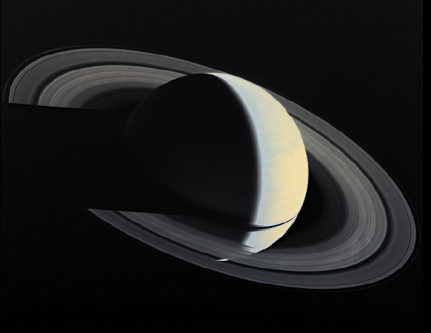
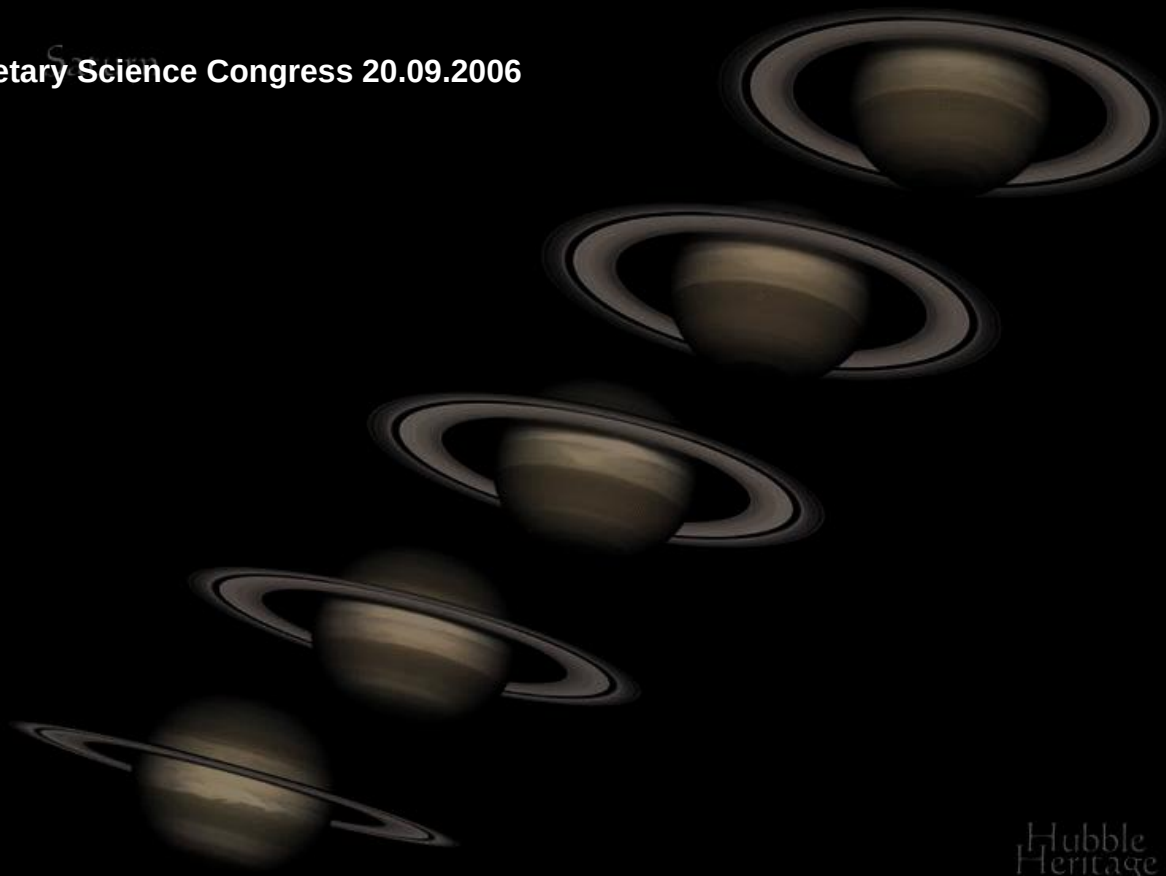
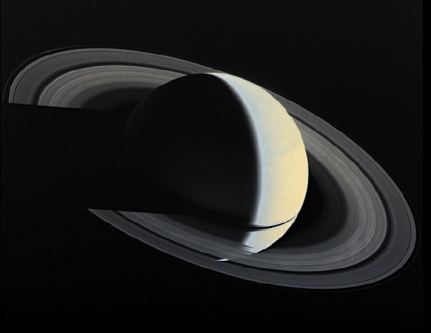


Numerical Survey of
Self-gravity wakes in Saturn's rings

Heikki Salo (Oulu, Finland)

European Planetary Science Congress 20.09.2006





TOPICS

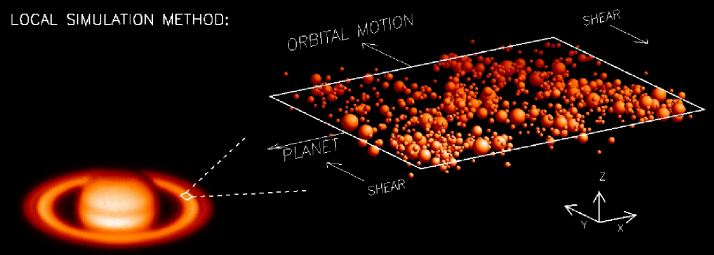
- What are self-gravity wakes?
- Why to call them *WAKES?*
- How do they manifest in observations?

Collaborators:

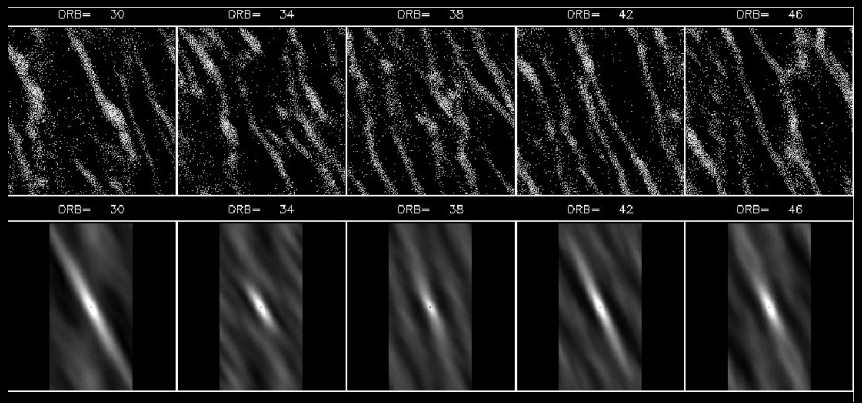
* **Dynamics of dense rings:** J. Schmidt, F. Spahn (Potsdam)
* **Modeling of Voyager, HST, Arecibo, VIMS data:** R. French (Wellesley), P. Nicholson (Cornell)

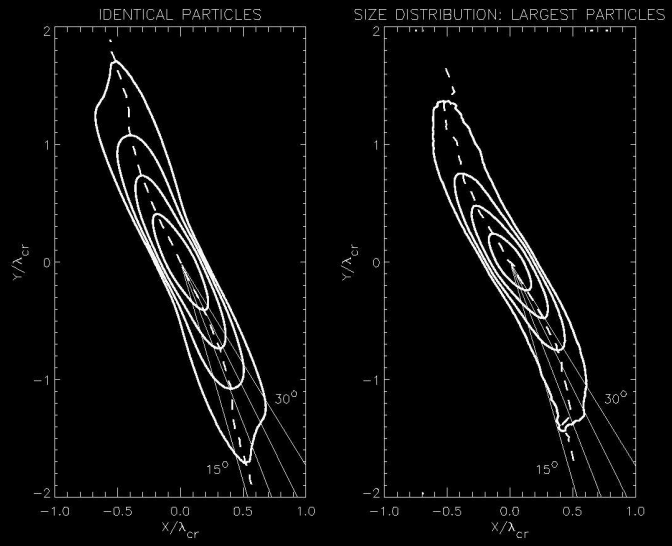
Methods:

* **N-body simulations** (Salo 1992, Nature)
* **Monte Carlo ray tracing calculations** (Salo et al. 2004 Icarus 170)



WHY WAKES?





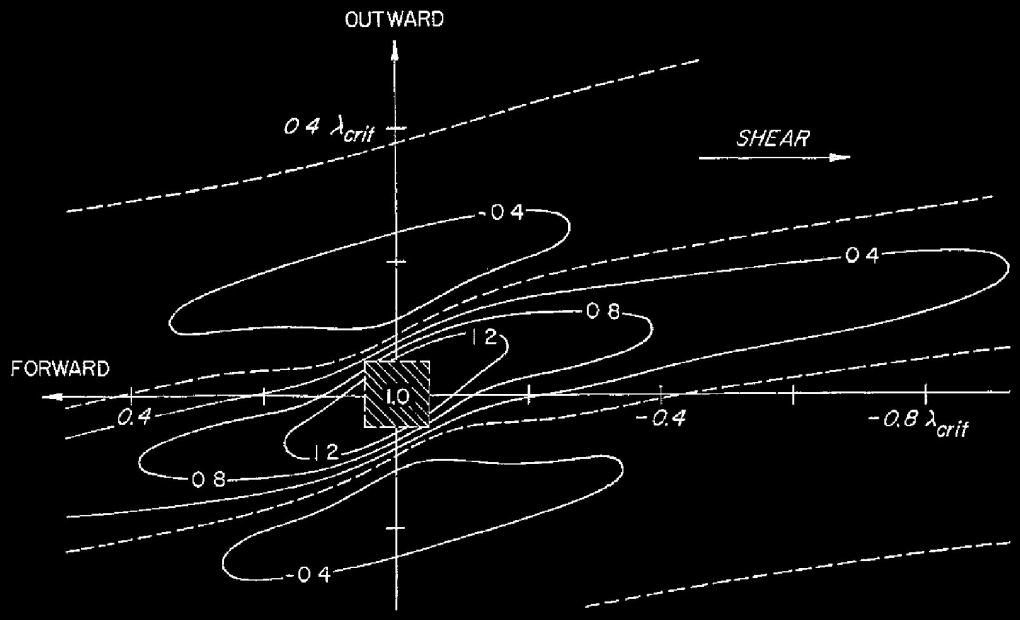


FIG 9 —Same as Fig 7, except Γ = 1 5 (i e , a locally Keplerian rotation law)

ANALOGUES TO JULIAN & TOOMRE (1966) WAKES

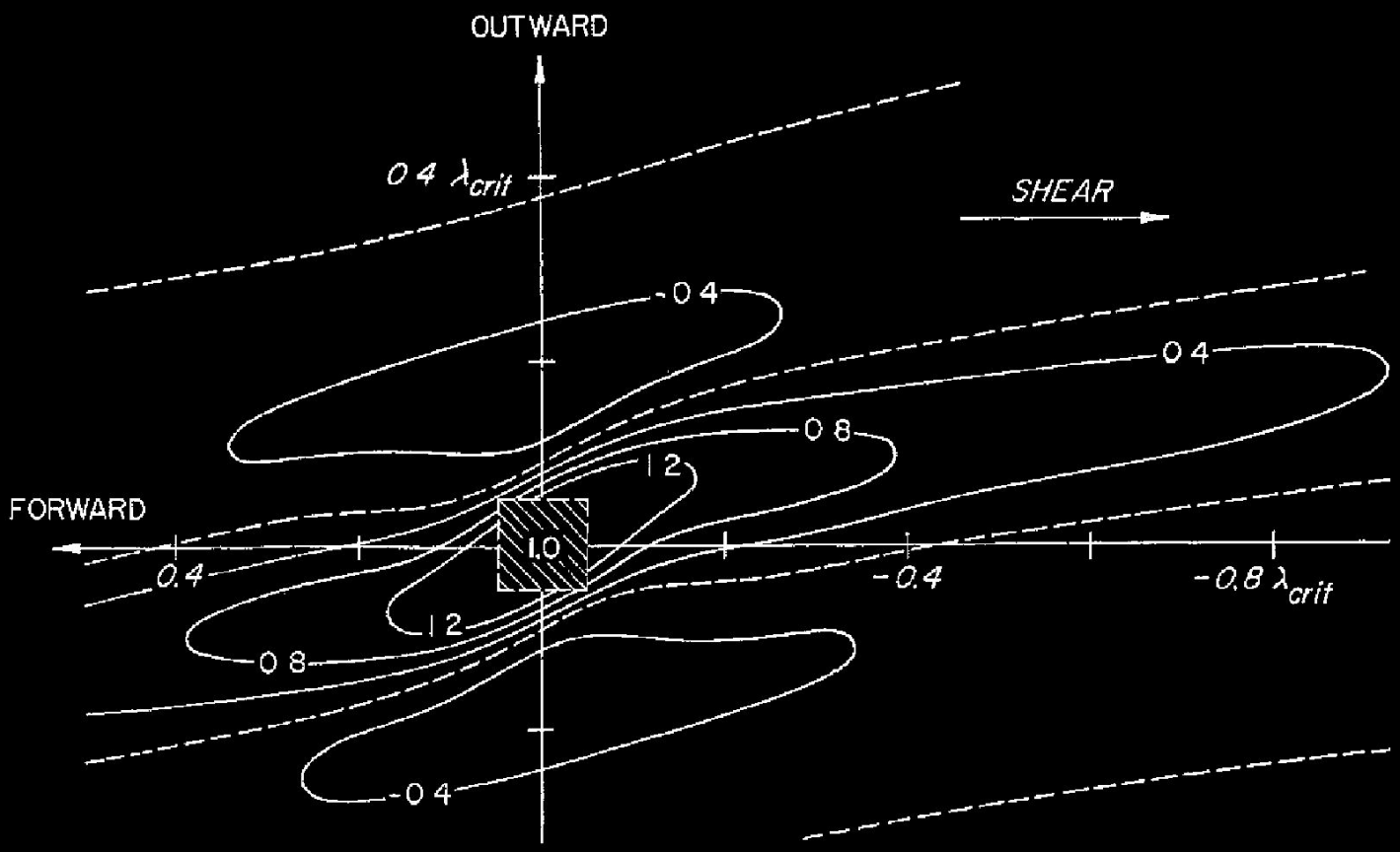
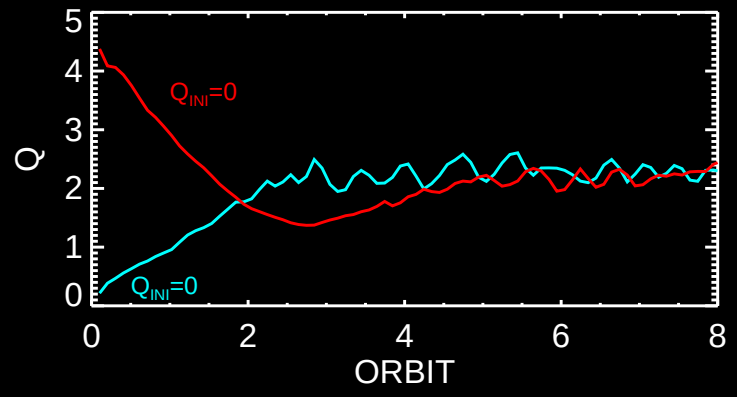
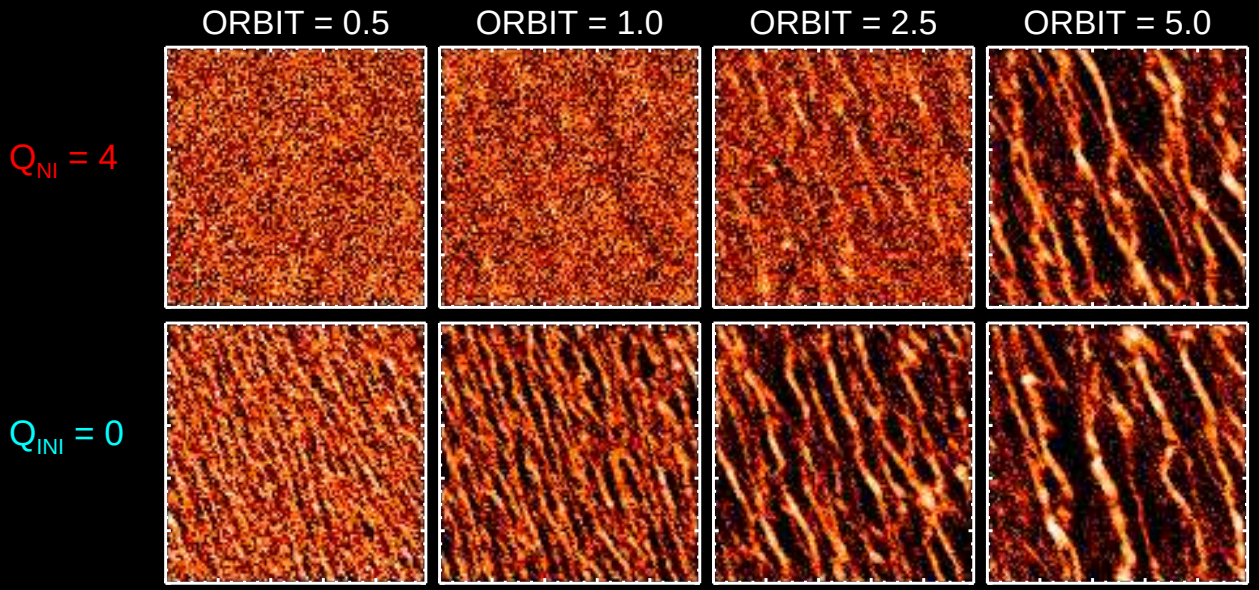


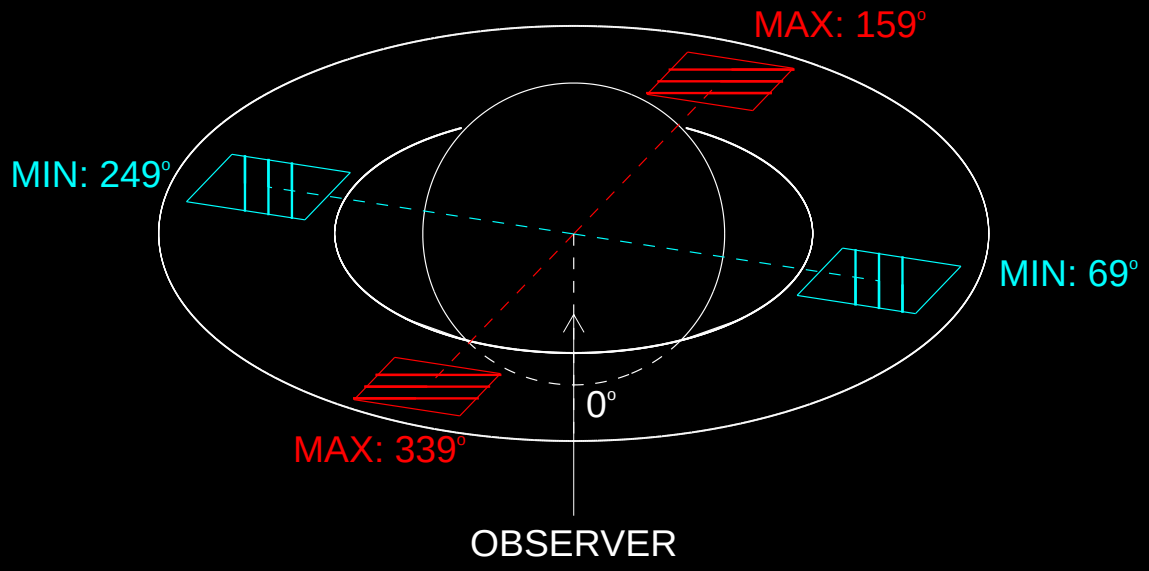
FIG 9 —Same as Fig 7, except $\Gamma = 1.5$ (i e , a locally Keplerian rotation law)

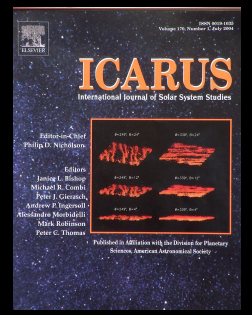
EVOLUTION FROM HOT/COLD INITIAL STATE





WAKES AT DIFFERENT LONGITUDES

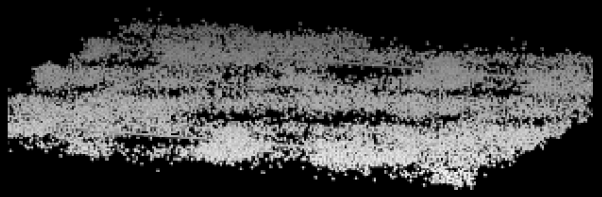




θ=249°, B=12°

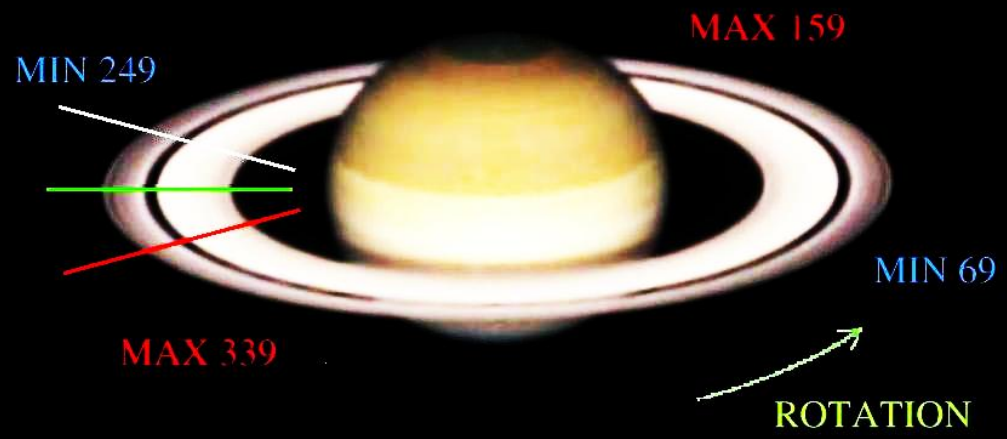
θ=339°, B=12°

MINIMUM: VIEWING ALONG WAKES

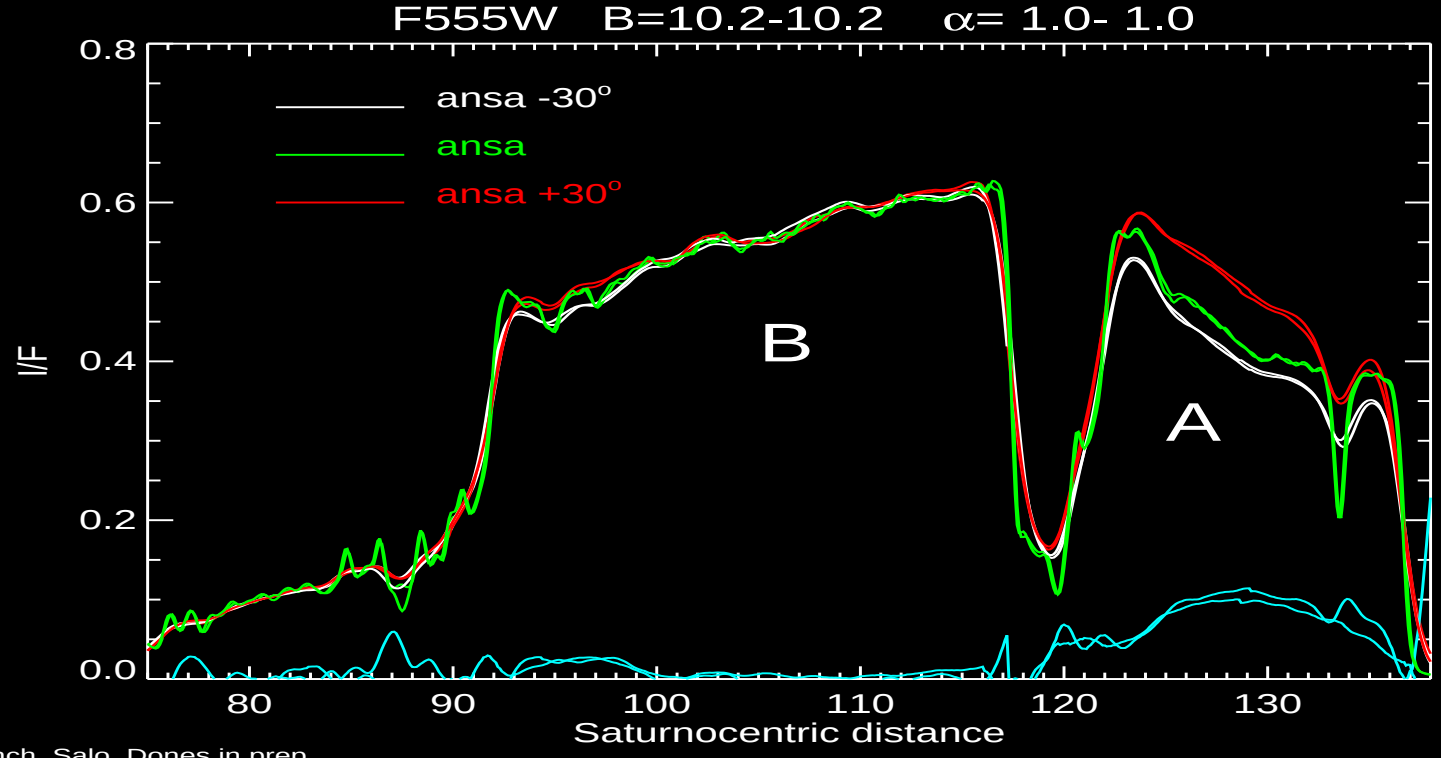


MAXIMUM: WAKES VIEWED PERPENDICULARLY

AZIMUTHAL BRIGHTNESS ASYMMETRY:



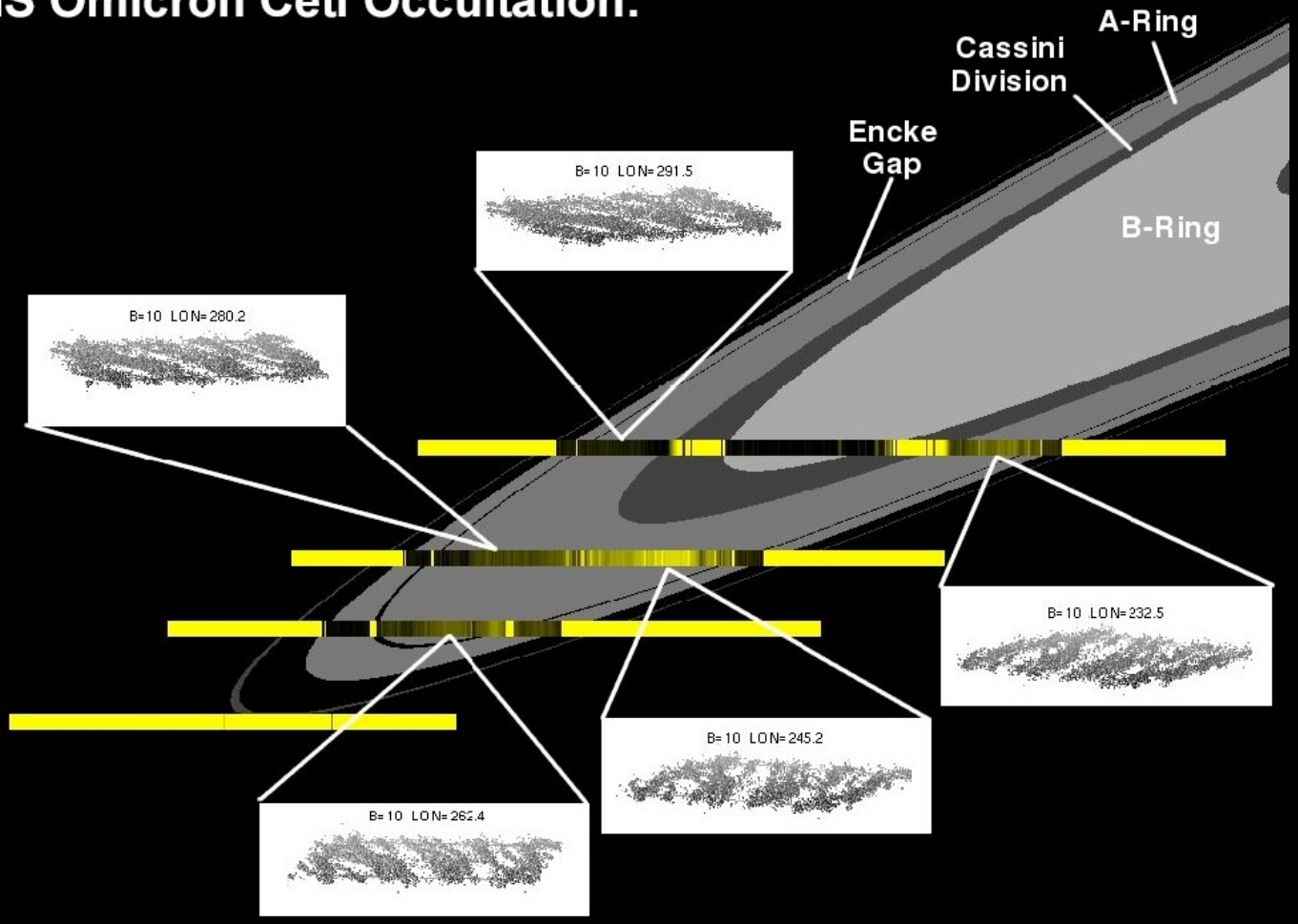
HST



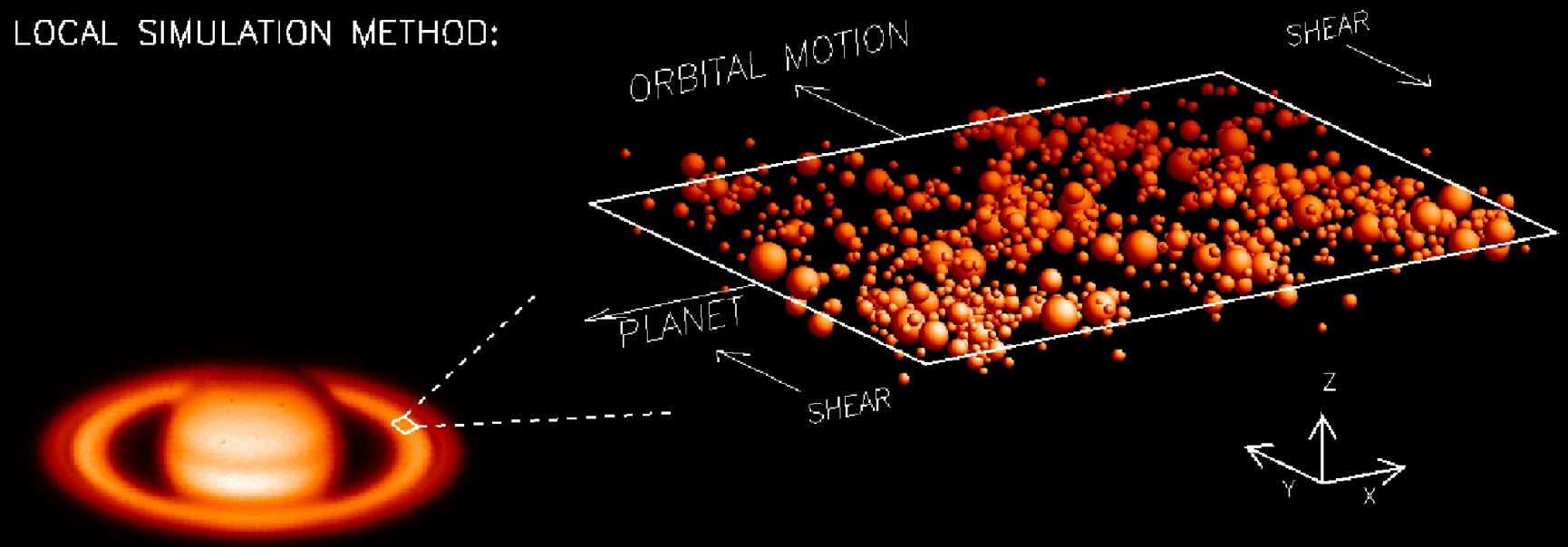
French, Salo, Dones in prep.

OPTICAL DEPTH DEPENDS ON RING LONGITUDE:

VIMS Omicron Ceti Occultation:



N-BODY SIMULATIONS



- **CO-MOVING CALCULATION REGION**
- **PERIODIC BOUNDARY CONDITIONS accounting for shear (Wisdom & Tremaine 1988, Toomre & Kalnajs 1990)**

- **CALCULATION OF IMPACTS:**

  * **Instantaneous velocity changes**
  * **Force model** (Salo 1995)

- **SELF-GRAVITY:**

  * **nearby pairs: particle-particle method**
  * **distant forces: FFT in shearing coordinates** (Salo et al. 2001)
    up to $N = 60\,000$ self-gravitating, colliding particles

- **APPLIED TO:**

  Study of local steady-state ($L < 100m$) $\rightarrow$ viscosity
  Viscous evolution of small-scale radial structure ($L \sim km$)

LOCAL ENERGY BALANCE

COLLISIONAL DISSIPATION = VISCOUS GAIN

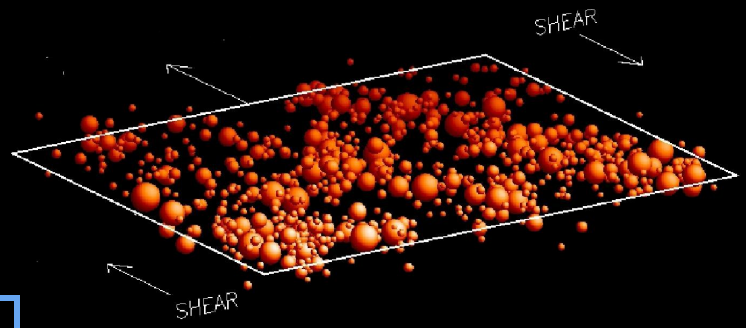
VISCOSITY:

- momentum transfer via radial excursions (local viscosity)
- transfer at physical impacts (nonlocal viscosity)
- transfer via gravitational forces (gravitational viscosity)

ENERGY BALANCE TIME-SCALE: 10-100 impacts/particle

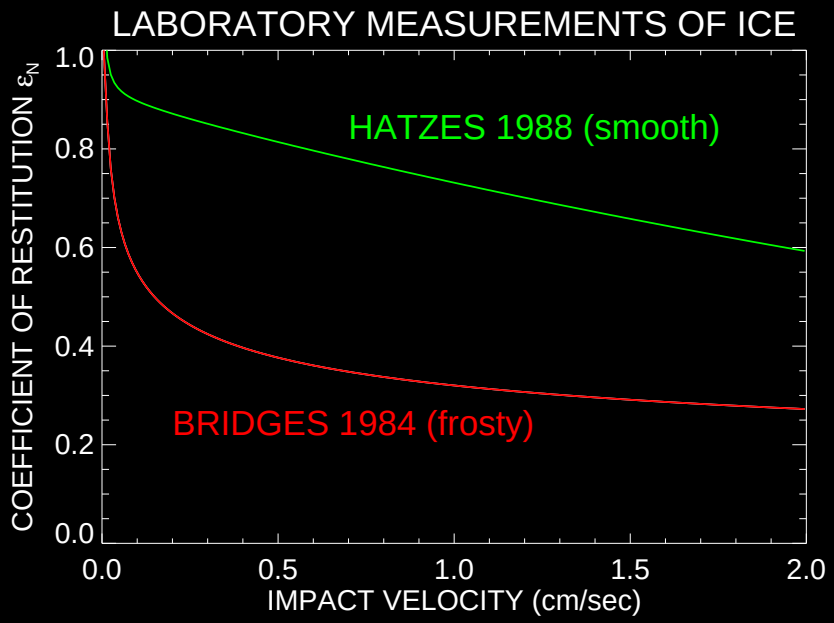
RANDOM VELOCITY, THICKNESS, VISCOSITY depend on:

- elasticity of impacts
- particles internal density
- optical depth
- particle size distribution



⇒ **VISCOSITY vs DENSITY RELATION**

CRUCIAL ROLE OF PARTICLE ELASTICITY



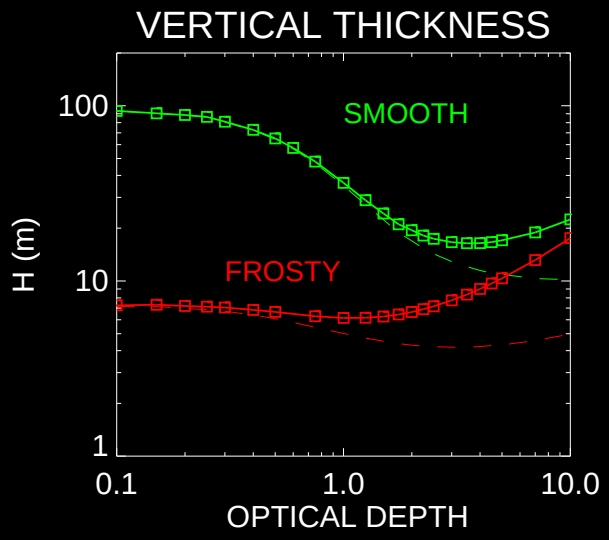
⇒ **'THICK' RING:**

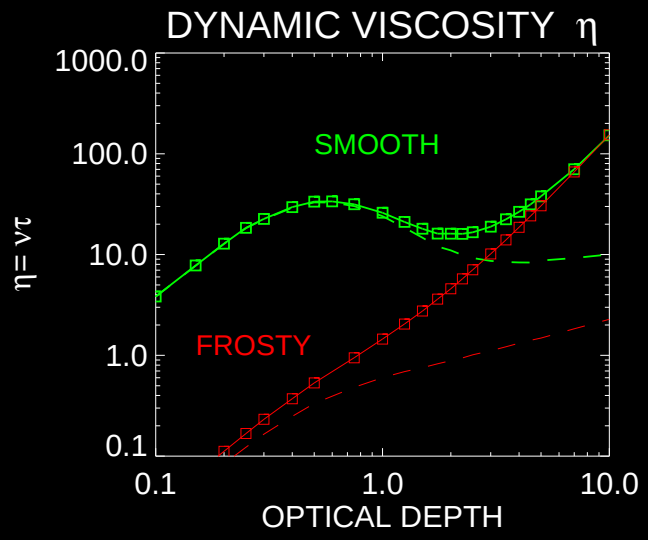
VISCOSITY MAY DECREASE WITH DENSITY

⇒ **FLATTENED RING:**

VISCOSITY INCREASES WITH DENSITY

SELF-GRAVITY ENHANCES THIS TENDENCY





SELF-GRAVITATION I

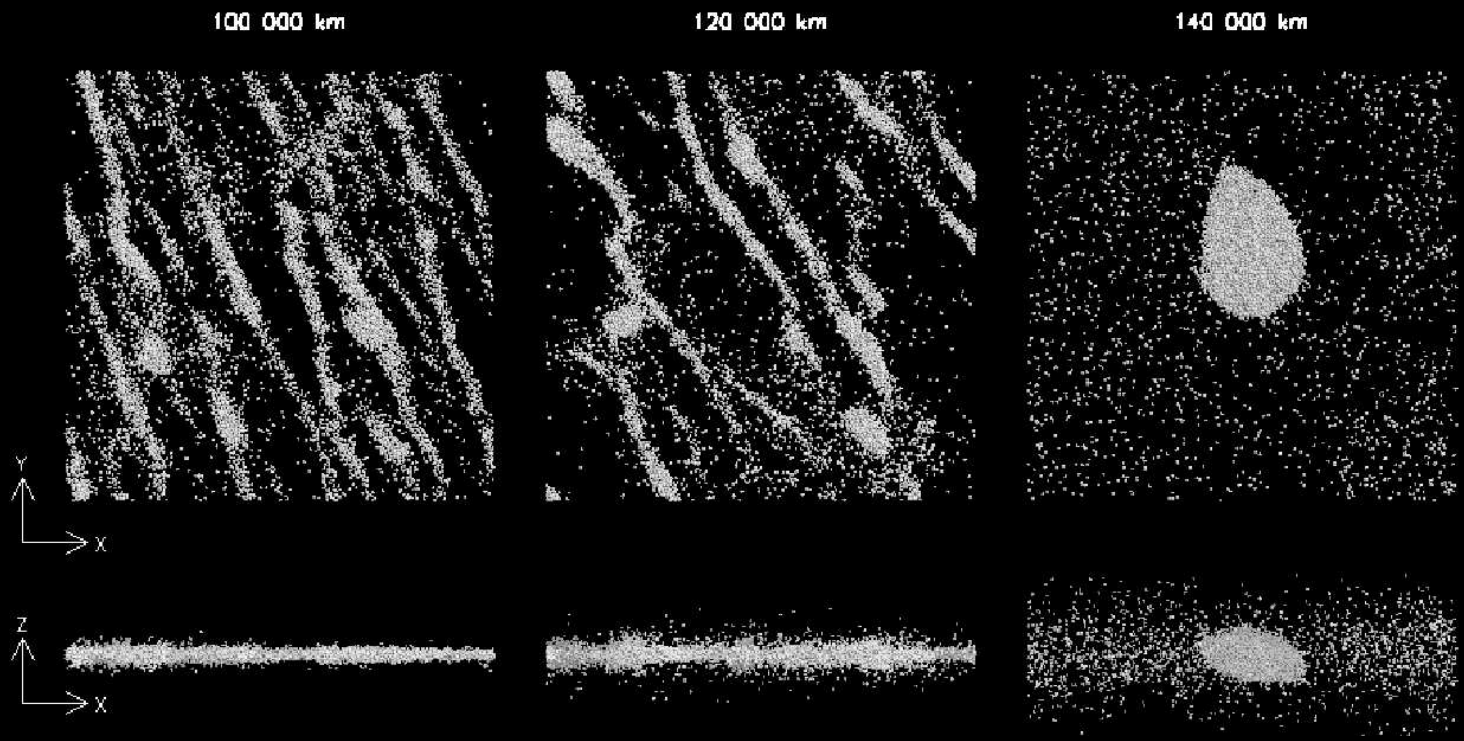
- **AXISYMMETRIC STABILITY (Toomre 1964)**

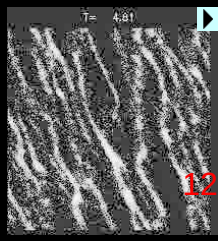
$$Q_T = \frac{c\Omega}{\pi G \Sigma} > 1$$

  $Q_T > 1$ corresponds to $H > 10m$ for $\tau \sim 1$

- **HOW DOES THE NEAR-INSTABILITY MANIFEST IN SHEARING, DISSIPATIVE RING?**

(Salo 1995)





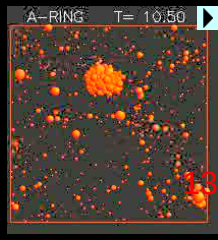
SELF-GRAVITATION II

$\Rightarrow$ **GRAVITATIONAL WAKES IN SATURN'S RINGS**

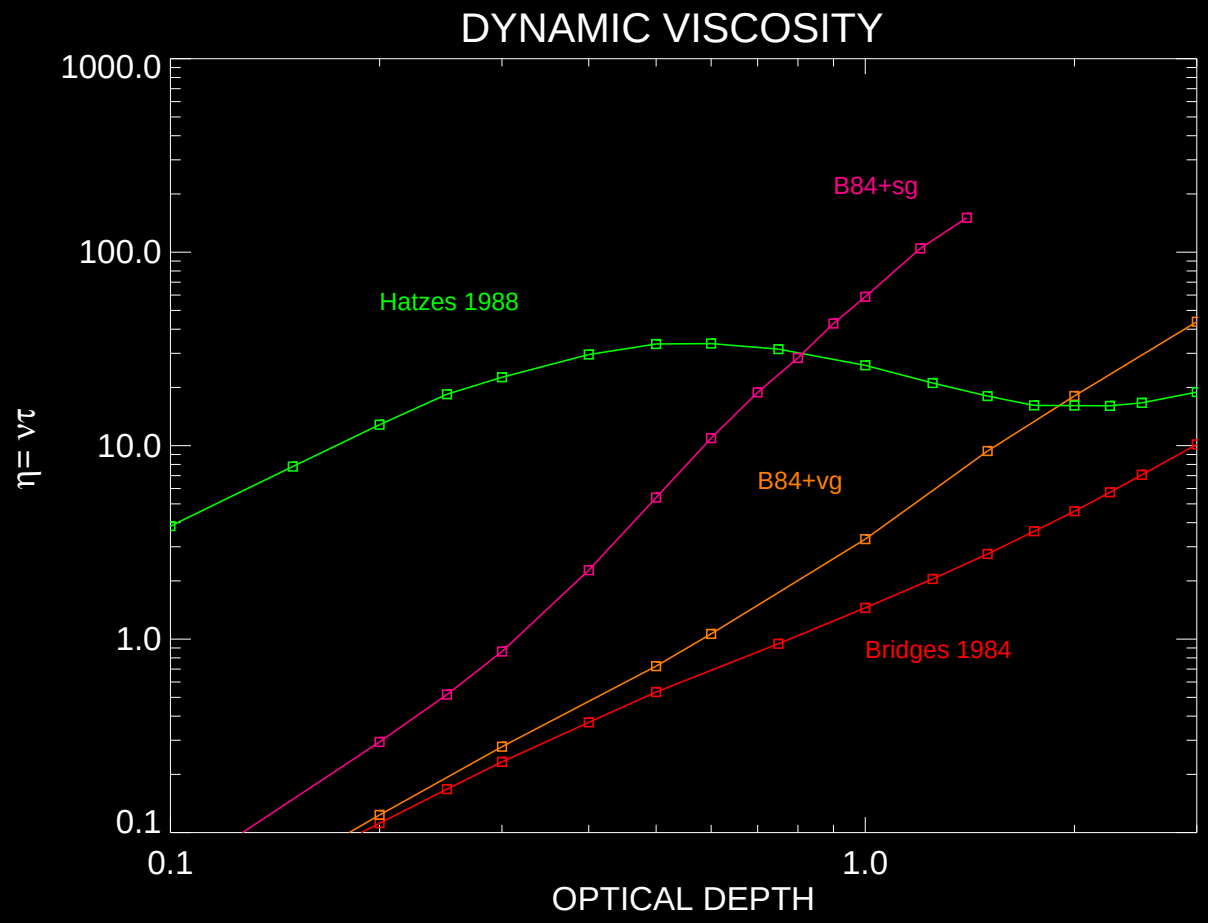
(Salo 1992, in *Nature*)

- Analogous to Julian & Toomre (1966) wakes in stellar systems:
  radial scale: $\lambda_{cr} = 4\pi^2 G\Sigma/\Omega^2 \sim 10 - 100m$ (instead of KPC)
  pitch-angle: $\sim 20^0$ (Keplerian velocity field)
- RINGS: Dissipation balances the heating by wakes
  $\Rightarrow$ statistical steady-state with $< Q_T > \sim 1 - 2$
- WAKES: additional gravitational viscosity $\nu_{grav} \propto \tau^2$
- RING OUTER EDGE WAKES $\Rightarrow$ LOCAL AGGREGATES

DPS-meeting 1992:



GRAVITATIONAL VISCOSITY



HOW TO ESTIMATE THE RING THICKNESS/ PARTICLE ELASTICITY/ VISCOSITY ?

PHOTOMETRIC MODELING OF RINGS

- **RING BRIGHTNESS VS. VIEWING ELEVATION AND PHASE ANGLE (tilt and opposition effects)**

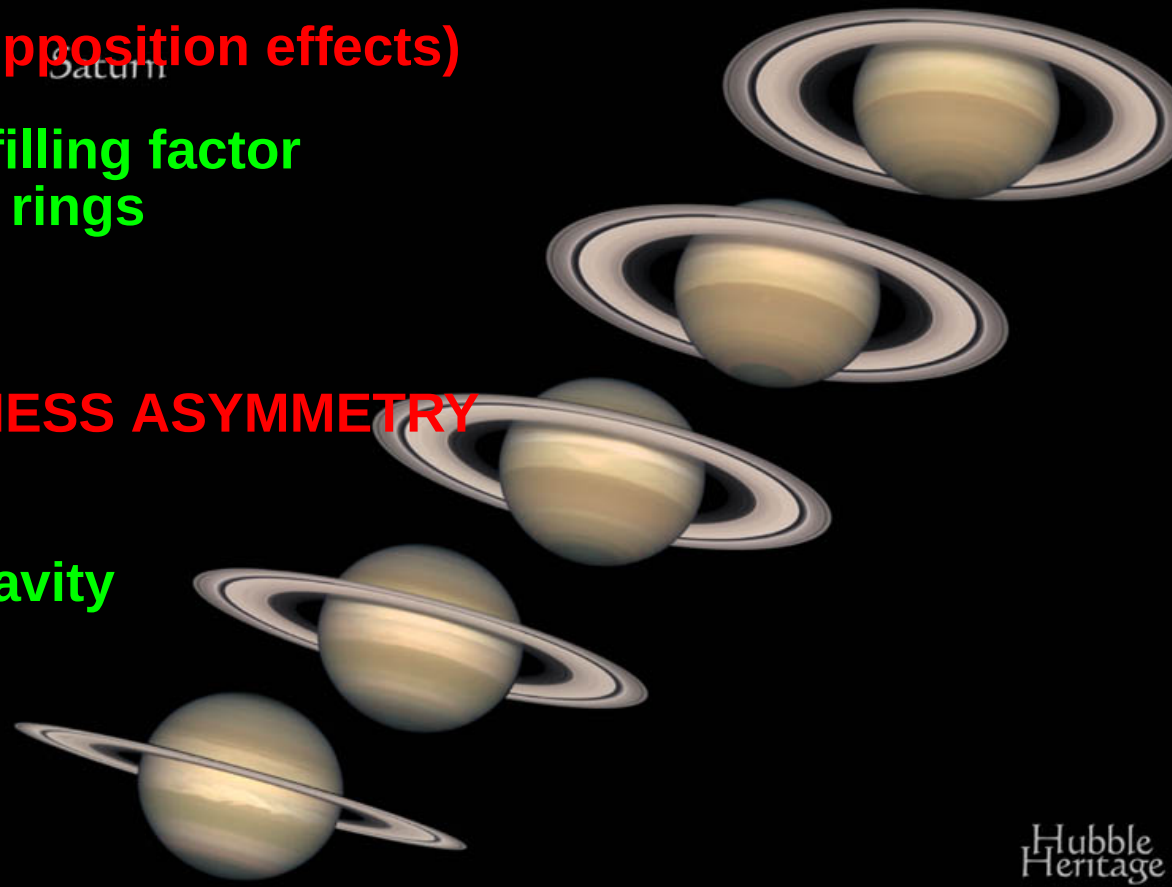
  ⇒ **constrain ring volume filling factor dynamically dense, flat rings**

  Salo and Karjalainen 2003 (Icarus 164, 428-460):

- **A-RING AZIMUTHAL BRIGHTNESS ASYMMETRY**

  ⇒ **local inhomogeneities due to ring particles' self-gravity**

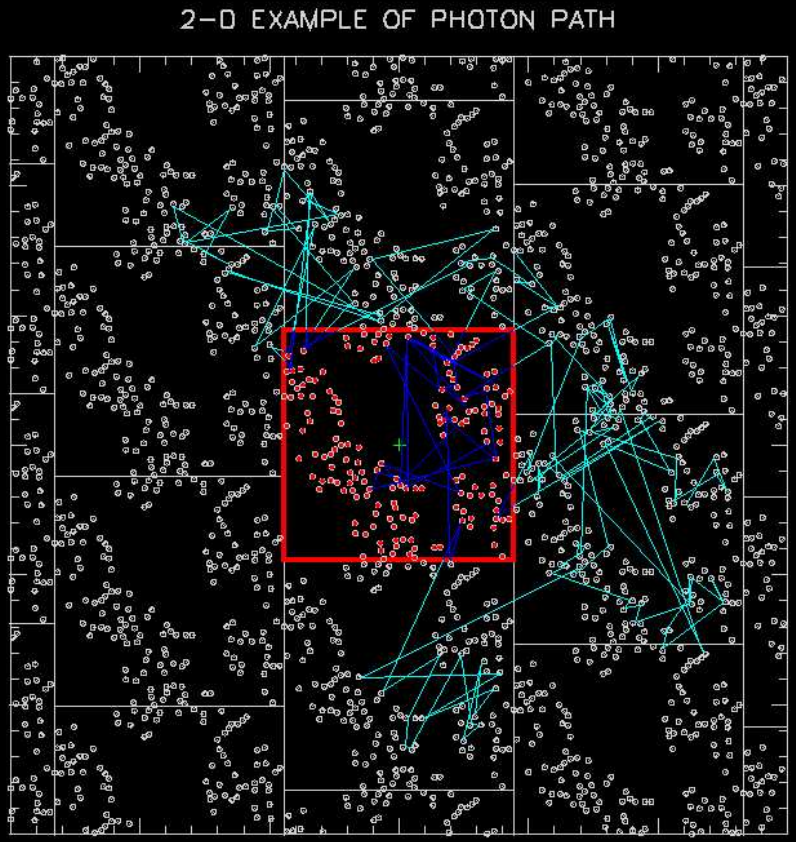
  Salo, Karjalainen, French, Icarus 2004:
  models for Voyager observations



Hubble Heritage

NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC01-15

PHOTOMETRIC MONTE CARLO CALCULATIONS



-PARTICLE FIELDS FROM DYN. SIMULATIONS (3D)

-INCLUDING PERIODICITY (important for low elevation)

-SINGLE AND MULTIPLE SCATTERING

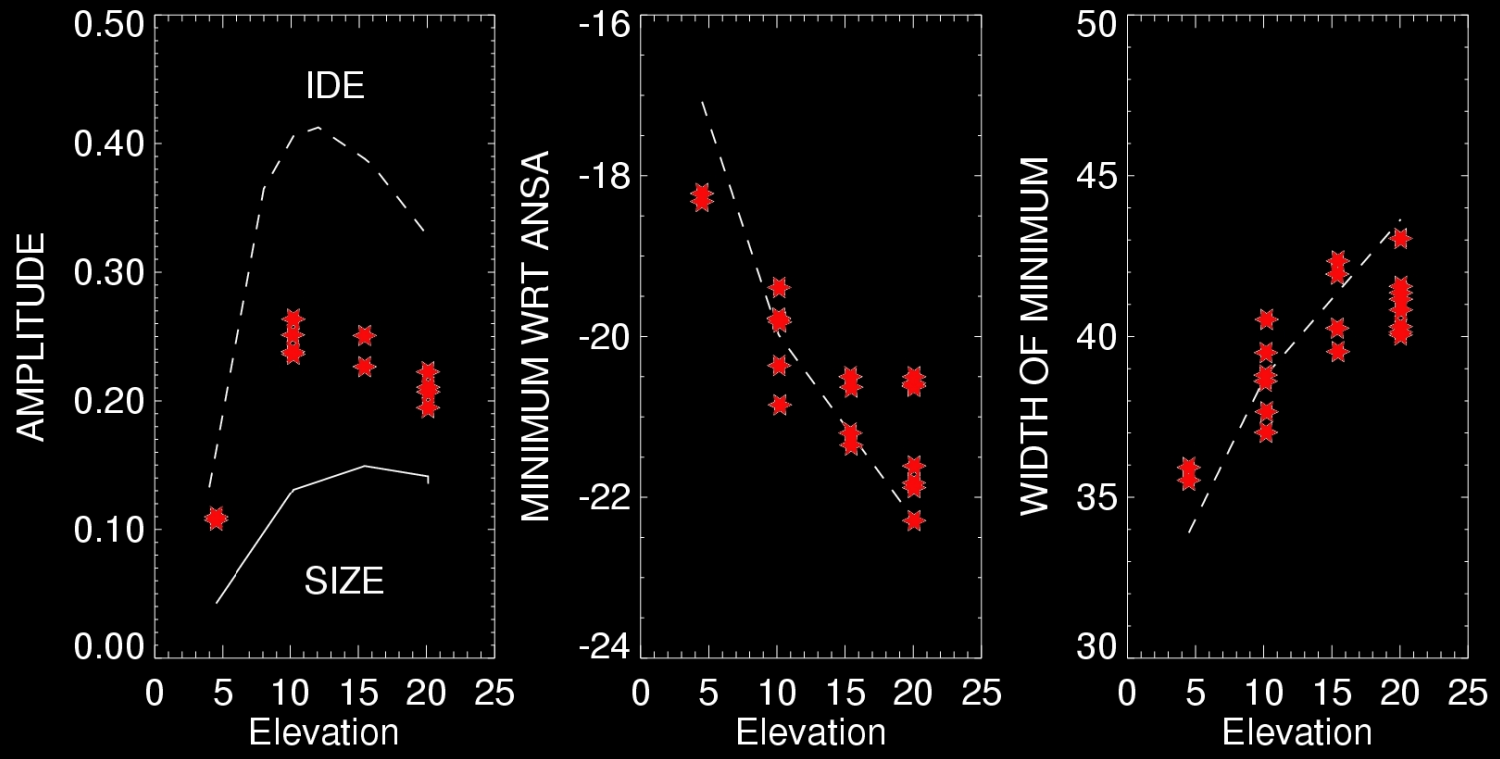
COMBINATION OF DIRECT AND INDIRECT MONTE CARLO

SIMULATIONS VS. HST OBSERVATIONS

(FRENCH, SALO, DONES IN PREP.)

Bridges-elasticity model

mid-A ring, $\tau = 0.5$

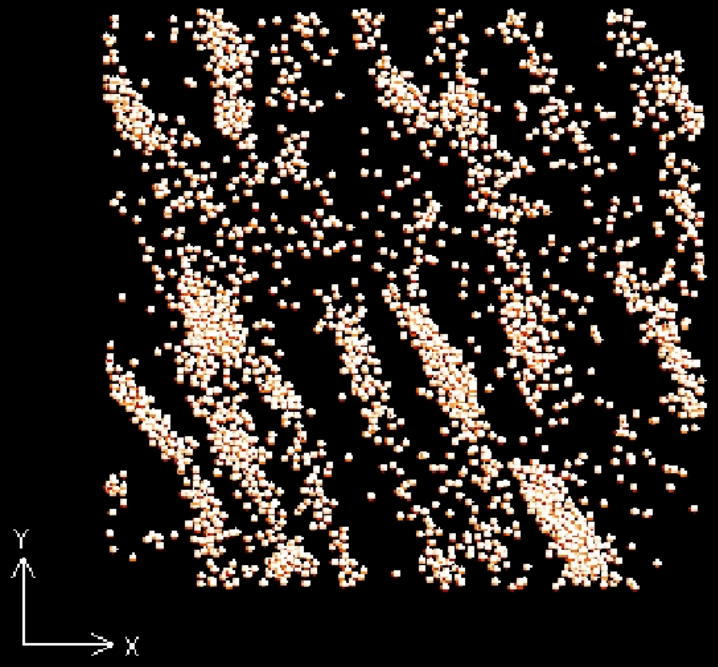


Same models applied for interpreting Arecibo radar-data (Nicholson et al 2004 DDA)

WAKE STRUCTURE SENSITIVE TO ELASTICITY

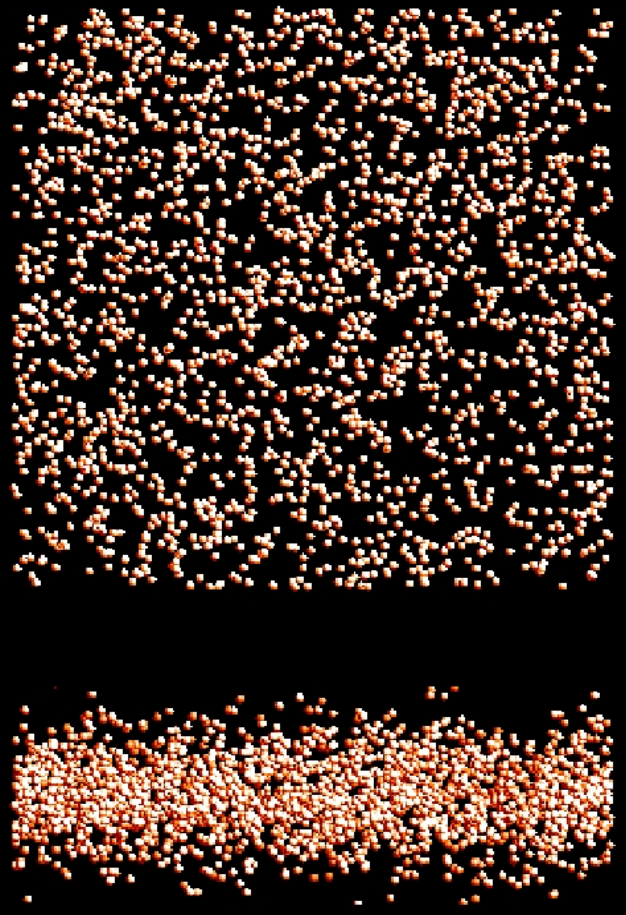
FROSTY ICE:

BRIDGES-ELASTICITY MODEL

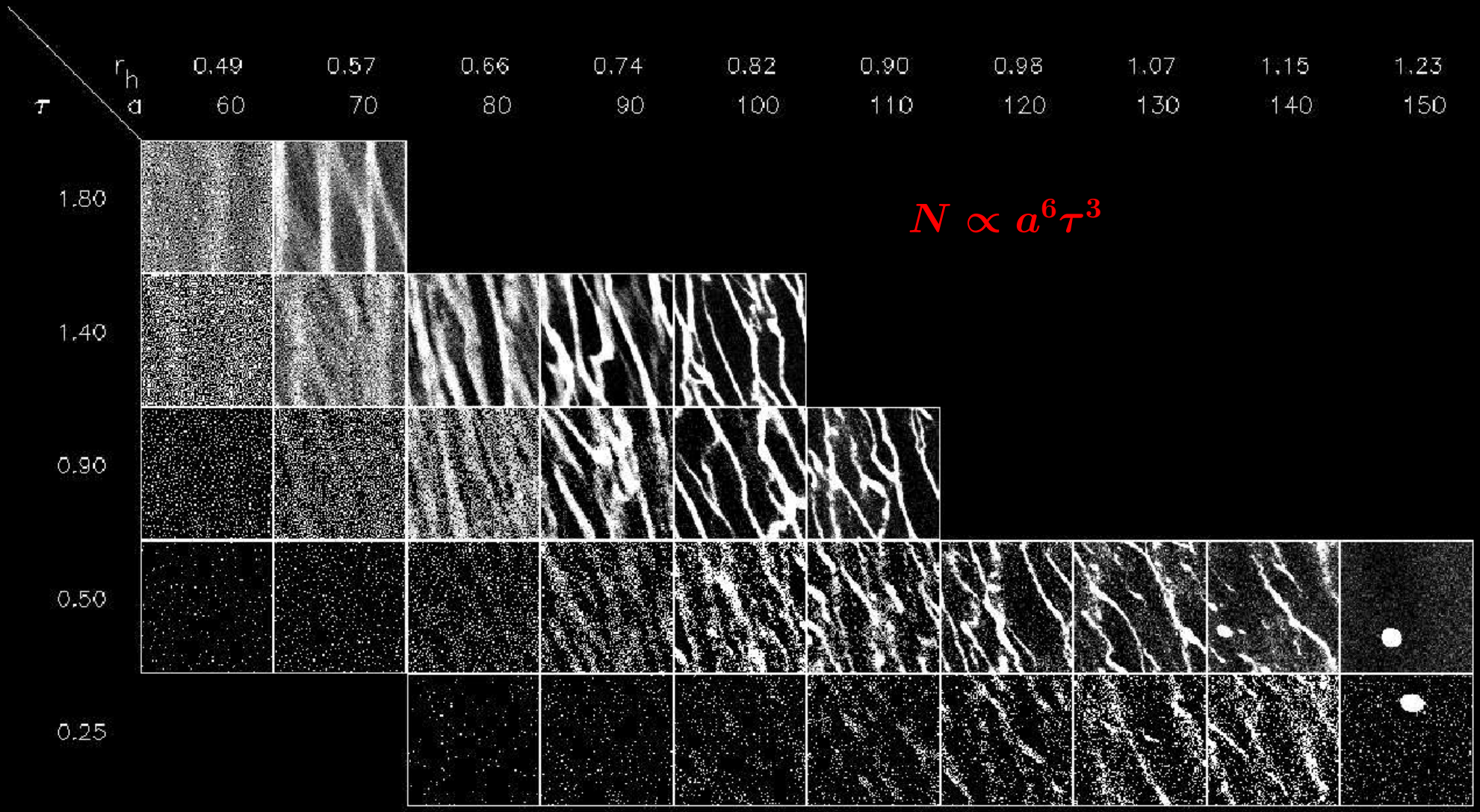


SMOOTH ICE:

HATZES-ELASTICITY MODEL

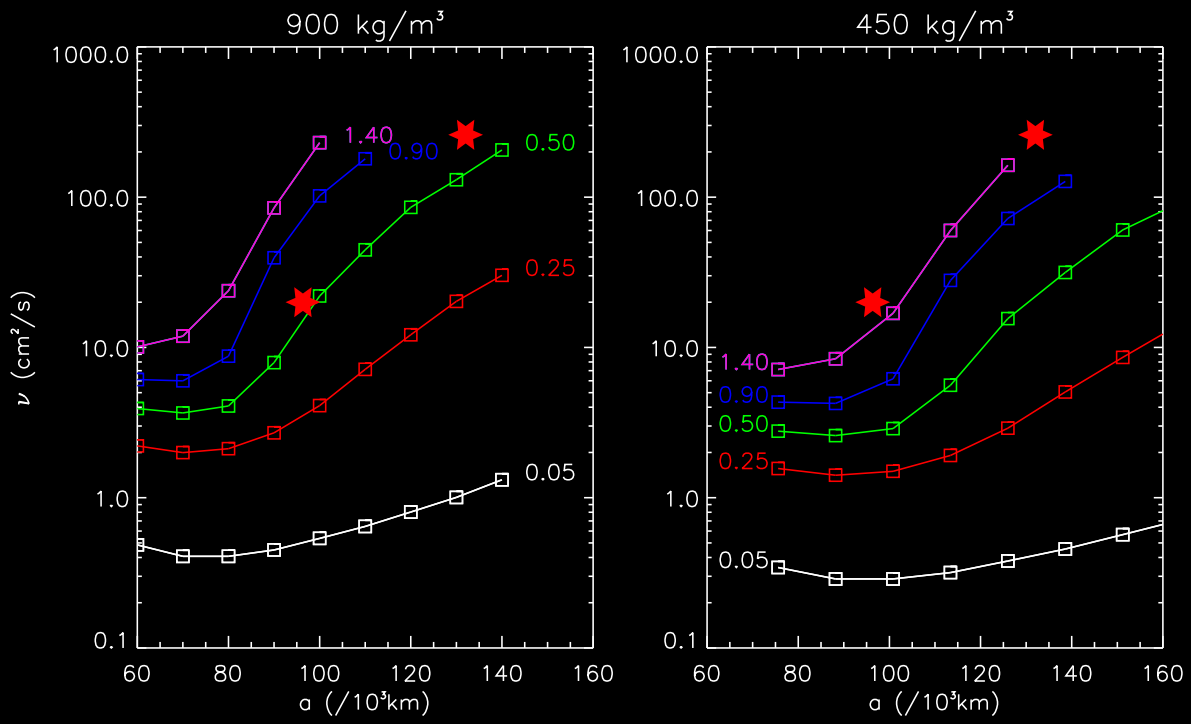


SURVEY OF SELF-GRAVITATING RINGS



$$N \propto a^6 \tau^3$$

VISCOSITY OF SELF-GRAVITATING RINGS



SUMMARY

UNCERTAIN ELASTIC PROPERTIES $\Rightarrow$ STABILITY PROPERTIES?

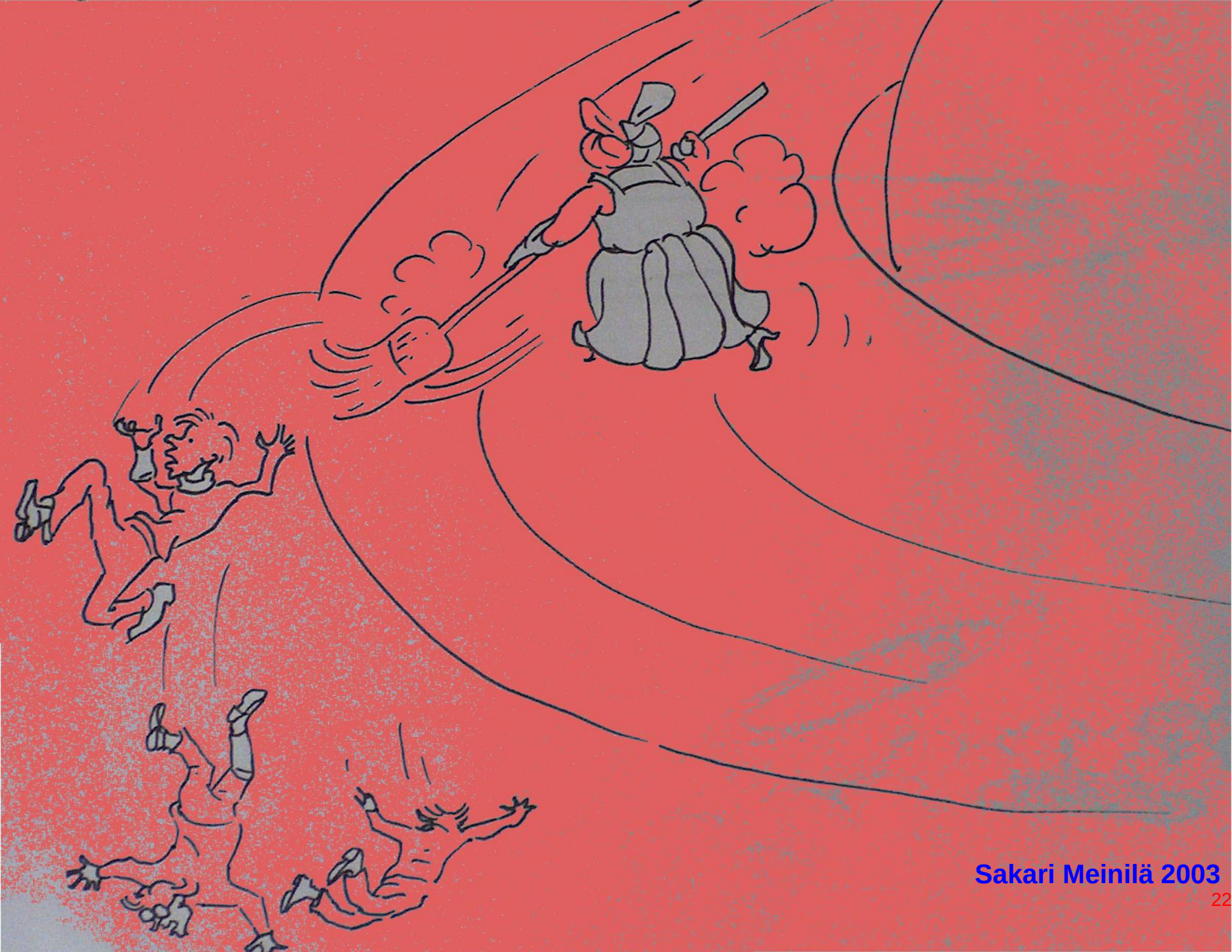
- B-RING OVERSTABILITY ?
- Particle properties can be constrained by combined dynamical and photometric modeling

GRAVITATIONAL WAKES IN A-RING $\Leftarrow$ VGR, HST, ARECIBO

- Non-axisymmetric wakes $\lambda = 30$ - 100 m
- Particle aggregates near outer edge?

CASSINI OBSERVATIONS

- Best resolution of images few hundred meters
  - $\Leftarrow$ "Monster wakes" visible at ring edges (Lewis and Stewart)
- Occultation profiles 10-100 meter resolution
  - $\Leftarrow$ A-ring wakes need to be taken into account in interpretation
  - $\Rightarrow$ constraints for possible B-ring overstability



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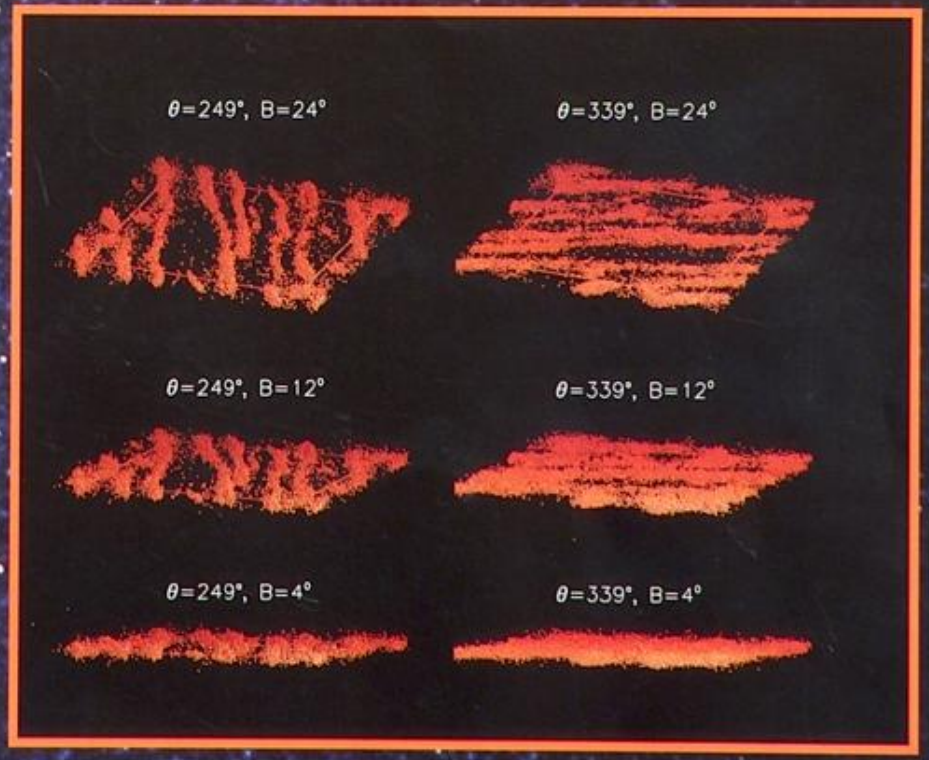

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