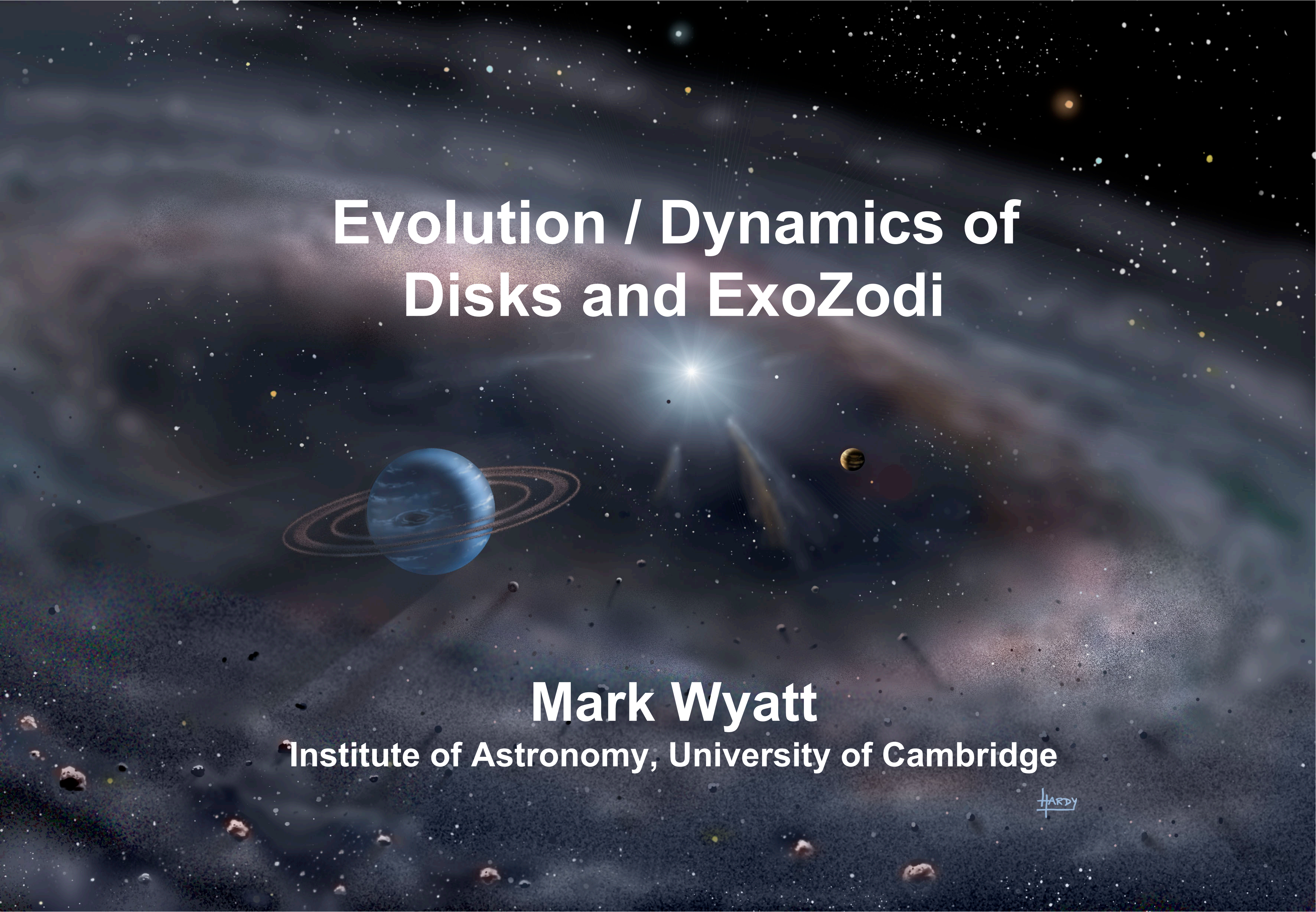


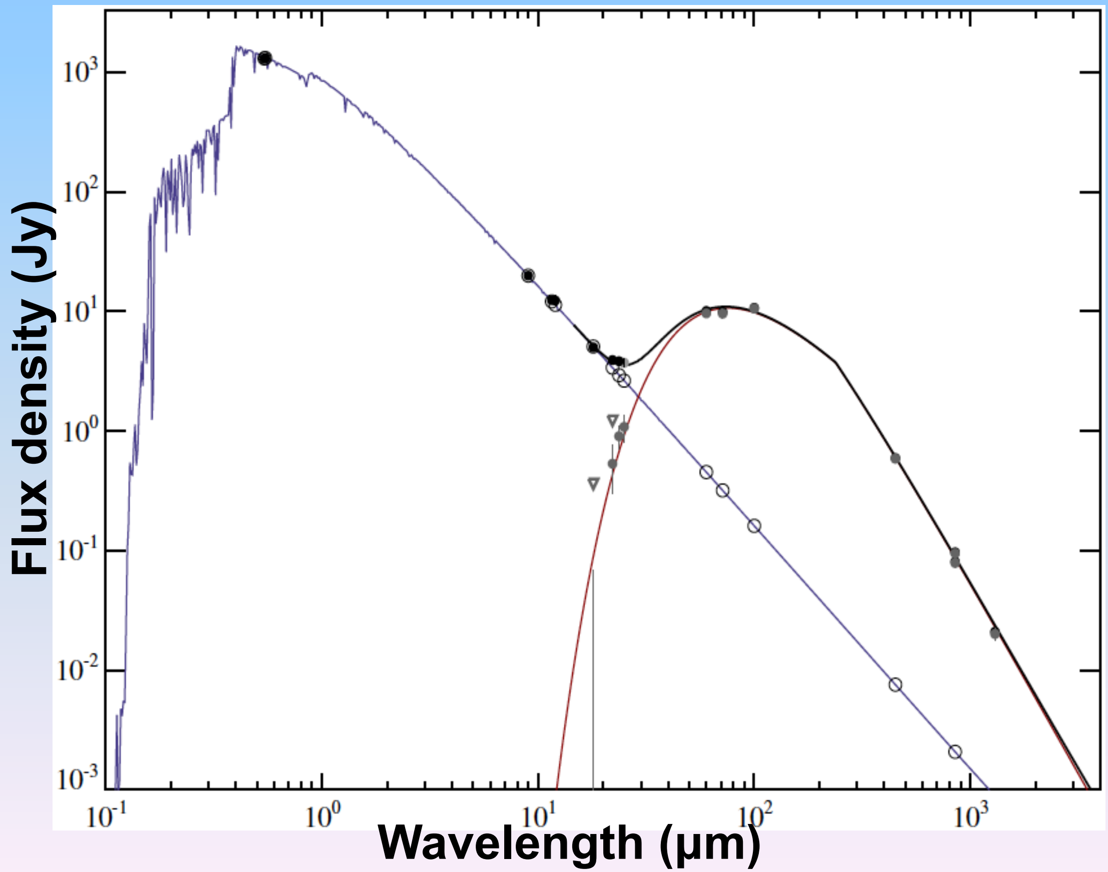
Evolution / Dynamics of Disks and ExoZodi

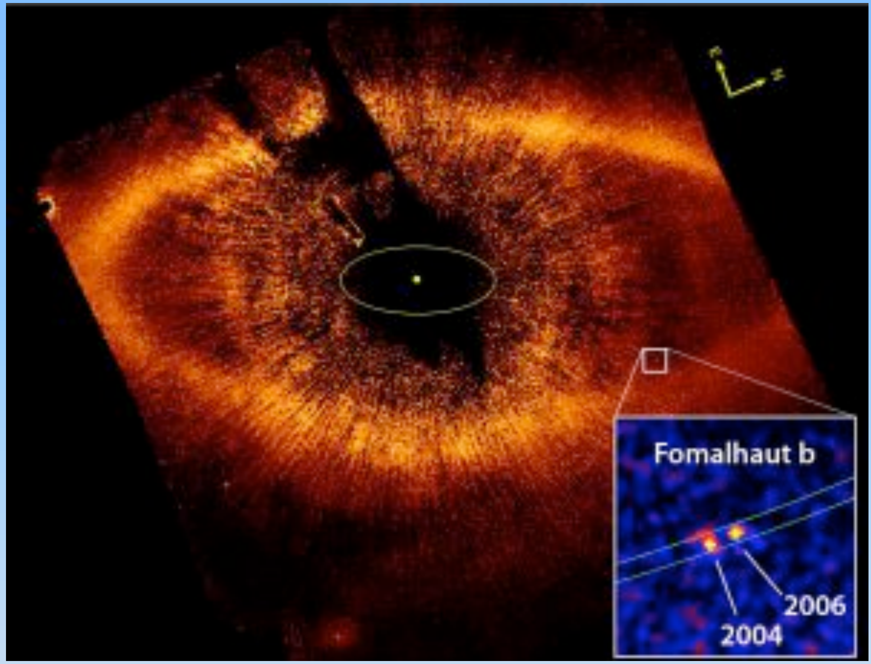
Mark Wyatt

Institute of Astronomy, University of Cambridge

Debris disk observables

Infrared emission of nearby main sequence stars brighter than photosphere: e.g., Fomalhaut has 70K excess



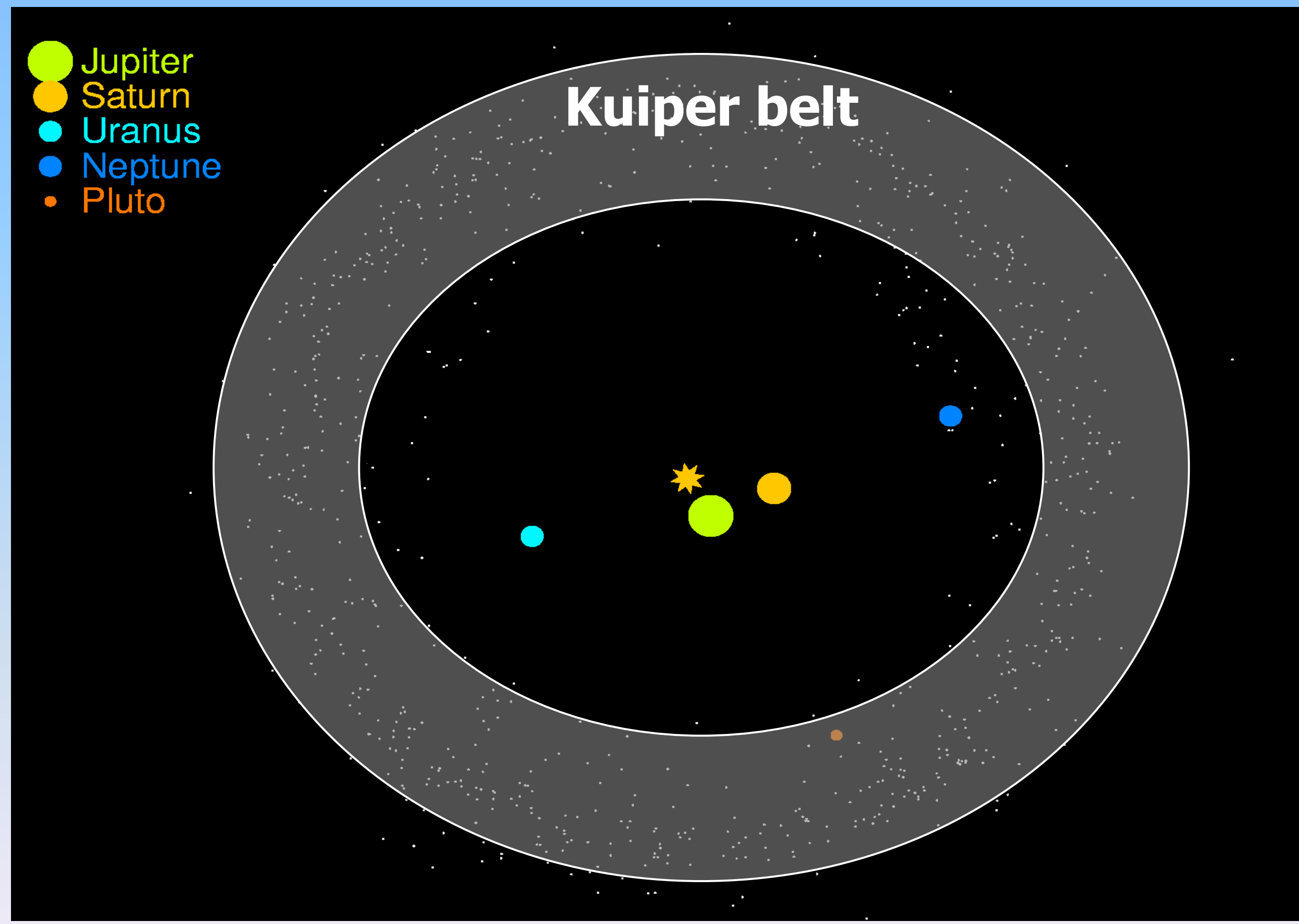


Imaging shows emission from dust in a ~130AU ring (Kalas et al. 2013)

Component of planetary system

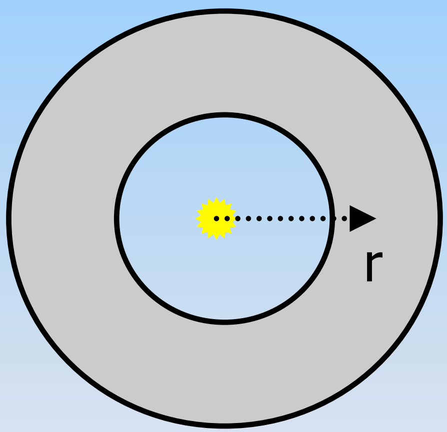
Debris disks are components of planetary systems, e.g., the Solar System's debris disk is the asteroid and Kuiper belts

They are descendants of the protoplanetary disk and are directly indicative of planetary architecture



Debris disk basics

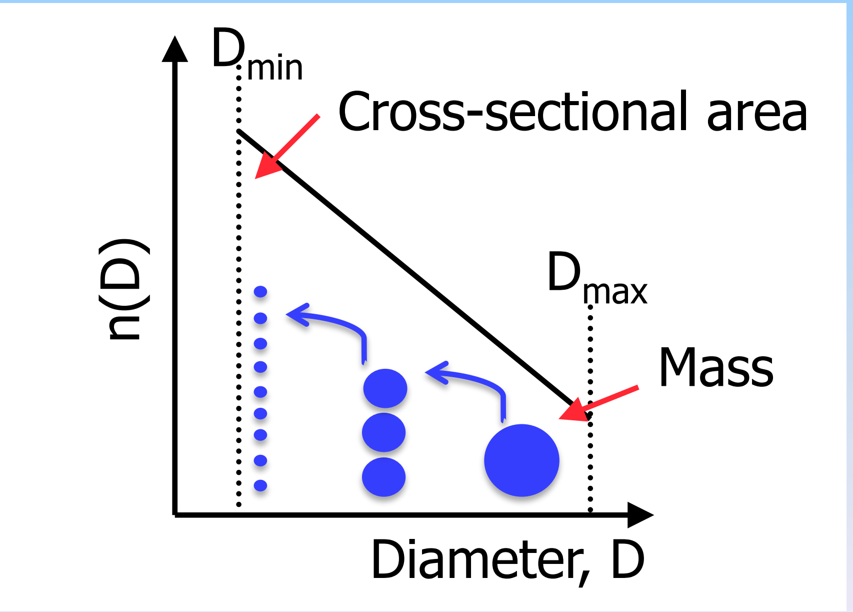
Simplest model for a debris disk has planetesimals orbiting the star confined to a belt



What we see from this belt is the result of the interplay between collisions and radiation forces

Collisions grind planetesimals into smaller and smaller fragments resulting in collisional cascade with a size distribution:

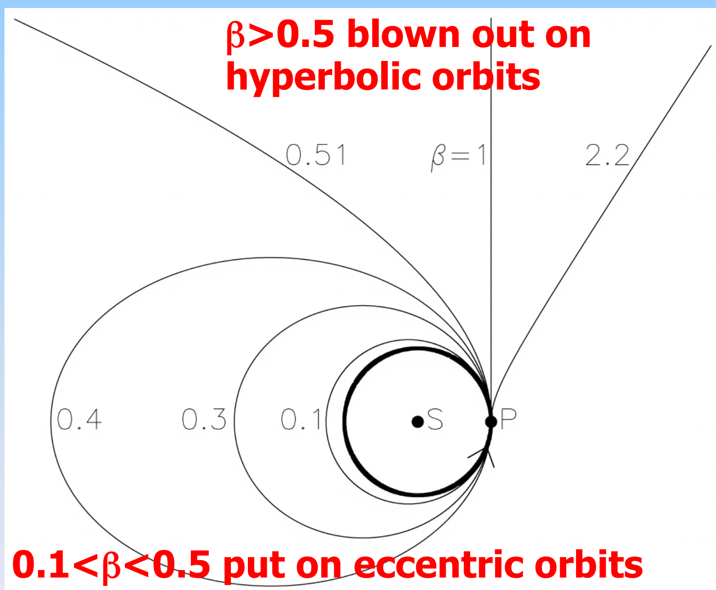
$n(D) \propto D^{-3.5}$



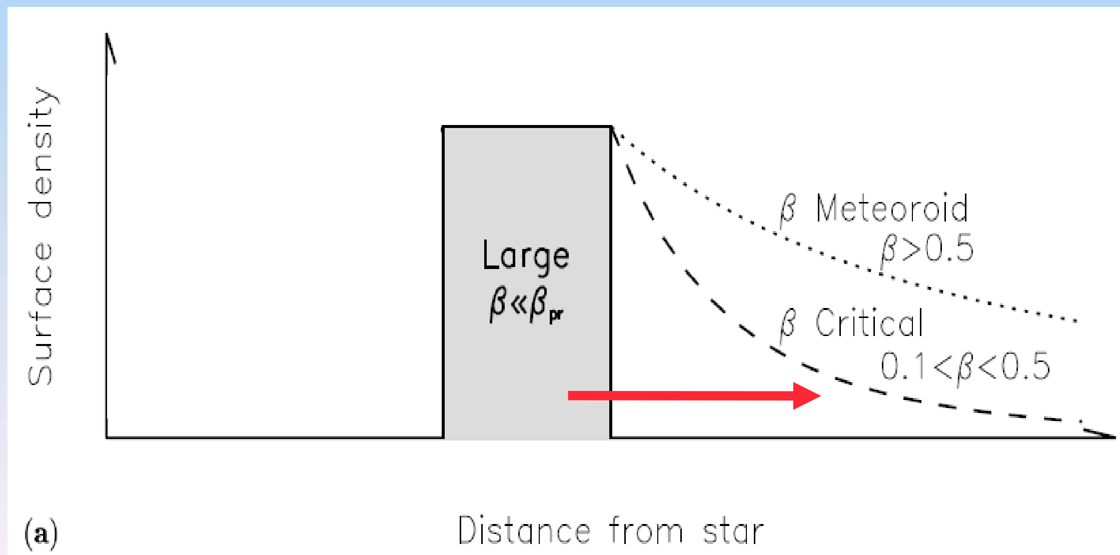
Radiation Pressure

Radiation pressure truncates the collisional cascade at small particles:

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



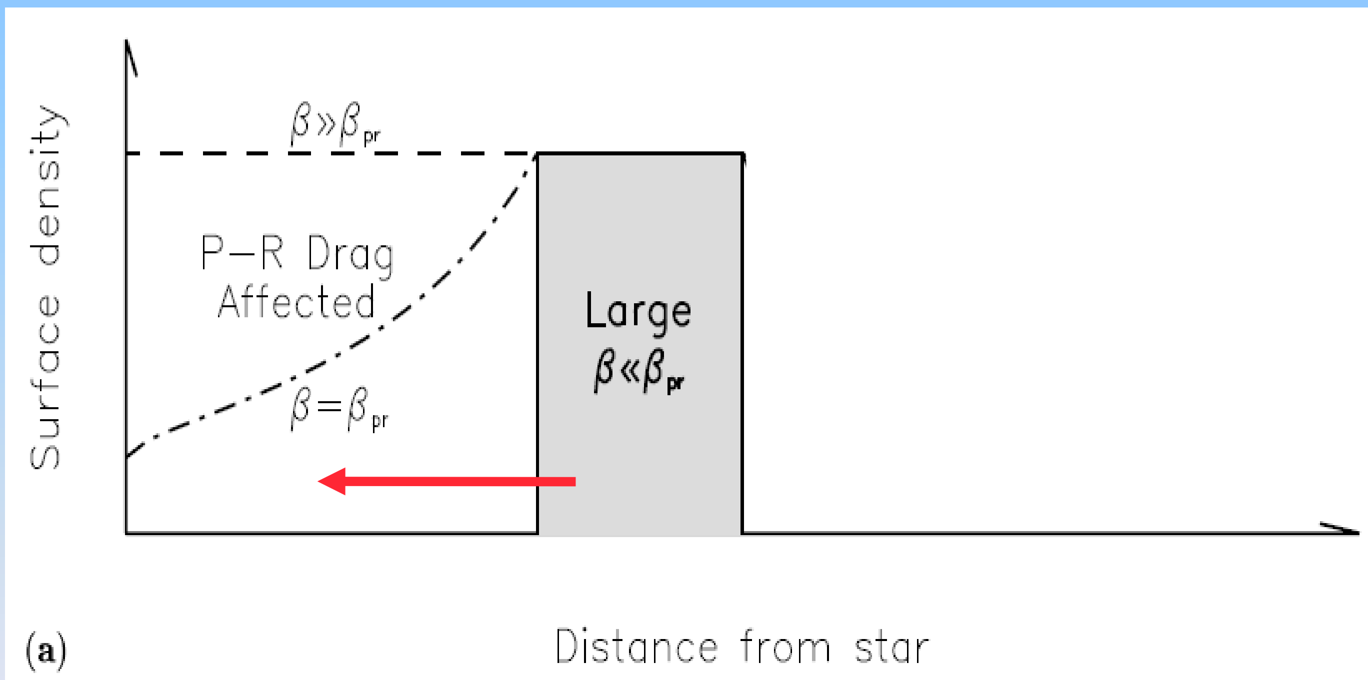
In addition to halo of unbound grains, bound particles close to blow-out limit extend far beyond their birth ring (Wyatt 1999, Krivov et al. 2000, Thebault & Augereau 2001, Strubbe & Chiang 2006)



P-R drag dominated disks

For low density disks, P-R drag makes particles migrate in before they are destroyed in collisions (Wyatt, Clarke & Booth 2011)

The Solar System's debris is such an example



Less important for extrasolar debris (Wyatt 2005), but recent observations are probing lower density disks…

Model size distribution evolution

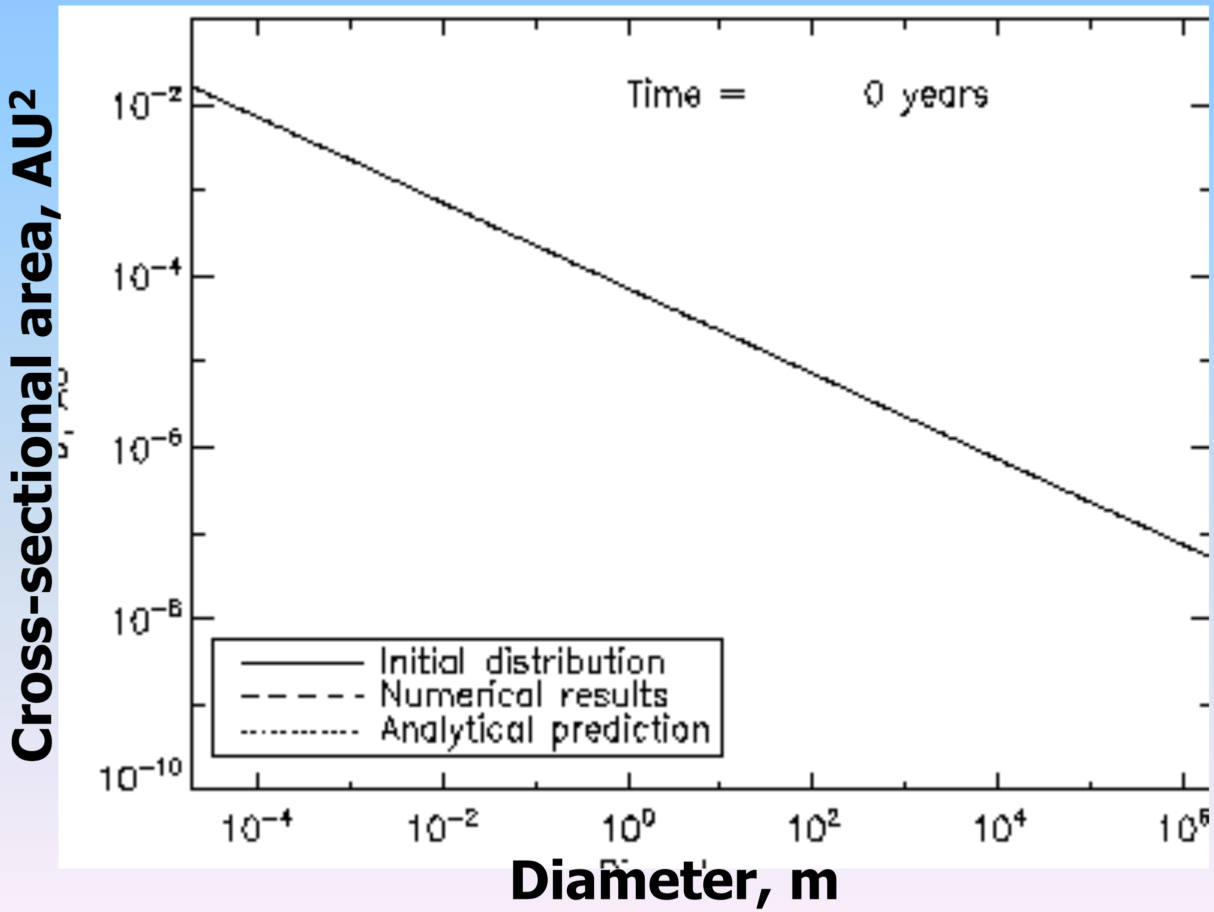
Solve $dm_k/dt = (dm_k/dt)^{gain} - (dm_k/dt)^{loss}$

Rippple from small-size cut-off
(Thebault & Augereau 2001)

Change in slope from strength-gravity scaling
(O'Brien & Greenberg 2003)

Ripple from that change in slope
(Durda et al. 1998)

Turn-over at late times when P-R drag becomes important
(Wyatt, Clarke & Booth 2011)

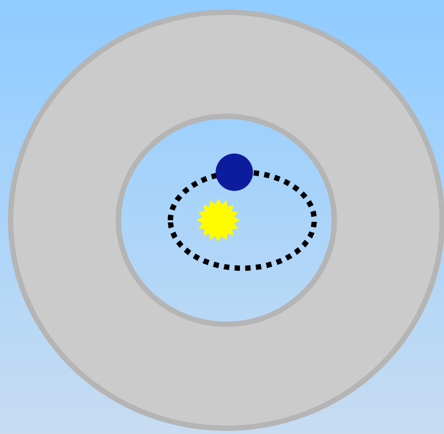


Slower evolution in mass than in area
(Lohne et al. 2008)

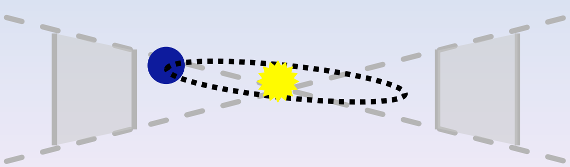
3 ways planets interact with disks

Debris (planetesimals/dust) can be affected by a planet's gravity in 3 ways:

1. Secular perturbations

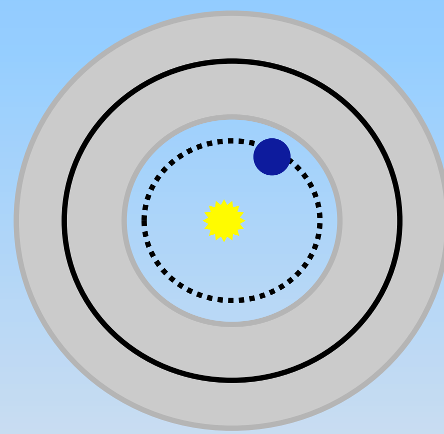


eccentric planet

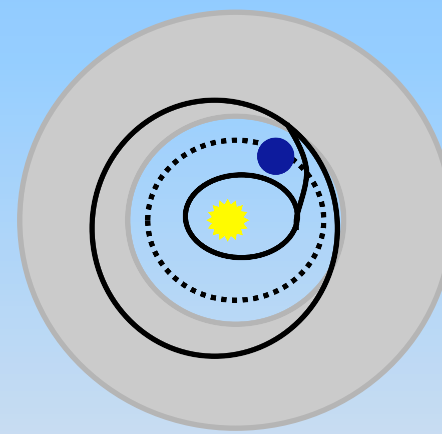


inclined planet

2. Resonances



3. Scattering



How to model disks

Combining collisions, planet interactions and drag is no simple task

• **N-body** (planet+drag): OK for tenuous disks (Dermott et al. 1994; Ozernoy et al. 2000; Moro-Martin & Malhotra 2002; Quillen & Thorndike 2002; Kuchner & Holman 2003; Deller & Maddison 2005)

• **Analytical** (planet+collisions): OK for dense disks (Wyatt et al. 1999; Wyatt 2003; Wyatt 2005)

• **Kinetic** (collisions+drag): OK when planets not important (Augereau et al. 2001; Krivov et al. 2005; Wyatt et al. 2011)

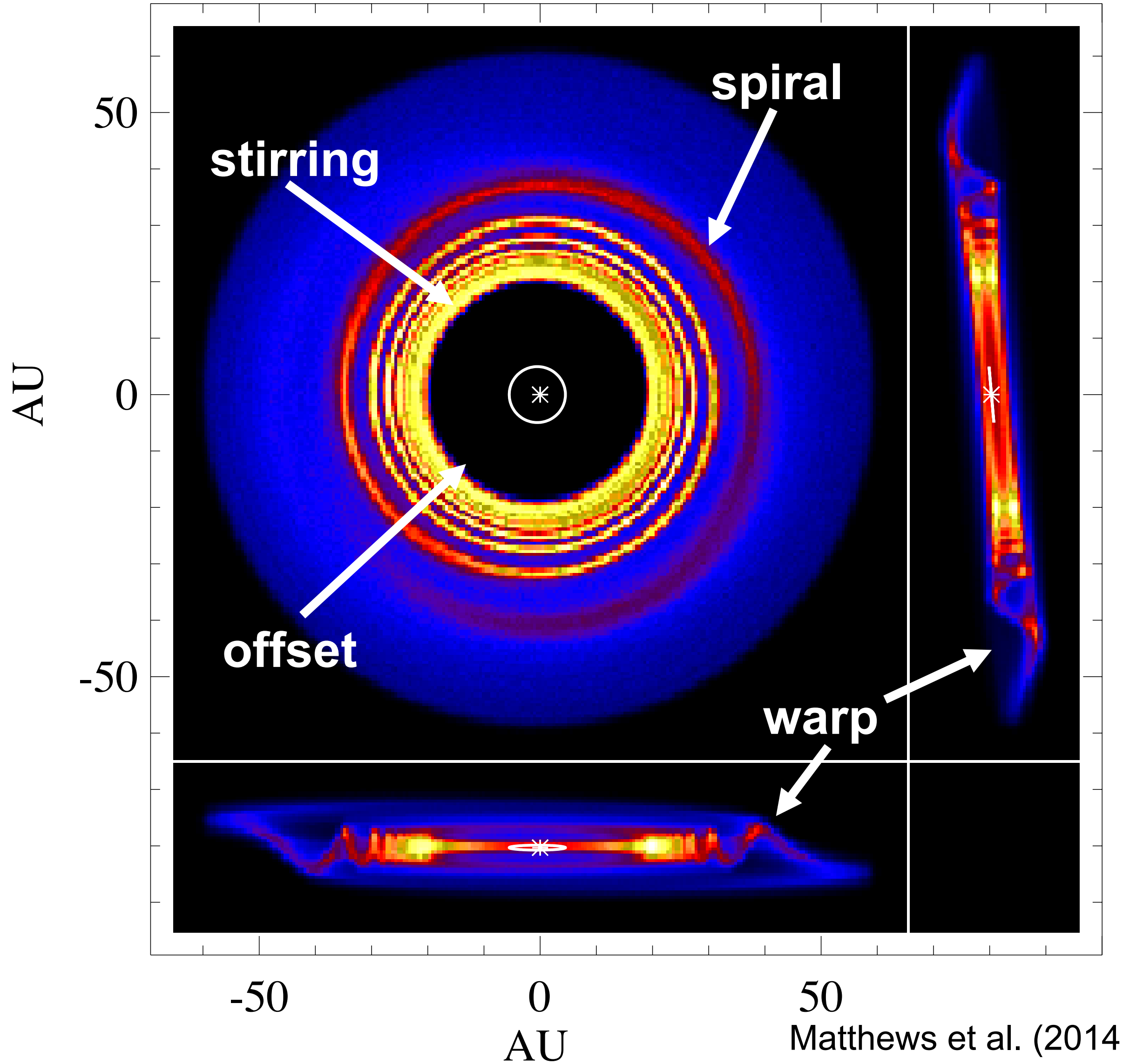
• **N-body** (planet+drag) **+ collisional grooming**: OK for all, but collisional prescription simplified (Stark & Kuchner 2009; Kuchner & Stark 2010; Thebault et al. 2014; Kral et al. 2013)

Secular perturbations

Planet:
$1M_{jup}$
5AU
e=0.1
I=5°

Disk:
20-60AU

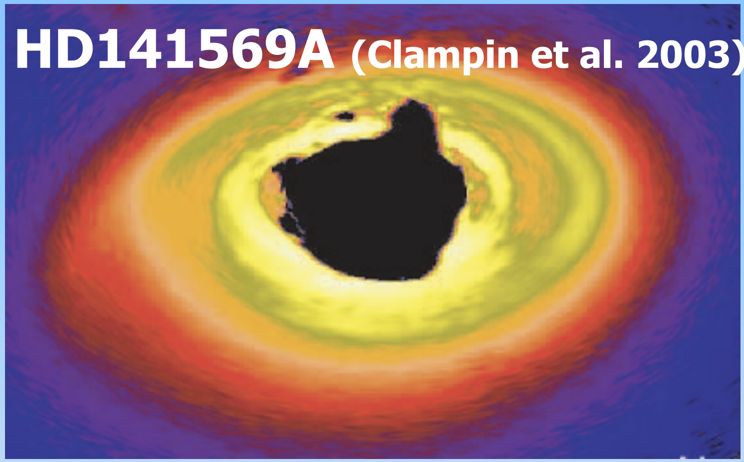
Time:
100Myr

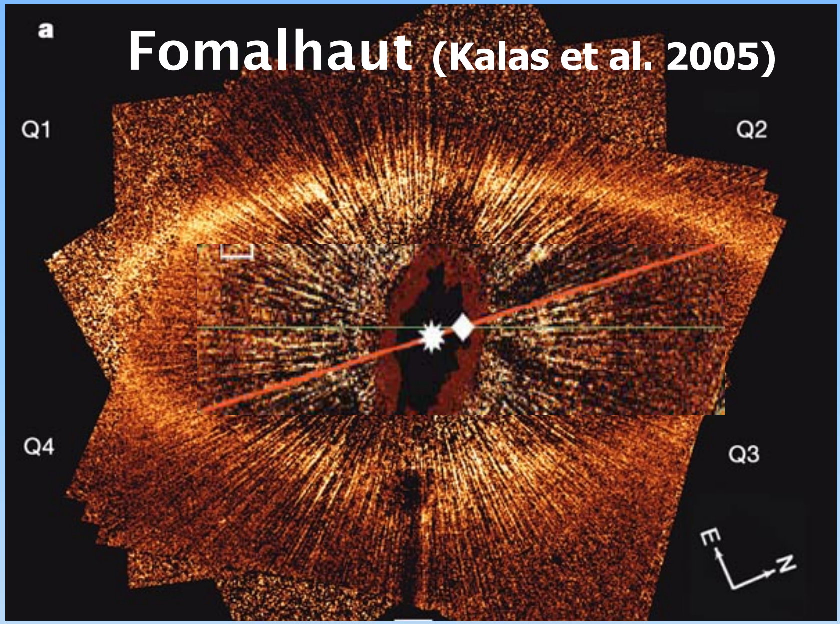


Matthews et al. (2014)

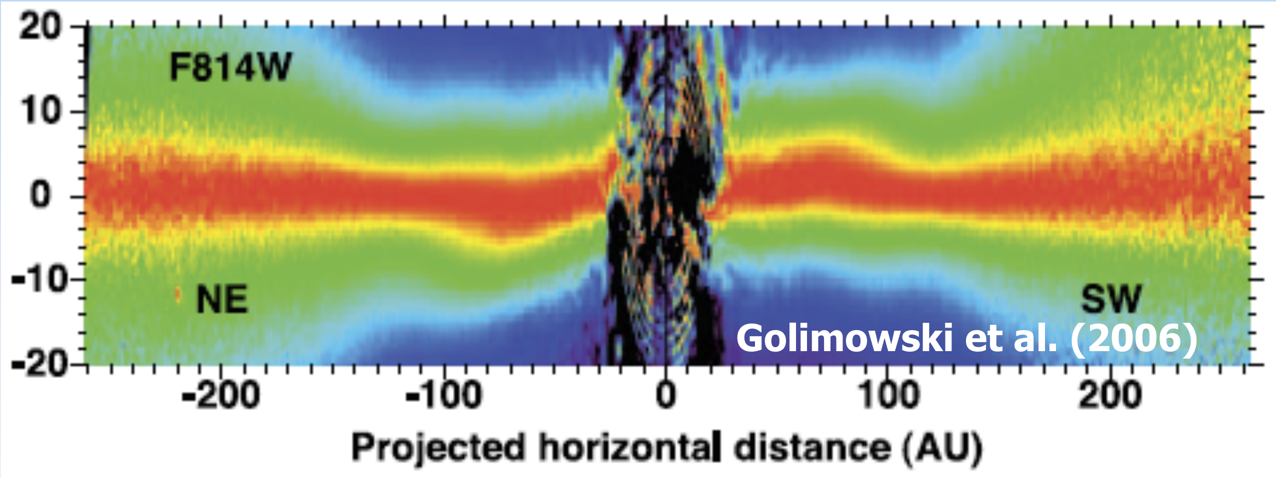
Observed secular structures

Eccentric planets cause tightly wound spirals and offset ring centres



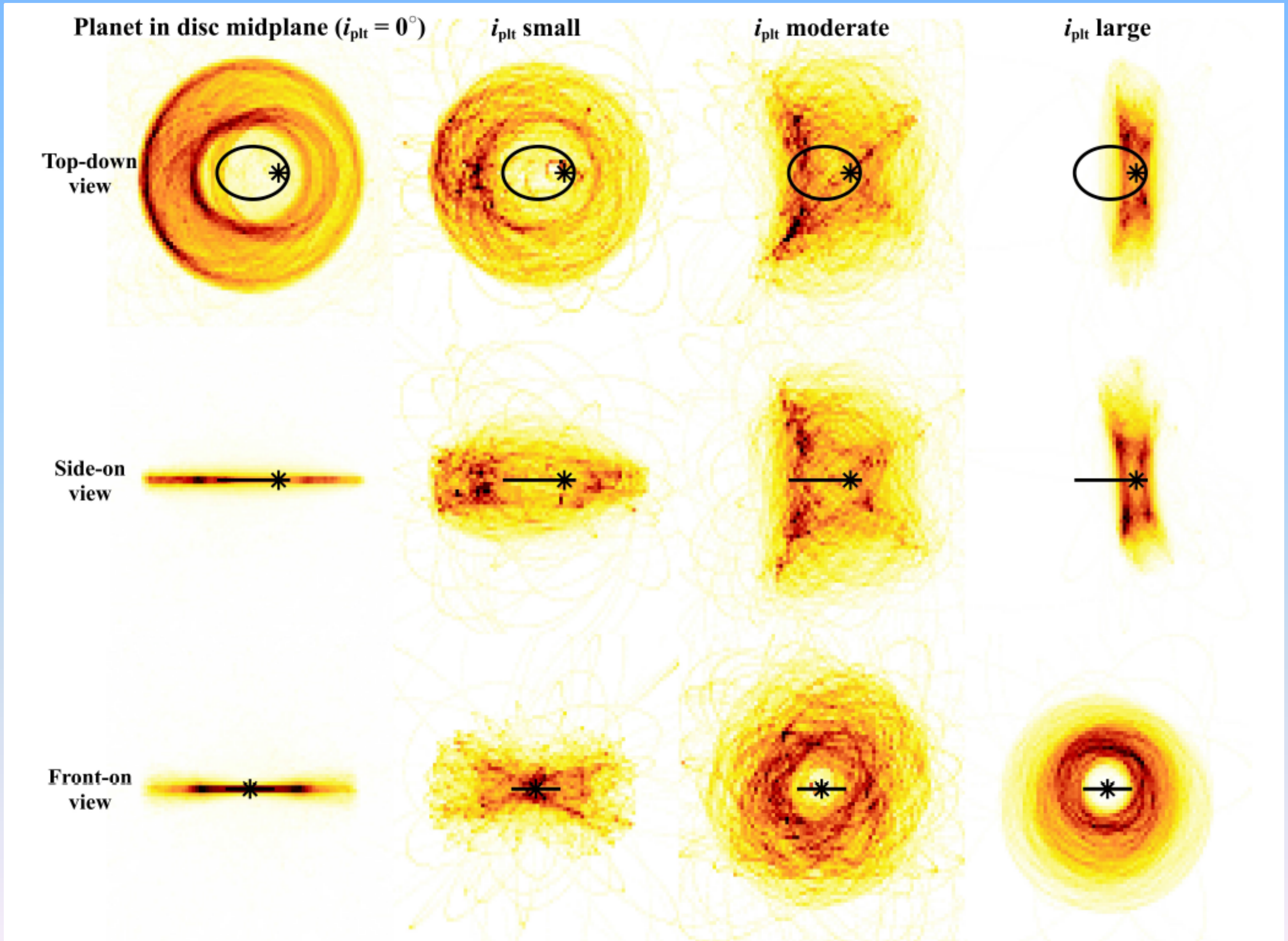


Inclined planets cause warps



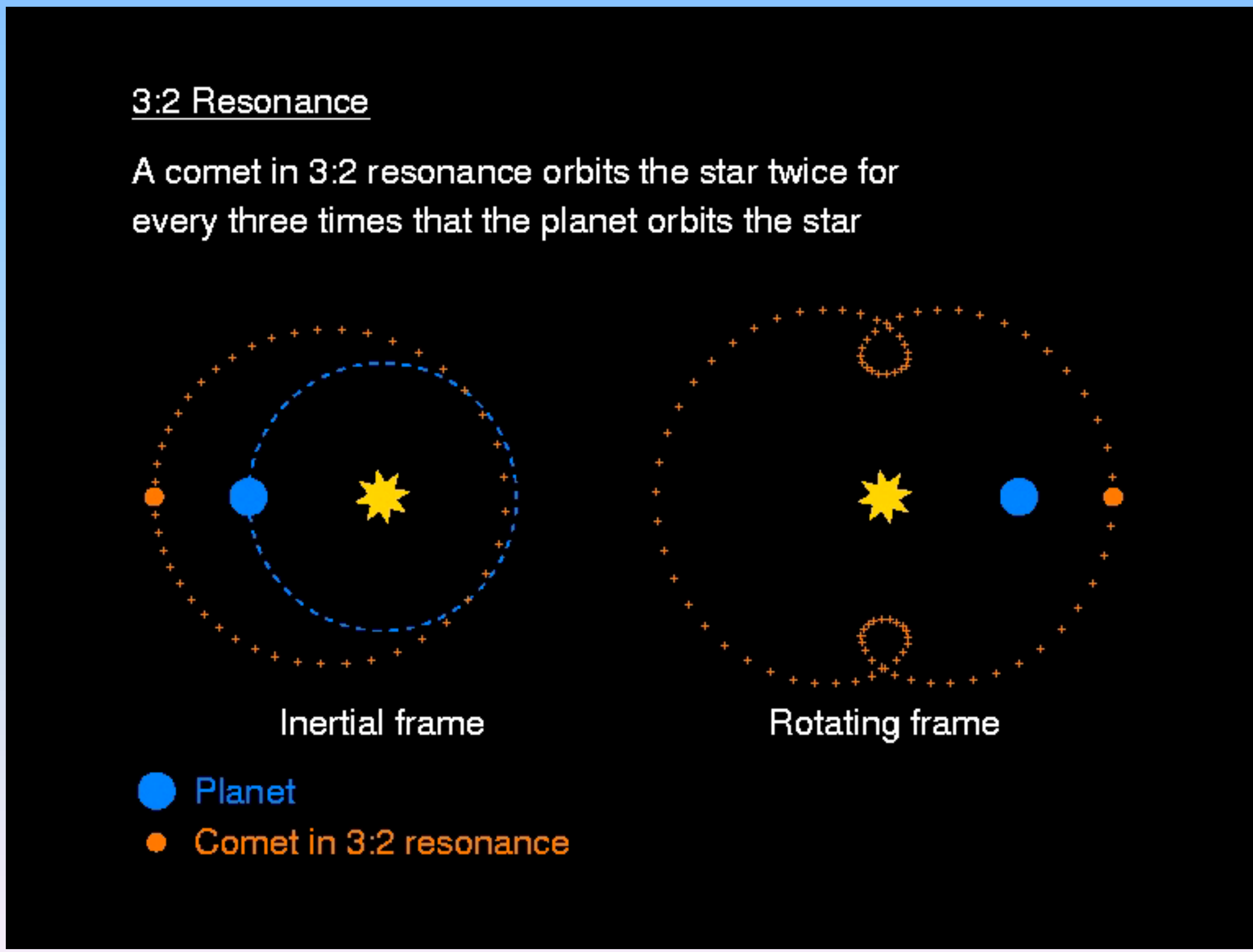
More extreme secular structures

A planet on a highly eccentric orbit can cause a highly eccentric coplanar disk, a bell shaped structure enveloping the planet, or an orthogonal disk, depending on its initial inclination (Pearce & Wyatt 2014; see also Beust et al. 2014, Tamayo 2014)



Geometry of resonance

Resonances are locations where the ratio of the planetesimal's orbital period to that of the planet is the ratio of two integers



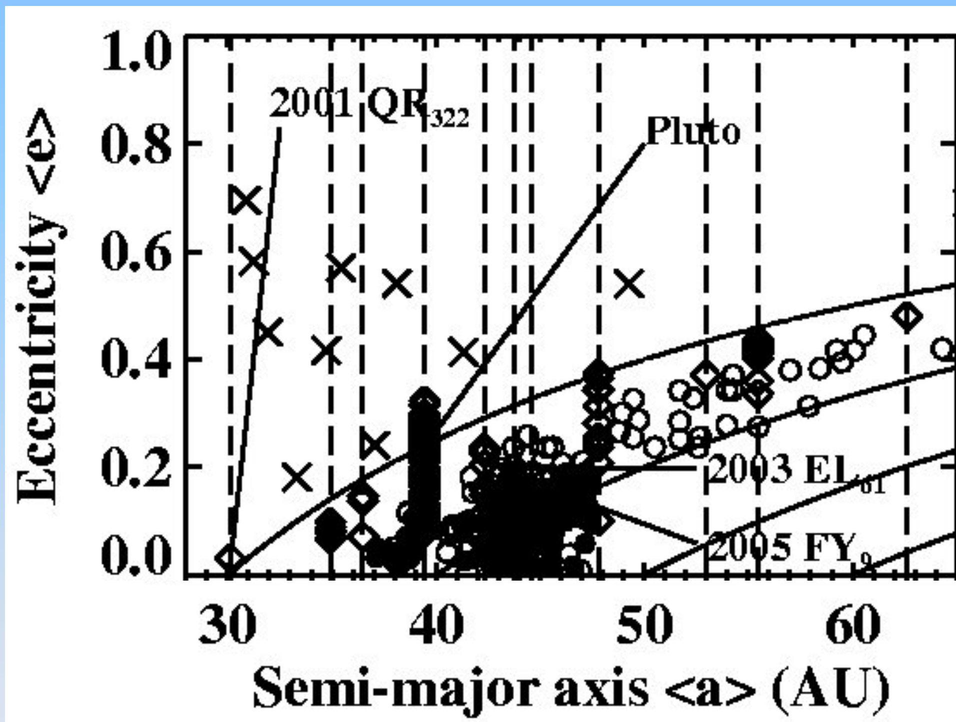
Geometry means planetesimals spend most time at certain longitudes relative to the planet

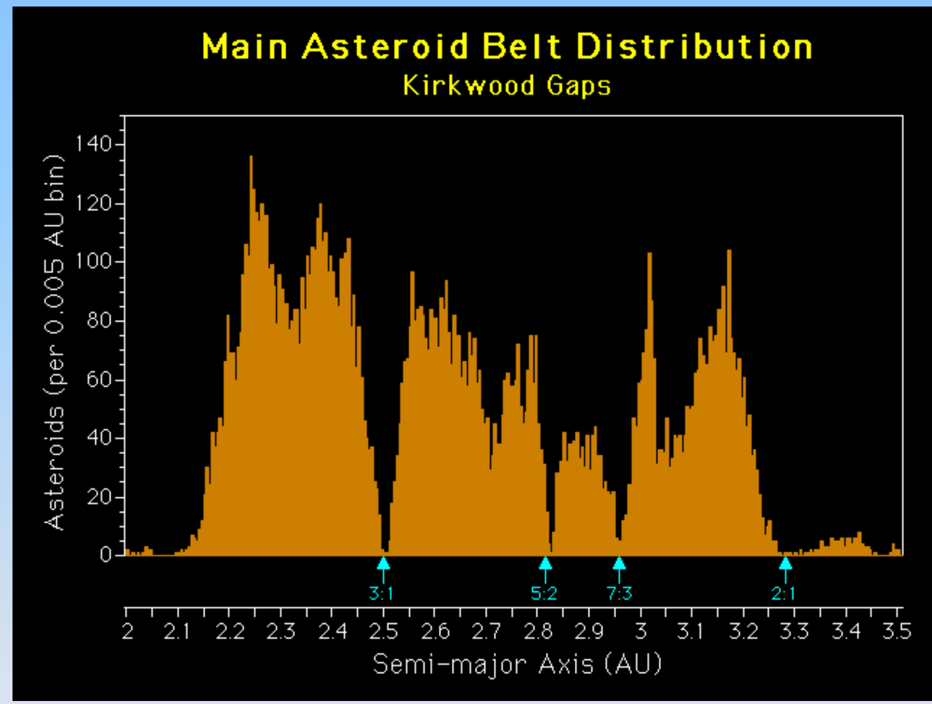
Also causes planetesimal to get periodic kicks from the planet's gravity… can be good or bad.

Resonances in the Solar System

Neptune's exterior resonances are over-populated in the Kuiper belt

Jupiter's interior resonances are under-populated in the asteroid belt

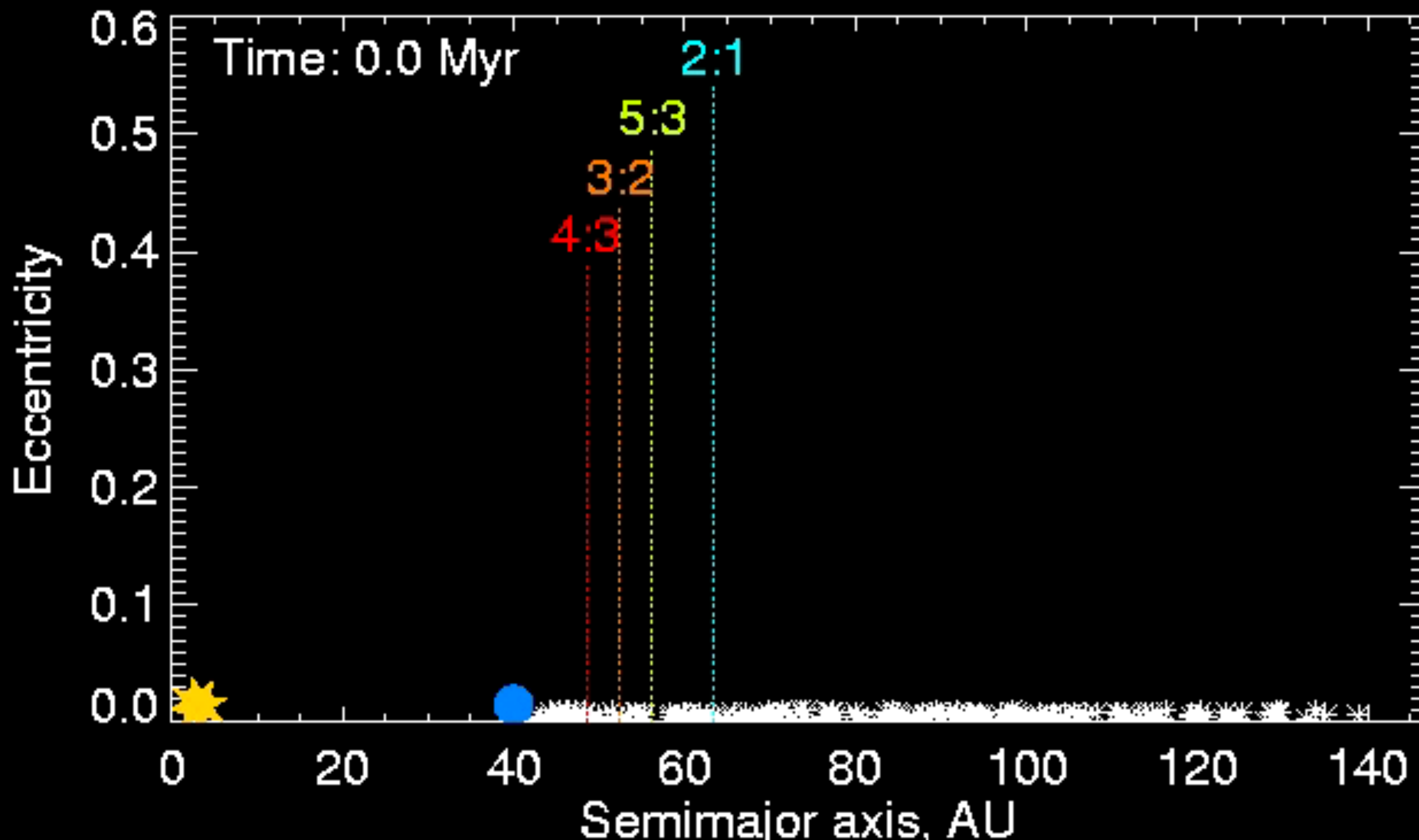




Resonances were filled when Neptune's orbit migrated out

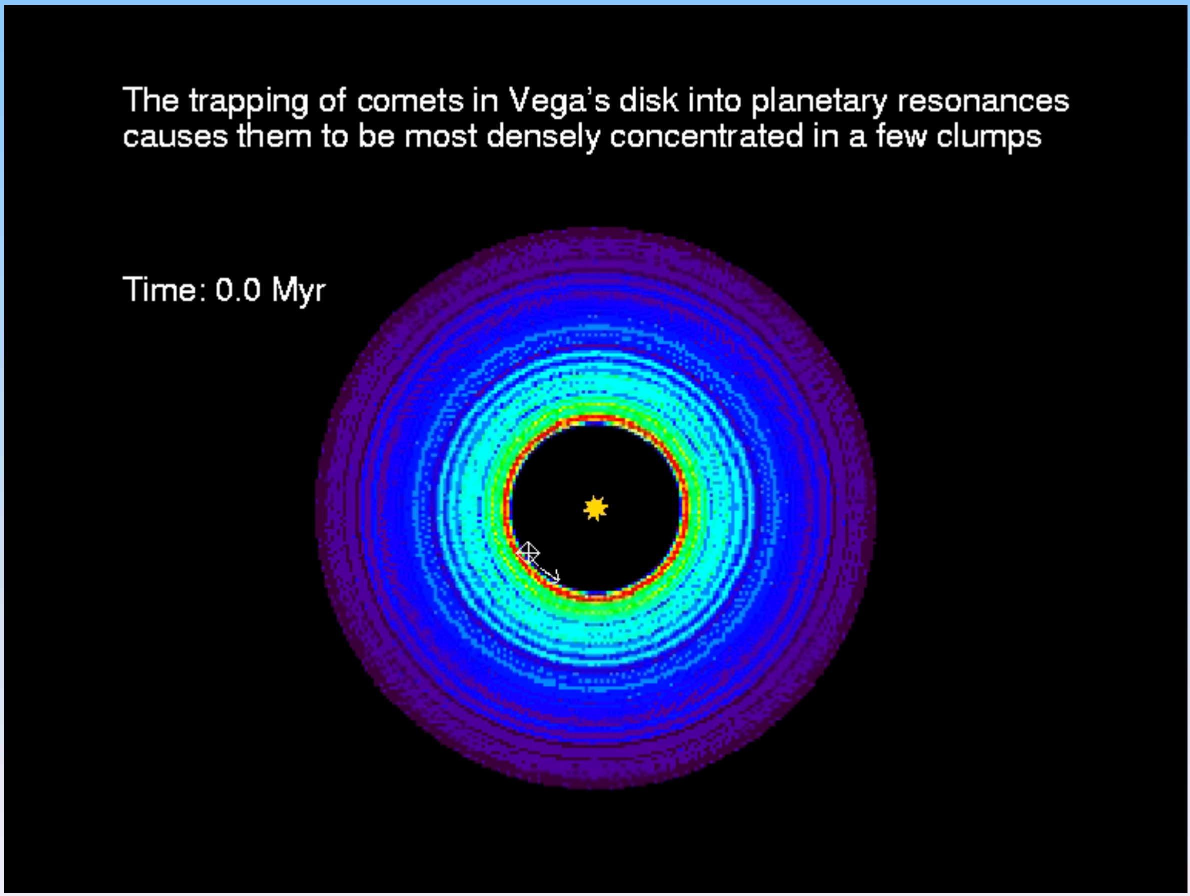
Kirkwood gaps are chaotic, and are origin of Near Earth Asteroids

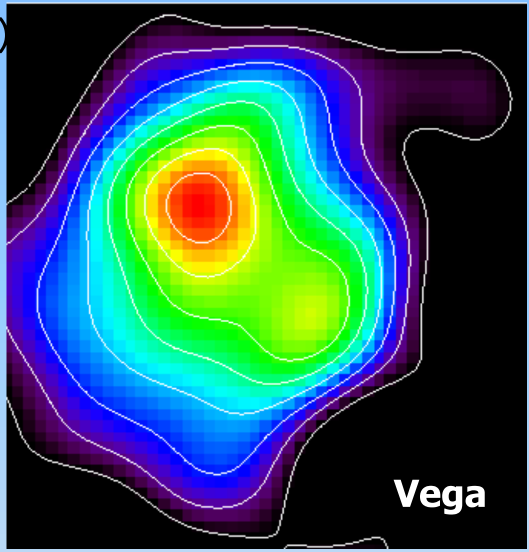
The outward migration of a Neptune mass planet (●) around Vega sweeps many comets (∗) into the planet's resonances

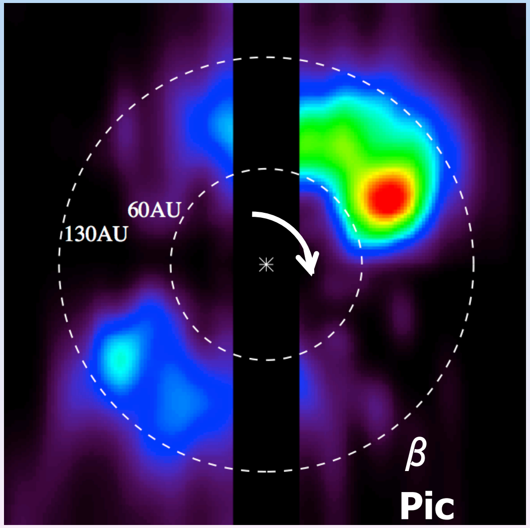


Resonance sweeping causes clumpy disks

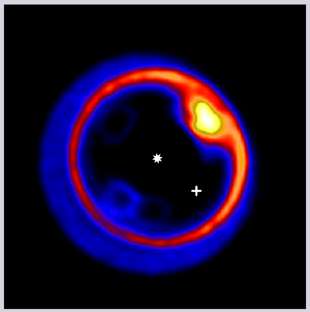
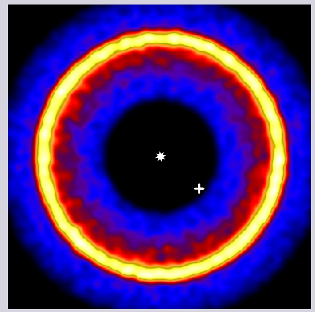
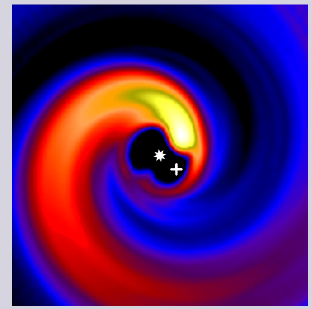
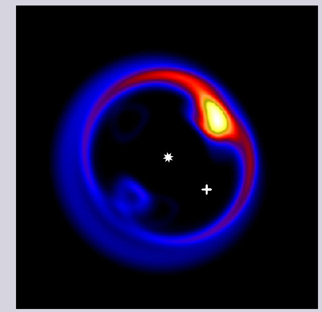
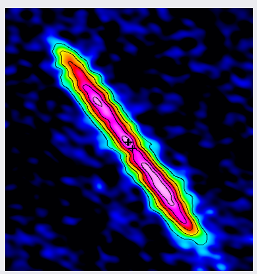
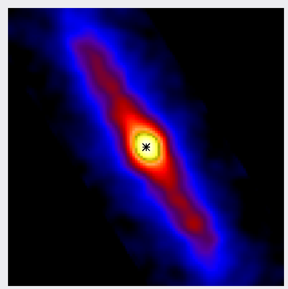
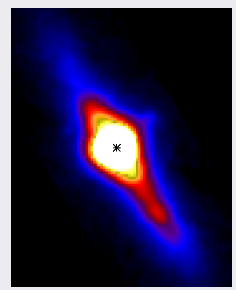
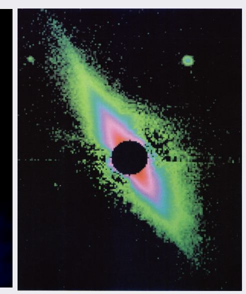
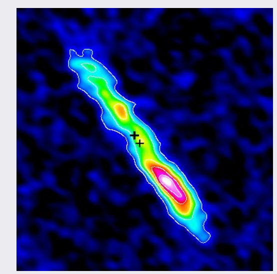
Vega's clumpy sub-mm disk (Holland et al. 1998, but see Hughes et al. 2012) explained by $1M_{neptune}$ which migrated 40-65AU over 56Myr (Wyatt 2003)? Similar explanation proposed for dust and gas clump in β Pic (Dent et al. 2014)







Wavelength dependent disk structure

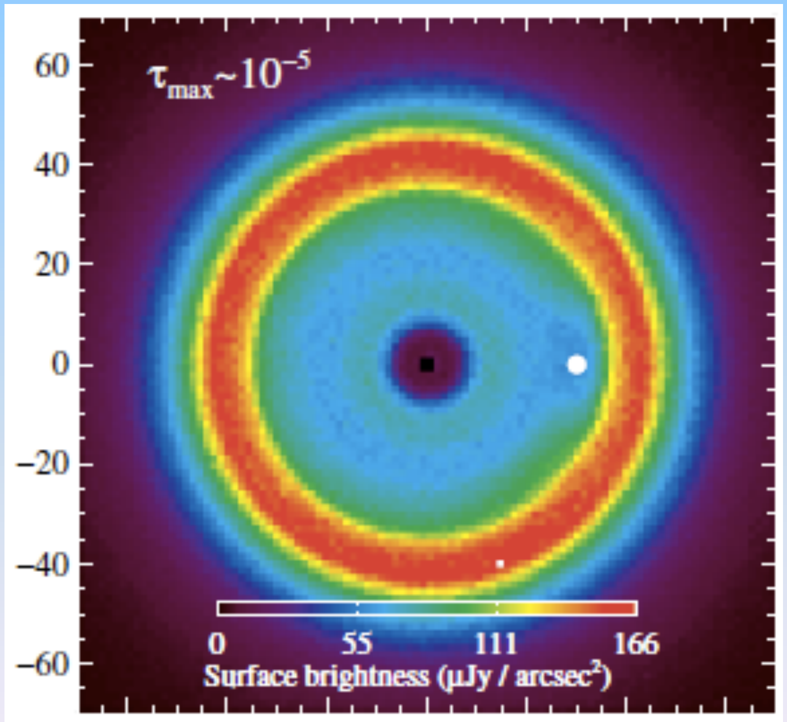
	Sub-mm continuum (planetesimals)	Mid-IR (small but bound dust)	Scattered light and short mid-IR (small unbound dust)	CO (short-lived gas)
Model (face-on)				
β Pic			 	

- Different wavelengths probe different grain sizes / species and so expect wavelength dependence of disk structure (Wyatt 2006)
- Clumps explained by $>30M_{earth}$ which migrated 40-60AU over 12Myr (exact numbers TBD)

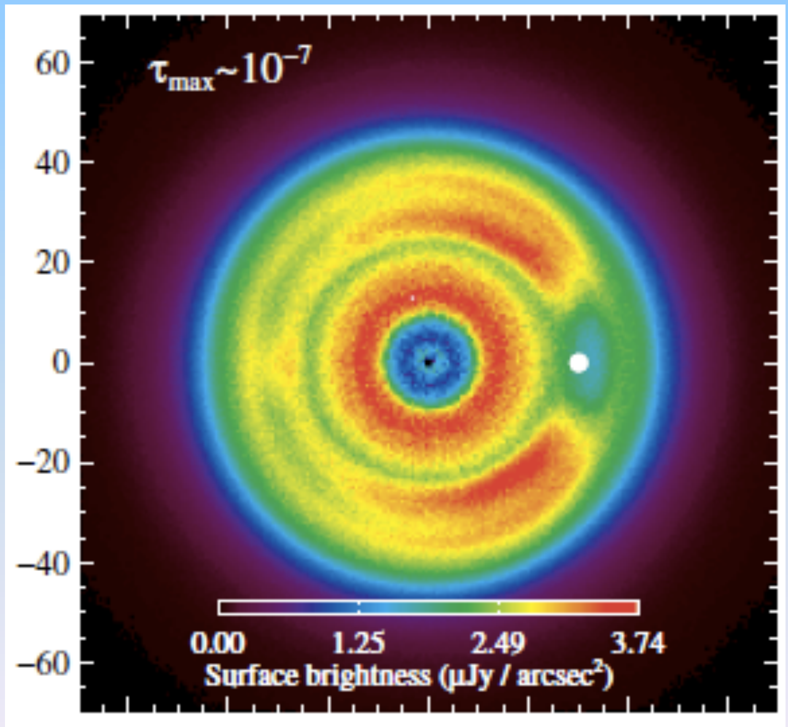
Drag induced resonant rings

Models predict clumpy structure from Kuiper belt dust, but only if the disk is tenuous (e.g., Kuchner & Stark 2010; Vitense et al. 2014):

P-R drag unimportant in dense disks



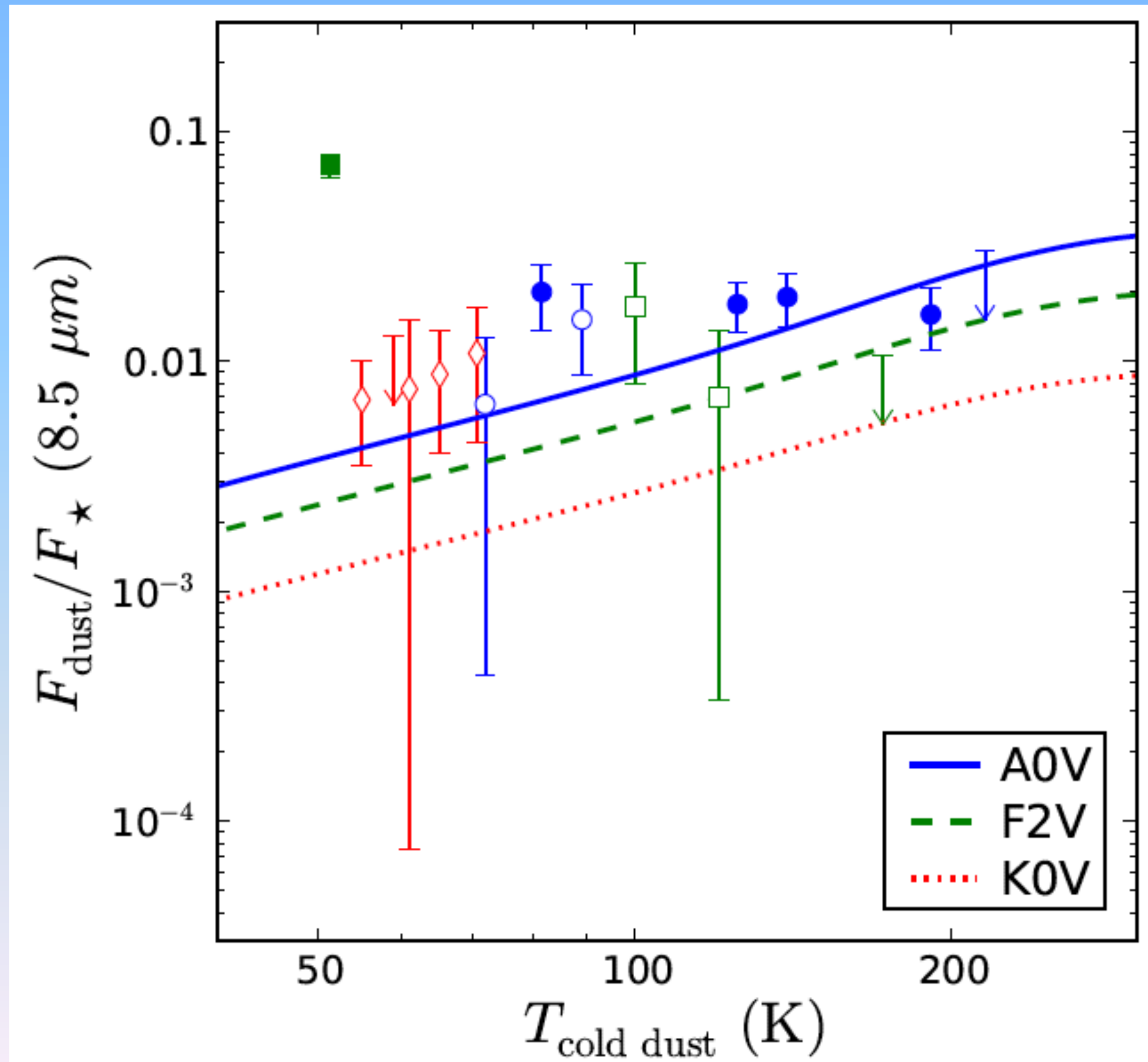
but very important in tenuous disks



PR dragged dust in planetary region is detectable

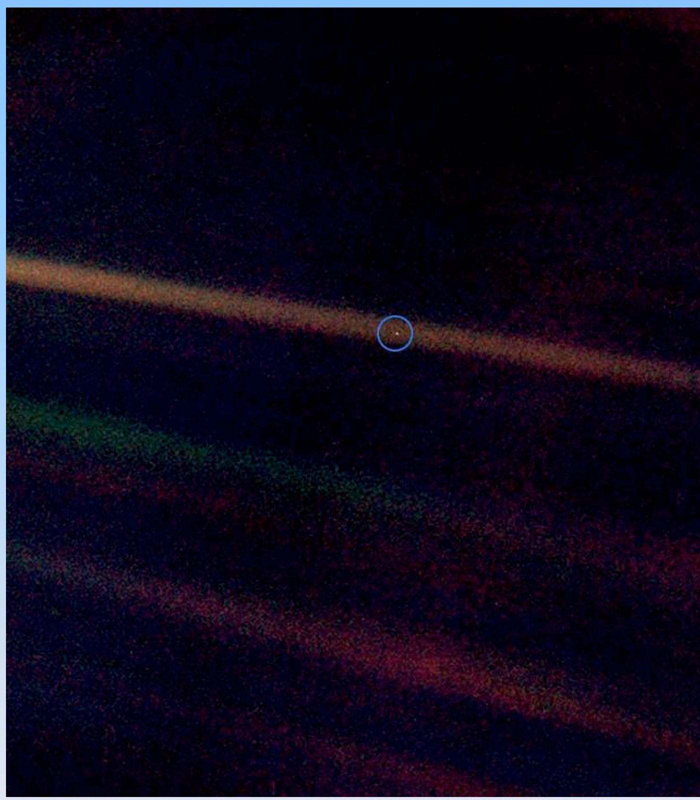
P-R drag may not dominate dense disk structure, but dragged in dust may be detectable

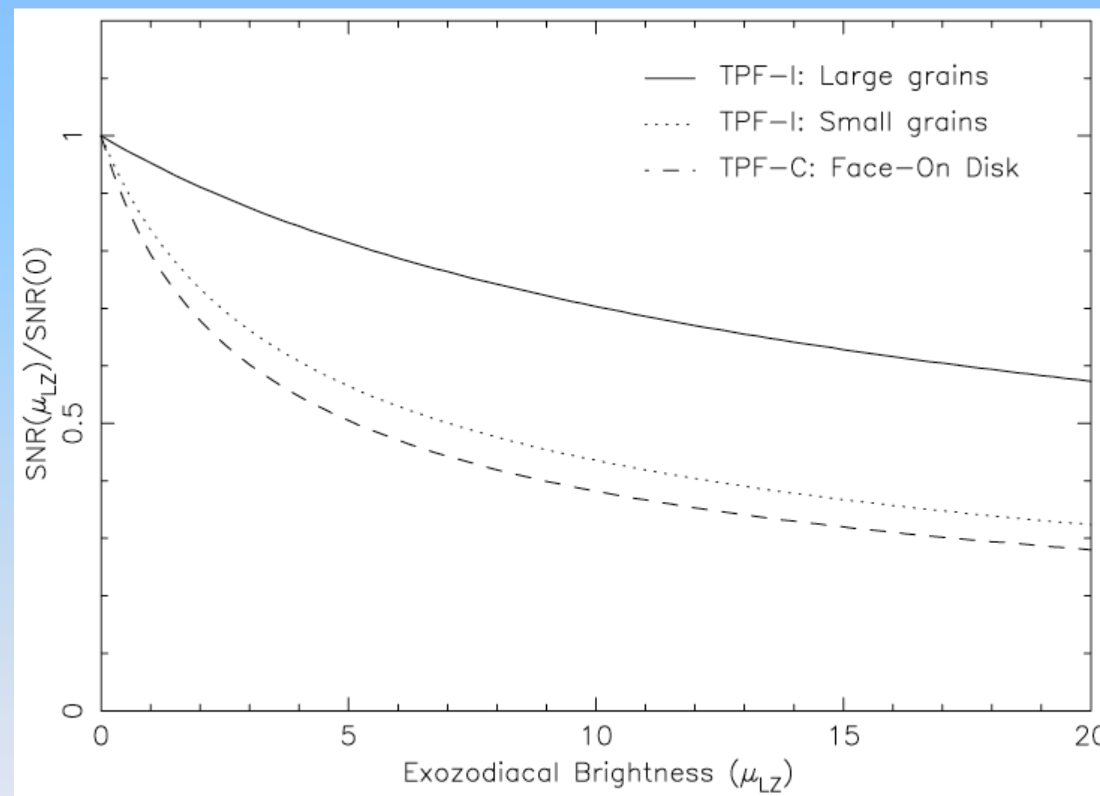
KIN detections of mid-IR excesses (Mennesson et al., submitted) are at predicted level (Wyatt 2005)



Such exozodiacal dust hinders Earth detection

Inner planetary system will be permeated with small dust from any outer belt, which acts as background noise that hinders the detection of Earth-like planets

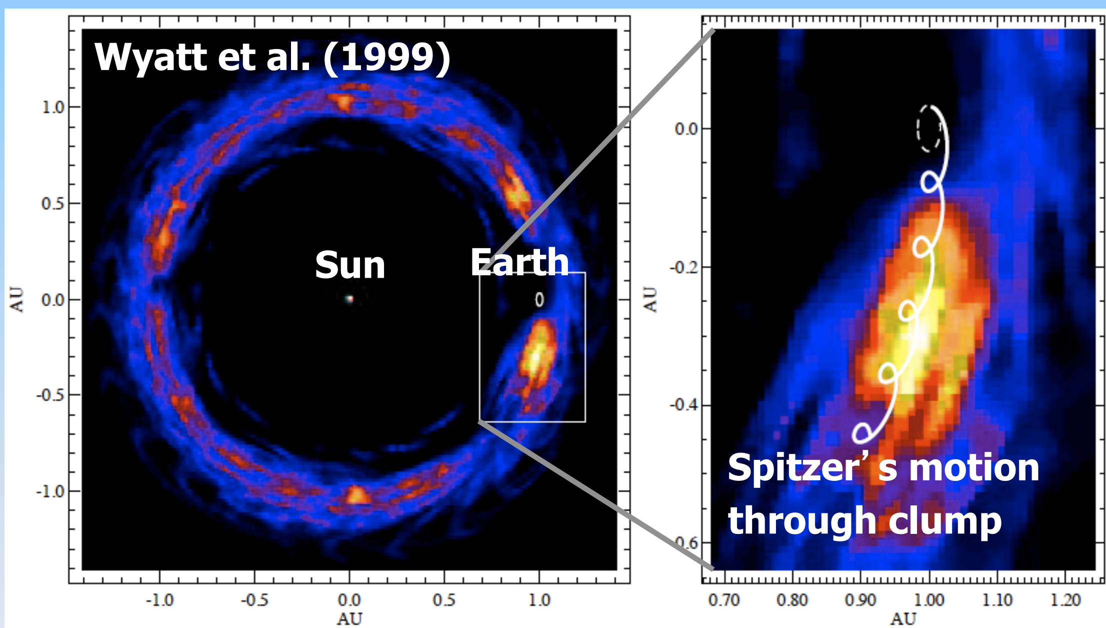


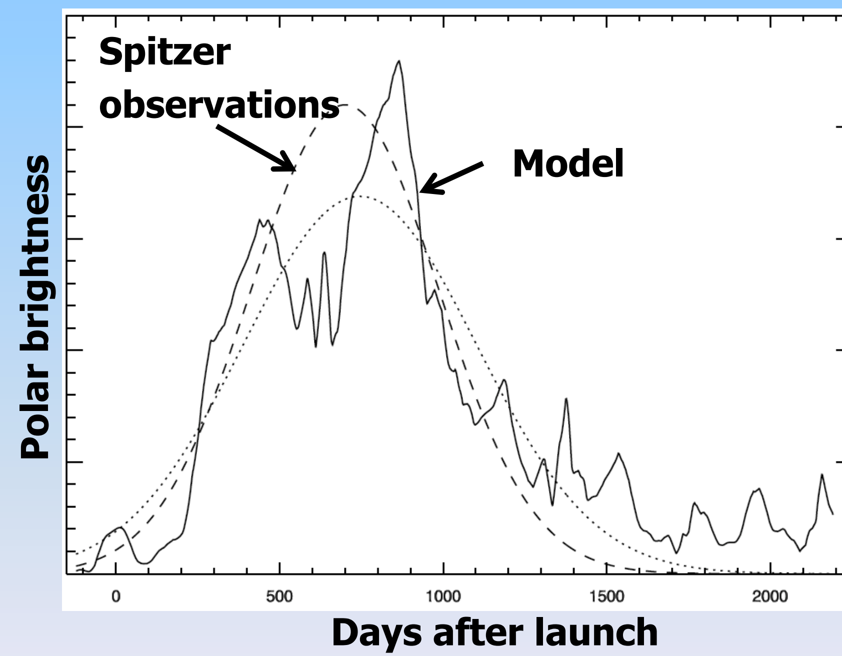


Pale blue dot detection not limited by zodi brightness, but exodot detections will be if exozodis are >10x Solar System level (Beichman et al. 2006; Roberge et al. 2012)

Trailing clumps: drag induced resonant rings

Asteroidal dust spirals past Earth by P-R drag encountering Earth's resonances; some gets trapped causing a dust clump that follows Earth (Dermott et al. 1994)





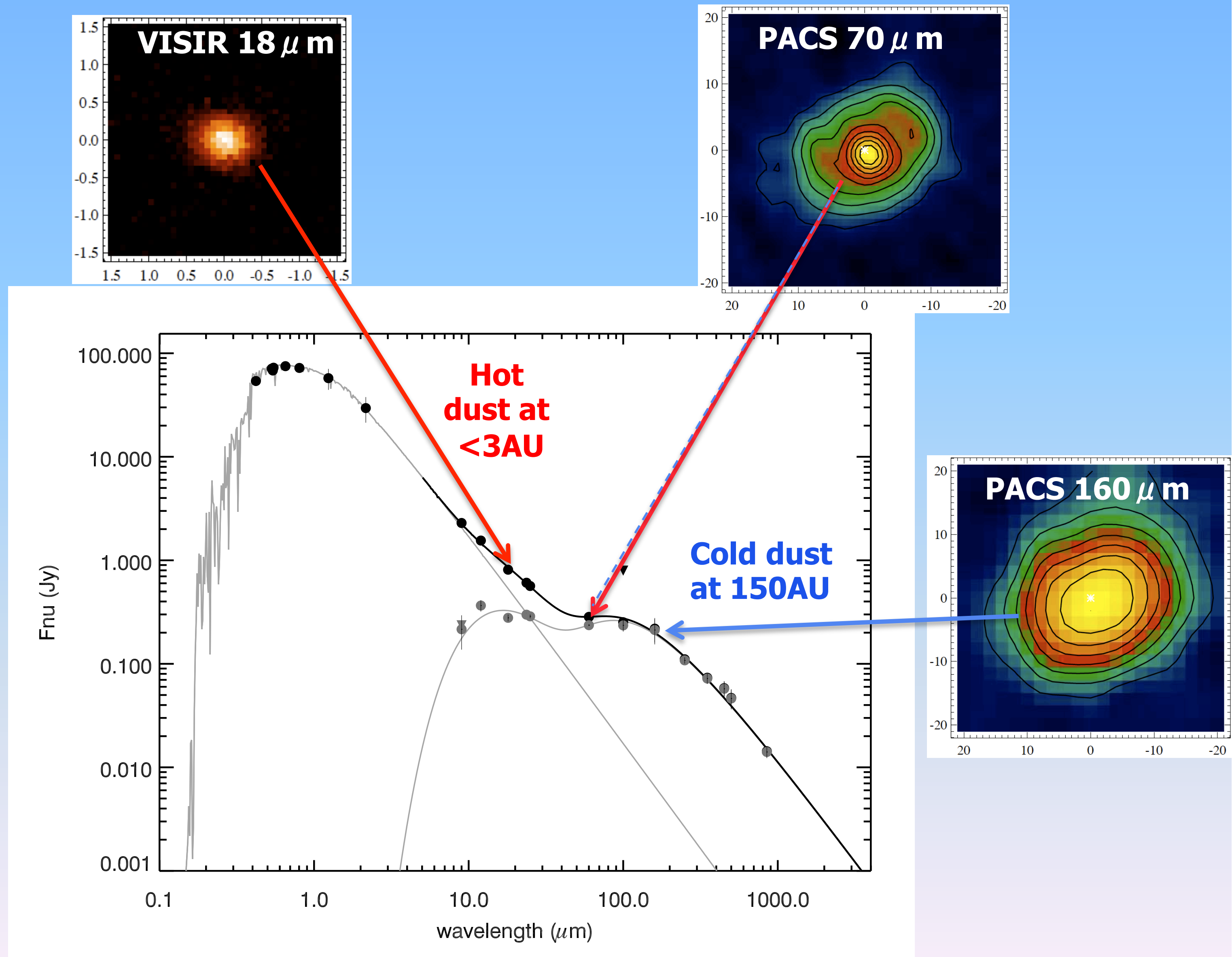
(Reach 2010; Shannon et al., in prep)

Dust hinders planet detection, but imaging structures induced by planets may help

Some hot dust can't have been PR dragged in

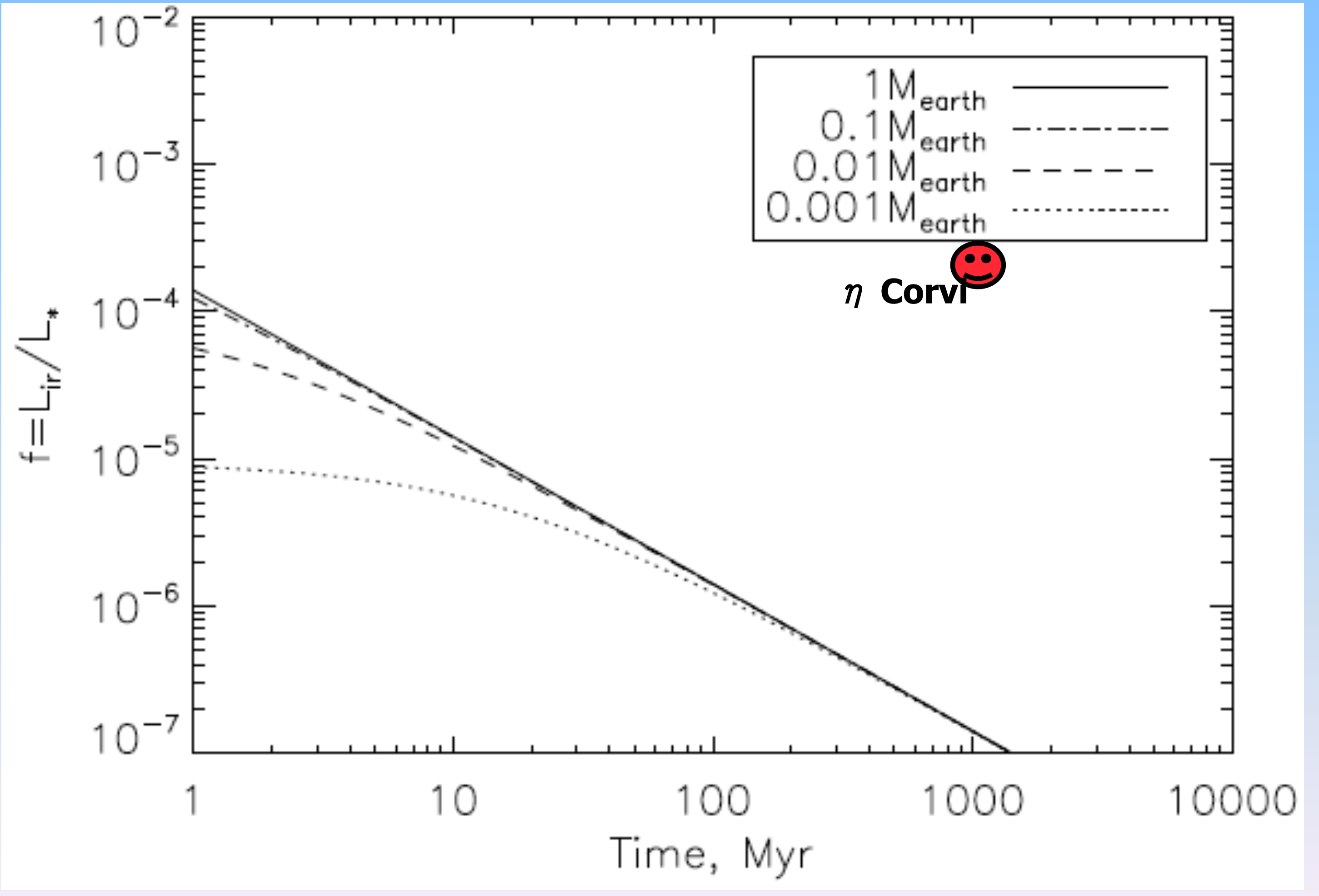
η Corvi is ~1Gyr F2V at 18pc with a two-temperature emission spectrum:

- 150AU ring resolved in sub-mm and far-IR (Wyatt et al. 2005; Duchene et al. 2014)
- unresolved dust at <0.16" (<3AU) seen in mid- to far-IR (Smith, Wyatt & Dent 2008; Duchene et al. 2014; Defrere et al., in prep)



Hot dust not from massive asteroid belt

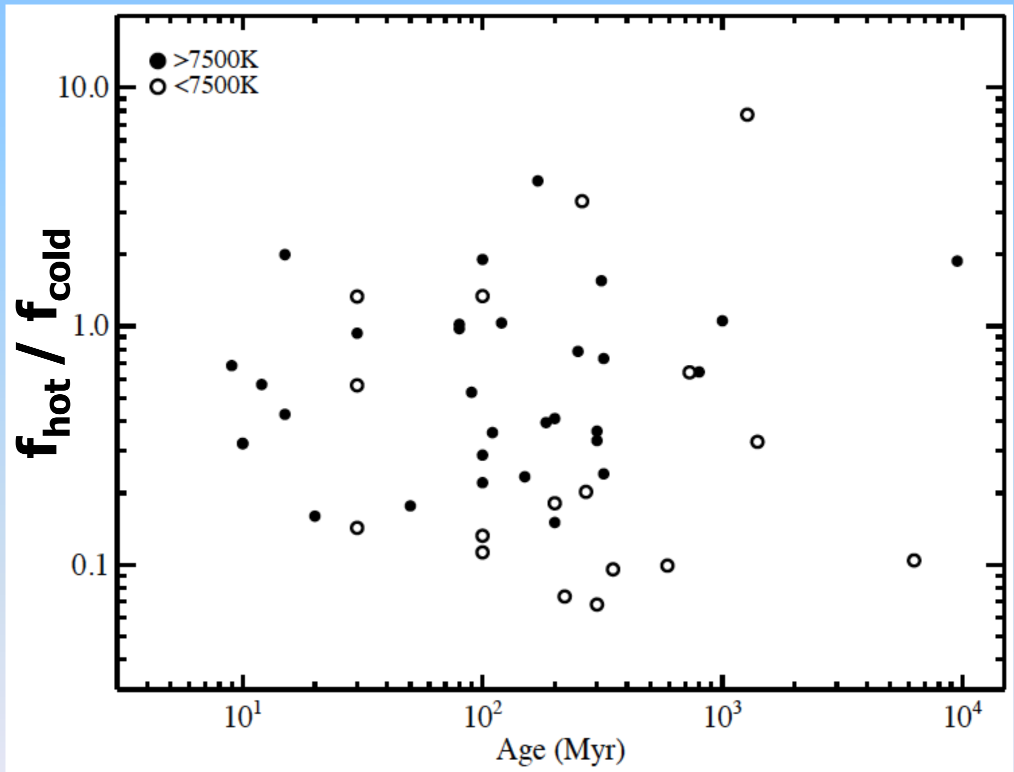
Collisional erosion means at late times an asteroid belt at 1au would be so low in mass that its dust would be below detection threshold
(Wyatt et al. 2007)



Lack of evolution of hot dust?

Many debris disks seen to have two temperature SEDs less extreme than η Corvi (e.g. Morales et al. 2011; Chen et al. 2014)

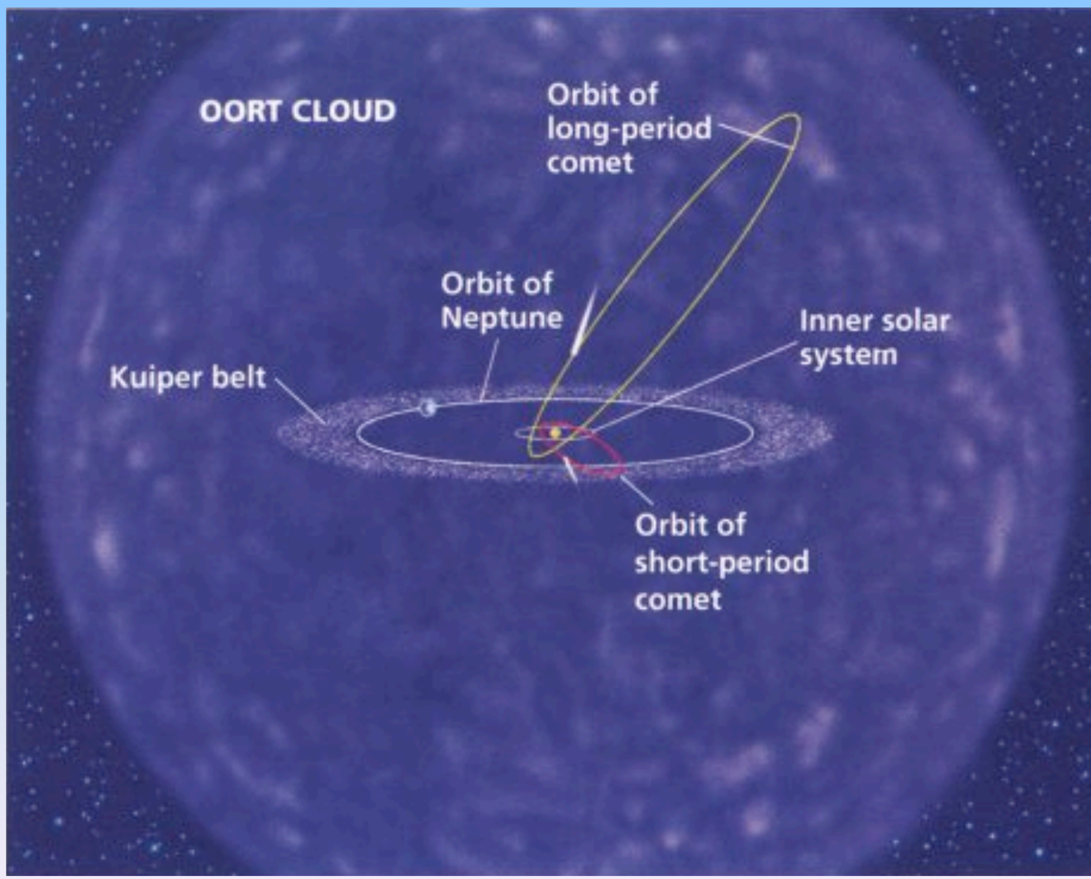
If steady state, the hotter component should evolve faster than the colder component, but no evidence for this (Kennedy & Wyatt, submitted)



Could indicate a process linked to the outer belt, but doesn't rule out a collisional origin, e.g., if the dust is replenished by a recent collision

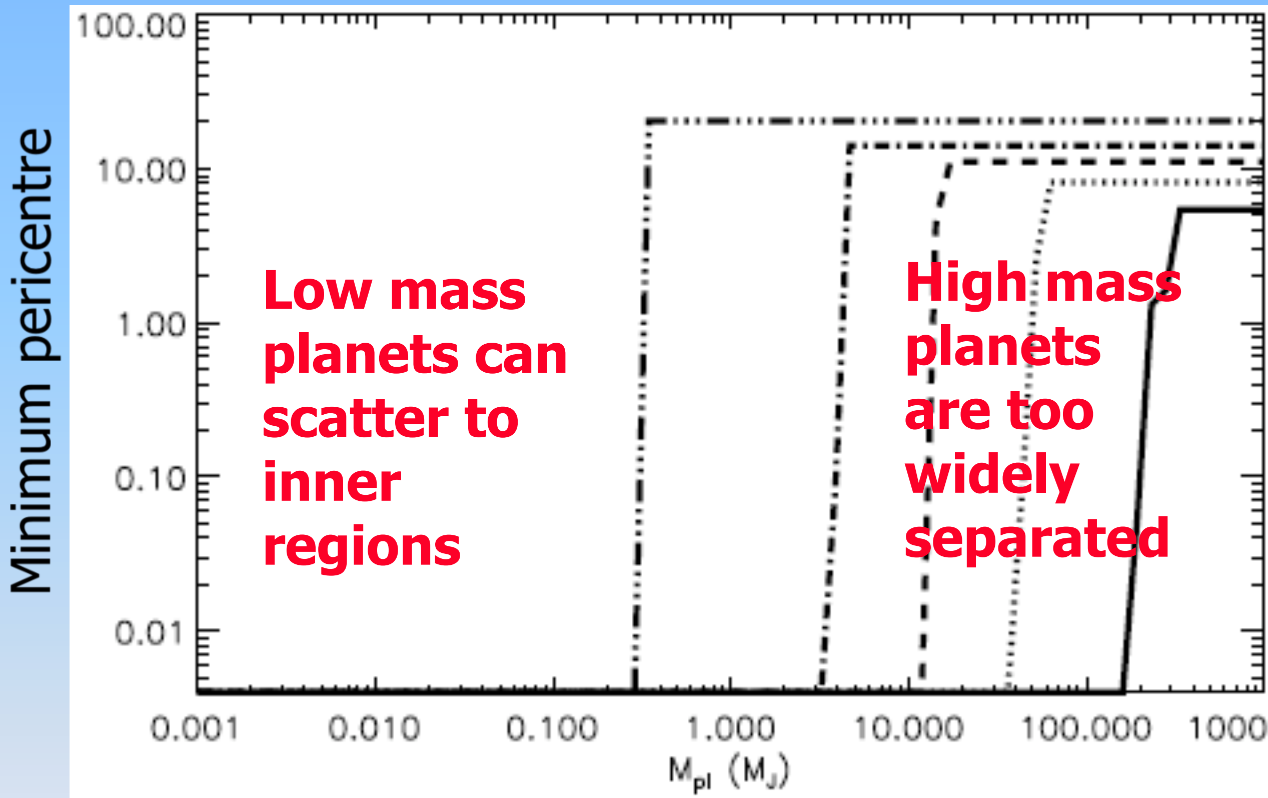
Scattering as origin of comets

Kuiper belt objects scattered in by outer planets become short period comets
Oort cloud comets were scattered out, possibly during formation of outer planets



In inner Solar System comets sublimate and fragment into dust replenishing the zodiacal cloud (Nesvorny et al. 2009)

Scattering depends on system architecture

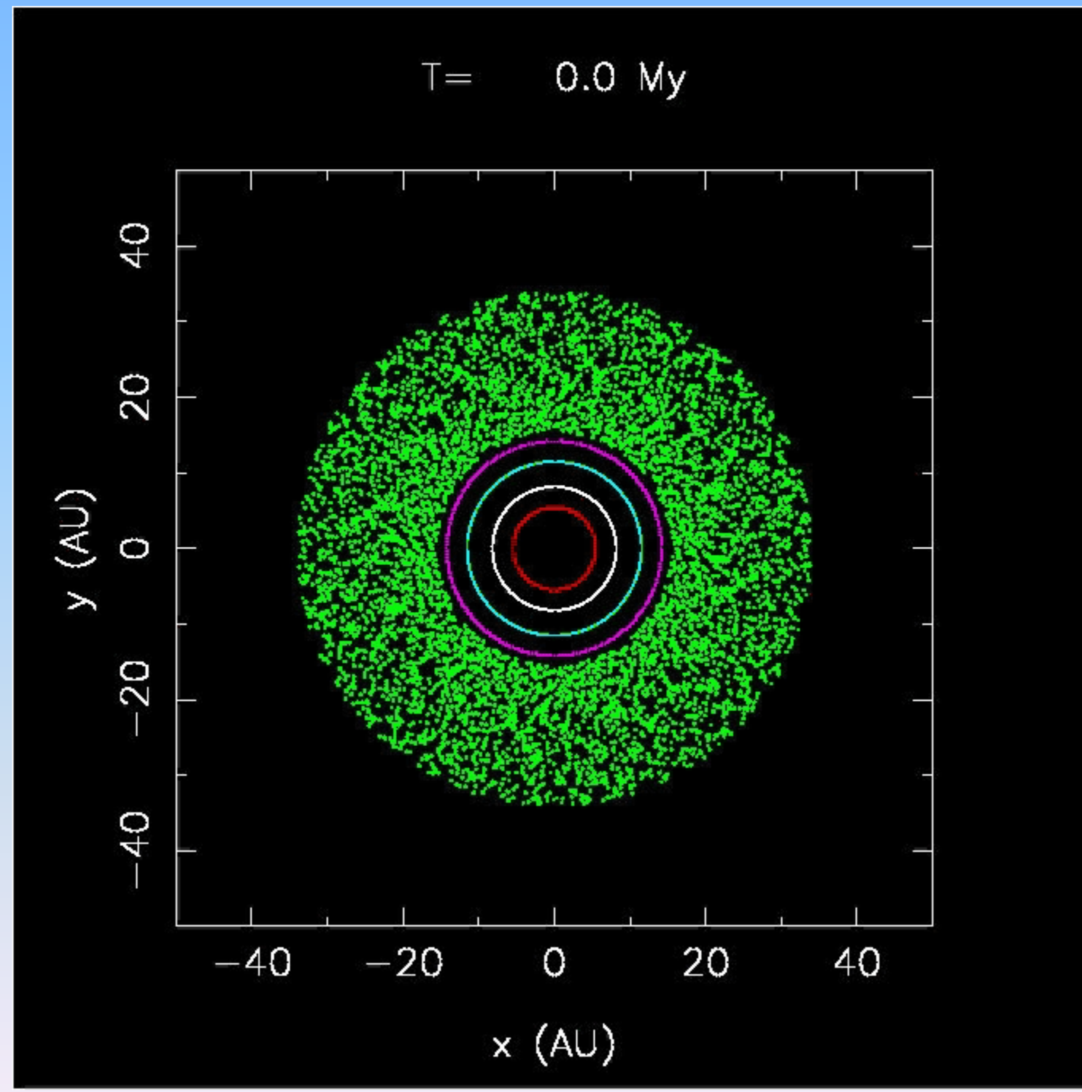


For a system packed with planets ($10R_{hill}$ separation) between 1-30AU and an outer belt, the minimum distance to which comets can be scattered depends on planet mass (Bonsor & Wyatt 2012; see Bonsor, Augereau & Thebault 2012)

Comet population (and so f_{hot} / f_{cold}) is set by planetary system properties, so provides an opportunity to learn about planetary system architecture

Scattering causes migration… and depletion

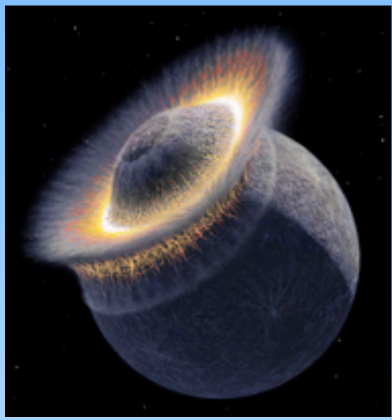
Is η Corvi in midst of Late Heavy Bombardment, ie comets thrown in by a dynamical instability (another consequence of scattering, as it causes planets to migrate, e.g., Gomes et al. 2005)

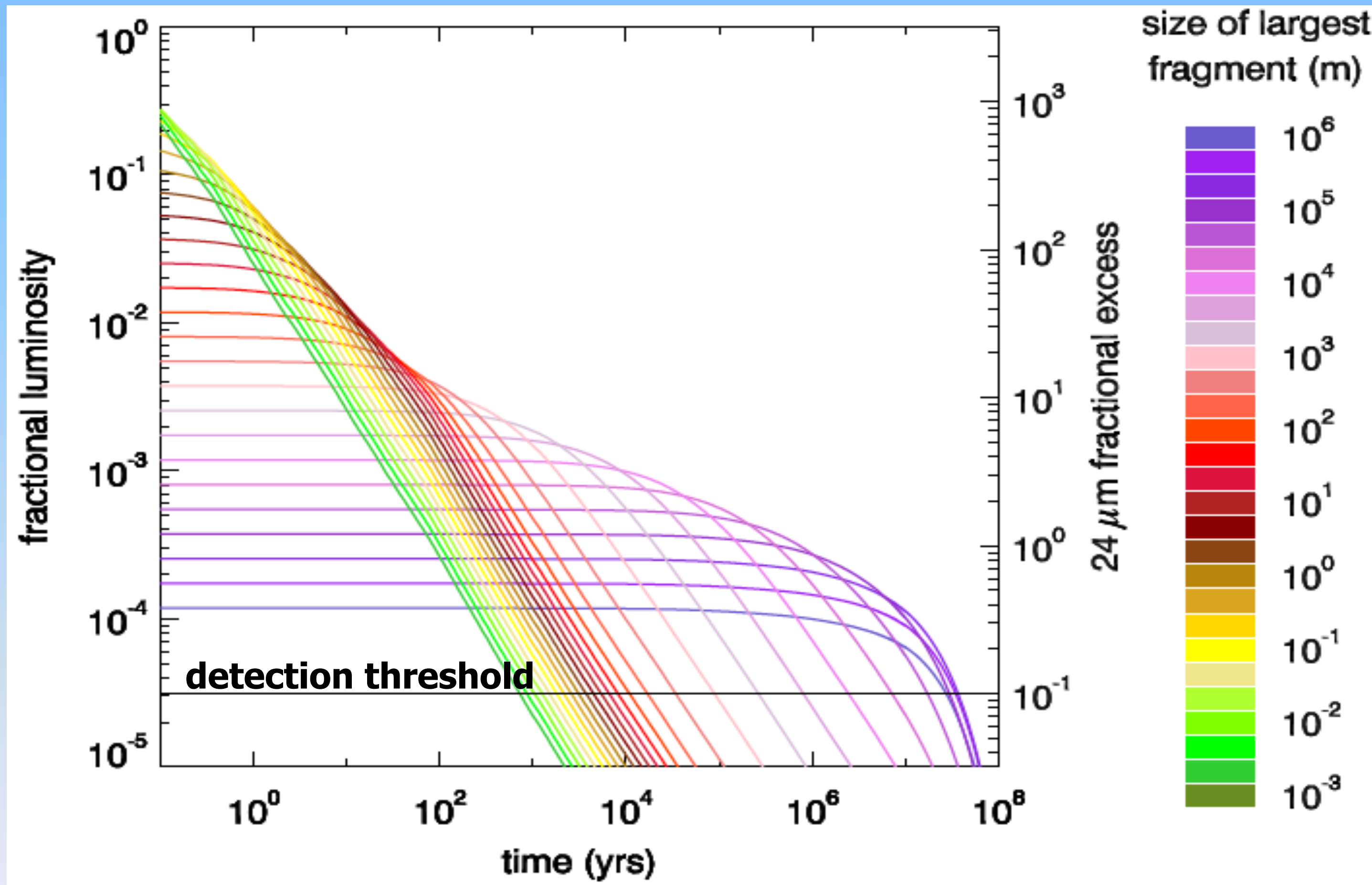


LHBs are short-lived and so could only explain rare systems (Booth et al. 2009; Raymond et al. 2012; Bonsor, Raymond & Augereau 2014)

Hot dust from giant impacts

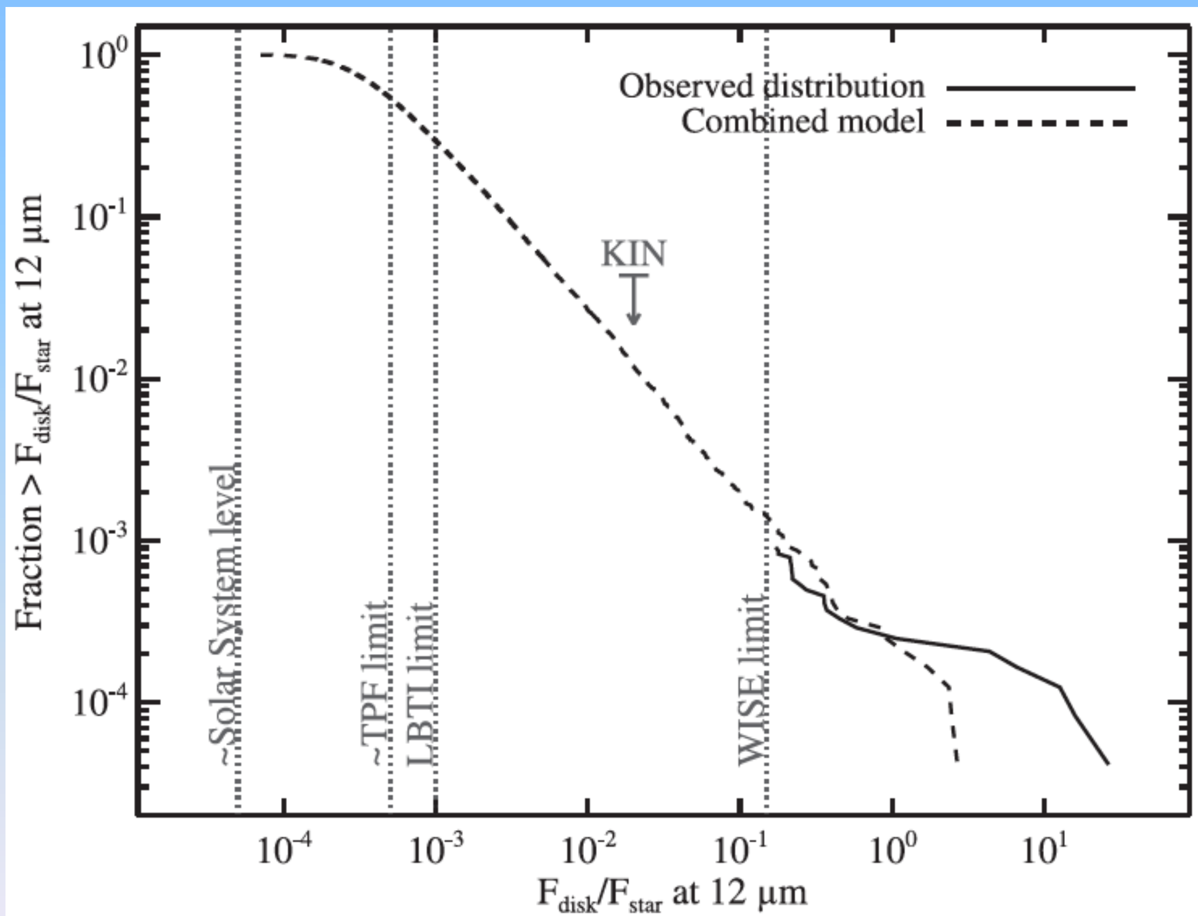
Impacts in inner Solar System: Moon-forming impact, Hirayama asteroid families





Debris is long-lived, depletes 1/age by collisions on a timescale set by unknown fragment size distribution (Jackson & Wyatt 2012)

Exozodi luminosity function



The exozodi luminosity function quantifies how common bright excesses are (Kennedy & Wyatt 2013)

Shape holds clues to the evolution of the dust if bright levels decay through lower levels

Extrapolation tells us how common faint excesses are that may hinder a TPF-like mission, which will be constrained by LBTI (Hinz et al.; Defrere et al., Millan-Gabet et al.)

Conclusions

Debris disk structure and evolution is set by a combination of collisions, radiation forces and interactions with planets

Planets interactions can be divided in secular, resonant and scattering processes, each with its own signatures, and these can be used to pinpoint unseen planets in disks

Exozodis (dust in inner planet region) have many possible origins, but levels are potentially high enough to impact exodot imaging, either from PR drag, comets, past giant collisions