Cassini-Huygens Mission to Saturn
4th Anniversary CHARM Presentation

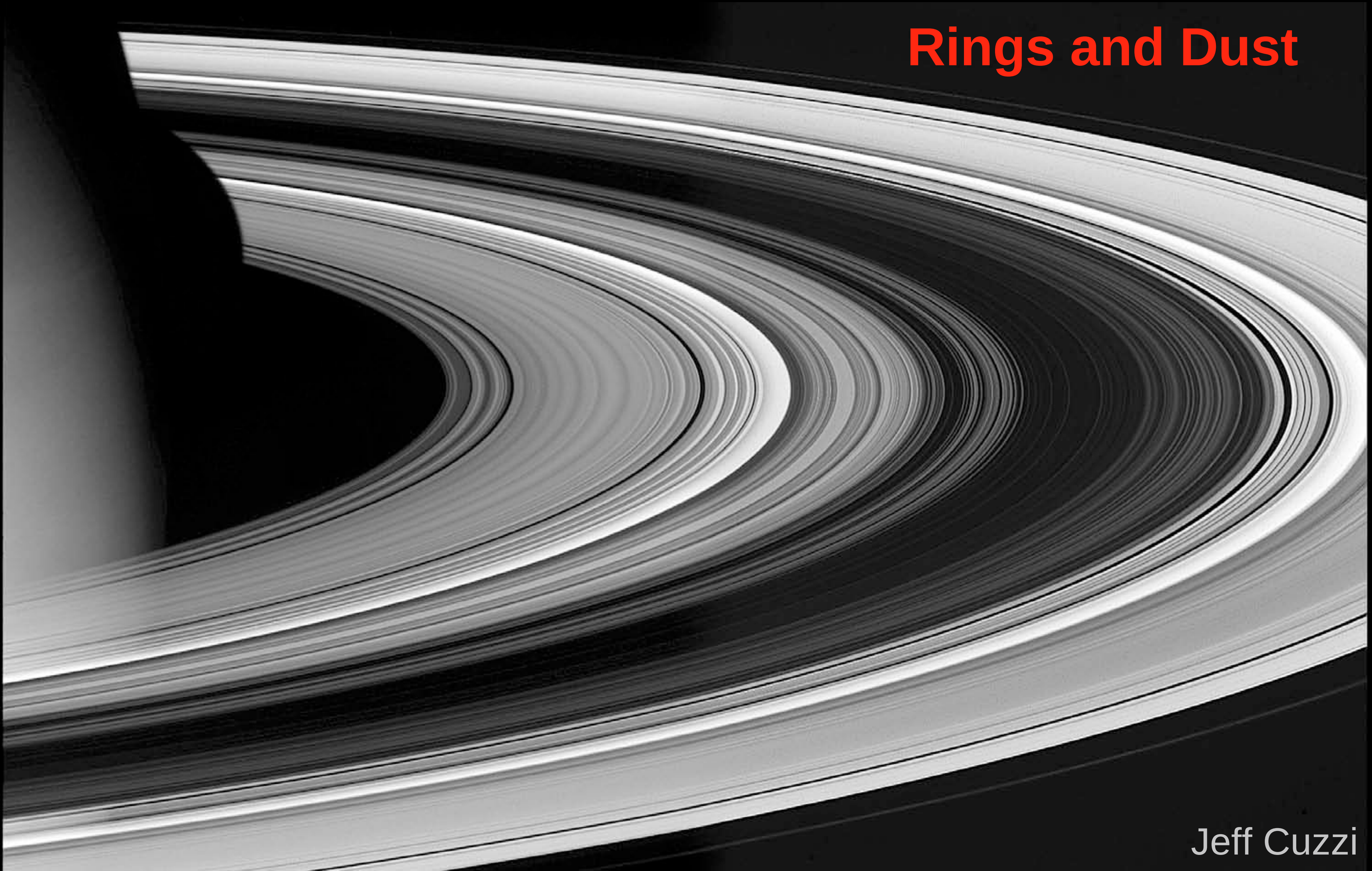
August 26, 2008

Part 3:

Jeff Cuzzi … Rings

David Seal … Cassini Equinox Mission

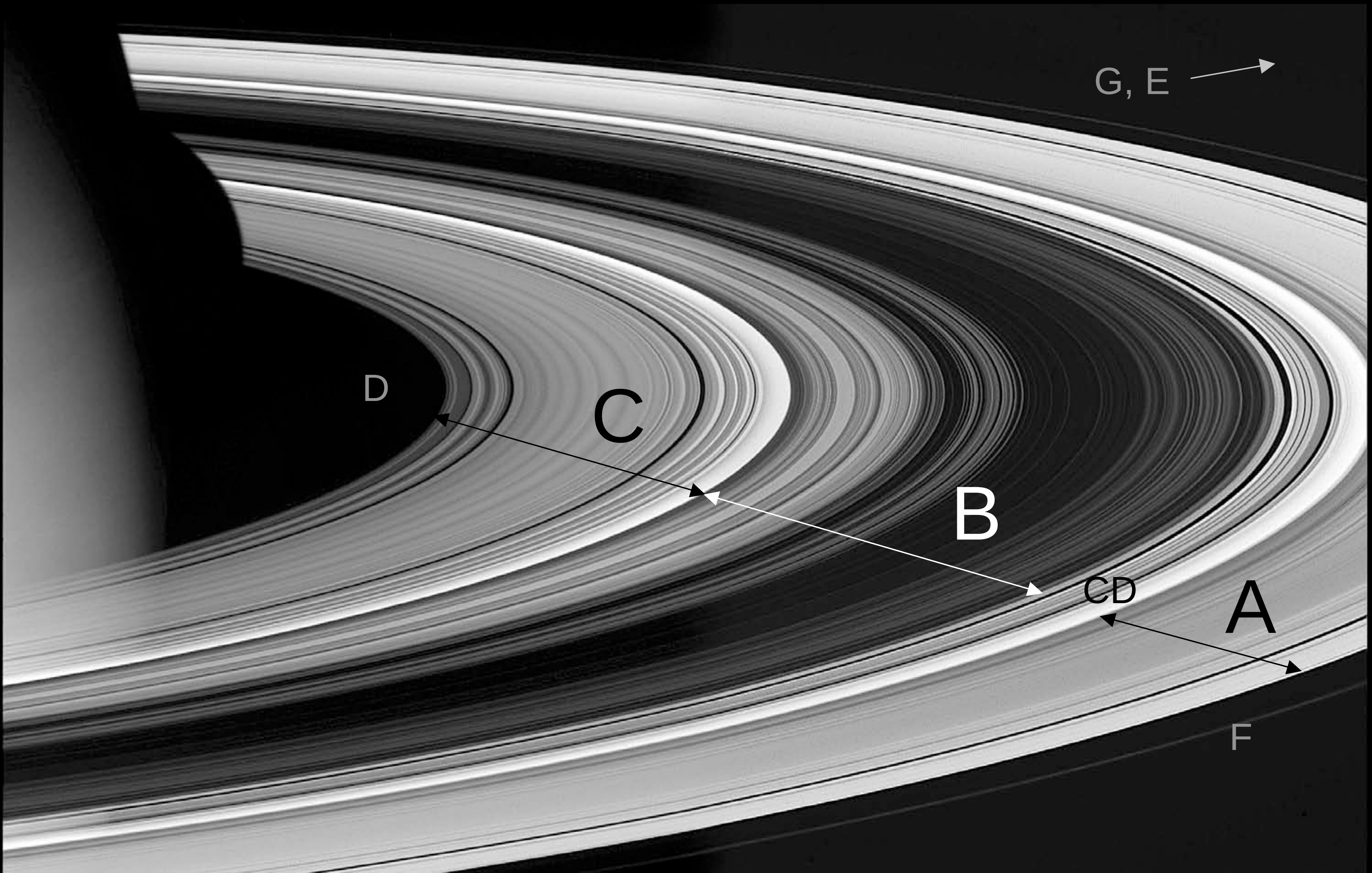
Cassini 4-year Prime Mission CHARM review



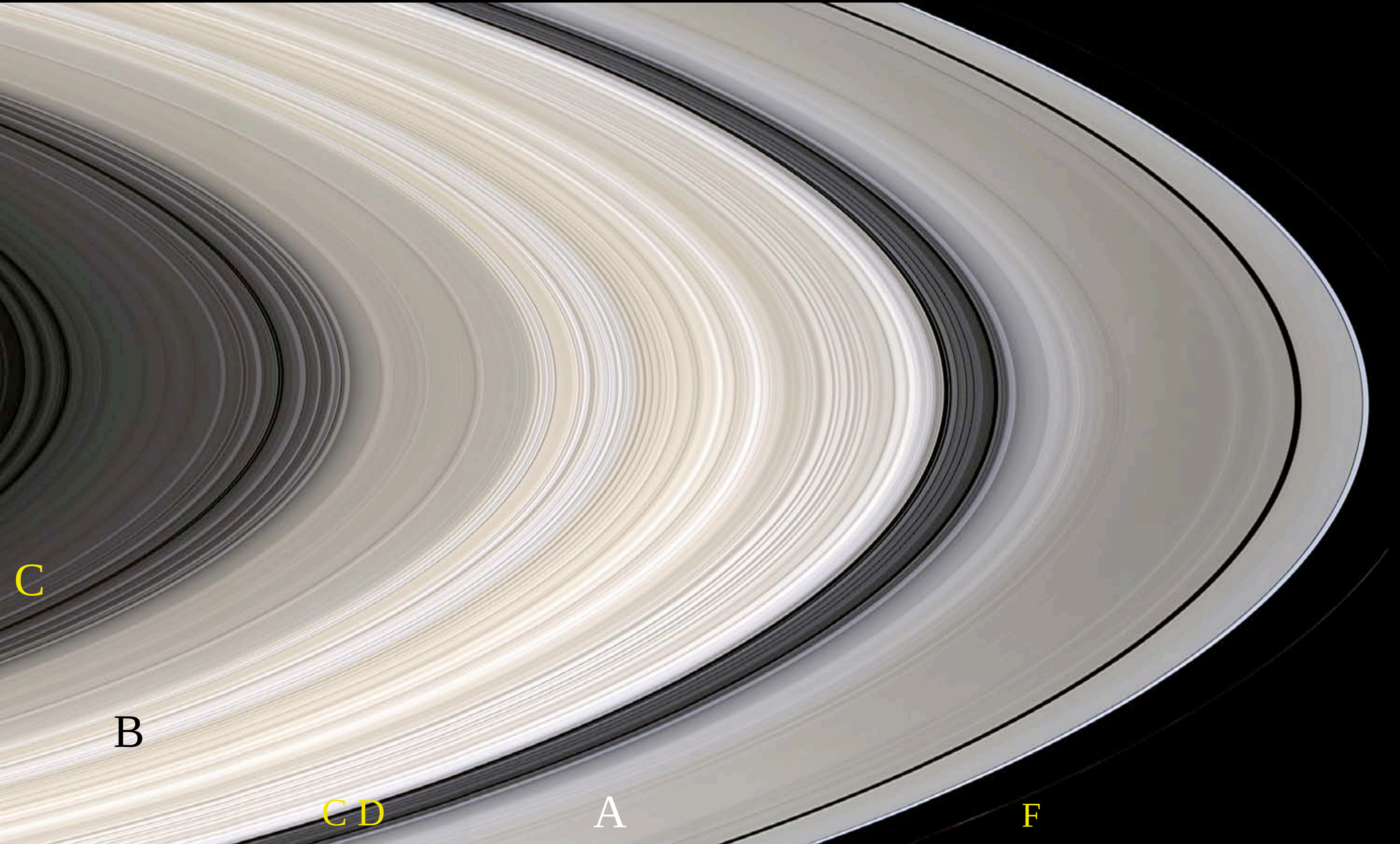
Rings and Dust

Jeff Cuzzi

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

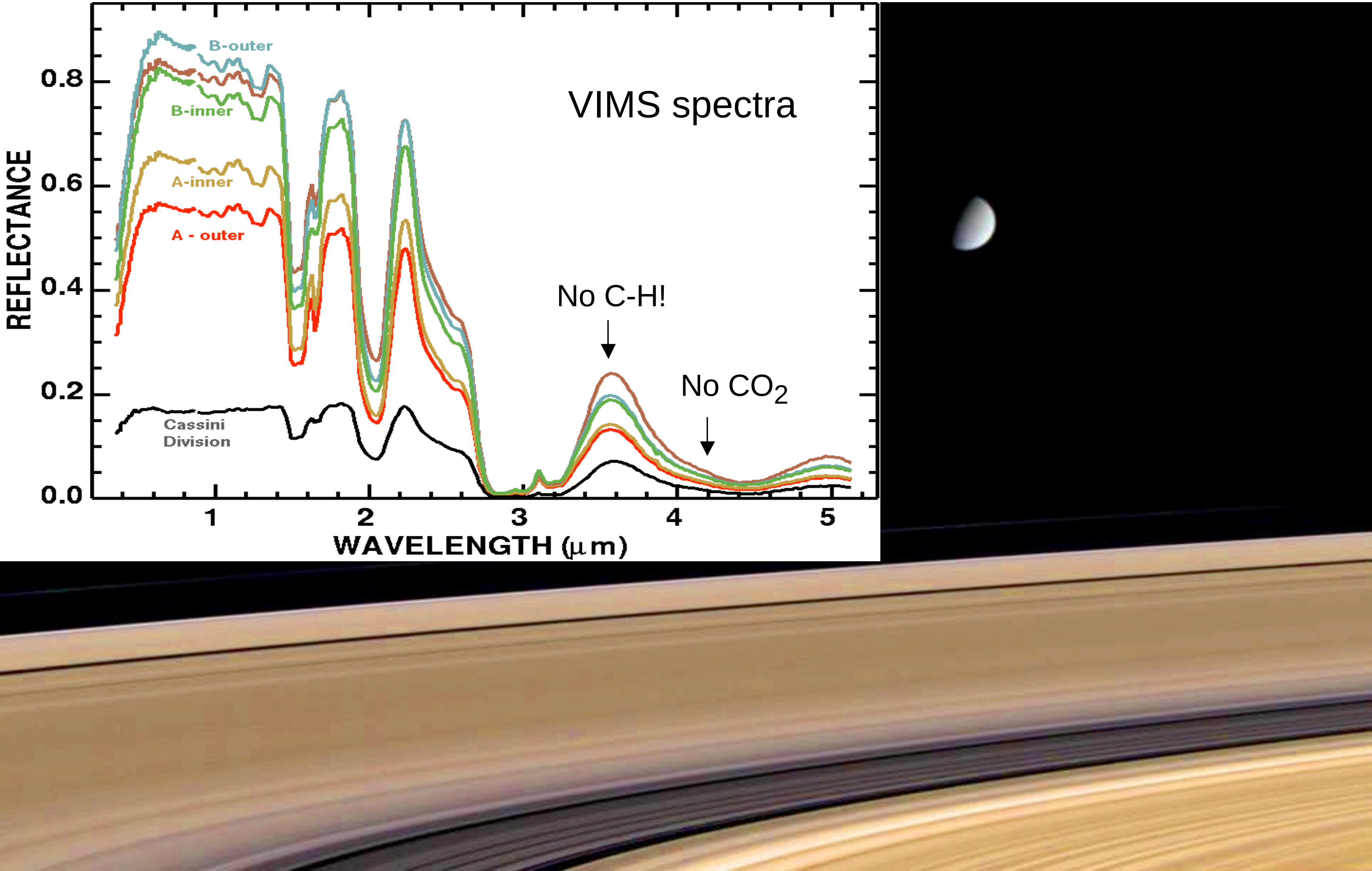
What gives the rings their reddish color?

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

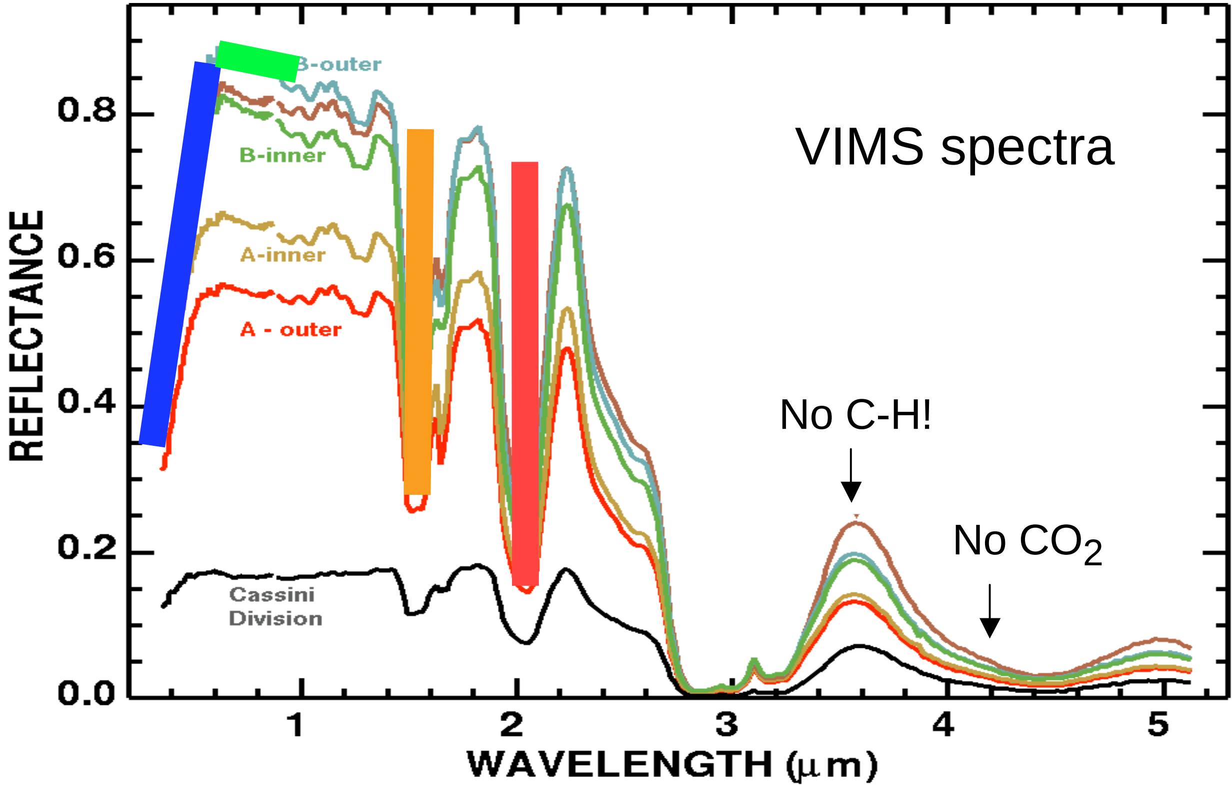
Fine structure throughout the B ring

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

Chemical composition and size distribution of ring material

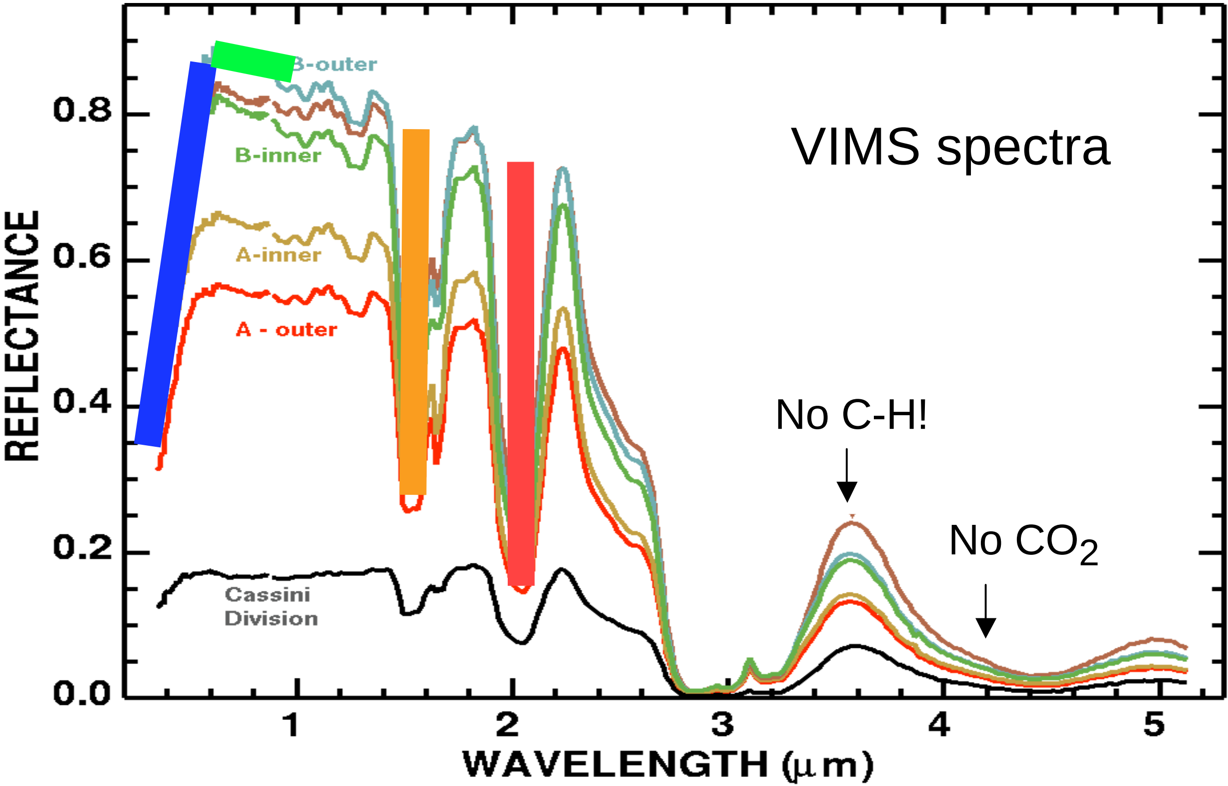


Chemical composition and size distribution of ring material



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

Chemical composition and size distribution of ring material



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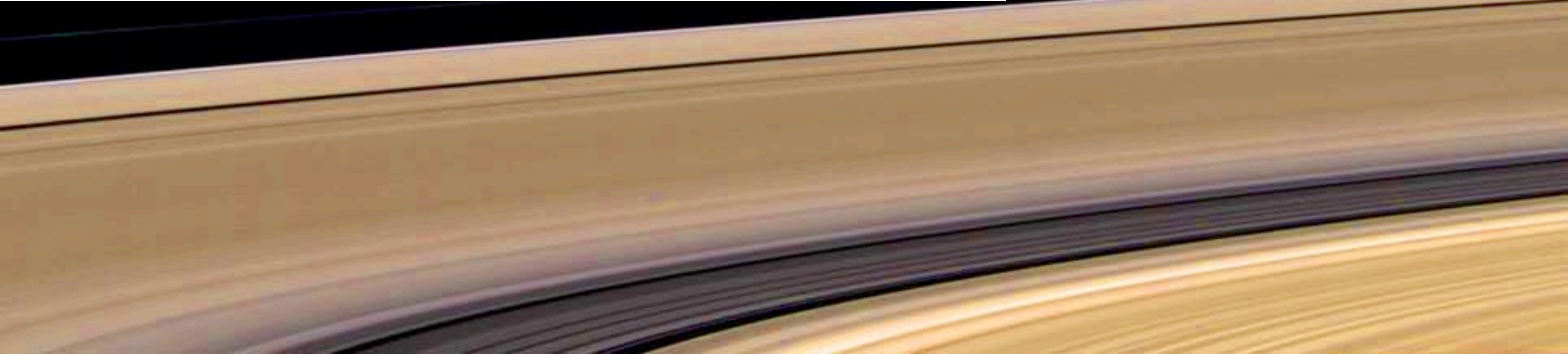
In particular, what material causes this “redness” at short visual wavelengths?



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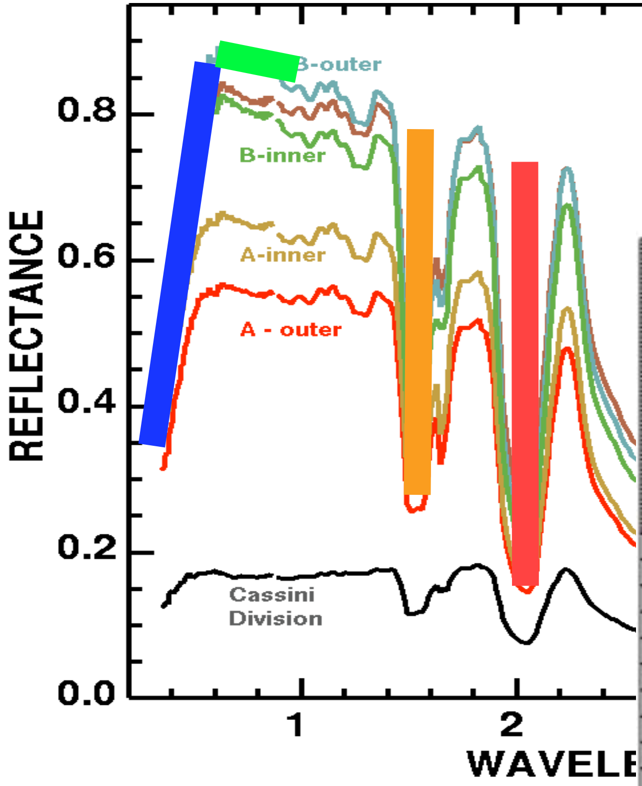

VIMS spectra

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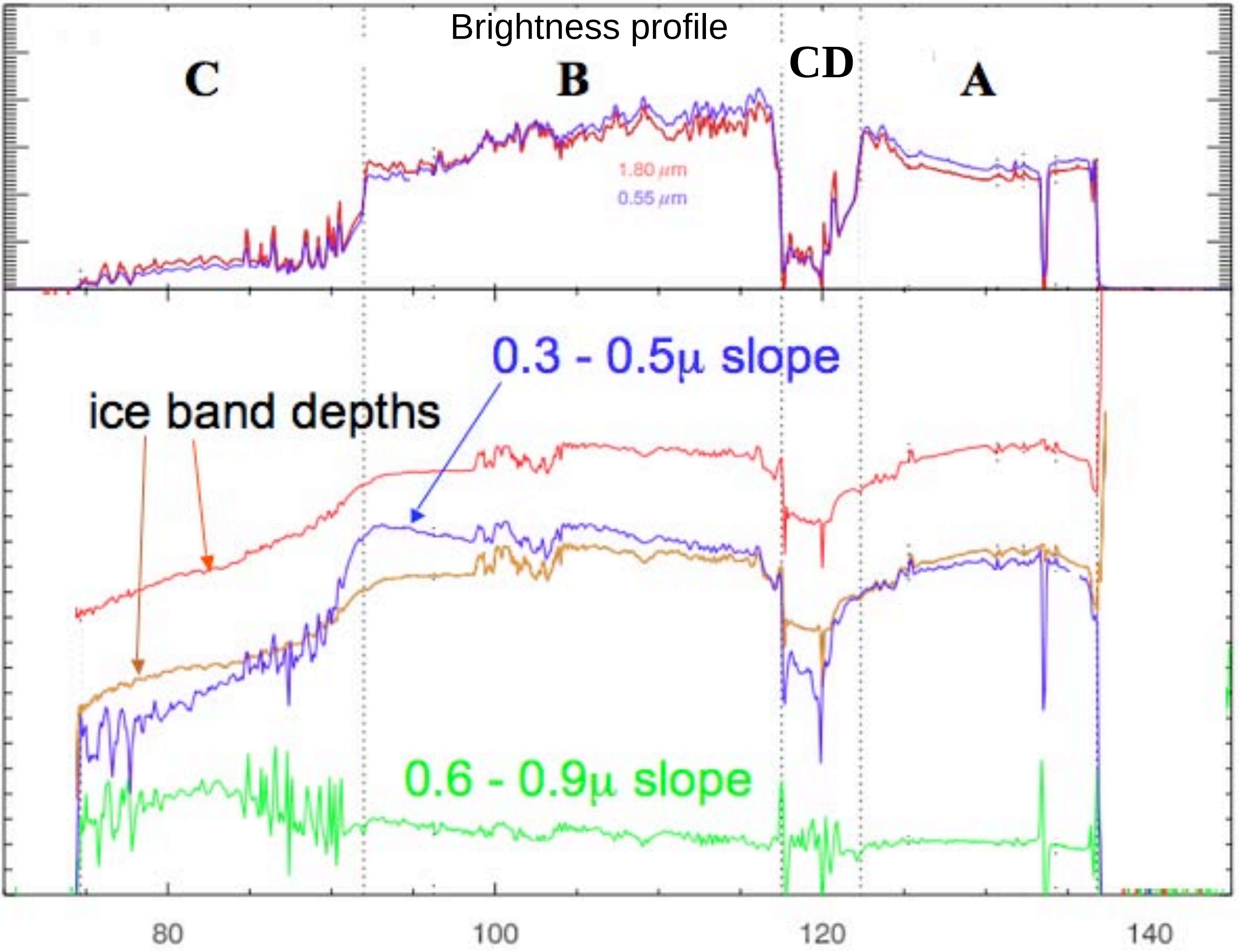

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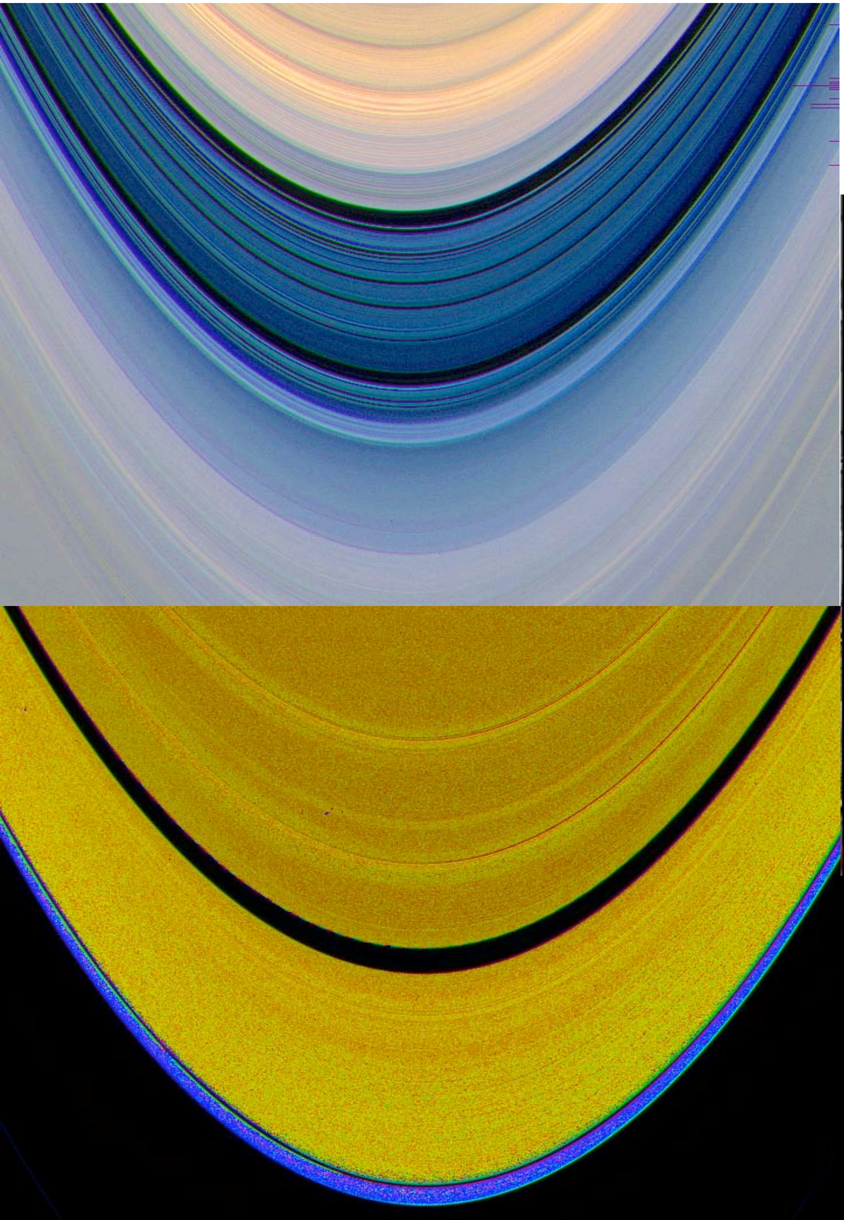
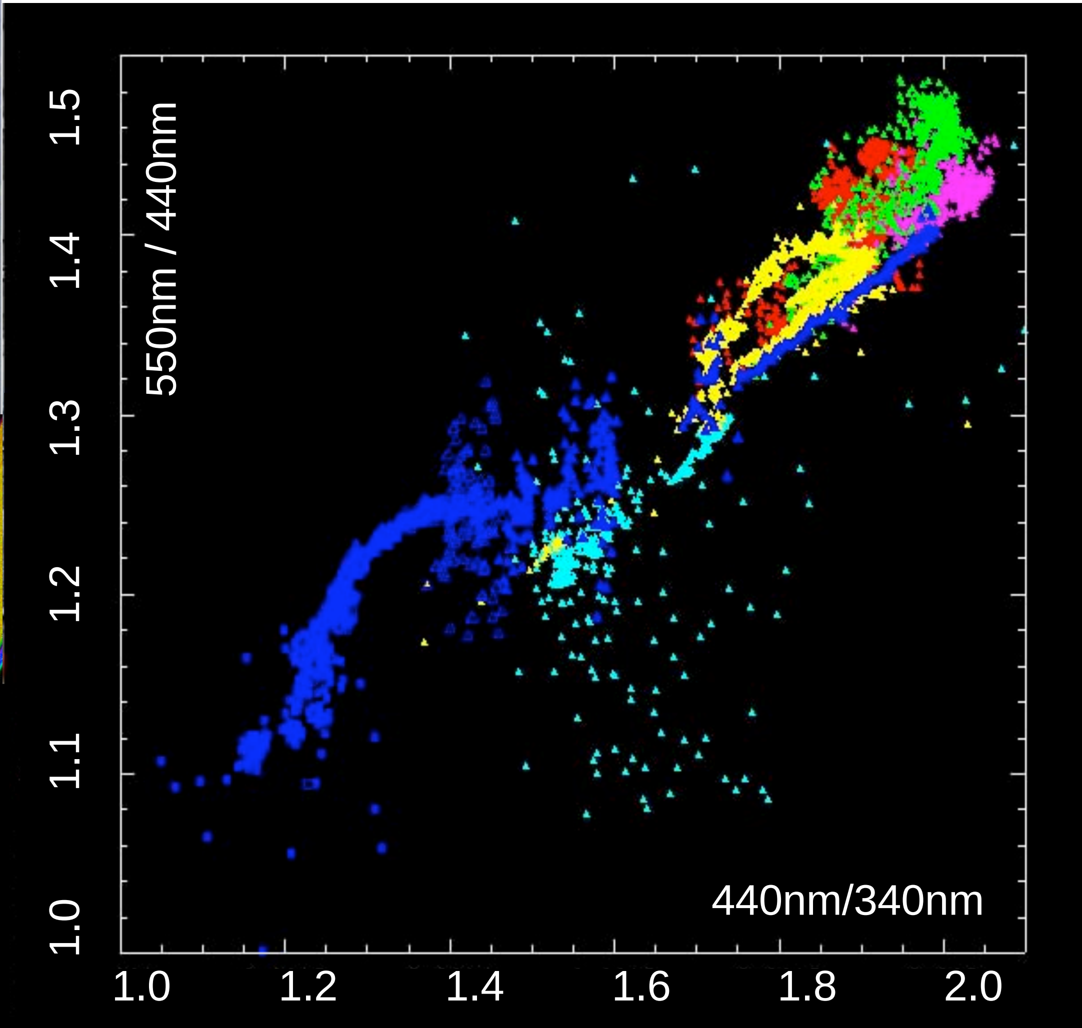


ISS 15-filter imaging has 10x higher spatial resolution than VIMS spectra



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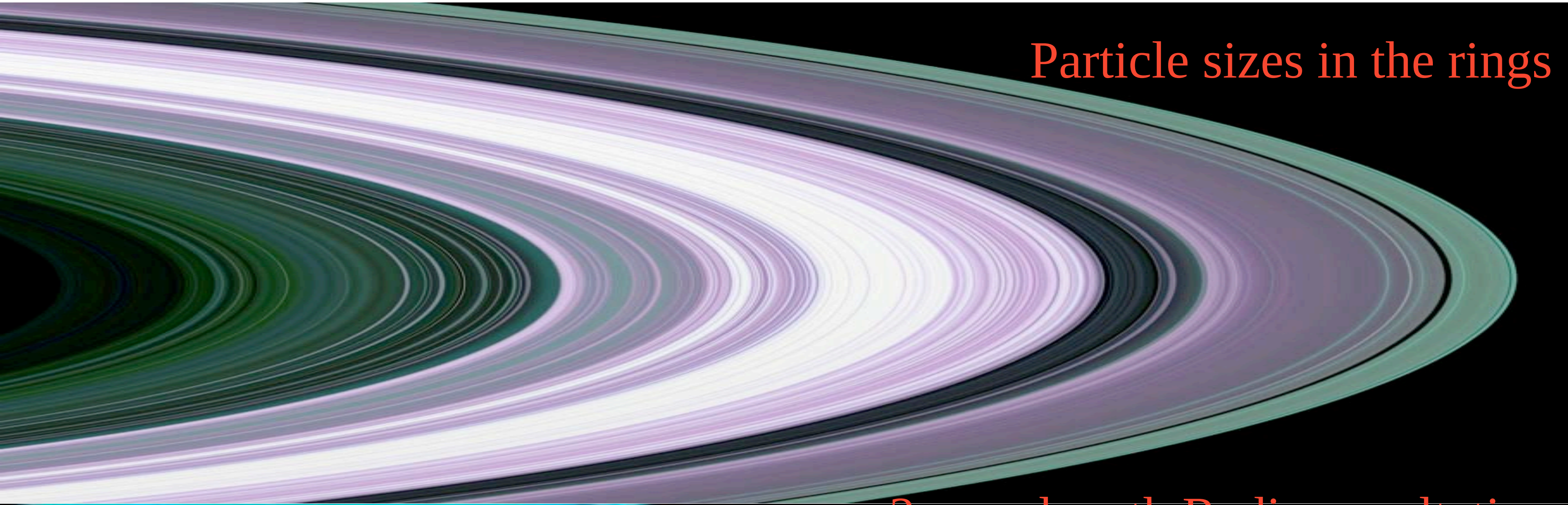
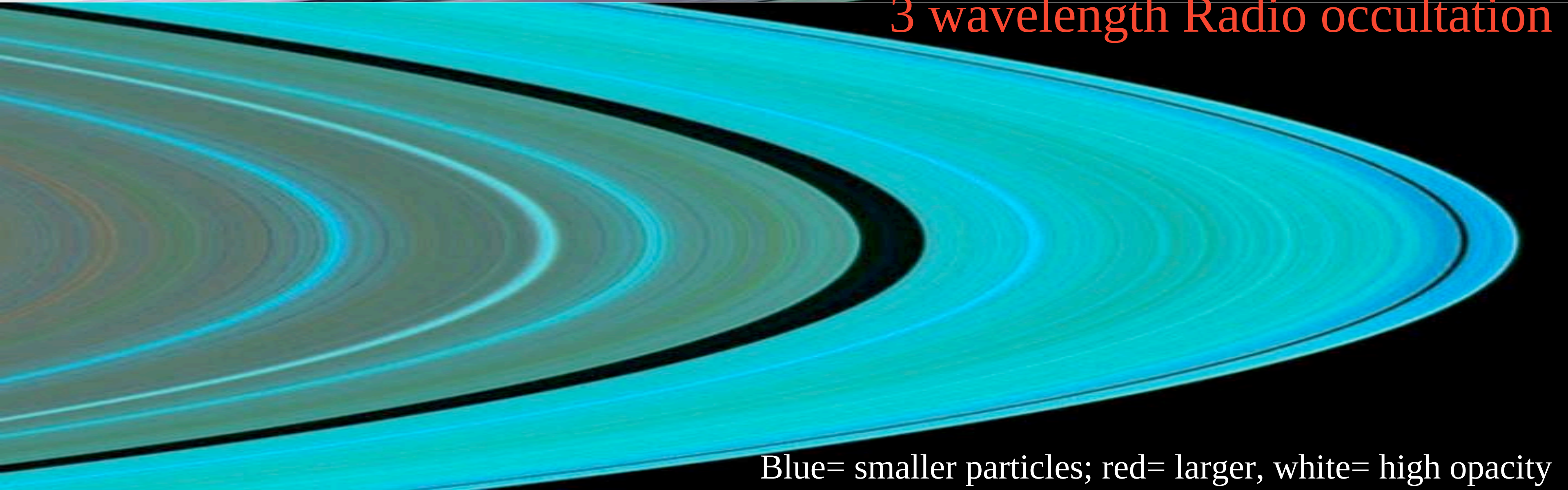
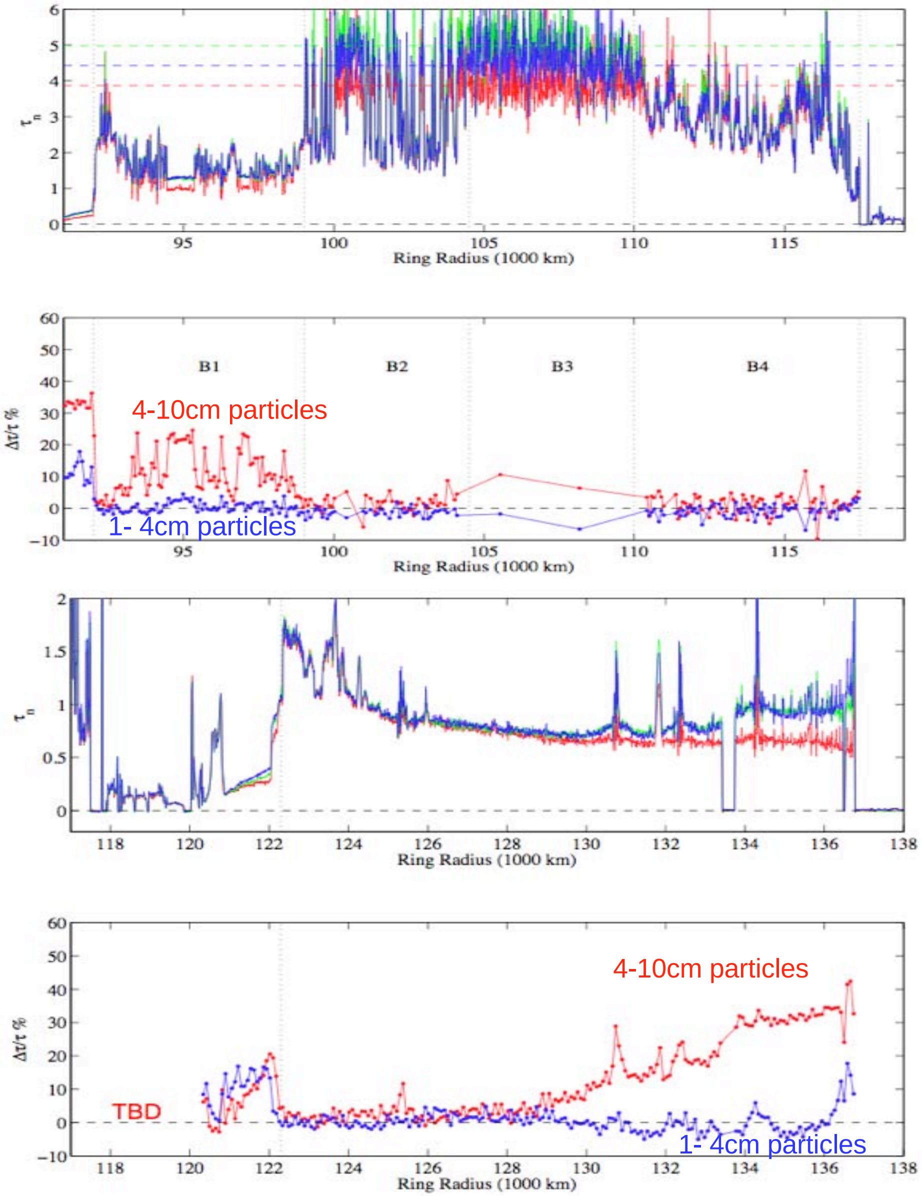

Particle sizes in the rings

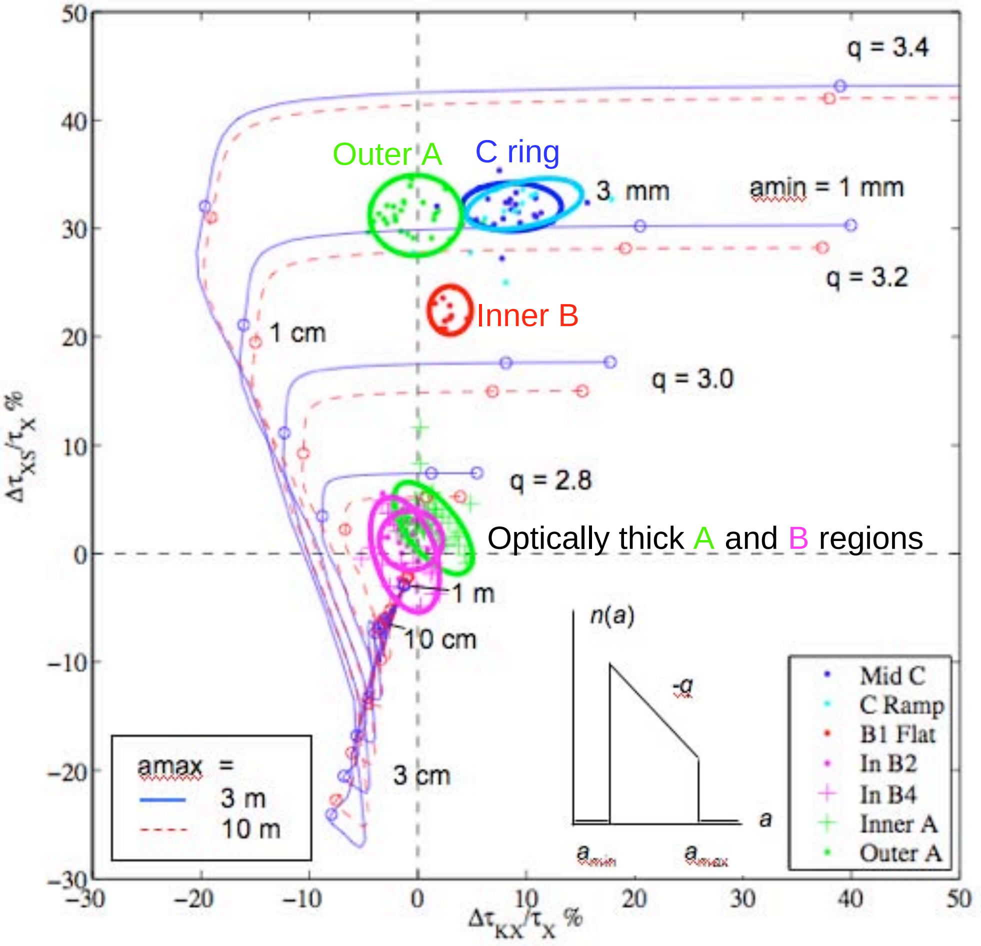

3 wavelength Radio occultation

Blue= smaller particles; red= larger, white= high opacity

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





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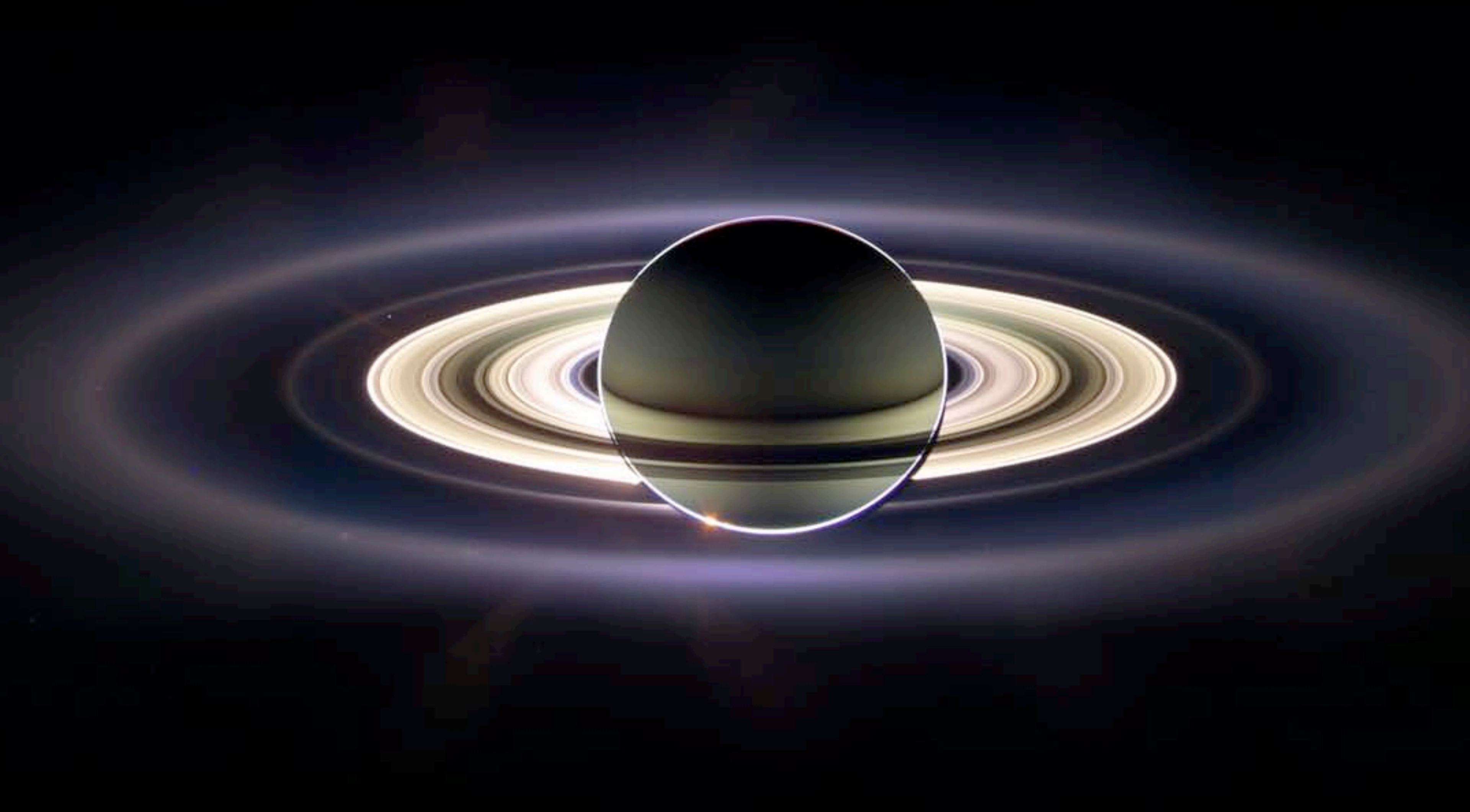

Chemical composition and size distribution of ring material

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

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

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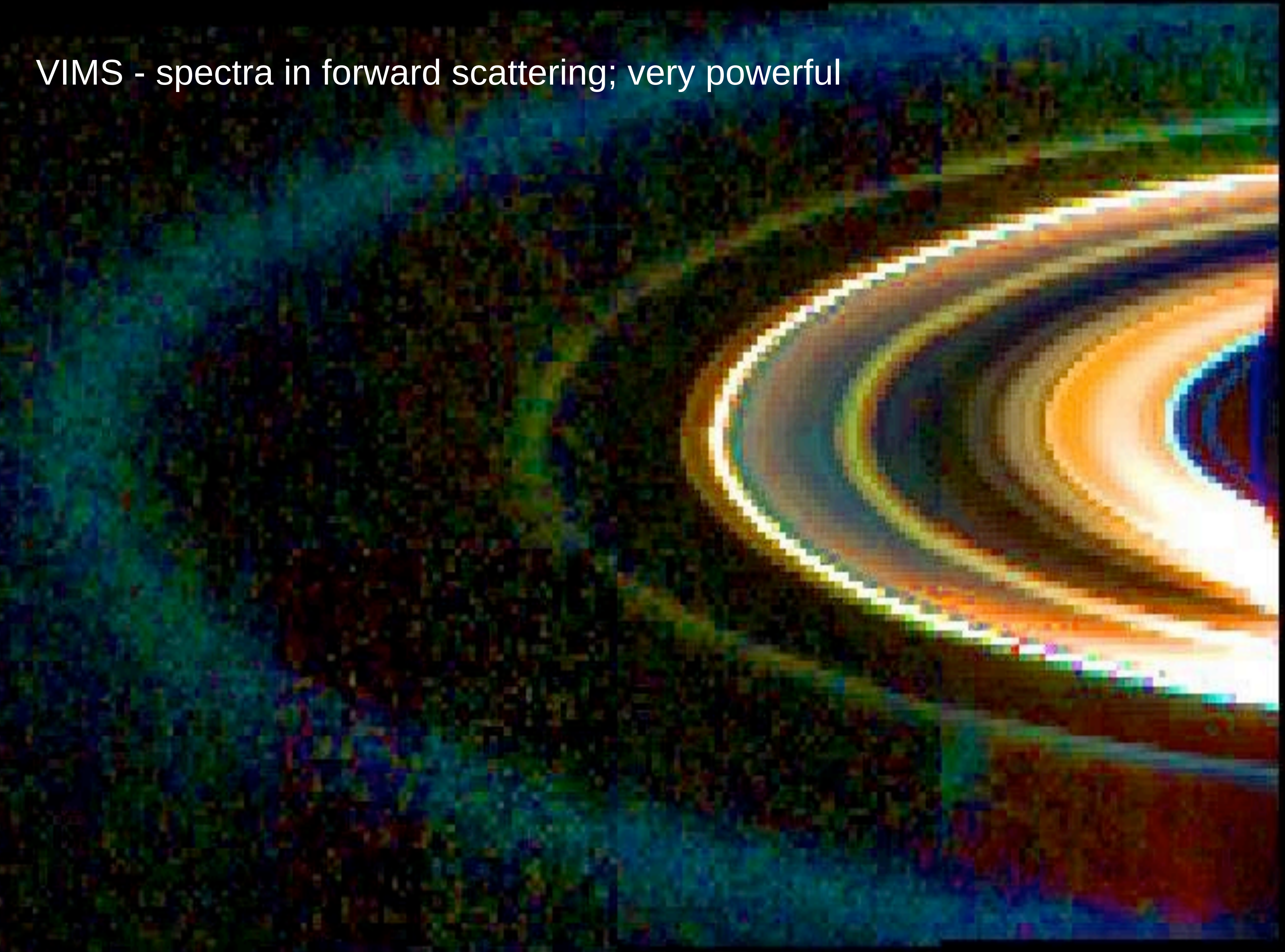
VIMS - spectra in forward scattering; very powerful



Chemical composition and size distribution of ring material

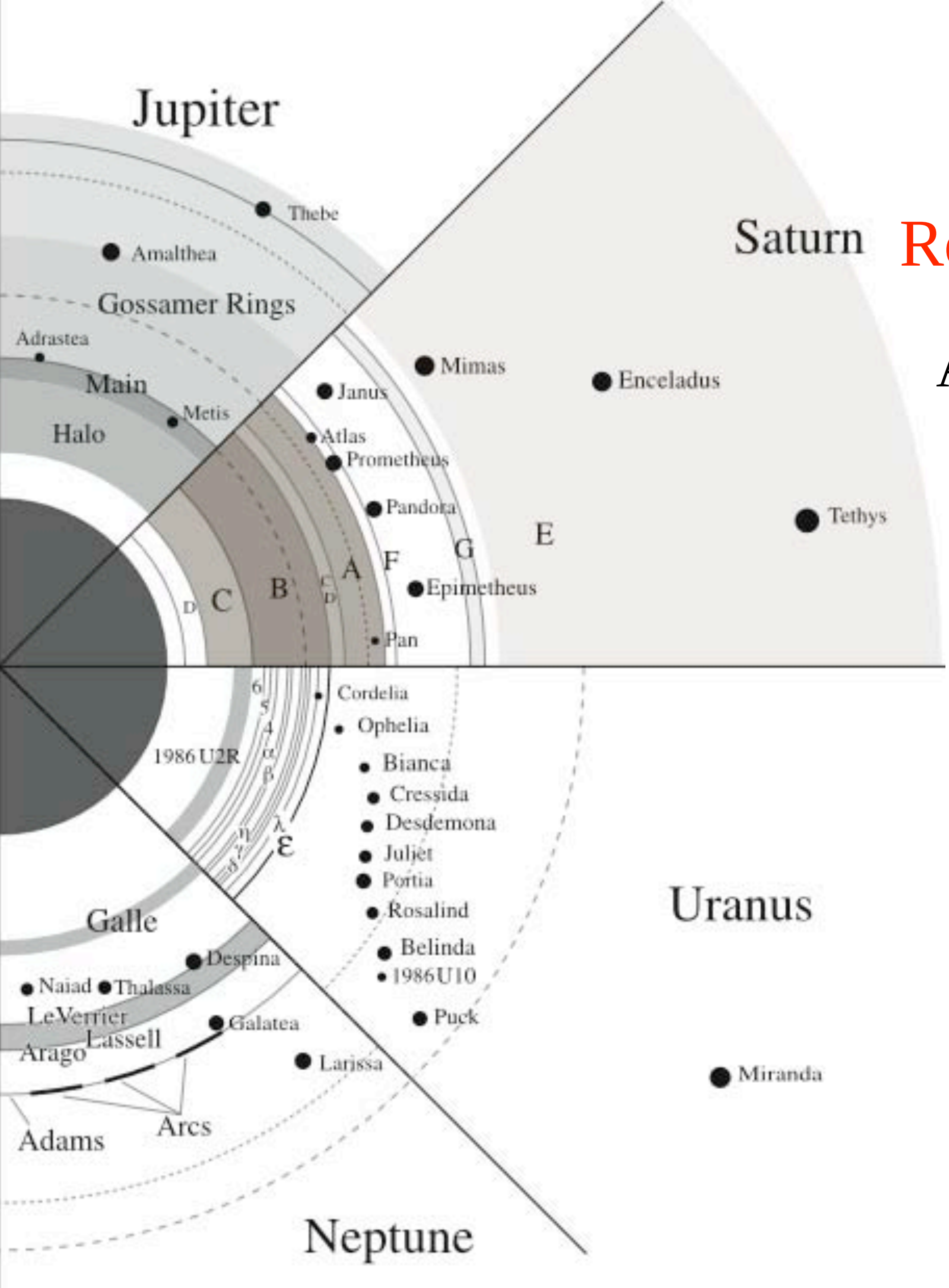
Major results:

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). Redness correlates with water ice band depth, and both vary with local optical depth in a way that suggests evolutionary processing. Meteoroid bombardment and the (O, O_2) ring atmosphere may each play a different evolutionary role.

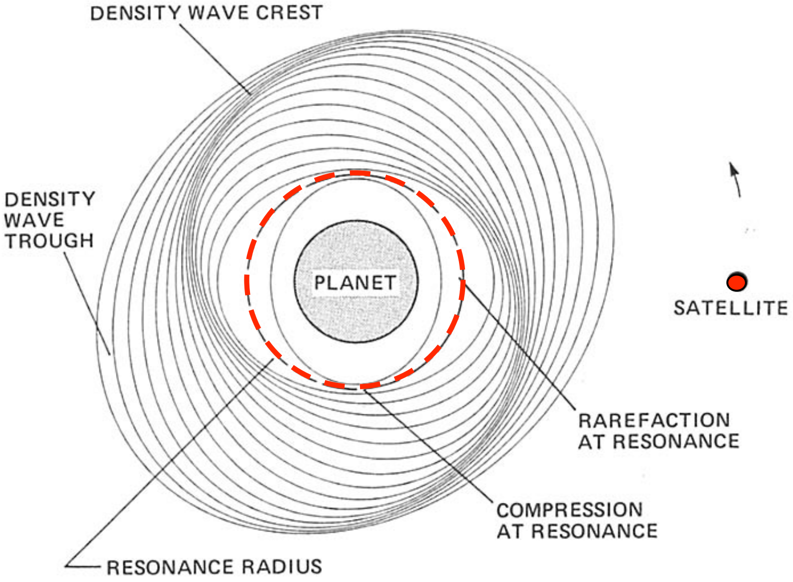
Cassini has characterized the mm-10m particle size distribution throughout the rings for the first time, by a combination of RSS occs and stellar occs. An increasing abundance of smaller particles (*eg* towards outer A ring) correlates with increased dynamical activity. Analysis is just beginning.

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?).

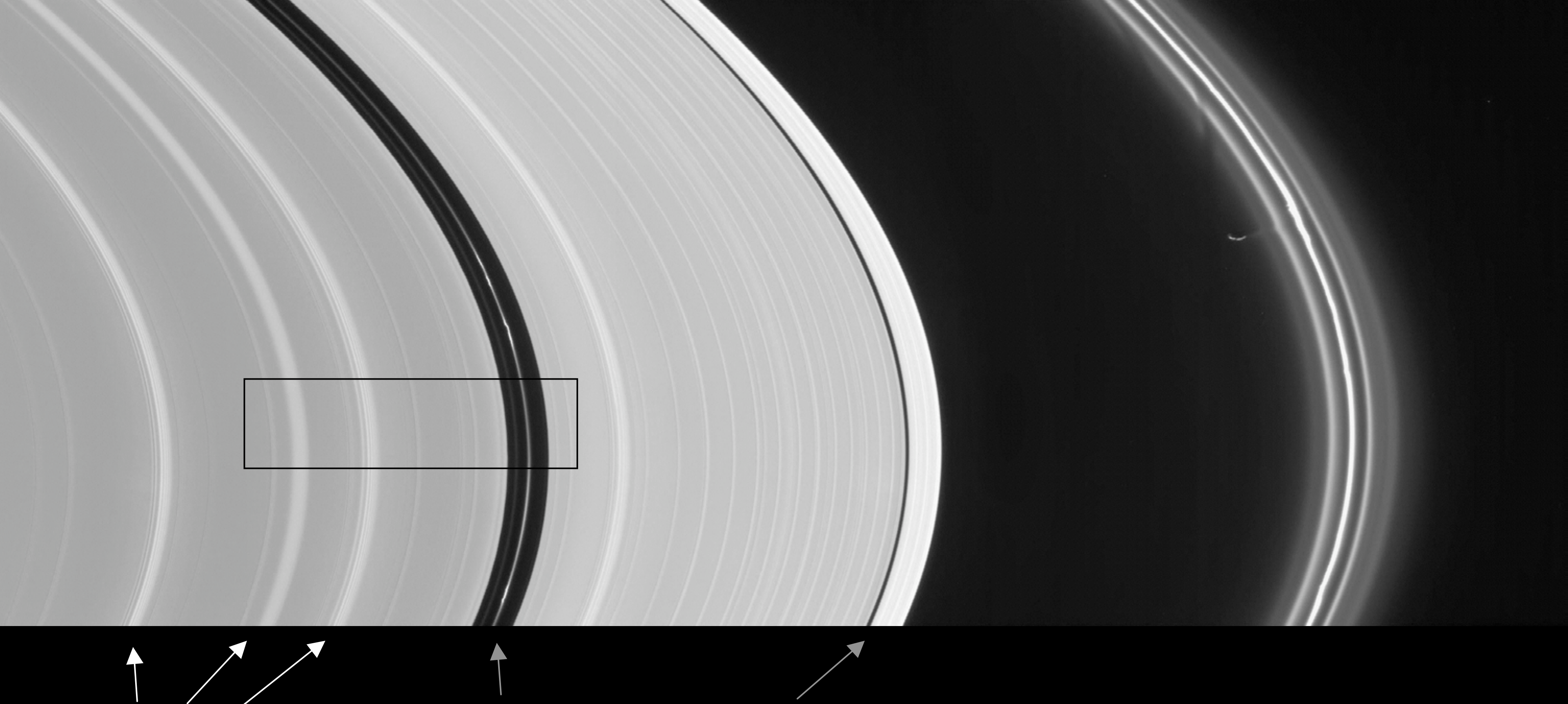
Rings and ringmoons closely mixed in and near Roche zones of parent planets



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



Ring self-gravity creates spiral pattern rotating with moon



Spiral density waves

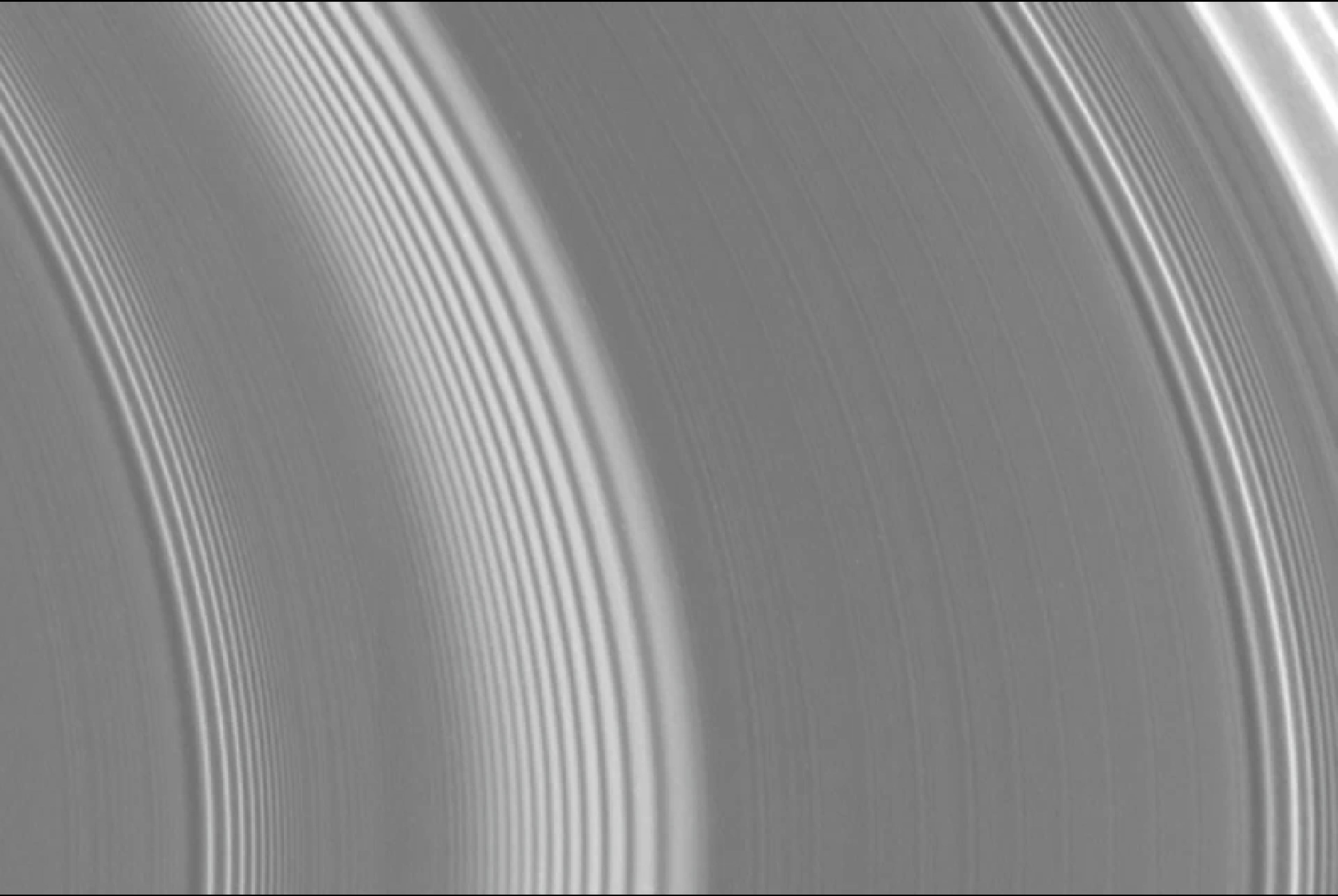
Encke and Keeler gaps contain moonlets Pan and Daphnis and multiple clumpy ring-arcs

Multiple strands; Prometheus, Pandora, and other new objects

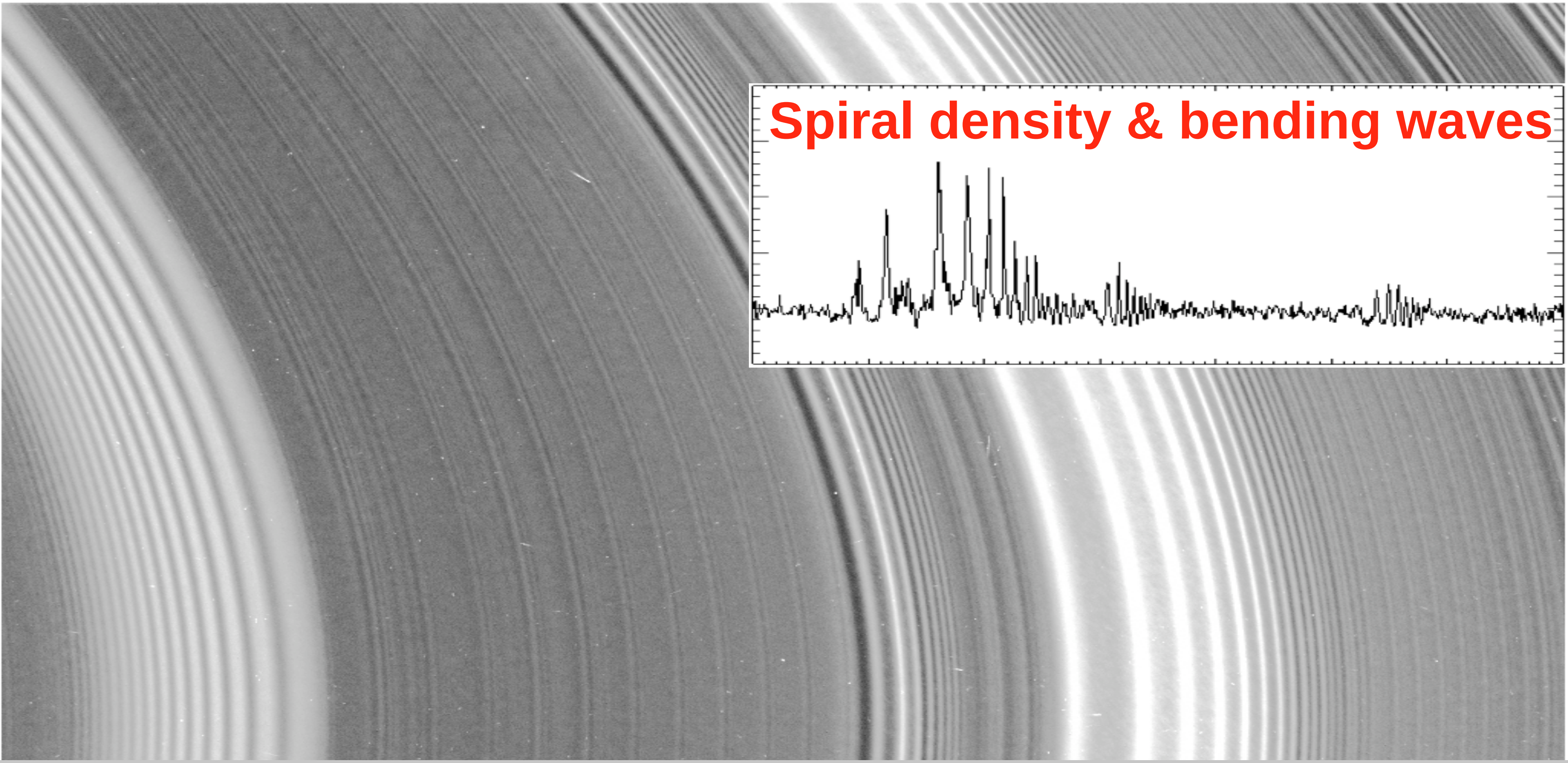
Outer A ring

F ring

10,000km or 6000 miles



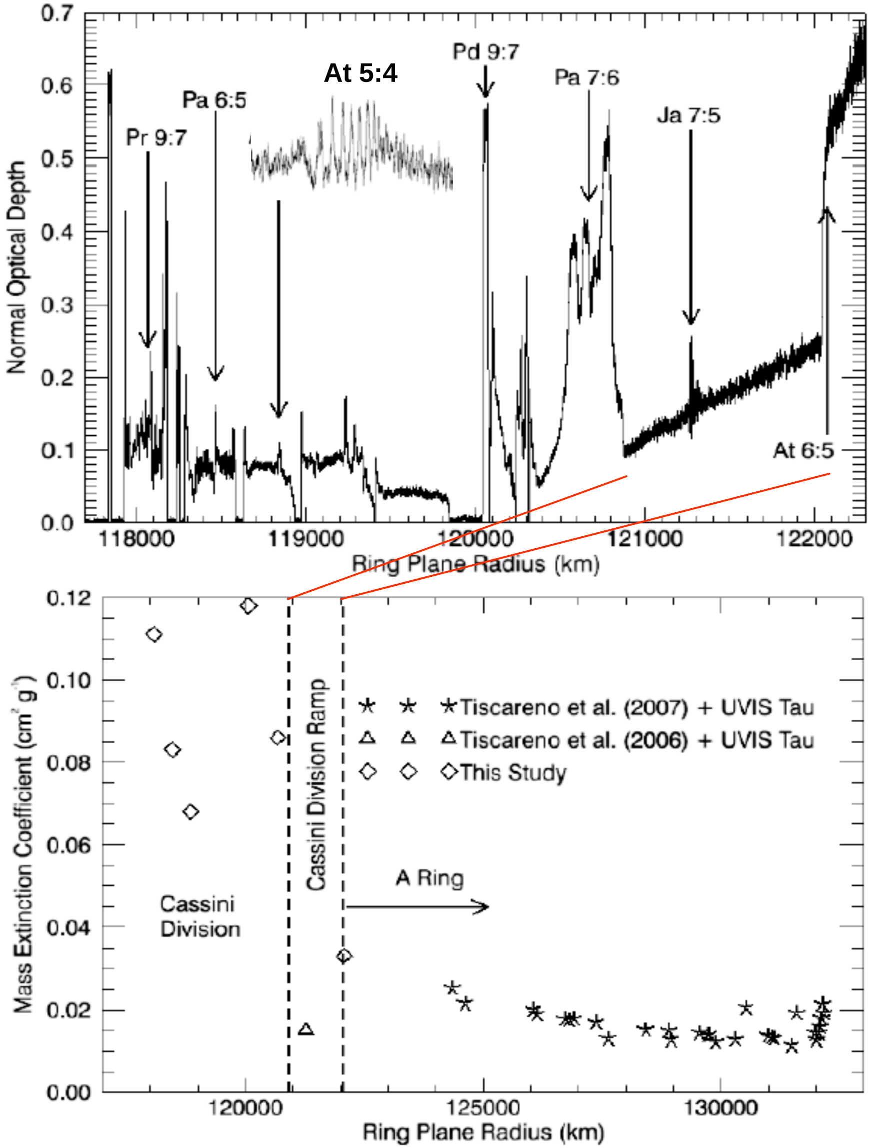
Dynamic processes responsible for ring structure



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

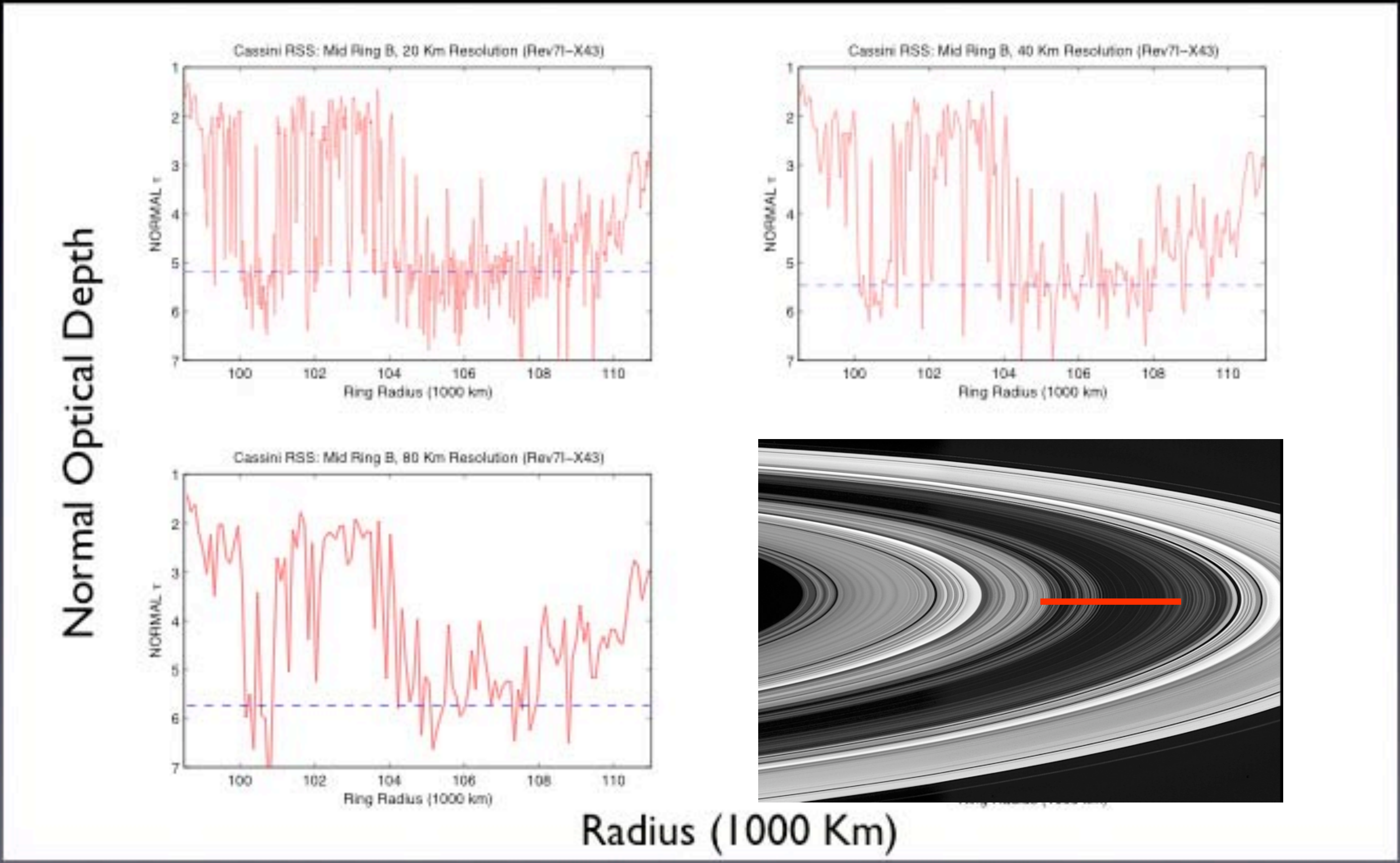
Cassini Division surface mass density variations from density waves

Stellar occultations (here by UVIS; Colwell et al 2008) observe tightly wrapped spiral density waves, the wavelength of which is a direct measure of the surface mass density in the local ring material (top plot). At the same time, the occultation measures the areal blockage of starlight or optical depth. The ratio is the opacity, a direct measure of the typical particle size (bottom plot). In this recent result, it has been found that the opacity in the inner part of the Cassini Division is nearly 5 times larger (particle size five times smaller) than in the “ramp” in the outer part of the Cassini Division, which itself is comparable to the values found in the A ring. This corresponds very well to the variation of the color and brightness of the particles in these regions: the “ramp” particles transition smoothly from reddish A ring colors to the more neutral colors found in the inner Cassini Division.



RSS occultations:

Widespread unexplained structure in the dense B ring !



Cassini RSS: Mid Ring B, 20 Km Resolution (Rev7I–X43)

Cassini RSS: Mid Ring B, 40 Km Resolution (Rev7I–X43)

Cassini RSS: Mid Ring B, 80 Km Resolution (Rev7I–X43)

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.

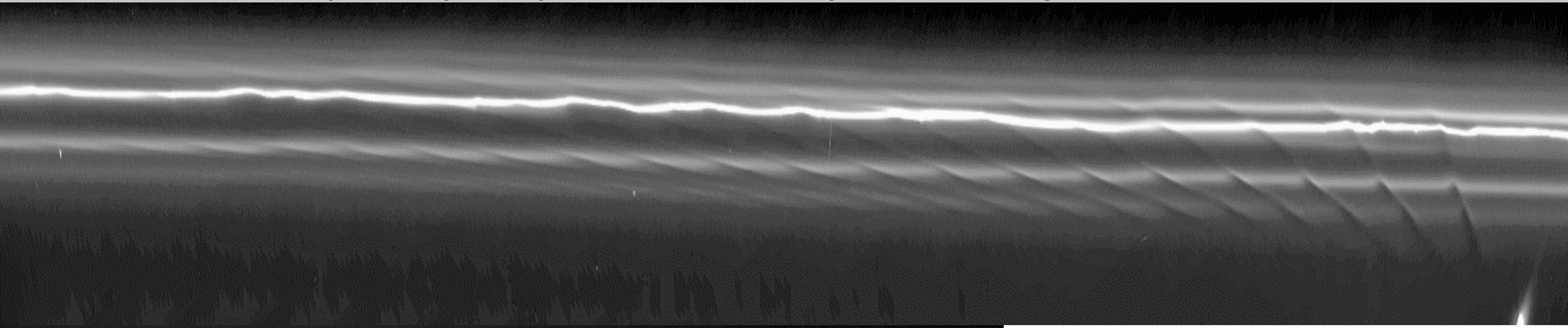
Models and observations suggest that the transparency of the B ring is dominated by a small fraction of nearly empty gaps between totally opaque clumps; thus the amount of material B ring might be far more than previously estimated.

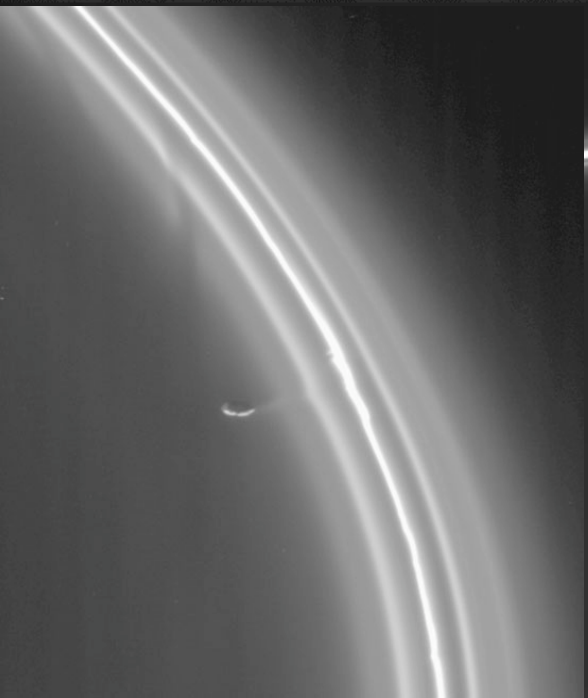
It has been argued that if the ring mass is much more than current estimates, and/or if the incoming meteoroid flux is much less than current estimates, then the rings might be as old as the solar system (*i.e.,* they could avoid becoming polluted by dark meteoroid material).

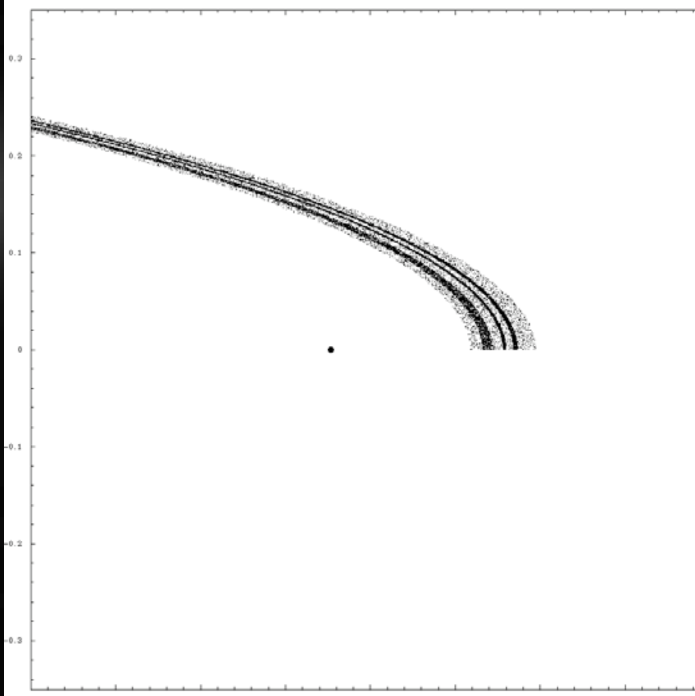
In the Extended Mission, Cassini will get one good measurement of the meteoroid flux. If we get a significant Extended-Extended mission, the end-of-life revs contain many close periapses which will allow the ring mass to be measured by their gravitational effects on the spacecraft

Dynamic processes responsible for ring structure

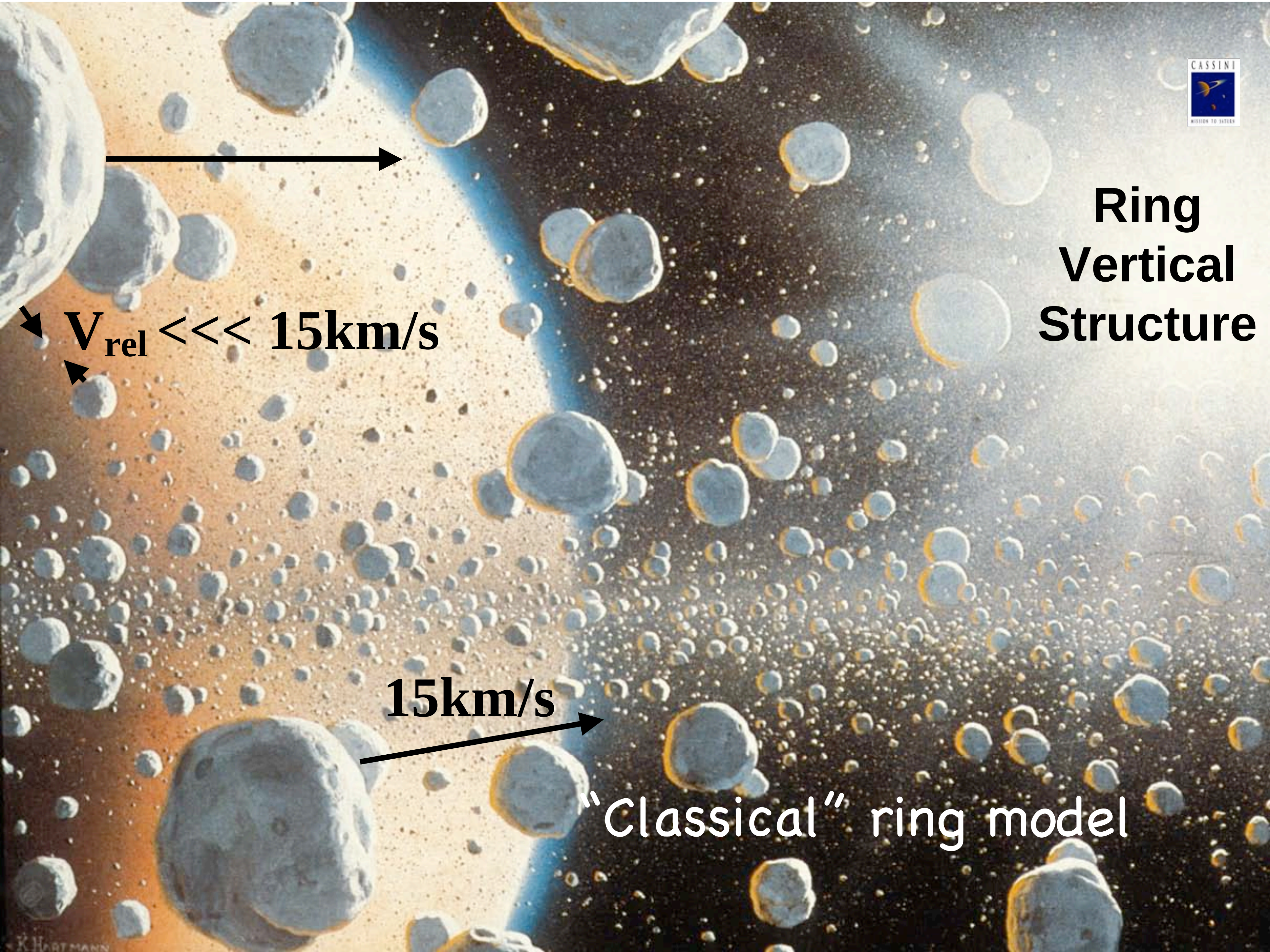
The stranded F ring has been a puzzle since Voyager. Cassini found that the number and location of the main strands changes on several month timescale, although the narrow “core” has remained constant. Gravitational effects of the nearby eccentric ringmoon Prometheus cause the channels and streamers.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







Ring Vertical Structure

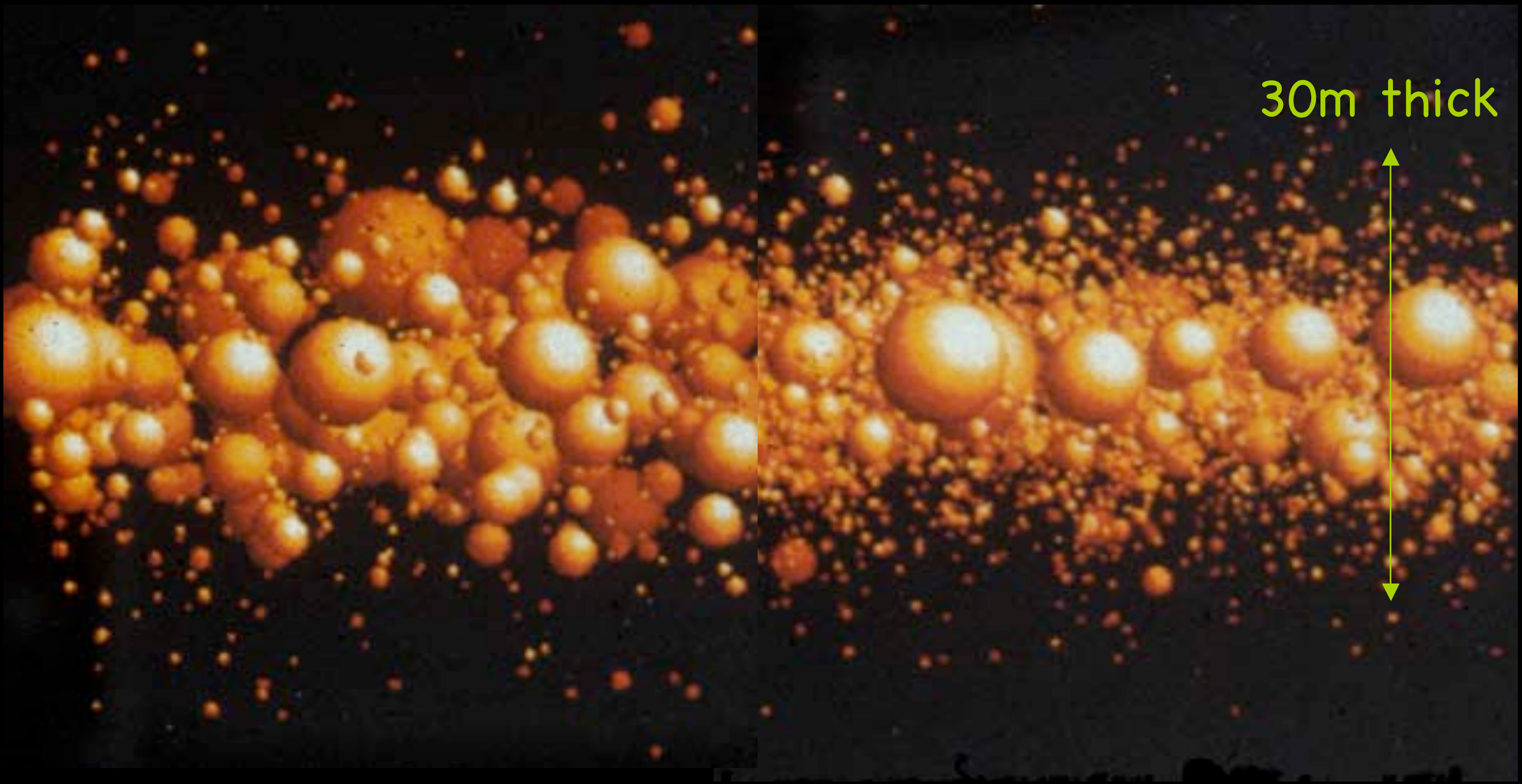


$V_{rel} <<< 15\text{km/s}$

15km/s

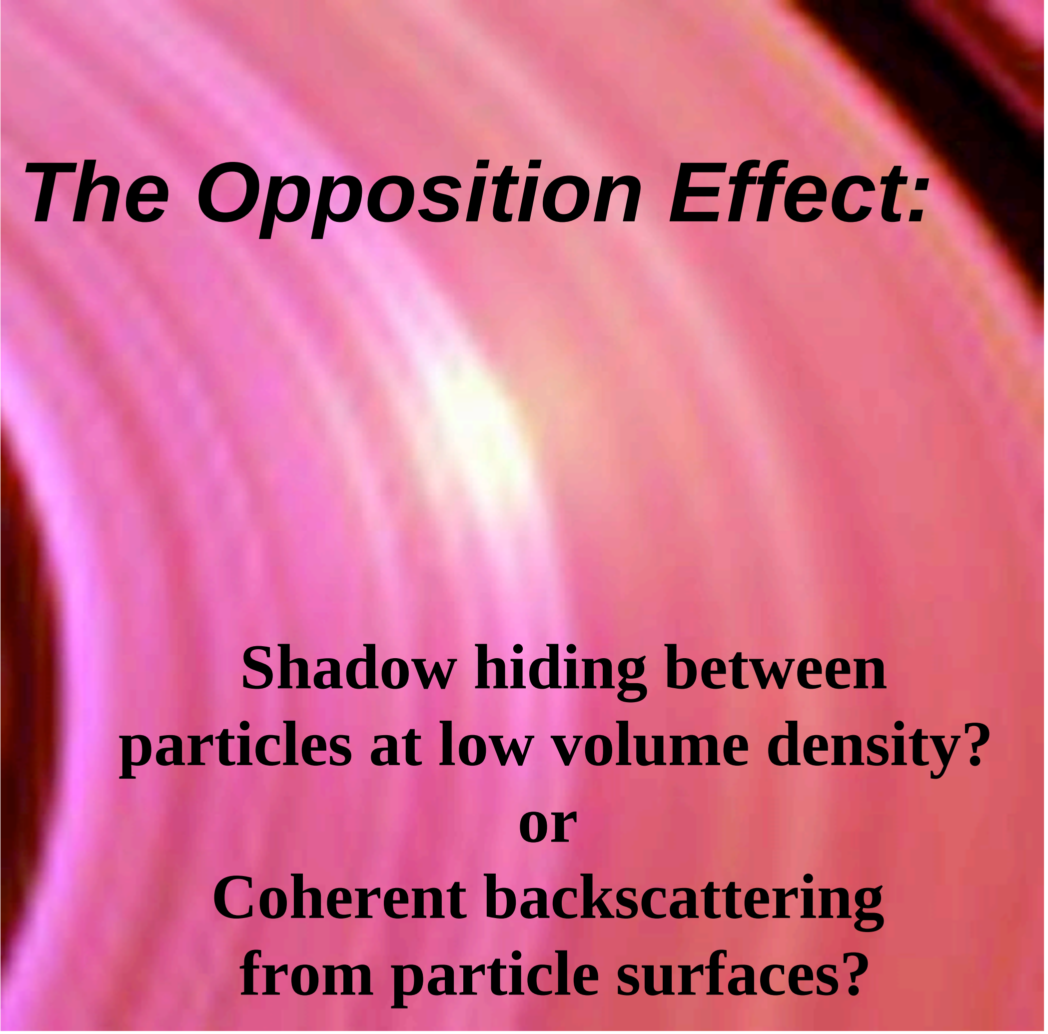
“Classical” ring model

A more modern, densely packed ring model



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

The Opposition Effect:



Shadow hiding between particles at low volume density?

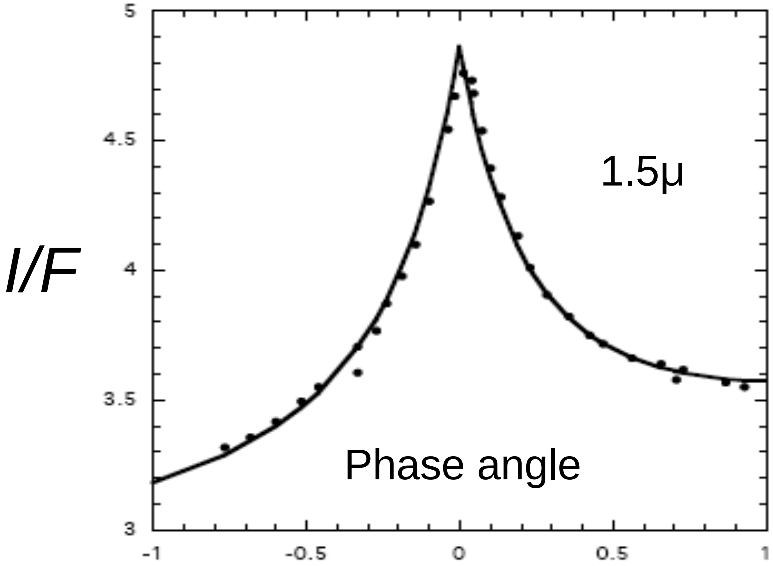
or

Coherent backscattering from particle surfaces?

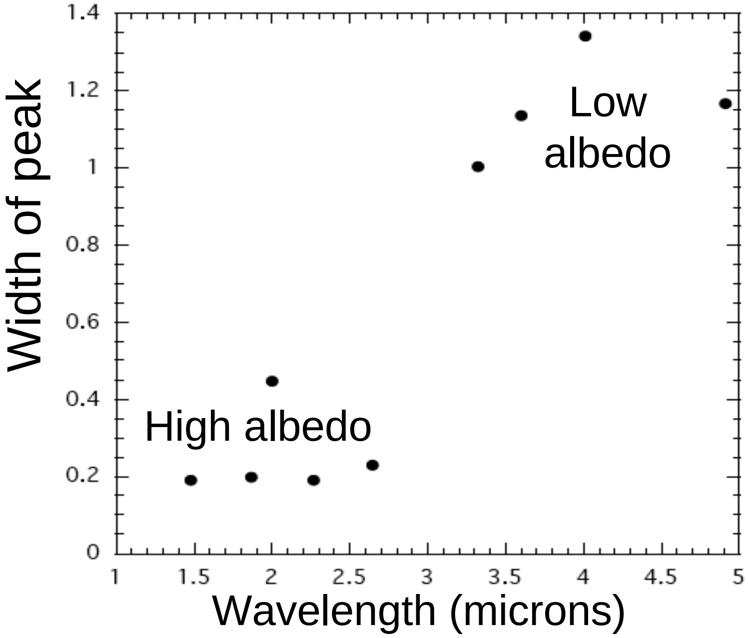
Cassini VIMS: large wavelength (albedo) range

Coherent backscattering fits better;
classical model not supported.
Rings seem highly flattened in general

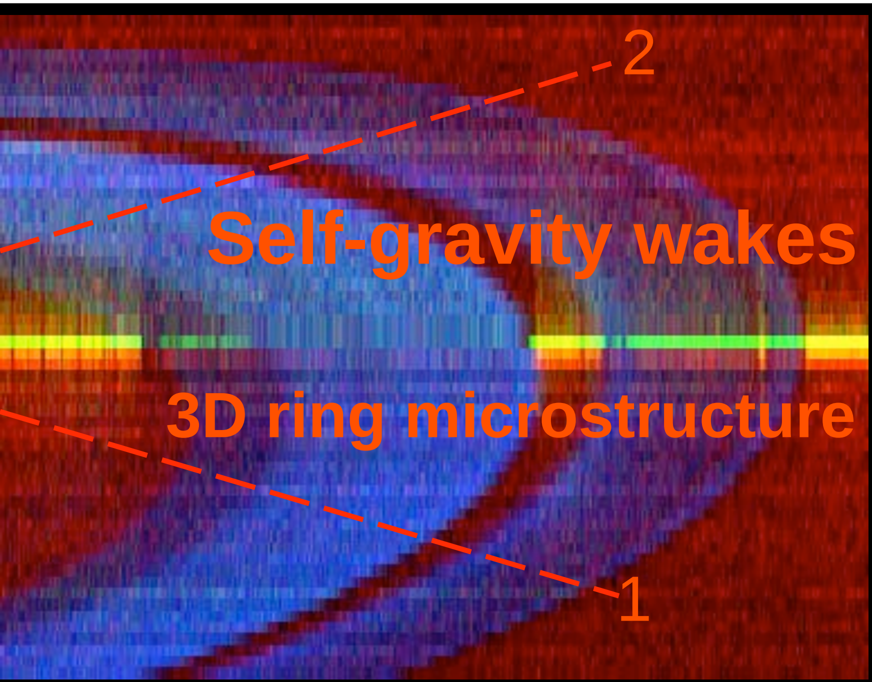
Mishchenko & Dlugach 1992;
Akkermans et al 1988; Hapke 2000

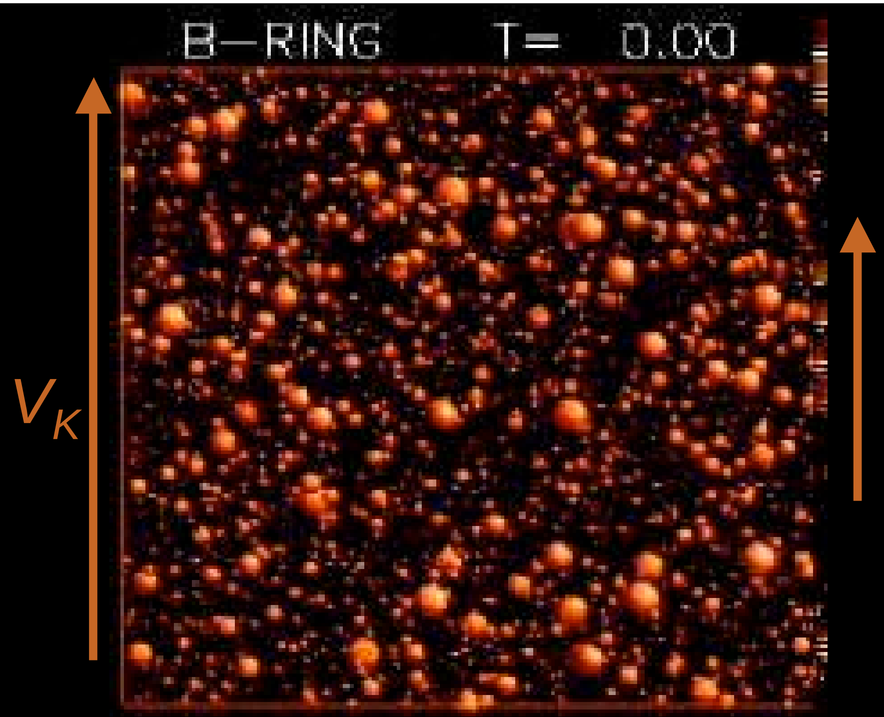


Nelson et al 2006; Hapke et al 2006 LPSC

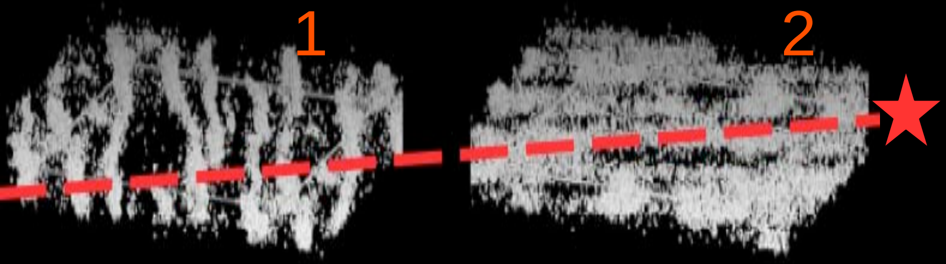


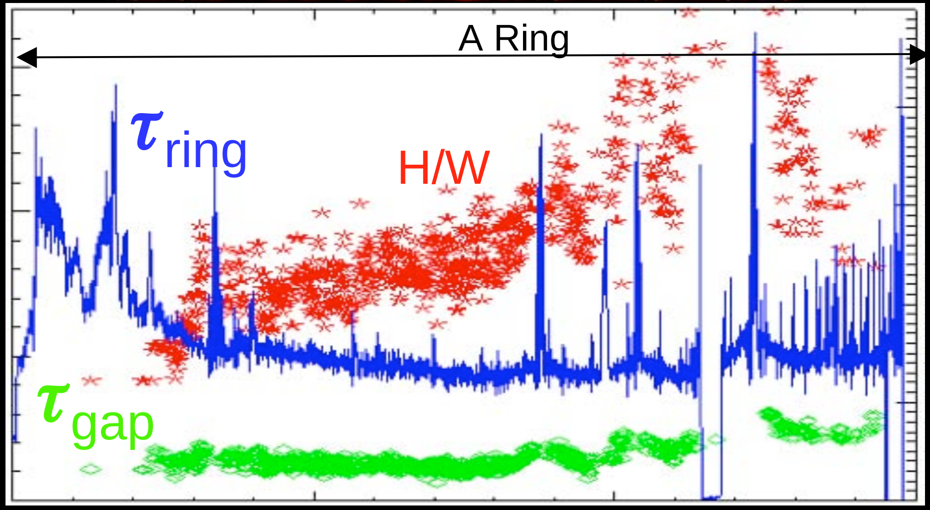
Dynamic processes responsible for ring structure: Self-Gravity wakes

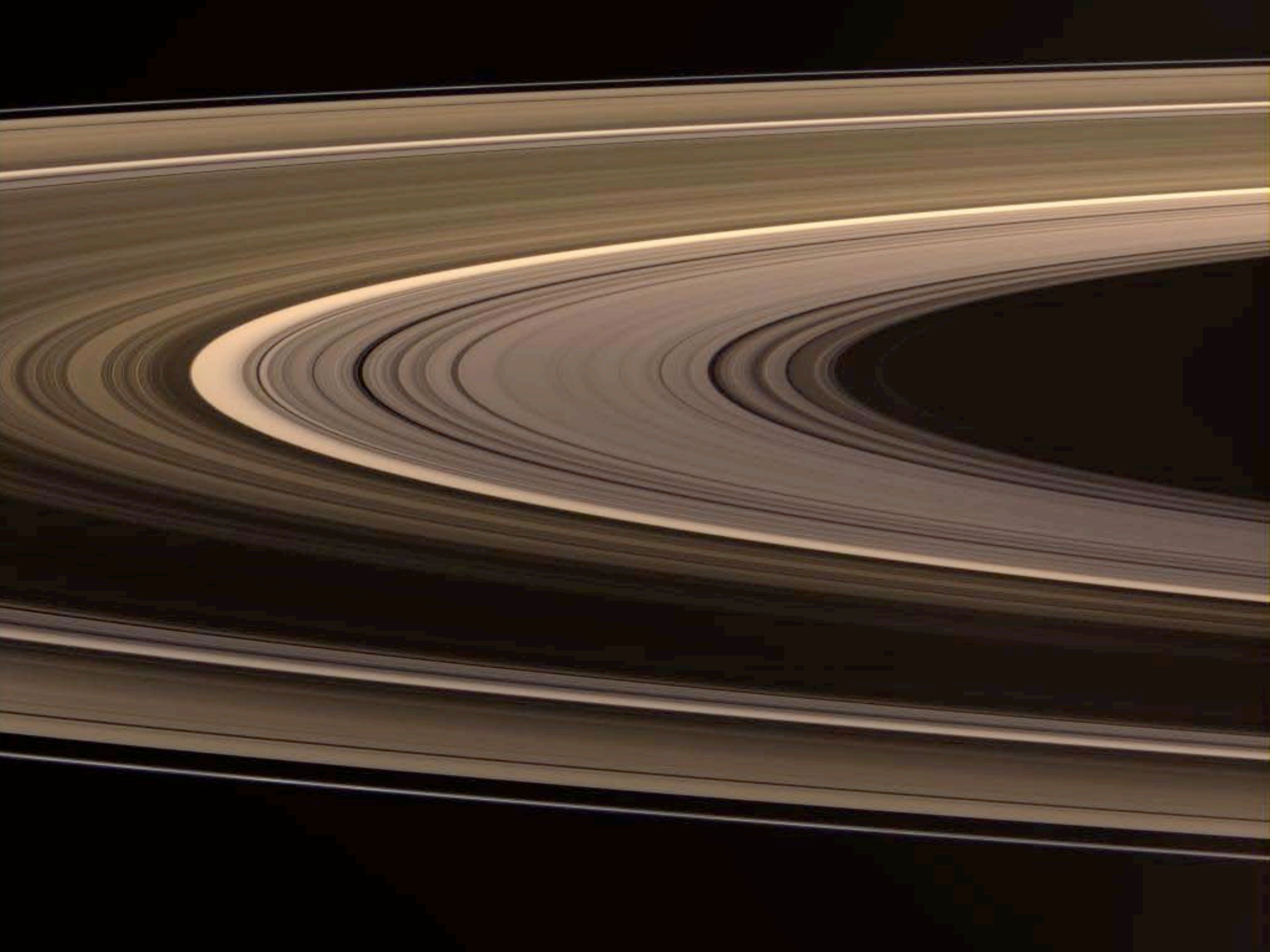




Stellar occultations by the rings give a 3D CAT-scan of ring microstructure on few-meter scales



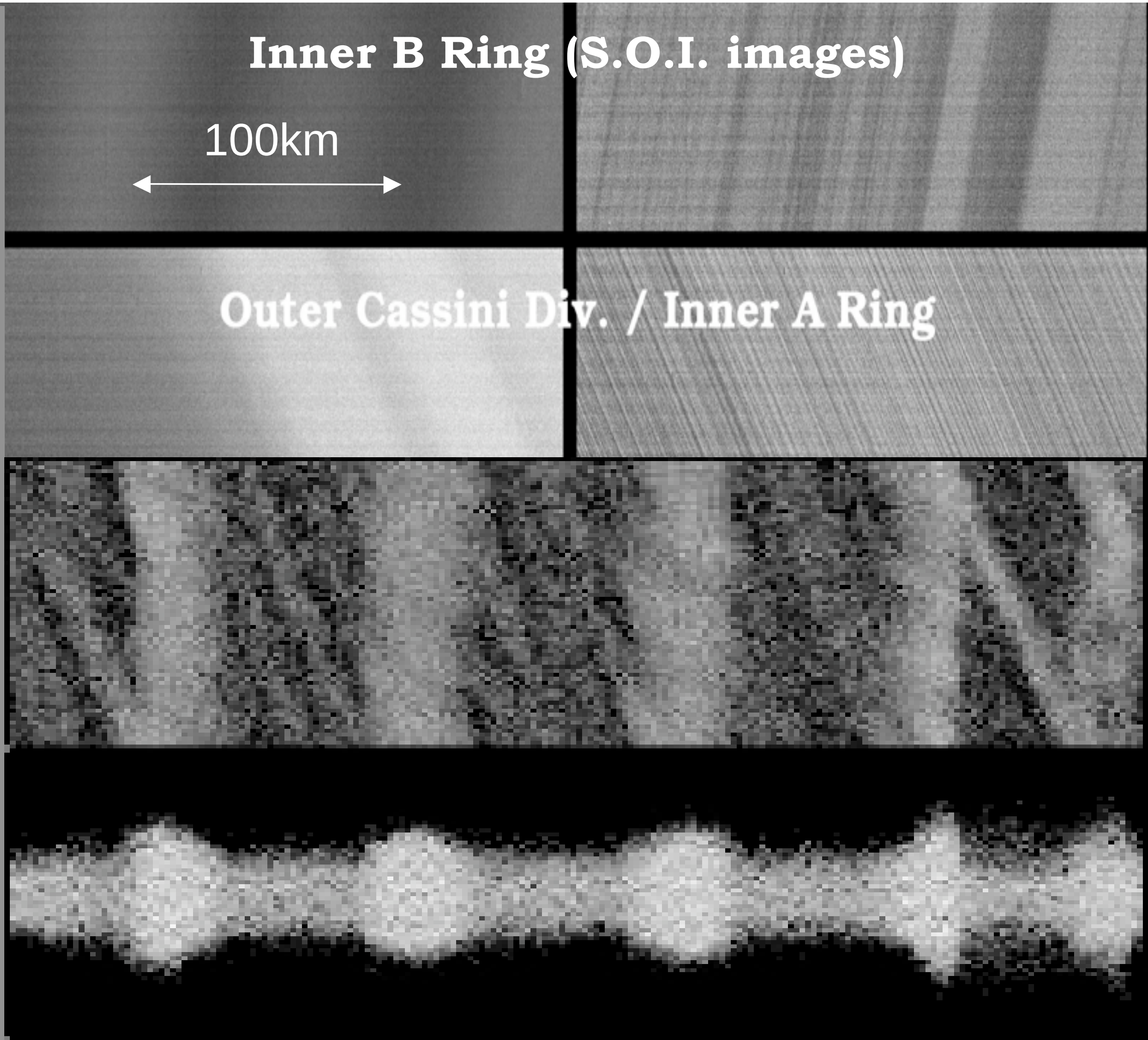




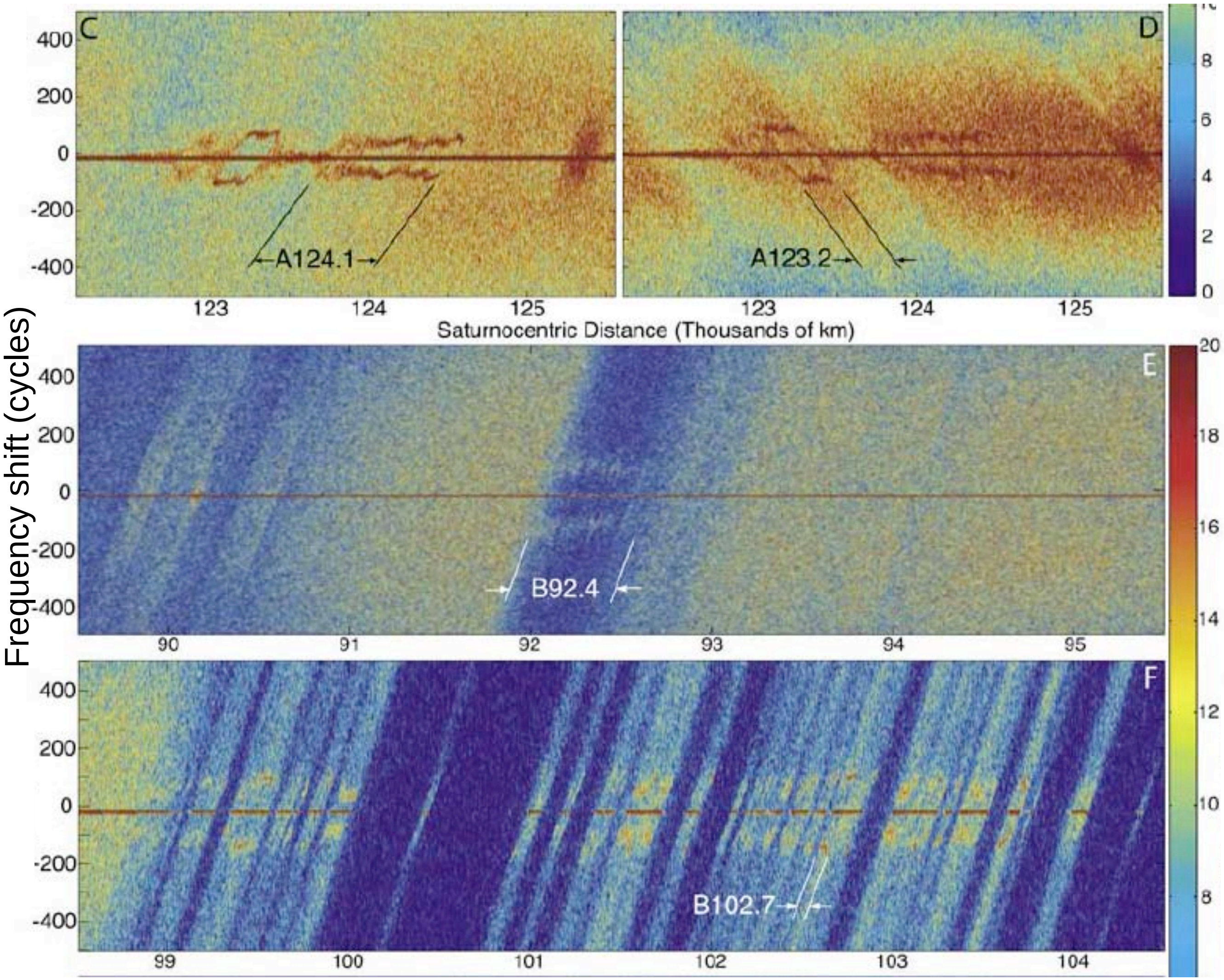
Dynamic processes responsible for ring structure: ultrafine radial structure

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



Feature Strength (db)

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).

Dynamic processes responsible for ring structure

Major results:

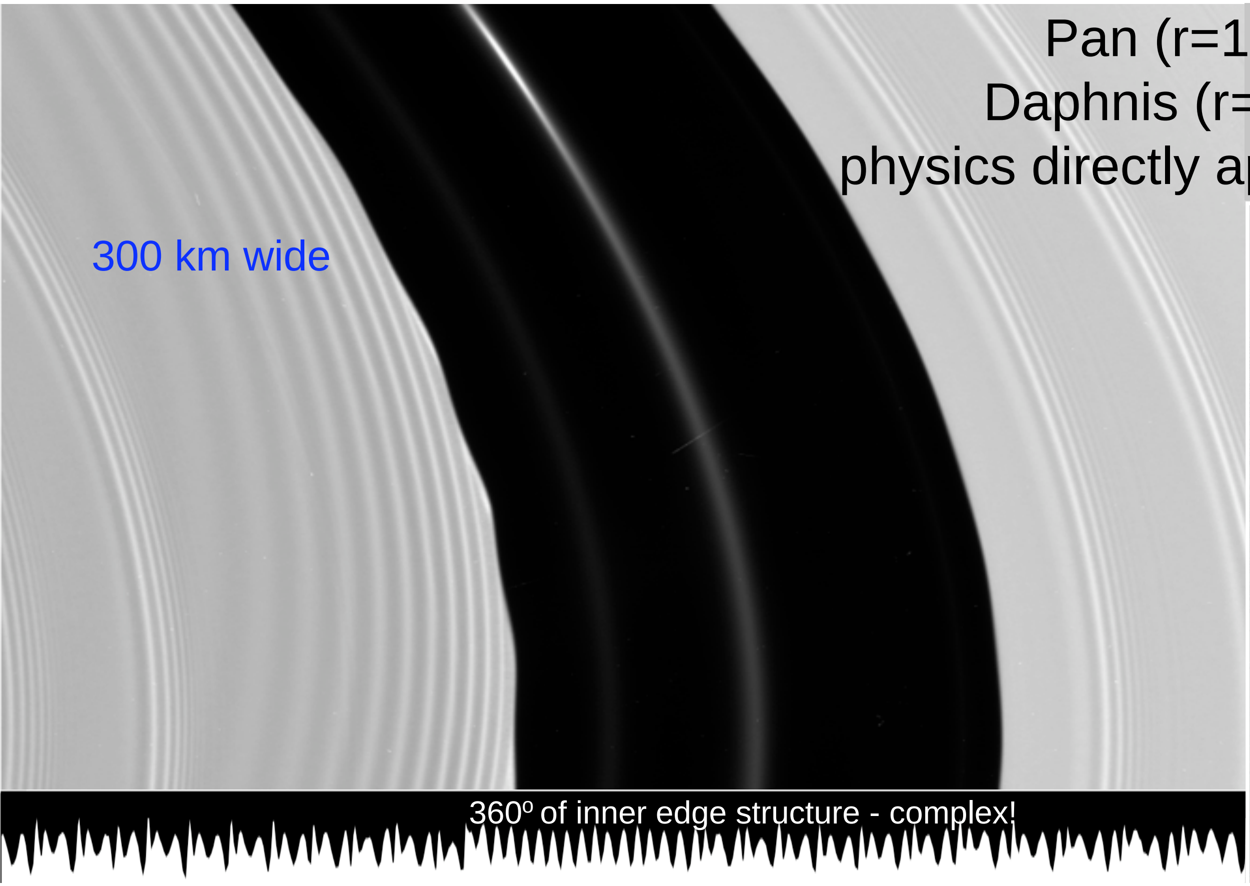
Cassini has extended our knowledge of radial structure into the most opaque ring regions, about which nothing was previously known. Spiral density and bending waves are becoming well enough understood to be a probe of underlying ring properties; other radial structure remains puzzling.

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.

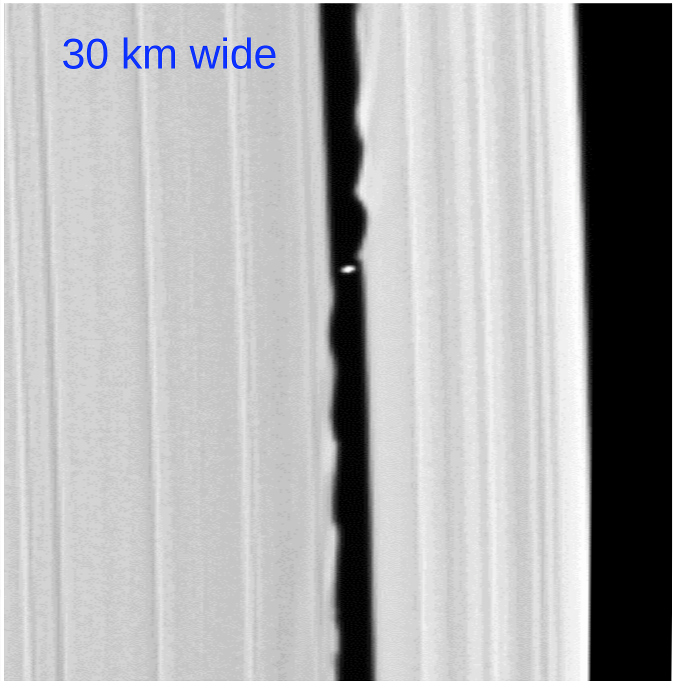
Most ring structure is the result of the interplay of the gravity of remote moons and/or local ring material with the fluid properties of the local material (viscosity and pressure), but some structure is driven electromagnetically and some by the feeble pressure of sunlight.

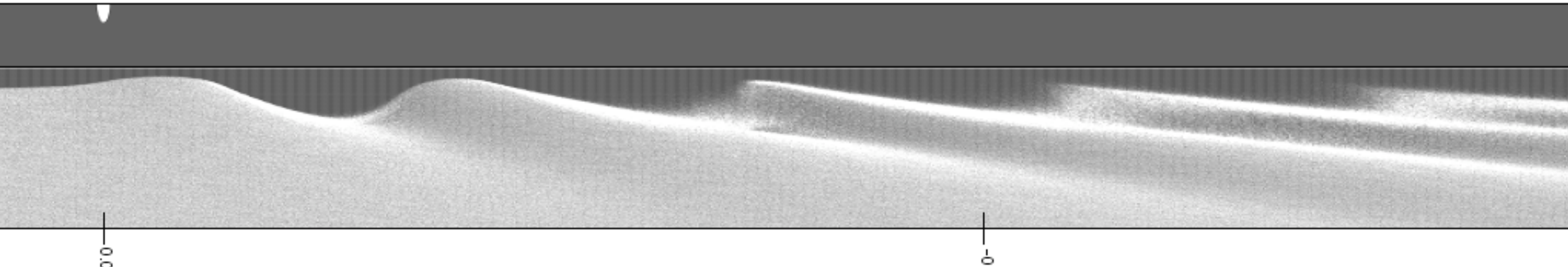
Inter-relationships of rings and satellites, including embedded satellites

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



360° of inner edge structure - complex!





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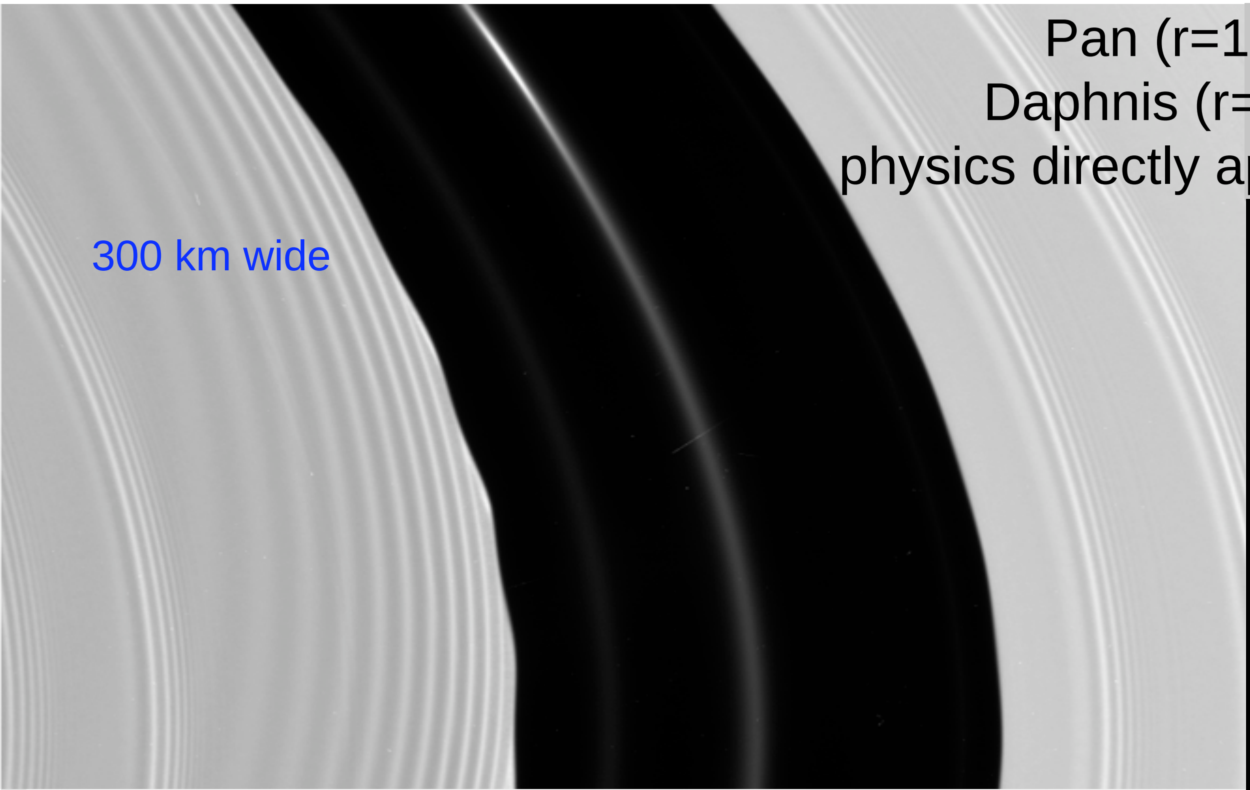

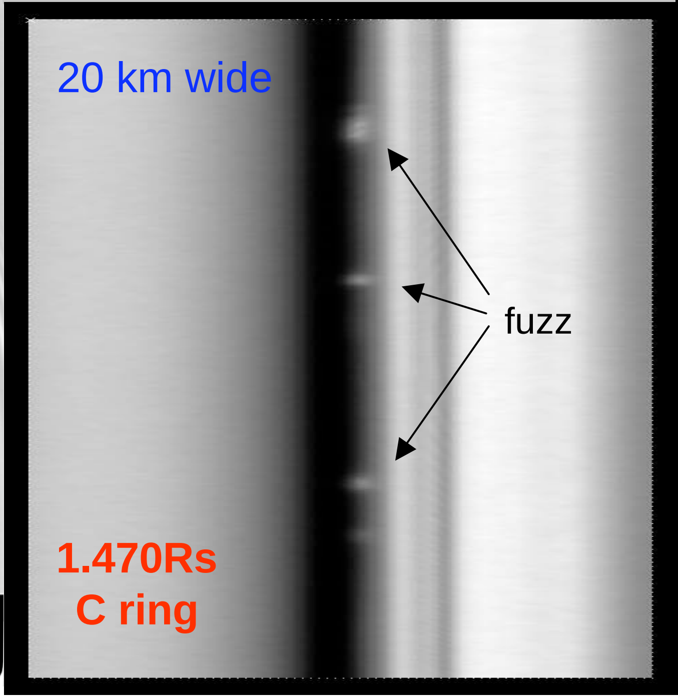


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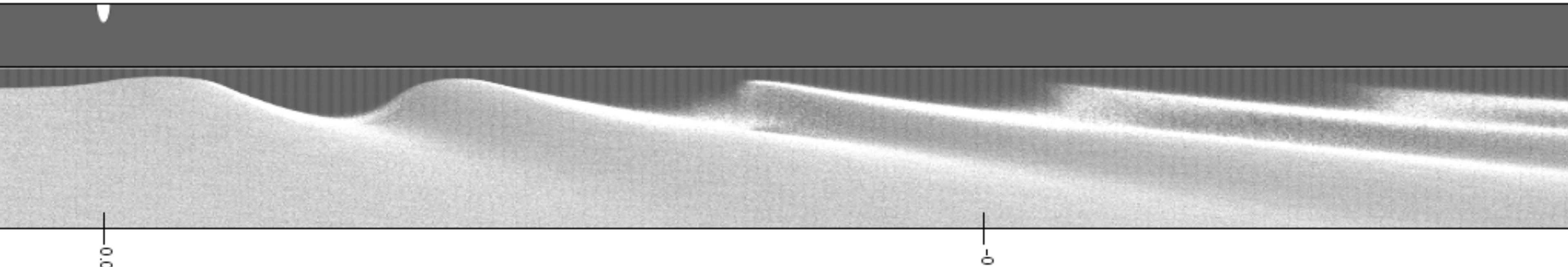
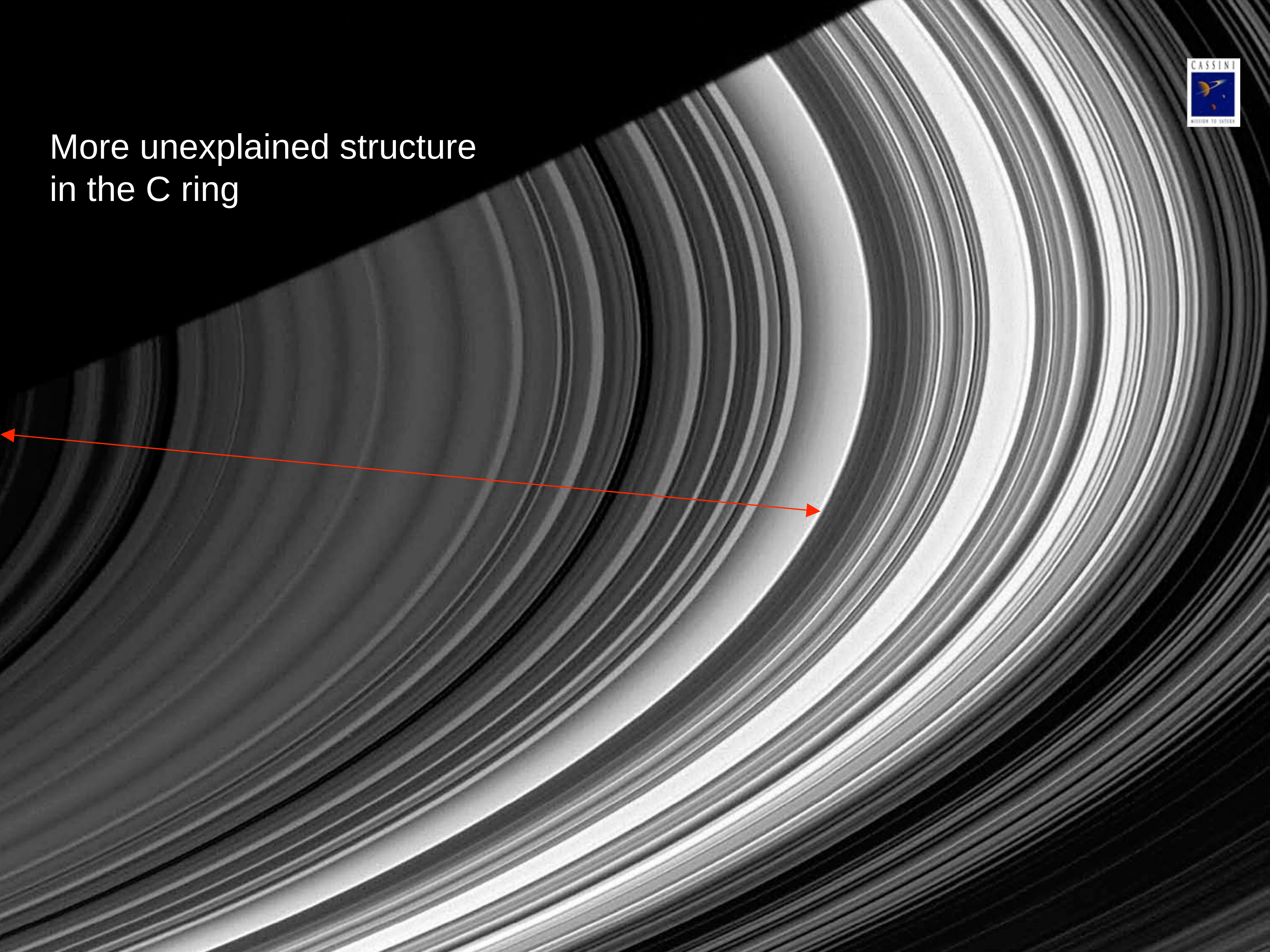


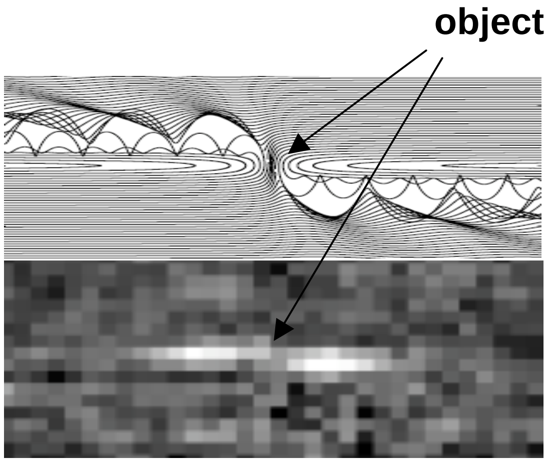
More unexplained structure in the C ring

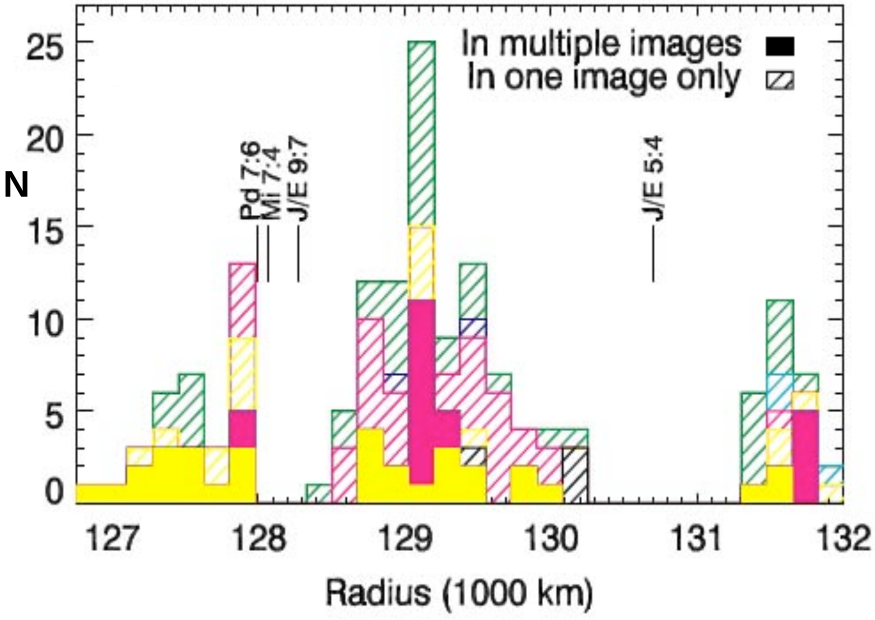


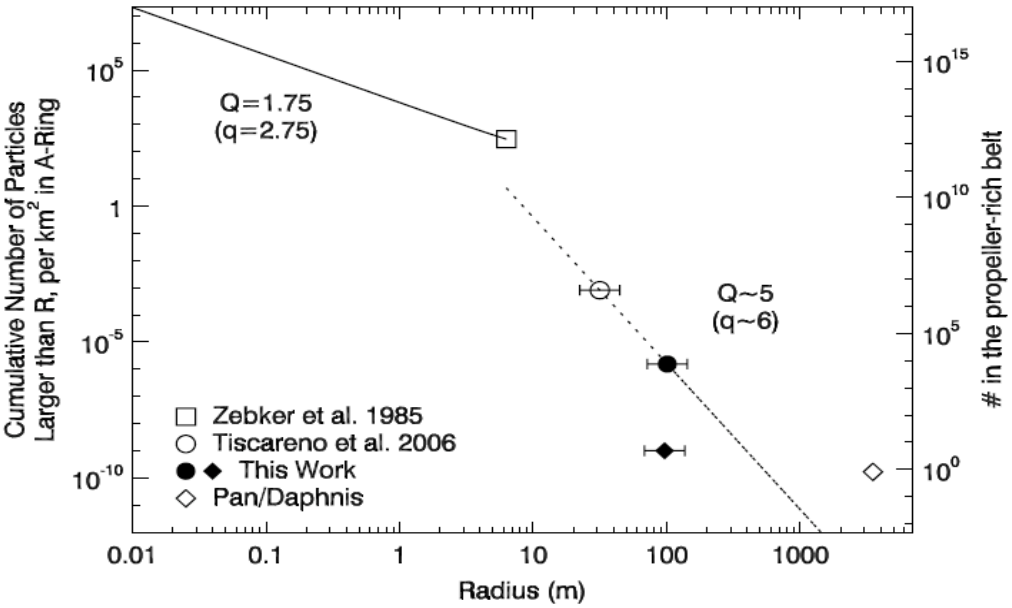
Inter-relationships of rings and satellites, including embedded satellites

Belts of “shards” in the A ring

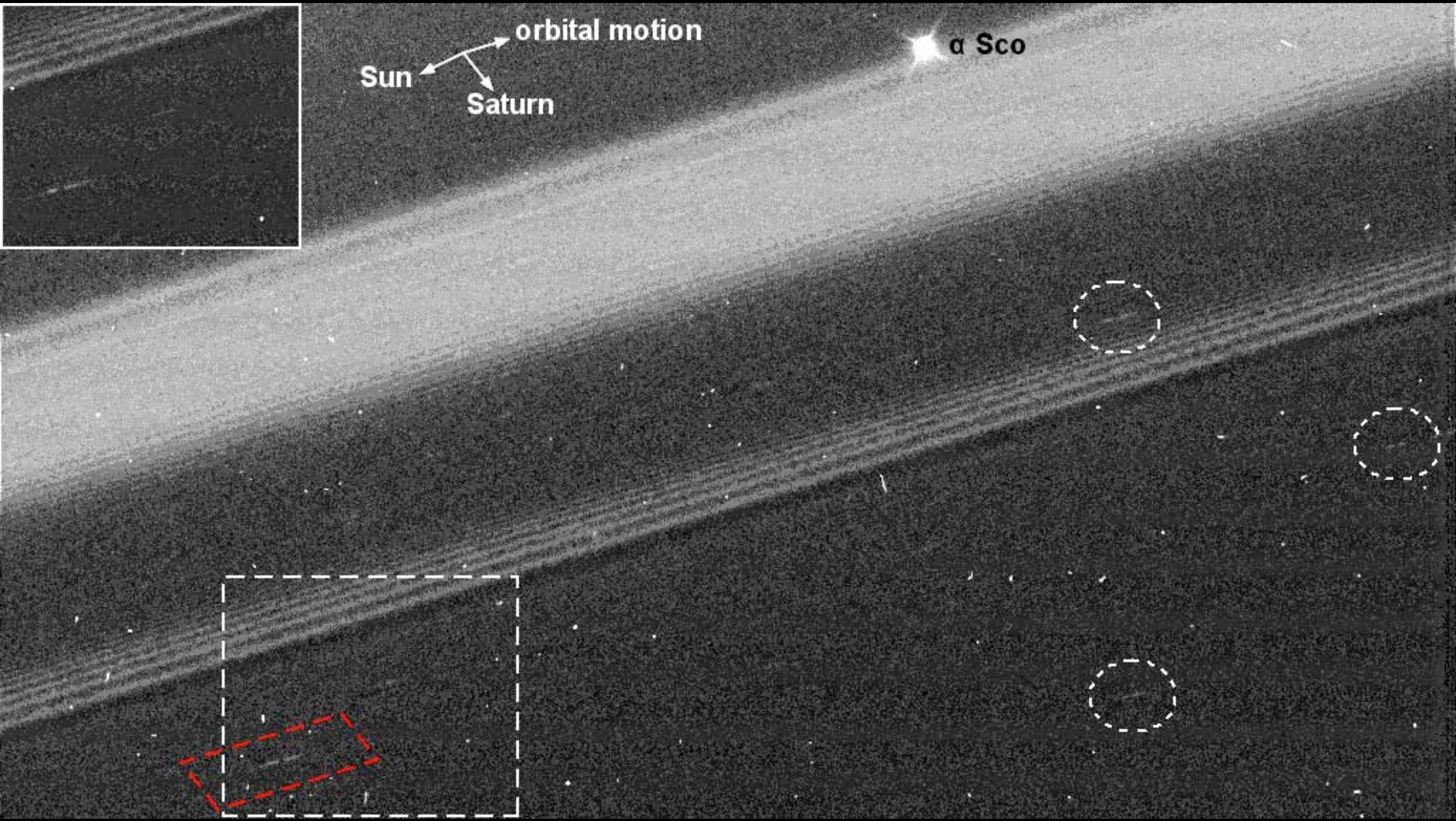
ISS observations of the A ring give indirect evidence for few-hundred-m size objects disturbing nearby ring material, and have shown that these objects populate three distinct bands in the outer A ring. It is not known if these objects are primordial “shards” or formed more recently in their local environment.



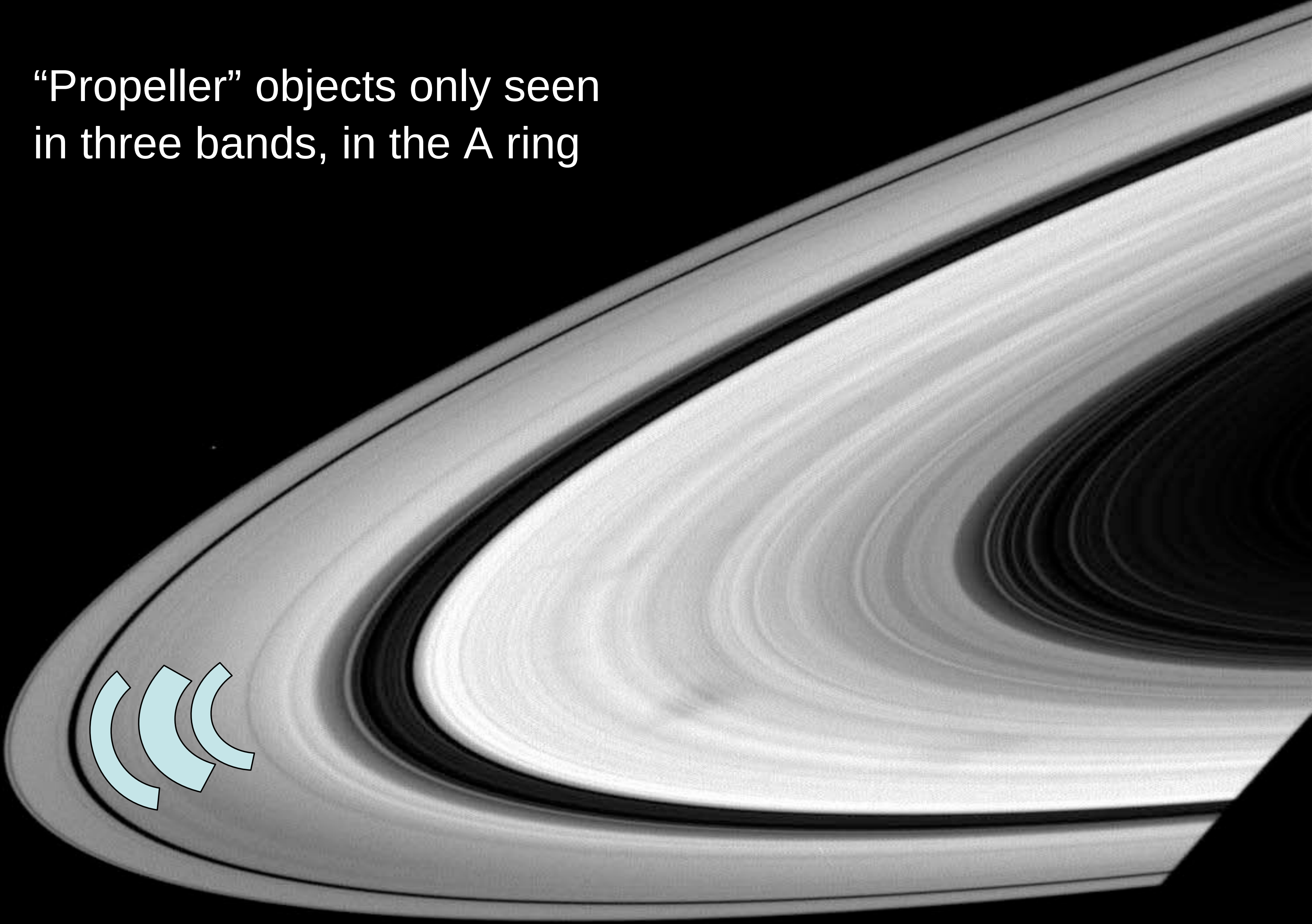




Typical appearance of “propeller” objects

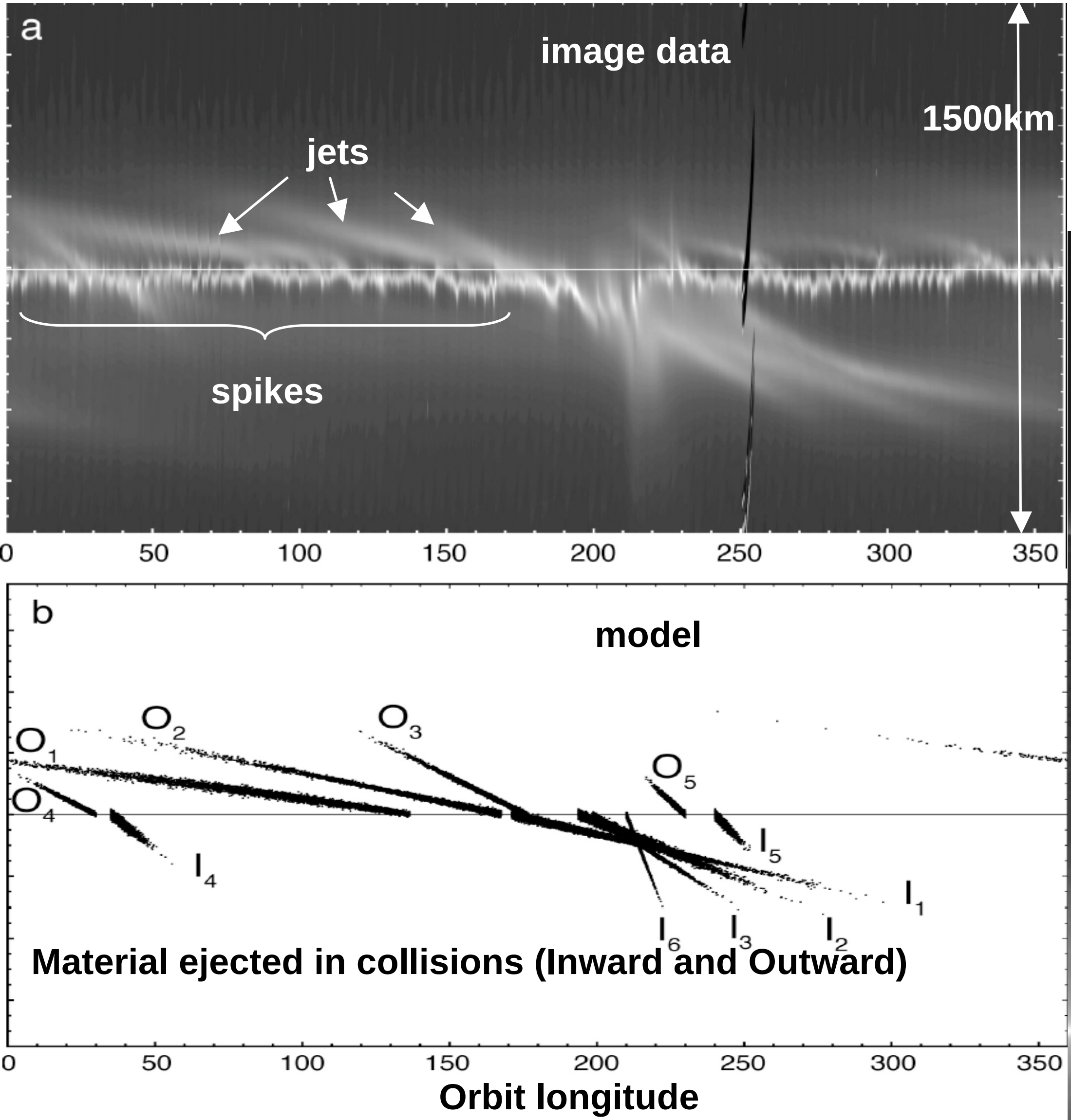


“Propeller” objects only seen in three bands, in the A ring

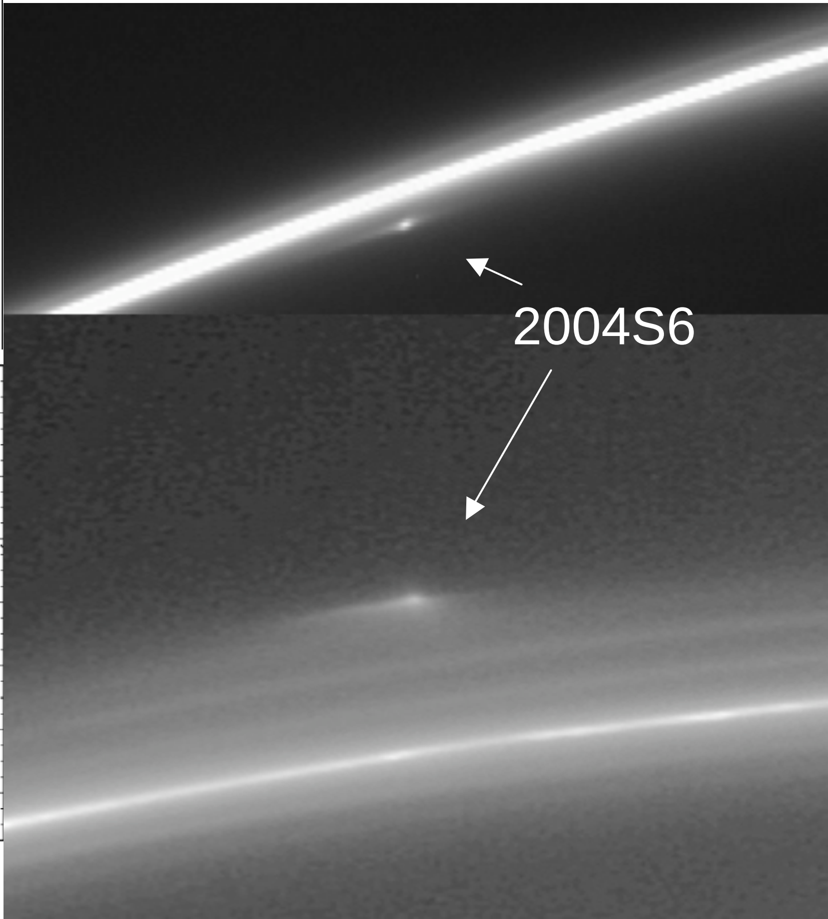


Inter-relationships of rings and satellites, including embedded satellites

F region contains numerous 1-10 km-size moonlets, which get excited by Prometheus and Pandora, and then disturb or collide with the ring strands

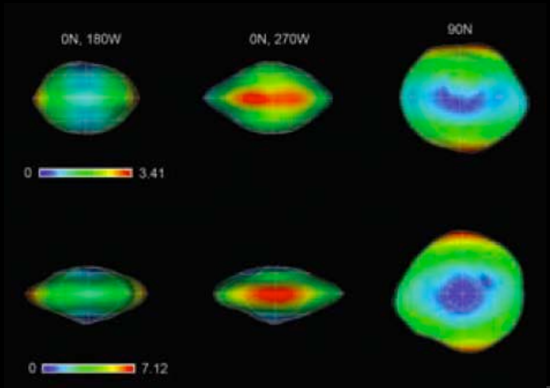


Below is one of these, 2004S6, having an eccentric orbit that crosses the F ring, leading to collisions with it



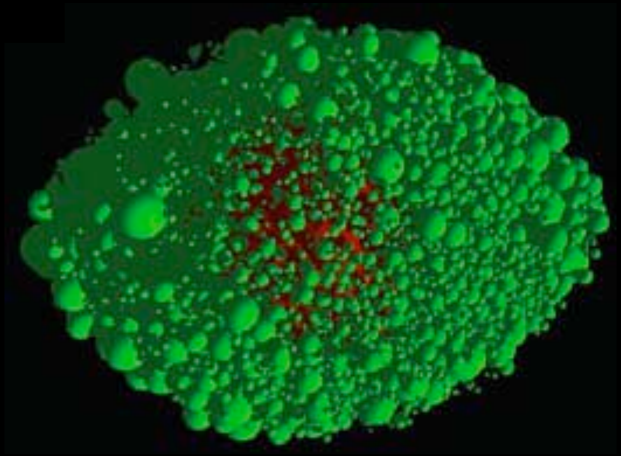
Inter-relationships of rings and satellites, including embedded satellites

All ringmoons are underdense, filling their “Roche lobes”, and are probably accretion-limited rubble piles with dense central cores



PAN

ATLAS



G ring contains an “arc” of rubble which supplies the dusty ring, and is in 7:6 corotational resonance with Mimas

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.

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.

Determine the dust and meteoroid distribution

Considerable progress on properties of dust in the Saturn system:

1) High-speed streams of tiny dust grains leaving the Saturn system were discovered far from Saturn (on approach), similarly to streams found leaving Jupiter.

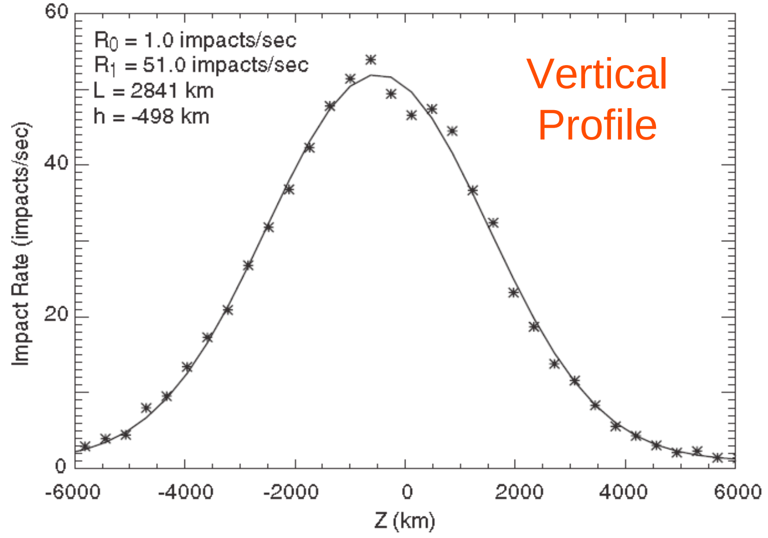
2) A density enhancement was found just outside Rhea’s orbit, of small grains which seem to be the source of the high-speed “dust streams”; these seem to be outwardly-evolving E ring grains that become resonantly trapped and eroded by sputtering until they are tiny enough to escape the system

3) The E ring is supplied by Enceladus. It extends out to Titan (at lower density) and has dust at higher elevation than previously known. It is “heliotropic” in that its apoapse follows the solar direction, as predicted by theory. The distribution of particle eccentricities is under study.

4) The grain size distributions in the D, E, F, and G rings are rather distinct

CDA: E-ring Dust Measurements *in situ*

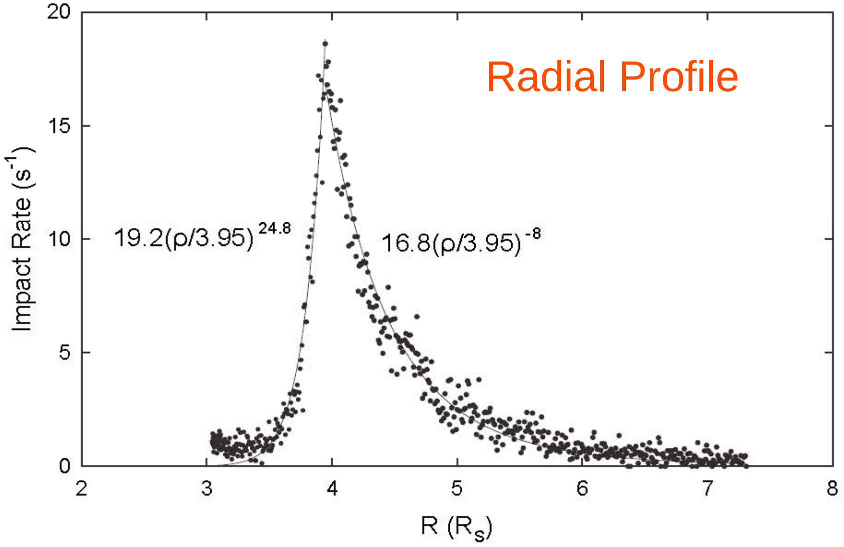
Cassini RPWS Gaussian Fit to Impact Rate
Orbit 7, May 2, Day 122, 2005



$R = R_0 + R_1 \exp\{-(z-h)^2/L^2\}$

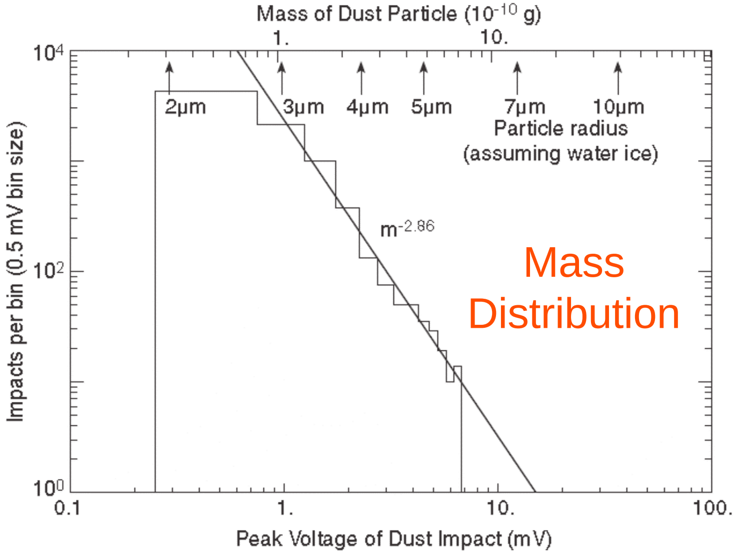
Vertical Profile

Cassini RPWS
Orbit 15, September 23, Day 266, 2005

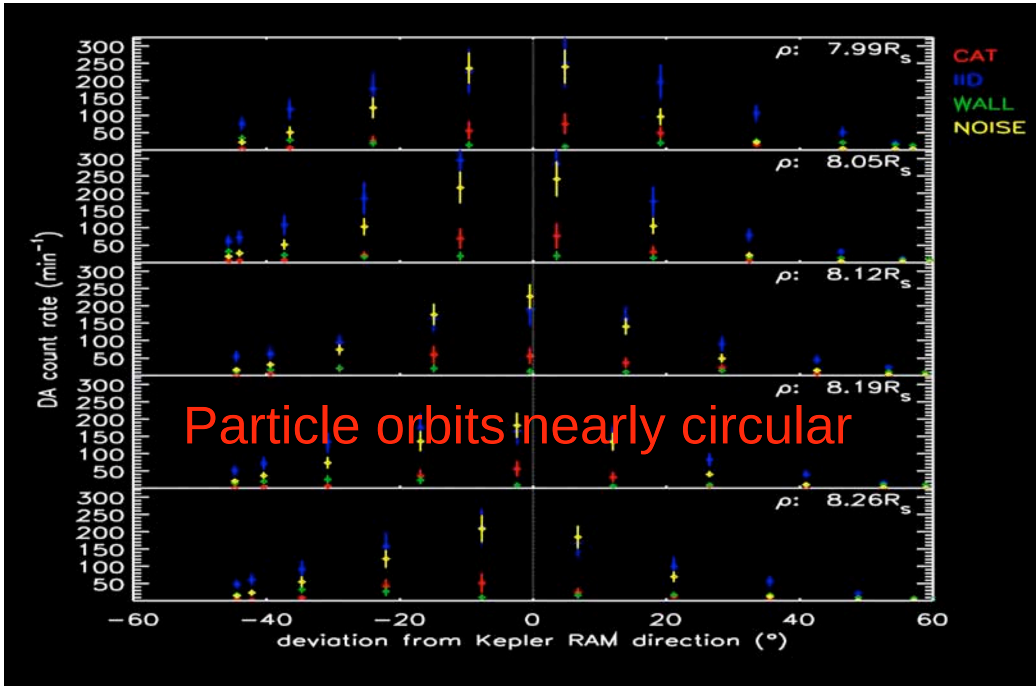


Radial Profile

RPWS Orbit 15 E ring Crossing Dust Size Distribution
16:00 - 19:00 September 23, Day 266, 2005

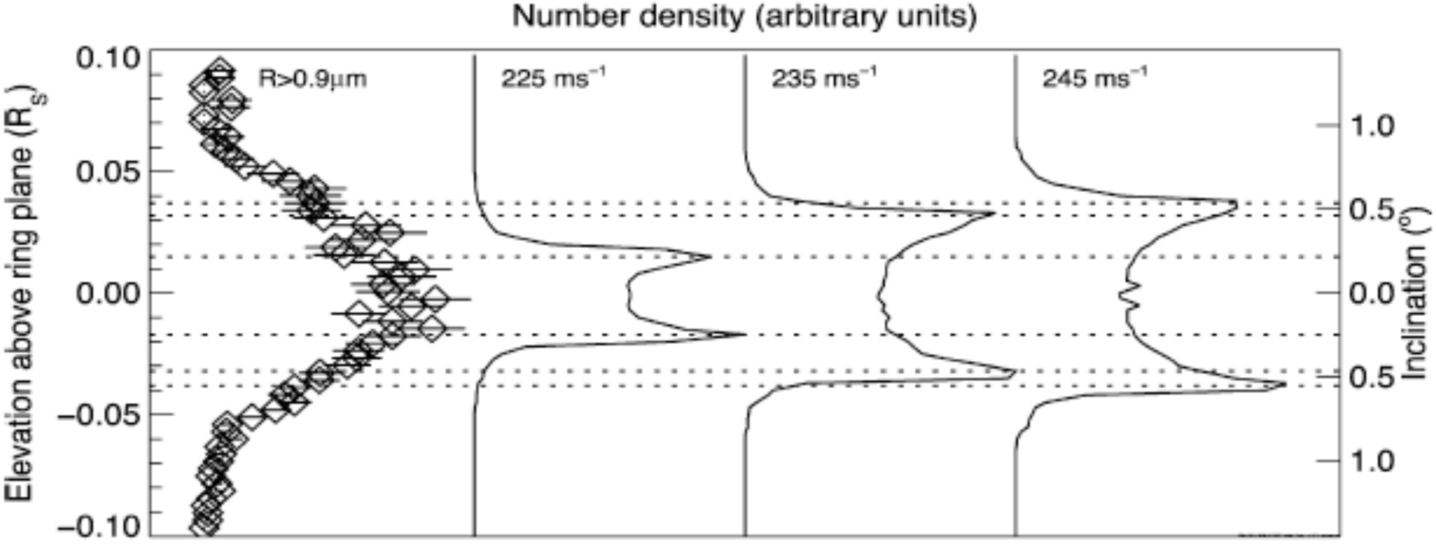


Mass Distribution



Particle orbits nearly circular

CDA measures vertical structure of E ring



- It is now thought that the entire E ring is maintained by water vapor and grains ejected by Enceladus. Constraints can be obtained on the ejection speed of the material, which can constrain the temperature at the source, from the vertical structure of the ring. Models show (curves at right) and ISS observations hint at a double peaked vertical structure, but CDA sees a smooth Gaussian generally. This might be explained by a velocity distribution instead of a single ejection velocity. In addition, numerous vertical profiles of the E ring near other icy satellites have been obtained (Kempf et al 2008).

Determine the dust and meteoroid distribution

However, a key objective remains to be achieved:

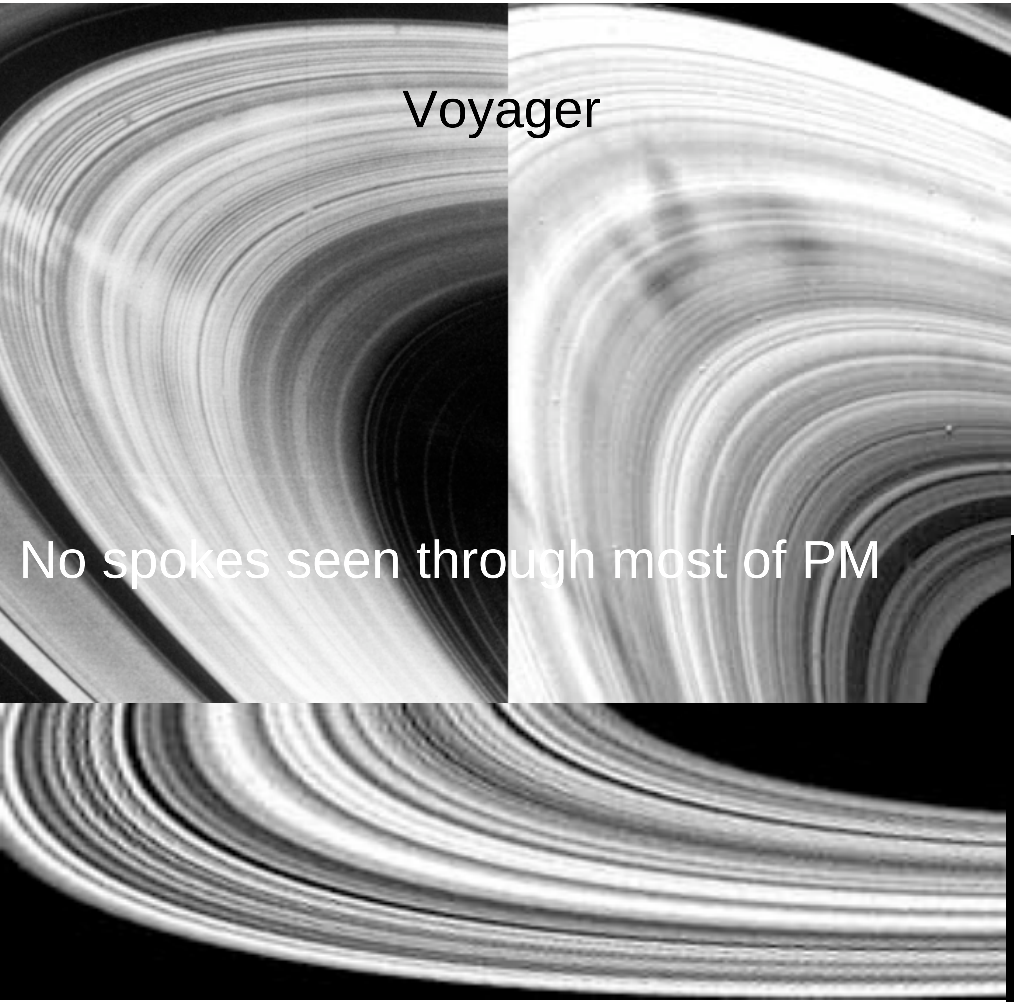
1) Spacecraft orientation restrictions precluded measurement of interplanetary flux during cruise, and while in tour, flux is dominated by Saturn-system material (E ring, *etc.*)

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)

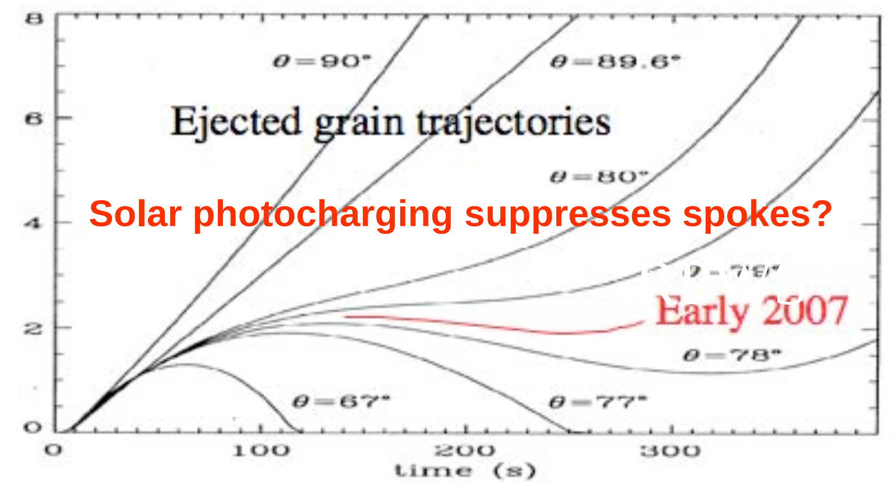
Ring-magnetosphere, -ionosphere, and -atmosphere interactions



Voyager

No spokes seen through most of PM

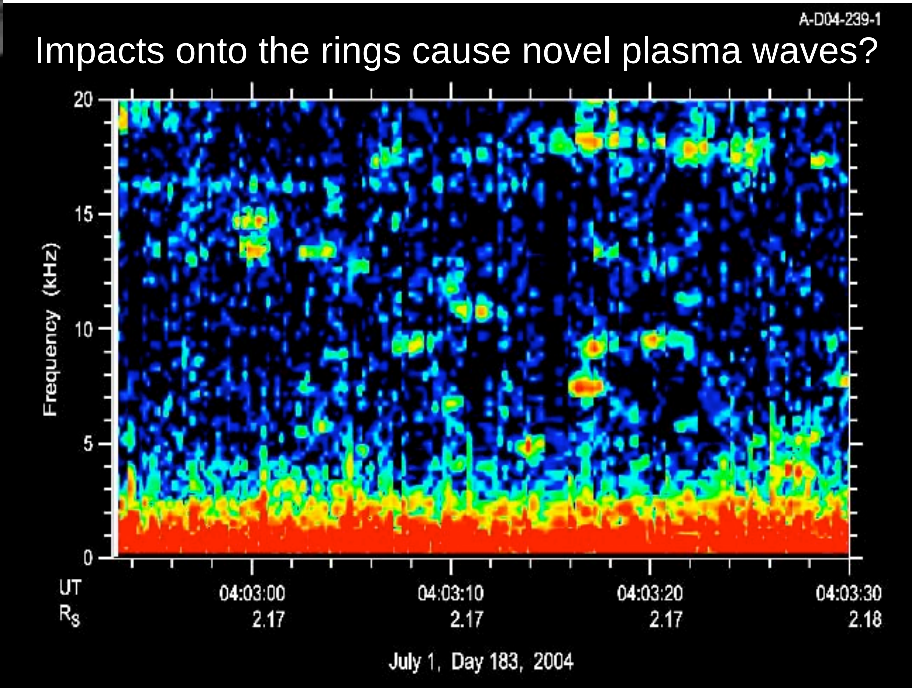
New type of electromagnetic (Lorentz) resonance seen in D, A-F regions might help constrain slipping SKR period



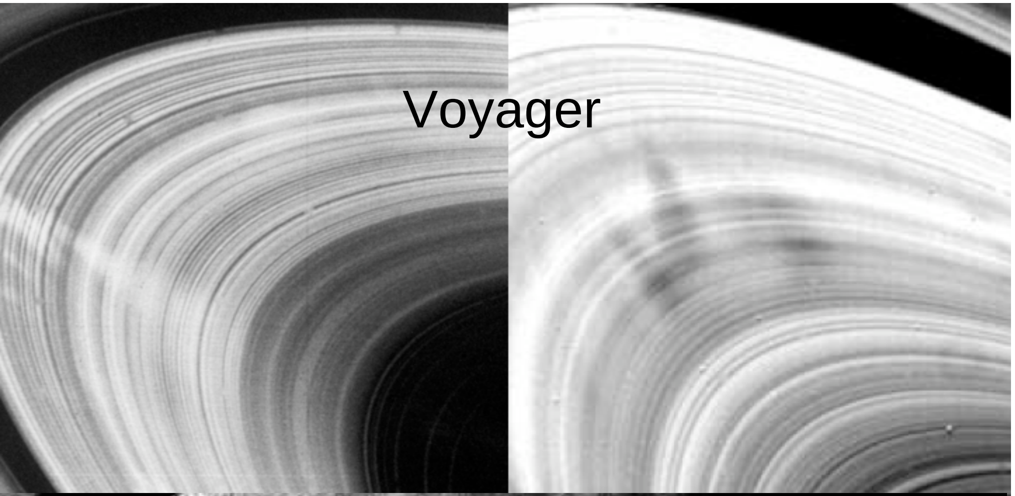
Solar photocharging suppresses spokes?

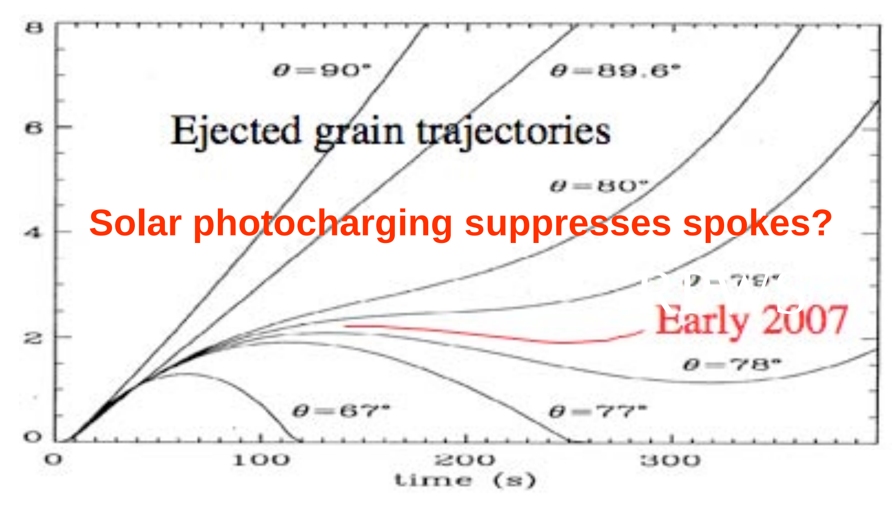
Early 2007

Impacts onto the rings cause novel plasma waves?



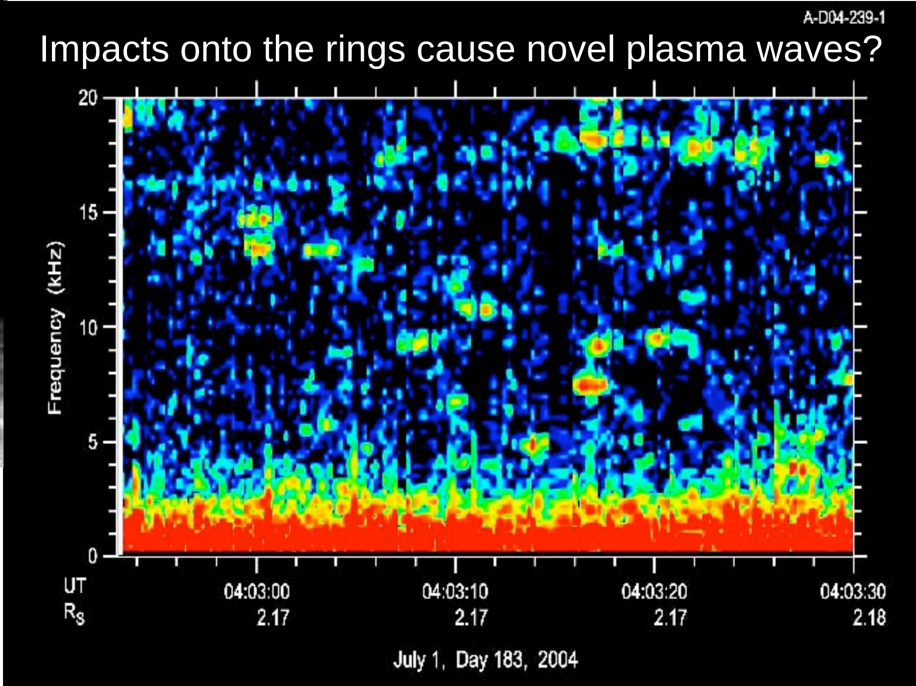
Ring-magnetosphere, -ionosphere, and -atmosphere interactions


Voyager



Solar photocharging suppresses spokes?


Cassini is starting to see spokes again.


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

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.

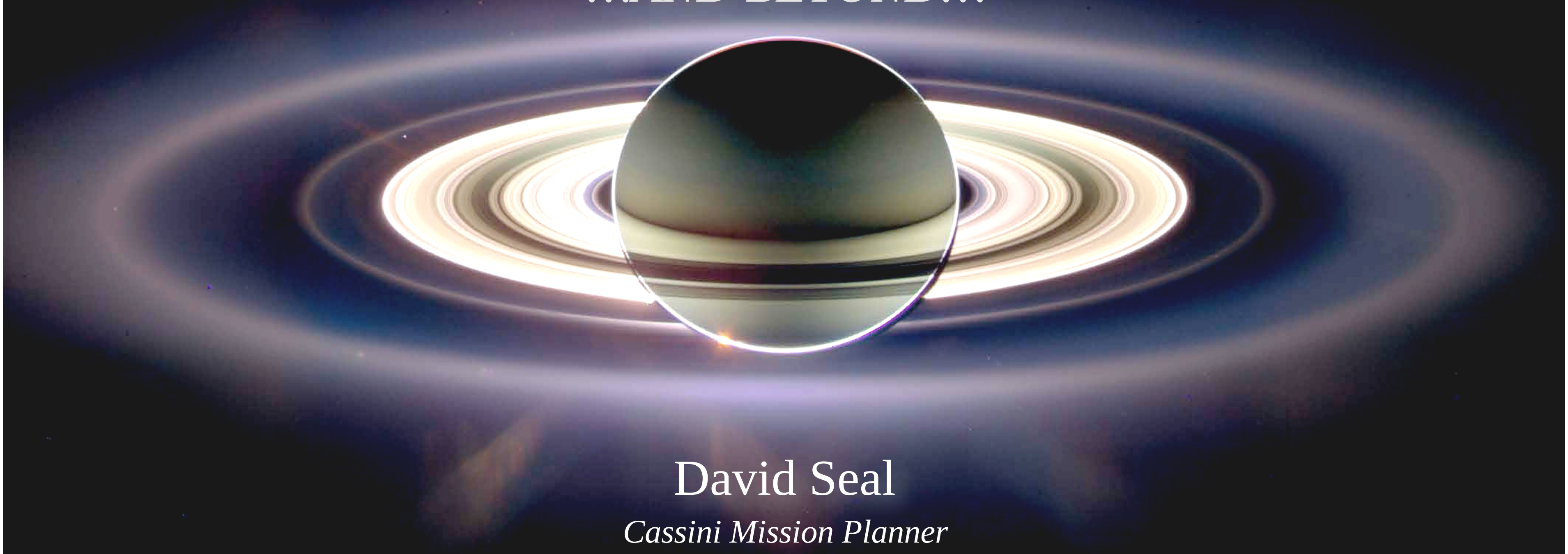
Ring composition is our best clue to ring origin; however, evidence and theory suggests ring composition has evolved with time. Recently emerging challenge to traditional interpretation of “redness” as organics. Need a better measurement of meteoroid flux to determine ring age.

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

THE CASSINI EQUINOX MISSION

…AND BEYOND…



David Seal

Cassini Mission Planner
CHARM Four-Year Anniversary

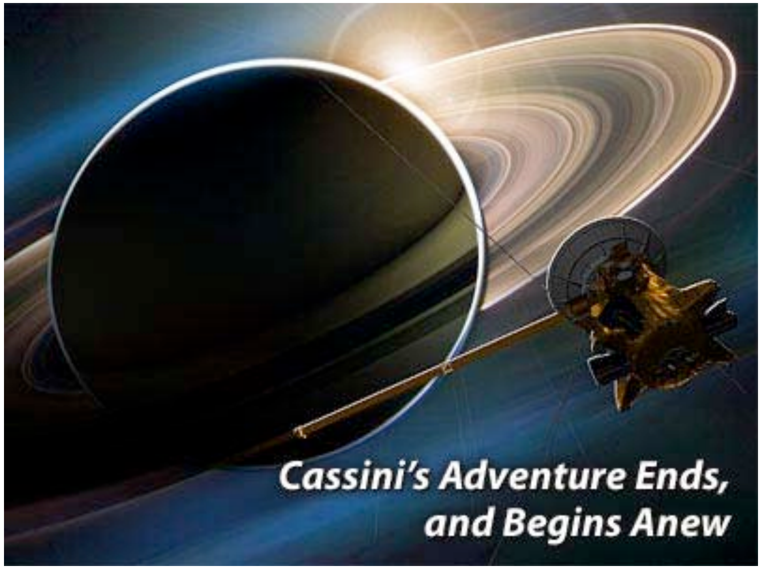
Why an Extended Mission

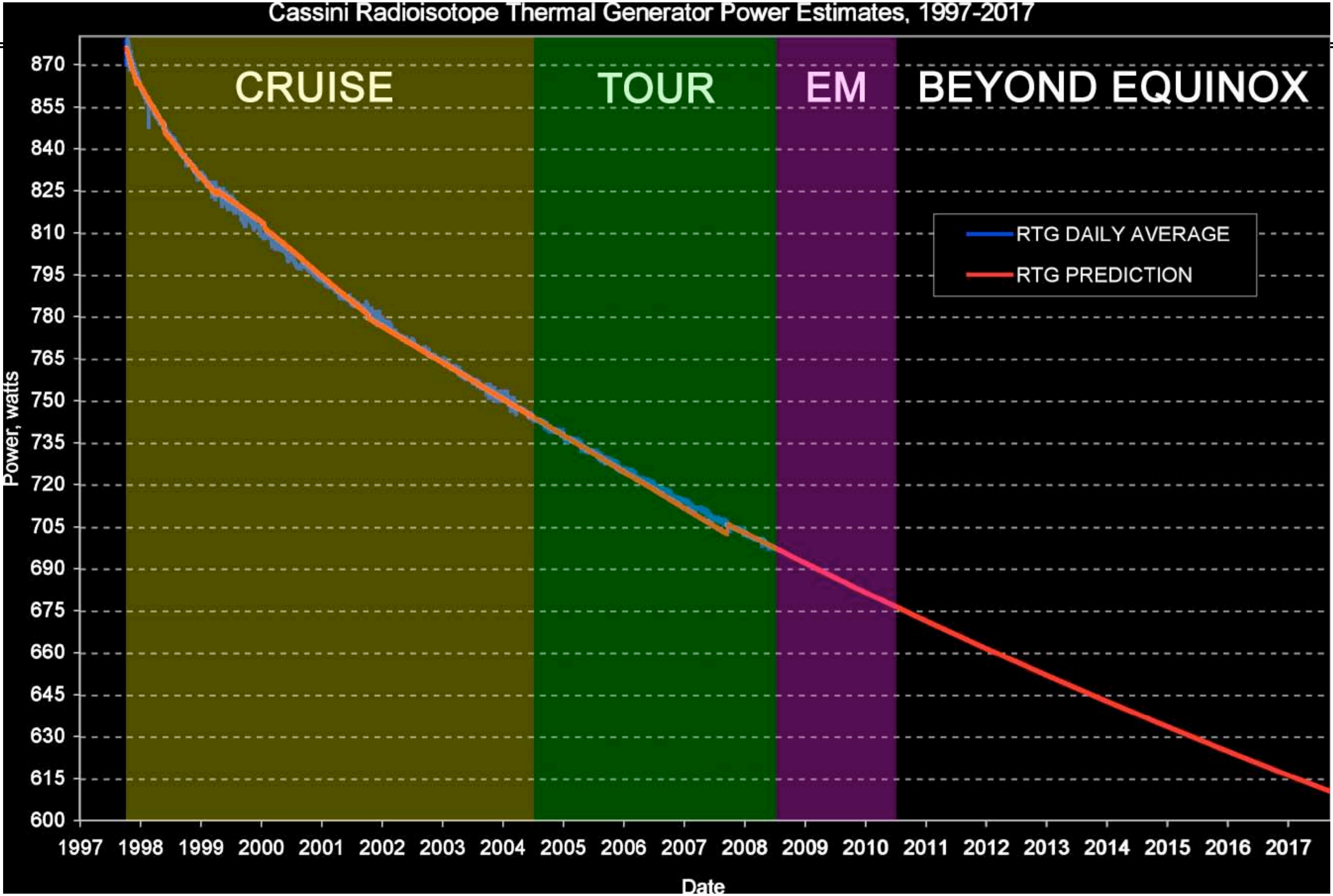
- Successful arrival, Huygens mission
- Full spacecraft and instrument health
- Substantial propellant margins
- Enceladus’ plume & other
- discoveries
- Target-rich environment
- Proven operability of most
- complex gravity-assist tour

- NASA HQ: explore two-year extension

Science Objectives

- Temporal - for seasonal studies or to increase time baseline
- Spatial - to complete coverage by attaining un- or poorly-sampled geometries
- Response to discoveries
- Round out PM objectives




Cassini Radioisotope Thermal Generator Power Estimates, 1997-2017
CRUISE
TOUR
EM
BEYOND EQUINOX
RTG DAILY AVERAGE
RTG PREDICTION
Power, watts
870
855
840
825
810
795
780
765
750
735
720
705
690
675
660
645
630
615
600
1997
1998
1999
2000
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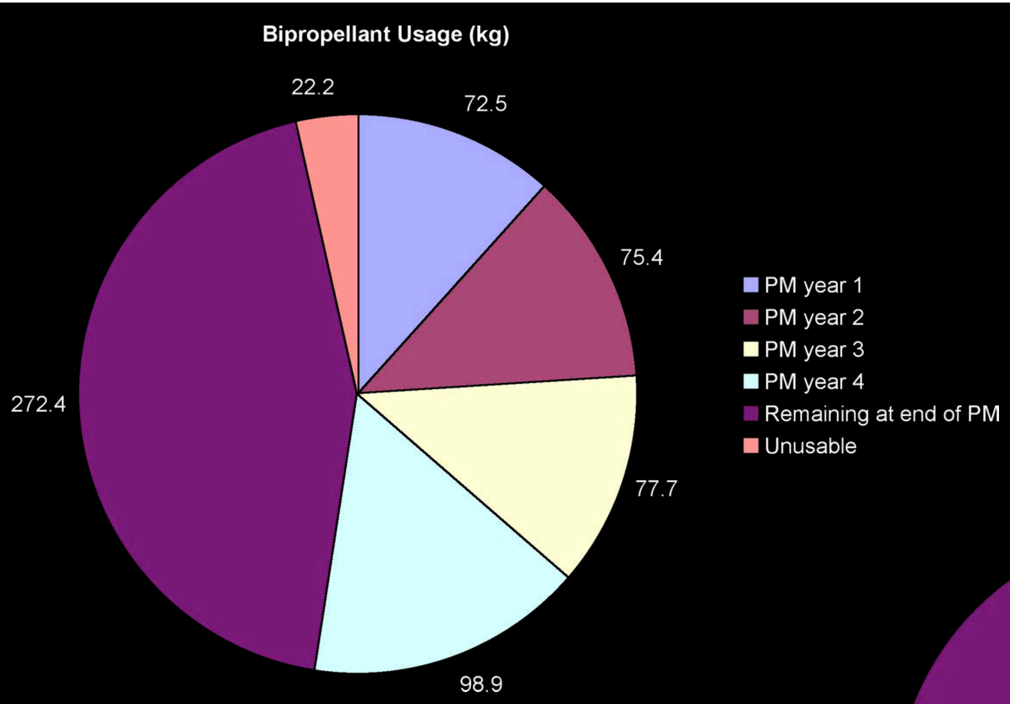
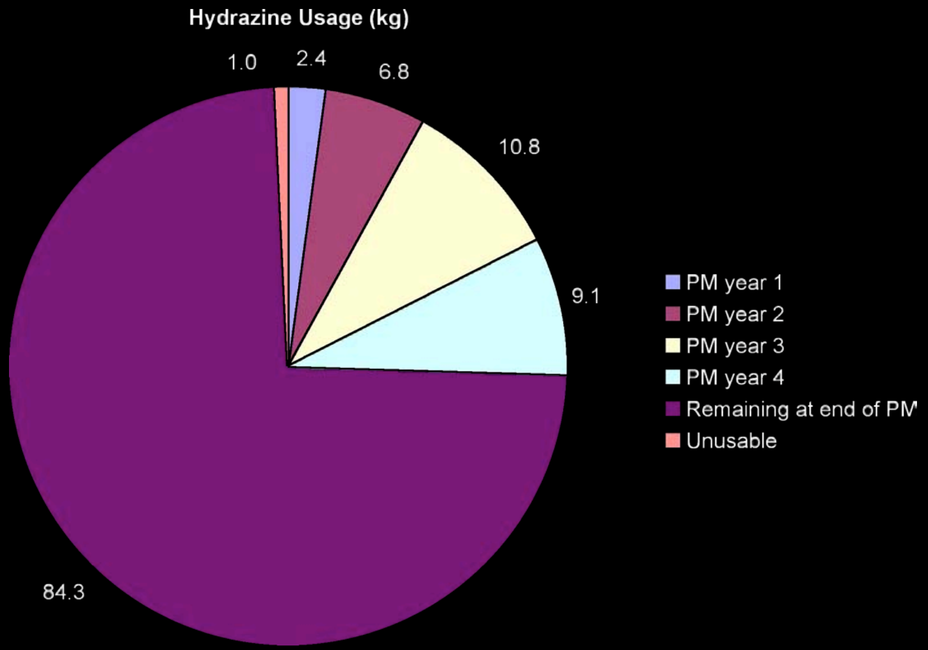
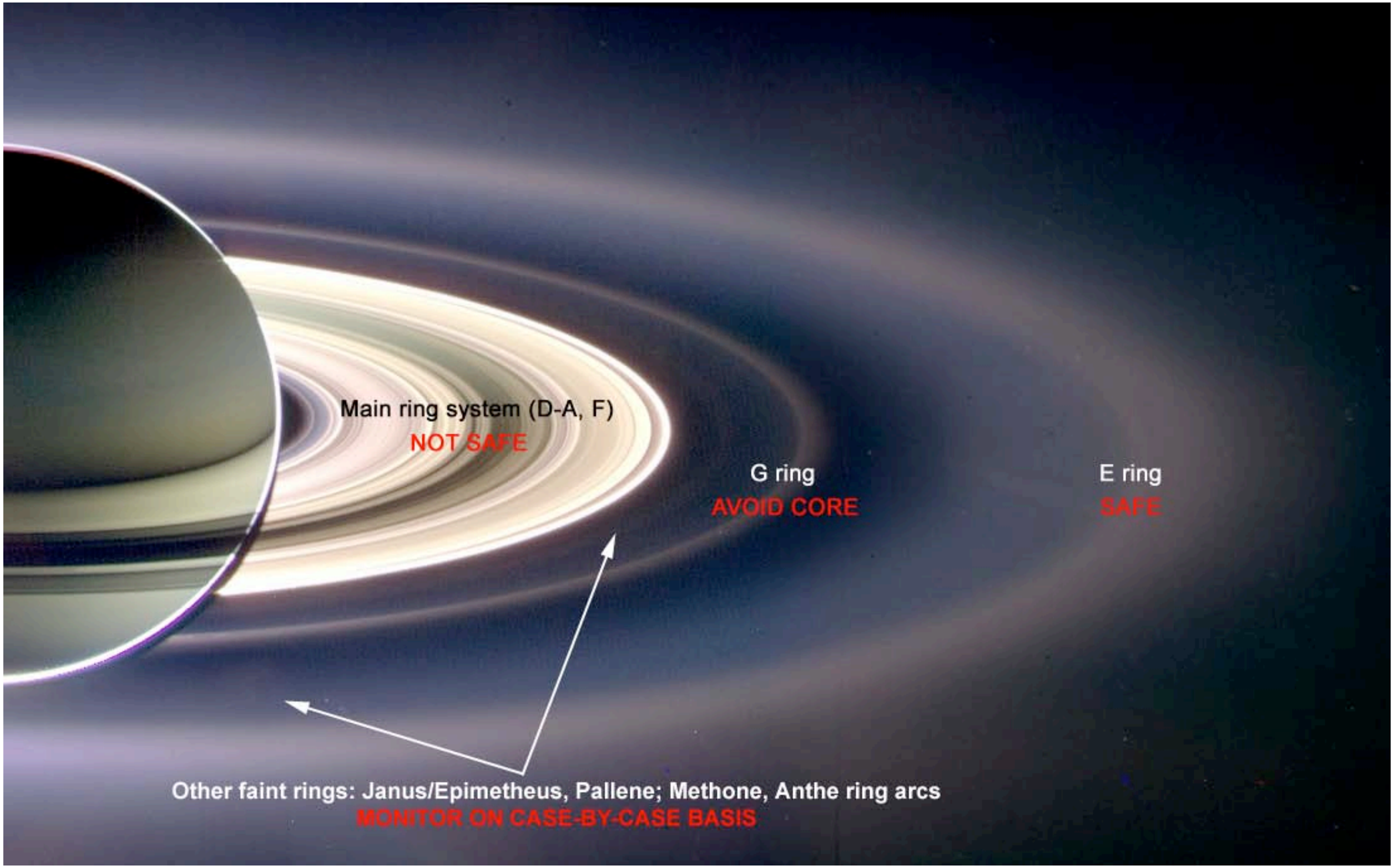
2014
2015
2016
2017
Date

Consumables

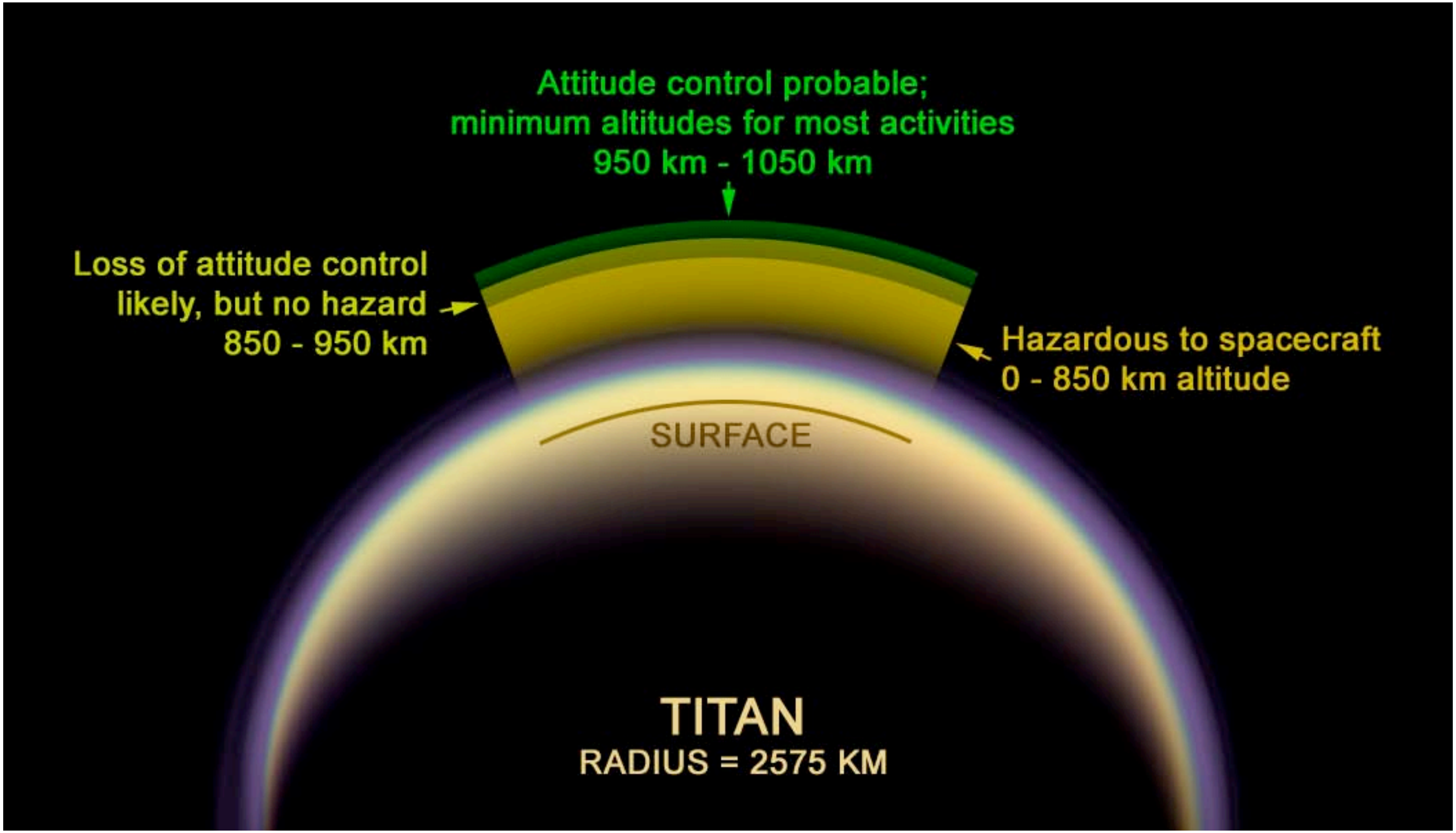




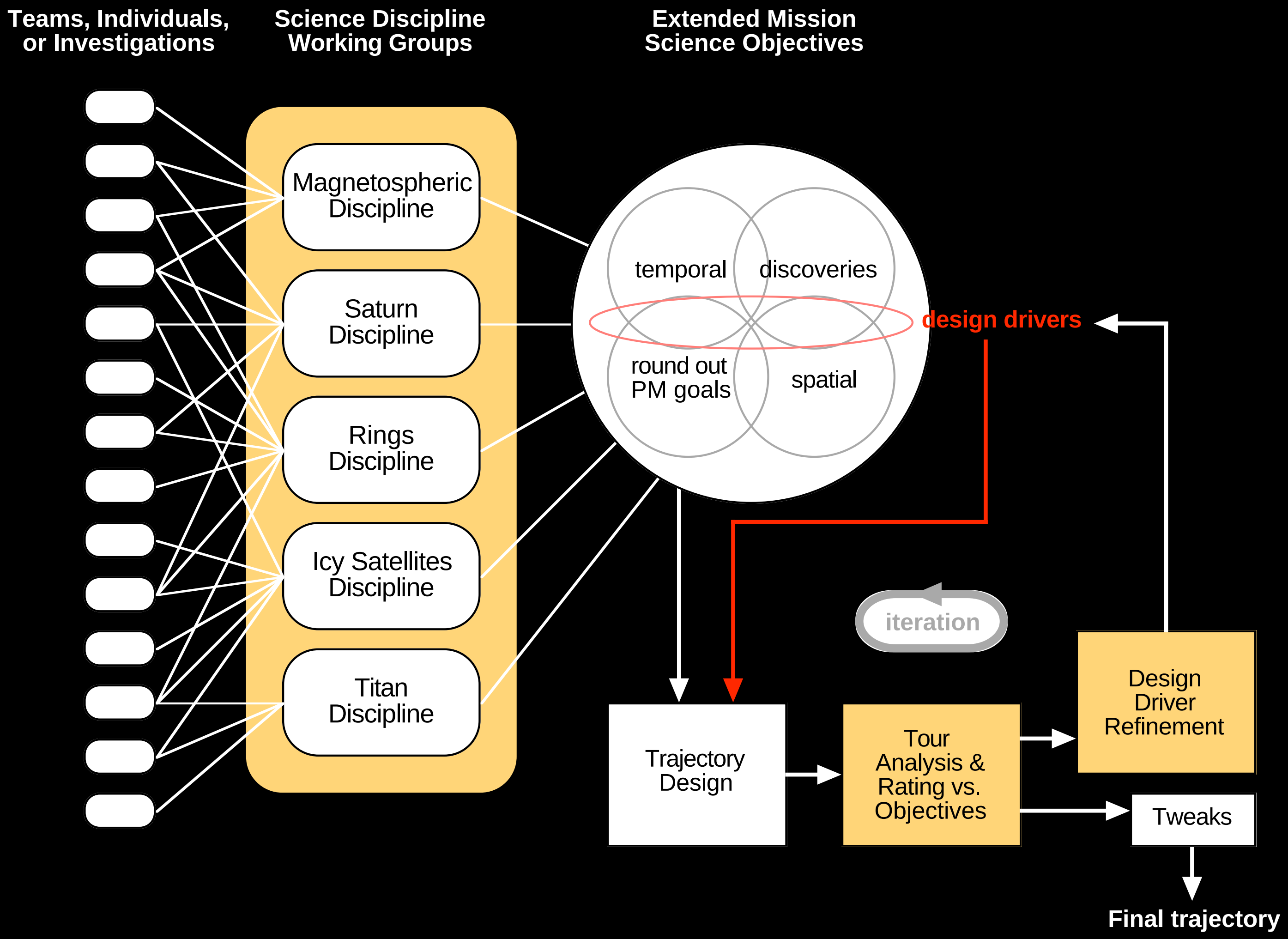
Environment - Dust Hazards



Environment - Titan Atmosphere



Tour Design Process

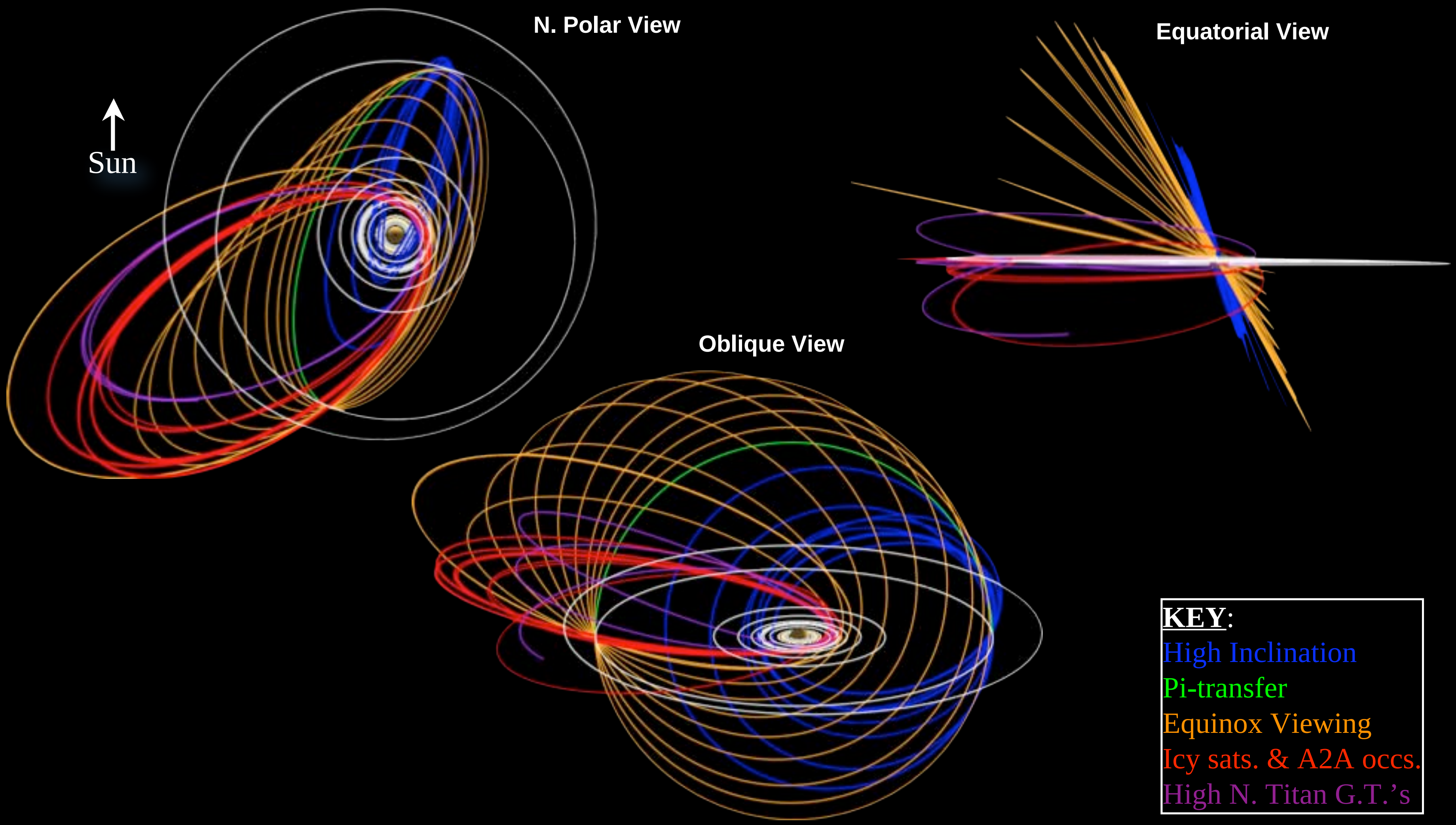


Cassini Mission Overview

Four-Year Prime Tour + Two-Year Equinox Mission, July 2004 - July 2010

					Equinox Mission		
Year of Tour	1	2	3	4	5	6	??
Orbits	11	15	22	27	39	21	
Titan	● ● ●* ● ● ● *Huygens Mission	● ● ● ● ● ● ● ● ●	● ● ● ● ● ● ● ● ● ● ● ● ● ● ● ● ● ● ●	● ● ● ● ● ● ● ● ● ● ●	● ● ● ● ● ● ● ● ● ● ● ● ●	● ● ● ● ● ● ● ● ● ● ● ● ●	
Enceladus	● ●	●		●	● ● ●	● ● ● ●	
Other Icy Satellites (under 10,000 km)	Phoebe	Tethys Hyperion Dione Telesto Rhea		Rhea Iapetus Epimetheus		Mimas Rhea Helene Dione	

The XM Trajectory



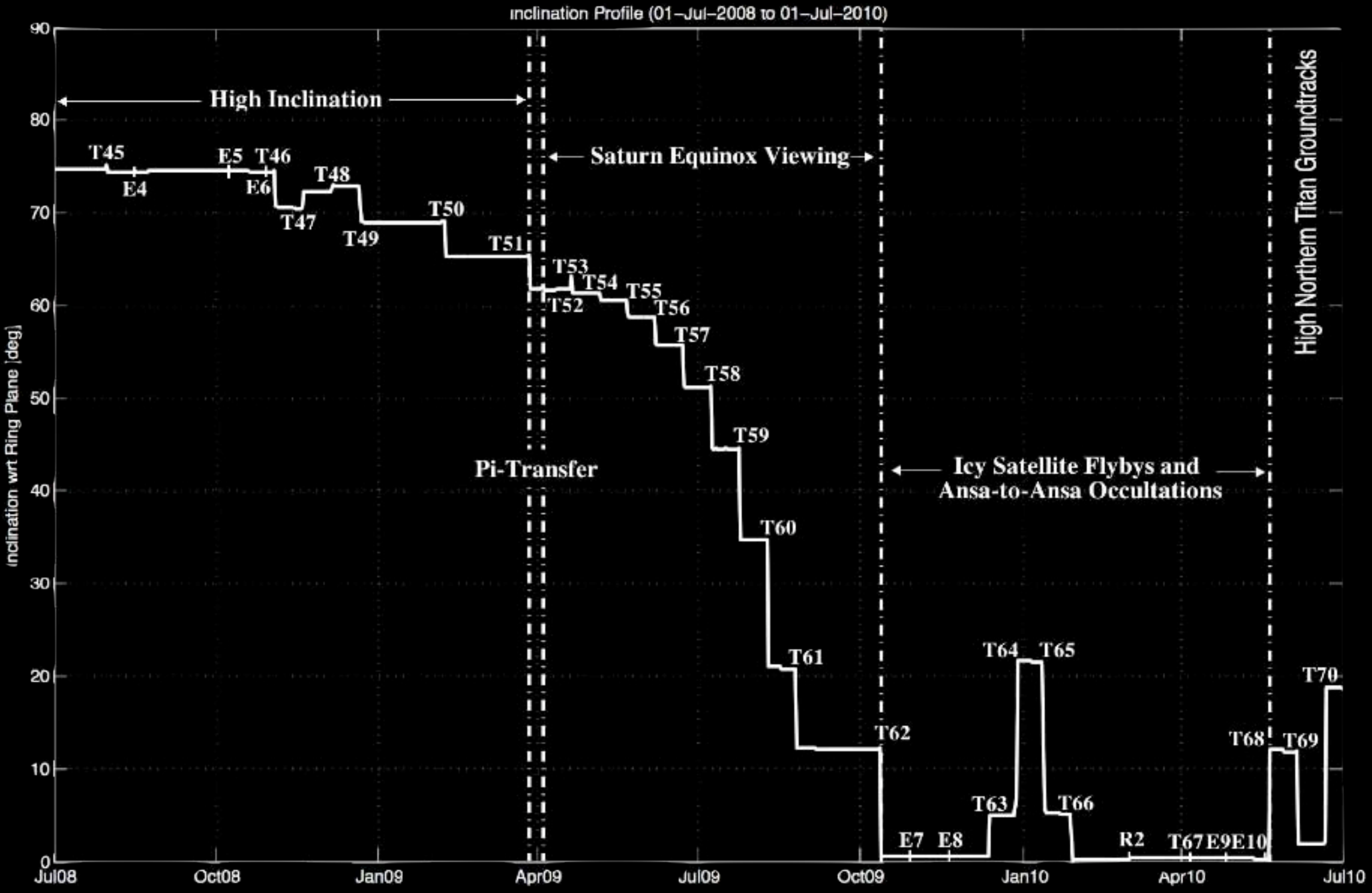
N. Polar View

Equatorial View

Oblique View

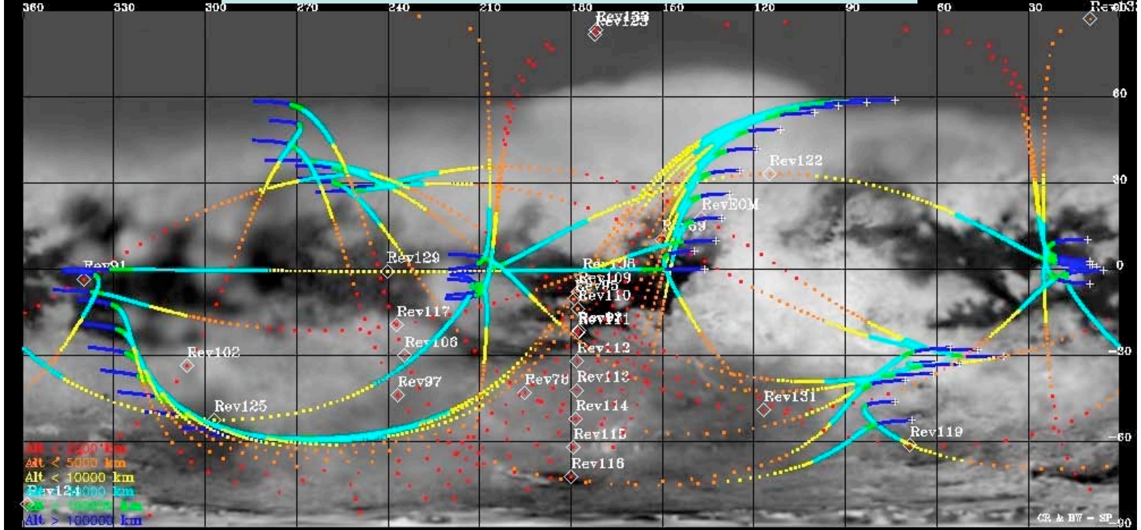
KEY:
High Inclination
Pi-transfer
Equinox Viewing
Icy sats. & A2A occs.
High N. Titan G.T.'s

XM Inclination Profile

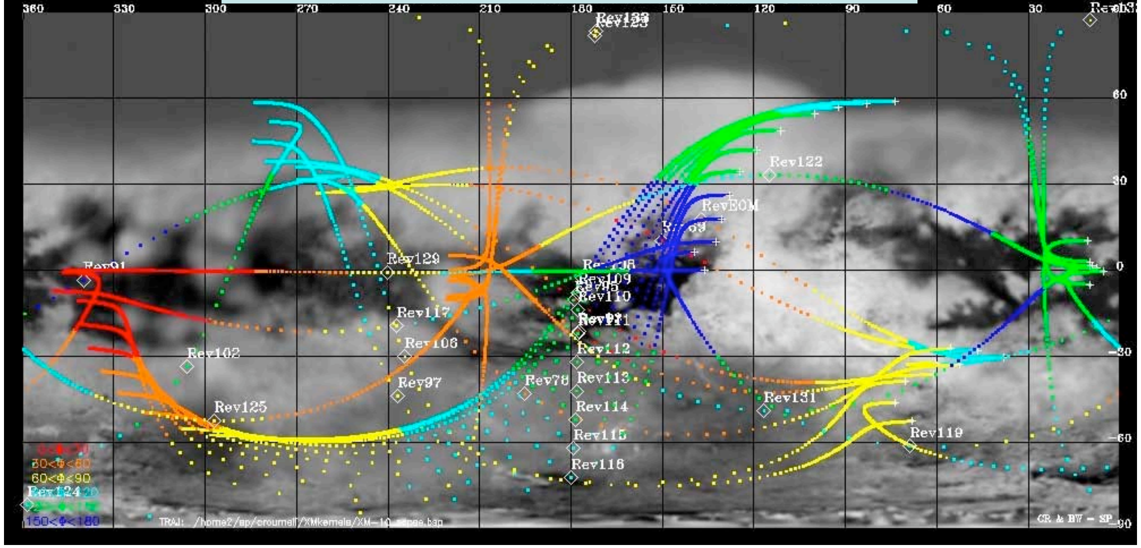


Titan Groundtracks

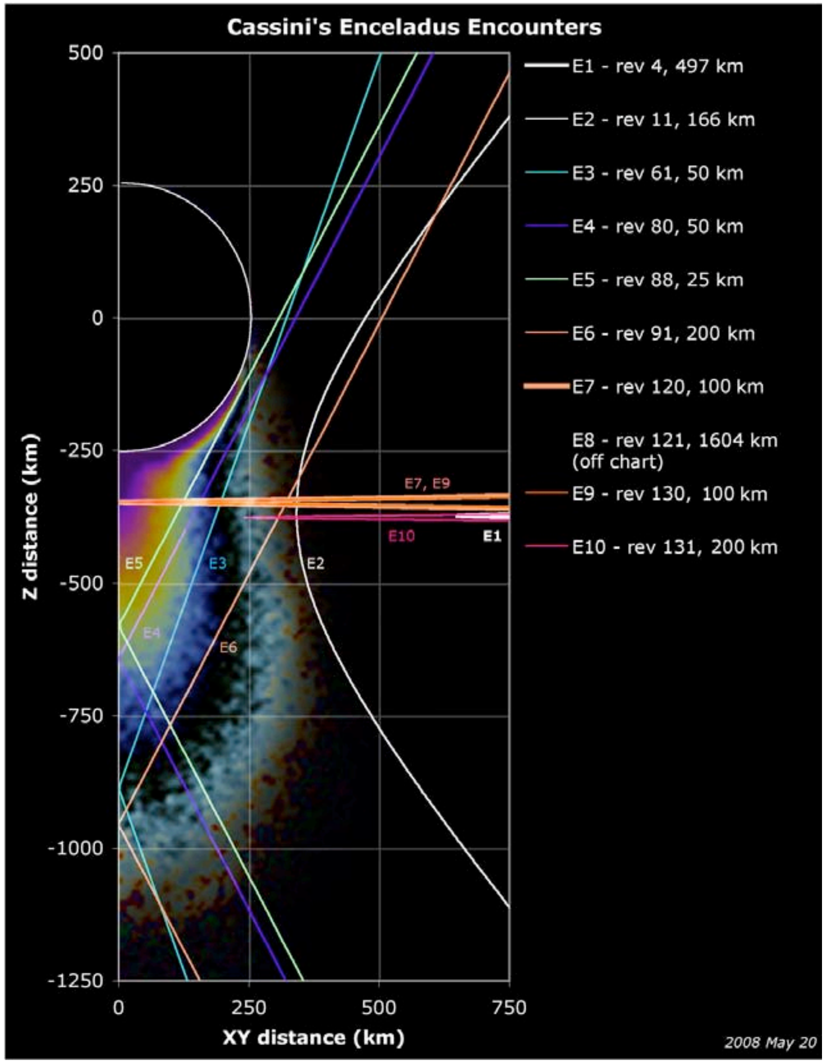
Titan Groundtracks +/- 16 hrs. from C/A (colored w/ alt)

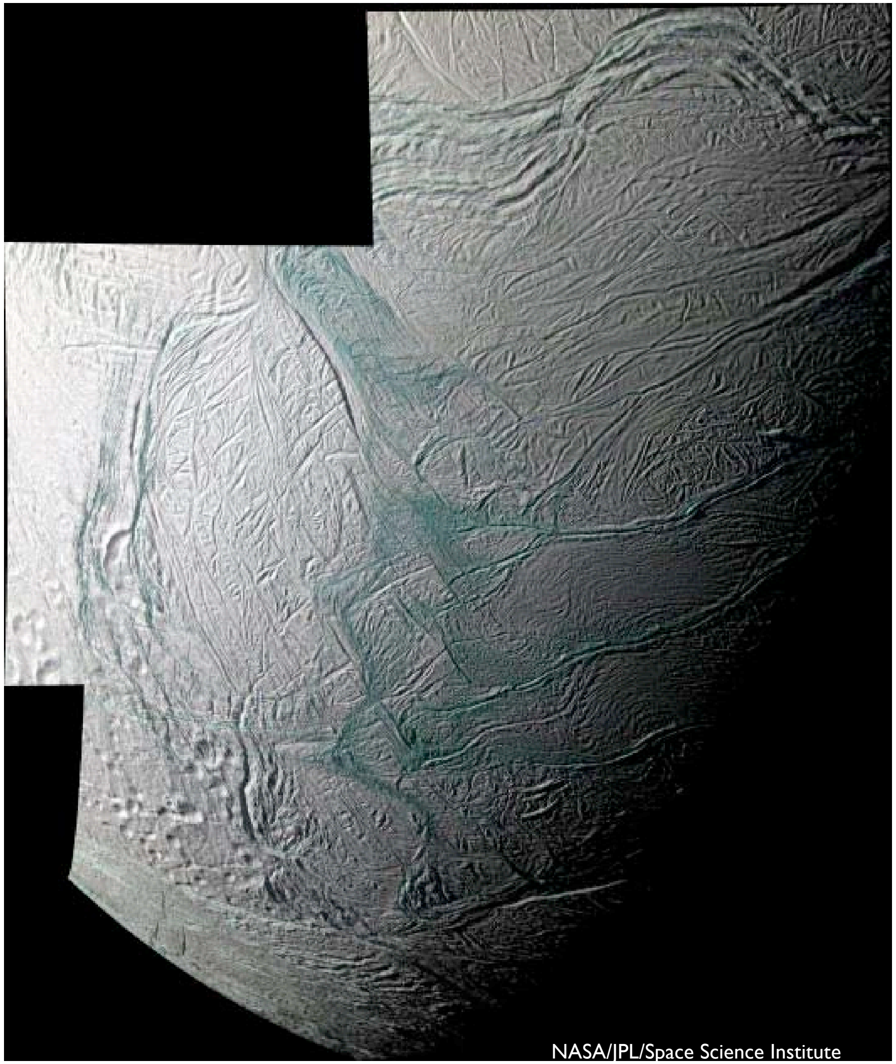


Titan Groundtracks +/- 16 hrs. from C/A (colored w/ phase)



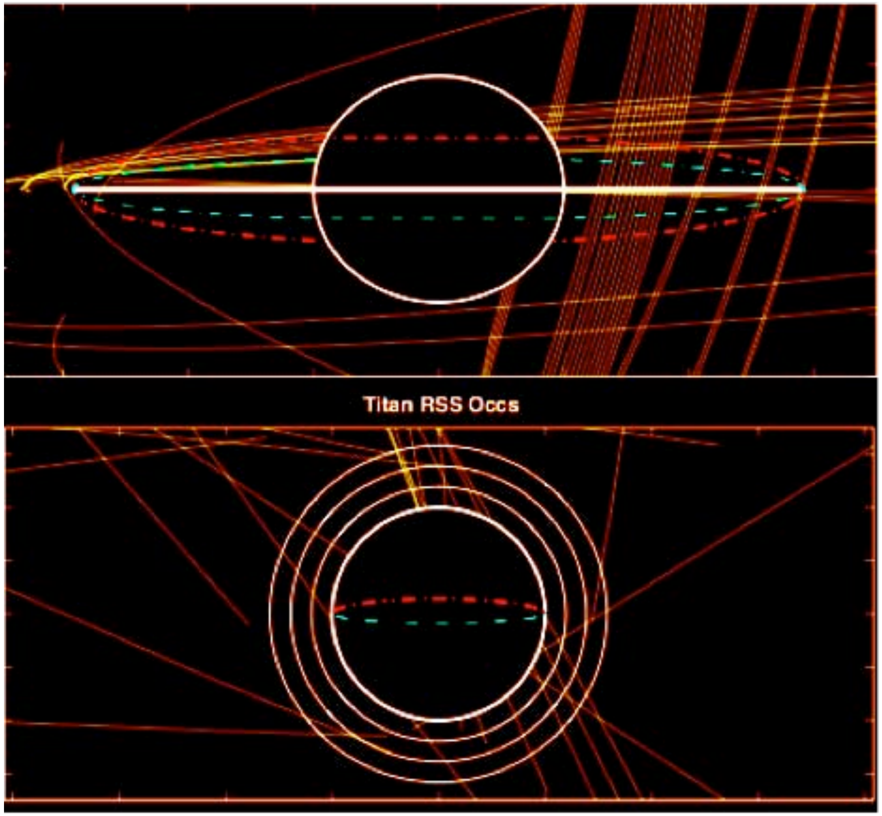
Enceladus Encounters



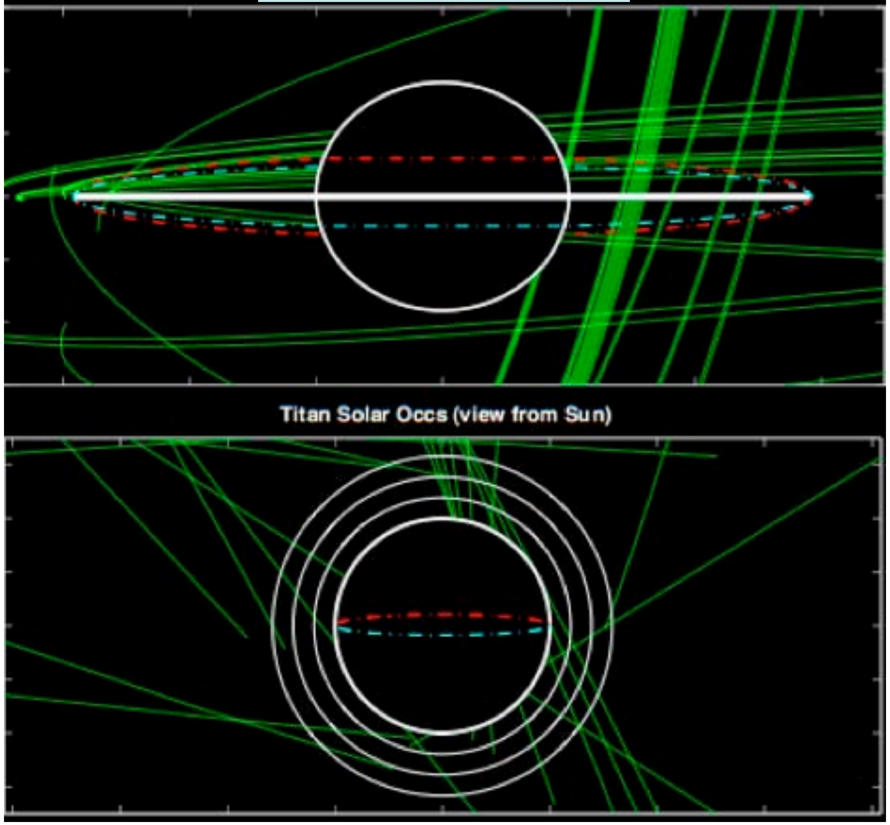

NASA/JPL/Space Science Institute

Occultations

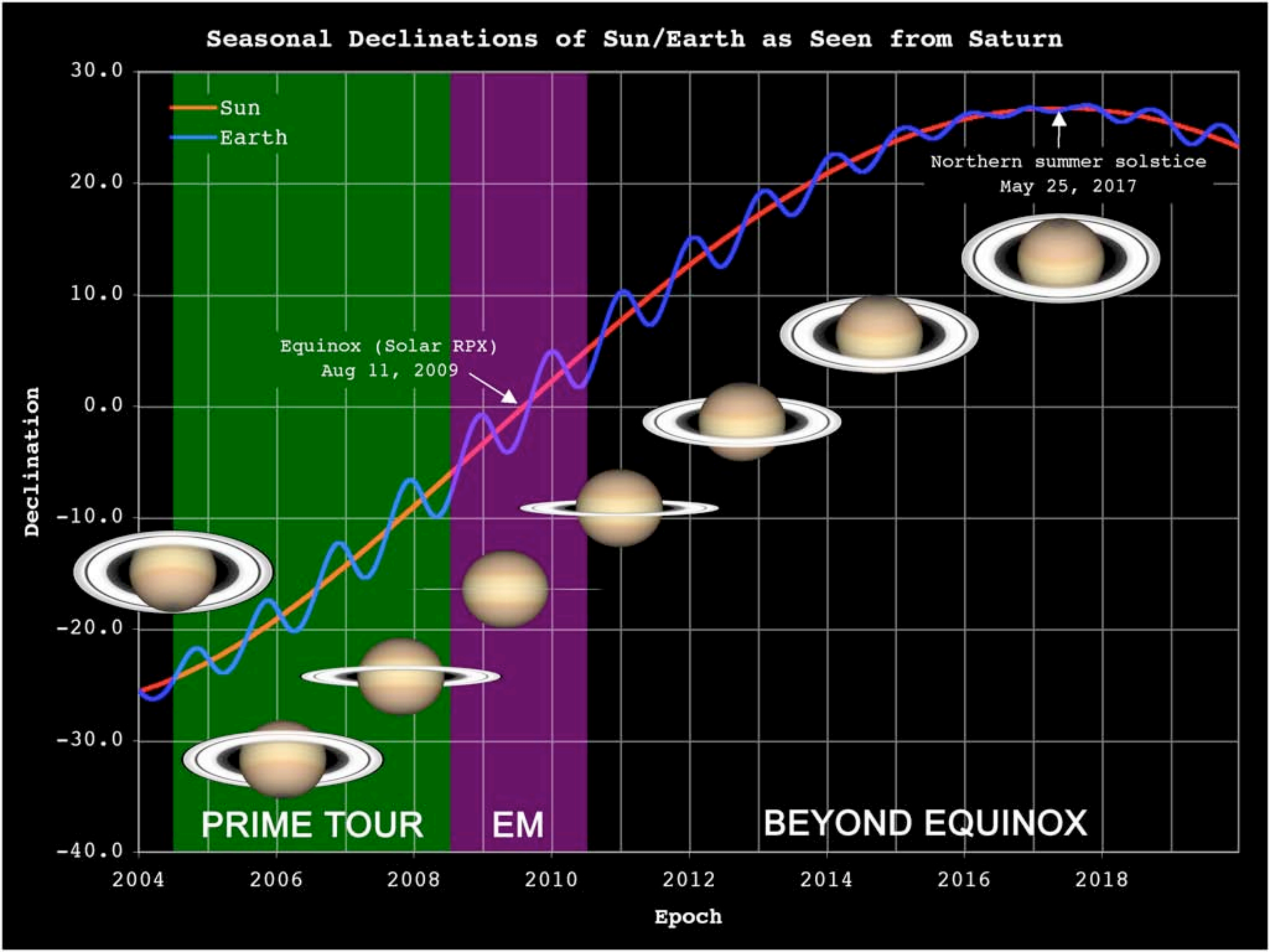
Saturn RSS Occs.



Saturn Solar Occs.

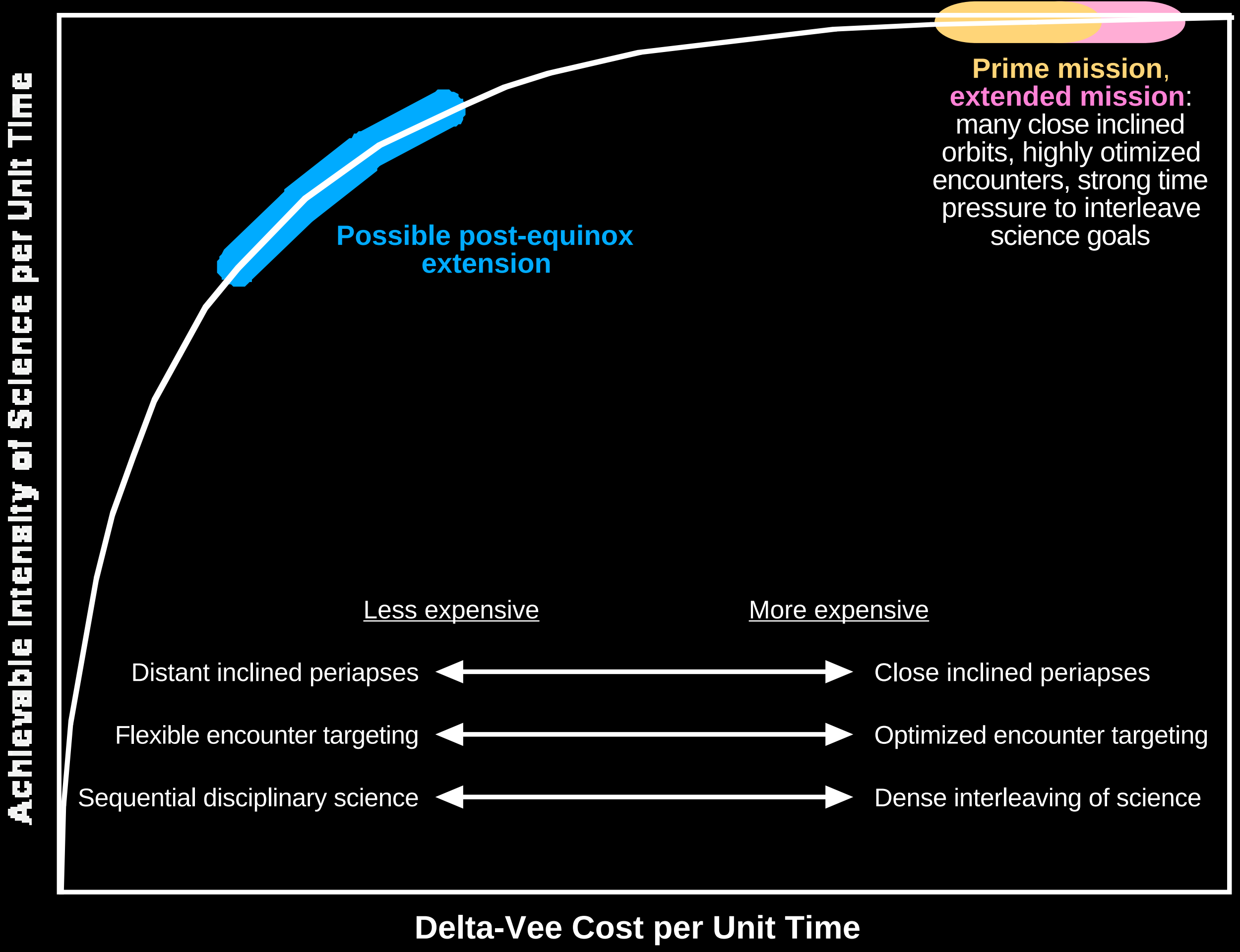


Beyond the Equinox



Beyond the Equinox

Conceptual Cost to Benefit Relationship of Cassini Tour Design

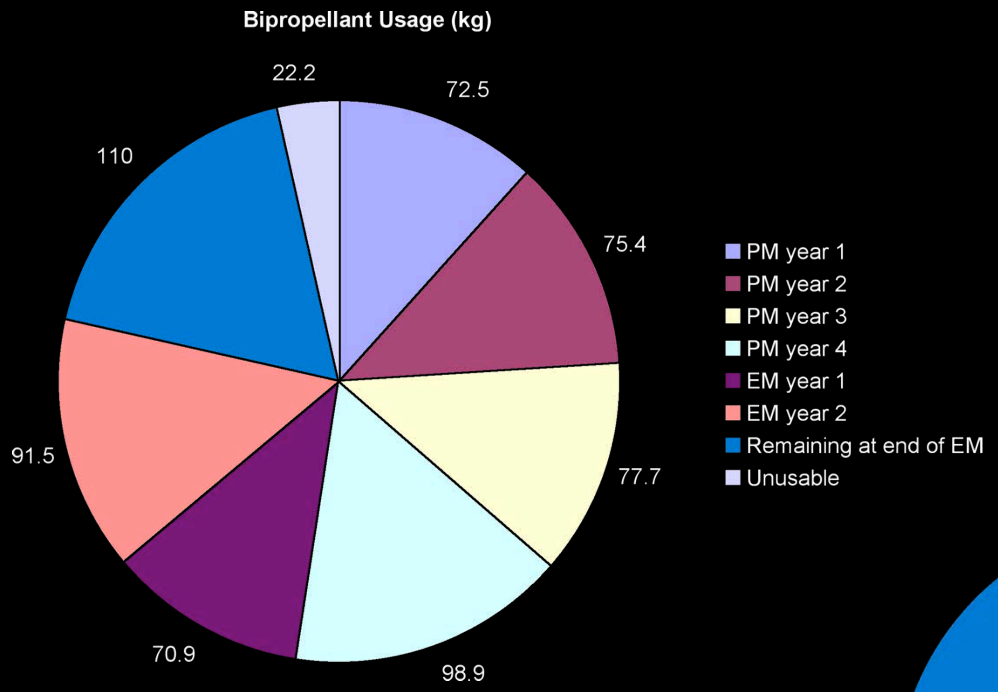


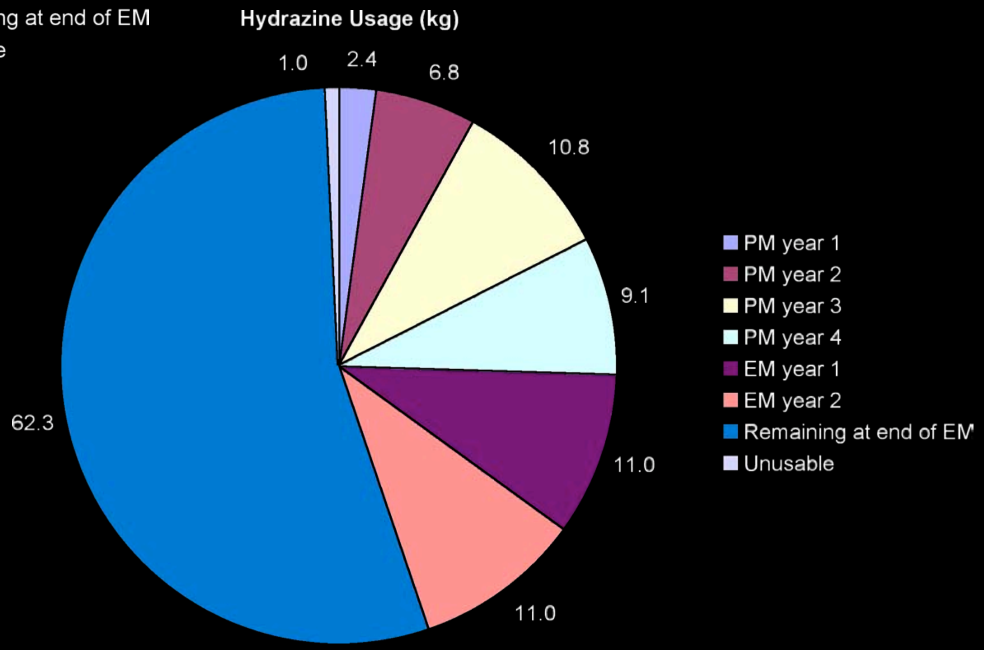
Possible post-equinox extension

Prime mission, **extended mission**: many close inclined orbits, highly otimized encounters, strong time pressure to interleave science goals

Less expensive		More expensive
Distant inclined periapses	↔	Close inclined periapses
Flexible encounter targeting	↔	Optimized encounter targeting
Sequential disciplinary science	↔	Dense interleaving of science

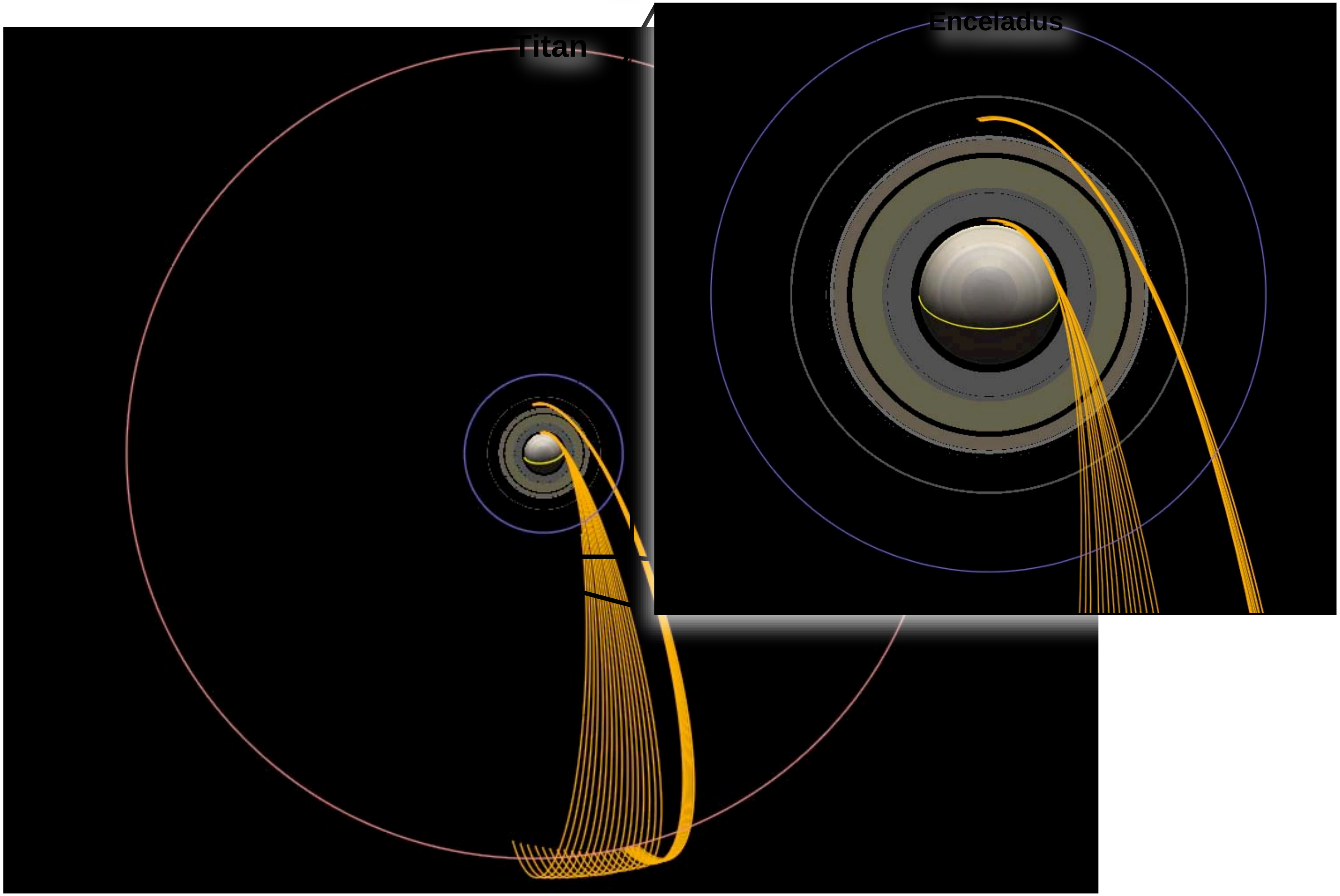
Beyond the Equinox - Consumables


Bipropellant Usage (kg)


Hydrazine Usage (kg)

Inner D Ring Option

[Sun ↑]

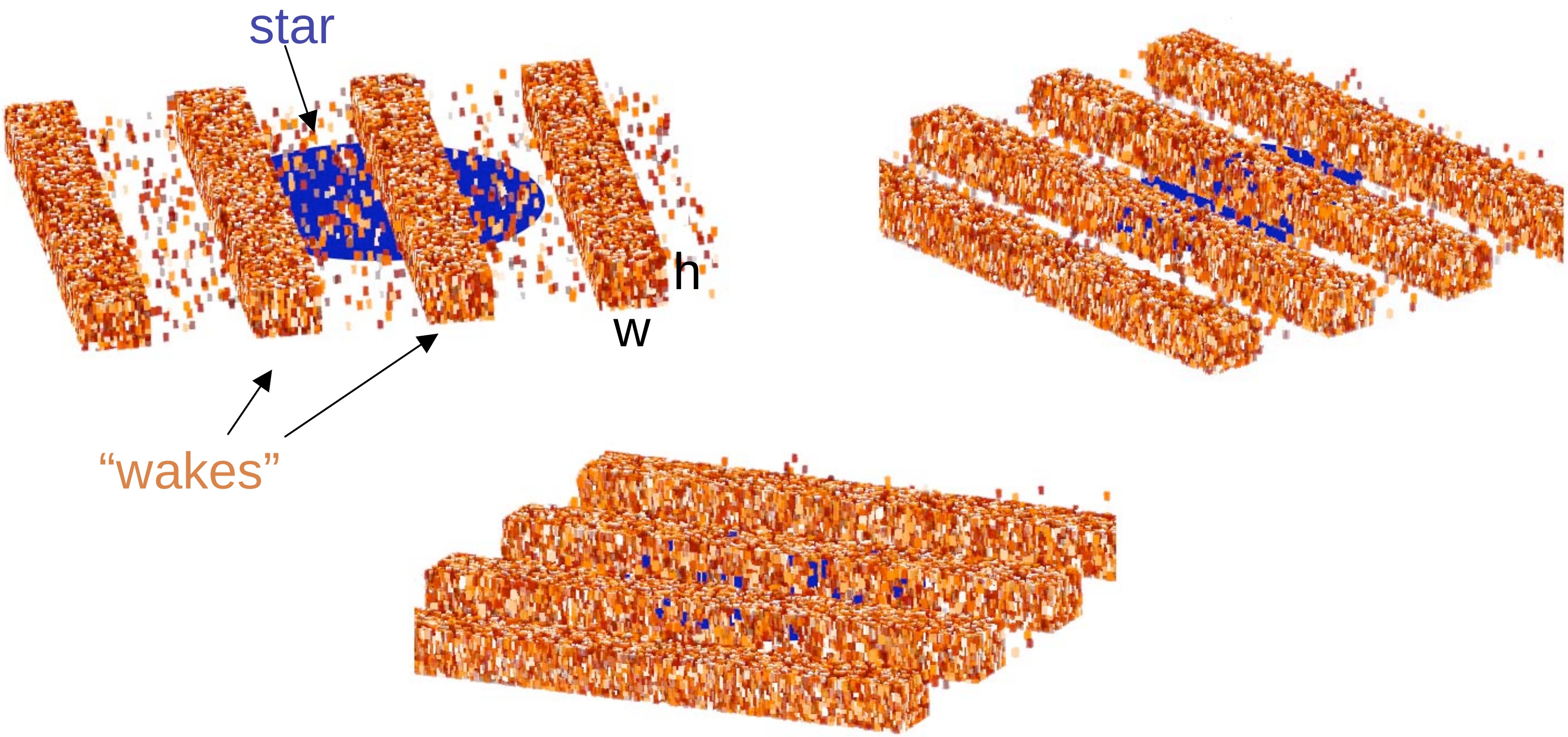


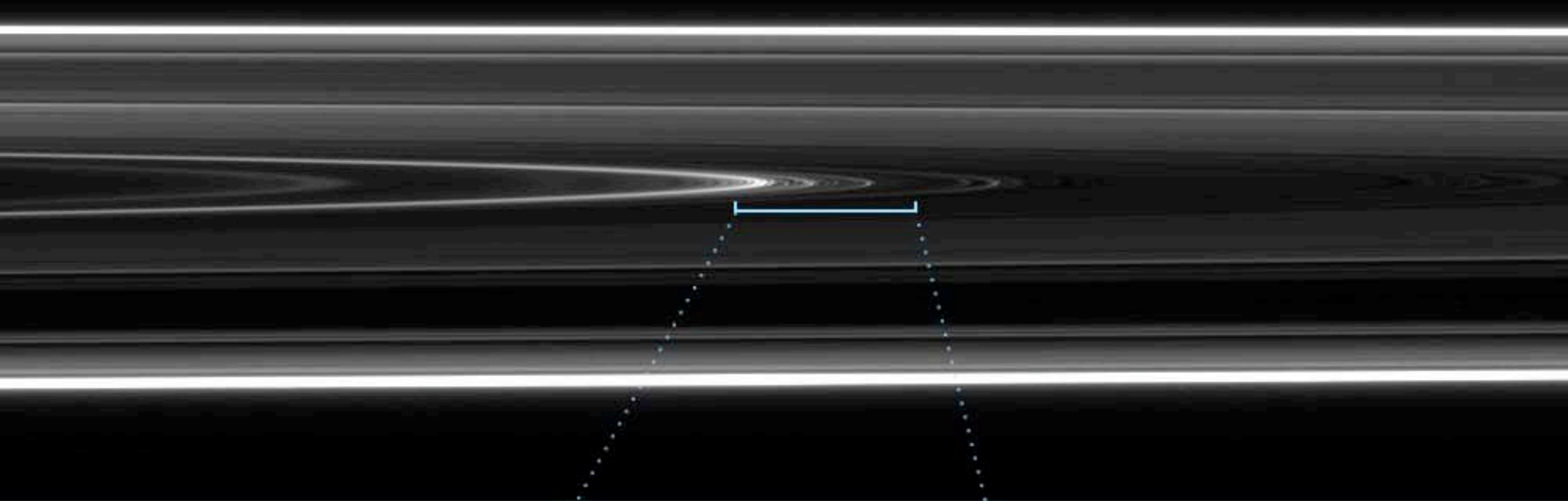
Cassini Program

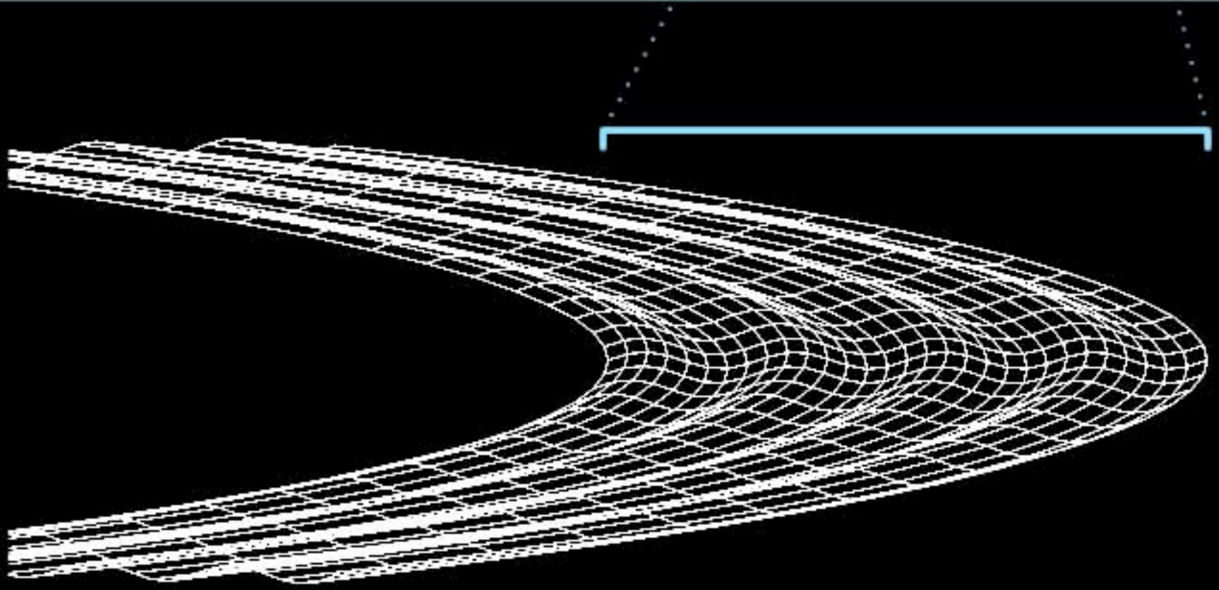
© 2006 Björn Jónsson

Backup

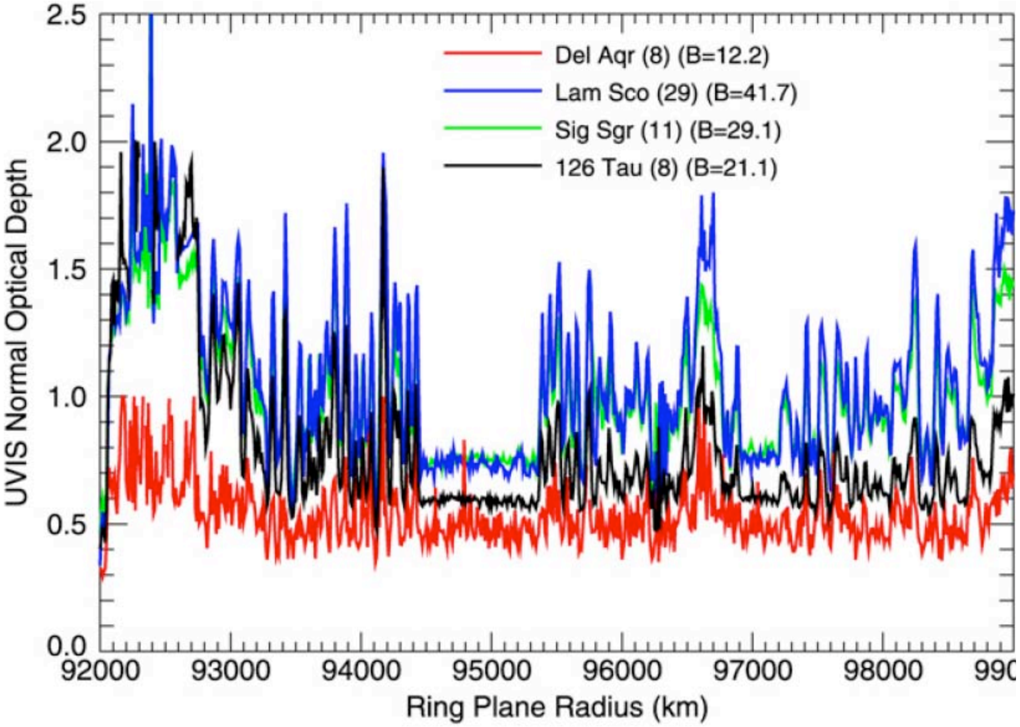
Azimuthal View Angle Determines Opacity

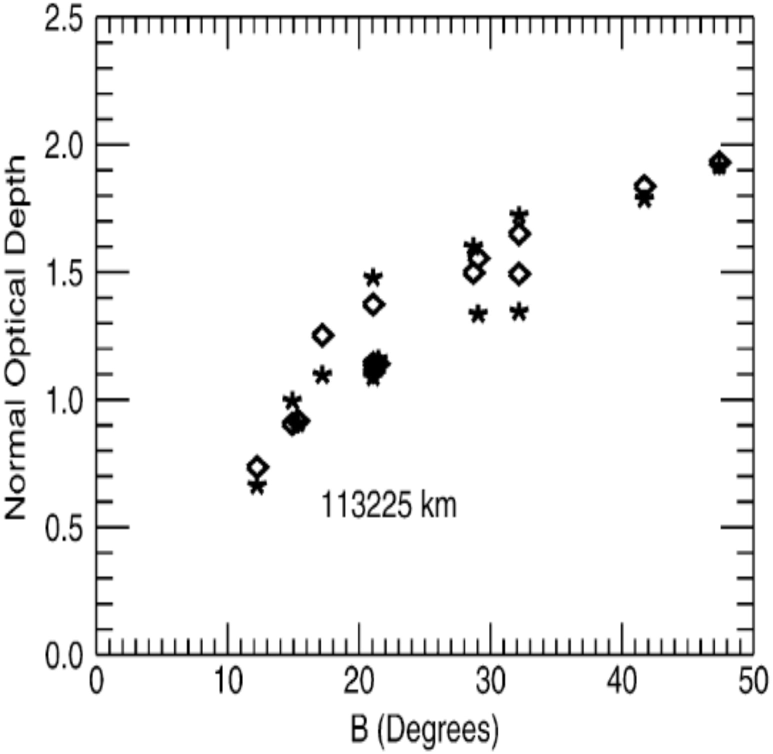






New “rippled” structure in D ring appears to have been formed only two decades ago, perhaps by impact of a large object. Wave is seen to be wrapping up with time.





- The ring optical depth is inferred from the light transmitted, depending on a particular model of a homogeneous, randomly populated ring. If this model were correct, we would obtain the same optical depth at all opening angles. However as the observed profiles at left, and the plot at right, show, the optical depth inferred in this way decreases significantly as the opening angle decreases (rings become more edge on). This suggests that the actual ring structure is heterogeneous, with some small percentage of low-optical depth regions sprinkled amongst the high-optical depth material (Colwell et al 2007).