Gas and Dust in Protoplanetary Disks

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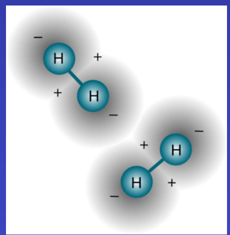
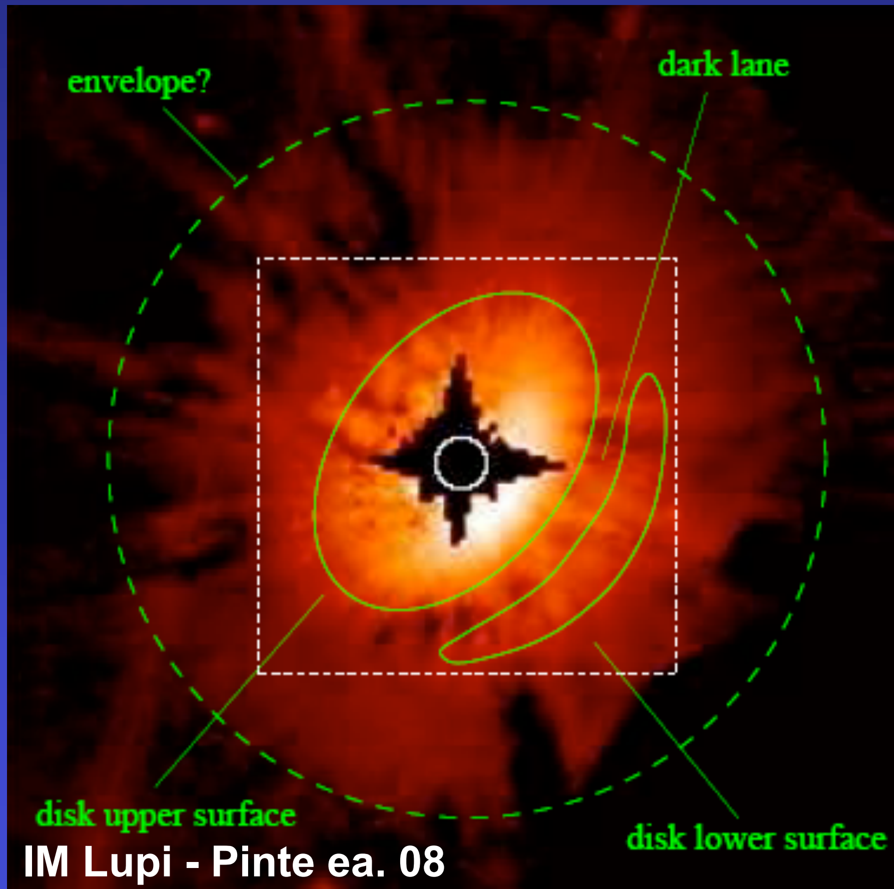
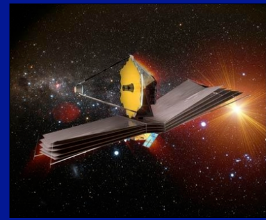




This Talk - Spectroscopy



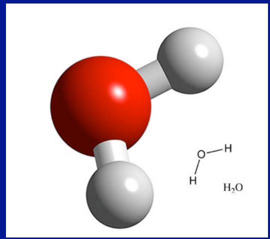
- How well are gas and dust coupled?
- What is the chemical composition of dust and gas?

  - The material inventory for planet formation -

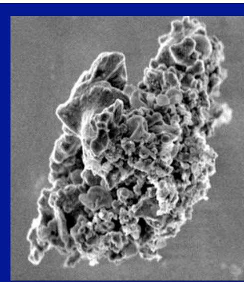
Collaborators

P. Abraham, D. Apai, J. Bouwman, A. Carmona, C. Dullemond, D. Fedele, M. Güdel, A. Glauser, G. Meeus, I. Pascucci, S. Quanz, T. Ratzka, A. Sicilia-Aguilar, R. van Boekel

M. Fang, V. Roccatagliata, A. Juhasz – PhD Students (all here)



Gas ***and*** Dust

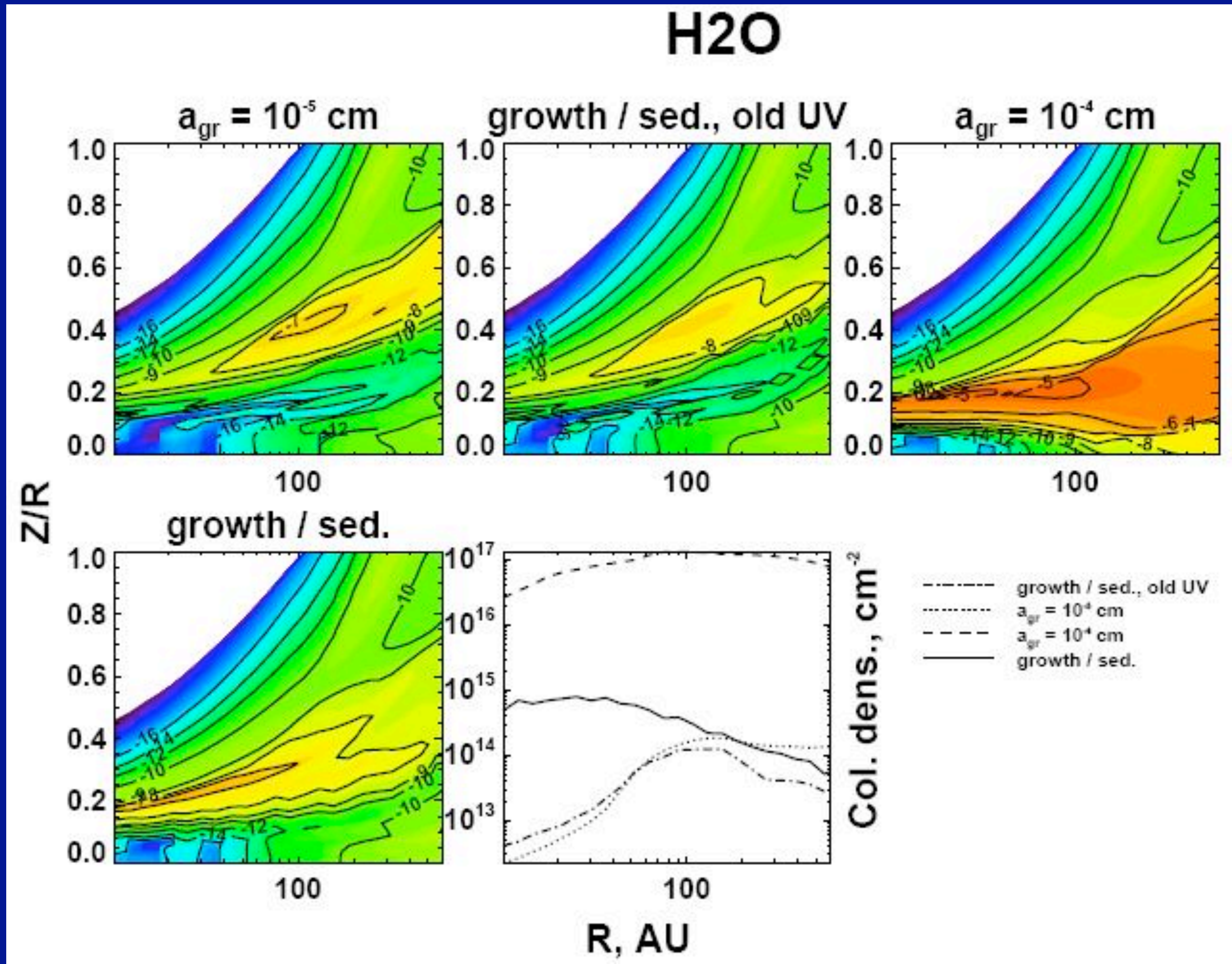


- Gas dynamics determines dust motion and grain growth
- Dust properties essential for thermal disk structure, disk chemistry and ionization state
- How well is gas and dust evolution coupled? Both components essential for planet formation

No water, no granites - No oceans, no continents

(Campbell & Taylor 1983)

An Example
Dust Evolution and Chemistry

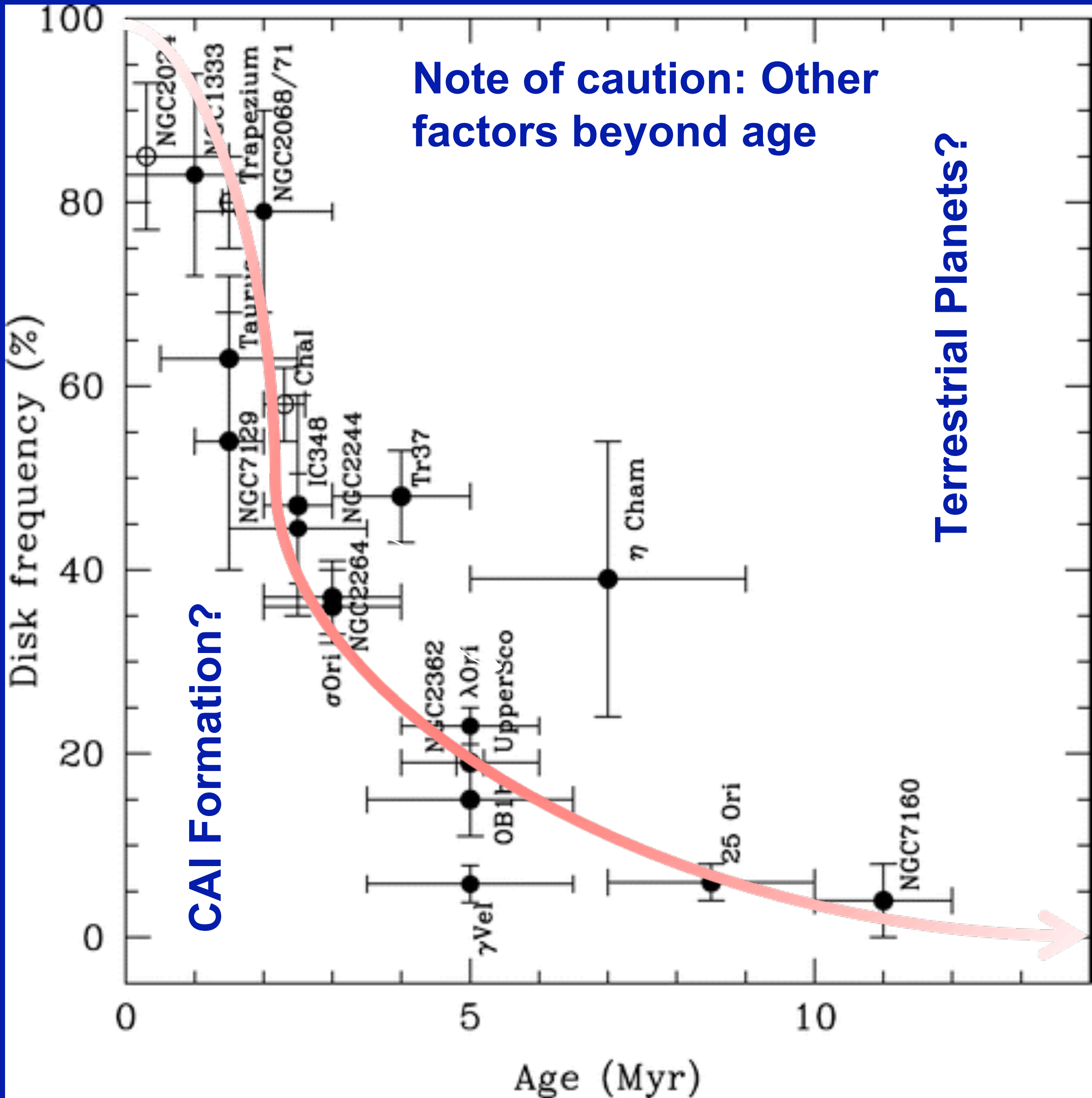


Poster A33
Fogel ea.

Talk: Pinte

Vasyunin, Birnstiel, Henning et al. (2010)

Dust Disk Lifetimes



Spitzer IRAC results

For low-mass stars

(<1 M_{sun}; ~90% stars!)

Hernandez et al. 2008

(see also

Haisch+2001,

Mamajek+ 2002, 2004,

Luhman+2008)

Disk fraction status:

Half gone by ~2-3 Myr

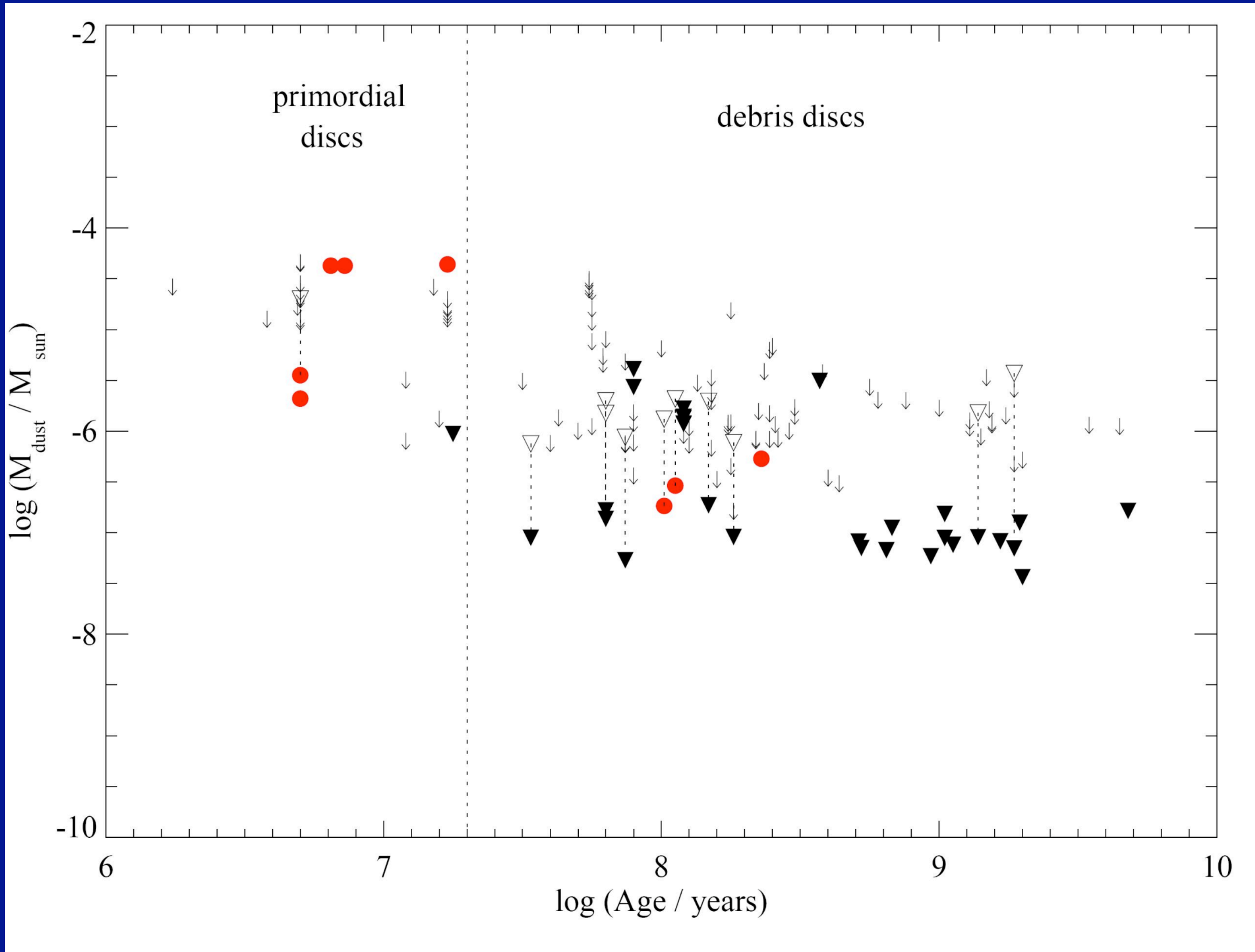
68% range: 1-6 Myr

<5% beyond 9 Myr

<1% beyond 13 Myr

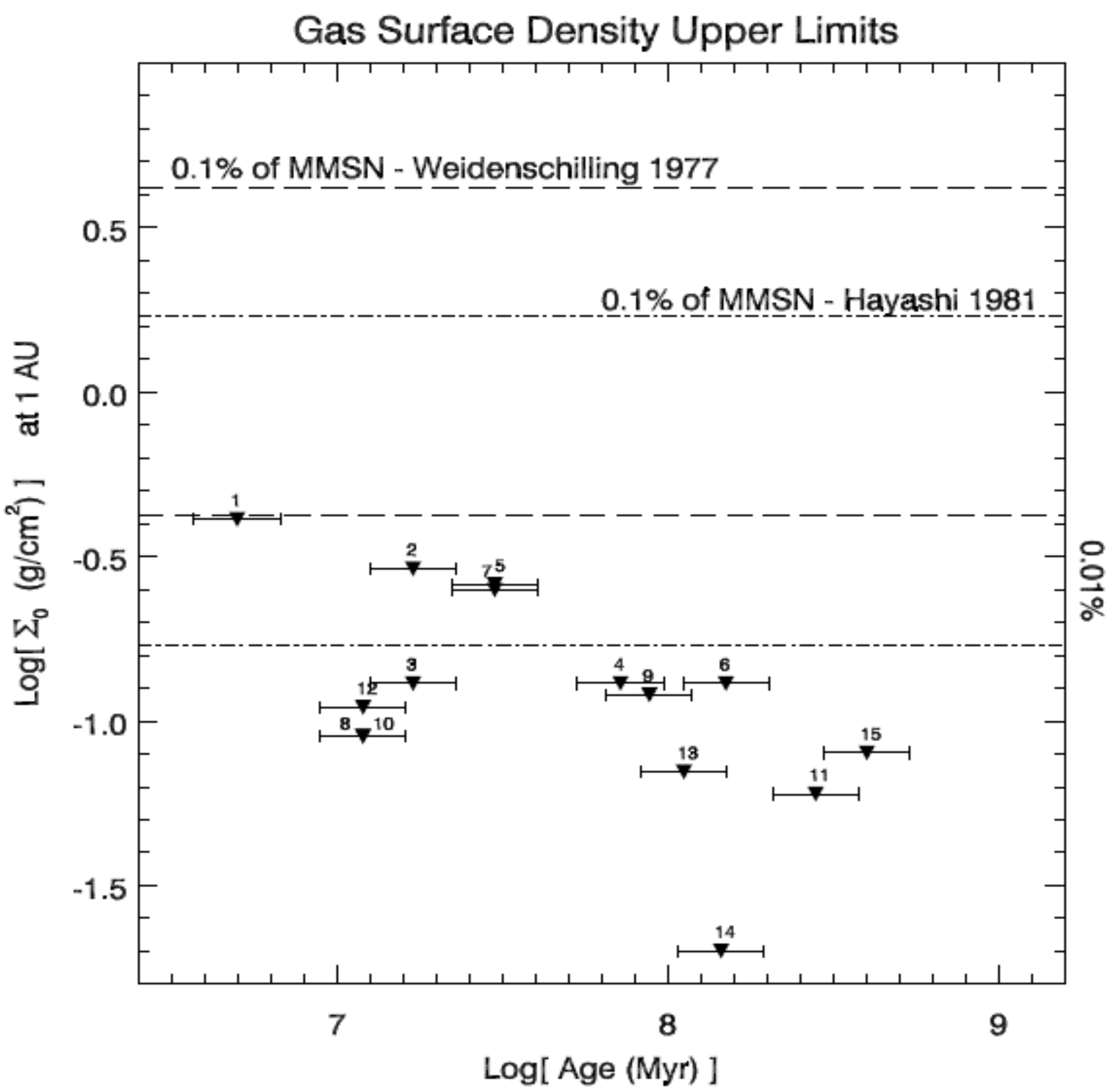
i.e. lifetime ~ $10^{6.4\pm0.4}$ yr

Dust Evolution – The Older Systems



Roccatagliata, Henning, Wolf et al. (2009)

Gas disk lifetimes appear to be < 10 Myr



FEPS Spitzer

Legacy IRS survey

20 stars with ages

3-100 Myr:

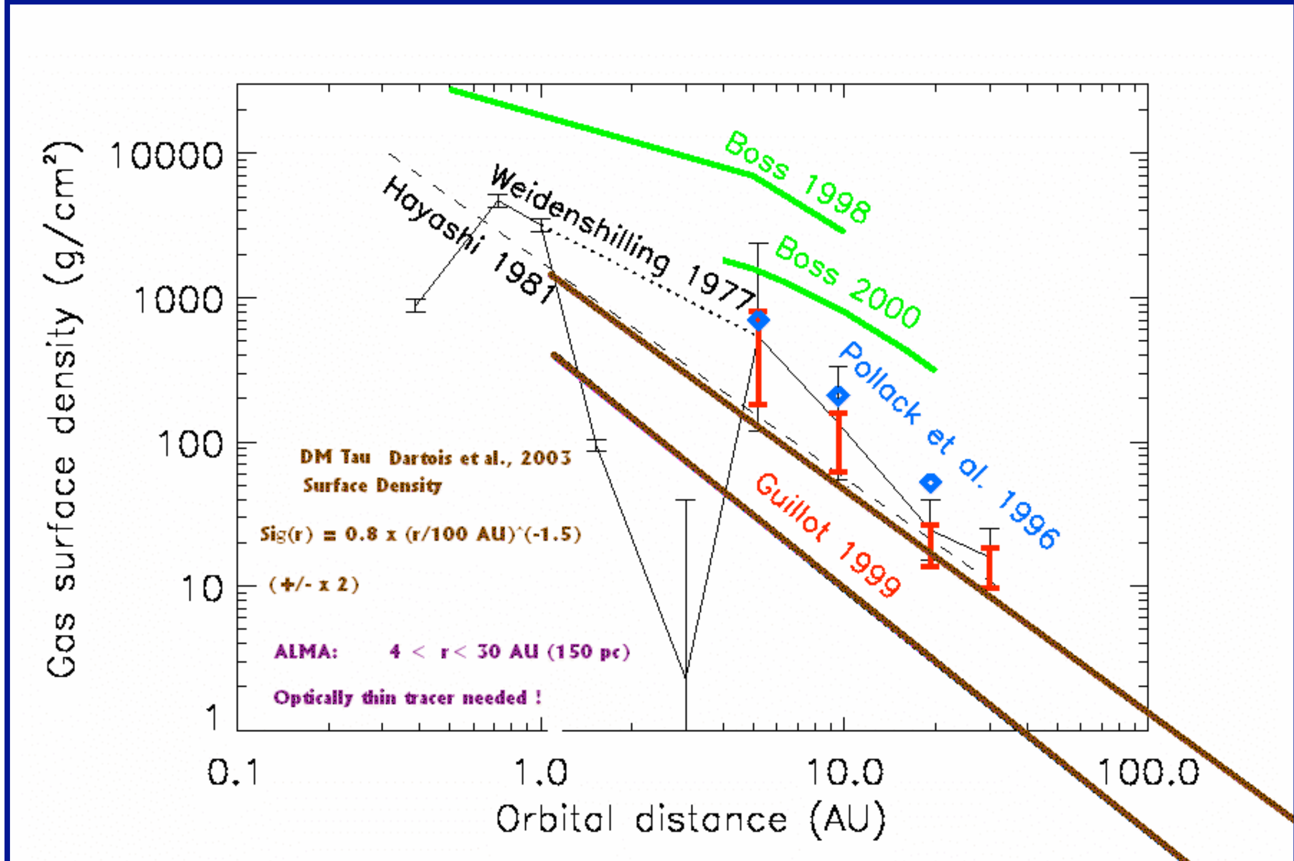
No gas-rich disks

(> 0.1 M_{Jup} detected)

Hollenbach et al. (2005), Pascucci et al. (2006)

See also: Ingleby ea. (2009) < 3 10^{-6} g cm^{-2} in inner debris disks from FUV HST observations)

Gas Distribution in Protoplanetary Disks



CO lines:
Chemistry,
Photodissociation,
Excitation

PdBI measurements of various CO isotopomers

Good S/N per velocity channel

The best angular resolution

30 AU @ 150 pc = 0.3 ''

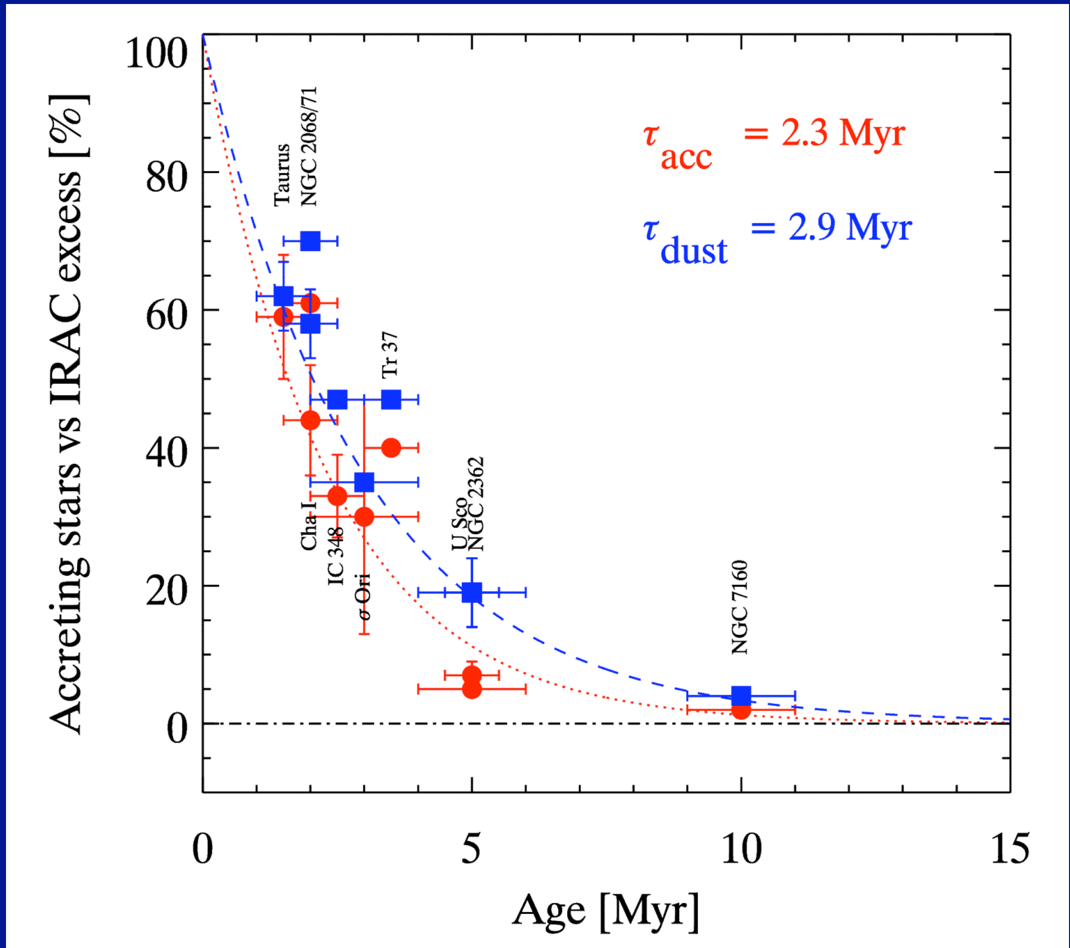
Guillot & Gladman (2000) - Σ compilation

Dartois et al. (2003) - Σ measurement in DM Tau

(Andrews & Williams 2007, for the dust)

Gas and Dust Evolution

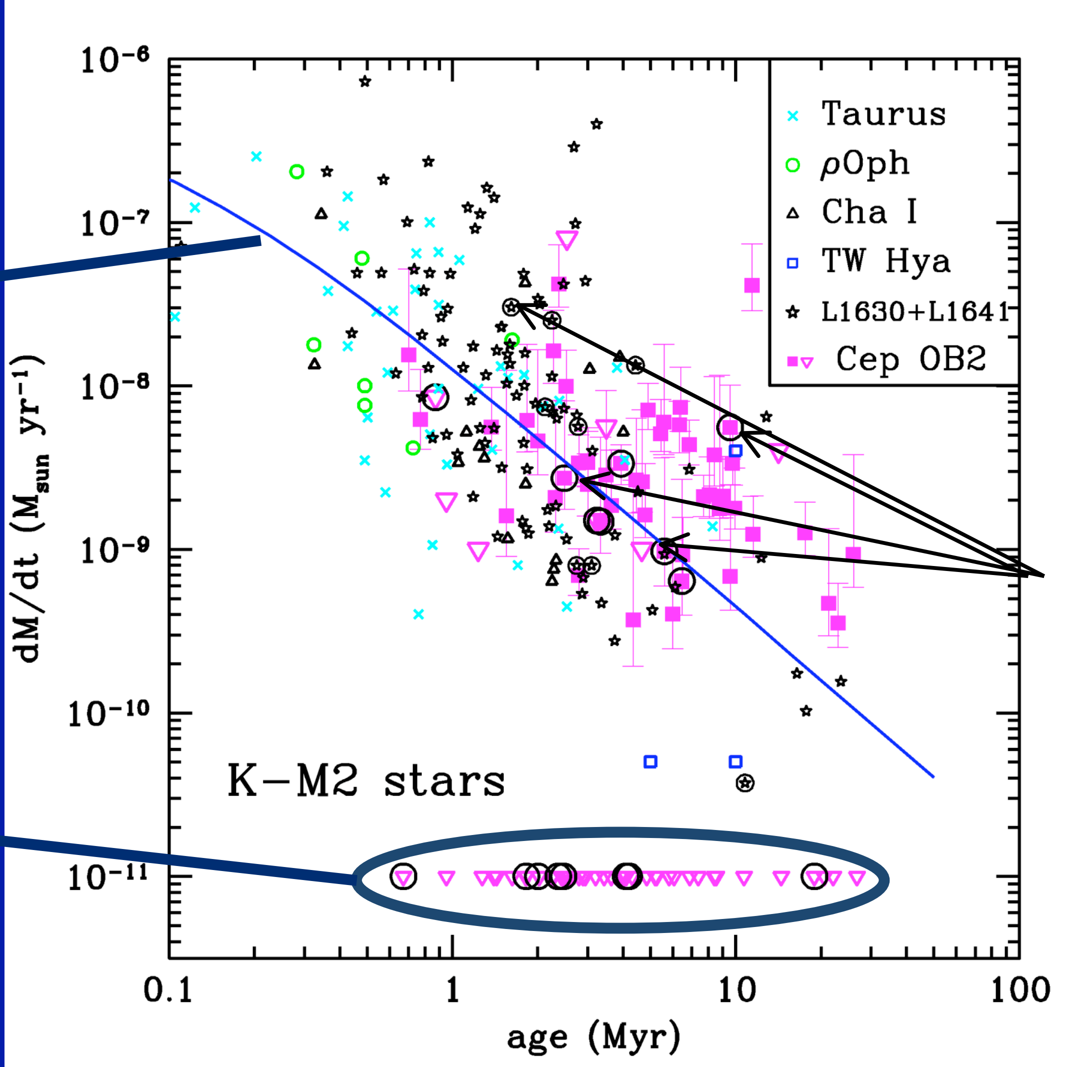
VIMOS Multi-object Spectroscopy and Spitzer/IRAC in concert



Fedele et al. (2009, Poster A 31)

Accretion evolution

Consistent with viscous evolution [Hartmann et al. 1998], but…

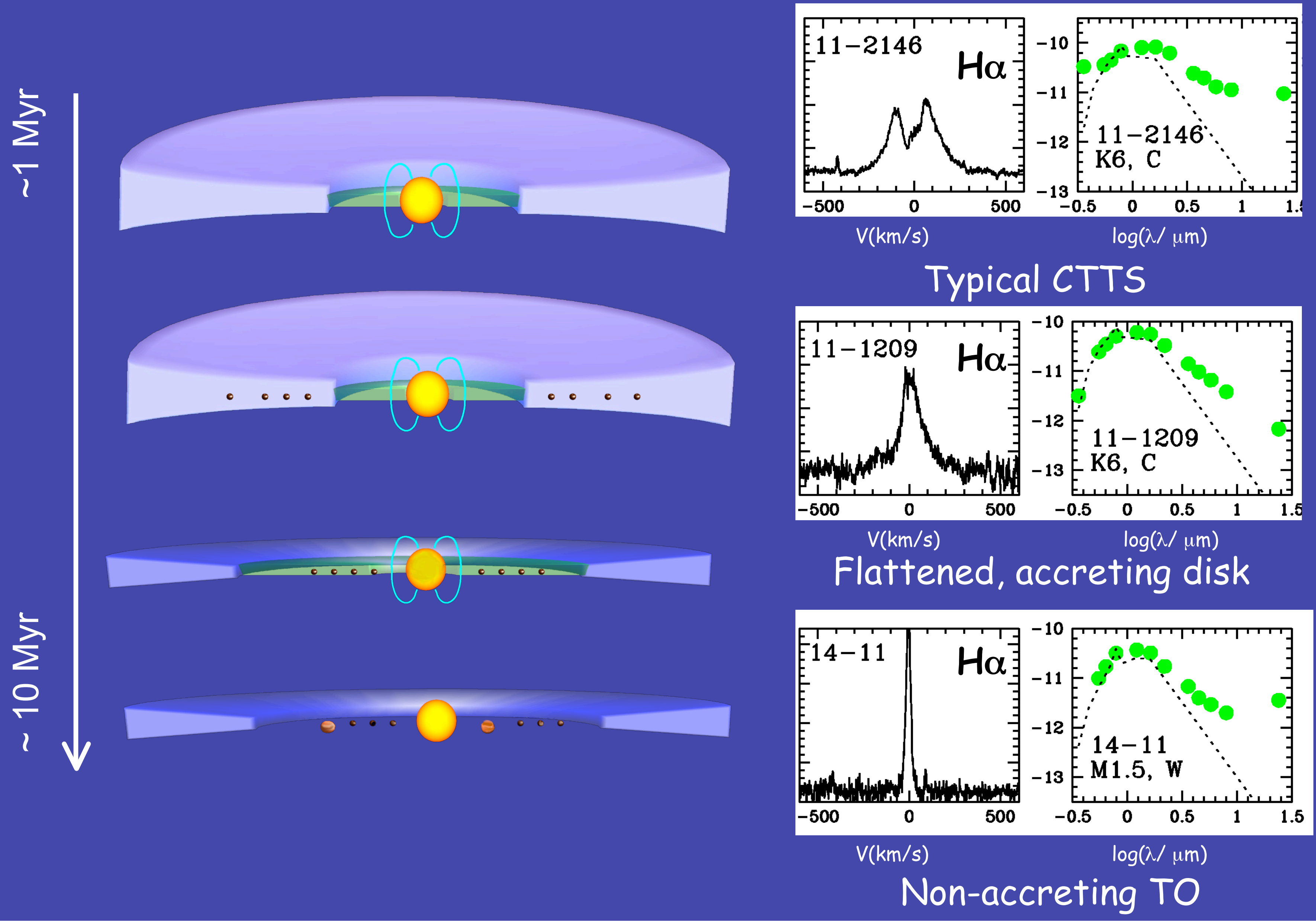


…at any given age, many objects are not accreting!

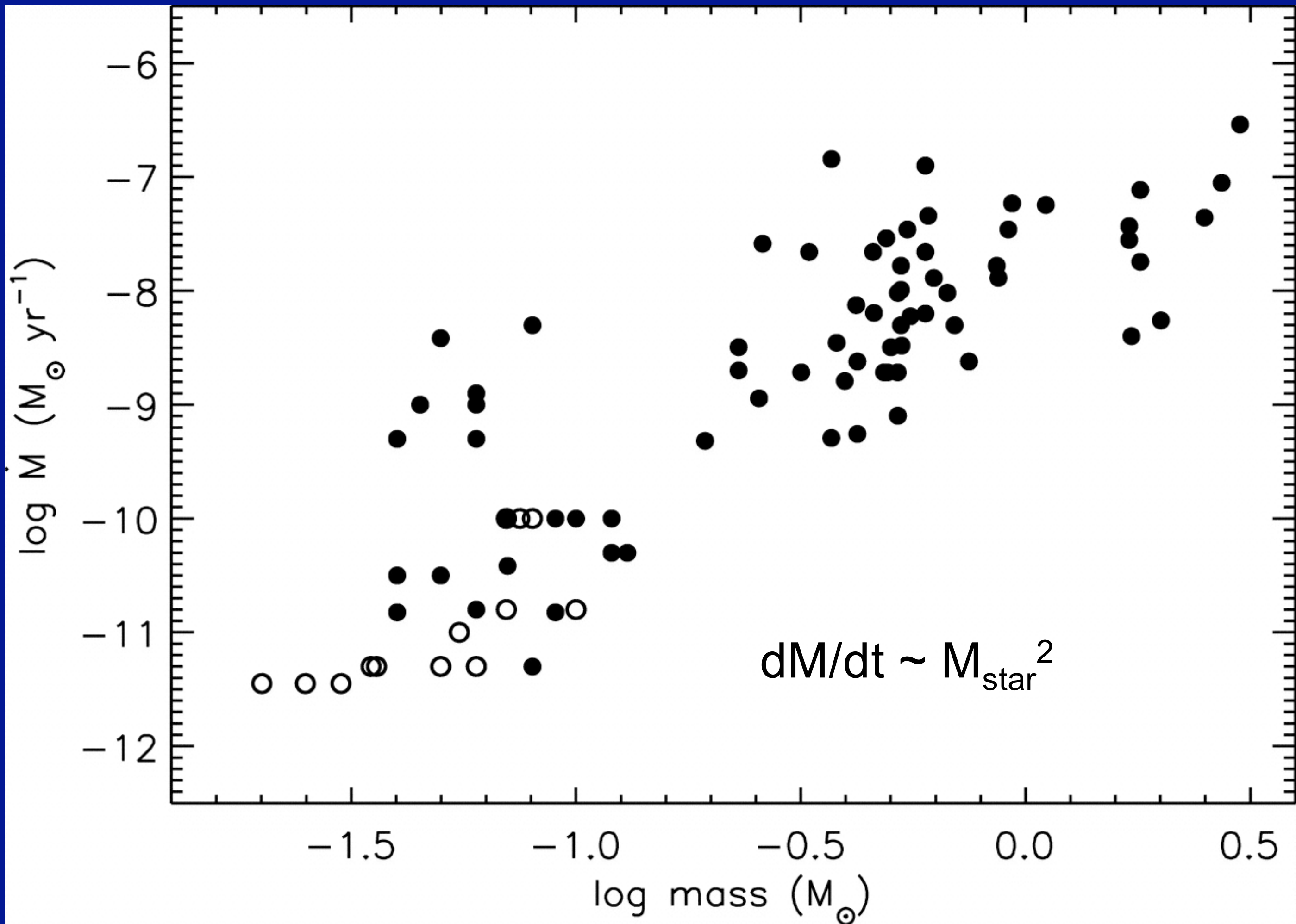
TO (marked with circles) do not have high dM/dt, but in Cep OB2 and Orion L1630+L1641, their accretion rates are similar to those of CTTS! [Sicilia-Aguilar+09; Fang+09]

(Sicilia-Aguilar, Henning, Hartmann, ApJ, submitted; see Poster B32)

The different stages of disk evolution



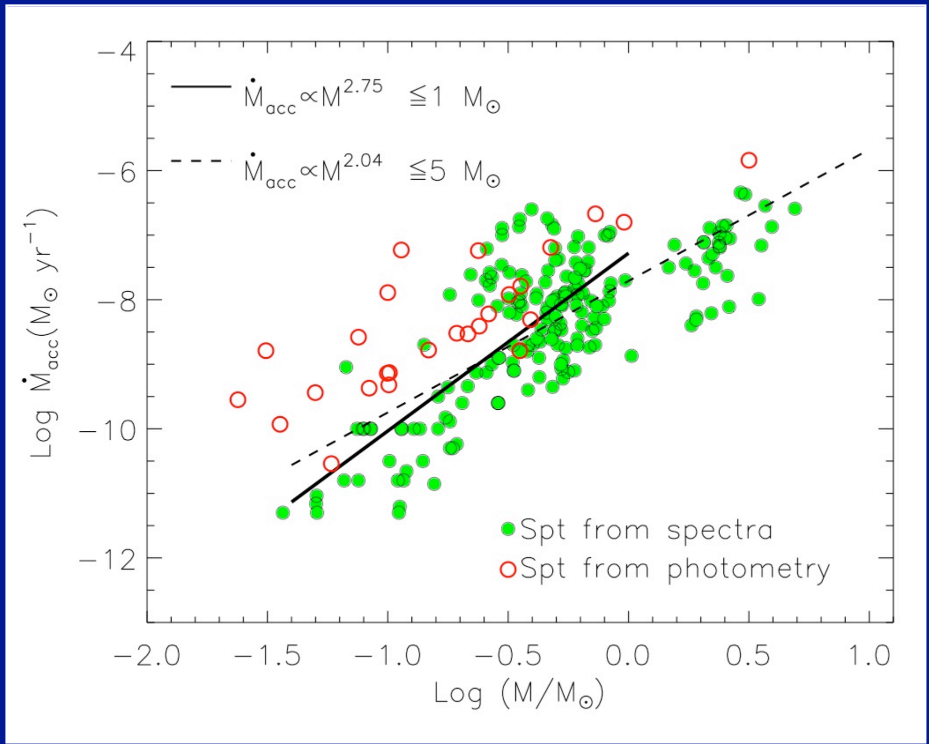
A new (surprising) relation …

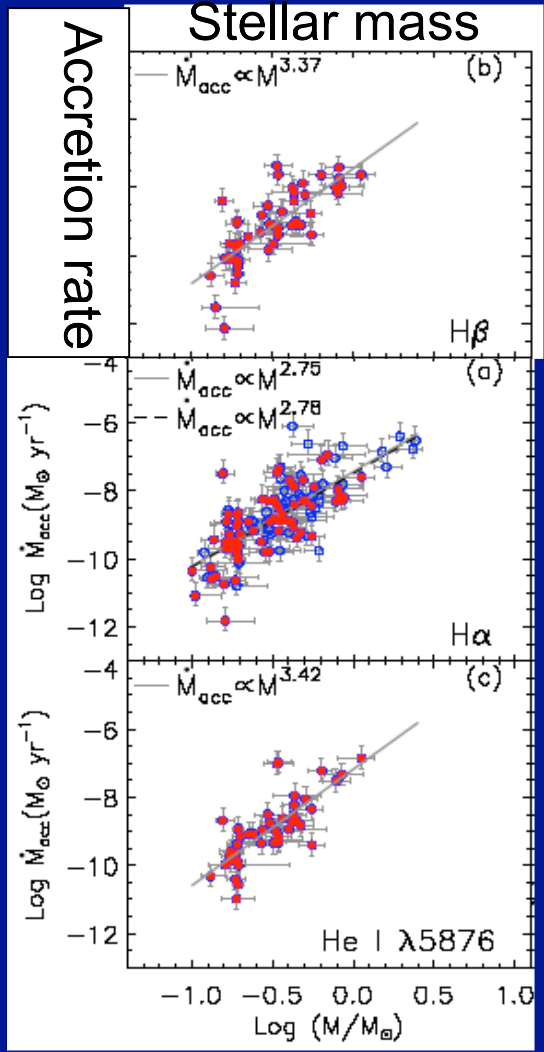


Muzerolle ea. (2005), see also Natta ea. (2004), Muzerolle ea. (2003), ….
See, e.g., Najita et al. (2007), Fang ea. (2009) for transition vs. non-transition objects

A recent result from Orion clusters …

dM/dt substantially steeper
(uniform spectrosopic determination
of stellar parameters)



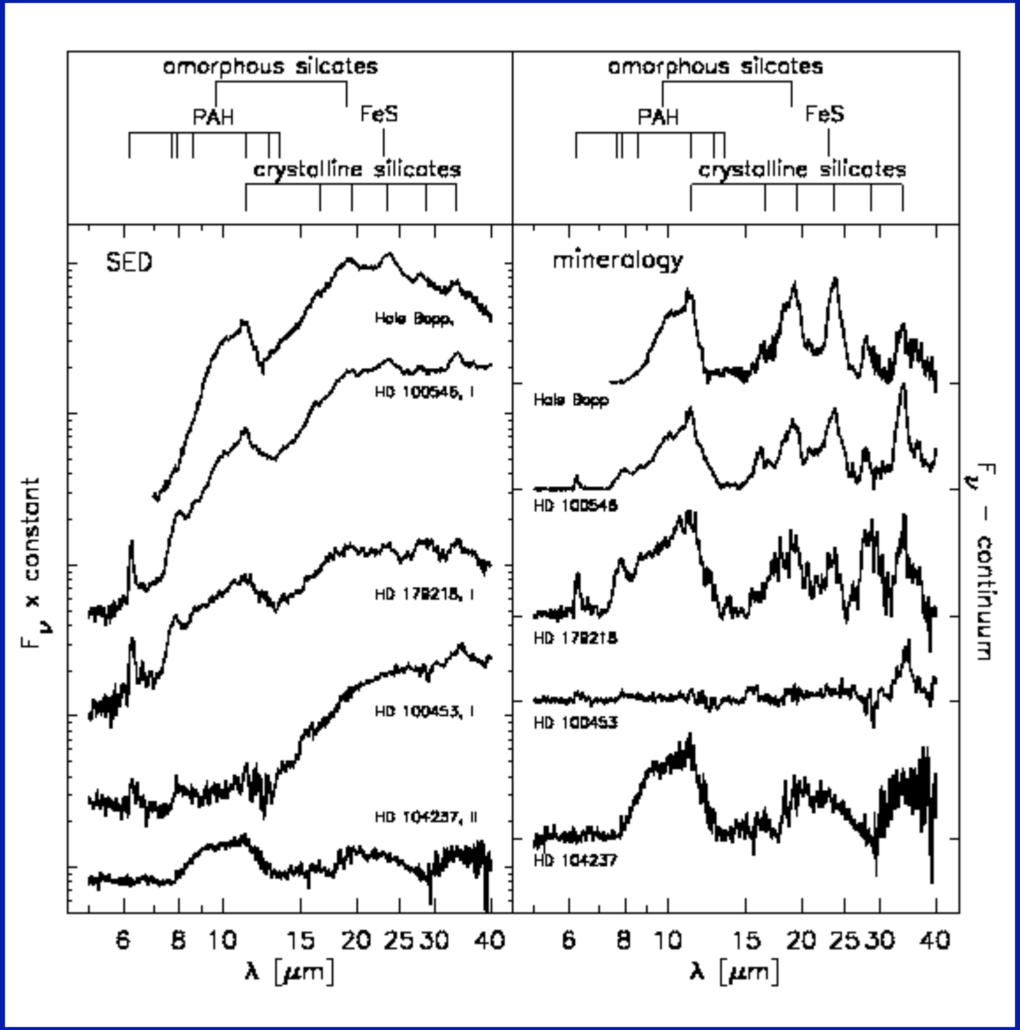


Fang et al. (2009, Poster A30)

The material inventory

- Dust – Composition and Structure
- Grain Growth and Settling
- Gas – The Spitzer Revolution

Disk evolution in Herbig Ae systems



- Dust mineralogy
  - Forsterite
  - Enstatite
  - FeS ???
  - Amorphous Silicates
  - PAHs
  - Silica
- Slope change
- Grain growth

See Meeus et al. 2001, van den Ancker et al. 1999, Malfait et al 1998, Bouwman et al 2001, VandenBusche et al. 2002 (ISO)

Systematic Spitzer study of HAeBe stars

•Sample selection: Targets identified in The et al 1994, van den Ancker 1998, Malfait et al. 1998, Sylvester et al 1996

•Spectral type A-F, late B

•Near- or far-IR excess

•Luminosity class III-V

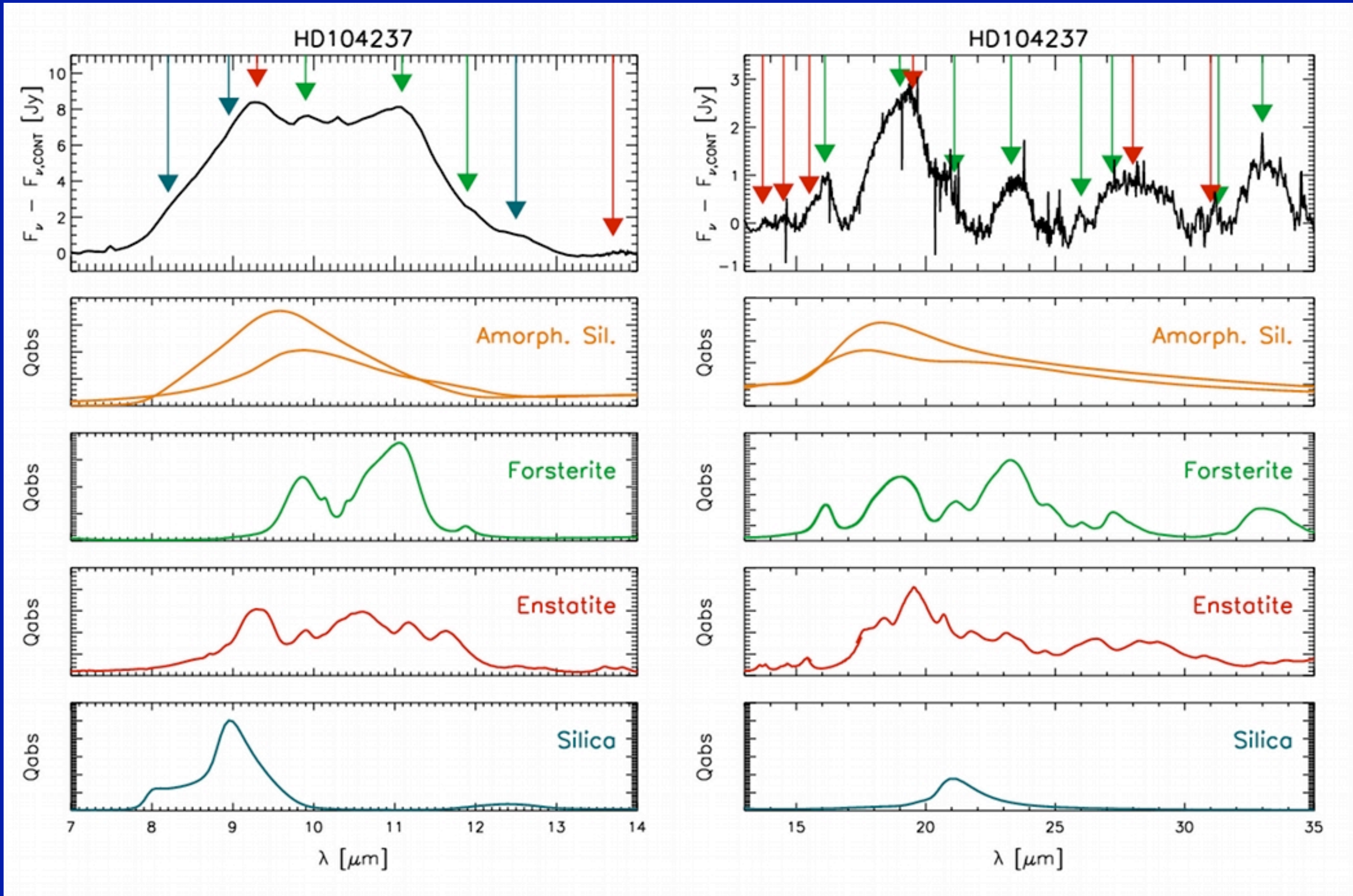
•Emission lines

•Checked the Spitzer data archive for all objects from the above studies observed with Spitzer (including large own program)

•Checked for misclassified objects (ABG stars, classical Be stars, debris disks etc.)

•Found 45 HAEBE systems without extended emission, i.e., emission only from disk , 30 objects from Heidelberg-Amsterdam HAEBE Program

Dust around Herbig Ae stars - The Spitzer Legacy …



Juhasz, Bouwman, Henning et al. (2009, submitted)

The material inventory

5.5 – 35 μm spectra with average S/N ratio of several 100

- Am. (Mg-rich) silicates with olivine and pyroxene stoichiometry
- Crystalline forsterite and enstatite (some Fe possible), silica

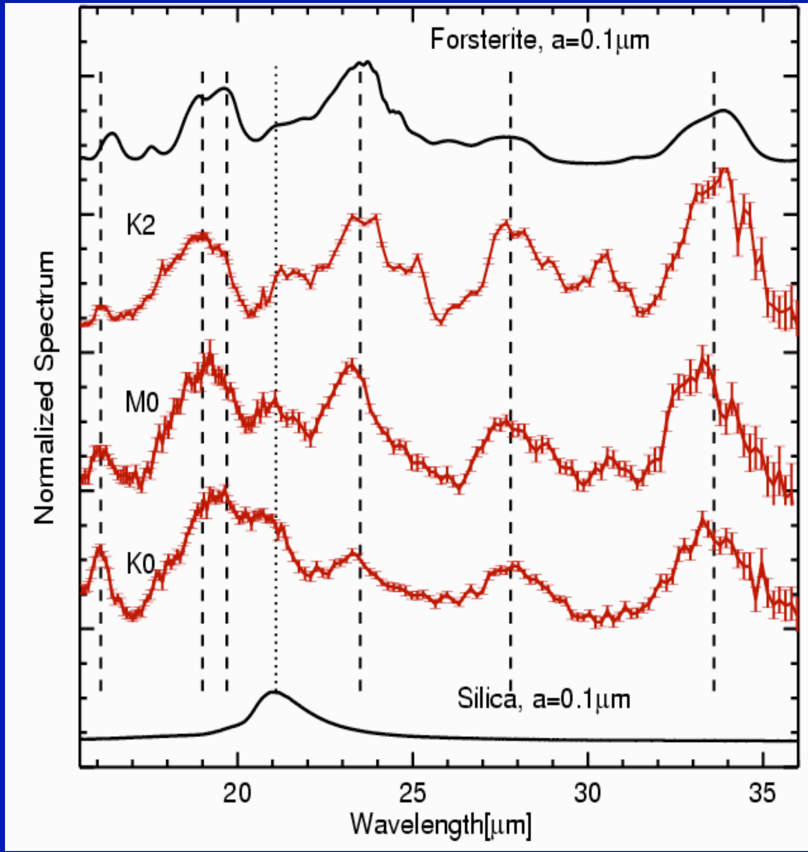
- Crystallinity does not correlate with any of the system parameters

- Forsterite to enstatite ratio increases with radius (7-17 μm vs. 17-35 μm) (see also Bouwman et al. 2008, Meeus et al. 2009, Oloffson ea. 2009 for T Tauri stars)

This is in contrast to equilibrium chemistry: Gail (2004)

Long-wavelength Observations of Disks
Crystals in Space – Forsterite

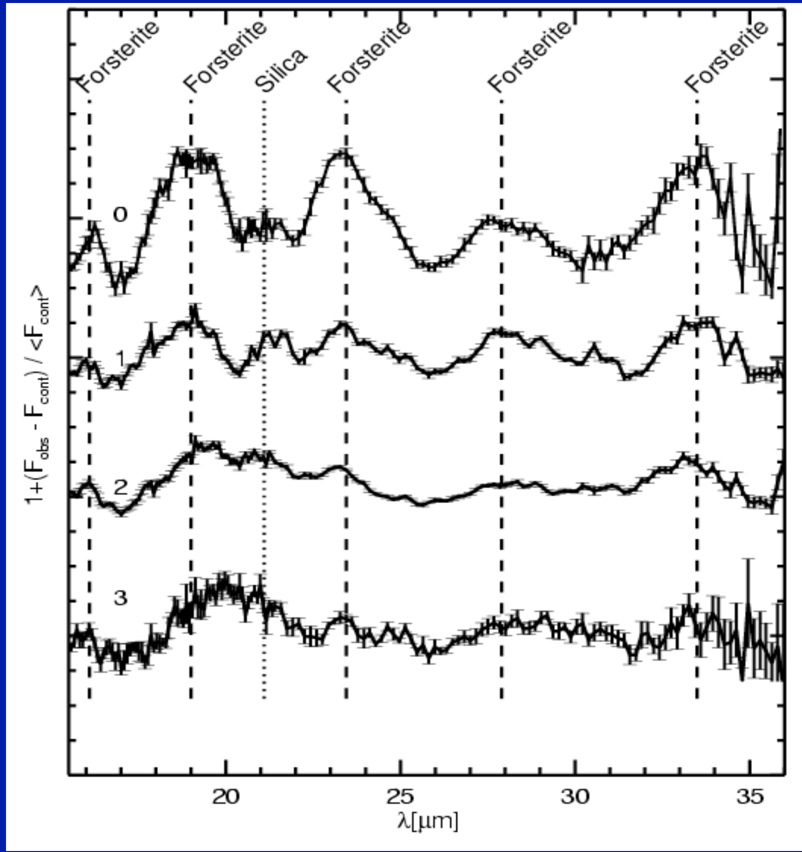
FEPS:TTS



D=140 pc

Age=5-10 Myr

Eta Cha: M stars

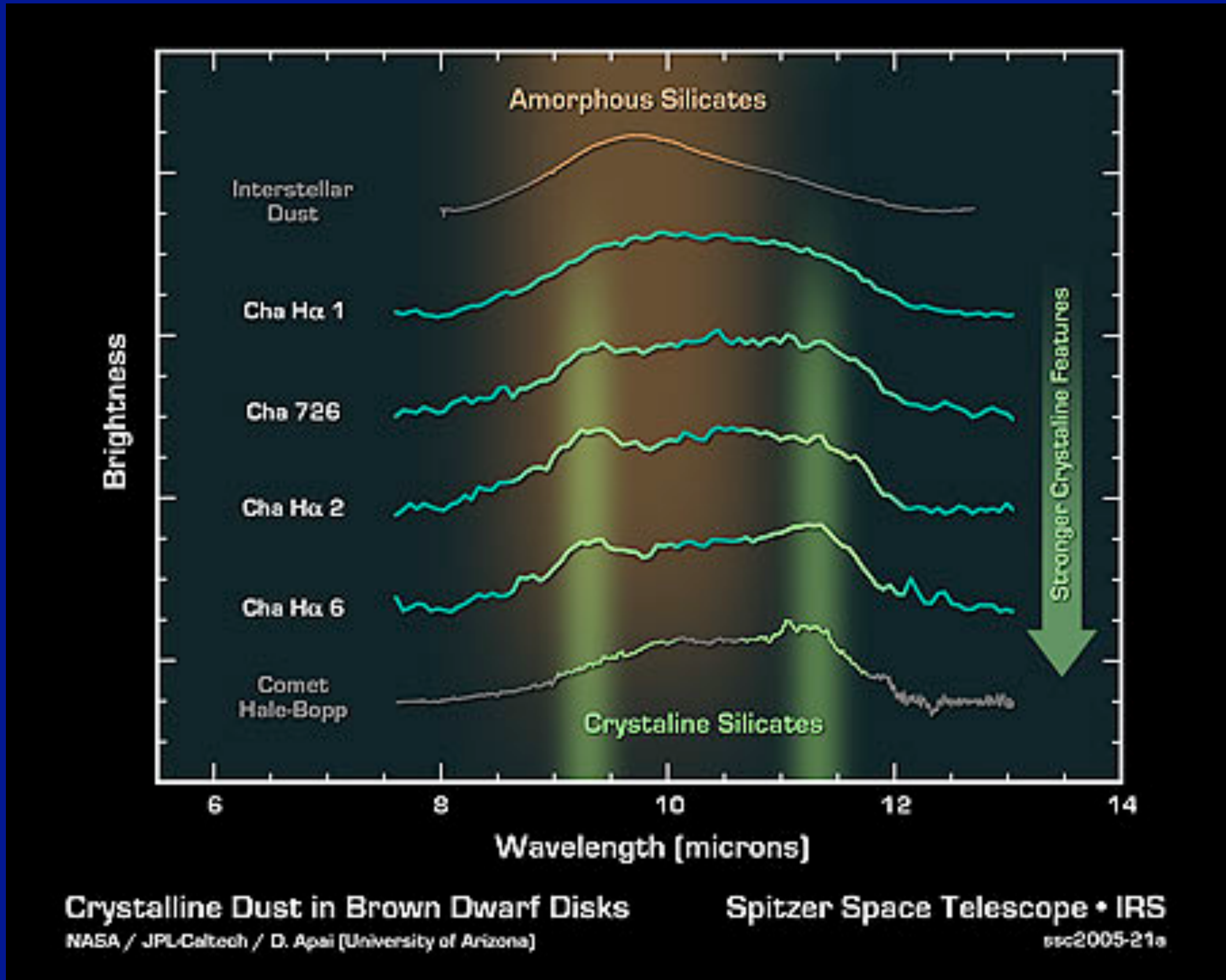


D=100 pc

Age=8 Myr

(see also Kessler-Silacci ea.06, Watson ea. 09, Olofsson ea.09, Meeus ea. 09, …)

Crystalline Dust in Brown Dwarf Disks

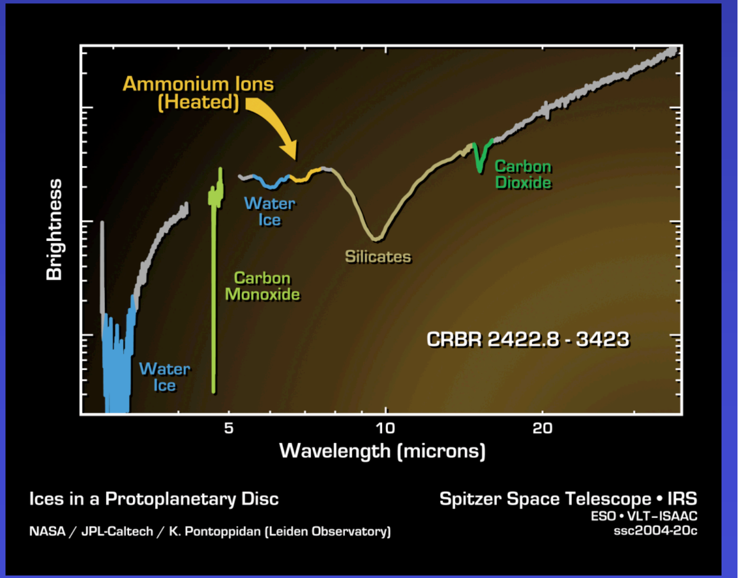


Riaz
Poster B2

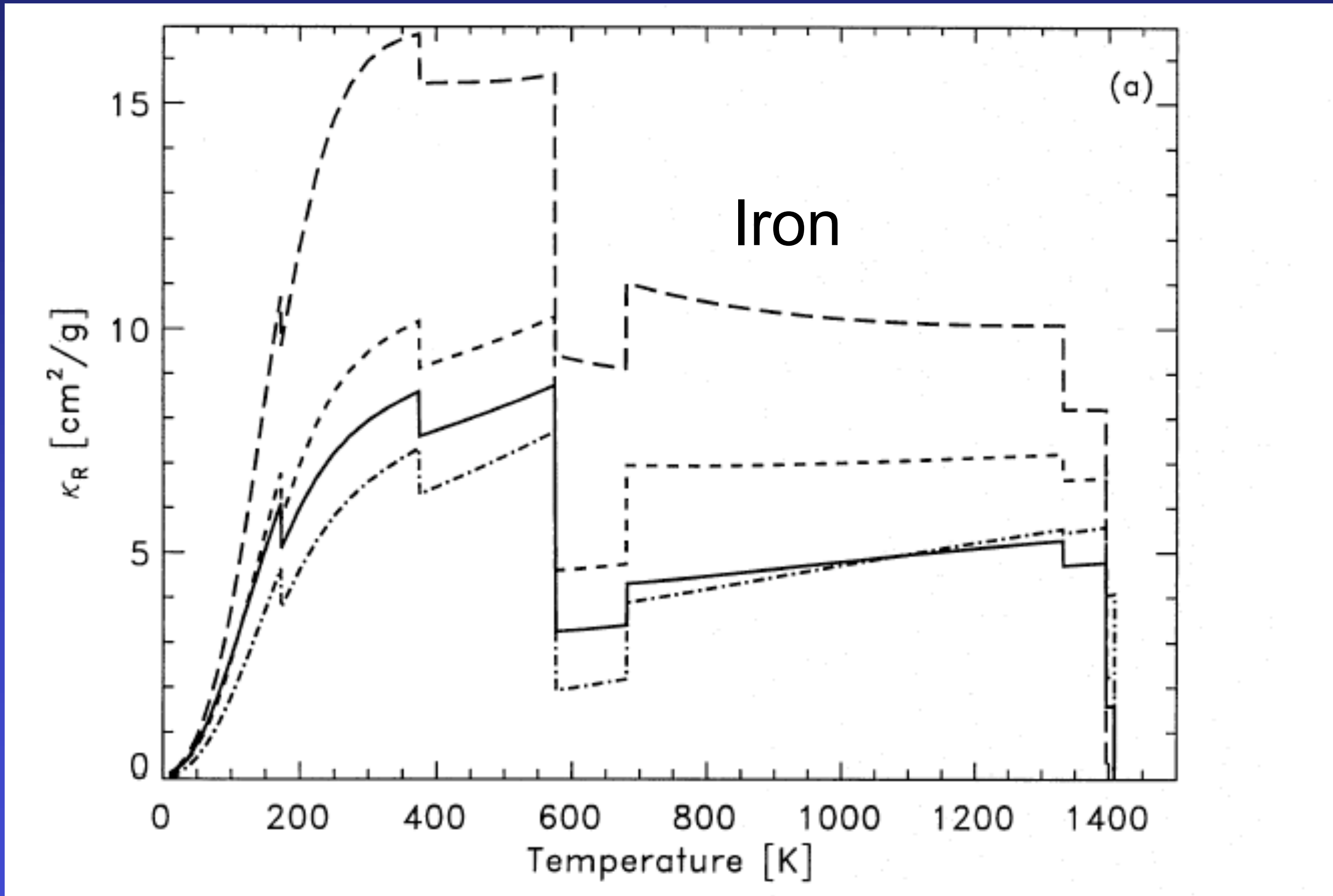
Apai et al. (Science, 2005) – The mJy flux scale

Dust composition from IR spectroscopy

- PAHs in some of the systems
- Amorphous silicates present
- Mg-rich crystalline silicates exist (radial variation in structure)
- Silica exists
- No (strong) evidence for FeS
- No evidence for „organics“
- Evidence for simple molecular ices

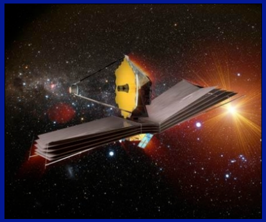


The Role of Iron



Henning & Stognienko (1996)

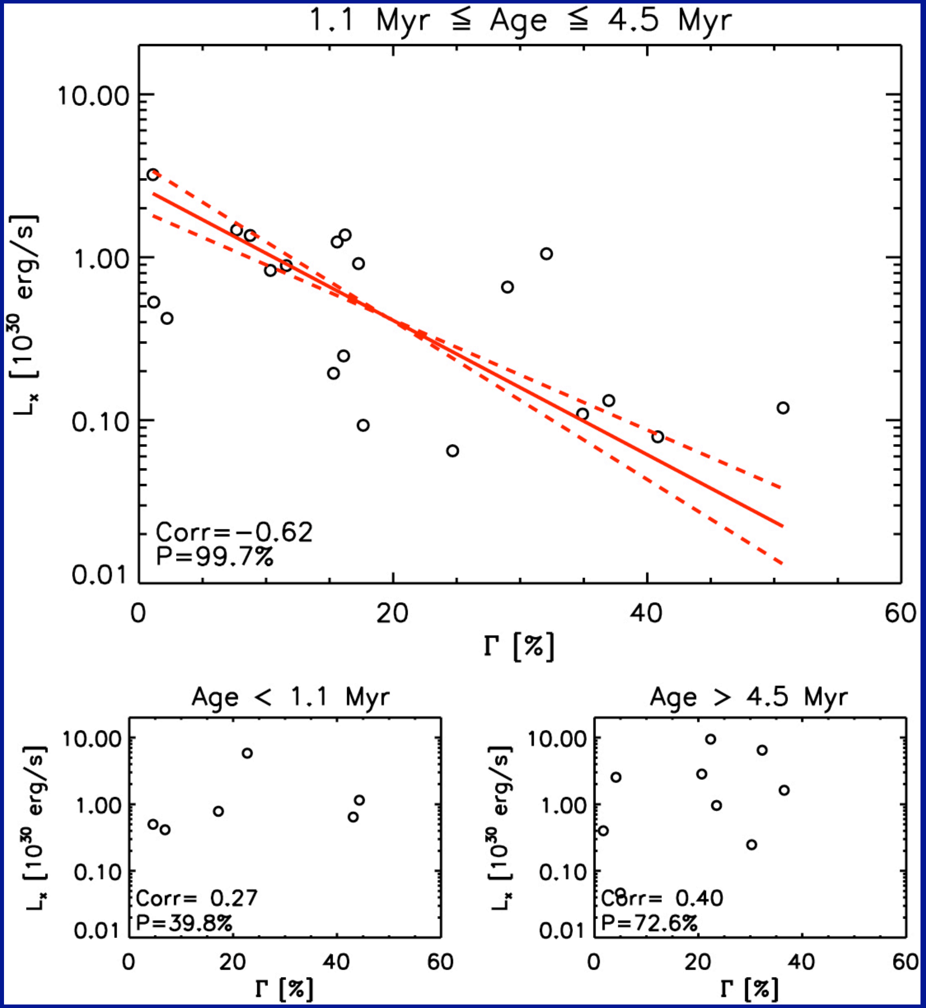
The story continues …

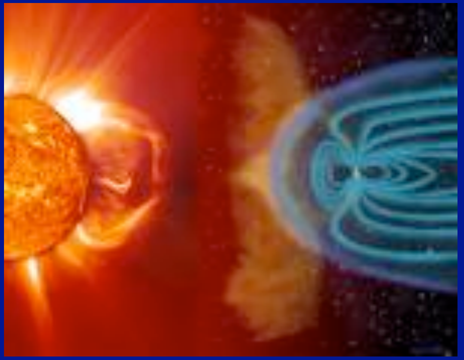


- The Role of Stellar Activity
- Crystals and Outbursts
- Crystals and Planets

Stellar Activity

X-ray luminosity vs. total crystalline masse fraction
(T Tauri stars in age range between 1 – 4.5 Myrs)

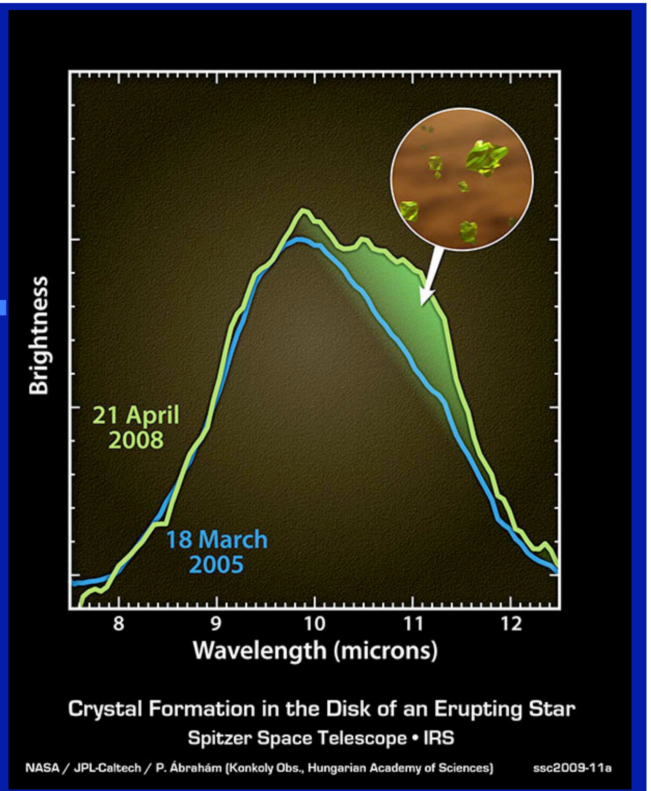




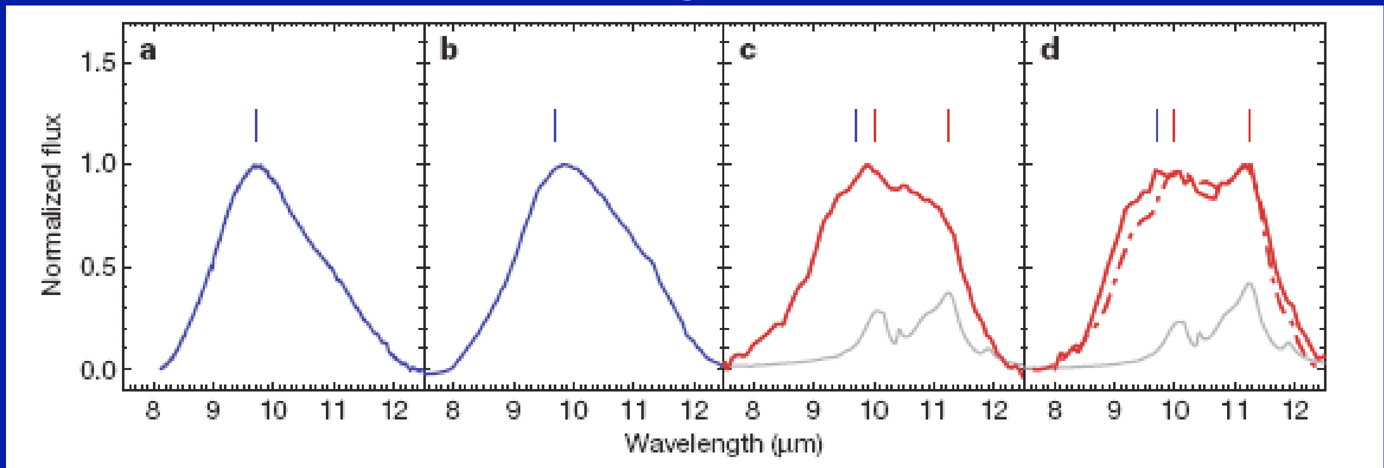
Glauser et al. (2009, Poster A37)

We cook crystals
EX Lupi

2008 Outburst (Brigthening by factor 100)



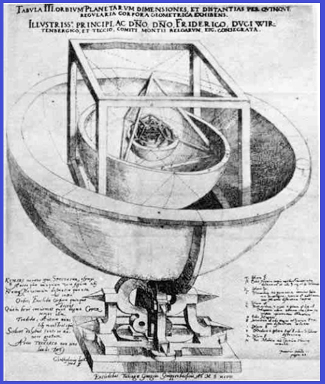
ISM quiet stage outburst comets

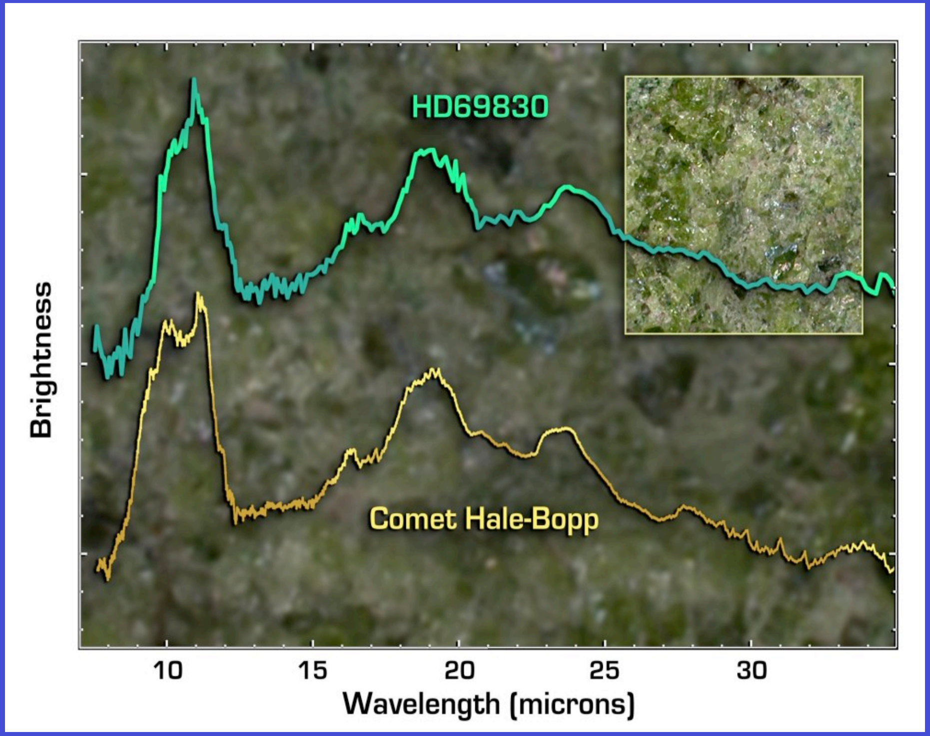


Poster B2
Juhasz ea.

Abraham, Juhasz et al. 2009 (Nature); No indications for crystals in FU Ori disk spectra (Quanz, Bouwman, Henning et al. 2007)

Planets and Crystals





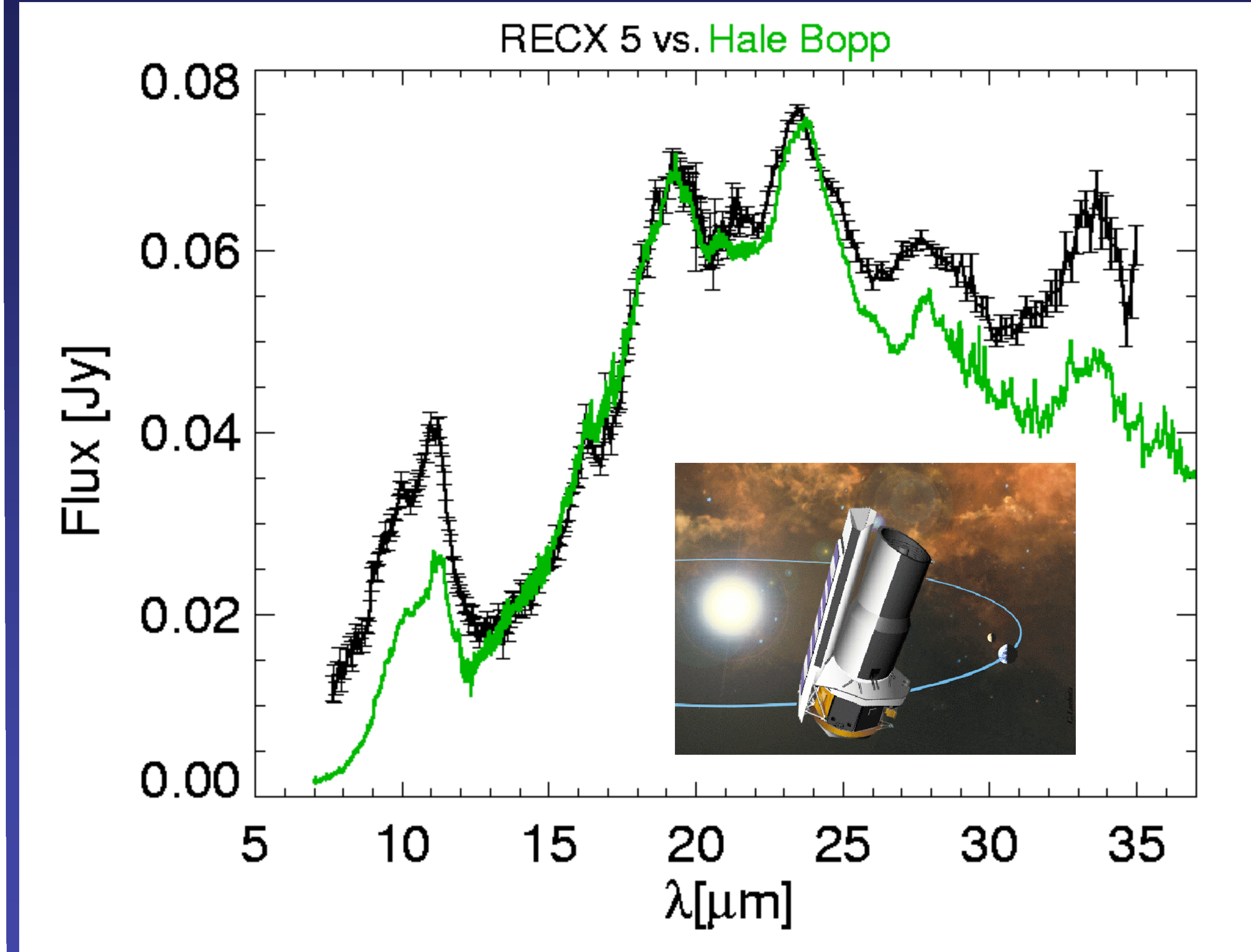
Warm Spitzer debris disks

(Beichman et al. 2005)

Detection of three Neptune-mass planets in this system (Lovis ea.2006)

Detection of about 20 warm debris disks around FGK-type stars
(e.g. Chen et al. 2005, Hines et al. 2006, Moor et al. 2009)

RECX5: Hale Bopp Formation around an M4 star?

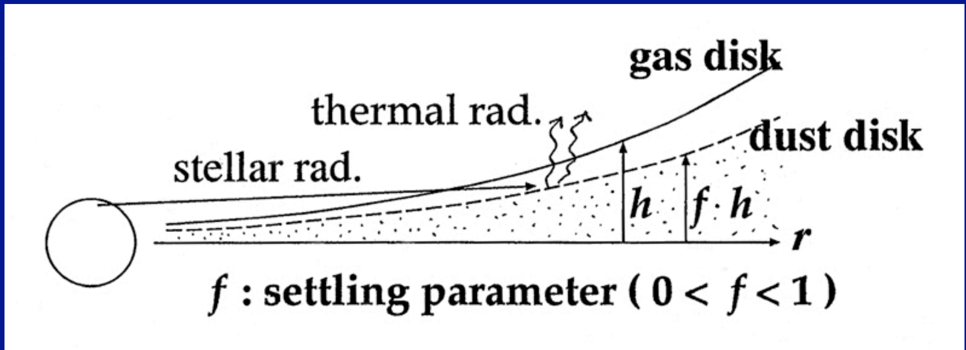


IRS (5-40 μm long slit, R=150, 10-38 μm echelle, R=600)

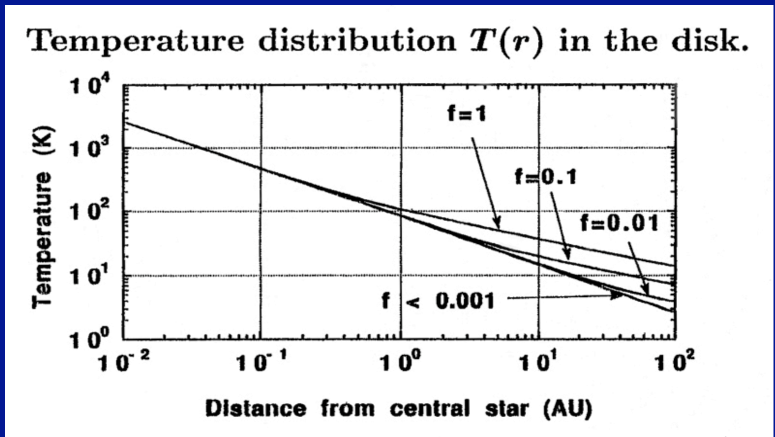
Crovisier et al. (1997), see also Wooden et al. (1999, 2000)

Bouwman et al. (2009, submitted)

Effect of settling on disk and SED

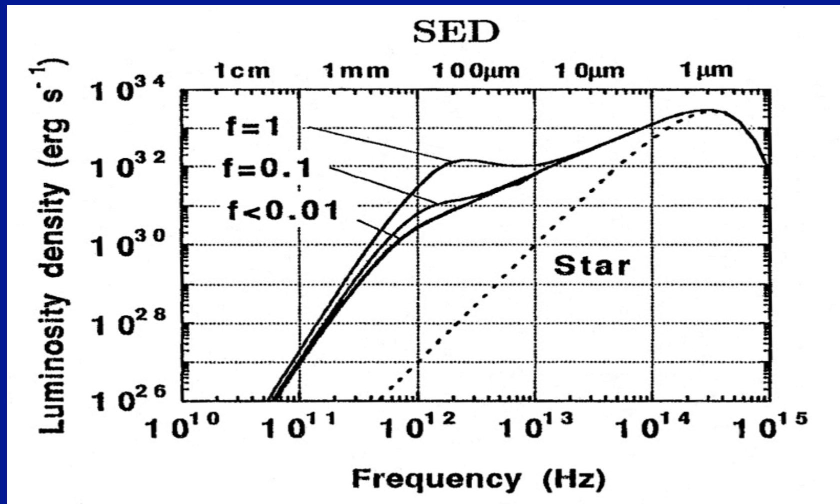


⇓



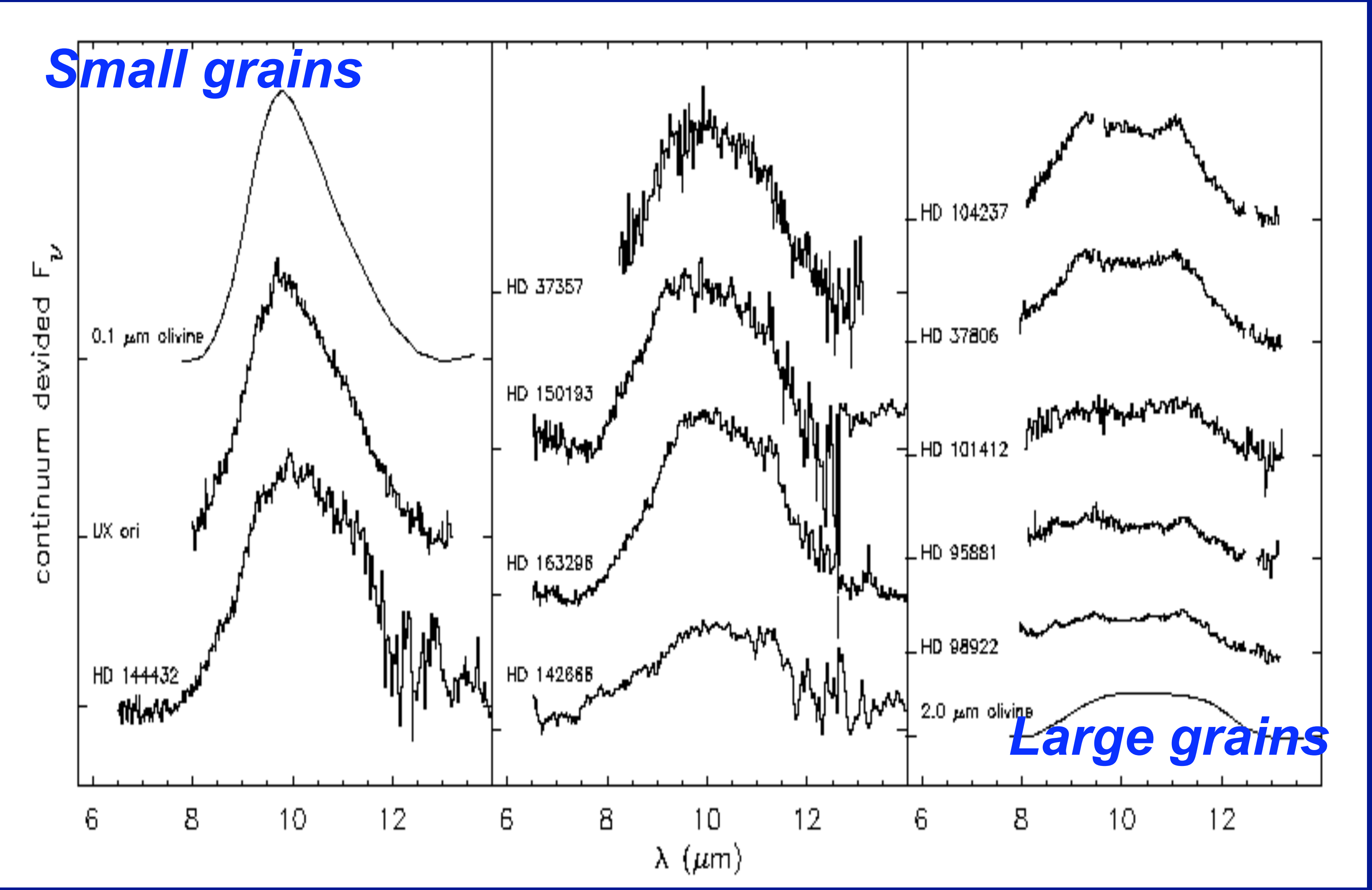
Particle settling leads to flatter disks (i.e., 0 ≤ *f < 1)* and the efficiency of the central stellar heating decreases with the shallower angle of irradiation.

Or even shadowing of the outer disk regions (Dullemond & Dominik 2004)



Miyake & Nakagawa (1995)

Evidence for grain growth

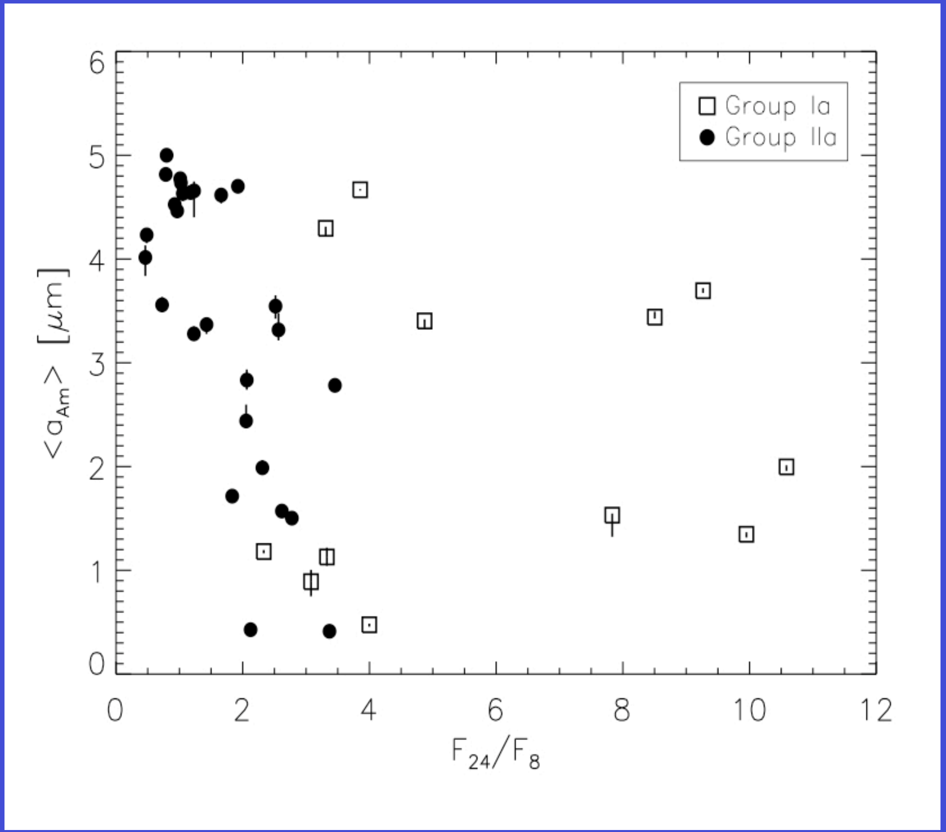


Grains grow to micron sizes …

v. Boekel et al. 2003

Vertical Protoplanetary Disk Structure

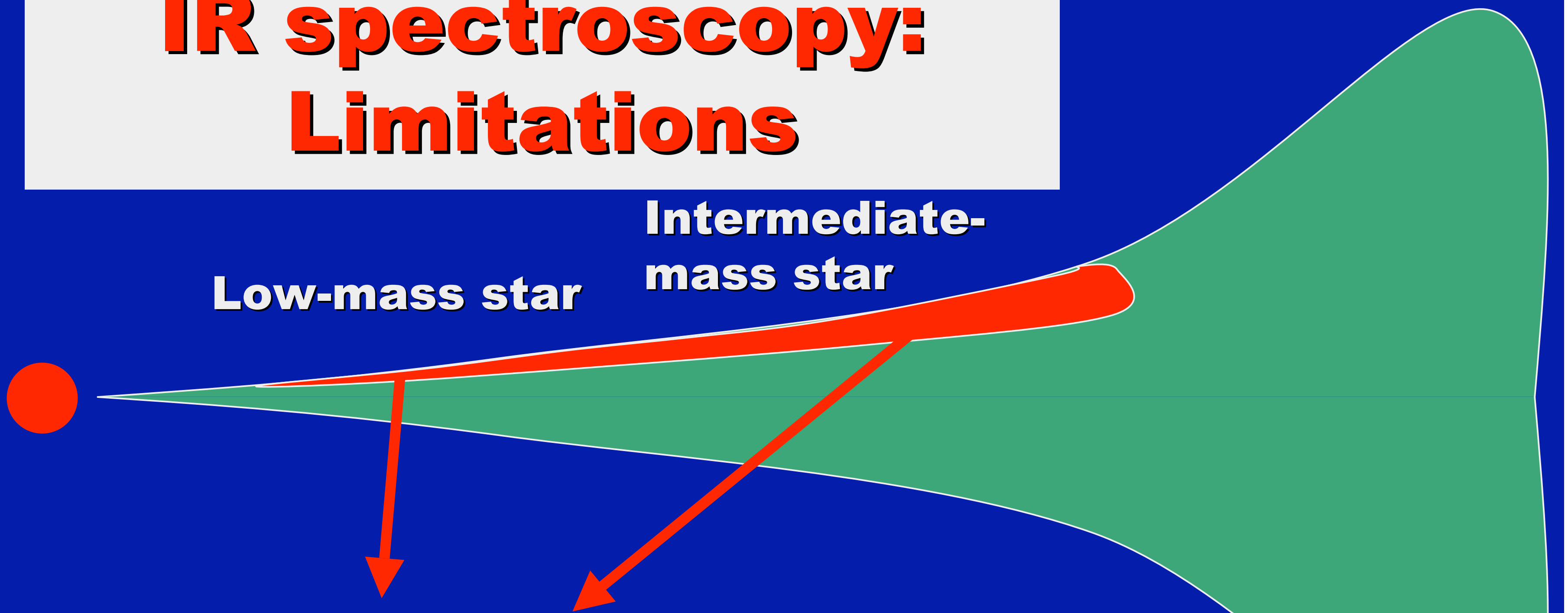
Grain Growth – Dust Sedimentation – Disk Flaring



Spitzer Sample of Herbig Ae/Be Stars
(Juhasz, Bouwman, Henning et al. 2009, submitted)

(For T Tauri stars: Bouwman ea. 08, Watson ea. 08, Olofsson ea.09)

IR spectroscopy: Limitations



- Predominantly probes the warm surface layer
- Depends on temperature distribution: stellar luminosity (Advantage of cometary studies)

  (Be careful with spectral fitting methods: Juhasz ea. 2009)
- Traces grains only up to micron sizes/Featureless metallic iron and am. carbon grains difficult to find

- Ground-based data: Small wavelength range
- Space-based data: Low spatial resolution

How to observe grain sizes with millimeter/centimeter observations?

- Flux density from a disk viewed face-on

$$F_\nu = \frac{1}{D^2}\int_{R_{\rm in}}^{R_{\rm out}} B_\nu(T(r)) \times \{1 - e^{-\tau(\nu,r)}\} \times 2\pi r \mathrm{d}r$$

$$\tau(\nu) \propto \kappa(\nu) \propto \nu^{\beta}$$

- Optically thin disk; Rayleigh-Jeans regime

$$F_\nu \propto \nu^2 \tau(\nu) \propto \nu^2 \kappa(\nu) \propto \nu^{(2+\beta)}$$

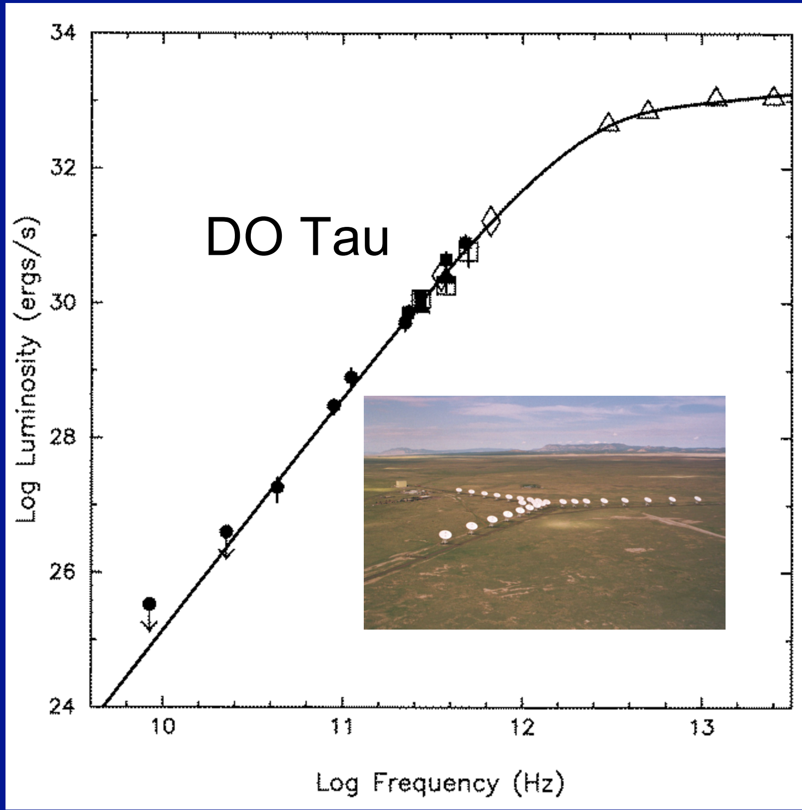
No contrast problem with star/bulk of mass is cold

The VLA 7mm Imaging Legacy

- **T Tauri star DO Tau**
  Koerner et al. (1995): ß=0.6±0.3

- **Low-mass star TW Hya**
  Calvet et al. (2002) ß=0.7

- **Intermediate-mass stars:**
  Testi et al. (2003) CQ Tau: ß=0.5-0.7
  Natta et al. (2004): ß=0.4-1.5



- **Wilner et al. (2005): VLA cm observations of TW Hya**

- **Rodmann et al. (2005): 7 mm VLA imaging of T Tauri stars**

Dust opacity indices

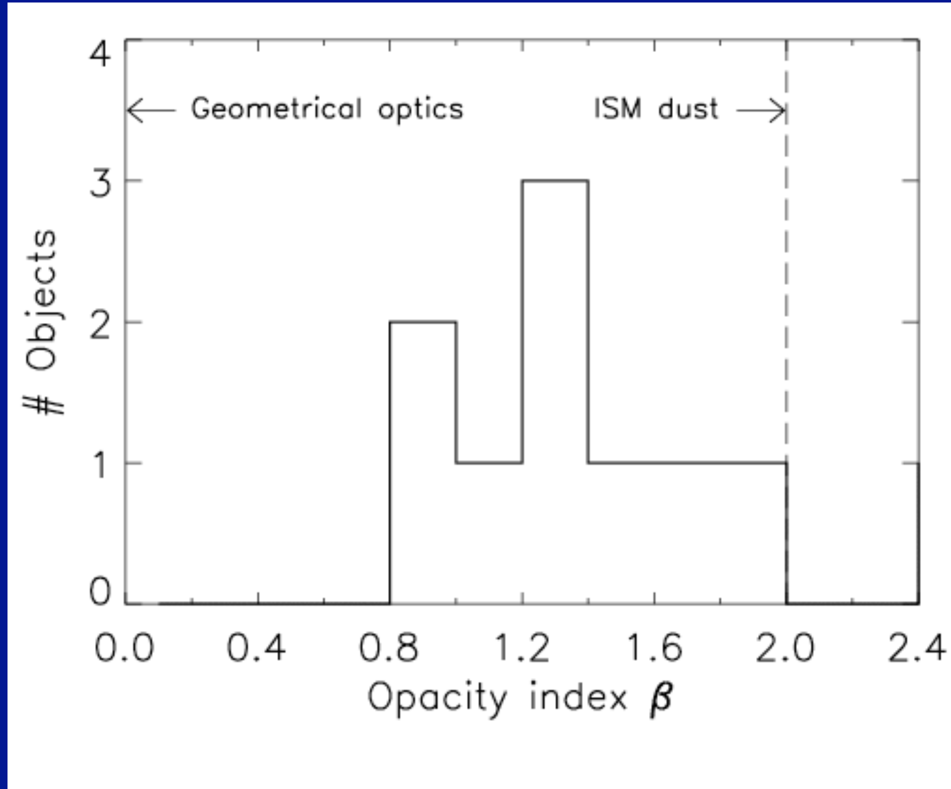
- All detected disks spatially resolved (7 fully, 3 part.)
- Spectral indices $\alpha < 4$
- Opacity indices

  $\beta = \alpha - 2 < 2$
- Small corrections:

  Rayleigh-Jeans &

  free-free emission

Rodmann et al. 2005

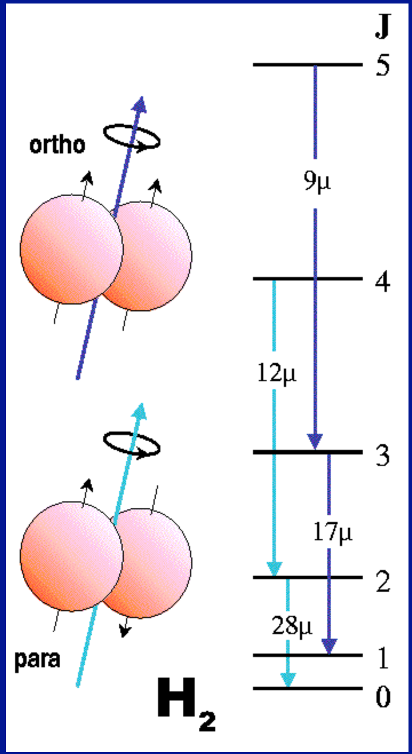


Grains grow to centimeter-sized boulders …

Stay tuned ---- More to come from the VLA and ALMA

H_2 is a challenging molecule to detect

IR rotational lines



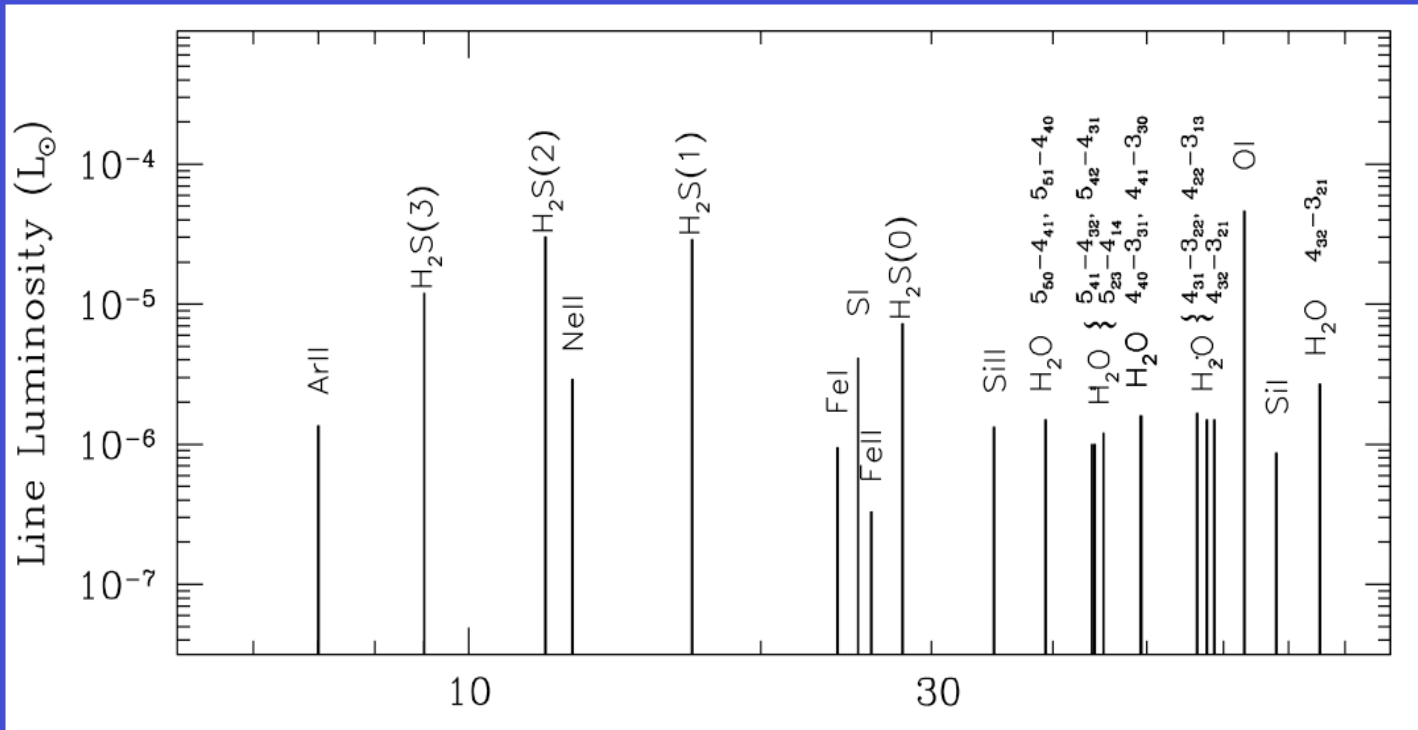
Carmona ea. (2008):
Not sensitivity, but disk structure
(disk interior is optically thick!)

Bitner ea. (2007, AB Aur)
Martin-Zaidi ea. (2009, HD 97048)

We have to use tracers for obtaining information about the gas.

The (Gas) Disk Tracers

- Atomic and ionic fine structure lines ([NeII], [SiII], [SI], …)
- IR molecular lines (H_2, H_2O, CO_2, CO, HCN, ….)
- Mm molecular lines (CO and CS isotopomers, CCH, HCO^+, …)



(Gorti and Hollenbach 2008, Star of 1 Ms)

(For [NeII] disk and outflow story: See talk by Manuel Güdel)

Probing the inner disk (R< 50 AU) with

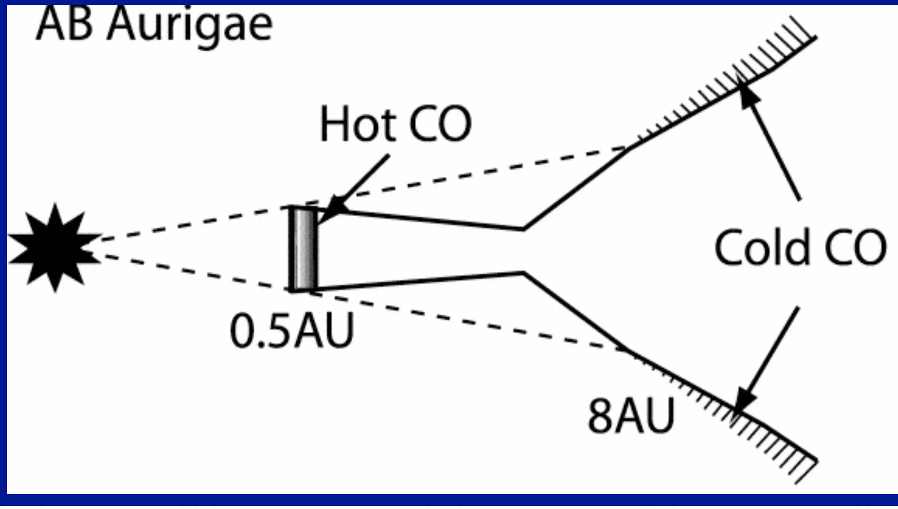
CO *ro-vibrational emission bands at 4.7 µm*

Mid-IR gas lines trace various depths in the warm inner disk (temperature and density profiling)

Gas-dust physics (sedimentation/PAHs) and general thermal structure

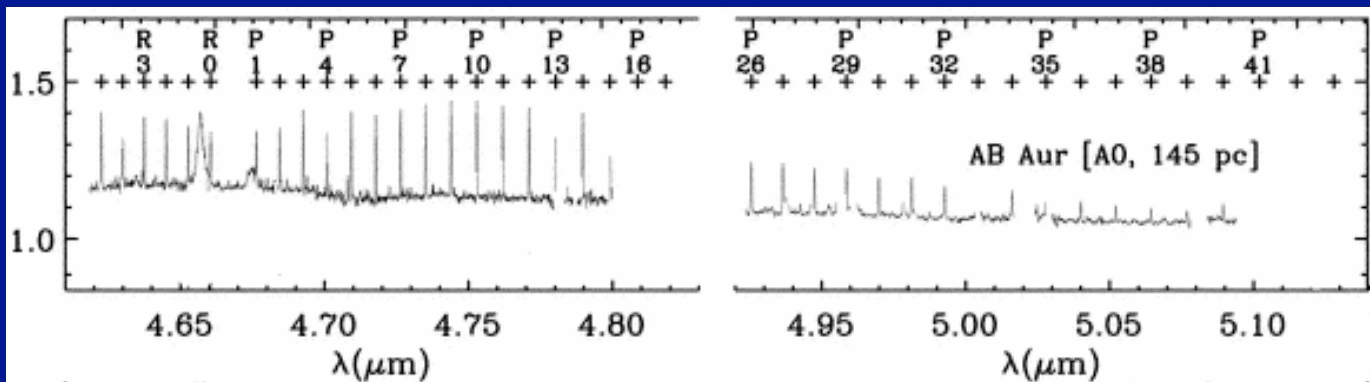
$\nu = 1 - 0$

IR excited



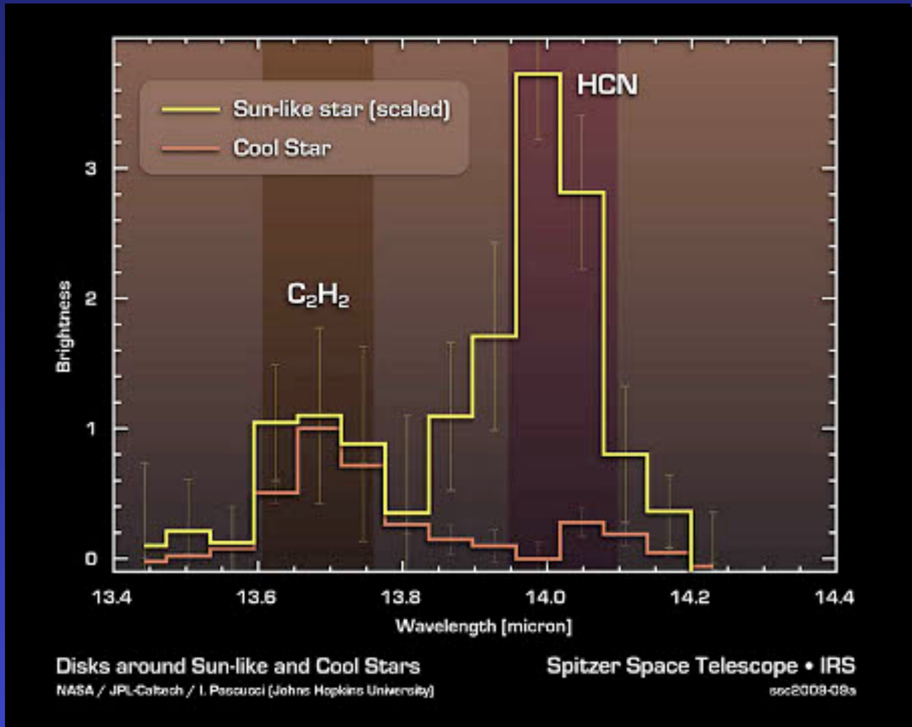
(Talk: Sean Brittain)

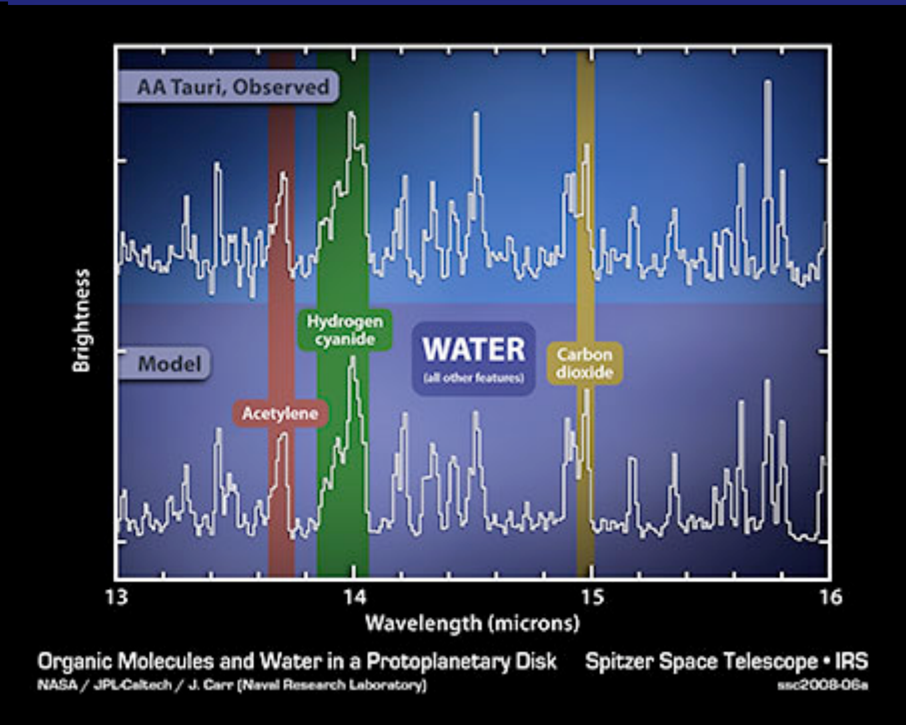
Brittain & Rettig 2003



Blake and Boogert 2004

Organic Molecules and Water in Inner Disks





Pascucci et al. (2008)

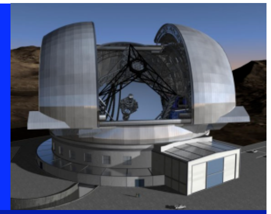
Carr and Najita (2008)

Availability of N atoms from photodissociation of N_2

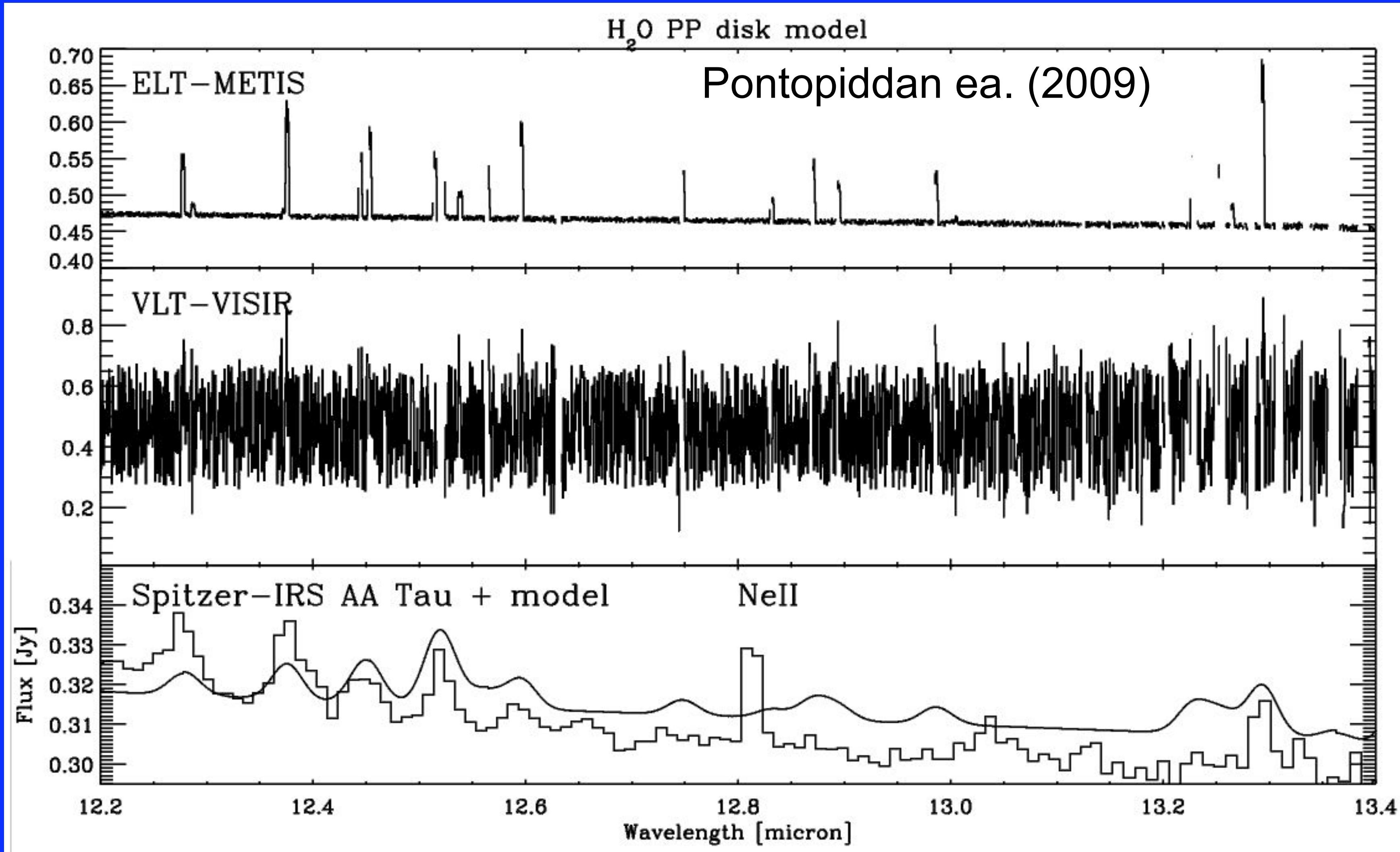
(see also Lahuis ea. 06, Gibb ea. 07, Salyk ea. 08)

(see also Salyk ea. 2008, Talk by Colette Salyk)

Comparison: METIS ⇔ VISIR



Molecular Spectroscopy: *Simulations of 1 hour VISIR and METIS in the 12 μm range as seen from Paranal (only H_2O is modelled)*



Transition disks

Definition:

Optically thin inner region surrounded by an optically thick outer disk

(no/weak excess shortward of 10 micron)

Examples: TW Hya, GM Aur, DM Tau, CoKu Tau/4, GO Tau, DN Tau, …

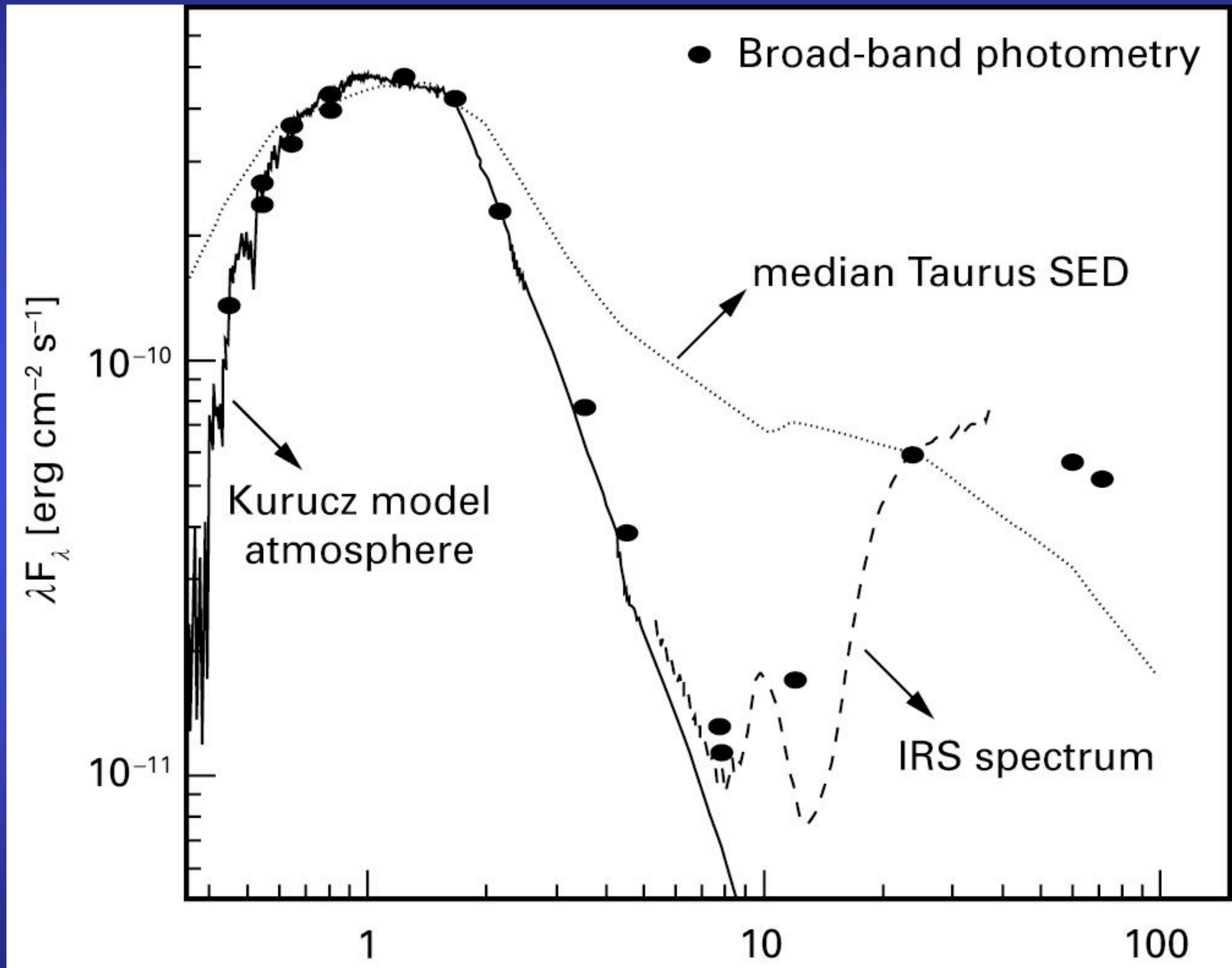
(different gap sizes (2-25 AU) and accretion rates, unresolved companions – CoKu Tau/4, later spectral types)

Strom et al. (1989)

Indication of lower accretion rates:

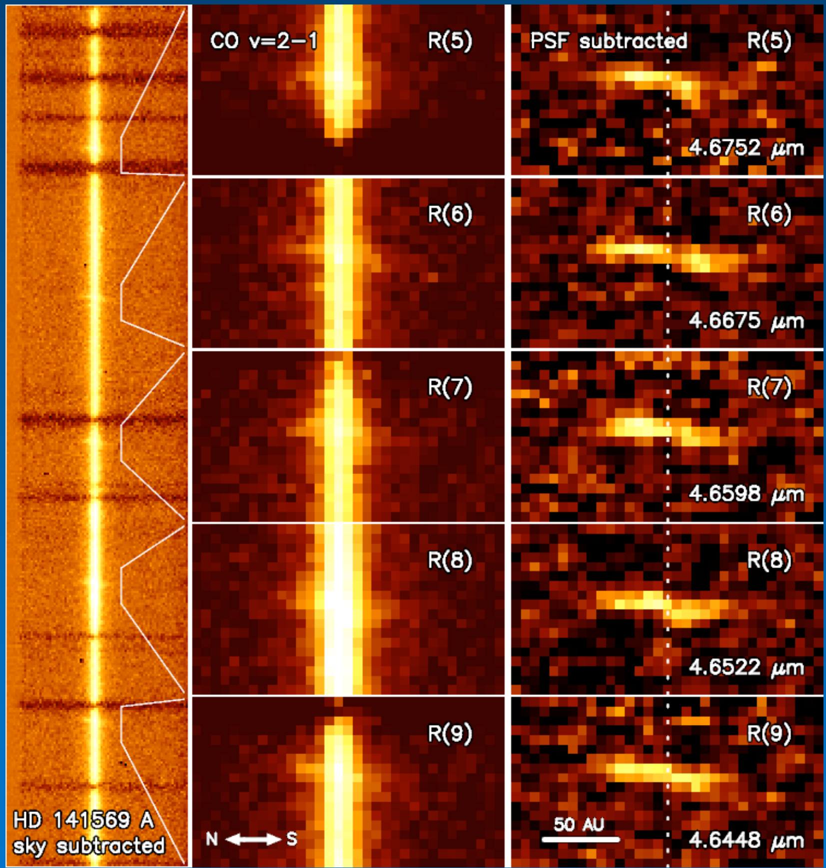
Sicilia-Aguilar et al.(2006), Najita et al. (2007)

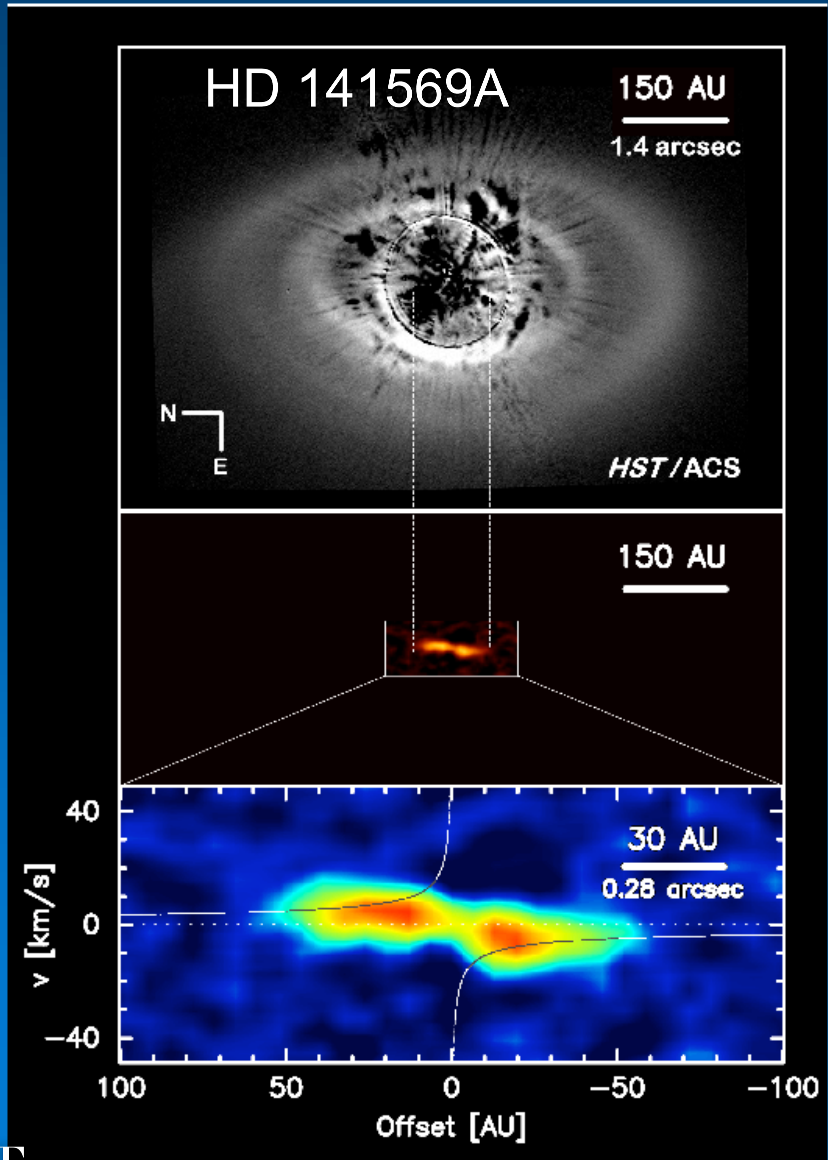
Transition Disks – Inner Gaps



SED of the transition disk around RX1852

A molecular disk at its edge – Beating HST



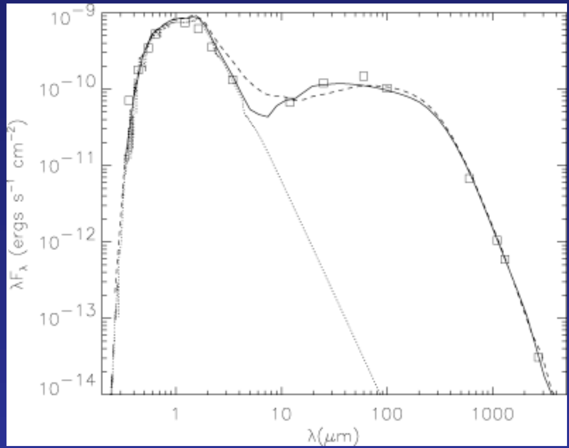


- CO emission at 4.7 μm
- Gas in Keplerian orbit
- Inner cavity (r~11 AU)
- Coming closer to the star than HST

Goto et al. (2006)

The GM Aurigae Discussion

Analysis of SED **(Rice et al. 2003)**



Inner hole created by a ~ 2 Mj planet orbiting at 2.5 AU in a disc with mass 0.047 M_{sun} and radius 300 AU

But: SED contains limited spatial information

(geometry / opacity problem) (dM/dt~10^{-8} M_{sun}/yr)

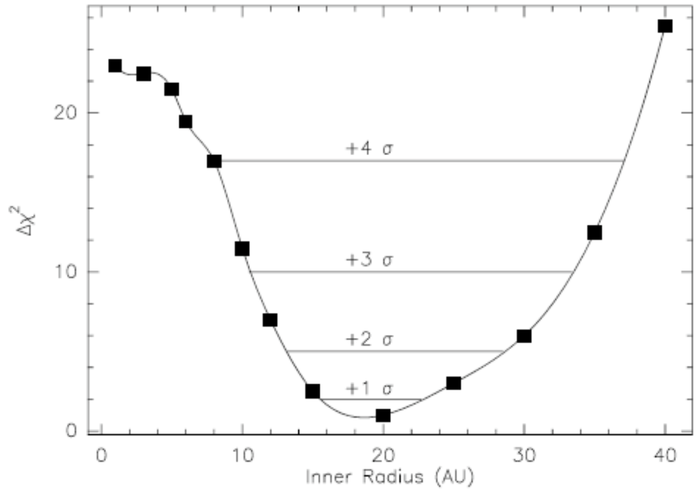
Boss & Yorke 1993, Steinacker & Henning 2003 (Opacity gap)

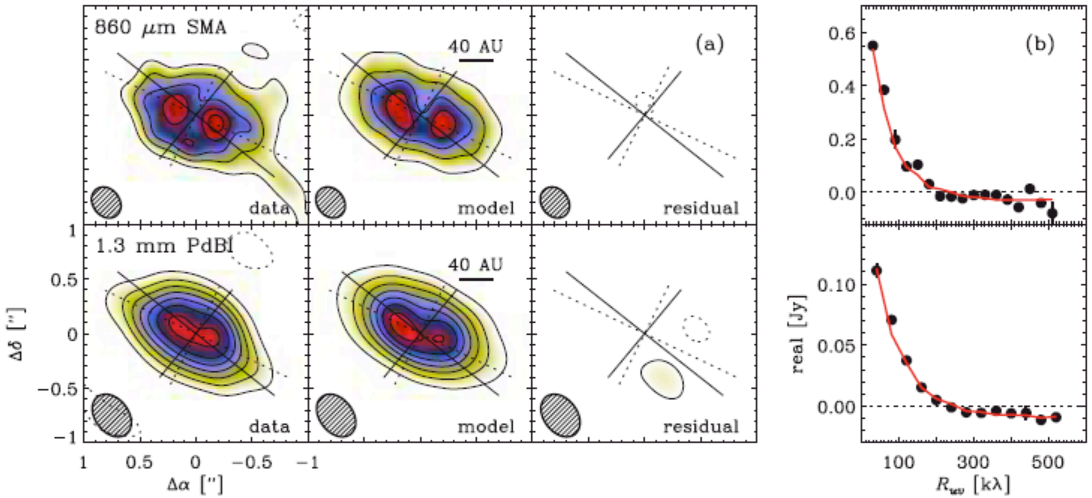
Presence of inner hole confirmed by millimetre interferometry – Deficit of material inside 20 AU (Dutrey et al. 2008, Hughes et al. 2009)

The GM Aur Case – Gas and Dust

Dutrey et al. (2008) → Rin = 20 AU
Spectroscopic detection

Hughes et al. (2009)– Same dust inner radius





Analysis 12CO, 13CO, C18O 1-0, 2-1
PdBI data

The cavity is «devoid » of dust and gas

CO line wings are tidally truncated « super resolution »
→Companion: Is this a giant planet ?

Cavity Radius < Pluto's Orbit

Other mechanisms

- Disc wind caused by photoevaporation ???
  (Clarke et al. 01, Alexander et al. 06, Gorti & Hollenbach 09)
- Higher temperature due to accretion shock front ???
  (d‘Alessio et al. 03)
- Destruction of grains by non-thermal processes ???
  (Lenzuni et al. 95, Finocchi et al. 97)
- Inside-out evacuation by MRI
  (Chiang & Murray-Clay 07)
- Drop of dust opacity due to grain growth
  (Strom et al. 89, Boss & Yorke 93, Steinacker & Henning 03)

Some more information

- Transition disks are found in young stars, but are more frequent in older clusters

- Higher fraction of TO among M-type stars compared with G-K stars (McCabe et al. 2006) ???

- Some low-mass SF regions have very high TO fractions (Megeath et al. 2005, Sicilia-Aguilar et al. 2008, 2009)

We may have a diversity of processes acting at different evolutionary stages and environments.

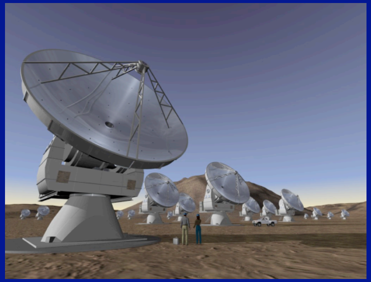
(see also Alexander & Armitage 2009)

New horizons …
Resolution, Resolution, Resolution

- SEDs + Interferometry data

  (Menshchikov, Henning, Fischer 1999,
  Wolf et al. 2003, van Boekel ea. 2004,
  Andrews & Williams 2007, Ratzka et al. 2007,
  Pinte et al. 2008, …)

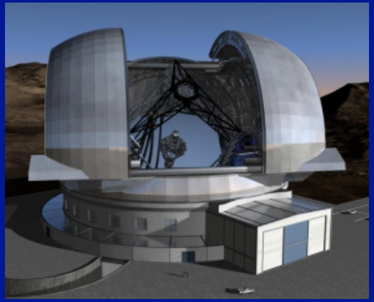
VLTI, LBTI, Keck/I



PdBI, SMA, CARMA, ALMA

- Study gas and dust together

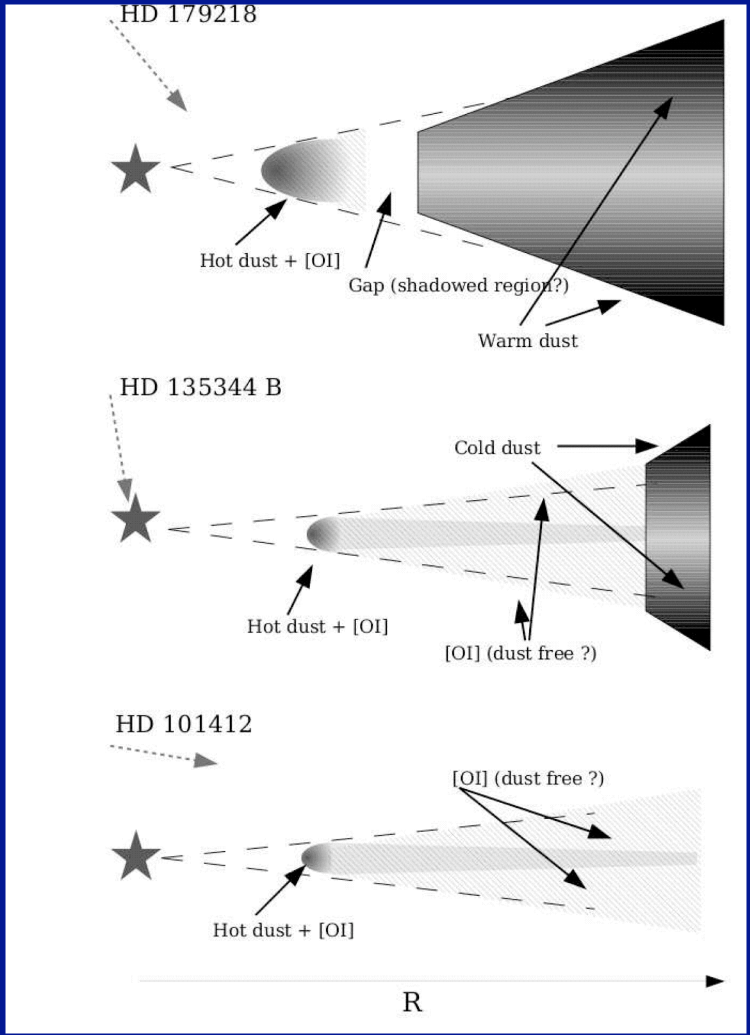
  (Fedele et al. 2008, 2009, Panic et al. 2009, …)



E-ELT, TMT, GMT

An Example

Dust *and* Gas Distribution



Fedele et al. (2008)

Summary

- Evidence for grain and gas evolution
- Material inventory of statistically relevant samples
- Bright Future (10m-class telescopes, ELTs, IR-Interferometry, Herschel, ALMA, JWST)

Reviews: Henning, Dullemond, Dominik, Wolf (2005)
Natta, Testi, Henning et al. (2007) PPV
Henning (2008), Henning & Meeus (2009)

Summary

- Evidence for rapid grain and gas evolution
- Material inventory
- Bright Future (10m-class telescopes, ELTs, Interferometry, Herschel, ALMA, JWST)