Physics of Planetary Rings

and Signposts of Planets

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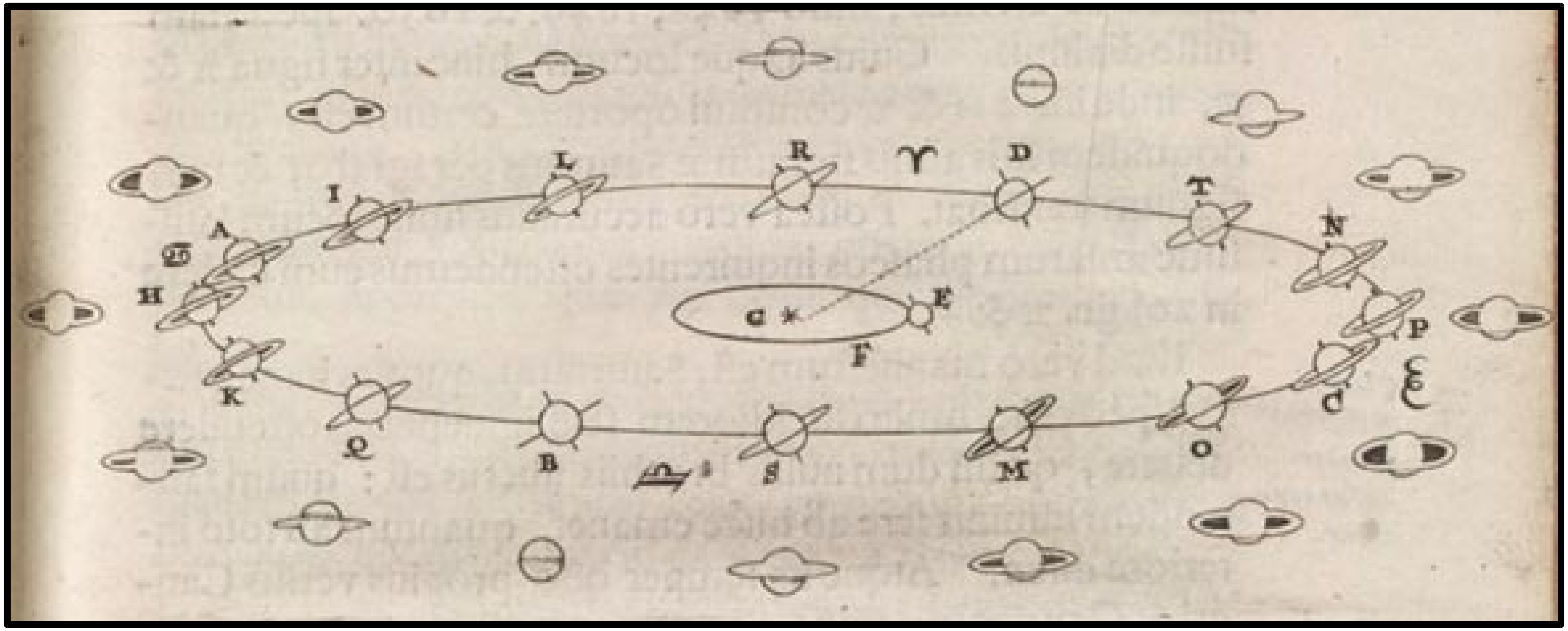
INTRODUCTION

1655: Huygens says that Saturn « is encircled by a ring, thin, plane, nowhere attached, inclined to the ecliptic.»



1675: Cassini discovers the Cassini division, and suggests that the rings are made of boulders orbiting Saturn, hitting each other.

INTRODUCTION: TIDES

Maxwell shows it can only be so, because of **tides**.

Saturn's tides > self-gravity :
the rings are inside the *Roche limit*.

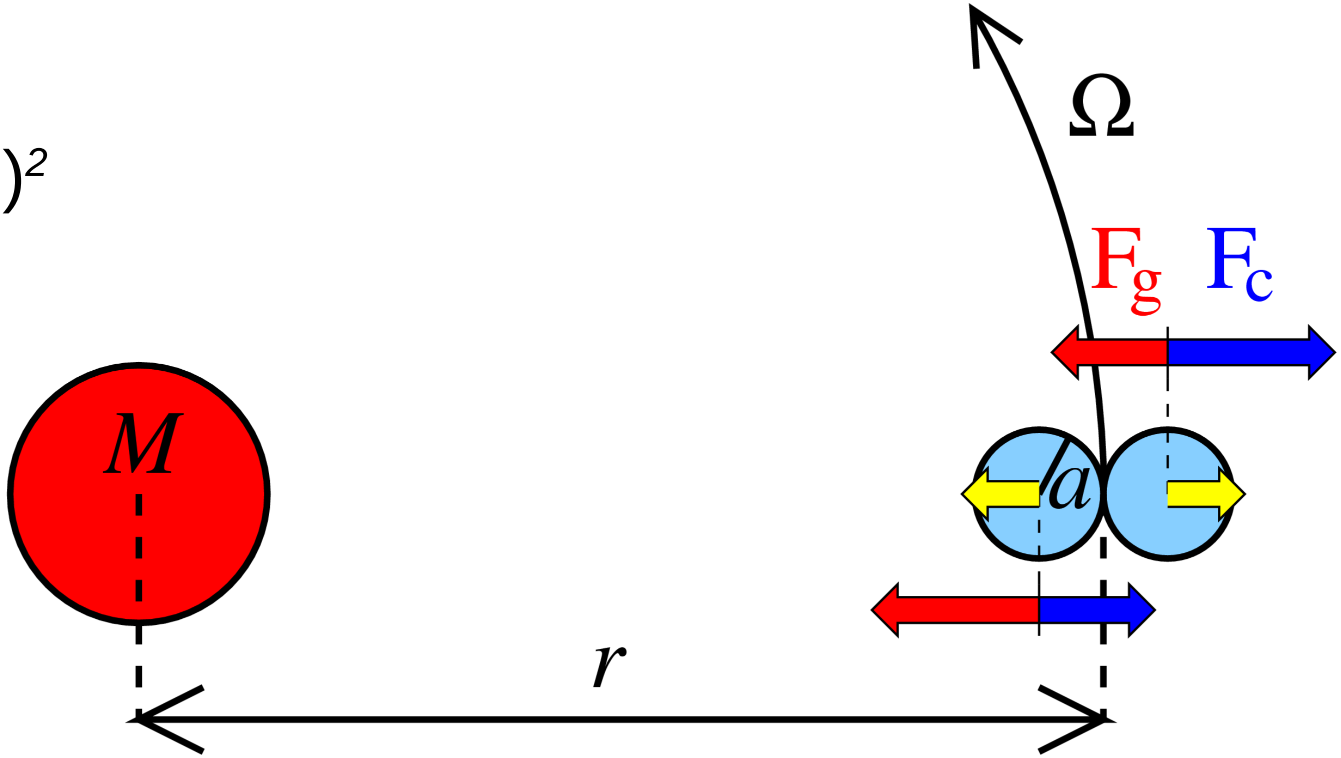
Reminder : Tidal forces (per mass unit) :

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

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

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

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



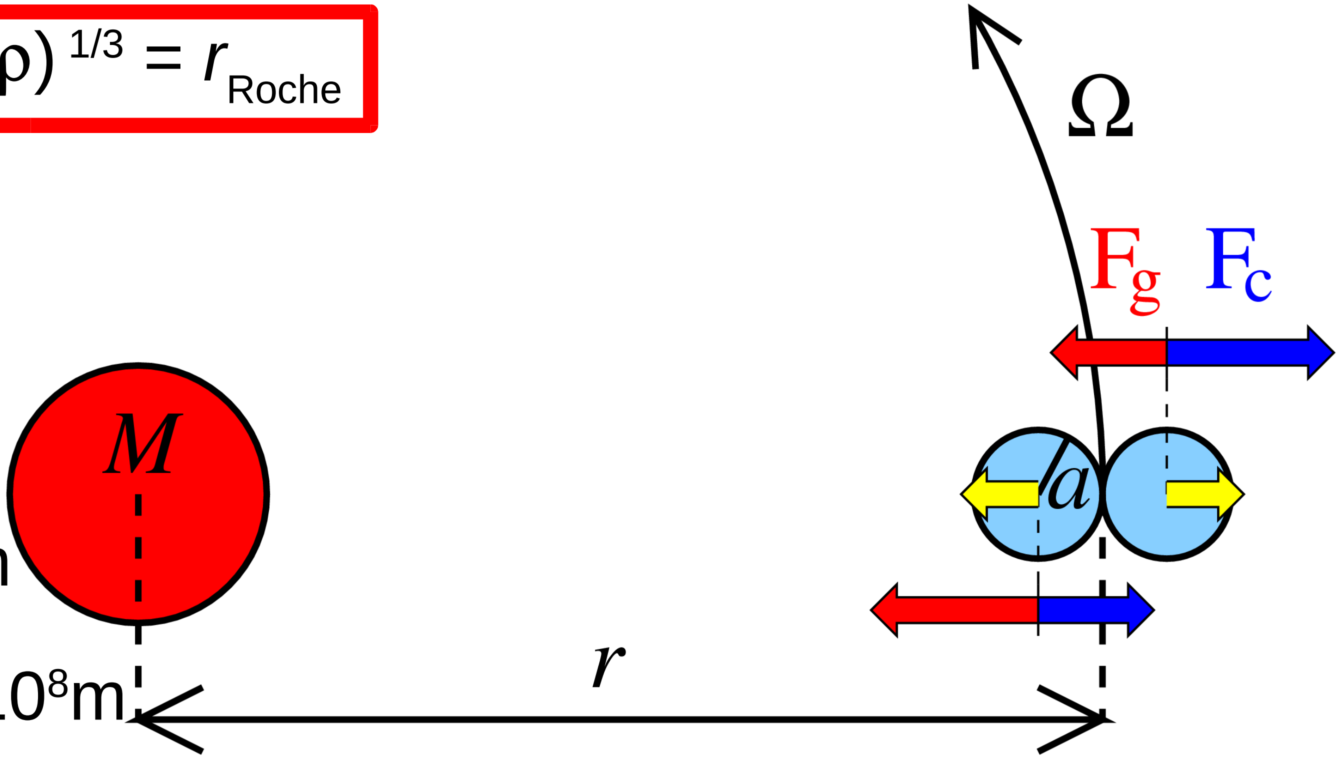
INTRODUCTION: TIDES

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

Self gravity force (per mass unit) : $F_{sg} = G_{\times}(4/3)\pi a^3\rho / (2a)^2$

Stability condition for the aggregate : $F_{sg} > F_{tides}$

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



Application:

$M = M_{Saturn}$,

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

$r_{Roche} = 1.4\ 10^8\ \mathrm{m}$

$r_{outer\ edge} = 1.36\ 10^8\mathrm{m}$

TIDES

In the rings, accretion and tidal disruption of aggregates are the norm.

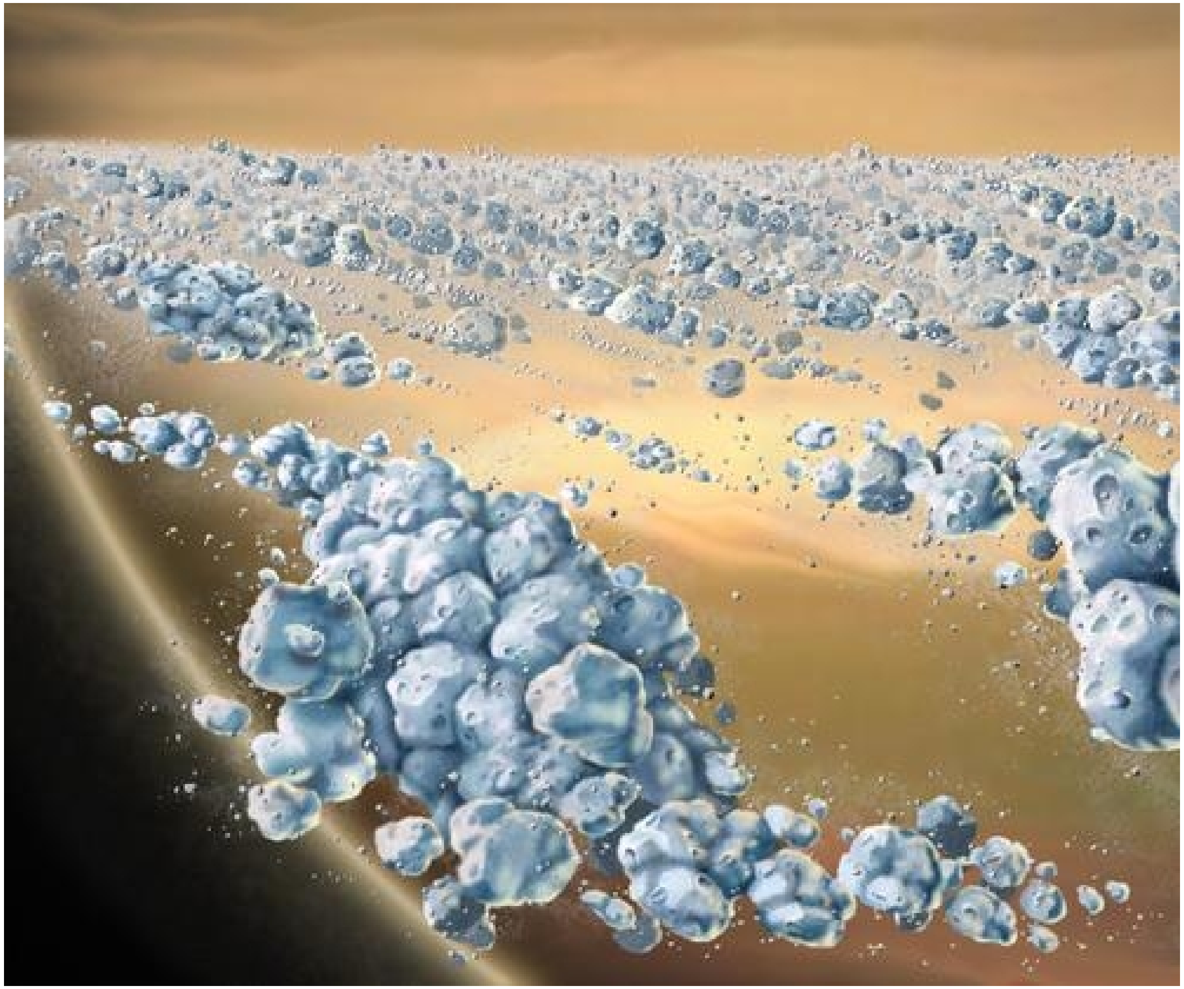
Movie by Hanno Rein, in a shearing box, in the frame corotating with the blue spot.

DYNAMICS: Main rings

Composition:

10cm-10m blocks (French & Nicholson 2000, Cuzzi et al. 2007) of more than 90% pure water ice (eg Cuzzi et al. 2010),

on circular, coplanar orbits :
e~0,
i~0 (H/r=10^{-7}).



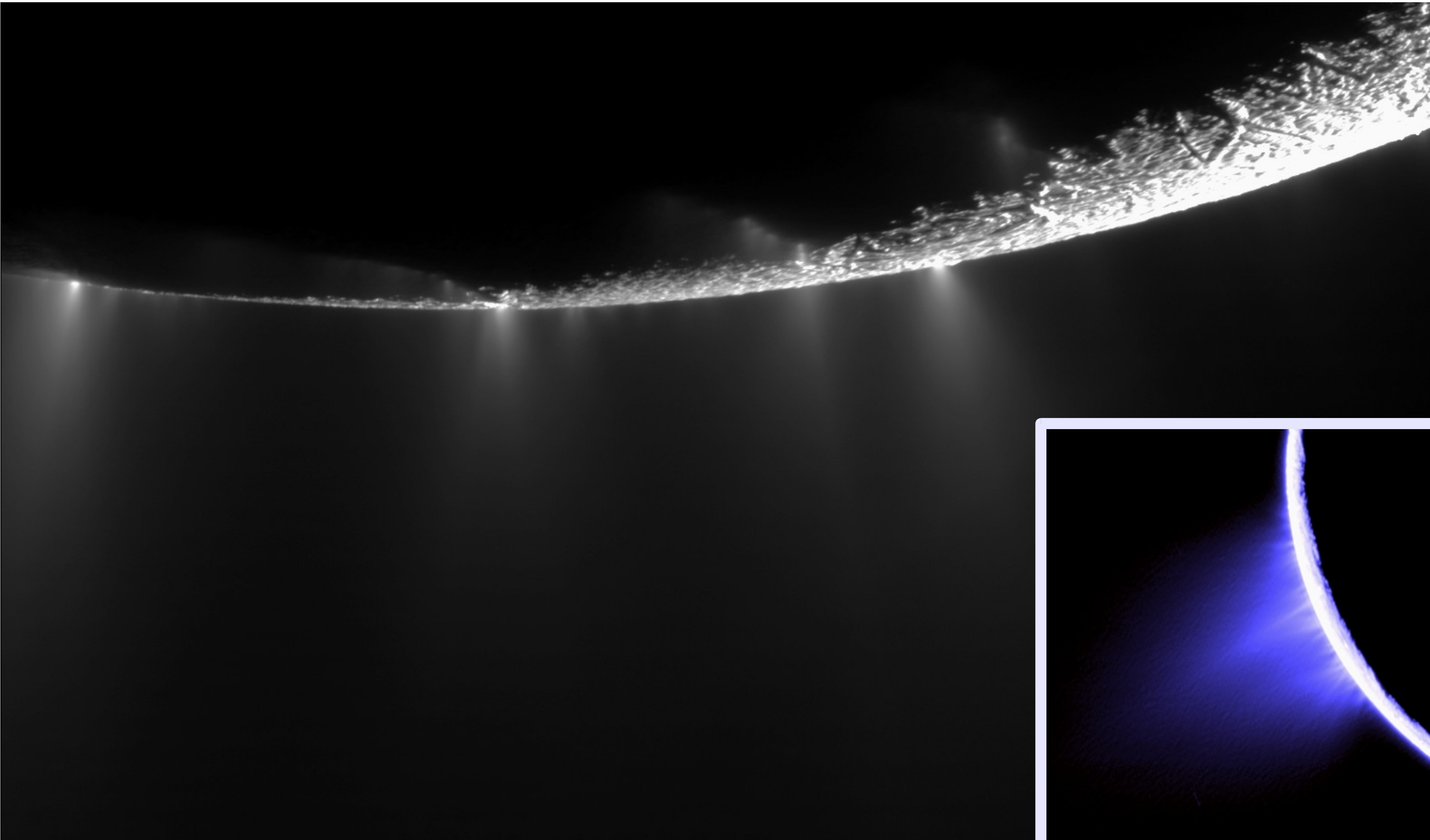
Saturn's main rings are dynamically cold, dominted by tides.

DYNAMICS: the E-ring

But the E-ring is beyond r_{Roche}, and thick.

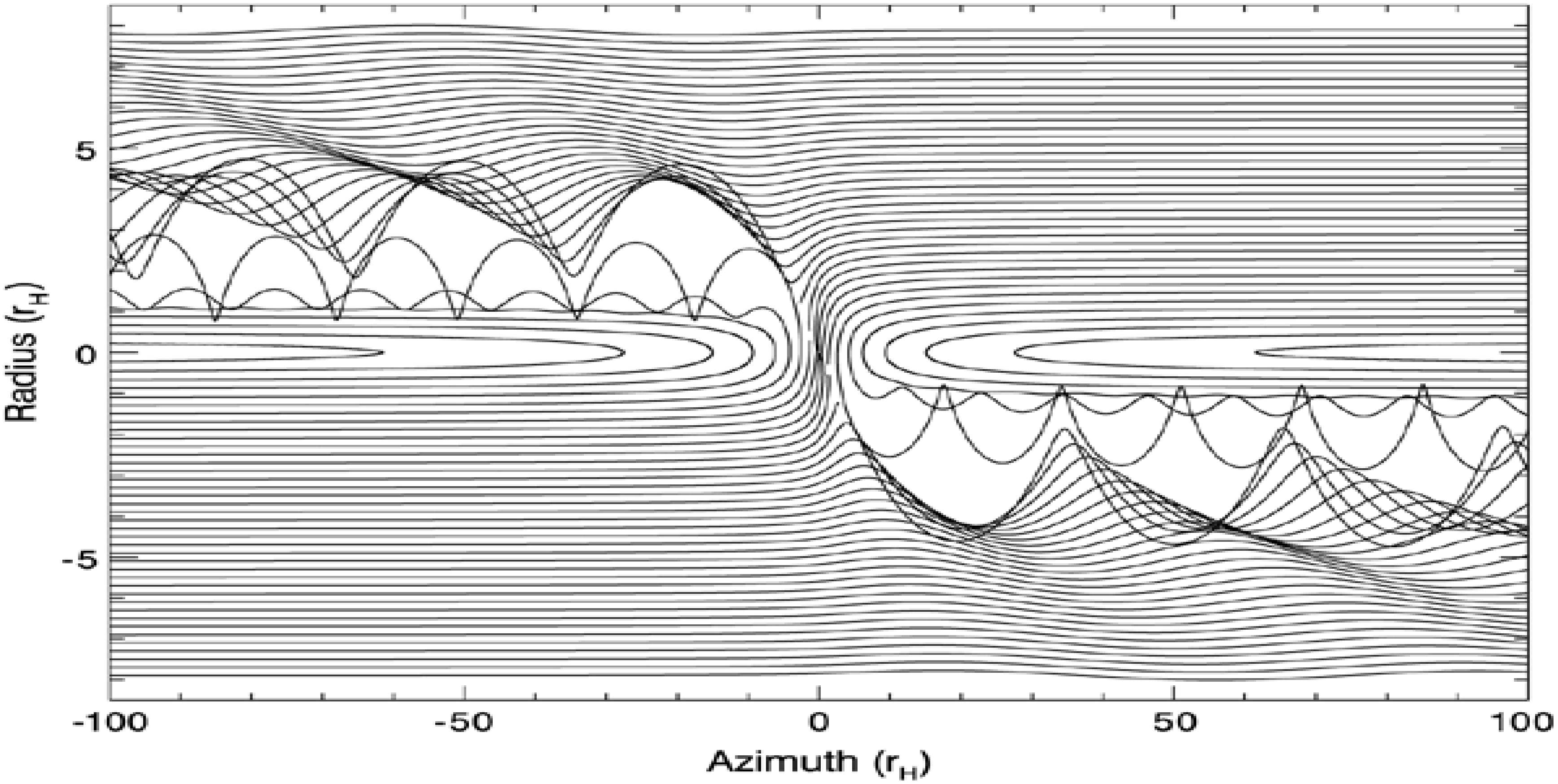
DYNAMICS: the E-ring

Comes from Enceladus geysers !

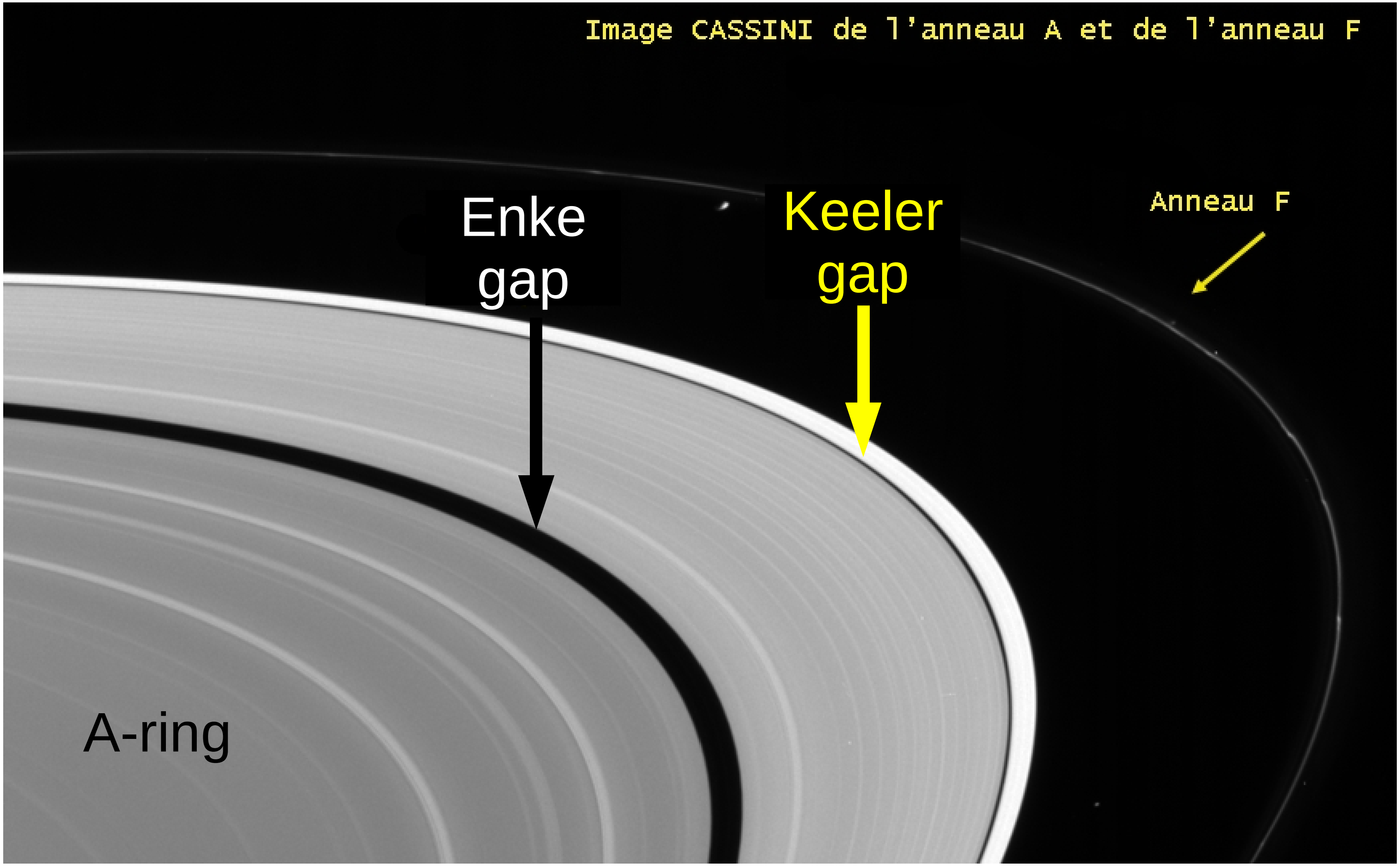


SIGNPOSTS

Trajectories of ring particles perturbed by a moonlet,
in the frame corotating with the moonlet
(Tiscareno et al. 2008)



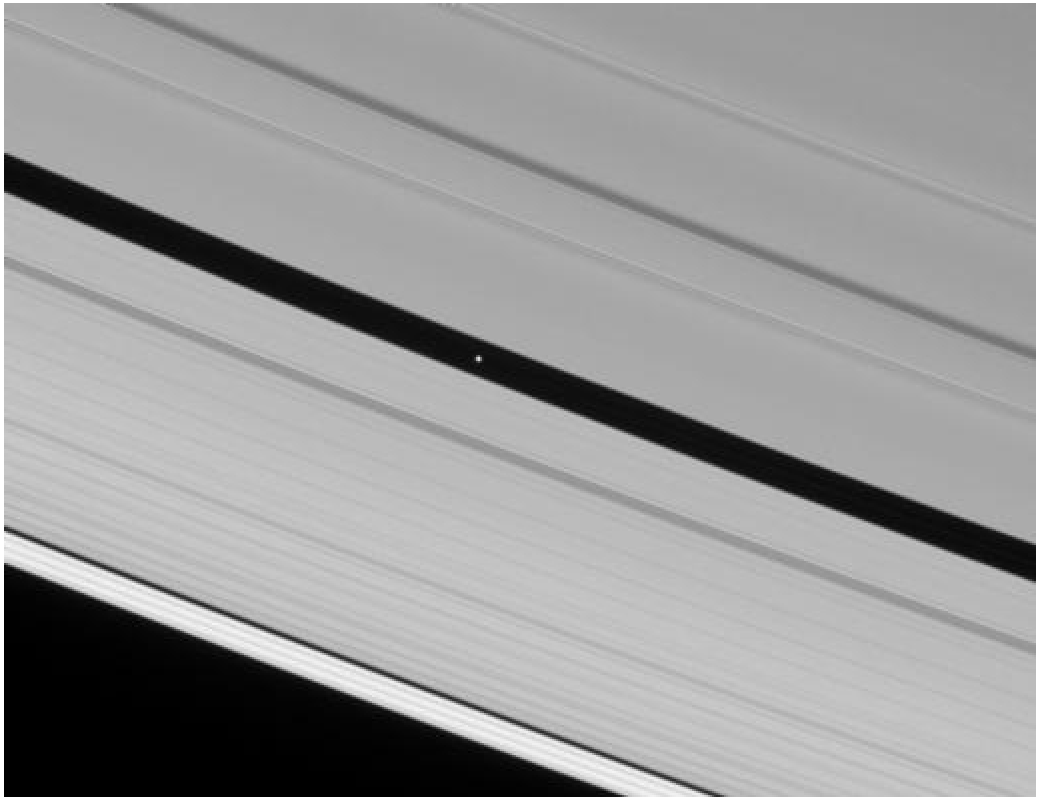
SIGNPOSTS of MOONLETS

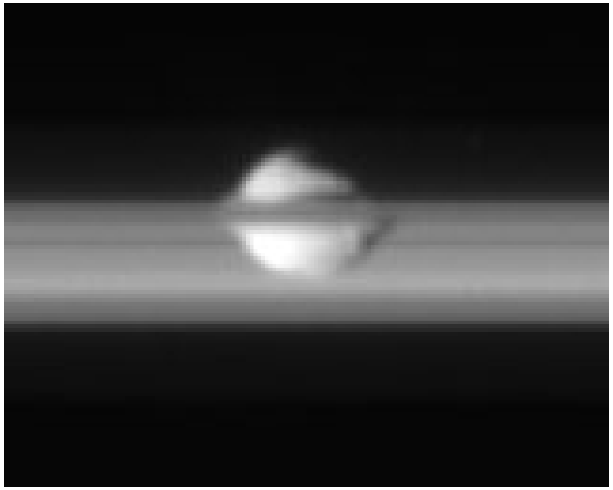


Gaps are open by a small satellite (Cuzzi & Scargle 1985).
Where is it ?

SIGNPOSTS of MOONLETS

Pan inside the Enke gap :





First discovered by Showalter (1990).

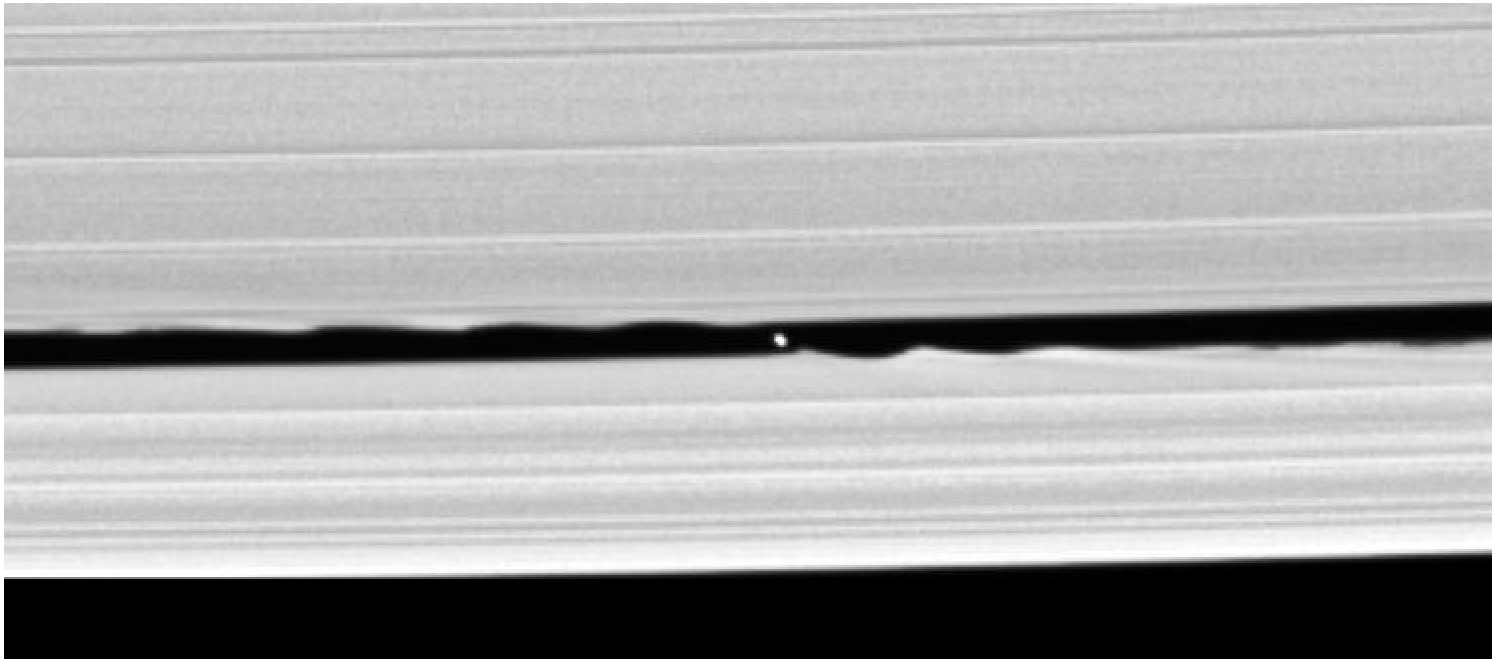
SIGNPOSTS of MOONLETS

Zoom on the Enke gap :

horseshoe region + waves associated to Pan.

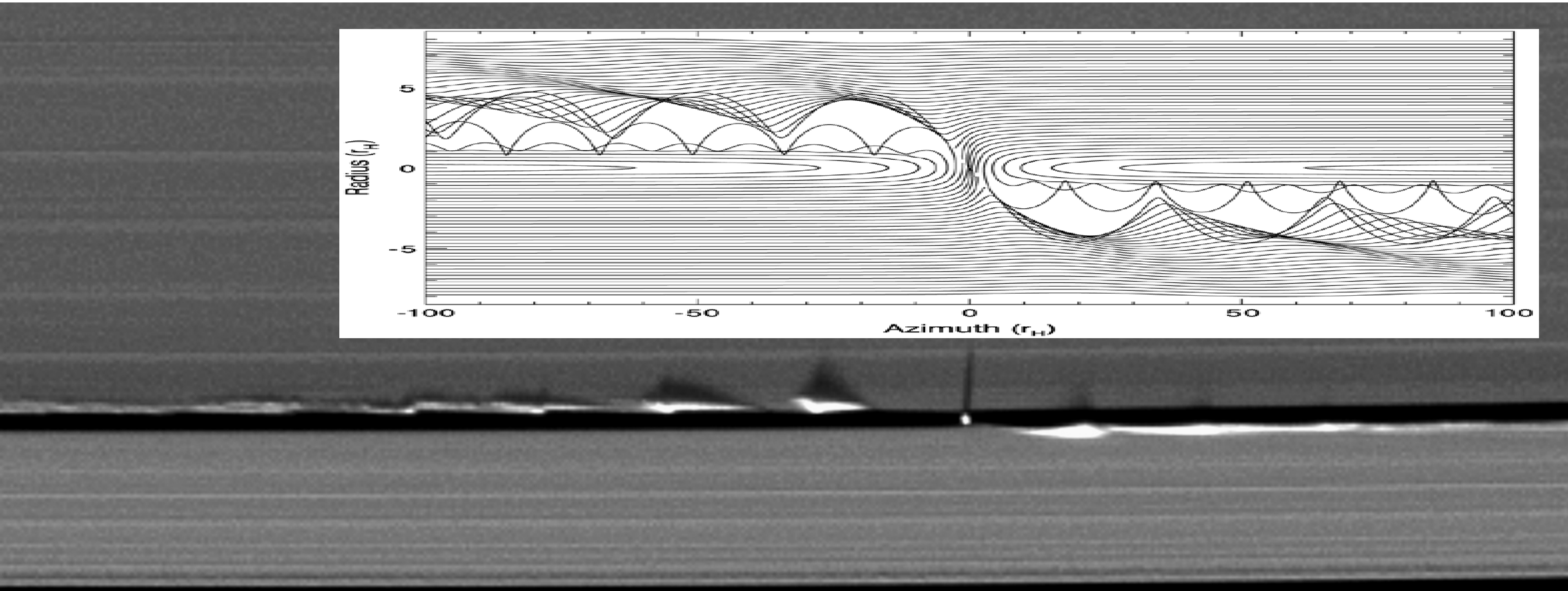
SIGNPOSTS of MOONLETS

Daphnis, as it scatters ring particles,
opening the Keeler gap :



SIGNPOSTS of MOONLETS

Daphnis, as it scatters ring particles, opening the Keeler gap :

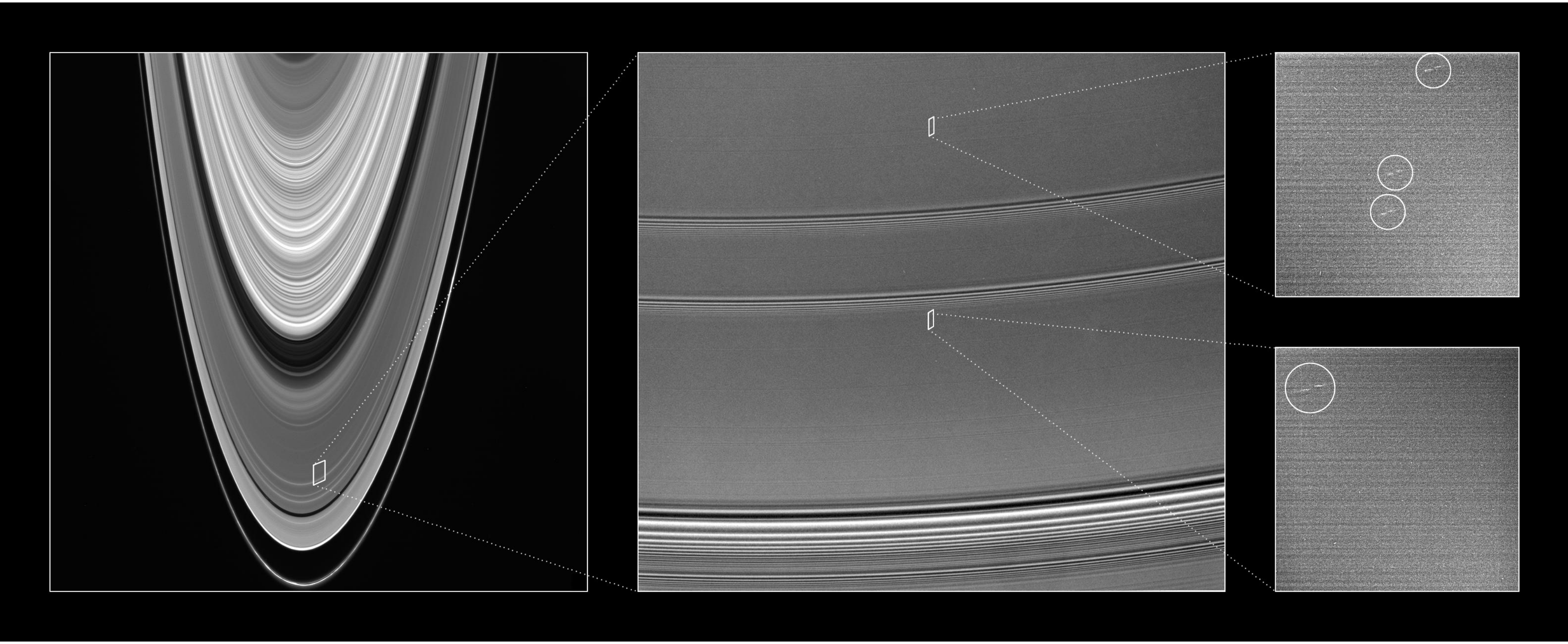


SHEPHERDING by MOONLETS

F ring : repeled outwards by Prometheus, inwards by Pandora.

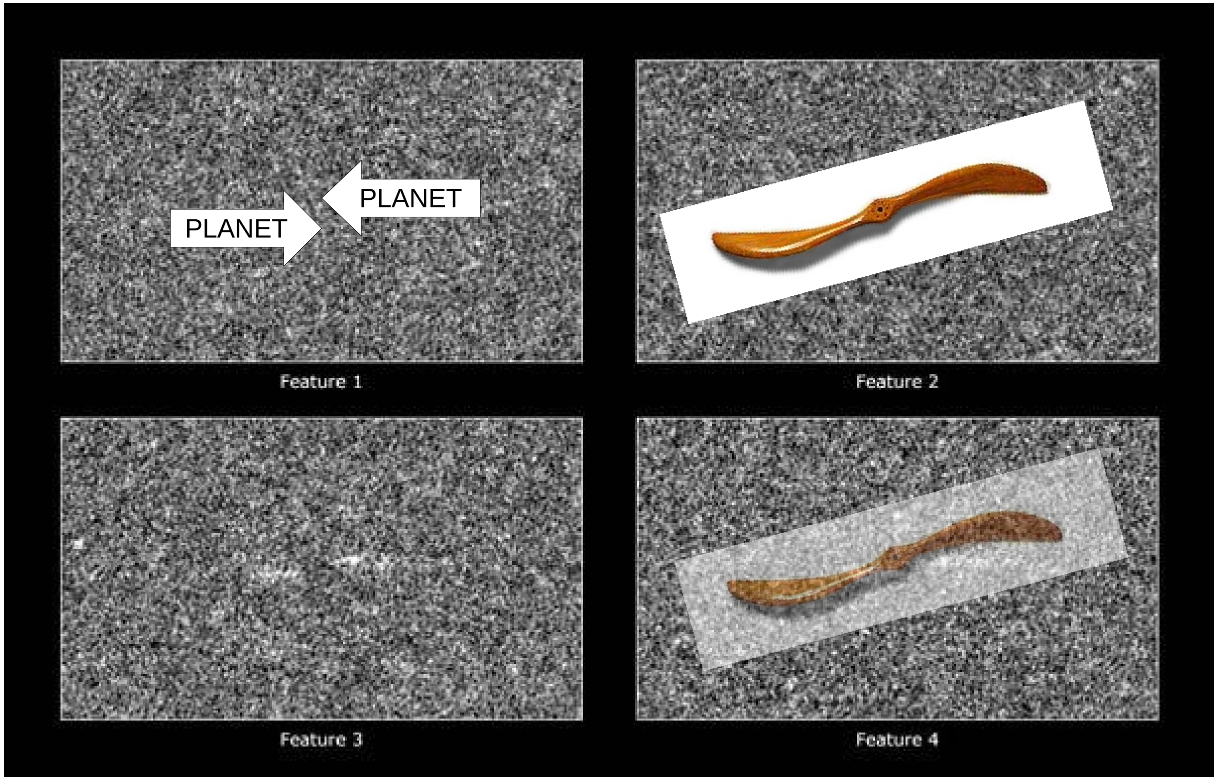
SIGNPOSTS: PROPELLERS

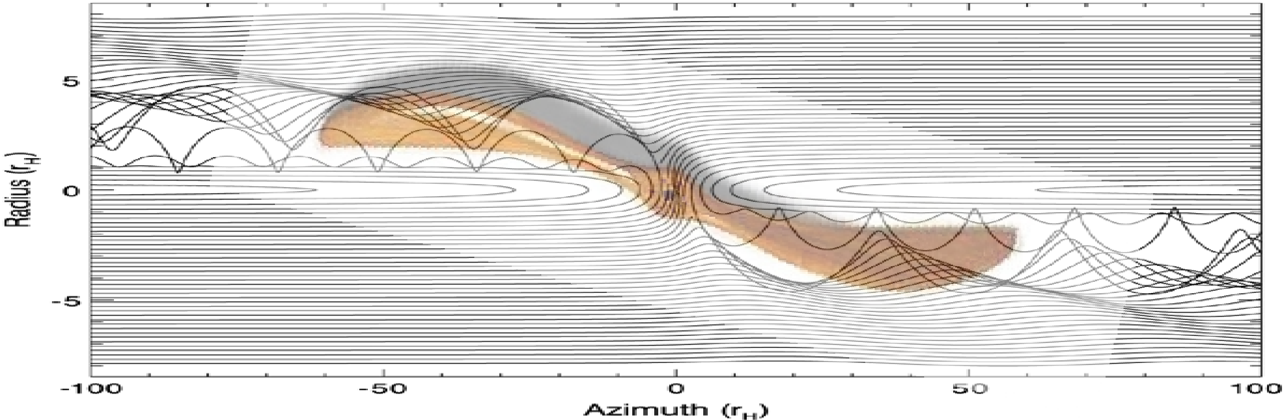
Tiscareno et al. (2006, 2008), Sremcevic et al. (2007)



SIGNPOSTS: PROPELLERS

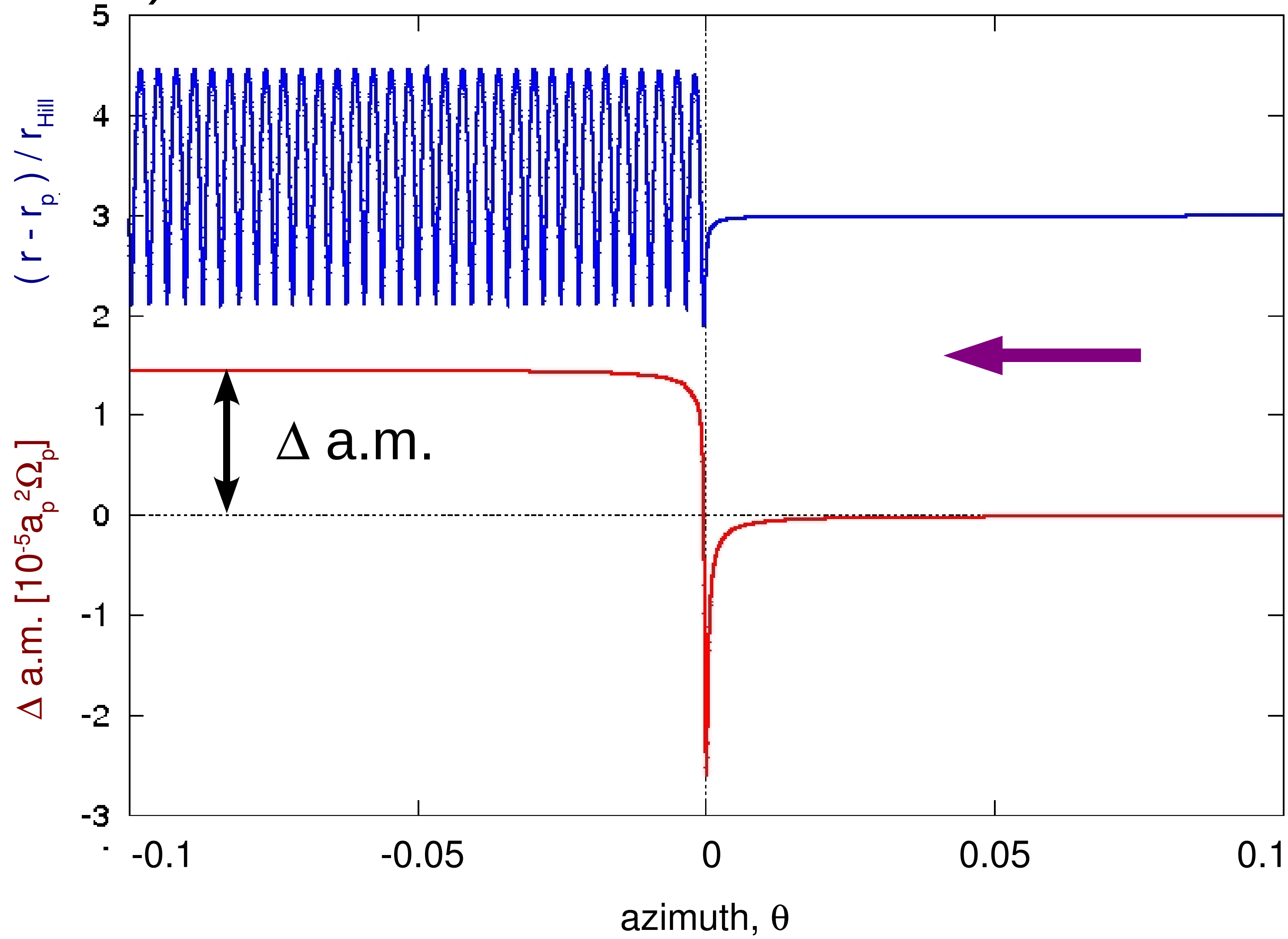
Tiscareno et al. 2008, 2009, 2010)





SIGNPOSTS: PROPELLERS

Trajectory integrated with Bulirsch-Stoer algorithm (Crida et al. 2010)

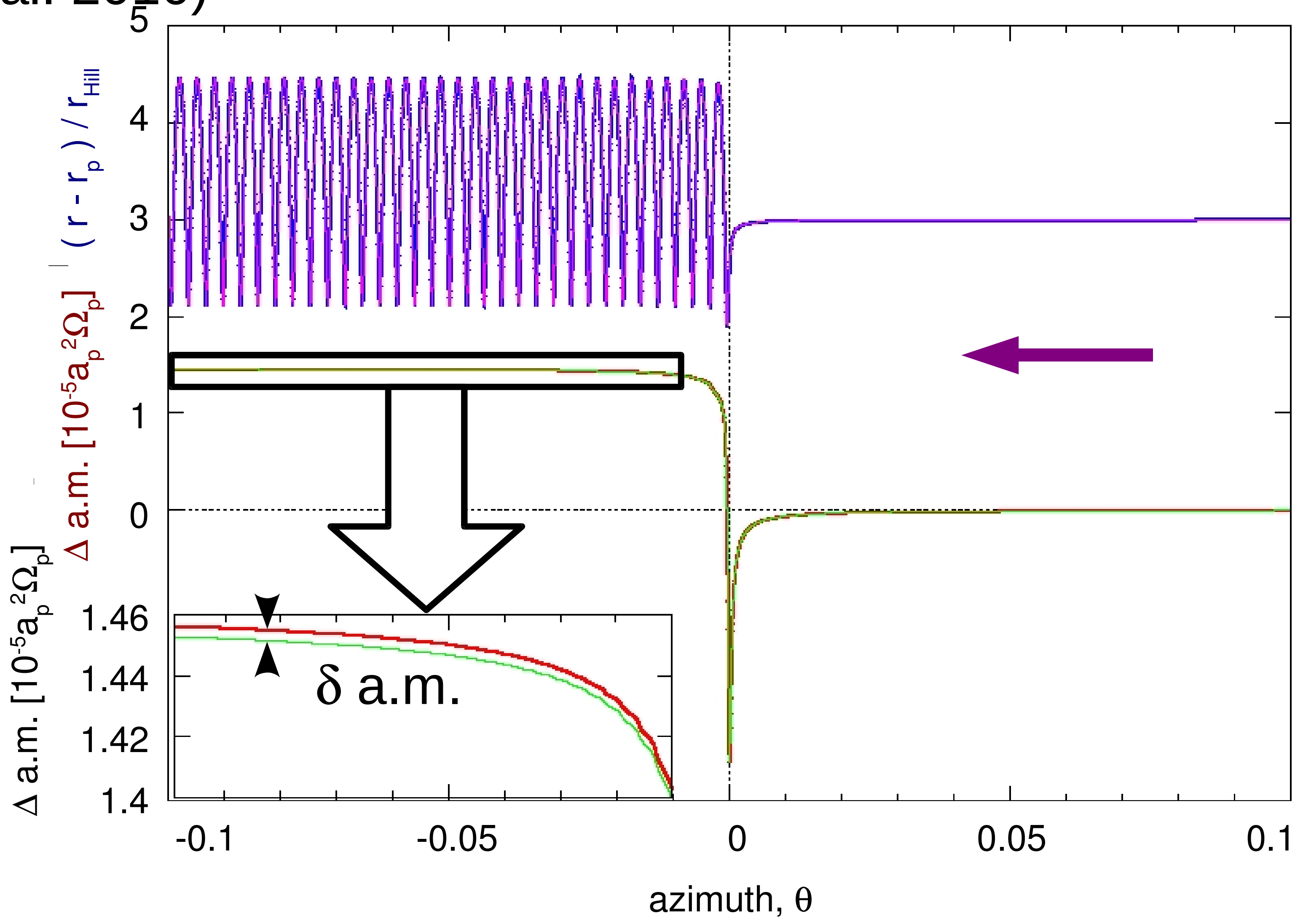


SIGNPOSTS: PROPELLERS

Integrated with Bulirsch-Stoer algorithm, to numerical precision. (Crida et al. 2010)

The difference between inner and outer trajectory can be measured:

δ a.m.



SIGNPOSTS: PROPELLERS

Result :

Torque on the planet = ~ $- 18 \, (\Sigma/M_{Sat} r_p^{-2})(M_p/M_{Sat})^{4/3} \, M_{Sat} r_p^{2} \Omega_p^{2}$

Not type I migration.

Not enough to account for observations.

(Crida et al. 2020)

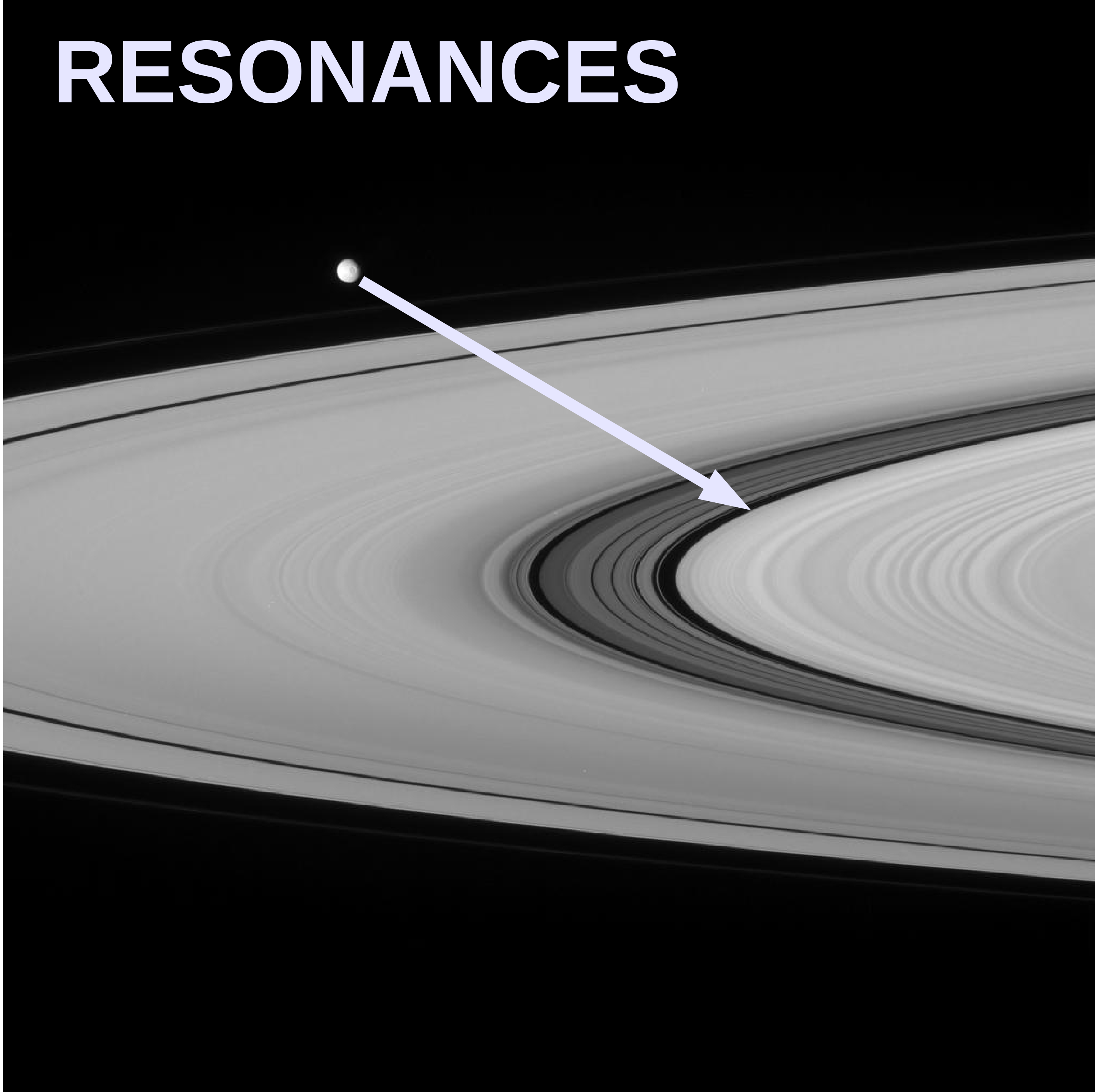
SIGNPOSTS: PROPELLERS

But the ring particles clump (Colwell et al. 2006, Hedman et al. 2007).
Random torques, and random walk (Rein & Papaloizou 2010).

- Explains the observed direction reversal of the migration.

- Compatible amplitude (depending on that of the clumping).

RESONANCES



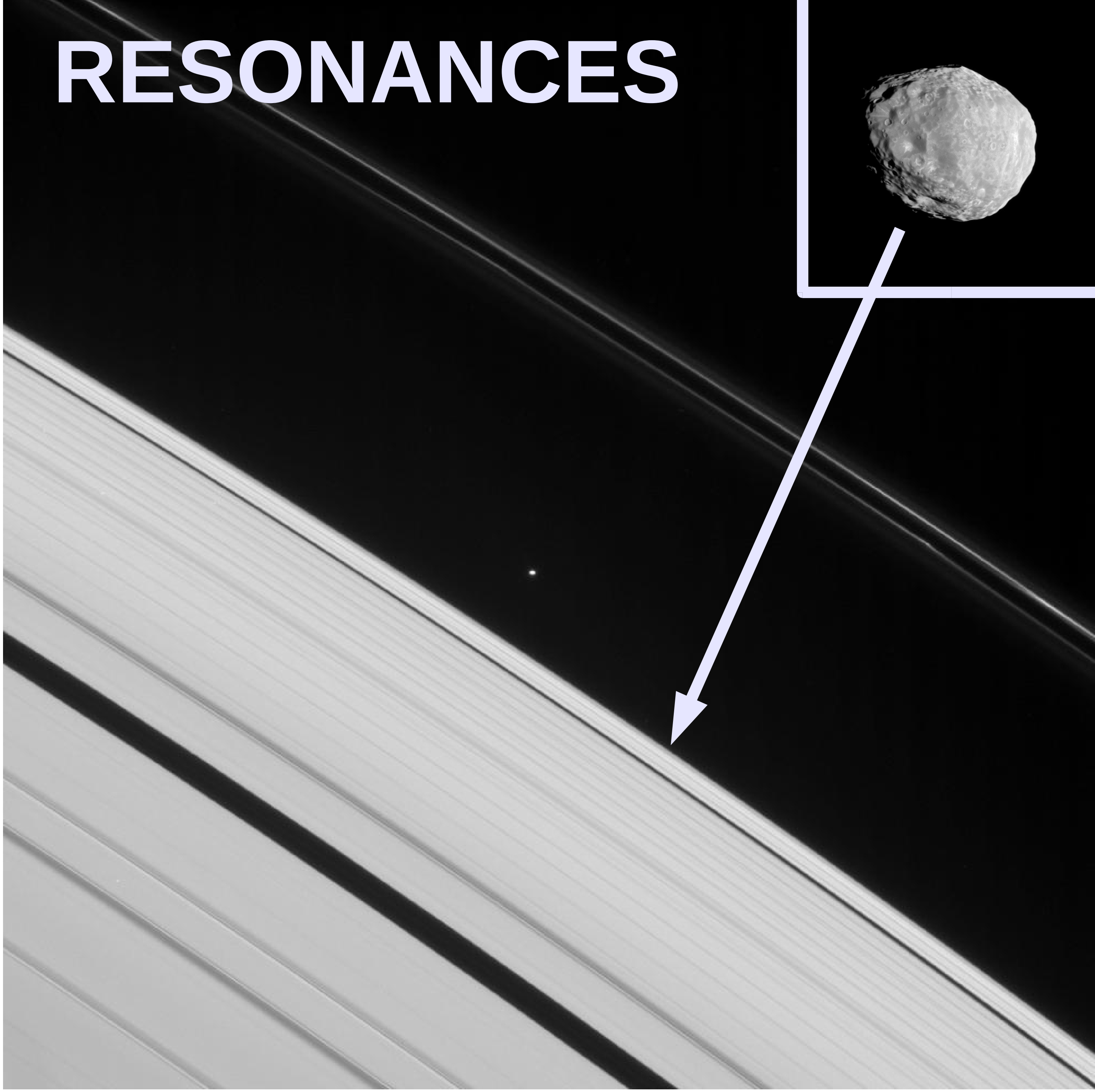
Mimas' 2:1 MMR marks the outer edge of the B-ring.

This edge has an m=2 shape (Nicholson et al 2009, 2011)

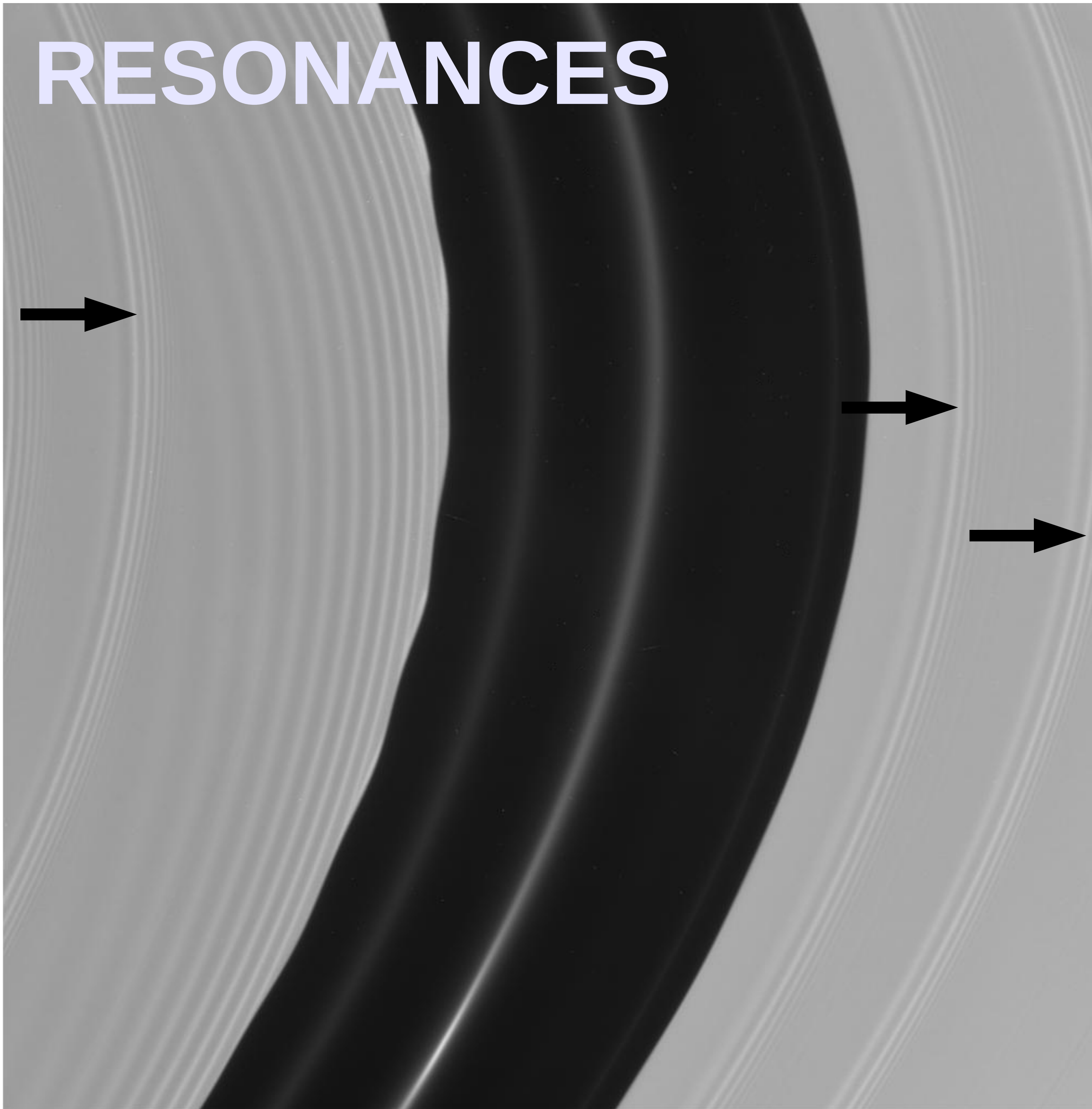
RESONANCES

Janus' 7:6 MMR marks the outer edge of the A-ring.

This edge has an m=7 shape.



RESONANCES

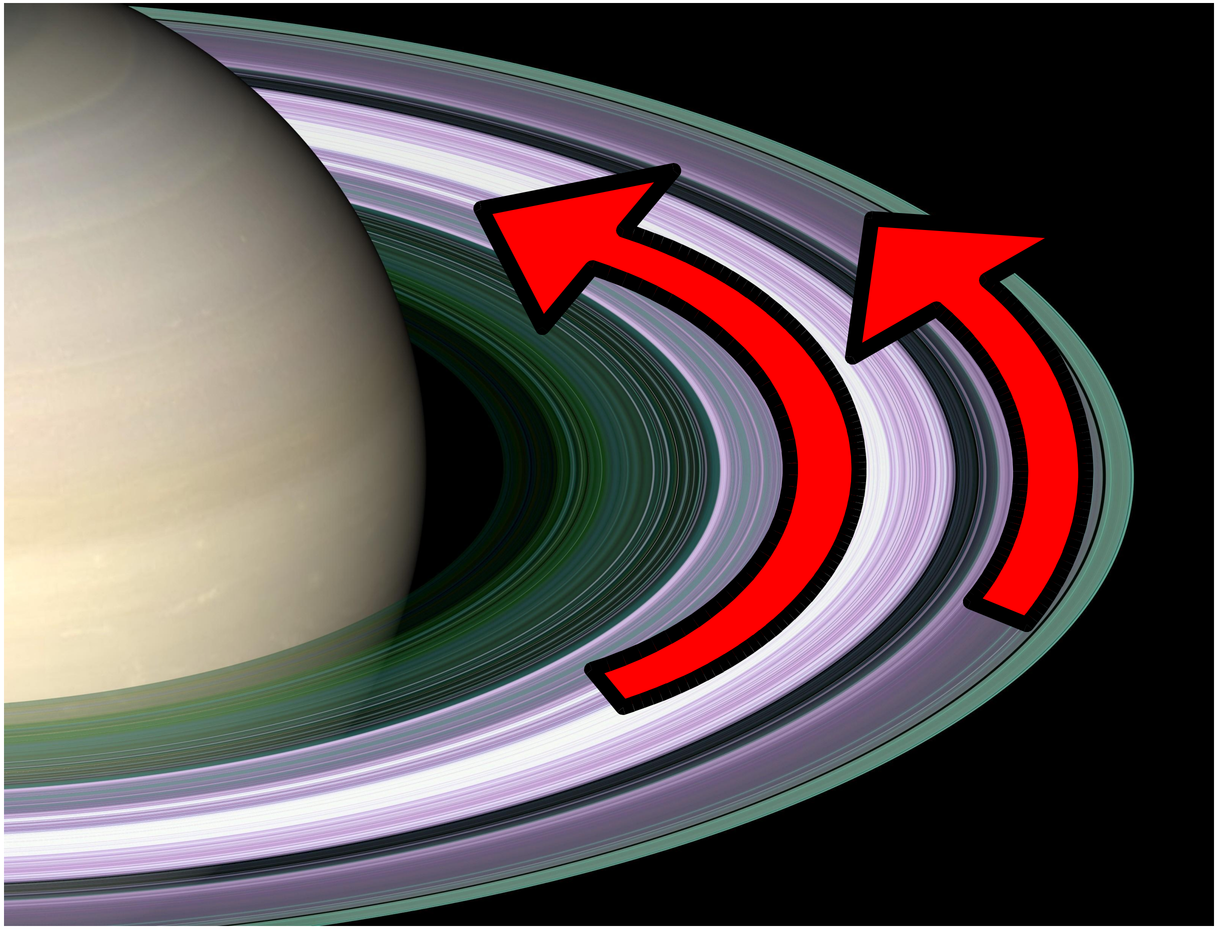


Many other resonances make waves.

Gravity supported, propagate towards the satellite.

RINGS EVOLUTION

Every astrophysical disk in Keplerian rotation spreads, because of viscous stress (see Lynden-Bell & Pringle 1974).



The inner disk rotates faster,

so the friction accelerates the outer disk,

and slows down the inner disk (that falls onto the central body).

RINGS EVOLUTION

Mass conservation :

$$r\frac{\partial \Sigma}{\partial t}+\frac{\partial}{\partial r}\left(r\,\Sigma\, v_r\right)=\blacklozenge$$

Angular Momentum Conservation :

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

Density evolution :

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

RINGS EVOLUTION

Viscosity in self-gravitation rings (Daisaka et al. 2001) :

$\nu = \nu_{coll} + \nu_{trans} + \nu_{grav}$.

Where ν_{trans} is the translational viscosity, the advection of a.m. due to the random motion of particles,

$\nu_{coll} = a^2\Omega\tau$ is due to collisions (τ=opacity),

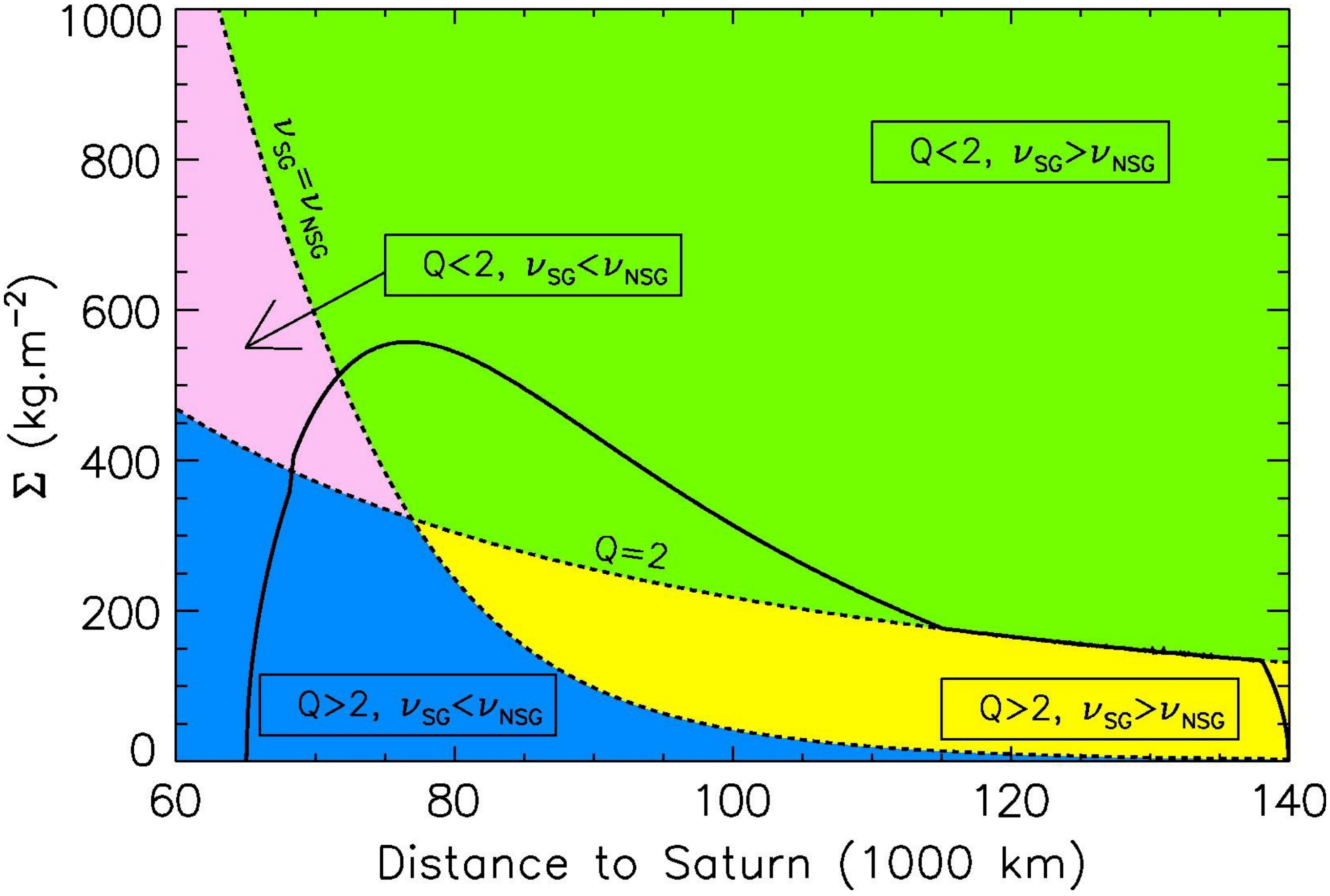
$\nu_{grav} = 0$ if $Q>2$, $\nu_{grav} = \nu_{trans}$ if $Q<2$.

Parameter Q of Toomre : $Q = \Omega\, \sigma_r / (3{,}36\, G\, \Sigma)$.

where $\sigma_r = v_r$ dispersion.

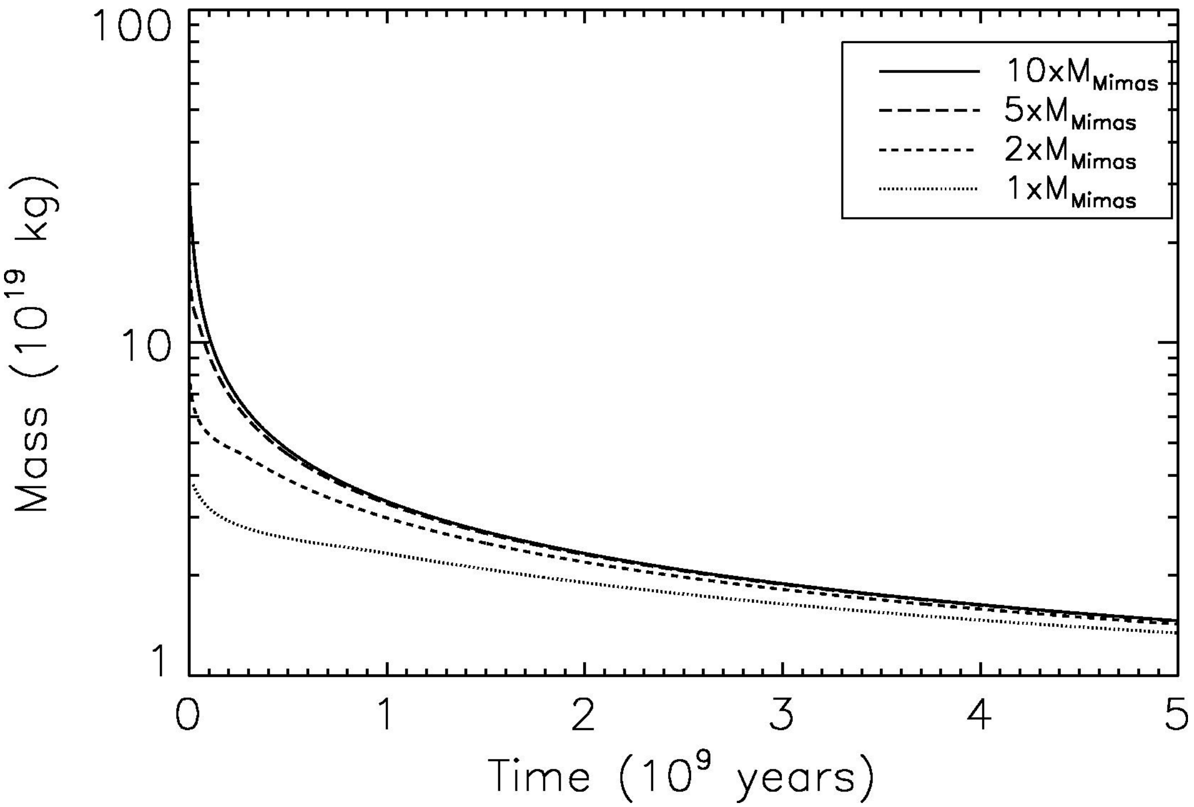
RINGS EVOLUTION

The spreading slows down as soon as Q>2 .



Convergence towards the Q=2 profile. (Salmon et al. 2010)

RINGS EVOLUTION



Whatever the initial mass, the mass of the rings after 4.5 Gyr is about the present mass (Salmon et al. 2010).

What happens to the lost material ?

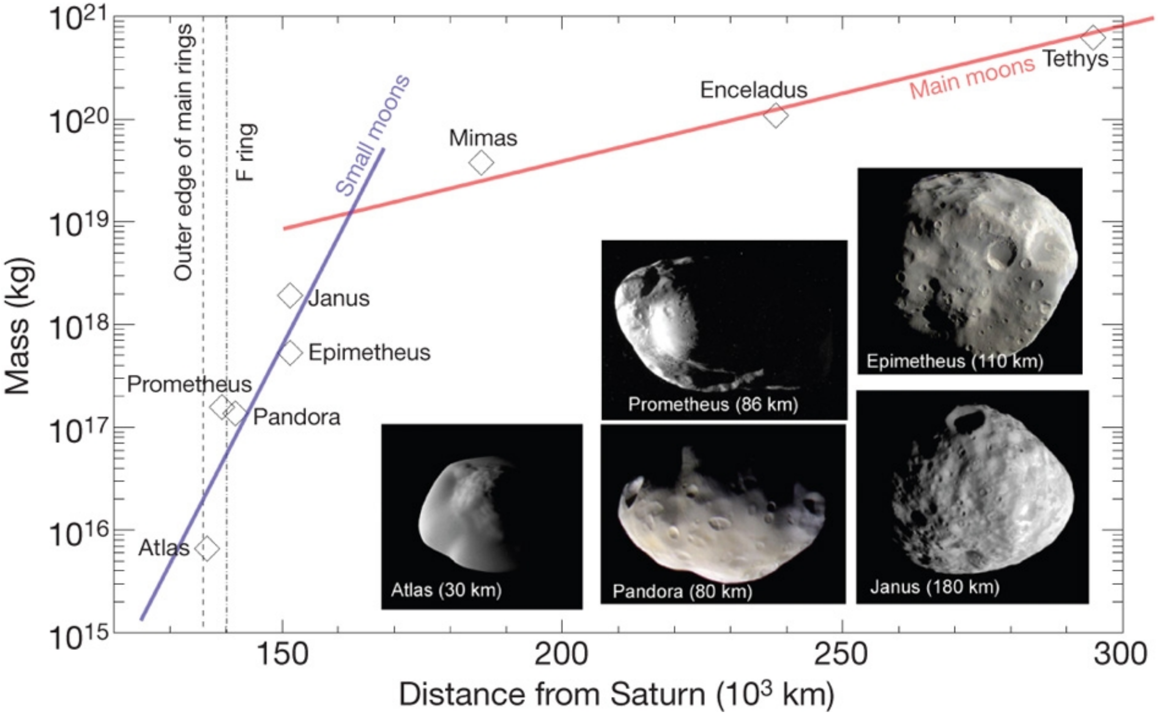
SATELLITES - RINGS

Outside the Roche limit, it aggregates and forms new satellites. They migrate away from the rings.

Janus, Epimetheus, Pandora, Prometheus, Atlas, are :

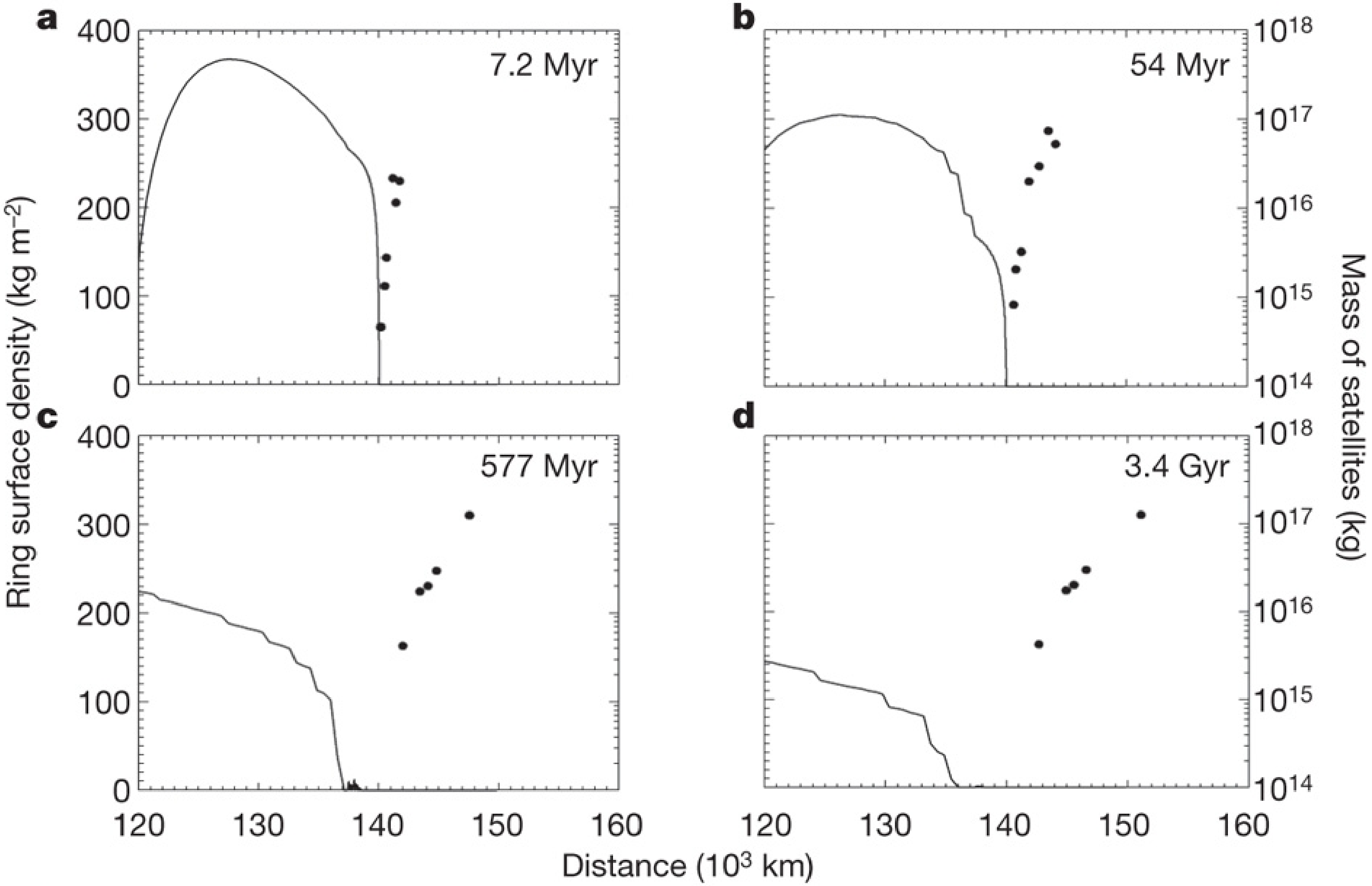
- under dense (~600 kg.m^{-3})
- same spectrum as the rings
- dynamically young
- young surfaces

They formed this way (Charnoz et al 2010).

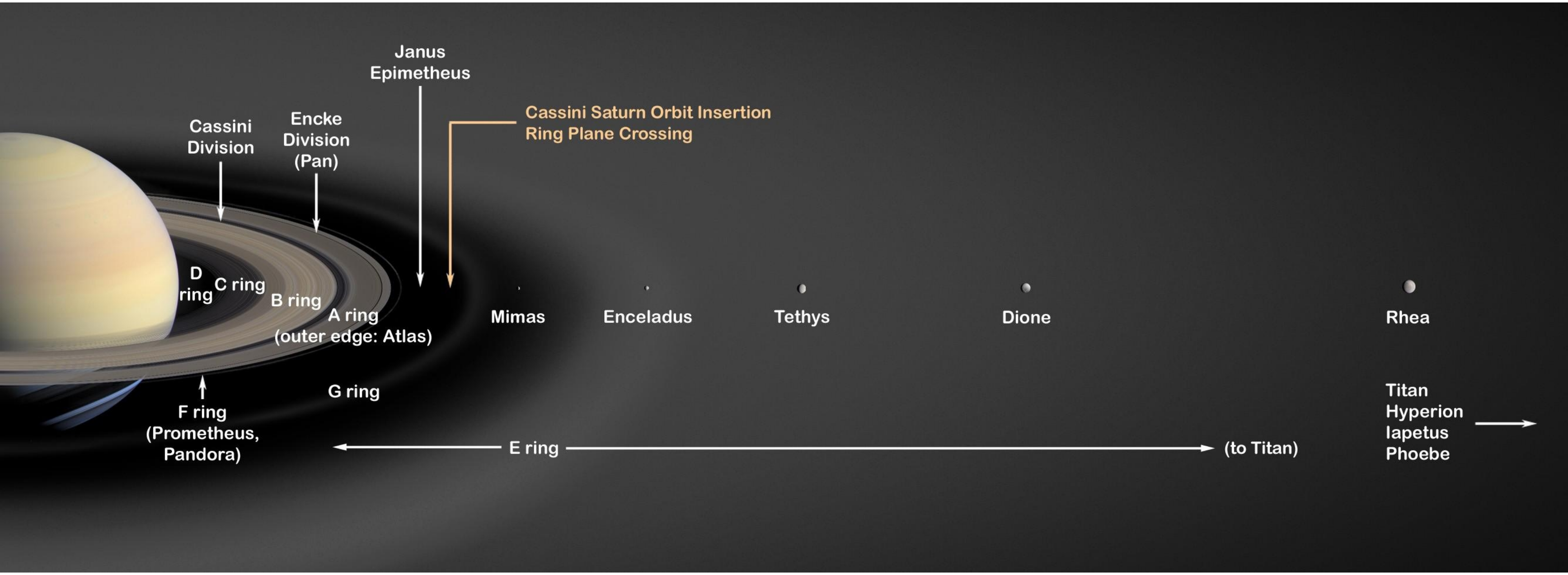


SATELLITES - RINGS

Numerical simulation of ring spreading with r_{Roche} = 140 thousand km.



SATELLITES - RINGS



Beyond ? There could have been enough mass in the rings intially to form all satellites until Rhea (Canup 2010).

SATELLITES - RINGS

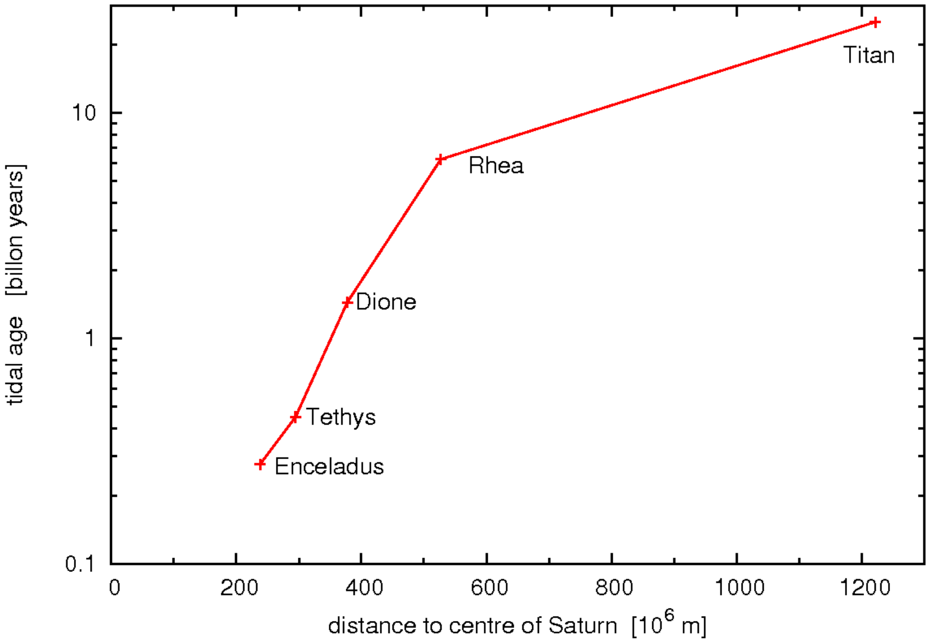
Beyond Mimas, no more MMR, no more migration ?

<u>Solution :</u>
tides from Saturne

$$\frac{da}{dt} = \frac{3\, k_{2p}\, M_{satellite} \sqrt{G}\, R_{Saturn}^{5}}{Q_{Saturn} \sqrt{M_{Saturn}}\, a^{11/2}}$$

enough if Q_{saturn}=1680, as suggested by Lainey et al.

« Tidal ages » of satellites are :
- smaller than 3.5 Gyrs.
- an increasing function of the orbital radius



SATELLITES - RINGS

Charnoz et al. 2011 :

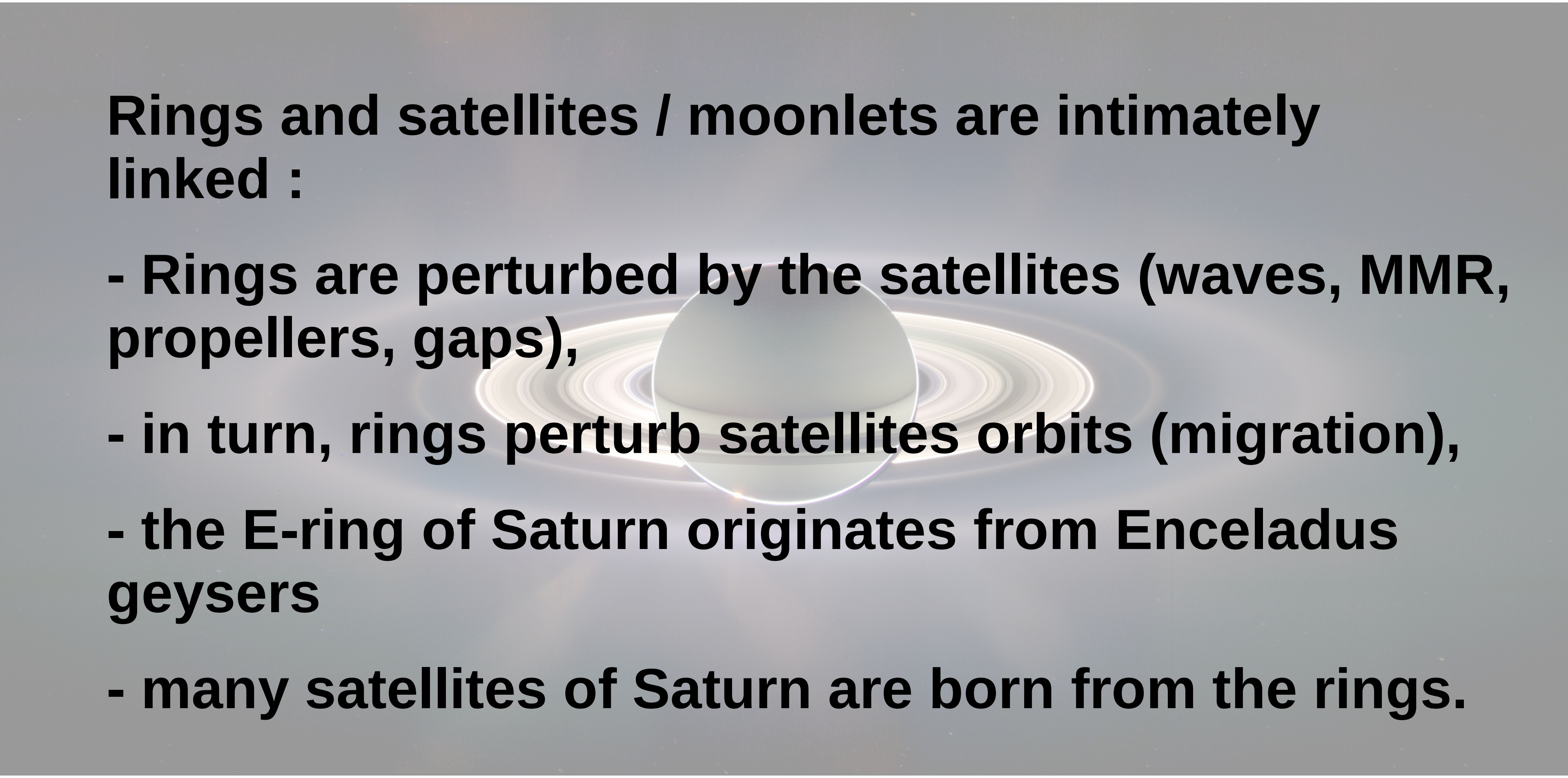
Initially, the rings were very massive, with a small fraction of silicates. Silicates are dense -> they accrete and form chunck, coated with ice, which migrate.

Some of them end outside the rings, and keep migrating outwards, while accreting ice fro mthe rings.

This makes a series of differentiated satellites of random silicate/ice ratio, and non spherical cores.

It also explains the mass-distance distribution (Crida & Charnoz 2011 DPS).

CONCLUSION



Rings and satellites / moonlets are intimately linked :

- Rings are perturbed by the satellites (waves, MMR, propellers, gaps),

- in turn, rings perturb satellites orbits (migration),

- the E-ring of Saturn originates from Enceladus geysers

- many satellites of Saturn are born from the rings.

Satellites enfants des anneaux