PLANETARY RINGS: THE OBSERVATIONS

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Helped by Matt Hedman and Matt Tiscareno

Outline:

Mission Profile

Ring Character (opacity, density, thickness, clumping)

Particle Sizes and Properties

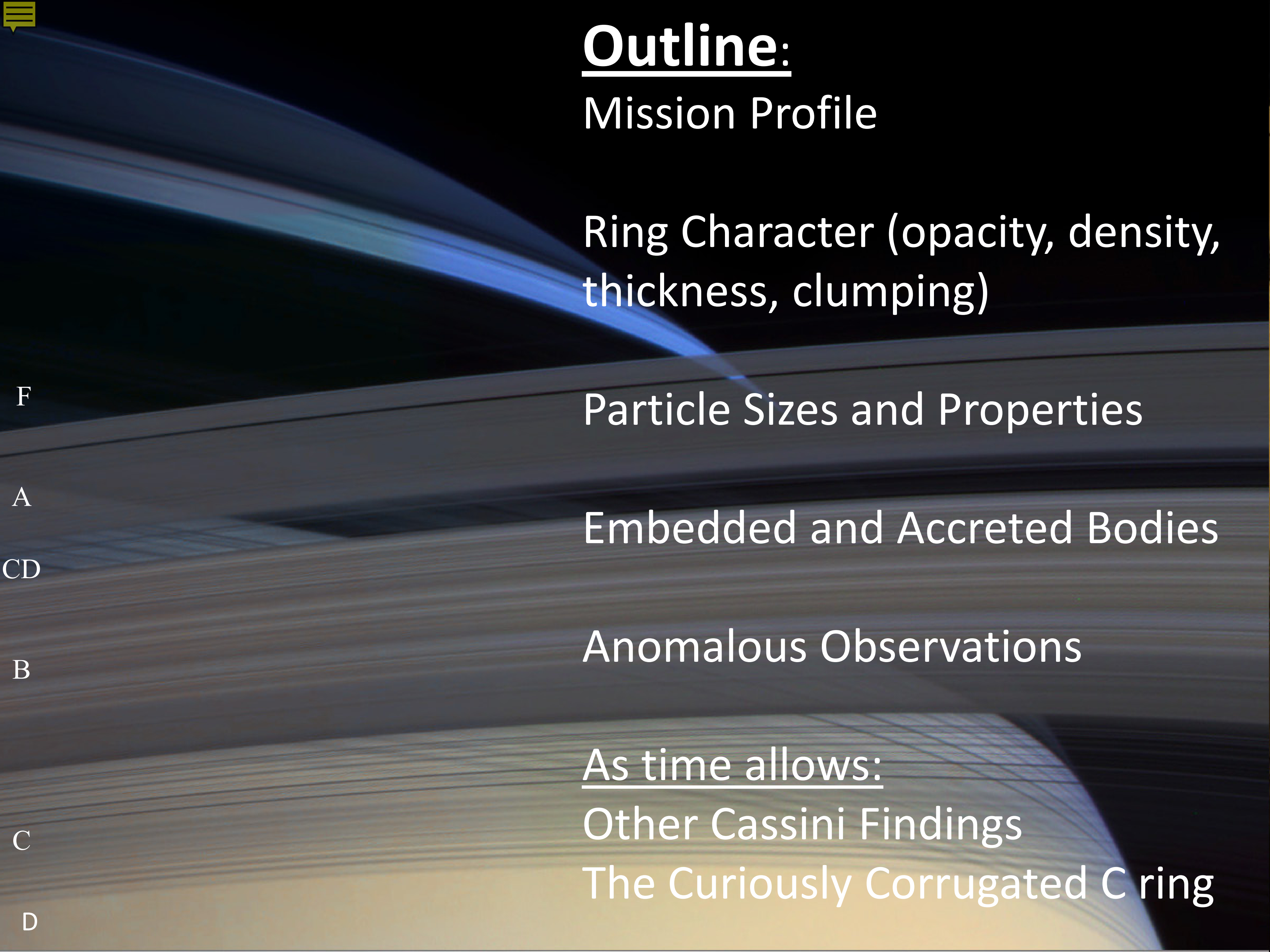
Embedded and Accreted Bodies

Anomalous Observations

As time allows:

Other Cassini Findings

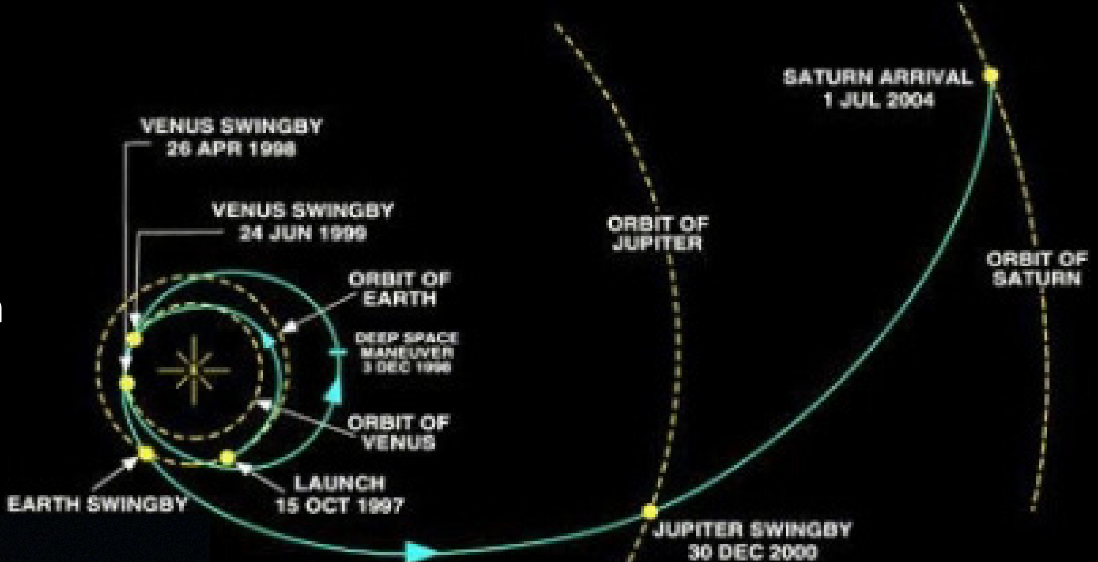
The Curiously Corrugated C ring



The Cassini-Huygens Mission

Arrived at Saturn on
1 July 2004

Launched 15 October 1997 from Cape Canaveral on Titan IVB/Centaur



The Cassini Spacecraft

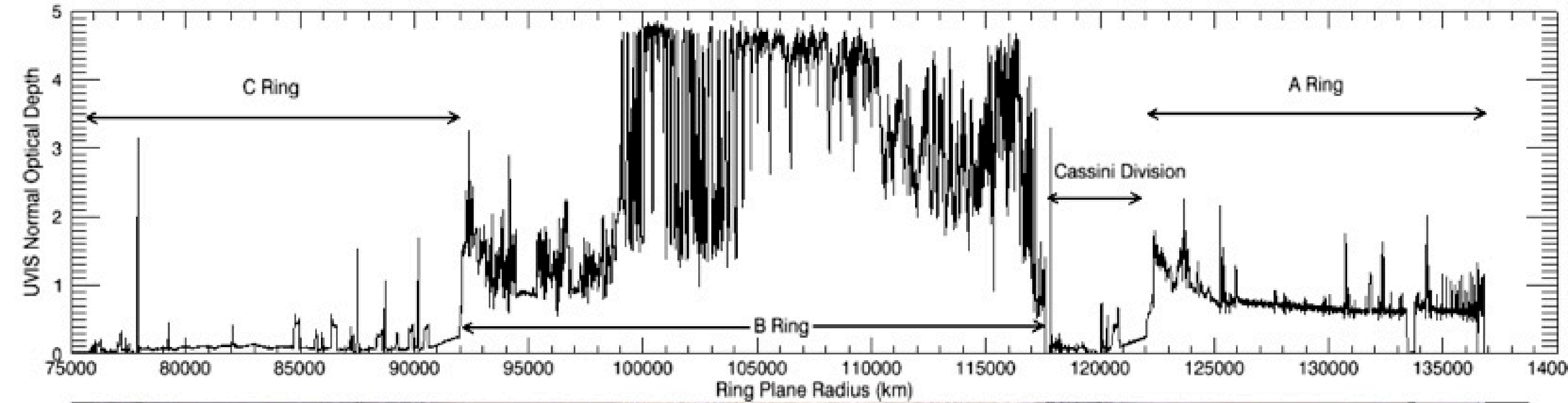
- Four remote-sensing instruments:
  - Two Cameras (ISS)
  - Visual/Near Infrared Mapping Spectrometers (VIMS),
  - Ultraviolet spectrometers (UVIS),
  - Thermal Infrared spectrometers (CIRS)
  - OCCULTATIONS
- Radio Antenna/RADAR
- Four in-situ instruments to measure dust, high-energy particles, and plasmas in the vicinity of the Spacecraft
- Two magnetometers – map Saturn's magnetic field

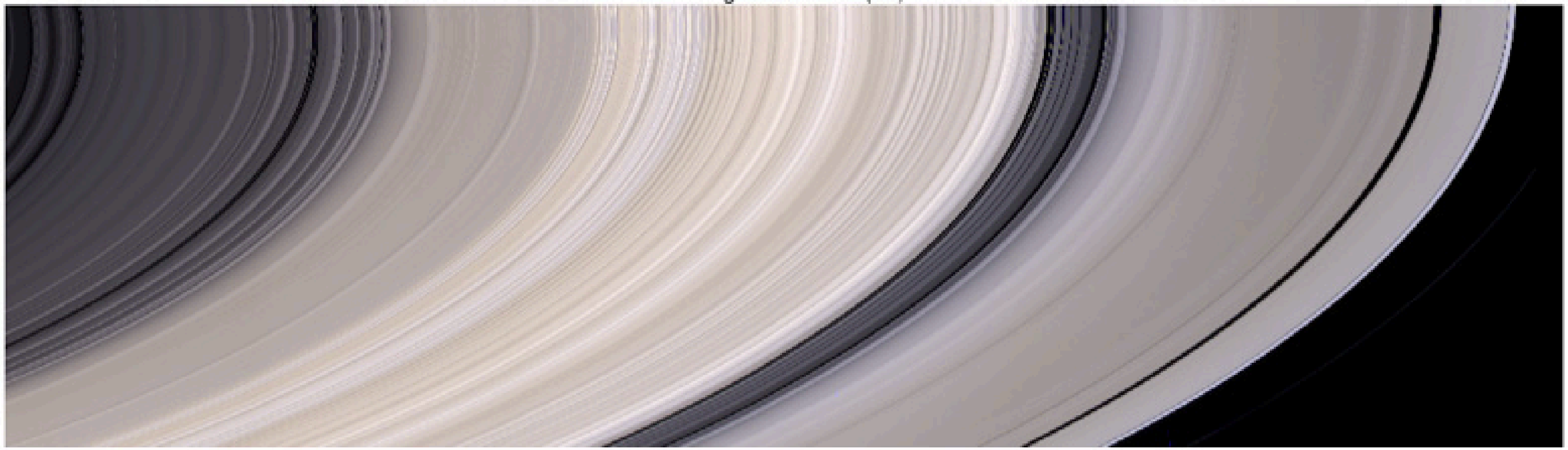
Cassini also carried the **Huygens Probe**, which landed on Titan in January 2005

Character of Saturn’s Rings

- Water ice with minor contamination
- Power-law size distribution between cm and m, very few large ones
- Typical optical depths $e^{-\tau} \sim 0.1- 5$
- Embedded and external moons drive the understood structure.

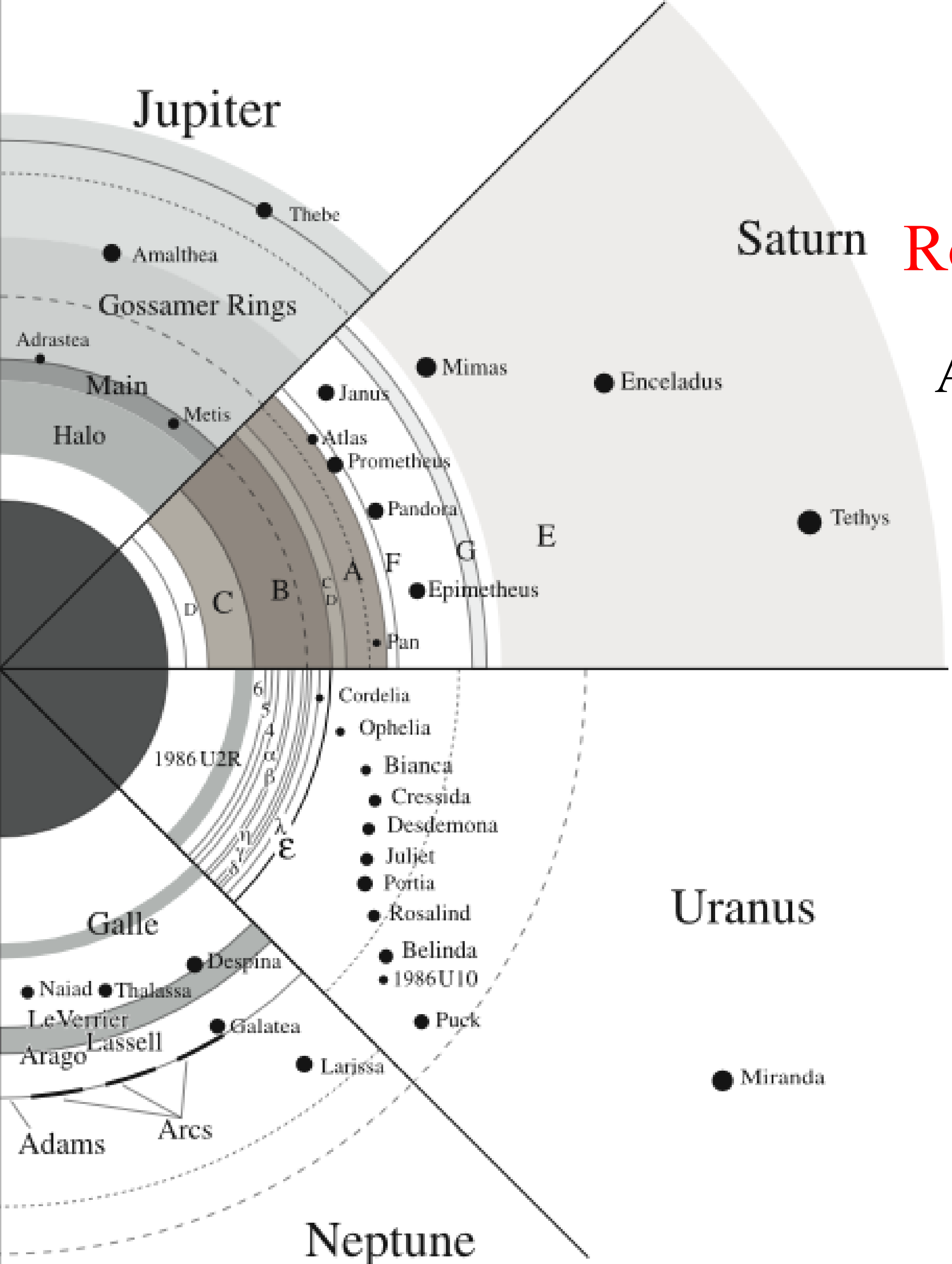
Typical image resolution = 1-10 km
Occultations resolve @ 10-100 m.



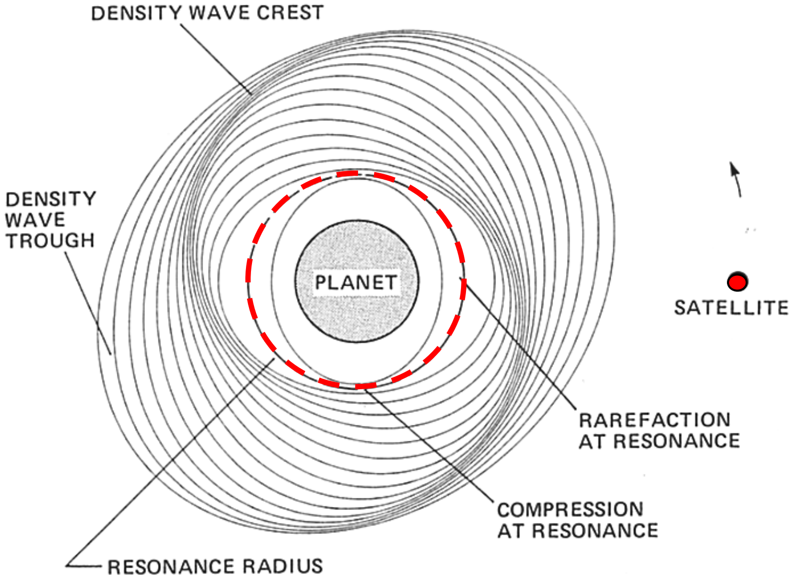


Occultations of stars (UV, IR) by the rings and transmission of radio signals (cm wavelengths) thru the rings gives optical depth & particle sizes.

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

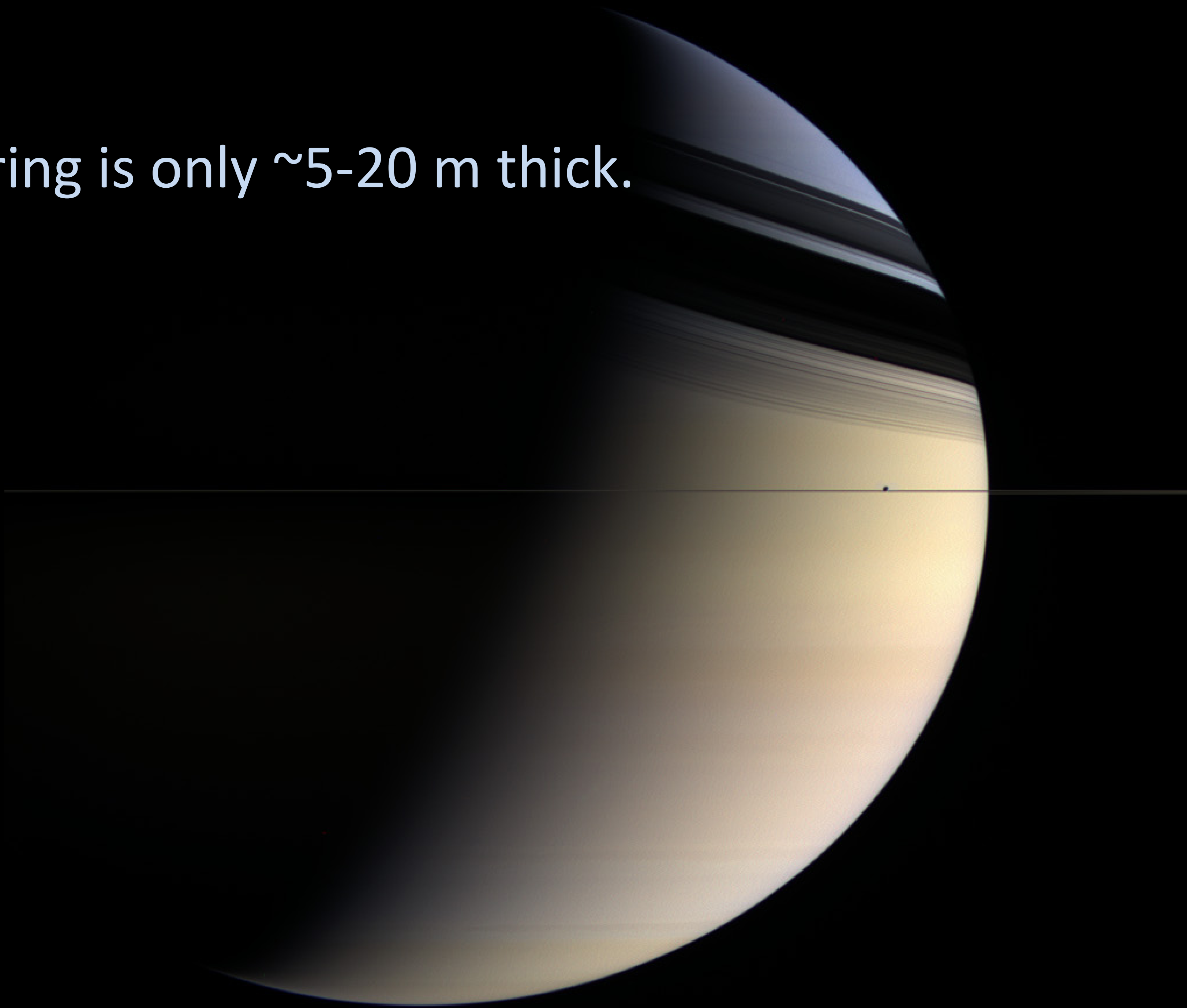


At orbit resonances, moons’ tiny forces are amplified many times



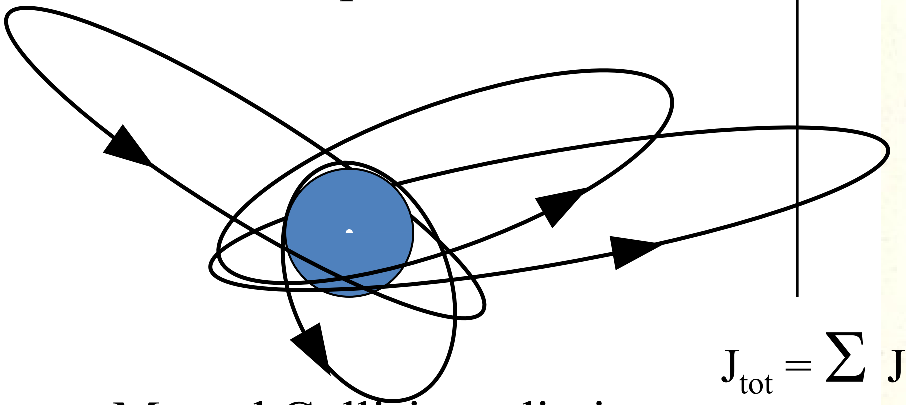
Ring self-gravity creates spiral pattern rotating with moon

The ring is only ~5-20 m thick.



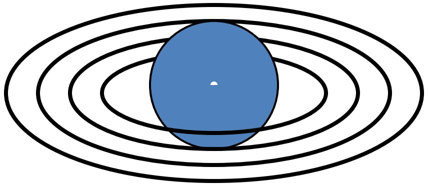
WHY DO FAT NEBULAE BECOME THIN FLAT DISKS?

Rotating cloud of gas and debris surrounds a point mass



$J_{tot} = \sum J_i$

Mutual Collisions dissipate energy but conserve $J_{tot.}$



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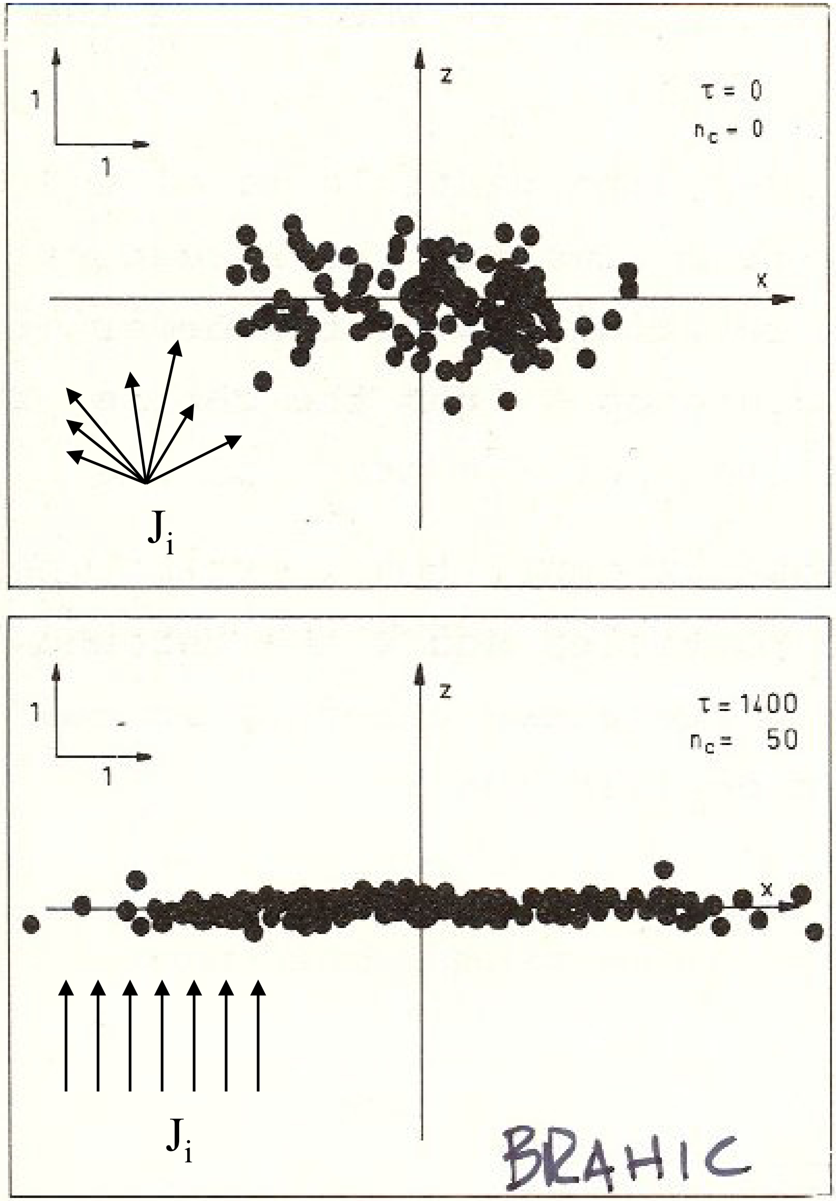
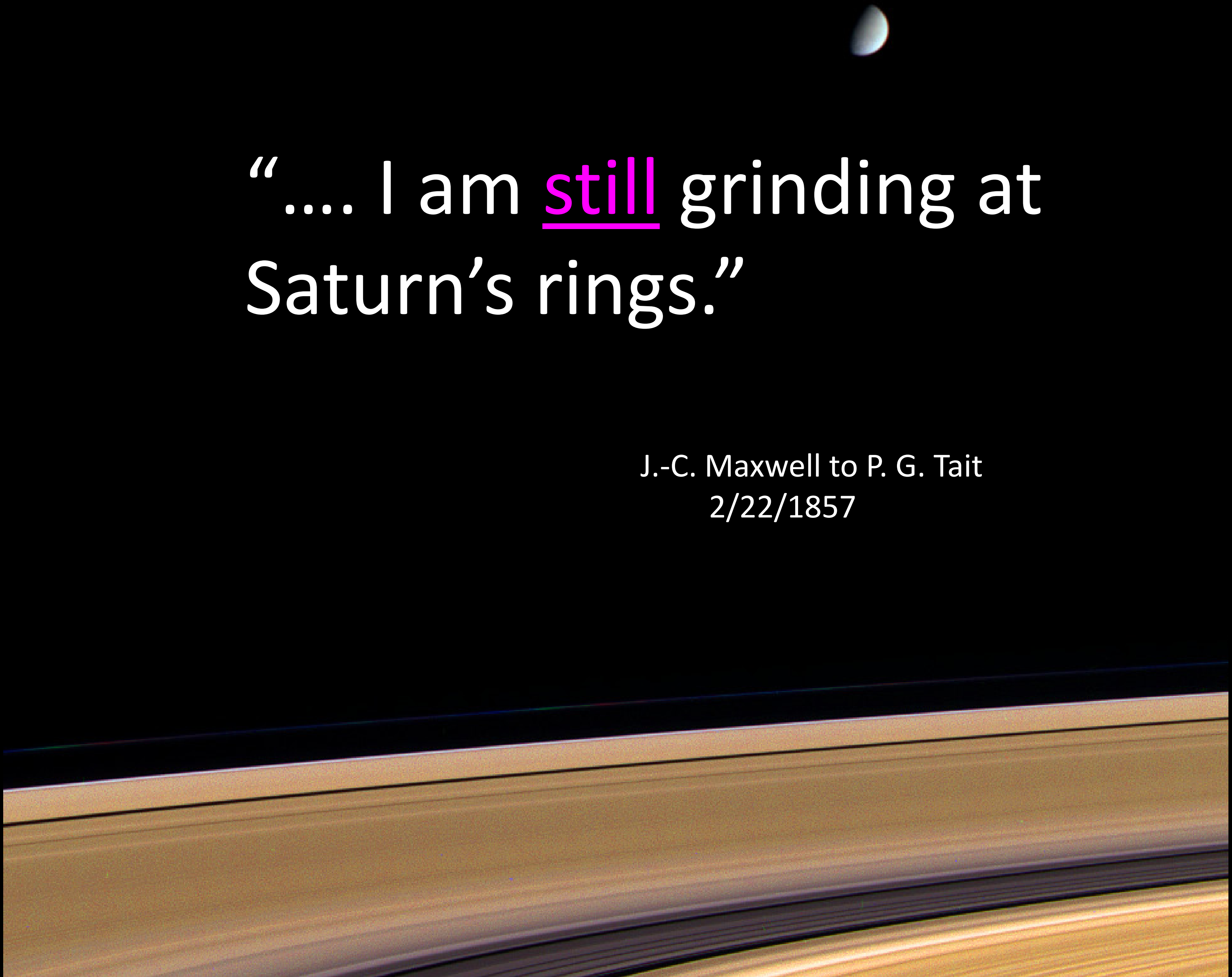


The minimum energy state consistent with a given total angular momentum is a disk. Subsequent collisions cause disks to spread radially.

Simulations of Ring Thickness

Morashima & Salo. 2006

Note: Larger particles settle to mid-plane.
Mean thickness ~ 10 m.



"…. I am <u>still</u> grinding at Saturn's rings."

J.-C. Maxwell to P. G. Tait
2/22/1857

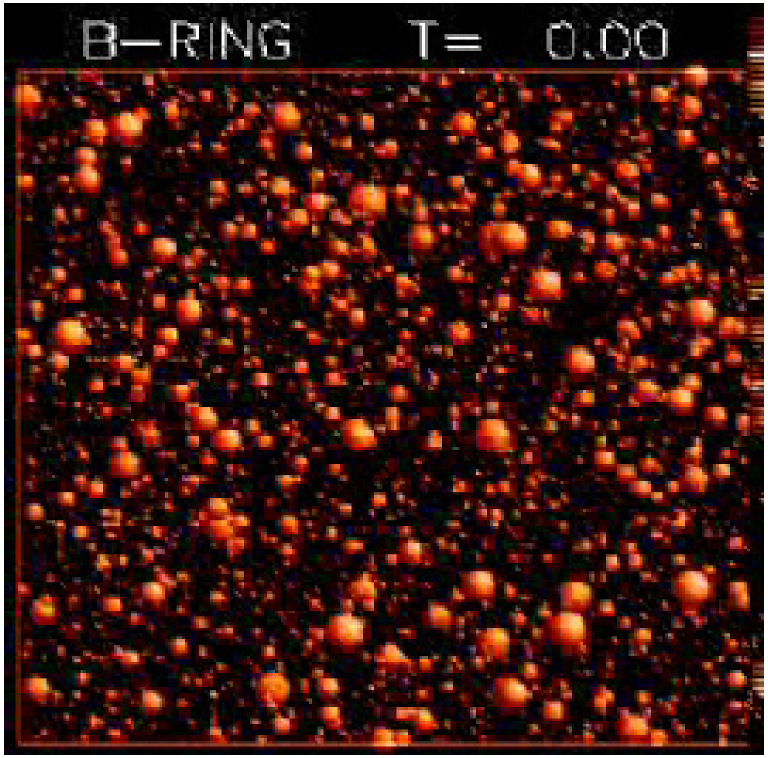
PLANETARY RINGS AS ASTROPHYSICAL DISKS

Sheets of gravitating material will be unstable to axisymmetric perturbations if Toomre number

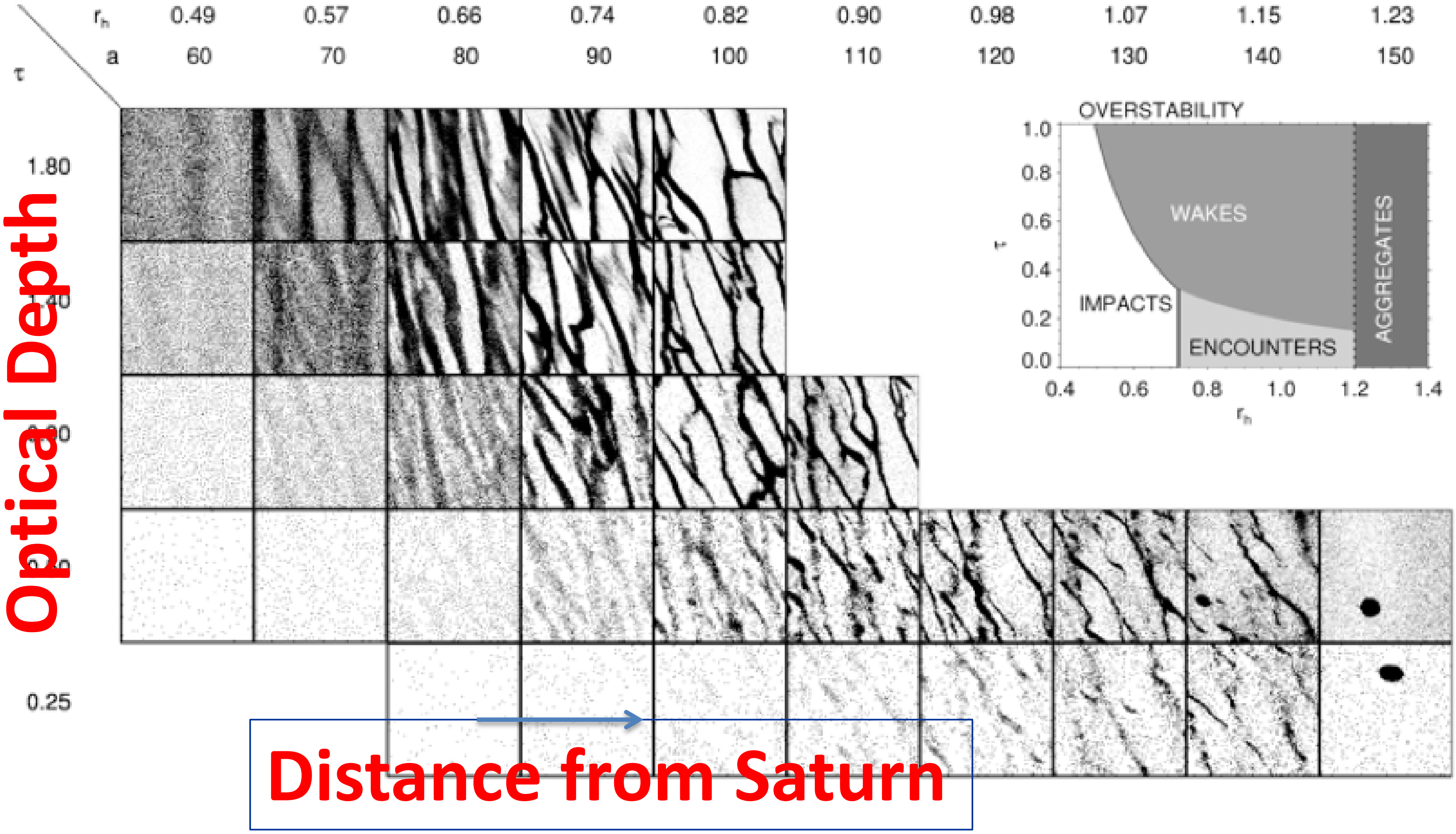
$$Q = (\Omega\, c_s/\pi\, G\, \Sigma) < 1.$$

Tidal effects of the central body are much stronger for planetary rings than they are for other astrophysical disks:

$$R_{Roche} = 2.45\ (\rho/\rho_P)^{1/3} R_{Planet}$$



Simulation of particles in B-Ring by Heikki Salo



Optical Depth

Distance from Saturn

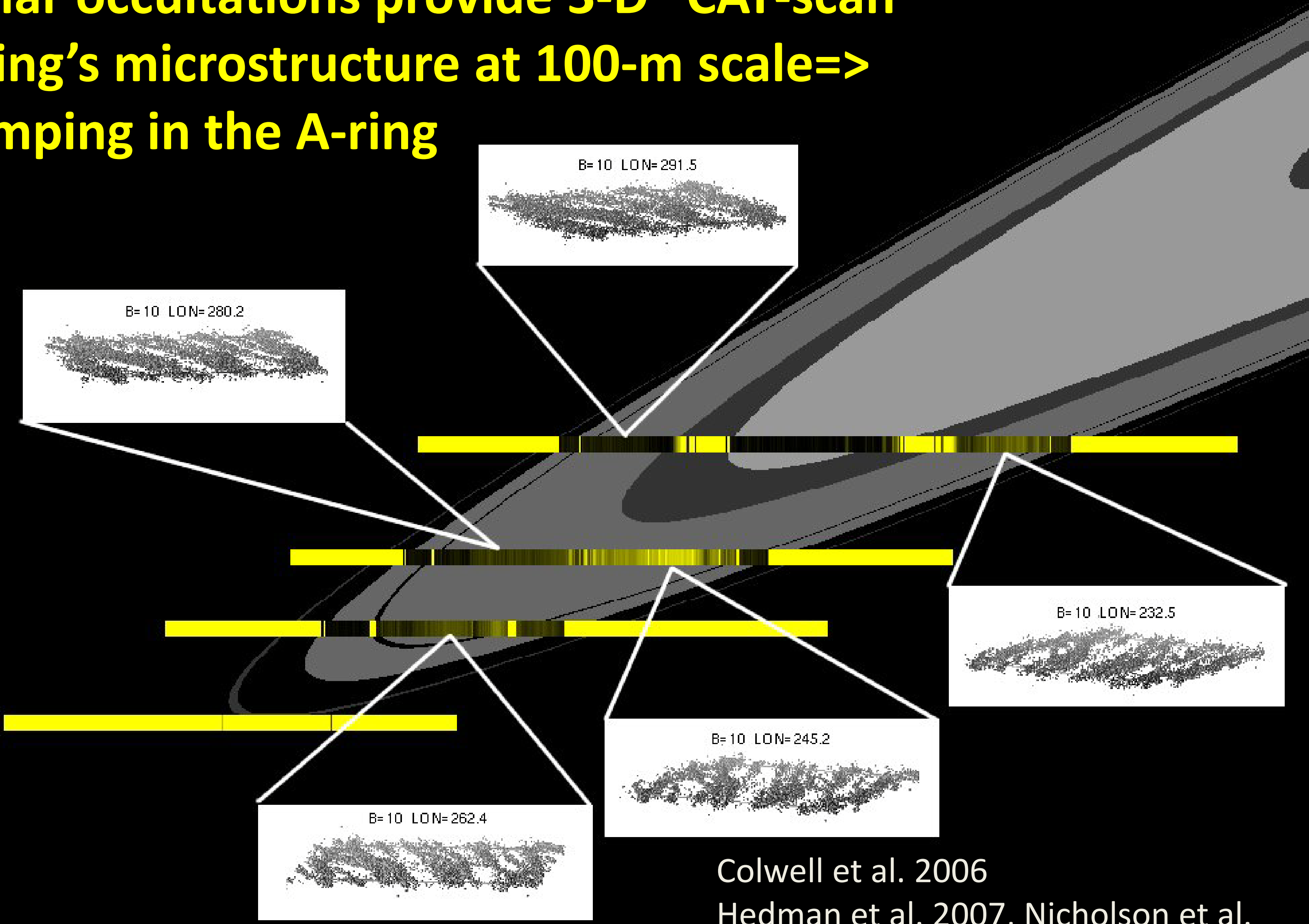
"SELF-GRAVITY WAKES"

Mutual gravity battles planetary tides

Explains ring's brightness asymmetry [Salo]

Self-gravity wakes

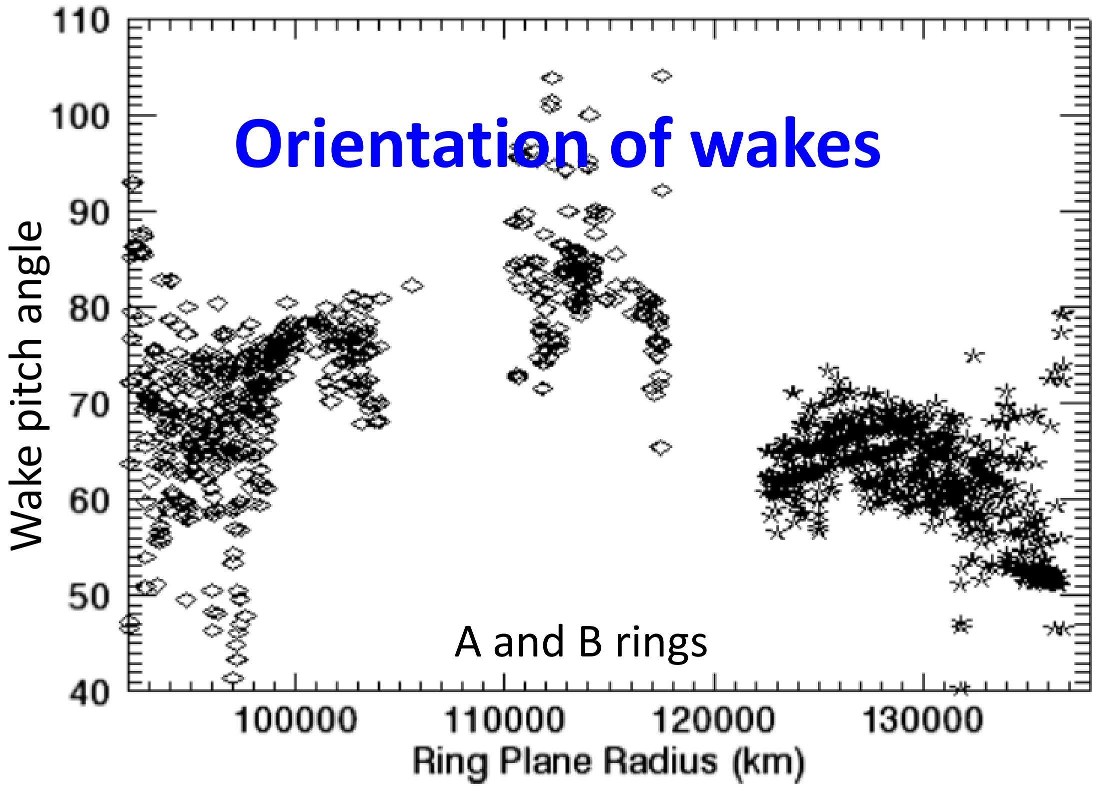
Stellar occultations provide 3-D "CAT-scan" of ring's microstructure at 100-m scale=> Clumping in the A-ring

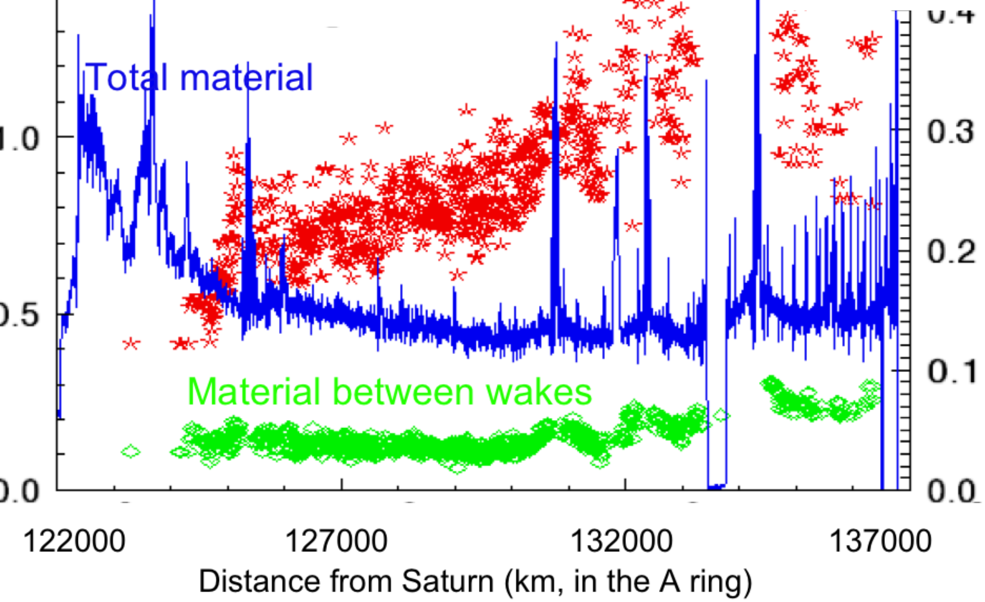


Colwell et al. 2006
Hedman et al. 2007, Nicholson et al.

cf. Salo 1992, 1995, 2001…

Ring breaks into elongated,
continually changing sausage
shapes (10:1). Tides frustrat
gravitational aggregation.
Much is open space.





Affects:

Photometric behavior

Visible mass?

Wave propagation?

“Propellers”?

A theoretical estimate of the wake wavelength λ comes from calculations of gravitational instabilities (Toomre 1966.):

Ring Surface Mass Density. Based on density waves, this parameter is ~ 40 g/cm^2

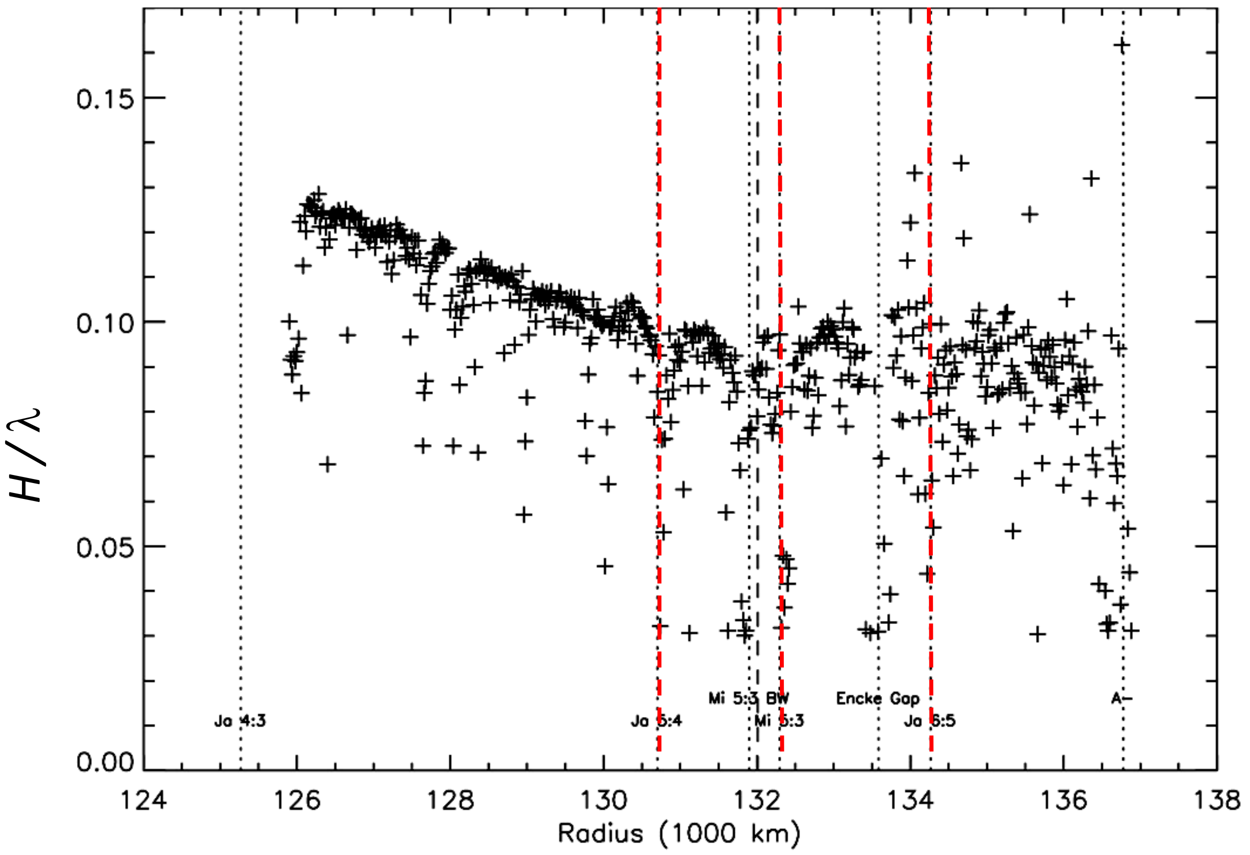
$$\lambda_T \approx \frac{4\pi^2 G\sigma}{\Omega^2} \approx 50m$$

Angular velocity of the ring material

Using this estimate of the wake wavelength, we find the height of the wakes and the thickness of the A-ring is:

H ~ 5 meters

However, we would like to measure λ directly….



Ring vertical structure:
many particles thick
or densely packed?

Affects random velocities,
viscosity, pressure,
ang momentum transport,
gap opening, etc…

Thickness, wave props,
photometry, thermal
measurements, wake models
all favor a "monolayer"
in the A ring at least.

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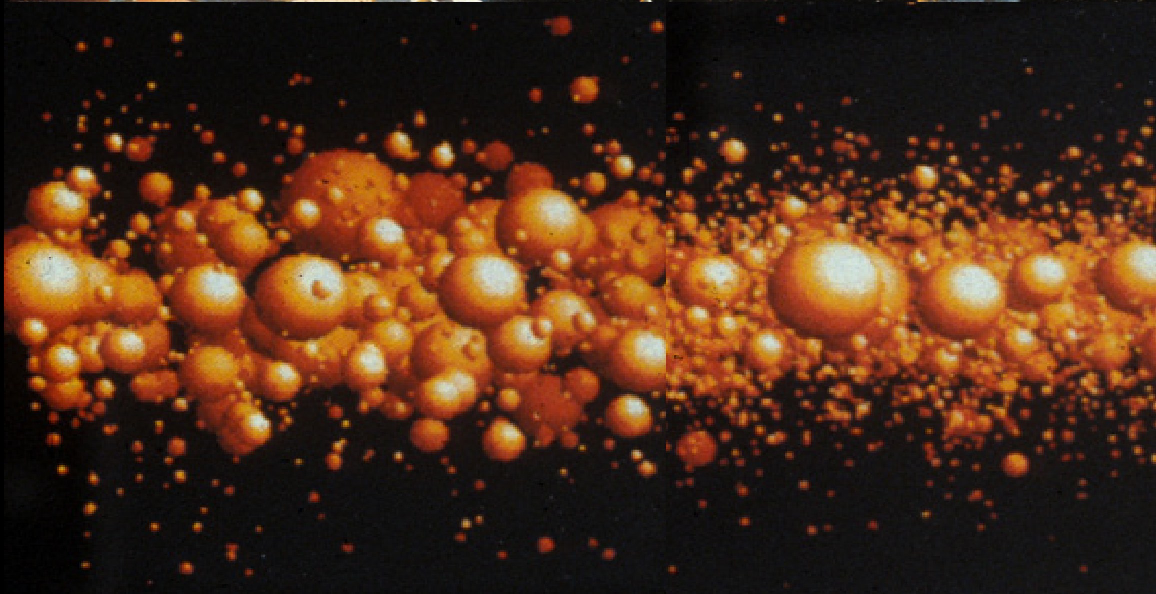
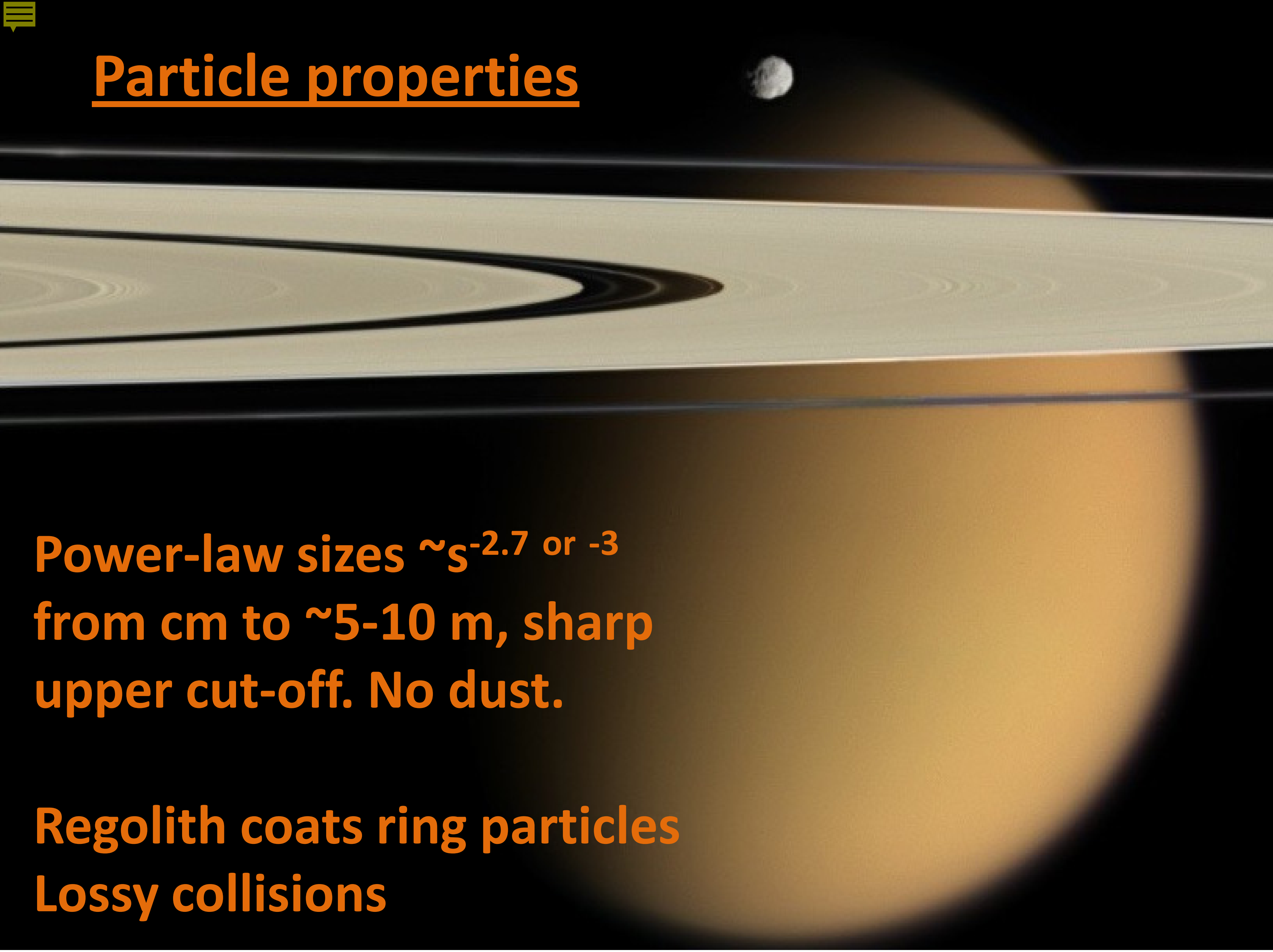
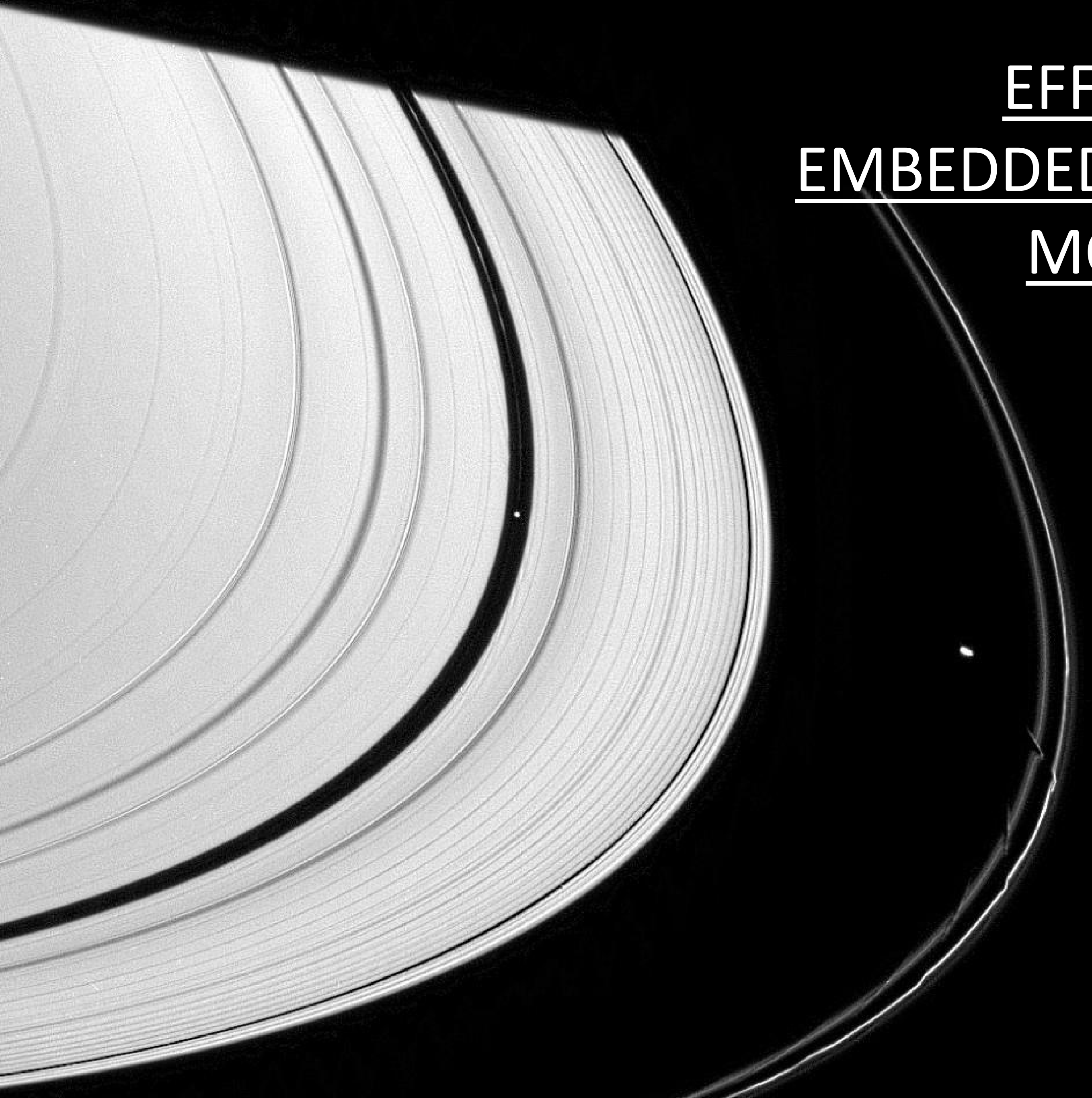


Particle properties



Power-law sizes $\sim s^{-2.7 \text{ or } -3}$ from cm to ~5-10 m, sharp upper cut-off. No dust.

Regolith coats ring particles
Lossy collisions



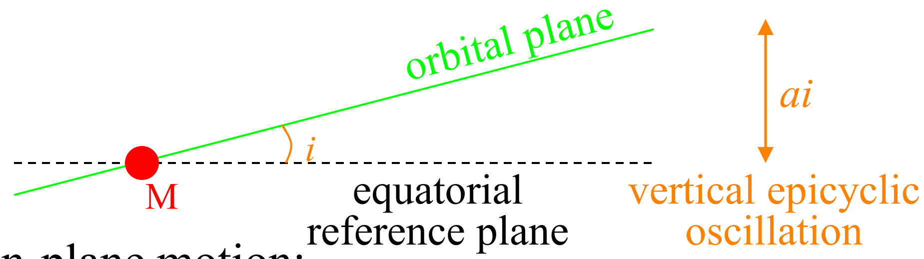
EFFECTS OF EMBEDDED & EXTERNAL MOONS

Wakes,
waves,
wiggles

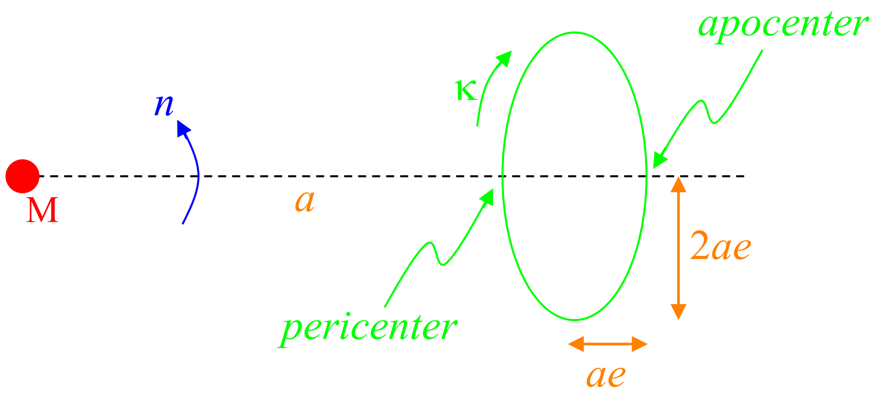
Epicycles:

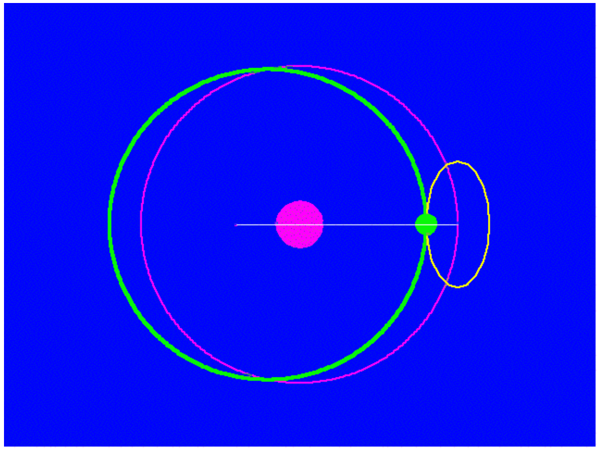
Orbital Motion as seen from Mean Circular Orbit

Vertical motion:



In-plane motion:





Epicyclic Frequencies about a Spherical Planet:
n (orbital) = κ (in-plane) = μ (vertical) ==> closed orbit
SIMPLE HARMONIC OSCILLATOR!

RESONANCE: PERIODIC FORCES AND RESPONSES

Motions contain periodic terms (epicycles) plus multiples thereof (non-linear problem).

Fundamental periods are near to orbital period.

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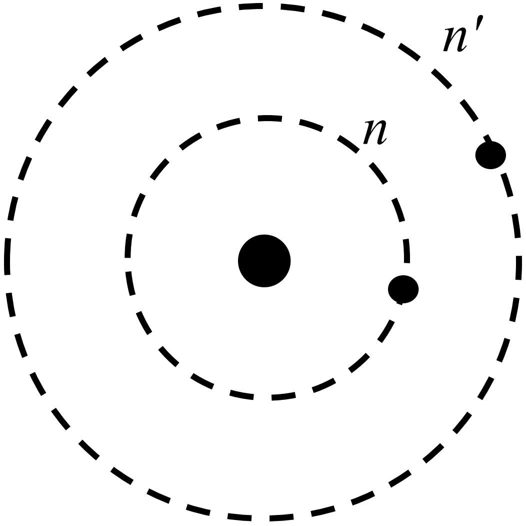
Forcing Frequencies

Interaction occurs at $n - n'$



RESONANCE: PERIODIC FORCES AND RESPONSES

Motions contain periodic terms (epicycles) plus multiples thereof (non-linear problem). Fundamental periods are roughly the orbital period.

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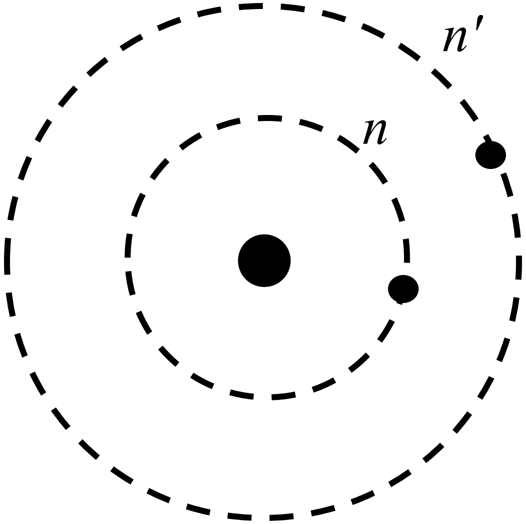


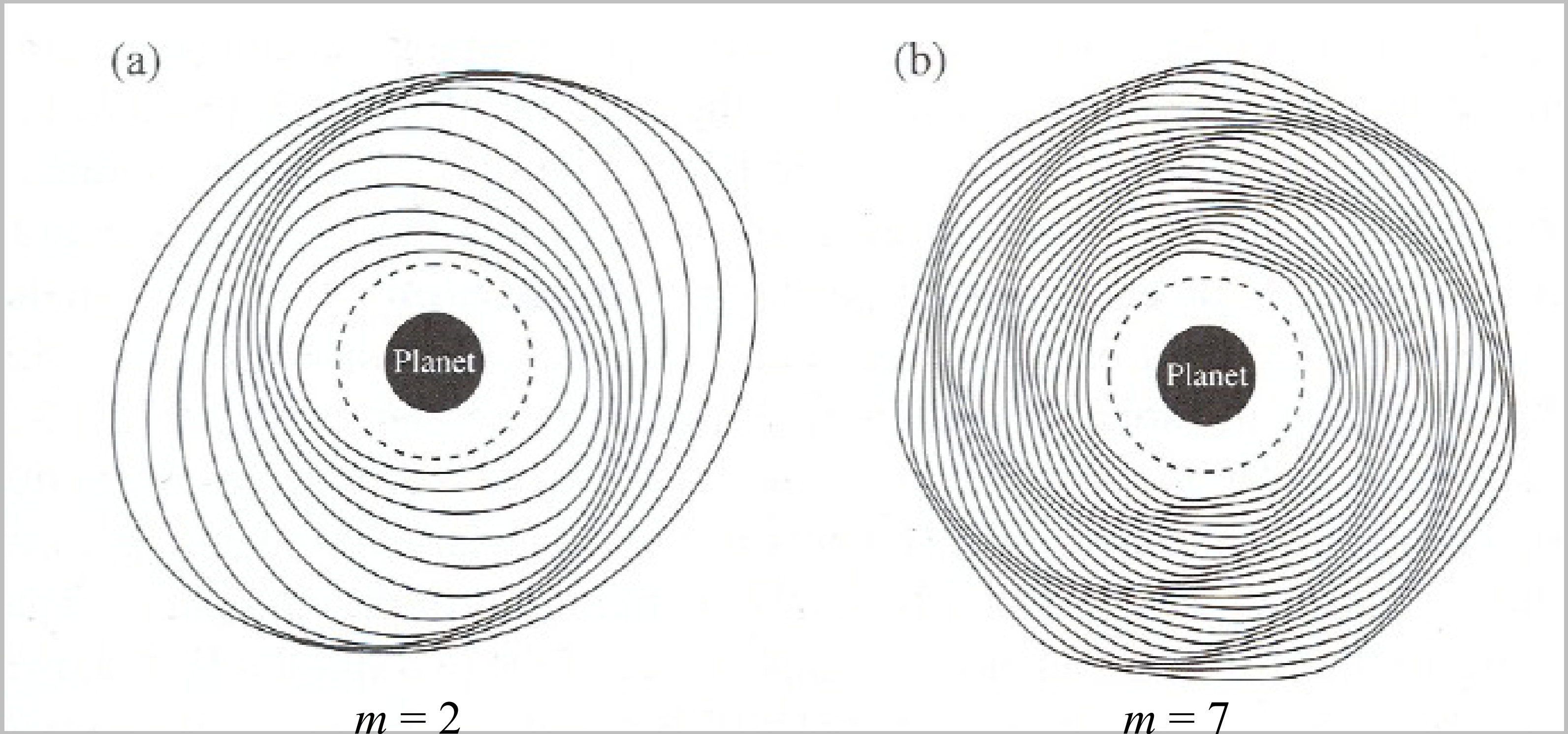
Simple Resonance Condition

$$n = j(n - n') \Rightarrow \frac{n}{n'} = \frac{j}{j-1}$$

2:1, 7:6, 43:42, etc.
interior or exterior perturber

LINDBLAD RESONANCES

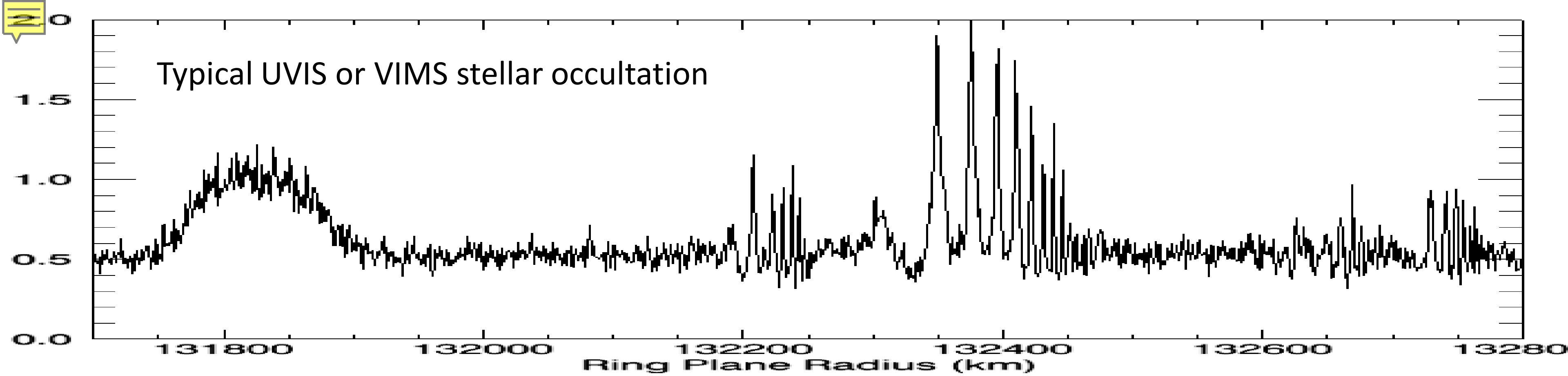
$$mn' - (m \pm 1)n \pm \dot{\varpi} = 0$$

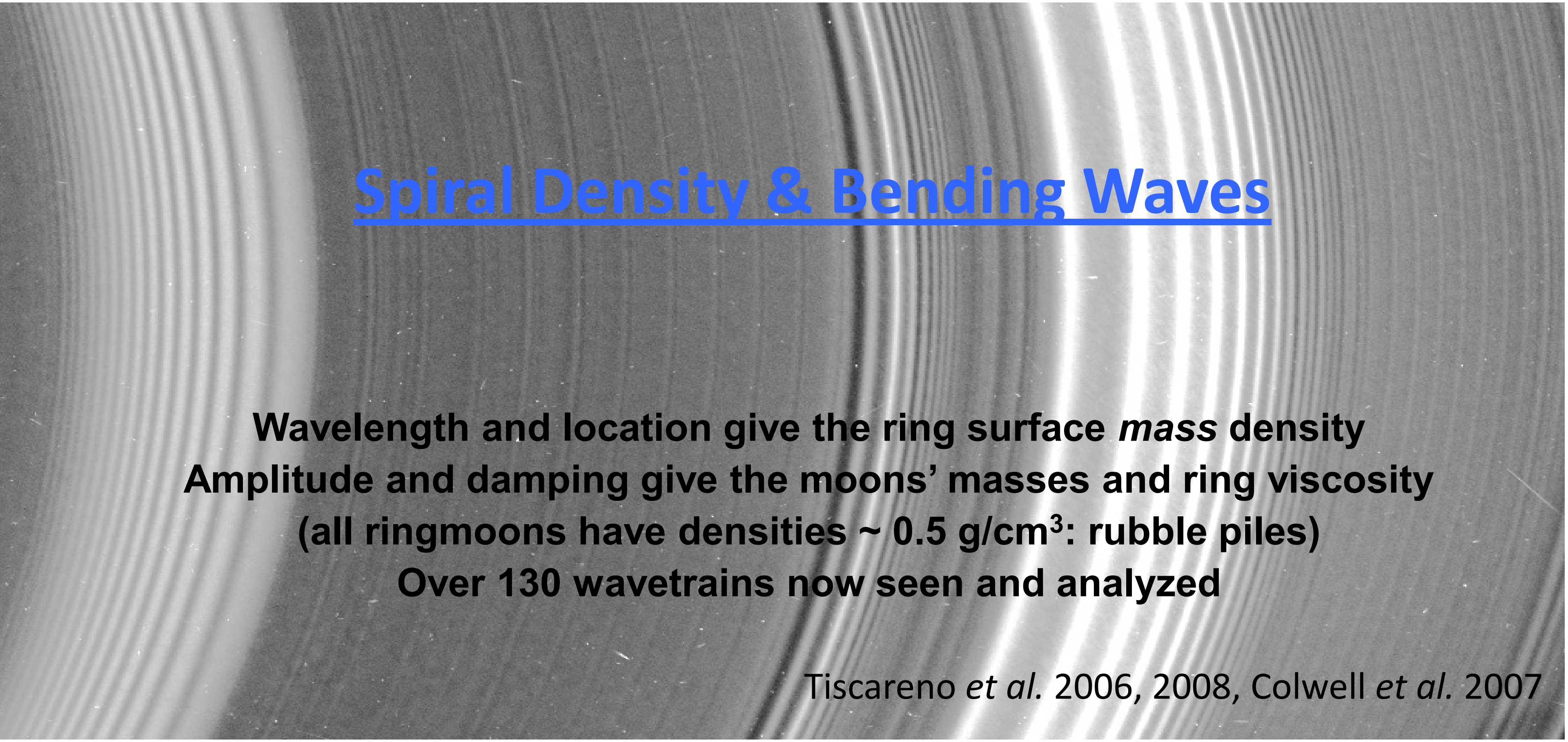


$m = 2$ $m = 7$

As seen in moon's reference frame.

Kinematic only, but drive waves. Tightly wound.





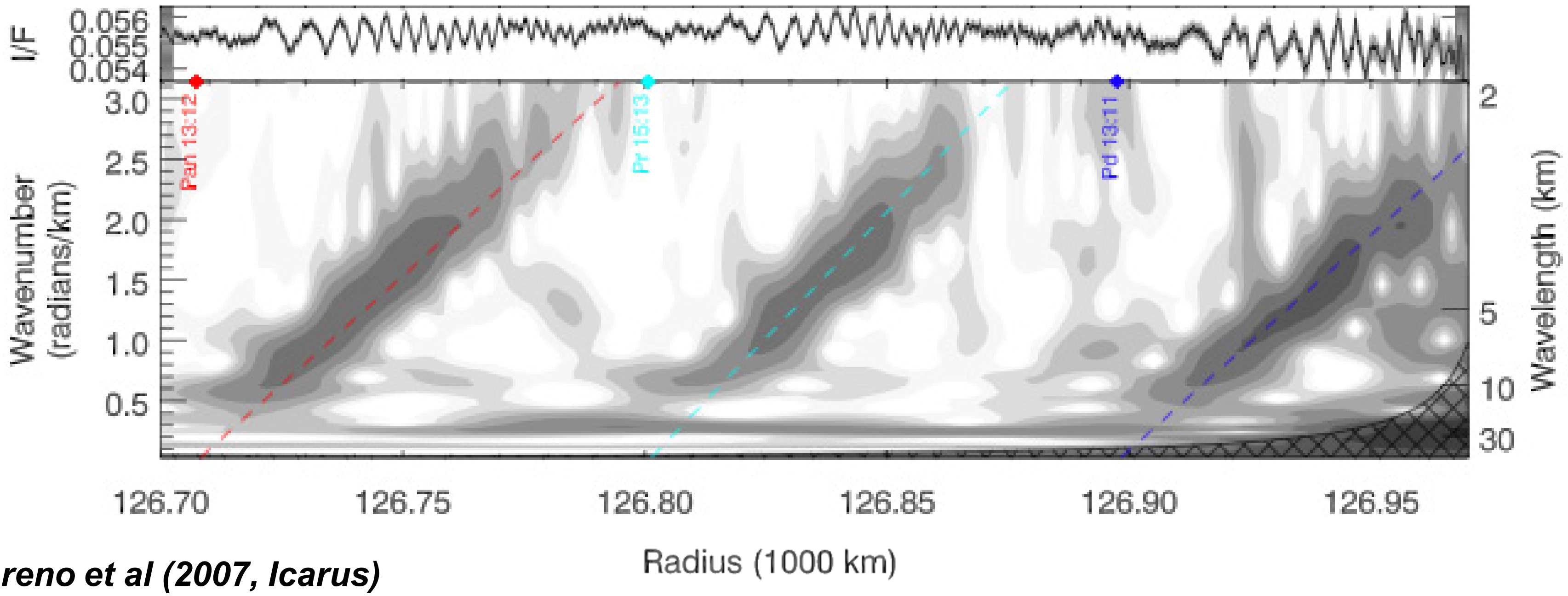
Spiral Density & Bending Waves

Wavelength and location give the ring surface *mass* density
Amplitude and damping give the moons' masses and ring viscosity
(all ringmoons have densities ~ 0.5 g/cm^3: rubble piles)
Over 130 wavetrains now seen and analyzed

Tiscareno *et al.* 2006, 2008, Colwell *et al.* 2007

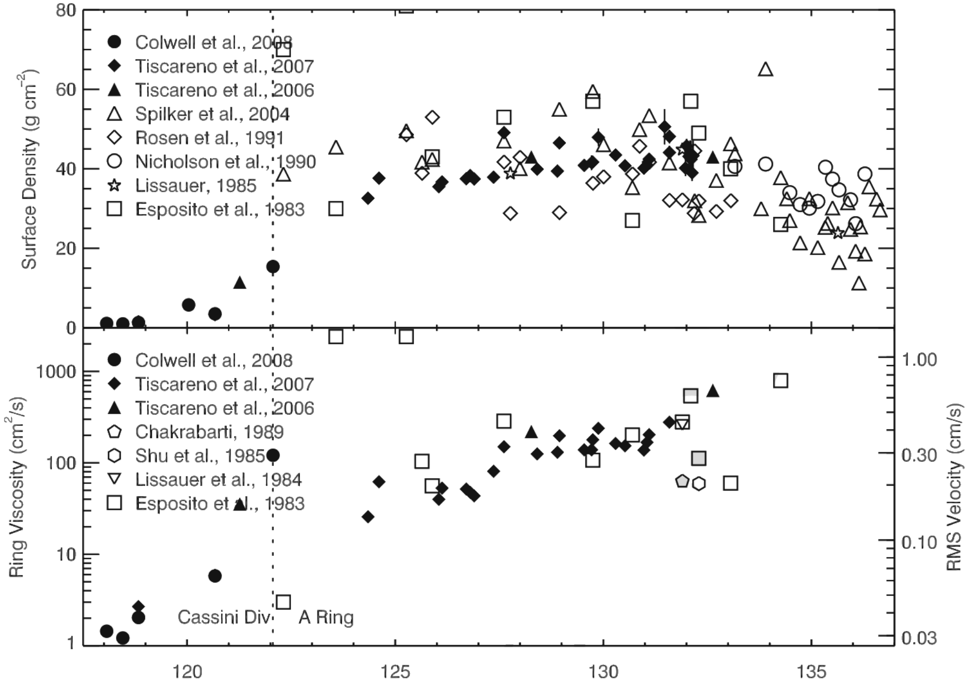
Spiral Waves as Scientific Instruments

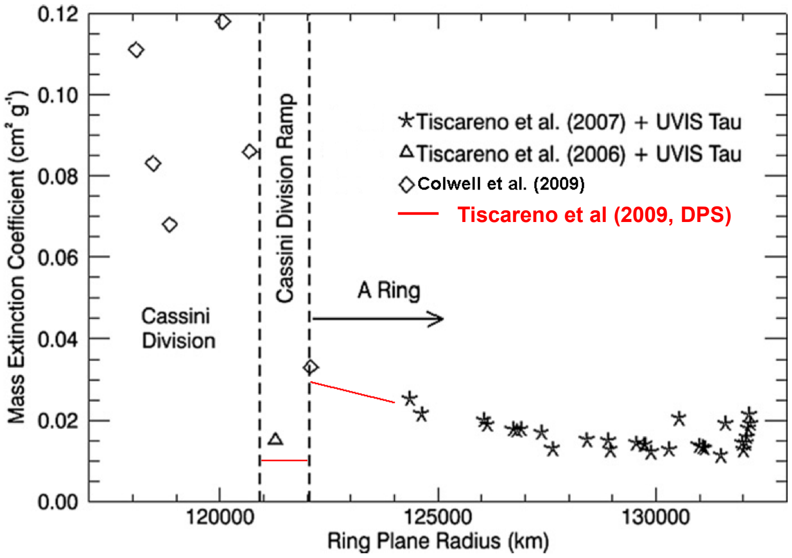
- Wavelet analysis (spatially-resolved power spectrum) helps to extract wave parameters from radial profile
- Wavenumber $k \approx (r\text{-}r_{res})/\sigma$ (may decrease)



Tiscareno et al (2007, Icarus)

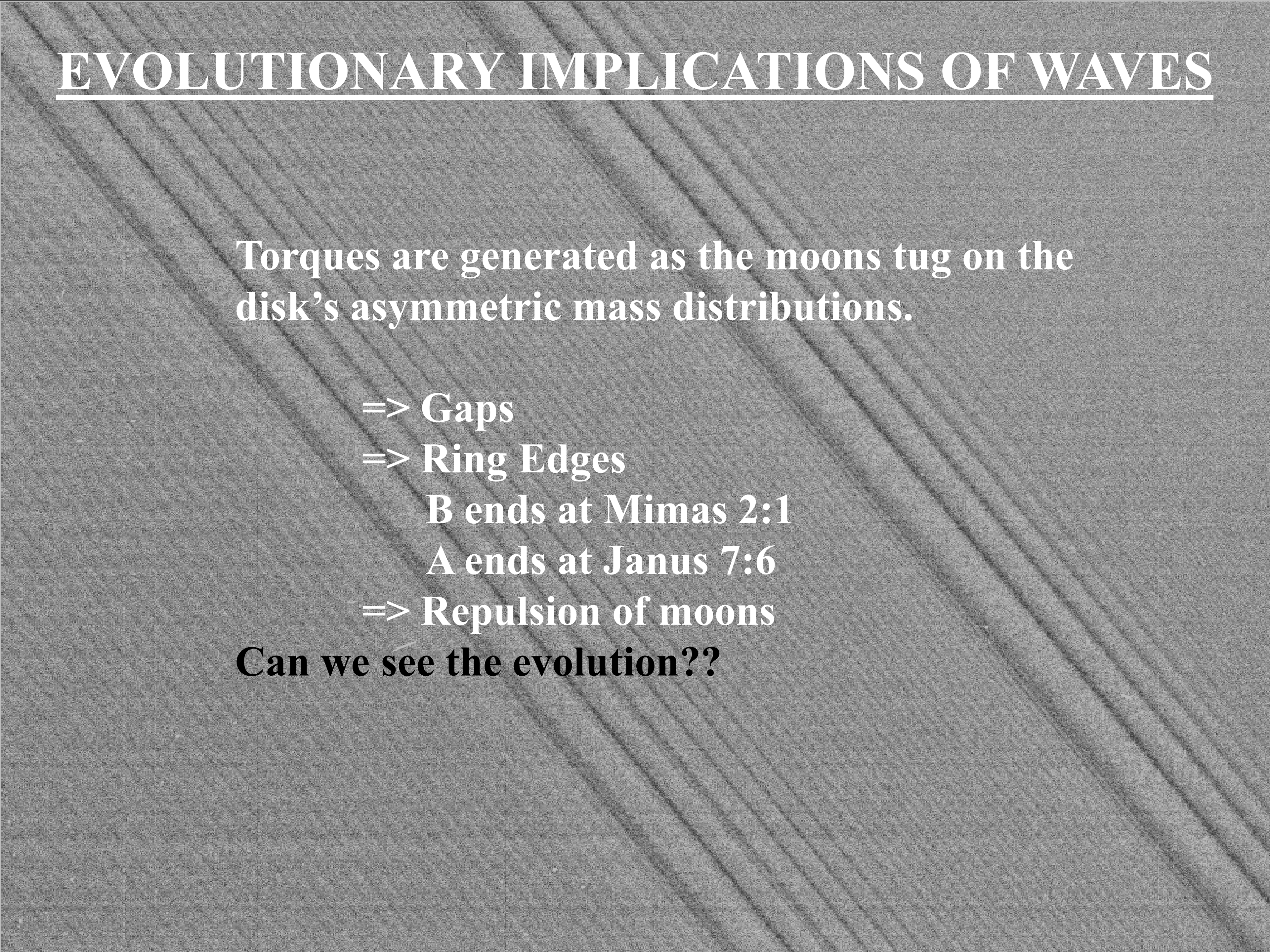
Spiral Density Waves





- Surface density σ peaks in mid-A Ring
- Dividing optical depth by σ gives mass extinction
  - Implies smaller particles in Cassini Division
- Viscosity places upper limit on vertical thickness
  - Meaningful in Cassini Division (few m) and inner A Ring (10-15 m)

Tiscareno et al 2007, Icarus
Colwell et al 2009, Icarus

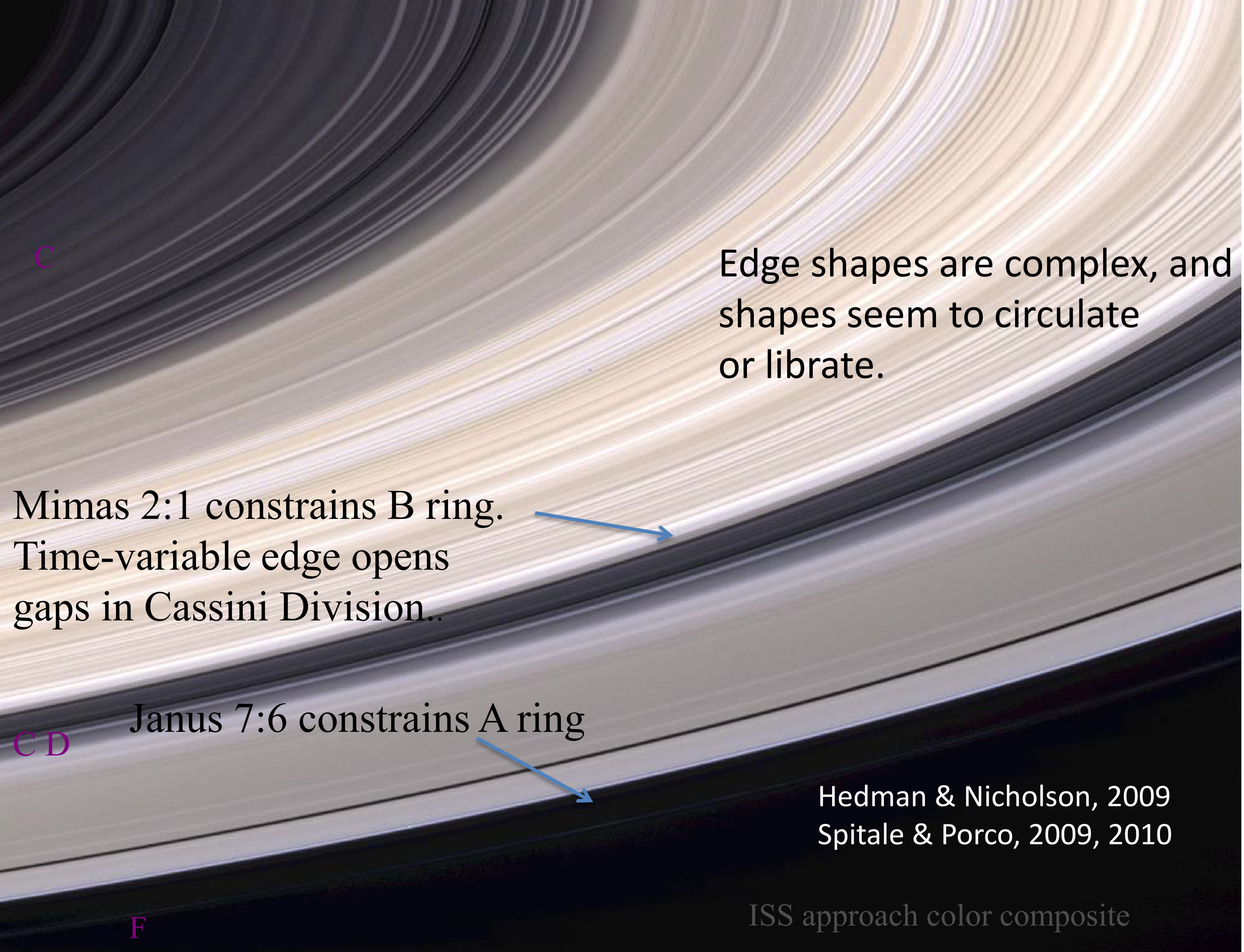


EVOLUTIONARY IMPLICATIONS OF WAVES

Torques are generated as the moons tug on the disk’s asymmetric mass distributions.

- => Gaps
- => Ring Edges
  - B ends at Mimas 2:1
  - A ends at Janus 7:6
- => Repulsion of moons

Can we see the evolution??



Edge shapes are complex, and shapes seem to circulate or librate.

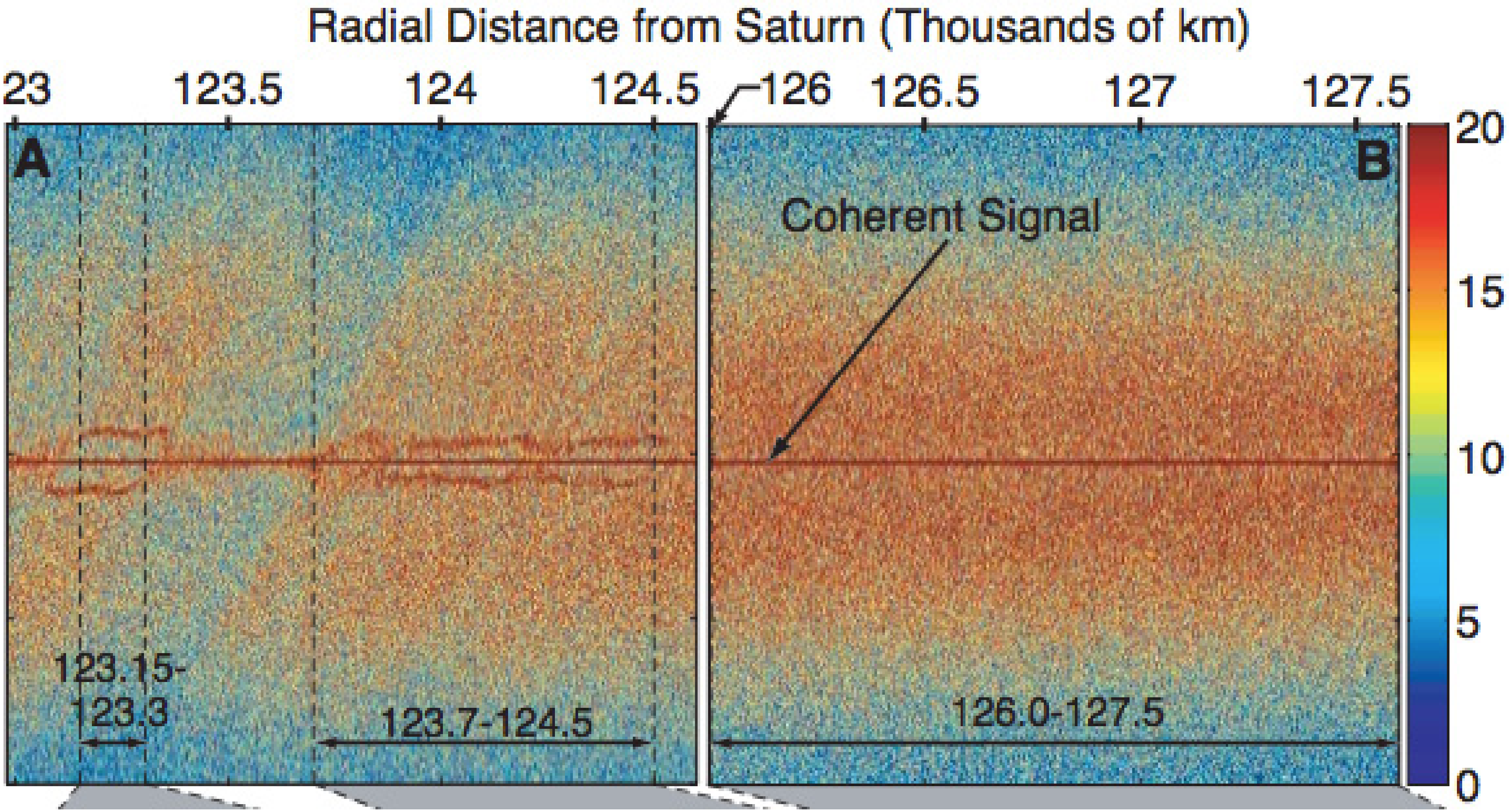
Mimas 2:1 constrains B ring. Time-variable edge opens gaps in Cassini Division..

Janus 7:6 constrains A ring

Hedman & Nicholson, 2009
Spitale & Porco, 2009, 2010

ISS approach color composite

Periodic Structures



Diffraction grating with 150-220-m spacing?? Viscous over-stability?

Thomson et al. 2007

EFFECTS OF EMBEDDED & EXTERNAL MOONS

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

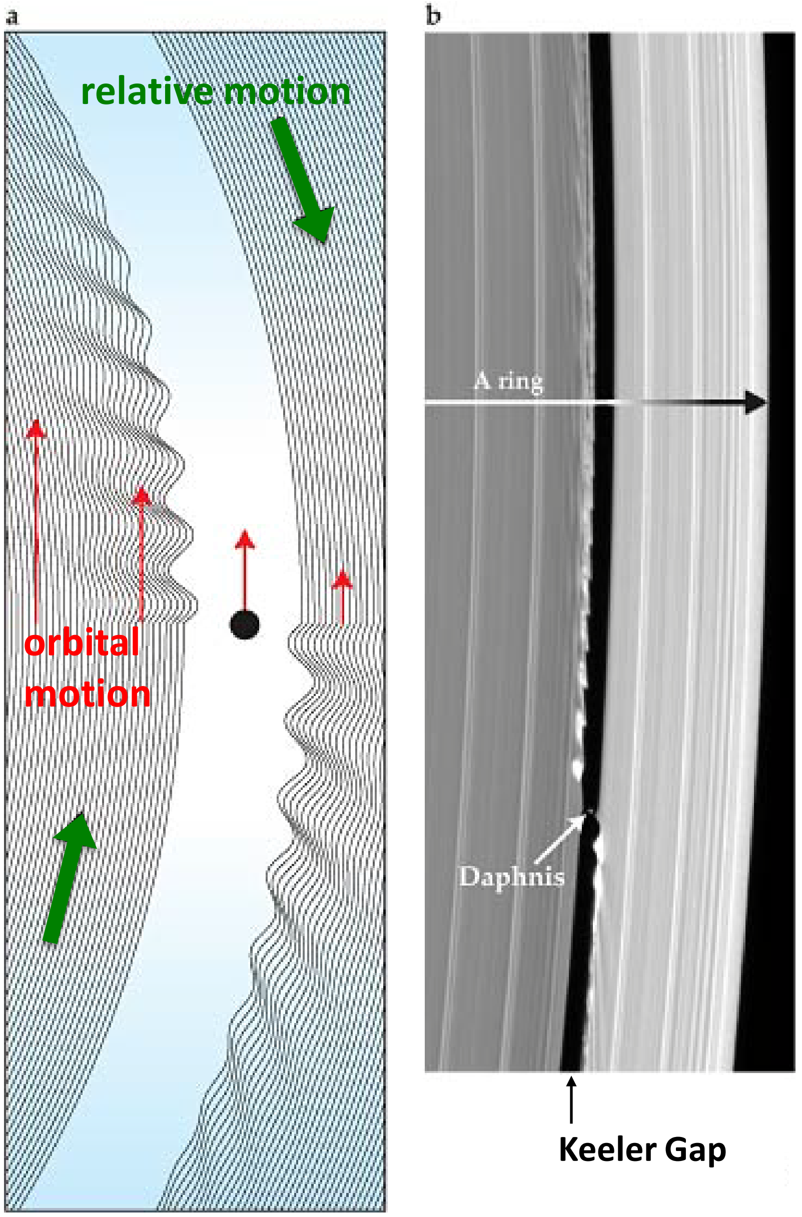
Outer A ring

F ring

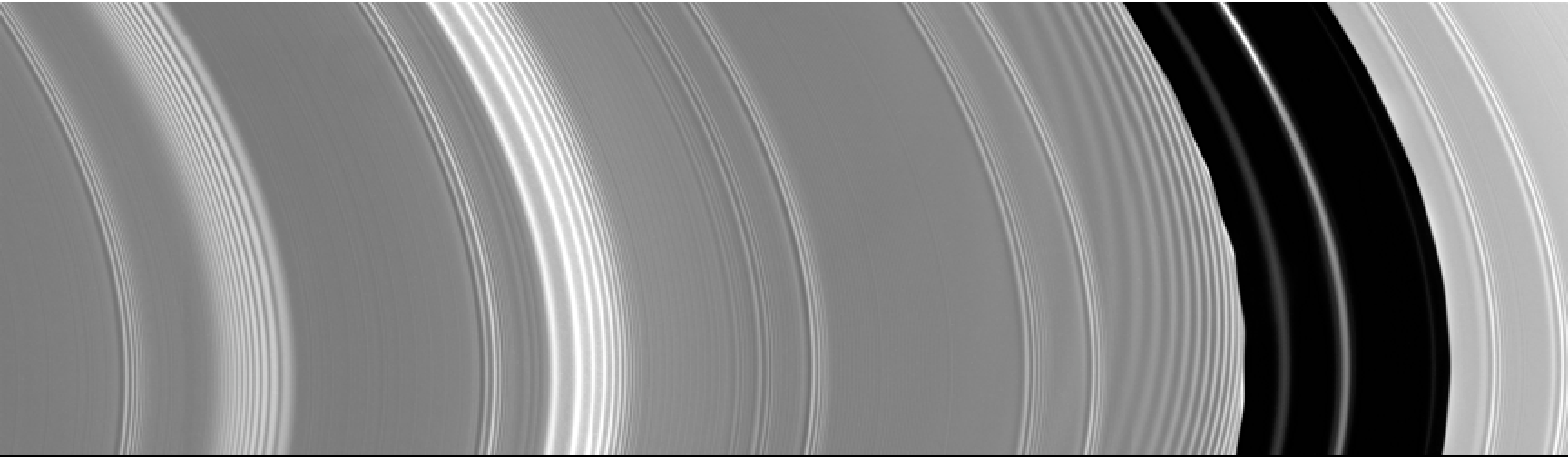
10,000km

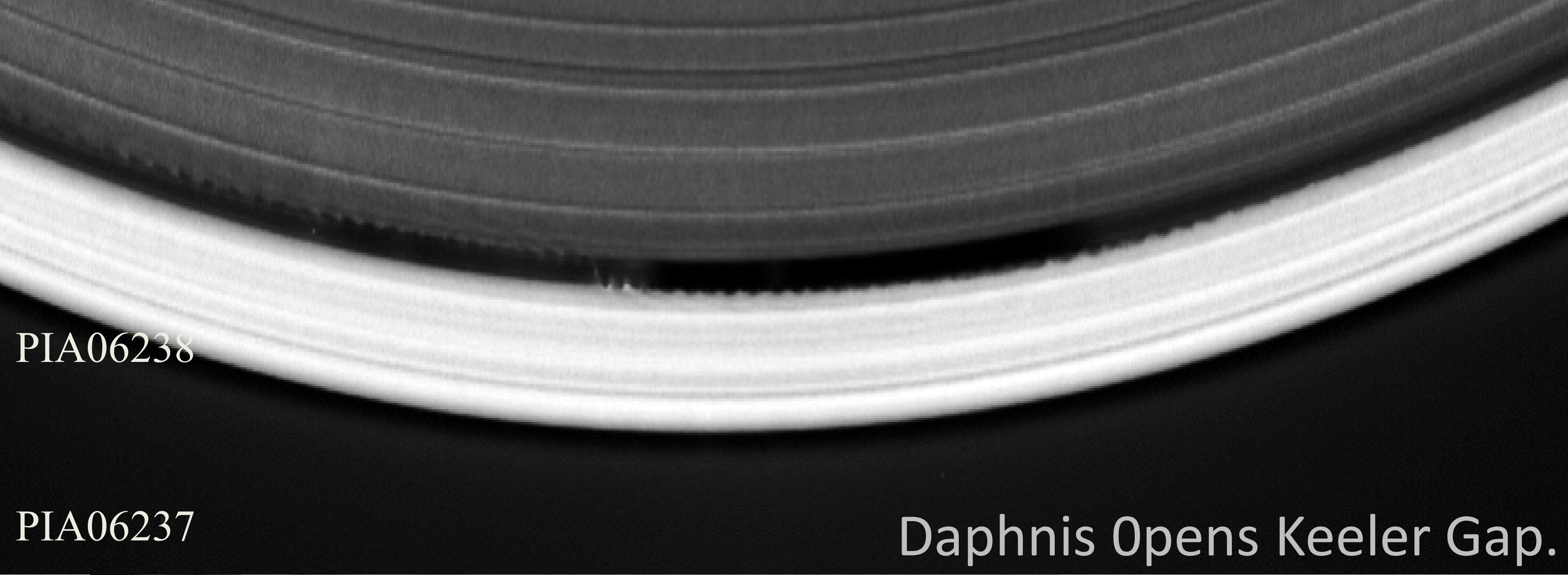
Gap Edges

- Moon gives passing ring particles an eccentricity, resulting in wavy gap edges
- It follows from Kepler’s 3rd Law that $\lambda = 3\pi\,\Delta a$
- λ□increases with Δa, forming “moonlet wakes” that penetrate into the ring *(Showalter et al 1986, Icarus)*
- Expect smooth sinusoidal edges, amplitude proportional to the mass of the moon, then decays as streamlines cross

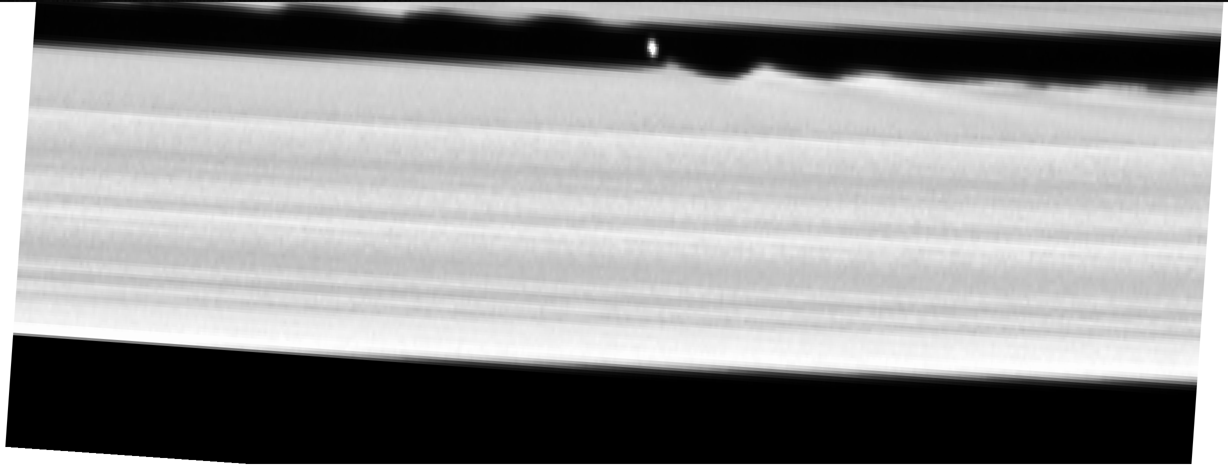


Murray 2007, Physics Today



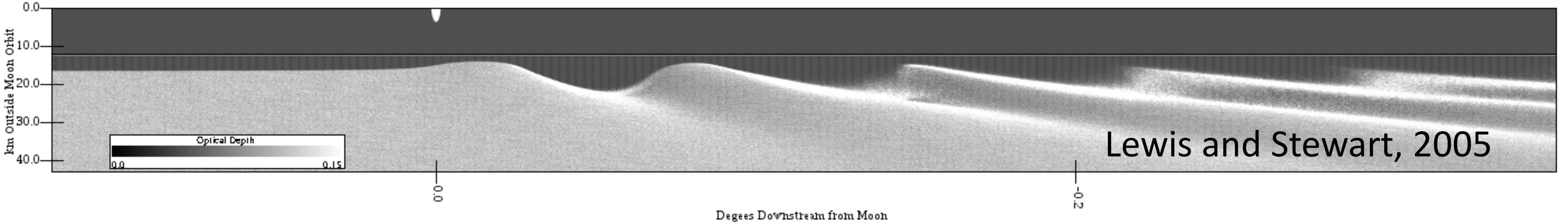


Daphnis Opens Keeler Gap.



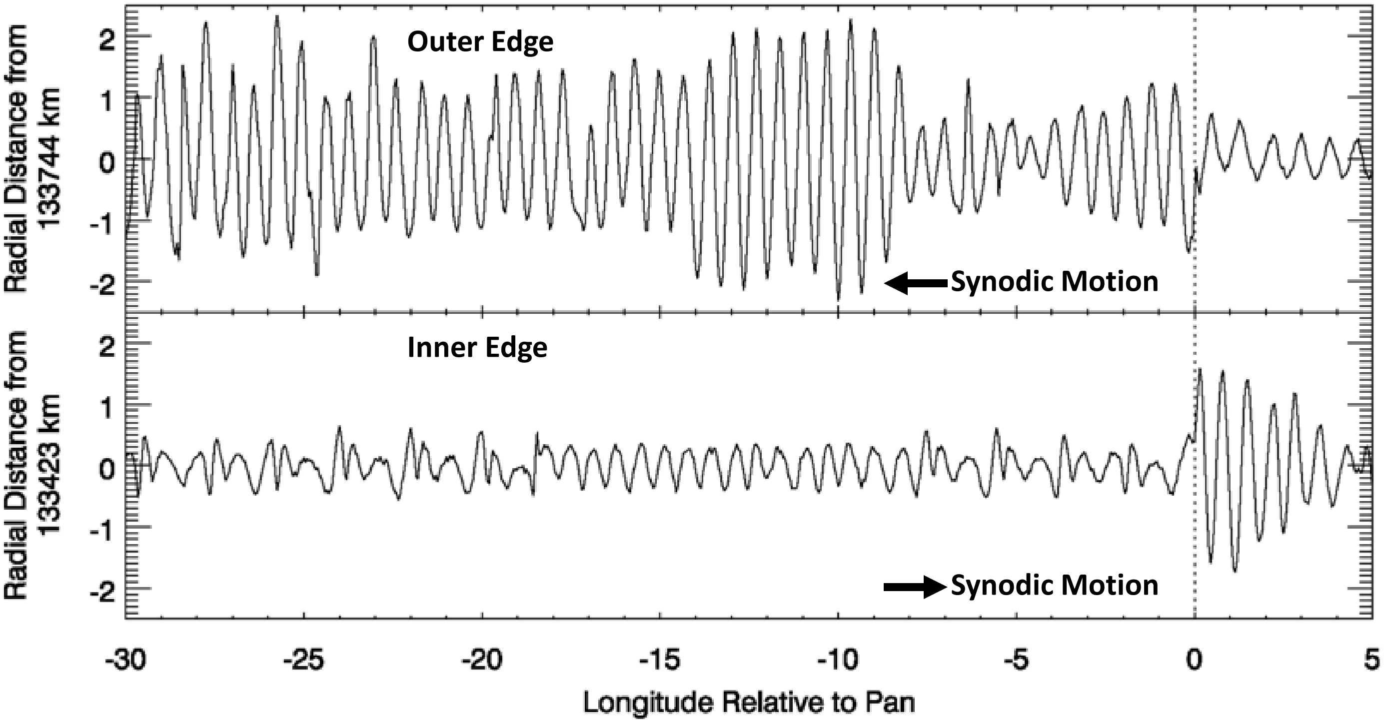
4-km moon clears
20-40 km gap

Inferred ρ = 0.4 g-cm



Lewis and Stewart, 2005

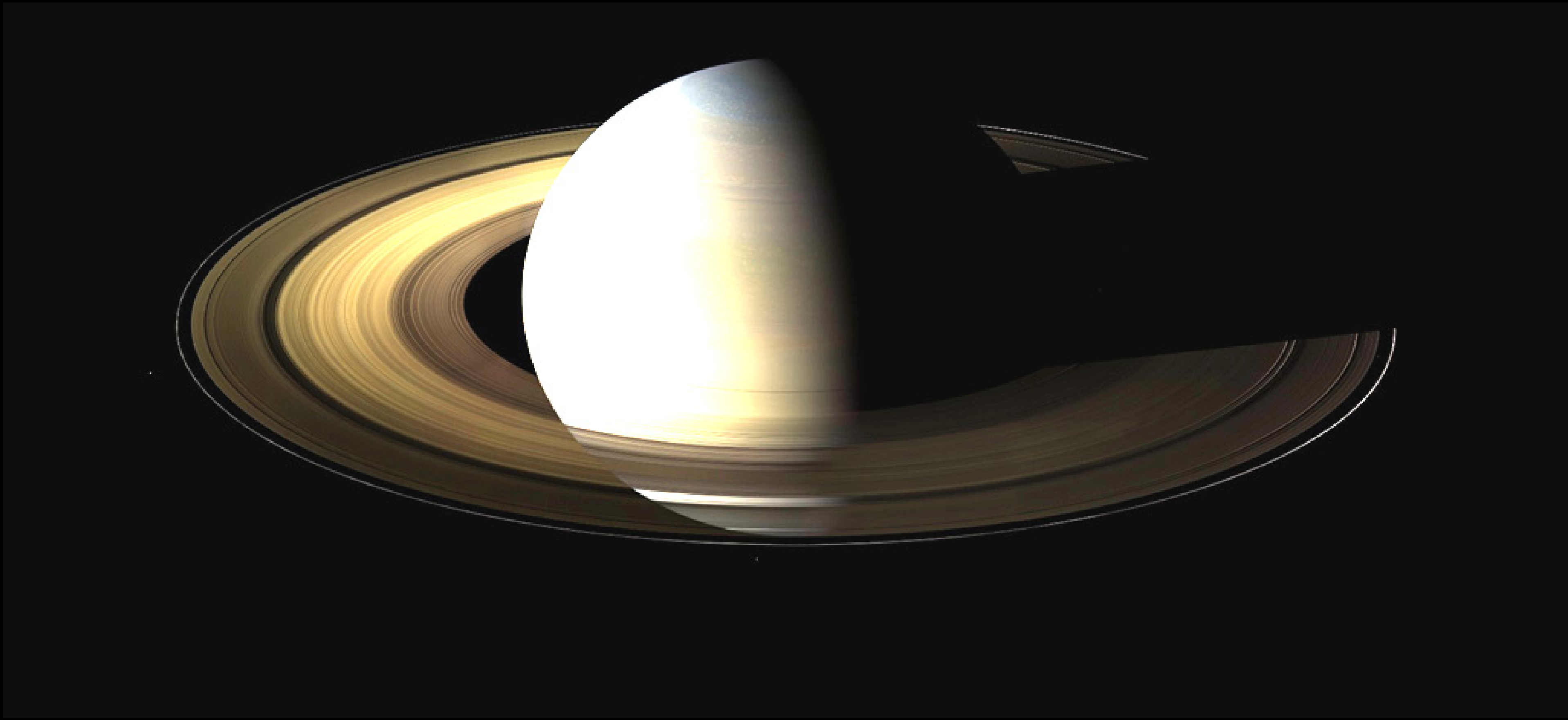
Encke Gap Wavy Edges



- Wavy edges persist until next encounter with Pan (~ 1000 orbits).
- Immediately after encounter, edges damp as expected, but far downstream, wavelength deviates from $3\pi s$, sometimes switches abruptly from sinusoid to "chirp".
- Widths of Keeler and Encke Gaps consistent with mass ratios.
- Is angular-momentum transfer affected?

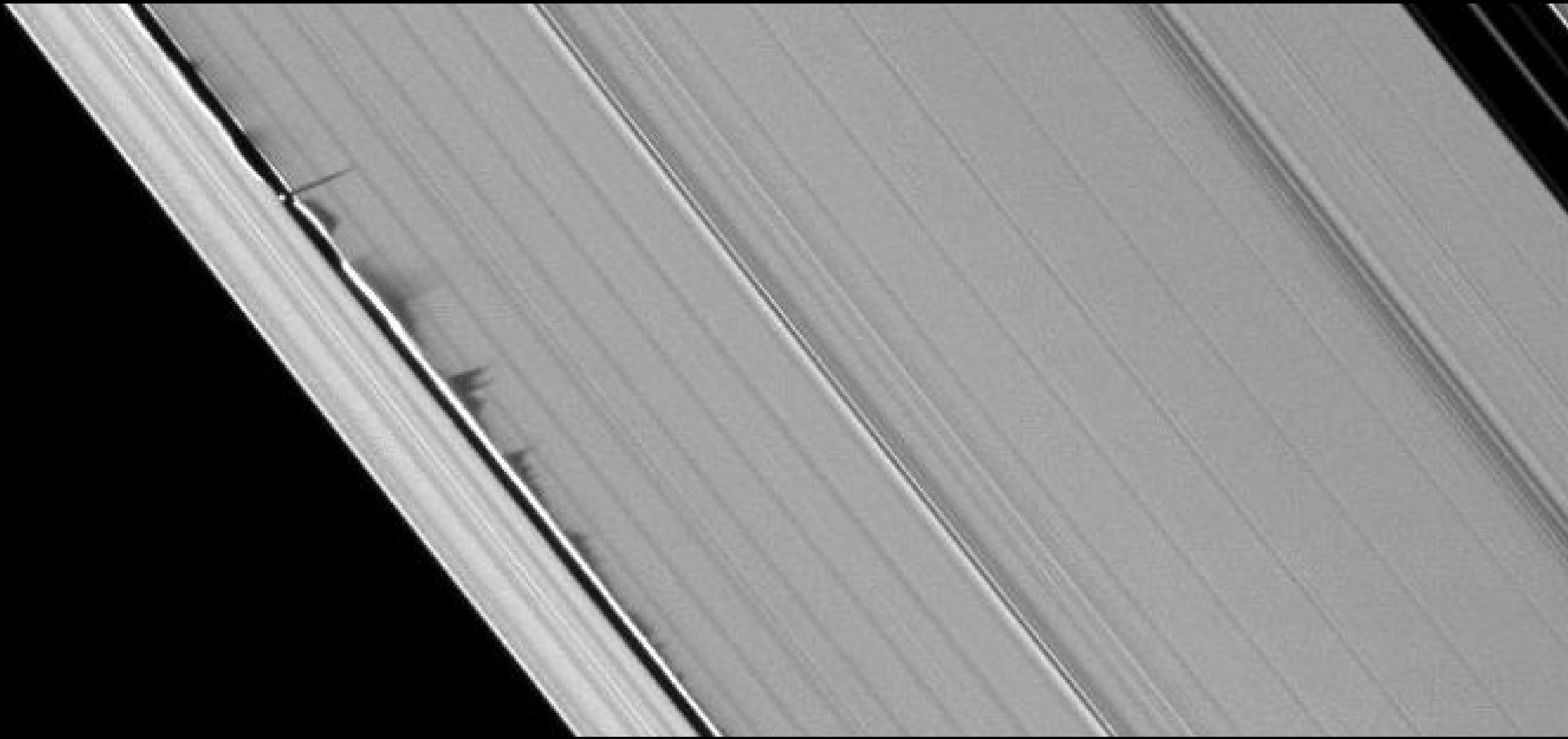
Tiscareno et al. 2006

Equinox was a special time for rings science….



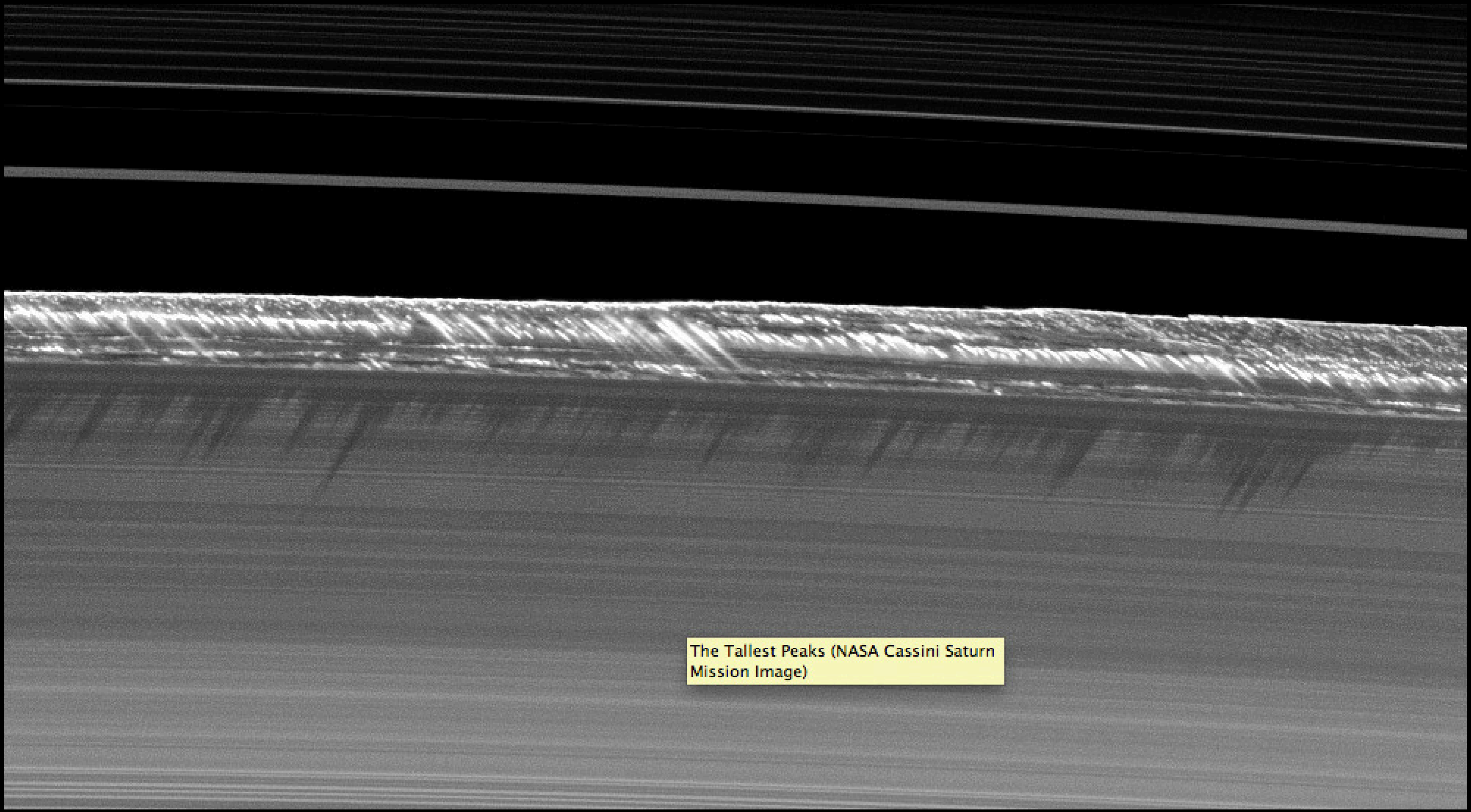
Saturn and the rings in 2009

Shadows in the Rings



- At equinox, the Sun shines nearly edge-on to the rings, casting long shadows
- Vertical structure in Keeler Gap edge is due to vertical excursions in Daphnis’ orbit

Vertical Splashing, Moons (?) at B-ring's edge

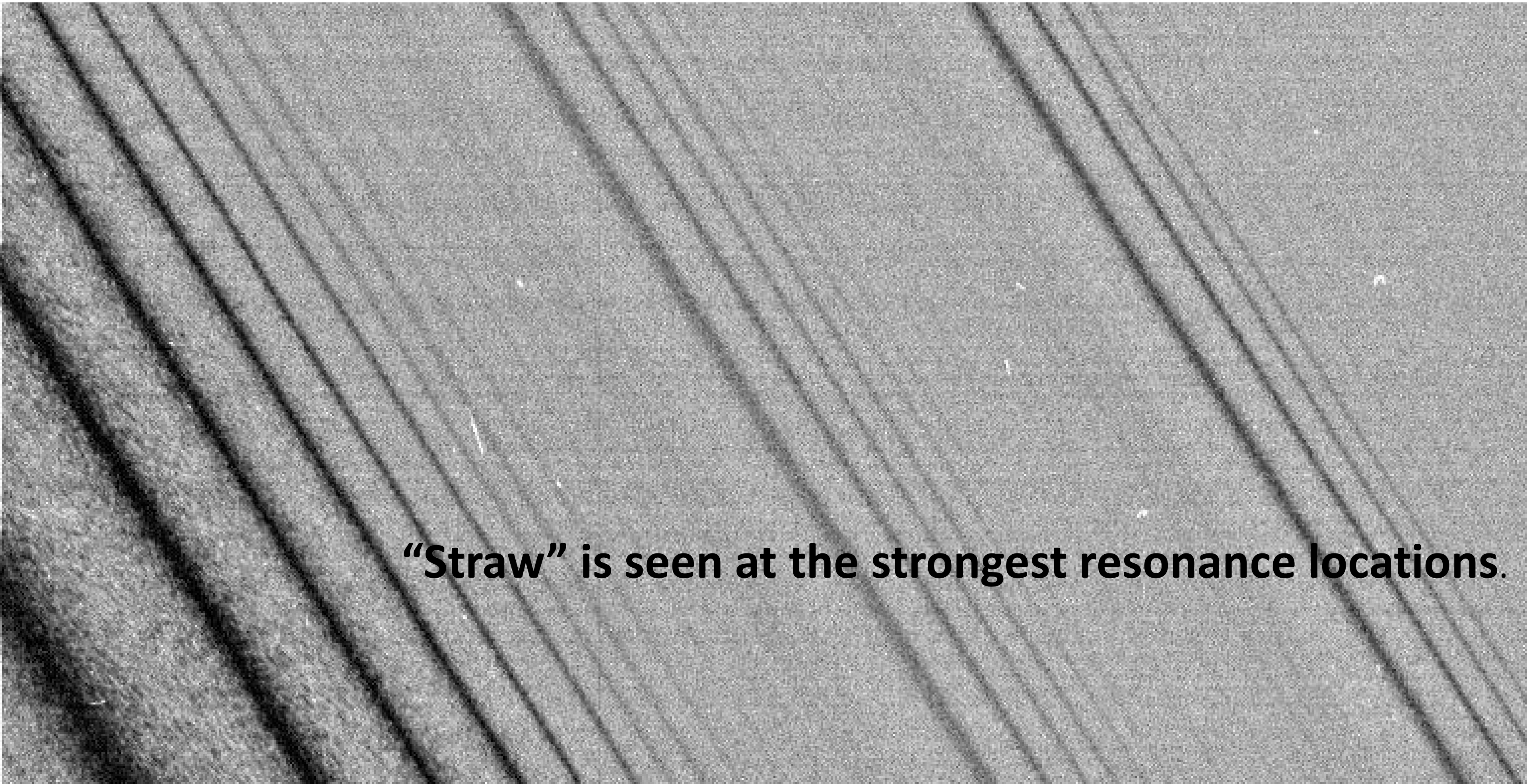


The Tallest Peaks (NASA Cassini Saturn Mission Image)

Ring Particle
Orbital Period=
5/6 Janus'
Orbital Period

Ring Particle
Orbital Period=
12/13 Pandora's
Orbital Period

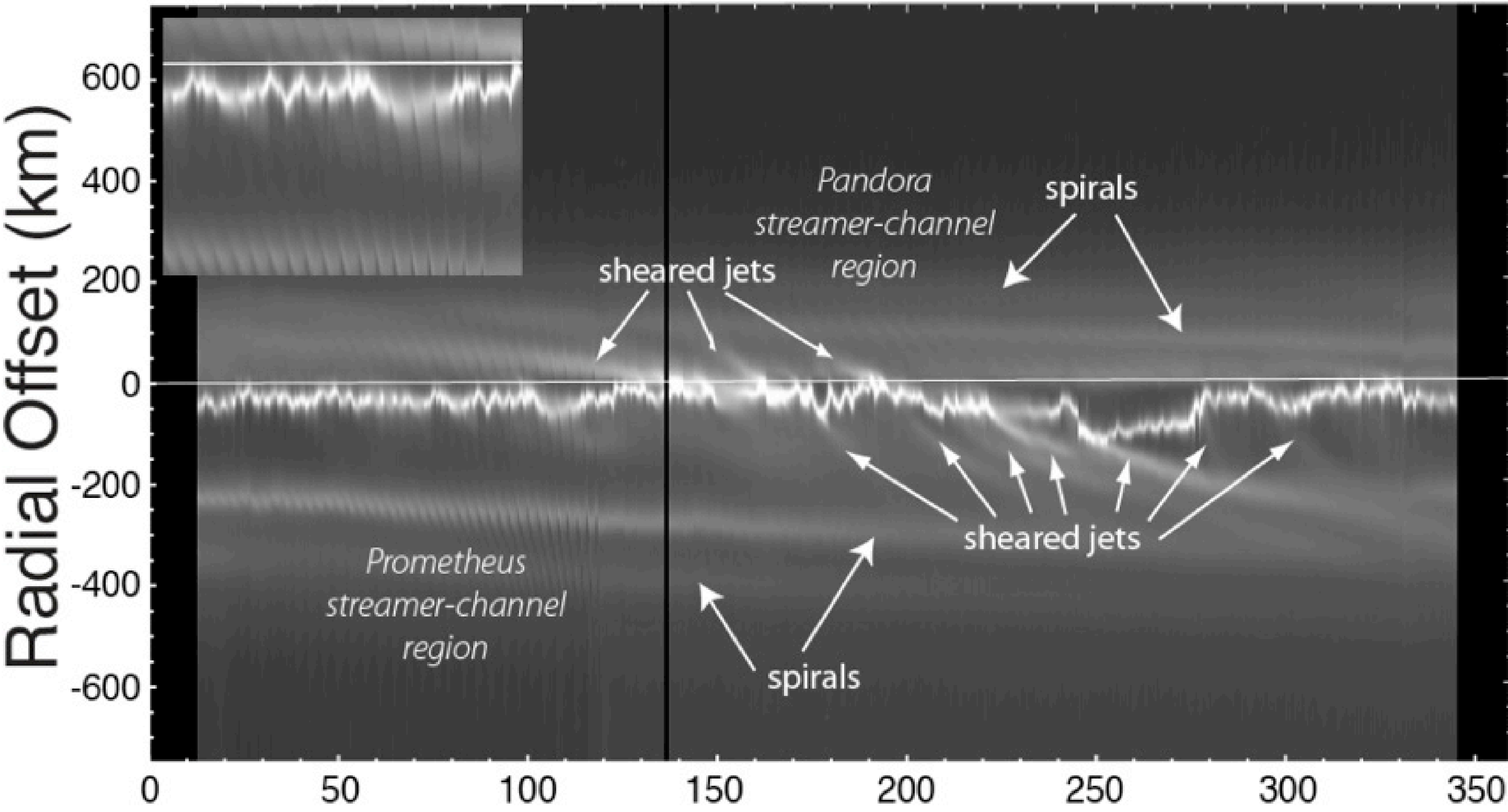
Ring Particle
Orbital Period=
18/19 Prometheus'
Orbital Period



"Straw" is seen at the strongest resonance locations.

F Ring Fireworks

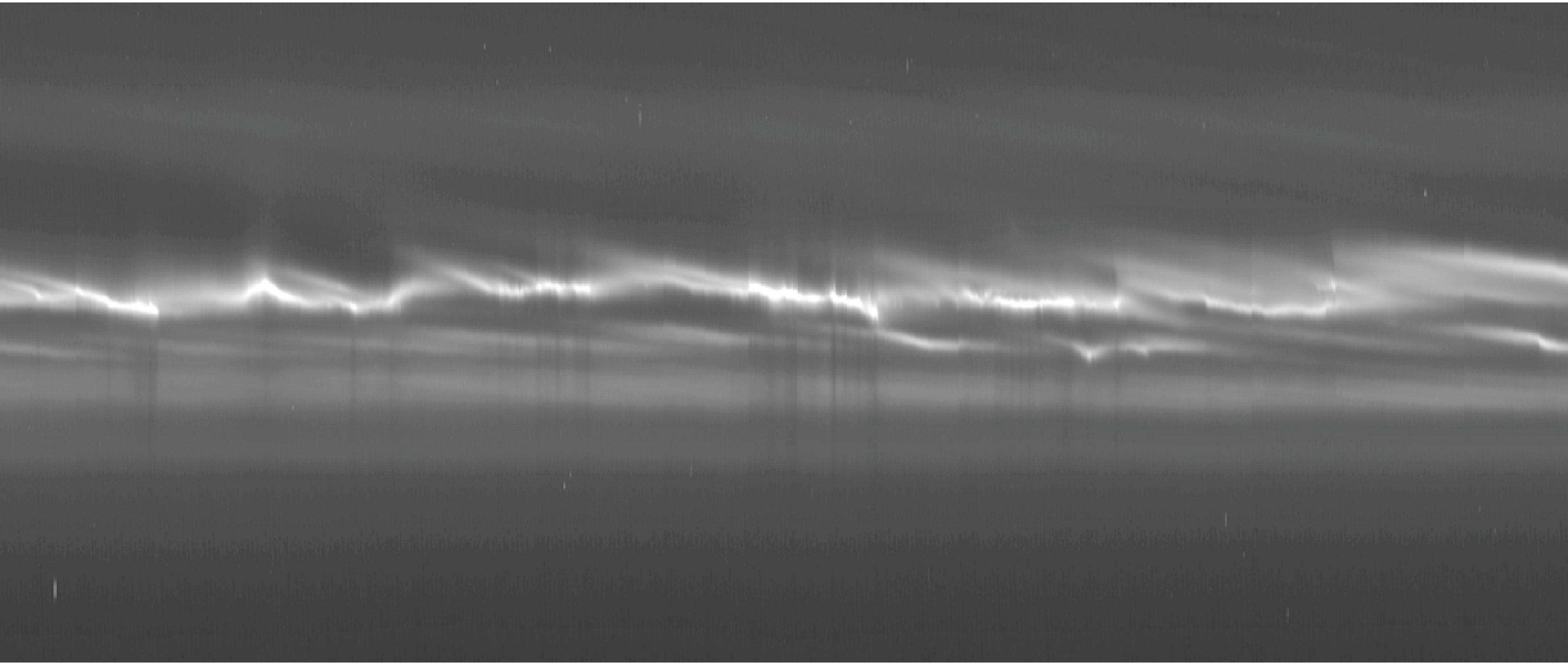
The most direct ring-moon interactions take place between Prometheus and the narrow F Ring



Murray *et al.* 2008

F Ring

Triggered Accretion in the F Ring



Bright knots, shown to be relatively dense by associated shadows, are correlated to regions recently affected by Prometheus

Beurle et al 2010, Ap. J. Ltrs

Clumping in Rings:

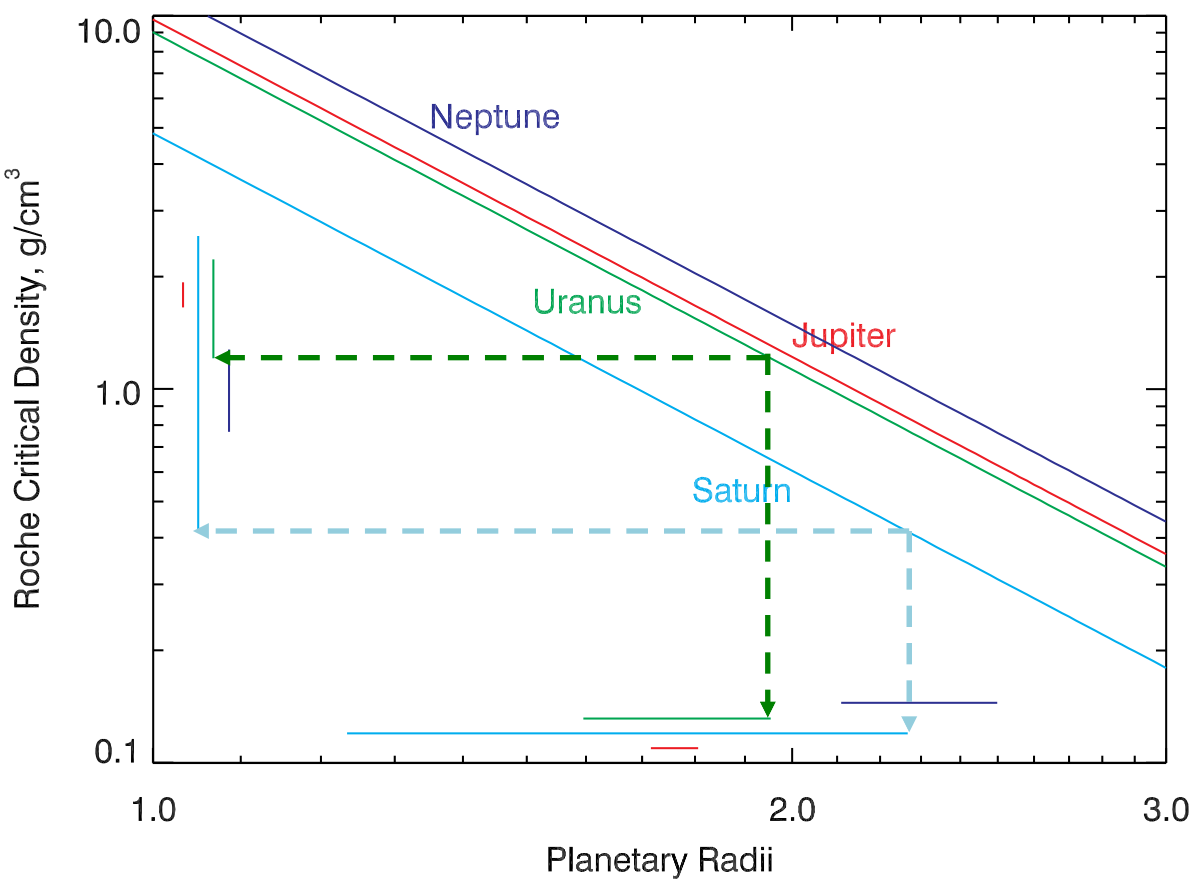
Moons and Almost Moons

Roche Critical Density

- Objects need $\rho > \rho_R$ to be held together by gravity
- Dense seeds accrete fluffy mantle until $\rho \approx \rho_R$ (object "fills its Roche zone")

$$\rho_R = \frac{3M_P}{\gamma a^3}$$

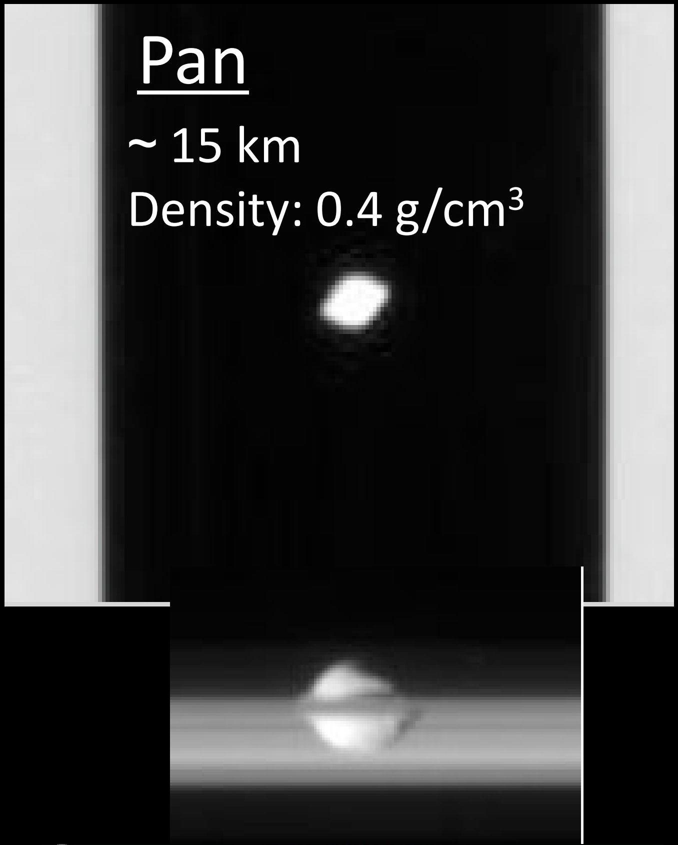
- At ring's outer edge:
  - Transient particles have $\rho > \rho_R$ OR
  - OR material for making rings is not abundant
- S ring material intrinsically less dense than U ring



Accretion in the Rings

Atlas

41 x 36 x 20 km
Density: 0.4 g/cm^3

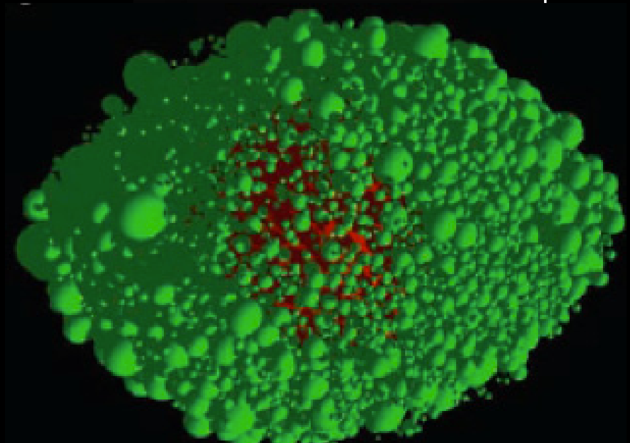


Pan

~ 15 km
Density: 0.4 g/cm^3

- Low densities, odd shapes
- Dense cores accrete porous mantle until they fill the zones dominated by their gravity

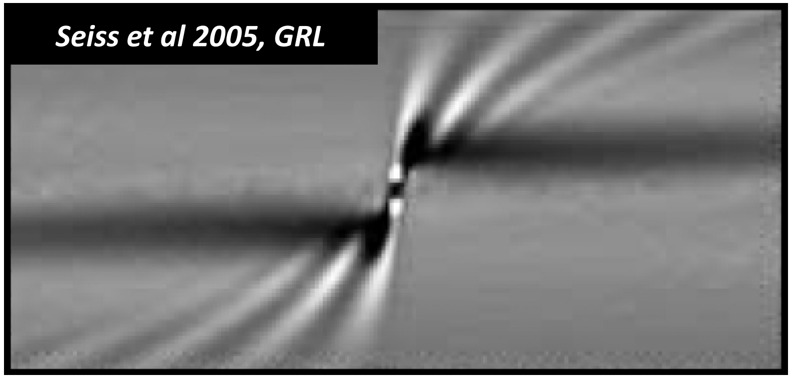
Porco et al. 2007; Charnoz et al. 2007



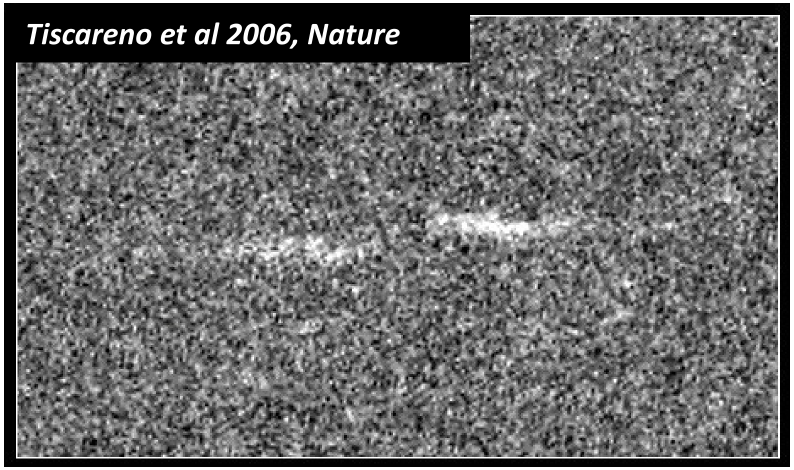
“Propellers”

- Small moons won’t open a full gap, but will disturb the locality. (Spahn and Sremcevic 2000, A&A; Sremcevic et al. 2002, MNRAS; Seiss et al. 2005, GRL)
- > 100s “propellers” have found by Cassini . (Tiscareno et al. 2006 Nature, 2008 AJ, 2010 AJ; Sremcevic et al. 2007 Nature). Tens of km long.

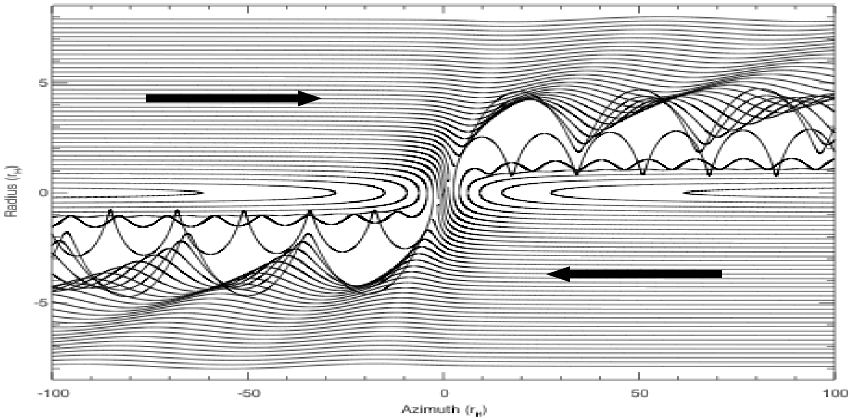
  Moonlets are tens of meters in size and are confined to three belts in the outer A ring.

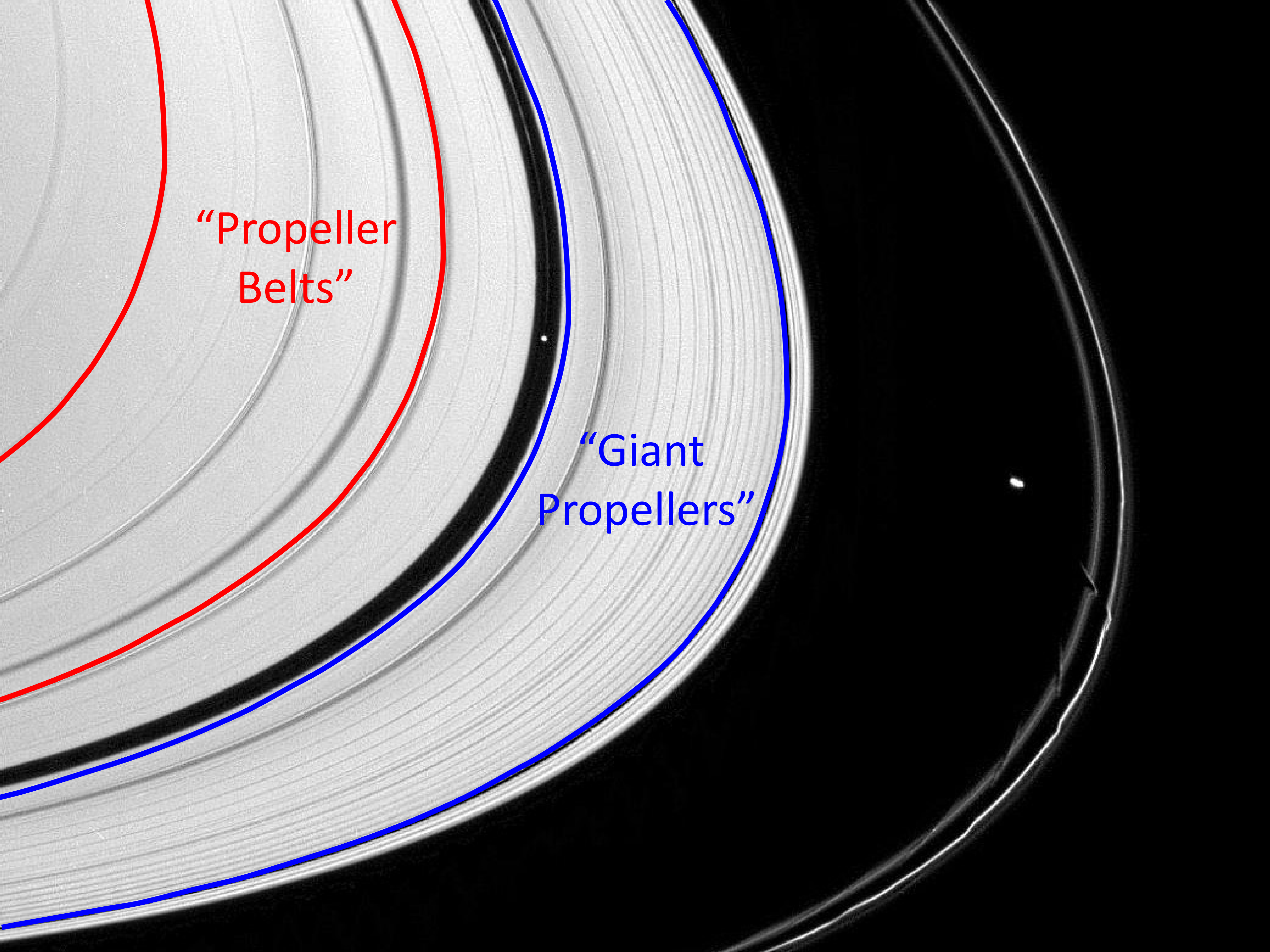


Seiss et al 2005, GRL



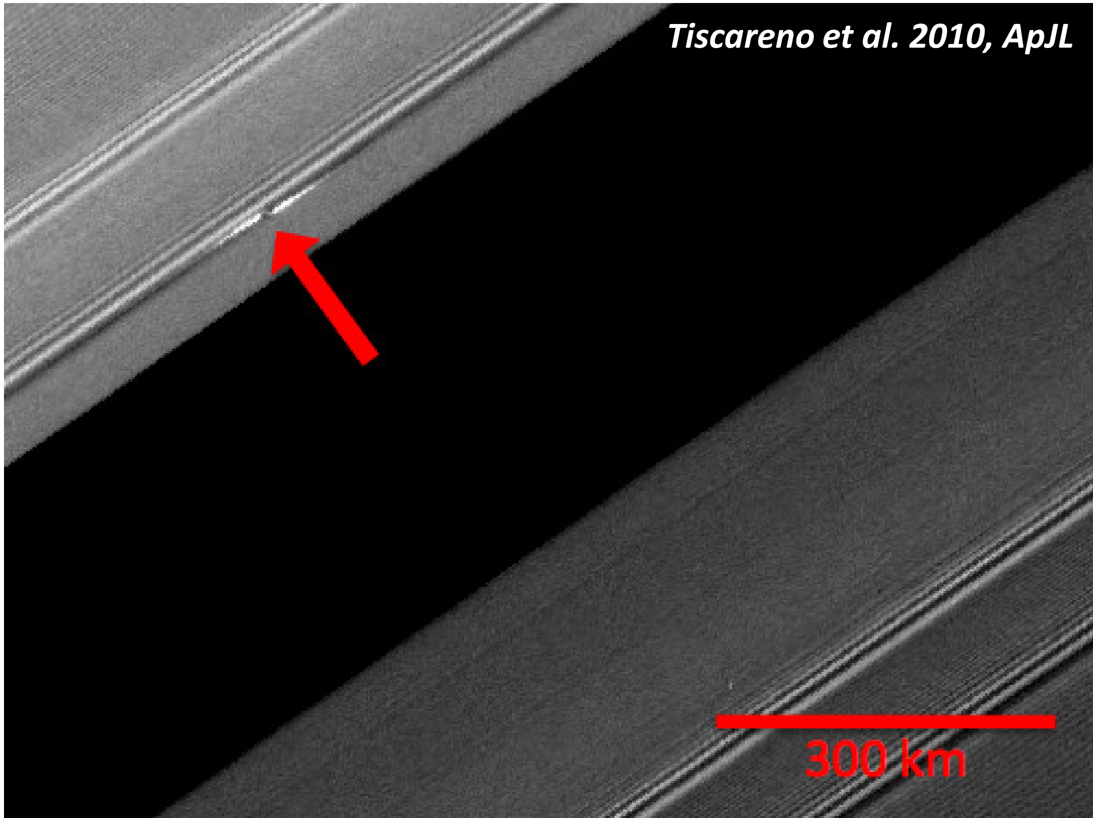
Tiscareno et al 2006, Nature




"Propeller Belts"
"Giant Propellers"

Giant Propellers

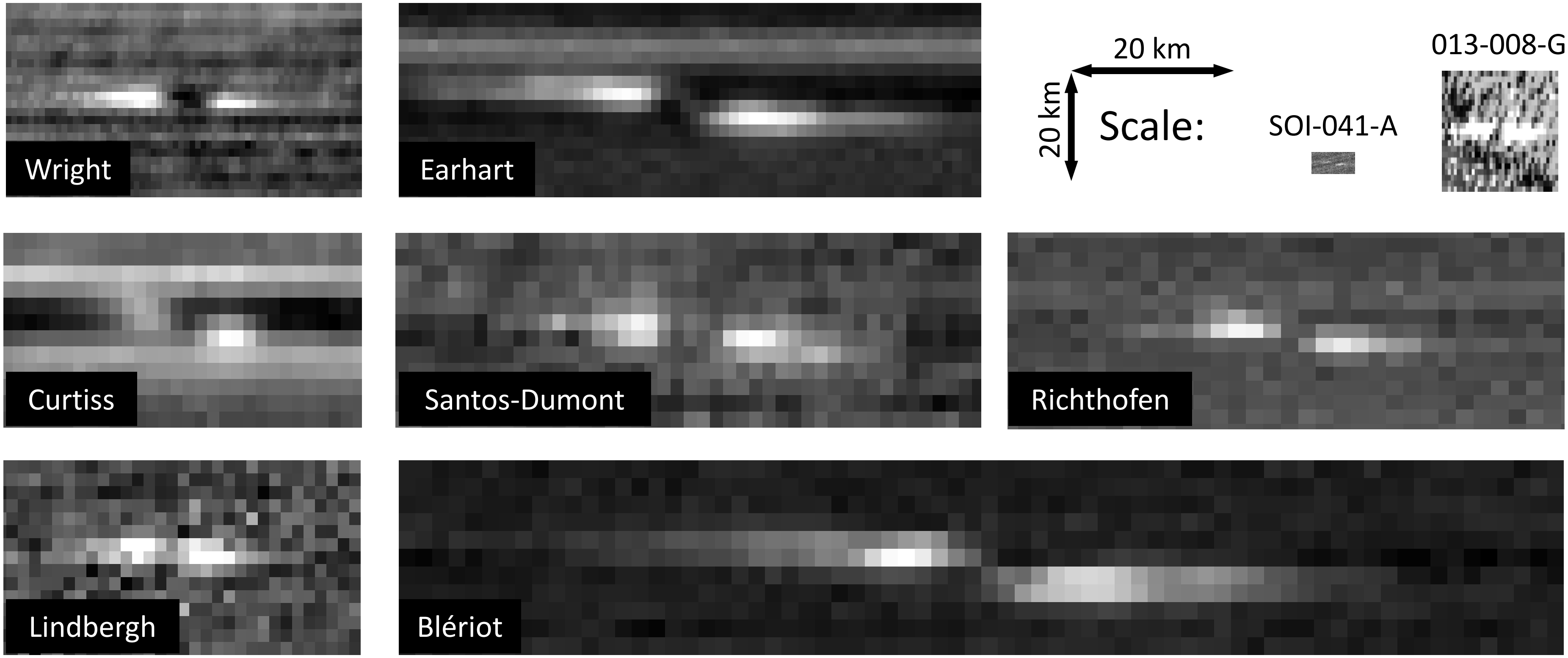
- "*Trans*-Encke" propellers are much larger (moonlets up to km-size) and rarer (many dozens, maybe 100+)
- This makes them easier to track individually
- Several followed for >1 yr, verifying their Keplerian orbits
- The largest propeller (nicknamed "Blériot") clearly exhibits, moves ~1km/30 yr
- First time moons have been tracked while orbiting in a disk!



Tiscareno et al. 2010, ApJL

The Big Ones!

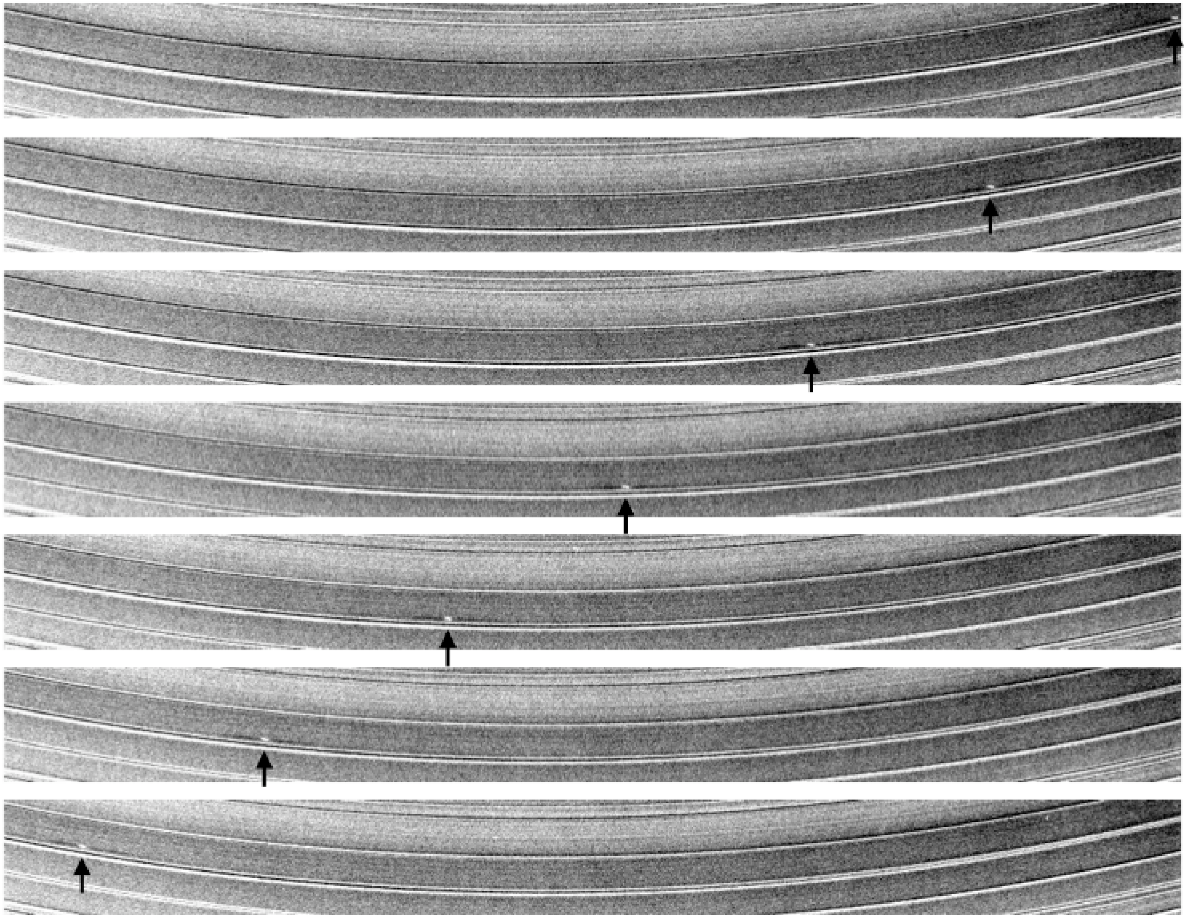
- Propellers outside the Encke Gap are much less common, But bigger, so found in low-res high-coverage movies
- Five of these have been seen in at least two apparitions separated by >1 yr, verifying longevity and Keplerian orbits for at least some, but some do not appear when expected



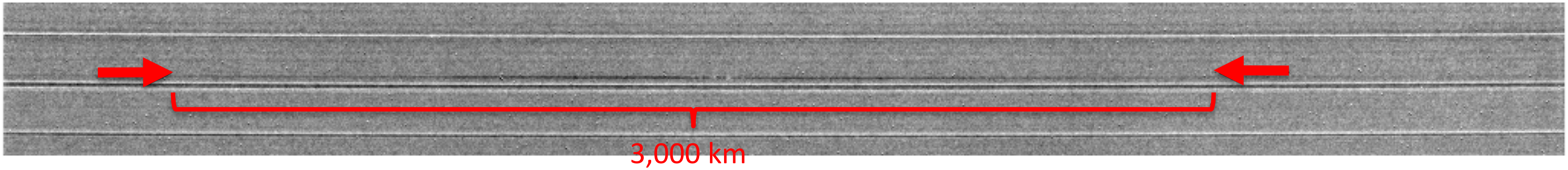
Tiscareno et al, in prep

The Adventures of Blériot

- In this “movie”, seven shots of Blériot moving serenely through the field of view
- Lit side, propeller has a bright center with dark wings that extend as much as 3,000 km tip-to-tip
- Length seems to vary with viewing

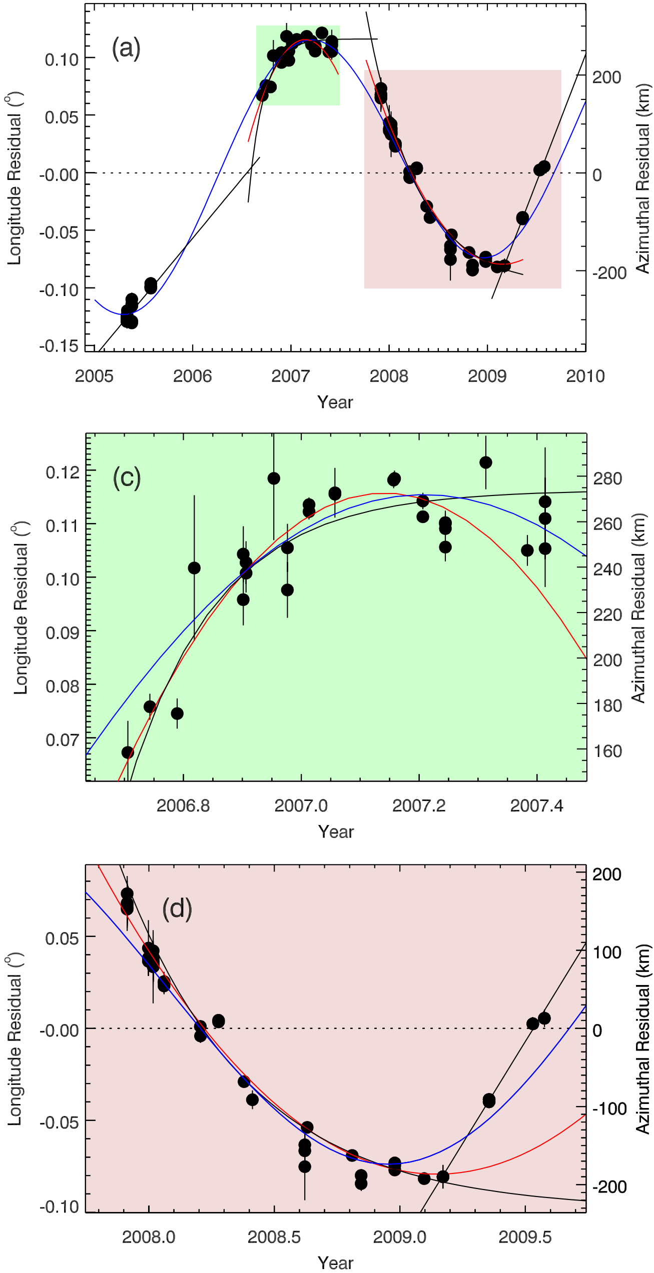


Tiscareno et al, in prep



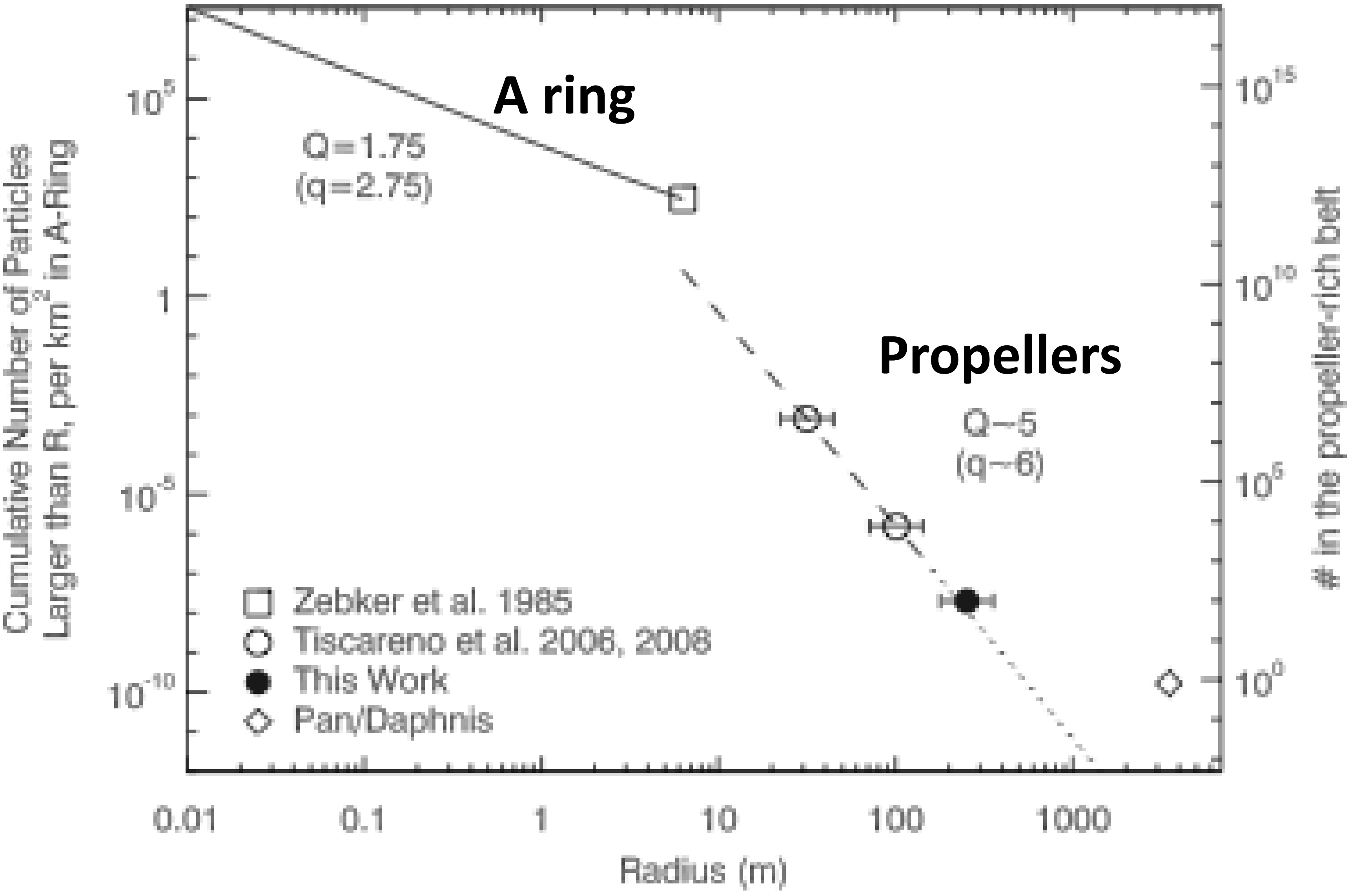
Non-Keplerian Orbital Motion

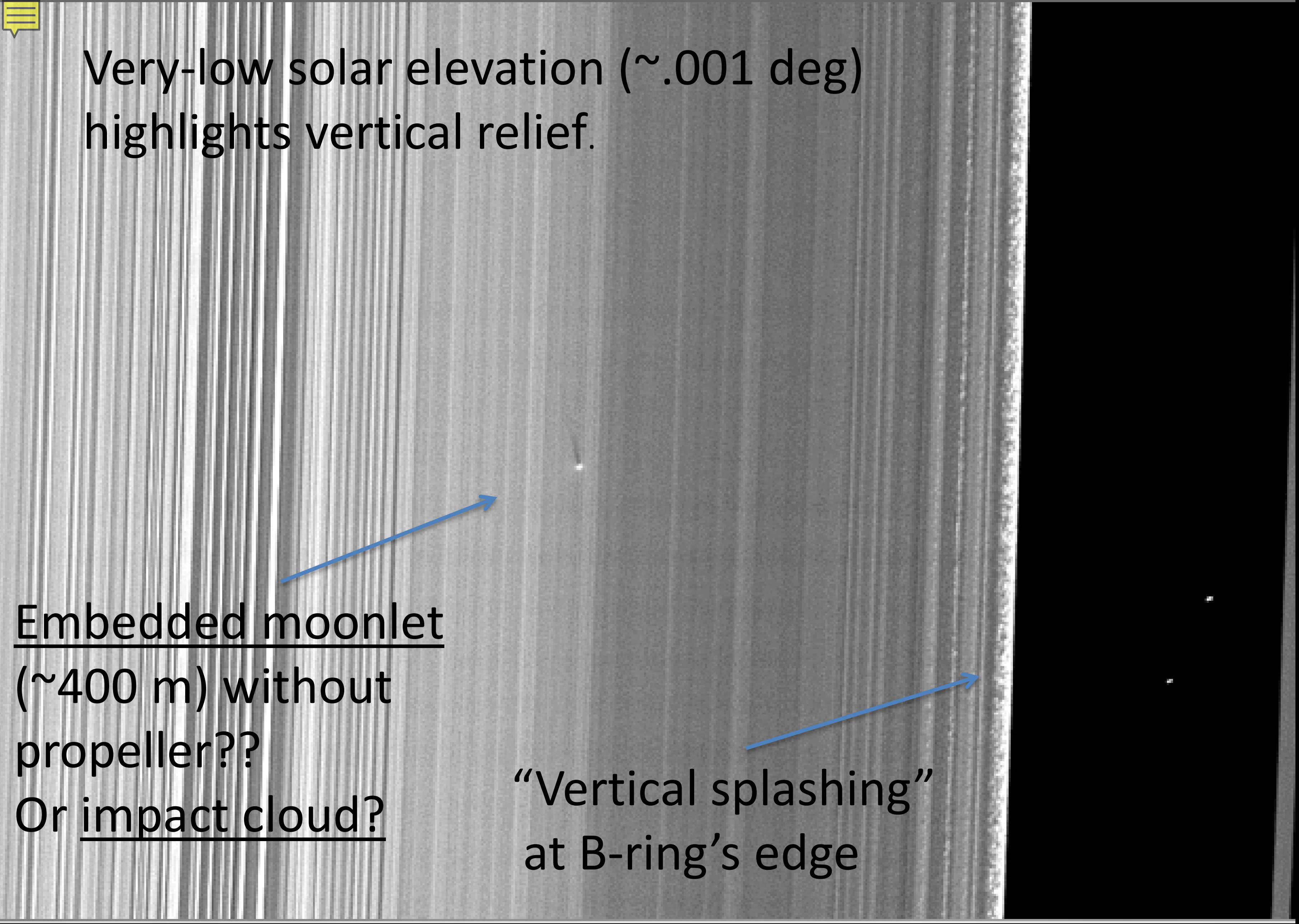
- What is the nature of the changes in Blériot’s orbit?
- **Resonant Libration?**
  - $\lambda(t)$ would be sinusoidal
  - Corotation resonance? *(M.Sremčević, pers. comm., 2011)*
- **Episodic Constant Drift?**
  - $\lambda(t)$ would be piecewise quadratic
  - Plausible *(Kirsh et al 2009, Icarus)*, needs more study
- **“Frog” mechanism?** ($\lambda(t)$ also sinusoidal)
- \- Pan & Chiang, *Ap.J. Ltrs.*, 2010
- **Random walk?**
- **Modified “Type I” Migration?**
  - Powered by radial surface density variation
  - $\lambda(t)$ would be exponential



Tiscareno et al 2010, ApJL
Tiscareno 2011, PS&S submitted

Size distributions of rings and propellers





Very-low solar elevation (~.001 deg) highlights vertical relief.

Embedded moonlet (~400 m) without propeller??
Or impact cloud?

“Vertical splashing” at B-ring’s edge

Planetary Rings

Saturn in eclipse

Granular Media

End of Mission:

_Cassini will fly between the rings and the planet twenty times, and then crash into the planet.