Herbig Ae/Be stars

Rens Waters
SRON
University of Amsterdam

George Herbig
1920-2013

Overview

- A bit of history
- Herbig Ae/Be stars and their disks
- Disk geometry
- Dust diagnostics
- Gas diagnostics
- Links to planetary systems
- Conclusions

Herbig Ae/Be stars

- First introduced as a group by George Herbig in 1960
- A or B type stars with IR excess, Hα emission, reflection nebulosity
- In star forming regions
- Surrounded by what we now know are proto-planetary/accretion disks, envelopes

- Later: criterion “association with reflection nebulosity” was relaxed

- See also e.g. Bastian et al. (1983), Lamers et al. (1998)

Confusion with post main sequence stars remains an issue

THE SPECTRA OF Be- AND Ae-TYPE STARS ASSOCIATED WITH NEBULOSITY*

GEORGE H. HERBIG
Lick Observatory, University of California
Received November 2, 1959

ABSTRACT

An argument based on the relative rates of contractive and nuclear (hydrogen-burning) evolution for stars of masses 3 to 20 $m_{\odot}$ enables an estimate to be made of the number of still-contracting stars of these masses within an observable distance of the sun. For example, within 1 kpc of the sun and 100 pc of the galactic plane one would expect there to be, somewhere in their contractive phase, about 18 stars that will in time reach the main sequence at types B2 and B3. A purely empirical attempt was made to identify some of these objects by examining in detail a list of 26 Be- and Ae-type stars that both lie in obscured regions and illuminate nearby nebulosity. The list contains such well-known variables as T Ori, AB Aur, RR Tau, Z CMa, and R Mon, as well as some newly found emission-line stars. In the course of the investigation two new variable nebulae were found. Two main types of stars were encountered: one with emission lines mainly of hydrogen plus absorption features due to a weak overlying shell; and another group with higher velocities of ejection, stronger emission lines, and line structure of the P Cygni type. Although it is entirely possible that this list of peculiar objects does contain examples of still-contracting stars of large mass, no convincing proof of this supposition could be found. The essential reason was that, although there are some striking spectroscopic peculiarities among the stars examined, at the dispersions employed in this investigation the peculiarities did not appear to be unique to this group: they may be found as well in stars that are not associated with nebulosity.

SRON

TABLE 3

Be AND Ae STARS ASSOCIATED WITH NEBULOSITY

	Star	Other Designation	α(1900)	δ(1900)	Magnitude*	Spectral Type	Nebula†
1....	LkHα 198	....	$0^{h}06^{m}1$	+58° 17′	*15*	A:ea	Anon.
2....	BD+61°154	MWC 419	0 37.5	+61 22	10.6	B2–B5 eq	Anon.
3....	AB Aur	HD 31293	4 49.4	+30 23	*7.2– 8.4*	B9e+shell	Anon.
4....	HK Ori	MWC 497	5 25.9	+12 05	*11.4–12.5*	Ae	Bar. Atlas no. 100
5....	T Ori	MWC 763	5 30.9	− 5 32	9.5–12.6	B–Aea+shell	(Orion)
6....	V380 Ori	−6°1253	5 31.6	− 6 47	9.7–10.3	B8–A2e	NGC 1999
7....	RR Tau	AS 103	5 33.3	+26 19	10.2–14.2	B8–B9e+shell	Anon.
8....	HD 250550	MWC 789	5 56.2	+16 31	*9.7*	B9eq	Anon.
9....	LkHα 208	....	6 02.1	+18 42	*13.0*	B5–B9e+shell	Hubble anon.
10....	LkHα 215	....	6 27.2	+10 14	10.7	Be+shell	NGC 2245
11....	HD 259431	MWC 147	6 27.6	+10 24	8.7	B5:e	NGC 2247
12....	R Mon	MWC 151	6 33.7	+ 8 50	*11.3–13.8*	e+shell	NGC 2261
13....	LHα 25	....	6 35.2	+ 9 53	13.0v?	B8pe+shell	(NGC 2264)
14....	Z CMa	MWC 165	6 59.0	−11 24	*8.8–11.2*	eq	Anon.
15....	HD 53367	MWC 166	6 59.7	−10 18	7.0	B0 IV:e	IC 2177
16....	MWC 297	....	18 22.4	− 3 55	*11.0*	?	Anon.
17‡...	R CrA	....	18 55.2	−37 06	*10.0–13.6*	Ae	NGC 6729
18‡...	T CrA	....	18 55.2	−37 06	*11.8–13.9*	F0ea	(NGC 6729)
19....	BD+40°4124	MWC 340	20 17.0	+41 03	10.6	Be	Anon.
20....	BD+41°3731	....	20 20.8	+41 58	9.9	B2–B3e	NGC 6914*b*
21‡...	HD 200775	MWC 361	21 00.4	+67 47	7.4	B3e+shell	NGC 7023
22....	BD+65°1637	AS 475	21 40.6	+65 39	11	B5e	NGC 7129
23....	LkHα 234	....	21 40.8	+65 39	*13*	Aeβ	NGC 7129
24....	BD+46°3471	AS 477	21 48.7	+46 46	10.1v?	A0e+shell	(IC 5146)
25....	LkHα 233	....	22 30.3	+40 08	*14.5*	A7ea	Anon.
26....	MWC 1080	....	23 12.9	+60 18	*13.0*	eq	Anon.

Samples of Herbig Ae/Be stars

- Original list of Herbig (1960) (26 objects, candidates)
- Herbig & Rao (1972) (T Tau and Herbig Ae/Be stars)
- Finkenzeller & Mundt (1984) (57 stars including candidate HAEBE stars)
- The et al catalogue (1994) (287 objects, including candidate HAEBE stars)

- Cross-referencing IRAS point source catalogue and optical star catalogues: e.g. Weintraub (1990), Oudmaijer et al. (1992), Malfait et al. (1998)

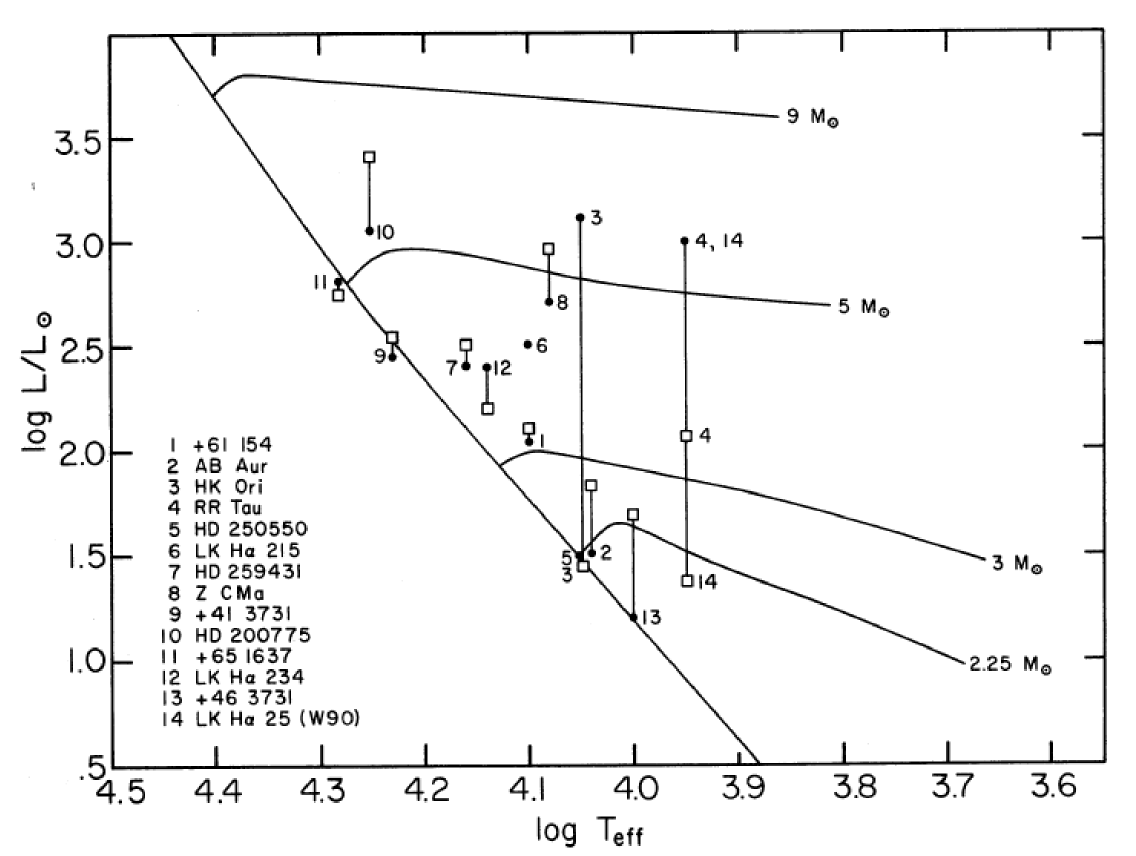
Searches for intermediate mass young stars in massive star forming regions (e.g. Hanson, Blum, Bik, Kaper)

Central star characterization

Strom et al. 1972

See also Cohen & Kuhi 1979

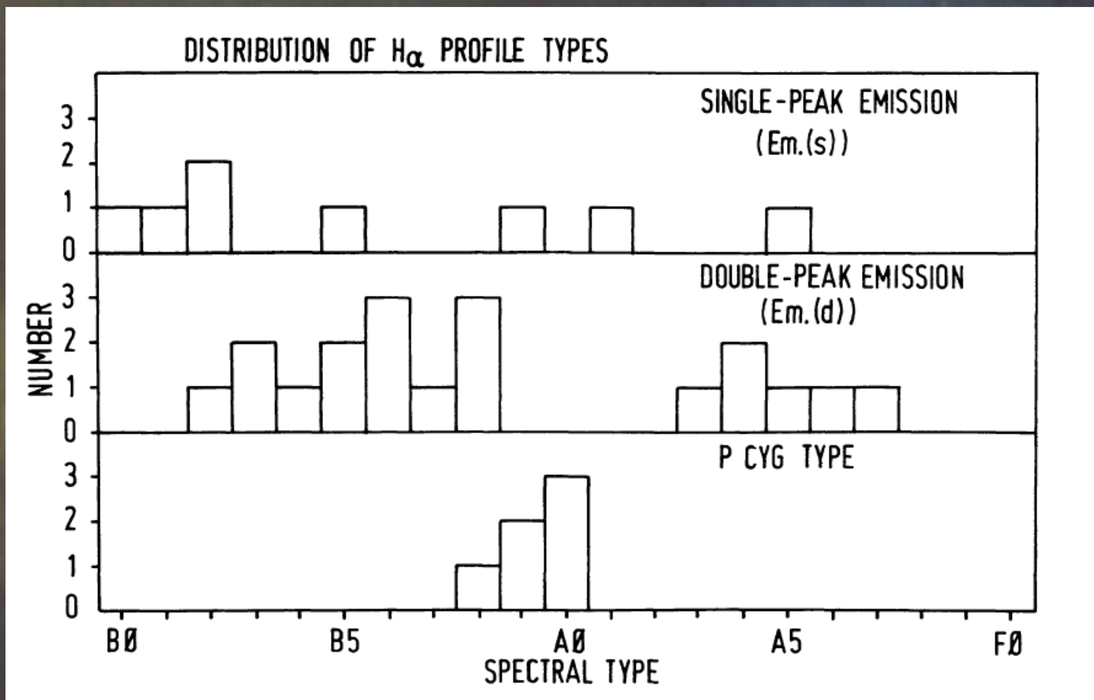
Acke & Waelkens 2004

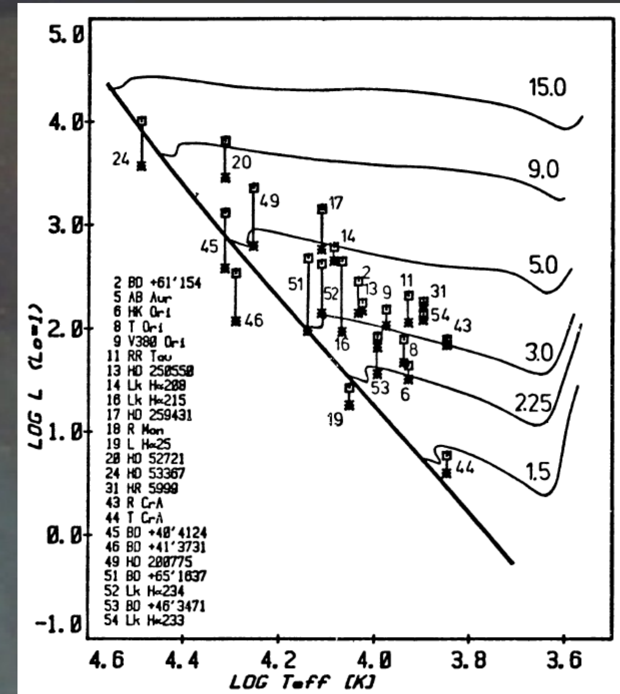


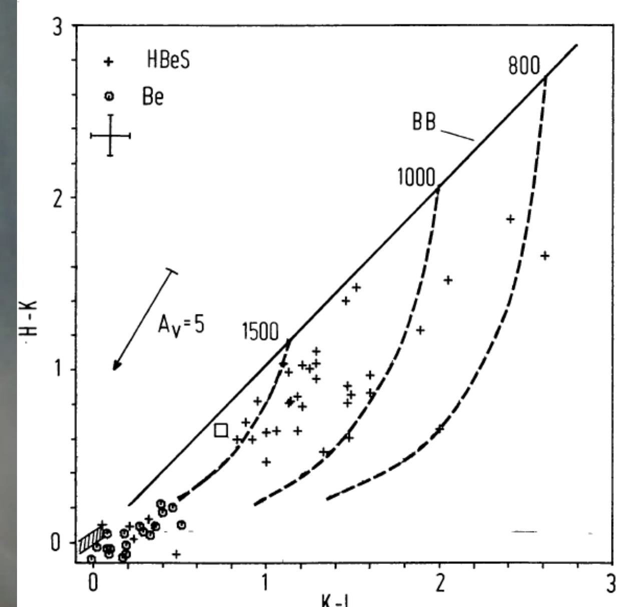
Strom et al. 1972

Chemical composition
Rotation speed
Magnetic fields
binarity

Finkenzeller & Mundt 1984

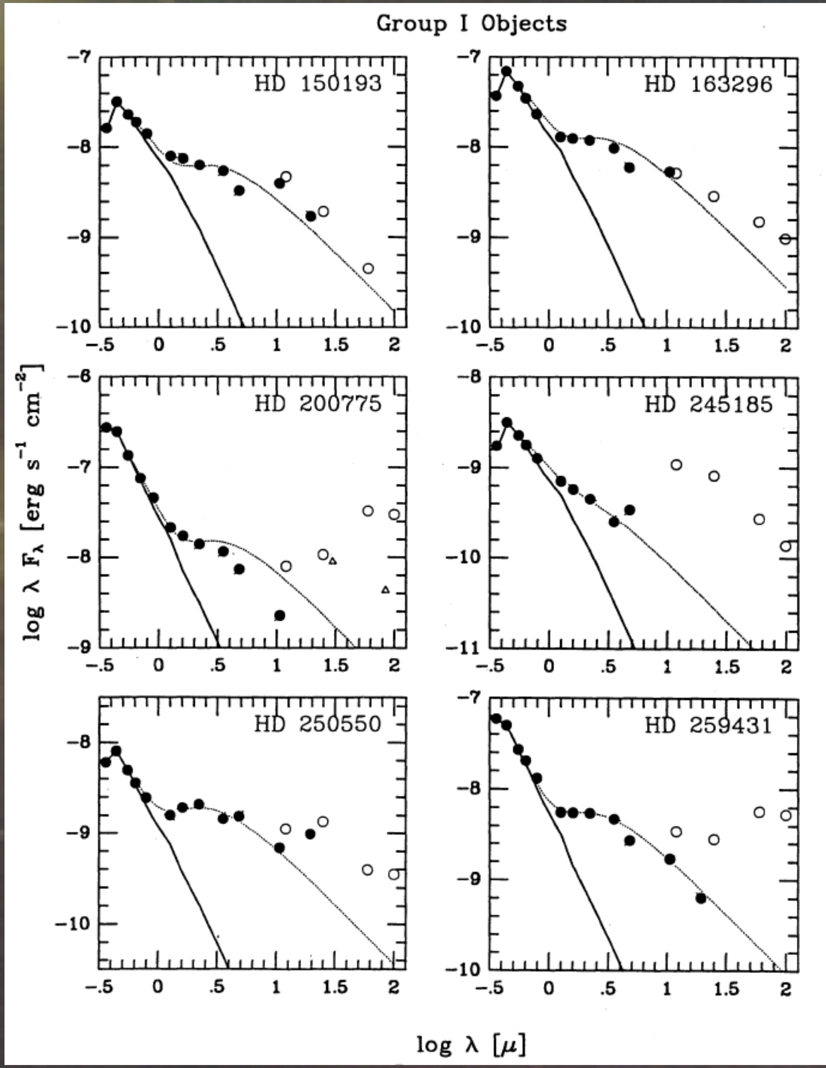


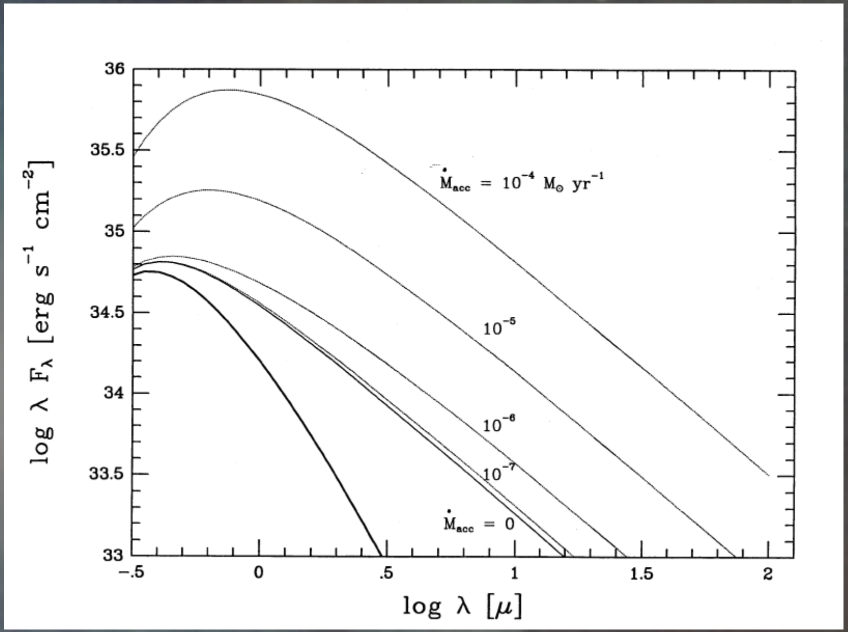




Outflows
IR excess due to dust

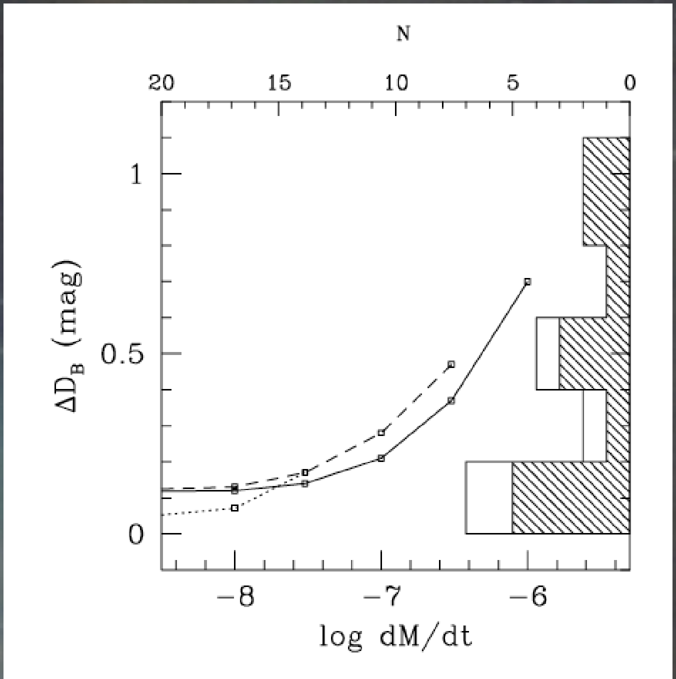
Spectral energy distributions





Hillenbrand et al. 1992

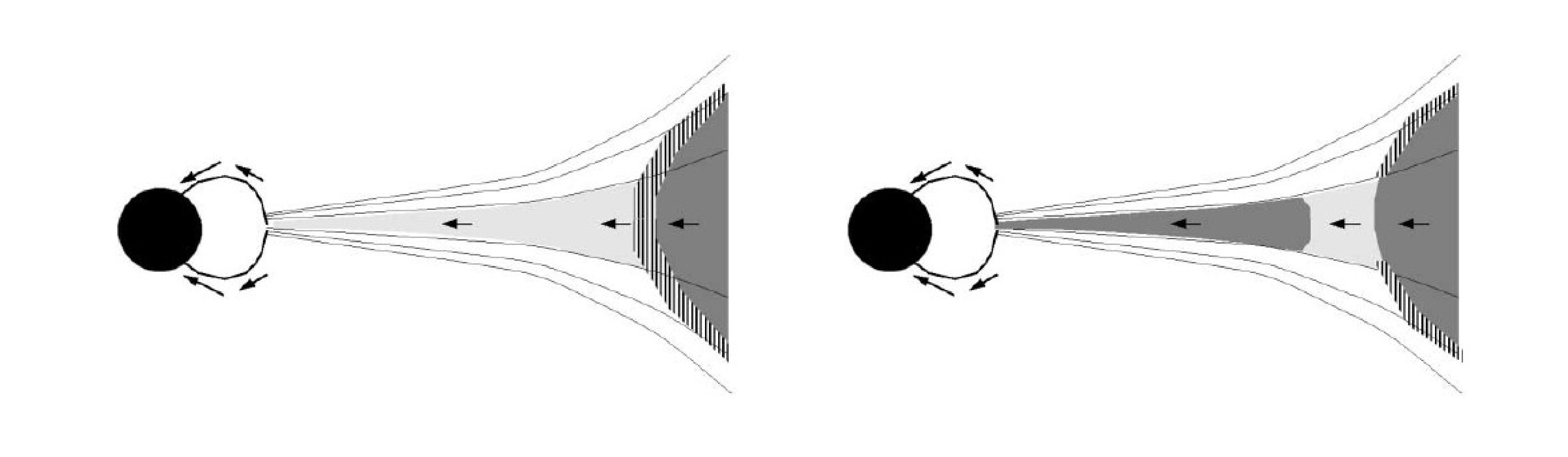
Mass accretion rates



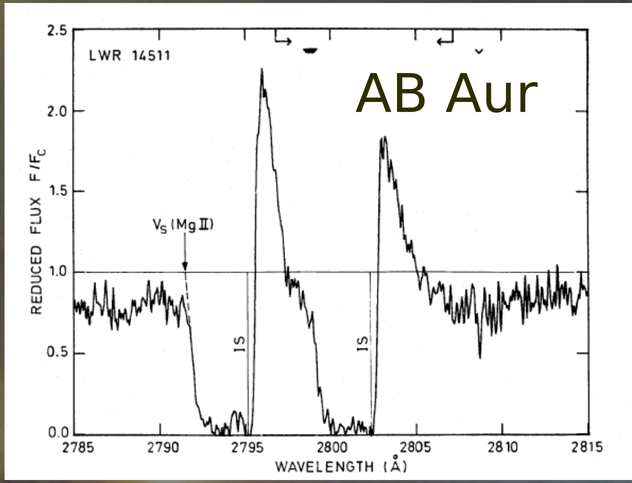
Skinner et al. (1993) from radio continuum

Muzerolle et al (2004)

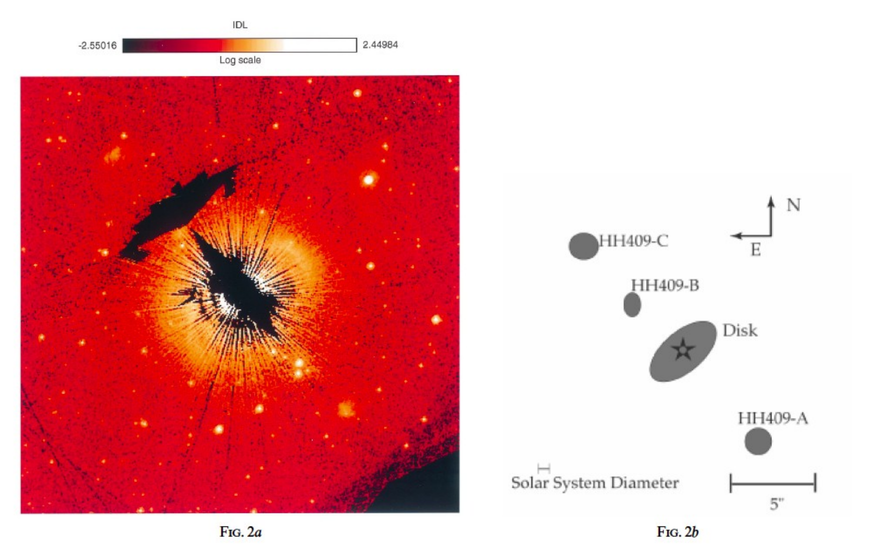
Typical accretion rates 10^{-8} to 10^{-7} M_o/yr



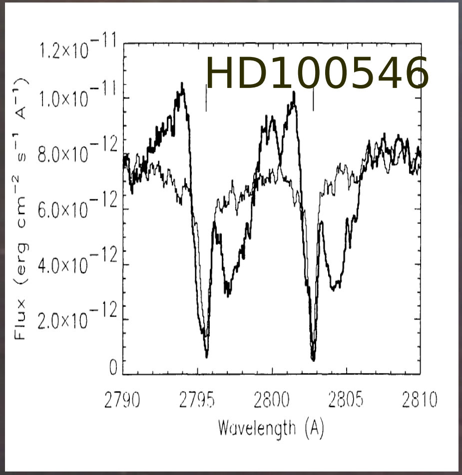
Outflows and accretion, Herbig Haro objects, jets



Praderie et al. 1986

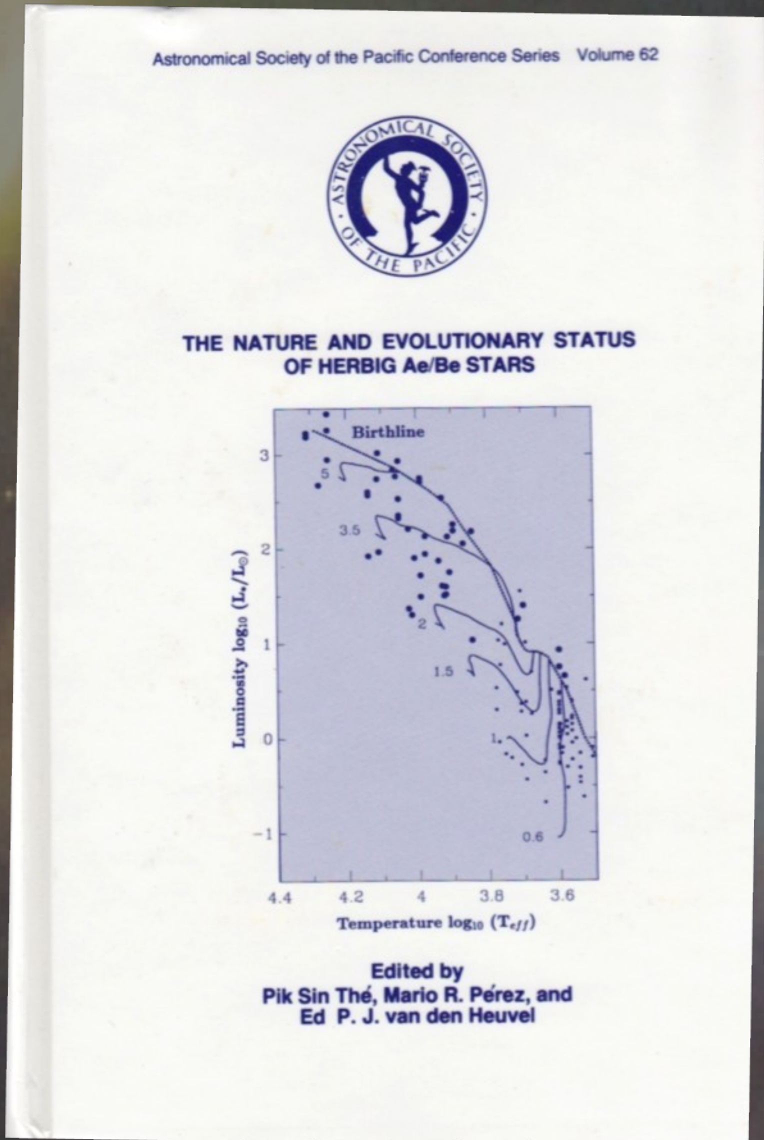


Grady et al.2000



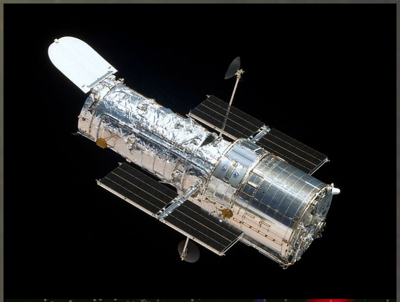
Grady et al. (1996)

Herbig stars show phenomena that are similar to T Tau stars

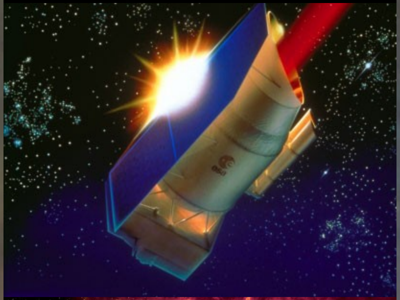


First international meeting on
herbig Ae/Be stars
Amsterdam, 1993

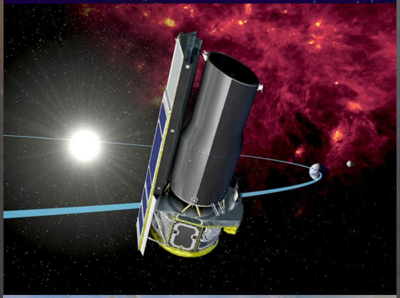
Tremendous progress in the past 20 years!



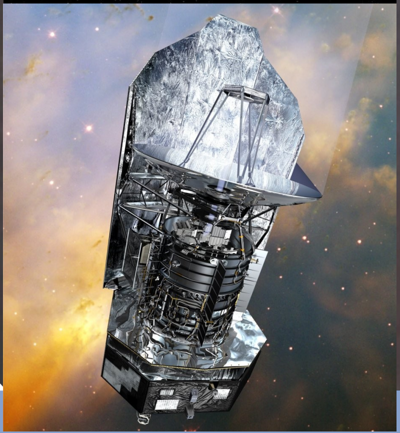
HST KECK



ISO VLT(I)

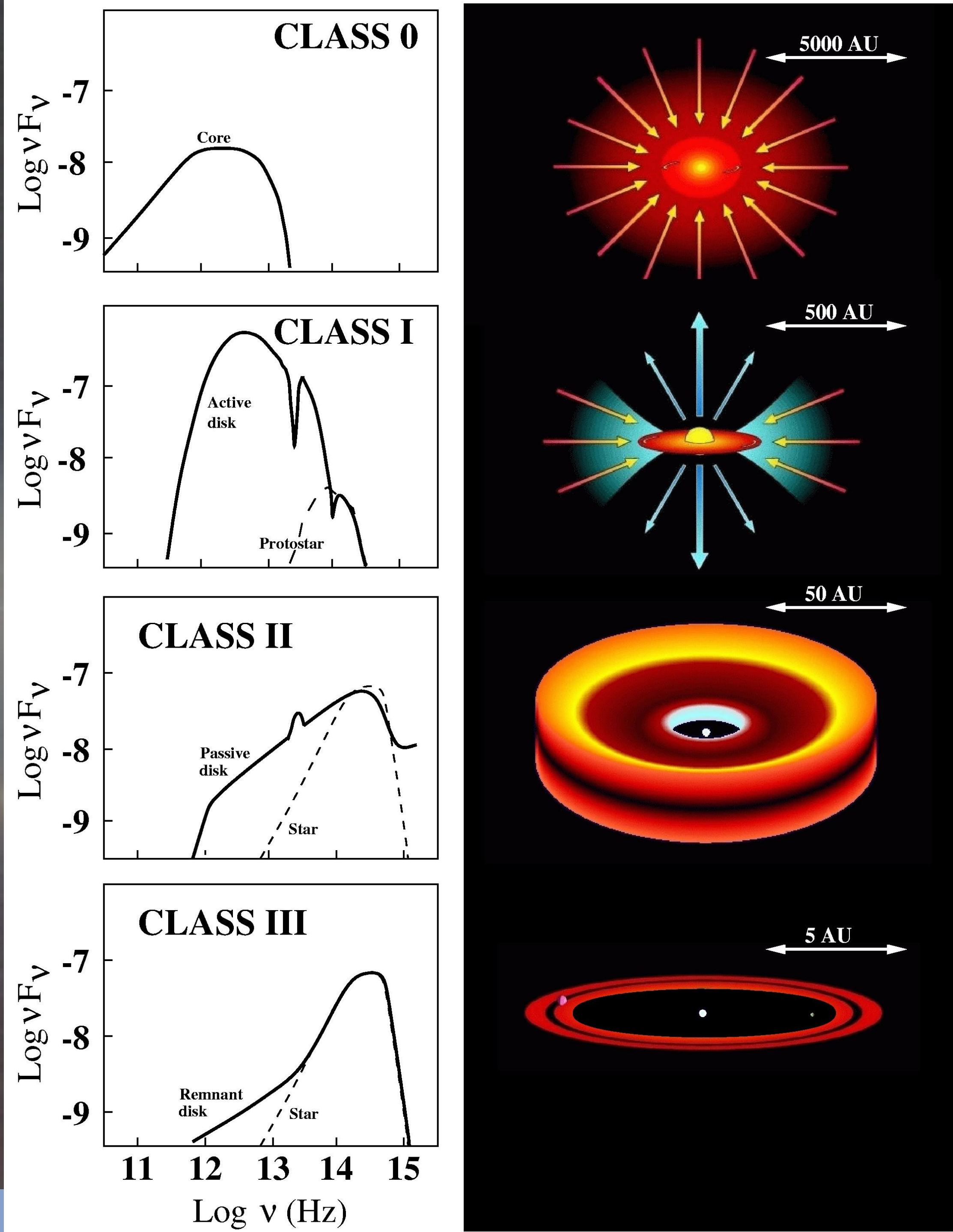


Spitzer Subaru



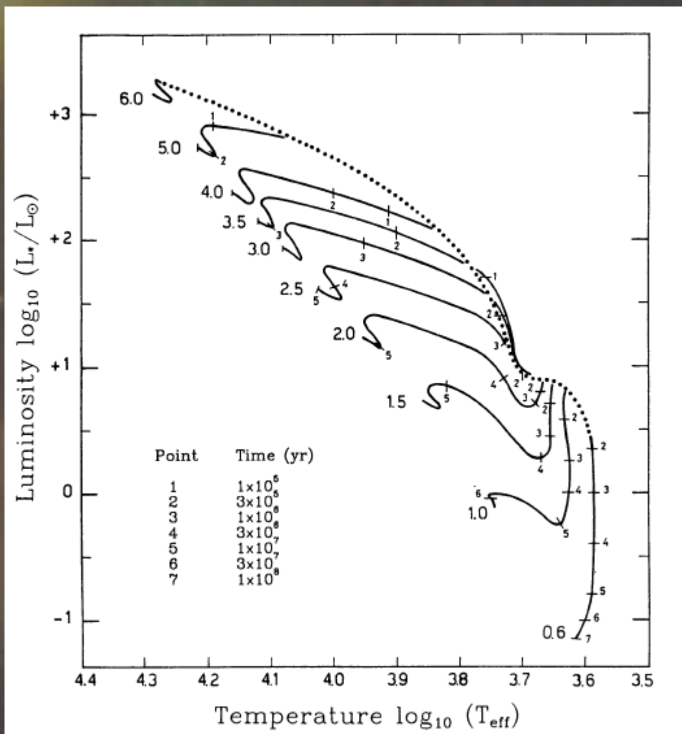
Herschel ALMA

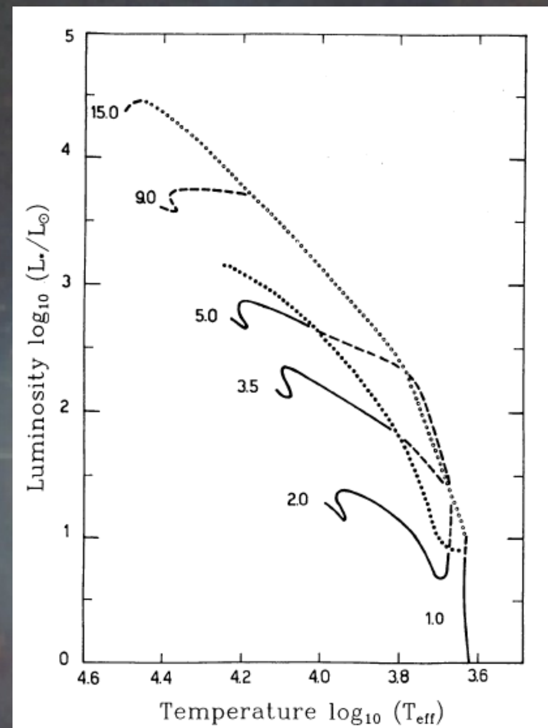
Spectral evolution during star and planet formation: picture for all intermediate mass PMS stars?

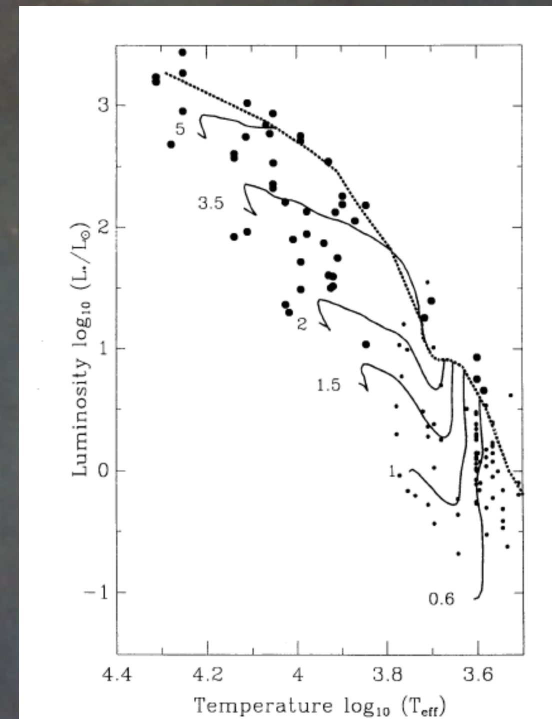


Van Boekel and refs therein (2004)

Evolutionary tracks: pre-main-sequence phase







Palla & Stahler 1990, 1993

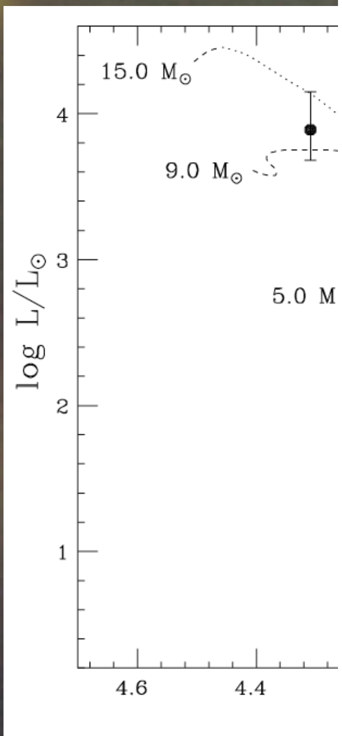
Birth line for Herbig Ae/Be stars

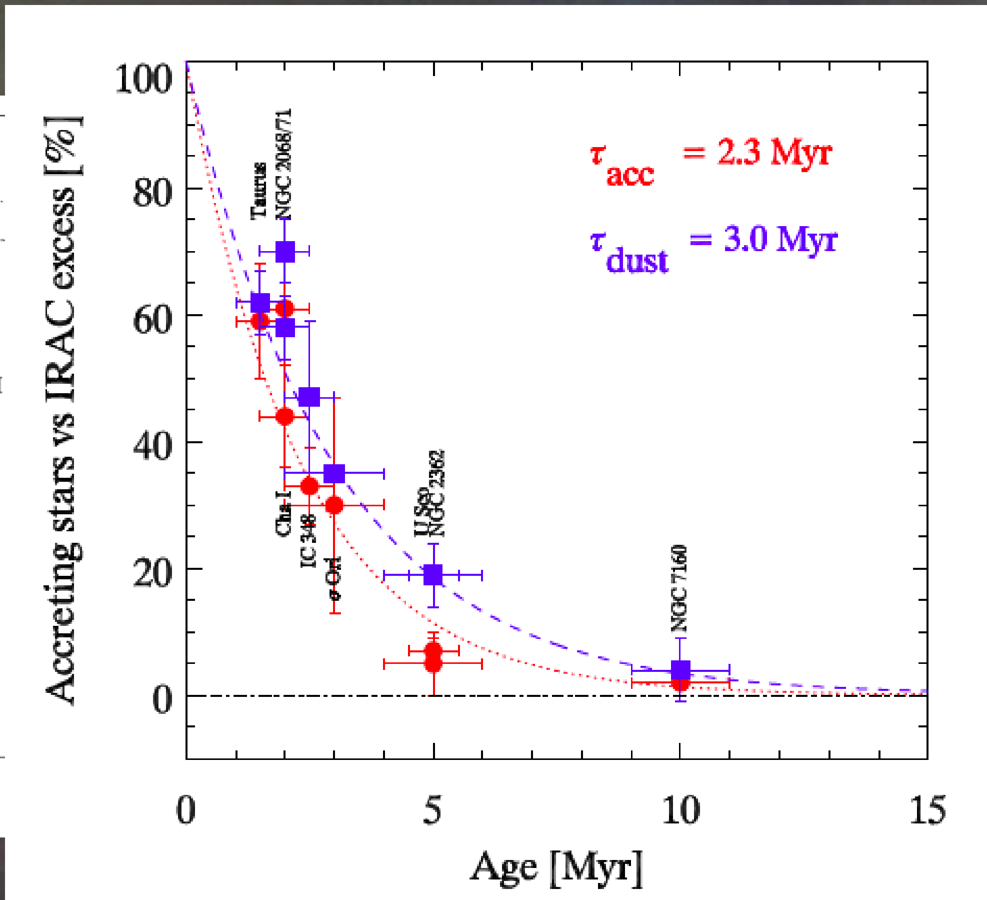
8 M_0 Upper mass limit for PMS phase

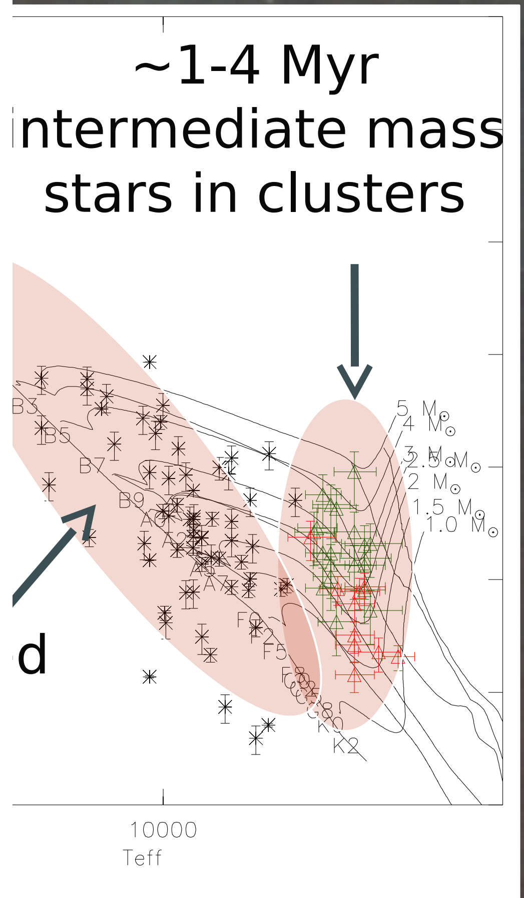
Faster evolution of intermediate mass PMS stars

SRON

Isolated Herbig Ae/Be stars: relatively old disks







Van den
1997

Fedele et al.

Bik, Maaskant

Progenitors of Herbig Ae/Be stars

- Herbig Ae stars: Intermediate mass T Tau stars
- Herbig Be stars: Massive, embedded YSOs

MASS ACCRETION RATES OF INTERMEDIATE-MASS TTS 1295

TABLE 1

STELLAR PROPERTIES

Object	Region	Spectral Type	$T_{\rm eff}$ (K)	L ($L_\odot$)	R ($R_\odot$)	M ($M_\odot$)	A_V	Age (Myr)
T Tau	Taurus	G6	5700.0 ± 140.0	7.8 ± 0.8	2.9 ± 0.2	1.9 ± 0.3	1.8 ± 0.1	7.3 ± 1.2
SU Aur	Taurus	G1	5945.0 ± 142.5	7.8 ± 1.2	2.6 ± 0.4	1.7 ± 0.2	0.9 ± 0.1	8.7 ± 0.7
RY Tau	Taurus	G1	5945.0 ± 142.5	9.6 ± 1.5	2.9 ± 0.4	2.0 ± 0.3	2.2 ± 0.2	7.6 ± 0.6
EZ Ori	Ori OB 1c	G3	5830.0 ± 87.5	5.9 ± 0.7	2.4 ± 0.3	1.6 ± 0.3	0.6 ± 0.1	9.7 ± 0.7
P2441	Ori OB 1c	F9	6115.0 ± 167.5	11.5 ± 2.1	3.0 ± 0.5	2.1 ± 0.3	0.4 ± 0.2	7.2 ± 0.6
V1044 Ori	Ori OB 1c	G2	5860.0 ± 115.0	6.7 ± 1.0	2.5 ± 0.3	1.6 ± 0.3	0.4 ± 0.1	9.2 ± 0.7
CO Ori	λ Ori	G0	6030.0 ± 170.0	22.3 ± 3.4	4.3 ± 0.6	2.5 ± 0.3	2.0 ± 0.2	3.3 ± 0.4
GW Ori	λ Ori	G0	6030.0 ± 170.0	61.8 ± 9.3	7.2 ± 0.9	3.7 ± 0.4	1.3 ± 0.1	1.0 ± 0.1
GX Ori	λ Ori	G9	5410.0 ± 275.0	3.2 ± 0.8	2.0 ± 0.5	1.5 ± 0.3	1.3 ± 0.3	9.6 ± 3.0

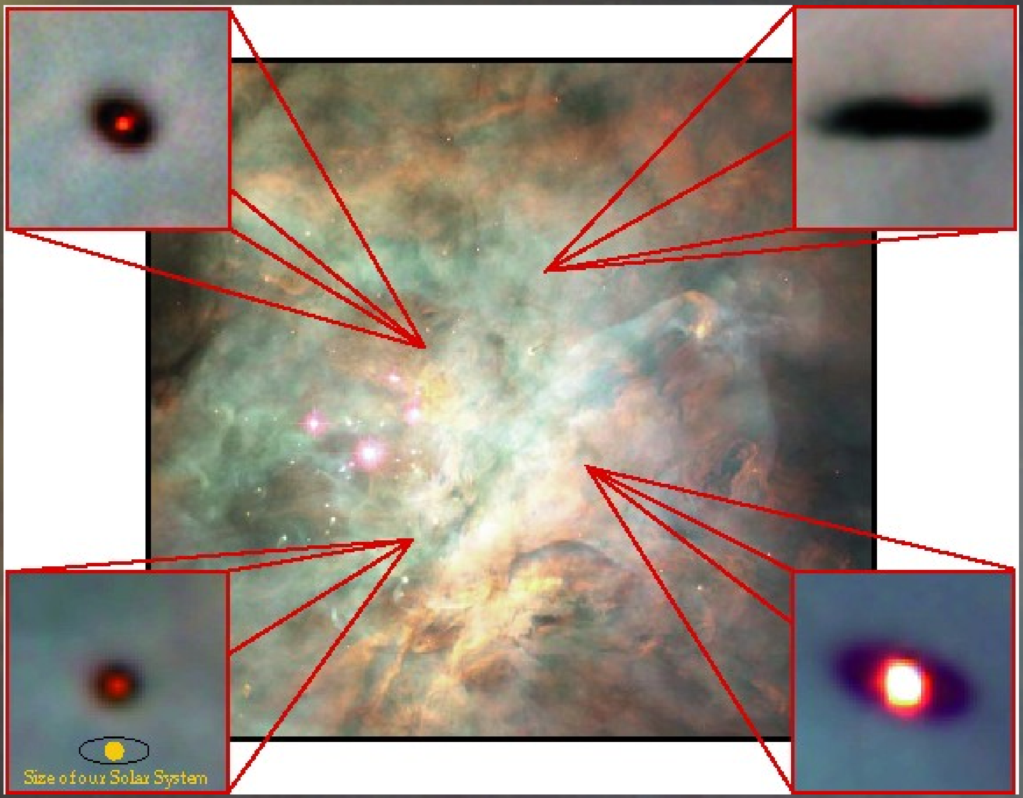
NOTE.—Errors in spectral type determinations are plus or minus two subclasses. Distances are taken as 140 pc for Taurus (Kenyon et al. 1994), 440 pc for Ori OB1c (Genzel et al. 1981), and 450 pc for the λ Ori ring (Dolan & Mathieu 2001).

Calvet et al. (2004)

Mass accretion rates ~3 10^{-8} M_o/yr

SRON

Isolation versus cluster environment



Odell & Wong 1996

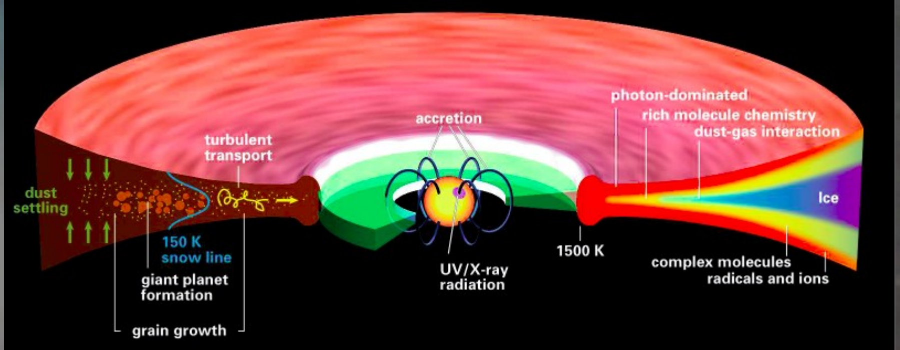
Triggered star formation

Disk evaporation timescale

Impact on planet formation

Disks, disks disks!

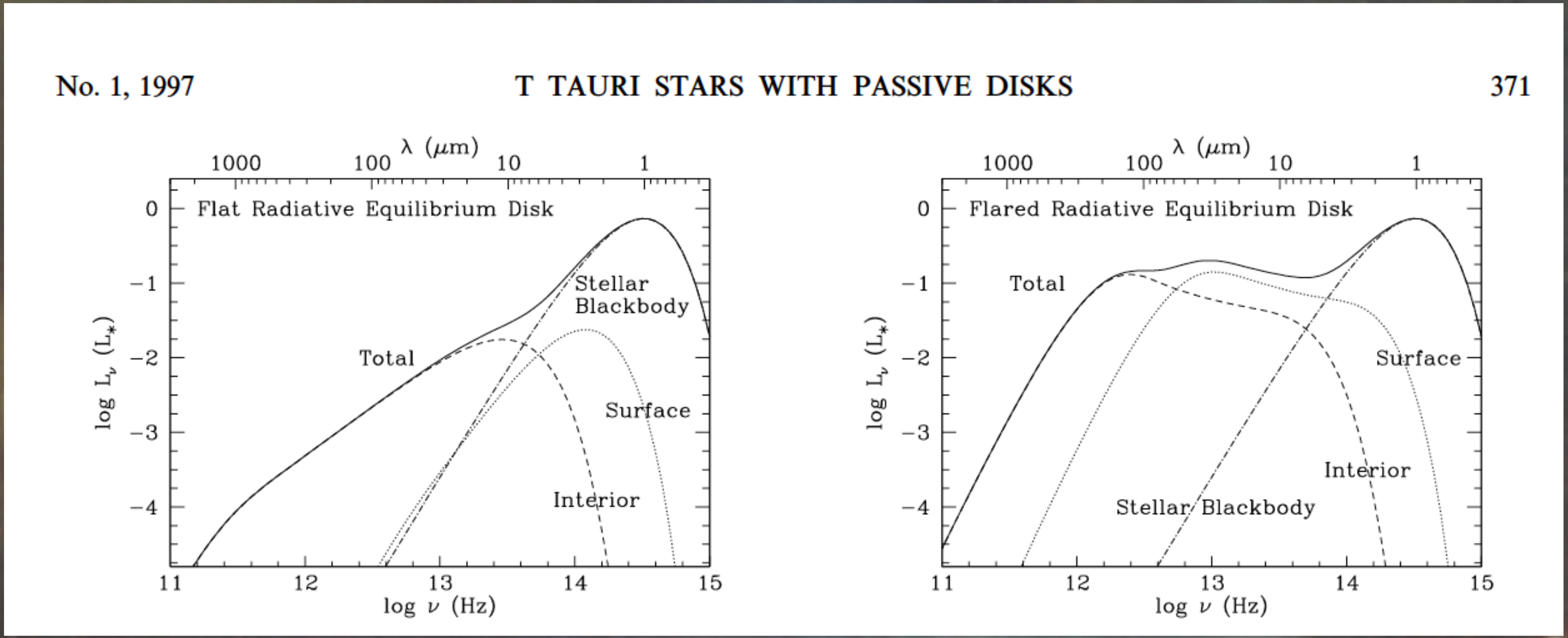
- How does planet formation proceed?
- How does it depend on stellar mass, environment?
- Which disks produce which planetary system architectures?
- What is the stellar upper mass limit for planet formation to proceed?



Henning & Semenov

Herbig stars are truly intermediate between massive YSOs and low mass T Tau stars

Disk models: Chiang and Goldreich

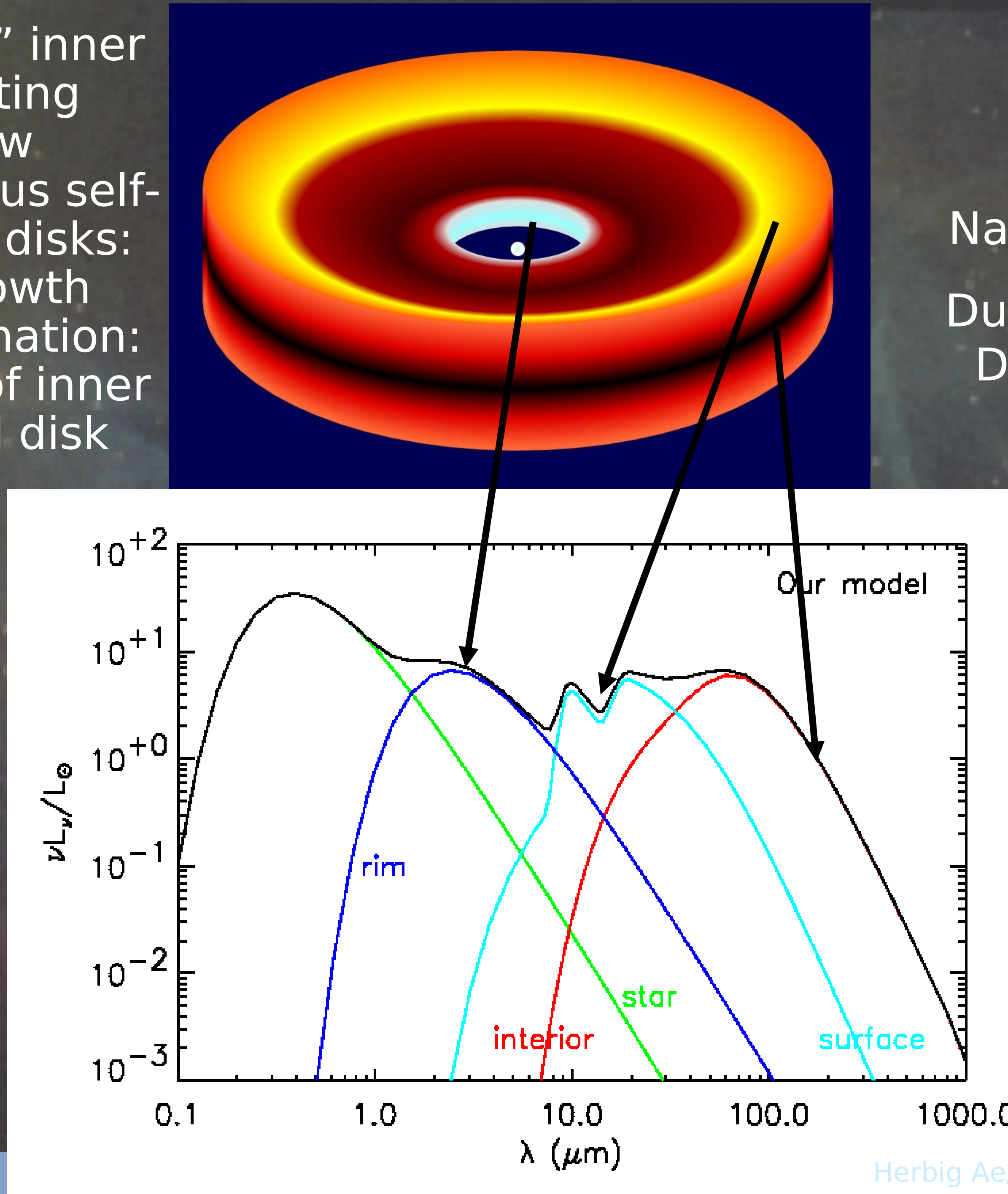


Chiang & Goldreich (1997)
Hydrostatic equilibrium disk models

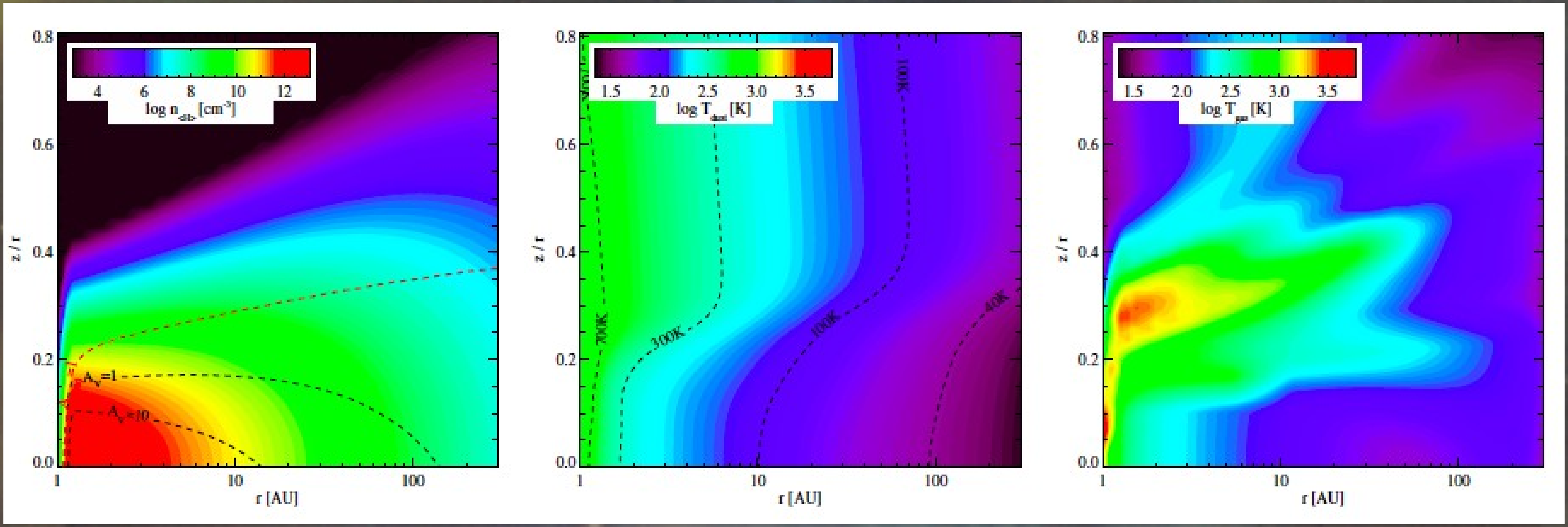
- “Puffed-up” inner rim, casting shadow
- Flaring versus self-shadowed disks: grain growth
- Planet formation: formation of inner holes and disk gaps

Natta et al;

Dullemond, Dominik, Natta



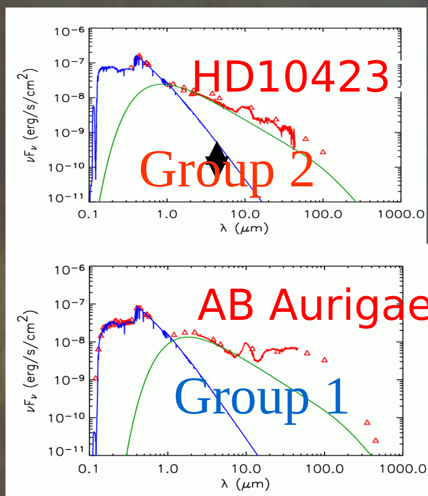
State of the art disk models



Prodimo (Woitke, Kamp, Thi)
Gas and dust treated separately
Chemical network

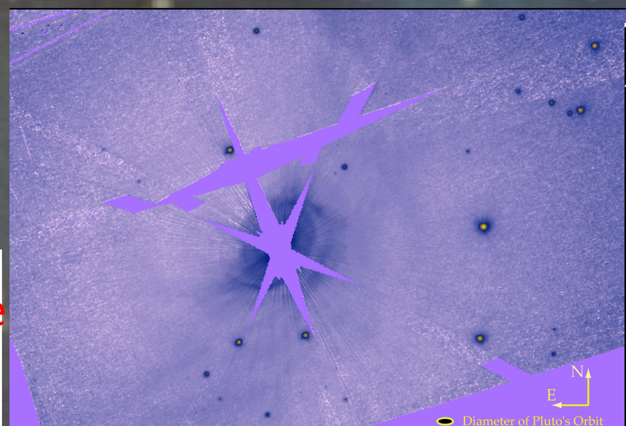
Disk geometry: signpost of planet formation

Flaring versus flat



Meeus et al. 2001

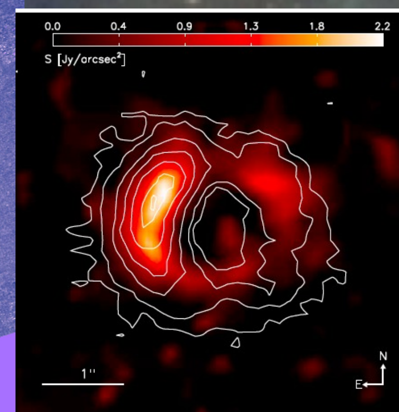
Spiral density waves



HD100546

Grady et al.

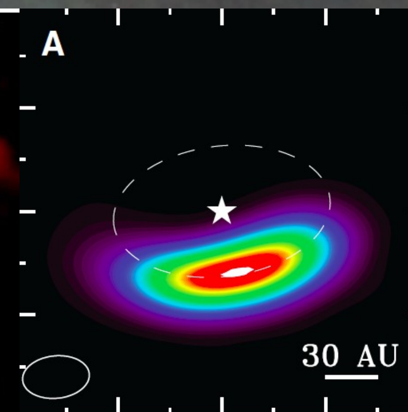
Disk gaps/holes



HD142527

Honda et al; Verhoeff et al.

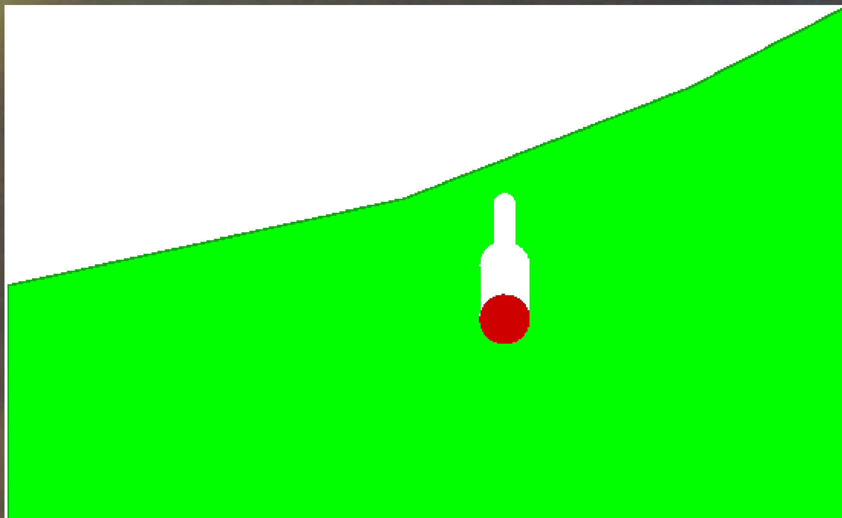
Dust traps

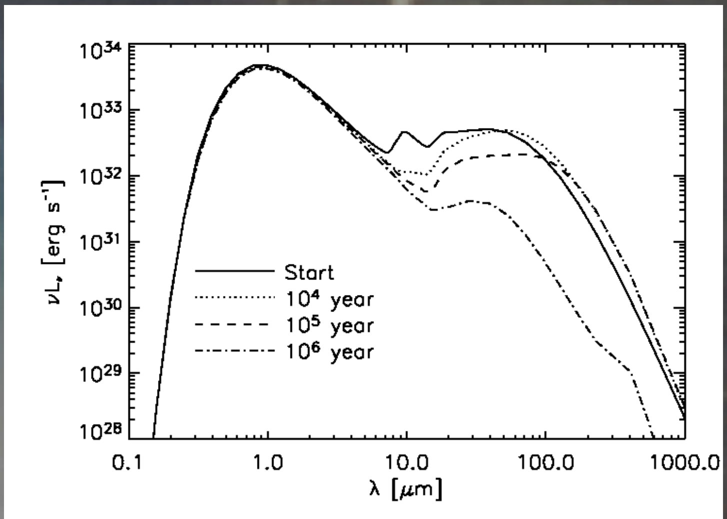


IRS 48

Van der Marel et al.

From flaring to self-shadowed disks





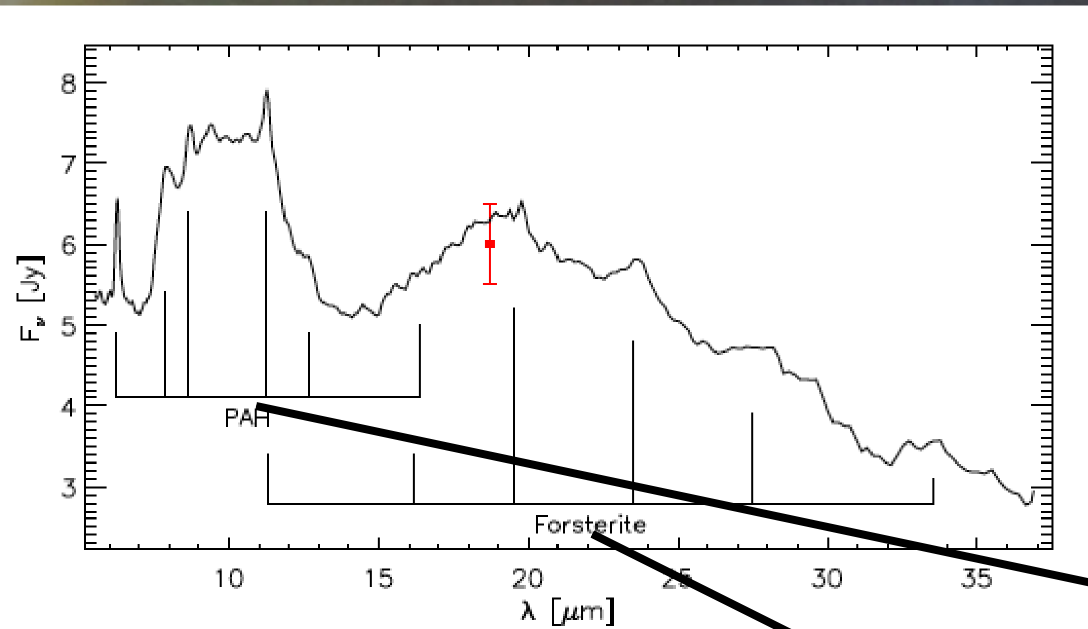
Dust settles and grows, removal of small grains from disk surface; gas disk remains flaring

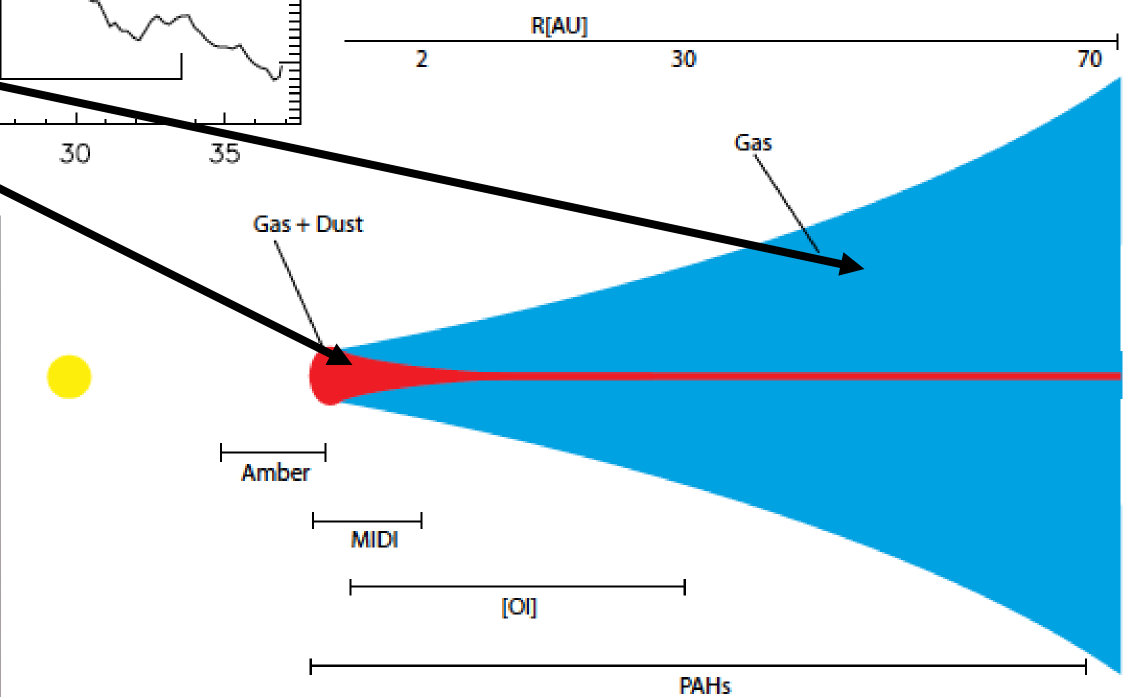
Dullemond & Dominik

Do disks evolve from flaring to self-shadowed disks?

Nakagawa et al. 1986

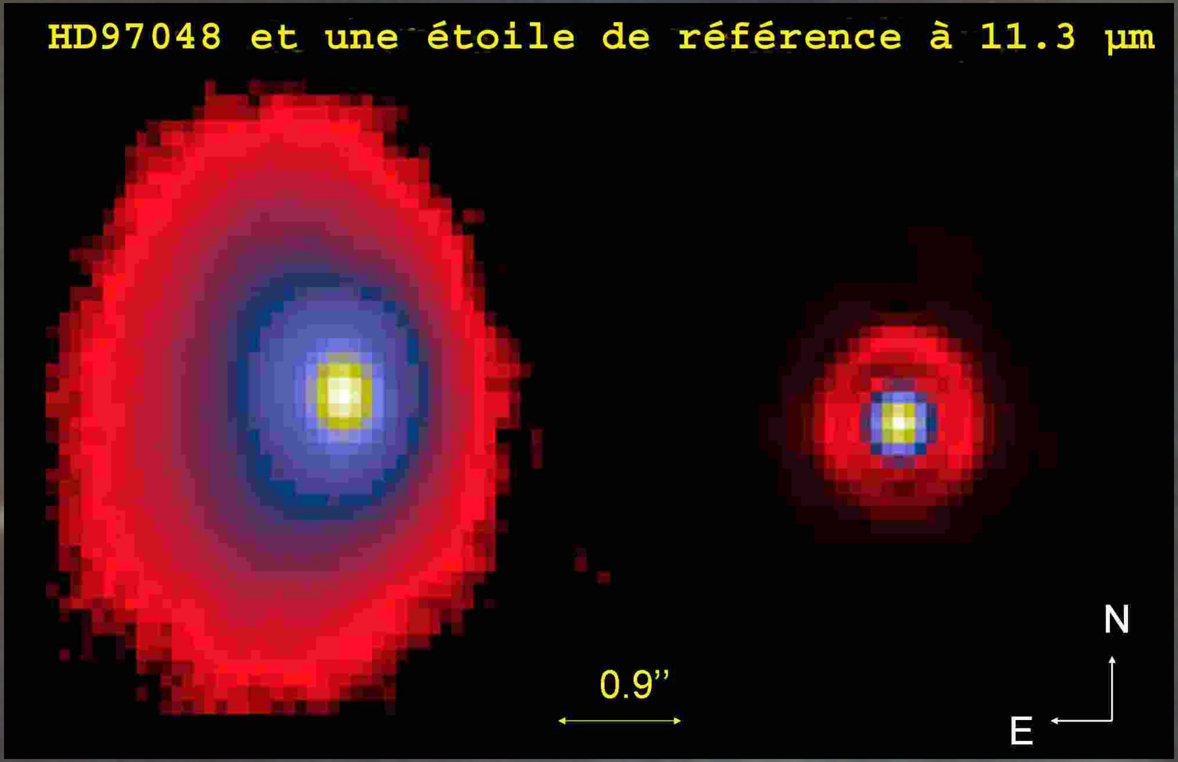
Gas-rich disk with dust settled to mid-plane





Verhoeff et al (2009)

Flaring *outer* disk in HD97048

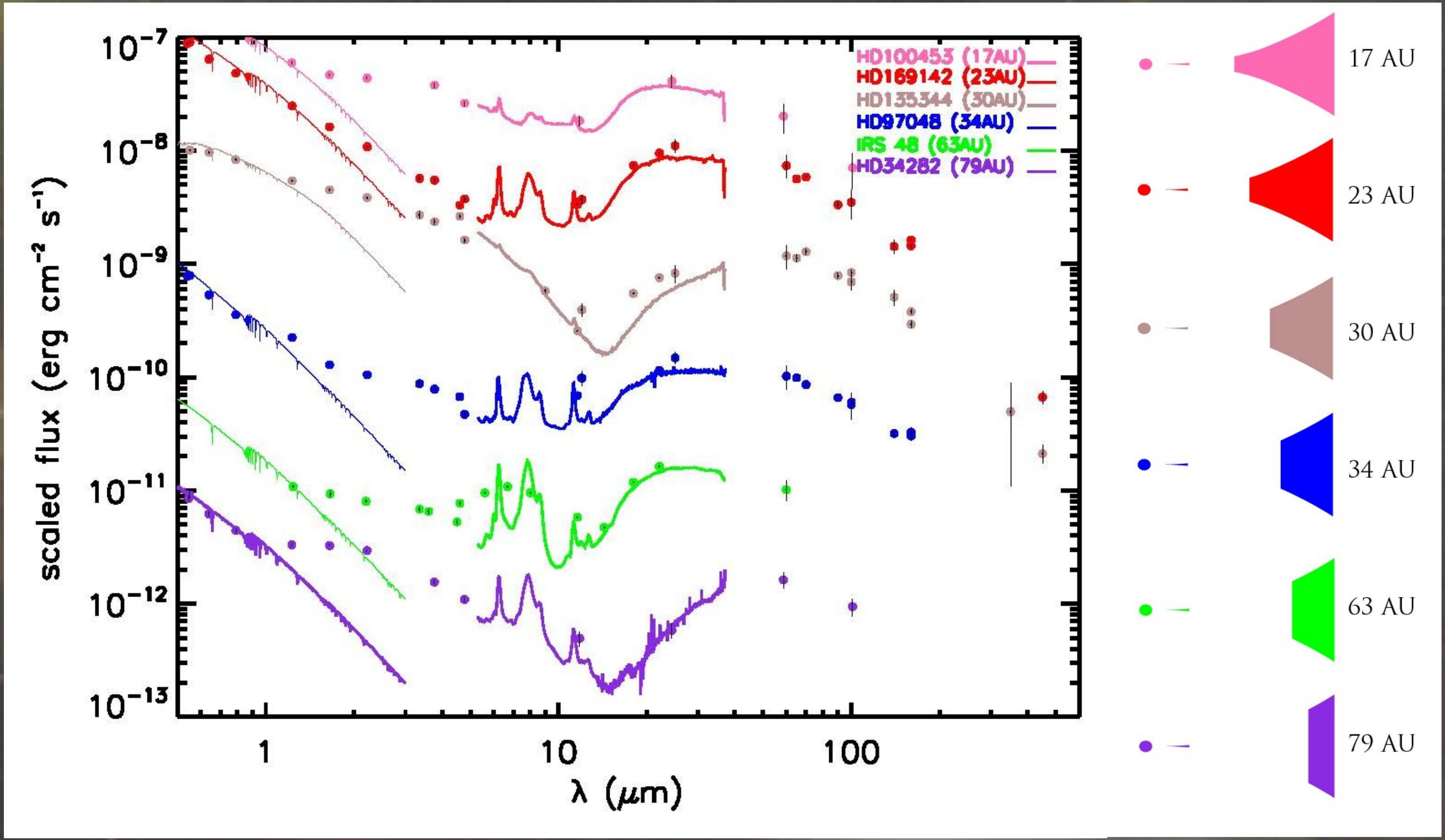


mid-IR imaging, Lagage et al. 2006 (Science)

Direct measure of outer disk flaring angle

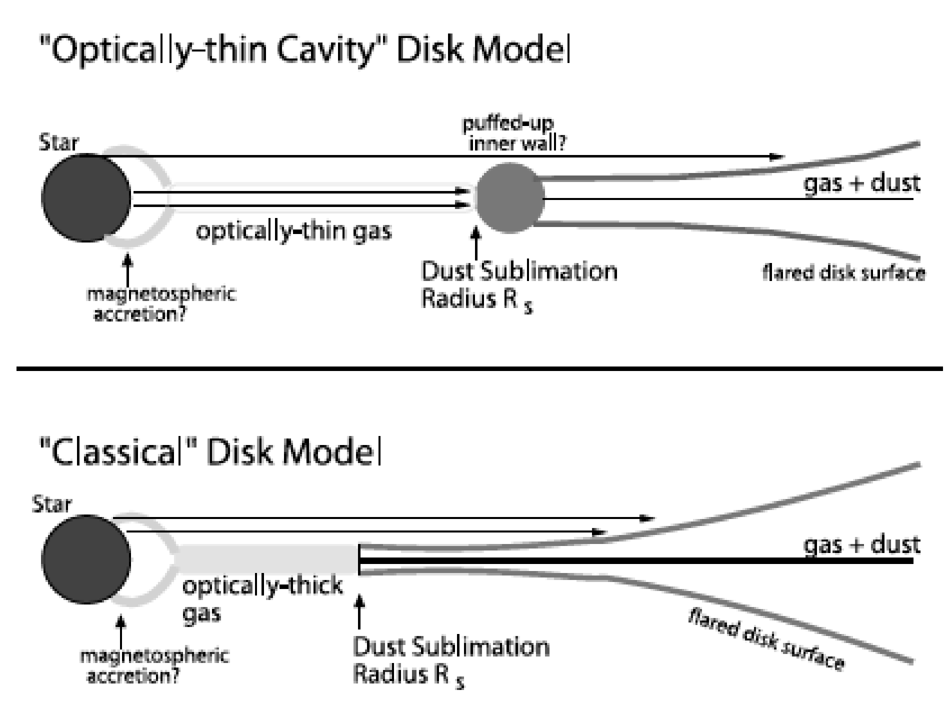
Agrees with hydrostatic equilibrium models

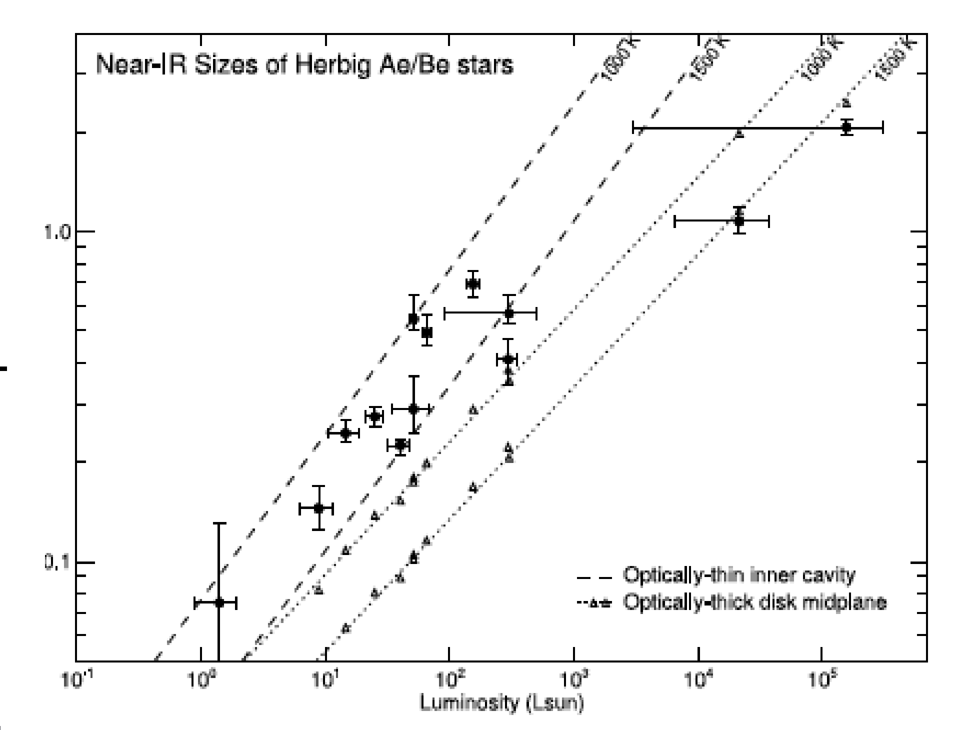
However… “Flaring disks” are transitional disks!



Khalafinejad, Maaskant et al. (in preparation)

Inner disk structure



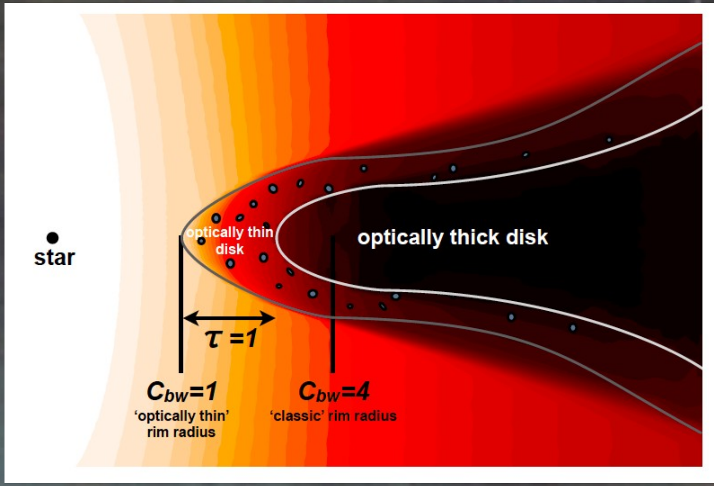


Near-IR interferometry: optically thin inner cavities, dust sublimation at ~1500 K

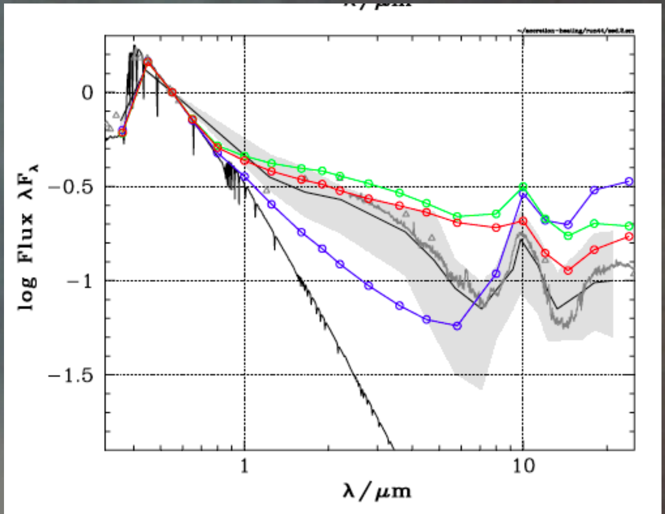
Monnier et al.

Inner disk structure

- Natta et al (2001), Dullemond et al. (2001): disk wall directiy irradiated
- Isella & Natta (2005): rounded off inner wall; Kama et al: optically thin inner region
- Problem: hydrostatic equilibrium disks do not produce enough near-IR flux
- Solutions:
  - optically thin halo (Vinkovic et al. 2006)
  - Extended disk atmosphere (Thi et al)
  - Magnetically supported region in disk atmosphere (turner et al. 2013)



Kama et al.

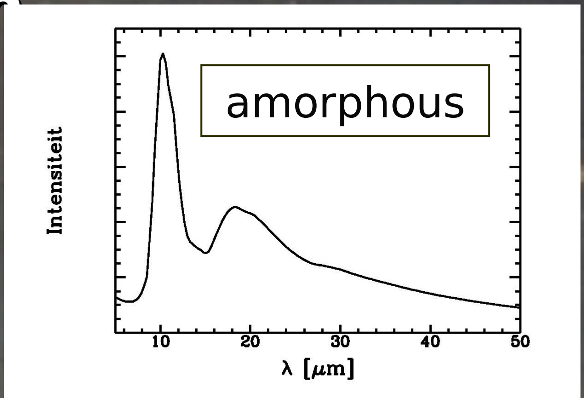


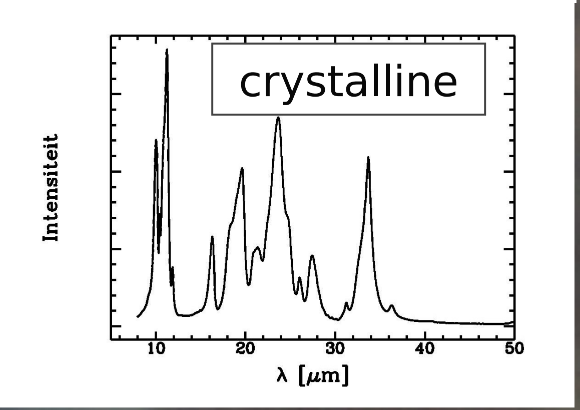
Turner et al.

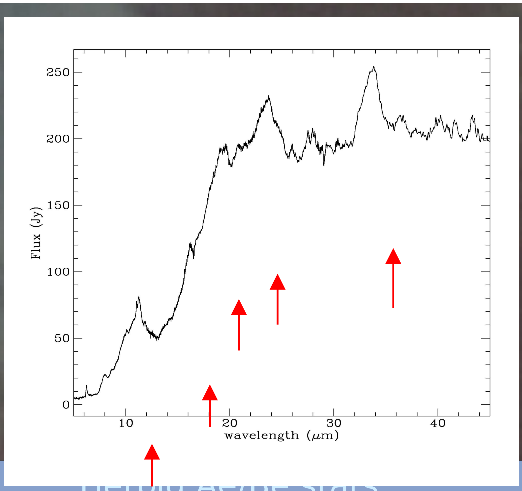
Dust as a tracer of planet formation

- Grain size:
  - Dust settling & growth: flaring to self-shadowed…
  - spatial distribution as a function of grain size (dust traps)
- Grain composition:
  - Thermal processing: thermal annealing of amorphous silicates, carbon combustion
  - Gas phase condensation of crystalline silicates in inner regions
  - Formation of new solids, e.g. FeS

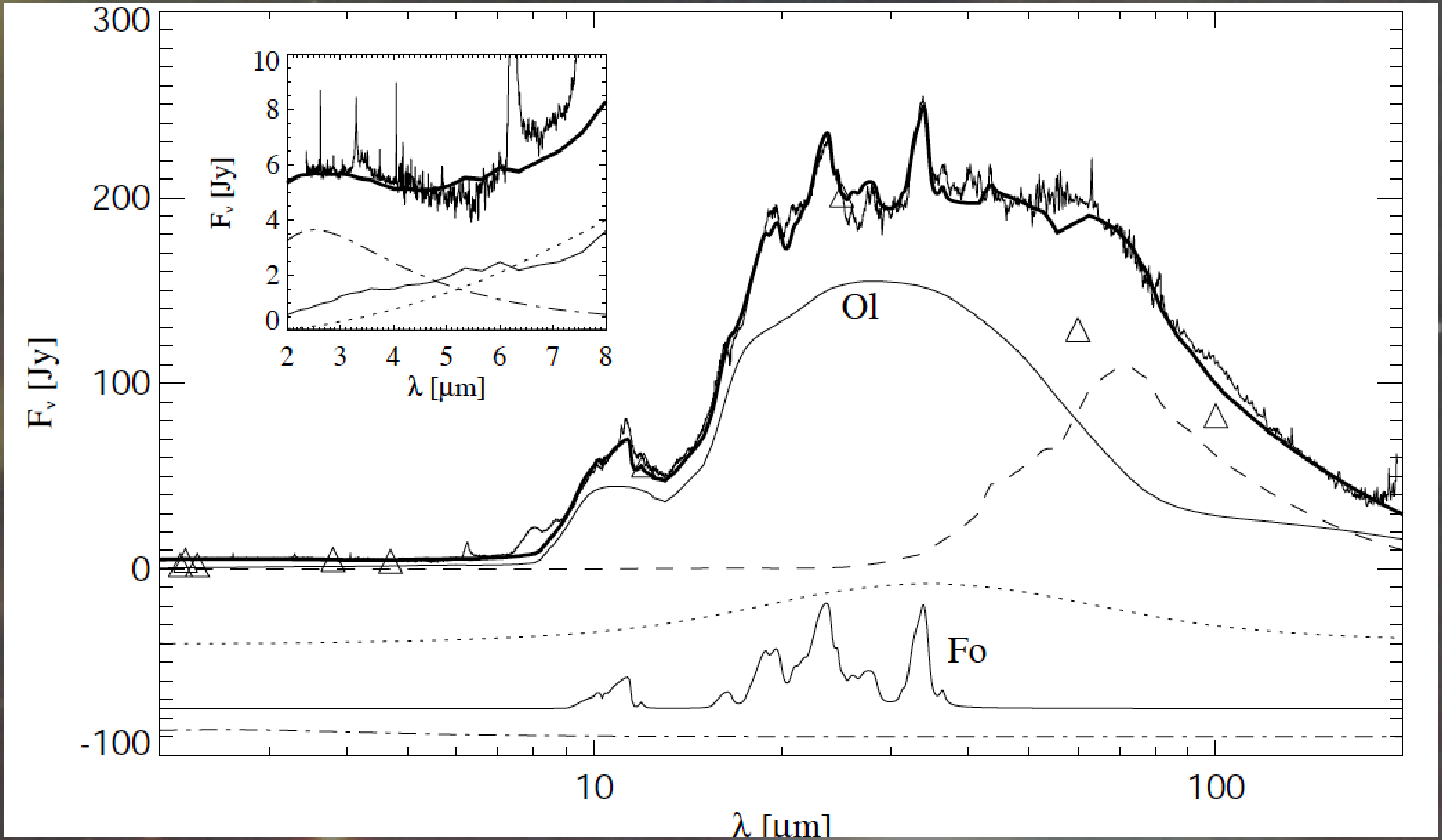
- Origin of crystalline silicates:
  - Thermal annealing near the star
  - Radial mixing to outer disk regions
  - Local processing: shocks caused by planet formation / gap formation







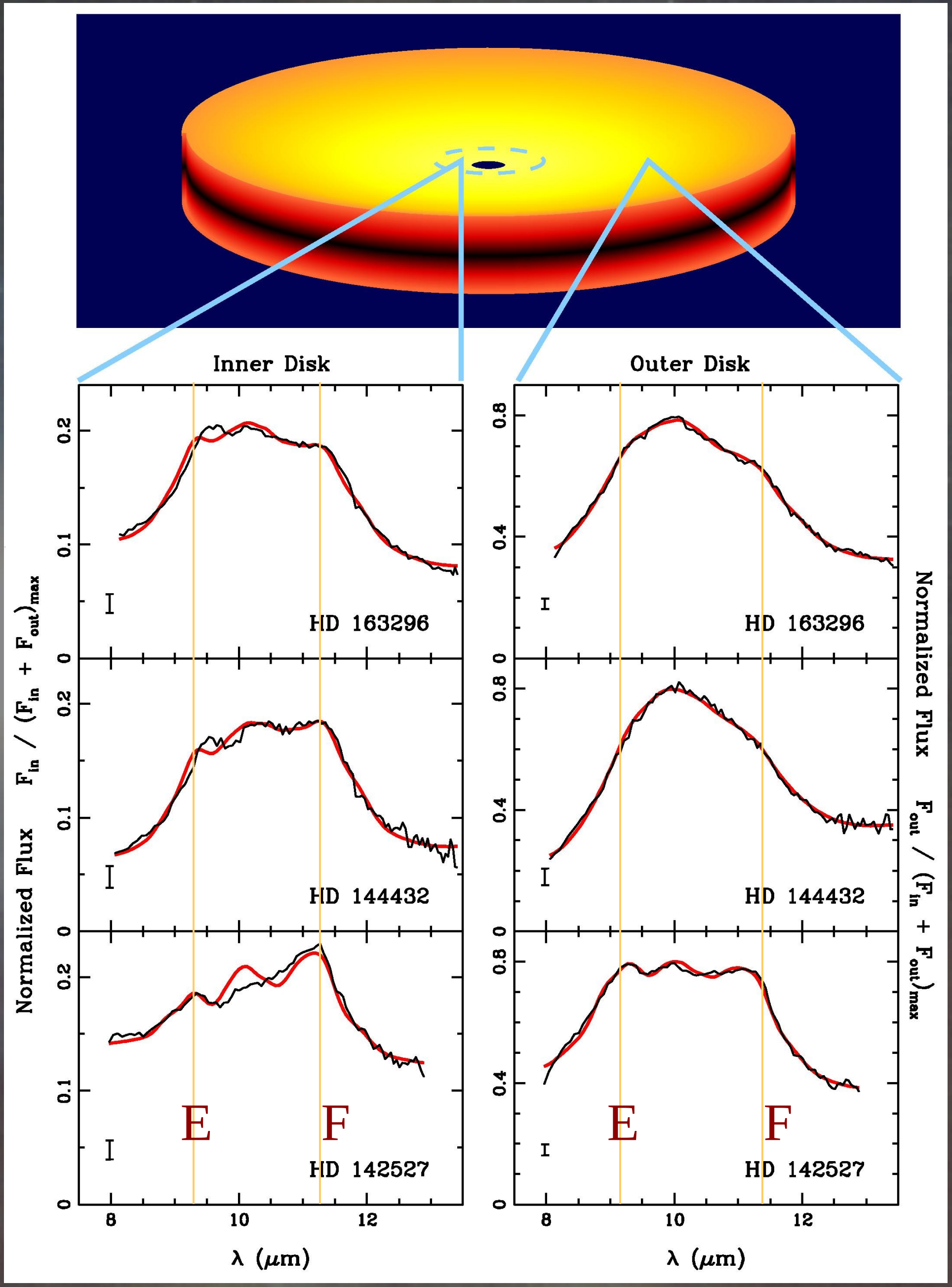
ISO opened a new view on HAeBe disks



e.g. Bouwman et al. 2003
Meeus et al. 2001
Acke & van den Ancker 2004

VLTI/MIDI : crystals form near the young star

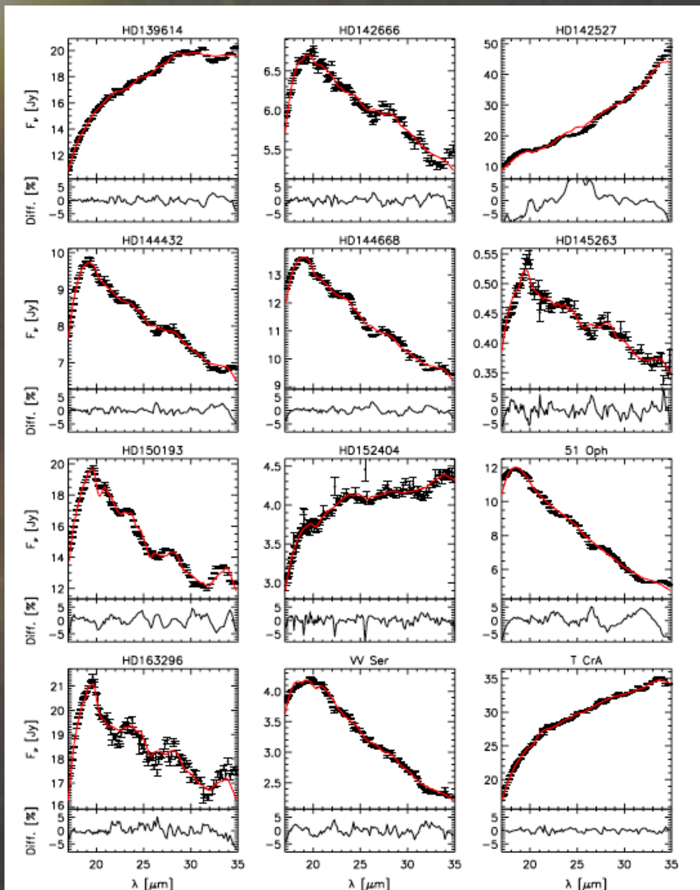
- Annealing, formation of forsterite and enstatite
- Chemical equilibrium reactions

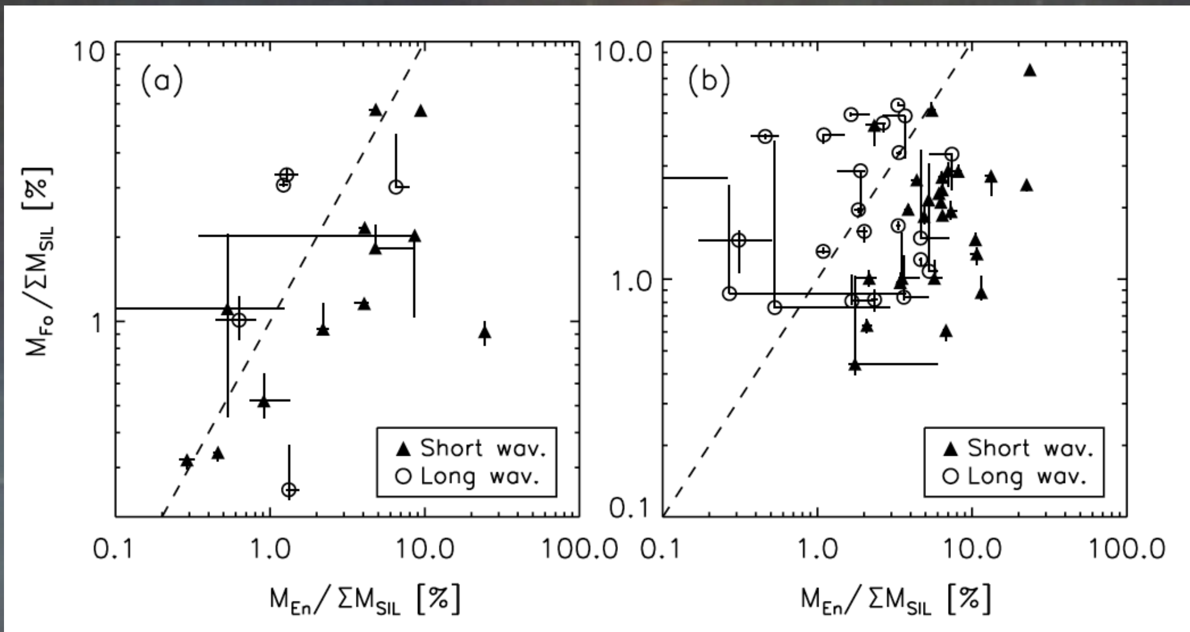


Van Boekel et al. 2004

SRON

Spitzer spectra: dust mineralogy

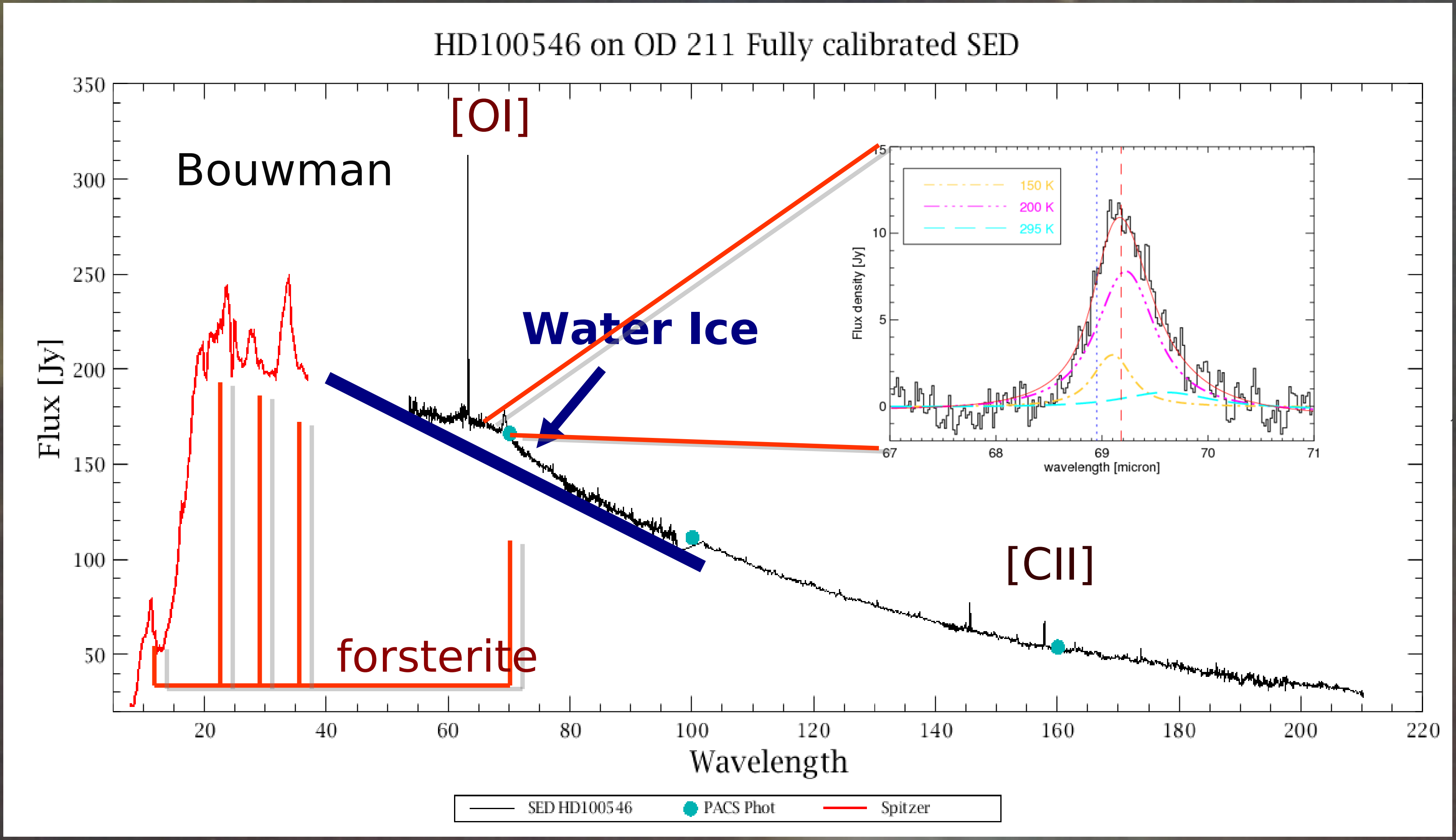




More enstatite in the inner disk
More forsterite in the outer disk
Traces formation history

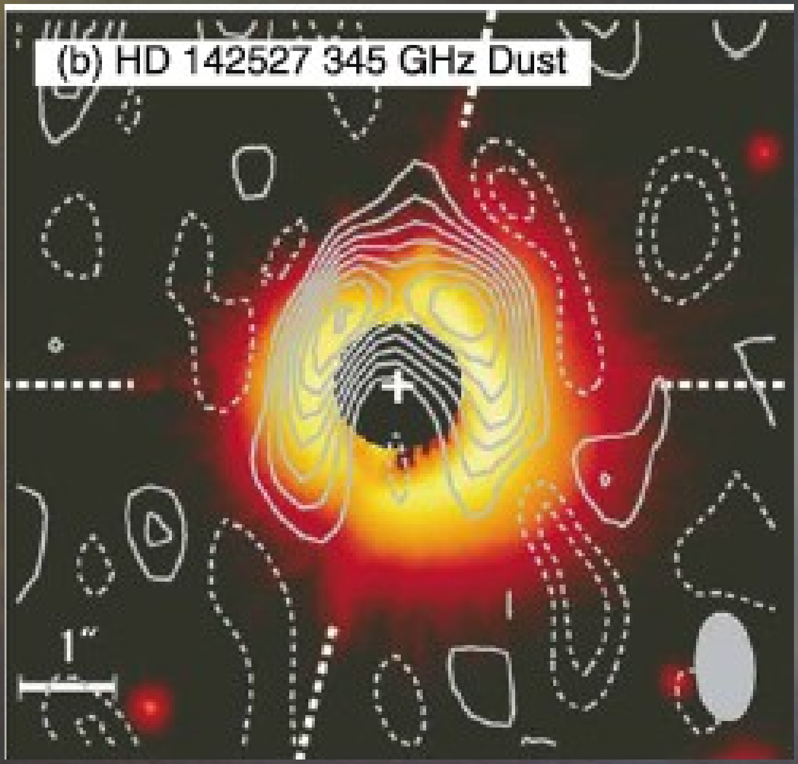
Juhasz et al.

Herbig Ae/Be star HD100546

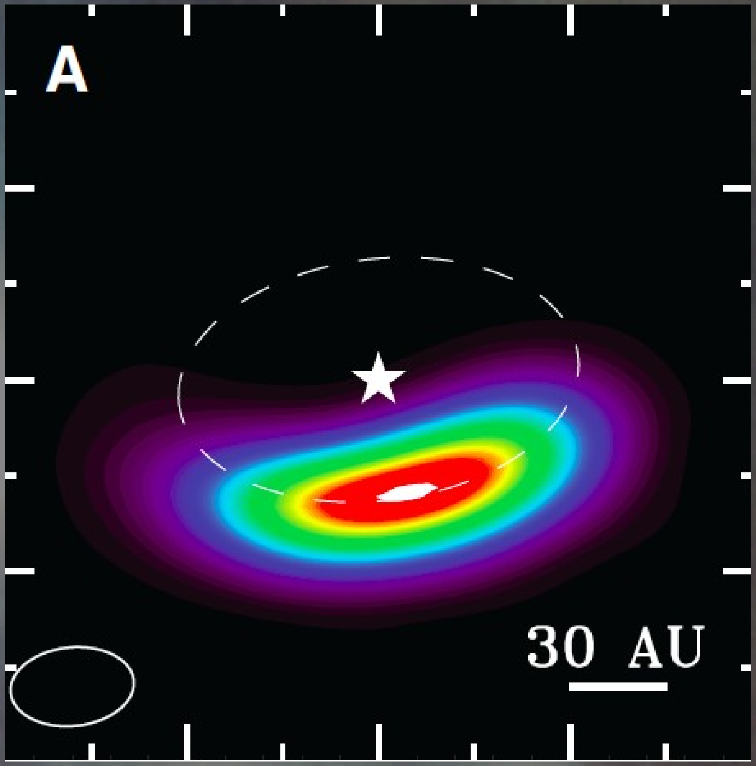


SRON (see also McClure et al. (2012) GQ Lupi disk spectrum)

Dust traps in herbig Ae/Be disks



Ohashi et al. (2007)

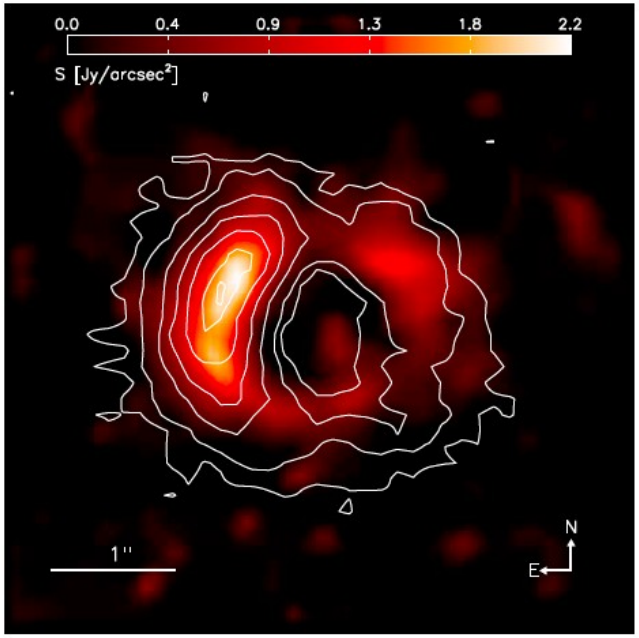


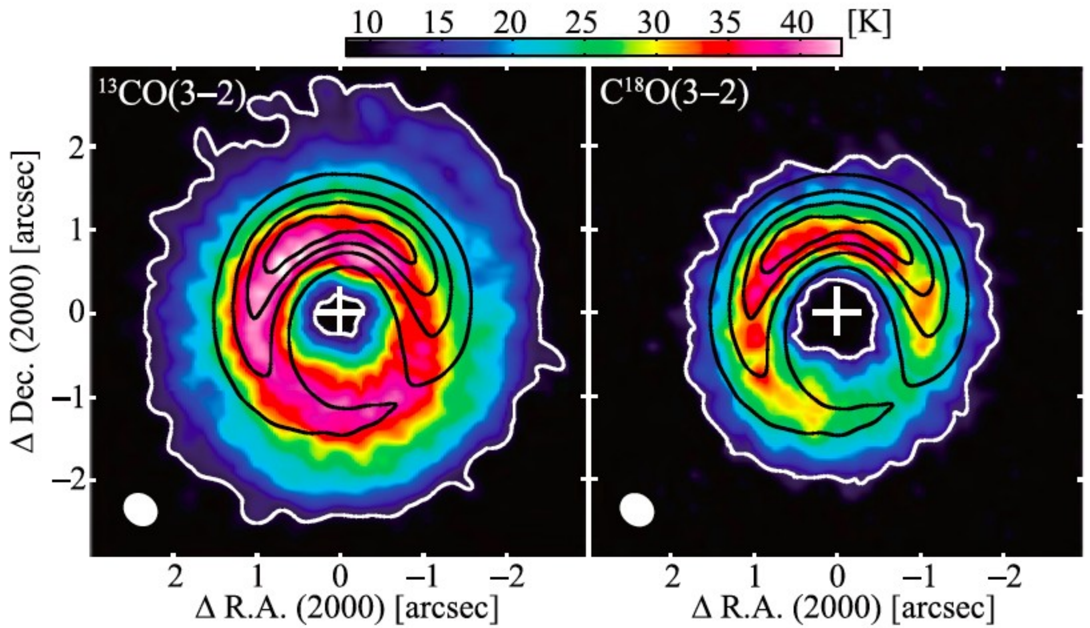
Van der Marel et al. (2013)

Vortex-shaped dust trap caused by companion

SRON

Dust traps in Herbig Ae/Be disks: HD142527





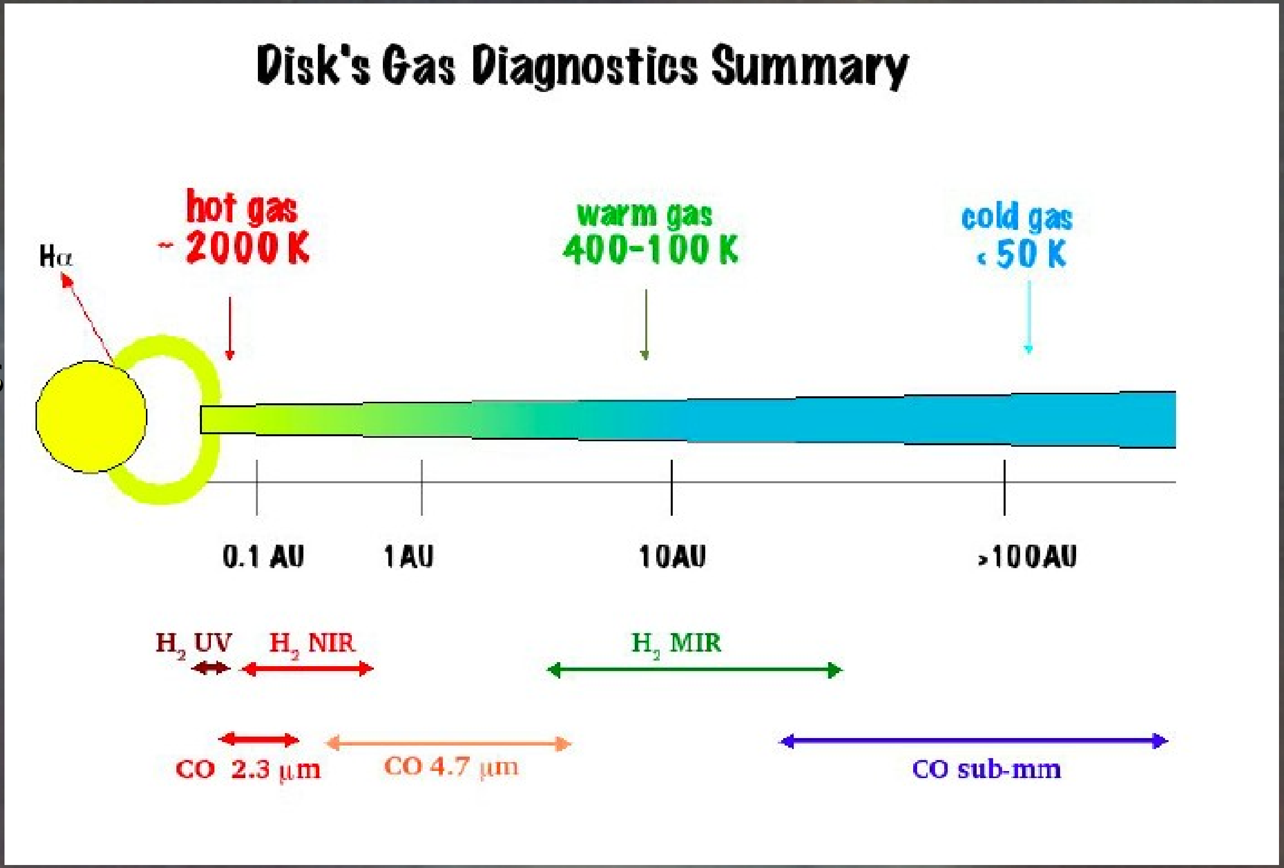
Mid-infrared imaging
Warm grains
Verhoeff et al. (2010)

Sub-mm imaging (ALMA)
Cold gas/dust
Fukagawa et al. (2013)

Gravitationally unstable outer disk?

Gas diagnostics

- Outflows
- Jets
- Accretion
- Disk structure
- Disk kinematics
- Chemistry



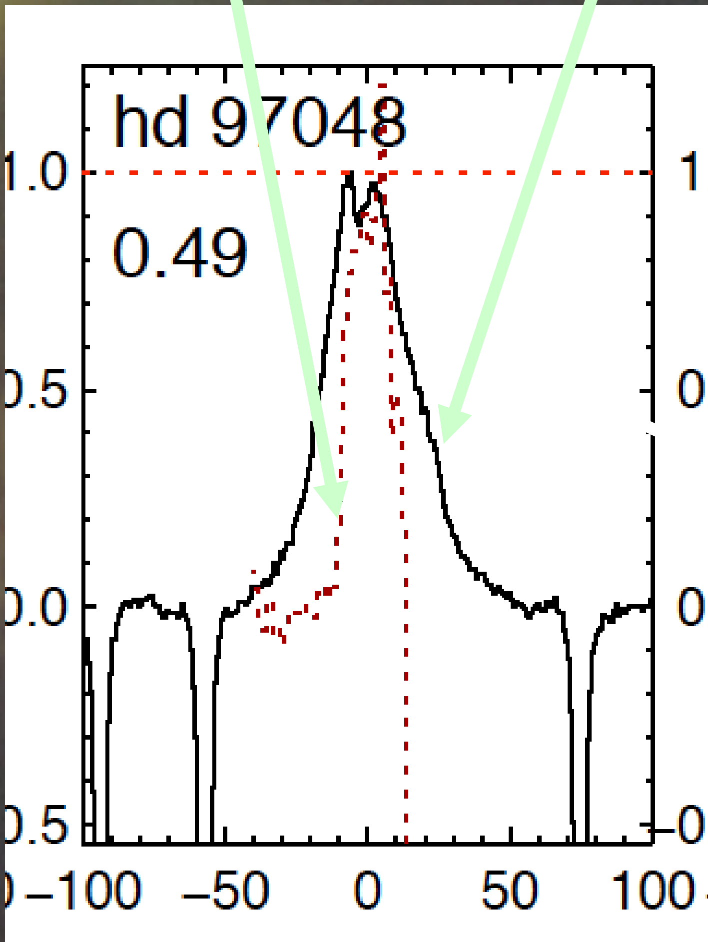
Many papers, ISO spectroscopy, Spitzer, Herschel, Keck, VLT, ALMA,...

A. Carmona (2009)

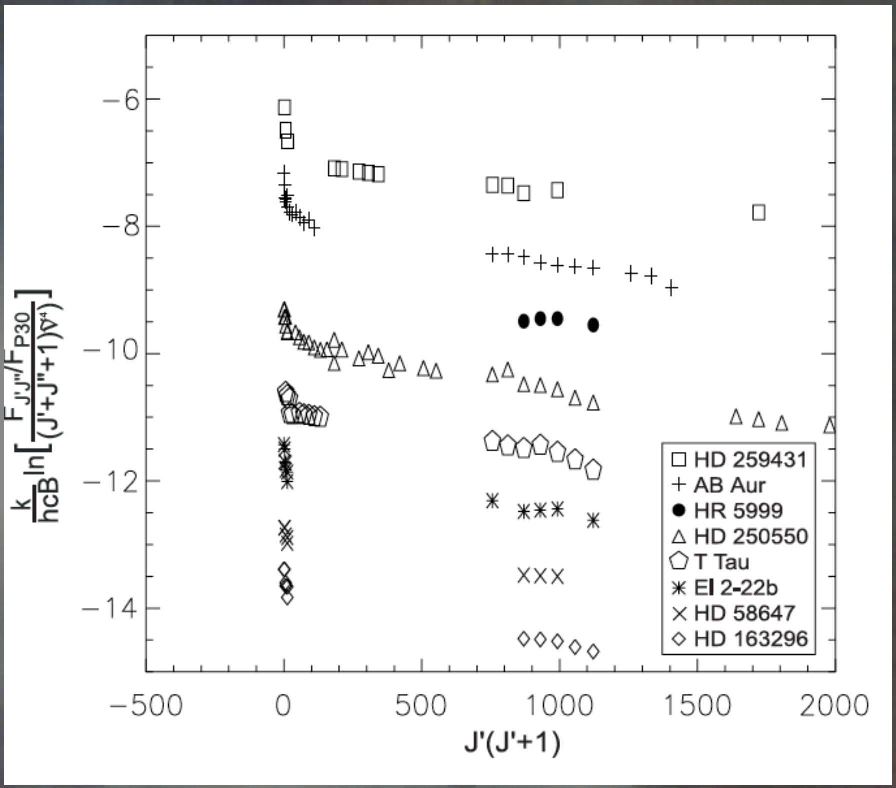
Gas in upper disk layers

CO ro-vibrational line

[OI] 6300 A



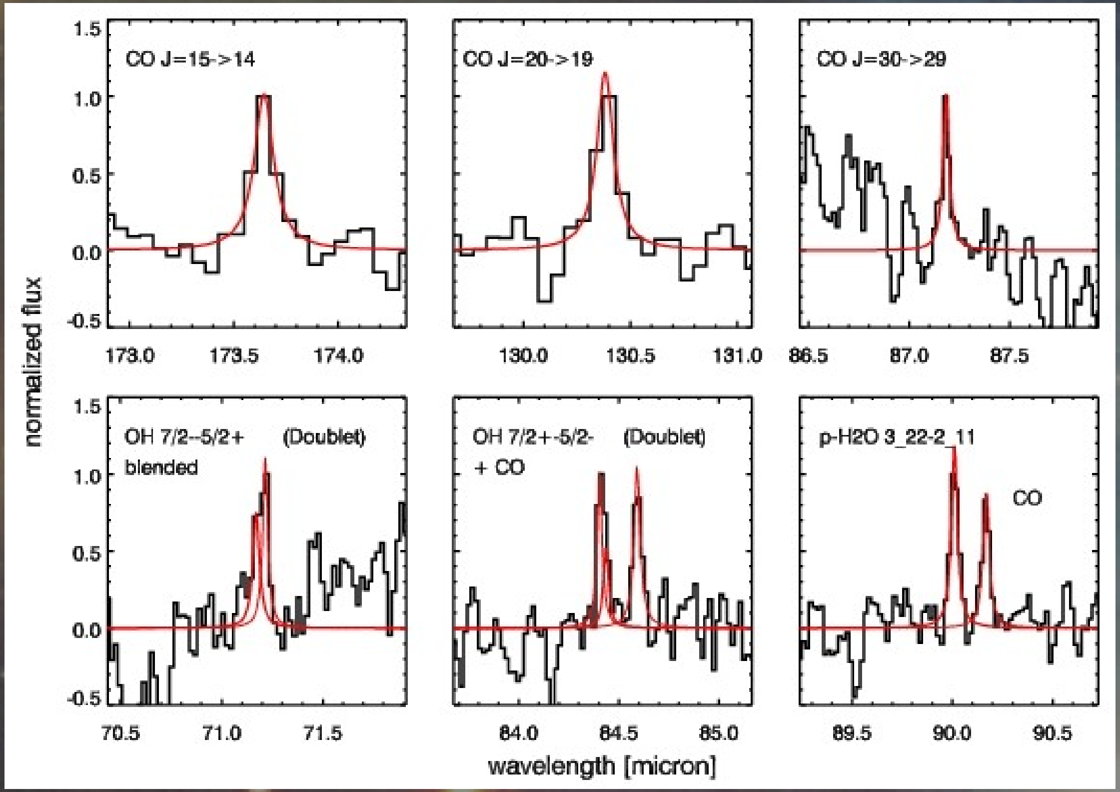
Van der Plas et al



Brittain et al.: CO ro-vibrational emission
T (gas) > 1000K

SRON

Herschel observations of cool gas in disks; example: Gas Lines in HD100546



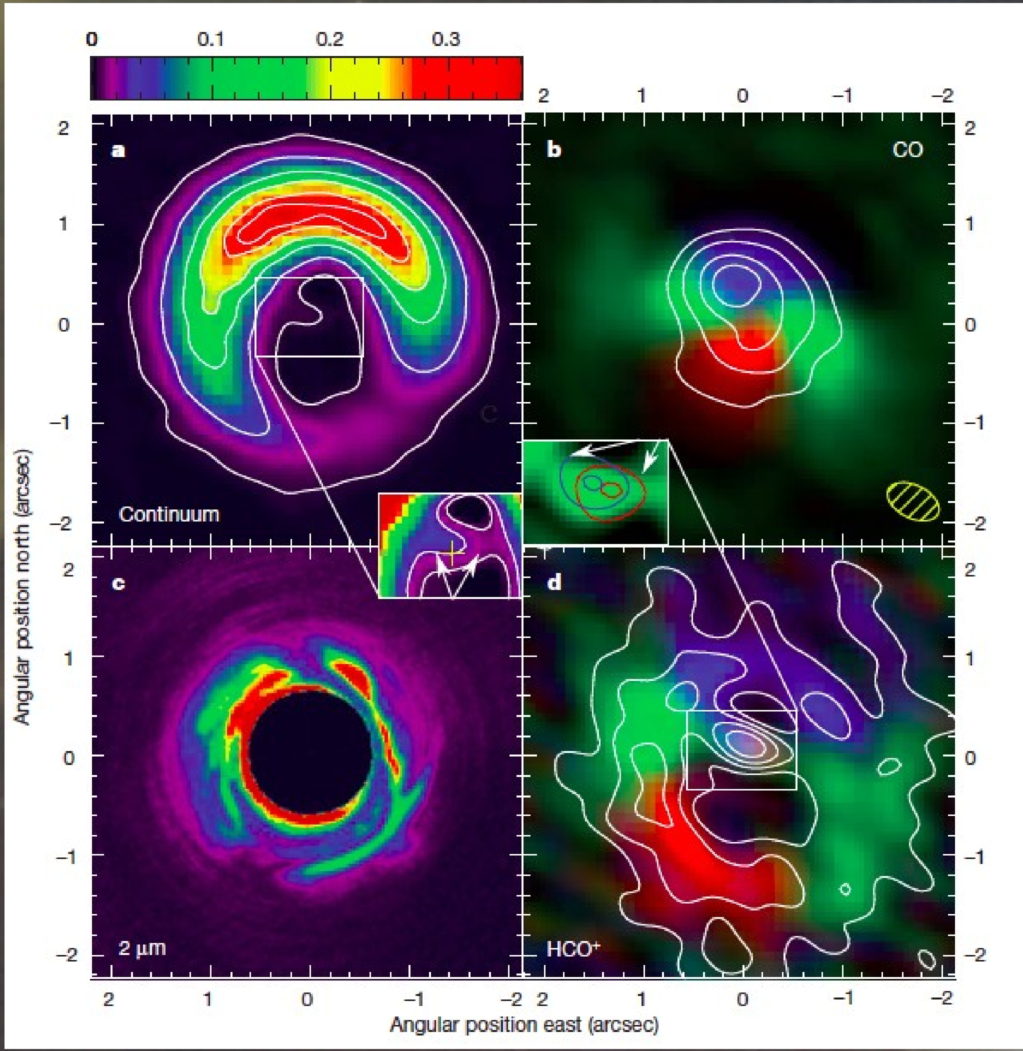
CO, OH, H_2O lines detected.
CO rotation diagrams:
T = 300, 800 K
N(CO) 10^{16} – 10^{17} cm^{-2}
B. Sturm et al. (2010)

See also Meeus et al. (2012)

CO modeling: gas temperature in disk atmosphere larger than dust temperatures (Bruderer 2012)

SRON

Cold gas traced in CO and HCO+

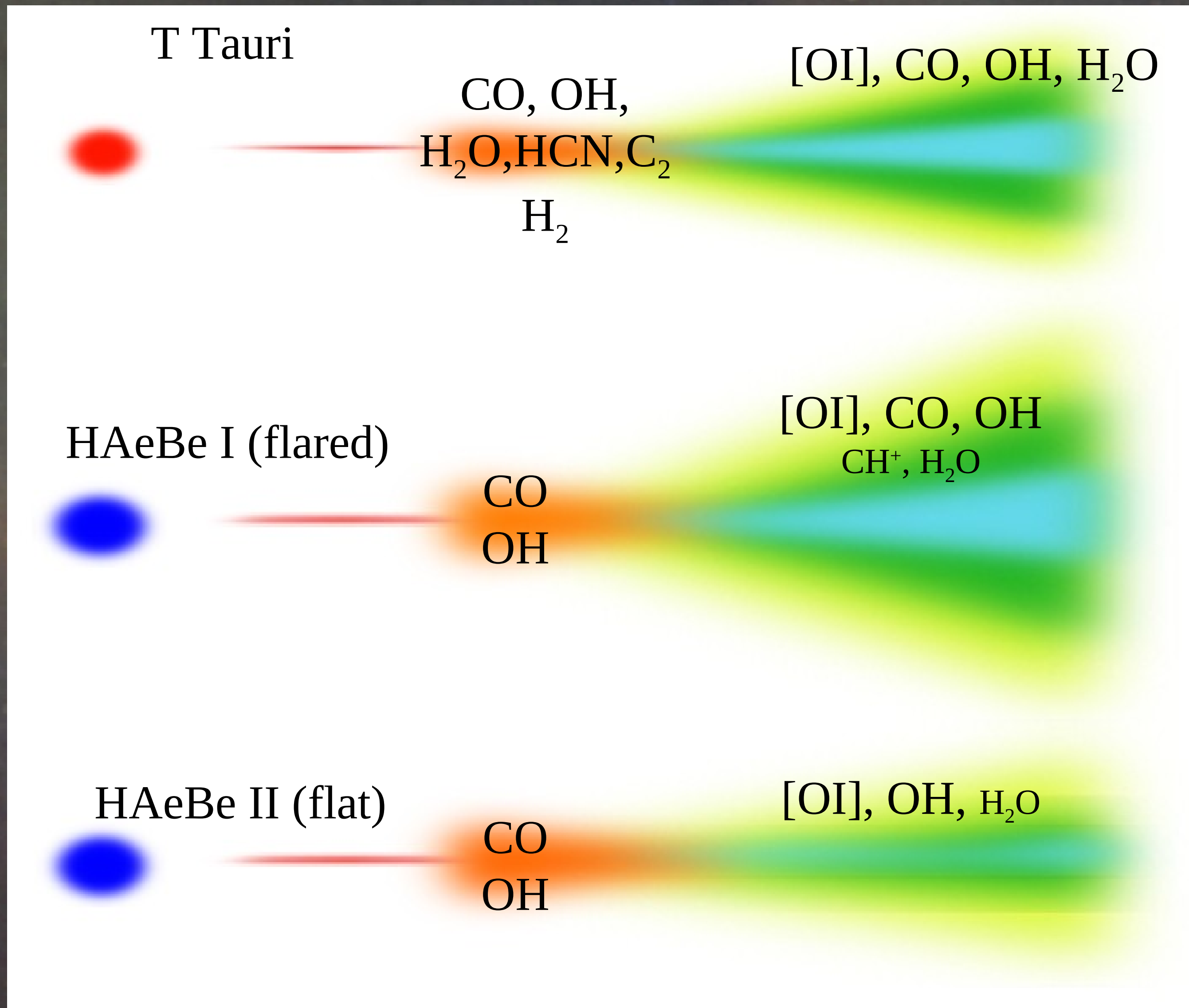


Casassus et al. 2013

Near-IR Far-IR

< 1.5 $M_\odot$

> 1.5 $M_\odot$



Evidence for planets orbiting intermediate mass stars

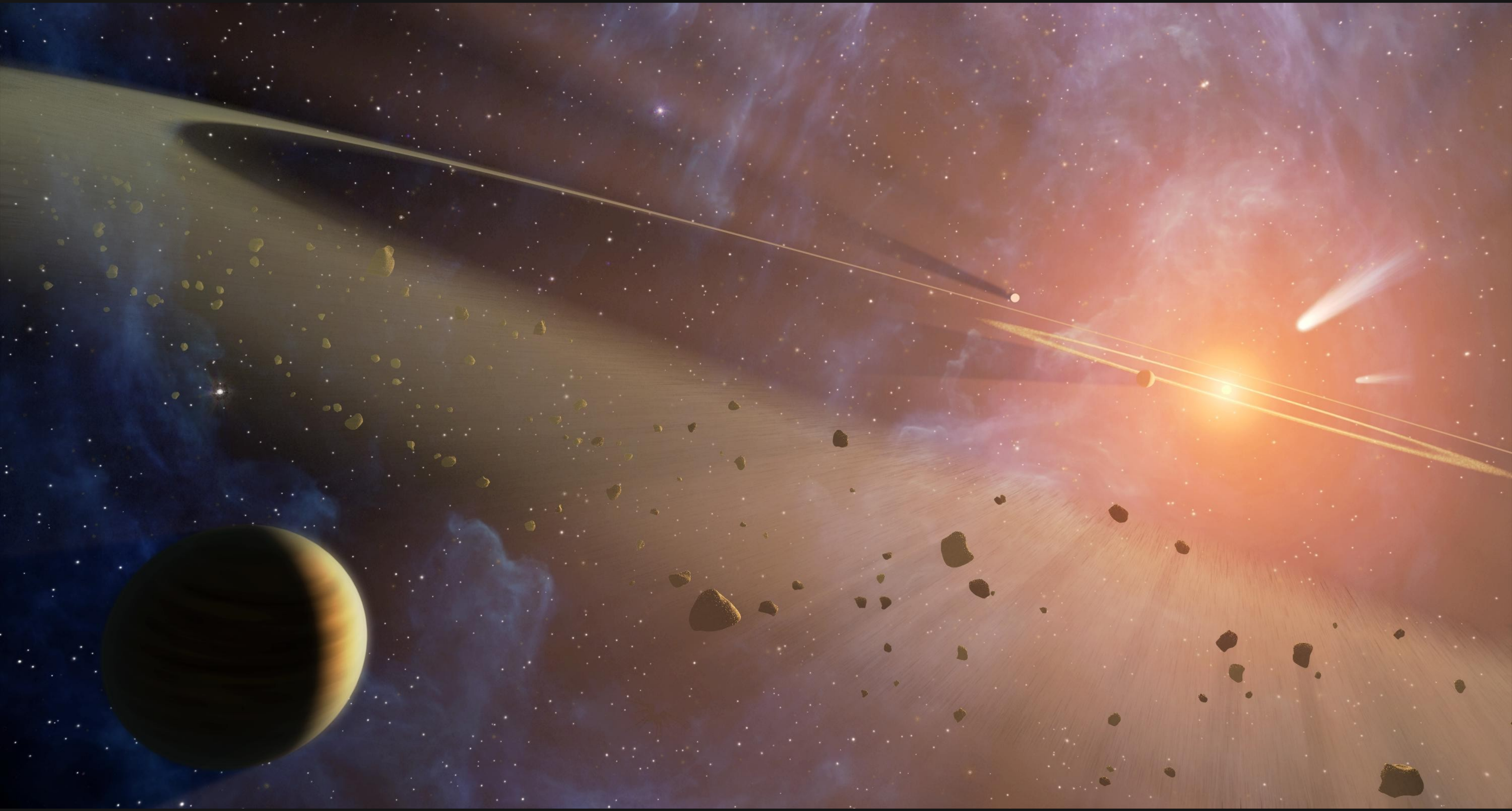
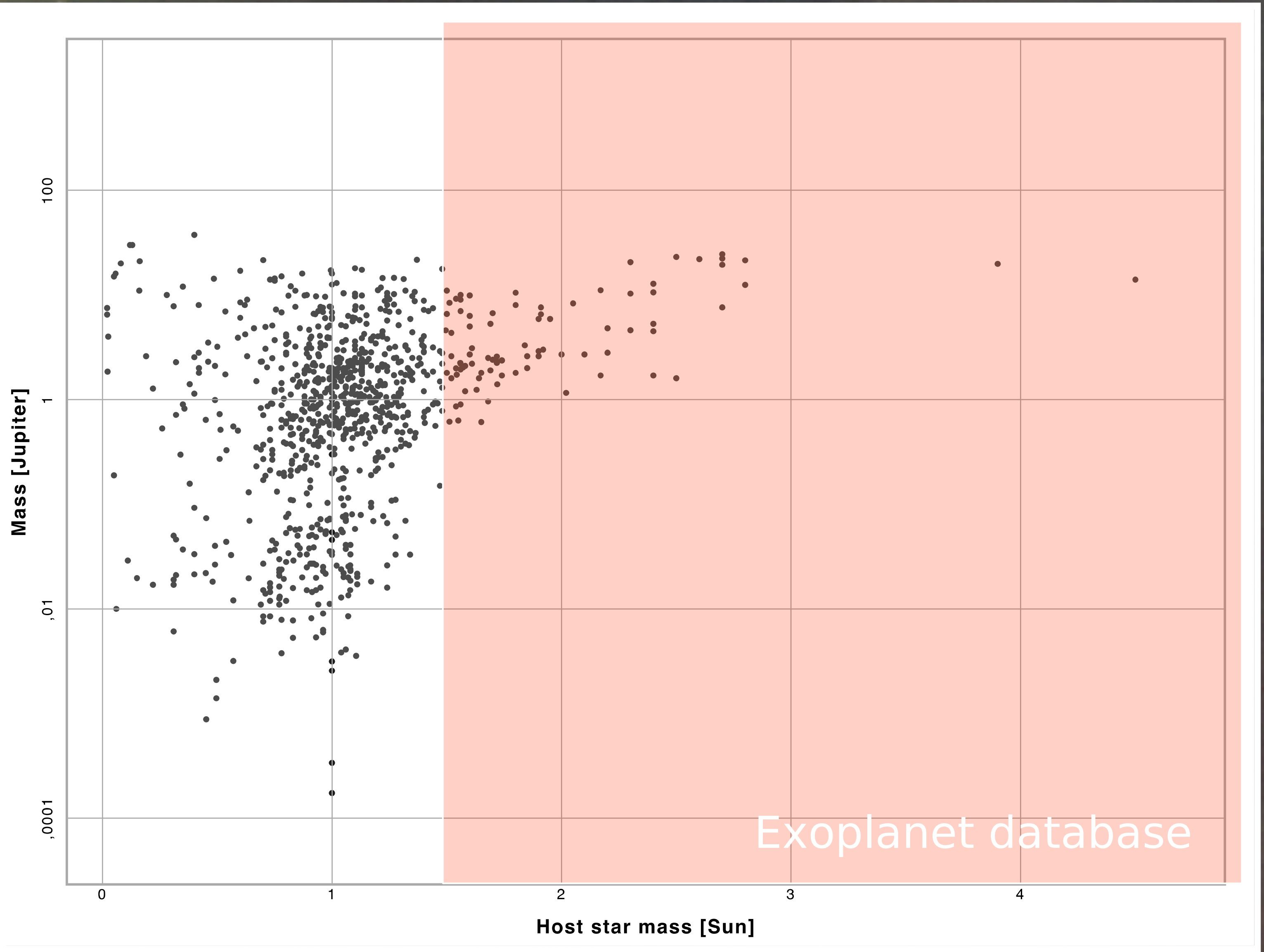


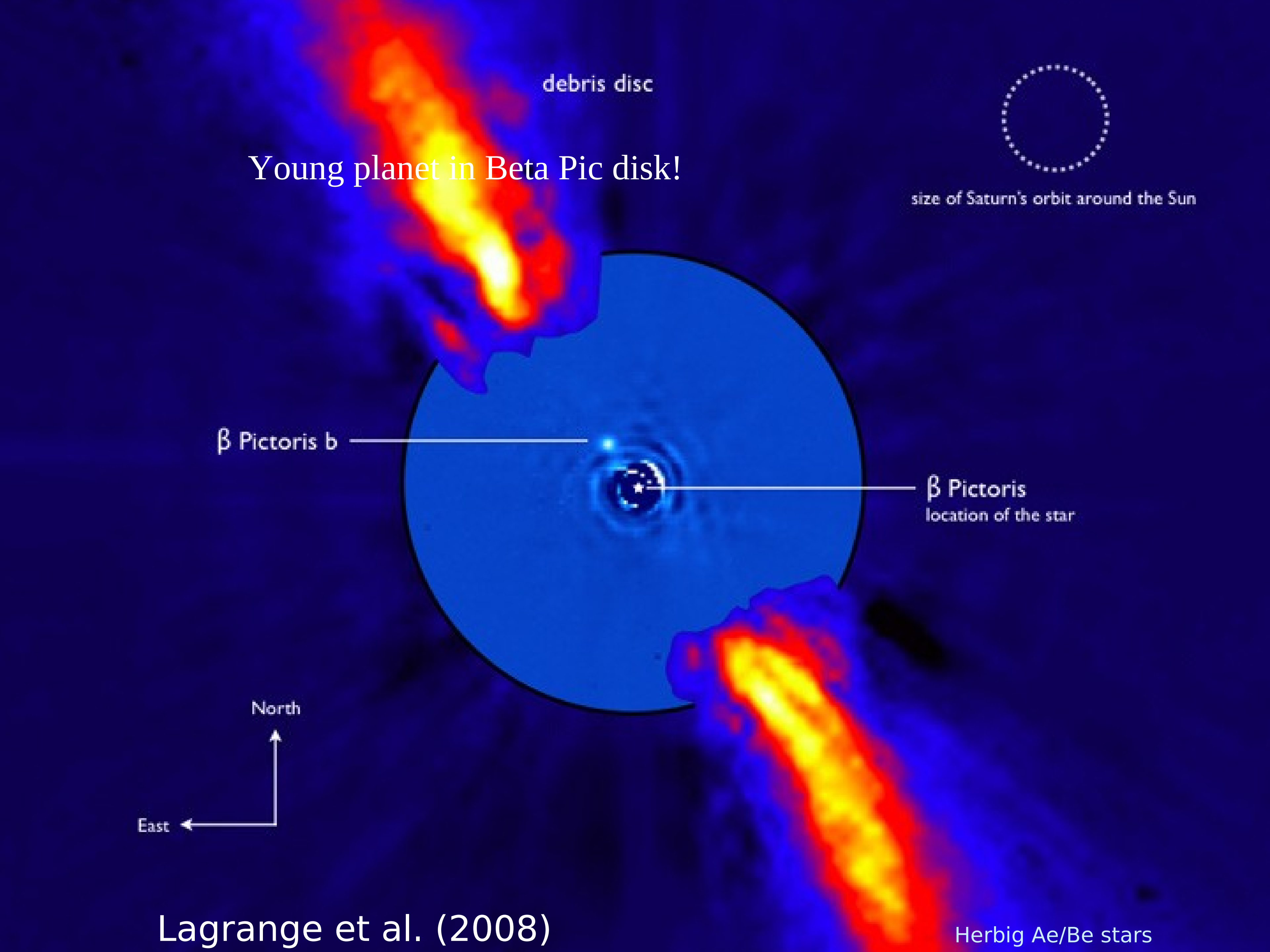
Image: NASA

Exo-planets orbiting intermediate mass stars



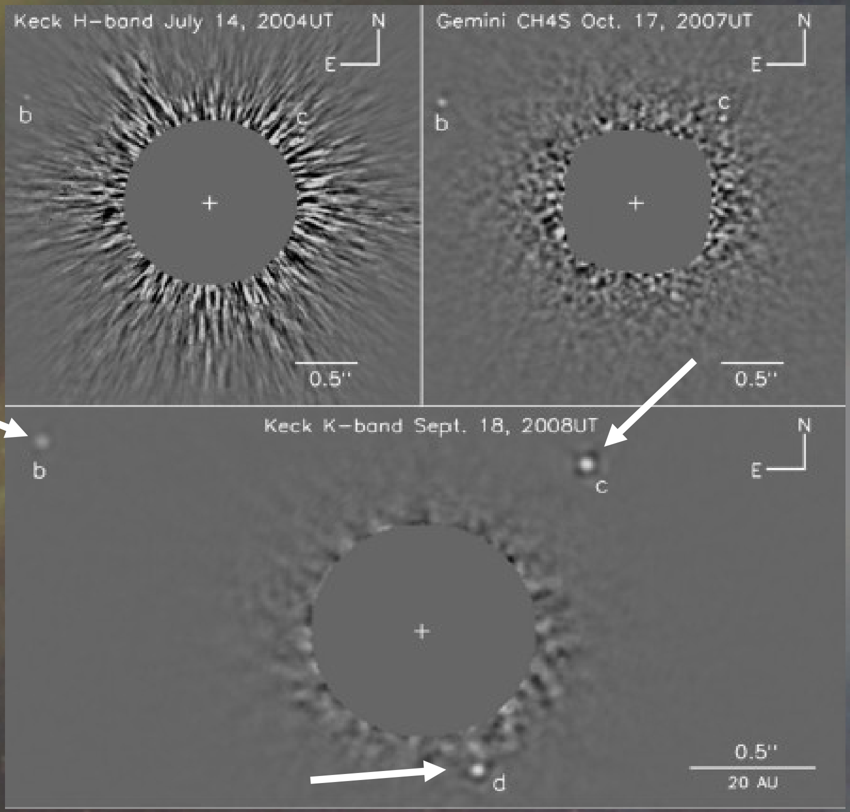
SRON

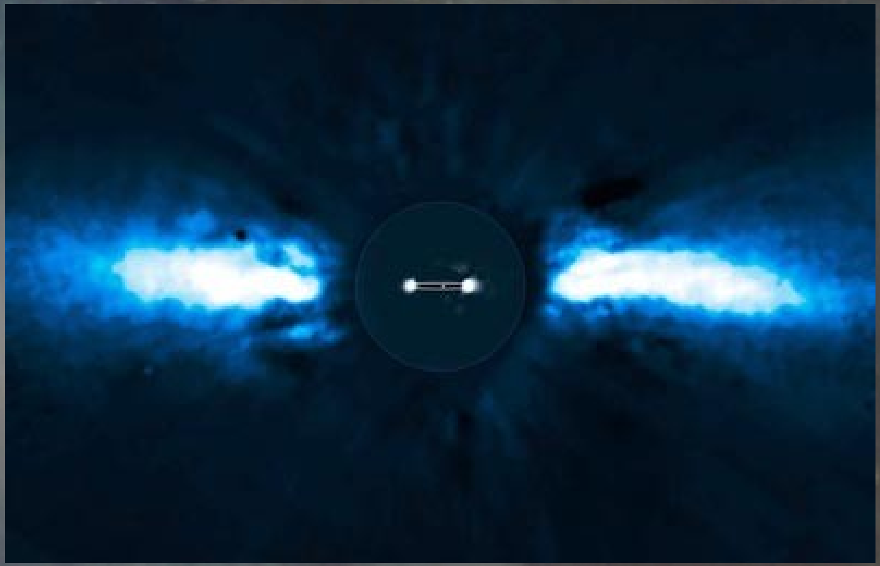
Young planet in Beta Pic disk!



Lagrange et al. (2008)

massive planets surrounding young intermediate mass stars

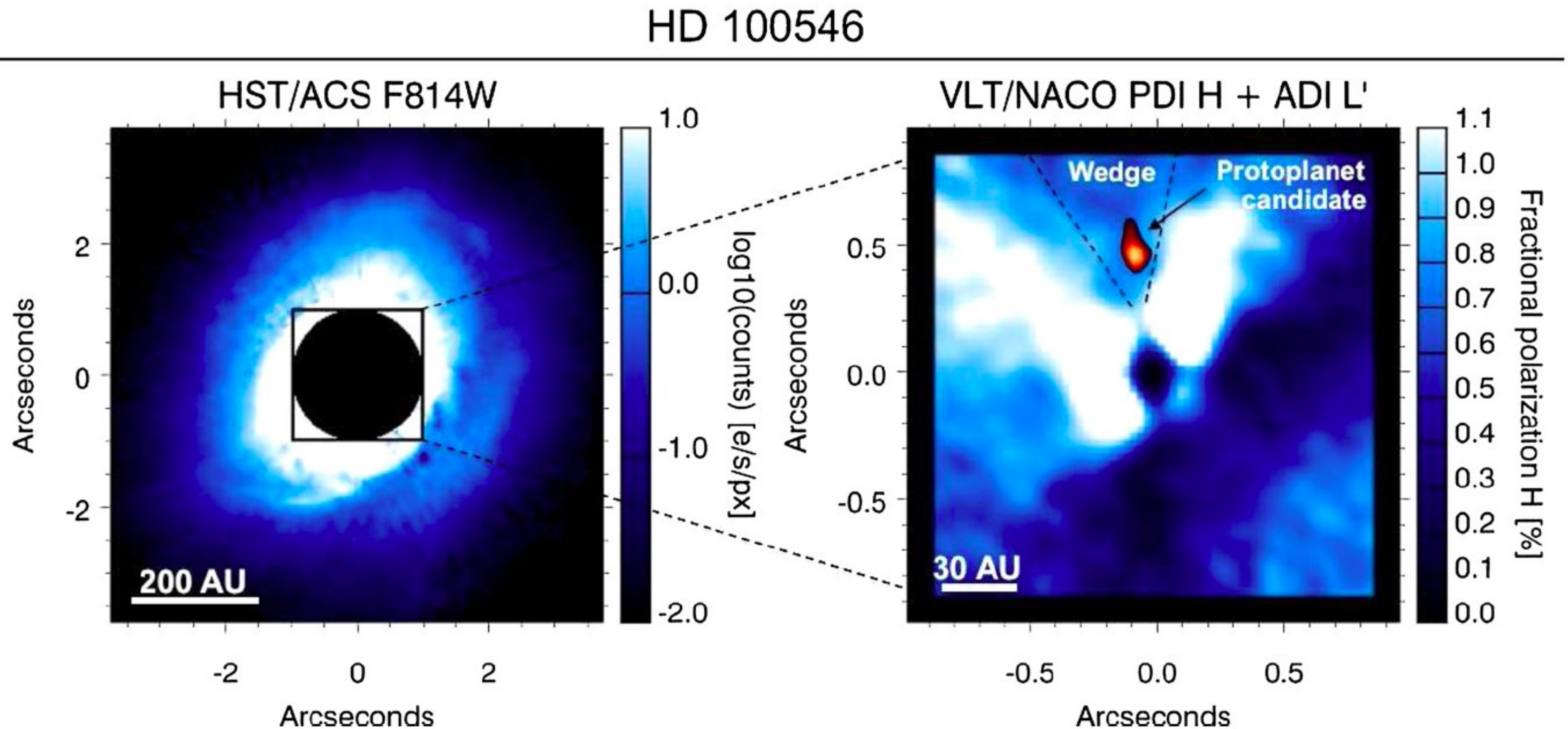




HR 8799
Marois et al 2008 Science

Beta Pic
Lagrange et al.

Proto-planet in HD100546?



Quanz et al. 2013

Questions/issues

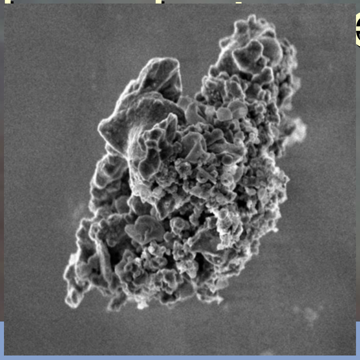
- How does disk evolution proceed?
- How does disk evolution/planet formation change as a function of stellar luminosity?
- Do all intermediate mass stars from planetary systems?
- What is the importance of environment on intermediate mass star & planet formation?
- How do disks evolve chemically?
- Can we link planetary system architecture to disk structure?

The end

Backup slides

Connection with solar system

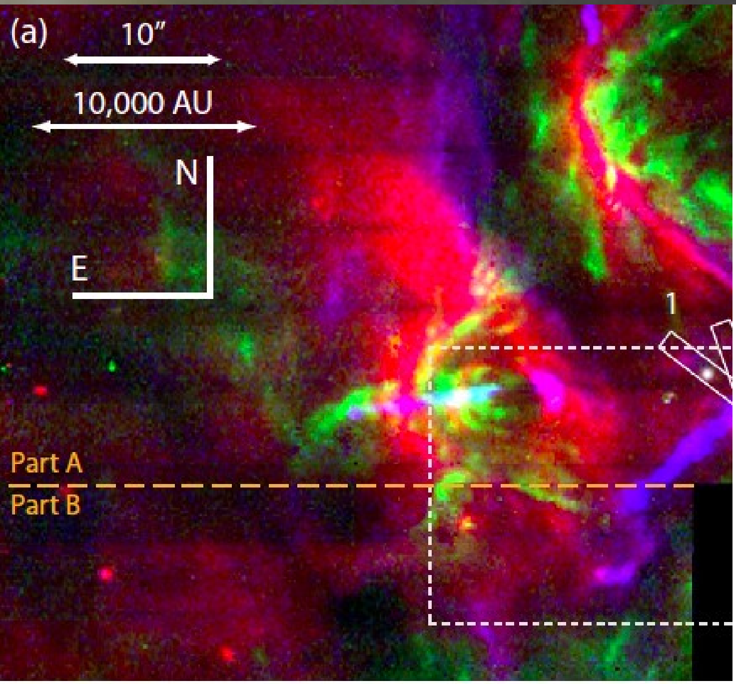
- Solid bodies and dust in solar system trace formation history
  - Rocky planets: memory of nature building blocks erased
  - Asteroids: high temperature condensation, processing in inner solar system
  - Comets: primitive, representing pristine materials?
  - Kuiper belt: icy bodies formed in outer regions solar system
  - Zodiacal dust: collis en asteroids, debris from comets

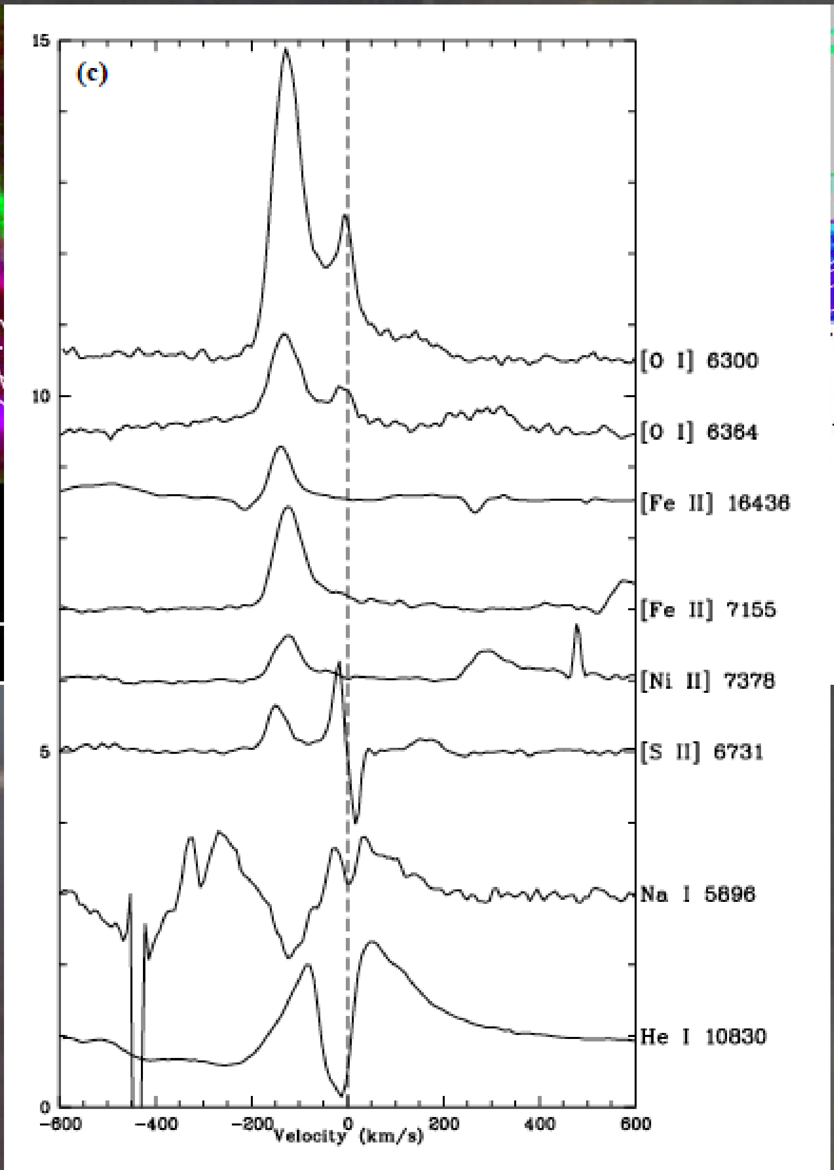


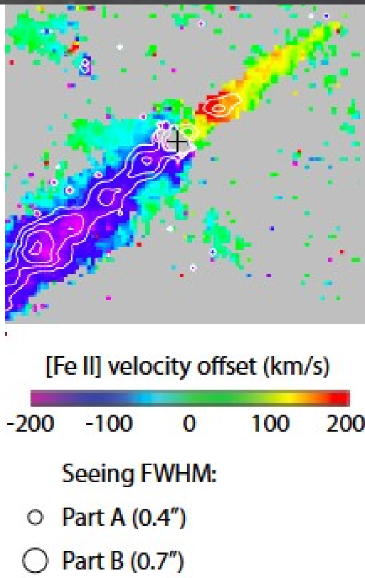
Herbig Ae/Be stars

SRON

… and even younger objects





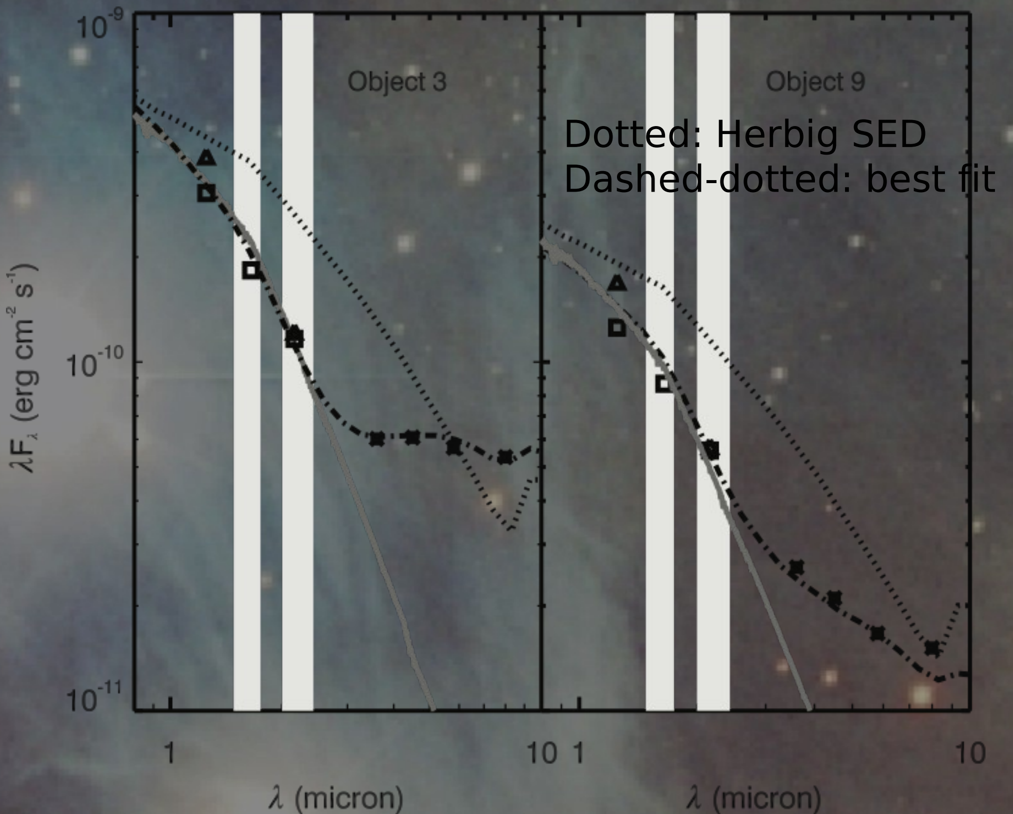


Ellerbroek et al.

IRAS08576n292
central star: temperature corresponds to mid-A spectral type

Disk structure

- MCMax (Min et al, 2009) modeling of SEDs (Maaskant et al, in prep)
  - Inner hole Lower inner rim temperature, excess starts at longer wavelength
  - Lower disk scale height.
- Future evolution of SEDs
  - Inner rim temperature becomes hotter as Teff of central star increases Herbig like SED
  - Transition disk; disk is disappearing (disk fraction declines strongly with age, Hernandez et al, 2008)

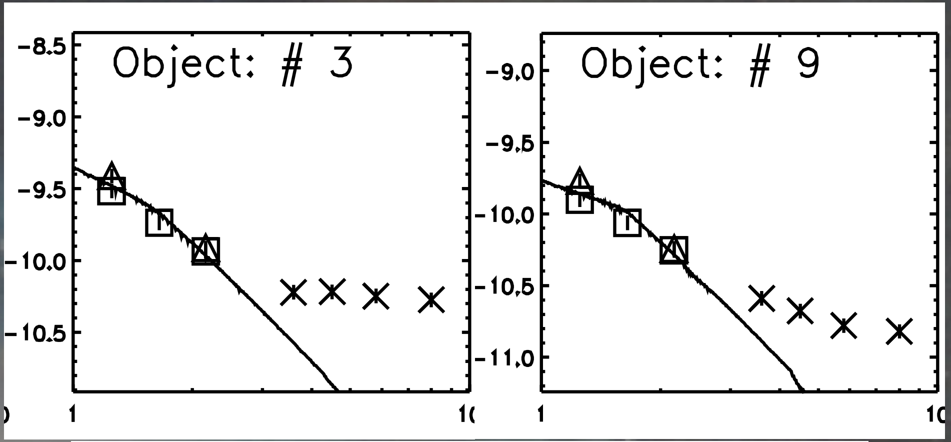


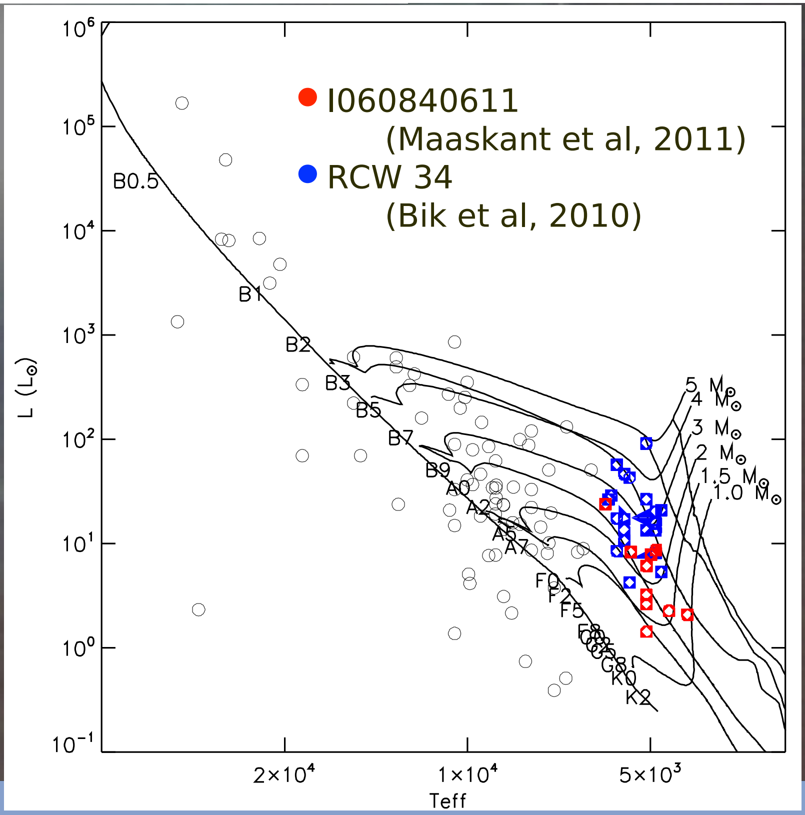
I06084-0611, Maaskant et al, 2011

SRON

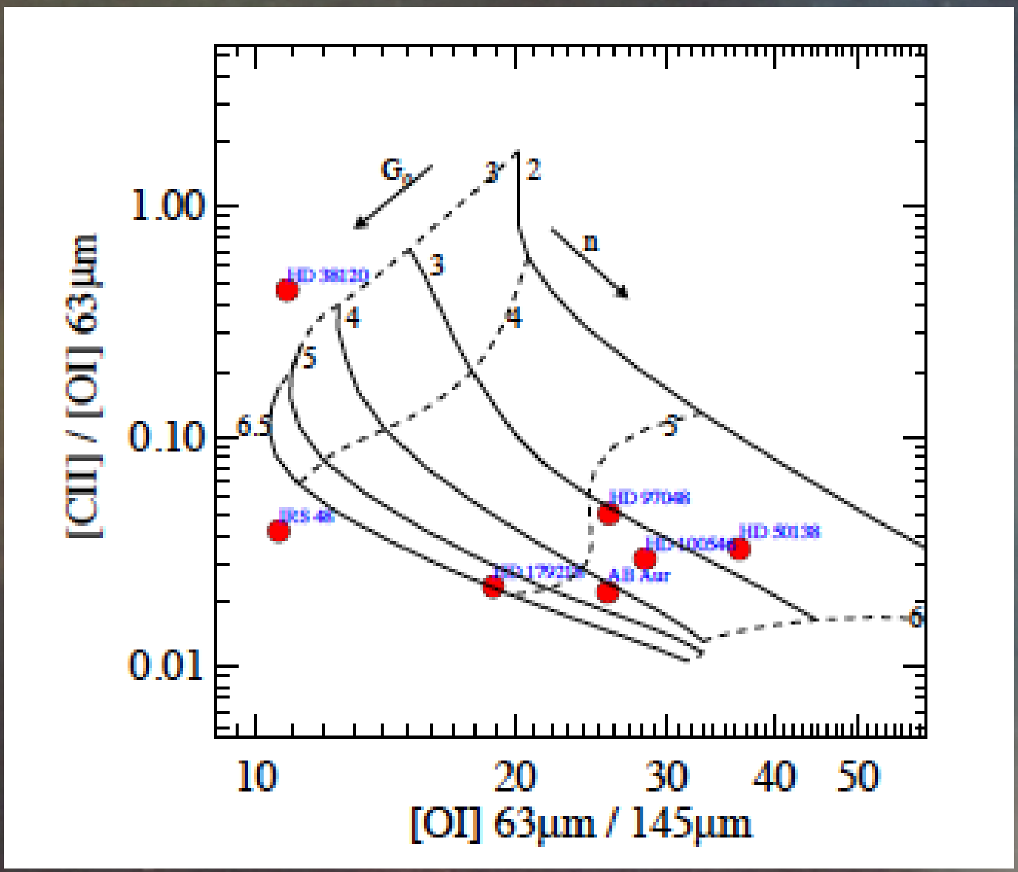
Herbig Ae/Be precursors?

- Masses similar to those of Herbig stars (1-5 Msun).
- Excess emission starts only at 3 micron
- They will evolve to A and B stars (HAeBe?)
- Different disk structure?
- Dissolving disks?



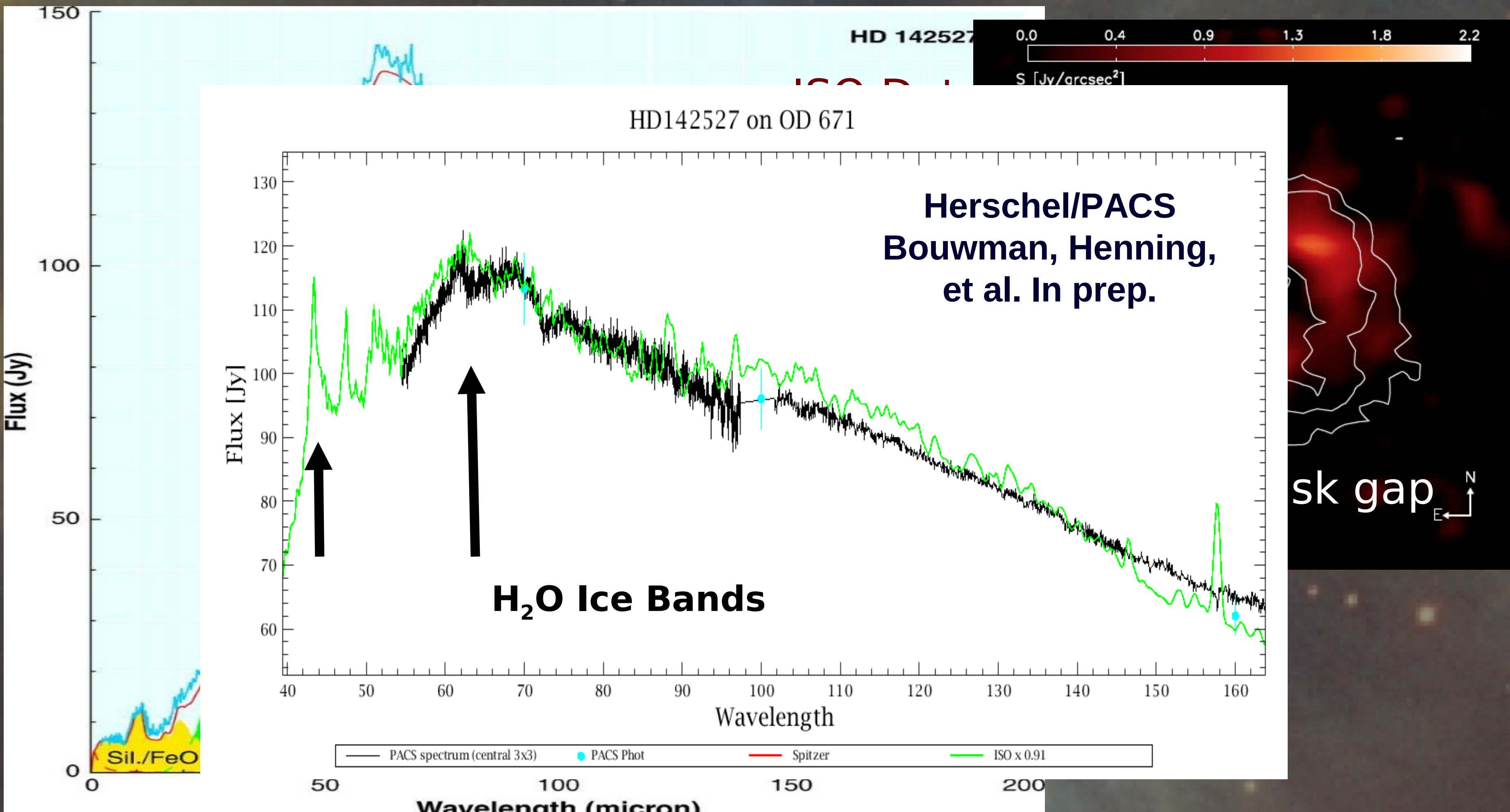


[OI] Excitation



Line ratios consistent with PDR models with densities of about 10^5 cm^{-3} and $G_0 = 10^3$ to 10^7 Because of possible contamination of [CII] by diffuse emission, densities and G_0 are lower limits.

Ices and Hydrosilicates in HD142527

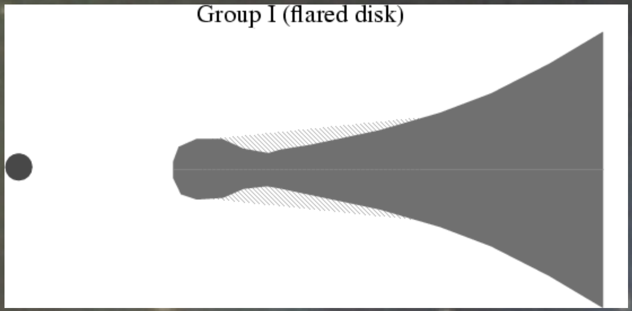


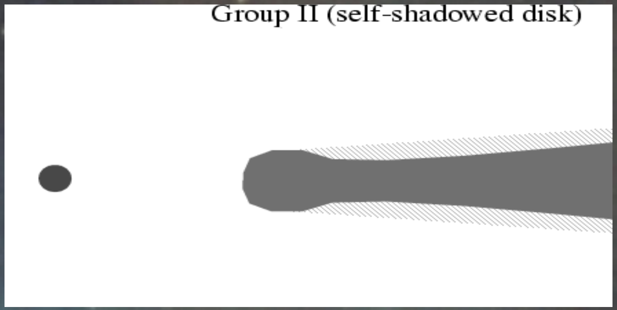
(Malfait et al 1999)

Amazingly strong water ice bands!

SRON

Flaring versus flat (self-shadowed) disks

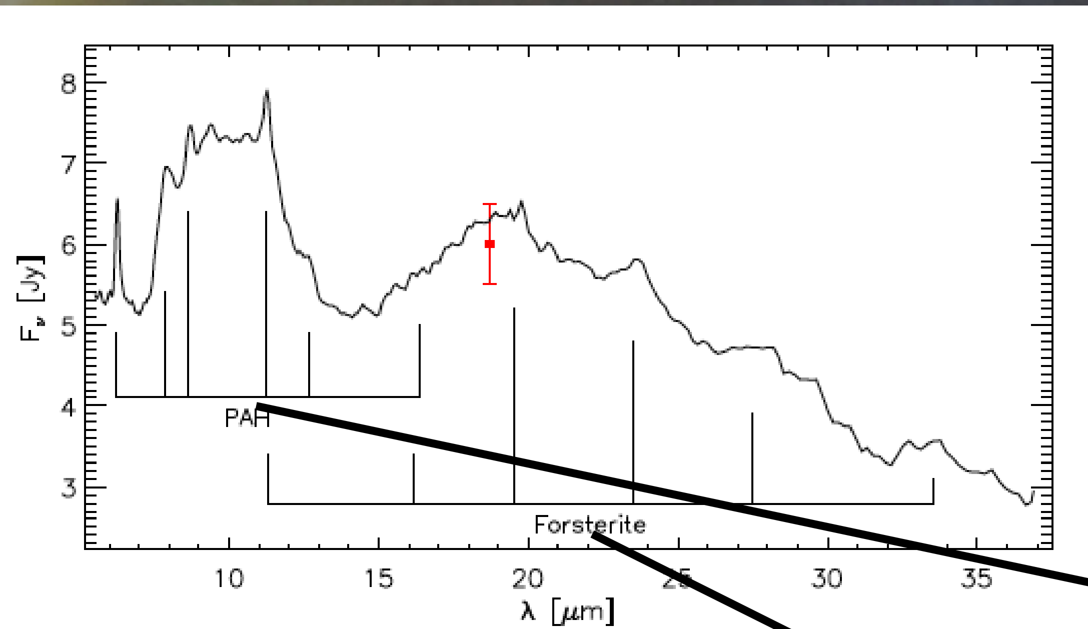


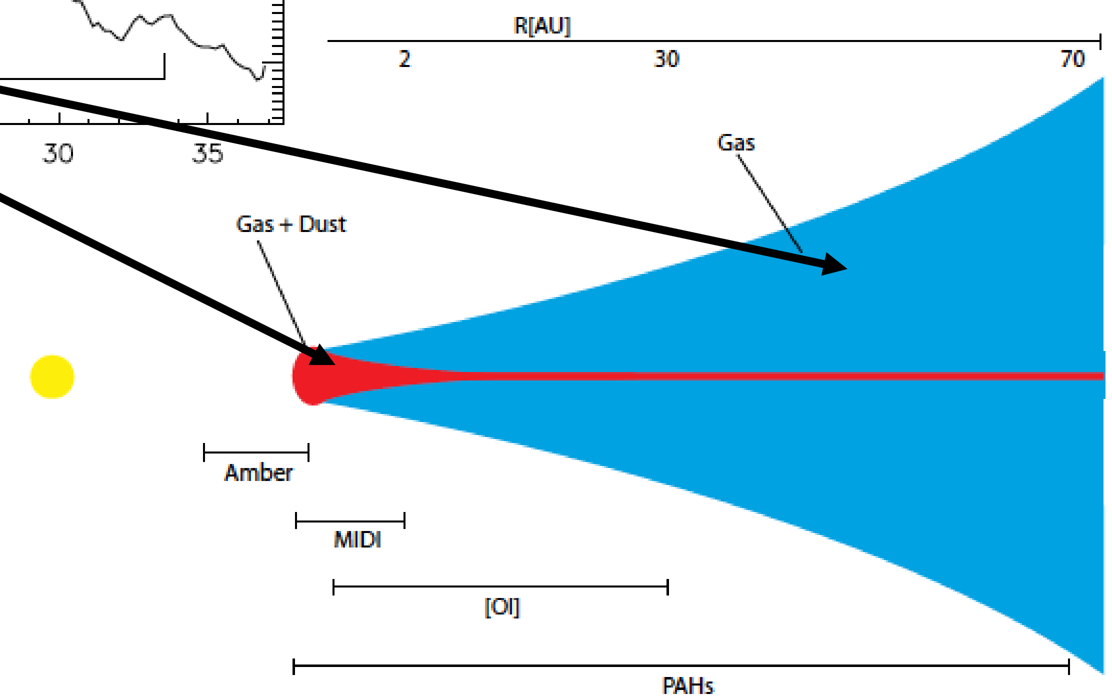


- Red IR spectrum
- (strong) [OI] 6300 A
- Strong PAH em.
- Spatially resolved PAH
- CO fund. 4.6 micron
- Scattered light
- Often no silicates
- Steeper mm continuum

- Blue IR spectrum
- Weak/absent [OI]
- Weak/absent PAHs
- Weak/absent CO fund.
- No scattered light
- Silicates detected
- Flat mm continuum

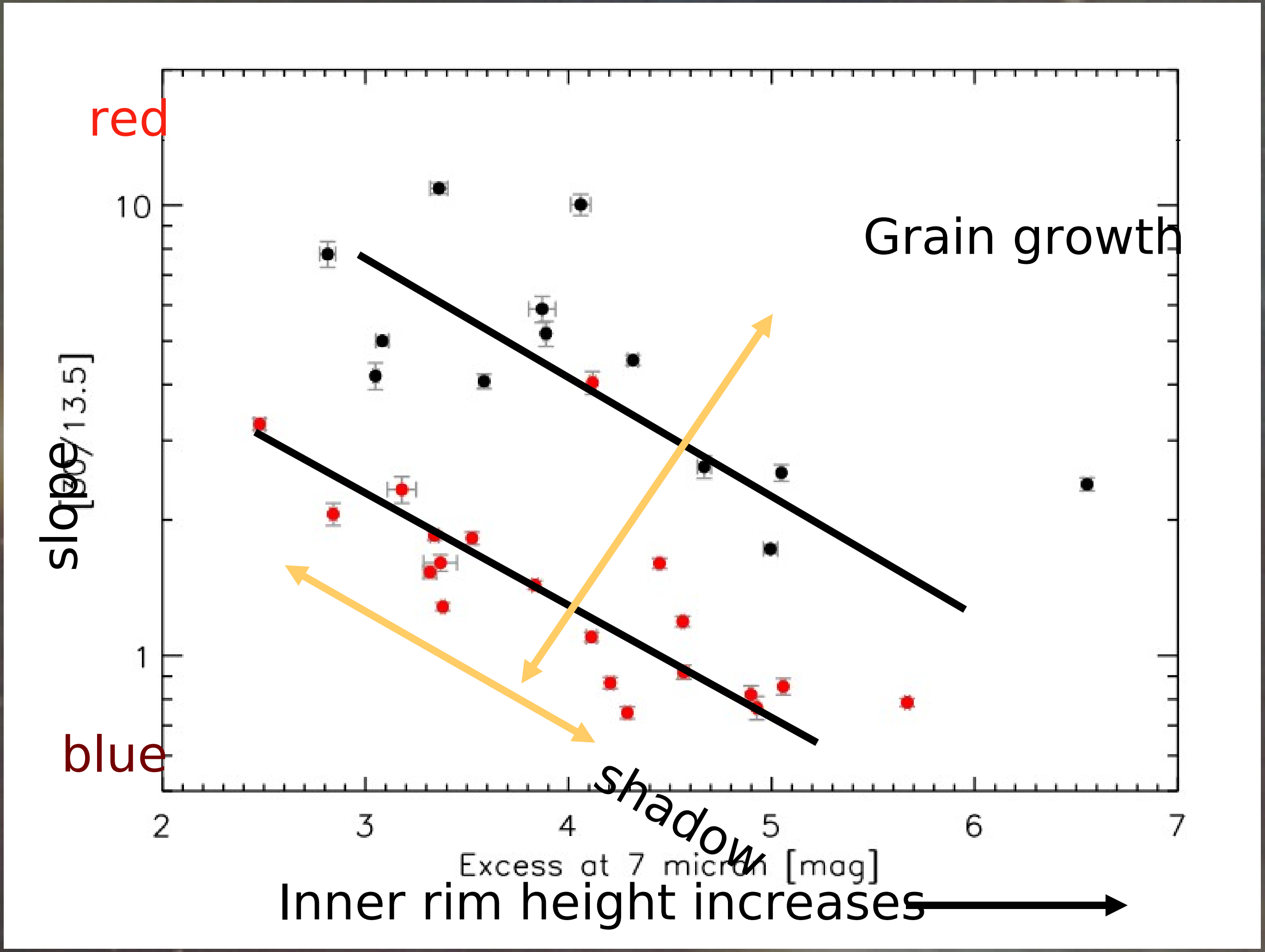
Gas-rich disk with dust settled to mid-plane





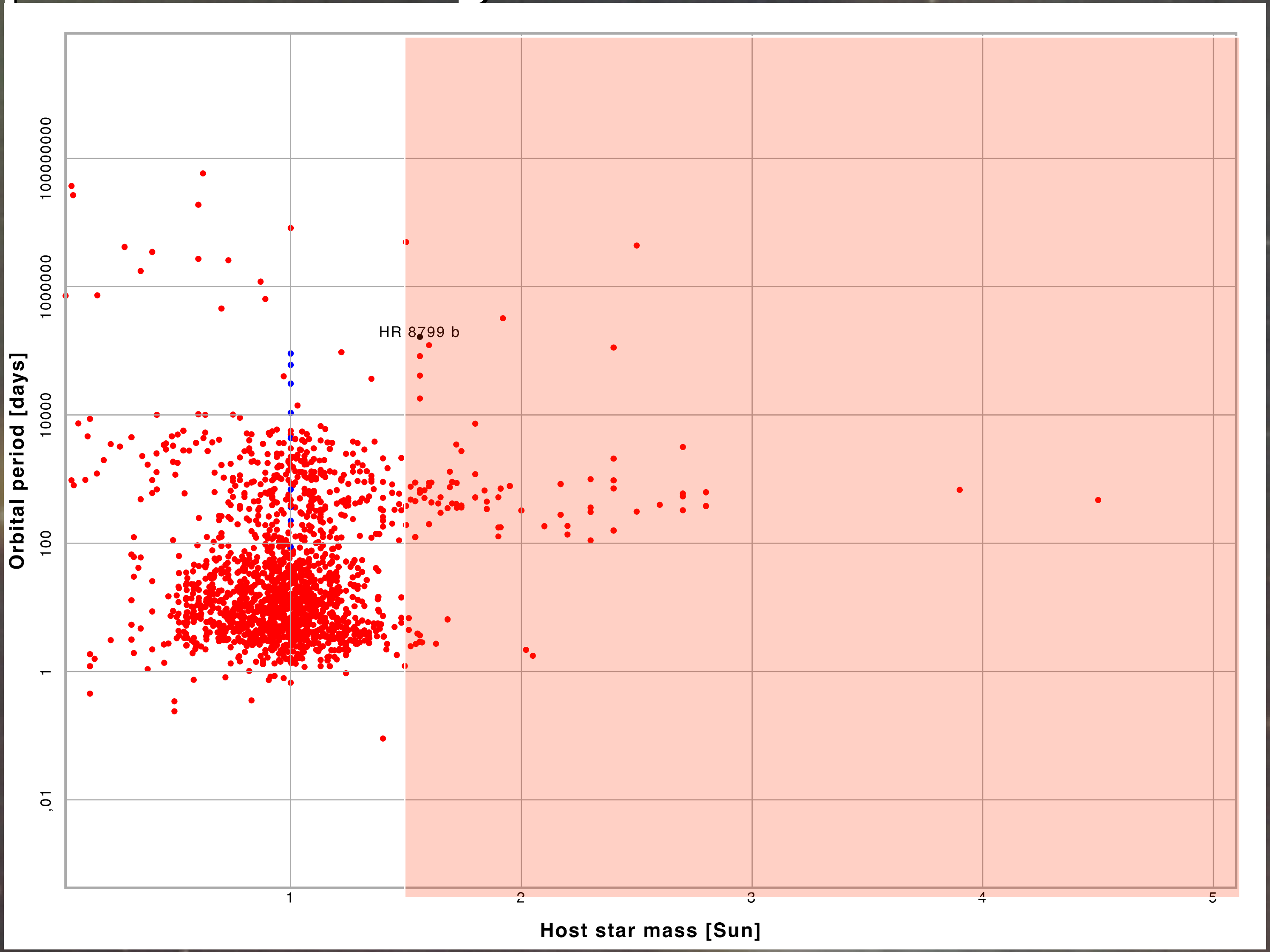
Verhoeff et al (2009)

Evidence for disk shadow: the outer disk knows about the inner disk



SRON Acke et al. (2009)

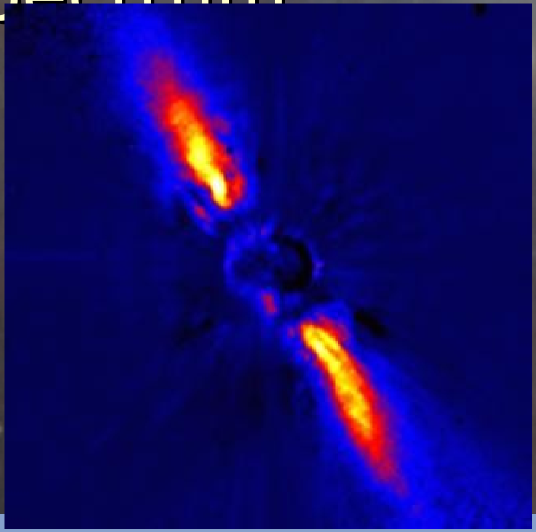
Exo-planets orbiting intermediate mass stars



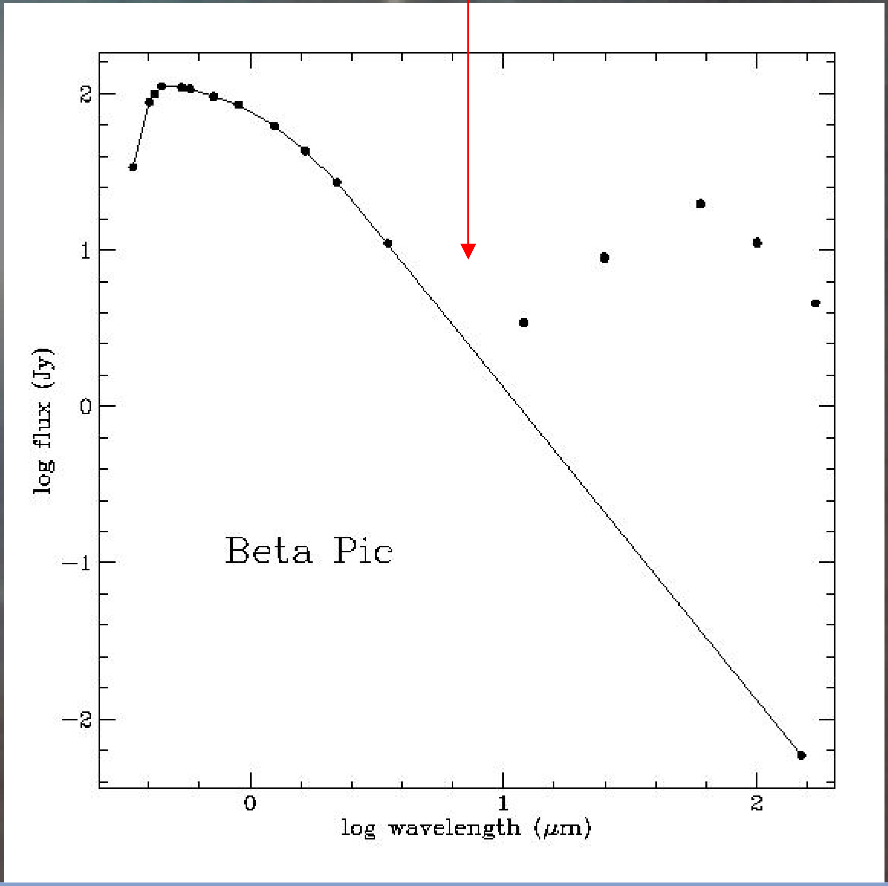
SRON

Disk gaps: planets!

- Planets clear orbit
- dust removed
- Lack of emission in part of IR spectrum

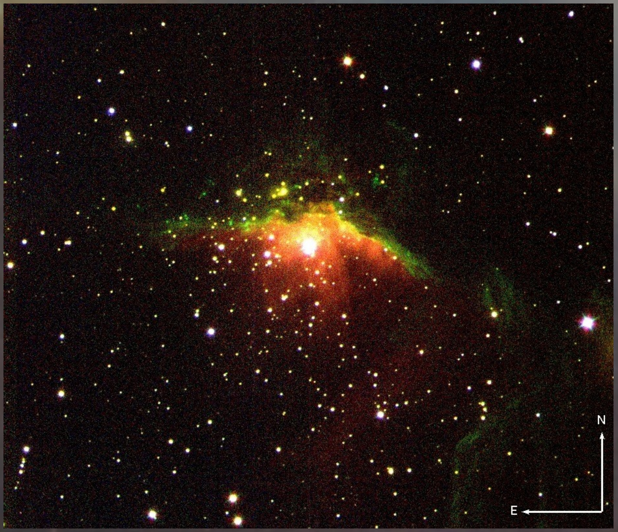


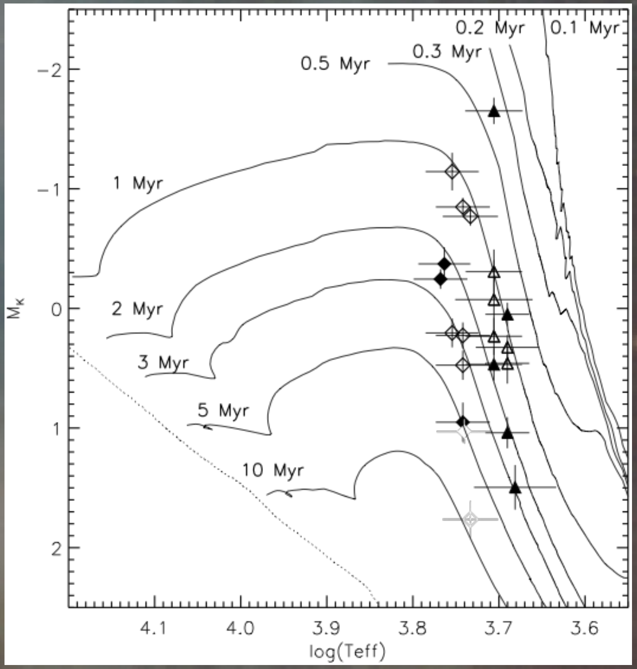
Lack of hot dust



Intermediate mass pre-main-sequence stars in embedded clusters

- Classification as G and K stars (Teff: 5000 - 6000 K)
- Surface gravity: lower than that of dwarfs, PMS stars, still contracting.
- 50 % sources: IR-excess detected with Spitzer
- Ages between 1 and 4 Myrs.

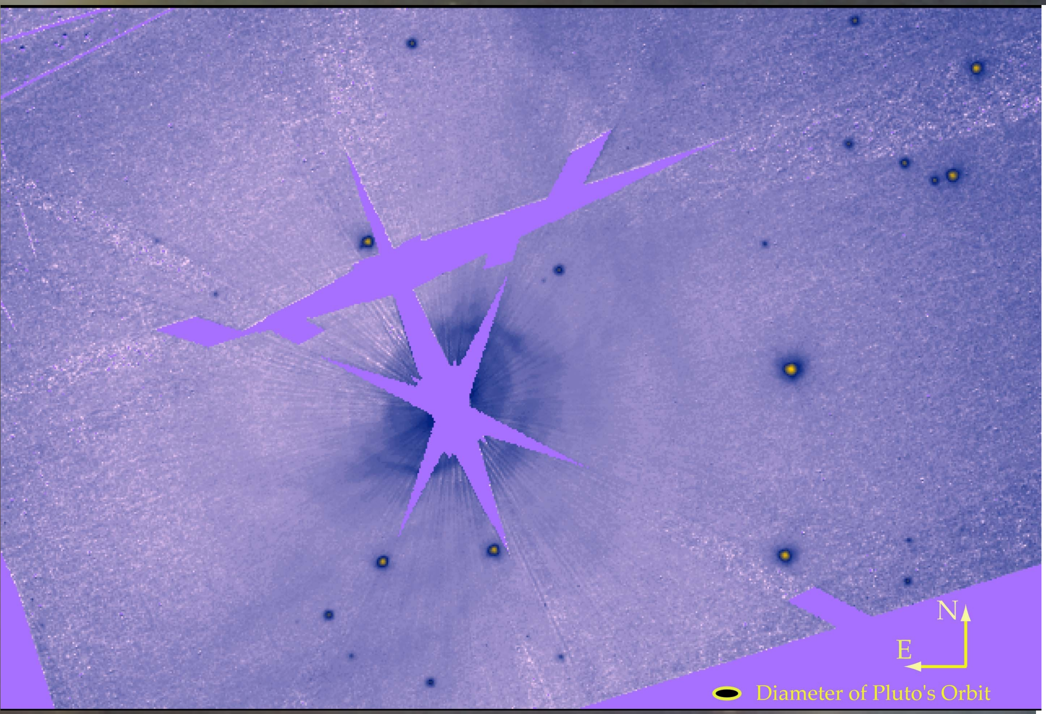




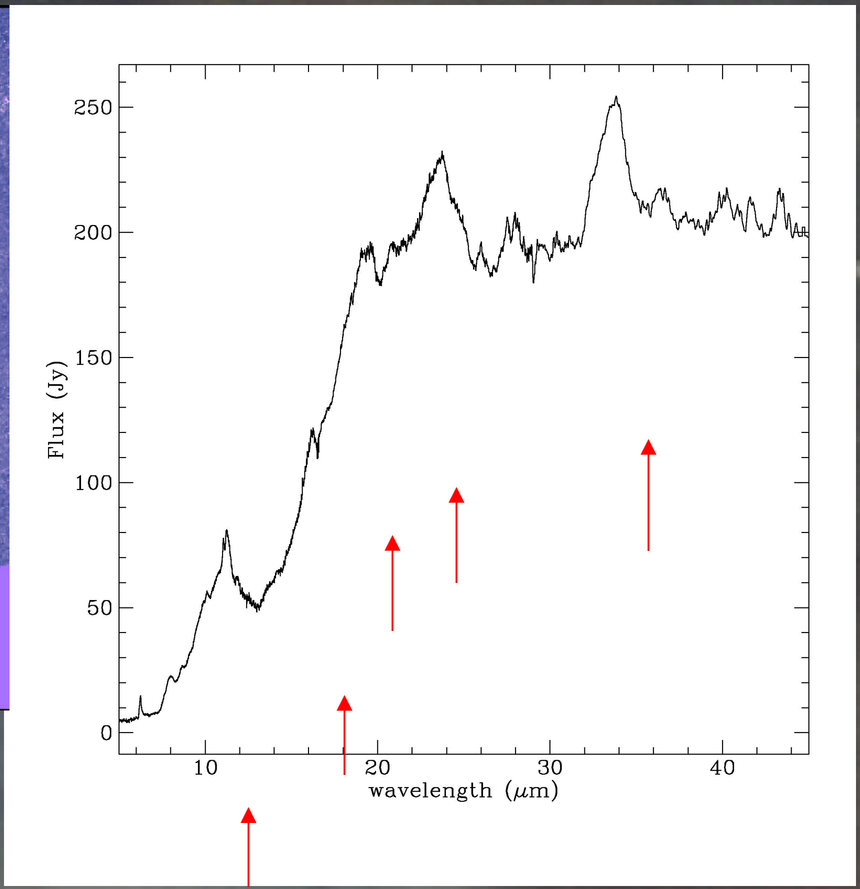
RCW34, Bik et al, 2010

SRON

HD 100546: a young star with *crystalline* silicates

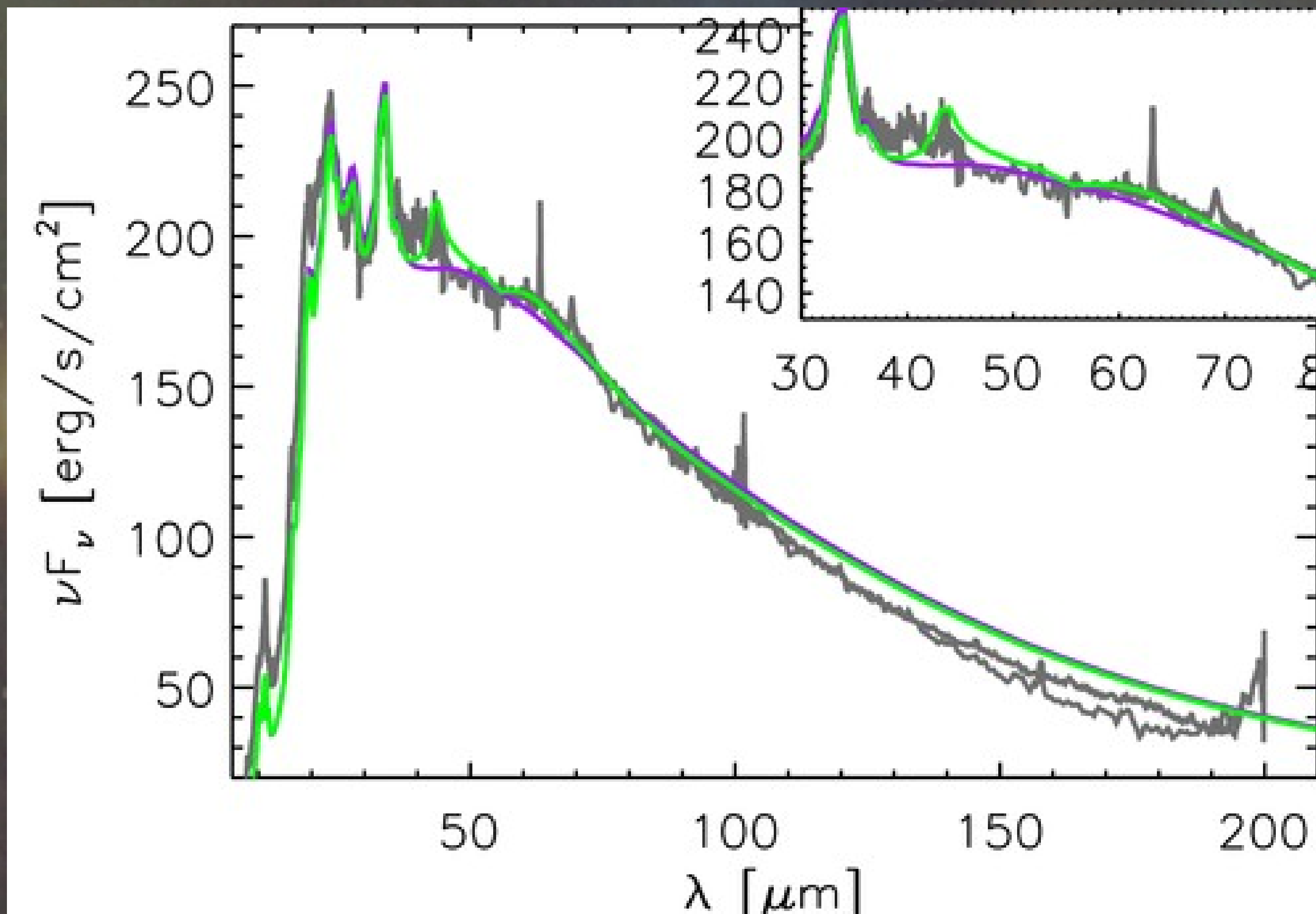


Grady et al, HST imaging

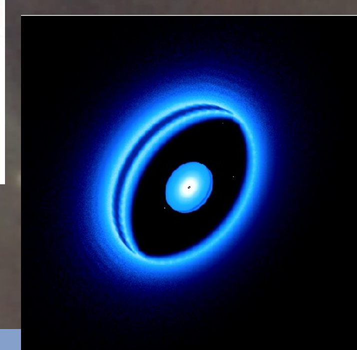


Malfait et al. ISO spectroscopy

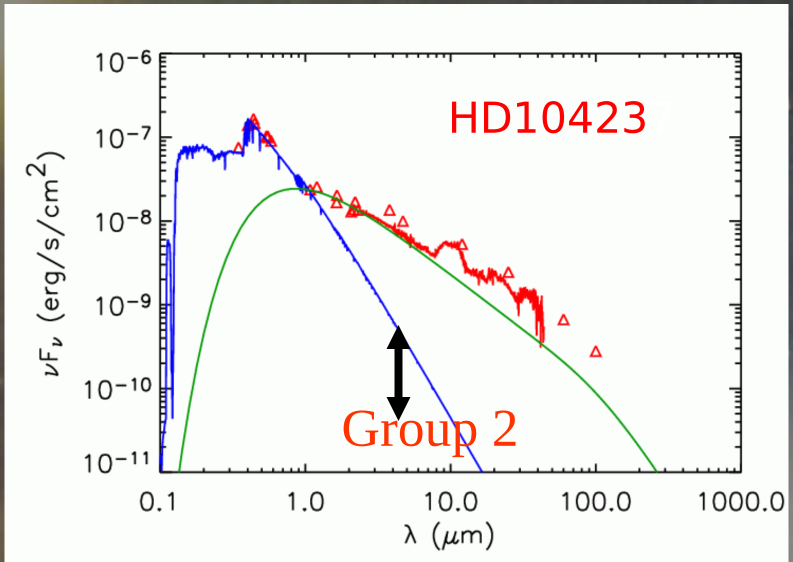
HD100546: Detailed Models

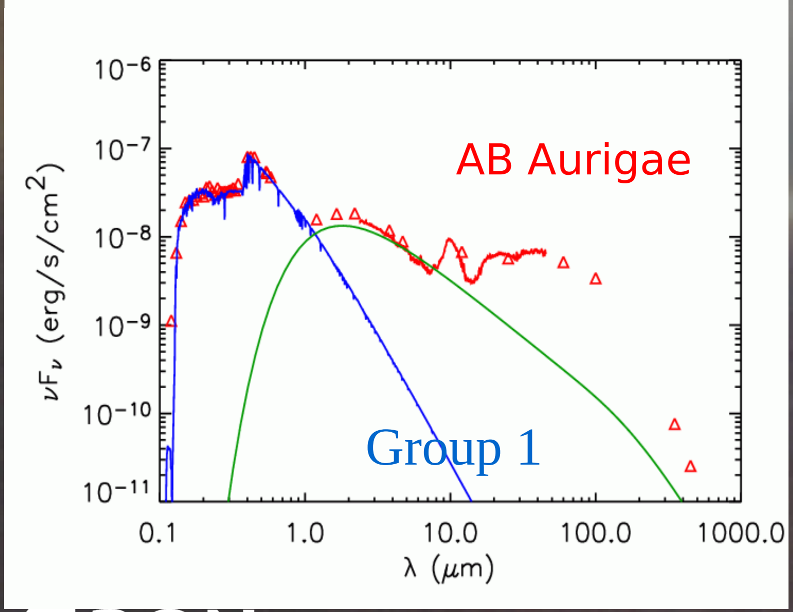


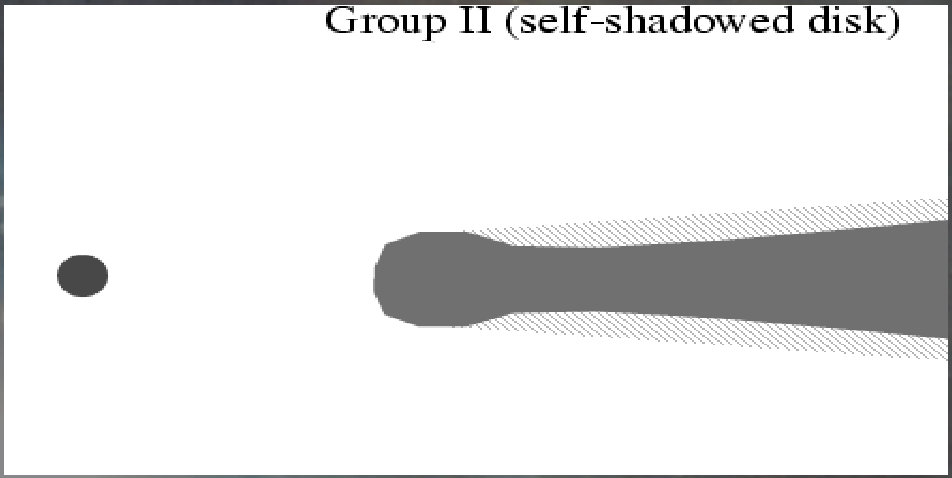
- isk
- IDPs
  - ~1% water ice
  - Snow line at 20 AU



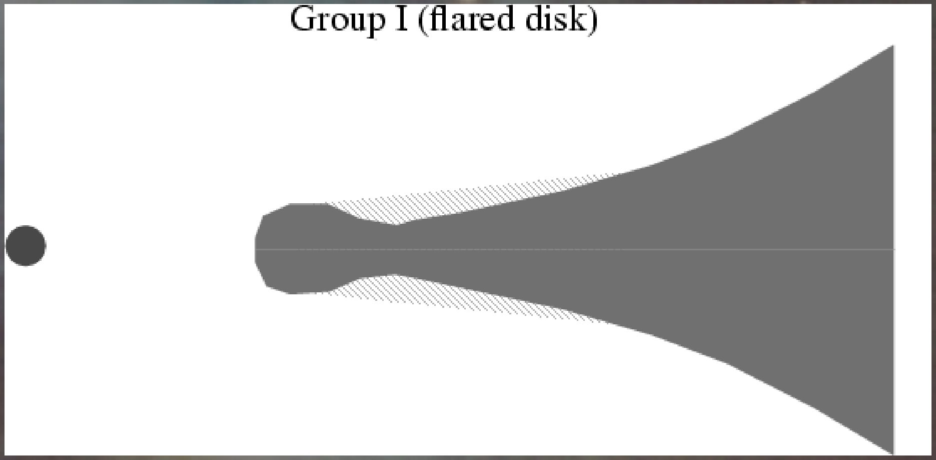
Division into two groups: flaring versus flat disks





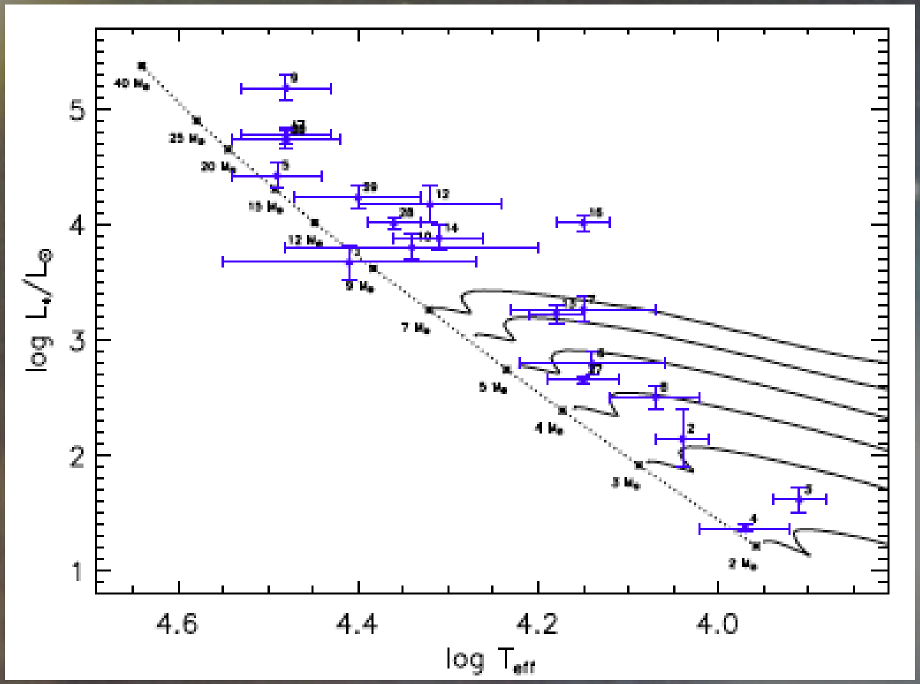


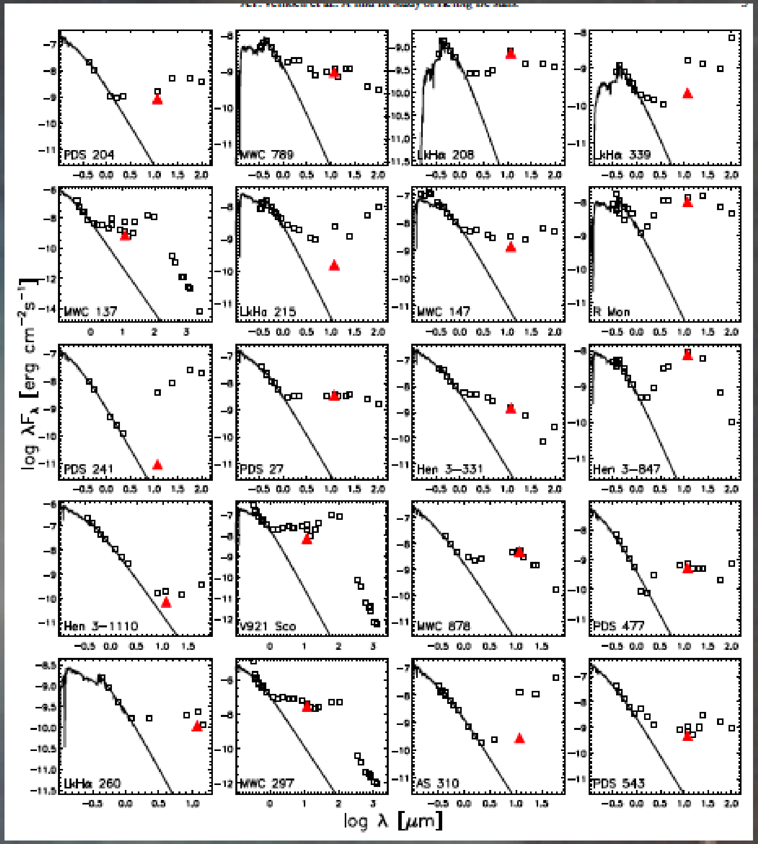
Meeus et al. 2001



SRON

SEDs of herbig Be stars: no flaring disks?





Verhoeff et al. 2010

Outer disk evaporation (Gorti & Hollenbach)
Dust settling timescale versus disk evaporation timescale
What is the stellar upper mass limit for planet formation?

HST imaging of scattered light from disks: flaring and self-shadowed

Grady et al. 2005

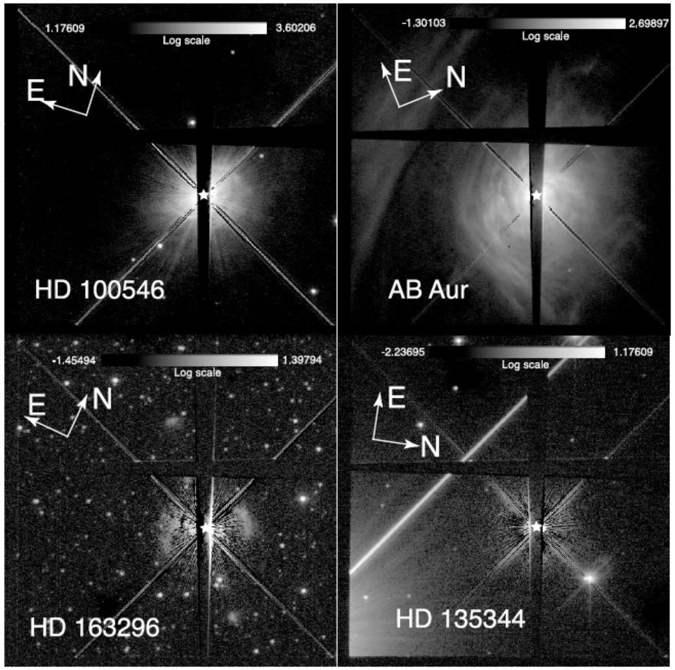


TABLE 4

STIS Surface Brightness Data

Star	log ($S(r = 3'')$)	Detection	Meeus Group	MM Data References	Comments
HD 100546	6.3 (0.1)	Yes	Meeus Ia	1	
HD 95881	<7.0 (0.3)	No	Meeus II		
AB Aur	5.8 (0.1)	Yes	Meeus Ia	2, 3	
HD 163296	6.7 (0.2)	Outer disk	Meeus II	2	
MWC 480	<7.0 (0.3)	No	Meeus II	4	
HD 36112..................	<7.2 (0.4)	No	Meeus Ia[a]	5	
HR 5999.....................	<6.8 (0.3)	No	Meeus II		Likely small disk
HD 104237	<6.8 (0.4)	No	Meeus II	6	$r_{outer} \leq 0''.6$
HD 142666	<7.0 (0.2)	No	Meeus II		
CQ Tau.......................	6.1 (0.2)	No	Meeus Ia[a]	5	Background 6.3
HD 135344	<7.0 (0.3)	No	Meeus Ib		