EVOLUTION OF SOLIDS & PLANET FORMATION REVEALED BY SUBARU

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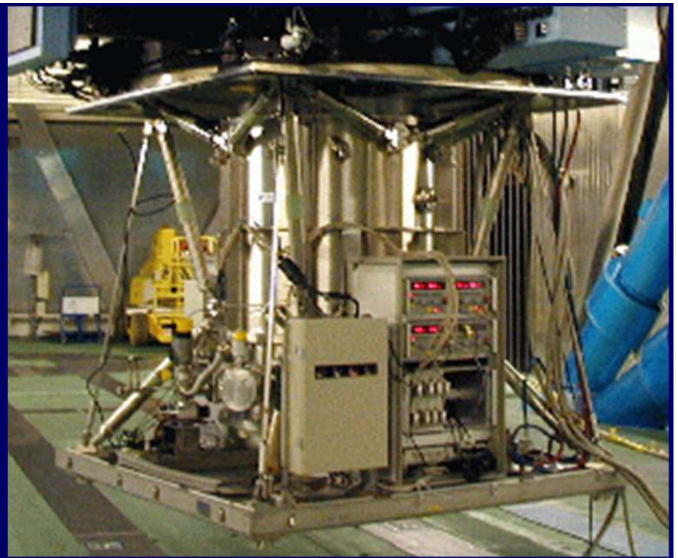
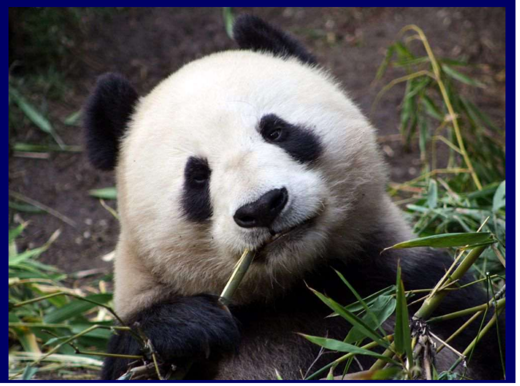
Thank you for giving me this opportunity

Mitsuhiko Honda



Mid-IR instrument COMICS

- COMICS team member
  - 2000～2004 upgraded AMPADC circuit boards
- 2005 Ph.D. based on Subaru/COMICS observations of protoplanetary disks
- I am biased to "ground-based mid-IR sciences"
  - COMICS will be decommissioned after S20A, ground-based MIR instrument is now endangered species… (conservation required !?)
  - To cover mid-IR wavelengths, new Mid-IR instrument that cover new parameter spaces (e.g. high-R) is desired (e.g. TMT/MICHI)



Outline

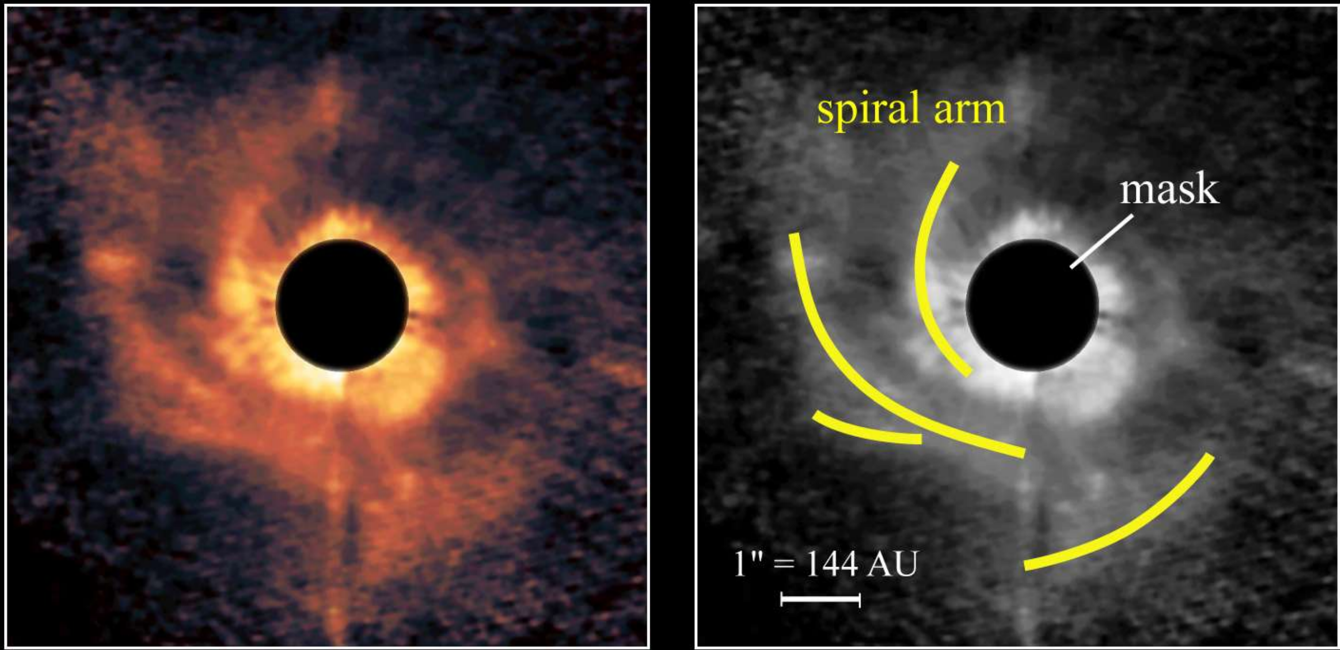
What Subaru has been done & will do for protoplanetary/debris disk sciences ?

- Disk imaging
  - 2000s : AO36, CIAO, IRCS, COMICS
  - 2010s : AO188, HiCIAO, SCExAO
  - 2020s : SCExAO
- Disk solid material evolution
  - Ice (mostly focus on H_2O)
  - Silicates

Disk imaging

Disk imaging (early 2000s) :

Spirals in the protoplanetary disks



Protoplanetary Disk Surrounding the Star AB Aurigae

Subaru Telescope, National Astronomical Observatory of Japan

CIAO+AO (H)

April 18, 2004

Subaru/CIAO+AO 36 in H-band

Protoplanetary disk around Herbig Ae AB Aur

Fukagawa et al. 2004

Spiral features are clearly recognized (like spiral galaxy !)

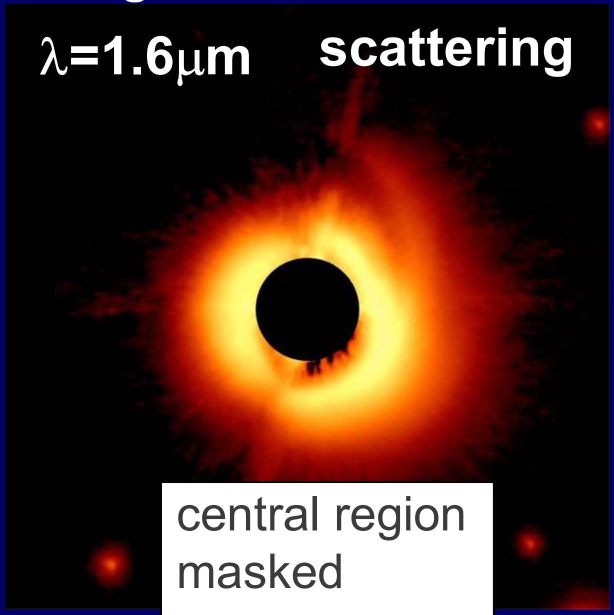
Disk self-gravitational instabilities vs. planet induced density wave are discussed (no clear conclusions yet) ask Muto-san !

Disk imaging (early 2000s) :

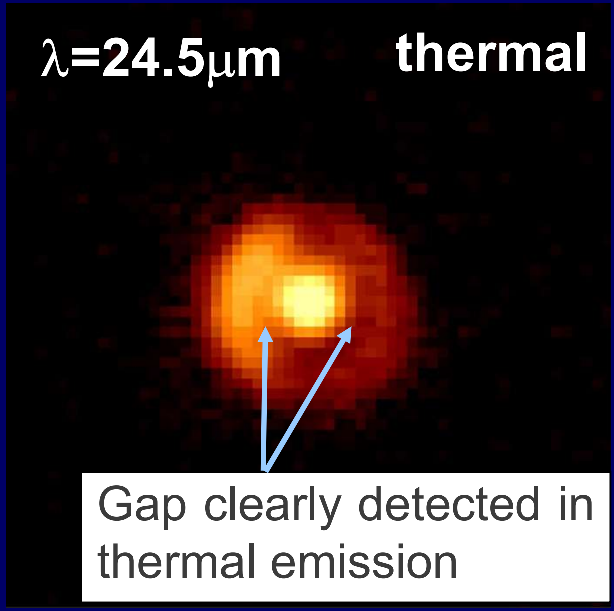
spiral and gap in the protoplanetary disks

- CIAO (*scattered light*) and COMICS (*thermal emission*) detected spiral and gaps in the Herbig Fe star HD142527 protoplanetary disk
- Good show case of multi-wavelengths approach
- Observing proto-Jupiter formation ?

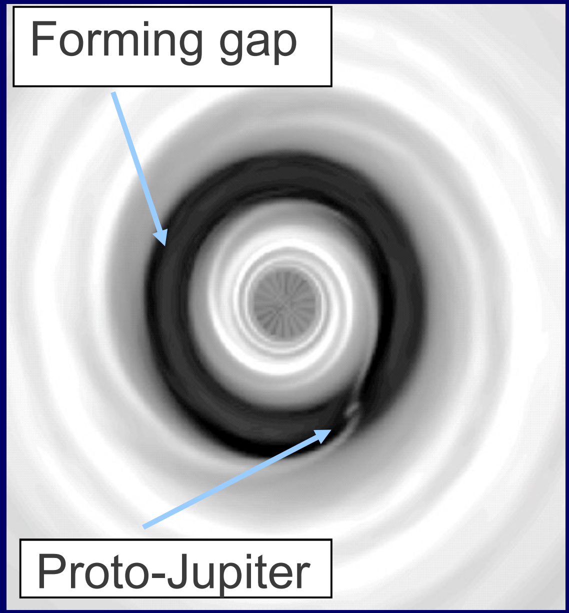
Fukagawa et al. 2006



Fujiwara, Honda, et al. 2006

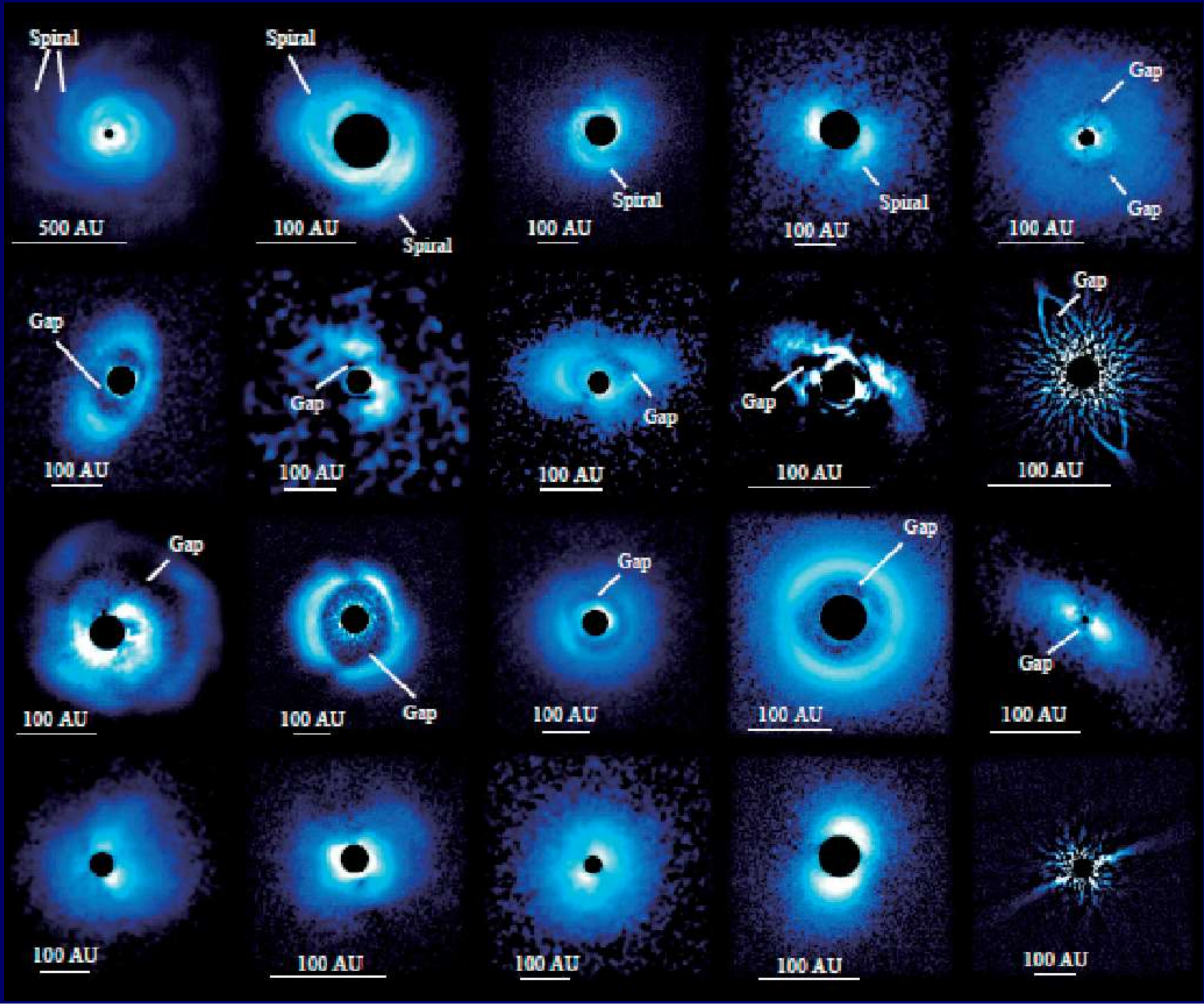


Model: Bryden et al. 1999



Disk imaging (2010s) : Subaru/HiCIAO+AO188 SEEDS project

gaps and spirals ubiquitous in disks

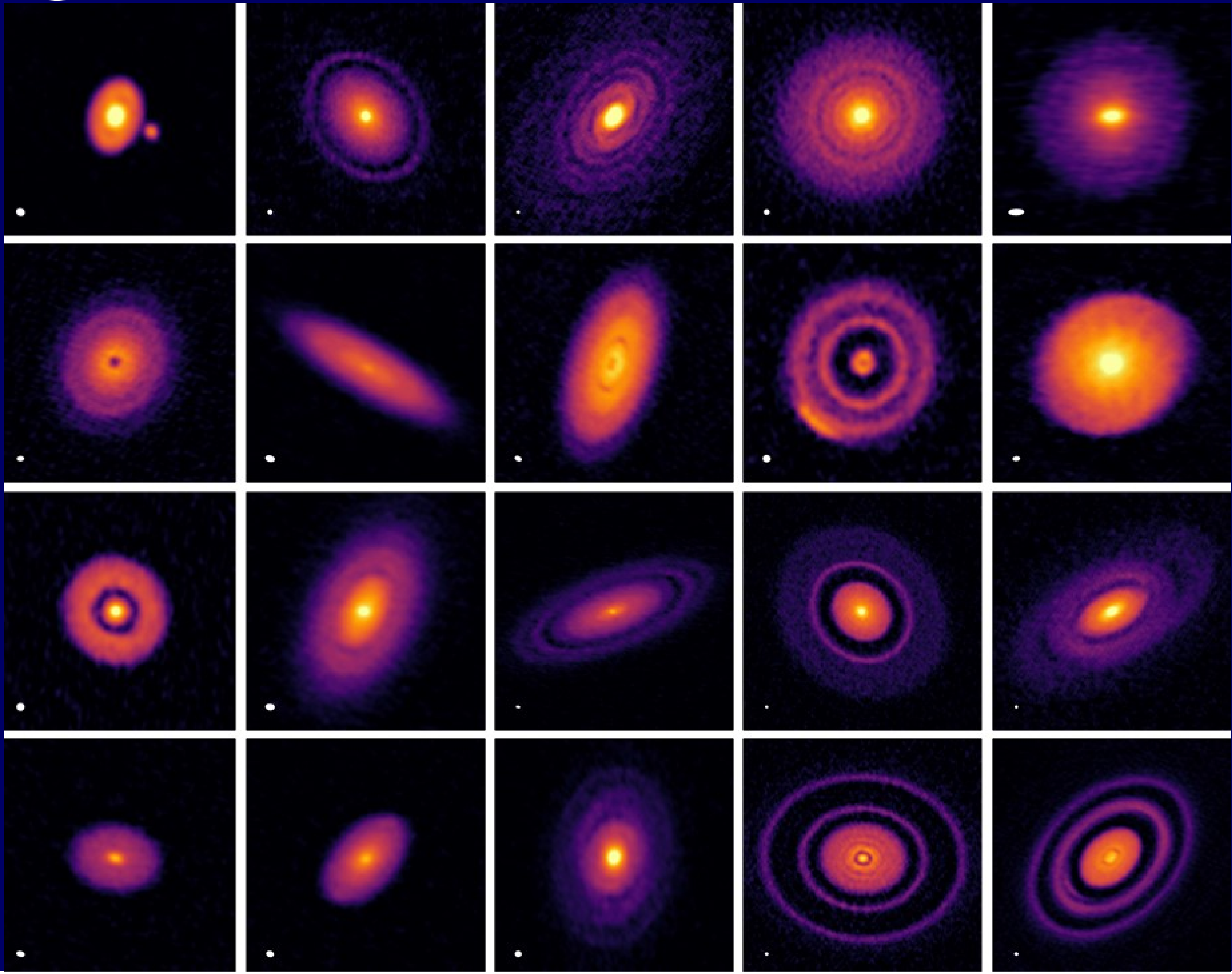


Better IWA and contrast achieved thanks to AO188

HiCIAO PDI mode is efficient for scattered light imaging of disk

Disk imaging (2010s) :   ALMA DSHARP

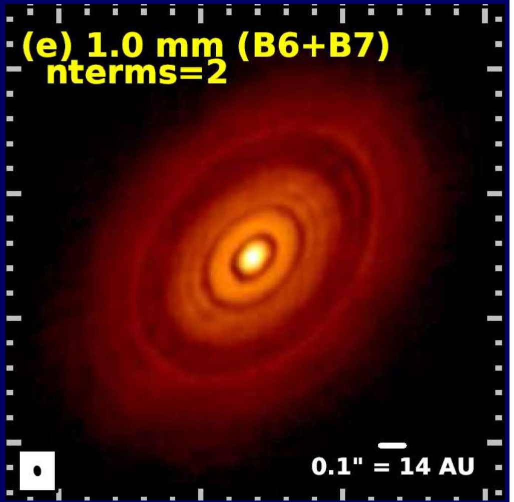
gaps and spirals ubiquitous in disks



Confirming ubiquity of gaps with higher spatial resolution

What causes gaps & spirals in disk ?

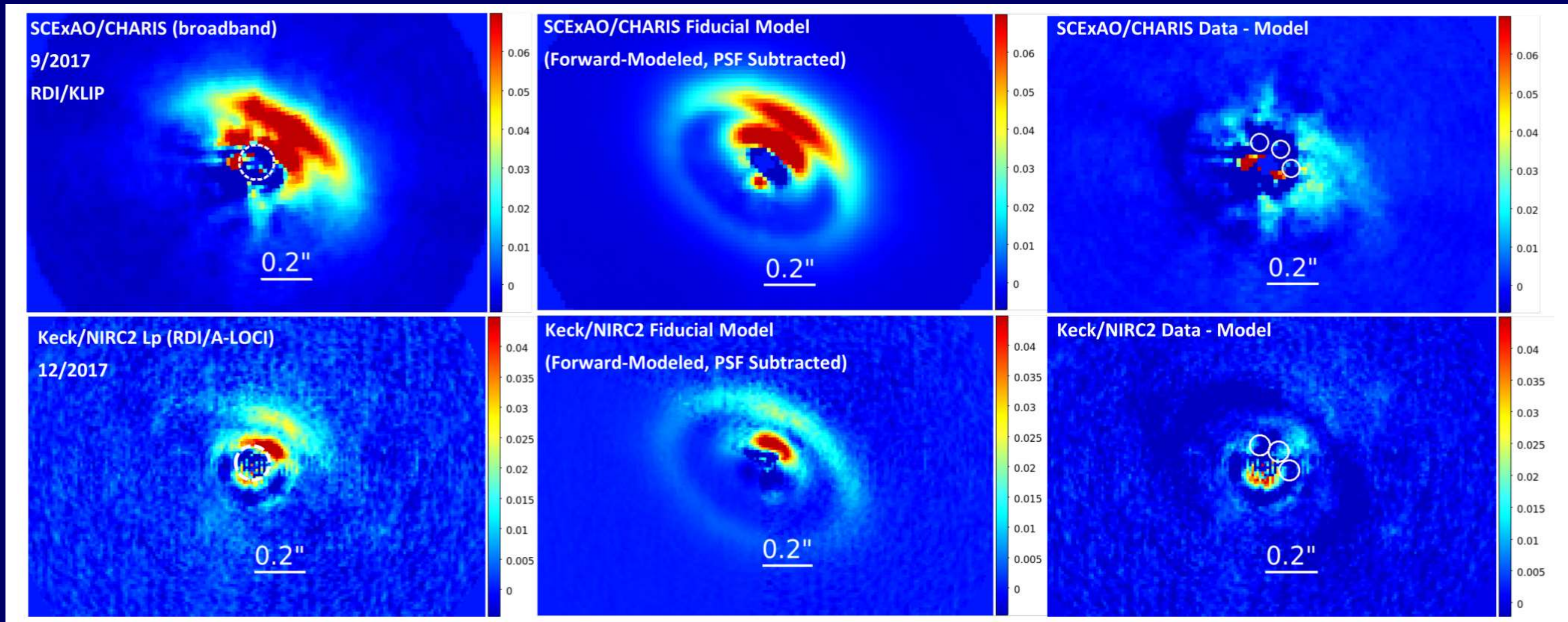
- naive guess : forming planets ! ☺
- interpretations other than planets
  - Snow line of various molecules (e.g. Zhang+2015, Okuzumi+2016,…)
  - Instabilities of disk (e.g. Takahashi & Inutsuka 2014)
  - etc…



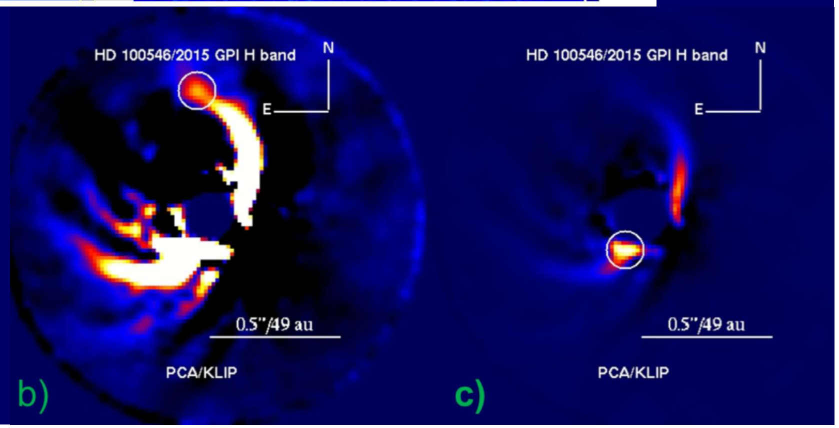
- At this moment, no clear conclusions yet
- How can we reach the truth ?
  - ***Detection/non-detection of the forming planets in the protoplanetary disk*** is the key

Forming planets in disks claimed ... but

- LkCa15 b,c,d (e.g. Kraus&Ireland2012)
  → disk feature ? (Currie+2019)

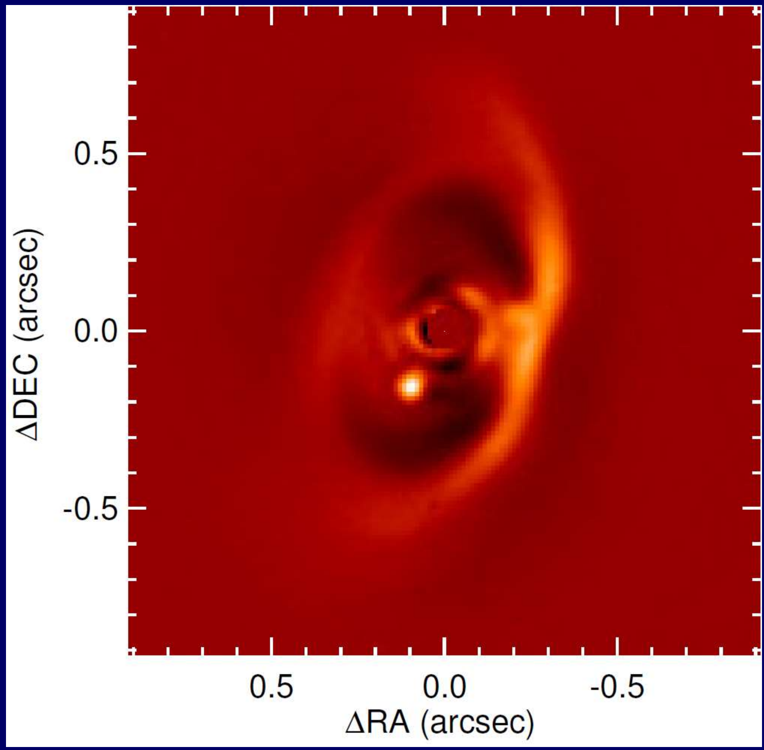


- HD100546 b,c **(Quanz+2013)**
  confirmation on-going
  (e.g. Currie+2018)



PDS70 b,c real forming planets in disk ?

- **PDS70b,c in the gap of transitional disk around PDS70** (Keppler+2018, Muller+2018)
- Follow-ups discovered associated Hα emission (accretion signature) (Wagner+2018)
- Forming planets finally confirmed in the disk
- Finally, "*protoplanetary*" disk is confirmed that it is *really forming planets* as assumed for long time (~50yrs?)

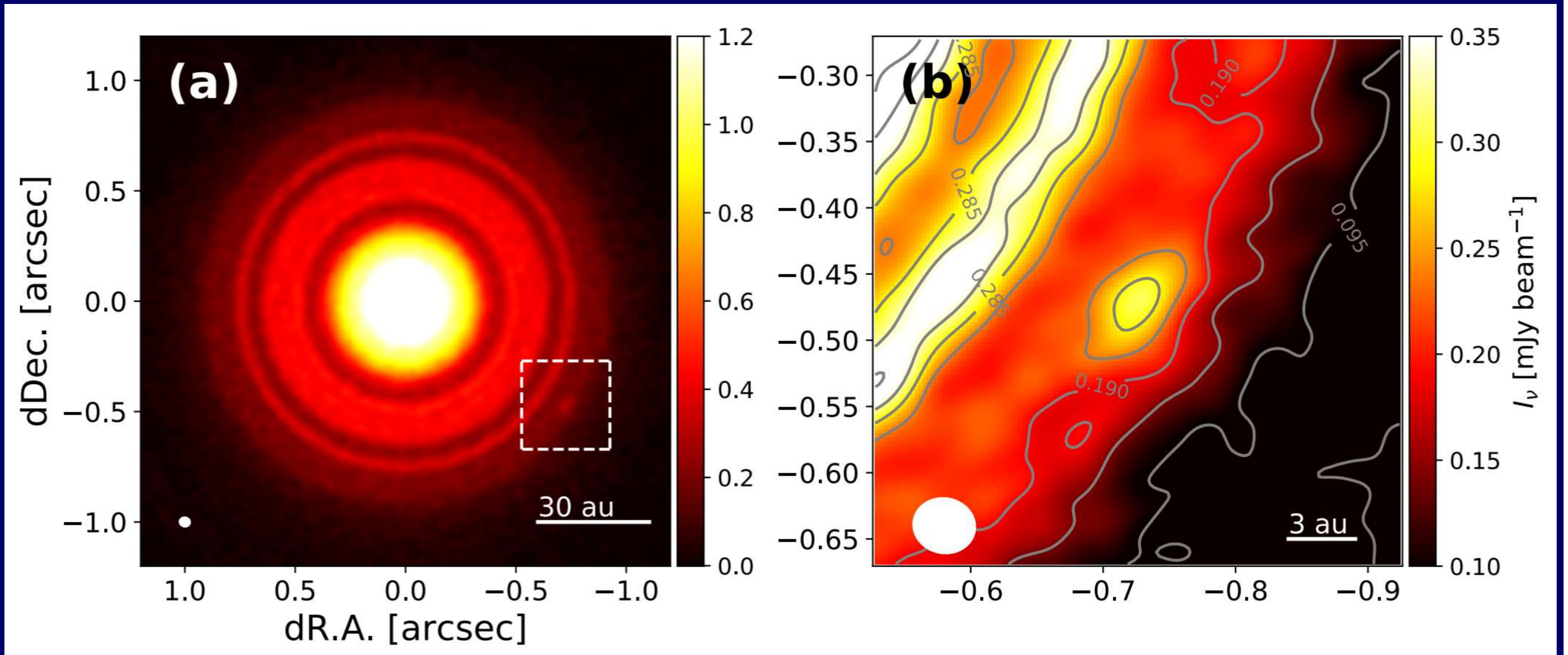


Disk imaging (2020s) :

what Subaru (&8-10m) do in next decades?

- SCExAO search for forming planet in disks
- Follow-ups of ALMA circumplanetary disk (CPD) candidates ?
  - Planet photosphere can only be traced in opt/IR
  - ALMA cannot distinguish CPD from dust clump

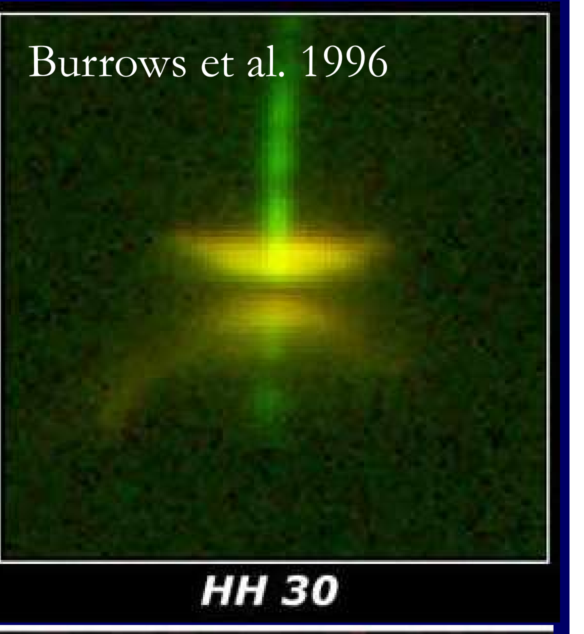
CPD candidate of Neptune-mass forming planet around TW Hya by ALMA (Tsukagoshi+ 2018)

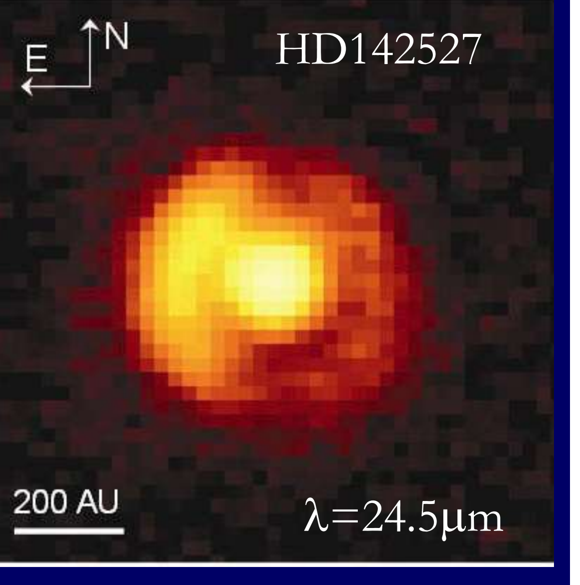


Disk solid material evolution
ice (H_2O) & silicates

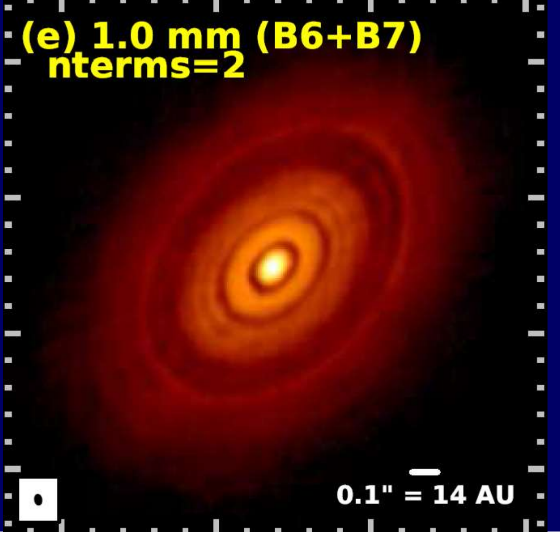
Continuum observations of protoplanetary disks

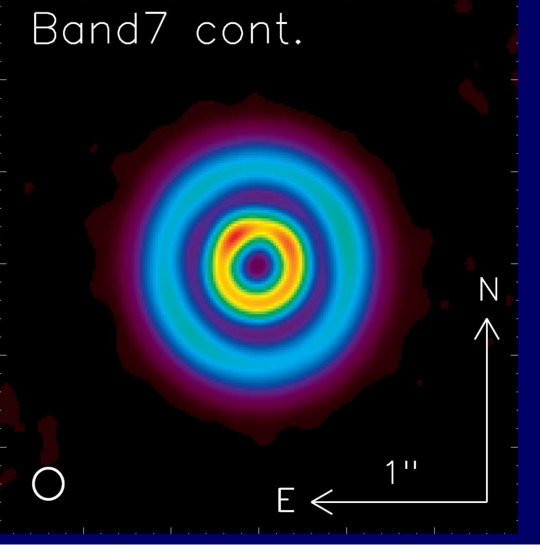
- Reflect structures of the disk
- ***Little information*** about its composition
- Need **spectra** to discuss the compositional information





Fujiwara, Honda+2006

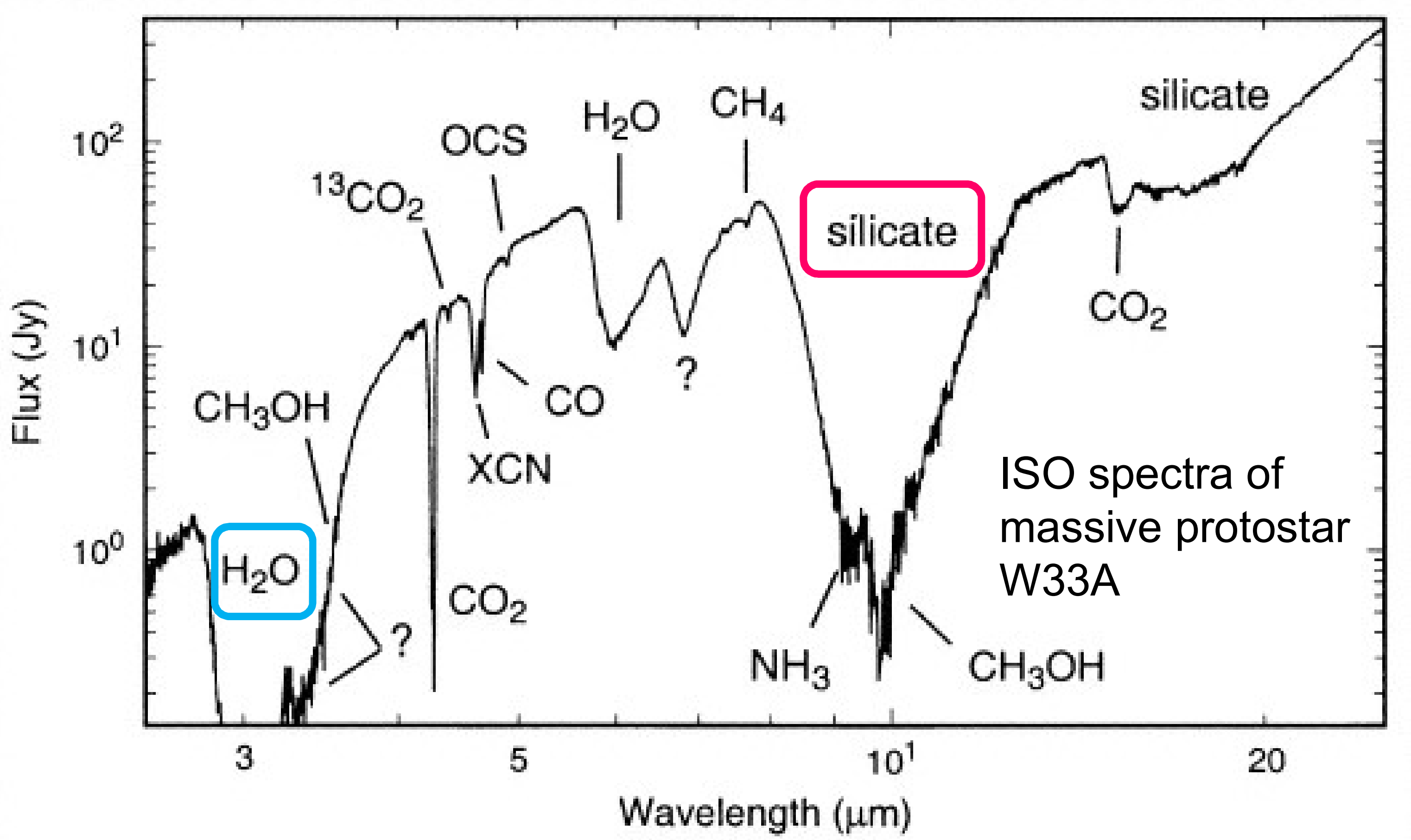




Solid state features of ices/solids in the thermal IR wavelengths

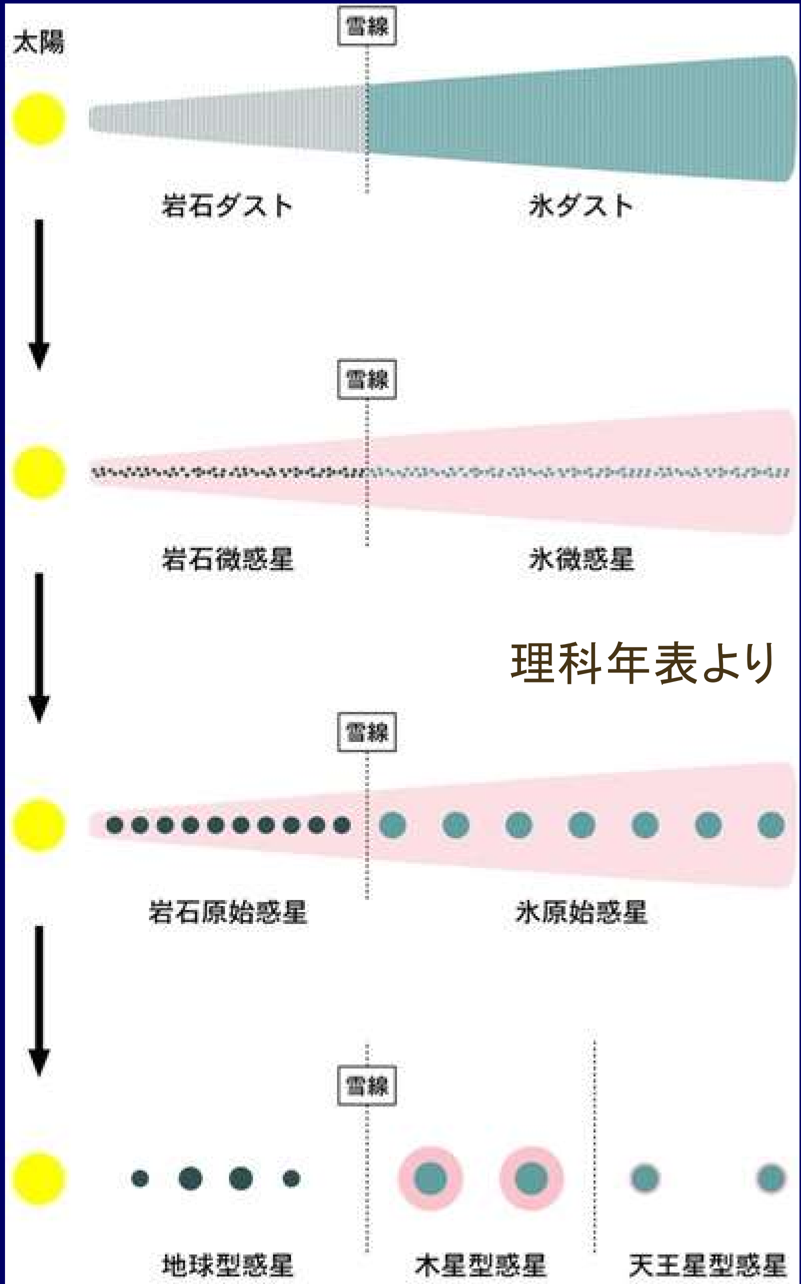
- In thermal IR (λ>~2μm), various solid state features exist
- Prominent ~10μm silicate features (Si-O vib.)
- Prominent ~3μm water ice absorption (O-H vib.)

NOT Available in radio wavelengths



ISO spectra of massive protostar W33A

Disk solid material evolution
ice (H_2O)

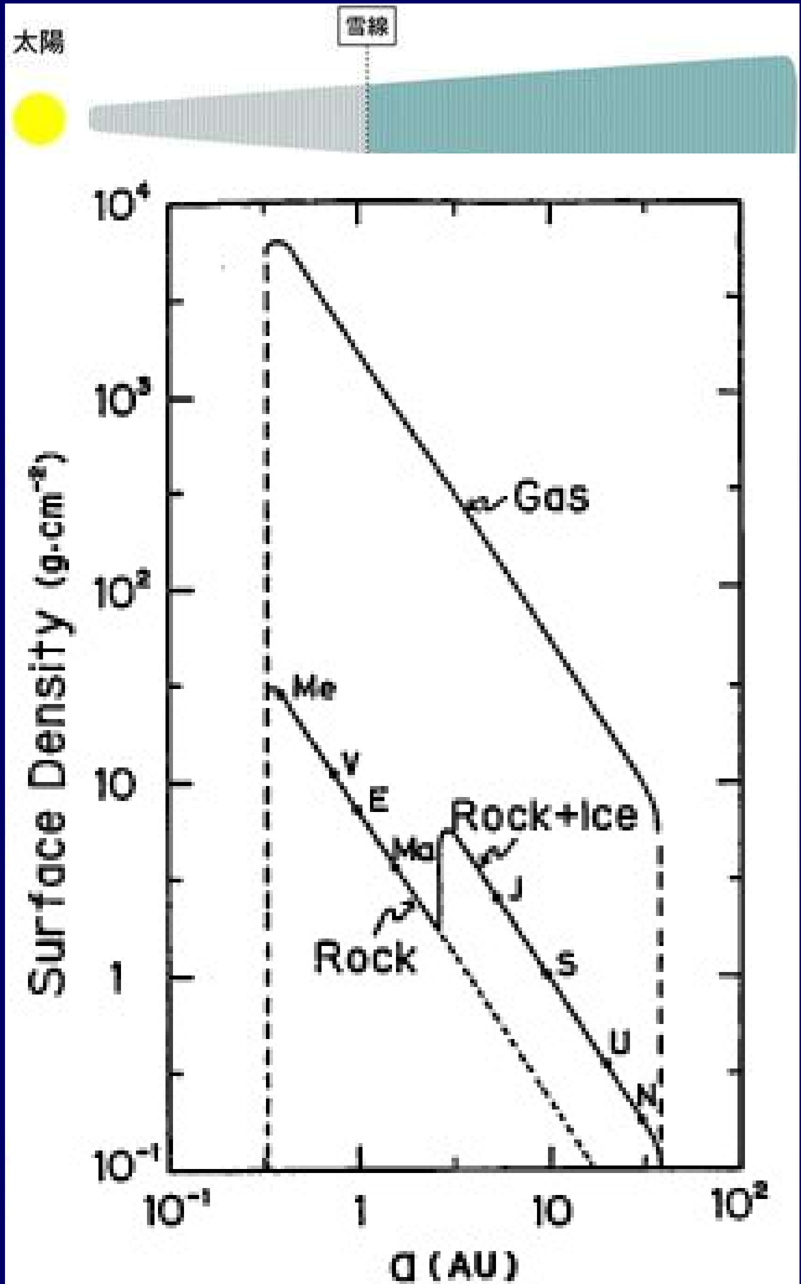


Solar System snowline ~2.7AU (Hayashi 1981,1985)

H_2O snowline and planet formation

- Role of H_2O ice grains in planet formation
  - enable formation of cores of gas giants (～$10M_E$)
  - Dividing regions of rocky terrestrial planet & gas giant planet regions
  - First planetesimals / protoplanets formed near snow line ? (e.g. Lecar+2006)
  - Water delivery to terrestrial planets (snow line <1AU ?)
- Observations of snowline (ice distribution) is important

H_2O snowline and planet formation



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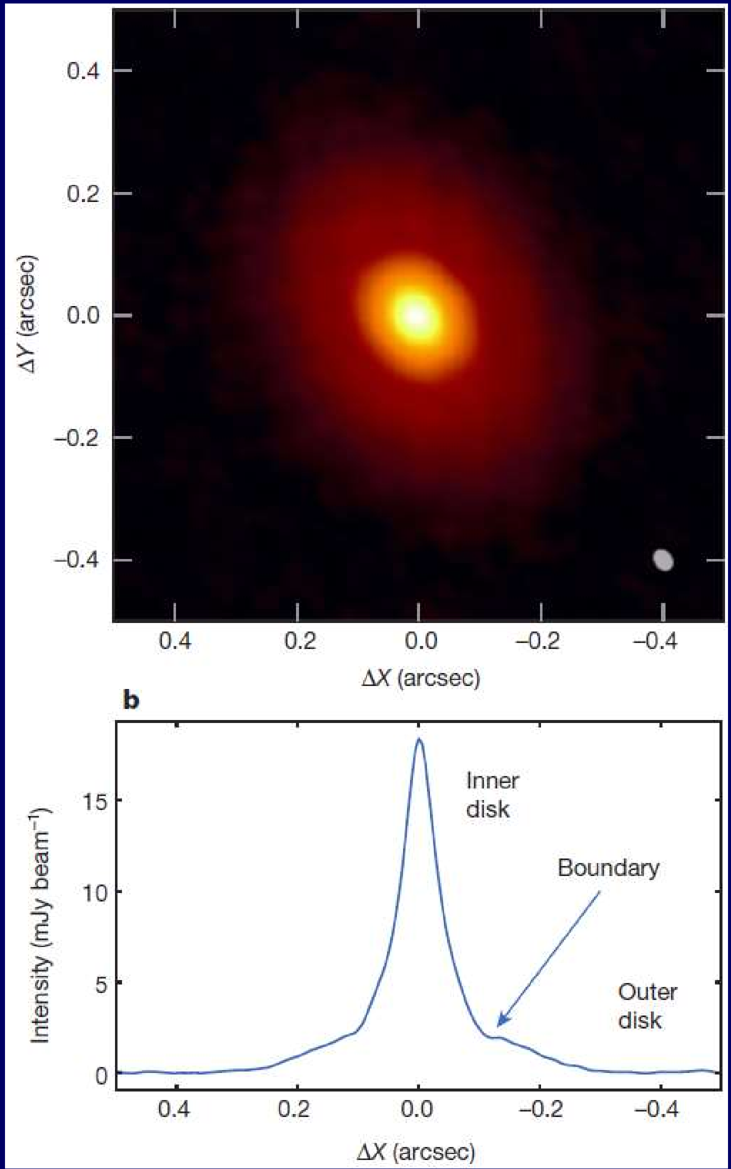
Solar System snowline ~2.7AU (Hayashi 1981,1985)

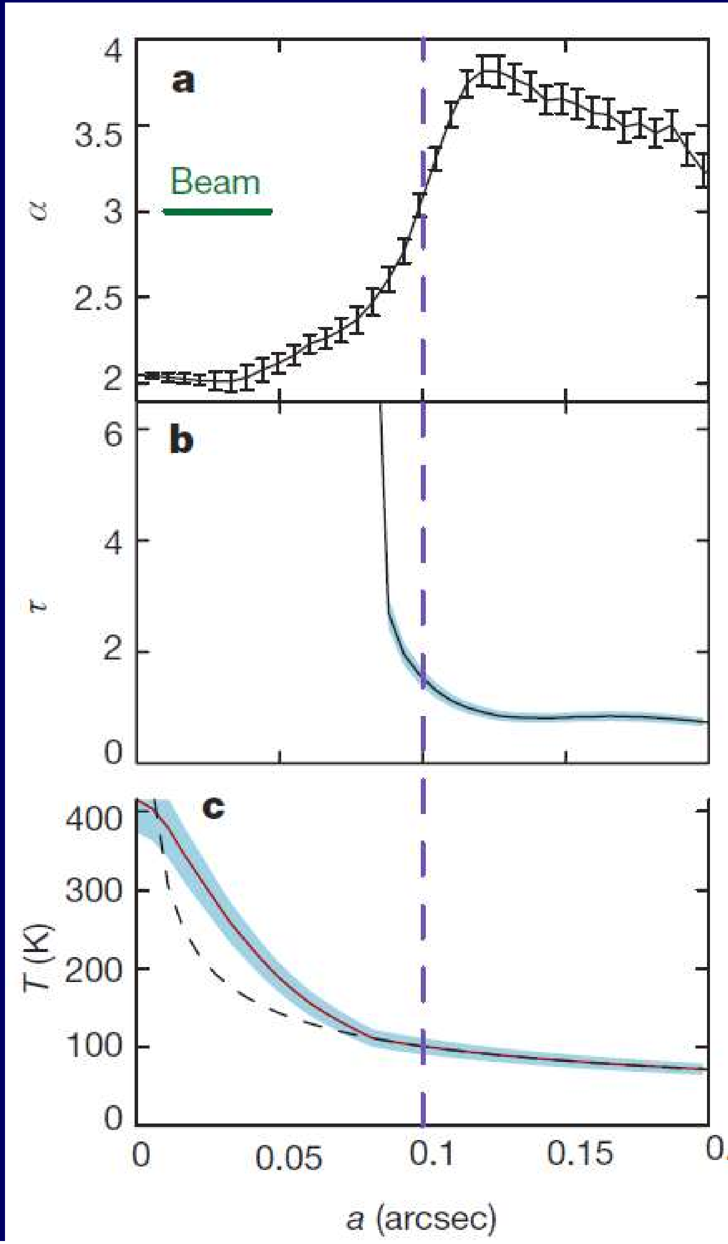
ALMA Detection of H_2O snow line !?

Cieza+2016, Nature



- V883 Ori (d~414pc)
  - FU Ori type-star
  - Episodic outbursting object
  - luminosity of $400L_\odot$
  - $\dot{M}= 7 \times 10^{-5} M_\odot$ per year
- ALMA Band 6 continuum
- Spectral slope α change at 0.1”(~42AU) →snowline ?

ALMA Detection of H_2O snow line !?



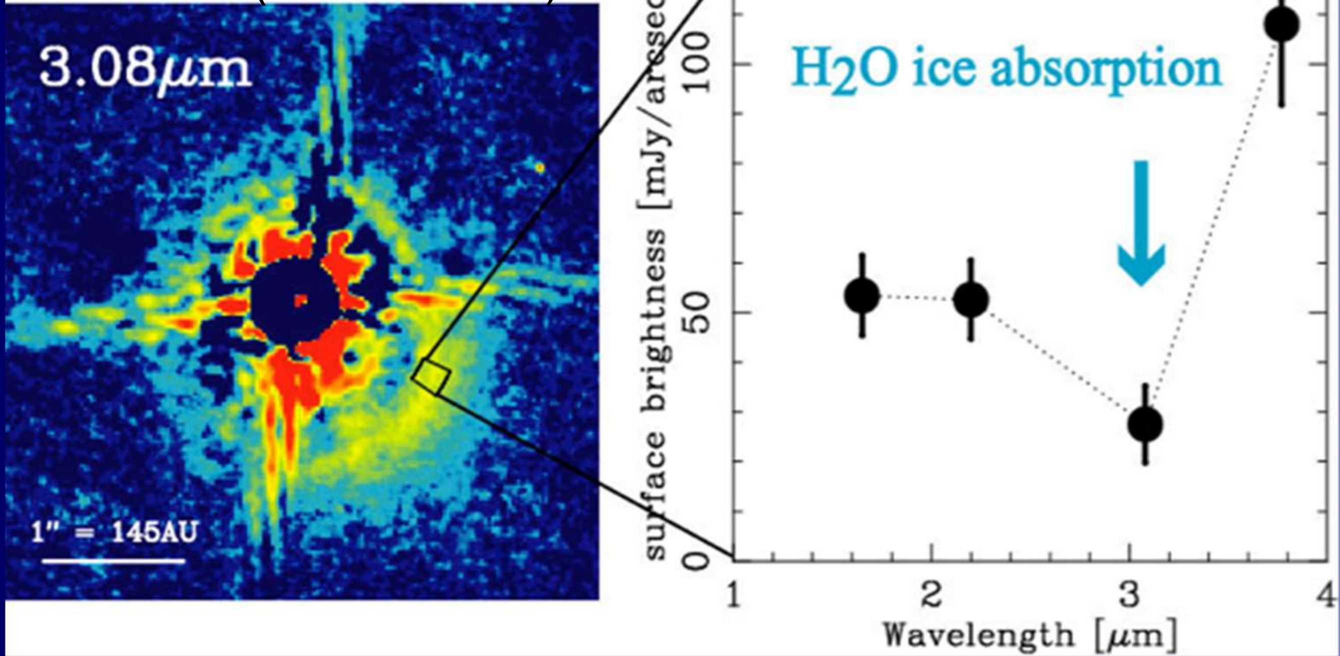
Cieza+2016, Nature

- Spectral slope α change at 0.1”(~42AU) →snowline ?
- Caution: this is just ***continuum*** observations !
- Indirect detection → ***direct observations of water itself is needed !***
  - $H_2^{18}O$ ***gas*** line in radio
  - Water ***ice*** band in IR

Ice absorption mapping to trace ice distribution

2-4μm "spectra" of face-on disk scattered light

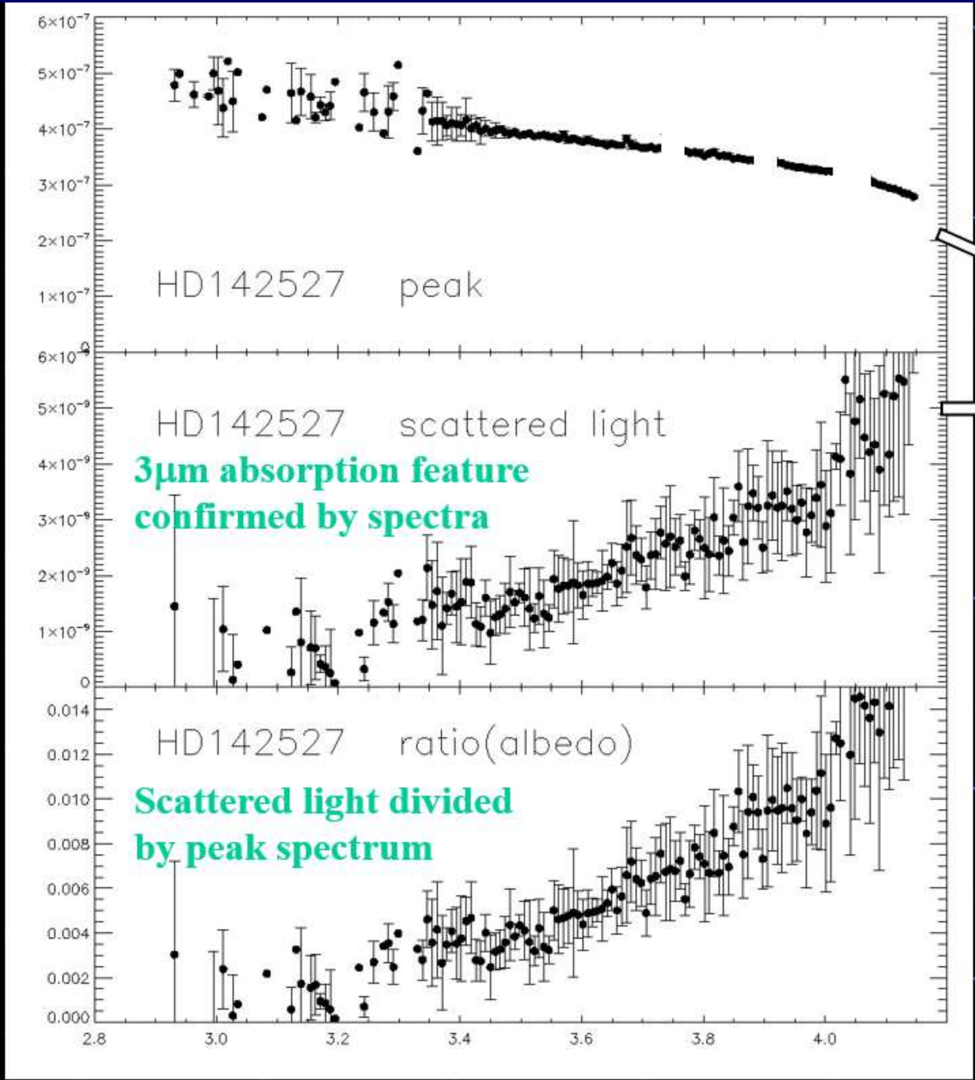
HD142527 (Honda+2009)

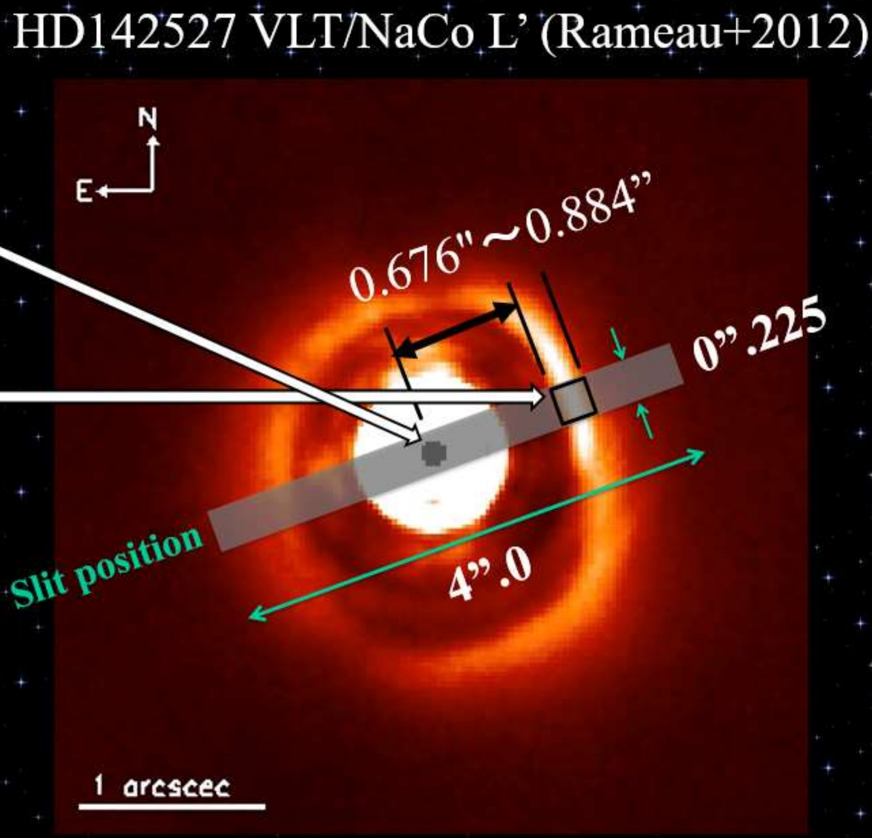


IWA~0.7"
→ much improvement needed…

- By high-spatial resoltuion **water ice absorption mapping,** we can reveal the water snow line
- However, the bright stellar speckle noise hampers us to trace inner regions → improvement of inner working angle (IWA) needed as close as ~0.1"

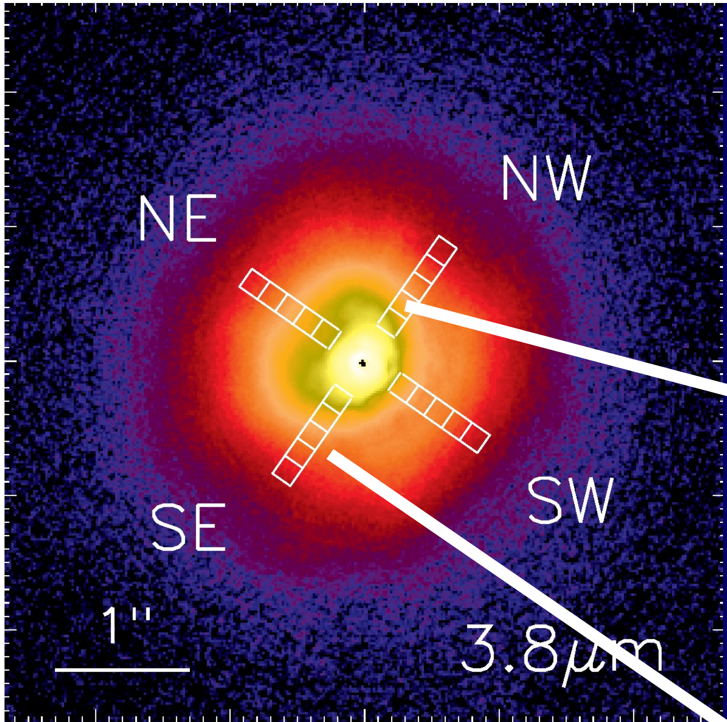
HD142527 disk revisited with Subaru/IRCS+AO188+POL Honda+in prep.



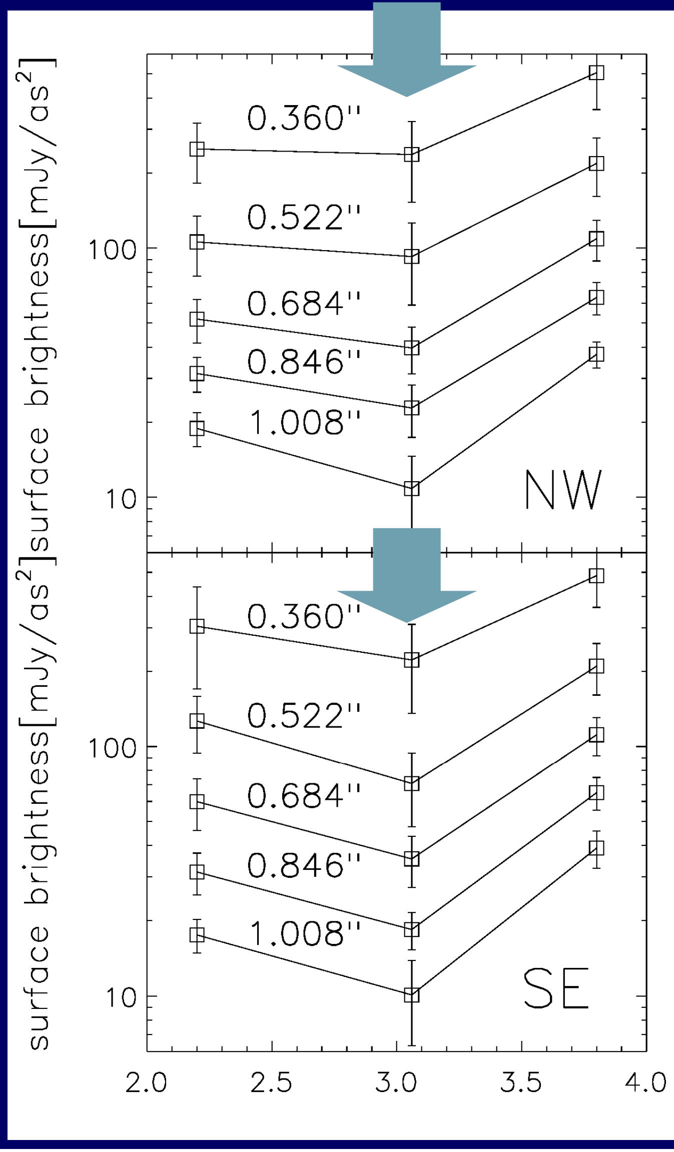


Confirmed water ice absorption feature by slit spectroscopy

2-4μm “spectra” of HD100546 disk scattered light



HD100546 disk by Gemini/NICI
(Honda et al. 2016)



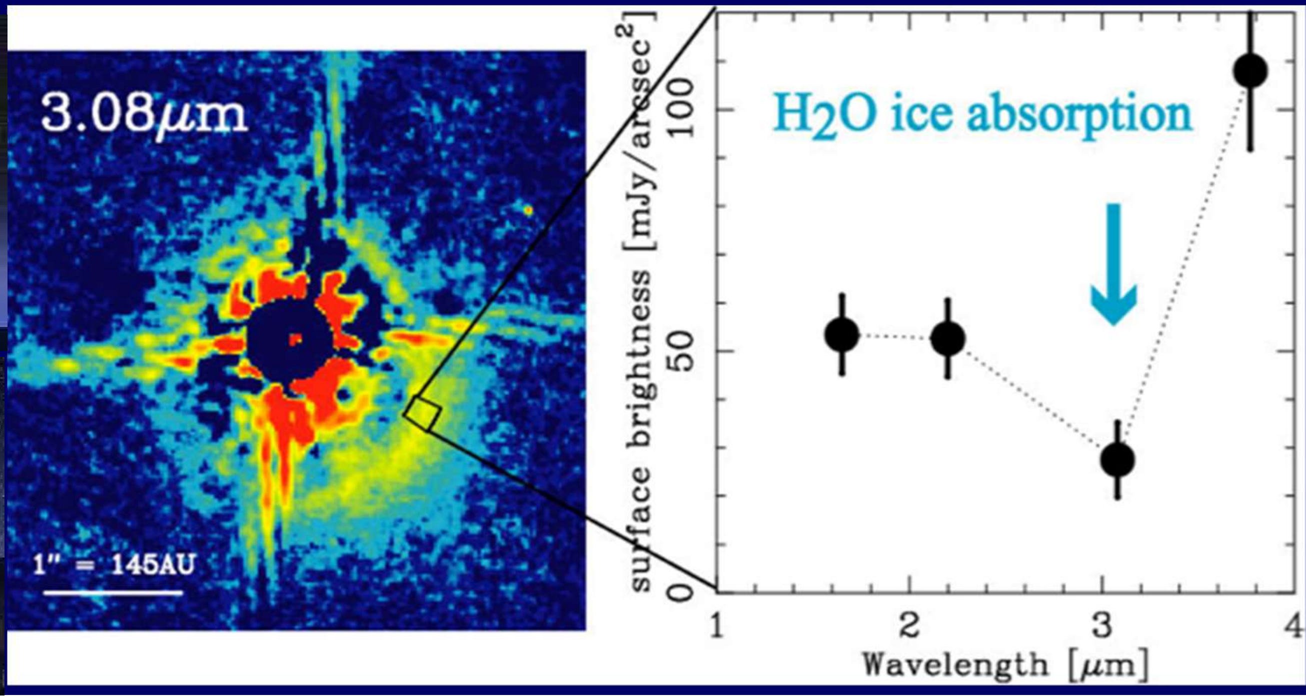
shallow 3.1μm water ice absorption detected as close as ~40AU to the star

IWA ~ 0.3”

→ Still IWA improvement needed to trace surface snowline

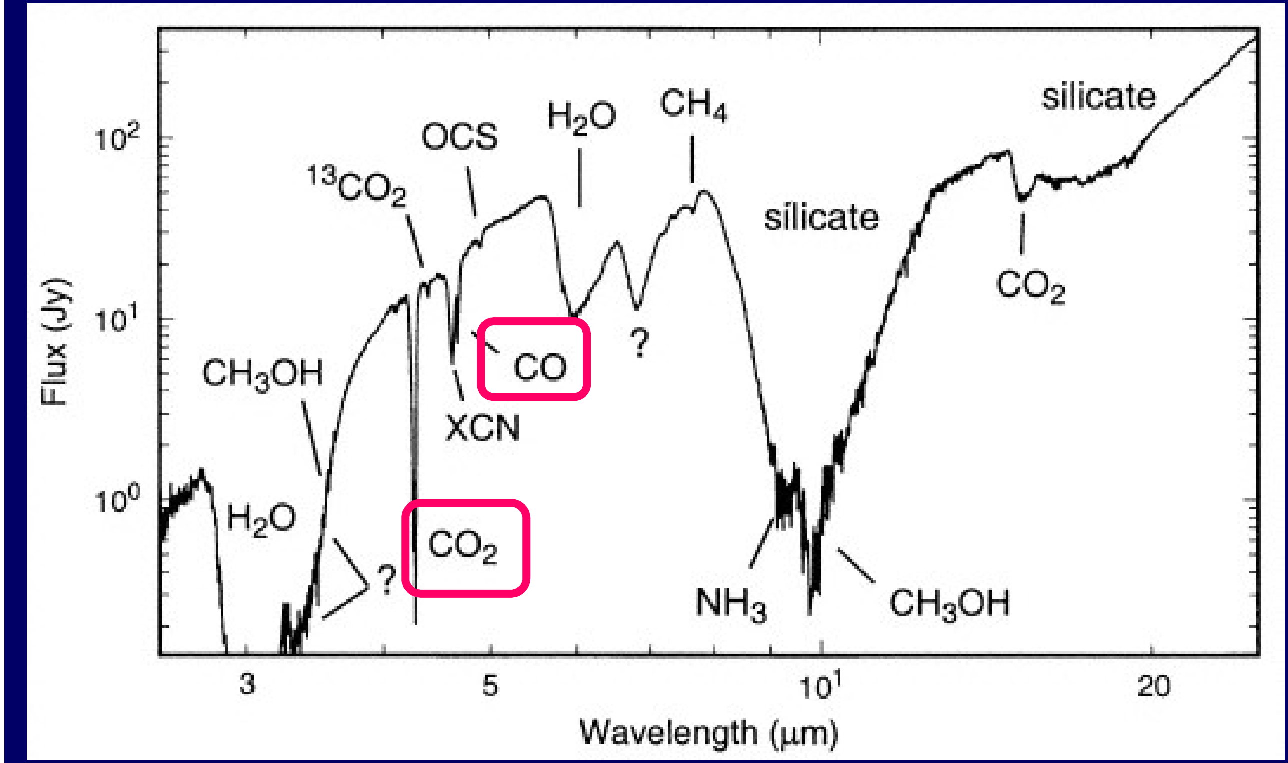
Go closer to see ice absorption disappear : snow line by TMT, GMT !

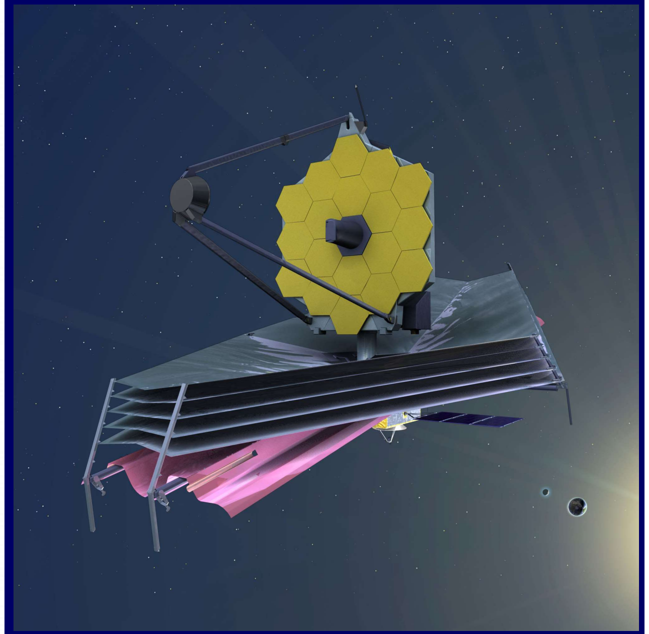
- Surface H_2O snow line is expected to be 10-20au for Herbig Ae disks → ~0.1” at 140pc
- TMT/GMT will enable us to trace H_2O snow line with smaller IWA



JWST mapping of ice in the disk

- JWST will provide much better sensitivity in $\lambda>2\mu m$
- Not only water ice, but also CO (4.67μm) and CO_2 ice (4.25μm) mapping possible
  - CO, CO_2 snow lines further than H_2O





Disk solid material evolution silicates

Star & Planet formation scenario from the observational point of view

ISM

0 Molecular cloud

10^5 protostar

10^6 T Tauri star

Herbig Ae/Be star

10^7

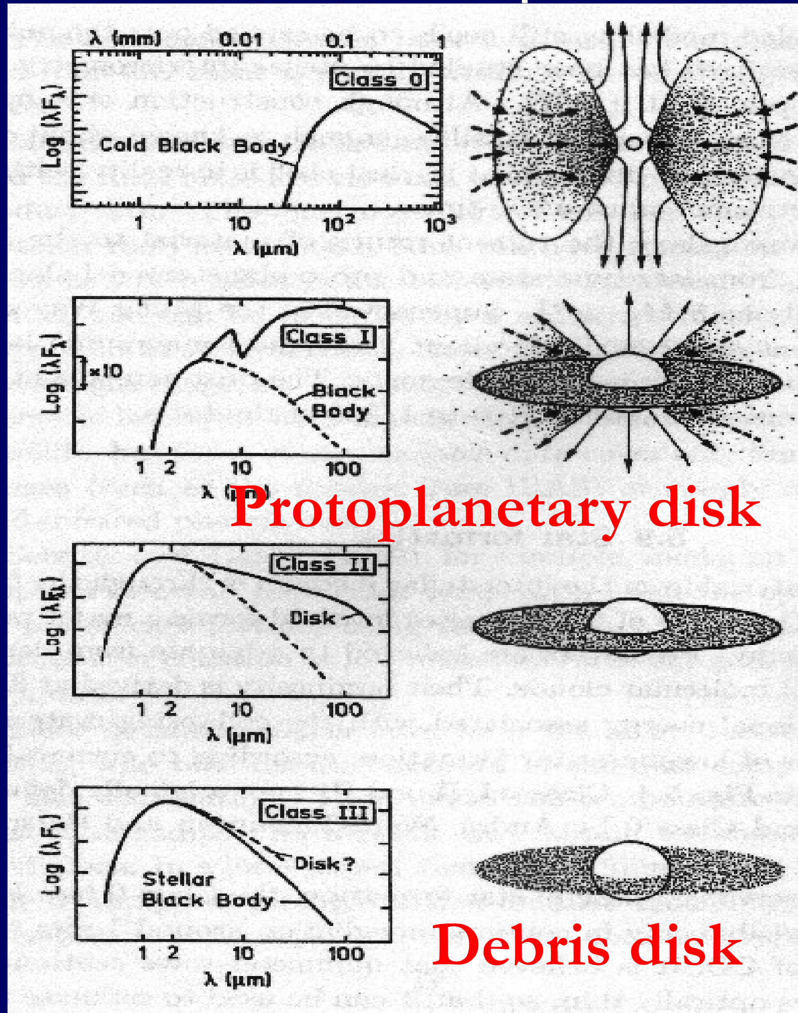
(main sequence star)

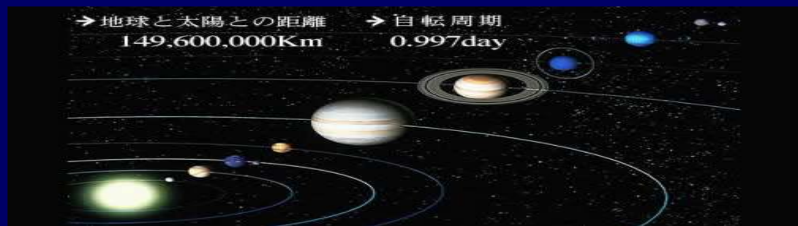
10^8 Vega-like star

10^9

Solar system

Planetary system



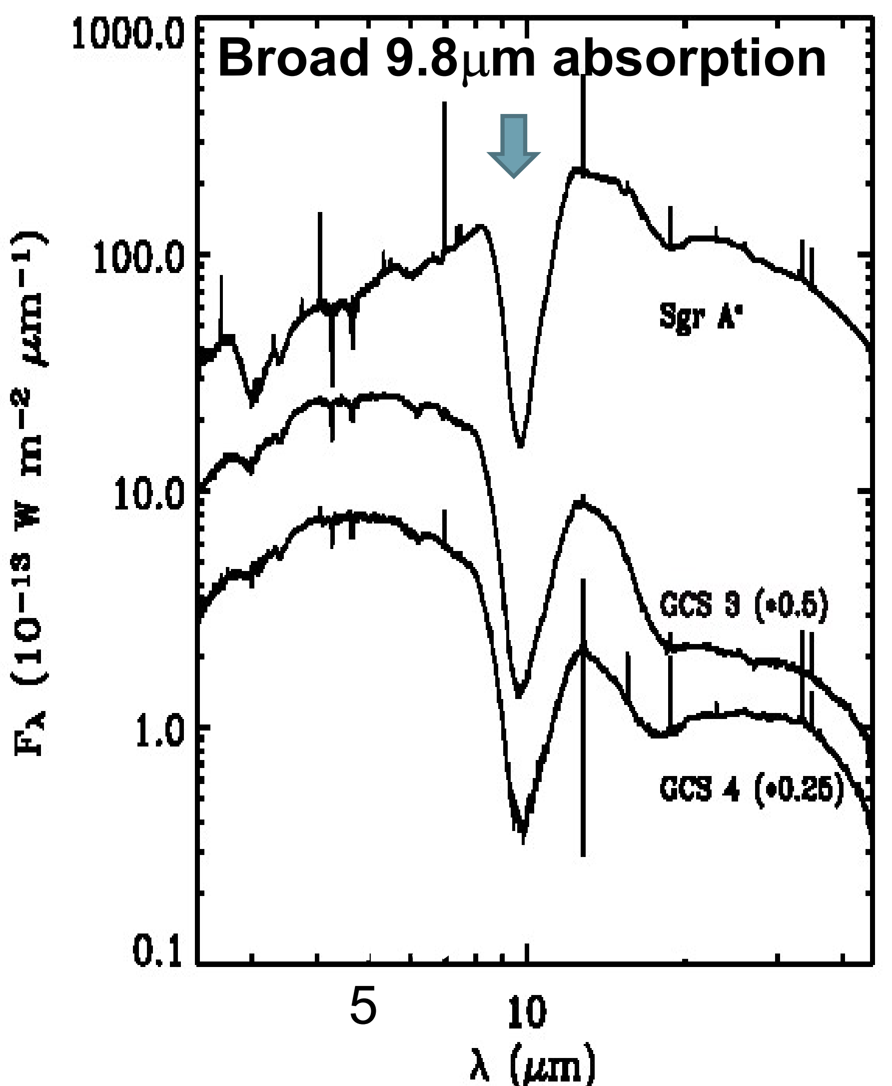


ISM

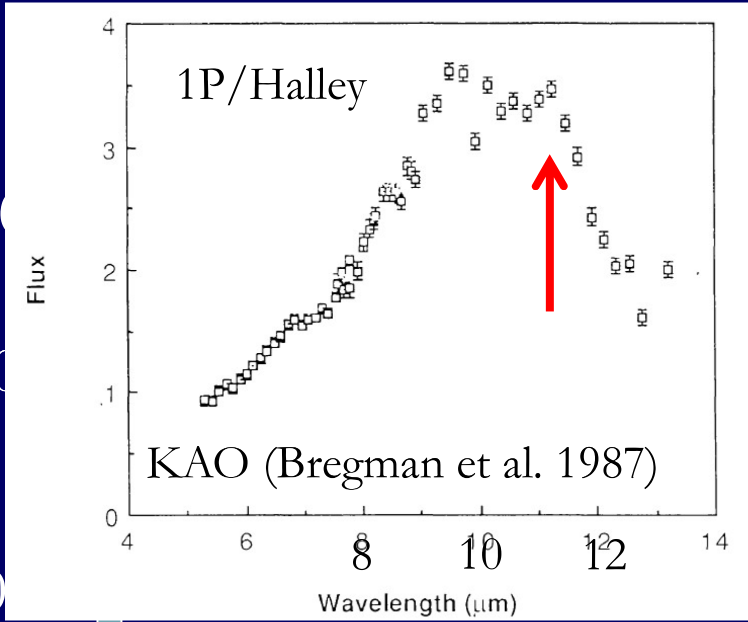
Molecular cloud

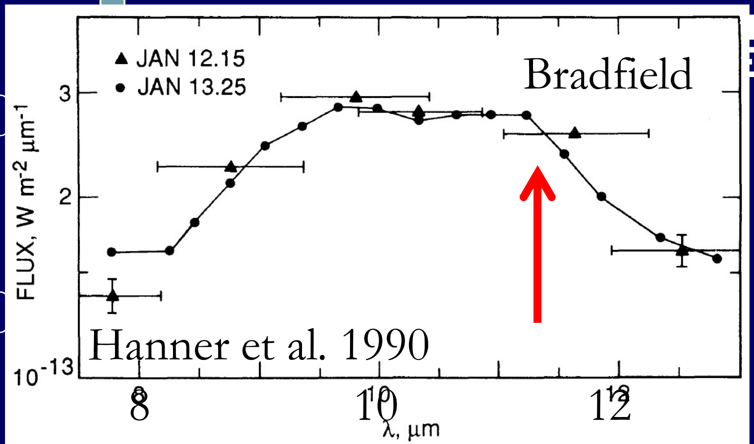
0

Silicate dust in the ISM



- Silicate dust in the ISM is almost completely amorphous
  - crystal < 0.4% (Kemper+2004)
- Protostellar envelope is also mostly amorphous



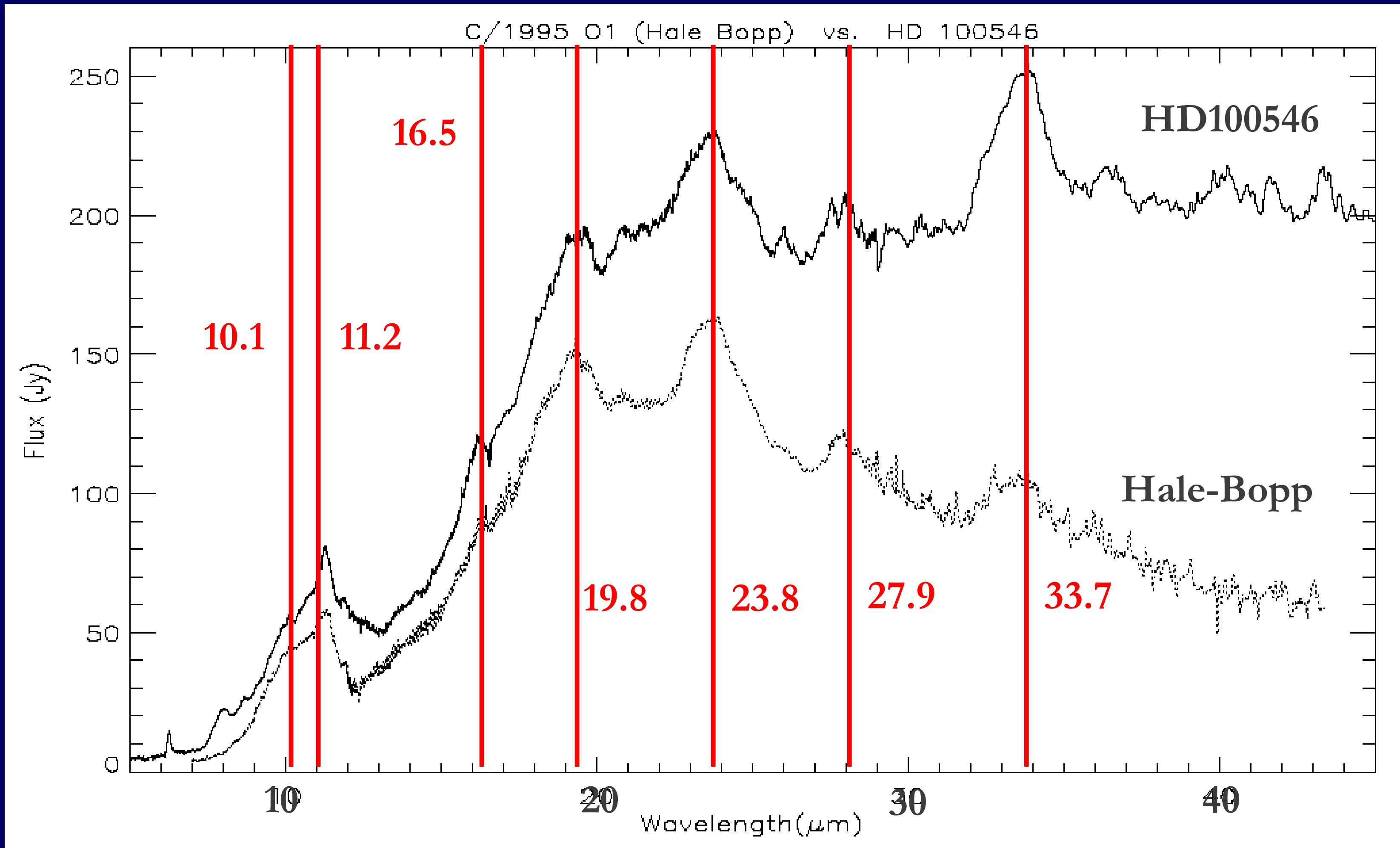


Solar system
Planetary system

Cometary silicates (80s ~ early 90s)

- Contain both crystalline and amorphous silicate
  - 11.2μm comet Halley (Bregman et al. 1987)
  - Comet Bradfield (Hanner et al. 1990)
- Origin of crystalline silicate in comets ?
  - T~1000K required to crystallize silicates
  - Mixture of high and low temperature material

ISO revealed silicate crystals present in Herbig Ae/Be protoplanetary disks (late 90s)



(Age 10Myr; Malfait et al. 1998)

ISM

0 Molecular cloud

10^5 protostar

10^6 **T Tauri star**

10^7 Herbig Ae/Be star

(main sequence star)

10^8 Vega-like star

10^9

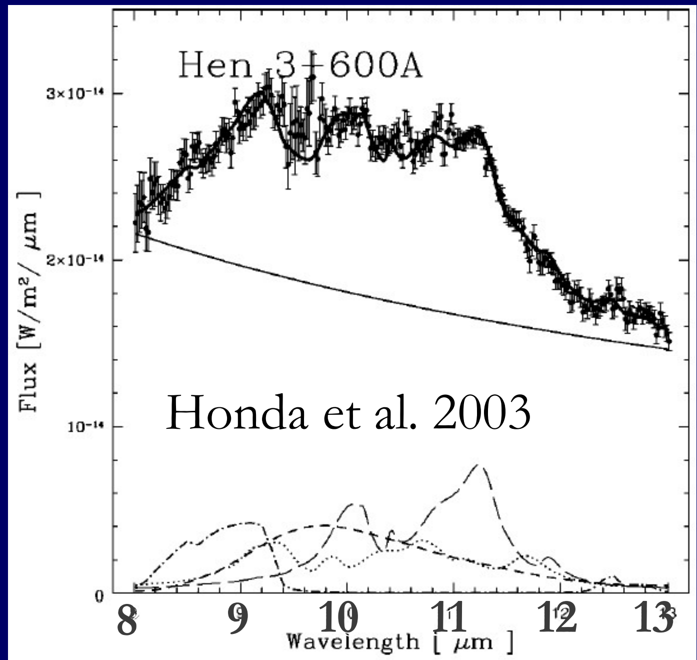
Solar system

Planetary system

T Tauri disk siliate (early 2000s)

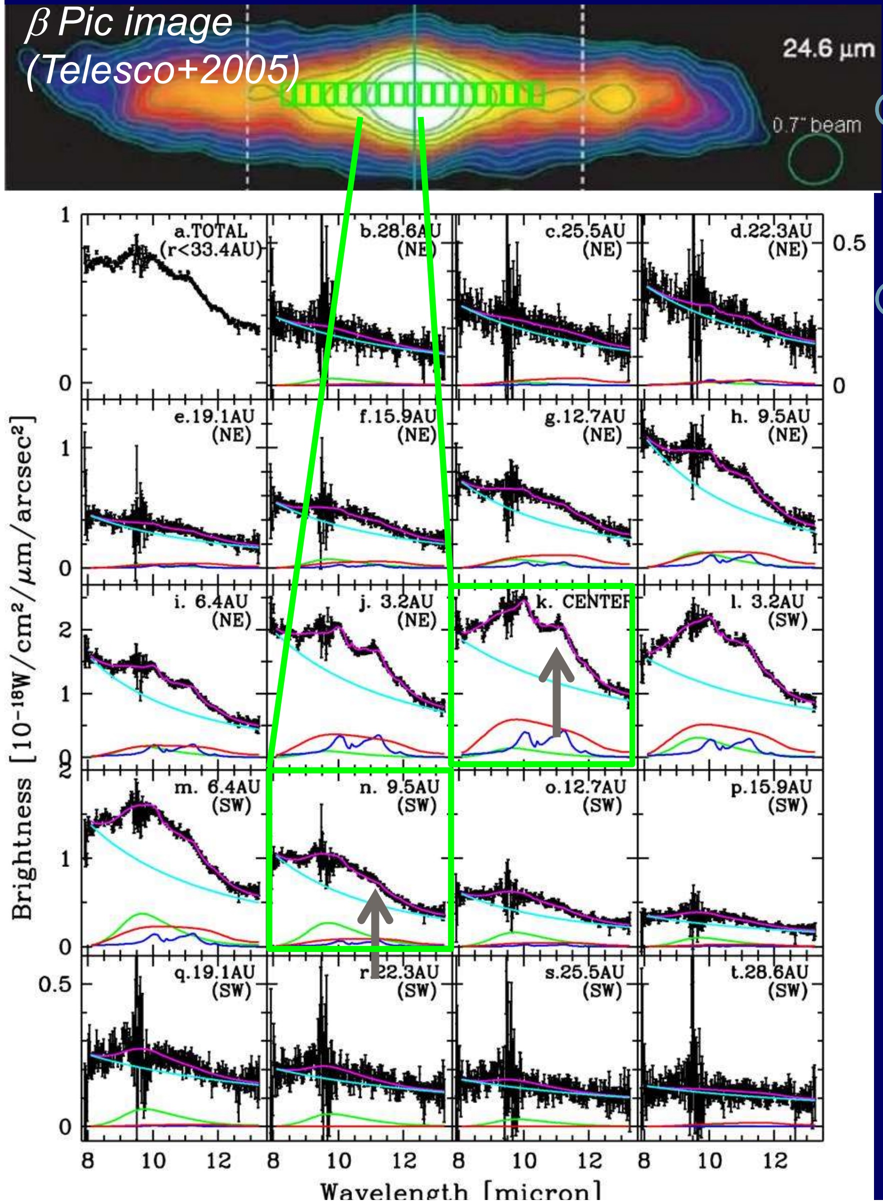
Clear detection of crystalline silicate toward T Tauri disks

(by COMICS ; Honda et al. 2003)



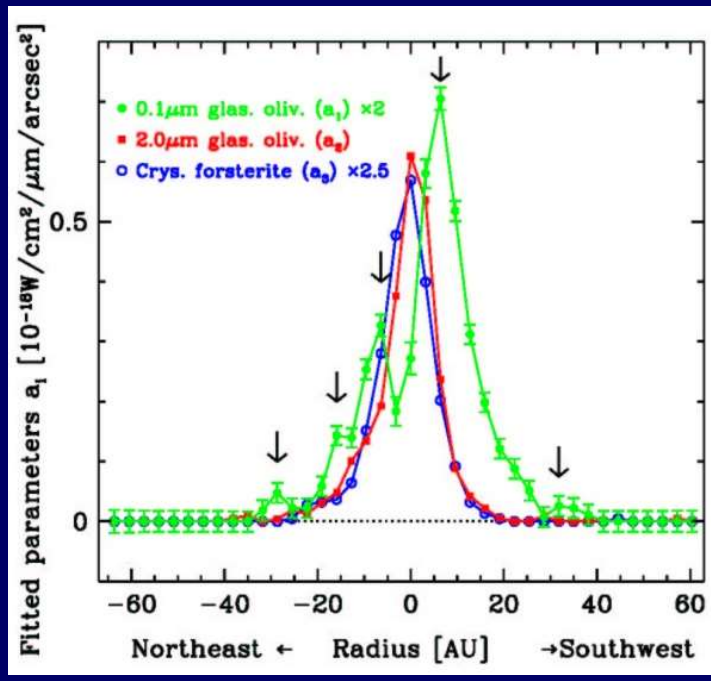
Any links with chondrule formation in our Solar system ?

N-band low-R spectroscopy of planet forming disks

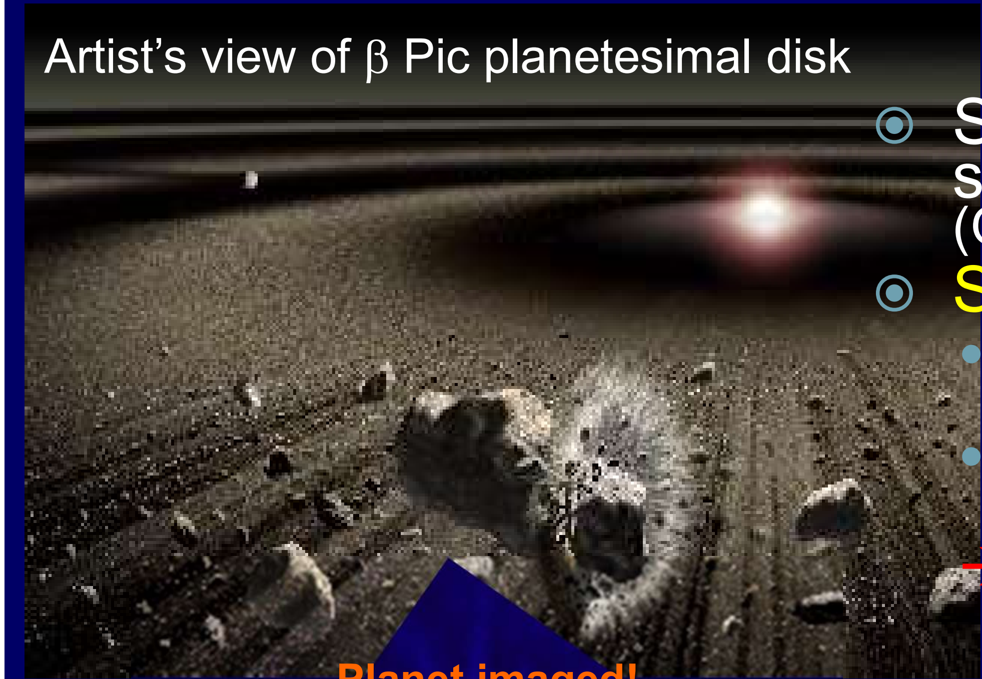


Spatially resolved spectra by Subaru (Okamoto+2004)

- Spatially resolved N-band spectra of β Pic debris disk (Okamoto+2004)
- Spatial difference of dust feature
  - Central condensation of crystalline silicate grains
  - Several local peaks of small amorphous silicate



N-band low-R spectroscopy of planet forming disks



- Spatially resolved N-band spectra of β Pic debris disk (Okamoto+2004)
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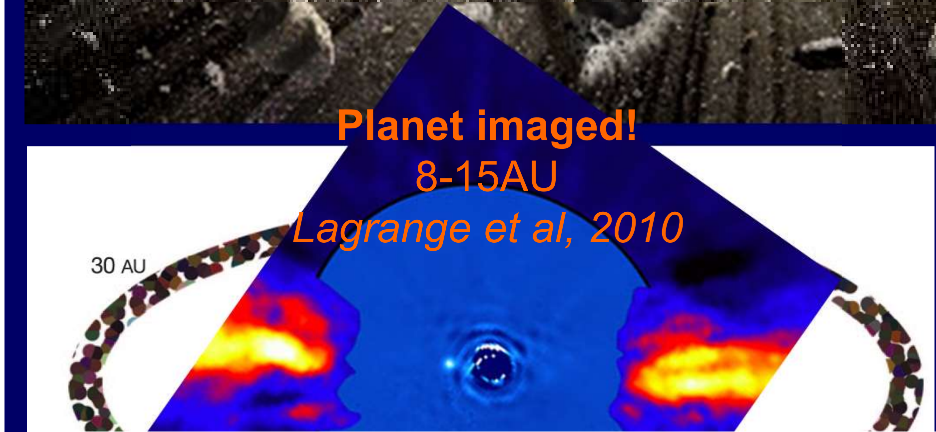
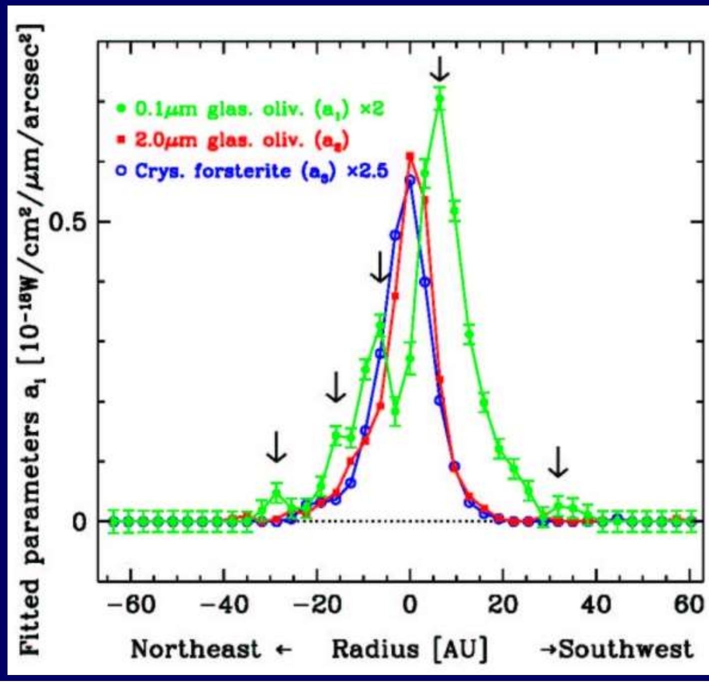
→ Multiple planetesimal belts





With TMT/MICHI, we can make this kind of observations toward ~30 young disks

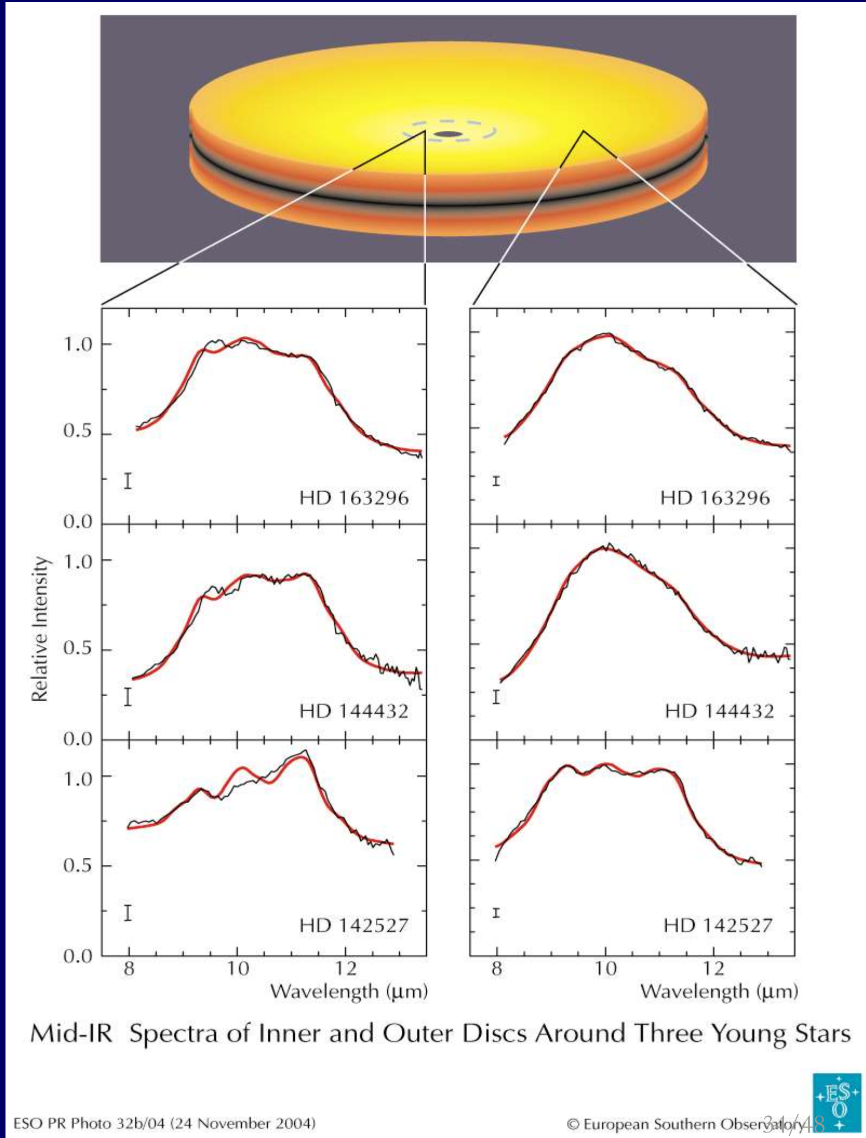
Crystalline olivine distribution in disk

Spatially resolved spectra

- β Pic
  (Okamoto et al. 2004)
- HAeBe
  (van Boekle et al. 2004)

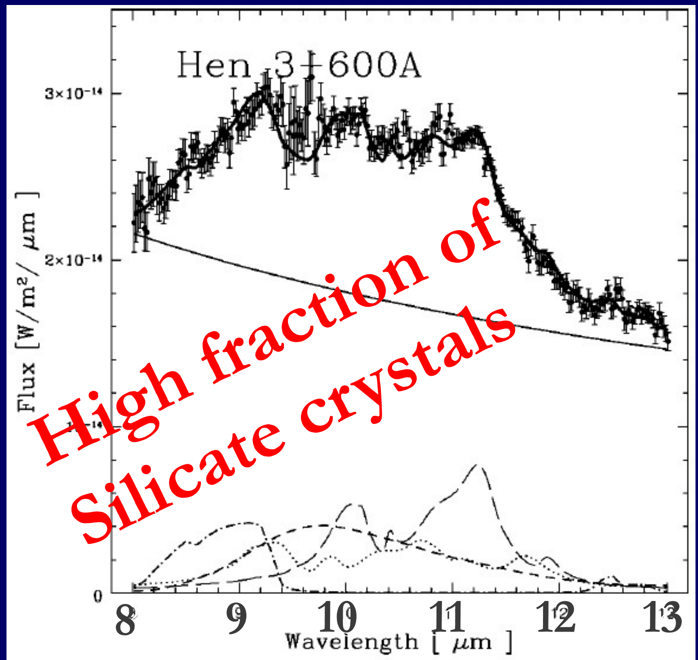
→**Showing crystalline silicate near the central star**

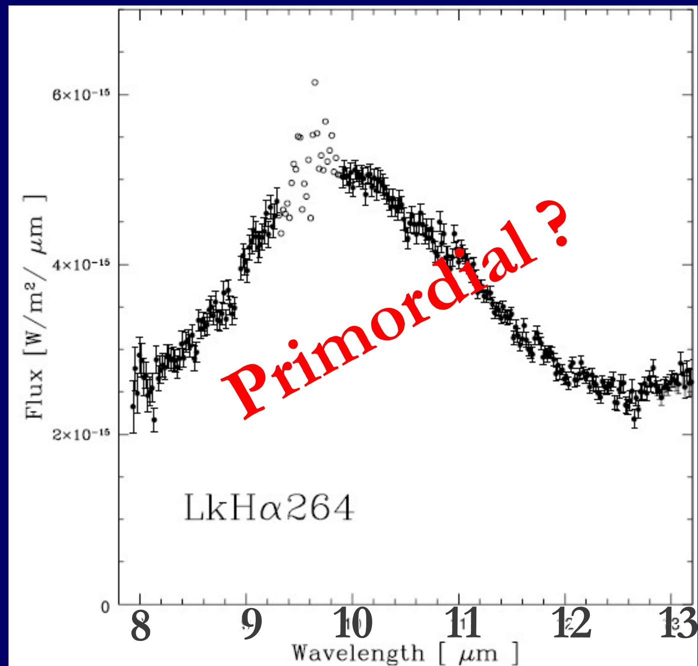
→**Crystallization at the hot central region ?**



Remaining questions : Origin of the diversity of silicate dust composition

- In protoplanetary disks, silicate dust composition shows large diversity
- No reliable correlation between crystallinity and physical parameter (age, M_d, $Lh\alpha$,…) is found so far (Sicilia-Aguilar+2007, Bouwman+2008, Oliveira+2011)



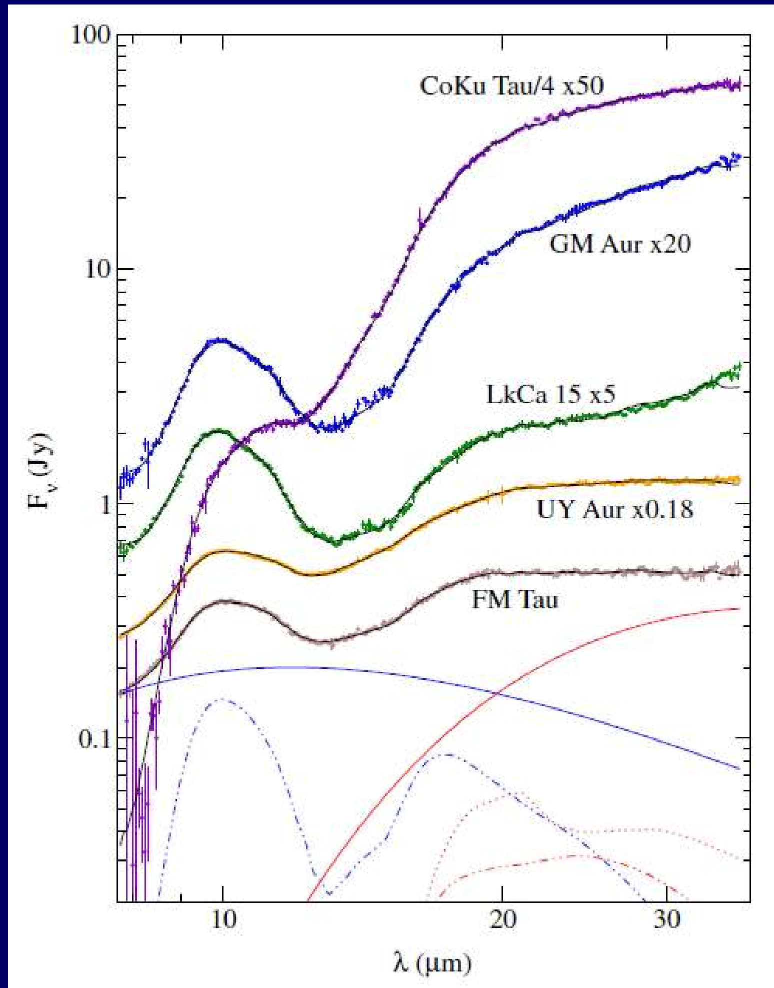


speculation for diversity of silicate compositions ?

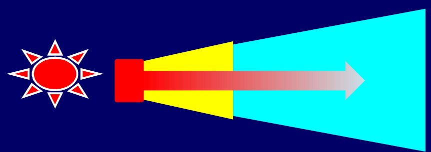
- "transitional disks (disks with hole/gap)" tend to show pristine silicate ?

  (Sargent et al. 2009, Manoj et al. in prep.)

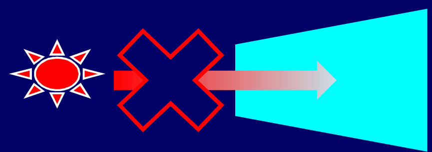
  - Early gap formation (~1Myr) prevented outward transport of hot inner material ?



Continuous disk



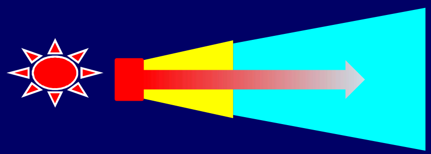
Transitional disk (gapped disk)



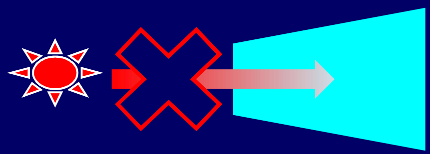
Outward transport not always occur ?

- It might depend on timing/location of gas giant formation that makes gap in the disk
  - In our solar system, Jupiter formation occurred later than ~1 My, which might be sufficient to transport crystalline material to the outer cold comet forming regions

Continuous disk



Transitional disk (gapped disk)

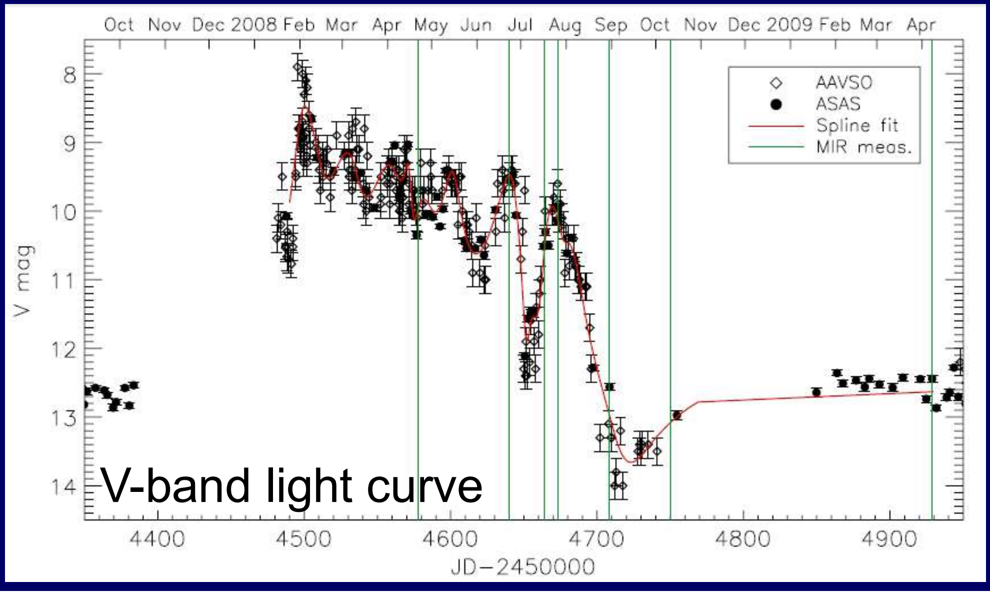


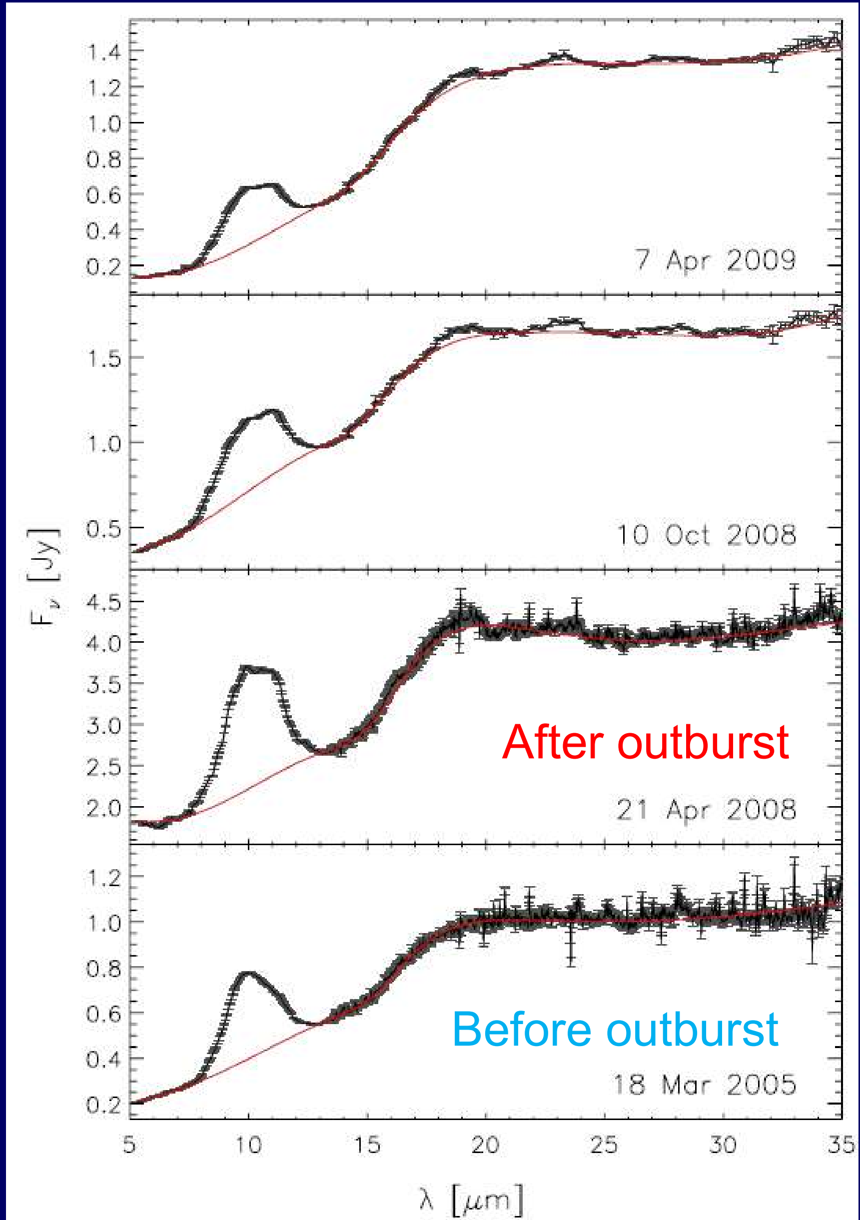
Outward transportation may not be 100% universal event in the disk ?

Silicate crystallization event observed during EX Lup outburst

Abraham et al. 2009

- Exor type variable
  - Episodic accretion
- Silicate crystal appeared after 2008 outburst





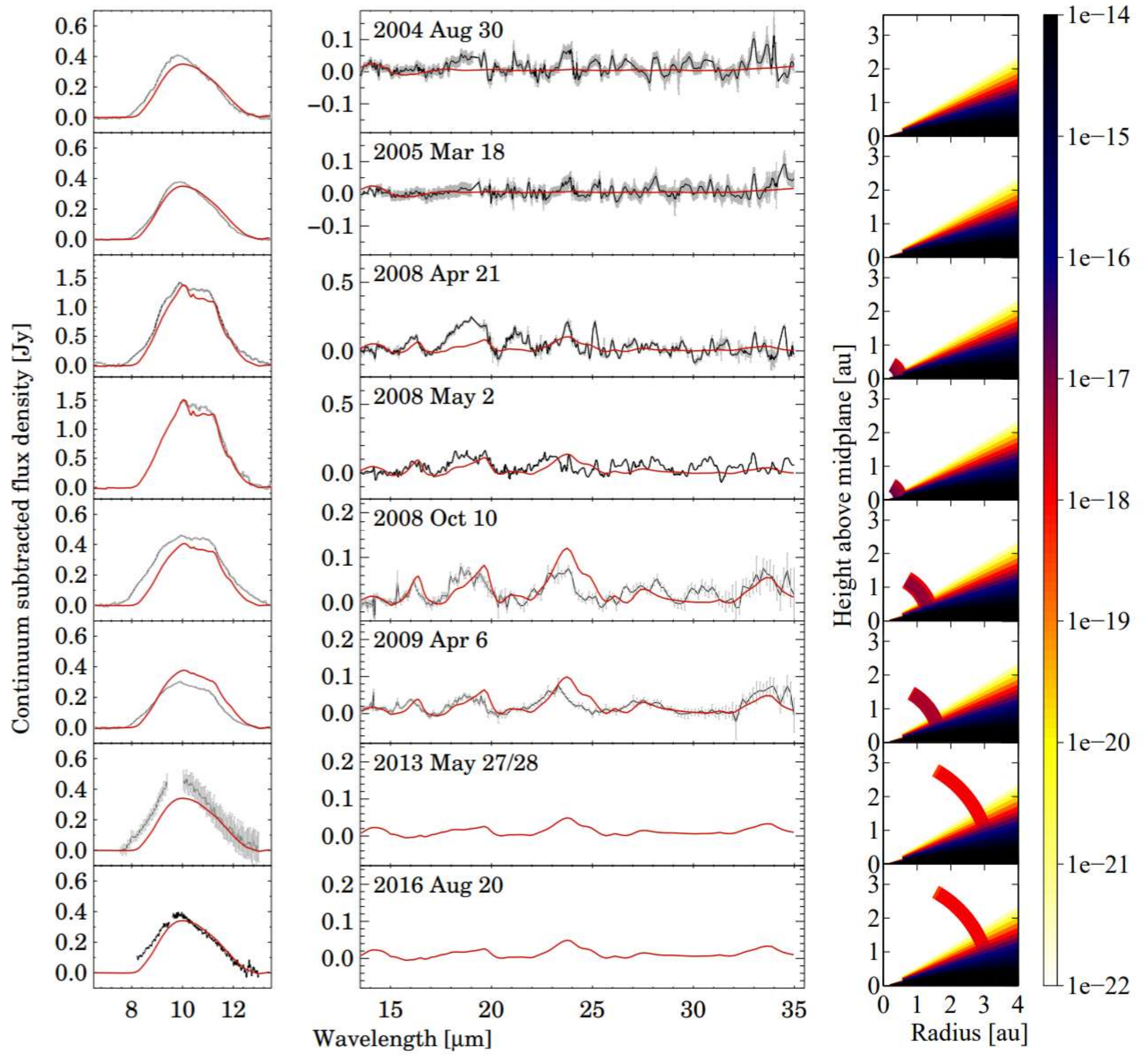
Crystallization at outburst and outward transport at the disk surface ?

After 2008 outburst, 10μm crystalline silicate feature disappeared in 5 yr (2013)

Possible outward transport of crystallized component is suggested

(Abraham et al. 2019)

Ground-based mid-IR spectroscopic monitoring is important



Summary

- Disk imaging
  - Subaru contributed finding gaps and spirals in the disks
    - CIAO, COMICS, HiCIAO(SEEDS)
  - Furthermore, SCExAO will contribute finding forming planets in the disks
- Disk solid material evolution
  - Ice : H_2O ice mapping observations done
    → TMT/GMT will trace snow line
  - Silicates : silicate crystallization found in disk
    → origin of crystallinity diversity is not clear
    further research required for understanding radial mixing in the protoplanetary disk