Simulating the formation of fine-scale structure in Saturn's Rings

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Yukawa Institute, Kyoto, 01.11.2011

Why are Saturn’s rings interesting?

- Cassini Orbiting Tour

  Close range images during SOI (July 2004)
  Solar Equinox (August 2009)

- Rings = Ideal Orbital Laboratory

  Many old ideas of galaxy dynamics apply much better to Saturn’s rings (e.g. Julian-Toomre wakes)

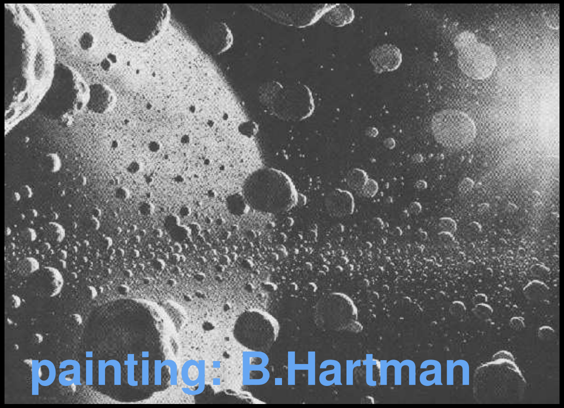
- Topics of this talk:
  Simulation modeling self-Gravity wakes,
  Viscous instabilities/overstabilities
  Briefly: propellers, damping of vertical corrugations

Collaborators:

* Dynamics of dense rings/embedded moonlets: J.Schmidt, F. Spahn, M.Seiss (Potsdam), M.Sremcevic, N. Albers (Boulder)

* Modeling Voyager, HST, Arecibo, Cassini VIMS data: R. French (Wellesley), P. Nicholson, M. Hedman (Cornell)

CIRS data: R. Morishima,, K. Ohtsuki (Kobe)



OVERVIEW OF SATURN'S RINGS

- $\sim 10^{16}$ METER-SIZED ICY PARTICLES

  Keplerian differential rotation $\Omega \propto a^{-1.5}$

  Power-law size distribution: $dN/dr \propto r^{-3}, \quad 1cm < r < 10m$

- FREQUENT MUTUAL IMPACTS $>$ 10/orbit

  Local vertical thickness $<$ 100 m (Ring diameter 270 000 km)

  $\Rightarrow$ Impact speeds $\sim 1cm/sec$ (orbital speed $V_{orb} \sim 20km/s$)

- DISSIPATIVE IMPACTS + CONSERVATION OF I_z

  Rapid local vertical flattening: timescale a few weeks at most

  Slow radial spreading: whole ring: timescale $> 10^8$ years

  $\Rightarrow$ LOCAL AND GLOBAL EVOLUTION CAN BE STUDIED SEPARATELY

- **SATELLITE PERTURBATIONS:** $M_{Mimas}/M_{Planet} \sim 10^{-7}$
- **SELF-GRAVITY:** $M_{ring}/M_{Planet} \sim 5 \cdot 10^{-8}$

COMPARED TO GALACTIC DISKS:

- Dynamically very old $T_{age} > 10^9 T_{dyn}$

- Extreme example of rotationally supported system: $v/\sigma \sim 10^6$

- Scale of gravity-related structures $<<$ system size

satellite-driven density waves $\lambda \sim 10\ km$
local gravity-wakes $\lambda \sim 100m$

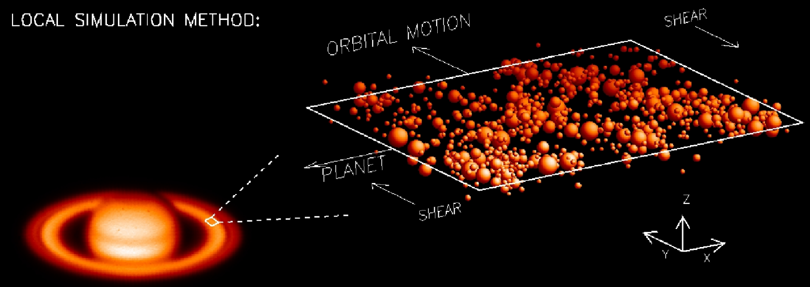
- Rings inside Roche zone - gravity limited by particles's physical density

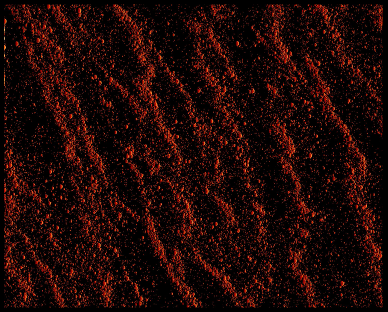
MODELING DENSE SELF-GRAVITATING RINGS

- INGREDIENTS
  - impacts + selfgravity + differential rotation
  - external satellites, embedded moonlets and “icebergs”
- METHODS
  - kinetic theory: Goldreich-Tremaine-Borderies, Araki, Shu, Stewart, Hämeen-Anttila, Latter & Ogilve
  - hydrodynamics Schmit & Tscharnuter, Schmidt & Salo & Spahn
  - N-body: Trulsen, Brahic, Lukkari, Salo, Richardson, Mosqueira, Lewis, Daisaka, Ohtsuki, Charnoz, ...

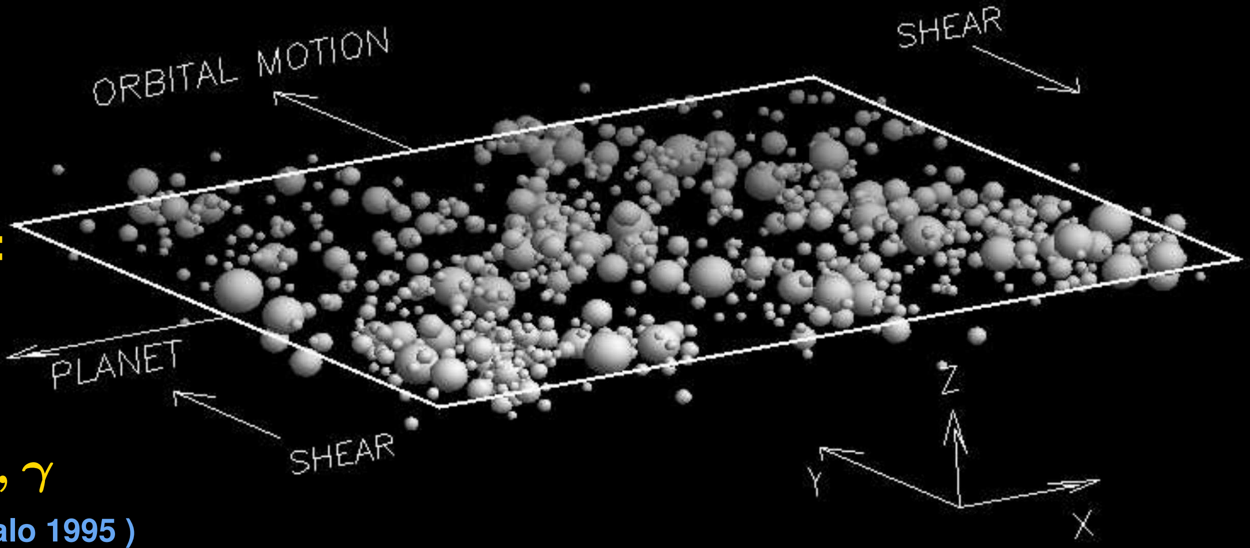
$\Rightarrow$ Local simulation method (Wisdom & Tremaine ; Toomre & Kalnajs)

$\Rightarrow$ combination with photometric simulations (Salo & French ; Porco & Richardson)





LOCAL SIMULATION METHOD



Equations:

- Co-moving coordinate system
- Linearized Hill-equations
- Periodic boundary conditions:
  - $\Rightarrow$ replicate particles

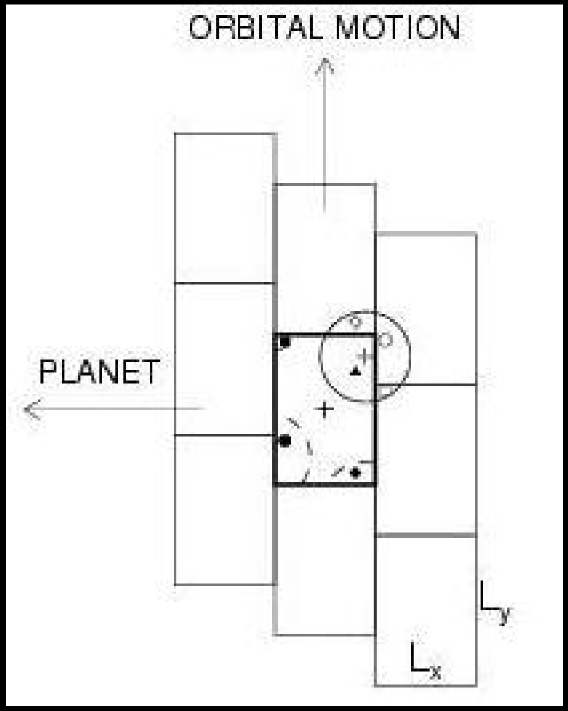
Collisions:

- Instantaneous impacts: $\epsilon_n, \epsilon_t, \gamma$

  or Force-model for impacs (Salo 1995)
  - $\Rightarrow$ modeling of gravity aggregates, adhesion

Gravity: (Note: compared to galaxy dynamics, need to be 'collisional')

- Nearby particles: PP forces ($\Delta < 0.5\lambda_{cr}$) (Salo 1992)
- Intermed. range: 3D FFT in shearing coordinates (Salo 1995)
- Distant gravity: F_z from infinite sheet



Tabulation:

Position+velocity+spin snapshots
Pressure tensor components P_{ij}
Fourier components, autocorrelation etc

LOCAL ENERGY BALANCE

COLLISIONAL DISSIPATION = VISCOUS GAIN $w_c(1-\epsilon^2)c^2 = \nu(\partial\Omega/\partial r)^2$

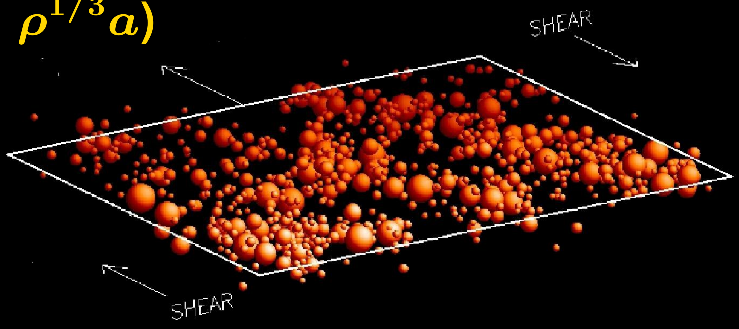
VISCOSITY: (from P_{xy})

- momentum transfer via radial excursions (local viscosity; WT87 relates to $< c_x c_y >$)
- transfer at physical impacts (nonlocal viscosity; WT87 $< \Delta x\, c_y >_{impacts} /(N\Delta t)$)
- transfer via grav. forces (gravitational viscosity; Daisaka et al. 2001 $< \int \Delta x F_y > /(N\Delta t)$)

$\Rightarrow$ TIME-SCALE OF LOCAL BALANCE: 10-100 impacts/particle

RANDOM VELOCITY, THICKNESS, VISCOSITY depend on:

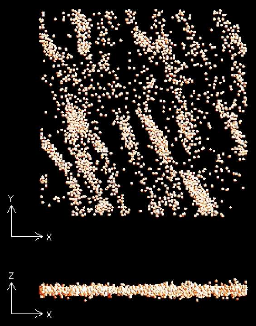
- elasticity of impacts, friction
- optical depth ($w_c \propto \tau_{dyn}$)
- particle size distribution
- particles' internal density (+distance via $r_h \propto \rho^{1/3} a$)



$\Rightarrow$ **VISCOSITY vs DENSITY RELATION**

determines linear stability properties

CRUCIAL ROLE OF ELASTICITY

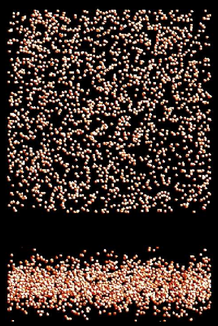


Frost-covered particles (Bridges et al. 1984 laboratory measurements)

⇒ flat ring: H ∼ 10 meters,

susceptible to gravitational instability

(also viscous overstability)



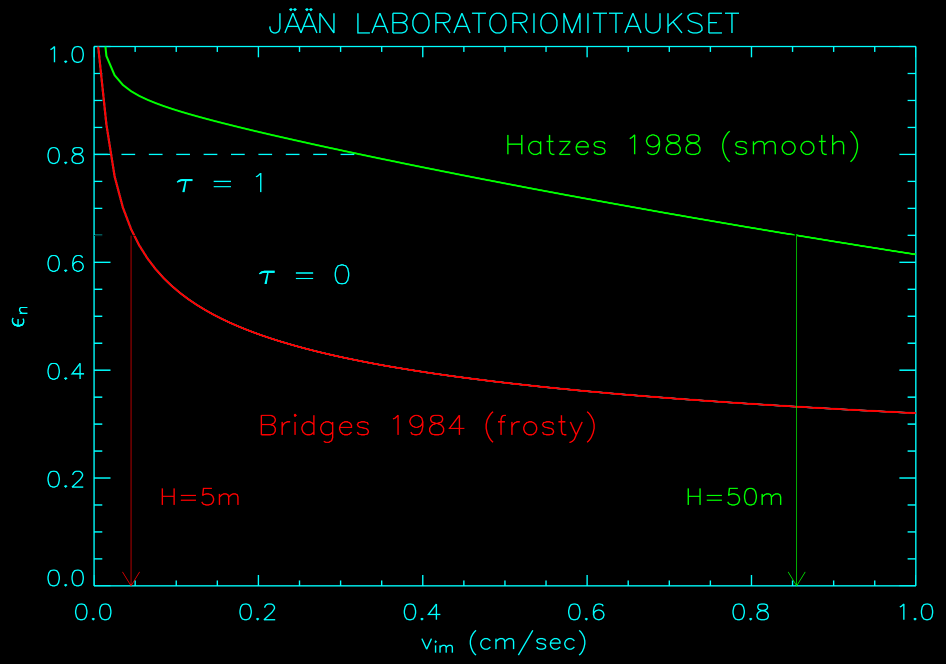
’Smooth’ particles (Hatzes et al. 1988 laboratory measurements)

⇒ “thick” multilayer ring H ∼ 100 meter,

gravitationally unresponsive

(may lead to viscous instability)

MEASUREMENTS OF PARTICLE ELASTICITY



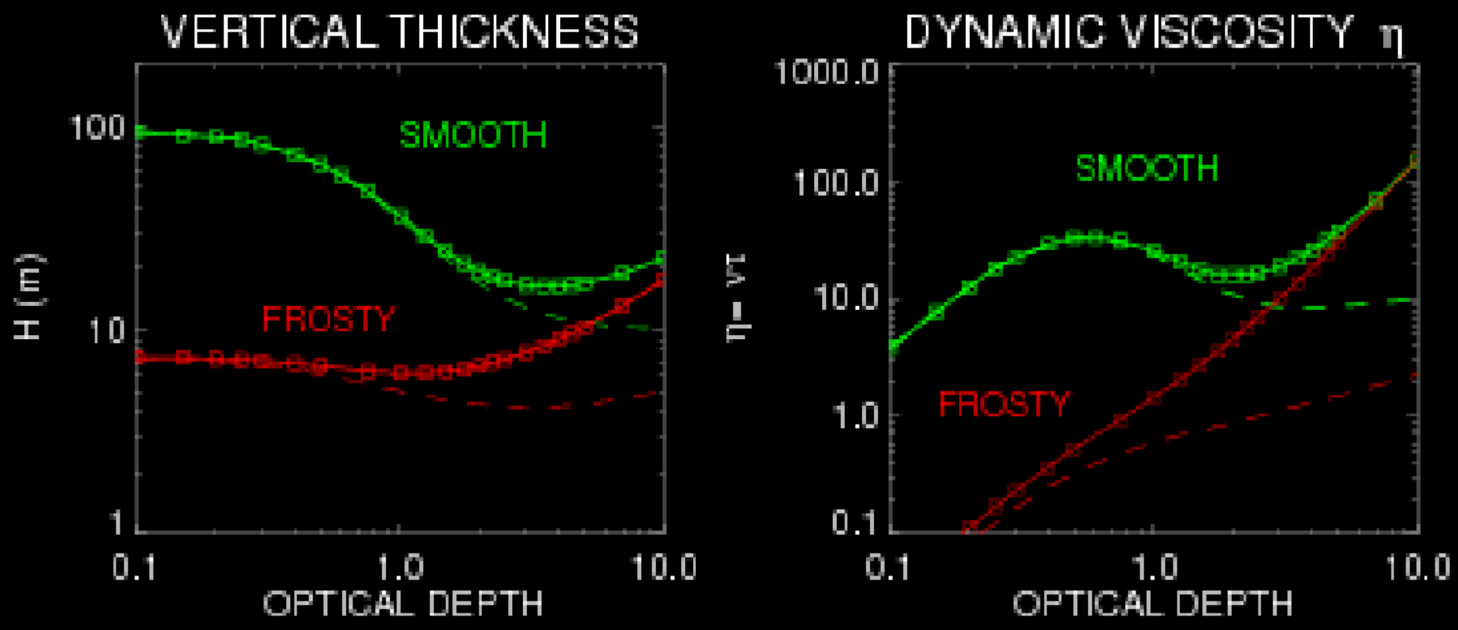
'THICK' RING:

⇒ **VISCOSITY MAY DECREASE WITH DENSITY**

FLATTENED RING:

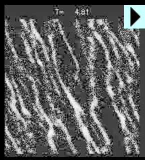
⇒ **VISCOSITY INCREASES WITH DENSITY**

SELF-GRAVITY ENHANCES THIS TENDENCY



SELF-GRAVITY WAKES

SELF-GRAVITY



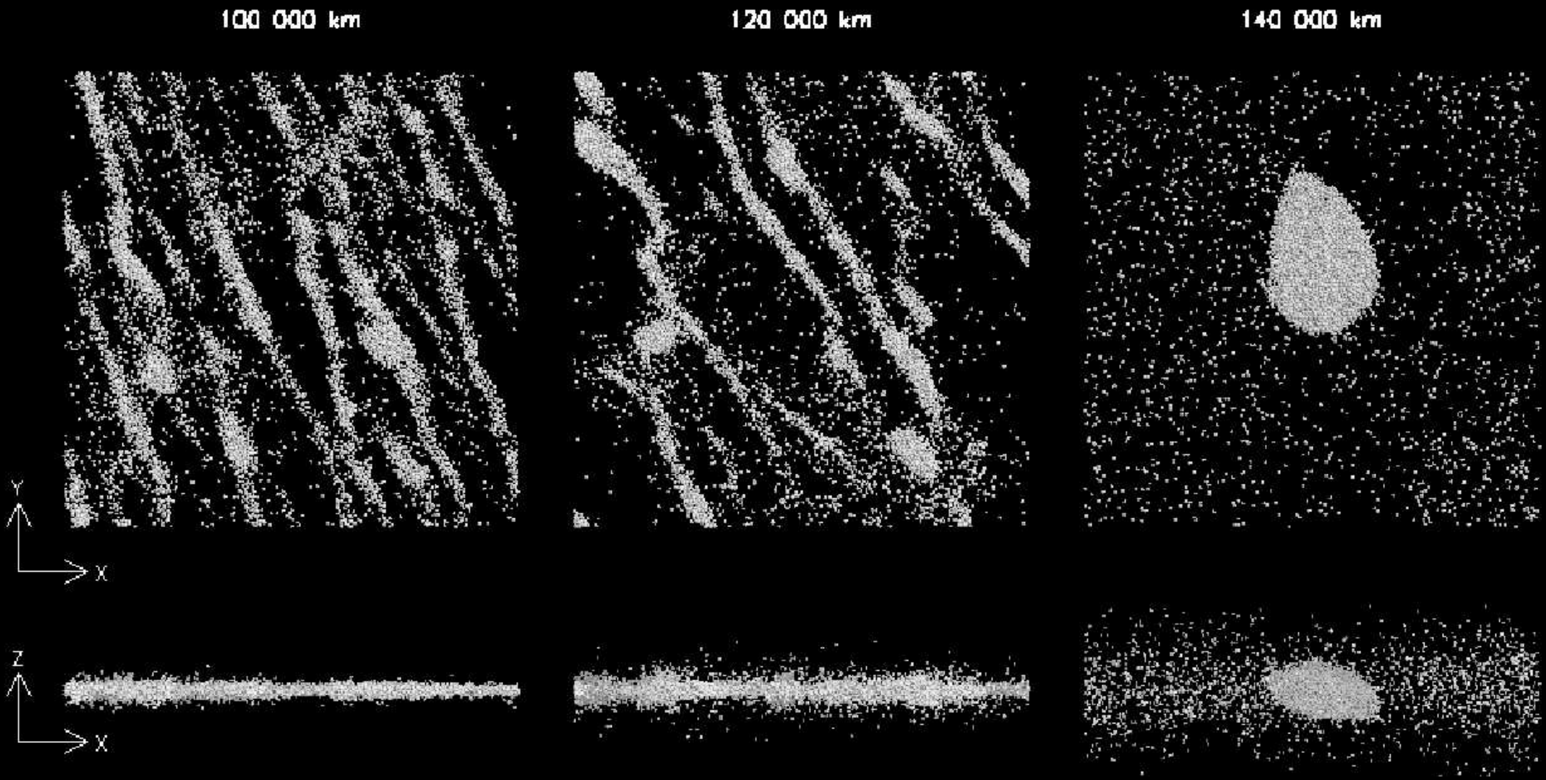
- **Gravitational collapse + dissipation + differential rotation**

  $\Rightarrow$ **Self-regulation** $\Rightarrow$ **minimum** $Q_{\mathrm{Toomre}} \sim 1 - 2$ **(corresponds to** $h \sim 10 - 20m$**)**

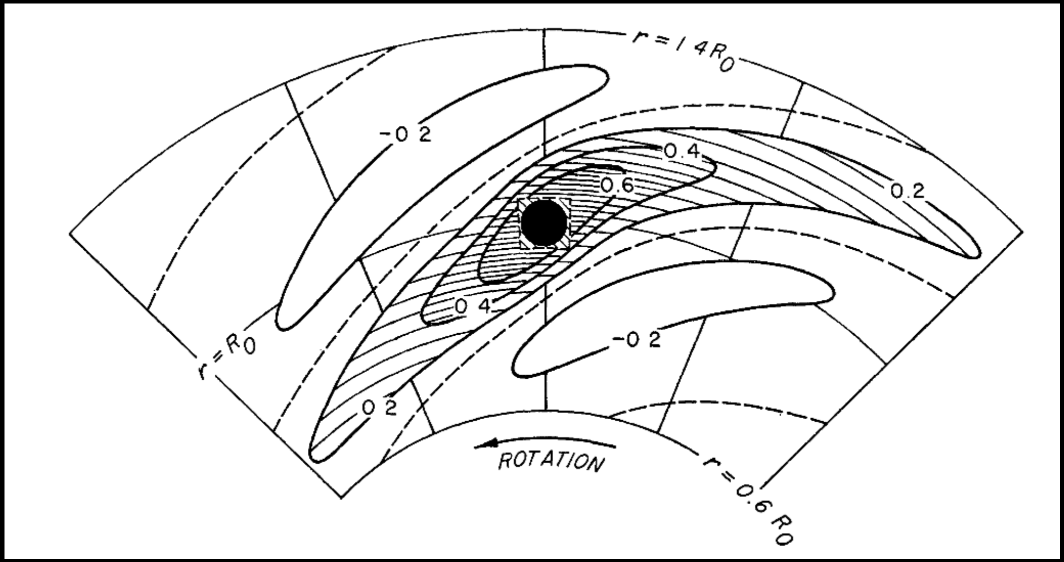
- **Spontaneous formation of gravity wakes** (Salo 1992 (Nature 359, 612))

  radial scale: $\lambda_{cr} = 4\pi^2 G\Sigma/\Omega^2 \sim 10 - 100m$

  pitch-angle: $\sim 20^0$ **(in Keplerian velocity field)**



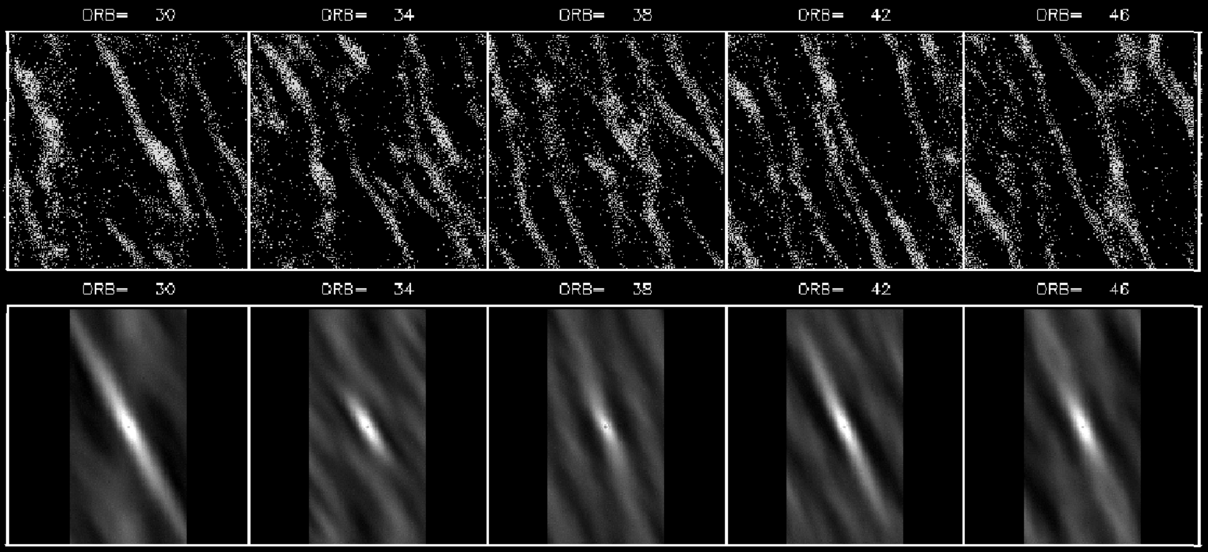
SELFGRAVITY WAKES RELATED TO JULIAN-TOOMRE WAKES



Julian & Toomre 1966:
response of gravitating stellar disk around orbiting mass enhancement
Toomre 1981:
'SWING-AMPLIFICATION'

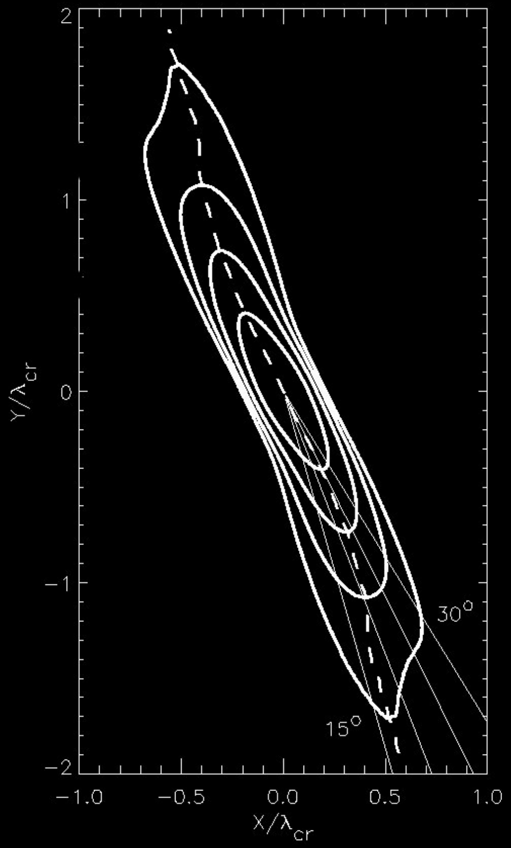
self-gravity wakes $\equiv$ **superposition of Julian-Toomre wakes excited around each ring particle**

ANALOGY TO JT-WAKES CONFIRMED BY AUTOCORRELATION ANALYSIS



Individual snapshots from a simulation

+ corresponding 2D autocorrelation plots ⇒



Average autocorrelation = JT Wake

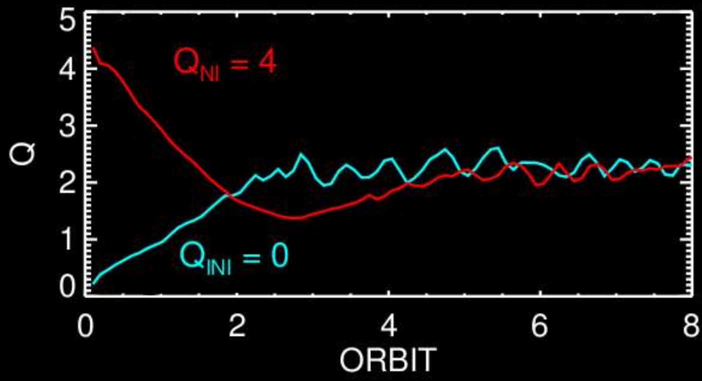
(see Toomre & Kalnajs 1991)

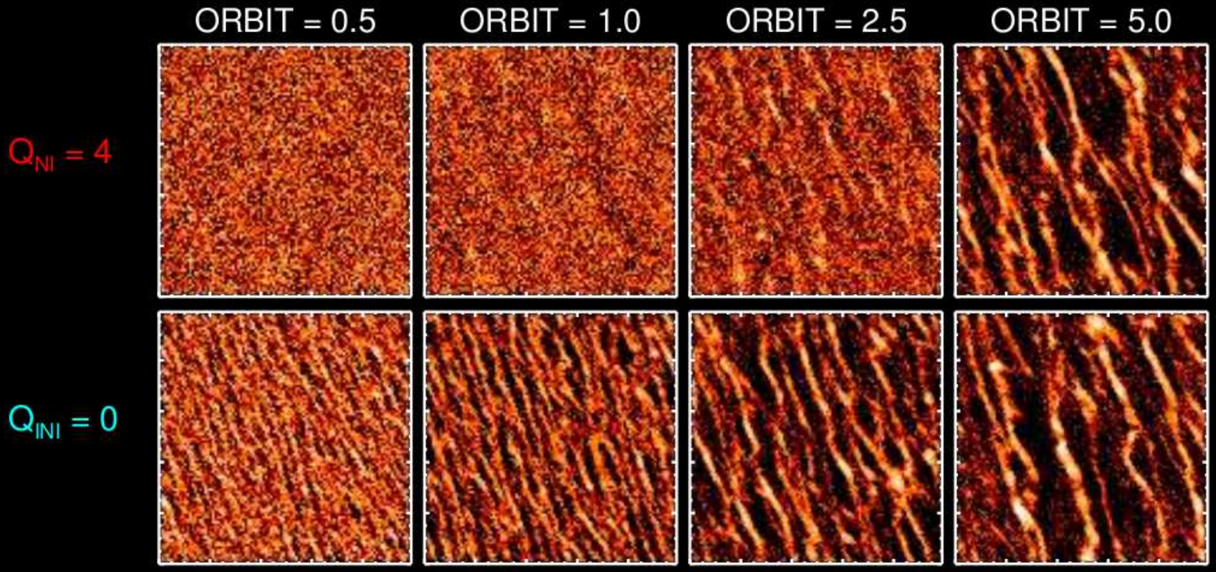
STELLAR SYSTEMS VS PLANETARY RINGS

- SCALE $\sim$ Toomre's λ_{cr} $\sim$ KPC in galaxies, $\sim$ 100 m in rings
- Dissipative impacts in rings $\equiv$ thermostate $Q \sim 2$

Stellar disks: heating via wakes makes the disk unresponsive

(unless fresh supply of cool material - though the timescale of heating increases with N)



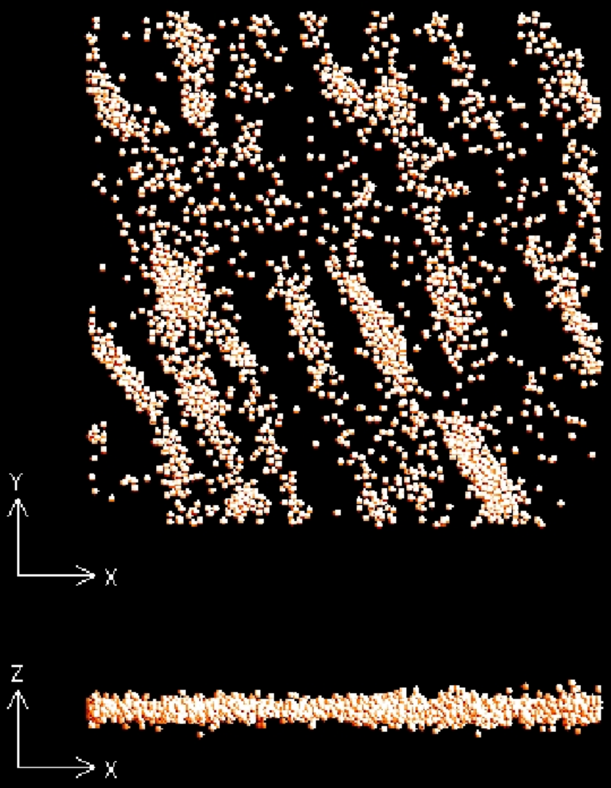


SG-WAKES SENSITIVE TO VELOCITY DISPERSION

If impacts are able to maintain thickness which corresponds to $Q > 2$
$\Rightarrow$ wake structure would be absent

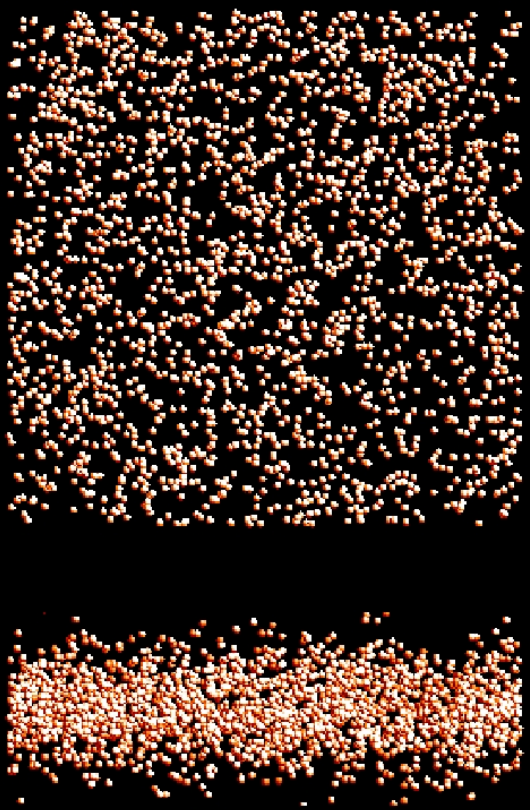
FROSTY ICE:

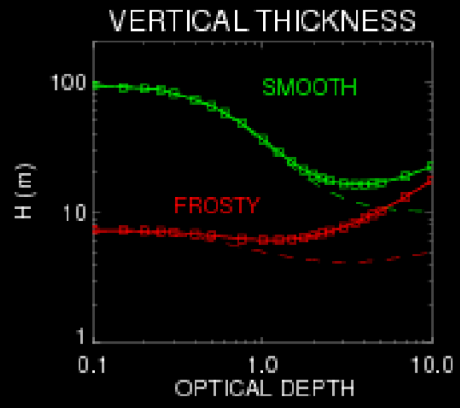
BRIDGES-ELASTICITY MODEL



SMOOTH ICE:

HATZES-ELASTICITY MODEL

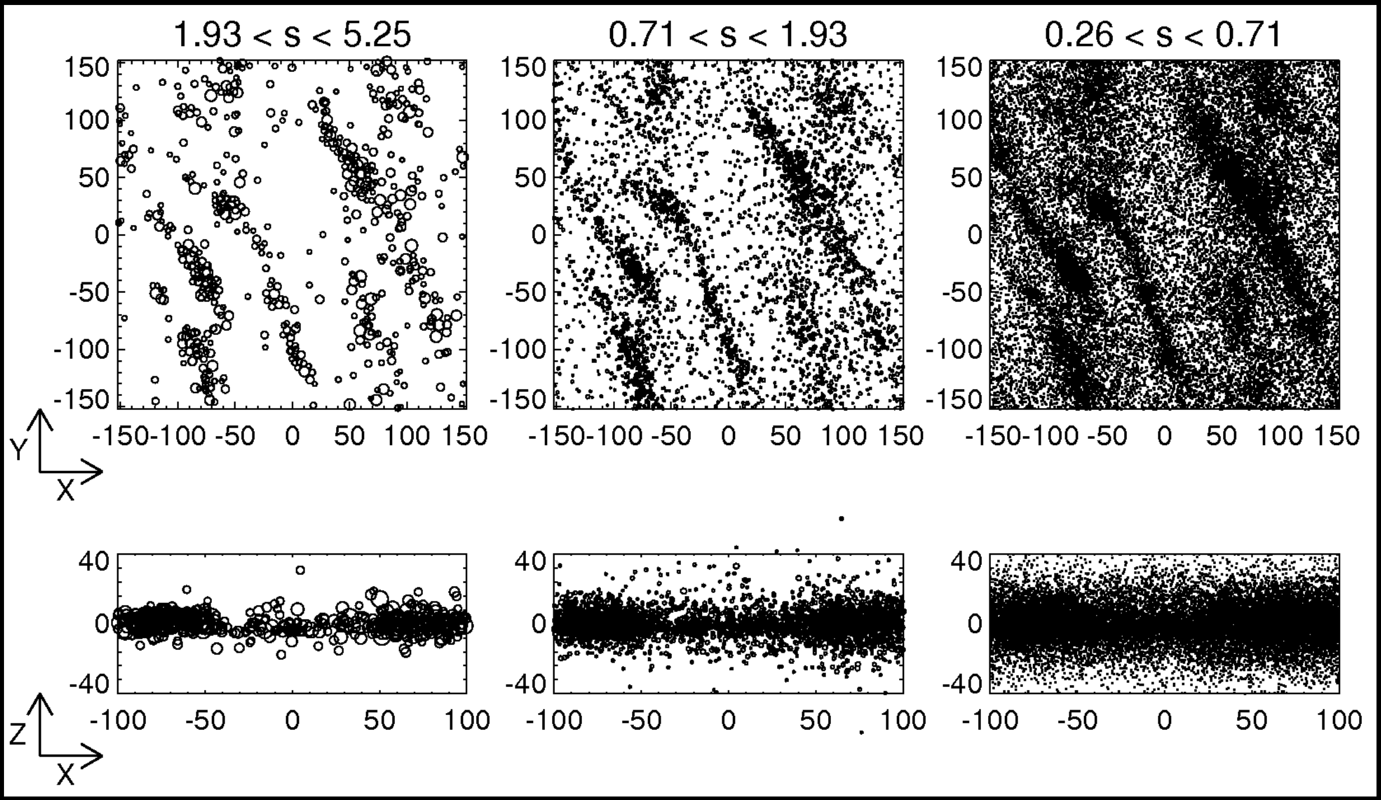




SG-WAKES AND SIZE DISTRIBUTION

Size distribution ⇒

$H_{small} > H_{large}$



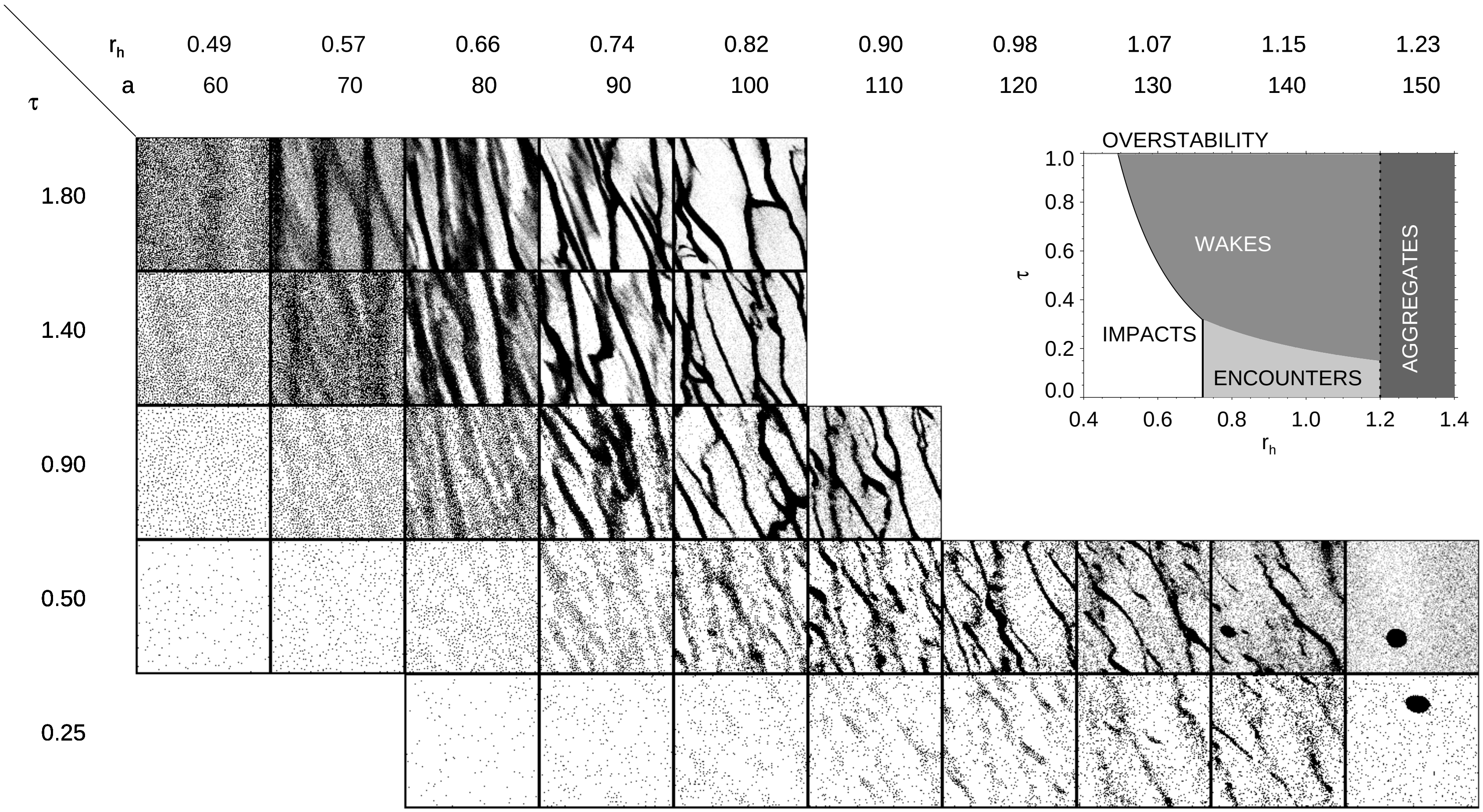
SG-wakes weaker

among small particles

(Salo, French 2004)

SIMULATED SG-WAKES VS DISTANCE AND OPTICAL DEPTH

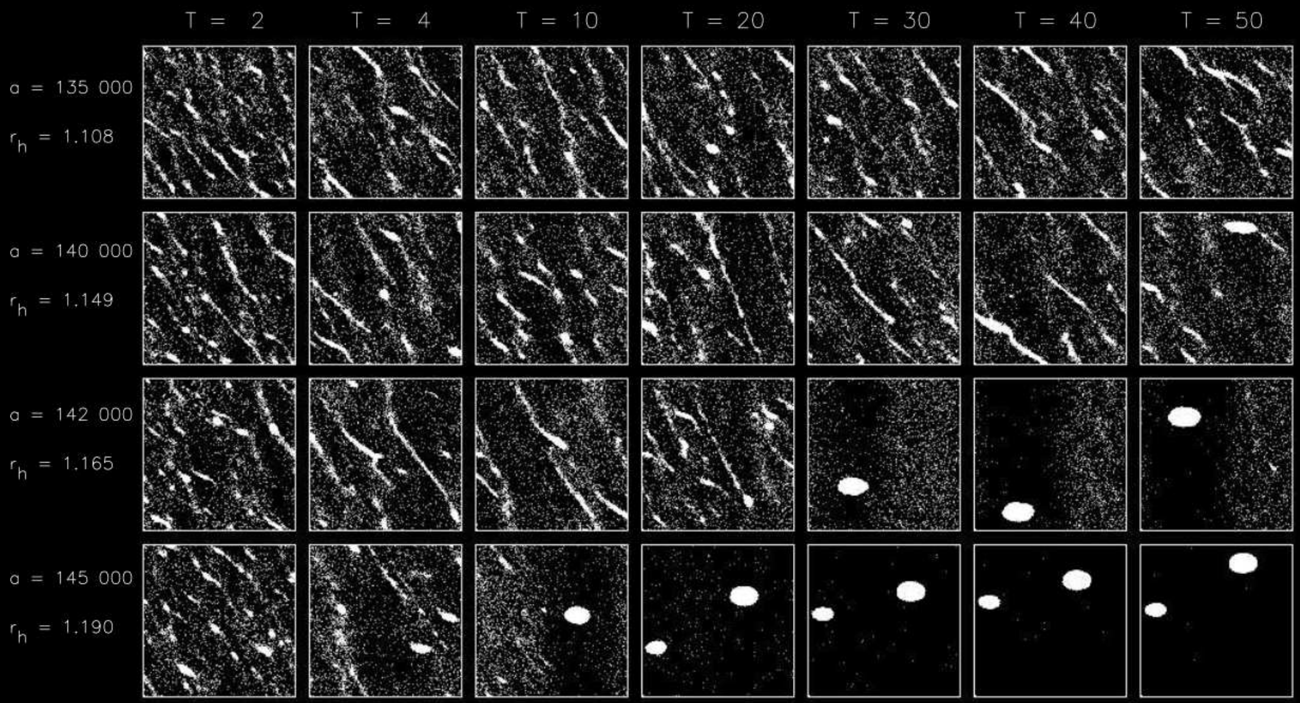
λ/R graininess, R_{Hill}/R pairwise sticking in tidal environment $\Rightarrow$



Salo et al. (2008); reproduced by Schmidt et al. 2009, Cuzzi et al. 2010

identical particles, $\rho = 900$ kg/m^3, $\epsilon = 0.5$ $4\lambda_{cr} \times 4\lambda_{cr}$ $N \propto a^6\tau^3$

APPROACHING ROCHE DISTANCE ⇒ ACCRETION



details depend on

ϵ_n, friction

size distribution

Karjalainen and Salo 2007

- Charnoz et al. 2010: viscous spreading spills rings over the Roche distance

  ⇒ formation of small moons outside the main rings

SIDESTEP I: ADHESIVE FORCES

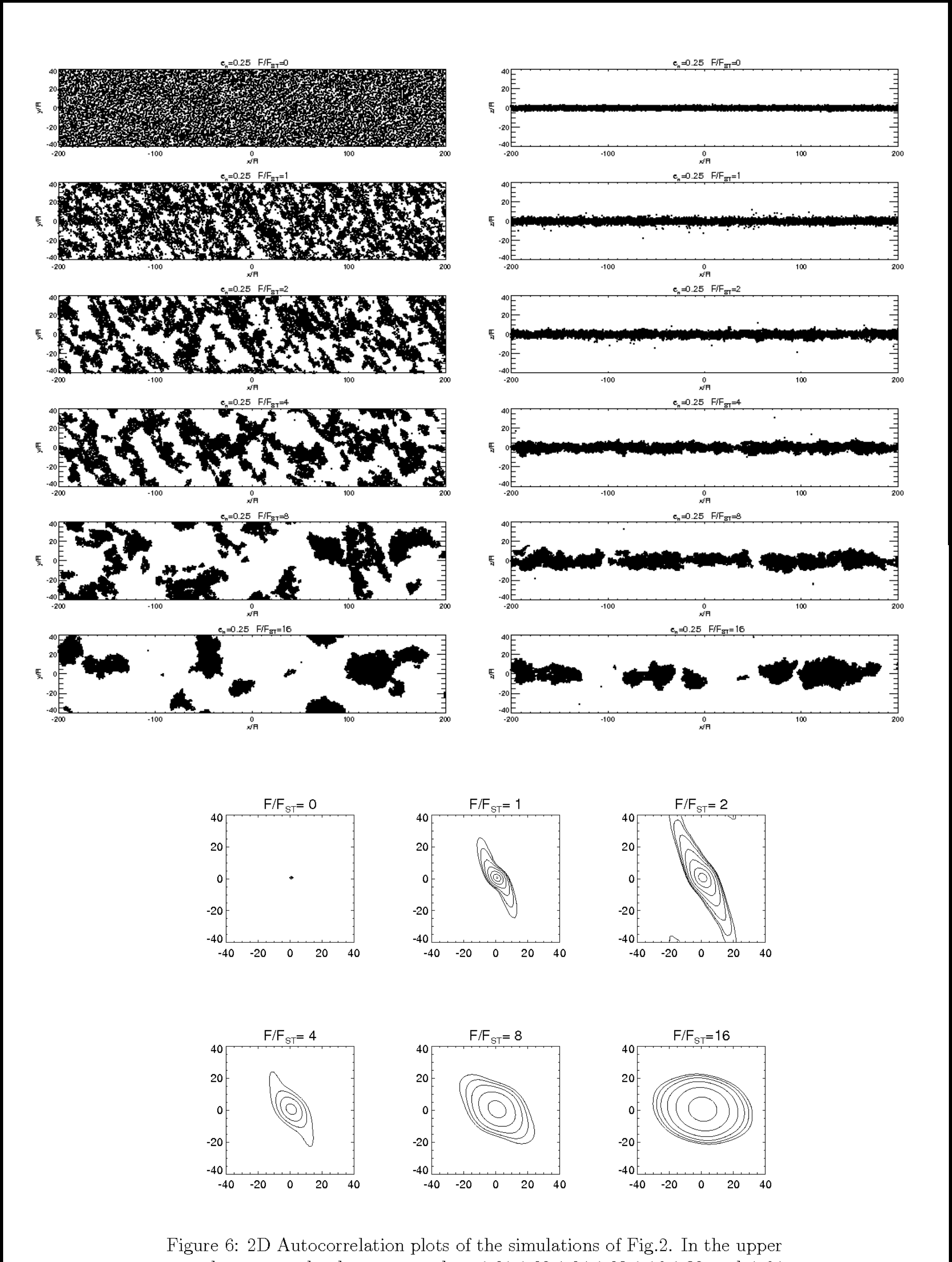


Figure 6: 2D Autocorrelation plots of the simulations of Fig.2. In the upper

Attractive force between overlapping pairs, normalized by min. velocity for sticking

2-fold force

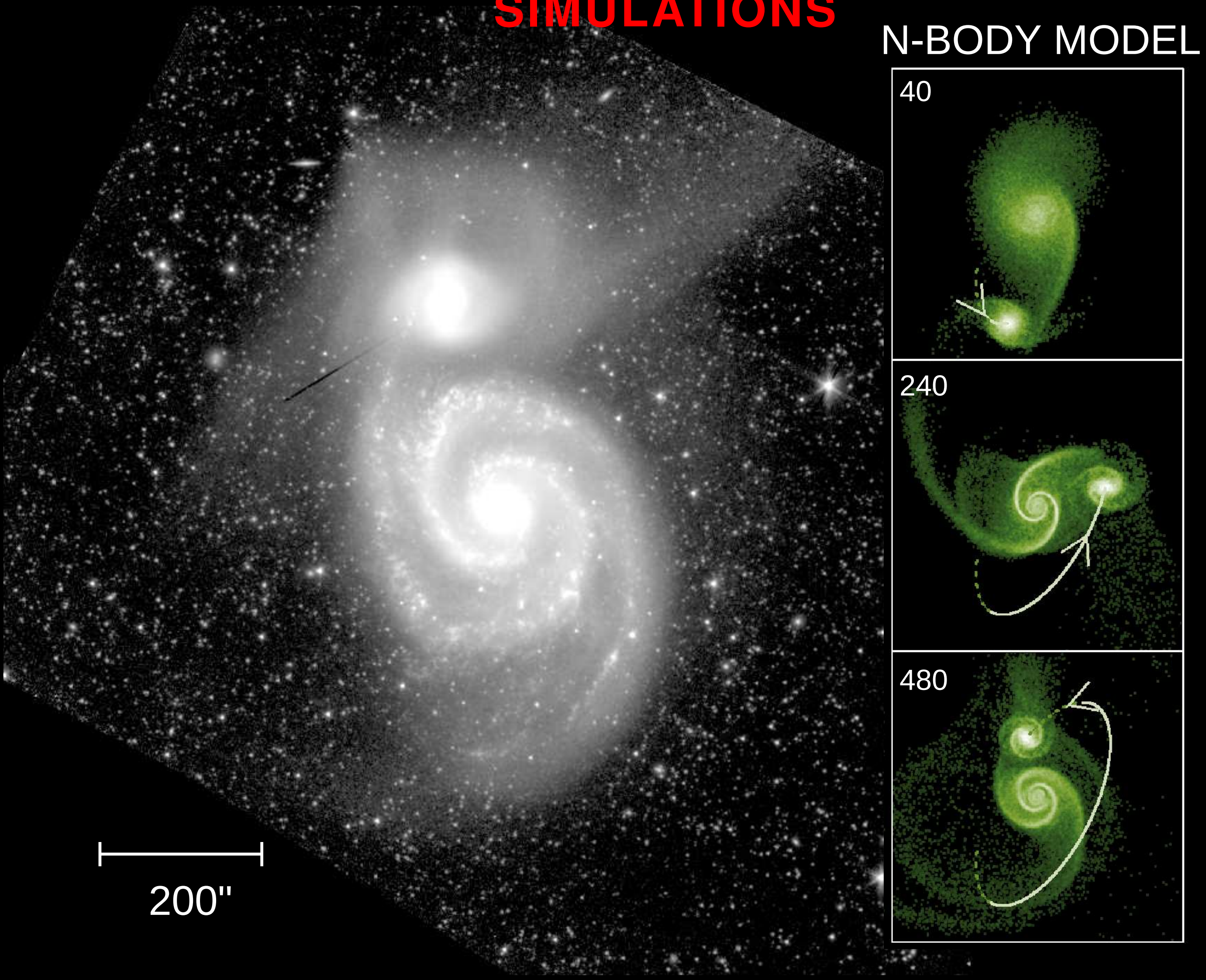
4-fold

8-fold

16-fold

Corresponding autocorrelation plots very similar to self-gravity case

SIDESTEP II: SWING AMPLIFIED SPIRALS IN GALAXY N-BODY SIMULATIONS



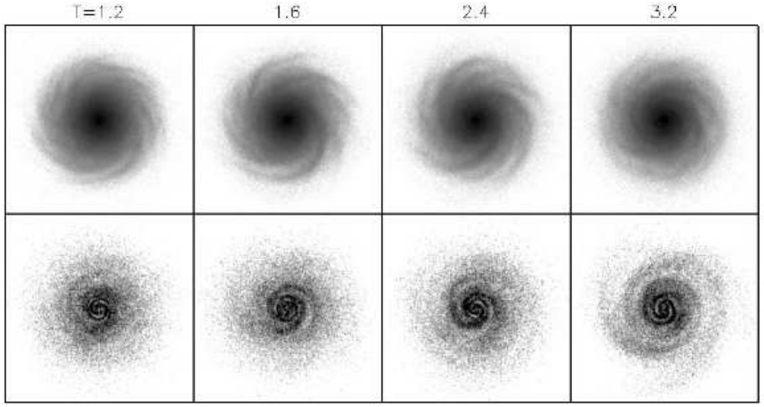


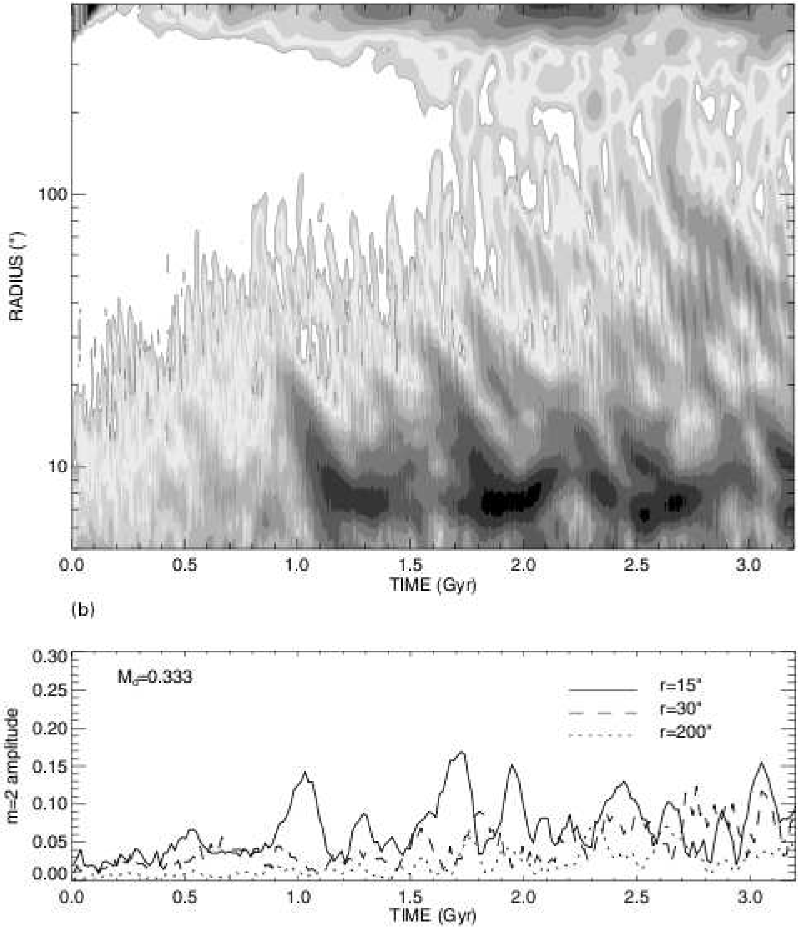
Figure 5. Evolution of the simulation disc during an isolated evolution of 3.2 Gyr with $M_d = 0.333$. The size of the upper frames is 1200 × 1200 arcsec, while the lower frames show the inner 200 × 200 arcsec region. $N = 4 \times 10^6$ particles are simulated with the improved resolution.

© 2000 RAS, MNRAS **319**, 393–413

Before making tidal model:

Try to understand isolated evolution

Salo and Laurikainen 2000, MNRAS



Individual packets

SPIRAL PACKET - COROTATING FRAME

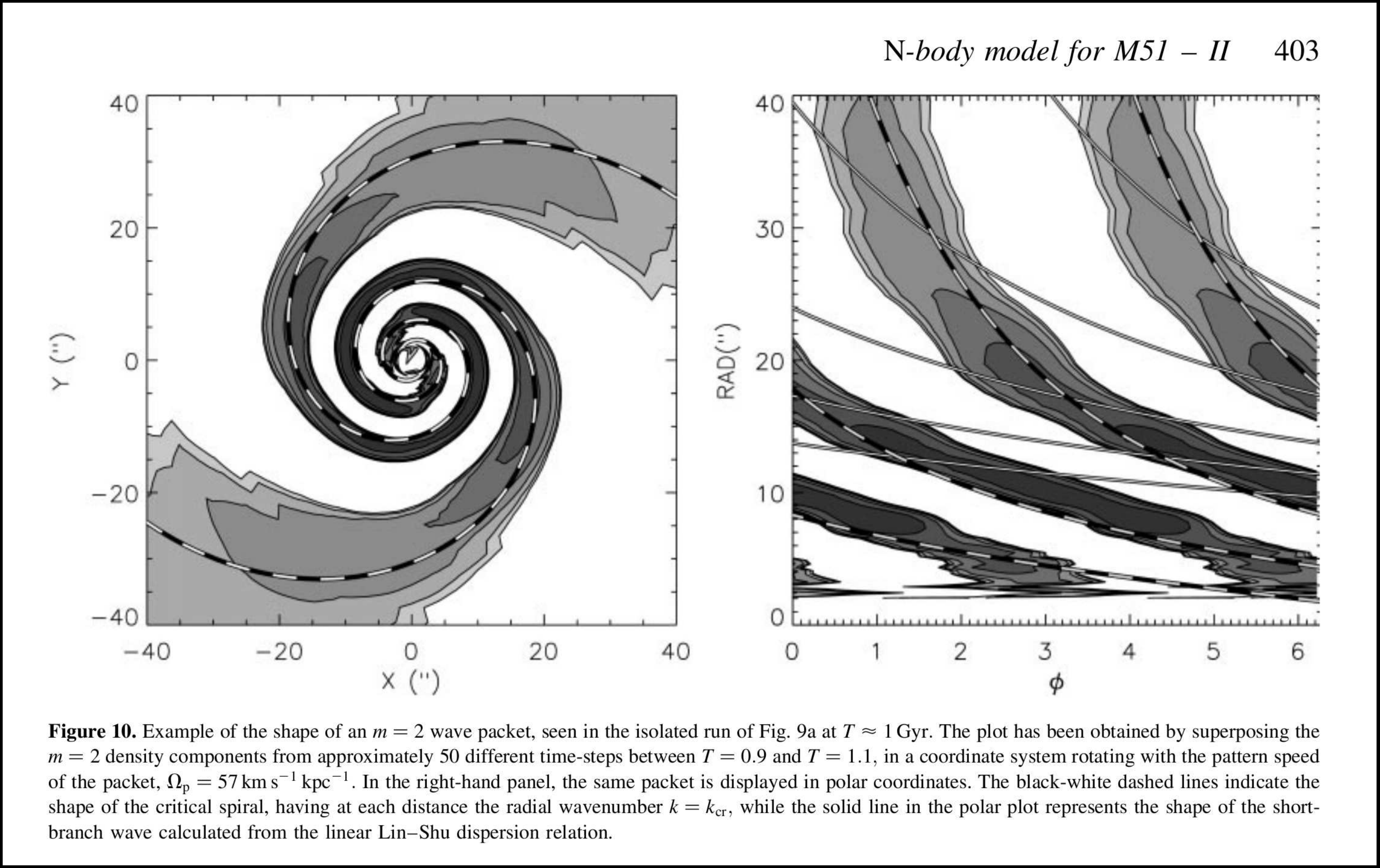
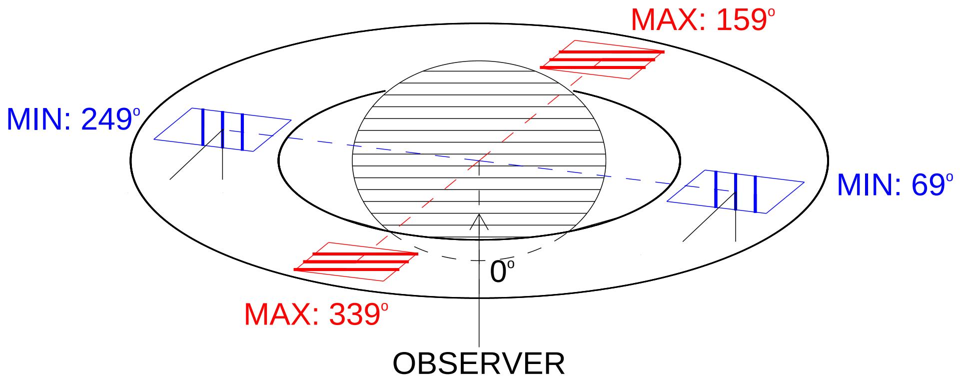
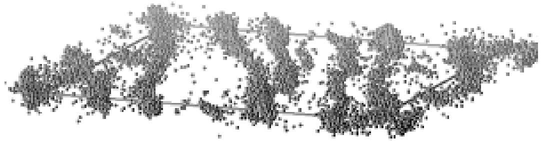


Figure 10. Example of the shape of an $m = 2$ wave packet, seen in the isolated run of Fig. 9a at $T \approx 1$ Gyr. The plot has been obtained by superposing the $m = 2$ density components from approximately 50 different time-steps between $T = 0.9$ and $T = 1.1$, in a coordinate system rotating with the pattern speed of the packet, $\Omega_p = 57\,\mathrm{km\,s^{-1}\,kpc^{-1}}$. In the right-hand panel, the same packet is displayed in polar coordinates. The black-white dashed lines indicate the shape of the critical spiral, having at each distance the radial wavenumber $k = k_{cr}$, while the solid line in the polar plot represents the shape of the short-branch wave calculated from the linear Lin–Shu dispersion relation.

Well described by λ_{cr} spirals! (see also Donner and Thomasson 1984)

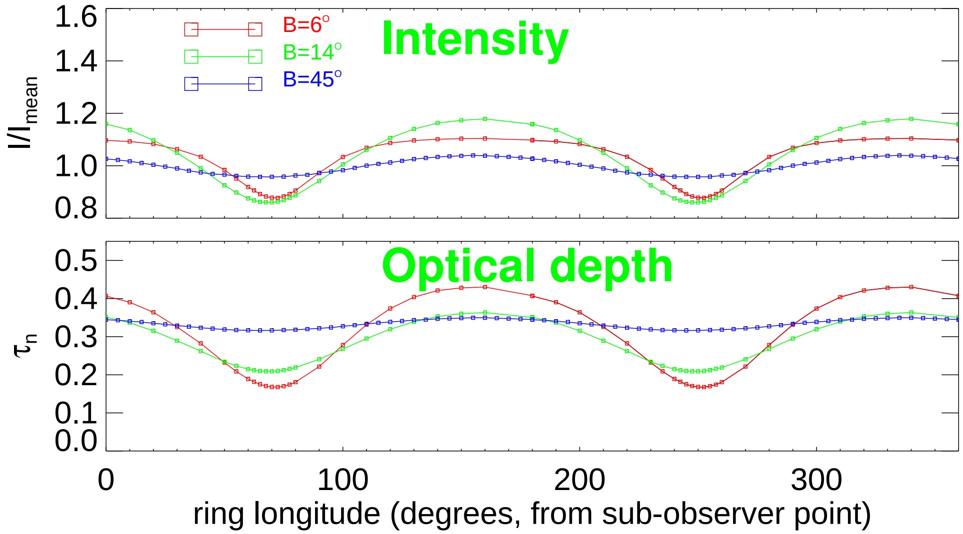
HOW DO SG-WAKES MANIFEST IN SATURN RING OBERVATIONS: AZIMUTHAL ASYMMETRY





θ=249°, B=12⁰

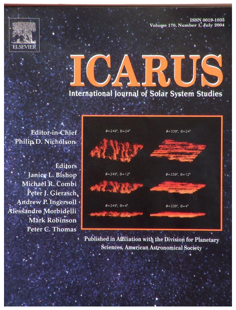
θ=339°, B=12⁰



Wakes unresolved, but have systematic $\sim 20^\circ$ pitch angle $\Rightarrow$

Ring photometric properties should depend on ring longitude and elevation

(Salo et al. 2004)

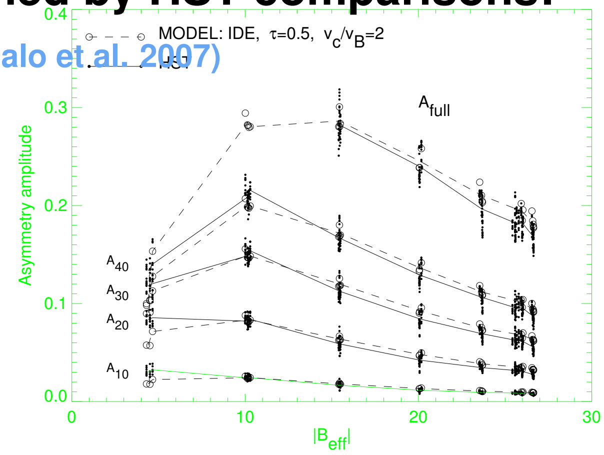


ICARUS

International Journal of Solar System Studies

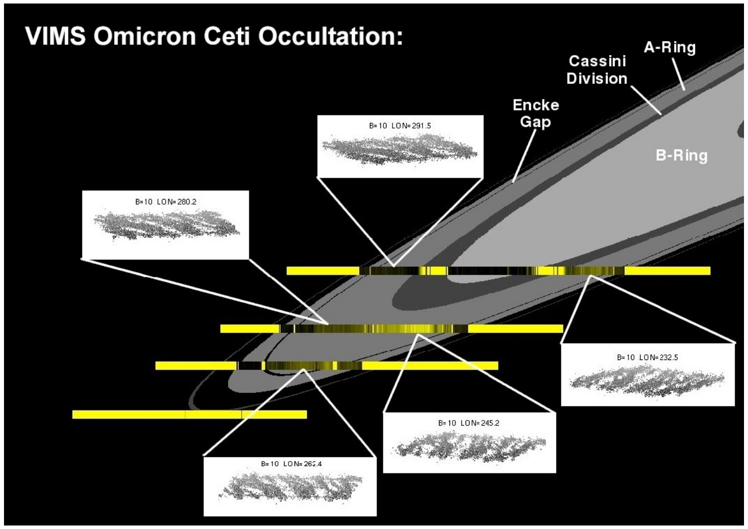
Confirmed by HST comparisons:

(French, Salo et al. 2007)



INDICATIONS OF SELF-GRAVITY WAKES

- **Azimuthal brightness asymmetry** (Dones et al. 1993, Salo etal 2004, French et al, 2007, Porco et al. 2008)
- **Ring's Arecibo radar echo:** (Nicholson et al. 2005)
- **Saturn microwave radiation** (Dunn et al. 2004, 2007)
- **Cassini occultation experiments**
  - **UVIS:** ((Colwell et al. 2006, 2007)
  - **VIMS:** (Hedman et al 2007)
  - **RSS:** (Marouf et al 2006)



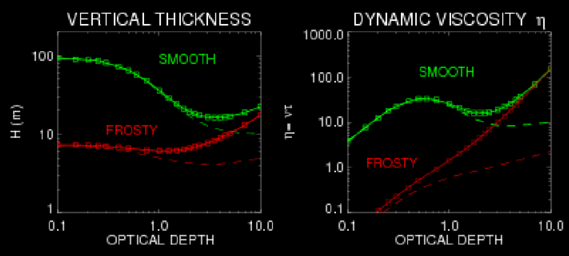
- **Cassini CIRS: ring filling factor** (Ferrari et al 2009)
- **Damping of satellite density waves** (Tiscareno et al. 2008) **consistent with gravitational viscosity** (Daisaka et al. 2001)
- **Strong peaking of asymmetry in the mid A-ring is a problem**

  (wakes perhaps hidden by debris = free-floating regolith released in fast impacts? Salo et al. 2007 DPS)

VISCOUS INSTABILITY AND OVERSTABILITY

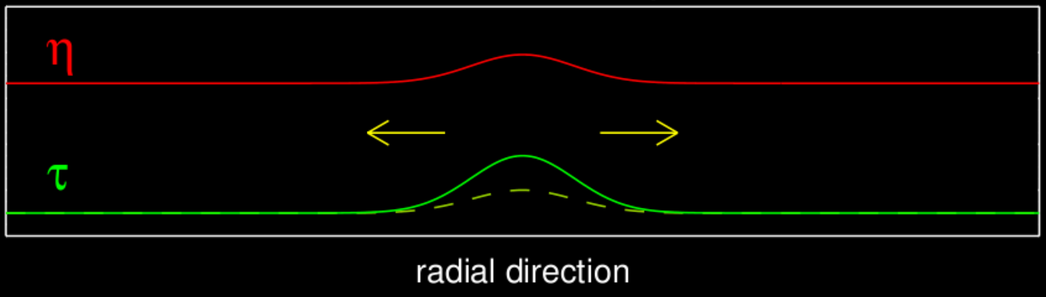
LINEAR STABILITY: DEPENDS ON $\eta(\tau)$

RADIAL MASS FLUX: $\tau u_r \sim -\partial\eta/\partial r$



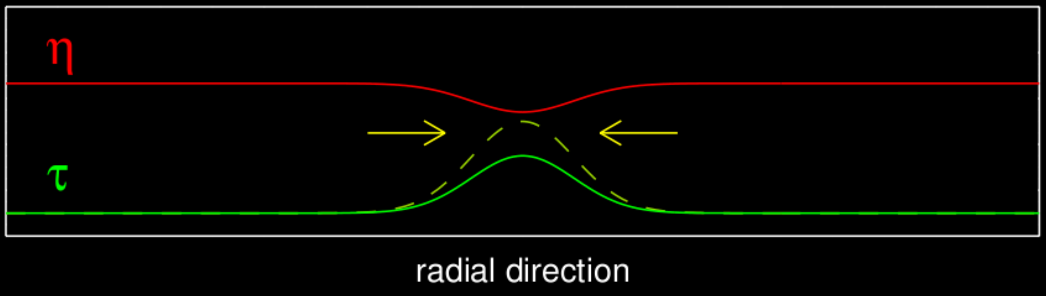
INTERMEDIATE CASE

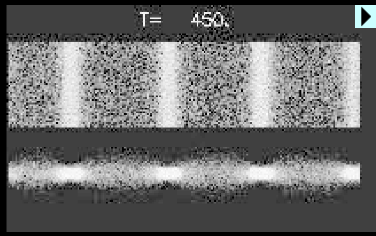
STABLE RING: ∂η/∂τ > 0



'THICK' RING

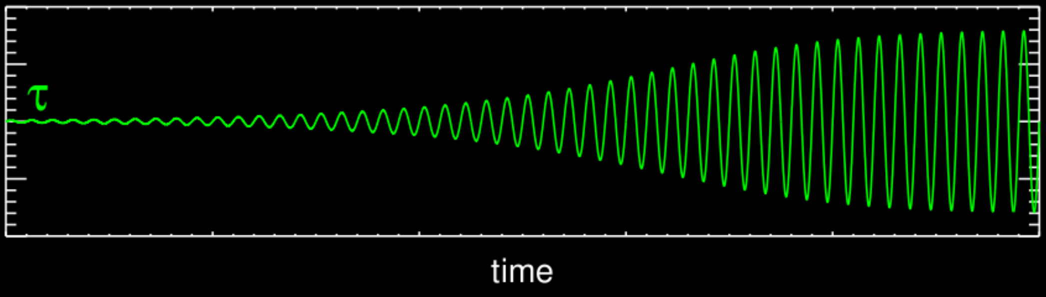
VISCOUS INSTABILITY: ∂η/∂τ < 0

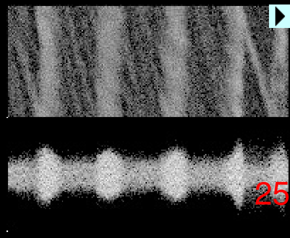




FLAT RING + SELF GRAVITY

VISCOUS OVERSTABILITY: ∂η/∂τ >> 0

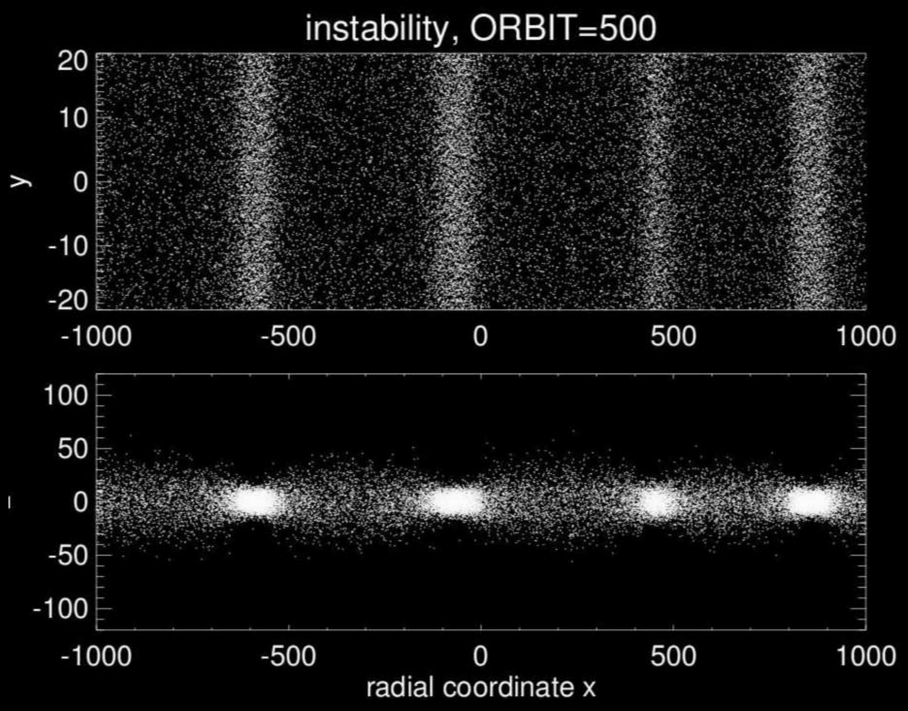




VISCOUS INSTABILITY

- **Particle flux directed toward density maxima**
  - Dense/cool ringlets
  - Hot/rarefied region

$\Rightarrow$ **BIMODAL**



= Original explanation for “ringlet structure” discovered by Voyager, but later discarded

Hämeen-Anttila, Lukkari, Ward, Lin &Bodenheimer

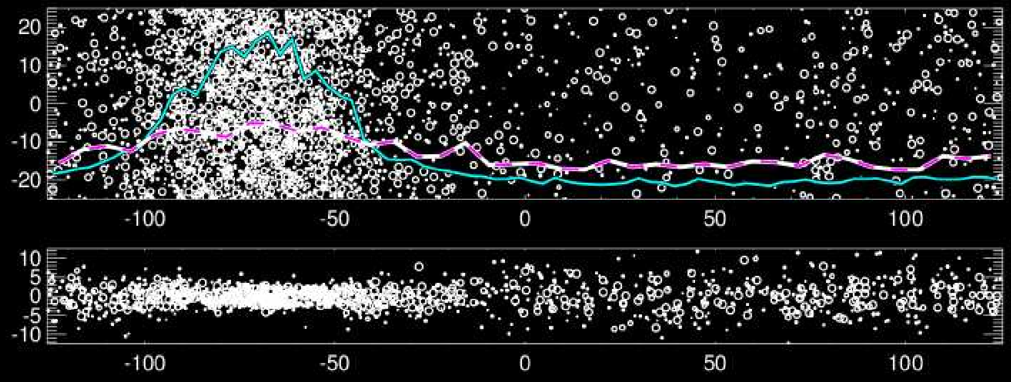
Requires smooth elastic particles, inconsistent with gravity wakes.

- **Size-dependent selective instability?**

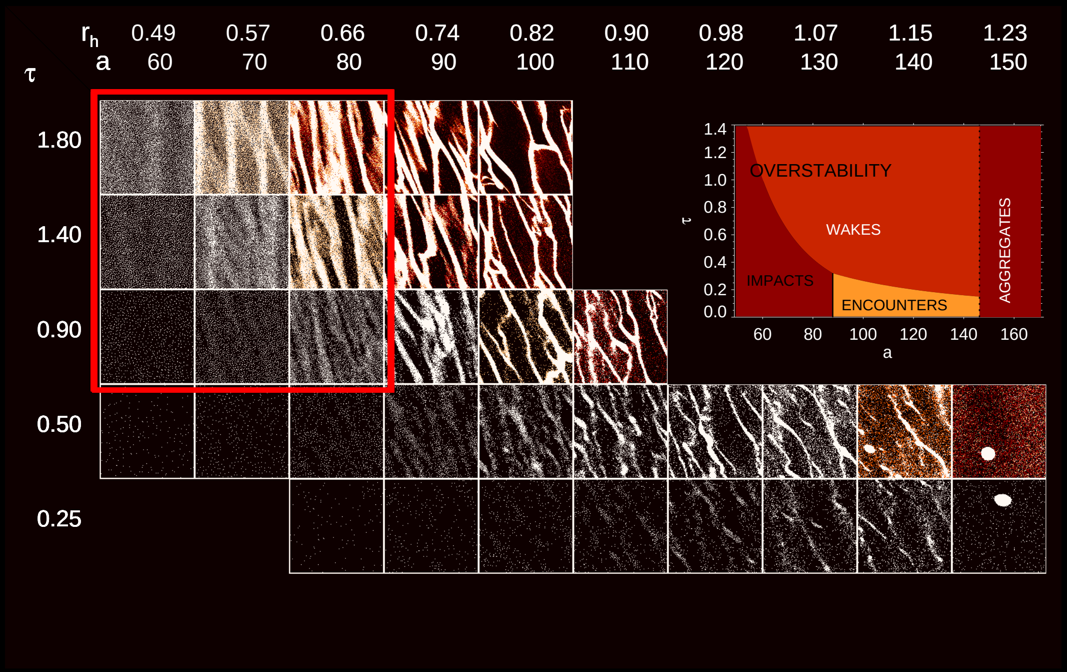
works also between two dense regions!

Salo & Schmidt (Icarus, 2010)

However, requires rather specific ϵ_n vs particle size dependence



OSCILLATORY INSTABILITY (VISCOUS OVERSTABILITY)



Upper left corner:

weak gravity, high impact frequency ⇒

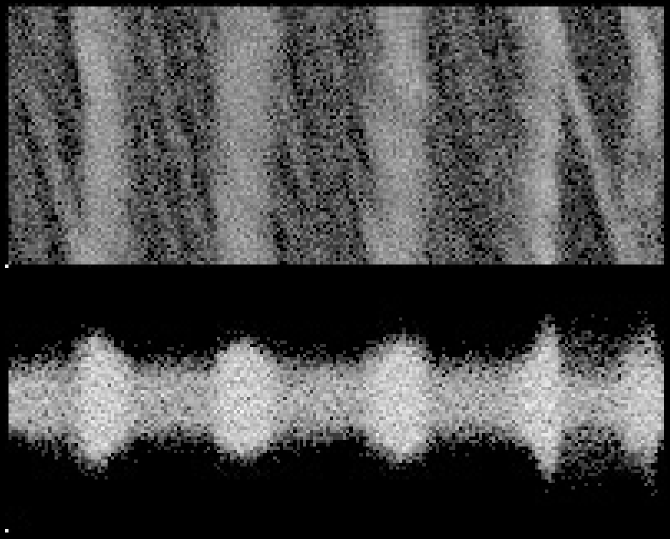
axisymmetric oscillations superposed on

inclined selfgravity wakes

Ring overshoots in smoothing density variations

due to steep rise of viscosity with density.

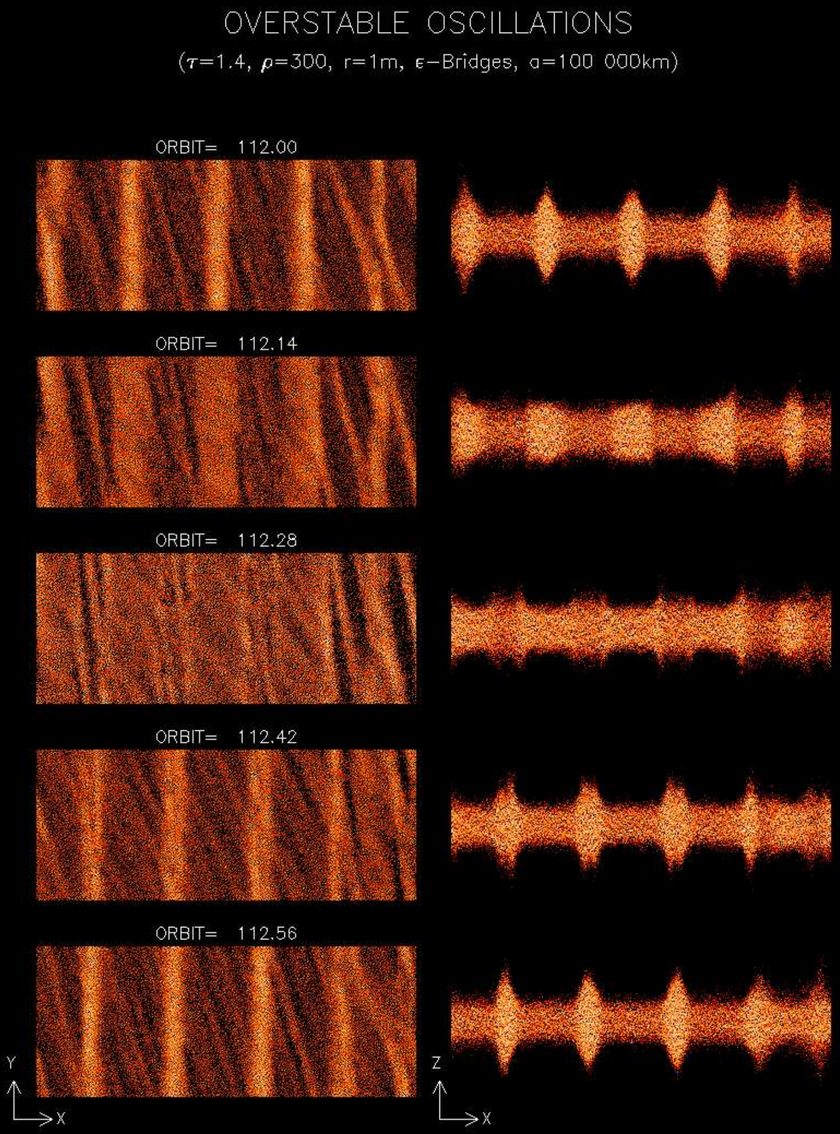
Salo et al. 2001, Schmidt et al. 2001



OVERSTABILITY II

Oscillations with epicyclic frequency

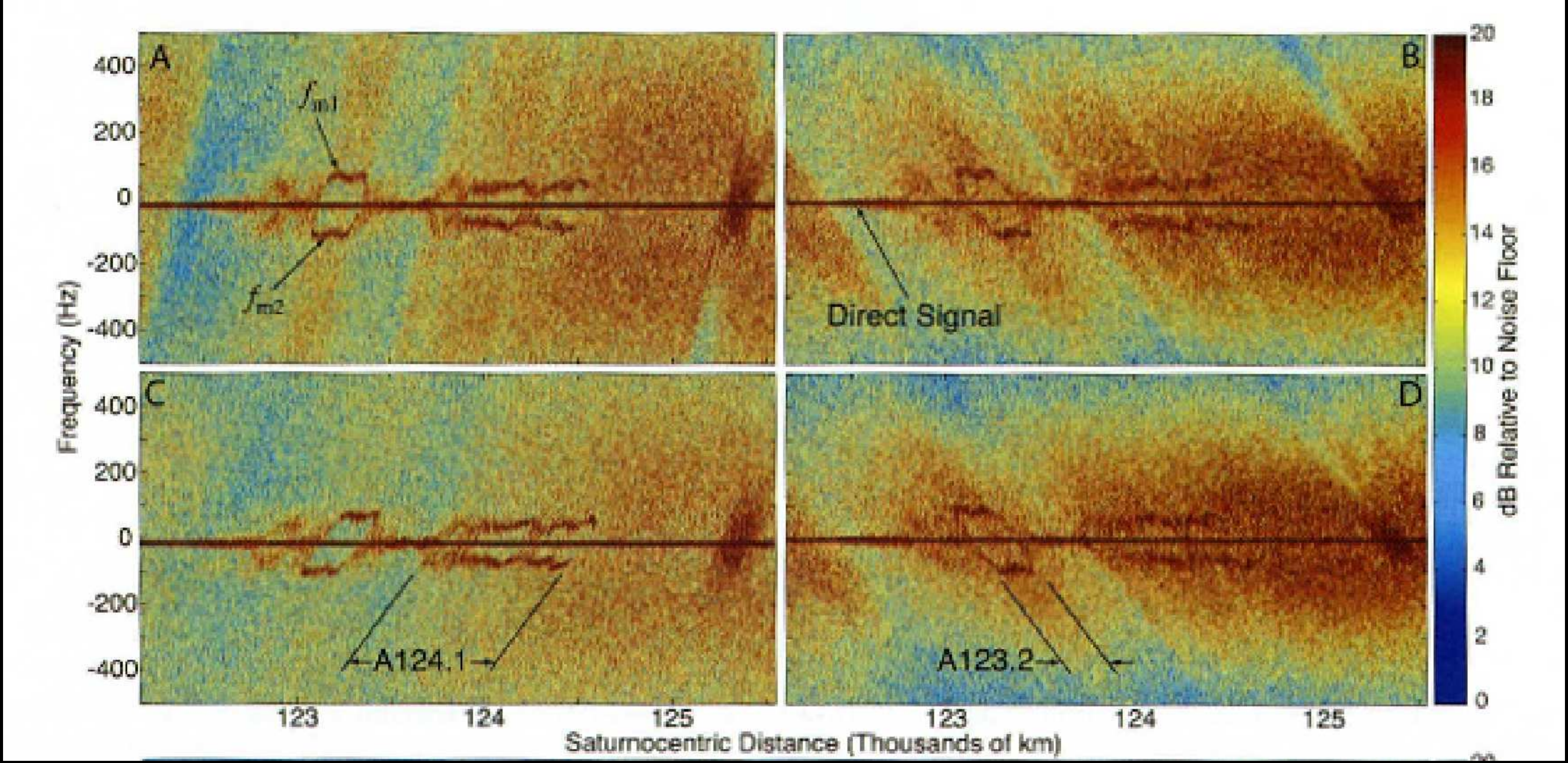
Time-evolution over 1/2 periods ⇒



- Hydrodynamical stability analysis
  Schmit & Tscharnuter 1995, 1995
  predicted too easy onset of overstability
- Disagreement with N-body simulations
  (Salo et al. 2001)
  ⇒ improved hydrodynamic models
  Schmidt et al. 2001, Schmidt & and Salo 2003)
- proper kinetic treatment
  Latter & Ogilve 2006, 2007

OSCILLATORY INSTABILITY III

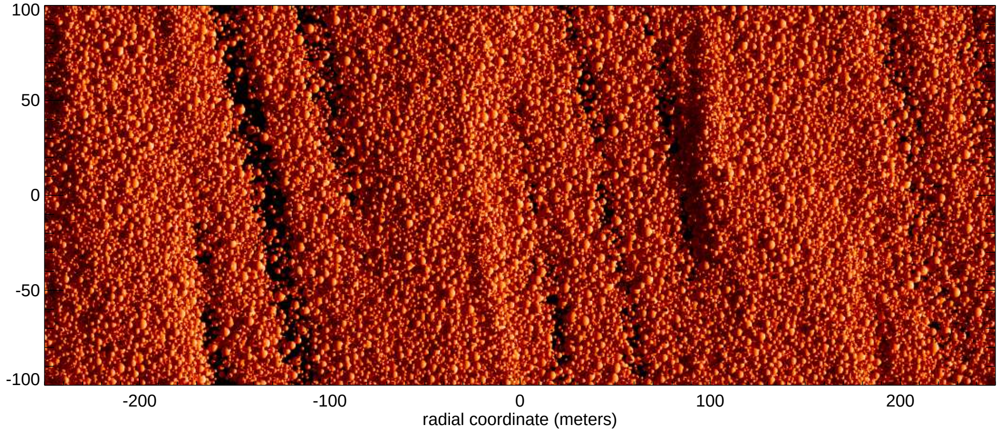
- **Cause of the 150m oscillations in RSS occultations?** (Thomsen et al 2007)
- **UVIS occultations: axisymmetric structures** (Colwell et al. 2007)



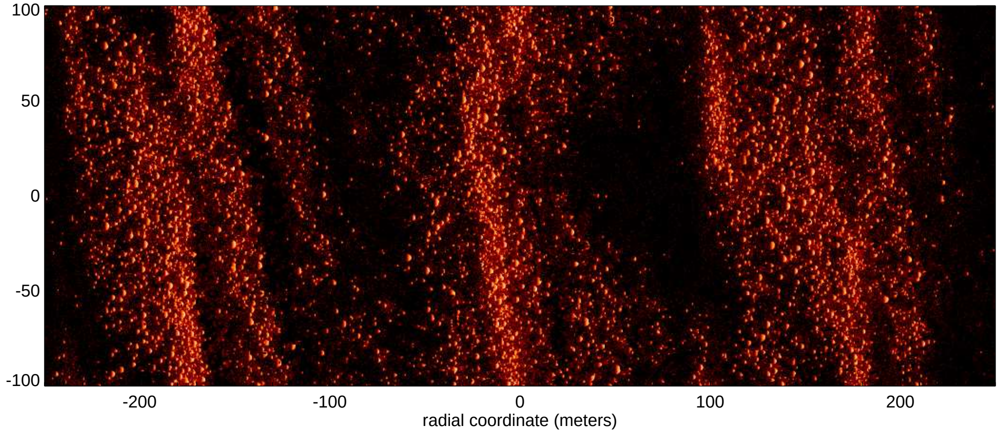
Matches the natural scale seen in simulations

VERTICAL SPLASHING - SHADOWS

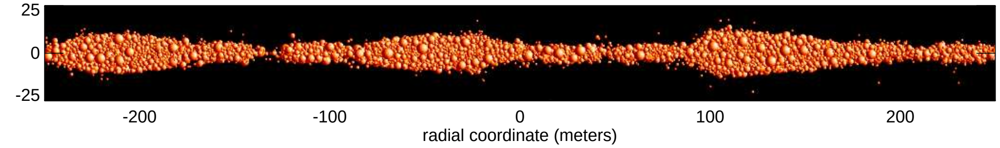
$B_{sun}=25^o$



$B_{sun}=5^o$



vertical cut



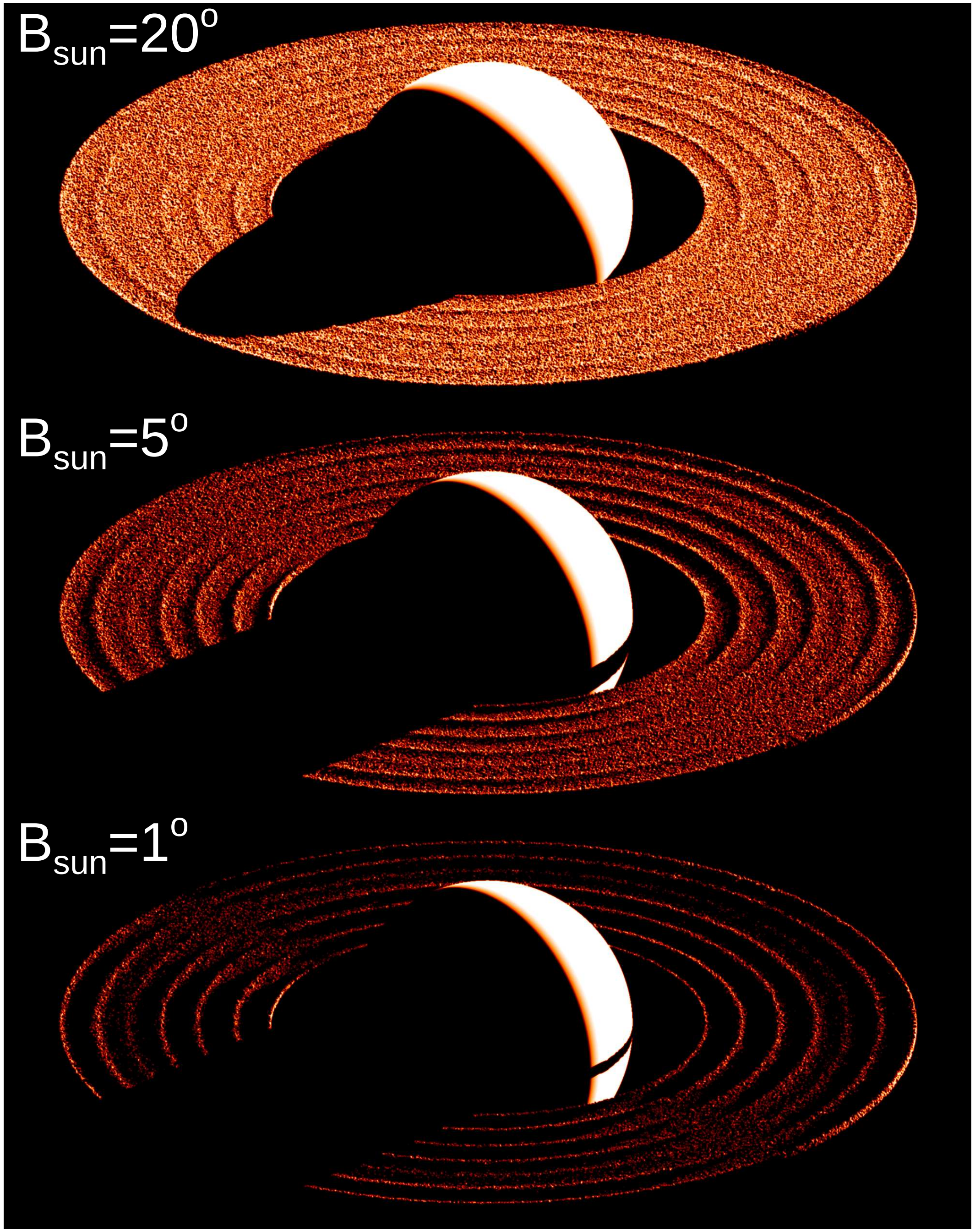
Dense rings nearly imcompressible

$\Rightarrow$ overstable oscillations associated with vertical 'splashing'

(Borderies, Goldreich, Tremaine 1984)

Effect strong enough to cause shadows (middle frame)

OBSERVABLE EFFECTS OF NON-RESOLVED SHADOWS?

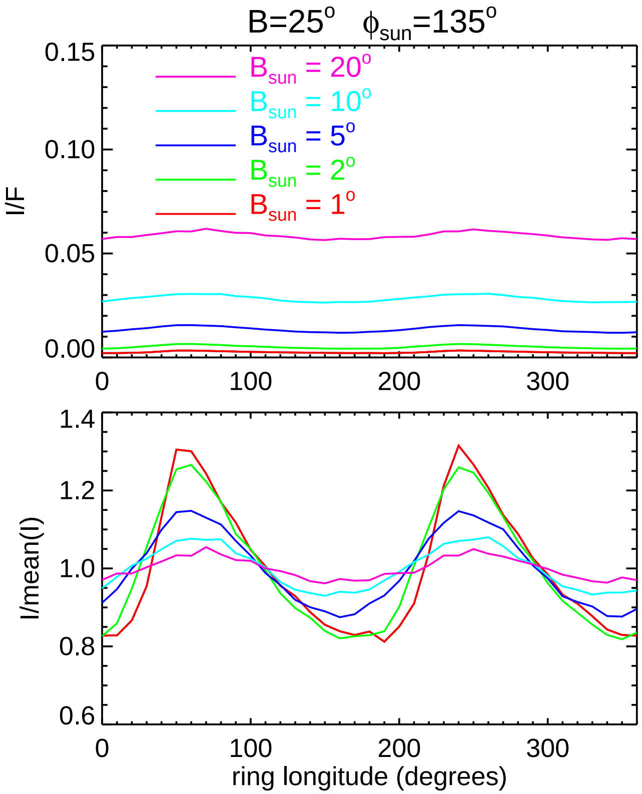


TOY-model (true shadows non-resolved!)

Mean brightess as function of azimuth:

Even 10% systematic variations predicted

Salo &Schmidt 2011 DPS



MODELING PROPELLERS

- Embedded moonlet > 1 km $\Rightarrow$ circumferential gap

  Smaller moonlets $\Rightarrow$ viscous diffusion limits the azimuthal extent of the gap

  s-shaped propeller Spahn & Sremcevic 2000

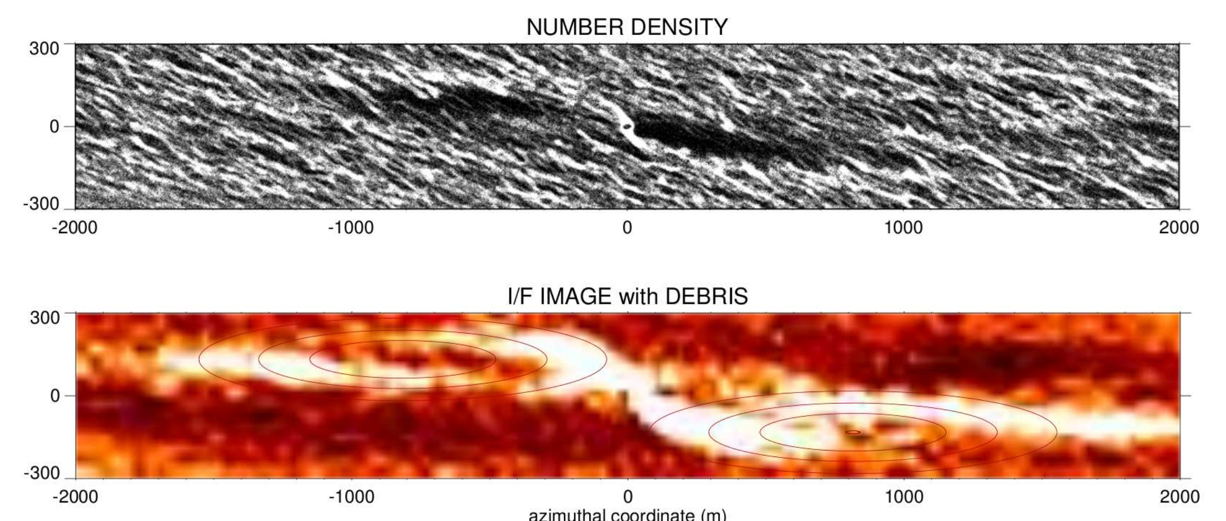
- First observed propellers: unlit side (Tiscareno, Burns et al 2006, Nature)

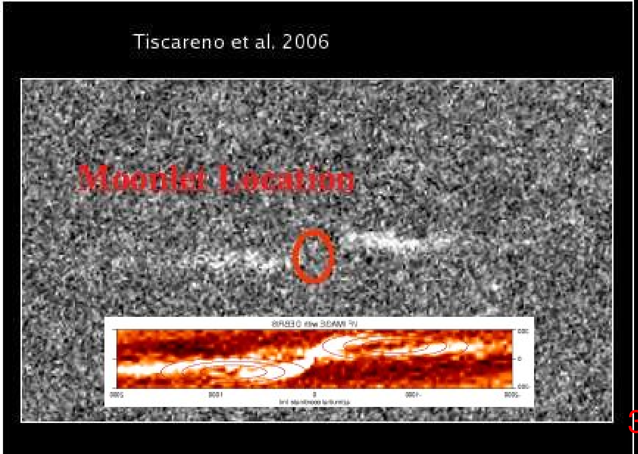
  $\Rightarrow$ uncertain whether bright streaks correspond to

  gaps (separation $\sim 2R_{HILL}$) or density crests (separation $\sim 4R_{HILL}$)

- Our photometric modeling (Sremcevic, Schmidt, Salo et al. 2007, Nature)

  supports bright density crests, mainly due to release of surface regolith

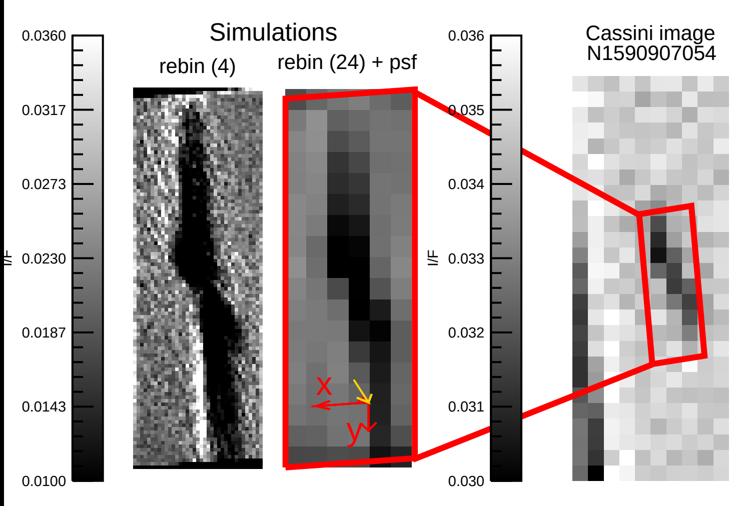


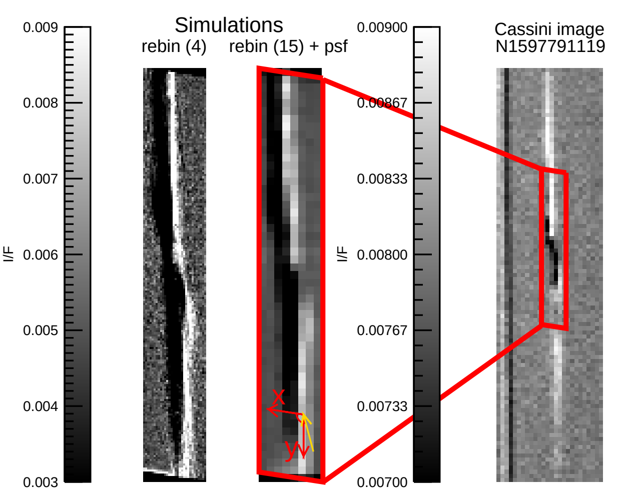


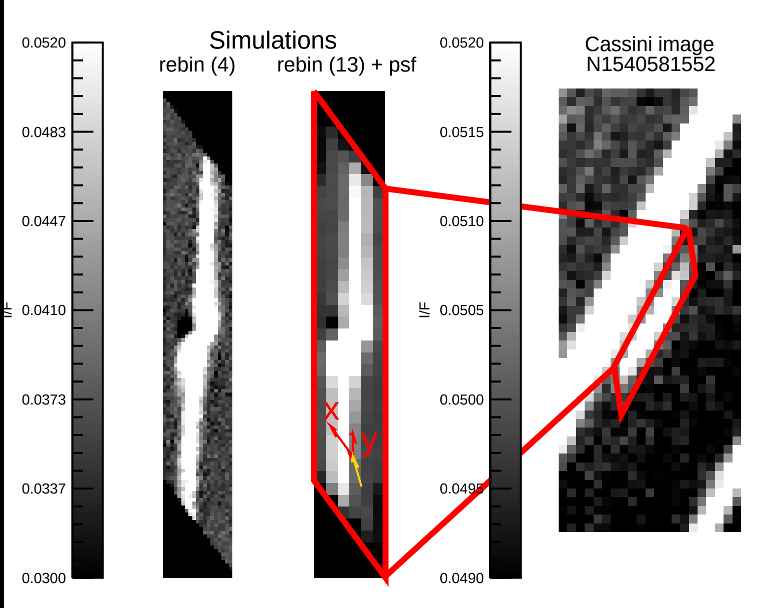
ONGOING PHOTOMETRIC MODELING:

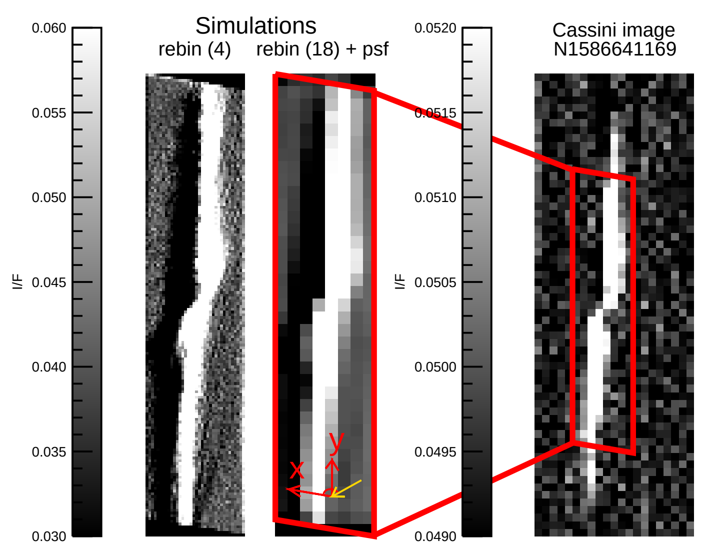
Same dynamical/debris model consistent with various lit/unlit observations of Bleriot

⇒ consistent estimate for moonlet size (Halme et al. in preparation)









RING FILLING FACTOR/PHOTOMETRY

OPPOSITION BRIGHTENING

Coherent backscattering
at particle surface regolith

or

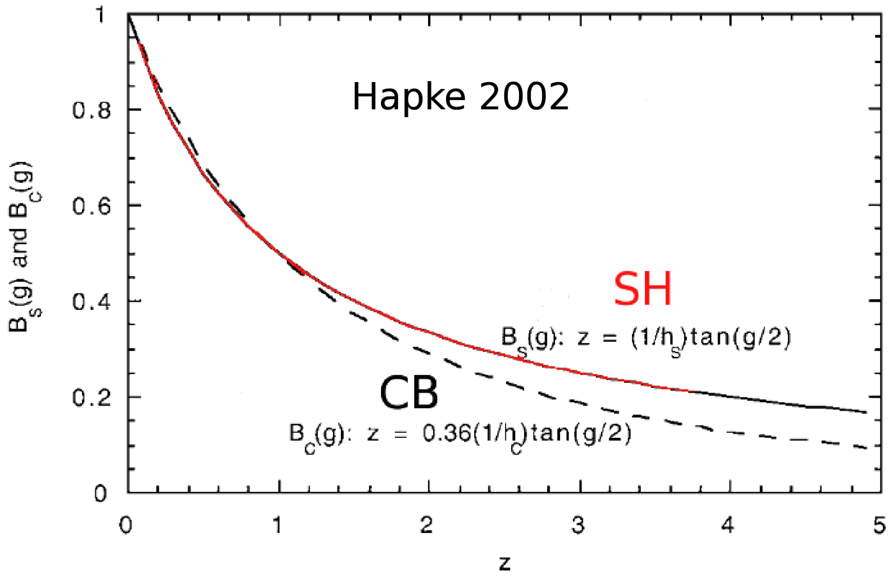
disappearence of mutual
shadow between particles ?

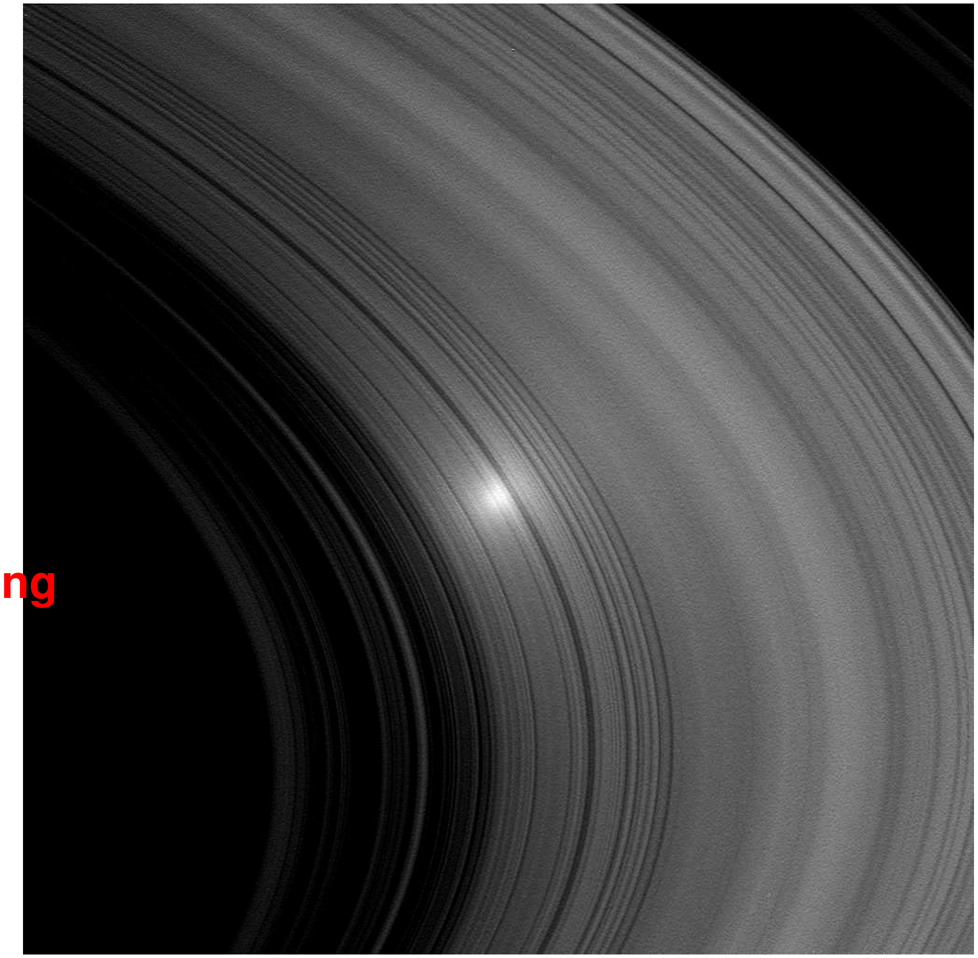
(Debated for over 50 years!)

Lumme et al. 1983: due mutual shadowing

⇒ filling factor 0.02

How to reconcile with dense rings?)

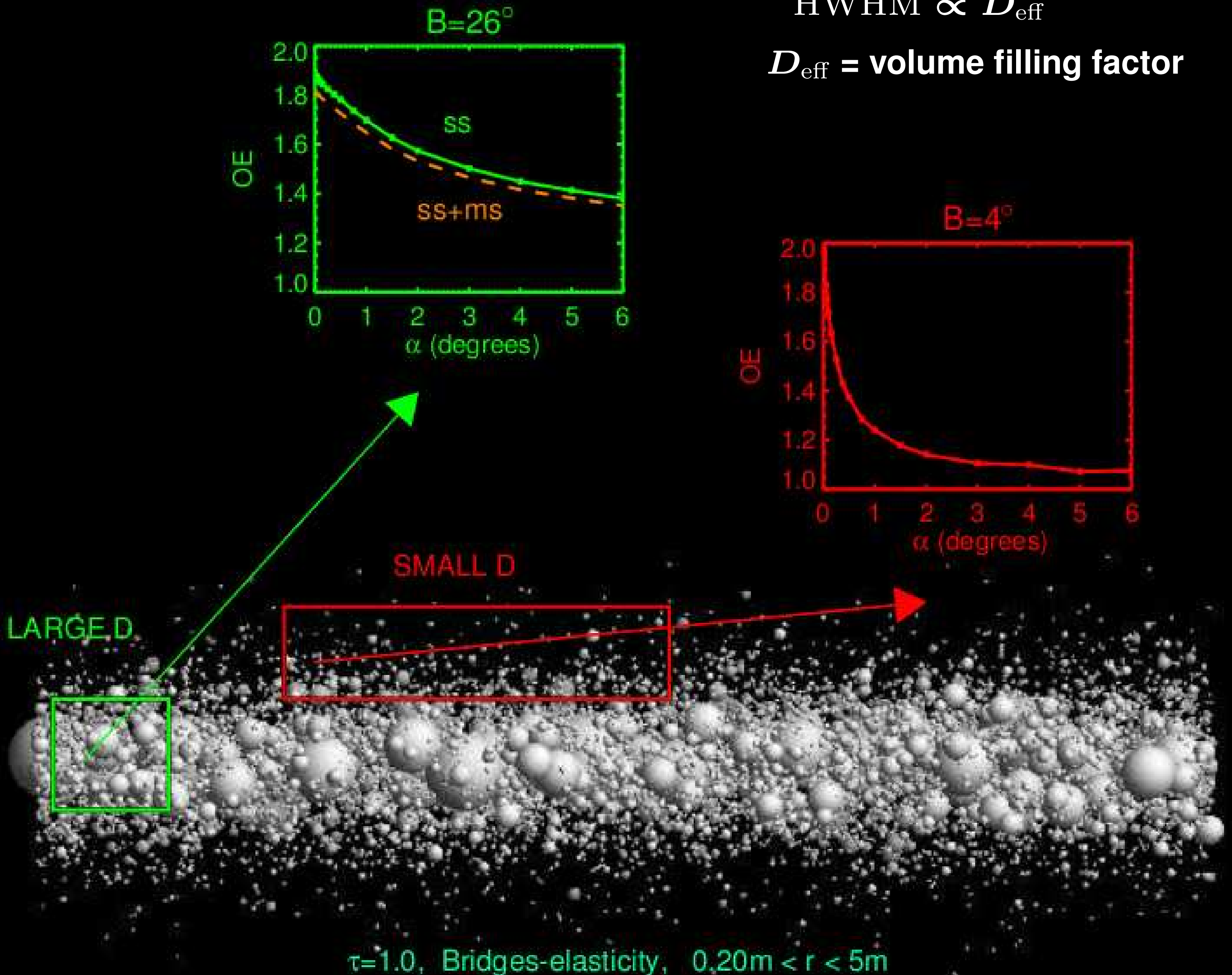




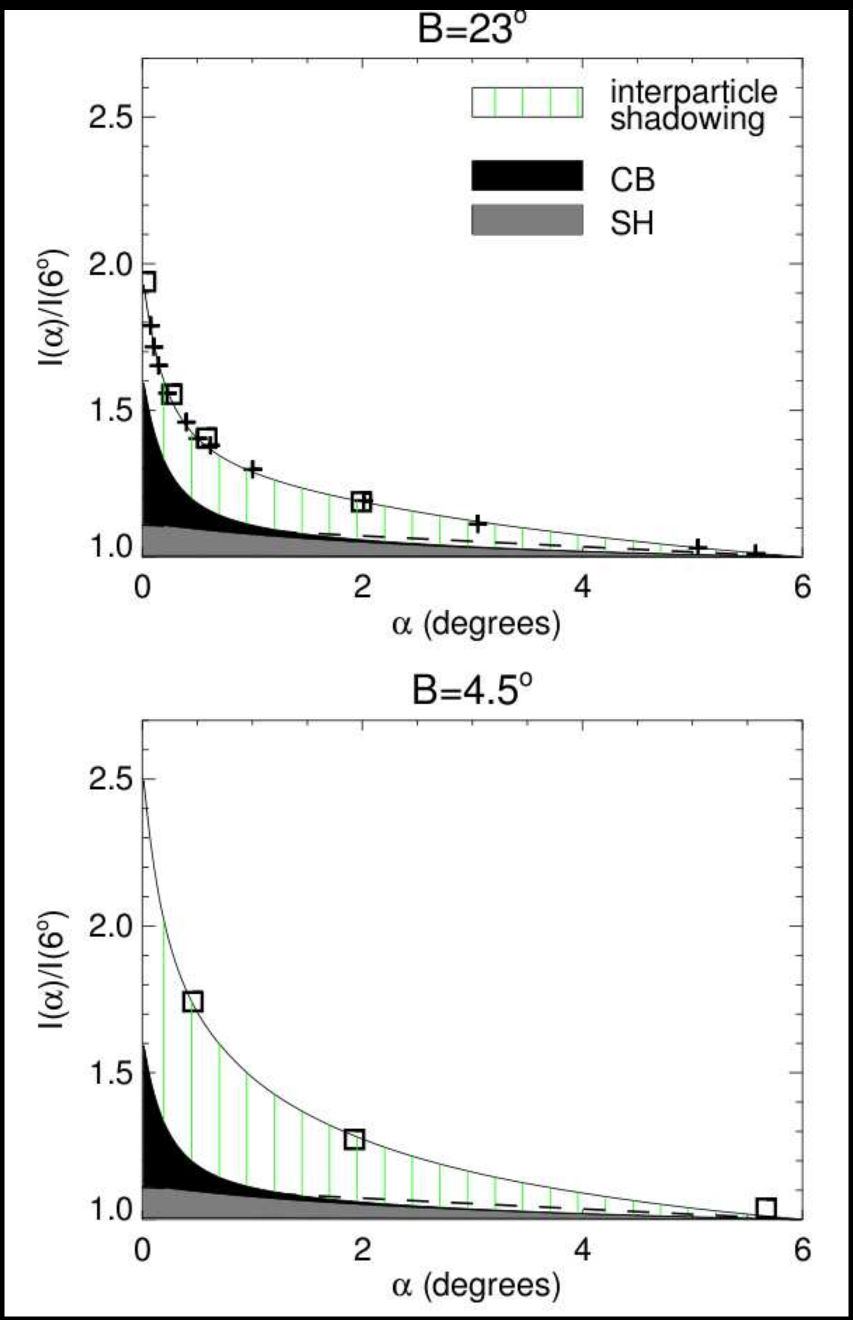
MUTUAL SHADOWING DEPENDS ON ELEVATION

$$\mathrm{HWHM} \propto D_{\mathrm{eff}}$$

D_{eff} = **volume filling factor**



- **Observed HST phase curves show elevation dependence!**



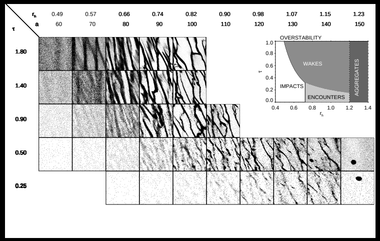
NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC01-15

Dick French

⇒ **Intrinsic and mutual shadowing can be separated! (Salo and French, Icarus 2010)**

Narrow peak consistent with flat dense ring predicted by dynamics

SUMMARY

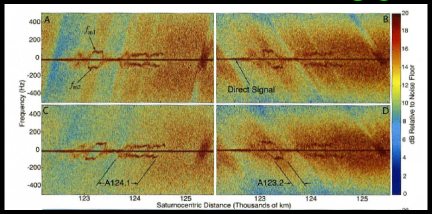


- **SG-WAKES WERE EXPECTED IN SATURN'S RINGS**
- **SELF-GRAVITY WAKES CAN ACCOUNT FOR:**

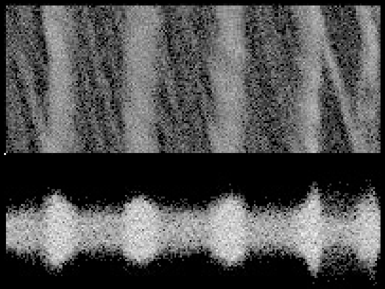
  A-ring and inner B ring asymmetry in HST observations
  Radar asymmetry
  Longitude and elevation angle dependent optical depth

- **OVERSTABILITY:**

  High density/weak gravity regime
  $\Rightarrow$ **150 m oscillations, modulations(?)**



150 meter fine-structure



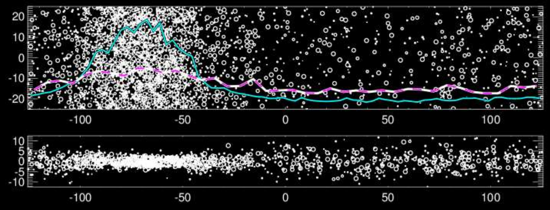
- **IMPLIED RING PARTICLE PROPERTIES:**

  internal density $\sim 300 - 450$ kg/m^3
  elasticity close to Bridges et al. 1984 'frosty ice'

- **STILL A PROBLEM: IRREGULAR VARIATIONS:**

  Role of selective intabilities?

- **Particle adhesion?**



SUMMARY

RINGS = IDEAL LABORATORY

- Dynamically old
- Impacts keep it cold
- Interesting mechanism can be treated locally

Self-gravity wakes and propellers

Excitation of forced spiral density waves and bending waves

Freely winding vertical corrugations

WHAT NEXT?

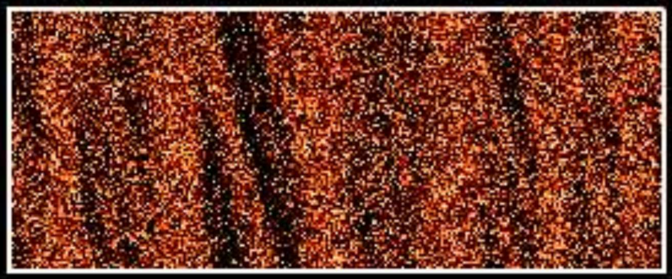
1991
1e3
0.5*0.5

SIZE DIST
GRAVITY

Particle number makes a difference on what problems can be attacked!

1996
1e4
2*2

SG-WAKE
SURVEYS



2001
N=1e5
10*4
OS

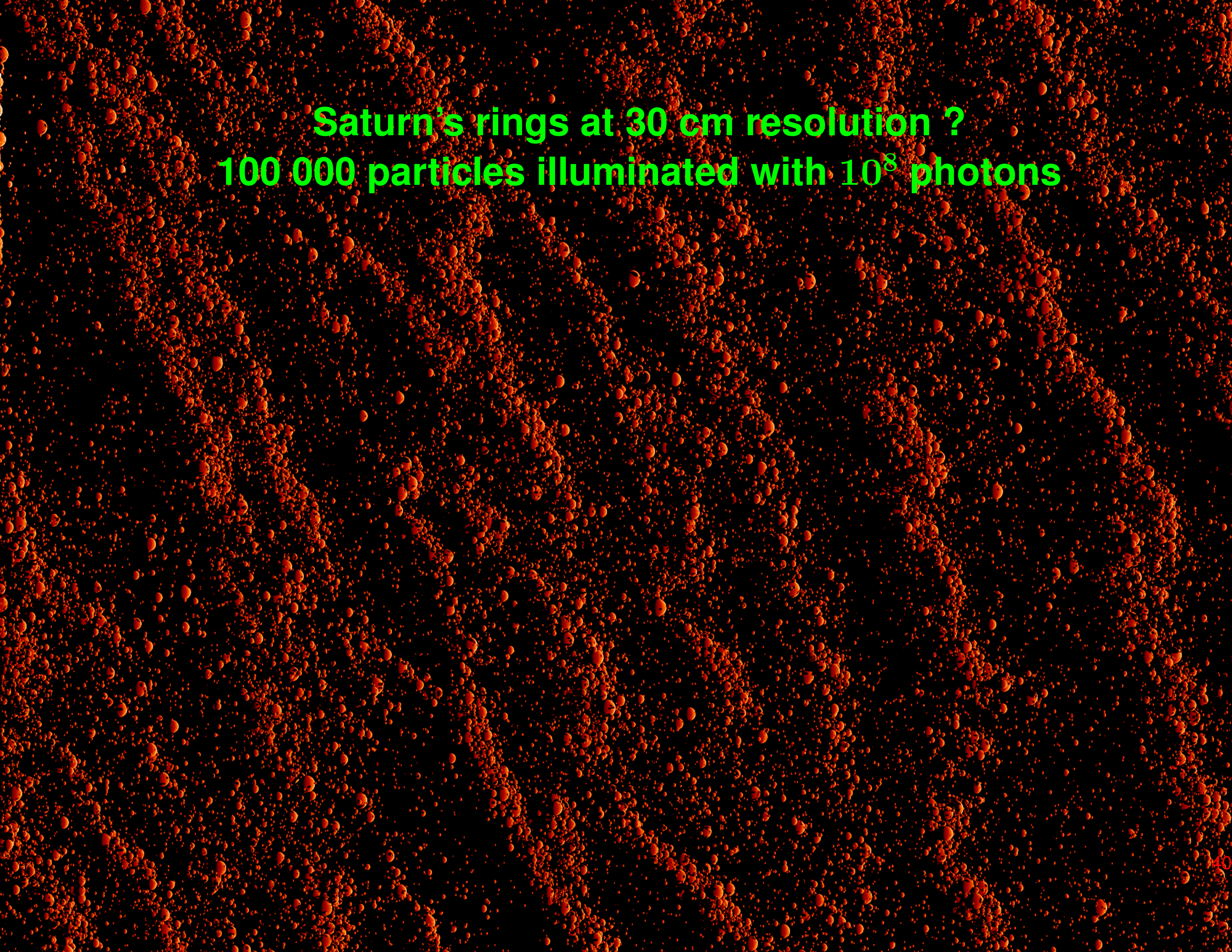
Poster by Fujii, Kokubo : using GRAPE-DR may enable $N >> 1e6$ in near future

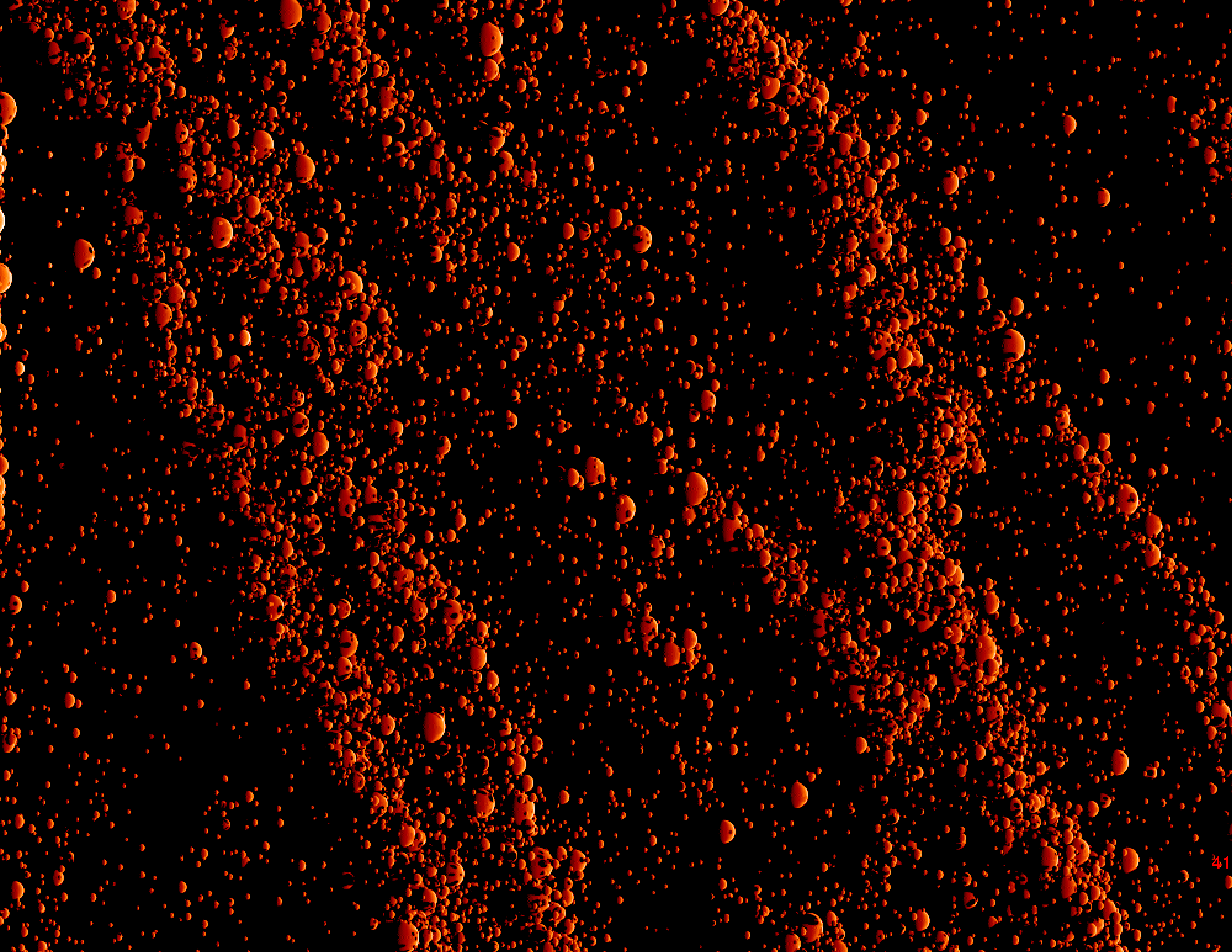
SOME POSSIBILITIES:

Propeller migration, Damping of density waves with realistic viscosity

Evolution of particle size distribution, ring vertical splashing etc.

Saturn’s rings at 30 cm resolution ?
100 000 particles illuminated with 10^8 photons

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Thank You!