From primordial to debris: the evolution of HAeBe disks

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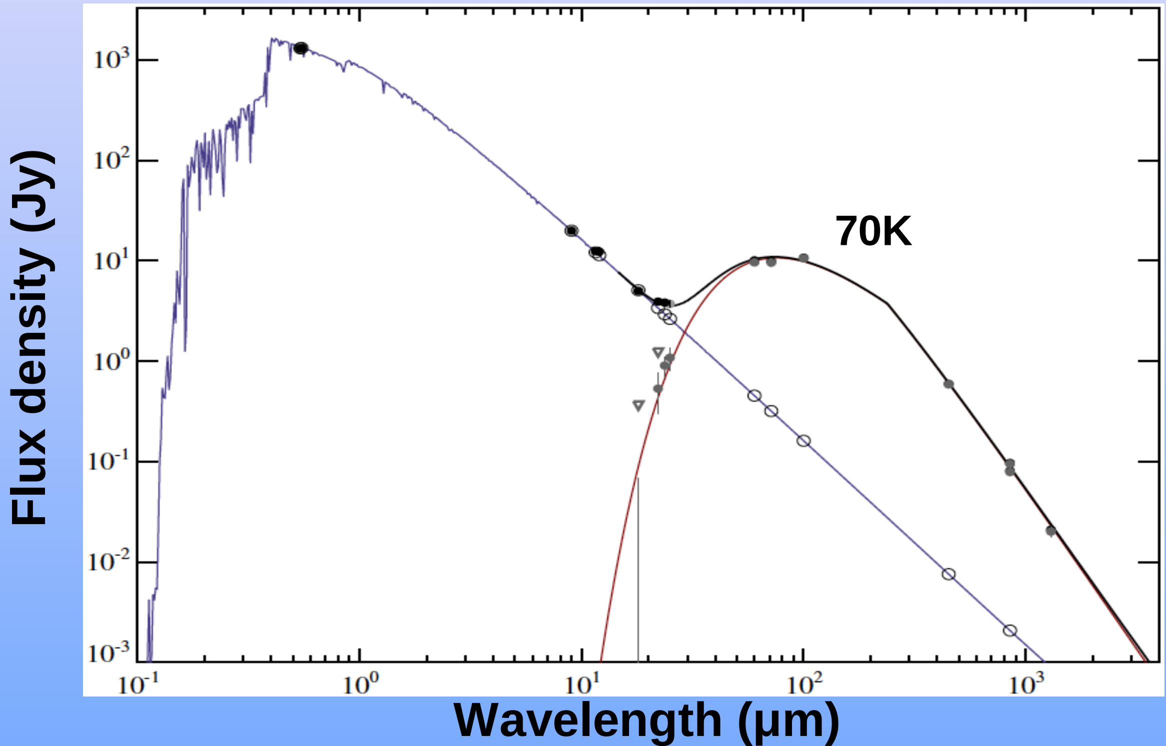
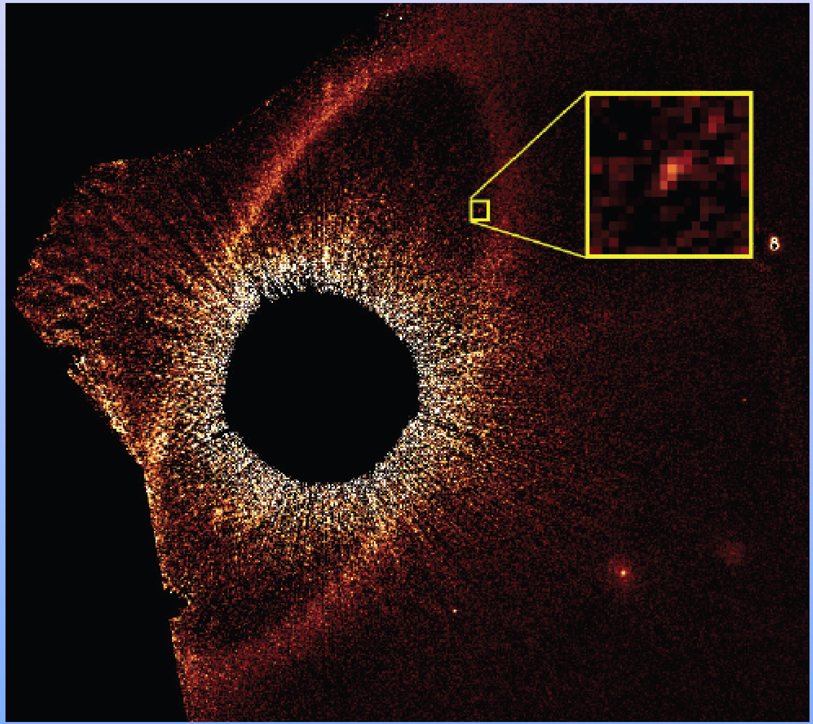
What is a debris disk?

Infrared emission of nearby main sequence stars above photosphere: e.g., Fomalhaut



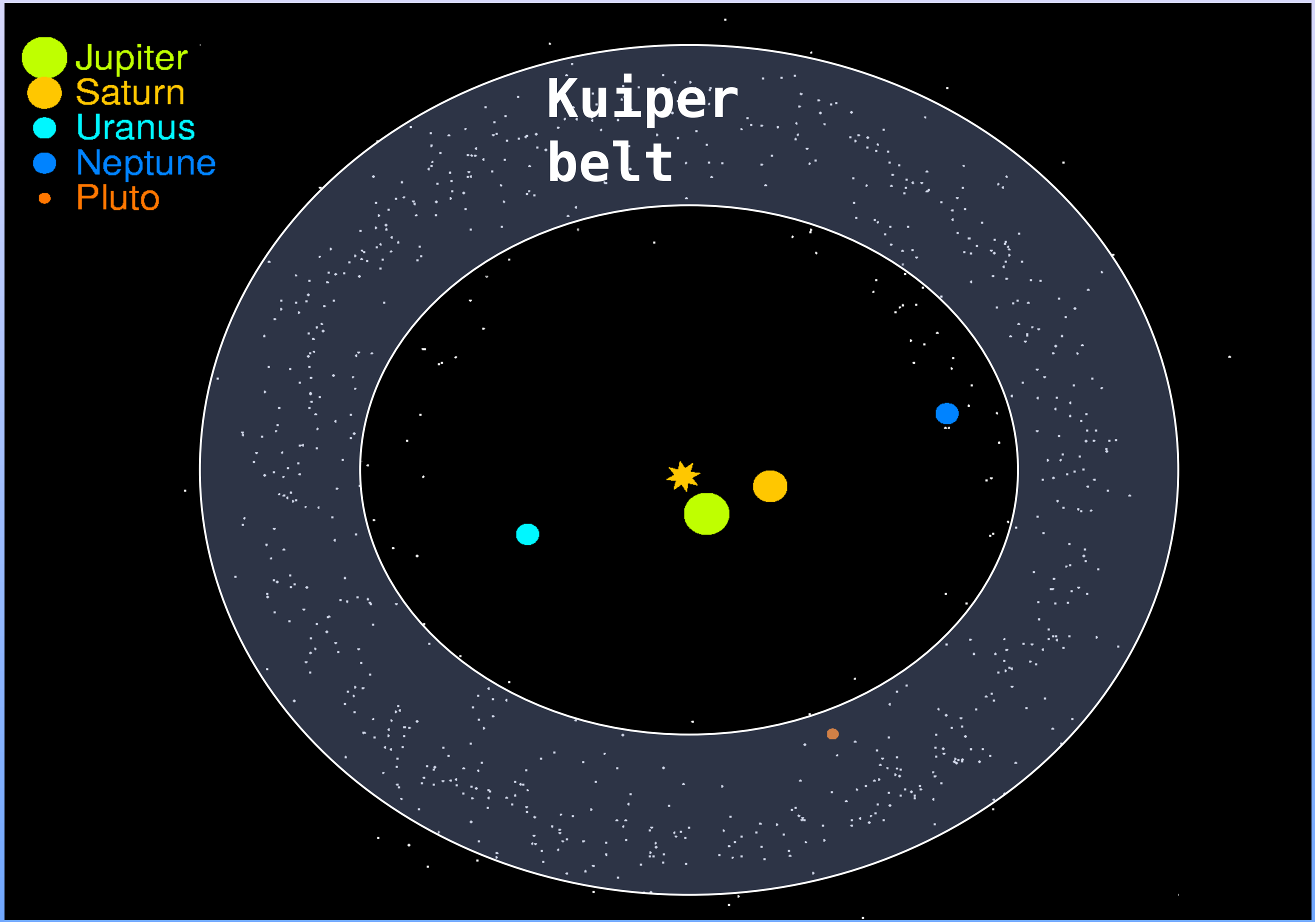
Imaging shows emission from 130AU dust ring with nearby planet-like object (Kalas et al. 2013)



Component of planetary system

Planetesimal belts are analogous to the Kuiper belt

Disk structure is indicative of the architecture of the planetary system

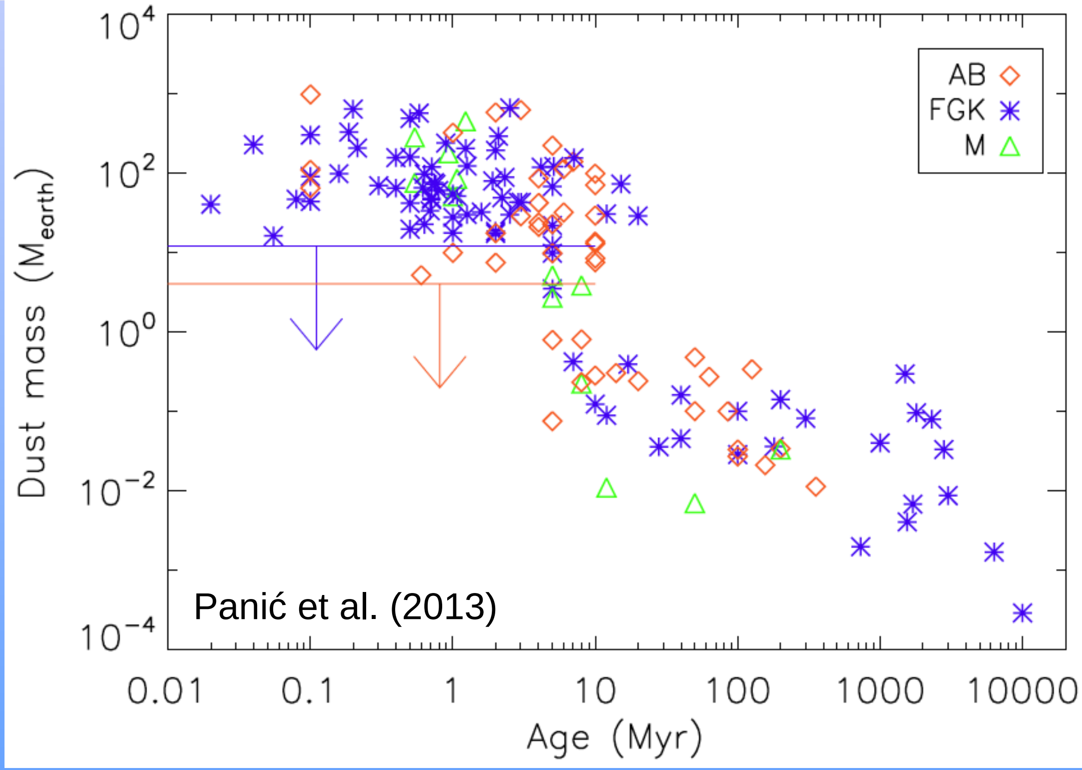


Descendant of proto-planetary disk

	Protoplanetary disk	Debris disk
Age	<10Myr	10Myr – 1Gyr
Dust	>10M_{earth}, optically thick, primordial	<1M_{earth}, optically thin, secondary
Structure	Broad 0.1-100AU	Narrow ~30AU ring
Gas	~100x dust mass	None, usually

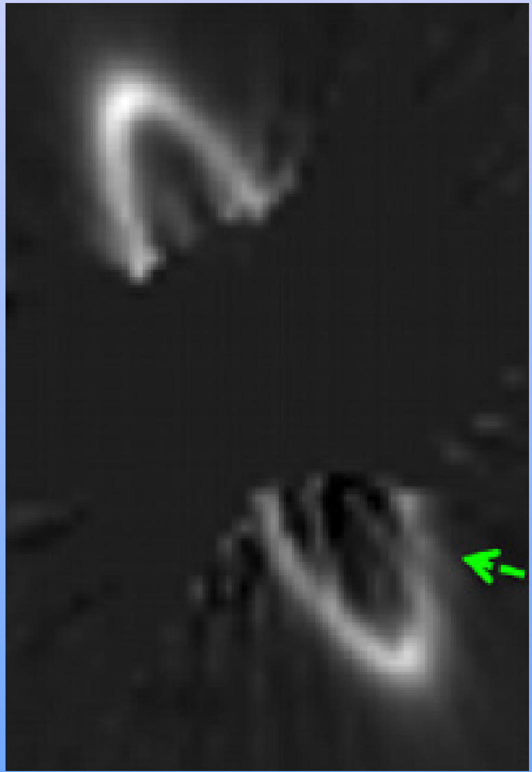
Transition from protoplanetary to debris disk is rapid and poorly constrained

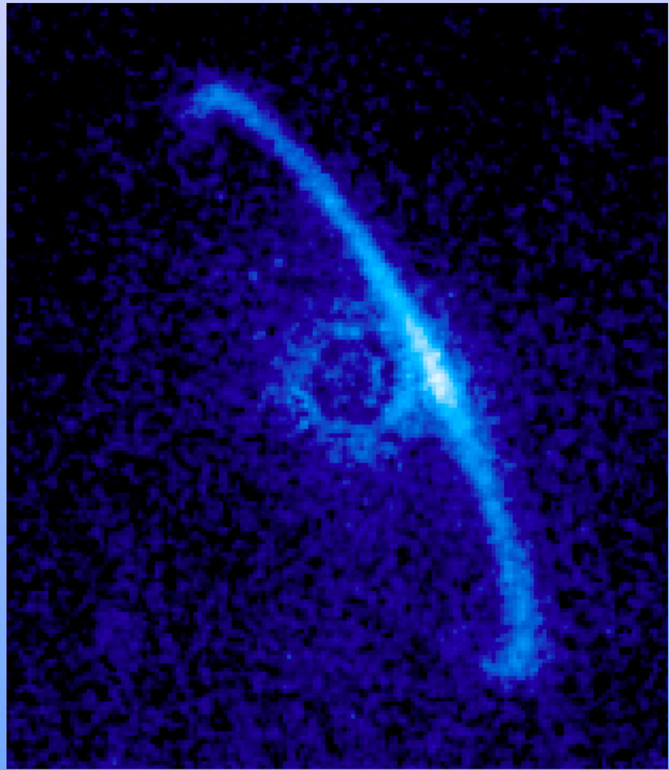
Consider recently formed (8-20Myr) A star debris disks in TWA and BPMG: 4/6 have disks



Debris disks are born as narrow rings

e.g., the μm-sized dust in the disk of 8Myr-old A0V HR4796 is concentrated in a narrow ring at 70AU (Telesco et al. 2000; Schneider et al. 2009; Thalmann et al. 2012; Perrin et al. 2014)

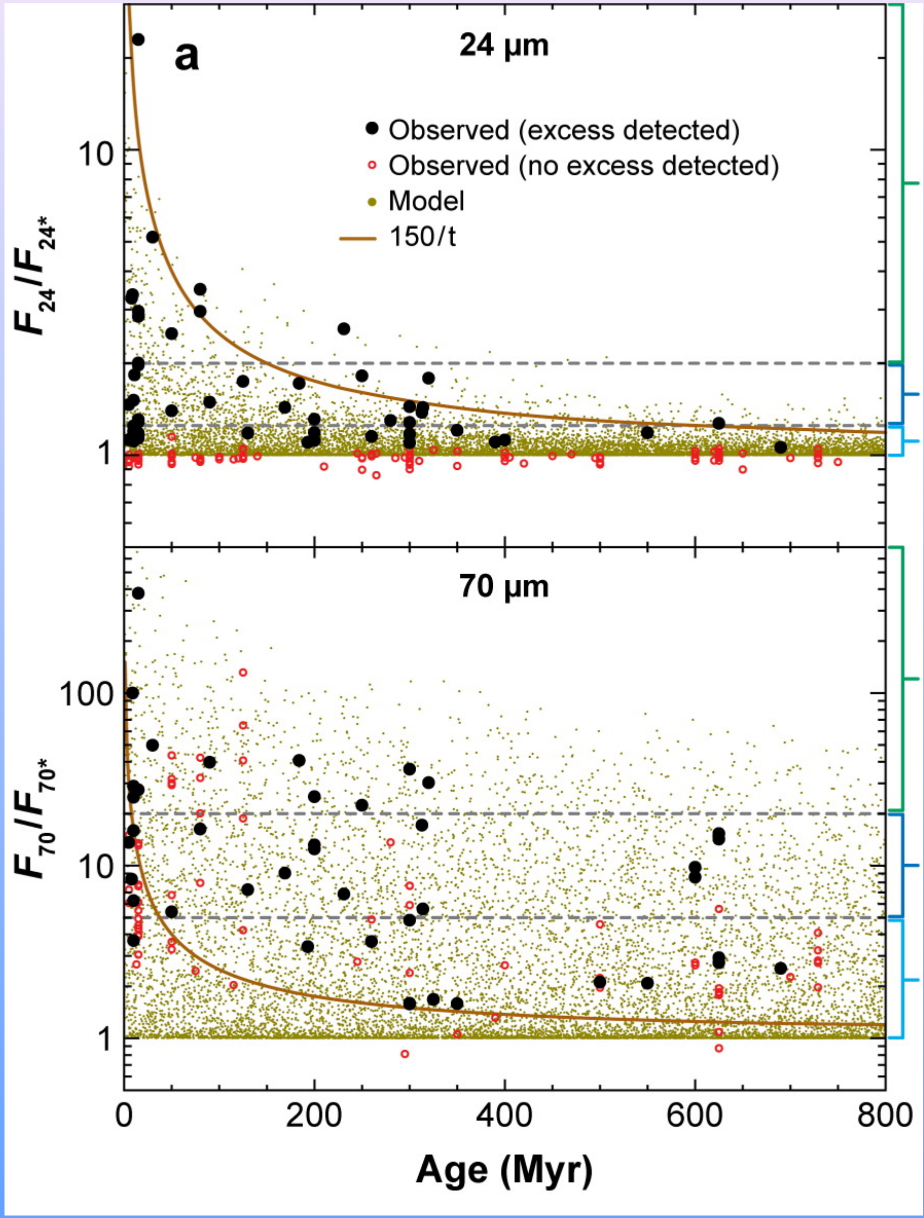




Age dependence from steady state evolution

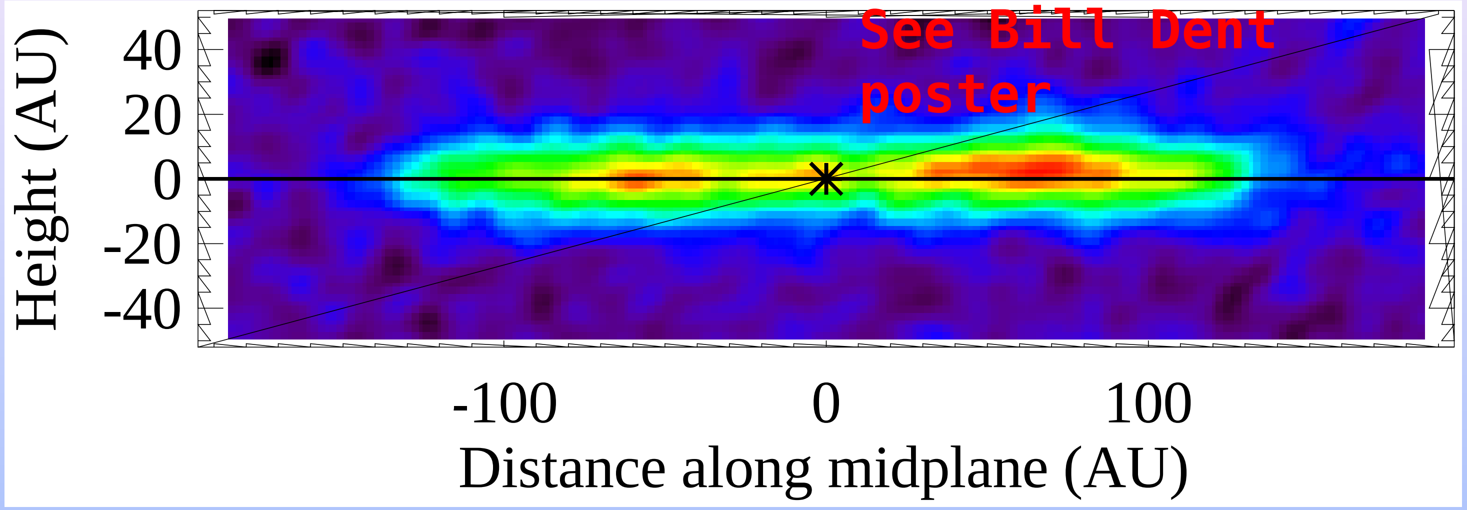
Statistics of detections at 24 and 70μm (Rieke et al. 2005; Su et al. 2006) well fitted assuming debris disks are born as narrow rings, with a distribution of radii, then decay by collisional erosion (Wyatt et al. 2007)

Same statistics not well fitted if the disks are radially broad (Kennedy & Wyatt 2010)

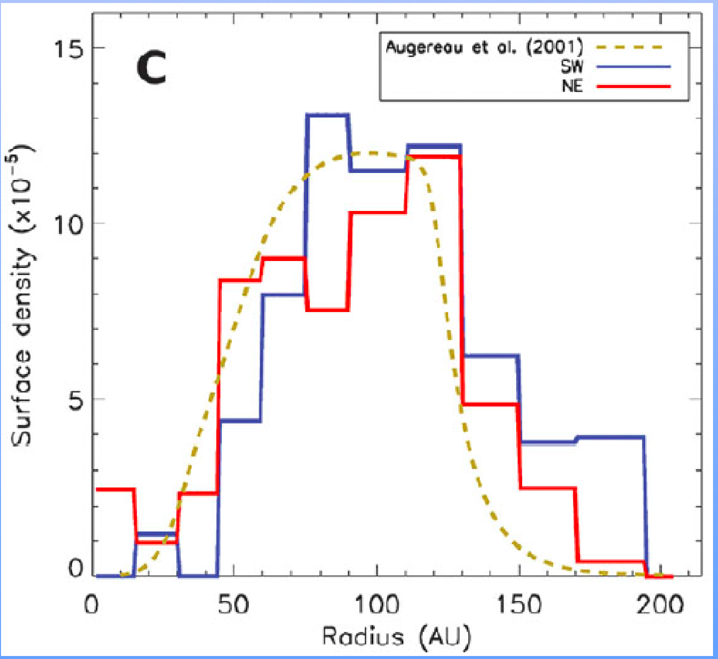


Are some debris disks born broad?

ALMA map of 850µm emission from the 20Myr-old β Pic debris disk at 0.5” (10AU) resolution (Dent et al. 2014)



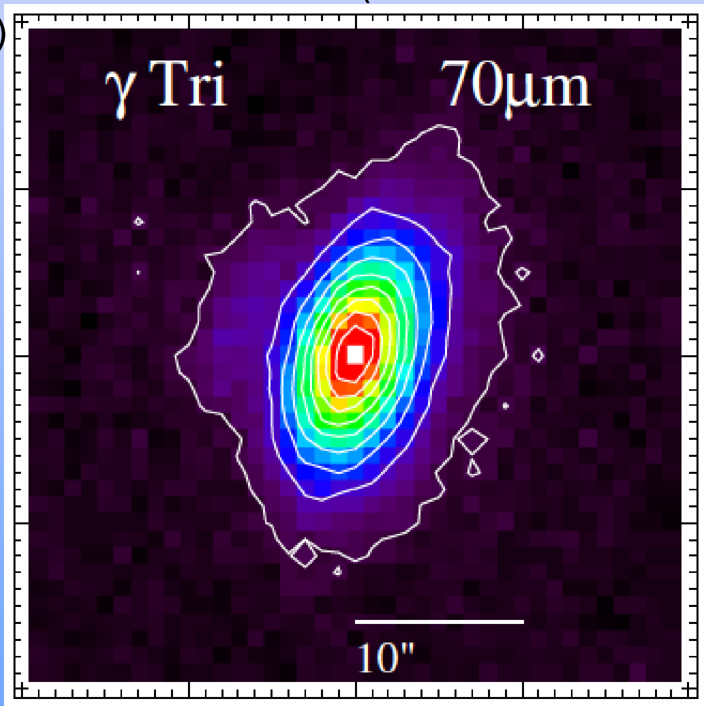
Deconvolving the radial distribution assuming axisymmetry finds the millimetre-sized dust is distributed over factor of 3-4 in radius



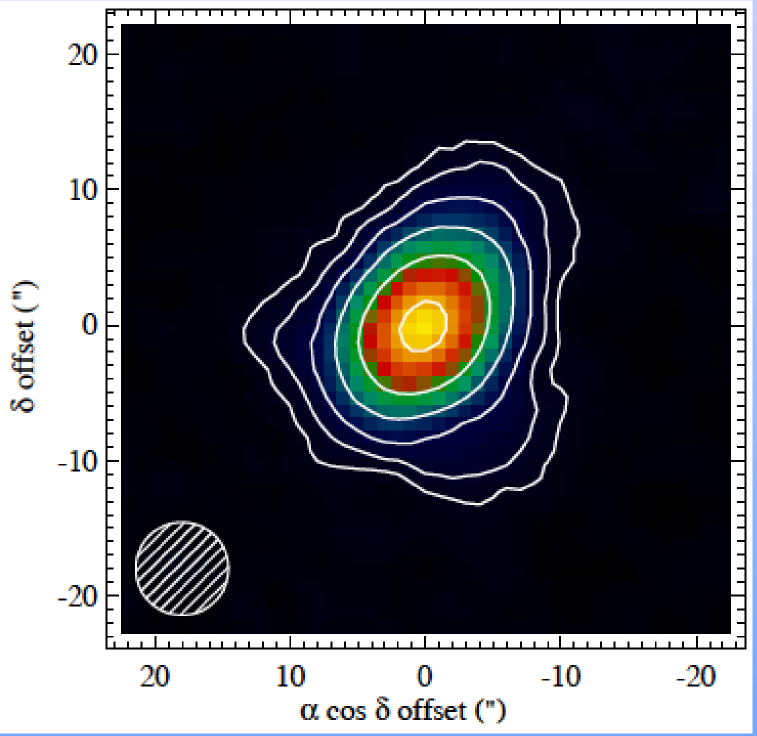
Is the β Pic disk evolving into a narrow ring, or is it a different outcome?

Broad disks can be long-lived

160Myr-old A1V γ Tri has a disk that can't be fitted as a narrow ring, which is the case for ~1/3 A stars resolved with Herschel (Booth et al. 2013)

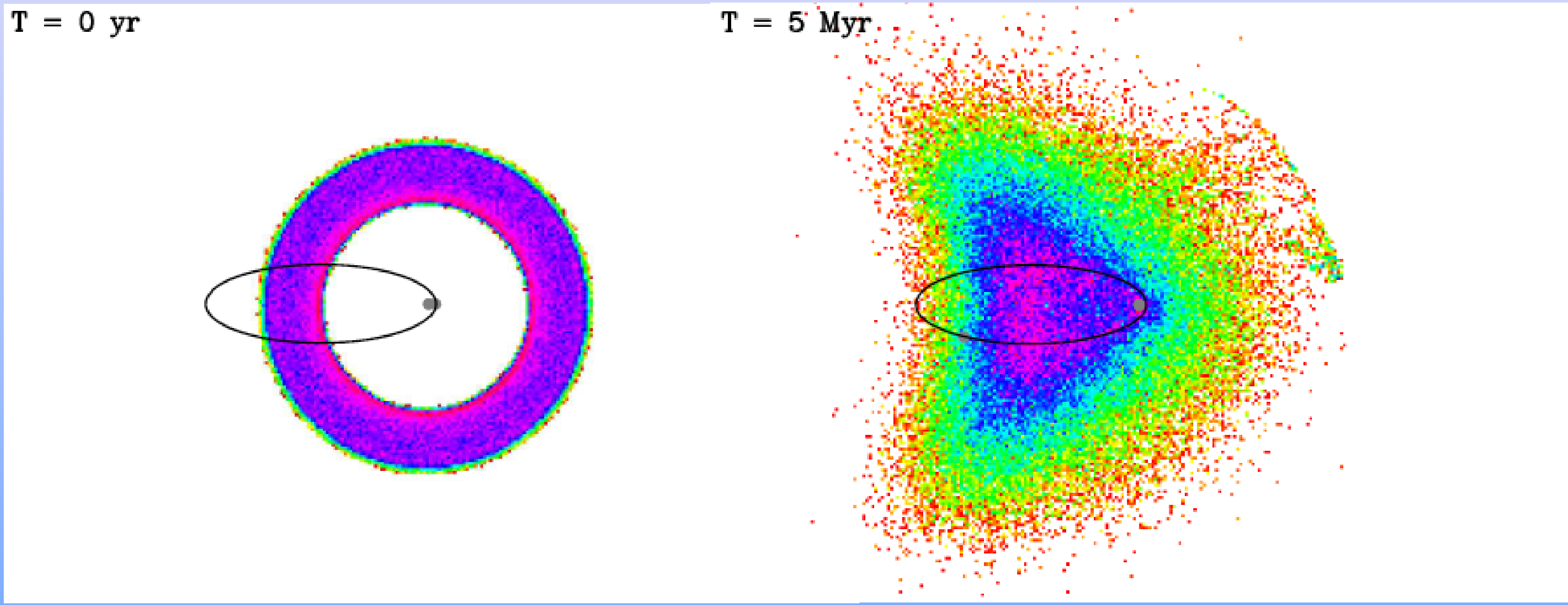


Retired A star (2.5Gyr, 1.8M_{sun}) κ CrB has a belt 20-220AU (Bonsor et al. 2013)



Planetary dynamics can broaden narrow rings

Planets can easily affect a debris disk, e.g., a planet scattered onto a highly eccentric orbit near a narrow ring (like Fom-b!) would quickly scramble the disk structure (Beust et al. 2014; Tamayo 2014; Pearce & Wyatt in



Perhaps all are born as narrow rings, as a special location where planetesimals can form, and broad disks are those affected by planetary dynamics?

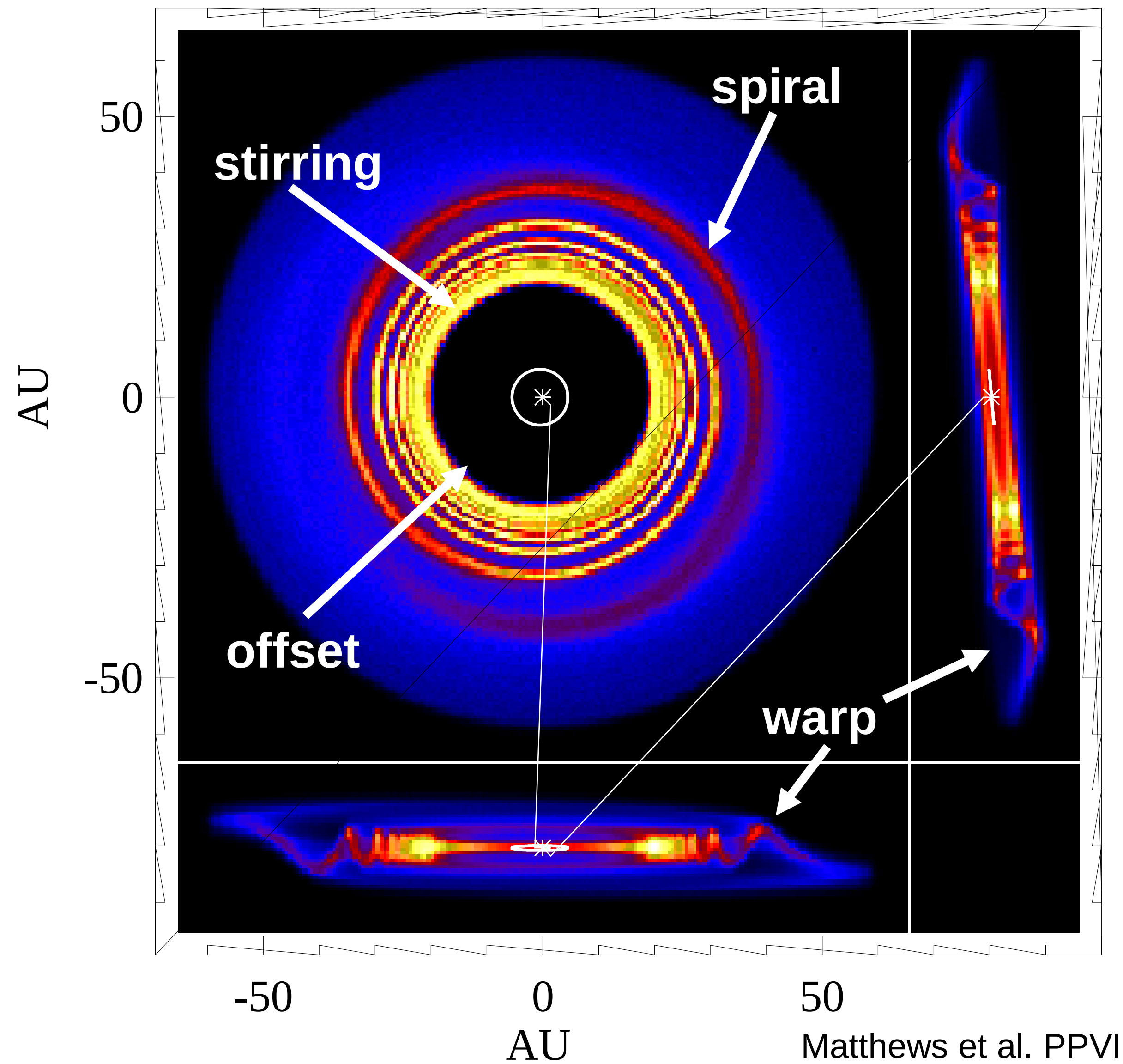
Distant planets also affect disk structure

Planet:
10M$_{jup}$
5AU
e=0.1
I=5^{o}

Disk:
20-60AU

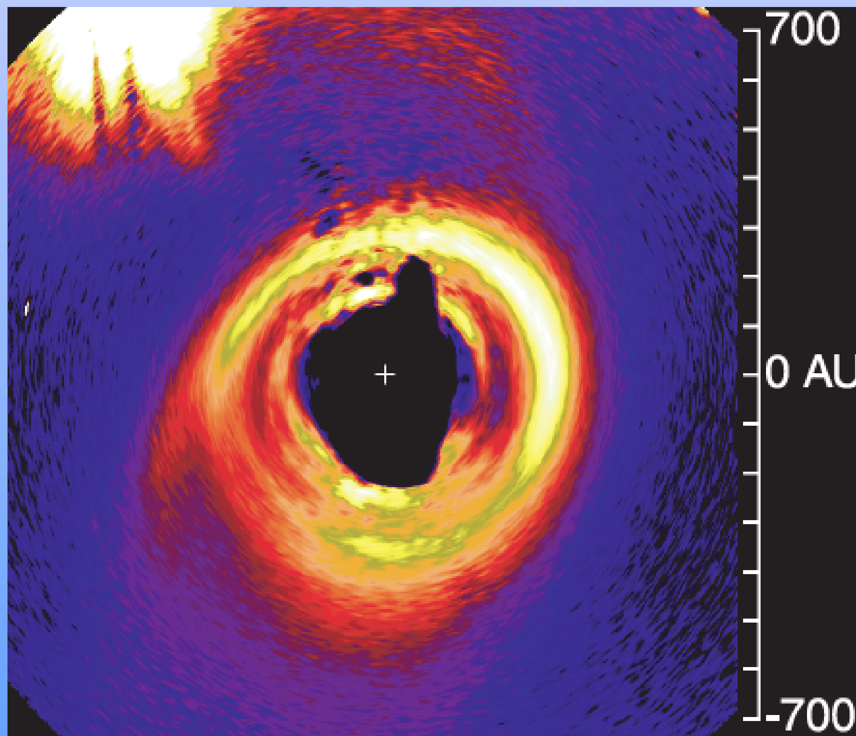
Time:
10Myr

See Ágnes Kóspál poster



Matthews et al. PPVI

Disk structures as planet indicators



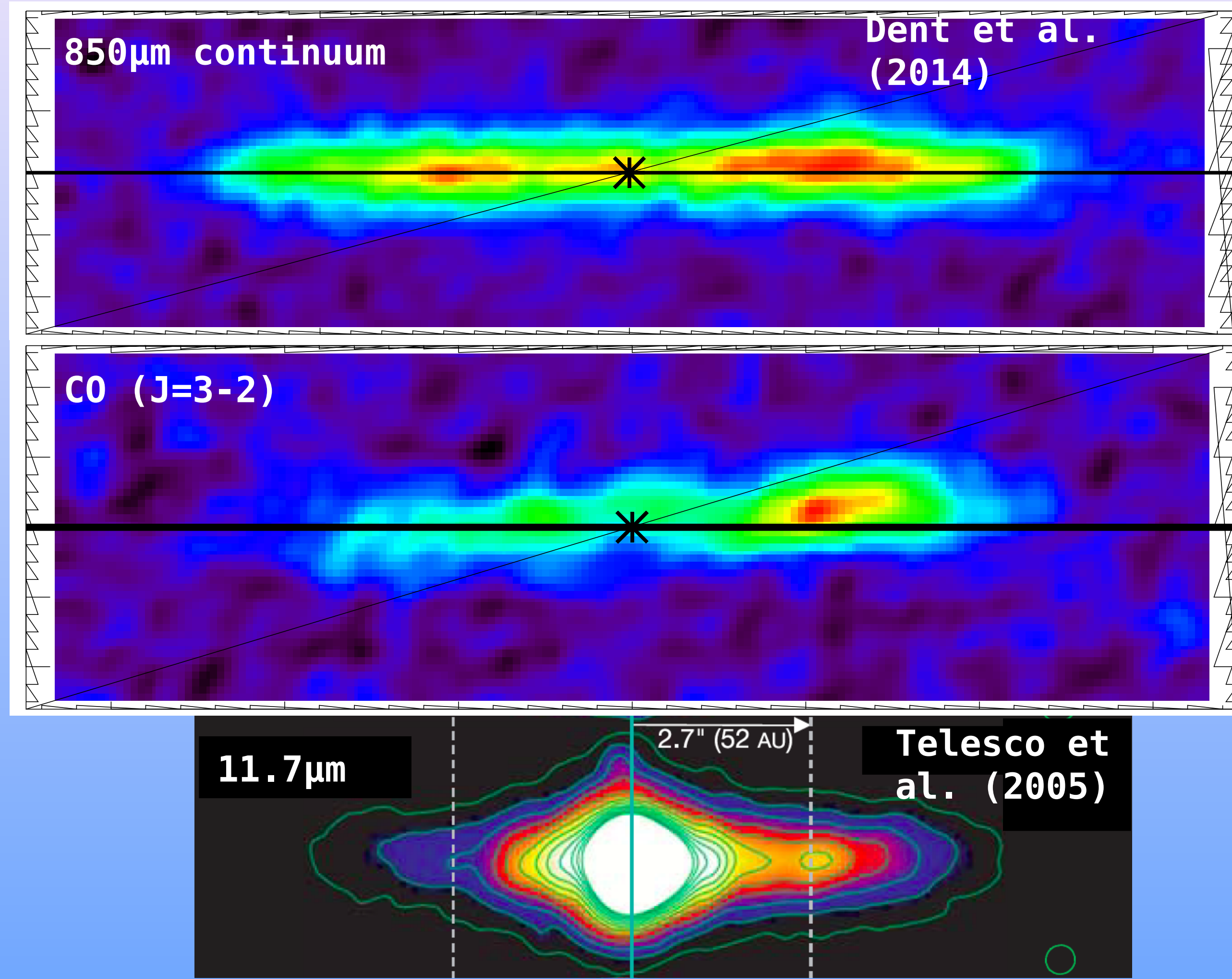
A warp in the β Pic disk at 80AU explained by misaligned ~9$M_{Jupiter}$ planet at 8AU after ~20Myr of evolution (Augereau et al. 2001; Chauvin et al. 2012)

Tightly wound spirals in the 5Myr HD141569 disk at 100s of AU may be explained by planets on eccentric orbits (Clampin et al. 2003; Wyatt 2005)

Brightness asymmetry in the β Pic disk

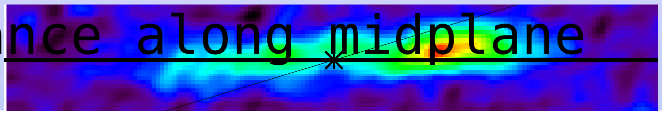
Maps of 850μm emission and CO toward β Pic show asymmetry at ~50AU projected separation, coincident with a similar asymmetry seen in mid-IR (and with warp)

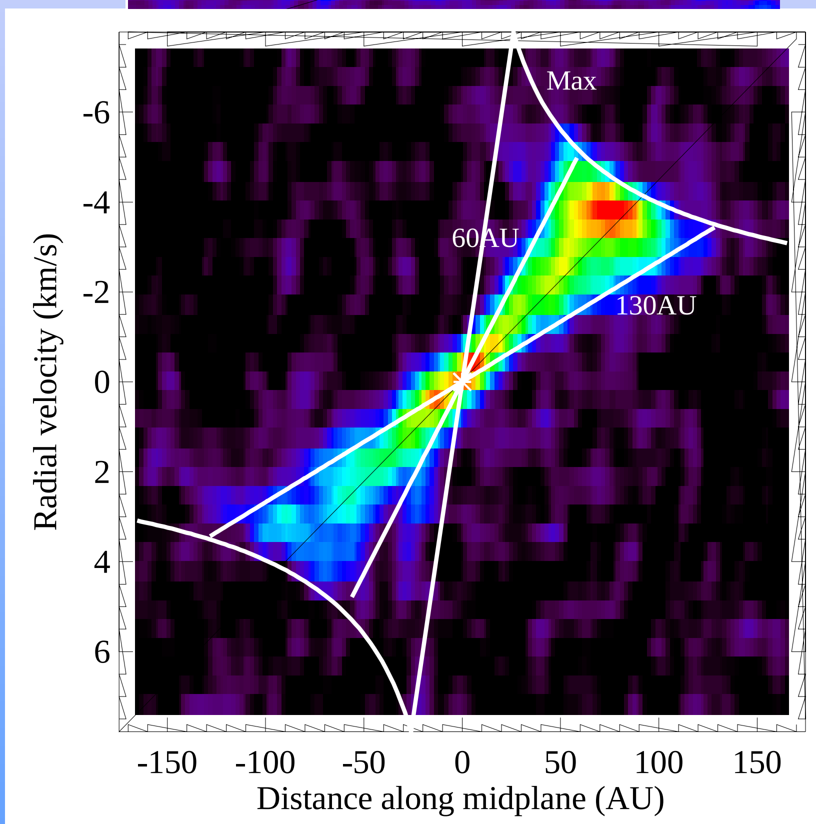
CO photodissociates in 120yr implying it is secondary – i.e., comet collisions continually replenish it at a rate ~0.1M_{earth}/Myr



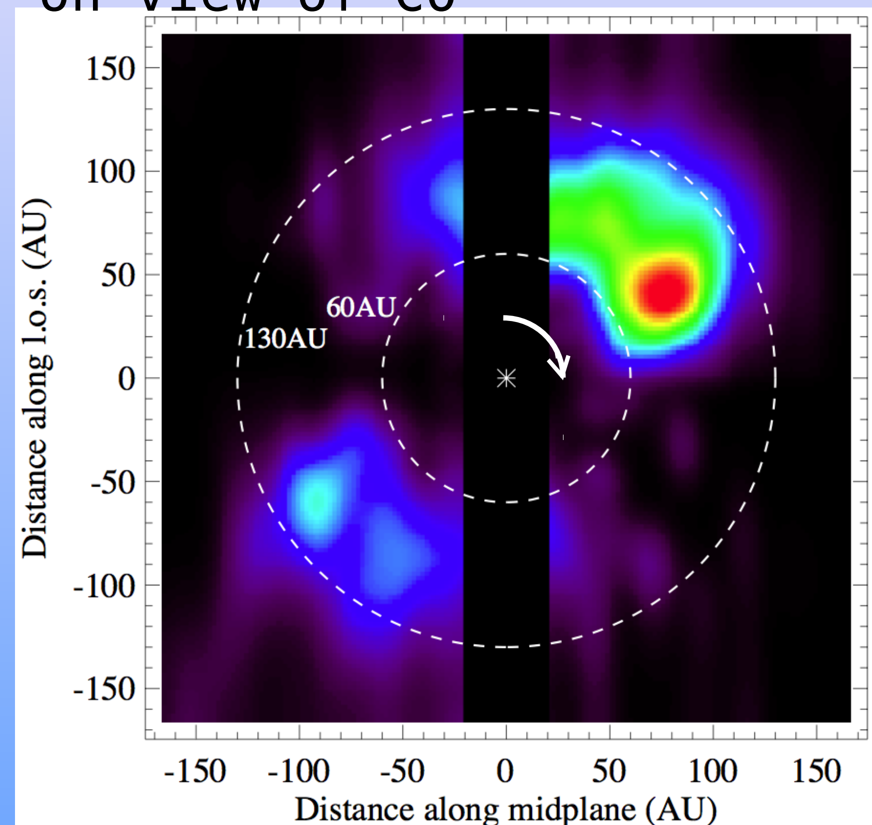
CO velocities show asymmetry is clump

Each pixel contains info on the CO radial velocity; P-V diagram shows distribution of velocities at each distance along midplane



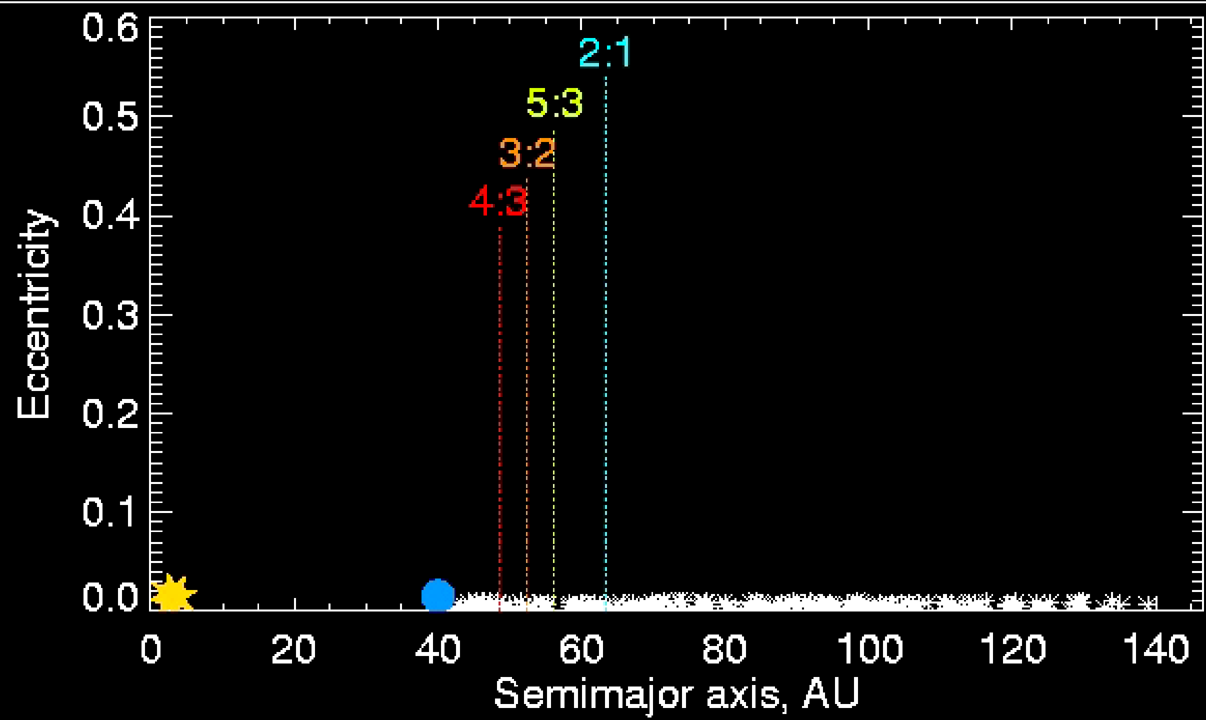


Assuming Keplerian velocities the P-V diagram can be deprojected to get face-on view of CO



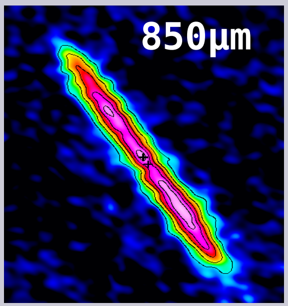
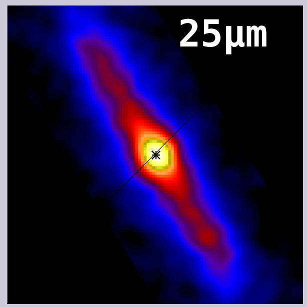
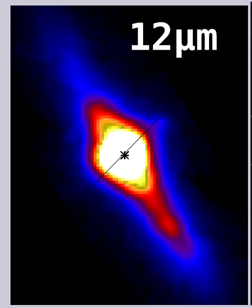
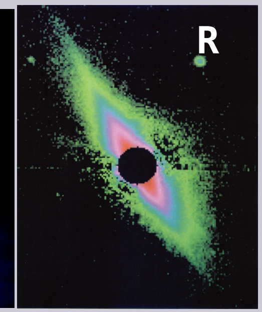
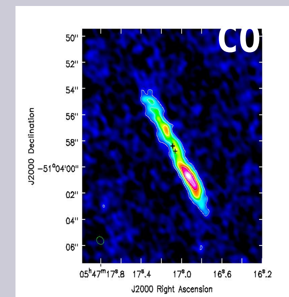
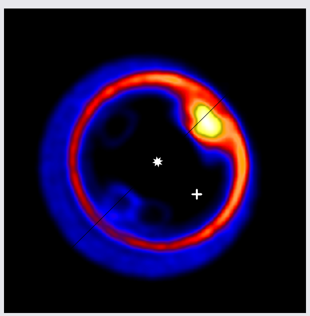
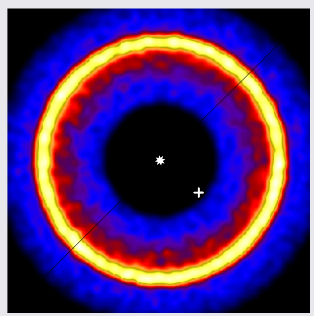
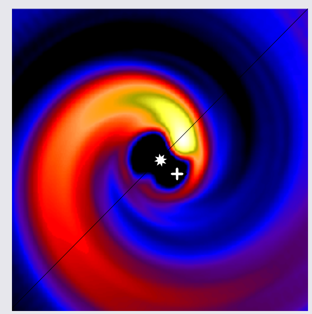
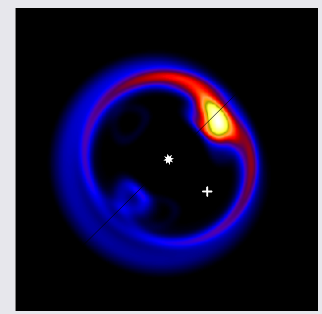
Resonance sweeping model

The outward migration of a Saturn-mass planet sweeps comets into its resonances

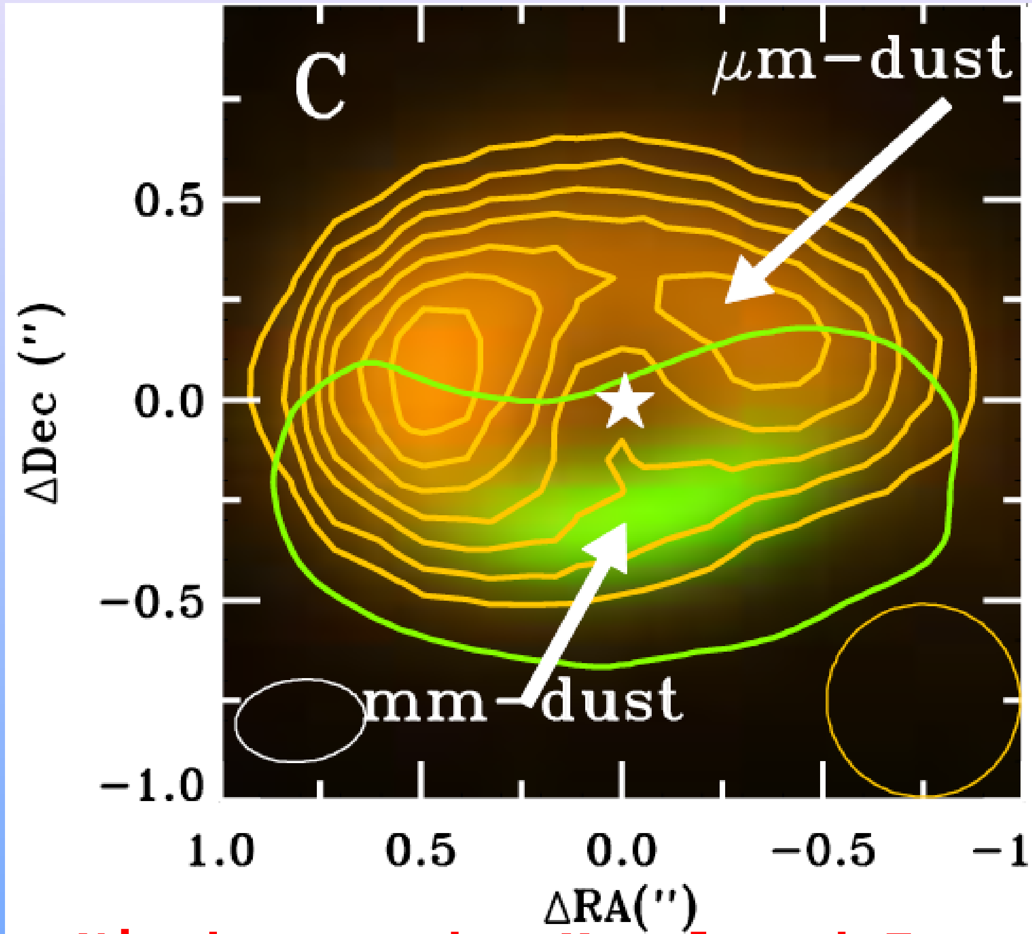


Wyatt (2003)

Explains 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)
β Pic observed			 	
Face-on resonance sweeping model (Wyatt 2006)				

Any relation between clump and horseshoes?



Similar wavelength dependent morphology seen in transition disks (van der Marel et al. 2013)

Could the beta Pic clump be a remnant of the horseshoe? Or does that structure dissipate when the gas goes.

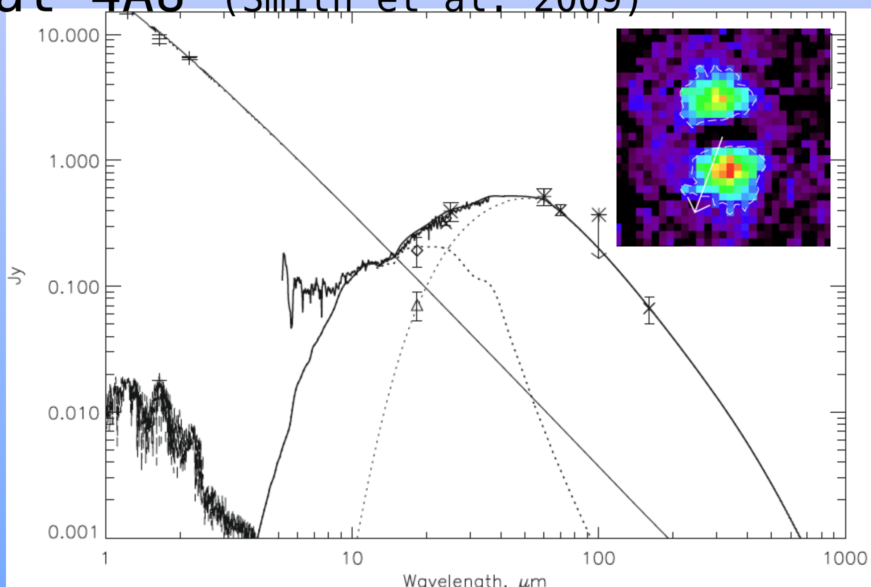
Could resonance sweeping contribute to the horseshoe? Or does large mass involved in horseshoe preclude this?

See Nienke van der Marel and Francois Ménard talks

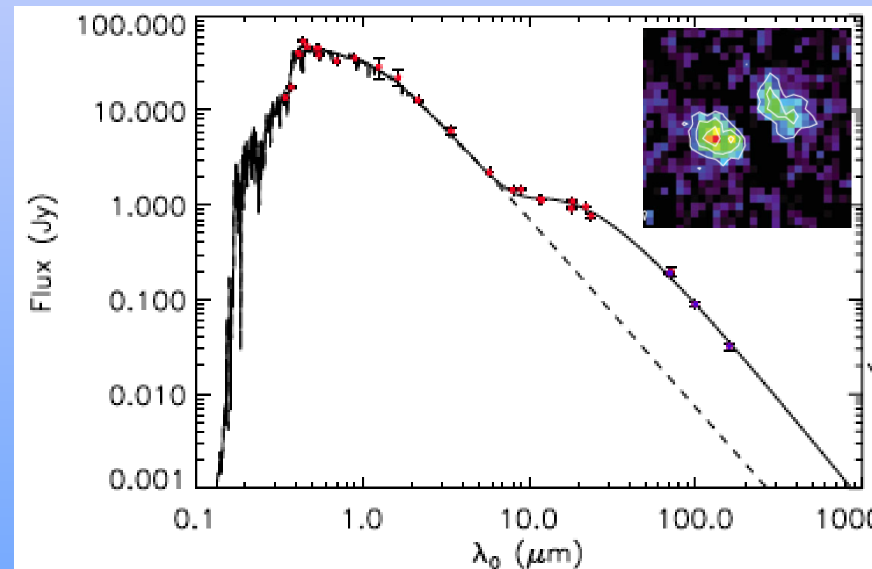
Hot dust

The other two A stars in the BPMG (i.e., at 20Myr just after protoplanetary disk dispersal) both have dust at a few AU

η Tel (A0V) has imaged belt at 24AU plus unresolved hot component at 4AU (Smith et al. 2009)

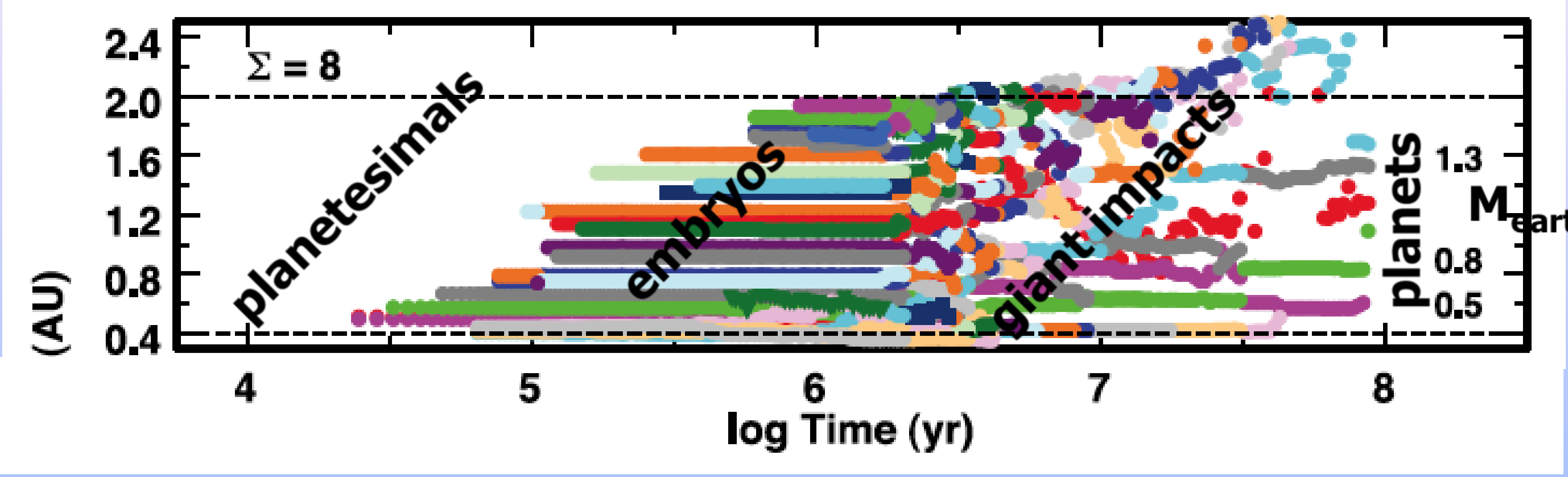


HD172555 has hot dust marginally resolved at 1-8AU (Smith et al. 2012)

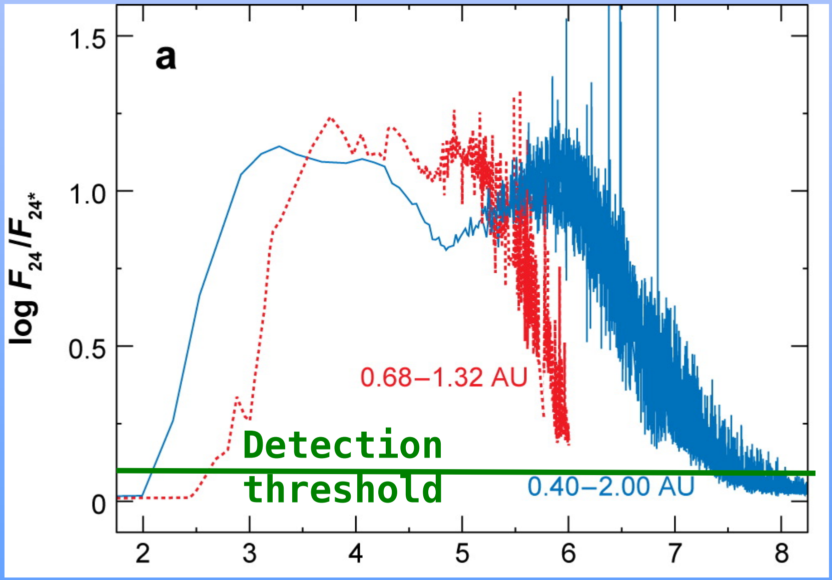


Is this hot dust originate in asteroid belt analogues, cometary sublimation, or ongoing terrestrial planet formation?

Terrestrial planet formation

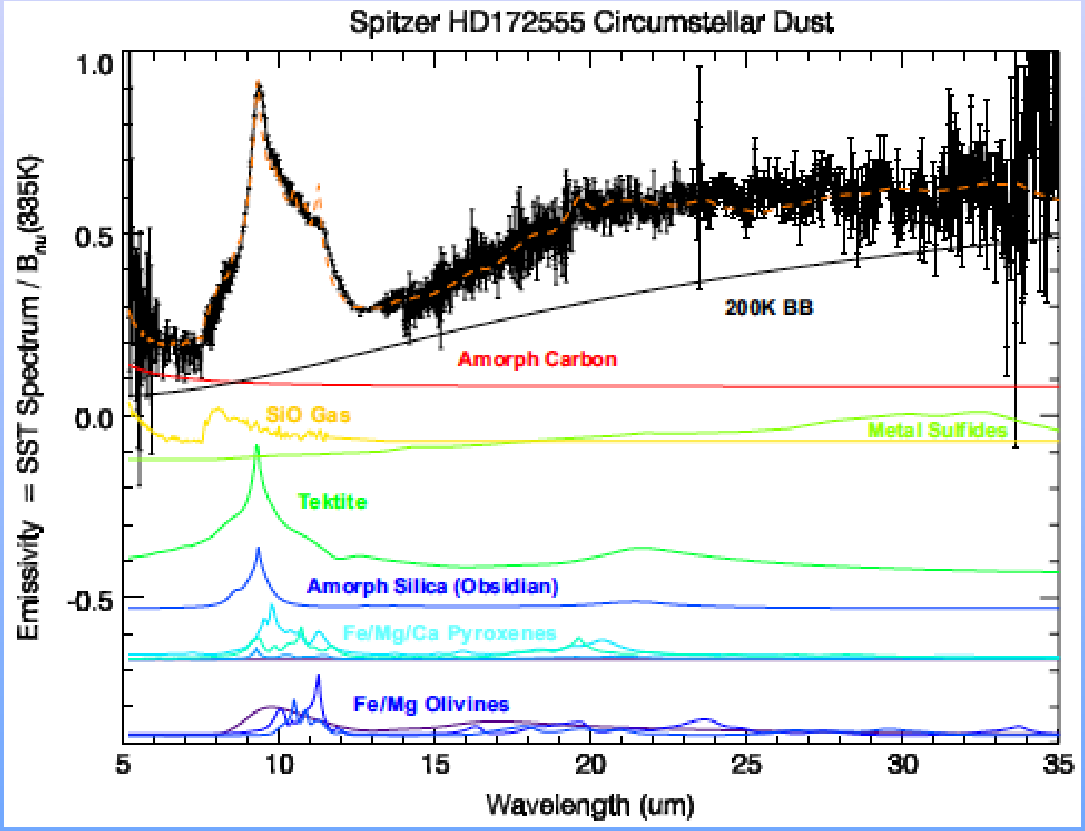


At 1 AU growth of km-sized planetesimals into Earth-sized planets is understood, and models predict detectable dust levels up to 100Myr (Kenyon & Bromley 2005).



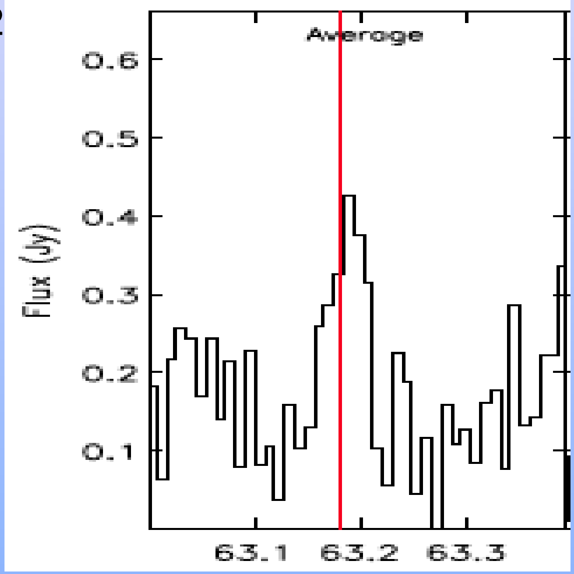
Giant impact origin?

Mid-IR spectrum of HD172555 shows silica that could originate in a high velocity collision (Lisse et al. 2009; Johnson et



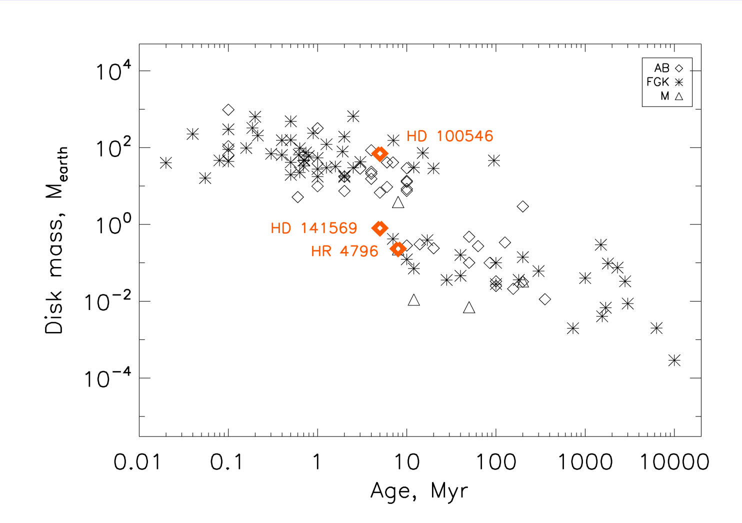
See Roy van Boekel talk

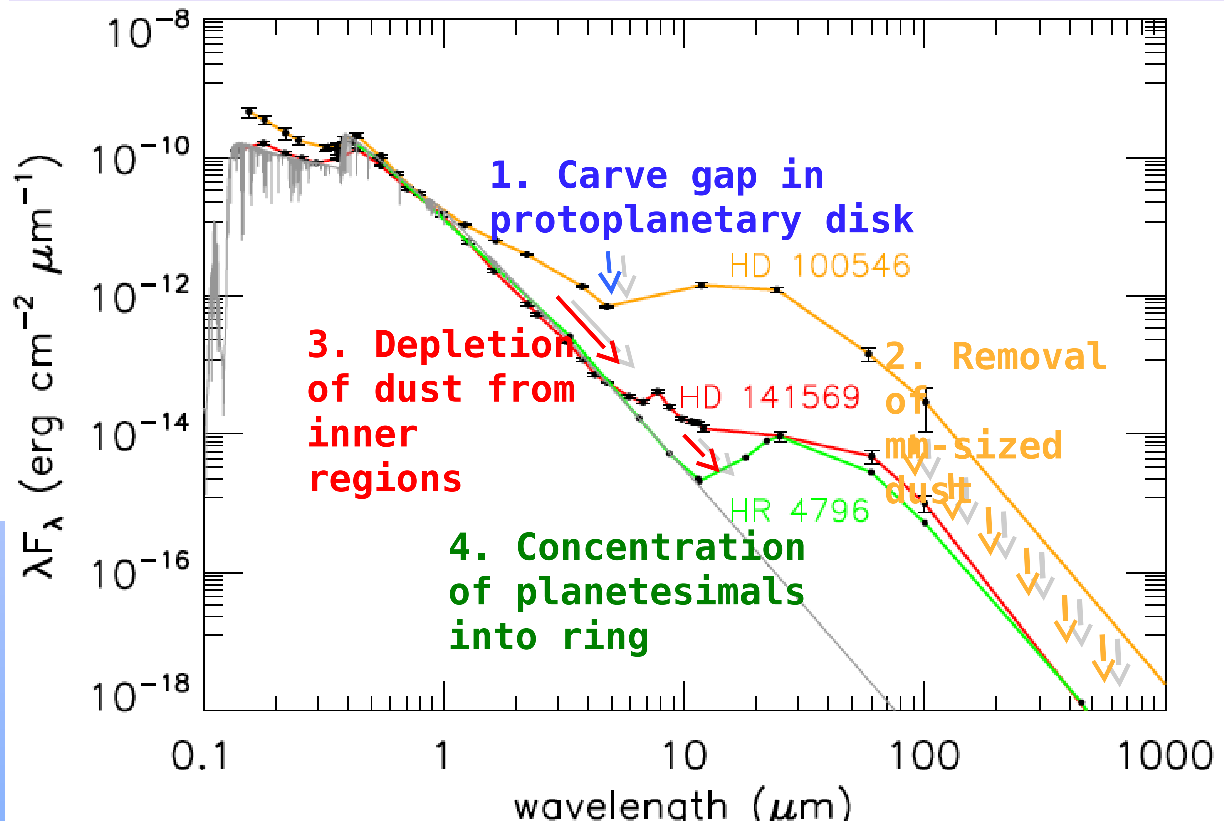
But $0.4M_{earth}$ of OI (Riviere-Marichalar et al. 2012), and CaII absorption (Kiefer et al. 2014), and CII detected in η Tel Riviere-Marichalar et al. 2



How much of the hot dust in protoplanetary disks originates in terrestrial planet formation?

From transition disk to debris disk





In dust, the transition involves 4 steps, but what is the order?

When are planetesimals concentrated in a ring – already there at the protoplanetary disk stage, or is that where mm-sized dust ends up?

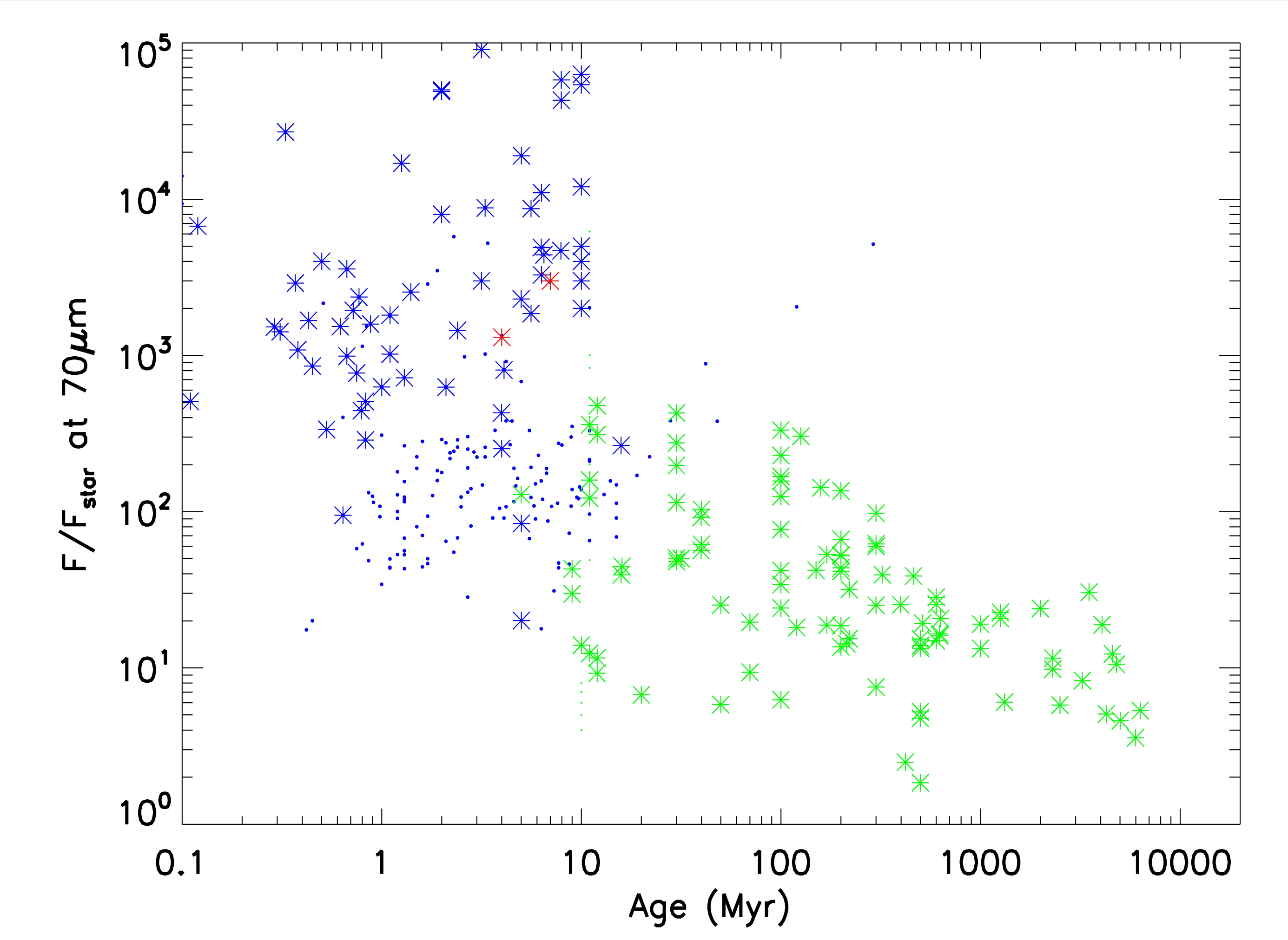
How much dust in inner regions is break-up of planetesimals and planets?

Classification as protoplanetary or debris disk

Difference seemed evident in sub-mm dust mass, but partly observational bias

Excesses at 70μm are more continuous

Classification is not well defined

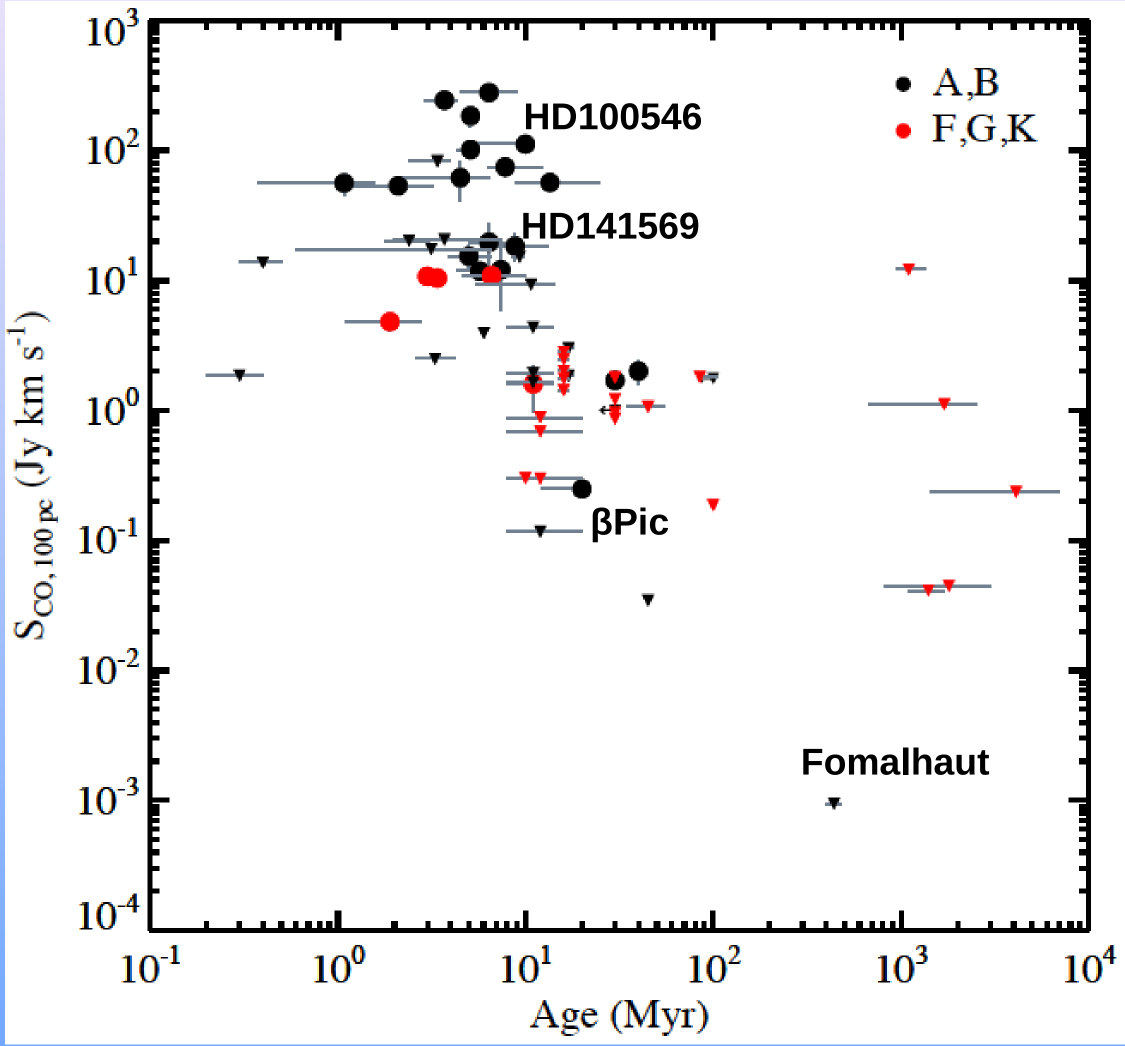


Evolution of gas mass

Gas is in general not detected in debris disks (Dent et al. 2005; Moór et al. 2011)

β Pic gas is secondary (Dent et al. 2014), likewise for 49 Cet (Zuckerman & Song 2012; Roberge et al. 2013), but some HD21997 gas primordial (Kóspál et al. 2013)

HD141569 has gas/dust~100 so likely primordial (Thi et al. 2014)

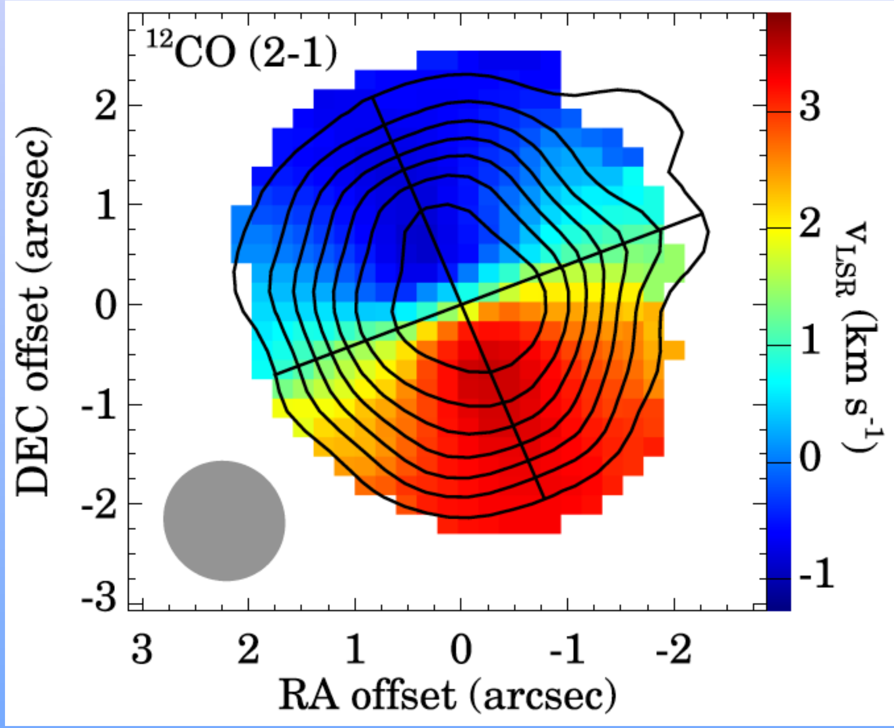


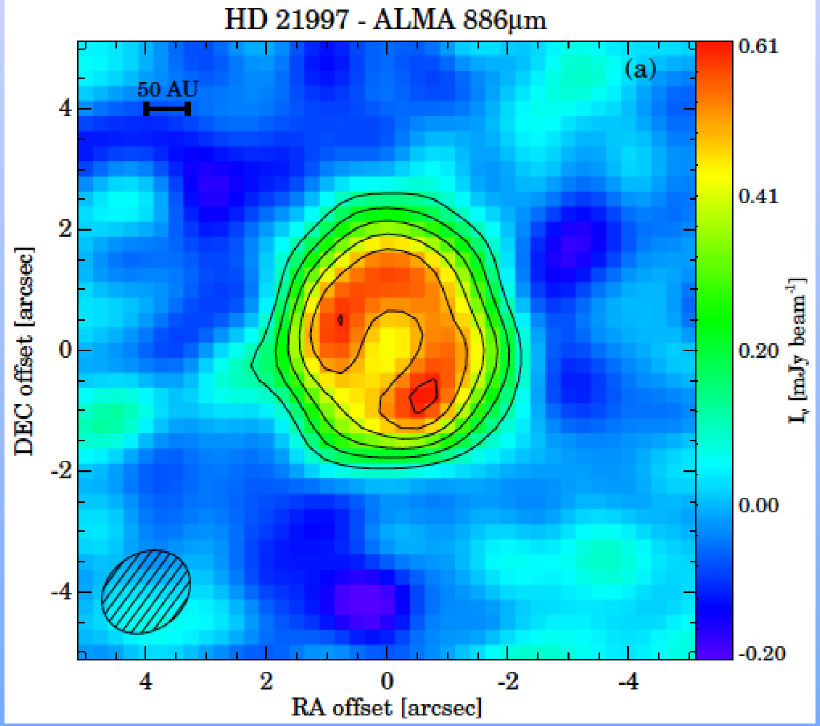
ALMA is pushing the limits of detecting CO in debris disks (Matrà et al. in prep)

Gas in debris disks: primordial or secondary?

CO gas in 30Myr HD21997 is consistent with Keplerian rotation in 26-138AU disk (Kóspál et al. 2013)

But dust is 55-150AU (Moór et al. 2013) so gas and dust are not co-located





See Ágnes Kóspál talk

Gas is both primordial and secondary

Conclusions

Debris disks are descendants of protoplanetary disks, born as narrow rings of planetesimals, though some "rings" may be broad

Radial and azimuthal structure (warps, clumps) caused by interactions with planets

Dust often seen at a few AU around young stars, possibly from terrestrial planet formation processes

Low levels of secondary gas seen in some debris disks, but does any primordial gas remain?

Transition involves 5 steps: (i) carving hole, (ii) removing mm-sized dust, (iii) clearing inner regions, (iv) removing CO, (v) concentrating planetesimals into ring

What stirs debris disks?

Collisions between planetesimals lead to growth in protoplanetary disk, but destruction in a debris disk; gas damps collision velocity in a PPD, but what stirs it in a DD?

Distant giant planets (Mustill & Wyatt 2009)

- But requires planets!

Growth of planetesimals to Pluto-sized objects (Kenyon & Bromley 2010)

- But requires planetesimals confined to a ring, and must be rapid

Unstirred debris disks may have been found by Herschel (Heng & Tremaine 2010; Eiroa et al. 2011; Krivov et al. 2013)

- But these may be galaxies!

Alternative explanation: giant collisions

Degeneracy in deprojection of CO shows tail could lead the clump.

Debris from impact onto 85AU Mars-sized parent escapes at ~4km/s, stays as clump <1 orbit (580yr), but is asymmetric for ~1000 orbits (0.6Myr), as orbits go through the collision point which has enhanced collision rate

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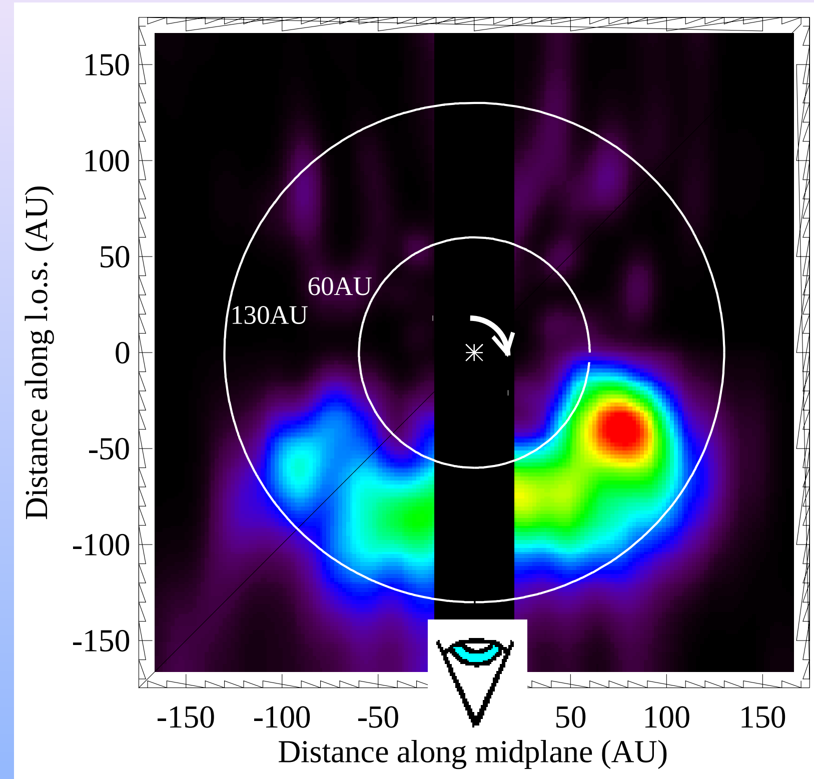
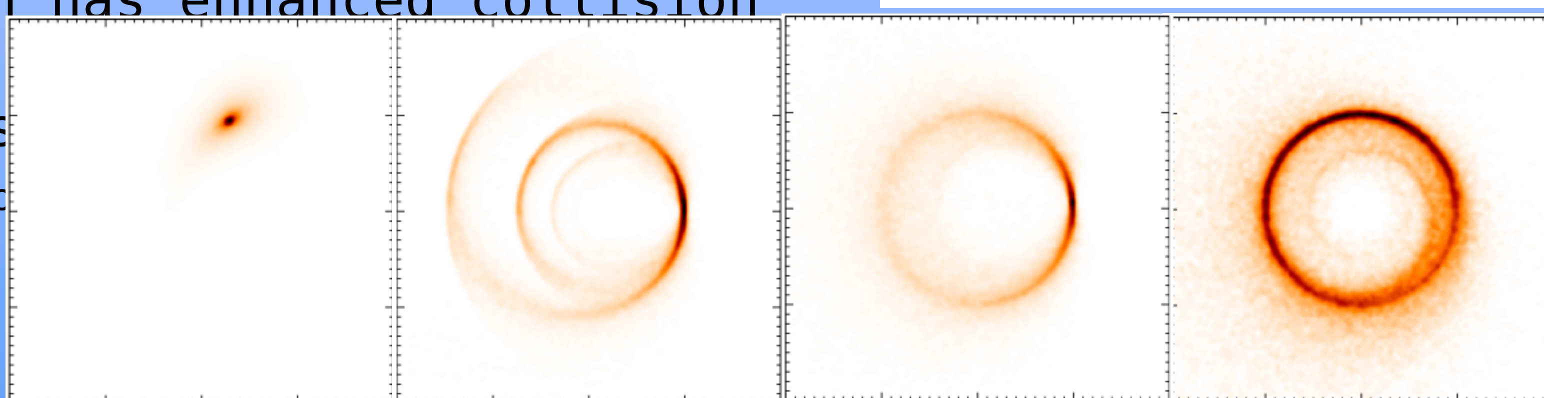
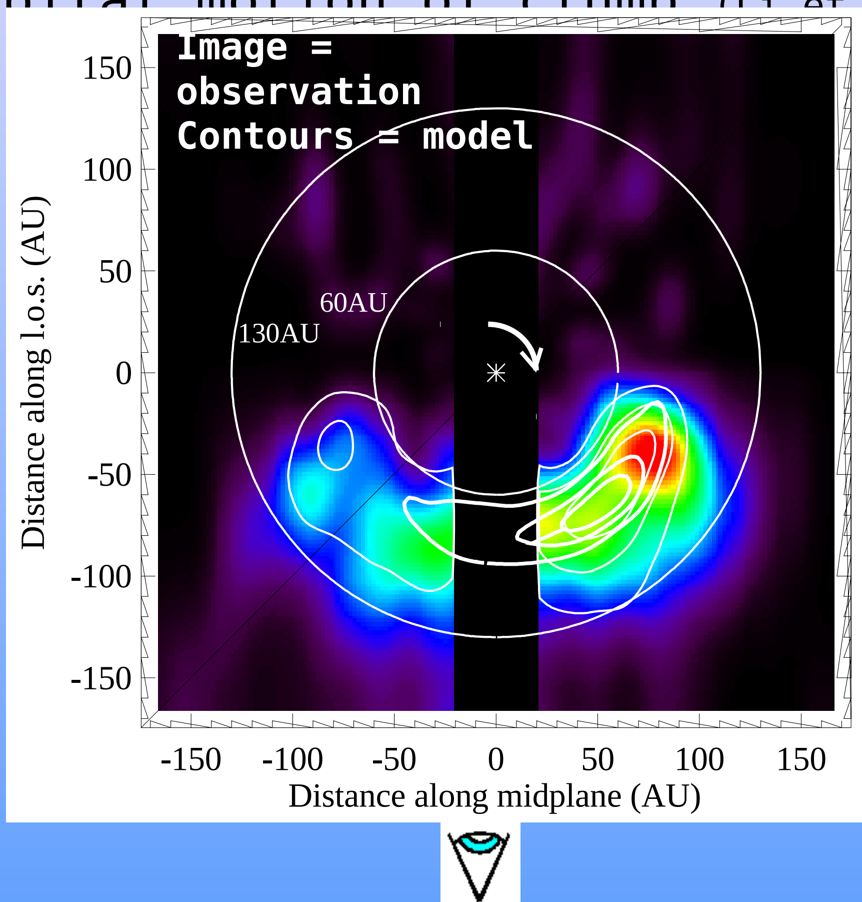




How big are the biggest objects in debris disks?

Reproduces the CO position-velocity diagram, but disfavoured due to tentative orbital motion of clump (Li et al.



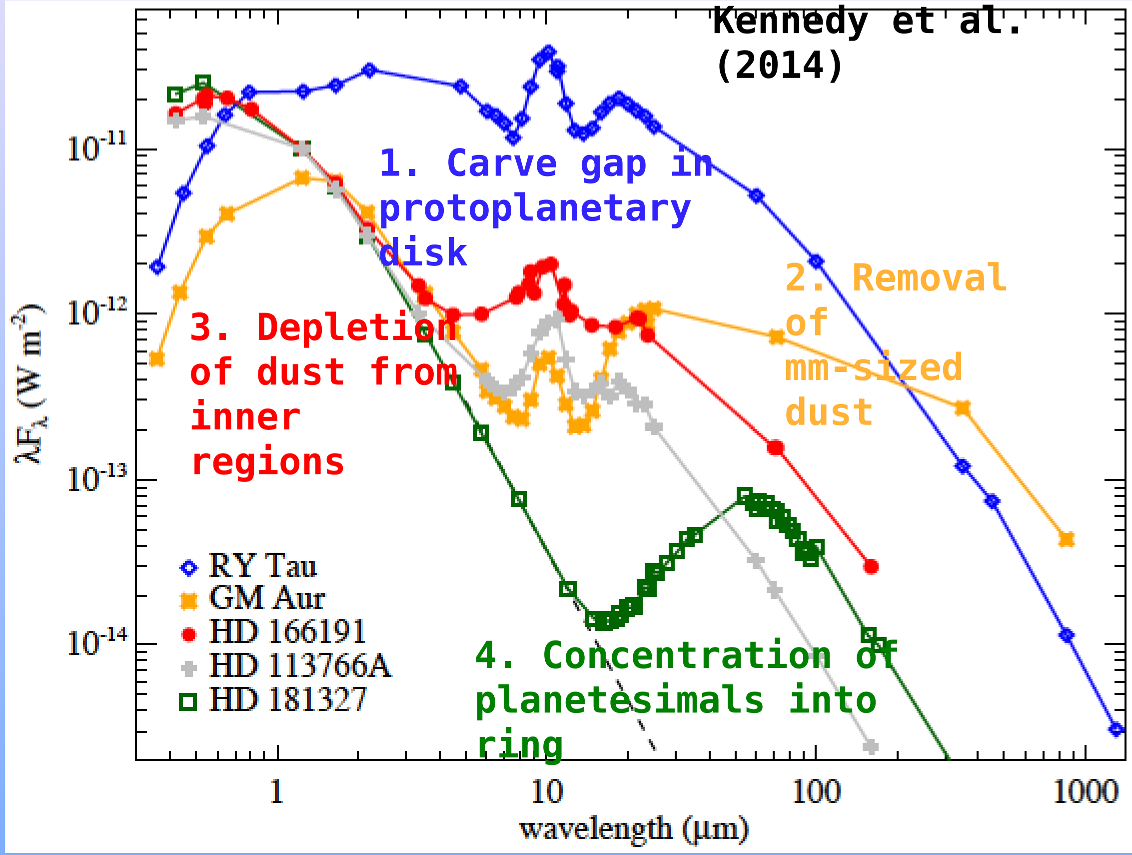
But, if correct, implies giant collisions are ongoing in outer regions of debris disks, and suggests planet formation processes are ongoing at 20Myr.

Also highlights our ignorance of size of largest objects in debris disks, since only km-sized

Open questions

When are planetesimals concentrated in a ring – already there at the protoplanetary disk stage, or is that where mm-sized dust ends up?

How much of the dust in the inner regions at all stages is from break-up of planetesimals and planets? (Note one collision sufficient to provide observed dust)



Classification as protoplanetary or debris disk

Similarly at 24µm there is no sharp dividing line
(Kennedy & Wyatt 2010)