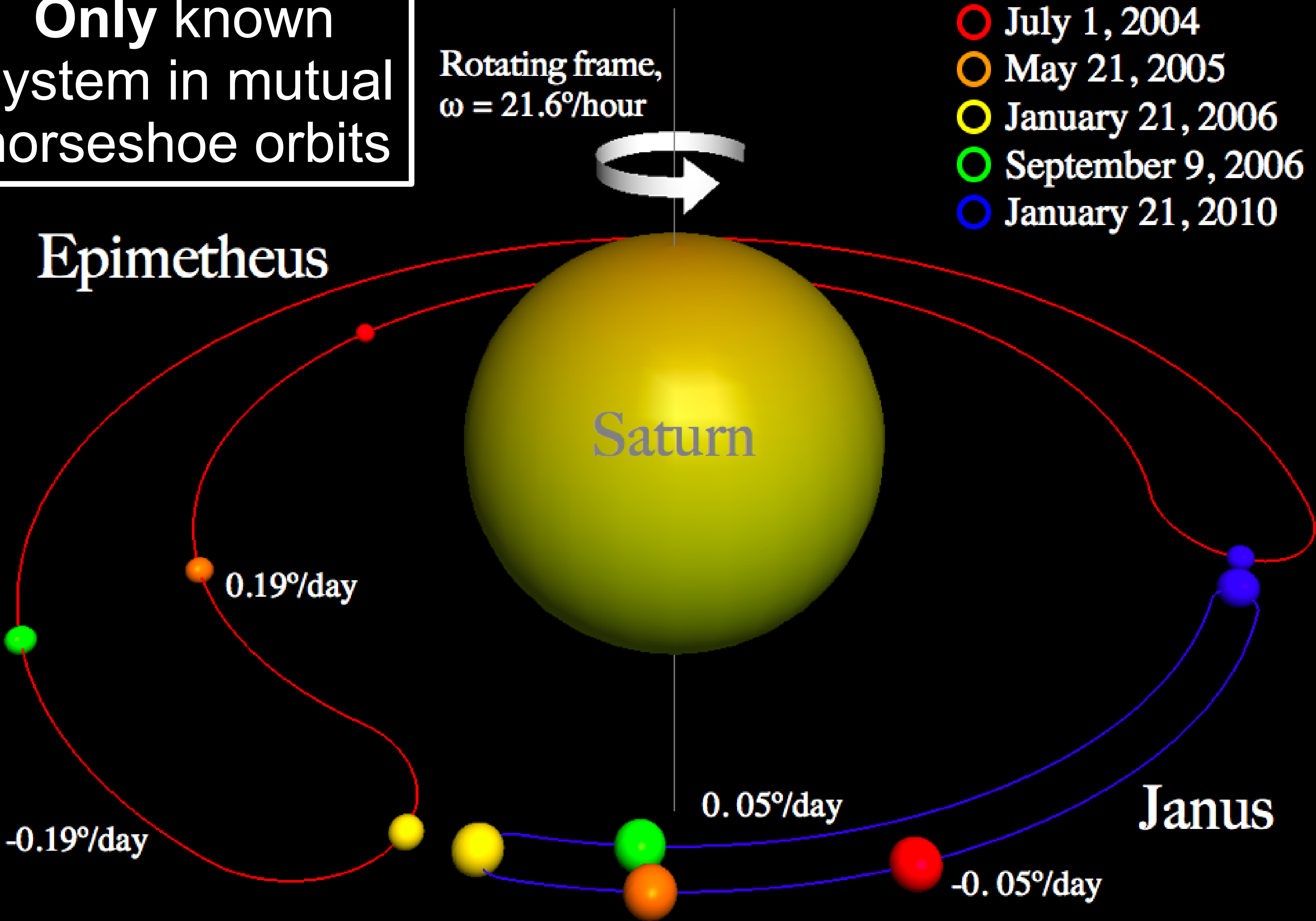
Masses : 2 & 0,5 x 10^{18}kg

Orbital radius : 151 000 km

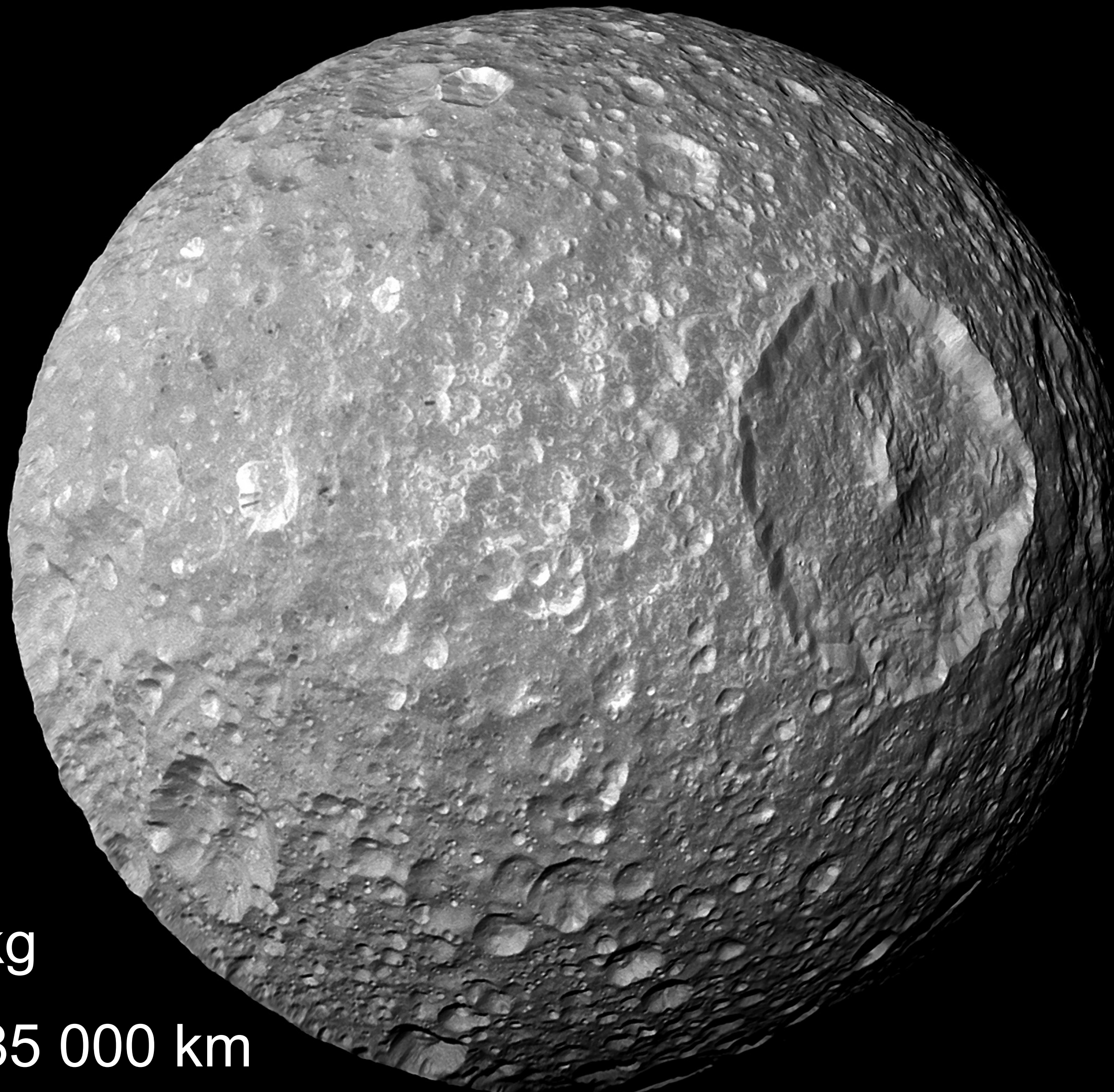
Distance to the rings : 11 000 km.

JANUS & EPIMETHEUS

Only known system in mutual horseshoe orbits



MIMAS



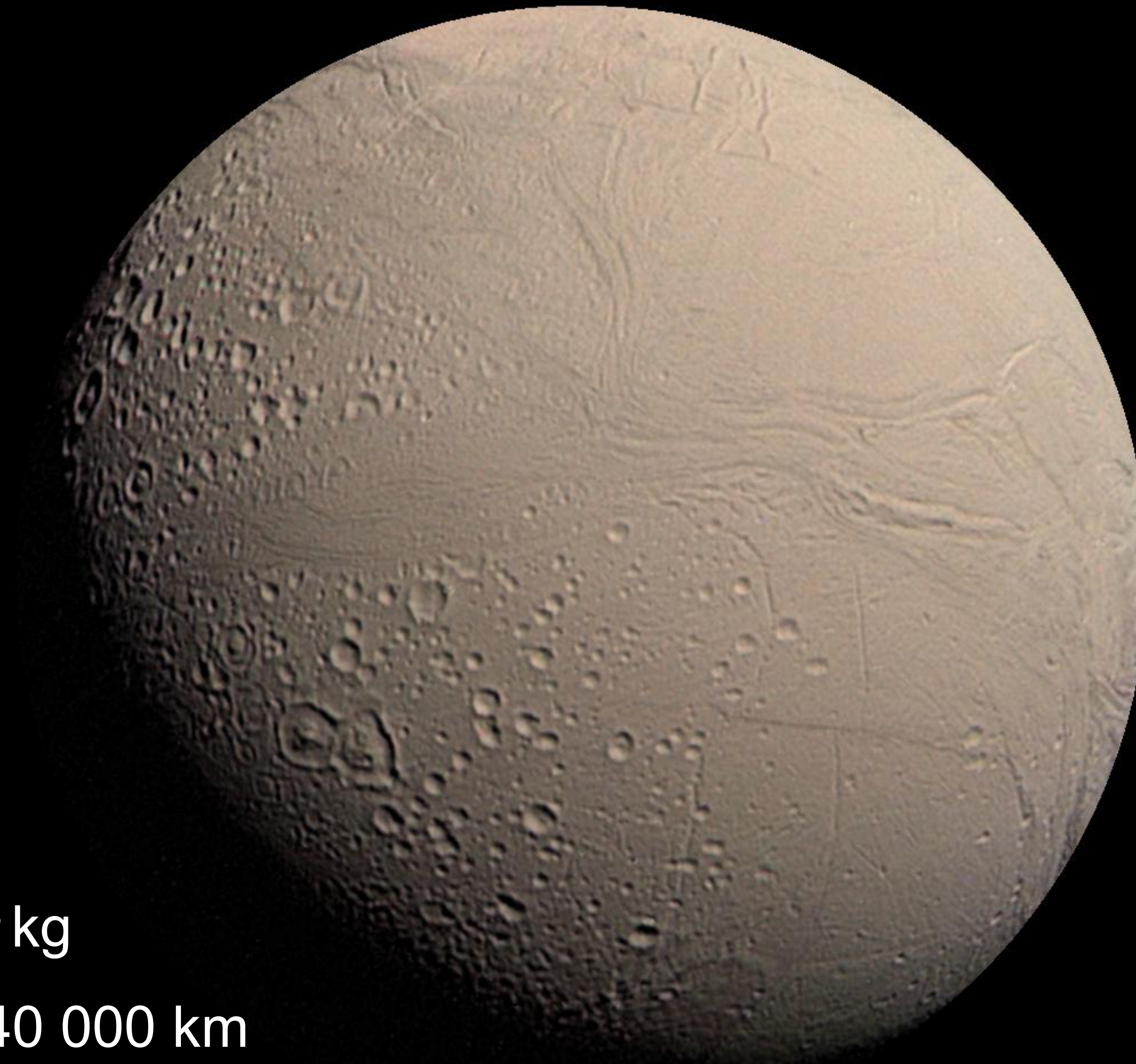
Size : 400 km.

Mass : 37 x 10^{18} kg

Orbital radius : 185 000 km

Distance to the rings : 45 000 km.

ENCELADUS



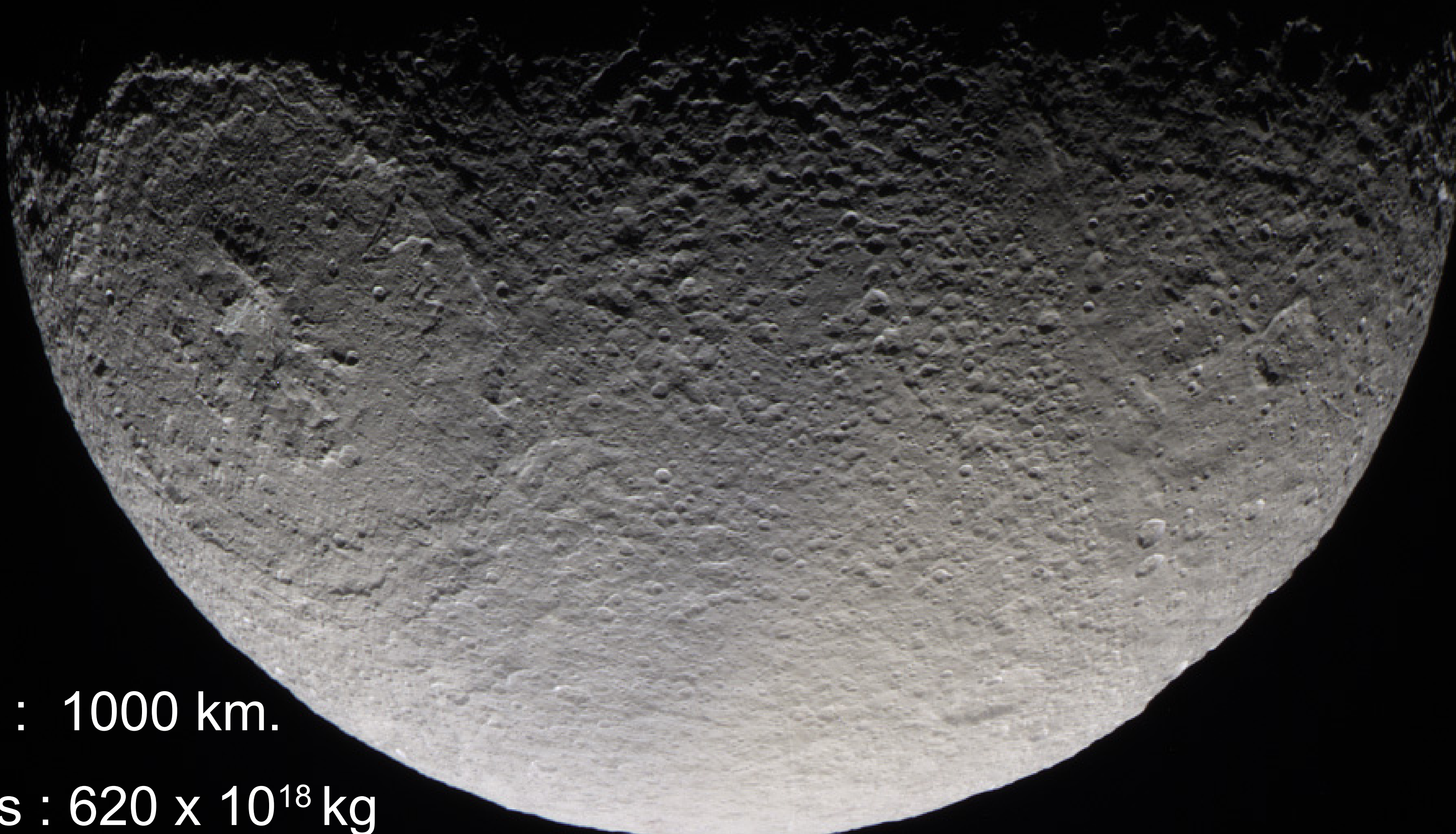
Size : 500 km.

Mass : 108 x 10^{18} kg

Orbital radius : 240 000 km

Distance to the rings : 100 000 km.

TETHYS



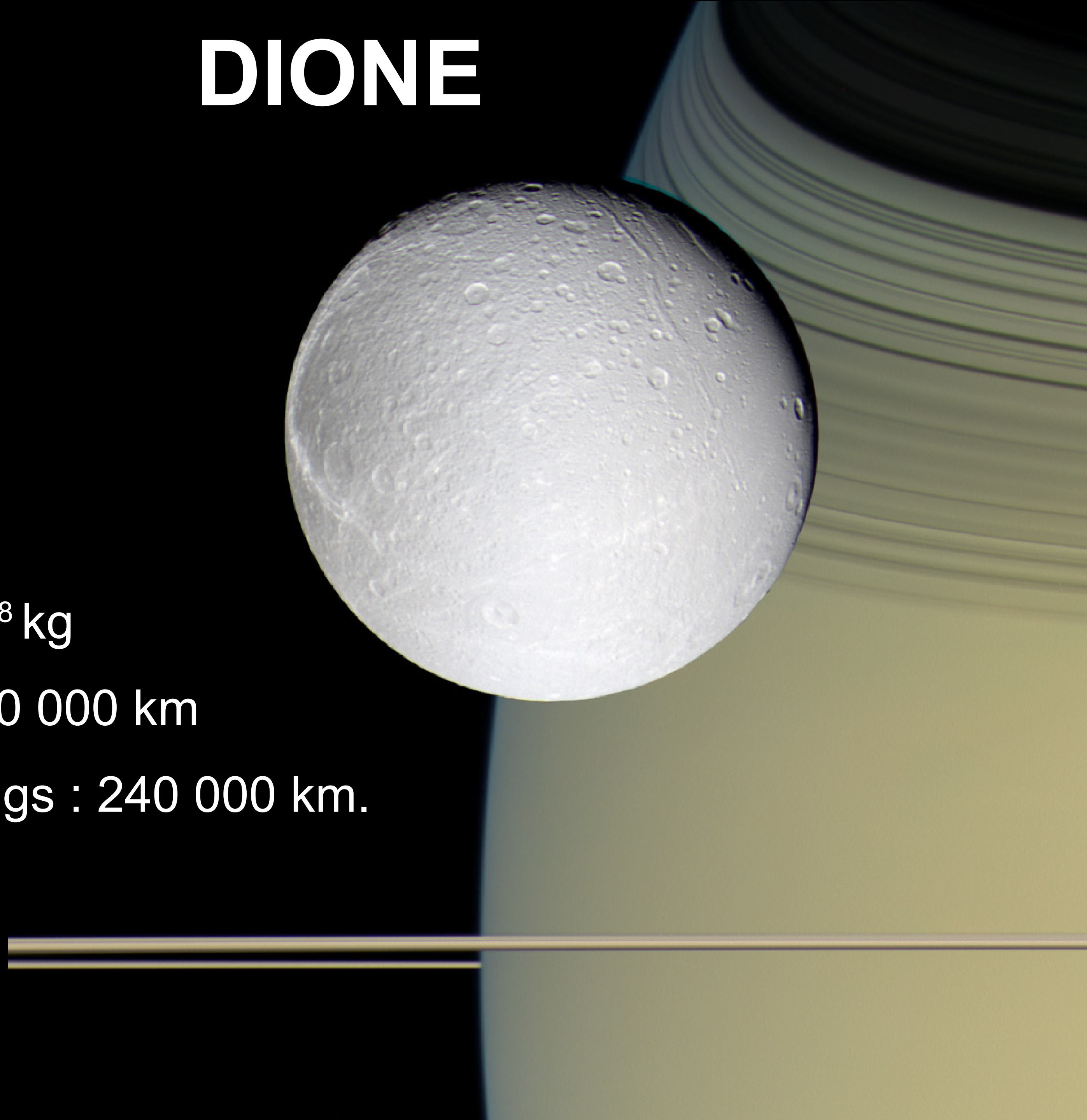
Size : 1000 km.

Mass : 620 x 10^{18} kg

Orbital radius : 300 000 km

Distance to the rings : 160 000 km.

DIONE



Size : 1120 km.

Mass : 1100 x 10^{18} kg

Orbital radius : 380 000 km

Distance to the rings : 240 000 km.

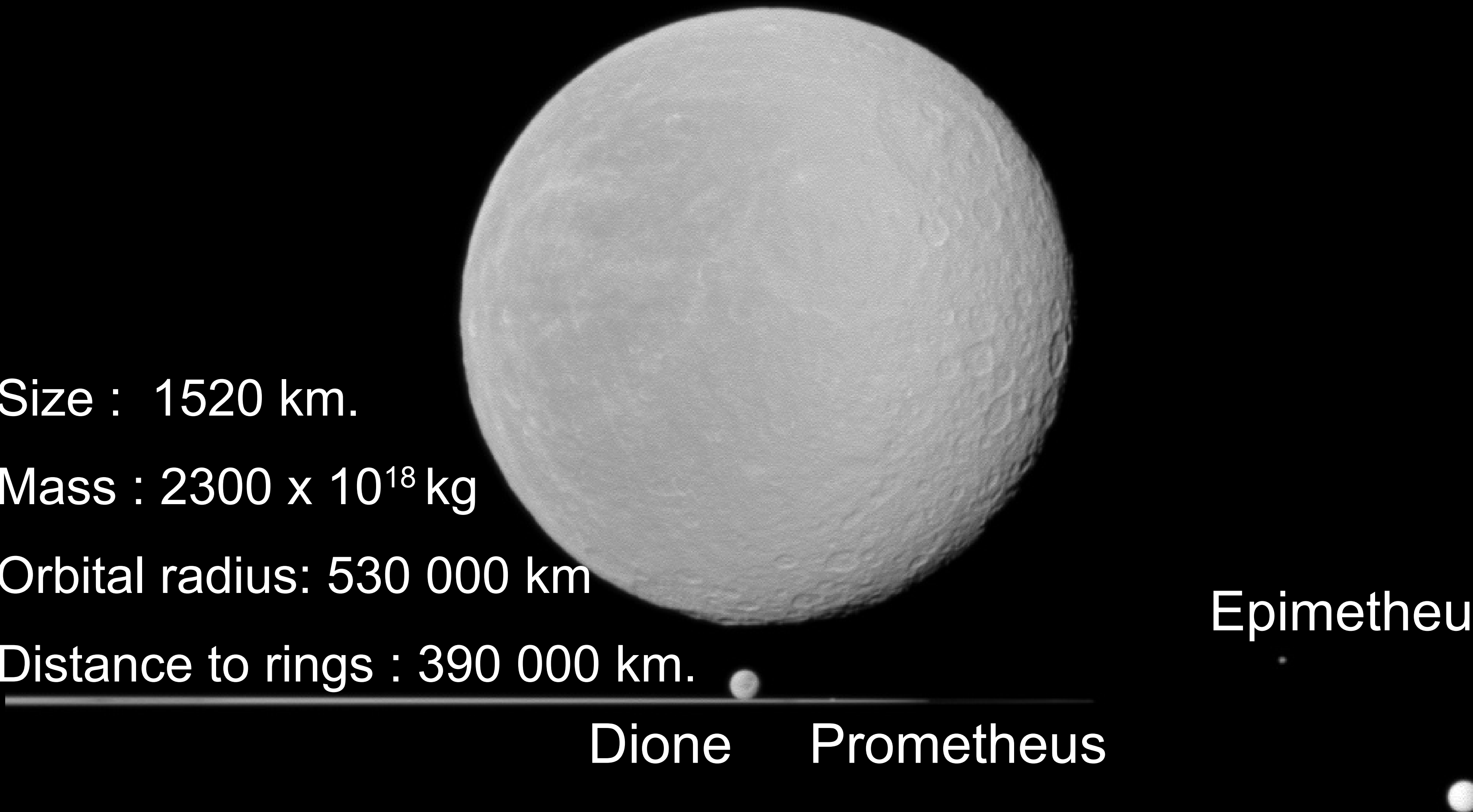
RHEA

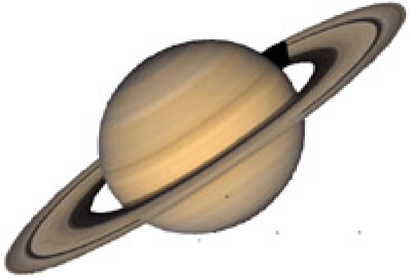
Size : 1520 km.

Mass : 2300 x 10^{18} kg

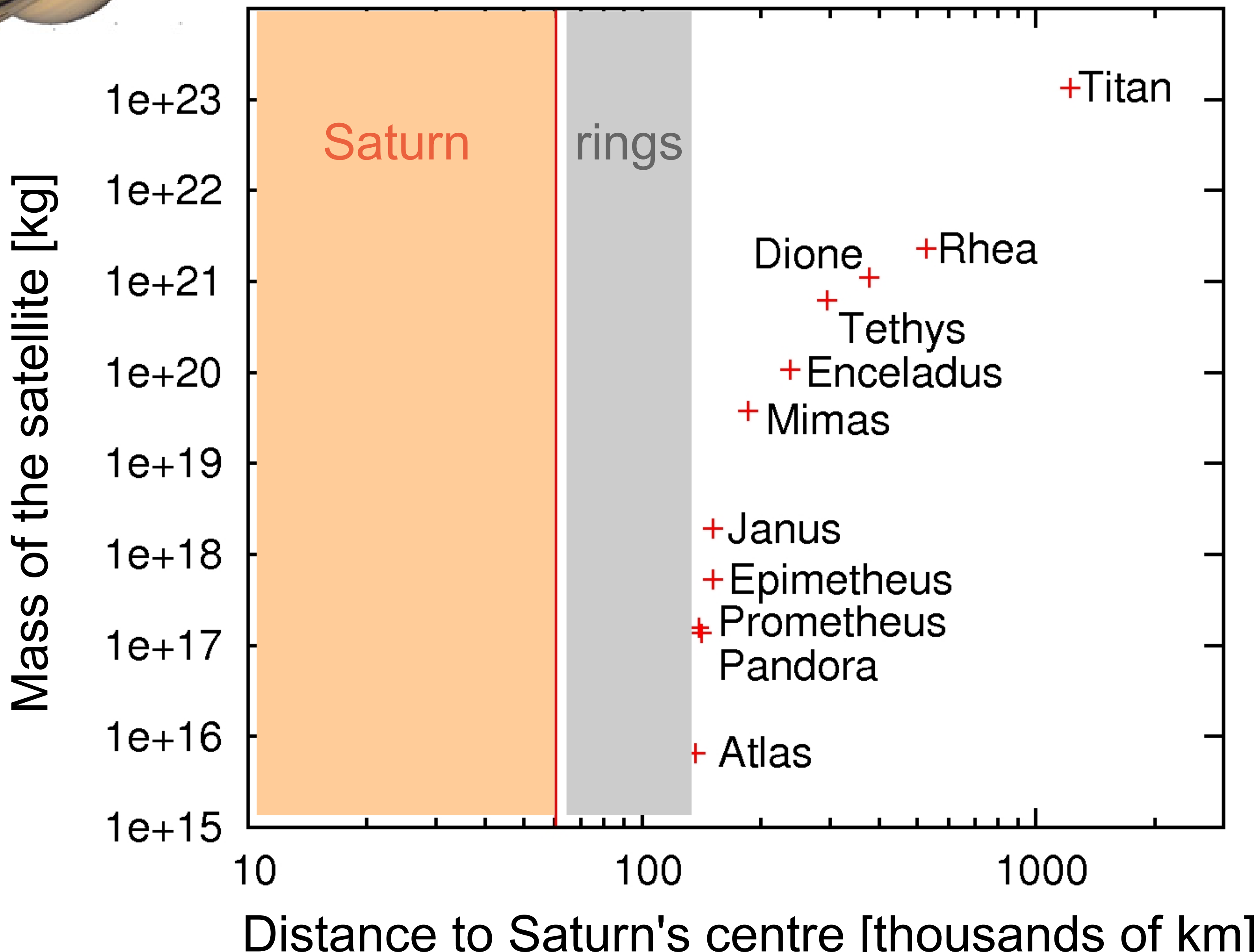
Orbital radius: 530 000 km

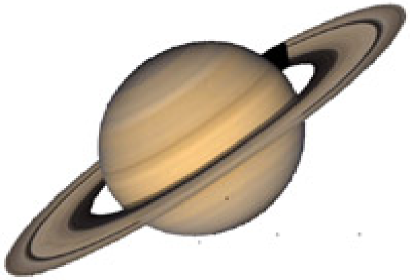
Distance to rings : 390 000 km.



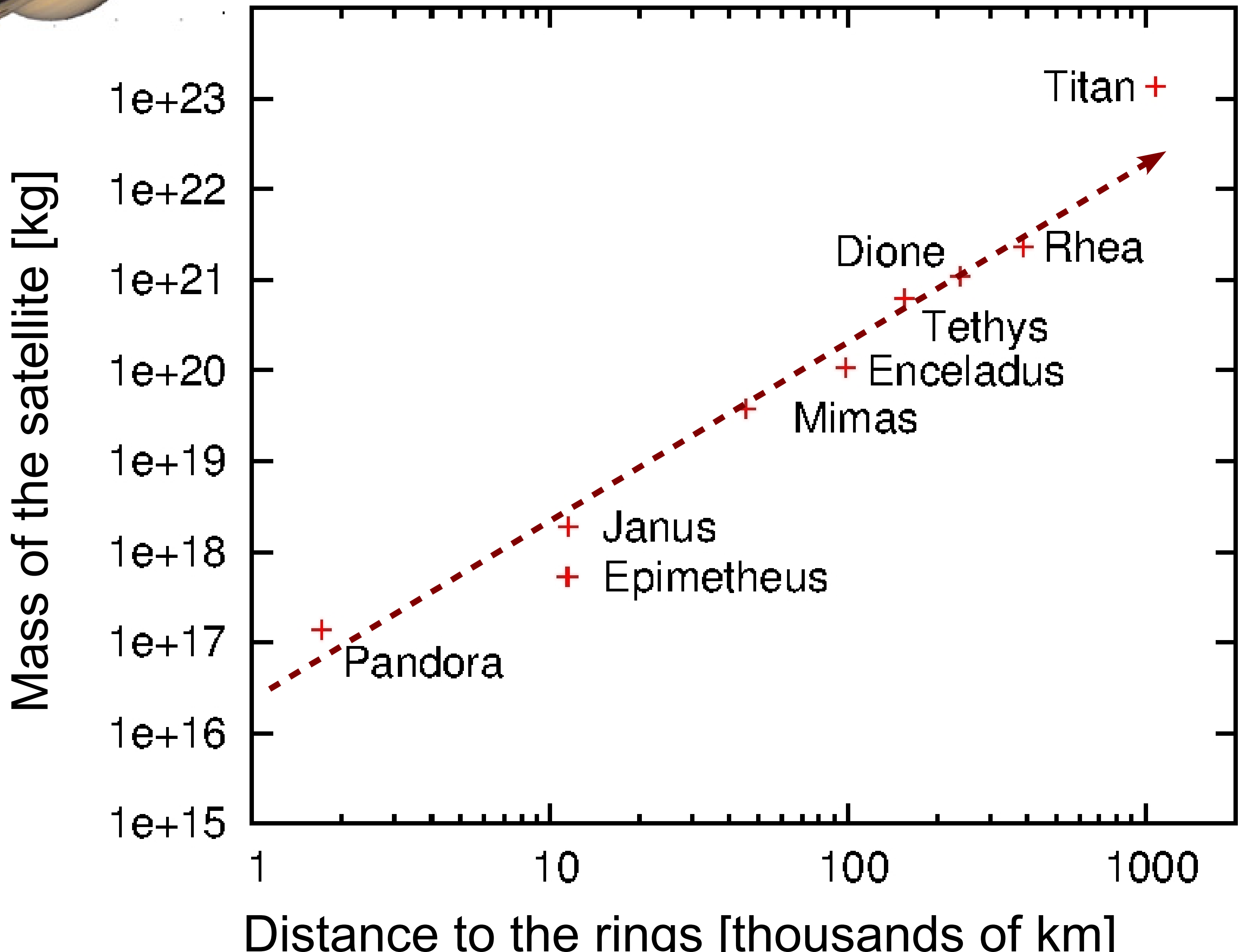


SATURN's SYSTEM





SATURN's SYSTEM



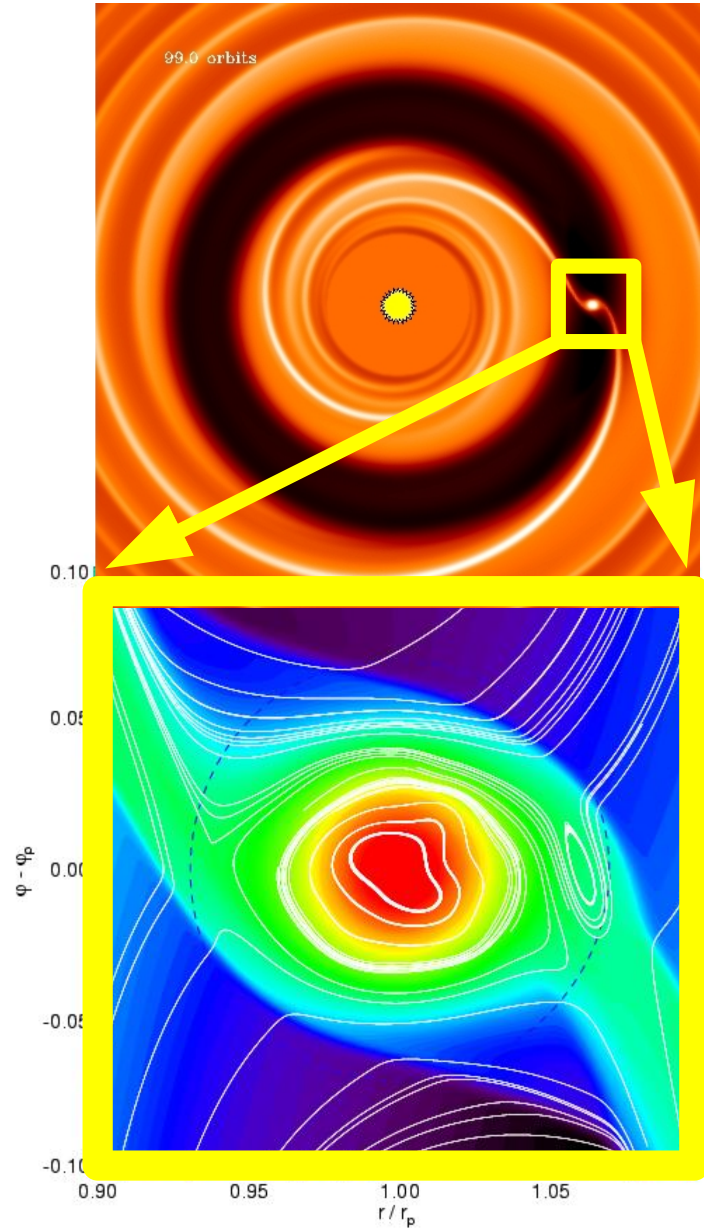
ORIGIN of the SATELLITES ?

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:

Kepler's law & rings spreading

Kepler's law

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

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

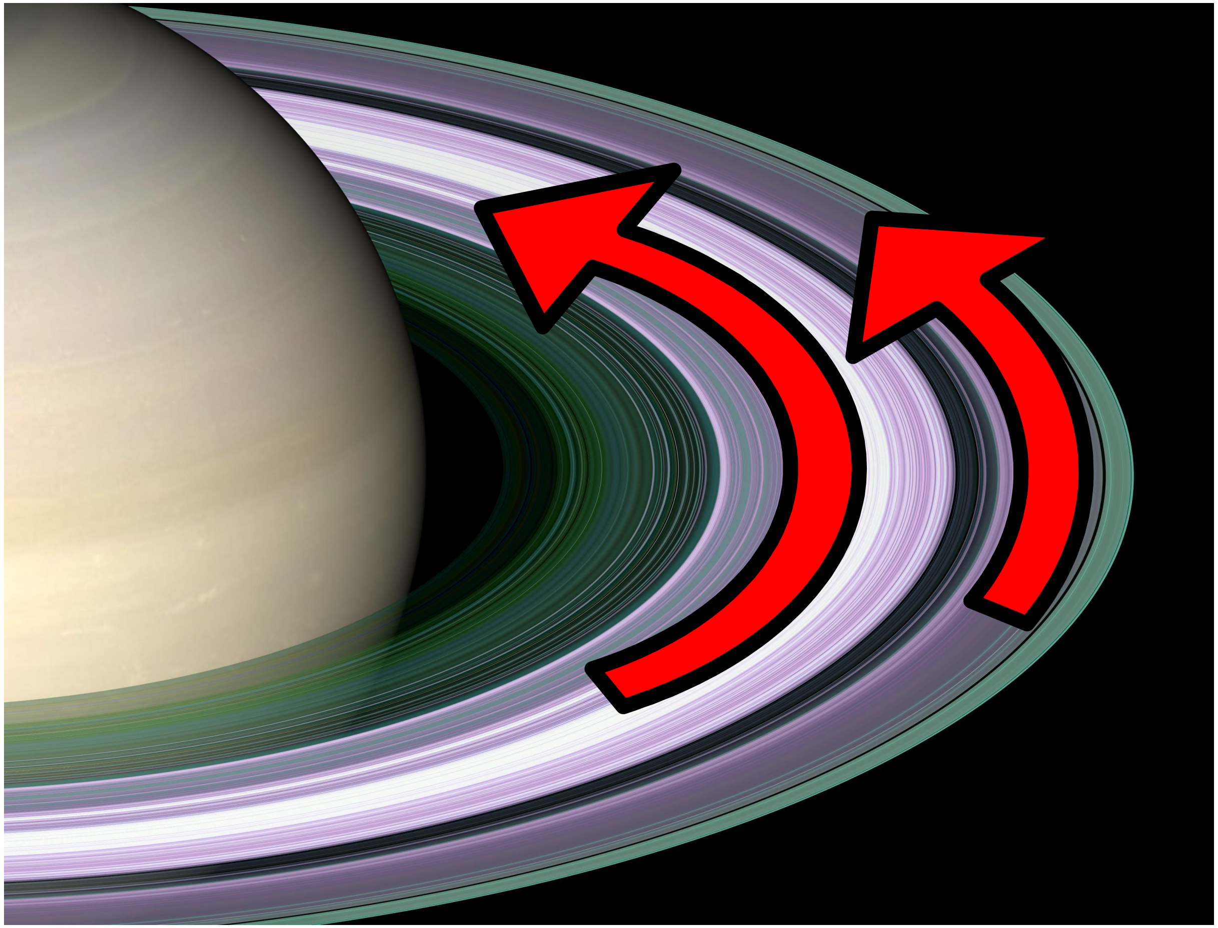
angular velocity : $\Omega=(GM_* \ / \ r^{\,3}\ )^{1/2}$

decreases with r .

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

increases with r !

Rings spreading



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).

Reminder:

Roche radius

Roche Radius

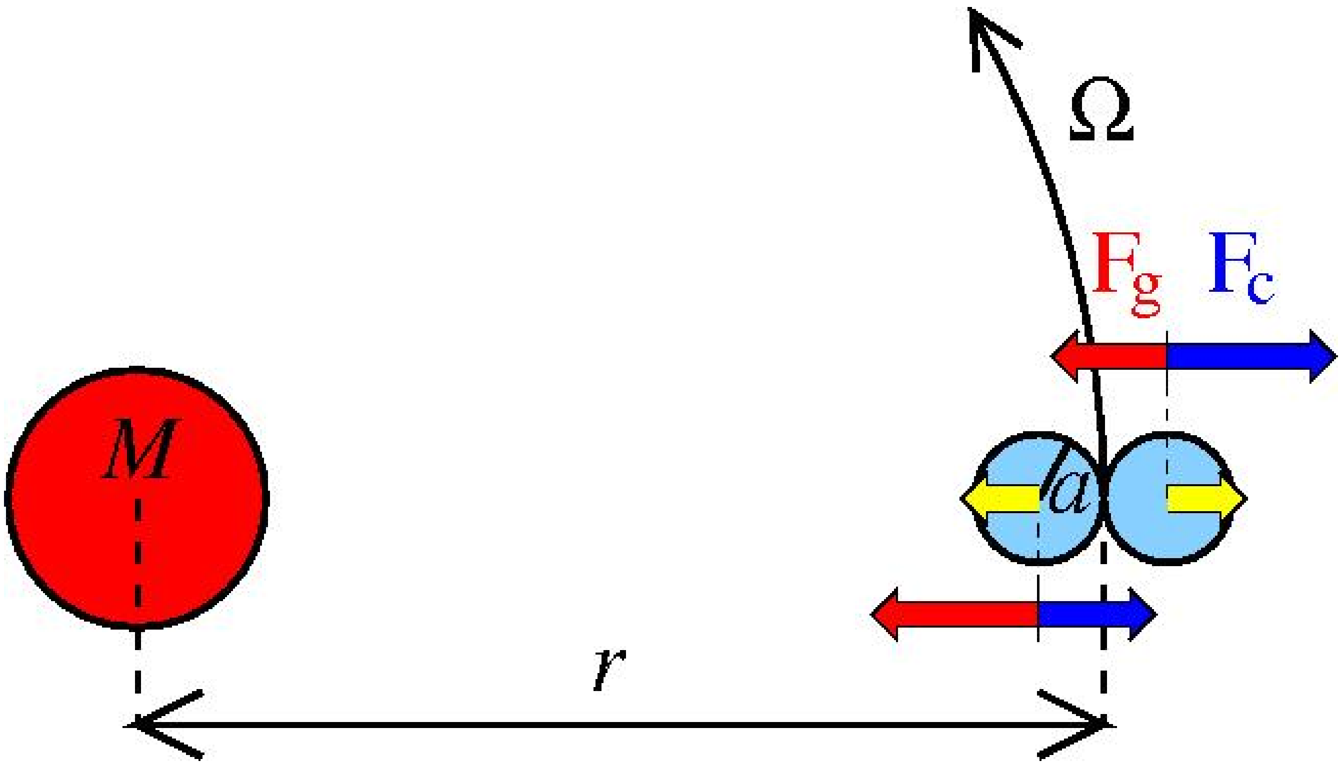
<u>Reminder :</u> Tidal forces (per mass unit) :

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

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

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

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



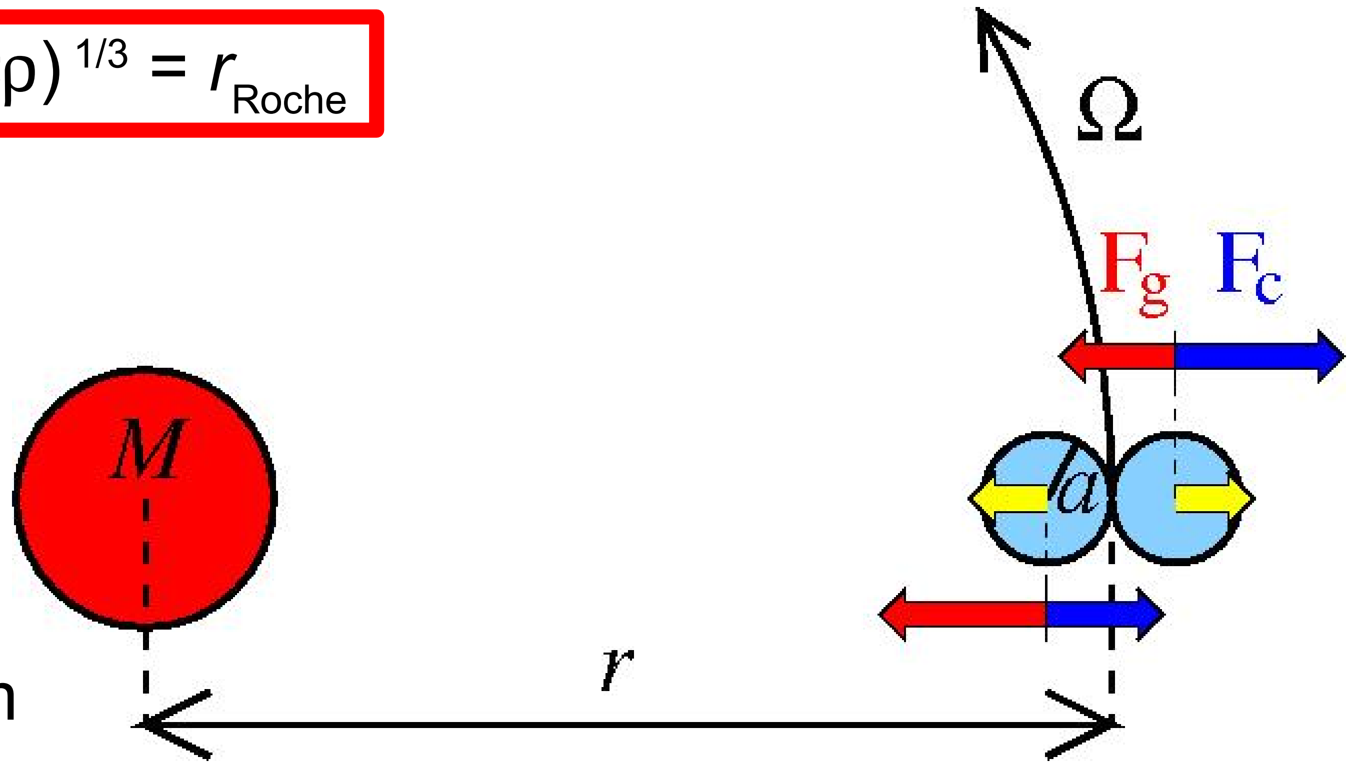
Roche Radius

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



<u>Application:</u>

$M = M_{Saturn}$,

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

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

Roche Radius

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<u>Application:</u>

$M = M_{\mathrm{Saturn}}$,

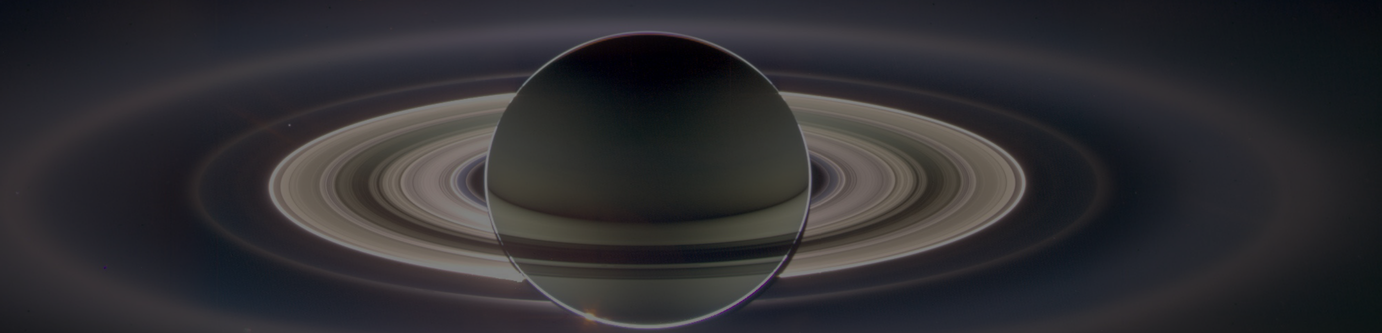
$\rho = 600\ \mathrm{kg.m^{-3}}$

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

This is why Saturn's rings remain rings.

(see movie)

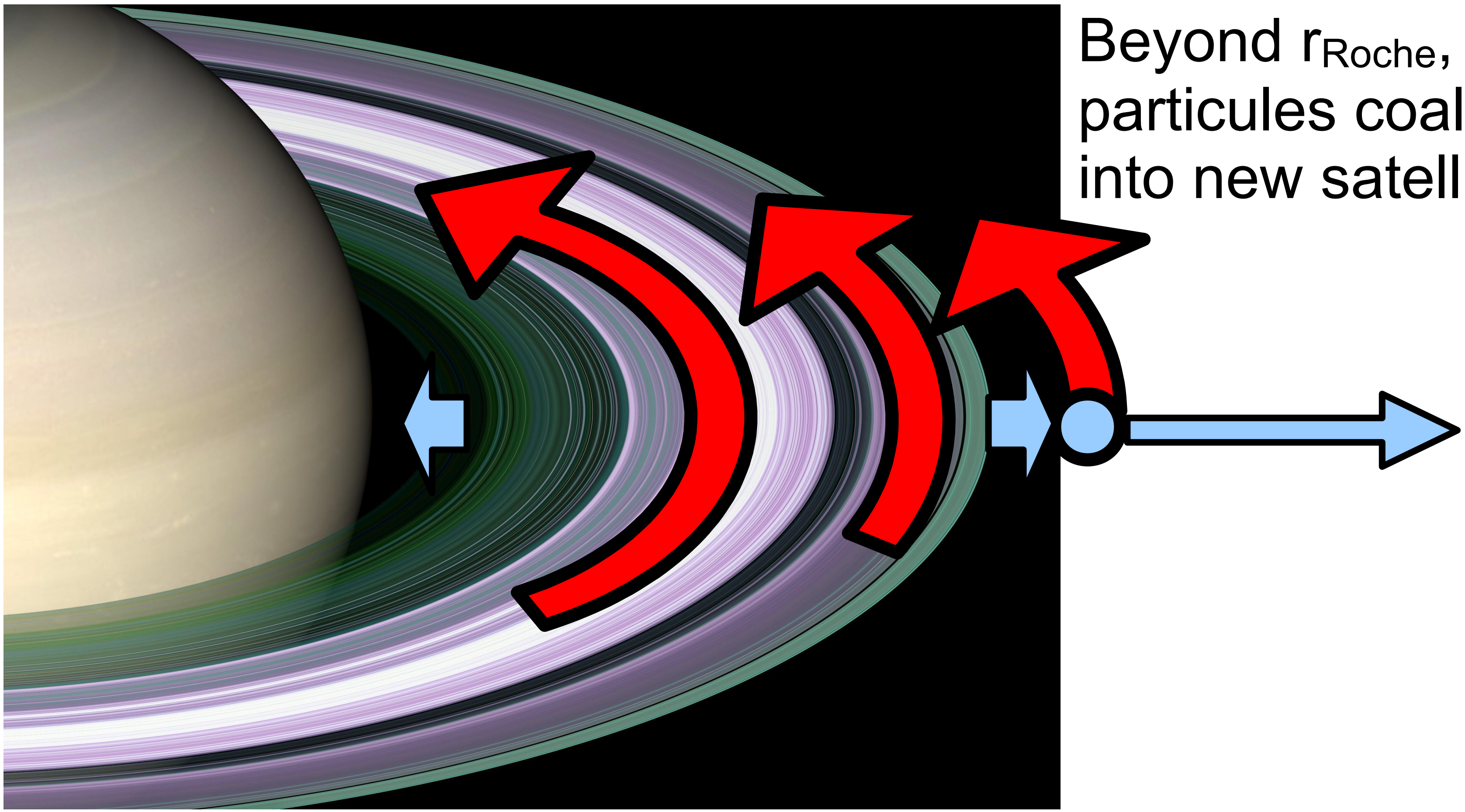
Put things together



1) the rings spread.

2) Beyond the Roche radius, self-gravity wins.

Satellites children of the rings



Beyond r_{Roche}, ring particules coalesce into new satellites !

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

Satellites children of the rings

Total torque : $$\Gamma = \frac{8}{27}\left(\frac{M_{satellite}}{M_{Saturne}}\right)^2 \Sigma\, r^4 \Omega^2 \Delta^{-3} \qquad \text{Eq.(1)}$$

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.

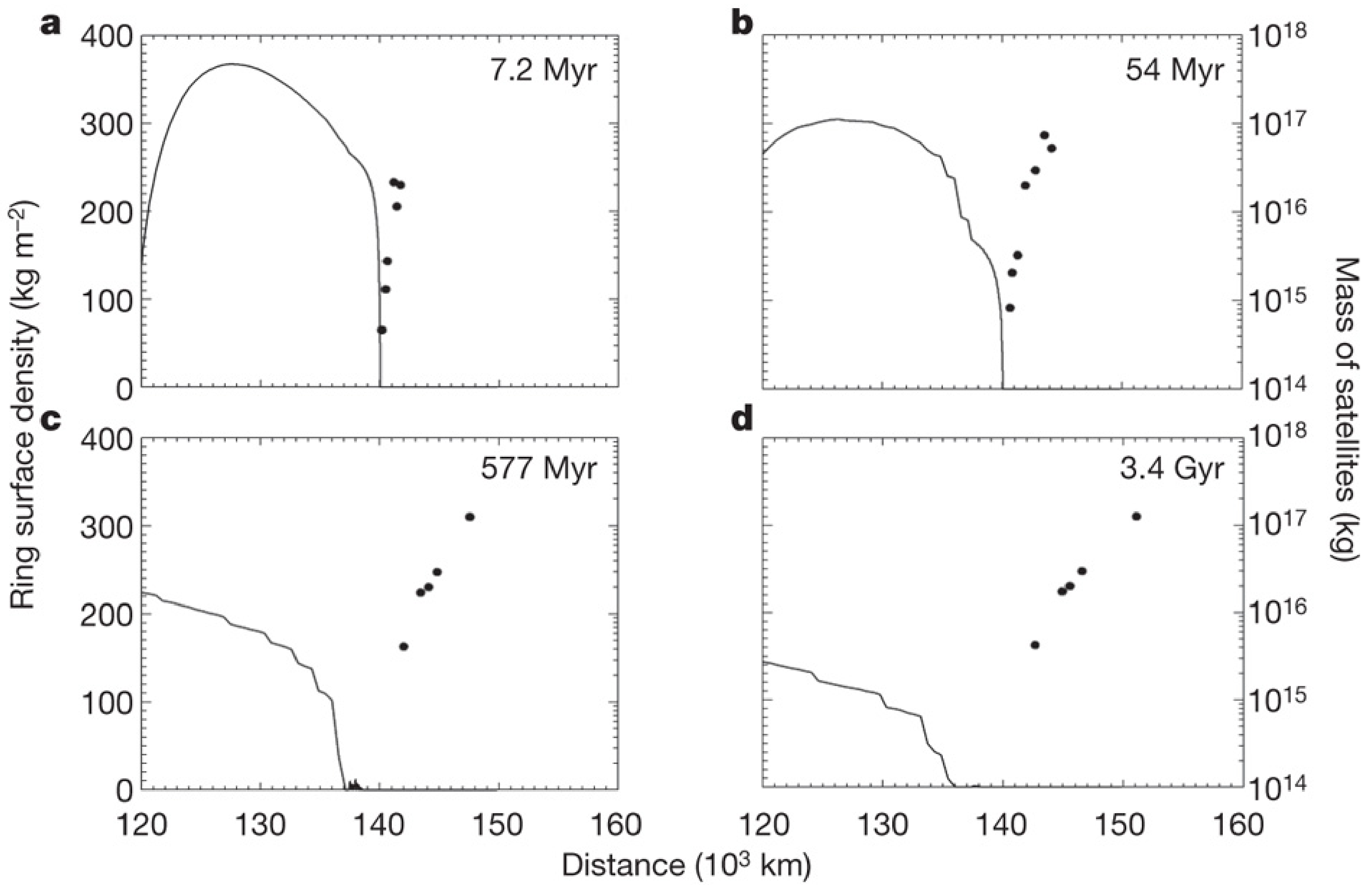
<u>Numerical application :</u>

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

Satellites children of the rings

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

Formation of Prometheus, Pandora, Epimetheus, Janus.

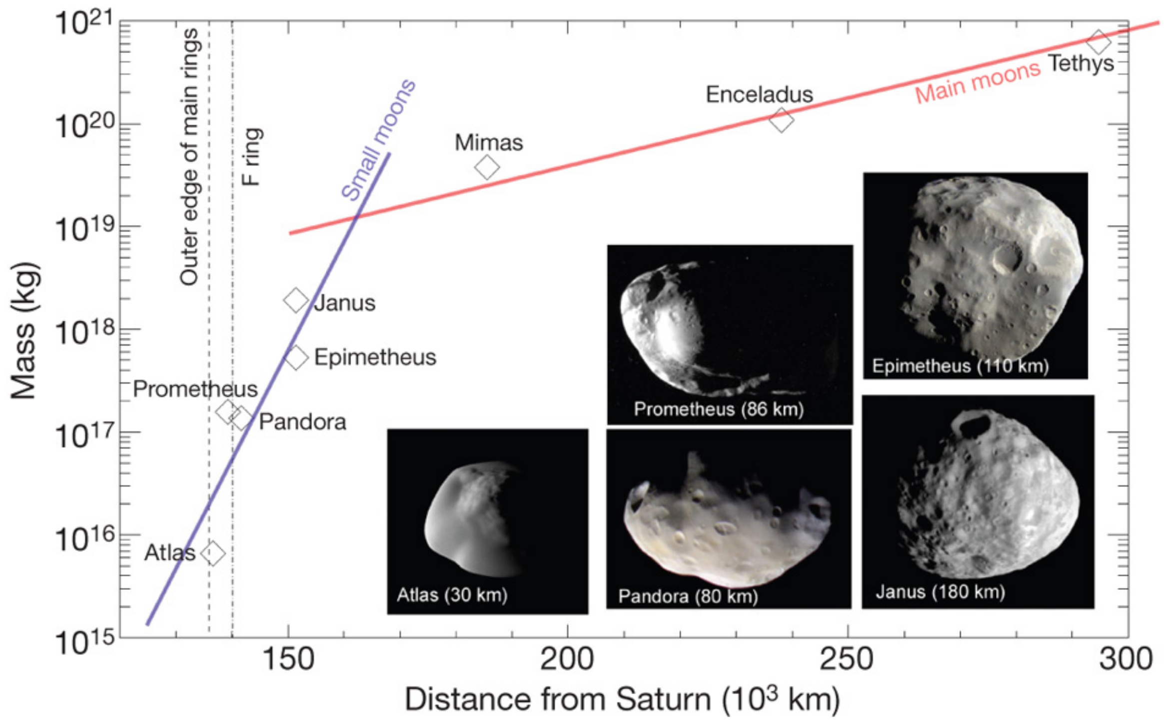


Satellites children of the rings

This explains surprising properties of the small moons :

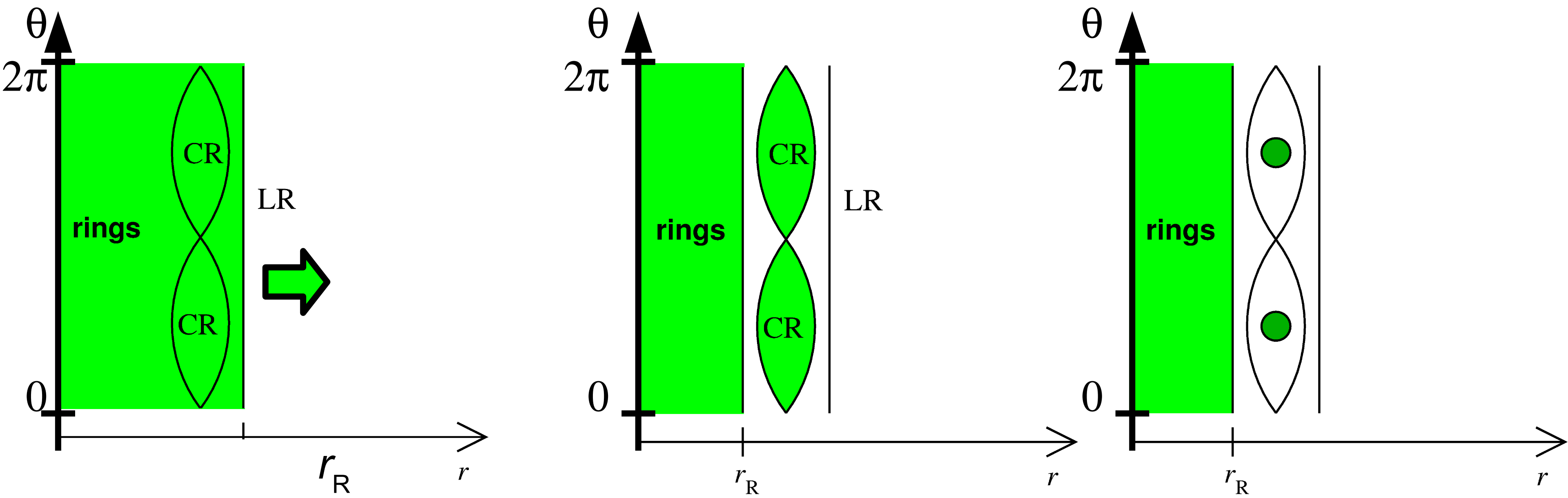
- underdense (~600 $kg.m^{-3}$)
- same spectrum as the rings
- dynamically young
- young surfaces

(Charnoz, Salmon, & Crida, 2010)



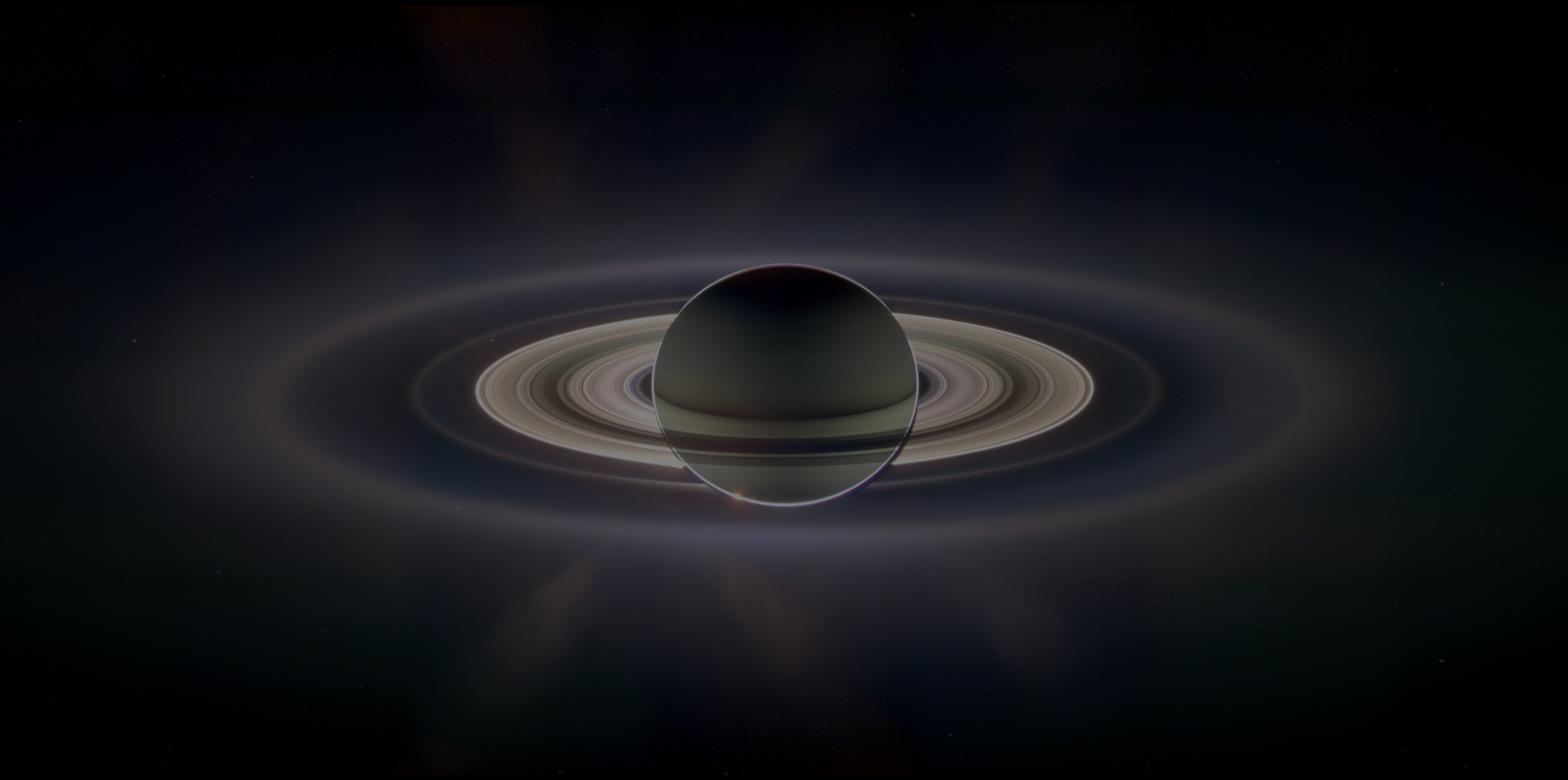
Janus & Epimetheus' horseshoe

Mimas used to confine the rings with its 2:3 Lindblad resonance. When Mimas receded, its 2:3 corotation resonance could have captured ring material and brought it beyond r_{Roche} → 2 bodies on the same orbit = seeds of Janus & Epimetheus ?



Work in progress. (Crida & El Moutamid, *DPS 2016*)

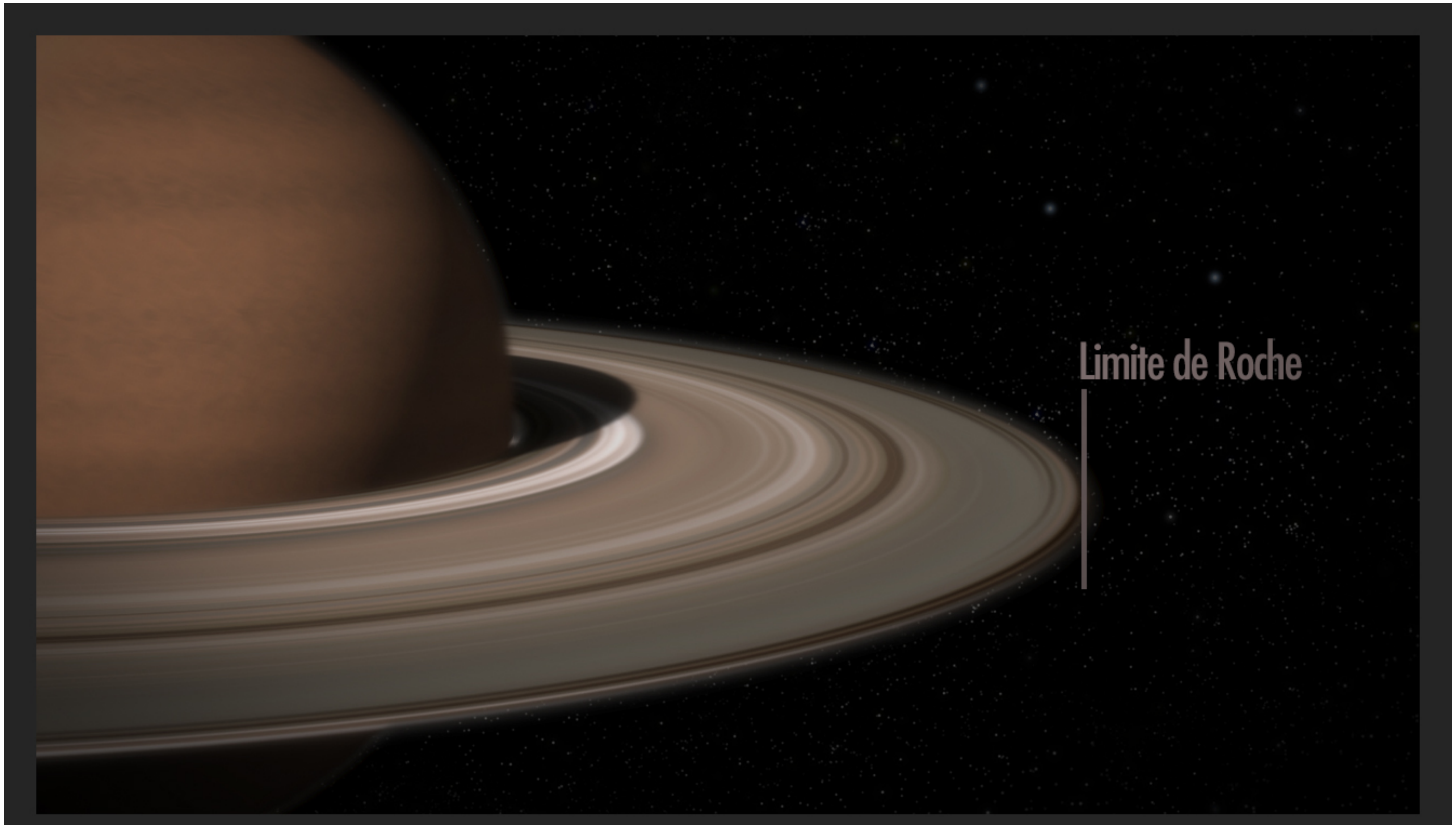
Do the maths



Notations

Be T_R the orbital period at the Roche limit r_R ,
F the flow through r_R, and

$\tau_{disk} = M_{disk} / FT_R$, the normalized life-time of the disk.



Notations

Be **T_R** the orbital period at the Roche limit **r_R** ,
F the flow through r_R, and

τ_{disk} = M_{disk} / FT_R , the normalized life-time of the disk.

The disk spreads with a viscous time $t_\nu = r_R^2/\nu$.

Using Daisaka et al. (2001)'s prescription for ν,
we find $\tau_{disk} = t_\nu / T_R = 0.0425\ D^{-2}$ where **$D = M_{disk}/M_p$** ,

and $F = 23\ D^3\ M_p / T_R$.

Continuous regime

Say 1 satellite forms. Its mass is : $\boxed{M = F\,t}$ (3)

It feels a torque from the disk : $\Gamma = \frac{8}{27}\left(\frac{M}{M_p}\right)^2 \Sigma r^4 \Omega^2 \Delta^{-3}$ (1)

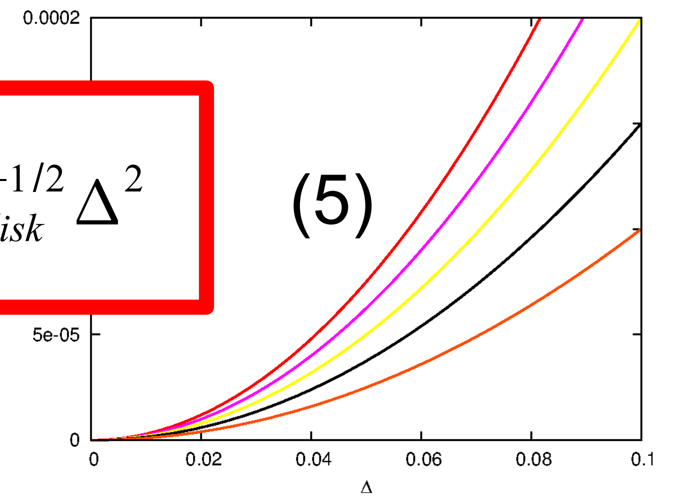
where $\Delta = (r-r_R)/r_R$.

→ Migration rate : $$\boxed{\frac{d\Delta}{dt} = \frac{32}{27} q\, D\, T_R^{-1} \Delta^{-3}} \quad (4)$$

where **q** = M / M_p .

Solution of (3) & (4) : $$\boxed{q = \left(\frac{\sqrt{3}}{2}\right)^3 \tau_{disk}^{-1/2} \Delta^2} \quad (5)$$

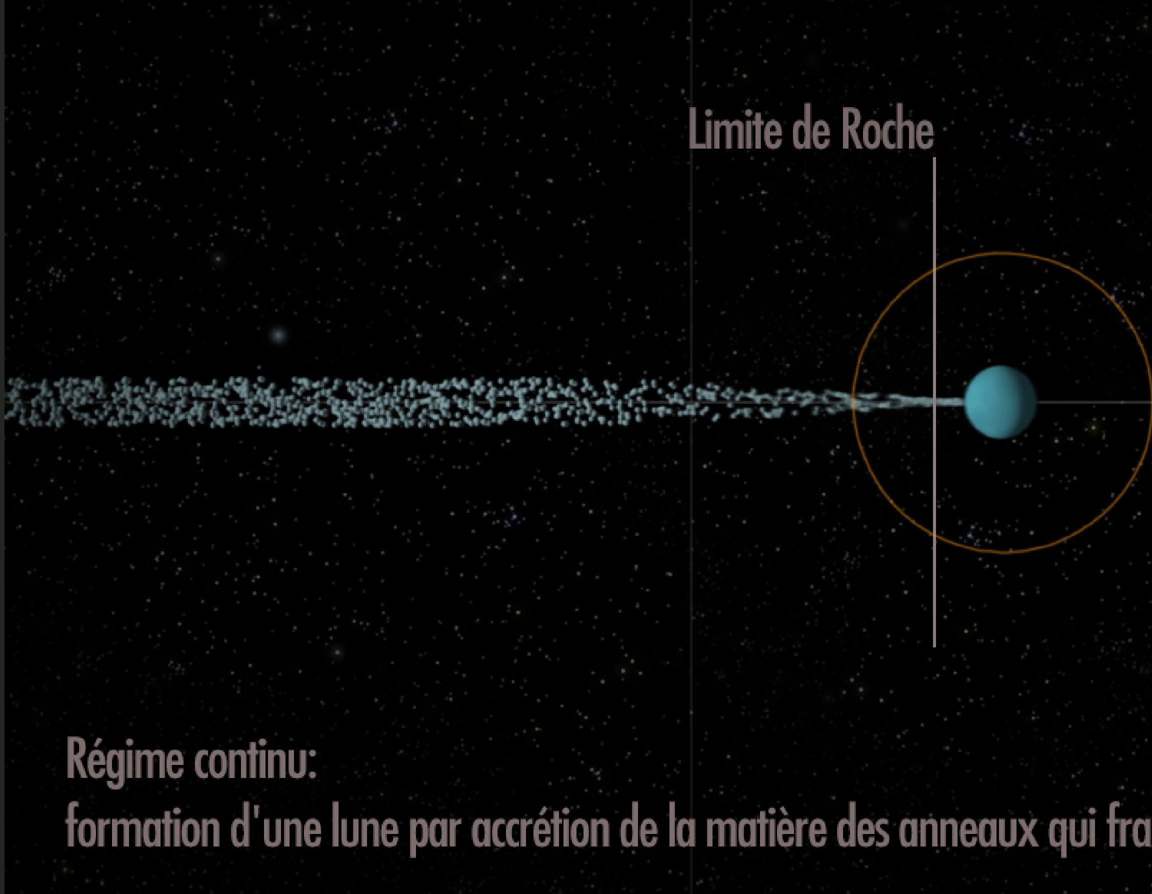
We call this the *continuous regime* .

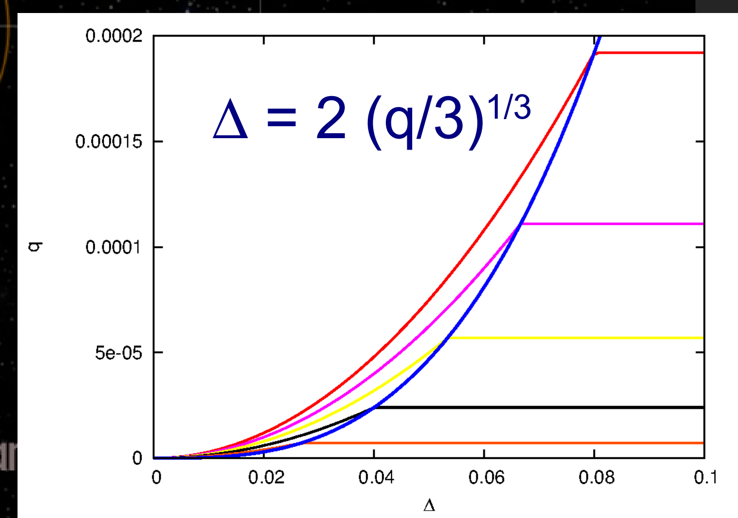


Continuous regime

This holds as long as the satellite captures immediately what comes through r_R.

That is, as long as $(r-r_R) < 2\ r_{Hill}$, or $\Delta < 2\ (q/3)^{1/3}$.





Continuous regime

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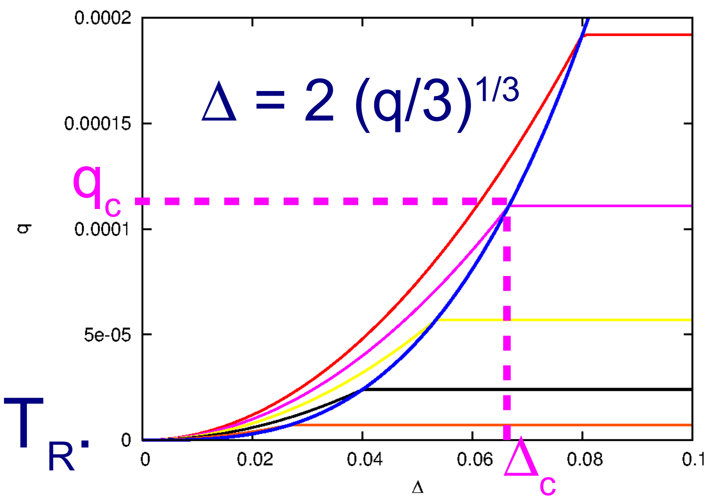
Input into Eq.(5), this gives a condition of validity for the continuous regime :

$$\boxed{\begin{aligned} \Delta < \Delta_c &= \sqrt{\frac{3}{\tau_{disk}}} = \sim 8.4\ D \\ q < q_c &= \frac{3^{5/2}}{2^3}\,\tau_{disk}^{-3/2} = \sim 222\ D^3 \end{aligned}}$$



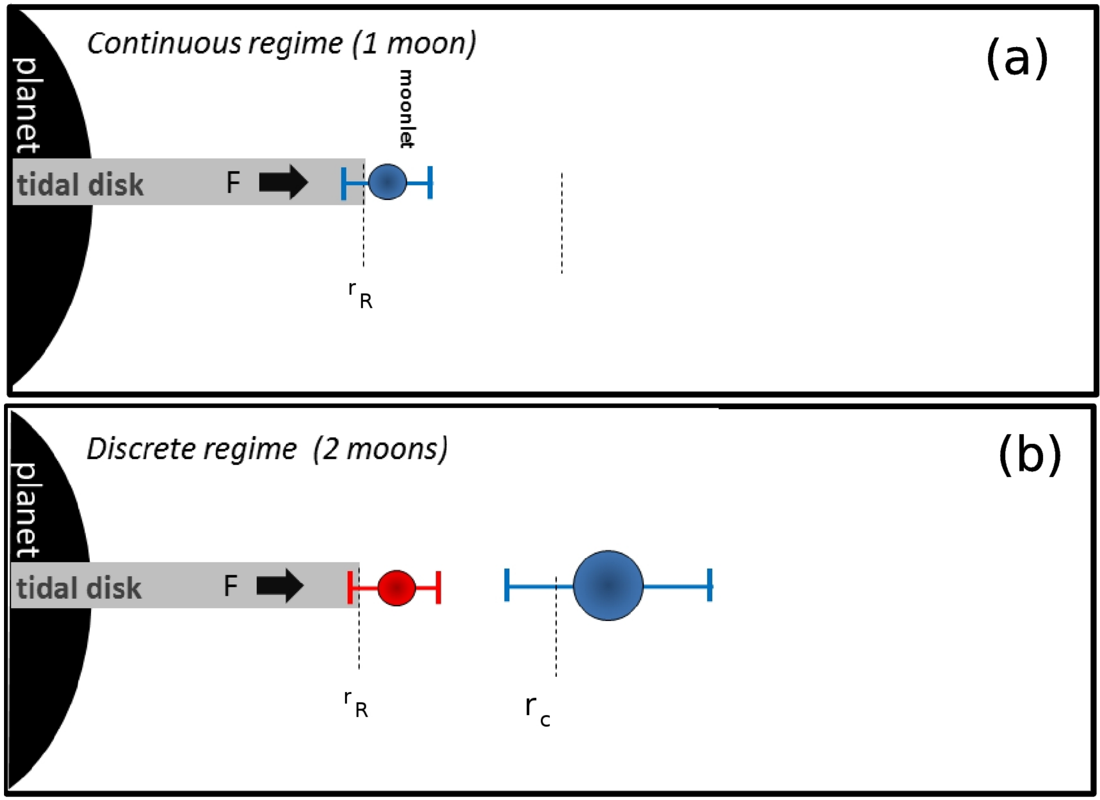
Duration of the continuous regime: 10 T_R.

Discrete regime

When the satellite is beyond Δ_c (or q_c), the material flowing through r_R forms a new satellite at r_R.

This new satellite is immediately accreted by the first one.

And so on...



The first satellite still grows as M=Ft, but by steps : *discrete regime*.

Discrete regime

This holds as long as $\Delta < \Delta_c + 2(q/3)^{1/3}$.

It gives the condition :

$$\boxed{\begin{array}{ll} \Delta < \Delta_d = 3.14\,\Delta_c & = \sim 26\ D \\ q < q_d = 9.9\,q_c & = \sim 2200\ D^3 \end{array}}$$

The duration of the discrete regime is ~100 T_R .

<u>Application :</u>

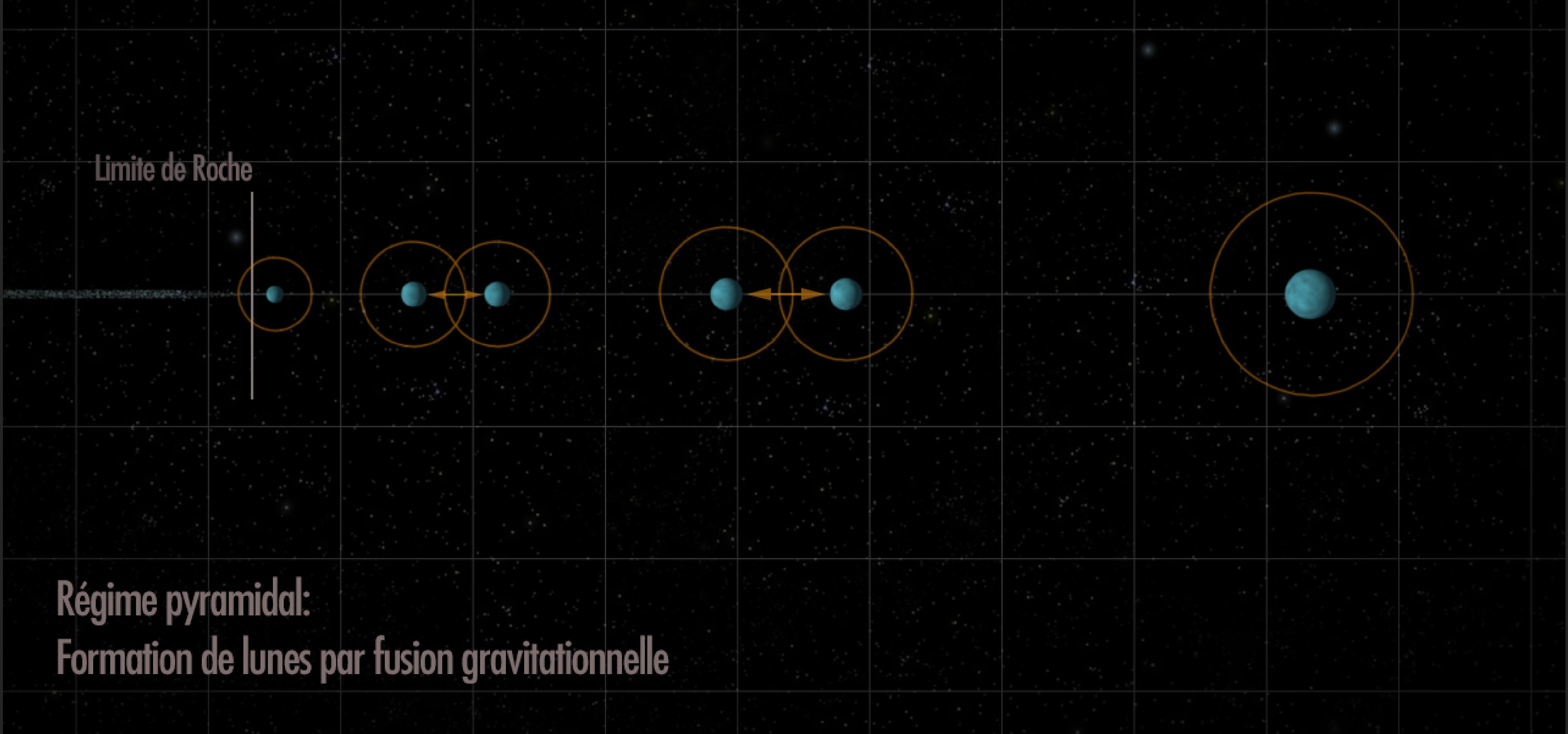
Saturn's rings : $q_d = \sim 10^{-18}$.

→ Only tiny things form. Then what ?

Pyramidal regime

Satellites of mass q_d are produced at Δ_d every q_d / F .

Then, many satellites of constant mass migrate outwards, at decreasing rates. They approach each other, and merge.



Pyramidal regime

Satellites of mass q_d are produced at Δ_d every q_d / F .

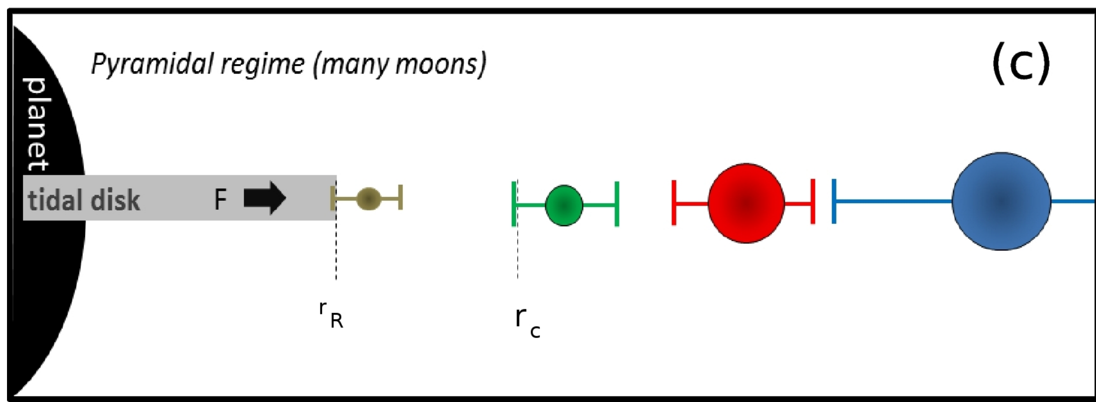
Then, many satellites of constant mass migrate outwards, at decreasing rates. They approach each other.

If their distance decreases below 2 mutual Hill radii, they merge.

=> Formation of satellites of masses $2q_d$, every $2\, q_d / F$, which migrate away and merge further...

And so on, hierachicaly...

We call this *the pyramidal regime*.



Pyramidal regime

- Using Eq.(4), we show that in the pyramidal regime, while the mass is doubled, Δ is multiplied by $2^{5/9}$.

Thus, $\boxed{q \propto \Delta^{9/5}}$.

In addition, the number density of satellites should be proportionnal to $1/\Delta$, explaining the pile-up.

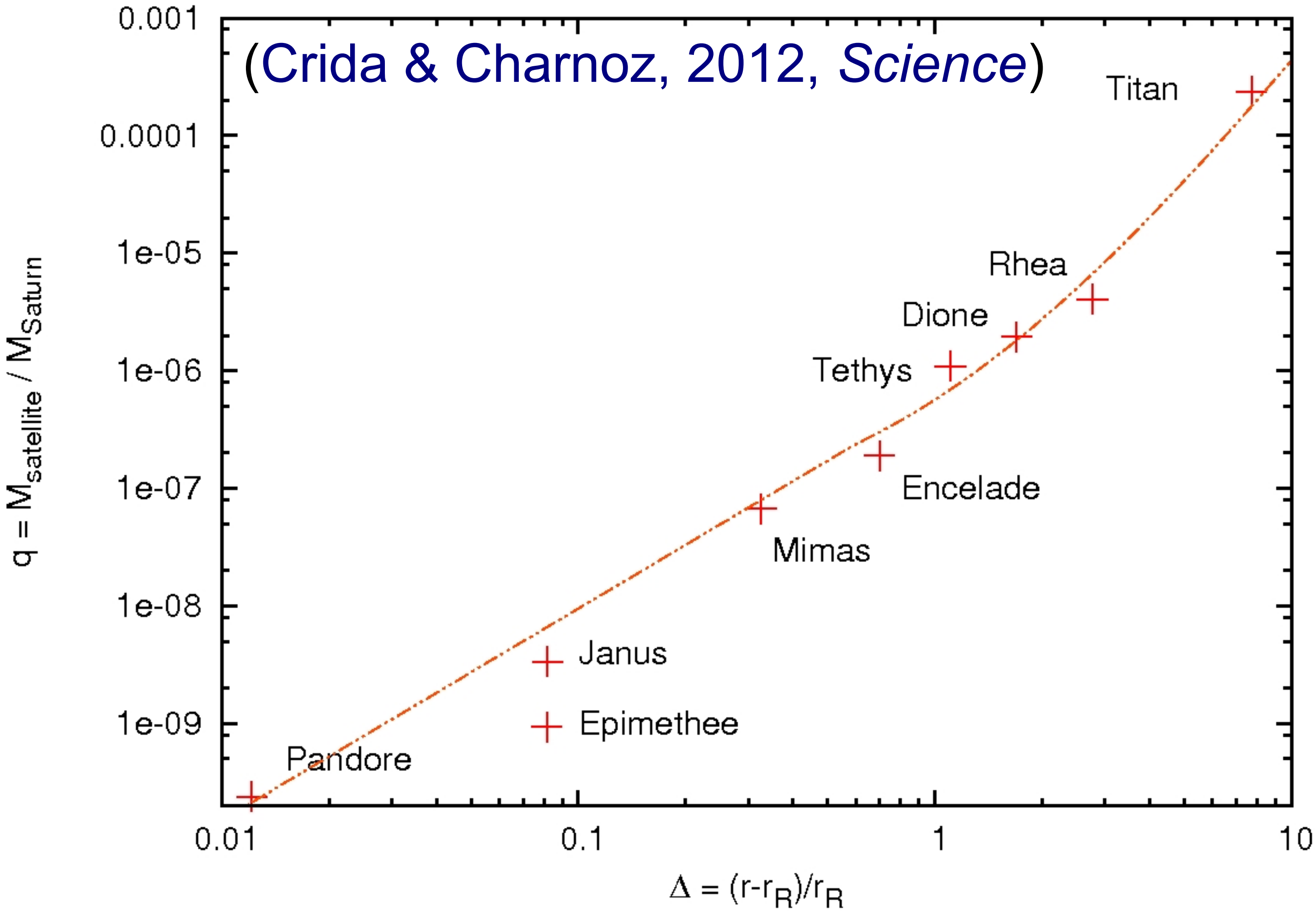
- Beyond the 2:1 Lindblad resonance with r_R (Δ=0.58), Eq.(4) doesn't apply. Migration is driven by planetary tides:

$$\frac{dr}{dt} = \frac{3\, k_{2p} M \sqrt{G}\, R_p^5}{Q_p \sqrt{M_p}\, r^{11/2}} \qquad (2)$$

Using Eq.(2), we find $\boxed{q \propto r^{3.9}}$.

Pyramidal regime

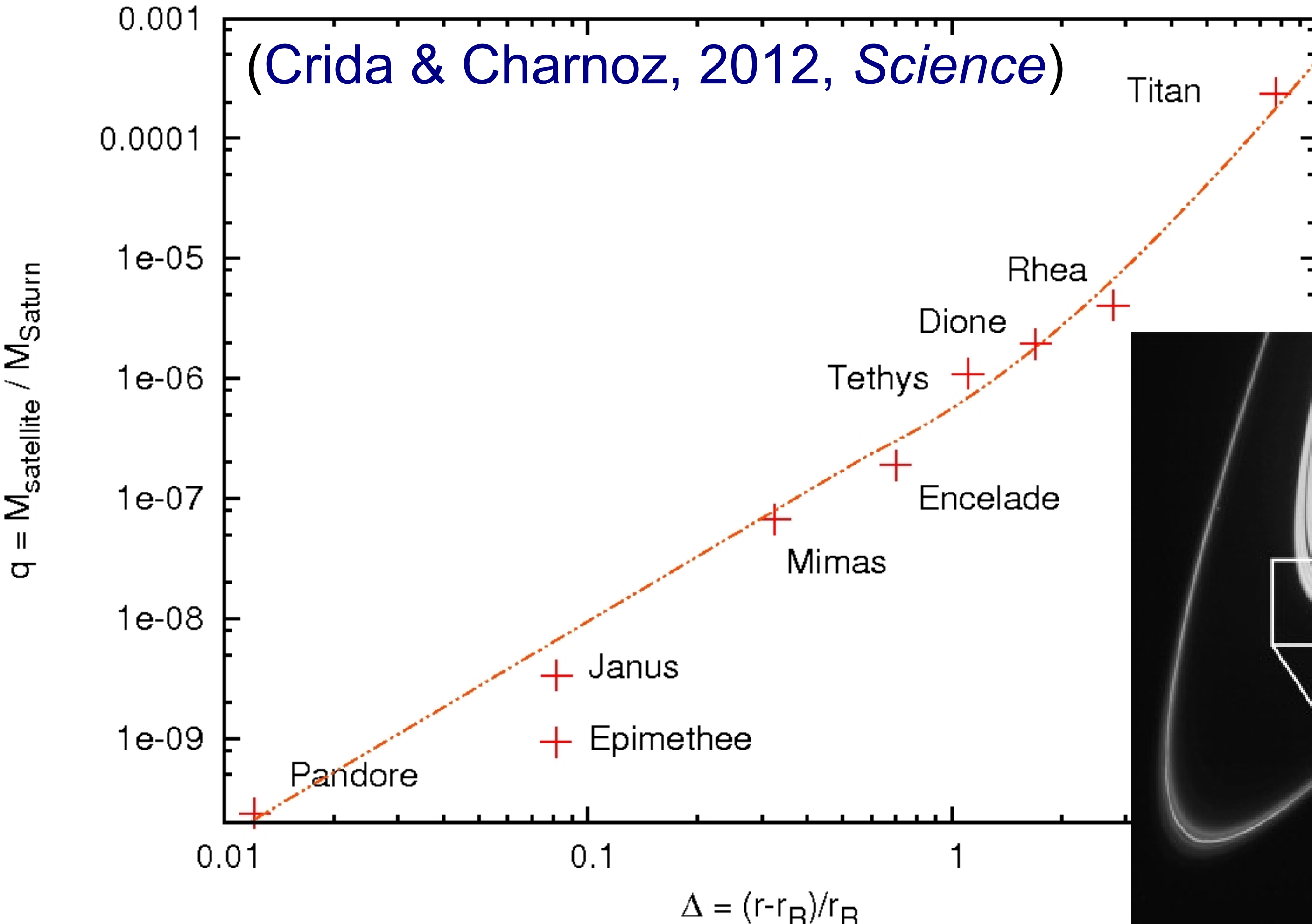
The result spectacularly matches the distribution of the Saturnian system !



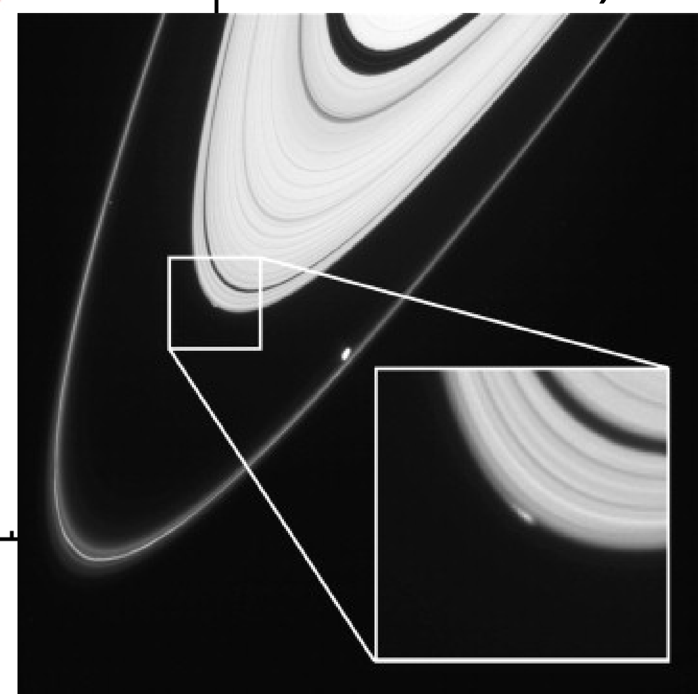
Note : the + symbols are **not** errorbars. Masses and positions are precisely nown.

Pyramidal regime

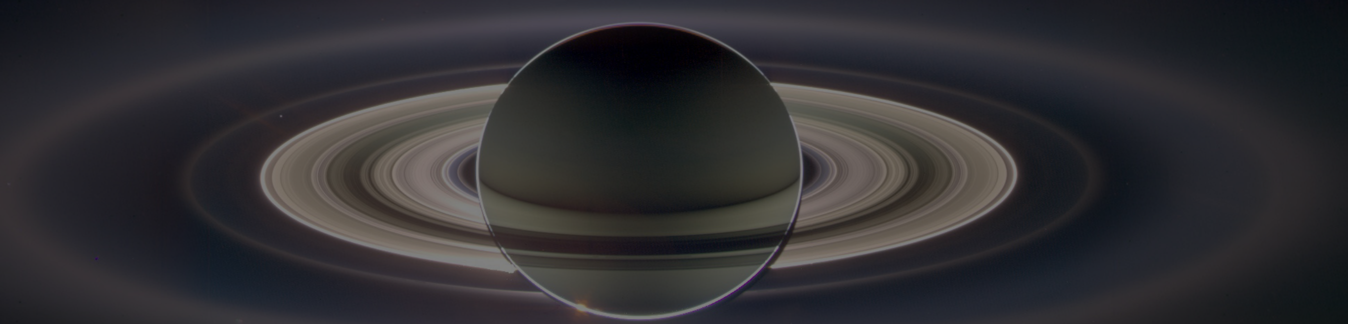
The result spectacularly matches the distribution of the Saturnian system !



An other observation ? (Murray et al. 2014) :



Can this be true ?



1) Was there enough mass in the rings ?

2) Was there enough time ?

Rings evolution: a first clue

Be T_R the orbital period at the Roche limit r_R , $\bar{t} = t / T_R$,

τ_{disk} the normalized life-time of the disk = M_{disk} / $(dM_{disk}/d\bar{t}\,)$.

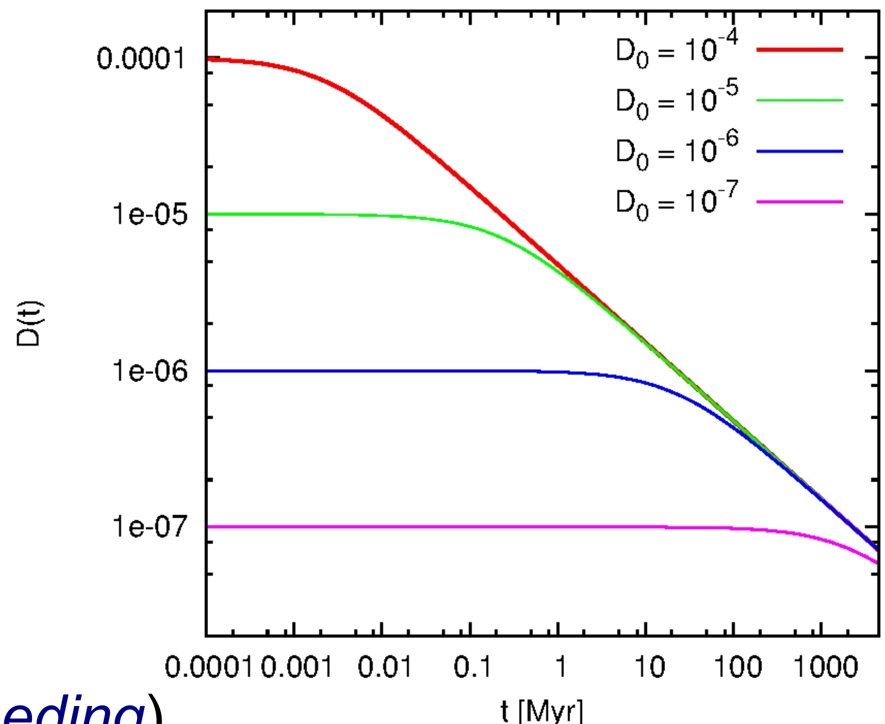
Using Daisaka et al. (2001)'s prescription for ν,
we find $\tau_{disk} = t_\nu / T_R = 0.0425\ D^{-2}$ where $D=M_{disk}/M_p$.

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

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

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 $\rightarrow$ D < $\sim 10^{-7}$.
Now, D = 8×10^{-8}...



(Crida & Charnoz 2014, *IAU proceeding*)

Rings evolution: simulations

Implicit 1D code solving :
(mass + momentum conservation)

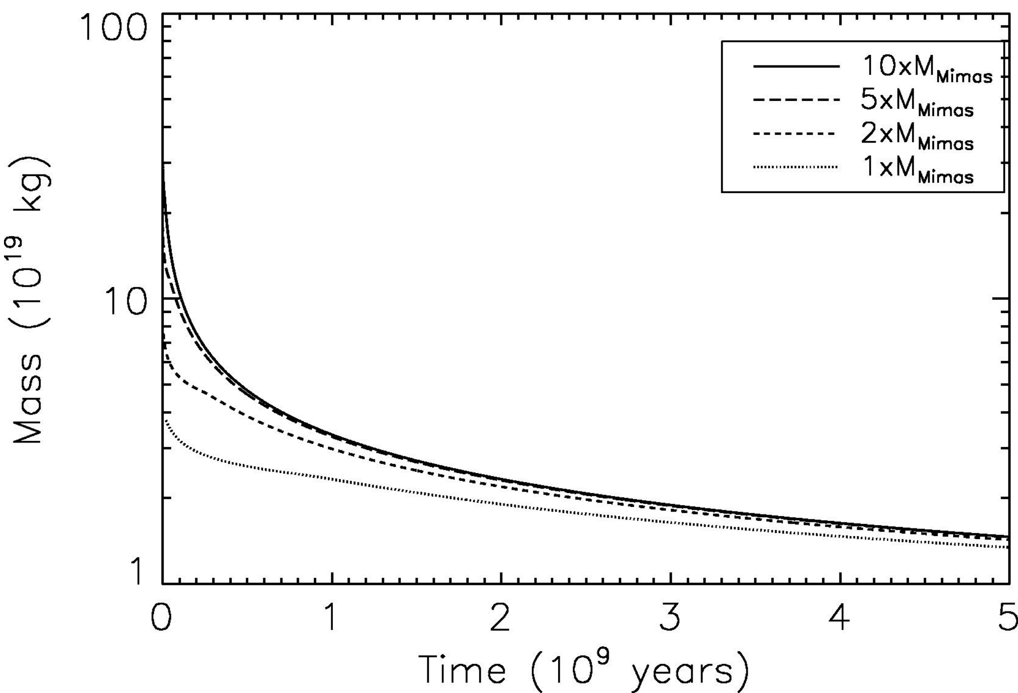
$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[\sqrt{r}\frac{\partial}{\partial r}\left(\nu \Sigma \sqrt{r}\right)\right]$$

With Daisaka et al (2001)'s viscosity $\nu(\Sigma)$,
the less massive the rings are, the slower they spread

→ with their present mass, they can survive for Gyrs.

→ they could have been more massive in the past: whatever their initial mass, they should have ~present mass after ~4.5 Gyrs.

(Salmon, Charnoz, Crida, & Brahic, 2010, *Icarus*)

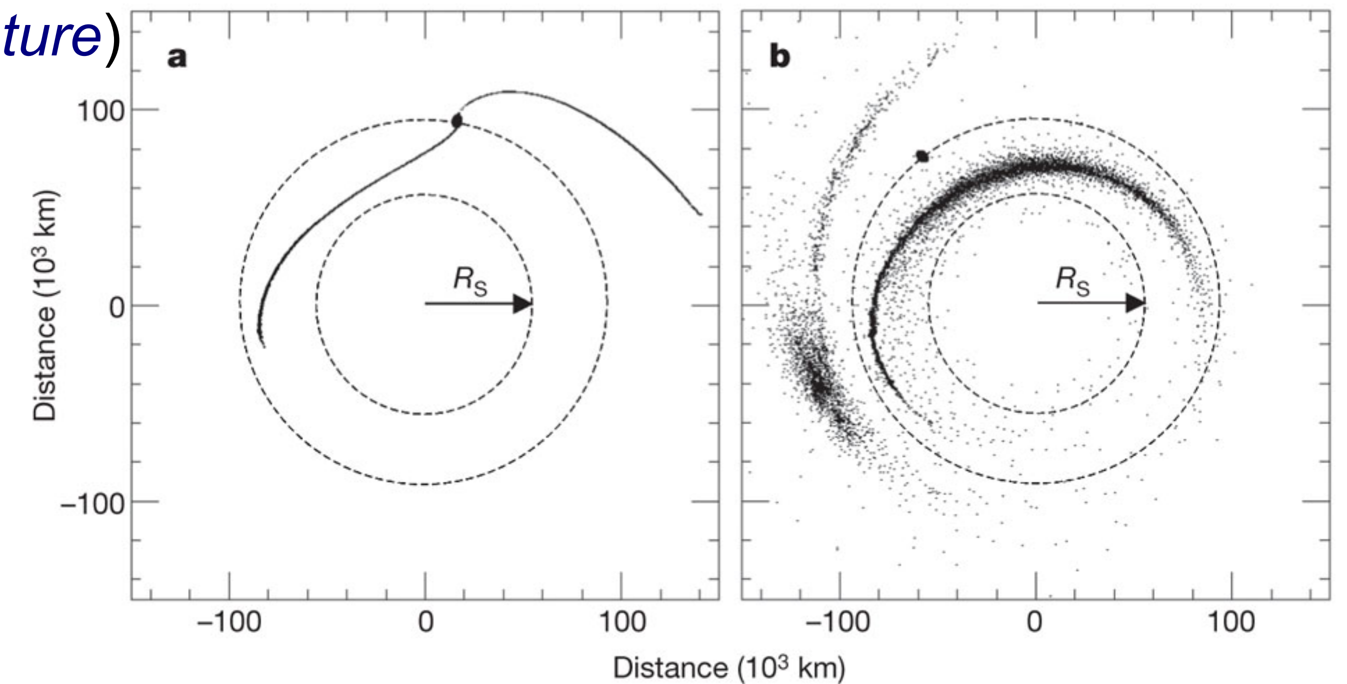


Origin of Saturn's rings

If a satellite forms in the circum planetary disk around Saturn, it migrates inwards, and can be lost (Canup & Ward 2002, 2006).

If differenciated, its icy mantle is pealed off by tidal forces inside the Roche limit, while the denser silicate core keeps migrating and falls inside Saturn.

(Canup, 2010, *Nature*)



Origin of Saturn's rings

Key points of Canup (2010)'s model :

- **differenciated** satellite => pure water ice

- **migration** =>
  progressive pealing off
  + get rid of the core

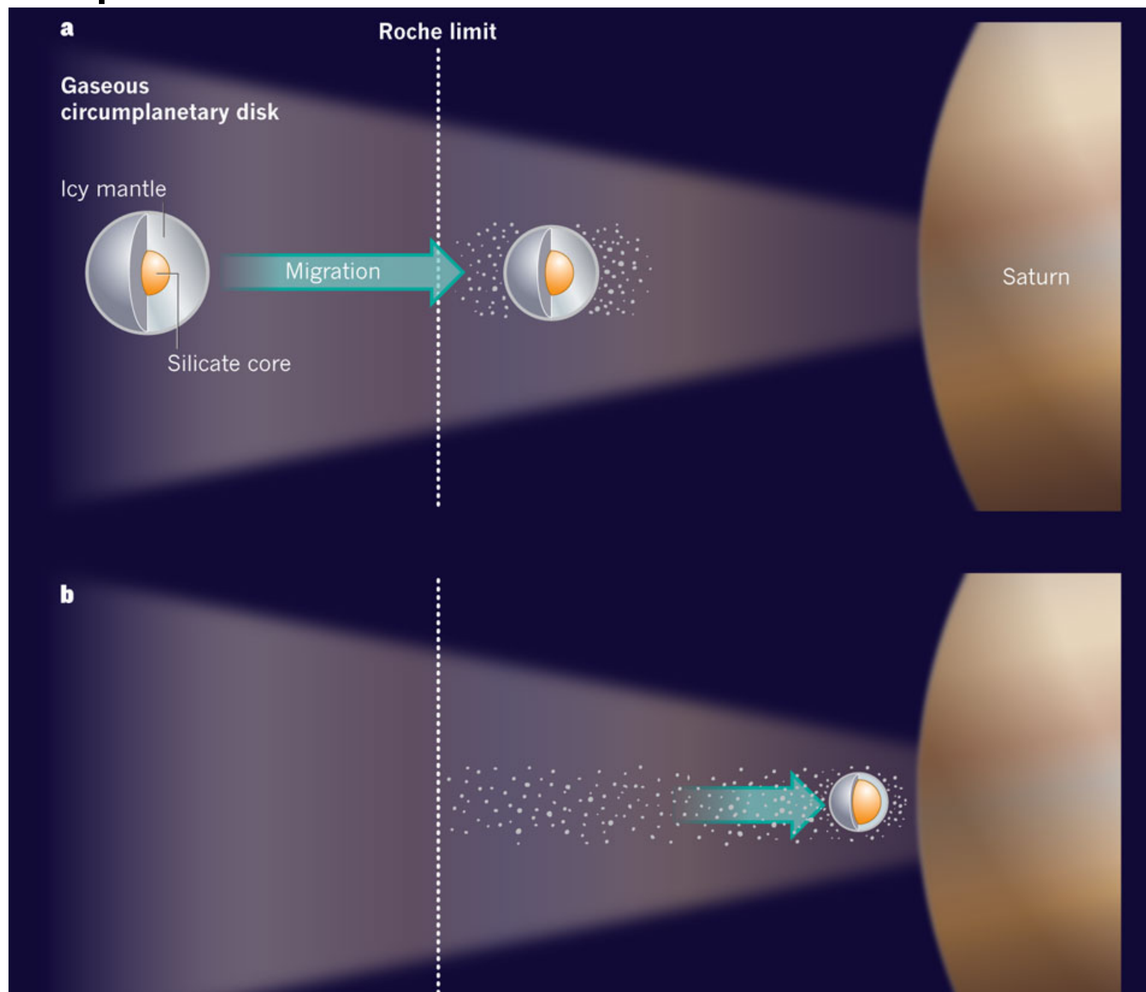
- **last** big satellite lost =>
  the debris stay there.

In the end :

- a **v** **ive** ring
(~T

- t **ago**.

- n between
the n itan.



Crida & Charnoz (2010, *News&Views*)

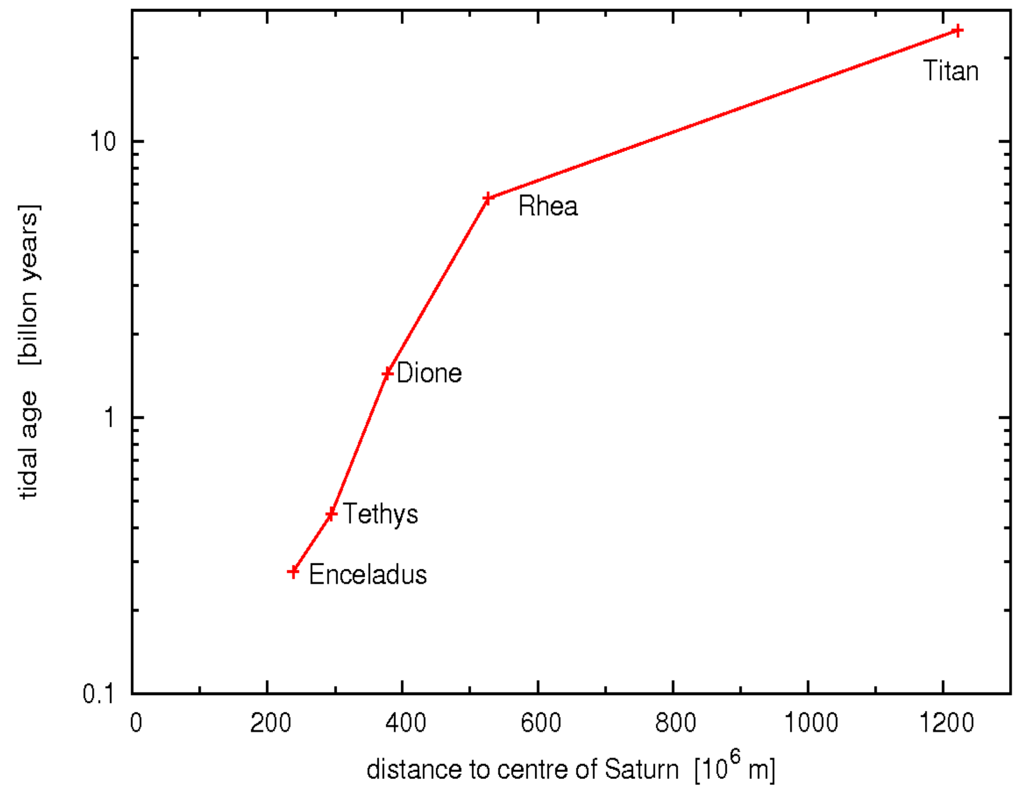
Timing: are tides efficient ?

Using this equation : $$\frac{dr}{dt} = \frac{3\,k_{2p} M_{satellite} \sqrt{G}\, R^5_{Saturne}}{Q_{Saturne} \sqrt{M_{Saturne}}\, r^{11/2}}$$ Eq.(2)

one finds the « **tidal age** » : how long it takes to bring the satellites at their present position from 222 000 km, where interactions with the rings vanish.

Standard Q_{Saturn}=18 000,
→ negligible migration.

With Q_{Saturn} = 1700
(Lainey *et al*. 2012, 2016, based on observations)
even Rhea is younger than the Solar System !



Other good aspects

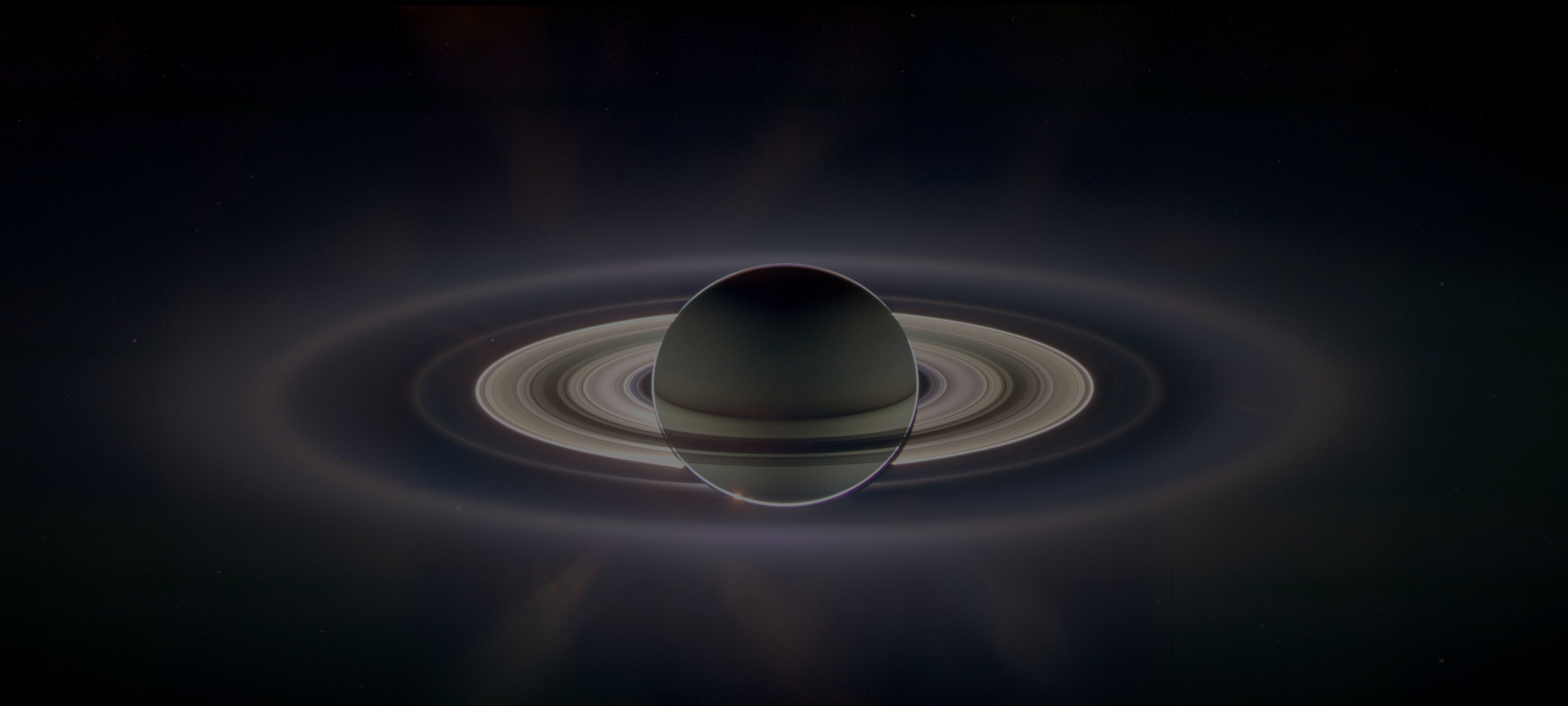
✔ Ages are ranked by distance : the further, the older.
→ formation of one after the other, in logical order.

✔ 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, *Icarus*)

It's not over yet !



What about the other planets ?

Discrete regime: our Moon

This holds as long as $\Delta < \Delta_c + 2(q/3)^{1/3}$.

It gives the condition :

$$\Delta < \Delta_d = 3.14\,\Delta_c \quad = \sim 26\ D$$

$$q < q_d = 9.9\,q_c \quad = \sim 2200\ D^3$$

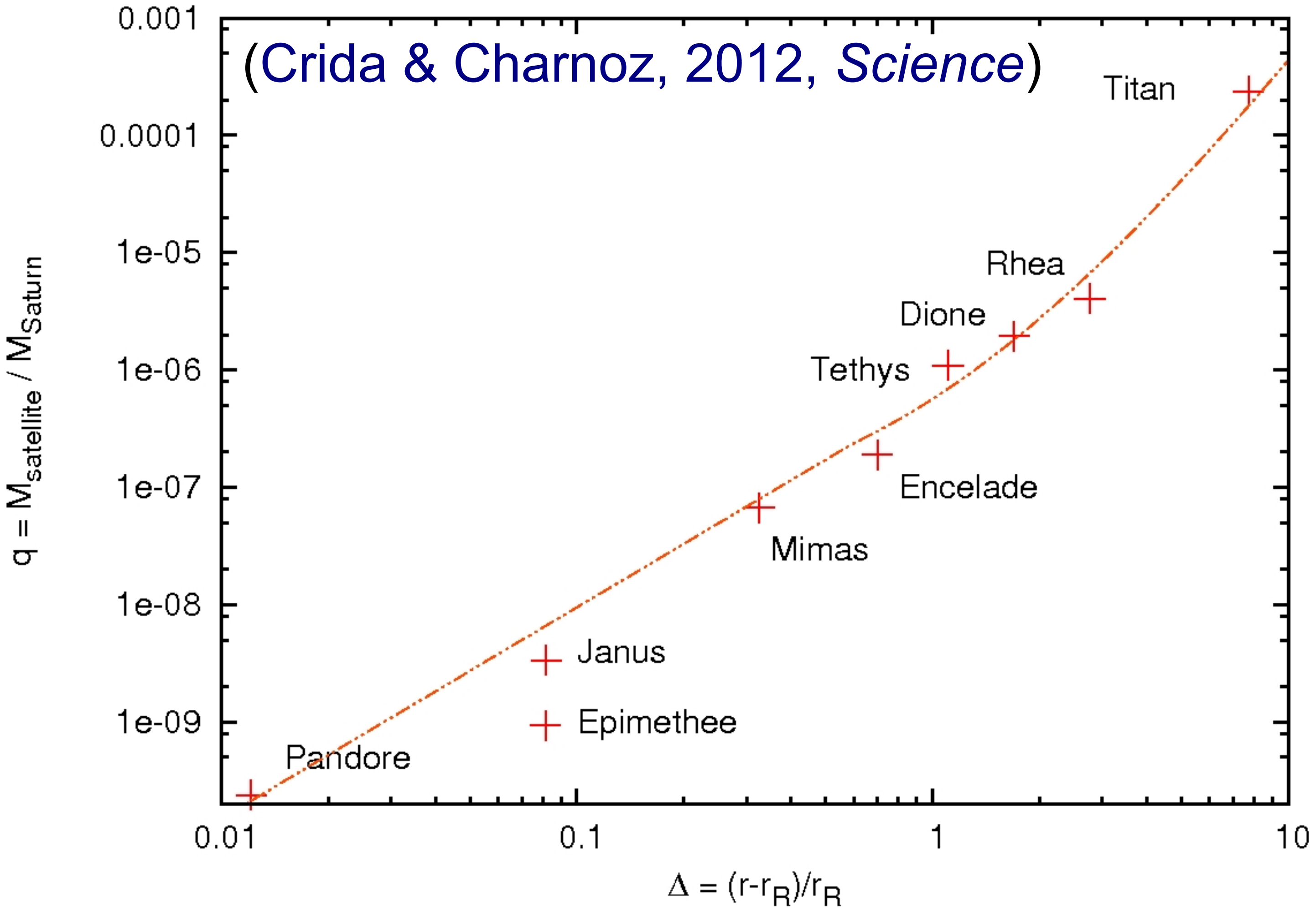
Gooooaaaaal !

<u>Application :</u>

Earth's Moon forming disk :
q_d = mass of the Moon !
→ Only 1 satellite formed, in ~1 month.

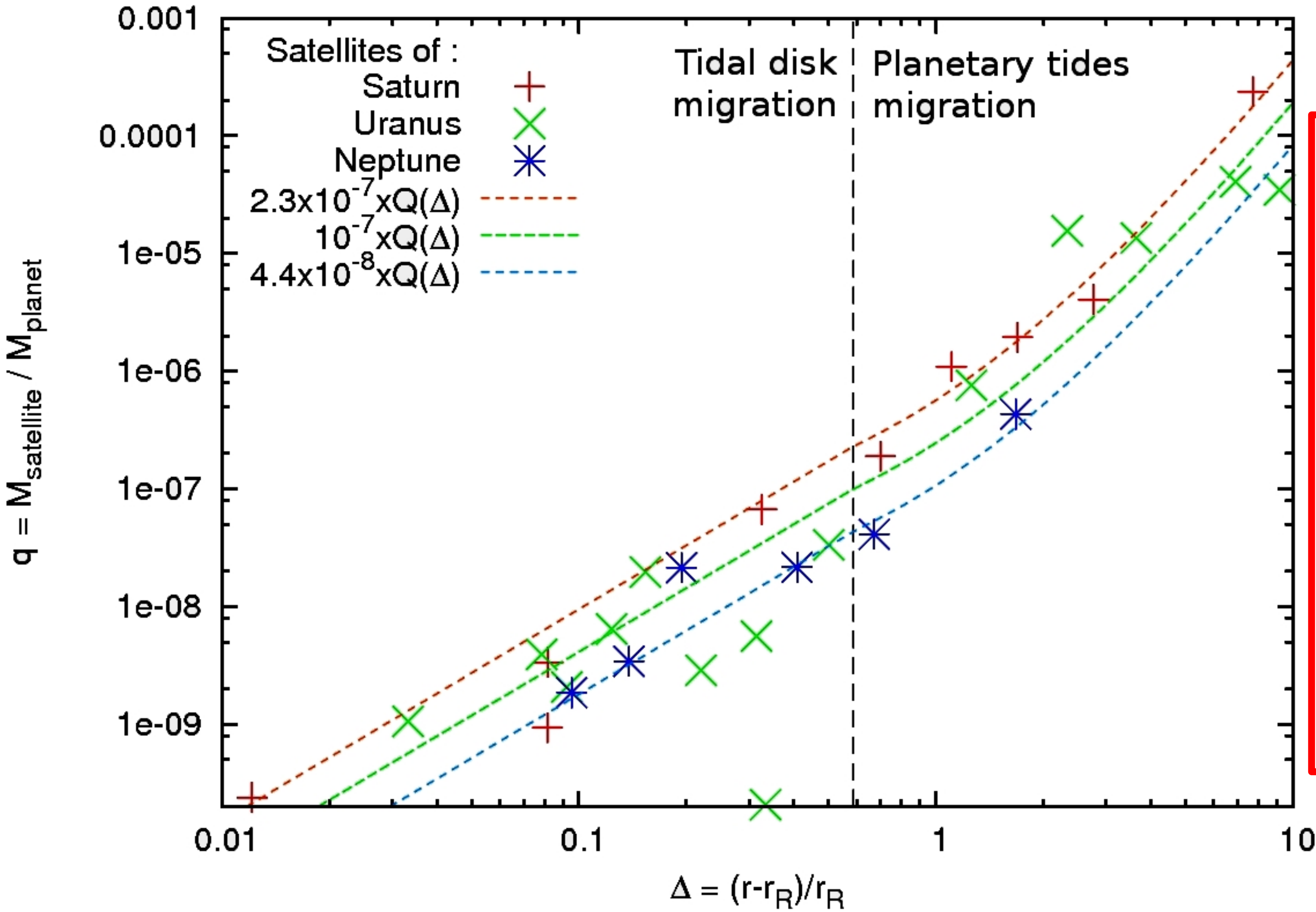
Pyramidal regime

The result spectacularly matches the distribution of the Saturnian system !



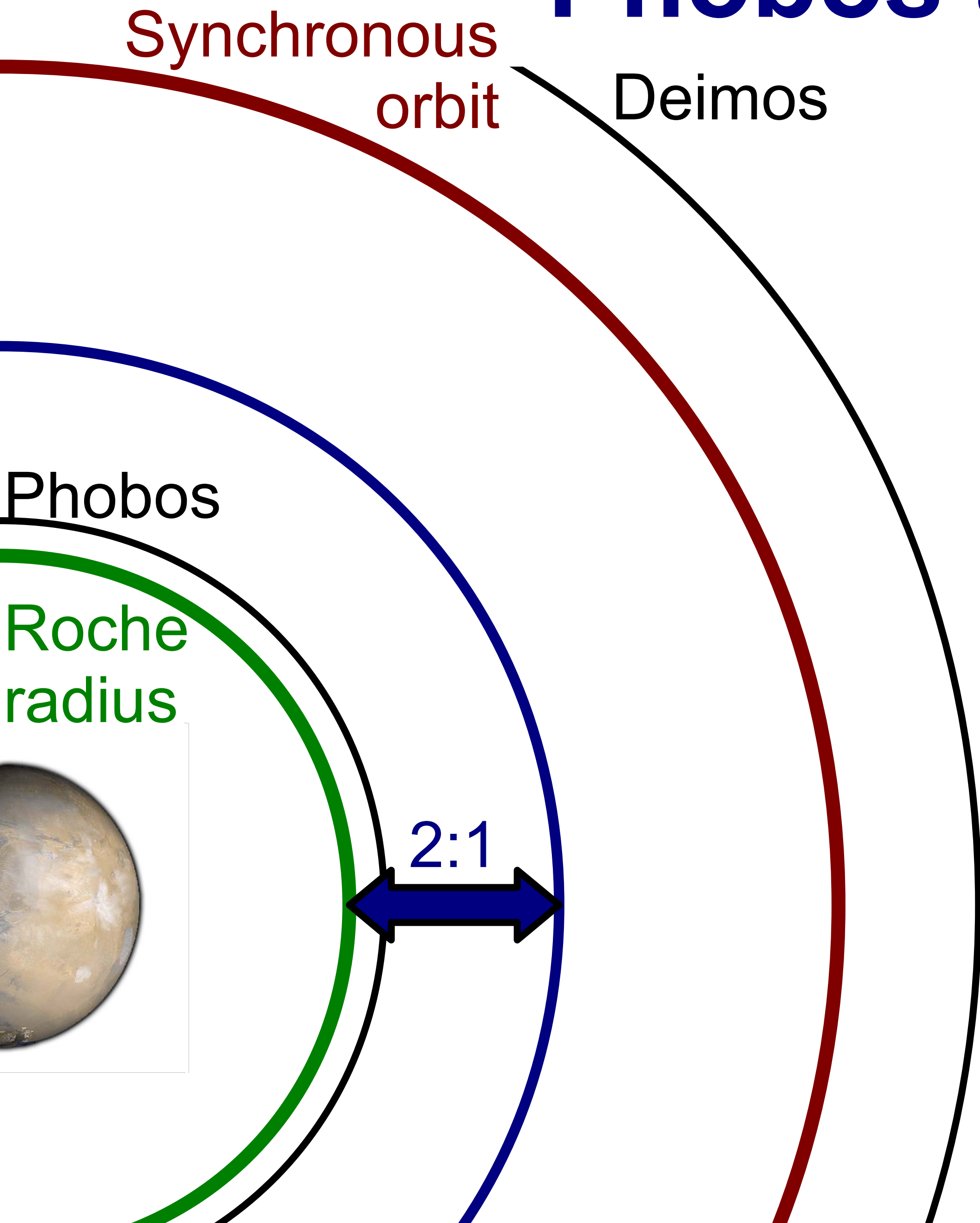
Pyramidal regime

The result spectacularly matches the distribution of the Saturnian, Uranian, and Neptunian systems !



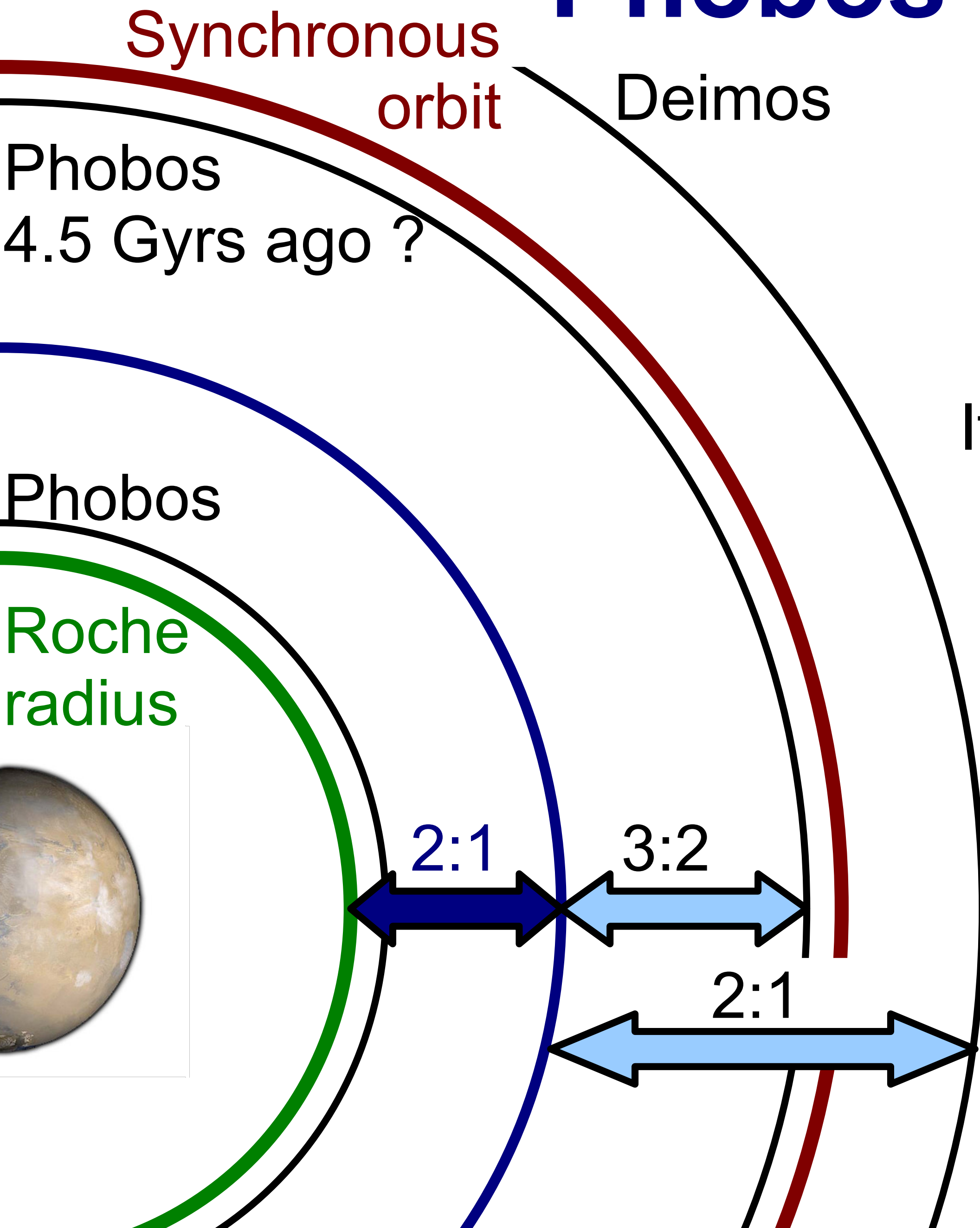
I claim that Uranus and Neptune had massive rings, from which their regular satellites were born.

Phobos and Deimos



Impossible to produce Phobos, and mostly Deimos by direct pyramidal regime.

Phobos and Deimos



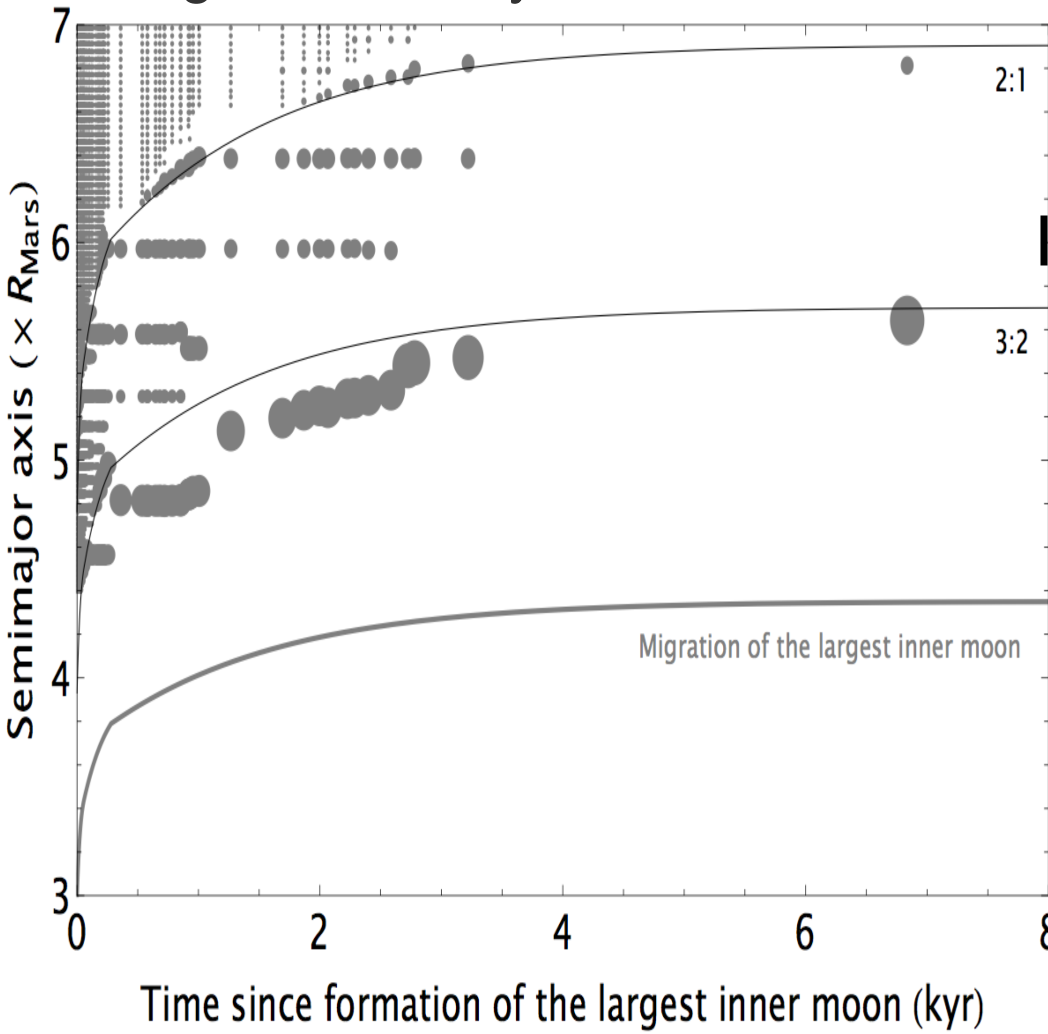
Impossible to produce Phobos, and mostly Deimos by direct pyramidal regime.

If a giant impact created a massive ring within r_{Roche} + debris beyond r_{Roche}, the debris are parked at resonances with satellites formed in the pyramidal regime, that later fall back onto Mars.

(Rosenblatt et al. 2016, *Nature Geoscience*)

Phobos and Deimos

Figure courtesy : S. Charnoz



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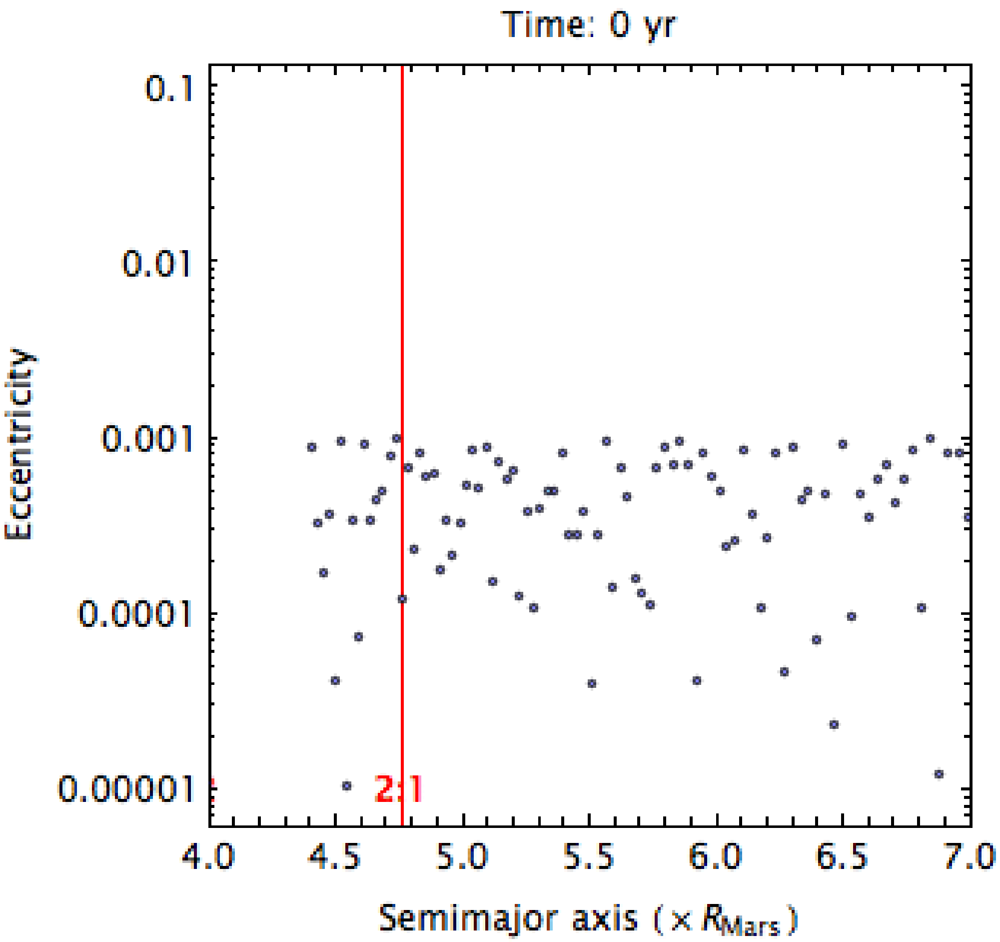
(Rosenblatt et al. 2016, *Nature Geoscience*)

Phobos and Deimos

Movie courtesy : S. Charnoz



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Summary

The spreading of a tidal disk beyond the Roche radius

✓ explains the mass-distance distribution of the regular satellites of the giant planets
(observational signature of this process)

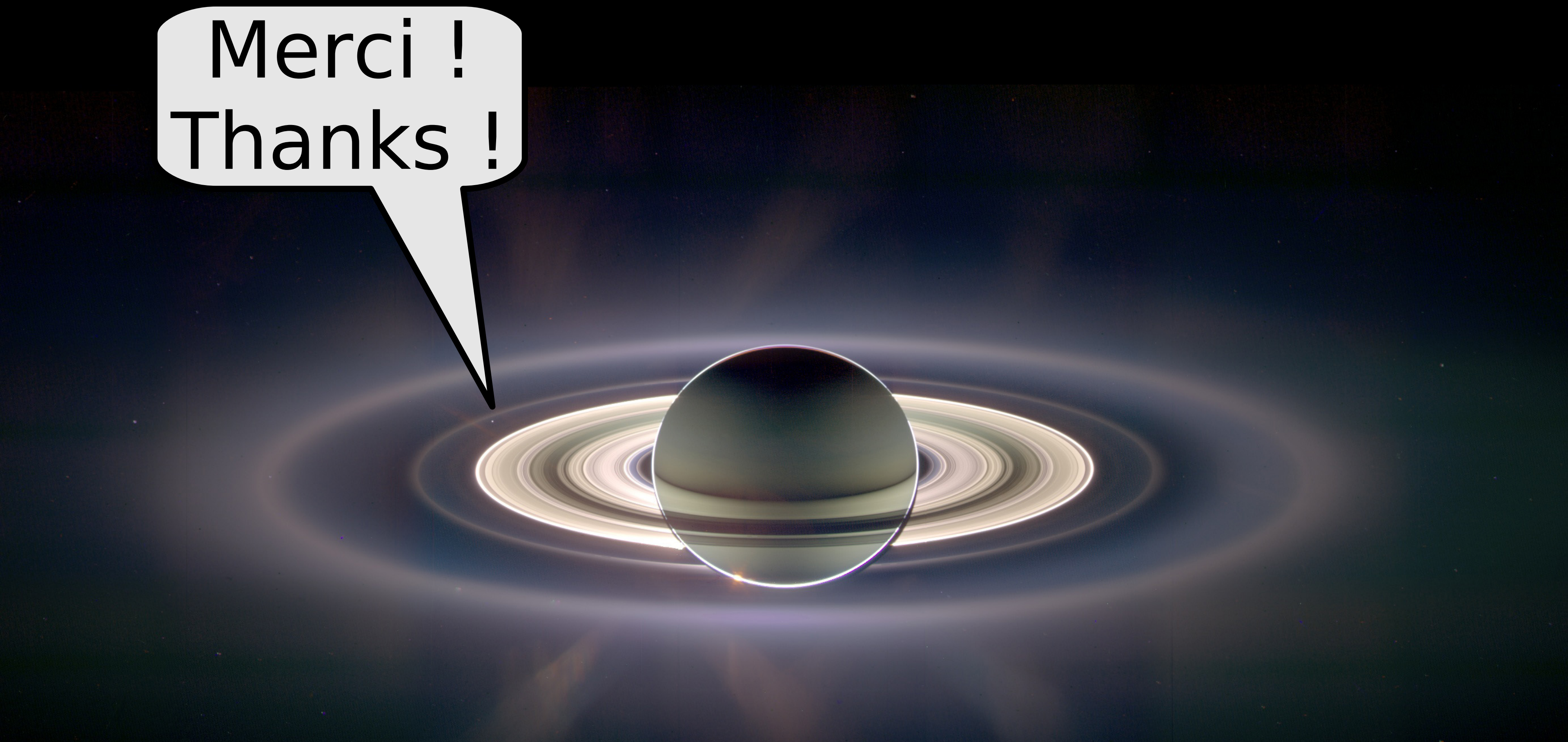
✓ unifies terrestrial and giant planets in the same paradigm.

✓ most Solar System regular satellites formed this way.

✗ Jupiter doesn't fit in this picture : probably formed in a circum-planetary disk (e.g. Canup & Ward 2002, 2006 ; Sasaki et al 2010)

• Titan fits very well in this picture, though its « tidal age » is too large... Coincidence ?

Caltech, Pasadena, 25 / 10 / 2016

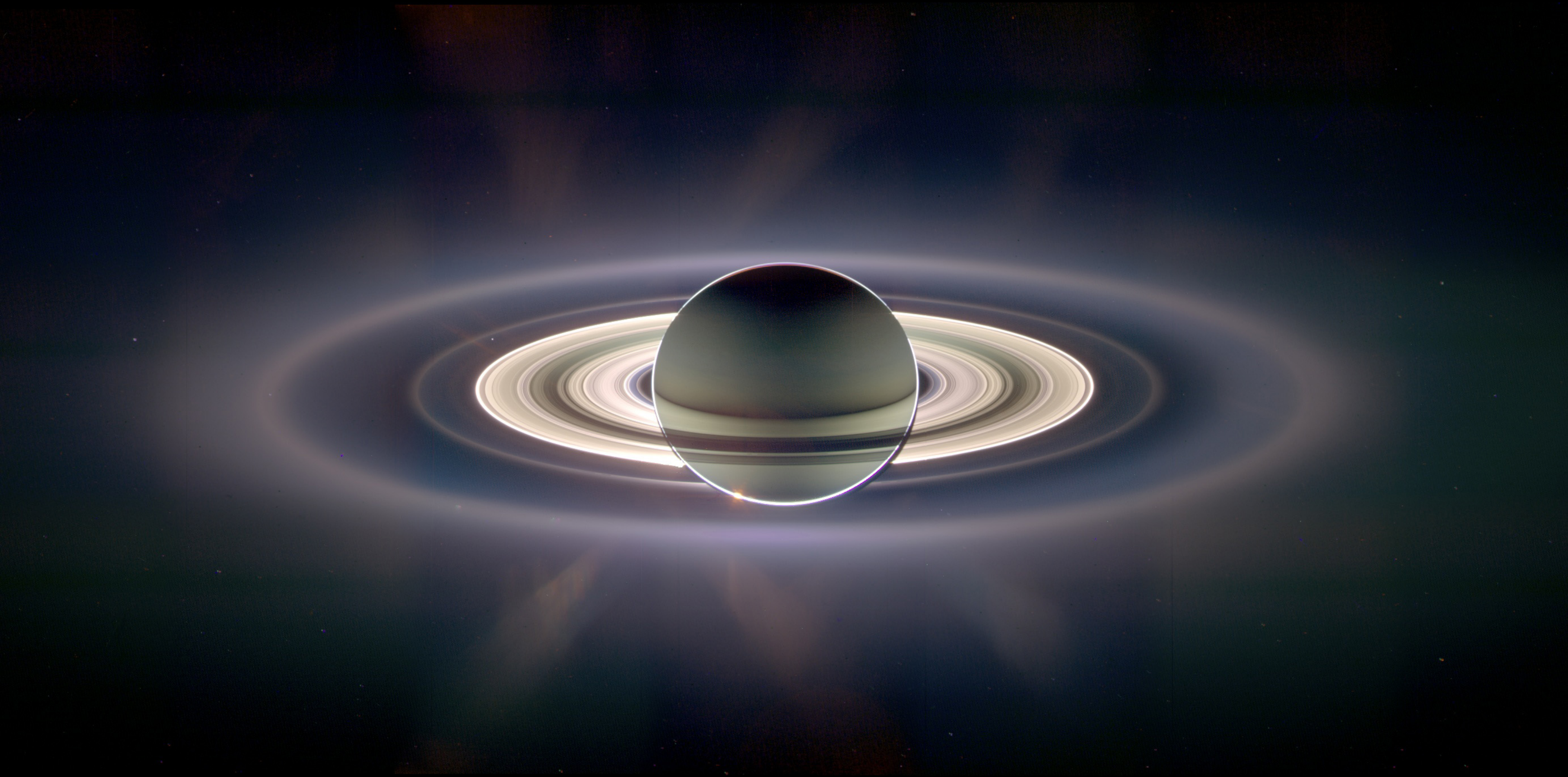


References : Crida & Charnoz (2014, IAU#310)

Crida & Charnoz (2012, *Science*)
Charnoz, Salmon, Crida (2010, *Nature*)
Charnoz, Crida, *et al*. (2011, *Icarus*)
Crida & El Moutamid (in prep.)

Canup (2010, *Nature*)
Lainey *et al*. (2012, *ApJ*)
Salmon *et al*. (2010, *Icarus*)
Rosenblatt *et al*. (2016, *Nature Geo*)

EXTRA SLIDES

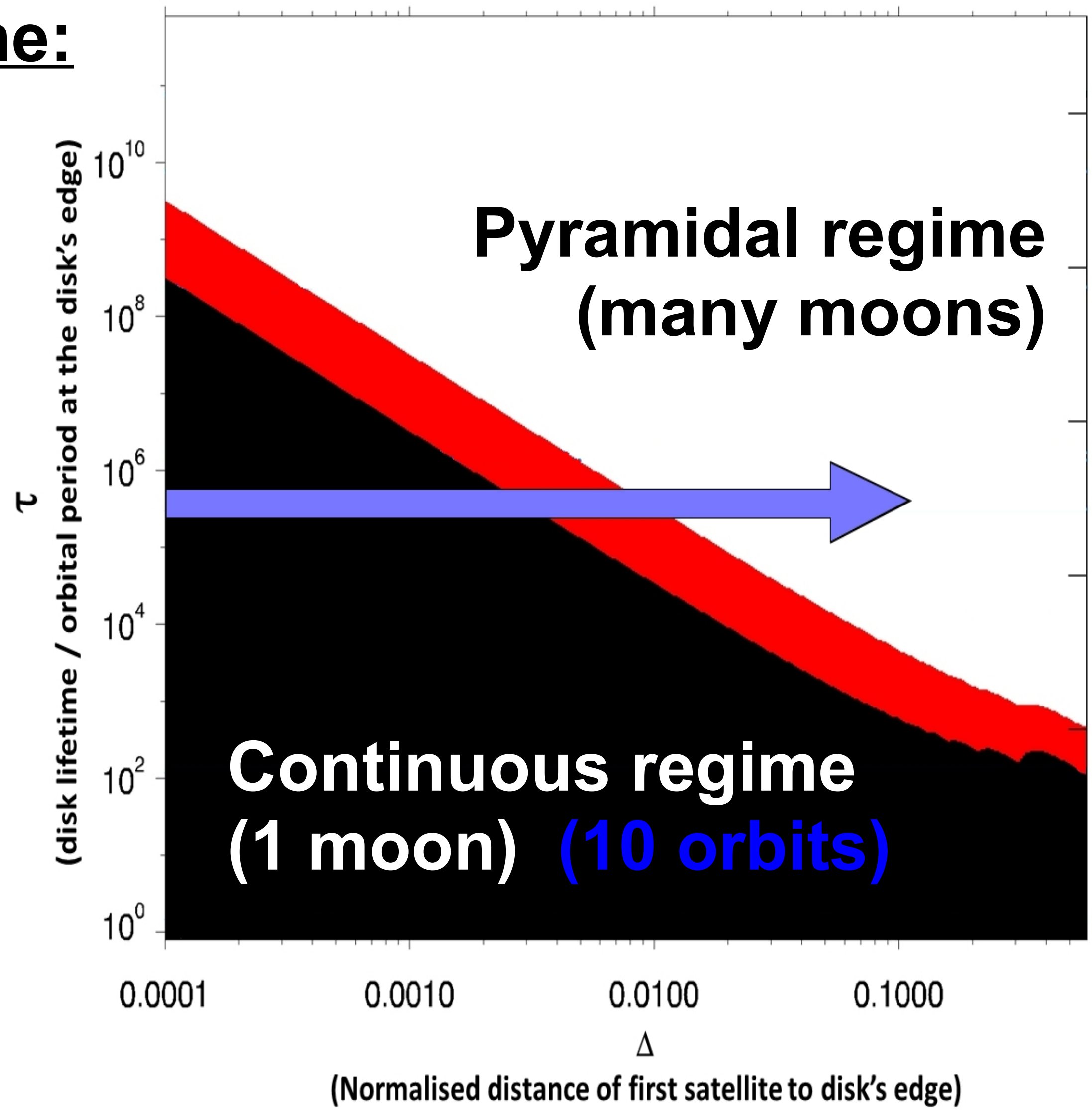


Summary

1) <u>Continuous regime:</u>
1 moon grows
$q \propto \Delta^2$
until Δ_c or q_c.

2) <u>Discrete regime:</u>
2 moons,
growth by steps
until Δ_d or q_d .

3) Pyramidal regime:
Many moons in the system.
$q \propto \Delta^{9/5}$ or $r^{3.8}$.

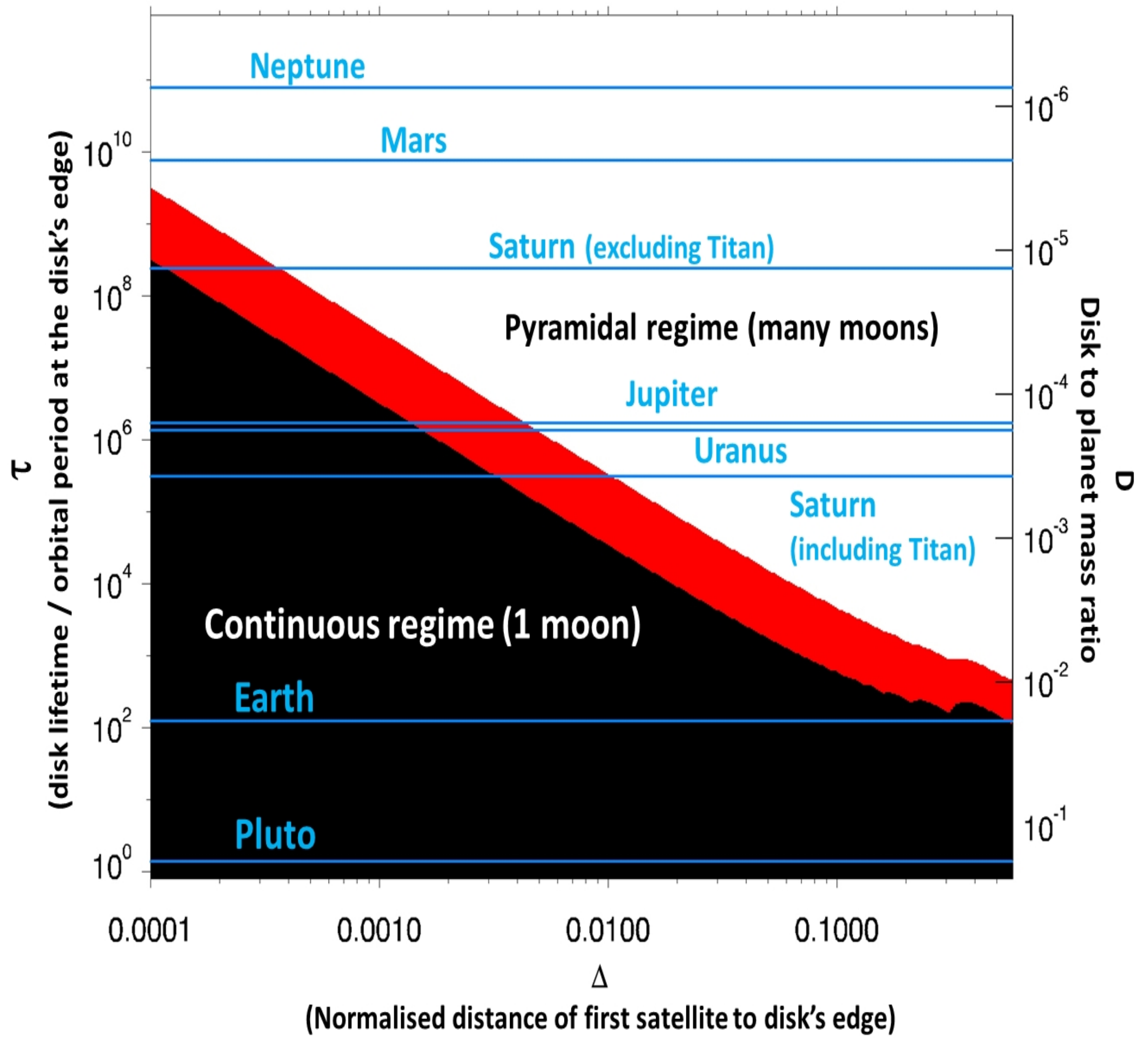


Summary

Take M_{disk} = 1.5 x the mass of the present satellite system.

Giant planets must be dominated by the pyramidal regime,

while we expect the Earth and Pluto to have 1 large satellite.



Evolution of Saturn's rings

Mass conservation :

$$r\frac{\partial \Sigma}{\partial t}+\frac{\partial}{\partial r}(r\,\Sigma\,v_r)=0$$

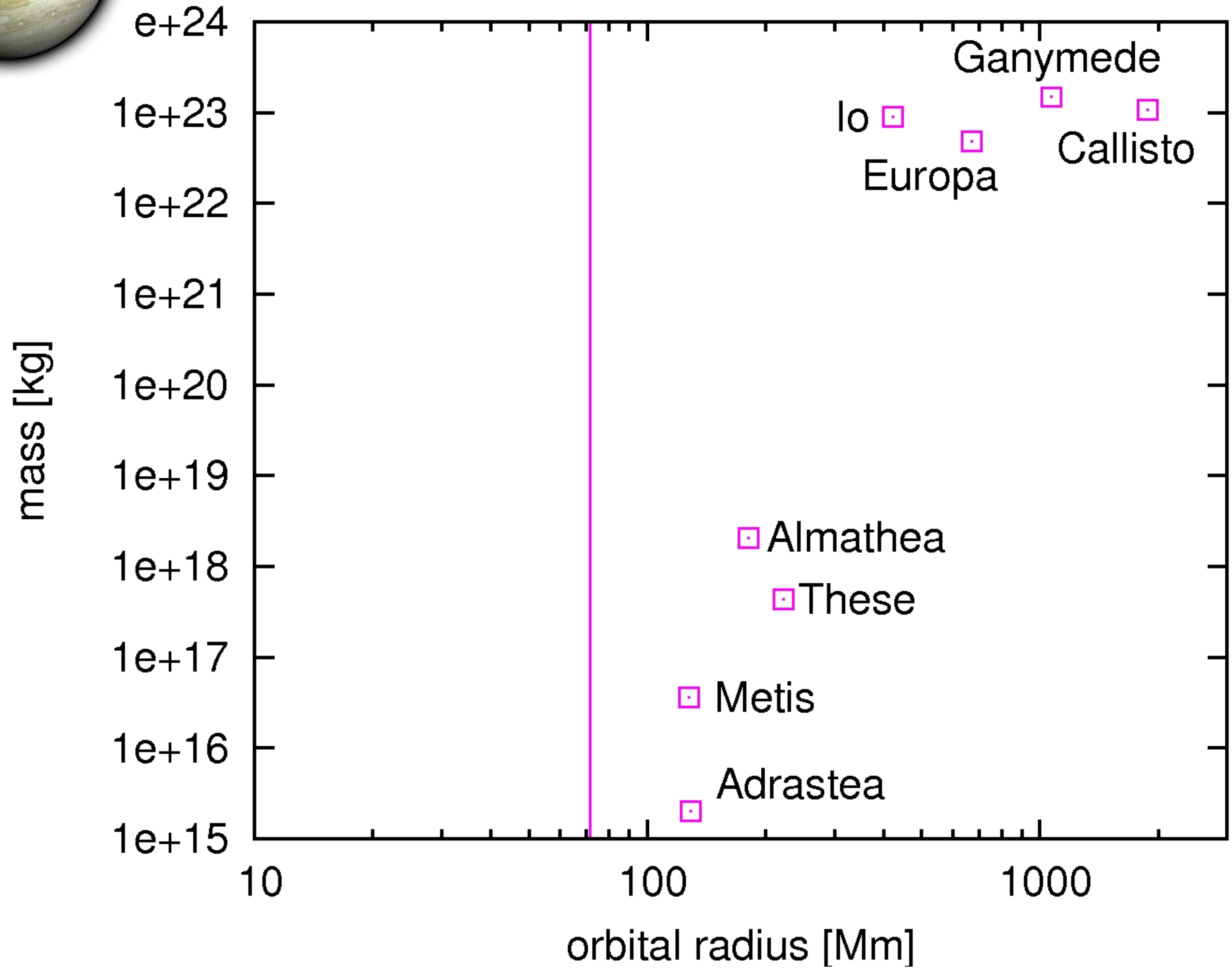
Angular momentum conservation :

$$\frac{\partial}{\partial t}(\Sigma\,r^2\,\Omega)+\frac{1}{r}\frac{\partial}{\partial r}\left(\nu\,\Sigma\,r^3\frac{\partial \Omega}{\partial r}\right)=0$$

Thus density evolution :

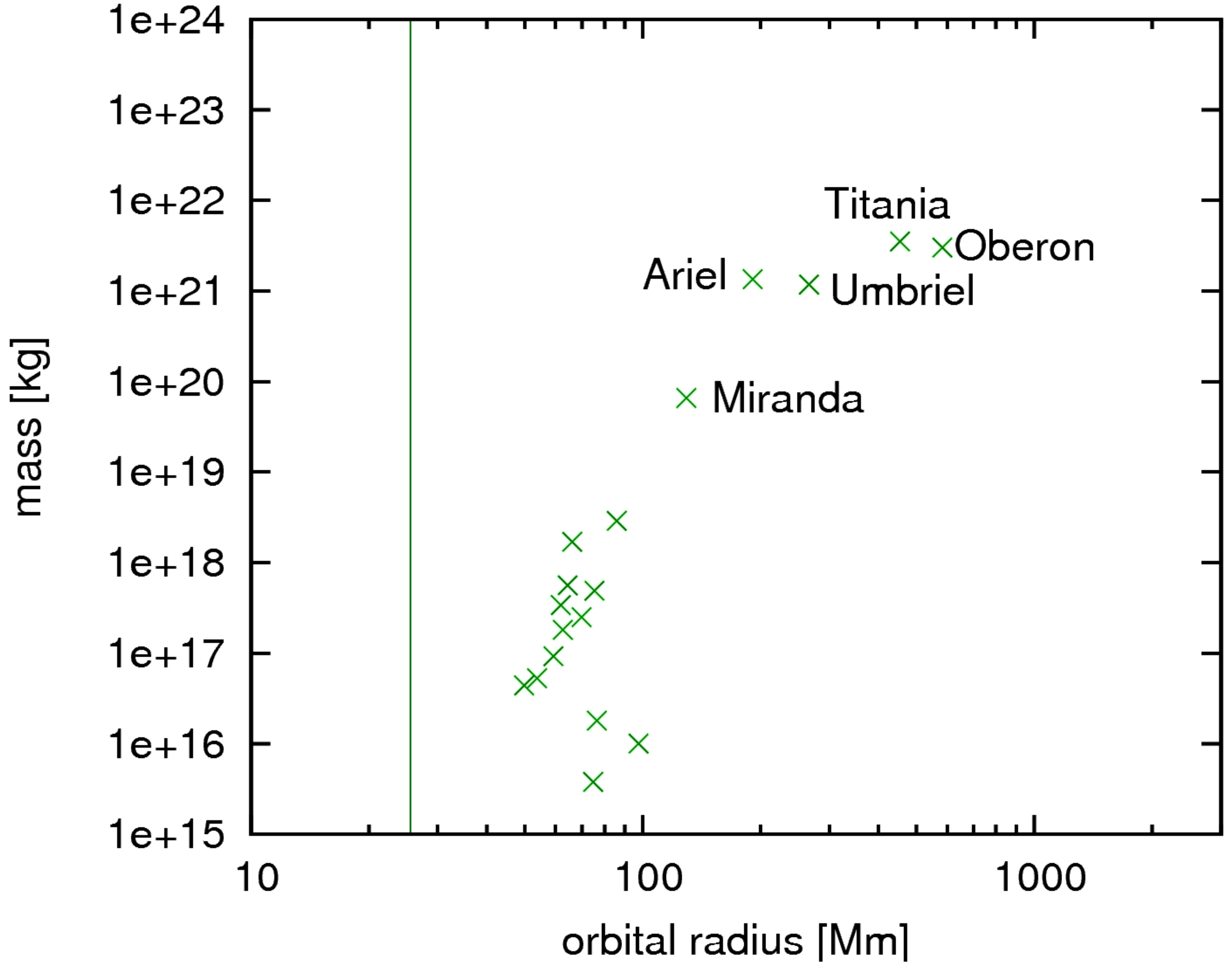
$$\frac{\partial \Sigma}{\partial t}=\frac{3}{r}\frac{\partial}{\partial r}\left[\sqrt{r}\frac{\partial}{\partial r}\left(\nu\,\Sigma\,\sqrt{r}\right)\right]$$

JUPITER



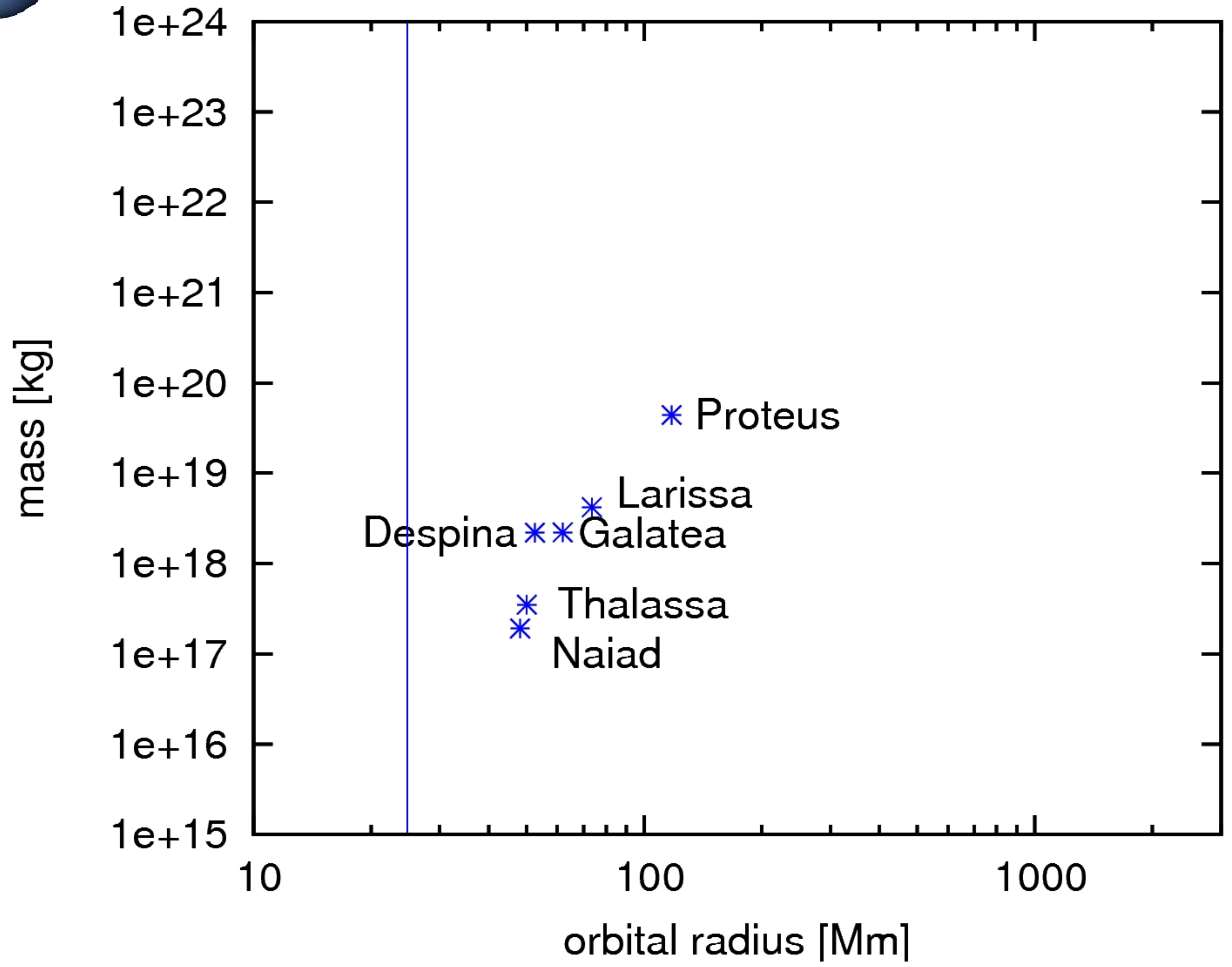
e+24
1e+23
1e+22
1e+21
1e+20
1e+19
1e+18
1e+17
1e+16
1e+15
mass [kg]
10
100
1000
orbital radius [Mm]
Ganymede
Io
Callisto
Europa
Almathea
These
Metis
Adrastea

URANUS



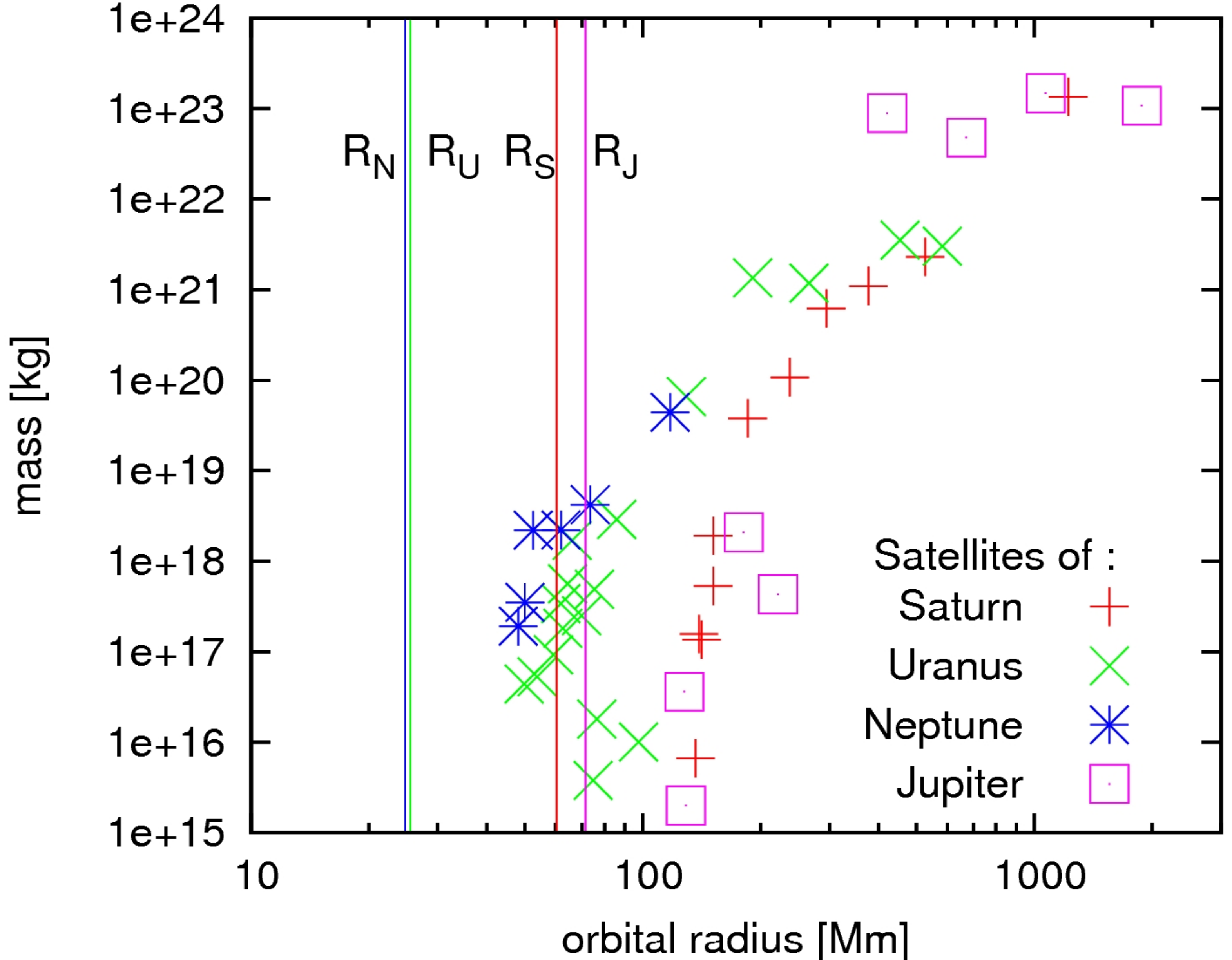
mass [kg]
1e+24
1e+23
1e+22
1e+21
1e+20
1e+19
1e+18
1e+17
1e+16
1e+15
10
100
1000
orbital radius [Mm]
Titania
Oberon
Ariel
Umbriel
Miranda

NEPTUNE



1e+24
1e+23
1e+22
1e+21
1e+20
1e+19
1e+18
1e+17
1e+16
1e+15
mass [kg]
Proteus
Larissa
Despina
Galatea
Thalassa
Naiad
10
100
1000
orbital radius [Mm]

ALL GIANT PLANETS



ALL GIANT PLANETS

Distributions of giant planets' regular satellites :

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

Why ?