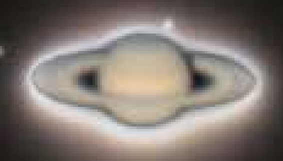
Final Origin of the Saturn System



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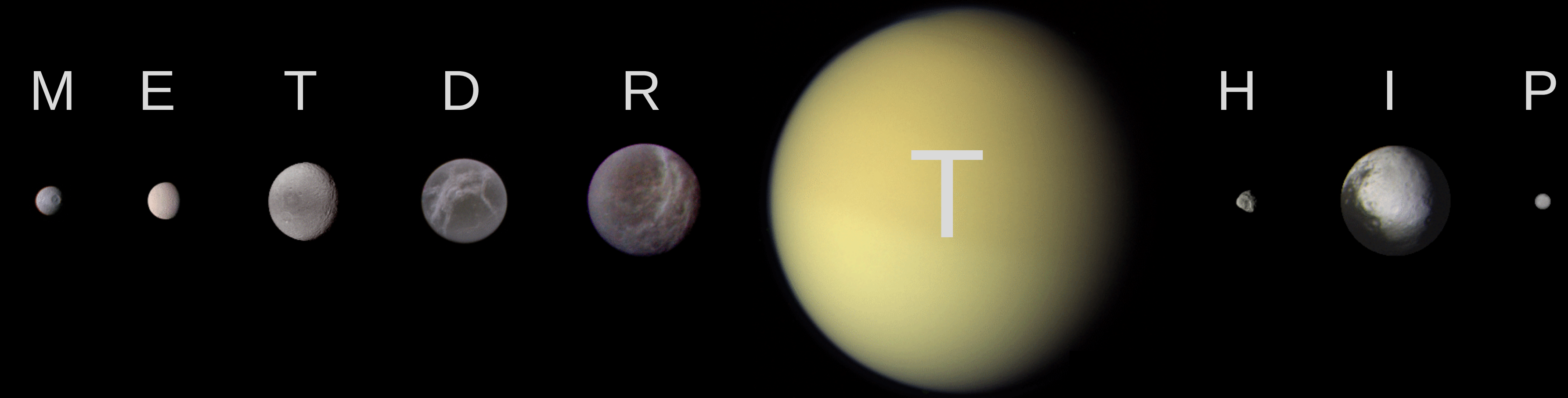
Formation and Evolution of Moons

ESLAB Symposium, Noordwijk, Netherlands, June 25, 2012

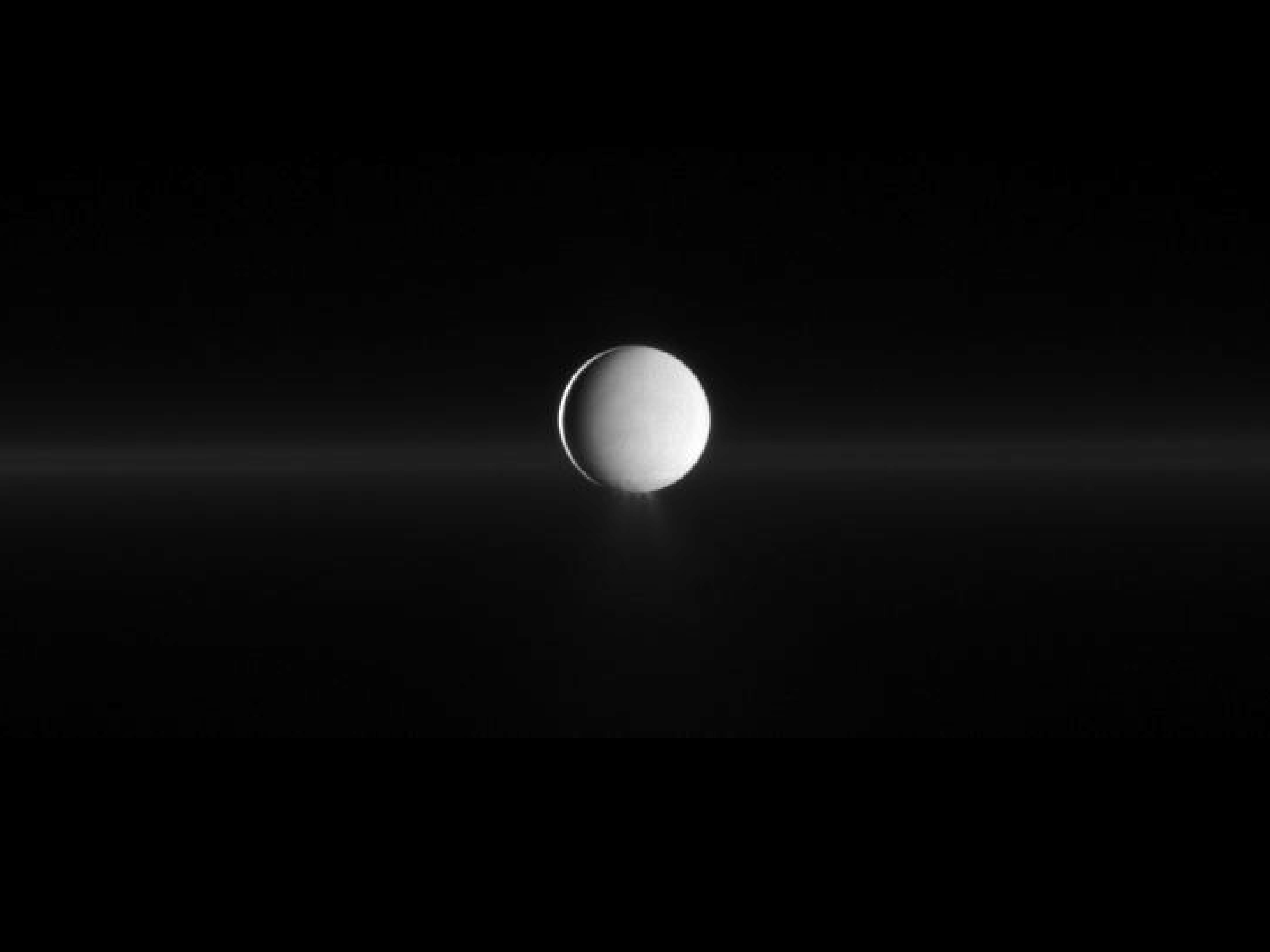
Titan and
Tethys

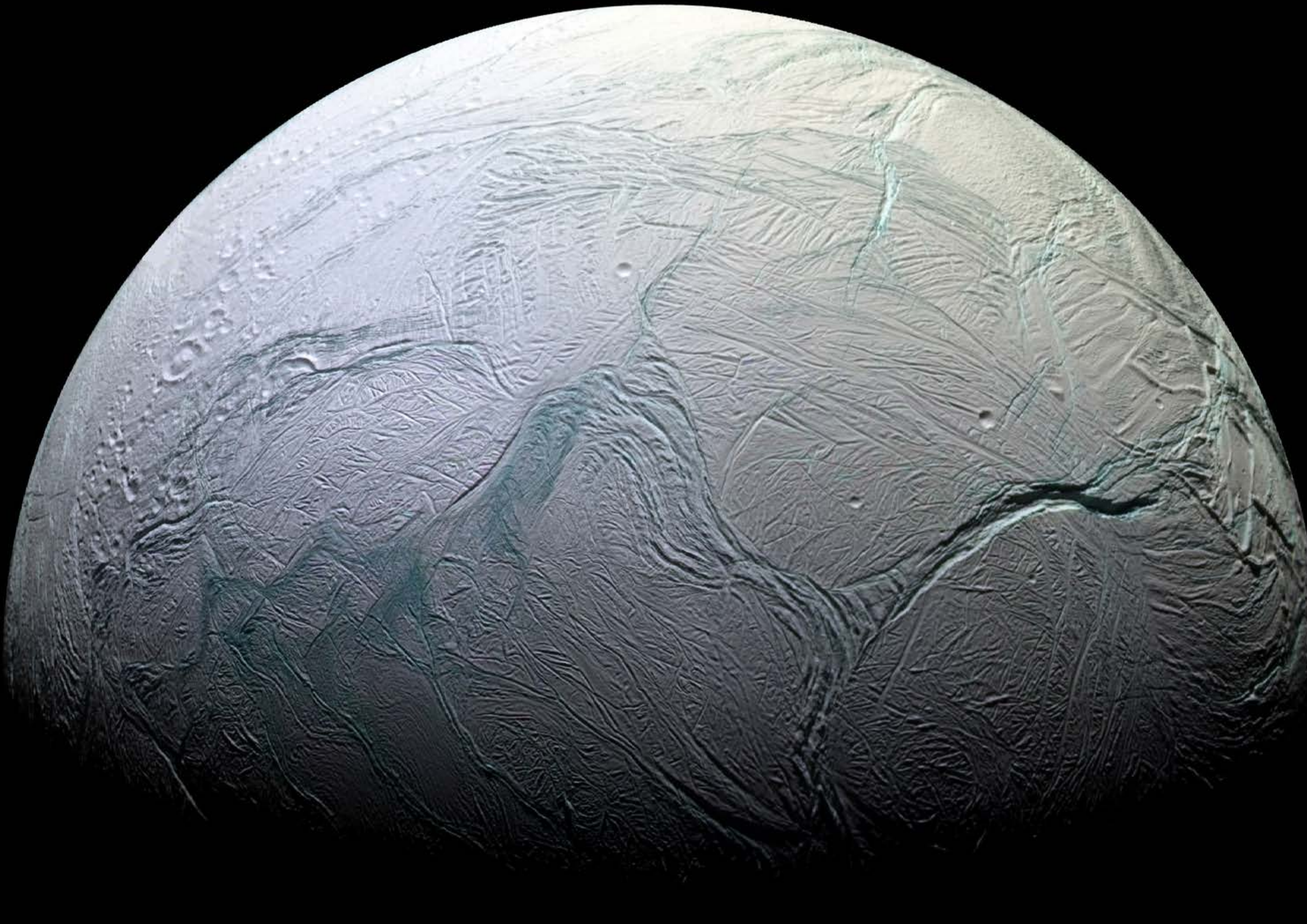
Titan
and
Rhea

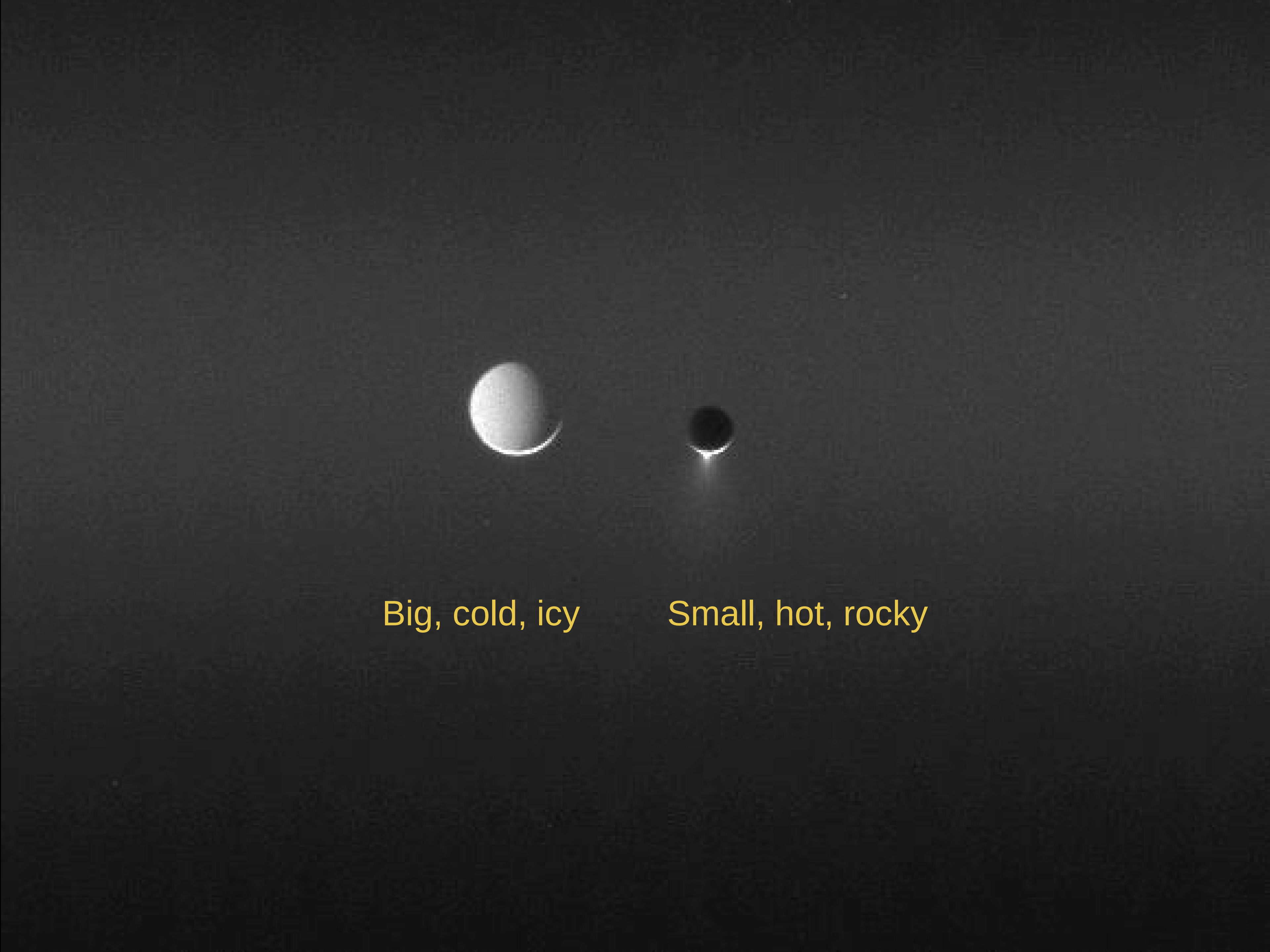
Saturn’s Regular Satellites



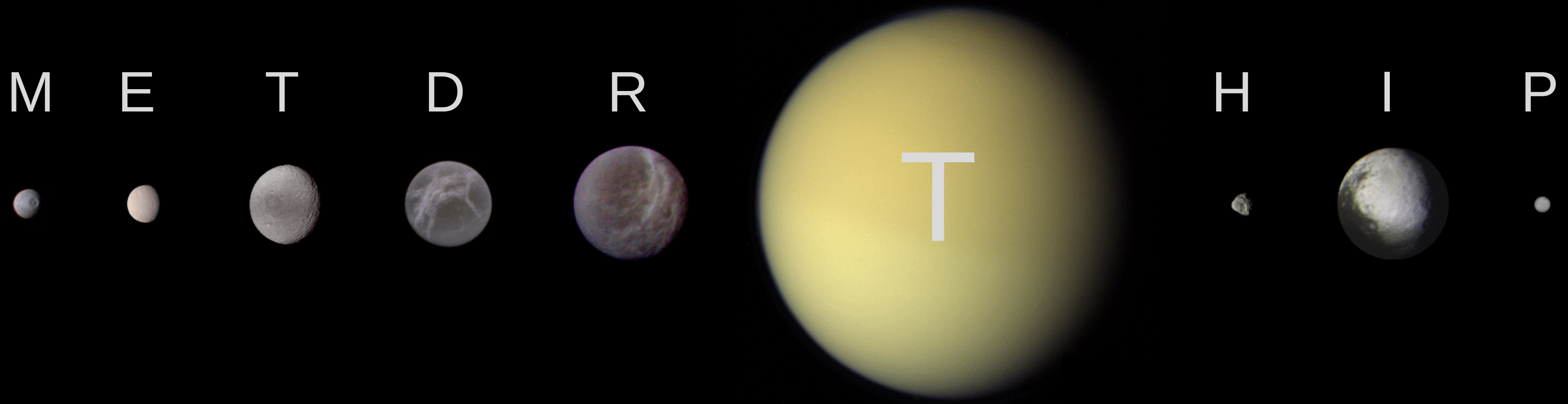
They vary without rhyme or reason (though size ~ distance)
The middle-sized moons (MSMs) possess 4% of the Saturn satellite system’s mass
Titan and Enceladus and Rhea (others?) are or have been active



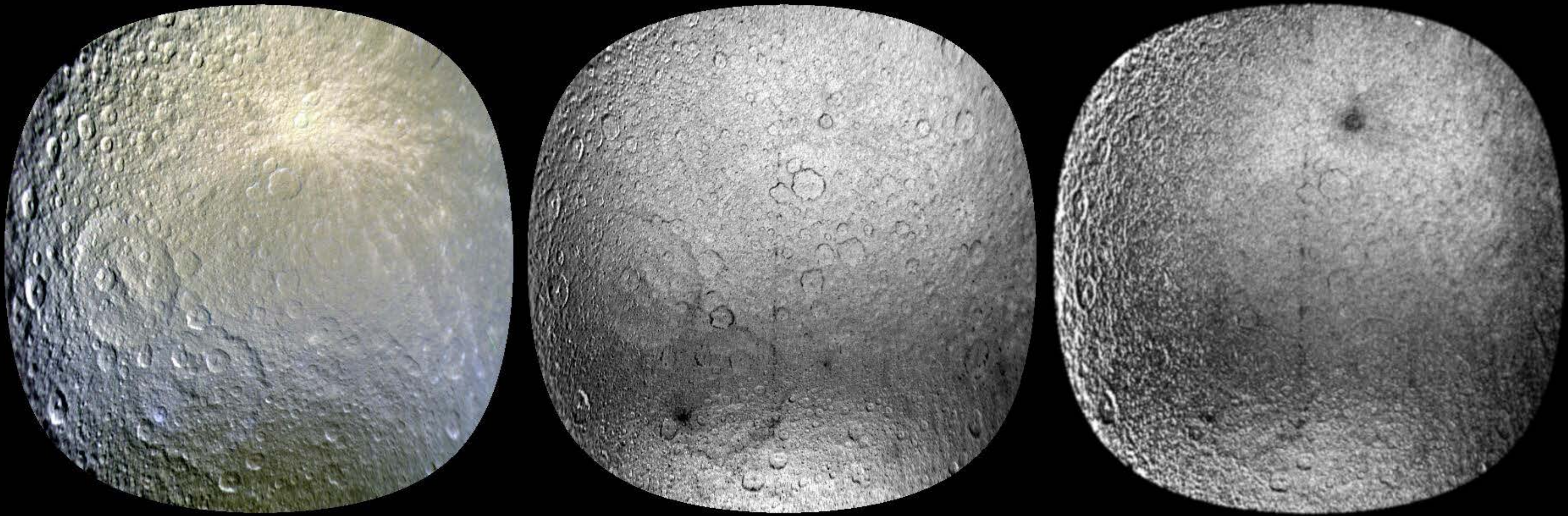



Big, cold, icy
Small, hot, rocky

Saturn’s Regular Satellites



They vary without rhyme or reason (though size ~ distance)
The middle-sized moons (MSMs) possess 5% of the Saturn satellite system’s mass
Titan and Enceladus and Rhea (others?) are or have been active



P. Schenk, D.P. Hamilton, R.E. Johnson, W.B. McKinnon, C. Paranicas, J. Schmidt, M.R. Showalter, “Plasma, plumes and rings: Saturn system dynamics as recorded in global color patterns on its midsize icy satellites”, *Icarus* (2011)

Fig. 6. Single-frame Cassini color observations of Rhea from orbit 18 along the boundary between the trailing (left) and leading (right) hemispheres. Top view is 3-color composite of IR, Green, and UV images; middle view is IR/UV ratio image (stretched to show 1.37–1.65 range); bottom view is IR/Green ratio image (stretched to 1.055–1.1 IR/UV). Views are centered near 145° W longitude, ~35° east of the boundary between leading and trailing hemisphere and clearly show the low IR/UV ratio band between the two hemispheres. The bright ray crater Inktomi at 12° S, 112° W is very prominent in the 3-color composite but is virtually invisible in the center IR/UV ratio image. The bright rays are moderately reddish (bright) while the proximal ejecta deposit is distinctly bluish (dark) in the IR/Green image. Image resolution is 1.75 km/pixel. Map extends from ~85° to 215° W.

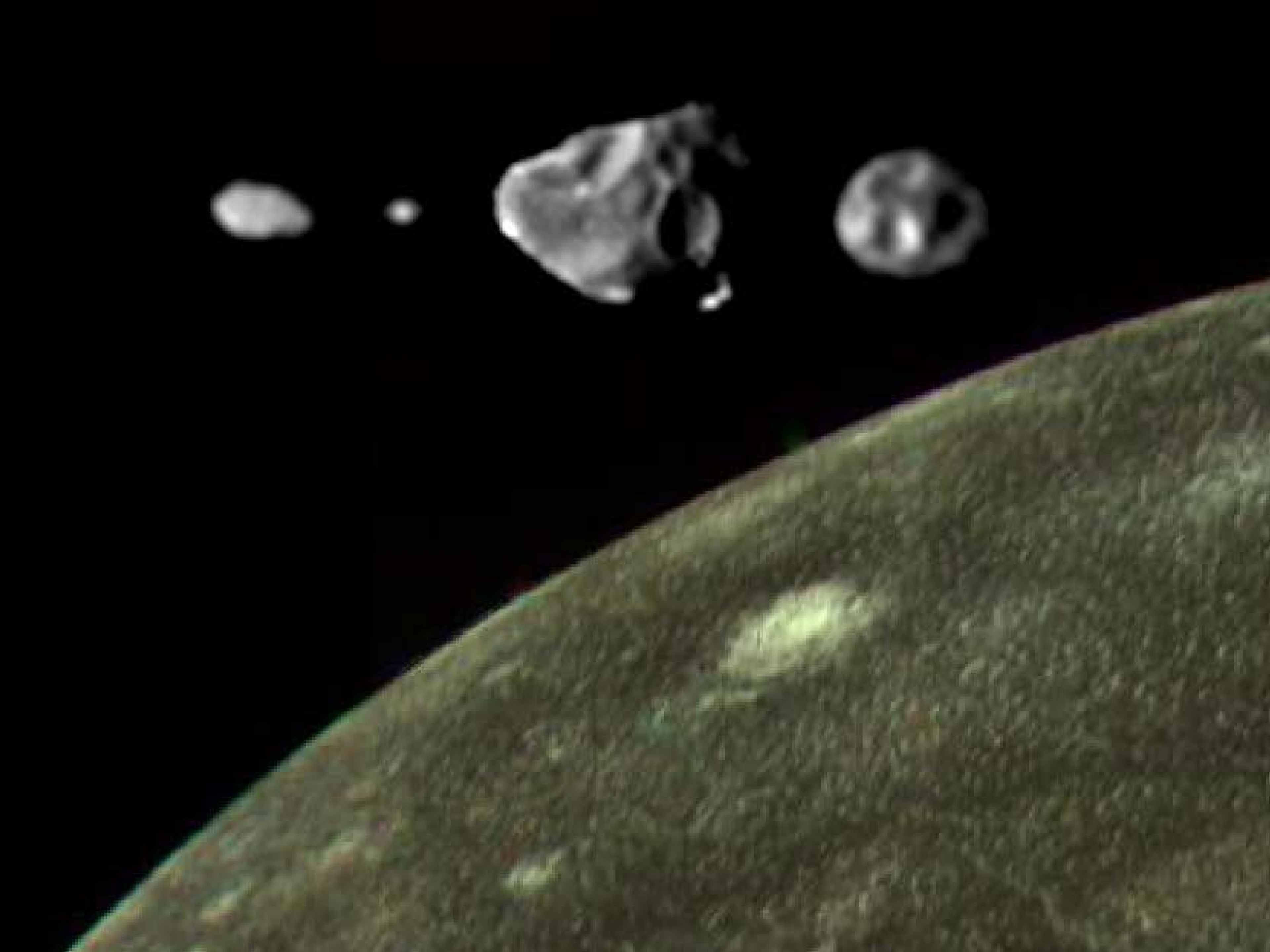
Blue equatorial splotches

How old can they be?

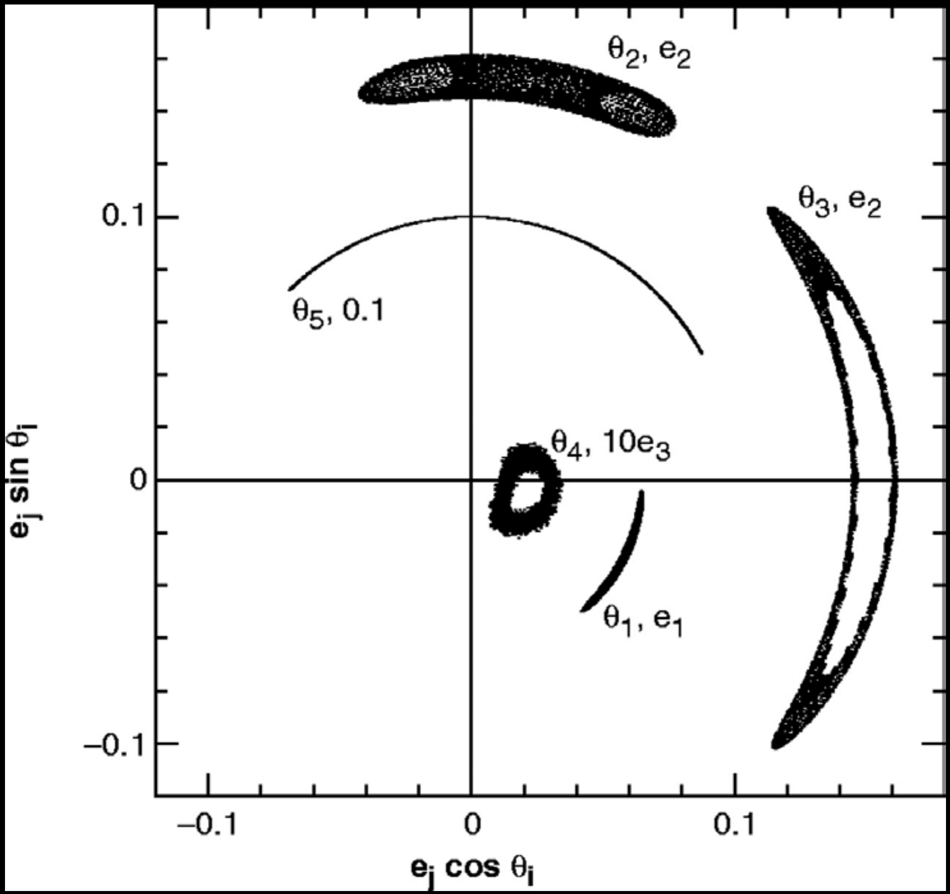
Was it a circularized disk? How?

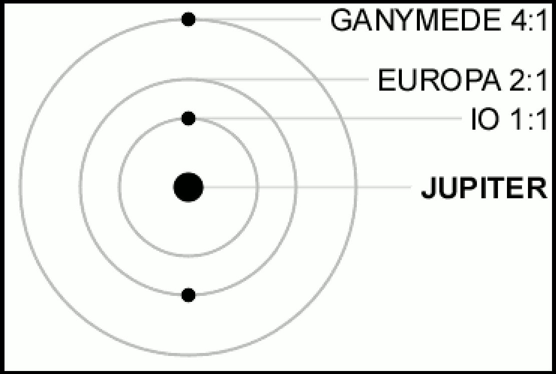
Jupiter's Moons

99.998% of the system mass
…there's not much else



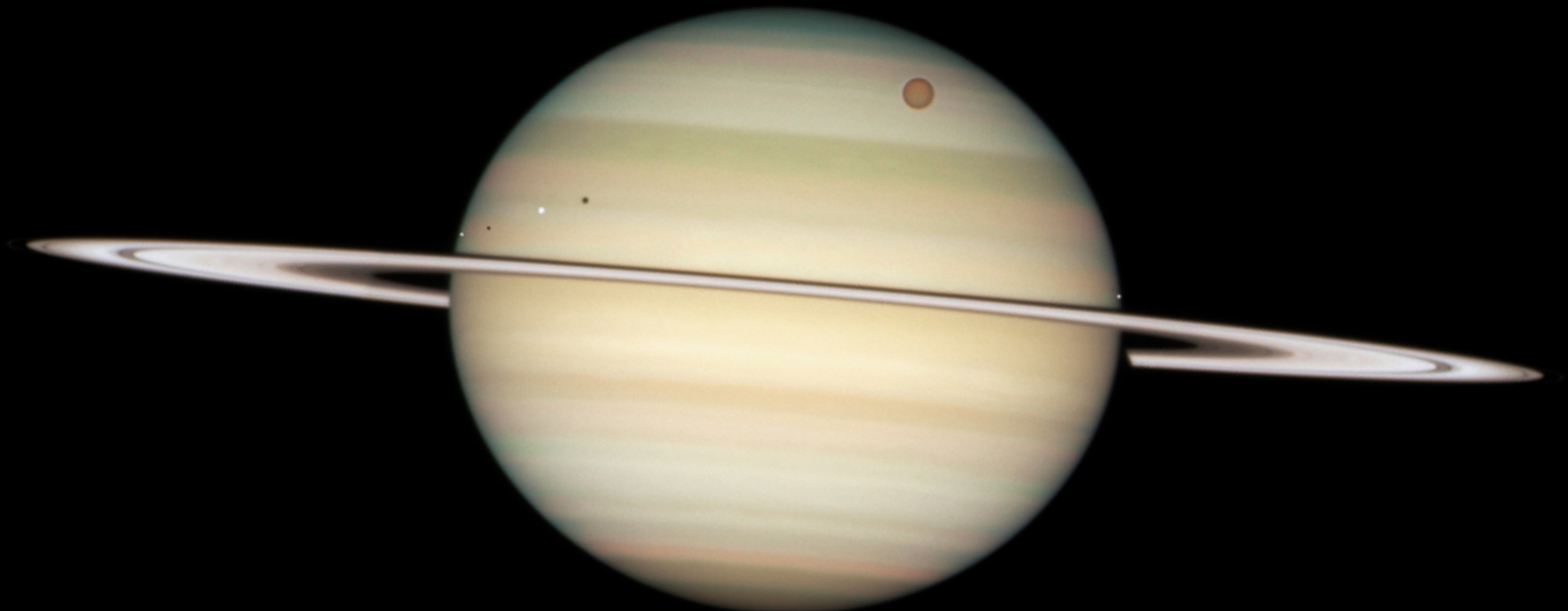
Laplace Resonance





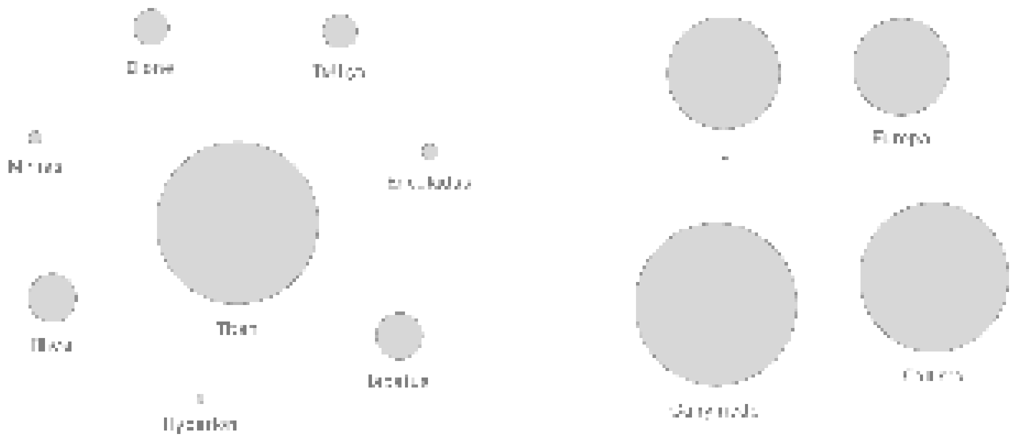
$n_1 - 3n_2 + 2n_3 = 0$

Peale and Lee (2002): modeled the attainment of the Laplace resonance in the context of the Canup and Ward (2002) model

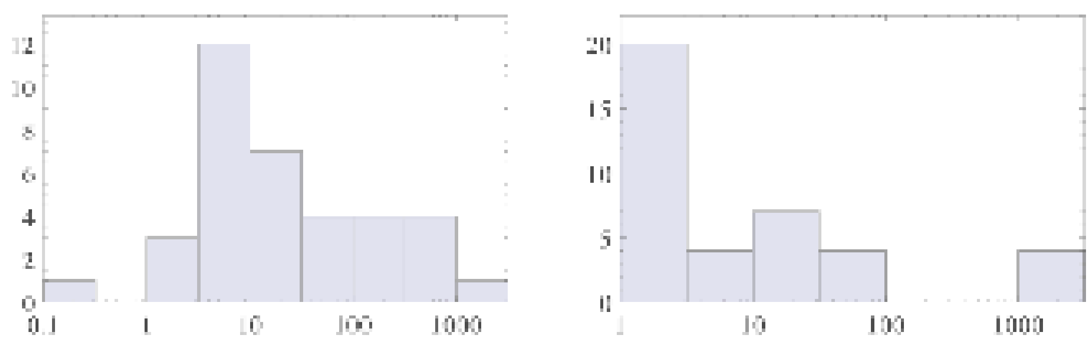


Saturn on the other hand…

2009 HST image showing Enceladus, Dione, Titan, Mimas, and their shadows.
Saturn's moons have a smattering of curious resonances but nothing like at Jupiter.



(a)



(b)

Figure 1: Two very different satellite systems. (a) All moons larger than 200 km diameter are plotted to scale for Saturn (left) and Jupiter (right). (b) Histogram of the populations. Almost 5% of the Saturn system is in bodies smaller than Titan, while less than 0.002% of the Jupiter system is in small bodies.

Can They Survive the LHB?

- Late Heavy Bombardment: system-wide?
- If so (Nice model) then Saturn's middle-sized moons (MSMs) may not survive
  - Charnoz et al. (2009) find Mimas ~50% likely to survive based on solid disruption scaling
  - Nimmo and Korycansky (2012) find the LHB considerably more devastating based on vapor production scaling of Kraus et al. (2011)
    - They propose LHB was 1/10 as intense, and stochastic

COLLISIONS PRIMER

Similar-Sized Collisions, a.k.a. Giant Impacts

- They happen early & late, small & large
- They are "slow" ($v_{imp} \gtrapprox v_{esc}$)

Lynette Cook

A smørgåsbord of origins:

- Binary accretion
  - Asteroids and meteorites
  - Chondrule formation
- Late stage giant impacts
  - Earth-Moon, Mercury
  - Pluto-Charon, Haumea, Titan?
- Splats
  - Comet layering (Belton model)
  - Lunar farside highlands (accretionary pile)
  - Interior accretion (core meets core)

Binary mergers at ≈v_{esc} are sloppy!

- Giant impacts take hours
  - $(G\rho)^{-1/2} \approx R/v_{esc} = \tau_{grav}$
  - Strain rate ≈ 10^{-3} s^{-1} → rheology
  - Gravity is non-central
  - Many kinds of waves and instabilities
- Volatiles, shocks, compressibility:
  - Degassing and d*P* evolution can fuel a merger
    - Enthalpy *h* is conserved in ascending material
  - Larger scale collisions → higher v_{esc} → higher v_{imp}
    - Melting and vaporization at planetary scales
    - No shock heating at planetesimal scales

Lynette Cook

- No such thing as perfect merger
  - Brings angular momentum exceeding rotational stability even at $v_{imp}=v_{esc}$
  - Colliding mass in a typical giant impact 'overshoots'

Lynette Cook

- Merger increases gravitational binding energy
  - $U \sim R^5$ while $R_F \sim (R_1+R_2)^{1/3}$, so U_F always $< U_1+U_2$
  - Astrophysical halos, spiral arms, decretion…
  - Goes into spin-up, orbital debris, escaping debris, heating

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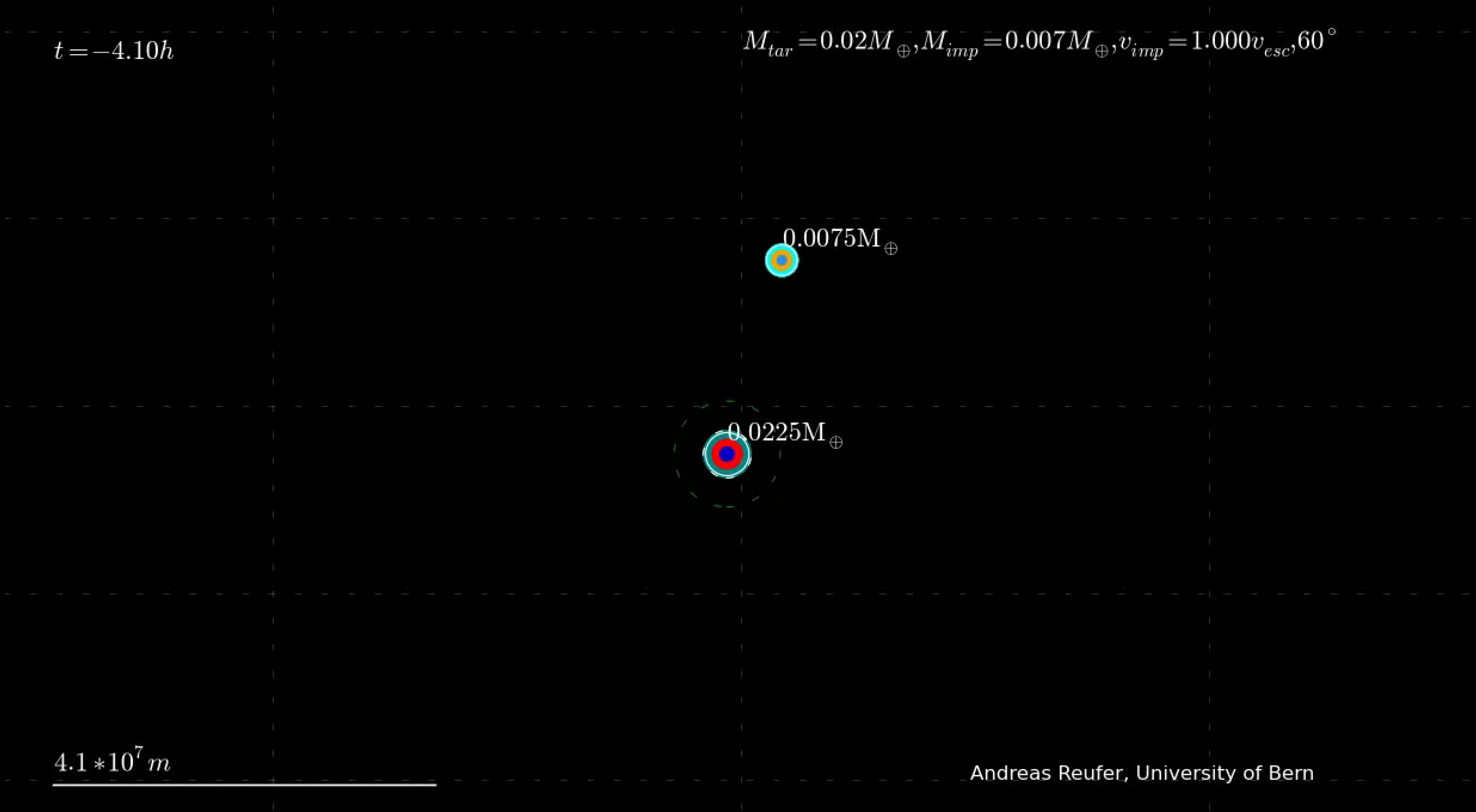
Binding energy deficit ~15% in a canonical Moon forming giant impact, and ~37% in an equal sized merger.

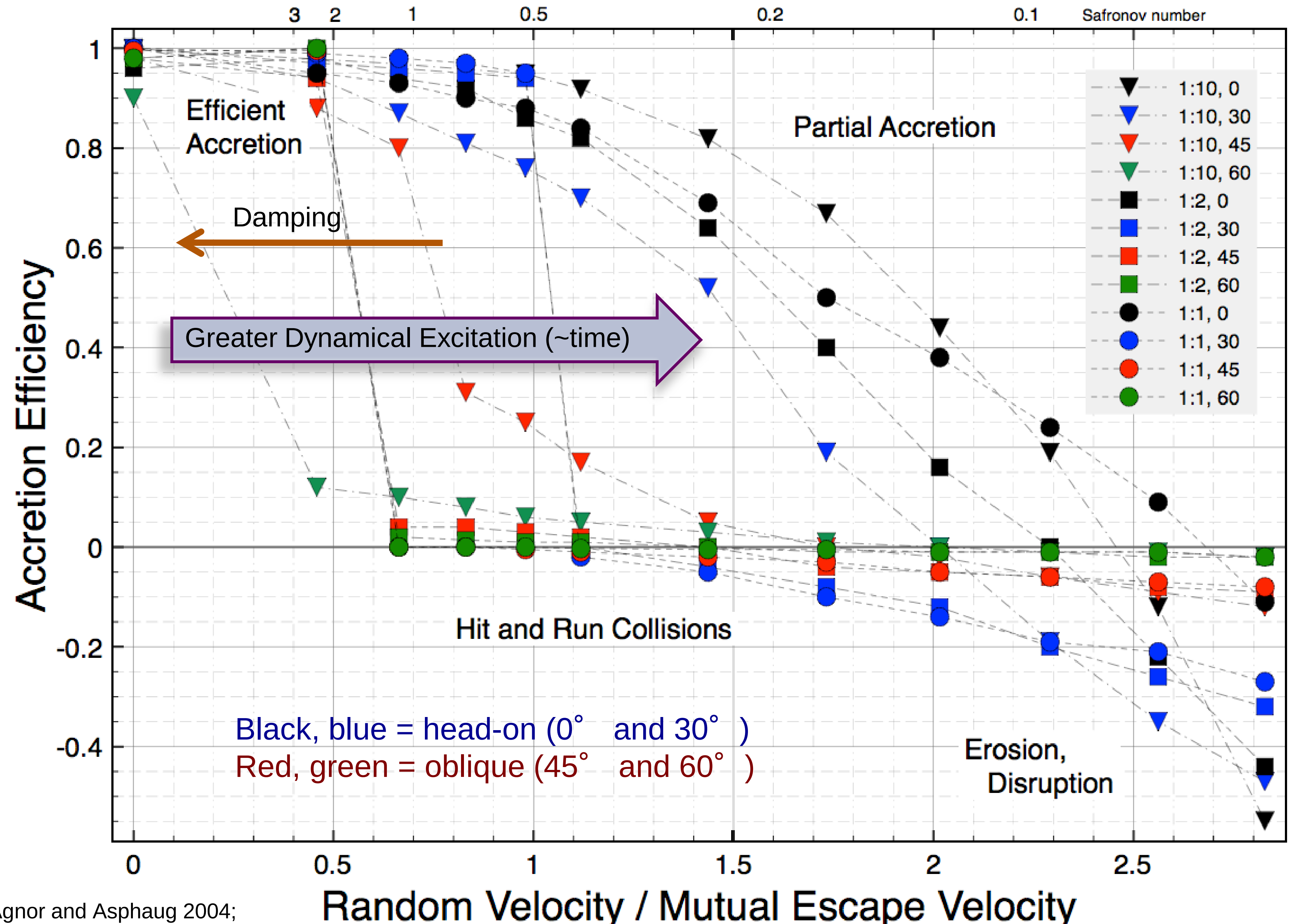
Hit or Miss

- Giant impacts are often thought of as having one of two major outcomes:
  - If $v_{random} <\approx v_{esc}$ (damped), planets merge
    - interesting consequences like satellite formation
  - At $v_{random} >> v_{esc}$ (turbulent or late stage) the target can be destroyed
- By implication, "early" was an epoch of accretion; "late" was an epoch of disruption

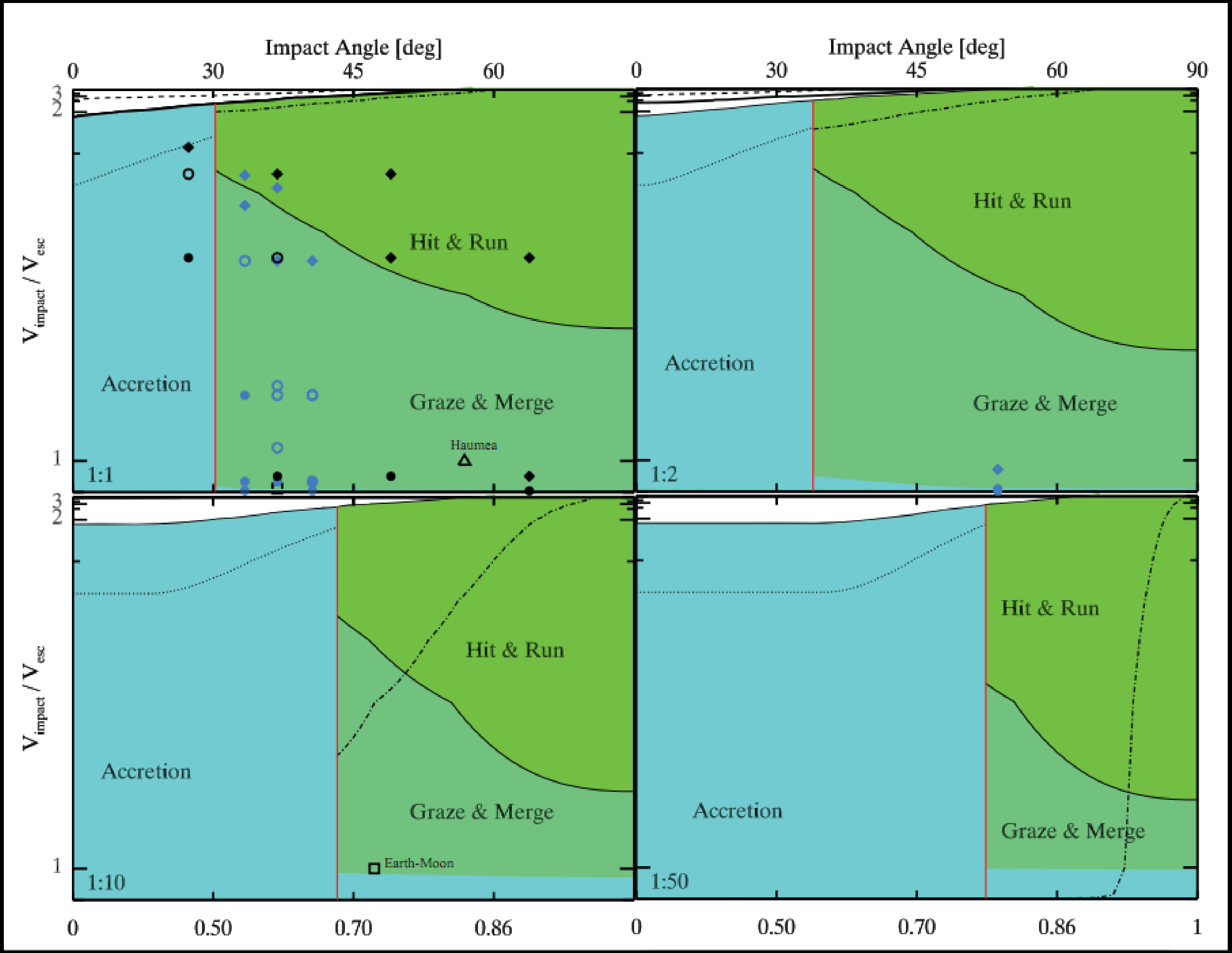
But

- There is a <u>vast middle ground</u> of messy, non-accretionary collisions, an idea that harken back to Chamberlin (1901), Jeans (1919), Jeffreys (1924):
  - Hit and run, at $1.2v_{esc}<\mathrm{H}v_{impact}<\mathrm{H}2.7v_{esc}$
    - Agnor and Asphaug (2004); Asphaug et al. (2006); Genda and Kokubo (2010); Sekine and Genda (2012)
  - Graze and merge at $1.0v_{esc}<\mathrm{H}v_{impact}<\mathrm{H}1.2v_{esc}$
    - Canup (2009); Asphaug et al. (2011); Leinhardt and Stewart (2012)

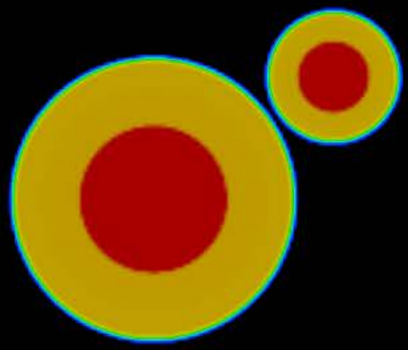

$t = -4.10h$
$M_{tar} = 0.02M_{\oplus}, M_{imp} = 0.007M_{\oplus}, v_{imp} = 1.000v_{esc}, 60^{\circ}$
$0.0075\mathrm{M}_{\oplus}$
$0.0225\mathrm{M}_{\oplus}$
$4.1 * 10^{7}\, m$
Andreas Reufer, University of Bern



Agnor and Asphaug 2004;
Asphaug 2009



Parameter study by Leinhardt and Stewart (2011) where equal area = equal probability of collision, for 1:1, 1:2, 1:10 and 1:50 mass ratio collisions, using velocity distribution data of Raymond et al. (2009)

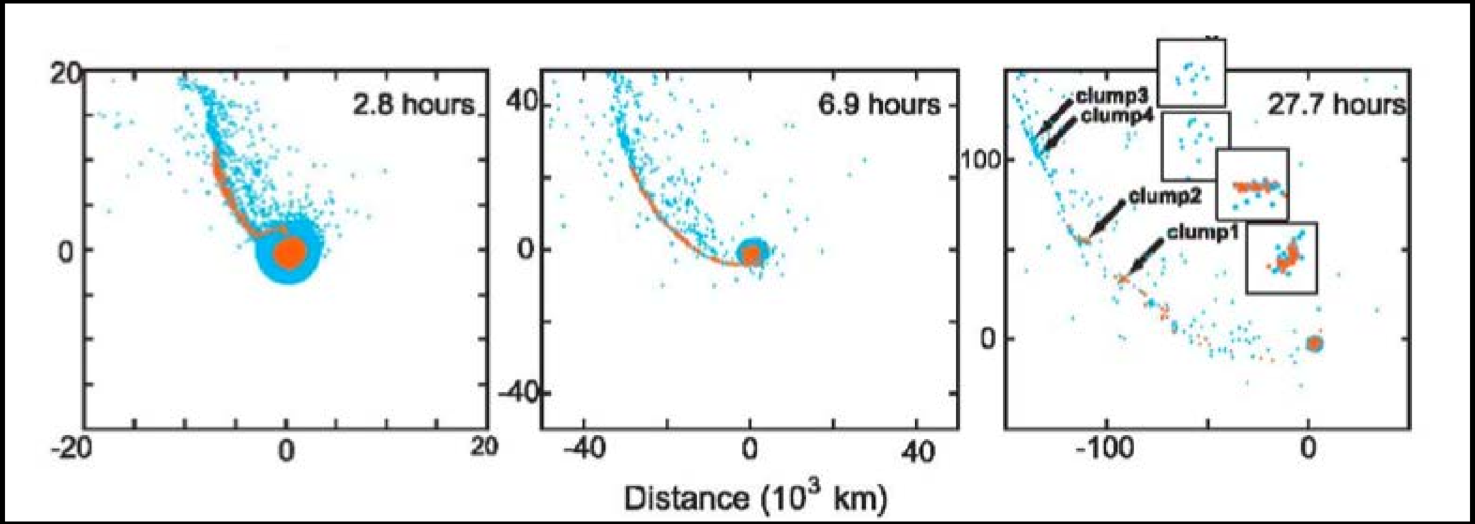


Simulation by M. Jutzi

Hit and Run

- End up with a chain of bodies, but
  - Why don't the MSMs accrete from crossing orbits?
  - How can the Titan-sized target disappear without a trace?

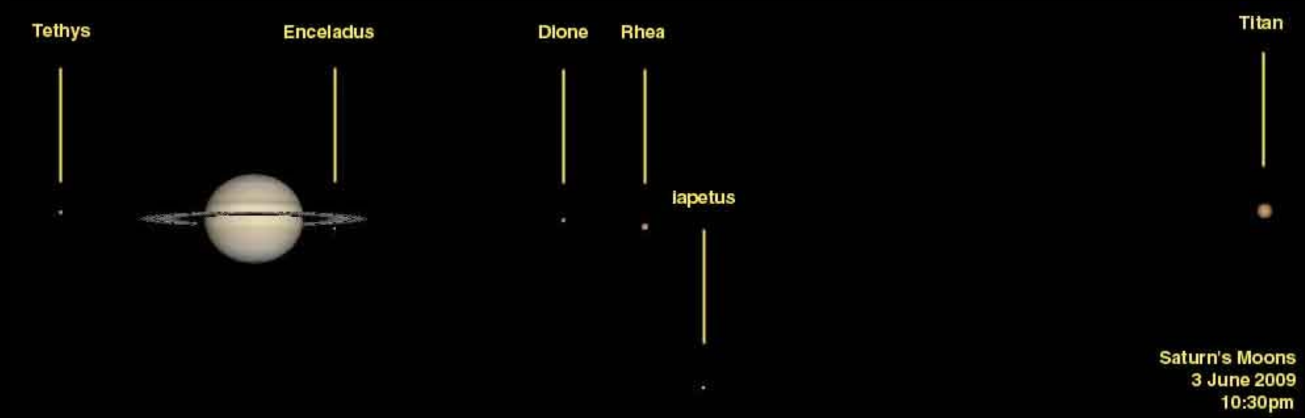
Sekine and Genda (2012)



Collision between 2000 km body and Titan-sized body during Type I migration

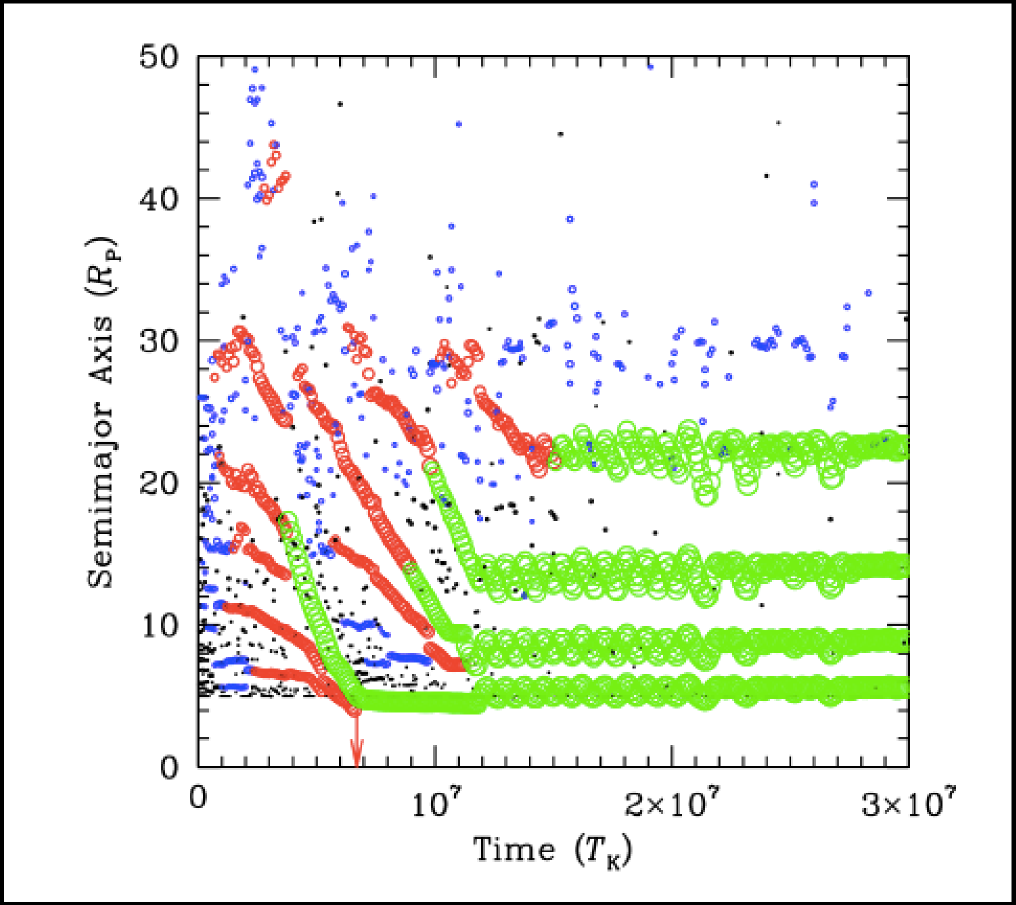
OK Back to Saturn’s Moons

- Middle-sized moons (MSMs)
  - Six bodies between 400 km and 1500 km diameter
    - Numerous mean motion resonances plus 2 sets of Trojans
    - Bizzarre active geology of tiny Enceladus
    - Evidence for rings about Rhea and Iapetus…
- Titan
  - About the same mass compared to Saturn, as all the Galilean satellites, compared to Jupiter
  - 3 times higher eccentricity than any of the Galilean satellites of Jupiter, no known forcing, and (likely) high dissipation (e.g. Sohl et al. 1995)



What if Saturn’s system was ‘once upon a time’ more like Jupiter’s, and experienced dynamical collapse?

Mergers and Resonances



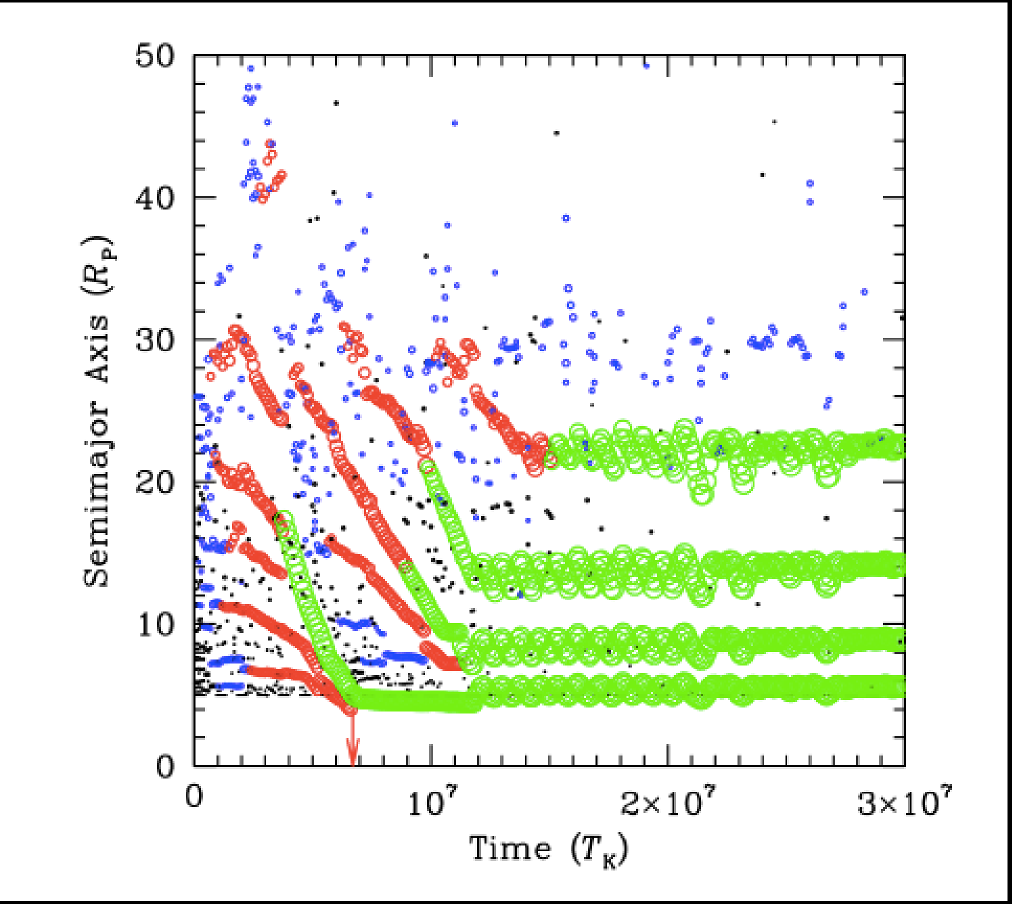
Ogihara and Ida (2012)

Systems of moons accreting in a late-stage of mergers in a jovian subnebula

Type I migration starts off the motion

Gap opening parks the first satellite and the rest come into Laplace-like resonance behind it

What If

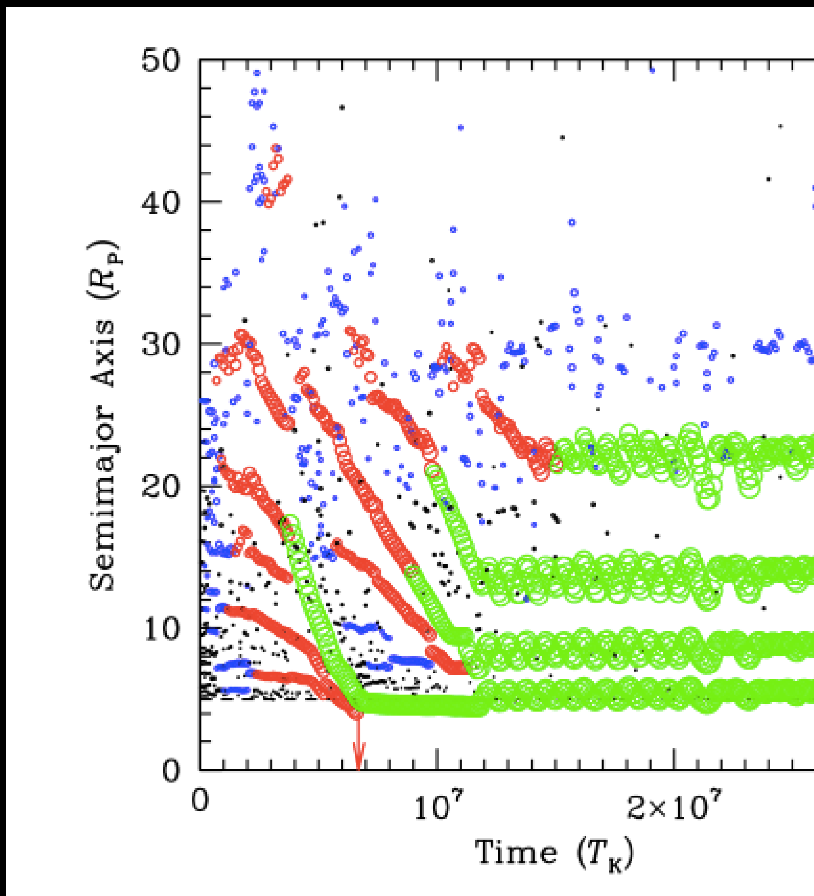


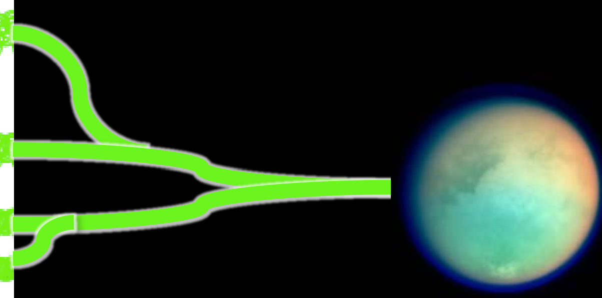
Ogihara and Ida (2012)

What if something destabilized the Saturn system, causing a later merger?

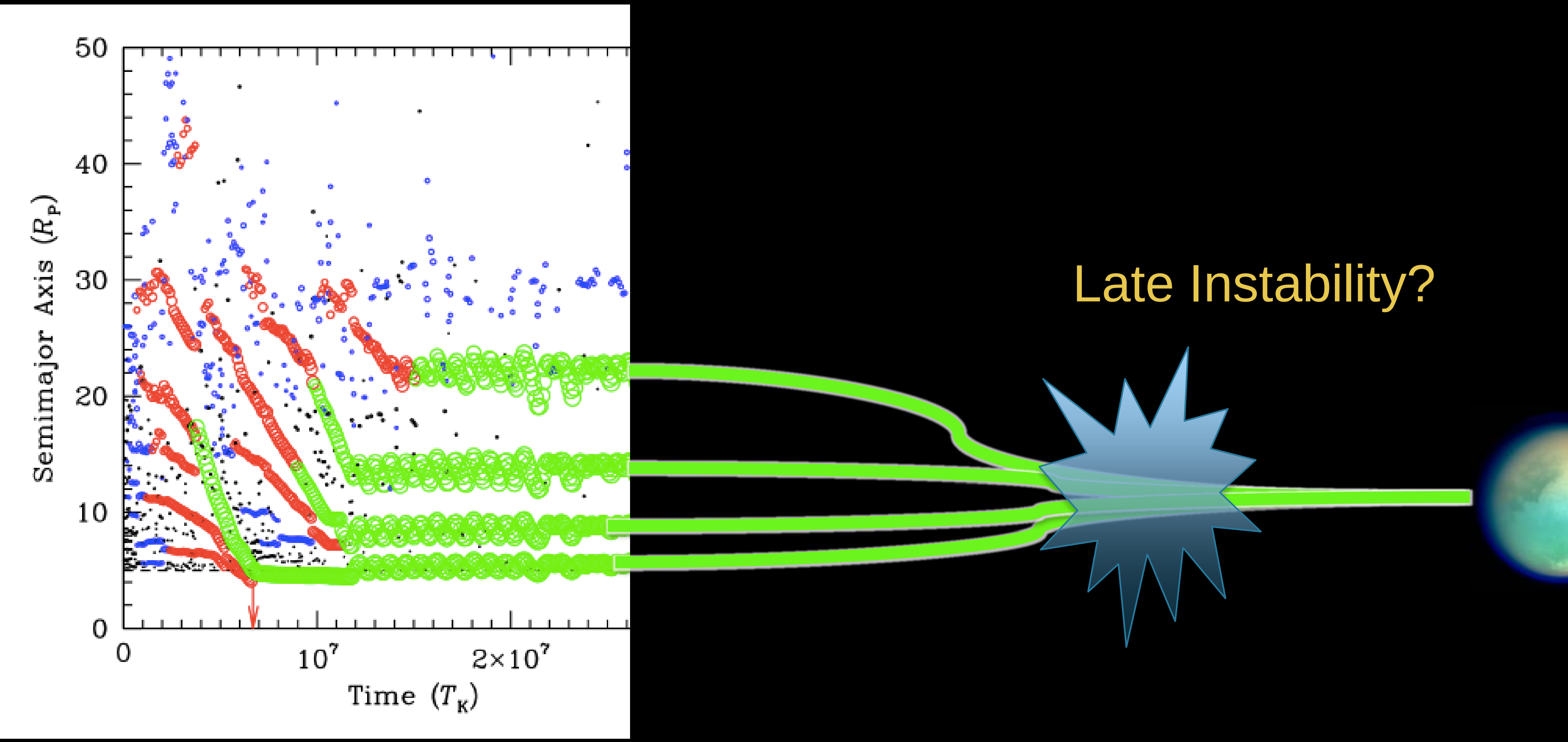
Alternatively, what if the system never achieved the same stability as Jupiter?

Original Instability





Ogihara and Ida (2012)



Late Instability?

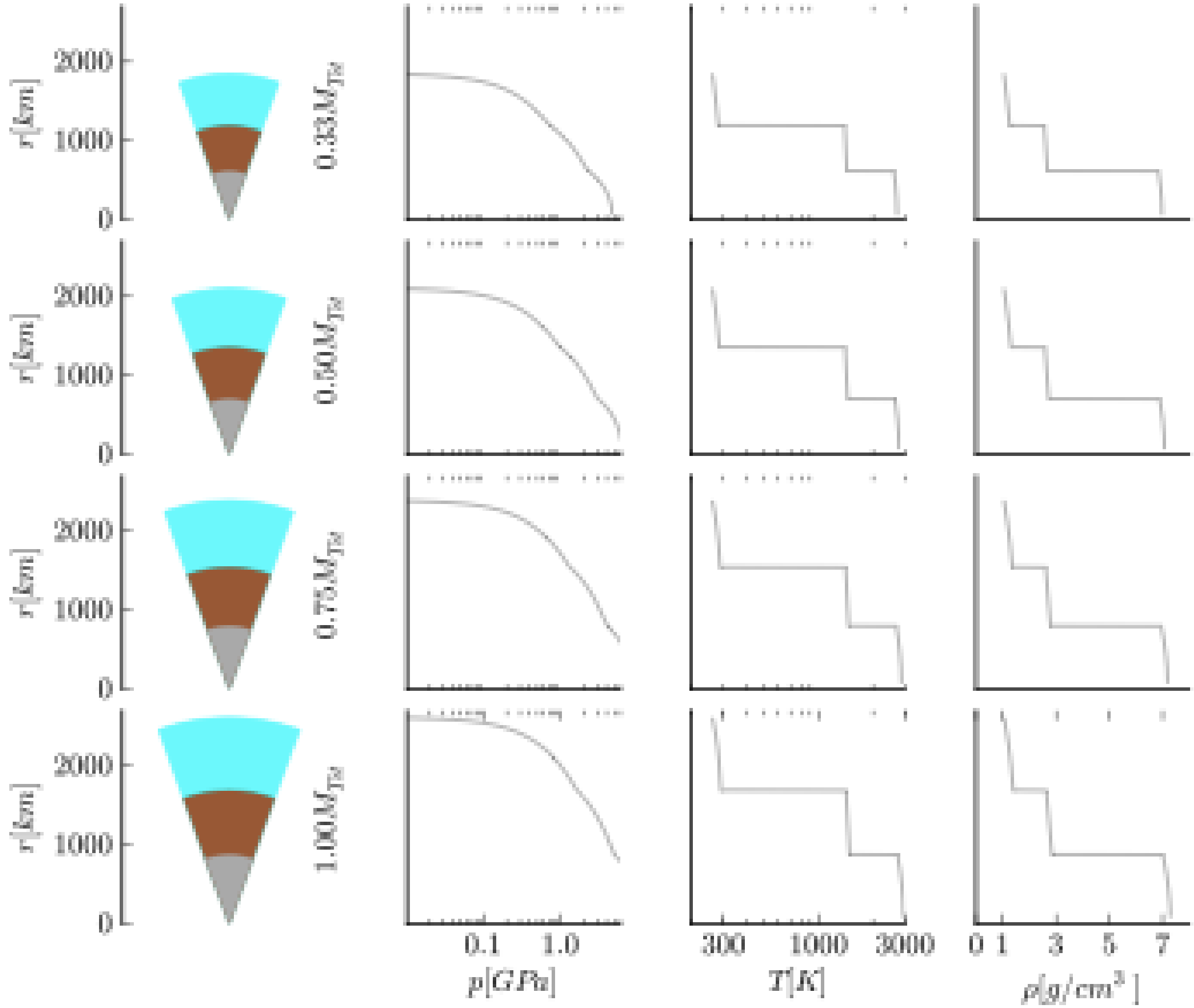
Ogihara and Ida (2012)

Possible Causes?

- Blame the Nice model
  - Late Heavy Bombardment
  - Jumping Jupiters (Brasser et al. 2009)
  - Massive debris disks?
- Or, a Primordial Instability
  - The MSMs would have to survive the LHB
- Or, Blame Saturn
  - Lower mass, has less stable Laplace resonances
  - Perturbed by Jupiter or a Jumping Jupiter?

Modeling the Mergers

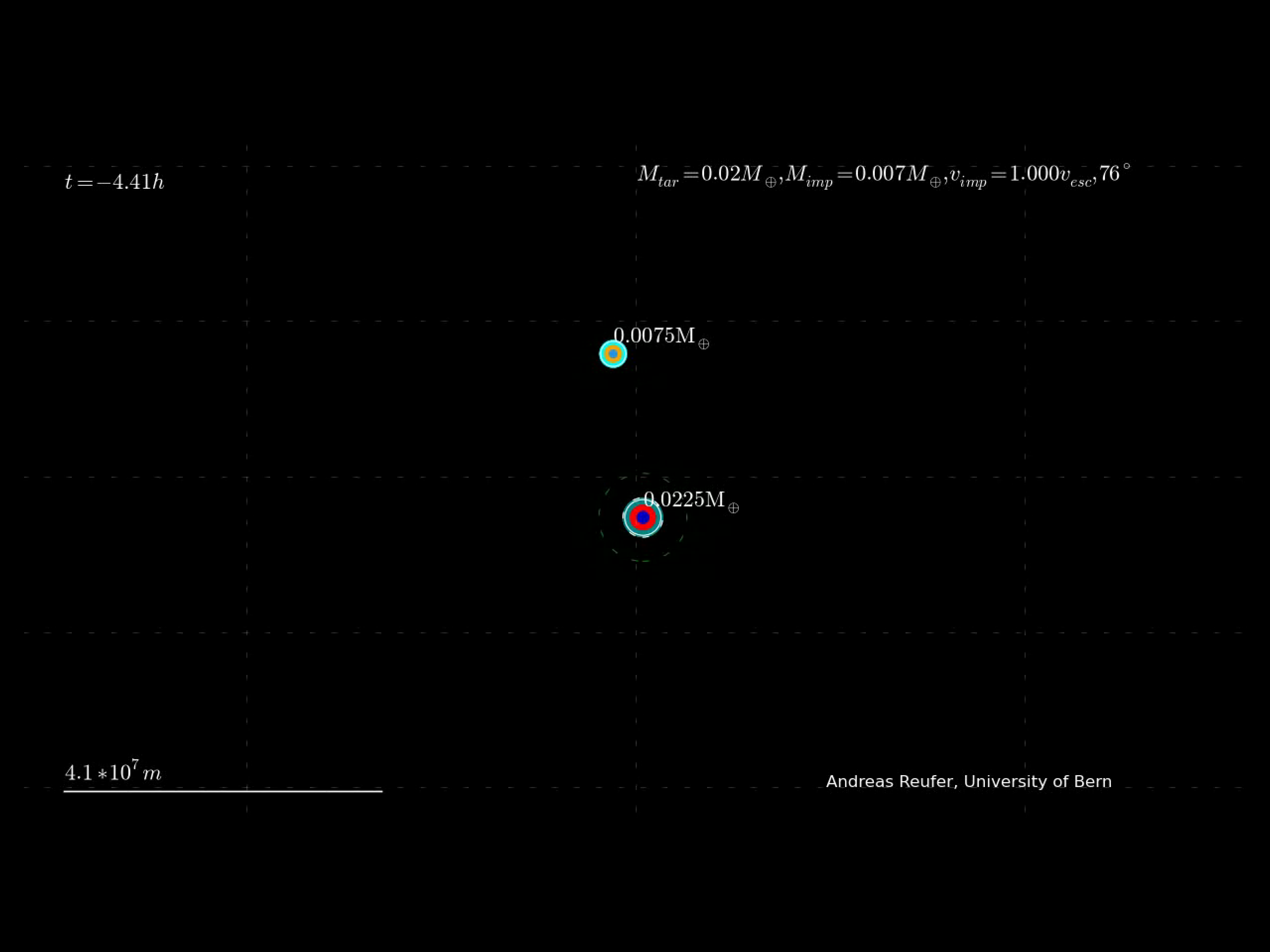
- Smooth Particle Hydrodynamics
  - Solves the PDEs of hydro, shock and self-gravity
  - Resolution elements are interpolation kernels
  - No such thing as a single particle in the hydro
  - Although, single particles serve as the gravitational potentials
  - You don’t have to grid up the empty space as in grid based methods (CTH, FLASH)



MODEL SETUP

3D SPH code, Barnes-Hut tree, tabulated ANEOS, >200,000 particles

Figure 3: Equilibrium structures for differentiated spherically symmetric bodies with masses 0.33, 0.50, 0.75, 1.00 times M_{Titan} composed of an iron core (15wt%), an inner silicate mantle (35wt%) and an outer H_2O mantle (50wt%). The layers are at constant entropy, representing temperatures corresponding to a melted initial state in the ANEOS equation of state. The chosen structures are representative, there being no consensus on the internal structure of Titan, let alone its precursors.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$0.0075\mathrm{M}_{\oplus}$
$0.0225\mathrm{M}_{\oplus}$
$4.1 * 10^7\, m$
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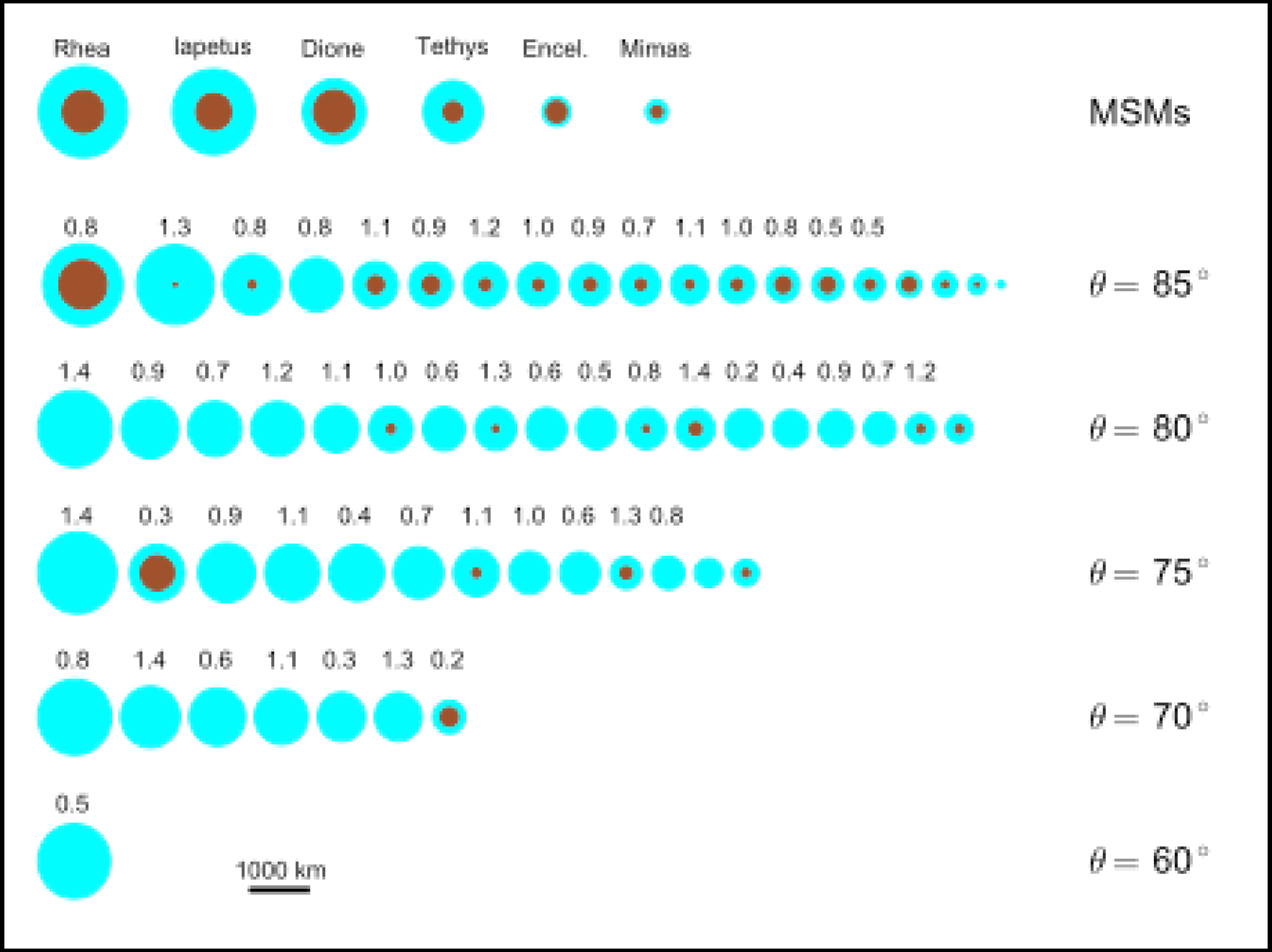
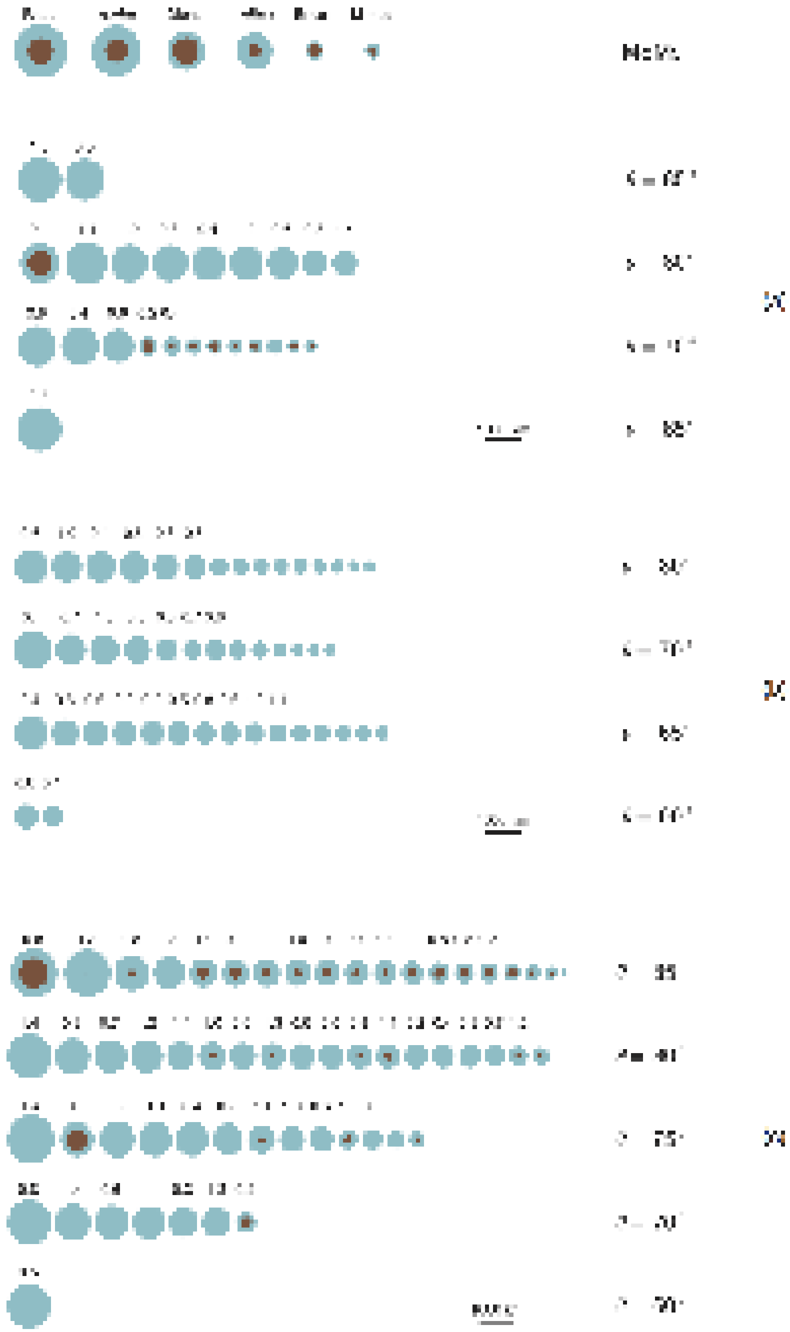
Sizes and Compositions



Outcomes of simulations where two satellites 3:1 mass ratio collide at v_{esc}

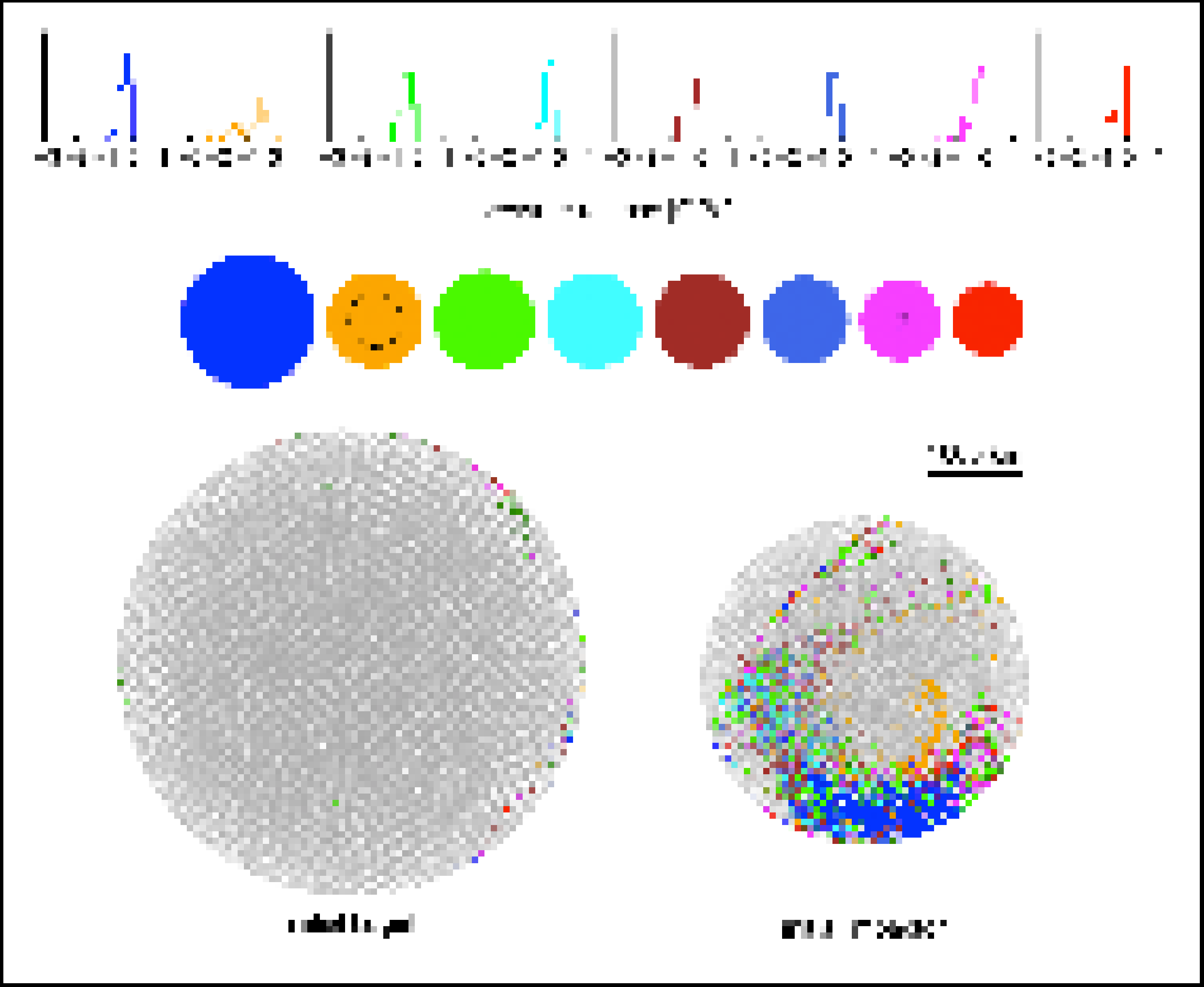


Results for various mass ratio collisions, in Titan masses:

Top: 50% into 75%
Middle: 33% into 75%
Bottom: 33% into 100%

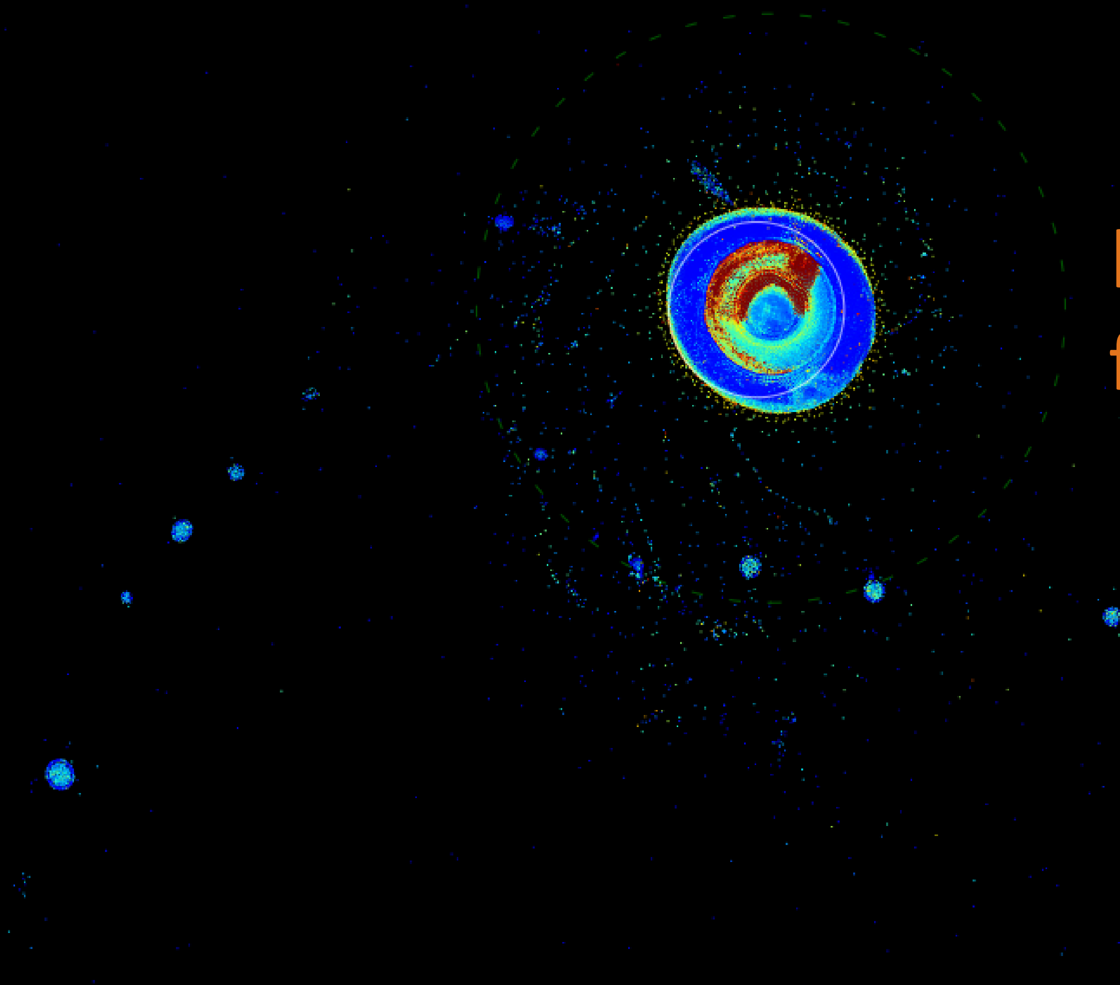
Enceladus-sized objects are resolved with 160 particles

Smaller objects and debris are under/unresolved



For the case of the 3:1 mass ratio collision at v_{esc}

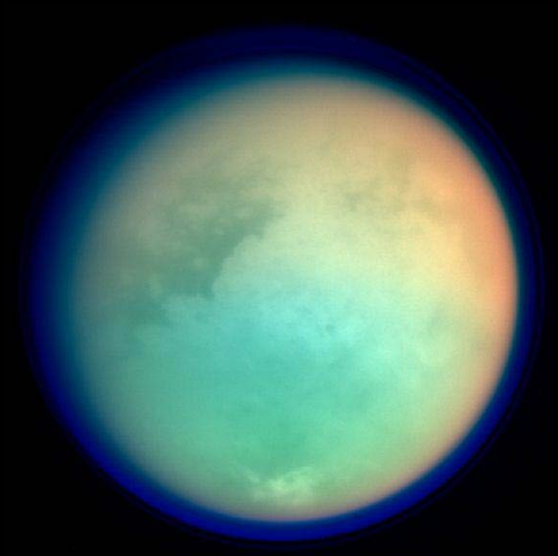
'Enceladus' (brown) includes material from ~kilobar pressures ~1000 km deep, while 'Tethys' comes from the water layer…

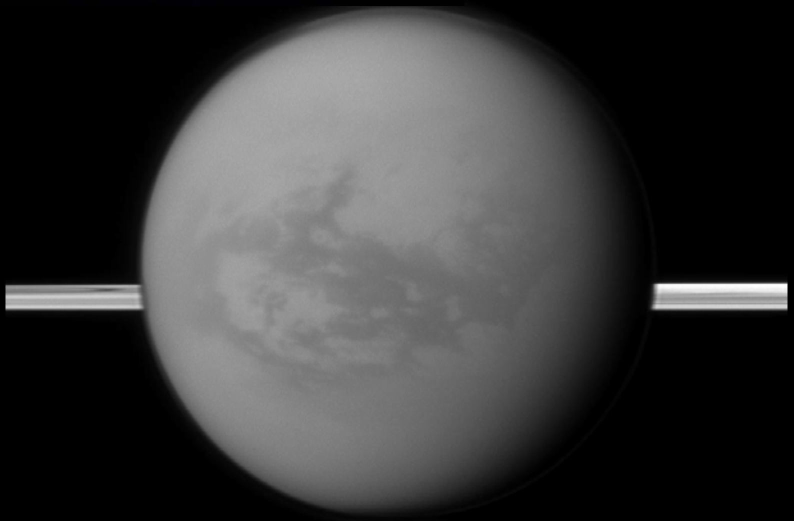


This fairy tale has a warm and fuzzy ending for Titan

Changes to Titan

- acquires its mass in ~four big wallops
- resurfaced/heated
- gets a big delta-v
  - can explain the eccentricity
- mergers deposit a deep heat source
- acquires a temporary system of moons





Main Problems

1. What would be required for a system of moons to collapse?

- Generally, how similar were Saturn and Jupiter in their satellite origins?
- There are certainly other ways to make one Titan (Sasaki et al. 2010; Canup 2010)

2. Can the finished middle-sized moons be saved from colliding with Titan?

- Their reaccretion timescale is short! Same as in Sekine and Genda (2012) model
- Probably would require the scattering action by multiple still-resonant moons

e.g. 4→3→2→1 final moons

If it happened (and when?)

TITAN

- Forms in a series of mergers or ‘splats’
- Globally resurfaced and internally heated (melted?)
- Gains orbital excitation
- Acquires a temporary system of sub-satellites

MSMs

- Obtain an overall ice rich composition and monomodal size distribution
- Form as diverse bodies, Enceladus-like to Tethys-like
- Some form with their own rings and sub-satellites

Geology will tell…