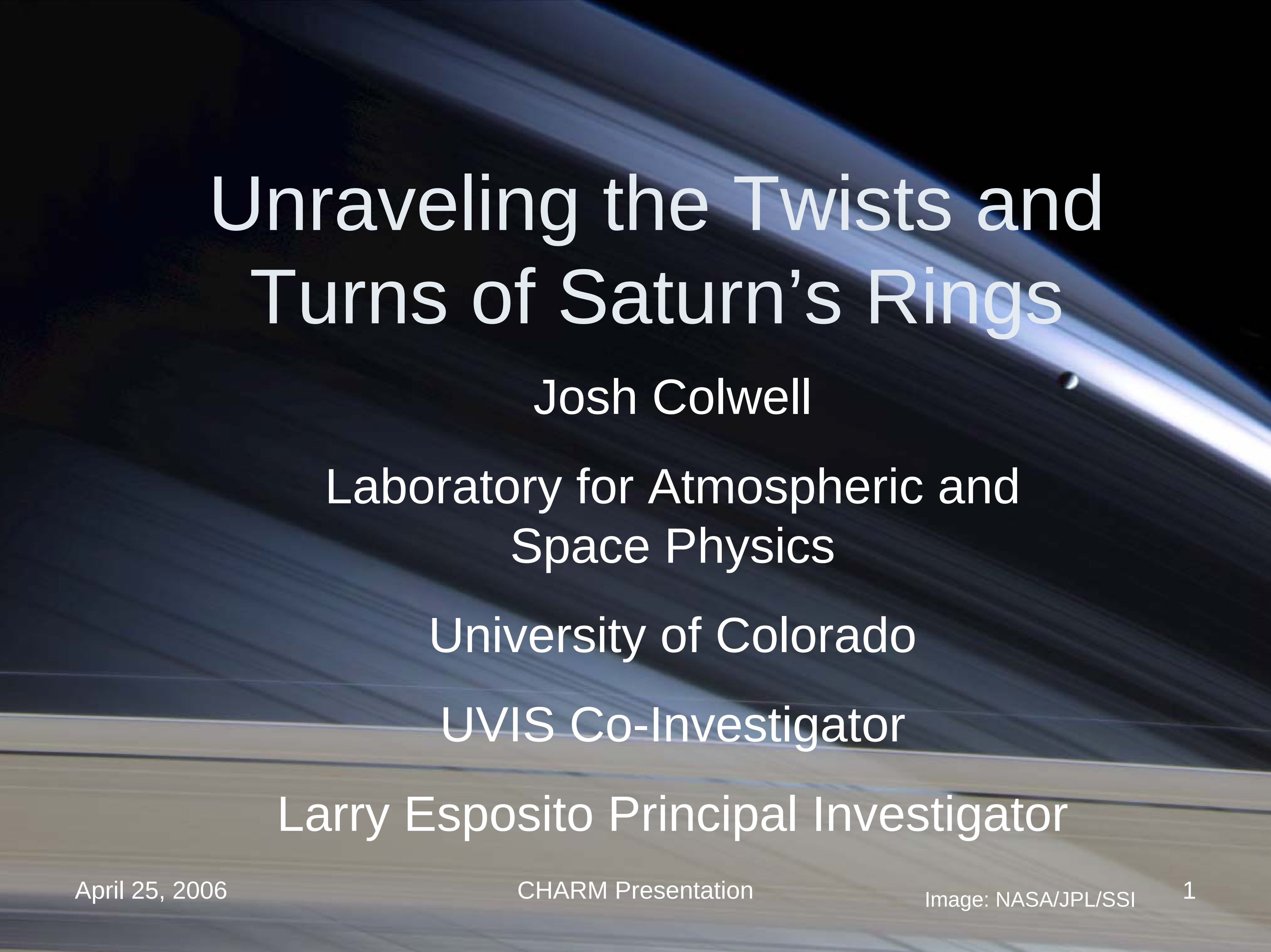


Unraveling the Twists and Turns of Saturn’s Rings

Josh Colwell

Laboratory for Atmospheric and Space Physics

University of Colorado

UVIS Co-Investigator

Larry Esposito Principal Investigator

Image: NASA/JPL/SSI

Outline

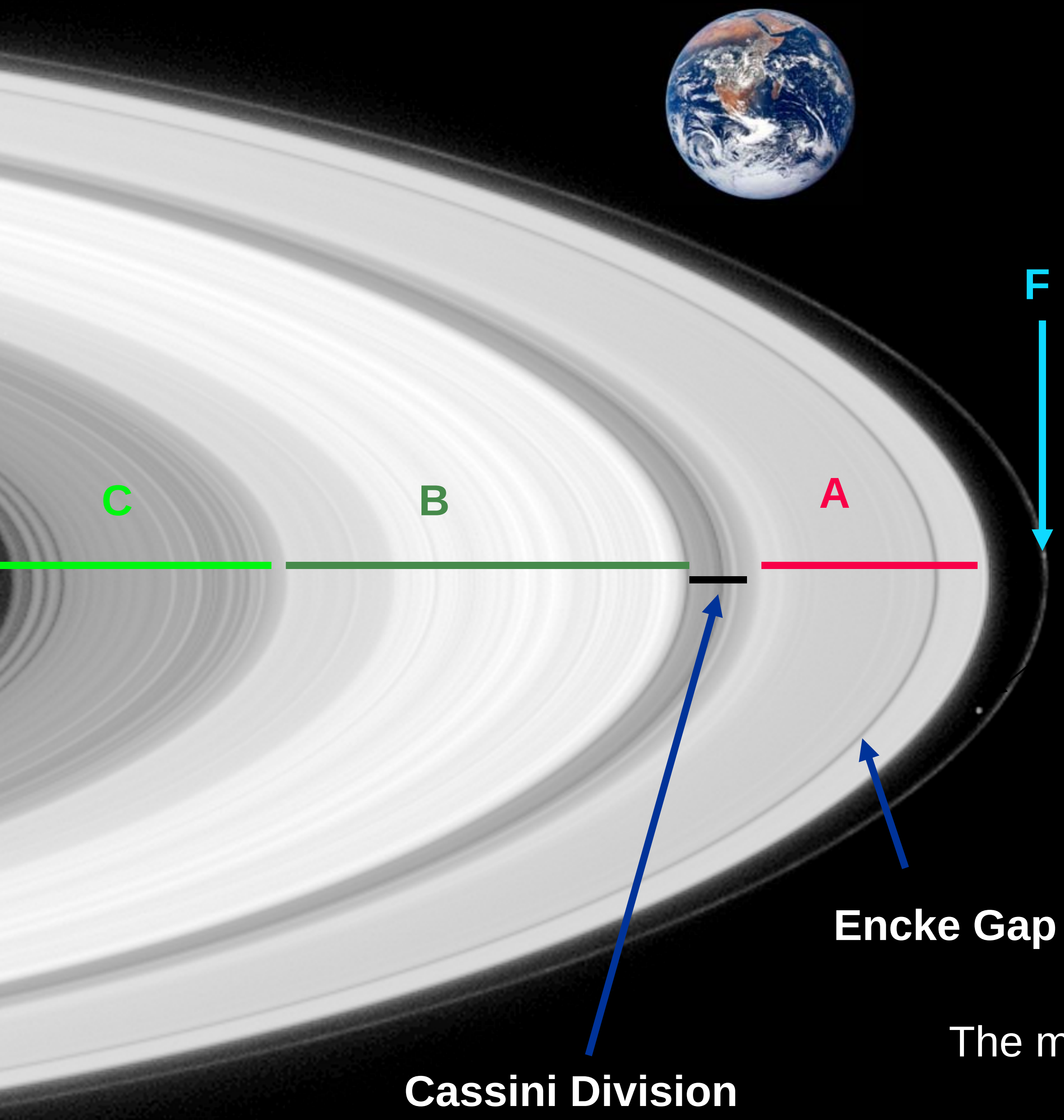
- Rings Tutorial: structure of the rings and the big picture.
- UVIS Occultation Results:
  - High resolution profiles of ring structure;
  - Three dimensional structure of rings;
  - Waves as probes of ring properties;
  - Some unexplained phenomena;
  - Where things stand and where we go from here.

Saturn’s Rings:

Age and origin unknown

Cassini ISS image: SSI (Boulder), NASA/JPL.

The main rings



Approach picture from Cassini:

May 10, 2004

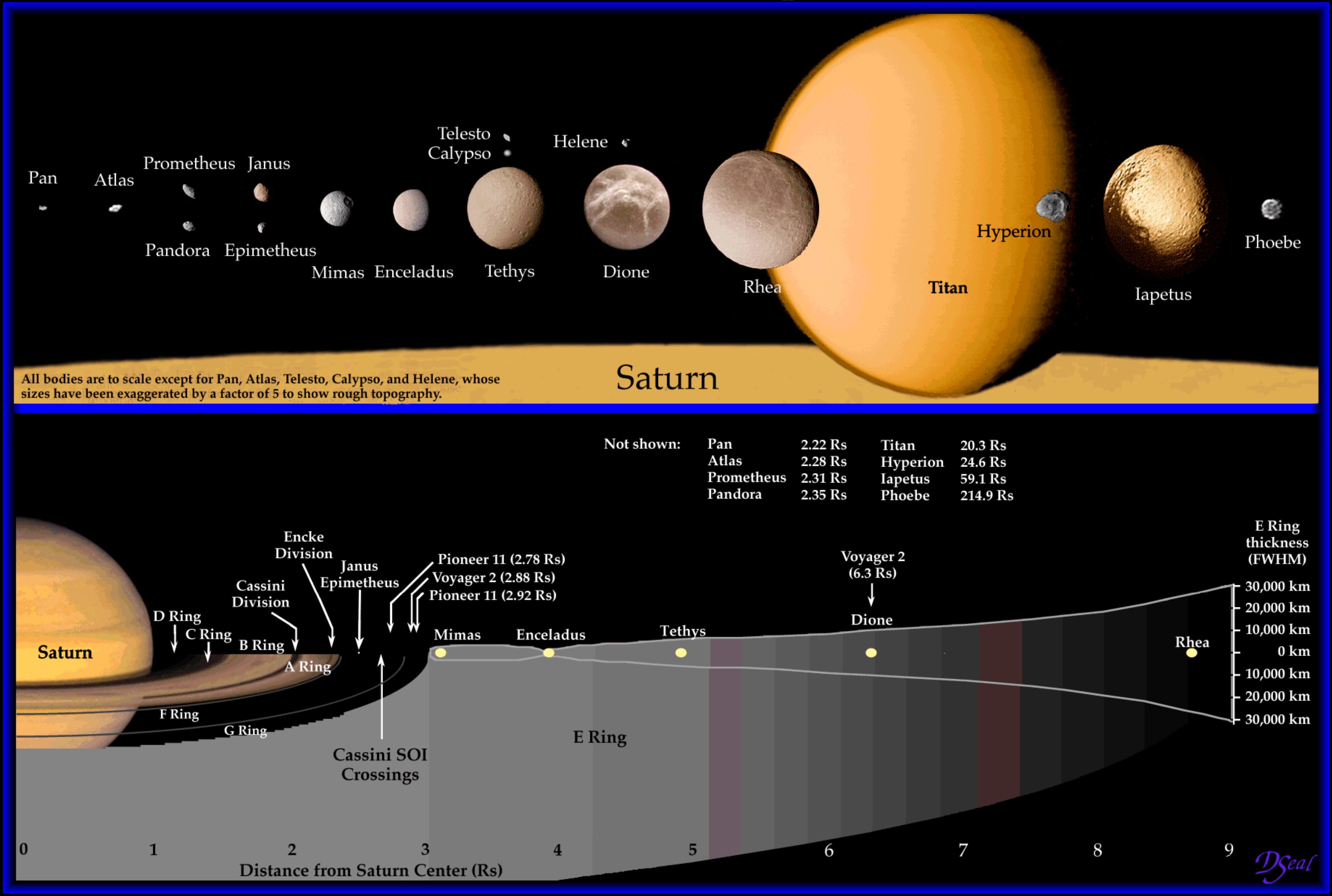
Dist: 27 million km.

Pixel: 161 km.

Moon: Prometheus

Cassini ISS image: Space Science Institute (Boulder), NASA/JPL.

Saturn's Satellites and Ring Structure



All bodies are to scale except for Pan, Atlas, Telesto, Calypso, and Helene, whose sizes have been exaggerated by a factor of 5 to show rough topography.

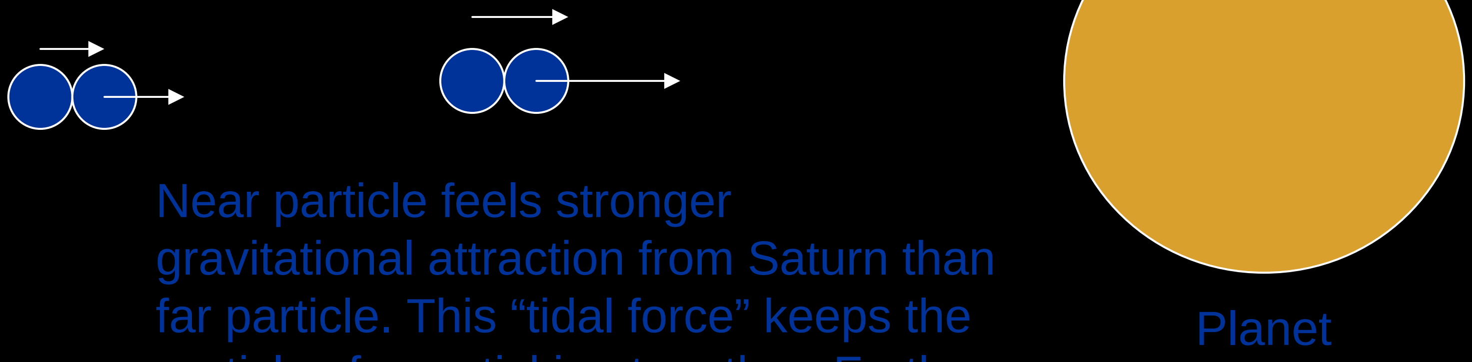
Not shown:

Pan	2.22 Rs	Titan	20.3 Rs
Atlas	2.28 Rs	Hyperion	24.6 Rs
Prometheus	2.31 Rs	Iapetus	59.1 Rs
Pandora	2.35 Rs	Phoebe	214.9 Rs

This graphic is available in color if required.

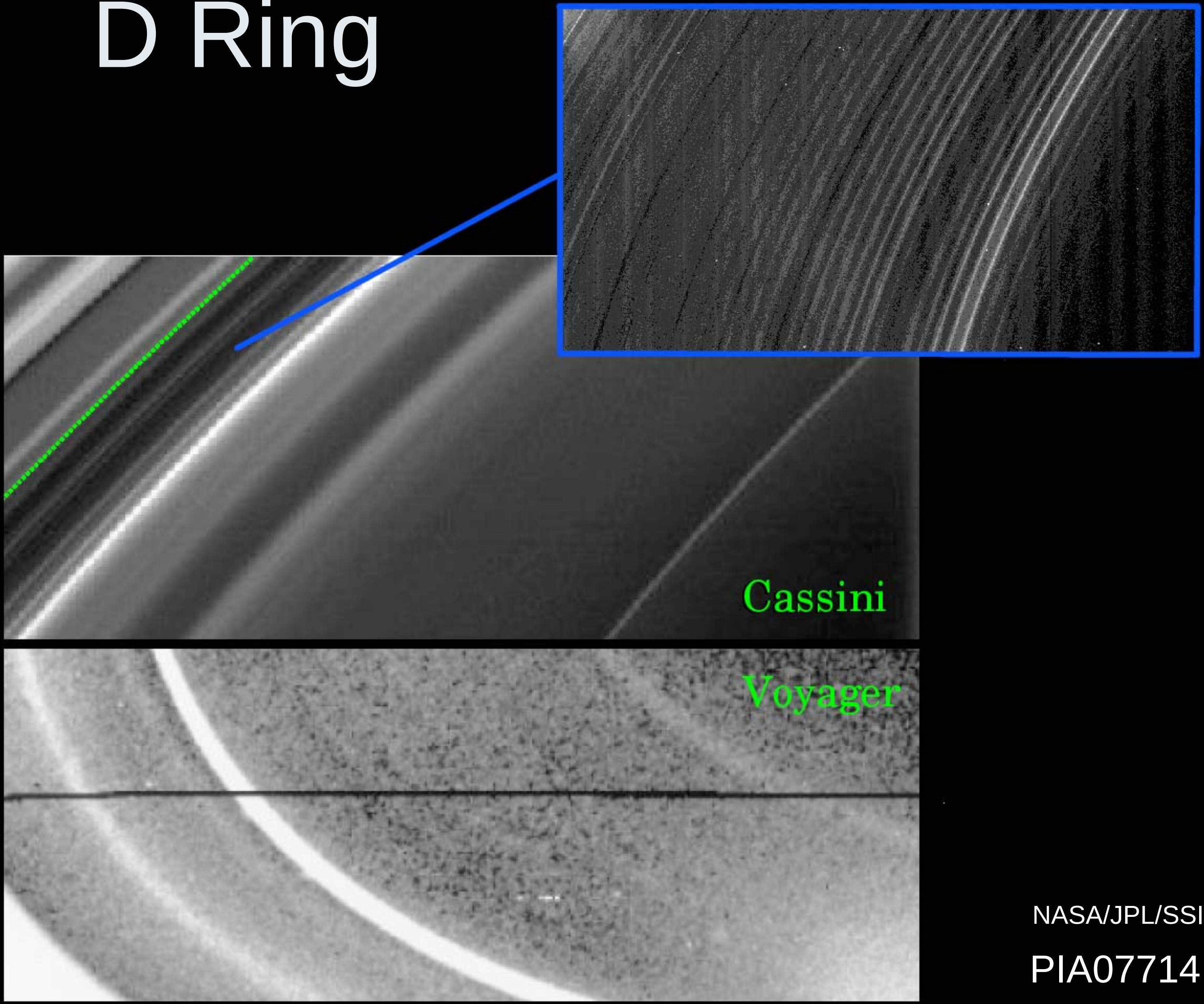
Saturn’s Rings

- Why don’t they make a moon?



Near particle feels stronger gravitational attraction from Saturn than far particle. This “tidal force” keeps the particles from sticking together. Further out, the difference is smaller so moons can form.

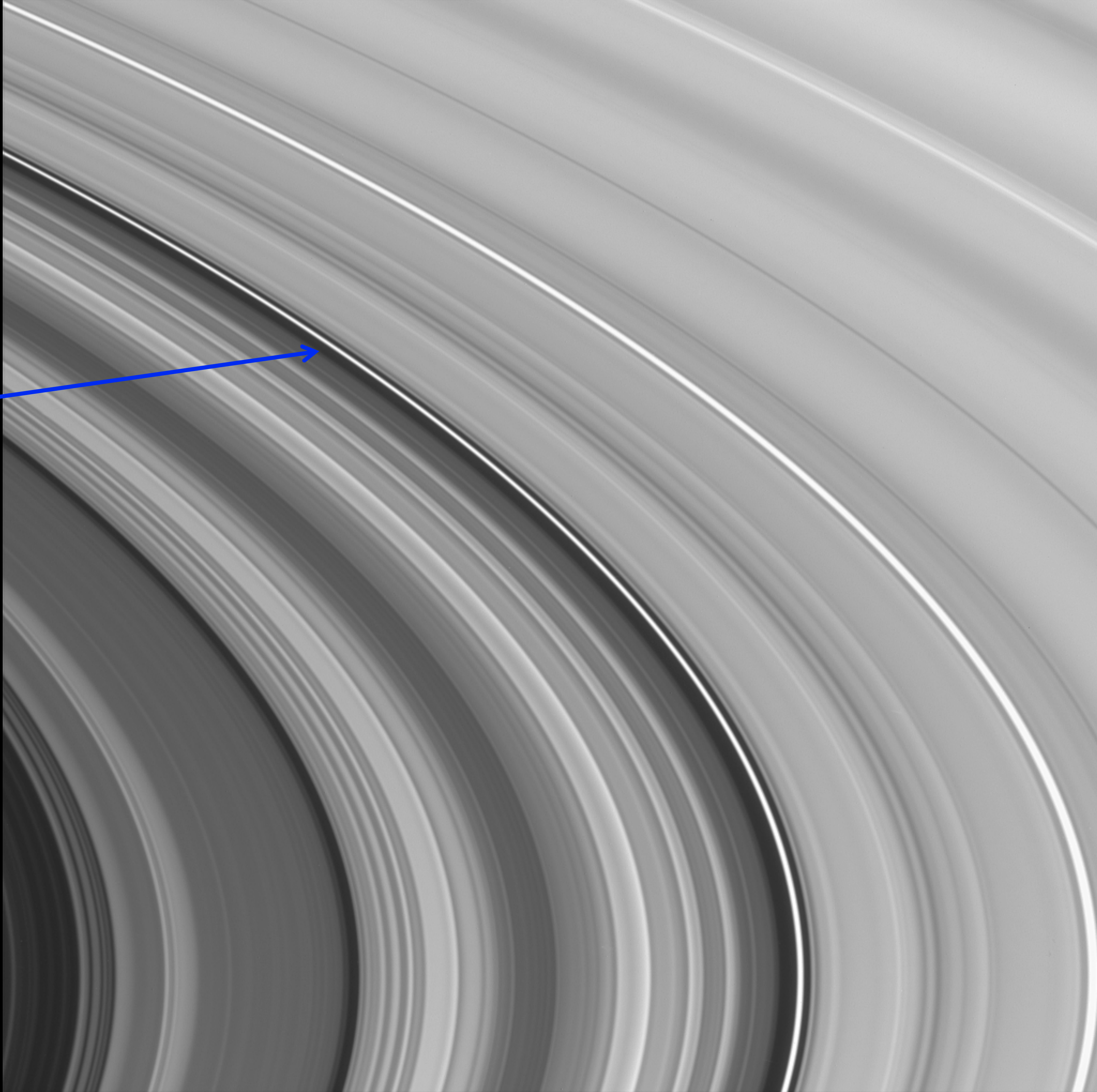
D Ring



NASA/JPL/SSI

PIA07714

Inner C Ring



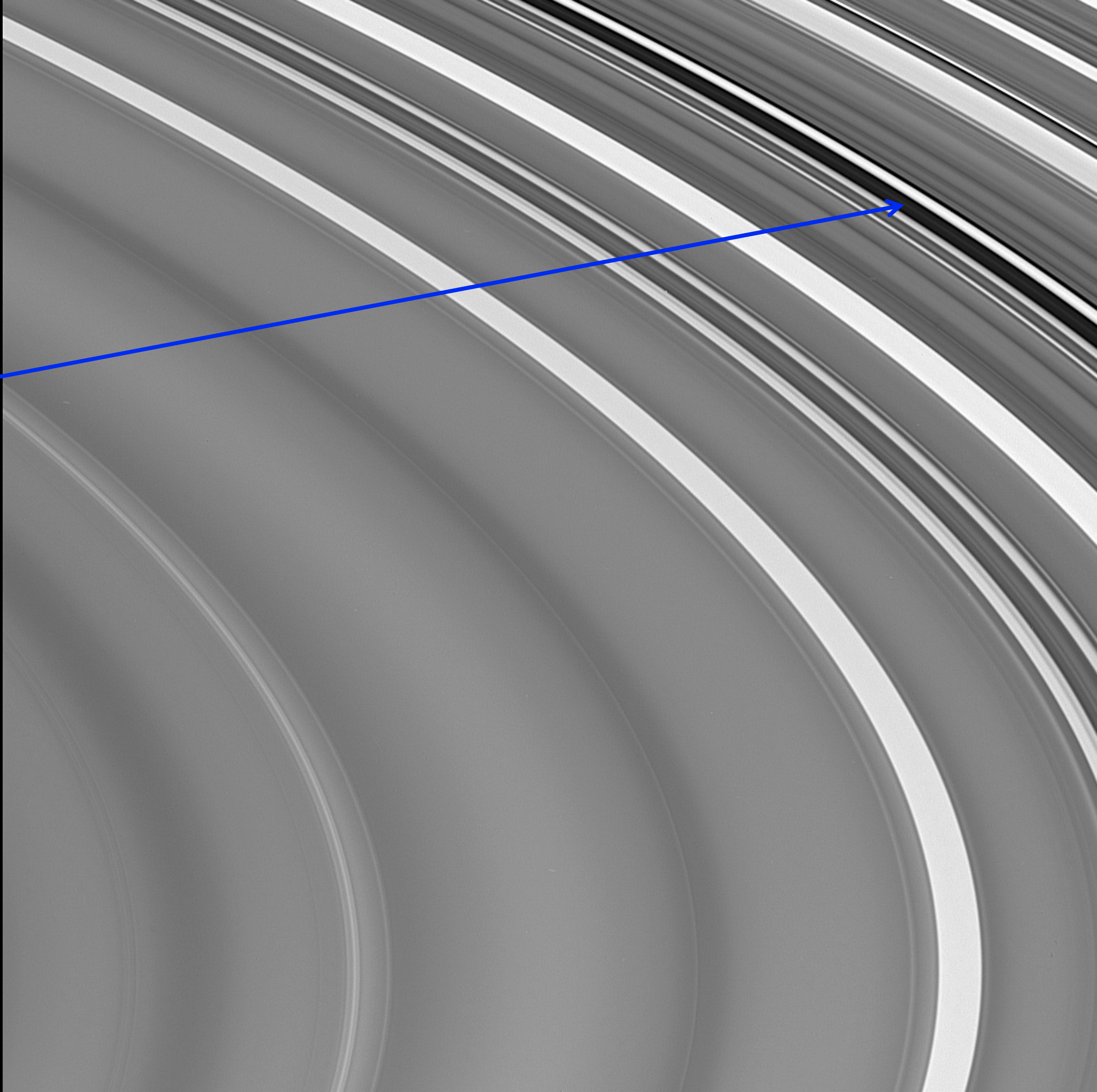
Titan 1:0 Ringlet

NASA/JPL/SSI

PIA06537

April 25, 2006

Outer C Ring



Maxwell Ringlet

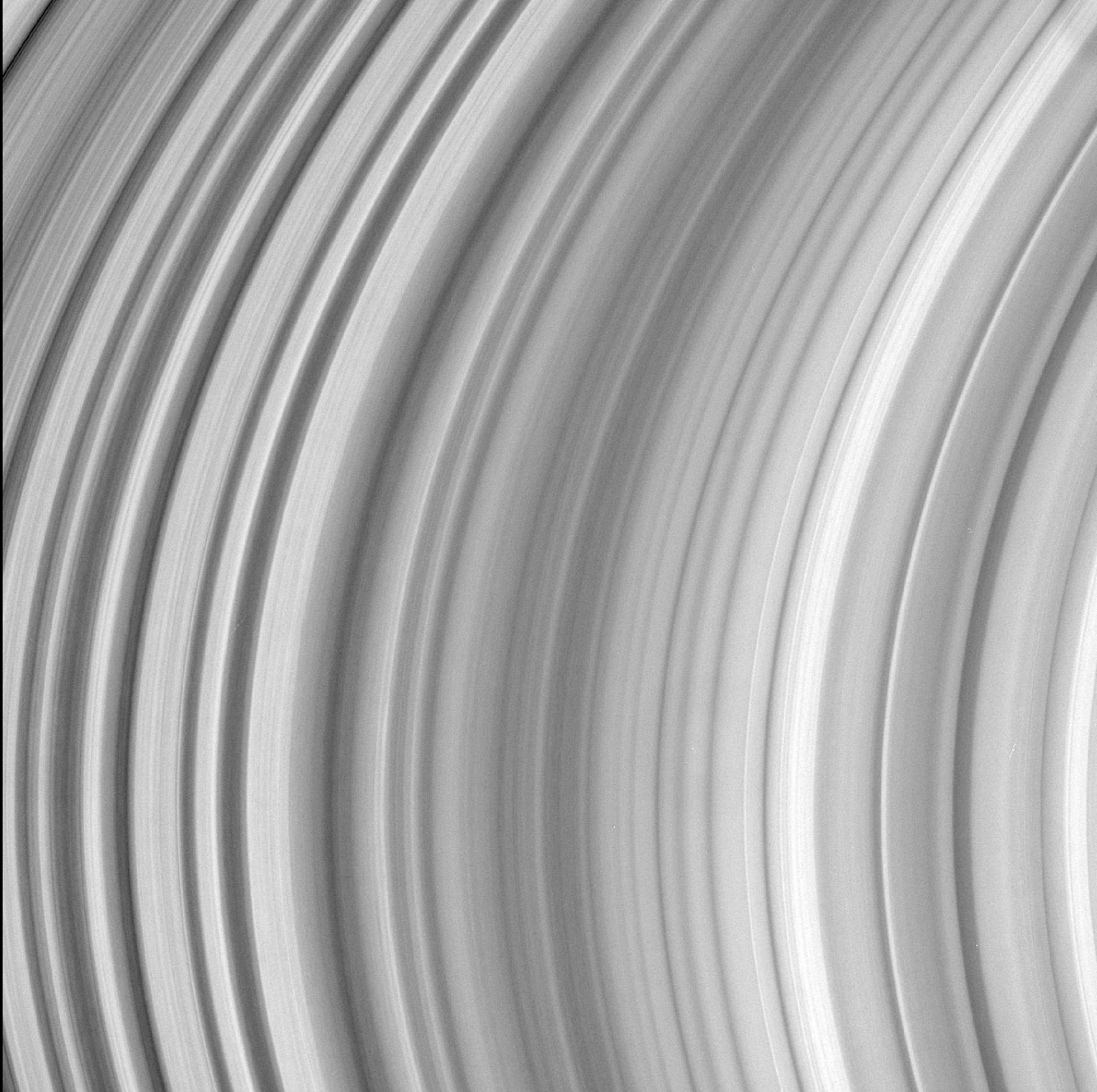
NASA/JPL/SSI

PIA06539

April 25, 2006

Central B Ring

Unexplained Structure

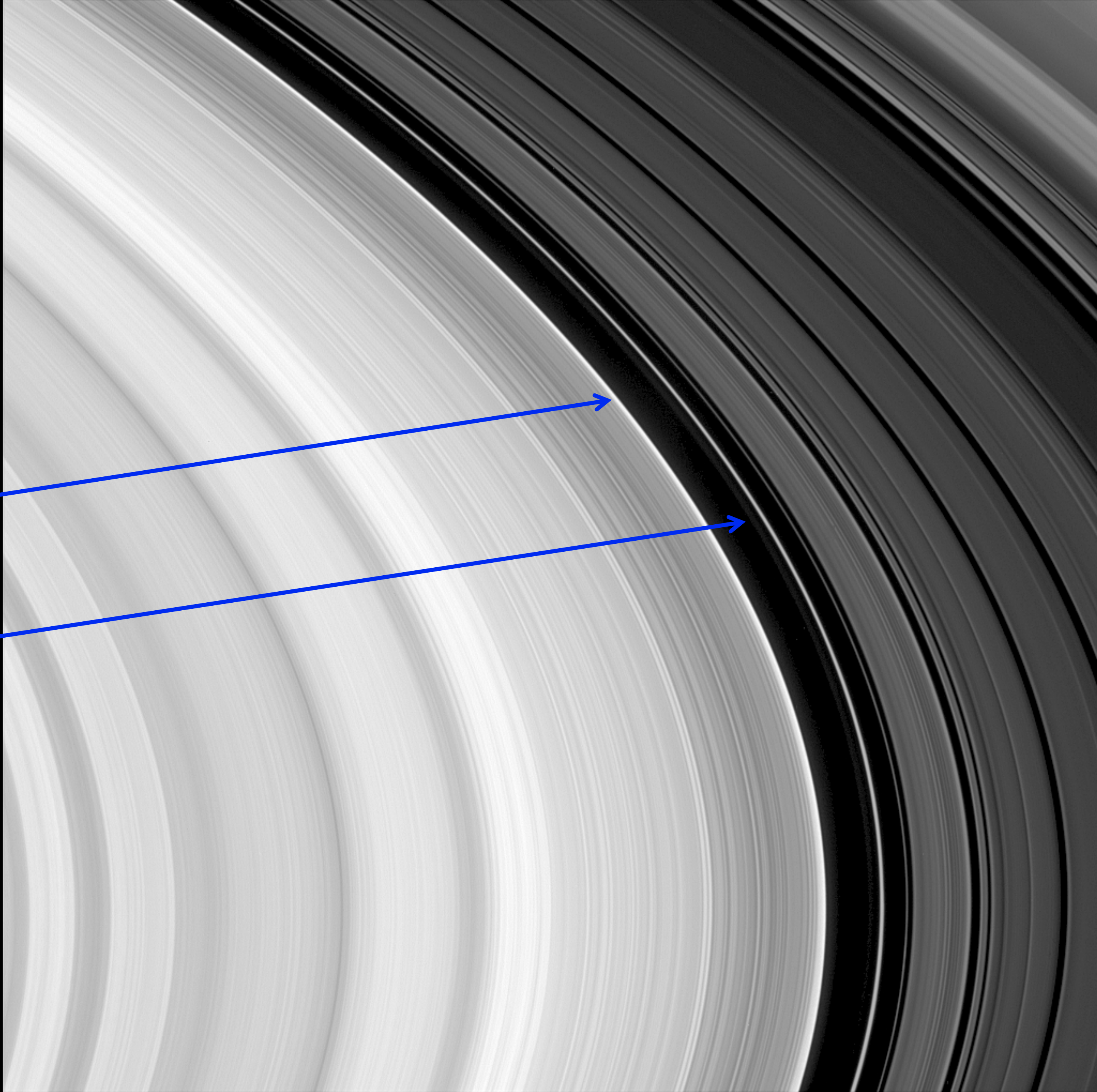


NASA/JPL/SSI

PIA07610

April 25, 2006

Outer Edge of B Ring, and Cassini Division



B Ring Edge

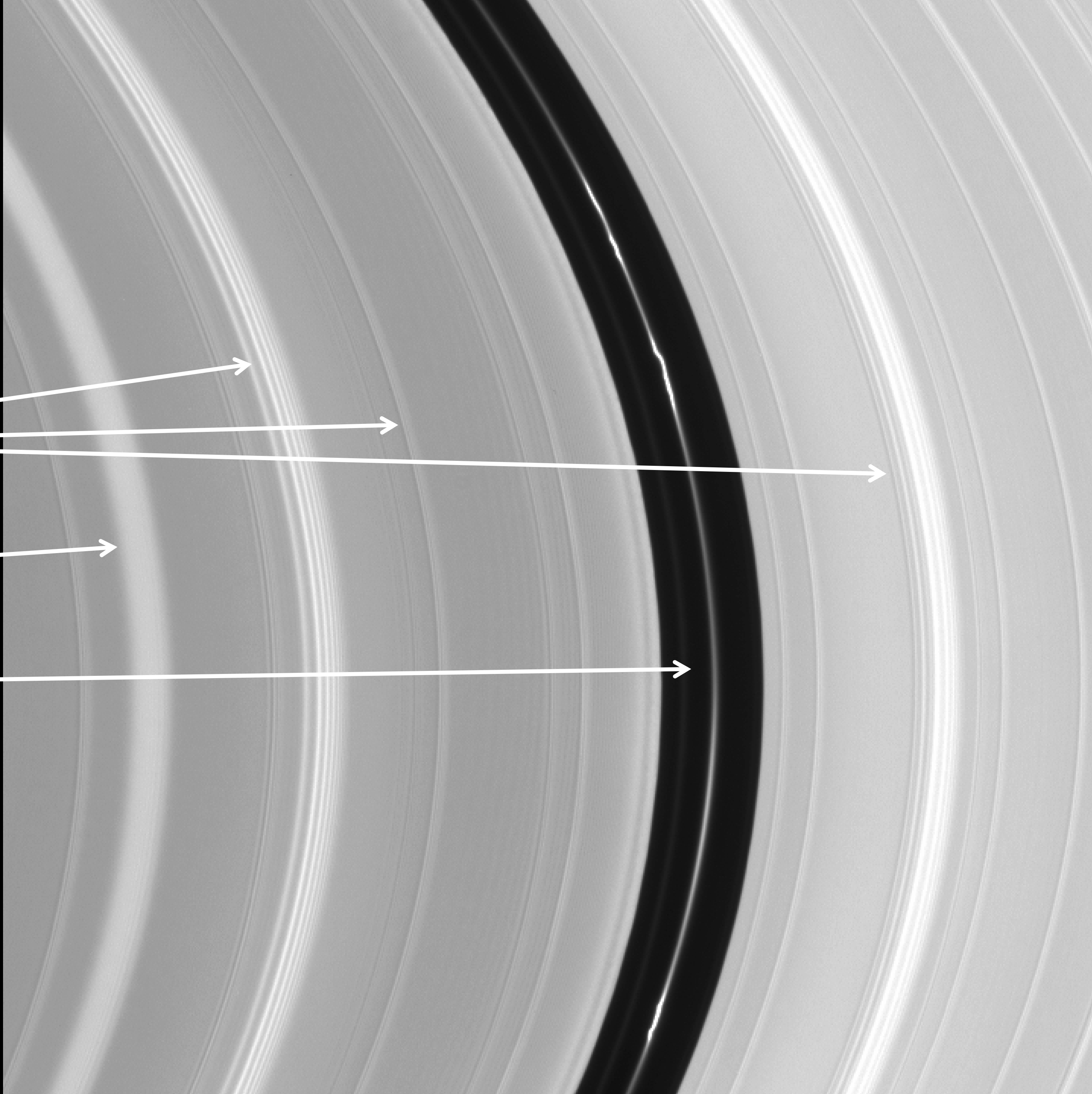
Huygens Ringlet

NASA/JPL/SSI

PIA06536

April 25, 2006

Outer A Ring and Encke Gap



Density Waves

Bending Wave

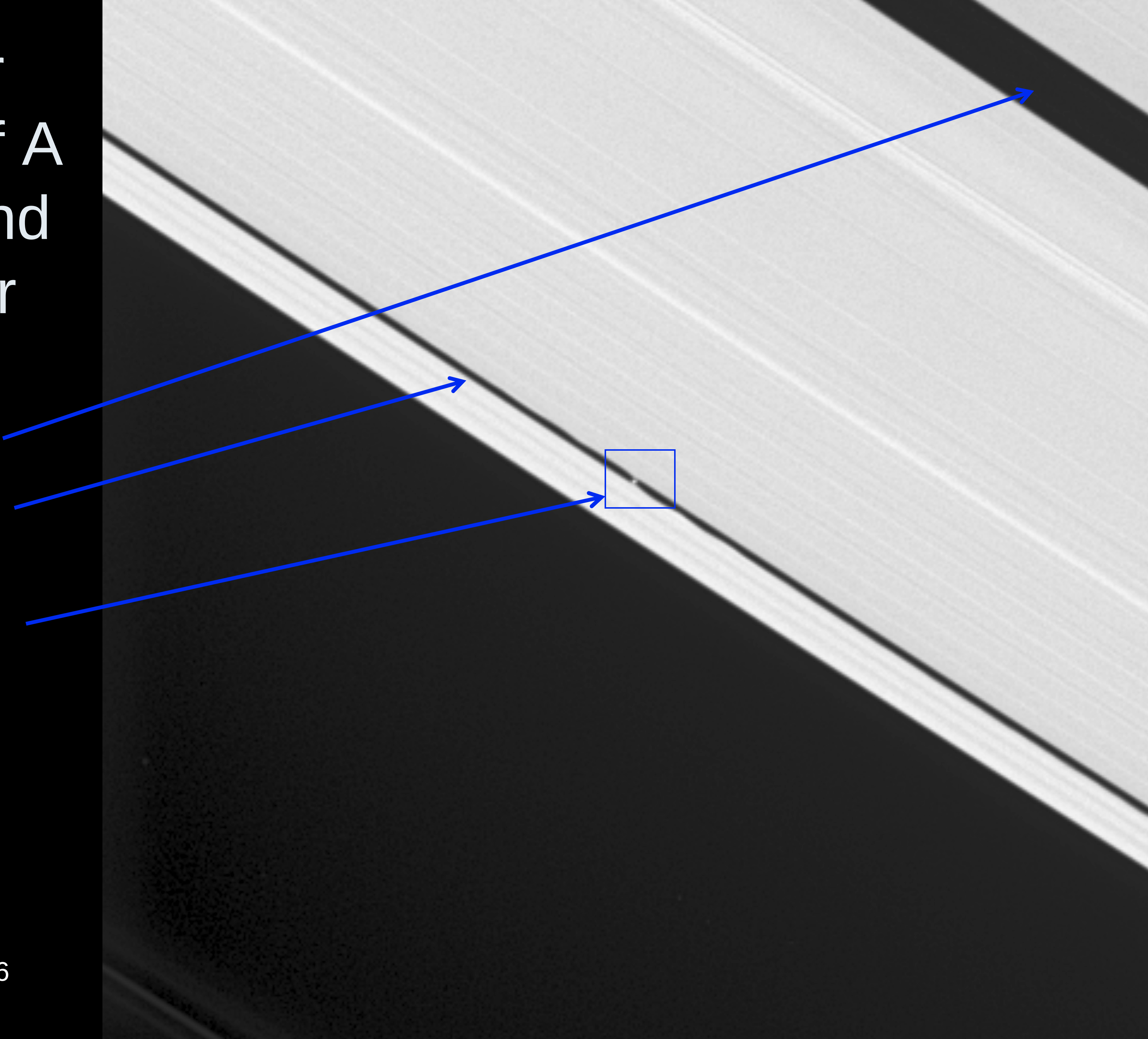
Encke Gap

NASA/JPL/SSI

PIA06534

April 25, 2006

Outer Edge of A Ring and Keeler Gap

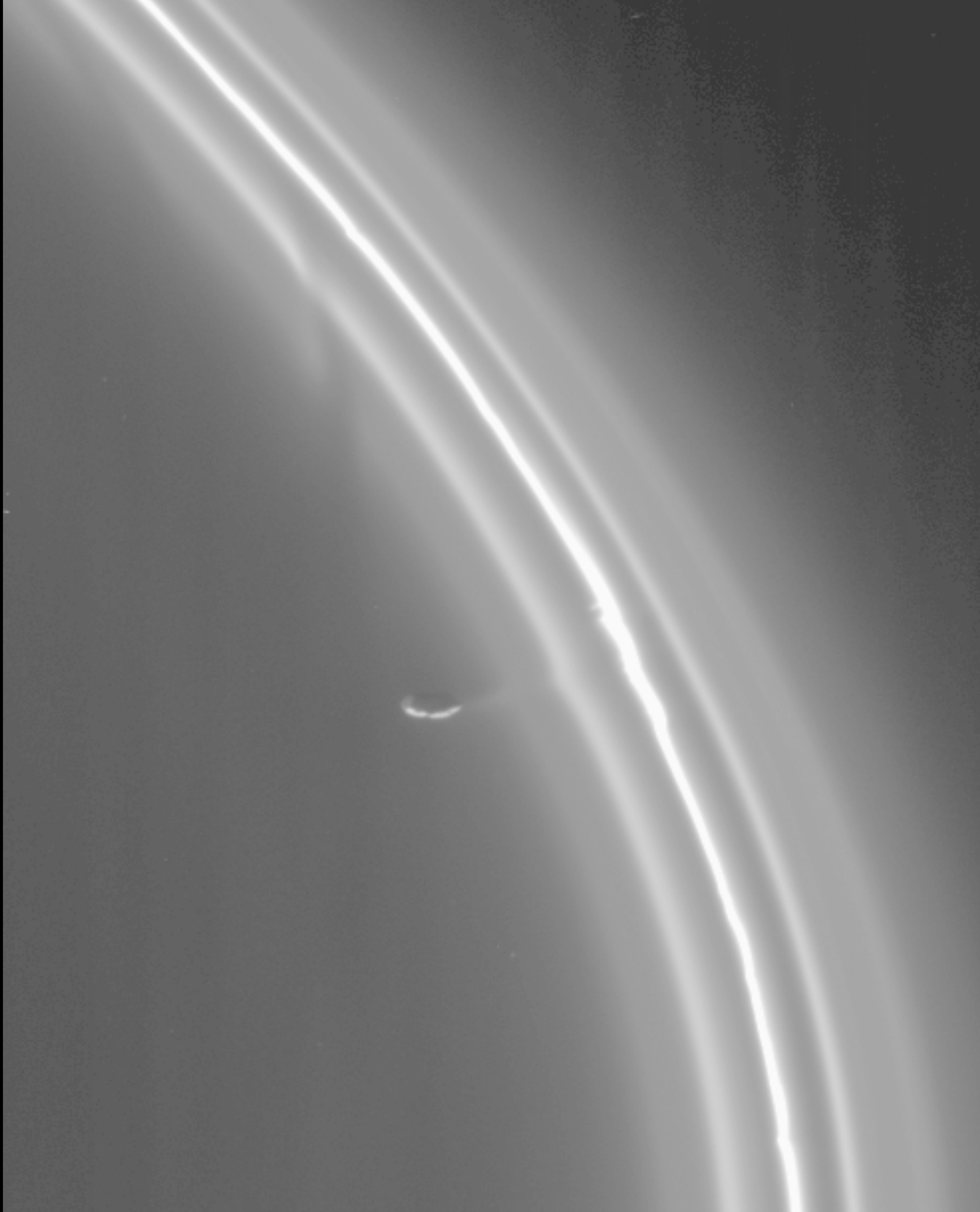


NASA/JPL/SSI

PIA07584

April 25, 2006

F Ring and Prometheus



NASA/JPL/SSI

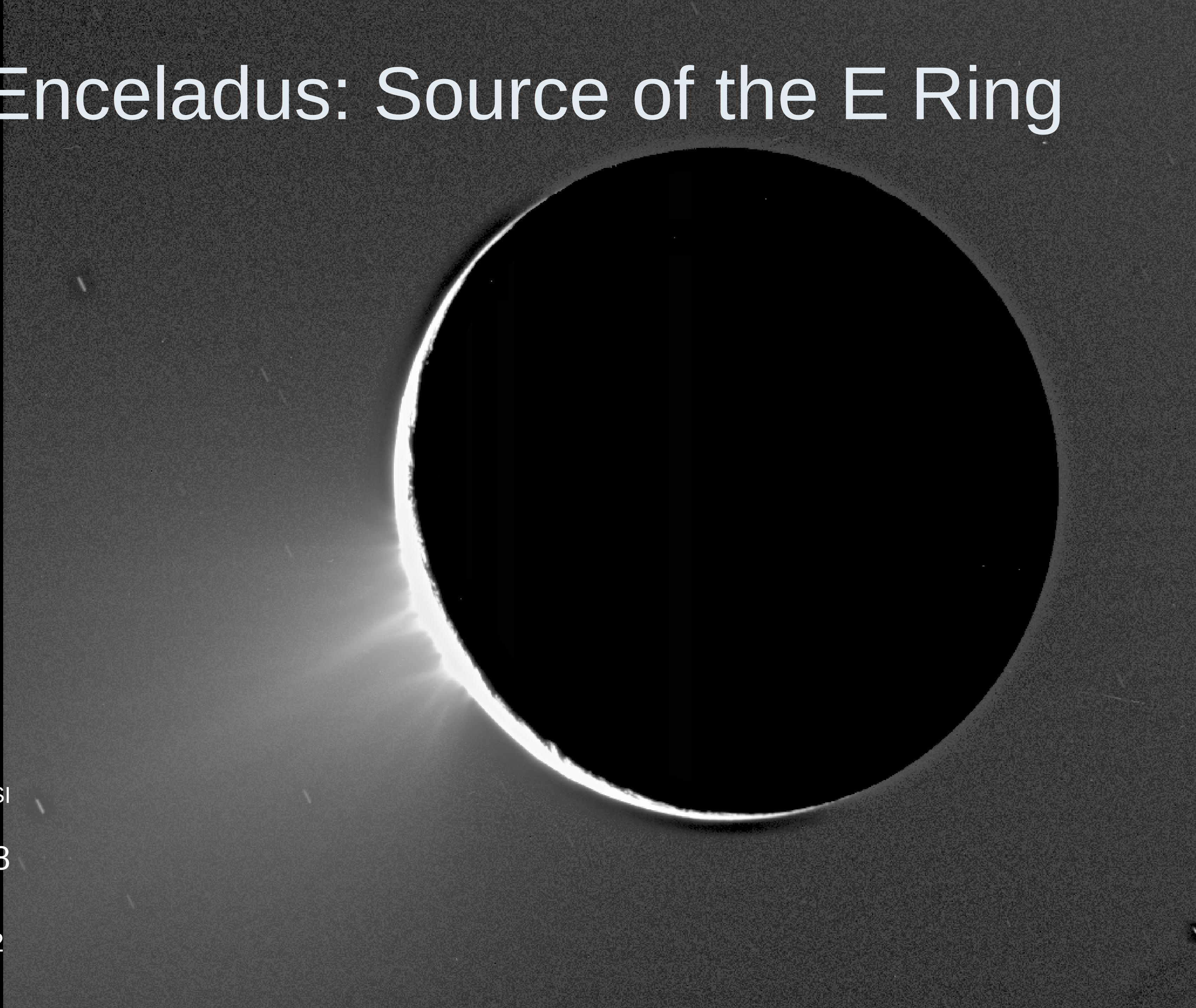
PIA06143

April 25, 2006

Diaphanous G Ring

PIA07643 NASA/JPL/SSI

Enceladus: Source of the E Ring



NASA/JPL/SSI

PIA07758

April 2

Ring Particle Orbital Dynamics

- Particles orbiting an oblate planet like Saturn have three natural frequencies of motion:
  - Azimuthal
  - Radial
  - Vertical
- The time for a particle to complete a radial oscillation is longer than the time for it to travel around the planet (azimuthal) which is longer than the time for it to complete a vertical oscillation.

Resonances and Density Waves

Density waves occur when the radial frequency of a ring particle is in resonance with the orbital motion of a moon:

$$\kappa(R_L) = m\Omega(R_L) - \overbrace{m\Omega_M - n\nu_M - p\kappa_M}^{-\omega}$$

m, n, p are integers, *M* refers to the moon, and R_L is the location of the inner Lindblad resonance. Strongest horizontal forcing when n=p=0 (no contribution from inclination or eccentricity of moon):

$$\kappa(R_L) = m[\Omega(R_L) - \Omega_M] \Longrightarrow \frac{\Omega(R_L)}{\Omega_M} \approx \frac{m}{m-1}$$

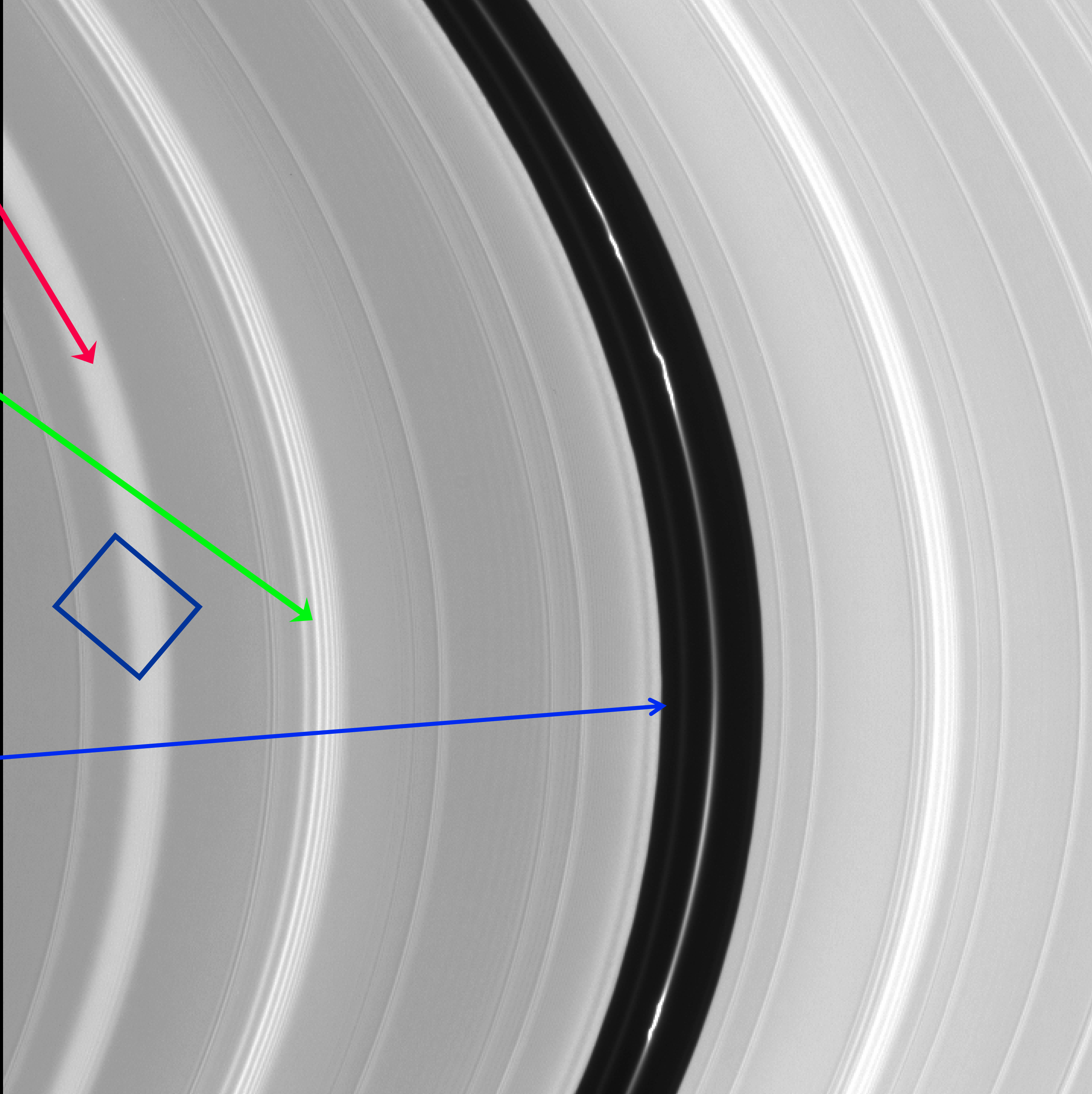
Bending waves depend on the vertical (inclined) motion of the moon.

Strongest vertical forcing when p=0 and n=1 (no eccentricity and first order in inclination):

$$m\Omega_M + \nu_M = m\Omega(R_V) - \nu(R_V) \Longrightarrow \frac{\Omega(R_V)}{\Omega_M} \approx \frac{m+1}{m-1}$$

More on resonances

- Strongest density wave resonances are m:m-1.
- 20:19 resonance, ring particle orbits 20 times for every 19 moon orbits. This is m=20 wave (pattern repeated 20 times around Saturn).
- Can have m=1 (1:0) resonance where orbital motion of moon equals precession rate of ring particle. Ringlet at Titan 1:0 in C ring.
- Strongest vertical resonances (produce bending waves) are m+1:m-1.



Mimas m=4
vertical (“bending”)
and horizontal
(“density”) waves:

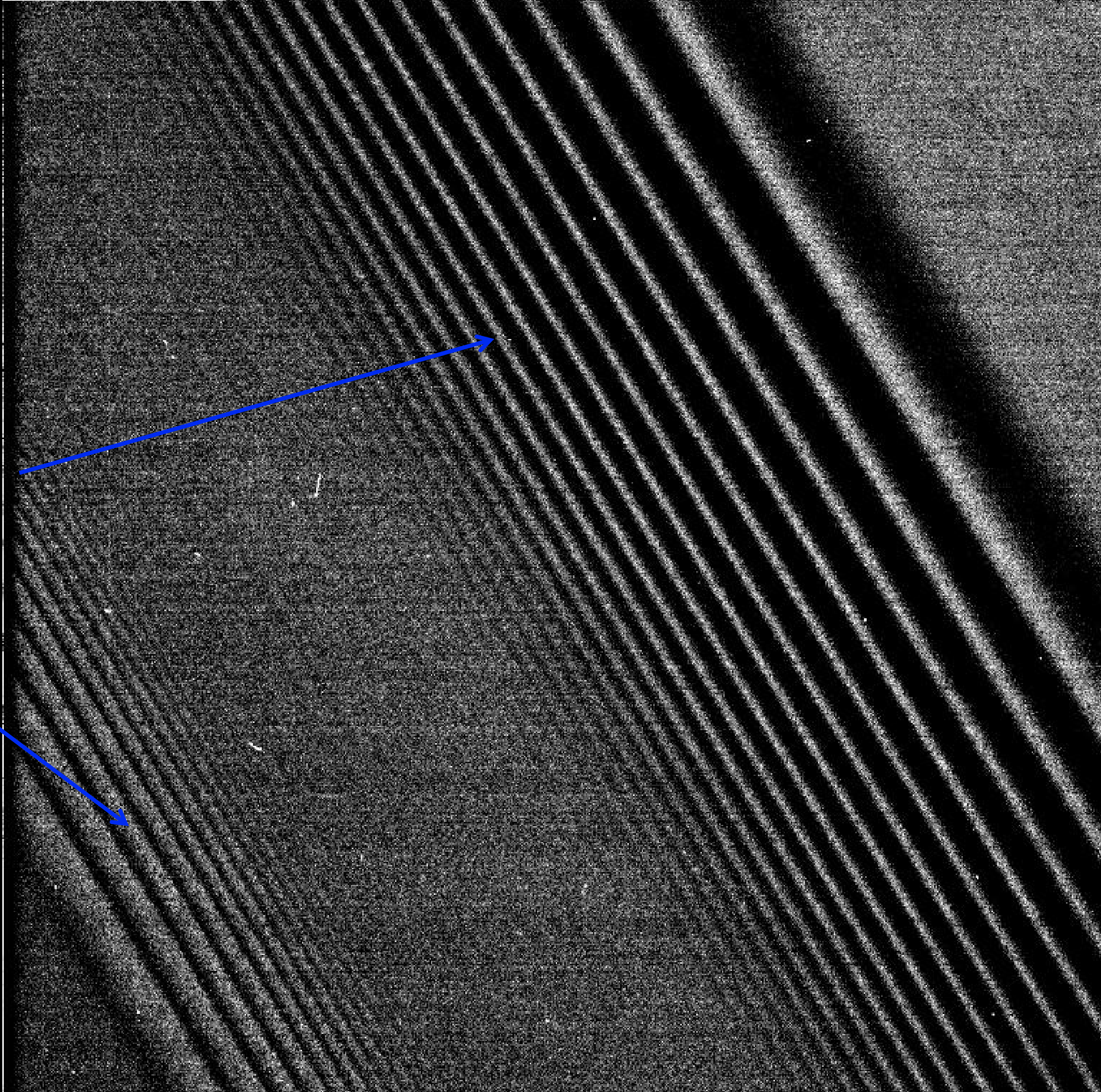
Encke Gap

Cassini ISS image:

SSI, NASA/JPL.

April 25, 2006

A bending wave and a density (horizontal) wave.



Mimas 5:3 Bending Wave

Prometheus 12:11 Density Wave

Cassini ISS image:

SSI, NASA/JPL.

April 25, 2006

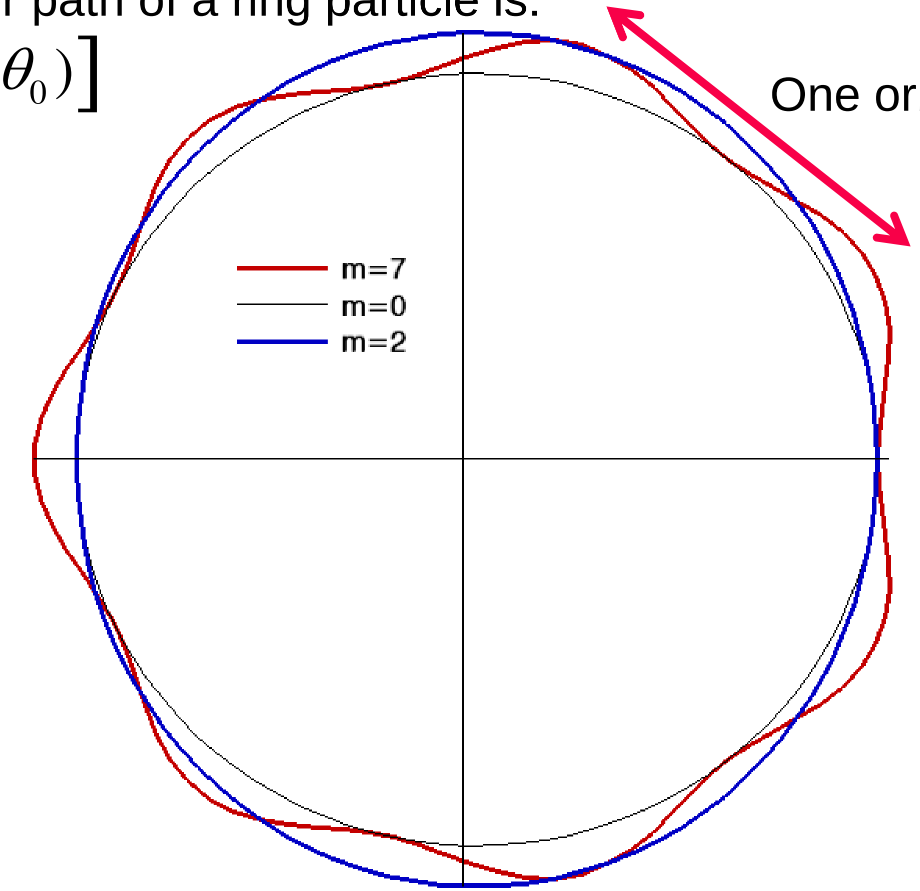
How Resonances Make Waves

Consider a perturbation from a satellite with orbital frequency Ω_M.

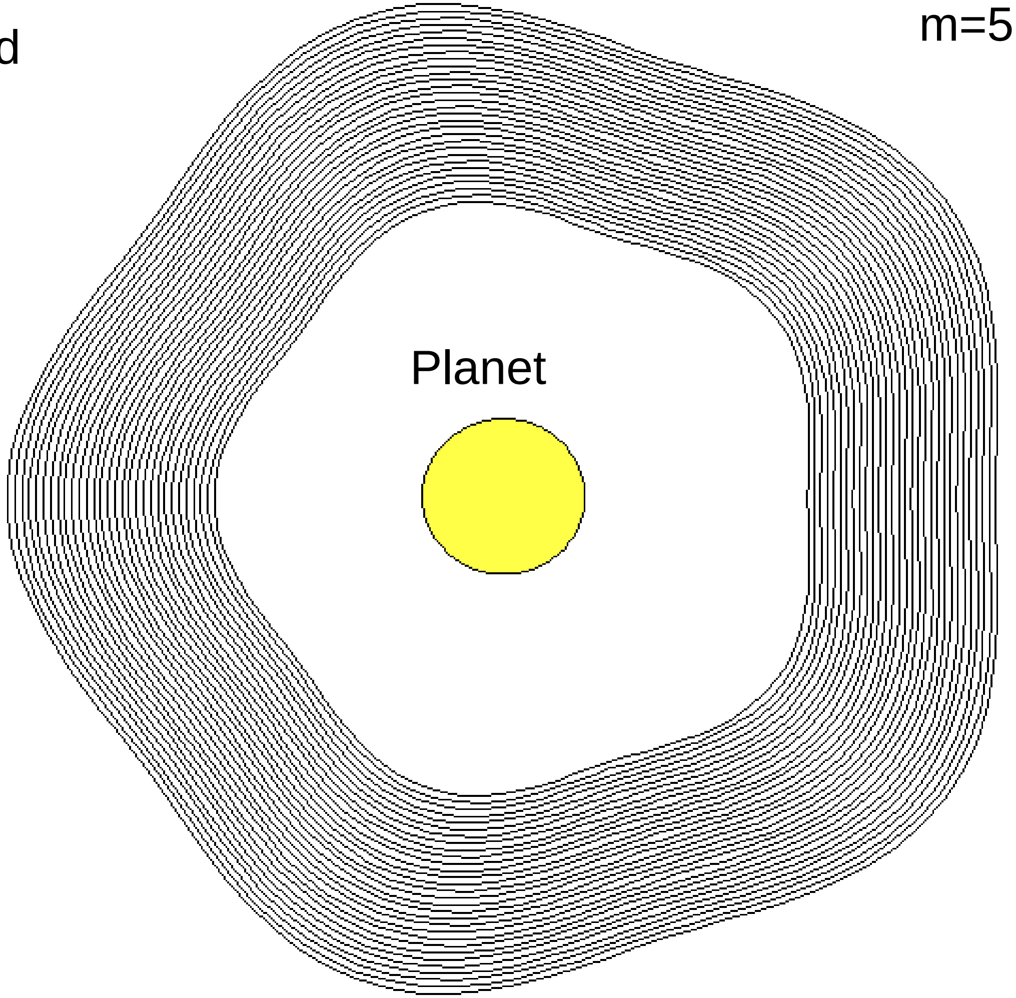
Following Goldreich and Tremaine (1978) and Shu (1984): In a frame rotating at Ω_M the streamline or path of a ring particle is:

$$r = a\left[1 - e\cos(m[\theta - \Omega_M t] + \theta_0)\right]$$

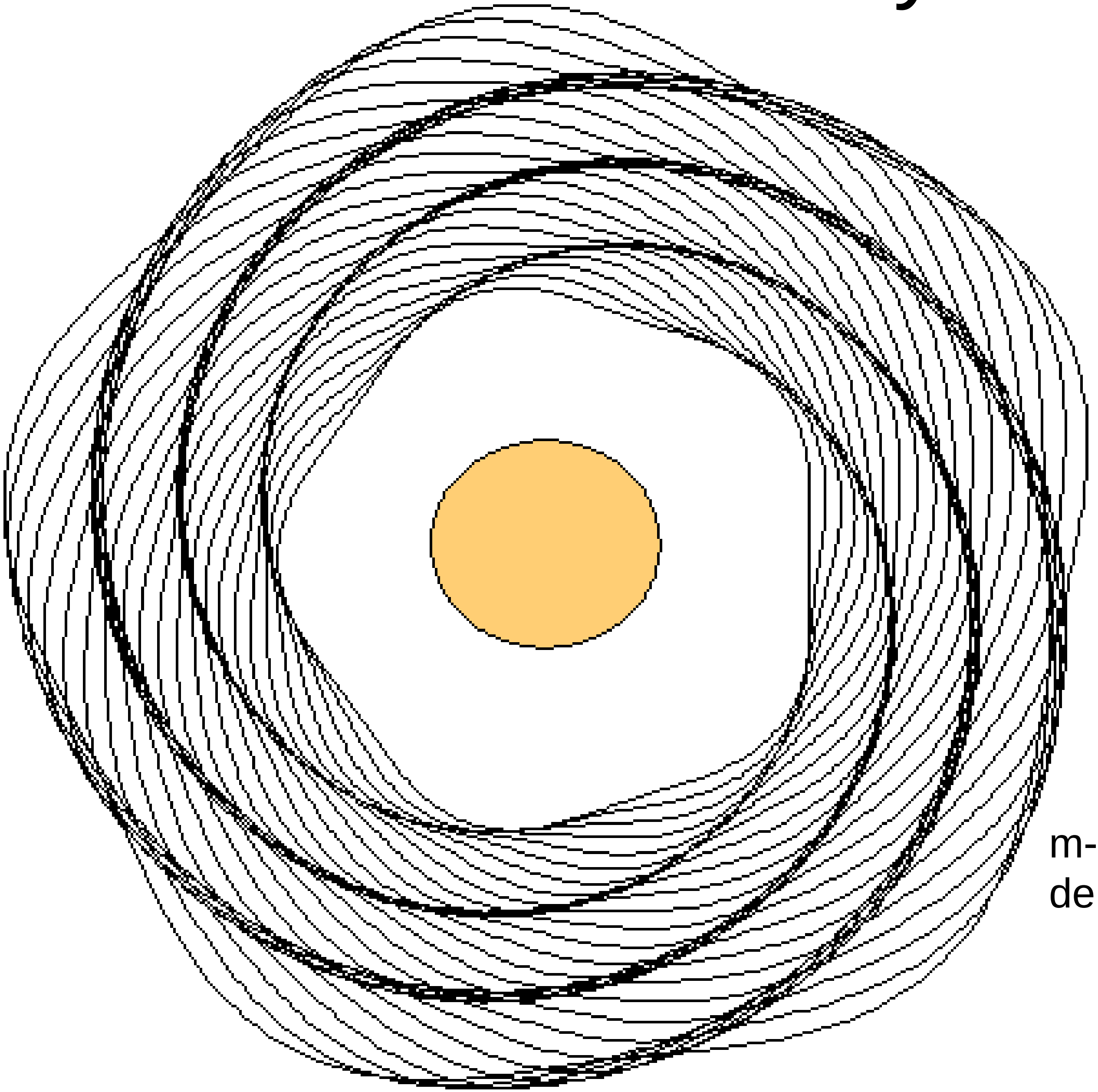
1. Gravity of satellite excites eccentricity of ring particles;
2. Acceleration due to satellite makes particles reach pericenter later (so pericenter advances to larger longitude);
3. This effect diminishes with increasing distance from resonance.



Streamline View of Density Wave



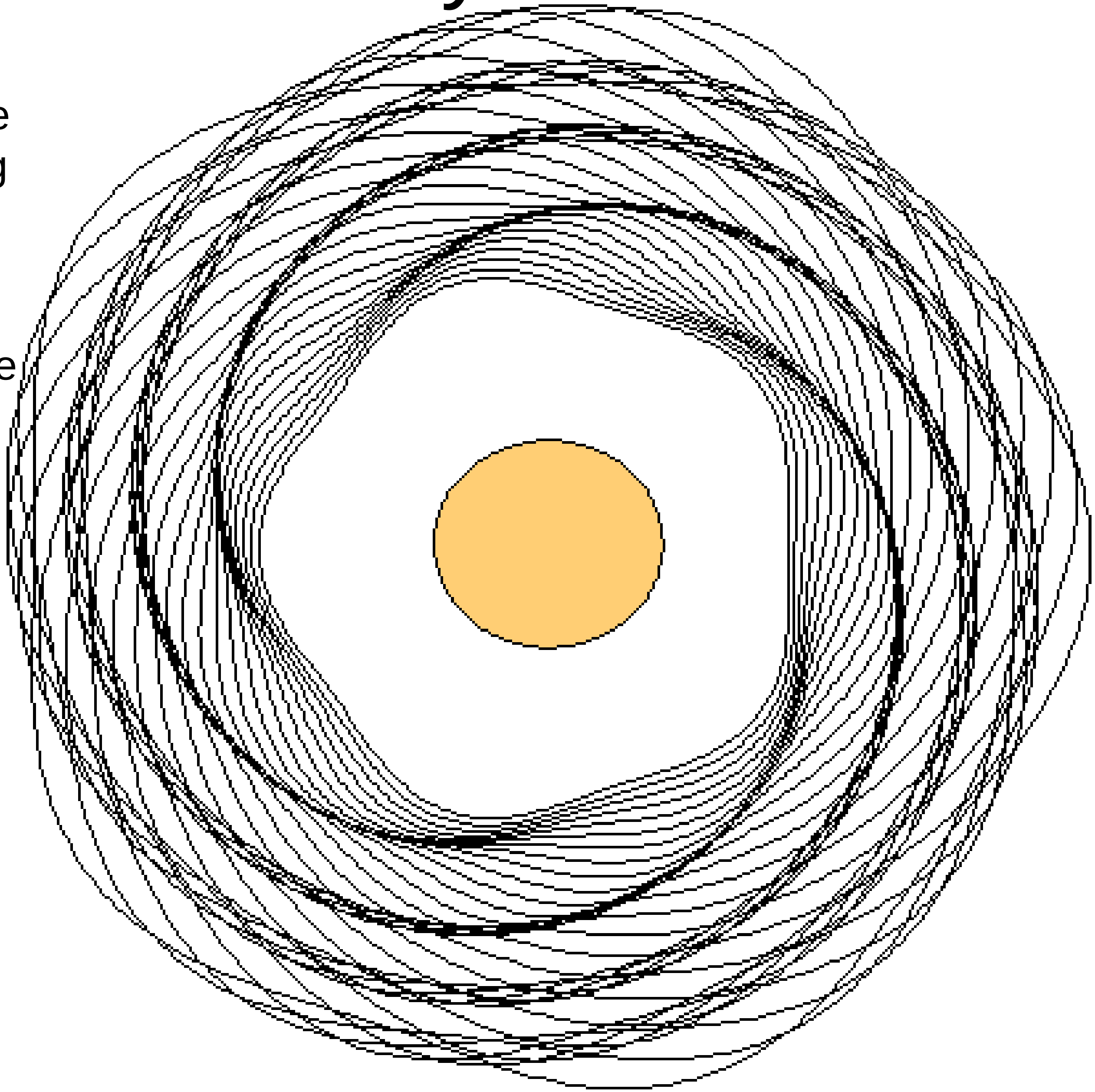
Streamlines Perturbed by Moon



m-armed spiral
density wave

Perturbed by Moon and Ring

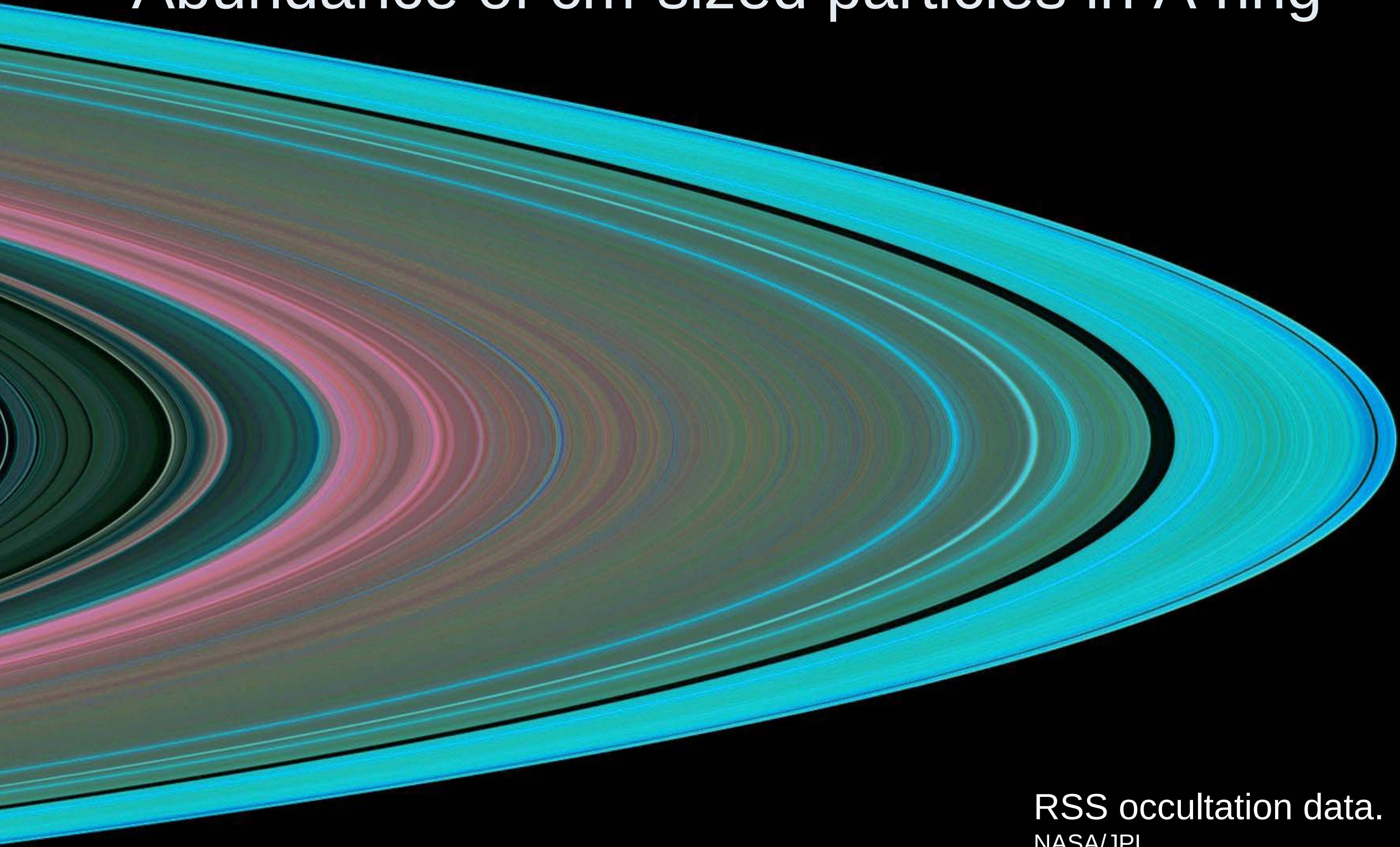
Disk gravity exerts a torque on neighboring ring particles resulting in tighter wrapping of the wave pattern.



Sizes of Particles in the Rings

- Broad distribution of sizes in main rings follows a power-law: $n(a) \sim a^{-q}$.
- $q \sim 3$ between ~1 cm and several m. Small particles more abundant than large particles.
- C, Cassini Division, F rings have more “dust” (sub-mm).
- G, E, and D rings are mainly dust.
- Moonlets coexist within rings.

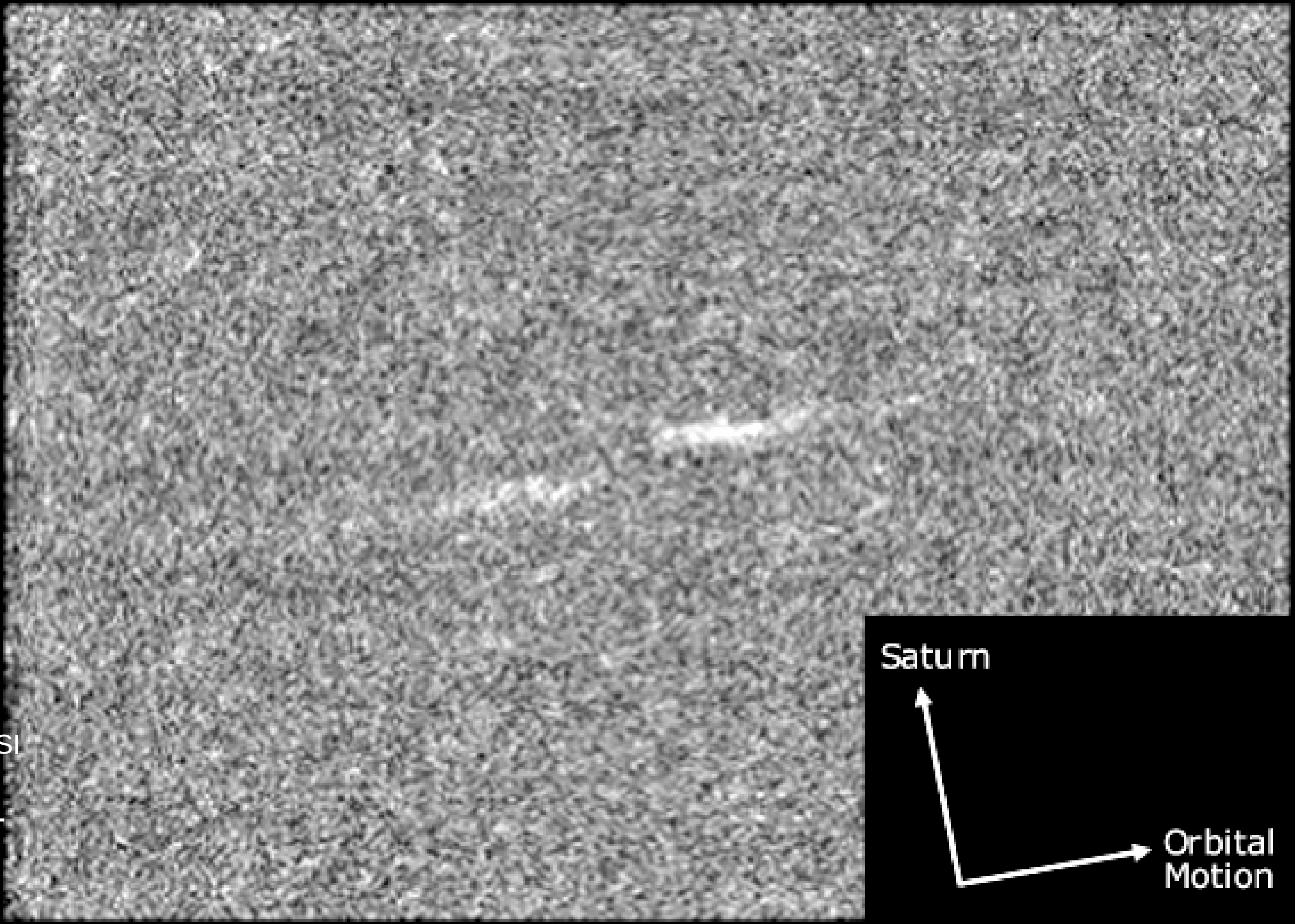
Abundance of cm-sized particles in A ring



RSS occultation data.
NASA/JPL

PIA07960

Evidence for 100 m Moonlet in A Ring



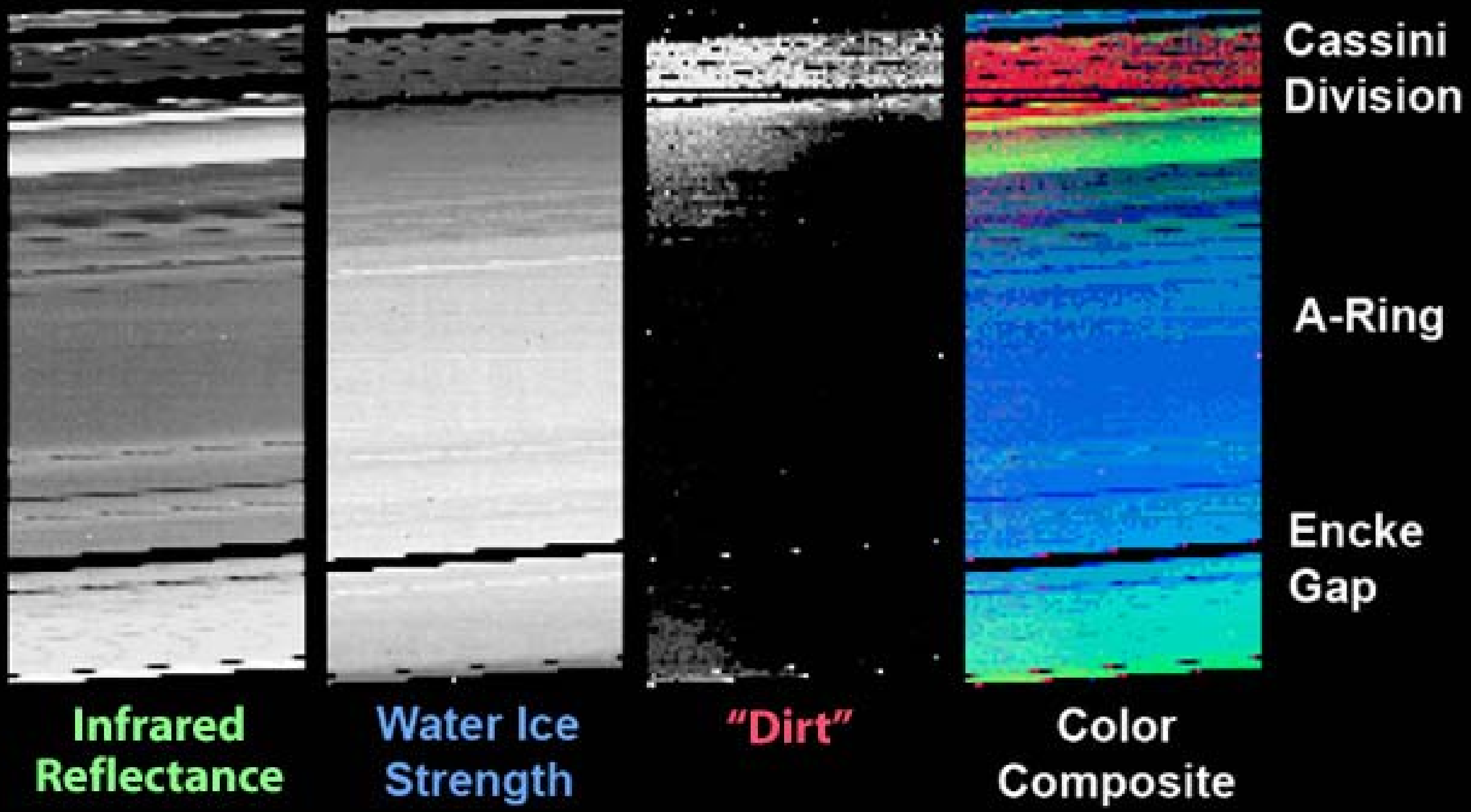
NASA/JPL/SSI

PIA07791

Composition of the Rings

- Water Ice
- And Dirt

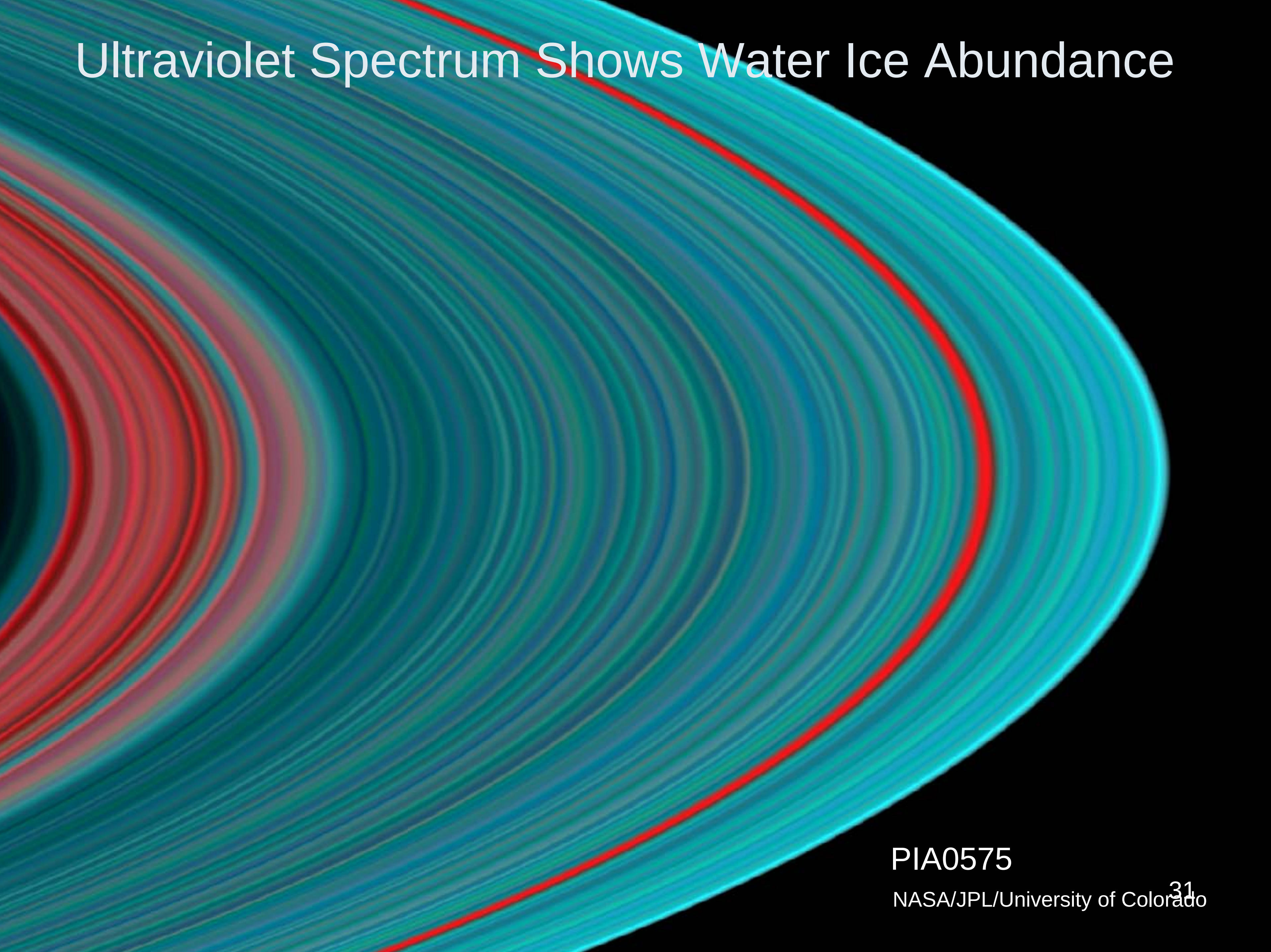
Infrared Spectrum Shows Distribution of Water Ice



PA06350

NASA/JPL/University of Arizona

Ultraviolet Spectrum Shows Water Ice Abundance



PIA0575

NASA/JPL/University of Colorado

Rings Summary

- D, E, G rings are broad and very tenuous and dusty.
- Main rings: C, B, Cassini Division, A, and F
  - C and Cassini Division have small particles, low opacity, and several gaps and narrow ringlets.
  - B ring is broad, most massive, lots of unexplained structure;
  - A ring has intermediate opacity, two gaps with known moons, and most observed structure are waves excited by moons.
  - Composition mostly water ice. Dusty rings are more contaminated by dark material.

The Age Problem

- The rings are bright: micrometeoroid impacts would darken pure ice to the present level in ~10^8 years.
- The rings are spreading: collisions transport angular momentum outward and dissipate energy. Moons act as gravitational bookends, but evolutionary timescales are also ~10^8 years.
- Moons are short-lived: embedded and nearby moons have lifetimes against impact disruption of 10^6-10^9 years.

Other Big Picture Problems

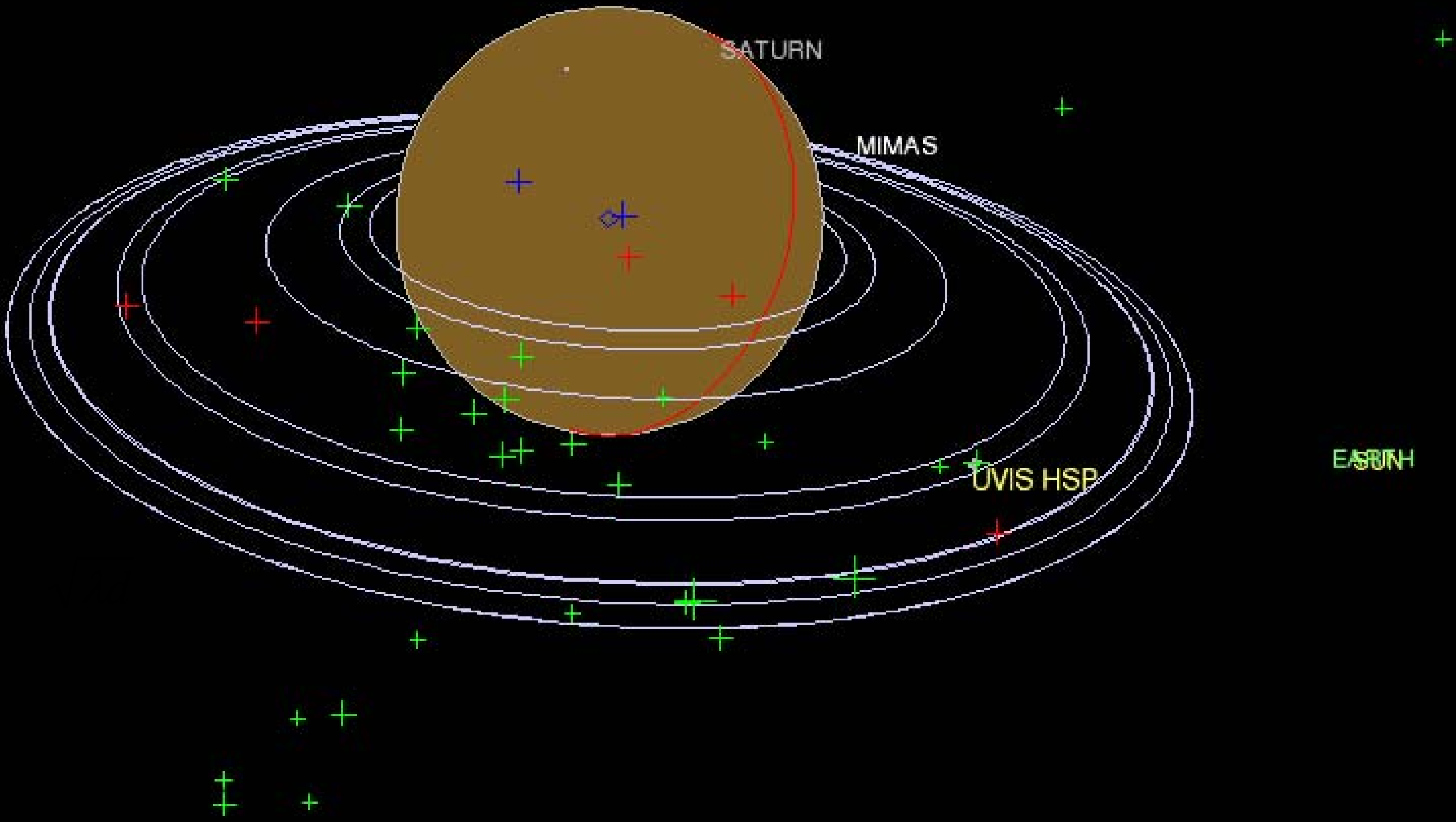
- What causes the structures on various scales in the rings?
- What role does limited accretion play?
- What did the rings look like 100 million years ago, and what will they look like in 100 million years?

Critical Pieces of Information

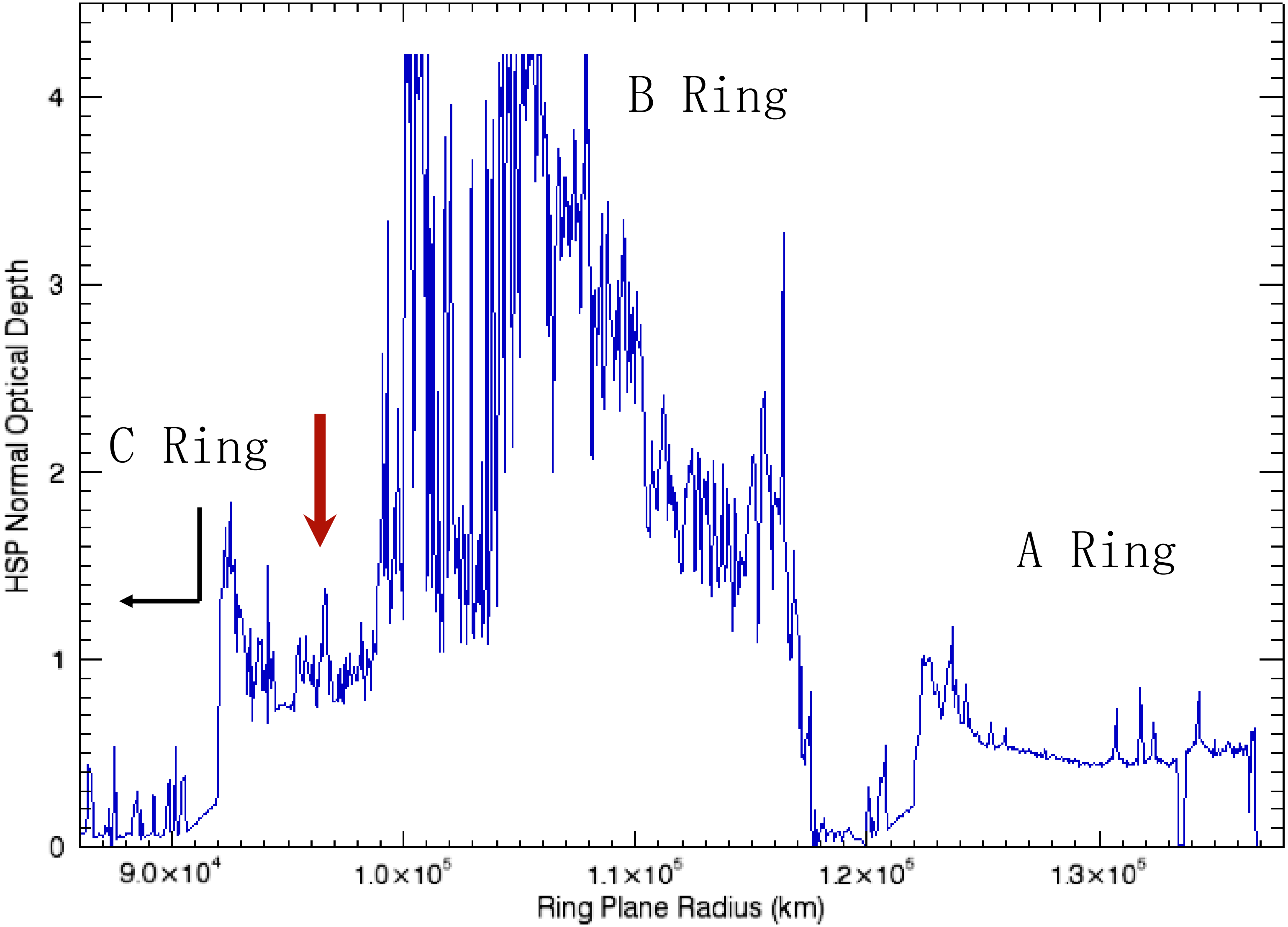
- Need to know mass of rings and size distribution of particles.
- Need to know energy dissipation in individual collisions.
- Need to know impact flux.
- Challenge is to extract this information from observations of the rings. Stellar occultations are highest resolution probes of ring structure and hence dynamics.

Stellar Occultation Geometry

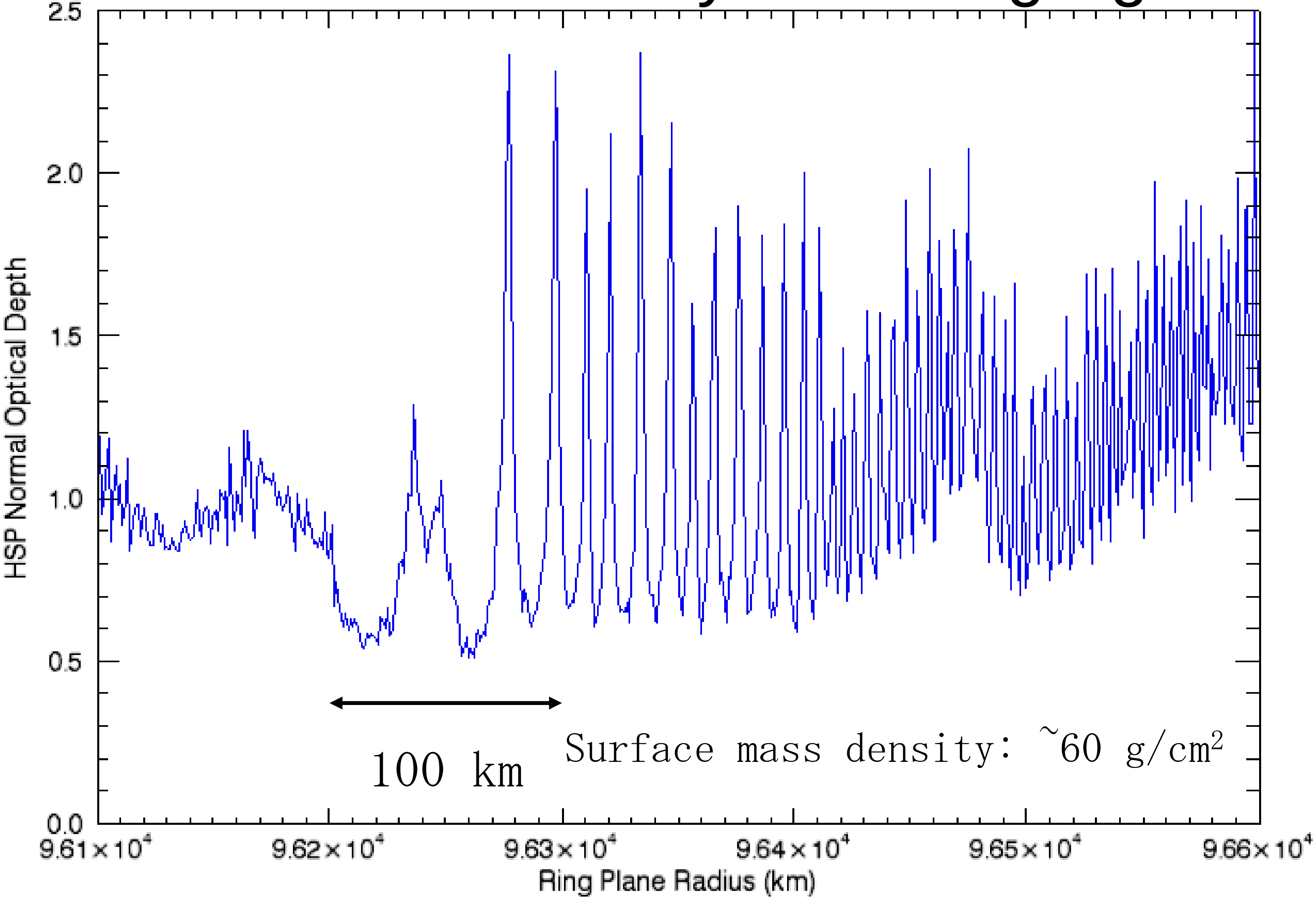
2 ms sampling provides ~7-20 m resolution.



Sig Sgr Stellar Occultation at 50 km Resolution

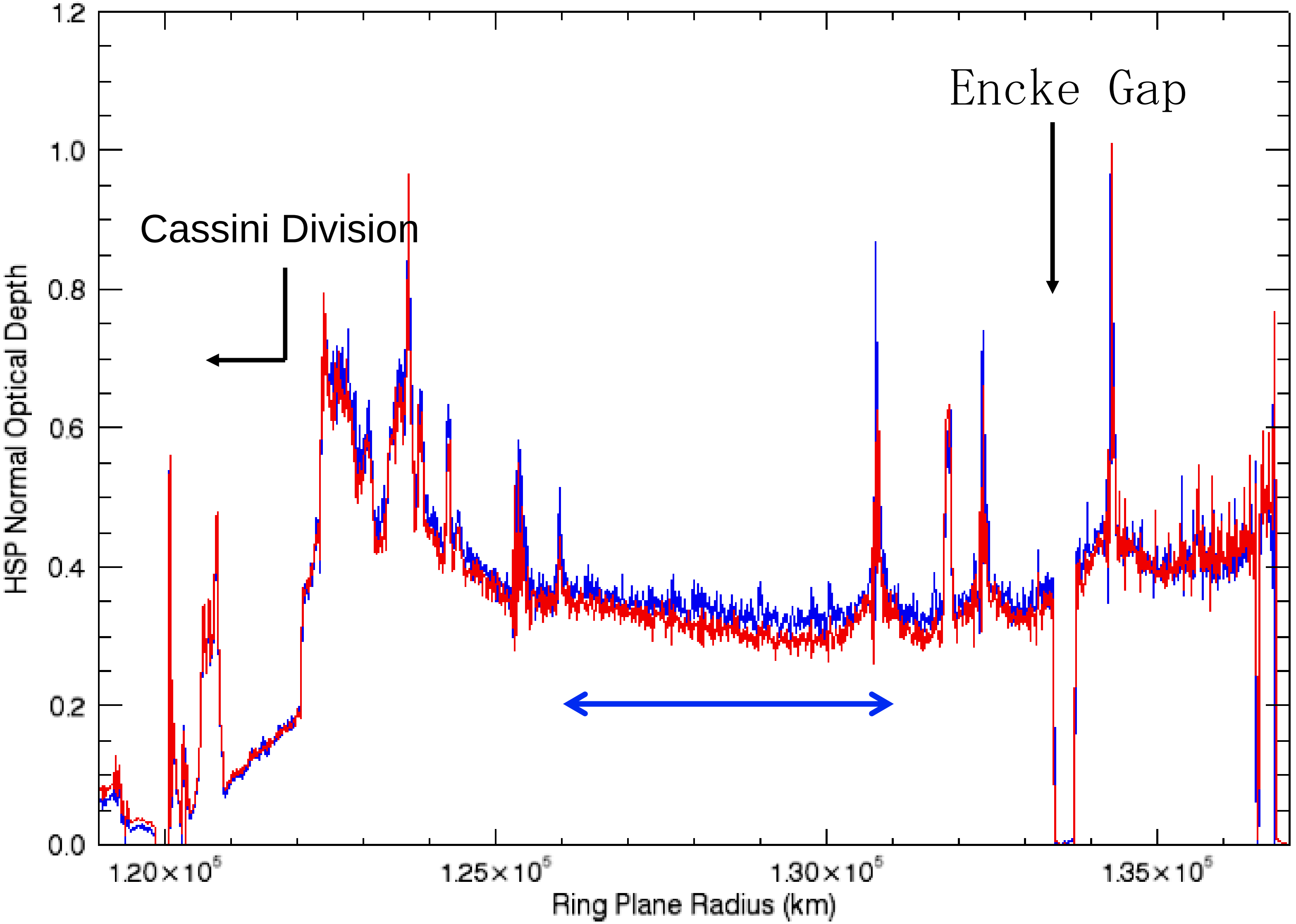


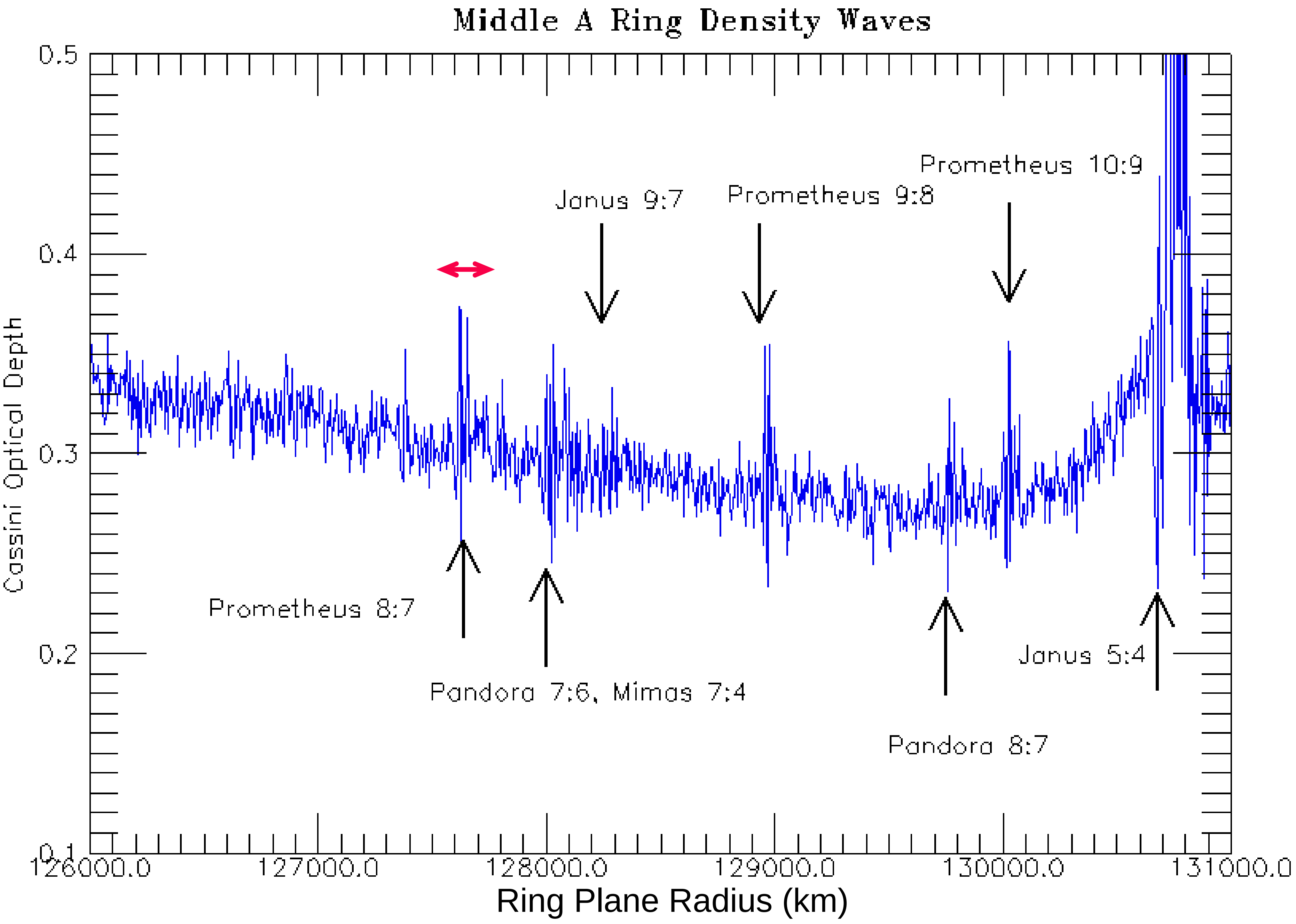
Janus 2:1 Density Wave Sig Sgr



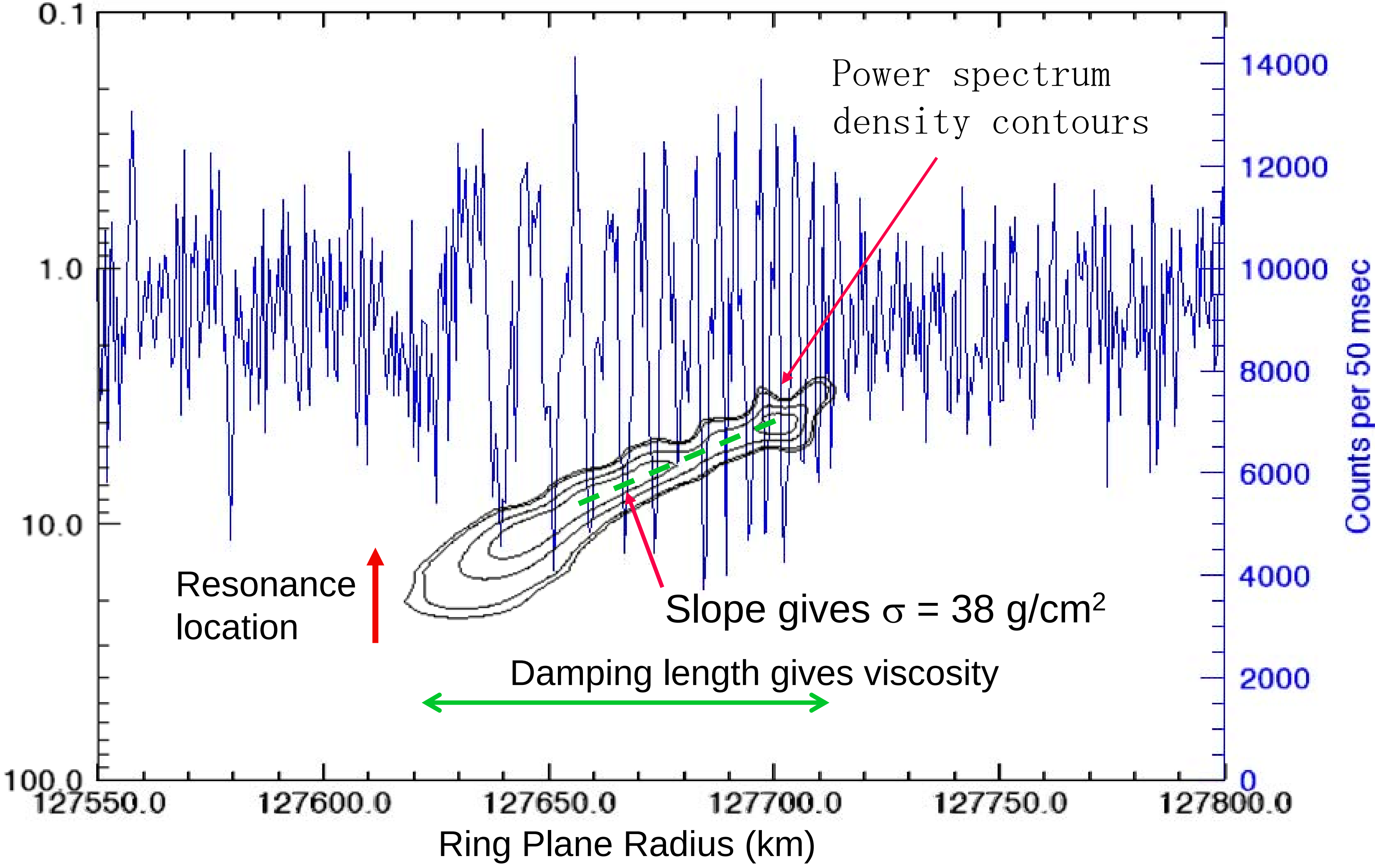
Surface mass density: ~60 g/cm^2

Alpha Virginis A Ring Opacities
Ingress and Egress at 10 km Resolution



Middle A Ring Density Waves
Cassini Optical Depth
Ring Plane Radius (km)
0.5
0.4
0.3
0.2
0.1
126000.0
127000.0
128000.0
129000.0
130000.0
131000.0
Janus 9:7
Prometheus 9:8
Prometheus 10:9
Prometheus 8:7
Pandora 7:6, Mimas 7:4
Pandora 8:7
Janus 5:4

Prometheus 8:7 Density Wave in A Ring



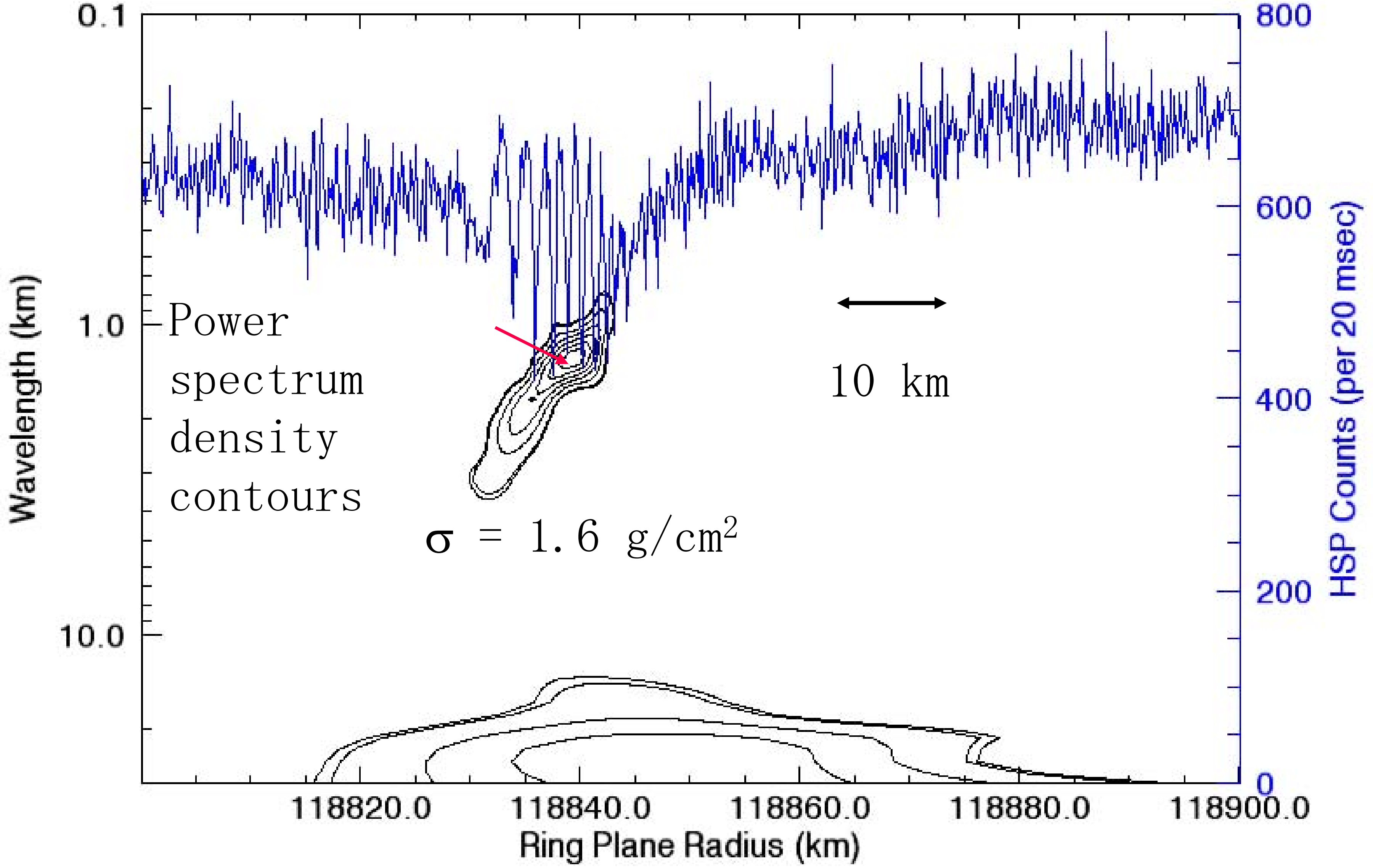
Power spectrum density contours

Resonance location

Slope gives σ = 38 g/cm^2

Damping length gives viscosity

Atlas 5:4 Density Wave in Cassini Division

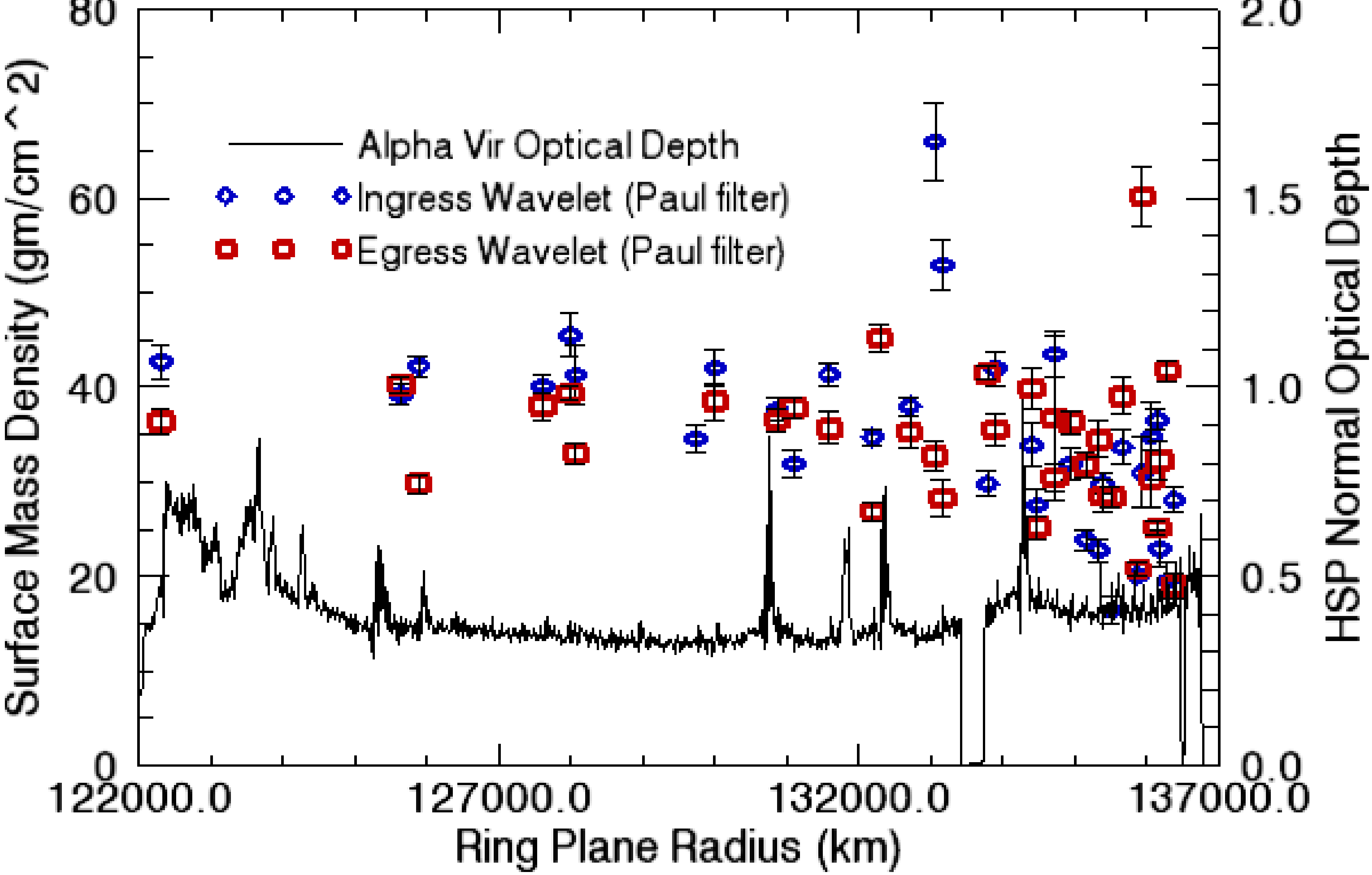


Power spectrum density contours

$\sigma = 1.6\ \mathrm{g/cm^2}$

Wavelet software from Torrence and Compo (1998).

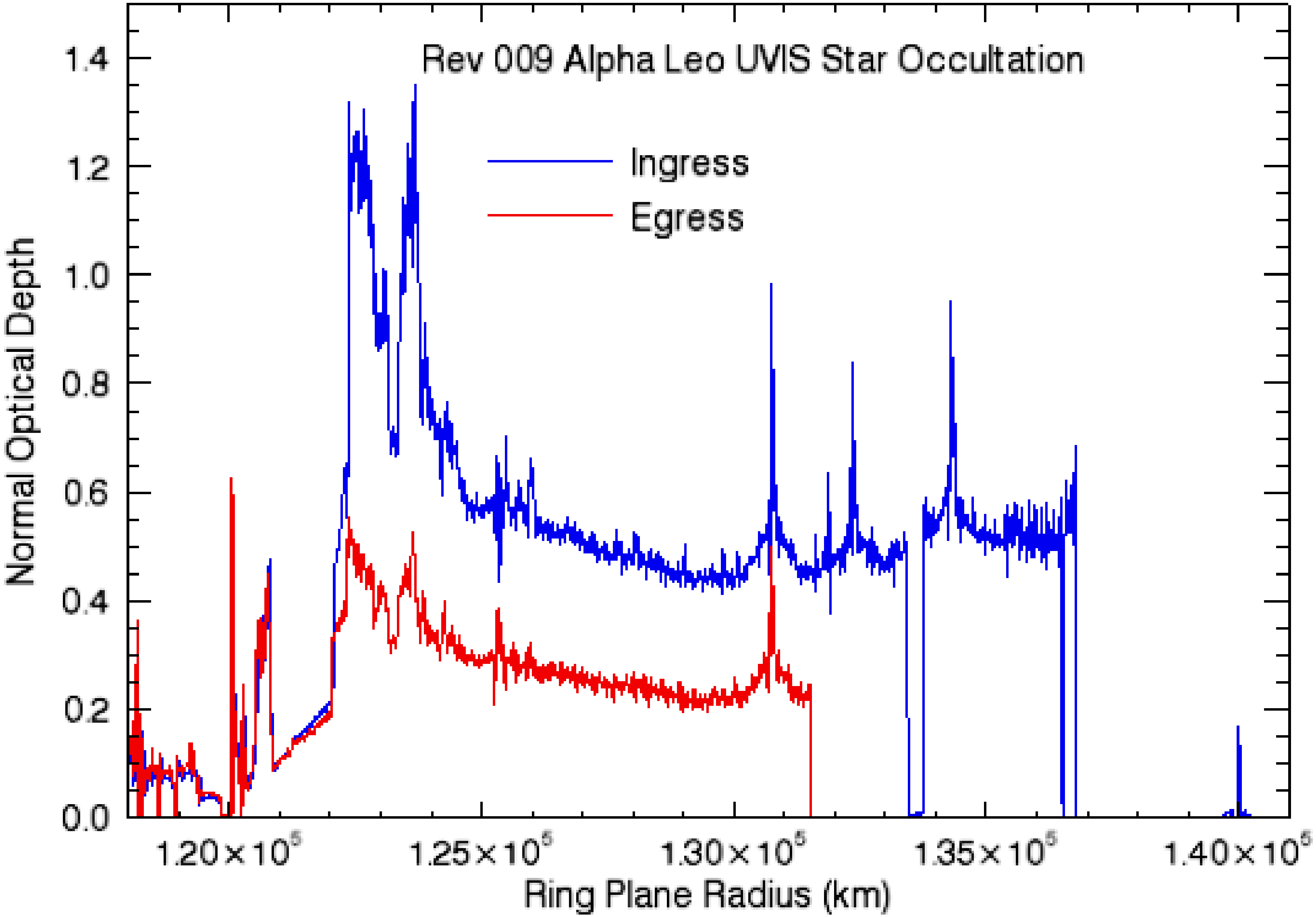
Measured Surface Mass Densities



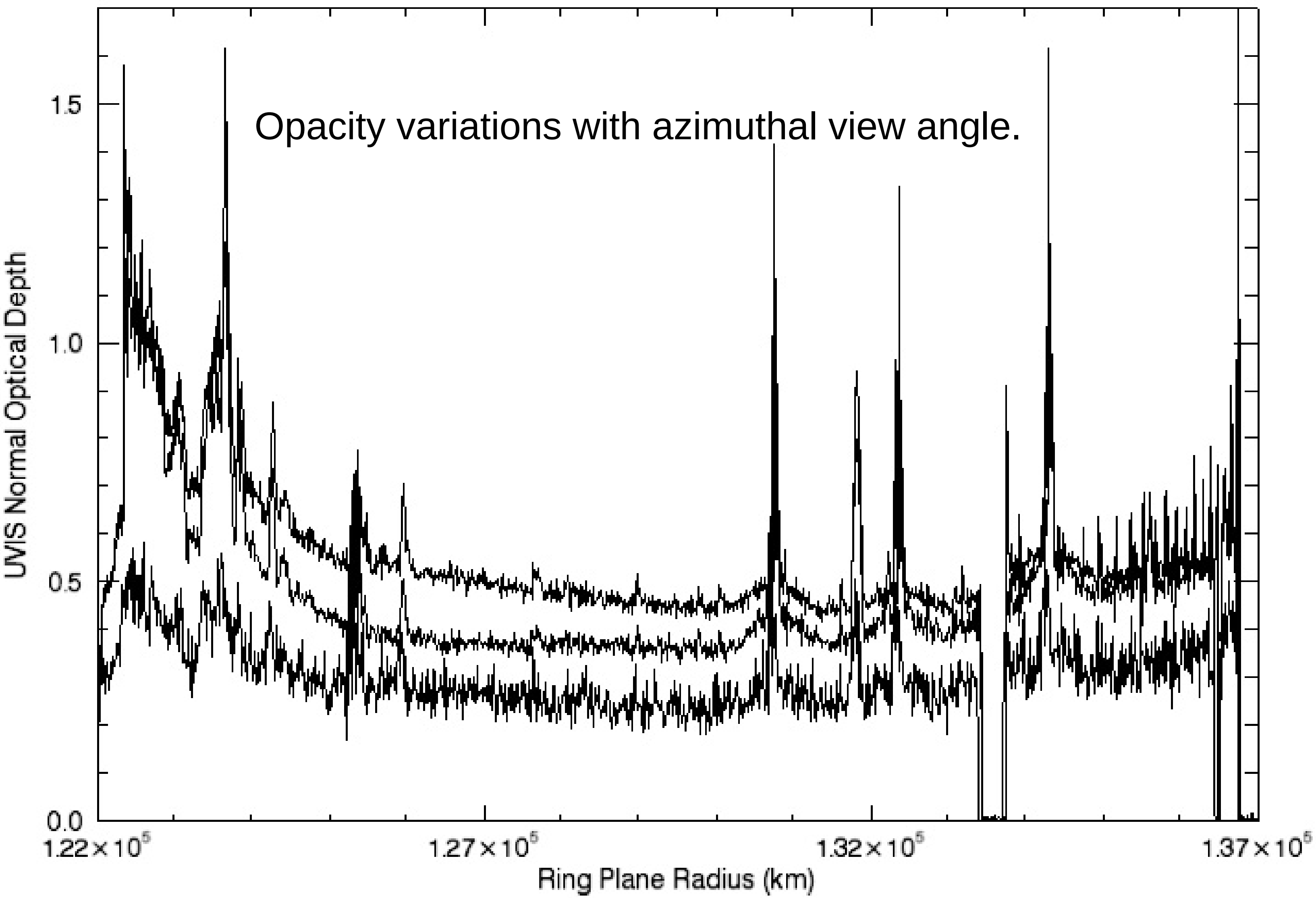
Density Wave Summary

- Mass of A ring ~ 4×10^{21} g (35 g/cm^2) equivalent moon radius ~ 100 km.
- Mass of B ring ~ 10^{22} g (60 g/cm^2).
- Equivalent moon radius of ring system: R_{moon} ~ 150 km
- Viscosity ~ 5 cm^2/s in Cassini Division gives H ~ 10 m. A ring: H ~ 20-30 m.
- Lifetime of 150 km moon is ~ 10^{10} years at current epoch.

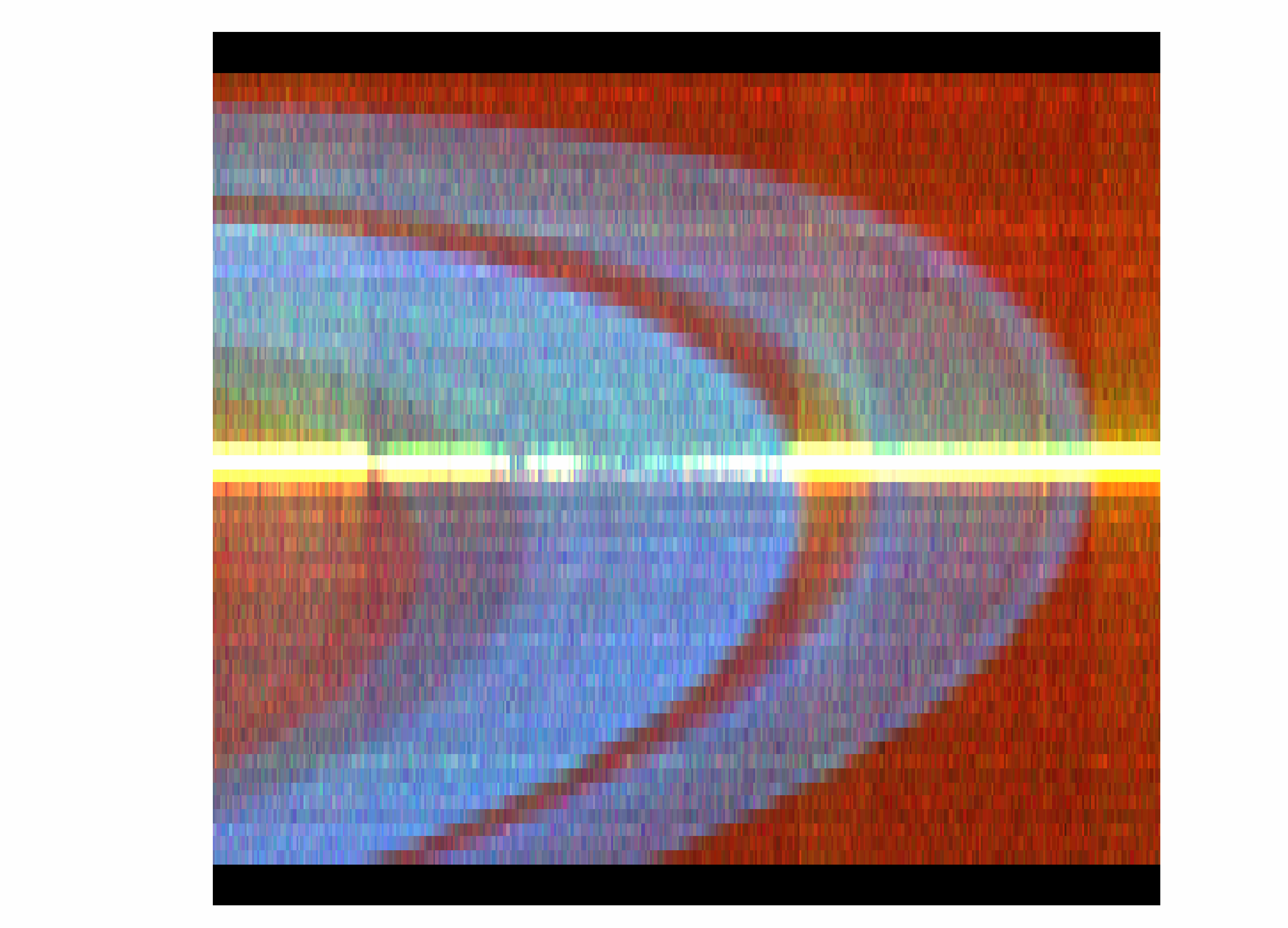
A Ring Azimuthal Transparency Asymmetry



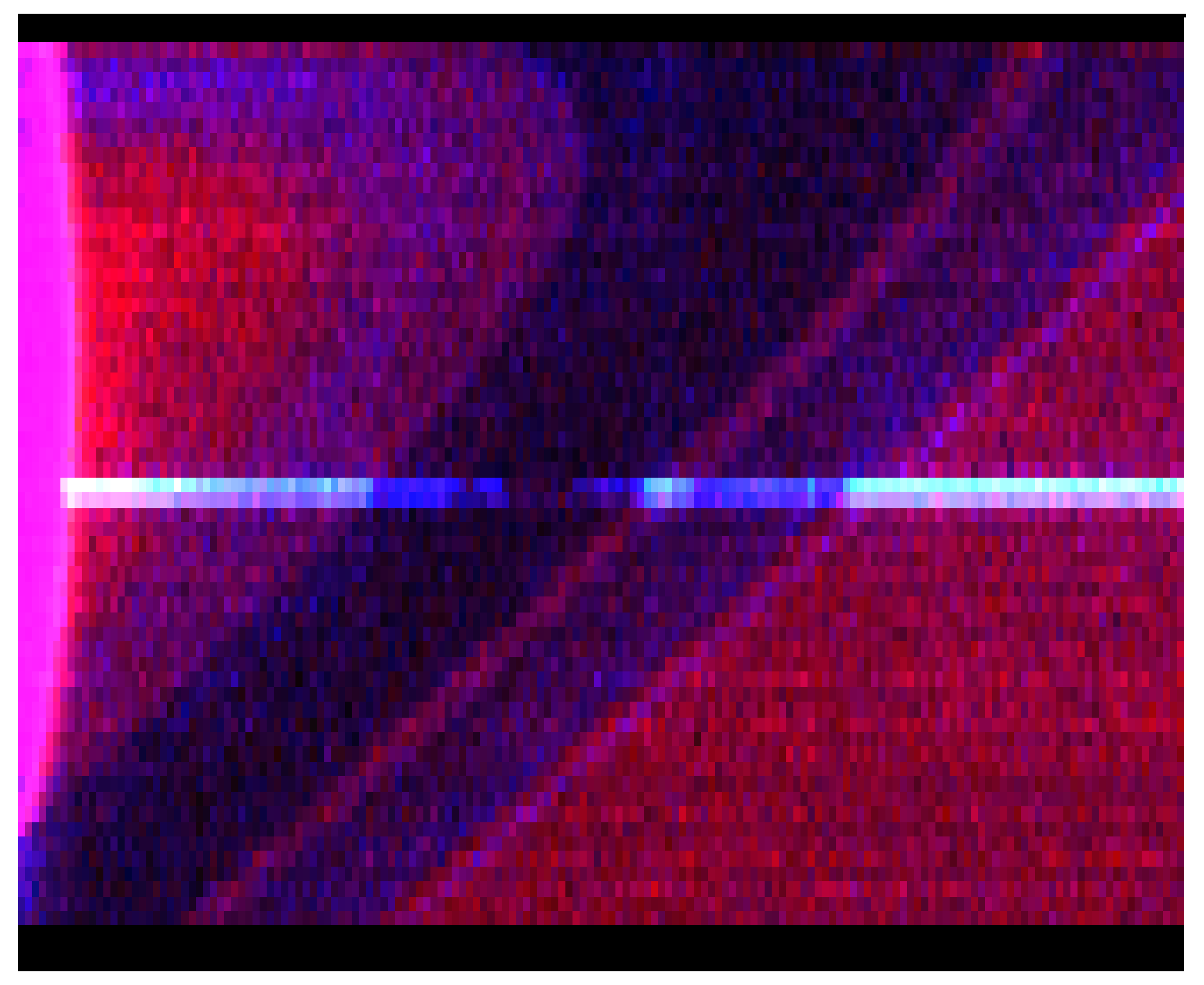
A Ring Azimuthal Transparency Asymmetry



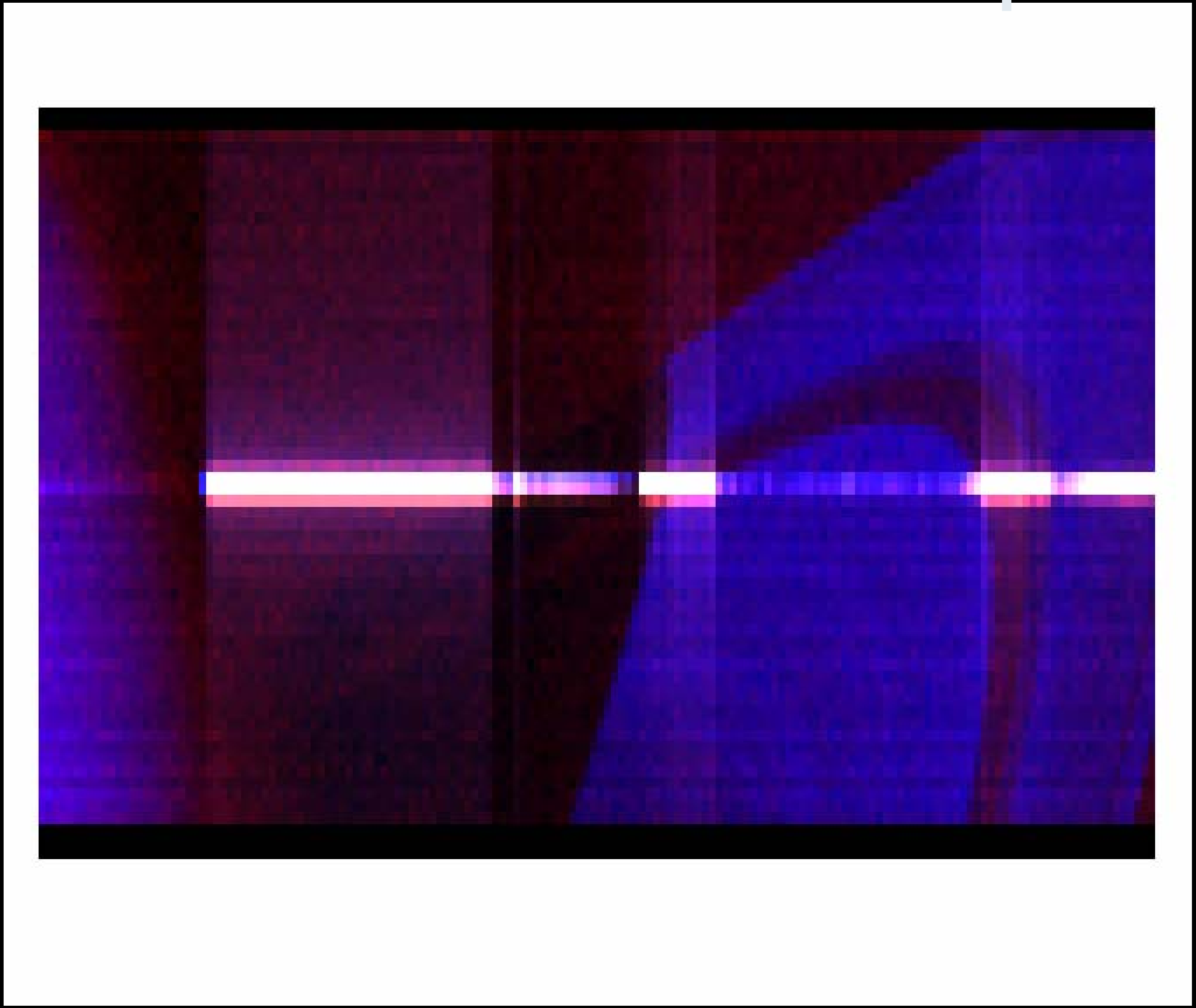
FUV Observation of 26 Tau (8)



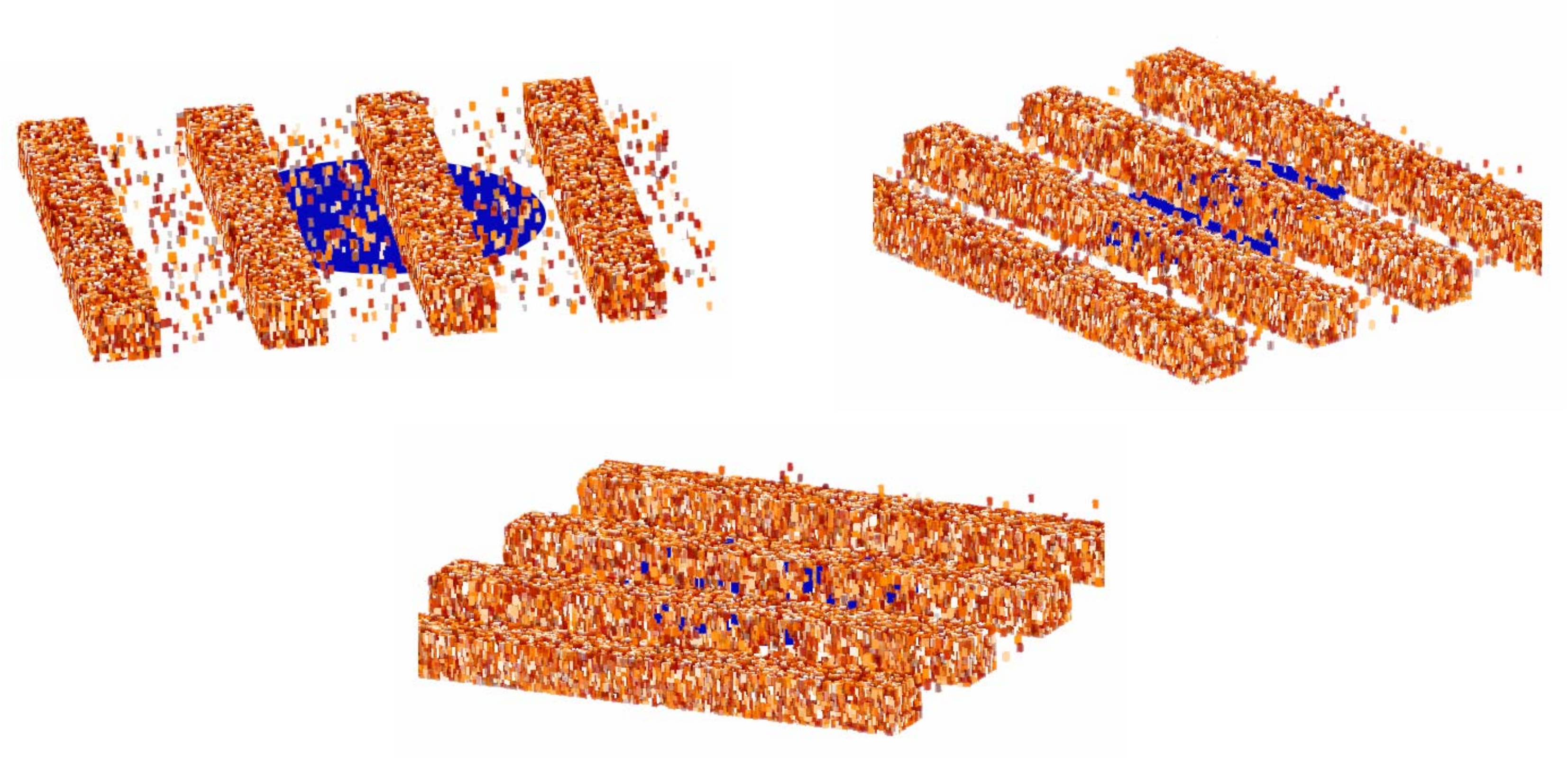
FUV Observation of Del Aqr



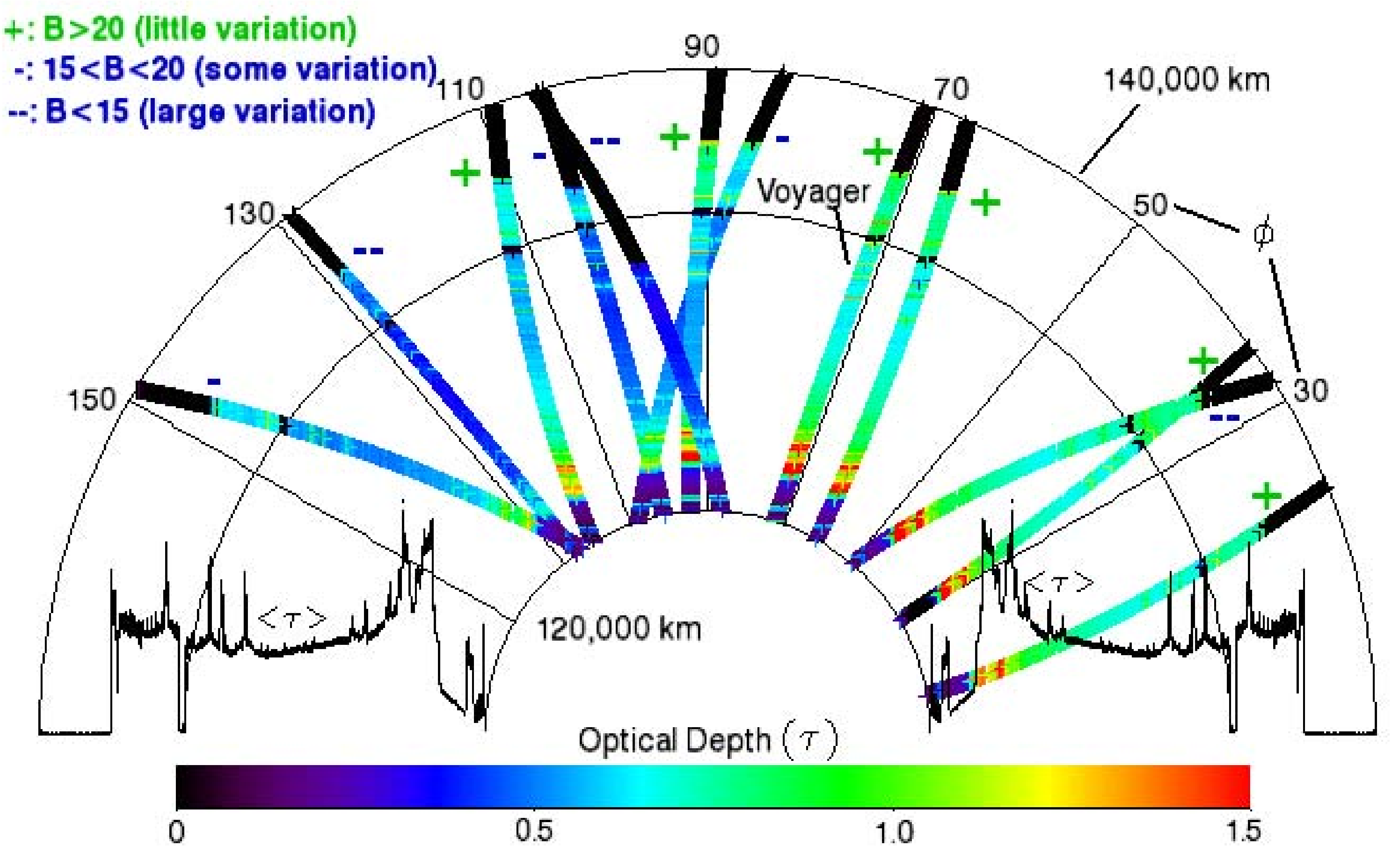
FUV Observation of Alp Leo



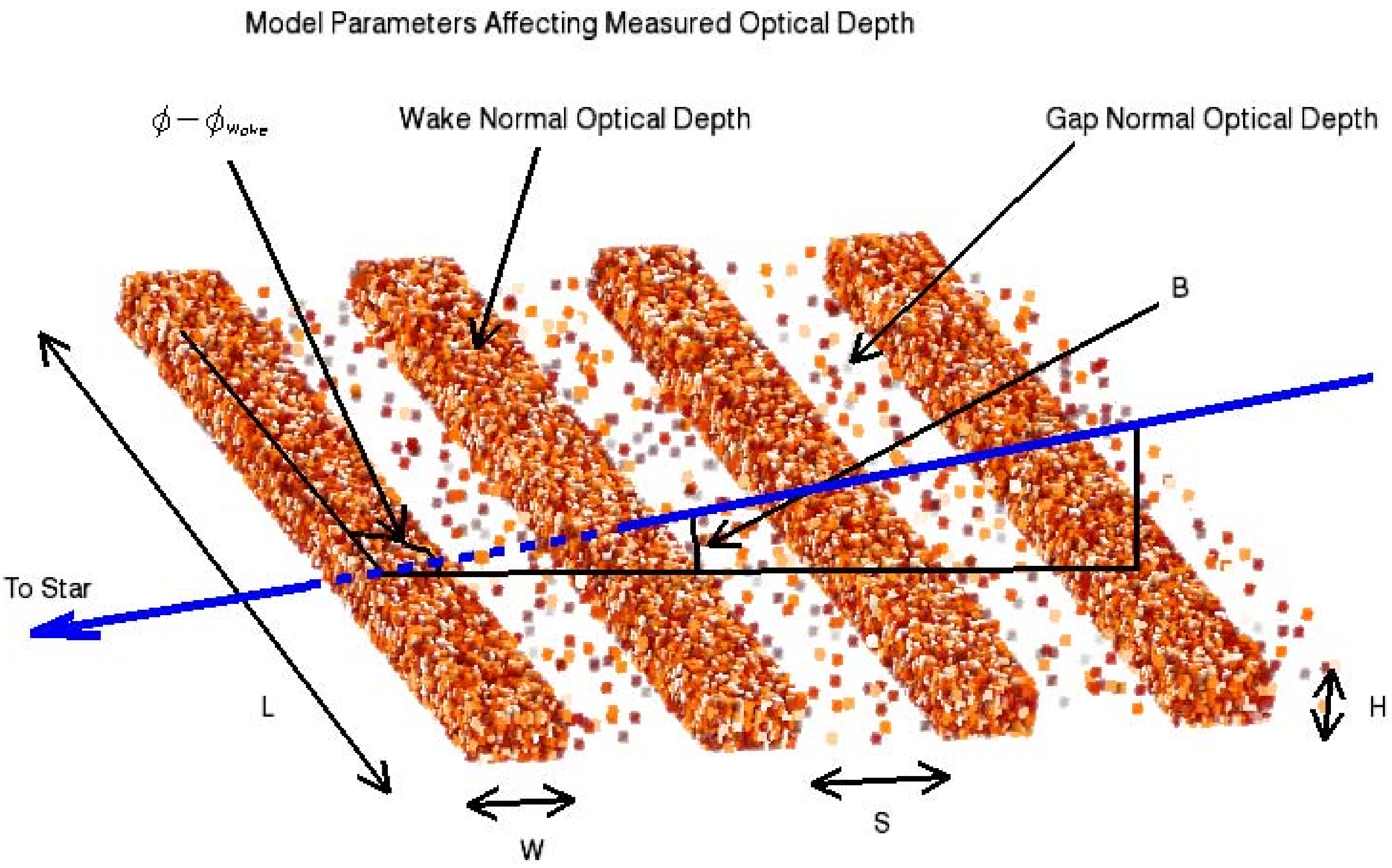
Azimuthal View Angle Dependence on Opacity



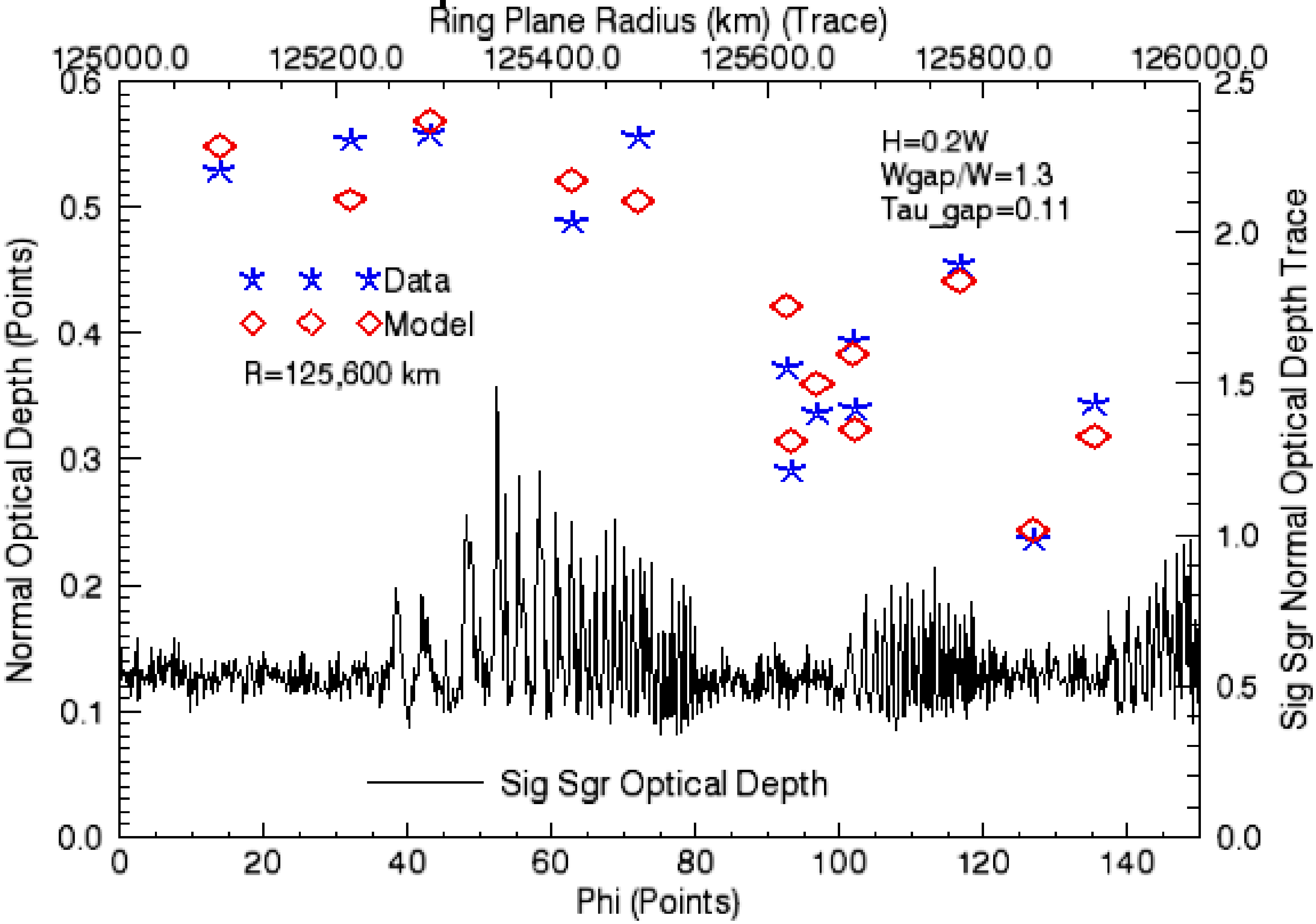
Stellar Occultation Variation Summary



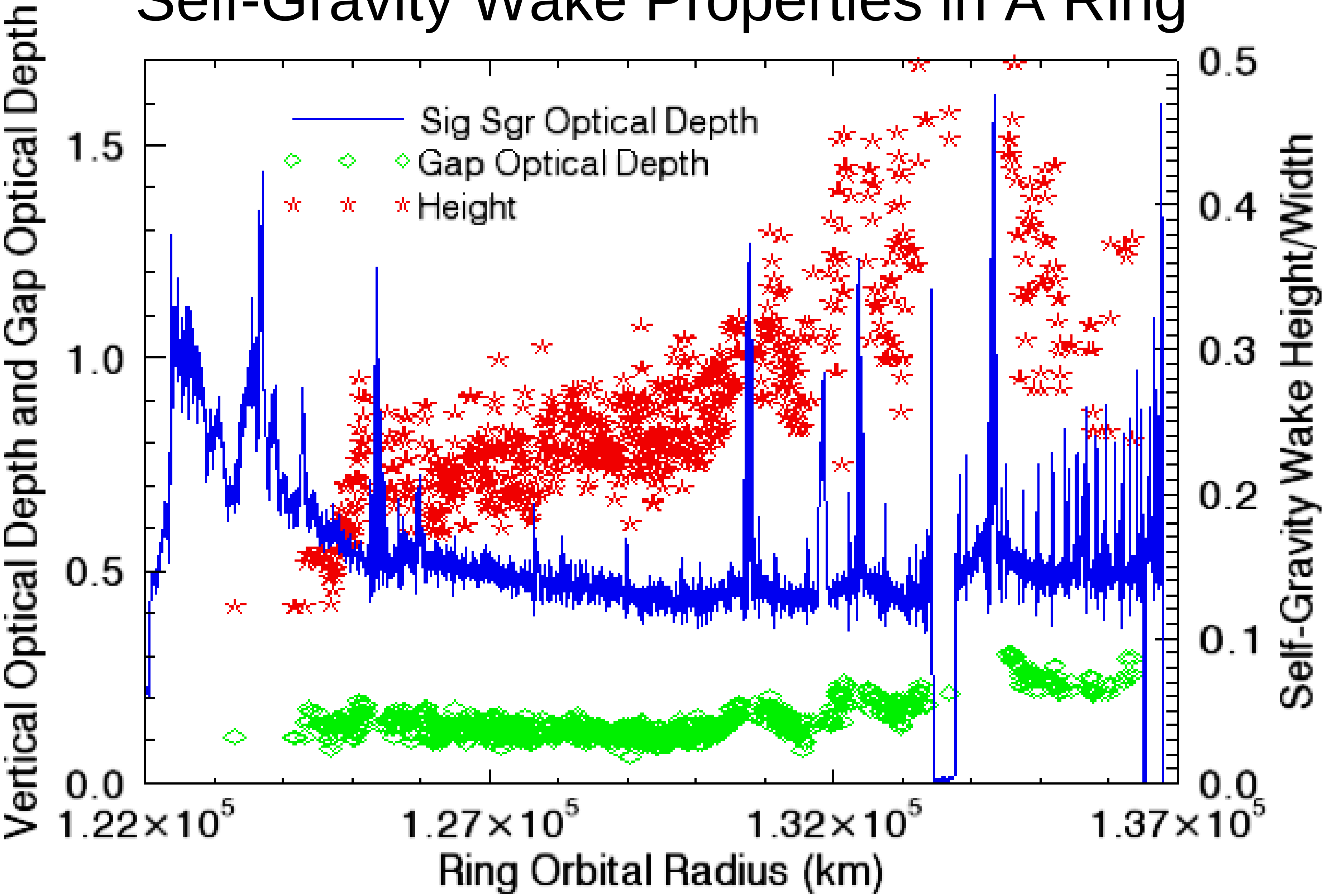
Self-Gravity “Wake” Model



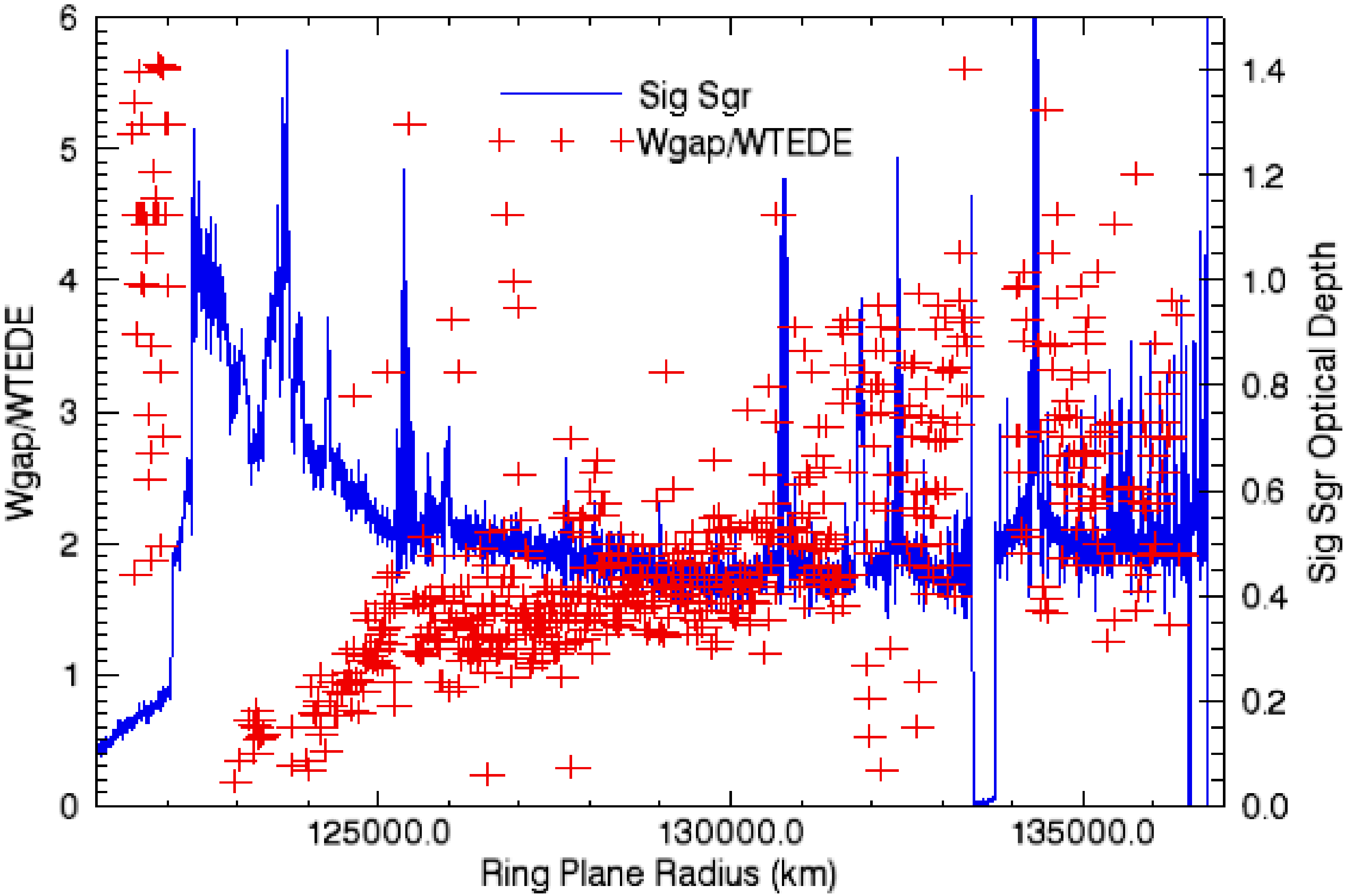
Example Model Fit to Data



Self-Gravity Wake Properties in A Ring

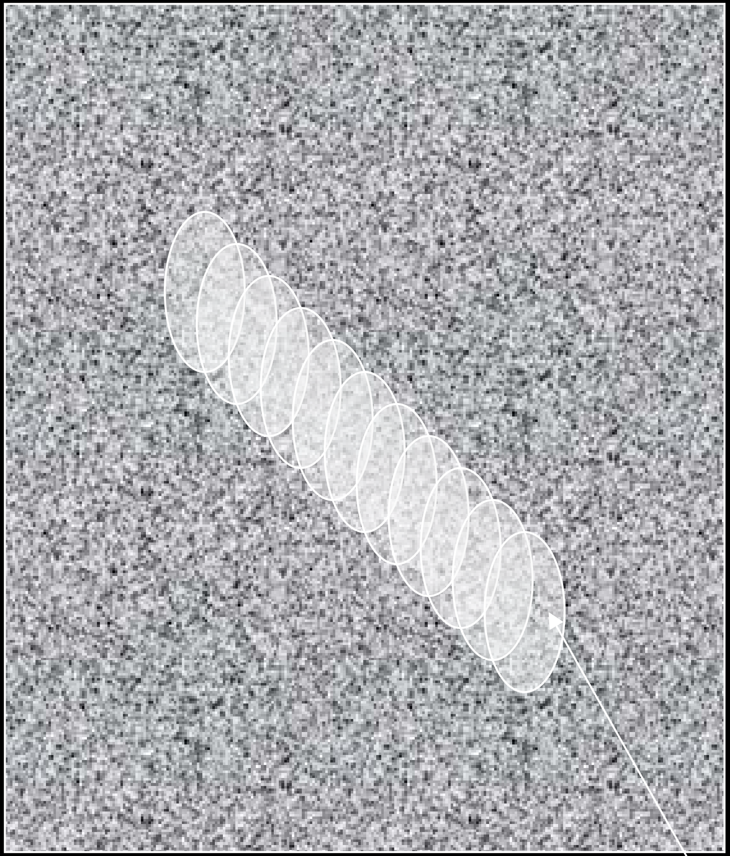


Spacing


Sig Sgr
Wgap/WTEDE
Wgap/WTEDE
0
1
2
3
4
5
6
Sig Sgr Optical Depth
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
125000.0
130000.0
135000.0
Ring Plane Radius (km)

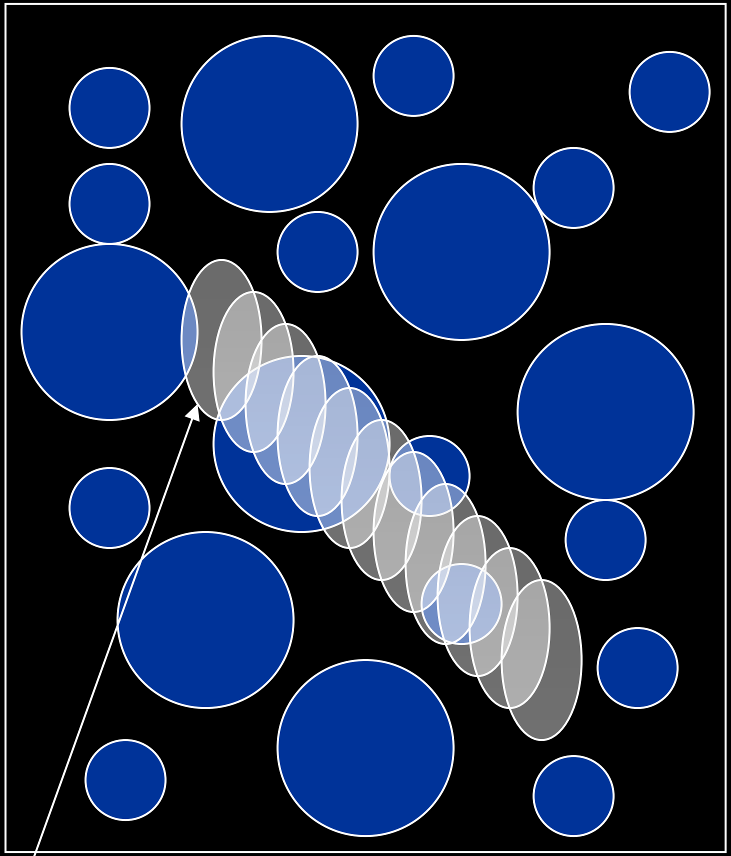
Measuring Self-Gravity Wake Sizes from Occultation Statistics

Particles << sample size.



Observed σ = Poisson σ

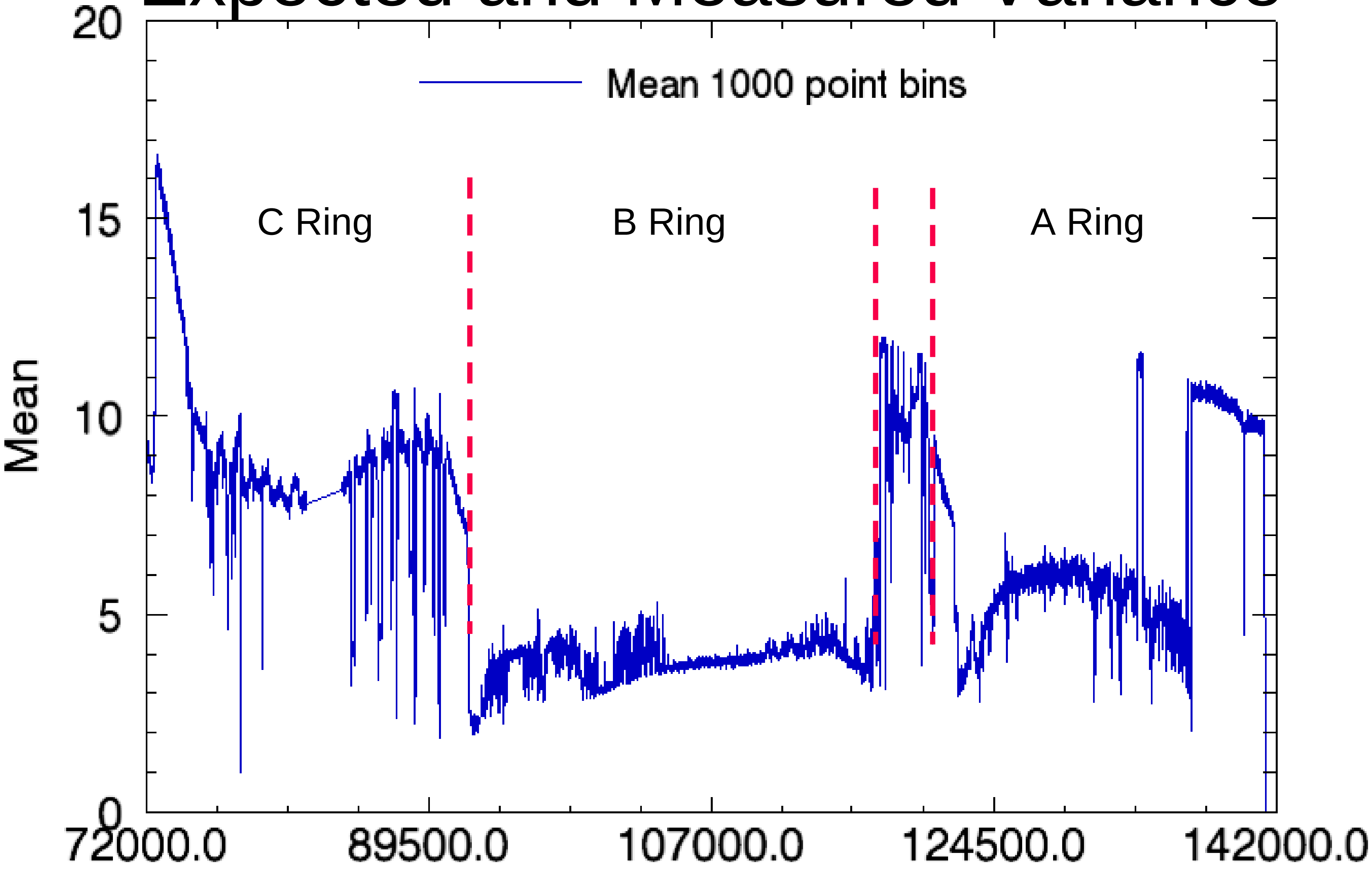
Particles (or clumps) ~ sample size.



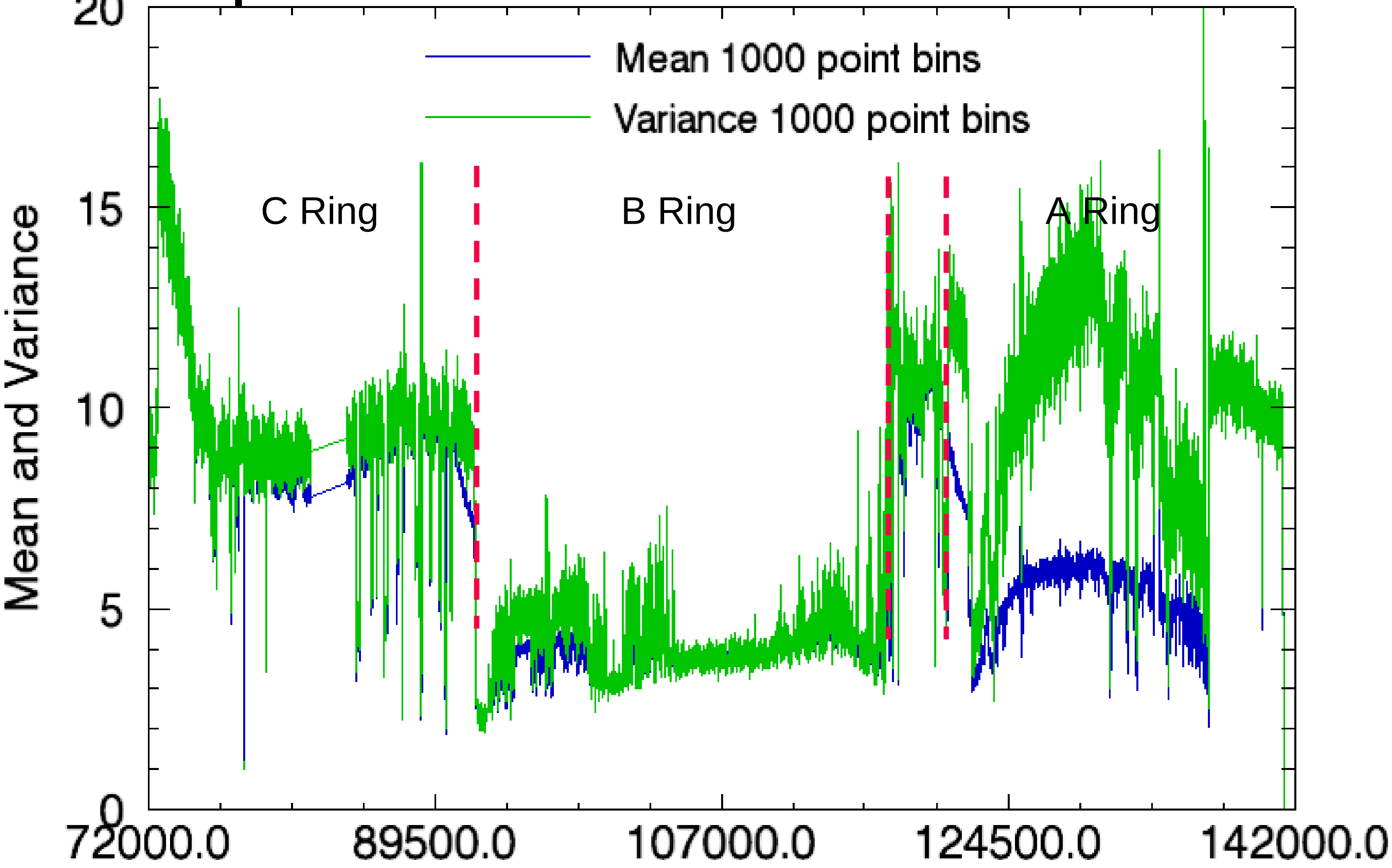
Observed σ > Poisson σ

Region of ring observed in one sample.

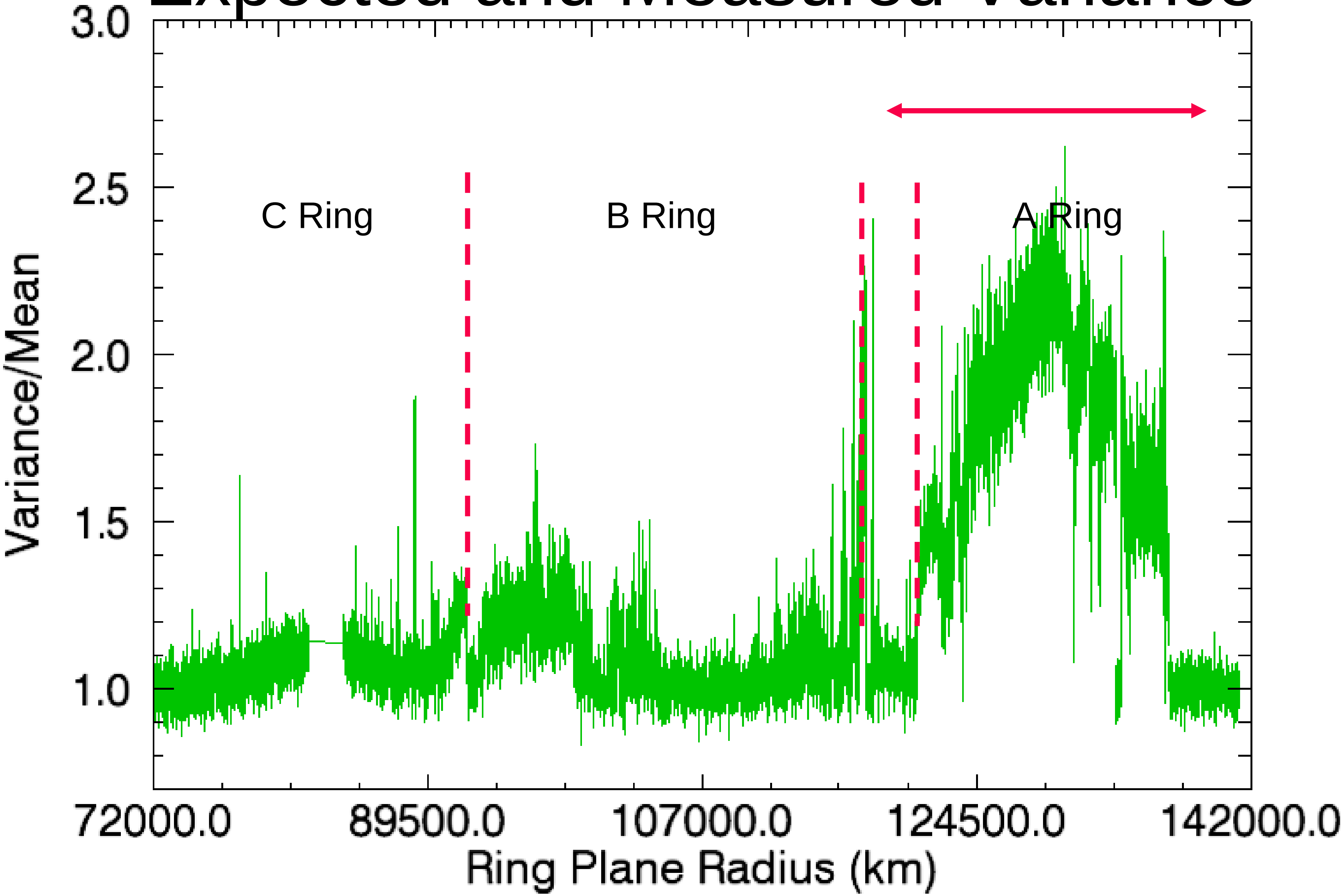
Expected and Measured Variance



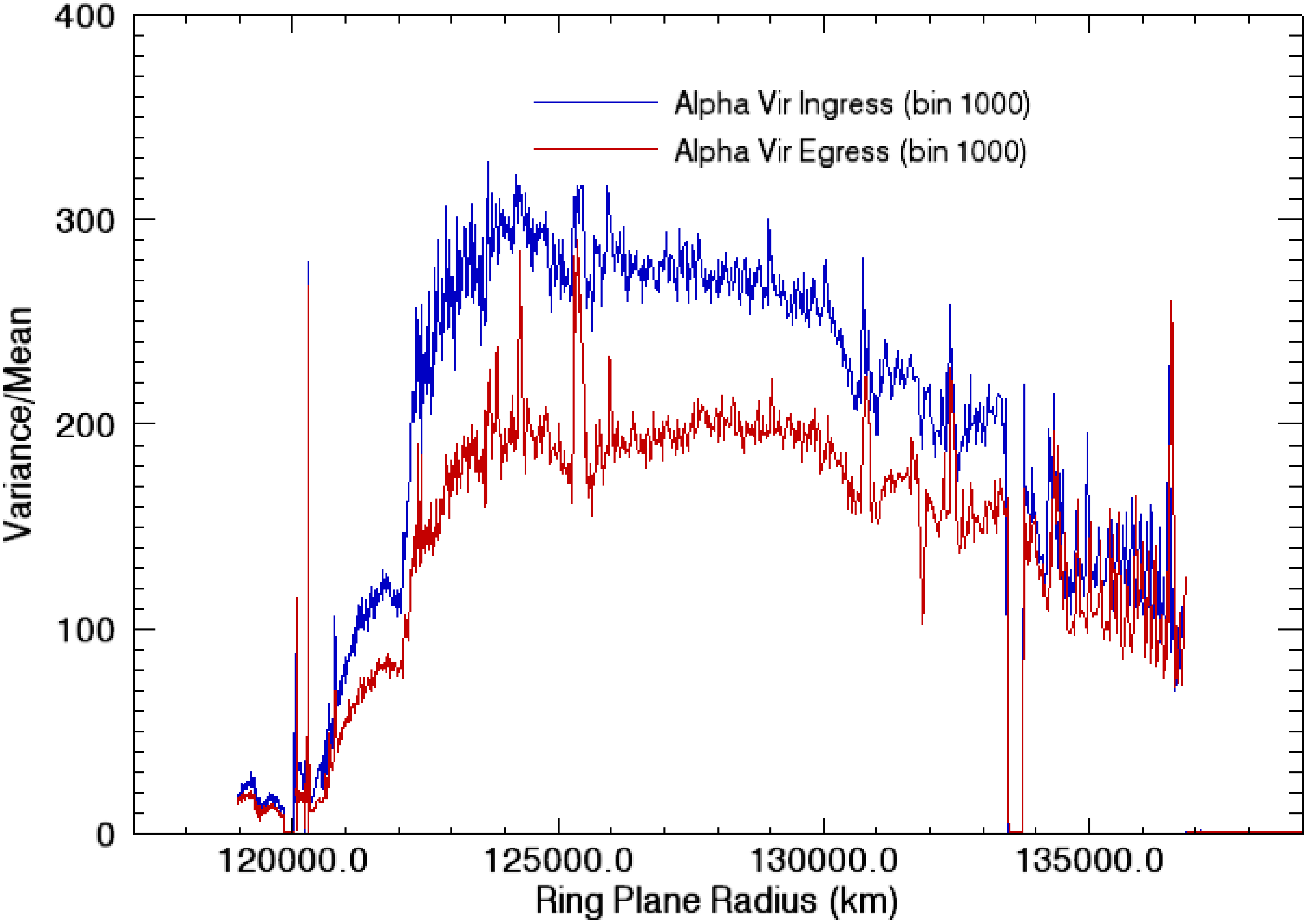
Expected and Measured Variance



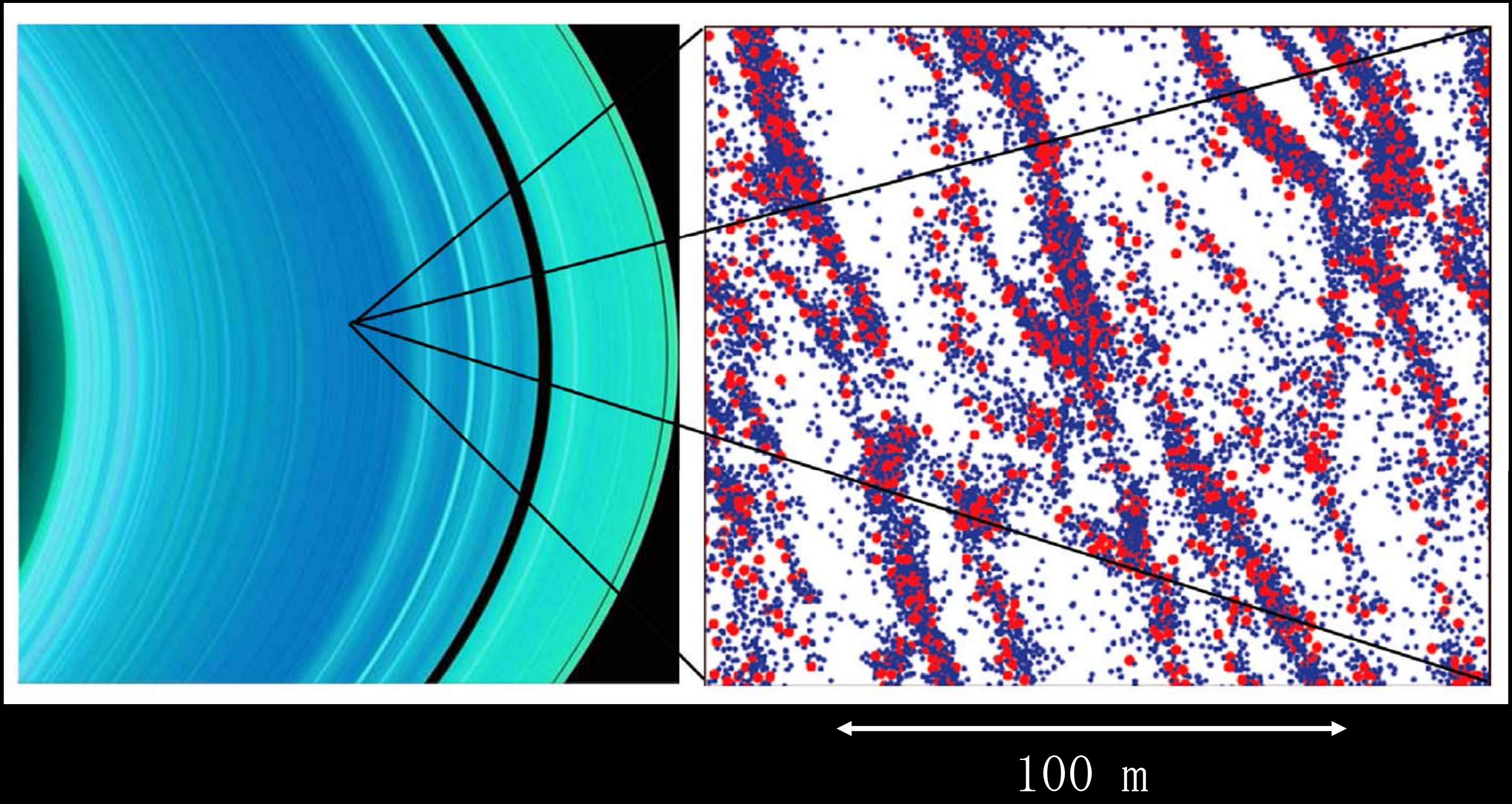
Expected and Measured Variance



Measuring 3D Structure of Clumps



Blue represents larger clusters of particles.
Bright represents higher opacity.

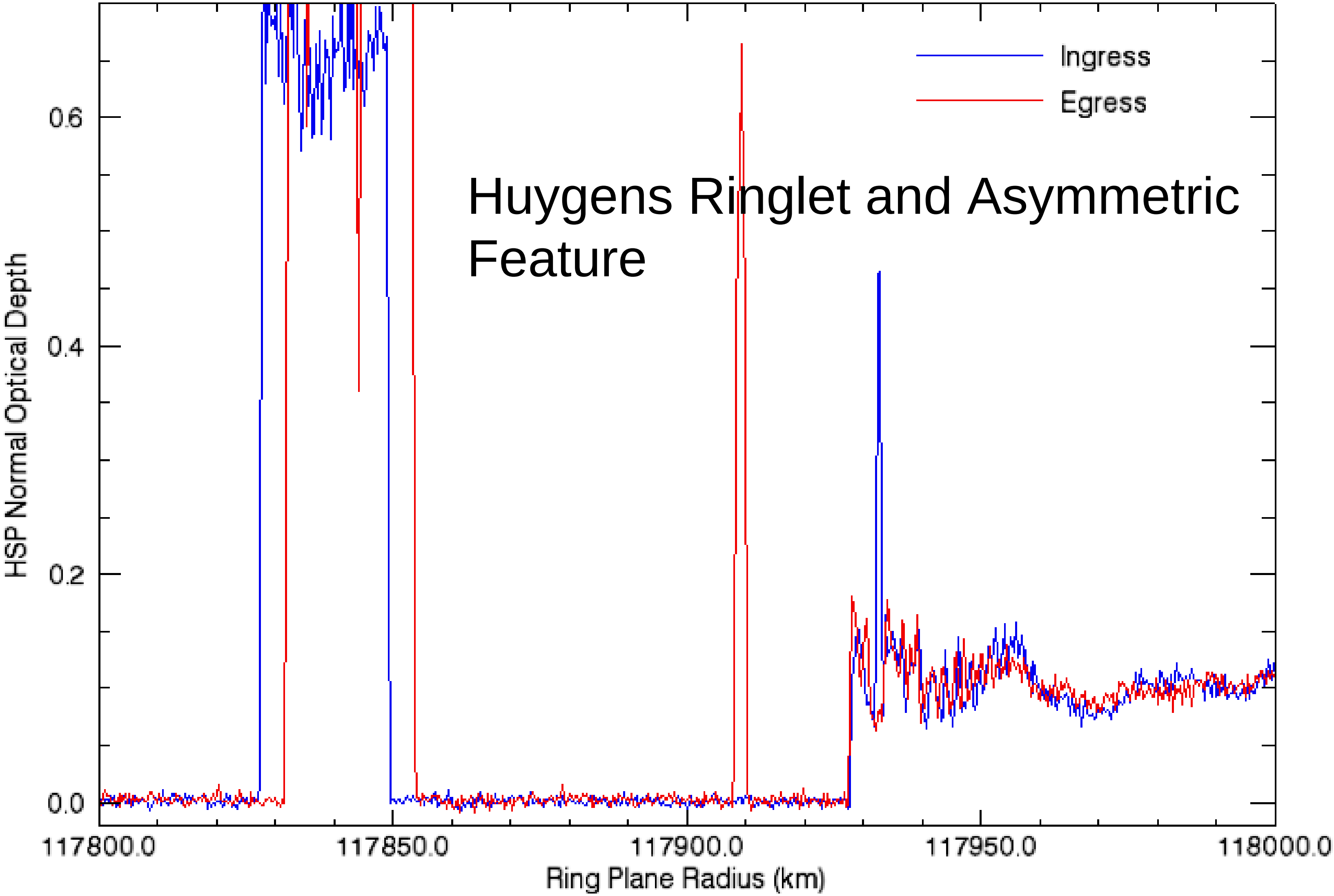


Simulation: John Weiss and Glen Stewart

Self-Gravity Wake Summary

- Self-gravity wakes are highly flattened (H/W~0.2) and relatively closely packed (Separation ~ Width).
- Inter-wake space is nearly empty (τ~0.1).
- Self-gravity wakes become less regular and organized in outer A ring (lower surface mass density).
- Auto-correlation lengths consistent with N-body simulations.
- Strong density waves disrupt wakes.

Huygens Ringlet and Asymmetric Feature



Huygens Ringlet and Asymmetric Feature