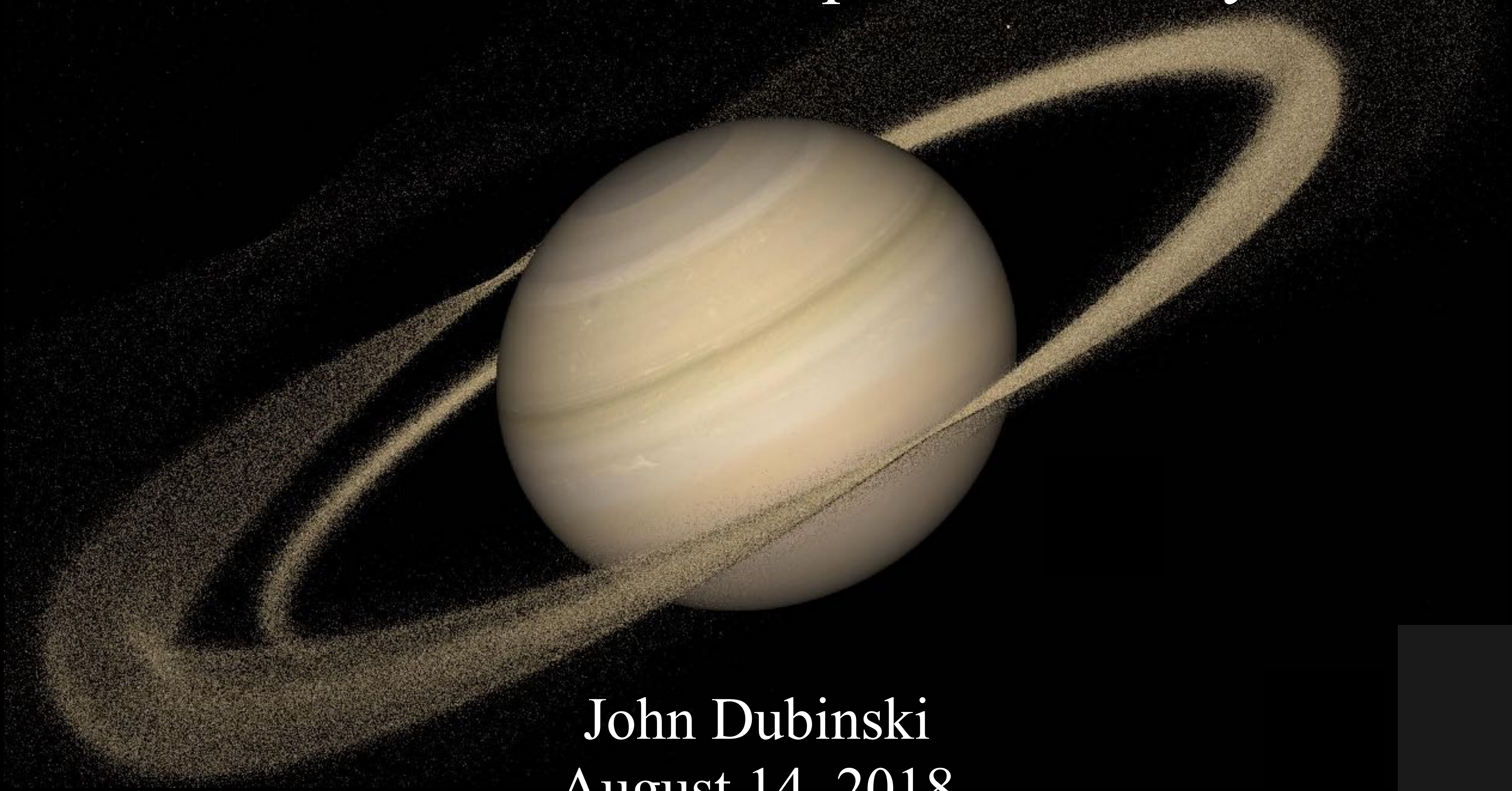
# A recent origin for Saturn’s rings from the collisional disruption of an icy moon



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# COLLISIONAL DISRUPTION THEORY

- Collisional erosion of small moons
  Soter 1971; Pollack, Summers and Baldwin 1973
- Post-Voyager: Catastrophic disruptions of icy moon(s)
  Shoemaker 1982; Smith et al. 1982; Harris 1984
- Charnoz et al. 2009 destruction during the LHB - but the rings are 4 Gyr old

## IDEA:

- Rings have a mass comparable to Mimas
- Mimas-sized moon (ring parent) within the Roche zone destroyed in a collision with an ecliptic comet - Single event? Recent?

## PROBLEMS:

- Rings are nearly pure ice while inner moons are about 60/40 ice/rock
- How do you form or move a Mimas inside of the Roche zone and keep it there?
- How (im)probable is a catastrophic collision?

# COLLISIONAL DISRUPTION THEORY

## MODIFIED COLLISION SCENARIO

- Differentiated Mimas-sized ring parent moon located just outside Roche zone
- Held in place by 4:2:1 MMR with Enceladus and Dione $\rightarrow a \approx 150000 \text{ km}$
- Incomplete disruption unbinds icy mantle leaving rocky core
- Icy proto-ring spreads viscously
- Inner migrating debris becomes the rings
- Outer migrating debris re-accretes onto rocky core becoming Mimas
- Mimas exchanges angular momentum with new rings migrates outwards rapidly
- Ring parent mass = mass of Mimas + mass of Rings = 1.5x Mimas?
- Ring parent J = J of Mimas + J of Rings $\rightarrow a \approx 157000 \text{ km}$
- Disruption time $T \sim 35$ Gyr so $P(t<200 \text{ Myr}) \sim 0.5\%$ - 3-sigma event

# Saturn system without rings

Watch on youtube: google “dubinski Saturn youtube”

−14.81 h

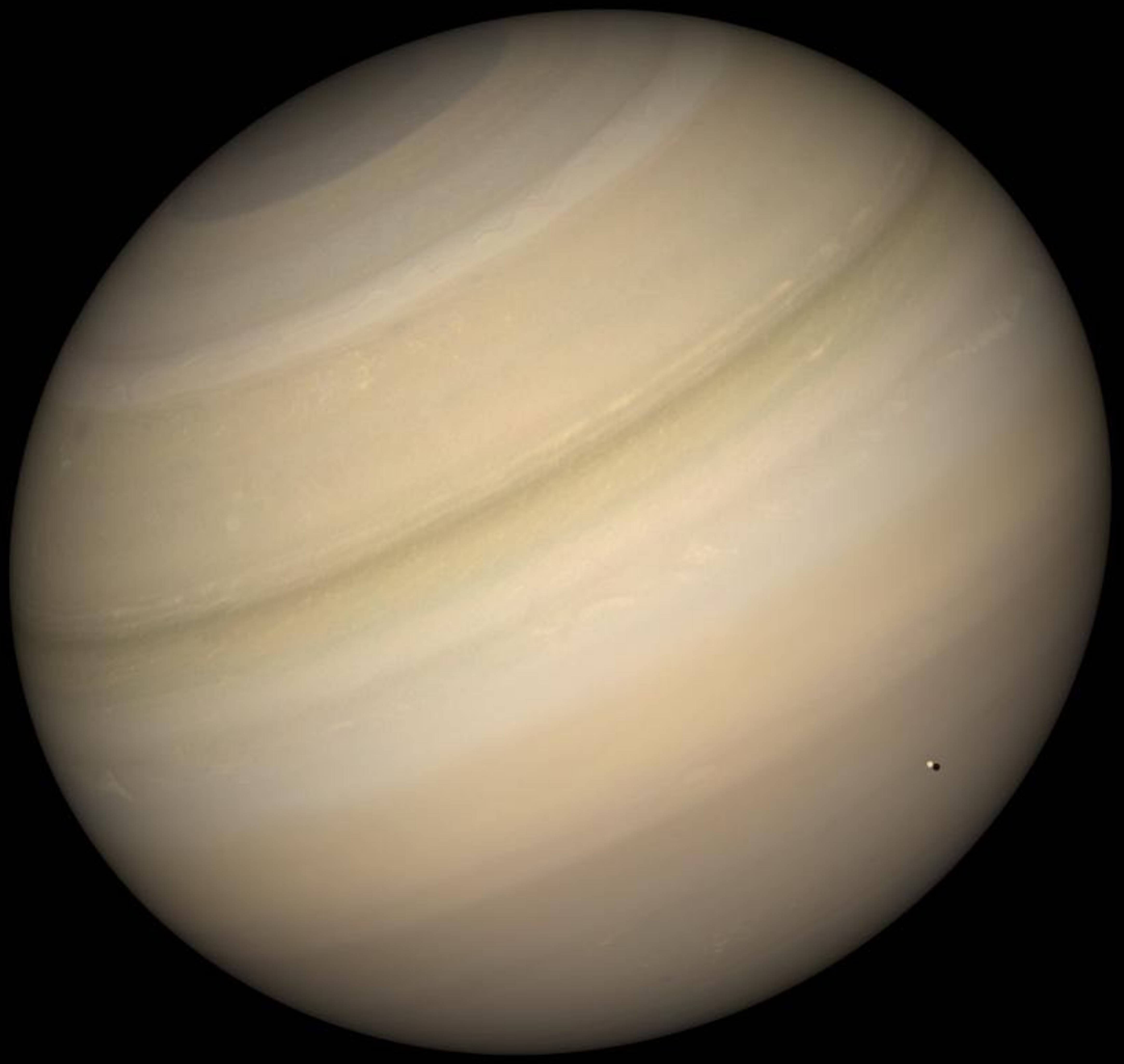

−13.33 h


−11.85 h

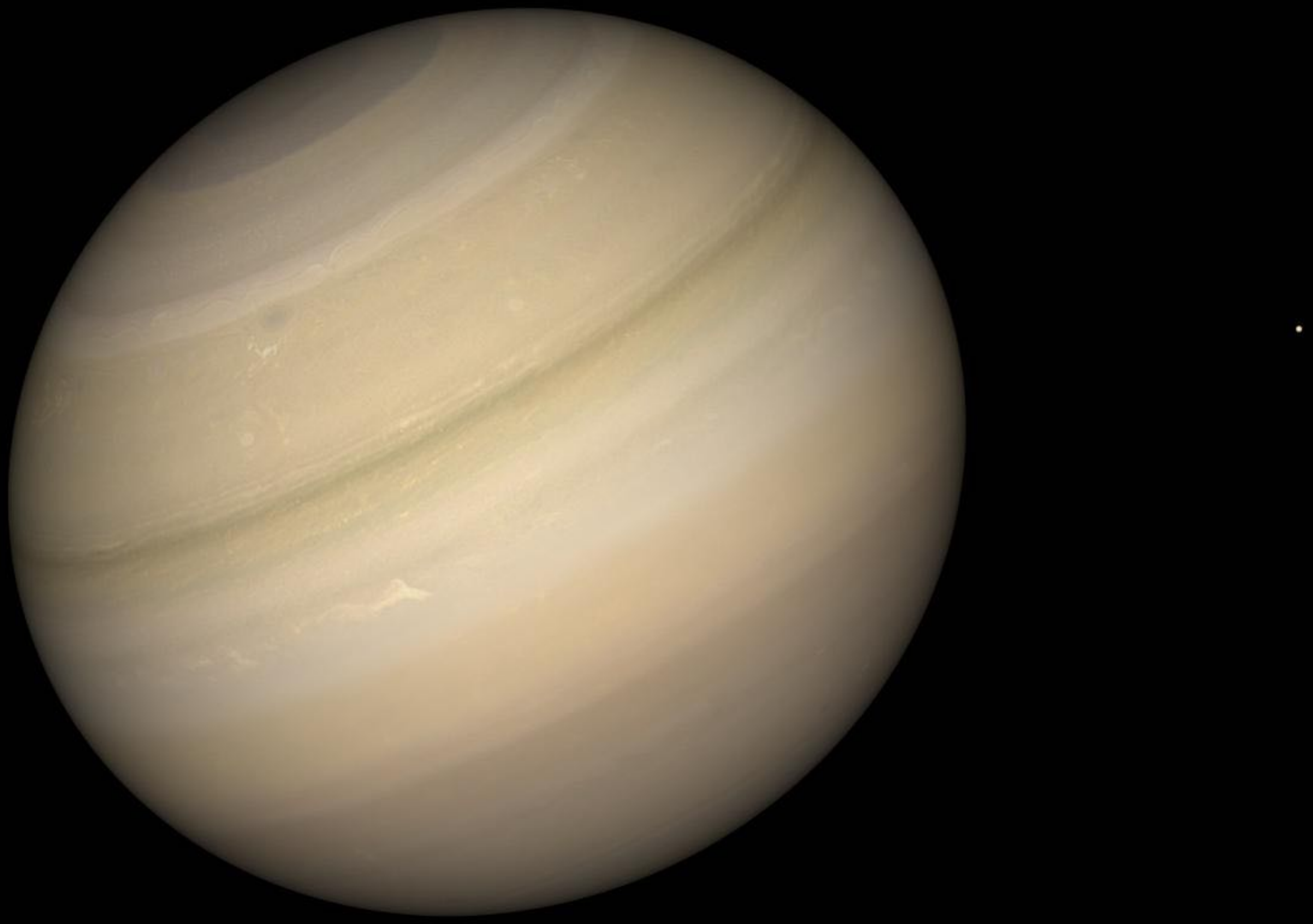

−10.37 h

−8.89 h


−7.41 h



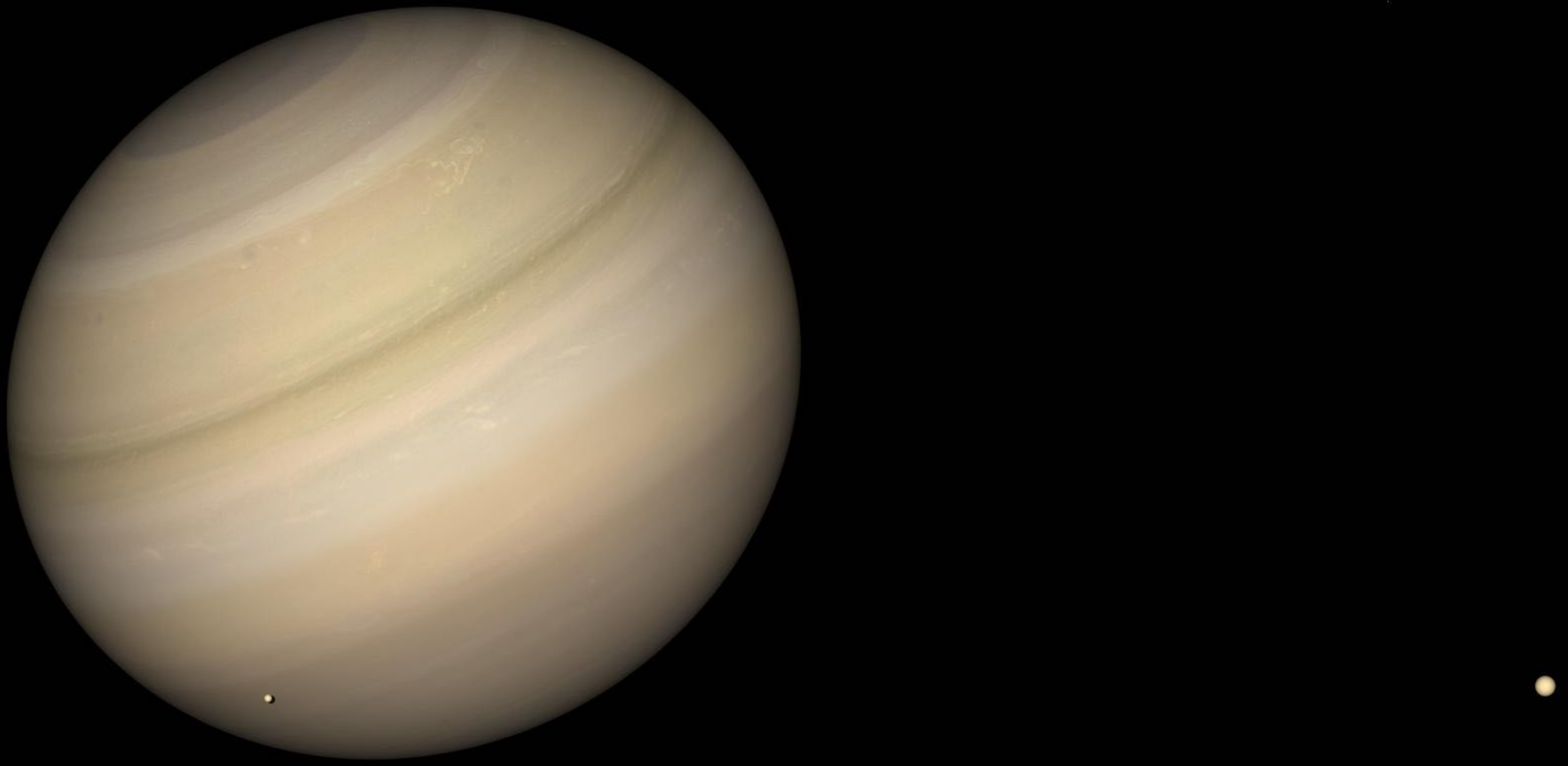
−5.92 h



−4.44 h


−2.96 h


Hypothetical
Ring Parent Moon
$M = 2M_{Mimas}$ ($1.5\ M_{Mimas}$?)
$a = 140000$ km
−1.48 h



−1.33 h

−1.18 h


−1.04 h


−3199 s


−2666 s

−2133 s


−1600 s


−1066 s


−533 s


−480 s


−427 s


−373 s


−320 s

Comet
$R = 22$ km
$v_i = 44$ km/s
$M_i = 10^{-3} M_{Mimas}$
Origin
- Oort Cloud
- Kuiper belt (more likely)
$v_\infty \approx 3$ km/s $7 < v_i < 40$ km/s
−267 s


−213 s


−160 s


−107 s


−53 s


Simulation begins
Moon: 10M particles
Comet: 50K particles
Particle radius: $r_p = 1.0$ km
Collisional N-body code
Hard-sphere EOS
0 s


5 s


Head-on Impact!
(extreme case)
10 s


15 s


20 s


25 s


30 s


35 s


40 s


45 s


50 s


100 s


Expanding cloud of debris
NOTE: individual particles are rendered larger for visibility
150 s


200 s


250 s


300 s


350 s


400 s


450 s


475 s


480 s


485 s


490 s


495 s


500 s


750 s


1950 s


1.93 h


3.32 h


4.71 h


6.10 h


7.49 h


Debris spreads along orbit
P = 14.8 h
10.26 h

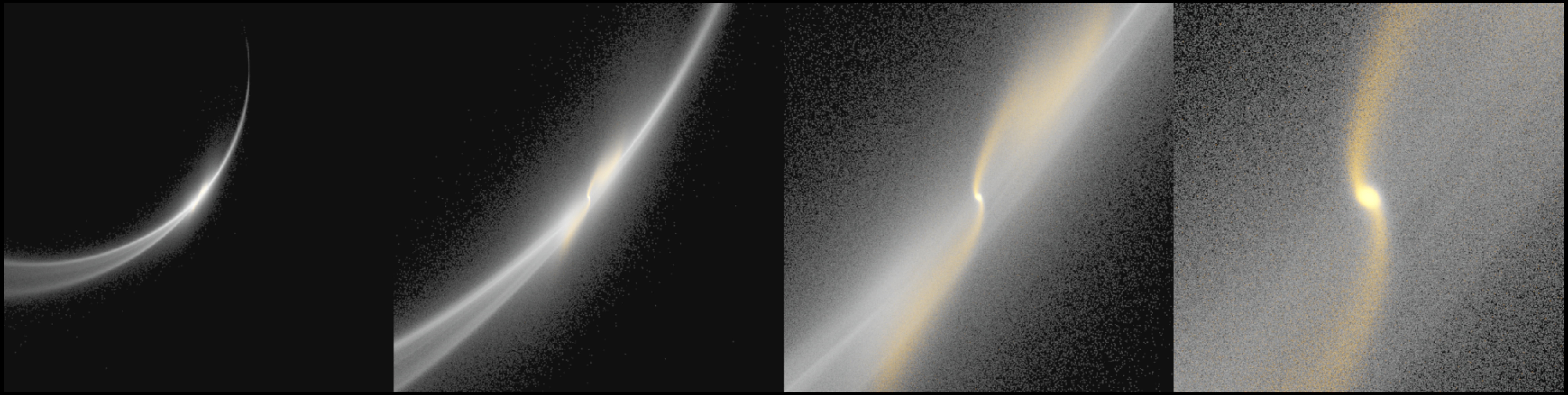

11.65 h


12.90 h


13.60 h


14.29 h

Zoom in on collision remnant after one orbit
Blue: ice
Red: rock



288000 km    72000 km    18000 km    288000 km

In this case, icy mantle is unbound completely.  Some rock is also released.
In lower energy impacts, the rocky core remains completely intact.


14.99 h


15.68 h


16.38 h


17.07 h


17.76 h


18.46 h


19.15 h


20.40 h


23.88 h


1.14 d


1.28 d


1.43 d


1.57 d


1.72 d


1.86 d

Orbital phase mixing/collisional dissipation

Rapid evolution $\sigma \approx 0.5\ \mathrm{km/s}$

Proto-ring settles and spreads on timescale of weeks

Collisional cascade likely but not simulated


2.15 d


3.60 d


5.05 d


6.49 d


7.94 d


9.39 d


10.83 d


12.28 d

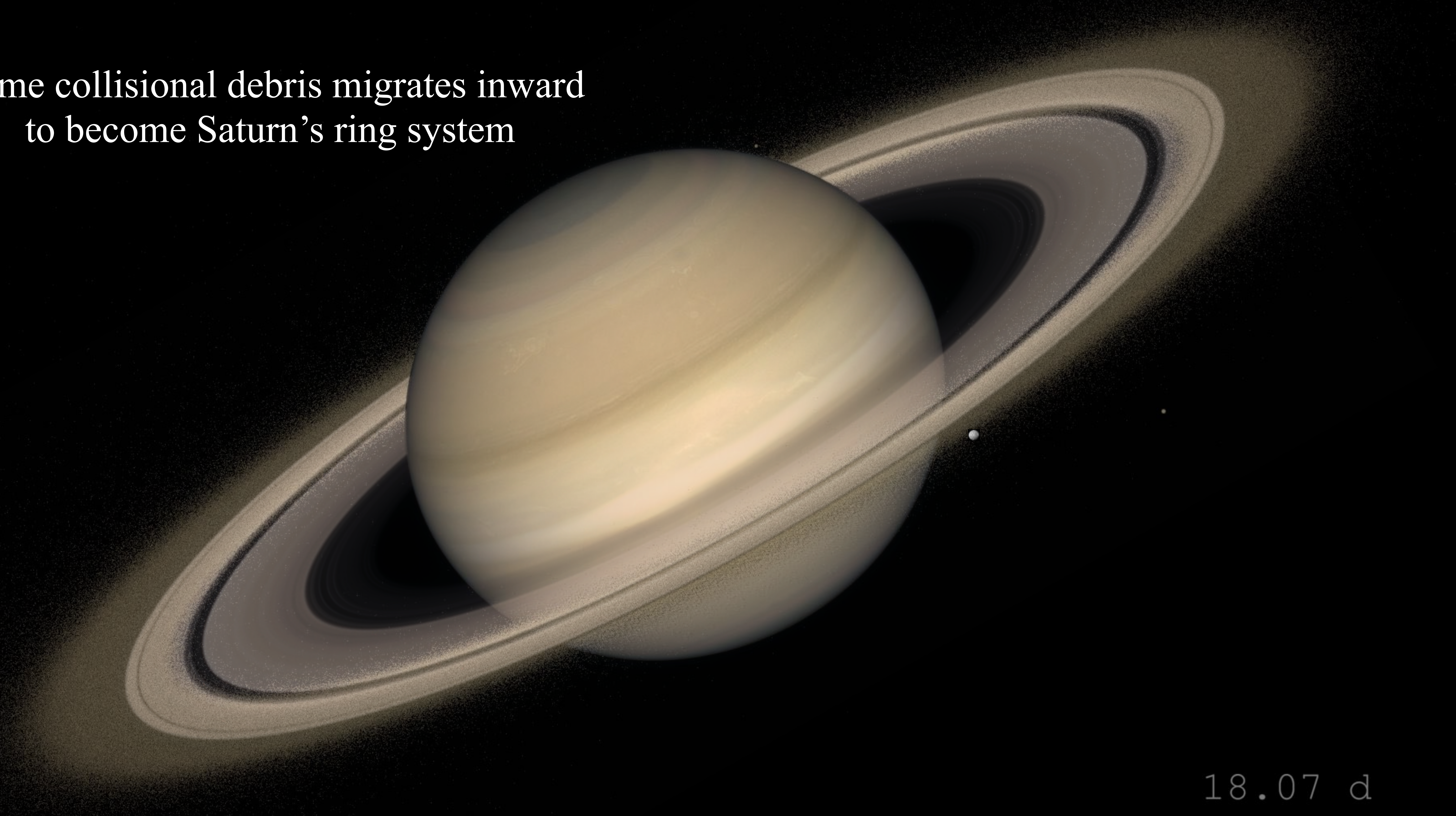

13.73 d

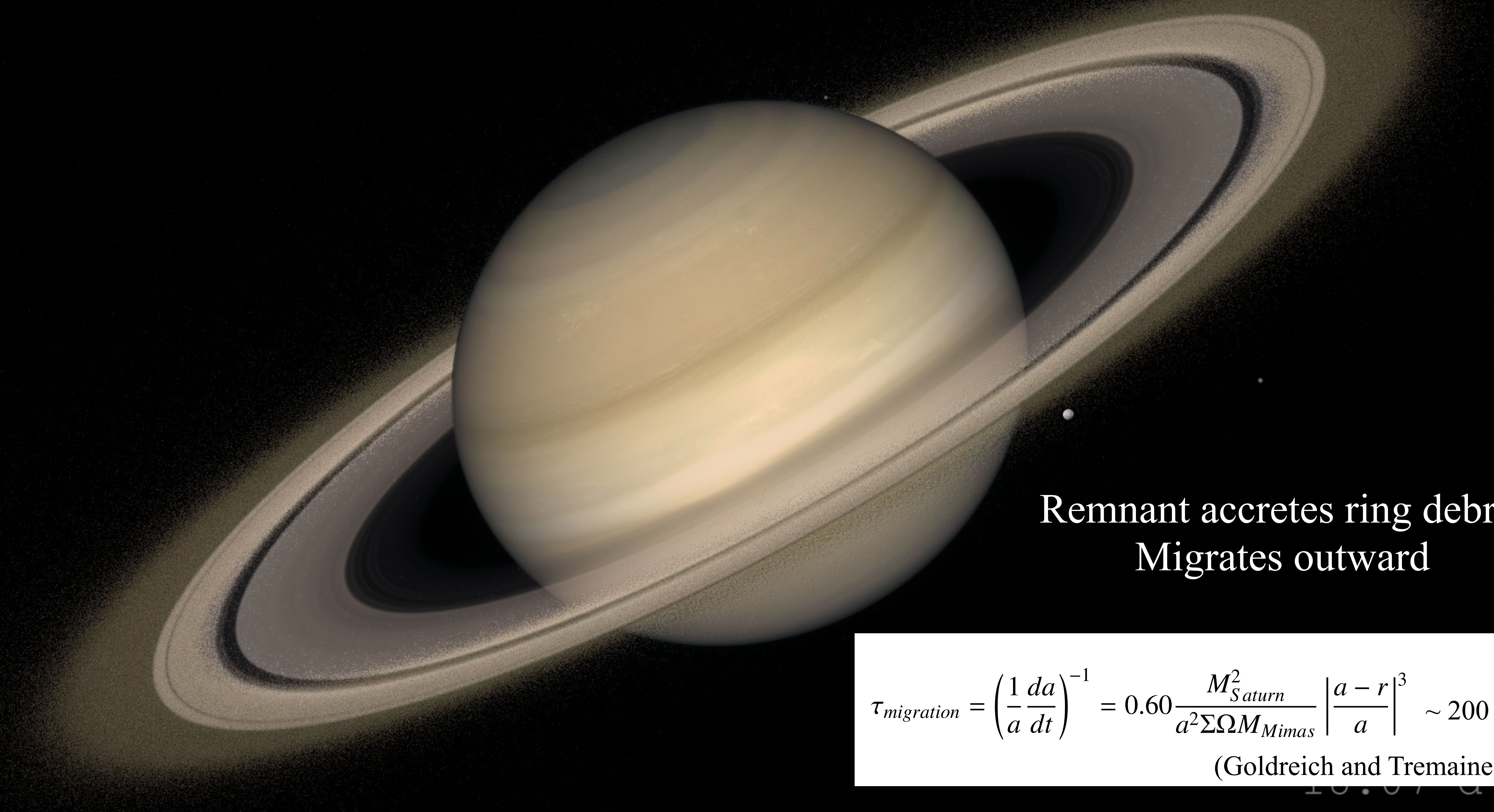

15.17 d


16.62 d


Icy proto-ring straddling the Roche radius
Remnant with rocky core
18.07 d

Some collisional debris migrates inward
to become Saturn’s ring system





Remnant accretes ring debris
Migrates outward

$$\tau_{migration} = \left(\frac{1}{a}\frac{da}{dt}\right)^{-1} = 0.60\frac{M_{Saturn}^2}{a^2\Sigma\Omega M_{Mimas}}\left|\frac{a-r}{a}\right|^3 \sim 200 \text{ Myr}$$

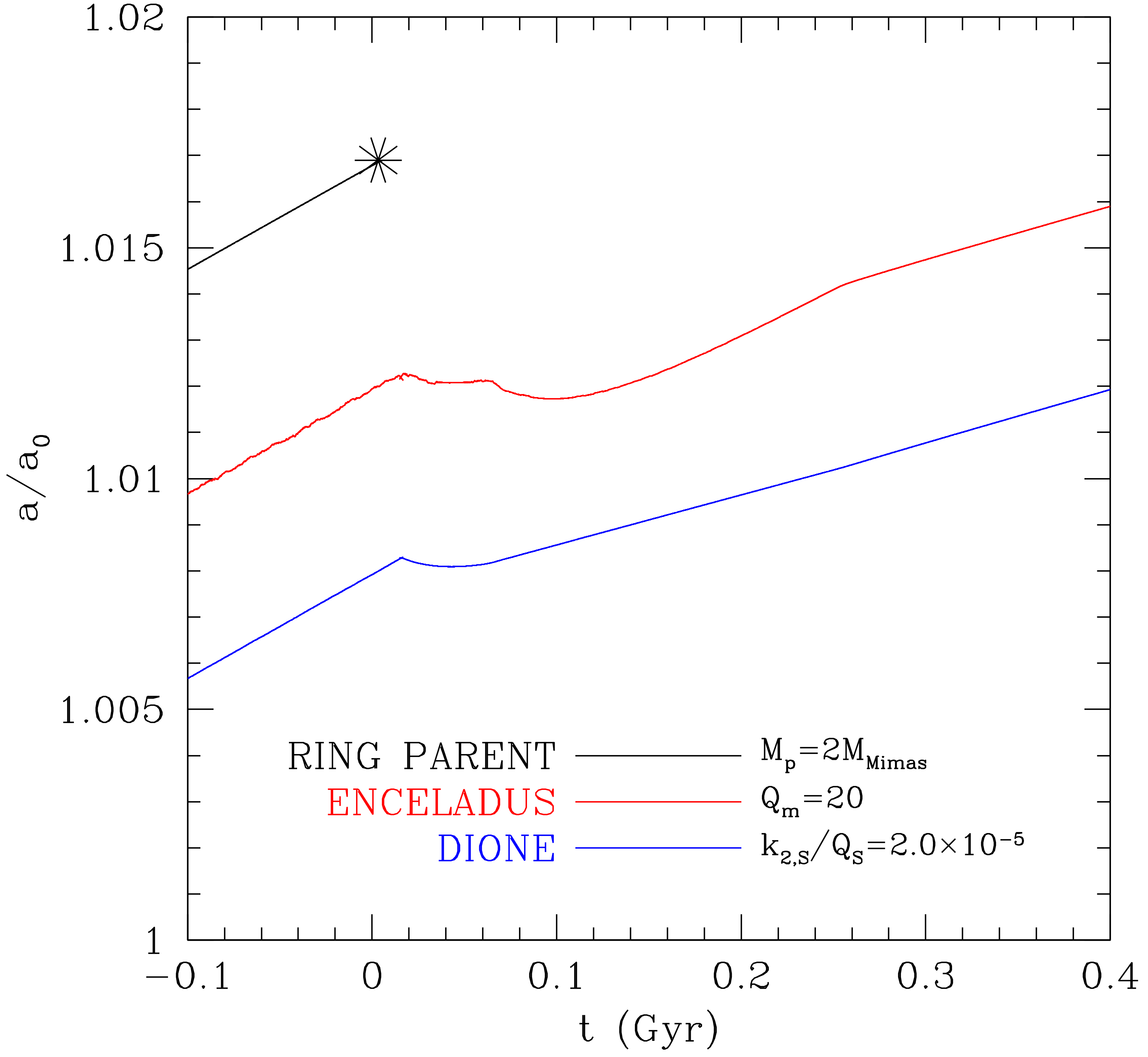
(Goldreich and Tremaine 1982)

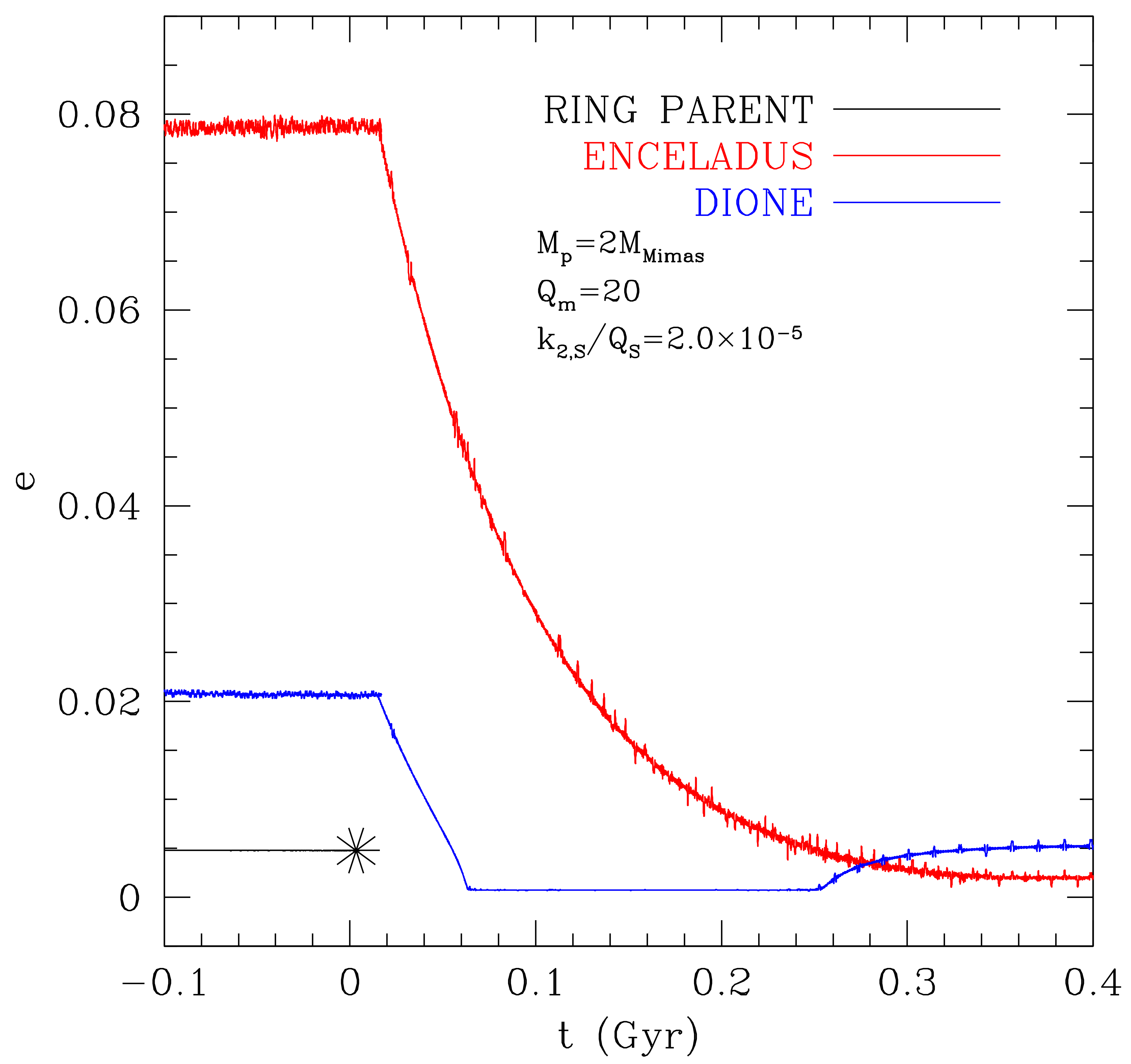

Saturn Today
Mimas
HST Image Oct-1997
200 Myr?

## **Results from 3 simulations**

| Collision | $v_{rel}$ (km/s) | $Q_D$ ($10^5$ J/kg) | $M_{remnant,i}/M_{Mimas}$ | Ring ice fraction |
|---|---|---|---|---|
| rear-end | 11.2 | 0.3 | 1.02 | 1.0 |
| side-on | 22.4 | 1.2 | 0.74 | 1.0 |
| head-on | 44.2 | 4.9 | 0.16 | 0.91 |

# Ring Parent, Enceladus and Dione in MMR 4:2:1




Orbital evolution after destruction of ring parent moon

Prior to destruction tidal heating of Enceladus is >100X larger

If $k_2/Q_S = 1.6 \times 10^{-4}$ the situation is more extreme…

# NEXT STEPS

- With a precise mass of the rings, the detailed parameters can be constrained
- Ring parent: mass, composition, orbital radius
- Comet: mass range, impact energy, probability of impact
- Hydro-code simulations needed
- Simulation of cold accretion for Mimas and ring spreading
- Is a young Mimas compatible with the observed cratering and internal structure?
- In situ analysis by a lander or sample return mission for Mimas and other icy moons to determine age