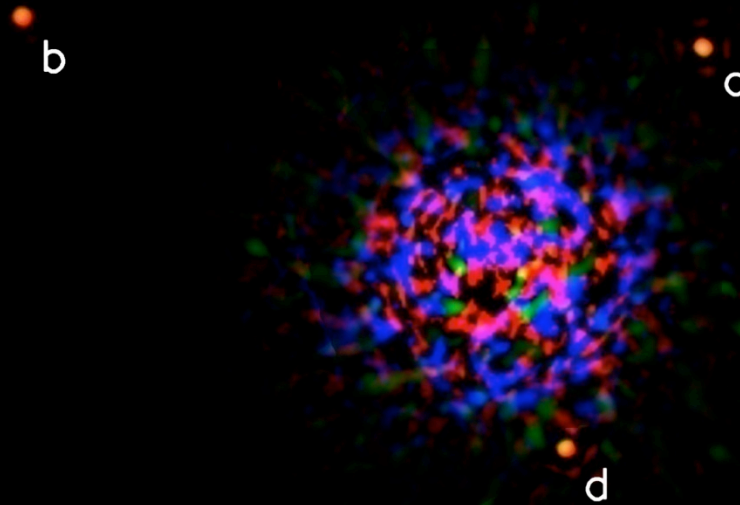


Where Giovanni and I (and Trevor) started:



# How far we have come!! Debris Disks and Planetary System Evolution

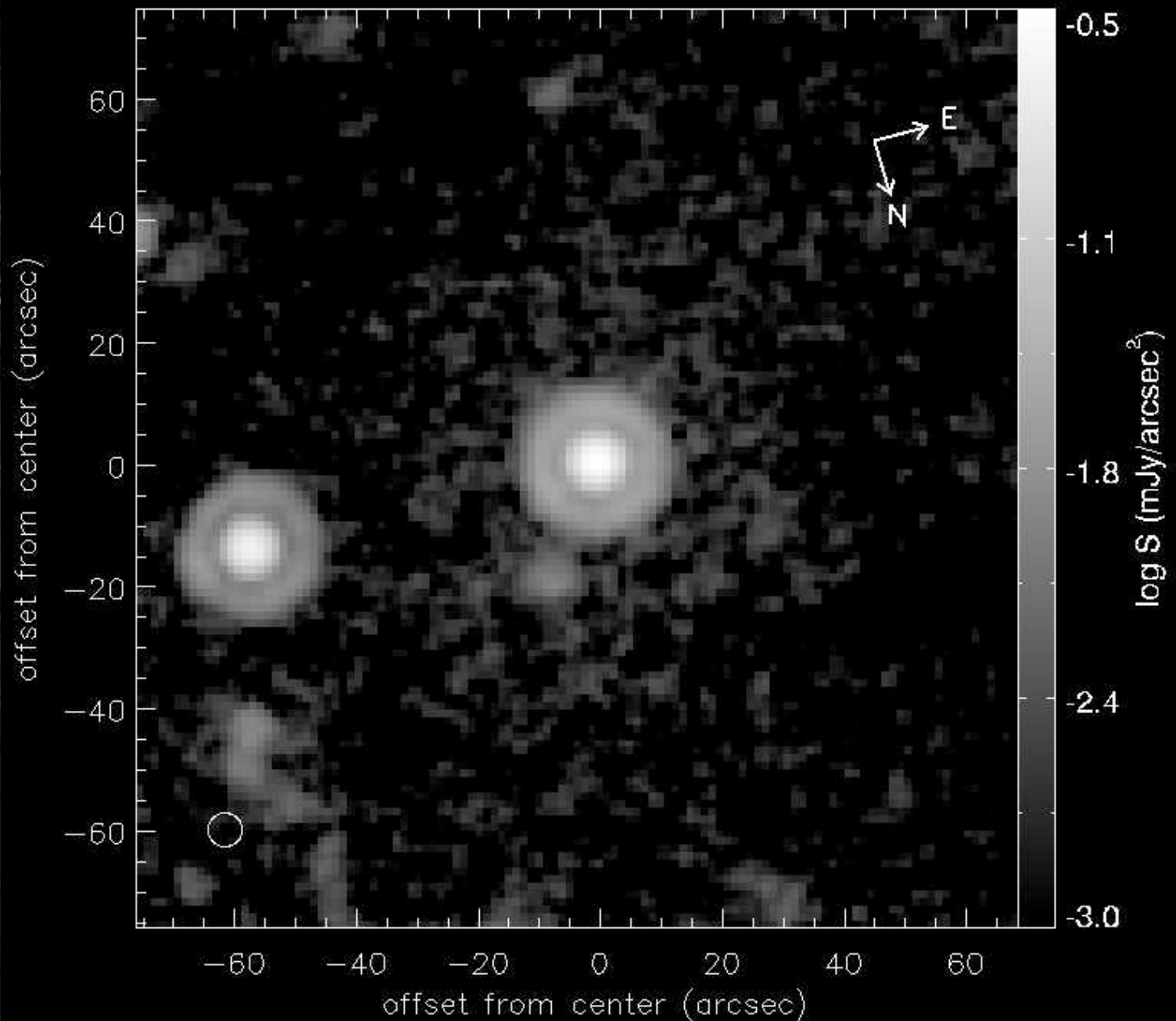
HR 8799 Planetary System  
(Sept. 2008)



0.5 arcsec  
20 AU

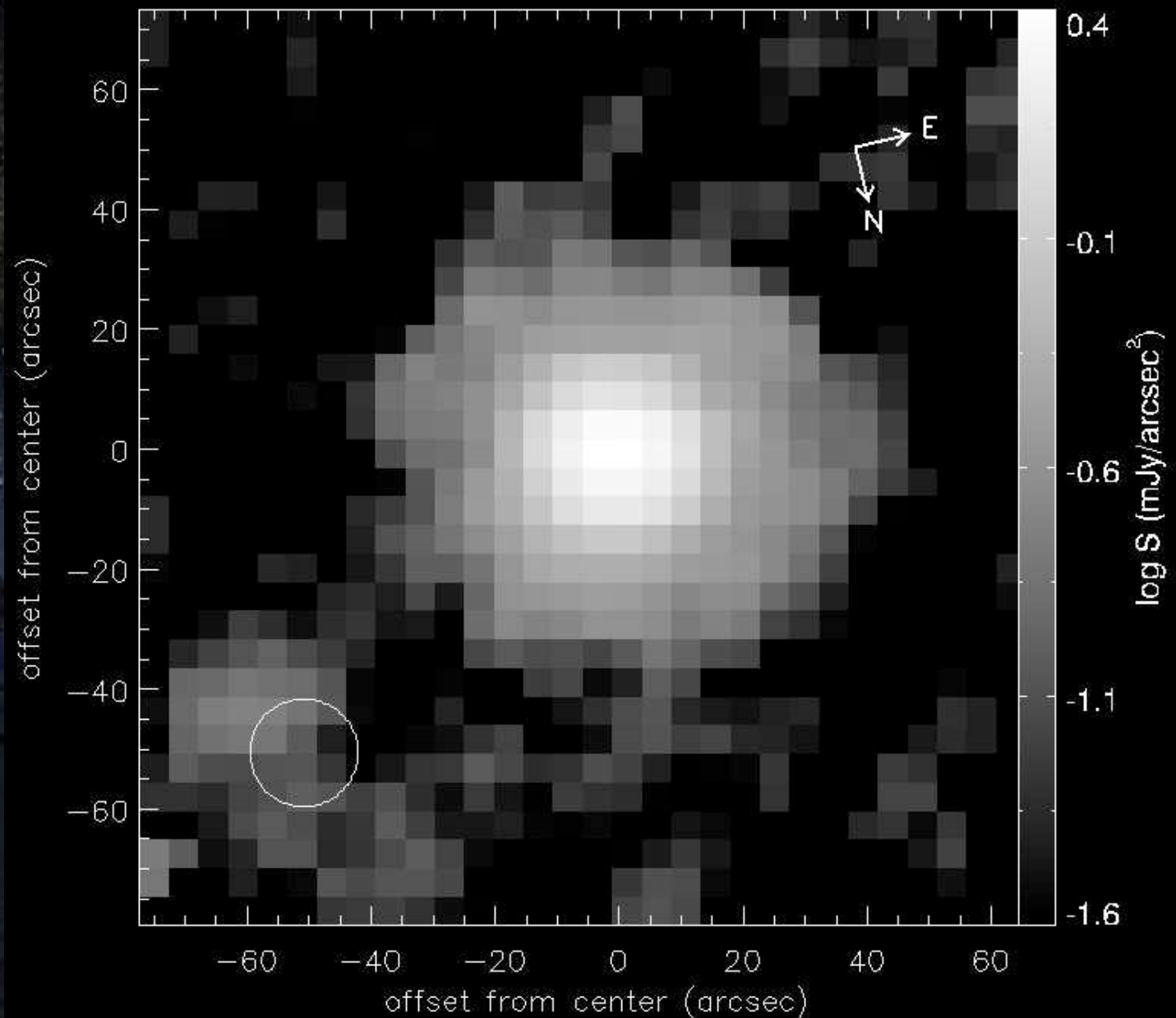
# HR 8799 at 24 $\mu\text{m}$

Ignore all but the central object (it is a PSF-subtracted image of HR 8799). The faint halo is real. Compare the scale with the preceding image, which was about 4 arcsec square.

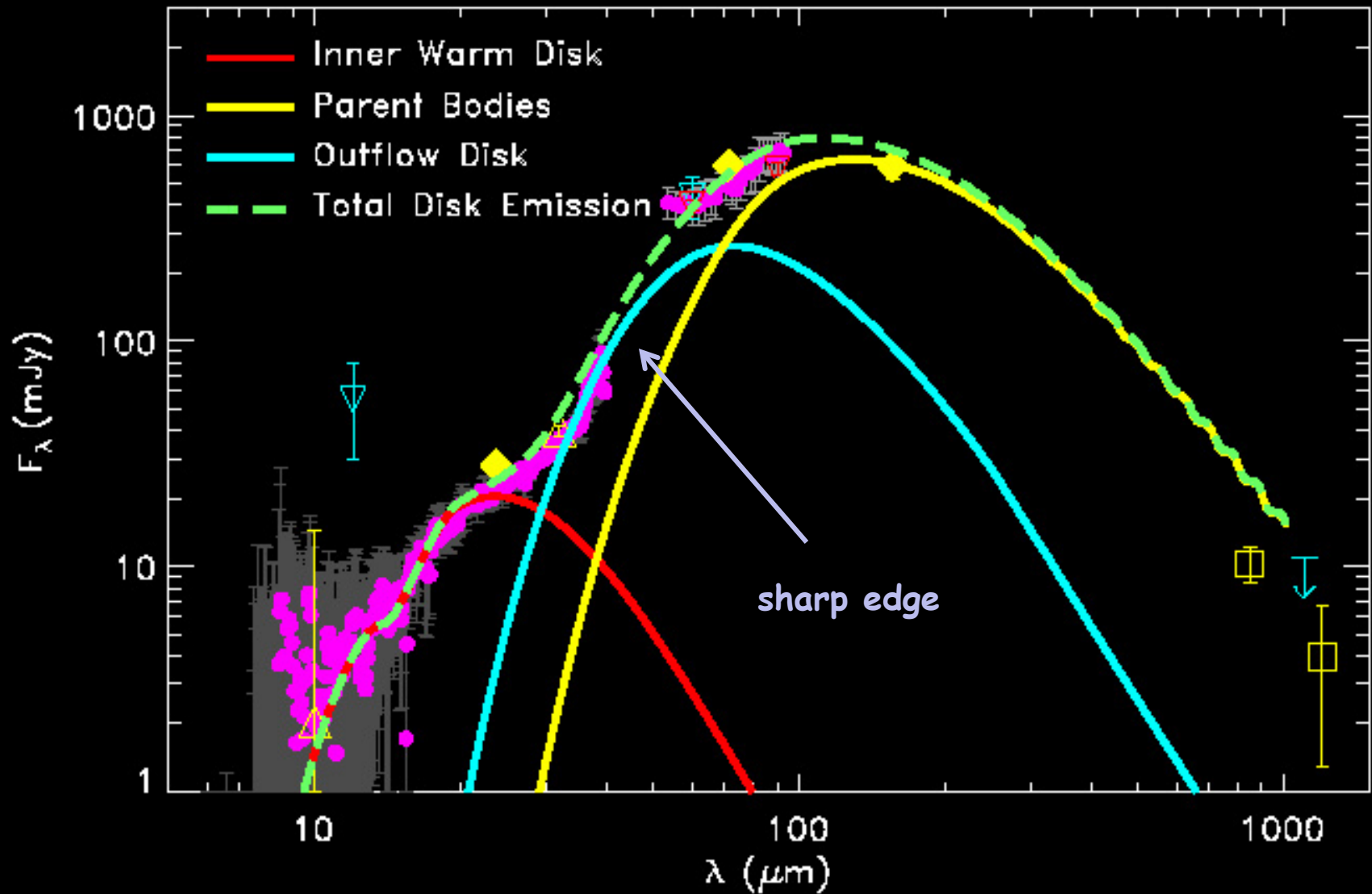


# HR 8799 at 70 $\mu\text{m}$

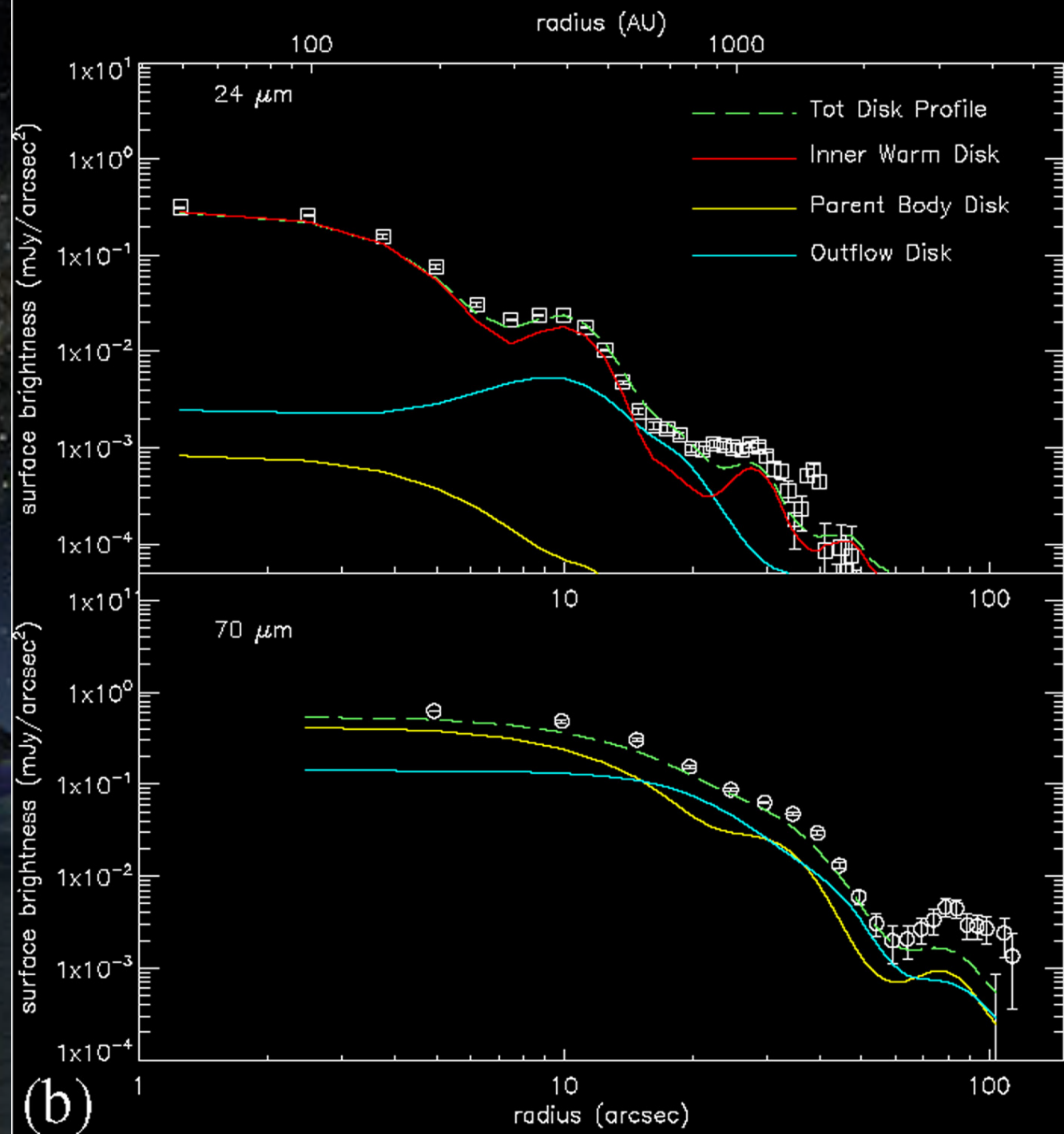
The system is huge!!! It is at least an arcmin in diameter at 70  $\mu\text{m}$ . At 40 pc, one arcmin is about 2400 AU.



The fit to the SED indicates an inner disk, just inside the orbit of the innermost planet, an outer parent body disk with a sharp inner edge just at the orbit of the outermost planet, and an outflow disk of small grains (model by Kate Su)



This model is also consistent with the images.

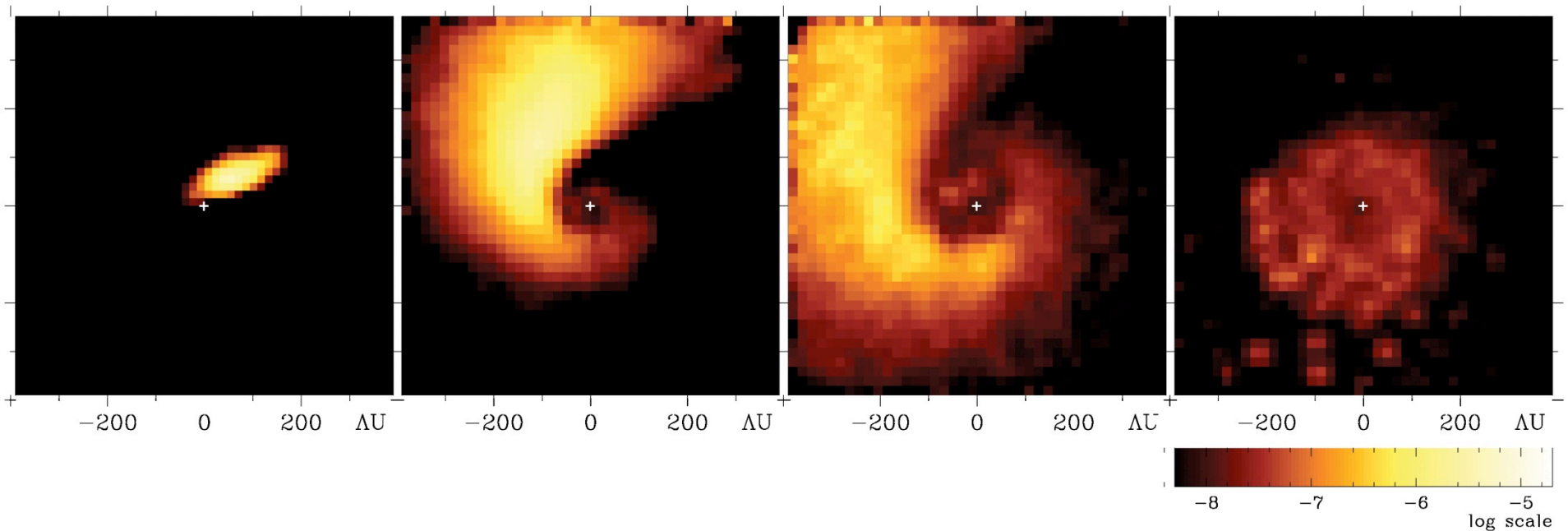


The extended system may result from a series of collisional avalanches, fueled by vigorous dynamical activity in the parent body disk. The planet system presumably does the stirring required.

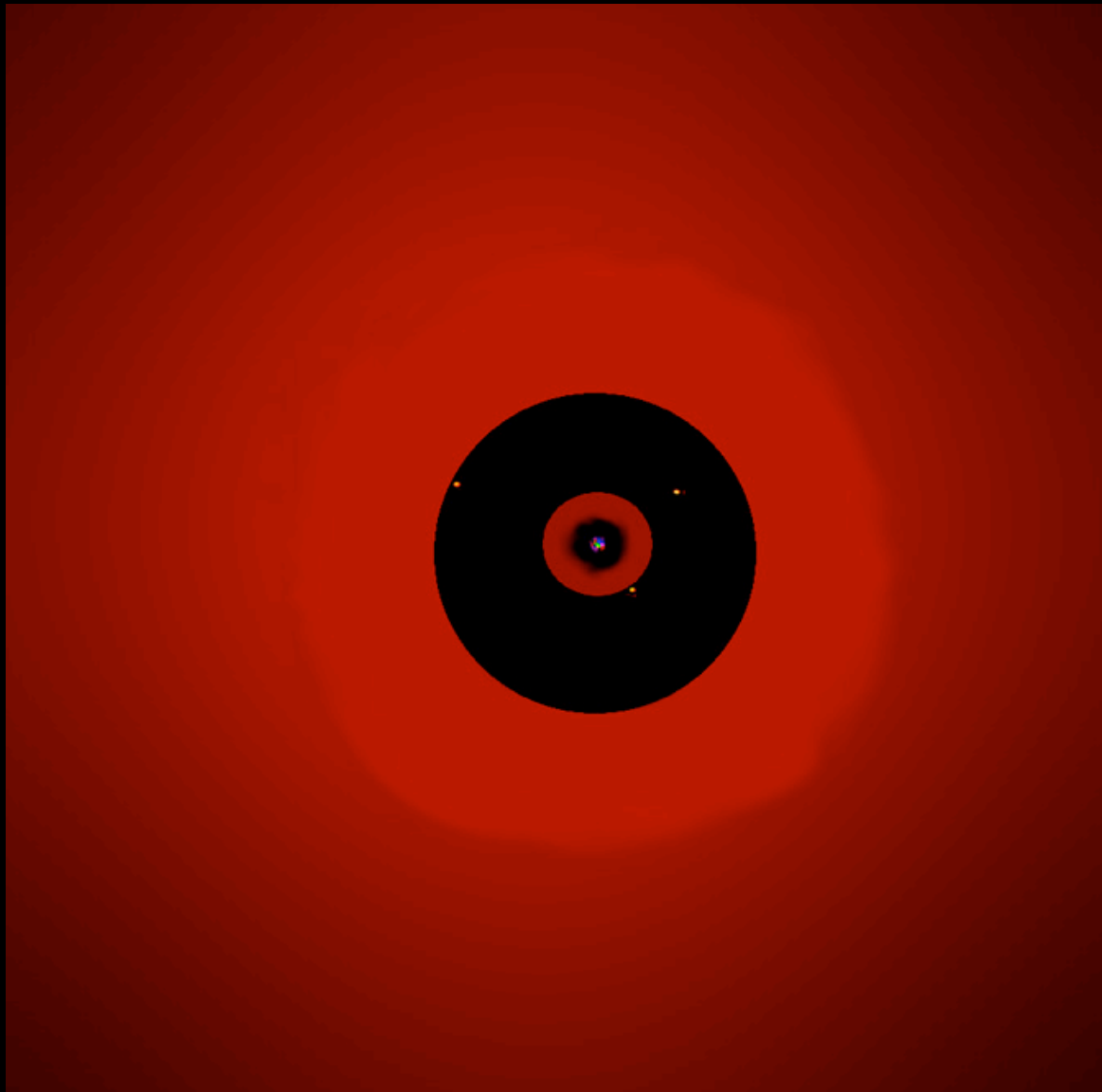
Below: development of a collisional avalanche from release of  $10^{-7}$  Earth masses of dust.

The small grains are expelled to large radius by radiation pressure. As they leave, they collide with larger ones still in orbit and break them up.

Grigorieva et al. 2006



A full view of the HR 8799 system:



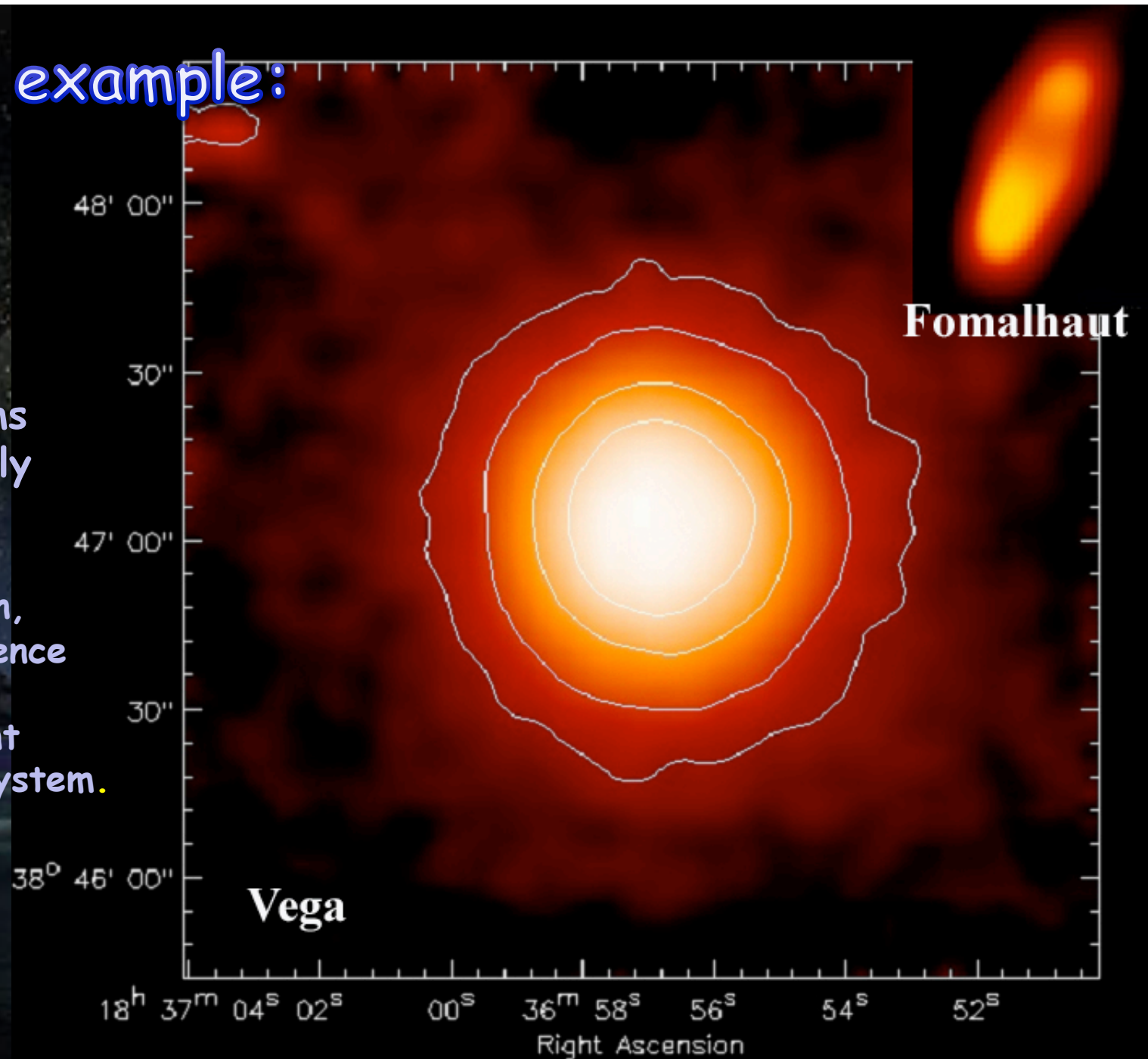


## Another example:

Although Vega and Fomalhaut are "twin" stars\*, their debris systems look completely different!

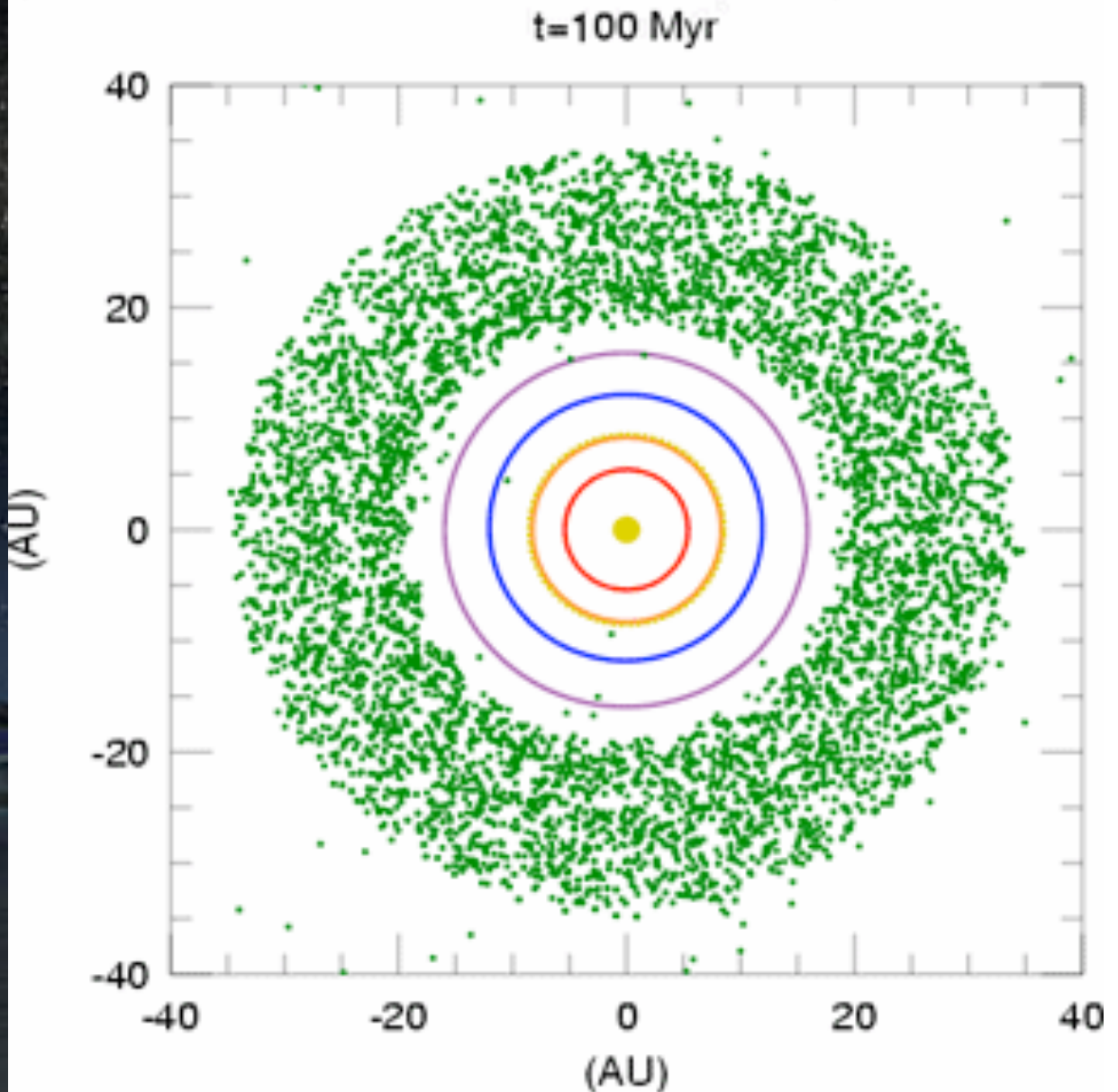
Vega is face on, but the difference of interest is the huge extent of its debris system.

\* They have similar masses, ages, distances, and spectral energy distributions.



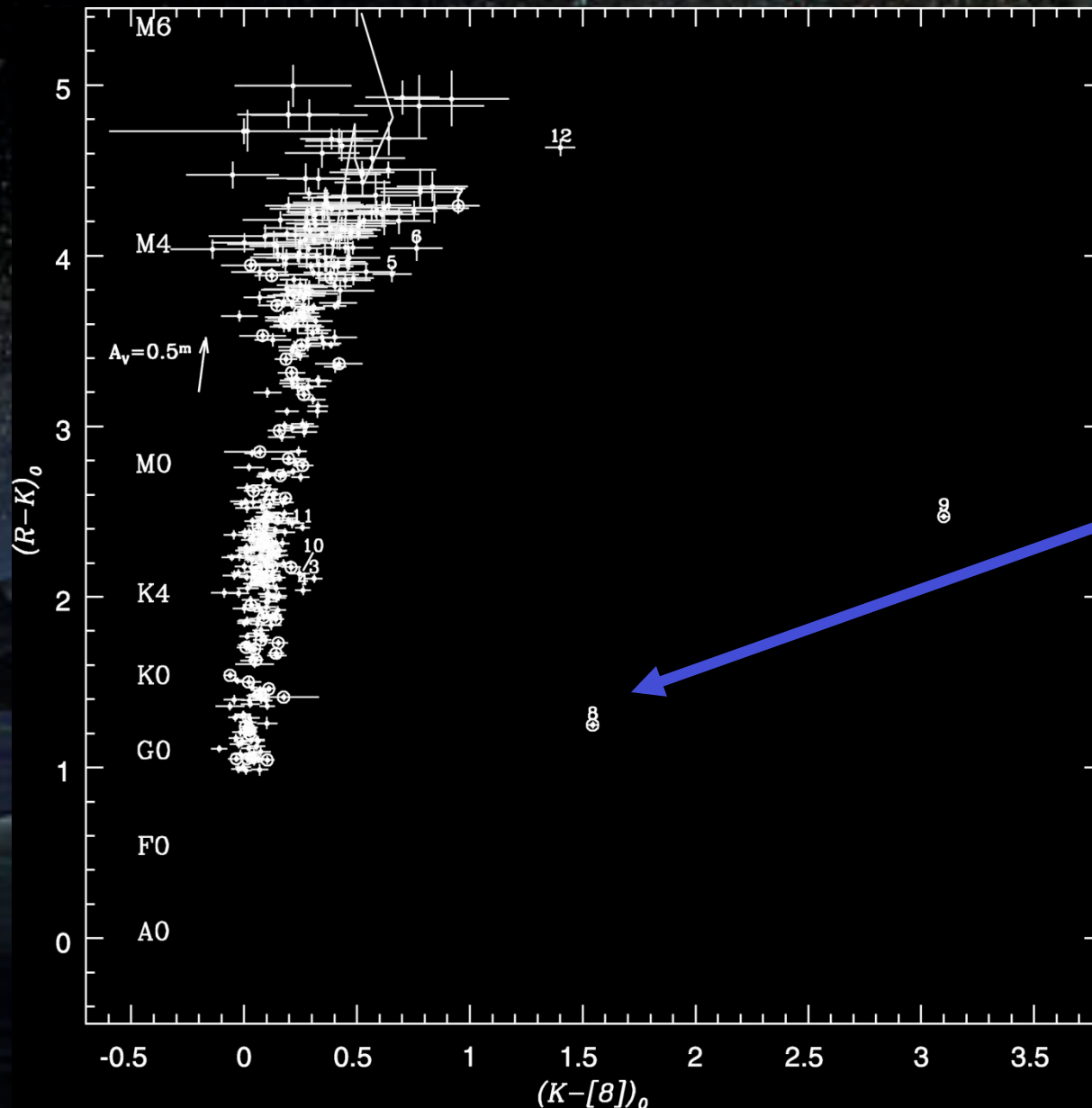
# Did the Solar System behave this way?

These systems may be undergoing transformations similar to the Late Heavy Bombardment that occurred about 700 Myr into the evolution of the Solar System. This animation shows the "Nice" model of this event.



(From Gomes, *et al.*, 2005, *Nature*, v. 435, p. 466-469.)

# We also see extreme behavior at younger ages



A couple of stars in the 40 Myr old cluster NGC 2547 have large excesses at  $8\mu\text{m}$ . One is a background object, but the other is a cluster member.

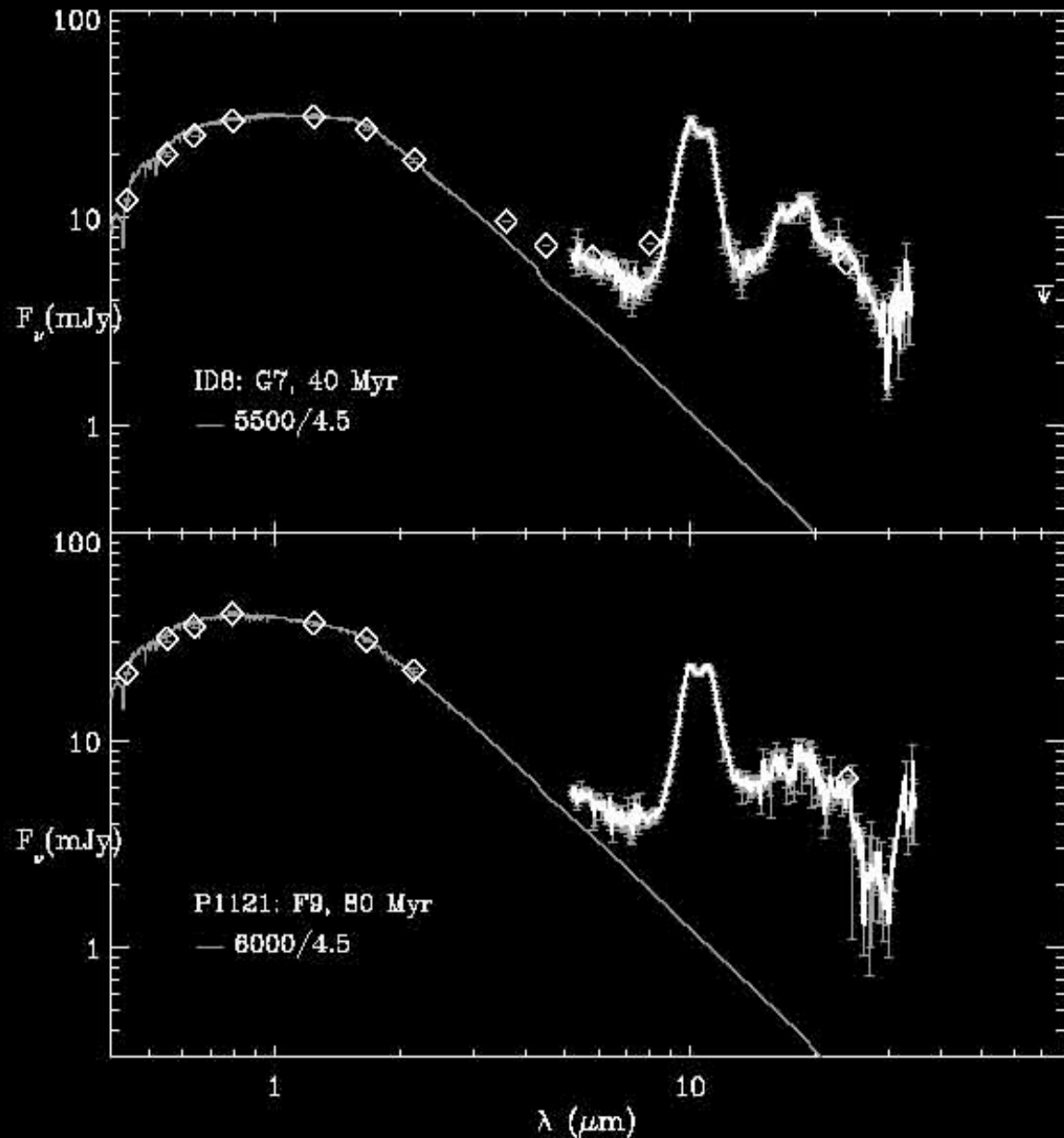
The Spitzer survey includes 400-500 cluster members, so the proportion of ones with strong excesses is very small.

Gorlova et al. 2007

In fact, in the 30 - 120 Myr age range, we know of only three such extreme systems.

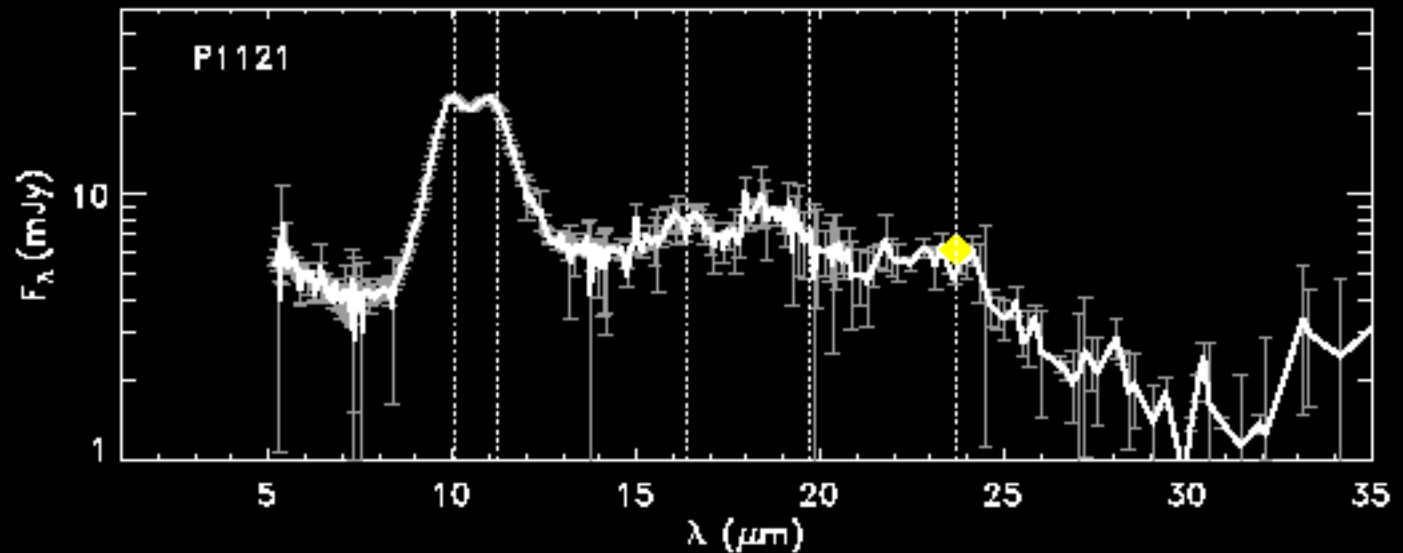
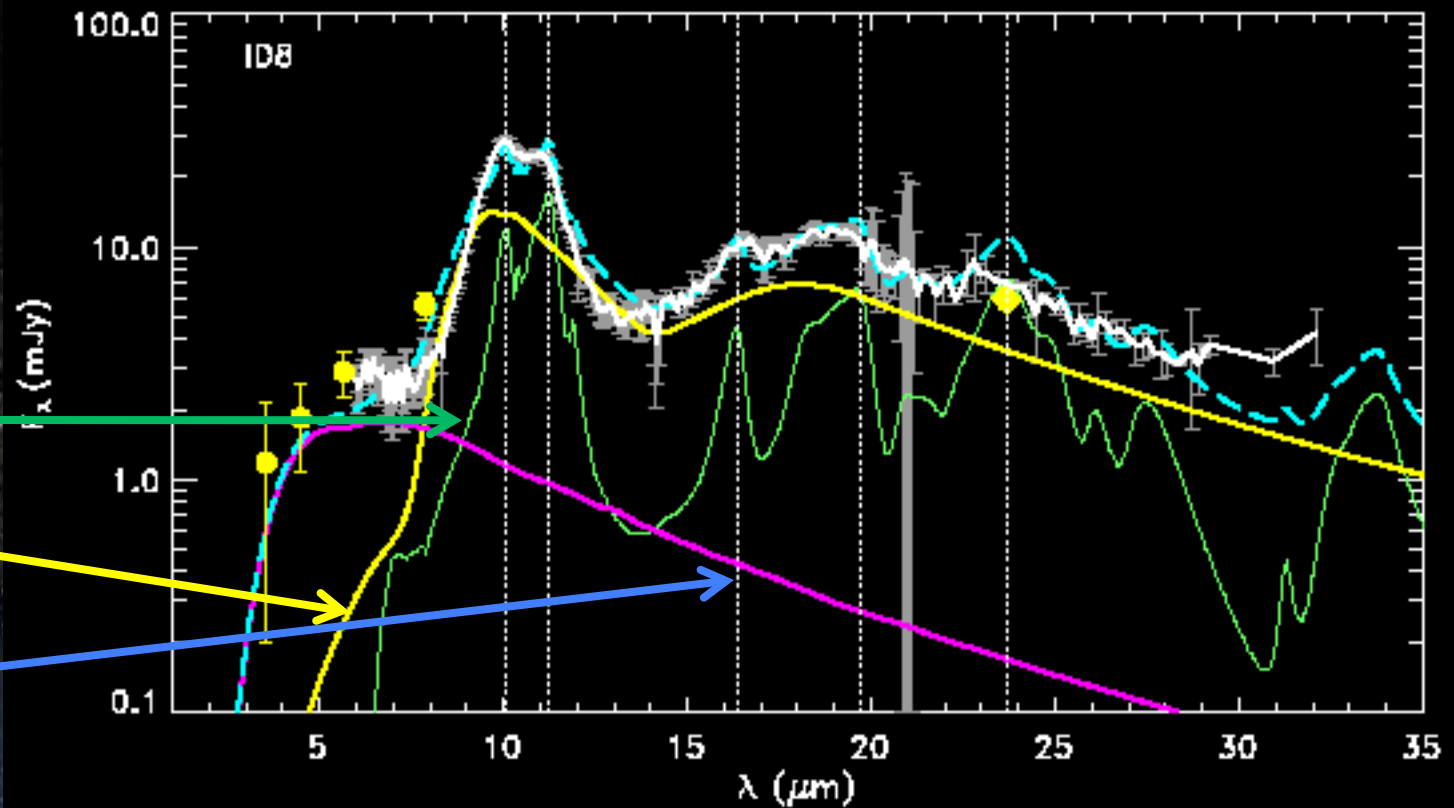
Here are the spectra of two of them (the upper one in NGC 2547, the lower in M47).

The strong spectral features require finely divided dust and indicate that some major dust-producing event has just occurred.  
- from Gorlova et al. in prep.

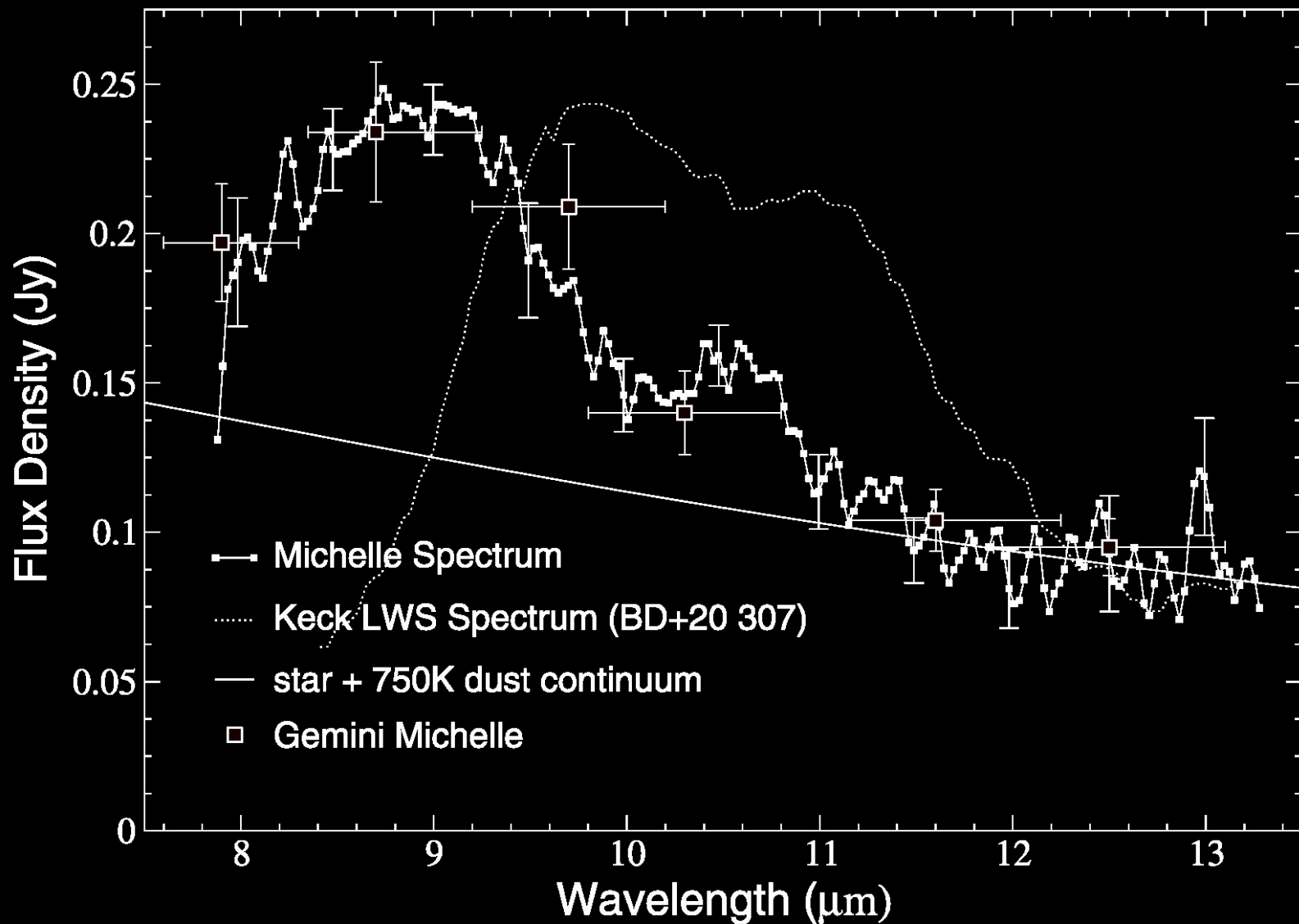


Model fits (by both Kate Su and Carey Lisse) show a mixture of crystalline and amorphous silicates, and carbon.

Roughly a lunar mass of material must participate in a collisional cascade to produce the required amount of dust.



The third object, HD 23514 (in the Pleiades) has an anomalous silicate feature centered at 9  $\mu\text{m}$  (Rhee et al. 2008) and matching the spectral behavior of smoke condensed out of silicate vapor.



These three systems have the expected signatures of colossal collisions such as the one that formed the moon when the solar system was 30 - 120 MYr old.

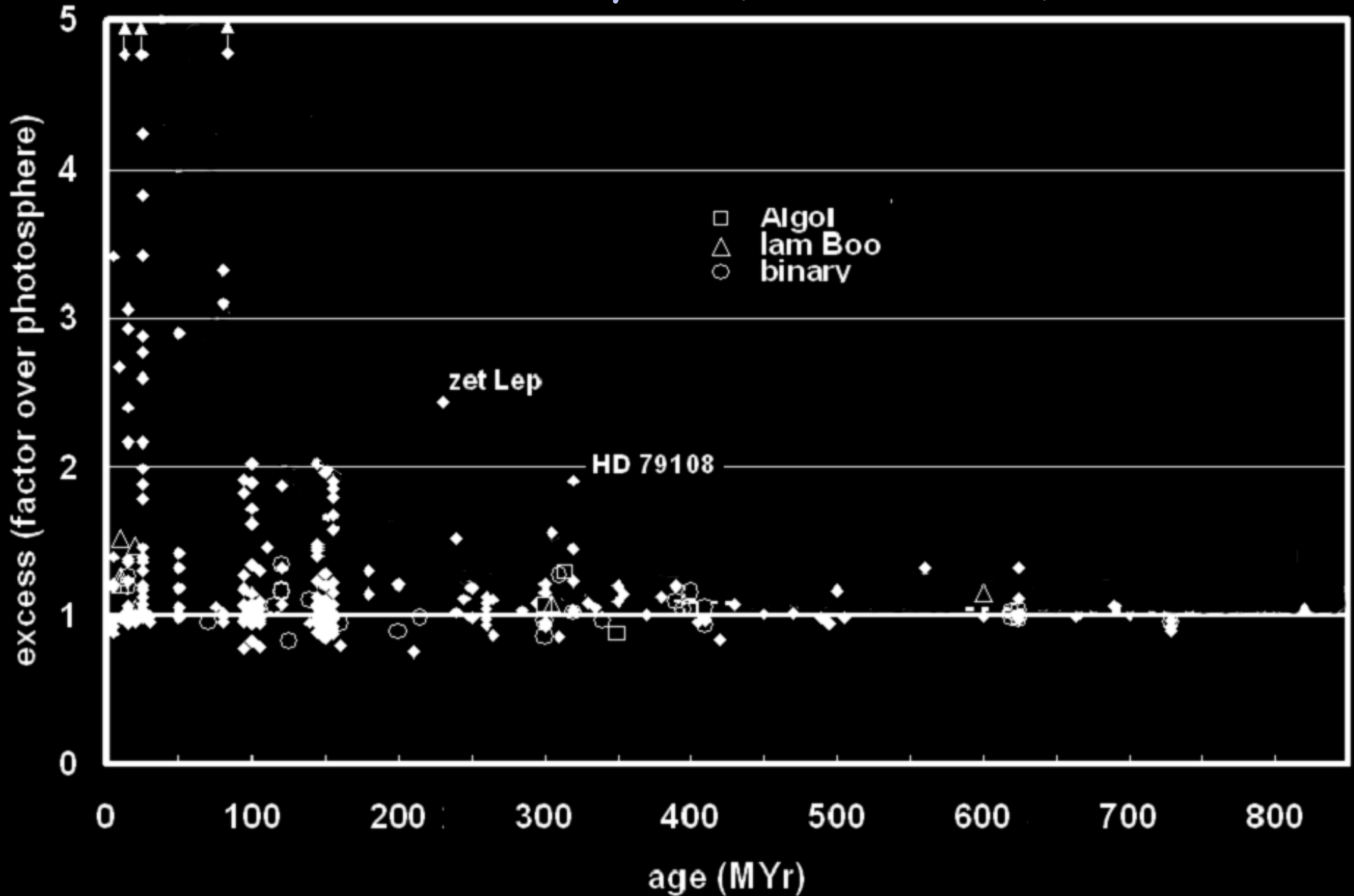


From Bill Hartmann, 1 hour after the collision



..... four hours later

We also see the decay of collisional activity much as hypothesized for the Solar System (Rieke et al. 2005).

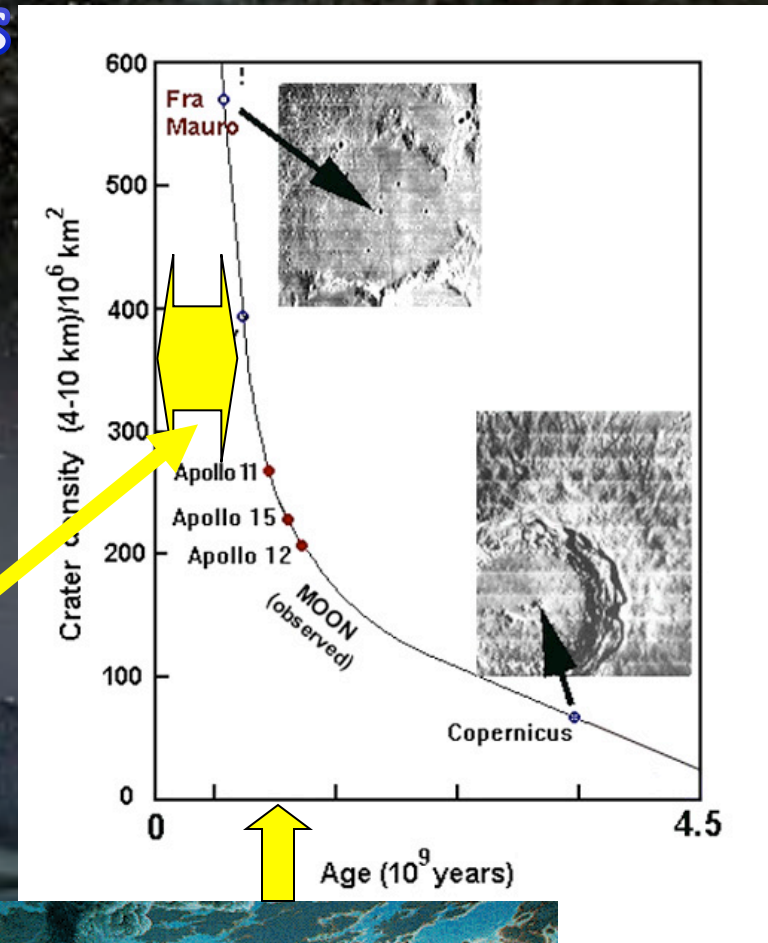




# We find all the major stages of Solar System evolution around other stars

## Summary of solar system evolution

- Huge events for tens of millions of Years
- Overall decay of activity
- High cratering rate ended in the Late Heavy Bombardment at ~ 700 Myr
- Life appeared almost immediately thereafter



**Region of preceding graph**

Painting by Peter Sawyer,  
copyright Smithsonian Institution



Who would have guessed?



# What Next?

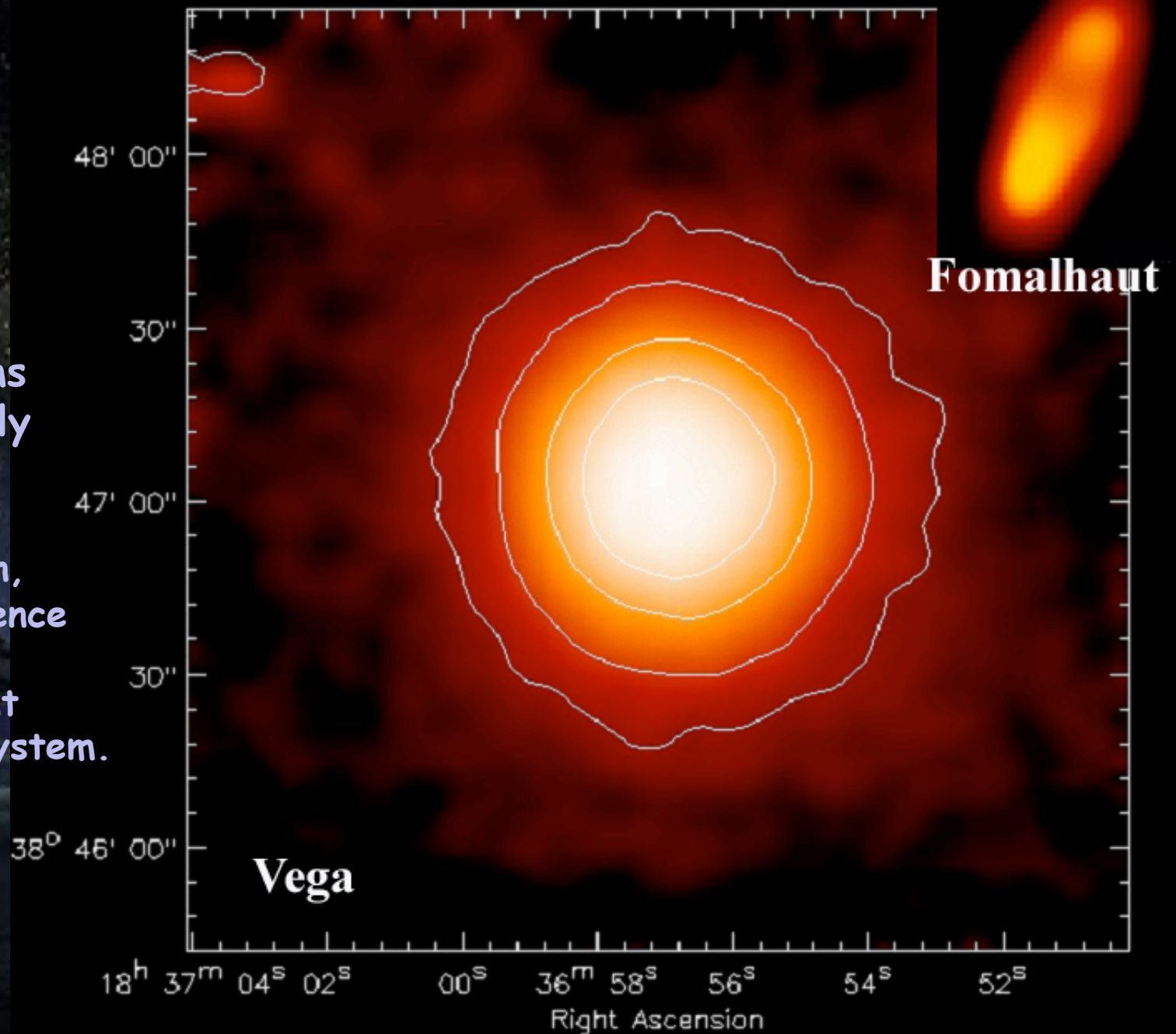
JWST will bring huge gains to our understanding of debris disks and other planetary systems



Although Vega and Fomalhaut are "twin" stars\*, their debris systems look completely different!

Vega is face on, but the difference of interest is the huge extent of its debris system.

\* They have similar masses, ages, distances, and spectral energy distributions.



The JWST view

