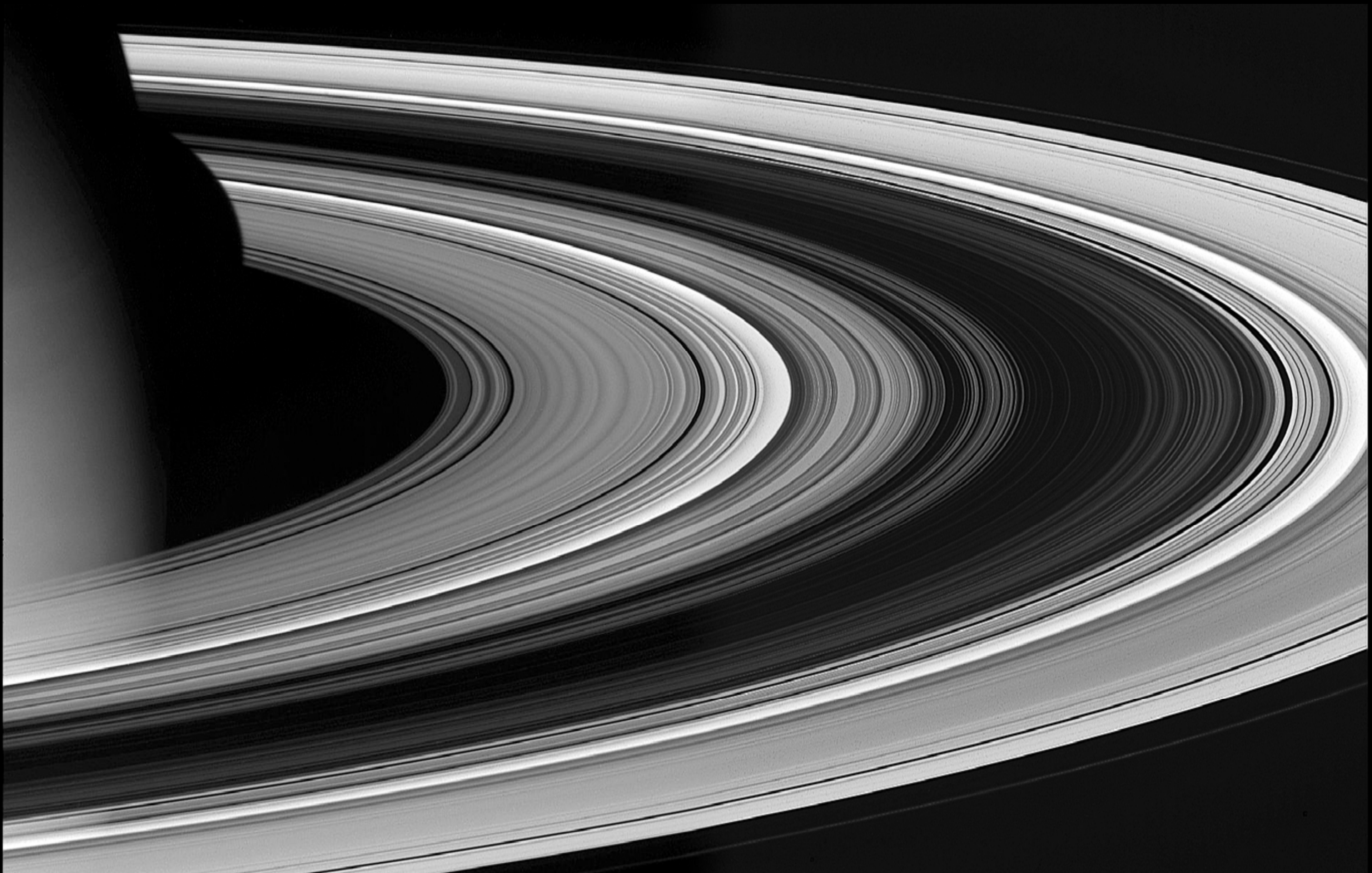
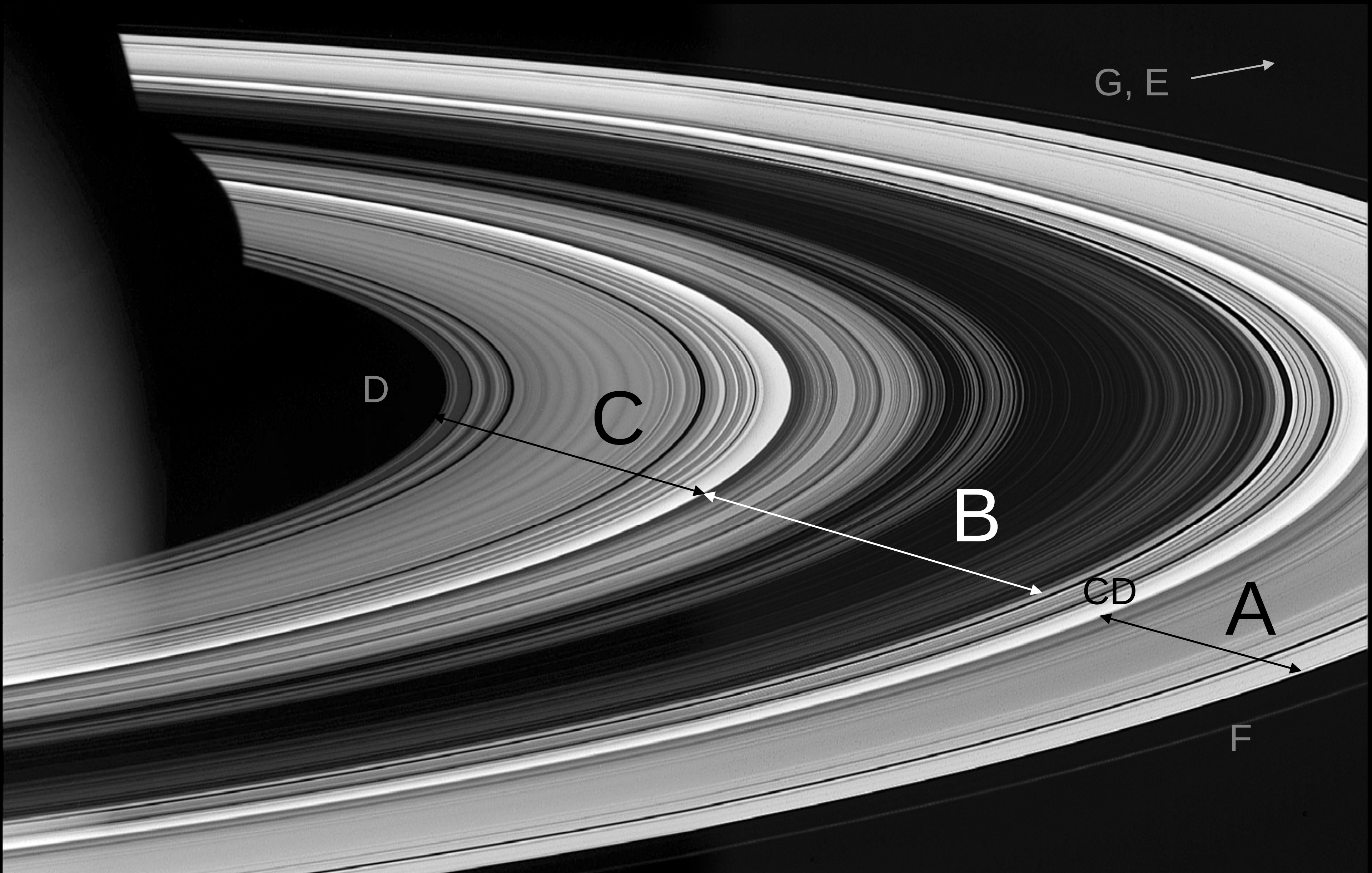
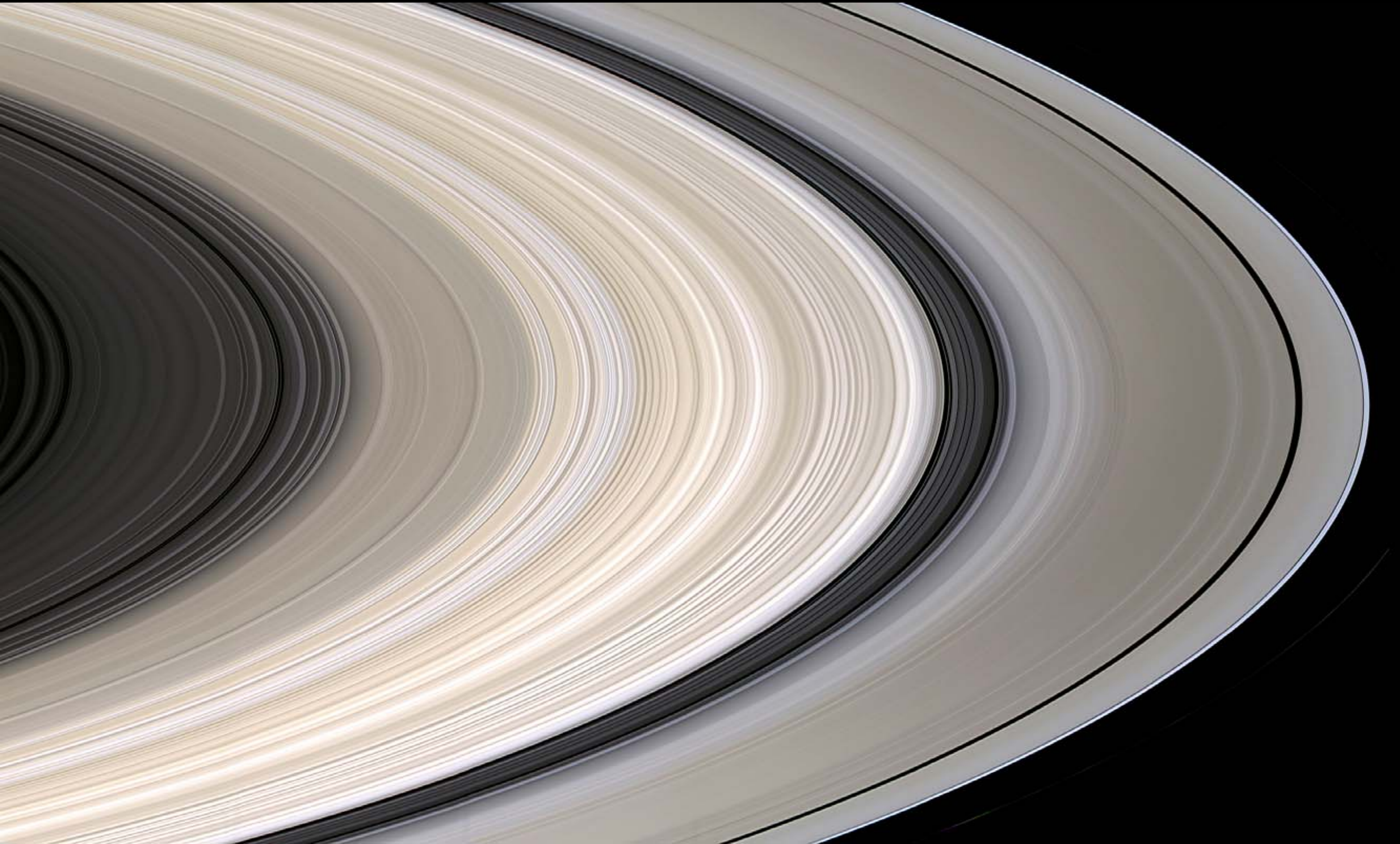
Cassini 5-year CHARM review



The Dark Side



Away from the Dark Side



Overview

Ring particle composition and size distribution

Ring structure: which processes explain it?

The role of moonlets - near the rings and embedded in them

Dust - in the Saturn system and from beyond

Electromagnetic processes; rings-ionosphere-magnetosphere

Key outstanding questions

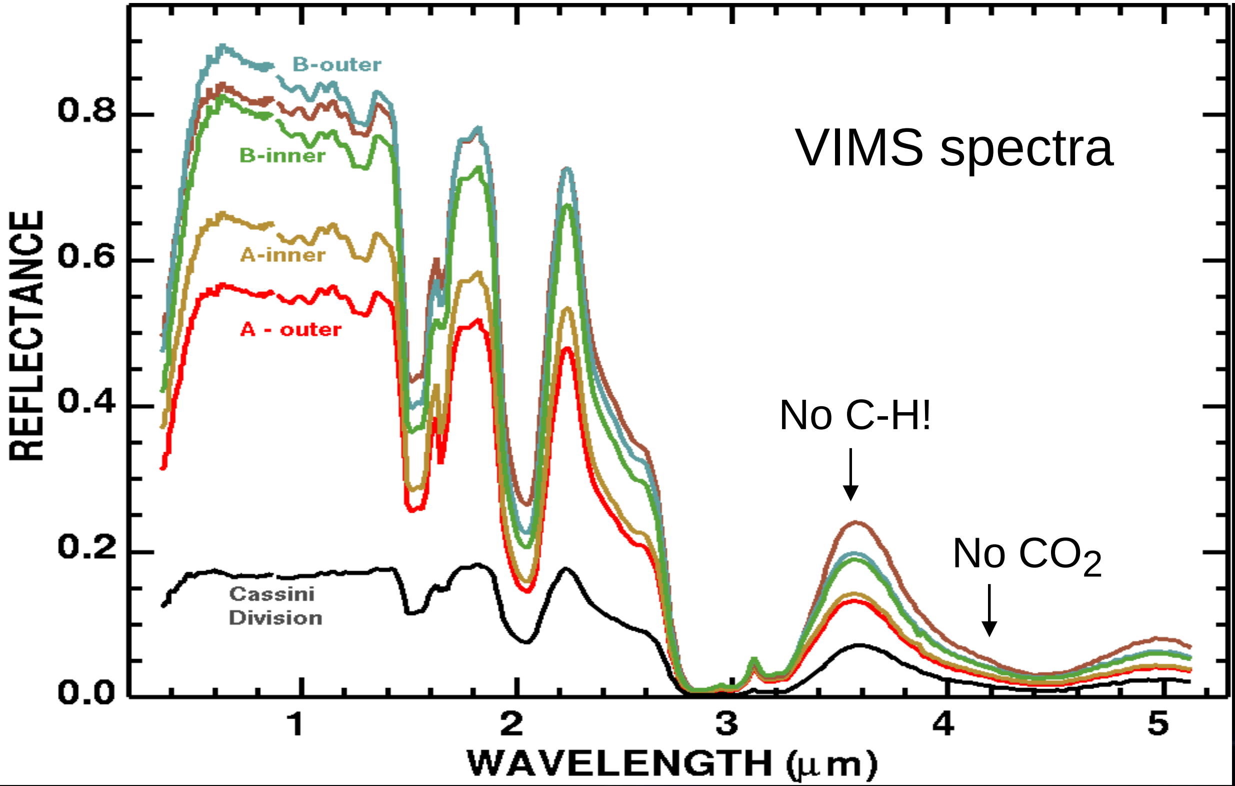
What gives the rings their reddish color?

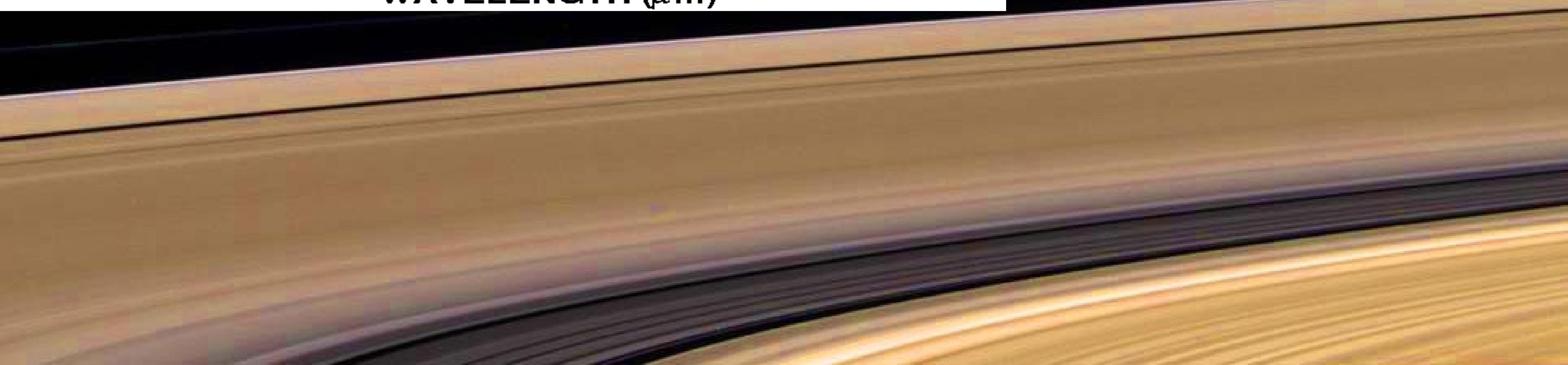
The age of the rings (their mass, incoming meteoroid flux)

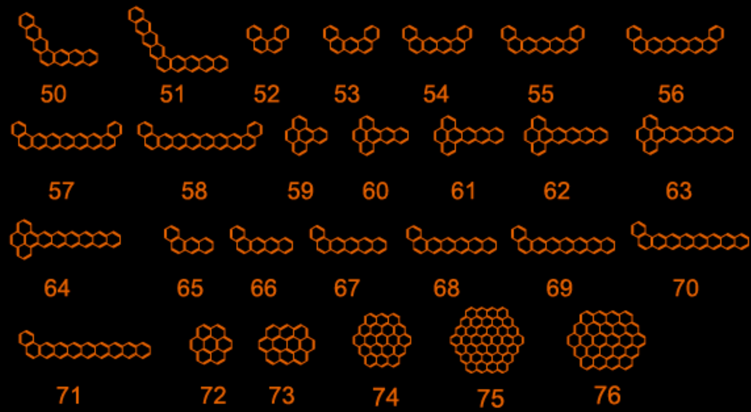
Fine structure throughout the B ring

Regular structure in the C ring (and where are its moonlets?)

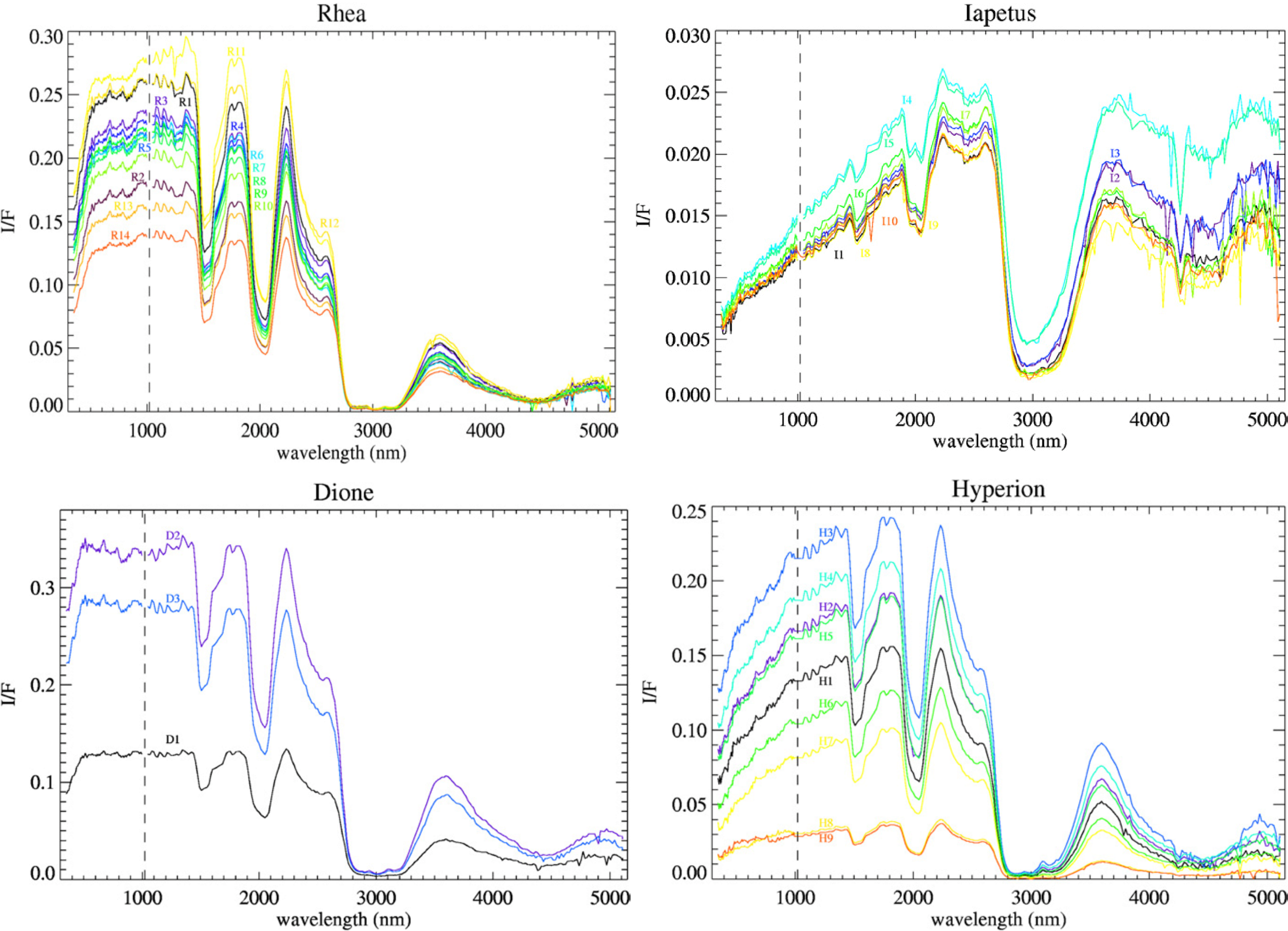
Chemical composition and size distribution of ring material



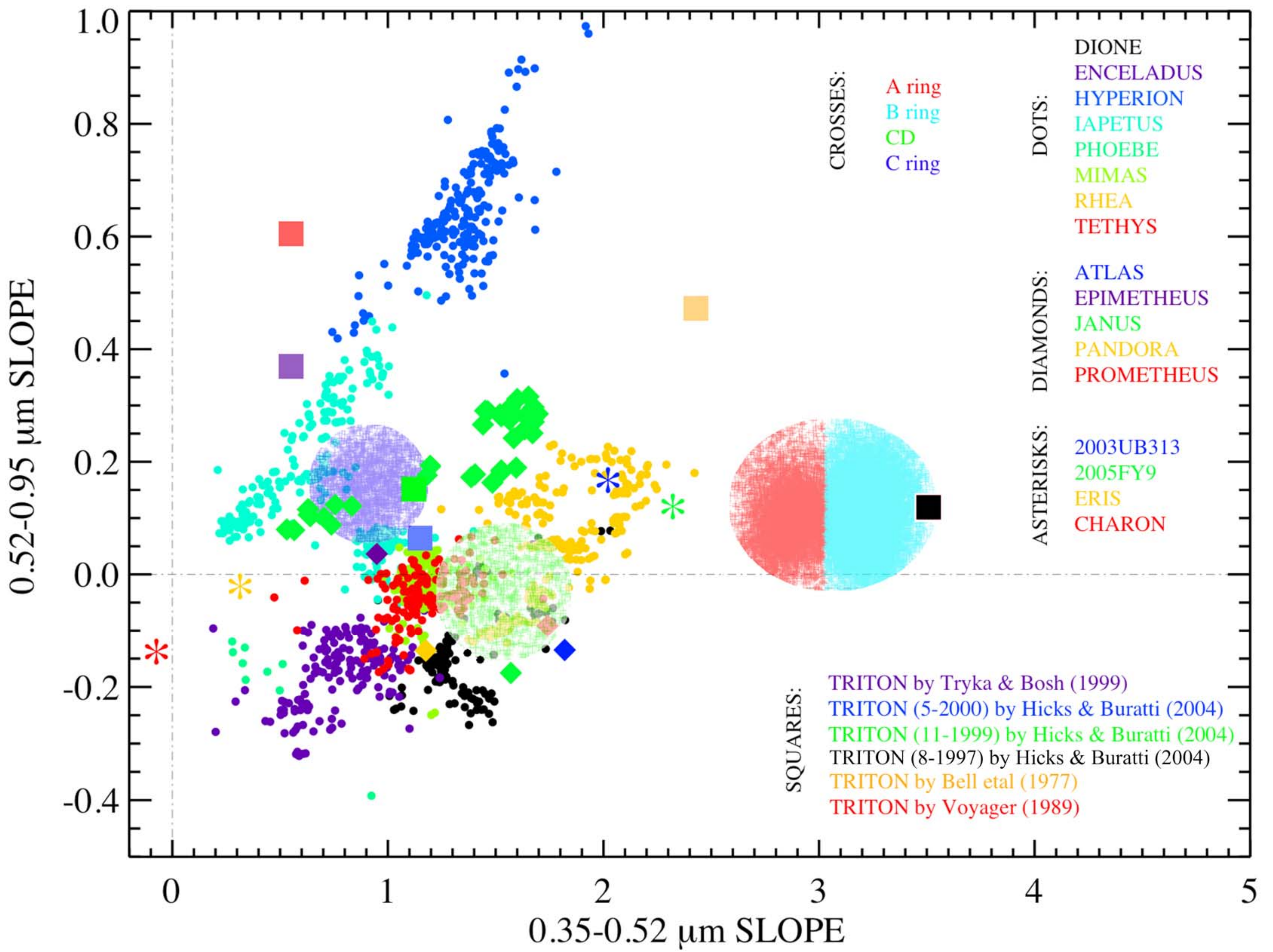




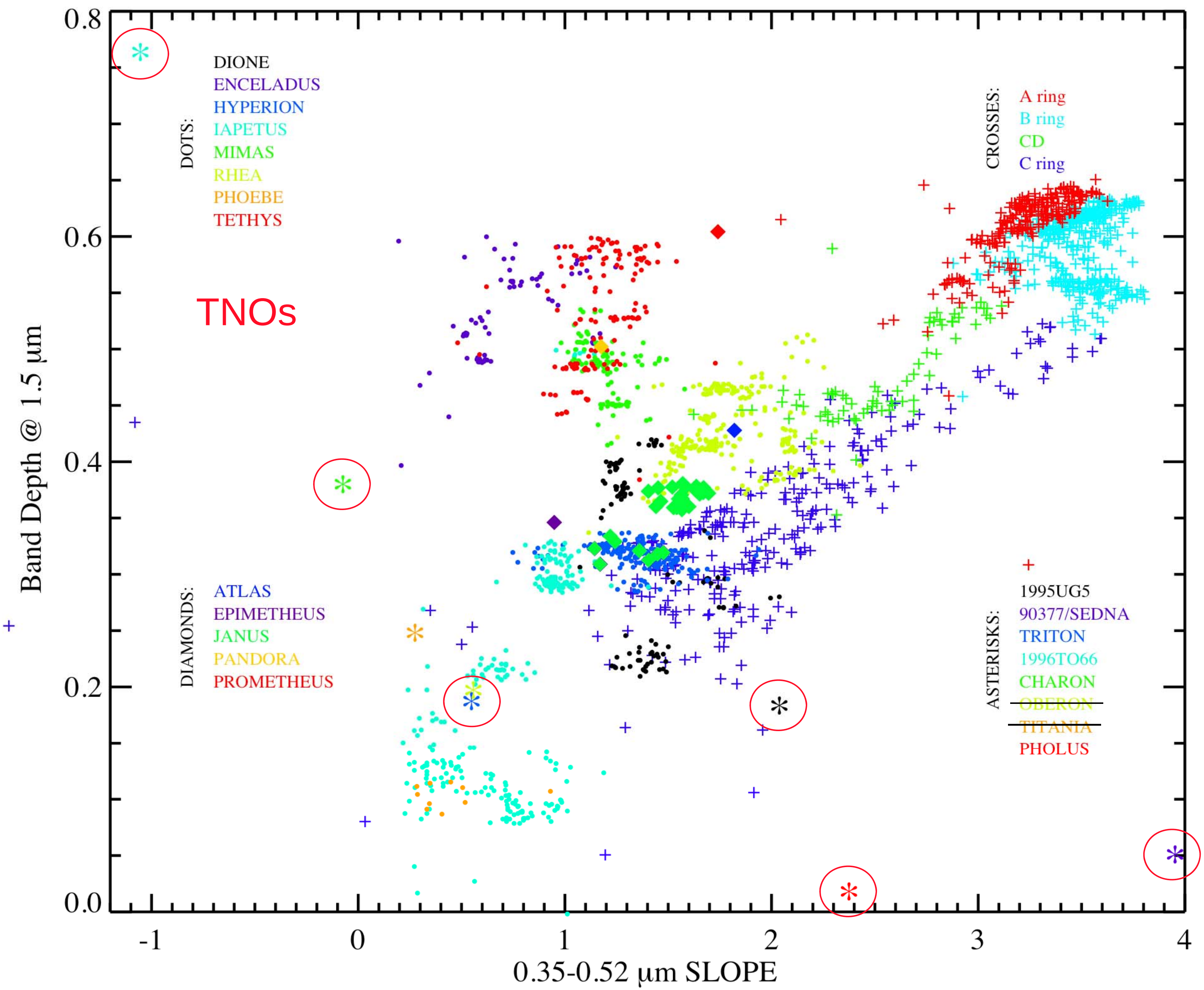
Why are the rings reddish?
“organic” or inorganic origin?
Lack of spectral features
Suggests nano-inclusions



Rhea
I/F
wavelength (nm)
R1
R2
R3
R4
R5
R6
R7
R8
R9
R10
R11
R12
R13
R14
Iapetus
I/F
wavelength (nm)
I1
I2
I3
I4
I5
I6
I7
I8
I9
I10
Dione
I/F
wavelength (nm)
D1
D2
D3
Hyperion
I/F
wavelength (nm)
H1
H2
H3
H4
H5
H6
H7
H8
H9

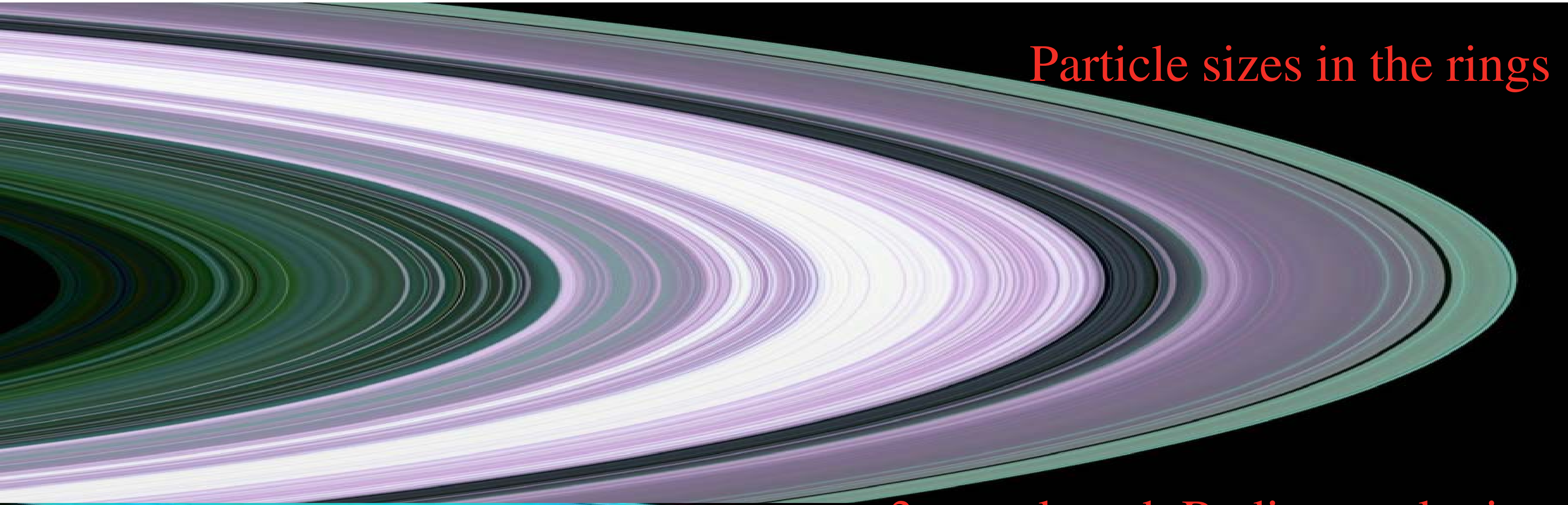


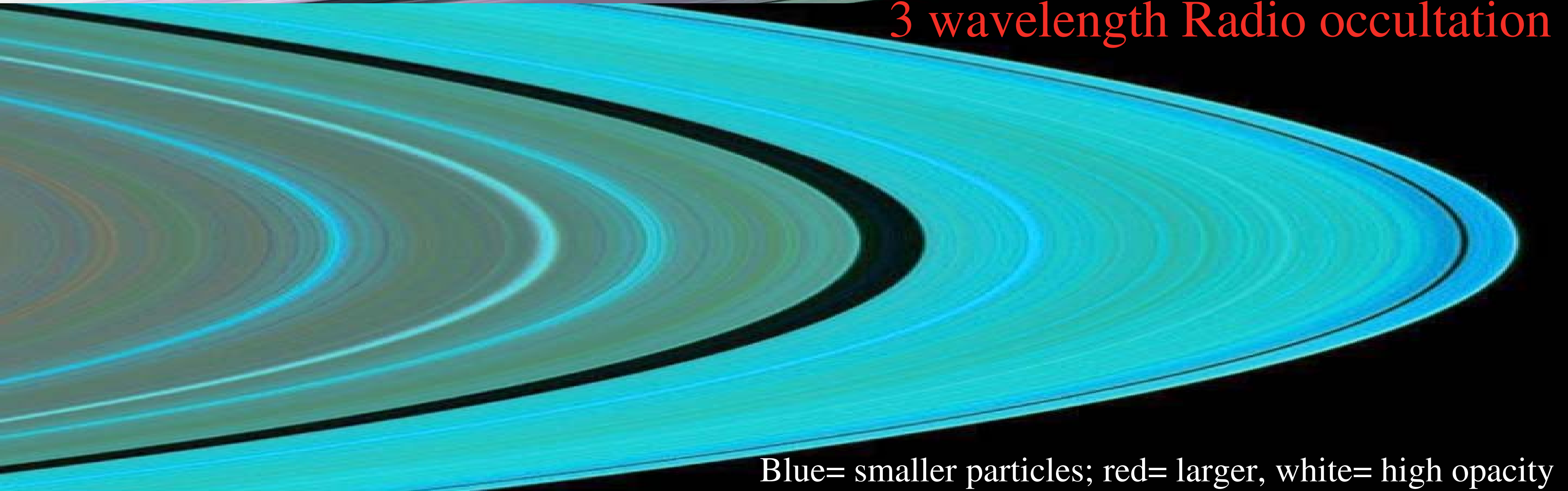
0.52-0.95 μm SLOPE
0.35-0.52 μm SLOPE
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0
1
2
3
4
5
CROSSES:
A ring
B ring
CD
C ring
DOTS:
DIONE
ENCELADUS
HYPERION
IAPETUS
PHOEBE
MIMAS
RHEA
TETHYS
DIAMONDS:
ATLAS
EPIMETHEUS
JANUS
PANDORA
PROMETHEUS
ASTERISKS:
2003UB313
2005FY9
ERIS
CHARON
SQUARES:
TRITON by Tryka & Bosh (1999)
TRITON (5-2000) by Hicks & Buratti (2004)
TRITON (11-1999) by Hicks & Buratti (2004)
TRITON (8-1997) by Hicks & Buratti (2004)
TRITON by Bell etal (1977)
TRITON by Voyager (1989)



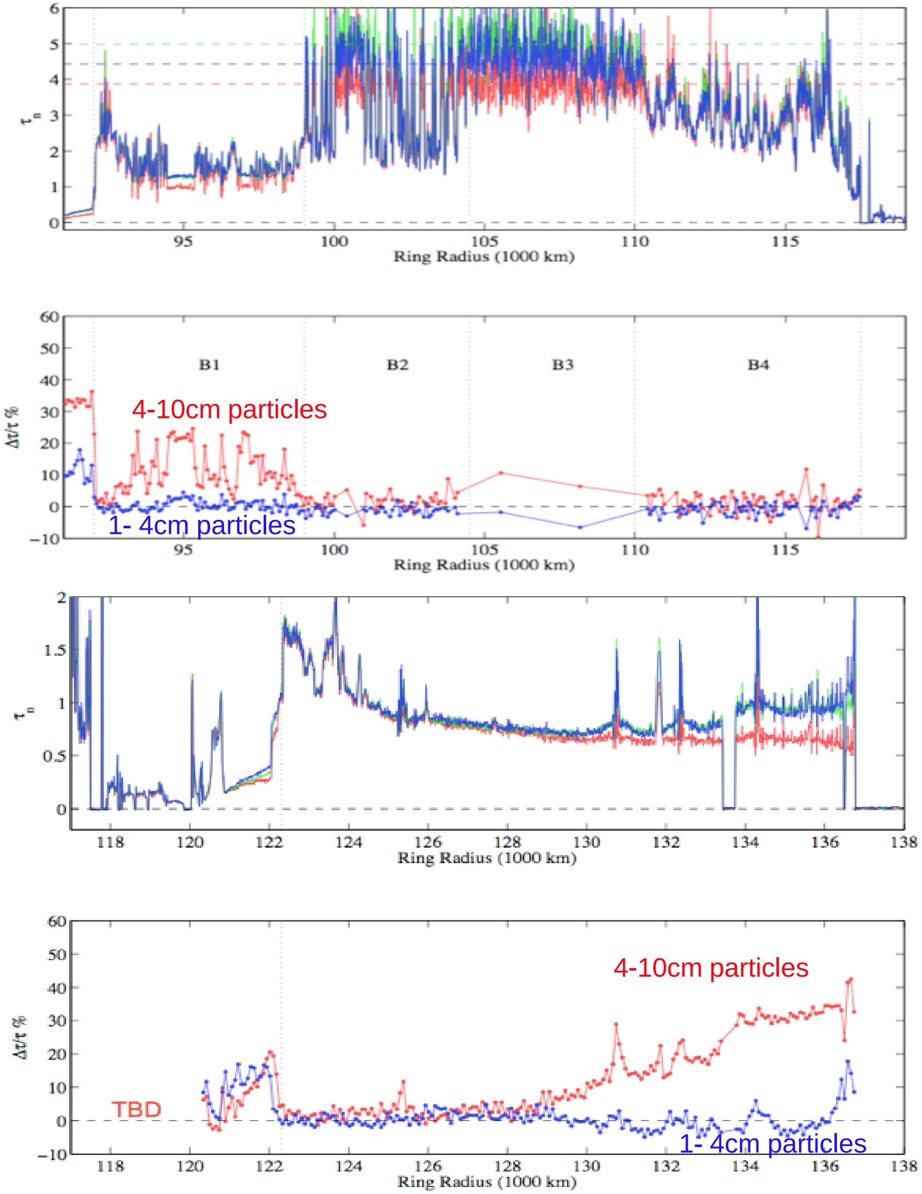
TNOs
DOTS:
DIONE
ENCELADUS
HYPERION
IAPETUS
MIMAS
RHEA
PHOEBE
TETHYS
CROSSES:
A ring
B ring
CD
C ring
DIAMONDS:
ATLAS
EPIMETHEUS
JANUS
PANDORA
PROMETHEUS
ASTERISKS:
1995UG5
90377/SEDNA
TRITON
1996TO66
CHARON
OBERON
TITANIA
PHOLUS
Band Depth @ 1.5 µm
0.35-0.52 µm SLOPE
0.0
0.2
0.4
0.6
0.8
-1
0
1
2
3
4

Chemical composition and size distribution of ring material

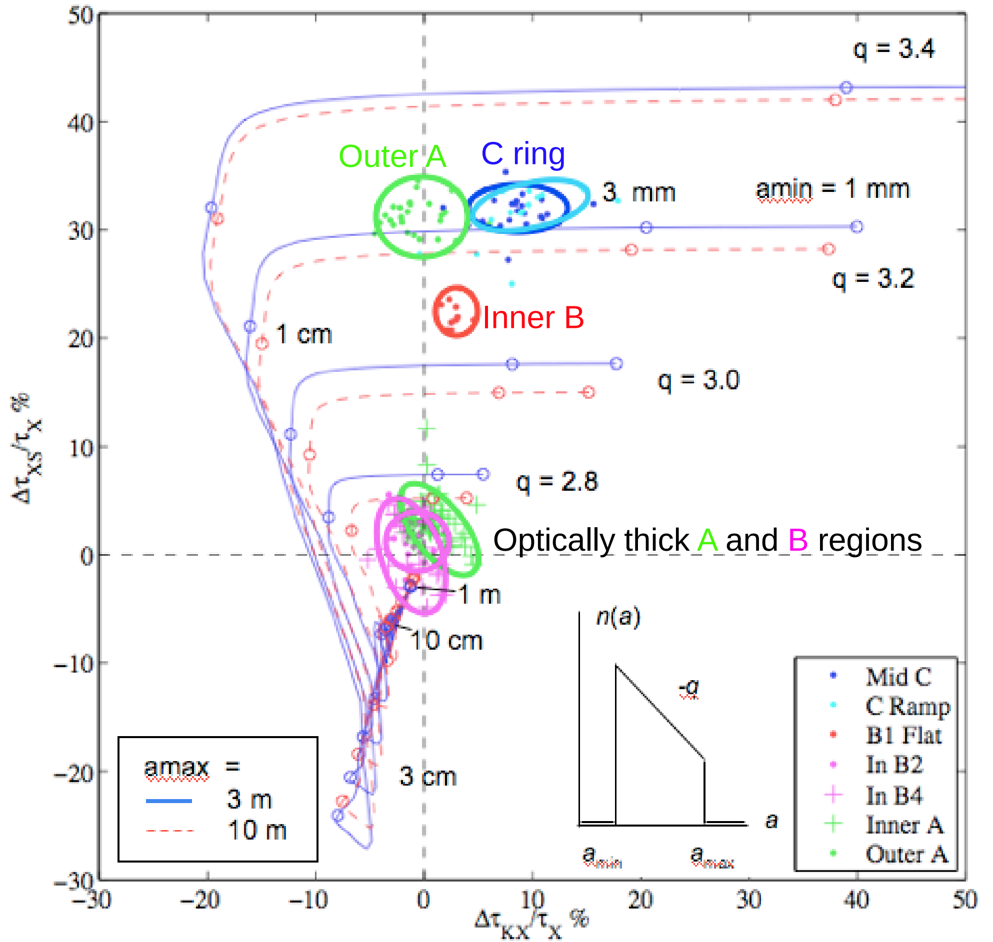




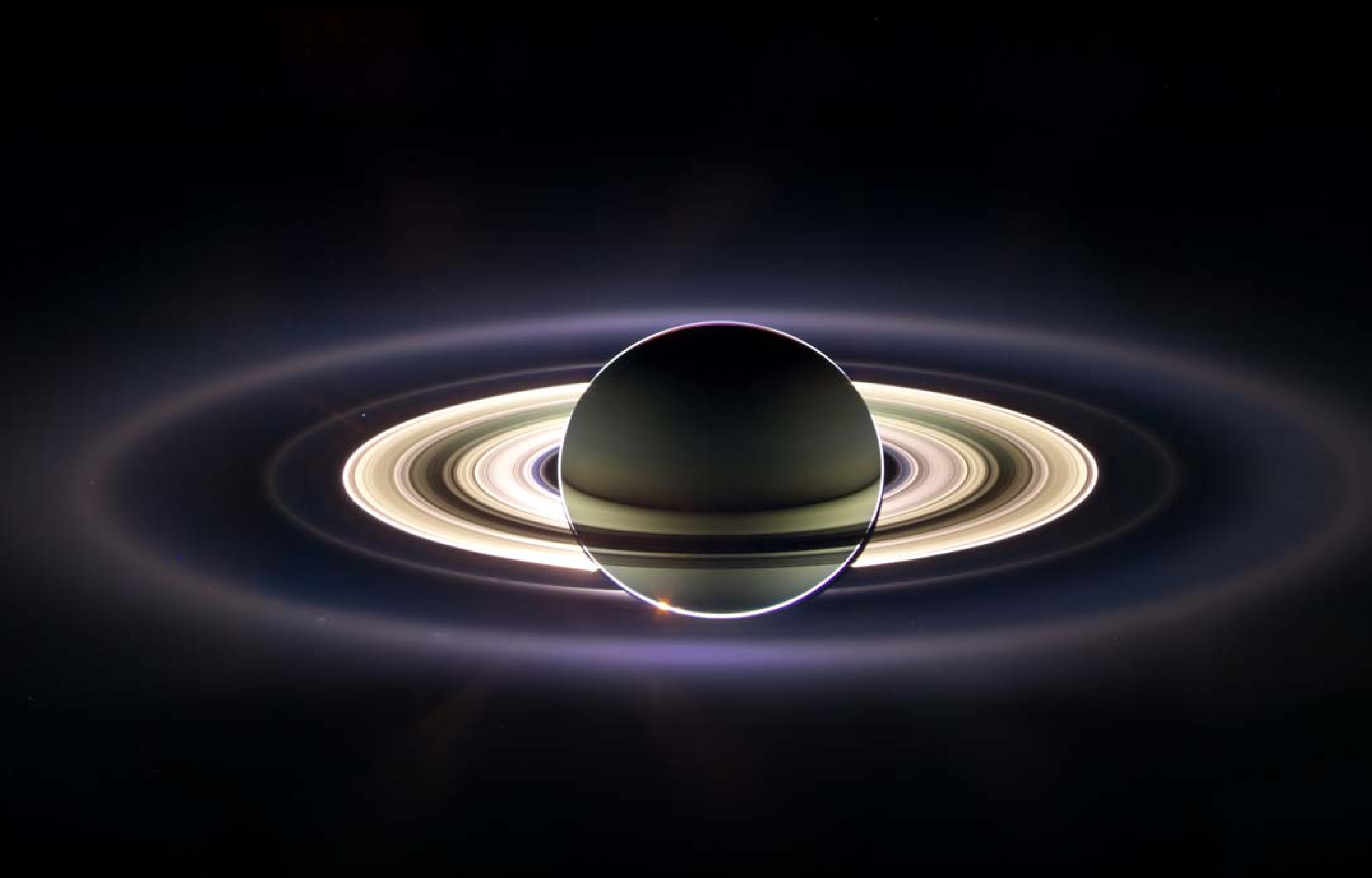
Chemical composition and size distribution of ring material



RSS occultations at 2, 4, 13cm now constrain properties of smaller size particles; analysis in progress will constrain largest particles at comparable accuracy and spatial resolution



Chemical composition and size distribution of ring material



Chemical composition and size distribution of ring material

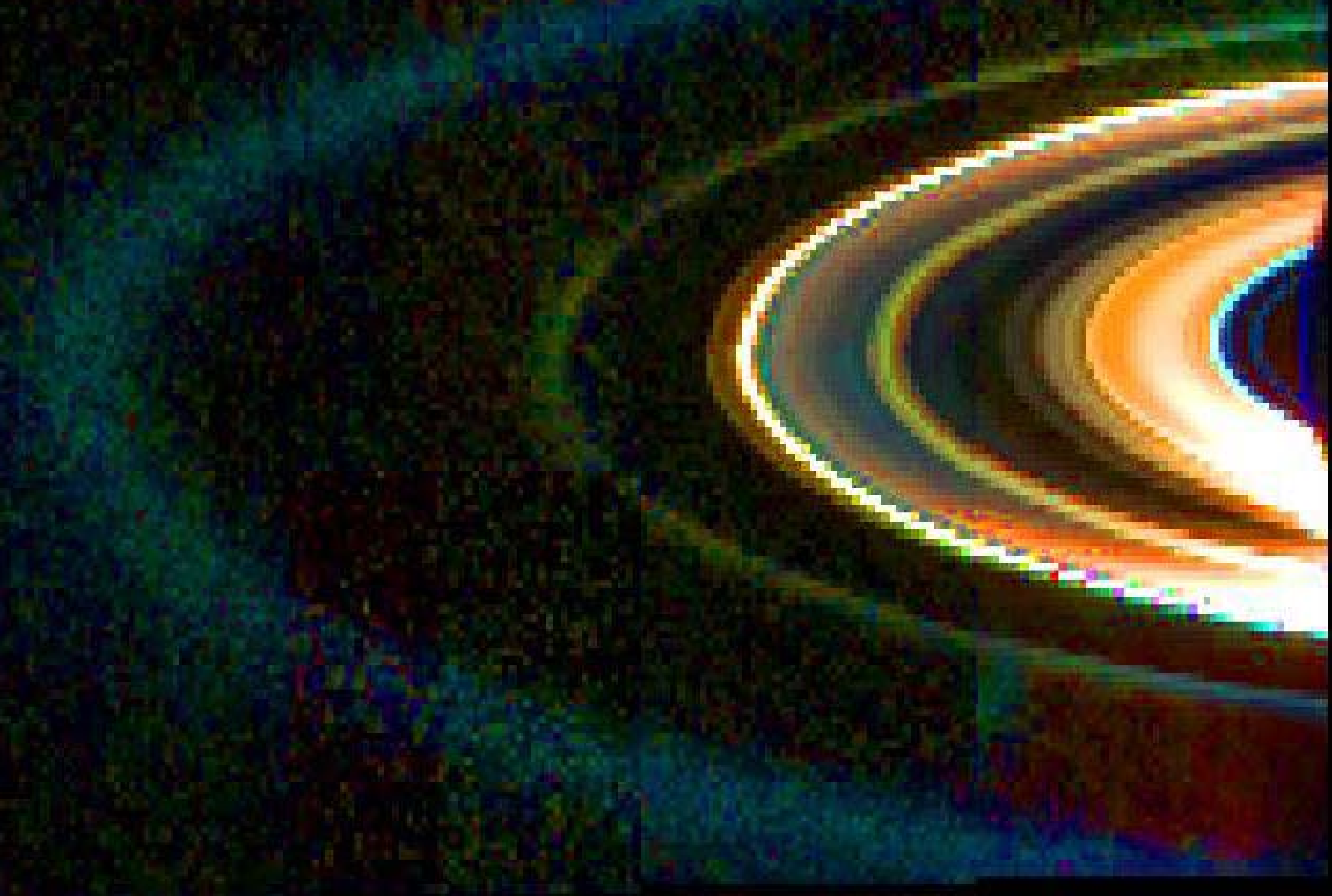
Grain size and shape distribution (solid or aggregate) in D, E, F, G rings

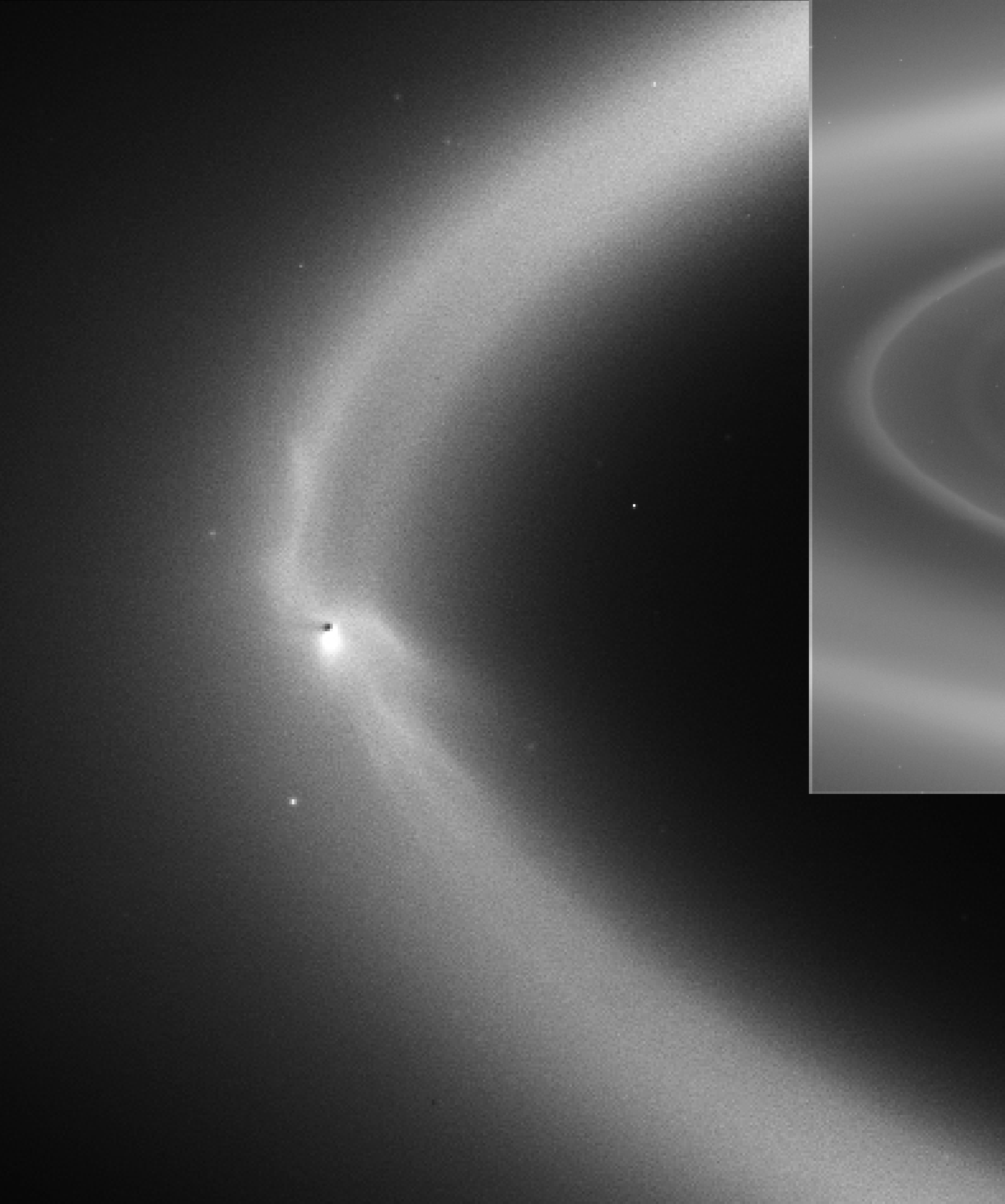
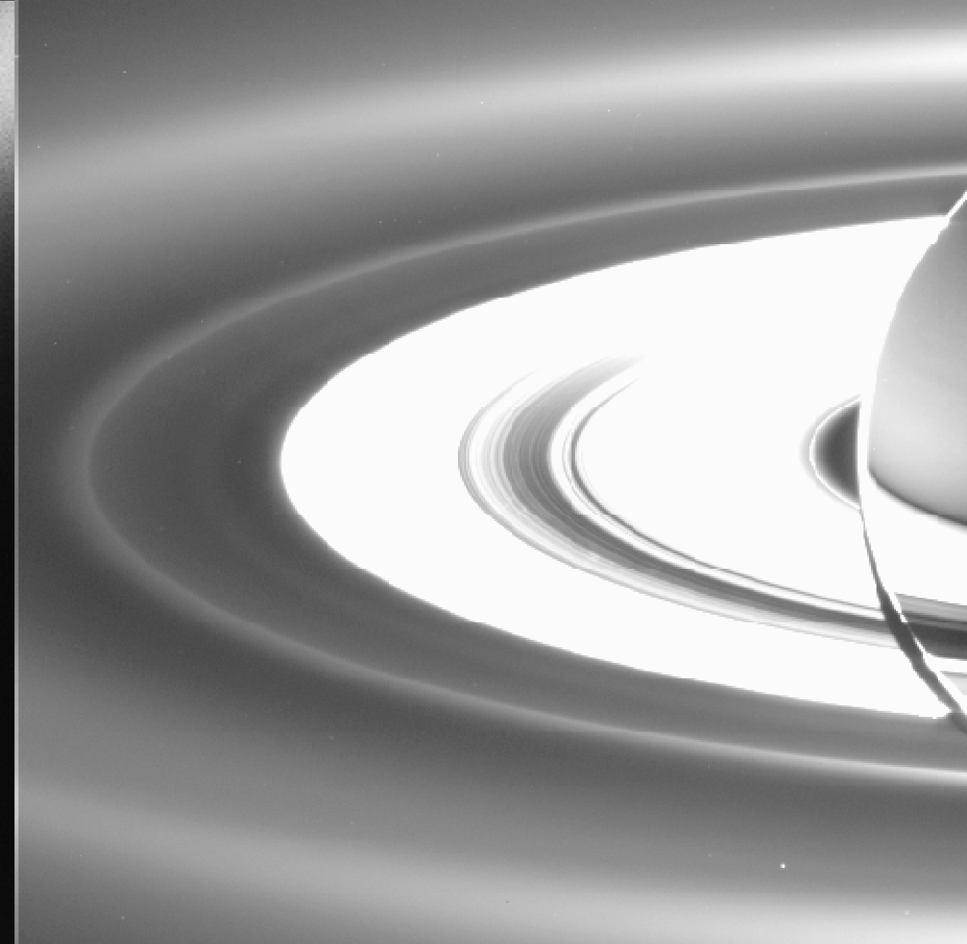
Discovery of two new rings (Janus and Pallene rings)

Discovery of arcs of debris librating with two other new ringmoons

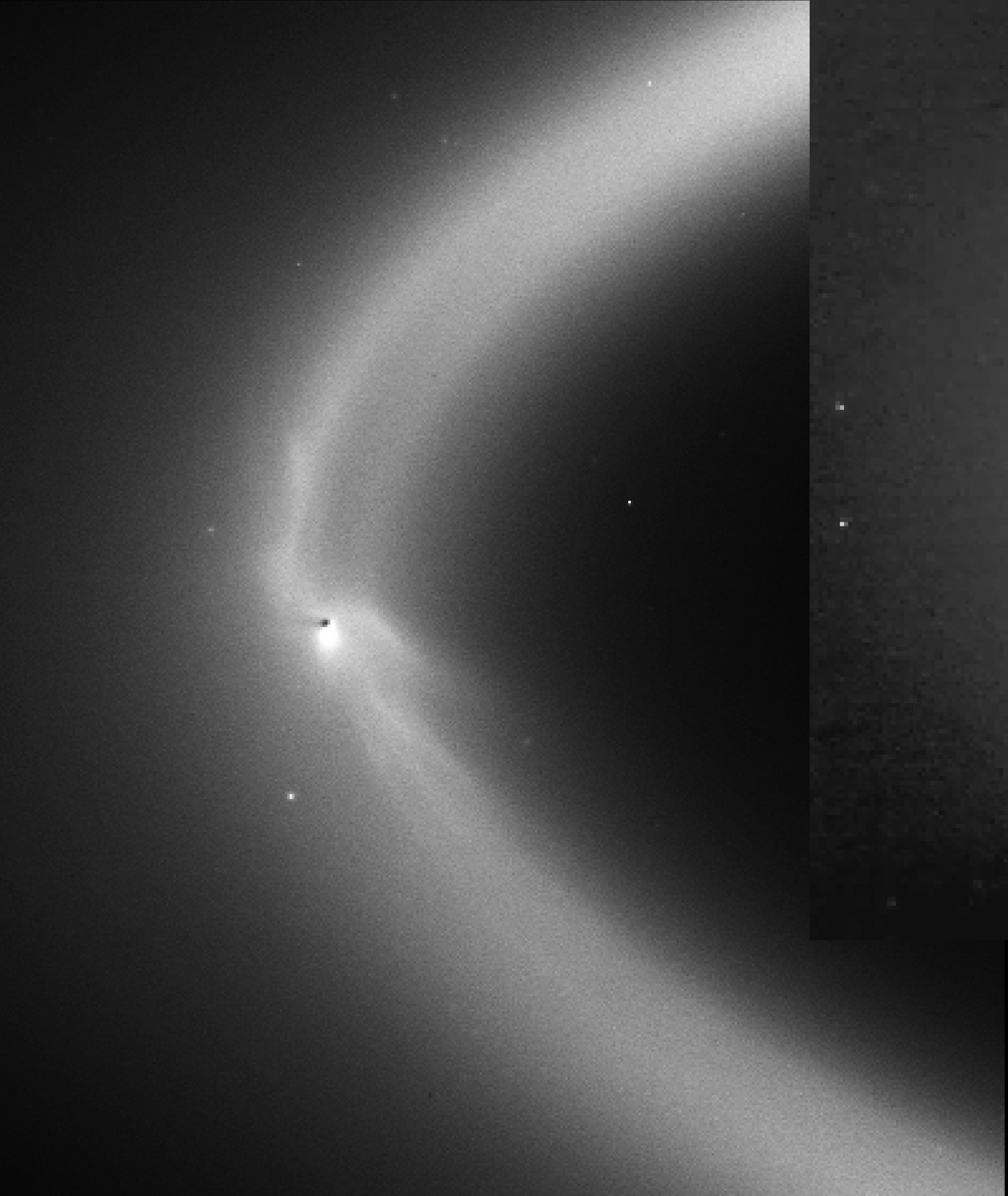
CDA *in situ* measurements show water, sodium, silicon in E ring grains, and even some metallic grains which may be on unusual orbits

VIMS - spectra in forward scattering; very powerful

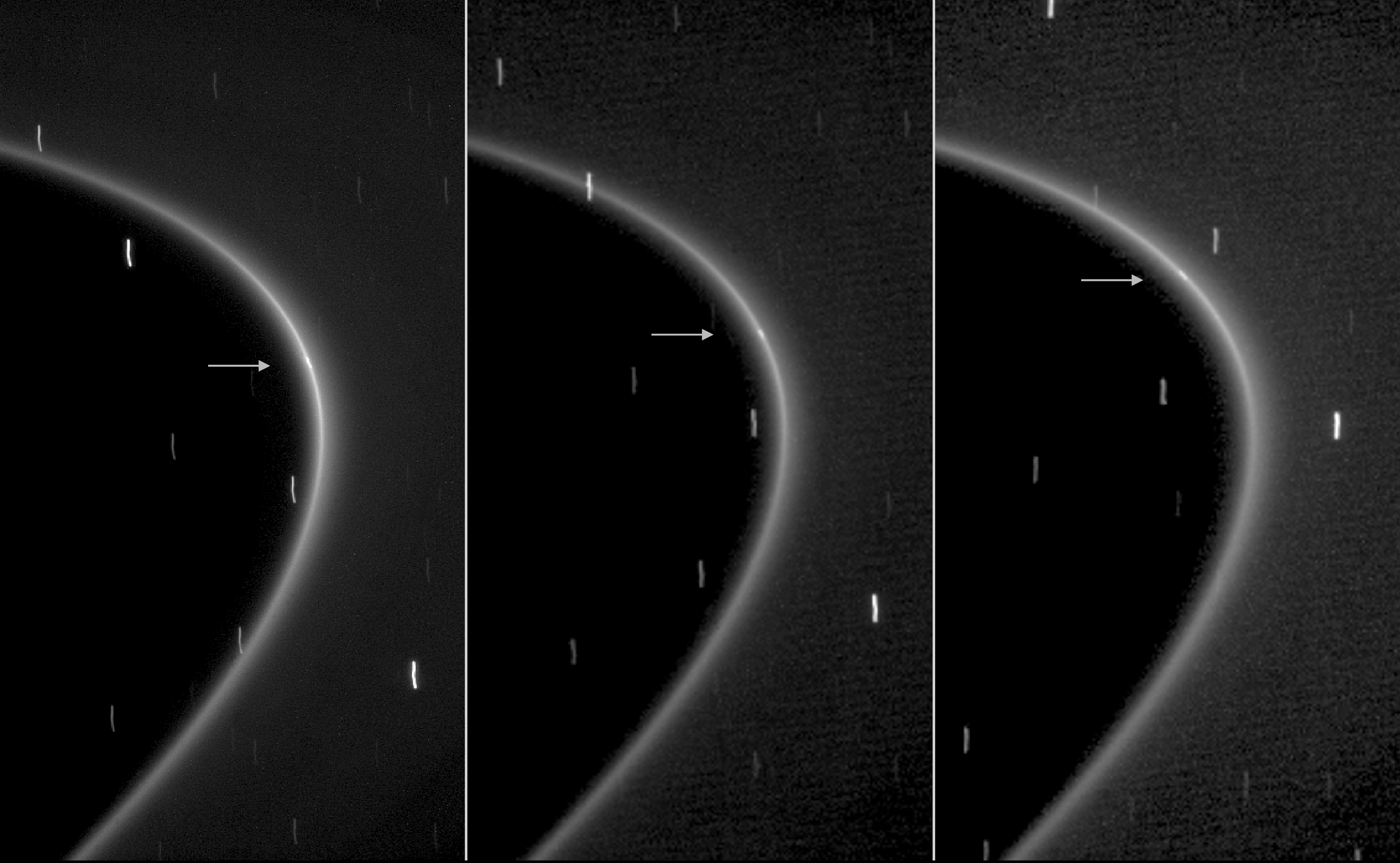


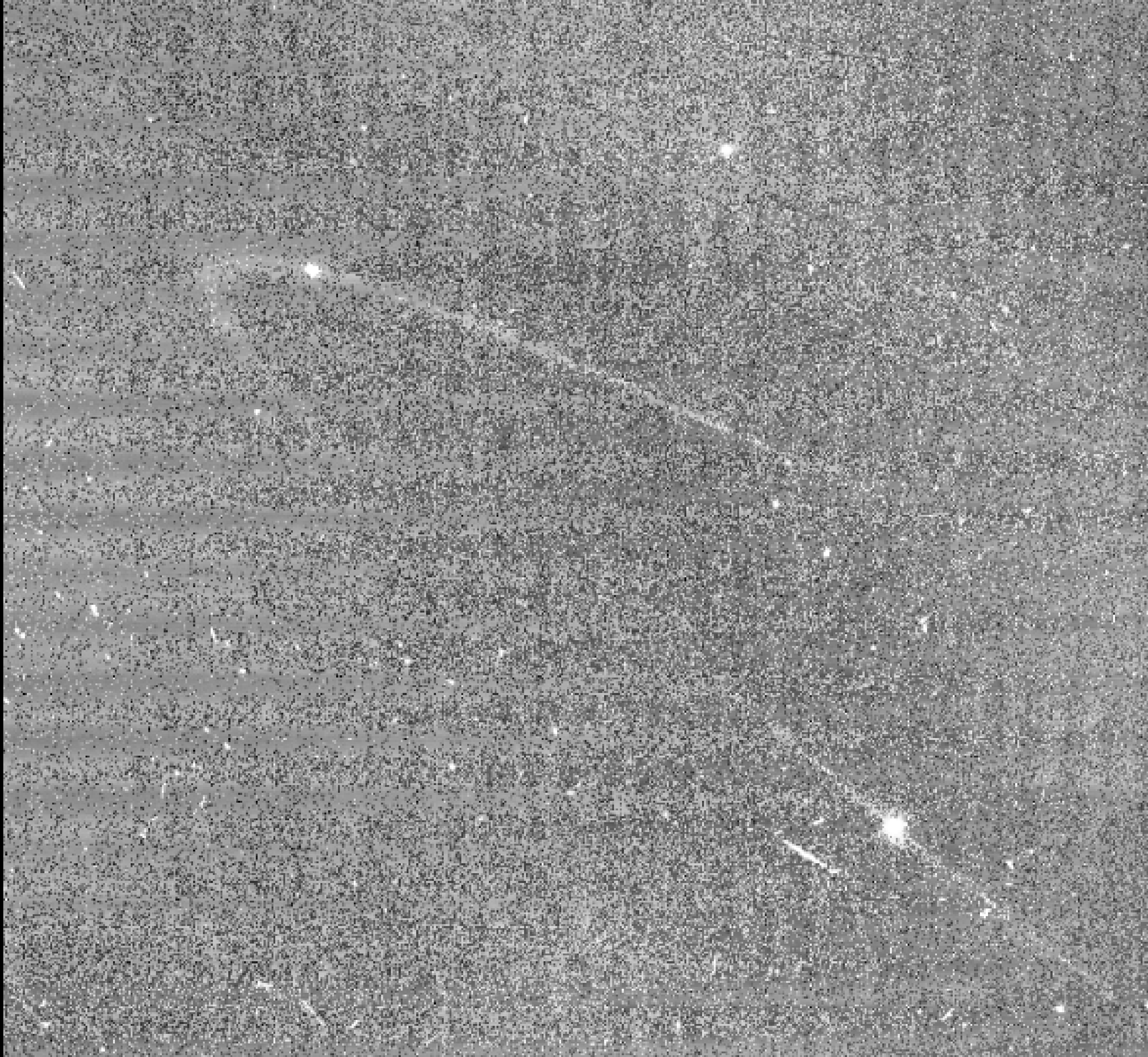
New ringmoon Pallene has its own ring; new ringmoons Anthe and Methone (trapped in different Mimas resonances) are associated with their own arcs of corotating rubble; all possibly G rings in the making.




G ring contains an “arc” of rubble which supplies the dusty ring



New moonlet (in a Mimas 7:6 resonance)
supplies the G ring arc, and ultimately the entire G ring



Chemical composition and size distribution of ring material

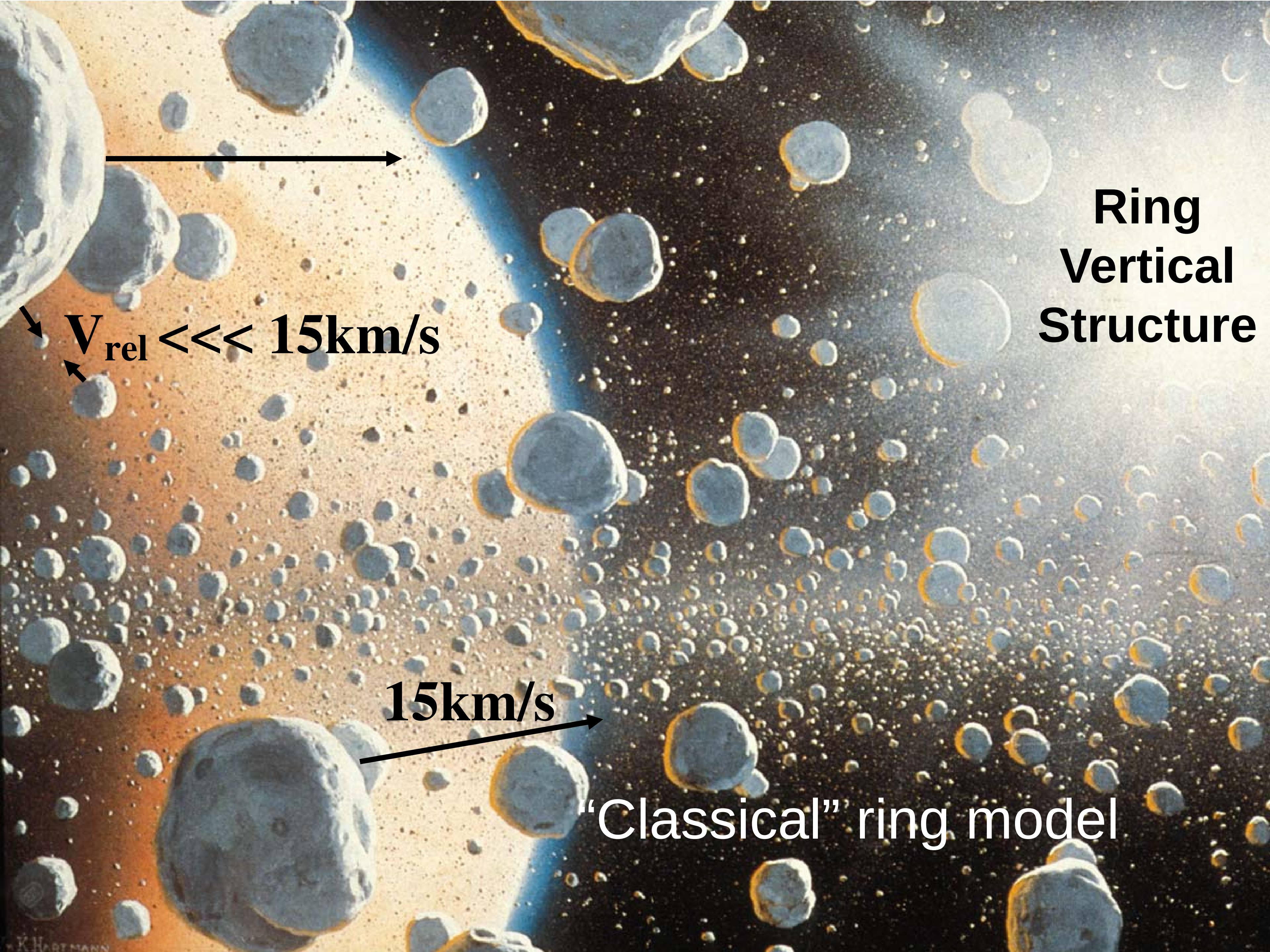
Major results:

A/B rings contain the purest water ice in the solar system, but are “redder” than any of Saturn’s icy moons. Spectra are not an ideal match for most red outer solar system objects (except maybe Triton), lacking signatures of low-T organics (C-H band, CO_2). Meteoroid bombardment and the (O, O_2) ring atmosphere may each play a different evolutionary role.

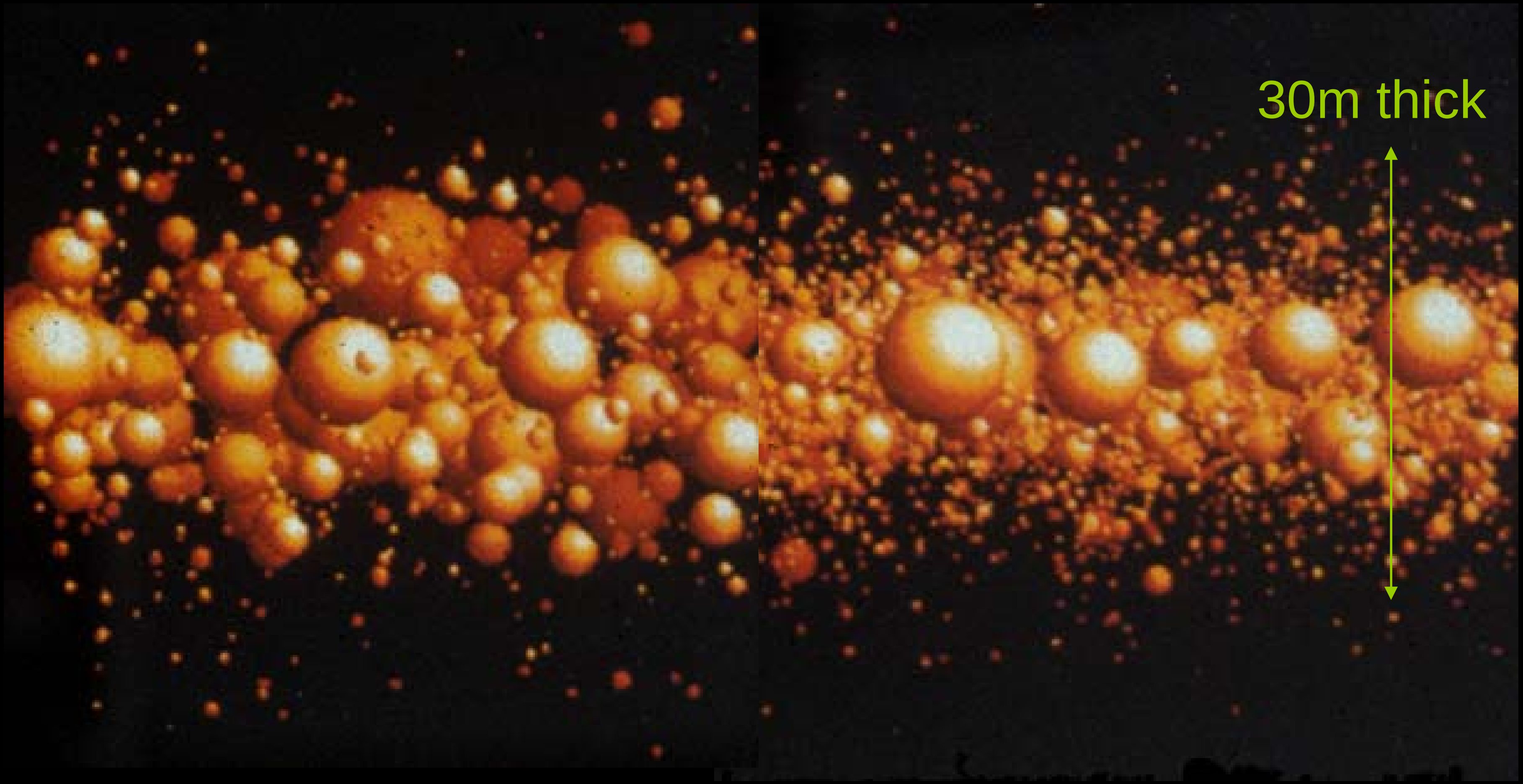
Cassini has characterized the mm-10m particle size distribution throughout the rings for the first time, by a combination of RSS occs and stellar occs. An increasing abundance of smaller particles (*eg* towards outer A ring) correlates with increased dynamical activity. Analysis is just beginning.

New constraints on particle size/composition in diffuse rings, even as to solid particles *vs* fluffy aggregates, are being provided by CDA, VIMS, and ISS. E Ring particles contain water, sodium (salt?), silicon (silicates?).

New diffuse ring at Pallene; new moonlet supplies the G ring; two other new moonlets also sport dusty rubble “arcs” - proto-G-rings?

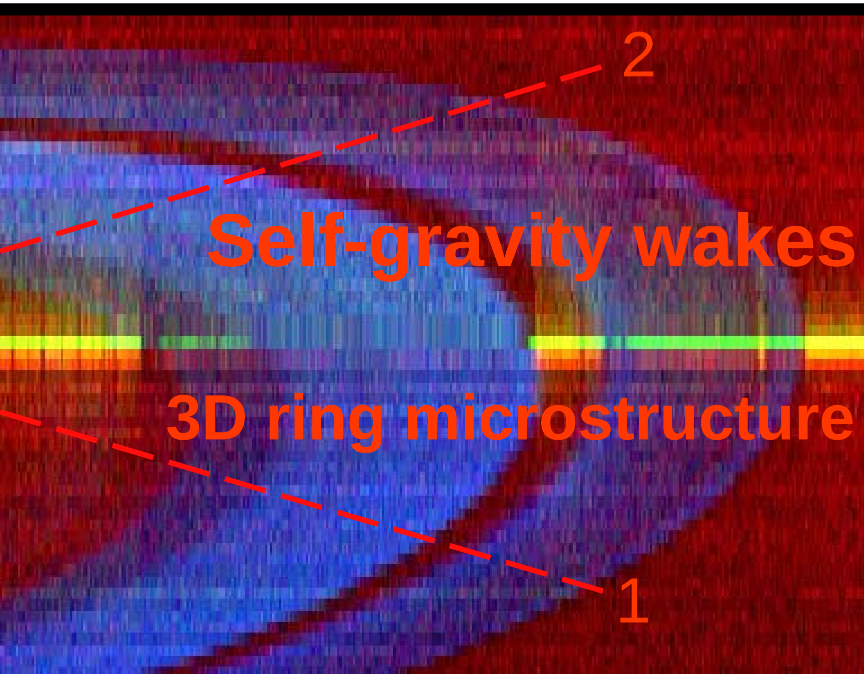

Ring
Vertical
Structure
V_{rel} <<< 15km/s
15km/s
"Classical" ring model

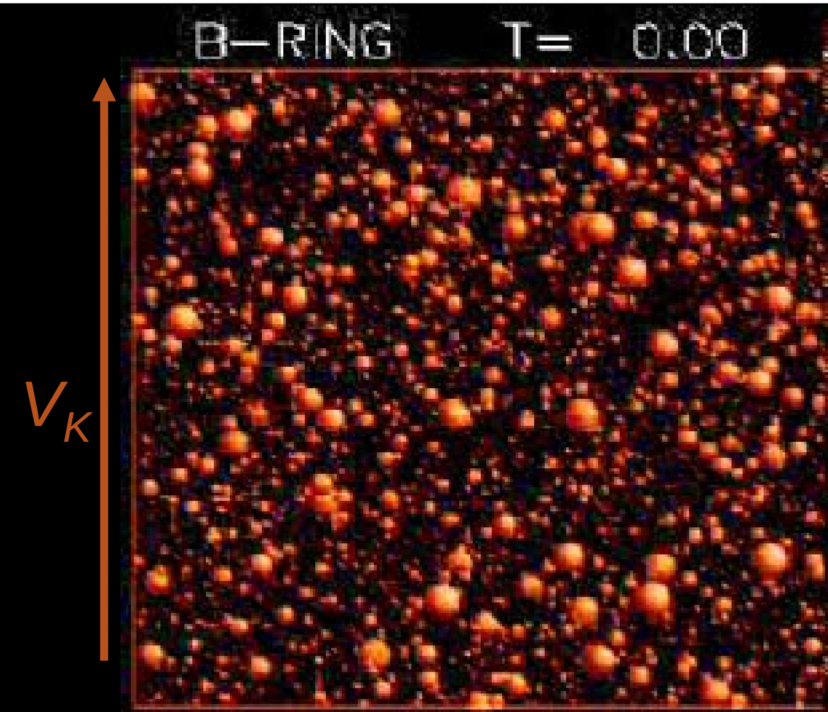
A more modern, densely packed ring model



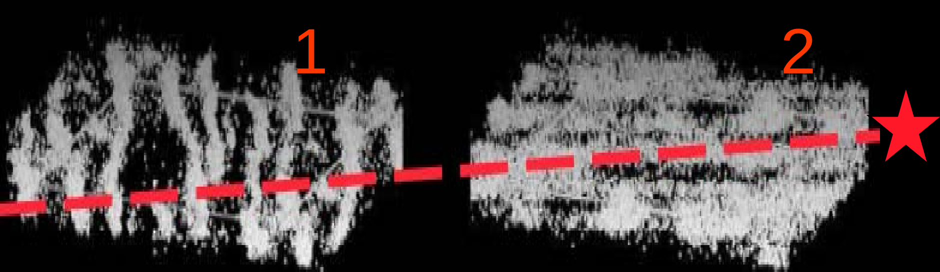
Gentle collisions & weak gravity between particles give the rings the quality of a viscous fluid

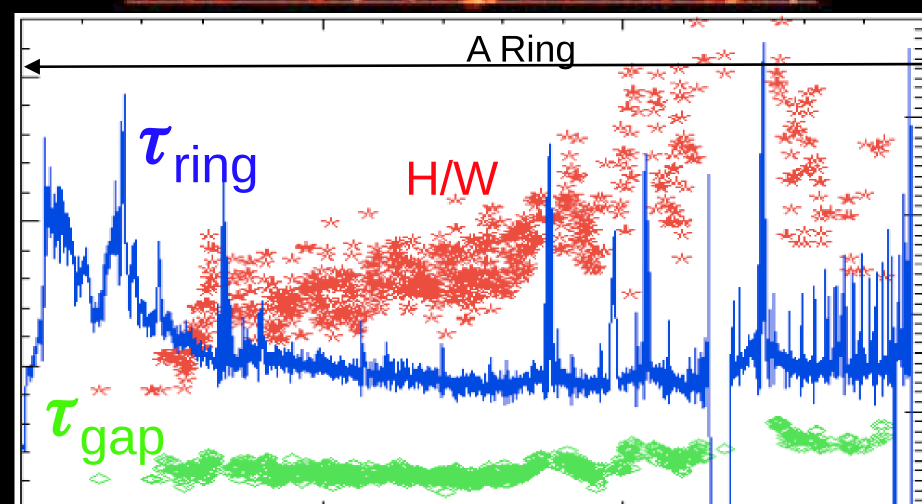
Dynamic processes responsible for ring structure: Self-Gravity wakes

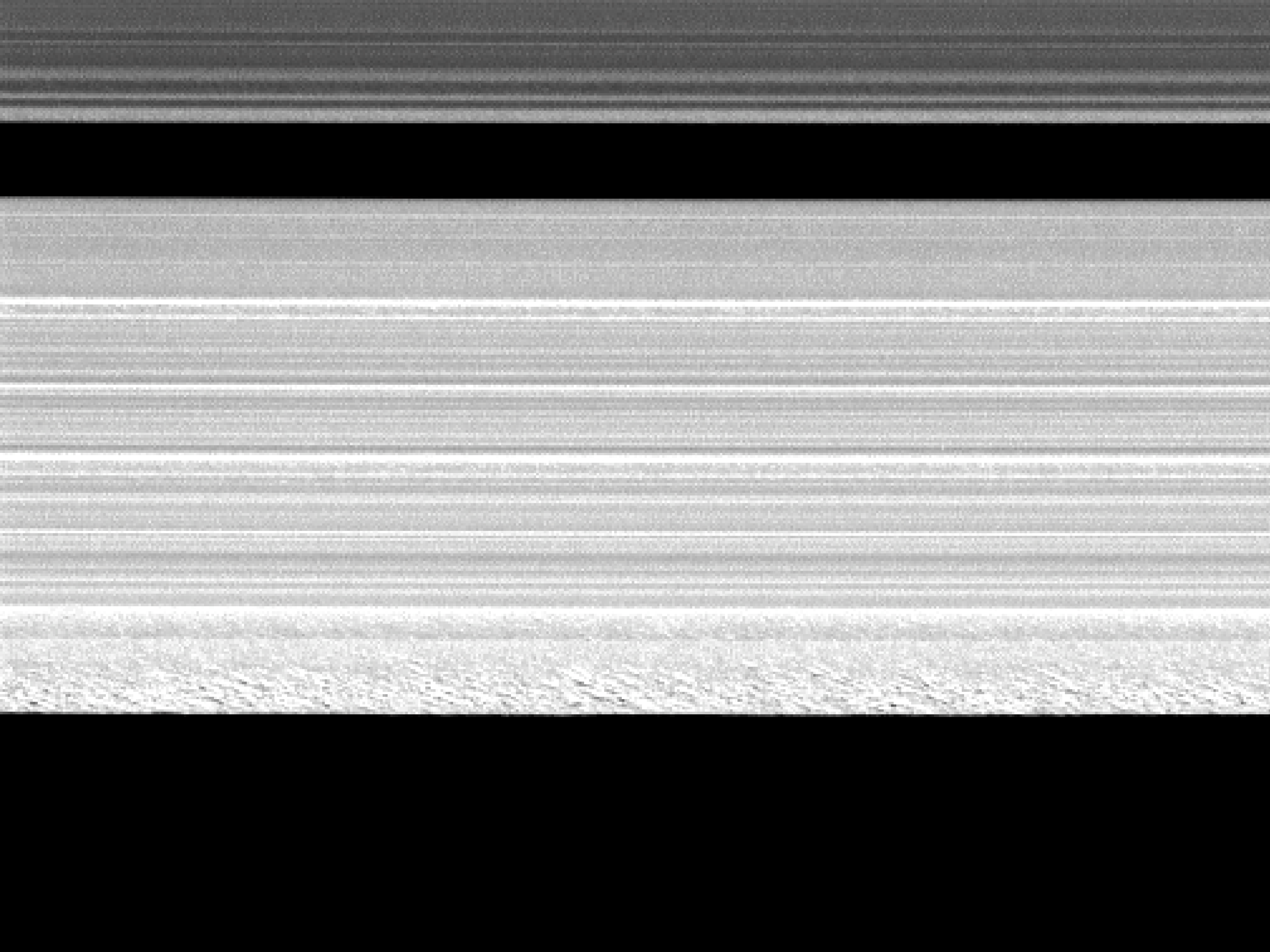


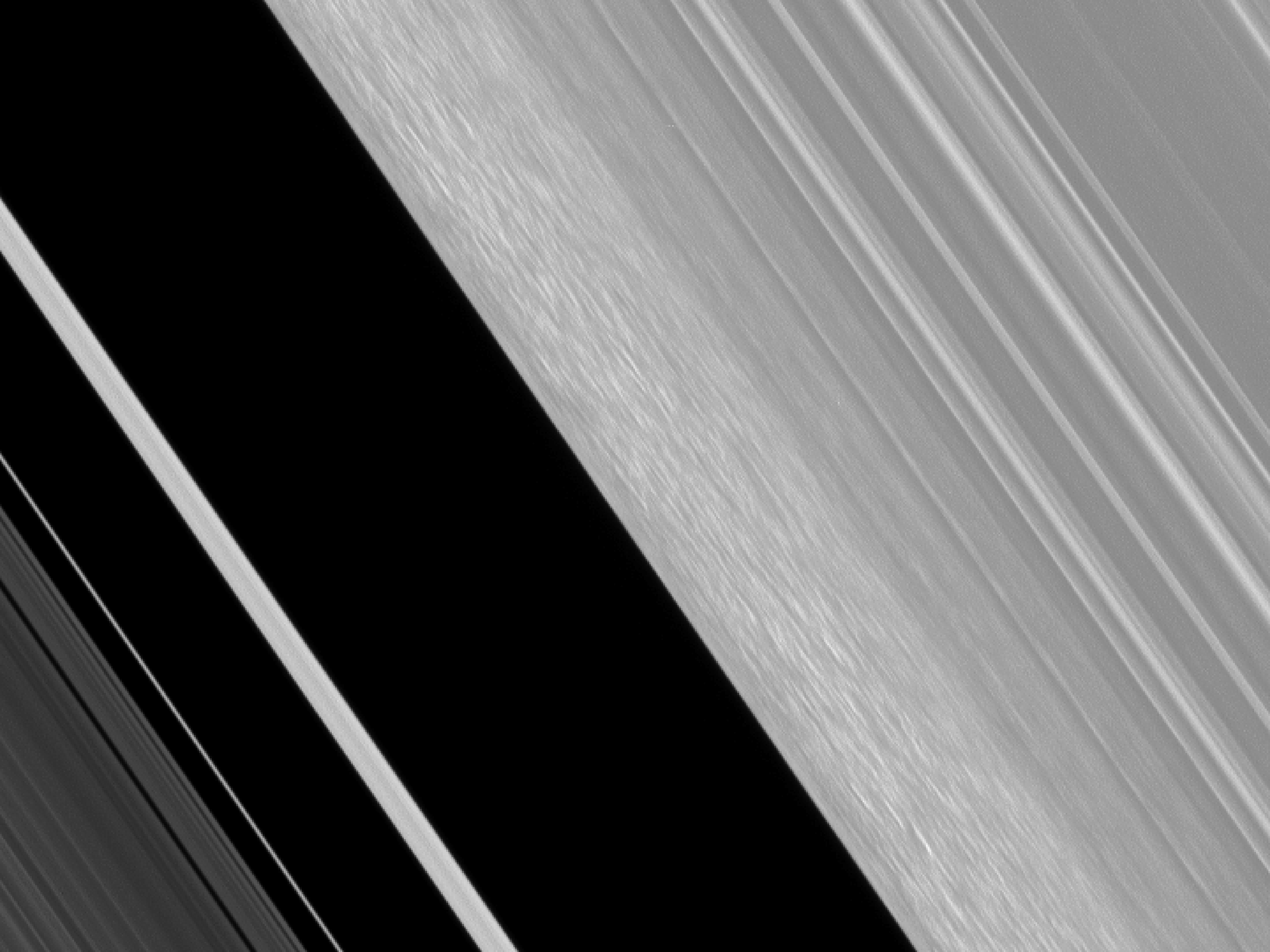


Stellar occultations by the rings give a 3D CAT-scan of ring microstructure on few-meter scales









Dynamic processes responsible for ring structure

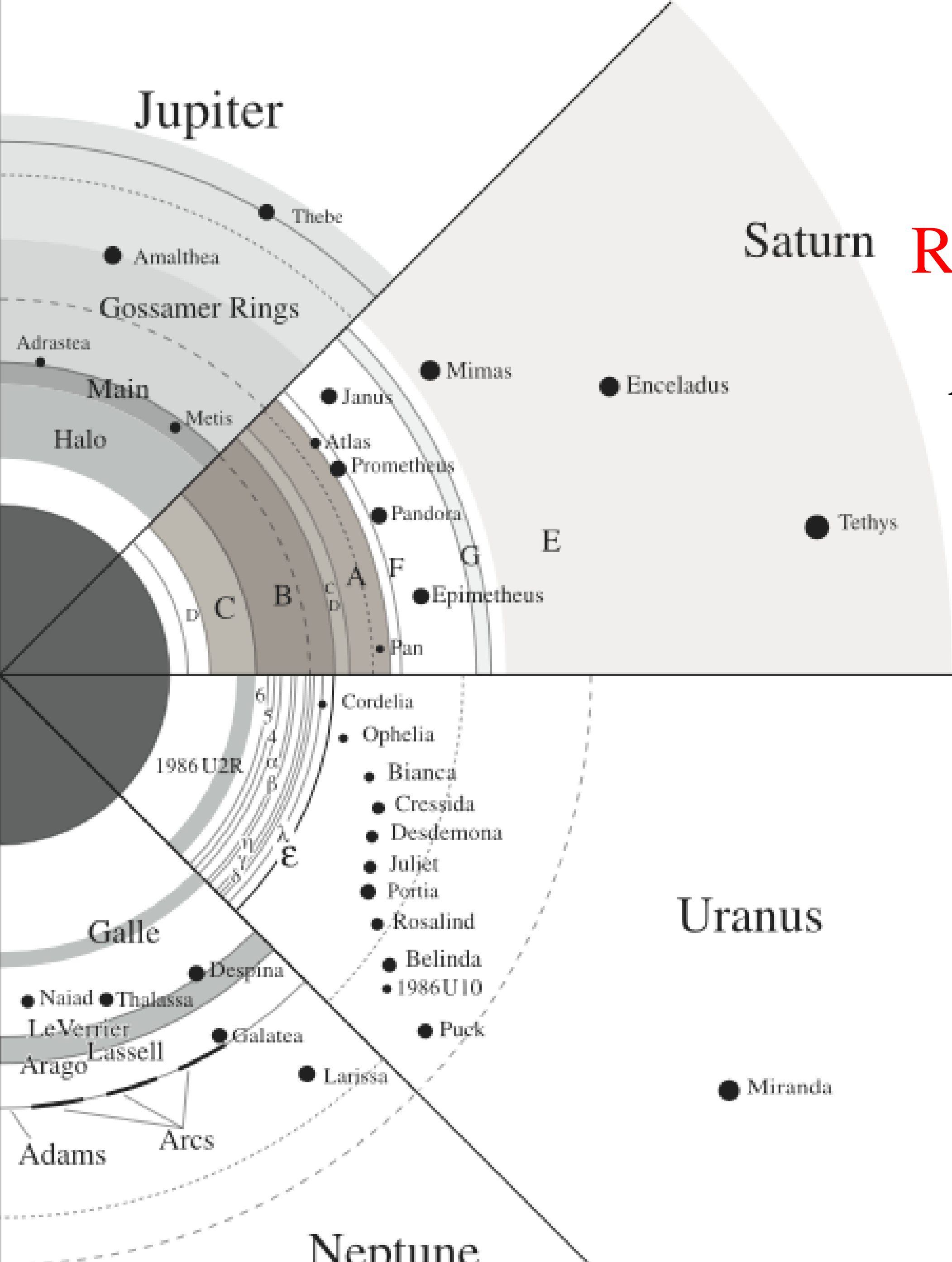
Major results:

Cassini has extended our knowledge of radial structure into the most opaque ring regions, about which nothing was previously known. Spiral density and bending waves are becoming well enough understood to be a probe of underlying ring properties; other radial structure remains puzzling.

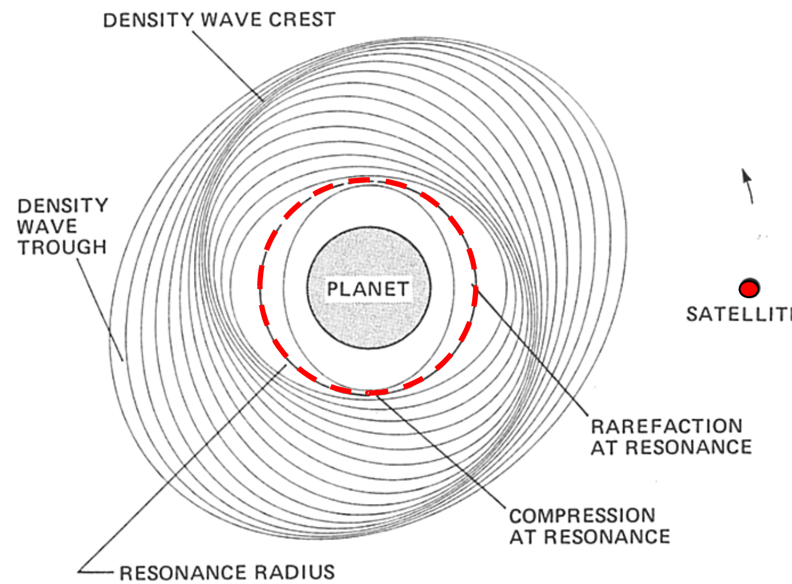
One of the most rewarding Cassini advances has been in the area of local ring “microstructure”, dominated by self-gravity wakes with lengthscale comparable to the local ring thickness (10-100m). The structure is nearly ubiquitous and is driving new model development to allow particle properties to be derived from imaging observations.

Most ring structure is the result of the interplay of the gravity of remote moons and/or local ring material with the fluid properties of the local material (viscosity and pressure), but some structure is driven electromagnetically and some by the feeble pressure of sunlight.

Rings and ringmoons closely mixed in and near Roche zones of parent planets

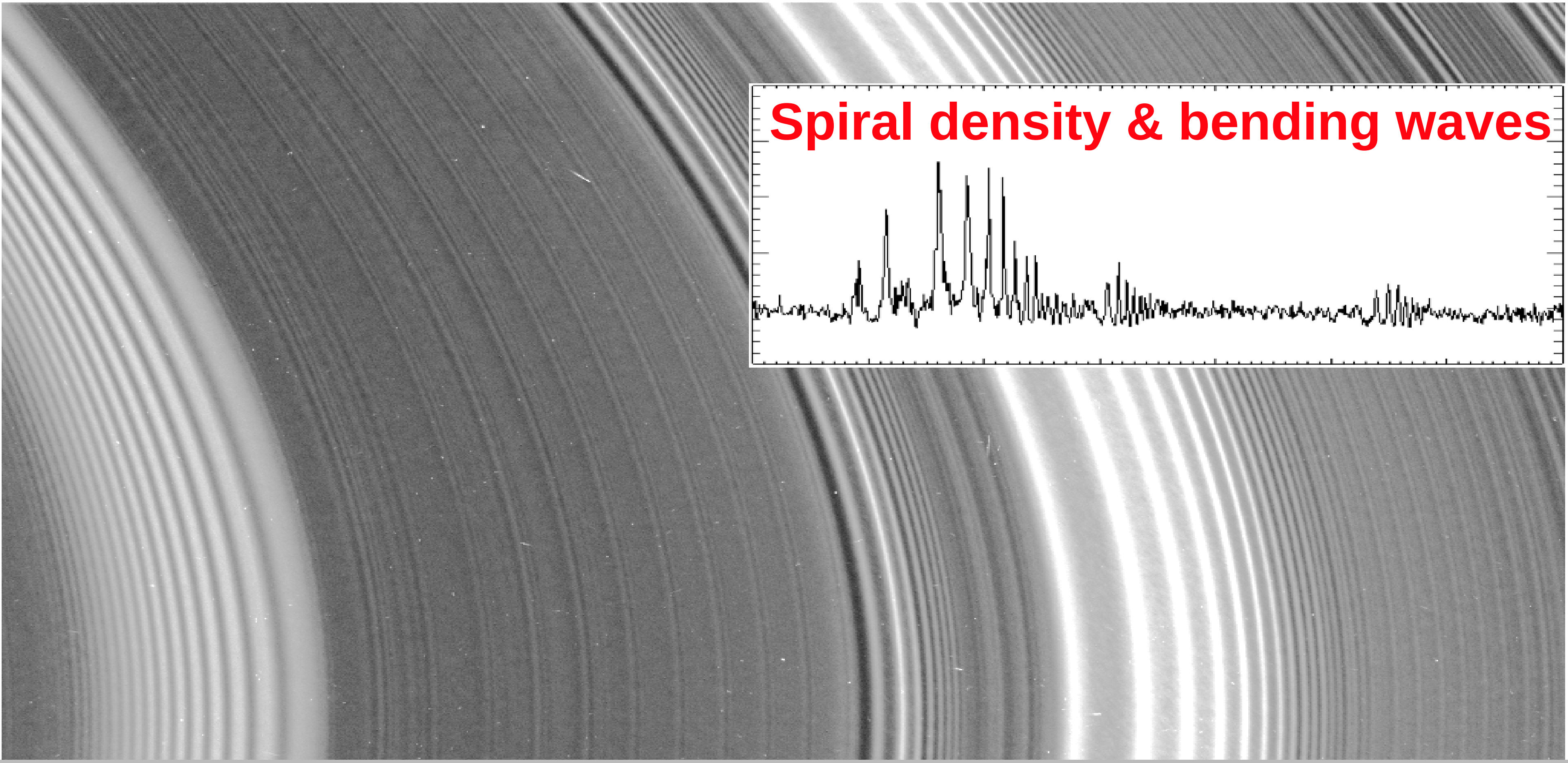


At orbit resonances, moons' tiny forces are amplified many times

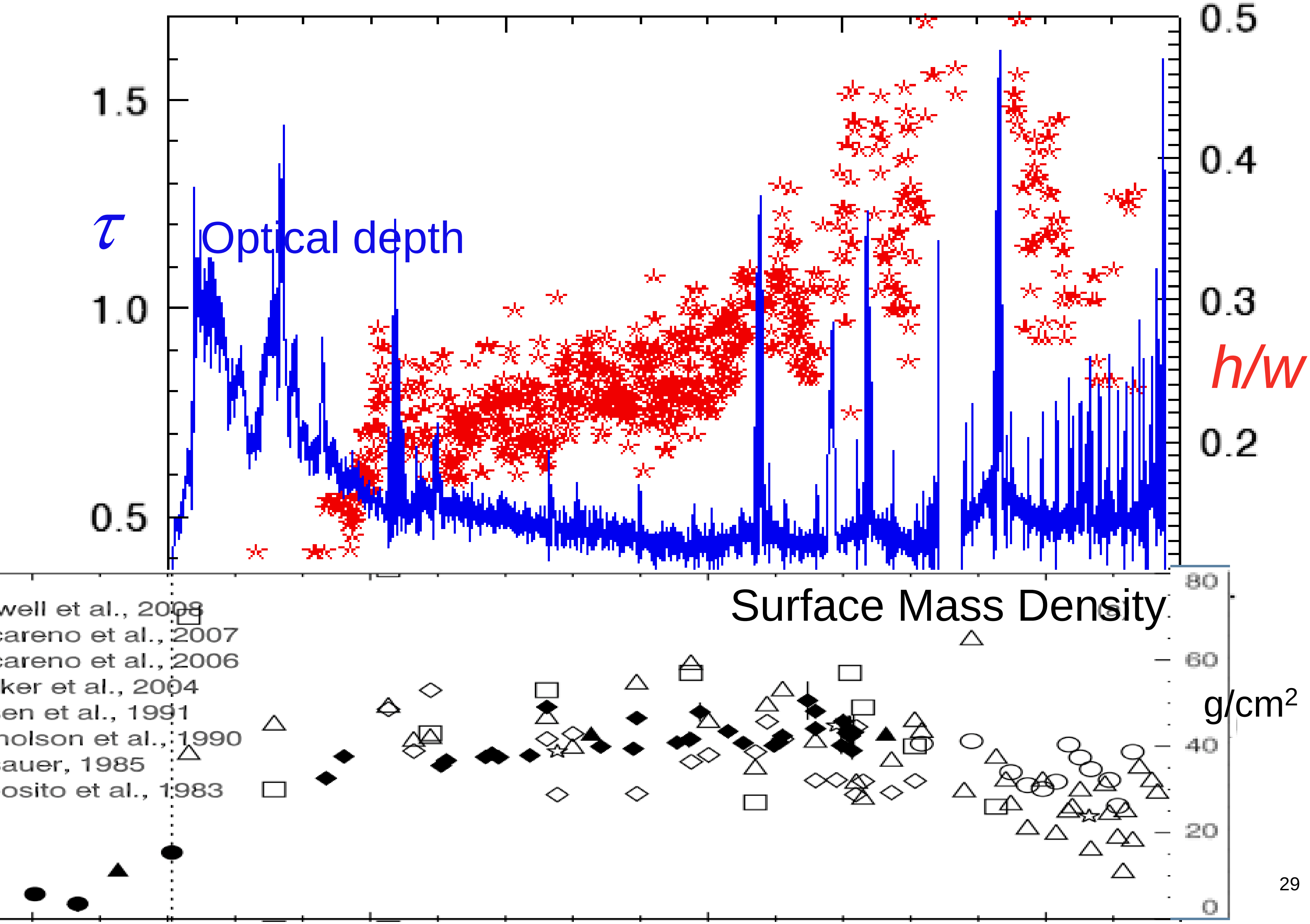


Ring self-gravity creates spiral pattern rotating with moon

Dynamic processes responsible for ring structure



Cassini UVIS, VIMS, and ISS data have observed 10x Voyager sample;
Wavelength and location: *ring surface mass density* (key for ring age)
Amplitude and damping: *moon's mass and* ring viscosity;
Showed that *all* ringmoons have densities ~ 0.5 g/cm^3: rubble piles


τ
Optical depth
h/w
Surface Mass Density
g/cm²
well et al., 2008
careno et al., 2007
careno et al., 2006
ker et al., 2004
en et al., 1991
holson et al., 1990
auer, 1985
osito et al., 1983
1.5
1.0
0.5
0.5
0.4
0.3
0.2
80
60
40
20
0

What is the mass of the rings?

Spiral density waves blanket the A ring, and have fair coverage in the C ring and Cassini Division; their masses are thus well known. However such waves are rare in the B ring, where most of the ring mass lies.

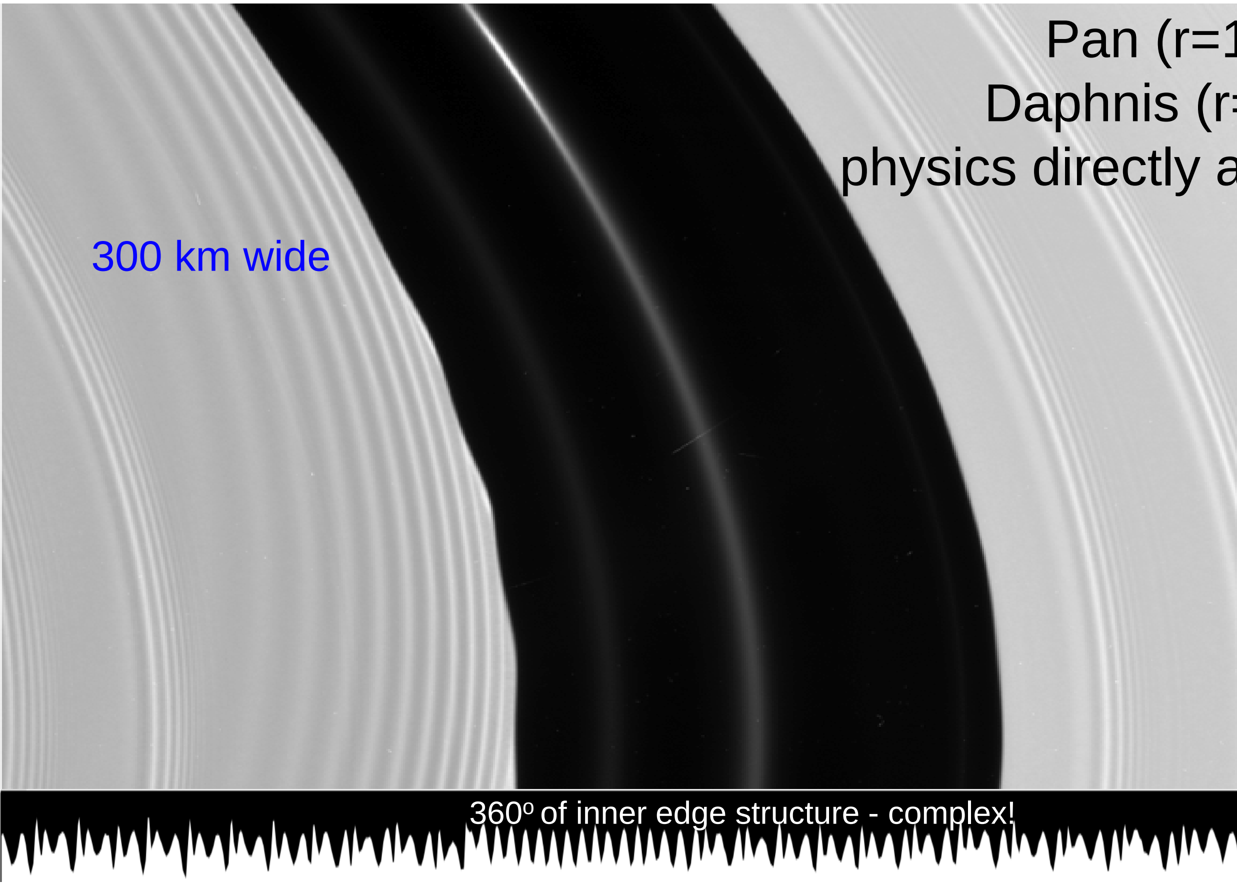
Models and observations suggest that the transparency of the B ring is dominated by a small fraction of nearly empty gaps between totally opaque clumps; thus the amount of material B ring might be far more than previously estimated.

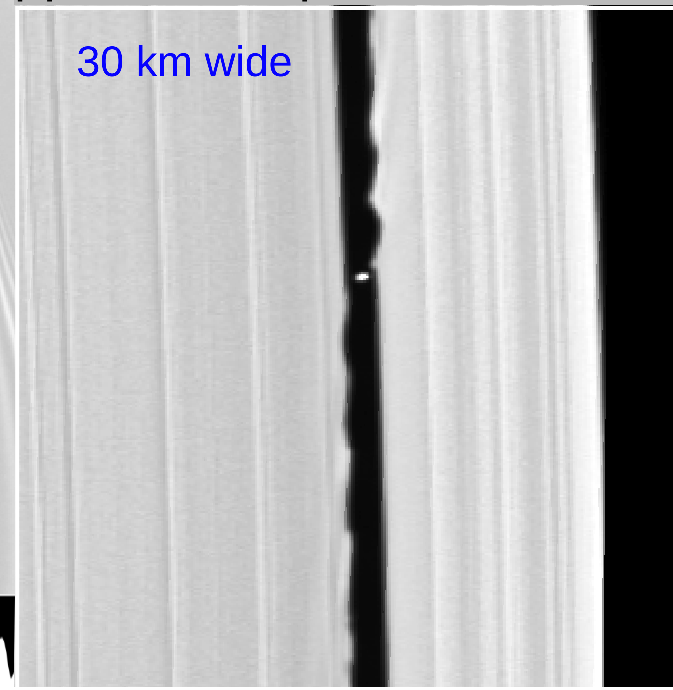
It has been argued that if the ring mass is much more than current estimates, and/or if the incoming meteoroid flux is much less than current estimates, then the rings might be as old as the solar system (*i.e.,* they could avoid becoming polluted by dark meteoroid material).

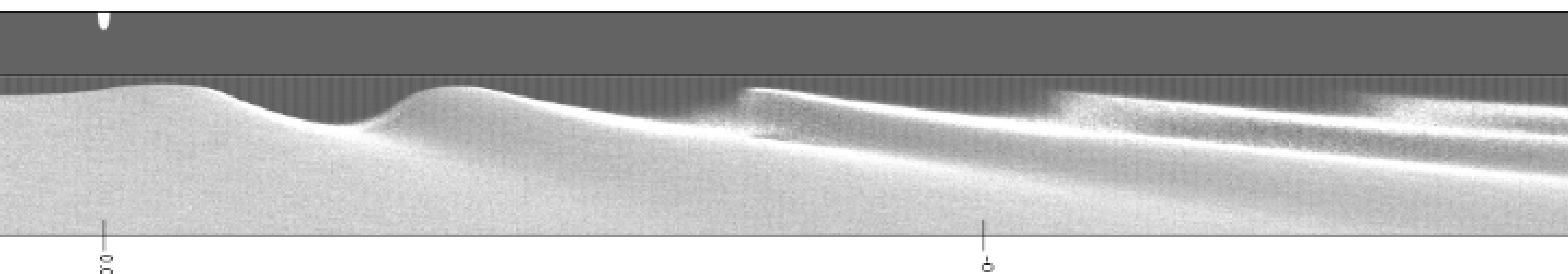
In the Extended Mission, Cassini will get one good measurement of the meteoroid flux. If we get a significant Extended-Extended mission, the end-of-life revs contain many close periapses which will allow the ring mass to be measured by their gravitational effects on the spacecraft

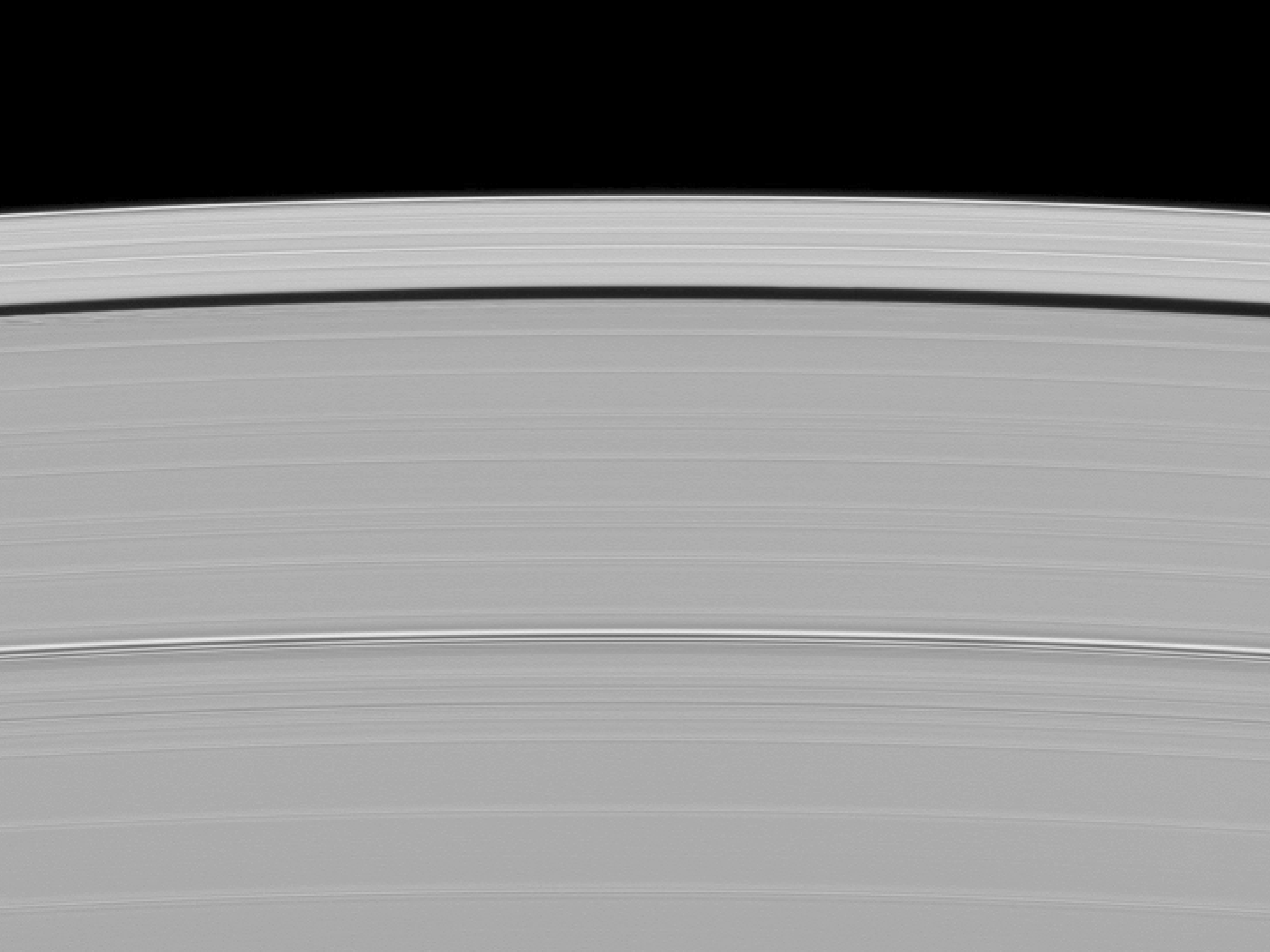
Inter-relationships of rings and satellites, including embedded satellites

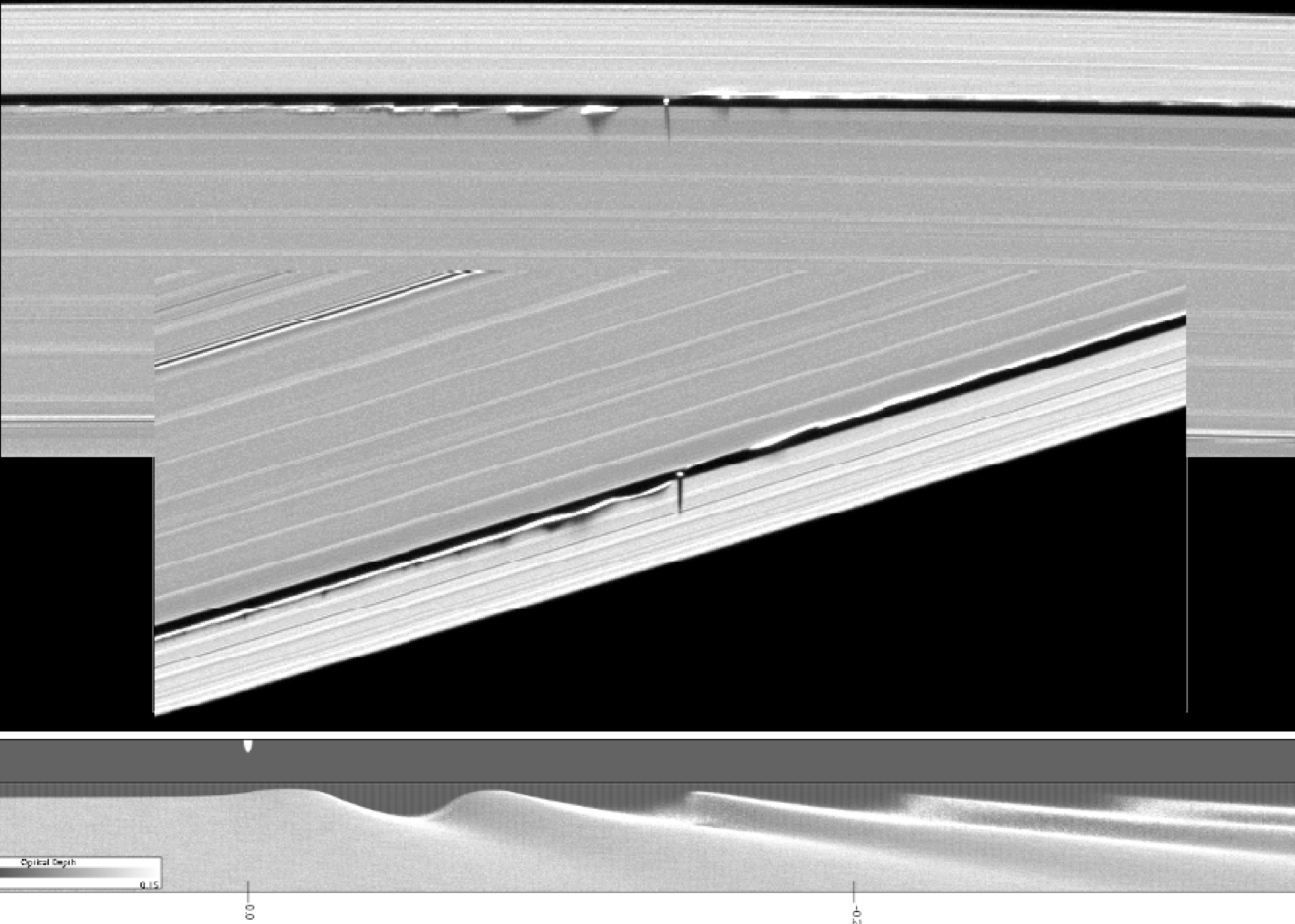
Pan (r=10km) in Encke gap,
Daphnis (r=3.5km) in Keeler gap;
physics directly applicable to planet formation





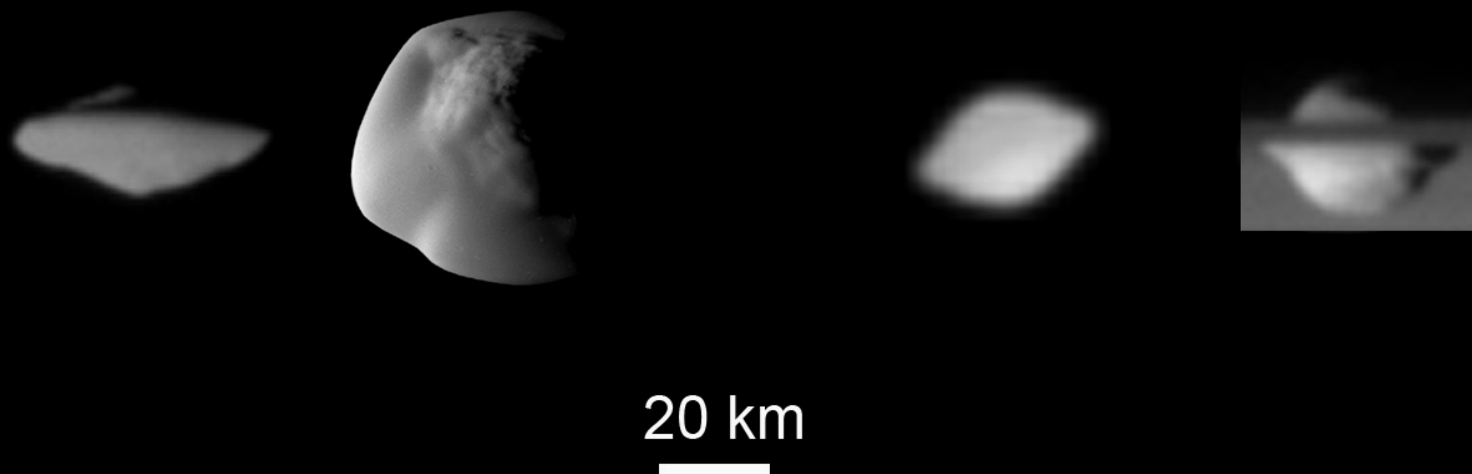


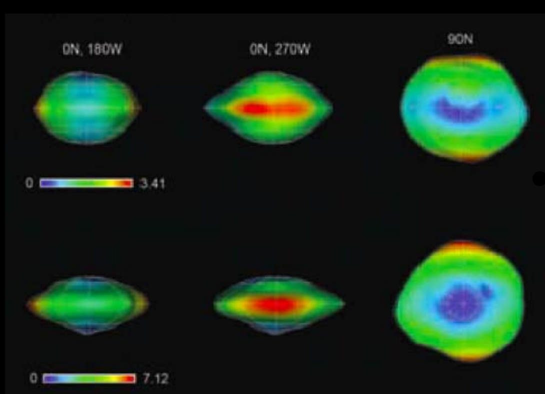


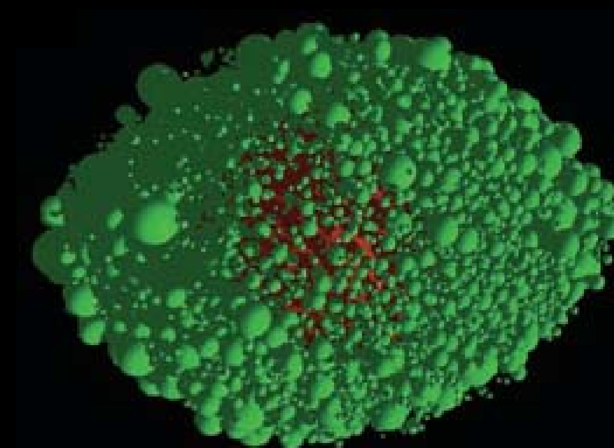


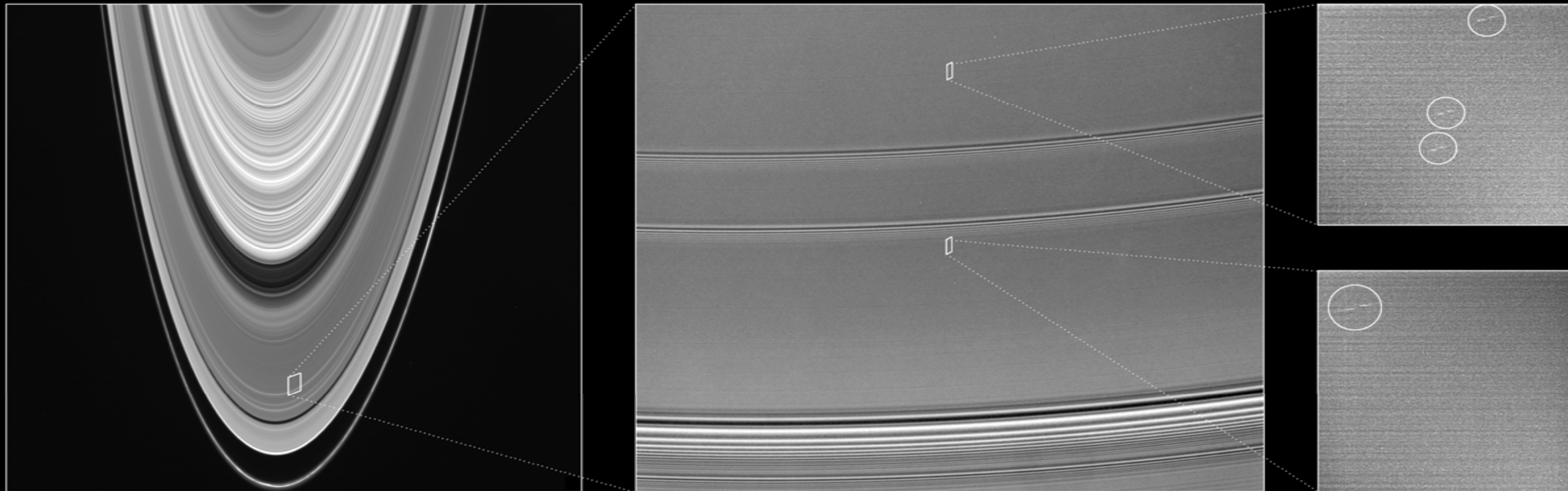
Optical Depth
0.15
0.0
-0.2

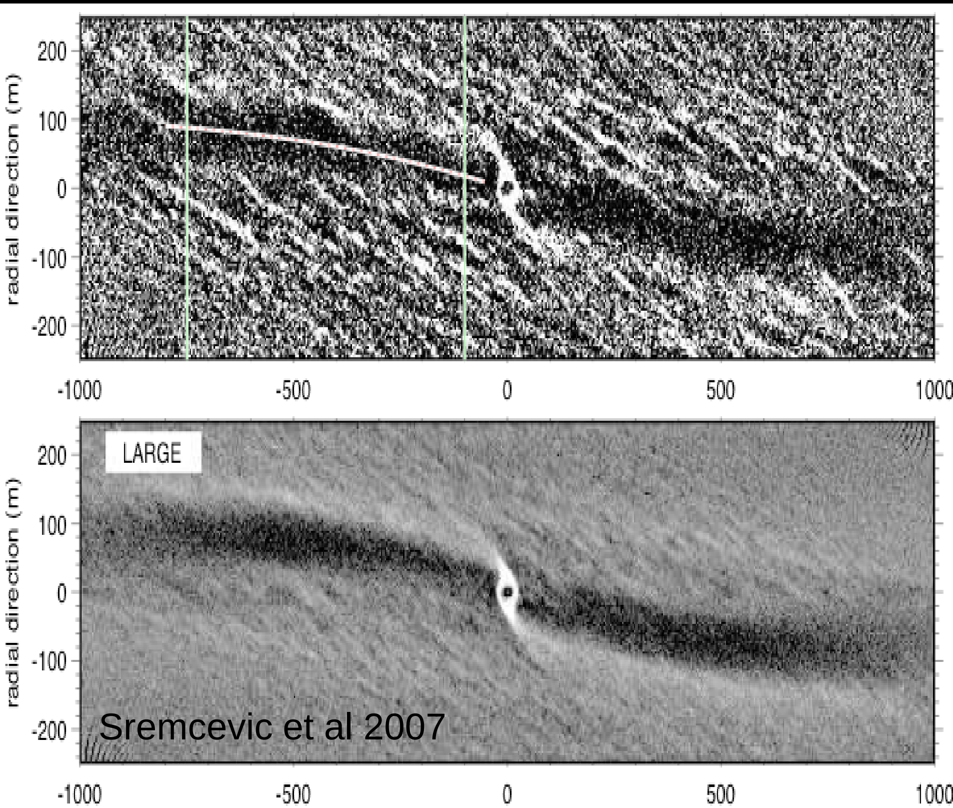
All ringmoons are underdense, filling their “Roche lobes”, and are probably accretion-limited rubble piles with dense central cores
(which might be of different composition)

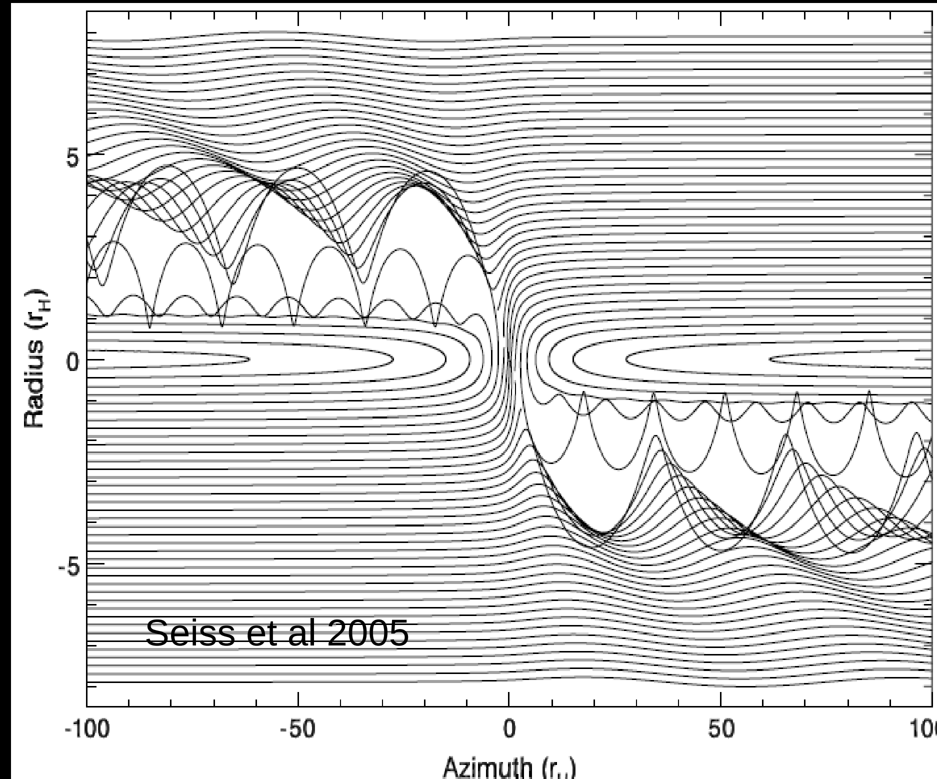


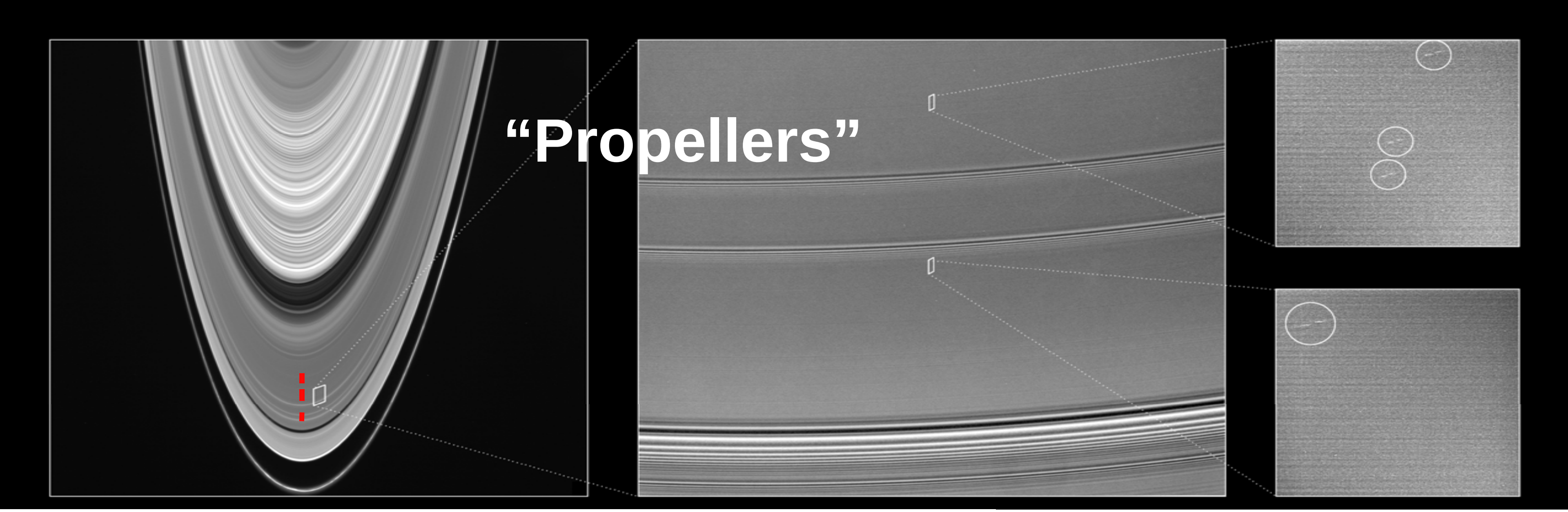


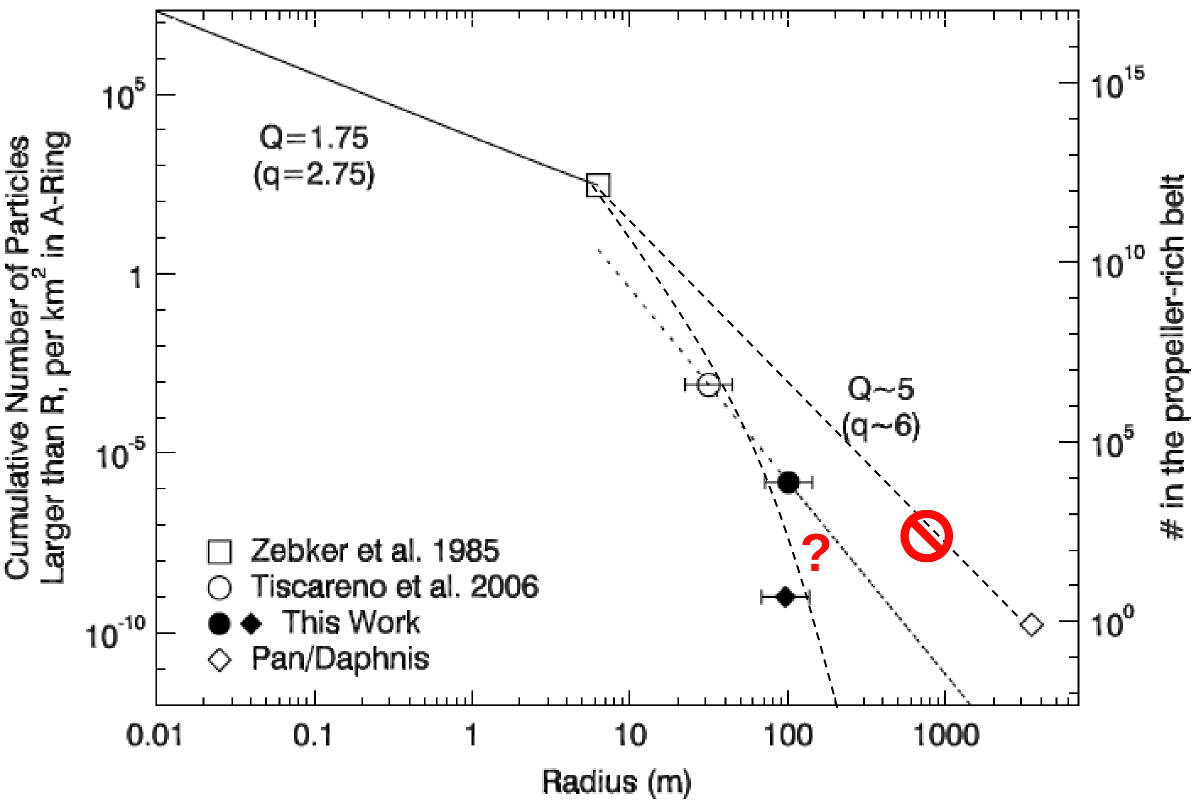





radial direction (m)
200
100
0
-100
-200
-1000
-500
0
500
1000
LARGE
radial direction (m)
Sremcevic et al 2007

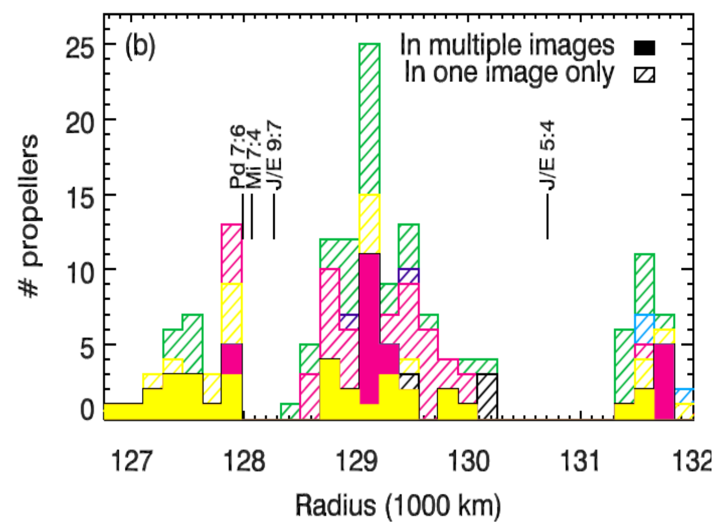

Radius (r_H)
5
0
-5
Seiss et al 2005
-100
-50
0
50
100
Azimuth (r_H)

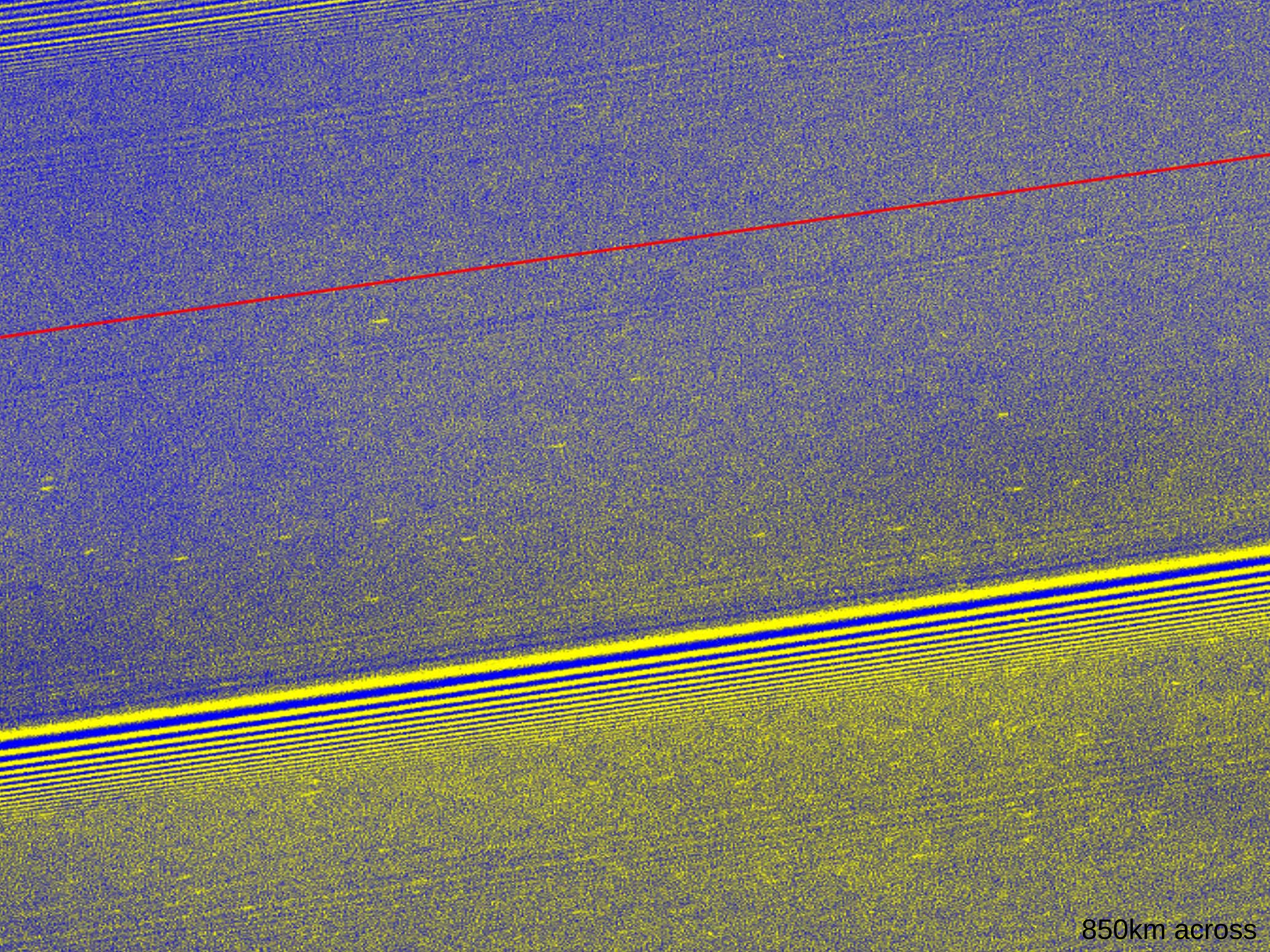




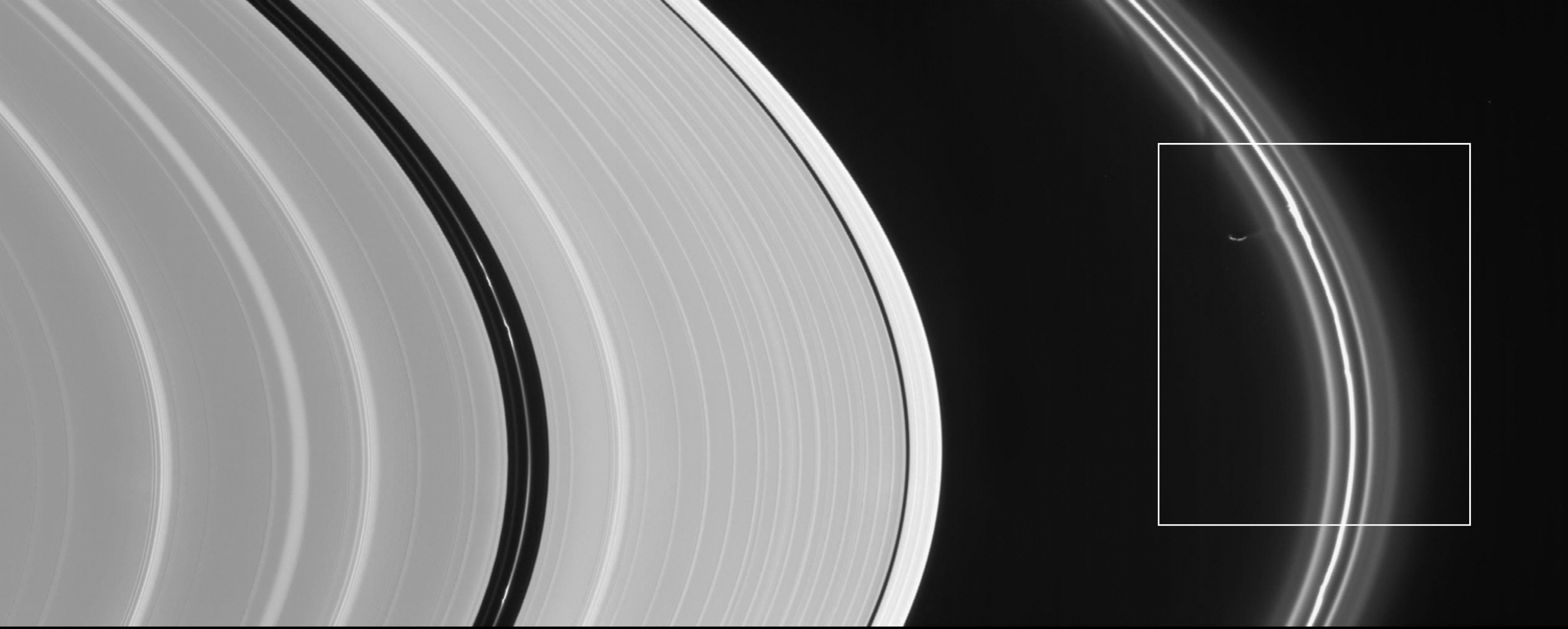
Sremcevic et al AJ 2007

- Tiscareno et al AJ 2007





850km across



Multiple strands;
Prometheus, Pandora,
and other new objects

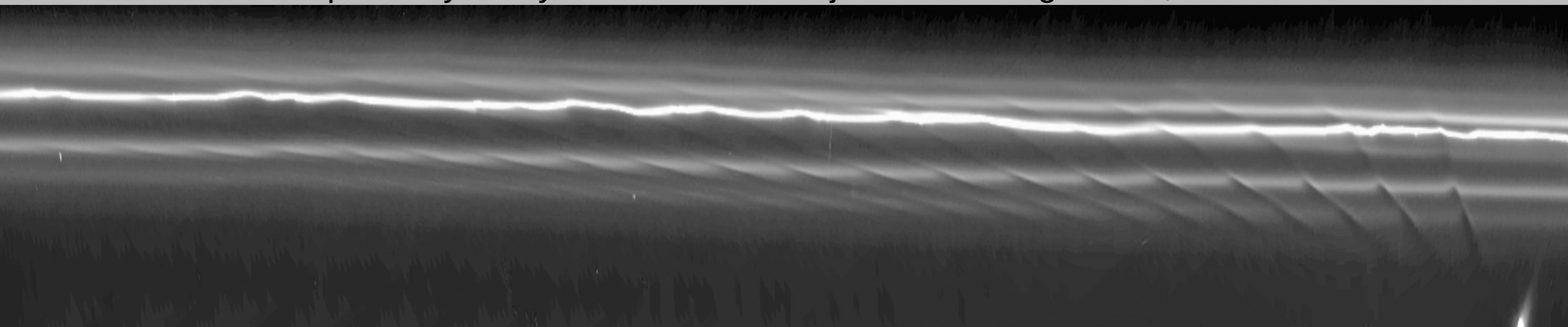
Outer A ring

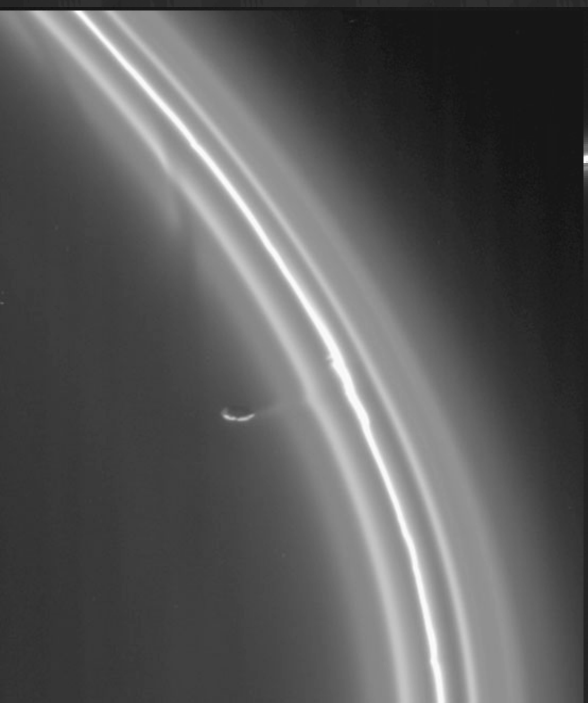
F ring

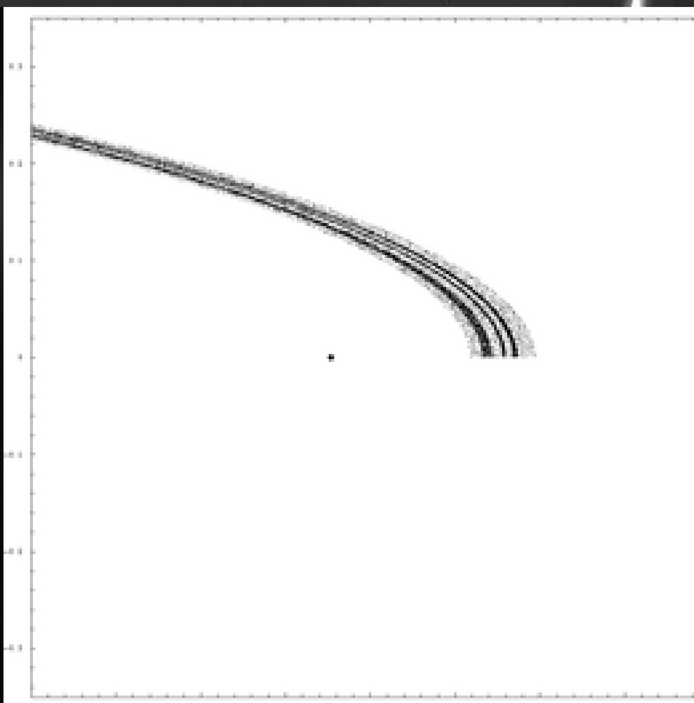
10,000km or 6000 miles

The F ring - a moonlet belt?

The stranded F ring has been a puzzle since Voyager. Cassini found that the number and location of the main strands changes on several month timescale, although the narrow “core” has remained constant. Gravitational effects of the nearby eccentric ringmoon Prometheus cause the channels and streamers. Both Prometheus and its companion “shepherd” Pandora are on chaotic orbits, and probably many other sizeable objects in the region are, as well.



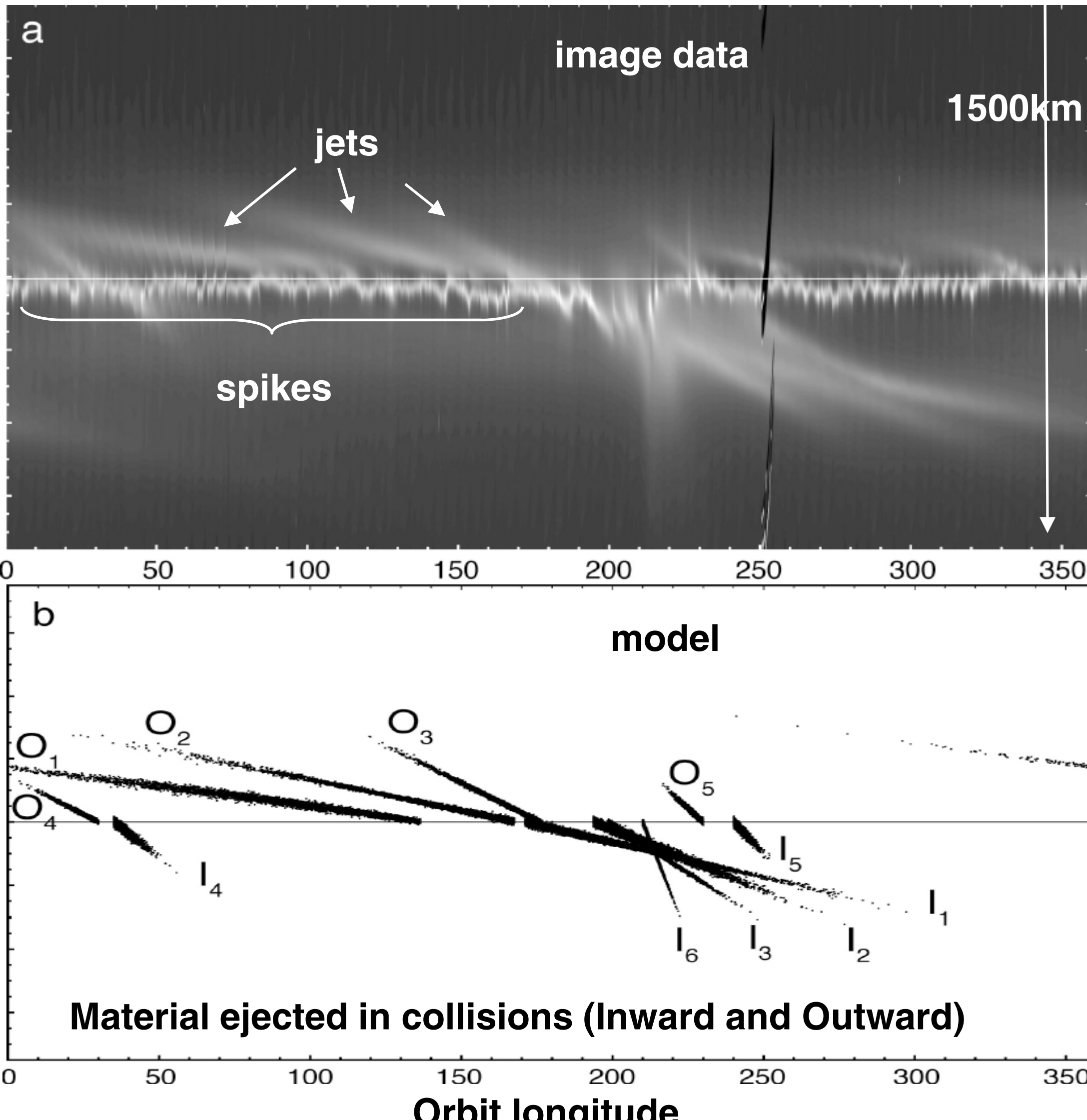




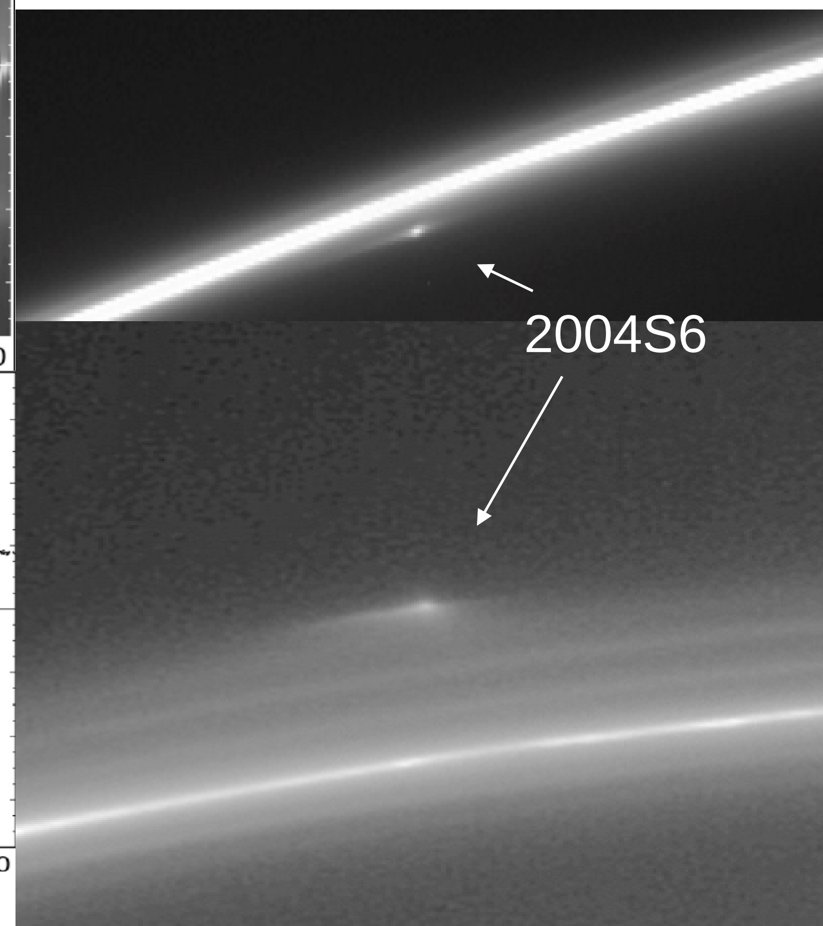
F region contains numerous km-size moonlets, which get excited by Prometheus and Pandora, and then disturb the ring strands,

AND

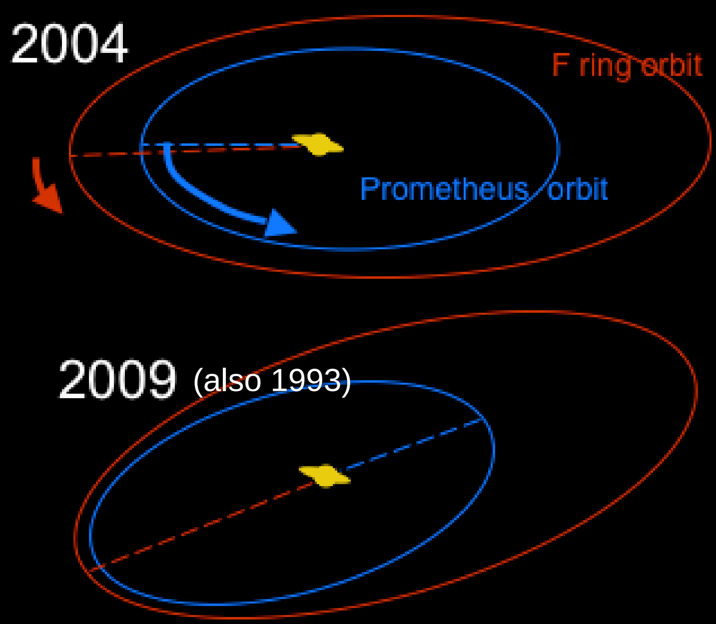
Fewer objects on more dramatically crossing orbits, few of which have been detected

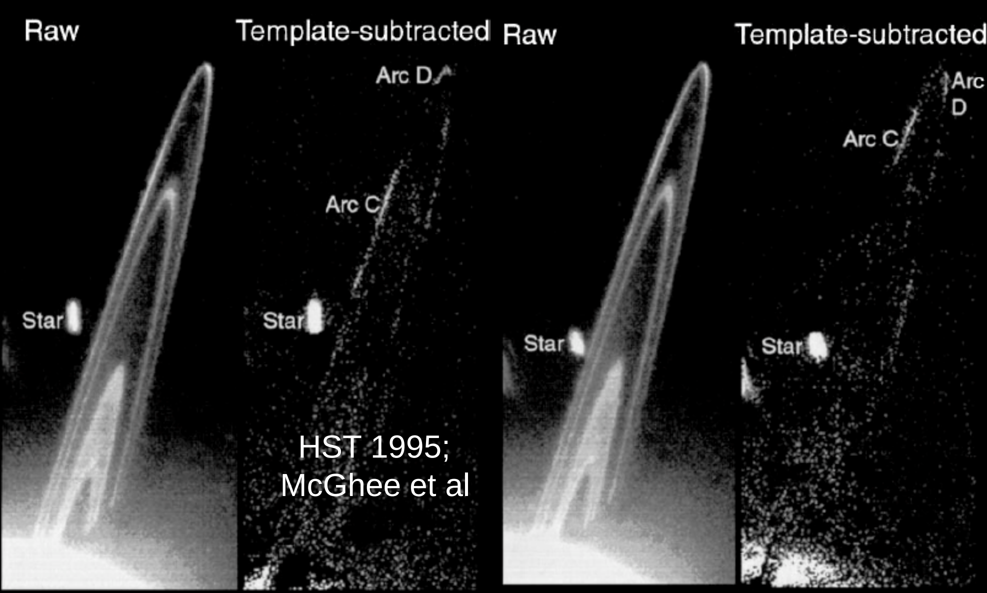


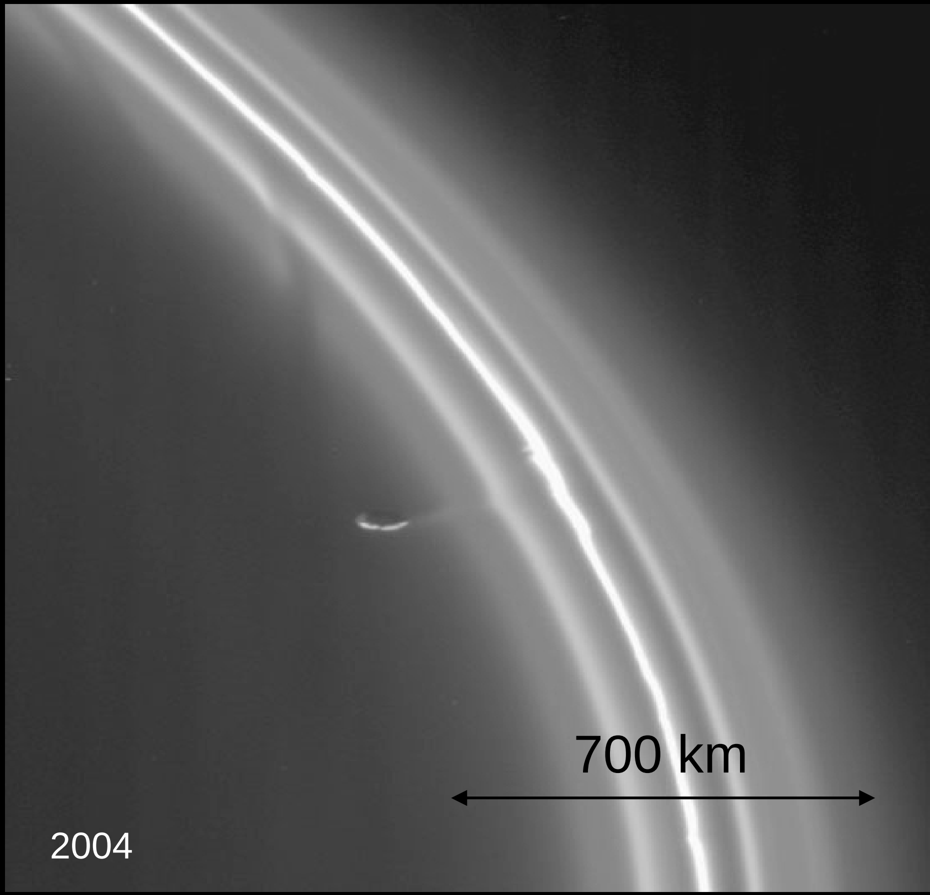
2004S6 has an eccentric orbit that crosses the F ring, leading to collisions

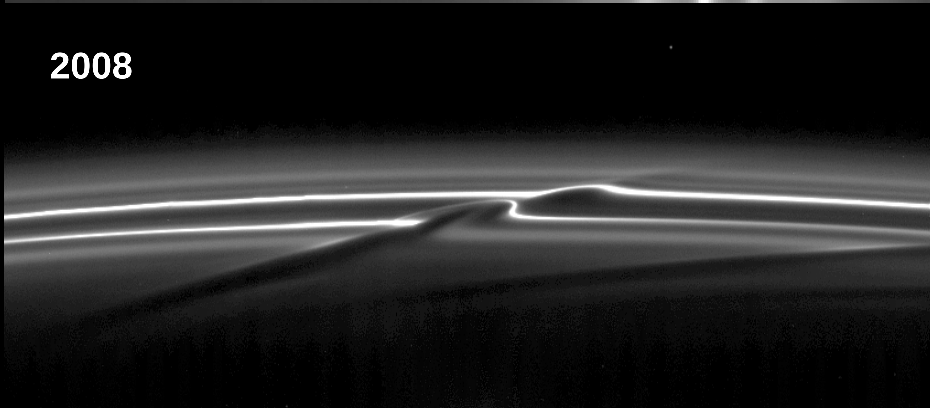


Prometheus: “Nemesis” of the F ring? Need a few more years to tell..

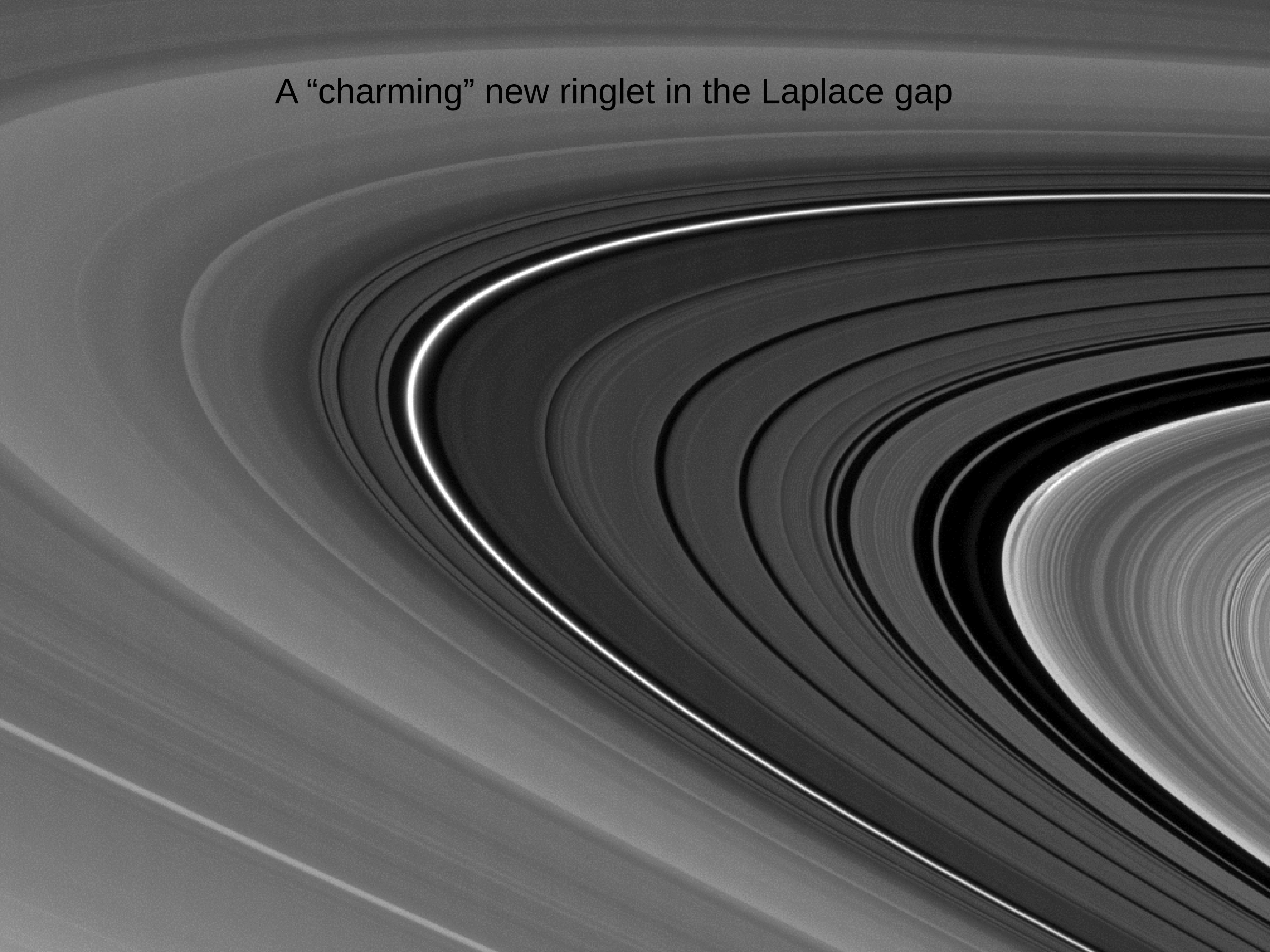








A “charming” new ringlet in the Laplace gap



Inter-relationships of rings and satellites, including embedded satellites

Major results:

Cassini discovered one new embedded ringmoon and conducted sensitive searches for others, finding none. The lack of obvious embedded moons in all C ring and Cassini Division gaps is a puzzle.

All of the embedded and nearby surrounding ringmoons have low density and a ellipsoidal shape that fills their Roche zone, suggesting they have grown from a dense central shard by accreting incoming material.

Cassini discovered a unique population of sub-km size objects, localized to three belts in the central A ring. It is not yet known if this population represents primordial shards or has grown in place.

The F ring complex is a chaotically interacting environment containing numerous km-size objects as well as the known F ring strands and “shepherd moons”, in which collisions are frequent.

New “charming” ringlet has appeared since Voyager

Determine the dust and meteoroid distribution

A key objective remains to be achieved:

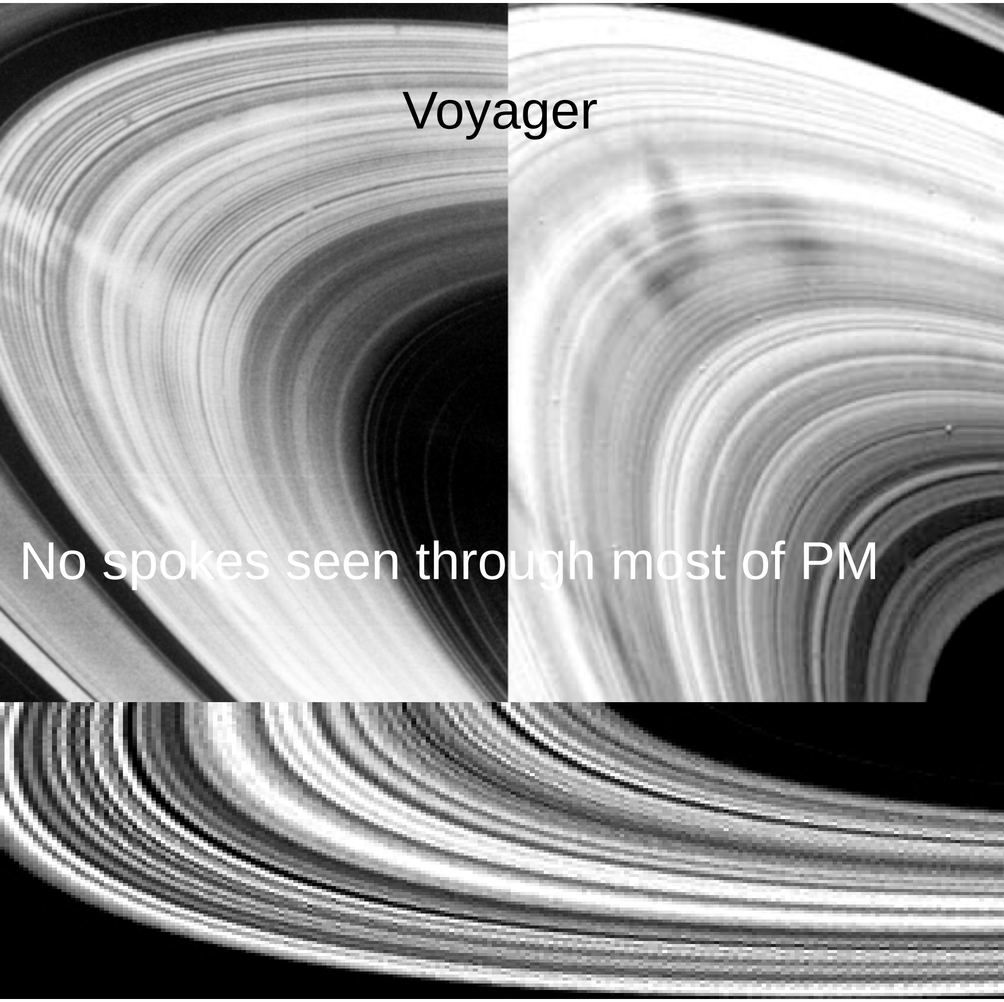
1) Spacecraft orientation restrictions precluded measurement of interplanetary flux during cruise, and while in tour, flux is dominated by Saturn-system material (E ring, *etc.*)

2) Novel planned observations to measure the UV flux from impacts of 10cm - m size objects onto the rings were withdrawn after models showed that impact plume photospheres were too cool for UVIS detection

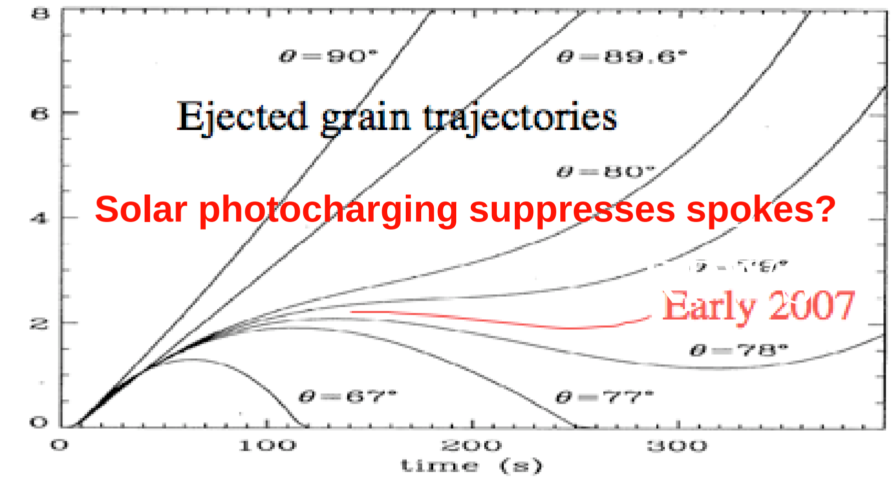
3) Unique plasma-wave “tones” seen by RPWS during SOI might be due to impacts, but there is as yet no theory connecting impacts to observations

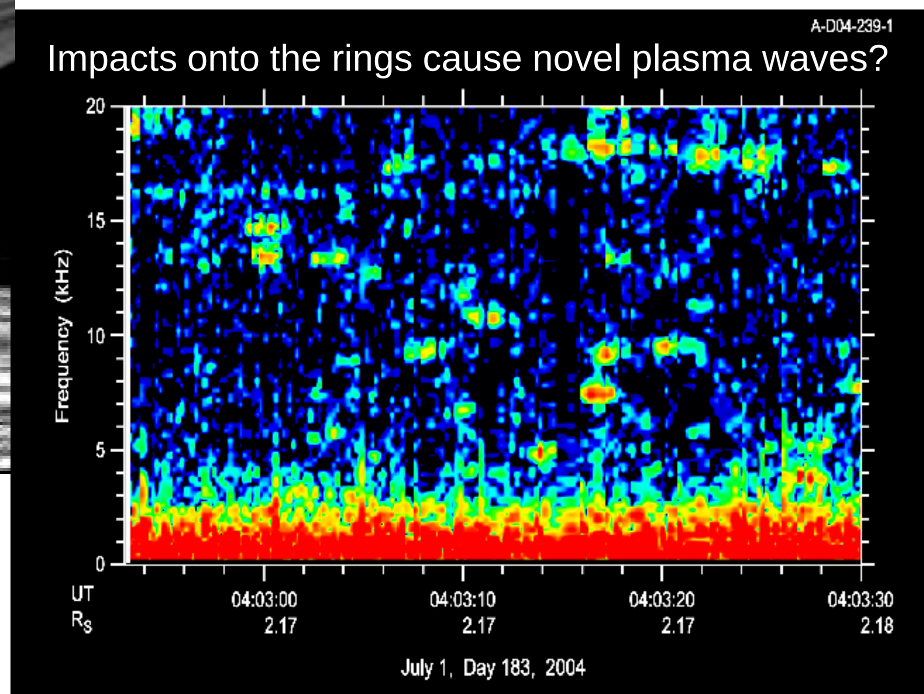
However, we are making plans to use an indirect measurement technique during XM (and XXM) like used by GLL in Jupiter system (measuring close-in dust halo of inactive icy moons). Single Tethys flyby to date is of little use (poor S/C orientation, E ring contamination)

Ring-magnetosphere, -ionosphere, and -atmosphere interactions

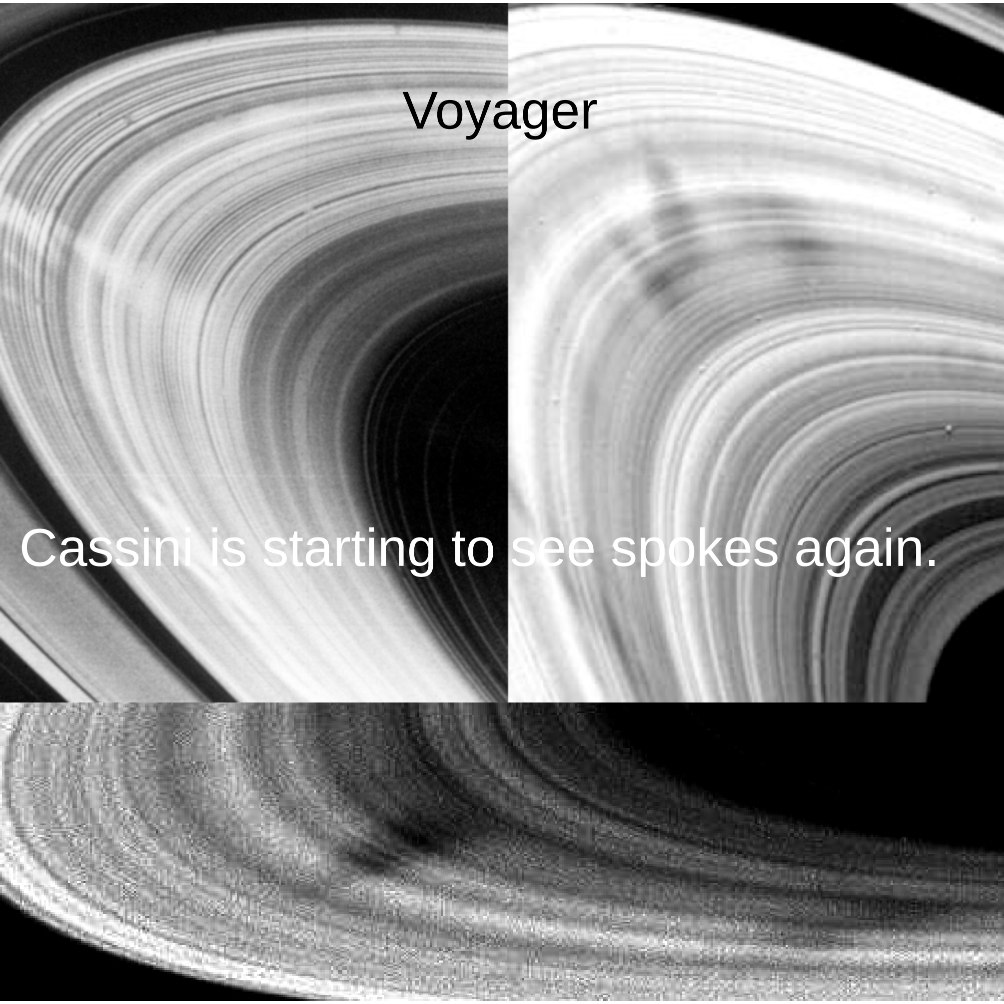


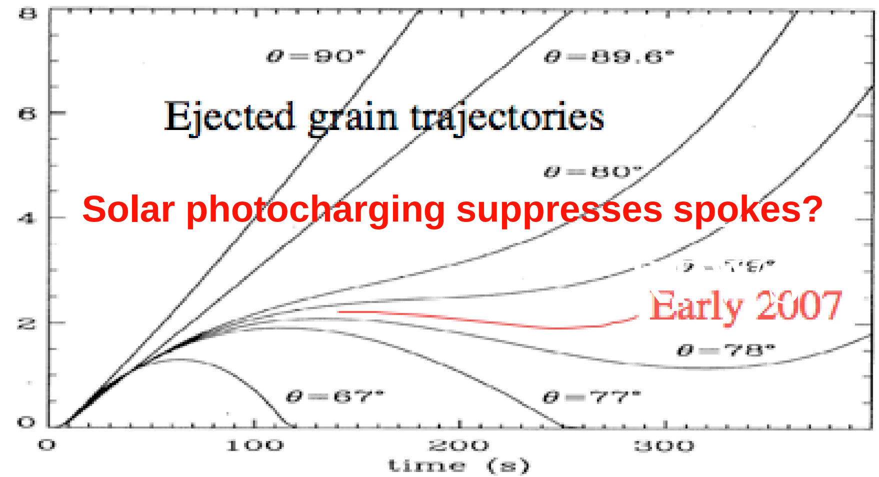
New type of electromagnetic (Lorentz) resonance seen in D, A-F regions might help constrain slipping SKR period





Ring-magnetosphere, -ionosphere, and -atmosphere interactions





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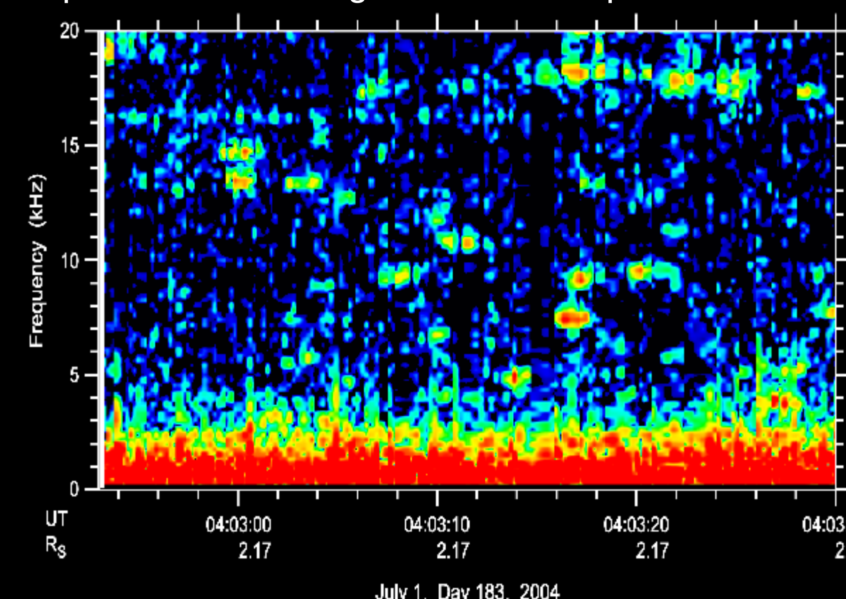
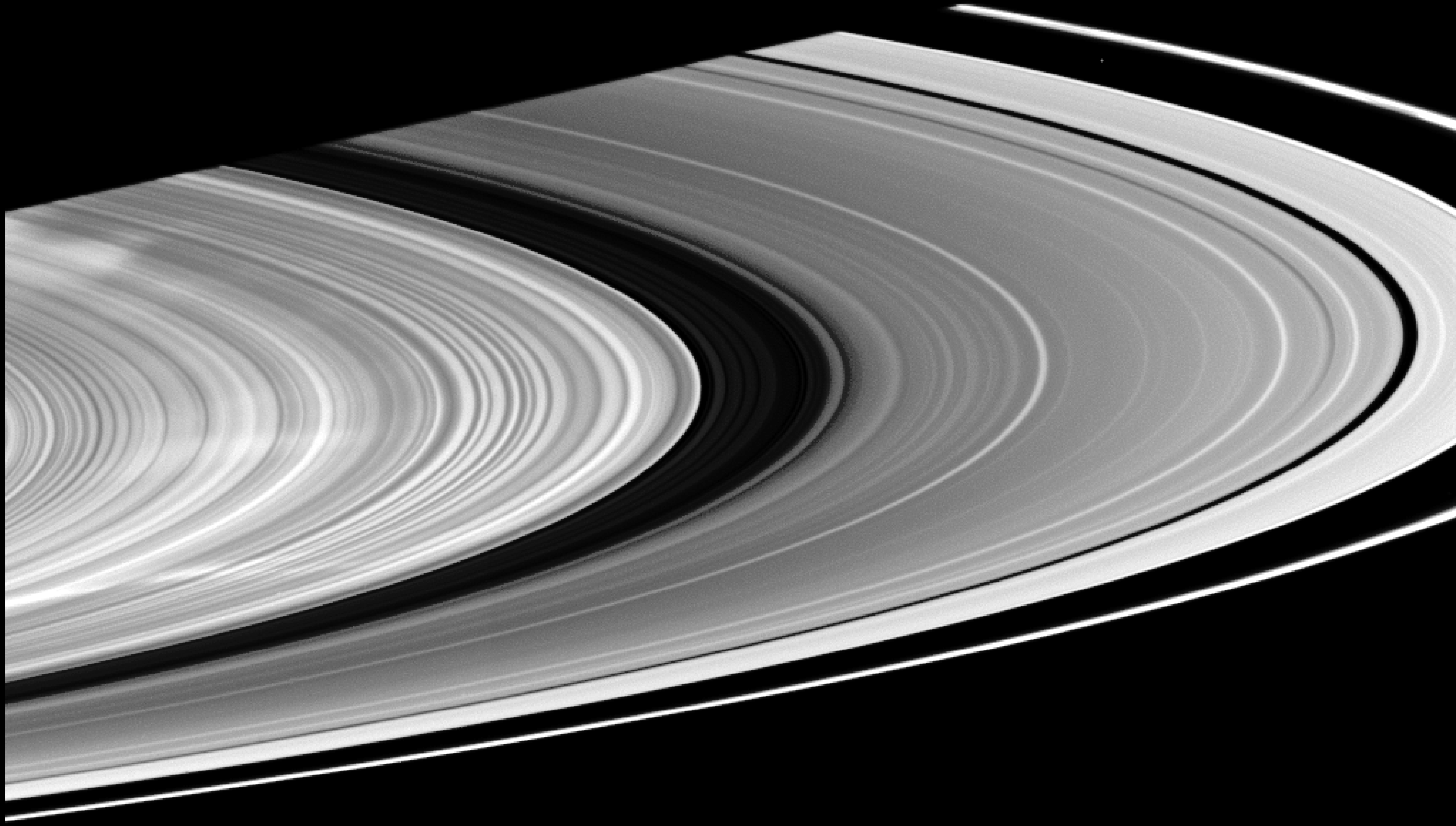
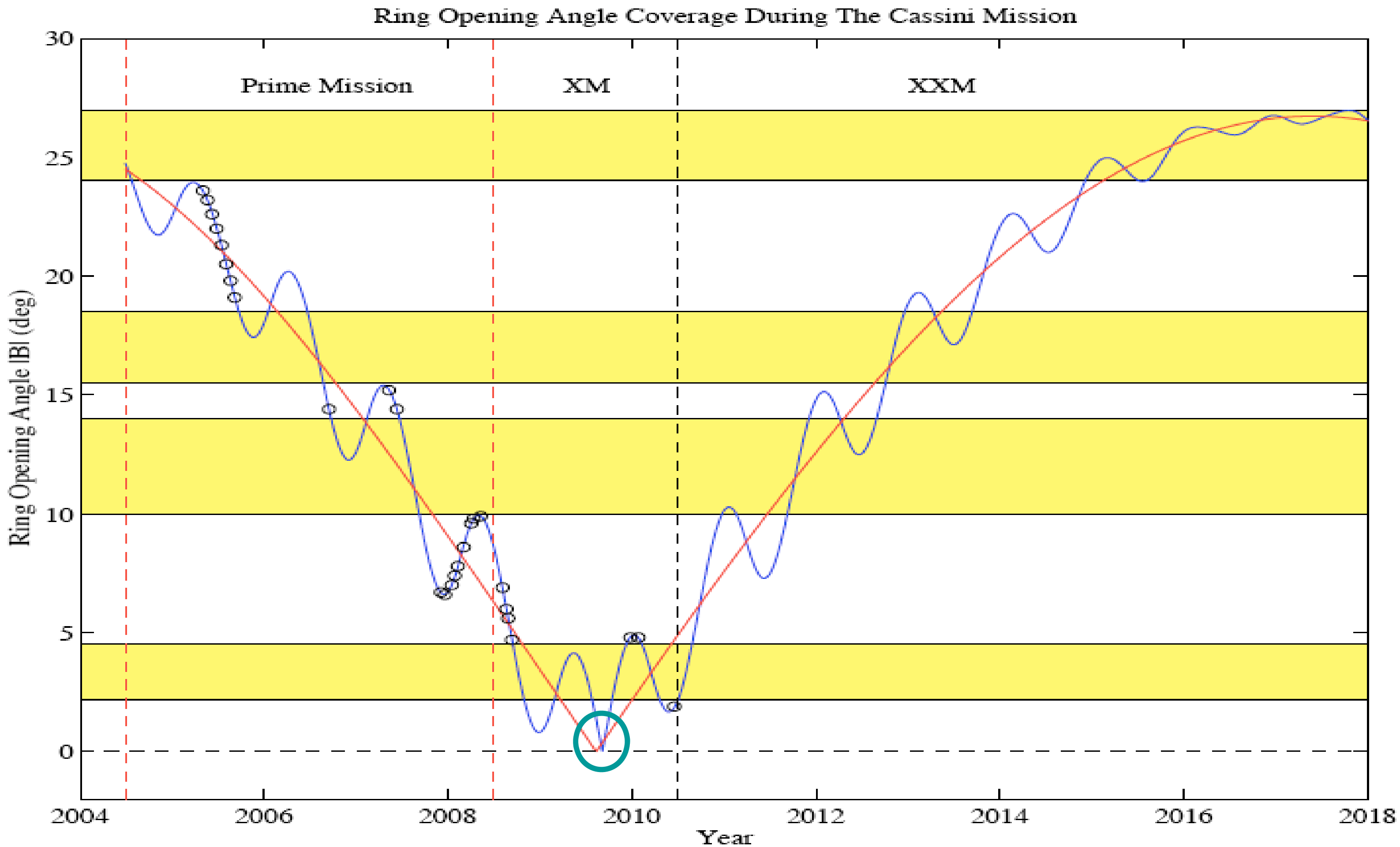
Impacts onto the rings cause novel plasma waves?



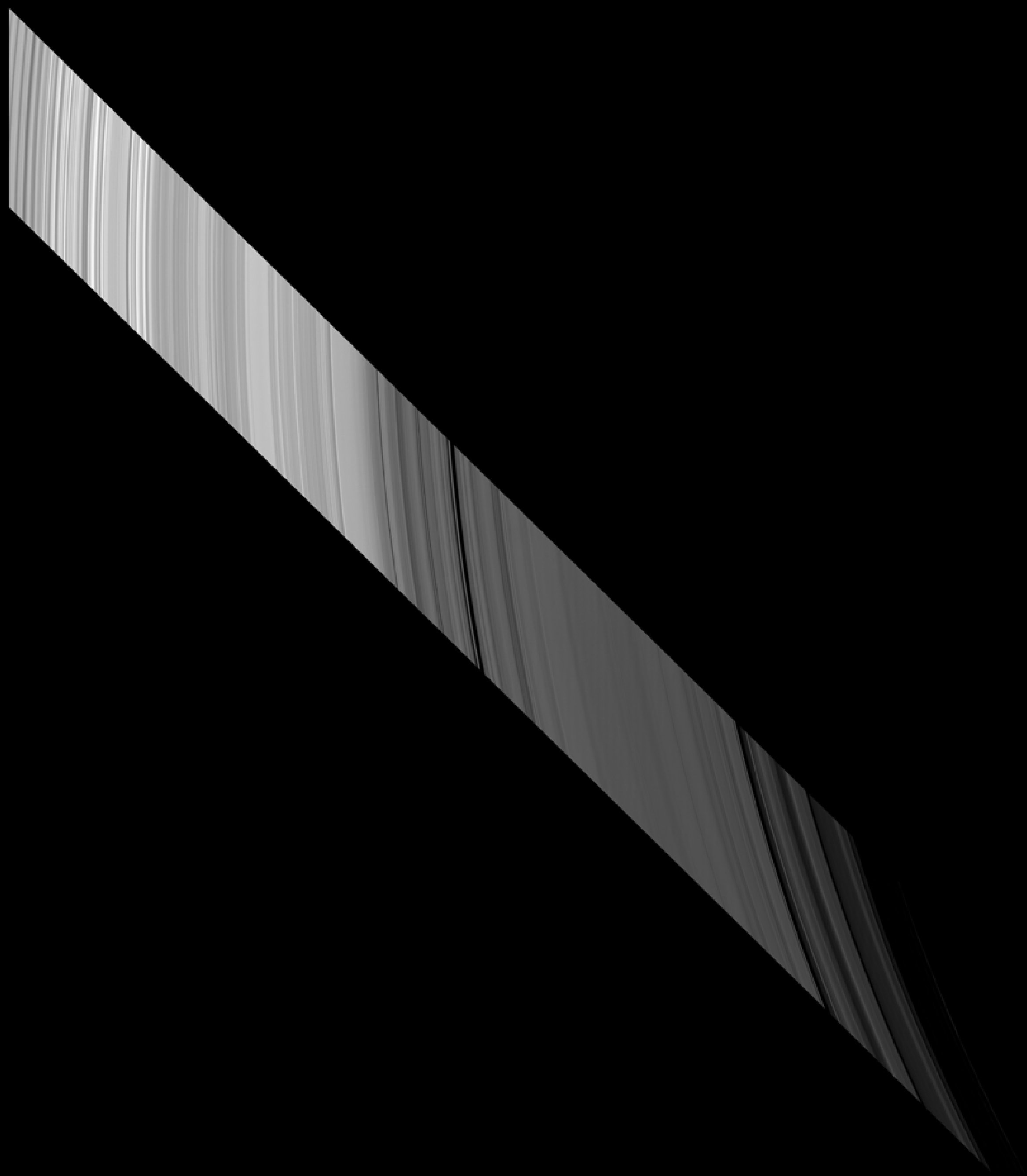
New type of electromagnetic (Lorentz) resonance seen in D, A-F regions might help constrain slipping SKR period



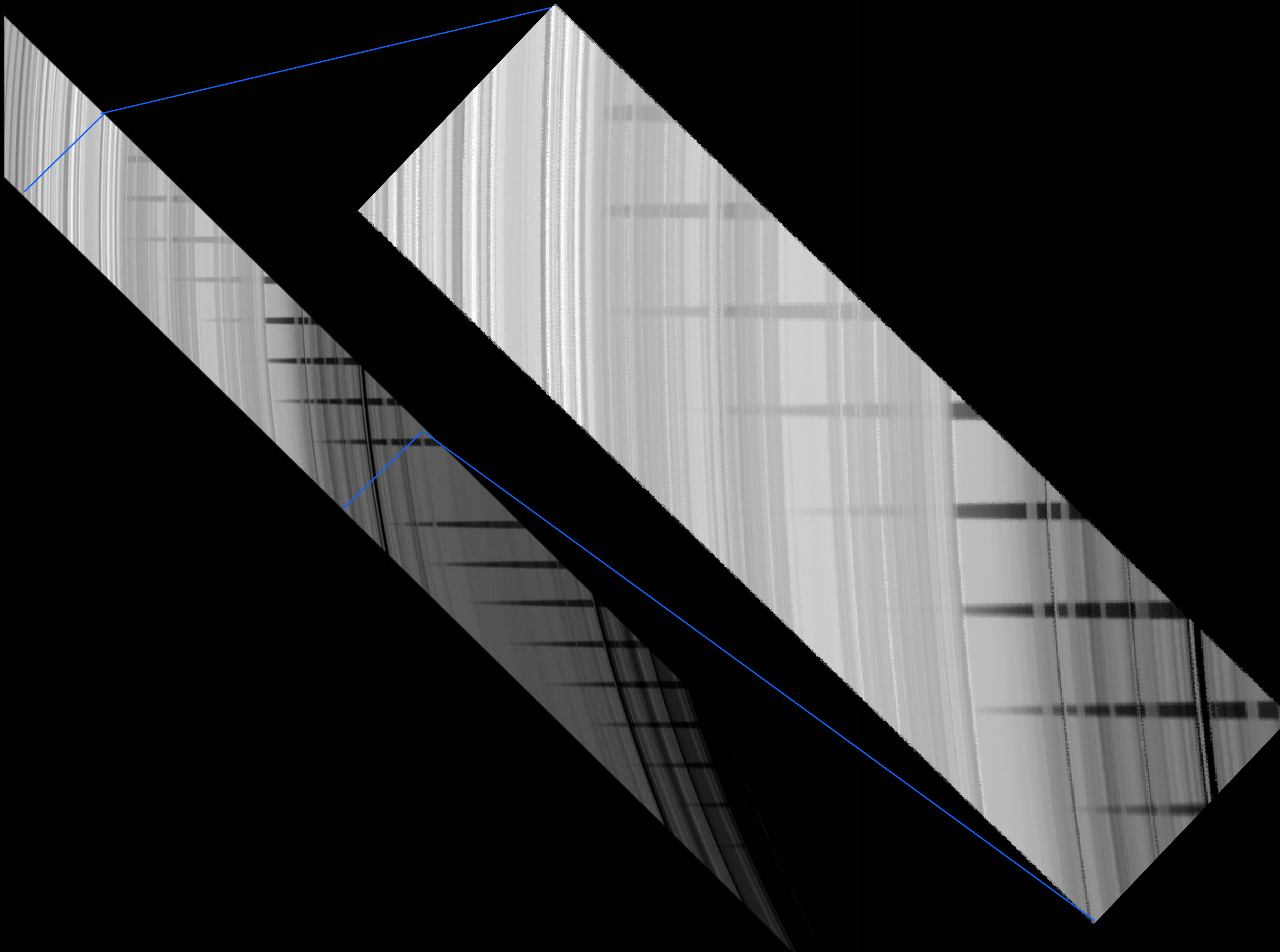
Equinox observations



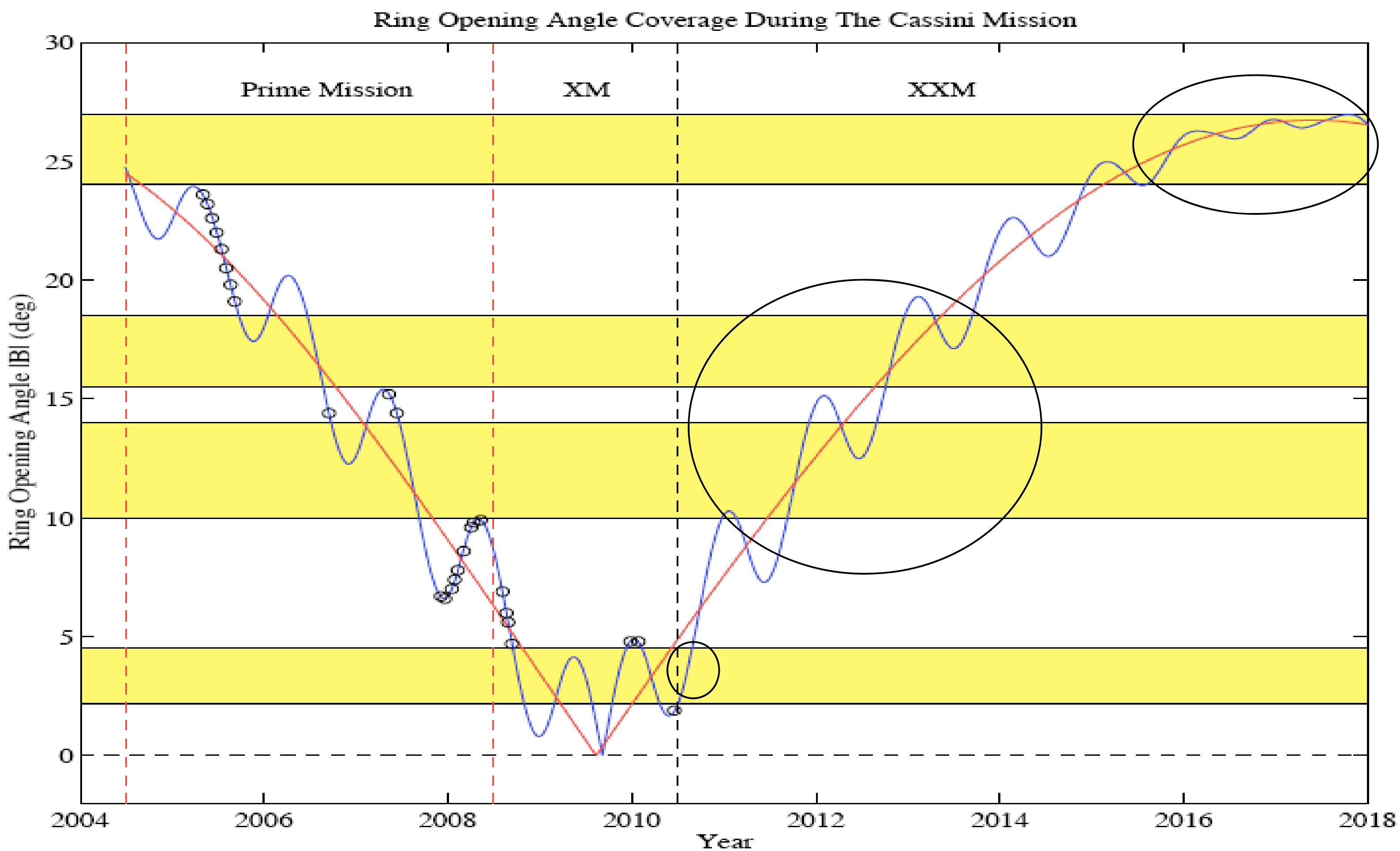
Opening angle affects insolation, ring temperature, RSS transmission, spoke occurrence frequency, diffuse ring structure



ISS Team Movie: Shadow of Mimas moving across the unlit face of the rings



Seasonal change in the rings: a look ahead



Opening angle affects insolation, ring temperature, RSS transmission, spoke occurrence frequency, diffuse ring structure

Summary

Overall, the rings are surprisingly dynamic and time-variable, changing in appearance as we watch. Features come and go on timescale of weeks and months, as well as decades.

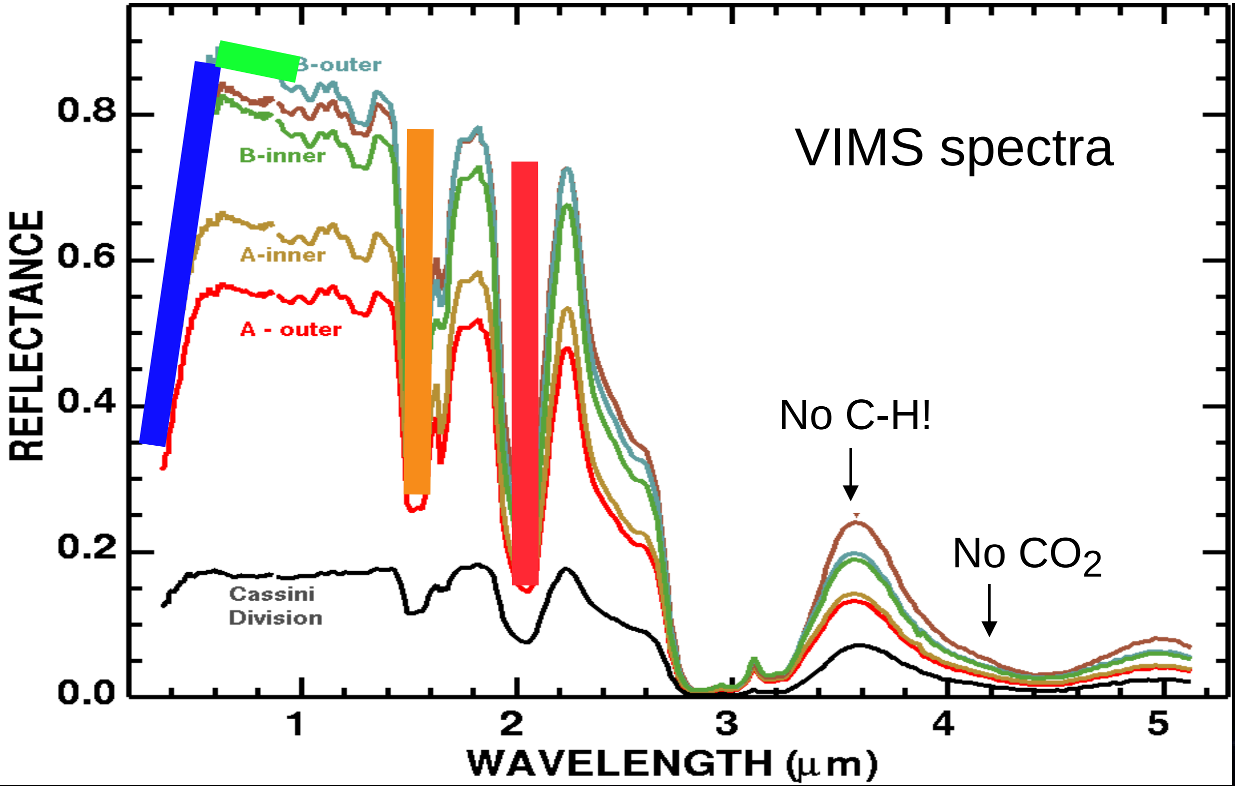
Ring composition is our best clue to ring origin; however, evidence and theory suggests ring composition has evolved with time. Recently emerging challenge to traditional interpretation of “redness” as organics. Need a better measurement of meteoroid flux to determine ring age.

Several known types of ring structure now very well understood; several new types of structure have verified predictions; several unexpected types also observed. Most ring radial structure remains unexplained theoretically.

Embedded and nearly moonlets now well observed; apparent chaotic region surrounding F ring; puzzling lack of moonlets in several gaps

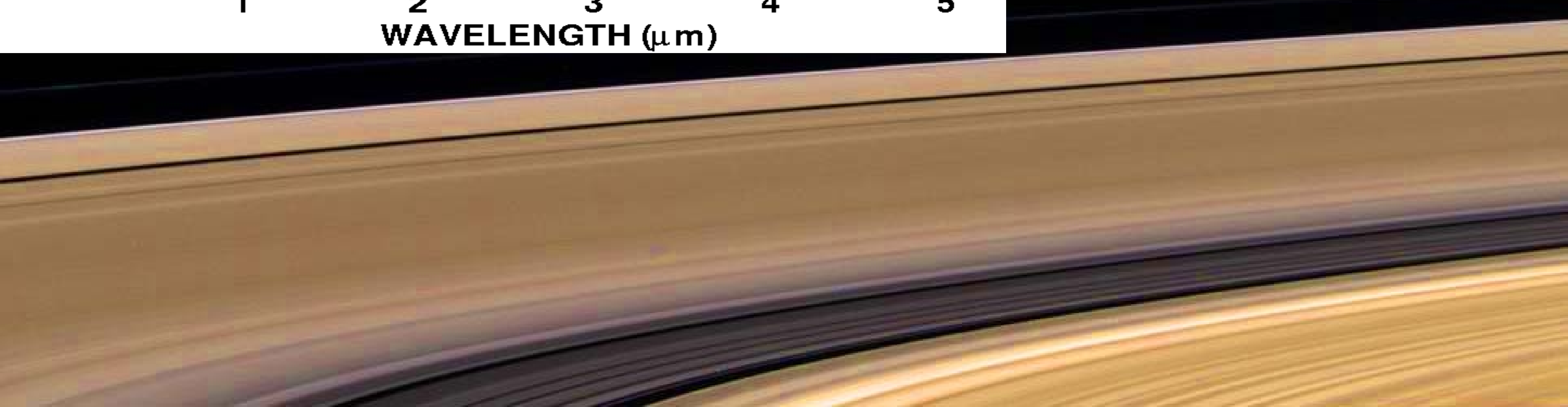
Backup

Chemical composition and size distribution of ring material

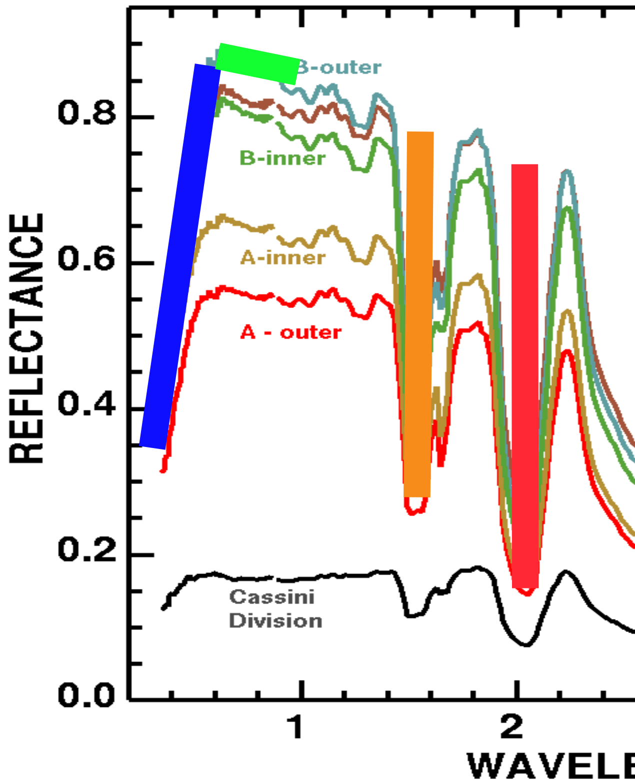


Pre-Cassini we had only one ring spectrum; now have thousands

In particular, what material causes this “redness” at short visual wavelengths?



Chemical composition and size distribution of ring material



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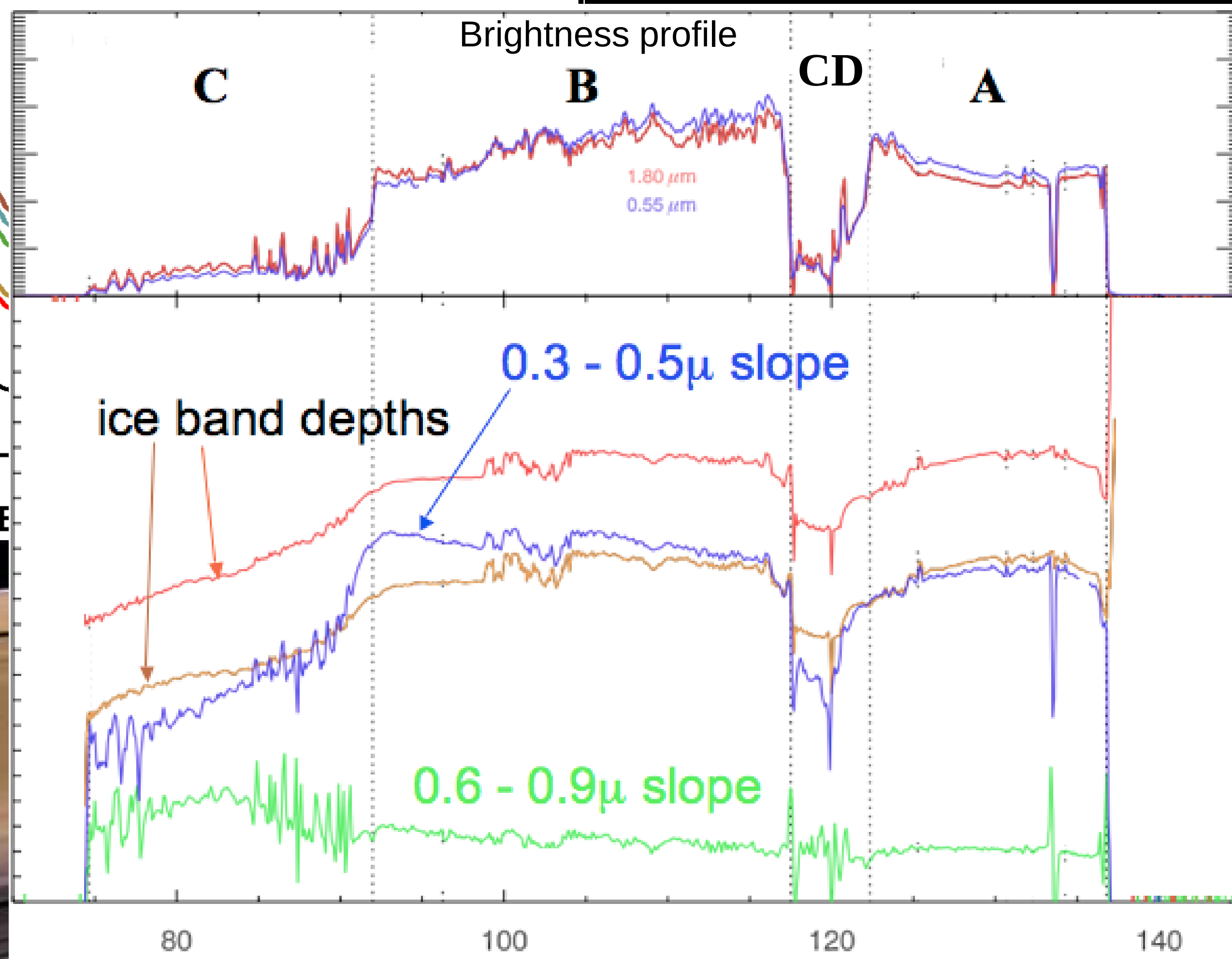
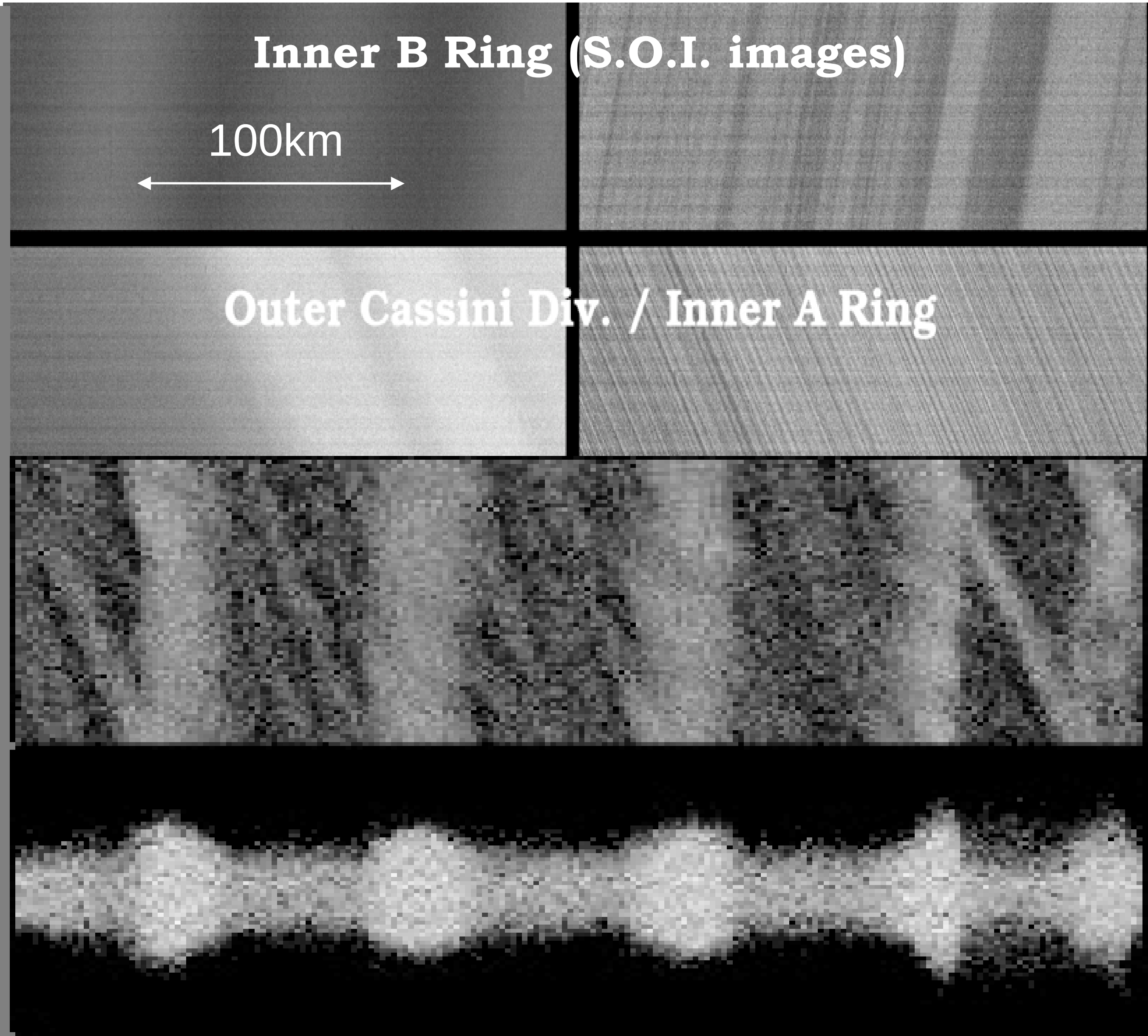


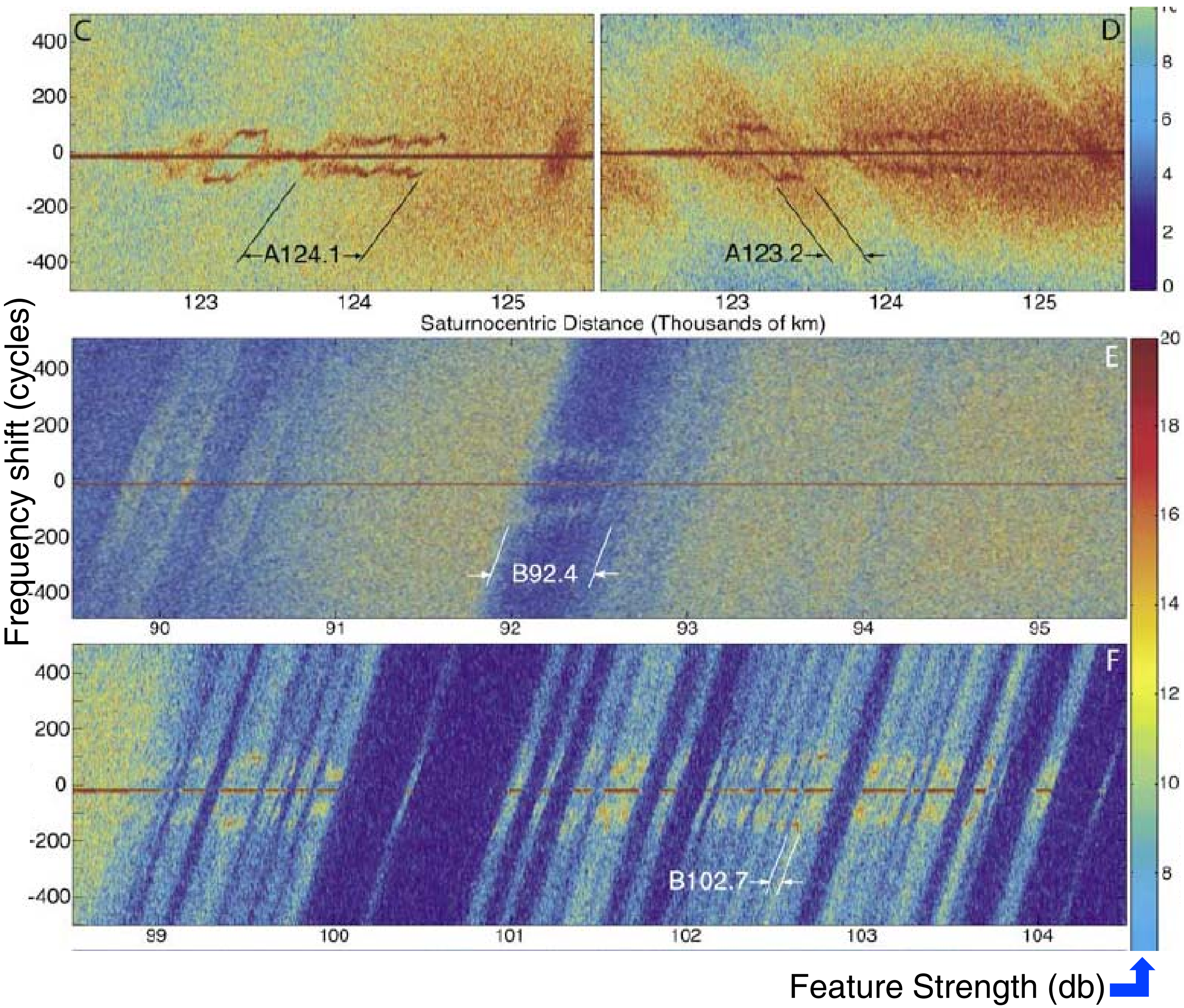
Dynamic processes responsible for ring structure: ultrafine radial structure

Radial microstructure is seen at even finer scales in RSS & stellar occultations, widely in optically thick regions. “Viscous overstability”, driven by competition between viscosity and coriolis force, speculated on for decades, seems to be confirmed by Cassini.

Pulsation period about one orbit; wavelength is about 10x ring vertical thickness; more detailed studies are underway..



RSS maps ultrafine radial structure in A and B rings



RSS occultations revealed peculiar signals which are symmetrically offset from the carrier by a small amount (100Hz) that is both somewhat variable from place to place, and also remarkably constant throughout large regions of the A ring (top panel) and B ring (bottom two panels). The underlying structure behaves like a diffraction grating of regular, azimuthally symmetric structure with wavelength of about 150-200 **meters** (Thompson et al 2007 GRL).