Rings around small bodies of the solar systems: surprising newcomers

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The main topics of this talk

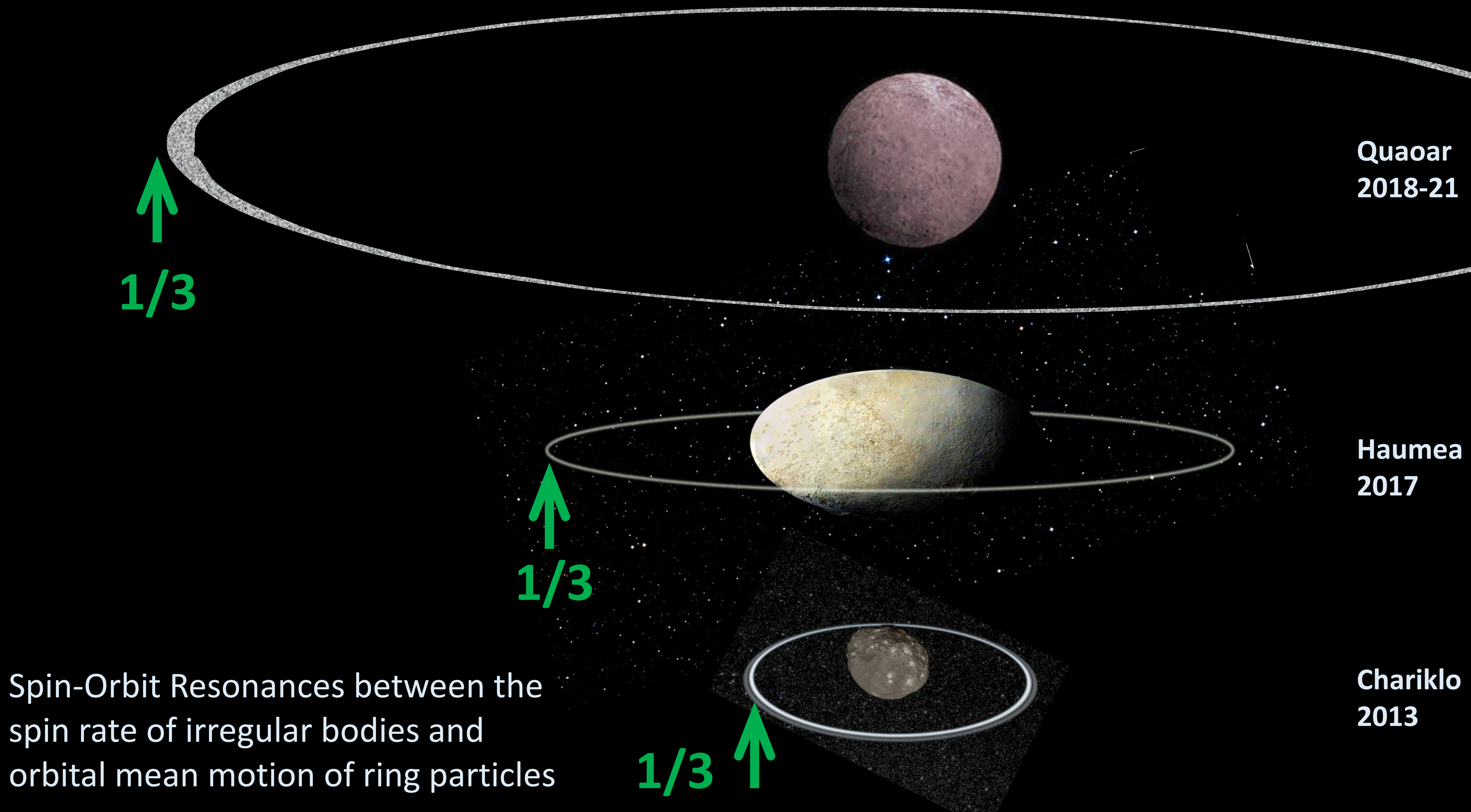
Rings are now seen around at least 3 small bodies of the solar system

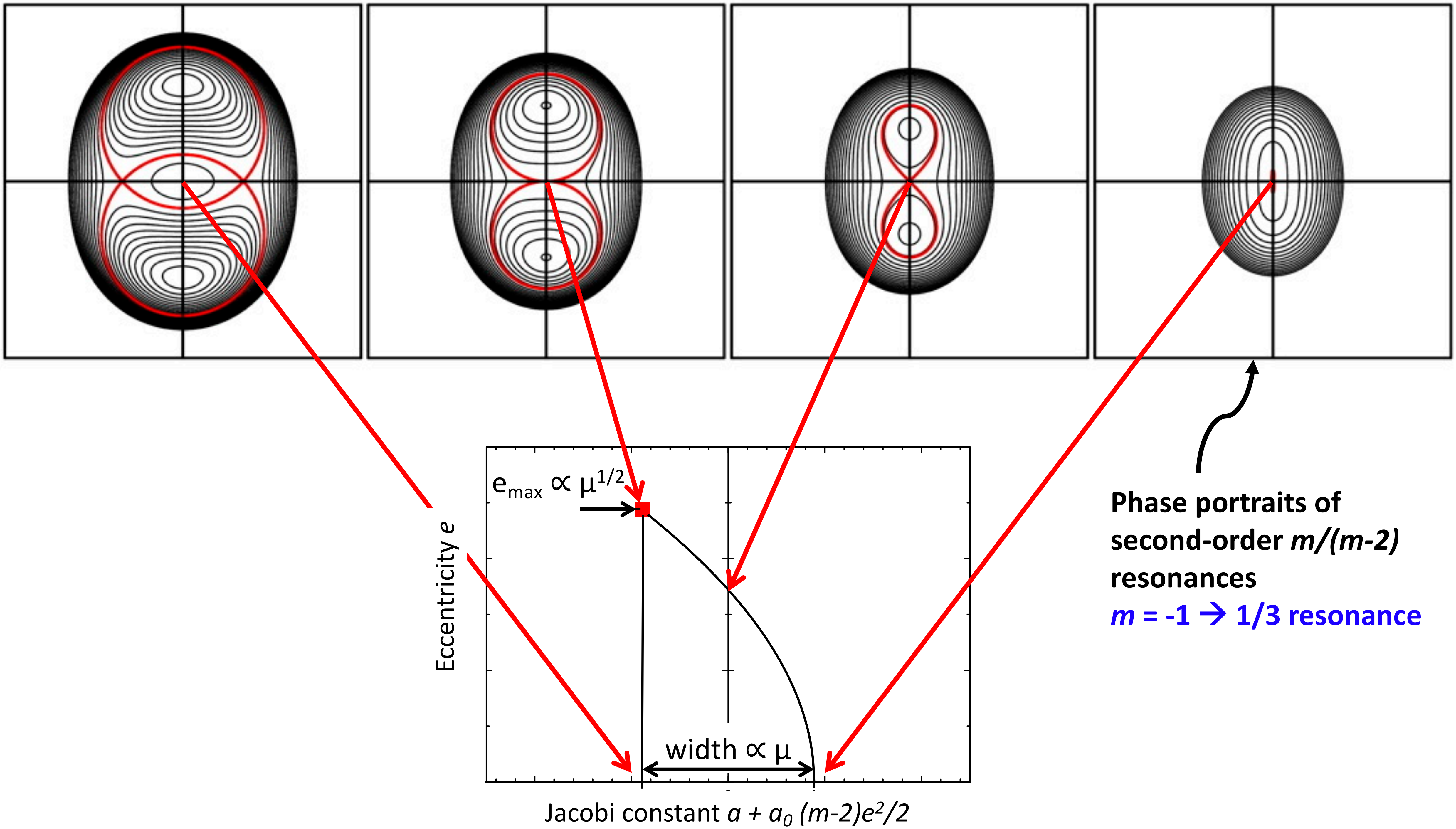
Why are they confined at second-order resonances, where they are not supposed to be confined?

Why is one of the ring systems (Quaoar’s) well beyond the Roche limit, where they it is not supposed to survive?

Work made in collabotaion with Heikki Salo
Oulu University, Finland
May/June 2023

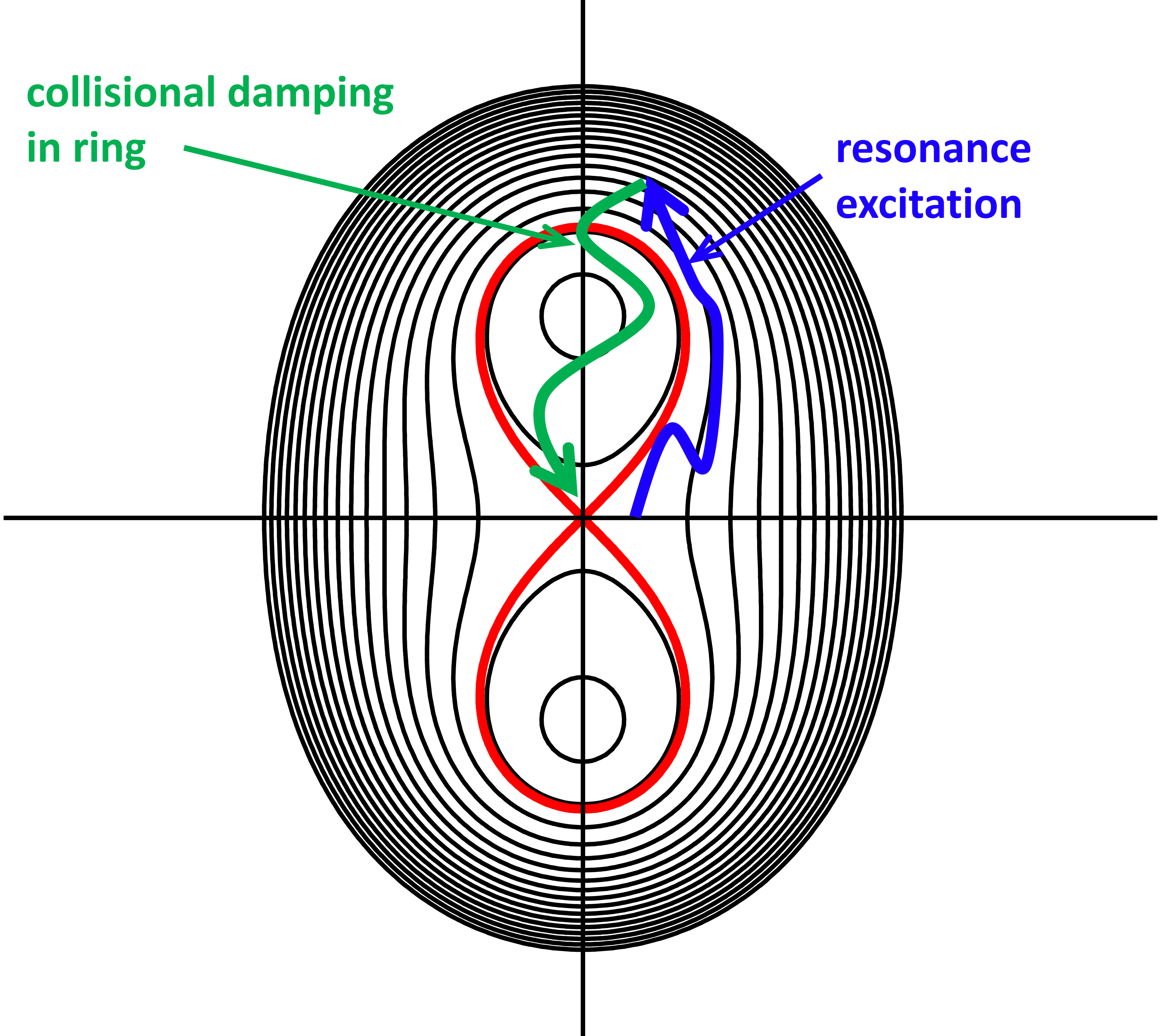
… making a ring on a desk …

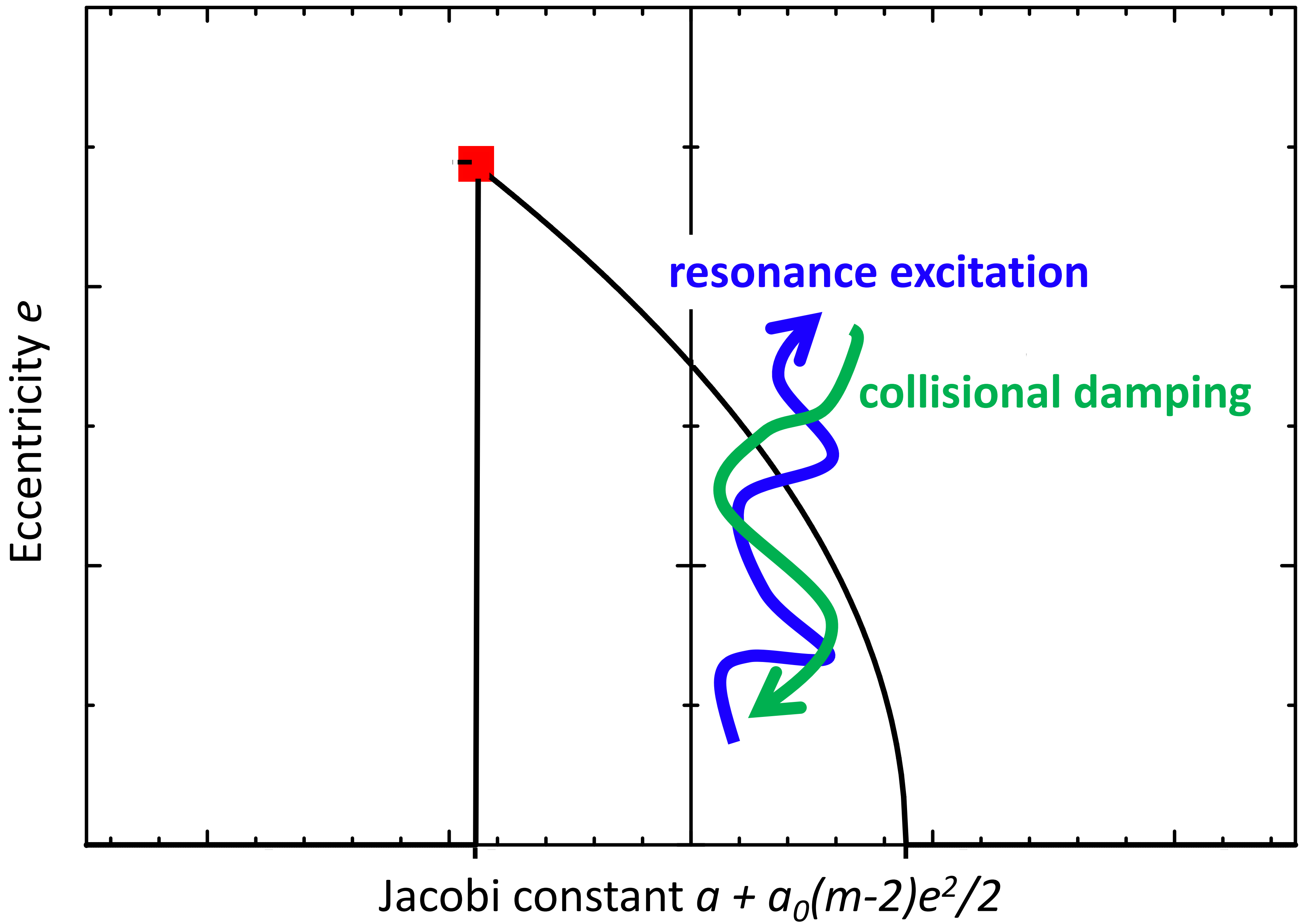

1/3
Quaoar
2018-21
Haumea
2017
1/3
Chariklo
2013
1/3
Spin-Orbit Resonances between the spin rate of irregular bodies and orbital mean motion of ring particles



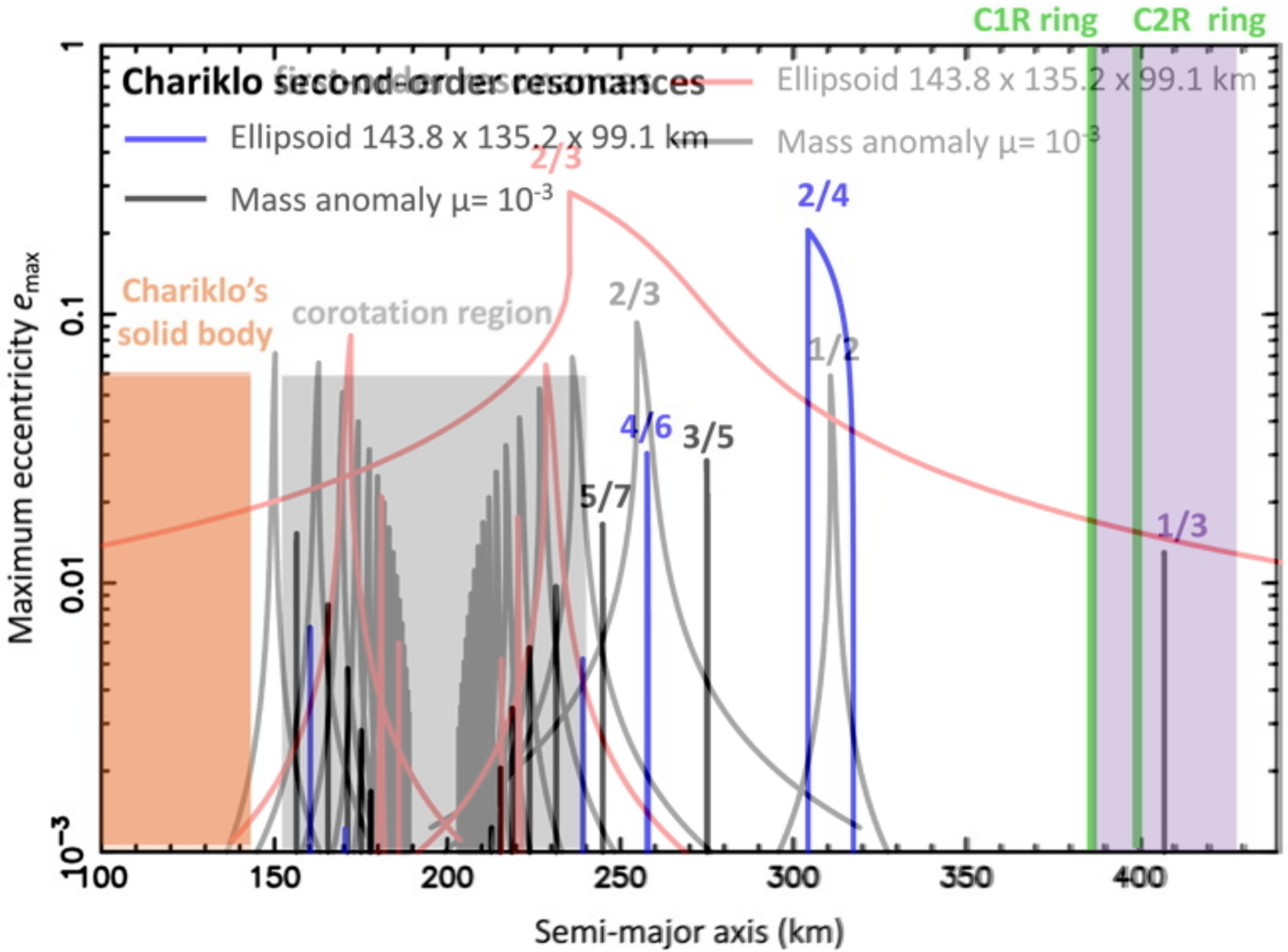
Phase portraits of second-order *m/(m-2)* resonances

***m* = -1 → 1/3 resonance**


collisional damping
in ring
resonance
excitation

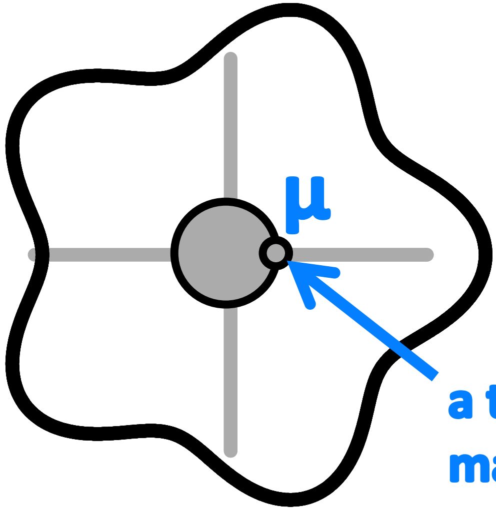


resonance excitation
collisional damping
Eccentricity e
Jacobi constant $a + a_0(m-2)e^2/2$


C1R ring
C2R ring
Chariklo second-order resonances
Ellipsoid 143.8 x 135.2 x 99.1 km
Mass anomaly μ= 10^-3
Ellipsoid 143.8 x 135.2 x 99.1 km
Mass anomaly μ= 10^-3
2/3
2/4
Chariklo's solid body
corotation region
2/3
1/2
4/6
3/5
5/7
1/3
Maximum eccentricity e_max
Semi-major axis (km)
1
0.1
0.01
10^-3
100
150
200
250
300
350
400

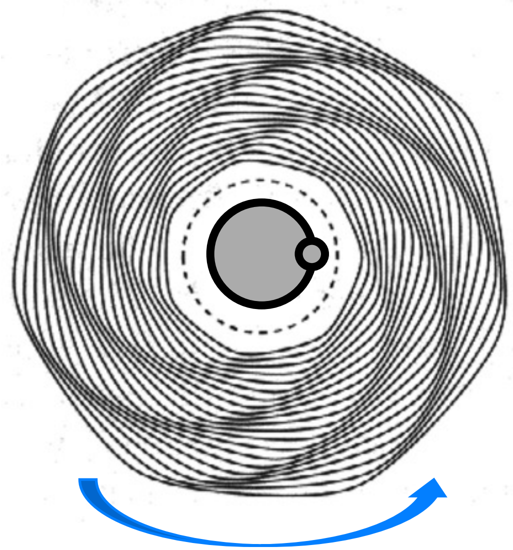
n/Ω= 5/6

1st order (Lindblad) resonance



n/Ω= 7/8

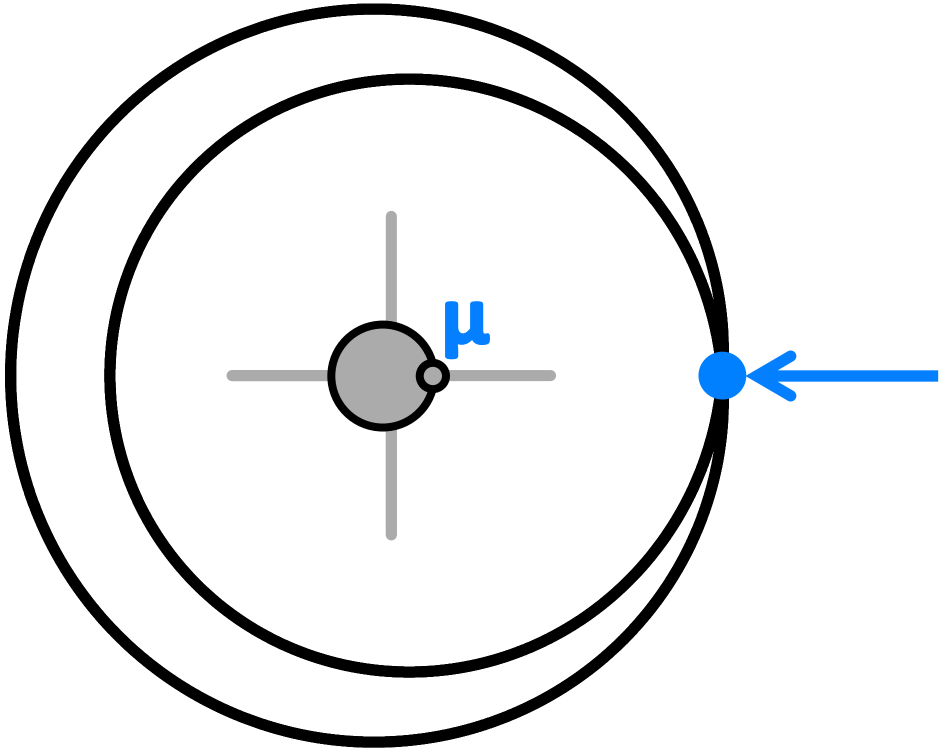
Murray & Dermott 2000



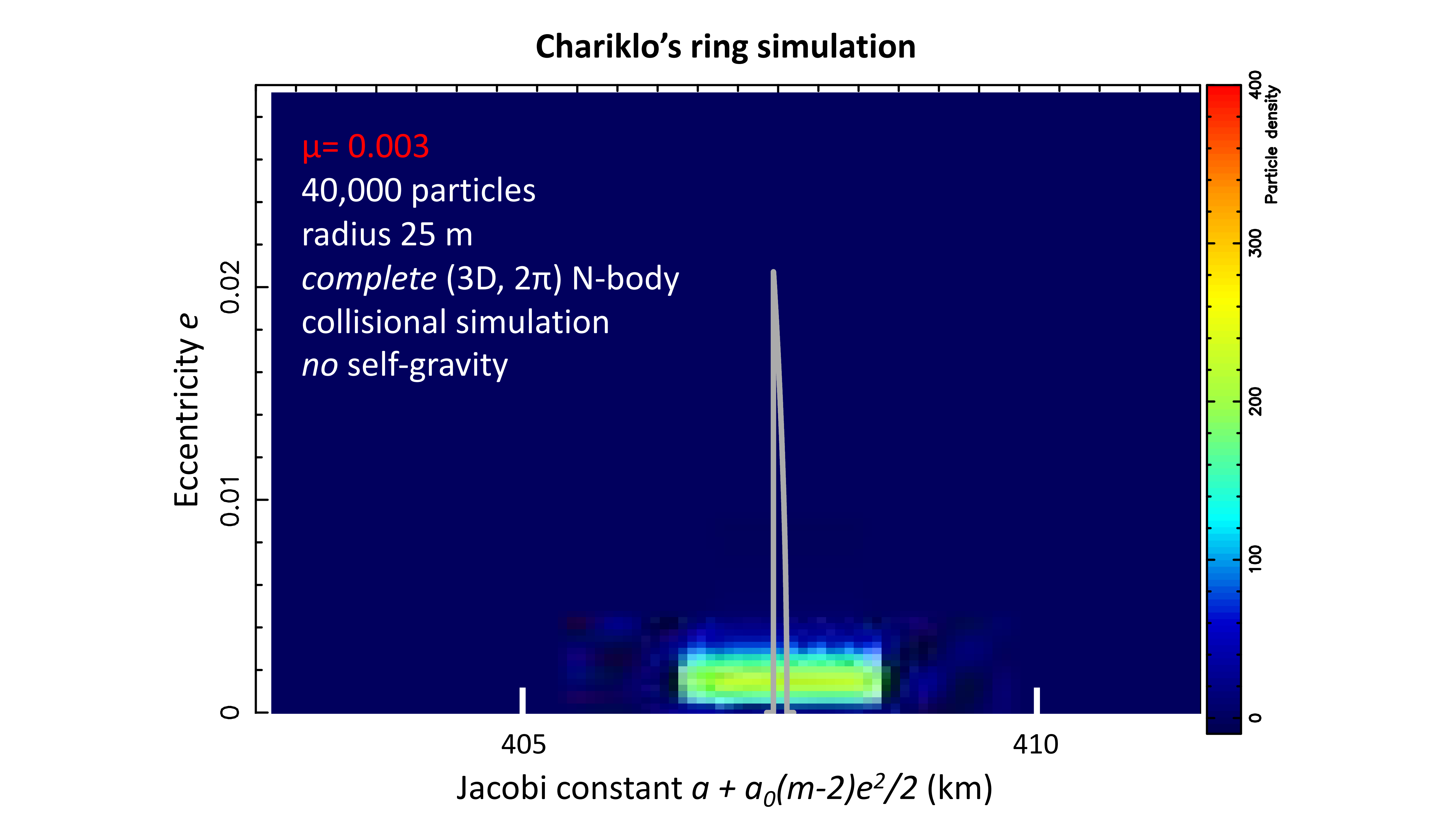
here wave pattern speed
= spin rate of body

n/Ω= 1/3

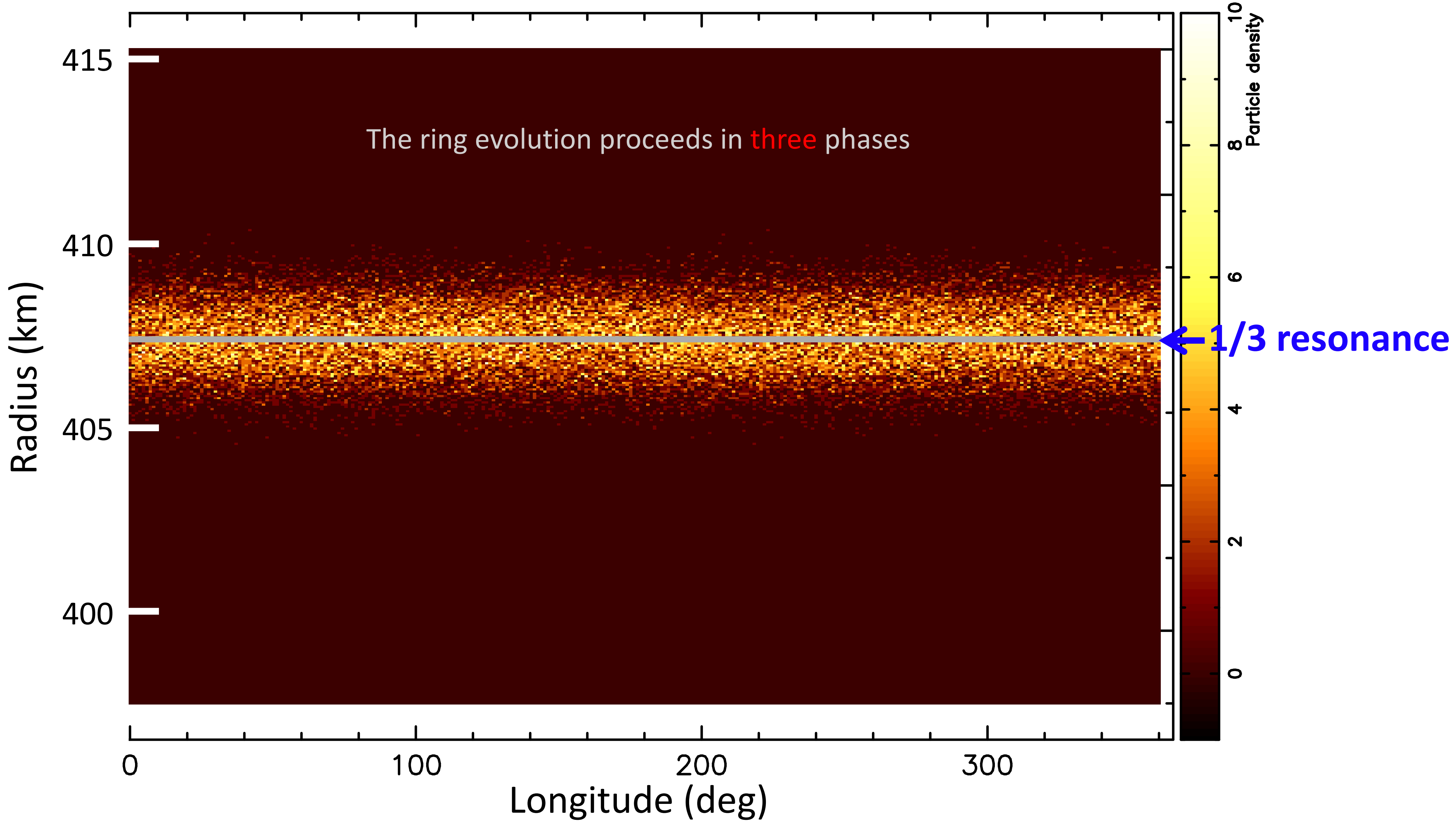
2nd order resonance



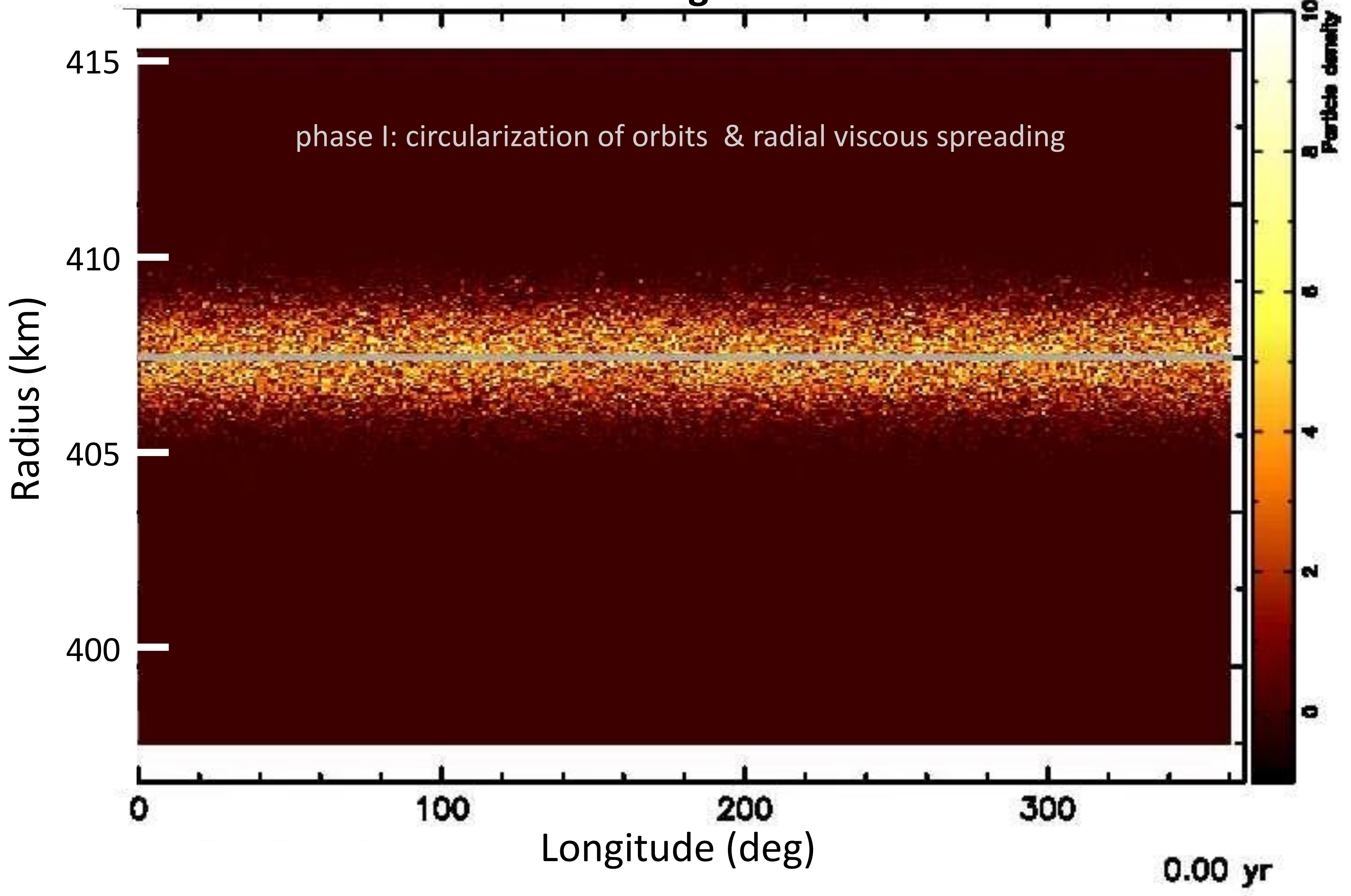
here we get a problem:
streamline self-crossing
→ this cannot be supported by a collisional disk


Chariklo's ring simulation
μ= 0.003
40,000 particles
radius 25 m
complete (3D, 2π) N-body
collisional simulation
no self-gravity
Eccentricity e
0
0.01
0.02
405
410
Jacobi constant a + a0(m-2)e2/2 (km)
Particle density
0
100
200
300
400

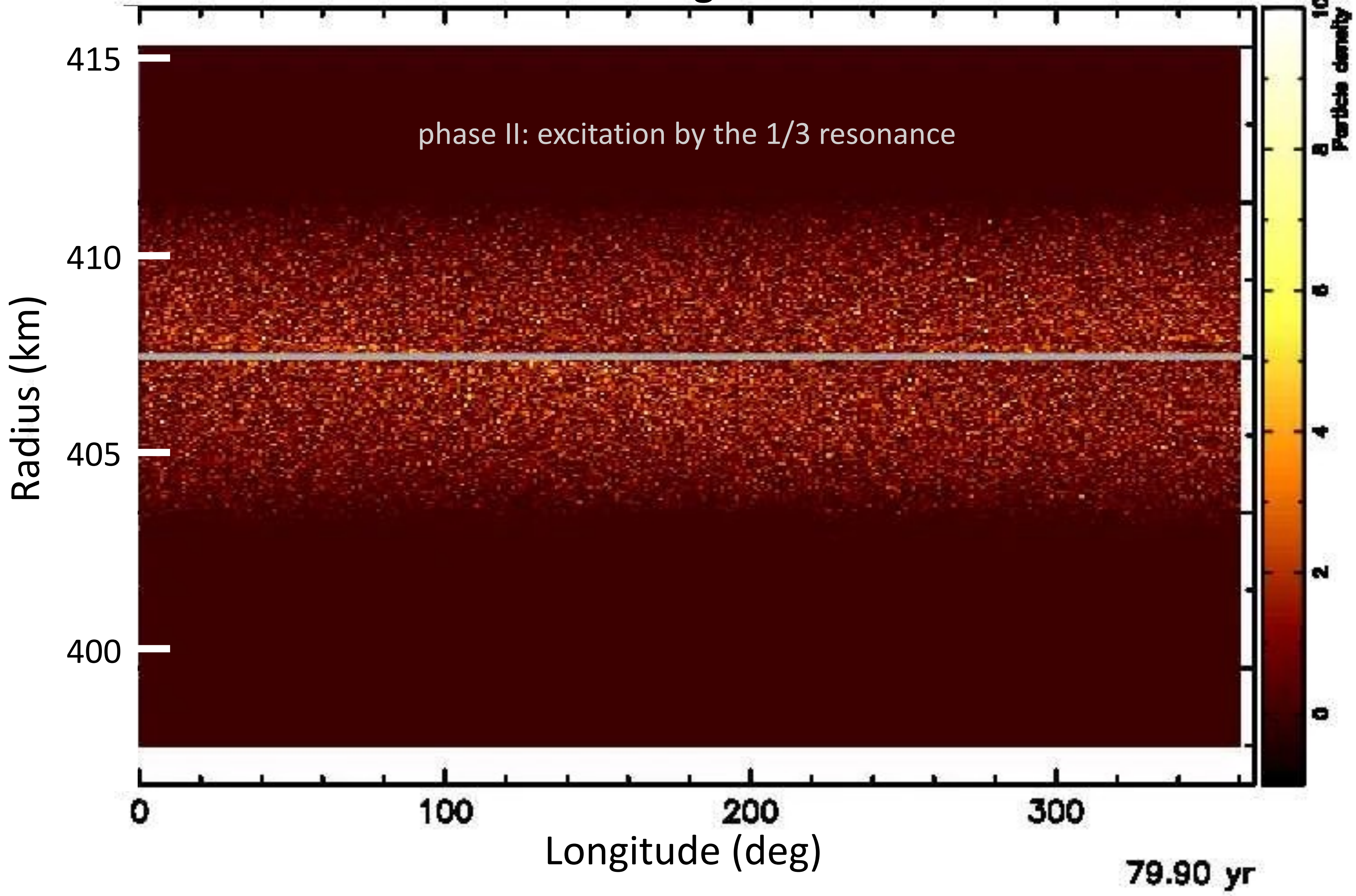
Chariklo's ring simulation



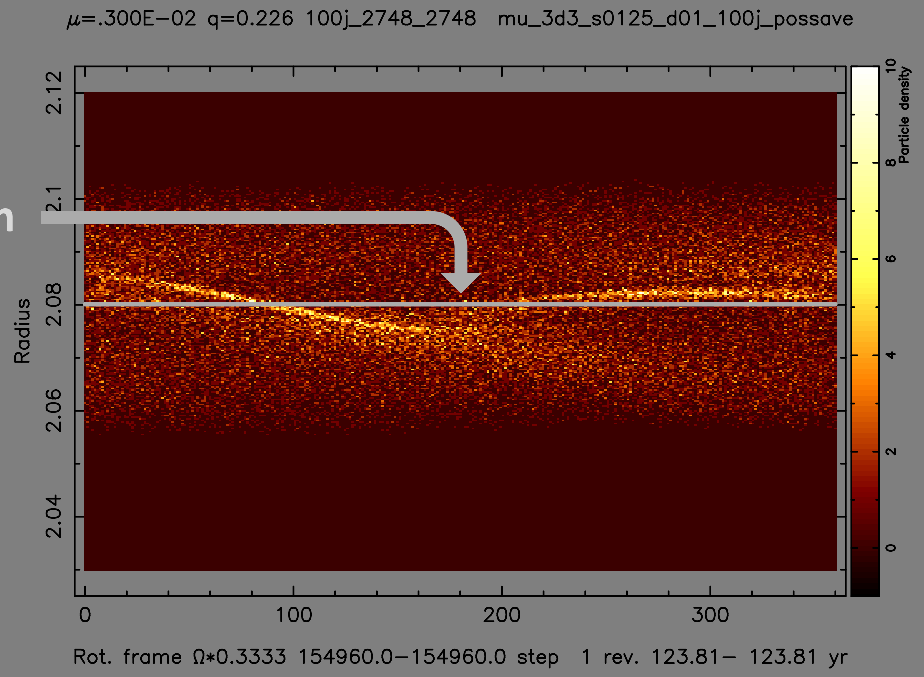
Chariklo's ring simulation



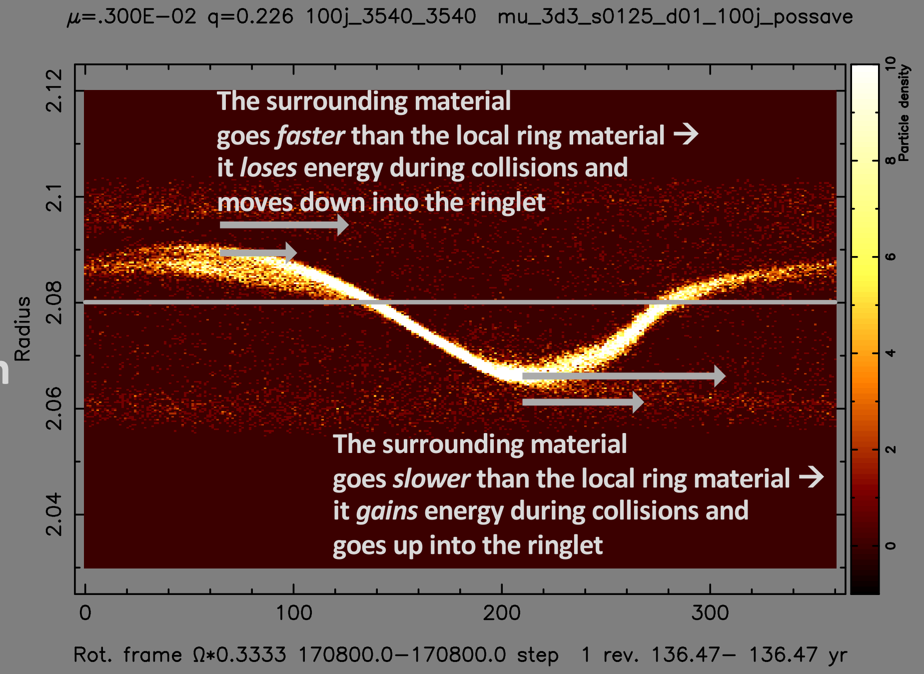
Chariklo's ring simulation



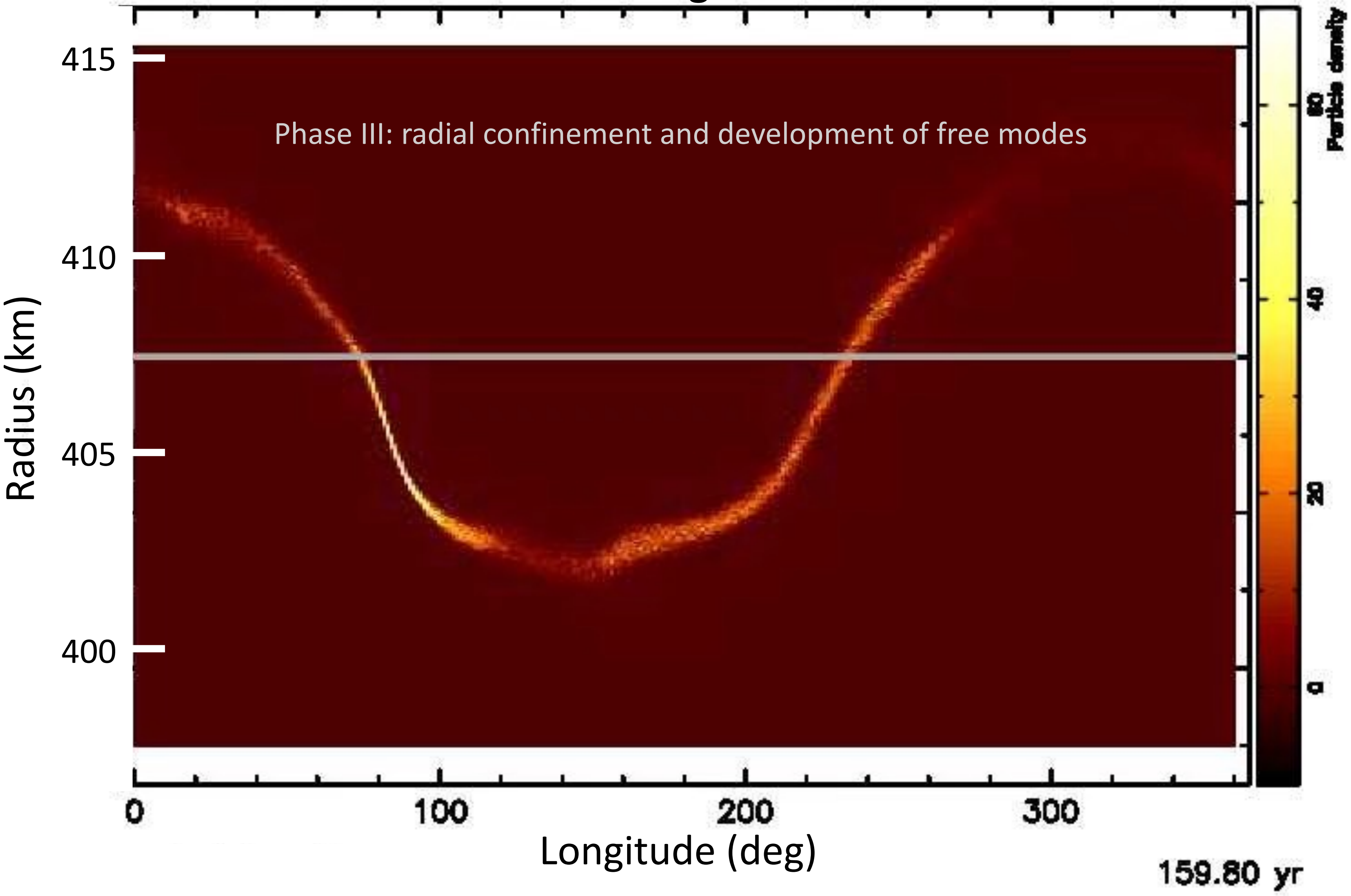
The 1/3 resonance tries
to force a periodic streamline,
but results in crossing problem



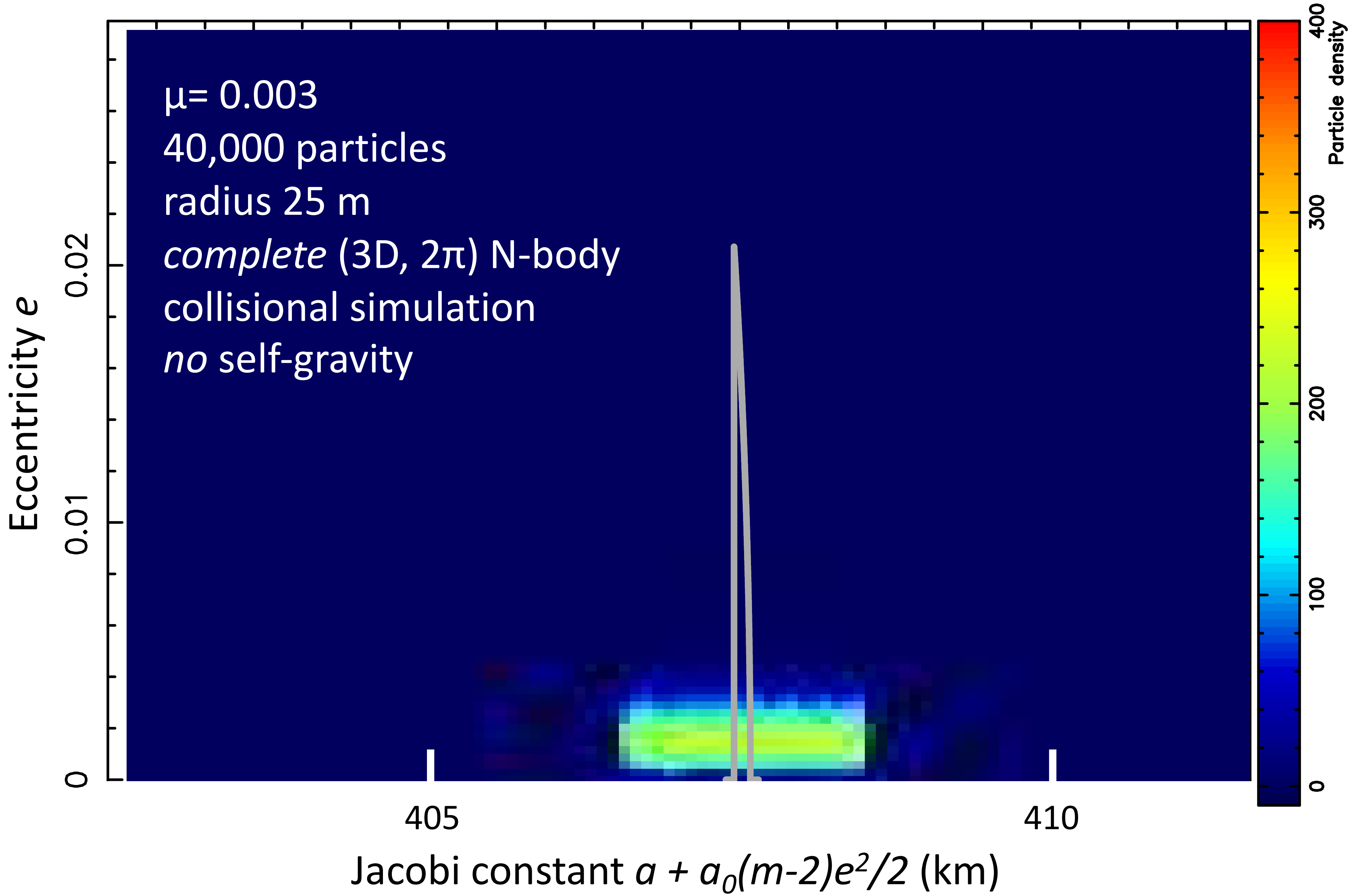
The streamline becomes
coherent (no Xing) and its
“sweeps” the surrounding
material through the inversion
of the velocity field



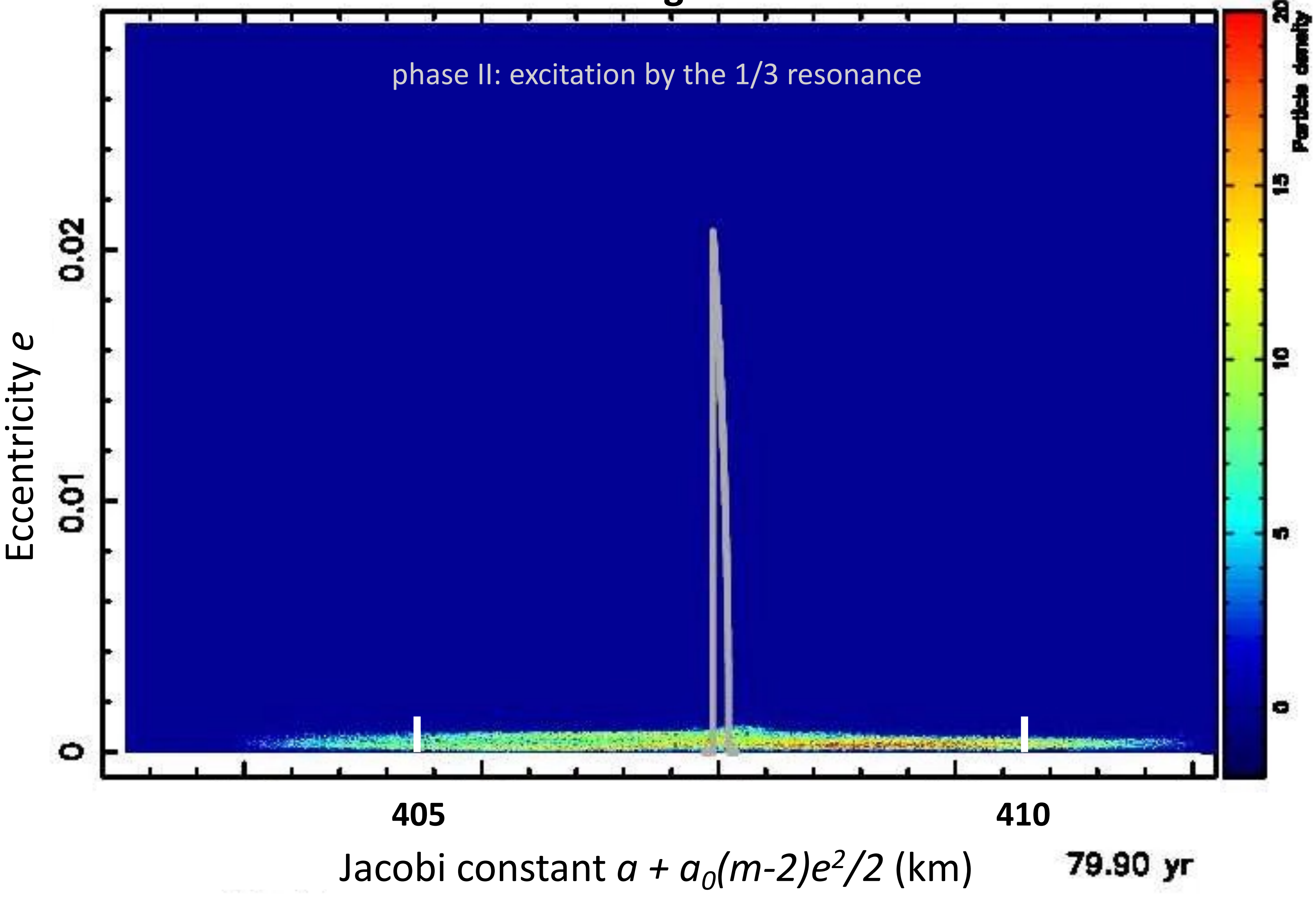
Chariklo's ring simulation

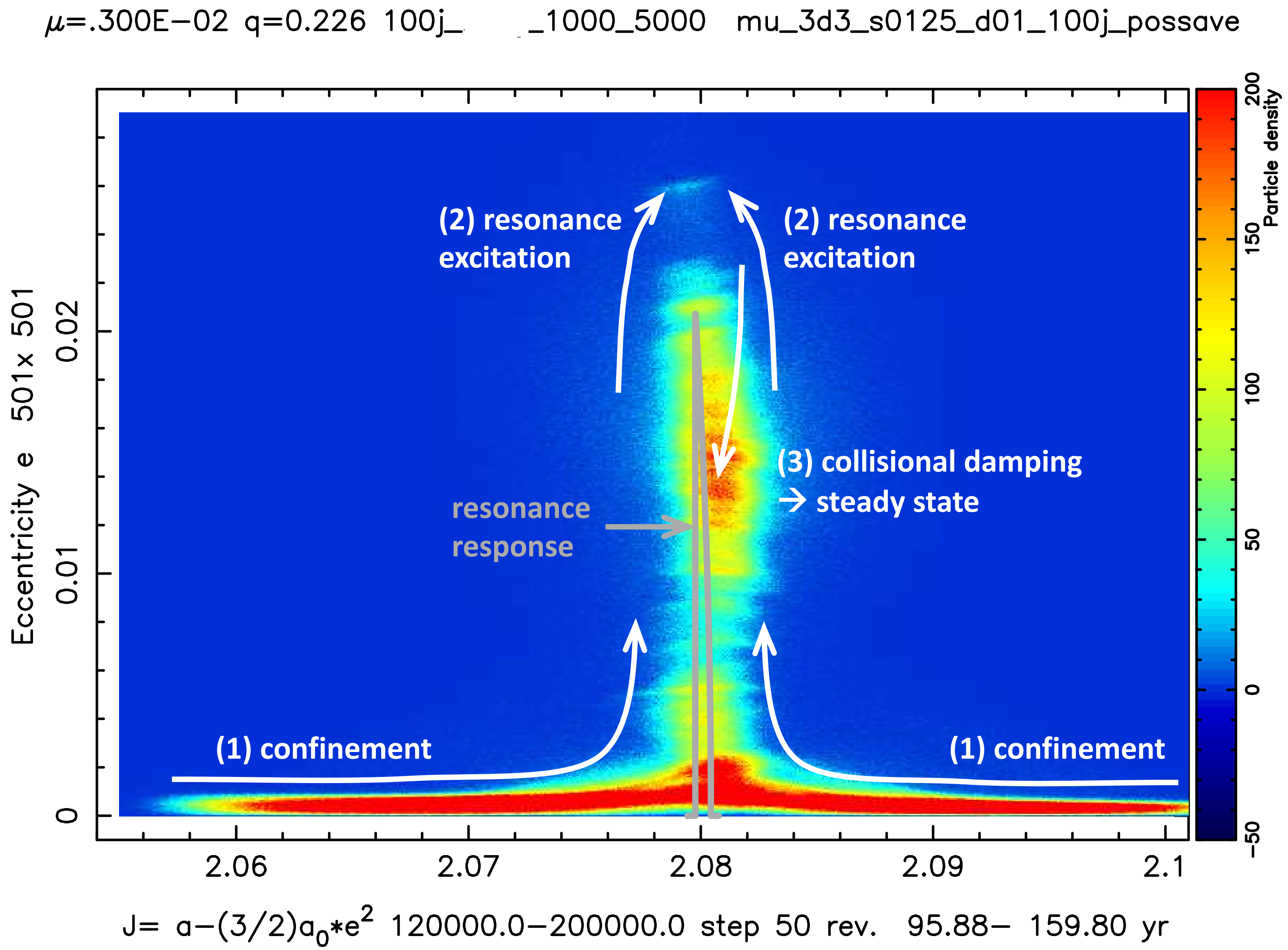


Chariklo's ring simulation

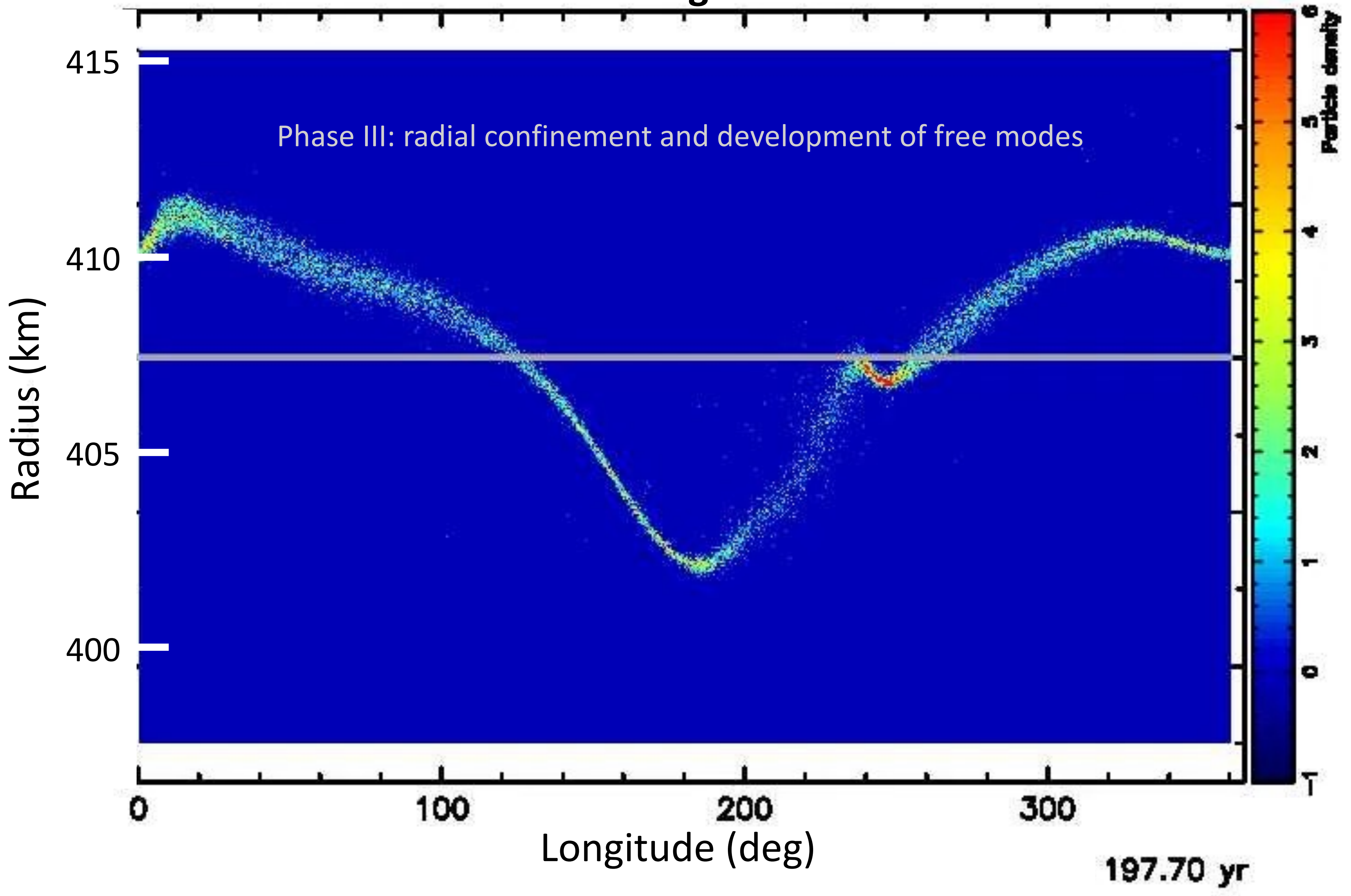


Chariklo's ring simulation

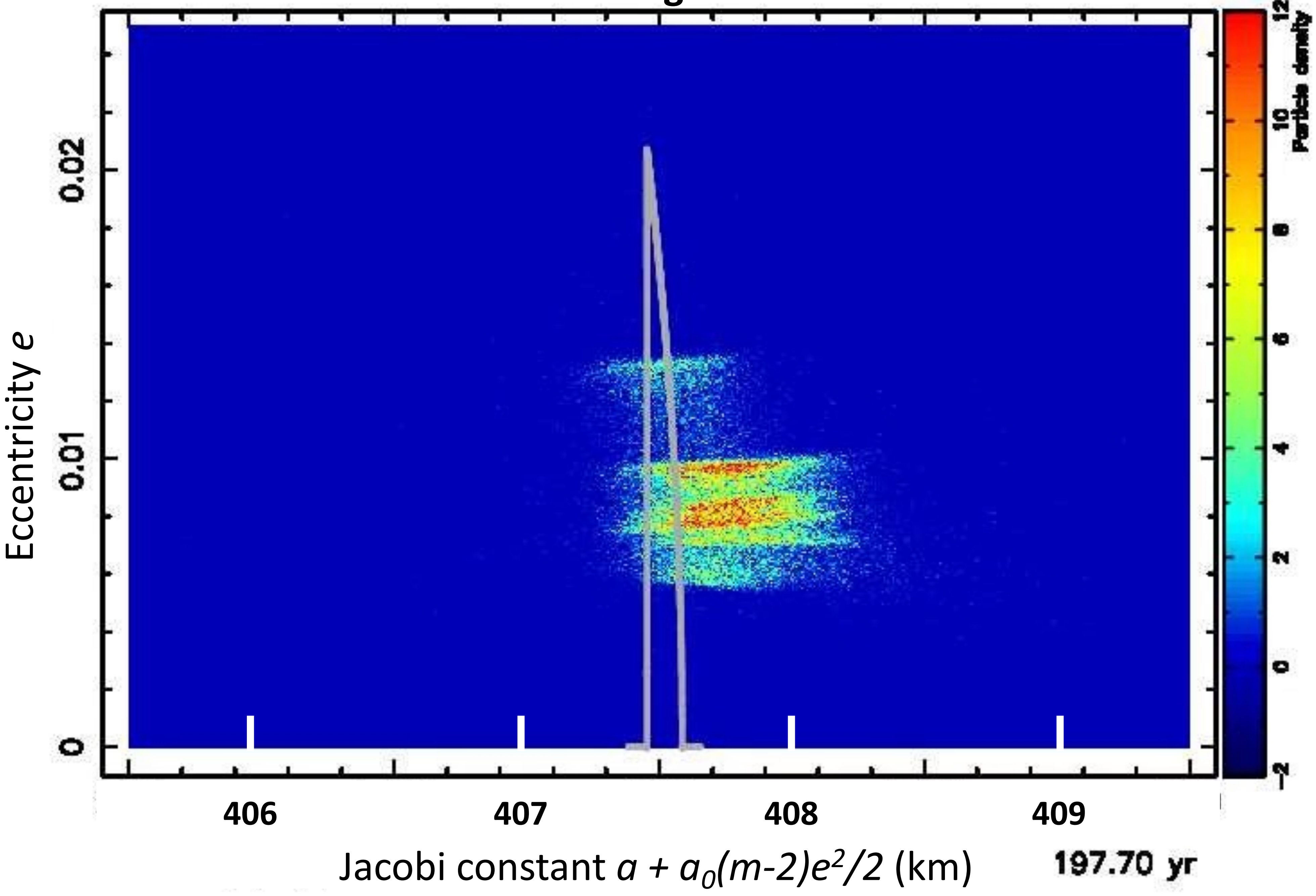



μ=.300E−02 q=0.226 100j_ _1000_5000 mu_3d3_s0125_d01_100j_possave
(2) resonance excitation
(2) resonance excitation
(3) collisional damping → steady state
resonance response
(1) confinement
(1) confinement
Eccentricity e 501x 501
0
0.01
0.02
2.06
2.07
2.08
2.09
2.1
J= a−(3/2)a0*e2 120000.0−200000.0 step 50 rev. 95.88− 159.80 yr
Particle density
−50
0
50
100
150
200

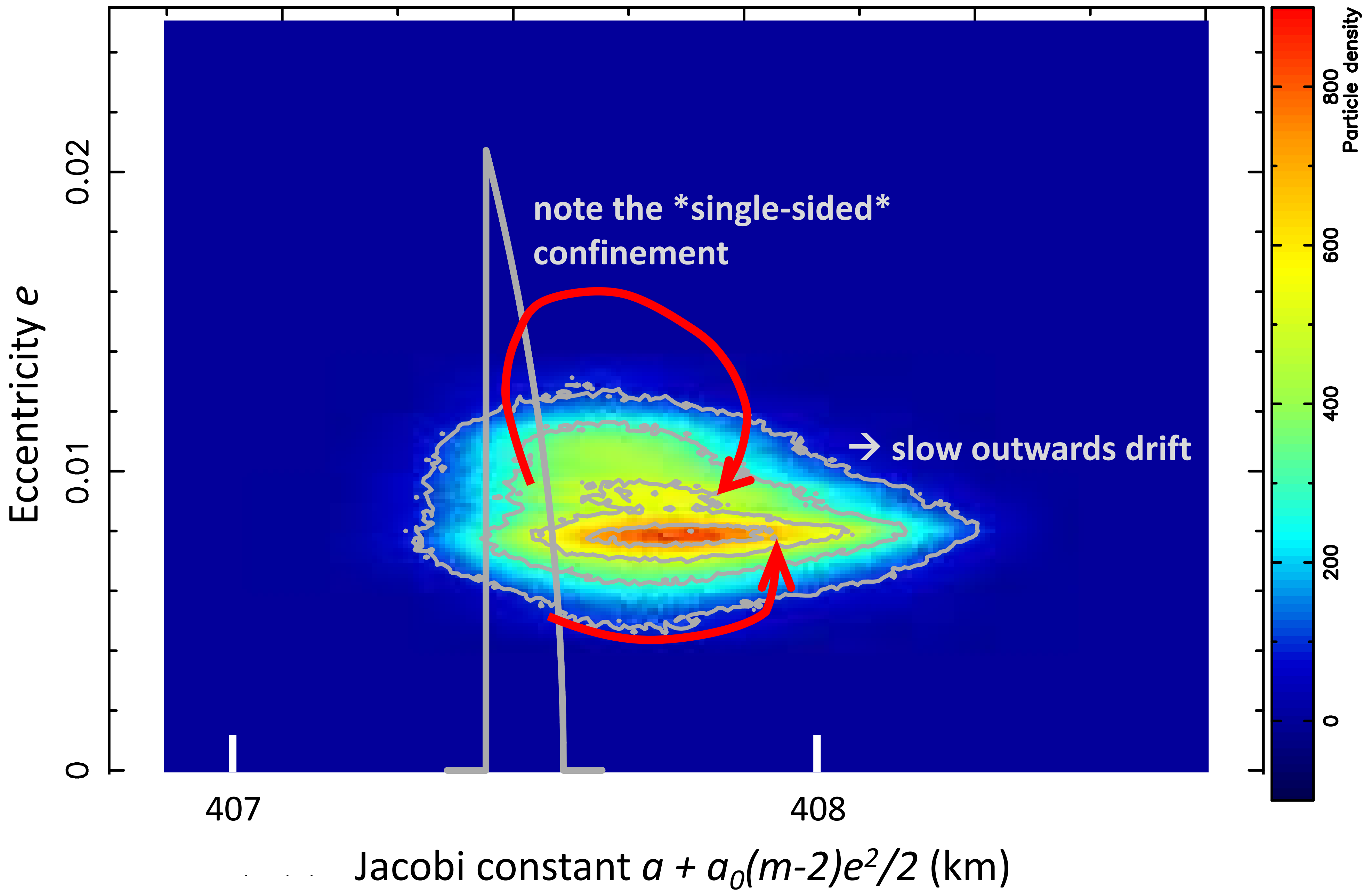
Chariklo’s ring simulation

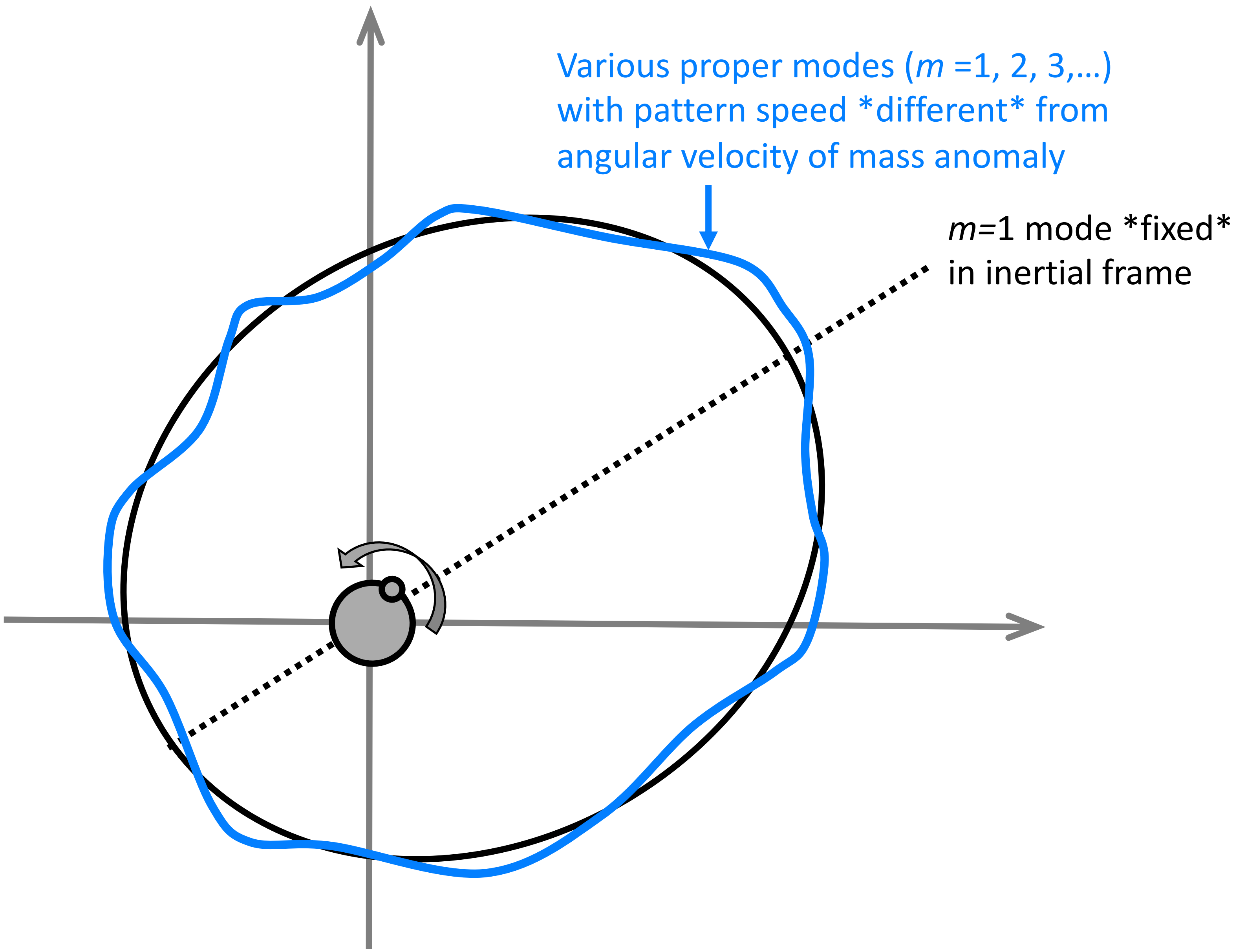


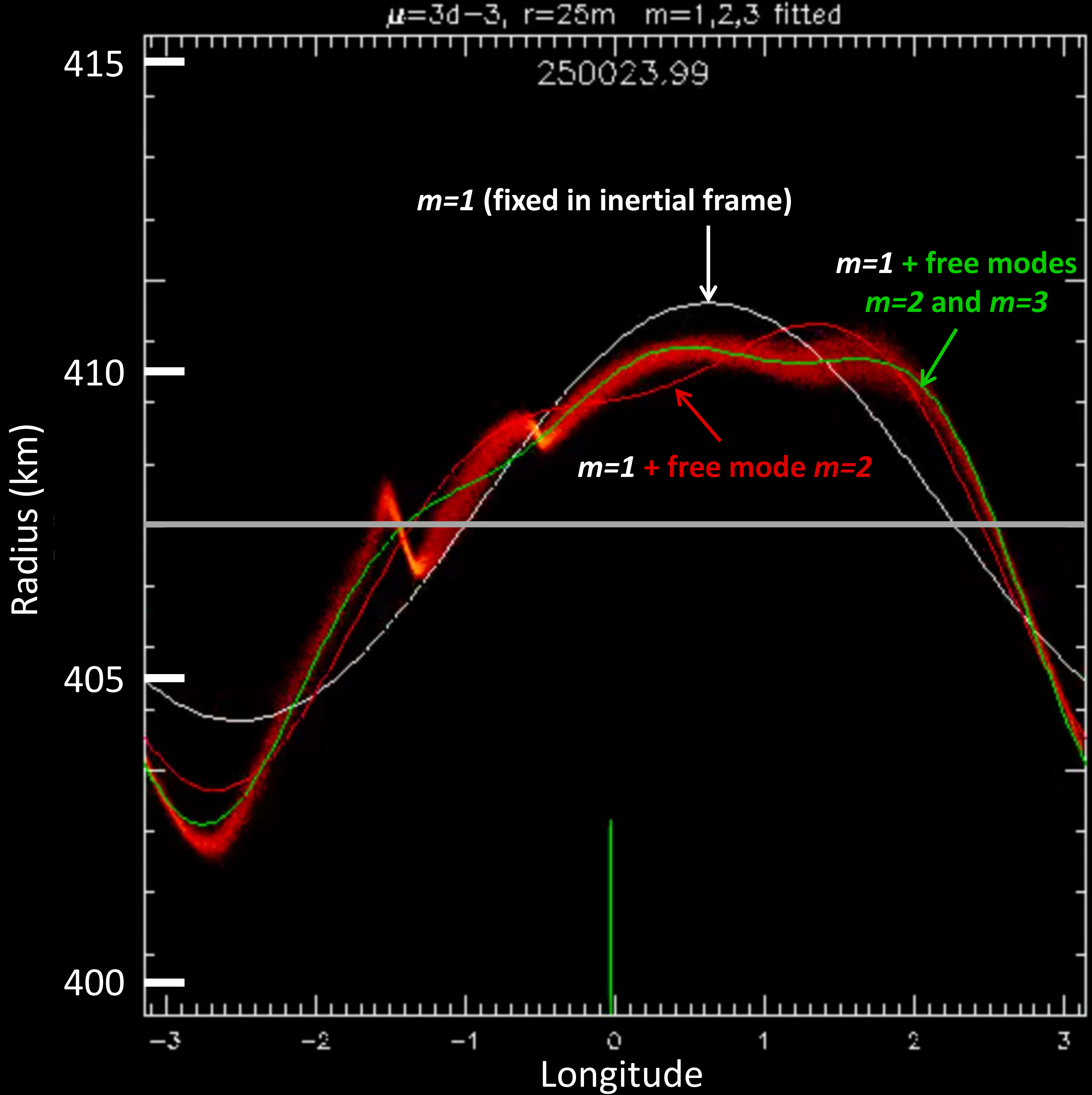
Chariklo's ring simulation



Chariklo’s ring simulation




Various proper modes (m =1, 2, 3,…)
with pattern speed *different* from
angular velocity of mass anomaly
m=1 mode *fixed*
in inertial frame



Free modes:
Lindblad-type
m-lobed oscillations

μ=0.003 1/3 resonance

final ringlet stage

rot=1/3 (co−rotating with the ringlet)

After subtracting the *m*= 1, 2 , 3 modes →

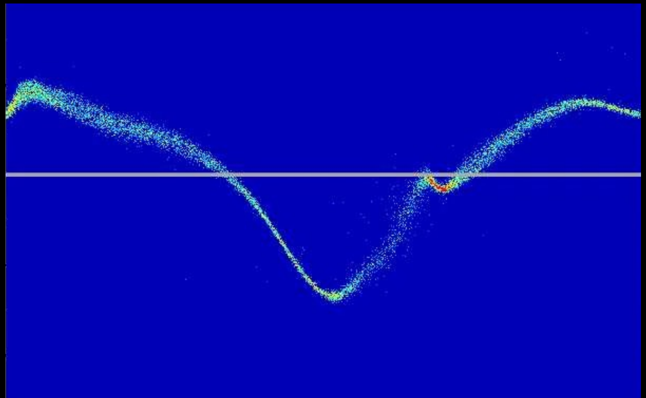
1 km

Conclusions

Our simulations show that the 1/3 resonance can confine a ring (self-organization is possible in spite of initial streamline-crossing problem)

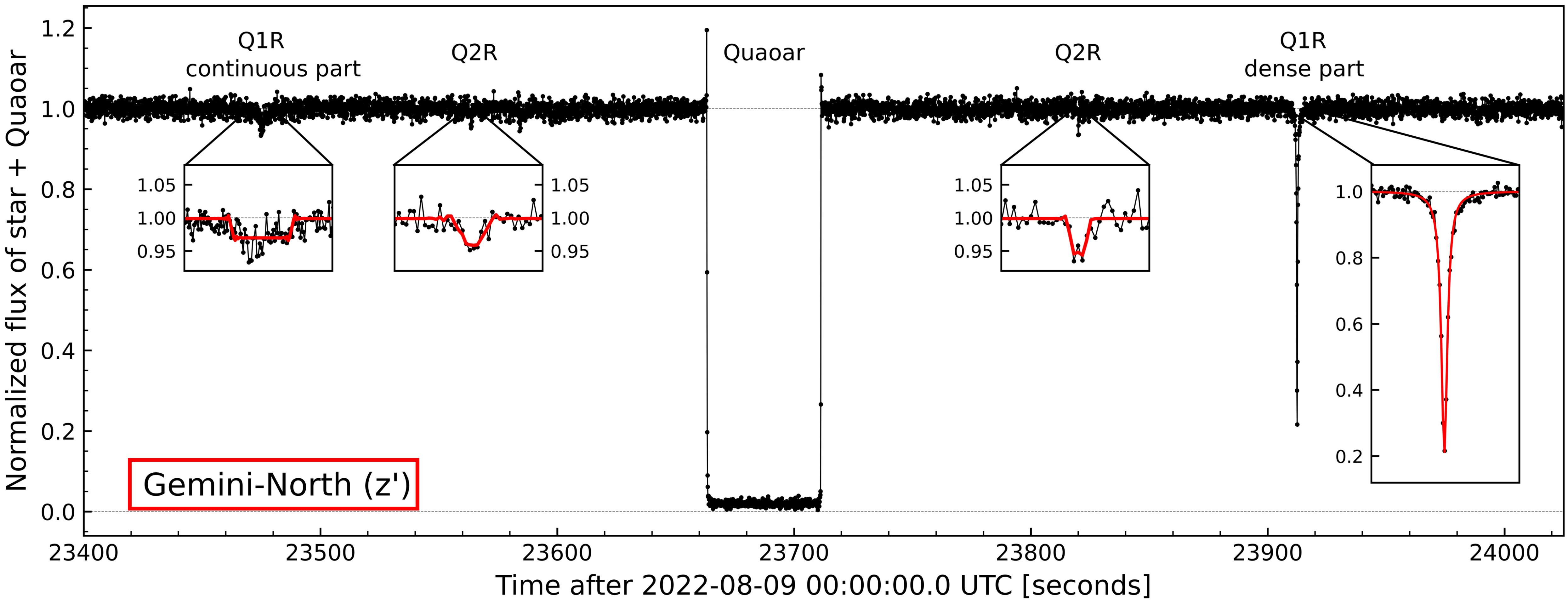
The 1/3 resonance excites the eccentricity but fails to lock the ring into a forced resonant motion (due to streamline crossings)

Instead, free modes are excited (m=1, 2, 3…). They create angular momentum flux reversal and lead to single-sided ring confinement

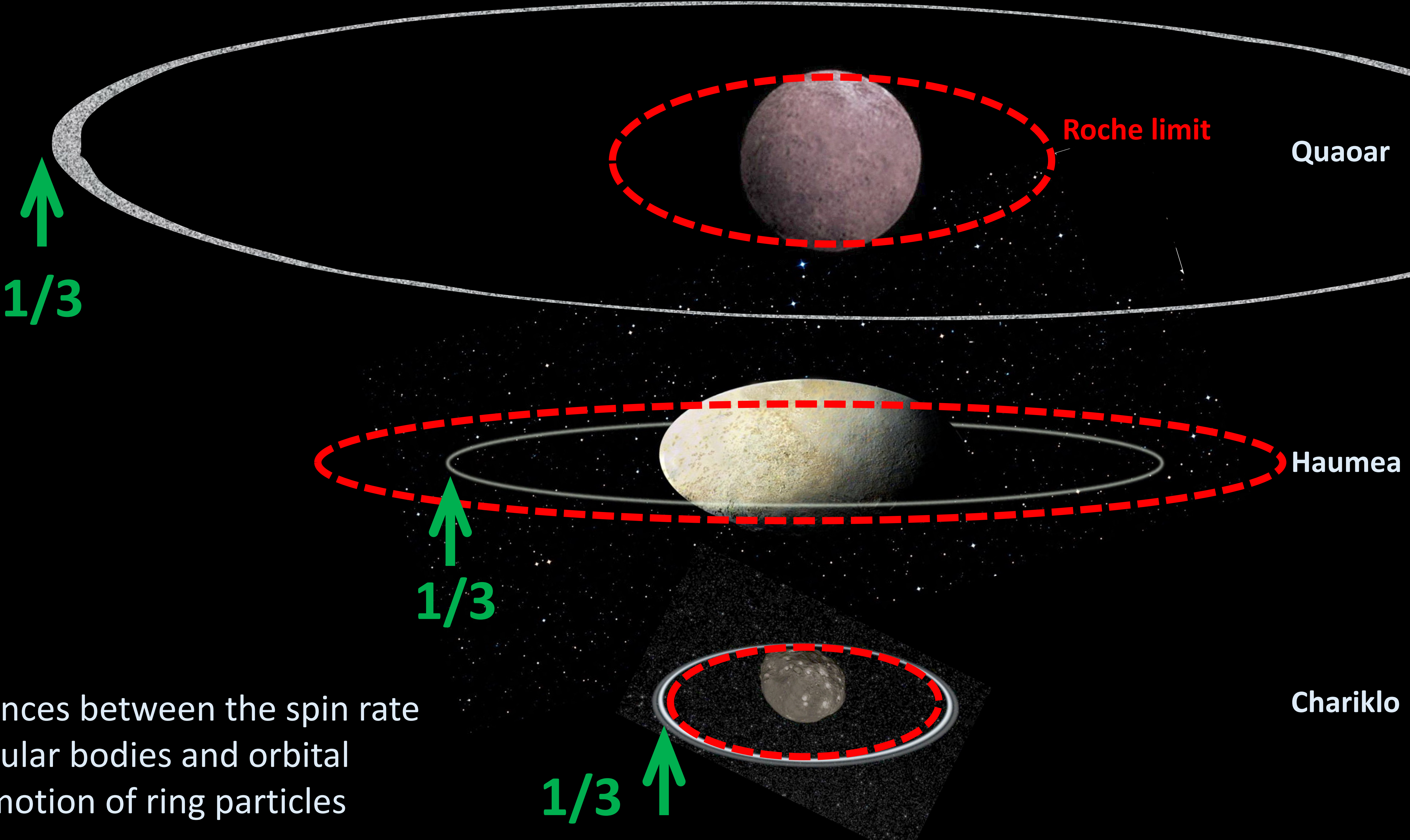


A problem remains

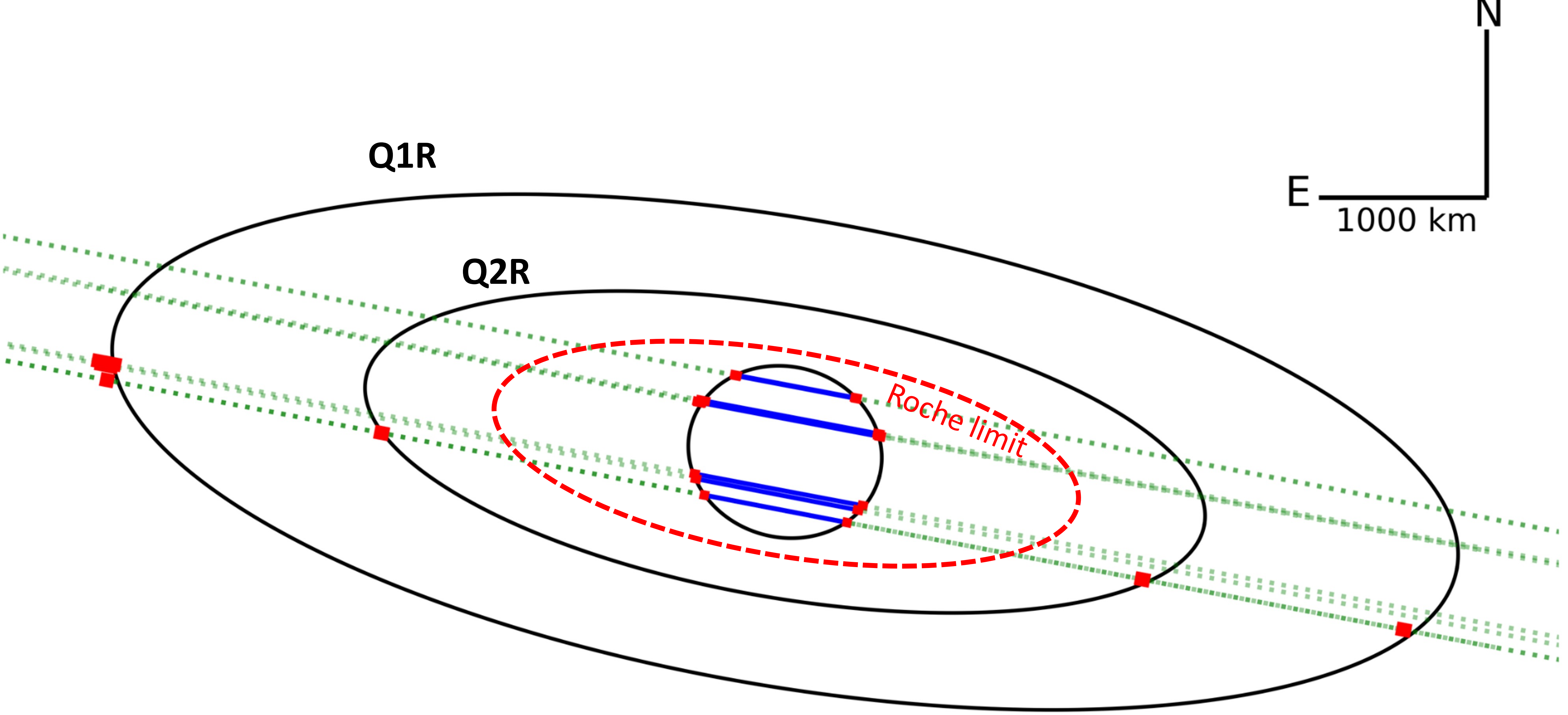
Quaoar's rings are well beyond the Roche limit of the body : they should disappear within a few weeks!



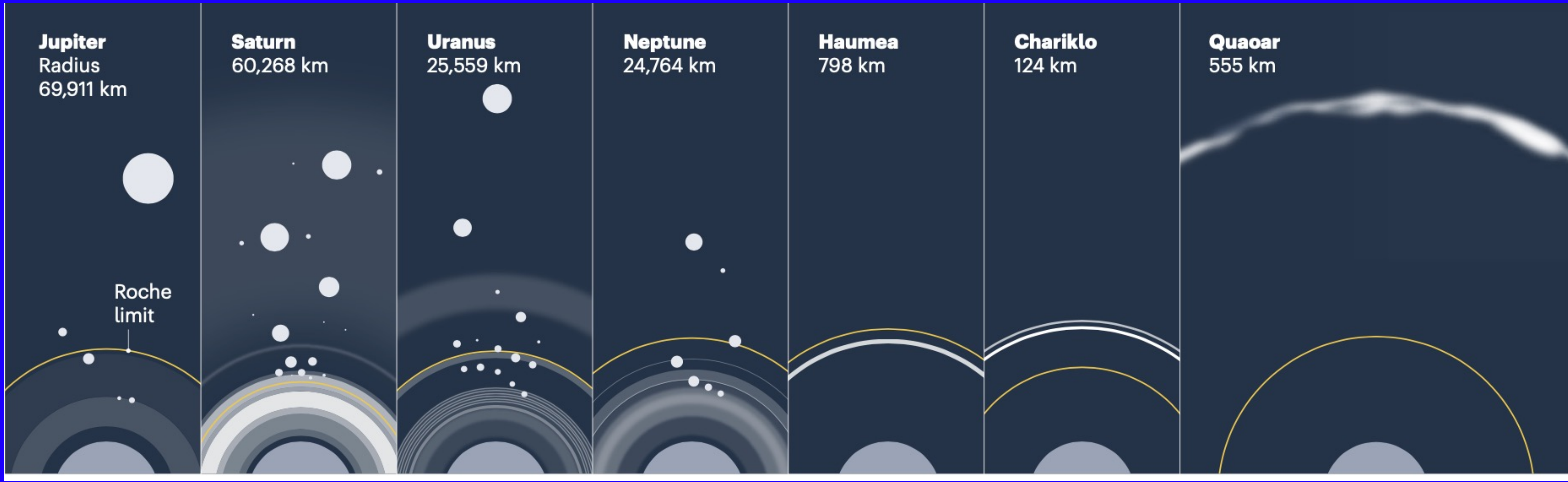
Q1R
continuous part
Q2R
Quaoar
Q2R
Q1R
dense part
Gemini-North (z')
Normalized flux of star + Quaoar
Time after 2022-08-09 00:00:00.0 UTC [seconds]



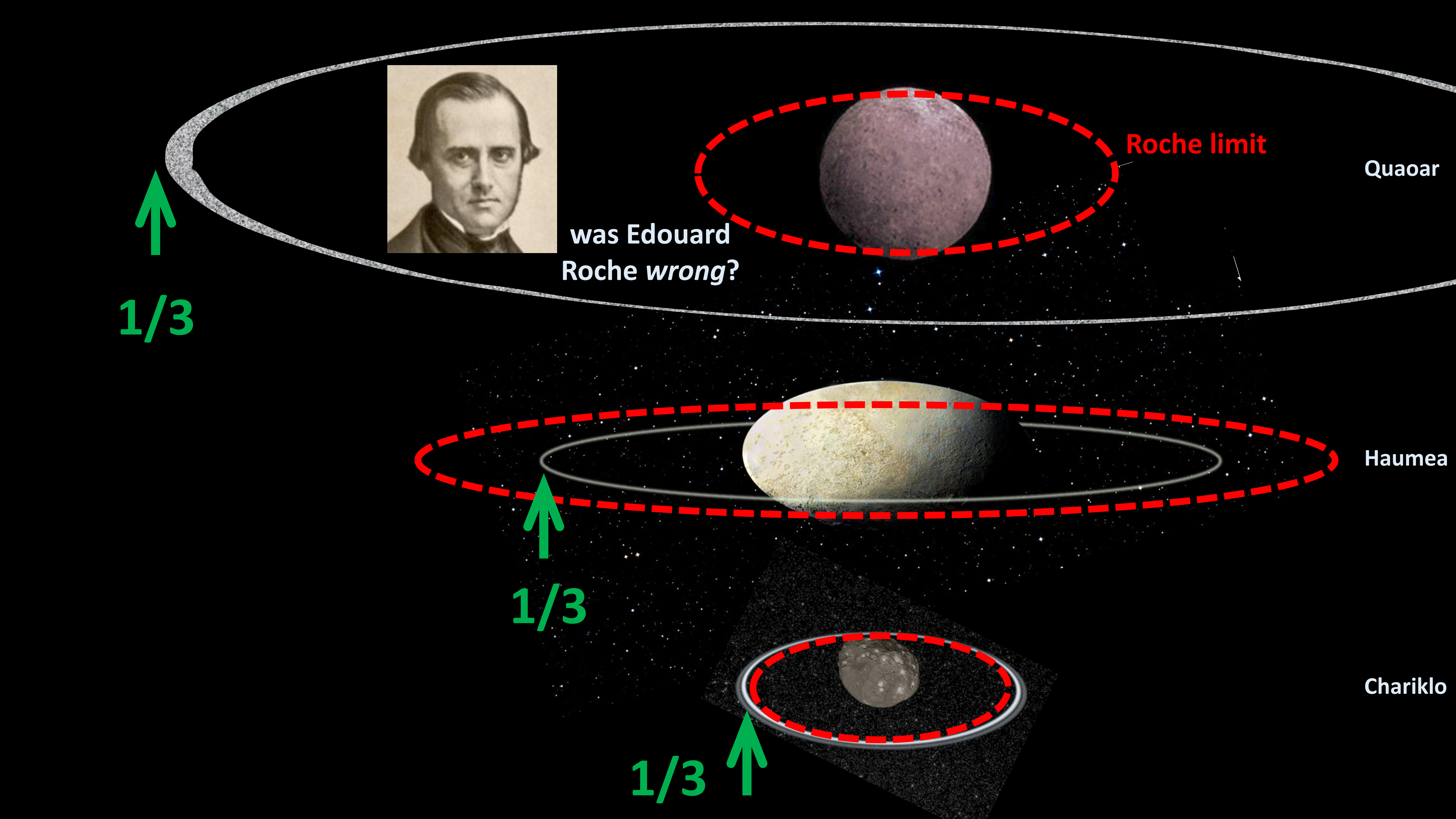
Resonances between the spin rate of irregular bodies and orbital mean motion of ring particles

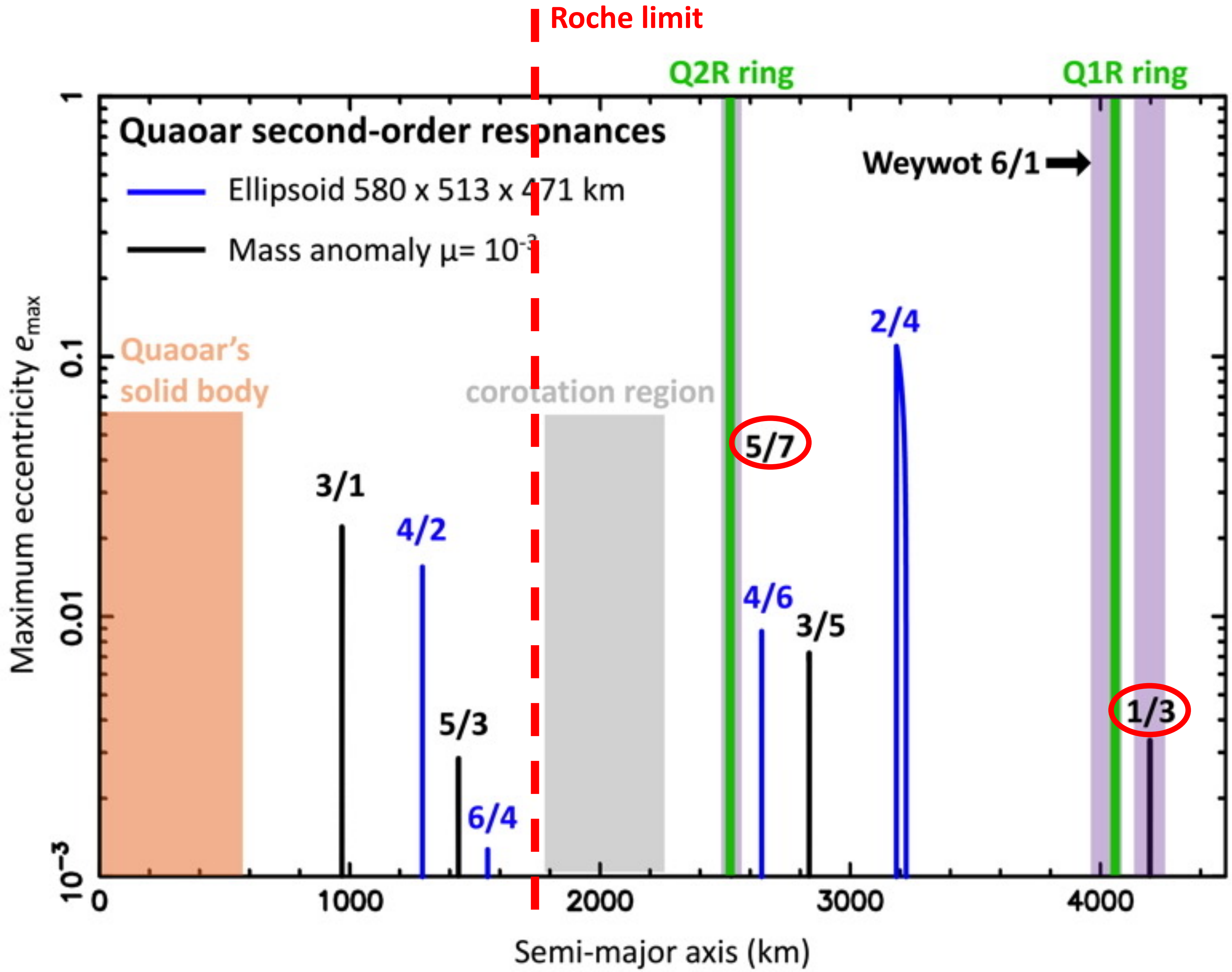


- Q1R's orbit coplanar with Weywot's orbit to within uncertainties
- Q2R's detections consistent with circular ring coplanar w/ Q1R
- Quaoar's limb (almost) consistent with the two rings equatorial

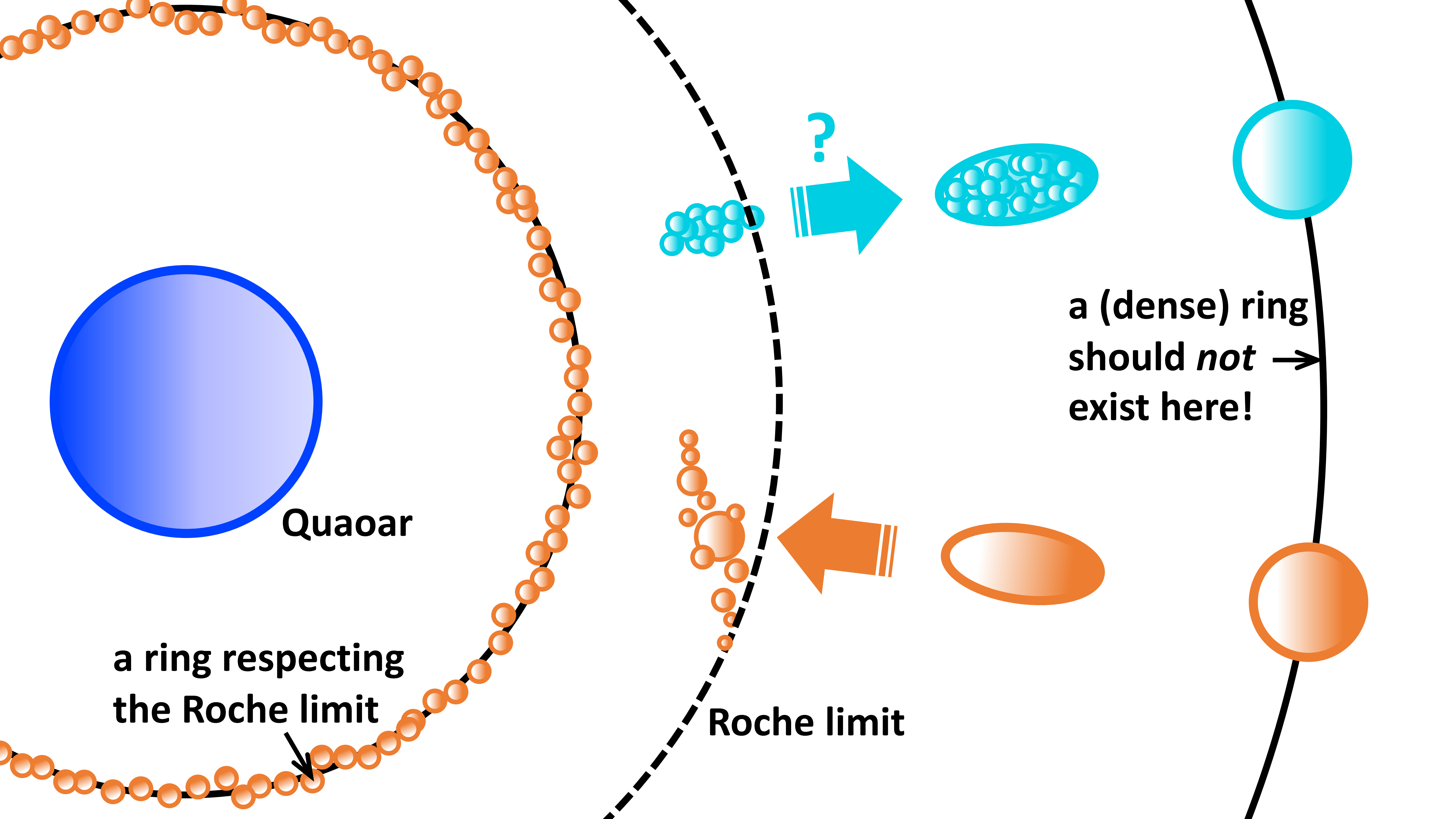


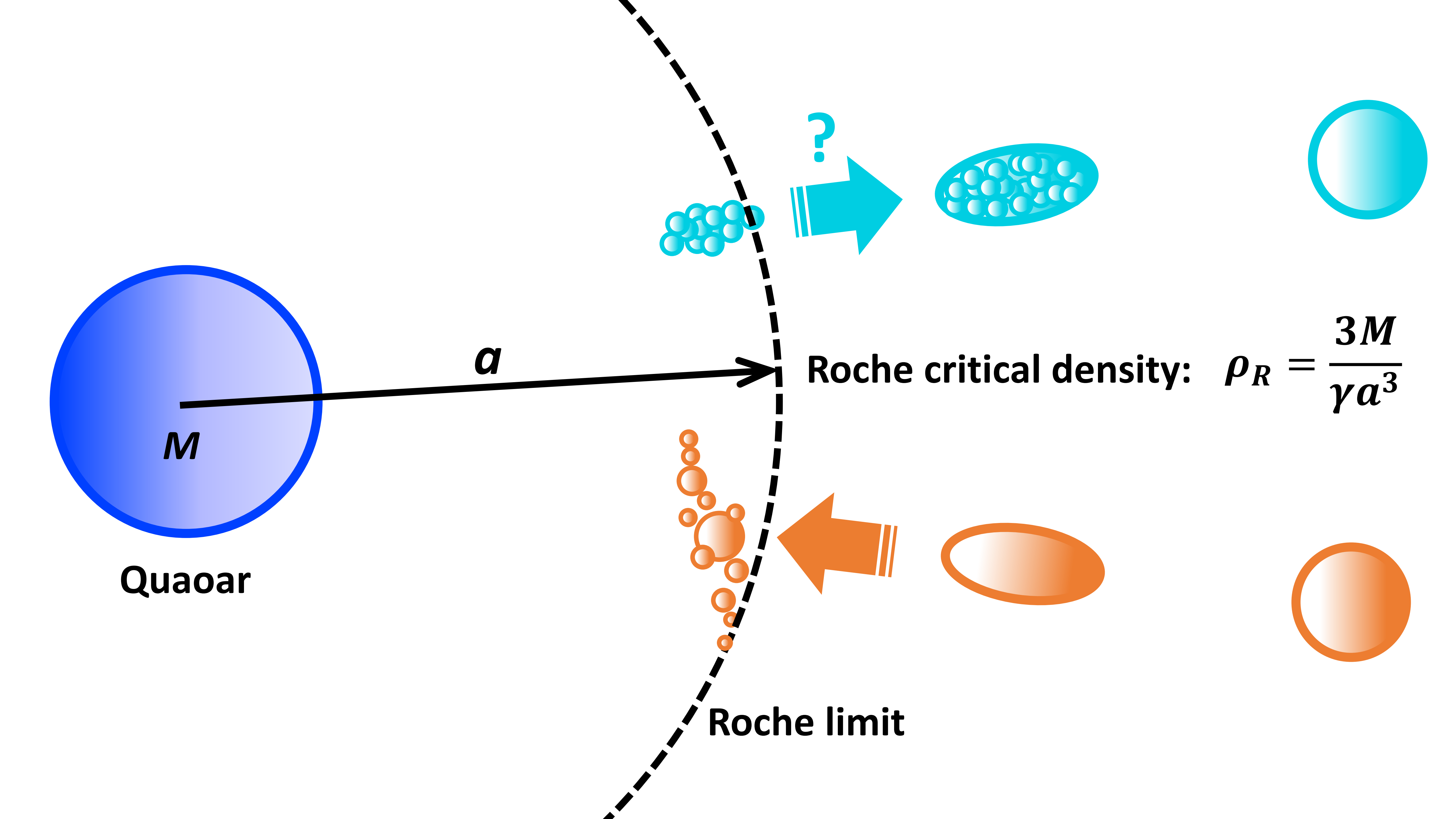
Matthew Hedman
‘News and Views’, *Nature*
9 Feb. 2023


was Edouard
Roche *wrong*?
Roche limit
Quaoar
1/3
Haumea
1/3
Chariklo
1/3



Roche limit
Q2R ring
Q1R ring
Quaoar second-order respnances
Ellipsoid 580 x 513 x 471 km
Mass anomaly μ= 10⁻³
Weywot 6/1
Quaoar's
solid body
corotation region
2/4
5/7
3/1
4/2
4/6
3/5
1/3
5/3
6/4
Maximum eccentricity e_{max}
1
0.1
0.01
10^{-3}
0
1000
2000
3000
4000
Semi-major axis (km)


?
a (dense) ring
should *not*
exist here!
Quaoar
a ring respecting
the Roche limit
Roche limit



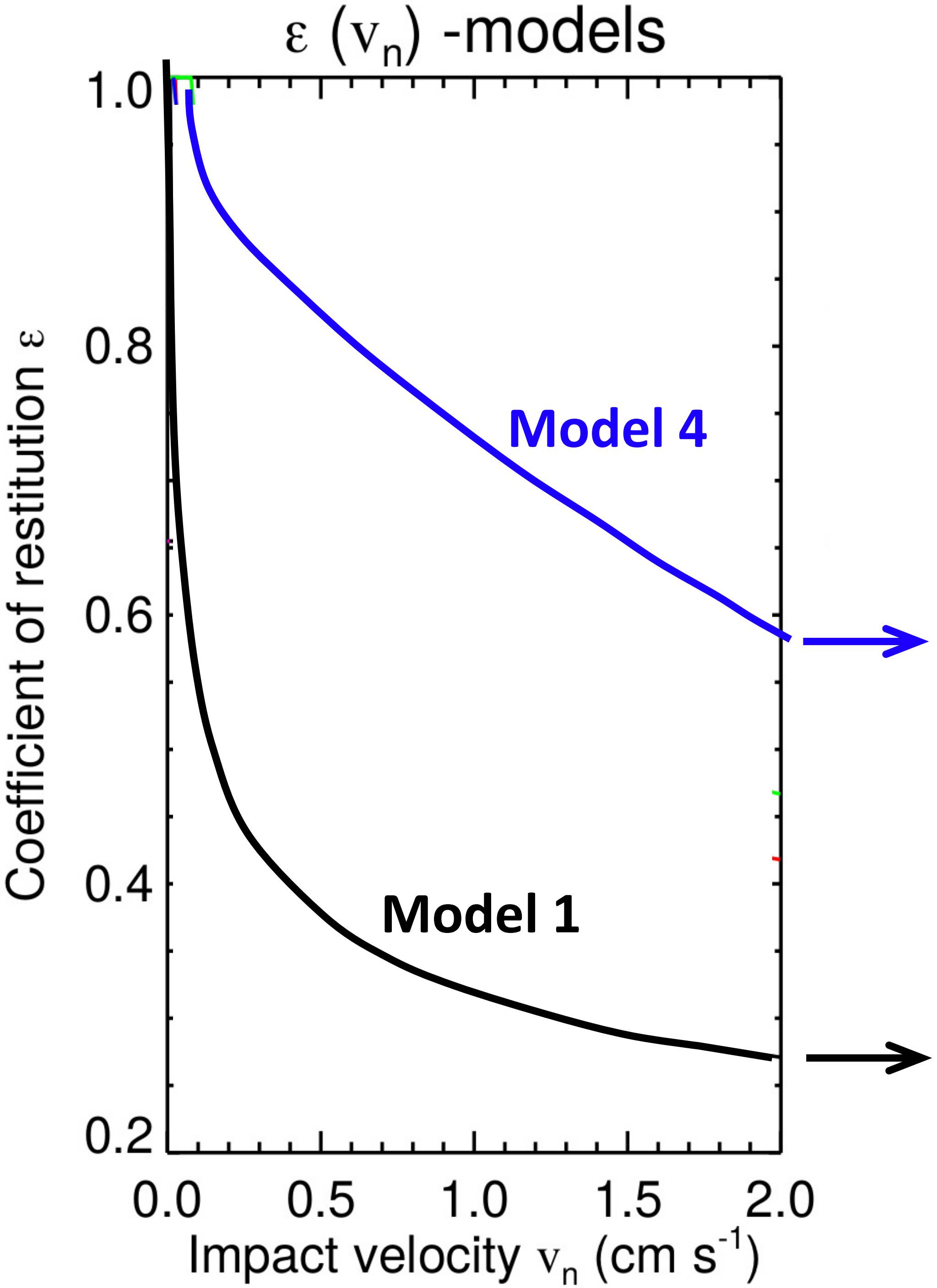
?
a
M
Quaoar
Roche critical density: $\rho_R = \frac{3M}{\gamma a^3}$
Roche limit

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

$$M = 1.2 \times 10^{21}\ \mathrm{kg}$$
$$\gamma = 1.6$$
$$a = 4150\ \mathrm{km}$$

$$\Longrightarrow \rho_R = 30\ \mathrm{kg\ m^{-3}}$$

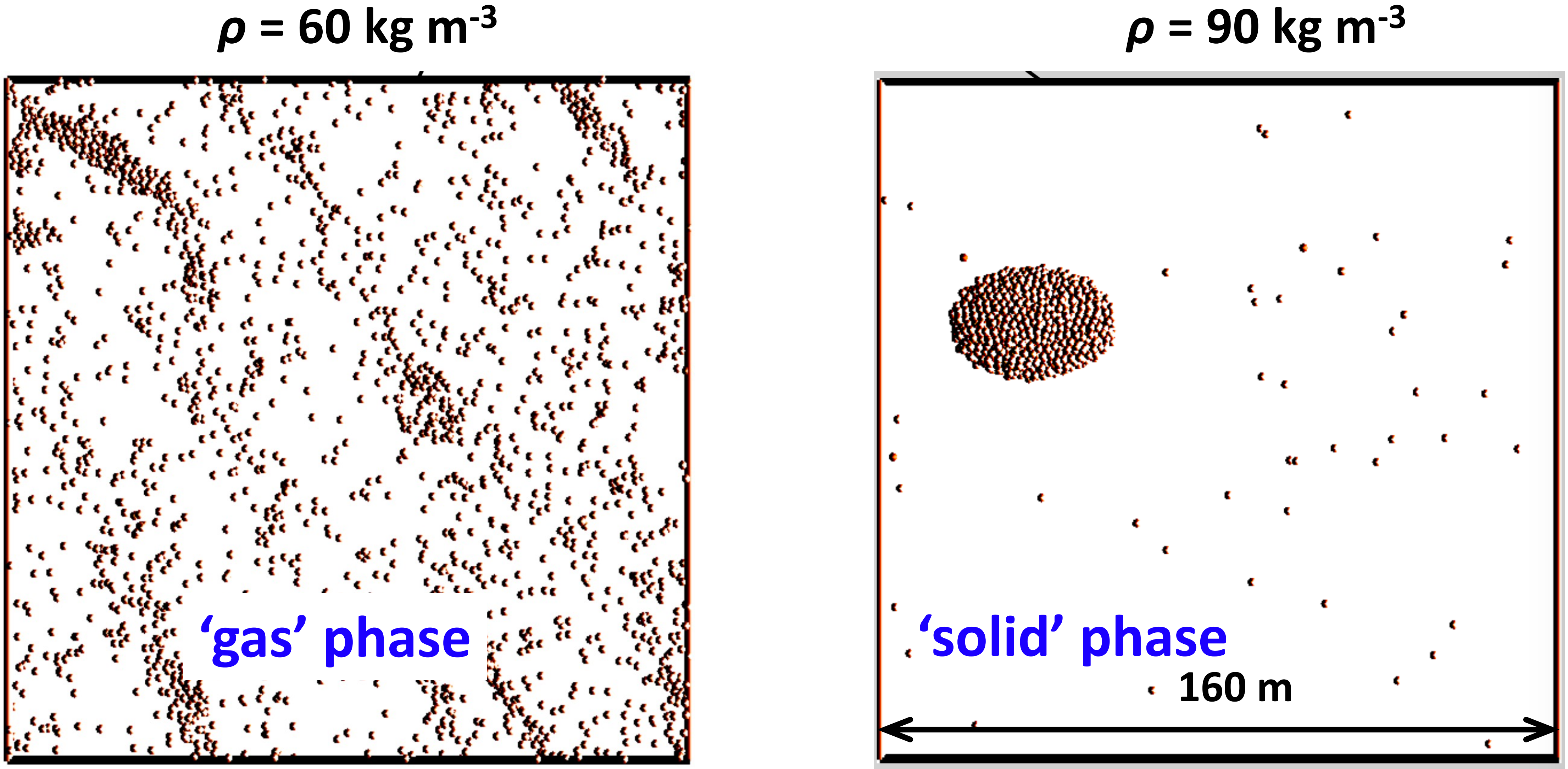
→ The classical Roche criterium requires *extremely* low bulk density of the particles for Quaoar’s ring to survive (i.e. avoid accretion)



Hatzes, Bridges & Lin
MNRAS 1988, *T* = 123 K

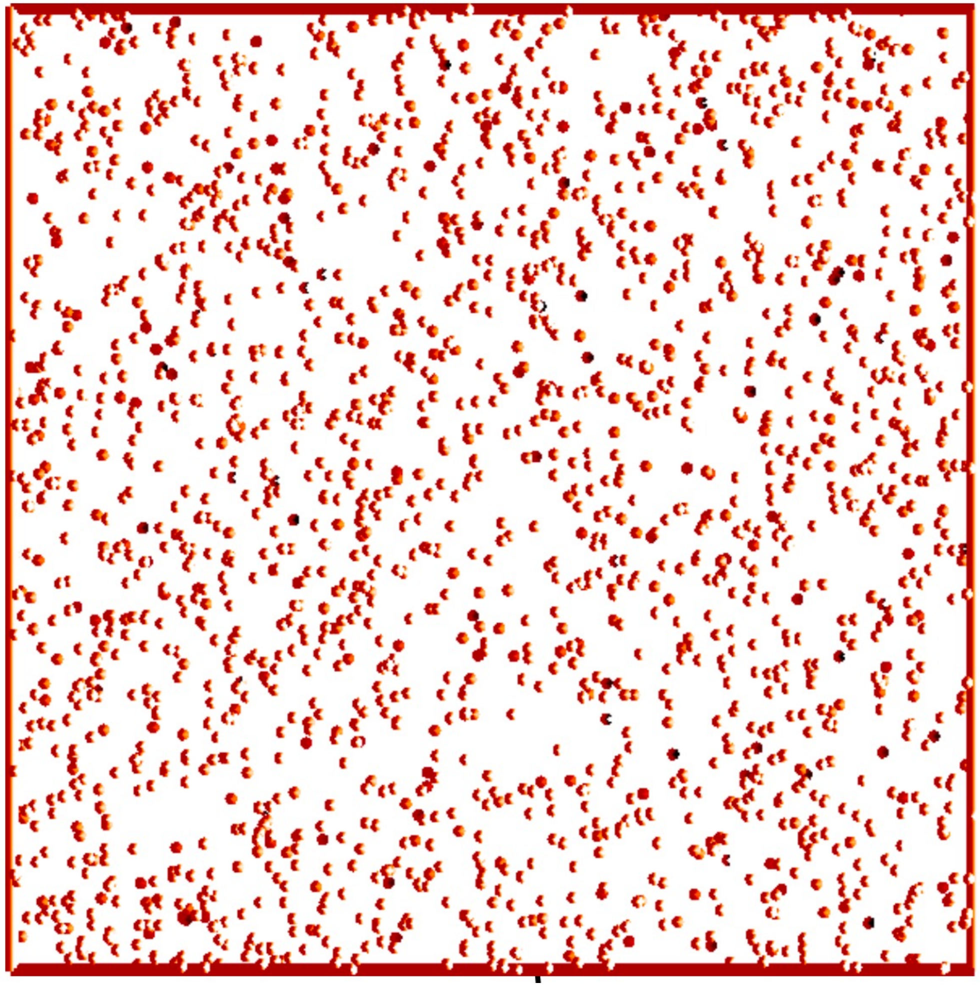
Bridges, Hatzes & Lin
Nature 1984, *T* = 210 K

Model 1 does *not* support a plausible Quaoar's ring with $\tau = 0.25$ and $R = 1$ m

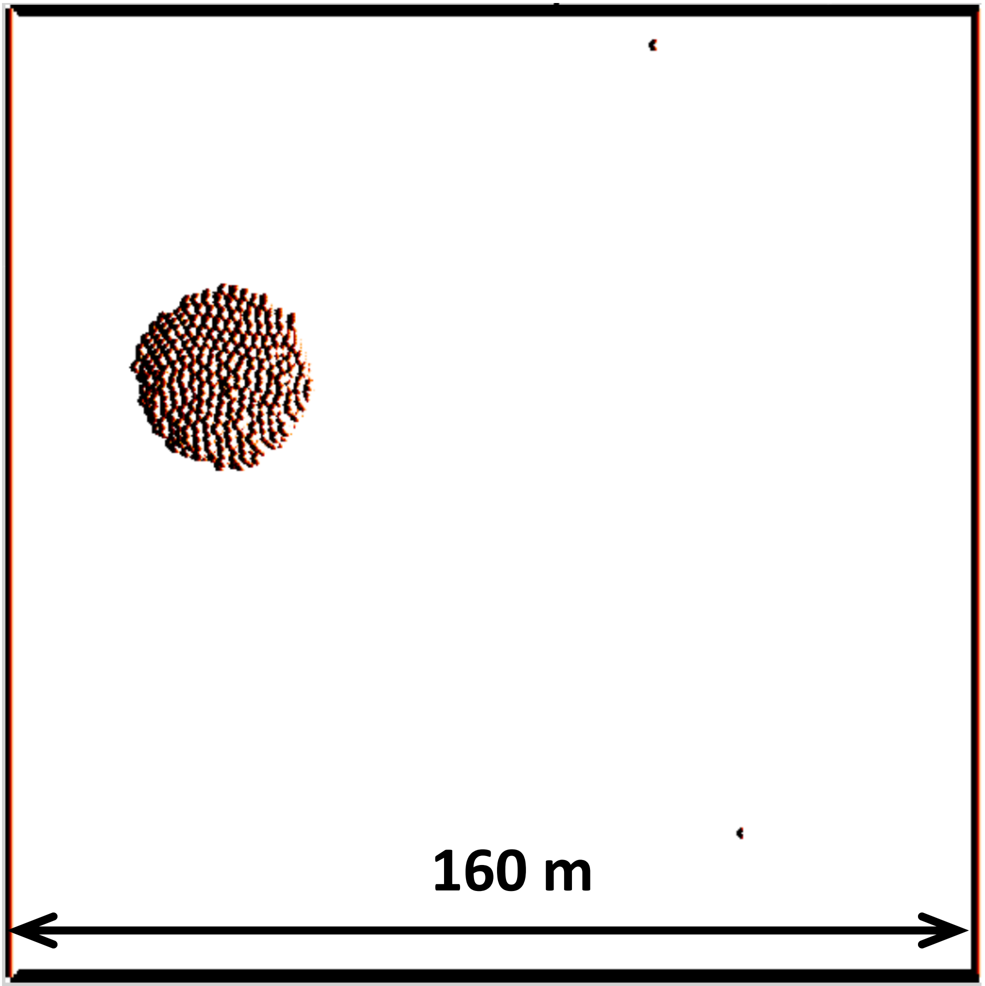


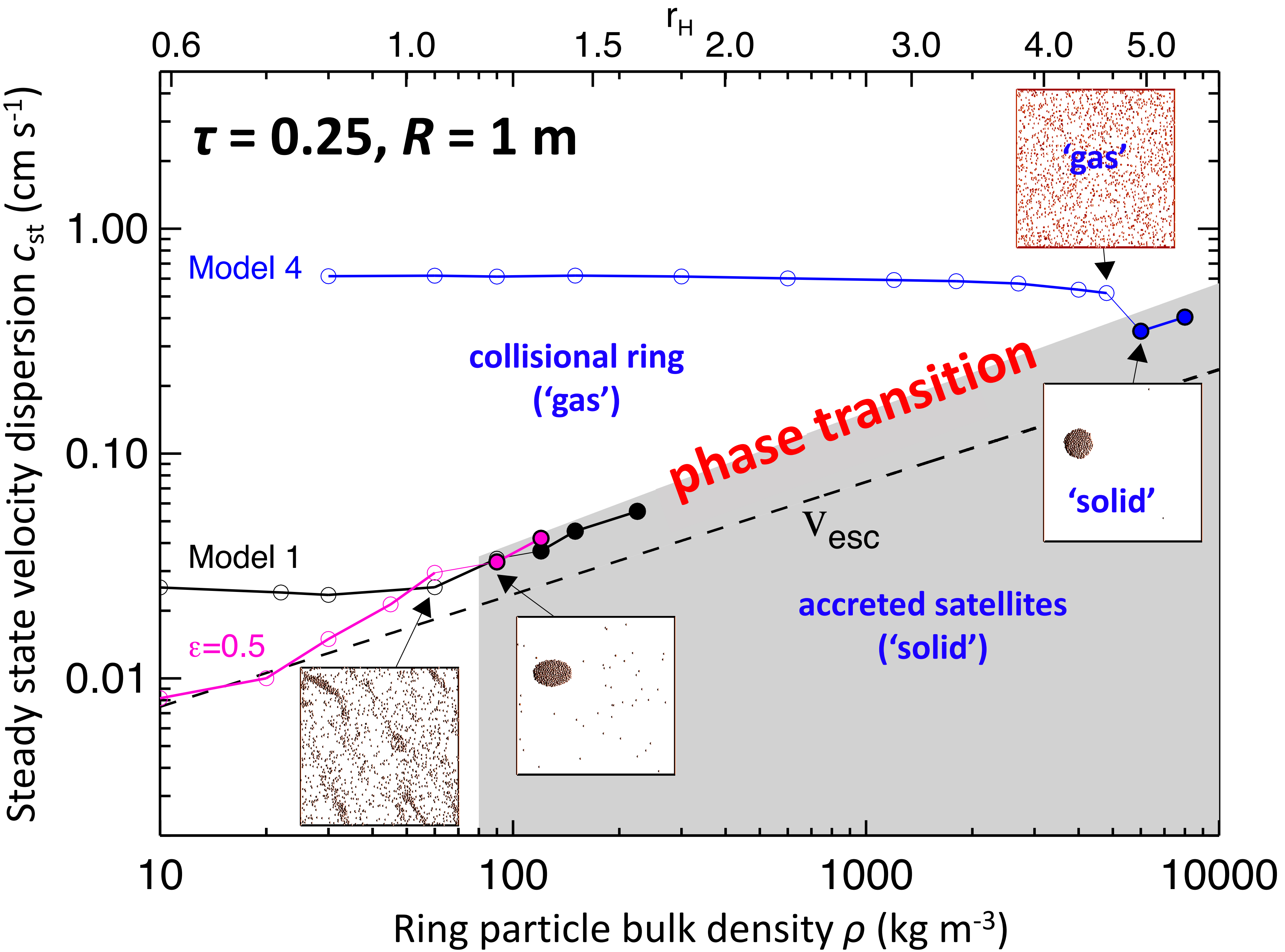
Model 4 *does* support a plausible Quaoar's ring with $\tau = 0.25$ and $R = 1$ m

ρ = 5000 kg m^{-3}



ρ = 6000 kg m^{-3}





r_H
0.6
1.0
1.5
2.0
3.0
4.0
5.0
τ = 0.25, R = 1 m
'gas'
1.00
Model 4
collisional ring
('gas')
phase transition
0.10
'solid'
v_esc
Model 1
accreted satellites
('solid')
ε=0.5
0.01
Steady state velocity dispersion c_st (cm s^-1)
10
100
1000
10000
Ring particle bulk density ρ (kg m^-3)

A problem remains

A high velocity dispersion prevents accretion but means a rapid radial dispersion of the ring

Thus the ring needs a confinement mechanism, which may be insured by the 1/3 resonance

Conclusions

QR1 is well beyond the Roche limit (7.4 Quaoar's radii), the first of its kind!
(same problem with Q2R)

Simulations show that Hatzes+ (1988) rebound coefficient law can inhibit accretion if collisions are sufficiently elastic (at low temperature)

Like Chariklo's and Haumea's rings, Q1R is close to the 1/3 resonance with the body, (and Q2R is close to the 5/7 resonance). This resonance may be may the cause of their confinements (supported by the simulations shown in the 1st part of this talk)