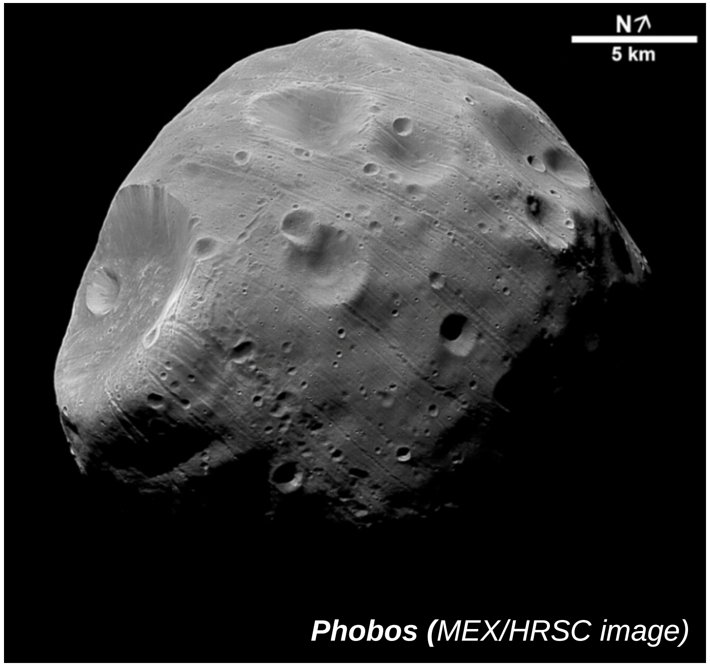
ROYAL OBSERVATORY
OF BELGIUM

On the formation of the Martian moons from a circum-Mars accretion disk

Rosenblatt P. and Charnoz S.

46th ESLAB Symposium: Formation and evolution of moons
Session 2 – Mechanism of formation: Moons of terrestrial planets
June 26th 2012 – ESTEC, Noordwijk, the Netherlands.

The origin of the Martian moons ?



Phobos (*MEX/HRSC image*)

Size: 13.0km x 11.39km x 9.07km


Deimos (*Viking image*)

Size: 7.5km x 6.1km x 5.2km

- *Unlike the Moon of the Earth, the origin of Phobos & Deimos is still an open issue.*

- *Capture or in-situ ?*

1. Arguments for in-situ formation of Phobos & Deimos

- **Near-equatorial, near-circular orbits around Mars**
  (→ formation from a circum-Mars accretion disk)

- **Mars Express flybys of Phobos**
  - Surface composition: phyllosilicates (*Giuranna et al. 2011)*
    => body may have formed *in-situ* (close to Mars' orbit)
  - Low density => high porosity (*Andert, Rosenblatt et al., 2010*)
    => consistent with gravitational-aggregates

2. A scenario of in-situ formation of Phobos and Deimos from an accretion disk

Adapted from Craddock R.A., Icarus (2011)

Giant impact on Proto-Mars

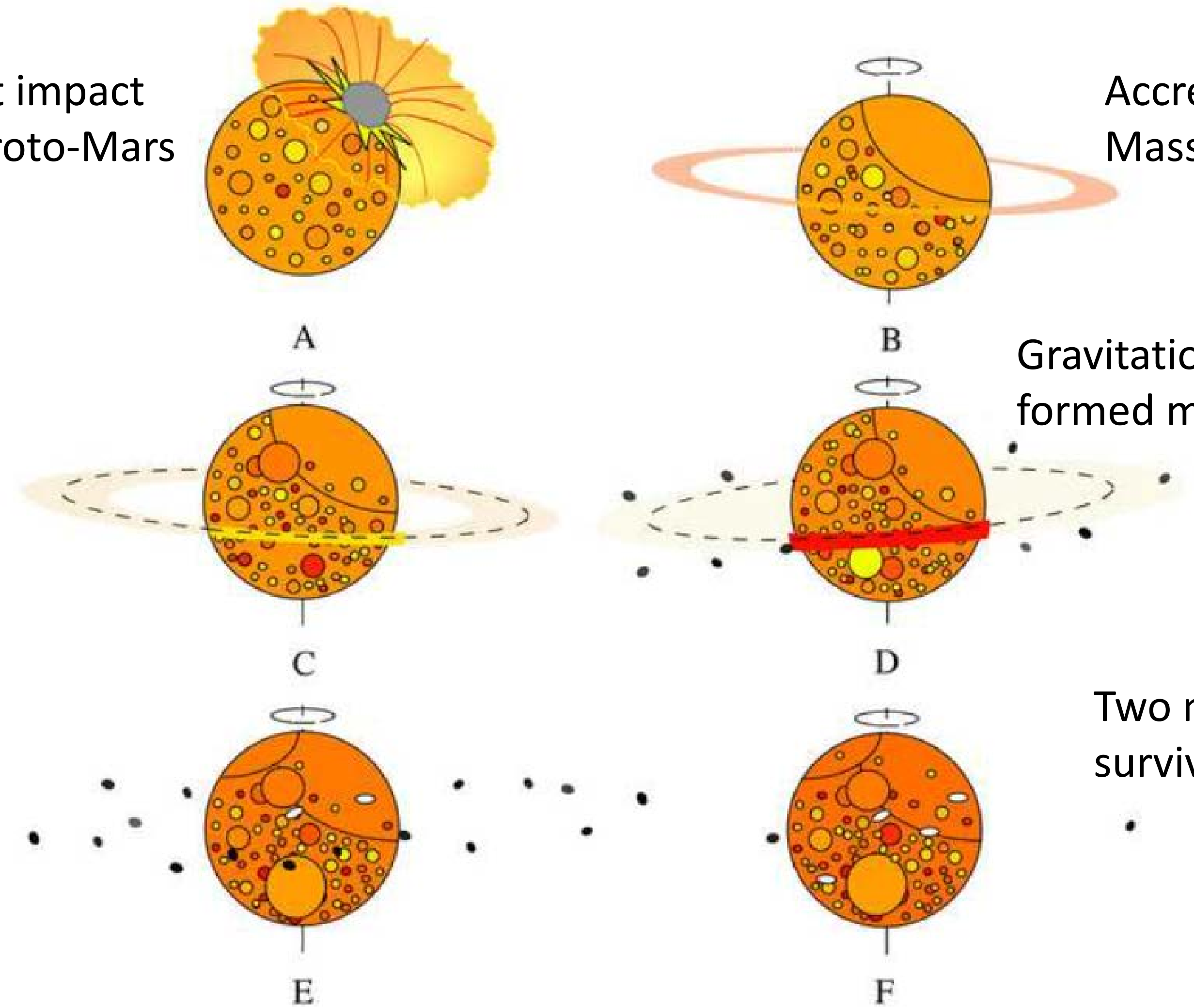
Accretion disk Mass: ~**10^{18}-10^{19} kg**

Gravitational instabilities formed moonlets

Moonlets fall back onto Mars

→ elongated craters

Two moonlets survived 4 Gy later



Physical modelling never been done.
What modern theories of accretion can tell us about that scenario?

3. Purpose of this work:
Origin of Phobos & Deimos consistent with theories of accretion?

✓ Modern theories of accretion : 2 main regimes of accretion.

- (a) **The strong tide regime** => close to the planet ~ Roche Limit

  Background :
  Accretion of Saturn's small moons (Charnoz et al., 2010)
  Accretion of the Earth's moon (Canup 2004, Kokubo et al., 2000)

- (b) **The weak tide regime** => farther from the planet

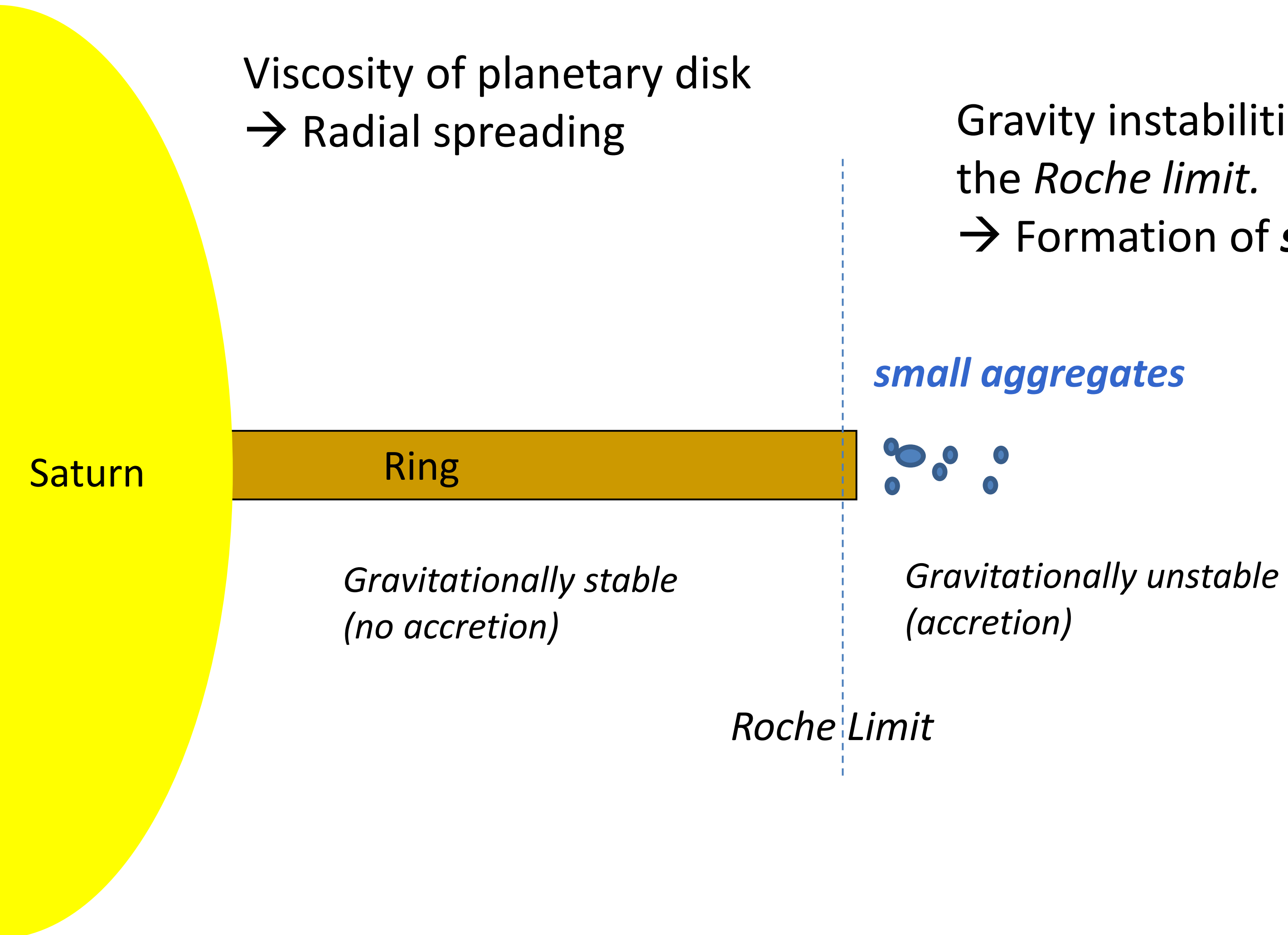
  Background :
  Accretion of big satellites of Jupiter & Saturn
  Accretion of planetary embryos (Lissauer 1987, Kokubo 2007, and works from G. Wetherill, S. Weidenschilling, R. Greenberg)

✓ We explore the consequences of these **regimes of accretion** for the *in-situ* formation of the Martian moons.

1. Accretion in a strong tide regime: basic physics of the disk

Viscosity of planetary disk
→ Radial spreading

Gravity instabilities develop beyond the *Roche limit.*
→ Formation of ***small aggregates***

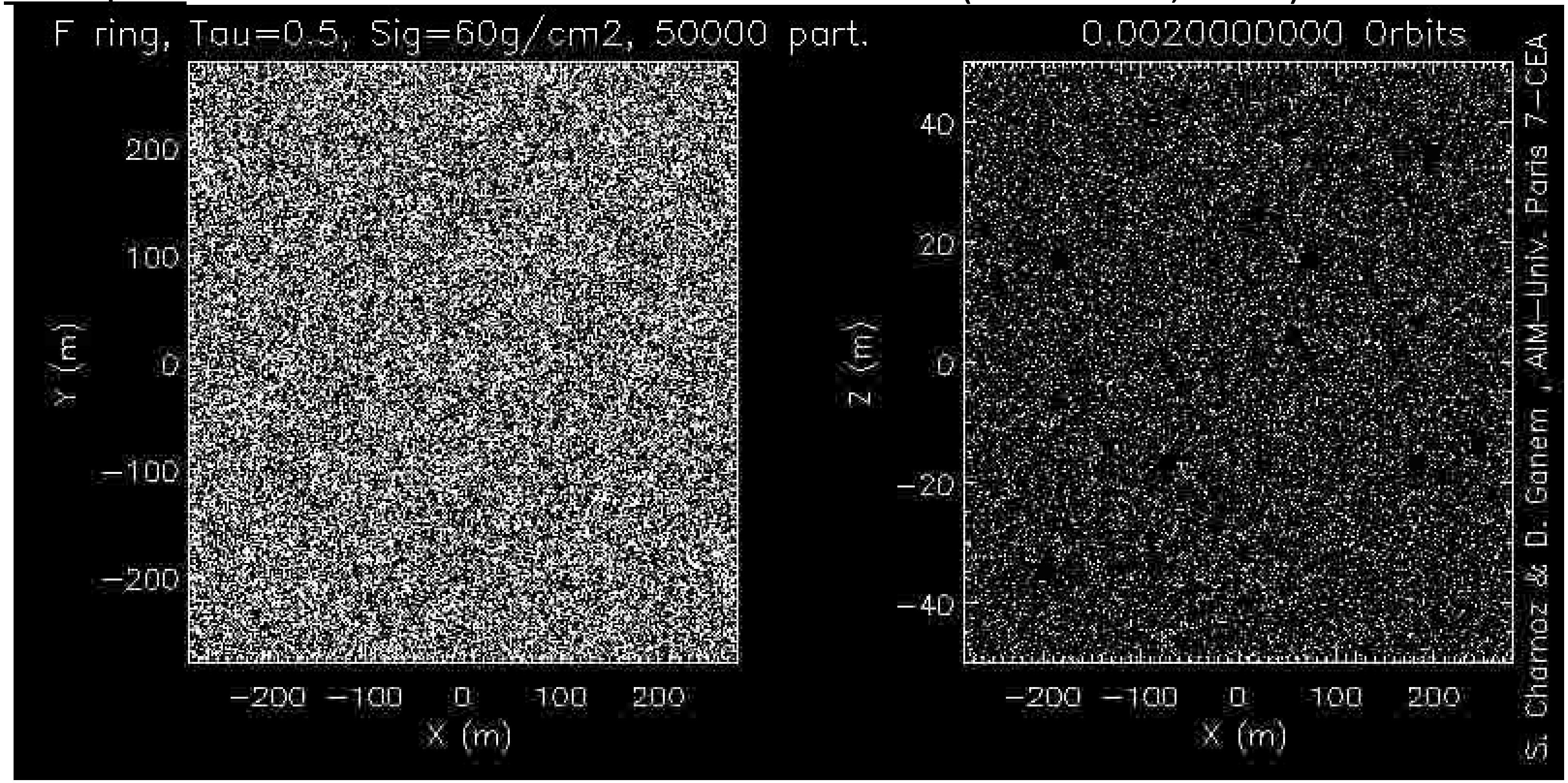


✓ This model explains the origin of Saturn's small Moons (*Charnoz et al., 2010*)

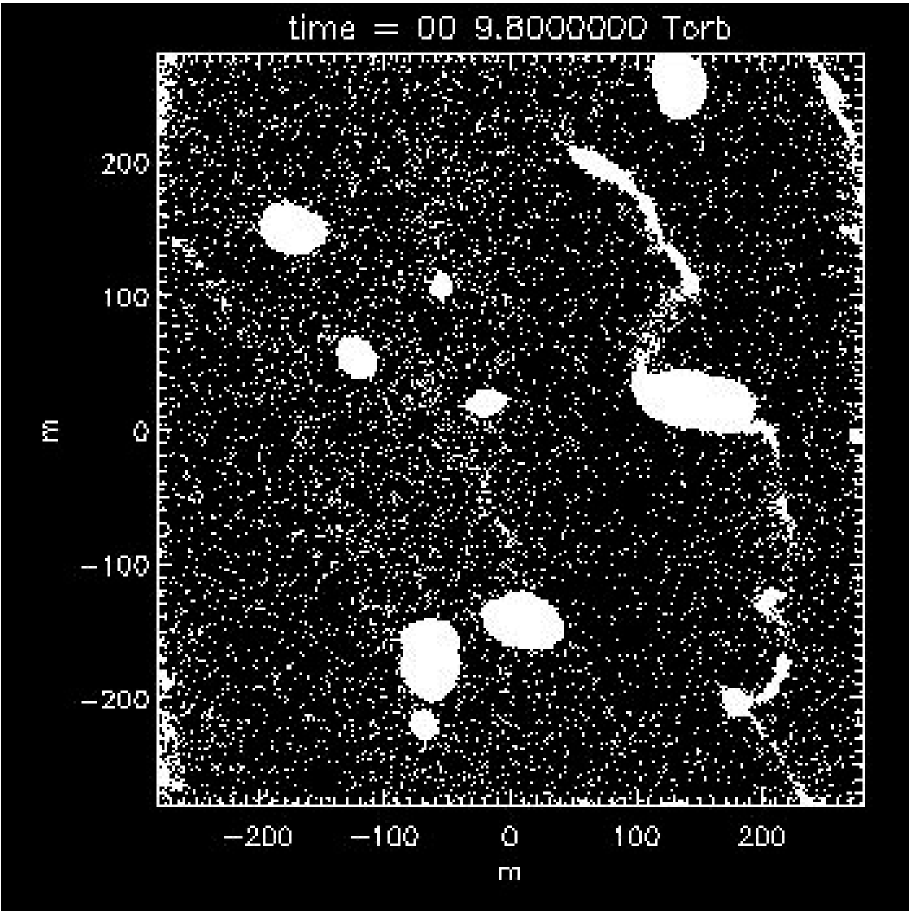
2. Accretion in a strong tide regime: Formation of gravitational instabilities

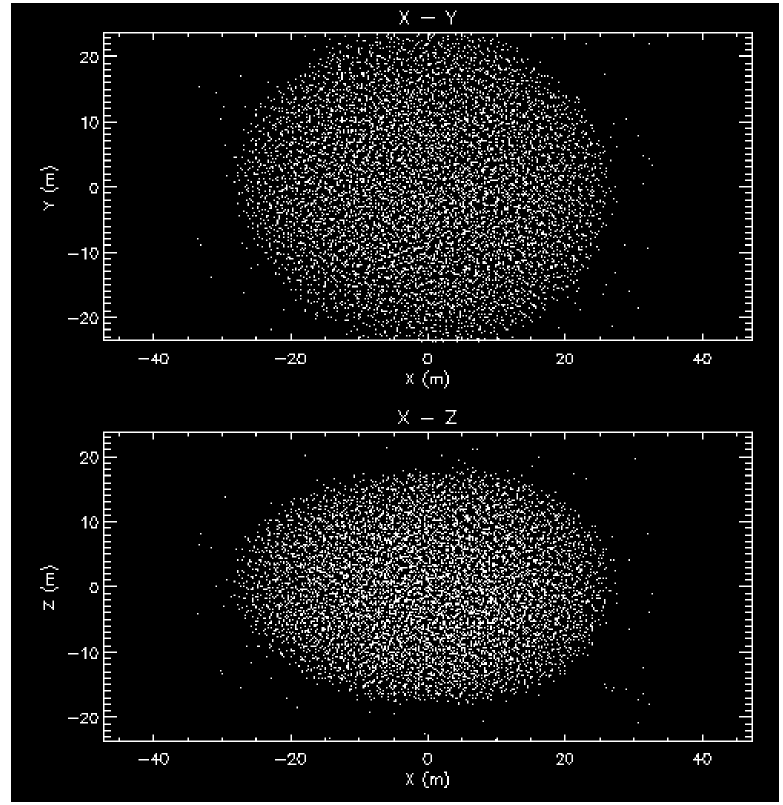
Accretion at the Roche Limit occurs on a short timescale ~ Orbital period

Example : moon formation at Saturn's Roche Limit (S. Charnoz, 2008)



3D local particle simulation (500 m x 500 m)
(Charnoz S., 2008)





Accretion of disk particule in the area of gravitational influence
(or Hill Sphere) of the instability:

→ Creation of elongated moons

With shape ~ Hill Sphere shape (Triaxial ellipsoid with axes ratio : 3:2:2)

3. Morphological properties of moons accreted at the Roche Limit

⇒ **Growth of the gravitational aggregate is limited by its Hill Sphere**

⇒ **A gravitational-aggregate fills ENTIRELY its Hill sphere**

The HILL SPHERE :

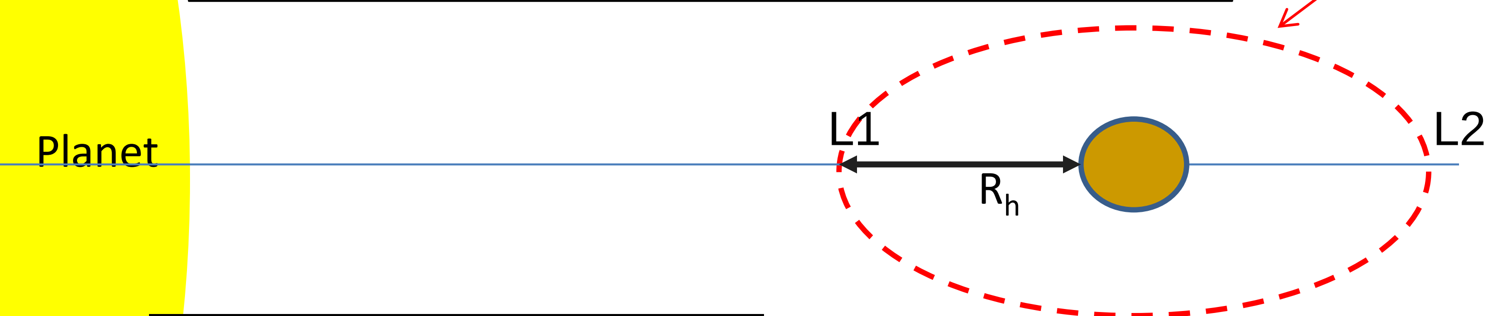
Tri-axial ellipsoid of gravitational influence

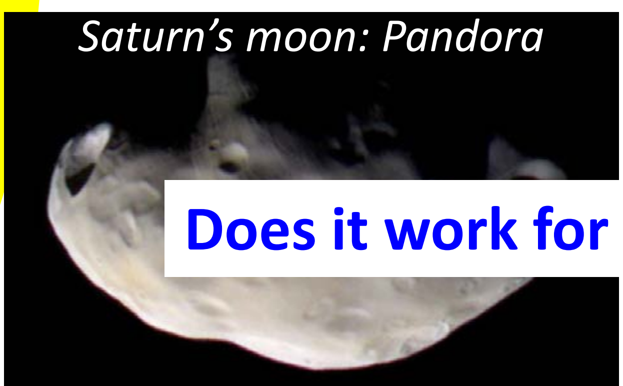
R_h =a(Ms/3Mp)$^{1/3}$ — **Volume : ~1.59 R_h^3**

Axes ratio 3:2:2 — **Density : ~Mp/(1.59 a^3)**

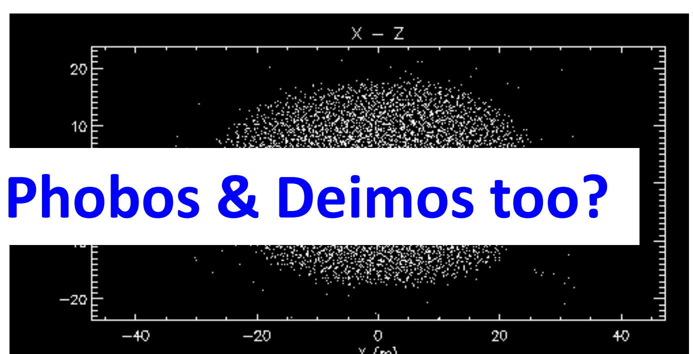
→ It works for Saturn's small moons.

« zone of accretion » of a gravitational-aggregate





Saturn's moon: Pandora



Simulated Grav. Aggregate

(S. Charnoz, 2008)

Does it work for Phobos & Deimos too?

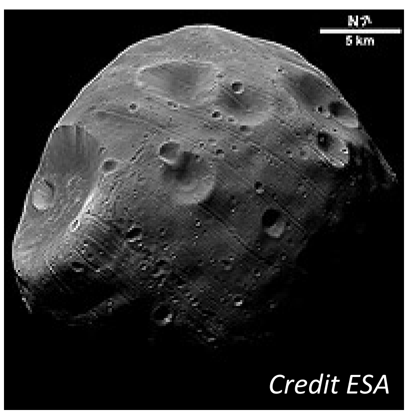
4. *Morphological properties of moon accretion at the Roche Limit: Shape of gravitational aggregates*

In high-tide accretion regime a gravitational-aggregate fills ENTIRELY its Hill sphere

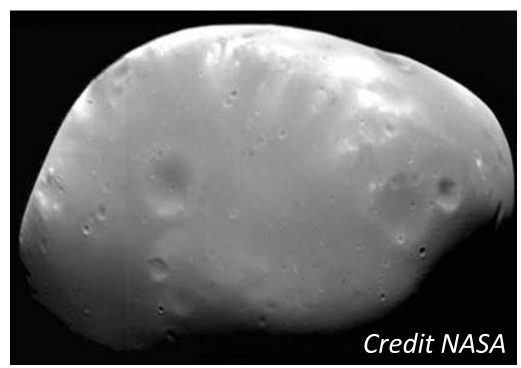
⇒ Shape of Hill Sphere ⇔ Shape of Satellite

⇒ COMPARISON WITH PHOBOS & DEIMOS AXES RATIO:

Phobos	Deimos
Triaxial ellipsoid: 13.0 km x 11.39 km x 9.07 km Axes ratio: 2.86:2.5:2 *(~3:2:2)*	Triaxial ellipsoid: 7.5 km x 6.1 km x 5.2 km Axes ratio: 2.88:2.34:2 *(~ 3:2:2)*



Credit ESA



Credit NASA

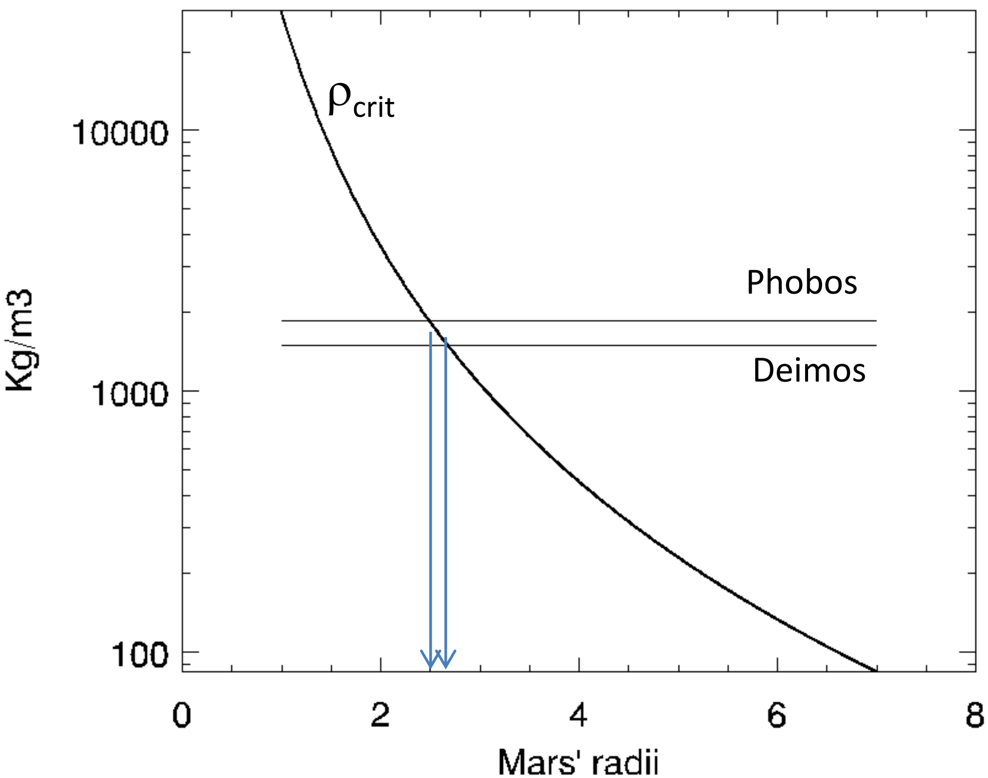
⇒ Axes ratio 3:2:2 roughly respected

5. *Morphological properties of accretion at the Roche Limit: Density of gravitational aggregates*

In a high-tide accretion regime a gravitational aggregate fills ENTIRELY its Hill sphere

=> Density of Hill Sphere ⇔ Density of Satellite

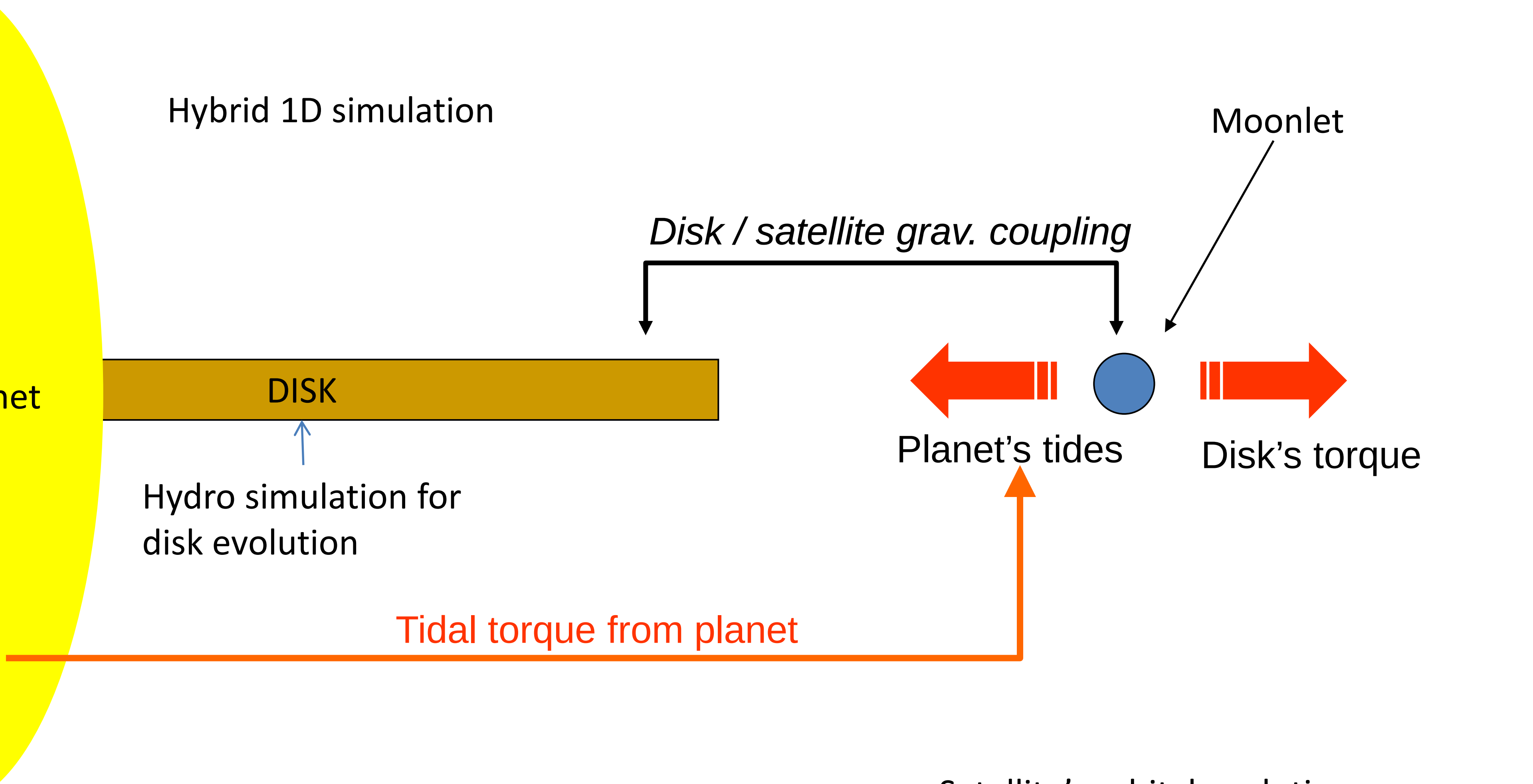
$$\rho_{crit.} \approx \frac{M_p}{1{,}59\ a^3}$$



✓ **Comparison with Phobos/Deimos density:**

Density of the Martian moons are compatible with the expected critical density at Mars' Roche limit ! (=2.5 Mars' radii)

6. Putting all things together in a (simple) large scale numerical simulation:



Disk's viscous evolution:

$$\frac{\partial \sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}(\nu\sigma r^{1/2}) - \frac{1}{3\pi(GM)^{1/2}}r^{1/2}T\right].$$

Viscous torque

Satellite torque

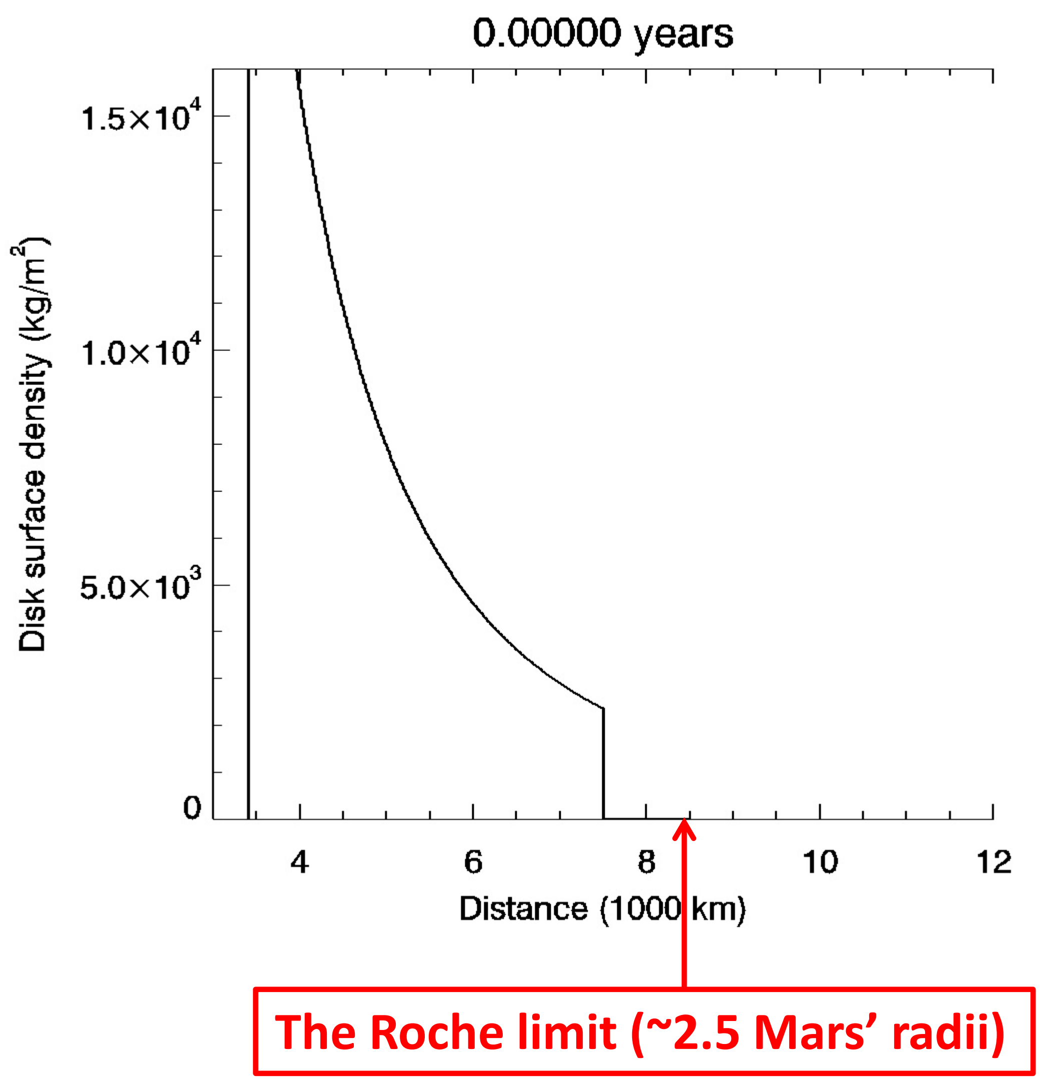
Satellite's orbital evolution
(distance to Mars - semi-major axis):

$$\frac{da_i}{dt} = \frac{3k_2^J n_i m_i (E_r)^5}{Q_J a_i^4 m_0}\left[1 + \frac{51 e_i^2}{4}\right] + \frac{2a_s^{1/2}\Gamma_s}{m_s(GM)^{1/2}}$$

Tidal dissipation in Mars

7. Results of numerical simulations with a disk of ~ 100 Phobos' mass:

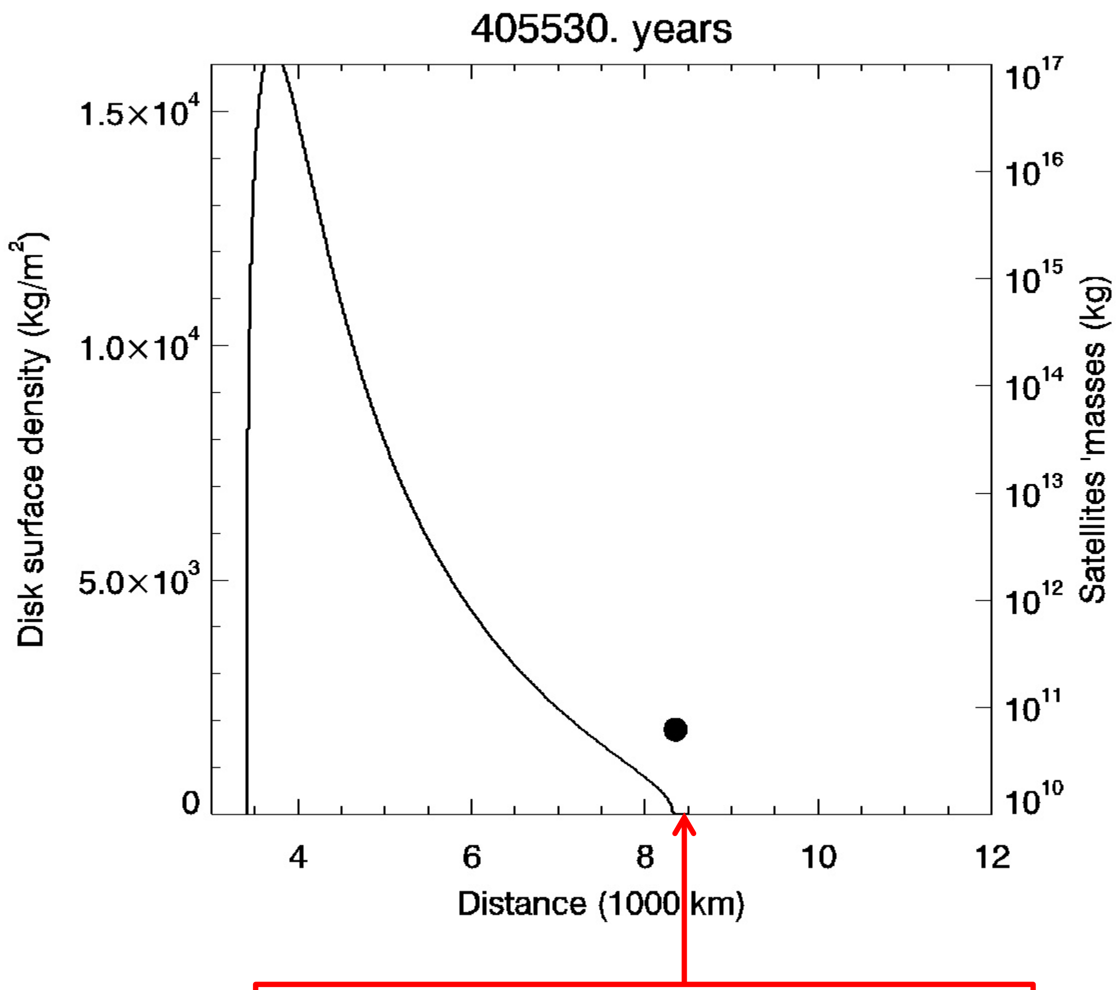
Initial mass of the disk = **10^{18} kg** (Craddock, 2011)



7. Results of numerical simulations with a disk of ~ 100 Phobos' mass:

Viscous spreading of the disk makes it crossing the roche limit

➡ *Moonlets form at the Roche limit with a relatively low mass (10^{11} kg)*

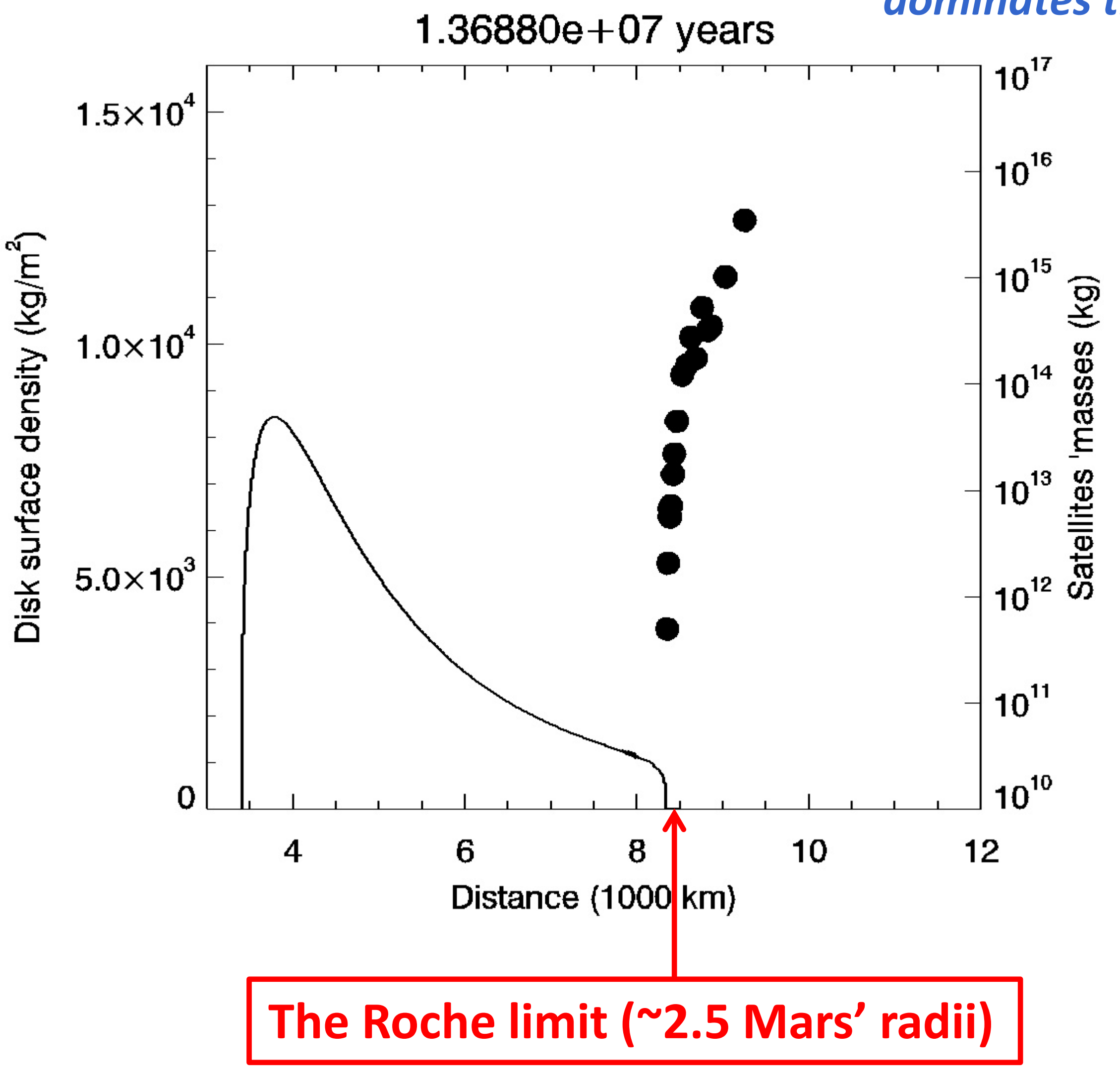


The Roche limit (~2.5 Mars' radii)

7. Results of numerical simulations with a disk of ~ 100 Phobos' mass:

As viscous spreading continues several tens of moonlets are formed after about 10 Ma

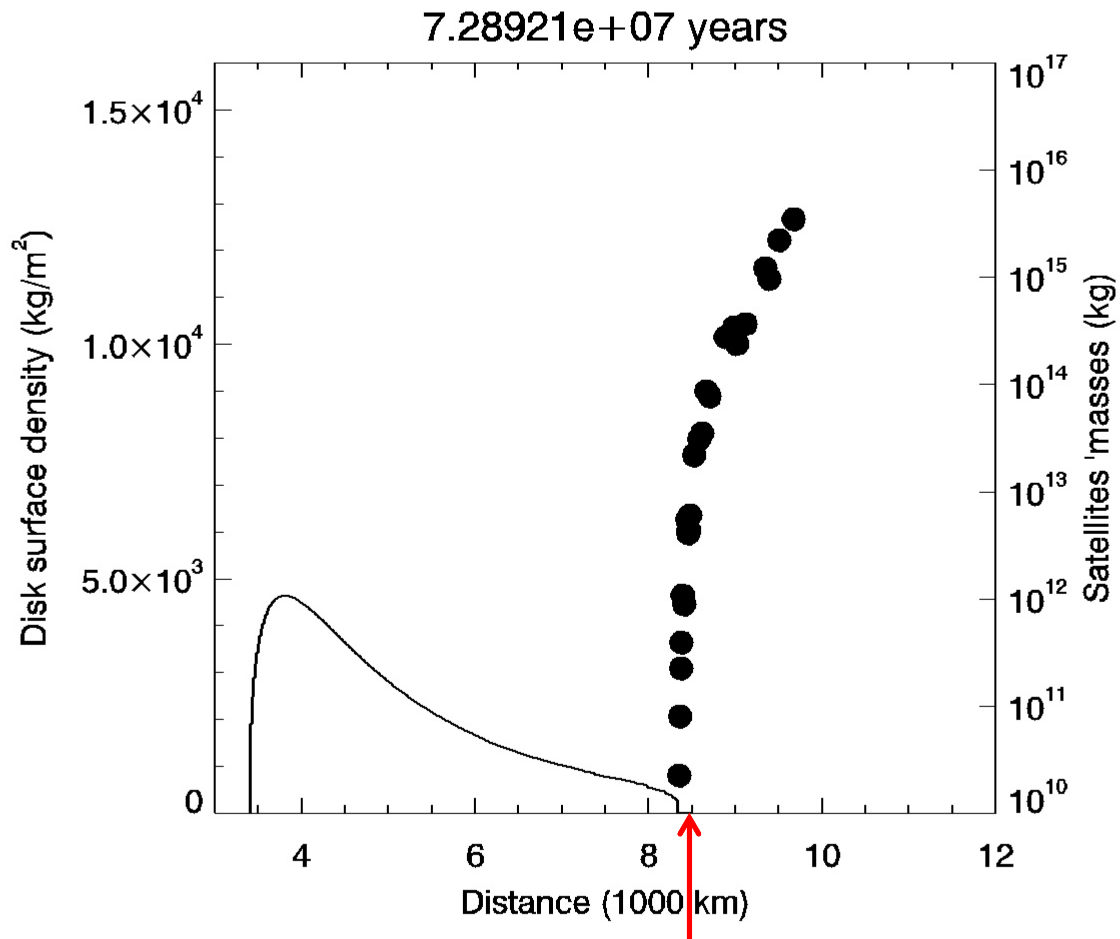
Moonlets can reach a mass up to to Deimos' mass (10^{15} kg). Disk gravitational torque dominates the orbital evolution.



7. Results of numerical simulations with a disk of ~ 100 Phobos' mass:

As the disk loses more and more mass, it is pushed below the Roche limit, stopping the accretion.

Moonlet orbits cannot reach Deimos' orbit beyond Mars synchronous limit (20000 km)

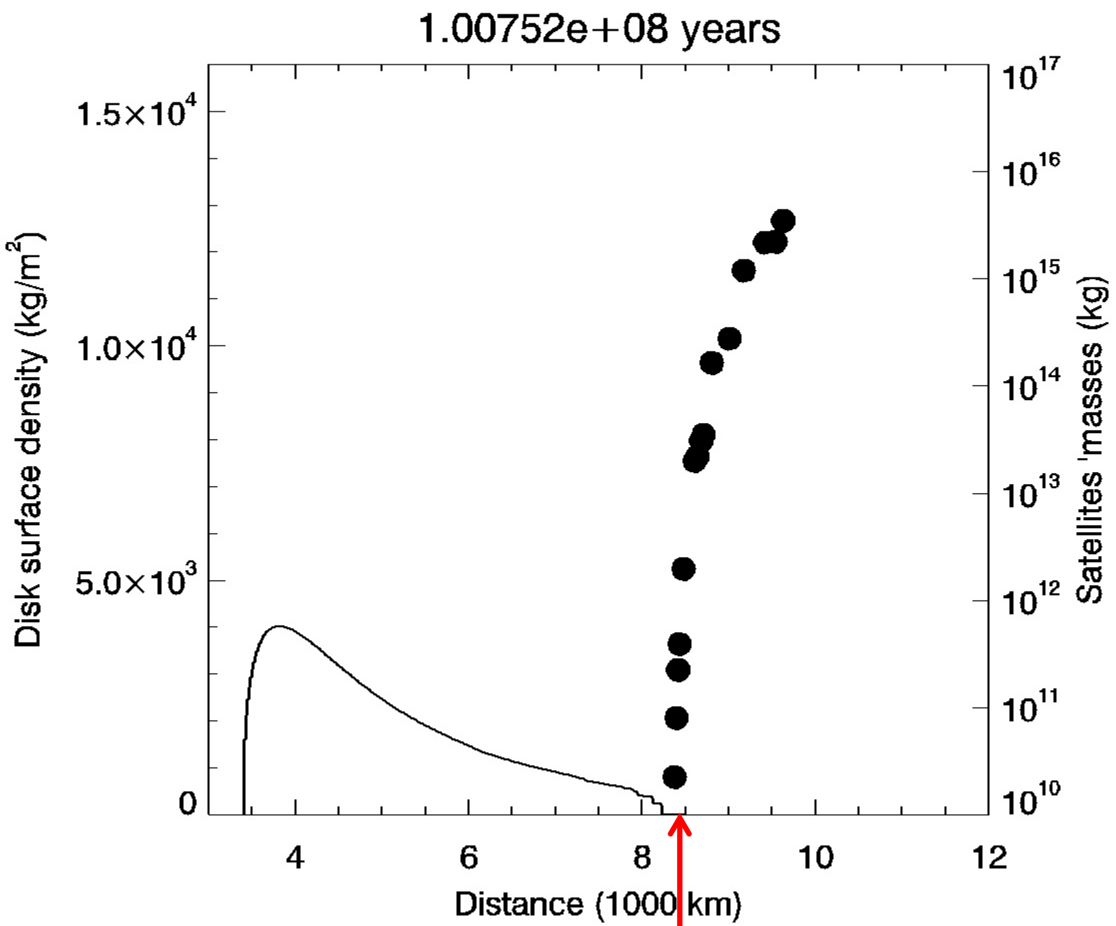


The Roche limit (~2.5 Mars' radii)

7. Results of numerical simulations with a disk of ~ 100 Phobos' mass:

After 100 Ma, the disk has lost most of its mass through its inner edge.

The evolution of moonlet orbit is now dominated by tidal decay. Moonlets recede back to Mars.

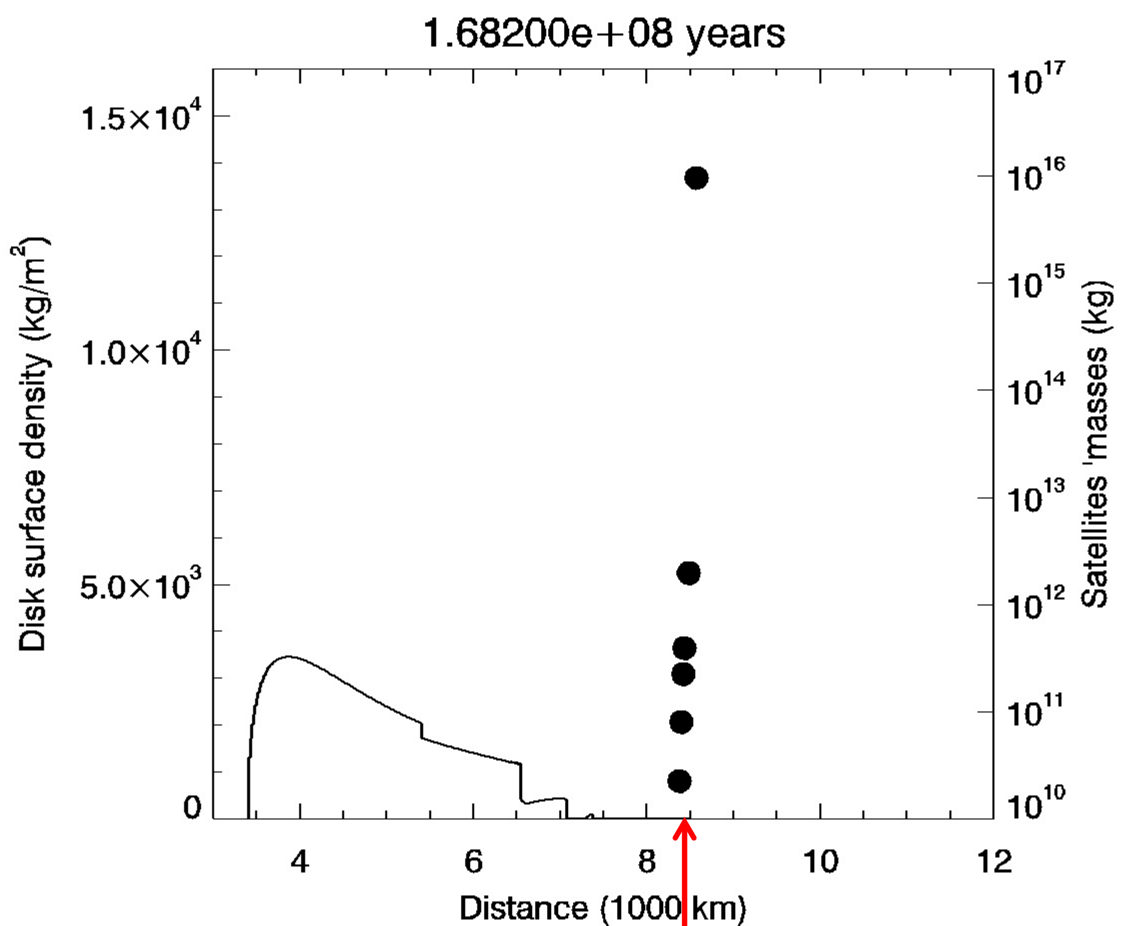


The Roche limit (~2.5 Mars' radii)

7. Results of numerical simulations with a disk of ~ 100 Phobos' mass:

The disk is pushed inward by the moonlets receding back to Mars.

Moonlets accrete together, reaching the mass of Phobos (10^{16} kg)

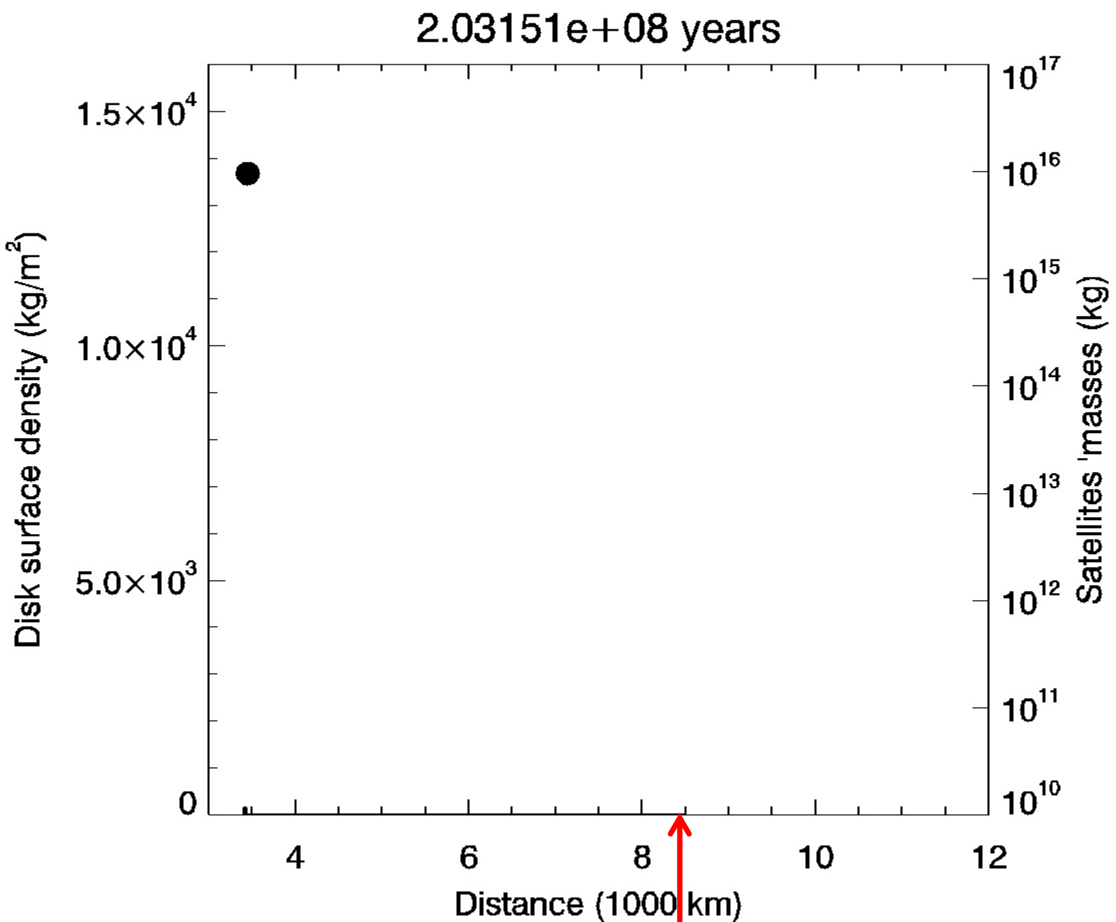


The Roche limit (~2.5 Mars' radii)

7. Results of numerical simulations with a disk of ~ 100 Phobos' mass:

In less than 1 Gyr, the disk disappeared
and all the moonlets have fallen back to Mars.

Inconsistent with 4 Gy old Martian moon system



The Roche limit (~2.5 Mars' radii)

Main conclusion about the strong tide regime of accretion

- GOOD:
  Moonlets with the shape & density of Phobos & Deimos can be formed in a Martian gravitationally unstable accretion disk (**strong-tide regime** of accretion) → **consistent with Craddock (2011)**

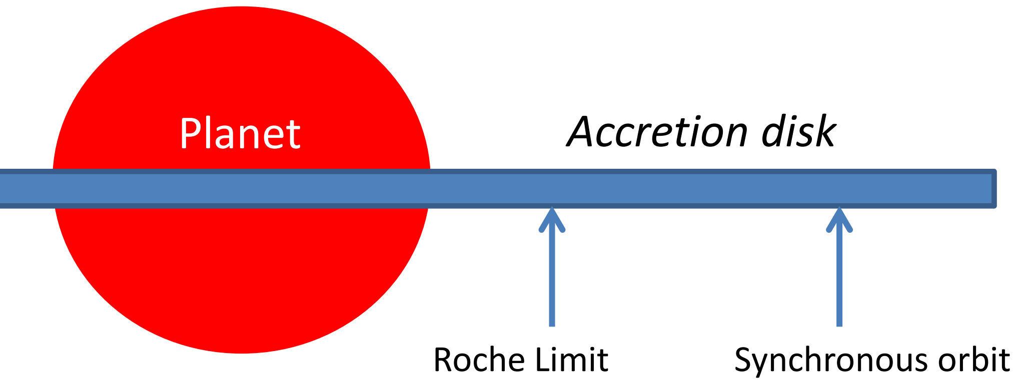
- BAD:
  This moonlet system is inconsistent with a 4 Gy old Martian satellite system and with Deimos' location (> synchronous orbit)
  → **inconsistent with Craddock (2011)**

- A less massive disk would last longer but would form less massive moonlets and could not still form a Deimos at its current location.

- Needs to explore the **weak tide regime** of accretion (more consistent with Deimos' location, …)

1. Weak tide regime (far from the planet): ~planet like accretion in a disk

- ✓ **The Hill sphere is much larger than the body size.**
- ✓ **Accretion is driven by two-bodies encounter.**



✓ **<u>Hypothesis :</u>**

Disk extends to the synchronous orbit (~6 Mars' radii).

Disk NOT gravitationally unstable (→ low dense and hot)

✓ **Accretion disk surface density profile:**

$$\sigma(r) = \sigma_0 \, r^q$$

with **$-5 < q < -0.5$** (inspired from p.p disks, simulation of moon formation)

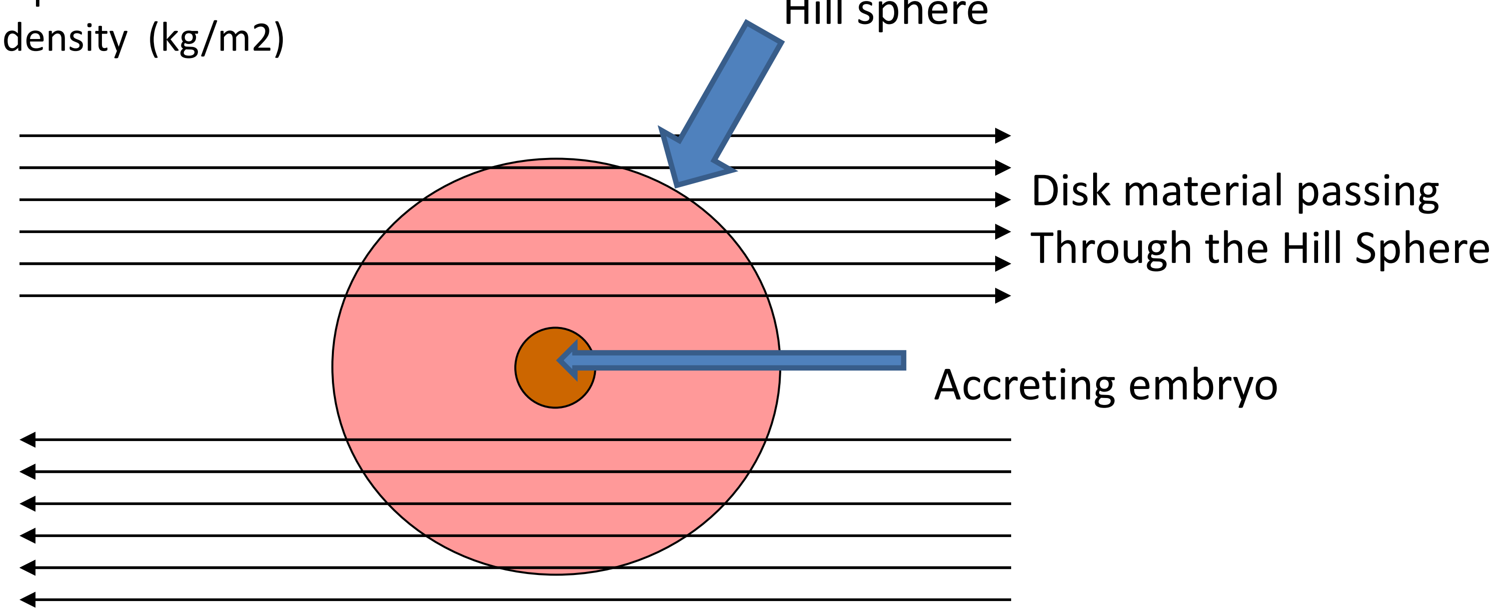
2. Weak tide regime (far from the planet): The Isolation Mass

- The mass of accreted bodies is limited by the amount of material in their feeding region (Hill Sphere).

➔ **Maximum growth mass = ISOLATION MASS « Mi »** (*Lissauer, 1987*):

$$Mi=(16\pi r^2\,\sigma)^{3/2} / (3\,M_p)^{1/2}$$

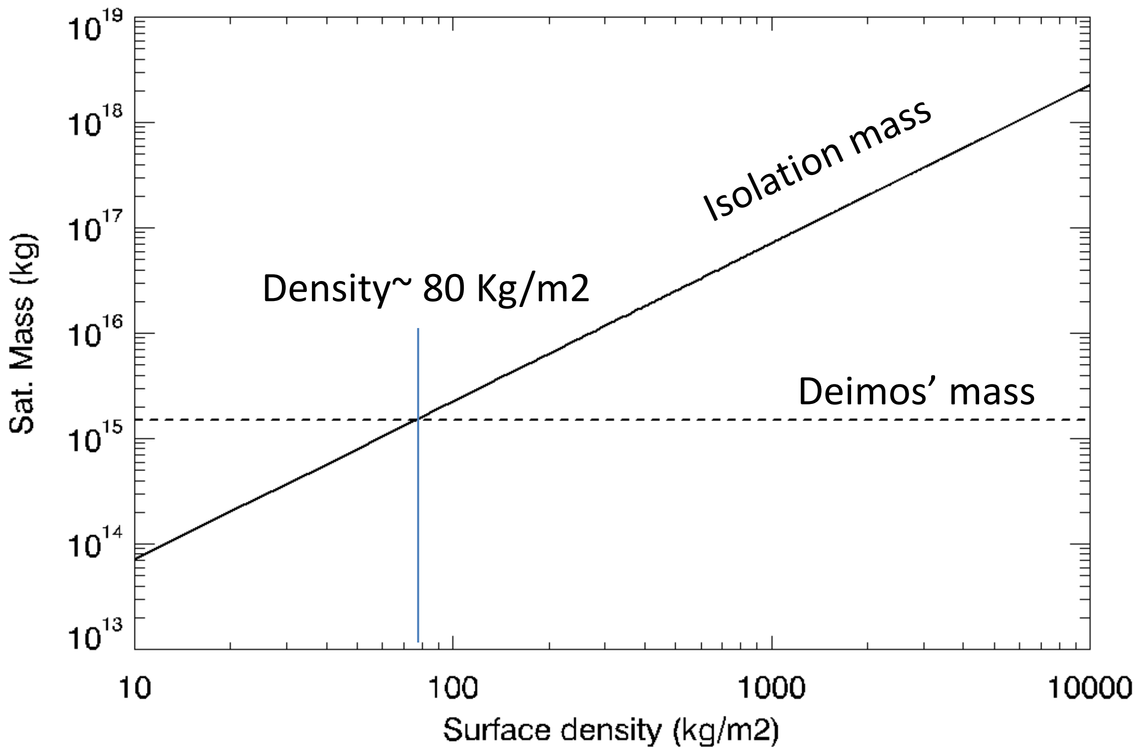
r = distance to Mars, Mp = Mars' mass
σ = local disk surface density (kg/m2)



- If Deimos formed near its current distance as a « satellite embryo », then we can derive the surface density of the disk @ Deimos location needed to reach the isolation mass.

3. Weak tide regime : Comparison with Deimos' mass

Disk surface density @ Deimos location



- ✓ Density of 80 Kg/m2 at 6 Mars' radii is compatible with a disk's mass of:

  1.2 10^{18} Kg (with q=-3)

  3.7 10^{18} Kg (with q=-4)

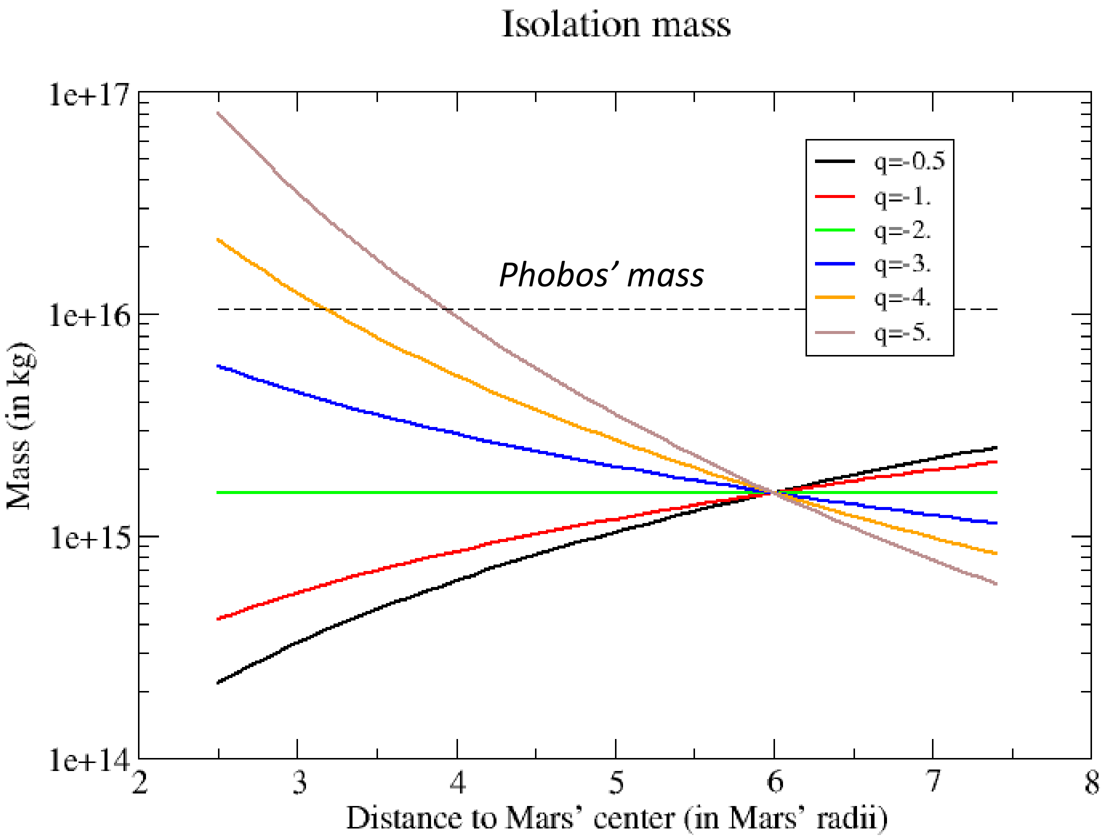
- ✓ Or with a disk of 10^{18} Kg extending from 1 Mars Radius to:

  70 Mars radii (with q=-1.5)

  40 Mars radii (with q=-1)

- ➢ Deimos' mass is compatible with the expected accretion disk's surface density at Deimos orbit for a disk's mass of ~ 10^{18} kg (Craddock, 2011).
- ➢ Deimos may be a satellite embryo too.
- ➢ However, the disk is required to extend beyond the synchronous orbit.

3. Weak tide regime : Comparison with Phobos' mass



- ✓ Isolation mass profile derived from disk's surface density profile (different *q* values)
- ✓ Each profile provides a mass equal to Deimos' mass at 6 Mars' radii

> Isolation mass can reach Phobos' mass
→ A Phobos' mass embryo can also be formed in the same disk as for Deimos.

> This embryo is formed closer to Mars (< 4 Mars' radii). Thus, expected to rapidly fall back to Mars due to tidal decay of its orbit.

> It requires that a Phobos' mass embryo be formed closer to synchronous orbit.

SUMMARY

- Phobos/Deimos formation in an accretion disk seems possible.

- **In a strong tide regime:**
  Consistent with shape/density of the moons
  Inconsistent with a 4 Gy old Martian satellite system
  with Deimos' location (> Synchronous orbit)

- **In a weak tide regime:**
  Consistent with Deimos' mass and location.
  Problems raised:
  Phobos' mass body at its current location?
  It may require specific properties of the disk
  (spreading farther from the planet , low density, …)

- **Further investigations**
  Numerical simulations of accretion in a disk extending primarily below the synchronous orbit.

BACKUP SLIDES

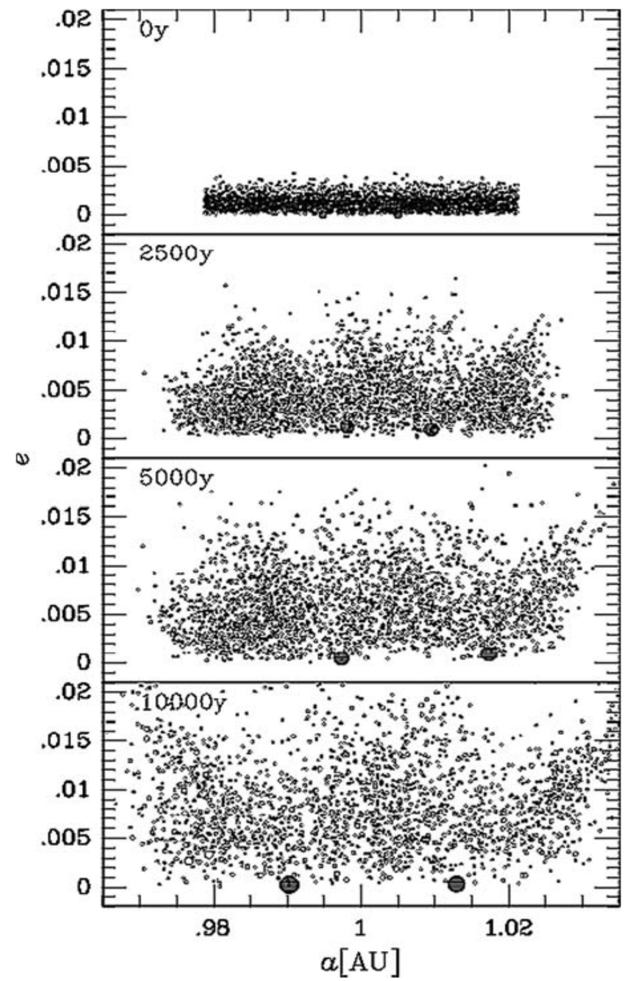
4. Low-tide regime (far from the planet): Number of moons formed

✓ **After the formation of embryos**

- Embryos tend to appear on orbits separated by 5-10 x the Hill Sphere radius

- A population of ~ 50-100 embryos may appear between ~Mars' Roche limit and Deimos' orbit

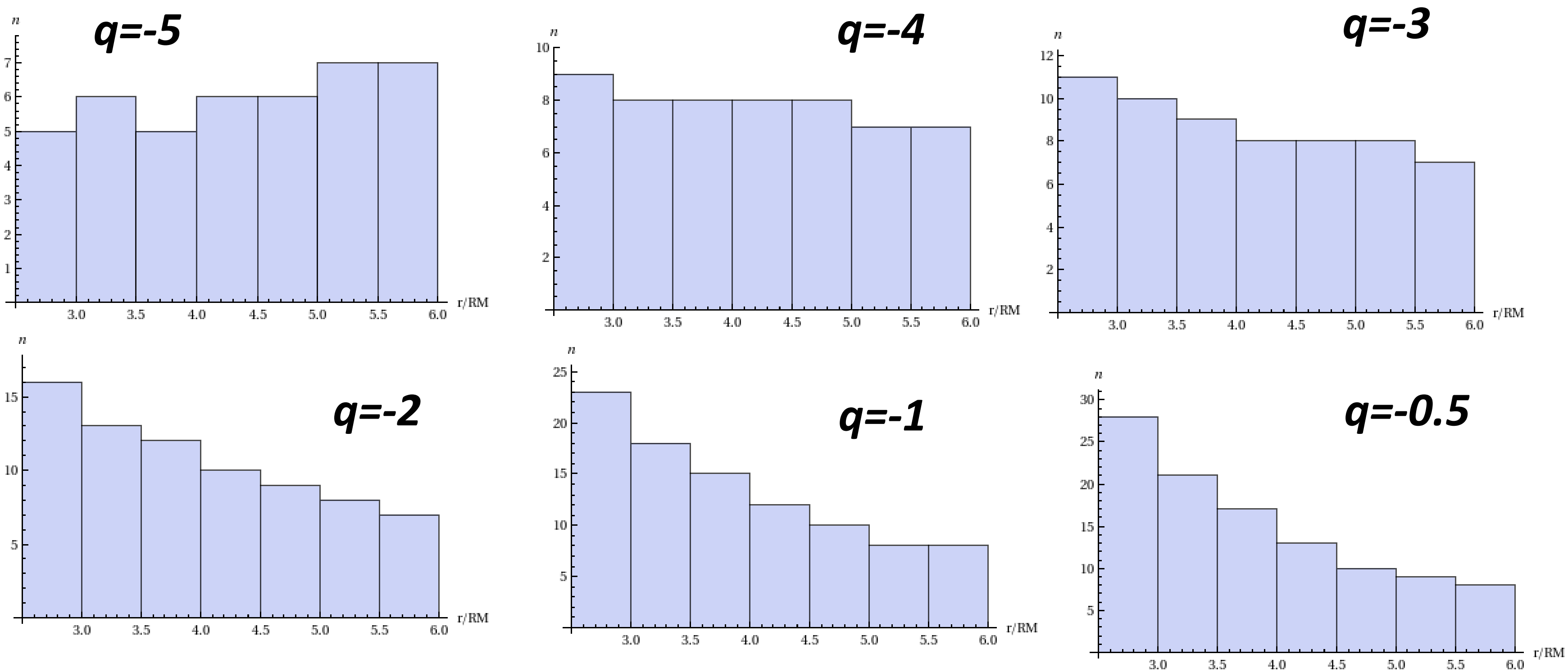
- Most of them may fall onto the planet (orbital tidal decay)
  → Consistent with Craddock (2011)



Thommes & Duncan 2007

✓ **<u>Questions:</u>**
Is Phobos the last representent of the falling population?
Is Deimos the single representent of the population > Rsyncronous ?

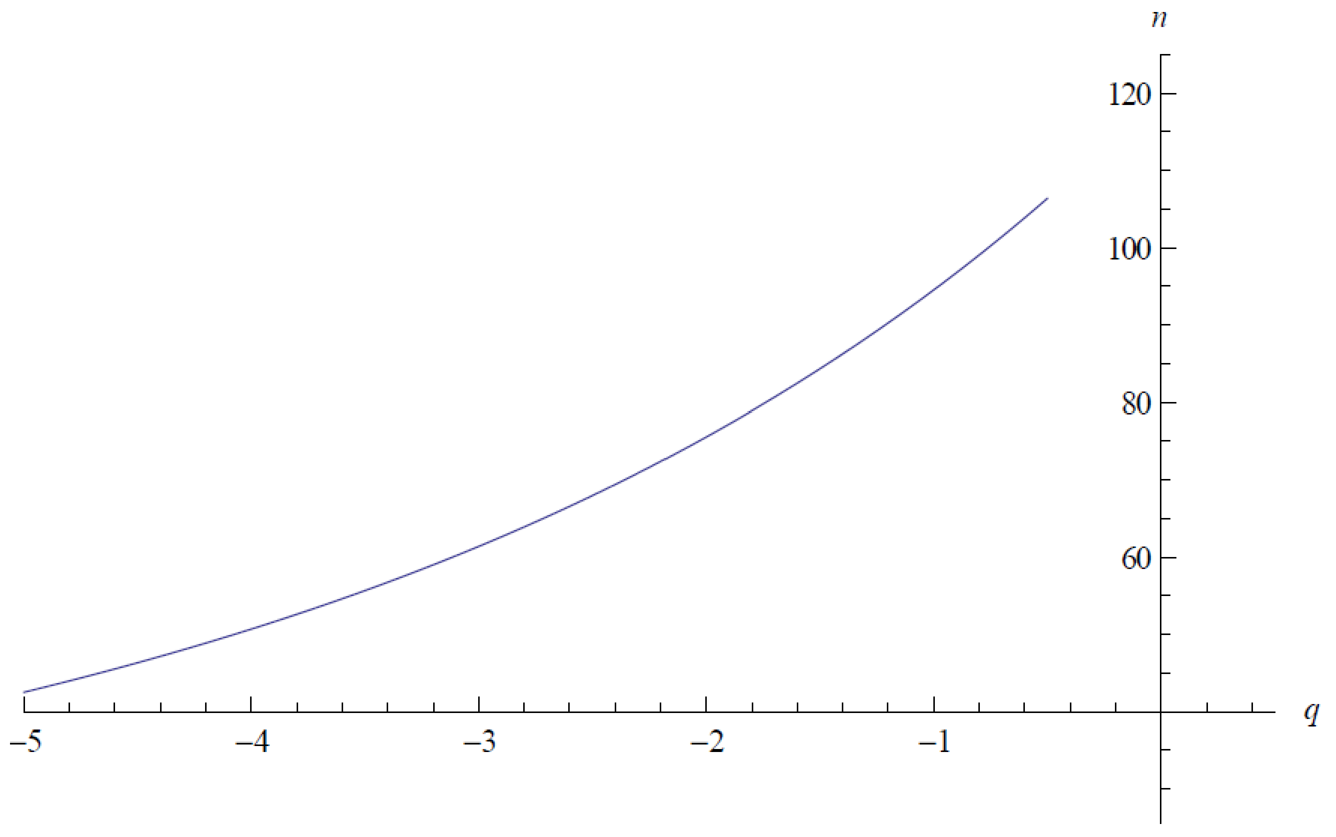
3. Weak tide regime :
Number of satellite embryos vs distance to Mars



- The number of satellite embryo expected at distances close to the synchronous limit (between 5.5 and 6 Mars' radii) is around **7** !

- As the mass of these embryos is close to Deimos' mass, and as Deimos' mass is **7** times Phobos' mass, then :
  → Can Phobos be formed by accretion of embryos near the synchronous limit?

3. Weak tide regime : Number of satellite embryos vs Mars' elongated craters



- The number of satellite embryo is ranging from 50 to 110 depending on the disk' surface density profile (*q* value).

- This number is just lower than the estimated elongated craters (102 to 174), which could have been fiormed from decaying moonlets.

Acknowledgements

This work was financially supported by the Belgian PRODEX program managed by the European Space Agency in collaboration with the Belgian Federal Science Policy Office.

BELGIAN SCIENCE POLICY

esa