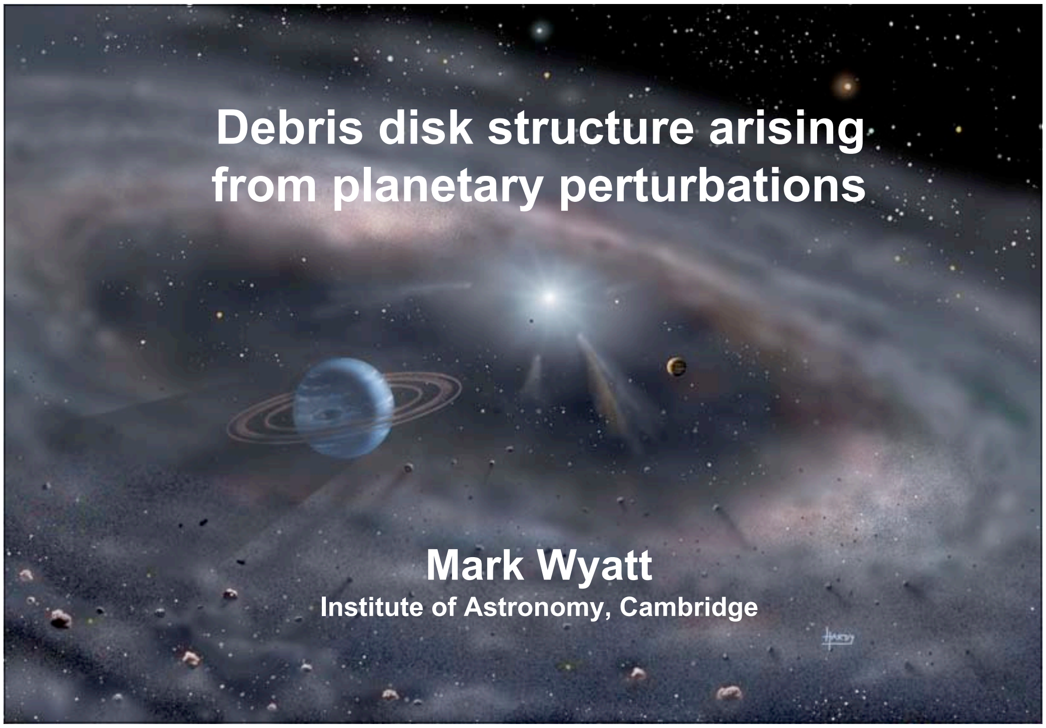
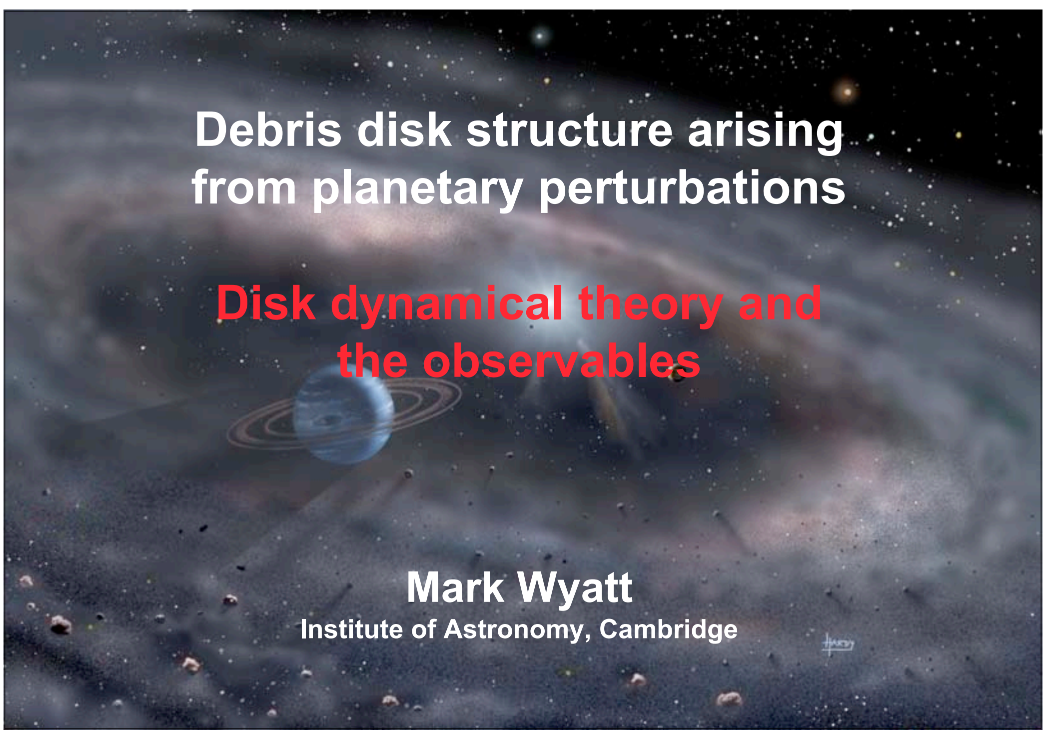
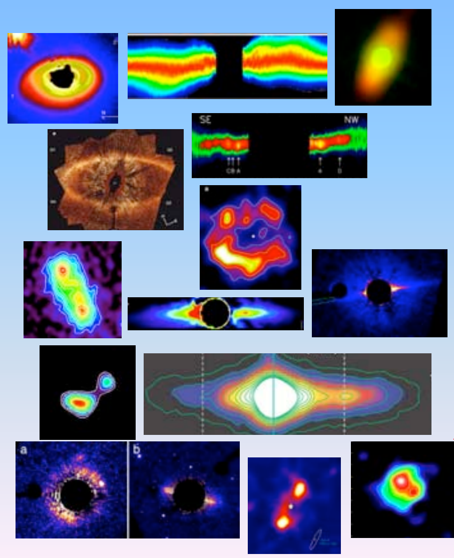

Debris disk structure arising from planetary perturbations
Mark Wyatt
Institute of Astronomy, Cambridge


Debris disk structure arising from planetary perturbations
Disk dynamical theory and the observables
Mark Wyatt
Institute of Astronomy, Cambridge

- More disks than planets (>15% of stars have disks)
- ~~16~~ 18 of these have resolved images



How do we get from here…

… to here?

Using disk dynamical theory!

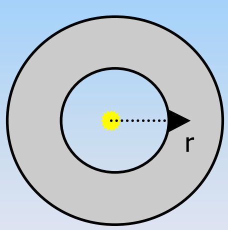
Disk dynamical theory: the basics

The dust must be replenished by the destruction of larger planetesimals

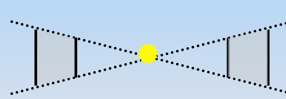
Simplest form of the theory: planetesimals orbit the star confined to a belt

No need to know origin of planetesimals or why they are confined to a ring

Face-on



Edge-on



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

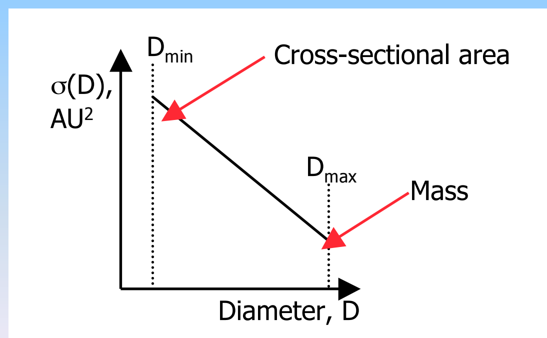
Answer: **the interplay between collisions and radiation forces**

Collisions

Existence of dust implies collisions are destructive and so the planetesimal belt has been stirred: e,I > 10^{-3} – 10^{-2}

Collisions result in collisional cascade with a size distribution:
$\sigma(D) \propto D^{-1.5}$

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

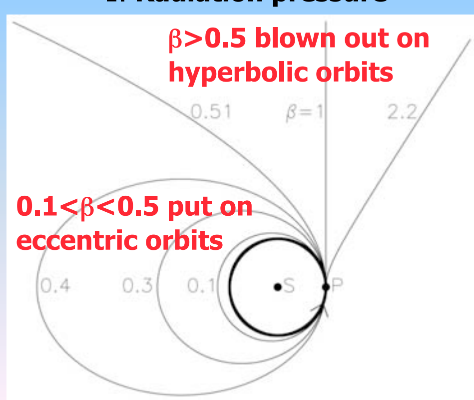


Radiation forces

Small grains interact with stellar radiation resulting in a force characterised by:

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

1. **Radiation pressure**



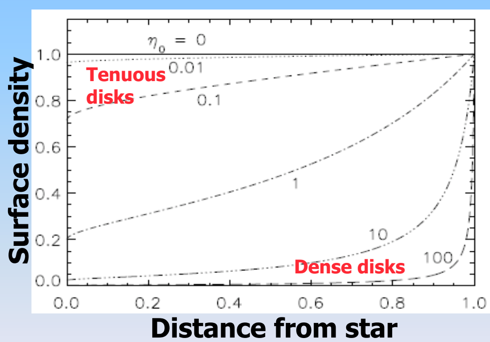
2. **Poynting-Robertson drag**

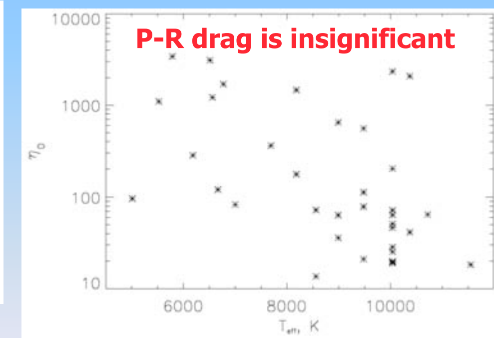
All dust grains spirals toward star on timescale
$t_{pr} = (400/M_*)r^2/\beta$ years

P-R drag is insignificant…

Distribution of dust due to loss in collisions and migration by P-R drag depends on η_0 **= $t_{pr}/t_{col} \propto D^{0.5}$**

If η_0 >> 1 for the smallest particles (β=0.5) then all dust remains confined to the planetesimal belt





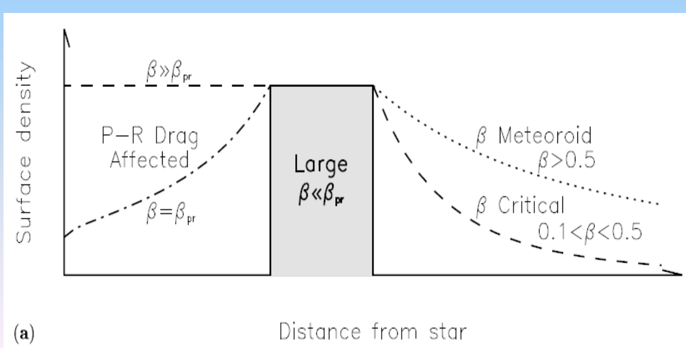
Wyatt (2005)

.. although stellar wind forces result in a drag component which may be important in M stars (Plavchan et al. 2005, Strubbe & Chiang 2006, Augereau & Beust 2006).

Disk particle categories

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

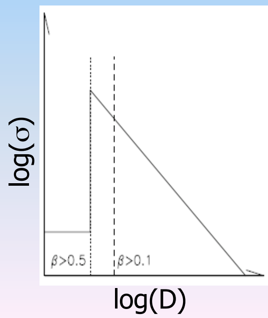


Not all types of particles exist in every disk

Collision dominated disk

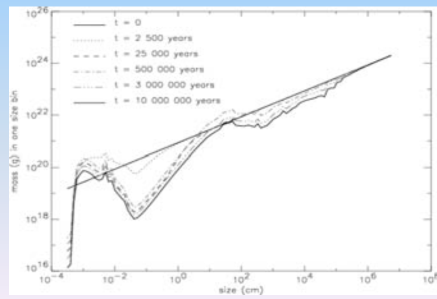
Simple model

Simple treatment of expected size distribution often suffices and is MUCH better than assuming single grain size (Wyatt & Dent 2002):



Details

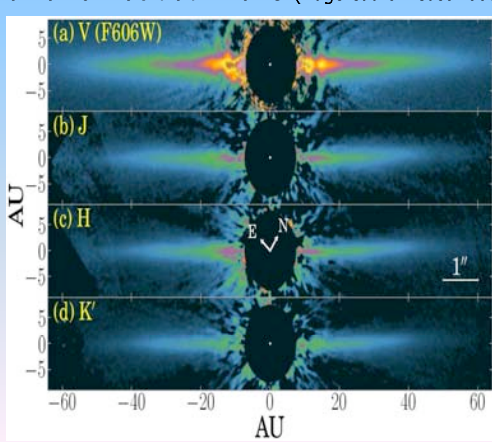
Expect wave in size distribution at small sizes (Thebault, Augereau & Beust 2003; Krivov, Mann & Krivova 2000)

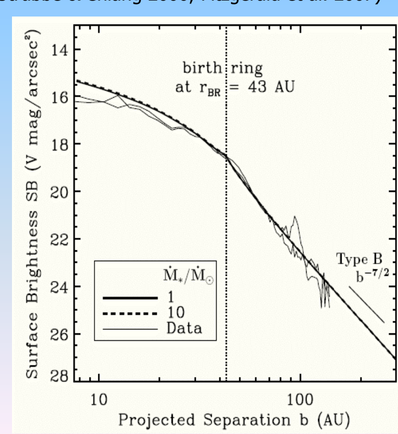


Details can be important

Short wavelengths probe smallest grains and so are dominated by the details (Thebault & Augereau 2007)

By including details, extended structure of AU Mic explained by dust created in a narrow belt at ~40AU (Augereau & Beust 2006; Strubbe & Chiang 2006; Fitzgerald et al. 2007)





Summary of disk dynamical theory basics

(1) Dust not necessarily at same location as planetesimals

(2) Usually dust extends beyond rather than inside planetesimals

(3) Now have physical model to consider non-axisymmetric structure

(4) While model *explains* even multiple wavelength observations of a disk, it can't *predict* what we will see

Advanced disk dynamical theory

Needed to explain the non-axisymmetric structures observed in debris disks:

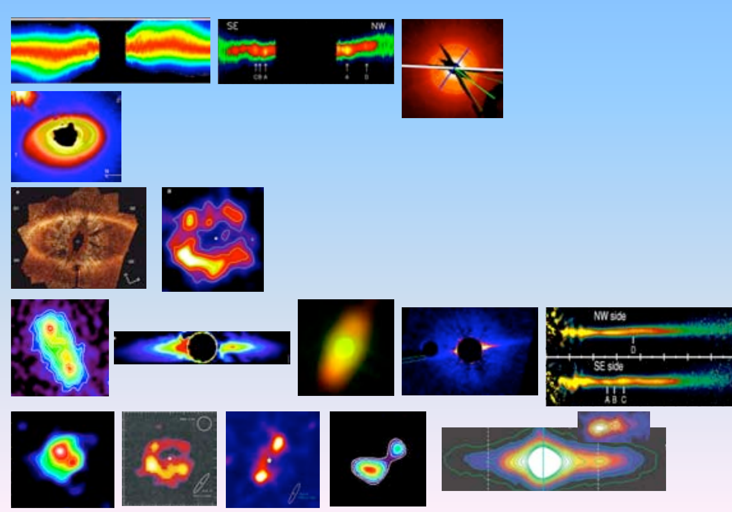
Warps

Spirals

Offsets

Brightness asymmetries

Clumpy rings

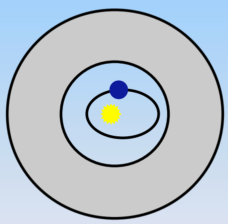


Planetary perturbations

Simple planetary system dynamics predicts exactly this set of features:

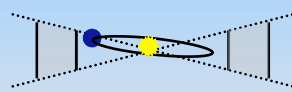
Consider the planetesimal belt + one planet

1. Secular perturbations of eccentric planet



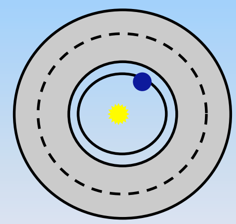
young disk = **spiral**
old disk = **offset+ brightness asymmetry**

2. Secular perturbations of inclined planet



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

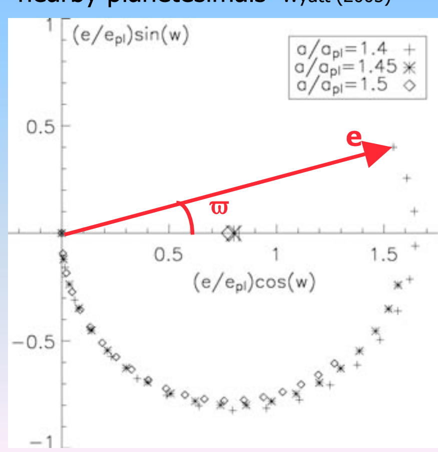
3. Resonant perturbations

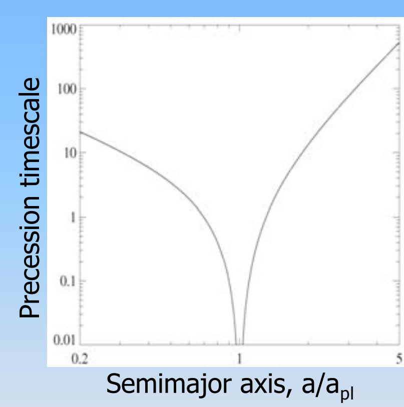


multiple planets = **clearing**
individual planet = **clumps**

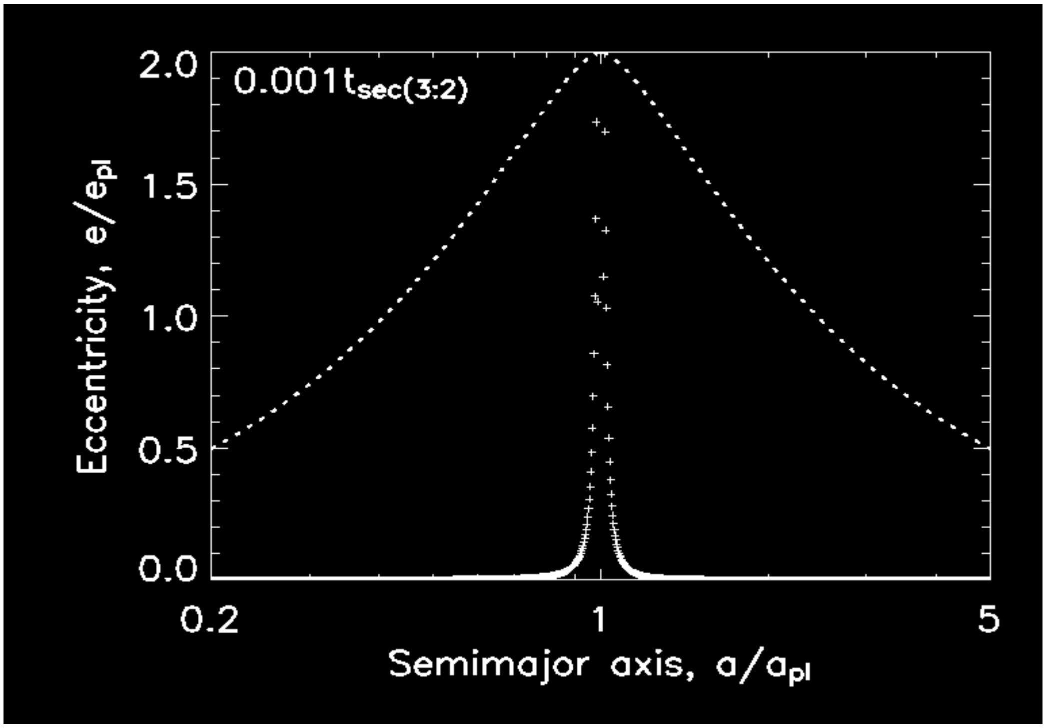
Secular perturbations of eccentric planet

Impact of sudden introduction of planet on eccentric orbit is to impose an eccentricity on nearby planetesimals Wyatt (2005)

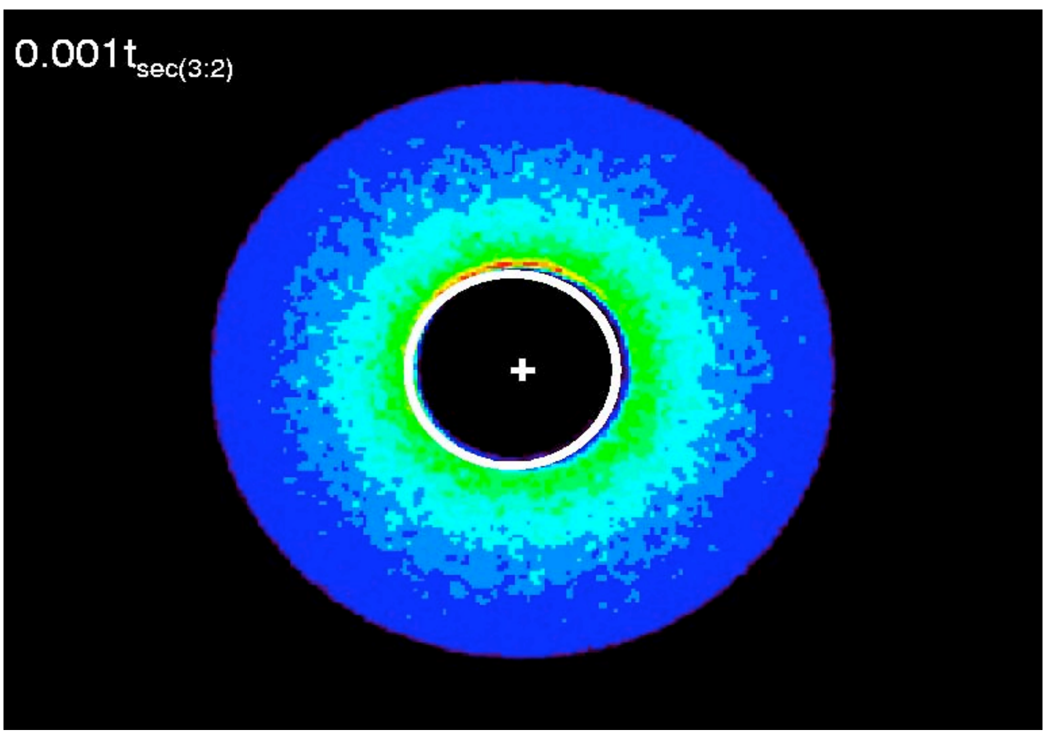




Precession rates are slower for planetesimals further from planet which means dynamical structure evolves with time



2.0
1.5
1.0
0.5
0.0
$0.001t_{sec(3:2)}$
Eccentricity, e/e_{pl}
0.2
1
5
Semimajor axis, a/a_{pl}

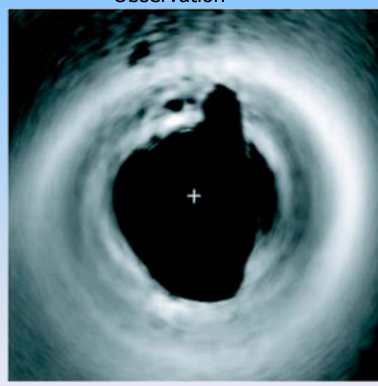


$0.001t_{sec(3:2)}$

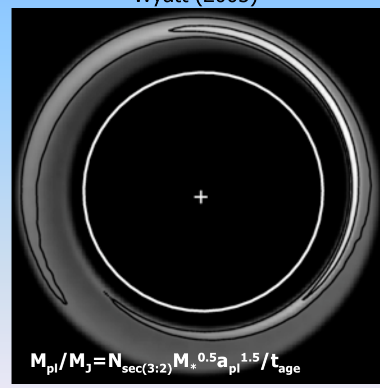
Spiral Structure in the HD141569 Disk

- HD141569A is a **5 Myr**-old **B9.5V** star at **99 pc**
- Dense rings at 200 and 325 AU with tightly wound spiral structure (Clampin et al. 2003)

Observation



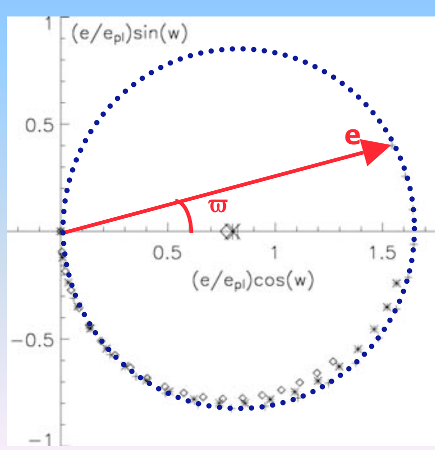
Wyatt (2005)



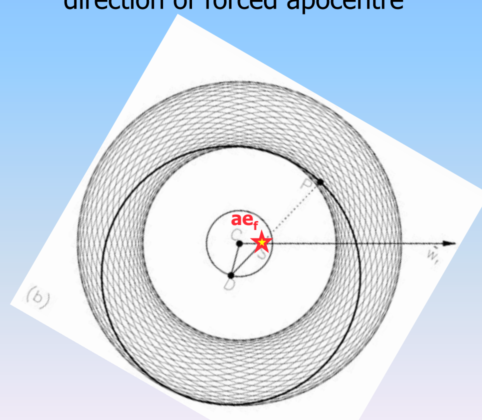
- Spiral at 325AU explained by $0.2M_{Jupiter}$ at 250AU with e=0.05 (Wyatt 2005)

Perturbations at late times in narrow ring

After many precession periods, orbital elements even for particles at same semimajor axis are distributed around circle centred on forced eccentricity



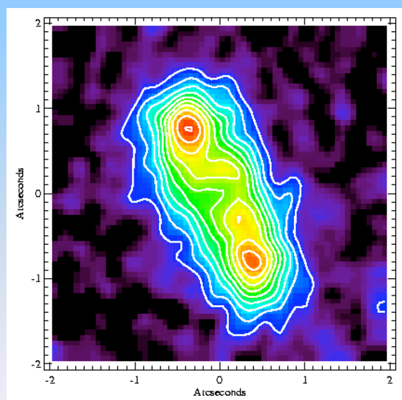
This translates into material in a uniform torus with centre of symmetry offset from star by ae_f in direction of forced apocentre

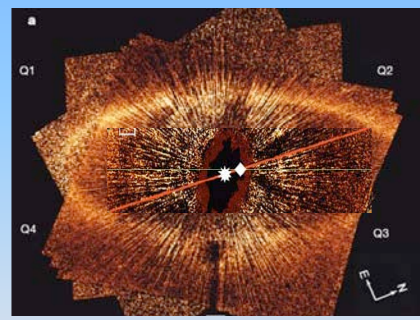


Wyatt et al. (1999)

Applications of pericentre glow

First predicted in dust ring of HR4796 (A0V , 10Myr) from 5% brightness asymmetry, implying a forced eccentricity of 0.02 (Wyatt et al. 1999)





First detected in Fomalhaut, a 133AU ring offset by 15AU implying a forced eccentricity of 0.11 (Kalas et al. 2005)

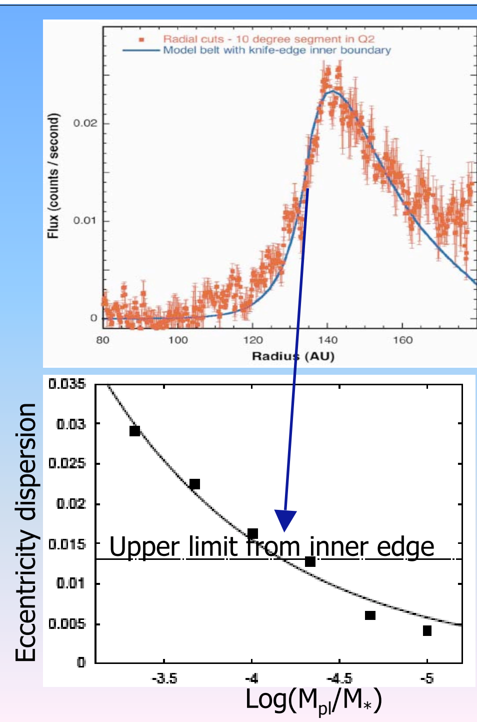
Plus offsets like HD10647 (Stapelfeldt poster)?

Further constraints on planets

Fomalhaut ring structure implies (Quillen 2006):

- Planet at a_{pl}=119 AU with e_{pl}=0.1
  - Inner edge from resonance overlap
  - Eccentricity from secular perturbations

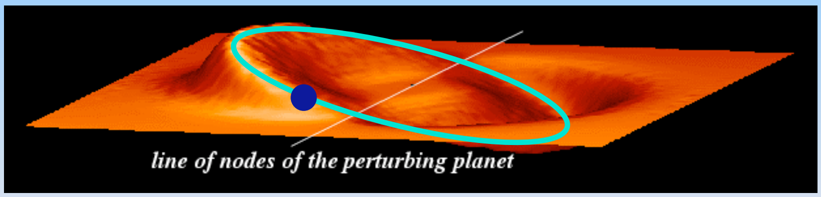
- Observed sharpness of inner edge implies eccentricity dispersion <0.013 and so M_{pl}<M_{saturn}



Secular perturbations: warps

Secular perturbations of a planet also affect the inclinations (ie. orbital plane) of nearby planetesimals

Introducing a planet into the disk on an orbit inclined to the disk midplane causes a warp to propagate away from the planet

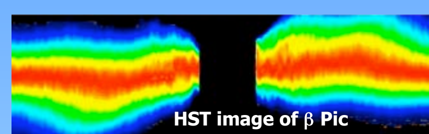


Augereau et al. (2001)

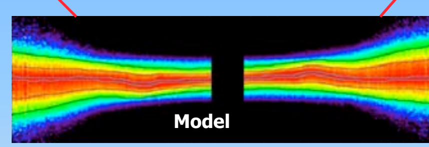
This causes disk near planet to become aligned with the planet, but that far away keeping the initial symmetry plane

Warp in β Pic

The warp in β Pic can be explained in this way by a 1-2$M_{jupiter}$ planet at 10AU inclined by 3^0 to the disk mid-plane which causes at warp at 70AU at 20Myr



Heap et al. (2000)



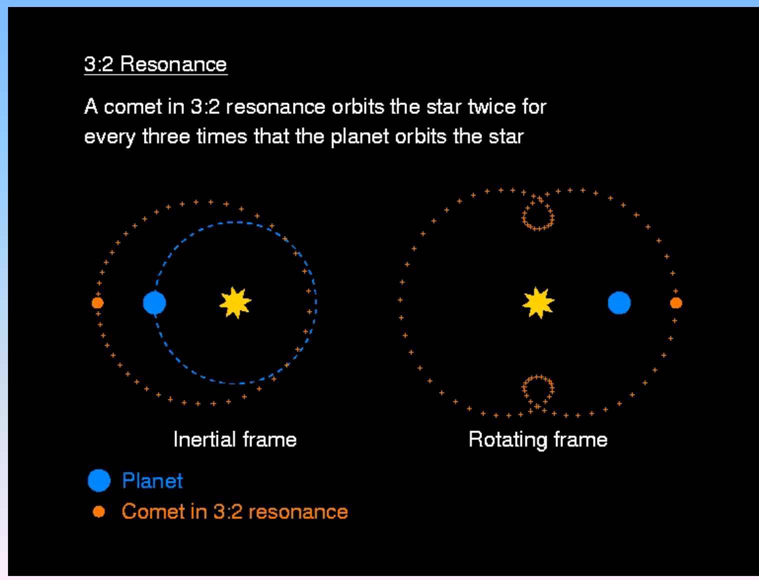
Augereau et al. (2001)

But still consistent with observation showing warp is two disks (Golimowski et al. 2006)?

Warps also if two planets on different orbital planes (Wyatt et al. 1999)

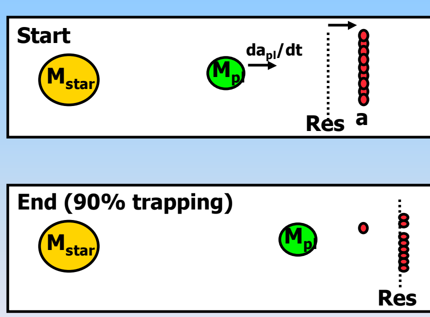
Geometry of resonance

• Resonances are special because of the periodic nature of the orbits and the way that planet and planetesimal have encounters

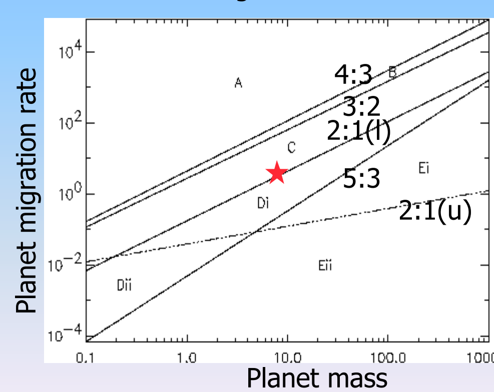


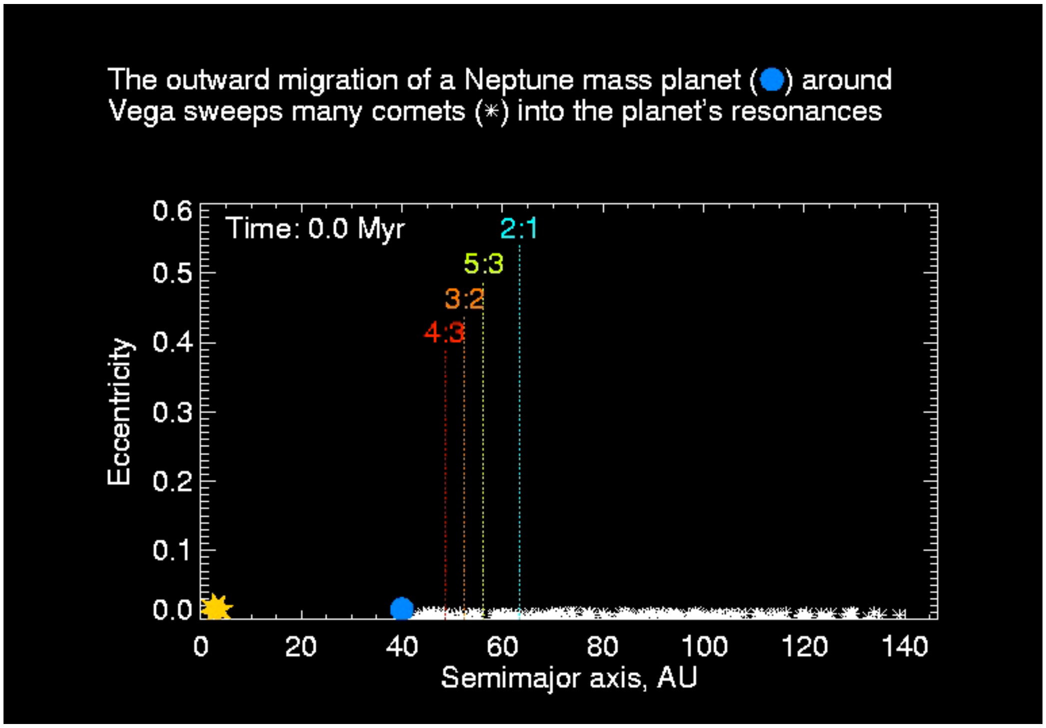
Capture by migrating planet

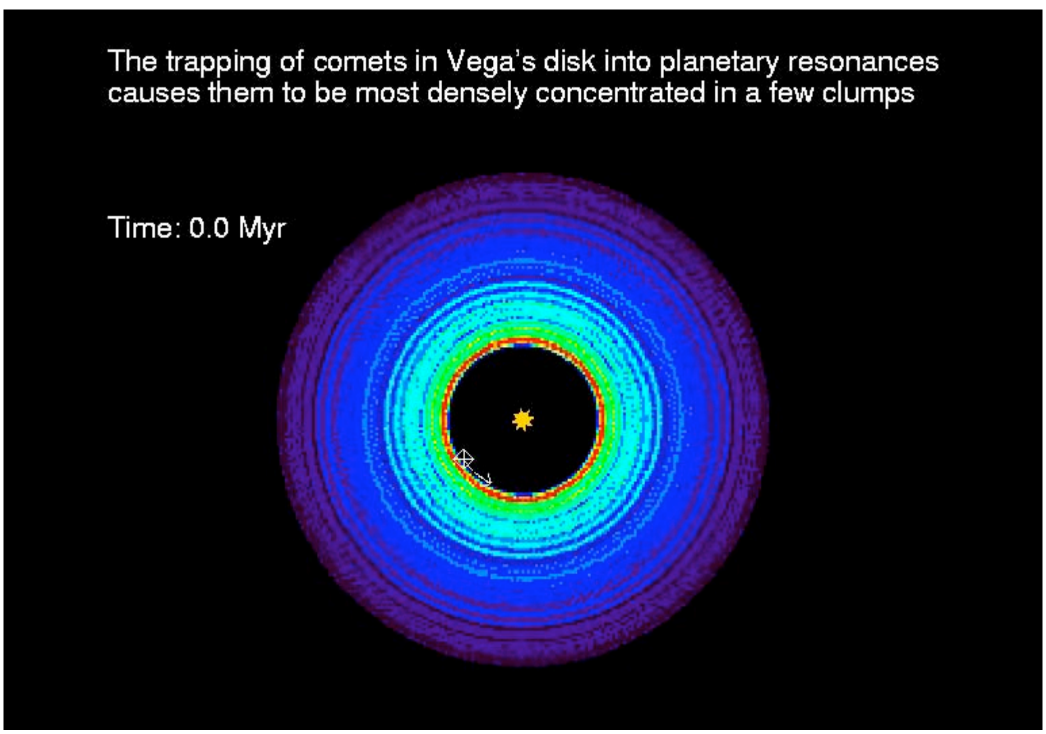
Planetesimals can become captured into the resonances of a migrating planet



Resonances which can be populated depend on planet mass and migration rate

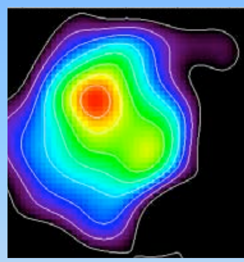



The outward migration of a Neptune mass planet (●) around Vega sweeps many comets (*) into the planet's resonances
Time: 0.0 Myr
2:1
5:3
3:2
4:3
Eccentricity
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
140
Semimajor axis, AU

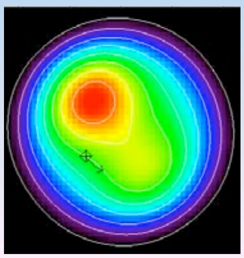

The trapping of comets in Vega's disk into planetary resonances causes them to be most densely concentrated in a few clumps
Time: 0.0 Myr

Constraints on Vega's planetary system

Observation

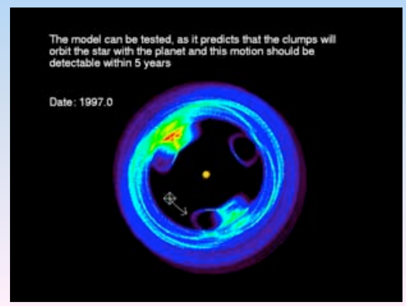


Model



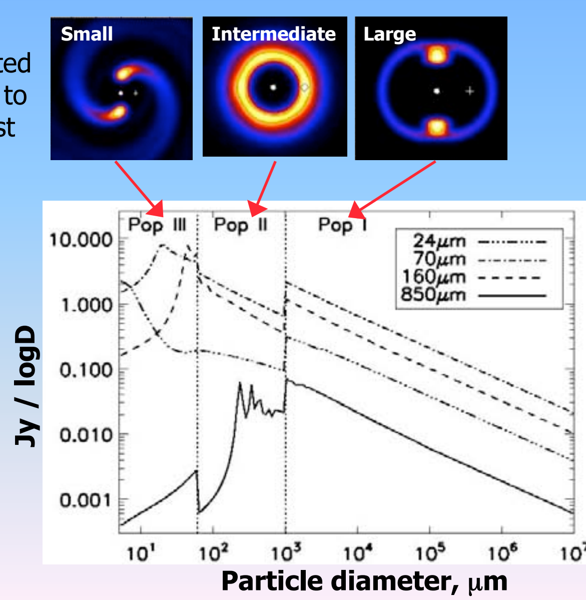
- This model can explain the clumpy structure of Vega (350Myr, A0V at 7.8pc) seen in sub-mm (Holland et al. 1998) and mm (Wilner et al. 2002; Koerner et al. 2002)
- Infers $1M_{neptune}$ which migrated 40-65AU over 56Myr, although $1M_{jupiter}$ over 3Myr also possible (Martin et al. 2007)

Predicts orbital motion of structure (Poulton et al. 2006)



Predictions for different wavelengths

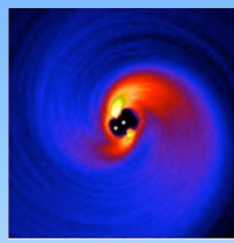
Radiation pressure causes intermediate-sized dust created from resonant planetesimals to fall out of resonance; smallest grains are removed on hyperbolic orbits (Wyatt 2006)



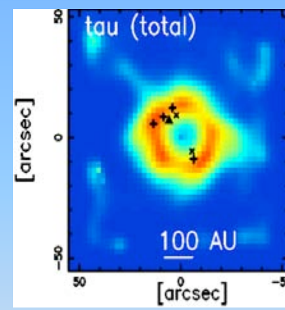
Since observations in different wavebands sample different grain sizes, these should show different structures

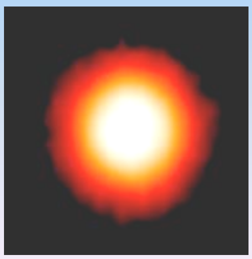
… and comparison with observations

Mid- to far-IR images should exhibit spiral structure emanating from clumps

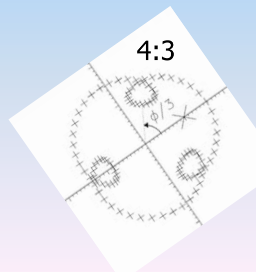


Meanwhile 350μm imaging shows evidence for 3 clump structure (Marsh et al. 2006)





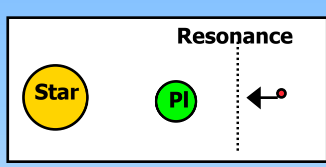
Not detected at present, but resolution of published Spitzer observations may not have had sufficient resolution to detect this (Su et al. 2005)



Possible evidence for a different size distribution of material in 4:3 resonance?

Dust migration into resonances

Dust can also migrate into planetary resonances:



Resulting structure depends on the planet mass and eccentricity (Kuchner & Holman 2003)

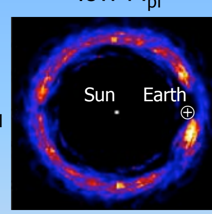
While P-R drag not important in currently detectable disks, relevant when $\tau<10^{-5}$ (Krivov et al. 2006)

(e.g., JWST, ALMA, TPF/Darwin)

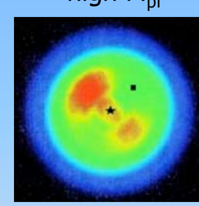
See poster by Stark

low M_{pl} | high M_{pl}

low e_{pl}

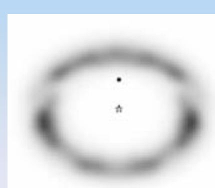


Dermott et al. (1994)



Ozernoy et al. (2000)

high e_{pl}

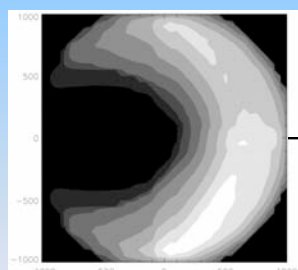


Quillen & Thorndike (2002)

Wilner et al. (2002)

Other causes of asymmetric structure

Sandblasting of a disk by interstellar dust grains
(Artymowicz & Clampin 1997)

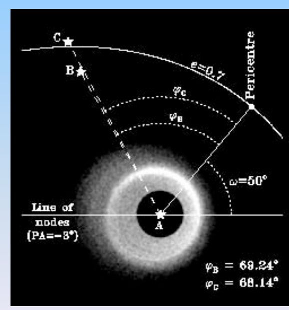


Motion relative to the ISM

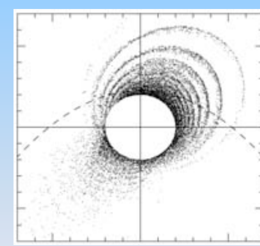
See talk by Hines

Dynamical perturbations from:

Binary companion
(Augereau & Papaloizou 2003)



Stellar flyby
(Larwood & Kalas 2001)

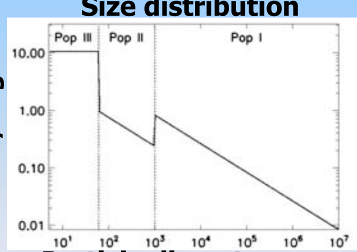


See poster by Kalas on HD15115

Problems: Origin of high mass loss in Vega

Mass loss rate in Vega due to radiation pressure is $2M_{\oplus}$/Myr which can't have been sustained for 350Myr (Su et al. 2005; Wyatt 2006)

Size distribution

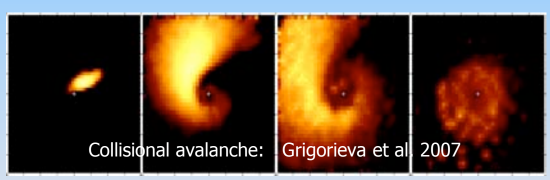


AU^2 / logD

Particle diameter, μm

What is the origin of the observed high mass loss rate?

(1) Mass loss is recent/transient
Recent collision or ignition of cascade
BUT… why so many small grains?



(2) Mass is not being lost
These are highly eccentric grains
BUT… why so hot and $\tau_{24,70} \propto 1/r$

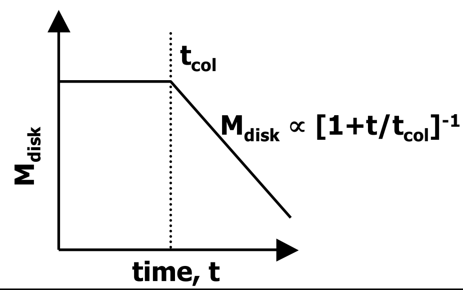
Rest of the A star disk population explained by disk dynamical theory + steady state evolution

Starting with the basic dynamical disk theory, and assuming:

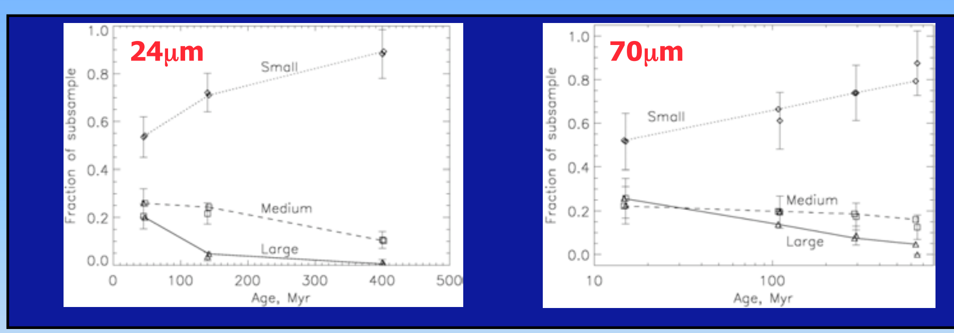
(1) All stars have one planetesimal belt
(2) Initial mass distribution of protoplanetary disks (Andrews & Williams 2005)
(3) Radius distribution: $n(r) \propto r^{\gamma}$
(4) Planetesimal belts evolve in steady state after their formation

Steady State Evolution

Disk mass falls off once largest objects are depleted in collisions on a timescale $\mathbf{t_{col}}$



Steady-state evolution explains 24 and 70μm stats



Wyatt et al. (2007b)

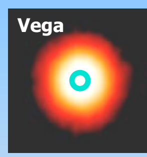
No need to invoke stochastic evolution for most disks to explain the stats

So:
- Is Vega an anomaly?
- Or would all systems exhibit such behaviour if imaged with sufficient sensitivity?
- Perhaps there's a stochastic element on top of a dominant steady-state evolution?

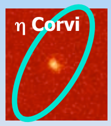
Radial location of dust

Comparing dust location expected from F_{24}/F_{70} with that from imaging shows that disks are:

Bigger



Smaller



Just right (ish)

We can explain this because:

Radiation pressure

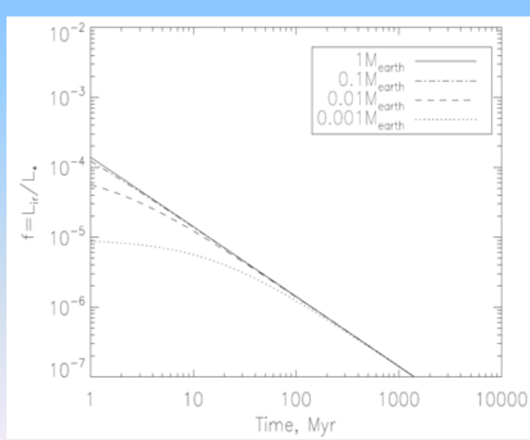
Multiple planetesimal belts

But we cannot predict which apriori

Only way to break degeneracies is by imaging

Problems: Hot dust around FGK stars

Steady state evolution of dust from planetesimal belt at 1AU (Wyatt et al., 2007a)



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

$$f_{max} = 0.16\times10^{-3}\, r^{7/3}\, t_{age}^{-1}$$

Good news for TPF (look at old stars)

Bad news for explaining systems with 25μm excess many of which have $f>1000f_{max}$ and so must be **transient**

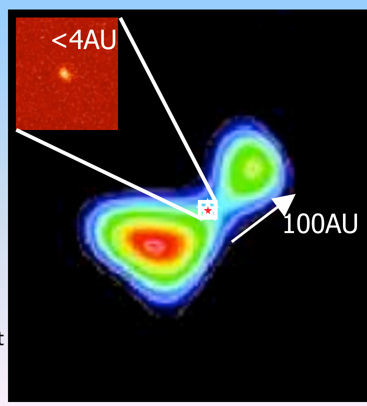
Origin of transient event?

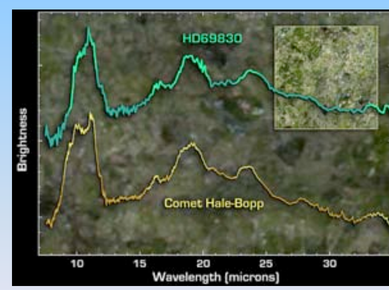
(1) Recent collision in asteroid belt
Chance of seeing collision <1:10^5
NO

(2) In situ planetesimal belt
Mass loss rate -> sustainable for <1Myr
NO

(3) Scattered in from outer planetesimal belt

An outer planetesimal belt is known to exist around η Corvi and could be feeding the hot dust closer in (Wyatt et al. 2005)



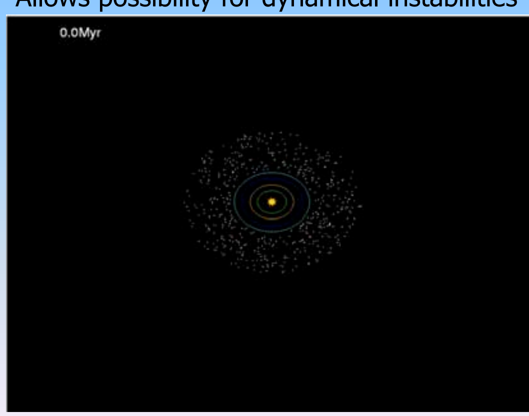


The composition of dust 1AU from HD69830 is similar to that of comets in the solar system (Beichman et al. 2005; Lisse et al. 2007)

The need for super-advanced dynamical theory

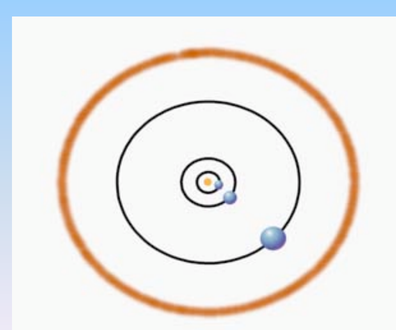
The one planet of "advanced dynamical theory" is not enough – need a super advanced dynamical theory with multiple planets

Allows possibility for dynamical instabilities



Late heavy bombardment model of (Gomes et al. 2005)

Besides we know planetary systems are multiple

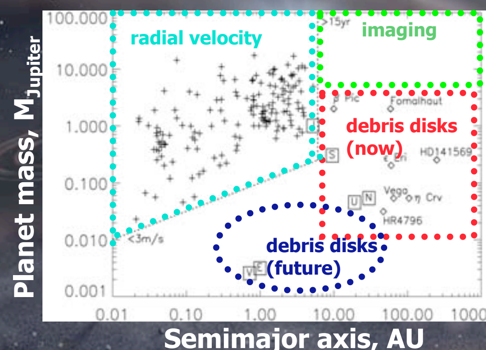


Planetary system of HD69830 (Lovis et al. 2006)

Conclusions 1 (Good news)

Most disk radial structure explained by steady-state evolution of a planetesimal belt due to collisions and radiation forces

Most non-axisymmetric structure explained as perturbations from planets



Disks are worth studying because they can tell us about the origin and evolution of planetary systems

Conclusions 2 (Outstanding Questions)

(1) Cannot predict small grain contribution
- steady state (dust physics?)
- stochastic (collisions, LHB?)

And how many have inner belts?

} Need more disk images

(2) Need planet predictions confirmed
- detections of planets
- ideally of disk and planet together!

} Need more planet detections

(3) Super advanced dynamical theory
- need more disk+planet systems

} Need more theory