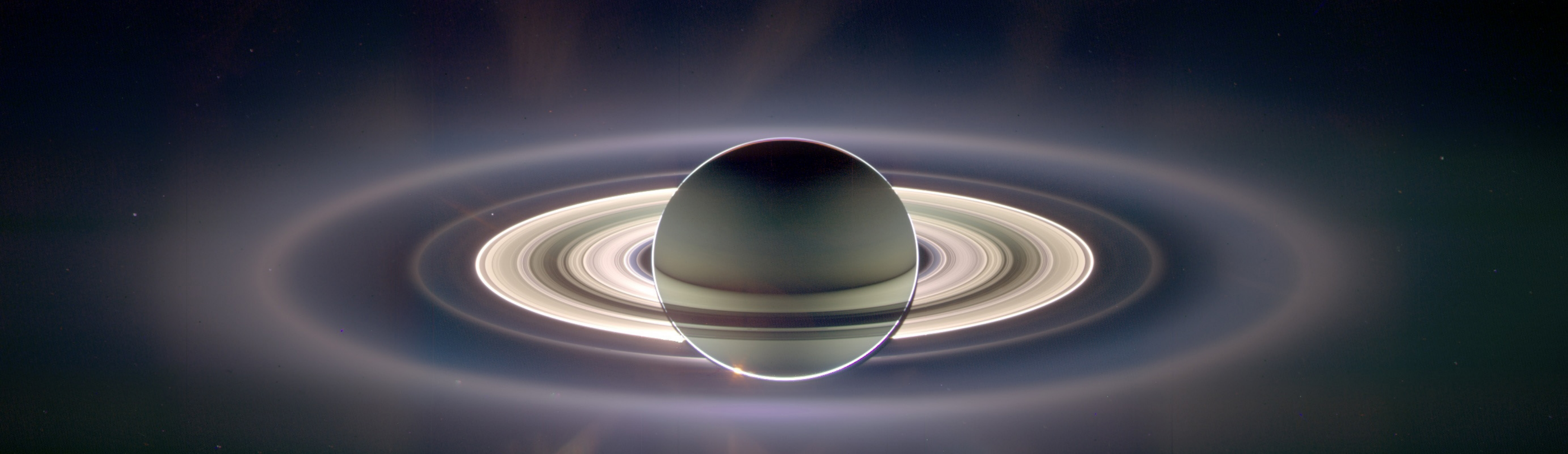
FORMATION OF SATELLITES from a tidal disk



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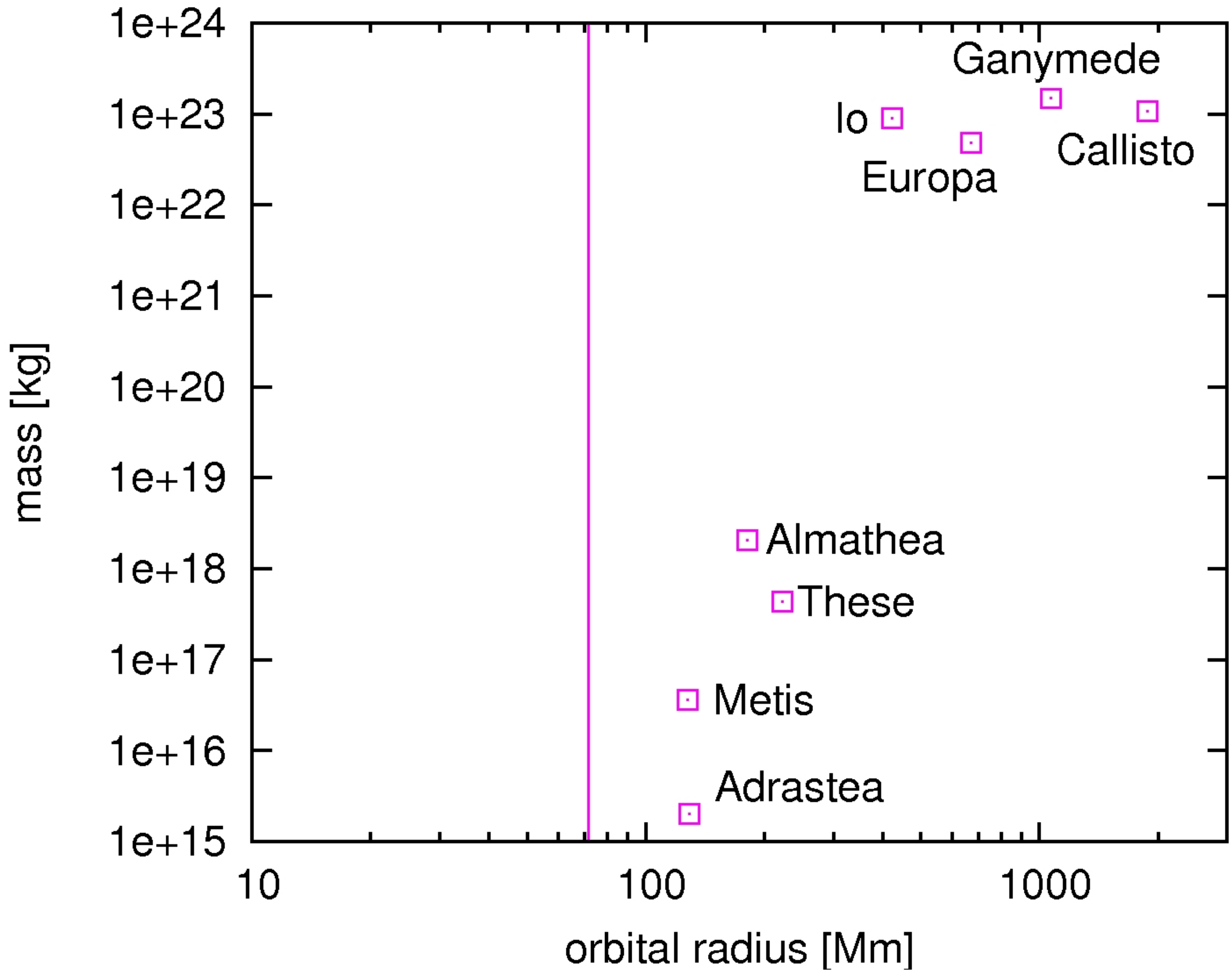
LAGRANGE

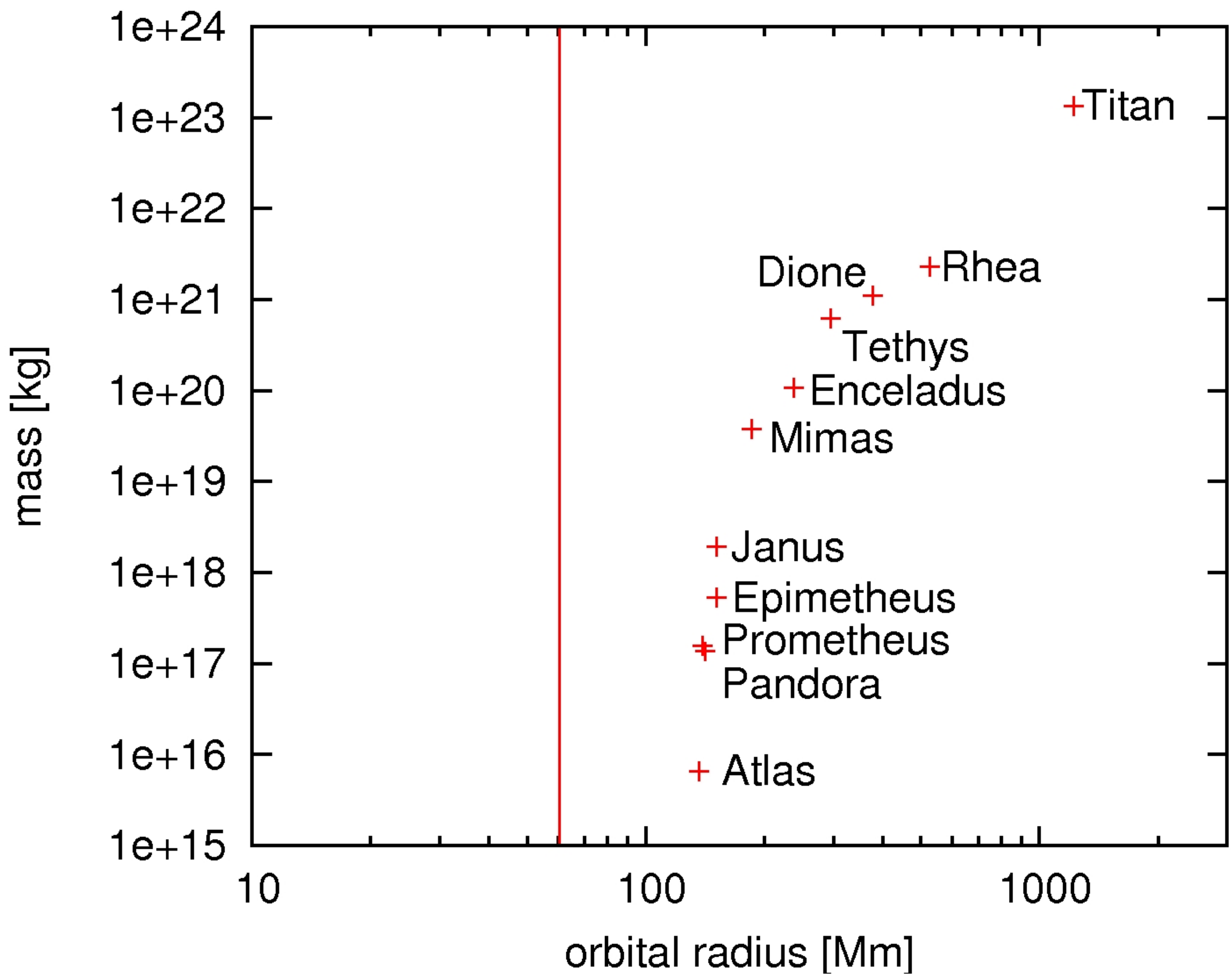
Observatoire de la CÔTE d'AZUR

JUPITER



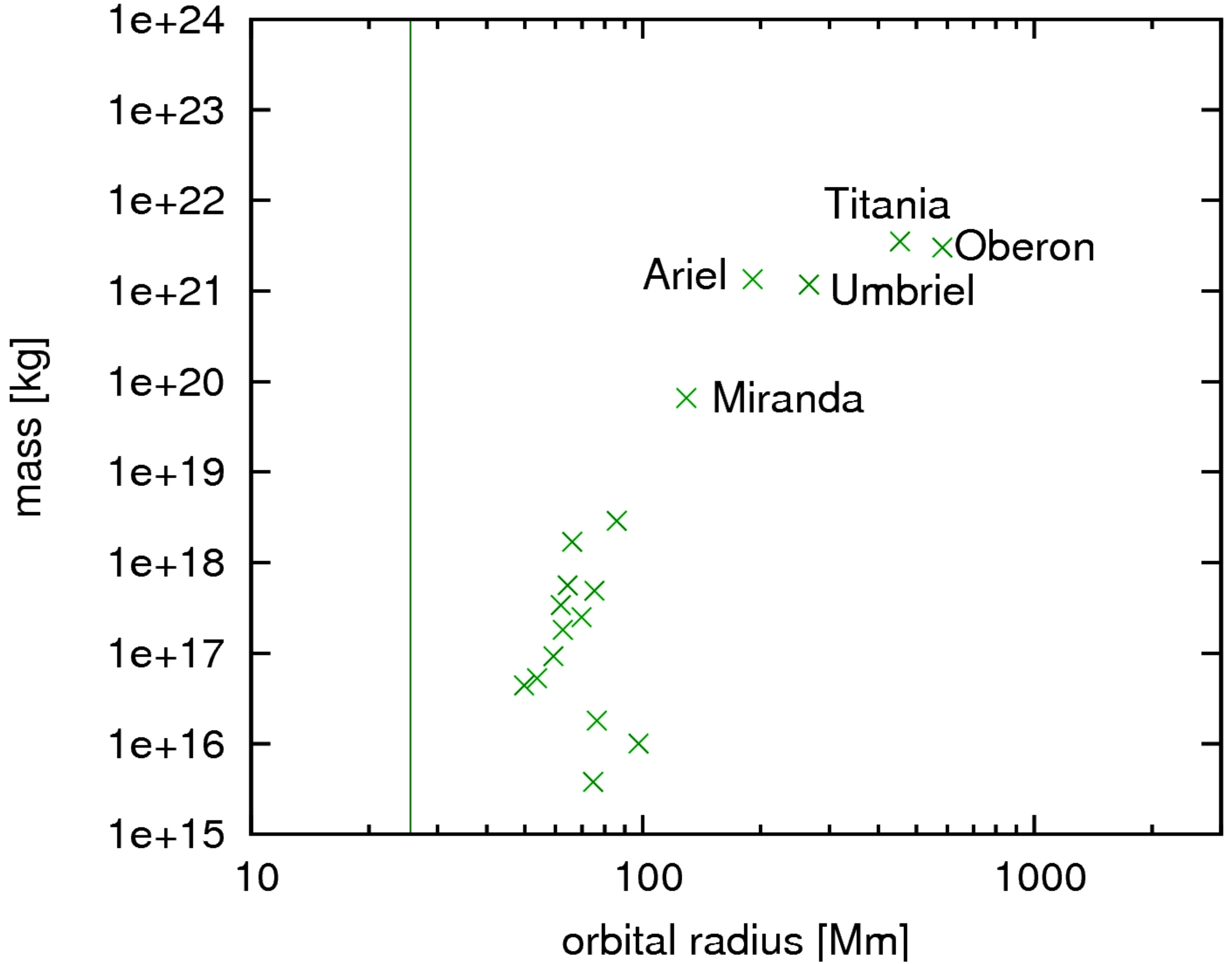
1e+24
1e+23
1e+22
1e+21
1e+20
1e+19
1e+18
1e+17
1e+16
1e+15
mass [kg]
10
100
1000
orbital radius [Mm]
Ganymede
Io
Callisto
Europa
Almathea
These
Metis
Adrastea

SATURN



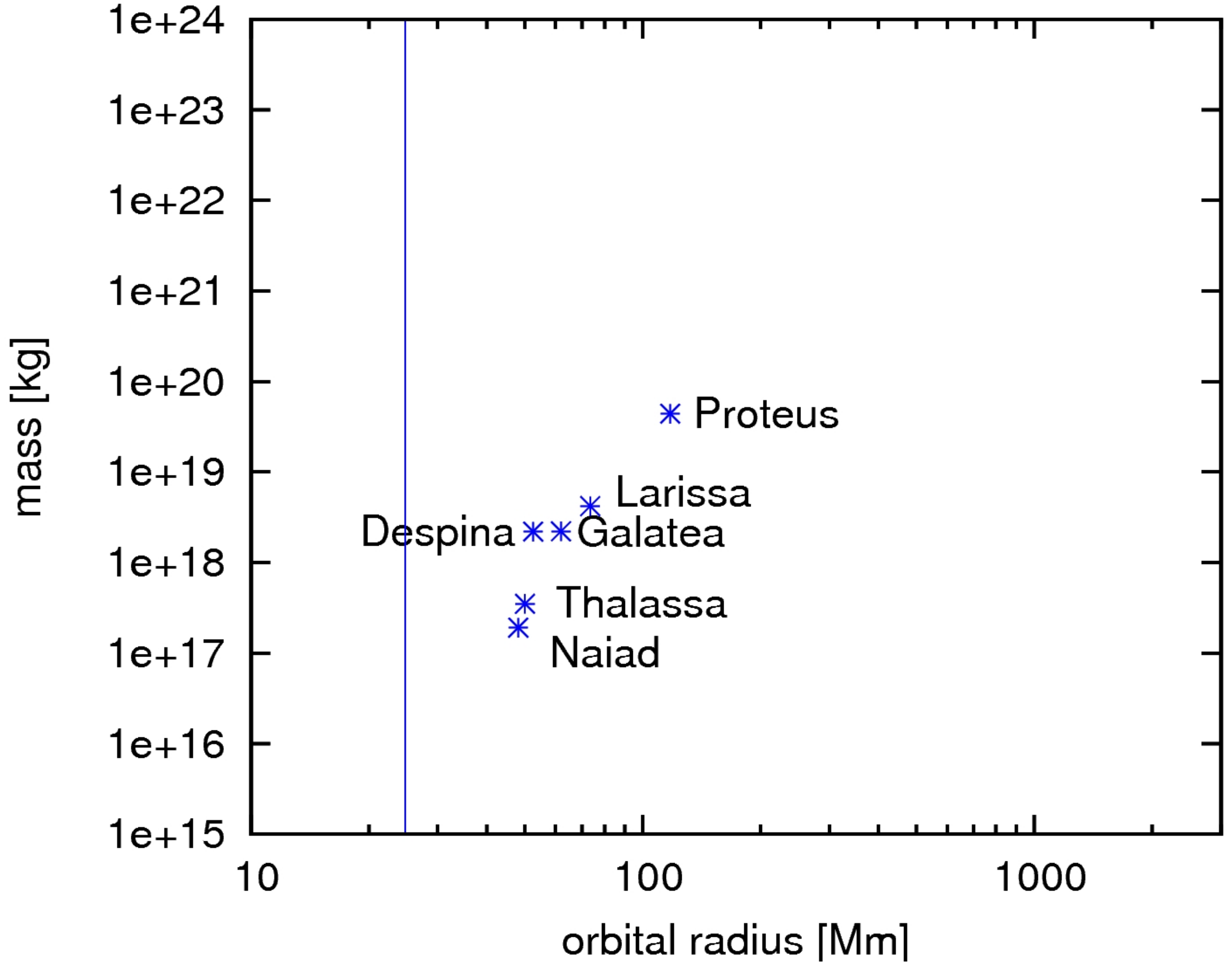
mass [kg]
1e+24
1e+23
1e+22
1e+21
1e+20
1e+19
1e+18
1e+17
1e+16
1e+15
10
100
1000
orbital radius [Mm]
Titan
Rhea
Dione
Tethys
Enceladus
Mimas
Janus
Epimetheus
Prometheus
Pandora
Atlas

URANUS



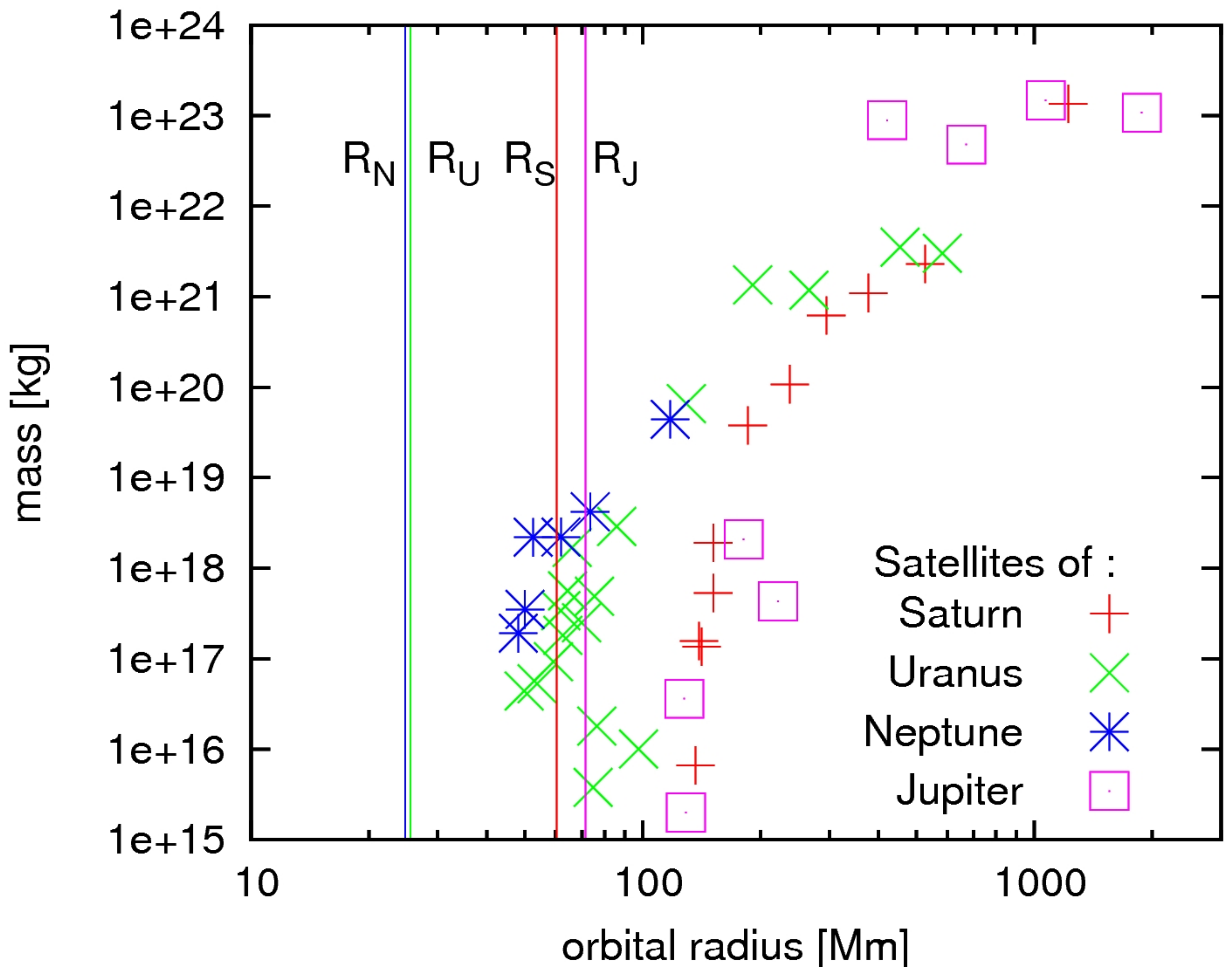
mass [kg]
1e+24
1e+23
1e+22
1e+21
1e+20
1e+19
1e+18
1e+17
1e+16
1e+15
10
100
1000
orbital radius [Mm]
Titania
Oberon
Ariel
Umbriel
Miranda

NEPTUNE



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

ALL GIANT PLANETS

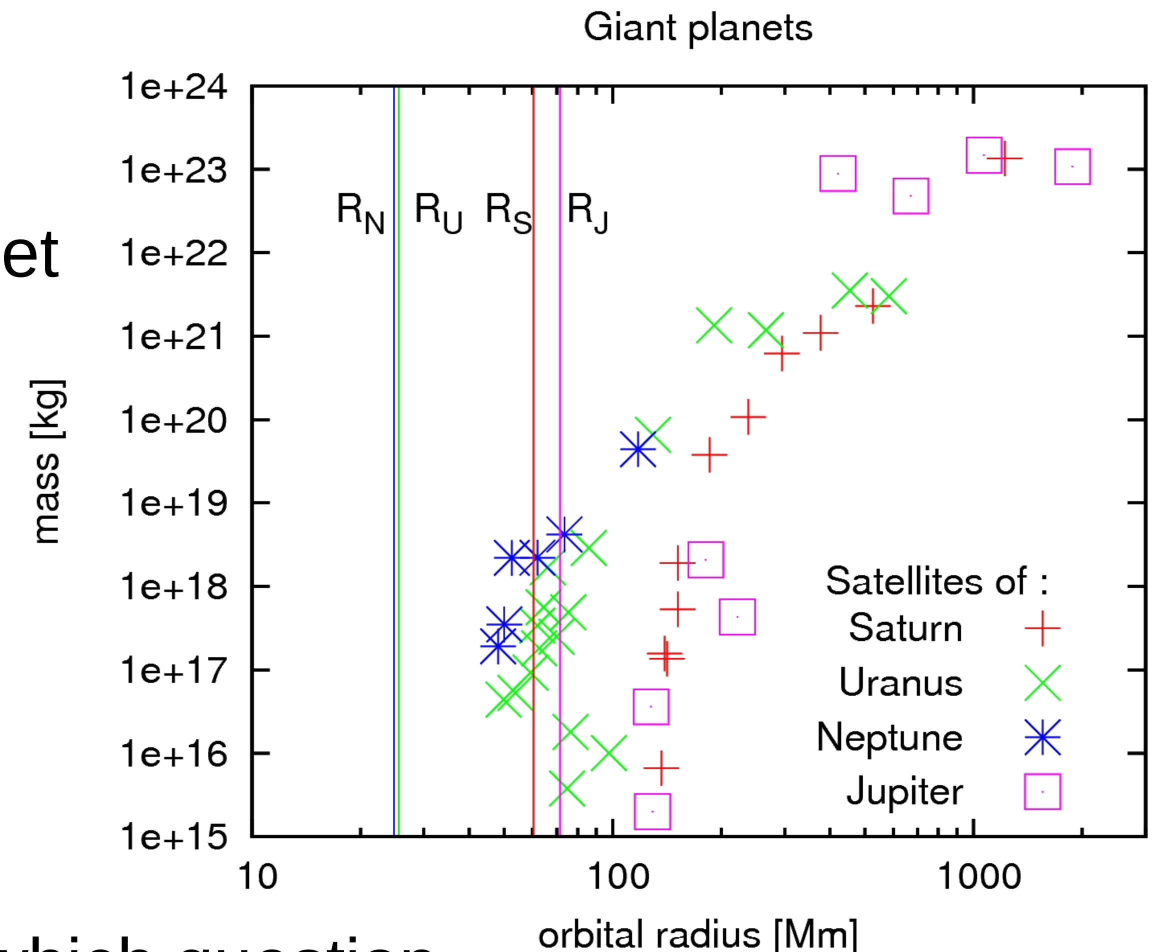


INTRODUCTION

Distributions of giant planets' regular satellites :

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

Why ?



It's not a power law, which question the Circum-Planetary Disc model...

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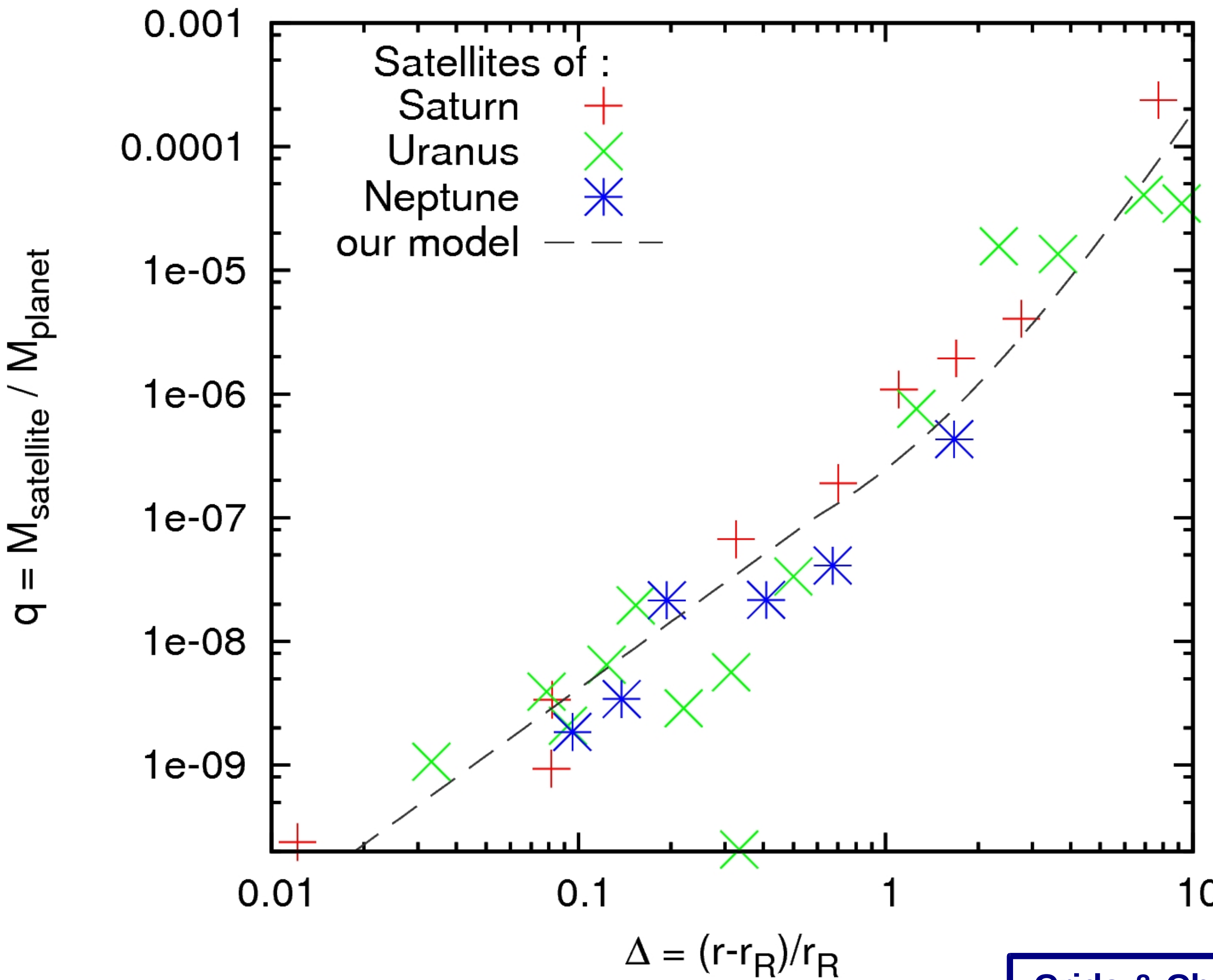
CONCLUSION



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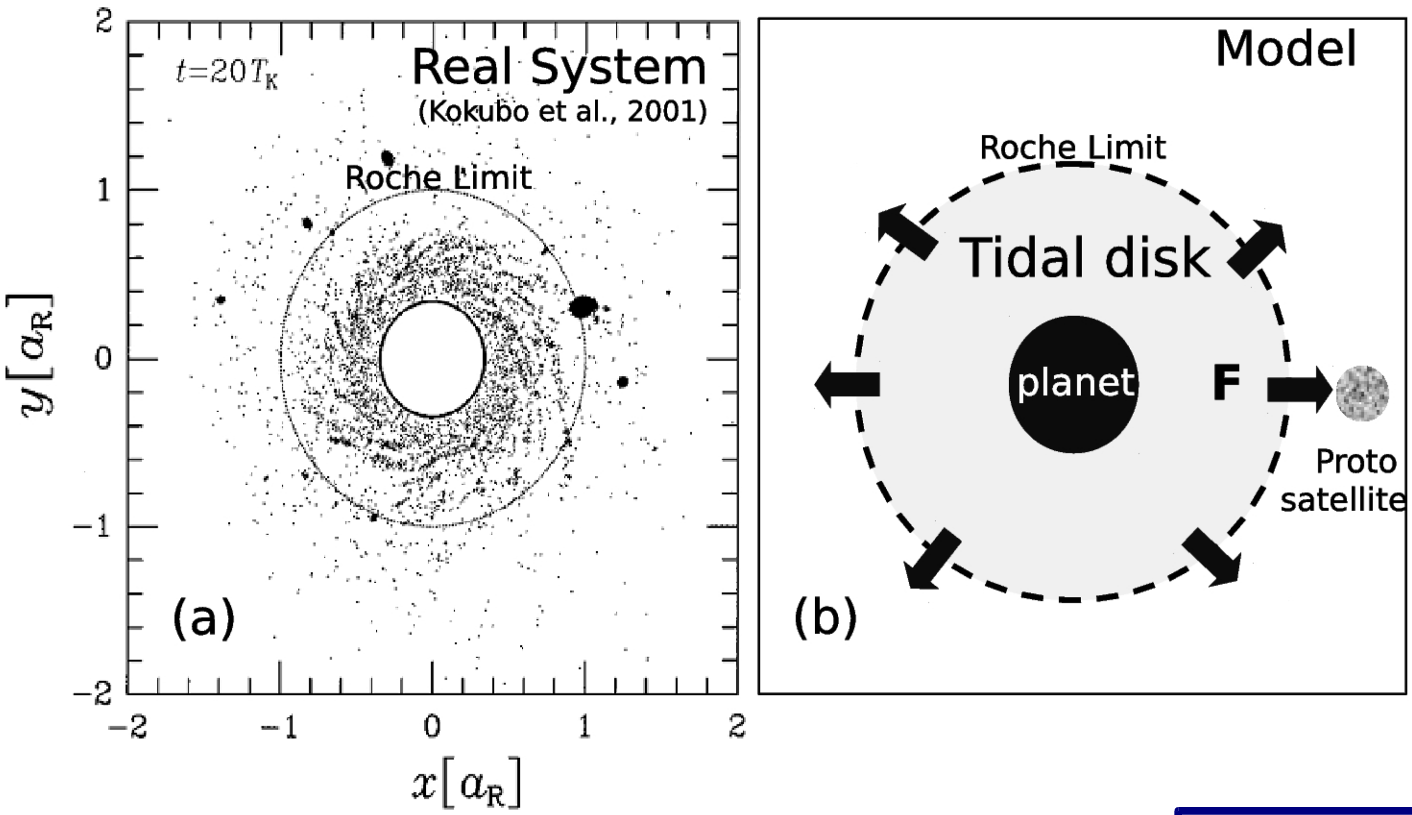
Spreading of a tidal disk

1D model.

Inside the Roche radius r_R, there is a « tidal disk », that spreads with a mass flux **F**.



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Notations

Be **T_R** the orbital period at r_R , and

$T_{disk} = M_{disk} / FT_R$, 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 $T_{disk} = t_\nu / T_R = 0.0425\ D^{-2}$ where **$D = M_{disk}/M_p$** ,

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

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Continuous regime

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

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

where $\Delta = (r-r_R)/r_R$ (Lin & Papaloizou 1979).

➔ Migration rate : $$\frac{d\Delta}{dt} = \frac{32}{27} q D T_R^{-1} \Delta^{-3}$$ (2)

where $q = M / M_p$.

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

We call this the *continuous regime* .

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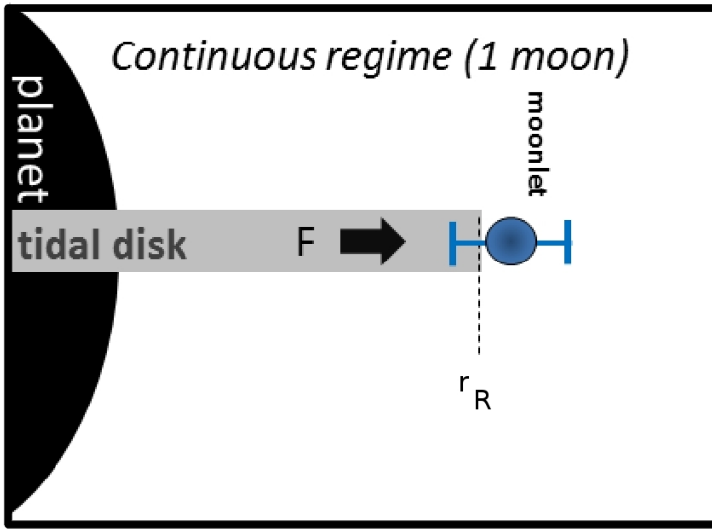
Continuous regime

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 $\Delta < 2\,(q/3)^{1/3}$.

Input into Eq.(3), this gives a condition of validity for the continuous regime :

$$\Delta < \Delta_c = \sqrt{\frac{3}{T_{disk}}} = \sim 8.4\ D$$

$$q < q_c = \frac{3^{5/2}}{2^3} T_{disk}^{-3/2} = \sim 222\ D^3$$

Duration of the continuous regime: 10 T_R .

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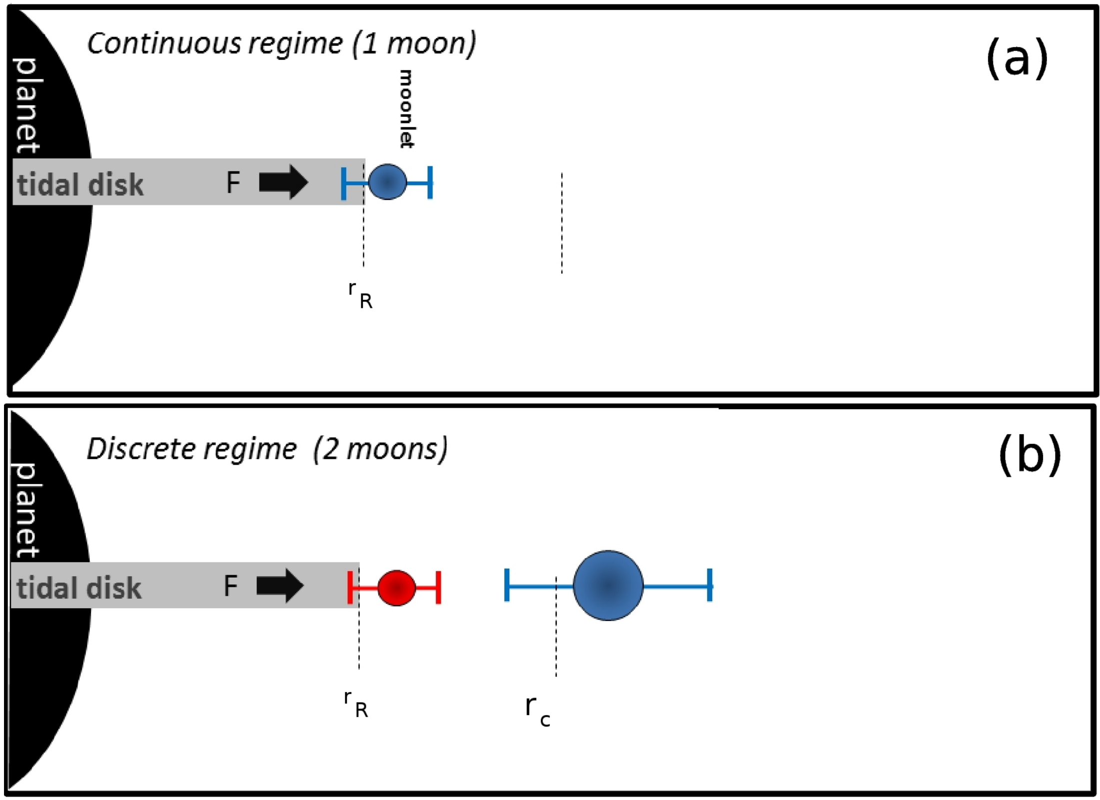
Discrete regime

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*.

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Discrete regime

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

It gives the condition :

$$\Delta < \Delta_d = \text{۳.۱۴}\,\Delta_c \quad = \sim 26\ D$$

$$q < q_d = \text{۹.۹}\,q_c \quad = \sim 2200\ D^3$$

The duration of the discrete regime is $\sim 100\ T_R$.

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Discrete regime

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

It gives the condition :

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

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

The duration of the discrete regime is ~100 T_R .

Applications :

1) Earth's Moon forming disk : q_d = mass of the Moon !
2) Charon never left the continuous regime.
3) Saturn's rings : $q_d = \sim 10^{-18}$.

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Pyramidal regime

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

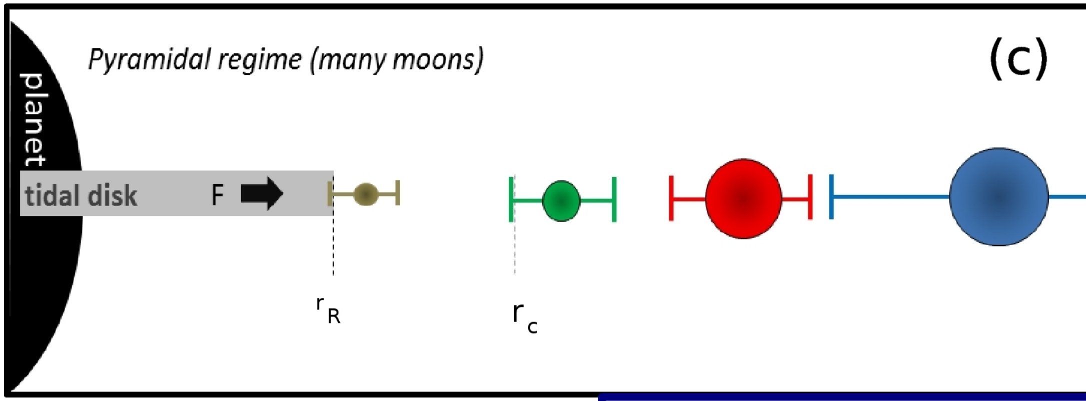
Then, many satellites of constant mass migrate outwards, at decreasing rates. They approach each other.

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

This leads to the formation of satellites of masses $2q_d$, every $2\,q_d / F$. They migrate away and merge further...

And so on, hierachicaly...

We call this *the pyramidal regime*.



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Pyramidal regime

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

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

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

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Pyramidal regime

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

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.(2) doesn't apply. Migration is driven by planetary tides:

$$\frac{dr}{dt} = \frac{3 k_{2p} M \sqrt{G} R_p^5}{Q_p \sqrt{M_p} r^{11/2}} \qquad (4)$$

Using Eq.(4), we find $q \propto r^{3.8}$.

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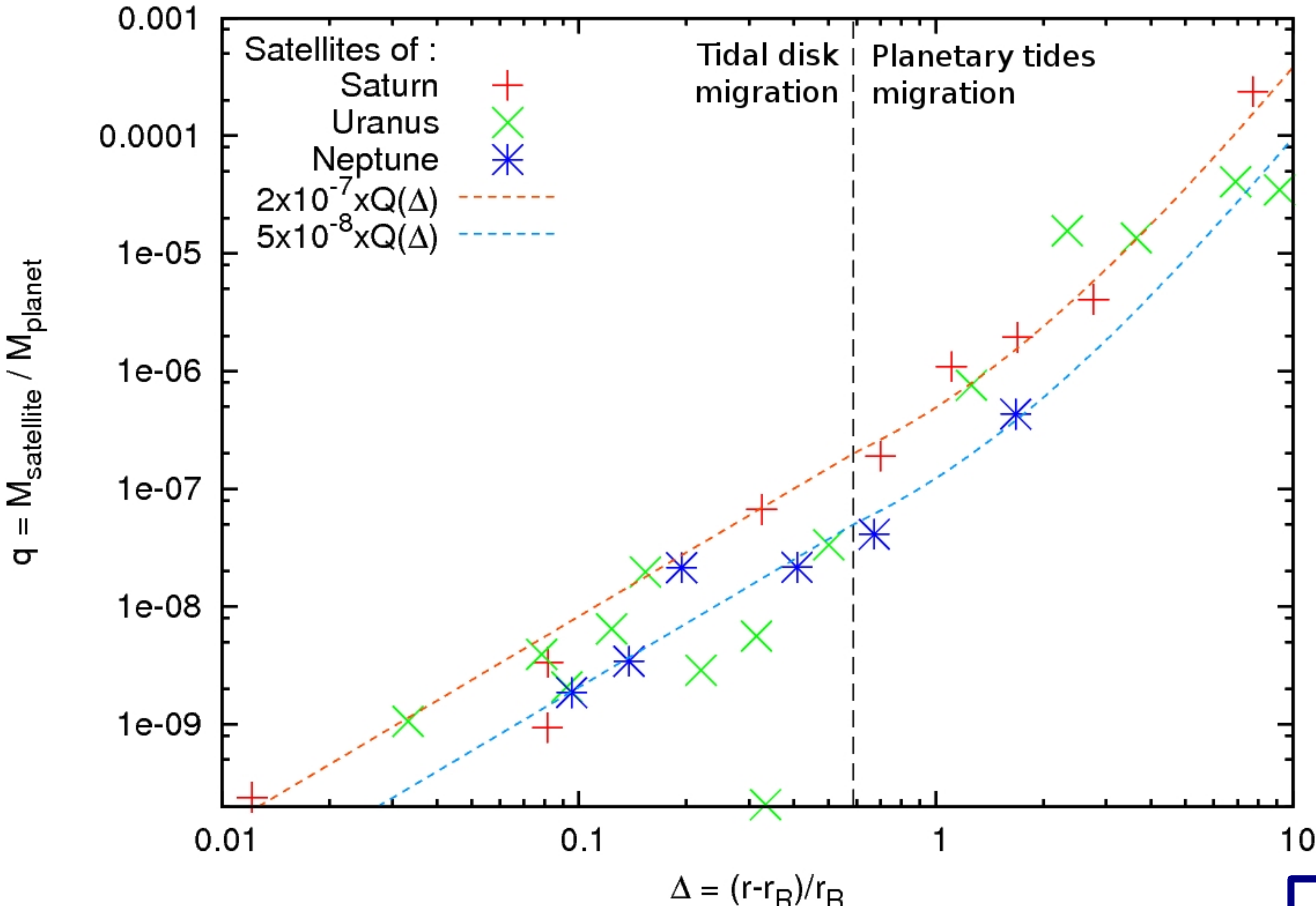
Pyramidal regime

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



Crida & Charnoz 2012

Pyramidal regime

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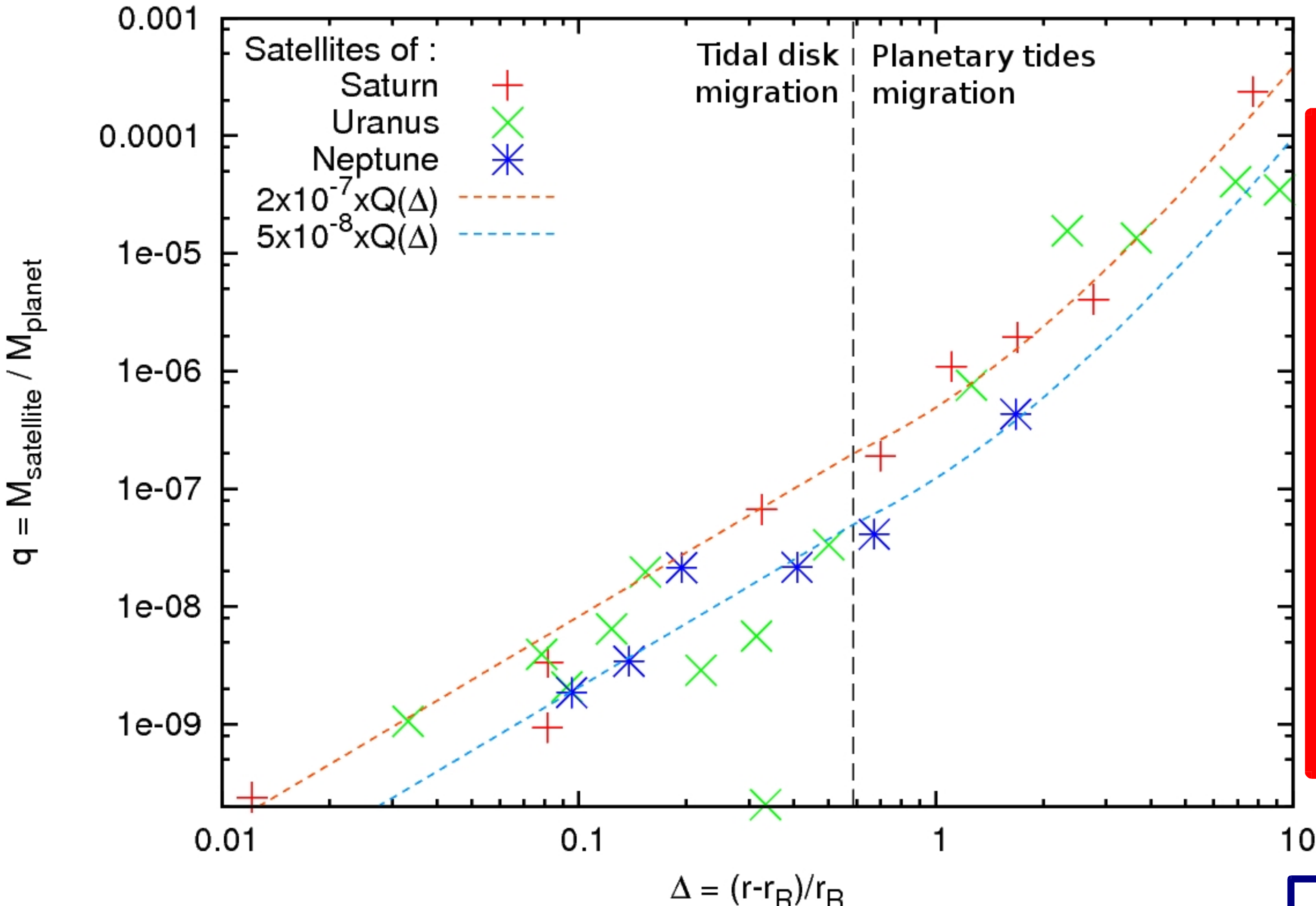

I claim that Uranus and Neptune had massive rings, from which their regular satellites were born.

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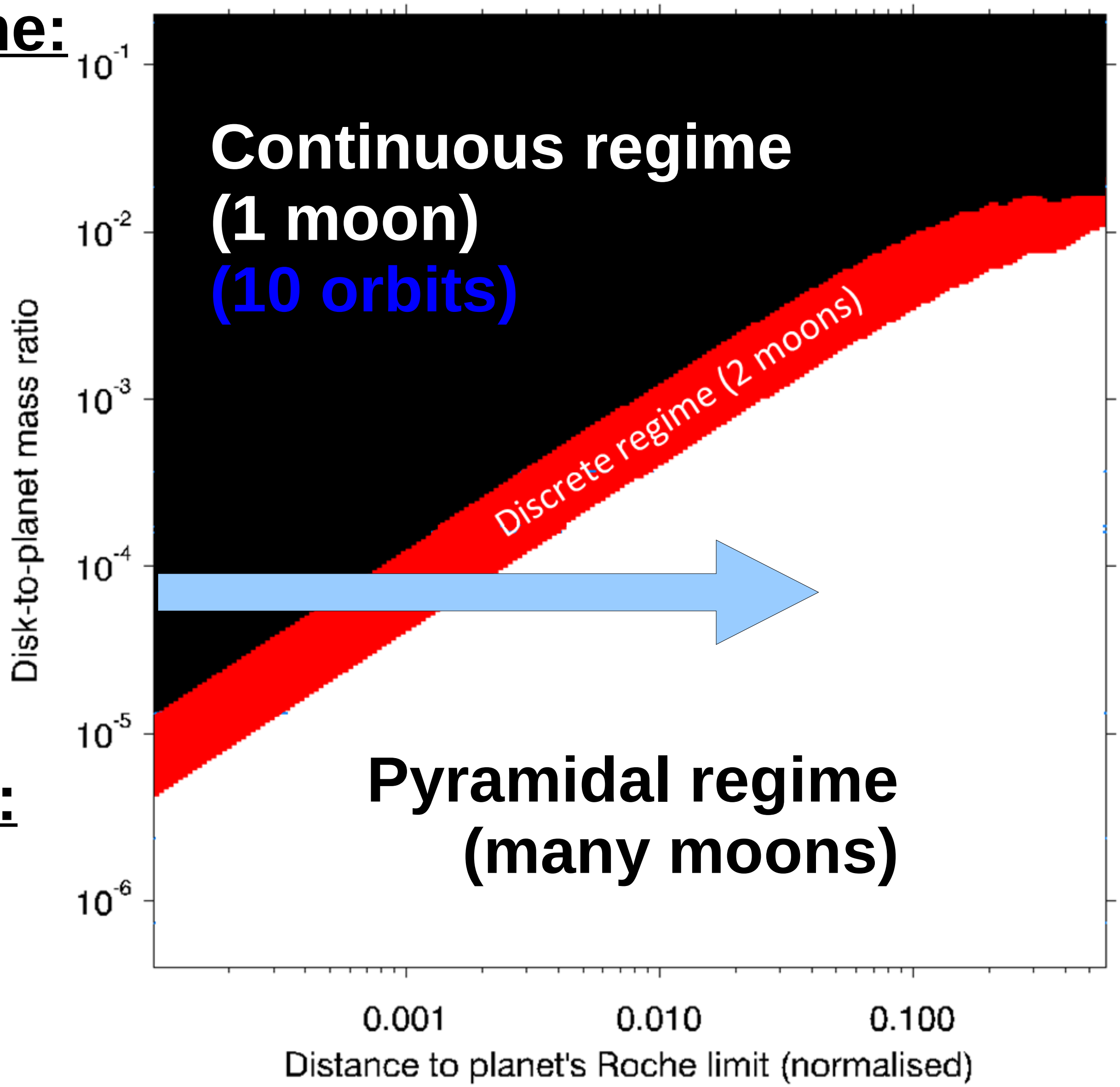
Summary

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

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

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

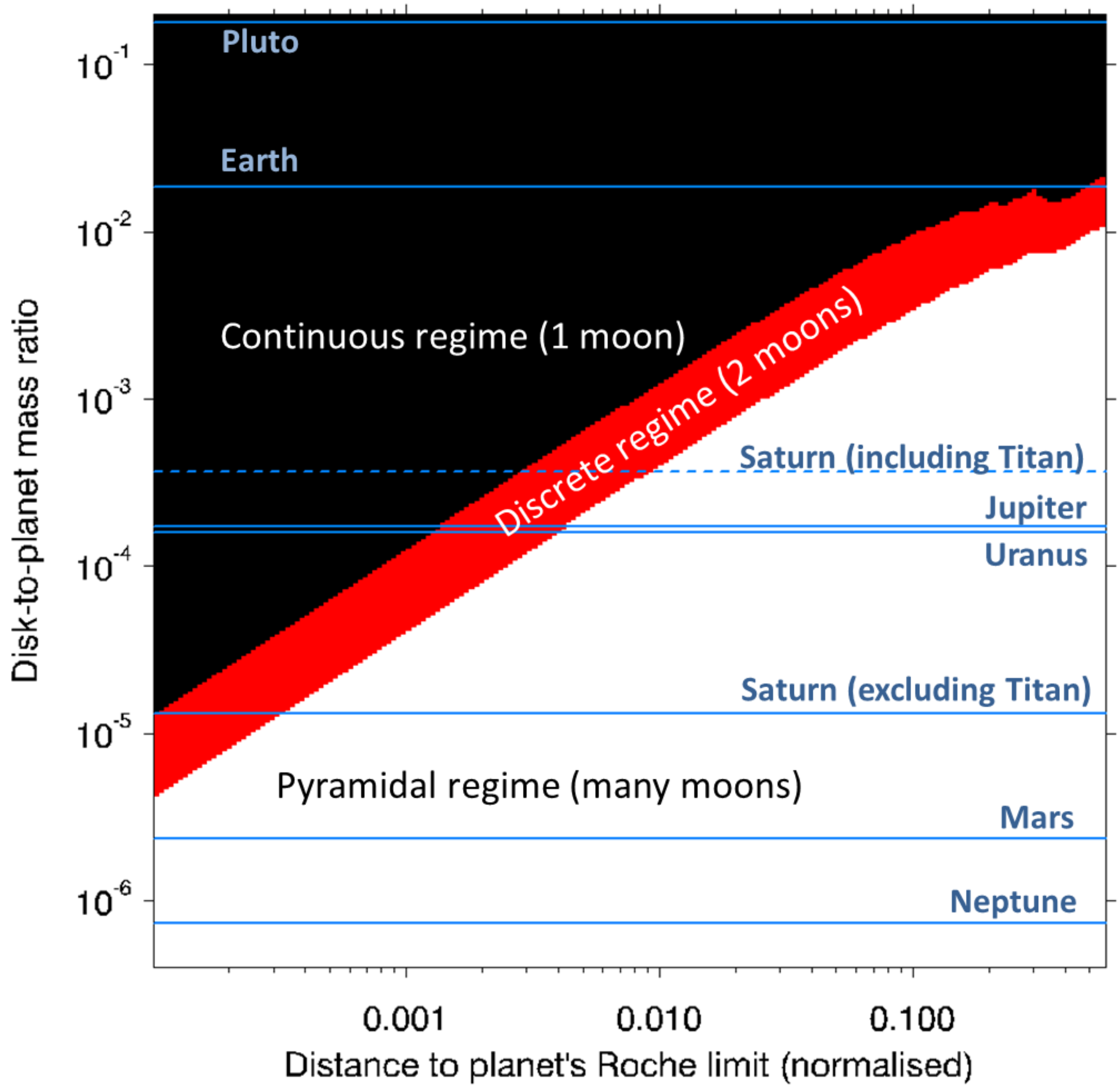


Summary

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.



Conclusion & Discussion

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 ?

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