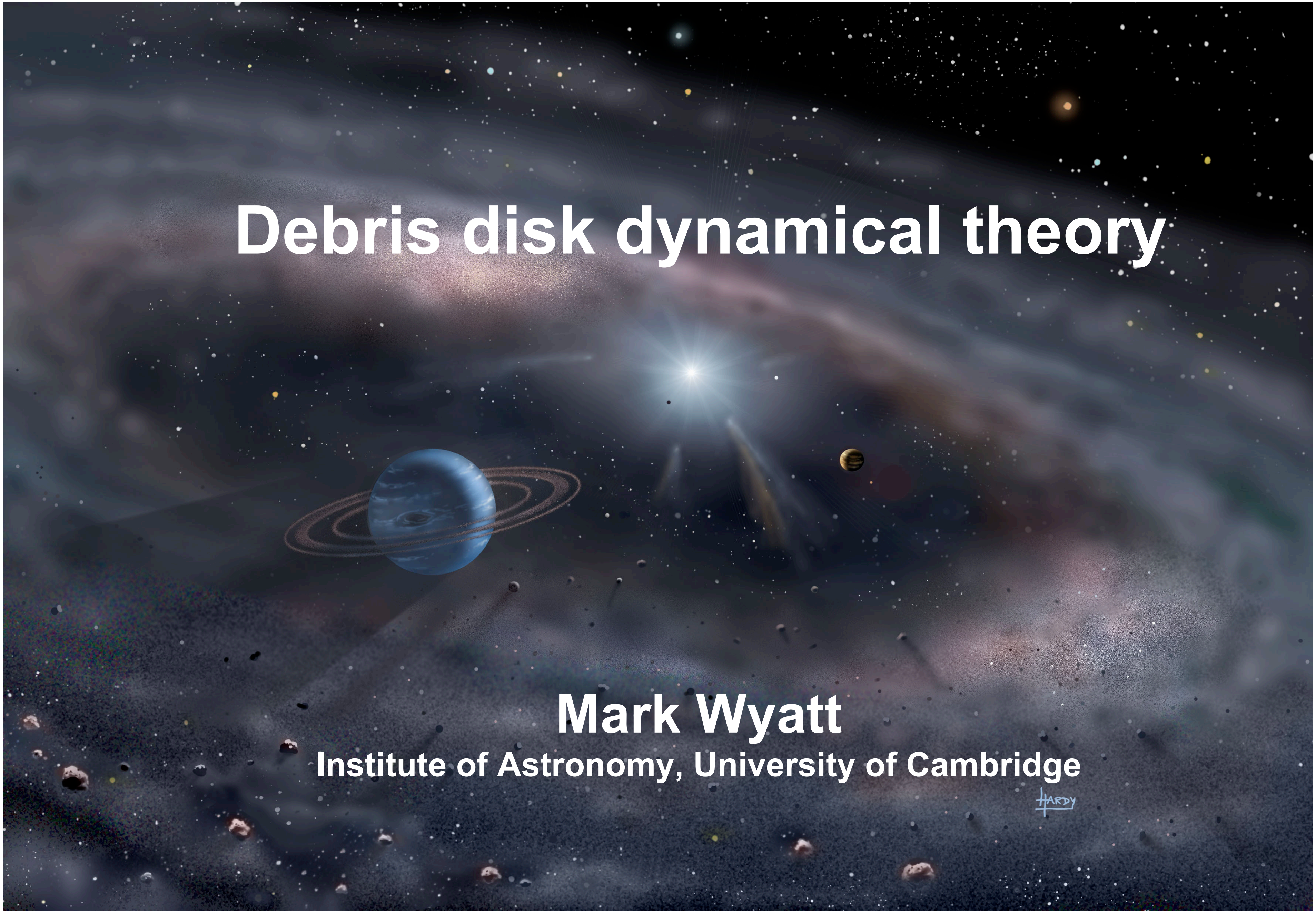
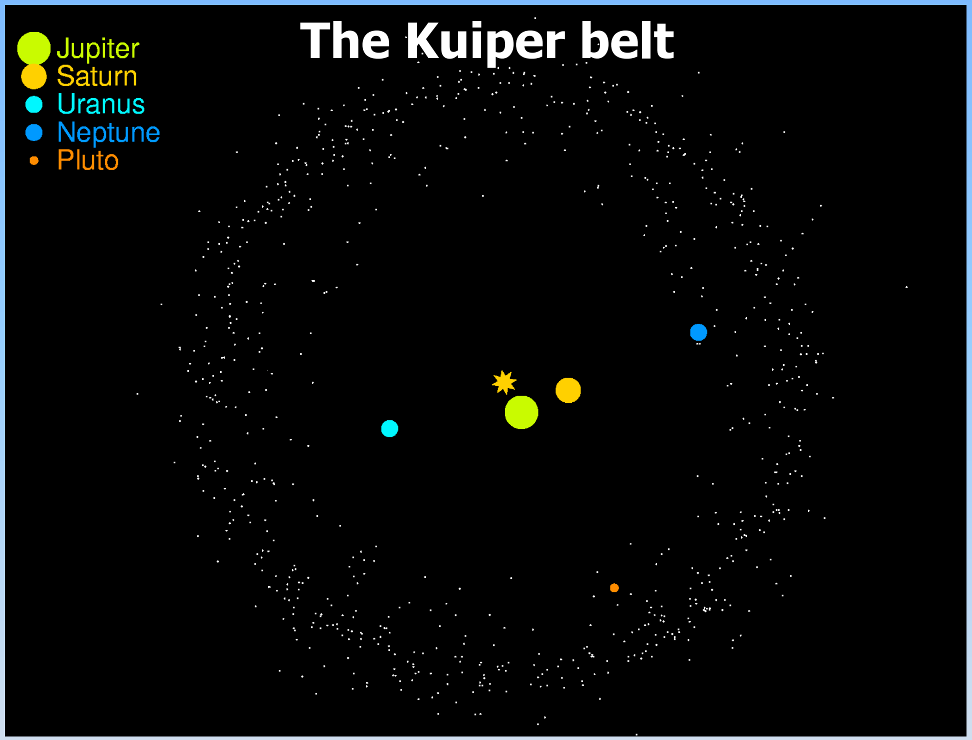
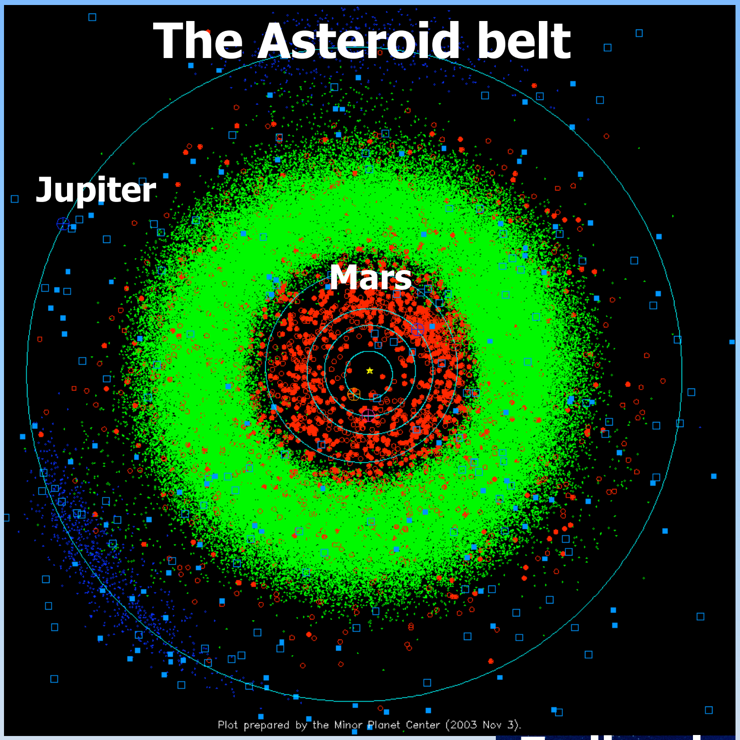


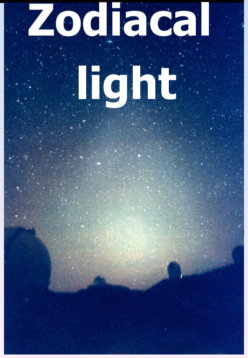
Debris disk dynamical theory

Mark Wyatt
Institute of Astronomy, University of Cambridge

The debris disk of the Solar System







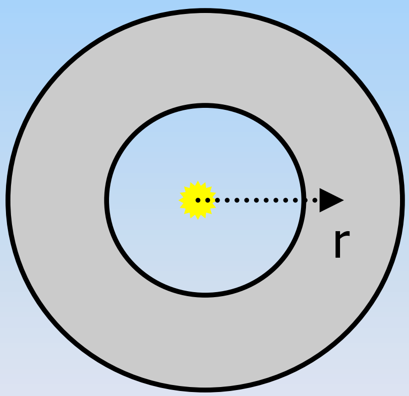
- The dust of debris disks must be replenished by the destruction of larger planetesimals
- Prevailing view that debris disks are analogues to Solar System comprised of planetesimals which failed to grow into planets

Simple debris disk dynamical theory

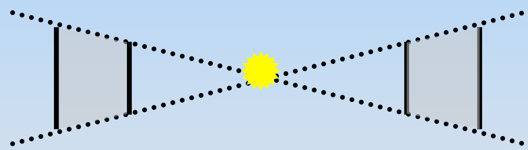
Planetesimals orbit the star confined to a belt

No need to know origin of planetesimals or why they are confined to a ring
(i.e., no prior assumption about confinement by planets)

Face-on



Edge-on



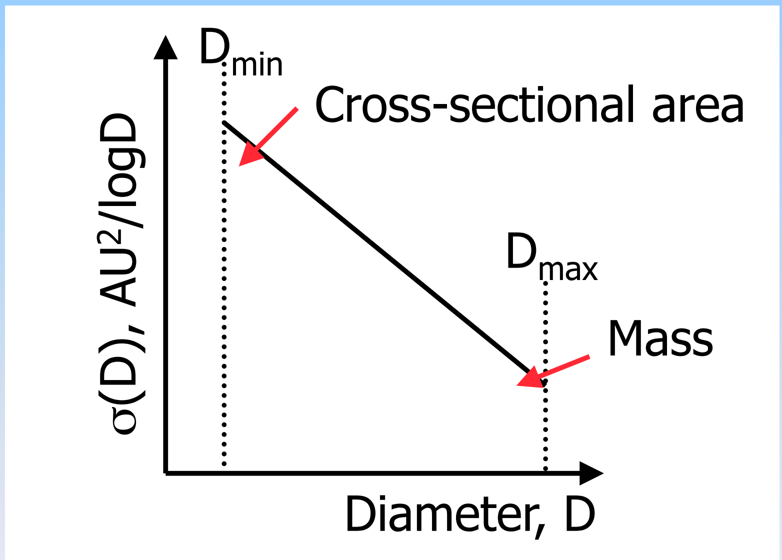
It then asks: **what would we expect to see from this belt?**

Answer: **the interplay between collisions and radiation forces**

Collisions and Radiation Pressure

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

$\sigma(D) \propto D^{-1.5}$

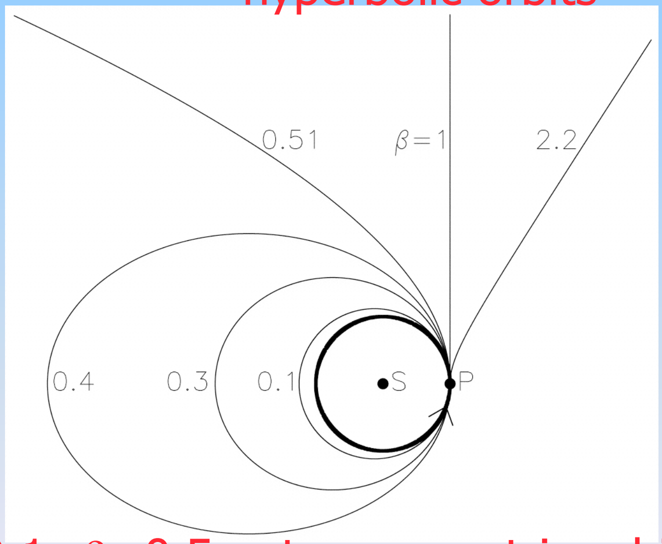


Collisional lifetime $t_{col} \propto D^{0.5}$

Radiation pressure truncates the collisional cascade at small particles:

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

β>0.5 blown out on hyperbolic orbits

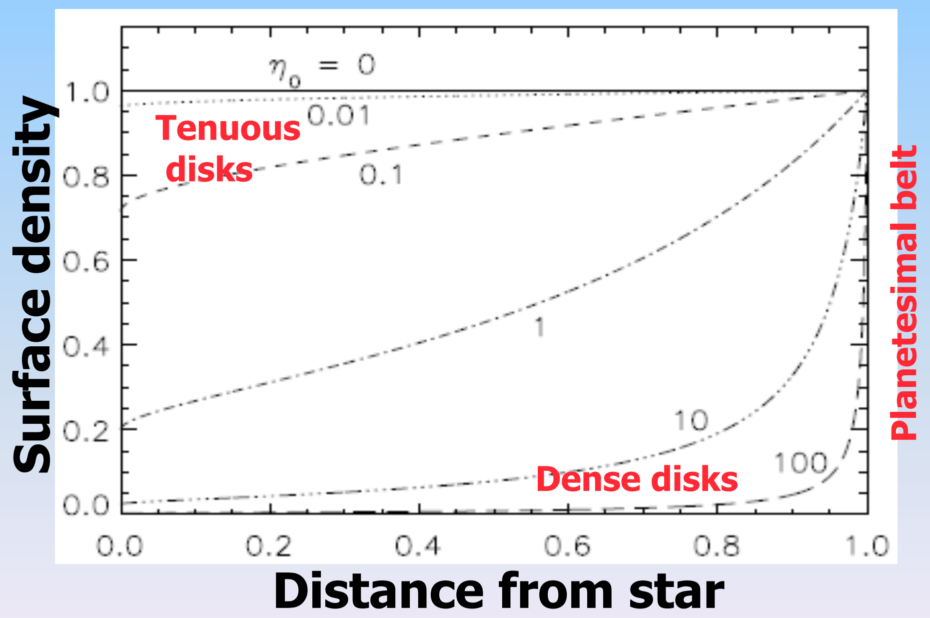


0.1<β<0.5 put on eccentric orbits

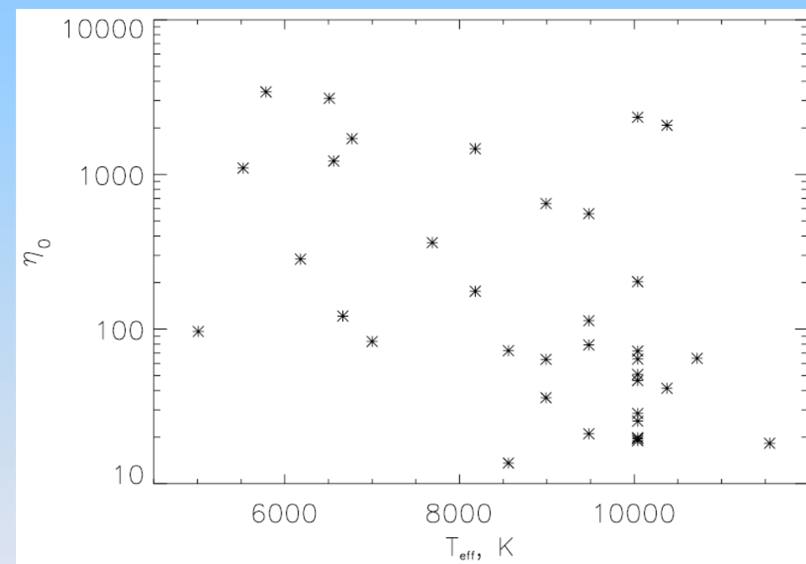
P-R drag dominated disks

Dust spirals toward star on timescale $t_{pr}=(400/M_*)r^2/\beta$ resulting in distribution dependent on

$\eta_0=t_{pr}/t_{col}=10^4\tau_{eff}(r/M_*)^{0.5}$



Debris disks detected by IRAS necessarily have η_0>10 and so P-R drag is negligible (Wyatt 2005)



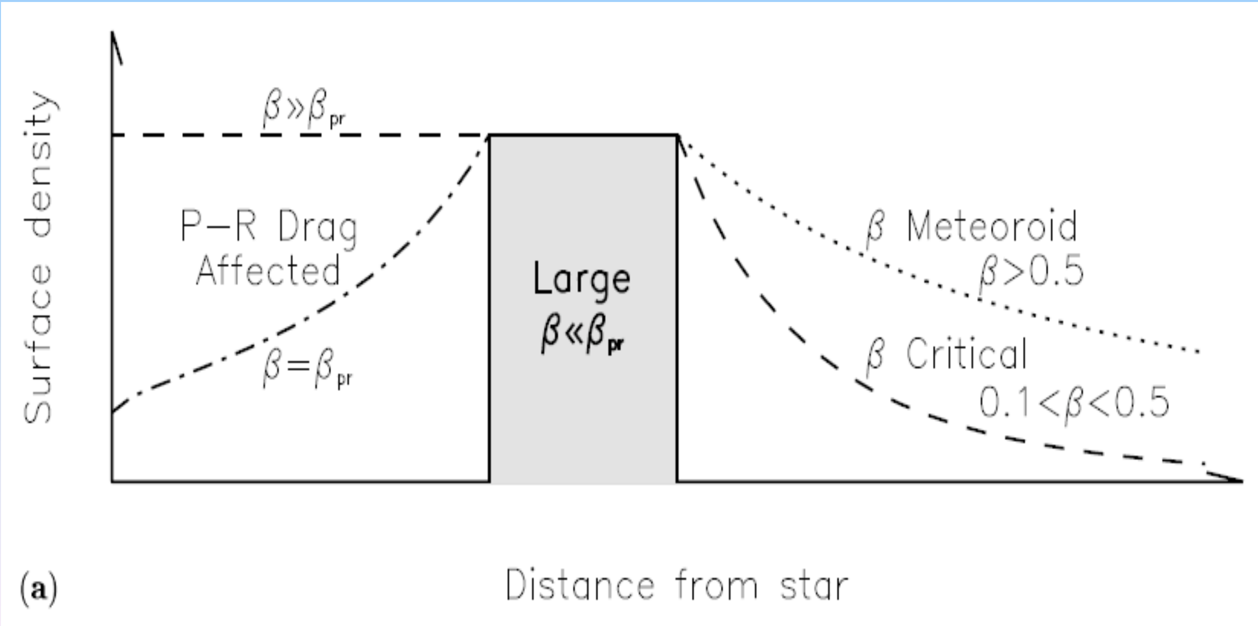
The Asteroid belt is more tenuous and has η_0=0.01 and so P-R drag is dominant

Debris disk dynamical theory summary

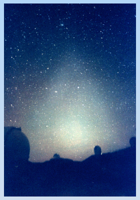
Particles of different sizes have different dynamics:

• $\beta << \beta_{pr}$	**large**	confined to belt
• $\beta \approx \beta_{pr}$	**P-R drag affected**	little depleted by collisions on way in
• $0.1<\beta<0.5$	**β critical**	bound, but extended distribution
• $\beta>0.5$	**β meteoroid**	blown out on hyperbolic orbits

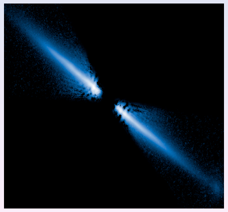
Theory explains most axisymmetric structures of debris disks



• Solar System
P-R drag dominated



• Extrasolar debris
Collision dominated

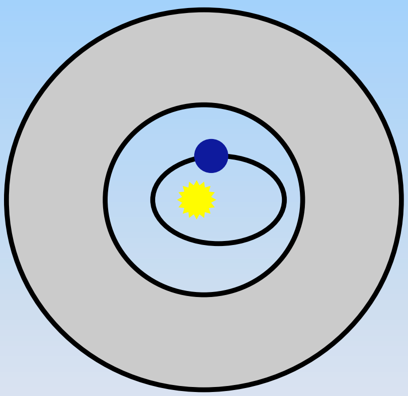


Modified debris disk dynamical theory

Consider the planetesimal belt + one planet

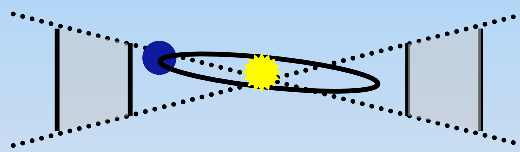
Simple planetary system dynamics predicts non-axisymmetric structures

1. Secular perturbations of eccentric planet



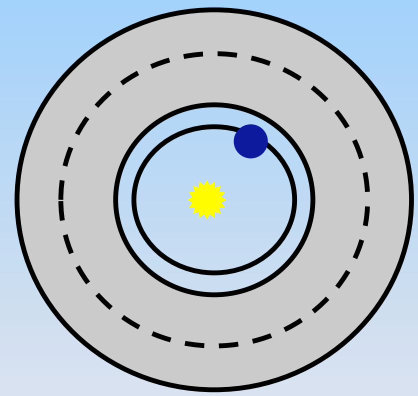
young disk = **spiral**
old disk = **offset+ brightness asymmetry**

2. Secular perturbations of inclined planet



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

3. Resonant perturbations



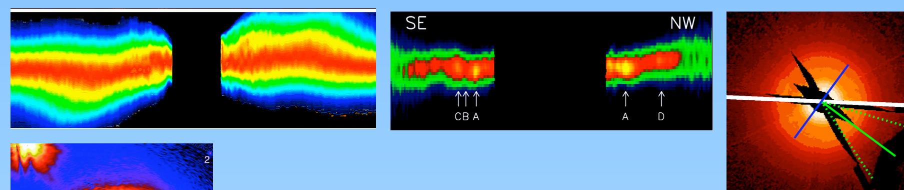
multiple planets = **clearing**
individual planet = **clumps**

See poster by Stark

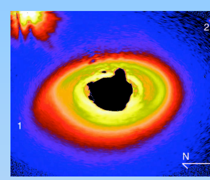
Explanation of asymmetries

The majority of the non-axisymmetric structures observed in debris disks can be explained by perturbations of a planetesimal belt by a nearby planet

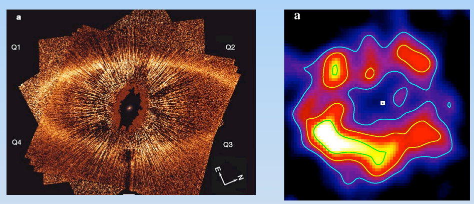
Warps



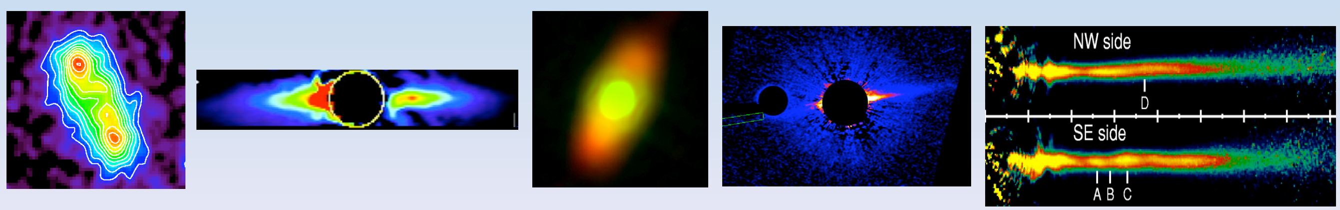
Spirals



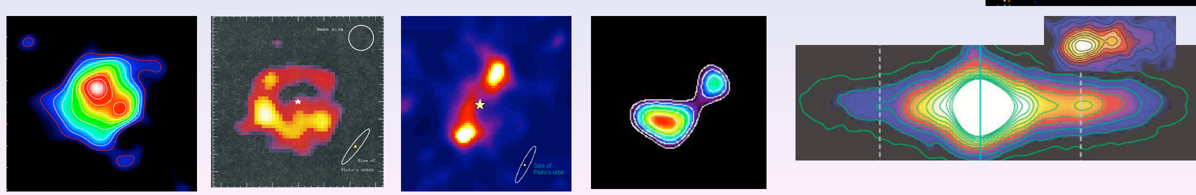
Offsets



Brightness asymmetries



Clumpy rings

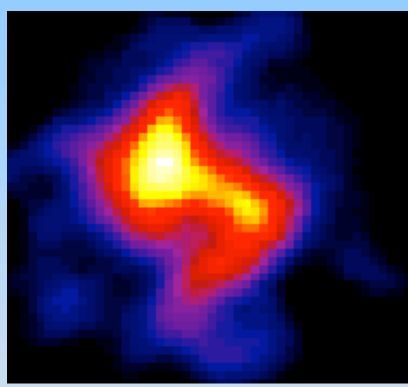


Spitzer imaging of Vega disk

The "surprise" from Spitzer was that it resolved the structure of Vega's disk, and that at 850μm the disk extends to 200AU, but to 1000AU at 24 and 70μm!

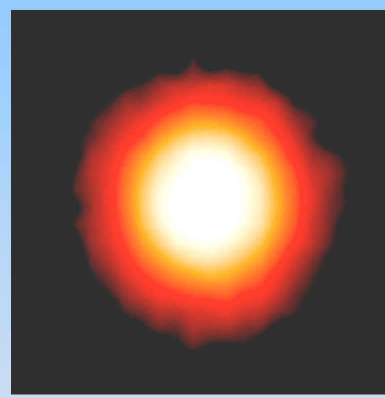
850μm

(Holland et al.)

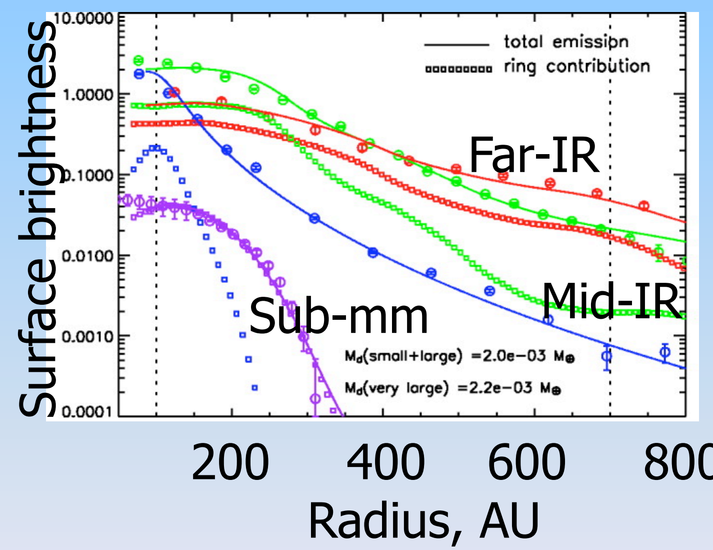


24 and 70μm

(Su et al. 2005)



Surface brightness distribution (Su et al. 2005)

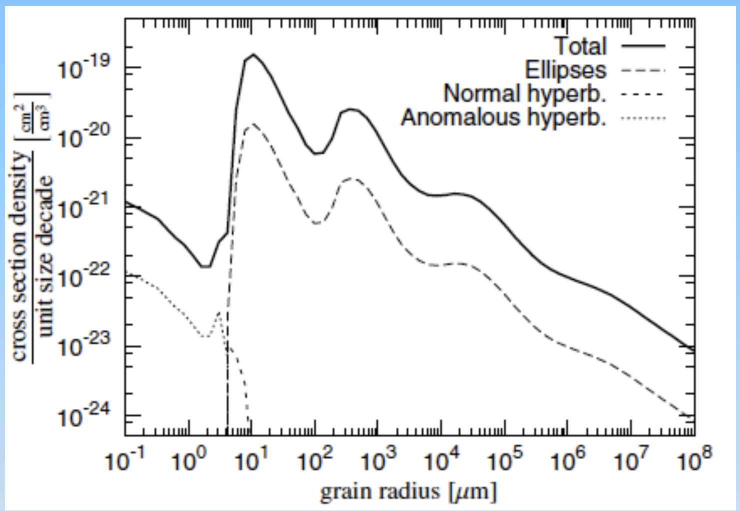


Good news: different wavelengths see different grain sizes and different structures

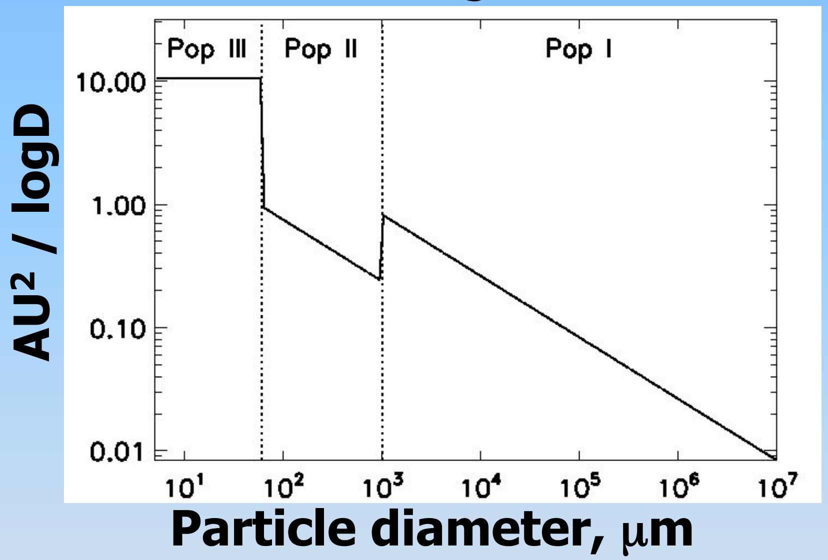
Bad news: both spatial distribution $\tau \sim 1/r$ and temperature of far-IR dust implies mass loss of $\sim 2M_\oplus$/Myr

Origin of high mass loss in Vega?

Size distribution expected in Vega's collisional cascade (Krivov et al. 2006)



Size distribution inferred from observations of Vega (Wyatt 2006)

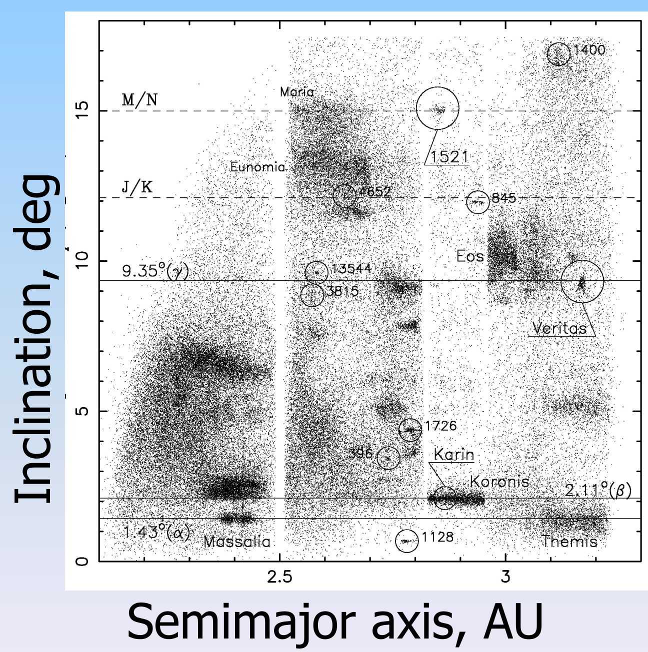


Mass loss is transient: $2M_{\oplus}$/Myr can't have been sustained for 350Myr

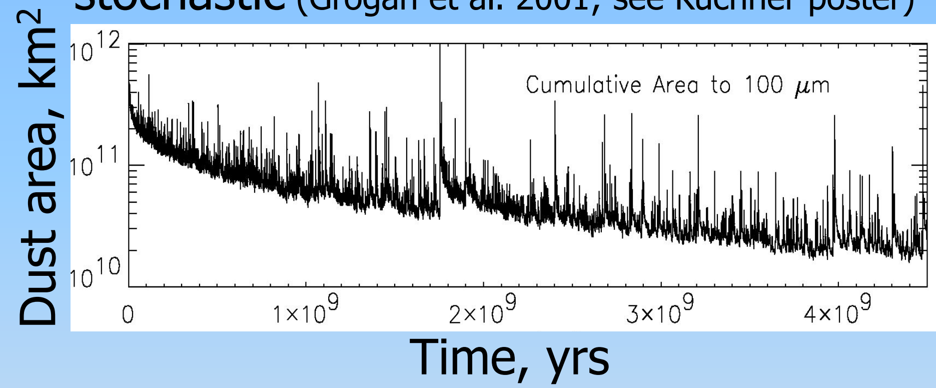
BUT… what caused this outburst?

Stochastic evolution of solar system dust

The asteroid belt is made up of large families from massive events Gyr ago, as well as smaller families from break-up of 10-100km asteroids ~10Myr ago (Nesvorny et al. 2003)

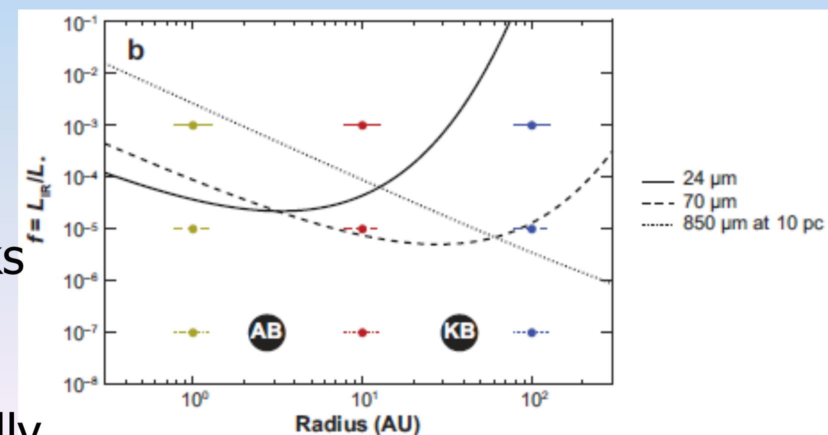


Significant input to zodiacal cloud and evolution of dust in inner Solar System is stochastic (Grogan et al. 2001; see Kuchner poster)



BUT: this does not mean that extrasolar debris disks evolve

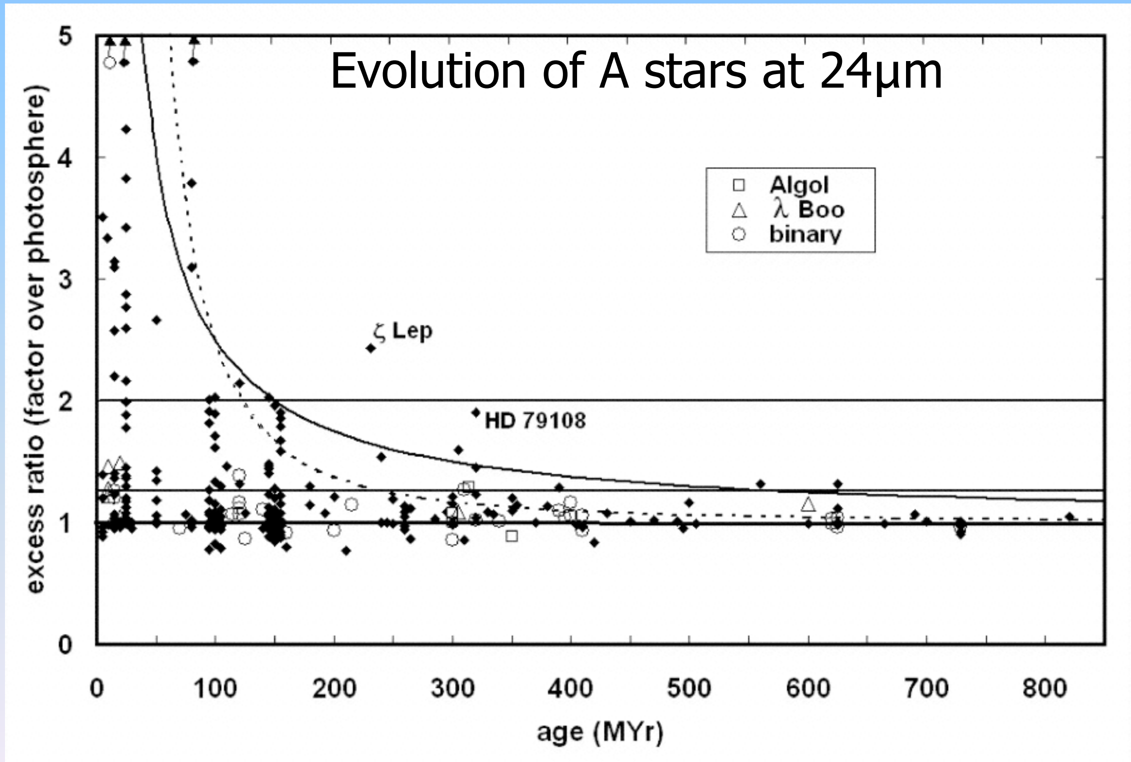
stochastically



Statistics, statistics, statistics

Sensitivity of Spitzer means it was extremely successful at detecting emission from debris disks and commitment of community has provided lots of statistics on incidence of debris as function of age, spectral type, binarity, etc (talk by Carpenter)

- Surveys of A stars at 24 and 70μm (Rieke et al. 2005; Su et al. 2006)
- Upper envelope falls off inversely with age on timescsale of 150Myr at 24μm



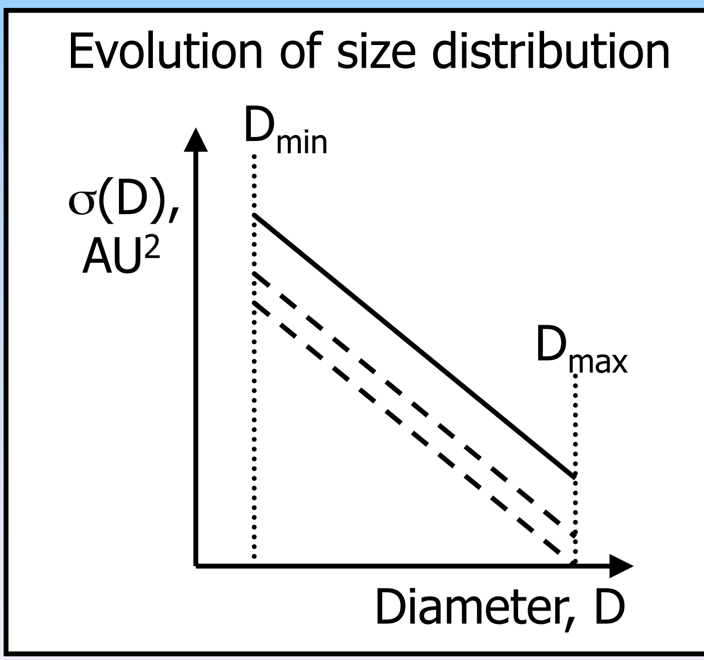
Do these statistics fit with the debris disk dynamical theory?

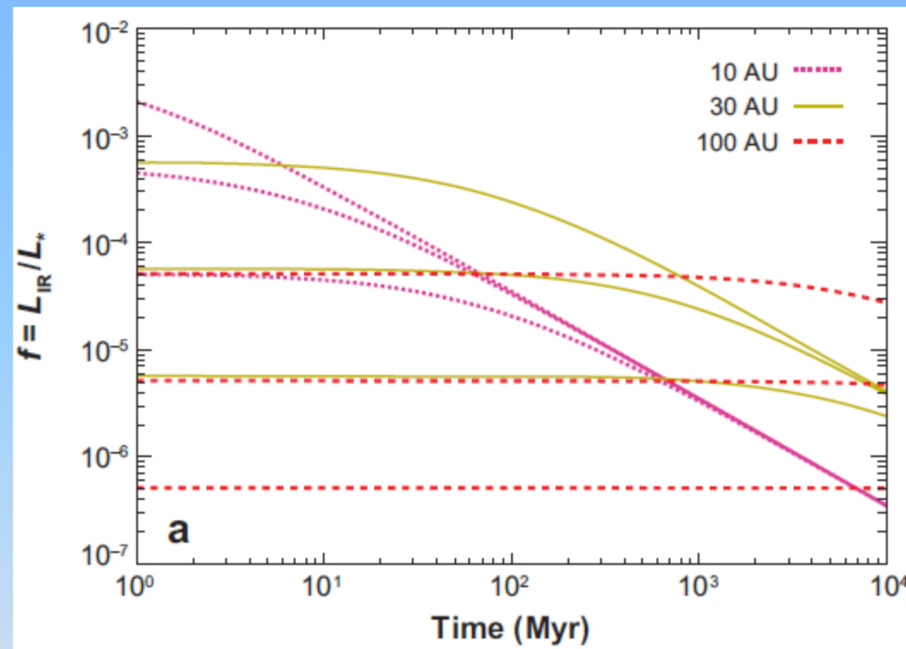
Steady state evolution model

Starting with the basic dynamical disk theory consider how size distribution evolves due to steady state collisions:

$dM_{disk}/dt = -M_{disk}/t_{col} \propto -M_{disk}^2$

$M_{disk} = M_0 [1+t/t_{col}]^{-1}$





Disk mass and fractional luminosity falls off once largest objects are depleted in collisions on a timescale t_{col}, a timescale which depends on initial disk mass and radius

Steady-state evolution explains 24 and 70μm stats

Comparison with statistics using a population model:

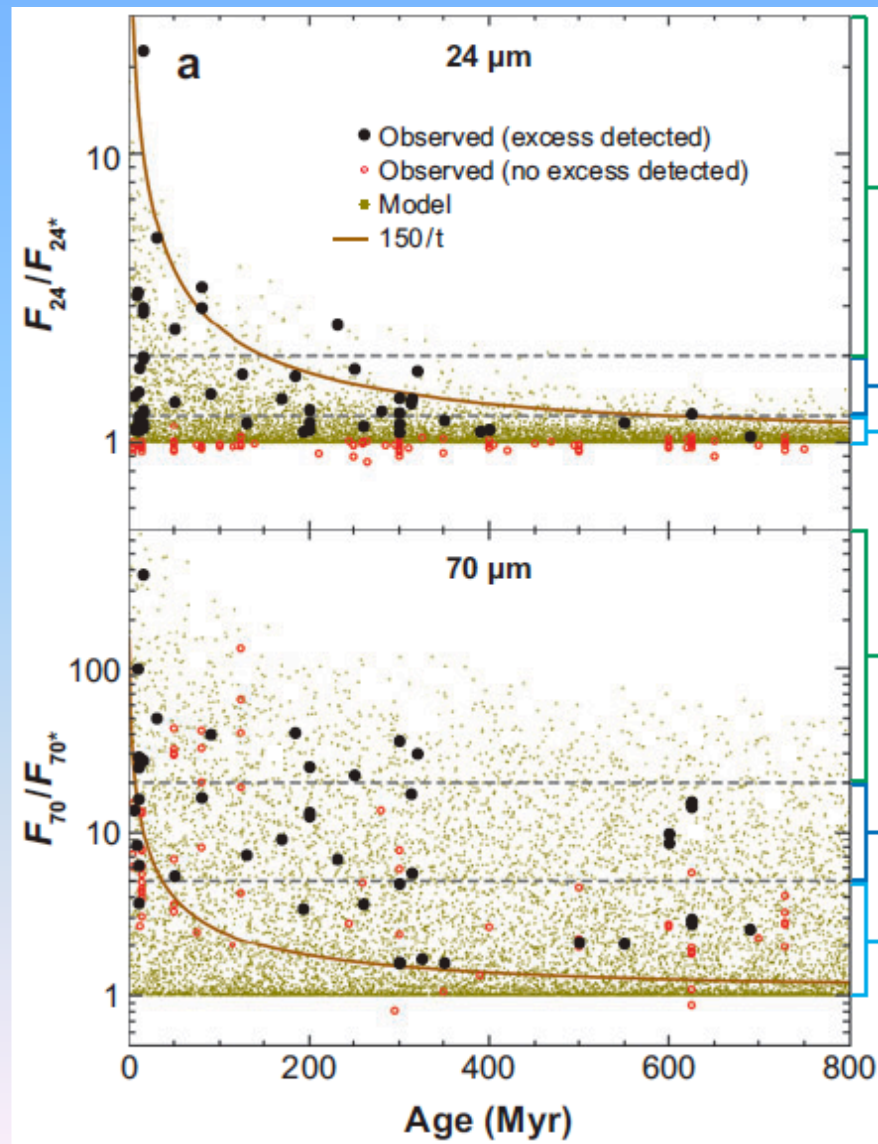
(1) All stars have one planetesimal belt

(2) Initial mass distribution of protoplanetary disks

(3) Radius distribution $n(r) \propto r^{\gamma}$

(4) Planetesimal belts evolve in steady state from t=0

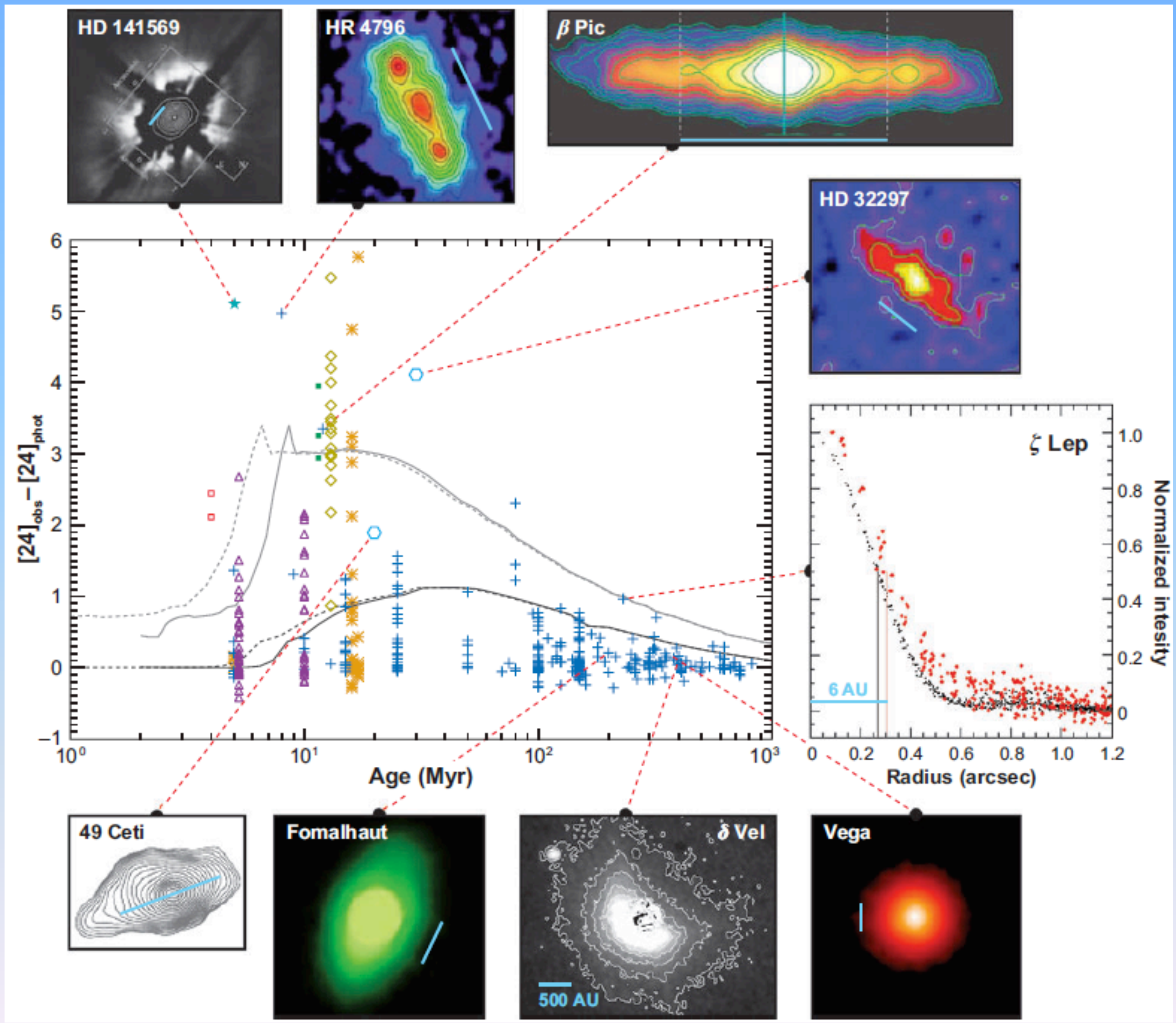
Statistics are fitted perfectly with steady state evolution, and no need to invoke stochastic evolution for most disks to explain the stats



Wyatt (2008)

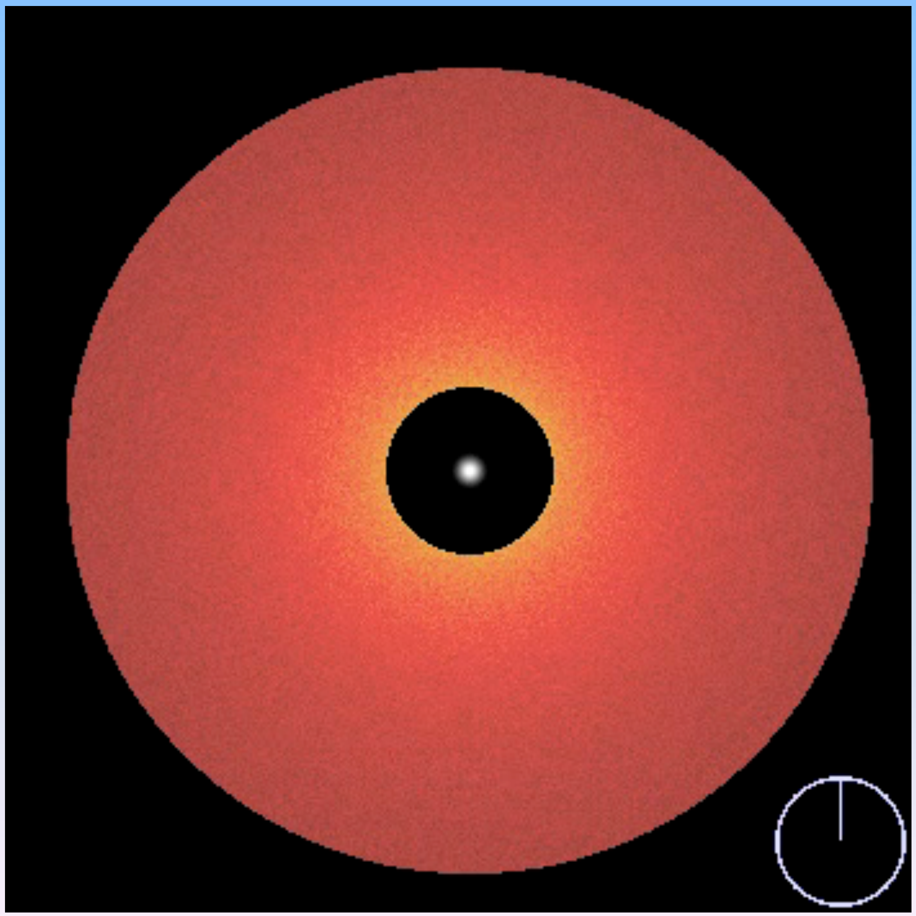
The birth of A star debris disks

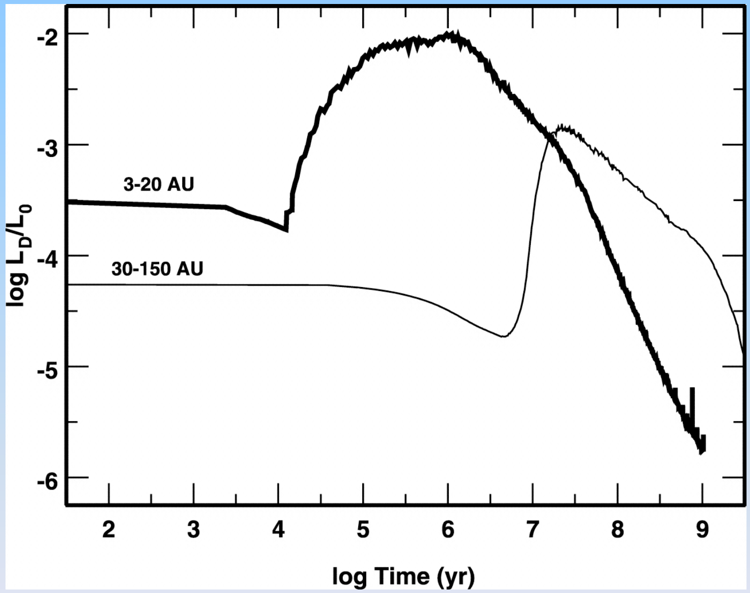
Following the dispersal of A-star protoplanetary disks on <5Myr timescales, the 24μm excess from debris disks increases to a peak at 10-15Myr (talk by Currie)



Self-stirred models

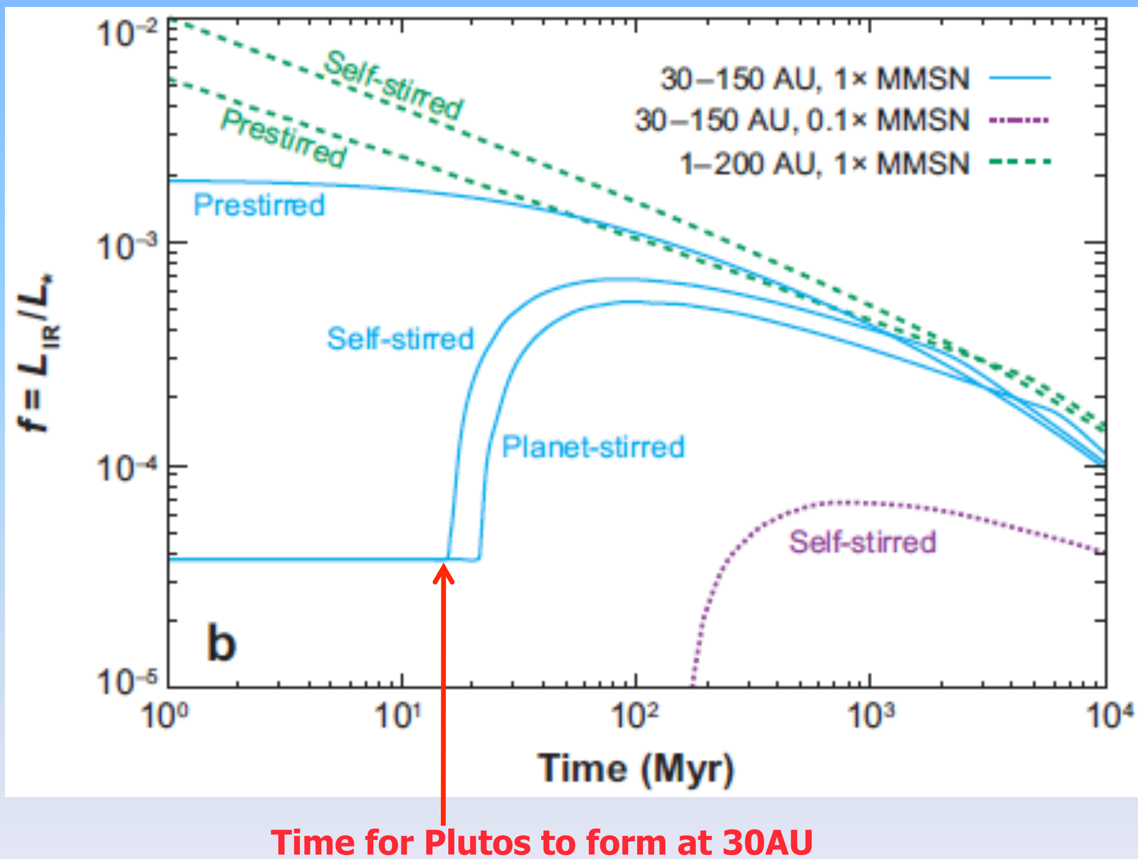
Planet formation models predict that planetesimal belts become bright when Pluto-sized objects form and stir the disk (Kenyon & Bromley 2004,2005)





Such models can have a peak at 10Myr

Peak requires inner hole

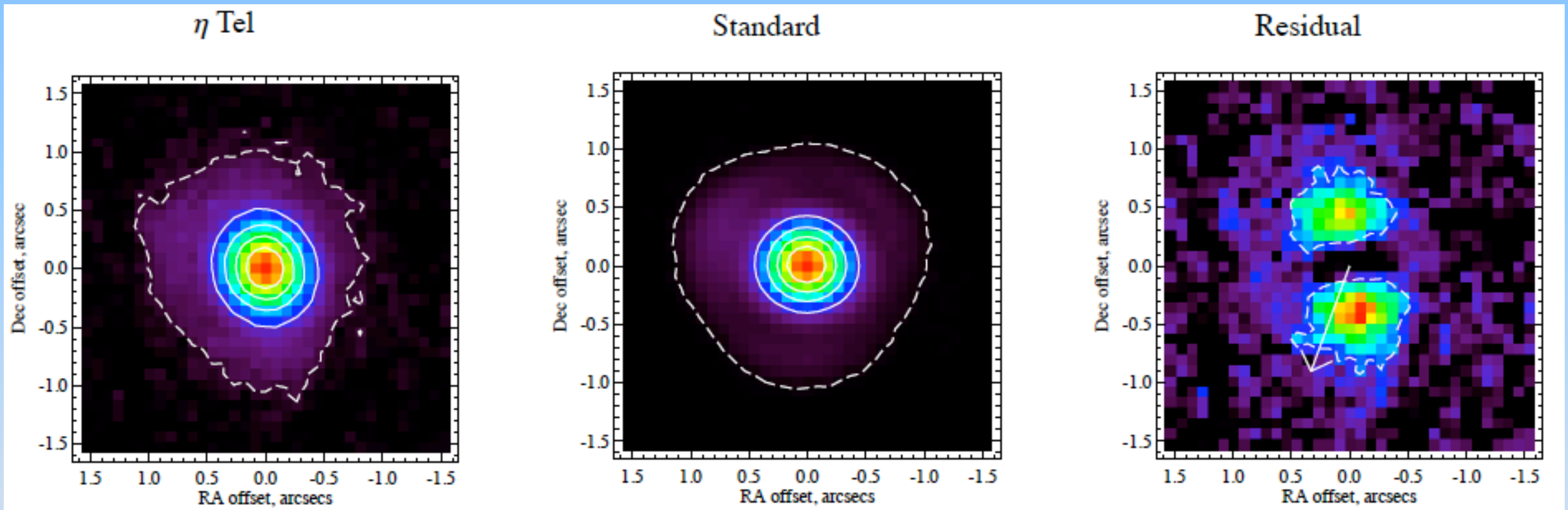


- Desirable effects of self -stirred models require inner 30AU hole
- Otherwise self-stirred model is similar to pre -stirred model; stirring could also come from inner planet (Wyatt 2008; Mustill & Wyatt in prep.)
- Is this hole related to presence of planets, or to the dispersal of protoplanetary disk?

- Fine-tuning problem (of hole radius and surface density) to get peak at 10Myr?

η Tel resolved imaging

η Tel is a 12Myr A0V star in β Pic moving group

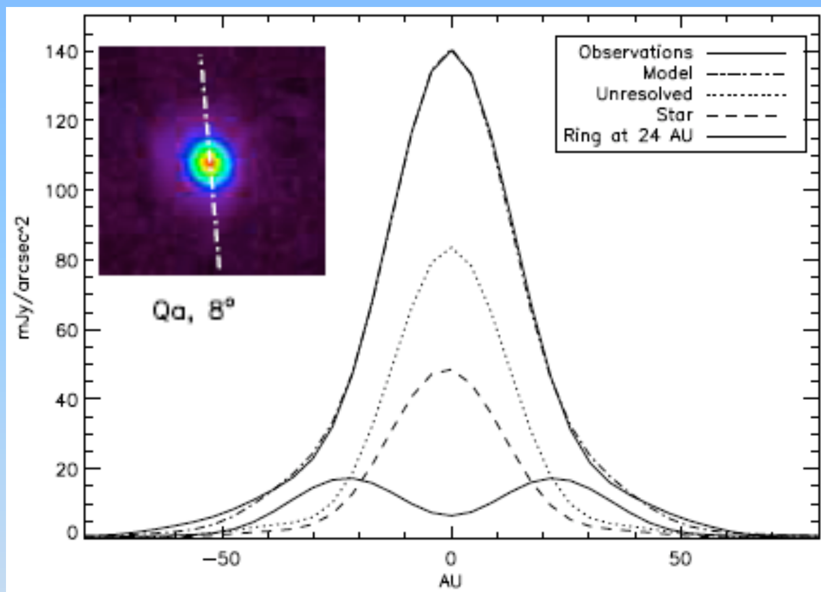


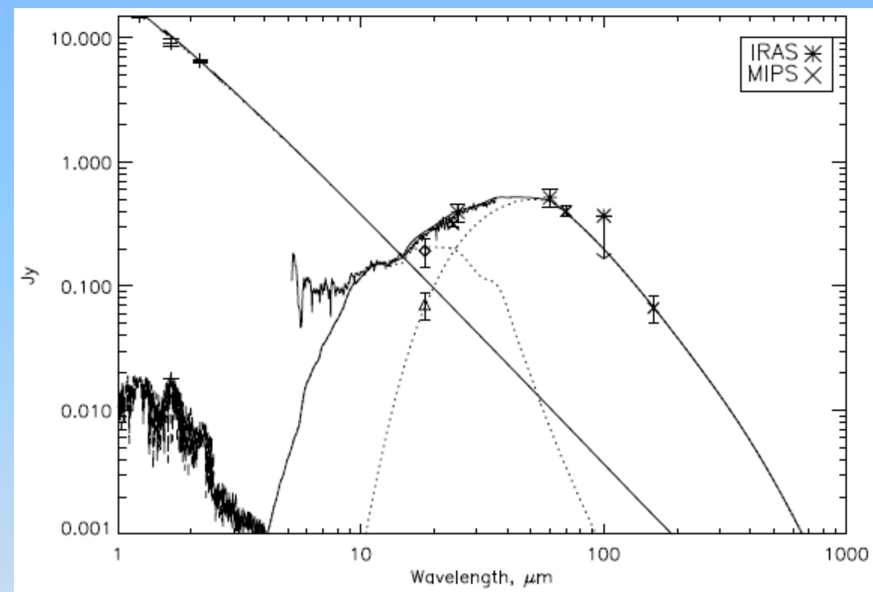
TReCS mid-IR 18μm imaging shows emission characteristic of near edge-on ring resolved at 24AU

Smith et al. (in press, 0810.5087); see poster by Churcher

η Tel: origin of multi-components?

Smith et al. (in press, 0810.5087); see poster by Churcher



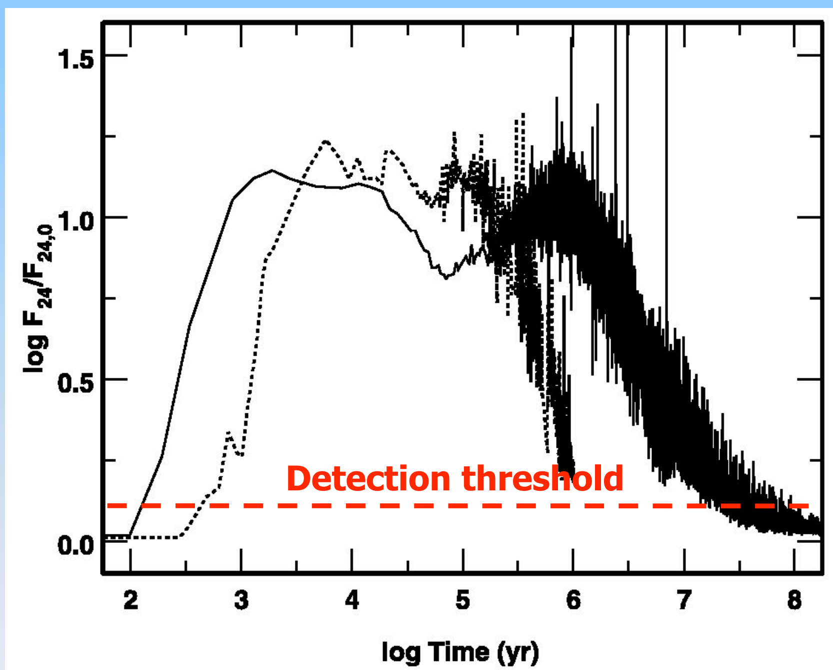


Modelling shows >50% mid-IR emission is from unresolved component at ~4AU
Should we be considering debris disks as 2 dynamically distinct components?

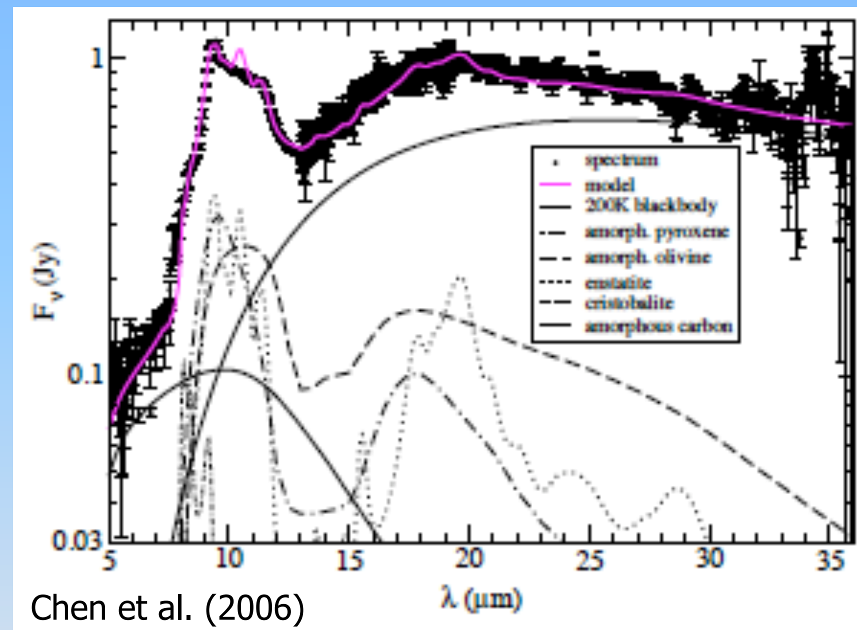
Young Solar System: 24AU ring is young KB, 4AU ring is young AB
Ongoing planet formation: 24AU is where Pluto's recently formed in a 0.7xMMSN disk, 4AU emission from terrestrial planet formation

Terrestrial planet formation models

Terrrestrial planet formation models predict observable levels of mid-IR emission (Kenyon & Bromley 2004)



BUT: no model yet of how much dust expected from Earth-Mars collisions

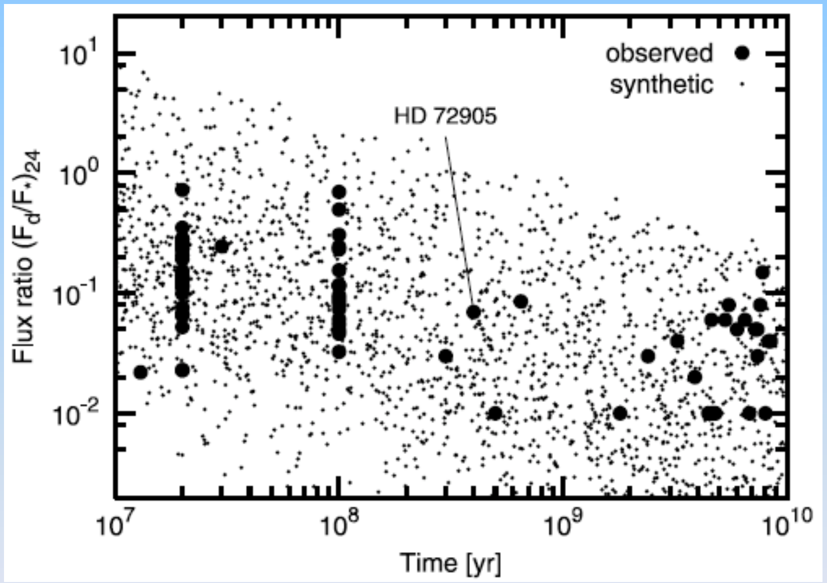


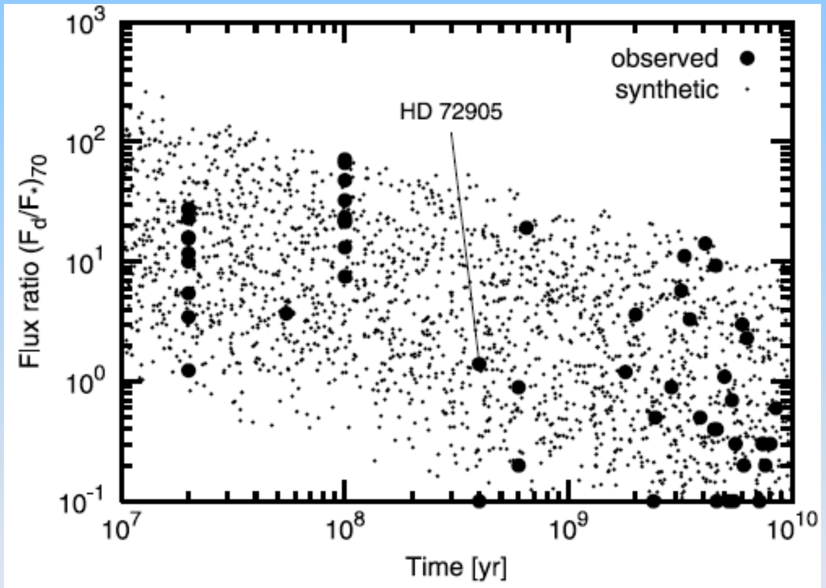
Chen et al. (2006)

Modelling of IRS spectra provides evidence of dust composition; e.g., silica feature in HD172555 is indicative of massive collision (see poster by Lisse)

Steady state evolution of sun-like star disks

Simple analytical theory for collisional evolution of planetesimal belts improved using numerical simulations in which size dependence of planetesimal strength results in a 3 phase size distribution (see Lohne talk)





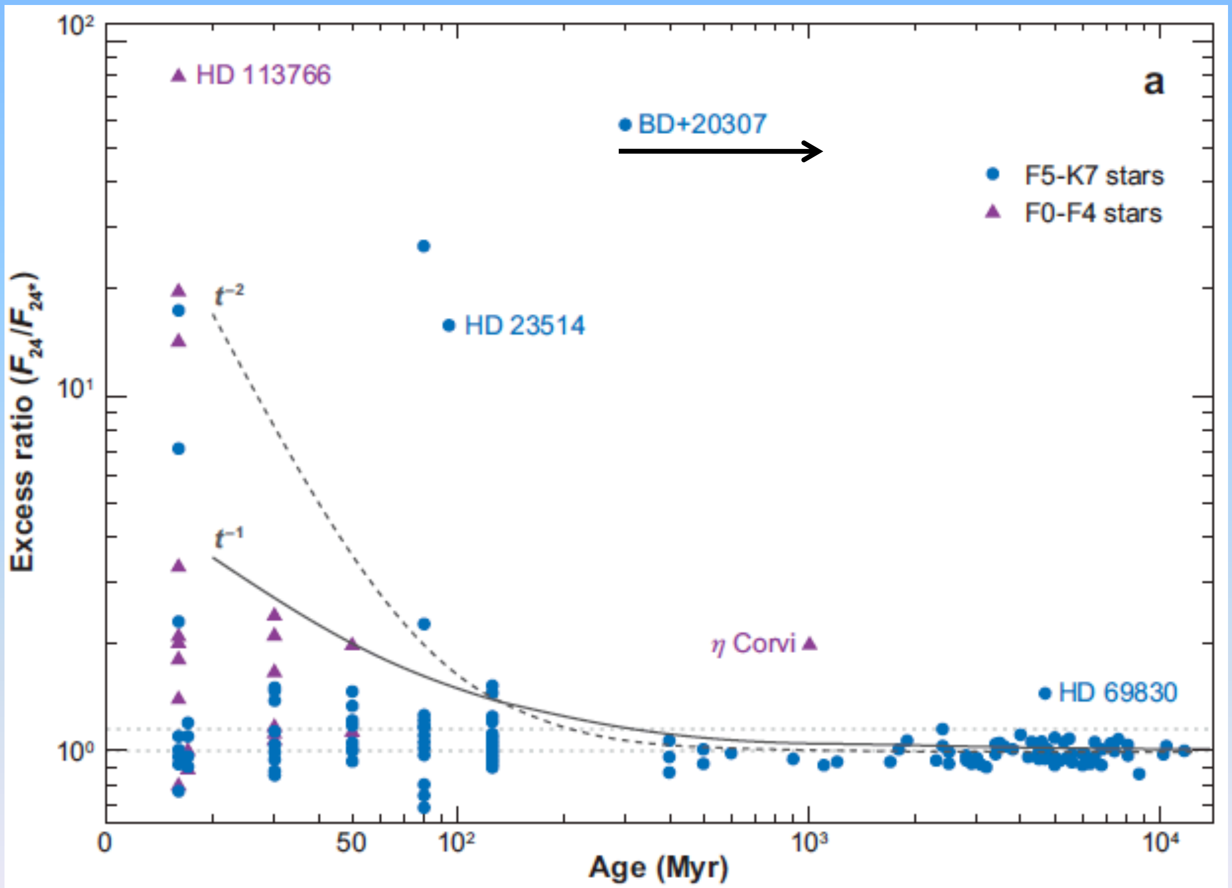
The statistics for sun-like stars can also be explained by steady-state evolution (Lohne et al. 2008)

Old sun-like stars with hot dust

Wyatt (2008)

Although the fall -off in 24μm excess at young ages may be steady state evolution, it is also suggested that this relates to terrestrial planet formation

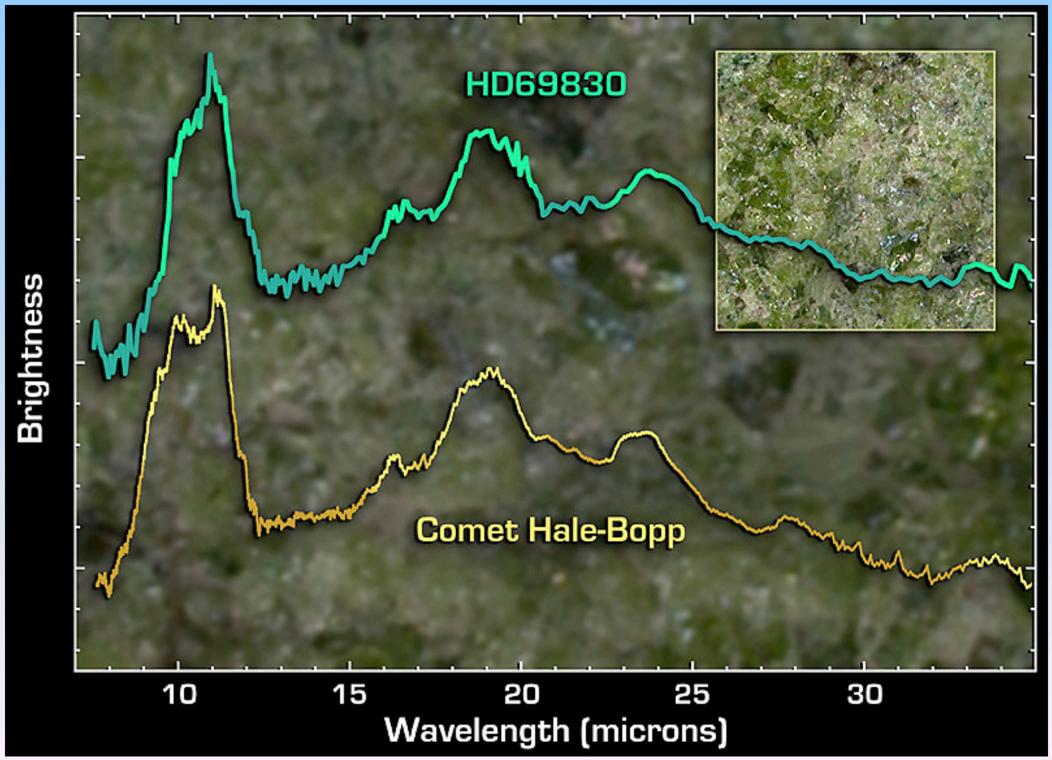
Regardless, some old Sun-like stars seem to defy either explanation

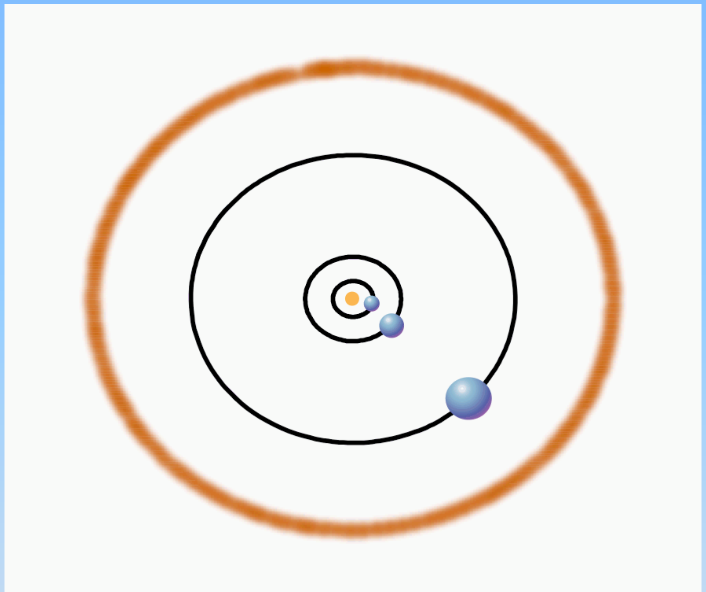


See posters by Abraham and Gorlova, talk by Zuckerman

The hot dust of HD69830

The mid-IR spectrum of 2Gyr HD69830 is similar to that of Hale-Bopp with a temperature of ~400K, shows dust is concentrated at 1AU (Beichman et al. 2005)





The dust is just outside 3 Neptune mass planets discovered in radial velocity studies (Lovis et al. 2006)

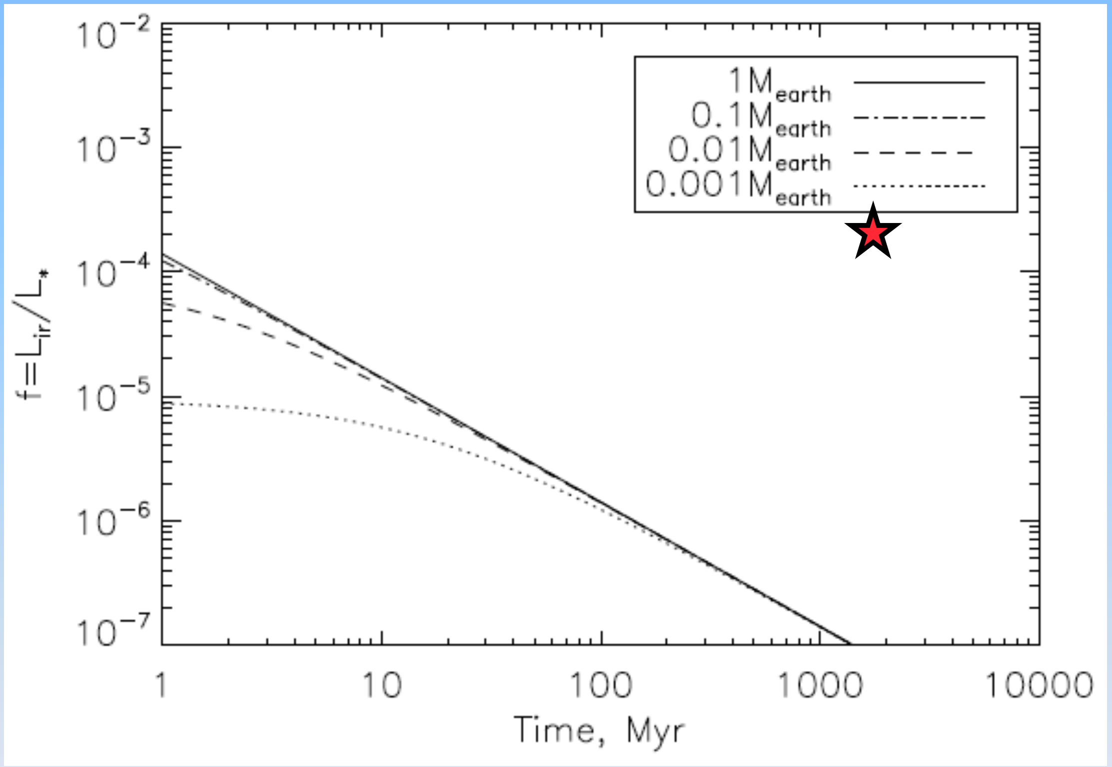
Dust can't originate in massive asteroid belt

There is a maximum luminosity (and mass) that a belt can have

(Wyatt et al. 2007a)

$$f_{max}=1.6x10^{-4}r^{7/3}t_{age}^{-1}$$

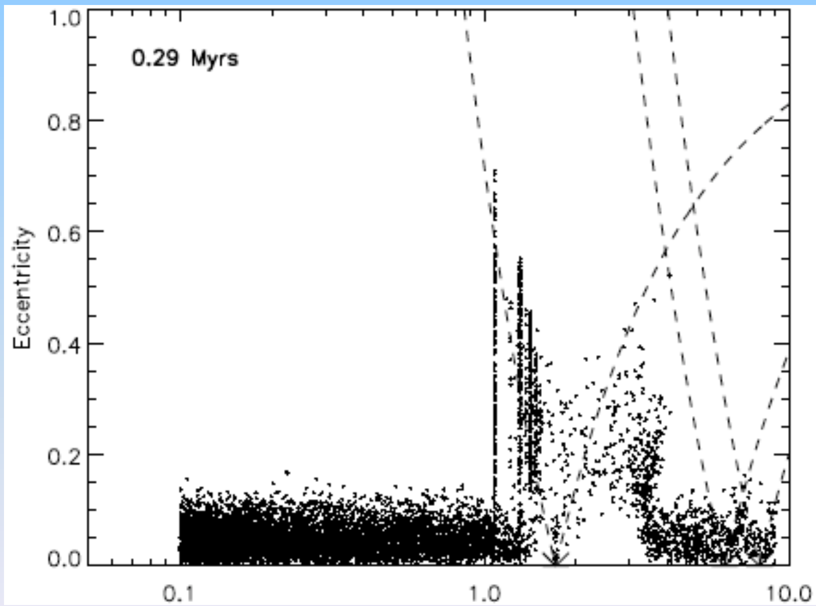
The hot dust of HD69830 has a luminosity >1000x this level and so it cannot be a steady state phenomenon

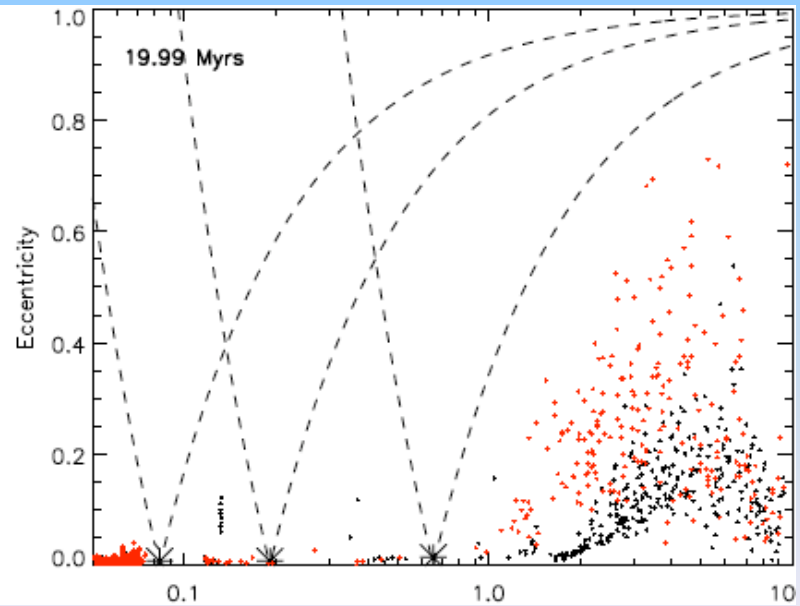


Similarly insufficient mass remains at this time for us to be likely to be witnessing the aftermath of a recent collision

Formation of eccentric planetesimal disk

Taking prescription for formation of HD69830 planets at 3, 6.5 and 8 AU followed by migration (Alibert et al. 2006), implies that a significant eccentric planetesimal population exists outside the orbits of the planets at the end of planet formation

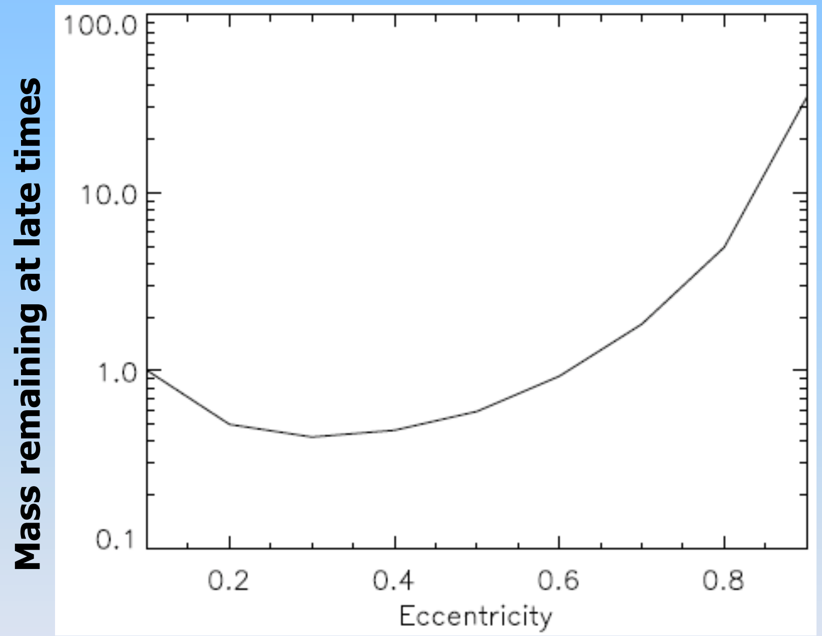


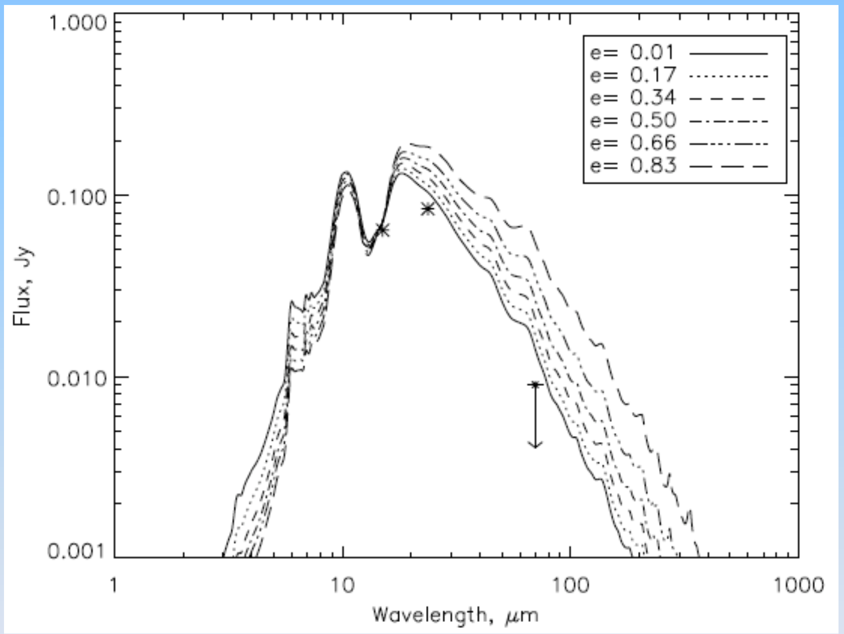


Payne et al. (submitted) – see poster by Payne

Is a long-lived eccentric disk the solution?

Consider the steady-state evolution of a planetesimal belt with pericentre fixed at 1AU, but increasing eccentricity:





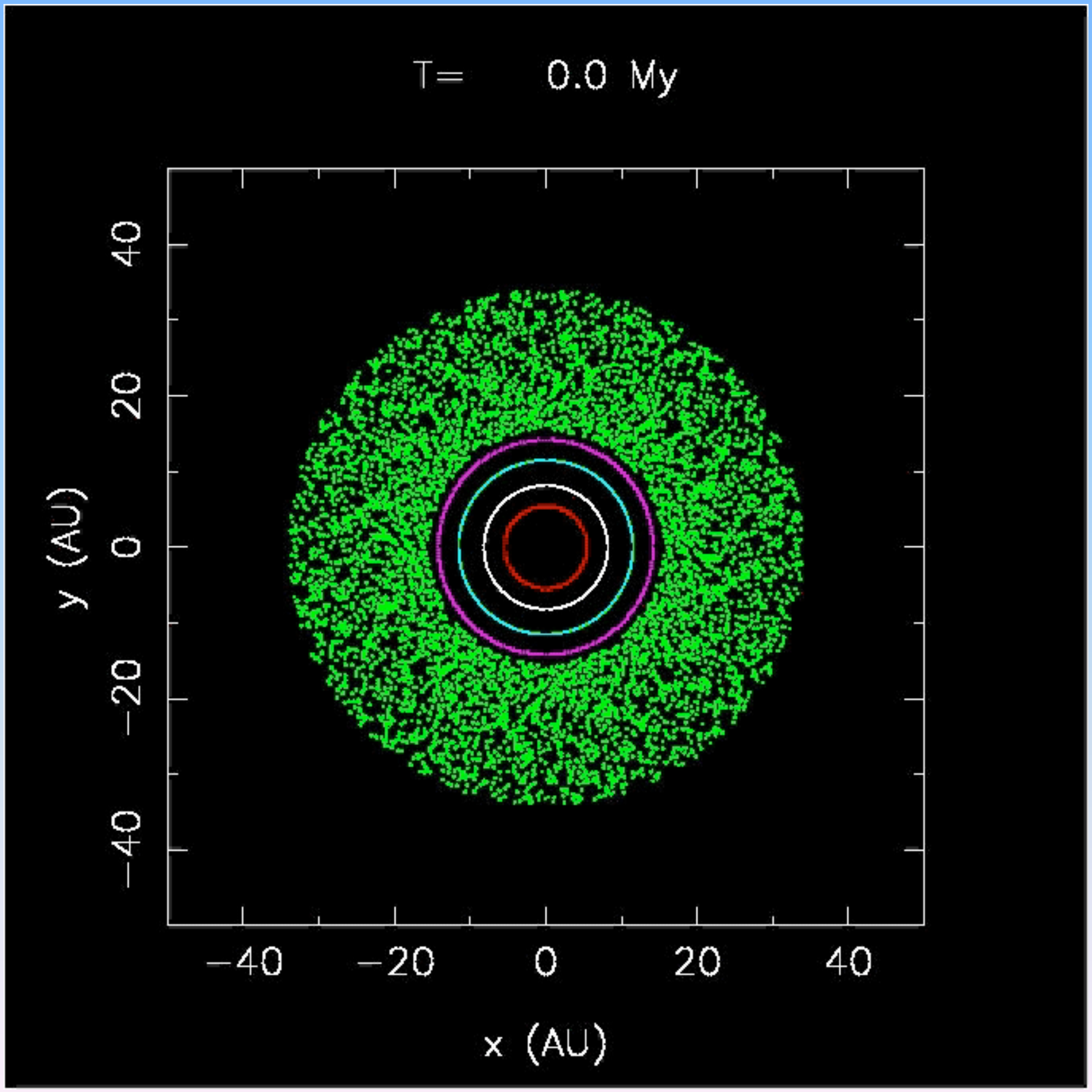
Mass remaining at late times increases (Wyatt et al. in prep)

This doesn't necessarily help us because there is the problem of lack of 70μm emission from disk

Origin in Late Heavy Bombardment?

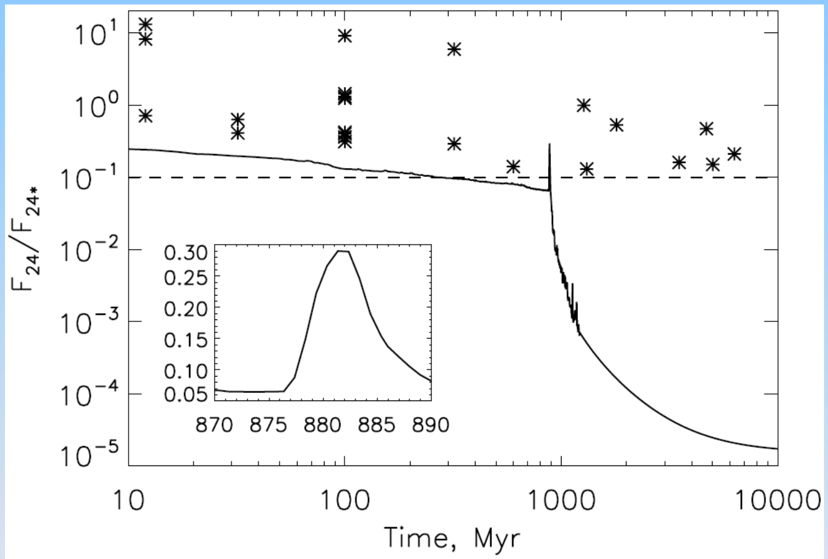
Alternative explanation for origin of hot dust is an LHB-like instability

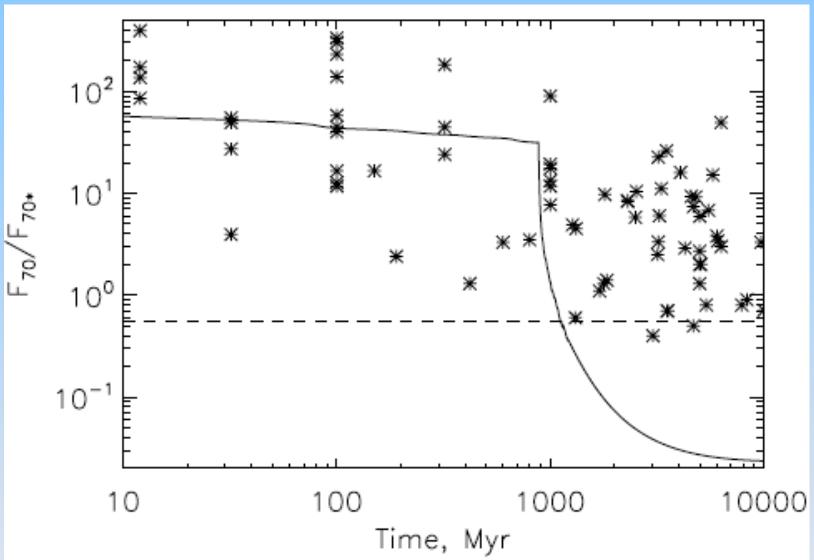
At ~800Myr the inner solar system underwent a period of heavy bombardment which has been explained as result of dynamical instability when Jupiter and Saturn crossed 2:1 resonance (Gomes et al. 2005)



LHBs are detectable…

Taking the Nice model for the evolution of the Solar System and considering the dust emission from collisions amongst KBOs (Booth et al., in prep)





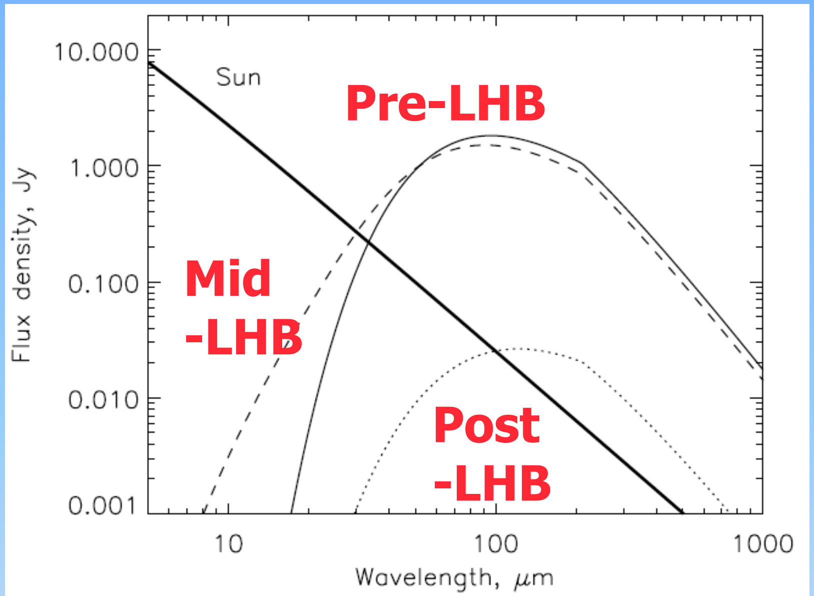
… but accompanied by cold emission

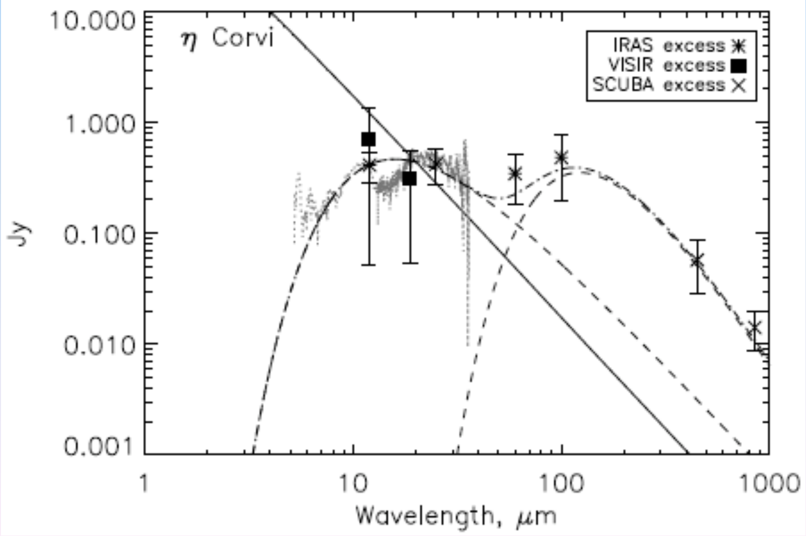
Mid-LHB SED

An LHB emission spectrum is characterised by emission at a range of temperatures resulting in a shallower increase in mid-IR flux with wavelength

Mid-IR emission during LHB would be enhanced by AB and cometary activity (Booth et al., in prep)

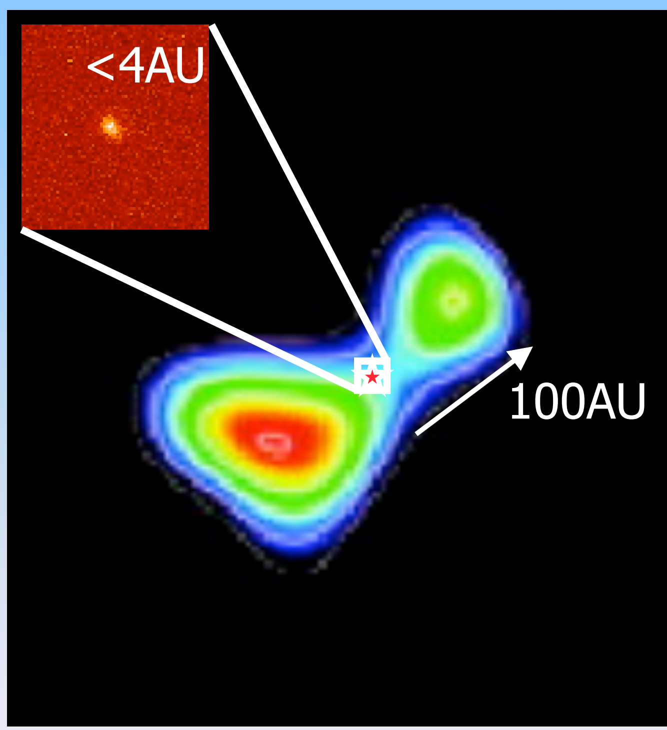
Systems like η Corvi may be undergoing an LHB



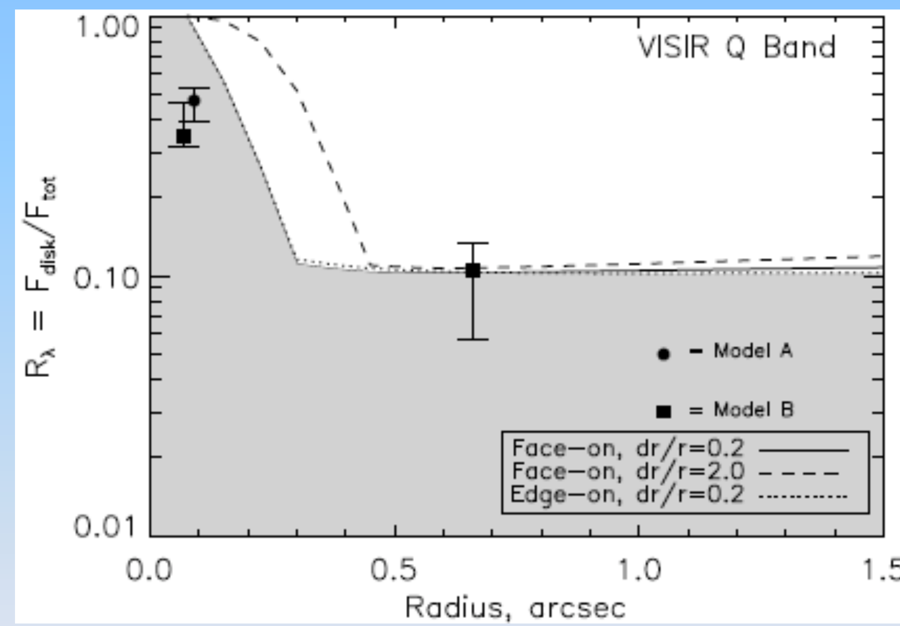


Testing LHB origin using resolved imaging

An outer planetesimal belt has been imaged at 450μm at 100-150AU (Wyatt et al. 2005; see also poster by Bryden)



Mid-IR 18μm emission is compact at <4AU and rules out additional component at 12AU (Smith, Wyatt & Dent 2008)



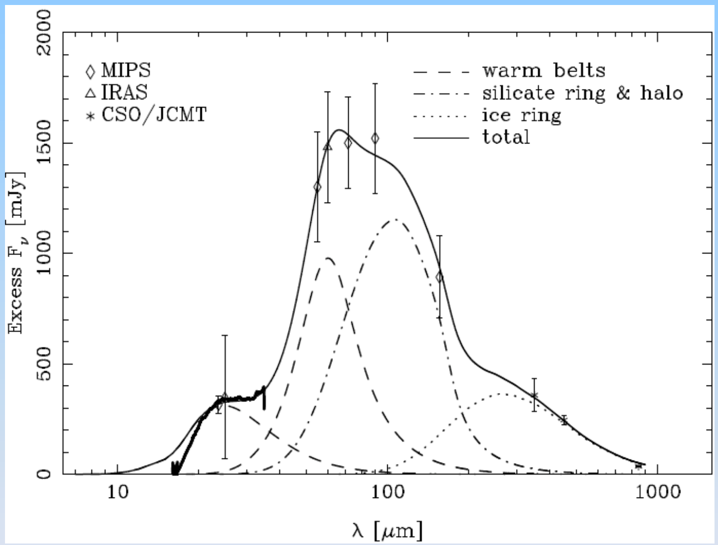
Imaging is required to break the degeneracy of SED interpretation

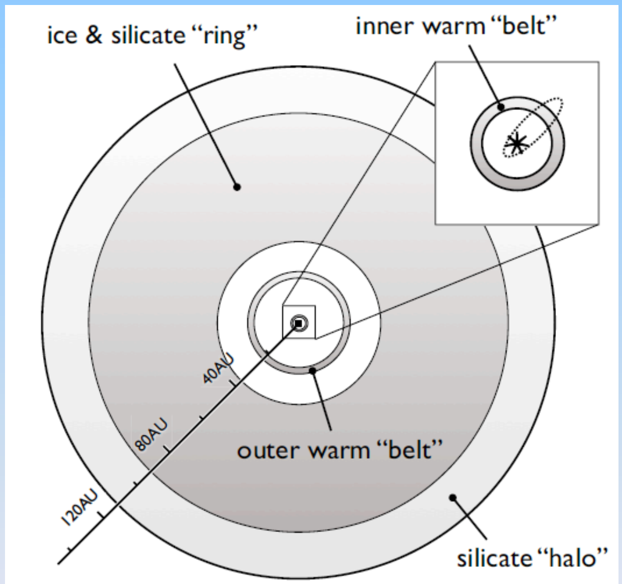
More important as IRS discovers more multi-temperature disks (see poster by Morales)

ε Eri's multi-component disk

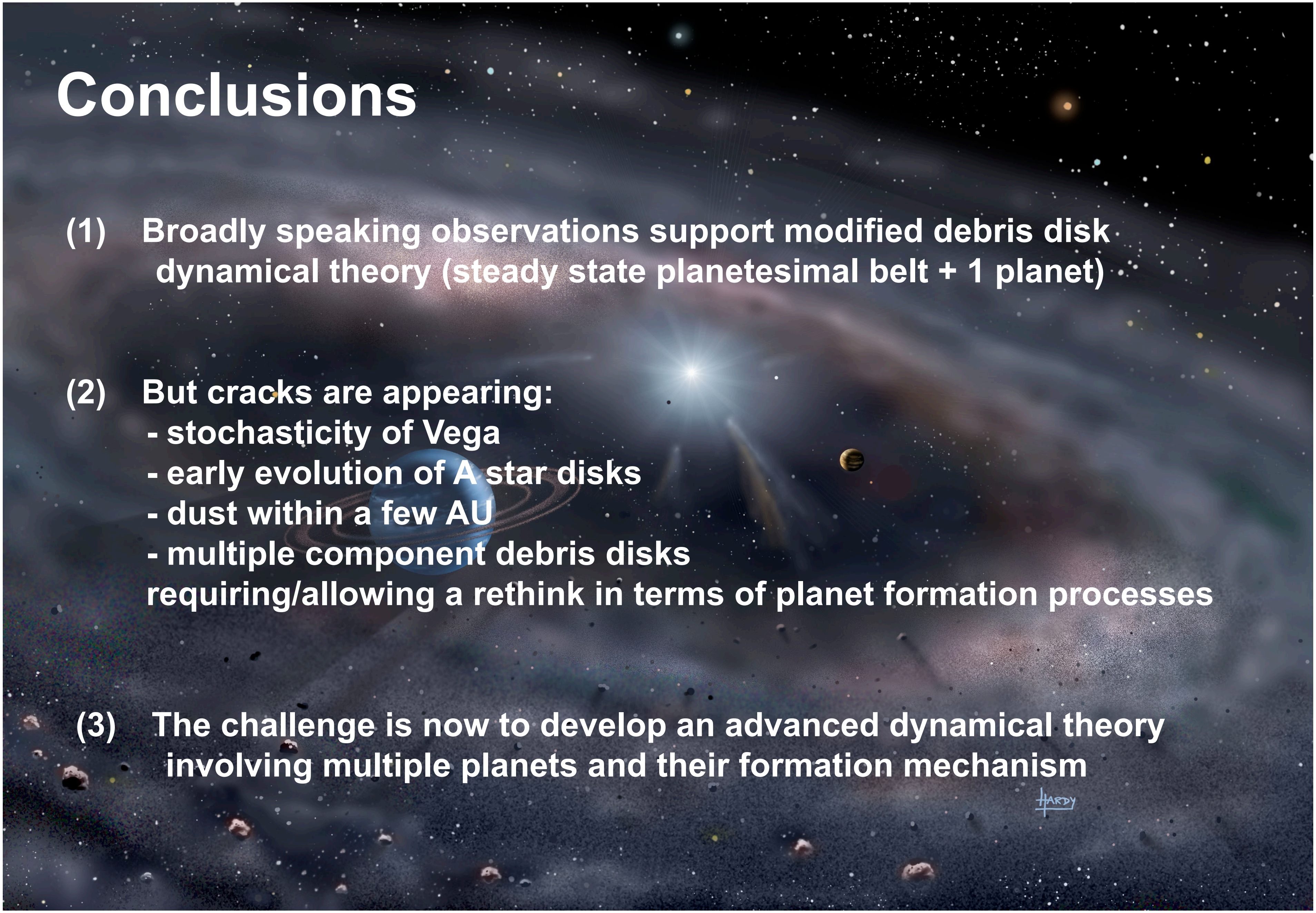
Backman et al. (2008); see poster by Marengo

For nearby systems with well characterised spectra and spatial constraints from resolved (and unresolved) imaging at a number of wavelengths, it is possible to infer the presence of multiple belts





So, with greater scrutiny debris disks become more complex, a view echoed by observations at other wavelengths (see talks by Su, Stapelfeldt, Akeson)



Conclusions

(1) Broadly speaking observations support modified debris disk dynamical theory (steady state planetesimal belt + 1 planet)

(2) But cracks are appearing:
- stochasticity of Vega
- early evolution of A star disks
- dust within a few AU
- multiple component debris disks

requiring/allowing a rethink in terms of planet formation processes

(3) The challenge is now to develop an advanced dynamical theory involving multiple planets and their formation mechanism