Subaru/COMICS view of star and planet formation

Yoshiko K. Okamoto (Ibaraki U)

Collaborators:
H. Kataza (ISAS/JAXA),
M. Honda (Kanagawa Univ.),
H. Fujiwara, I. Sakon, T. Onaka (UT),
T. Yamashita, T. Fujiyoshi (NAOJ),
T. Miyata, S. Sako (IoA, UT)

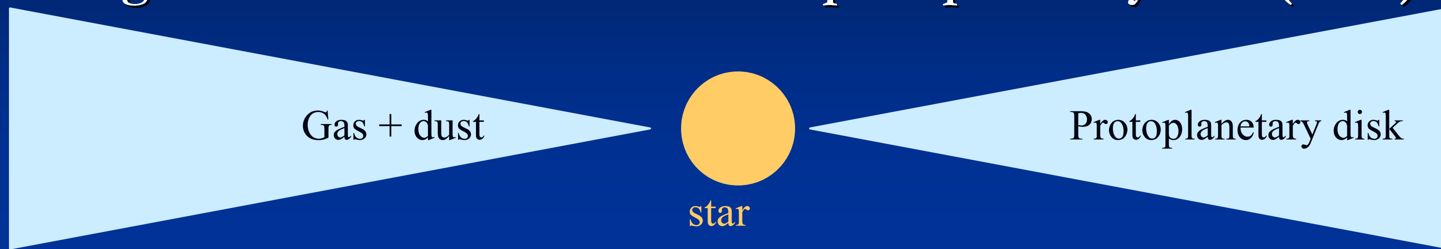
Outline

- Circumstellar disks related to star and planet formation
  - Planet formation in circumstellar disks around low to intermediate mass stars
    - Grain evolution in the disks
    - Structure and dust distribution in the disks
      - Appearance of early planetary systems
  - Disks related to massive star formation
- Summary and Future Prospects

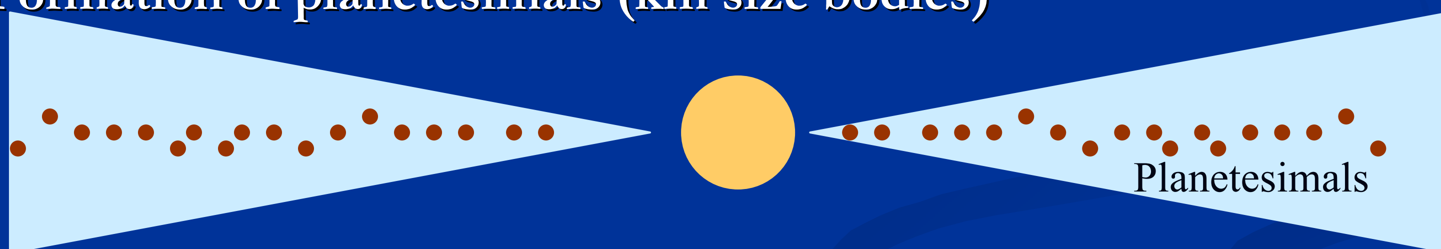
1. Planet formation in circumstellar disks around low to intermediate mass stars

Evolution of circumstellar disks and planet formation

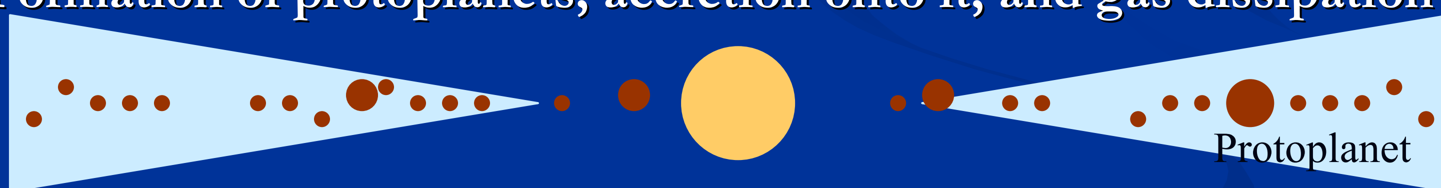
1. Grain growth and sedimentation in a protoplanetary disk (PPD)



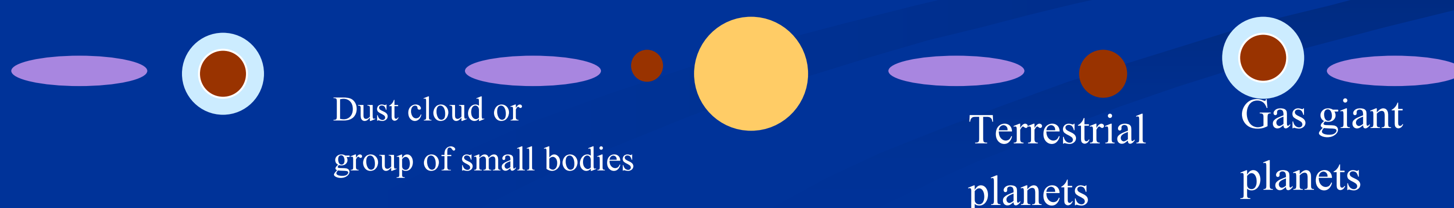
2. Formation of planetesimals (km size bodies)



3. Formation of protoplanets, accretion onto it, and gas dissipation



4. Planetary system – main sequence star sometimes w a debris disk (DD)

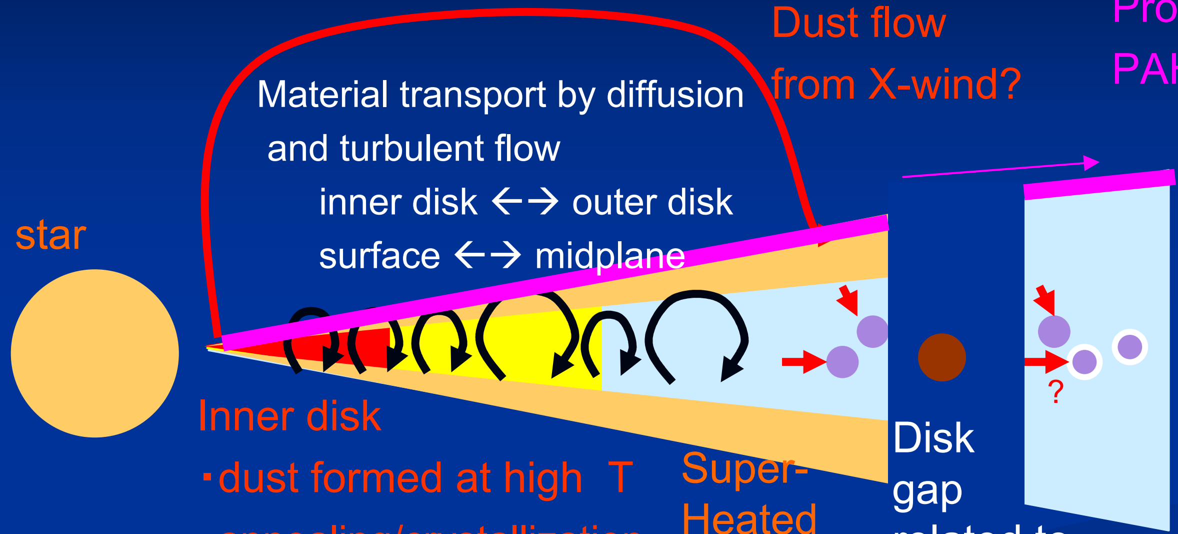


Dust processes in the disks

Dust in protoplanetary disks – change from the ISM dust

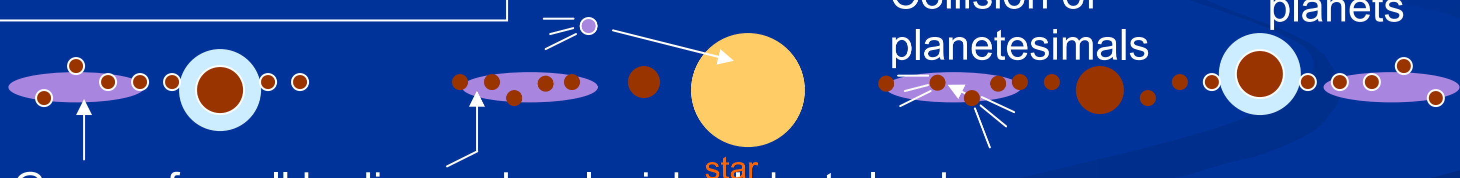
Dust flow from X-wind?

Probing the disk geometry w PAH emission which can be excited out to >100AU by the direct stellar UV



- Grain growth/sedimentation
- Flatening of disk
- Planetesimal formation
- Increased speed of grain growth due to ice outside of the snowline

Dust in debris disks
-replenished dust



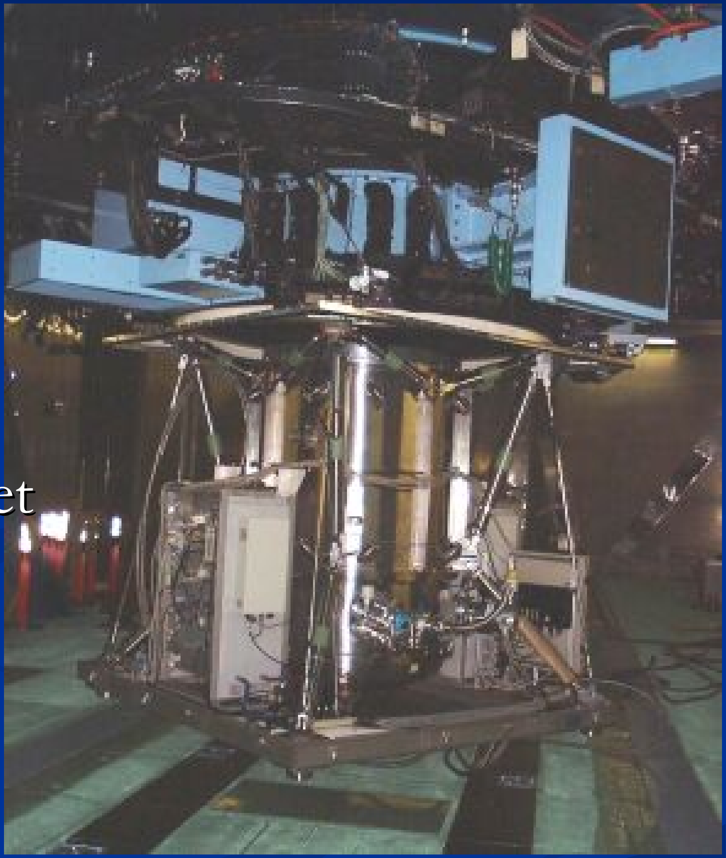
Group of small bodies and replenished dust cloud

- Dust dynamics dominated by radiation pressure, Poynting-Robertson drag, and resonance with planets

Observing disk dust w Subaru/COMICS

- Powerful to study dust processes
  - MIR imaging and spectroscopy w a slit viewer @10/20μm regions
  - Diffraction limited resolution (0.3”@10μm)
    - Observation/Reduction techniques are developed
    - Resolving bright circumstellar disks
  - Probe inner disks corresponding to planet forming region (<~50AU)
  - Many dust features in the MIR

    → Species, composition, temperature, size, crystallinity, and environment of grains
  - High sensitivity



→ Many disk observations

- grain evolution, disk structure, dust distribution in the disks

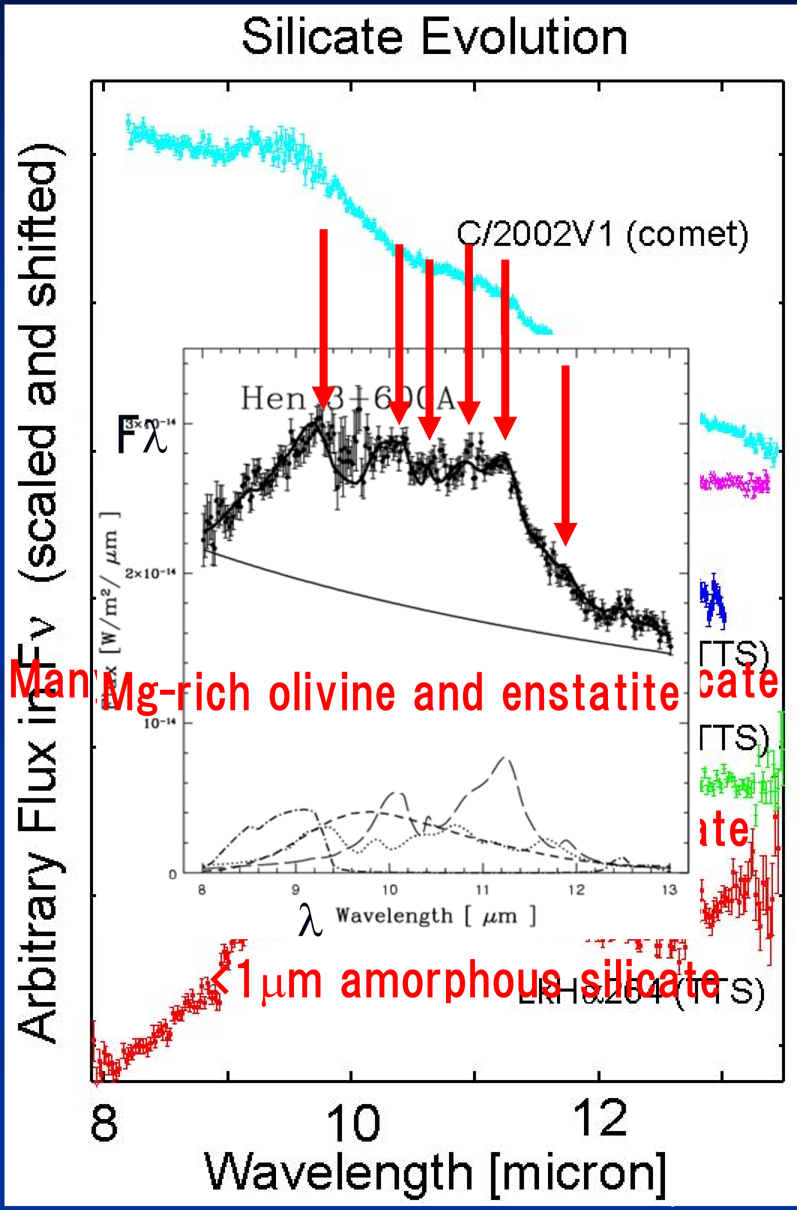
1.1 Grain evolution in the disks

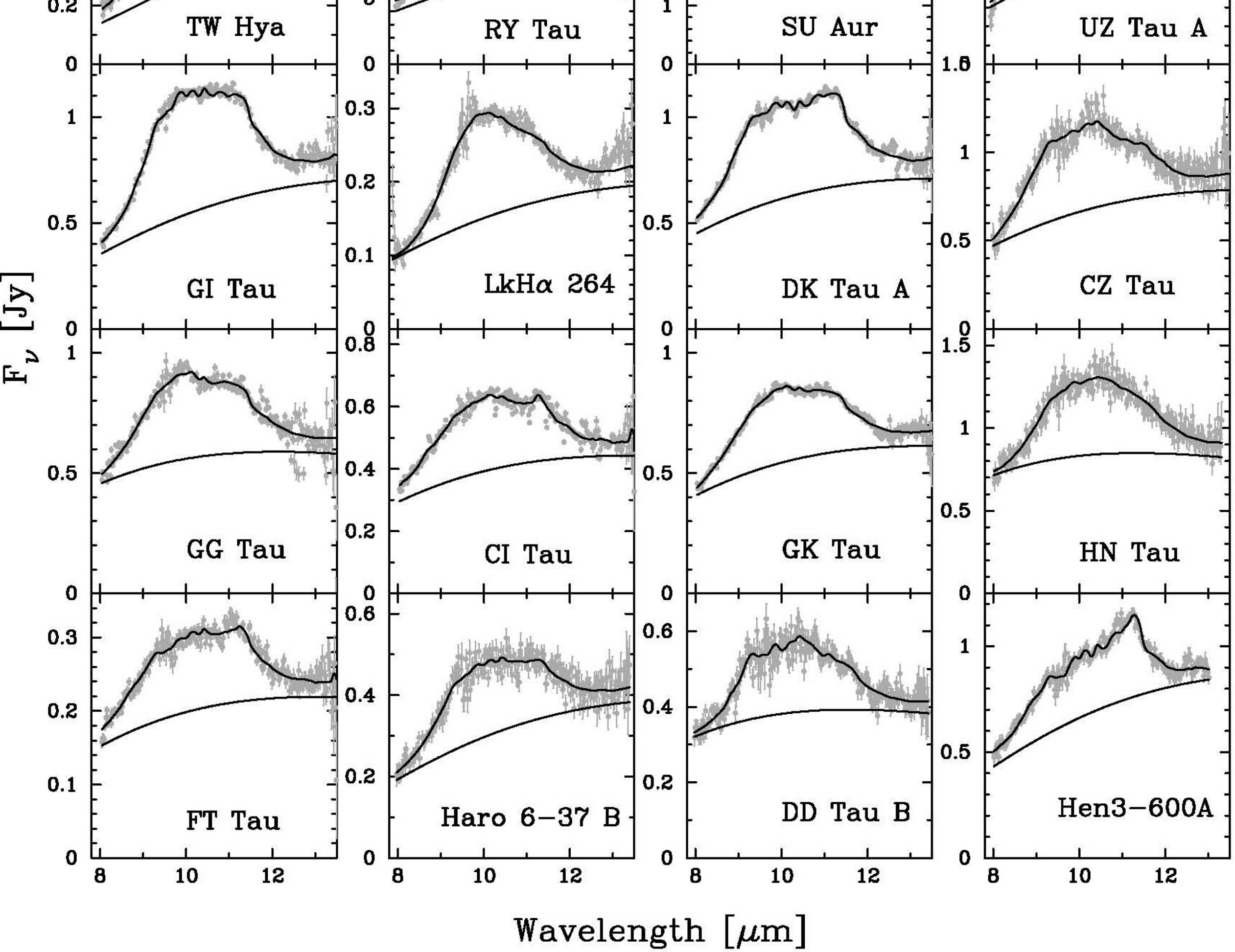
- Silicate features sensitively depend on
  - Grain size
  - Crystallization (T>~800K)
  - Composition
- Observing the silicate features in the disks is probing the grain evolution in the disks

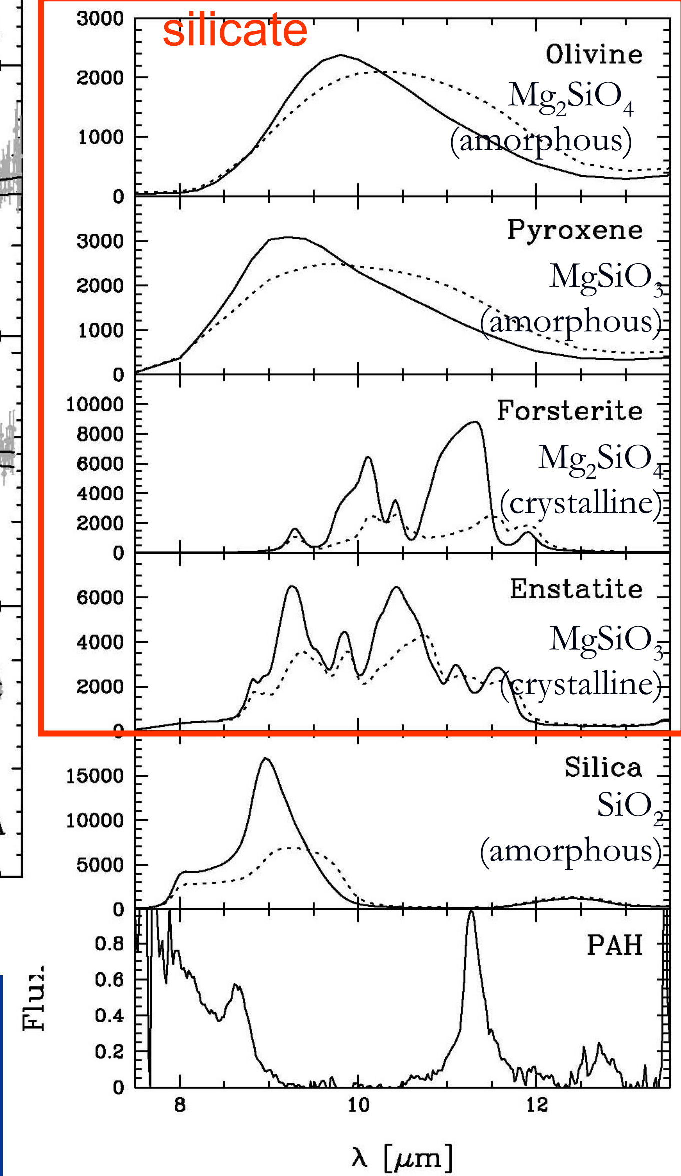
Evolution of silicate grains in TTS disks (Honda+2006)

- R~250 spectroscopy in the 10μm region of disks around 30 young low-mass stars
  - Grain growth
  - Crystallization related to high T processes

Drawn by using data observed with COMICS







- Composition analysis by spectral fitting

$$F_\nu(\lambda) = B_\nu(T,\lambda)\left\{ a_0 + \sum_{i=1}^{5} \sum_{j=0.1,1.5\ \mu\mathrm{m}} \left[a_{i,j}\kappa_{i,j}(\lambda) \right] \right\} + a_{\mathrm{PAH}} F_\nu^{\mathrm{PAH}}(\lambda),$$

$$f_{i,j}[\%] = \frac{100 a_{i,j}}{\sum_{i=1}^{5} \sum_{j=0.1,1.5\ \mu\mathrm{m}} a_{i,j}}.$$

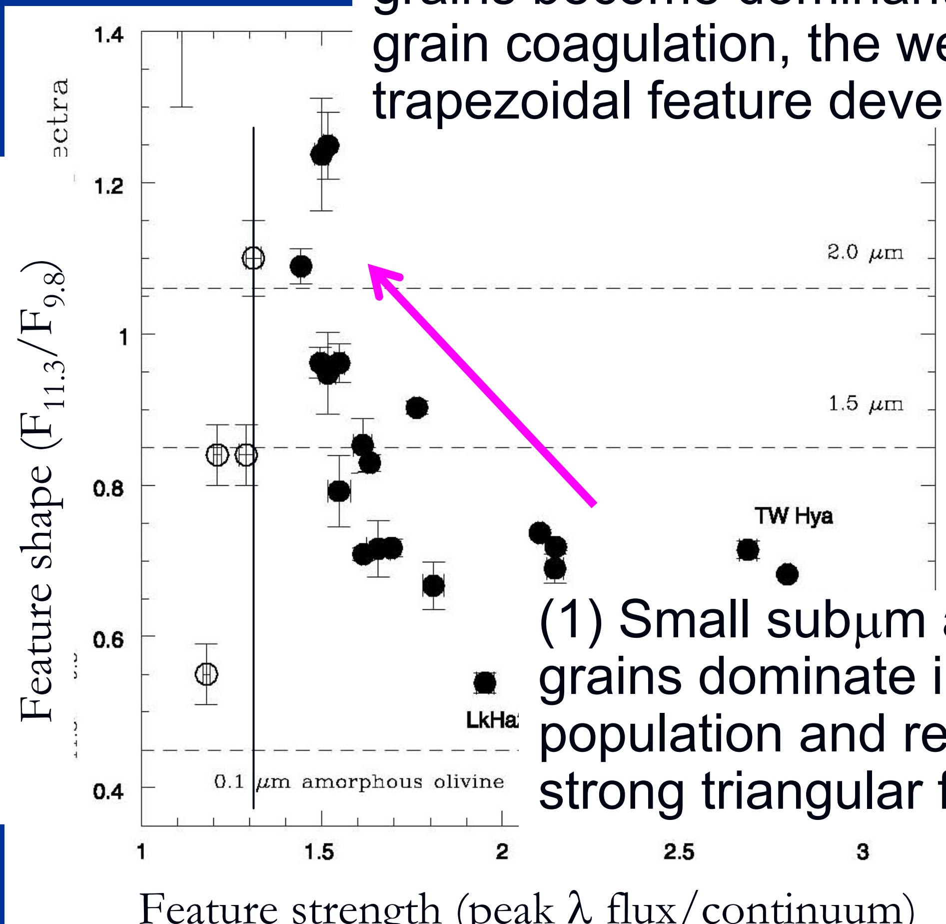
van Boekel+2005. For silicate, 0.1μm radius grains (solid lines) and 1.5μm radius grains (dotted lines)

- Correlation
  - between the feature strength and the feature shape
  - between the feature strength and the fraction of the big grains

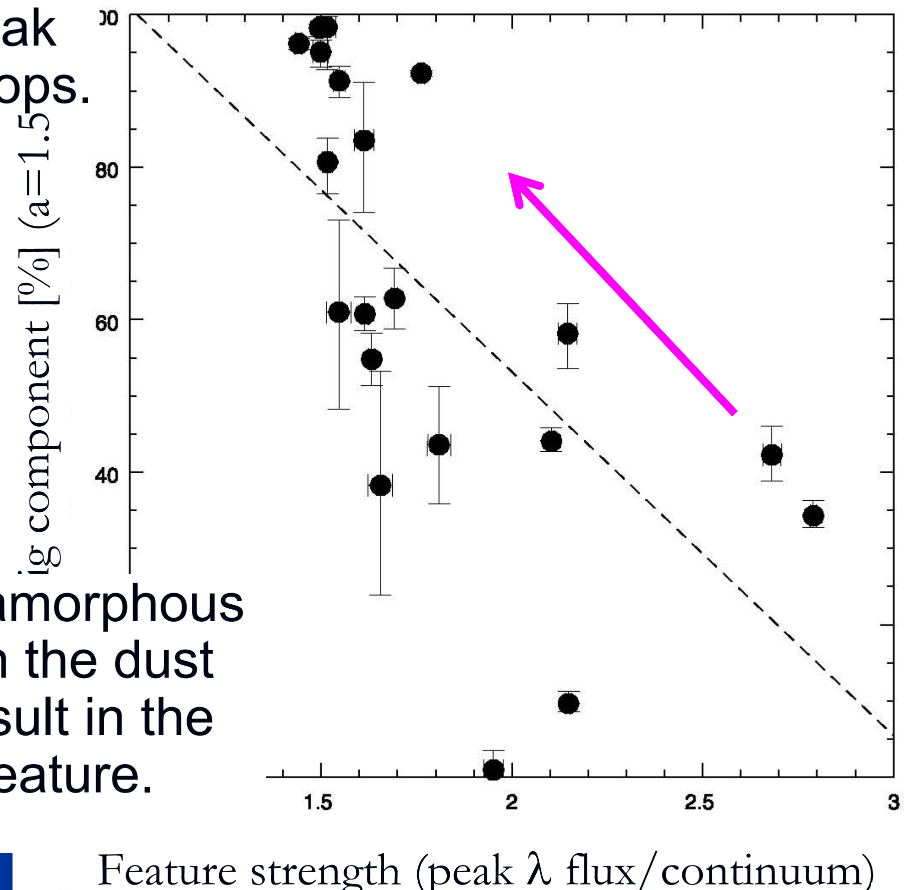
→ Suggesting grain growth

2) When large amorphous grains become dominant by grain coagulation, the weak trapezoidal feature develops.

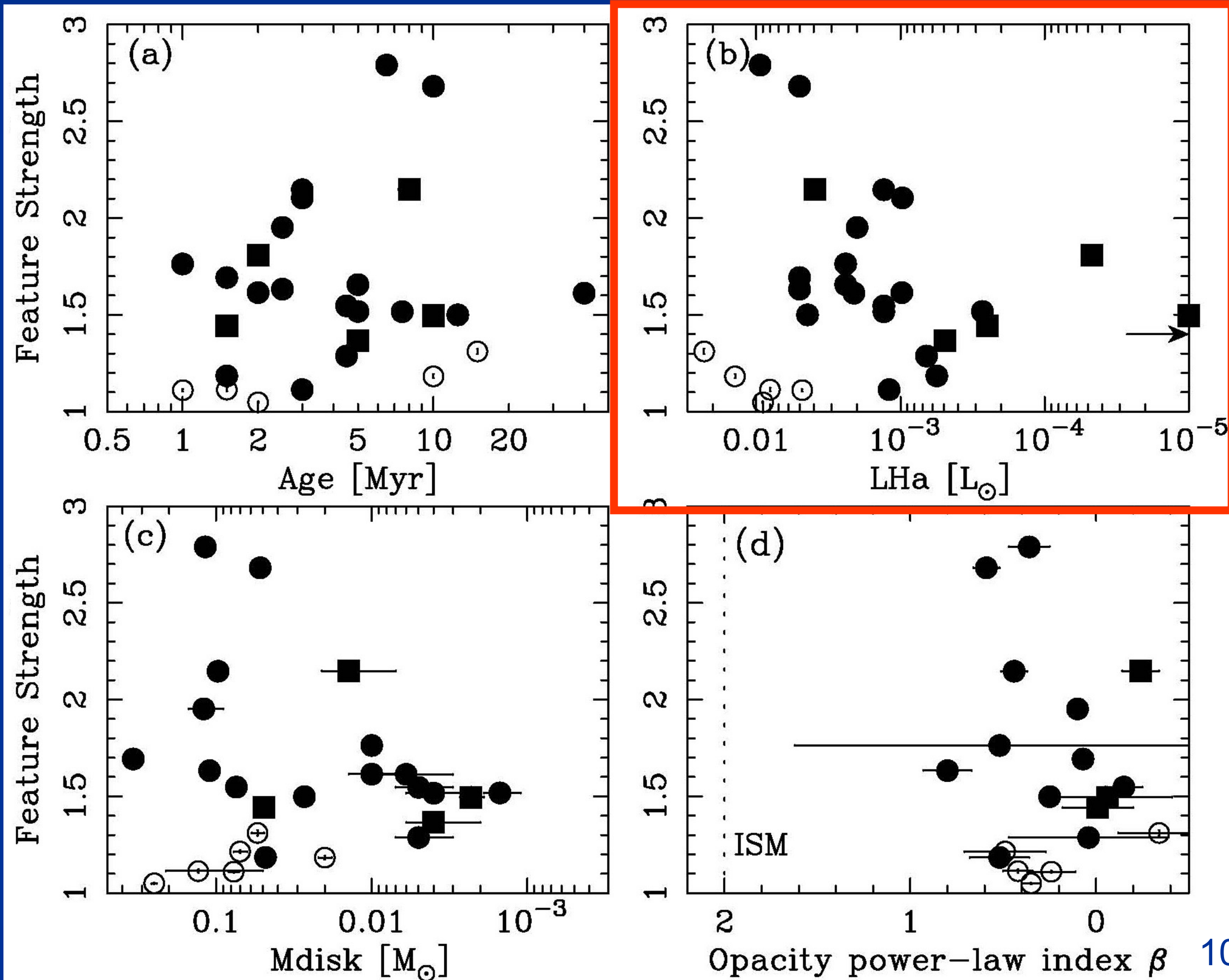
3) The feature vanishes when grains smaller than a few microns are depleted.



(1) Small subμm amorphous grains dominate in the dust population and result in the strong triangular feature.



- Relation between the dust and the stellar or disk properties
  - Silicate dust properties
    - Feature strength or crystalline fraction
  - Stellar or disk parameters
    - L(Hα) as an indicator of accretion activity
    - opacity power-law index β in the radio which probes the grain growth in cold regions
    - stellar age from HR diagram
    - M_{disk} from the radio
- Only correlation we found is between the feature strength and the L(Hα)



- Correlation between the feature strength and L(Hα)
  - The depletion of small sub-μm grains occurs as accretion activity ceases
    - Turbulence in the disks stirs the grains up to the surface layer and might make the small grains detectable during the active accretion
- No correlation between the feature strength and β
  - The timescale of the dust evolution differs between warm and cold regions
    - Rapid grain growth to mm-sizes
    - Rapid sedimentation of the grown dust grains to the midplane occurs

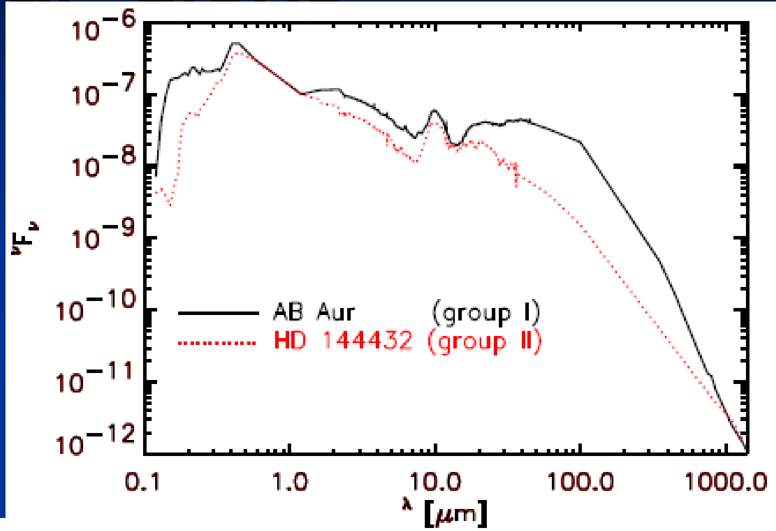
    → completing β evolution at an early TTS phase
- No correlation between the crystallinity and the stellar/disk evolution
  - 5-20% crystalline grains are regularly present in PPDs from young to old TTSs

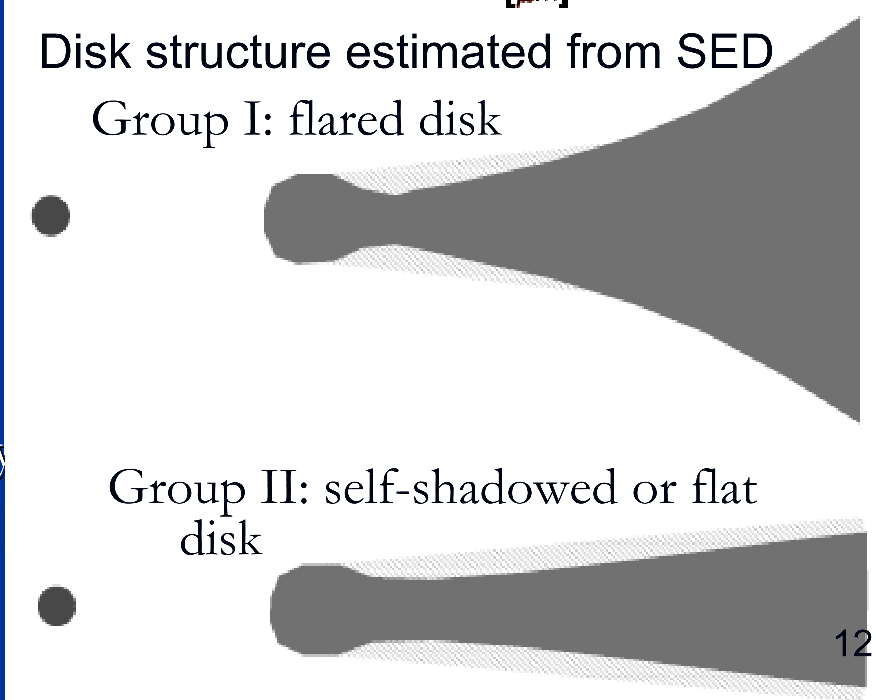
    → Crystallization of this level has completed at a very early stage of or before the TTS phase (probably at protostar and/or FU Ori stages)
  - Consistent with model calculation including radial material transport, which expects that the crystallinity comes in equillibrium within $\sim 10^6$yrs

1.2 Structure and dust distribution of the circumstellar disks

- Size of warm region is closely related to the disk geometry
  - Larger for the disks well irradiated by the stellar radiation to the outer regions
- High resol. imaging survey of disks in the 10 and 20μm-bands for nearby HAEBEs (Okamoto+2005; Honda+2005)
  - Direct test for the thermal structure estimated from SED
  - ~300K~150K region w 0.3-0.6” PSF
- Group I disks tend to be extended
  - In size or in the fraction of extended samples

  → roughly consistent with the prediction by SEDs but there is variety



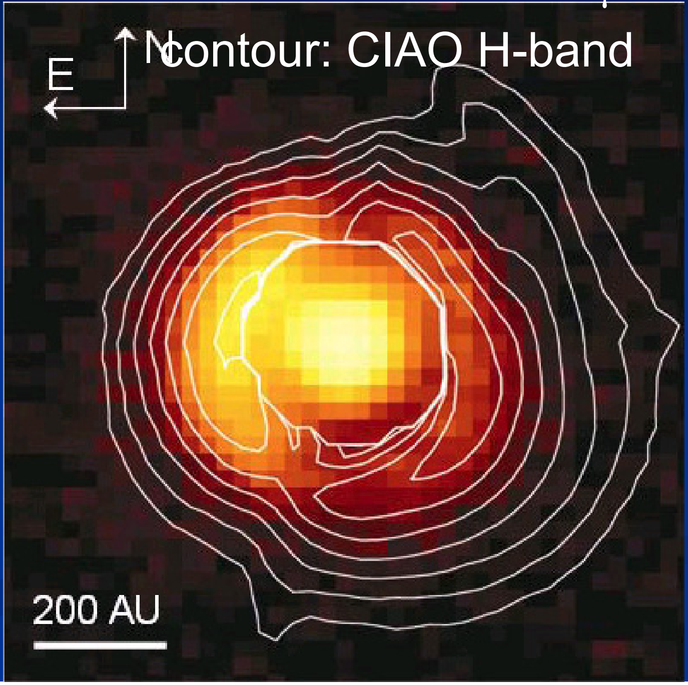


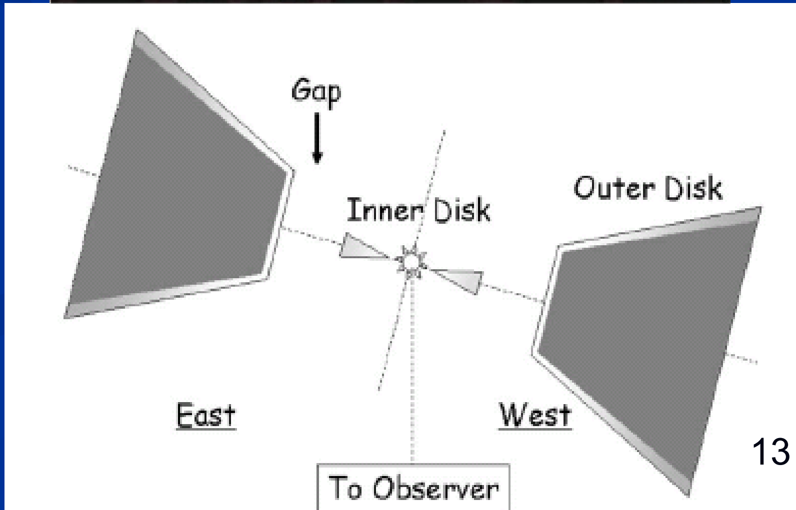
24.5μm image of HD142527

(Fujiwara+2006)

- COMICS image resolved the cool outer disk of this group I HAE
  - 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

Color: COMICS 24.5μm

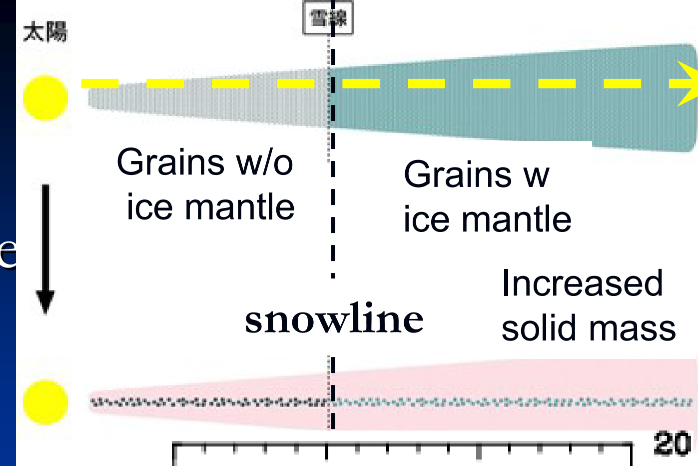


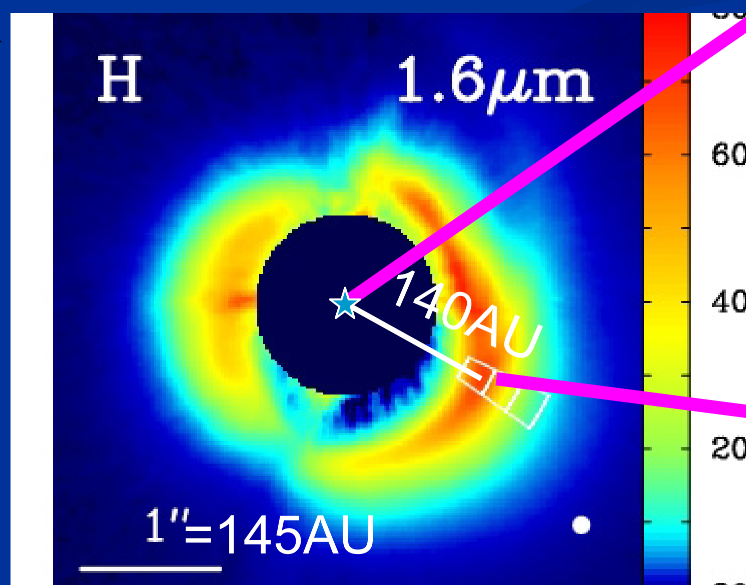


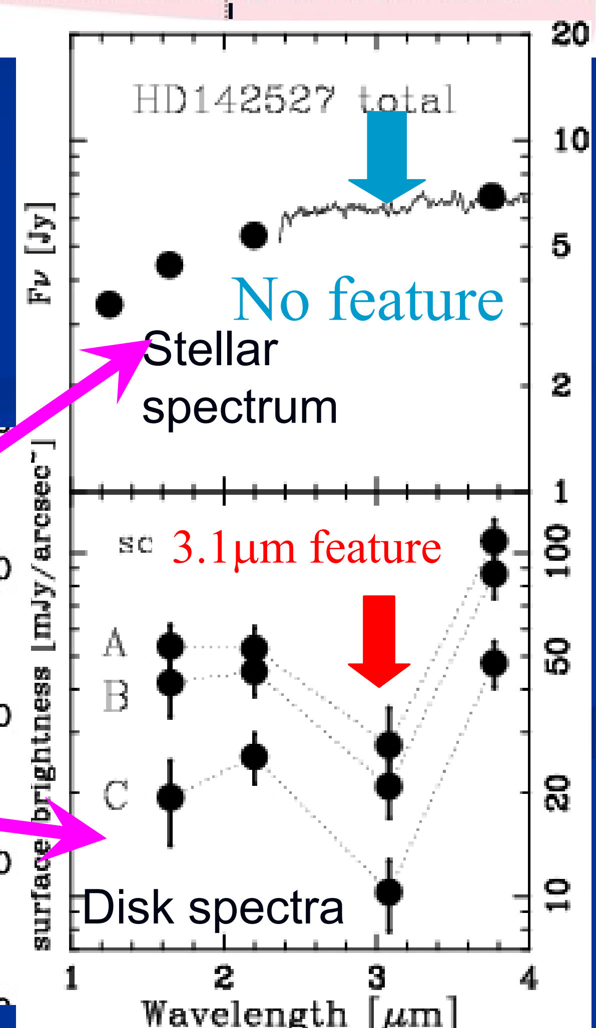
H_2O ice in HD142527 disk

(Honda+2009, poster)

- Ice condensation increases solid mass outside the snowline
  - It helps formation of cores of gas giant planets
  - The radial distribution is important
- Coronagraph multi-band imaging of HD142527 w Subaru/CIAO
  - At H (1.6μm), K (2.2μm), H_2O (3.08μm), L' (3.8μm)
- The 1st detection of H_2O ice absorption at 3.1μm in the scattered light spectra
  - H_2O ice is ubiquitous at the observed region (R>140AU)





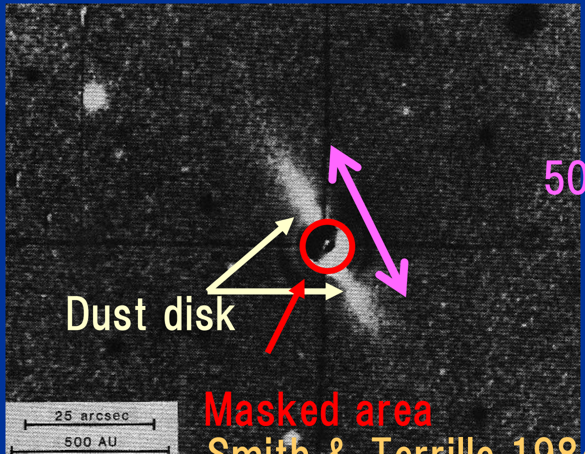


High spatial resolution spectroscopy of the extended debris disk β Pic

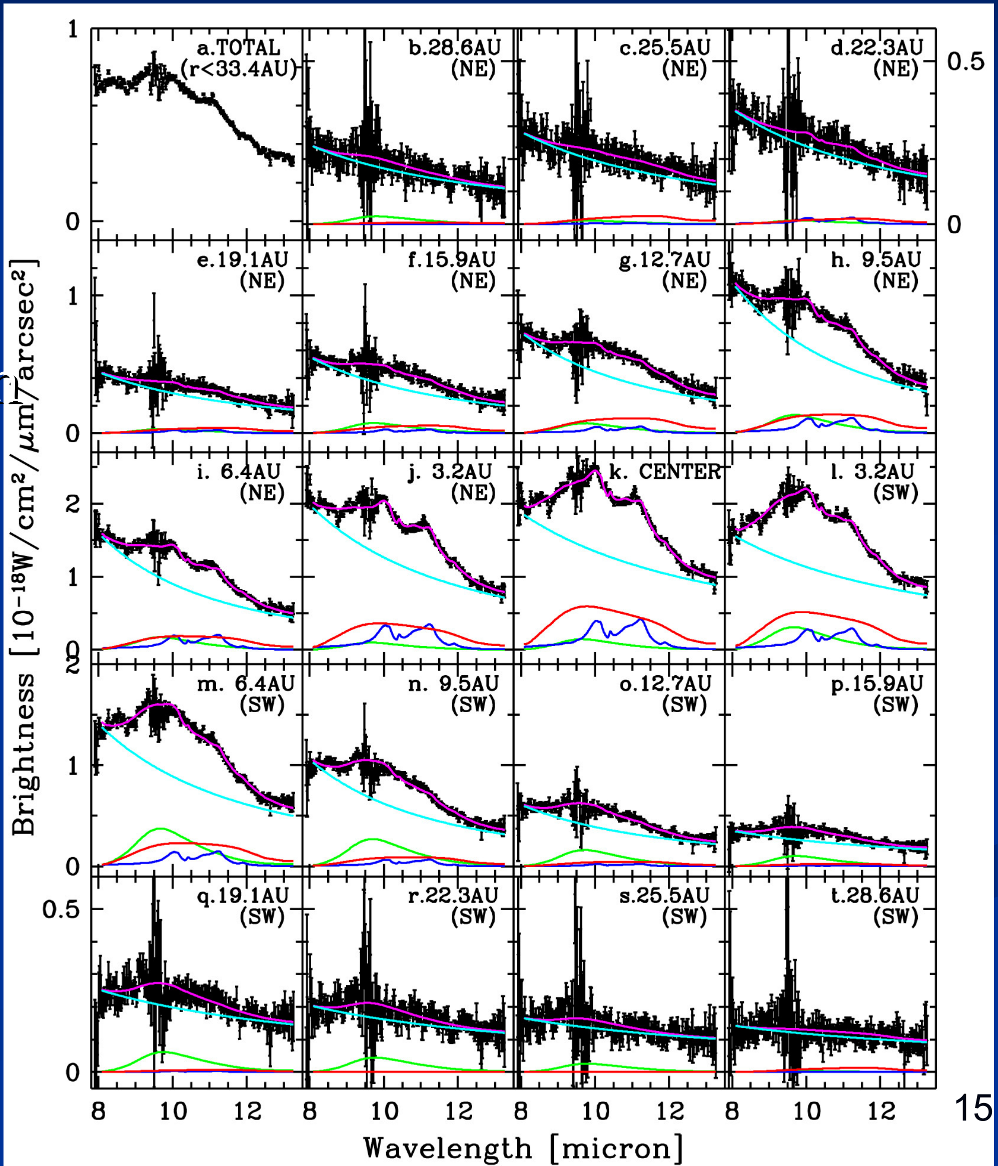
(Okamoto+2004)

- Study of the 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)



Smith & Terrille 1984

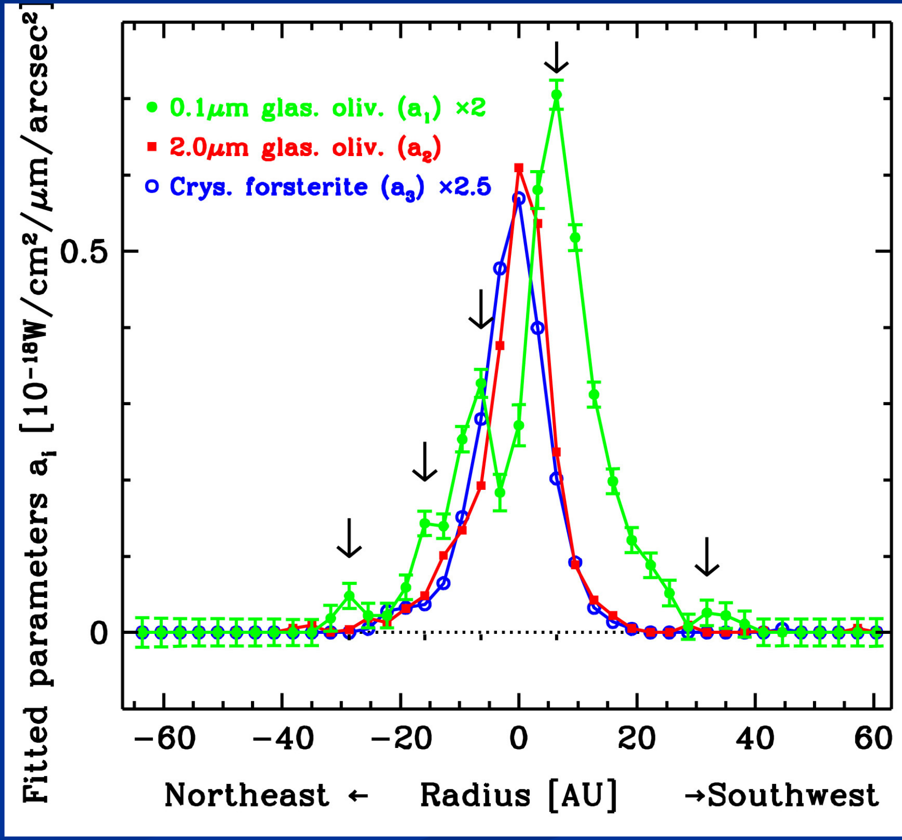


Okamoto et al. 2004, Nature

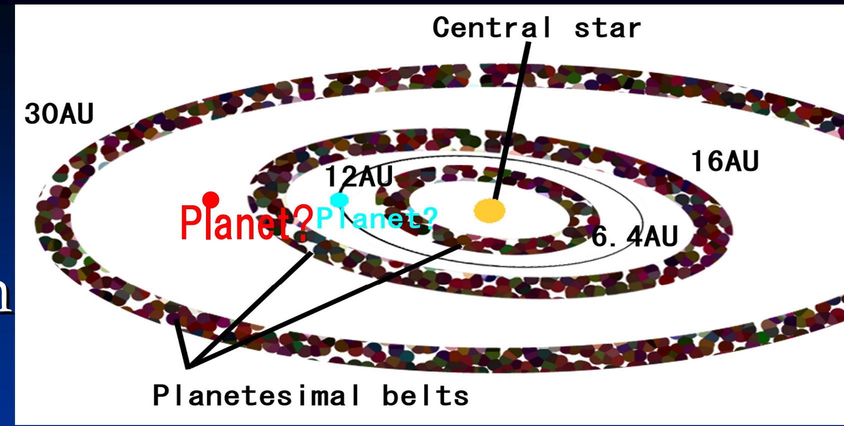
Distribution of sub-μm grains shows location of dust replenishment

- 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.

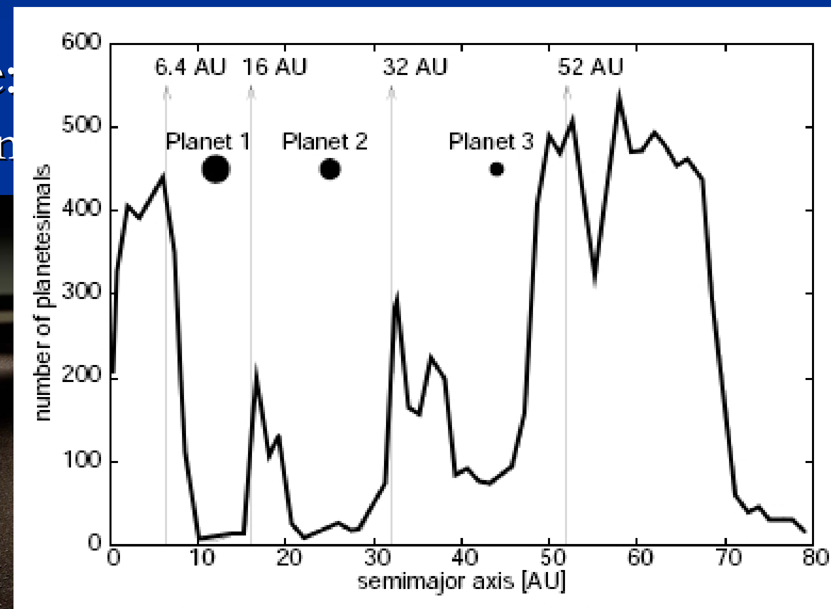
10μm brightness of each silicate feature



Planetesimal belts replenishing grains



- Ring-like planetesimal distribution
  - Grain replenishment: $10^{15\text{-}16}$kg/yr
    - $10^{5\text{-}6}$ times larger than that of zodiacal dust
  - The belts seem to be in resonance:
    - We predicted that they are in resonan with planets
- Confirming simulations (Freistetter+2007)
  - 2-5M_J planet at 12AU, e<~0.1
    - Warp, 6&16AU belts, FEBs
  - Two more at 25 & 45 AU likely
  - Planet masses are estimated
- Lagrange+2008
  - Direct detection of 8MJ planet at ~8AU?



Planet	m $[M_J]$	a [AU]	e
1	$2.0^{+3}_{-0.5}$	12 ± 0.5	$0.01^{+0.1}_{-0.01}$
2	0.5 ± 0.1	25 ± 1	$0.01^{+0.05}_{-0.01}$
3	$0.1^{+0.1}_{-0.03}$	44 ± 1	$0.01^{+0.05}_{-0.01}$

2. Formation of Massive Stars

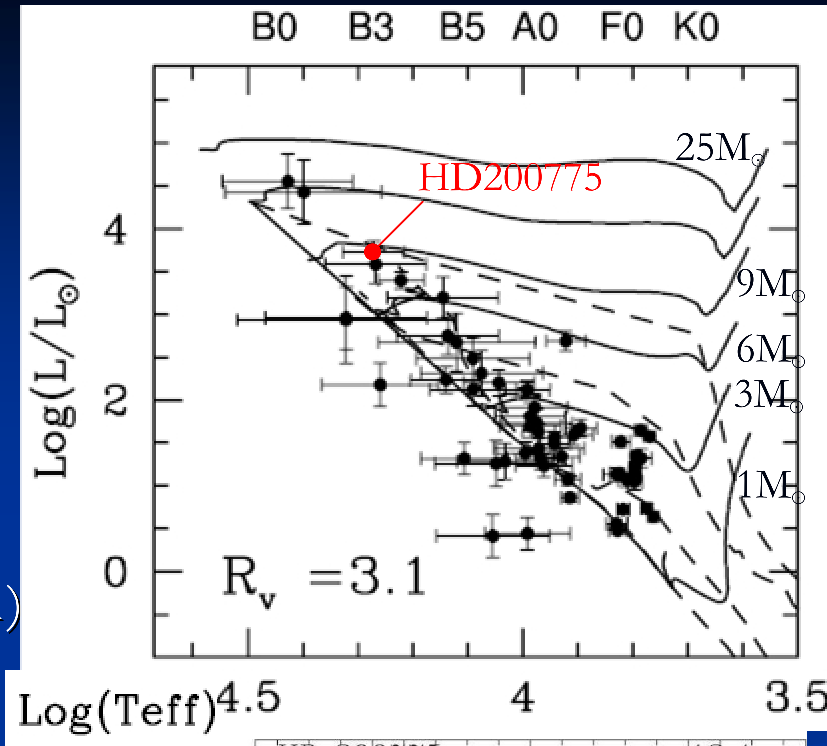
Disks and massive star formation ($\geq 8M_{\odot}$)

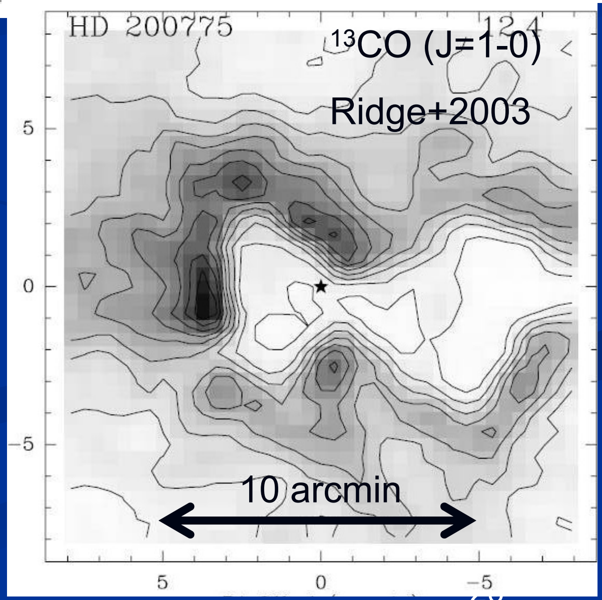
- Massive star formation is much less understood than the formation of lower mass stars
  - For very massive stars (a few tens $M_{\odot}$), radiation pressure of the forming star may stop the accretion onto the forming star.
  - Rapid evolution and formation in cluster
    - difficult to see the forming massive stars very clearly and separately
  - Accretion through disks or merging of lower-mass stars?
    - There are about a dozen of disk candidates around massive YSOs up to $M_{*}\sim 10\text{-}20M_{\odot}$ stars
    - Interferometric observations at mm and sub-mm wavelengths
    - Rotating gas fragments with velocity gradient perpendicular to the outflow
    - Little clear disk image in the infrared regions so far
      - In contrast with the situation for the lower-mass stars

Discovery of a disk around HD200775

(Okamoto+ submitted)

- HD200775
  - d=430 $^{+160}_{-90}$ pc (Hipparcos)
  - Herbig B3 (±1) e star
    - Based on optical lines (Hernandez+2004)
    - 5400$L_{\odot}$ (if Rv=3.0) to 15000$L_{\odot}$ (if Rv=5.1)
  - Exciting star of the reflection nebula NGC7023
    - Located near the center of the E-W extending outflow cavities seen in the CO and FIR
  - Closed binary (Pogodin+2004; Monnier+2006)
    - Semi-major axis 15mas=6.5AU@430pc
    - M1+M2=10.4 $M_{\odot}$, M1/M1+M2=0.825
  - Binary of two massive stars ?(Alecian+2008)
    - 10.7±2.5 $M_{\odot}$ + 9.3±2.1 $M_{\odot}$

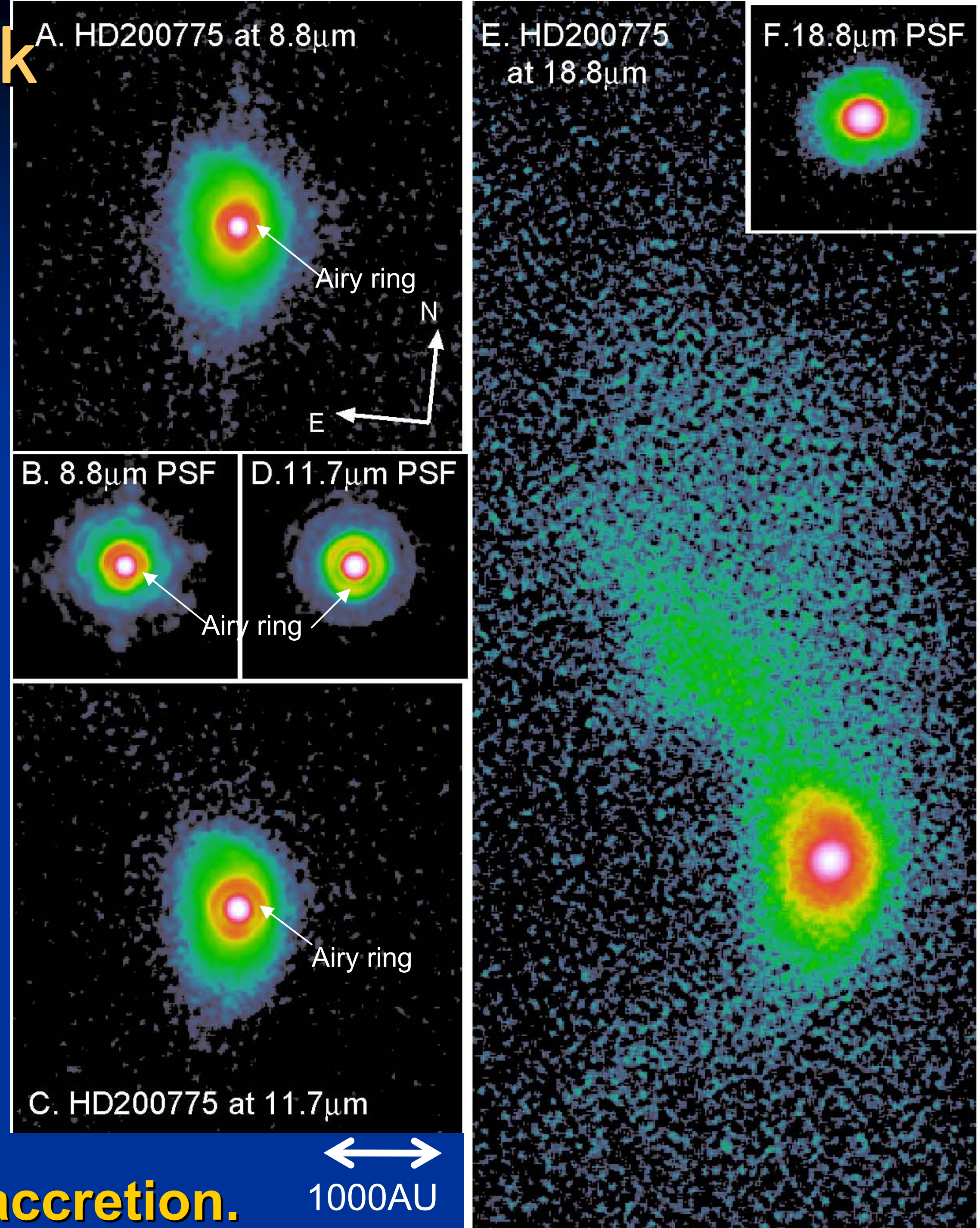




N-S extending disk emission

- Unresolved peak emission + diffuse elliptical emission
  - Likely inclined circumbinary disk
- Perpendicular to the outflow cavity
- Parallel to the projected major axis of the closed binary orbit
- 750~1000AU in radius
  - Similar to the radius of disk (candidates) around massive YSOs and lower-mass stars

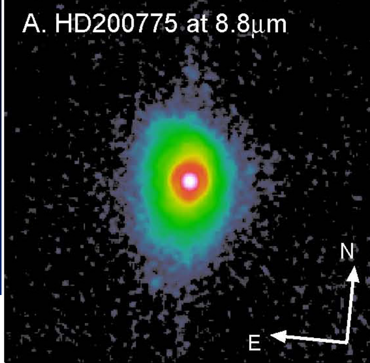
→ 1^{st} detailed IR disk image around $\sim 10 M_{\odot}$ star

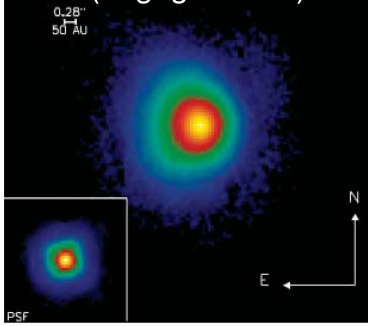


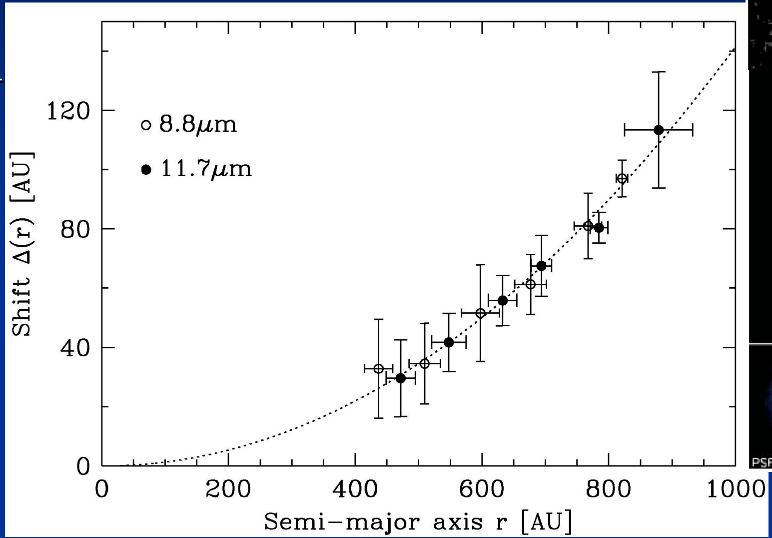
HD200775 seems to have formed through the disk accretion.

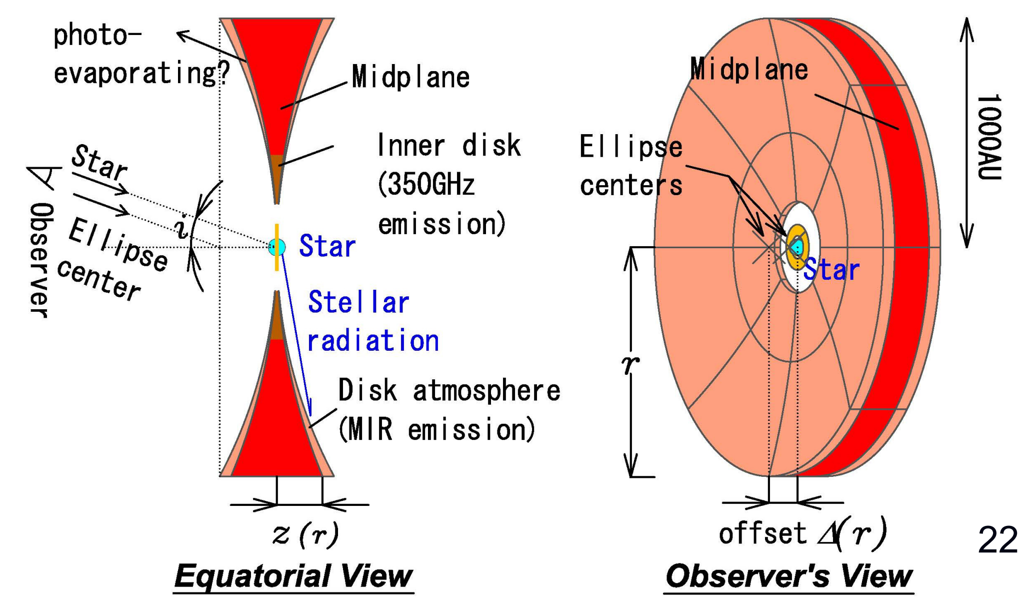
Flared disk geomtetry

- Centers of the elliptical contours of the diffuse disk emission are shifted from the unresolved peak emission source
  - Shift Δ is larger for the fainter contours
  - Characteristic to a flared disk geomtetry
  - Similar to the Herbig A0e star HD97048 (2.5$M_\odot$, Lagage+2006)
- Simple model fitting
  - Axisymmetric disk only whose surface emits in the MIR
  - From r_{in} to r_{out}
    - $z(r) = z_0 (r / r_0)^\alpha$
    - Surface brightness $= F_0 (r / r_0)^\beta$
  - Inclination i
  - Convolution of the model disk with the observed PSF

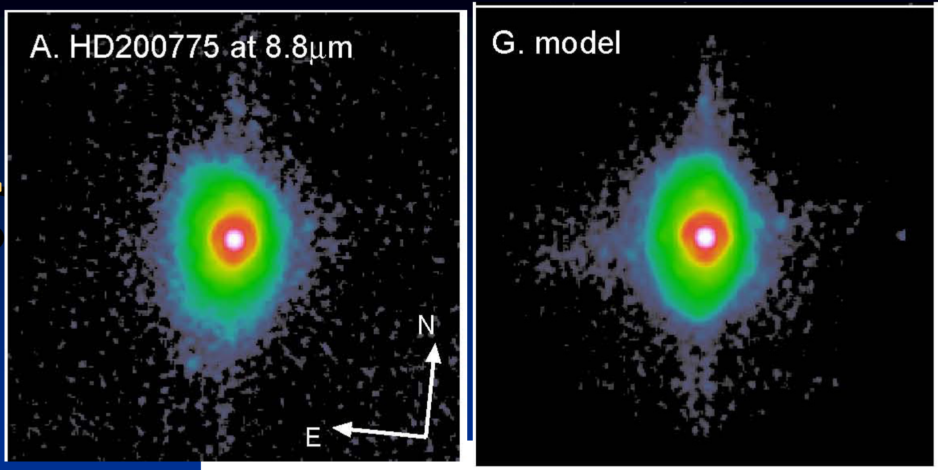




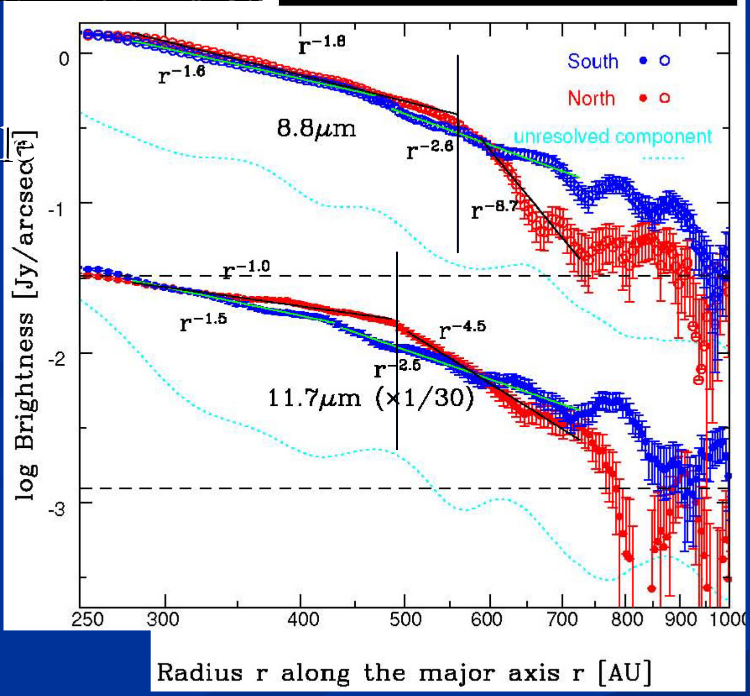




Disk geomtetry derived by the fitting

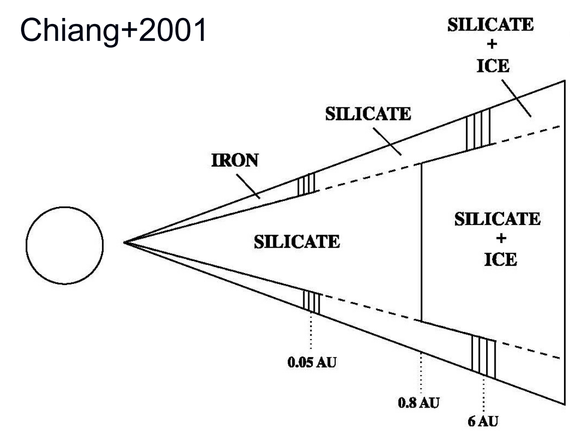


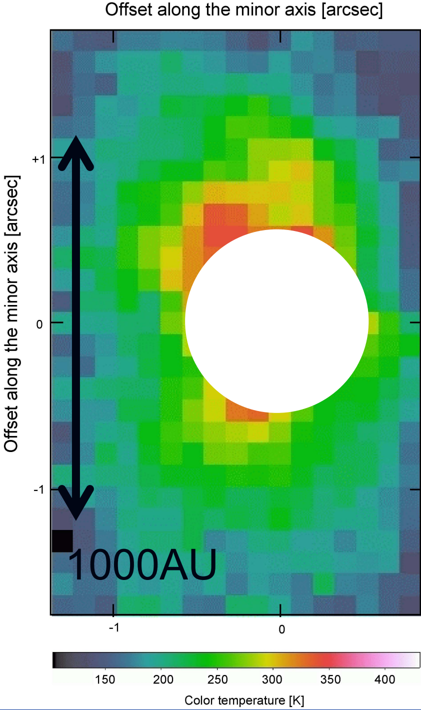
- Model images reproduce the observed images very well
- Parameters of the disk
  - r_{out}=665±8AU
    - ~ radius where the observed brightness profile becomes much steeper in the north
  - *Brightness* $F \propto r^{1.5\pm0.2}$
    - ~ brightness profile inside r_{out}
  - i=55.5deg
    - ~ inclinations of the binary orbit and of the stellar rotation (Alecian+2008)
  - r_{in}=140±14AU
    - Might be larger than the real inner radius due to the fitting procedure.
  - $z(r)[AU] = (16.8\pm2.8) \times (r[AU]/280AU)^{2.1\pm0.9}$
    - Not a hydrostatic disk (α<1.5) ?



Properties of the disk

- Color temperature from $I_{11.7\mu m}/I_{18.8\mu m}$
  - 180-330K
  - >> T_{dust} of black grains
    - 149K@430AU, 97K@1000AU
  - → effectively heated small grains (~0.1μm radius) in the disk atmosphere
  - Vertical thermal structure similar to that modeled for passive disks around lower-mass stars





Okamoto+2009
Color T of HD200775

- τ_v of $10^{-3} - 10^{-5}$ for the diffuse emission
  - << the value expected by usual disk models (~z(r)/r~0.1)
  - Surface ripples due to themal waves? (Watanabe & Lin 2008)

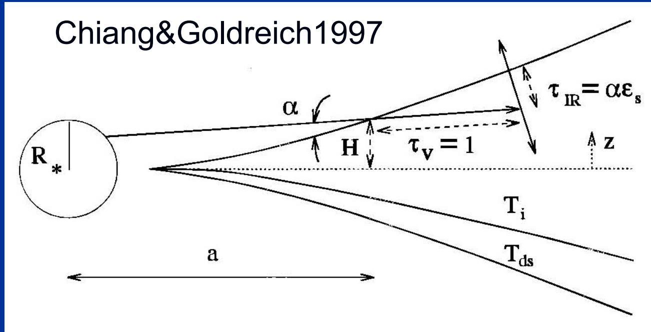
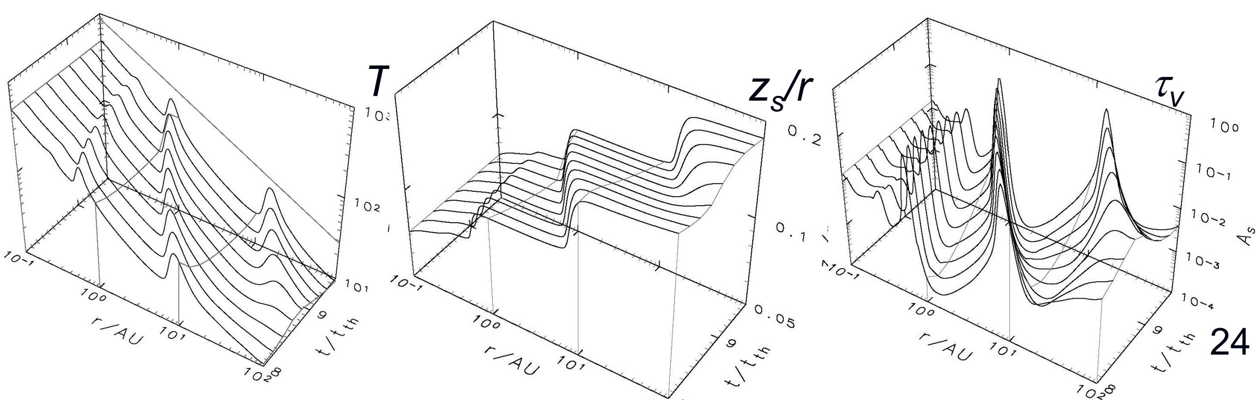


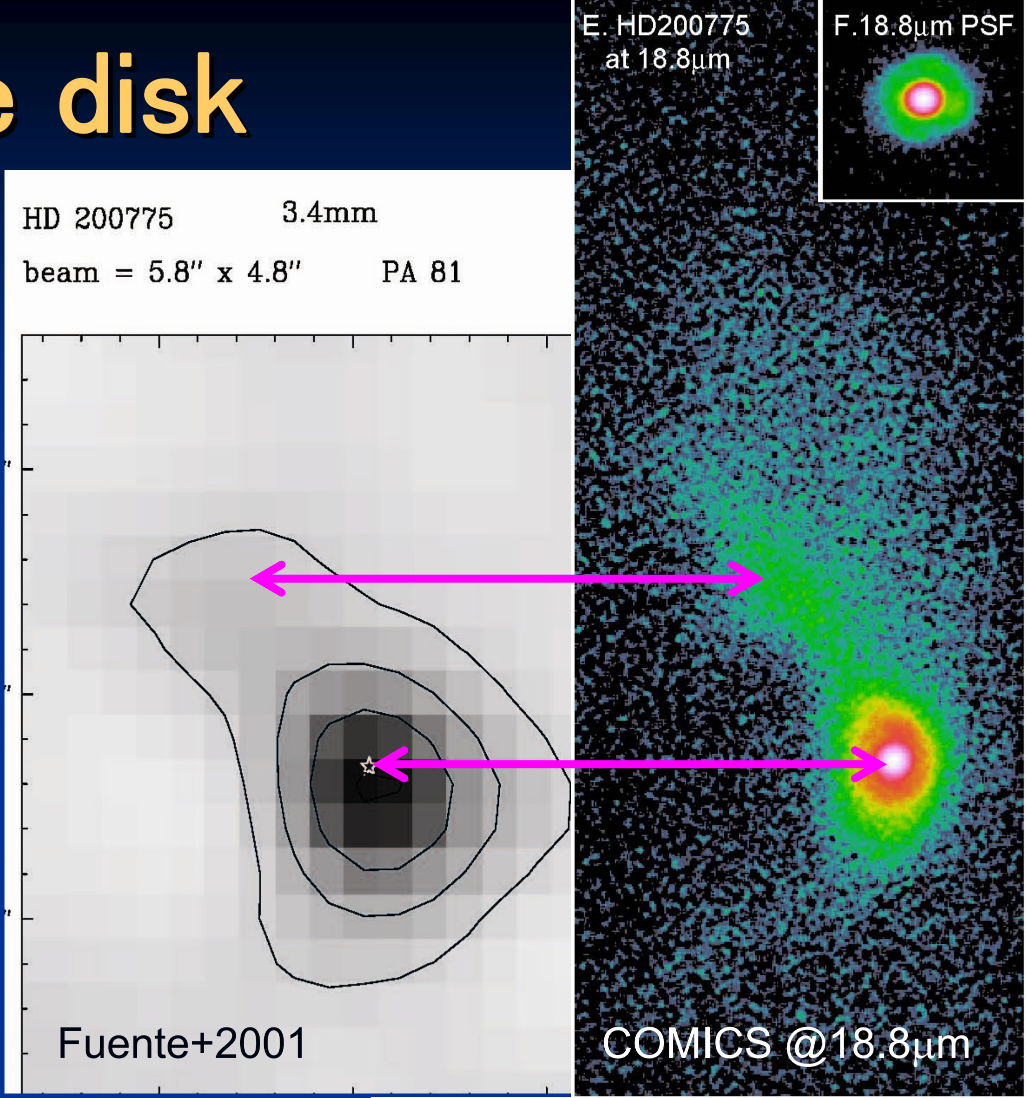
FIG. 3.—Radiative transfer in the passive disk. Stellar radiation strikes the surface at an angle α and is absorbed within visible optical depth unity. Dust particles in this first absorption layer are superheated to a tem-



Properties of the disk

- Photoevaporation from the disk surface
  - 3.4mm free-free emission by Fuente+2001 is very similar in size and shape to the MIR disk and tail emission
  - Photoevaporation radius
    - Inner radius where the sound speed of ionized gas exceeds the escape speed against stellar gravity
    - $r_g \sim 70$AU for a $10M_\odot$ star
    - Possible ionized gas flow from the disk surface at

      $r > r_g$



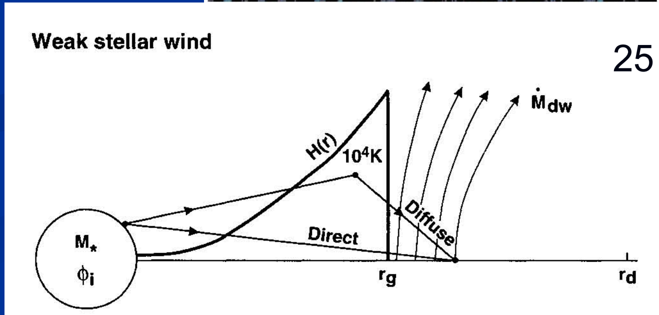
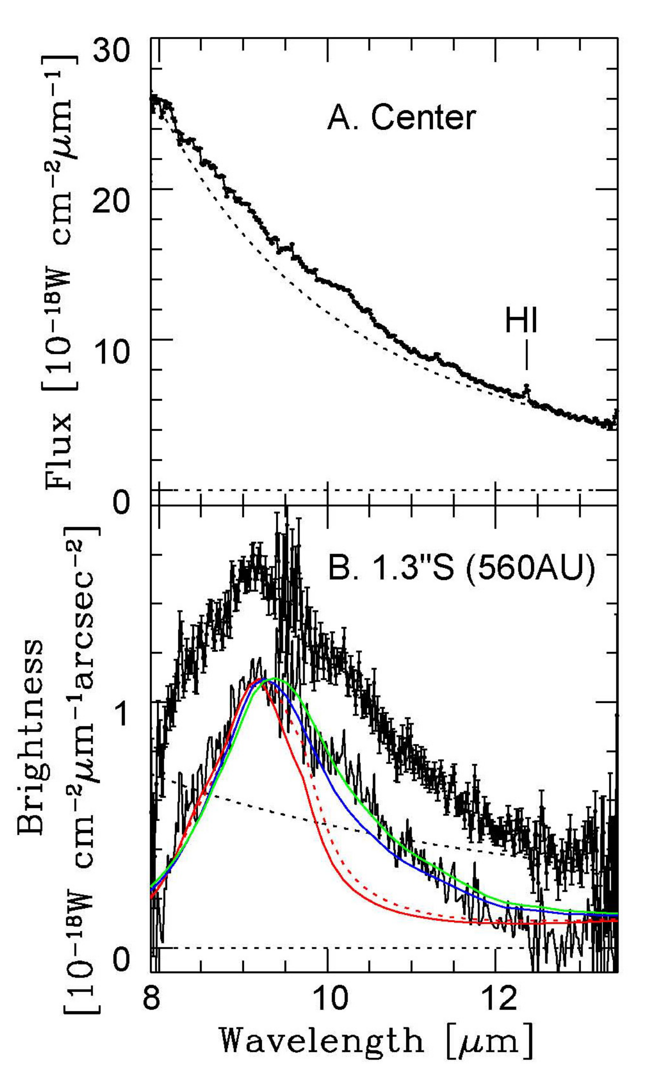


FIG. 1a

Hollenbach+1994

Inner disk and dust in the diffuse disk

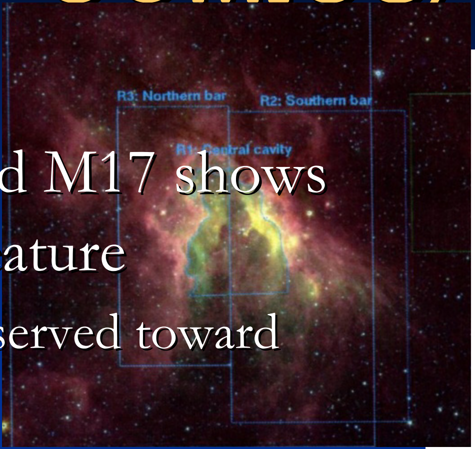
- The unresolved peak emission
  - Featureless, ~1600K (>1000K w 1σ error) blackbody
  - Circumprimary (or circumsecondary) disk
- Diffuse disk emission
  - Amorphous silicate feature with a peak ~9.2μm
    - Shorter than the peaks of silicate features of circumstellar disks around young lower-mass stars, ISM extinction, and envelopes around massive YSOs
    - Likely from pyroxene ($MgSiO_3$) or amorphous silicate with more SiO_2 fraction
- Grain properties characteristic to massive stars may be revealed by separating the disk emission with high spatial resolution.



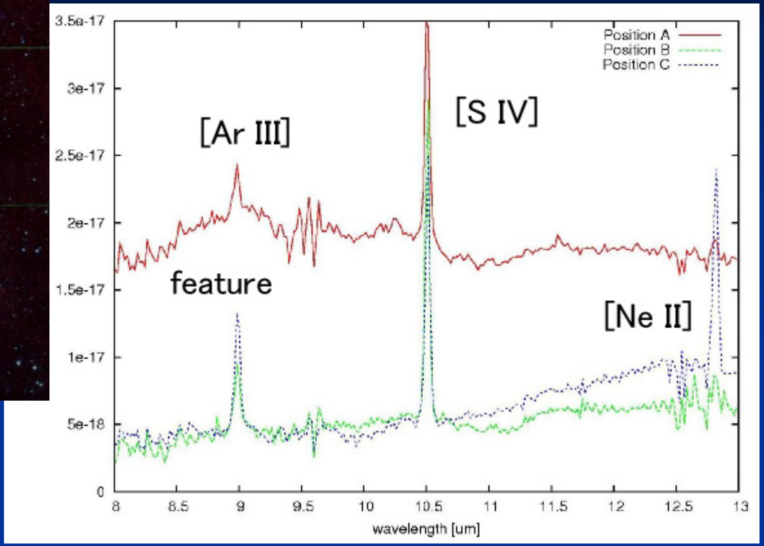
Amorphous pyroxene ($MgSiO_3$) : 0.1μm radius (dotted) 1μm radius (solid)
Amorphous $Mg_{0.7}SiO_{2.7}$: 0.1μm radius (blue) 1μm radius (green)

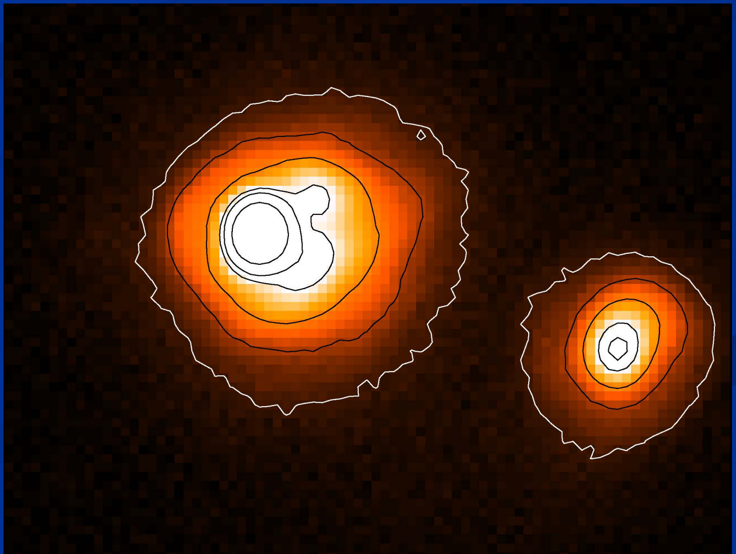
More results by COMICS/MIR

- Takahashi+ poster
  - Dust emission toward M17 shows characteristic 9μm feature
    - Relation to those observed toward HD200775?
- de Wit+ 2009 (also poster)
  - 24.5μm images of massive YSOs
  - ~1000AU scale density structure revealed by model fitting to the image and SEDs
  - Density profile shallower than larger scale observed by the radio
  - Some sources cannot be explained w spherical density distribution



Takahashi+ poster

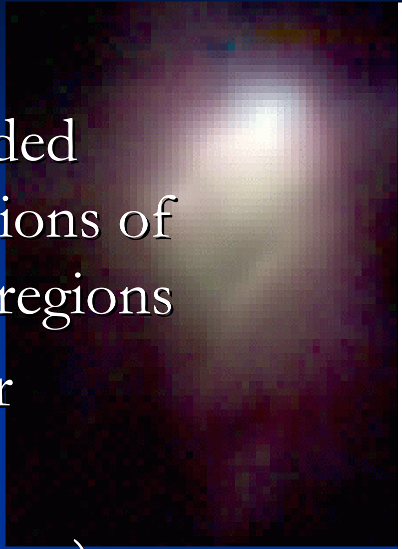


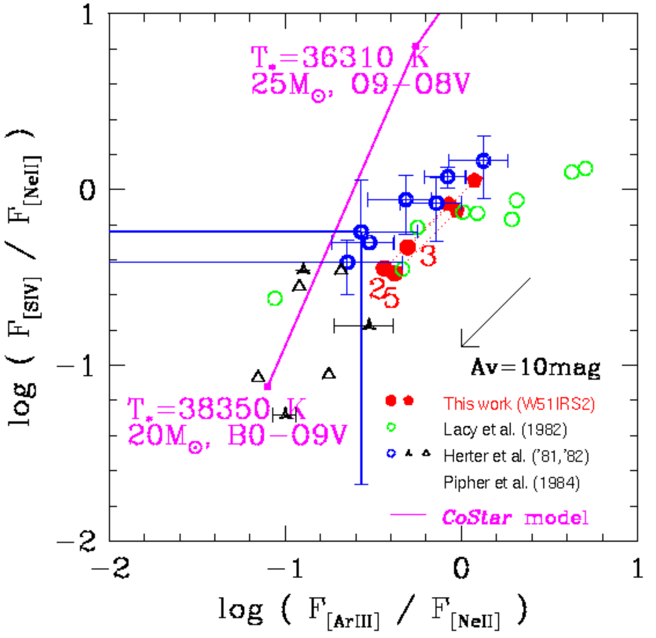


AFGL961 resolved @ 24.5μm
de Wit+2009, poster

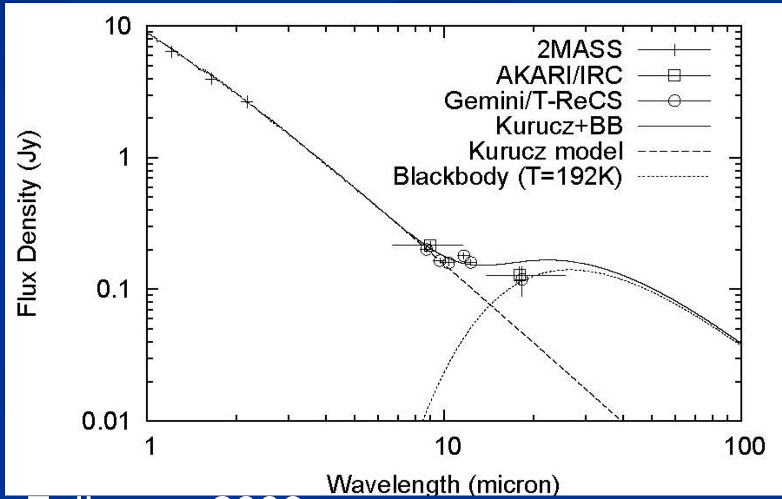
More results by COMICS/MIR

- Okamoto+ 2003
  - Diagnostics of the embedded massive YSOs from emissions of their surrounding ionized regions
  - See also Crowther+ poster (Development w Gemini)





- Fujiwara+ 2009 (also poster)
  - Follow-up observations of debris disks with COMICS and Gemini/T-ReCS by AKARI, the Japanese IR satellite
  - For HD106797, 10-13μm excess is detected
  - Td~190K, dust ring of r~14AU



Fujiwara+2009

Summary and future prospects

- Many results from Subaru/COMICS MIR observations to understand the star and planet formation
  - Grain evolution in the PPDs
  - Thermal structure of the disks
  - Grain distribution in the PPDs and DDs
  - Early planetary systems
  - Disks, dust, and density distribution of massive YSOs, etc…
- Future prospects
  - Further study w Subaru/COMICS
    - Detailed dust distribution of resolved disks
    - Search for the embedded massive YSOs and their properties
  - Realizing MIR observations w TMT
    - Improved spatial resolution (0.08") is very powerful to resolve the planet forming regions with 1 to 10AU scale