Debris Disks as Planetary Signposts (Theory)

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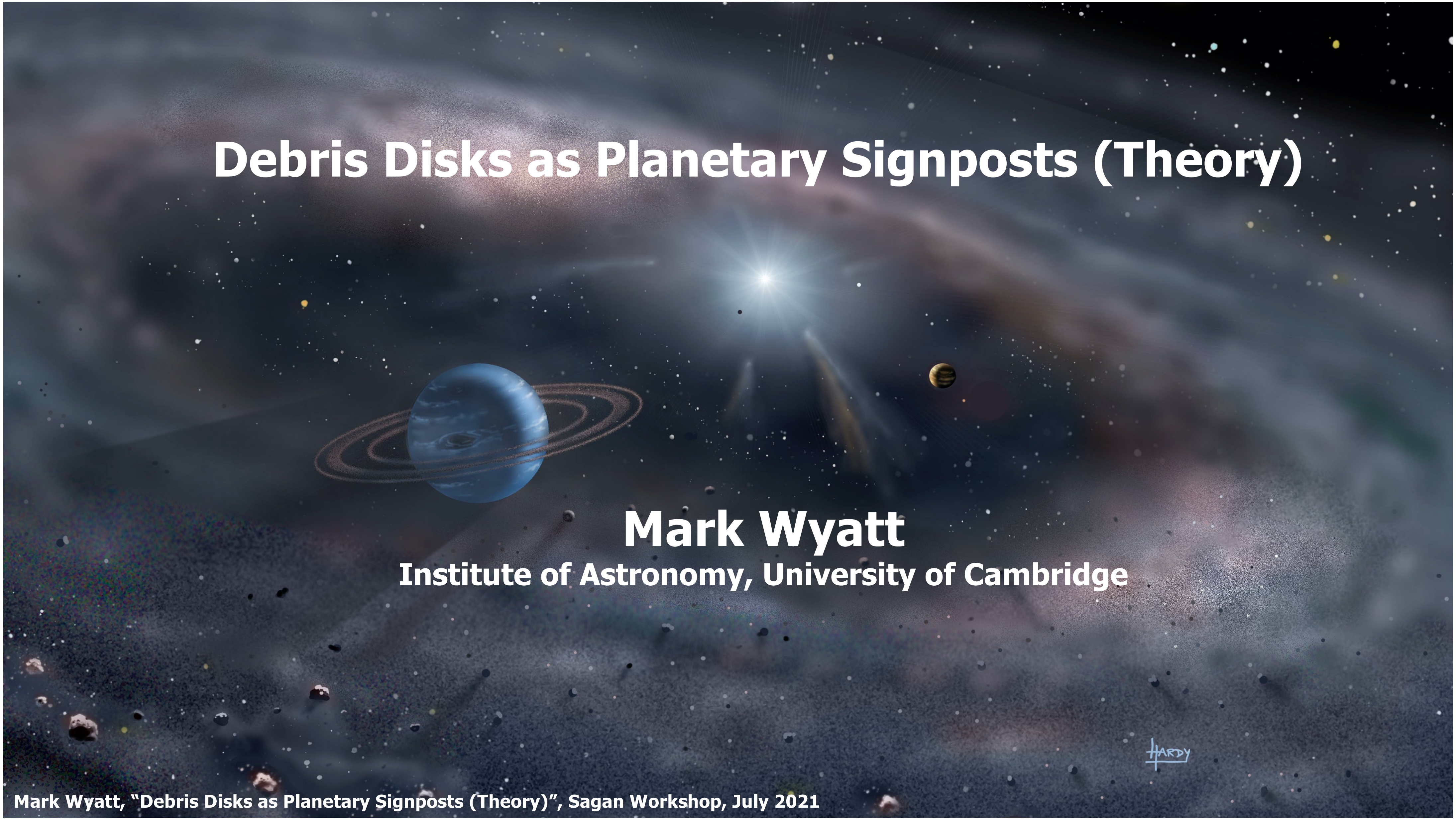
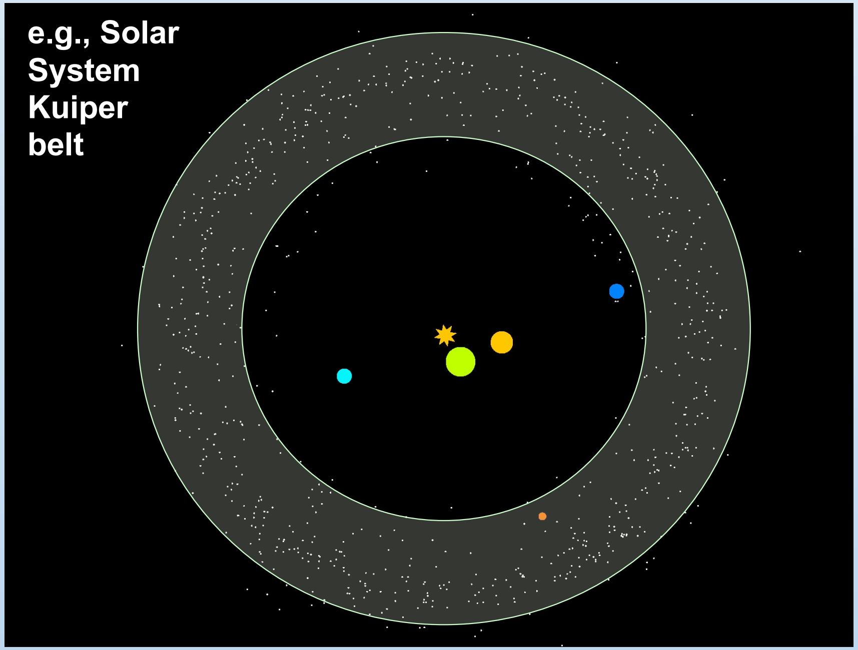
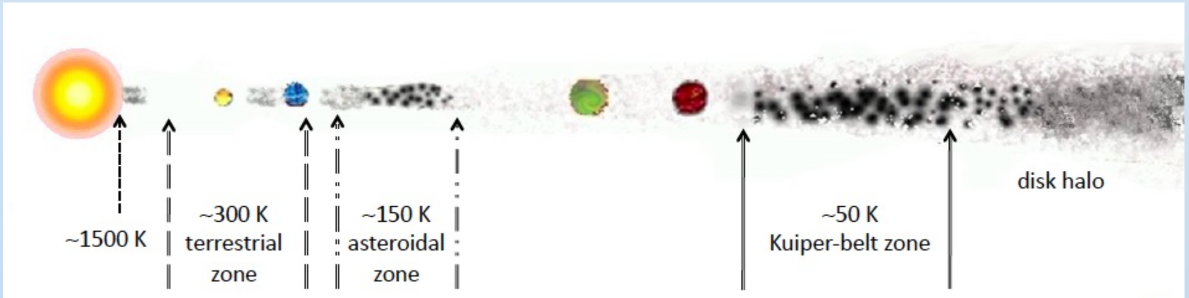


What is a debris disk?

Non-planetary component of a planetary system



Picture inferred from debris disks: planets interspersed with planetesimal belts, and dust(+gas) created in those belts

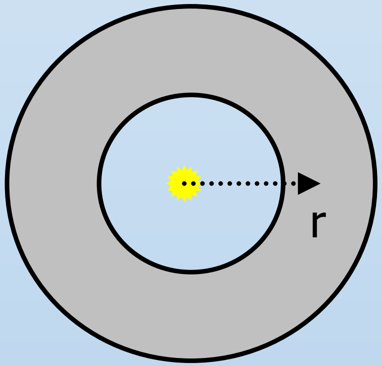


Su et al. (2013)

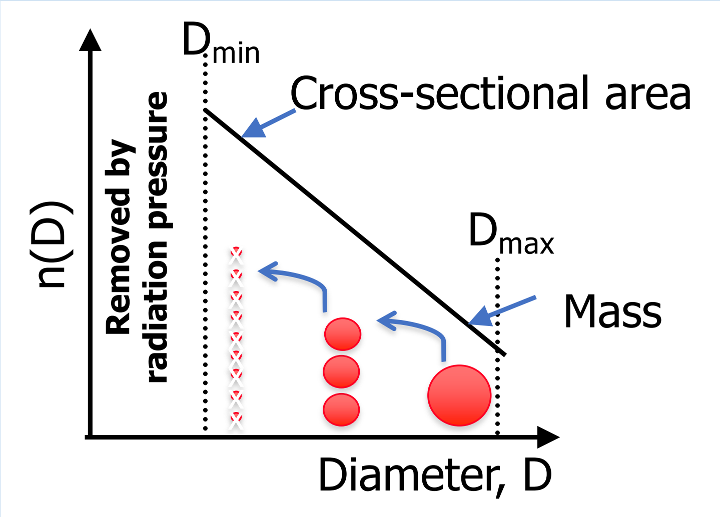
Can say something about unseen planets because these will inevitably impose structure on a disk

Debris disk primer

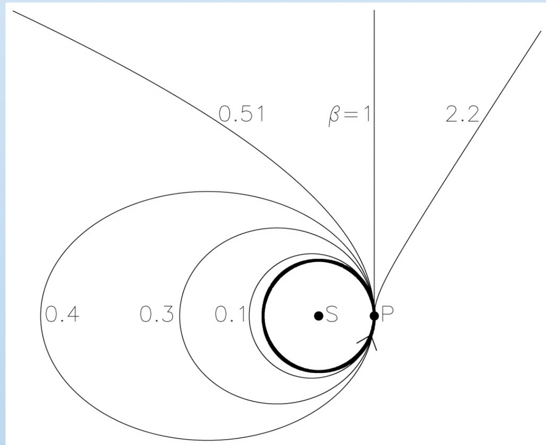
Simple model: planetesimals orbiting the star in a belt



Collisions grind planetesimals into smaller and smaller fragments resulting in collisional cascade with a size distribution $n(D) \propto D^{-3.5}$



Radiation pressure puts small dust on eccentric orbits, creating a halo outside the belt



+ P-R / stellar wind / gas drag + sublimation + viscous evolution + gravity (self and planets)

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)

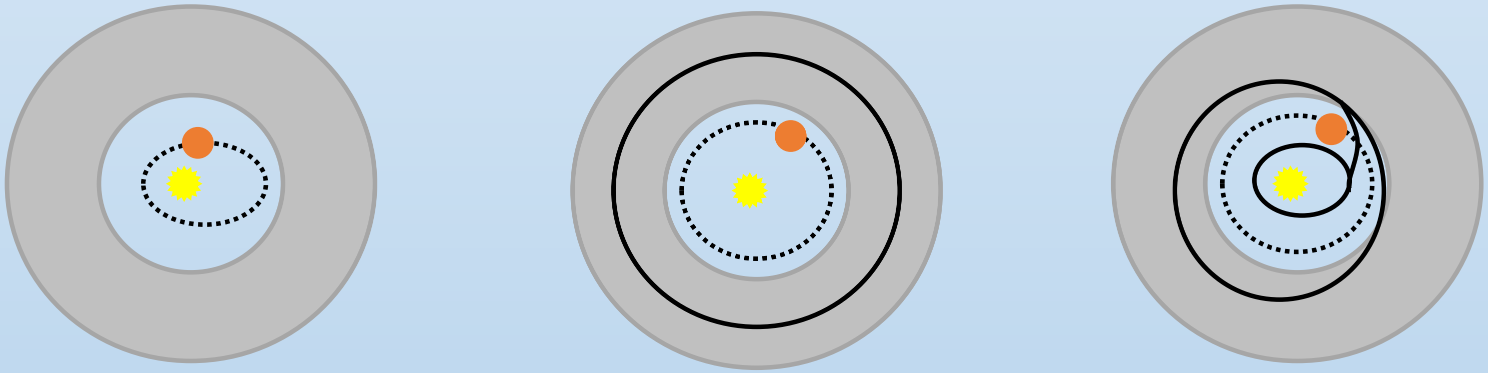
Or take a more analytical or empirical approach (e.g., Wyatt et al. 1999)

Radiative transfer usually considered separately, using e.g., Mie Theory for optical properties of dust – e.g., Hands-on Session on Disk Models

Planets perturb orbits

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

1. **Secular perturbations**
2. **Resonances**
3. **Scattering**



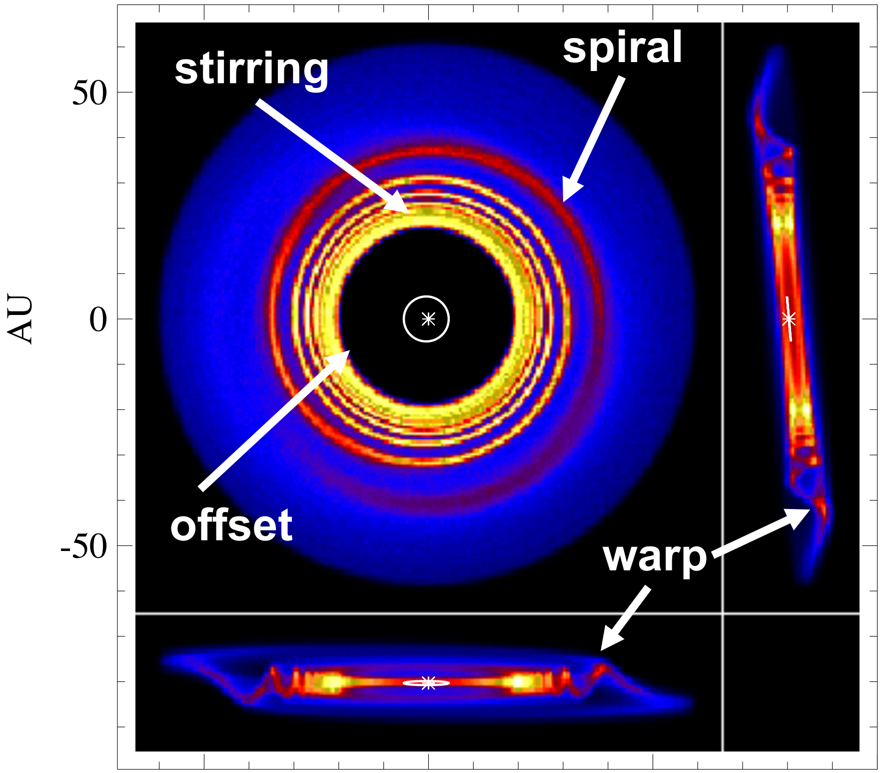
Secular perturbations: planetesimal structures

Single planet, low eccentricity and inclination

Planet:
$1M_{jup}$
5au
e=0.1
I=5°

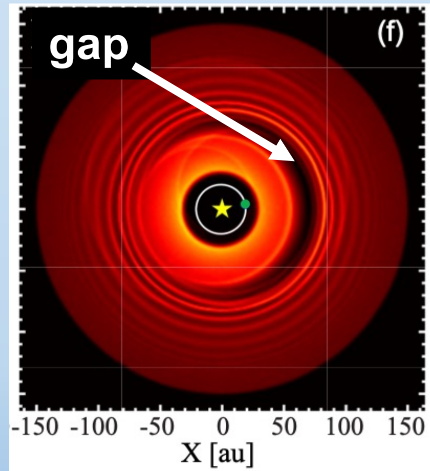
Disk:
20-60au

Time:
100Myr
after
formation



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

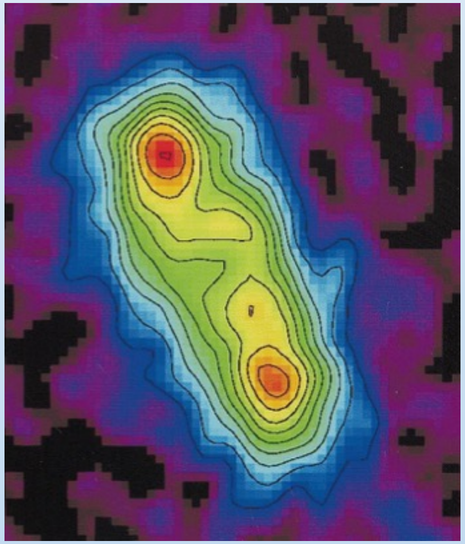
High
eccentricity
and
inclination
planet

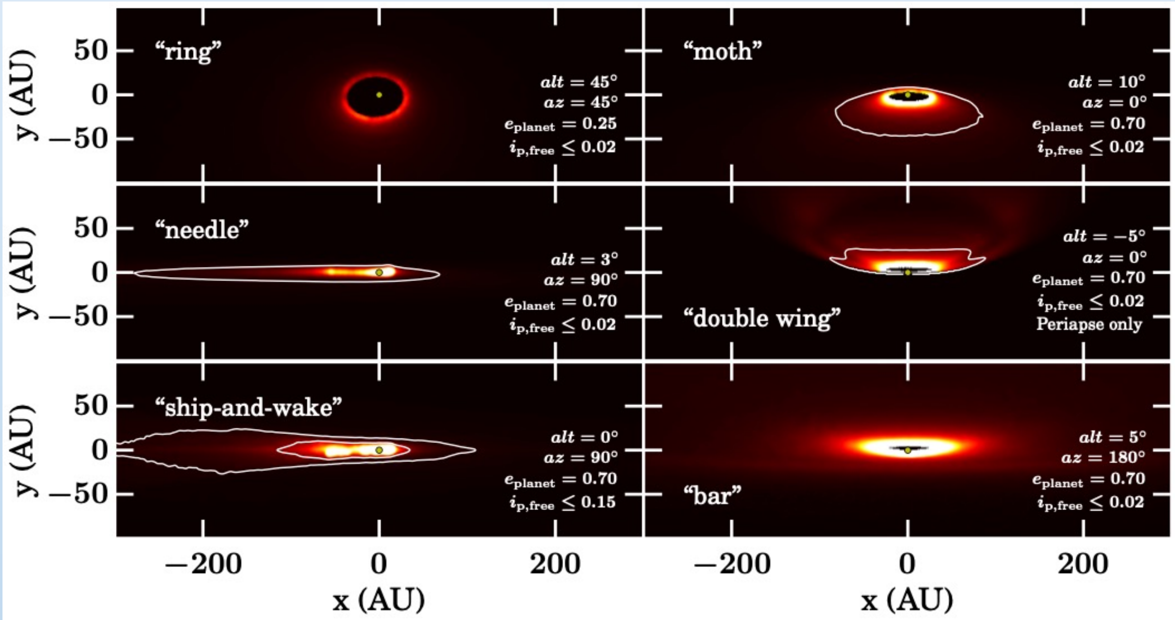


Multi-planet
system or
massive
disk

Secular perturbations: dust observables

e.g., observational manifestations of eccentric ring:



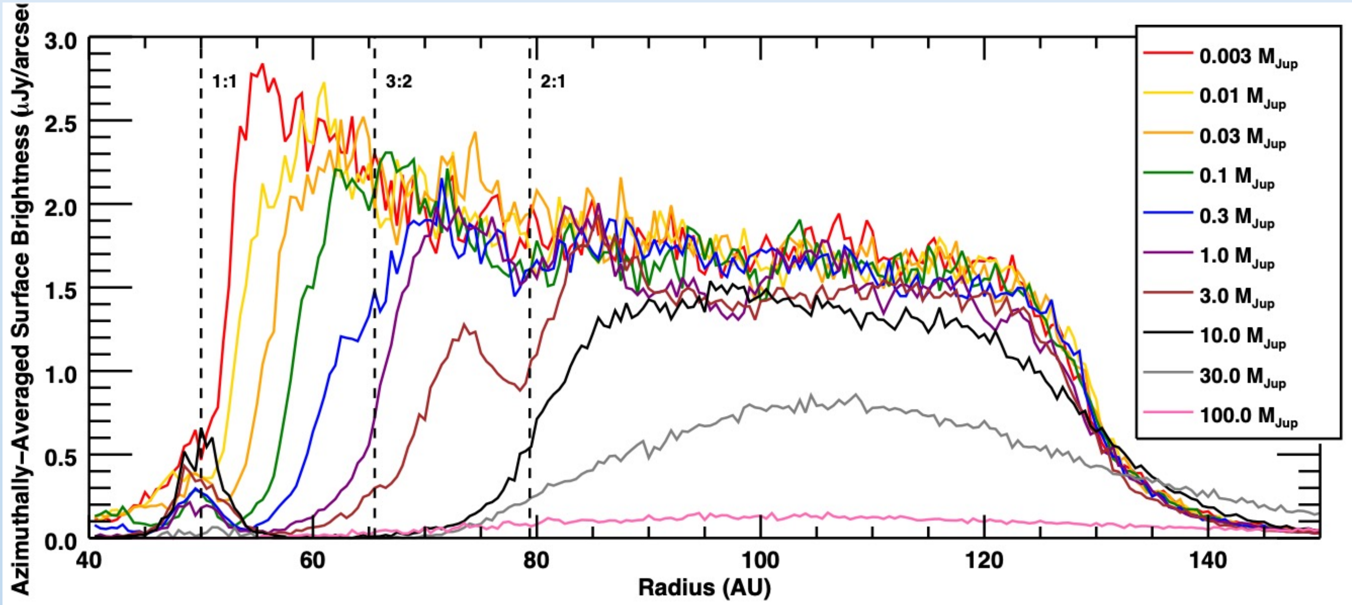


At low resolution thermal emission exhibits either pericentre or apocentre glow (Wyatt et al. 1999; Pan et al. 2016)

Scattered light sees halo with range of morphologies depending on viewing orientation (Lee & Chiang 2016) possibly misaligned with parent belt (Sende & Lohne 2019)

Mean Motion Resonances Can Be Bad = Clearing

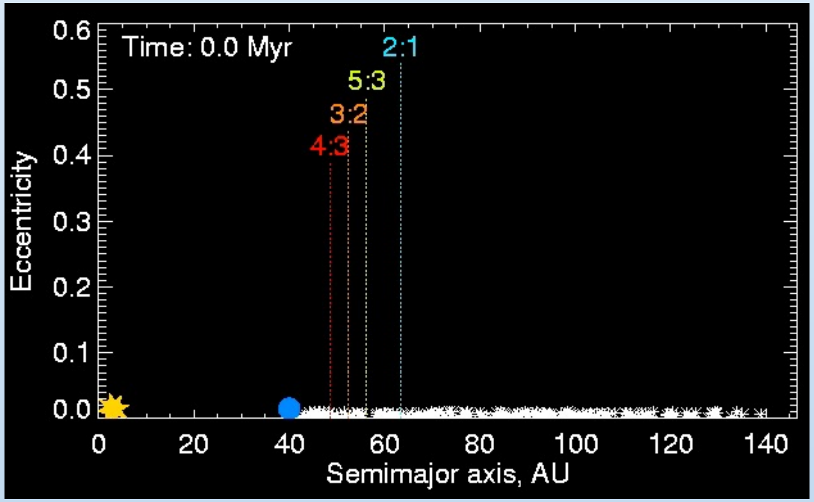
Gaps: Overlapping 1st order resonances near planet cause gap, width/shape of which set by planet mass (+eccentricity+age)
(Chiang et al. 2010; Mustill & Wyatt 2012; Nesvold et al. 2015; Marino 2021)

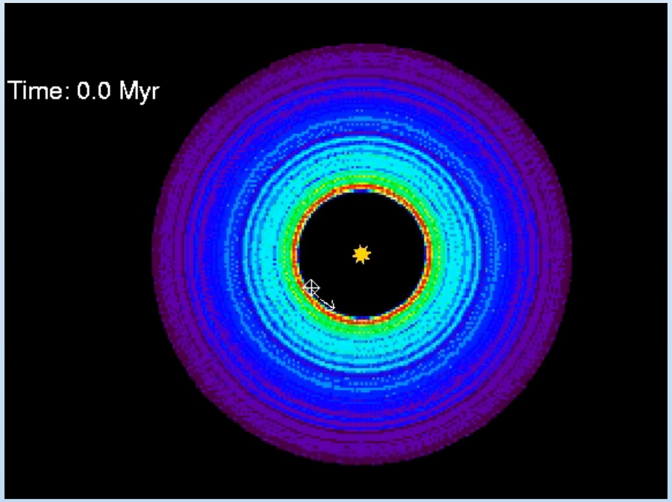


An eccentric planet's MMRs become depopulated causing narrow gaps and throwing exocomets towards the star (Beust & Morbidelli 2000; Tabeshian & Weigert 2017; Faramaz et al. 2017)

Mean Motion Resonances Can Be Good = Clumps

Outward migrating planet traps planetesimals in MMRs causing clumps (Wyatt 2003; Reche et al. 2008).
Small dust axisymmetric due to radiation pressure (Wyatt 2006)



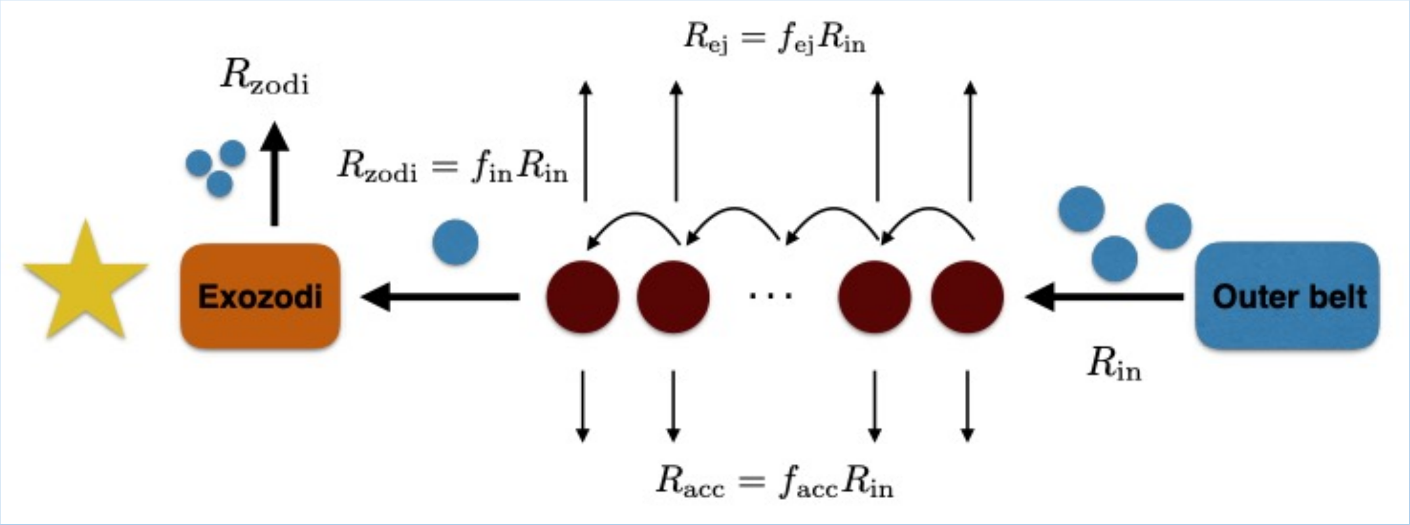


Resonances protect against close encounters with planet so can be only long-term survivors (Pearce et al. 2021)

Scattering = Clearing and Exocomets

A planet in a disk will eject planetesimals so disk gaps used to constrain planet mass given the time required to carve them (e.g., Faber & Quillen 2007; Shannon et al. 2016)

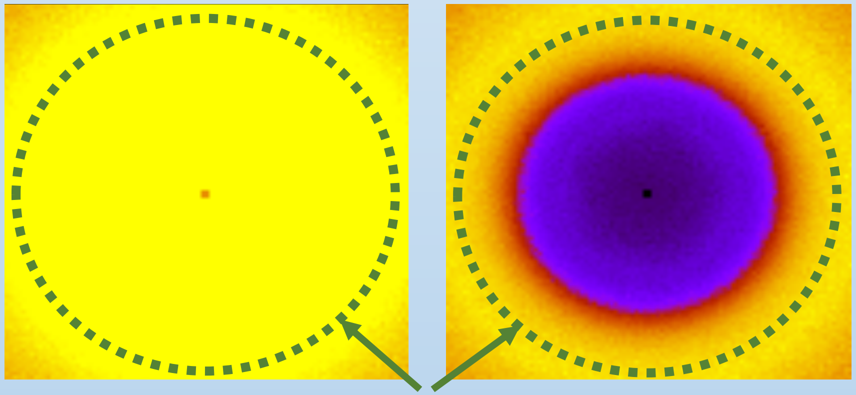
While being ejected planetesimals may reach inner system = exocomets (e.g., Marino et al. 2018) potentially depositing dust and gas to explain exozodi



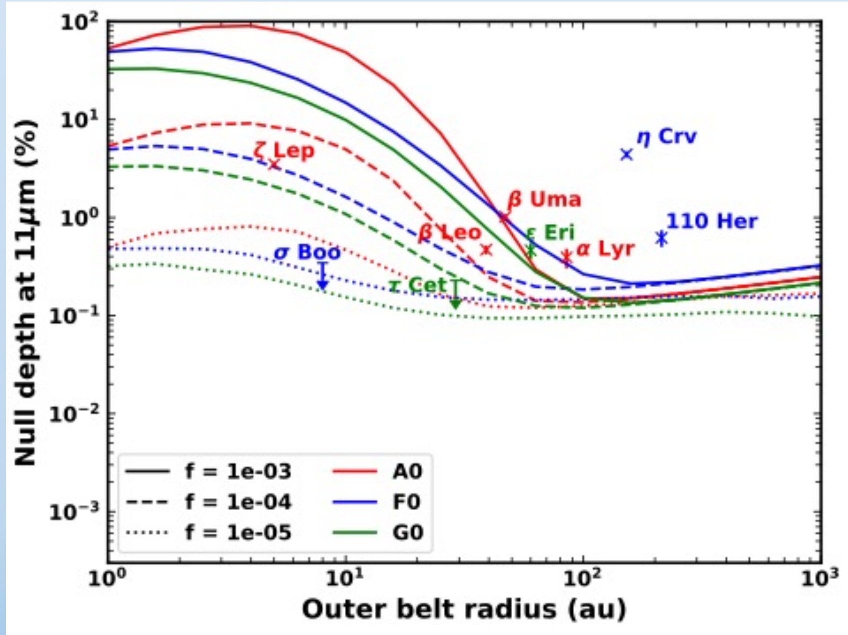
Exozodi as dust dragged in from outer belt?

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

Detectable disks must be dense, so collisions deplete the dust before it reaches inner region (Wyatt 2005)



But some dust inevitably reaches the star, and this is now detectable with nulling mid-IR interferometry (Kennedy & Piette 2015; Rigley & Wyatt 2020)

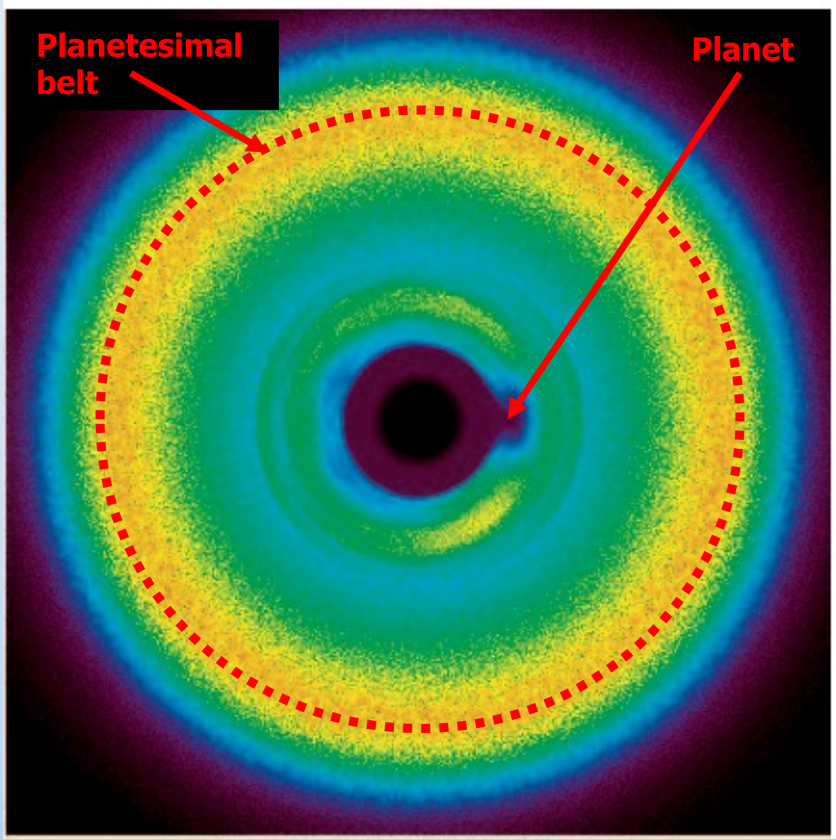


Mid-Planetary System Dust

Dust migrating past a planet can be trapped resonances (Shannon et al. 2014) or ejected (Bonsor et al. 2018)

Models need improvement, but implications for exoplanet imaging (Stark et al. 2009):

- Clumps (and gaps) are planet signatures
- But also provide confusion



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