Formation and dynamical history of the β Pictoris system

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European Research Council
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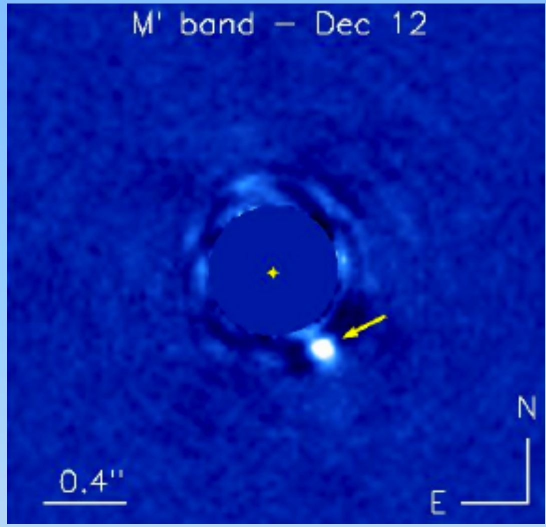
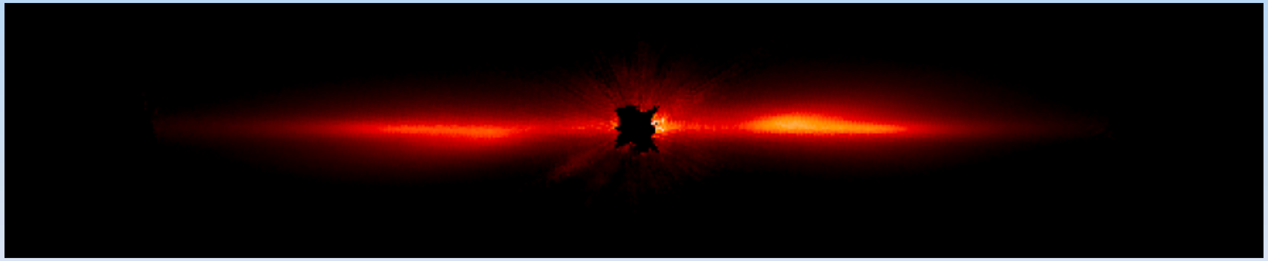
Main dynamical indicators

The planet beta Pic-b (its orbit and spectrum)

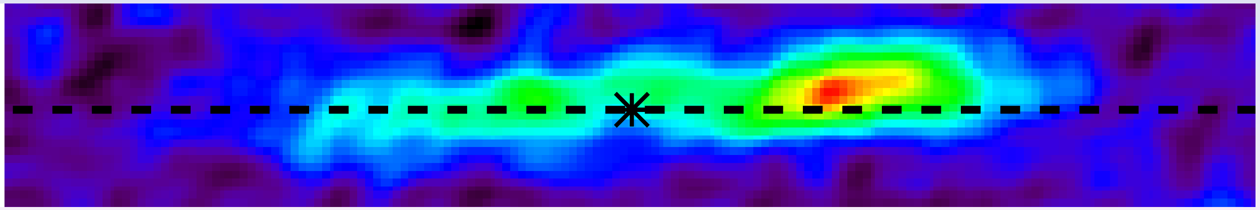


FEBs (velocity distribution)

Warp in outer disk



Clump in outer disk



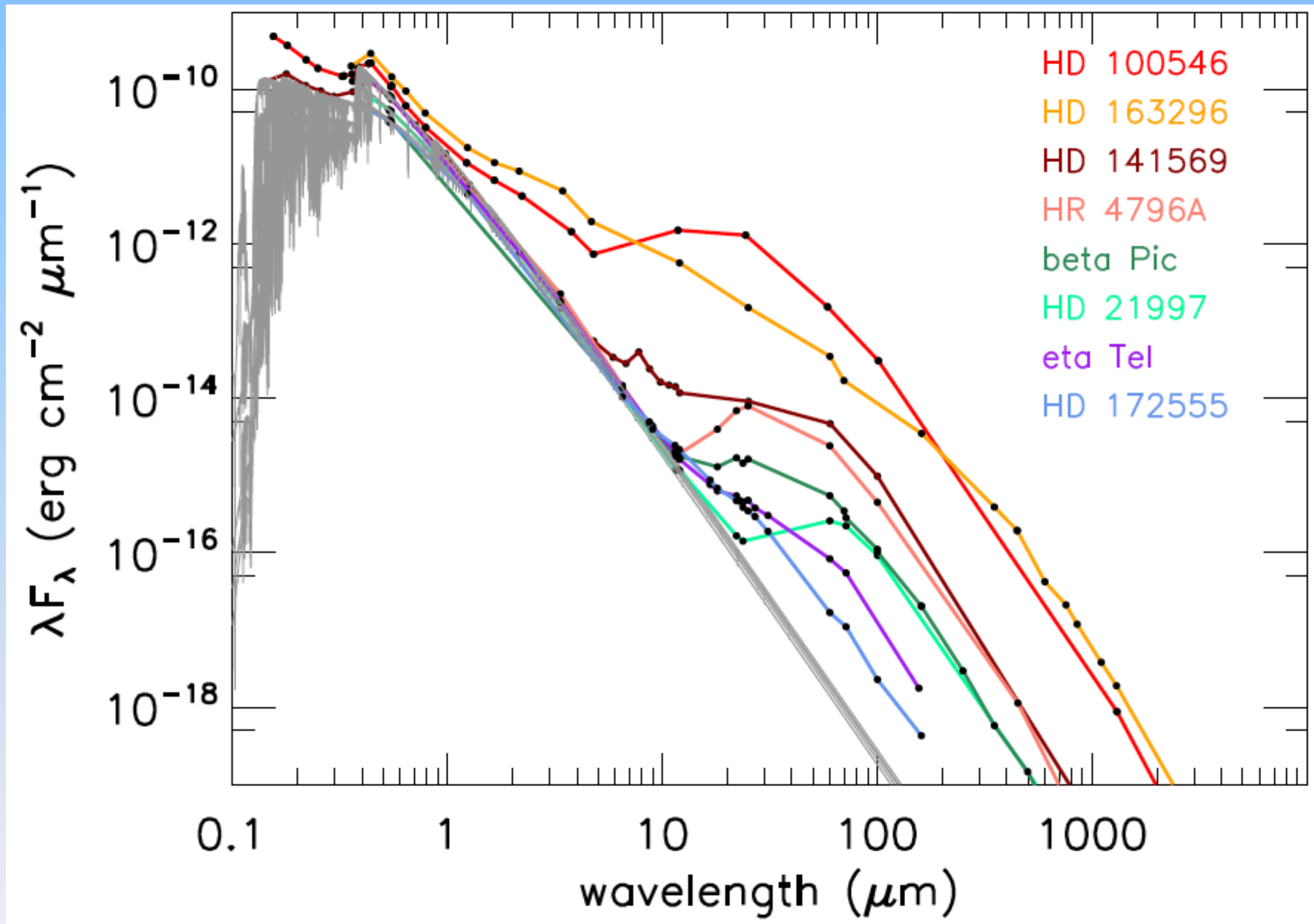
Descendant of protoplanetary disk

System formed in protoplanetary disk akin to Herbig Ae stars

PPDs last a few Myr then disperse rapidly… somehow

β Pic has relatively bright disk, possibly because it is young

Wyatt et al. (in prep)

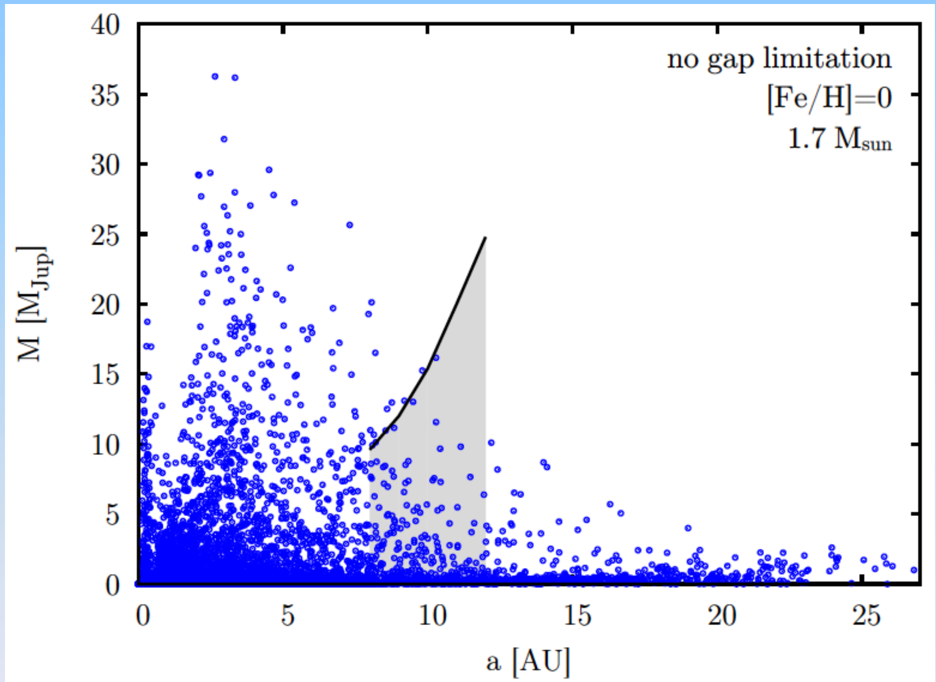


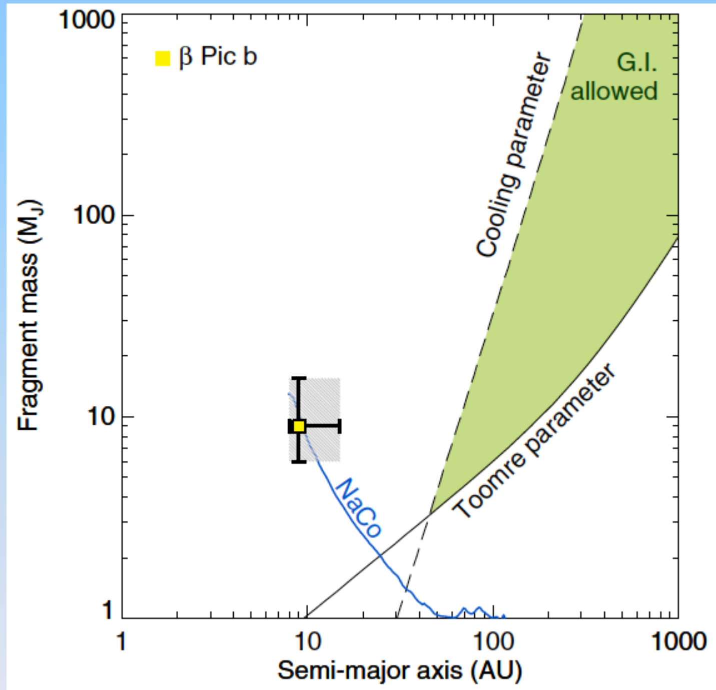
Formation mechanism for β Pic-b

See Mickael Bonnefoy's talk

Can be formed in core accretion models implying a core of ~200M_{earth} (Bonnefoy et al. 2013)

Hard to form in situ by gravitational instability (Rameau et al. 2013)



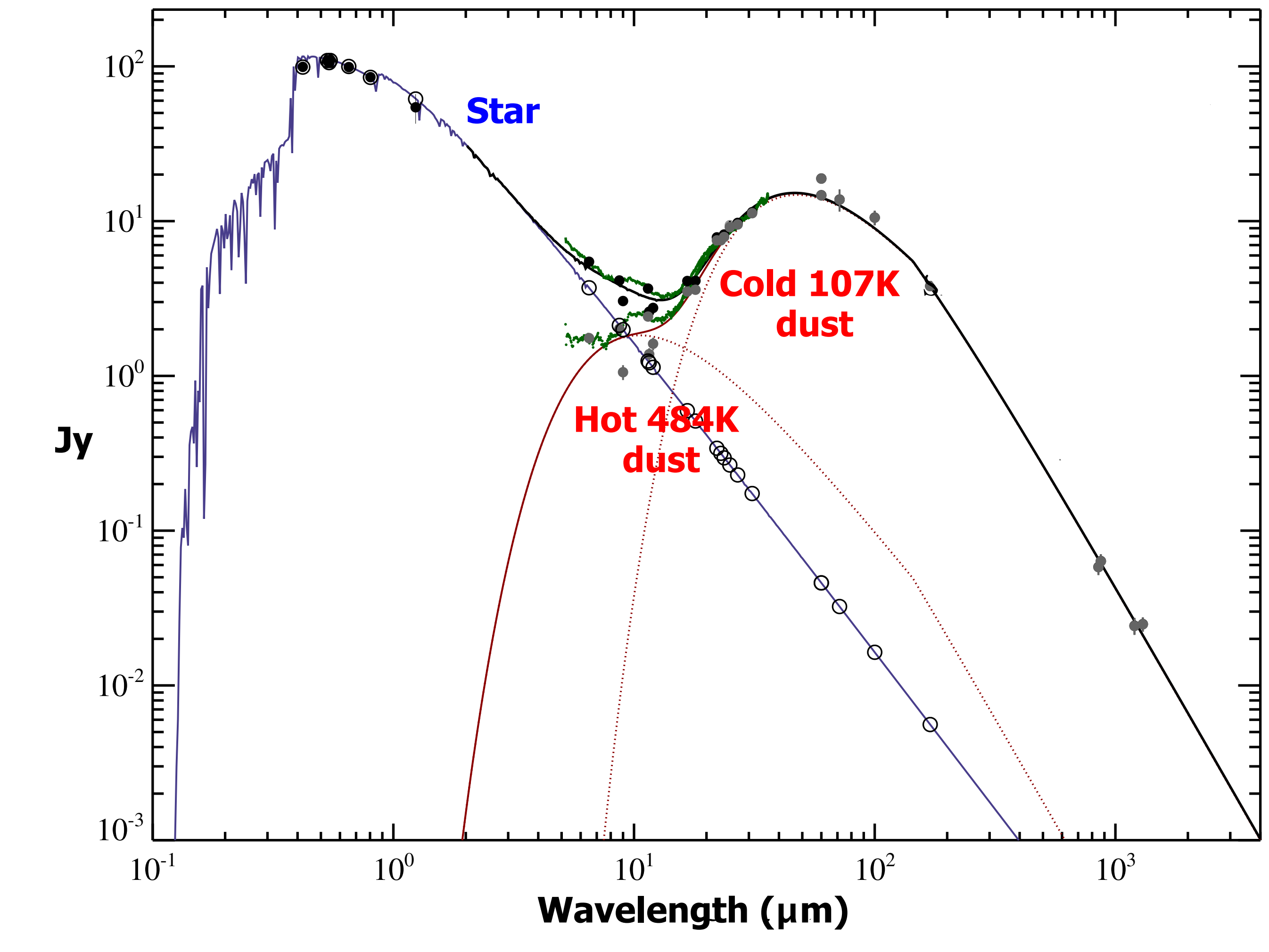


- But could have migrated, and model assumptions are somewhat flexible
- Implications for other planets in system (e.g., why just one core?)
- Regardless, formed in PPD

Two temperature β Pic debris disk

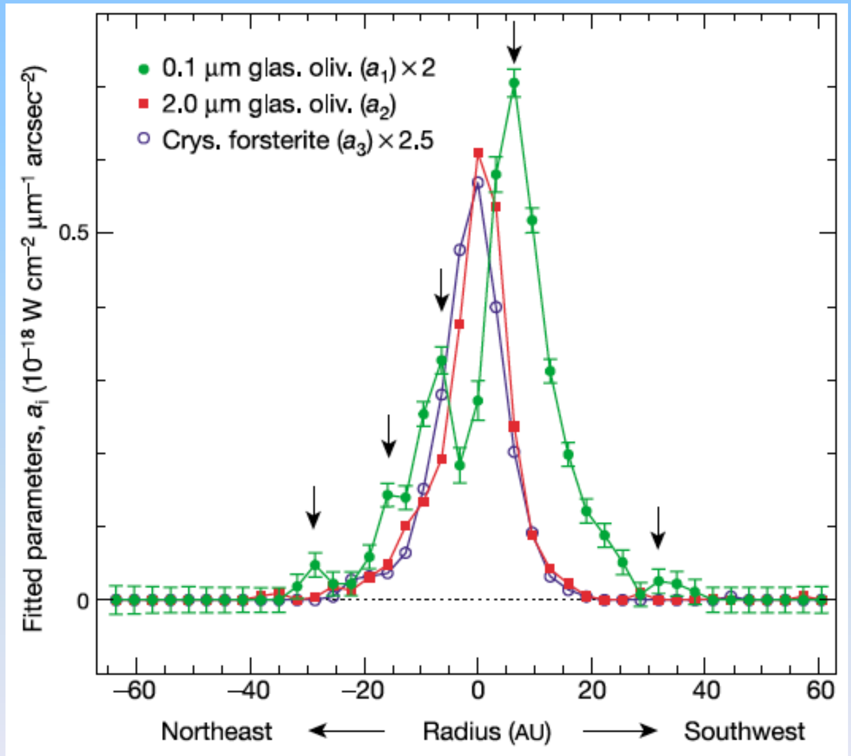
Spectrum shows thermal emission from dust at a range of wavelengths

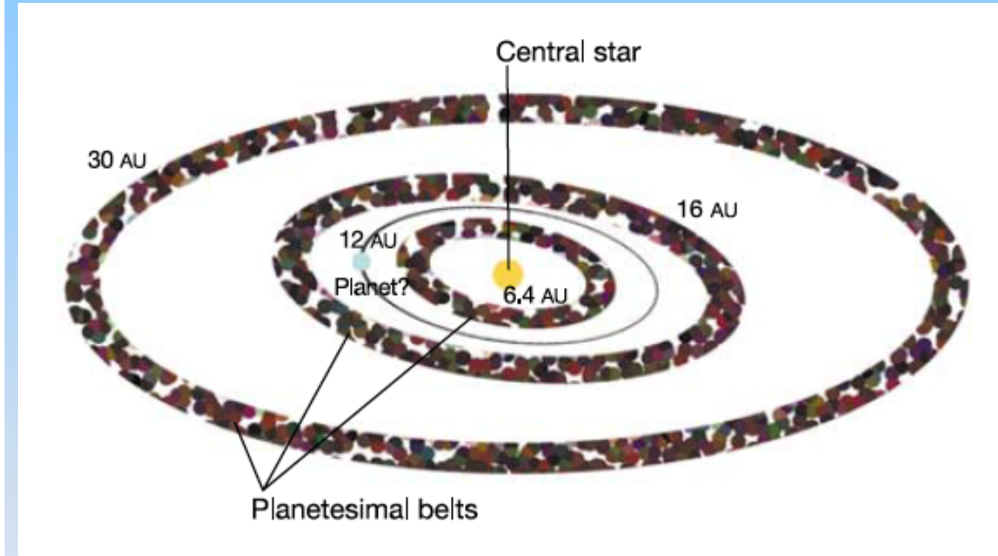
Reasonable fit with two (modified) black bodies at 484 and 107K suggesting two spatially distinct regions



Inner planetesimal belts?

Inner component poorly constrained as small and next to bright star, but fit to mid-IR spectrum inferred multiple belts (Okamoto et al. 2004)





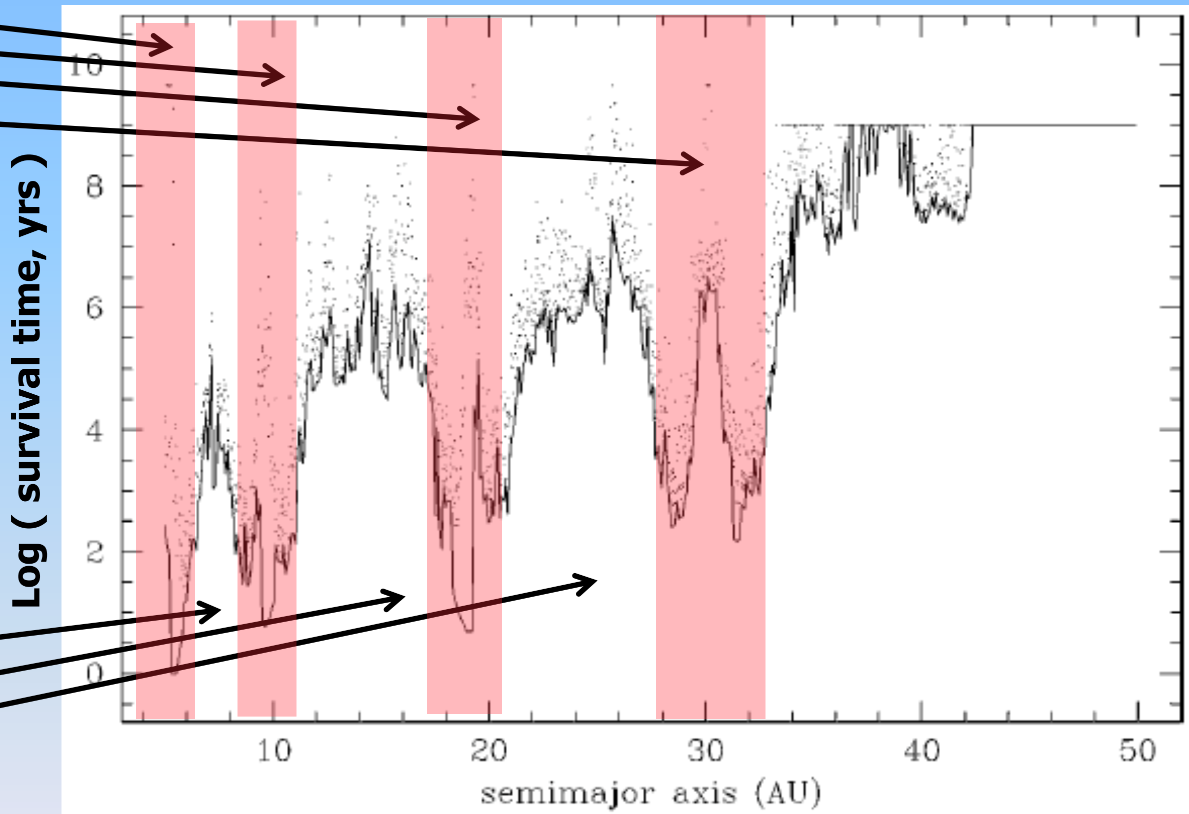
Makes sense dynamically that gaps in distribution are caused by planets

Dynamical lifetimes in planetary systems

Overlapping resonances near planets quickly clear gaps (Wisdom 1980)

$a/a_{pl} = 1 \pm 1.3(M_{pl}/M_{*})^{2/7}$

Chaotic region extends further for multi-planet systems, but these regions are cleared on 10Myr timescales

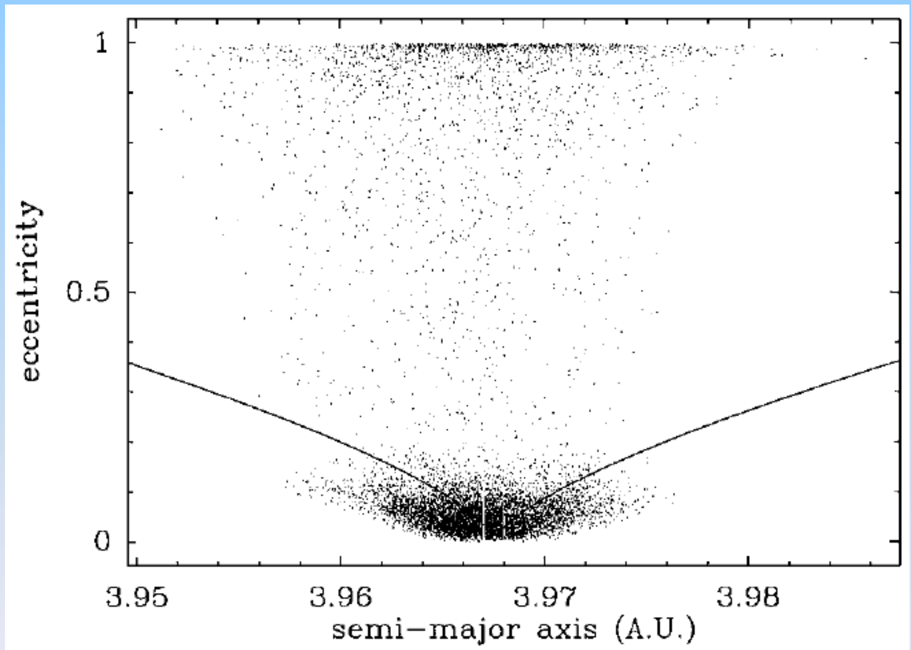


Asteroid and Kuiper belts only locations in Solar System stable for >4.5Gyr (Lecar et al. 2001); perhaps 6au and >60au regions are analogous for β Pic?

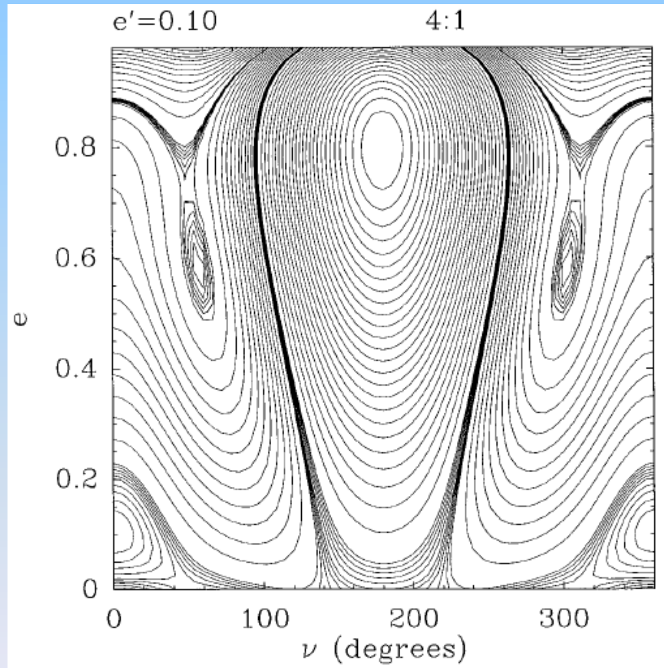
Falling Evaporating Bodies

See Herve Beust's talk

Transient absorption features explained by interior resonances (4:1 or 3:1) with β Pic-b where eccentricities can be driven to >0.9 (Beust & Morbidelli 1996, 2000)



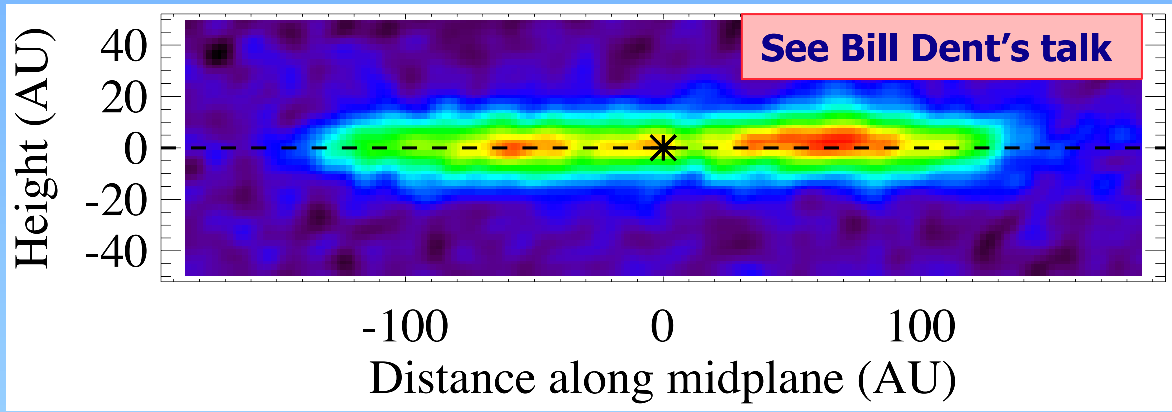
Dynamics explains predominantly red-shifted absorption features (for e_b=0.05-0.1) , but do blue-shifted features imply interior planets?



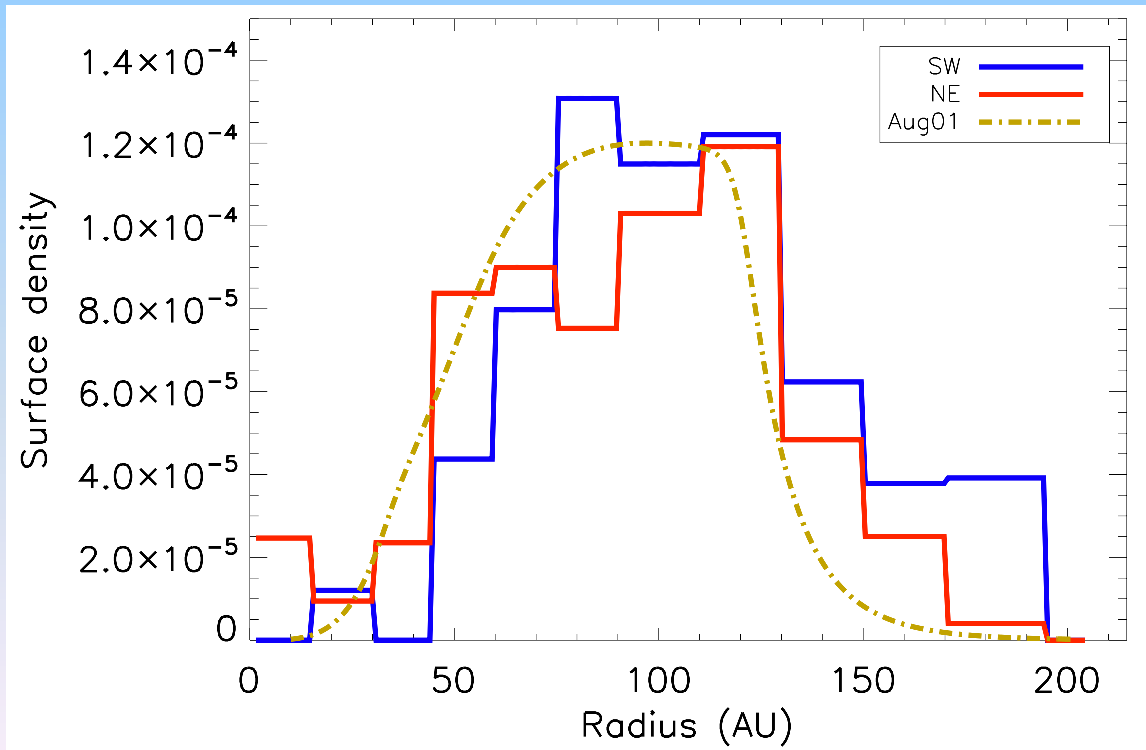
Also, what is the mechanism feeding the resonance – collisions in the belt, ongoing migration (Thebault & Beust 2001)?

Where are planetesimals in outer disk?

ALMA mapped 850μm emission from mm-sized grains at ~0.5″ (~10AU) resolution down to star
(Dent et al. 2014)

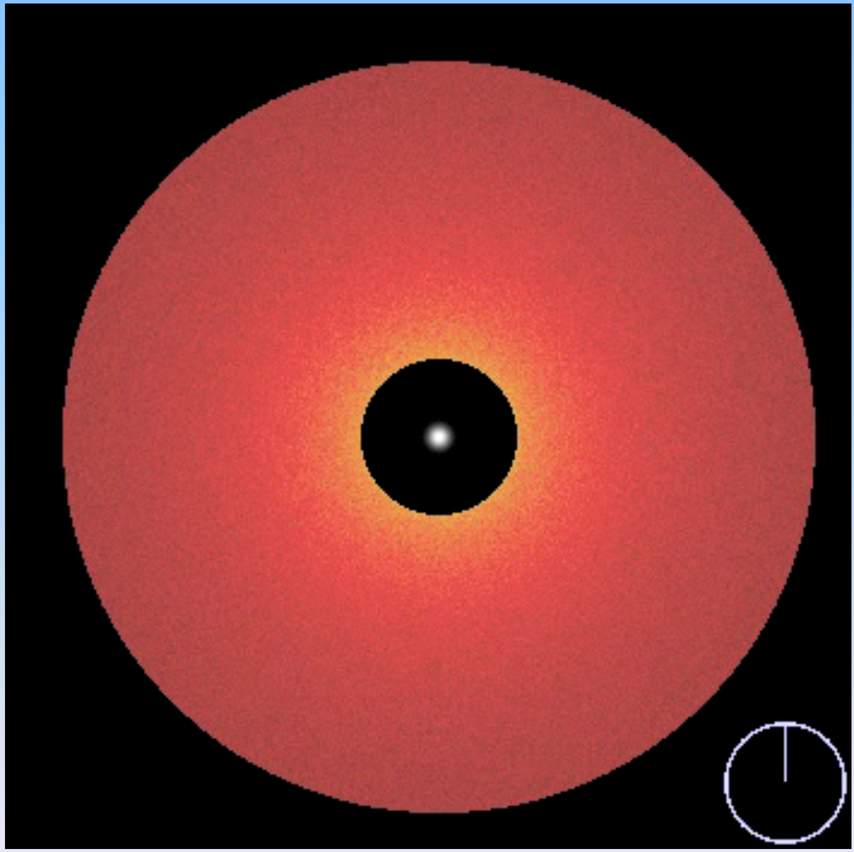


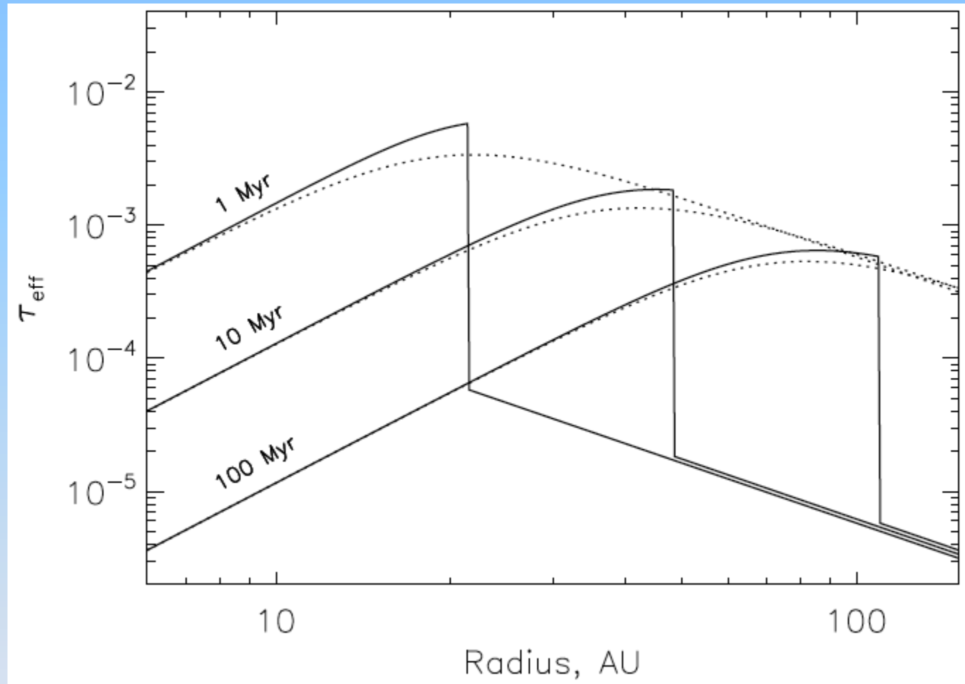
Fit to surface brightness profile shows planetesimals in broad belt 60-130au (Dent et al. 2014) as expected from fit to scattered light
(Augereau et al. 2001)



How are the planetesimals stirred?

Initially km-sized planetesimals grow to Pluto-size, stir their immediate vicinity igniting a collisional cascade and producing dust (Kenyon & Bromley 2004; 2010)

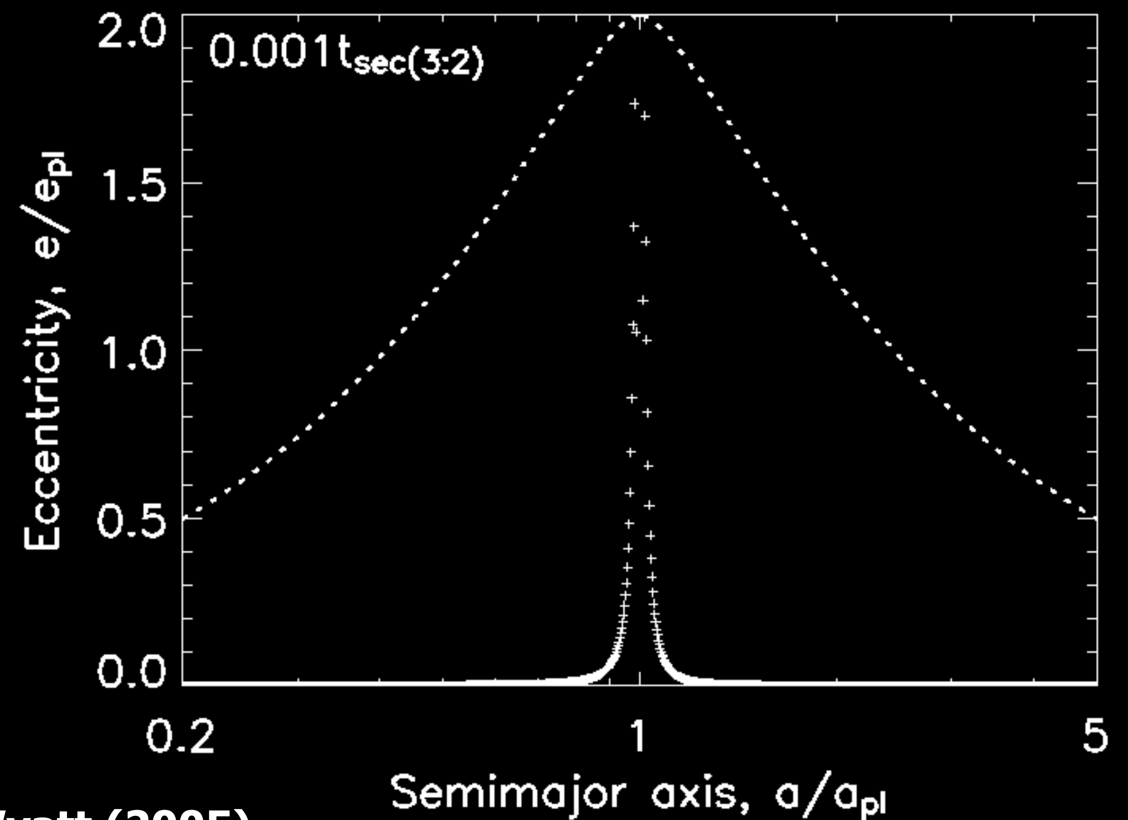




Resulting surface brightness profile peaks where Plutos recently formed
(Kennedy & Wyatt 2010)

If so, inner regions are collisionally depleted and Plutos at 60-130au

Stirring from β Pic-b



Wyatt (2005)

If β Pic-b is eccentric stirring is inevitable

Secular perturbations cause eccentricity pumping and differential precession, ultimately leading to orbit crossing (Mustill & Wyatt 2009)

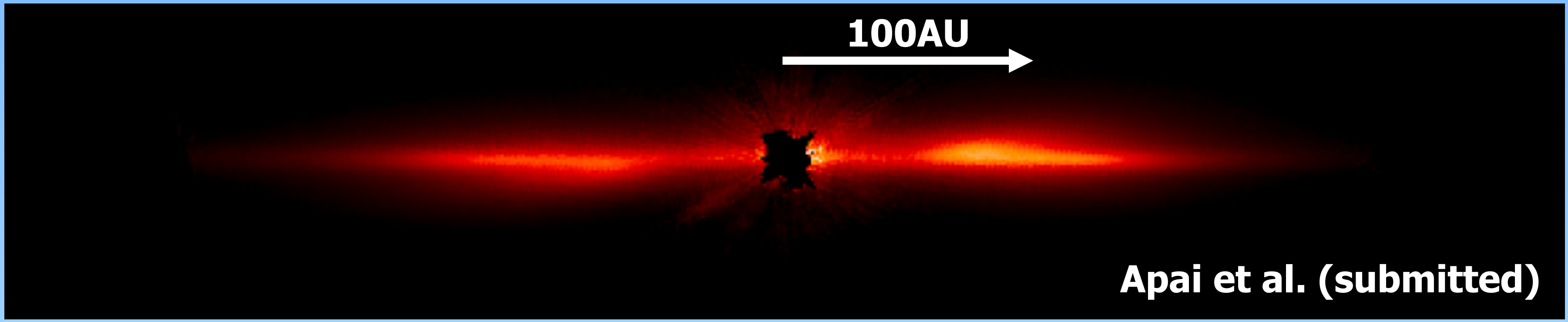
Timescale is

$t_{cross} \sim a^{9/2}\ a_{pl}^{-3}\ M_{pl}^{-1}\ e_{pl}^{-1}$

12Myr at 75au for β Pic-b

Warp in outer disk

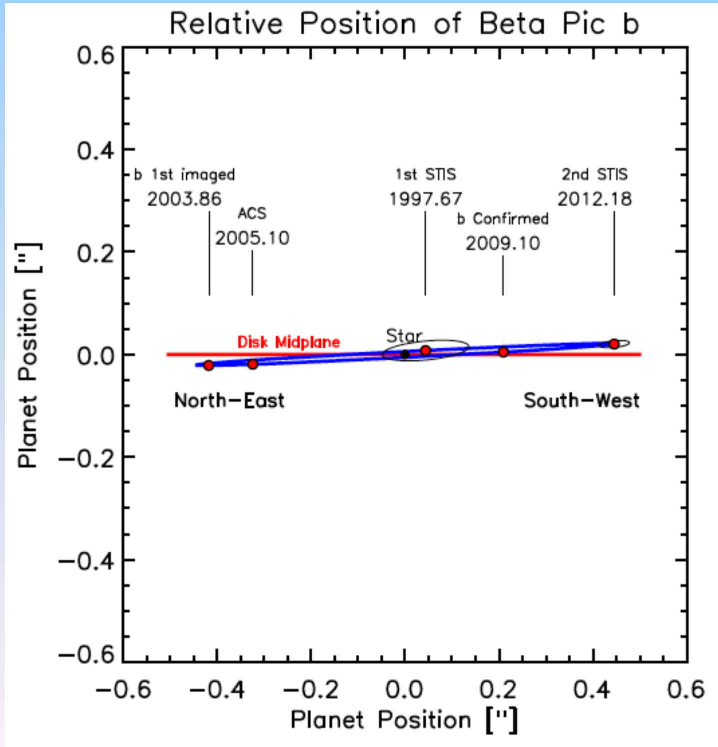
See Daniel Apai's talk



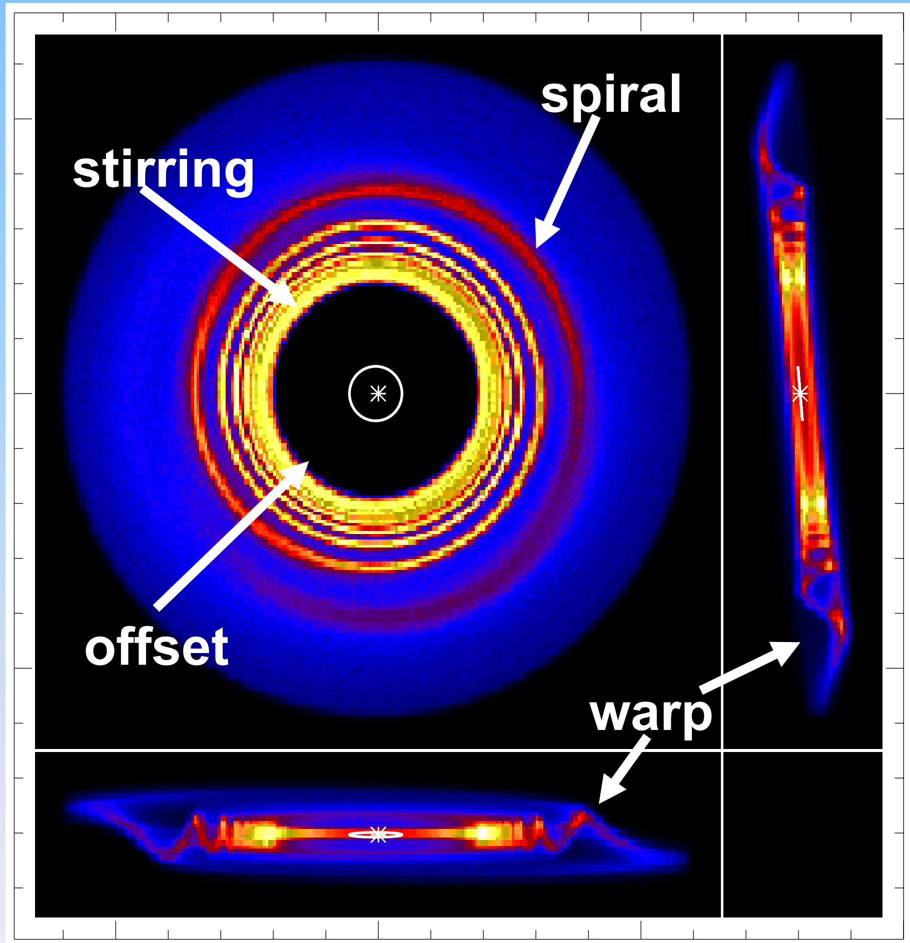
Same perturbations also cause a warp if β Pic-b is misaligned with disk mid-plane (Mouillet et al. 1997; Augereau et al. 2001)

The disk is warped from 50-100AU

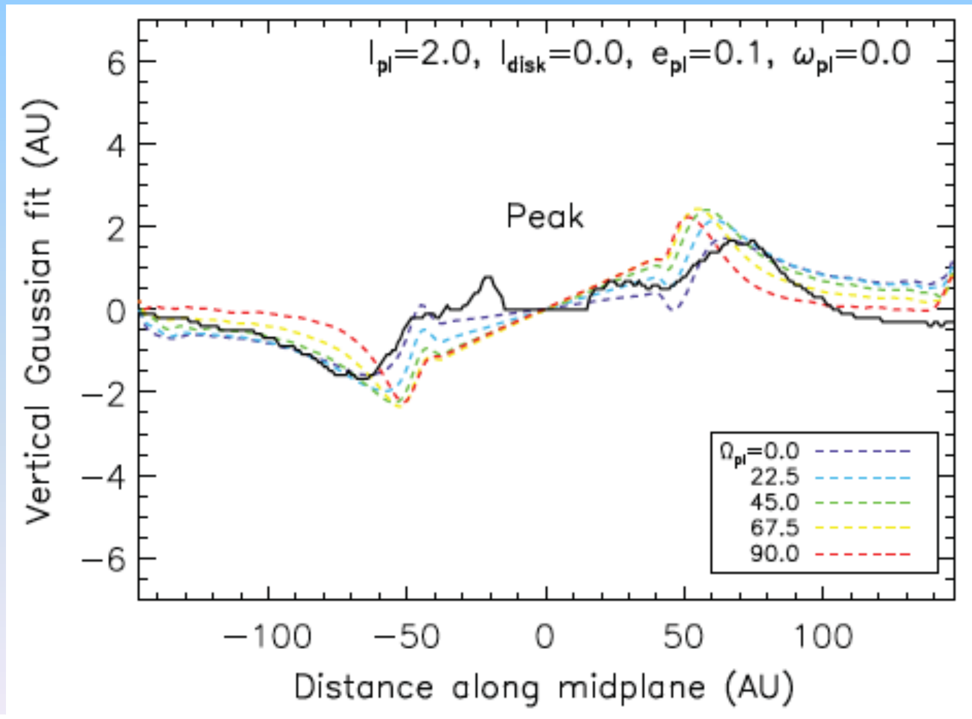
Orbit of β Pic-b is plausibly aligned with the warp rather than the outer disk mid-plane (Lagrange et al. 2012)



Is orbit of β Pic-b aligned with disk?



Orientation of the line of nodes affects both magnitude of warp (Mouillet et al. 1997) and shape particularly in inner disk (Matthews et al. 2014; Apai et al. submitted)



Note that outer disk has some vertical extent – it has already been stirred?

Do inner planets help?

See Bekki Dawson's talk

Secular perturbations acting on outer disk are sum of those from all planets in system so alignment of outer disk with β Pic-b is not inevitable (Dawson et al. 2011)

But a planet that perturbs the outer disk would also perturb β Pic-b

A multiple planet system would also have unstable secular resonances that could deplete disk

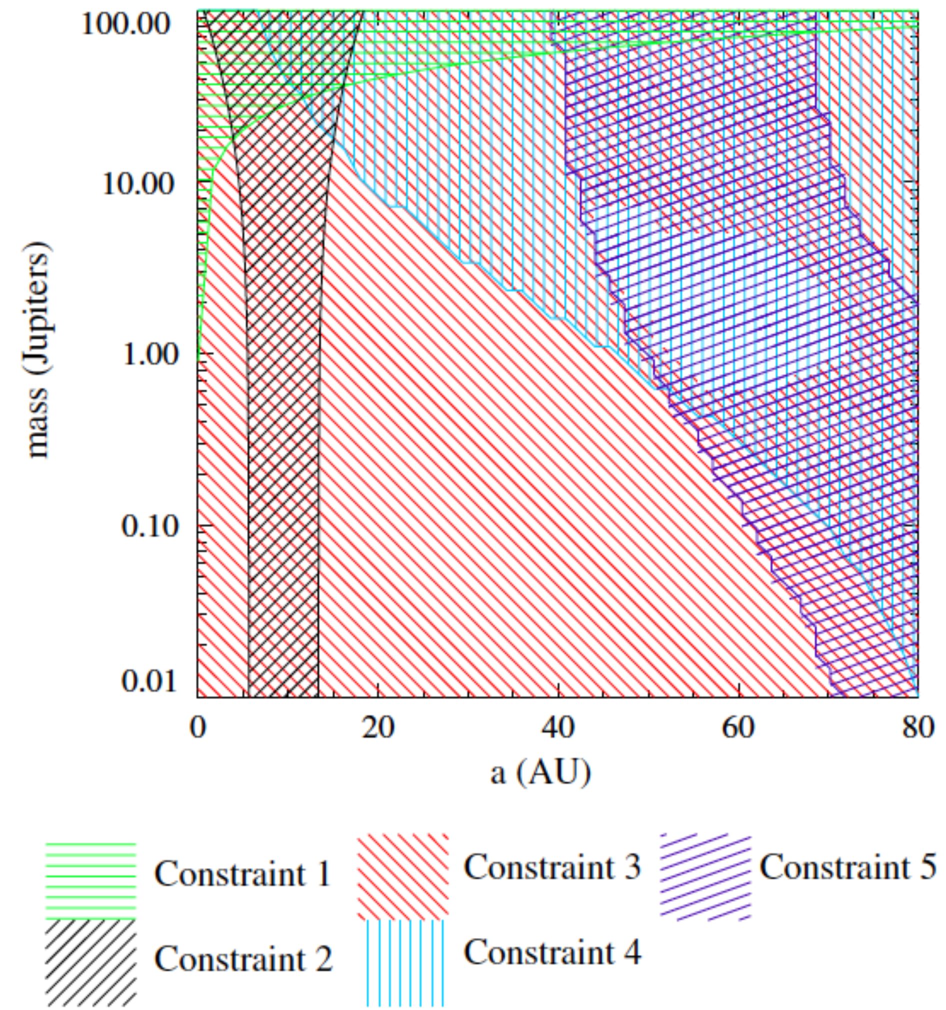
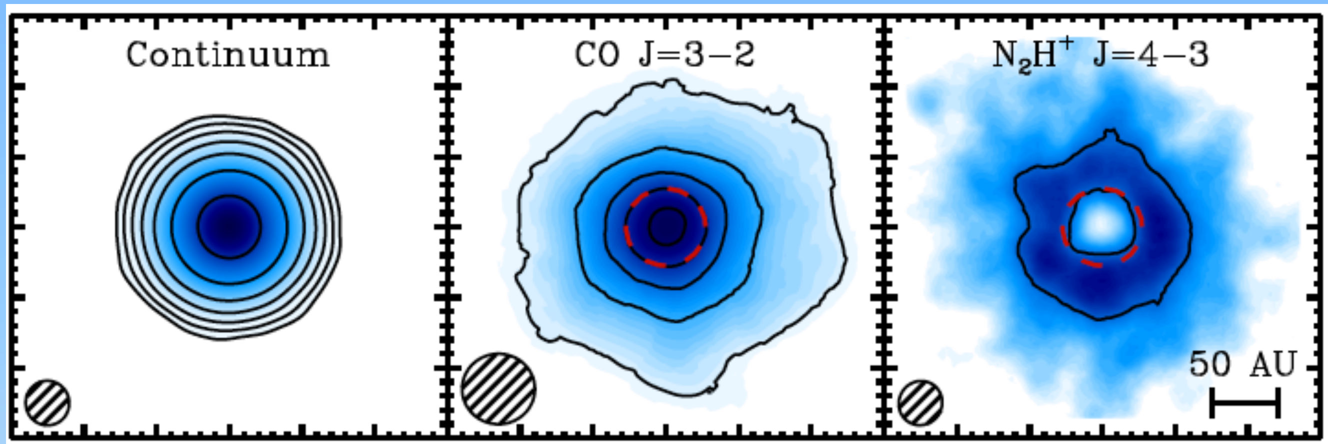


Figure 3. Constraints on a_c and m_c. The region shaded in horizontal green stripes violates Constraint 1 (lack of RV detection), upward-slanted black violates Constraint 2 (stability), downward-slanted red violates Constraint 3 (produces disk morphology without exciting planet b), vertical-striped blue violates Constraint 4 (timescale consistency), and shallow-slant purple violates Constraint 5 (secular resonances in the outer disk). See the text for details.

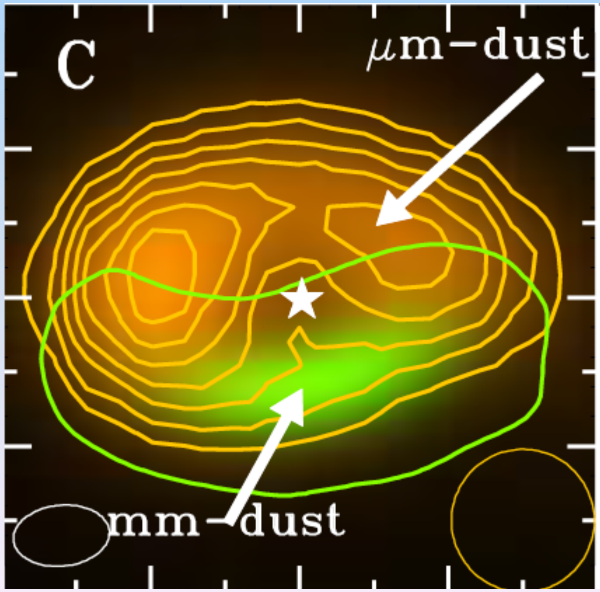
Origin of inner hole?

Outer planetesimals are icy (Dent et al. 2014) – is inner edge at CO snow-line?

e.g., at 30au for TWHya Qi et al. (2013)



Or is it related to the mechanism causing the inner hole in transition disks (van der Marel et al. 2013; Pinilla et al. 2014)?

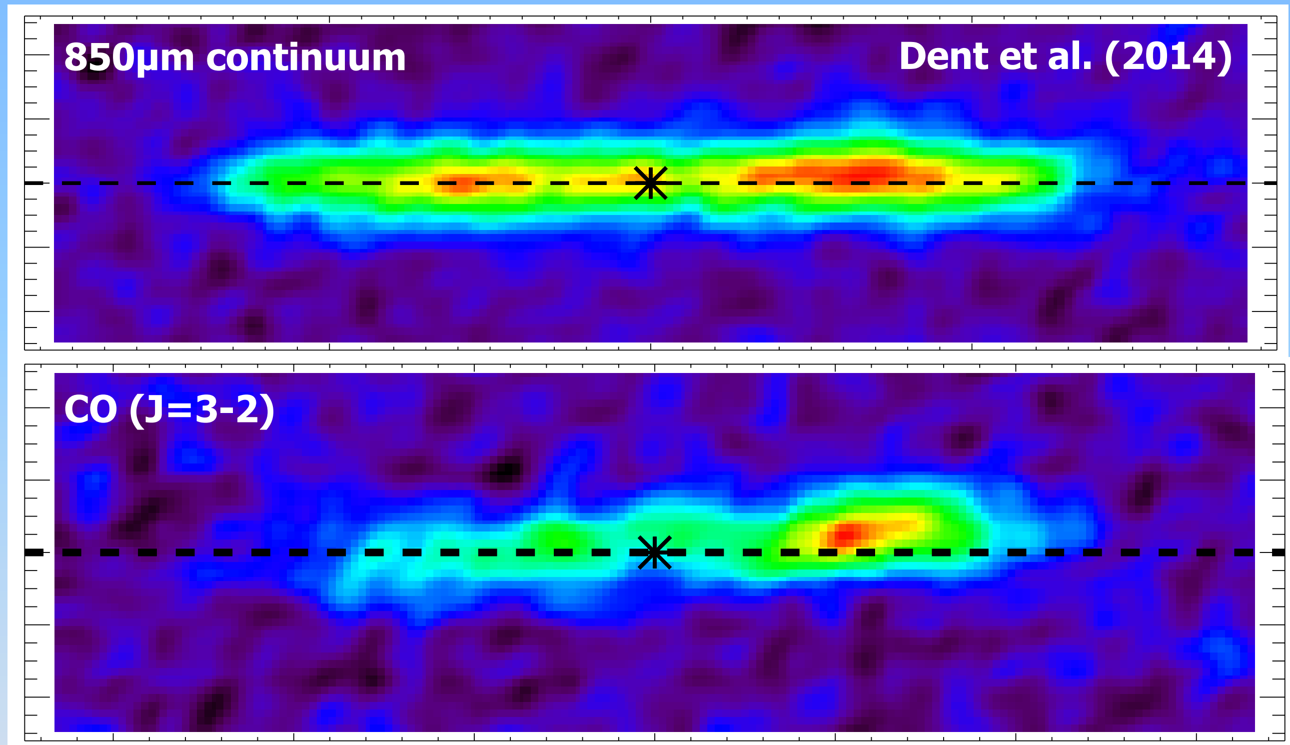


Or are the inner regions collisionally depleted (Kennedy & Wyatt 2010)?

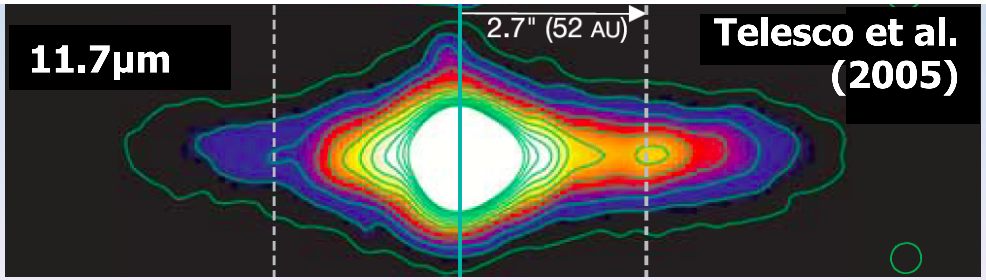
Or are they cleared by planets?

Brightness asymmetry from clump

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)



Originates in a clump at 80au projected separation (from CO velocity information)



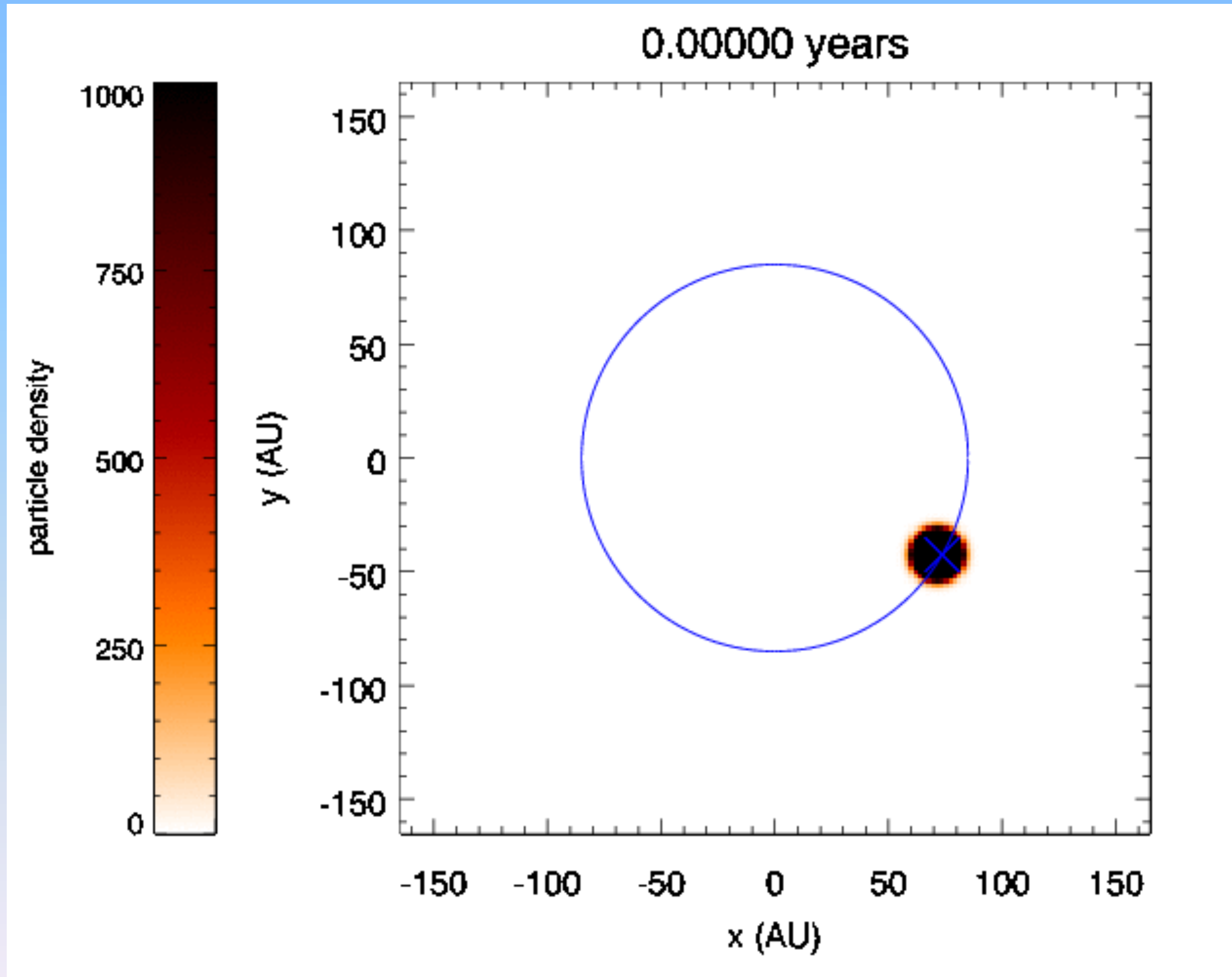
Giant impact debris model

See Alan Jackson's talk

Giant impact at 85AU onto Mars-sized parent, debris escapes at ~4km/s (Jackson et al. 2014)

Stays as clump <1 orbit (580yr), but asymmetric for ~1000 orbits (0.6Myr), as orbits go through the collision point

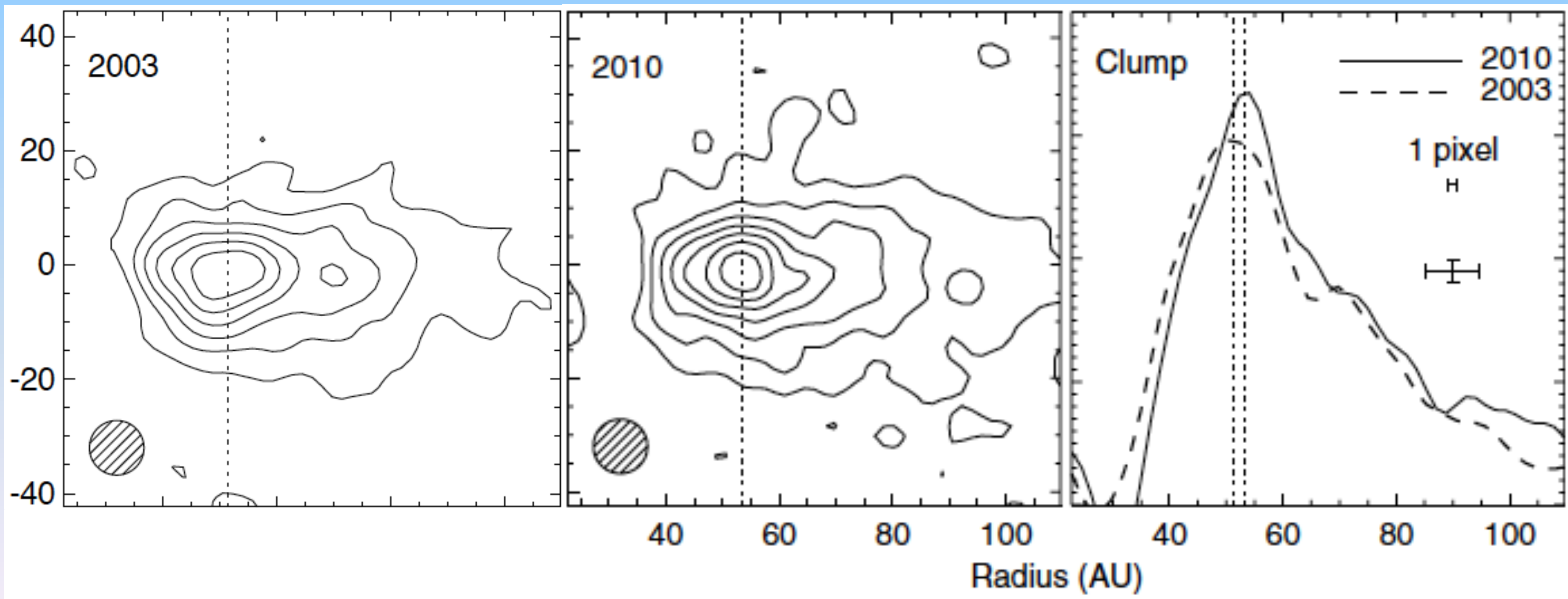
Collision rate enhanced at bottleneck where most CO and small dust produced



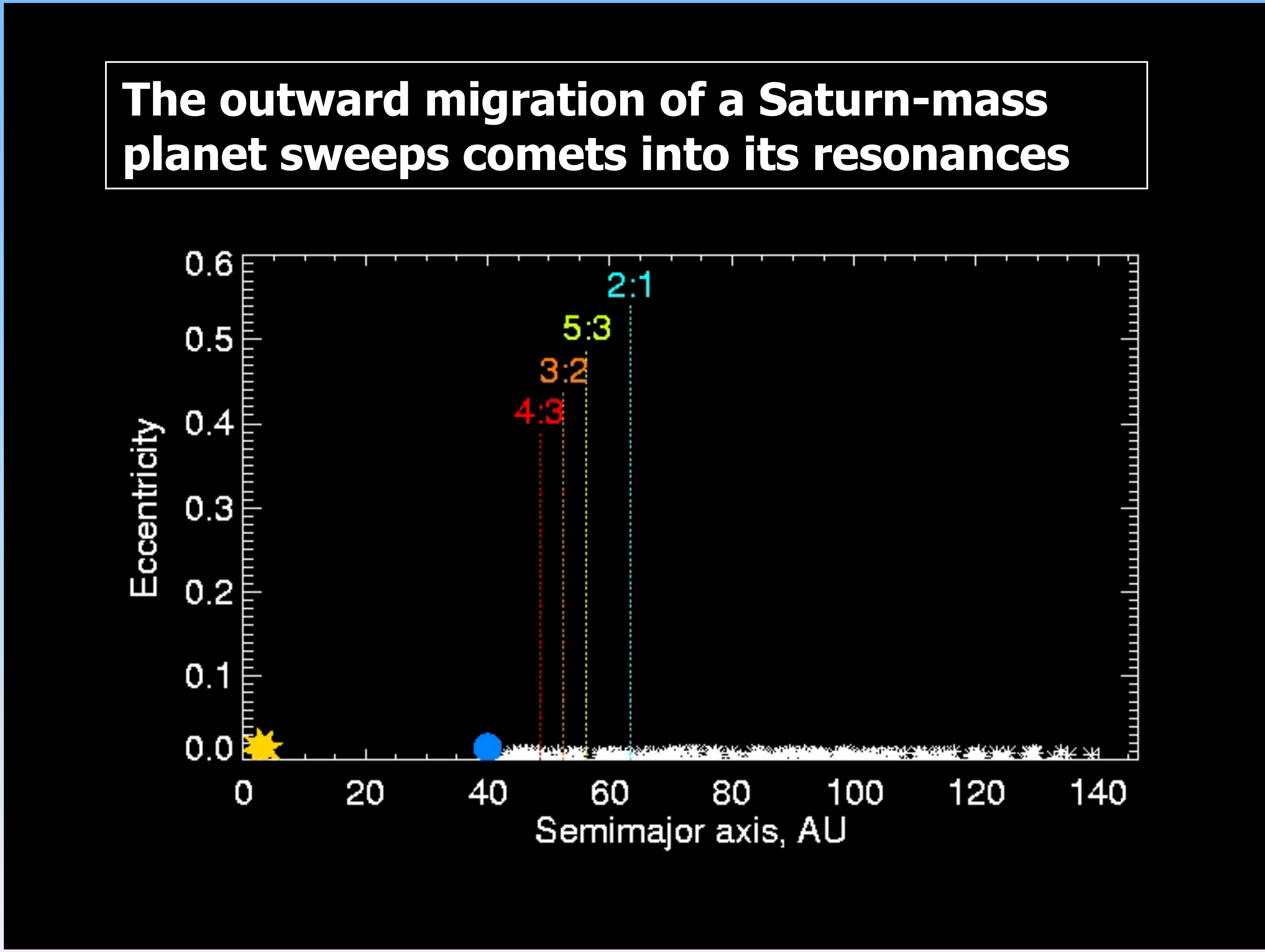
Problem: clump should be stationary

In the giant impact model the clump remains fixed at the point at which the first impact occurred

Reimaging at 11.7μm after 7 yrs shows a 2AU (3.6σ) move to right (Li et al. 2012)

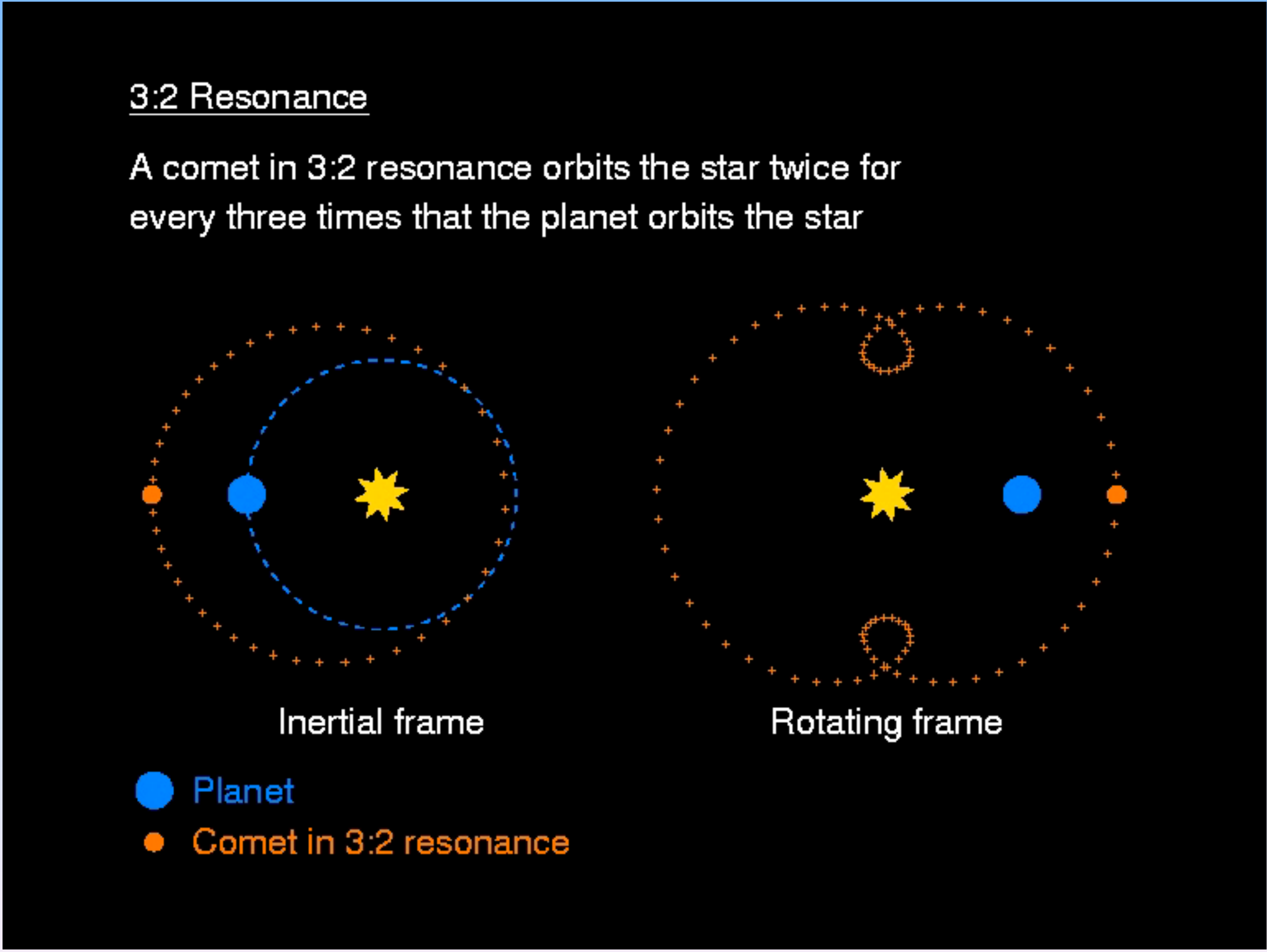


Resonance sweeping model



Wyatt (2003)

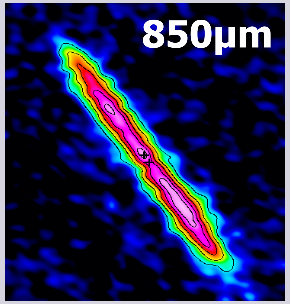
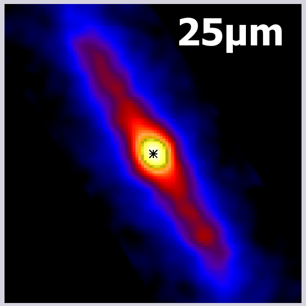
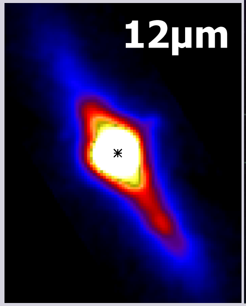
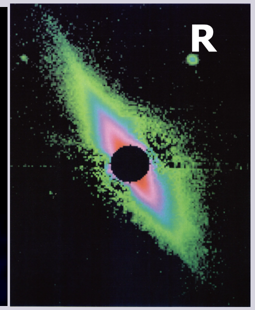
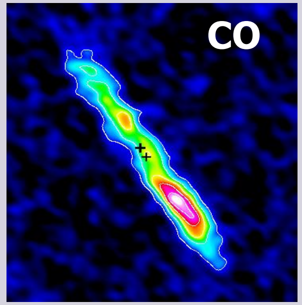
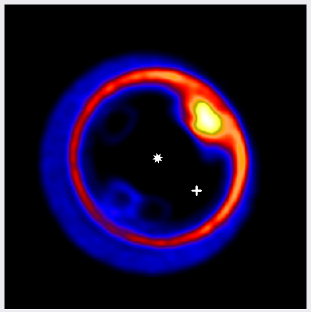
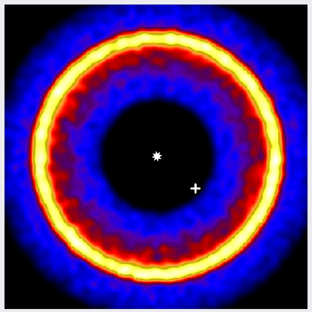
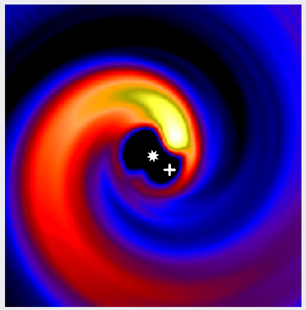
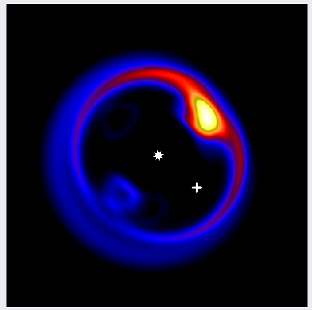
Geometry of resonance



Geometry causes planetesimal to get periodic kicks from the planet’ s gravity, which can cause some to become trapped

Also means planetesimals spend most time at certain longitudes relative to the planet

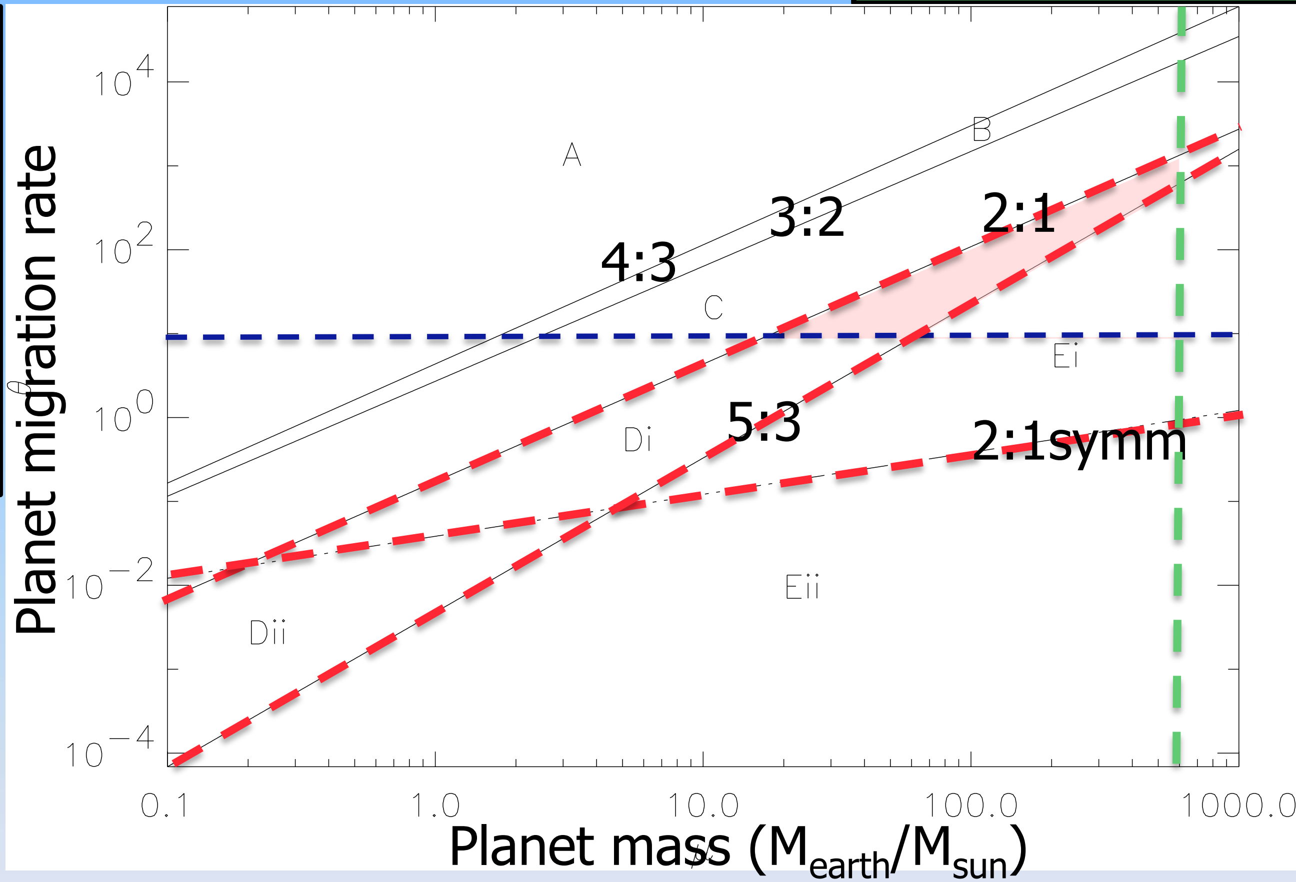
Explains wavelength dependent disk structure

	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)				

Constraints on β Pic-c planet

Less angular momentum than βPic-b

Requires migration rates of
Δa~15AU
Δt<12Myr
a~80AU
$M_* = 1.75 M_{sun}$



Trapping into 2:1, which is also asymmetric but none in 5:3

- Limited parameter space; $M_{pl} > 35 M_{earth}$
- Migration from planetesimal scattering or interaction with gas?
- But this model is not without problems

Conclusions

- Overall: Most dynamics dominated by β Pic-b, but more precise orbit required
- Inner (<10au) planets poorly constrained, but very likely inner planetesimal belt
- Origin of 10-60au clearing unknown, but outer clump possibly explained by outward migration of Saturn-mass planet
- >60au filled with icy planetesimals and possibly embryos, since unlikely to be stirred by β Pic-b alone