Theoretical modelling of debris disk structure

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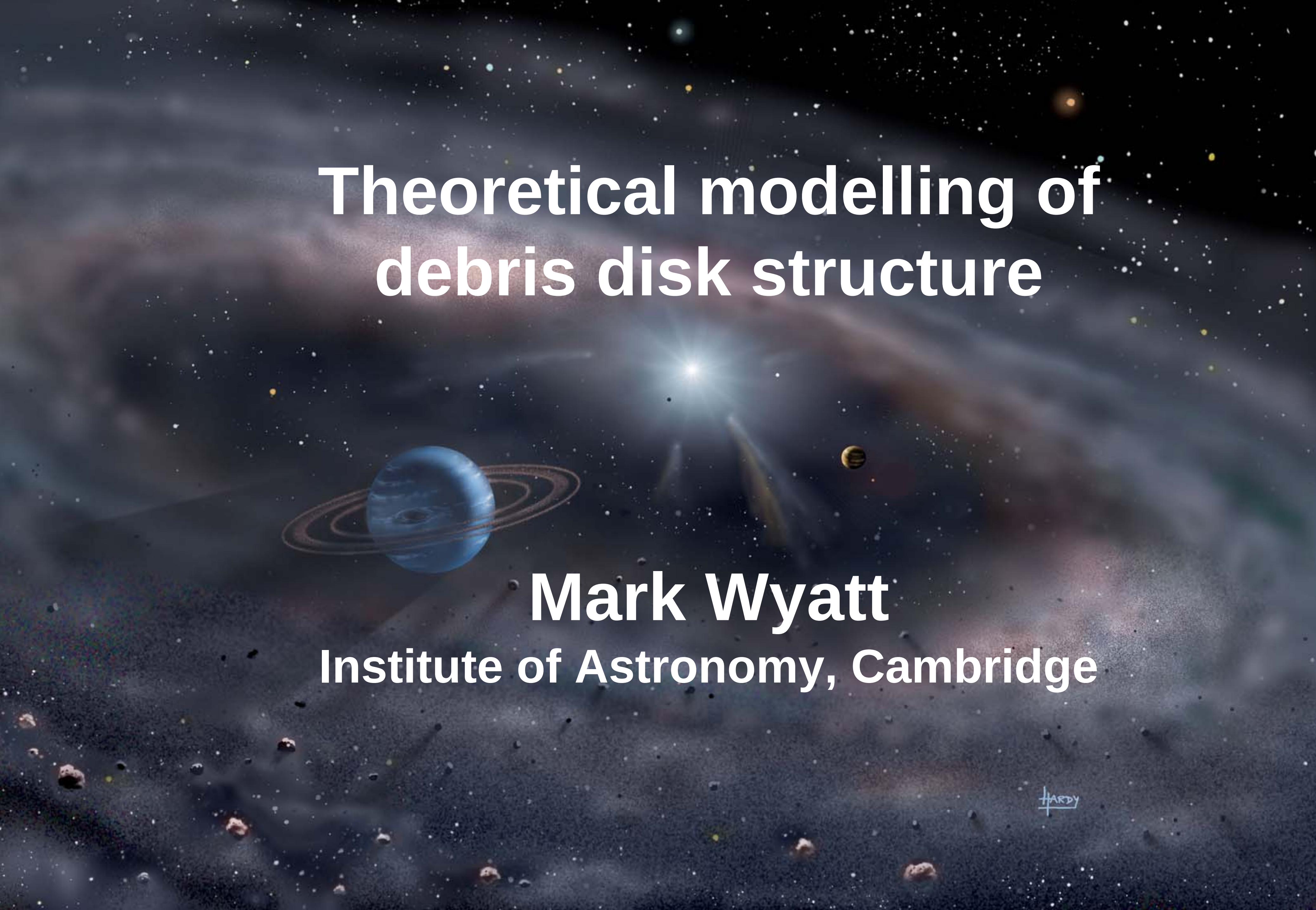


Outline

(I) **Radial structure**
- Flux vs radius and wavelength

Most can be explained by dust produced in steady-state collisional evolution of planetesimal belts…

(II) **Non-axisymmetric structure**
- Clumps and asymmetries

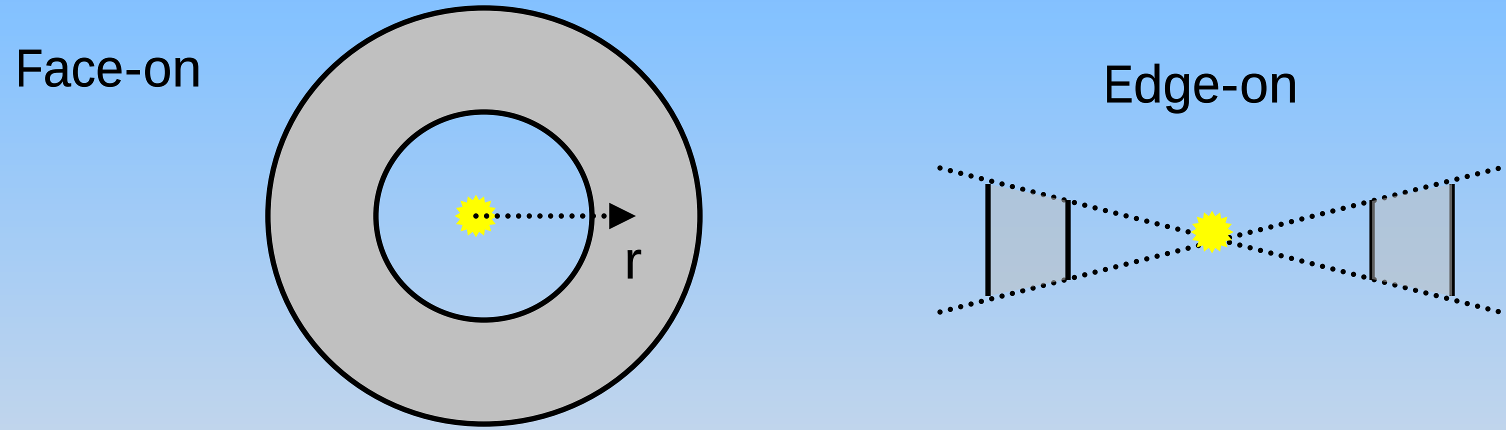
Most can be explained by perturbations to that evolution…

(III)

… but there are EXCEPTIONS

(I) Radial structure

The axisymmetric structure of debris disks can be explained as the consequence of a belt of planetesimals orbiting the star



- No need to know origin of planetesimals or why they are confined to a ring
- But understanding interplay between collisions and radiation forces is essential

Collisions

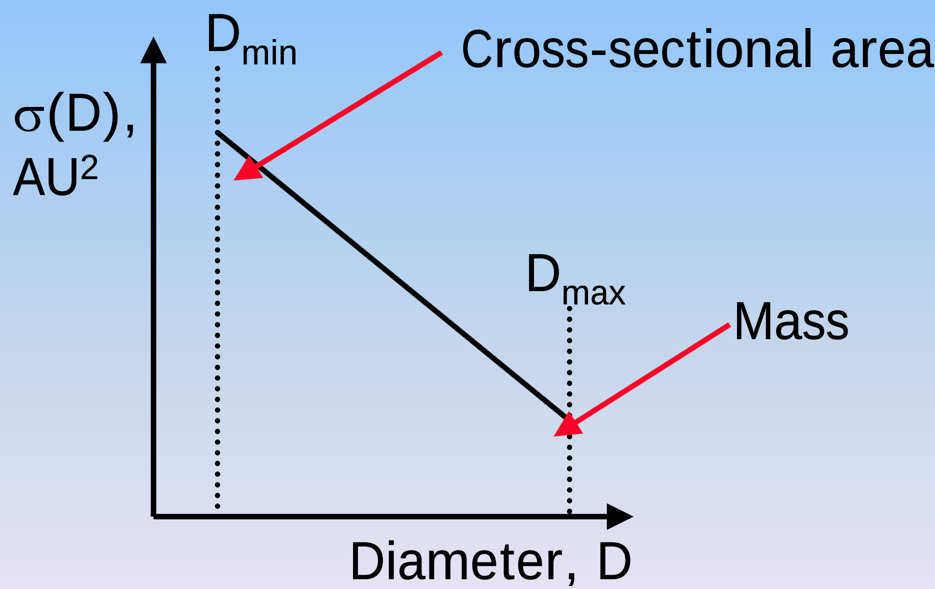
Existence of dust implies collisions are destructive and so the planetesimal belt has been stirred:

$e, I > 10^{-3} – 10^{-2}$ (e.g., talk by Kenyon)

Collisions result in collisional cascade with a size distribution:

$\sigma(D) \propto D^{-1.5}$

Collisional lifetime $t_{col} \propto D^{0.5}$

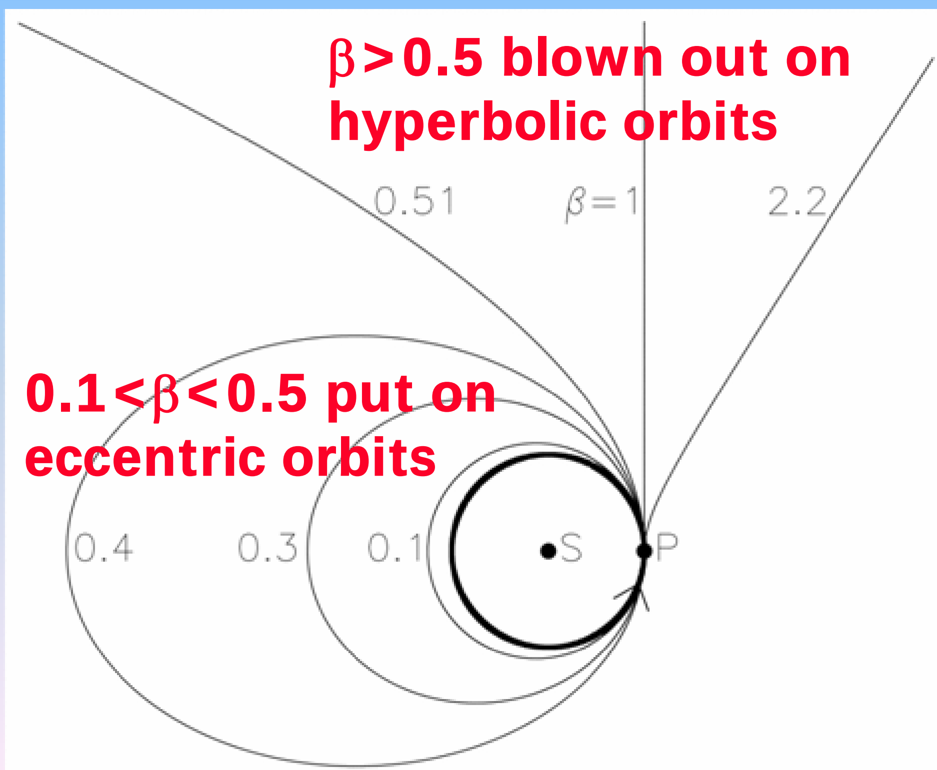


Radiation forces

Small grains interact with stellar radiation resulting in a force characterised by:

$\beta = F_{rad}/F_{grav} \approx (0.4/D)(L_*/M_*)$

1. **Radiation pressure**



2. **Poynting-Robertson drag**

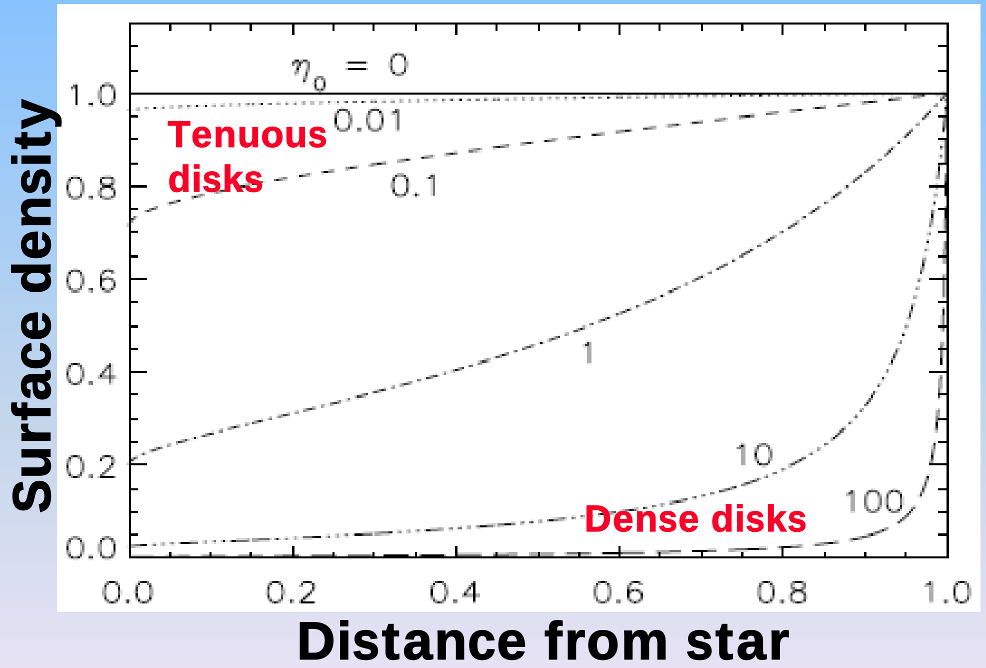
All dust grains spirals toward star on timescale

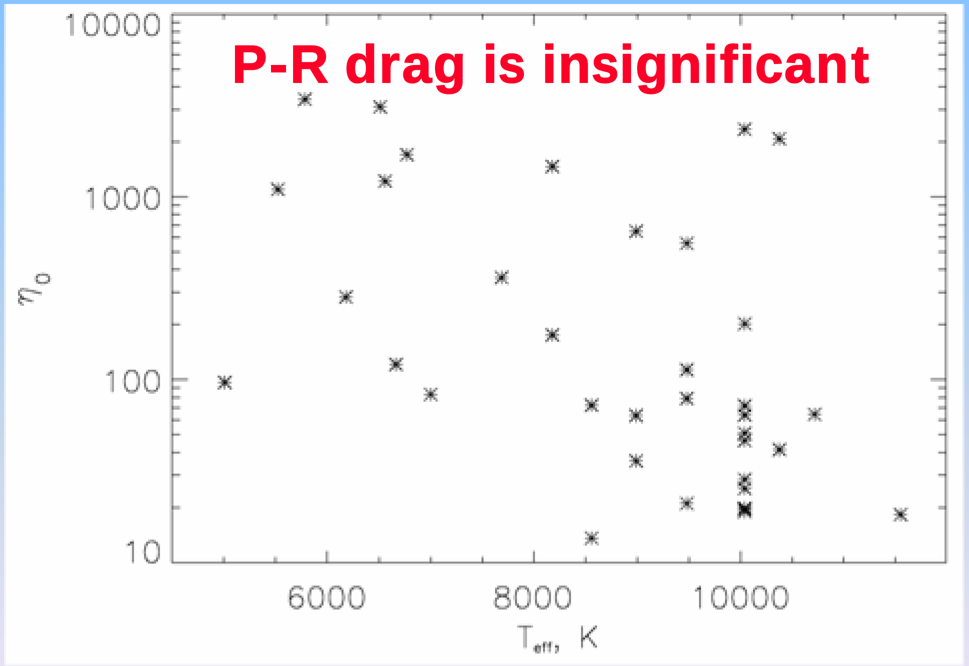
$t_{pr} = (400/M_*)r^2/\beta$ years

P-R drag is insignificant…

Distribution of dust due to loss in collisions and migration by P-R drag depends on η_0 **= t_{pr} / $t_{col} \propto$ D$^{0.5}$**

If η_0 >> 1 for the smallest particles (β=0.5) then all dust remains confined to the planetesimal belt



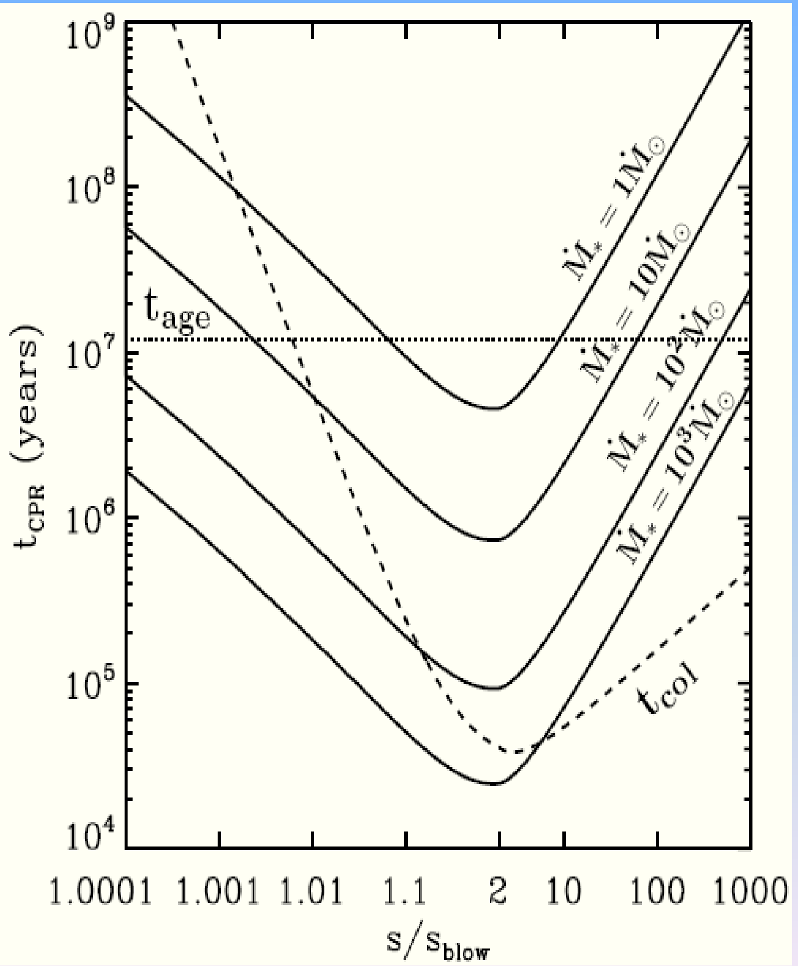


Wyatt (2005)

… but stellar wind drag may be significant for M stars

Stellar wind forces also result in a pressure and drag component, and these can be characterised by β_{sw}.

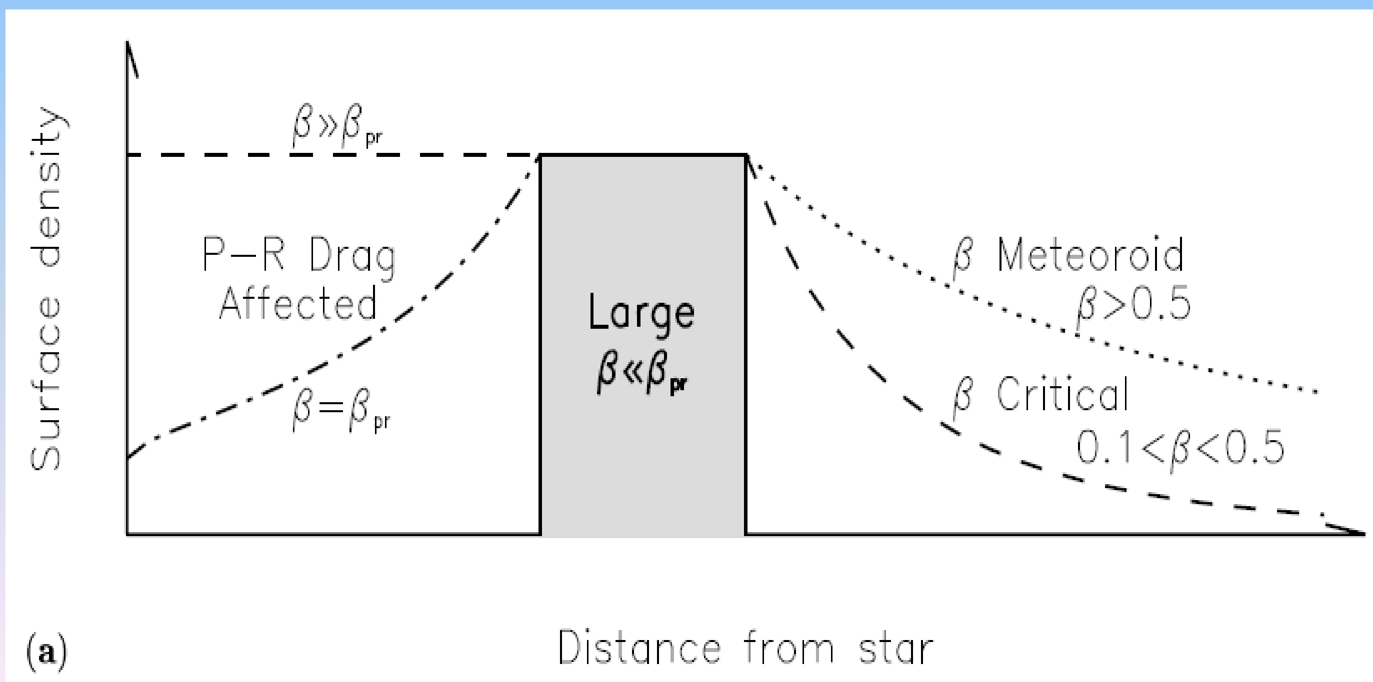
In the solar system β_{sw}/β_{rad} = 1/3, but in M stars β_{sw}/β_{rad} >> 1 as low luminosity and high mass loss rate (Plavchan et al. 2005, Strubbe & Chiang 2006, Augereau & Beust 2006).



Disk particle categories

Particles of different sizes have different dynamics:

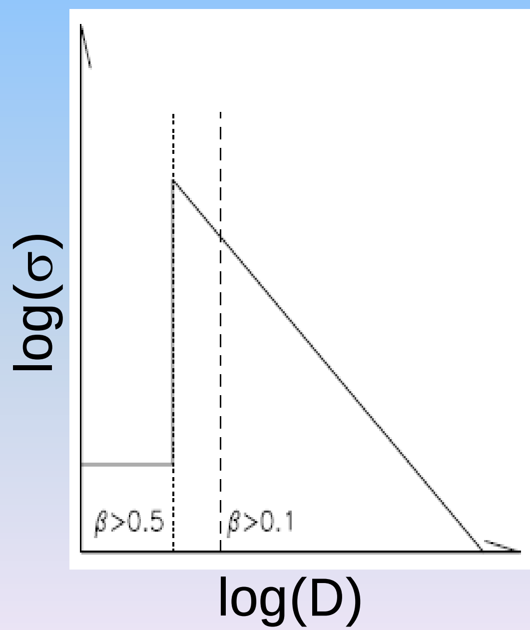
• $\beta << \beta_{pr}$	**large**	confined to belt
• $\beta \approx \beta_{pr}$	**P-R drag affected**	little depleted by collisions on way in
• $0.1<\beta<0.5$	**β critical**	bound, but extended distribution
• $\beta>0.5$	**β meteoroid**	blown out on hyperbolic orbits



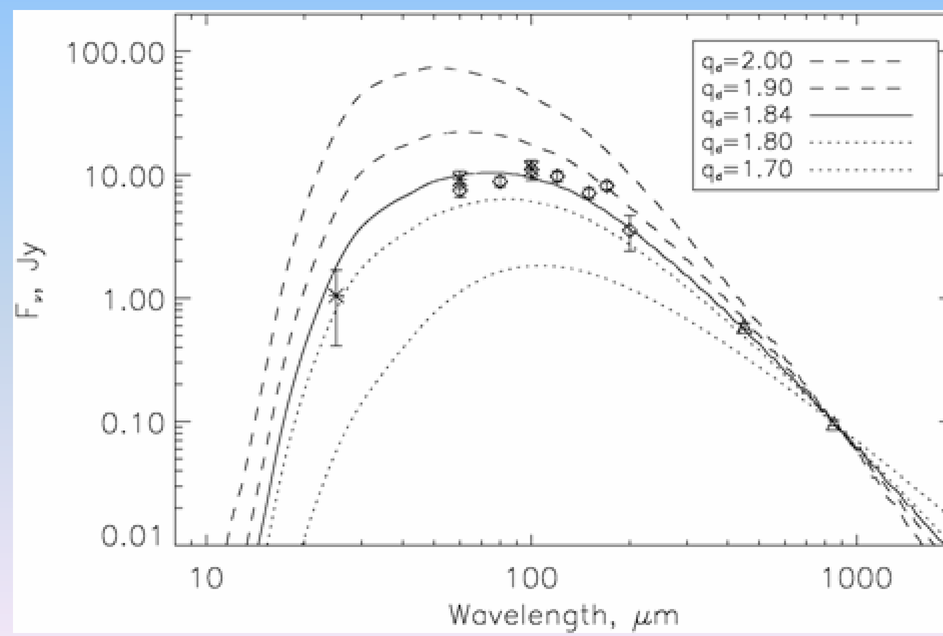
Not all types of particles exist in every disk

Collision dominated disk: simple model

Simple treatment of expected size distribution often suffices and is MUCH better than assuming single grain size



The emission spectrum of Fomalhaut, for which radius is well known, implies collisional cascade size distribution (Wyatt & Dent 2002)

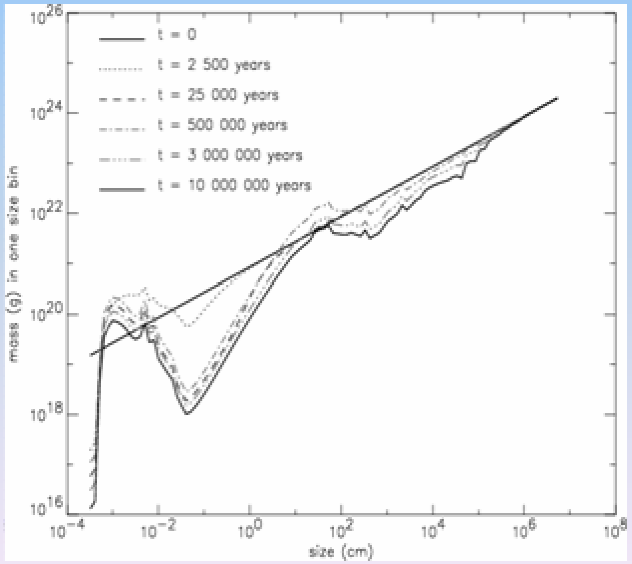


Collisional evolution models: wavy size distribution

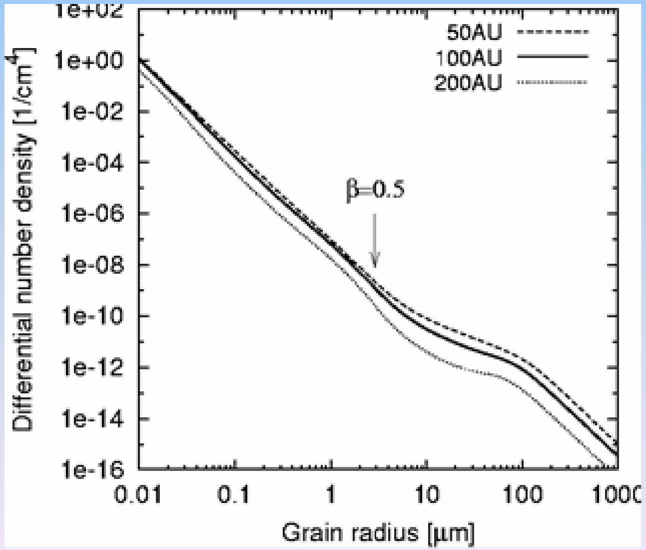
See posters by Thebault, Krivov

Collisional evolution for realistic cascades is followed numerically showing details

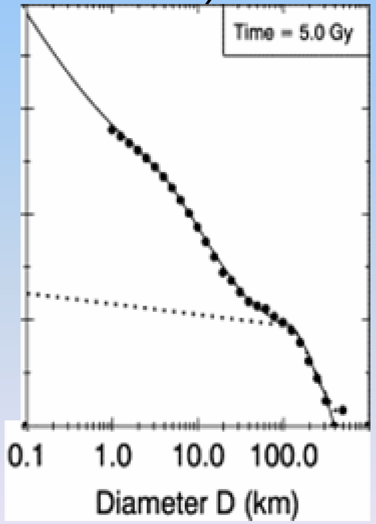
Lack of β>0.5 dust causes a wave (Thebault, Augereau & Beust 2003)



Abundance of β>0.5 dust eroded the smallest bound grains (Krivov, Mann & Krivova 2000)



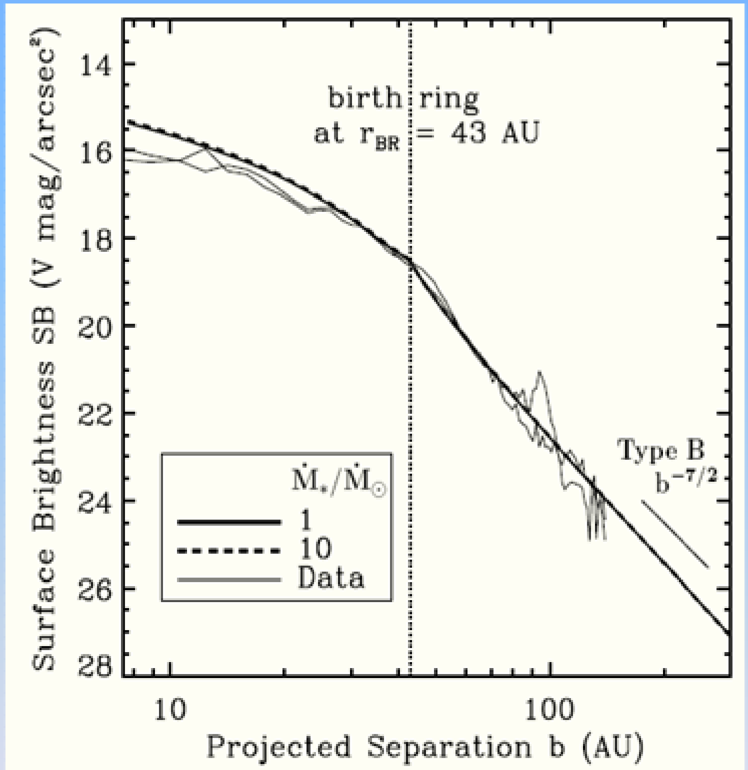
Size dependence of planetesimal strength causes wave at 150m (Bottke et al. 2005)

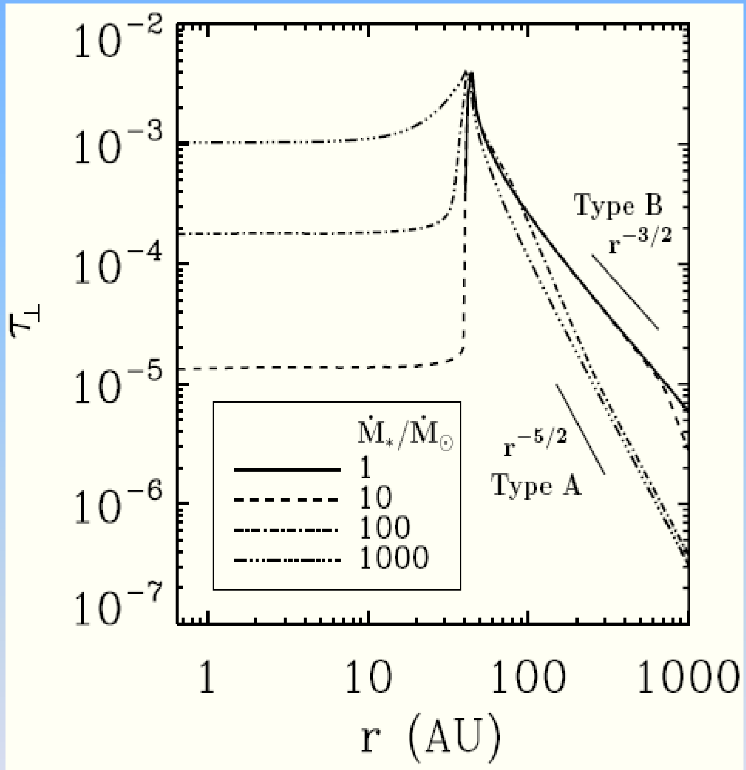


Details can be important

Short wavelengths probe smallest grains and so are dominated by the details

By including details, extended structure of AU Mic explained by dust created in a narrow belt at ~40AU (Augereau & Beust 2006; Strubbe & Chiang 2006)





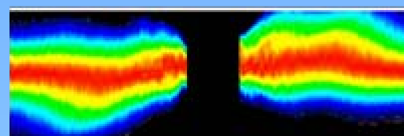
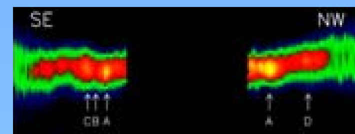
Understand this model before considering non-axisymmetric structure

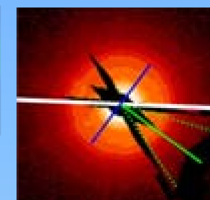
Extended dust distribution does not mean planetesimals are extended

(II) Non-axisymmetric structure

Different types of structures observed in debris disk images (talk by Greaves):

Warps

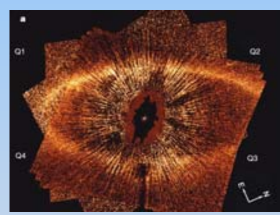
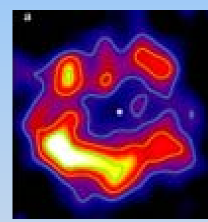





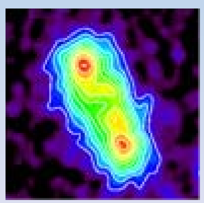
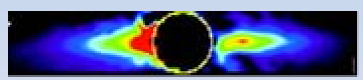
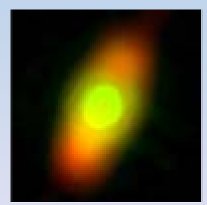
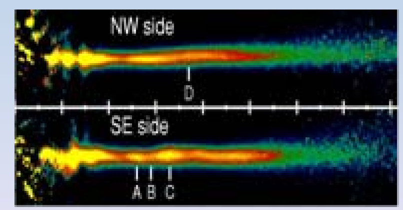
Spirals

All of these structures can be explained by dynamical perturbations from unseen planets orbiting the star

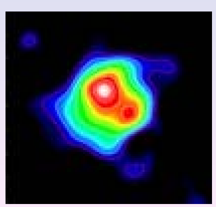
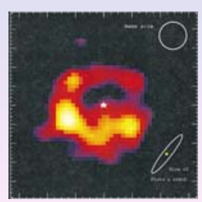
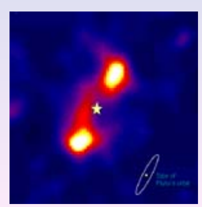
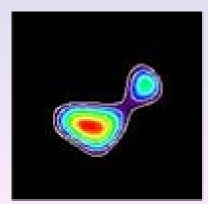
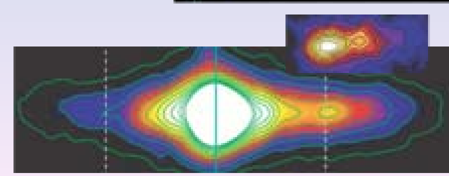
Offsets

Brightness asymmetries

Clumpy rings

Planetary perturbations

Planetary system dynamics predicts exactly this set of features

Two types of perturbations:

(1) Secular perturbations

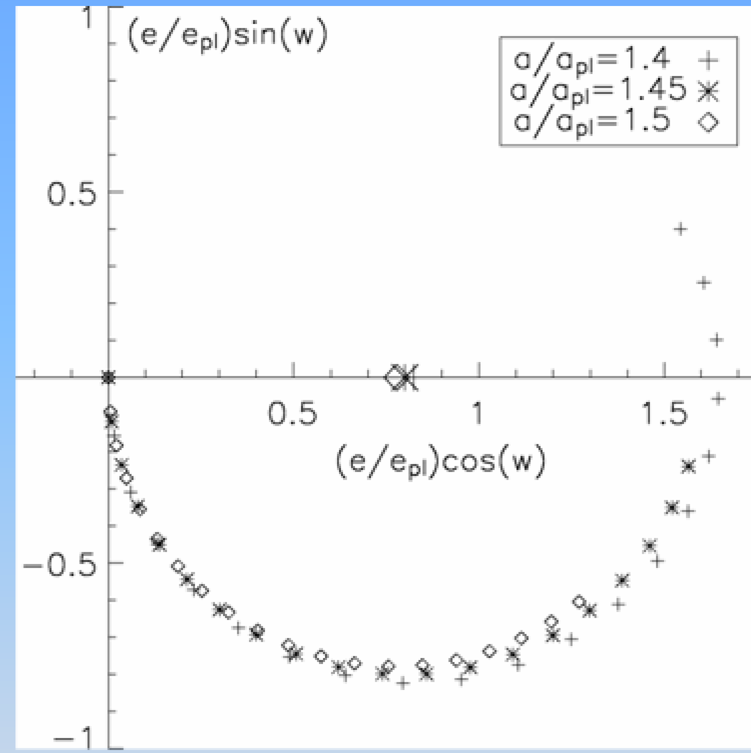
- eccentric planet
  - young disk = **spiral**
  - old disk = offset = **brightness asymmetry**
- inclined planet
  - young disk = **warp**
  - multiple planets in old disk = **warp**

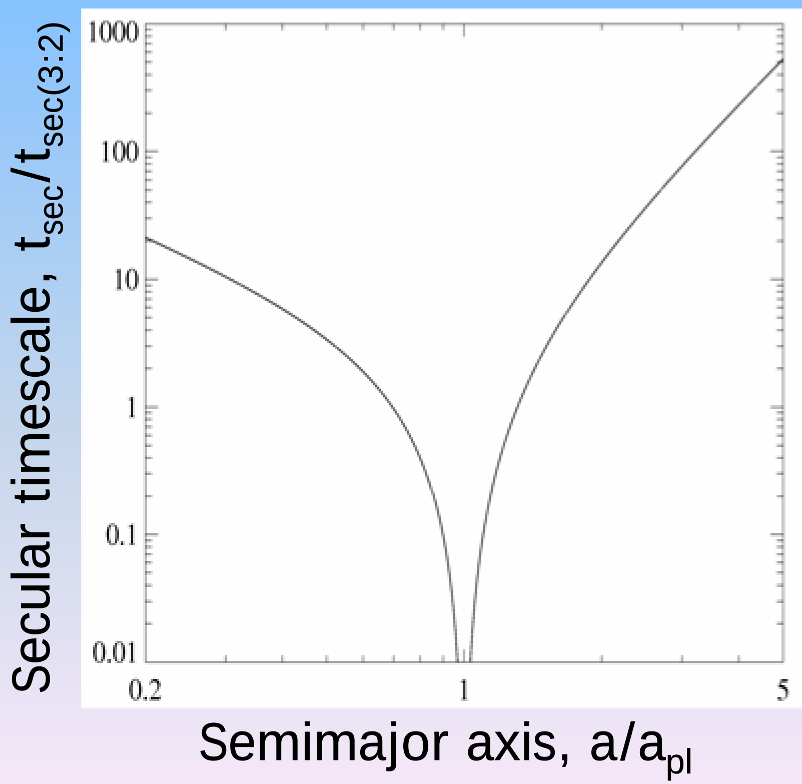
(2) Resonant perturbations

- multiple planets = **cleared region**
- individual planet = **clumps**

Secular perturbations of eccentric planet

Impact of sudden introduction of planet on eccentric orbit is to impose an eccentricity on nearby planetesimals

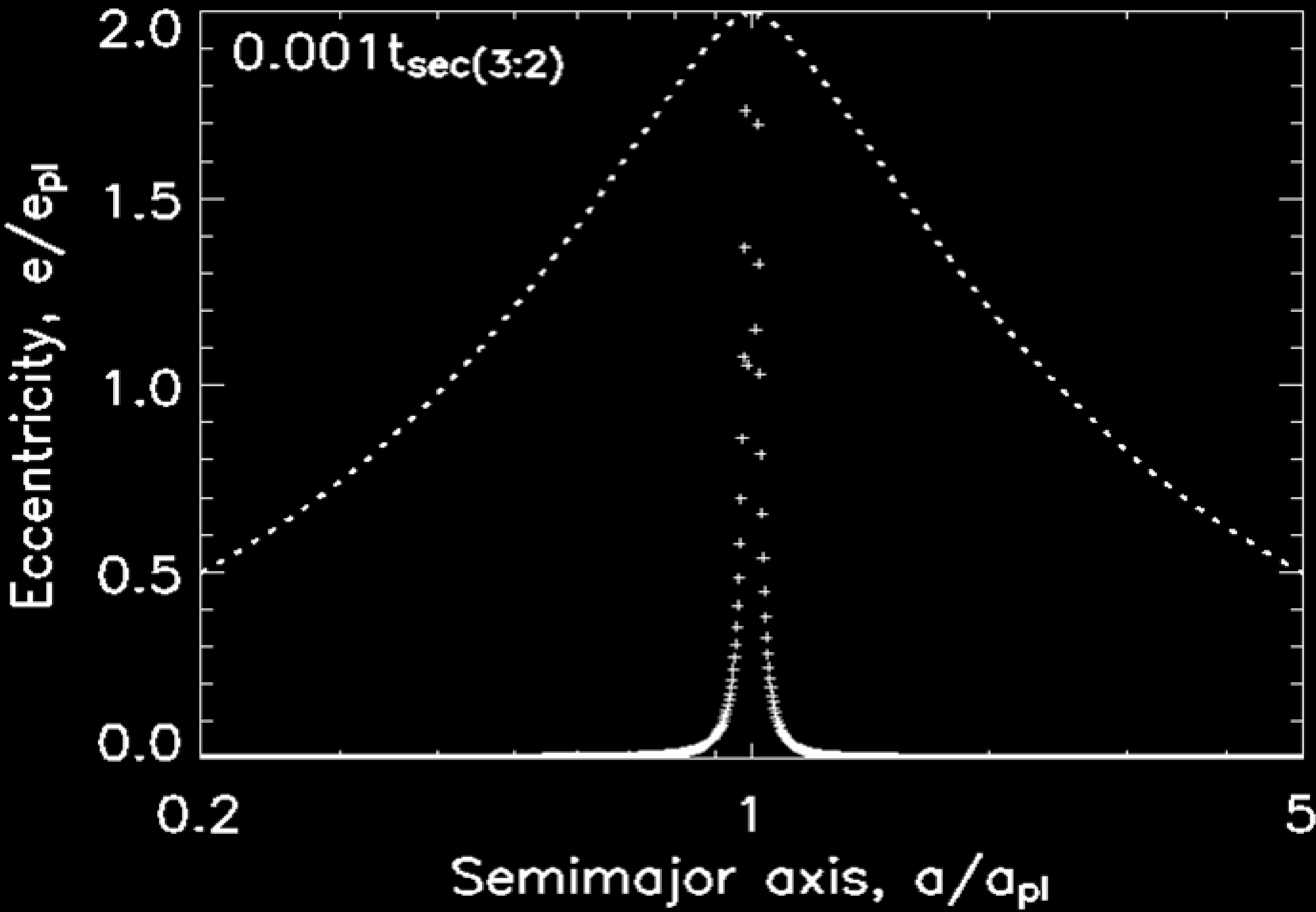




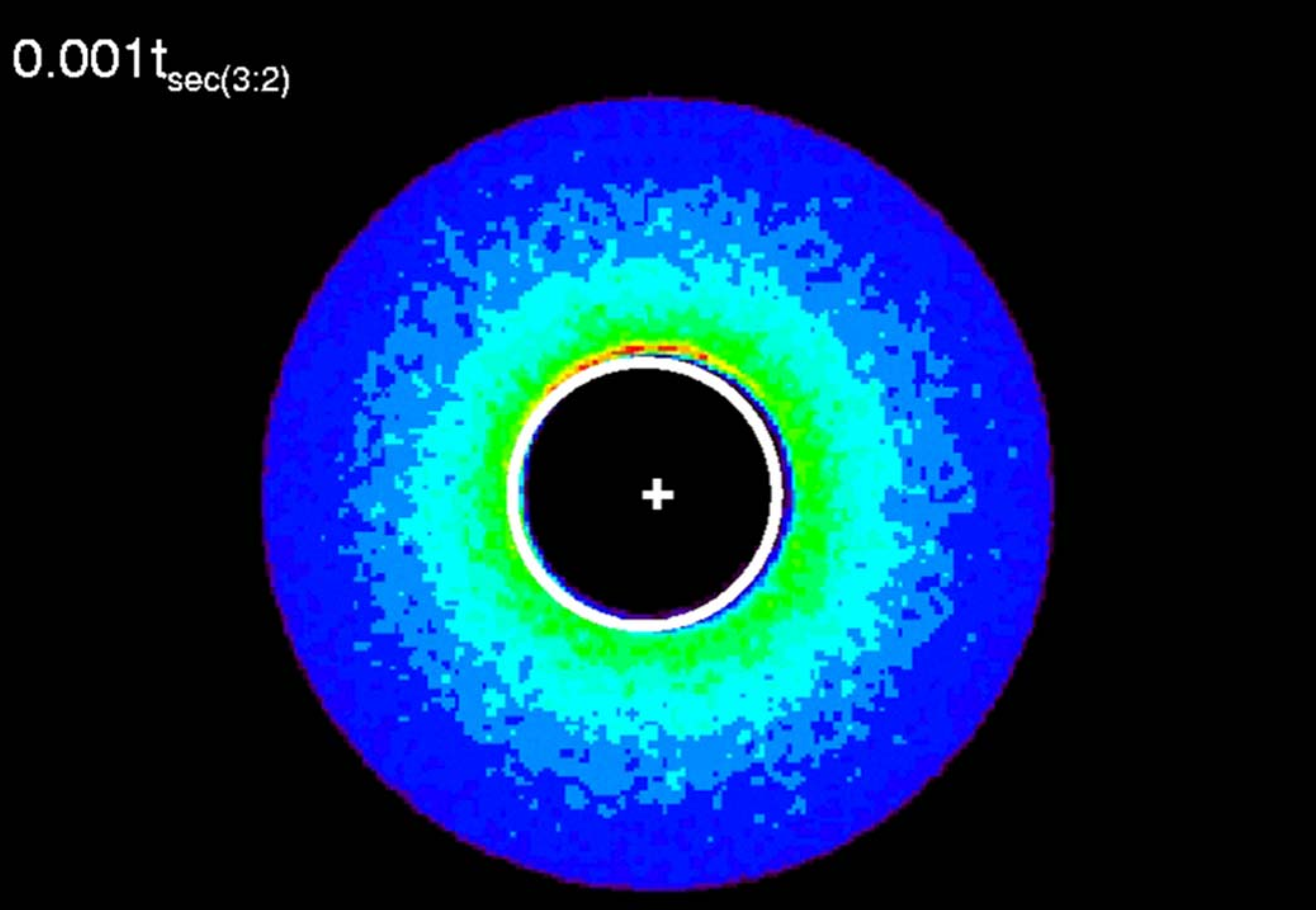
Precession rates are slower for planetesimals further from planet which means dynamical structure evolves with time

$$t_{sec(3:2)} = 0.651 t_{pl}/(M_{pl}/M_{star})$$

Wyatt (2005)



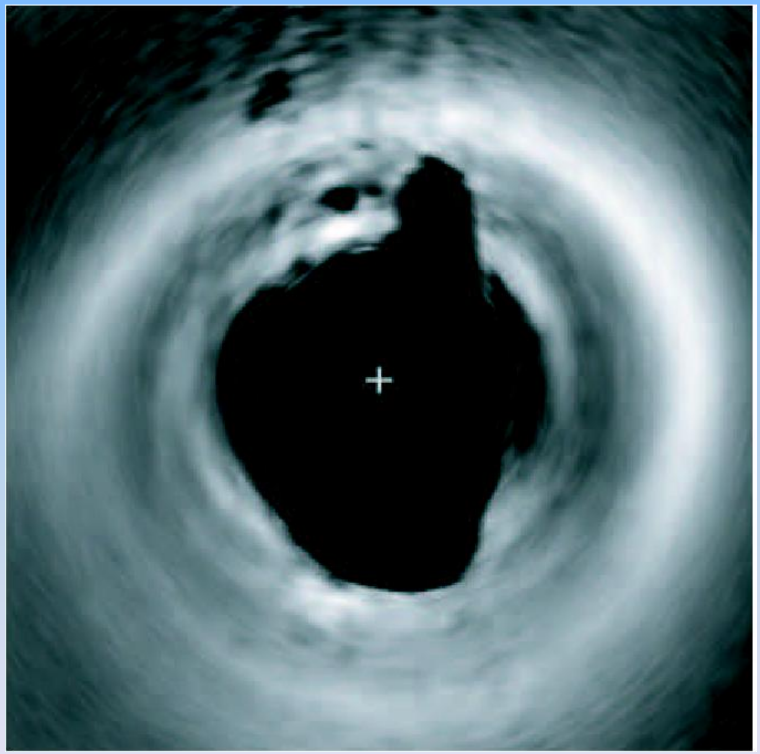
0.001t_sec(3:2)
Eccentricity, e/e_pl
2.0
1.5
1.0
0.5
0.0
0.2
1
5
Semimajor axis, a/a_pl


$0.001t_{sec(3:2)}$

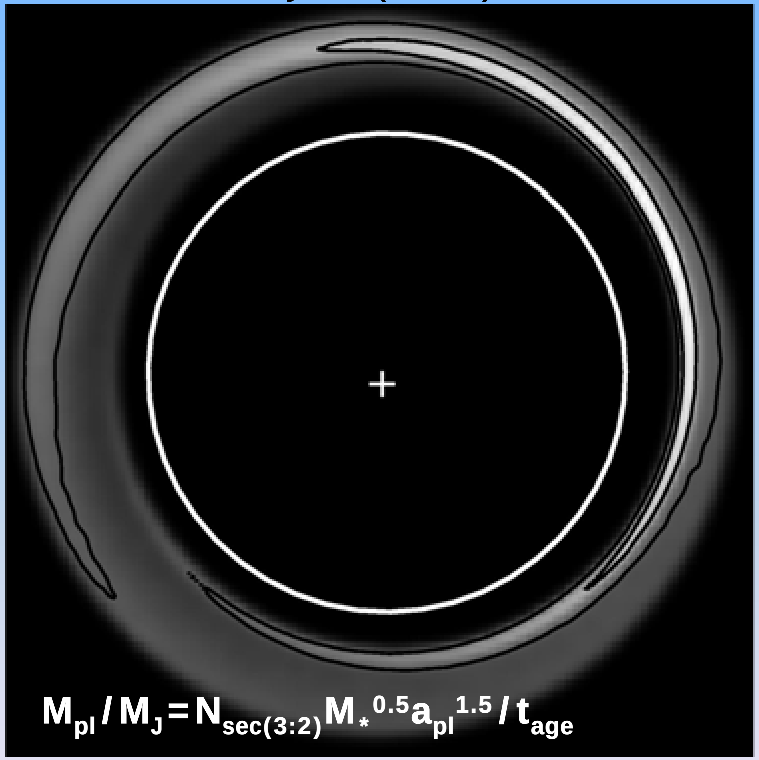
Spiral Structure in the HD141569 Disk

- HD141569A is a **5 Myr**-old **B9.5V** star at **99 pc**
- Dense rings at 200 and 325 AU with tightly wound spiral structure (Clampin et al. 2003)

Observation



Wyatt (2005)

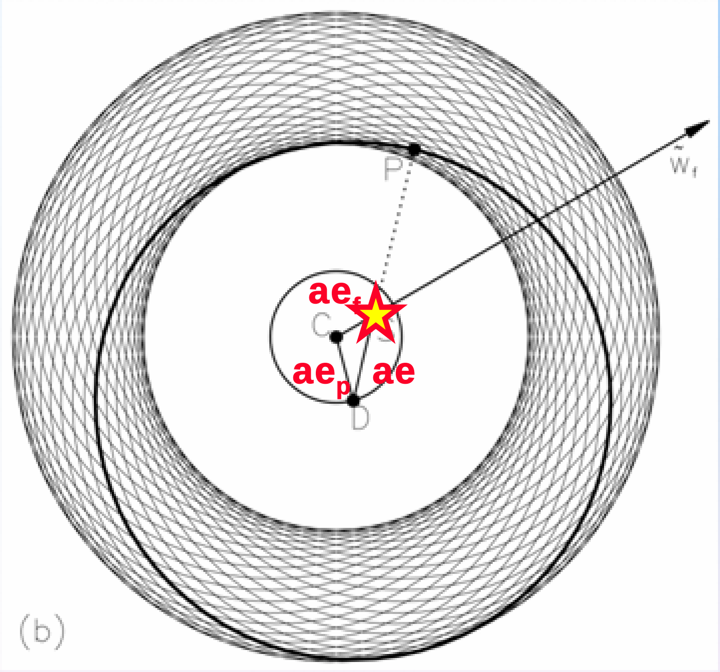


- Spiral at 325AU explained by $0.2M_{Jupiter}$ at 250AU with $e=0.05$ (Wyatt 2005)

Perturbations at late times in narrow ring

After many precession periods, orbital elements distributed around circle centred on forced eccentricity

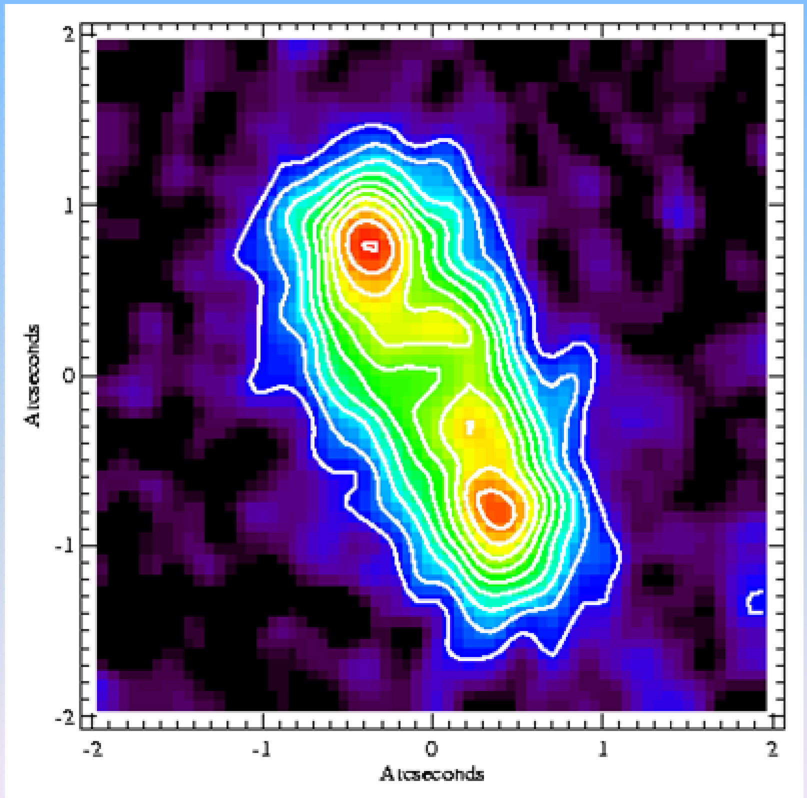
This translates into material in a uniform torus with centre of symmetry offset from star by ae_f in direction of forced apocentre

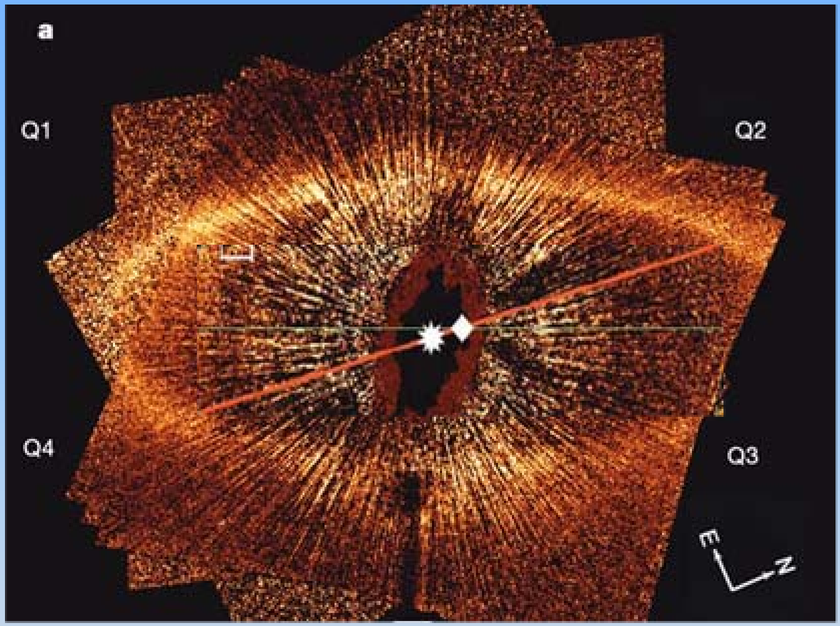


Wyatt et al. (1999)

Applications of pericentre glow

First predicted in dust ring of HR4796 (A0V , 10Myr) from 5% brightness asymmetry, implying a forced eccentricity of 0.02 (Wyatt et al. 1999)



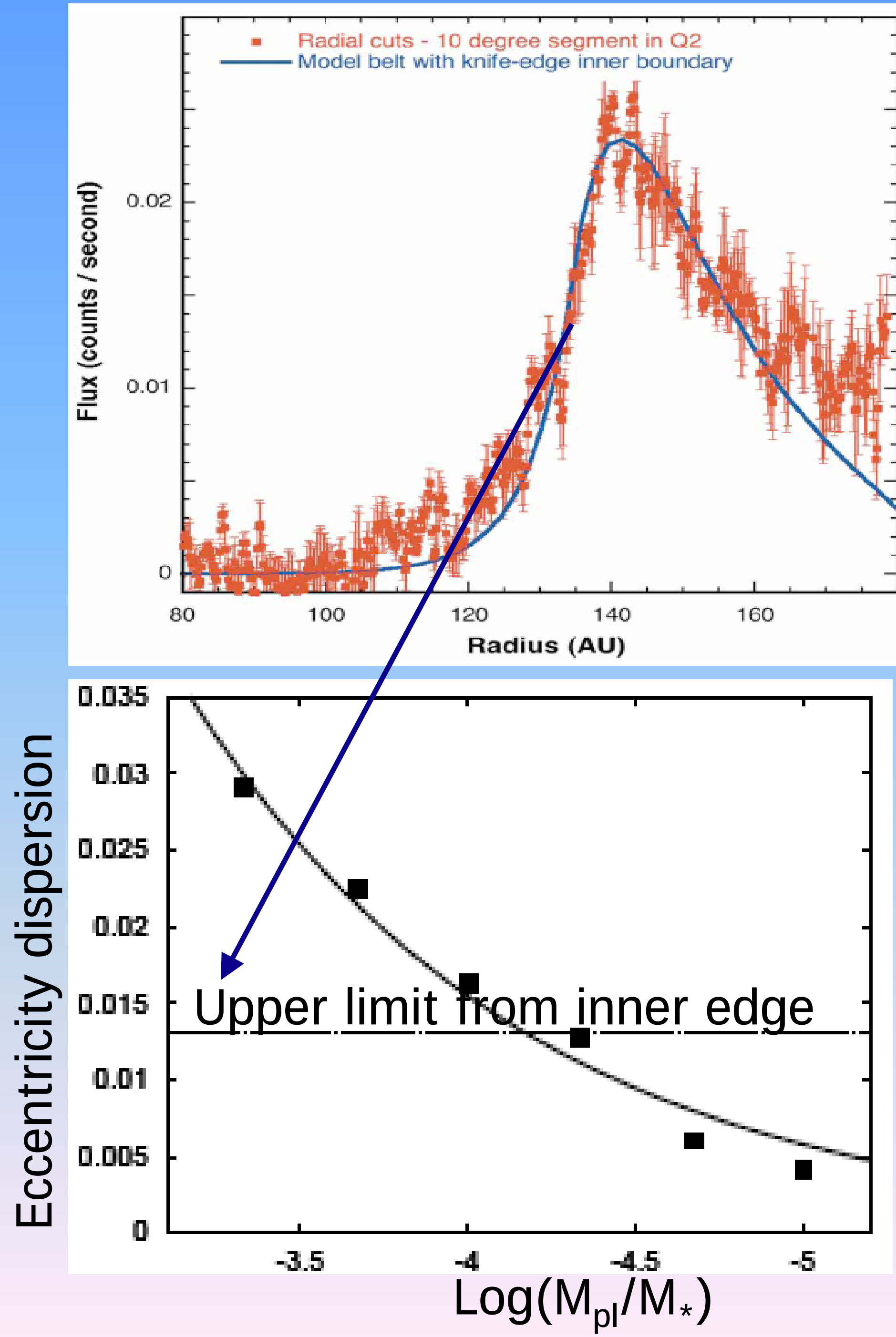


First detected in Fomalhaut, a 133AU ring offset by 15AU implying a forced eccentricity of 0.11 (Kalas et al. 2005) (Talk by Kalas)

Further constraints on planets

Quillen (2006) model the Fomalhaut ring and conclude:

- Planet is at a_{pl}=119 AU with e_{pl}=0.1
- Inner edge from resonance overlap
  $da/a_{pl} = 1.3(M_{pl}/M_*)^{2/7}$
- Eccentricity dispersion at the inner edge affects its slope
- Observed sharpness of inner edge implies eccentricity dispersion <0.013 and so $M_{pl}<M_{saturn}$



Secular perturbations: warps

Secular perturbations of a planet also affect the inclinations (ie. orbital plane) of nearby planetesimals

Introducing a planet into the disk on an orbit inclined to the disk midplane causes a warp to propagate away from the planet

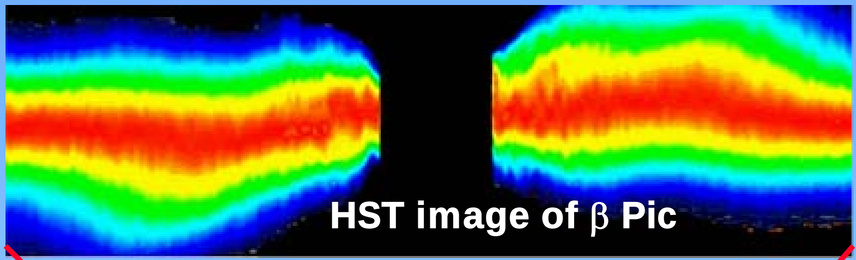
Augereau et al. (2001)

This causes disk near planet to become aligned with the planet, but that far away keeping the initial symmetry plane

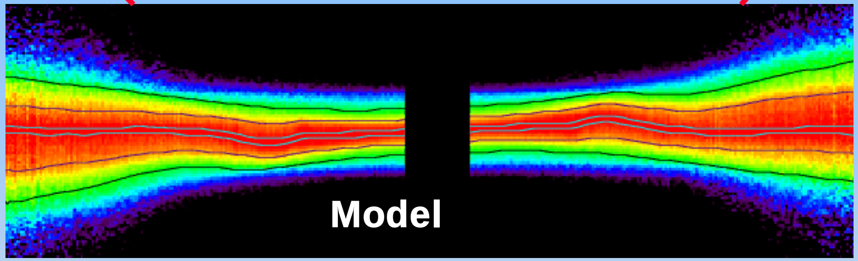
Warp in β Pic

The warp in β Pic can be explained in this way by a 1-2$M_{jupiter}$ planet at 10AU inclined by 3^0 to the disk mid-plane which causes at warp at 70AU at 20Myr

Model explains all observations by dust produced by planetesimals, including effects of radiation pressure



Heap et al. (2000)

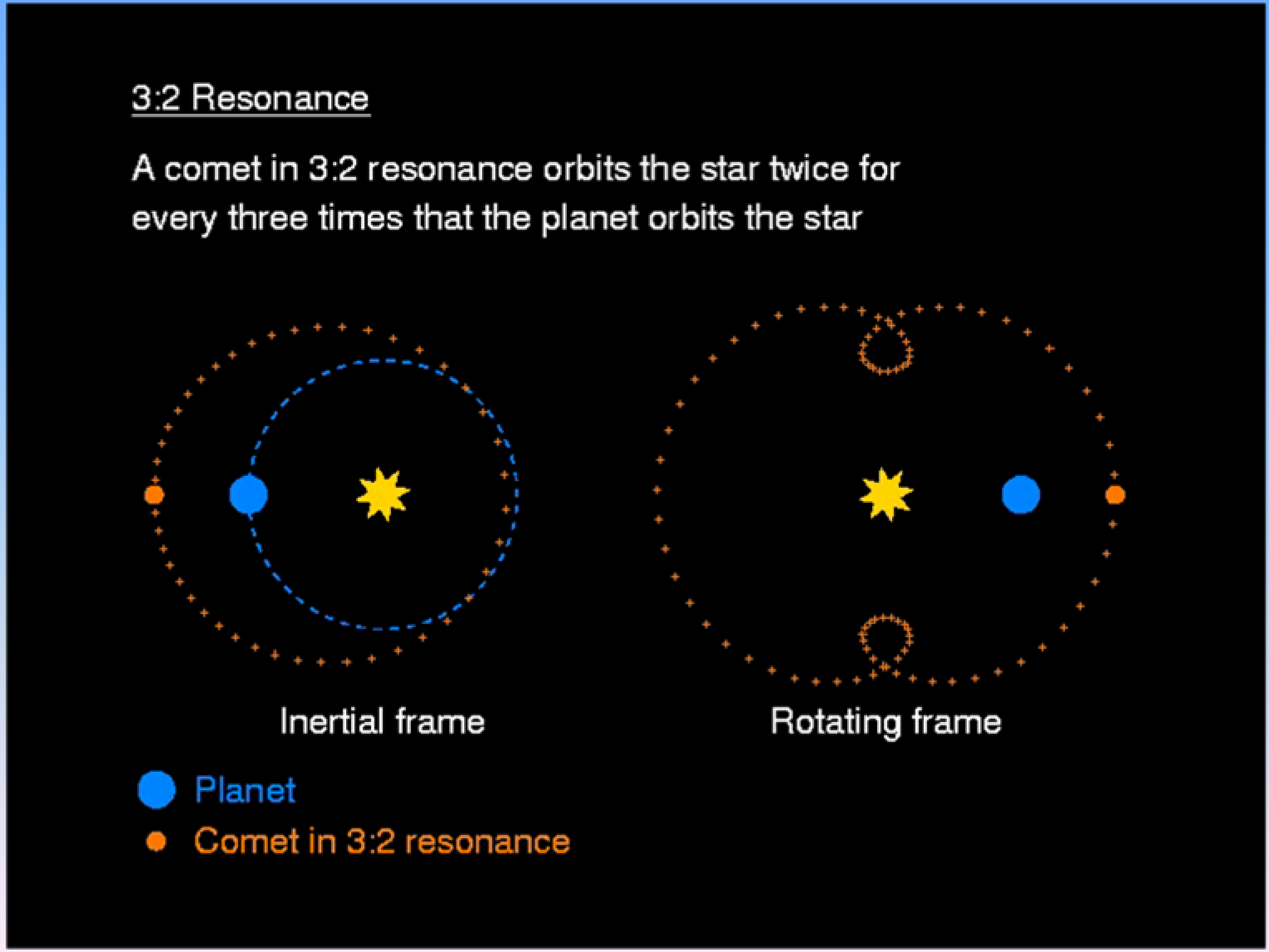


Augereau et al. (2001)

Warps can be present in old systems too if there are two planets on different orbital planes (Wyatt et al. 1999)

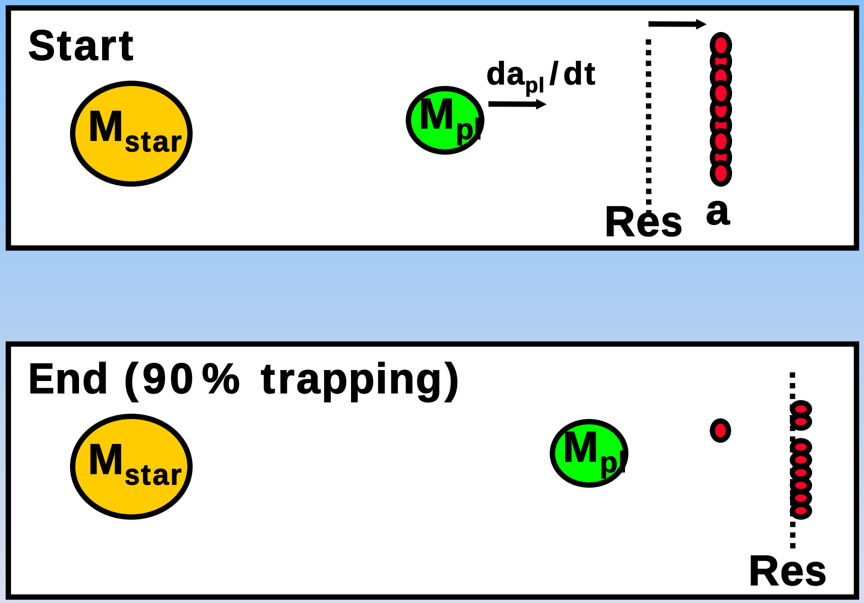
Geometry of resonance

- Resonances are special because of the periodic nature of the orbits and the way that planet and planetesimal have encounters

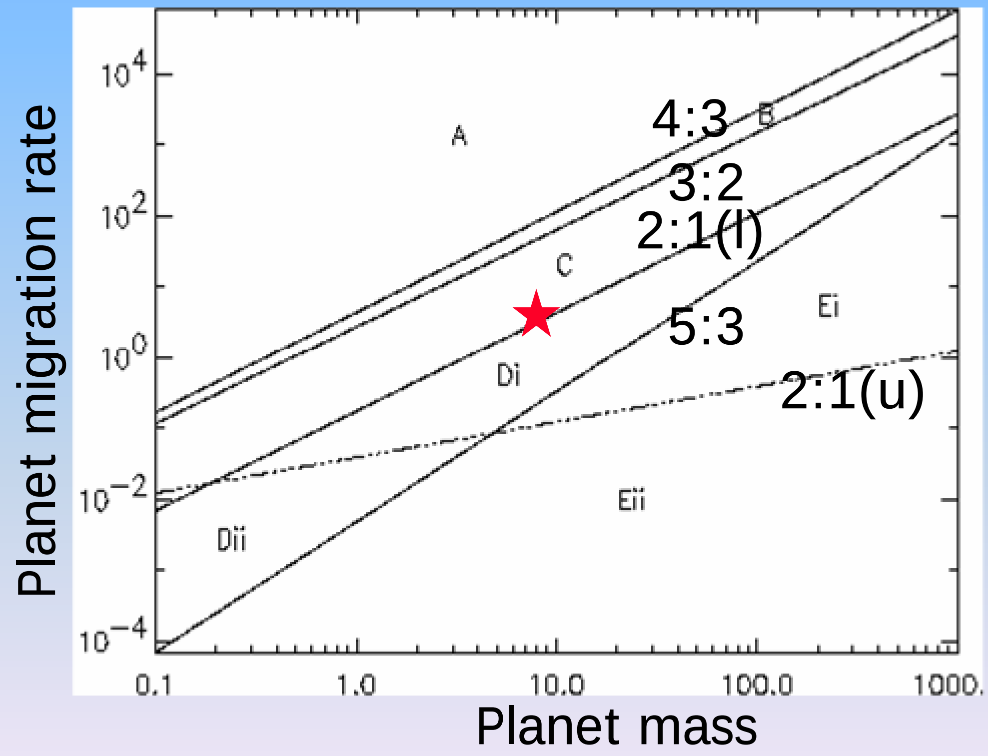


Capture by migrating planet

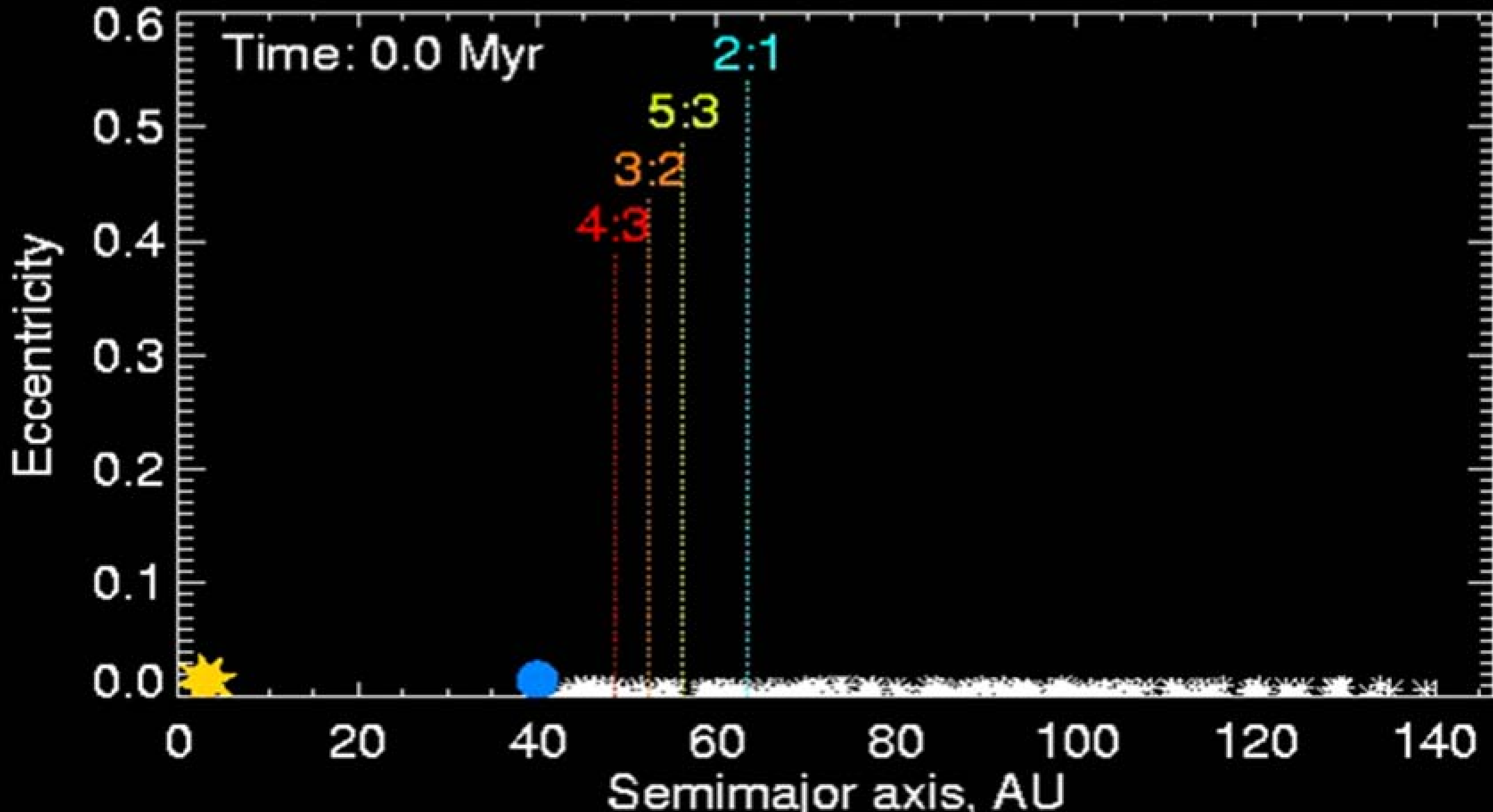
Planetesimals can become captured into the resonances of a migrating planet



Resonances which can be populated depend on planet mass and migration rate

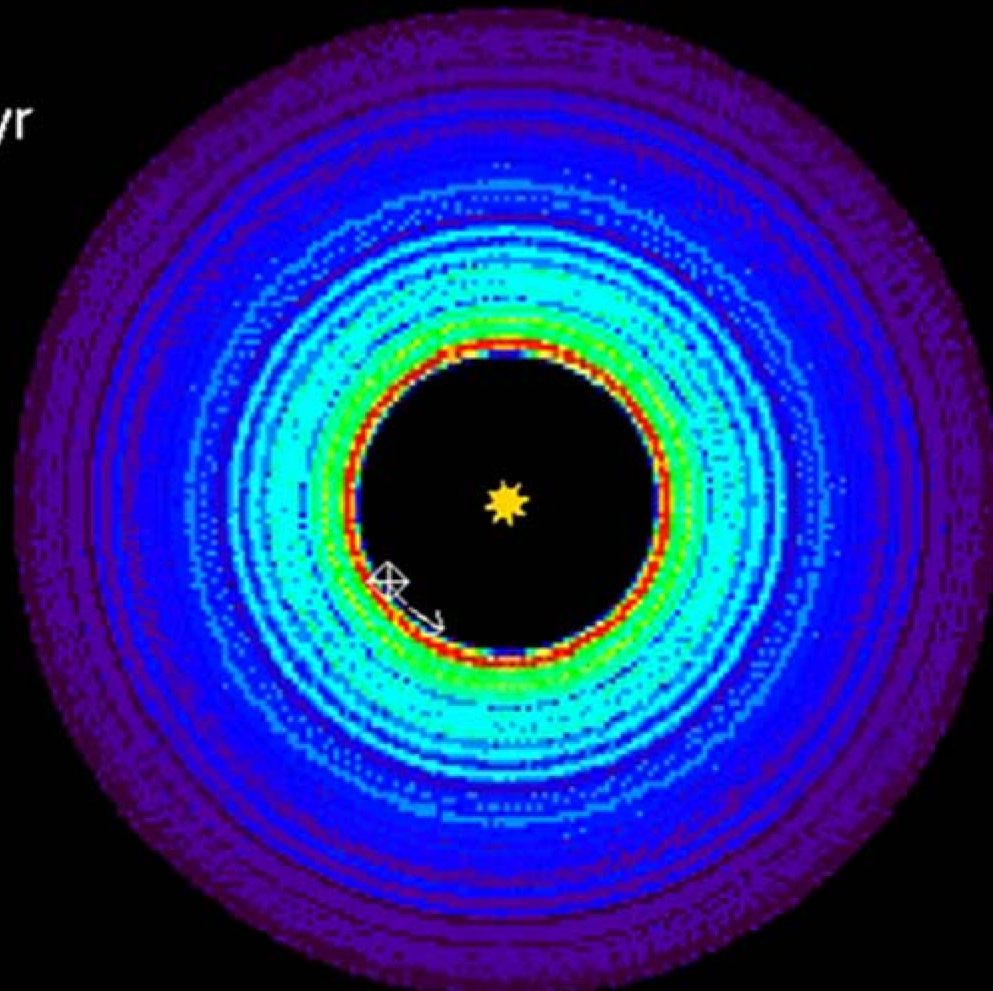


The outward migration of a Neptune mass planet (●) around Vega sweeps many comets (*) into the planet's resonances



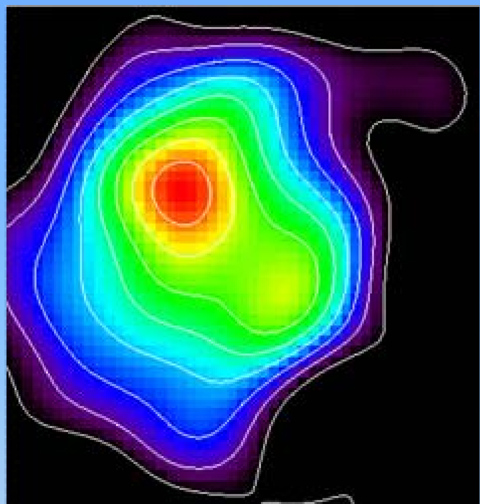
The trapping of comets in Vega's disk into planetary resonances causes them to be most densely concentrated in a few clumps

Time: 0.0 Myr

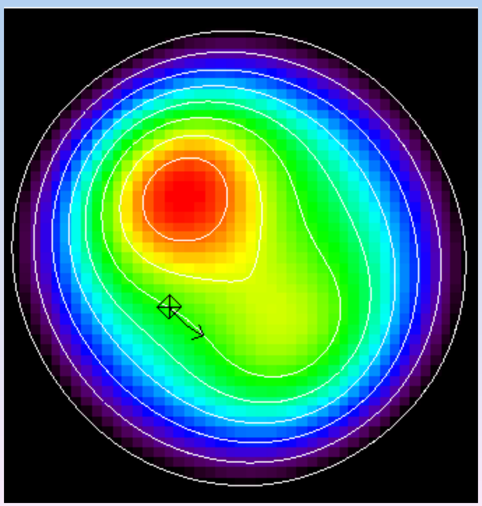


Constraints on Vega's planetary system

Observation



Model



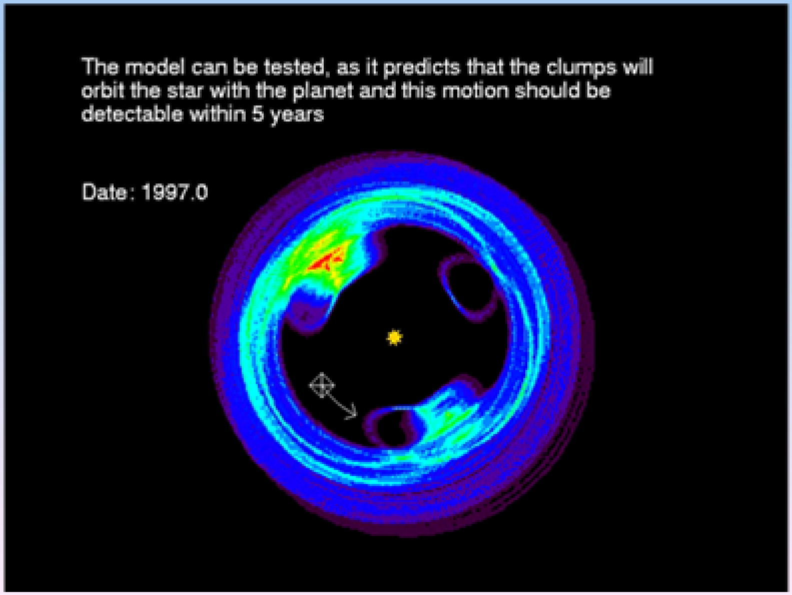
- This model can explain the clumpy structure of Vega (350Myr, A0V at 7.8pc) seen in sub-mm (Holland et al. 1998) and mm (Wilner et al. 2002; Koerner et al. 2002)

- Infers $1M_{neptune}$ which migrated 40-65AU over 56Myr (although $1M_{jupiter}$ over 3Myr also possible, see poster by Martin)

- See also poster by Reche for migration of eccentric planet

Predictions:

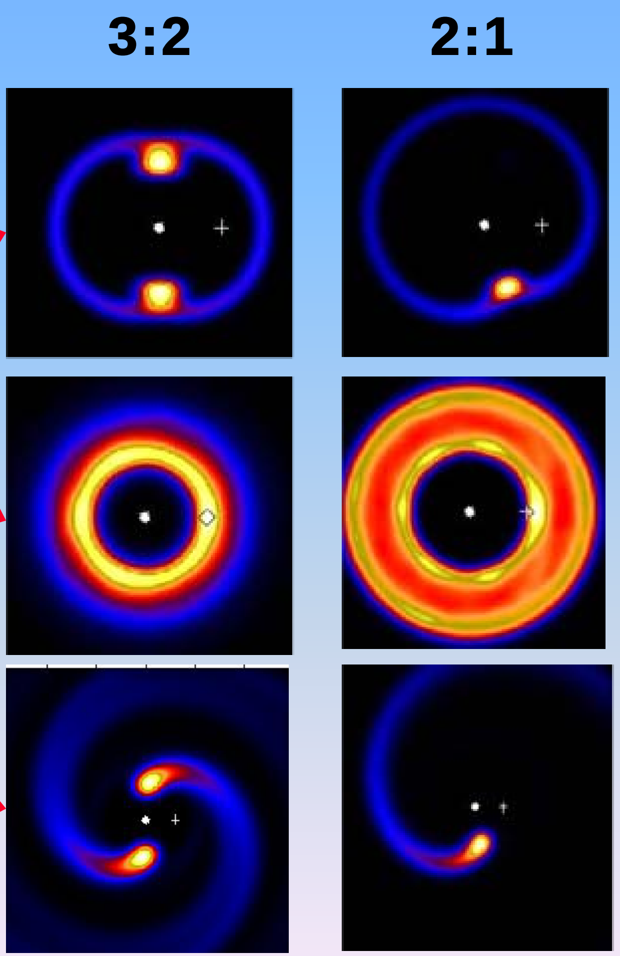
- orbital motion of structure (Poulton et al. 2006)
- multiwavelength structure



Particle populations in a resonant disk

Radiation pressure causes dust created from resonant planetesimals to fall out of resonance; smallest grains are removed on hyperbolic orbits

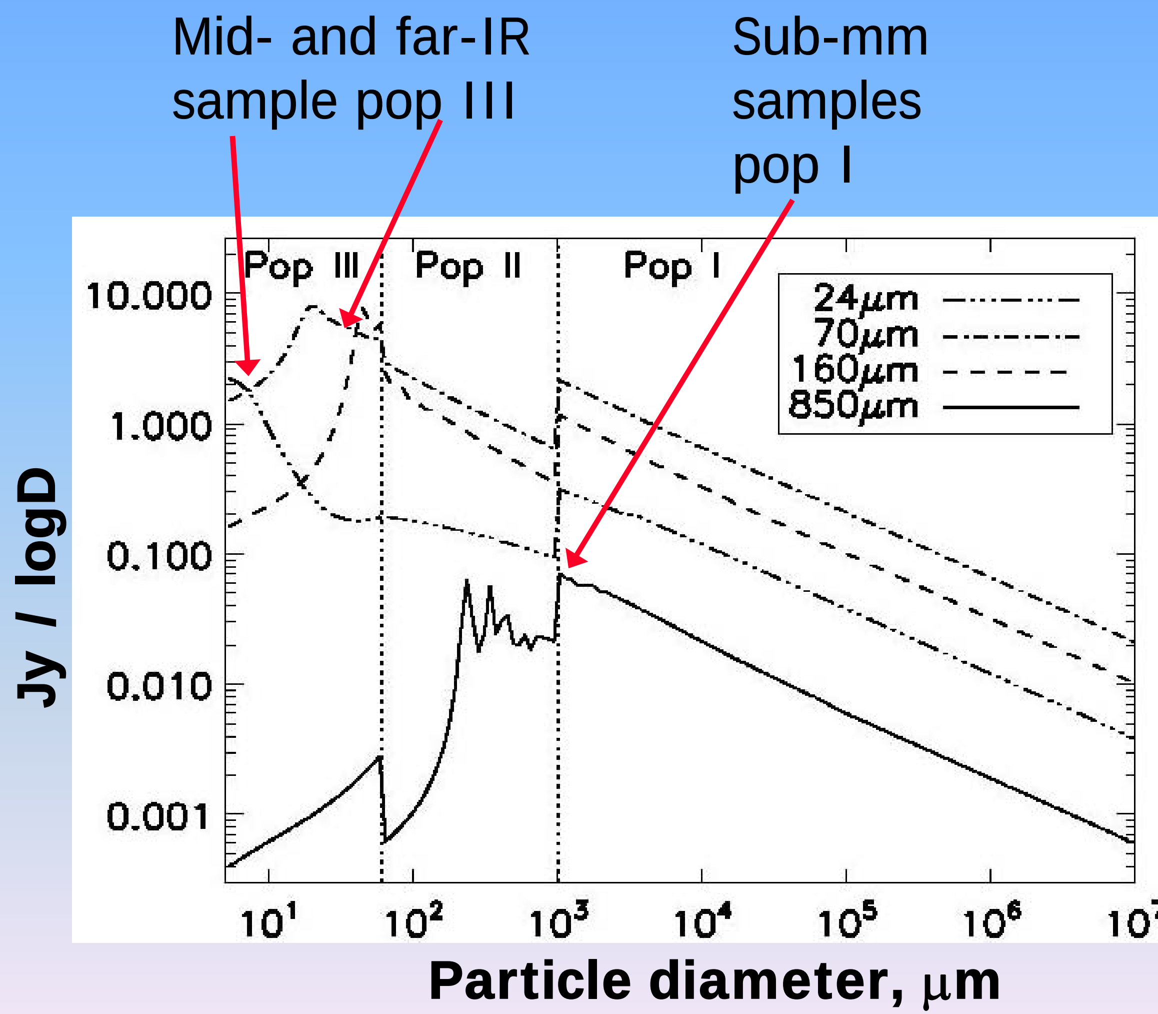
Grain Size	Population	Spatial distribution
Large	I	Same clumpy distribution as planetesimals
Medium	II	Axisymmetric distribution
Small	III	$\tau \propto r^{-1}$ distribution
	IIIa	Spiral structure emanating from resonant clumps
	IIIb	Axisymmetric distribution



Wyatt (2006)

Multiwavelength imaging predictions

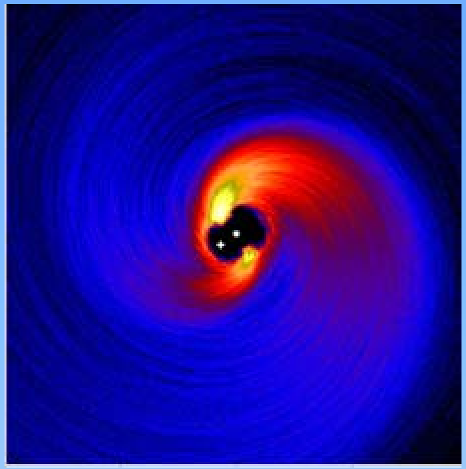
Observations in different wavebands sample different grain sizes and so should show different structures



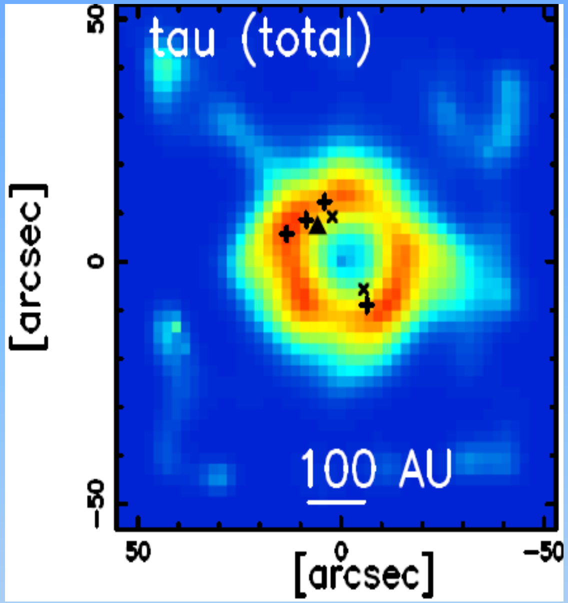
Wyatt (2006)

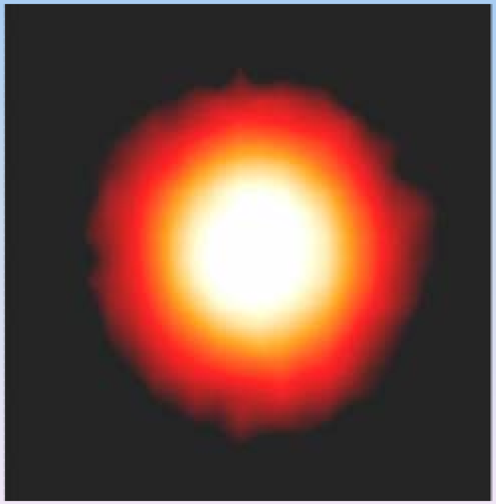
... and comparison with observations

Mid- to far-IR images should exhibit spiral structure emanating from clumps

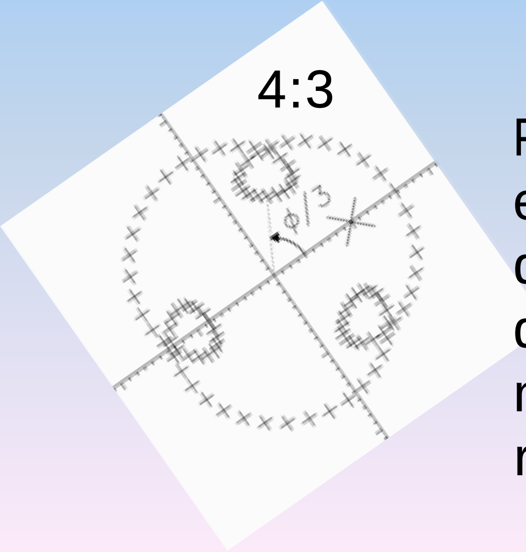


Meanwhile 350μm imaging shows evidence for 3 clump structure (Marsh et al. 2006)





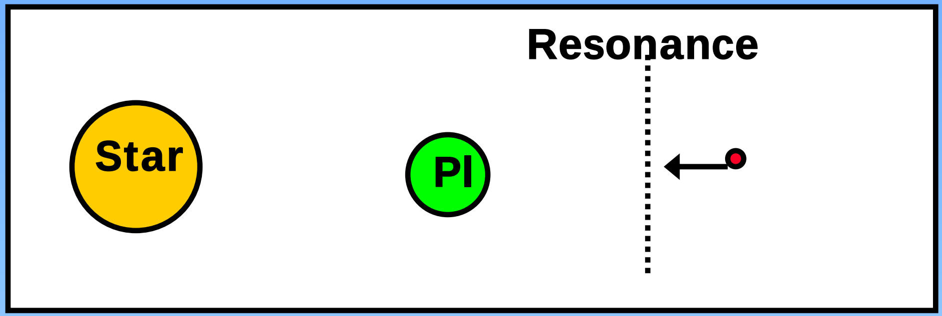
Not detected at present, but resolution of published Spitzer observations may not have had sufficient resolution to detect this (Su et al. 2005)



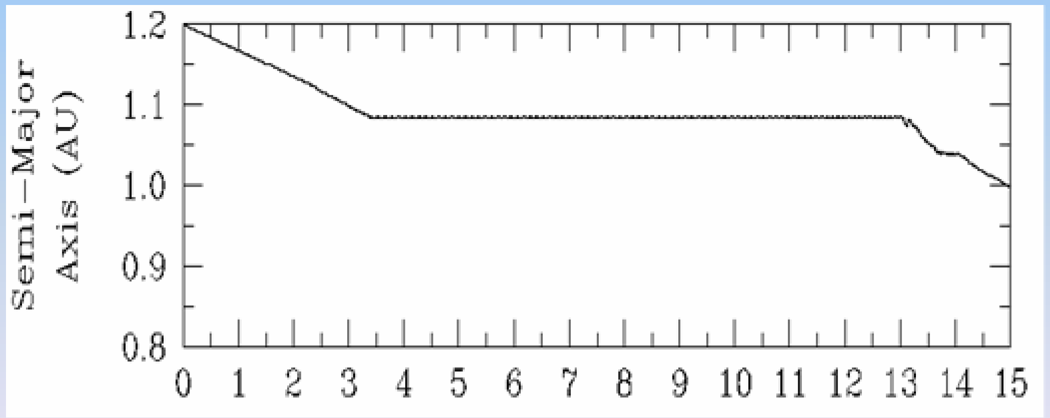
Possible evidence for a different size distribution of material in 4:3 resonance?

Dust migration into planetary resonances

Resonances can also be filled by inward migration of dust by P-R drag, since resonant forces can halt the migration



For example dust created in the asteroid belt passes the Earth's resonances and much of it is trapped temporarily (~10,000yrs)



Time, 1000 years

See also talk by Krivov

Structures of resonant rings

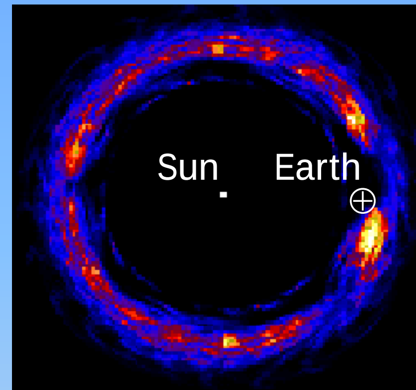
The structure expected when dust migrates into planetary resonances depends on the planet's mass and eccentricity (Kuchner & Holman 2003)

However...

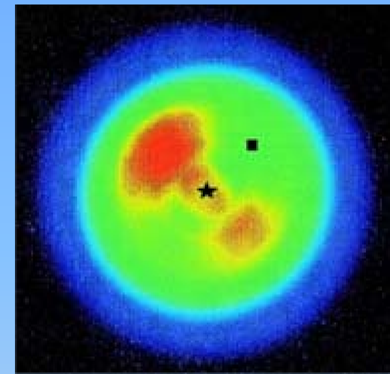
- P-R drag is not important in detectable debris disks

low M_{pl} | high M_{pl}

low e_{pl}

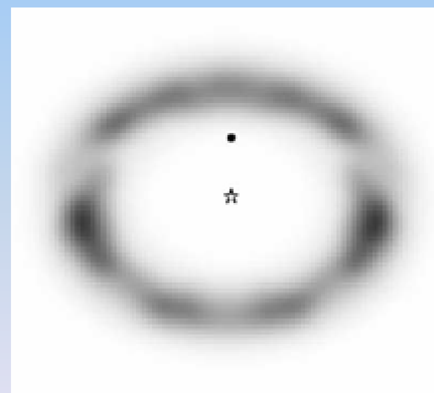


Dermott et al. (1994)

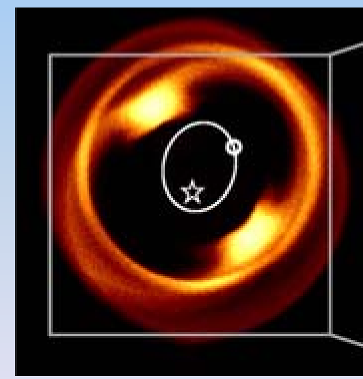


Ozernoy et al. (2000)

high e_{pl}



Quillen & Thorndike (2002)



Wilner et al. (2002)

Will be important when disks in which P-R drag is important can be detected (e.g., JWST, ALMA, TPF/Darwin)

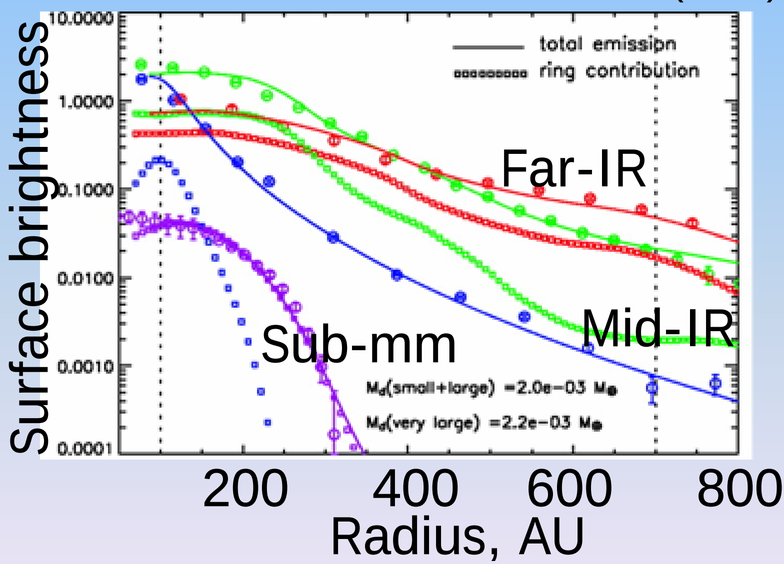
(III) Exceptions: Vega!

Our “archetype” is exceptional!

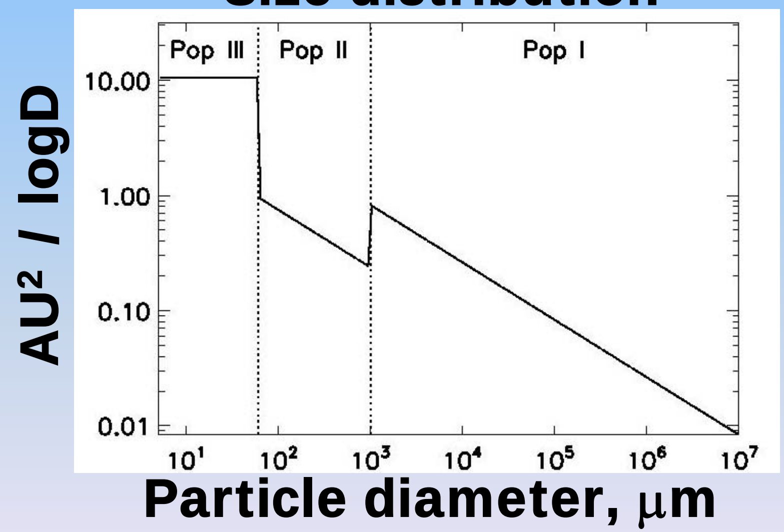
Why? because of the large dust mass being blow-out by radiation pressure

Pop. III grains removed at $2M_{\oplus}$/Myr

Su et al. (2005)



Size distribution



Wyatt (2006)

What is the origin of the observed high mass loss rate?

Origin of large mass loss in Vega

(1) Initially a very massive disk

- $2M_{earth}$/Myr for 350Myr -> $M_{disk}/M_* = 0.1$
- Collisional processing in pop I is ~$2M_{earth}$/Myr

BUT… why so many small grains produced in collisions?

(2) Mass is not being lost

- These are bound grains, e.g., on highly eccentric orbits,

BUT… must reproduce $\tau_{24,70} \propto 1/r$ and temperature of 2-18μm grains

Perhaps low $T_{equator}$ of star important (Aufdenberg et al. 2006)?

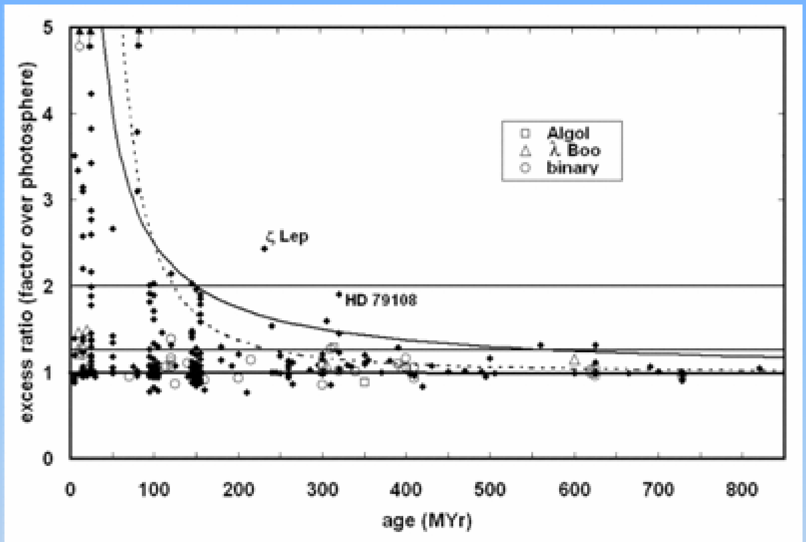
(3) Mass loss is recent/transient

- Recent collision, or recent ignition of collisional cascade

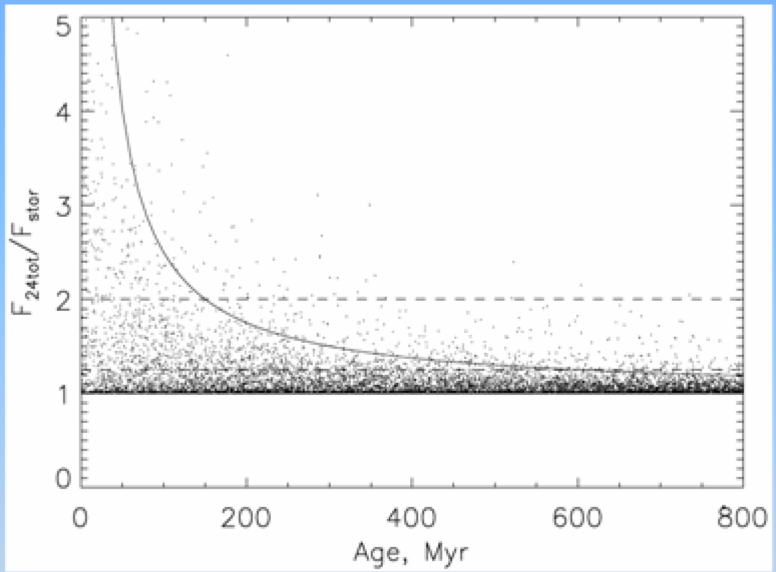
BUT… why so many small grains produced in collisions?

Rest of A star population explained by steady-state evolution

Rieke et al. (2005) suggested that debris around A stars is transient



Rieke et al. (2005)



Wyatt et al. (in prep)

Model population of 10,000 debris disks with:

- Initial masses inferred from protoplanetary disk mass distribution
- Initial radii inferred from 70μm/24μm flux distribution
- Subsequent collisional evolution...

Statistics can be explained by steady-state evolution in collisions

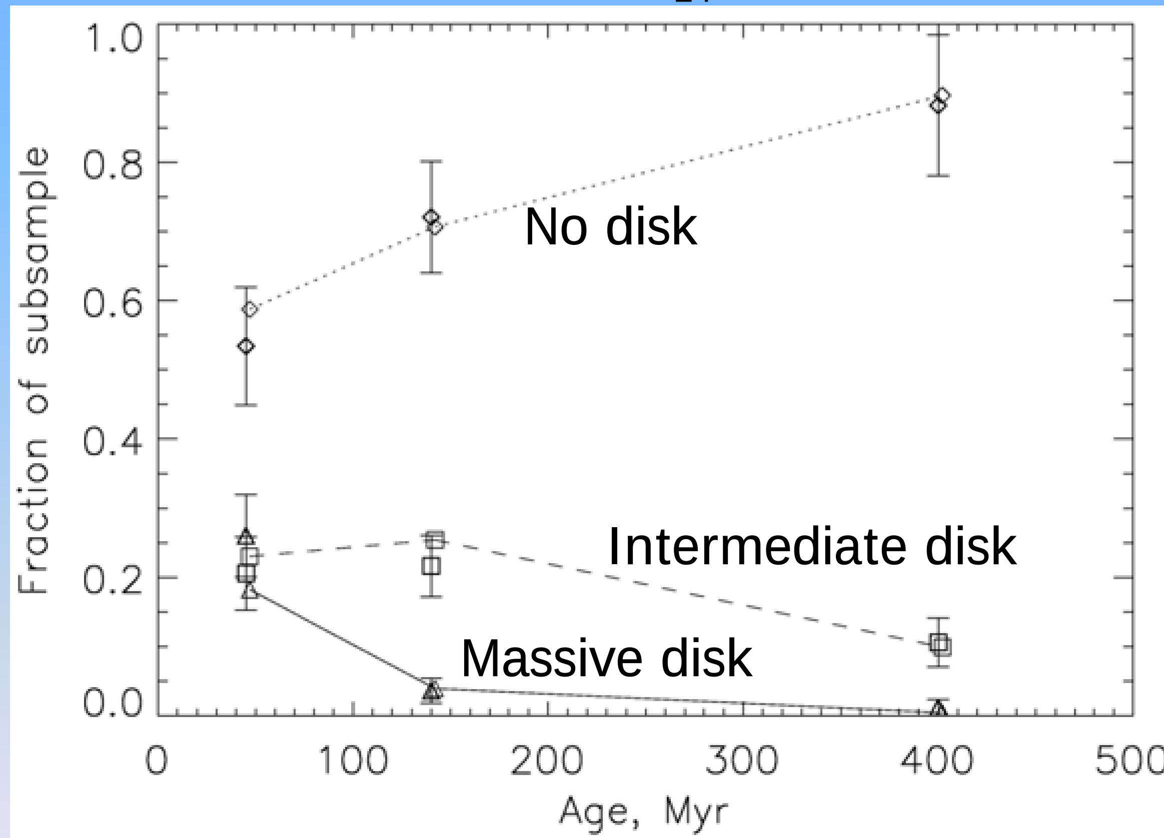
Detailed comparison of disk stats

- More quantitative proof that the statistics can be explained by steady-state evolution in collisions:

- Testable by predictions at 70μm – comparison with poster by Su

Vega is exceptional in A star population in showing evidence for transience

Fraction of disks in different age bins with F_{24}/F_{*} in range



Wyatt et al. (in prep)

(III) Exceptions: Hot dust around FGK stars

2% of sun-like stars have 25μm excess indicative of dust <10AU
(Bryden et al. 2006; Hines et al. 2006; Laureijs et al. 2002; Gaidos 1999)

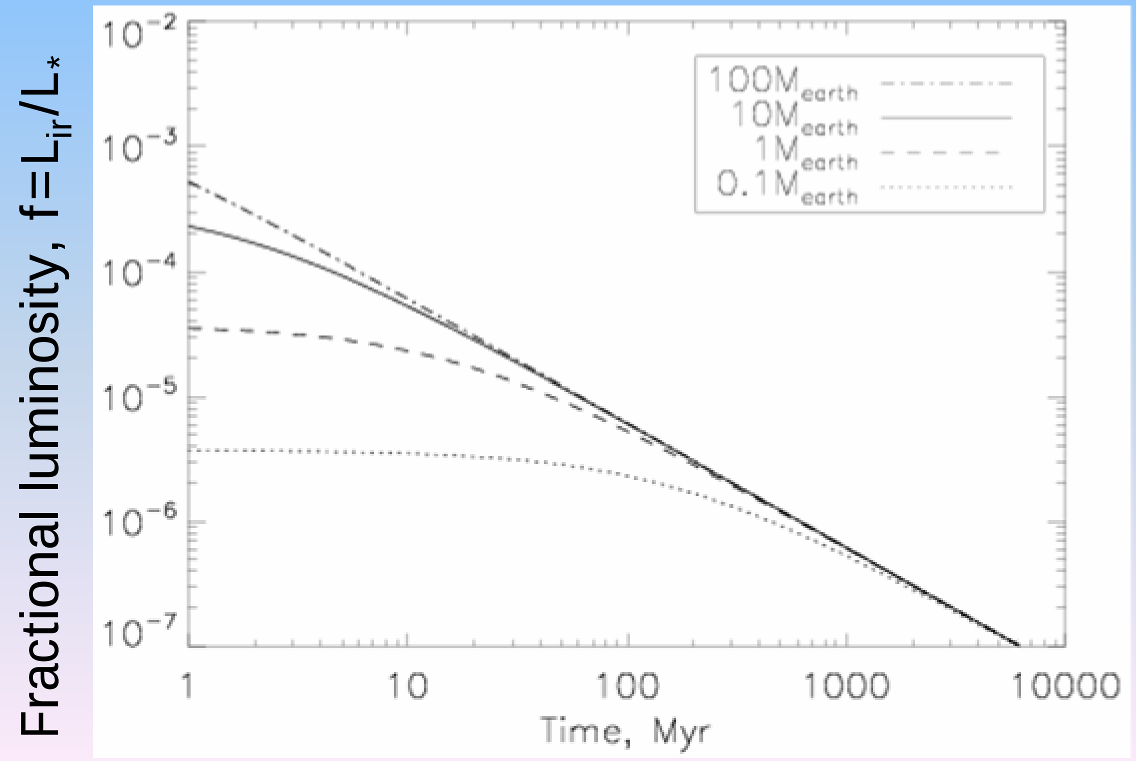
This dust cannot be produced in a planetesimal belt coincident with the dust, rather it must be **transient** (Wyatt et al., submitted)

Why?

There is a maximum luminosity (and mass) that a belt can have:

$$f_{max} = 0.16 \times 10^{-3} r^{7/3} t_{age}^{-1}$$

HD69830, η Corvi, HD72905, BD+20307, and HD128400 have $f > 1000 f_{max}$



Origin of transient event?

(1) Recent collision in massive asteroid belt

NO

- Too few big enough objects remain
- Chance of witnessing collision $<1:10^5$

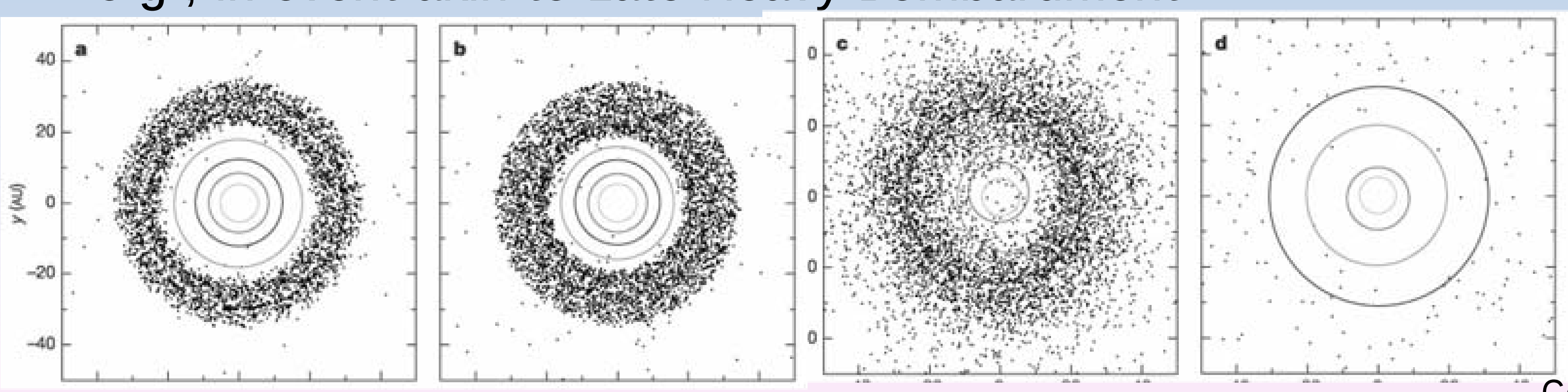
(2) In situ planetesimal belt

NO

- Mass loss rate too high
- Mass remaining at ~1AU at this age implies duration << 1Myr
- 2% detection fraction implies 100Myr duration

(3) Scattered in from outer planetesimal belt

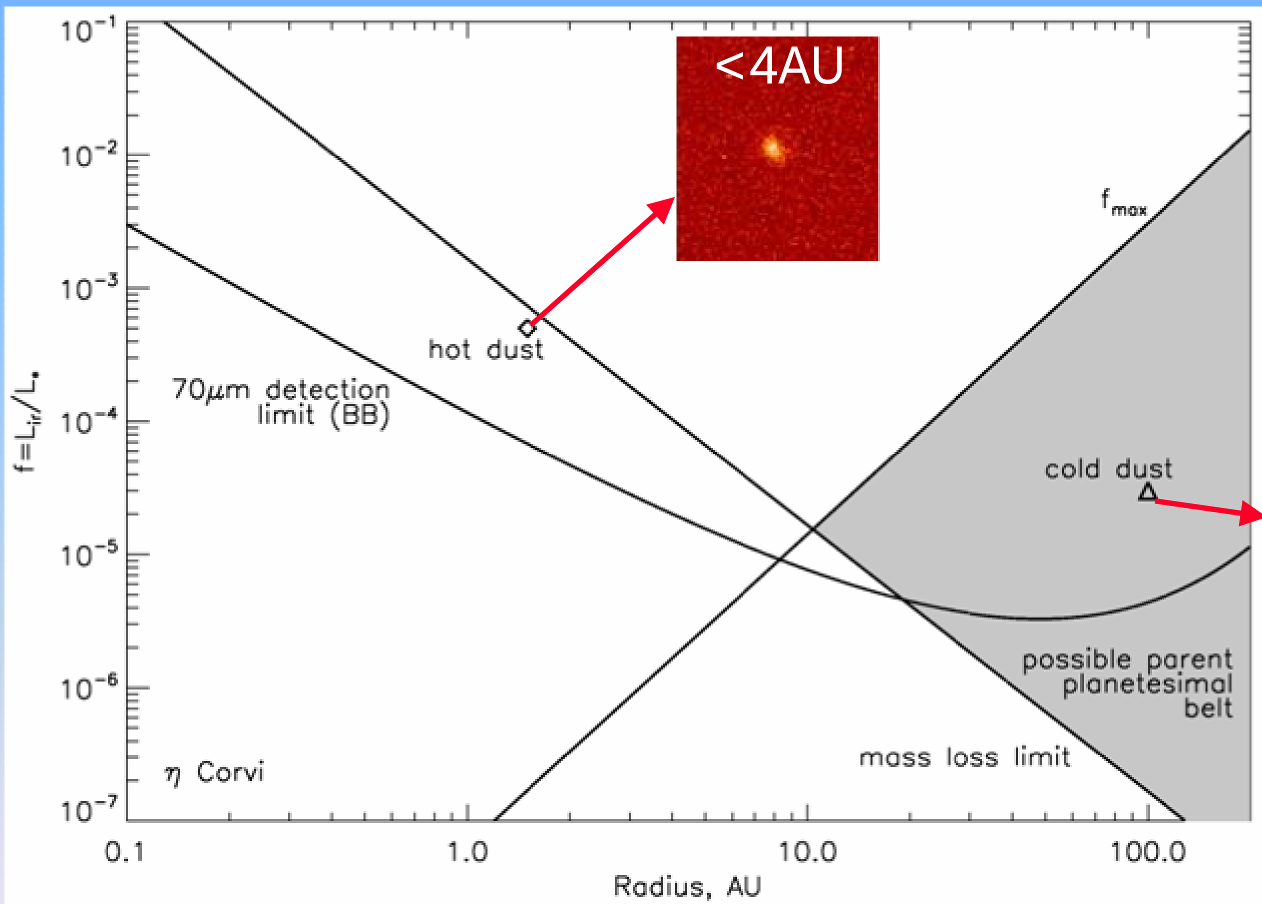
- e.g., in event akin to Late Heavy Bombardment



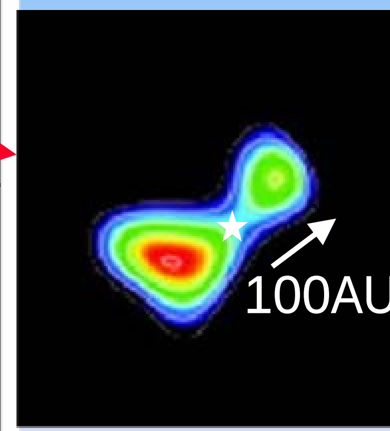
Gomes et al. (2005)

Constraints in η Corvi

Poster by Smith
Talk by Chen

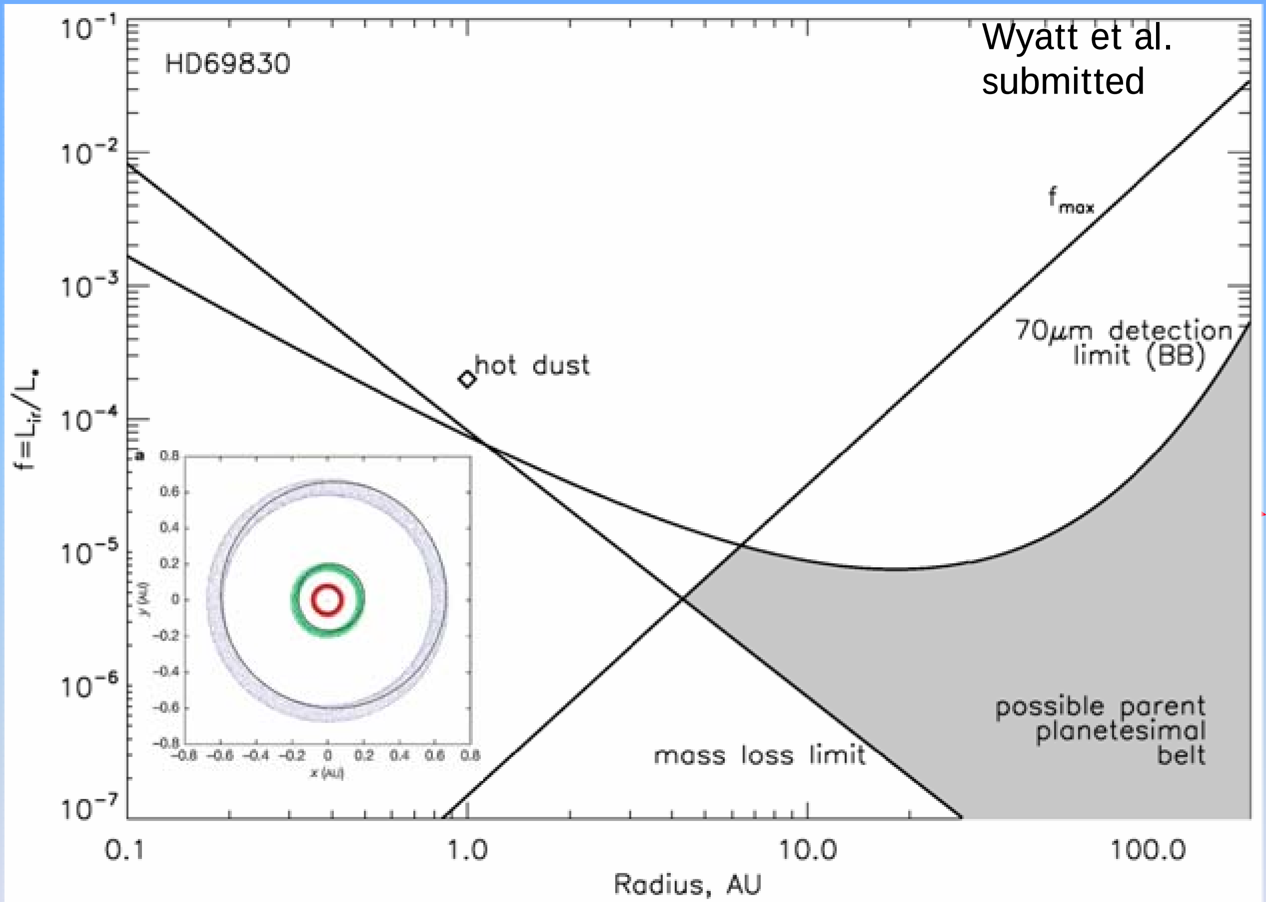


An outer planetesimal belt is known to exist around η Corvi and could be feeding the hot dust closer in



Wyatt et al. (2005)

Constraints in HD69830



Far-IR upper limit does not rule out the existence of an outer planetesimal belt

Planetary system at <0.8AU provides potential for dynamical instability (Lovis et al. 2006)

The presence of hot dust around Vega (Absil et al. 2006; talk by Absil) could indicate the system is undergoing a similar transient phase of evolution?

Conclusions

Most of the radial structure of debris disks explained by steady-state evolution of a planetesimal belt due to collisions and radiation forces

Must be taken into account when interpreting observations

Non-axisymmetric structures explained as perturbations to this model, particularly due to planets

Rare exceptions may be systems undergoing periods analogous to Late Heavy Bombardment

Bottom Line: Modelling of debris disks can tell us about the origin and evolution of planetary systems