

# Debris Disks and the Evolution of Planetary Systems...

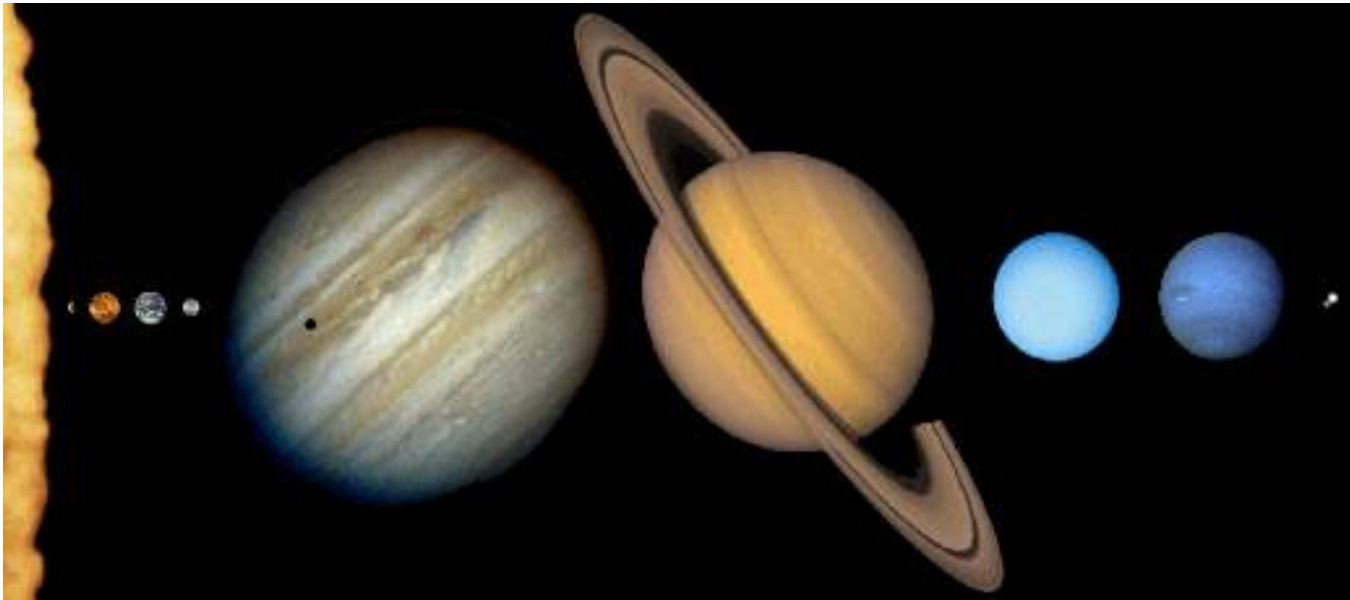


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September 1, 2009

# Why Study Circumstellar Disks?

- How common is the architecture of our solar system (terrestrial planets, asteroid belt, Jovian planets, and Kuiper Belt)?
- What were the physical conditions in the early solar system?
- How do the physical conditions of the disk impact the formation of planets and subsequent orbital evolution of planets and small bodies?

# Our Solar System



Terrestrial Planets

Asteroid Belt

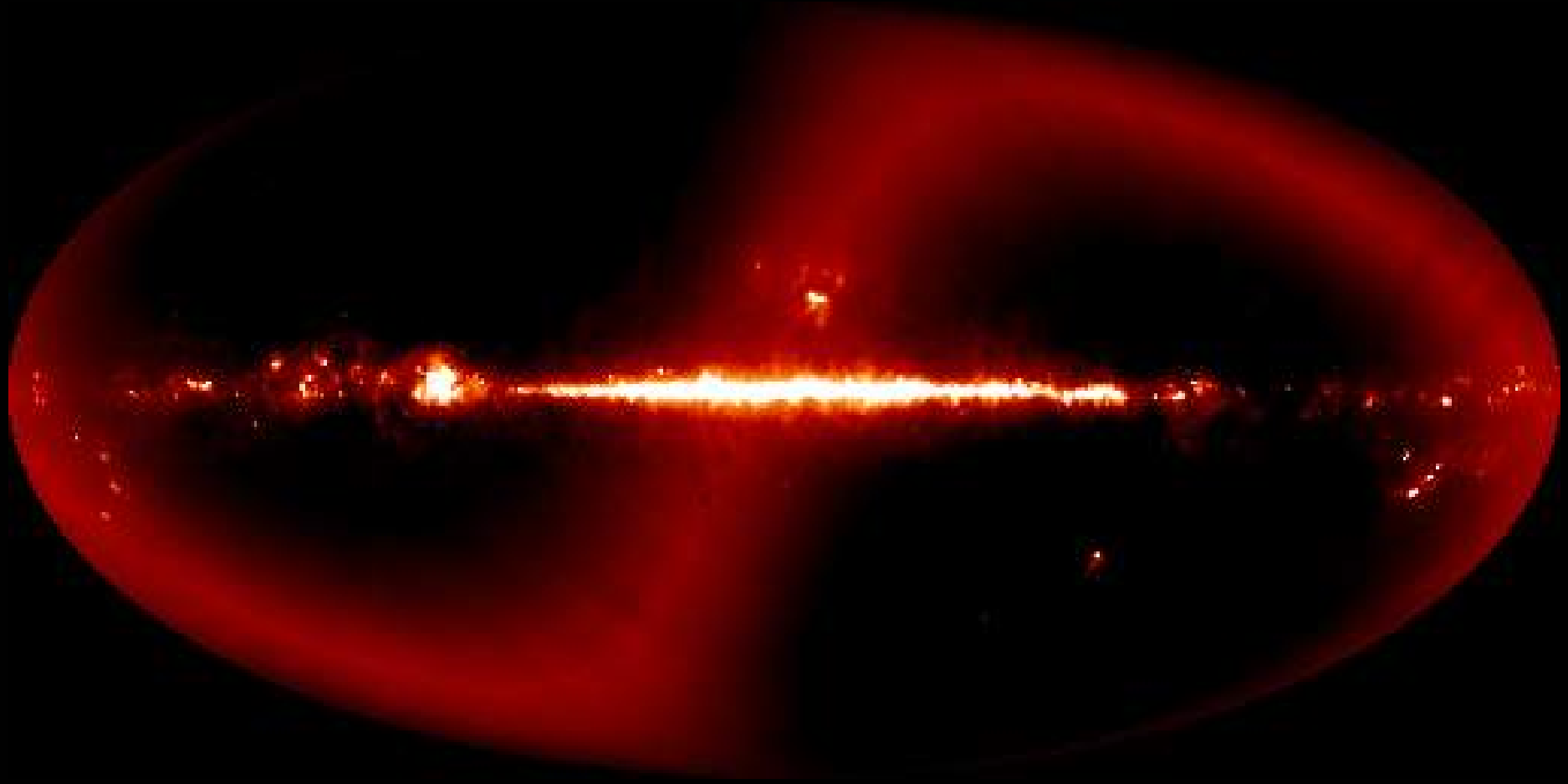
Jovian Planets

Kuiper Belt

Ice Dwarf Planets

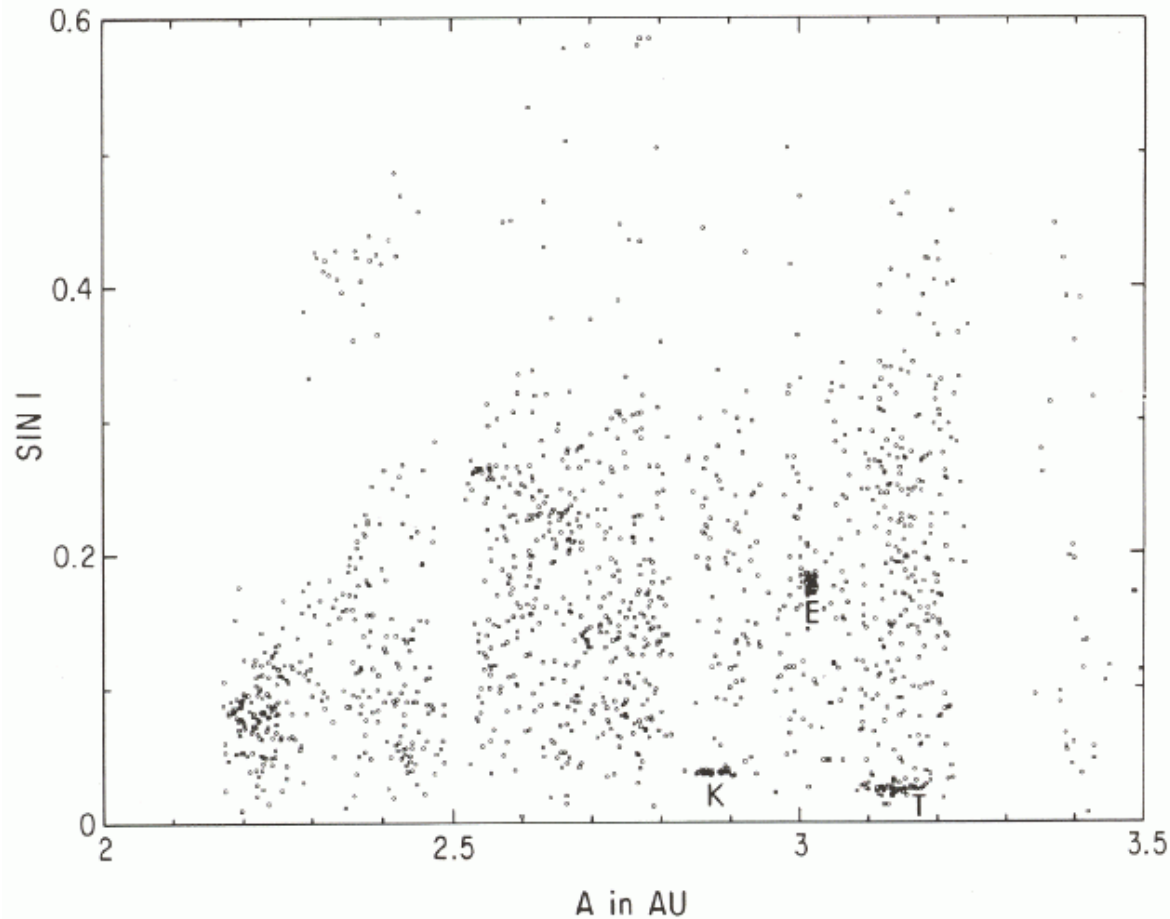
Oort Cloud

# The Zodiacal Light



$$M_{\text{dust}} = 2 \times 10^{20} \text{ g} = 10^{-10} M_{\text{planets}} = 10^{-4} M_{\text{MAB}}$$
$$L_{\text{IR}}(\text{dust}) = 100 L_{\text{IR}}(\text{planets})$$

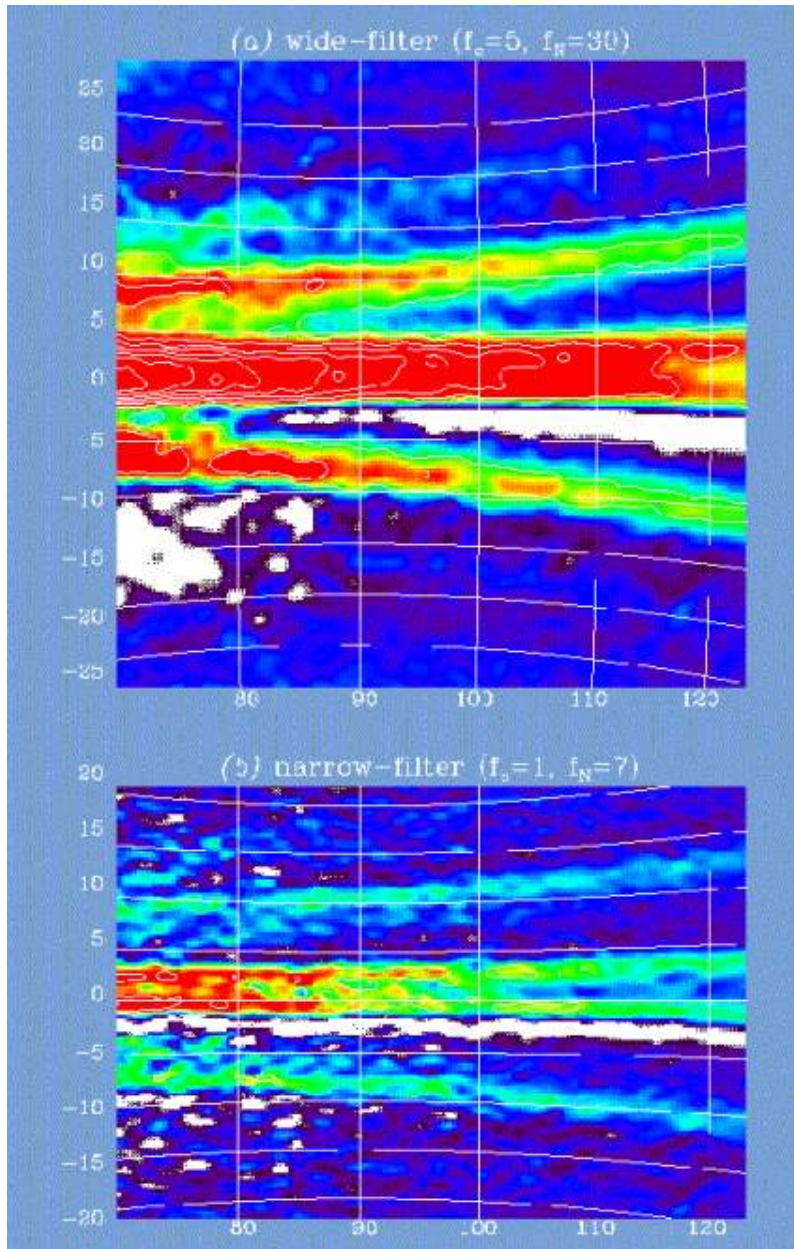
# Asteroid Families



Distribution of the proper sine of inclination vs. semi-major axis for the first 1500 numbered asteroids. The Hirayama families Themis (T), Eos (E), and Koronis (K) are marked. Kirkwood gaps are visible. The detached Phocaea region is at upper left. Chapman et al. (1989)

- In 1918 Hirayama discovered concentrations of asteroids in  $a-e-i$  space (osculatory orbital semi-major axis, eccentricity and inclination) he named “families”.
- It is widely believed that these families resulted from the break up of larger parent bodies.

# Origin of Dust Bands in the Zodiacal Light

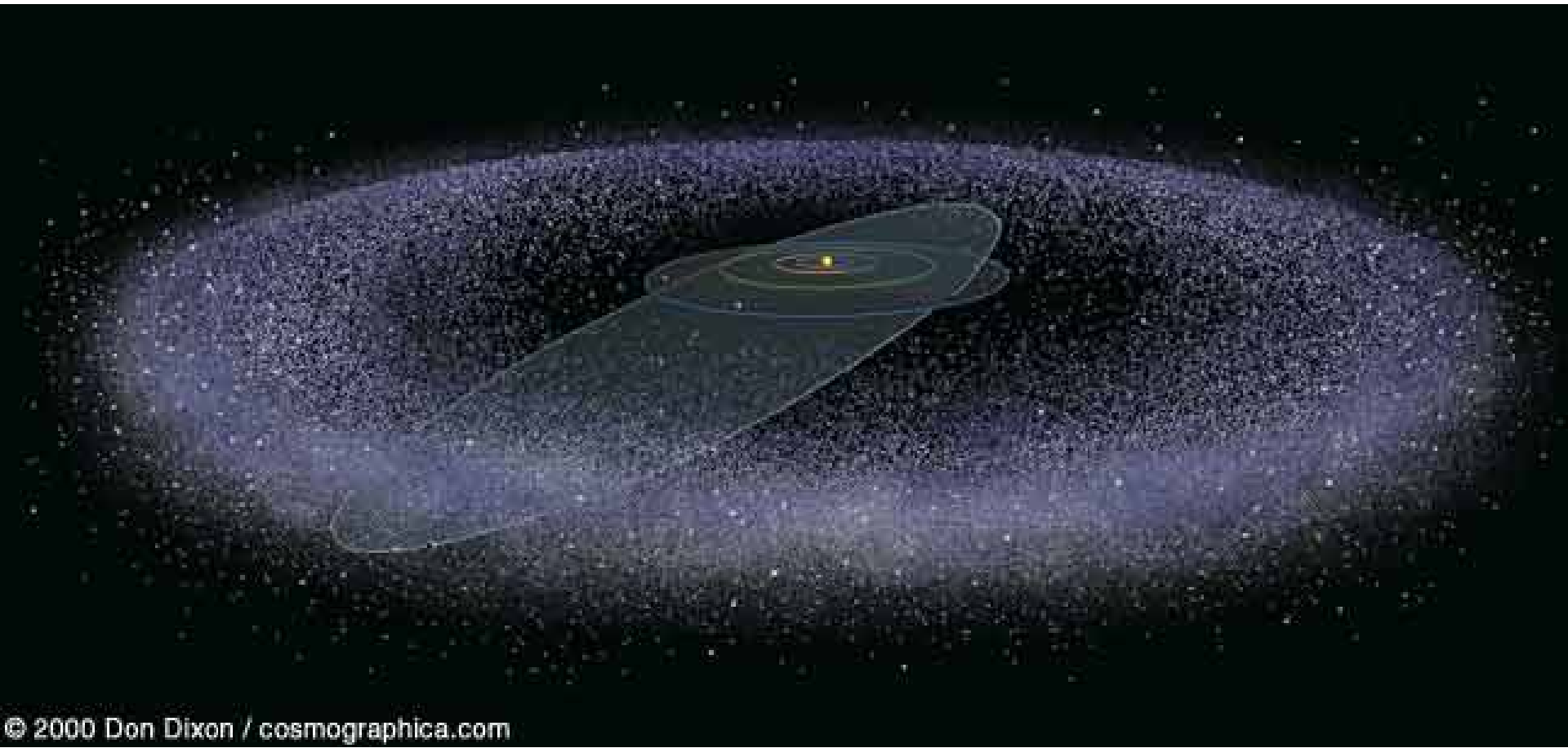


- The  $\alpha$ ,  $\beta$ ,  $\gamma$  dust bands in the Zodiacal Light are believed to have been generated by mutual collisions within the Themis, Koronis, and Eos families.
- Other dust bands are not found in association with other major asteroid families with the possible exception of the Io family.
- The Koronis family has a greater dust population than the larger Themis family.
- The majority of dust bands were probably produced by large random collisions among individual asteroids.

# Non Equilibrium Dust Band Formation

- Orbits of asteroids experience precession of their apsides and nodes because of gravitational perturbations from Jupiter and other planets.
- Dust bands are formed when orbits of collisional debris precess at different rates, due to small difference in their orbital parameters, and collide with one another.
- Particles in a dust-band torus are destroyed through collisions with background IPDs, both cometary and asteroidal in origin.

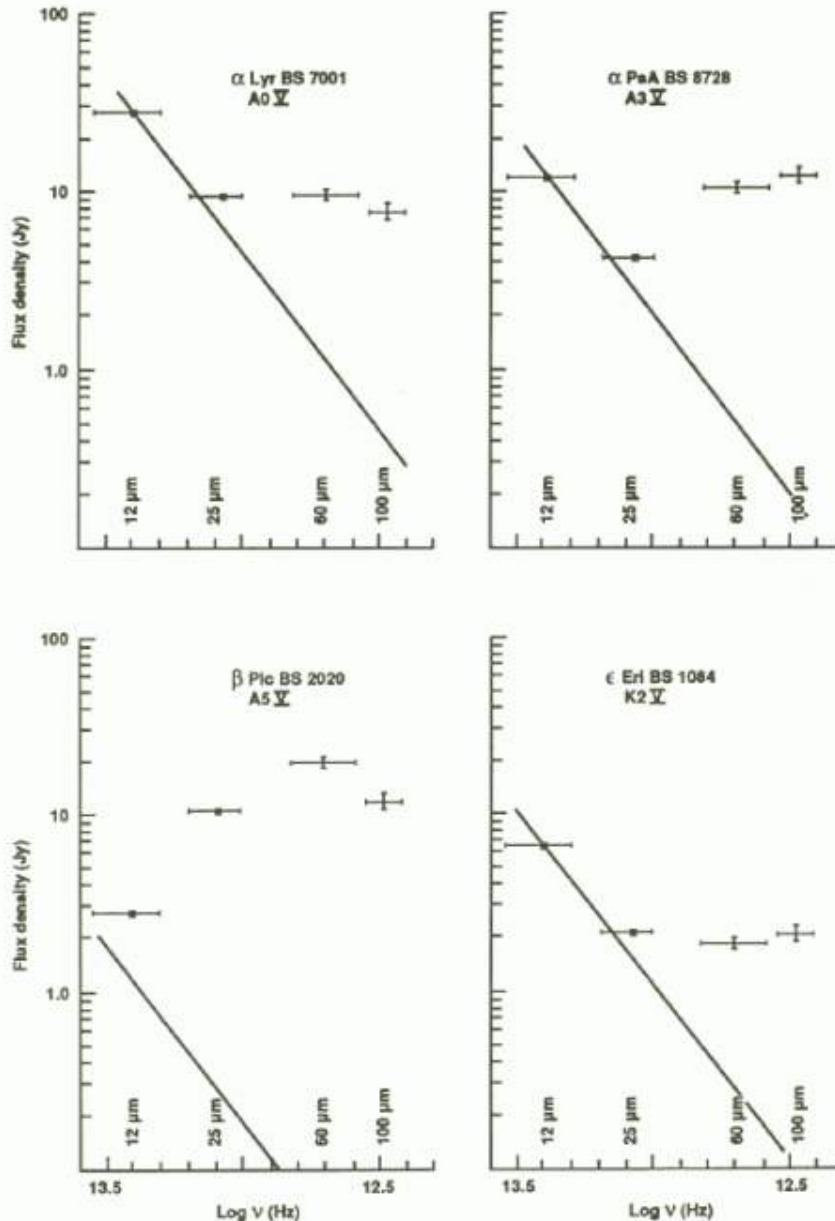
# The Kuiper Belt



© 2000 Don Dixon / cosmographica.com

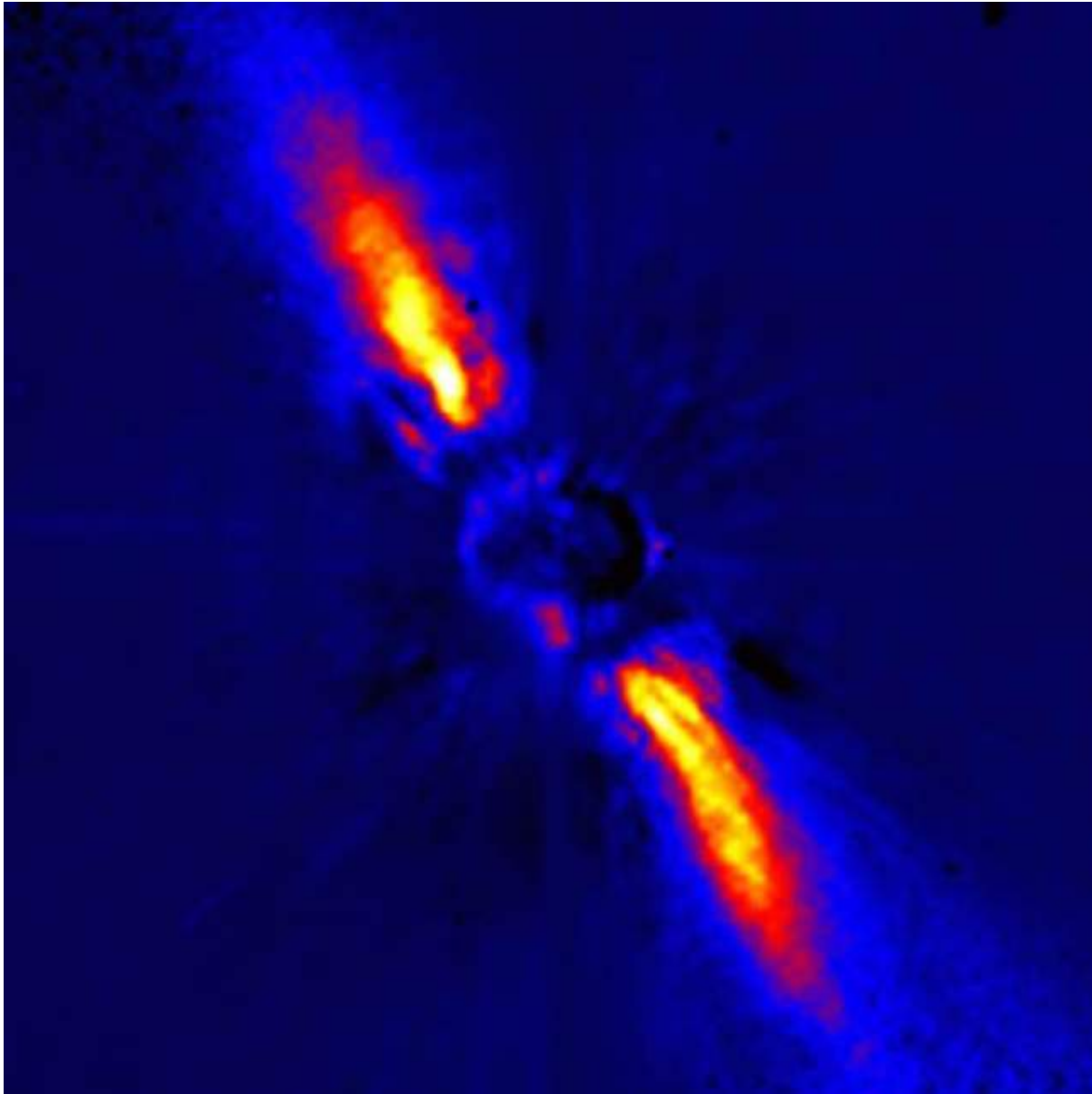
More than one thousand km-sized KBOs have now been discovered. Although, no dusty disk has yet been detected, one is believed to exist.

# The Vega Phenomenon



- Routine calibration observations of Vega revealed 60 and 100  $\mu$  m fluxes 10 times brighter than expected from the stellar photosphere alone.
- Subsequent coronagraphic images of  $\beta$  Pic revealed an edge-on disk which extends beyond 1000 AU in radius.
- Infrared excess is well described by thermal emission from grains.

# A Circumstellar Disk Around $\beta$ Pictoris!



Spectral Type: A5V

Distance: 19.3 pc

$T_{\text{dust}}$ : 85 K

$L_{\text{IR}}/L_*$ :  $3 \times 10^{-3}$

$M_{\text{dust}}$ :  $0.094 M_{\oplus}$

$R_{\text{dust}}$ : 1400 AU

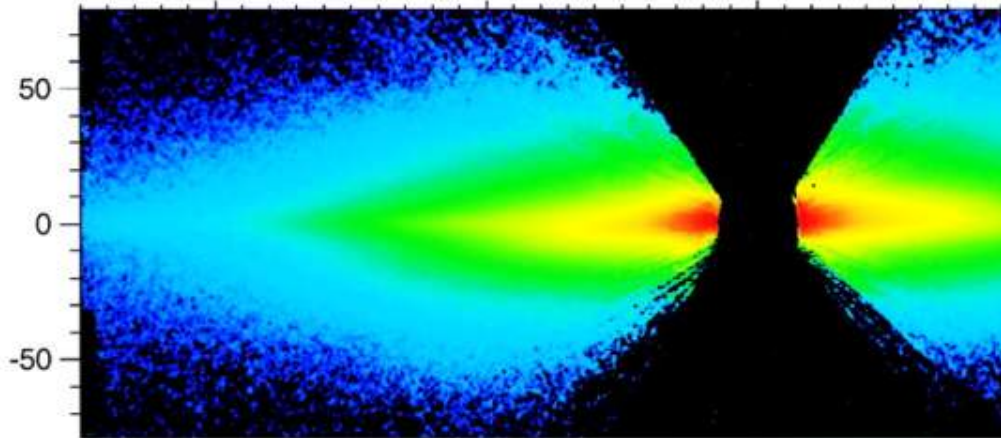
Inclination: 2-4°

Age:  $20 \pm 10$  Myr

Mouillet et al. (1997)

# A Possible Planet in the $\beta$ Pic Disk?

Log Flux



$$D_{warp} \propto (M_P a^2 t_{age})^{2/7}$$

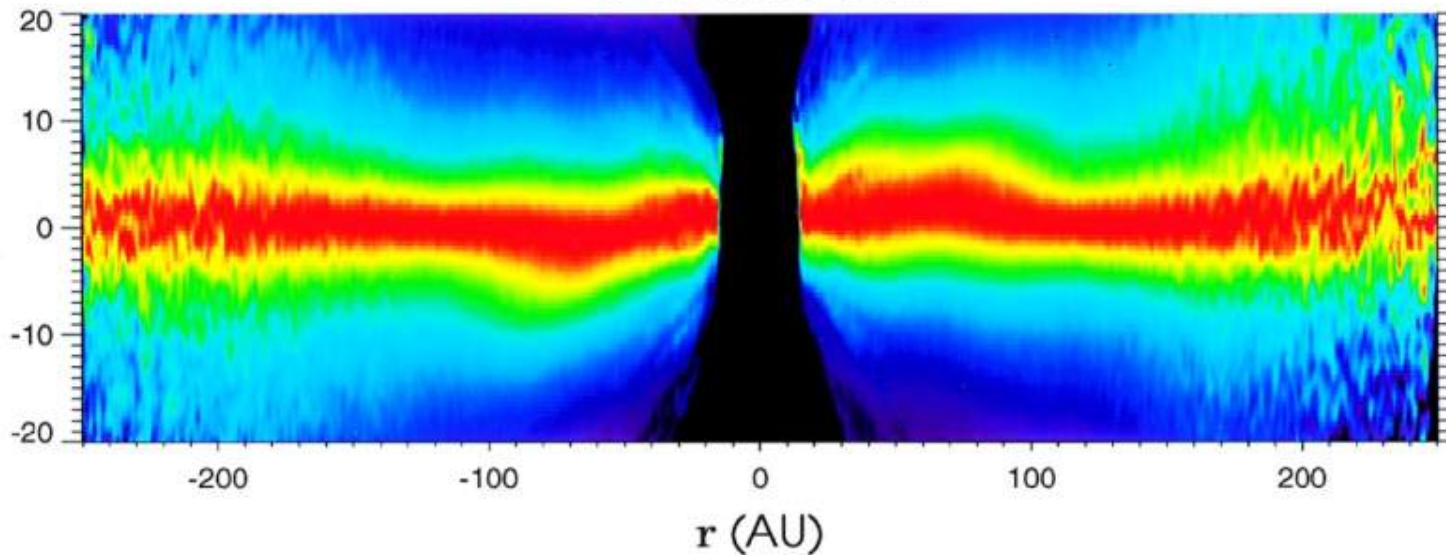
Observed  $D_{warp} = 70$  AU

48  $M_{Jup}$  brown dwarf at  $< 3$  AU

Or

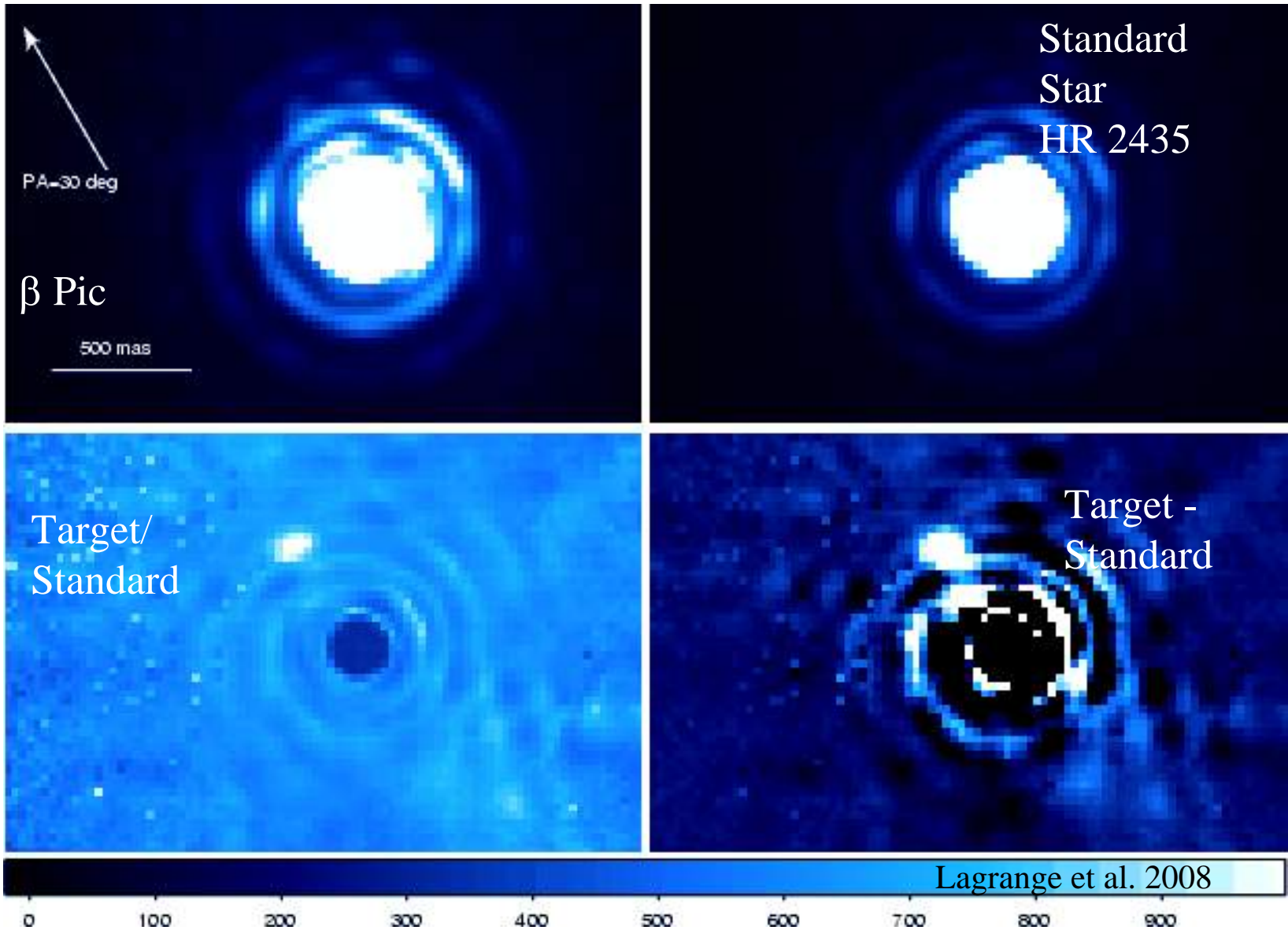
17.4  $M_{Jup}$  – 0.17  $M_{Jup}$  planet at  
5 – 150 AU

Normalized Flux

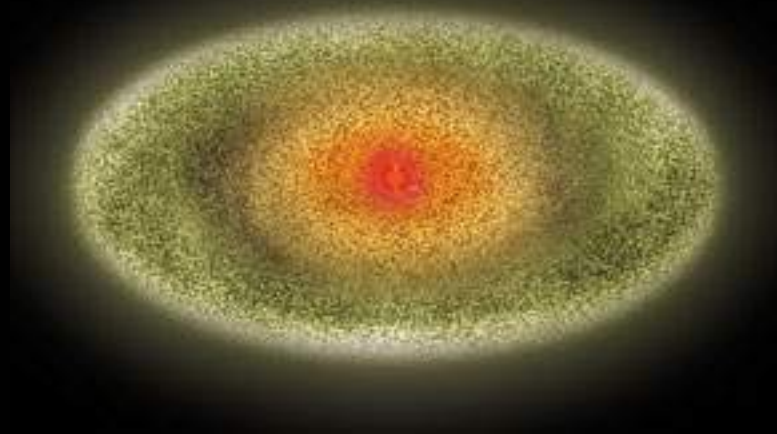


STIS/CCD coronagraphic images of the  $\beta$  Pic disk. The half-width of the occulted region is 15 AU. At the top is the disk at a logarithmic stretch. At bottom is the disk normalized to the maximum flux, with the vertical scale expanded by a factor of 4 (Heap et al. 2000)

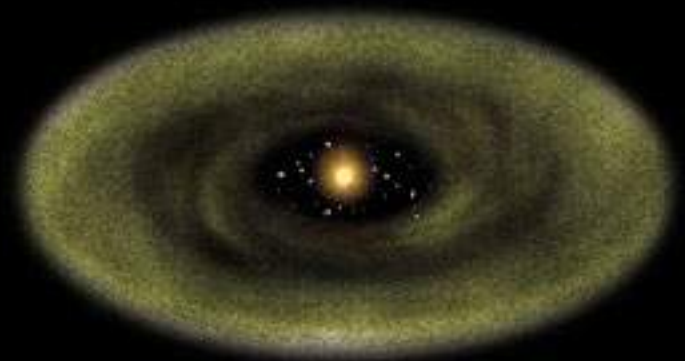
# Possible Direct Images of the $\beta$ Pic Planet



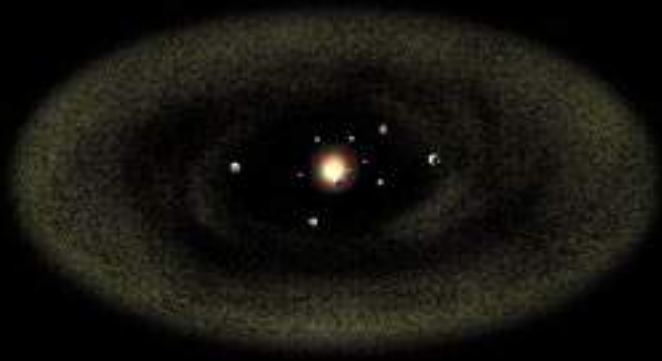
# Gradual Disk Evolution?



1 Myr



10 Myr



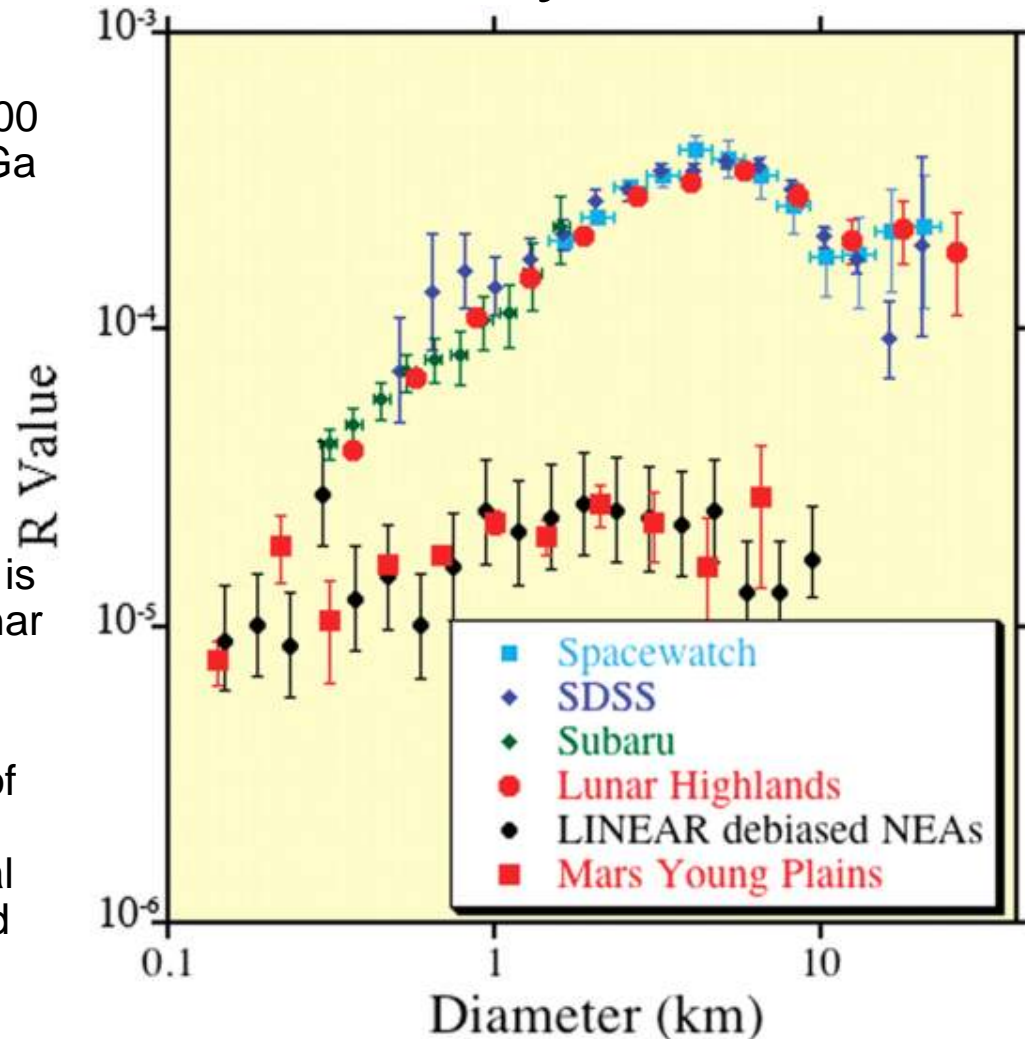
100 Myr



500 Myr

# Stochastic Processes: Giant Planet Formation and Migration in Our Solar System

- The moon and terrestrial planets were resurfaced during a short period (20-200 Myr) of intense impact cratering 3.85 Ga called the Late Heavy Bombardment (LHB)
- Apollo collected lunar impact melts suggest that the planetary impactors had a composition similar to asteroids
- Size distribution of main belt asteroids is virtually identical to that inferred for lunar highlands
- Formation and subsequent migration of giant planets may have caused orbital instabilities of asteroids as gravitational resonances swept through the asteroid belt, scattering asteroids into the terrestrial planets.



# Mid-Infrared Spectroscopy: Determine the Radial Distribution of Dust

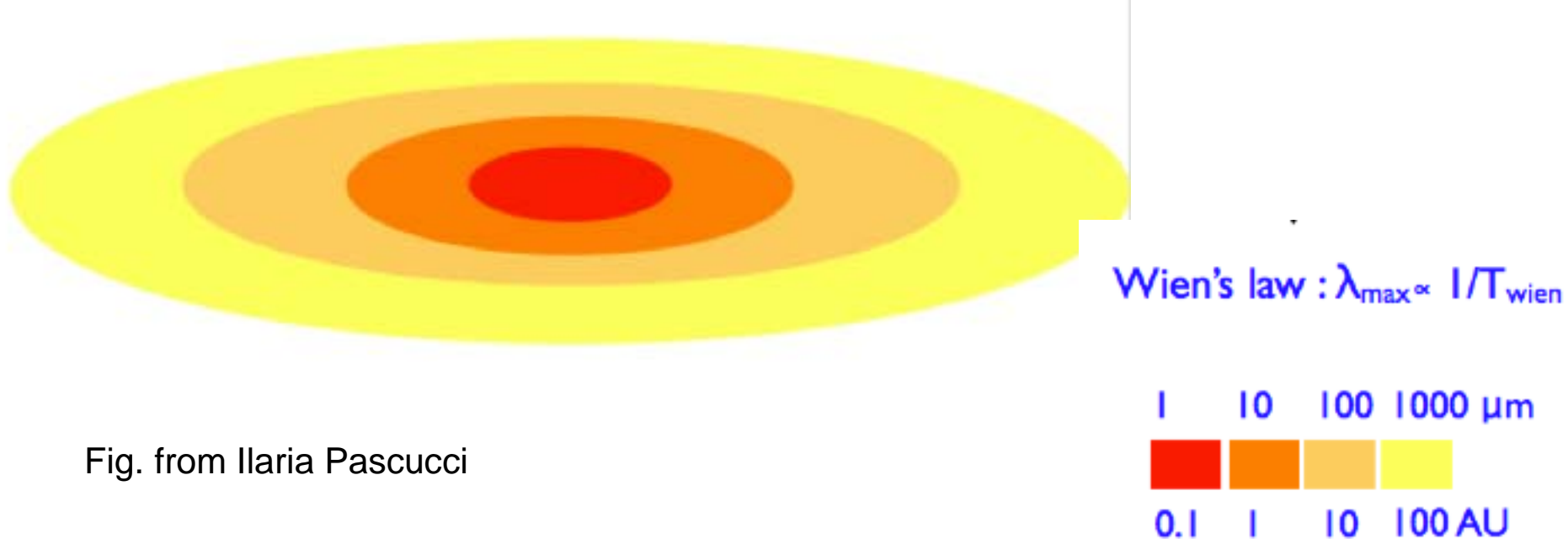


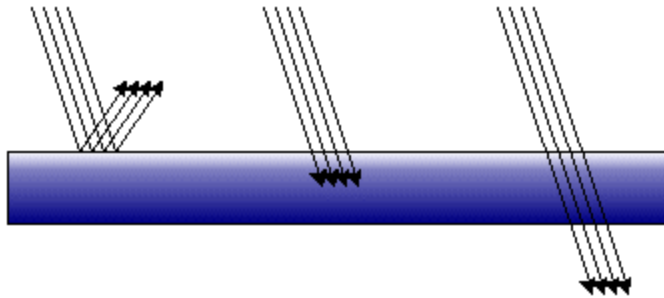
Fig. from Ilaria Pascucci

- If dust is located in a ring, then the spectral energy distribution should indicate dust of a single temperature (Single Temperature Black Body).
- If dust is located in a continuous disk, then dust at a variety of temperatures should be observed (Uniform Surface Density Disk).

# Radiation Effects

## Radiation Pressure Coefficient

© Blaze Labs Research



Total Reflection

$$Q_{PR} = 2$$

Total Absorption

$$Q_{PR} = 1$$

Total Transmission

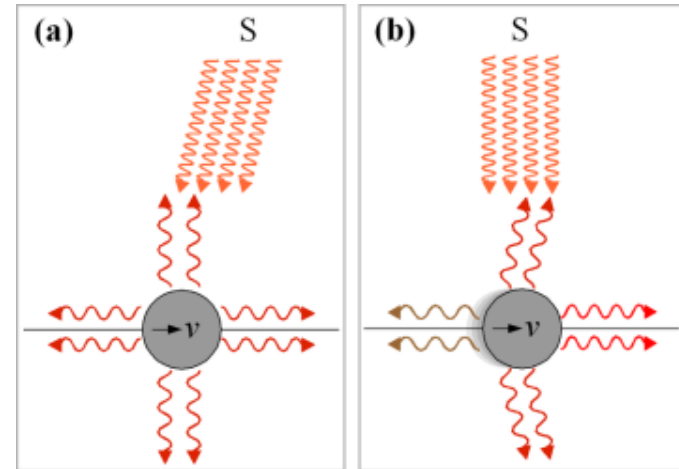
$$Q_{PR} = 0$$

## Radiation Pressure

If  $F_{rad} > F_{grav}$  (or  $\beta > 1$ ), then small grain will be radiatively driven from the system

$$\beta > \frac{3L_* \langle Q_{pr}(a) \rangle}{16\pi GM_* ca\rho}$$

Artymowicz (1988)



## Poynting-Robertson Drag

Dust particles slowly spiral into the orbit center due to the Poynting-Robertson effect. The lifetime of grains in a circular orbit is given by

$$t_{PR} = \frac{4\pi a \rho_{gr} c^2 D^2}{3L_*}$$

(Burns et al. 1979).

# Solar Wind Drag



The solar wind is a stream of protons, electrons, and heavier ions that are produced in the solar corona and stream off the sun at 400 km/sec

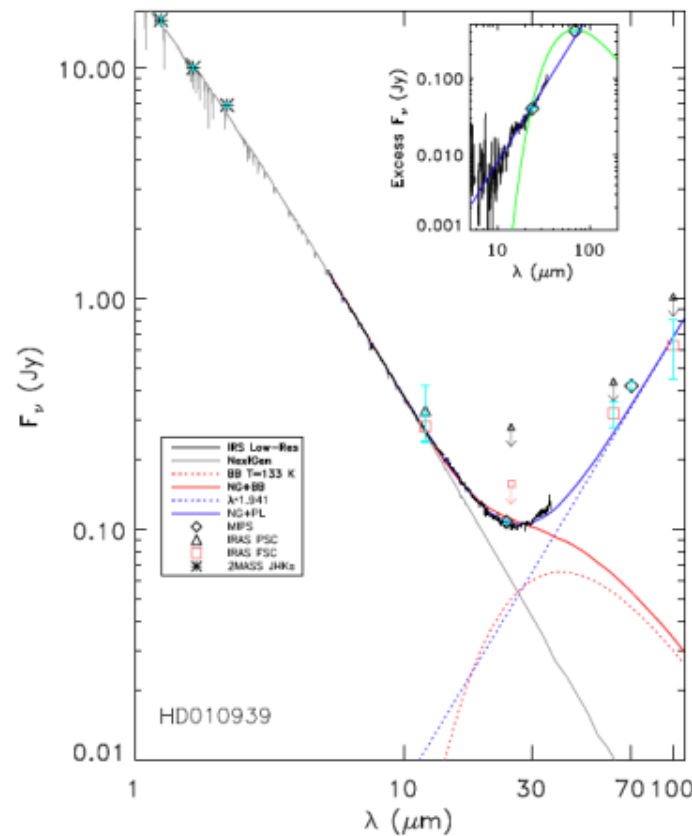
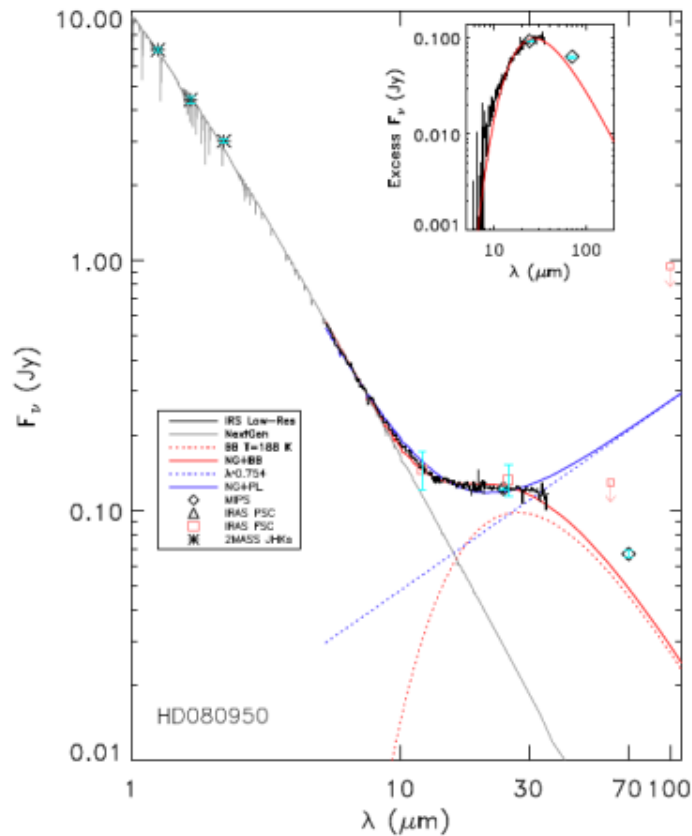
Typically,  $F_{sw} \ll F_{grav}$ ; therefore, stellar wind does not effectively drive dust out of the system radially.

However, they do produce a drag force completely analogous to the Poynting-Robertson effect

$$t_{sw} = \frac{4\pi a \rho_{gr} D^2}{3Q_{sw} \dot{M}_{sw}}$$

(Plavchan et al. 2005)

# Poynting-Robertson Drag Dominated Disks?



Morales et al. (2009)

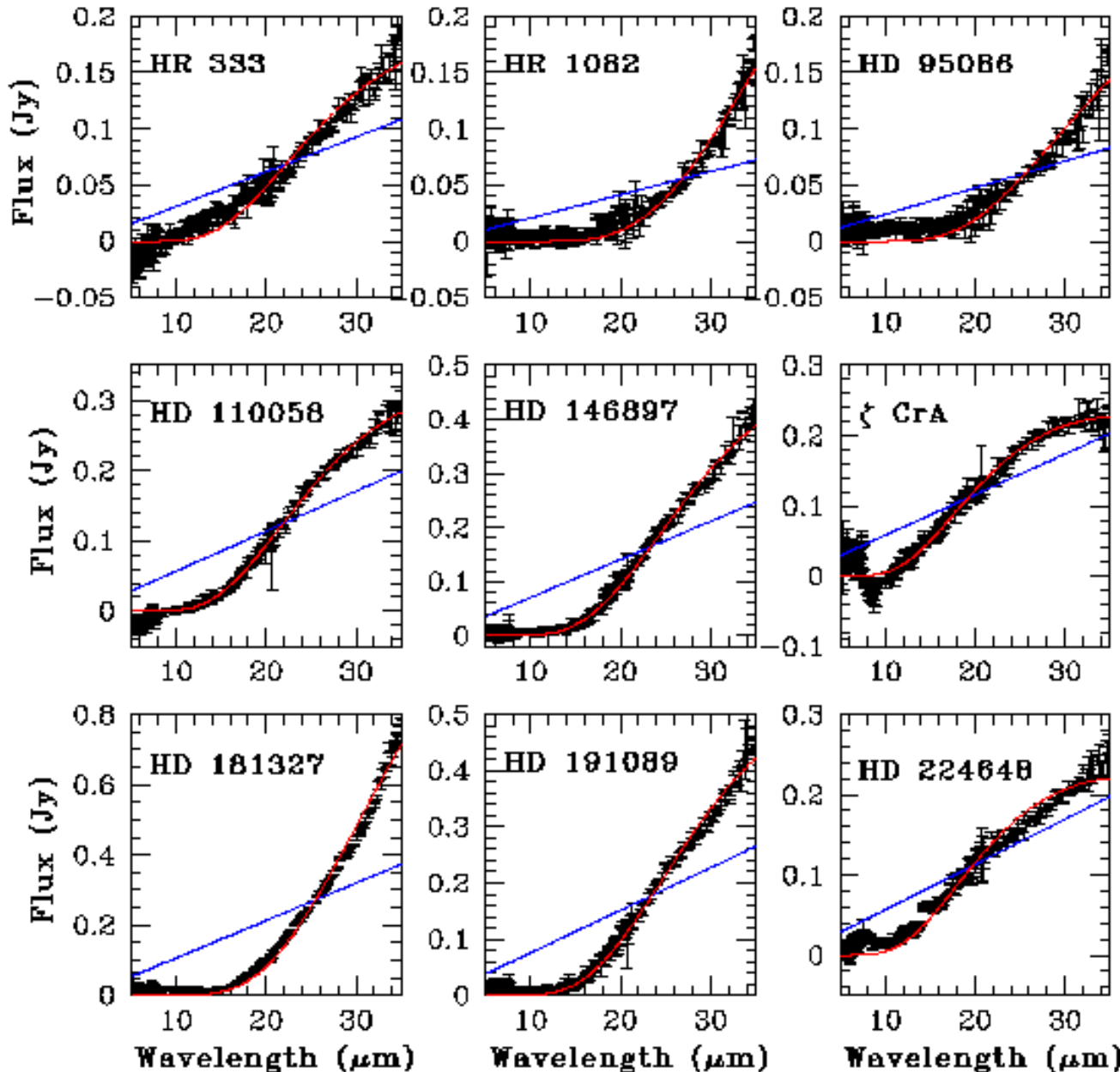
- The flux from a radially extended disk is expected to have a wavelength dependence,

$$F_v \propto \lambda^{3-2q-0.5pq+0.5p}$$

(Jura et al. 1998) where the dust emissivity,  $\kappa_v \propto \lambda^{-p}$ , and the dust density,  $n \propto D^{-q}$

- Objects discovered thus far appear to be Poynting-Robertson drag dominated at 15  $\mu\text{m}$

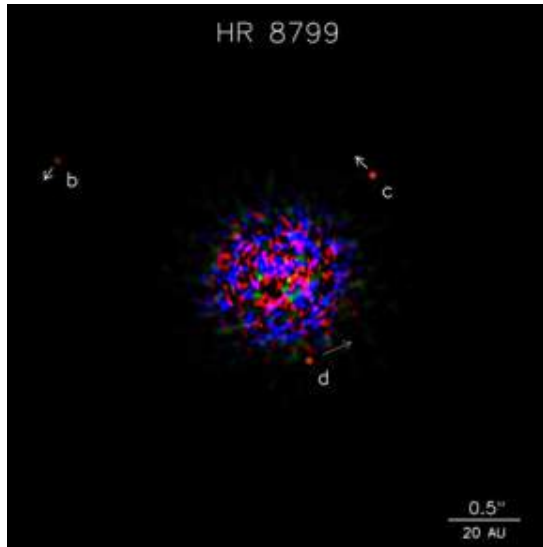
# Mid-Infrared Spectra of Debris Disks



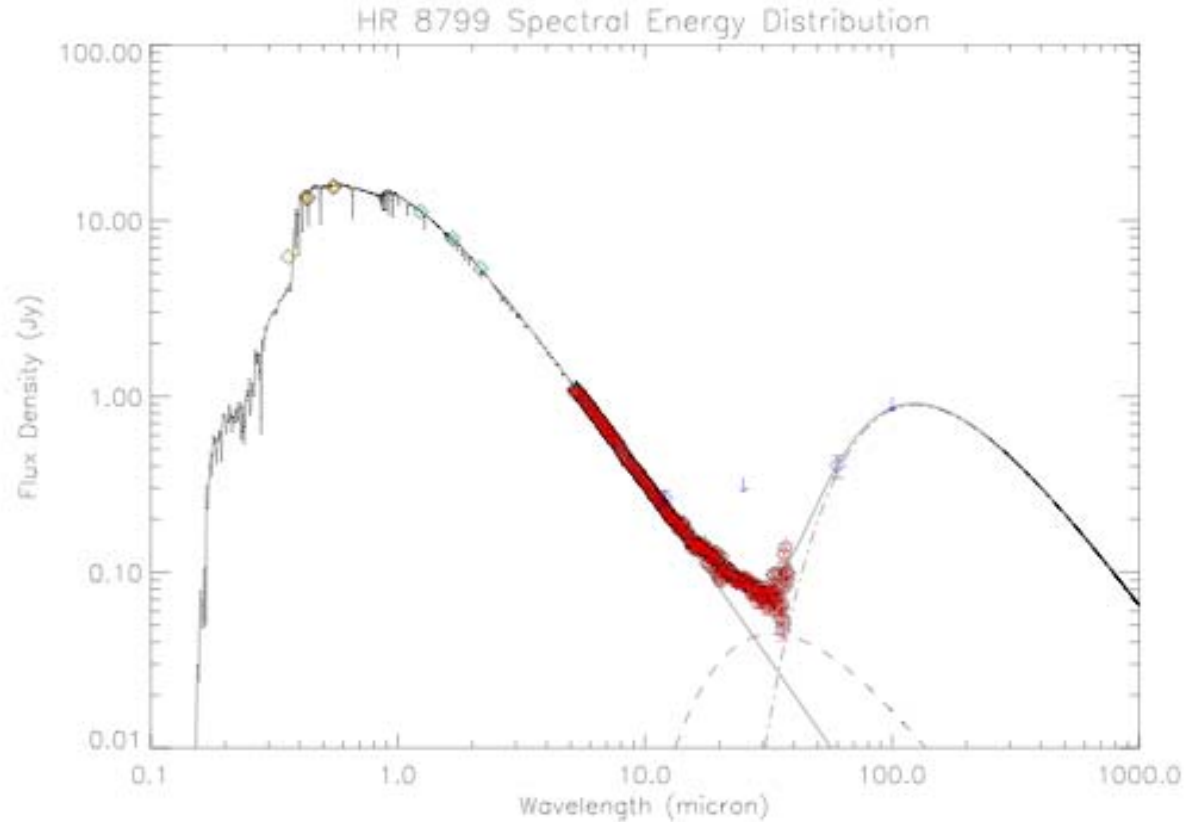
Spectra reveal no composition information

SED modeling suggests that the dust is located in a thin ring which can be modeled assuming a single temperature distribution

# Multiple Parent Body Belts?



Marois et al. (2008)



- The SED of HR 8799 is best fit using two single temperature black bodies with temperatures,  $T_{\text{gr}} = 160$  K and 40 K
- These temperatures correspond to distances of 8 AU and 110 AU, respectively.

# What Could Create Central Clearings in Disks?

## Grain/Disk Properties?

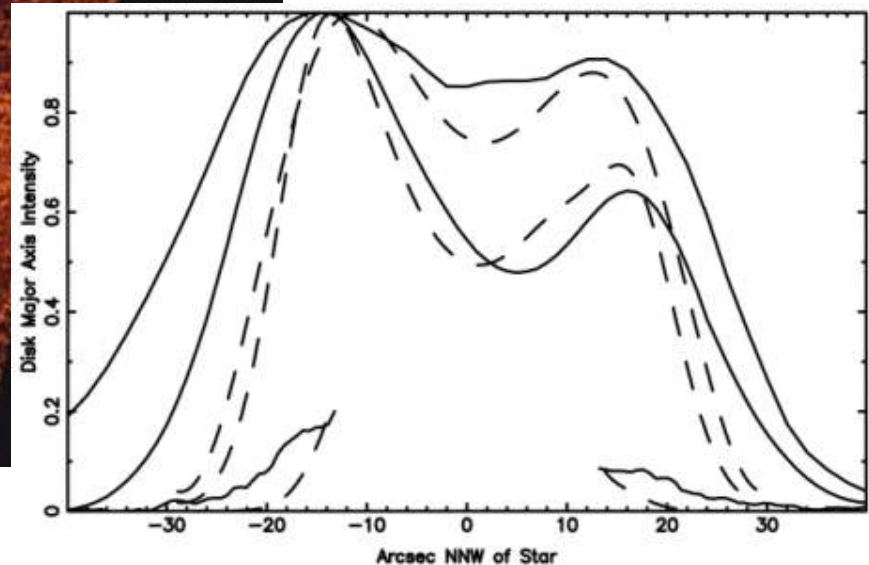
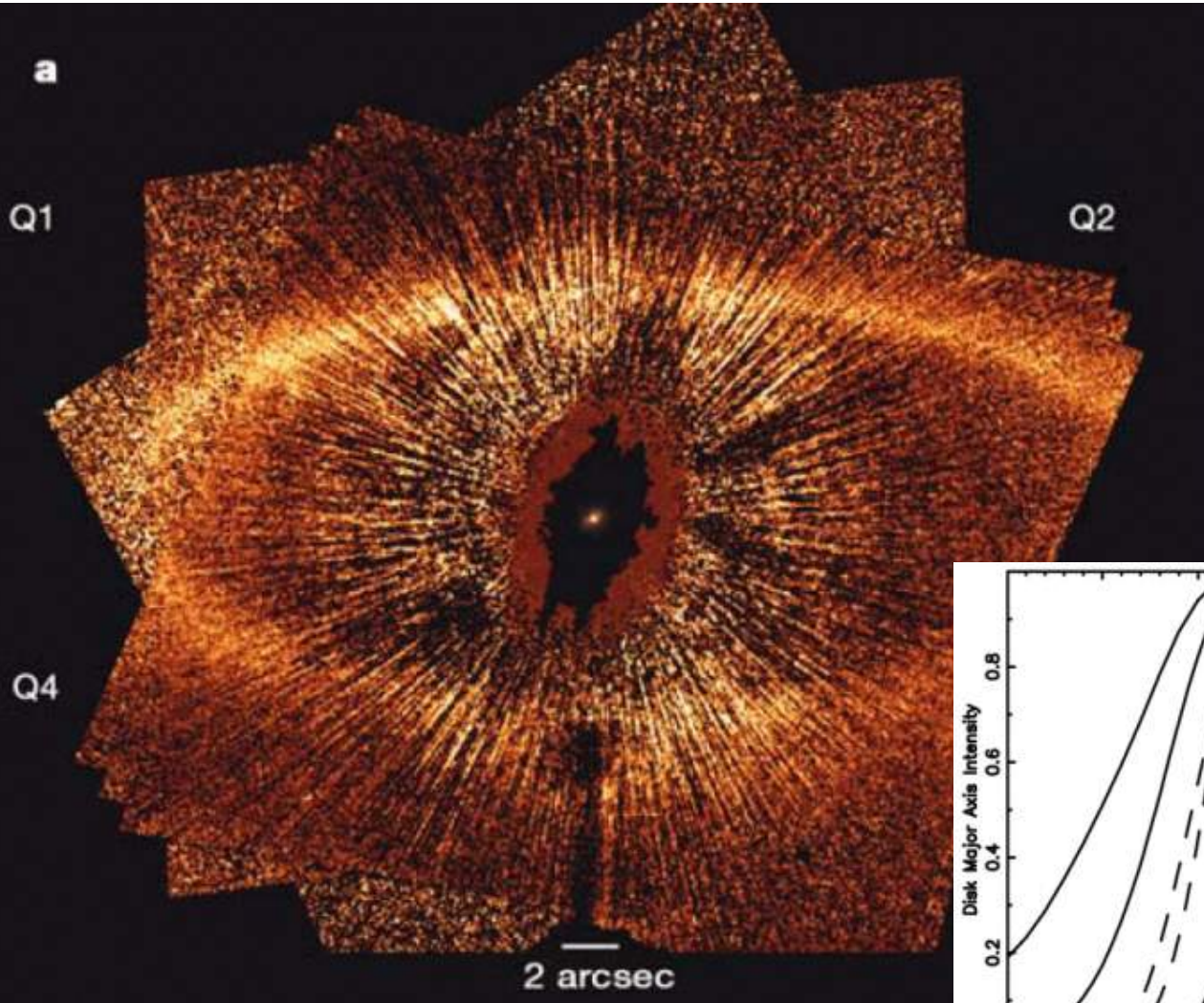
- Radiation pressure if the grains are small (disk is collisionally dominated)
- Sublimation if the grains are icy
- Gas-grain interactions in disks with gas:dust ratios 0.1 – 10 (Takeuchi & Artymowicz)

## Planets?

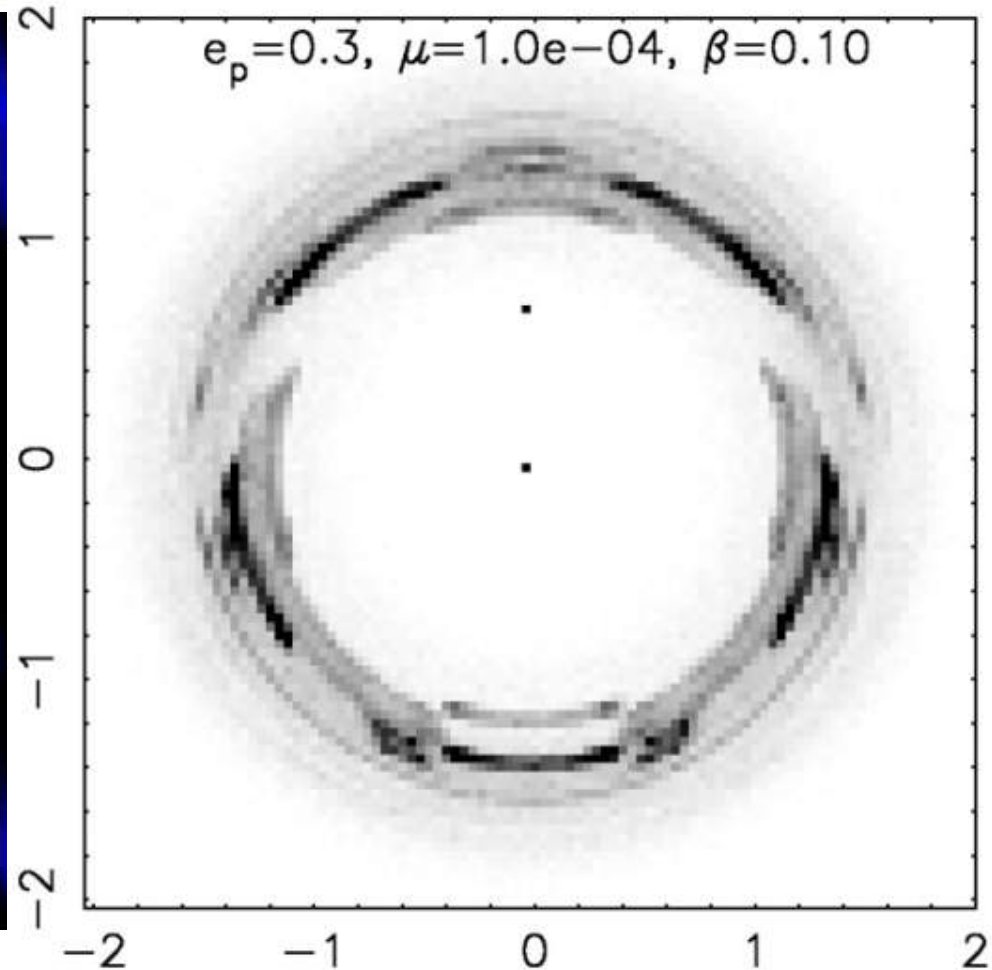
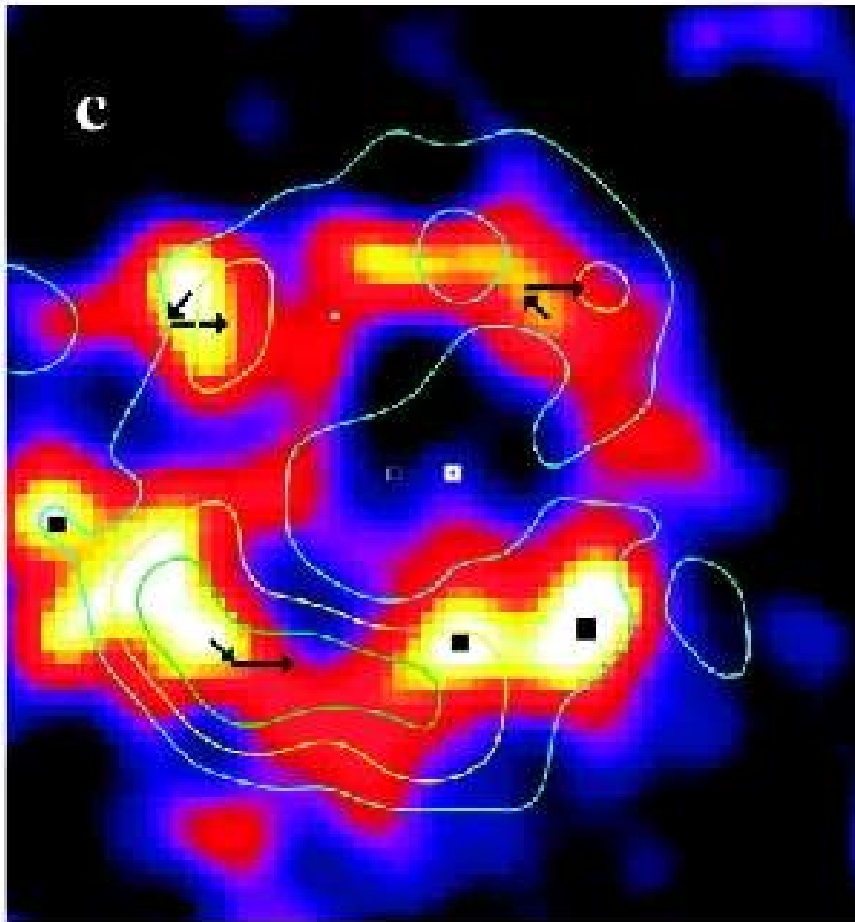
- Gravitational scattering of dust grains out of the system
- Trapping grains into mean motion resonances (Liou & Zook; Quillen & Thorndike 2002)

# Dust in Pericenter Alignment with a Planet Around Fomalhaut?

The Fomalhaut disk ansae possess a brightness asymmetry which may be caused by secular perturbations of dust grain orbits by a planet with  $a = 40$  AU and  $e = 0.15$  which forces grains into an elliptical orbit with the star at one focus (Stapelfeldt et al. 2005)



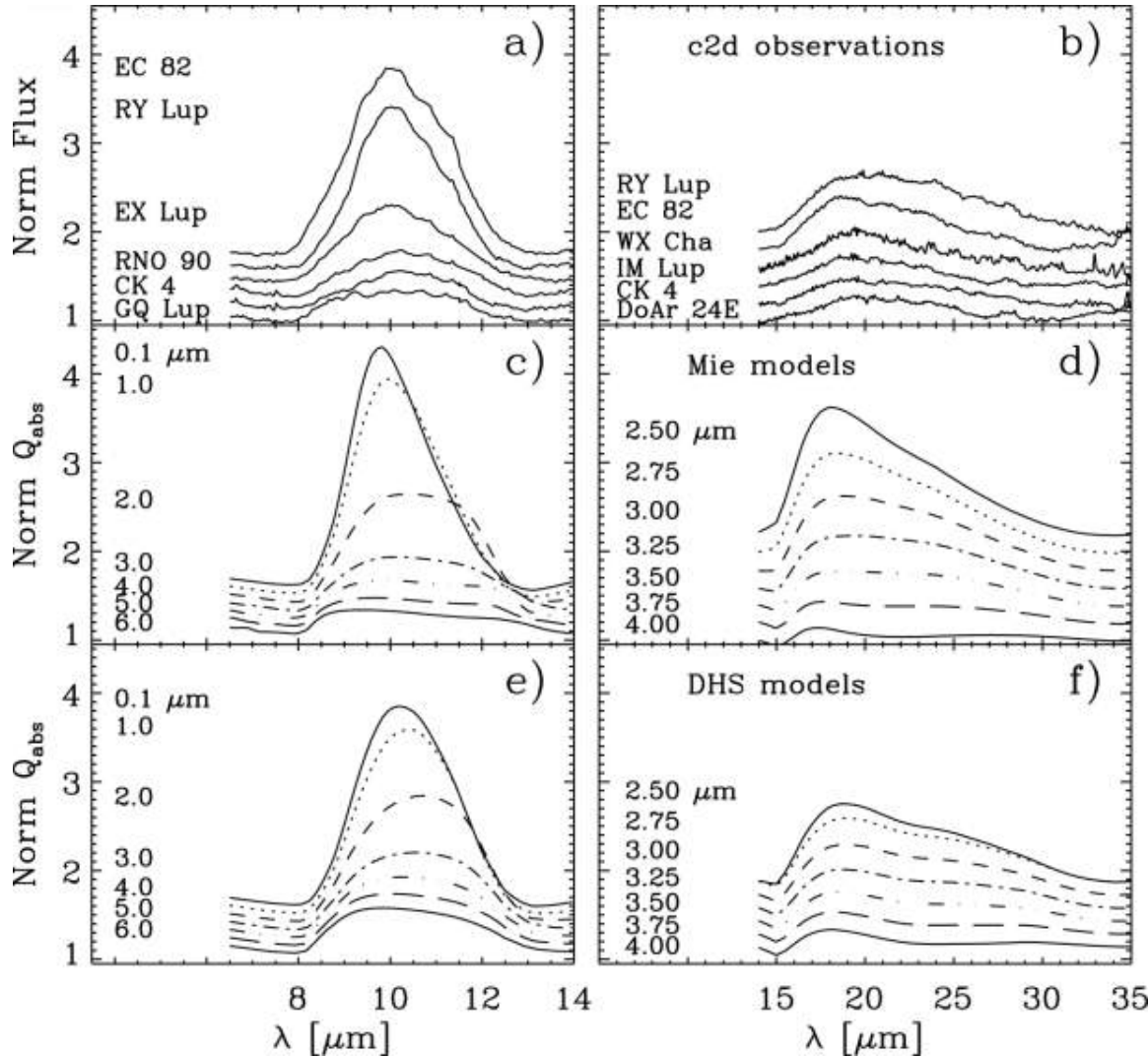
# Dust in Mean Motion Resonances Around $\epsilon$ Eri?



Greaves et al. (2005)

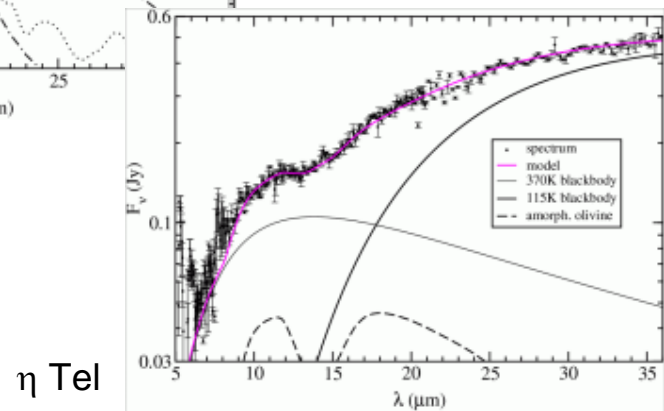
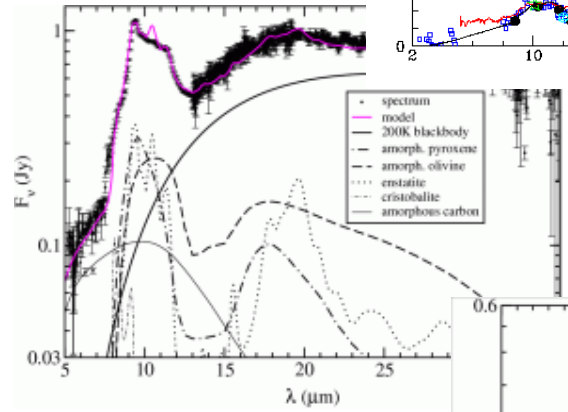
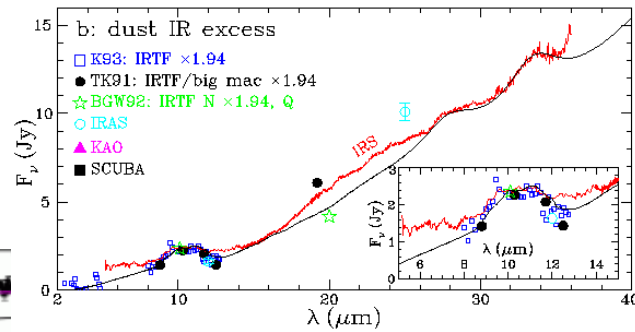
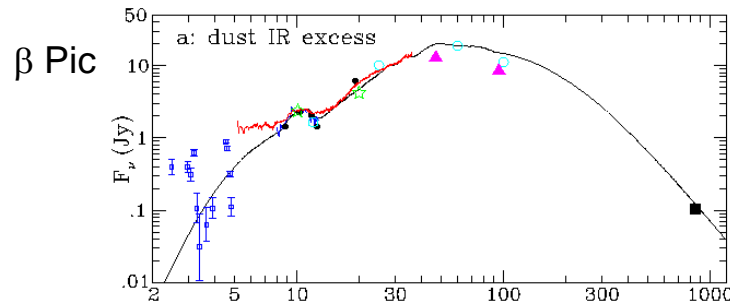
Quillen & Thorndike (2002) model of dust captured into 5:3 and 3:2 exterior mean motion resonances of a 30 M planet with  $e = 0.3$  and  $a = 40$  AU.

# Mid-Infrared Spectroscopy: Characterizing Silicates



- The shape of the 10  $\mu\text{m}$  Si-O and 20  $\mu\text{m}$  O-Si-O bending mode features can be used to diagnose grain size
- The peak and the width of the features are dependent on the vacuum volume fraction

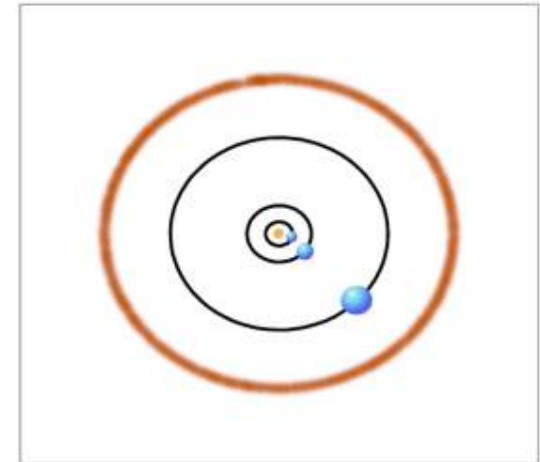
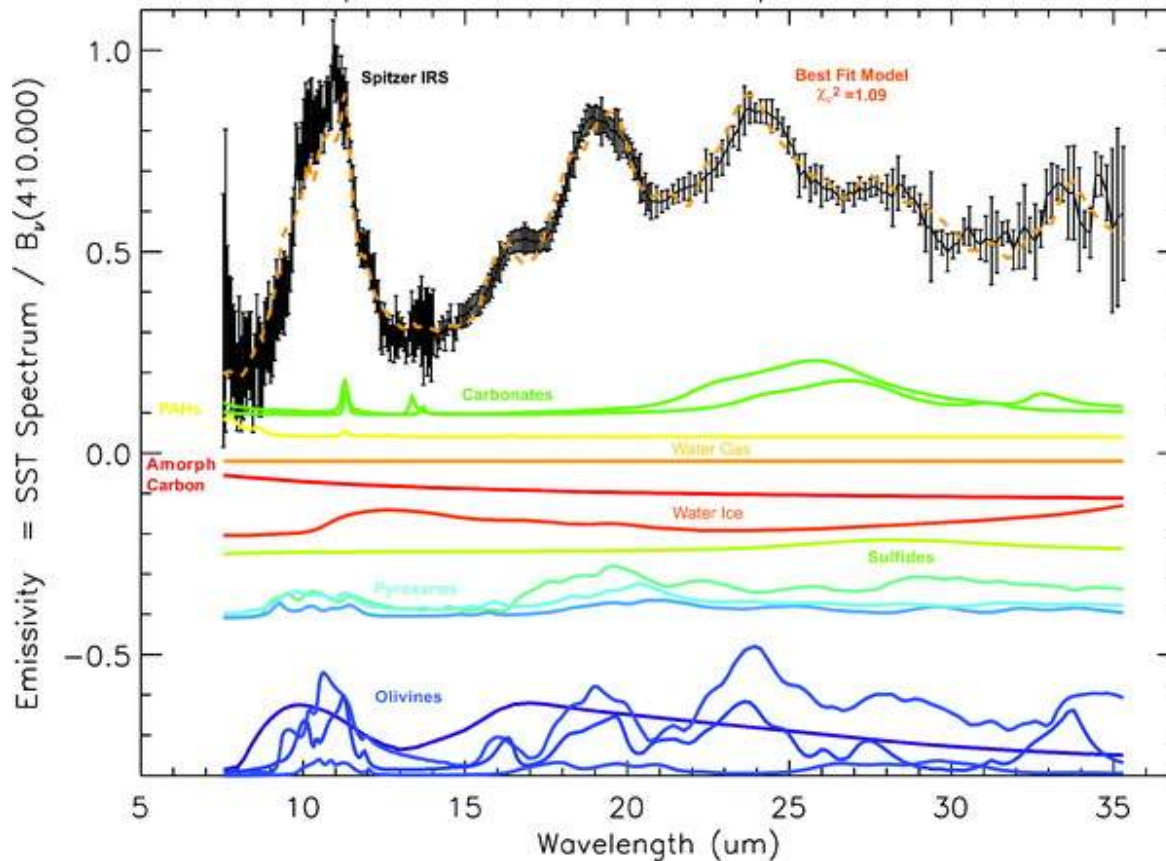
# Silicate Emission Features



- Predominantly associated with intermediate-age disks with ages  $< 50$  Myr
  - 80% of the systems observed may possess crystalline silicates
  - Warm Dust Component ( $T_{gr} = 290$  K – 600 K): silicate emission features that are well-fit using large grains (radii above the blow-out limit)
  - Cool Dust Component  $T_{gr} = 80$  K – 200 K): single temperature black bodies (required to fit the remaining continuum)
- $\Rightarrow$  Multiple parent body belts may exist around these objects

# Period of Late Heavy Bombardment

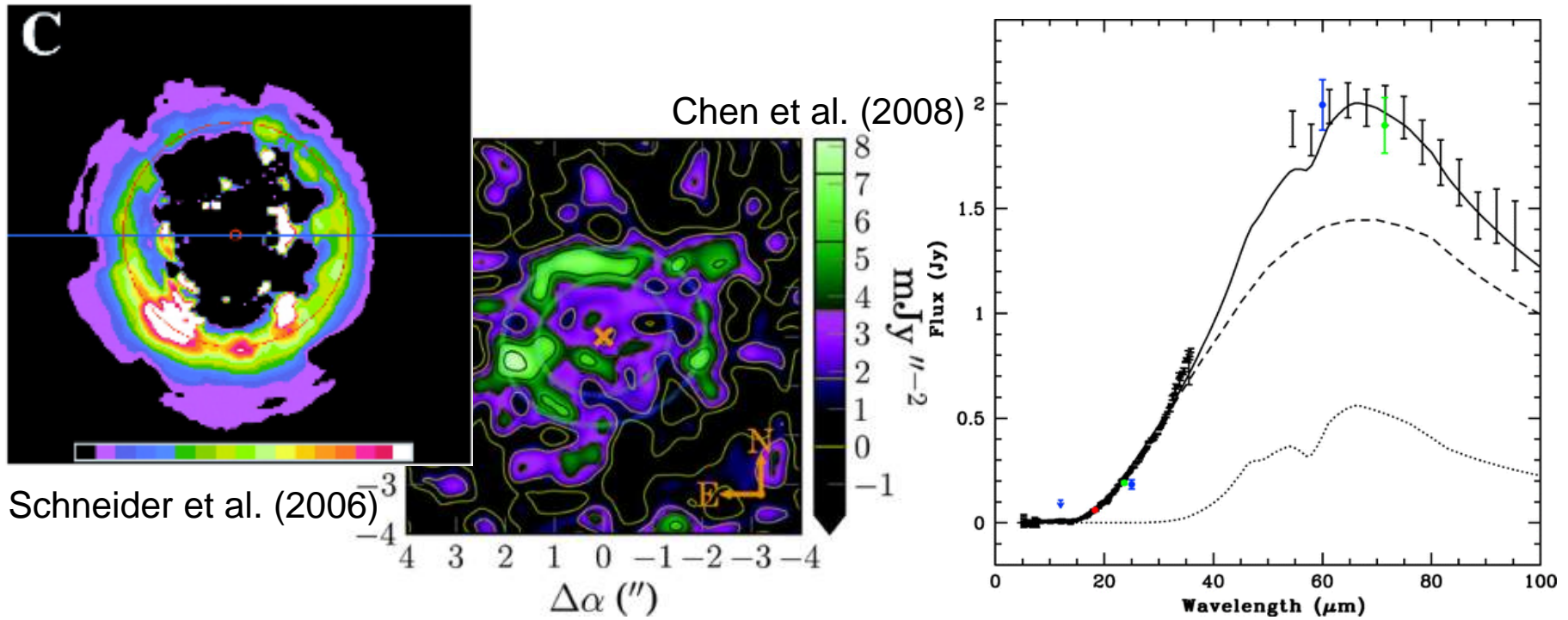
Spitzer HD69830 Disk Spectral Model



Lisse et al. (2007)

- HD 69830 is a 2 Gyr K0V star, located at a distance of 12.6 pc, with a  $L_{IR}/L_* = 2 \times 10^{-4}$  and three radial velocity planets
- Best fit temperatures  $T_{gr} = 340 - 410$  K, corresponding to a distance of  $\sim 1$  AU
- Lacks carbonaceous and ferrous materials found in comets but similar to disrupted P- or D-type asteroid

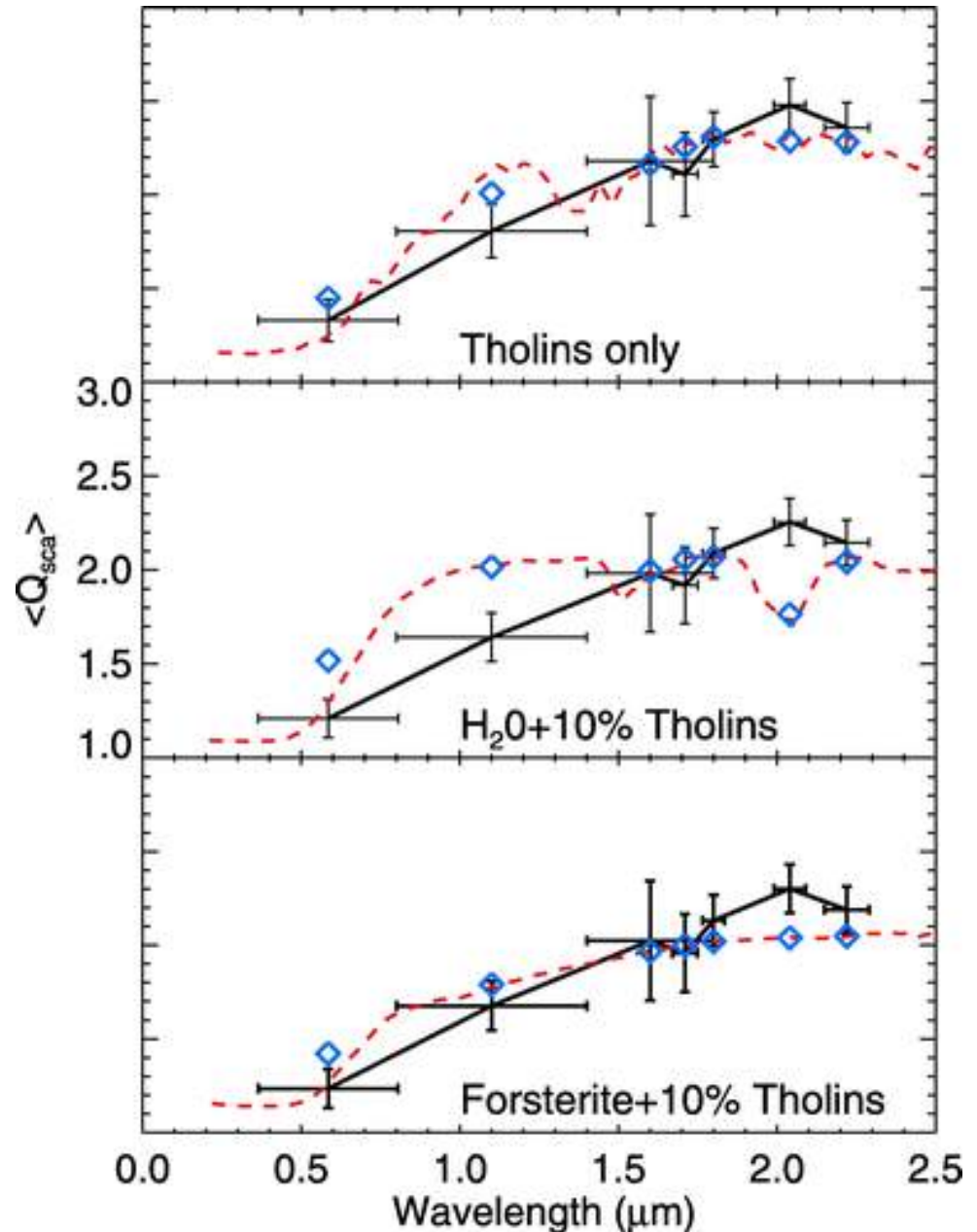
# Exo-Kuiper Belt Disks



- Models that reproduce scattered light, thermal emission, and spectral energy distribution provide a holistic view of the disk (density, temperature, composition)
- For example, HD 181327 may possess density enhancements that impact asymmetric scattering coefficient inferred from scattered light. This imaging and SED data for this disk has been reproduced using a size distribution of amorphous silicate and crystalline water ice grains.

# Organics in Debris Disks?

- ACS, STIS and NICMOS spectro-photometry can be used to constrain grain composition via scattered light.
- Inferred dust scattering coefficients for HR 4796A (using STIS and NICMOS coronagraphic images) can be reproduced using Tholins (Debes, Weinberger & Schneider 2008)
- Silicates may also be consistent with the current data (Li et al. 2008).



# Conclusions

- Debris disks are dusty (gas-poor) disks around main sequence stars
- Our solar system possesses a debris disk (Asteroid and Kuiper Belts) and underwent period of high dust production (epoch of terrestrial planet formation and period of Late Heavy Bombardment)
- Debris disks are common around young stars and may indicate the presence of planets
- The composition of the dust grains is similar to that found in our Solar System