Irregular Satellite Collisions: A Formation Mechanism for Circumstellar Debris Rings

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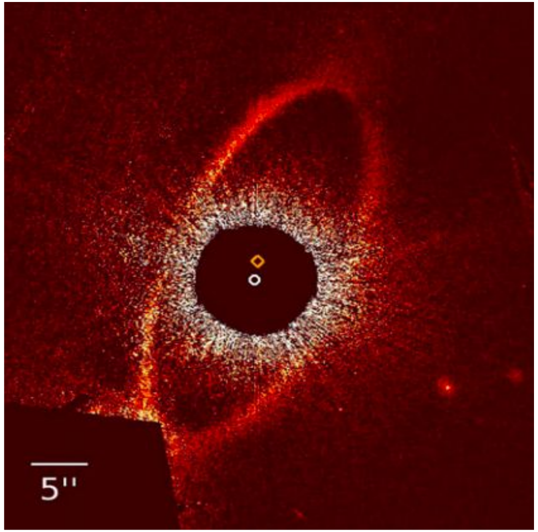
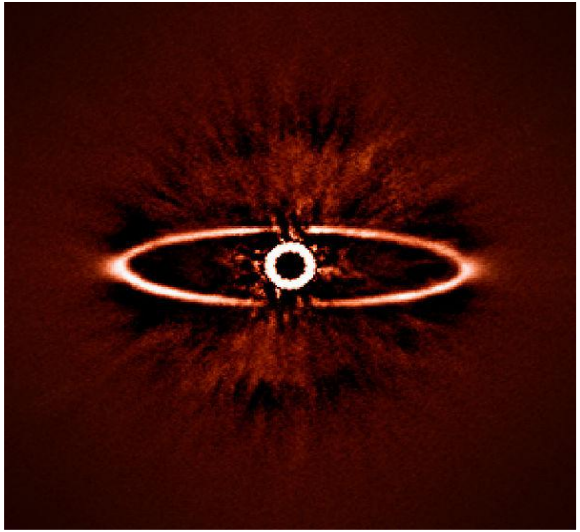
Some directly imaged debris disks exhibit thin rings

- Fomalhaut
- HR 4796A



Kalas et al. (2013)

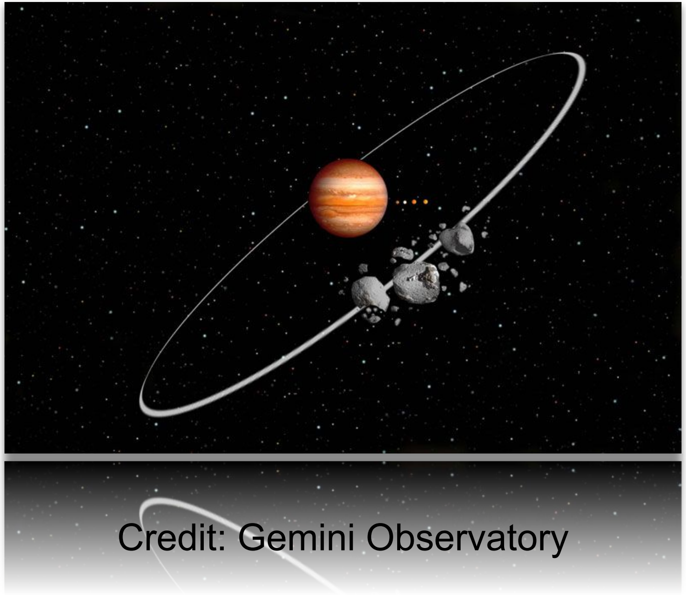


ESO image of HR 4796A in 2014

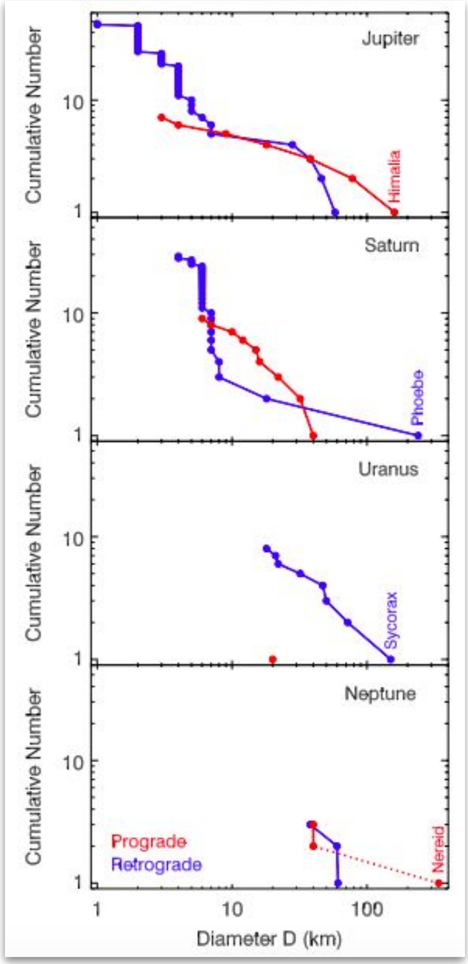
Are thin ring structures indicative of a hidden exoplanet and exomoon cloud?

What are irregular satellites?

- Minor bodies of the Jovian planets
  - Large semimajor axes, eccentricities, and inclinations
- Bottke et al. (2010) show they are highly collisionally evolved today
  - Have lost ~99% of starting mass (~0.001 lunar masses) over 3.9 Gyr
- Jewitt & Sheppard (2004) postulate they might be a generic consequence of giant planet formation



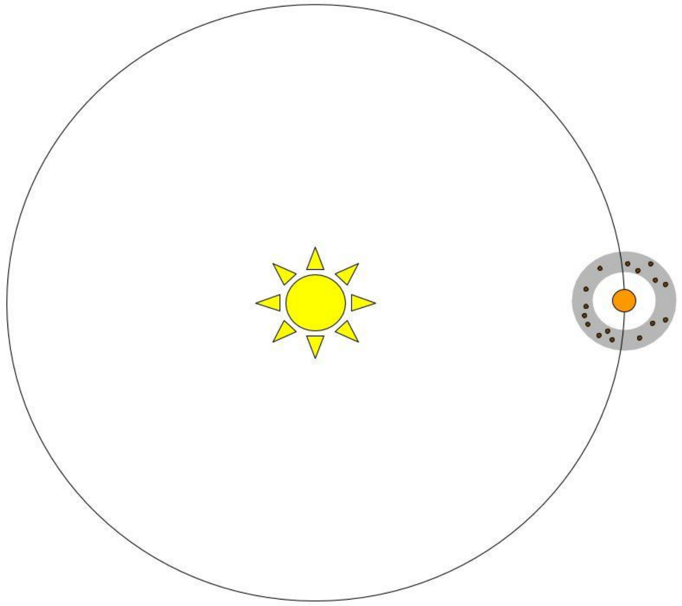
Credit: Gemini Observatory



Bottke et al. (2010)

Our Model: Irregular Satellite Collisions

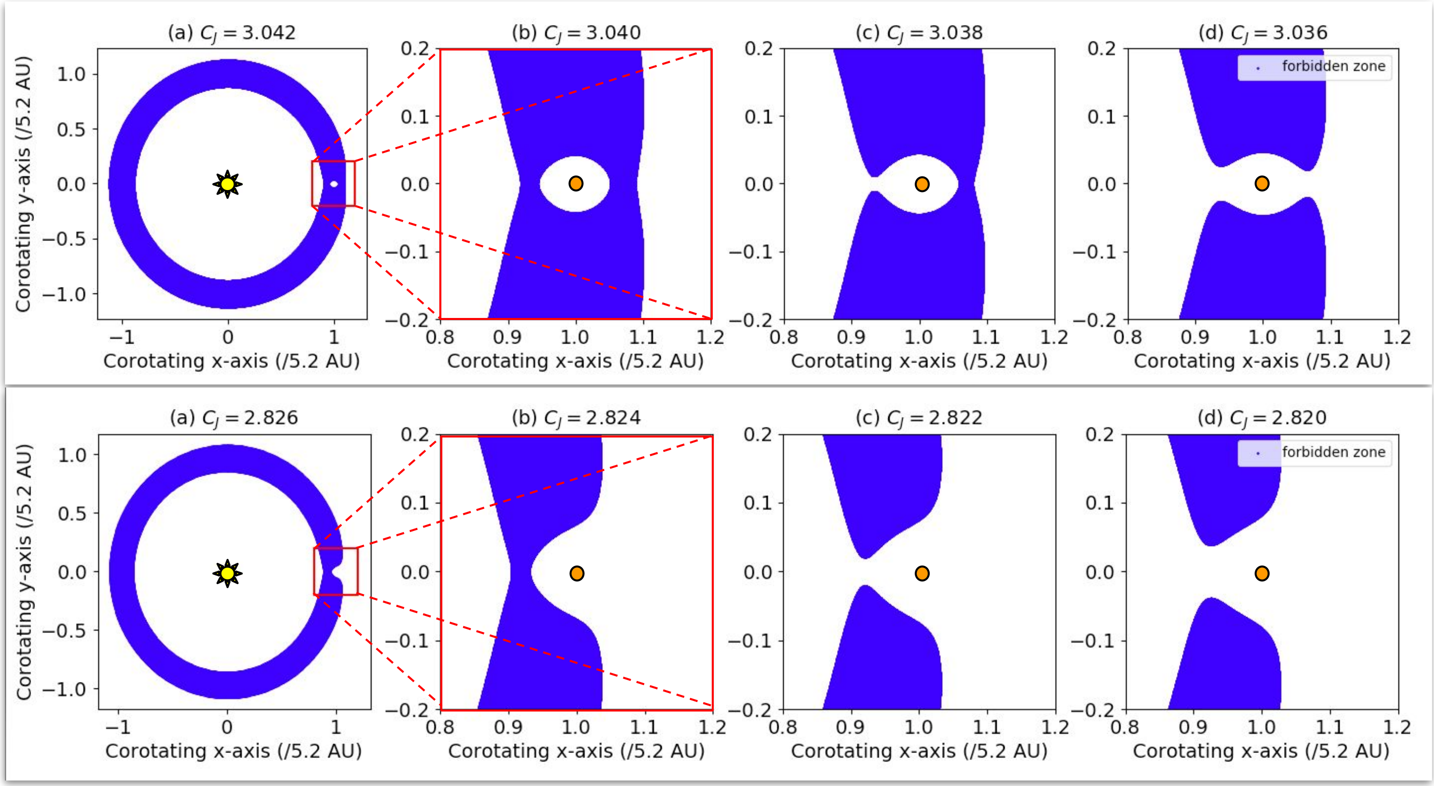
- Collisions among irregular satellites produce the dust found in debris disks
- Released dust is subject to radiation pressure, and thus may spread into a ring around star



Motivation: fundamental shift in forbidden zone when radiation pressure is “turned on”

β = 0

β = 0.1



permitted region ($v^2 > 0$)

forbidden zone ($v^2 < 0$)

$$v^2 = 2U - C_J$$

decreasing C_J

increasing v

Hayakawa & Hansen 2018 (*in prep*)

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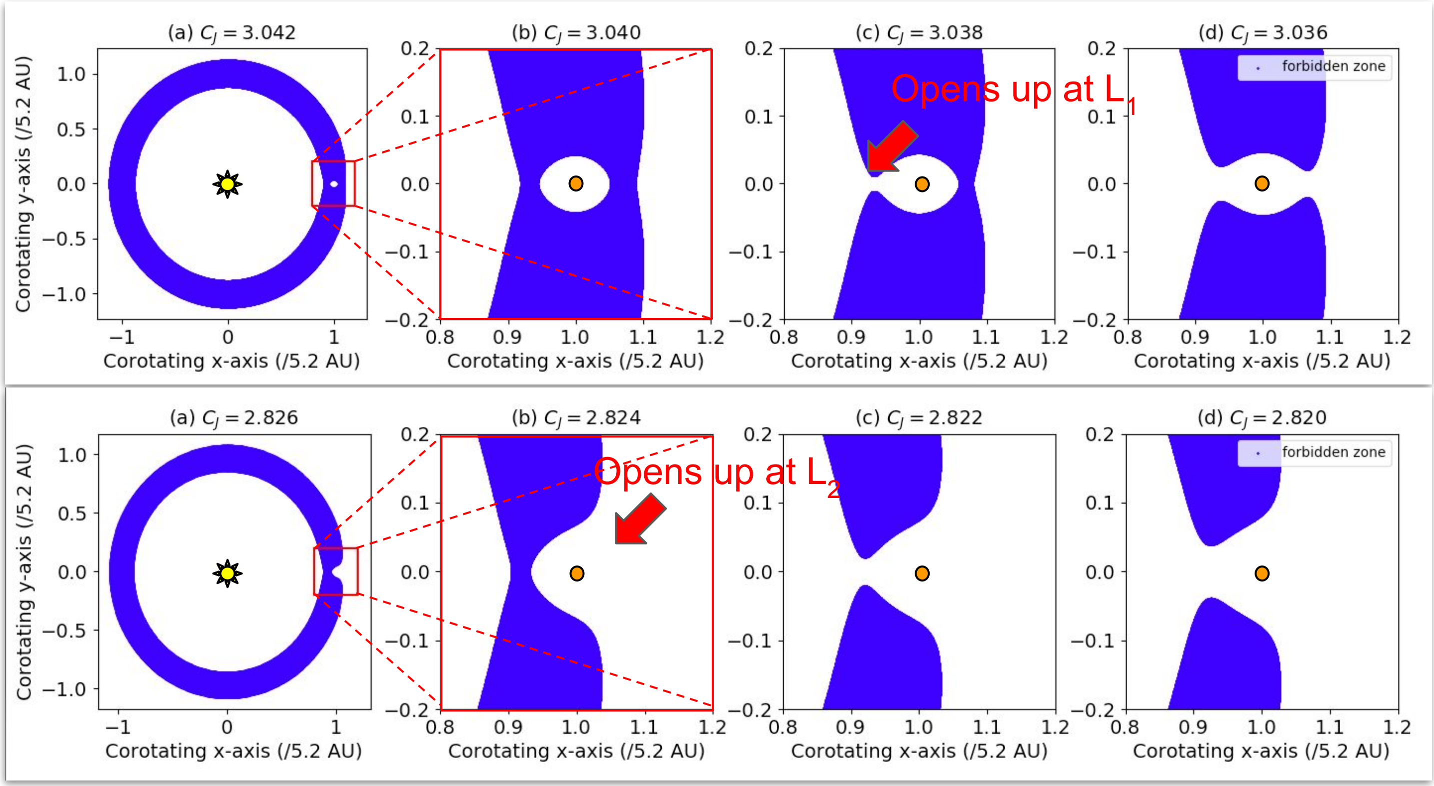

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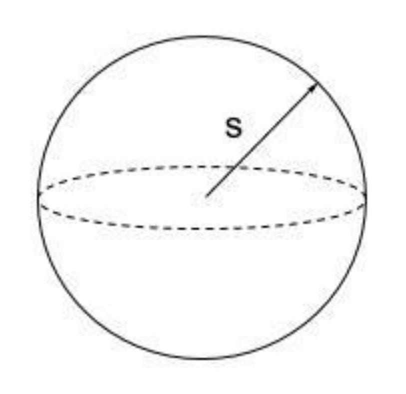
β scales inversely with grain size

$$\beta = \frac{3L_* \langle Q_{rad} \rangle}{16\pi G M_* c \rho s},$$

Burns et al. (1979)

$$\beta \approx 0.1 \Big(\frac{s}{1\ \mu m} \Big)^{-1}$$

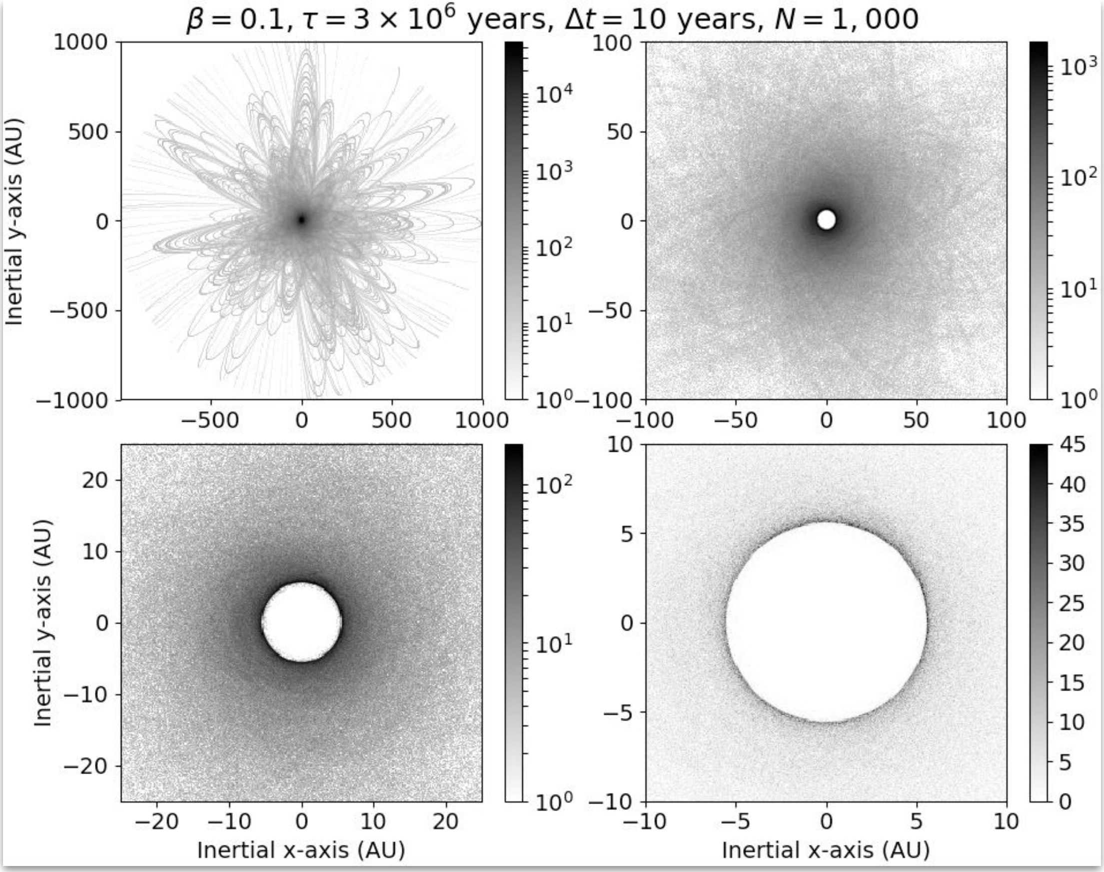
	Wavelength	β
Visible	400 - 700 nm	0.14 - 0.25
Near IR	780 - 2500 nm	0.04 - 0.13
Mid IR	2.5 - 15 μm	0.007 - 0.04
Far IR	15 - 1000 μm	10^{-4} - 0.007



We consider six representative values of β: 0, 0.01, 0.03, 0.05, 0.1, and 0.3

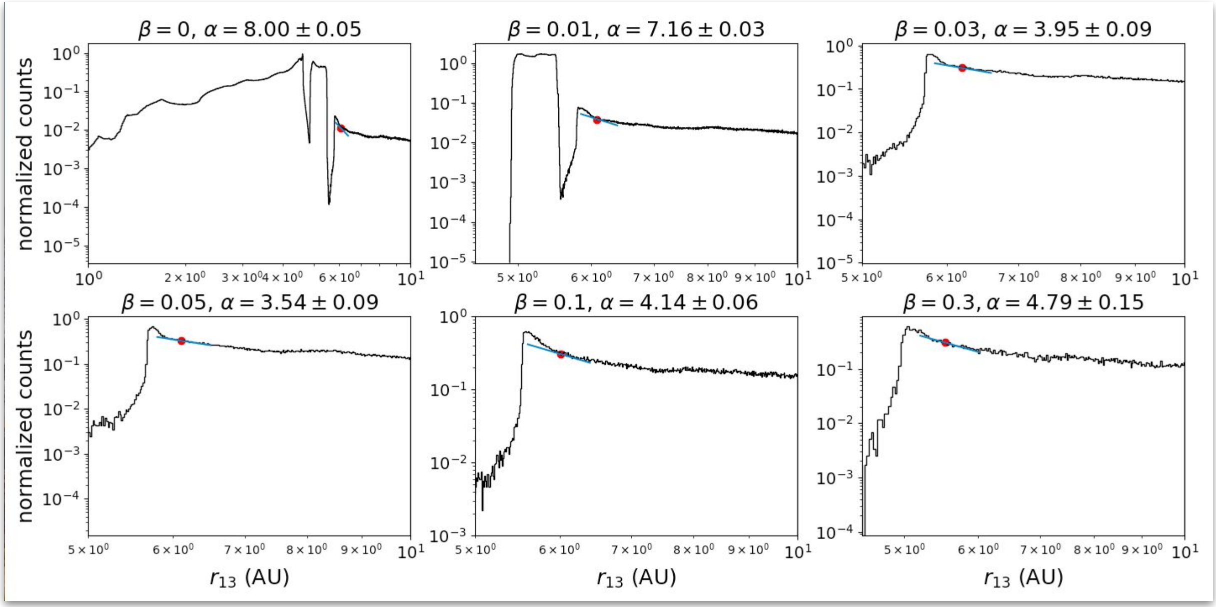
Synthetic images

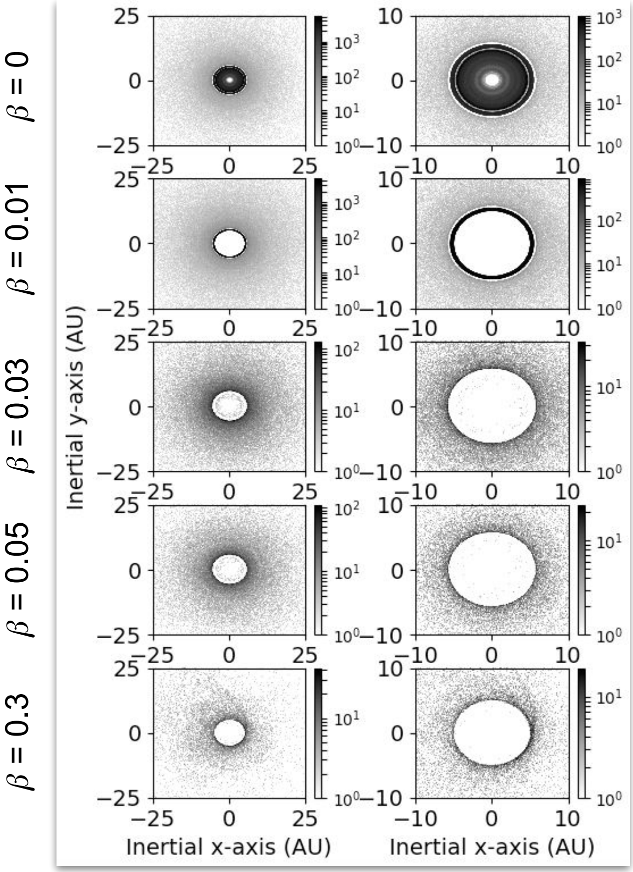
- Library of orbits
- Effective probability distribution of where dust grains are spending most of their time



Hayakawa & Hansen 2018 (*in prep*)

Synthetic images (cont.)



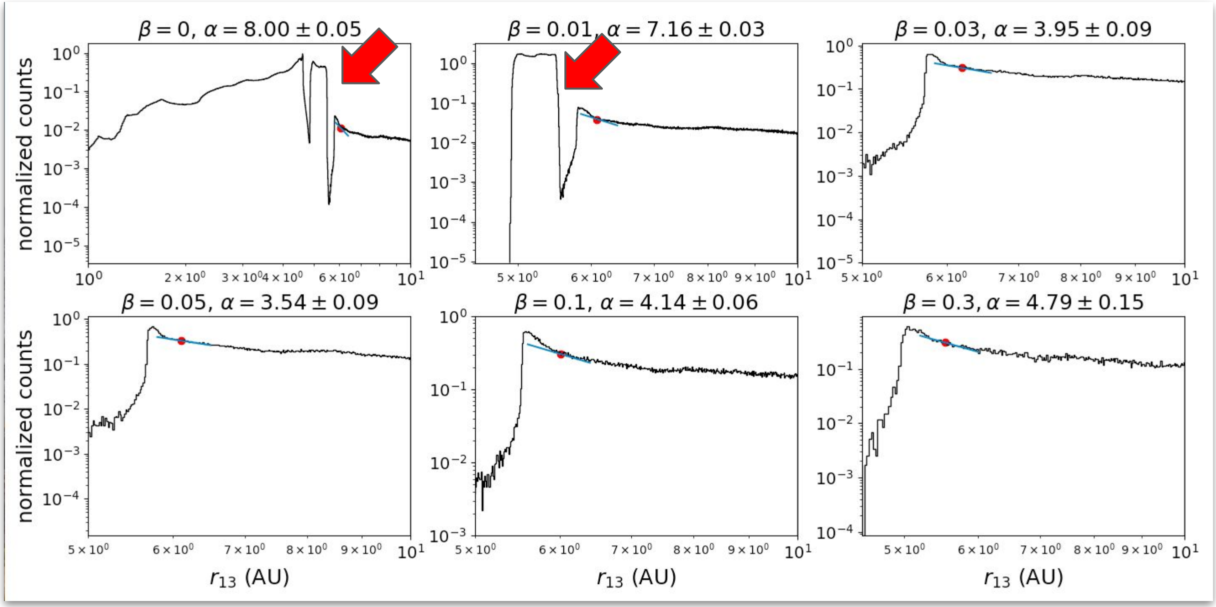


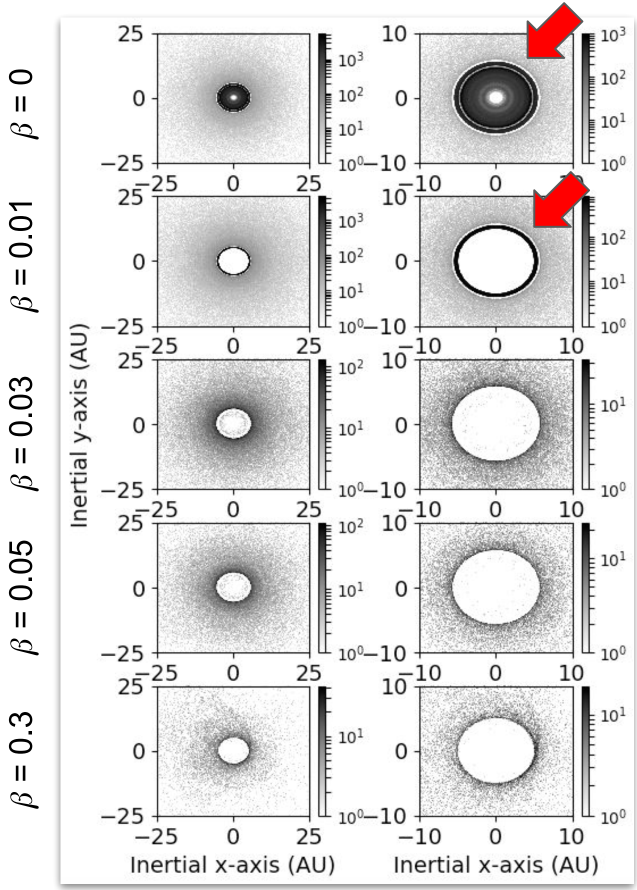
$$\beta \approx 0.1\left(\frac{s}{1\ \mu m}\right)^{-1}$$

Hayakawa & Hansen 2018 (*in prep*)

Synthetic images (cont.)

False positives!



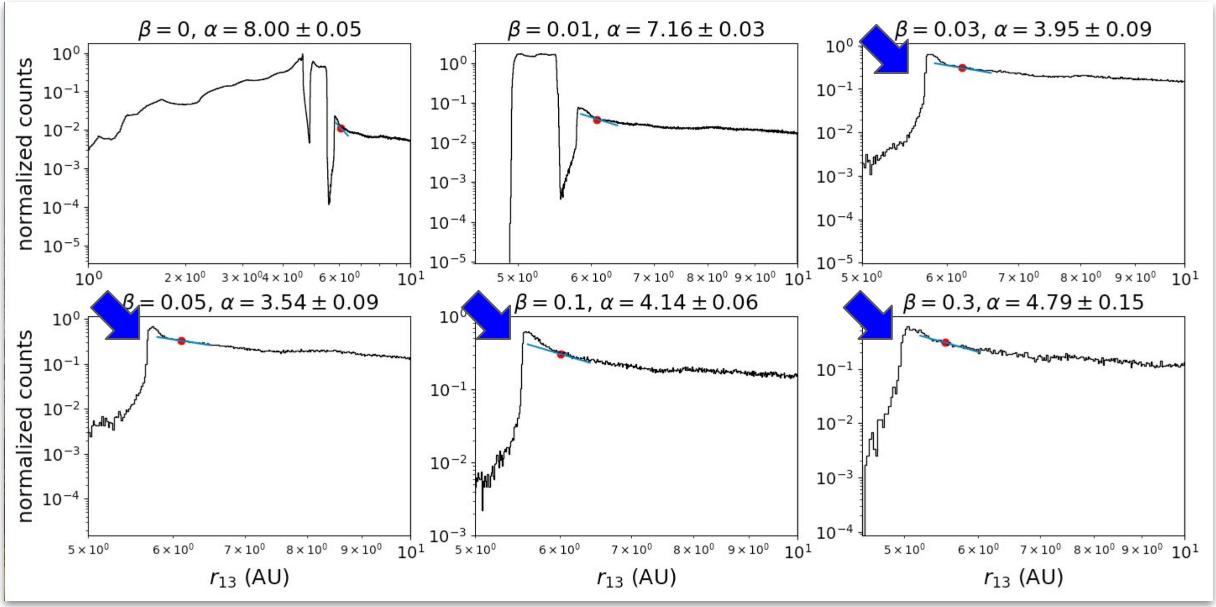


$$\beta \approx 0.1\left(\frac{s}{1\ \mu m}\right)^{-1}$$

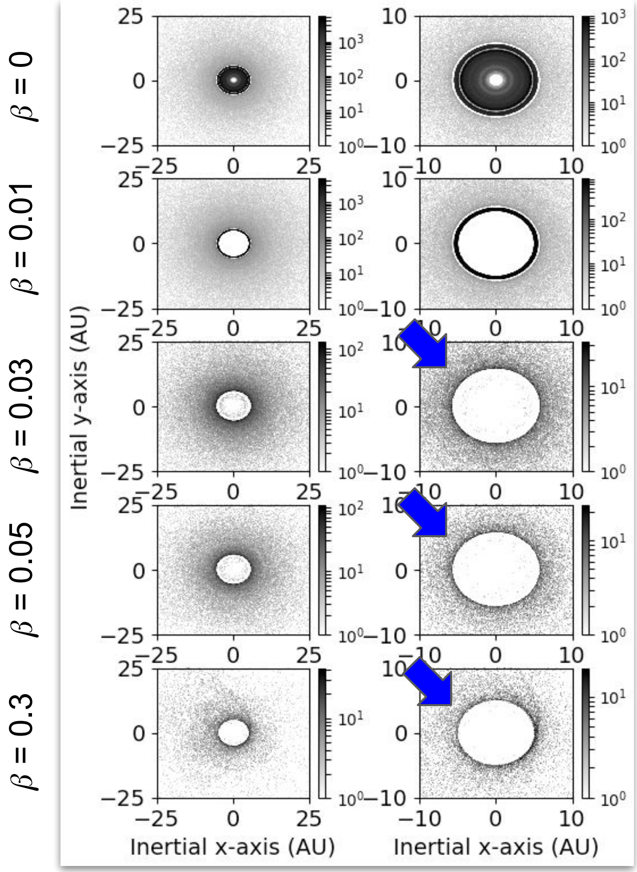
Hayakawa & Hansen 2018 (*in prep*)

Thin rings just outside forbidden zone

Synthetic images (cont.)



$$\beta \approx 0.1\left(\frac{s}{1\ \mu m}\right)^{-1}$$



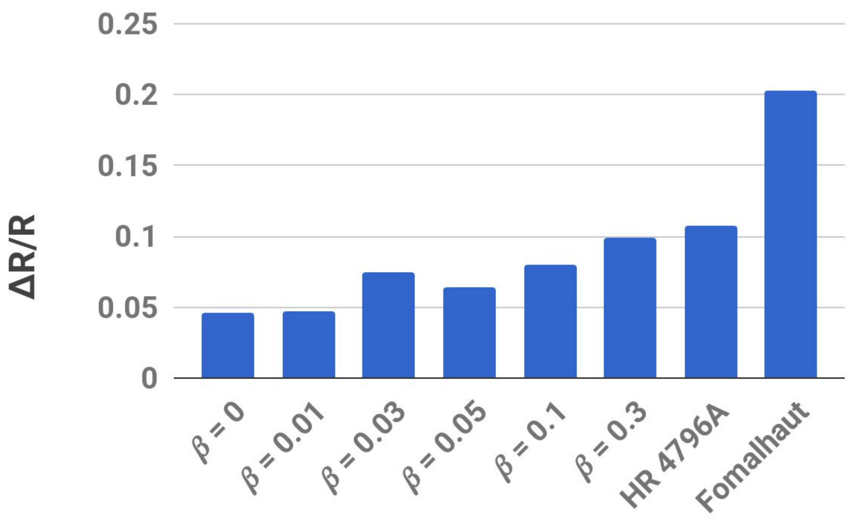
Hayakawa & Hansen 2018 (*in prep*)

Thin rings revisited

$$\beta \approx 0.1\left(\frac{s}{1\ \mu m}\right)^{-1}$$

- Criterion for thin rings as laid out in Hughes et al. (2018):

$\Delta R/R \lesssim 0.5$



β	ΔR (AU)	R (AU)	$\Delta R/R$
0	0.267	5.81	0.046
0.01	0.275	5.81	0.047
0.03	0.433	5.77	0.075
0.05	0.369	5.74	0.064
0.1	0.445	5.57	0.080
0.3	0.500	5.03	0.099
HR 4796A	8.02	74.4	0.108
Fomalhaut	25	123	0.203

Hayakawa & Hansen 2018 (*in prep*)

Summary

- Our goal was to test the plausibility of irregular satellite collisions reproducing the thin rings observed in Fomalhaut and HR 4796A
- Used N-body simulations and the Jacobi integral to investigate this hypothesis
- Identified a behavioral shift at β = 0.02 (s = 5 μm) in both density profiles and eccentricity distributions
- Successfully reproduced thin rings similar to HR 4796A in a proof-of-concept model