# Silicate dust evolution around low-mass young stars

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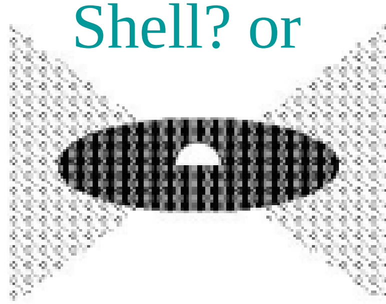
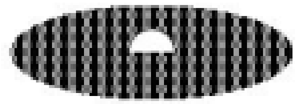
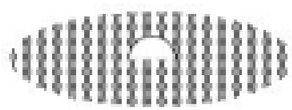
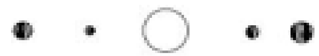
# Contents


- ✓ Short review of silicate feature observations
- ✓ COMICS 10 micron spectroscopic observations of low-mass young stars (T Tauri stars)
- ✓ Evidence for grain growth in TTS
- ✓ crystalline silicate in TTS
- ✓ Summary

# Standard scenario of star formation

| | Age | |
|---|---|---|
| Molecular cloud | | Shell? or  Disk + Envelope |
| protostar | $10^5$yr | |
| T Tauri Star / Herbig Ae/Be star | $10^5$～$10^7$yr |  Circumstellar disk |
| (Vega-like star) / Vega-like star | $10^7$～$10^8$yr |  Debris Disk |
| Our Solar System | ～$4.6 \times 10^9$yr |  Planetary System |

Frozen reservoir of primordial material: **Comet**

# Silicate dust feature (amorphous)

Molecular Cloud

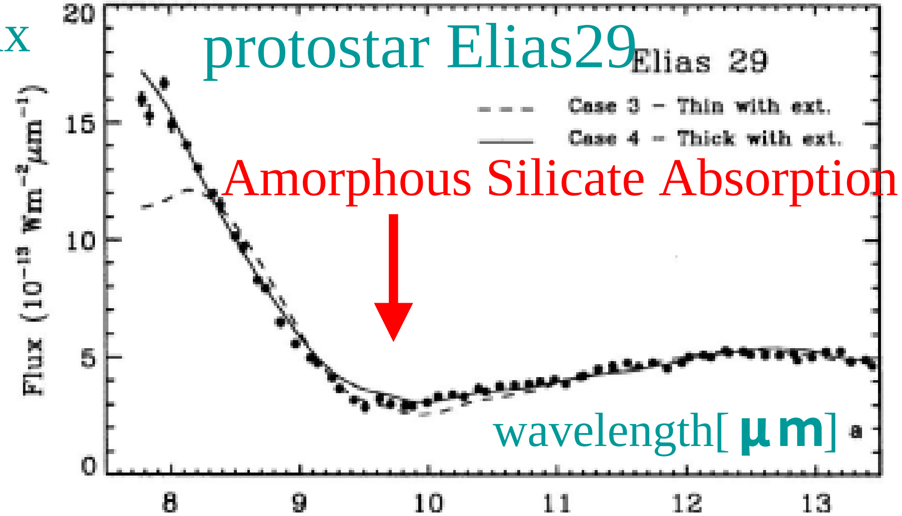
protostar

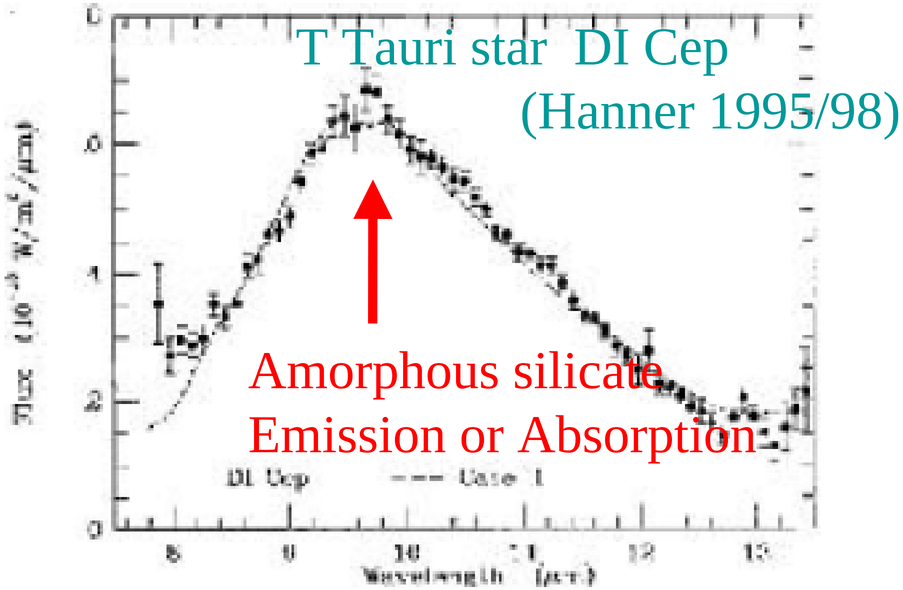
T Tauri star Herbig Ae/Be star

(Vega-like star) Vega-like star

Our Solar System

Frozen reservoir of primordial material: **Comet**



# Silicate dust feature (Comet)

Molecular Cloud

↓

protostar

↓

T Tauri star　　Herbig Ae/Be star

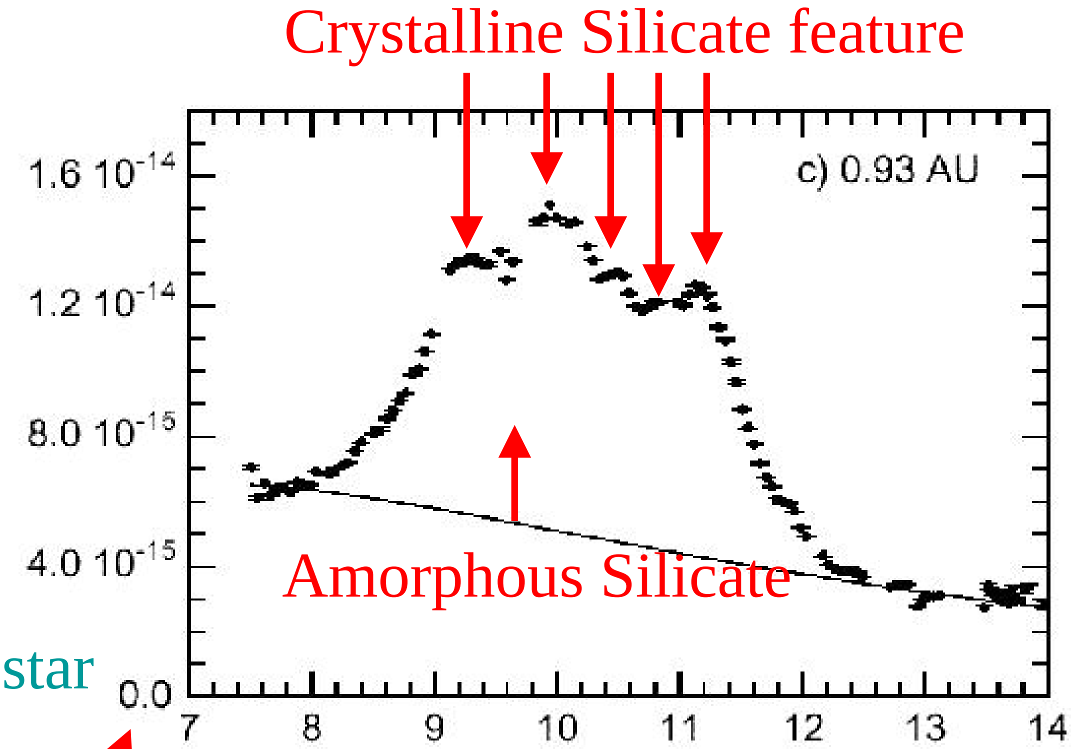
↓　　↓

(Vega-like star)　　Vega-like star

↓

Our Solar System

Frozen reservoir of primordial material: **Comet**




**Comet Hale-Bopp** (Wooden et al 1999)

How these crystalline silicate were formed and incorporated to comets?

# Silicate dust feature (Comet)

Molecular Cloud

protostar

T Tauri star

Herbig Ae/Be star

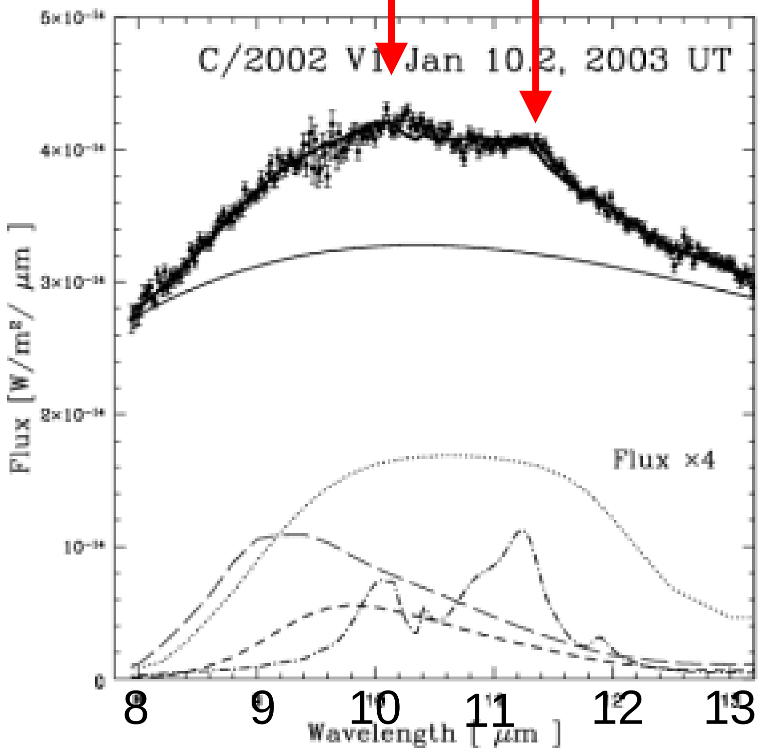
(Vega-like star)

Vega-like star

Our Solar System

Frozen reservoir of primordial material: **Comet**

Crystalline Silicate feature




**Comet C/2002 V1** taken with COMICS (Honda et al. submitted to ApJ)

10-20 % of silicate grains are in crystalline form

# Silicate dust feature (Vega-like star)

Molecular Cloud

↓

protostar — Similar to comets' spectra

↓

T Tauri star　　Herbig Ae/Be star

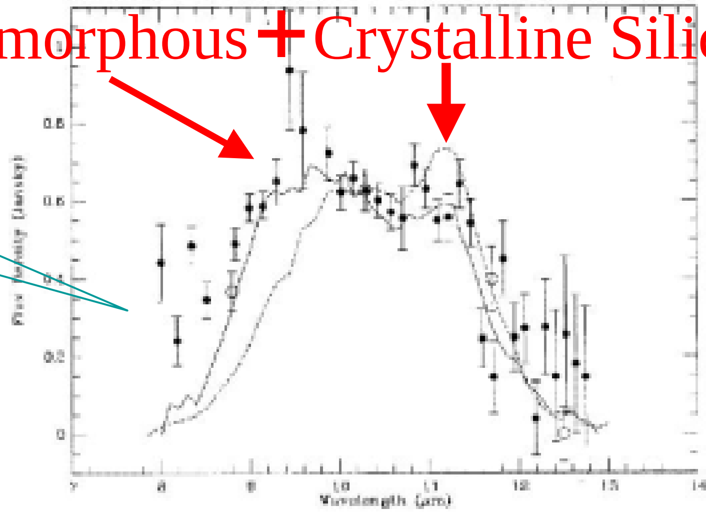
↓　　↓

(Vega-like star)　Vega-like star

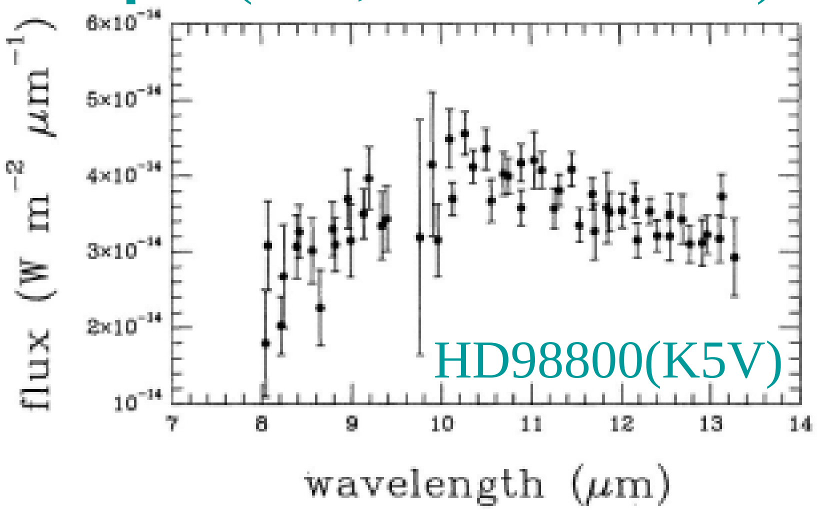
↓

Our Solar System

Frozen reservoir of primordial material: **Comet**




β Pic(A5V,Knacke et al 1993)




Broad silicate feature (Skinner et al 1992)

# Silicate dust feature (HAeBe)

Molecular Cloud

↓

Protostar

↓

T Tauri star → (Vega-like star)

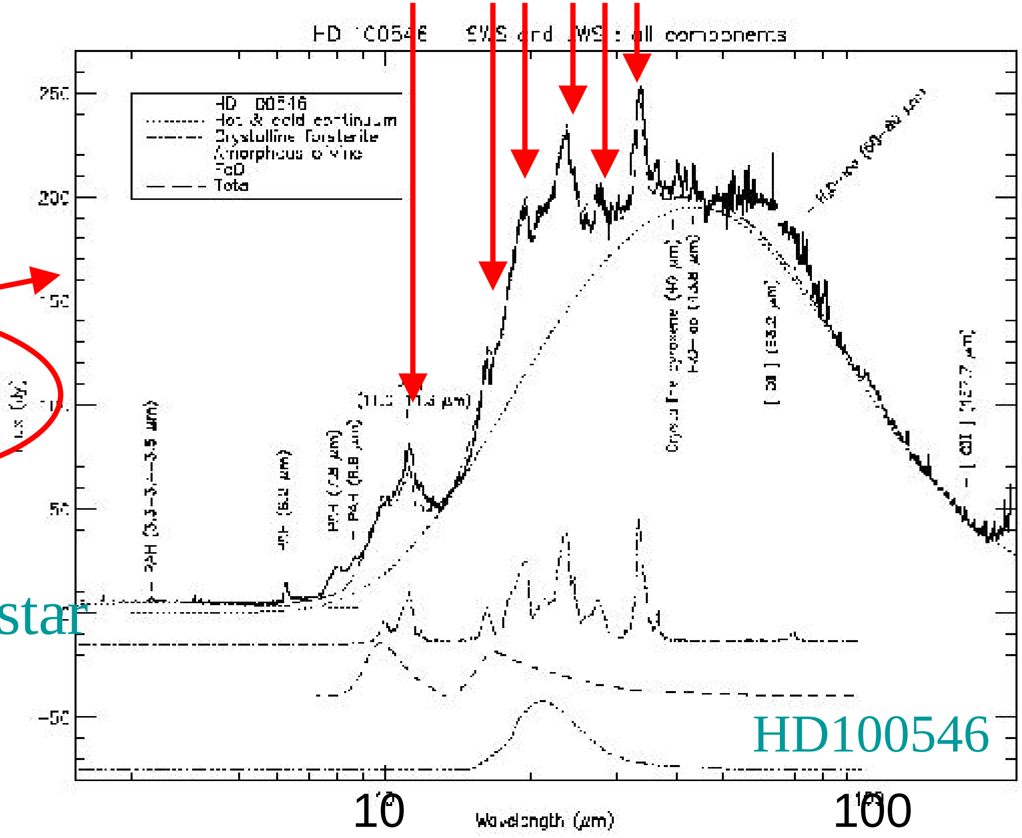
Herbig Ae/Be star → Vega-like star

↓

Our Solar System

Frozen reservoir of primordial material: **Comet**

Crystalline silicate feature




(Mailfait et al 1998)

ISO revealed that crystalline silicate appear among HerbigAe/Be stars

# Silicate dust feature (T Tauri stars)

Molecular Cloud

↓

Protostar

↓

T Tauri star | Herbig Ae/Be star

↓ | ↓

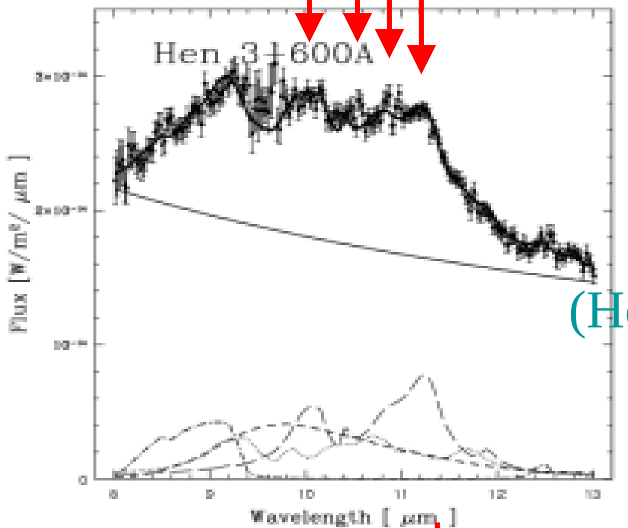
(Vega-like star) | Vega-like star

↓

Our Solar System

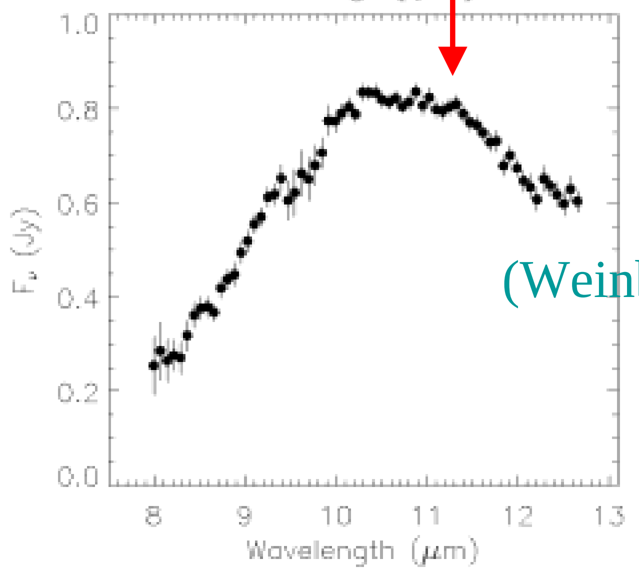
Frozen reservoir of primordial material: **Comet**

Crystalline silicate features




Hen 3-600A

(Honda et al. 2003)




TW Hya

(Weinberger et al. 2002)

# Silicate dust feature (summary)

presence of crystalline silicate

| age | Low-mass (〜2M◎) | intermediate (2M◎〜10M◎) |
|---|---|---|
| $10^5$yr | protostar ✕ | |
| $10^6$〜$10^7$yr | T Tauri star<br>TWHya,Hen3-600 | Herbig Ae/Be star<br>HD100546,HD163296,<br>HD150193,HD31648,etc… |
| $10^7$〜$10^8$yr | (Vega-like star)<br>HD98800 | Vega-like star<br>β Pic |
| 〜4.6✕$10^9$yr | Comet<br>Halley,HaleBopp,Bradfield,Levy,etc.… | – |

Dust composition about TTS, Vega-likes stars are not well-constrained….

# Why we focused on low-mass young stars ?

- To compare Solar system formation (Our Sun is low-mass stars)
- Dust evolution around low-mass young stars are not well understood compared to that of HAeBe stars. (ISO focused on Herbig Ae/Be)
- Previous studies are limited to bright and younger stars (～1Myr)… COMICS on Subaru can observe fainter and older young stars (～10Myr).

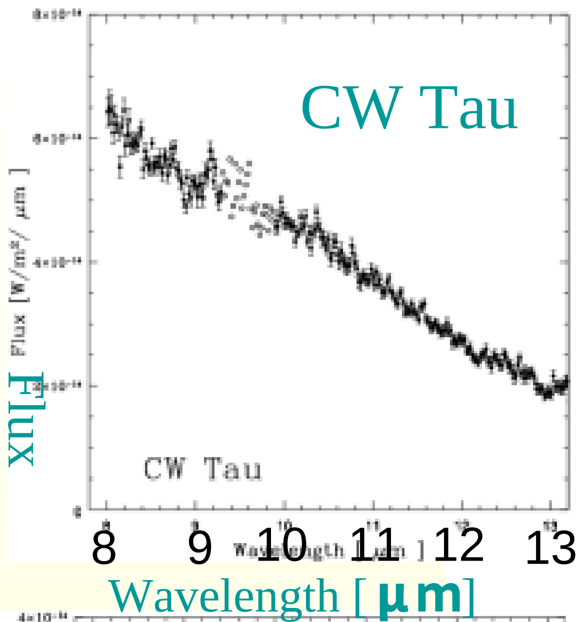
# Observation with COMICS＋SUBARU

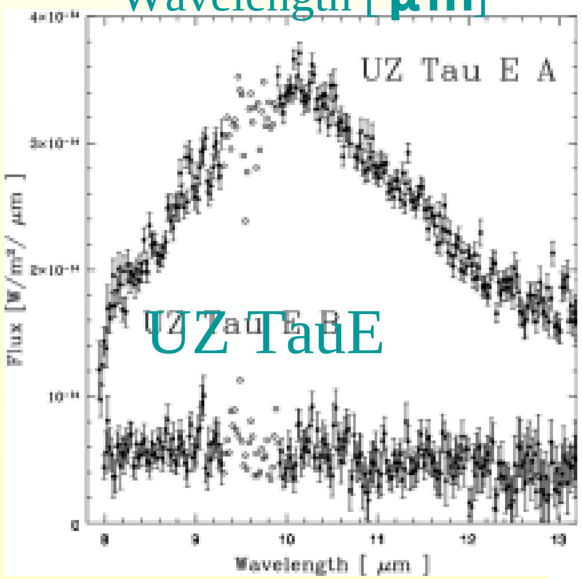
- N-band（8～13 μm）Spectroscopy（R～250)
- 14 objects (18 spectra)
- Taurus-Auriga, TWHya Association, MBM12, β Pic moving group, isolated TTS

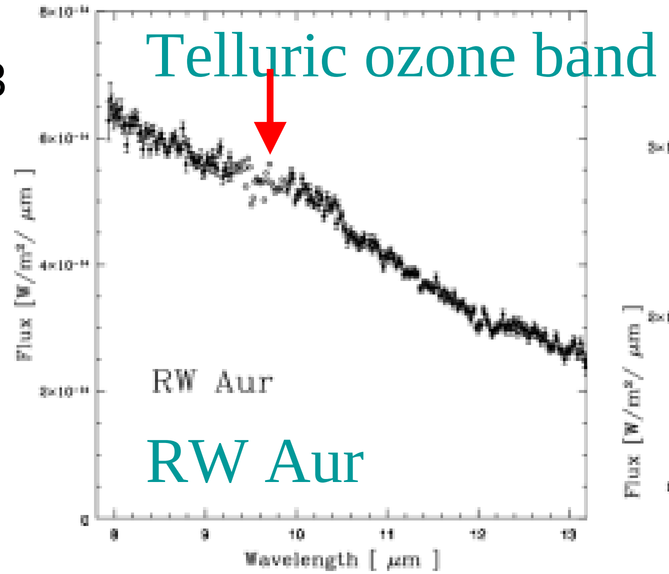
Targets：possibly ～5Myr old young star (by literature)
UZ Tau, CZ Tau, HN Tau, Haro6-37, RY Tau, DD Tau, FV Tau, RW Aur, CW Tau, HD98800, Hen3-600, TW Hya, HD358623, LkHa264, V4046 Sgr

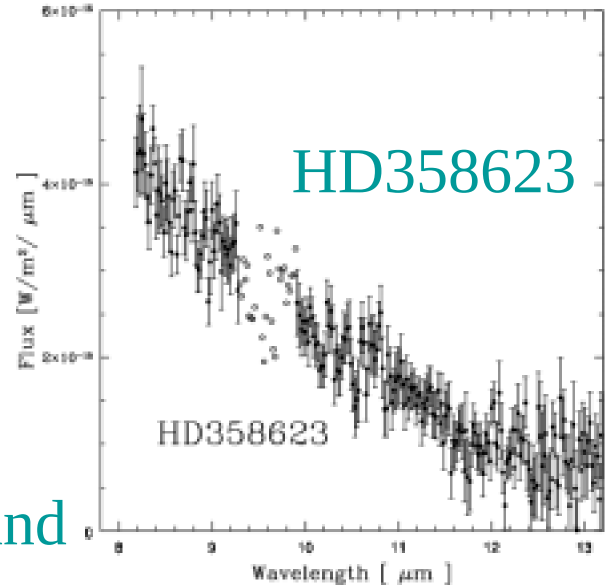
# Observed spectra (1)

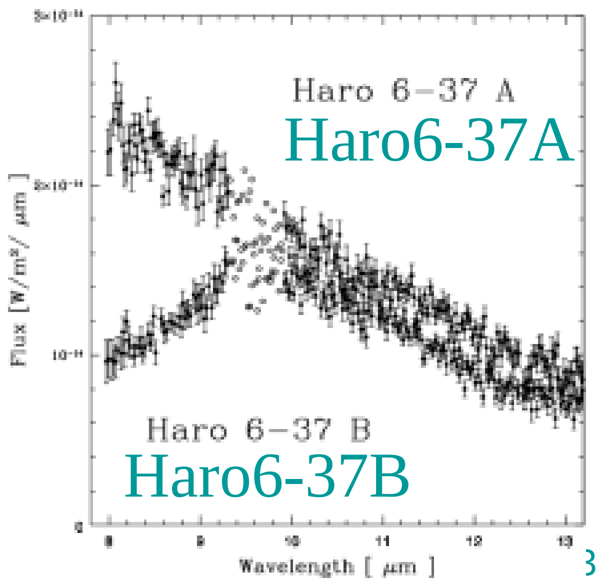
Featureless
(5/18)



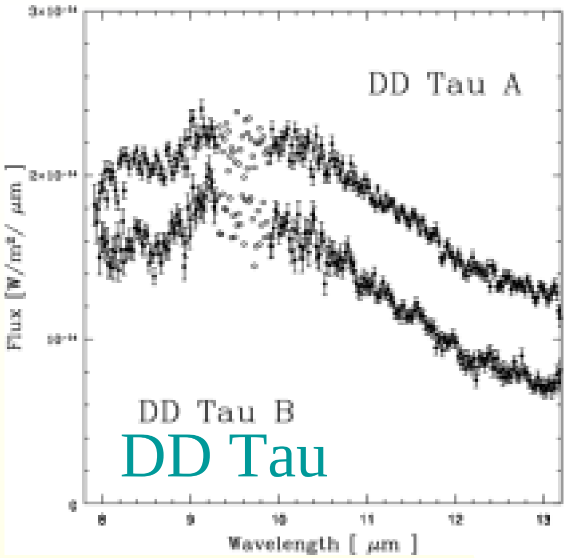



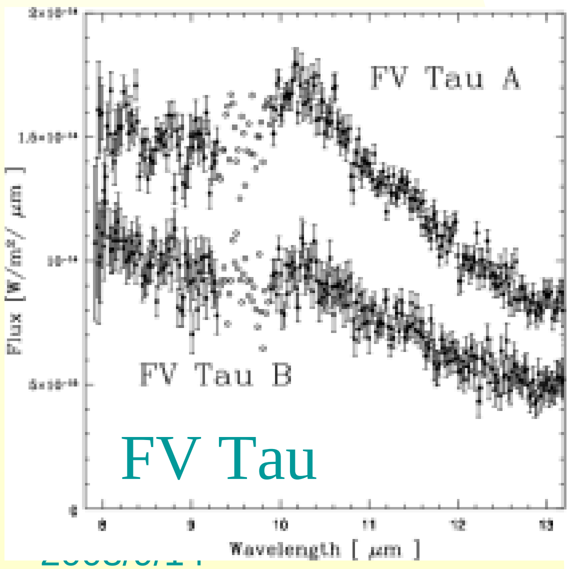



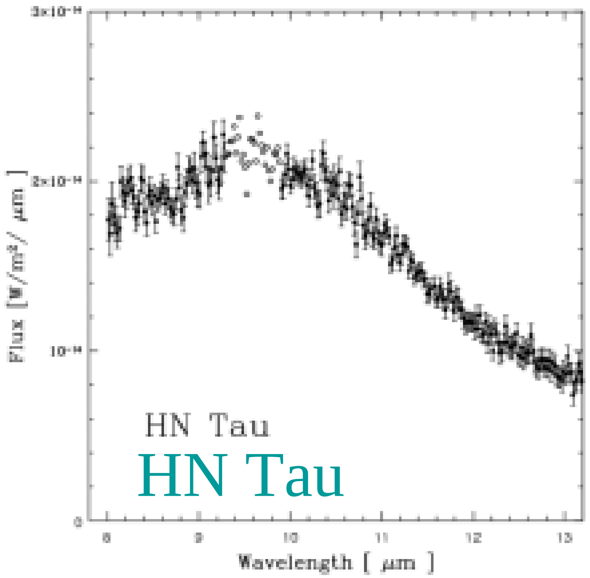



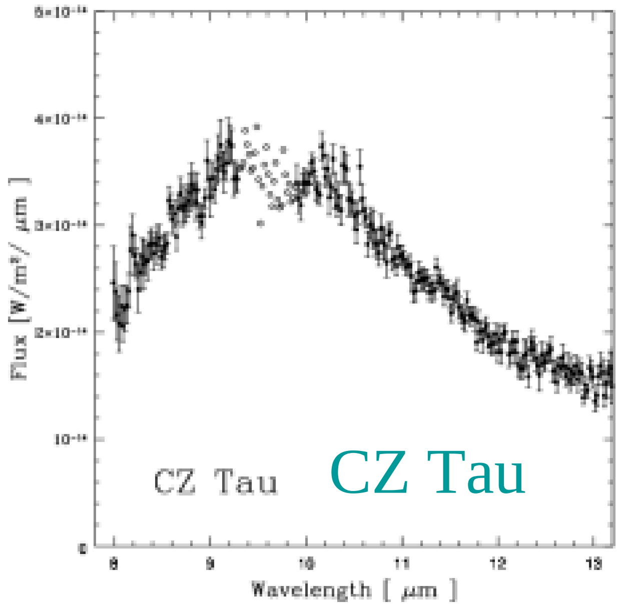
# Observed spectra (2)

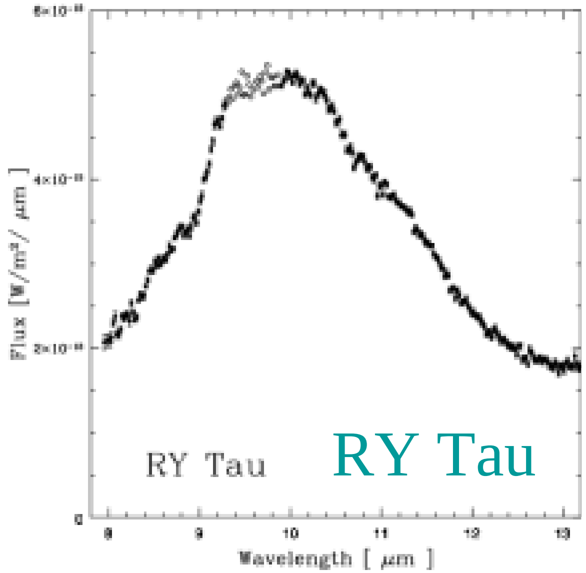
Amorphous silicate feature (9/18)



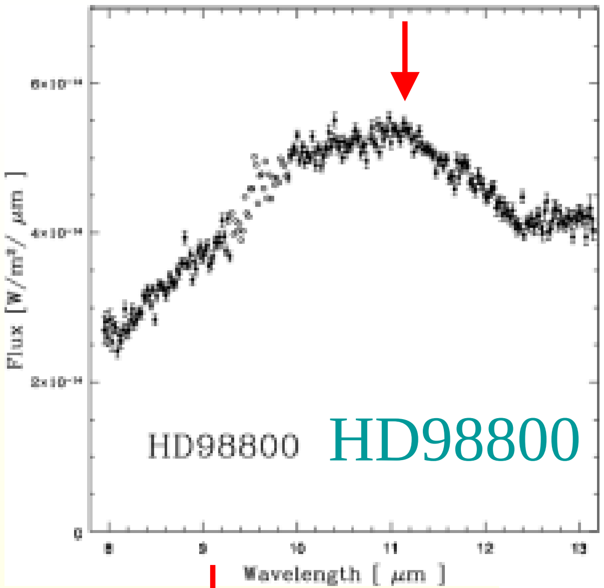



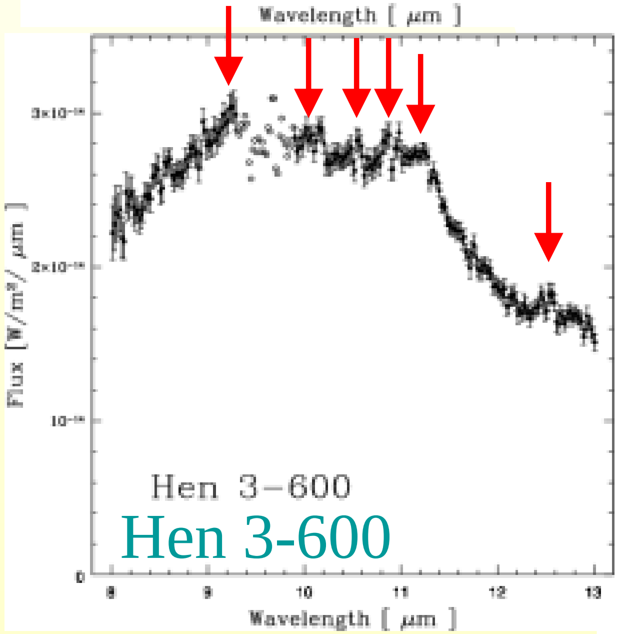



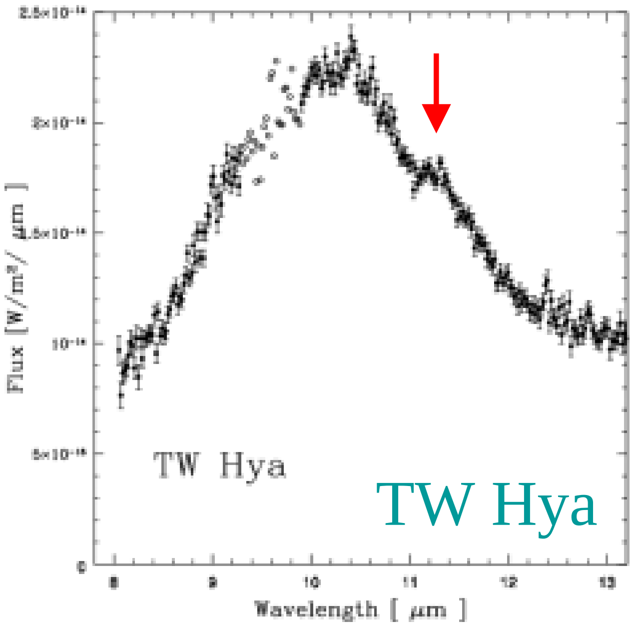



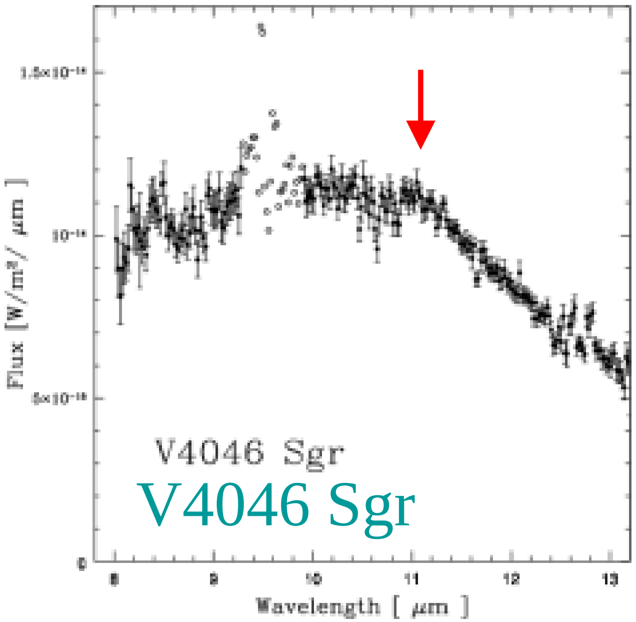
# Observed spectra (3)



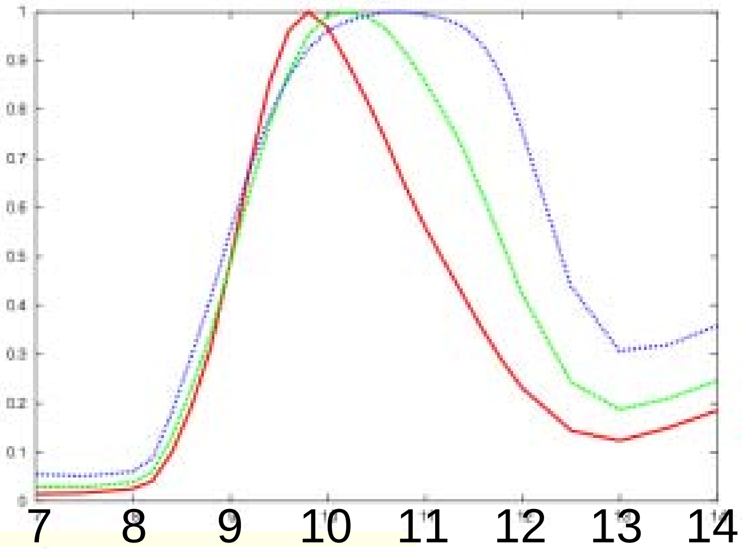



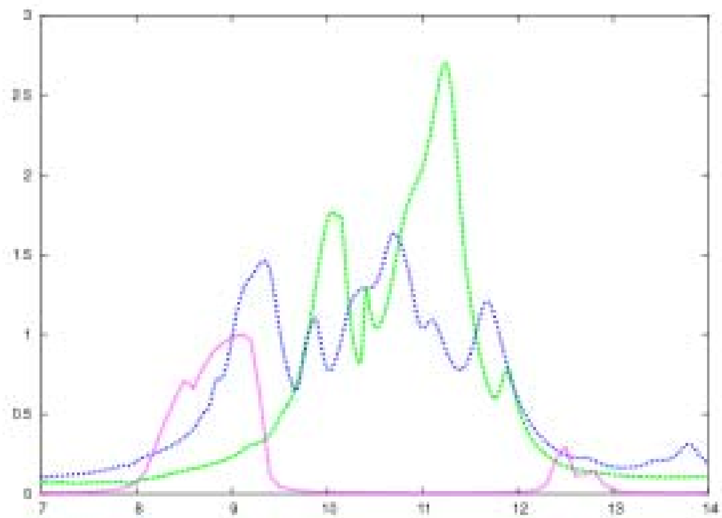

Silicate feature with signature of processed dust (4/18)



# Dust species used for fitting



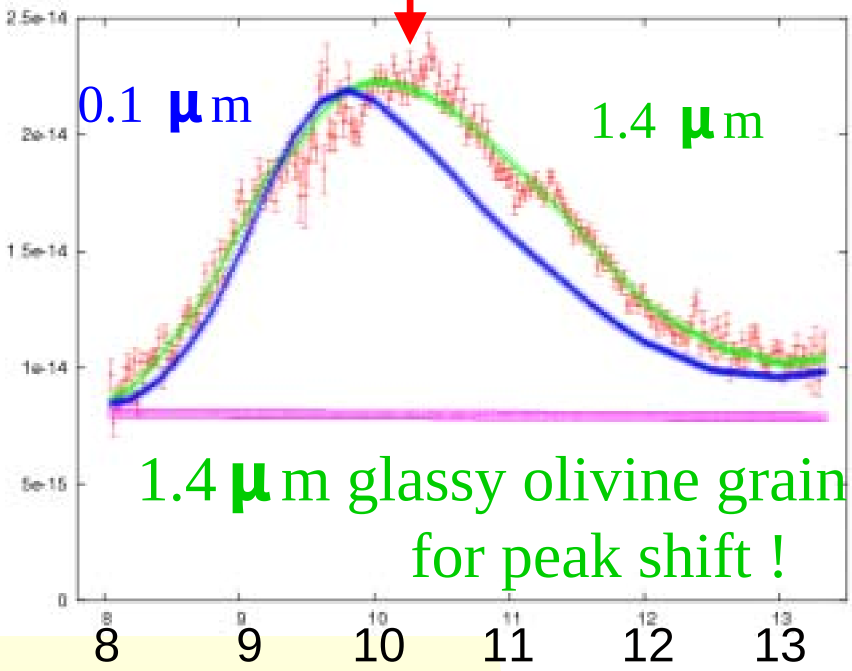
similar fitting procedure as proposed by Bouwman et al. 2001

Amorphous Silicate：
0.1, 1.4 and 2.0 micron
Glassy olivine grains($MgFeSiO_4$)
(Dorschner et al 1995)

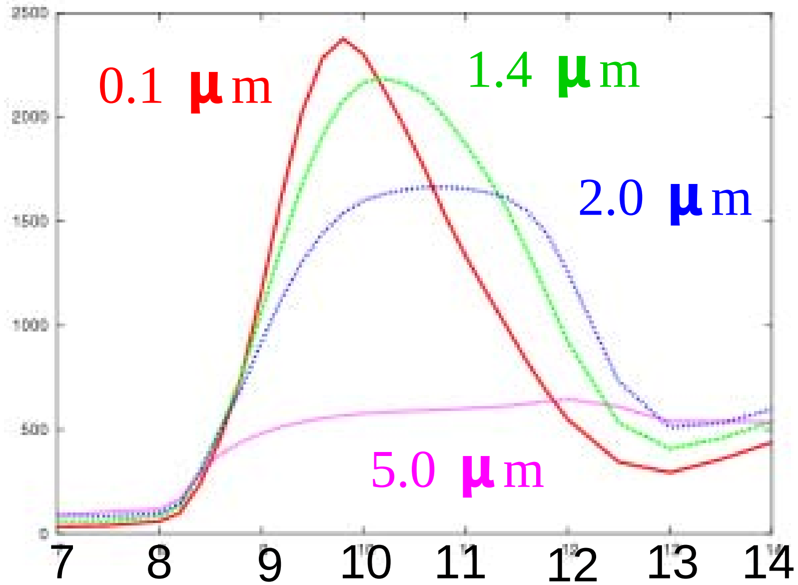
Crystalline Silicate:
Crystalline olivine （forsterite,$Mg_2SiO_4$)
（Koike et al 2003)
Silica ($SiO_2$) (Spitzer and Kleinman 1961)
and occasionally….
Crystalline pyroxene (enstatite,$MgSiO_3$)

# Why 1.4 micron glassy olivine is needed?

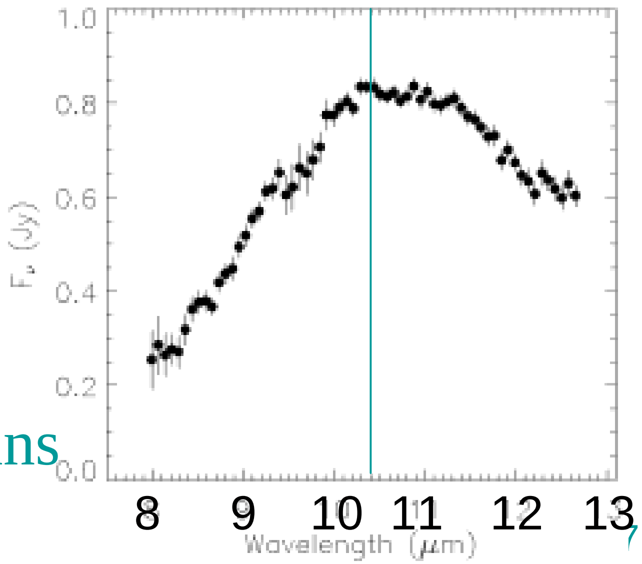
Peak shift as seen toward TW Hya




1.4 μm glassy olivine grain account for peak shift !




Also seen in the spectrum by Weinberger et al. 2002




10 μm feature is sensitive to 1-3 micron grains

# Fitting formula

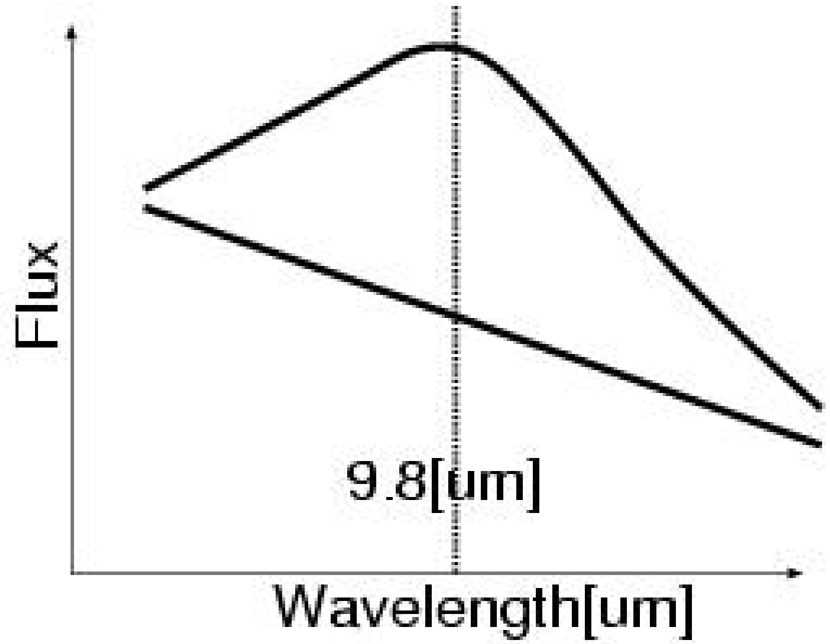
$$\lambda F_\lambda = (a_0 + \sum_{i=1} a_i \kappa_i)(\frac{\lambda}{9.8})^n$$

Model Flux

continuum emission

Optically thin emission

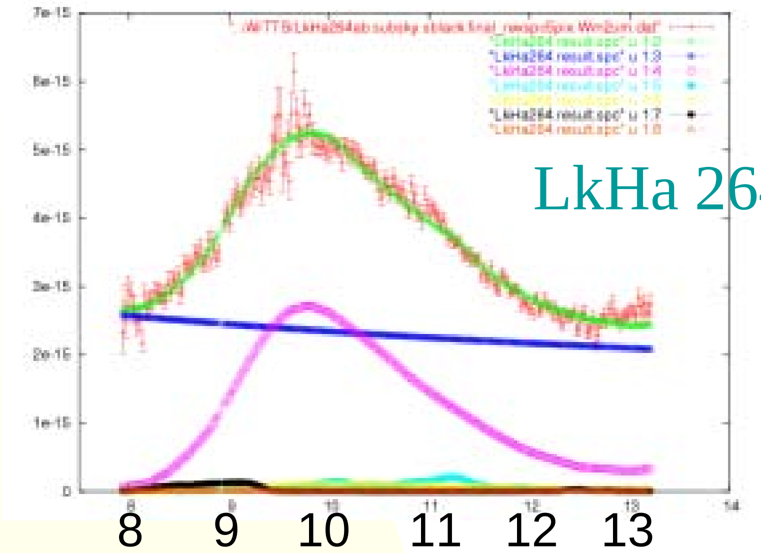
Chi-squared minimization method



# Examples of fitting results (1)

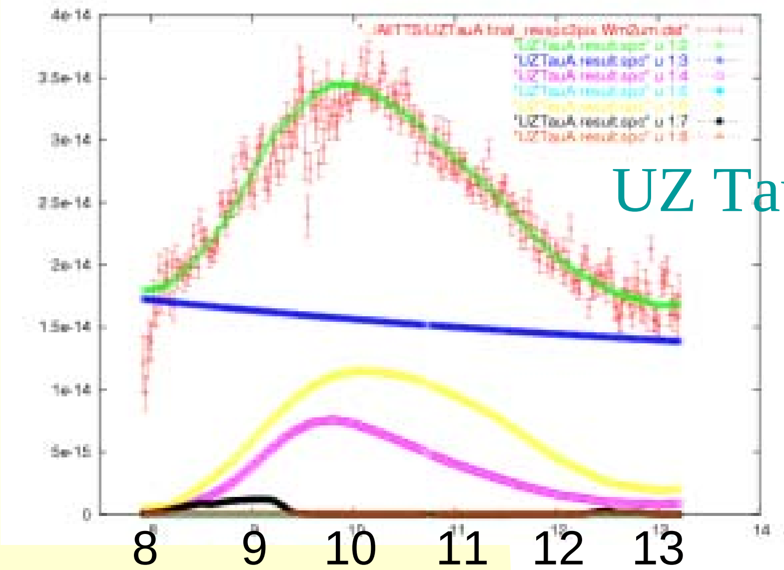
Glassy olvine 0.1 micron grains

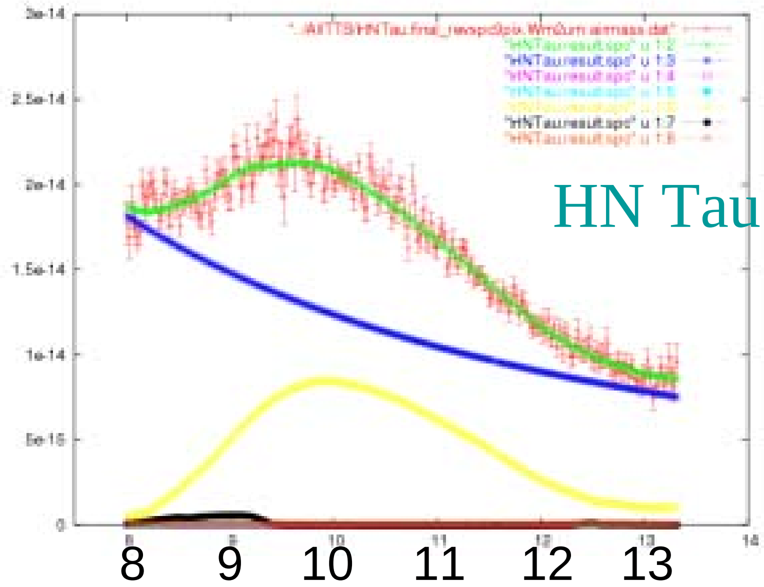
Glassy olivine 1.4 micron grains



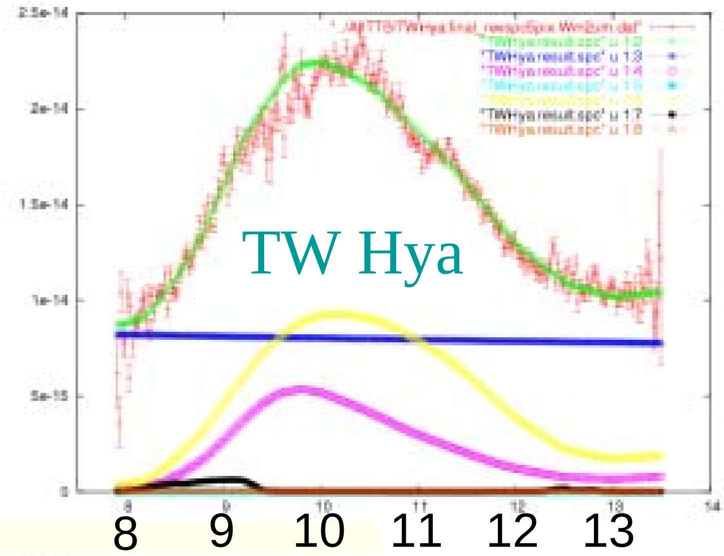

0.1 μm grains dominant

1.4 μm grains dominant



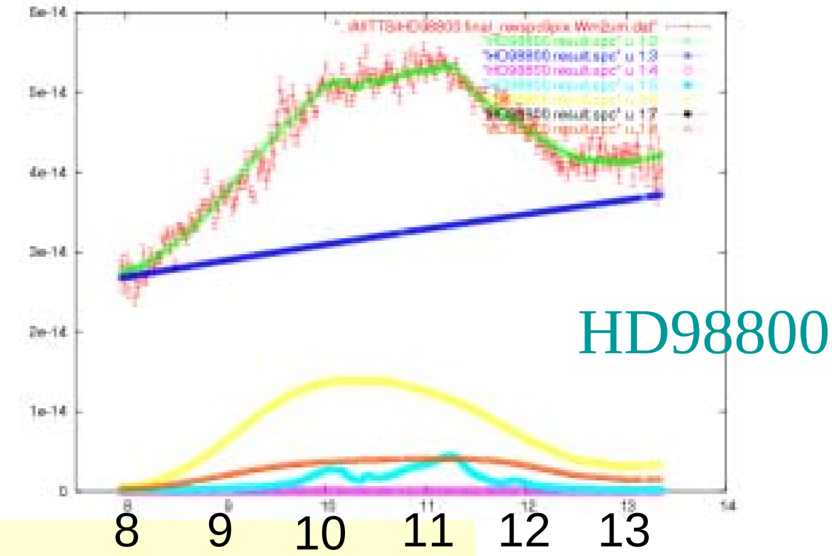



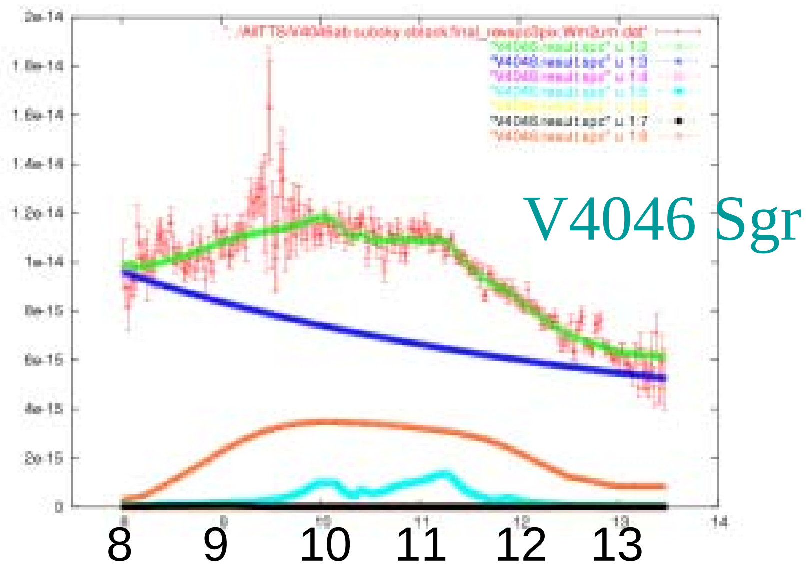
# Examples of fitting results (2)




Glassy olvine 0.1 micron grains
Glassy olivine 1.4 micron grains
Glassy olivine 2.0 micron grains

Presence of large (2.0 μm) grains
and
Crystalline silicate grains



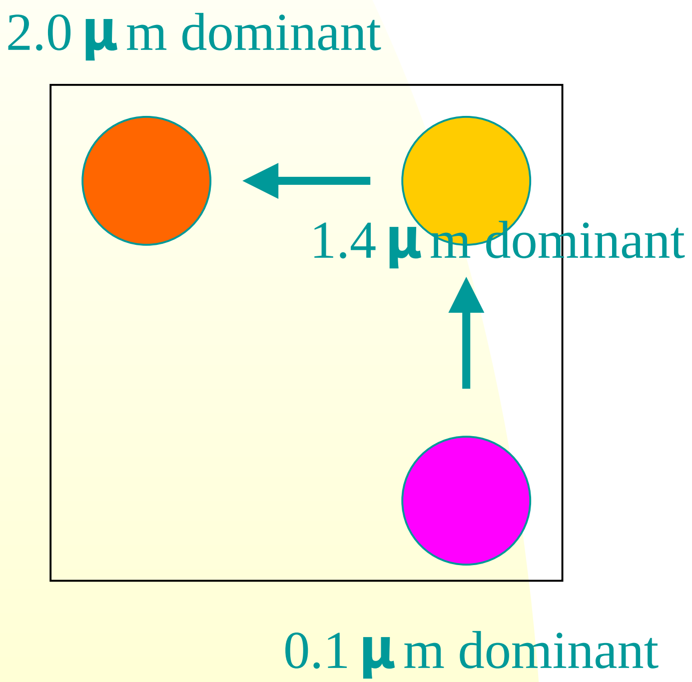
# fitting results summary

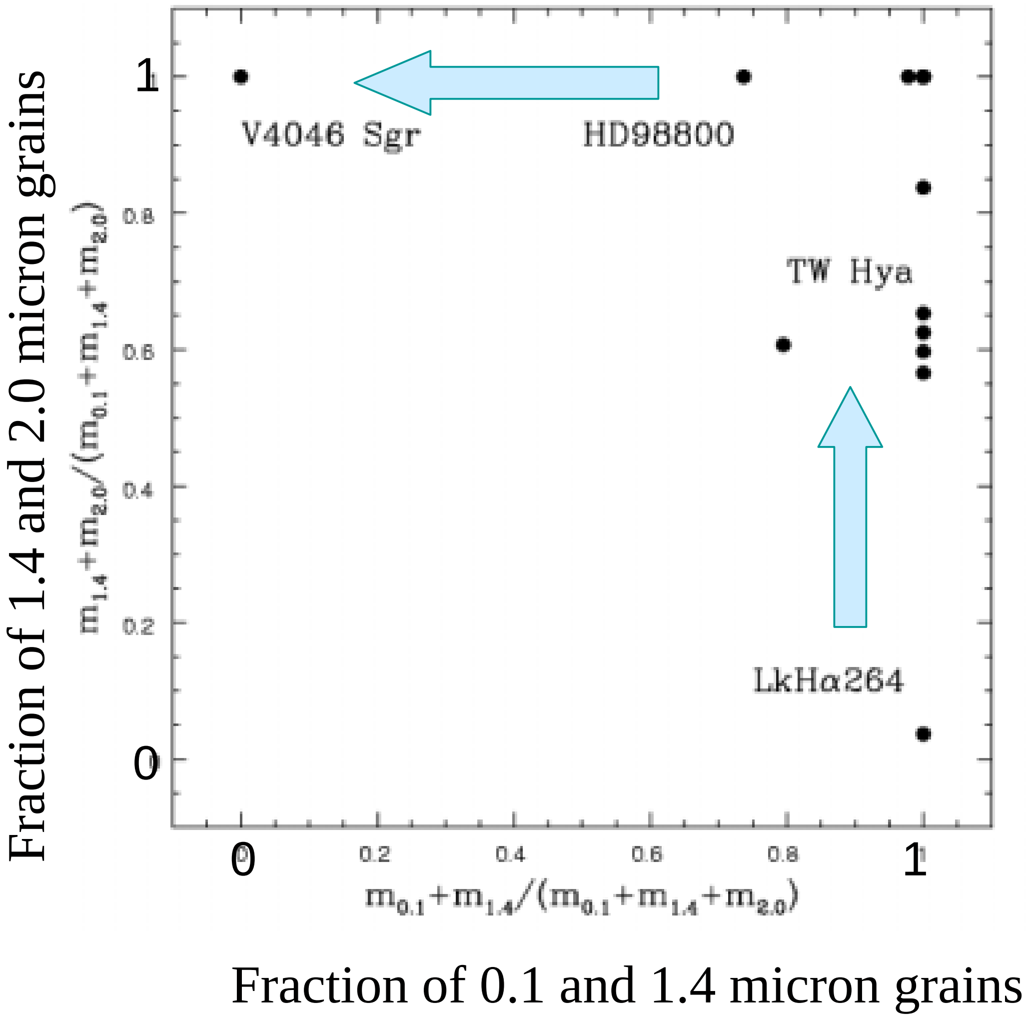
| name | 0.1 a. oliv. | forst | 1.4 a. oliv. | sio2 | 2.0 a. oliv. |
|---|---|---|---|---|---|
| LkHa264 | 93±4 | 3±31 | 4±8 | 0.6±0.4 | 0±8 |
| RYTau | 39.8±1.1 | 0.9±10.9 | 59.0±2.2 | 0.3±0.1 | 0±2.3 |
| CZTau | 42±7 | 0±54 | 55±14 | 3±0.7 | 0±15 |
| UZTauA | 37.2±4.5 | 0±41.9 | 62.0±9.9 | 0.8±0.5 | 0±10.3 |
| Haro6-37B | 37±8 | 3±63 | 38±18 | 1.8±0.9 | 19±18 |
| TWHya | 34.5±2.5 | 0±24.7 | 64.9±5.8 | 0.6±0.3 | 0±5.8 |
| DDTauB | 16±7 | 0±53 | 82±18 | 2±0.9 | 0±18 |
| DDTauA | 0±6 | 0±38 | 98±14 | 1.5±0.7 | 0±14 |
| FVTauB | 0±9 | 0.2±67 | 99.8±19 | 0±1 | 0±20 |
| HNTau | 0±8 | 0.2±59 | 99±16 | 0.7±0.9 | 0±17 |
| Hen3-600 | 0±6 | 21±42 | 74±13 | 6±0.7 | 0±14 |
| FVTauA | 0±29 | 4±206 | 94±61 | 0±3.4 | 2±66 |
| HD98800 | 0±4 | 7±28 | 69±7 | 0±0.4 | 25±8 |
| V4046Sgr | 0.0±6.7 | 9.6±42.5 | 0±15.2 | 0.1±0.8 | 90.3±15.5 |

Weight percent (%) of dust species

# Evidence for grain growth

**Glassy olivine grain size population change**

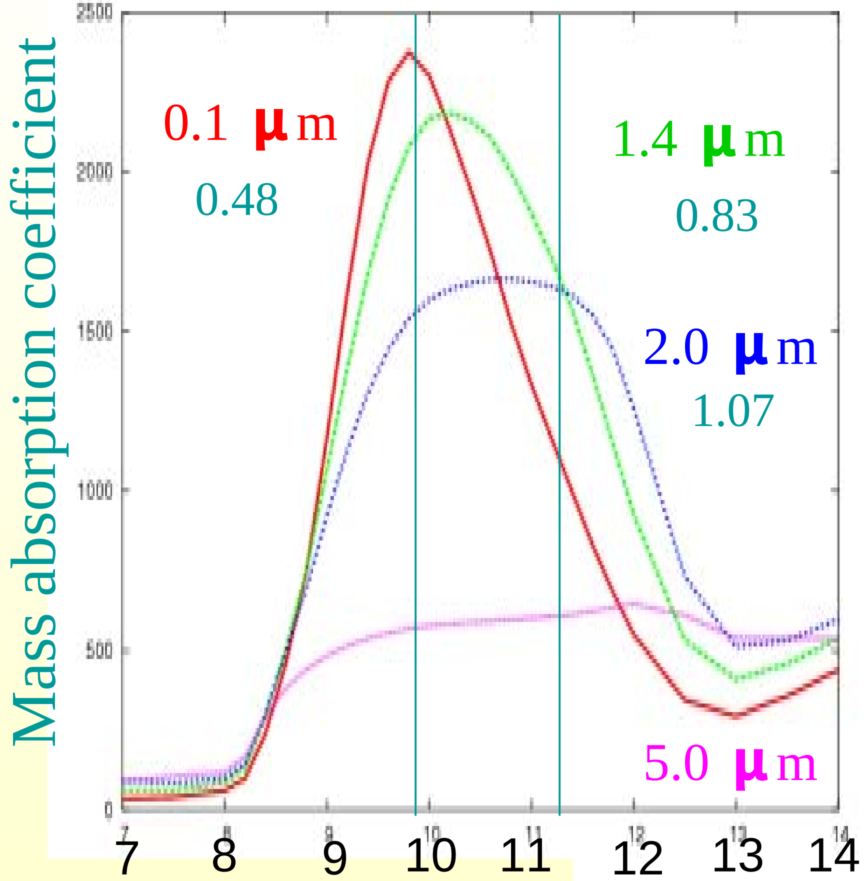


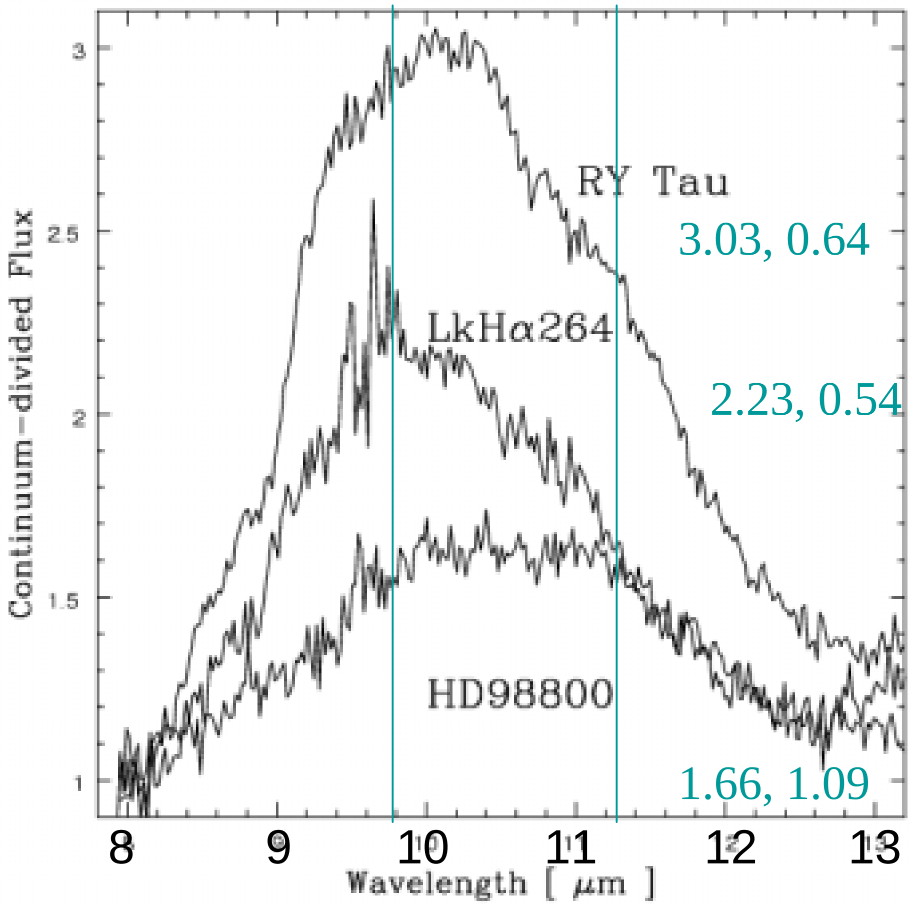



# Evidence for grain growth

It is natural to expect **grain growth** will lead to **change feature profile** and to **decrease feature strength**

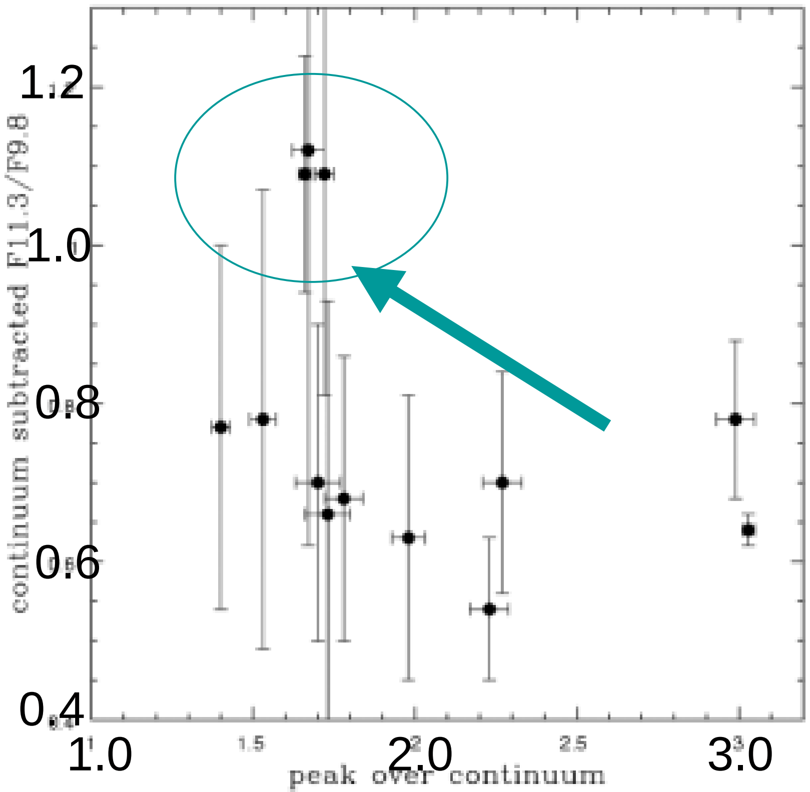
F11.3/F9.8 (feature shape indicator) have a correlation with feature strength?



# Evidence for grain growth

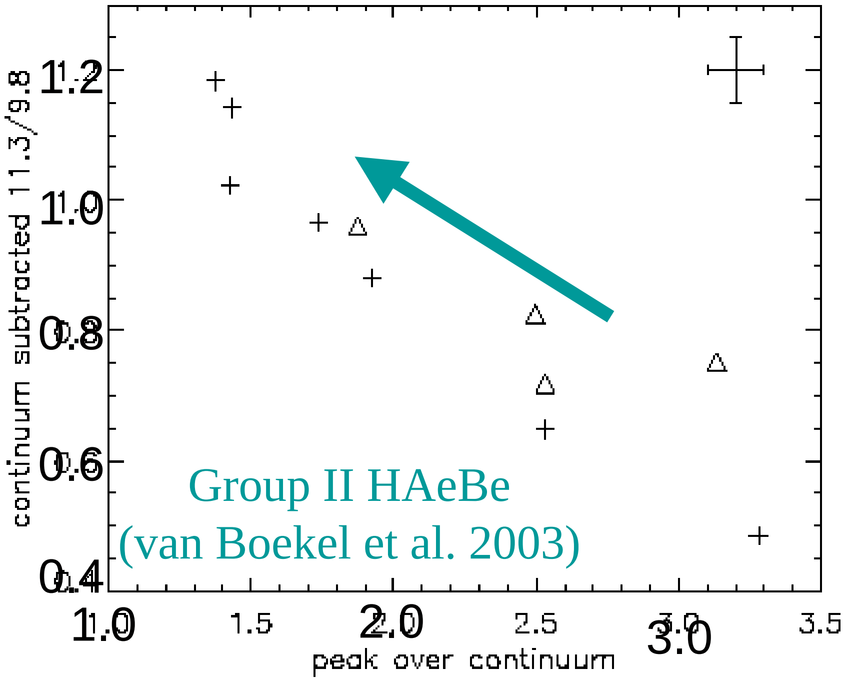
Processed dust




Our sample (TTS)

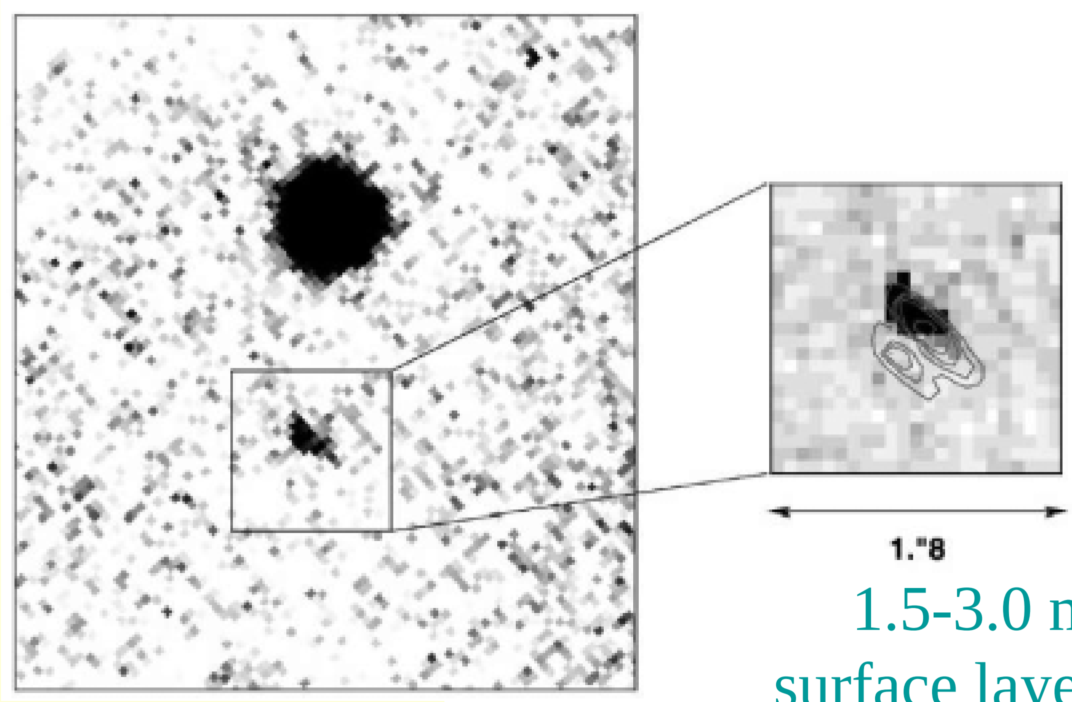
F11.3/F9.8 (grain shape indicator) have a correlation with feature strength?

Yes…



# Evidence for grain growth

Grain growth among these T Tauri stars is consistent with recent results of detection of MIR scattered light toward HK Tau B (McCabe et al. 2003)




Keck + LWS image at 11.8 micron

1.5-3.0 micron grains at the surface layer of this T Tauri disks

# Crystalline silicate abundance increase with stellar age ?

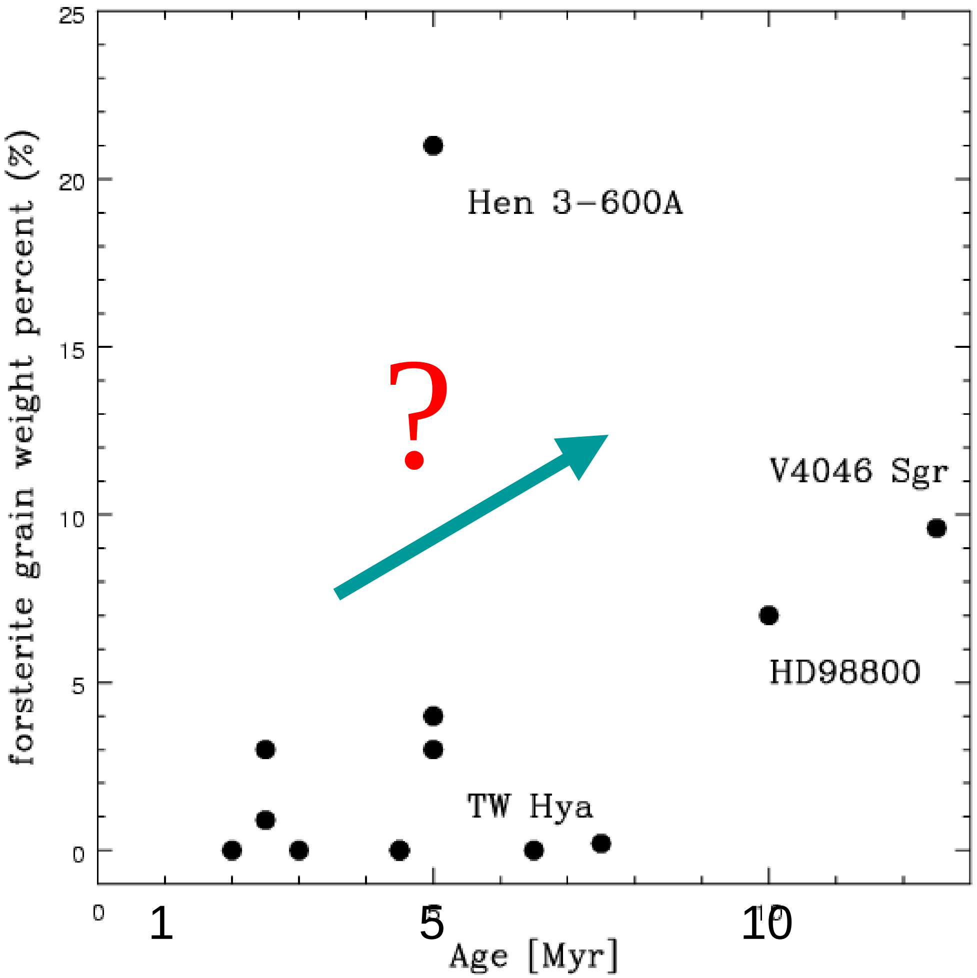
It seems that the old TTSs show crystalline silicate… but more sample is clearly needed!

Amorphous silicate is common among TTSs

⇩

Dust around T Tauri stars evolves more slowly than HAeBe stars?

Re-estimated stellar age using Siess et al. 2000 model



# Summary

- Amorphous silicate dust is common among T Tauri stars
- Large grains (1.4 micron or even more ) seems to be exist around T Tauri stars
- Some T Tauri stars exhibits crystalline silicate
- Possible tendency to appear in older system?

⇨ More sample is needed to clarify silicate dust evolution around low-mass young stars