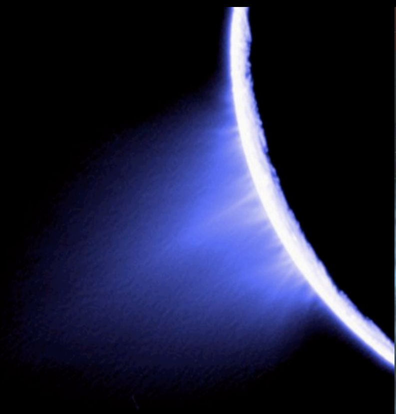
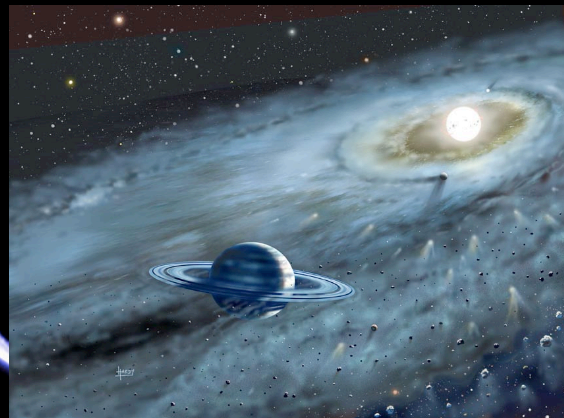
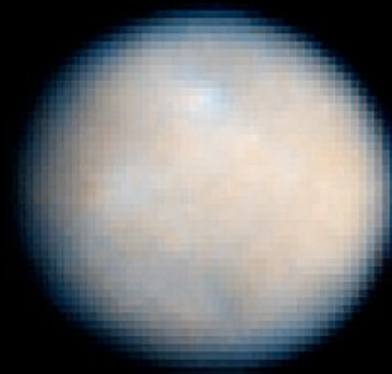
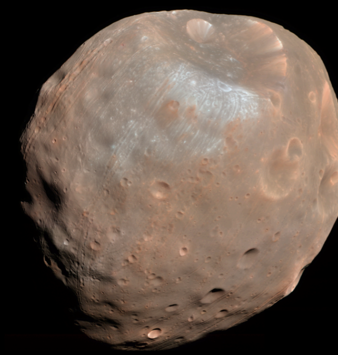
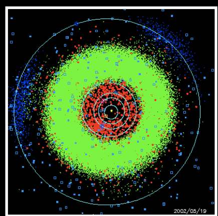


SYSTEM SCIENCE and ORIGINS

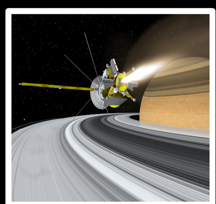
Julie Castillo-Rogez
JPL/Caltech

KISS WORKSHOP – SMALL BODIES INSTRUMENTS SHORT COURSE

Outline



Introduction



System science: How *Cassini-Huygens* changed our understanding of satellite system formation

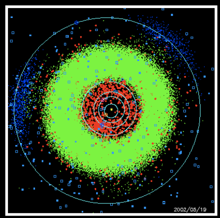
No system science: The Origin of Phobos/Deimos remains a mystery

The way forward

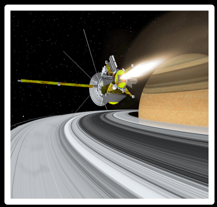
System Science

- System exploration encompasses rings, dust fields, satellites, planet, magnetosphere, atmospheres
- Observed relationship is a function of origin (common or not) and field interaction
- Study of giant planet systems is key source of information to understand our Solar system, exoplanet systems
  - Satellites fed from Solar nebula materials

Outline



Introduction



System science: How *Cassini-Huygens* changed our understanding of satellite system formation

No system science: The Origin of Phobos/Deimos remains a mystery

The way forward

SATURN'S SYSTEM

- 60 satellites

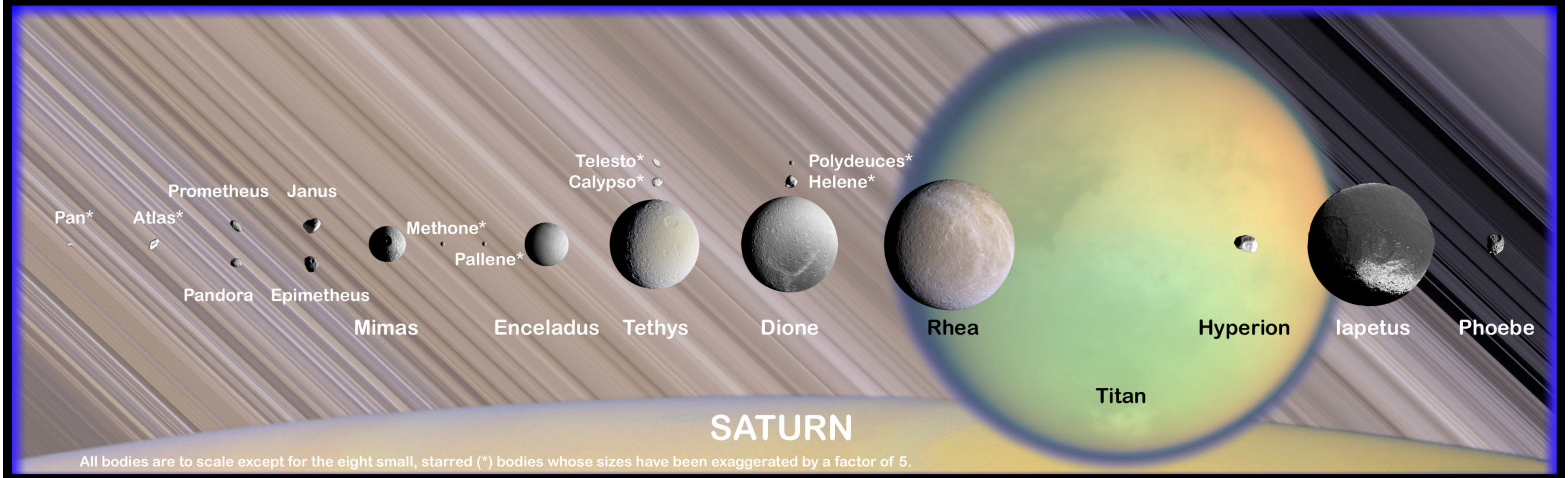
Largest ring system

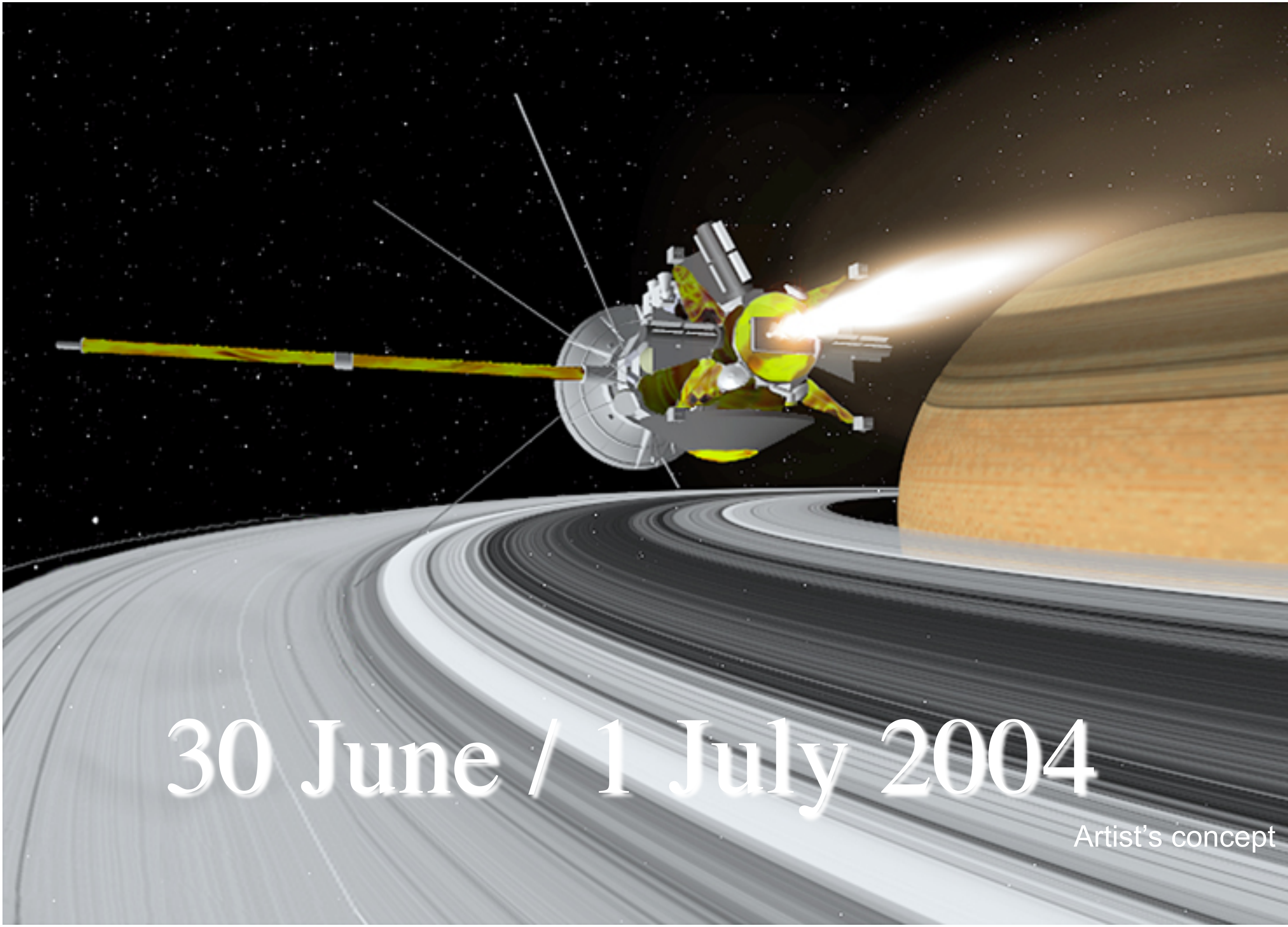
5+ different types of satellites

Why does it matter?

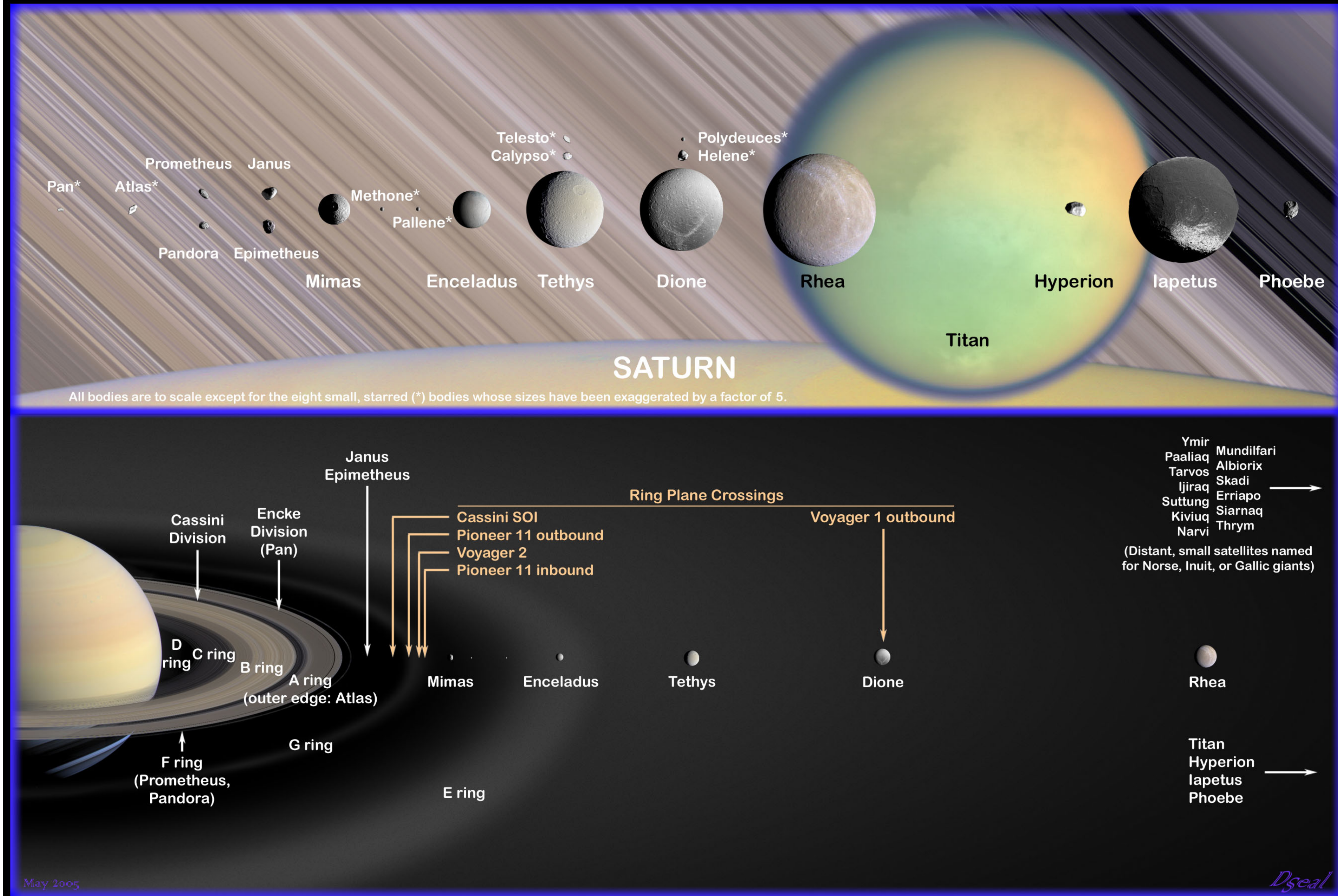
The Saturnian system has been extensively explored by the *Cassini Huygens* mission – can help understand other systems

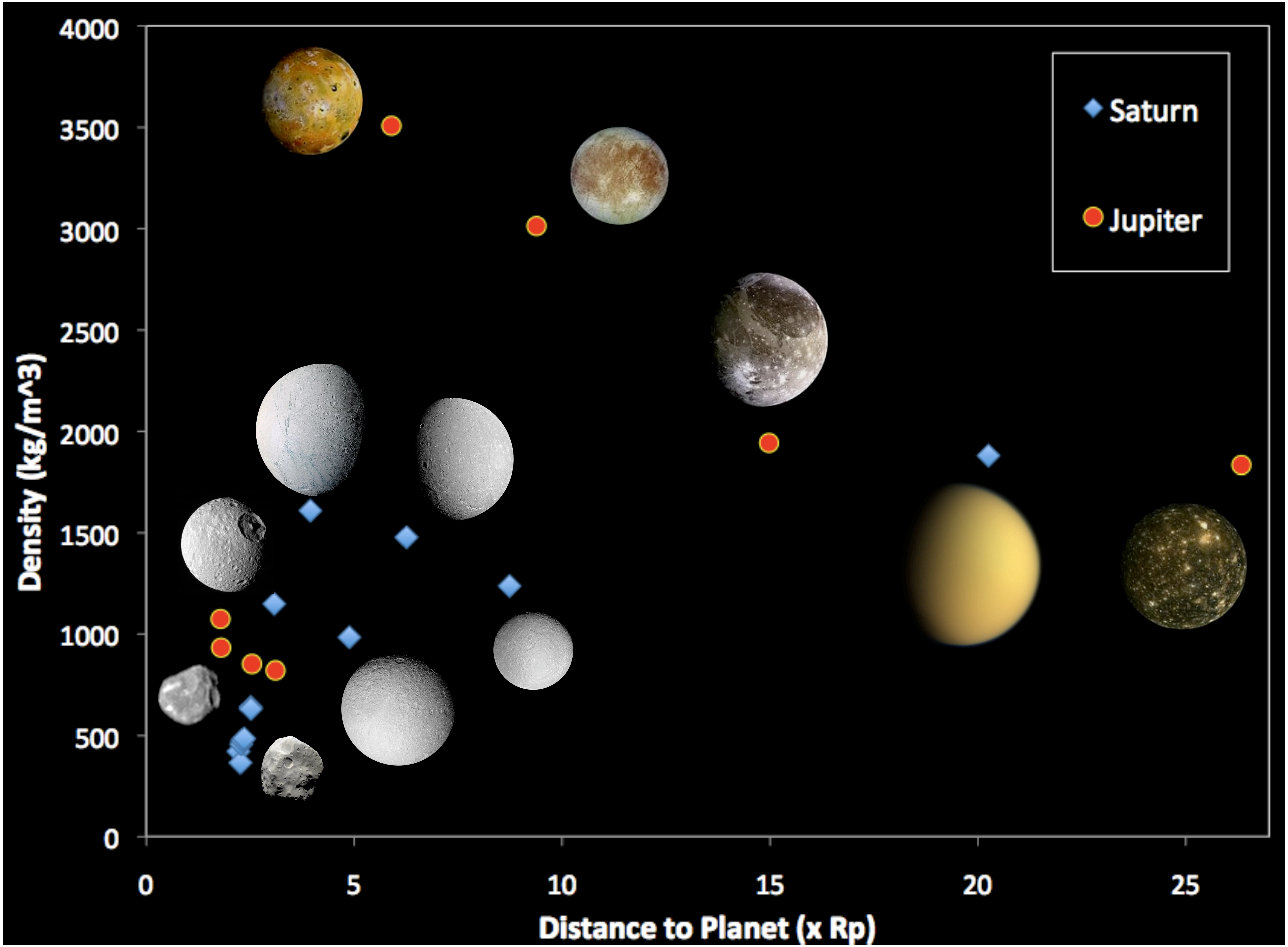
Home of two astrobiological targets



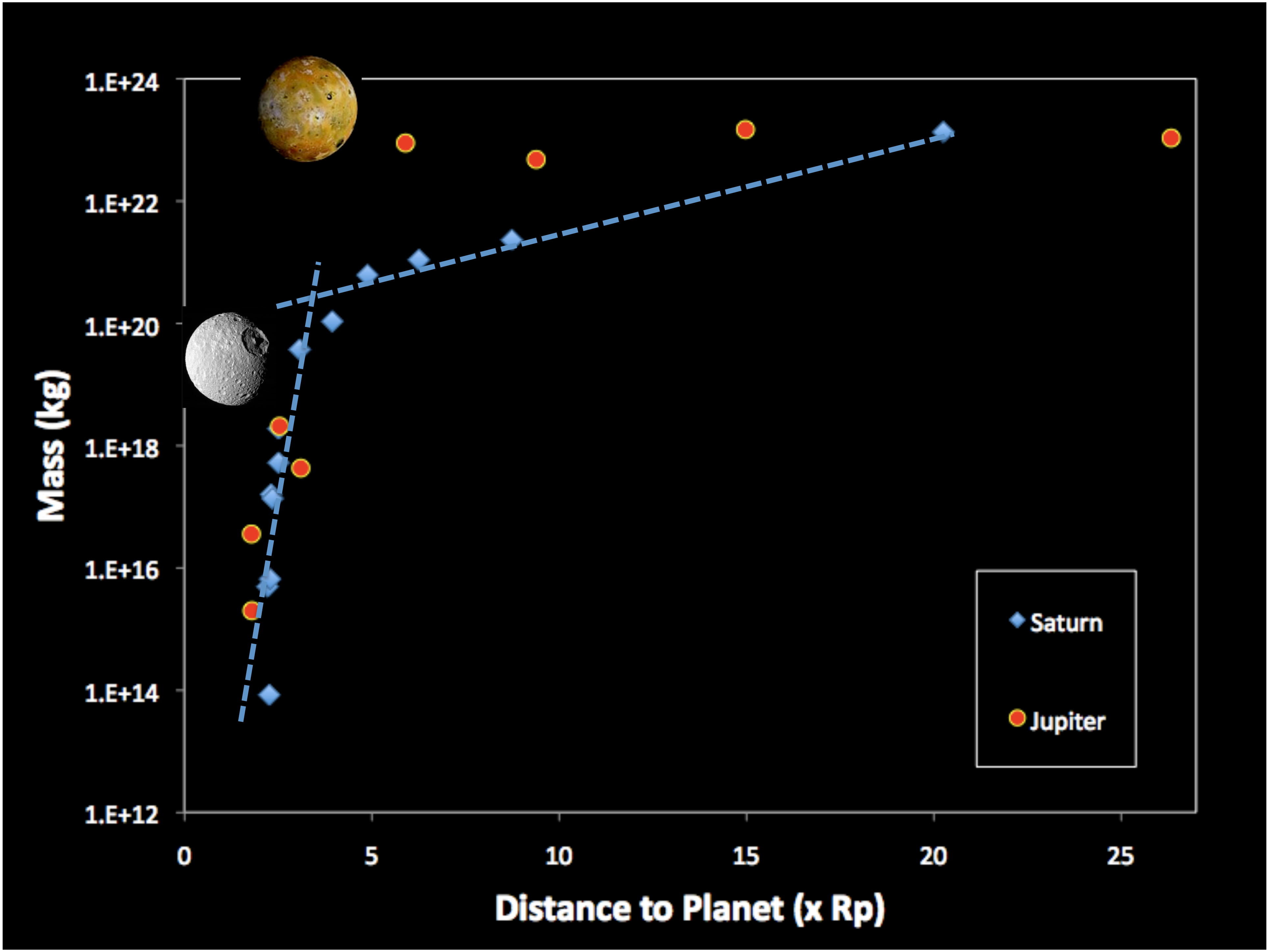

30 June / 1 July 2004
Artist's concept

THE SATURNIAN SYSTEM





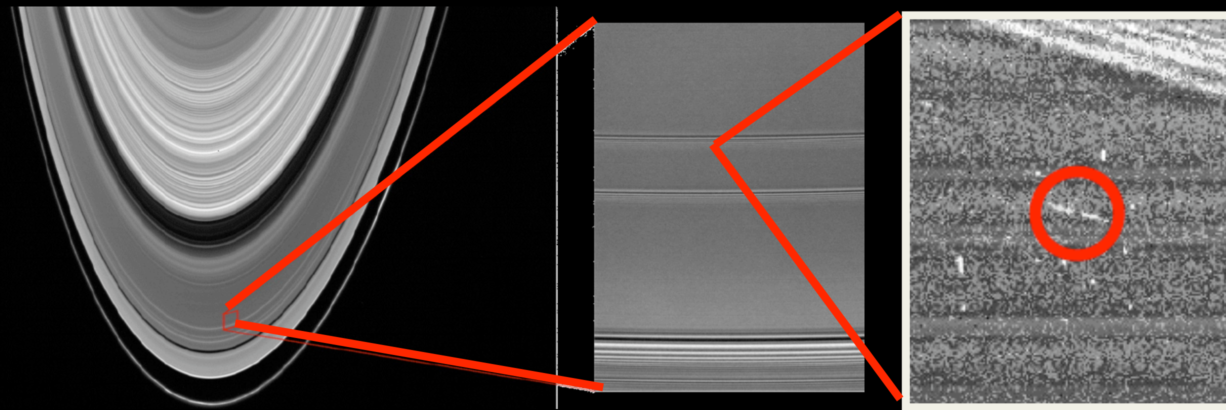
Saturn
Jupiter
Density (kg/m^3)
Distance to Planet (x Rp)
0
500
1000
1500
2000
2500
3000
3500
4000
0
5
10
15
20
25



1.E+24
1.E+22
1.E+20
1.E+18
1.E+16
1.E+14
1.E+12
Mass (kg)
0
5
10
15
20
25
Distance to Planet (x Rp)
Saturn
Jupiter

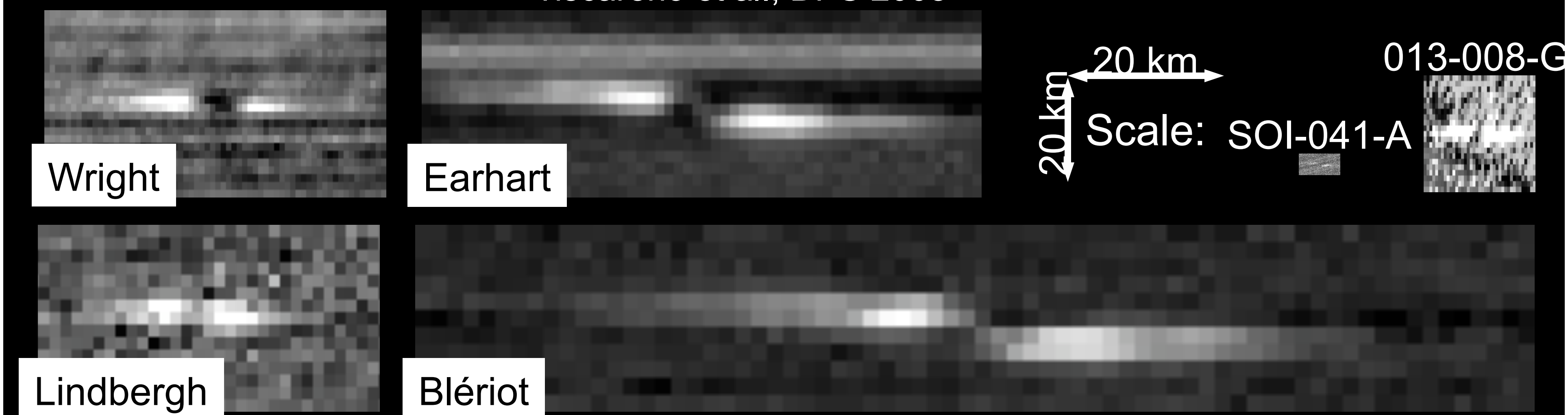
CLUE # 1 - Giant Objects Embedded in A ring

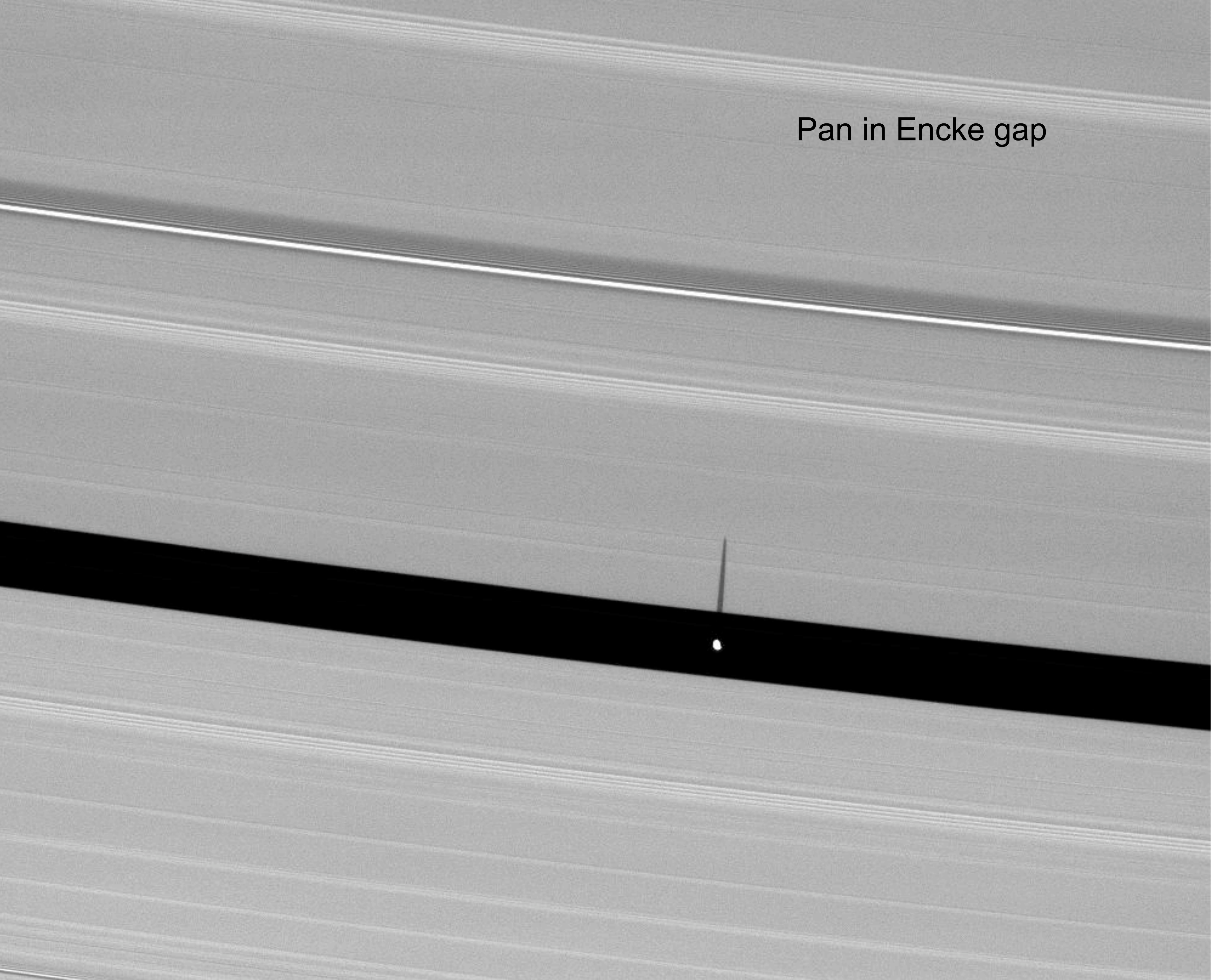
100-m size objects discovered in images by their “propeller” like disturbances in passing ring material. These objects lie in 3 distinct belts inside Encke gap.

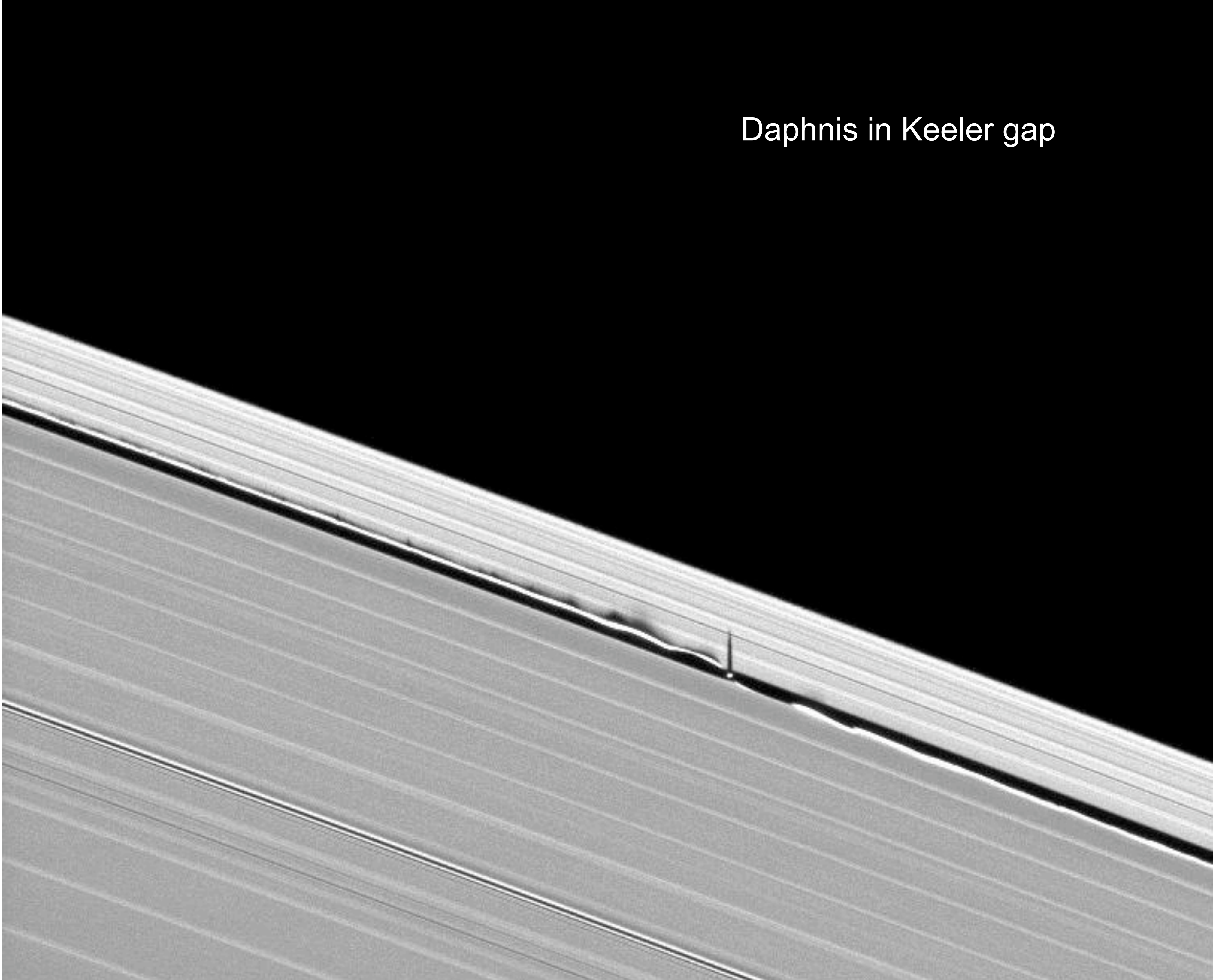


Discovery of “giant” objects outside Encke gap, with sizes 0.5-1km! Some appear to be drifting radially.

Tiscareno et al., DPS 2008




Pan in Encke gap

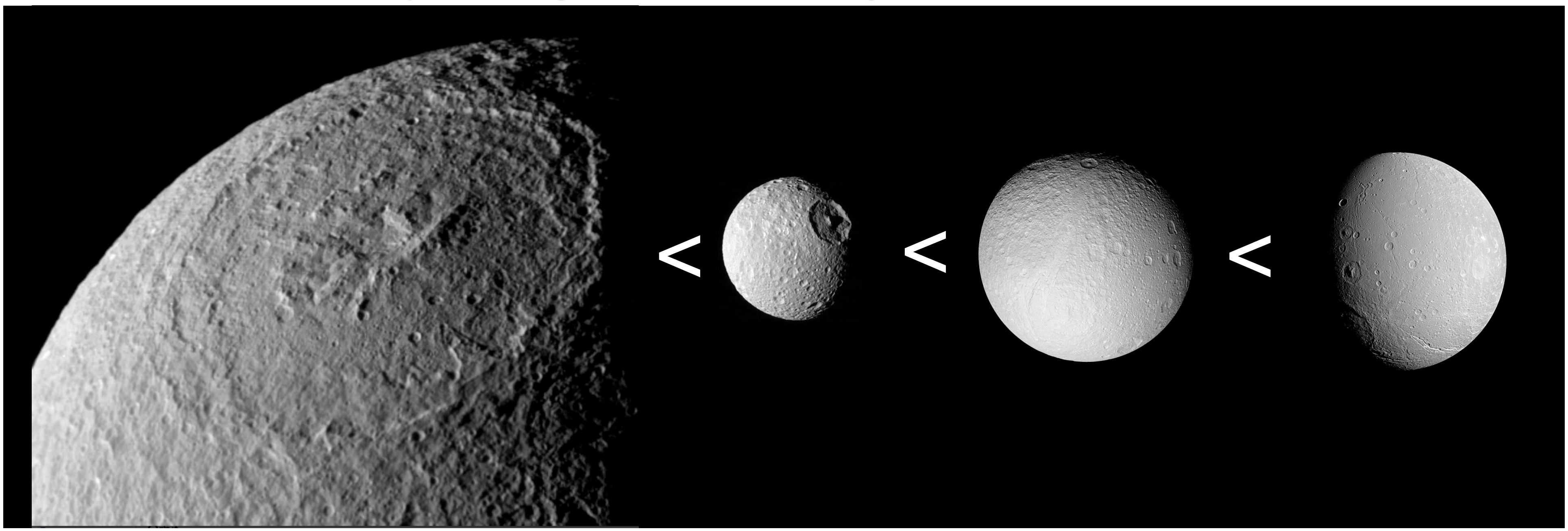

Daphnis in Keeler gap

CLUE #2 – Surface Age

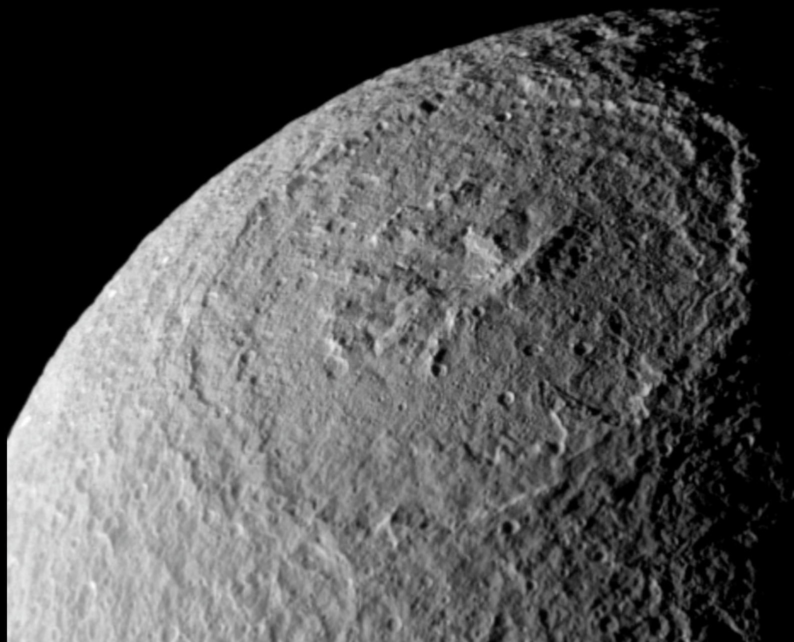
Table 4
Relative terrain ages for $D \geqslant 5$ km.

Terrain	Cumulative crater density	Scaled density[a]	Relative age to Odysseus[b]	Relative age to Dione-*sp*[b]	Relative age to Mimas[b]
Mimas	4497 ± 136	844 ± 59	4.2–7.3	1.0–1.3	–
Tethys-*cp*	2978 ± 272	910 ± 188	3.8–8.9	⩽1.6	⩽1.4
Tethys–Odysseus	717 ± 71	156 ± 33	–	–	–
Dione-*cp*	2723 ± 1467	1089 ± 823	1.4–15.5	⩽2.8	⩽2.4
Dione-*sp*	2327 ± 112	743 ± 63	3.6–6.6	–	–
Rhea-*cp*	2759 ± 480	1422 ± 531	4.7–15.9	1.1–2.9	1.0–2.5
Iapetus-dark	2687 ± 1501	2687 ± 1501	6.3–34.0	1.5–6.2	1.3–5.3
Iapetus-bright	1846 ± 112	1846 ± 112	9.2–15.9	2.2–2.9	1.9–2.5
Phoebe	2233 ± 1117	1117 ± 790	1.7–15.5	⩽2.8	⩽2.4

Note: *cp* – cratered plains, *sp* – smooth plains.
[a] Cumulative crater density for $D \geqslant 5$ km scaled to Iapetus (see text for description).
[b] Values are the ratio of the scaled density of the terrain specified in the row to the terrain specified in the column header.



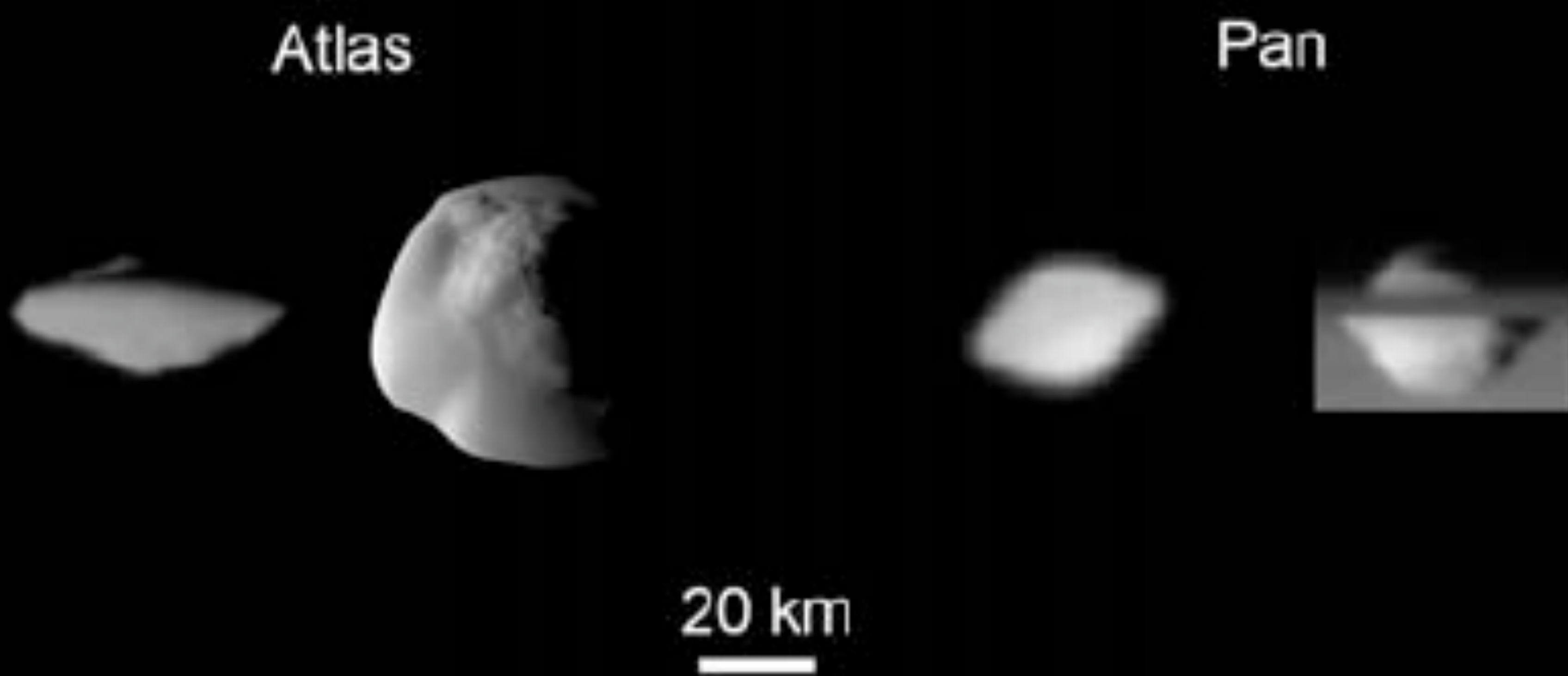
Planetocentric Impactors



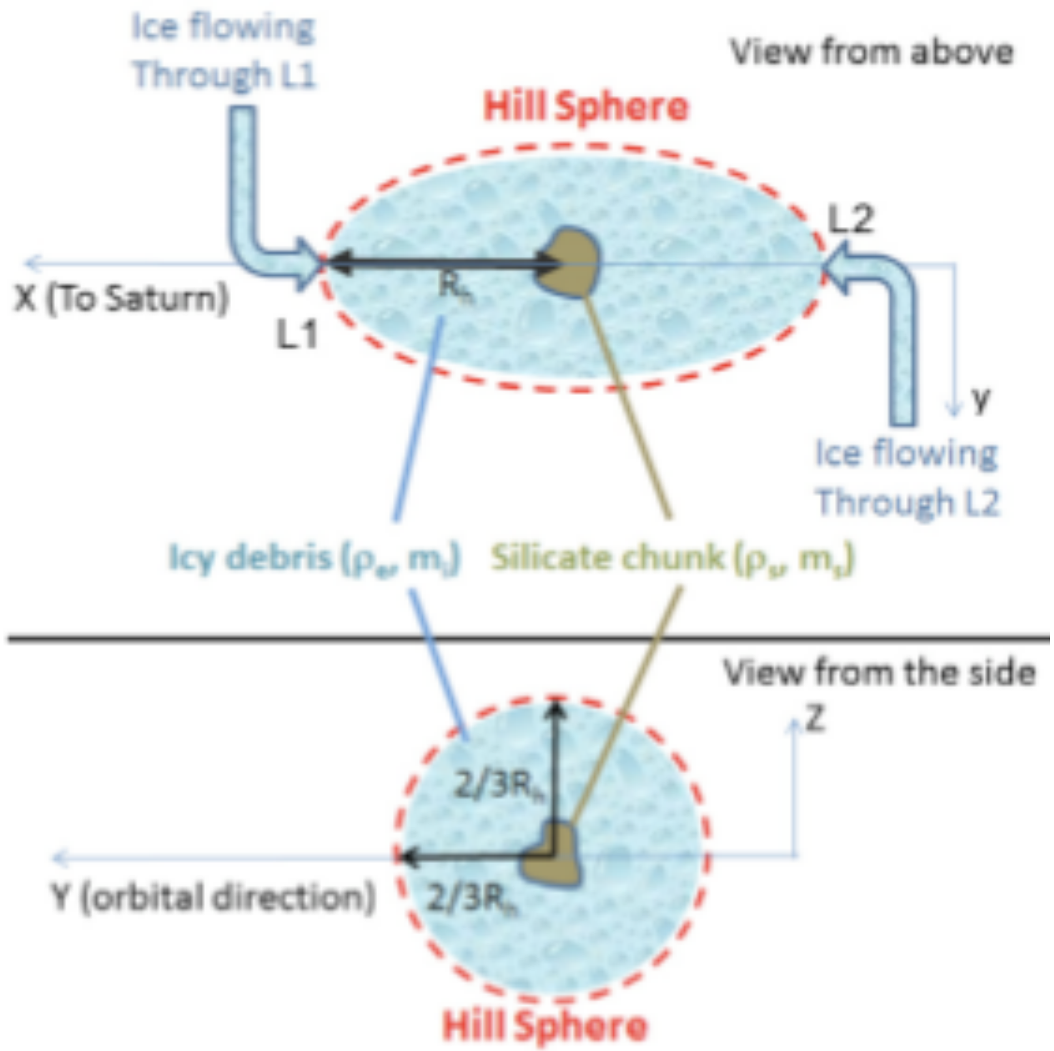
Odysseus on Tethys

Herschel on Mimas

CLUE #3 – SHAPES!



The Solution? Heterogeneous Accretion in a Ring

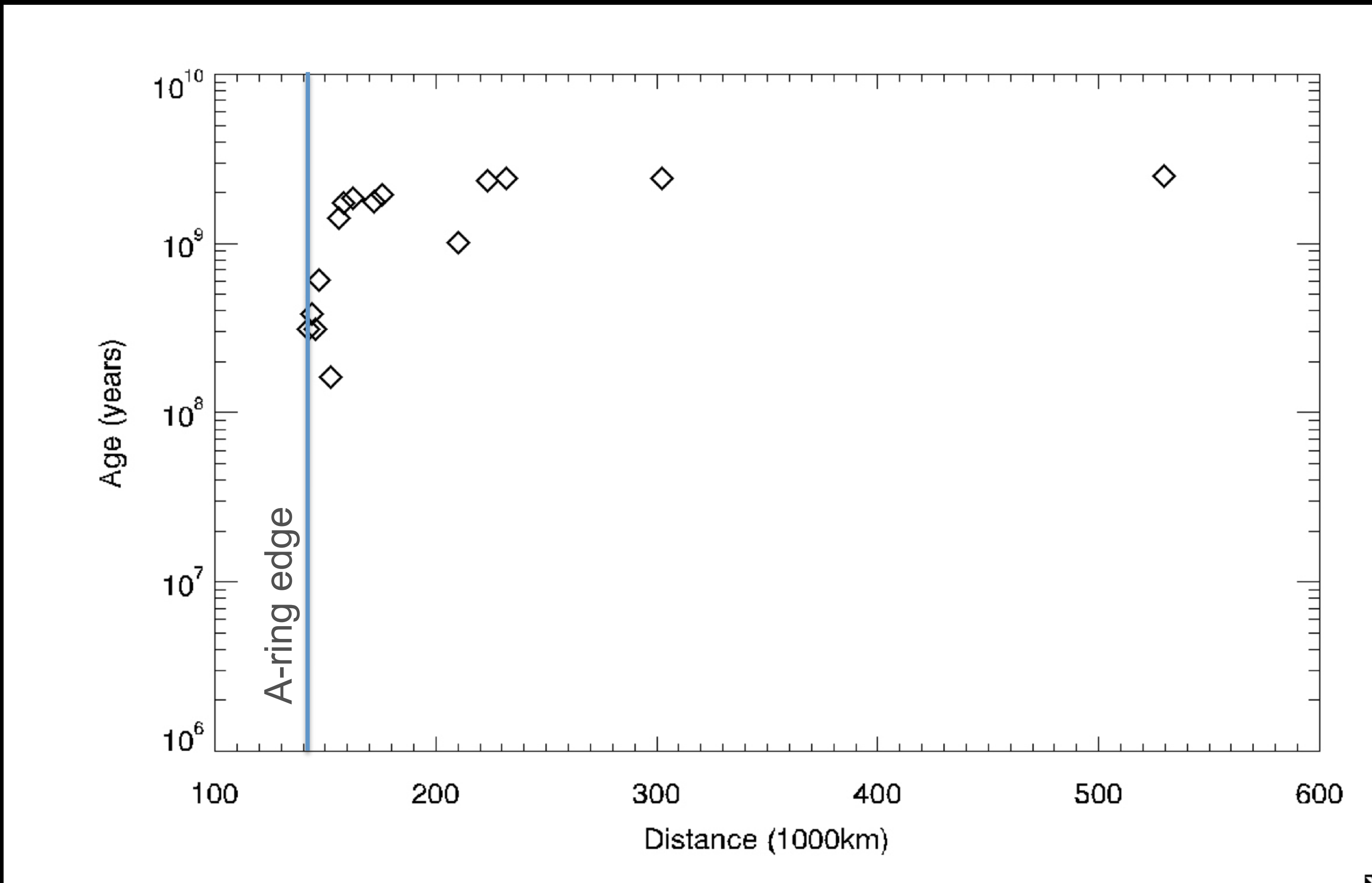


Charnoz et al. (2011)

Accretion in Rings

- Chunks of silicates accrete an ice shell
- Proto-moons migrate outward by tidal interaction with the rings
- Ice-dominated satellites formed at the ring outer edge (beyond Roche limit)
- Final silicate mass fraction is a function of chunk size and collision between rock-rich and ice-dominated proto-moons prior exit

Far = Old, Close = Young



Implications

- Satellite age is tied to the ring time of formation and then the distance to the ring
  - Mimas and Miranda are “young”
- Satellite composition is determined by the ring progenitor
  - A large proto-satellite (Canup 2010)
  - A large TNO (Charnoz et al. 2009)
- Large basins likely due to co-orbitals
  - Surface dating from crater density is not applicable (planetocentric + heliocentric impactors)

Geophysical Consequences

- Satellites accreted differentiated
- New generation of geophysical models of very porous, differentiated bodies remains to be developed
- Extent of endogenic activity is a function of time of formation
  - Certain satellites may not go through a stage of ice melting
  - Miranda should have evolved little since formation

Geophysical Consequences

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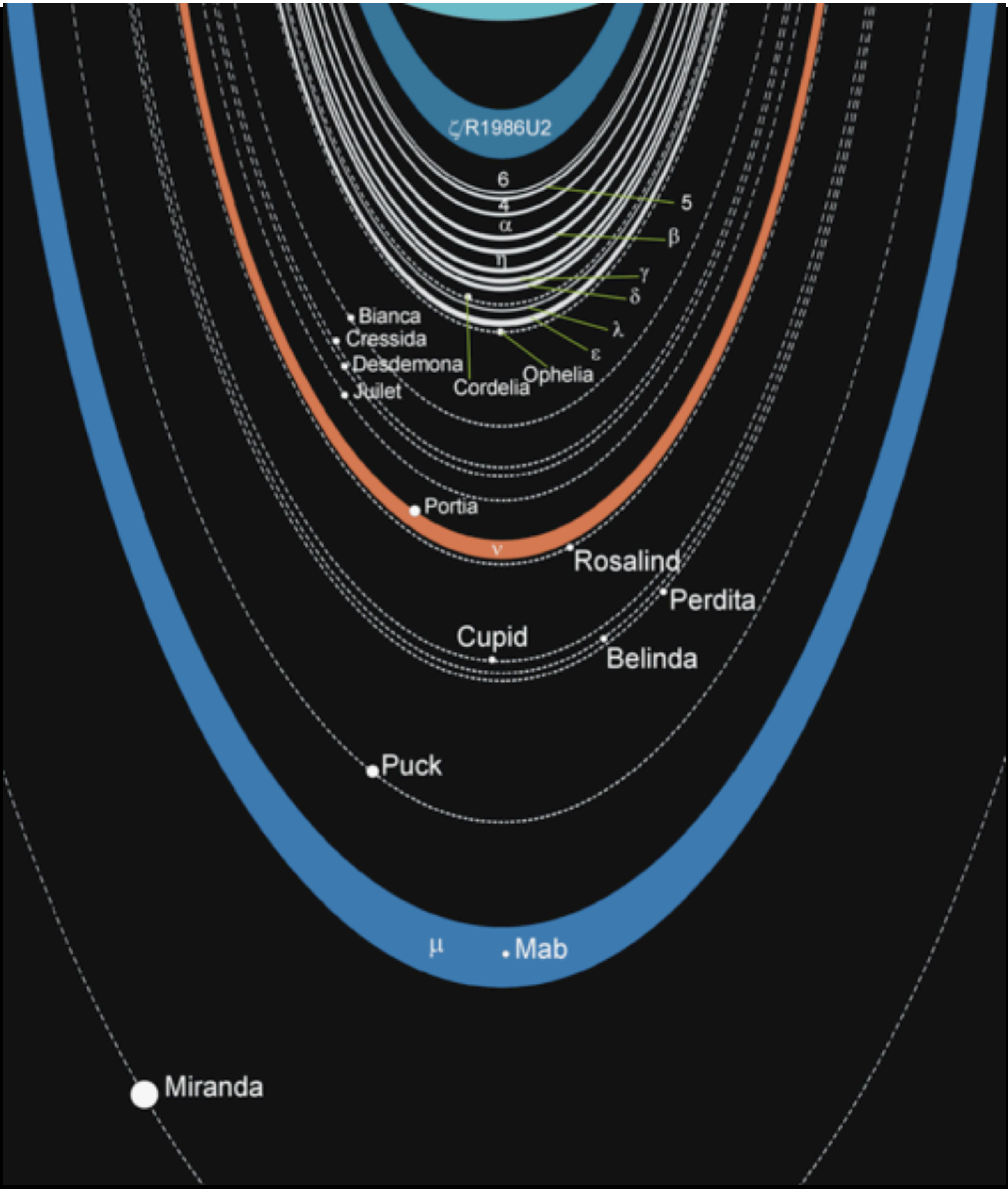
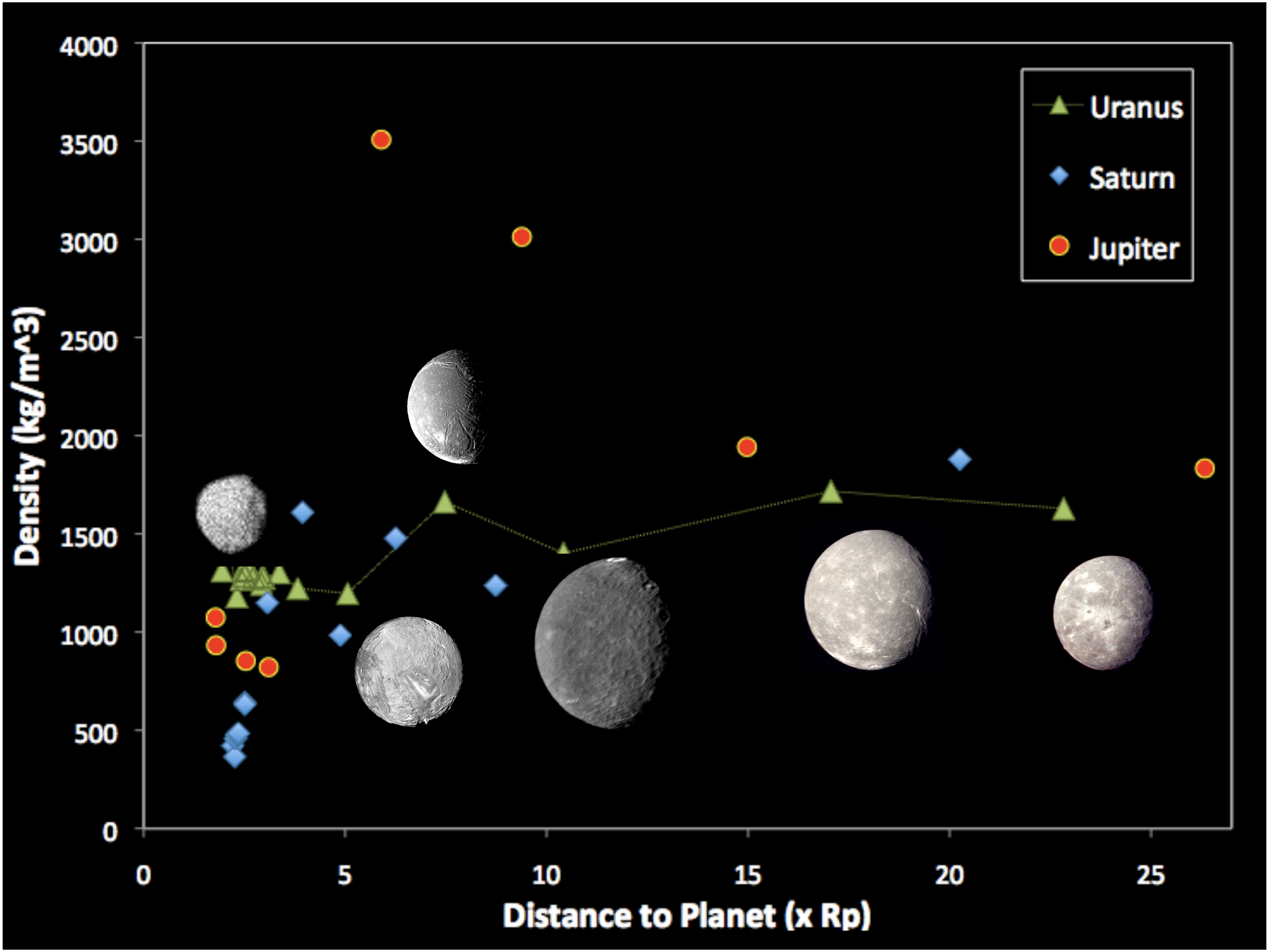
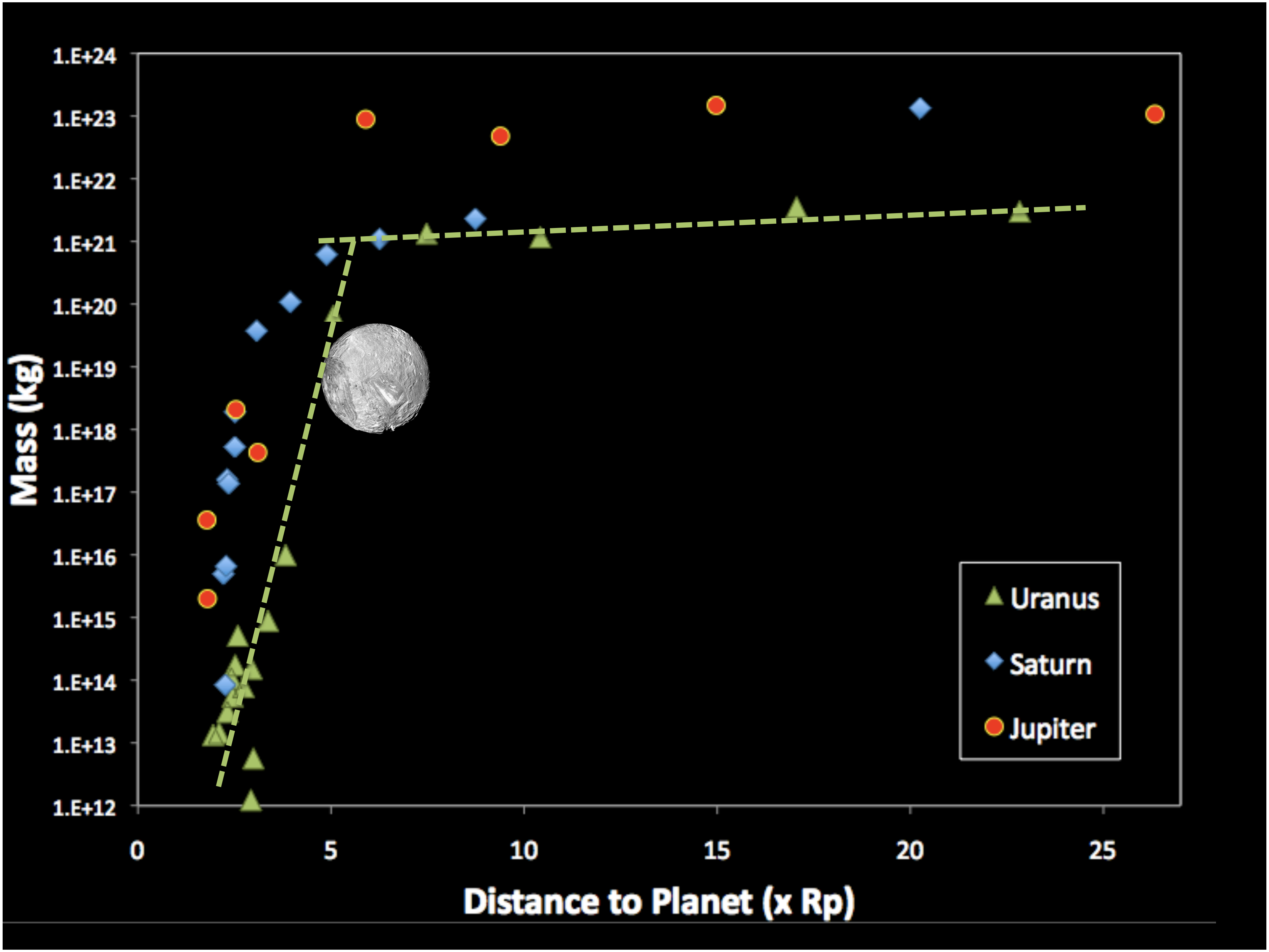
SATELLITE SCIENCE IN THE URANIAN SYSTEM

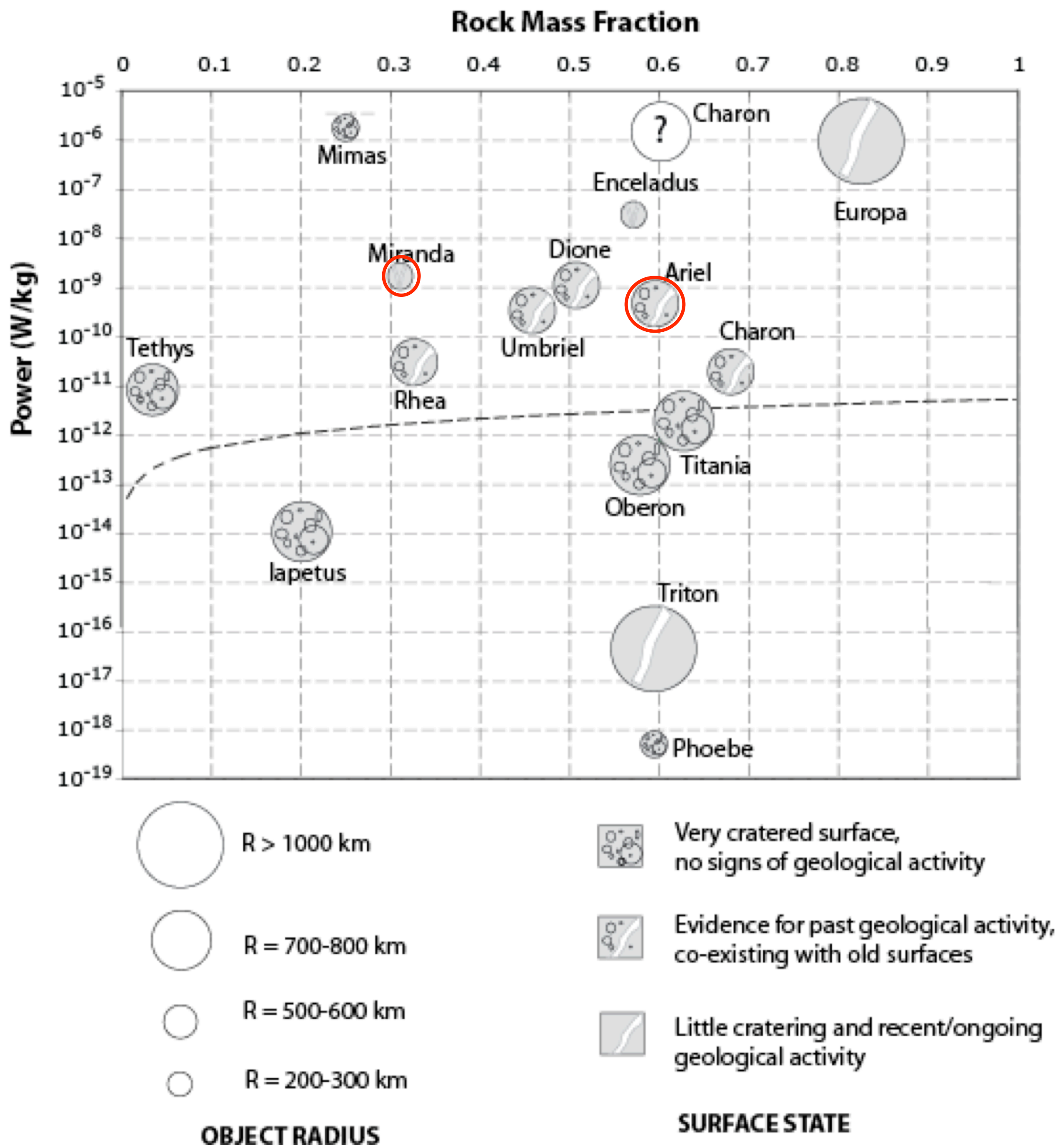




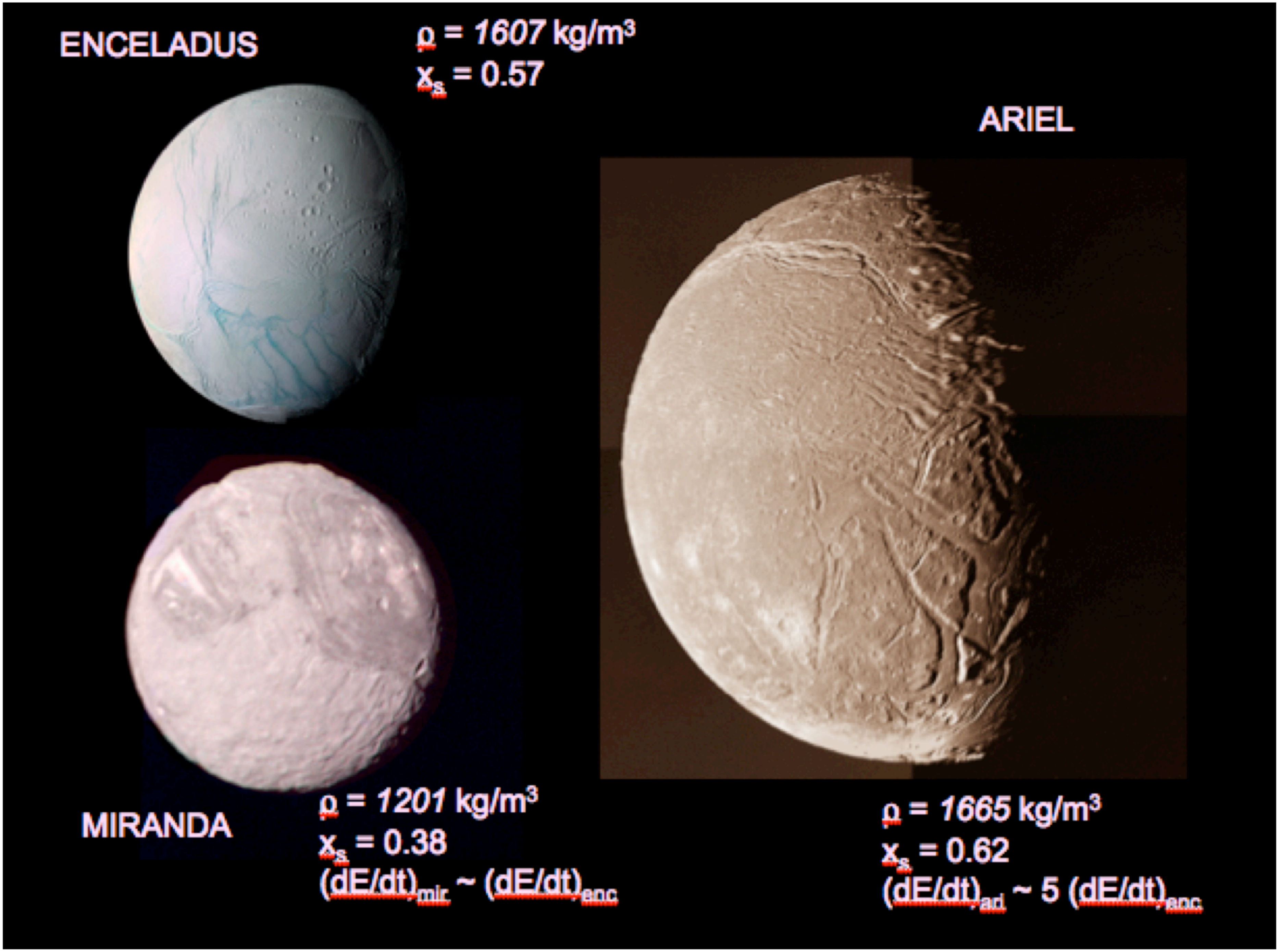
Uranus
Saturn
Jupiter
Density (kg/m^3)
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
Distance to Planet (x Rp)



1.E+24
1.E+23
1.E+22
1.E+21
1.E+20
1.E+19
1.E+18
1.E+17
1.E+16
1.E+15
1.E+14
1.E+13
1.E+12
Mass (kg)
0
5
10
15
20
25
Distance to Planet (x Rp)
Uranus
Saturn
Jupiter



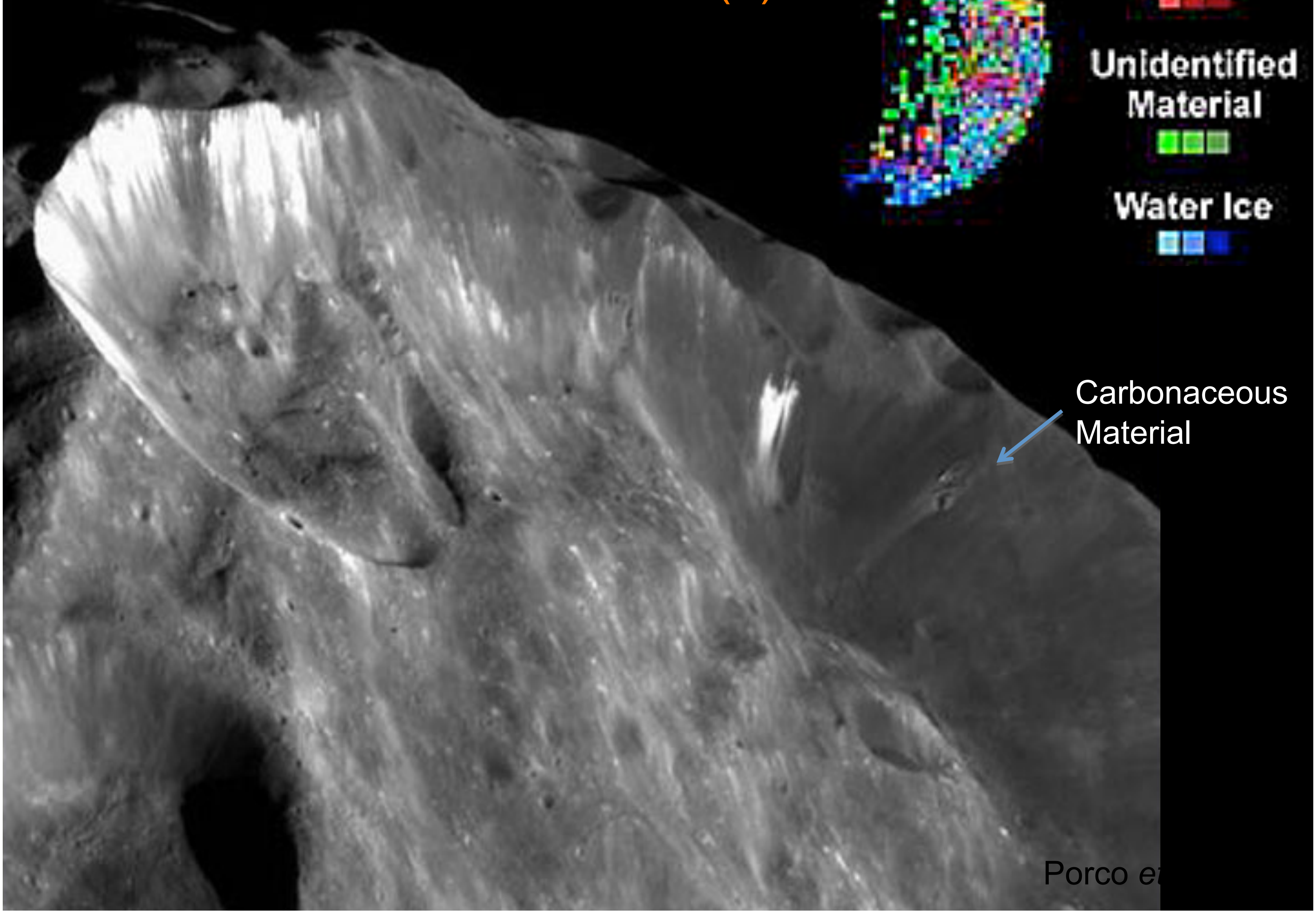
Castillo-Roge
Lunine, CUP,

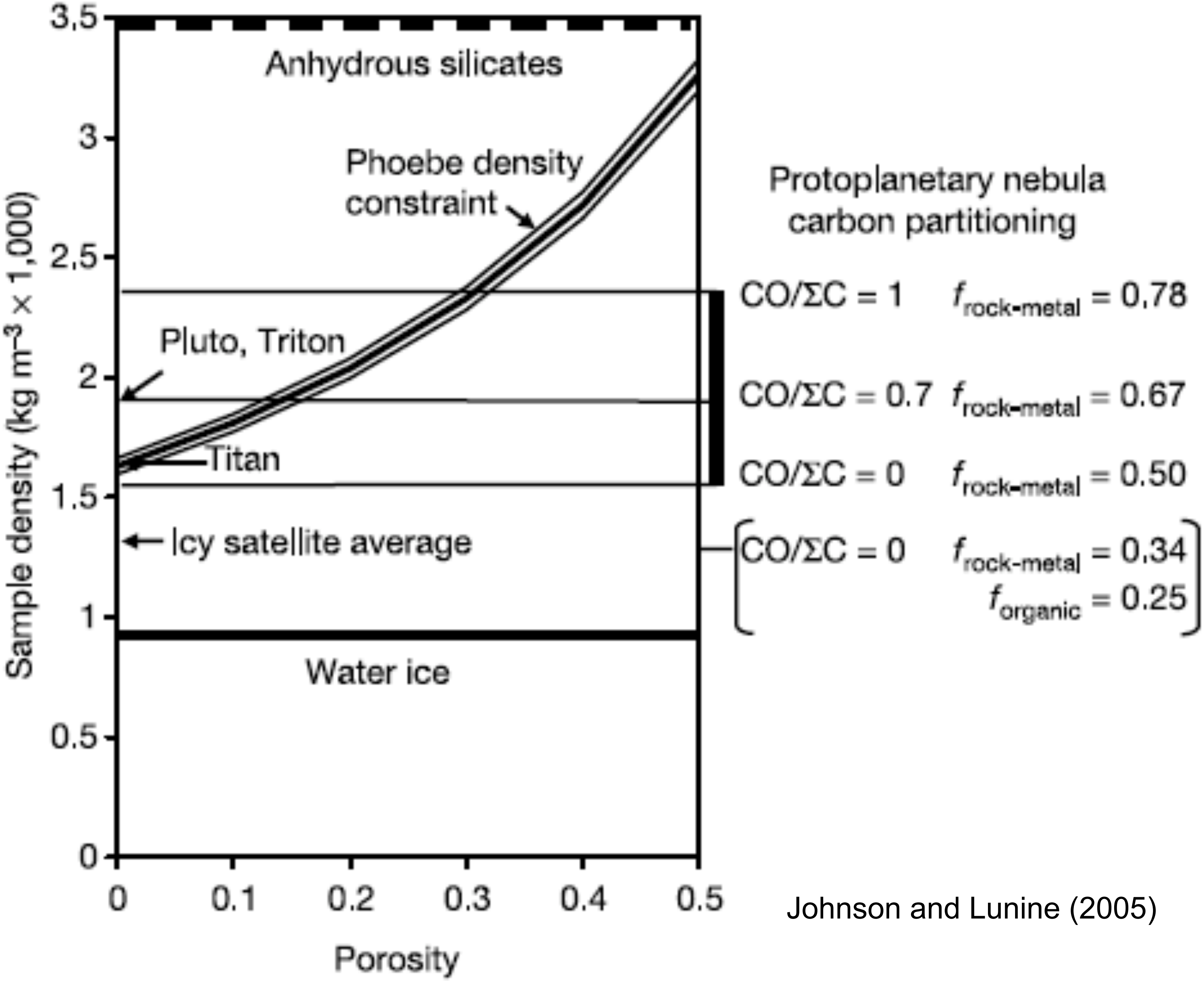

ENCELADUS
ρ = *1607* kg/m^3
x_s = 0.57
ARIEL
MIRANDA
ρ = *1201* kg/m^3
x_s = 0.38
$(dE/dt)_{mir} \sim (dE/dt)_{enc}$
ρ = *1665* kg/m^3
x_s = 0.62
$(dE/dt)_{ar} \sim 5\ (dE/dt)_{enc}$

Irregular Satellites

- ~200 km in diameter
- Same population as Saturn's Phoebe, Jupiter's Himalia, Uranus' Sycorax, Neptune's Nereid, and possibly Trojan asteroids (e.g., 624 Hektor)
- Large outer SS planetesimals formed fast (~100 km in ~1 My)

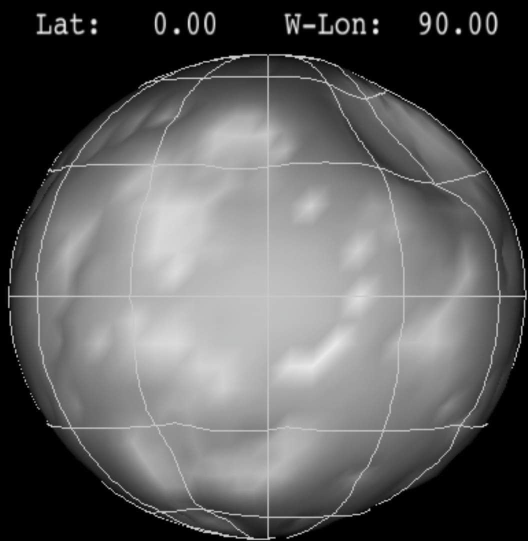
Phoebe – Best Observed KBO(?)





Johnson and Lunine (2005)

Phoebe is Spherical!



- "*When you're small, it's hard to get spherical*" – Johnson and McGetchin (1973)
- Spherical and close to relaxed ellipsoid
- Not an observational bias (no crater sculpting
- Implies that object was much weaker than expected for a porous icy body

Cassini Finds Saturn Moon has Planet-Like Qualities

Two possible models:

* Phoebe was composed of "weak" ices (amorphous ice, nitrogen, methane)

And/or

* Phoebe formed early enough to undergo partial melting by short-lived radioisotopes (< 3 My)

Oligarchic growth models in Kuiper Belt
produce r > 10 – 100 km objects in first 2-3 million years.

e.g. Kenyon *et al.*, 2008, in *The Solar System Beyond Neptune*

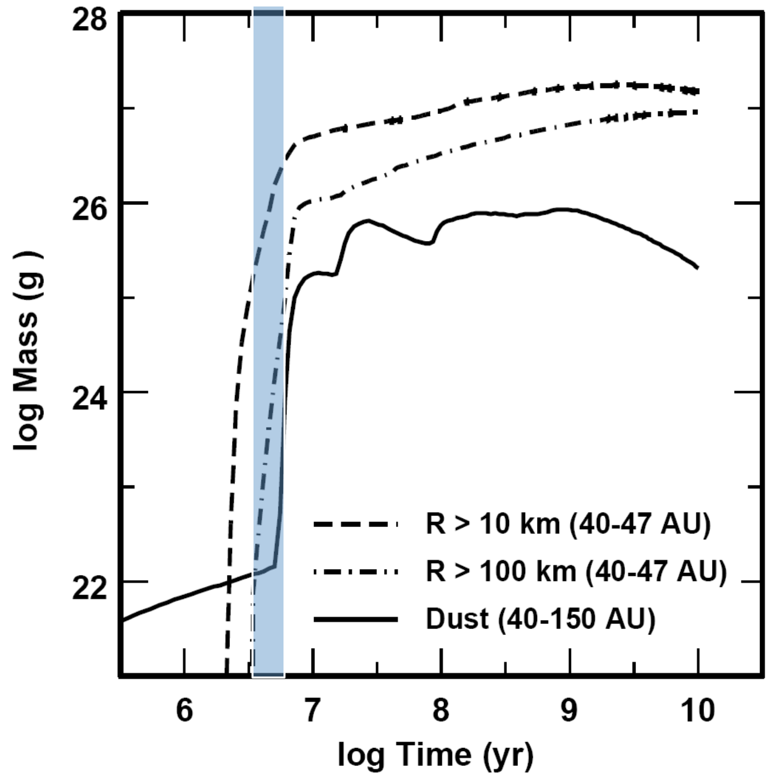


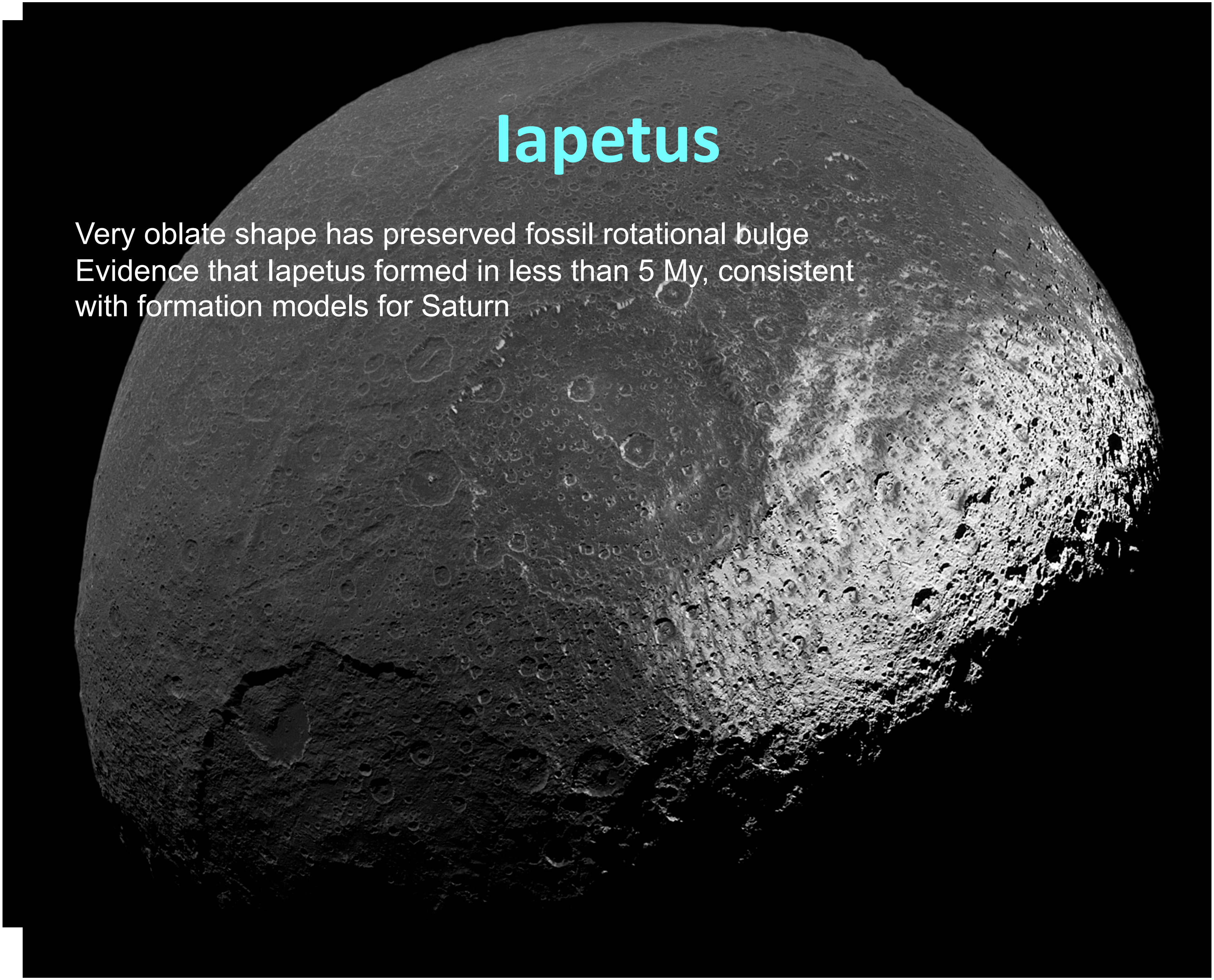
Fig. 3.— Time evolution of the mass in KBOs and dust grains. Solid line: dust mass ($r \lesssim 1$ mm) at 40–150 AU. Dashed (dot-dashed) lines: total mass in small (large) KBOs at 40–47 AU.

Phoebe – Implications

- Phoebe represents planetesimals involved in the formation of larger satellites (e.g., Titan) and contributed volatiles to giant planets
- Phoebe formed in less than 3 My
- Implies an early phase of hydrothermal activity
  - Redistribution of major elements between core and volatiles
- There is potential evidence that Titan's core is dominated by hydrated materials (Castillo-Rogez and Lunine)

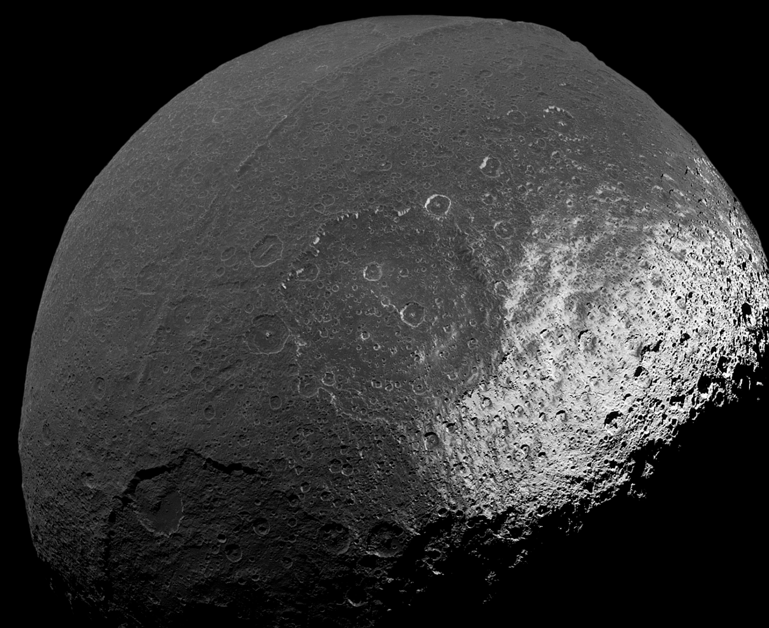
Iapetus

Very oblate shape has preserved fossil rotational bulge
Evidence that Iapetus formed in less than 5 My, consistent with formation models for Saturn



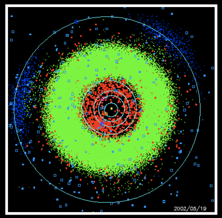
More Science Questions at Saturn

- Geophysical evidence for new accretion model?
- Origin of the rings progenitor?
- Time of formation of the satellite system?
- Origin of activity in Enceladus?
- Origin of Iapetus?
- What about Hyperion?

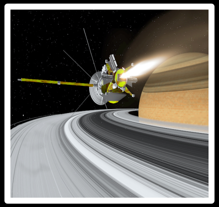


ISS_00CIA_LIMBT0P0B001 (860 m/pxl)

Outline



Introduction



System science: How *Cassini-Huygens* changed our understanding of satellite system formation

No system science: The Origin of Phobos/Deimos remains a mystery

The way forward

CASE STUDY #2
MARS' MOONS

Phobos (22 km) and Deimos (12 km)

No *successful* dedicated mission

Phobos imaged by multiple missions

Deimos is mostly unknown

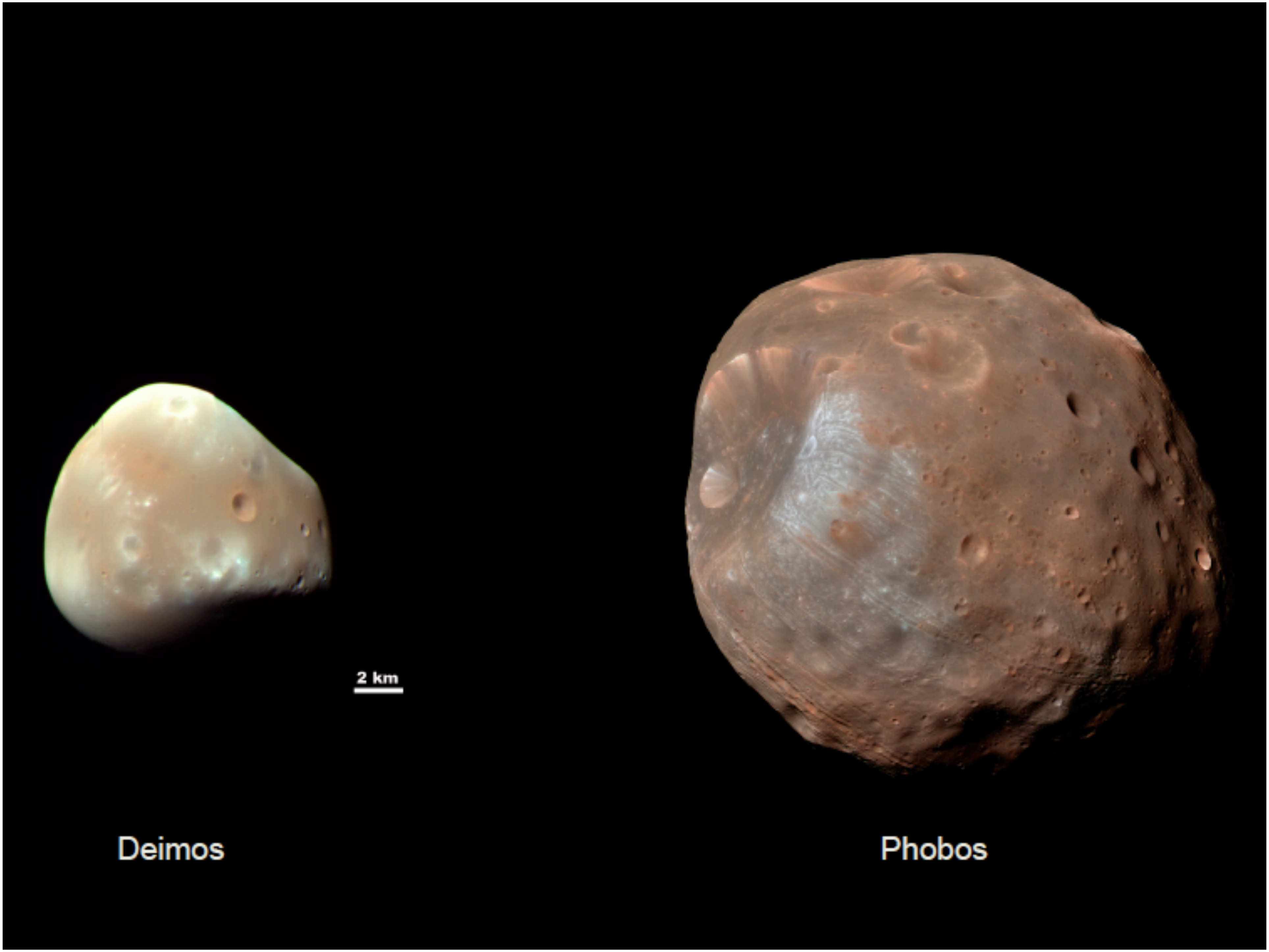
SIGNIFICANCE

Well, it's Mars

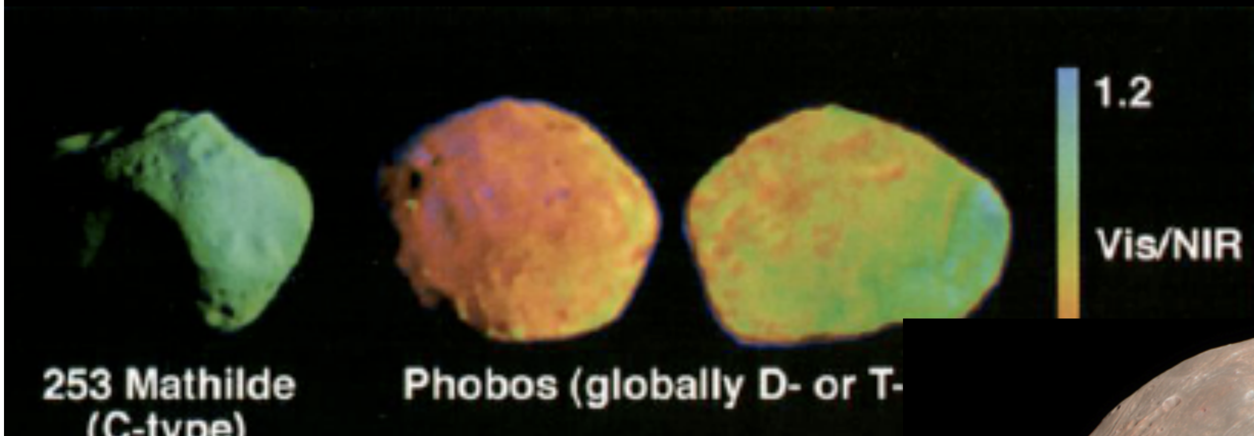
Phobos' surface presents similar spectral properties with Mars

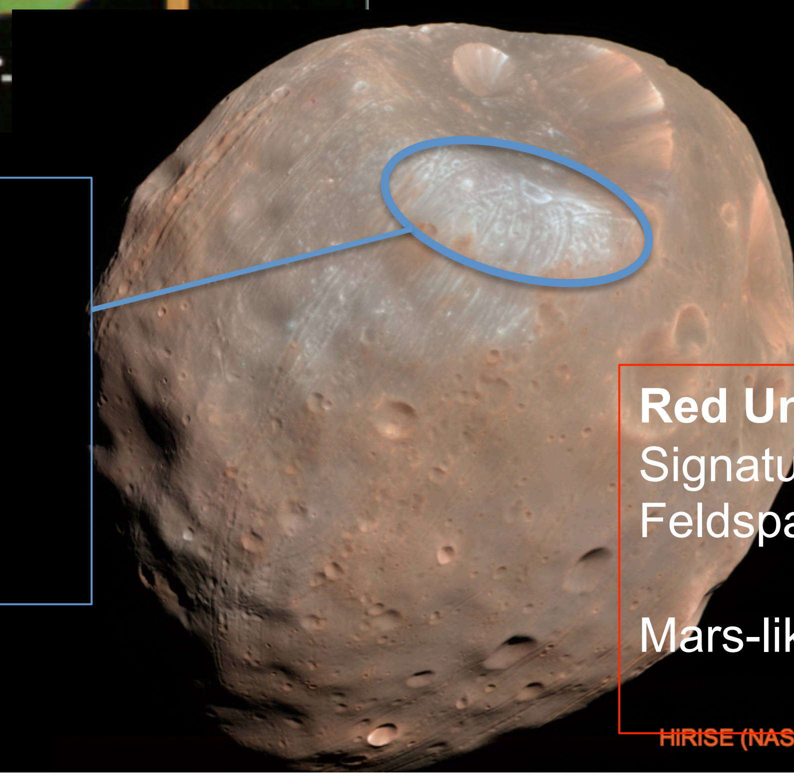
Recent suggestion that it was formed from Mars' ejecta – astrobiological target?

Phobos/Deimos represent outstanding vantage points for Human exploration


2 km
Deimos
Phobos

A Complex Object





Blue Unit
Signature of Phyllosilicates

Dehydrated carbonaceous chondrites?

Red Unit
Signature of Feldspar

Mars-like?

Murchie et al. (1999)

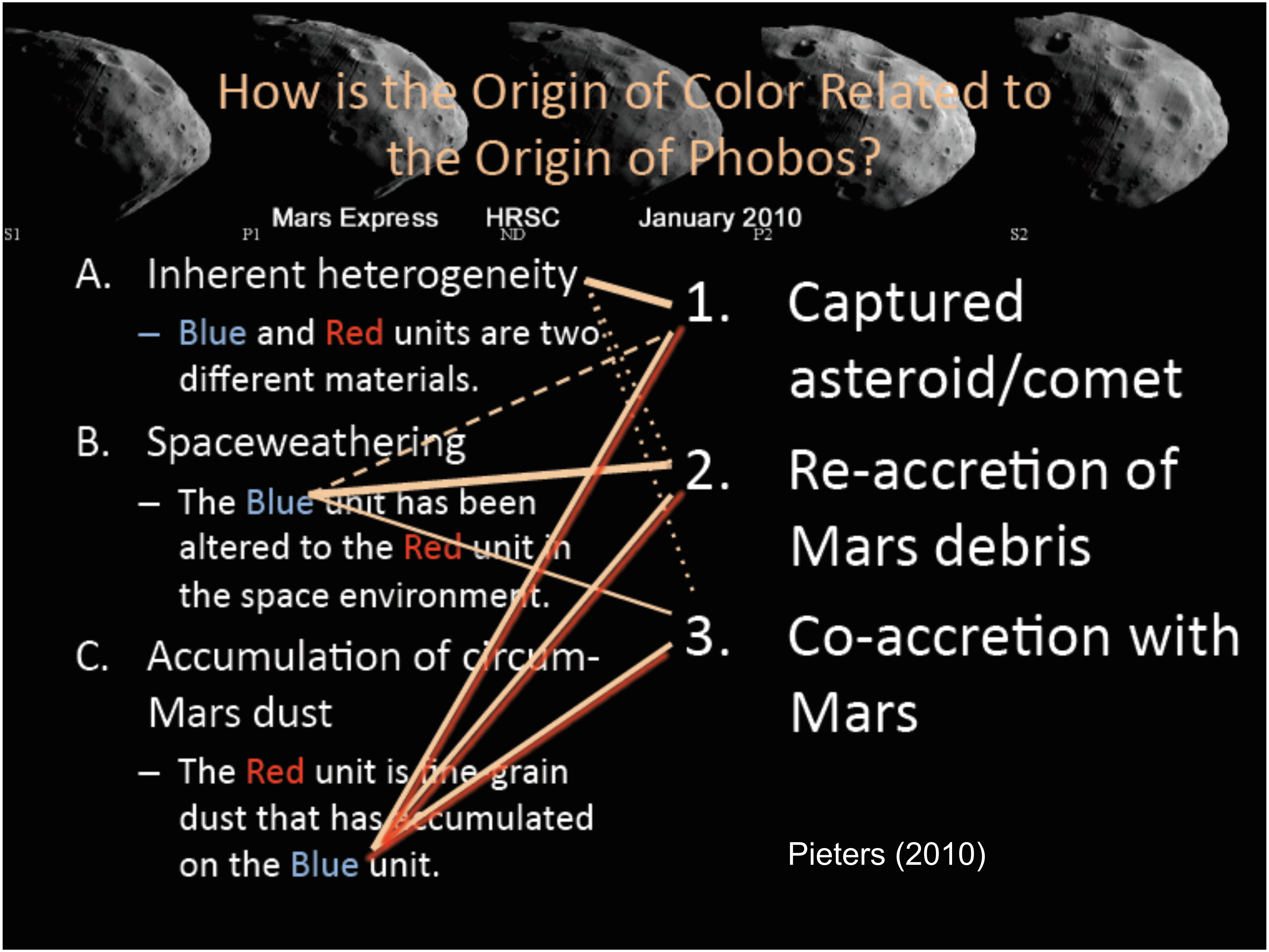
Summary Truth Table

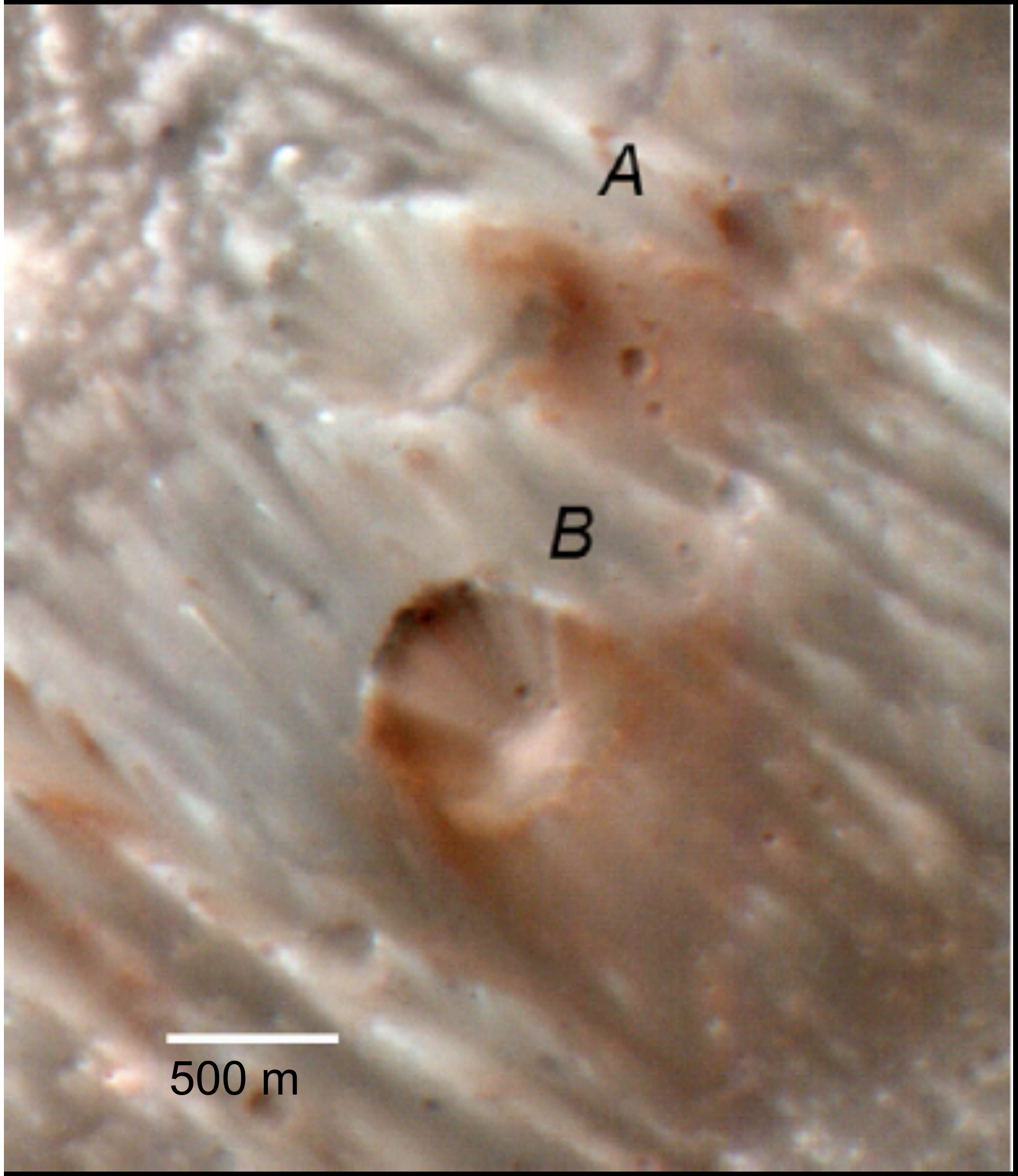
Origin	Property	TIR	VNIR
Capture	carbonaceous chondrite	N	P
	D-type Asteroid	N[1]	N
	Volatiles	Y	N
	Organics	N	N
	HEDs	P	N
	SNCs	P	N
In-Situ	Silicates	Y	Y
	ordinary chondrites	N	N
Ejecta	Mars-like silicates	Y	Y[2]
	space weathered basalt	P	Y[2]

N= No P= Possibly Y= Yes

[1]assuming Tagish Lake is representative, [2]Lunar Mare analog

Giuranna et al (2011)

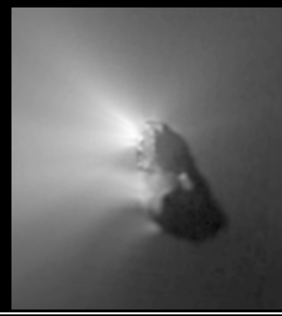

How is the Origin of Color Related to the Origin of Phobos?
Mars Express HRSC January 2010
S1
P1
ND
P2
S2
A. Inherent heterogeneity
– Blue and Red units are two different materials.
B. Spaceweathering
– The Blue unit has been altered to the Red unit in the space environment.
C. Accumulation of circum-Mars dust
– The Red unit is fine grain dust that has accumulated on the Blue unit.
1. Captured asteroid/comet
2. Re-accretion of Mars debris
3. Co-accretion with Mars
Pieters (2010)



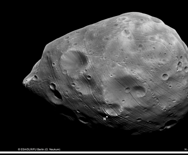
Thomas et al. (2010) (HiRISE)
Unsharp masked and contrast-enhanced version of a section of PSP_007769_0900. The bluer material draped over the side of Stickney appears to have been modified significantly in two areas which reveal relatively red material. The two areas are shown in this figure.

Rubble-Pile vs. High-Porosity

<1 km
1.95±0.14 g/cm^3
Grain density is 3.4 g/cm^3,
ϕ > 40%



15x8x8 km
0.6 g/cm^3
Ice, organics, silicates
ϕ >70%



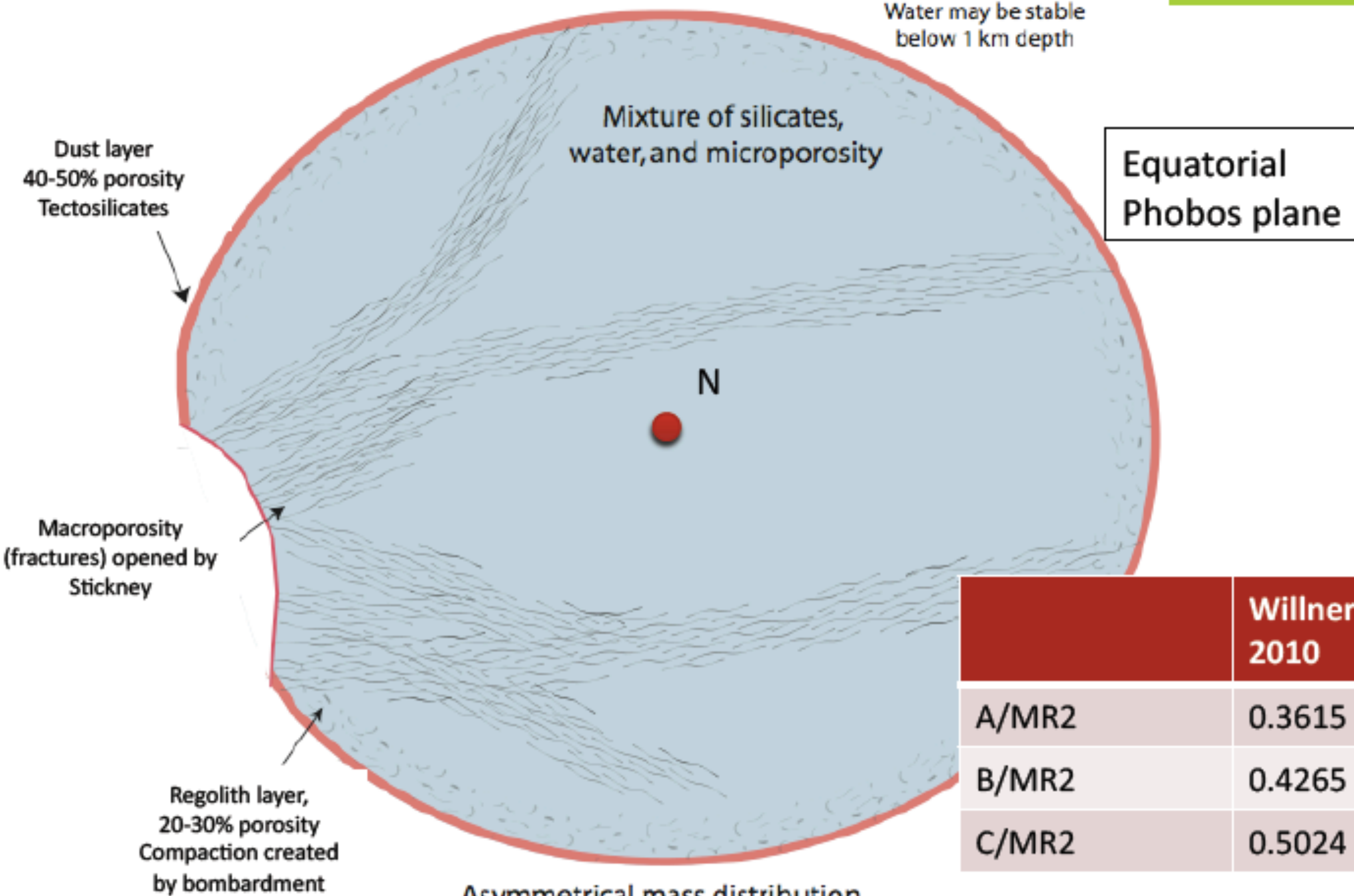
26.8 × 22.4 × 18.4 km
1.876 g/cm^3
Type?
ϕ ???

66 x 48 x 46 km
1.3 g/cm^3
C-type
ϕ > 40%

328 x 260 x 214 km
0.567±0.103 g/cm^3
Ice, organics, rock?
ϕ >70%

230 x 220 x 210 km
1.634 g/cm^3
C-type, Ice-rock mixture,
ϕ <10%

Working Geophysical Model
For Tidal Evolution Modeling



Asymmetrical mass distribution
explains librational angle of ~1 deg.

	Willner etal 2010
A/MR2	0.3615
B/MR2	0.4265
C/MR2	0.5024

Castillo-Rogez et al. (2012)

The Future of Phobos/Deimos Exploration

- We need to get to know Deimos better (system exploration)
- Characterize the flux (direction, abundant) of material across the system
- *In situ* characterization of multiple areas at the surface of Phobos/Deimos, requiring different instruments

Summary

- Small bodies are complex objects
  - Large diversity within a given class
  - Large diversity at the same object

- A sample returned from 1-2 locations at a few objects would not go far…

- Geochemical measurements need to be implemented in a systematic manner, in multiple locations on bodies within a system