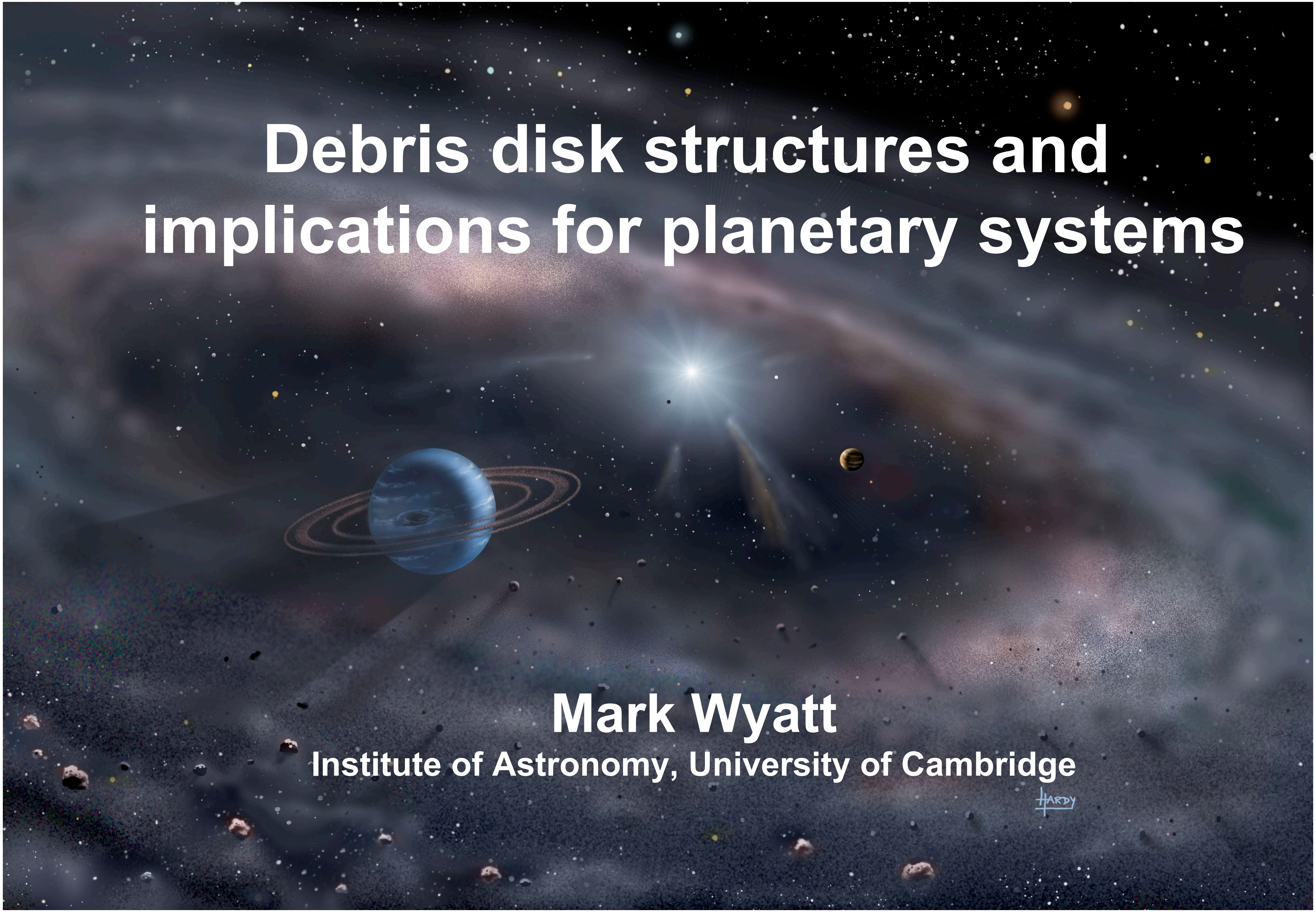
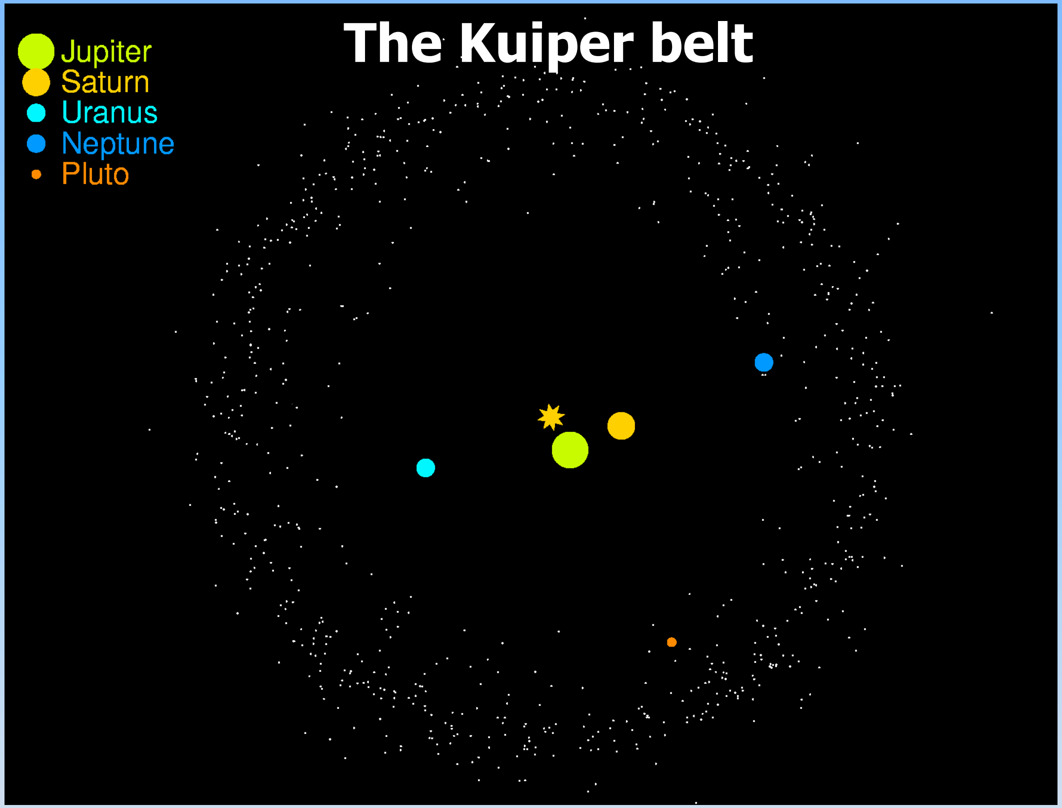
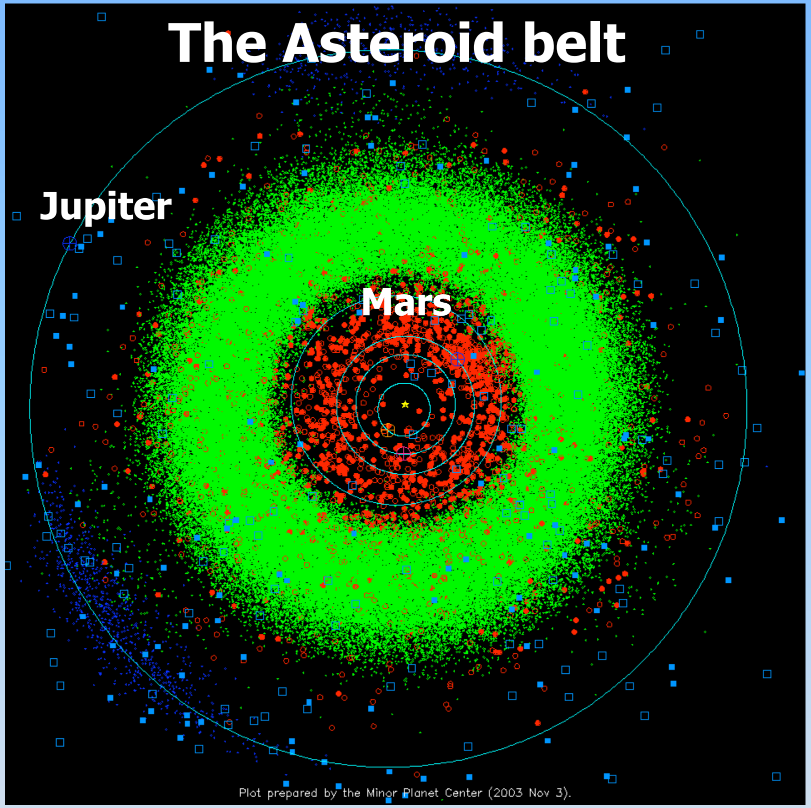
Debris disk structures and implications for planetary systems



Mark Wyatt
Institute of Astronomy, University of Cambridge

The debris disk of the Solar System


The Kuiper belt


The Asteroid belt

Plot prepared by the Minor Planet Center (2003 Nov 3).

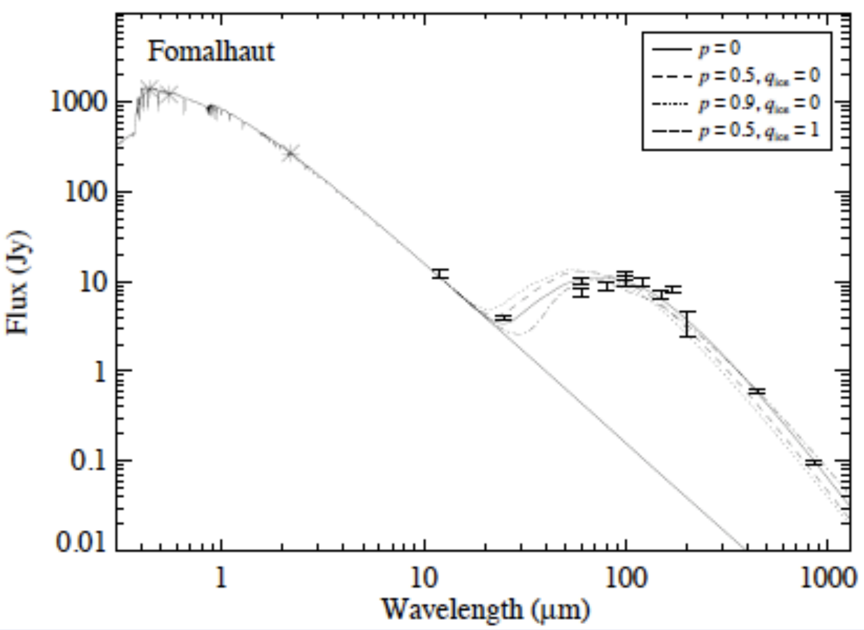
The dust in Solar System's debris disk is replenished by the destruction of planetesimals which lie in belts

Structure with implications for planets? The radius of the belts

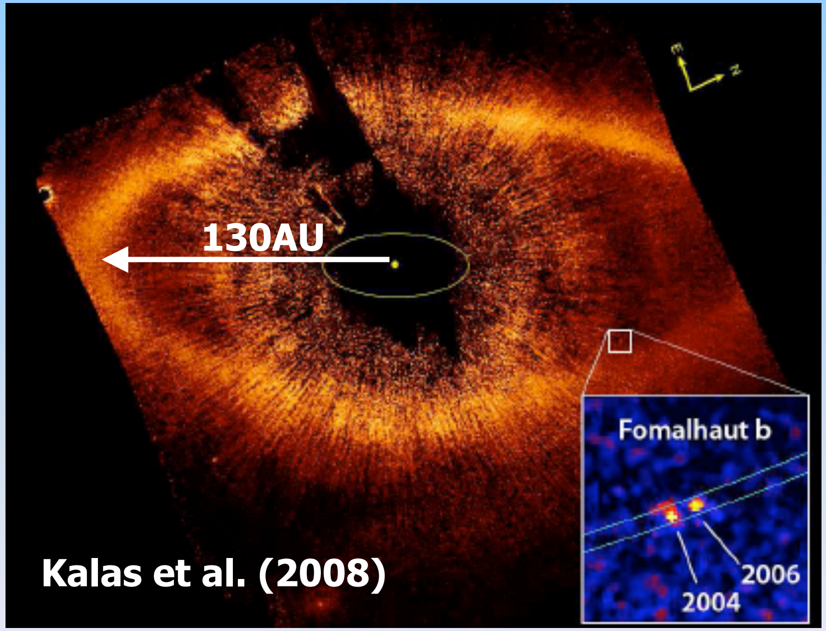
Extrasolar debris belts

Dust in extrasolar debris disks is typically inferred to originate from planetesimal rings analogous to the Kuiper belt

First evidence from SED: emission at a single (cold) temperature



Then confirmed in imaging



Kalas et al. (2008)

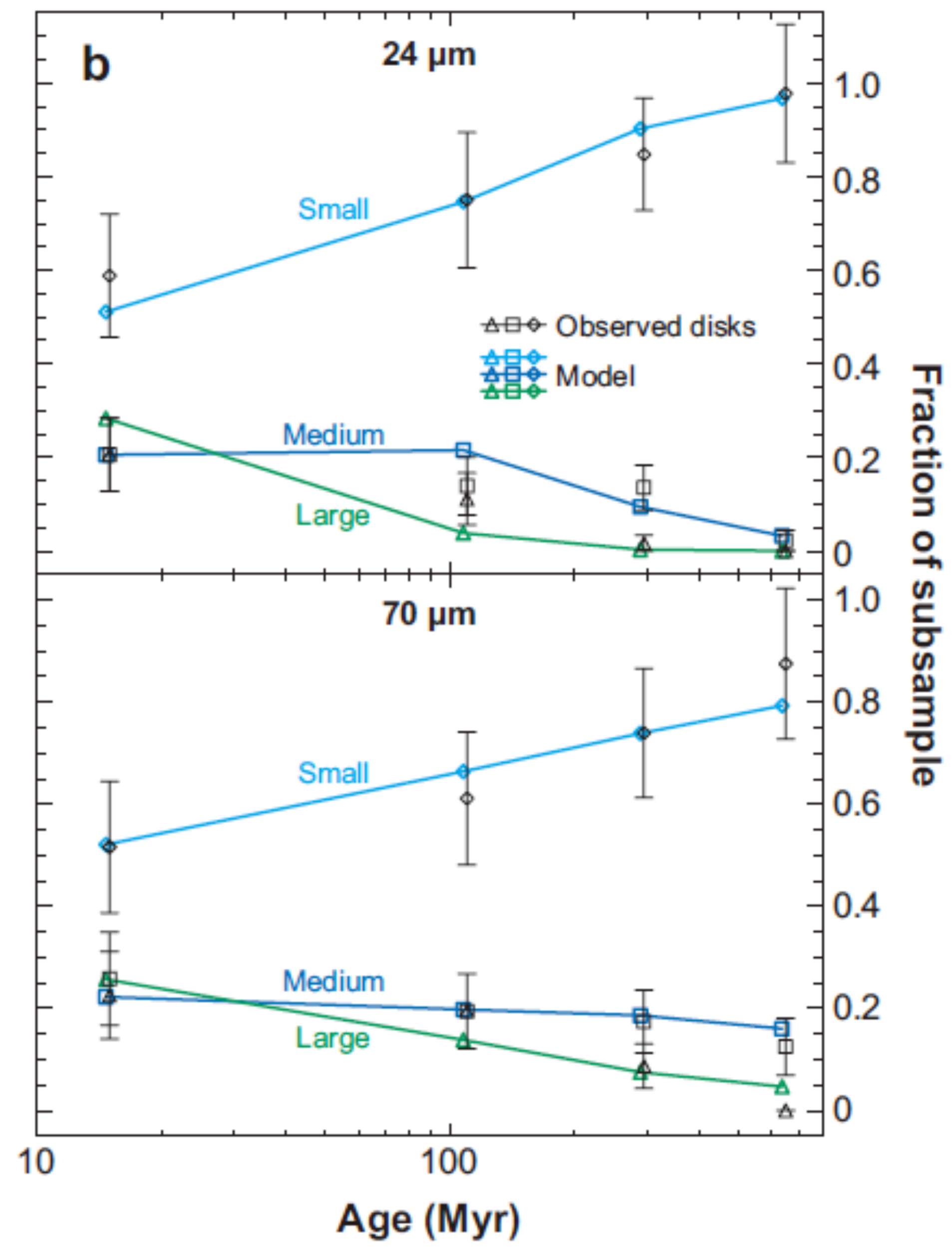
Discovery of planet at inner edge (Kalas talk) reinforces that ring radius indicative of planetary system structure

What is distribution of disk radii?

Small radii belts evolve faster than those at large radii, and small radii belts are detected at shorter wavelengths -> detection statistics as a function of age and wavelength are indicative of radius distribution

24 and 70µm statistics for A stars explained with population models:

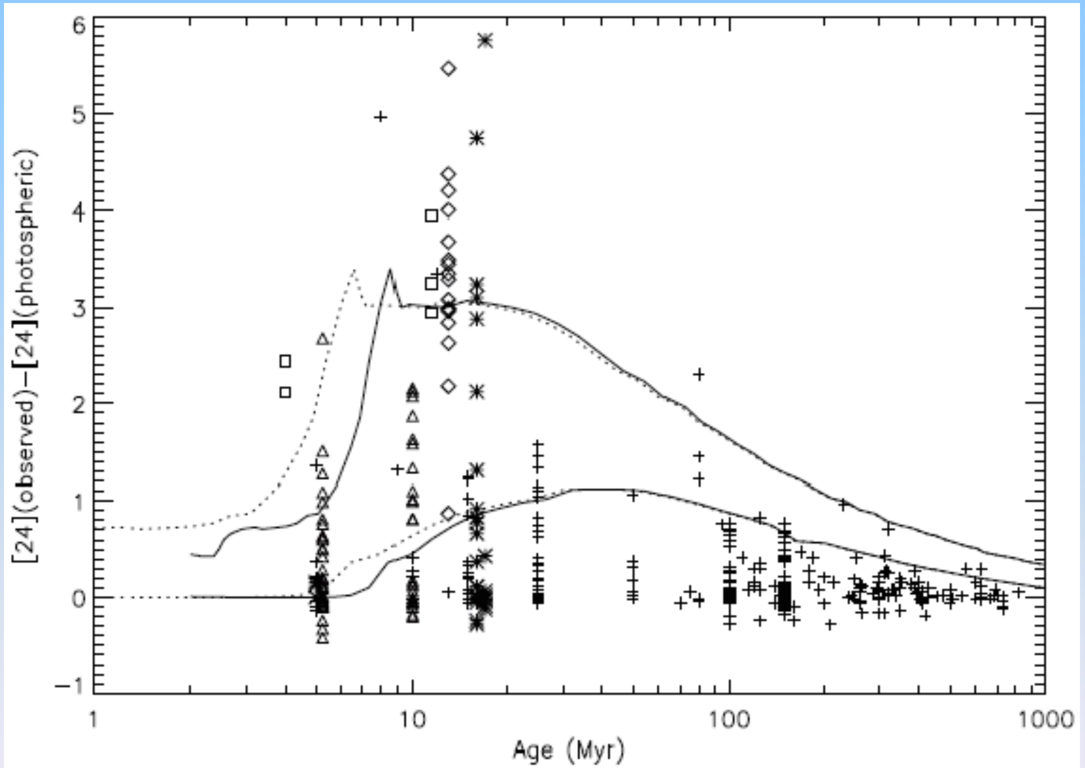
- All stars have one planetesimal belt that evolves in steady state from t=0
- Those belts have the same initial mass distribution as protoplanetary disks and radii $n(r) \propto r^{-0.8}$

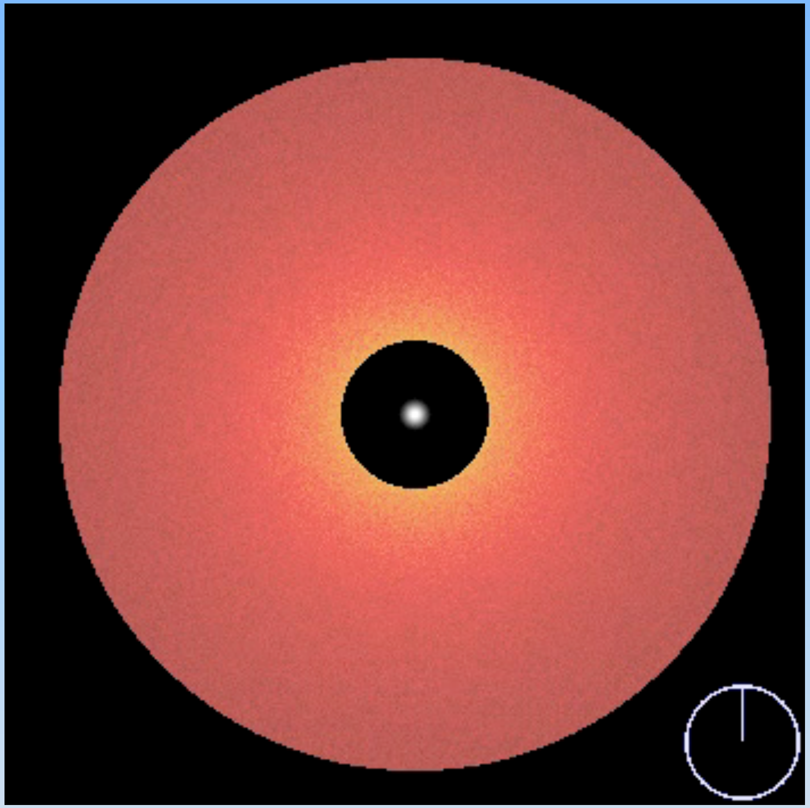


Wyatt et al. 2007

Peak of 24µm excess at 10-30Myr

After protoplanetary disk dispersal, 24µm excesses of A stars peak 10-30Myr (talk by Currie)



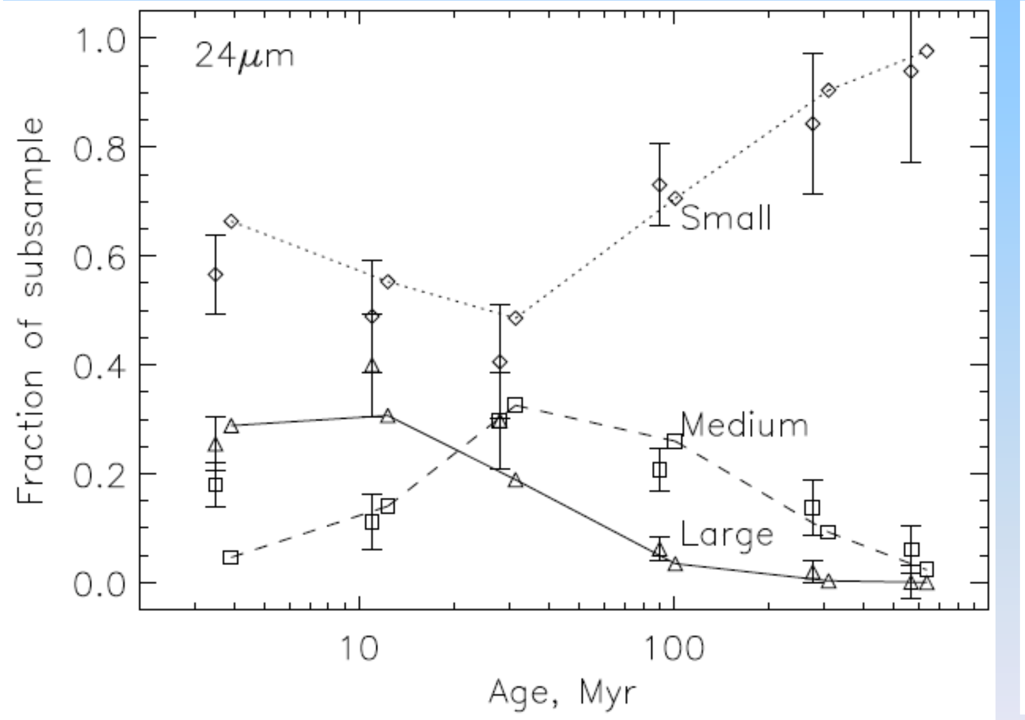


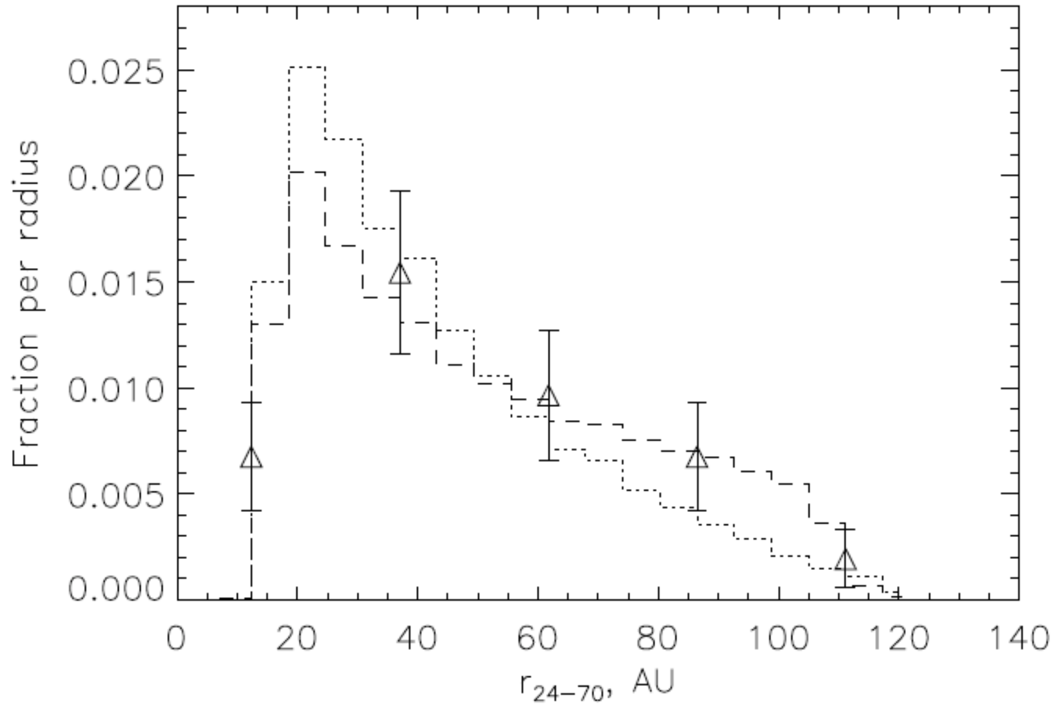
Typically interpreted as self-stirring (Kenyon & Bromley 2008)

Inferred radius distribution

Reanalysis of A star stats: reproduces peak in large-medium excesses at 10-30Myr with self-stirring (Kennedy & Wyatt, submitted):

Radius distribution: n(r) oc $r^{-0.8}$ between 15 and 120AU, and stats NOT fitted with extended disks

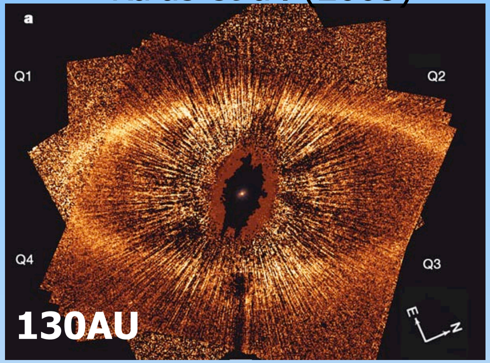




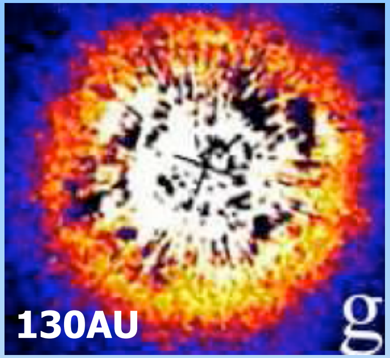
But are debris disks rings at predicted radii?

Imaging says: most often yes, but radii $\sim 2r_{24\text{-}70}$ as dust hotter than black body

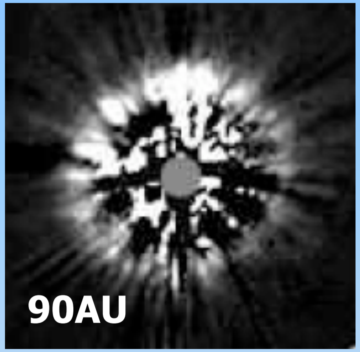
Fomalhaut
Kalas et al. (2005)



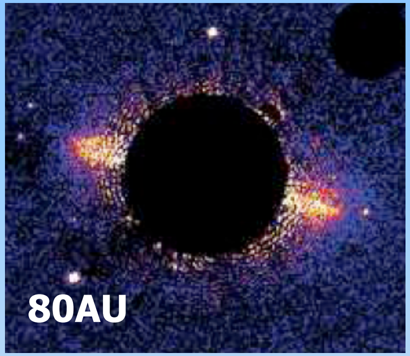
HD107146
Ardila et al. (2004)



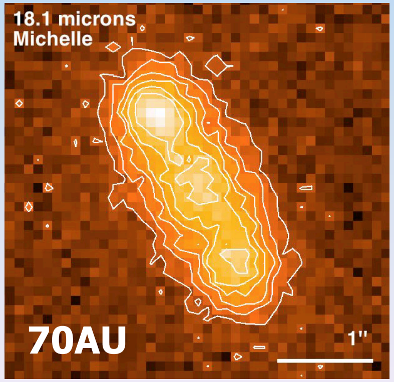
HD181327
Schneider et al. (2006)



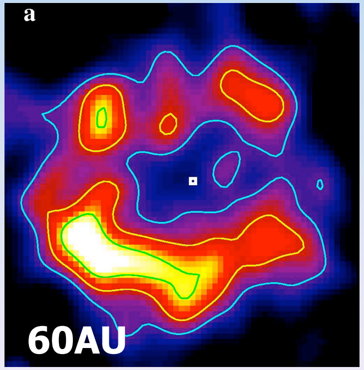
HD139664
Kalas et al. (2006)



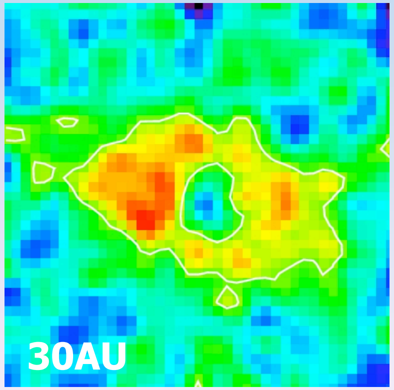
HR4796
Moerchen et al. (see poster)



ε Eridani
Greaves et al. (2005)



HD191089
Churcher et al. (in prep)

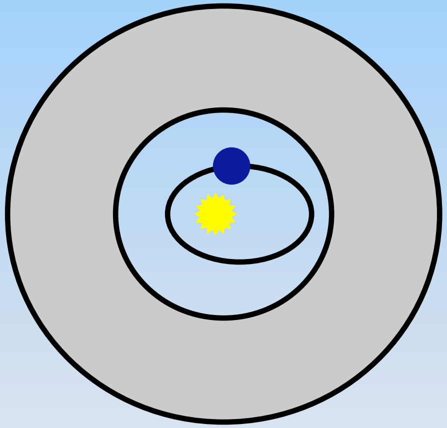


Is this radius distribution indicative of distribution of planetary system sizes?

Other evidence for planets at inner edge?

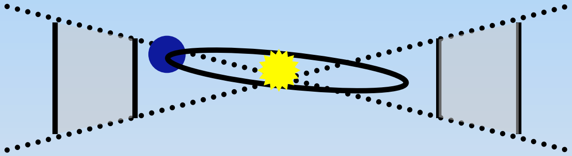
Consider planetesimal belt + one planet: simple planetary system dynamics predicts non-axisymmetric structures

1. Secular perturbations of eccentric planet



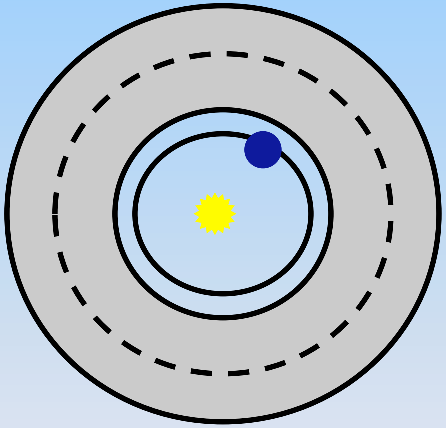
young disk = **spiral**
old disk = **offset+ brightness asymmetry**

2. Secular perturbations of inclined planet



young disk or multiple planets in old disk = **warp**

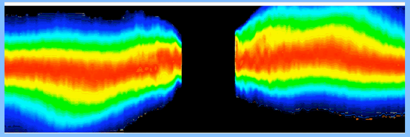
3. Resonant perturbations

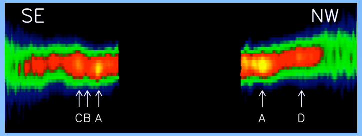


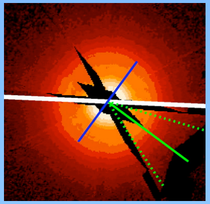
multiple planets = **clearing**
individual planet = **clumps**

Extrasolar debris disks are asymmetric

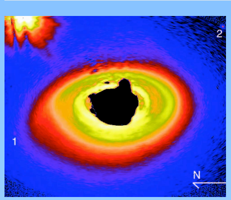
Warps



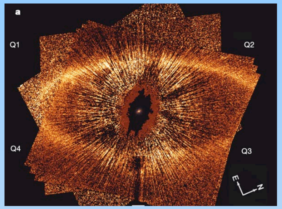


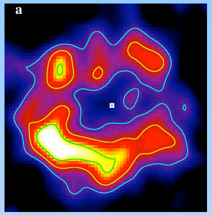


Spirals



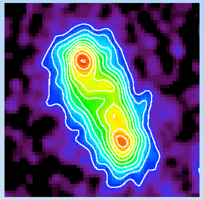
Offsets

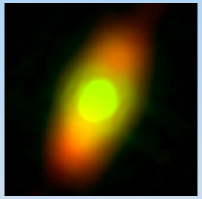


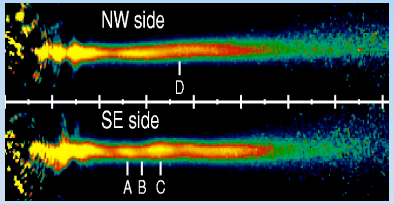


This set of structures is exactly that observed in disk images

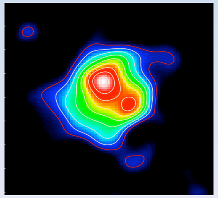
Brightness asymmetries

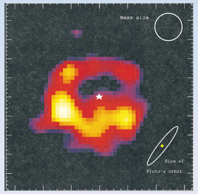


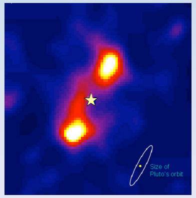


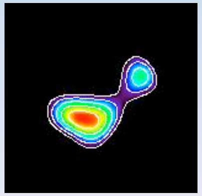


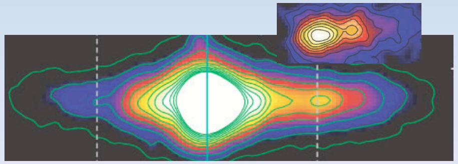
Clumpy rings







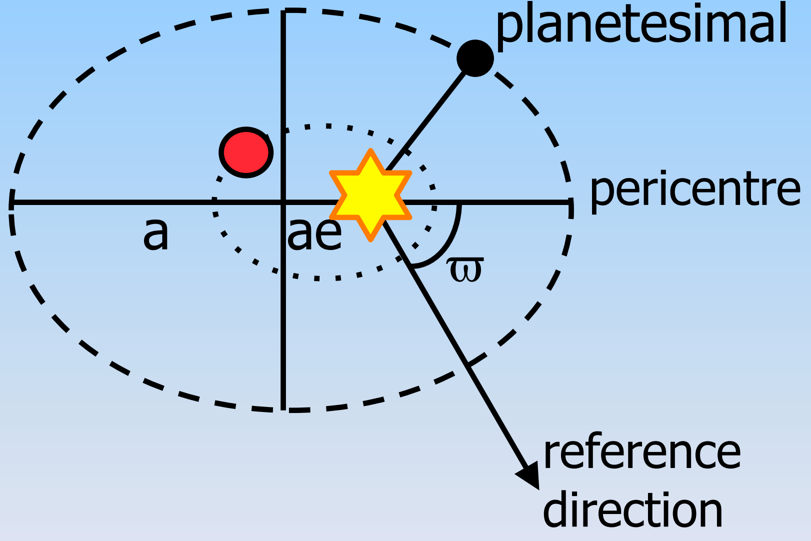


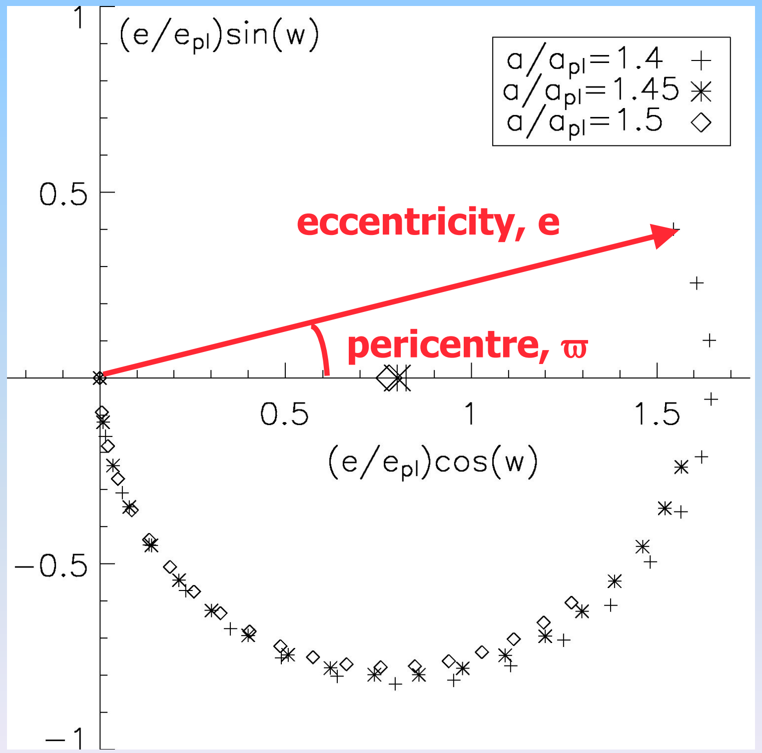


Most structures interpreted as planetary perturbations, although other explanations possible in some cases (posters by Manness and Debes)

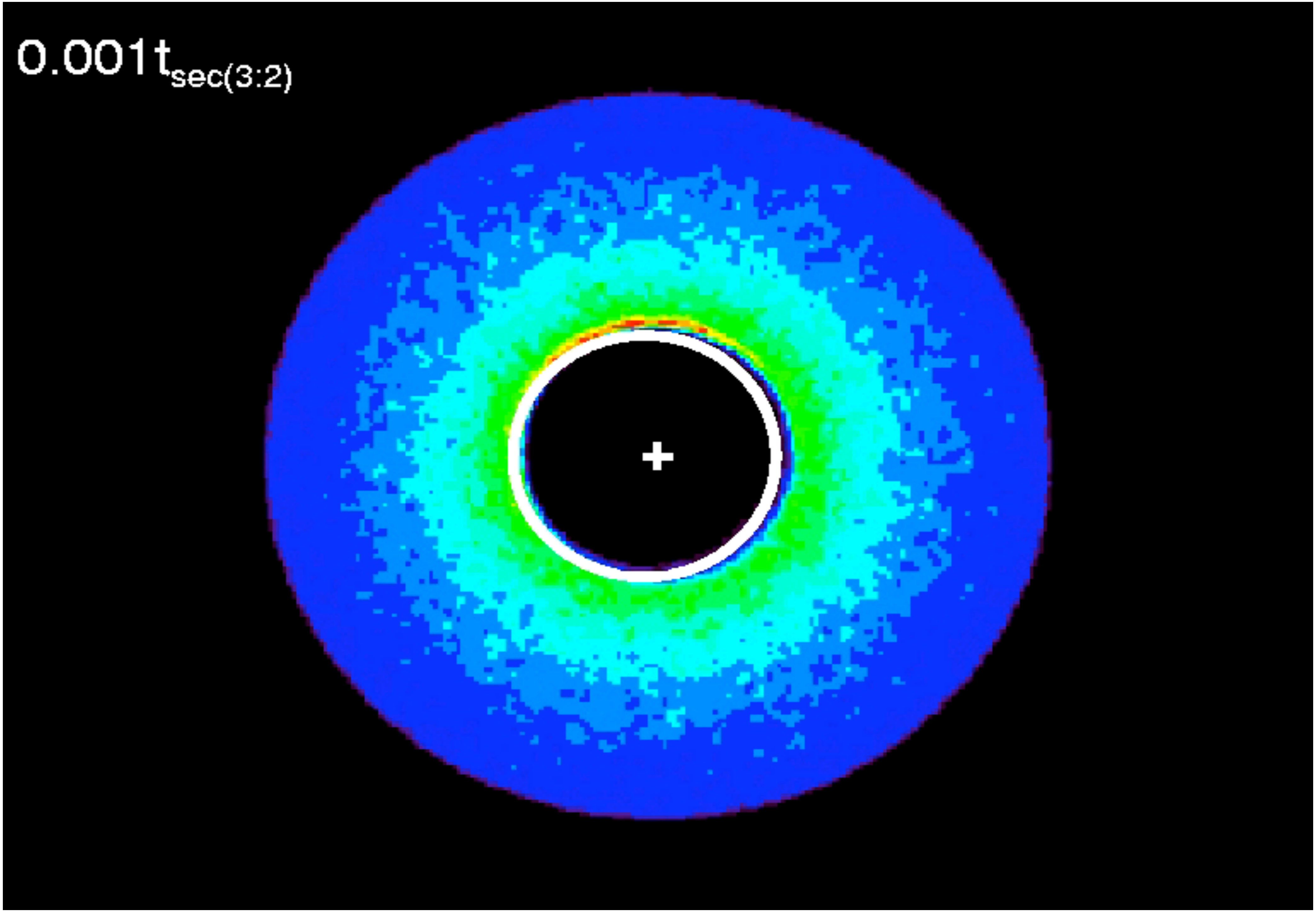
Secular perturbations of eccentric planet

The secular perturbations of a planet on an eccentric orbit make the eccentricity vectors of planetesimals precess around a forced eccentricity with a rate that is slower for planetesimals further from planet



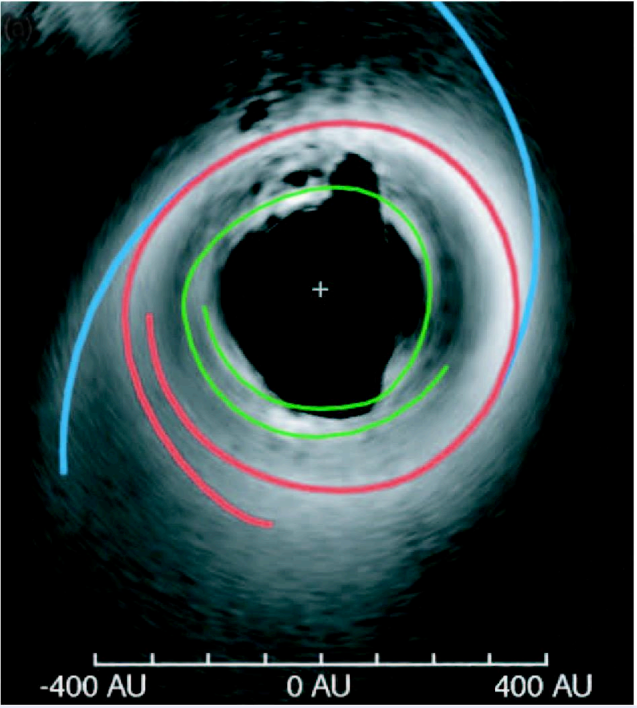


Wyatt (2005)


0.001t_sec(3:2)

Consequences of eccentric planet

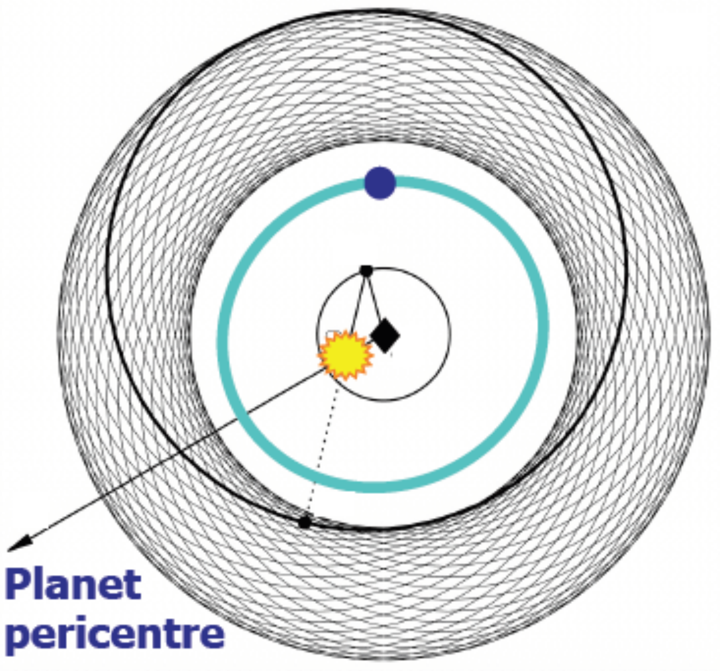
- Imposes spiral structure on extended disk which may be seen in young disks like HD141569 (Wyatt 2005)



Clampin et al. (2003)

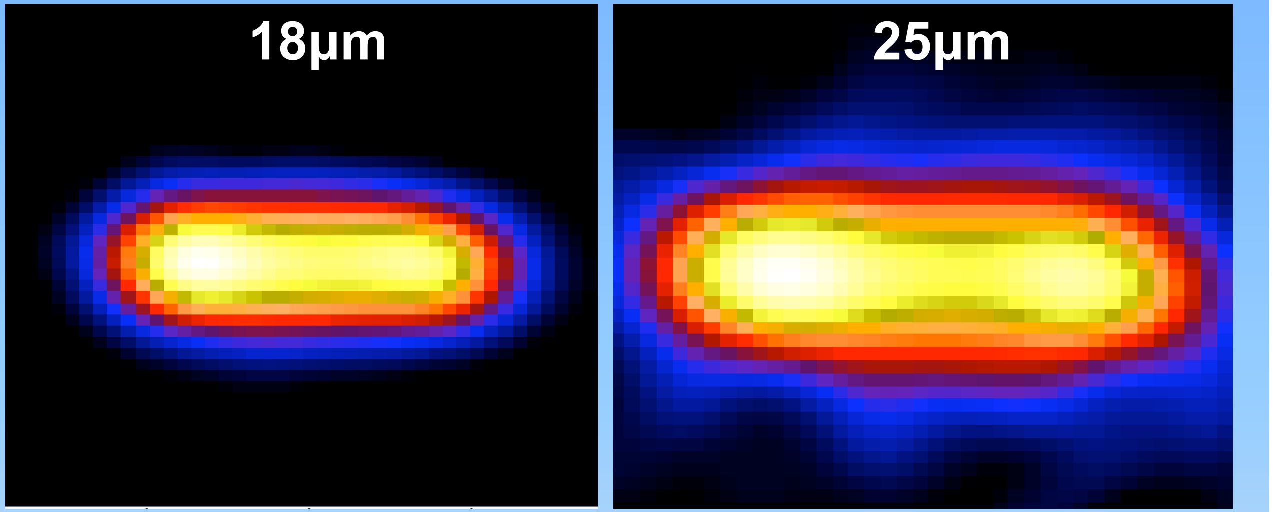
- Stirs planetesimal velocities truncating planet growth and igniting collisional cascade (Mustill & Wyatt 2009)

- Causes old rings to have centre of symmetry offset from star (Wyatt et al. 1999)

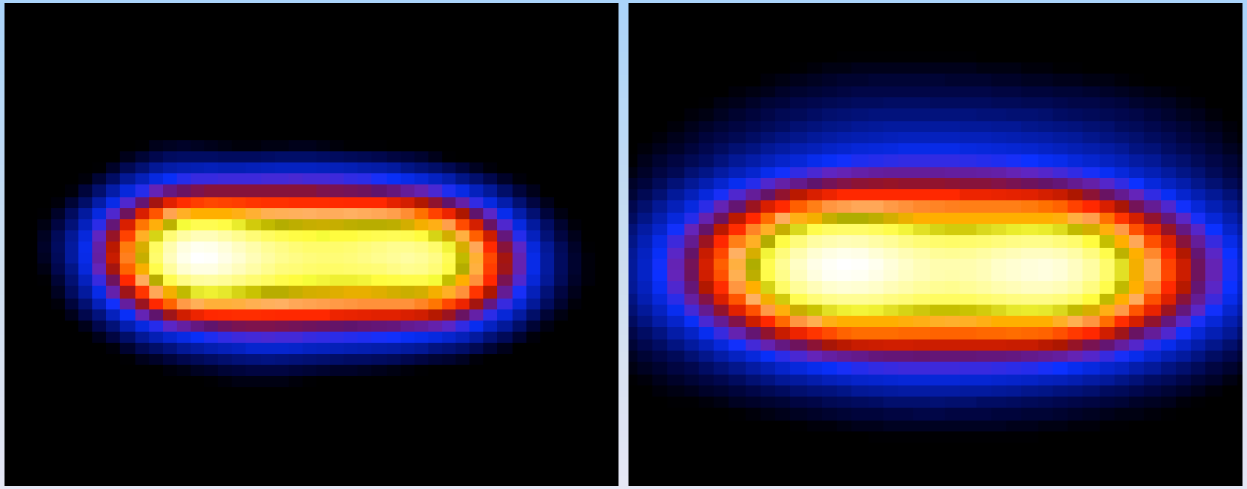


Pericentre glow in HR4796

Observations of the 70AU radius ring of HR4796 (A0V, 10Myr) confirm 13-15% brightness asymmetry at 18 and 25µm (Moerchen et al. in prep, see poster)



Images simultaneously fit by "pericentre glow" model: planet with $e_{pl}=0.06$ causes offset centre to ring causing one side to be hotter and brighter

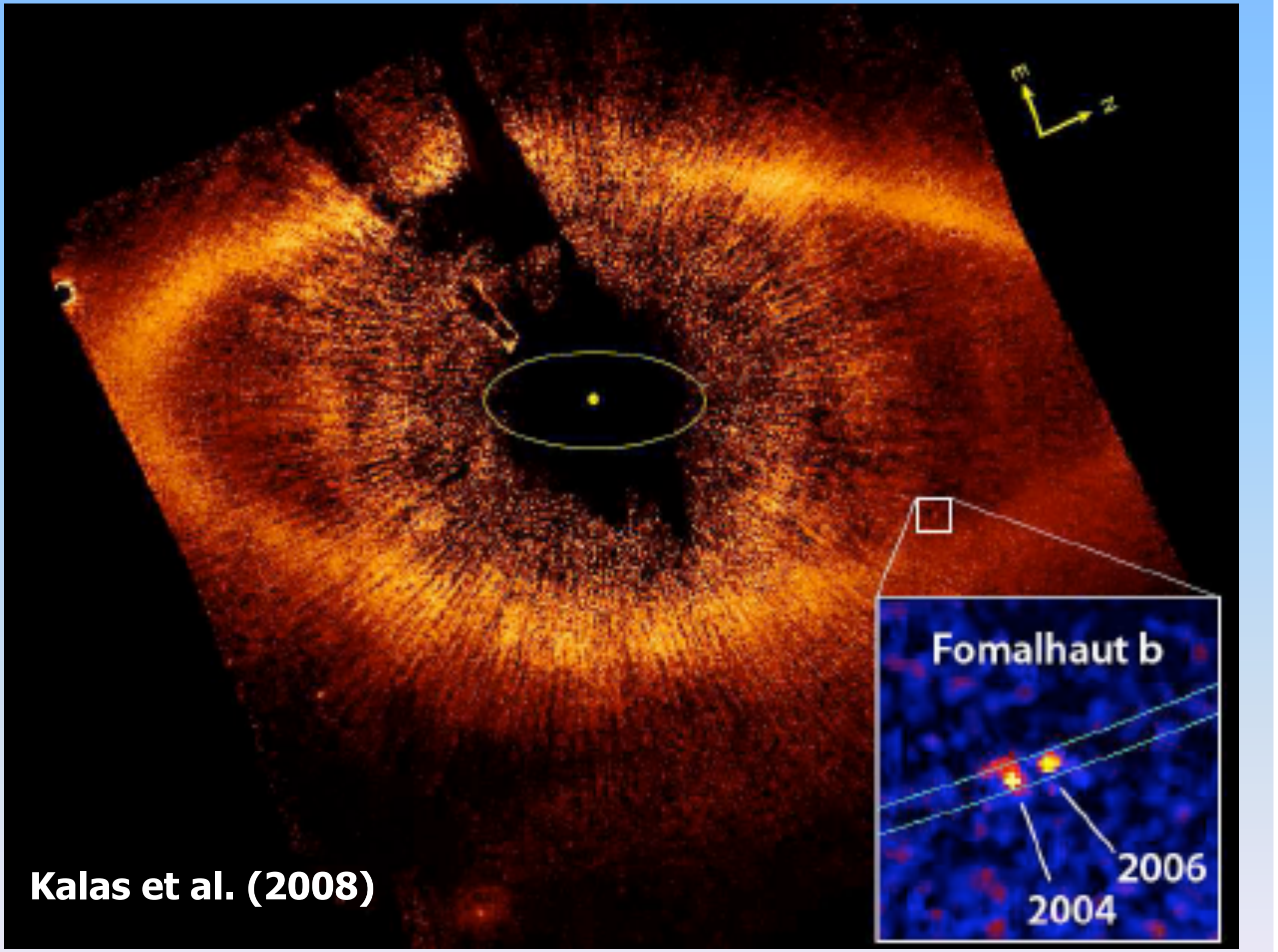


Offset and asymmetry tentatively seen in scattered light too (Schneider et al. 2009)

Offset in Fomalhaut

Offset confirmed in HST imaging of Fomalhaut showing 133AU radius ring with 15AU offset implying forced eccentricity of 0.1 (Kalas et al. 2005)

Eccentricity and sharp inner edge used to predict planet close to inner edge (Quillen 2006), now confirmed (Kalas et al. 2008)

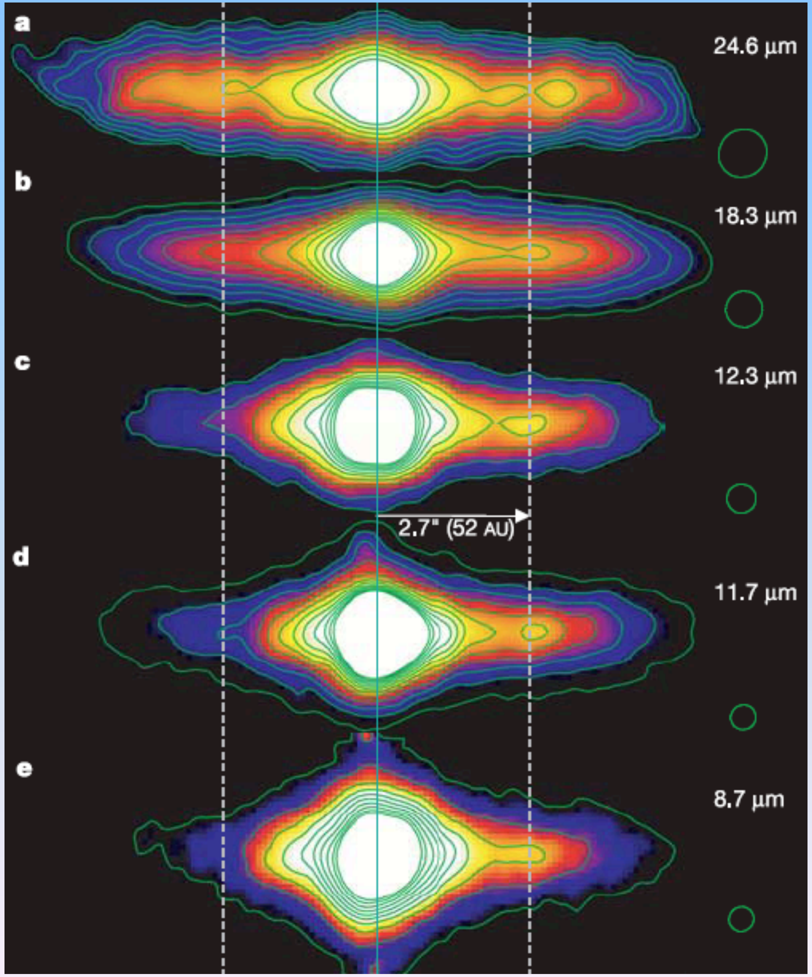


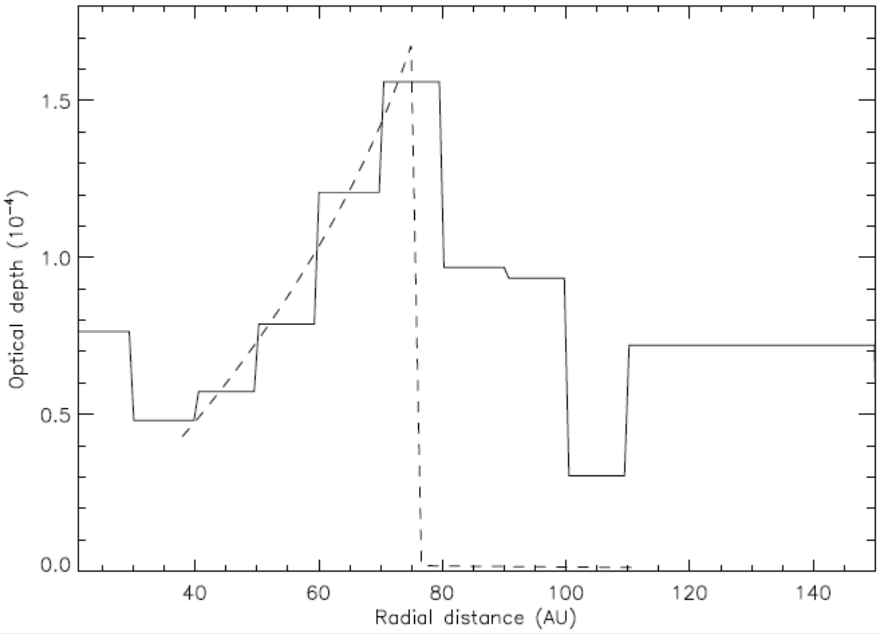
Kalas et al. (2008)

NB: sharp inner edge needed to say where planet is, as eccentricity could be caused by distant planet

Shallow inner edge from distant planet

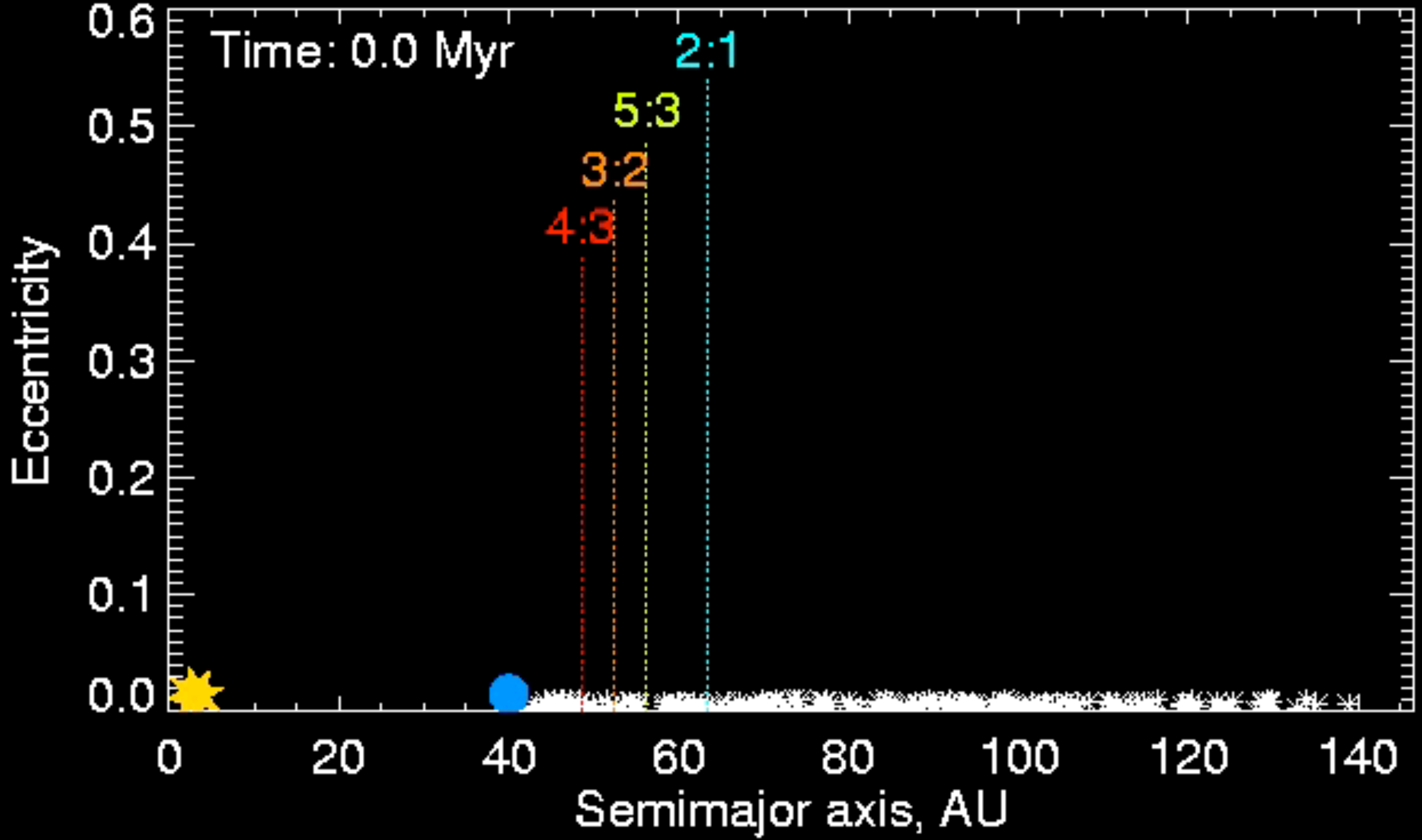
The β Pic disk has a shallow inner edge determined from multiwavelength mid-IR imaging (Telesco et al. 2005)



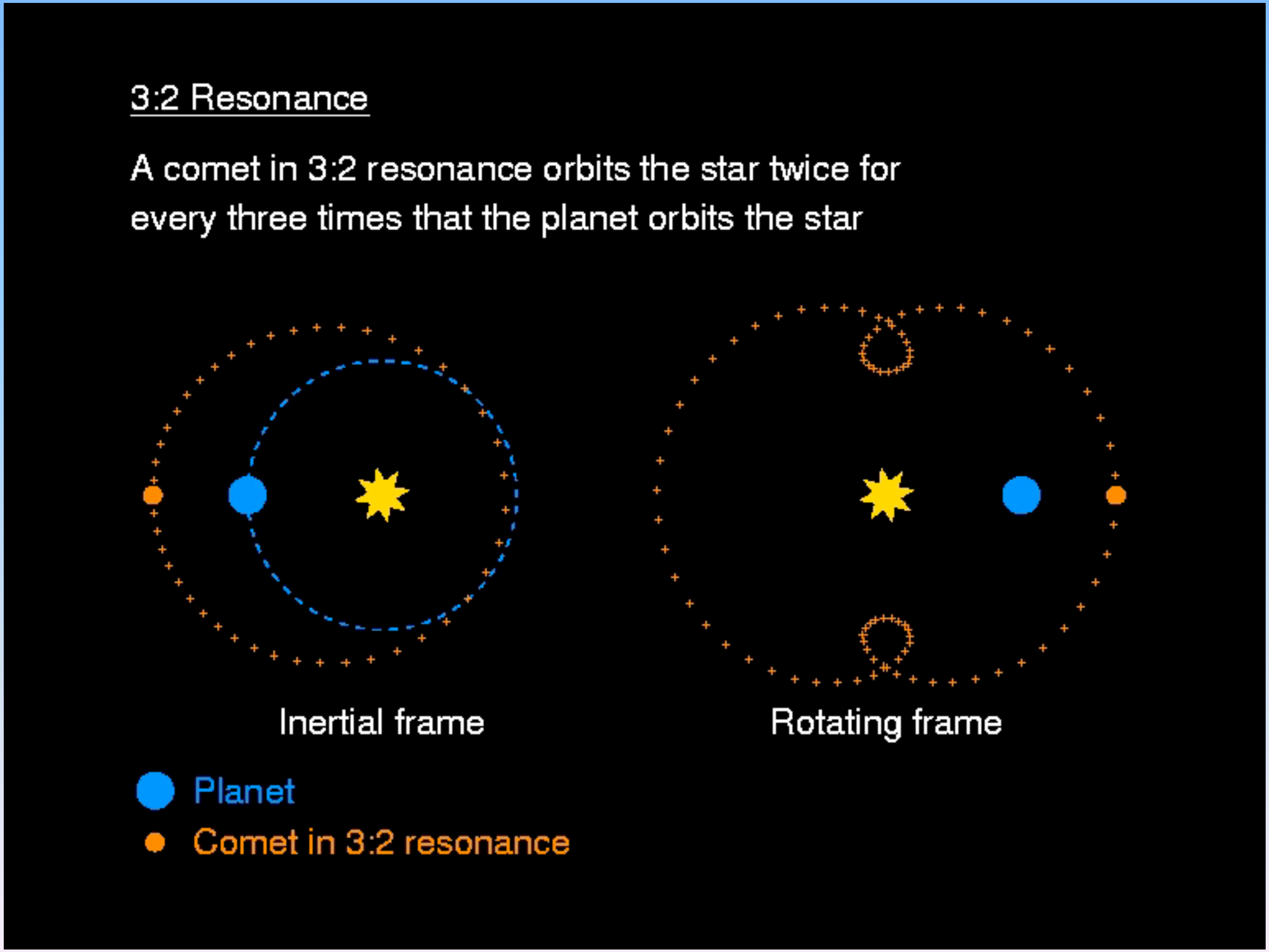


Consistent with stirring by secular perturbations (Mustill & Wyatt 2009) from the giant planet at 10AU (Lagrange et al. 2008) where 75AU is recently stirred region inside of which has been depleted in collisions (Kennedy & Wyatt submitted)

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



Geometry of resonances



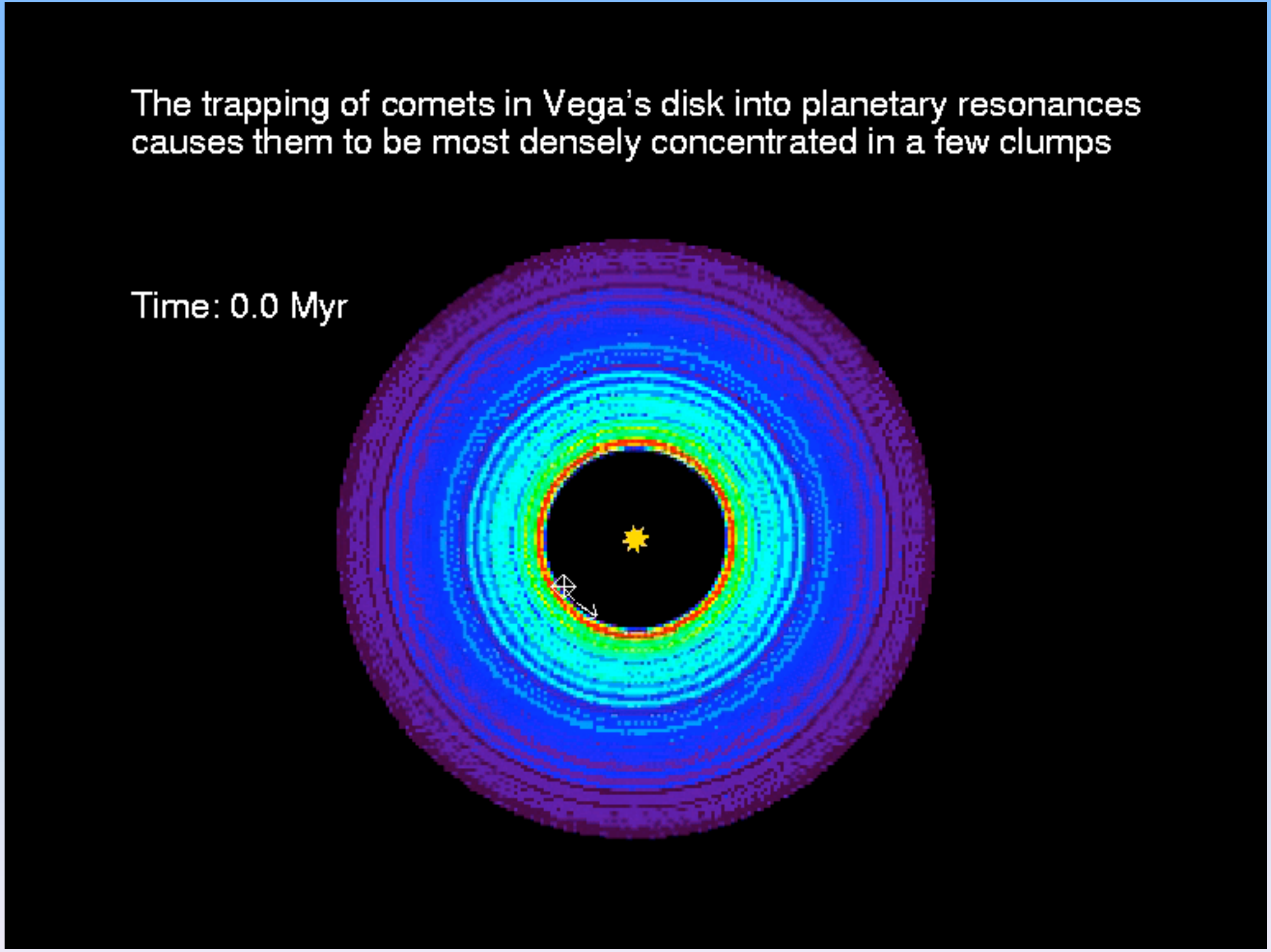
3:2 Resonance

A comet in 3:2 resonance orbits the star twice for every three times that the planet orbits the star

Clumps constrain planet parameters

The geometry of resonant orbits makes the disk clumpy

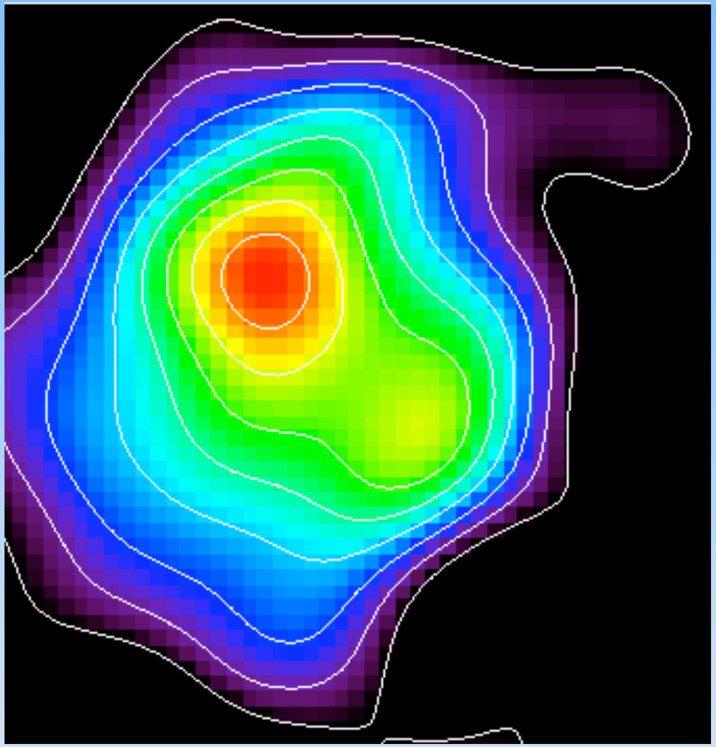
Resulting clumpy structure depends on planet mass, migration rate and eccentricity so these can be constrained from observations of a clumpy disk



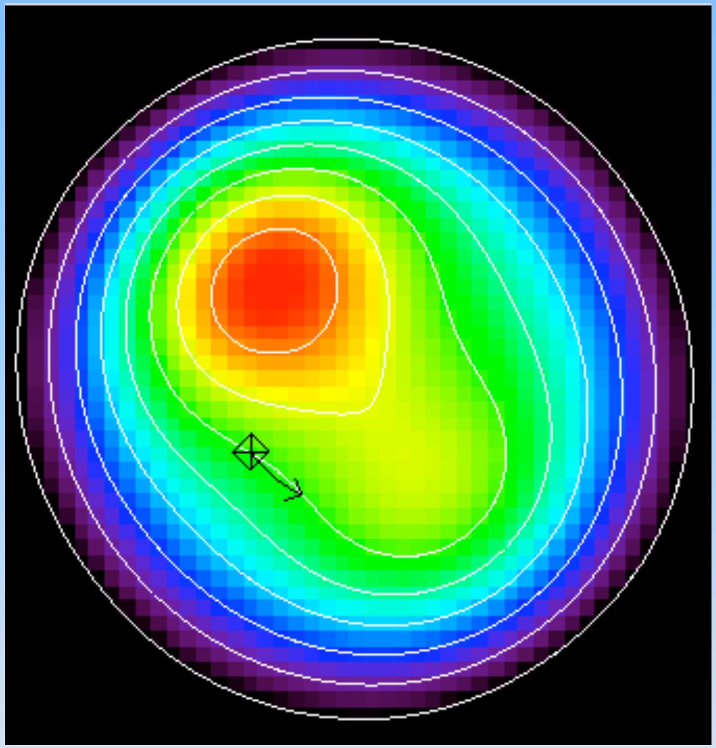
The trapping of comets in Vega's disk into planetary resonances causes them to be most densely concentrated in a few clumps

Prediction for Vega’s evolutionary history

Observation



Model



This model explains the clumpy structure of Vega’s sub-mm disk (Holland et al. 1998)

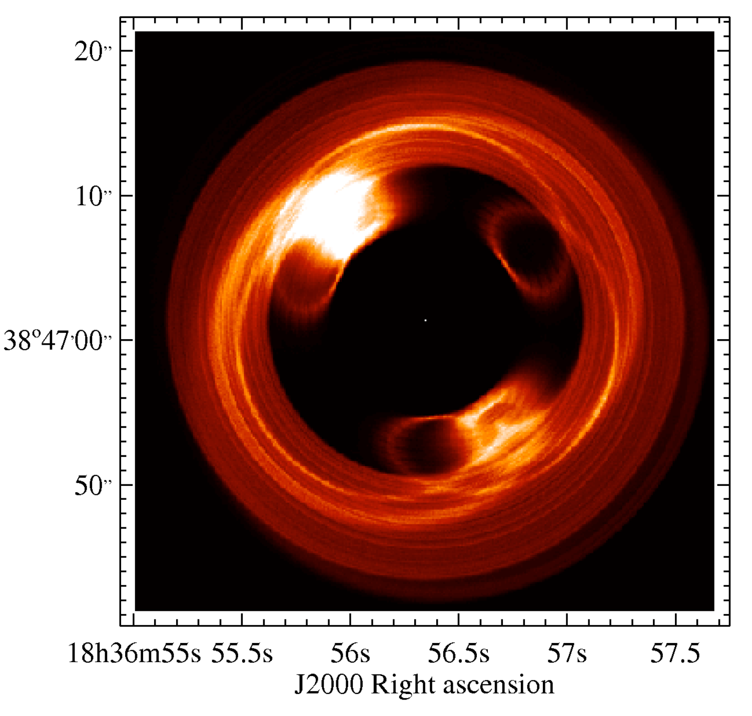
Prediction: there is a $1M_{neptune}$ which migrated 40-65AU over 56Myr, although a more massive planet with faster migration is also possible (Wyatt 2003)

Testing prediction

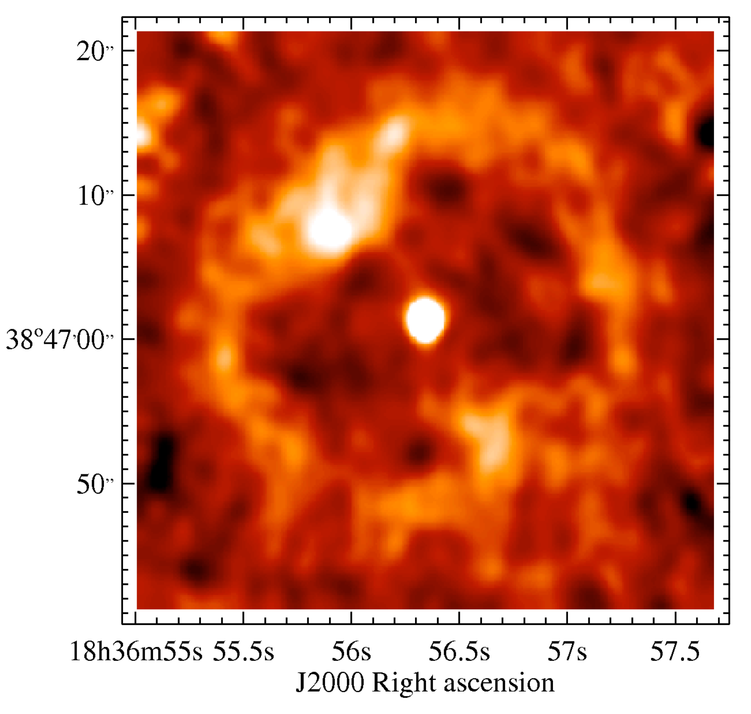
Model predicts:

- orbital motion (test with SCUBA2)
- detailed structure (further constrain planet mass and migration history)

Model surface brightness



Simulated ALMA observation

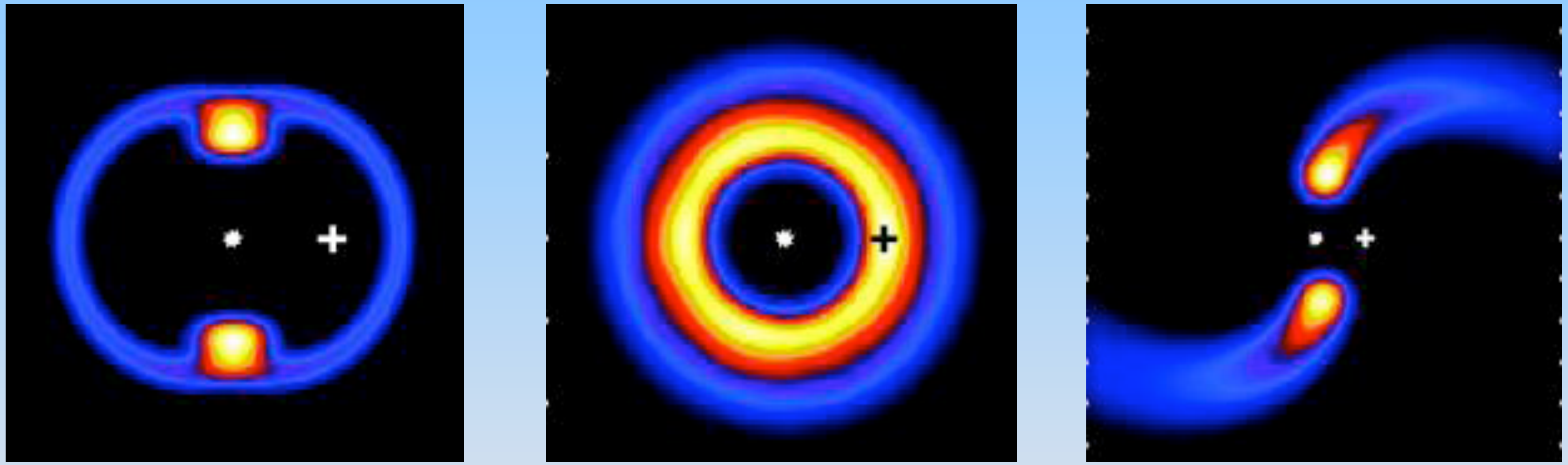


CASA almasimmos tool using 12 hours of observations over 3 configurations and ACA

Main disk features can be resolved by ALMA at 850μm (Rob Reid and Rachel Smith)

Multiple wavelengths help constrain model

Clumpy resonant structure is a function of grain size, as small grains fall out of resonance by radiation pressure (Wyatt 2006)

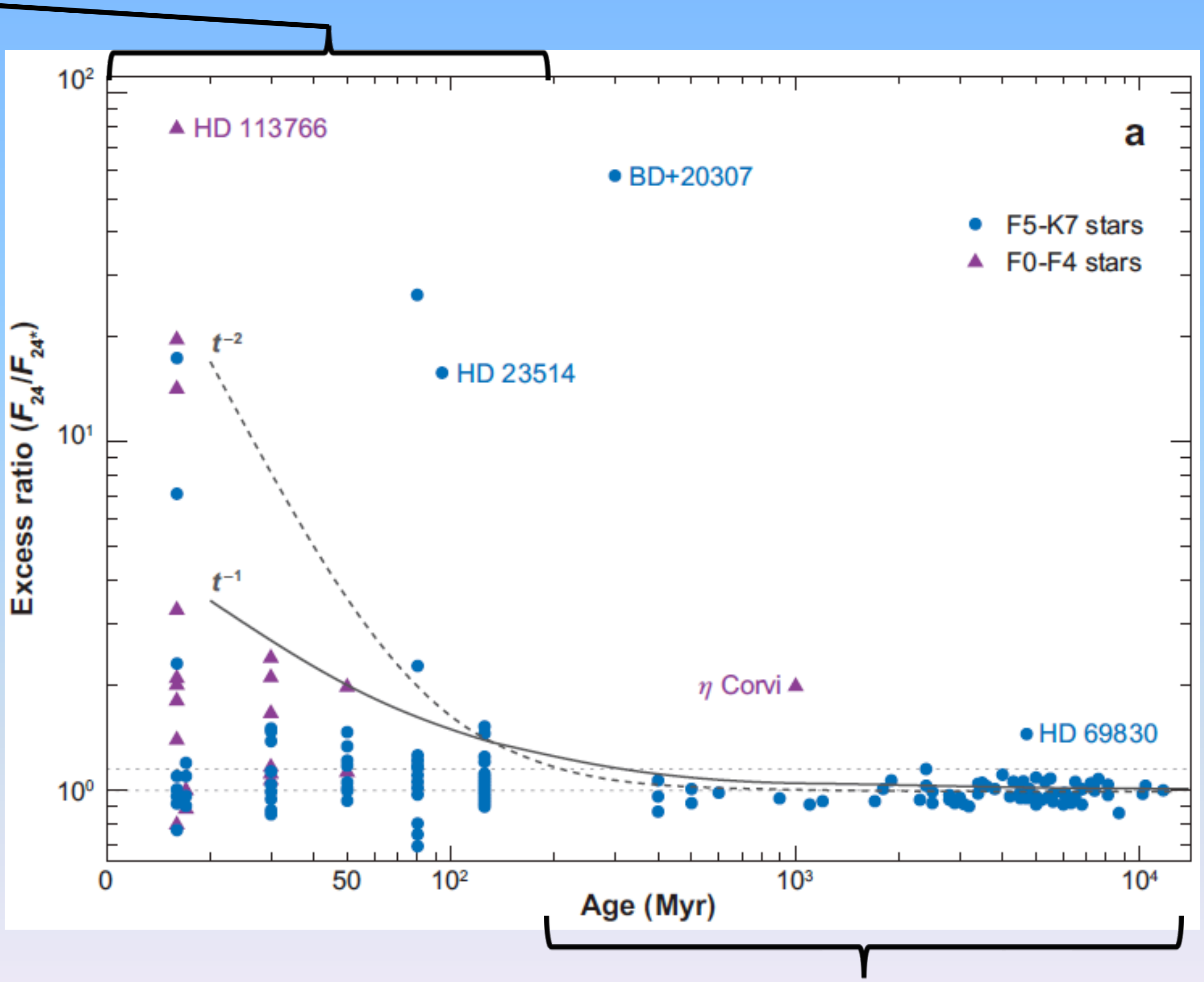


Grain size	Large	Medium	Small
Wavelength	>850µm	100-850µm	<100µm

Observations at different wavelengths probe different grains sizes and the predicted transition from clumpy to smooth structure occurs in the sub-mm

Rarity of hot dust

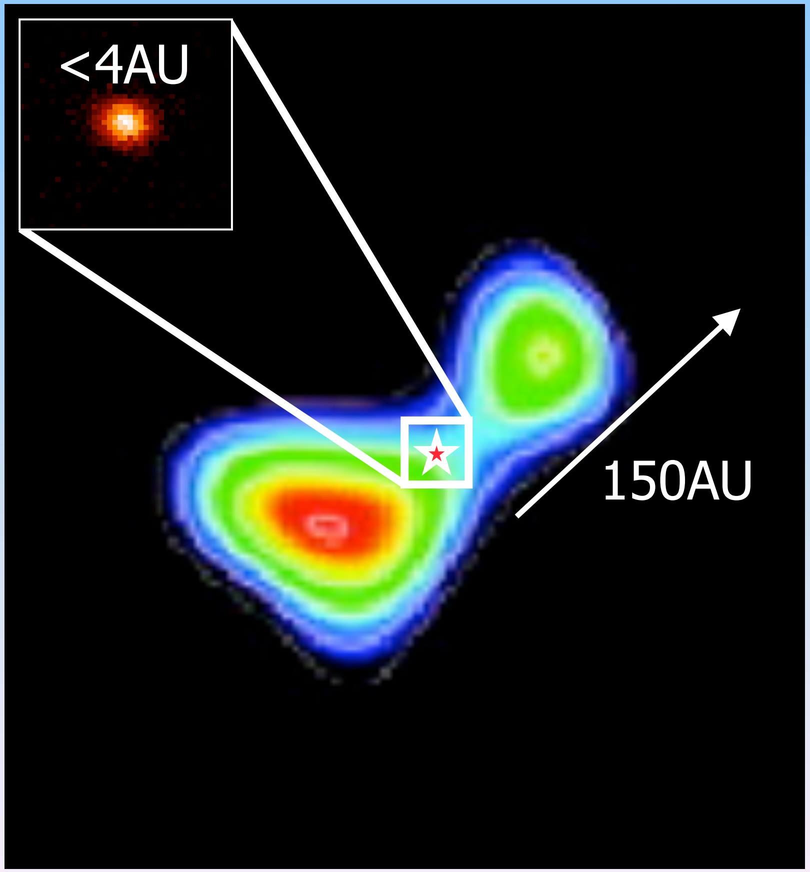
Hot dust present around <200Myr Sun-like stars, some may be terrestrial planet forming impacts (Lisse et al. 2008,2009)

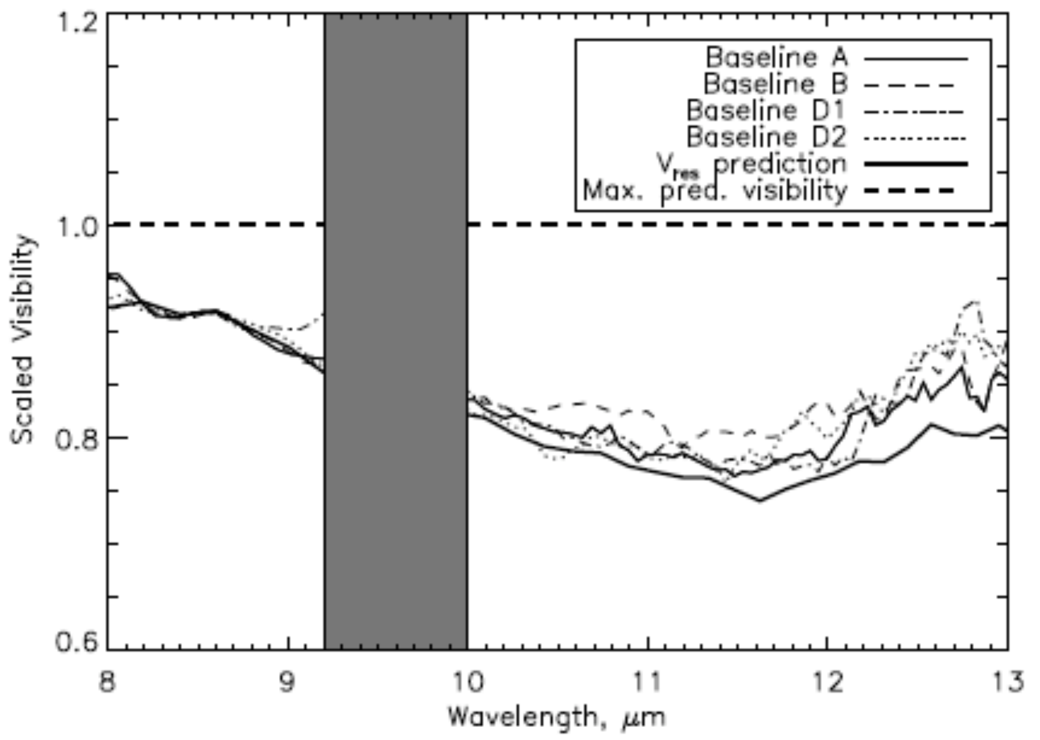


But hot dust is rare >200Myr occurring around < few %

η Corvi's multiple component disk

150AU planetesimal belt imaged at 450µm (Wyatt et al. 2005) but 18µm emission is <4AU (Smith, Wyatt & Dent 2008)

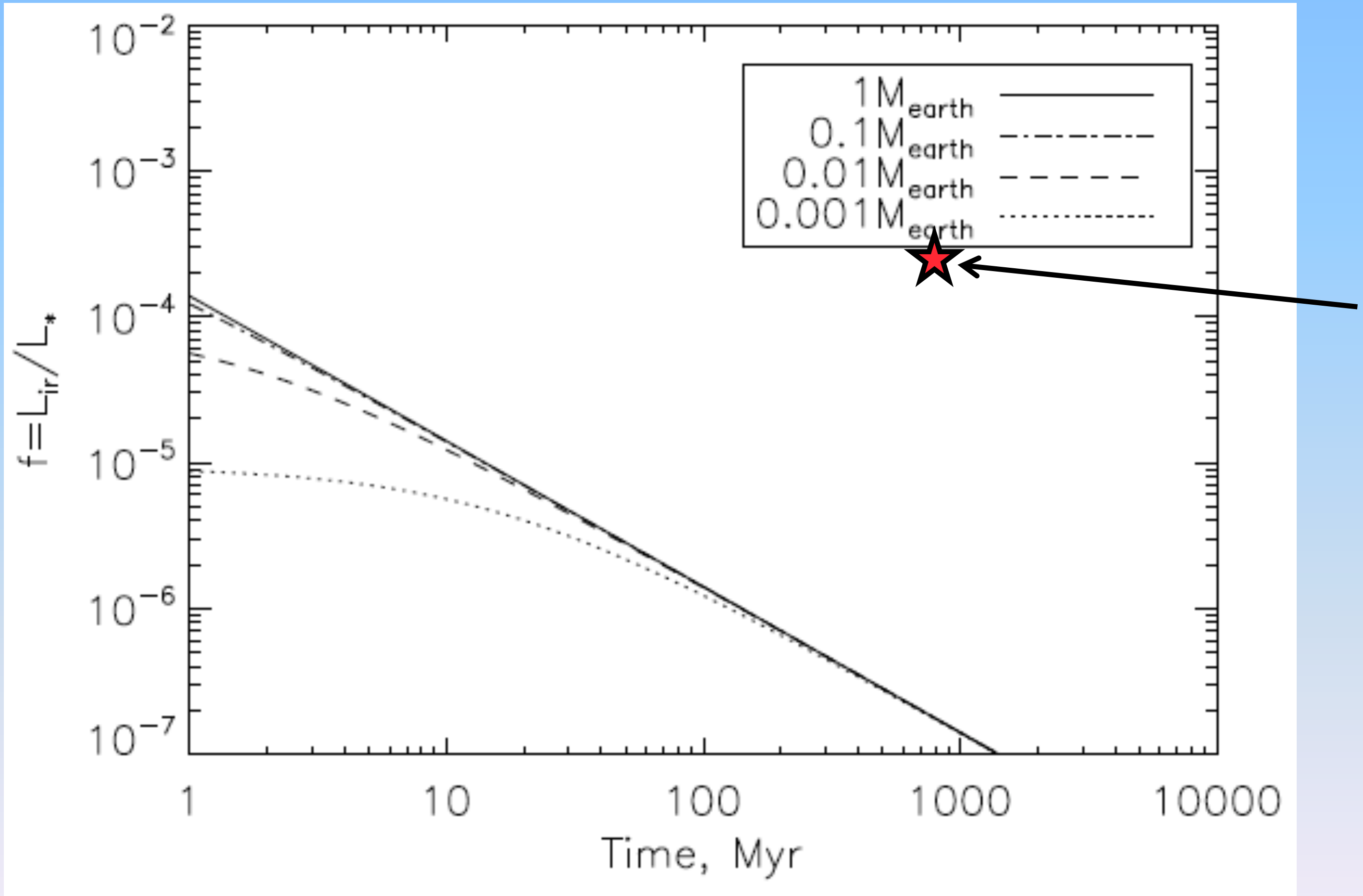




MIDI visibility vs wavelength across 8-13µm implies completely resolved so >0.5AU (Smith, Wyatt & Haniff 2009)

Transience of hot dust

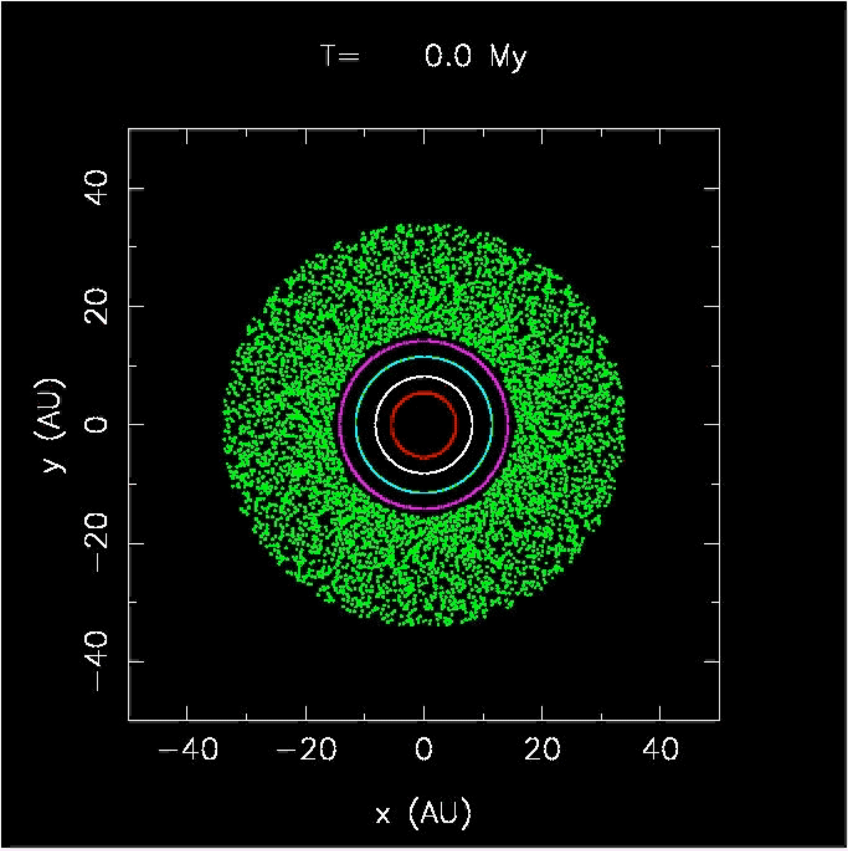
Not asteroid belt as close-in disks quickly drop below detection threshold by collisional erosion; e.g., luminosity evolution of 1AU belt (Wyatt et al. 2007):

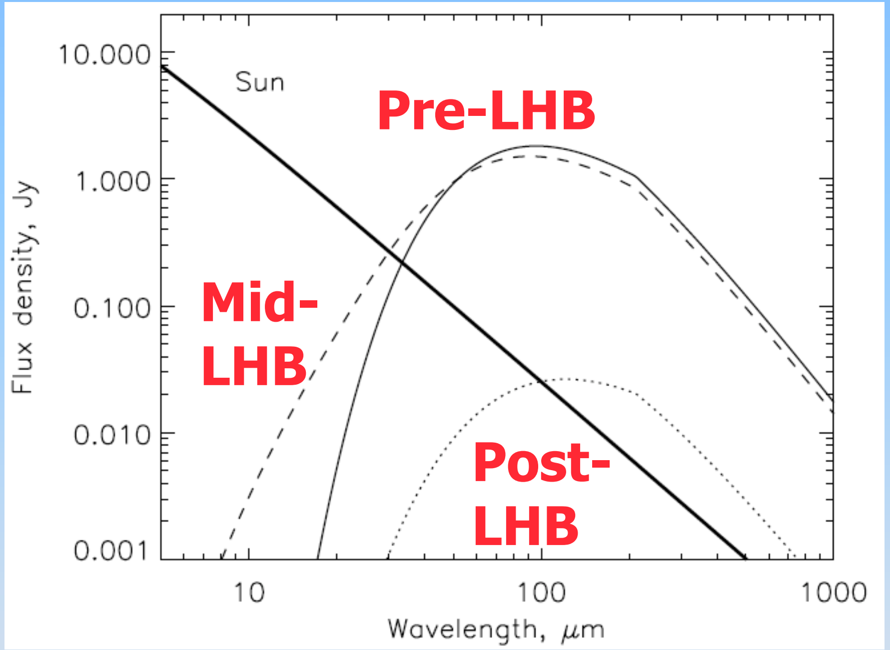


η Corvi is several orders of magnitude too bright for its age

Origin in Late Heavy Bombardment?

Hot dust could be event like the LHB when the inner solar system bombarded due to dynamical instability when Jupiter and Saturn crossed 2:1 resonance (Gomes et al. 2005)

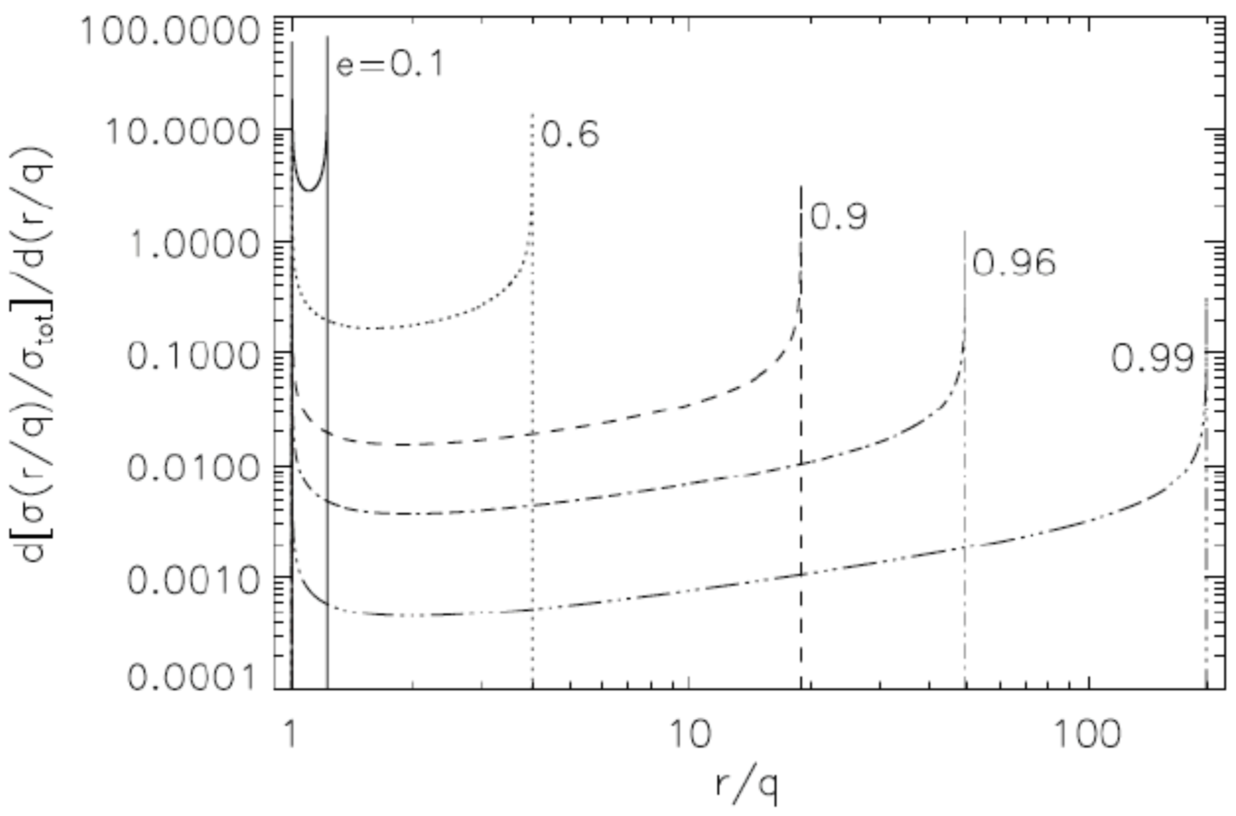




Predict that mid-IR emission would be increased during LHB (Booth et al., 2009)

Is a long-lived eccentric disk the solution?

Consider steady-state evolution of planetesimal belt with pericentre fixed at 1AU, but increasing eccentricity (Wyatt et al., in press):



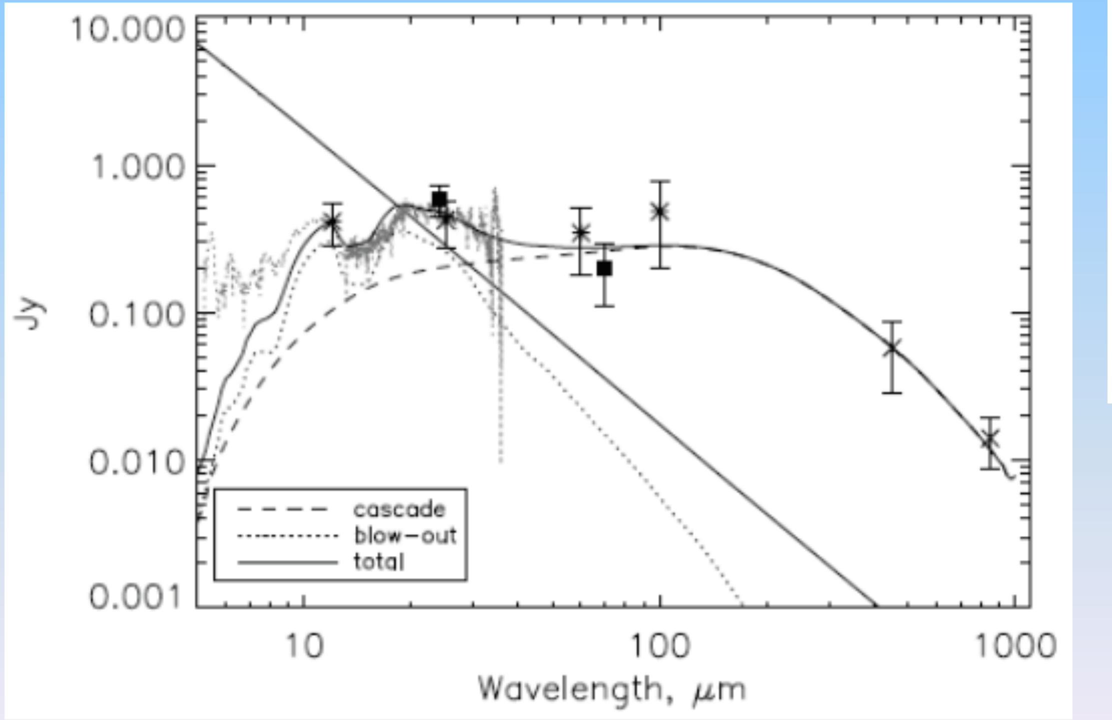
- Density peaks at pericentre and apocentre

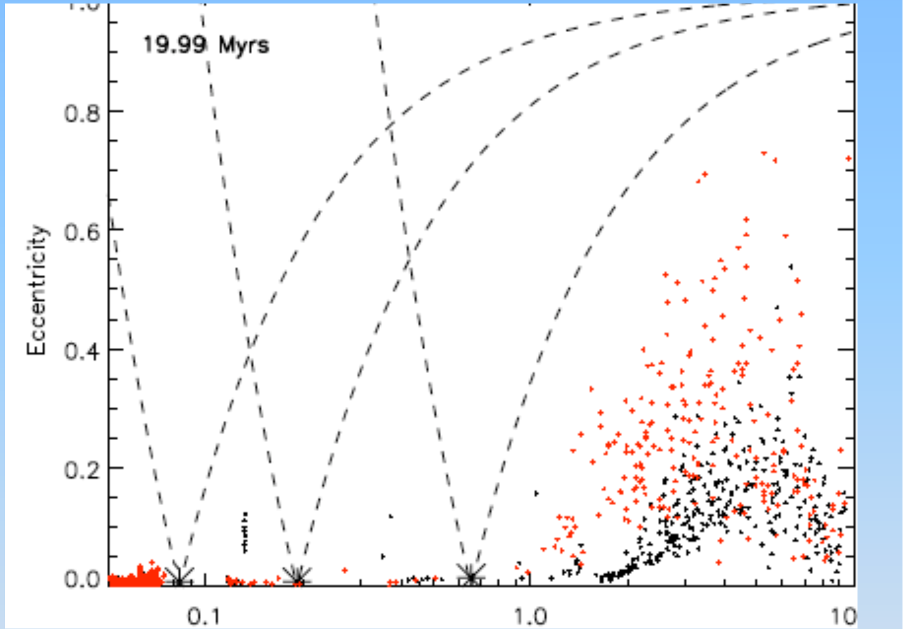
- Collision timescale increases

- Most collisions occur at pericentre: wind of particles blown out from pericentre by radiation pressure

An alternative model for η Corvi

The emission spectrum and all imaging constraints can all be explained with a planetesimal belt that has a pericentre at 0.75AU, an apocentre at 150AU, and current mass $5M_{earth}$ (Wyatt et al., in press)

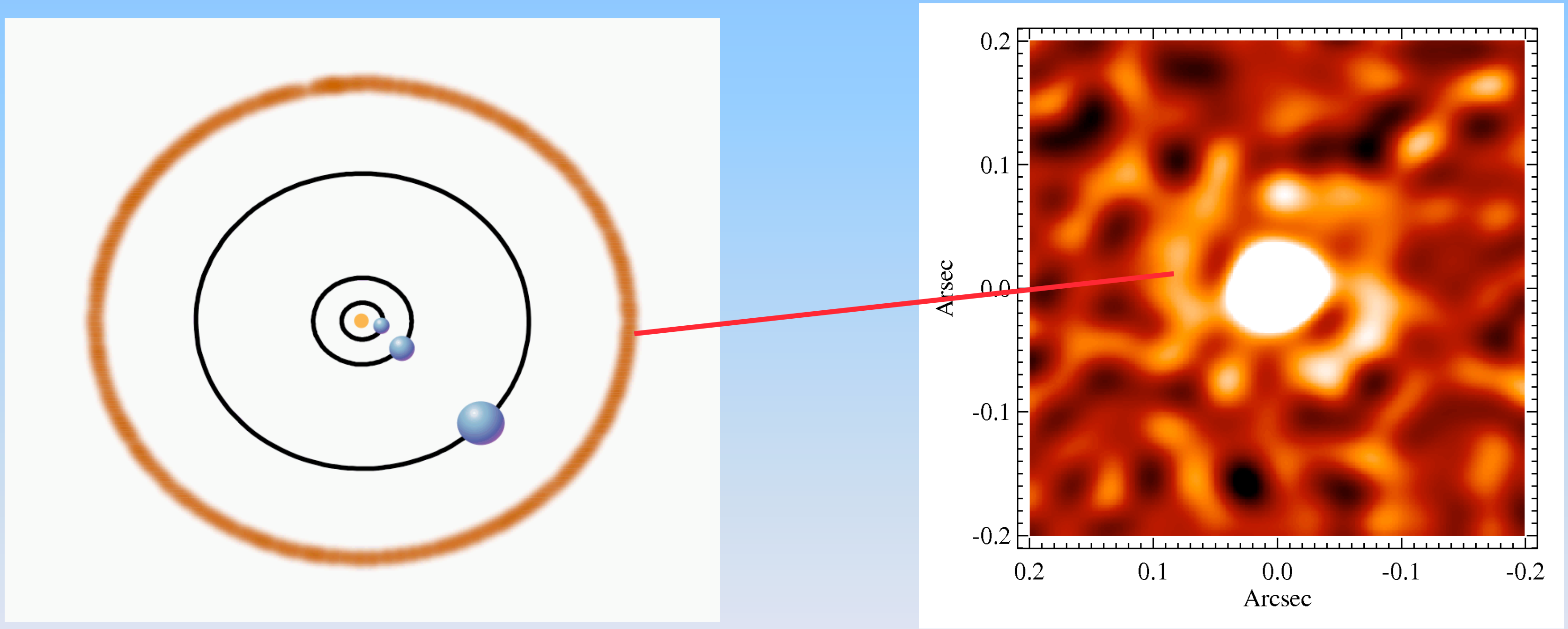




Could such an eccentric ring be an extreme outcome of planet formation, e.g. by migration of planets through planetesimal disk (Payne et al. 2009)

Imaging terrestrial planet region with ALMA

Simulation of 1AU (0.1arcsec) ring around HD69830 in 12 hours
with ALMA at 850μm using multiple configurations

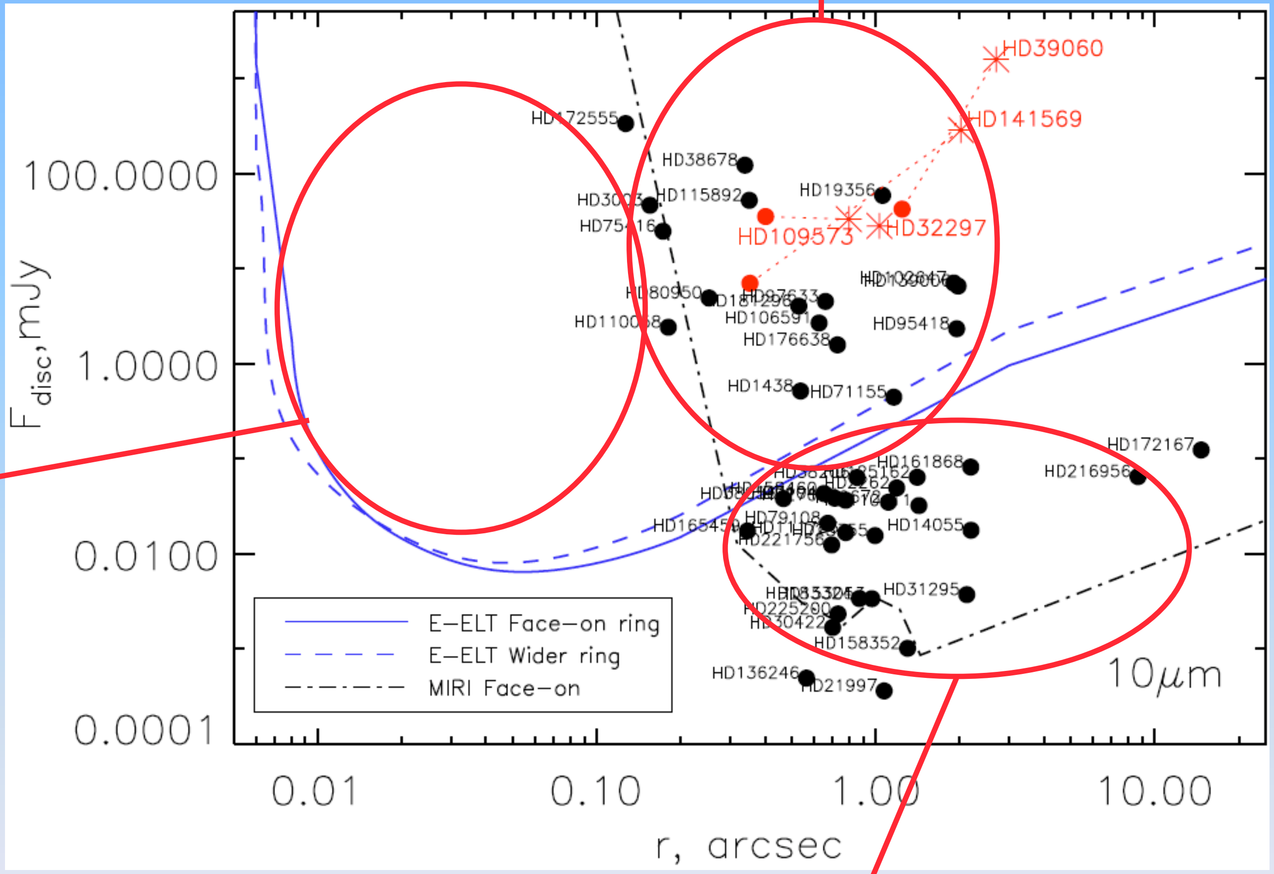


So, it will be possible to resolve emission in terrestrial planet region,
search for evidence of dynamical interactions and so formation history

Resolving power of E-ELT

Predictions for resolving power of METIS on E-ELT at 10µm in 2 hours on source (Smith & Wyatt, submitted)

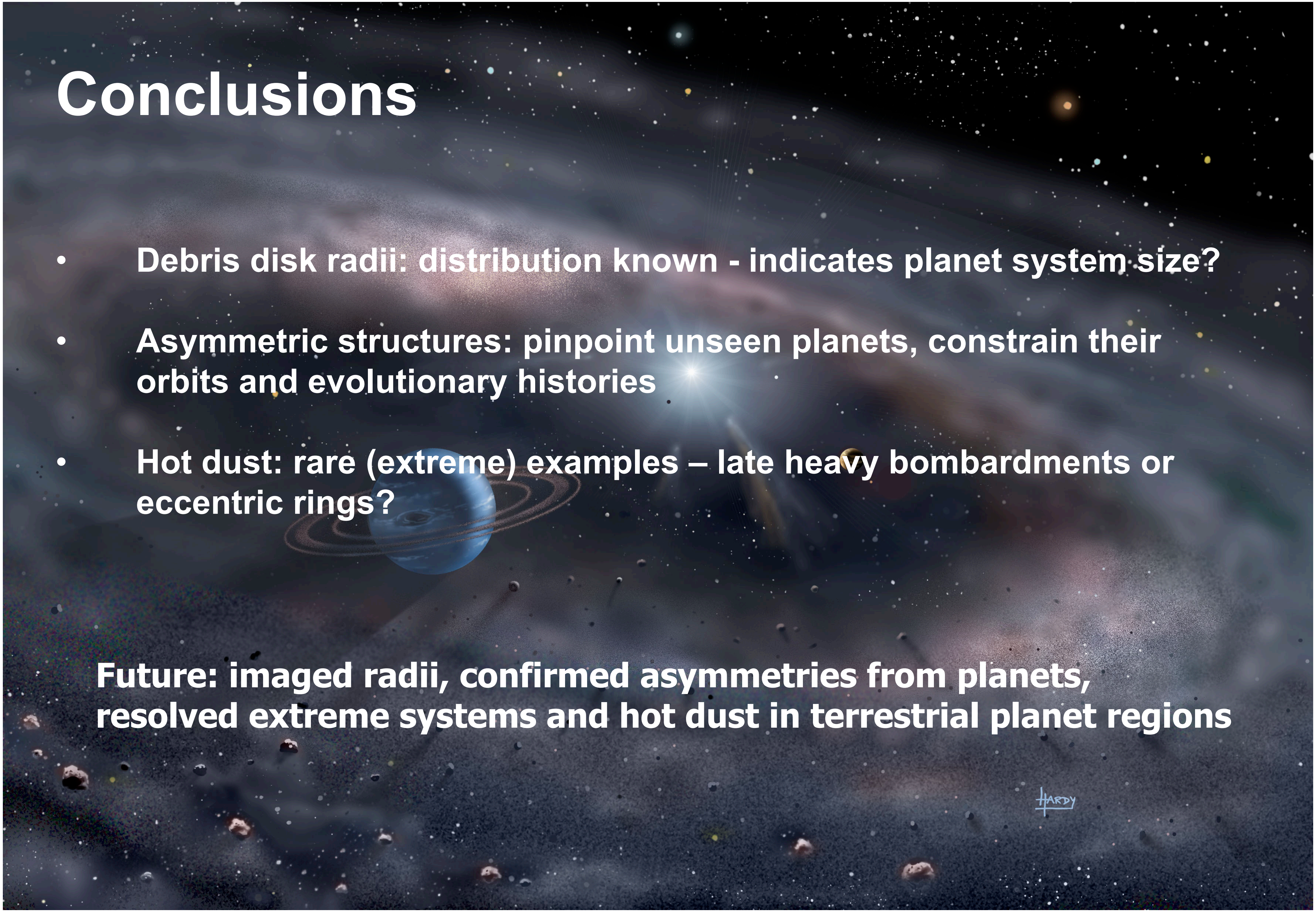
Can resolve the majority of the known A star disks



Can resolve the population of close-in disks that cannot currently be detected due to photospheric confusion

The rest would be accessible with MIRI on JWST (or with E-ELT 18µm imaging)

Conclusions



- Debris disk radii: distribution known - indicates planet system size?
- Asymmetric structures: pinpoint unseen planets, constrain their orbits and evolutionary histories
- Hot dust: rare (extreme) examples – late heavy bombardments or eccentric rings?

Future: imaged radii, confirmed asymmetries from planets, resolved extreme systems and hot dust in terrestrial planet regions