Mid-IR Observations of Protoplanetary Disks and Debris Disks with High Spatial Resolution

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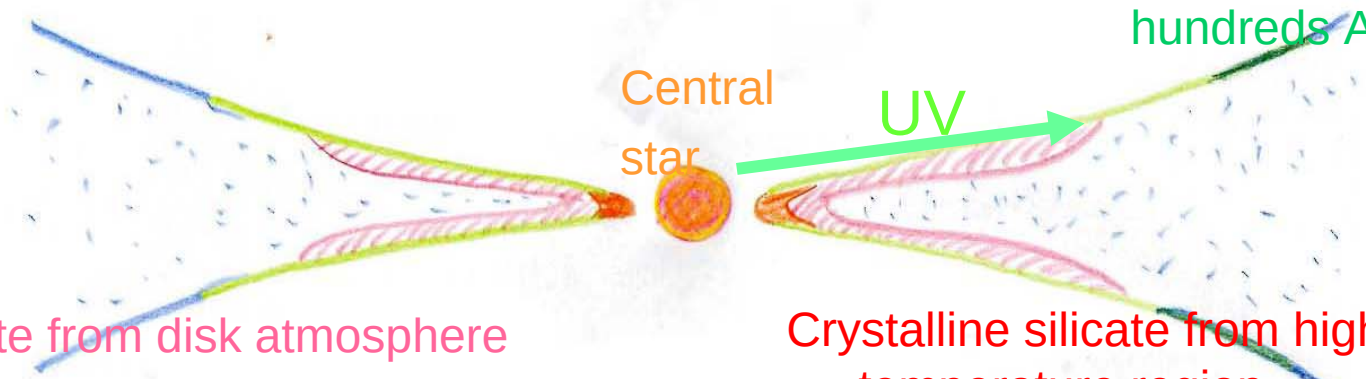
Dust in circumstellar disks

- Dust grains in circumstellar disks
  - Their properties and distribution probe the condition of disks as sites of planetary system formation
    - Initial, ongoing, and final condition of the formation
  - Infrared spectra are a good probe for grain properties such as species, composition, temperature, size, crystallinity, and environment of grains, which are dependent on disk condition
- MIR observations (imaging/spectroscopy) with high spatial resolution
  - helpful to investigate such dust and disk properties directly.
  - 8m Subaru/COMICS observations resolving bright disks of HAEBEs and Vega-like stars

What resolved by MIR observations

- Protoplanetary disks (PPDs)
  - Growth and sedimentation of grains
  - Formation of planetesimals and planets



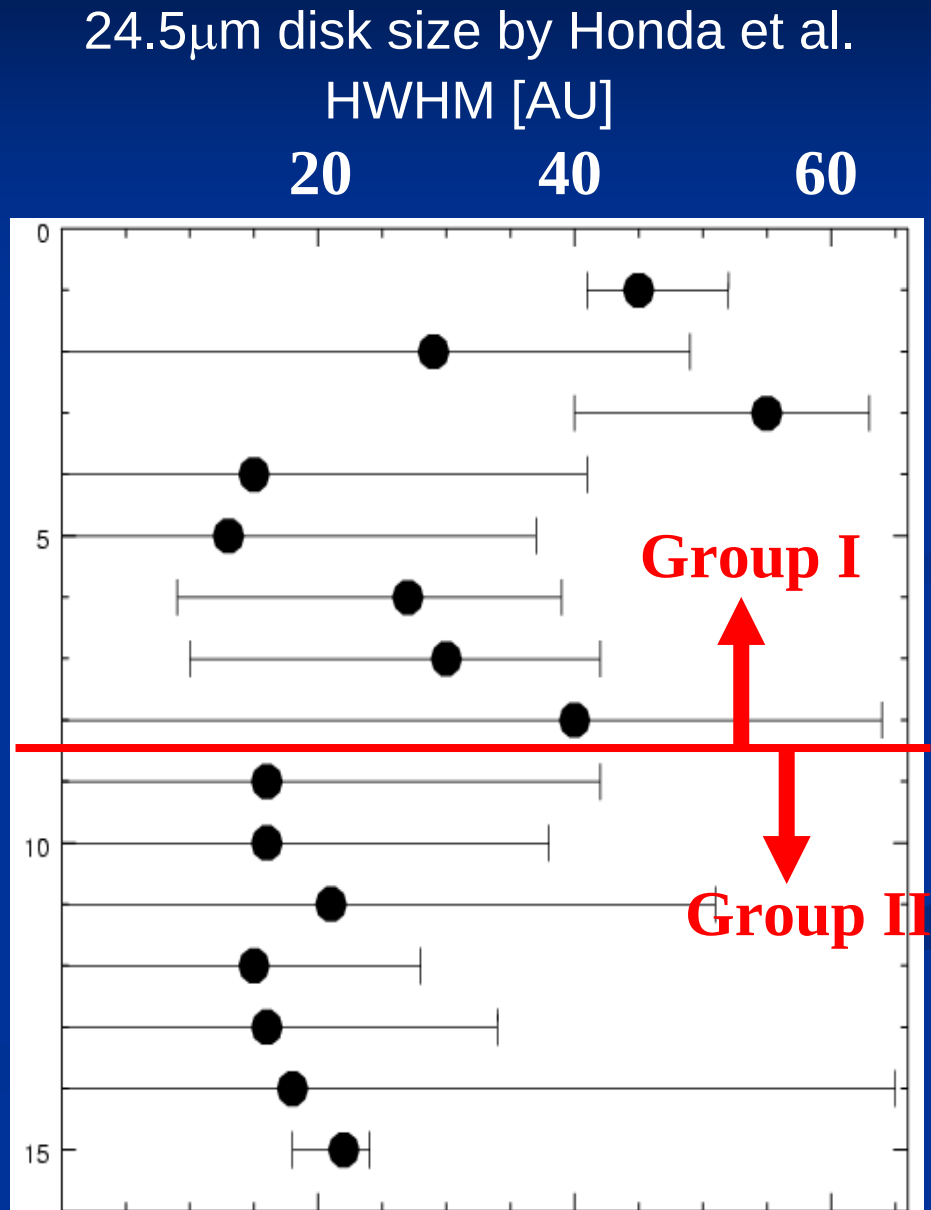
- Debris disks (DDs)
  - Secondary grains replenished from small bodies
  - Planets in the system?

Grains from planetesimal collisions and/or comet evaporation

Grains infalling and/or trapped in resonance orbits

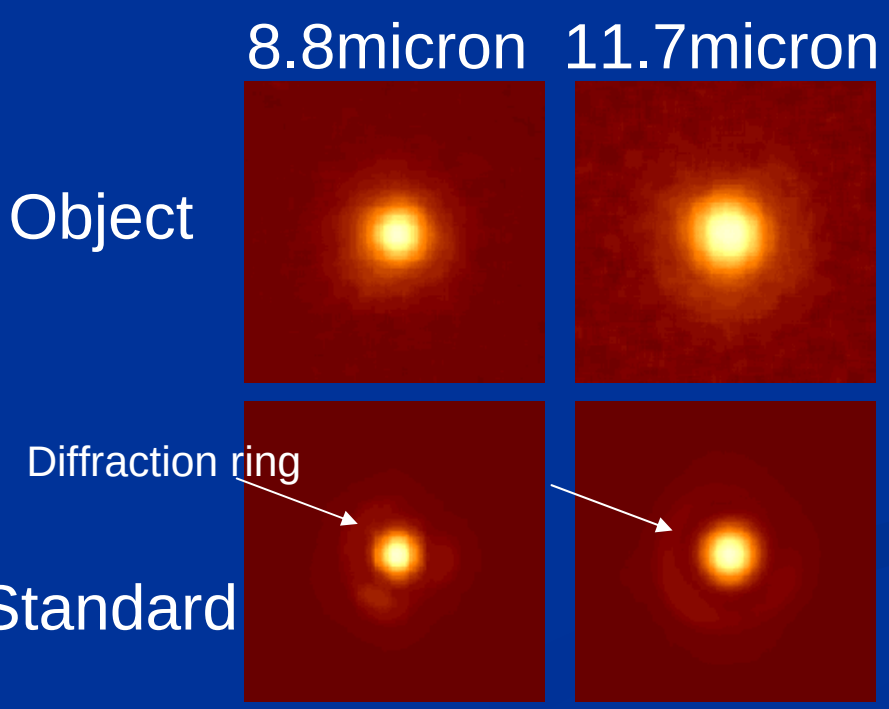
1. High resolution imaging of PPDs

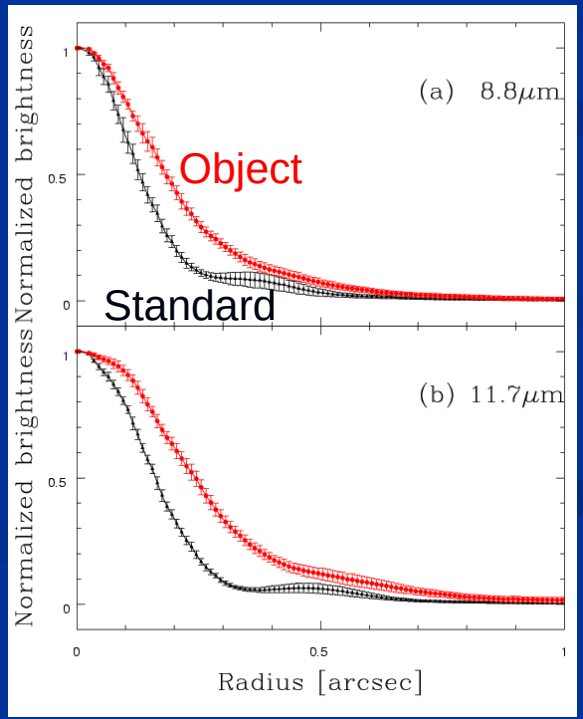
- N(10μm) / Q(20μm)-bands imaging of nearby HAEBEs
  - PSF size:
    - 0.3" for N-band
    - 0.6" for Q-band
  - T structure of disks through size of effectively heated disk atmosphere
    - N-band for ~300K
    - Q-band for ~150K
- 24.5μm images (Honda et al. PPV, also in prep)
  - Group I tend to be extended



- Imaging at 8.8 and 11.7μm (Okamoto et al.)
  - 8.8: continuum + 8.6μm PAH, 11.7: mainly continuum

  →HAEBEs are extended even in the 10μm region
  - Group I tends to have extended emission
    - 4/6=66%, Typical size r~ 5 to a few tens AU
  - Group II tends to have no extended emission (0/4=0%)
- The results suggest that the group I HAEBEs have disk atmosphere extended to larger radii than group II disks.

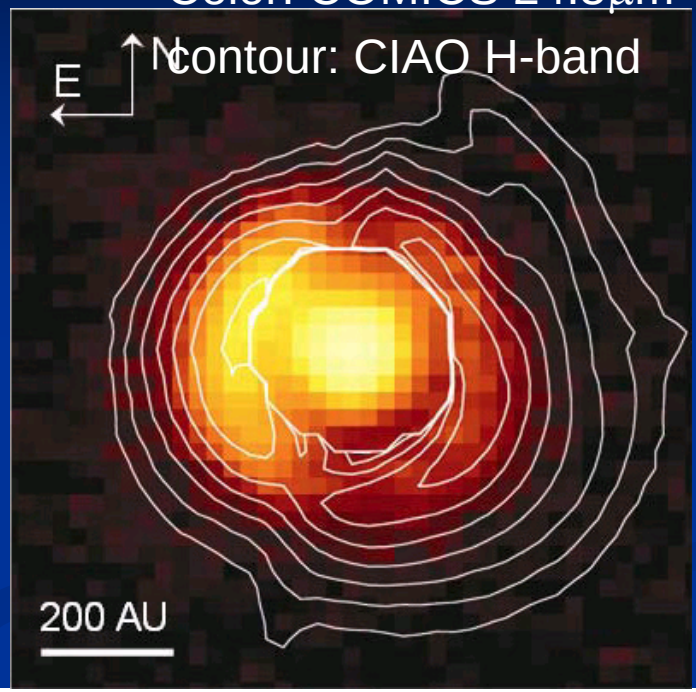


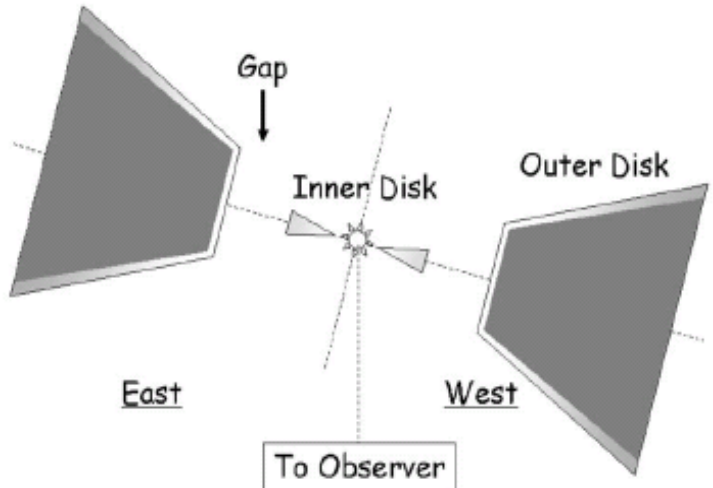


24.5μm image of HD142527

(Fujiwara et al. 2006)

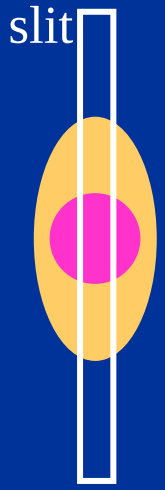
- COMICS image resolved the cool outer disk of this group I HAEBE
  - Gap between the inner and the outer disks
    - r~0.85" (170AU) for outer component
  - Larger τ for E (0.057) than W (0.018)
- Color temperature from 18.8/24.5μm
  - Almost the same (82-85K)for E and W components
- Inverse flux distribution for MIR against NIR suggests a disk with a gap inclined
  - MIR thermal emission
    - E rim exposed to us, while W rim obscured
  - NIR scattered light
    - Forward-scattered light in the western side

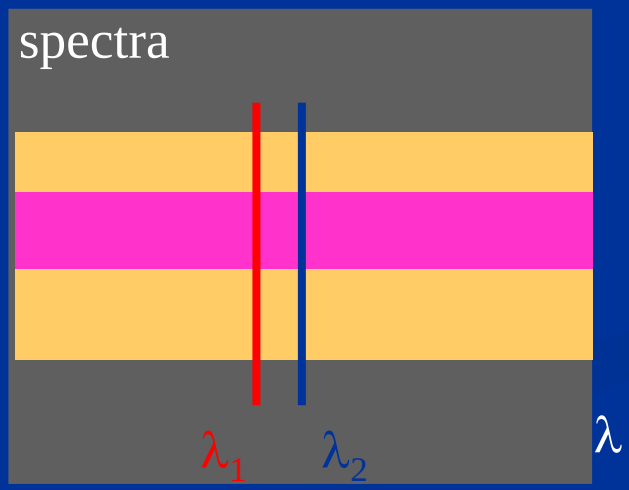


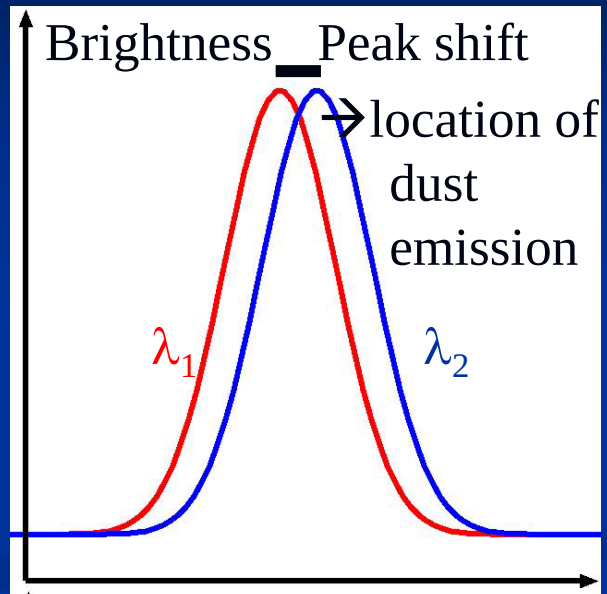


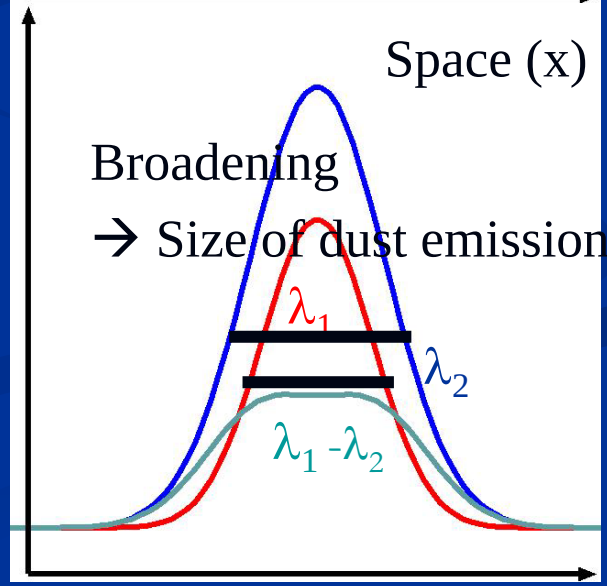
2. High resolution spectroscopy: Spectroastrometry of HAEBE disks

- More sensitive to extended emission than imaging
  - Adjacent continuum can be used as a reference
- To derive spatial extension at each λ
  - Integrate objects relatively long time,
  - Cut the obtained high S/N spectra along slit direction at different wavelengths and compare them



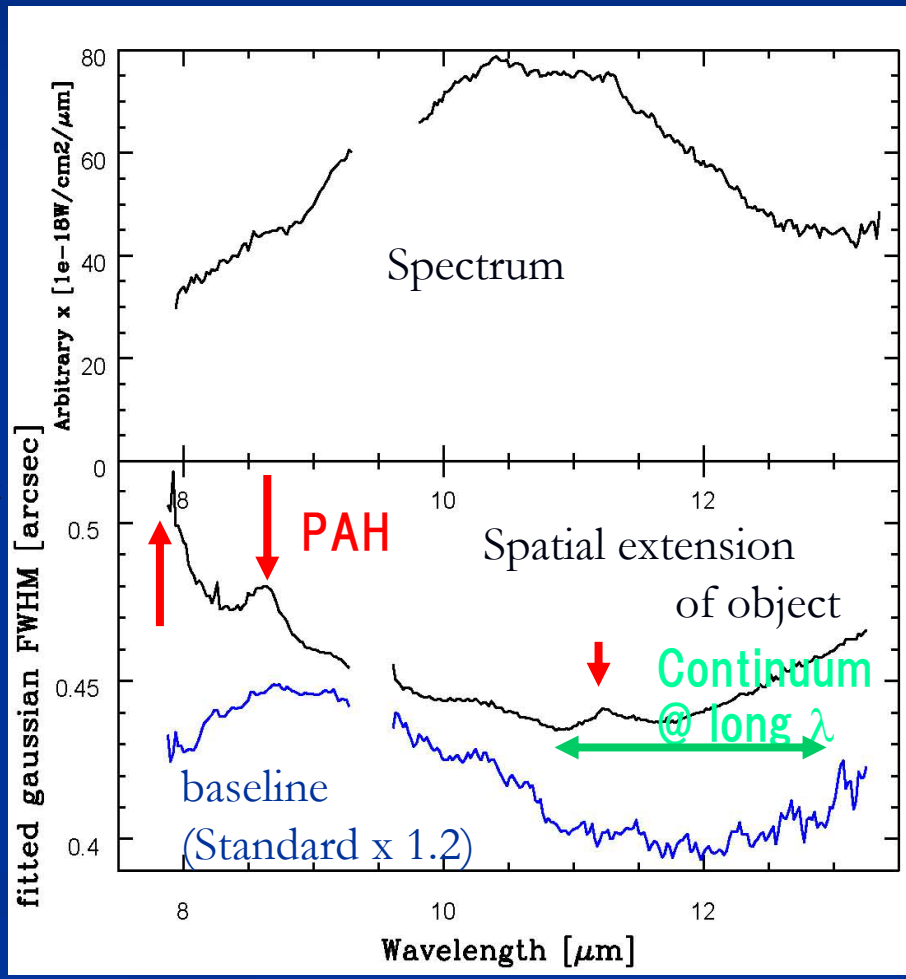






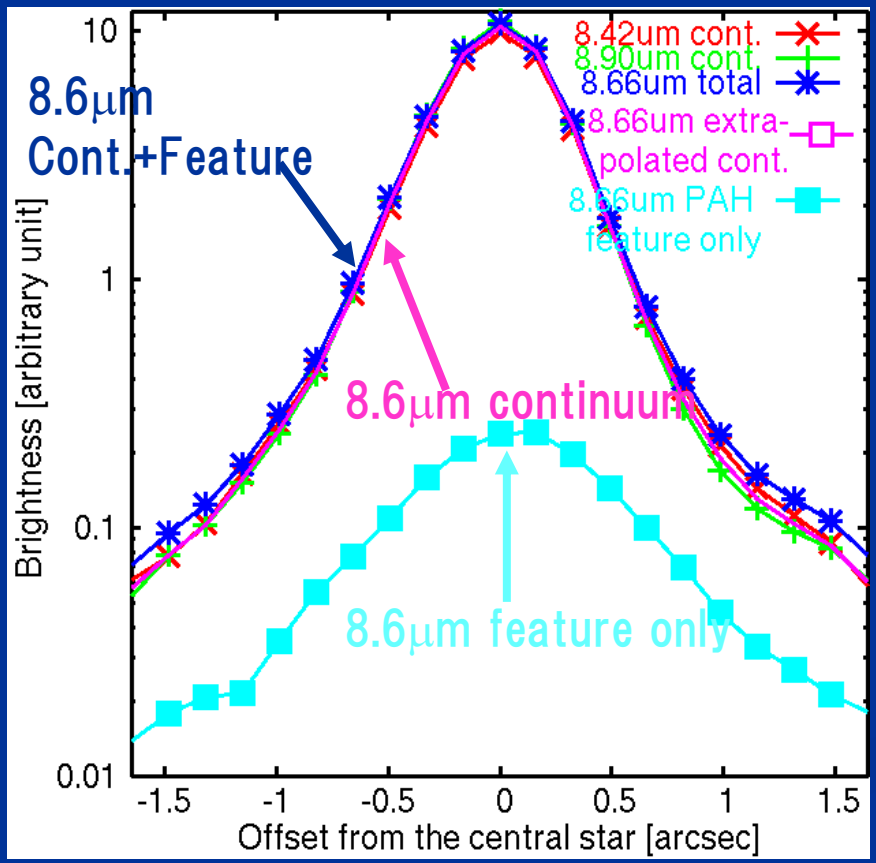
Extended PAH emissions

- Simple fitting with gaussian
  - To detect relatively compact component and/or bright extended emission
  - Fit each spatial profile at each λ with a single gaussian.
  - The gaussian FWHM values are plotted
- Extended emissions of PAHs and continuum at longer wavelengths are clearly seen
  - Up to now, PAH emitting HAEBEs are all resolved in PAH emission
  - This object;
    - r_{PAH} >50AU
    - $r_{13\mu m}$ continuum ~50-60AU



Size of PAH emissions

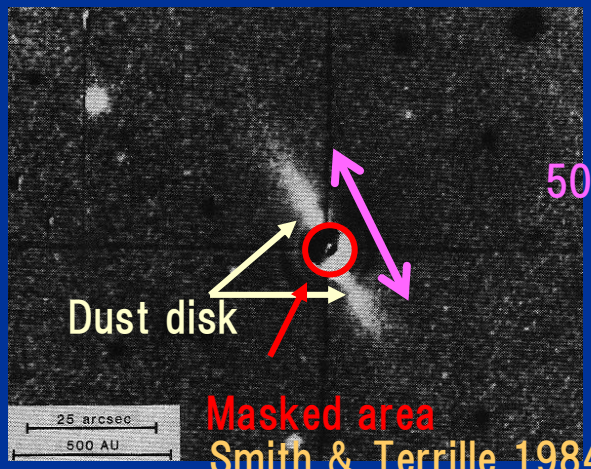
- PAH emission size by deriving feature emission profile
  - Subtracting adjacent continuum profile from the profile at the feature emission



- Larger extended emission than the value suggested by simple gaussian distribution at the former type of reduction.
  - This object:
    - r(FWHM)~120AU for 8.6μm PAH
  - Suggesting diffuse extended distribution
  - Agree with Habart et al. 2004 model
    - Consistent with one UV photon excitation
  - Probe of disk surface well irradiated by UV

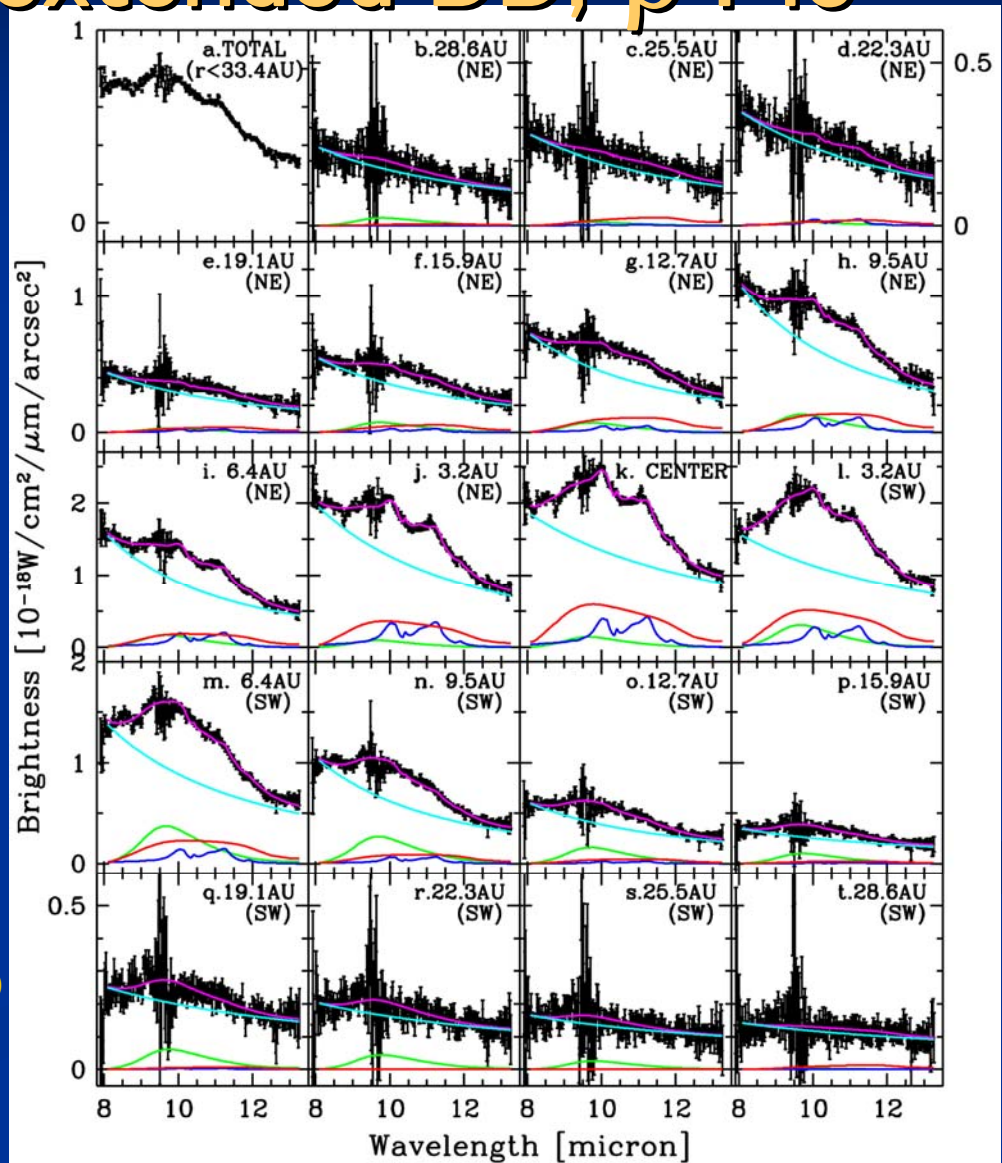
3. High resolution spectroscopy: spectroscopy of extended DD, β Pic

- COMICS N-band long-slit spectroscopy (Okamoto et al. 2004)
  - Reveal silicate dust distribution in planet forming region (<50AU)
  - Obtained spectra fitted with
    - 0.1μm amorphous olivine (green)
    - +2μm amorphous olivine (red)
    - +Crystalline forsterite (blue)
    - +Power-law continuum (cyan)
    - =Total (magenta)



Masked area
Smith & Terrille 1984

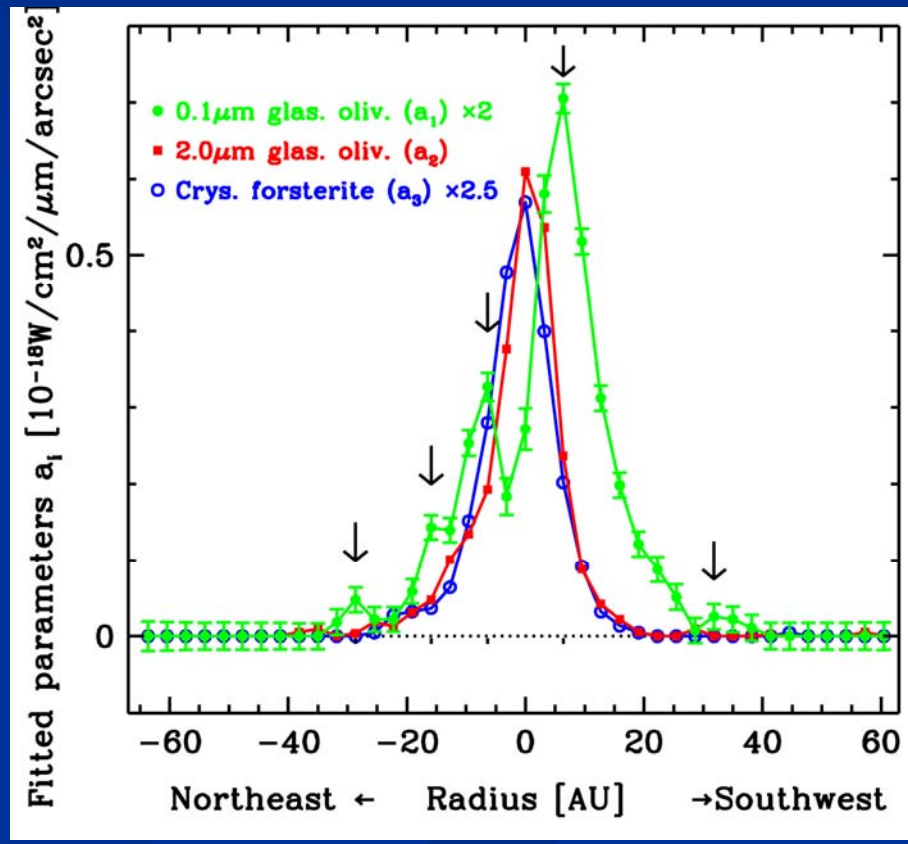
Okamoto et al. 2004, Nature



Distribution of sub-μm grains shows location of dust replenishment

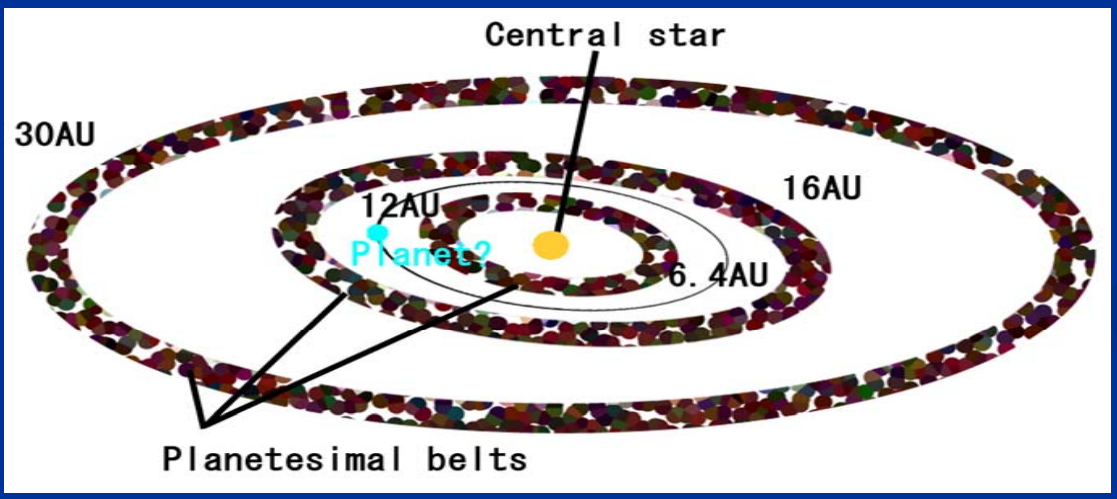
- Small amorphous silicate grains have distribution peaks at 6, 16, & 30AU
- Grains are replenished there.
  - Since such small grains are blown-out by radiation pressure quickly (~10yr).
  - Larger grains replenished there infall toward the star due to PR drag.
  - Near the star, grains are crystallized by heating due to stellar radiation.
- Crystallinity of replenished grains: <10% at 6.4AU

10μm brightness of each silicate feature



Planetesimal belts replenishing grains

- Ring-like planetesimal distributions, or 'planetesimal belts'
  - Like the asteroid belt in our solar system
  - Similar grain masses (of small grains) for each rings (~10^{16}kg)
  - The belts may be in resonance orbits with possible planets



- Grain replenishment rate: >$10^{15\text{-}16}$ kg/yr (for 0.1μm dust)
  - $10^{5\text{-}6}$ times larger than the replenishment rate of zodiacal dust
  - The system is at a violent planetesimal collision stage in an early solar system.

Summary

- Dust distribution in disks have gradually become resolved spatially.
  - PAHs, silicate & continuum emission in HAEBE disks
  - Silicate dust in a debris disk
- Such observations have just start revealing
  - Disk properties such as radiation field and temperature (PPDs)
  - Processes related to planet formation such as heating history and dynamical evolution (DDs)
    - The results on β Pic has revealed existence of planetesimal belts.