Predator-Prey Model for Haloes in Saturn's Rings

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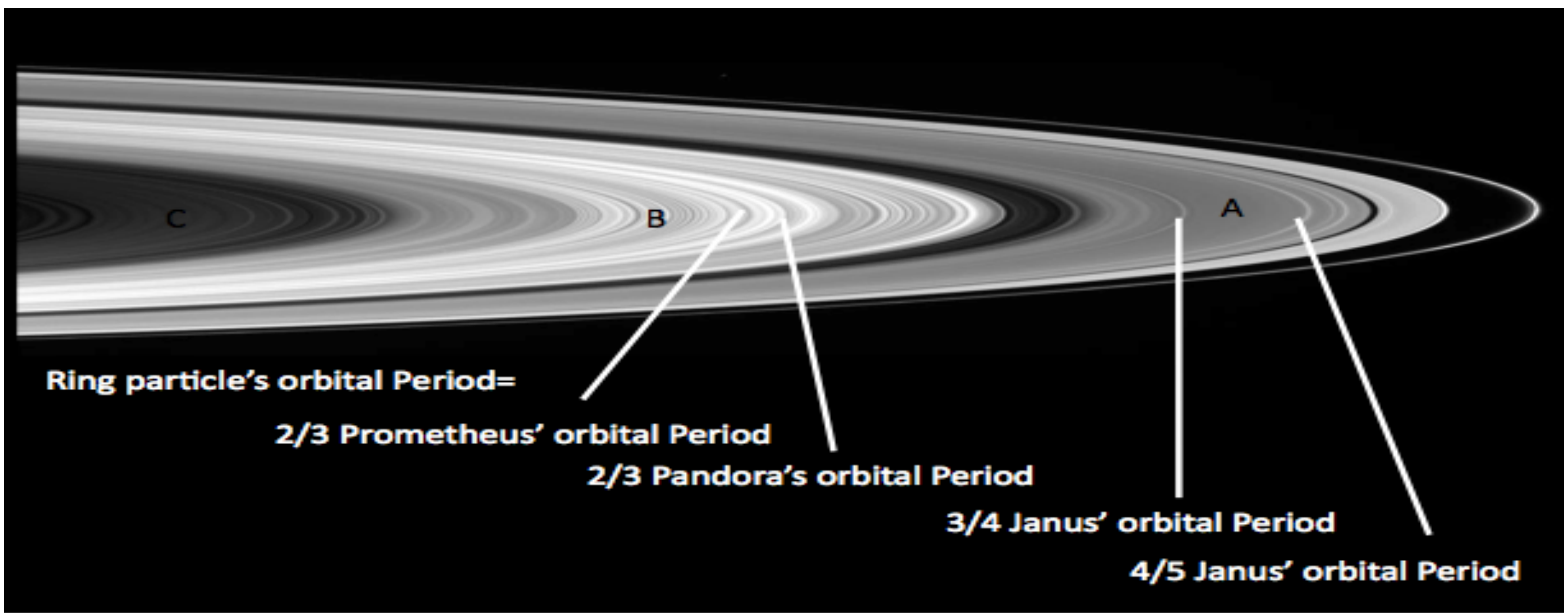
Cassini Observed 'Haloes' in Saturn's A Ring

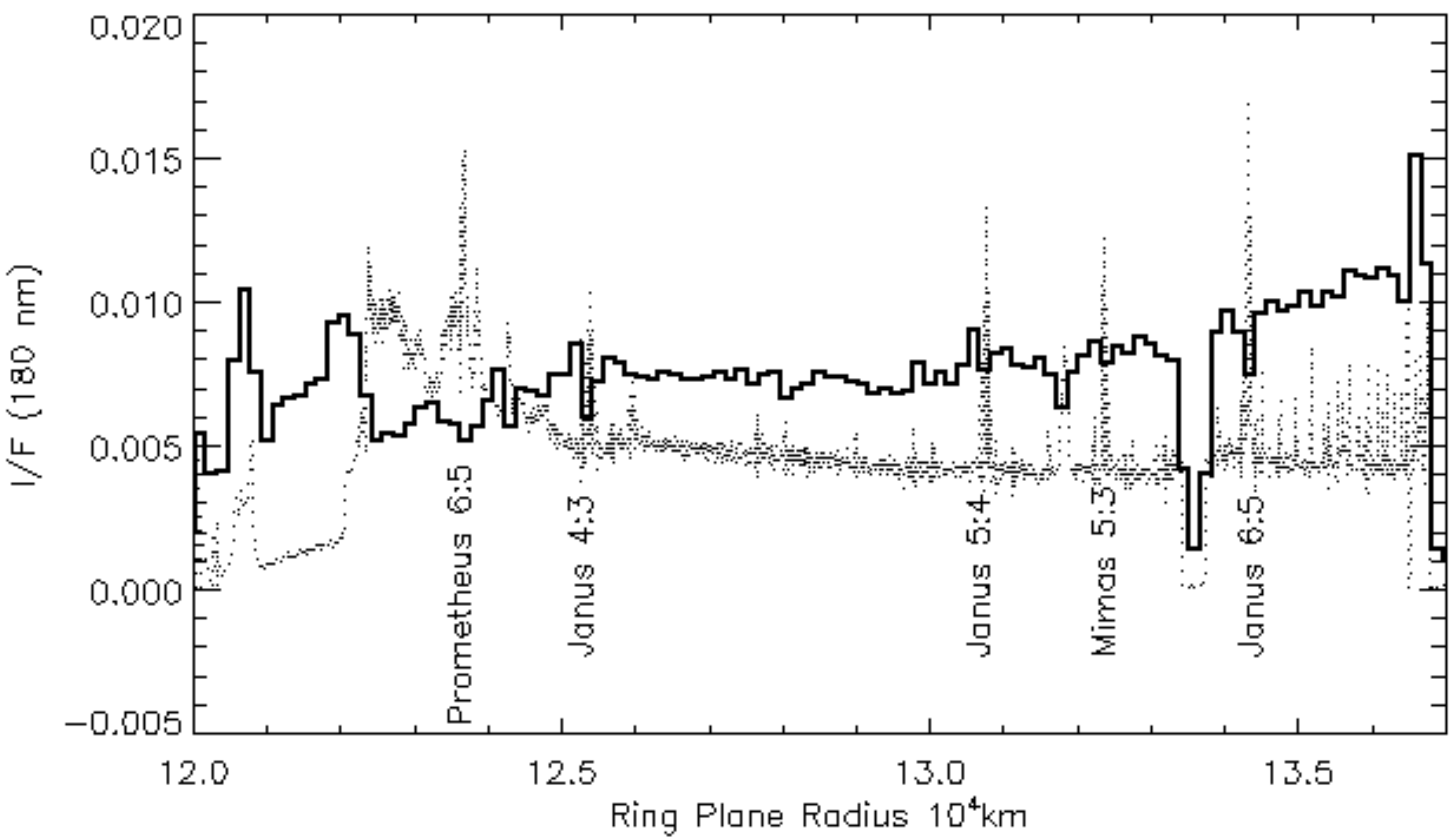
- Annuli of increased brightness were seen by VIMS and UVIS at Saturn Orbit Insertion
- Found at strongest density waves, but not at Mimas 5:3 bending wave



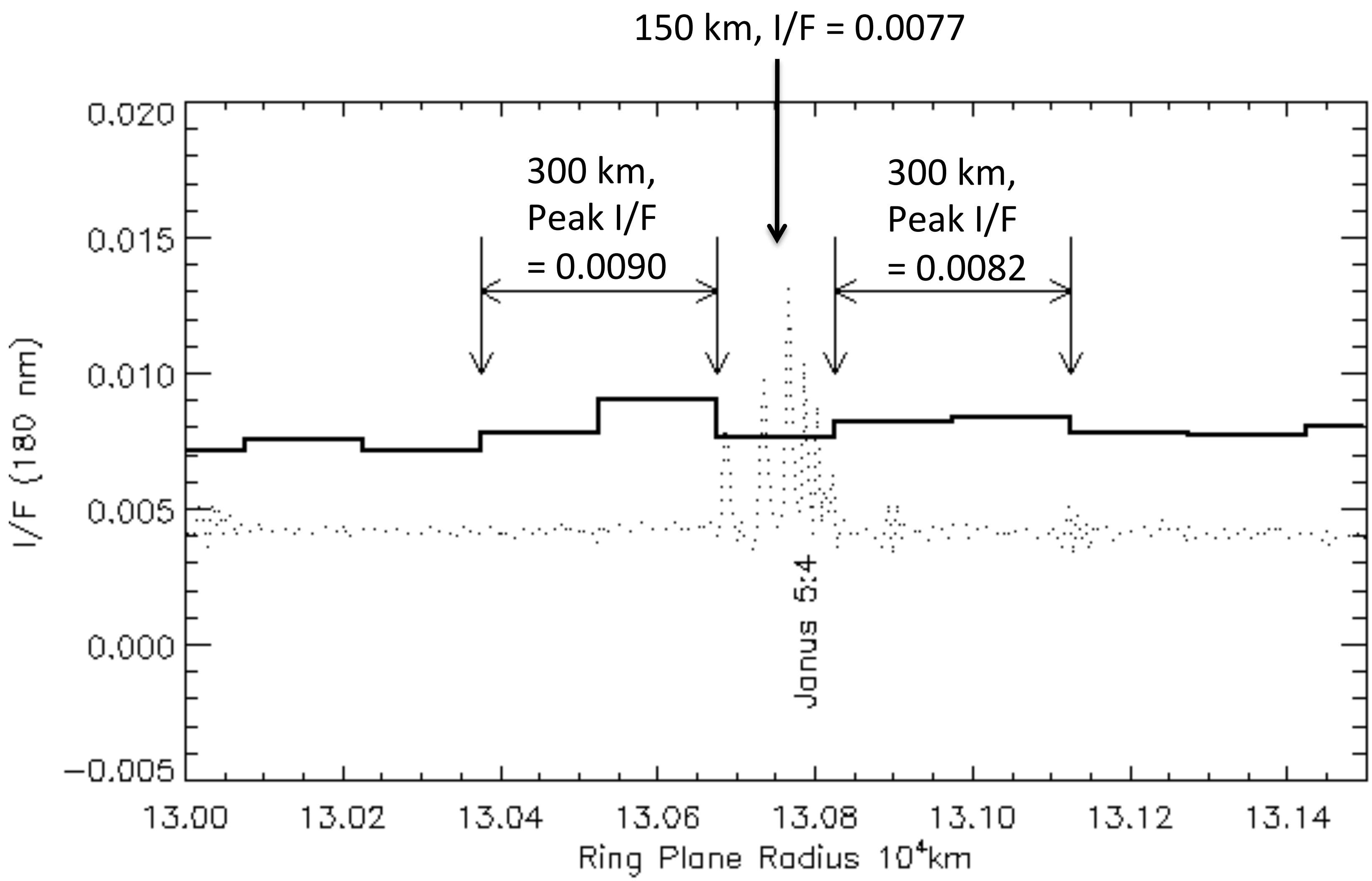
Halo Morphology

- UVIS & VIMS: centered about 100km outside the resonance, a bright region extending about 450 km away from the center;
- VIMS sees a region of increased grain size, with a half-width of about 100km, and smaller grain sizes in symmetric bands about 500 km wide; smallest grain size about 200 km away;
- UVIS sees smaller correlation lengths at the wave location, the lows are coincident with the density wave crests: size distribution changes in hours!
- ISS sees ‘straw’ in the troughs of strong density waves;
- Radio occultations also show a signature (Marouf, private communication).

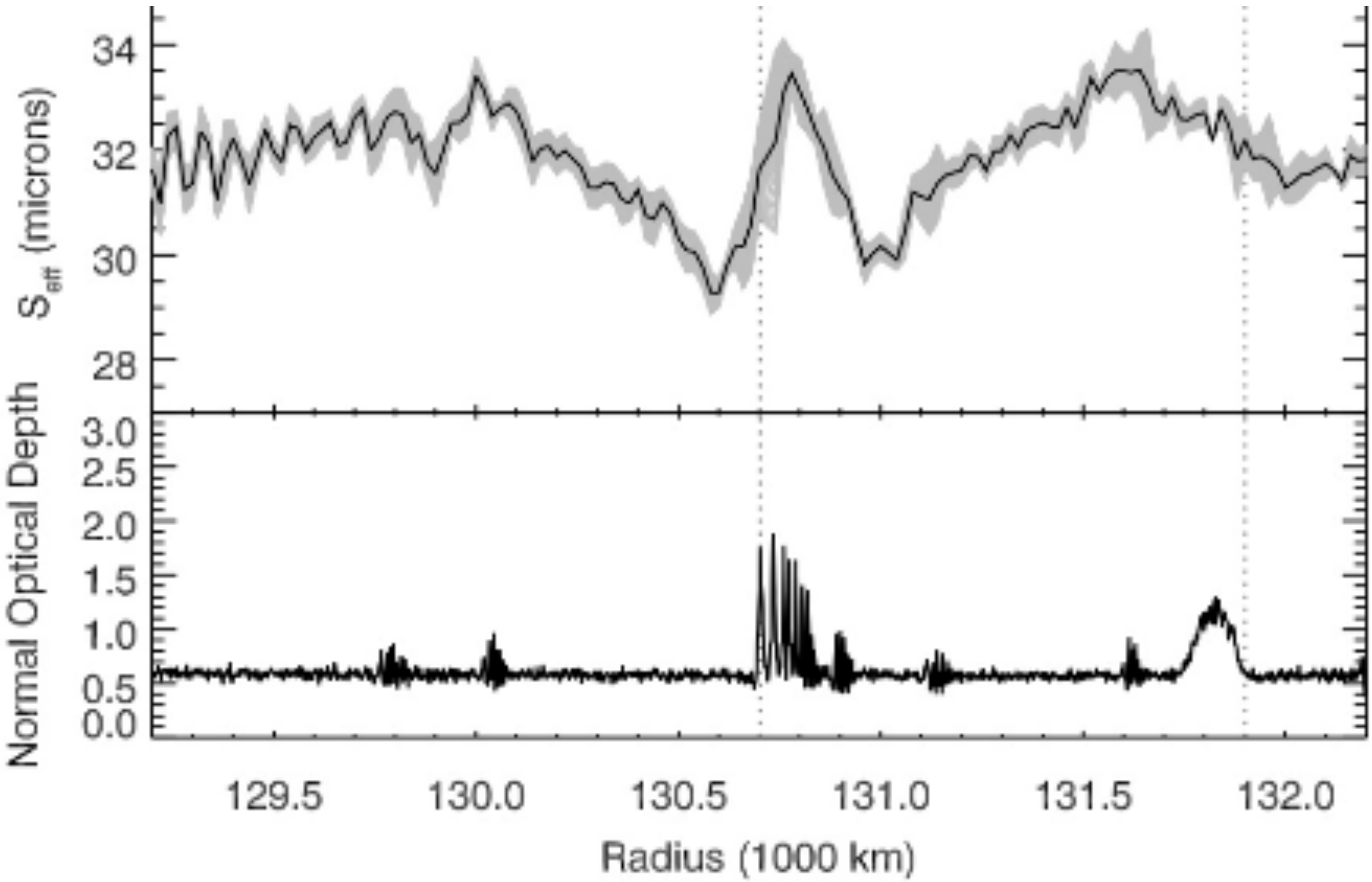
UVIS SOI (150 km resolution elements)



Close-up of UVIS SOI reflectance at Janus 5:4 density wave

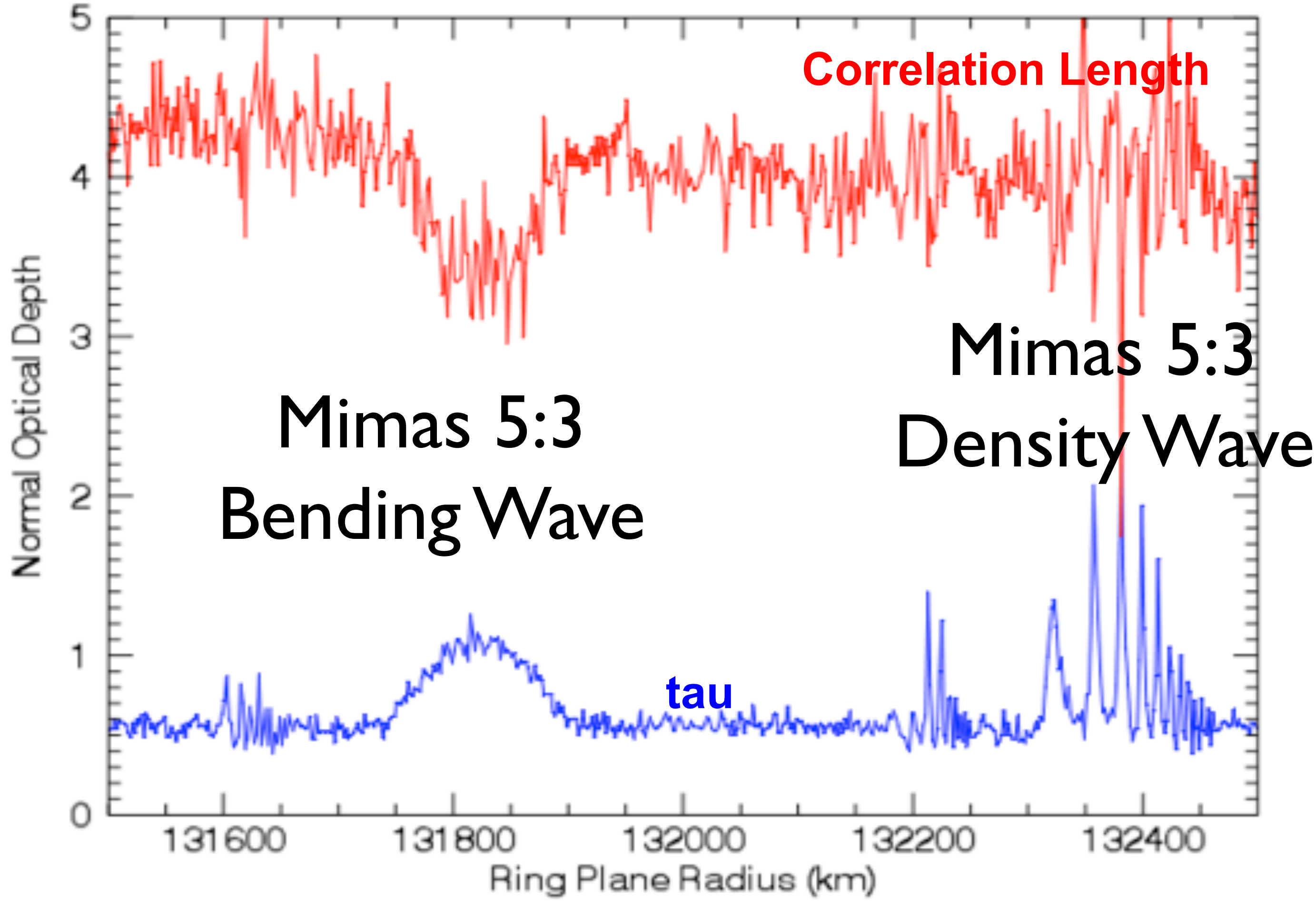


VIMS effective grain size at Janus 5:4 resonance



From Hedman etal Icarus 2013

Particle Scale in Waves



From Colwell etal 2013

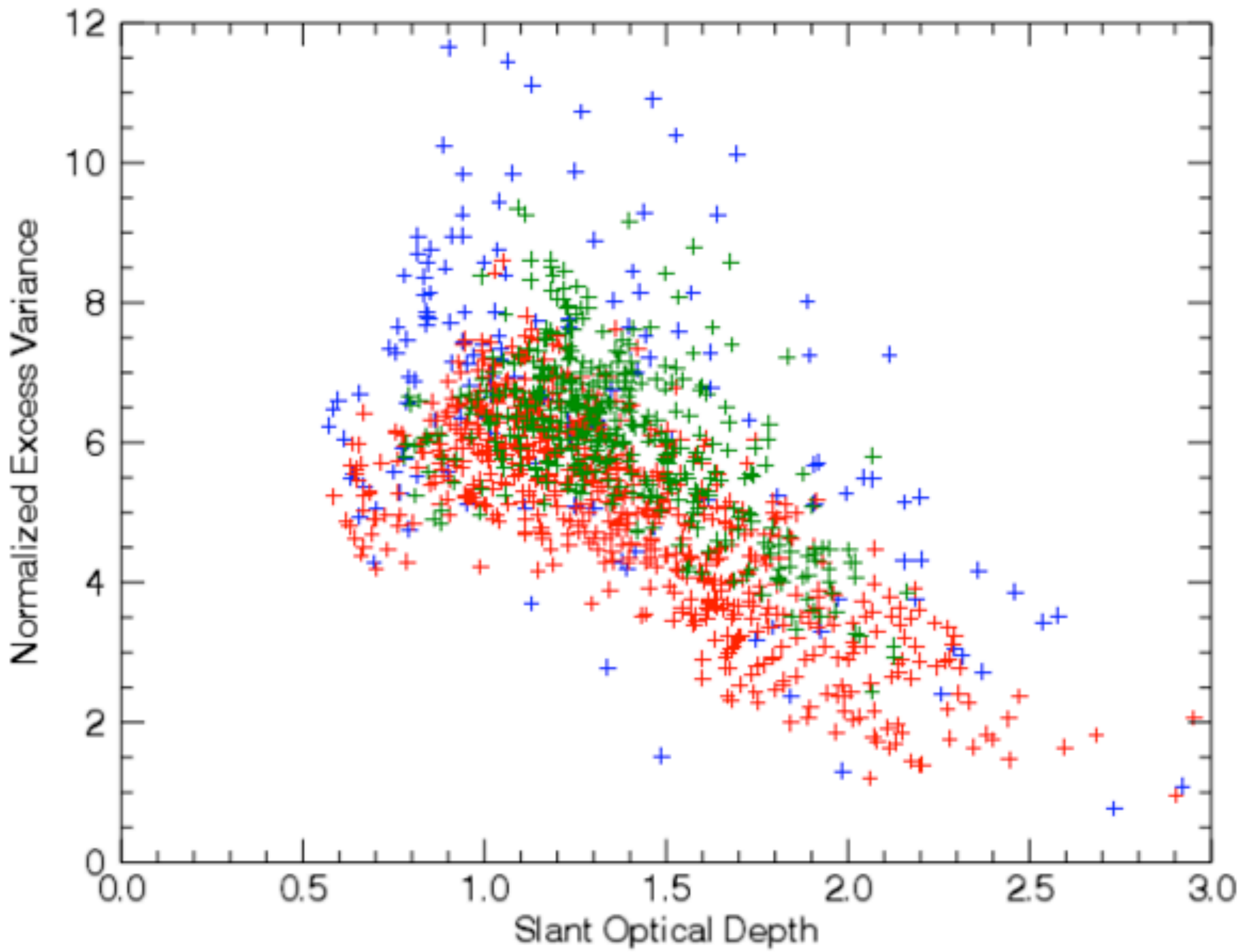
We See Both Smaller and Larger Correlation Lengths in Density Waves

- Inferred sizes from excess variance are anti-correlated with optical depth, as predicted in the Predator-Prey model for moonlet-triggered accretion: mass aggregates and peak collision velocity are out of phase
- Straw in SOI images between the wave crests
- The Janus 2:1 density wave region shows both larger and smaller particles than in nearby comparable regions in the B ring

Janus 2:1 DW

Blue points: Janus 2:1 DW

Red and green points: "red bands"



What's to Explain?

- Connection to strongest resonances *[Predator-prey model of moon-triggered accretion]*
- Halo morphology: Width, shape, why they are centered outside resonance *[Stirring by aggregates, transport and diffusion]*
- Photometry: Brighter in UV, visible, IR *[Production of new grains on exposed surfaces]*
- Spectroscopy: Larger particles in VIMS spectra, surrounded by smaller particles at greater distances *[Aggregate stirring, grain production and transport]*

Predator-Prey Model: Use this to simplify ring dynamics

- Periodic forcing from the moon causes streamline crowding
- This damps the relative velocity, and allows aggregates to grow
- About a quarter phase later, the aggregates stir the system to higher relative velocity
- The limit cycle repeats each orbit, with relative velocity ranging from nearly zero to a multiple of the orbit average: 2-10x is possible

Predator-Prey Equations for Ring Clumping

$M = \int n(m)\, m^2\, dm \;/\; \langle M \rangle;$

$V_{rel}^2 = \int n(m)\, V_{rel}^2\, dm \;/\; N$

$dM/dt = \quad M/T_{acc} \qquad - V_{rel}^2/v_{th}^2\, M/T_{coll}$

[accretion] *[fragmentation/erosion]*

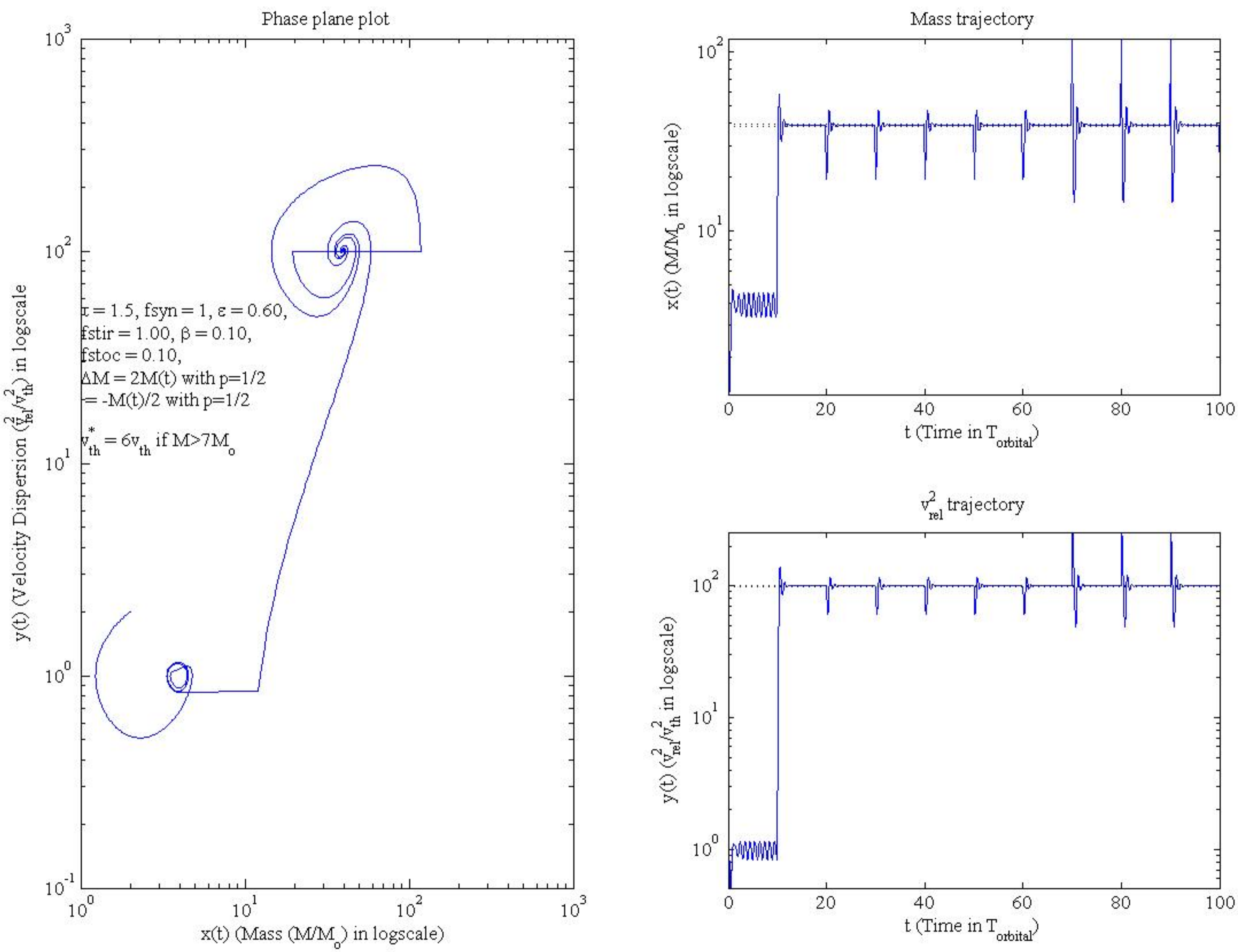
$dV_{rel}^2/dt = -(1-\varepsilon^2)V_{rel}^2/T_{coll} + (M/M_0)^2\, V_{esc}^2/T_{stir}$

[dissipation] *[gravitational stirring]*

$- A_0 \cos(\omega t)$ *[forcing by streamline crowding]*

Upgrades to Predator-Prey Model: Collisions among Ring Particles

- Add stochastic forcing to simulate aggregate collisions: Random outcome doubles or halves aggregate mass. Previously, no collisions.
- Add threshold for gravity-bound aggregates: above this it is harder to disrupt aggregates. Previously, erosion of aggregates from Blum (2007). Results in higher collisions speeds!
- This allows us to find the fixed points, their stability, basins of attraction, and asymptotic behavior, not easy for N-body codes



Gravity-dominated clumps give a new fixed point

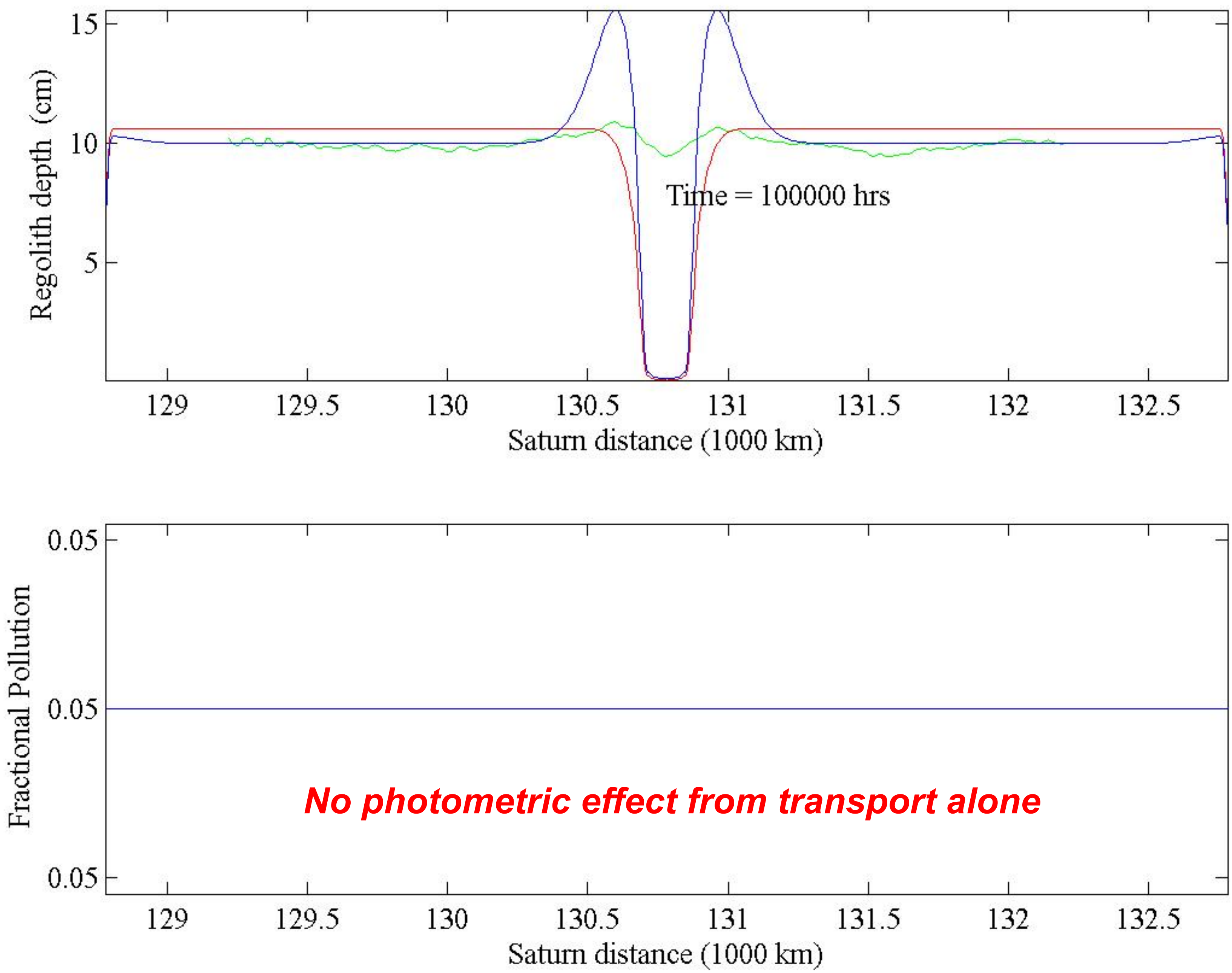
Transport Model: Collisions cause thermal diffusion; Model this, following Feller (1971)

- Random walk on the line, with particle jumps distance Δx_j, every time step ΔT.
- In the production region (where we observe the density wave damping, $\pm x_D$~100km), mean Δx_j= 200km, ΔT= 100 T_{orb}
- Outside the production region, we set mean Δx_j= 0.5km
- The jumps are drawn from a Gaussian distribution

Effects of Transport

- The higher collision velocity arises from stirring by aggregates, whose formation is triggered by streamline crowding in the wave, as hypothesized in the Predator-Prey model
- Gravitationally bound aggregates can form, which provide even higher peak velocities, up to 10 m/s near them
- This preferentially removes the regolith in the production region, exposing fresh ice surfaces to collisions and meteoritic bombardment, as in the model of Elliott and Esposito

Transport but no production

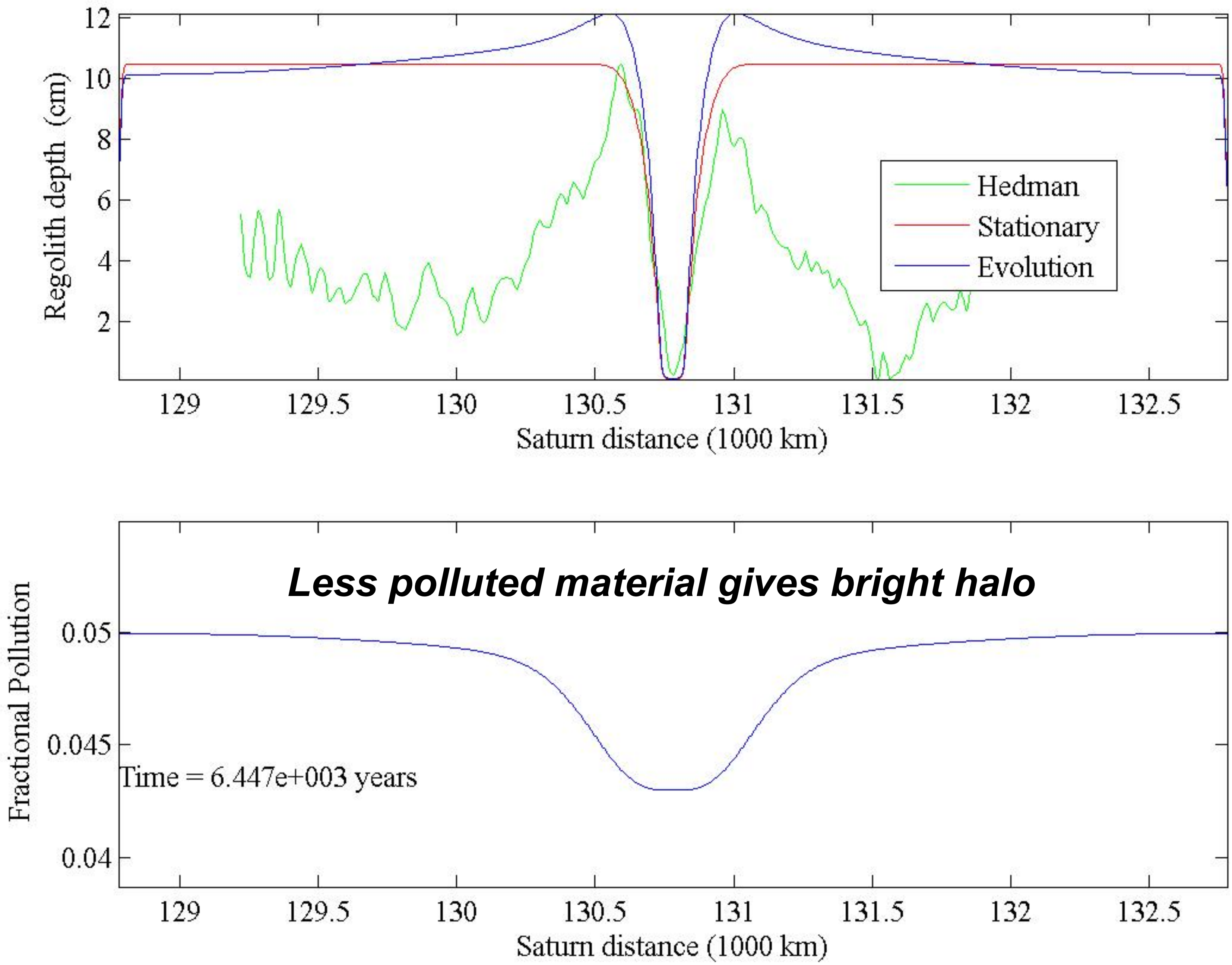


Production Model

- Meteorites produce new regolith material if the regolith is thin enough, $h(r,t) < h_{threshold}$.
- This fresh material is then transported by the Brownian motion random walk transport
- We assume an initial regolith depth of 10cm, with pollution of 5% (Elliott and Esposito)
- We assume complete vertical mixing after each transport, and track the pollution to predict the reflectivity profile of the halo

Model results: We can fit the UVIS and VIMS morphology if

- Perturbation centered 100km outside the ILR: this is the location of max damping, see X_D from Esposito 1983
- Jump distance for Brownian motion is 200km, corresponding to V_{ej} = 10m/sec
- Production rate is 10^{-4} cm/yr
- Diffusion in A ring back ground region is small: $100cm^2$/sec, corresponds to jump distance 200m in $\Delta T=100T_{orb}= 4.8x10^6$sec


Regolith depth (cm)
12
10
8
6
4
2
Hedman
Stationary
Evolution
129
129.5
130
130.5
131
131.5
132
132.5
Saturn distance (1000 km)
Less polluted material gives bright halo
Fractional Pollution
0.05
0.045
0.04
Time = 6.447e+003 years
129
129.5
130
130.5
131
131.5
132
132.5
Saturn distance (1000 km)

Summary

- A predator-prey model for ring dynamics produces transient structures like 'straw' that can explain the halo structure and spectroscopy:
  - Cyclic velocity changes cause perturbed regions to reach higher collision speeds at some orbital phases, which preferentially removes small regolith particles
  - Surrounding particles diffuse back too slowly to erase the effect: this gives the halo morphology
- This requires energetic collisions ($v \approx 10$m/sec, with throw distances about 200km, implying objects of scale $R \approx 20$km)

Ring dynamics and history implications

- Moon-triggered clumping at perturbed regions in Saturn's rings creates both high velocity dispersion and large aggregates at these distances, explaining both small and large particles observed there
- This confirms the triple architecture of ring particles: a broad size distribution of particles; aggregate into temporary rubble piles; coated by a regolith of dust
- Aggregates can explain many dynamic aspects of the rings and can renew rings by shielding and recycling the material within them