Debris Disks as Planetary Signposts (Theory)

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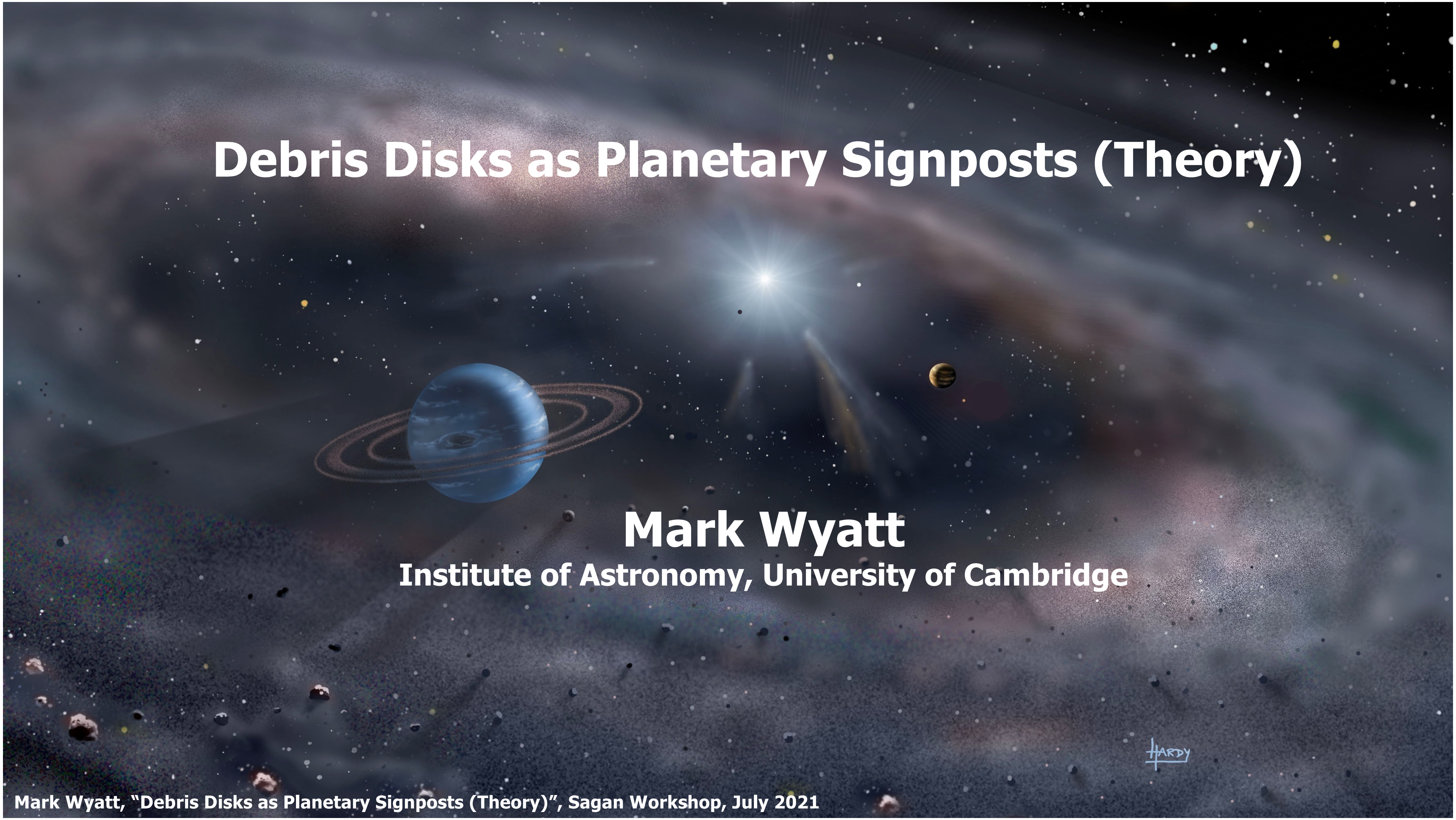
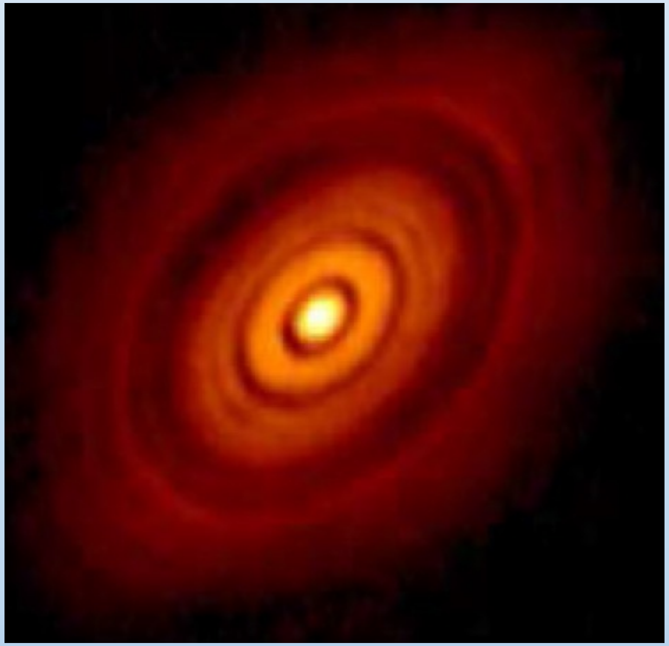
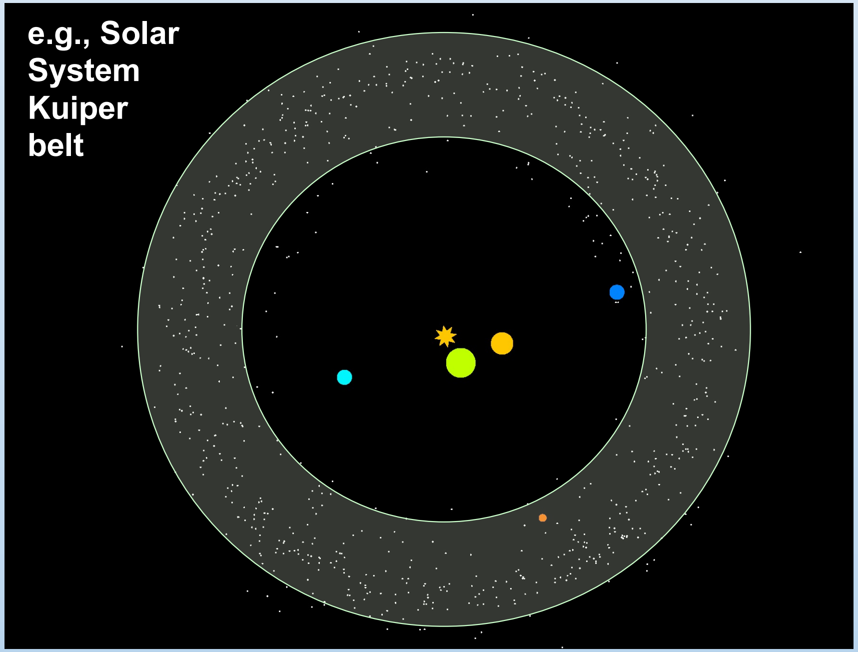


What is a debris disk?

Descendant of a star's protoplanetary disk

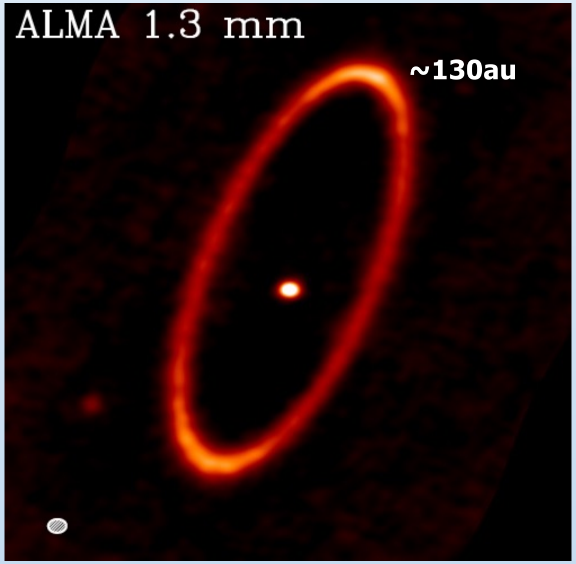


Non-planetary component of a planetary system

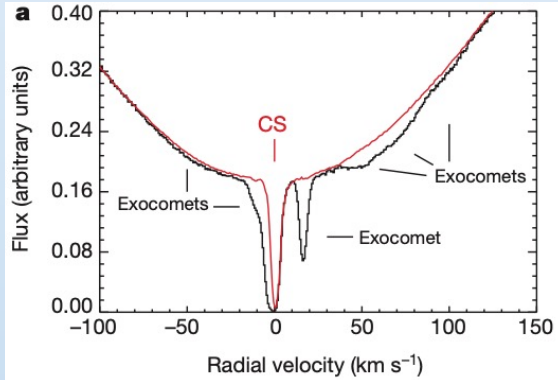


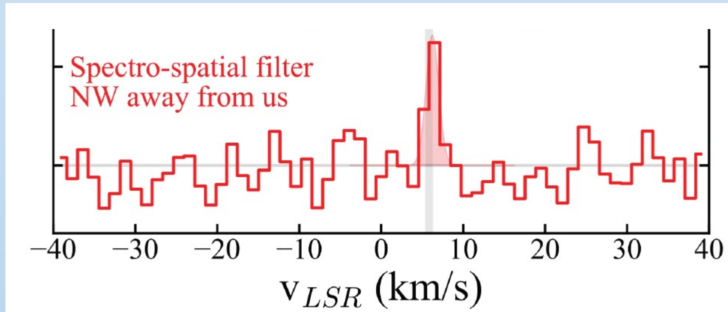
Debris disk observables

Imaging

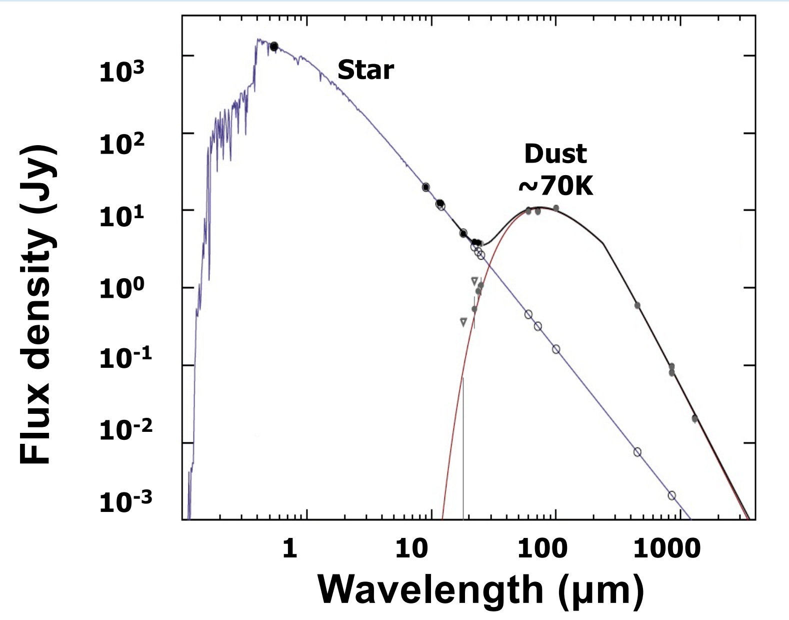


Spectroscopy



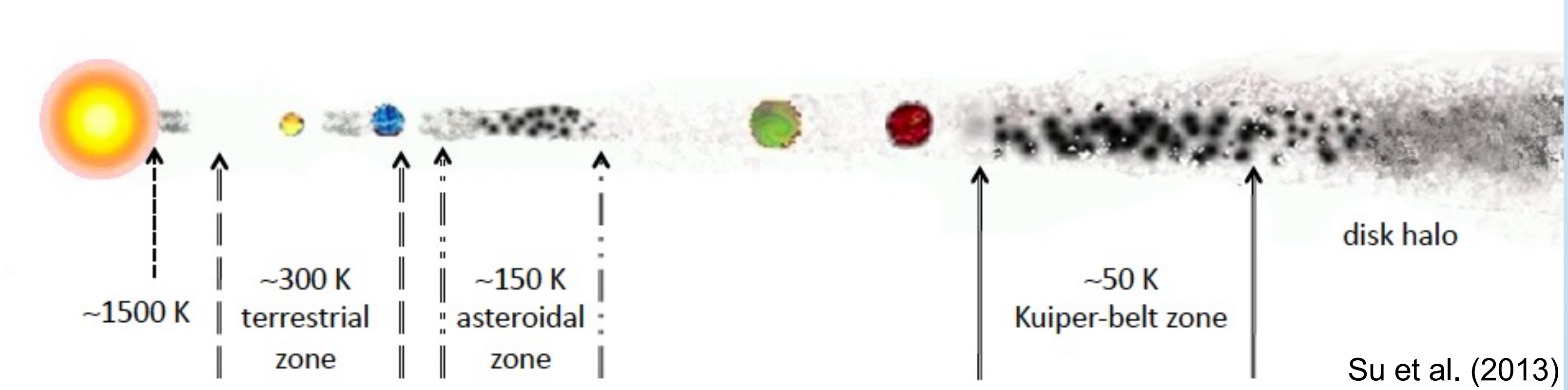


Photometry



Typical structure of a planetary system?

This is the picture of planetary systems inferred from debris disk observations, i.e., planets interspersed with planetesimal belts, and dust created in those belts in (somewhat) radially confined locations



Su et al. (2013)

But can we really say anything about yet unseen planets?
Yes! Any planets in a system will inevitably impose structure on a debris disk

Debris disk physics

- Stellar gravity – most things orbit the star
- Gravitational perturbations from planets – those orbits change
- Radiation forces – important for small dust (which dominate observations)
- Collisions – affects mass/size
- Stellar wind, sublimation, gas drag, viscous evolution, self-gravity, Lorentz forces – may also be relevant
- Radiative transfer – needed to interpret observations

How to Model Debris disks

Either follow individual particles, e.g., r(t)*N

- N-body based codes (e.g., Mercury, REBOUND)
- N-body with collisional destruction (Stark & Kuchner 2009; Thebault 2012; Nesvold et al. 2013)
- N-body with collisional production (LIDT-3D; Kral et al. 2014)

Or follow the phase space, e.g., n(r,D,t)

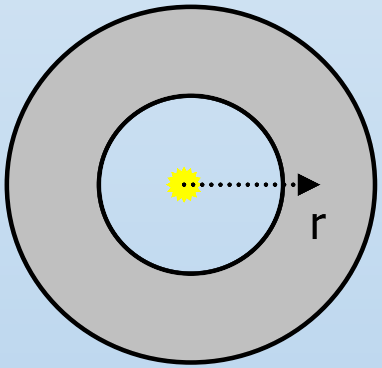
- Kinetic codes (e.g., ACE - Krivov et al. 2006; Thebault & Augereau 2007; van Lieshout et al. 2014)
- Kinetic codes with dynamics (e.g., Sende & Lohne 2019)

Or take a more analytical or empirical approach (e.g., Wyatt et al. 1999)

Often radiative transfer is considered in a separate step, using e.g., Mie Theory for optical properties of dust

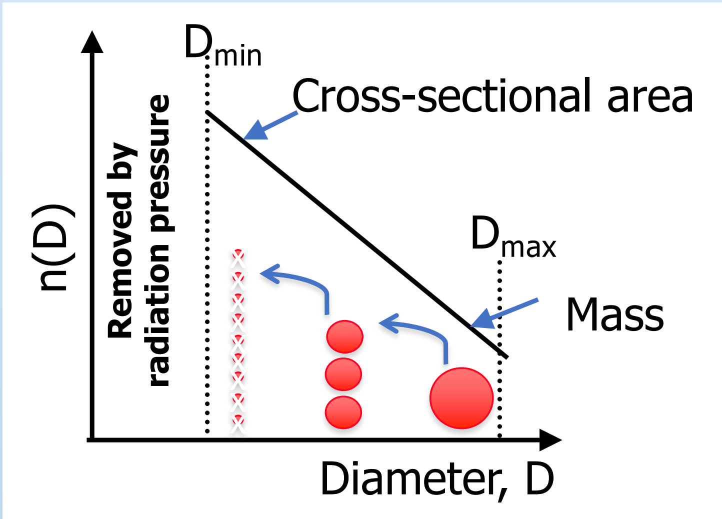
Debris disk primer

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



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

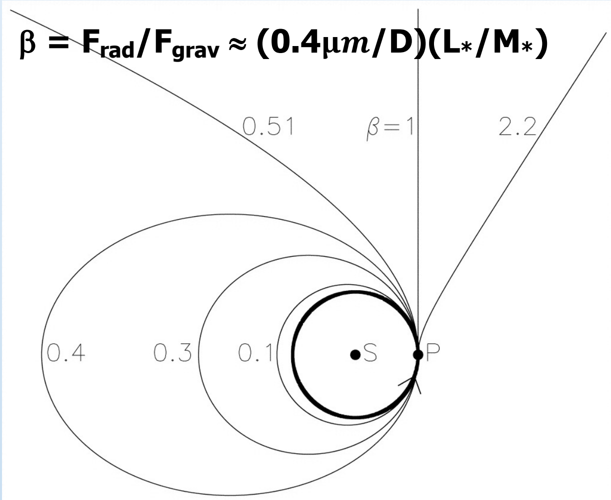
$n(D) \propto D^{-3.5}$

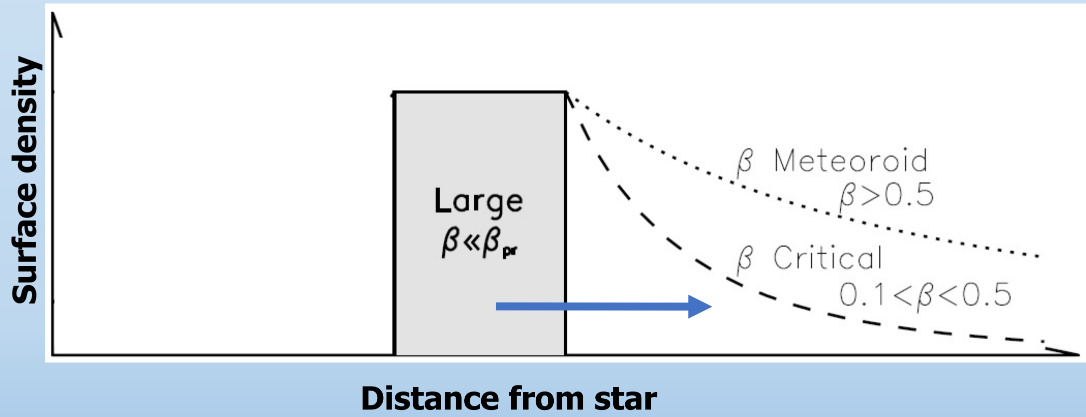


(For more detailed changes in slope and wiggles in the distribution, see Thebault & Augereau 2007; Wyatt et al. 2011)

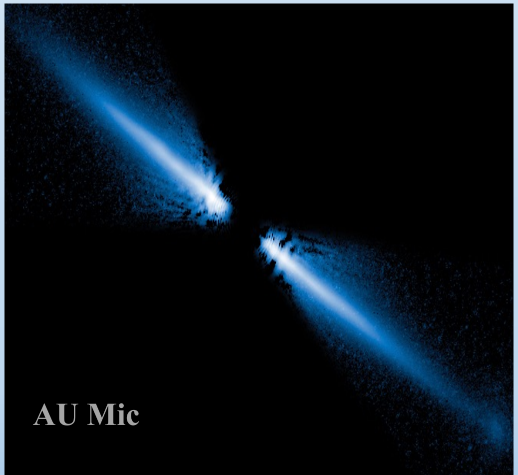
Radiation pressure halo

Large particles confined to belt, but a population of small bound and unbound grains extends to large radii (Wyatt 1999, Krivov et al. 2000, Thebault & Augereau 2001, Strubbe & Chiang 2006)





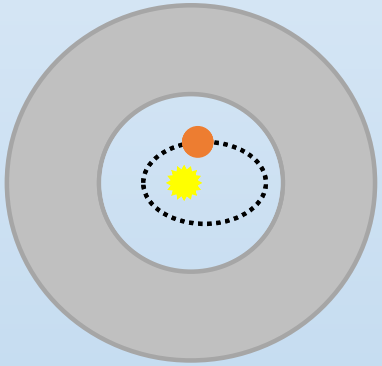
Explains structure of most known extrasolar debris disks, noting different wavelength observations probe grain sizes comparable with wavelength



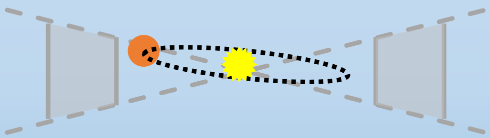
Planets perturb orbits

Three ways in which planets inevitably perturb orbits of disk particles (e.g., Murray & Dermott 1999)

1. Secular perturbations

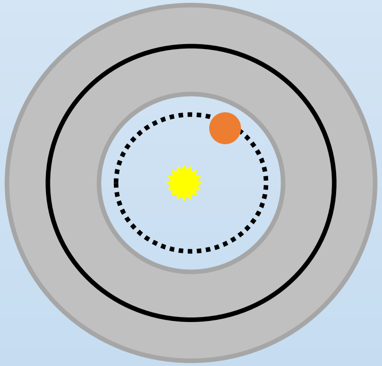


eccentric planet

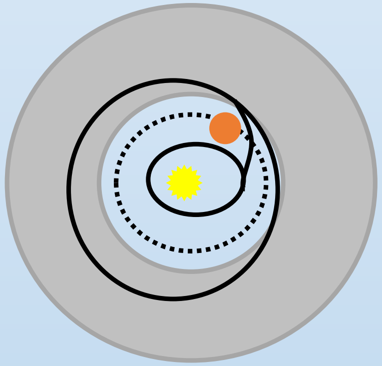


inclined planet

2. Resonances



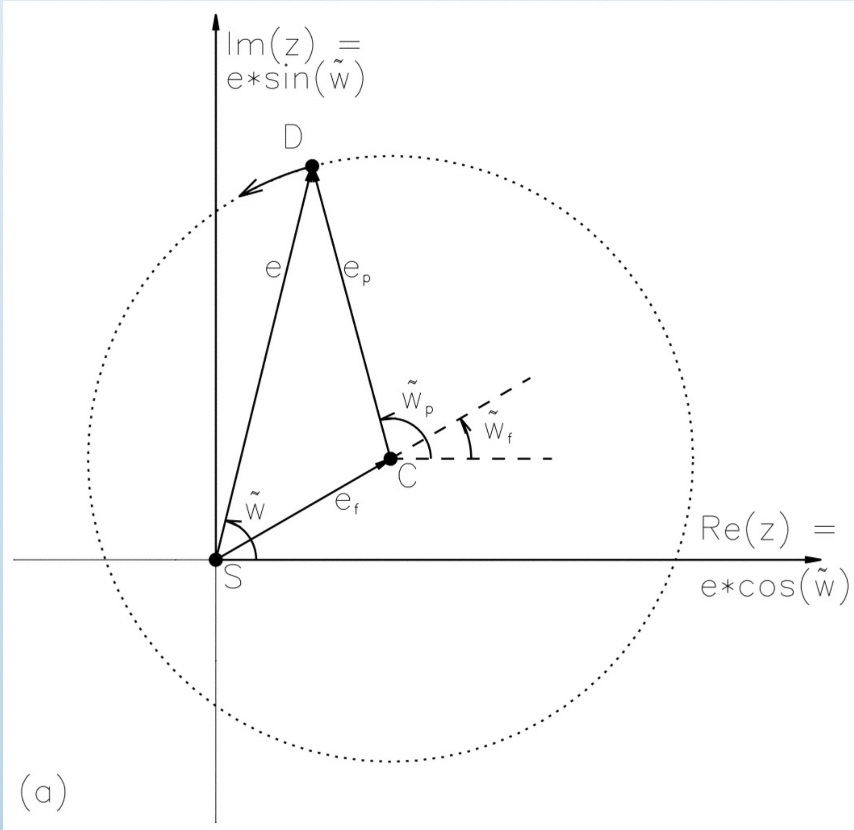
3. Scattering



Secular perturbations: the basics

Physics: Disk particles orbit in a potential of the star plus a wire defined by the planet's orbit

Maths: Particle orbits precess around a circle whose centre is set by the planet, aka the "forced elements", as is the precession rate

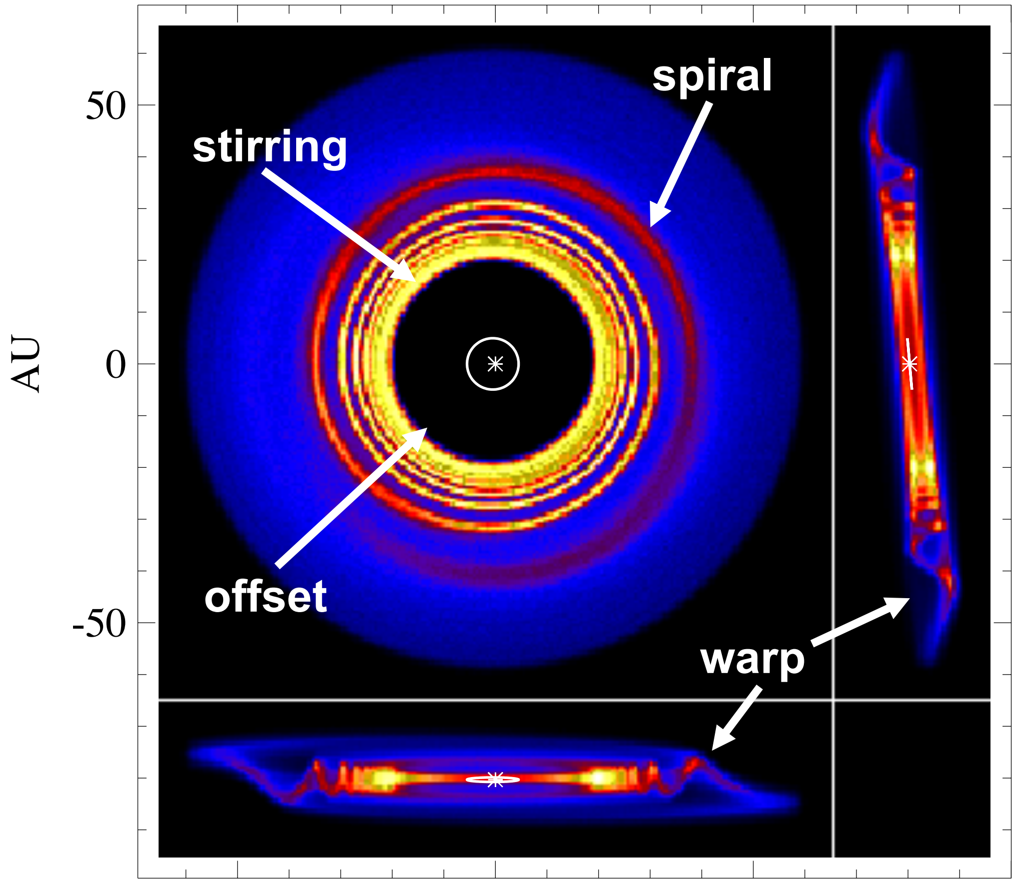


Secular perturbations: low eccentricity and inclination

Planet:
1M$_{jup}$
5AU
e=0.1
I=5^o

Disk:
20-60AU

Time:
100Myr
after
formation

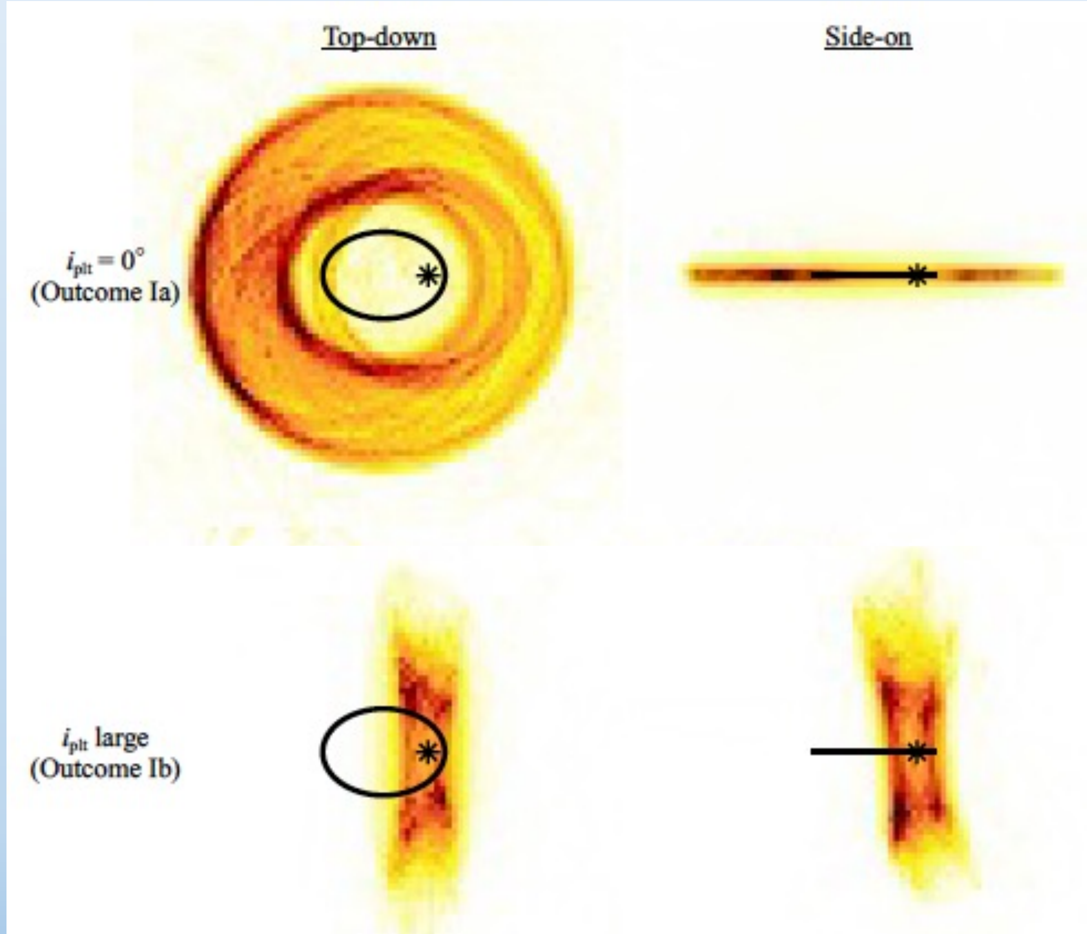


Mouillet et al. 1997; Wyatt et al. 1999; Wyatt 2005; Mustill & Wyatt 2009; Matthews et al. 2014; Nesvold & Kuchner 2015

Secular perturbations: high eccentricity and inclination

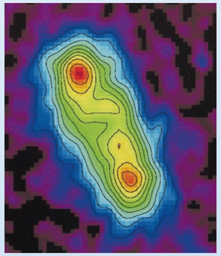
High eccentricity planet in low mass disk (Pearce & Wyatt 2014):

- Coplanar = aligned eccentric hole
- Highly inclined = bell-shape
- Polar disks have been observed in circumbinary disks (Kennedy et al. 2012, 2019)

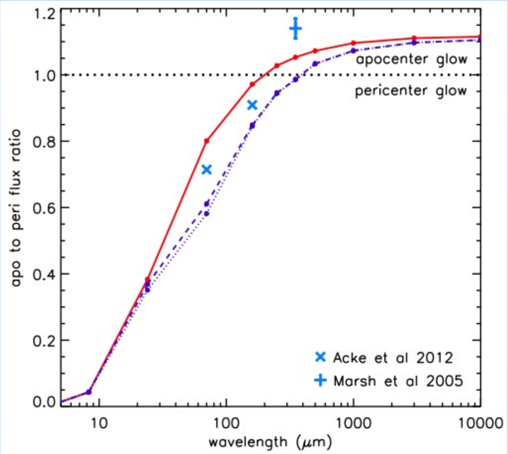


Secular perturbations: eccentricity observables

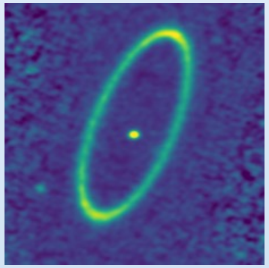
At low resolution thermal emission from an eccentric ring either exhibits

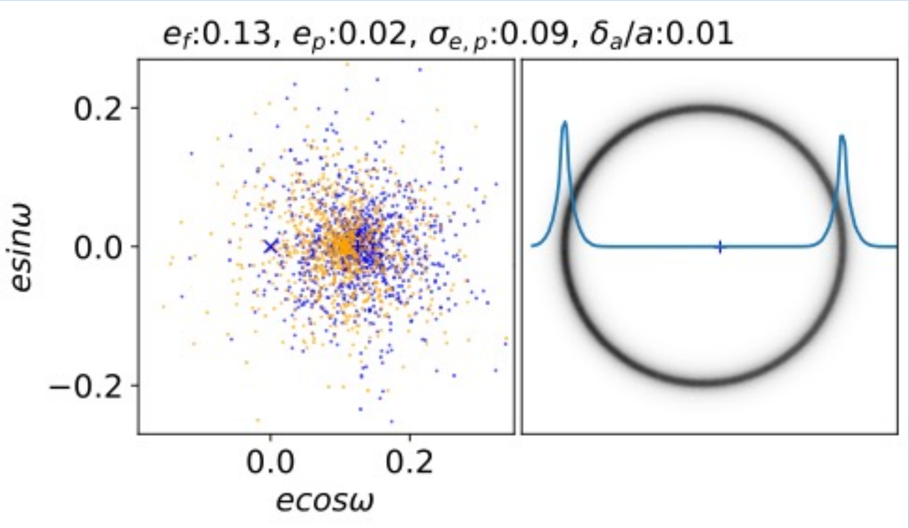


- pericentre glow because pericentre is hotter (Wyatt et al. 1999)
- or apocentre glow because particles move slower there (Pan et al. 2016)



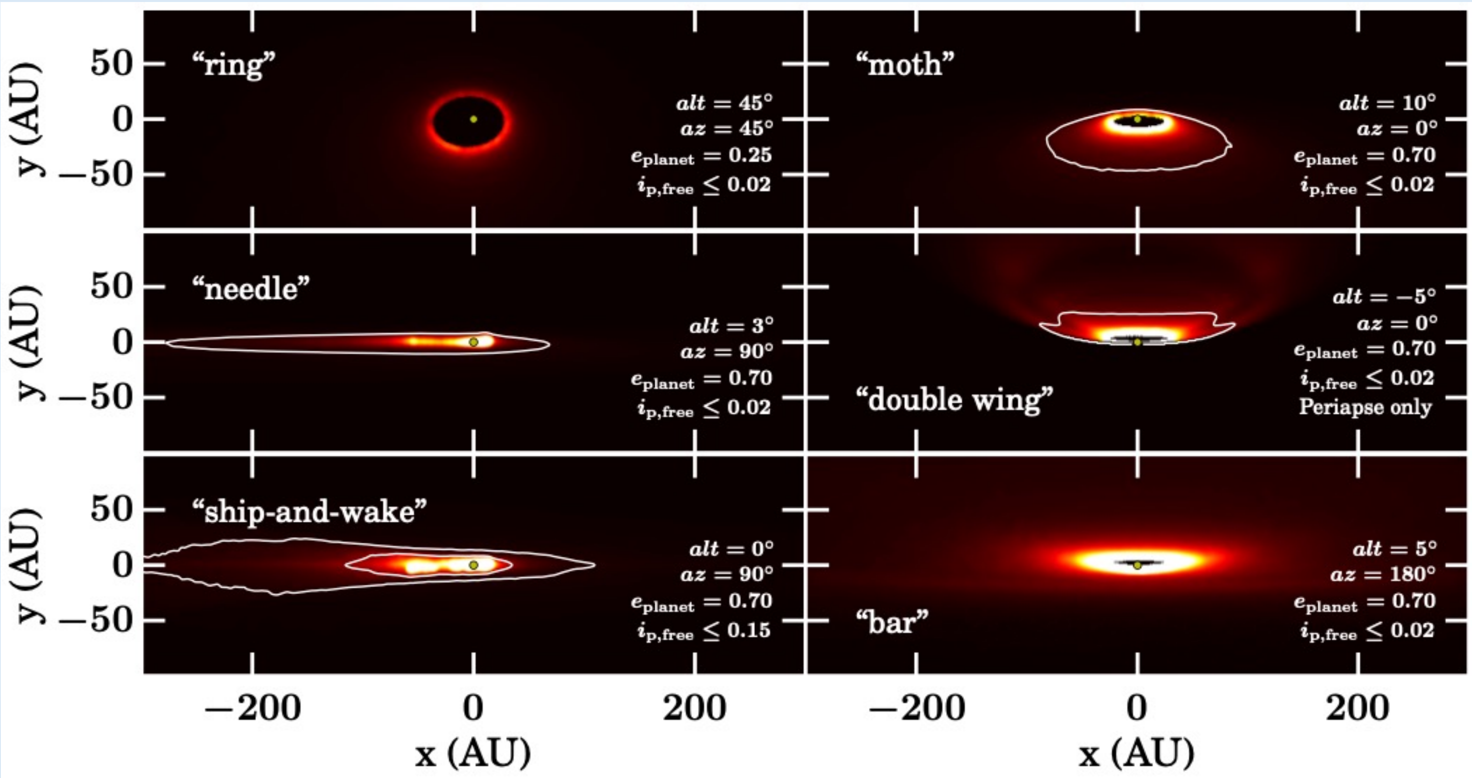
At high resolution we can use ring structure to constrain the distribution of orbital elements (Kennedy 2020)





Secular perturbations: eccentricity observables

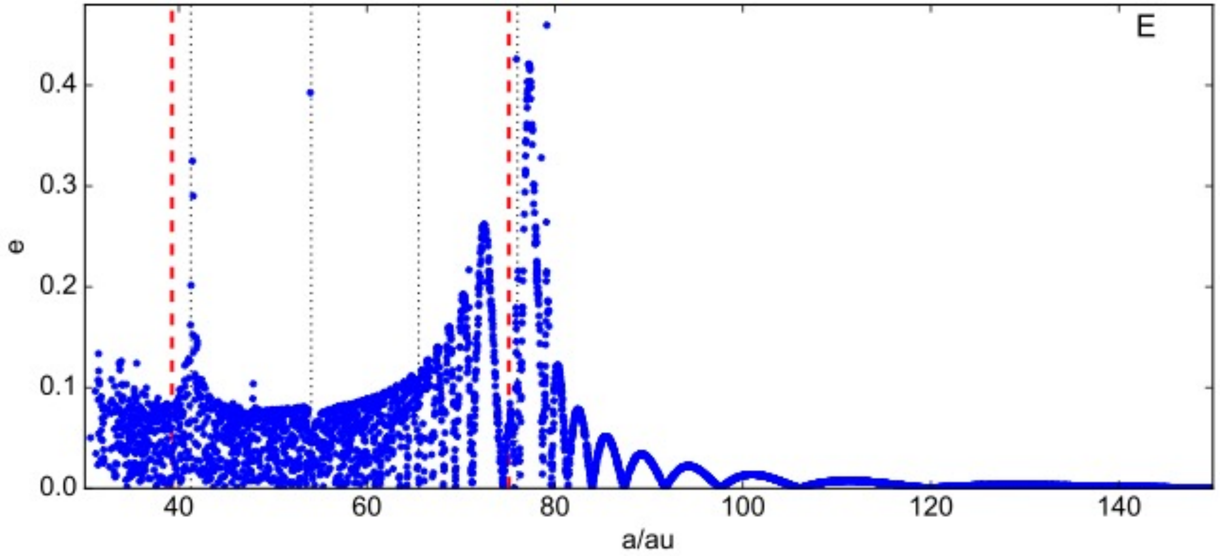
The small dust affected by radiation pressure can result in a range of morphologies when created in an eccentric disk and observed at different inclinations (Lee & Chiang 2016)

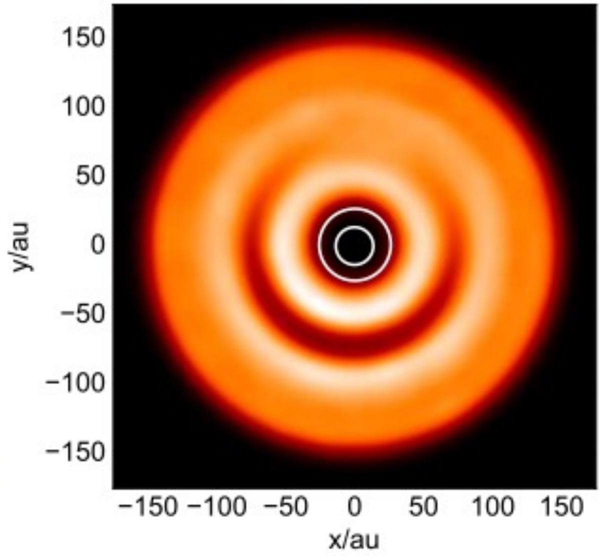


Differential precession for radiation pressure can twist the halo relative to the parent belt (Sende & Lohne 2019)

Secular resonances in multi-planet system

In a 2-planet system the planets' orbits precess due to their mutual interaction, and for particles that precess at the same rate a secular resonance causes large eccentricities and gap clearing that is accentuated by faster collisional depletion

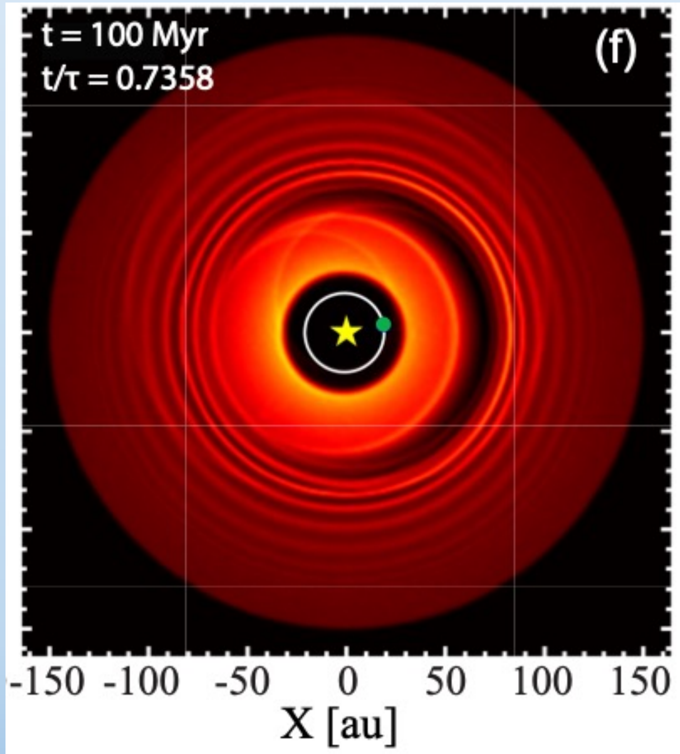


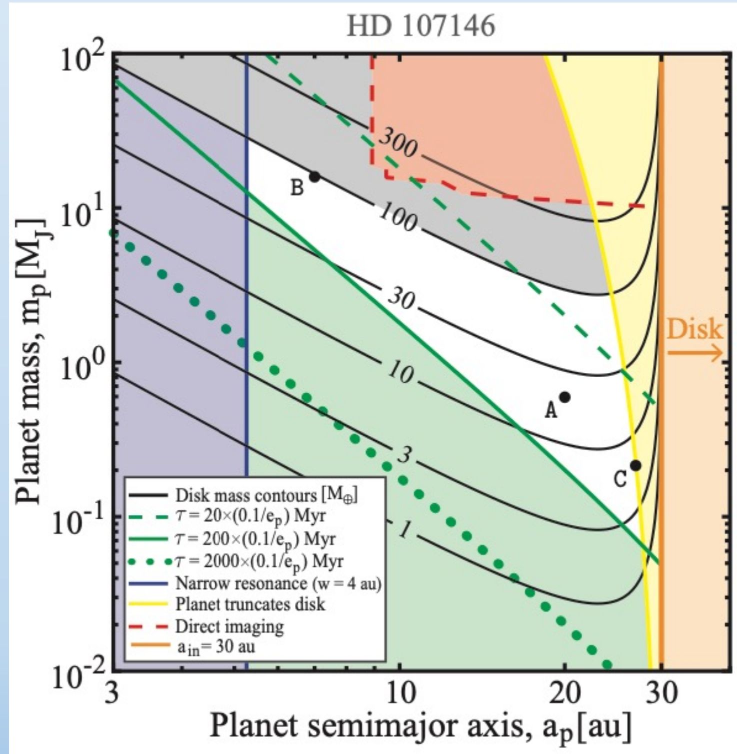


Yelverton & Kennedy (2018)

Secular resonances in single-planet system

In a 1-planet system the planets' orbits can precess due to interaction with a massive disk, resulting in similar gap clearing, and can use an observed gap location to constrain planet (or if planet is known, measure the disk mass) (Sefilian et al. 2021)



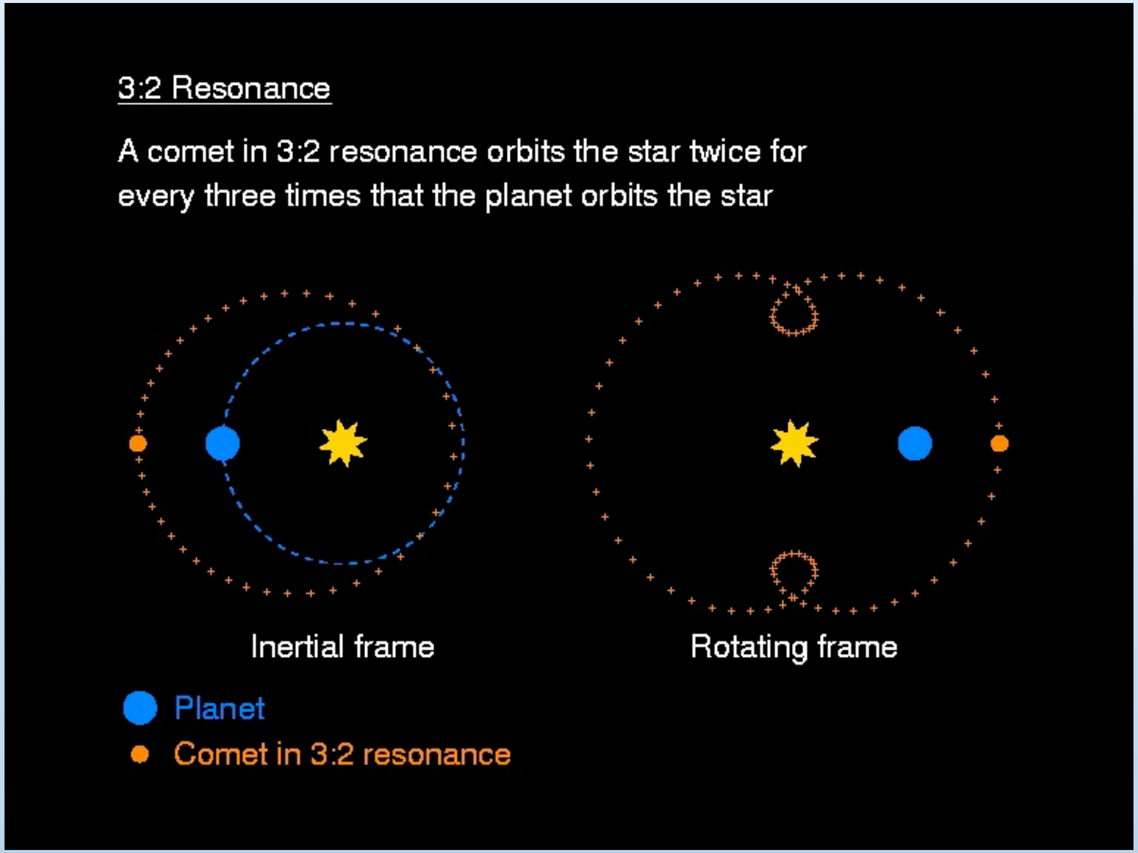


Mean Motion Resonances

Physics: It's all down to geometry – the orbits of particles with integer ratio periods relative to the planet have close encounters at the same point in the orbit

Maths: It's a pendulum

Also to know: Resonances occur at specific semimajor axes, but have finite width, and first order resonances are strongest

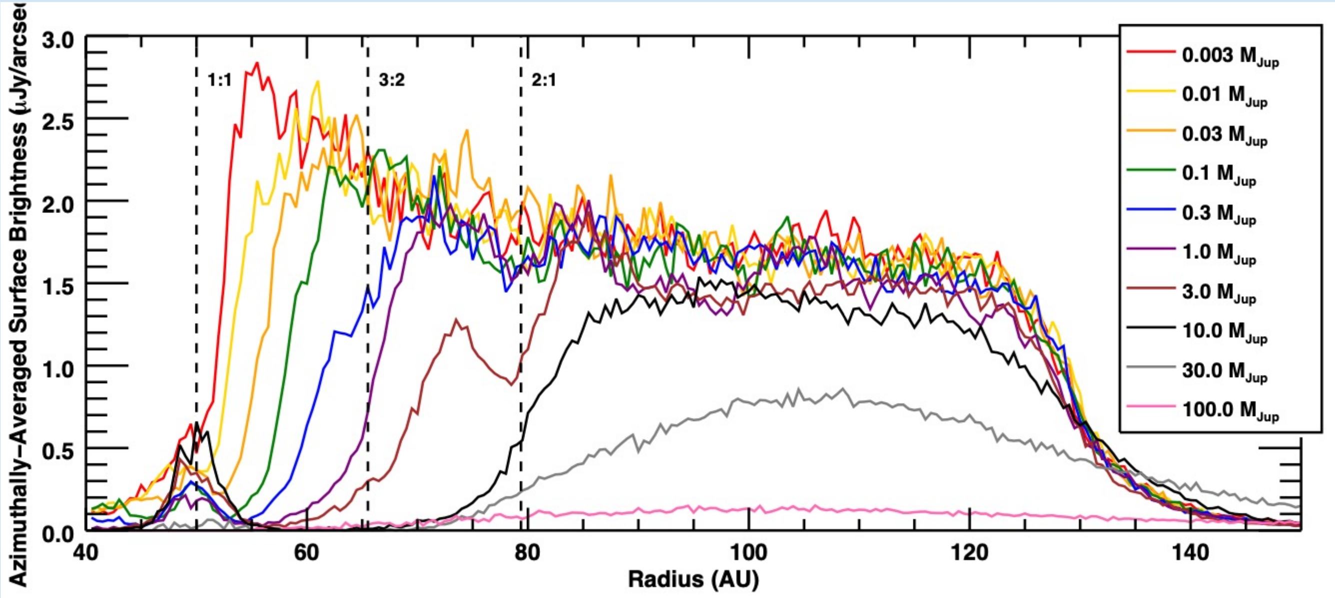


Resonance Overlap

Gaps: Overlap of first order resonances near a planet causes gap along planet's orbit of width (Wisdom 1980): $\Delta r = 1.3 r_{pl} (\frac{M_{pl}}{M_*})^{2/7}$

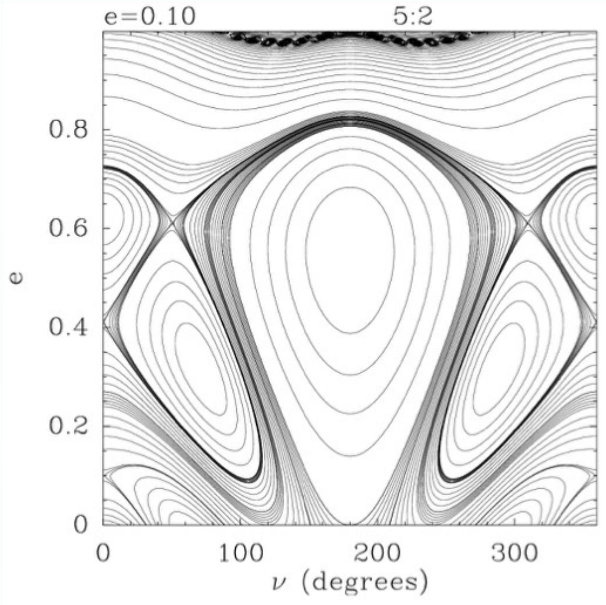
Inner edges: Same process could shape inner edge of a disk, sharpness of which is determined by planet mass (Chiang et al. 2010)

Shape of disk's inner edge is both planet mass and eccentricity dependent (Mustill & Wyatt 2012; Marino 2021) and dependent on age when collisions are included (Nesvold et al. 2015)

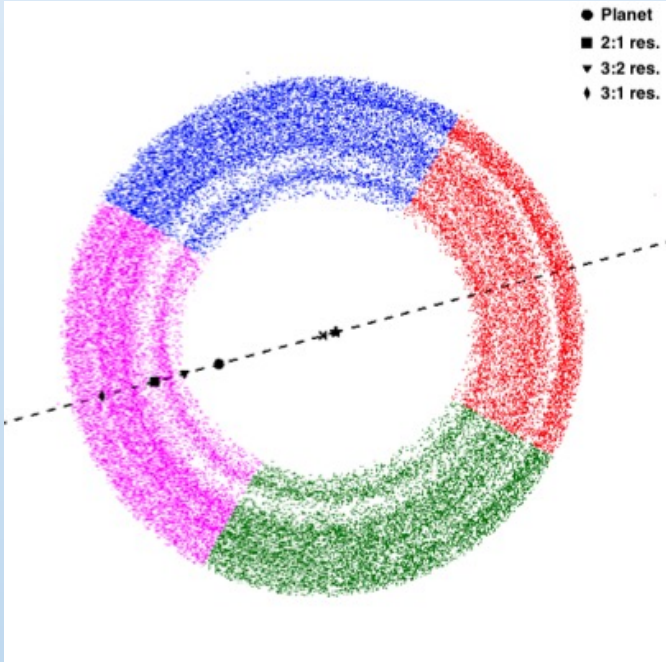


Clearing by mean motion resonances

Jupiter's interior resonances are under-populated in the asteroid belt (the Kirkwood gaps) and are the origin of Near Earth Asteroids



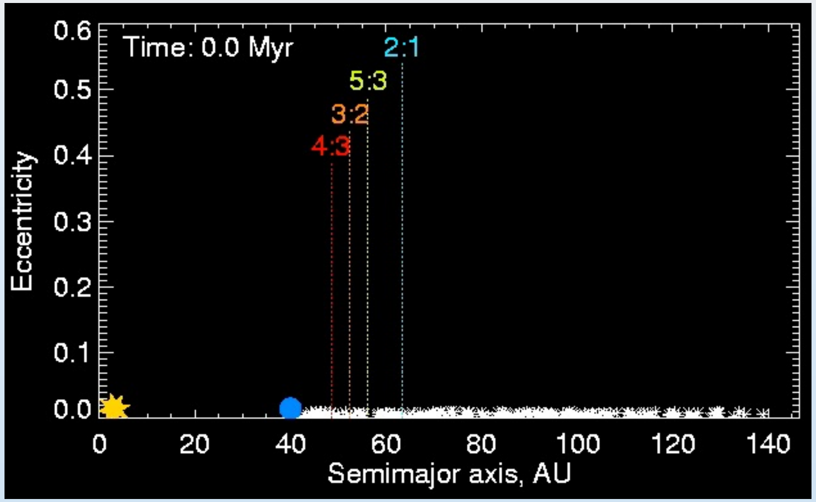
For eccentric planet, resonant particles get high eccentricities; proposed as origin of exocomets (Beust & Morbidelli 2000; Faramaz et al. 2017)

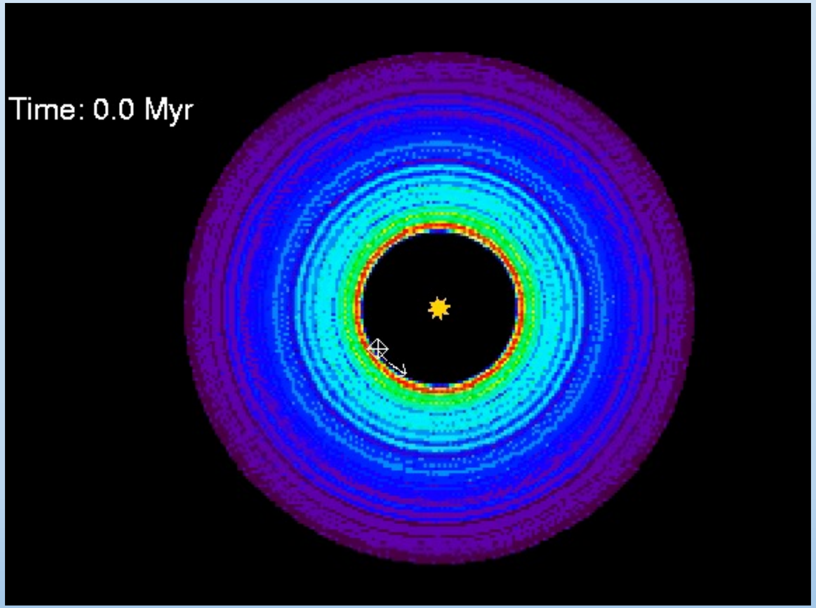


Also clears gap which while narrow may be detectable (Tabeshian & Wiegert 2017)

Resonance trapping

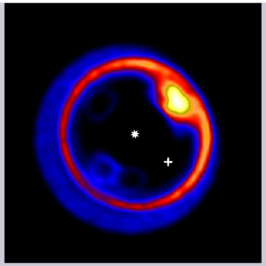
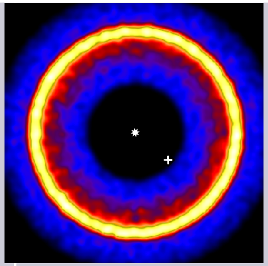
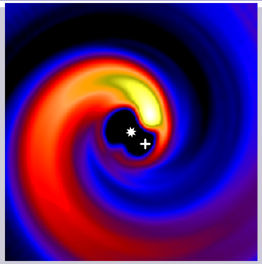
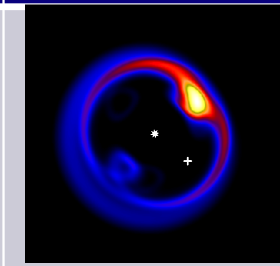
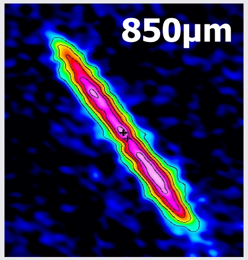
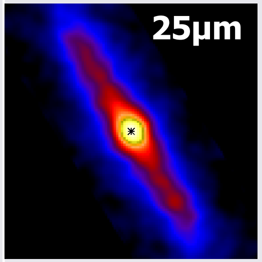
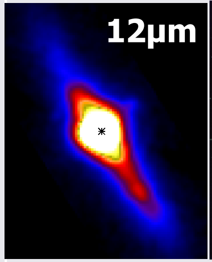
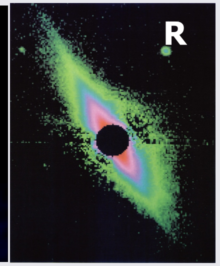
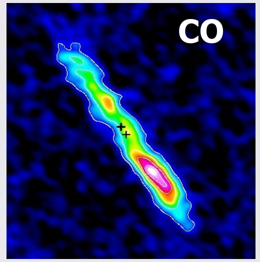
- Planetesimals can be trapped in resonances that sweep through a planetesimal belt as the planet migrates out (Wyatt 2003)
- Geometry of resonances means the planetesimal distribution becomes clumpy
- Planetesimals move in and out of clumps that appear to orbit with planet
- Resonances populated, and hence clumpy structure, depends on planet mass migration rate and eccentricities (Wyatt 2003; Reche et al. 2008)





Resonant trapping: smaller debris

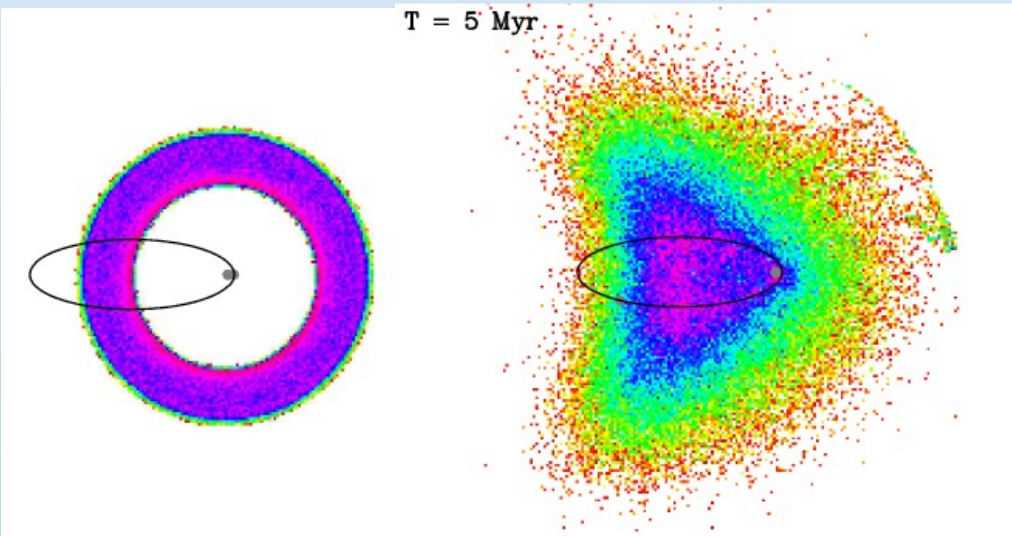
Radiation pressure causes small bound dust to fall out off resonance washing out clumps, but collisions are more frequent in clumps so the smallest unbound dust (and gas) start in clumps before being quickly lost
(Wyatt 2006)

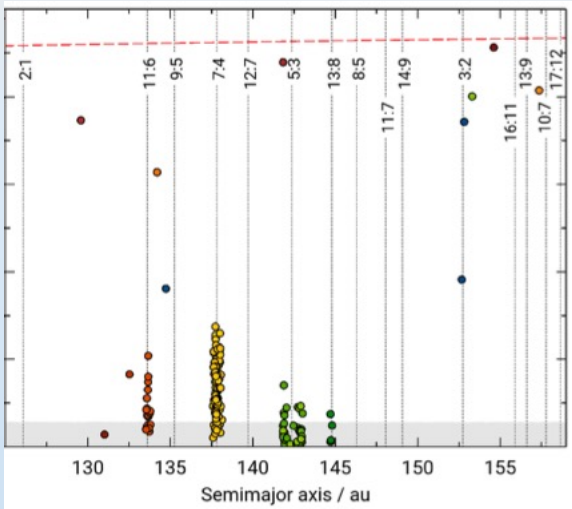
	Sub-mm continuum (planetesimals)	Mid-IR (small but bound dust)	Scattered light and short mid-IR (small unbound dust)		CO (short-lived gas)
Face-on resonance sweeping model					
β Pic observed					

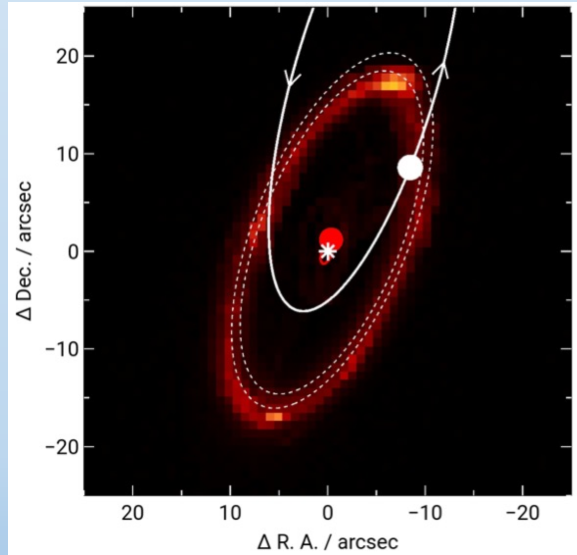
Multi-wavelength observations of β Pic explained by a Saturn-mass planet migrating to ~60au.

Resonance Protection

Planets on orbits that cross a belt quickly destroy the belt structure because of secular perturbations and scattering (Beust et al. 2014; Tamayo et al. 2015)





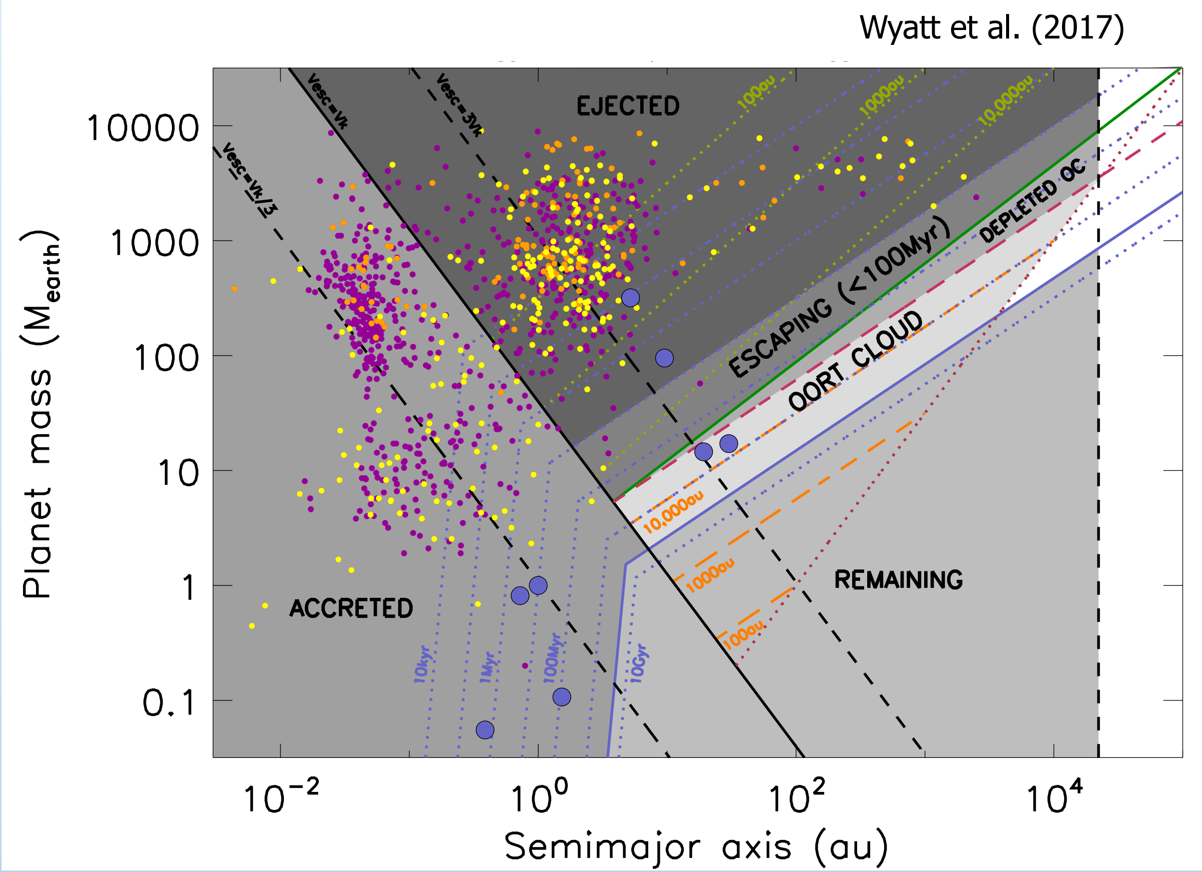


Resonances can be the only dynamically stable orbits in a system, e.g., (Pearce et al. 2021)

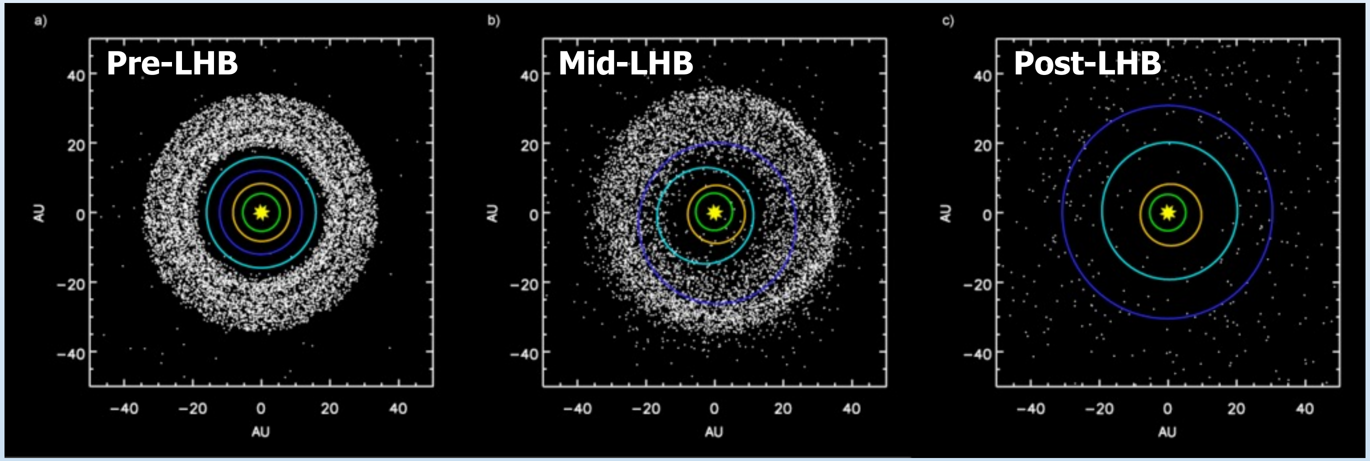
Scattering

Physics: Interactions are probabilistic, treated as a hyperbolic trajectory about planet which causes impulsive change in circumstellar orbit

Outcome: See shading, and note importance of V_{esc}=V_{kep} line, as well as timescale



Clearing by Scattering (e.g., Late Heavy Bombardment)



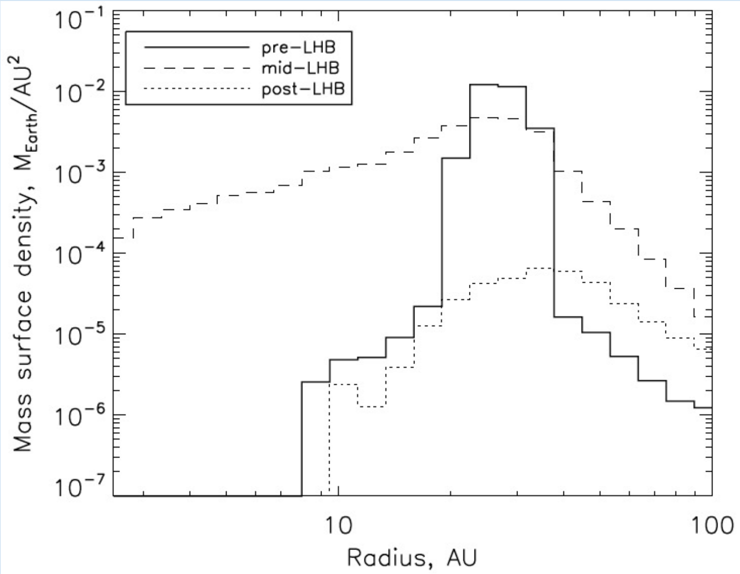
A planet embedded in a disk will eject planetesimals and so deplete the disk (e.g., the Solar system's Kuiper Belt was depleted 99% by Neptune; Gomes et al. 2005)

Dynamical friction will also cause the planet's orbit to circularise and migrate (e.g., Pearce & Wyatt 2015)

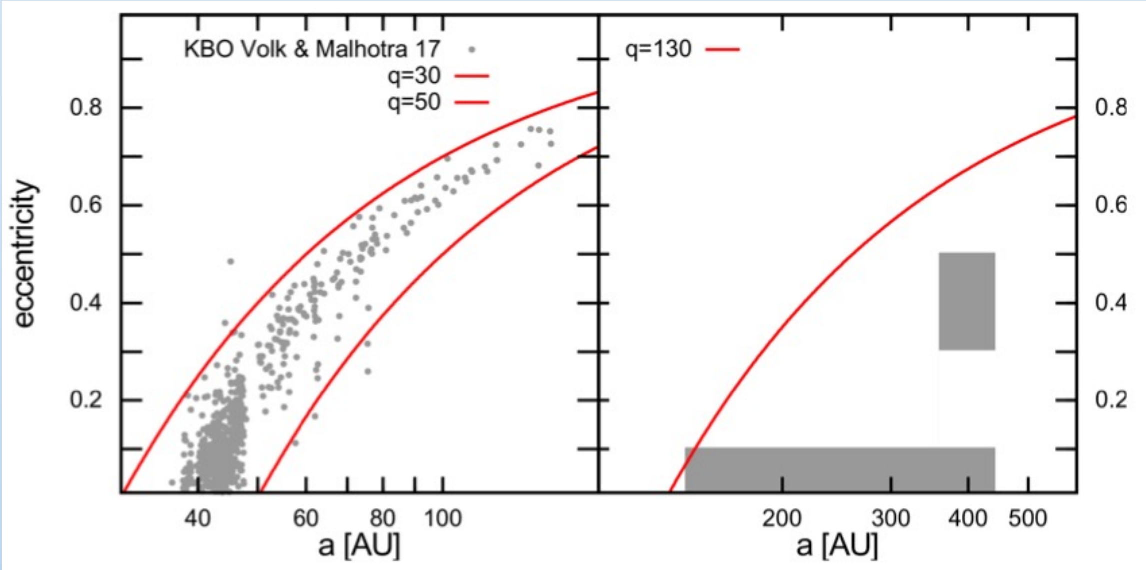
Gaps in disks can be used to constrain planet mass given the time required to carve them (e.g., Faber & Quillen 2007; Shannon et al. 2016)

Broad Disk = Scattered Disk?

The distribution of material in the process of being ejected is radially broad (Booth et al. 2009)

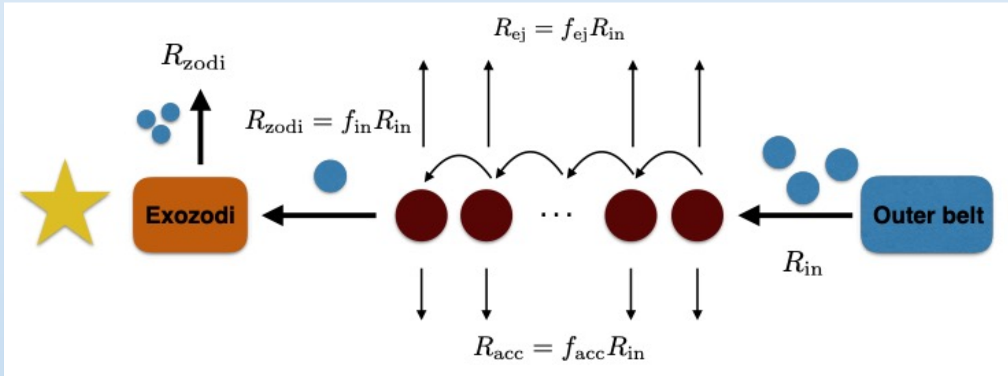


Such a broad disk is still present in the Kuiper belt, called the Scattered Disk, and an analogous feature has been inferred around HR8799 (Geiler et al. 2019)



Scattering as Origin of Exocomets and Exozodi

The zodiacal cloud in the Solar system is predominantly fed by comets scattered in from the Kuiper belt



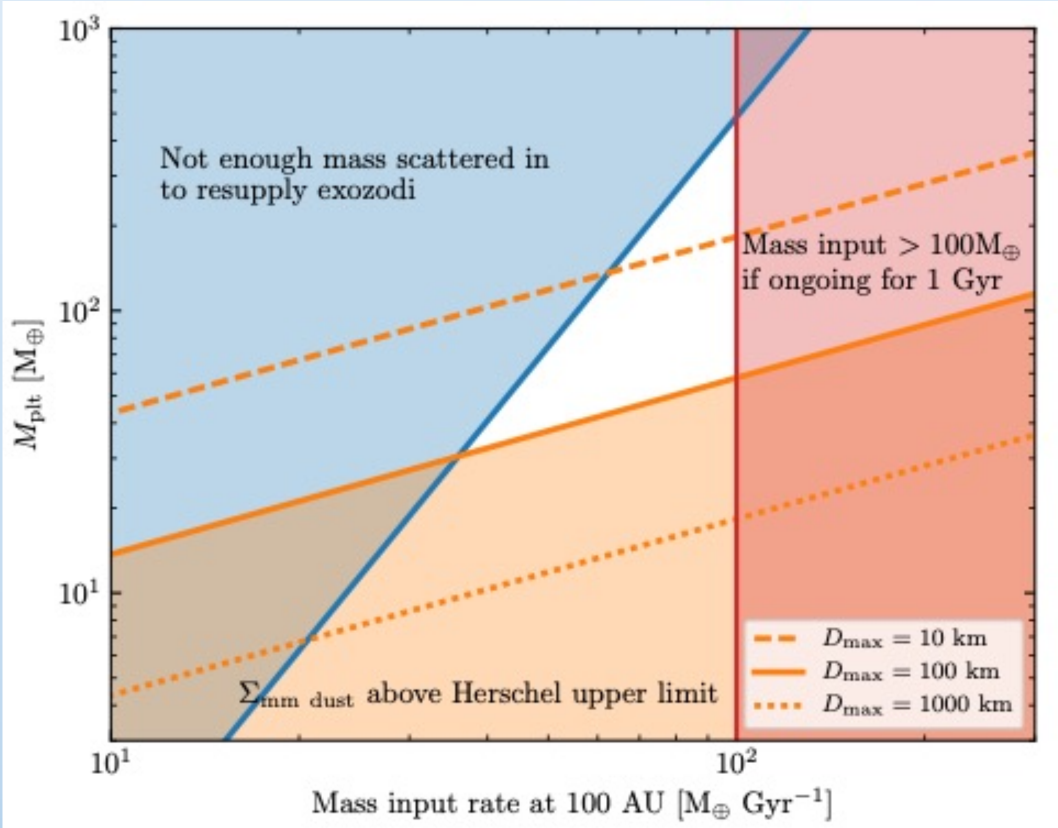
A similar process may be feeding exozodi around other stars (i.e., a planetesimal's fate of ejection or accretion is avoided by depositing its mass in dust by sublimation or disintegration)

Using Exozodi to Constrain Planetary Systems

If exozodi are fed by exocomets, their level and structure is indicative of the scattering planetary system

However, scattering in a multi-planet system is complicated and requires N-body simulations (Marino et al. 2018)

And the process of creating dust and its subsequent evolution not well characterised (but see Marboeuf et al. 2016; Sezestre et al. 2019)

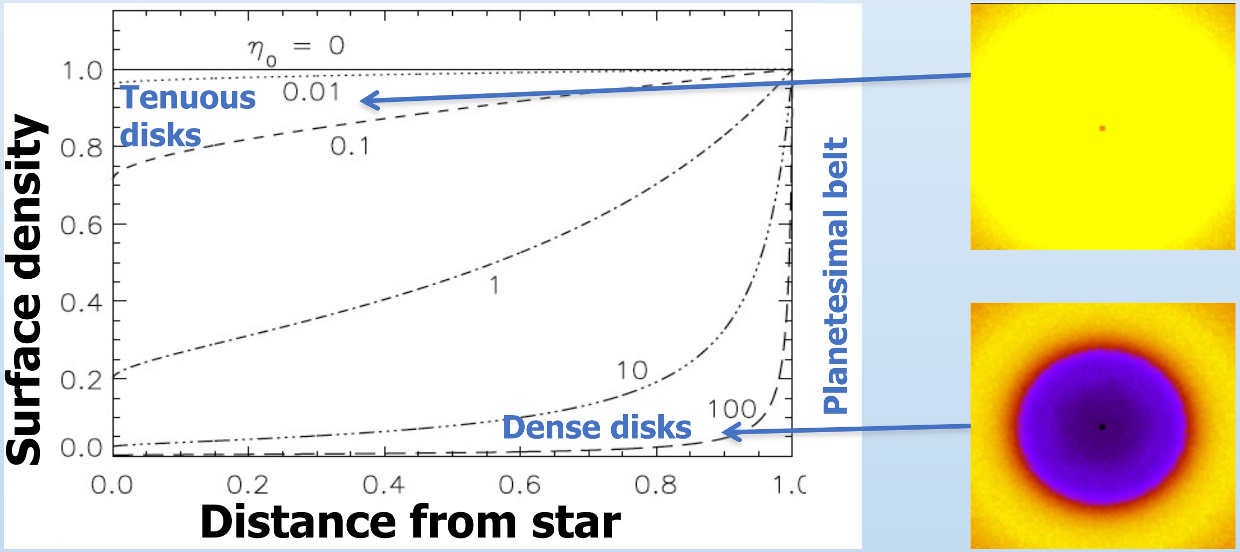


Exozodi as dust dragged in from outer belt?

For low density disks P-R drag makes dust migrate in before it is destroyed in collisions

Simple model: planetesimal belt producing dust of one size results in dust distribution depending on
$\eta_0 = t_{pr}/t_{col} = 10^4 \tau_{eff} (r/M_*)^{0.5}$
(Wyatt 2005)

Detectable disks must be dense, so PR drag is necessarily insignificant (i.e., $\eta_0 > 1$)



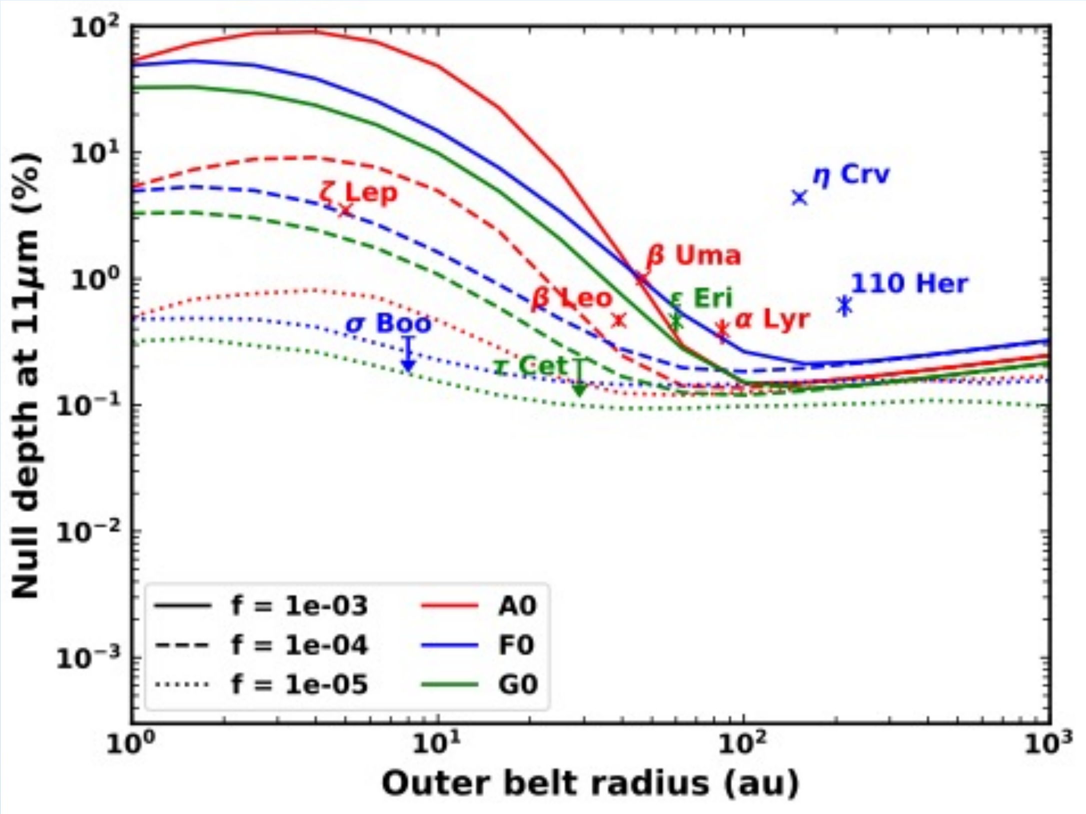
PR drag not so insignificant!

But some dust always makes it in, and close to the star it will emit potentially detectable emission in the mid-IR

More complex models include a size distribution for the dust (Wyatt et al. 2011) and account for dust produced in collisions (Reidemeister et al. 2011; van Lieshout et al. 2014)

Or use those results to inform better analytical models (Kennedy & Piette 2015; Rigley & Wyatt 2020)

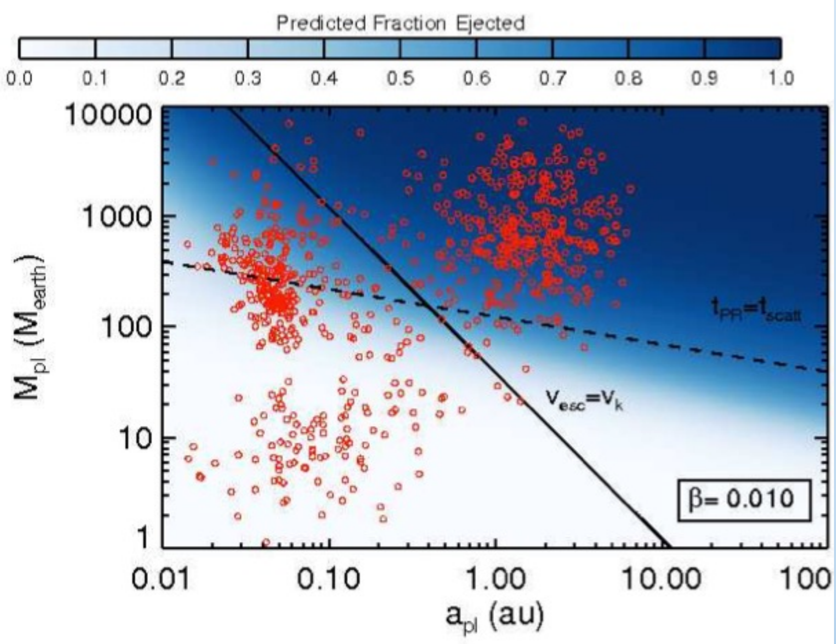
Observed dust levels are comparable to those predicted: this component is both inevitable and detectable!

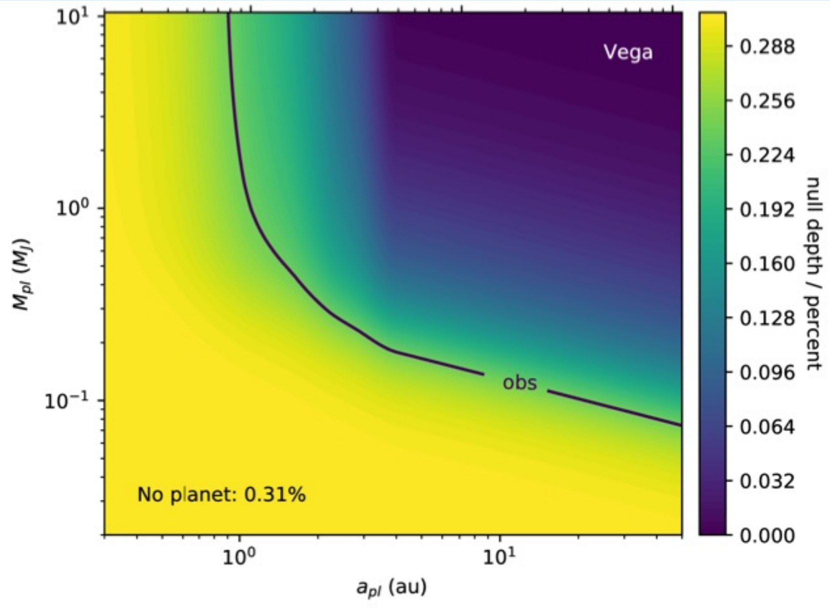


But what about PR drag with planets?

If there is a planetary system inside the belt then the dust will interact with the planets as it migrates in towards the star.

Scattering causes some dust to be ejected which can create a hole (Bonsor et al. 2018)



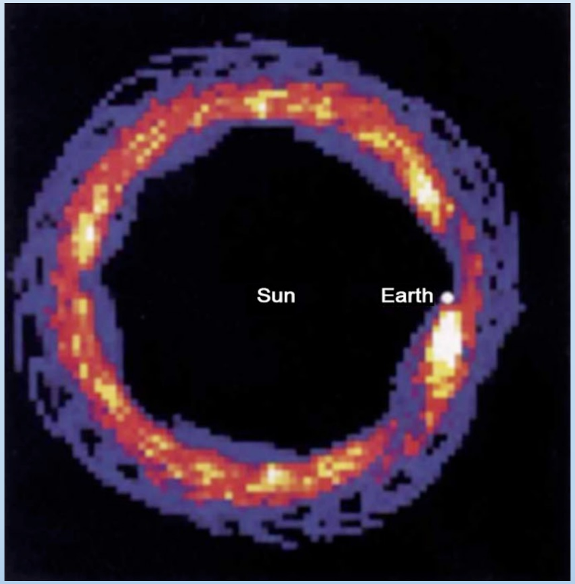


If this explains the lack of mid-IR emission in some systems then constraints can be placed on required planets (Bonsor et al. 2018)

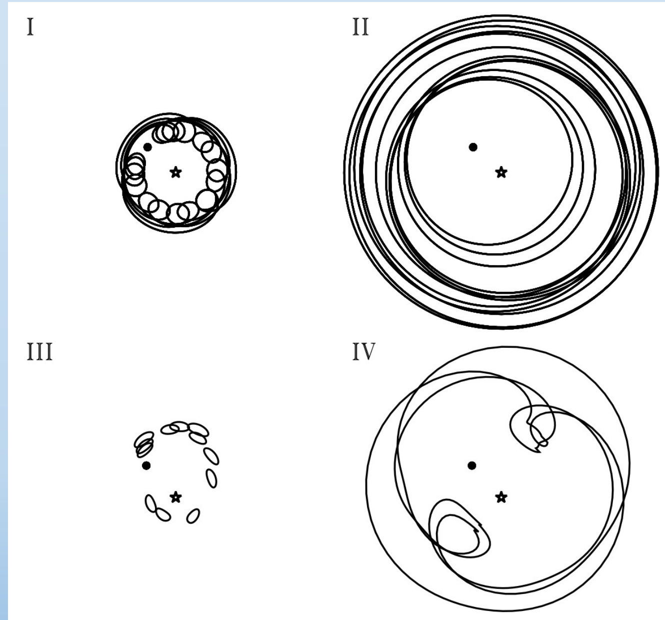
Resonant ring

Dust can also get (temporarily) trapped in resonance with the planets causing a clumpy overdense ring near a planet

The Earth has such a ring with a trailing clump (Dermott et al. 1994) and rings also reported for Venus and Mercury (Jones et al. 2017; Stenborg et al. 2018)

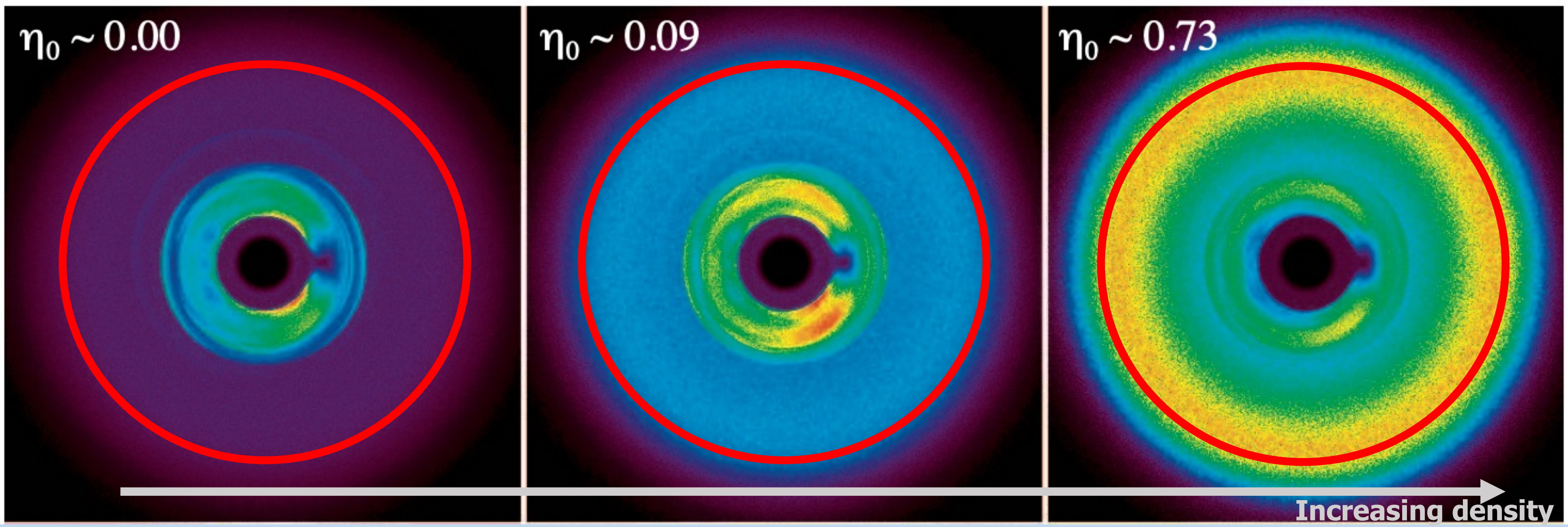


Application to extrasolar debris disks showed how structure depends on planet mass and eccentricity, but ignored collisions (e.g., Ozernoy et al. 2000; Kuchner & Holman 2003; Stark & Kuchner 2008; Shannon et al. 2014)



Resonant ring including collisions

Collisional grooming models follow dust evolution past a planet using N-body codes and then deplete dust in post-processing (Stark et al. 2009)



Models still need improvement, but significant implications for exoplanet imaging:

- Clumps can provide confusion
- Clumps can also be a signature of a planet

Conclusions

- Debris disks are to first order belts of planetesimals at 10s of au getting depleted by mutual collisions

- Planets perturb these belts, and the dust derived from them in multiple ways
  - Secular Perturbations (Warps, Offsets, Spirals, Gaps, Polar Disks)
  - Resonant Perturbations (Gaps, Edges, Rings, Clumps)
  - Scattering (Clearing, Stirring, Exocomets)

- There's still a long way to go in improving the realism of the models when multiple processes are acting

- Observing these features (or not) can be used to constrain the planetary system and is important for long-term goals like exo-Earth detection

HARDY