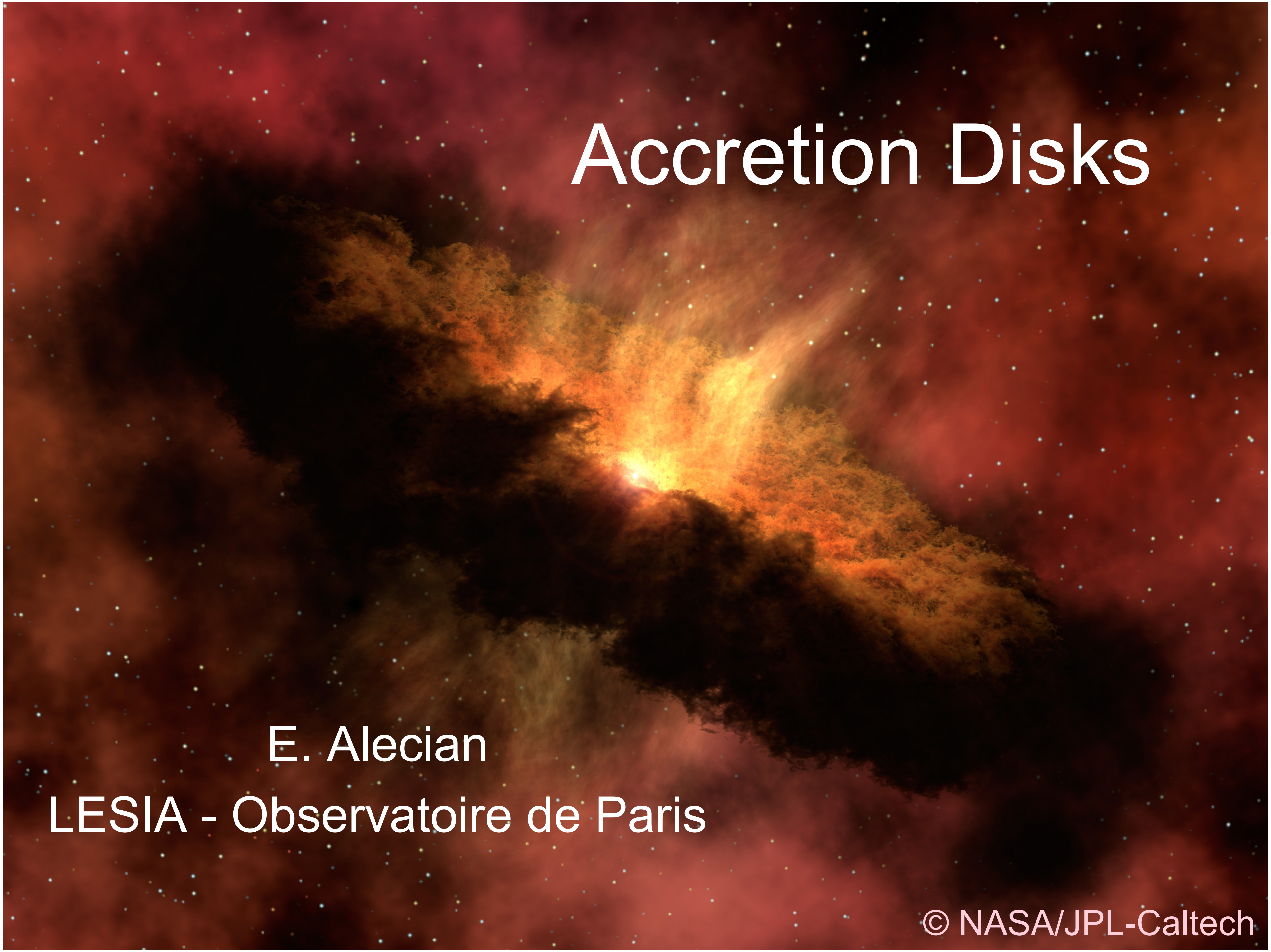
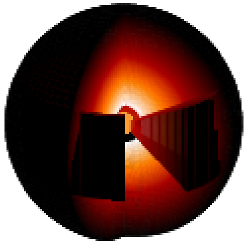
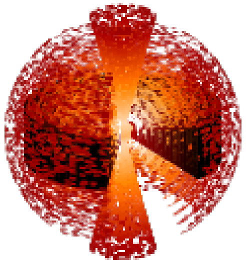
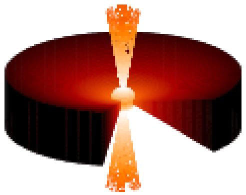
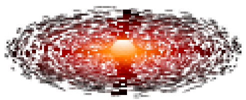


Accretion Disks

E. Alecian
LESIA - Observatoire de Paris

© NASA/JPL-Caltech

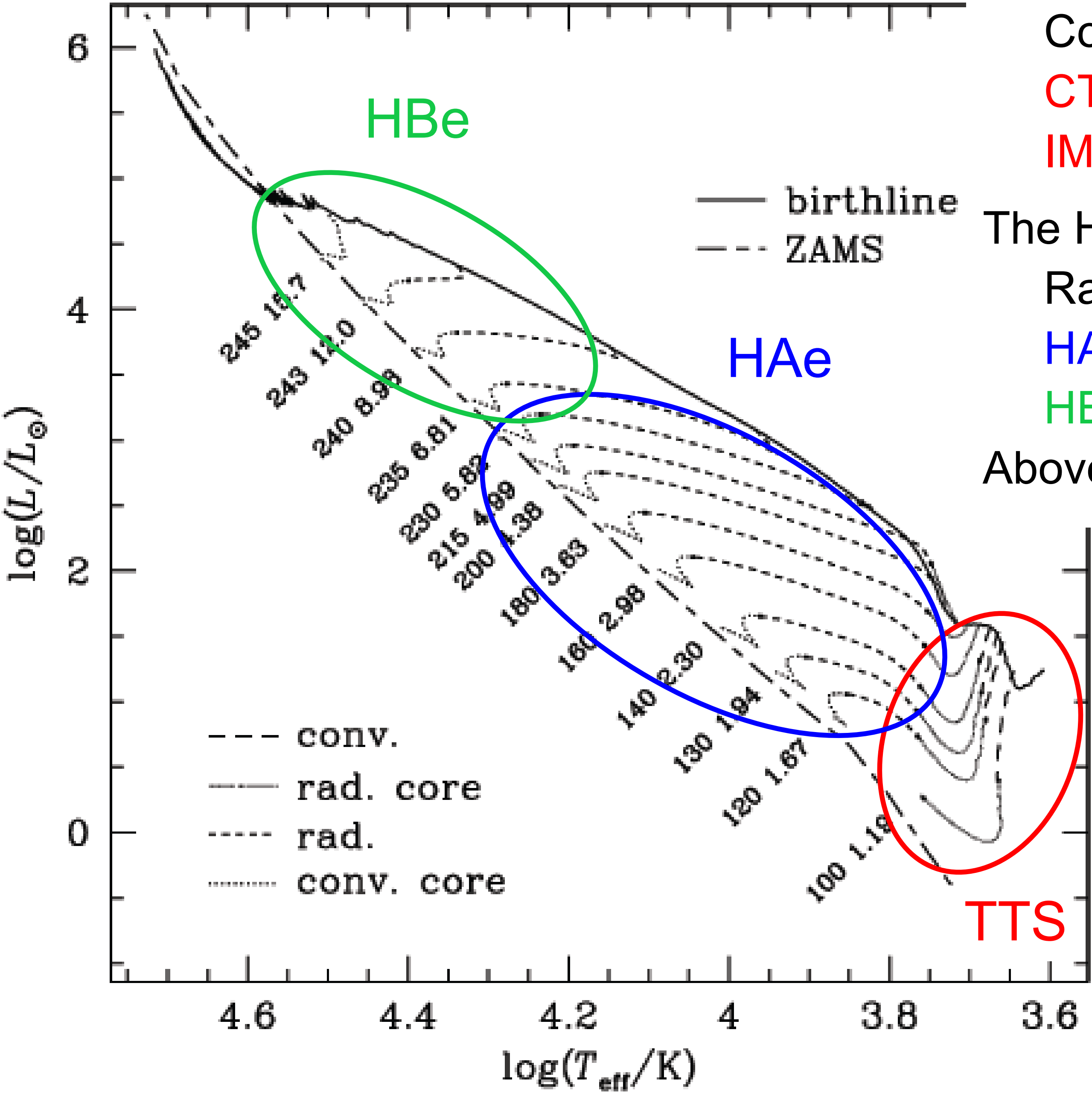
Star formation

		Low to intermediate mass stars	High mass stars
Protostellar phase		**Class 0** Age ~ 10^4 yr Accretion start	**Class 0** Age ~ 10^4 yr Accretion start
		**Class I** Age ~ 10^5 yr Accretion from a spherical cocoon	**Class I** Age ~ 10^4-10^5 yr Accretion from a spherical cocoon
PMS phase		**Class II: CTTS, HAe** Age ~ 10^6 yr Optically thick accretion disks	**Class II: HBe** Age ~ 10^5 yr Optically thick accretion disks ?
		Transition	
		**Class III: WTTS, HAe** Age ~ 10^7 yr Debris disk	**Class III: MS OB** Age ~ 10^6 yr Debris disk

Time

adapted from Pinte (2006)

PMS evolution



The T Tauri stars (TTS):

Convective envelope

CTTS + WTTS : $M < 1.5\ M_\odot$

IMTTS : $1.5 < M < 2\ M_\odot$

The Herbig Ae/Be stars:

Radiative (convective core)

HAe: $1.5 < M < 6\ M_\odot$

HBe: $6 < M < 20\ M_\odot$

Above 20 $M_\odot$: no PMS phase

Behrend & Maeder (2001)

Overview

1. Observed characteristics of Class II
2. Why an accretion disk ?
3. The disk structure
4. The disk evolution

What are the differences between low-, intermediate- and high-mass stars ?

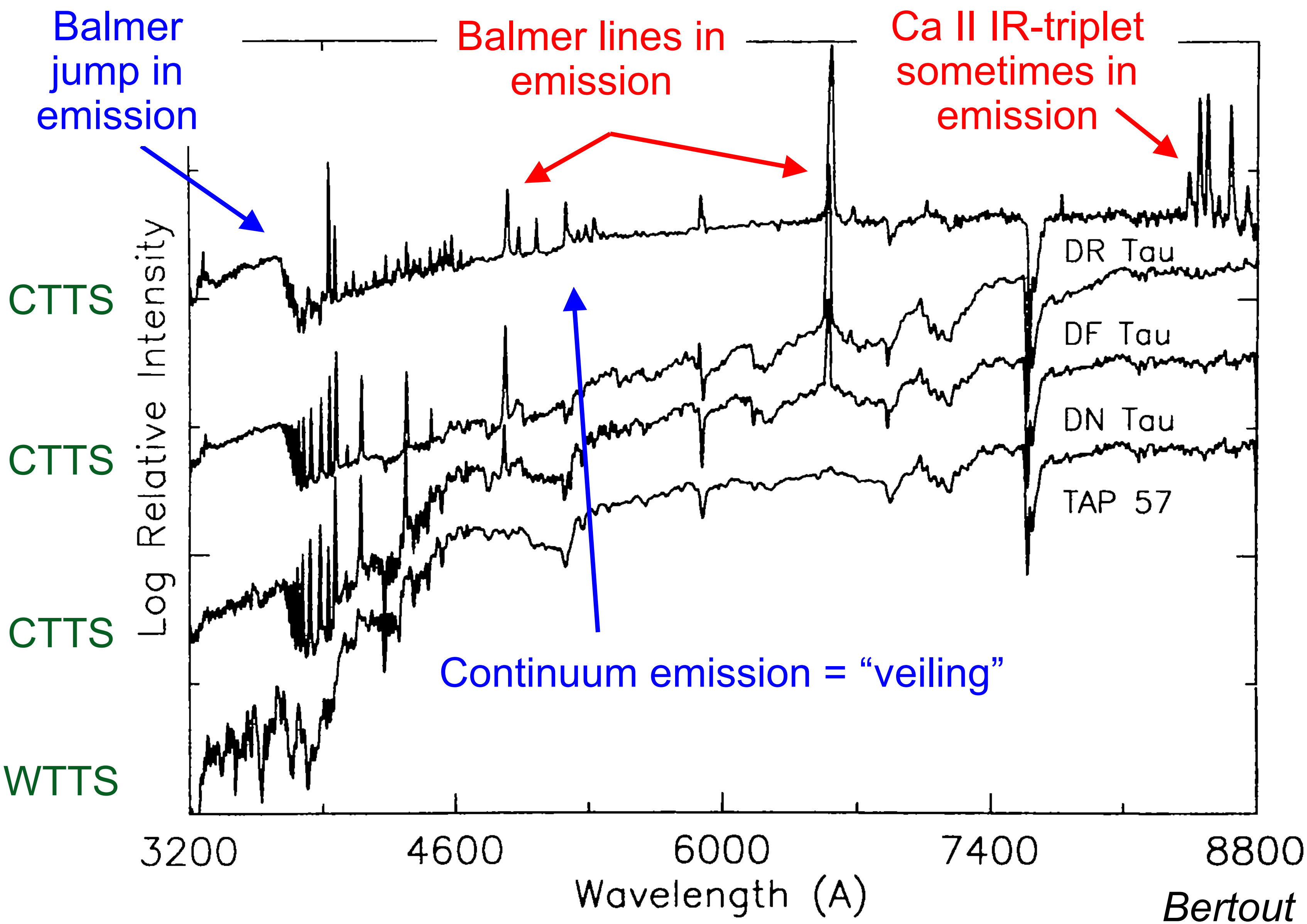
CTTS / HAe / HBe

1. Observed characteristics of Class II stars

The Class II stars

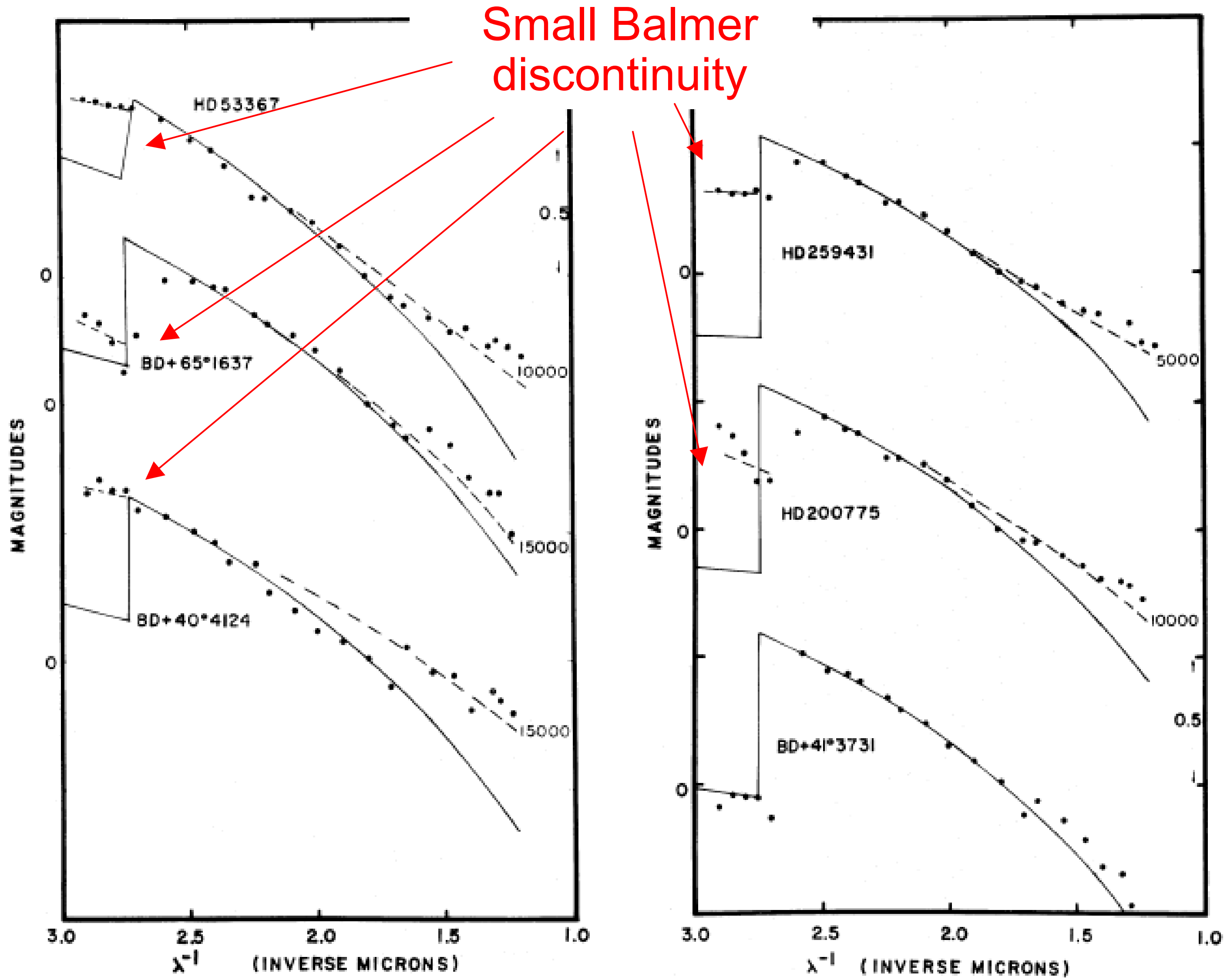
- Main observable characteristics
  - Broad emission lines (T+H)

Optical spectrum of CTTS



Bertout (1989)

The Balmer jump of HAeBes

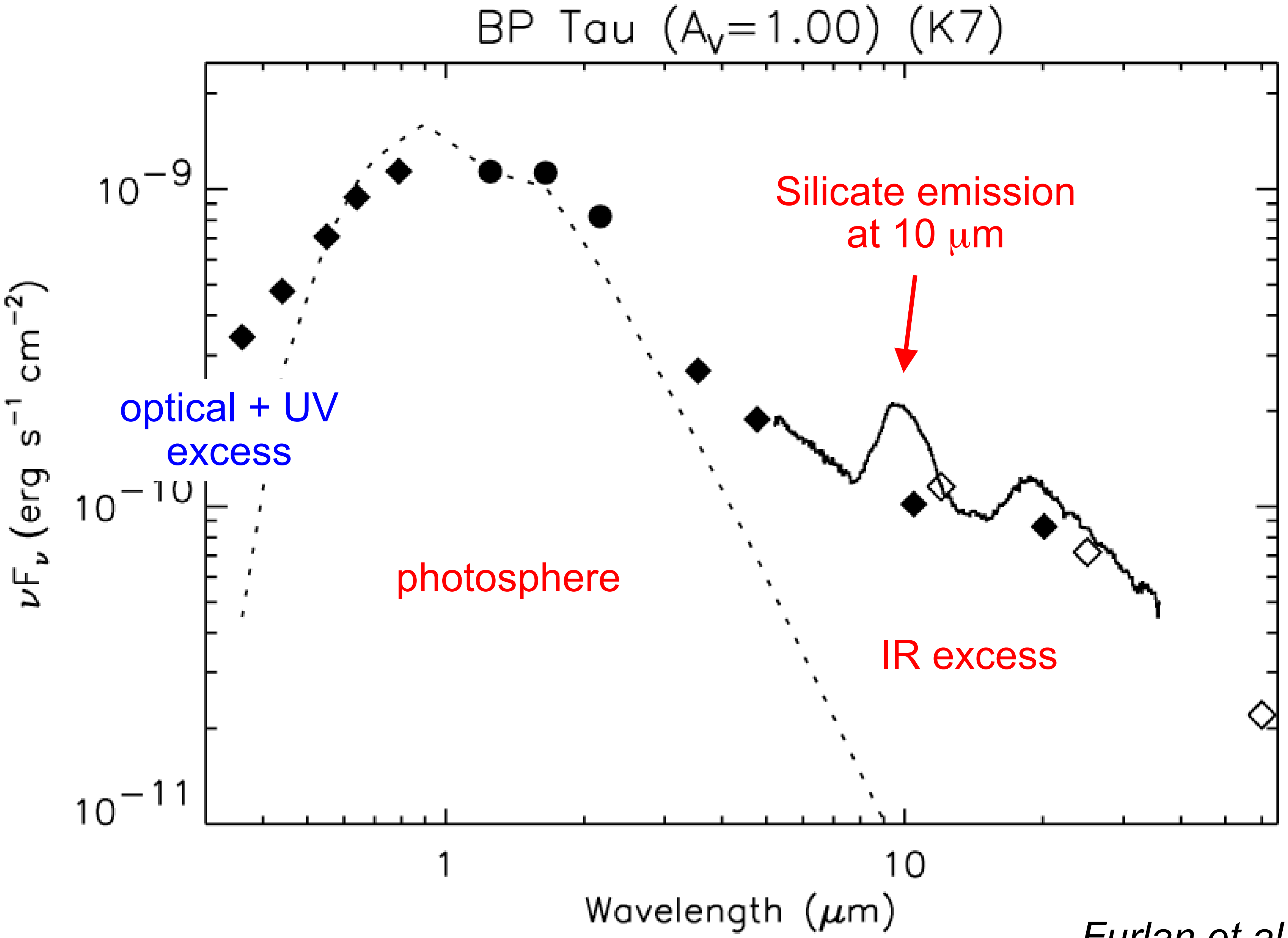


Garrison (1978)

The Class II stars

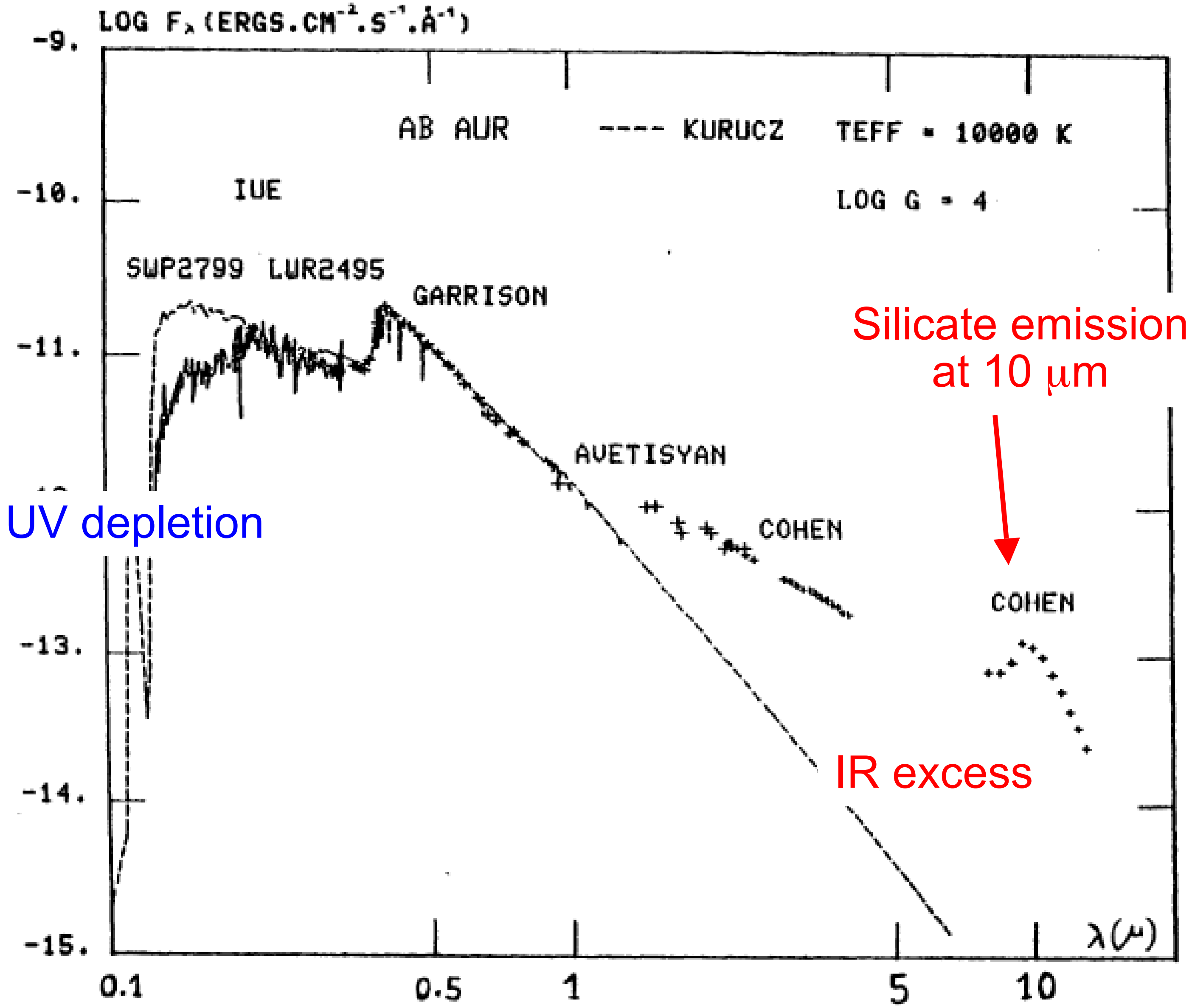
- Main observable characteristics
  - Broad emission lines (T+H)
  - UV, optical excess emission (T)
  - IR excess (T+H)

Typical SED of CTTS



Furlan et al. (2006)

The typical SED of HAeBe



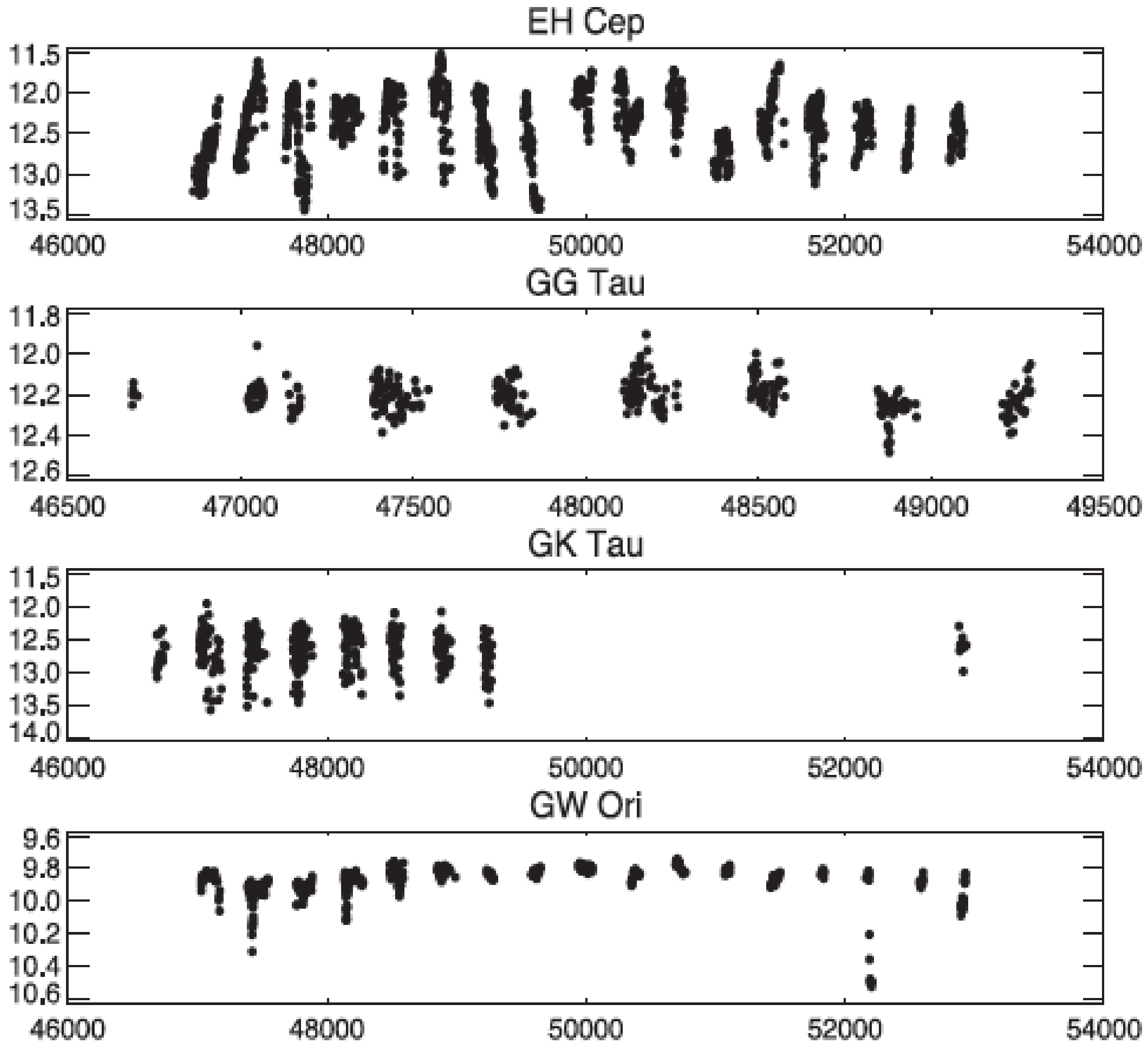
Catala (1989)

The Class II stars

- Main observable characteristics
  - Broad emission lines (T+H)
  - UV, optical excess emission (T)
  - IR excess (T+H)
  - Spectroscopic and photometric variability (T+H)

Photometric variability of CTTS

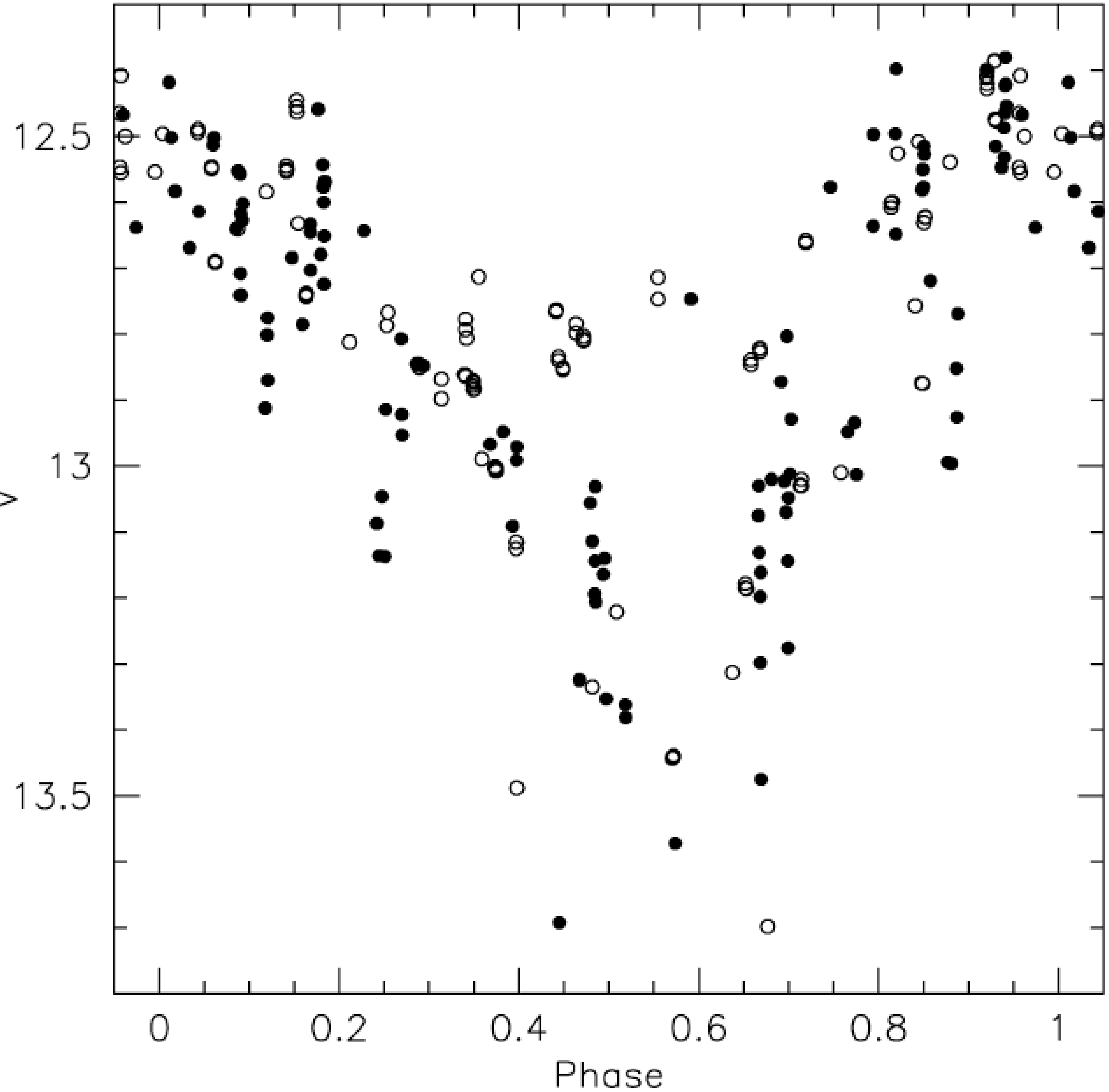
– 0.1 - 2 mag
– Mainly Irregular



Grankin et al. (2007)

Photometric variability of CTTS

- 0.1 - 2 mag
- Mainly Irregular
- Quasi-periodicity:
  - P ~ 1-20 d
  - Variable F_{min}

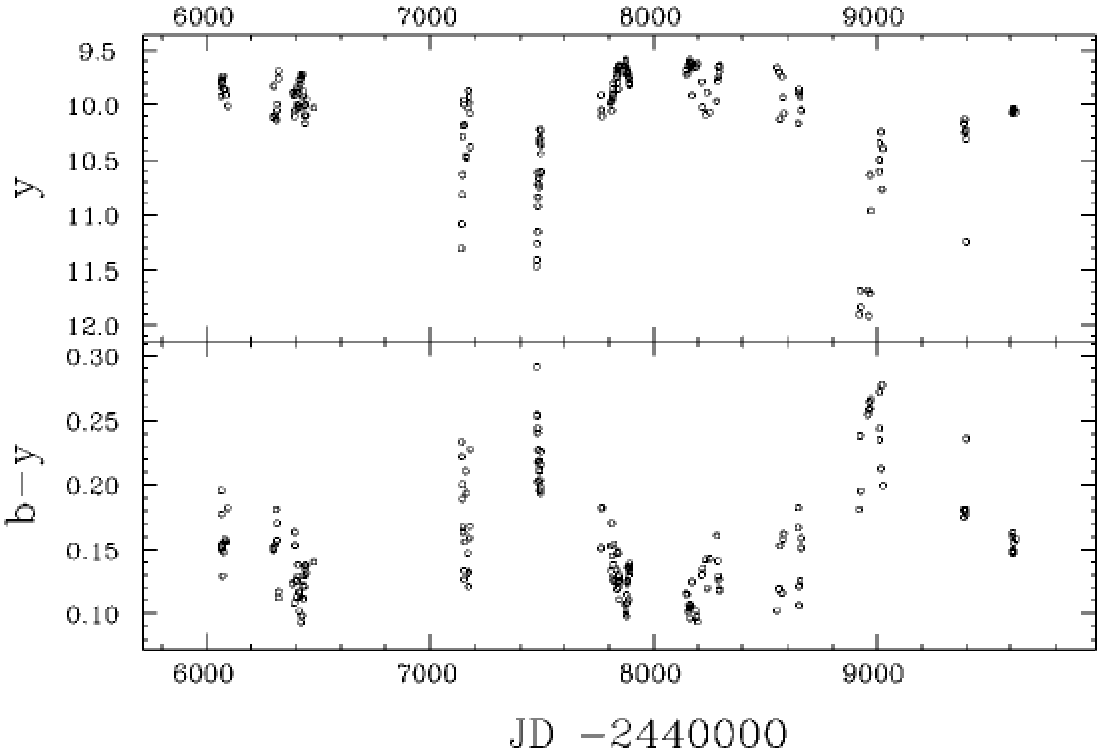


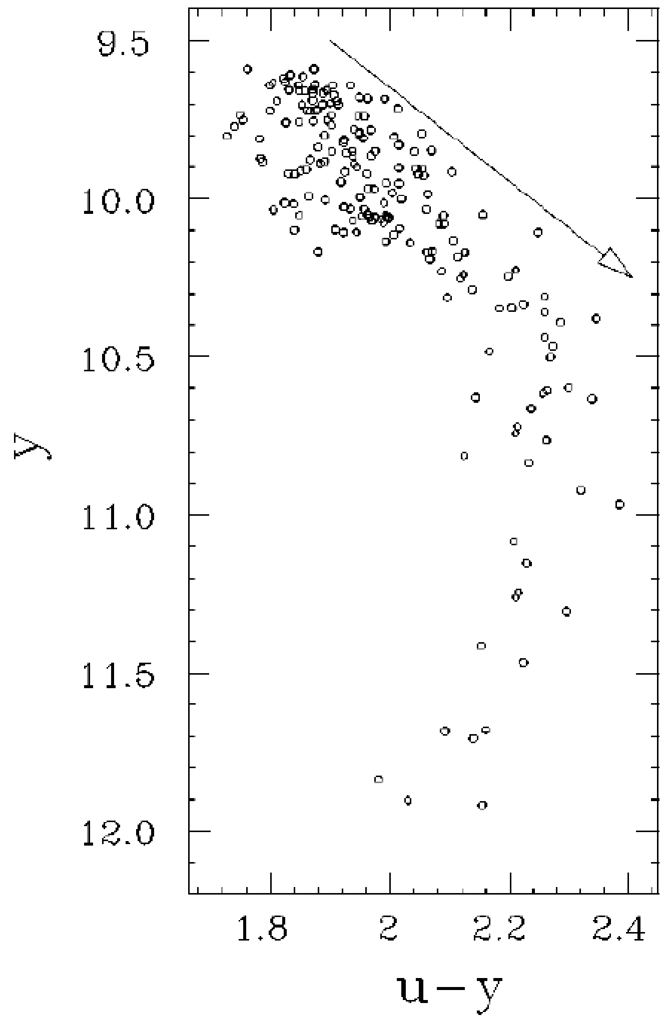
AA Tau

Bouvier et al. (2007)

Photometric Variability of the UXORs

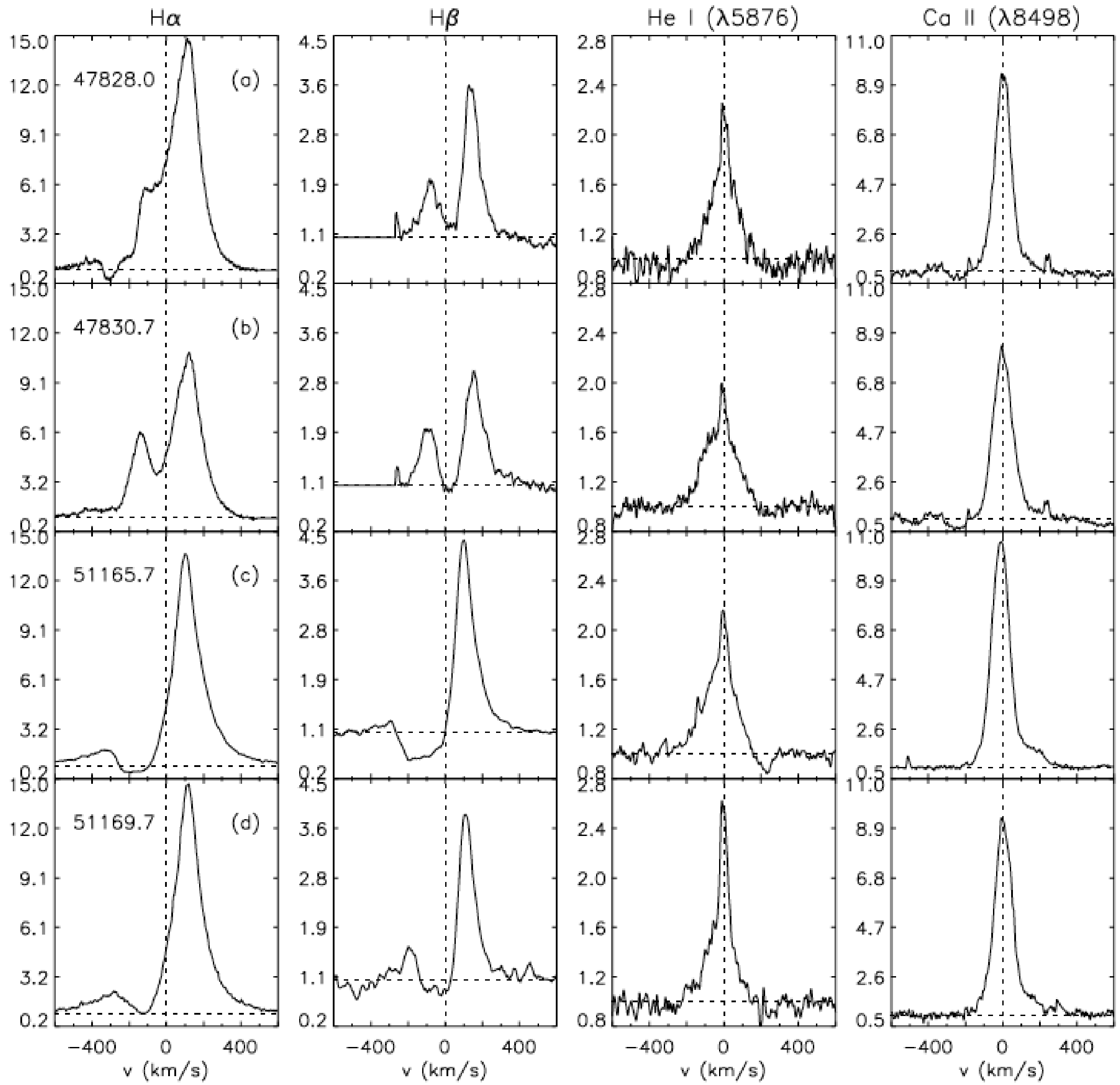
– HAeBe stars: no strong V variability except in UXOR-type stars
– UXORs:
  – Strong drop of luminosity up to 3 mag + blueing effect
  – Only among HAe stars





Sp. variability of CTTS and HAeBe

– Highly-variable emission lines



DR Tau

Alencar et al. (2001)

The Class II stars

- Main observable characteristics
  - Broad emission lines (T+H)
  - UV, optical excess emission (T)
  - IR excess (T+H)
  - Spectroscopic and photometric variability (T+H)

	CTTS	HAeBe
Magnetic fields	In many CTTS Small-scale structure B ~ kG	In ~5% HAeBes Large-scale structure B ~ kG
X-rays	In many CTTS Highly variable with flares Hard spectrum Lx ~10^{28} - 10^{32} erg/s L_X/L_{bol} ~ 10^{-5} - 10^{-3}	In 3 HAe Slowly variables, no flares Soft spectrum Lx ~10^{29} - 10^{30} erg/s L_X/L_{bol} ~ 10^{-6} - 10^{-5}

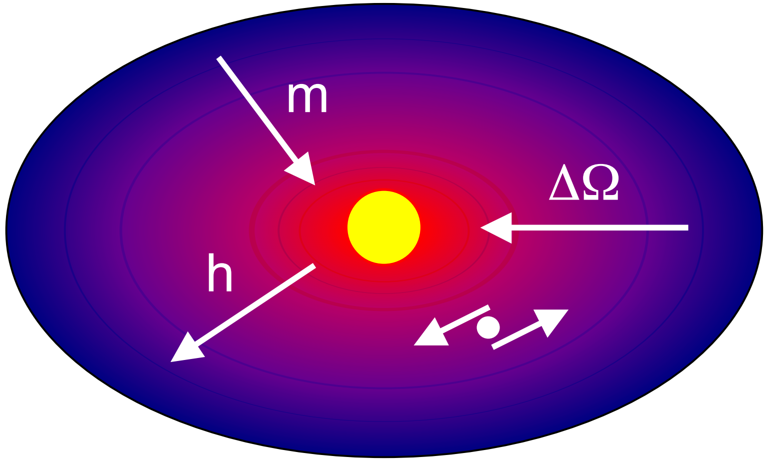
Refs: e.g. Hernandez et al. (2007), Johns-Krull et al. (1999), Alecian et al. (2009), Testa et al. (2008)

2. Why an accretion disk ?

Accretion disk

- Rotating molecular cloud contraction
  => Protostar + Keplerian disk
- $\Omega = (GM/R^3)^{1/2}$
- Shearing + conservation of the AM
  => AM is transported outward
  => M is transported inward
  => accretion

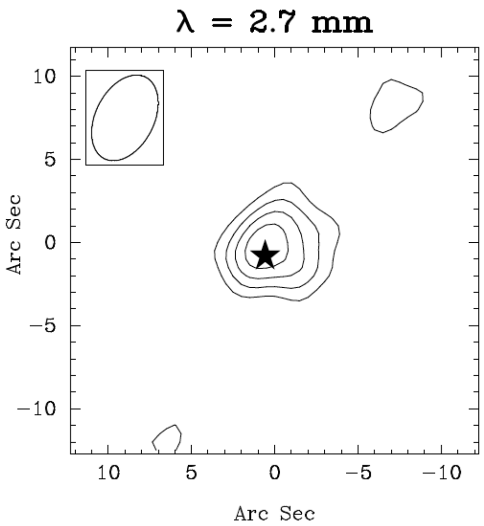
The accretion disk

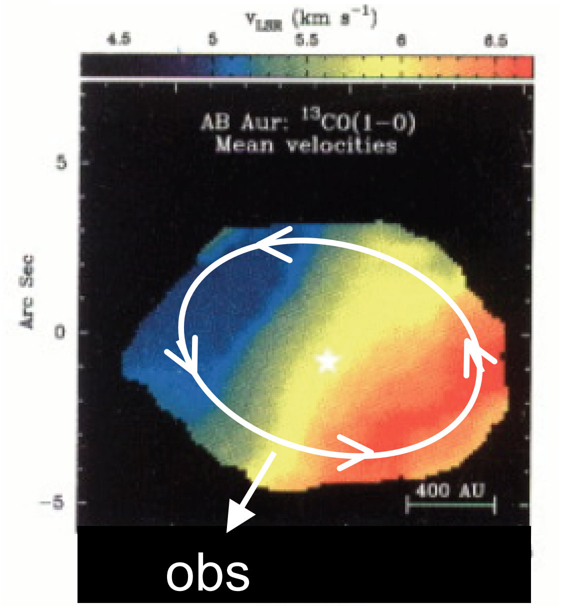


Lynden-Bell & Pringle (1974)

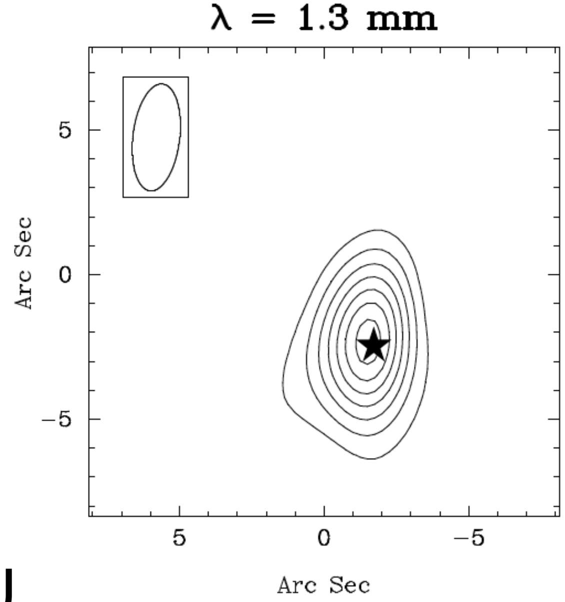
Keplerian molecular disks

AB Aur





HD 163296



OVRO millimeter
continuum contours

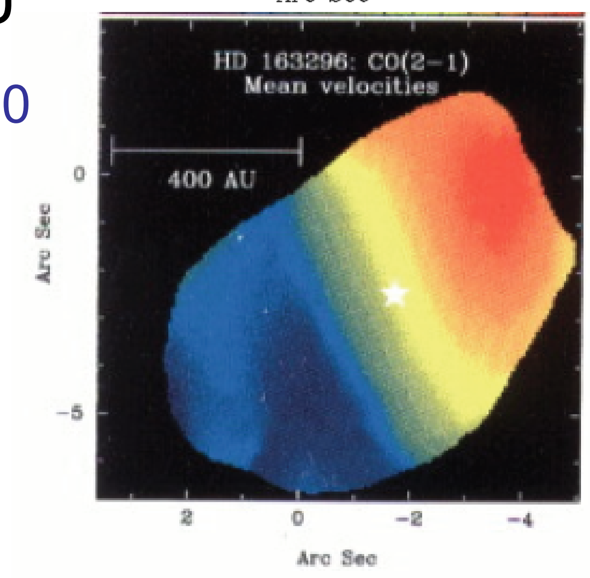
-Elongated structure

-Keplerian rotation

-Scales from 85 to 700 AU

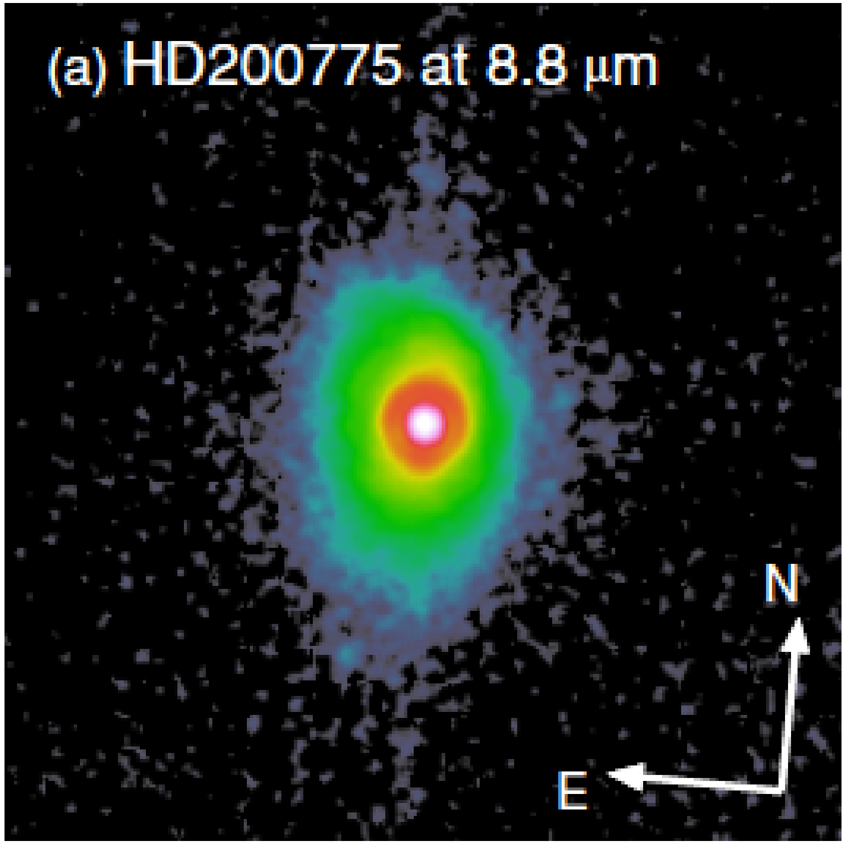
Mannings & Sargent 1997, 2000

Velocity structure



Hot disk - direct detection

- Coronography
- Adaptive Optic
- Interferometry
- IR Imagery



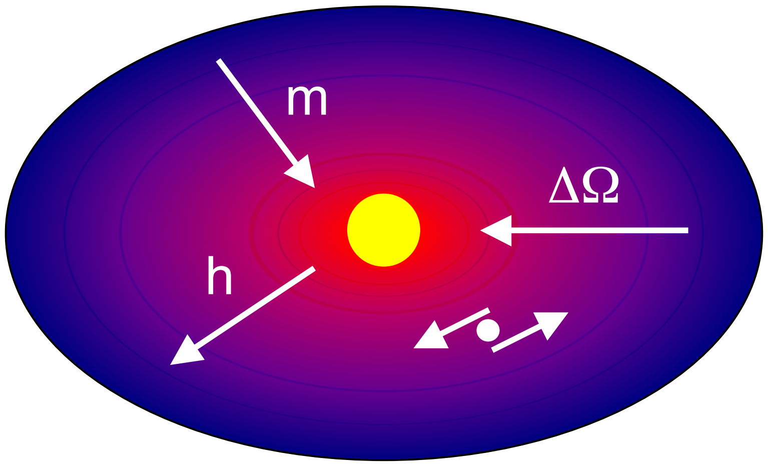
HD 200775 (HBe)

Okamoto et al. 2009

Accretion disk

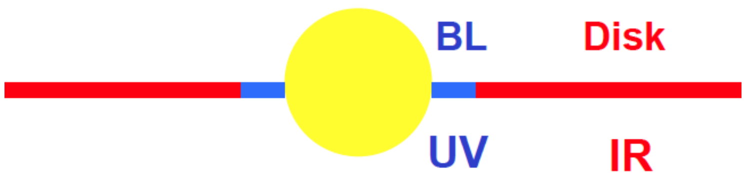
- Rotating molecular cloud contraction
  => Protostar + Keplerian disk
- $\Omega = (GM/R^3)^{1/2}$
- Shearing + conservation of the AM
  => AM is transported outward
  => M is transported inward
  => accretion

The accretion disk



- Boundary layer model:
  - Viscous dissipation in disk
    => IR excess
  - Shear equatorial boundary layer
    => UV emission

The boundary layer model

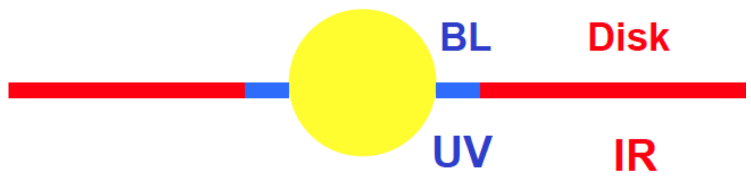


© *S. Alencar*

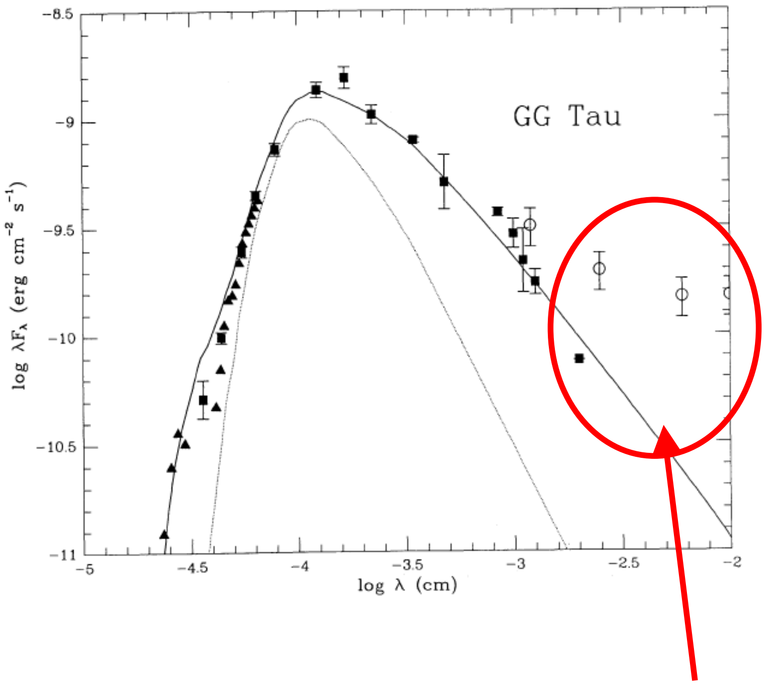
Lynden-Bell & Pringle (1974)

The boundary layer vs observations

- Flat disk
- Viscous dissipation in the disk
- Lost of kinetic energy in the boundary layer



© *S. Alencar*



Star	Sp. Type	A_v	$R_*/R_\odot$	$\dot{M}/M_\odot\ yr^{-1}$	$M_*/M_\odot$	i^0
BP Tau	K7	0.4	3.0	2×10^{-7}	0.8	80
DF Tau	M0	1.2	3.8	3.5×10^{-7}	0.8	65
				$6.5^{a} \times 10^{-7}$		
GG Tau	K7	1.1	3.5	4×10^{-7}	0.8	75
DS Tau	K4	0.6	1.8	6.5×10^{-8}	1.0	75
SU Aur	G2	0.45	3.1	6×10^{-8}	2.0	40

Bertout et al. (1988)

3. The disk structure

The flared disk

– Hydrostatic equilibrium:

⇒ flared disk
$H_d(R) = H_0(R/R_*)^{9/8}$
$H_0 \sim 0.05 - 0.1\ R_*$

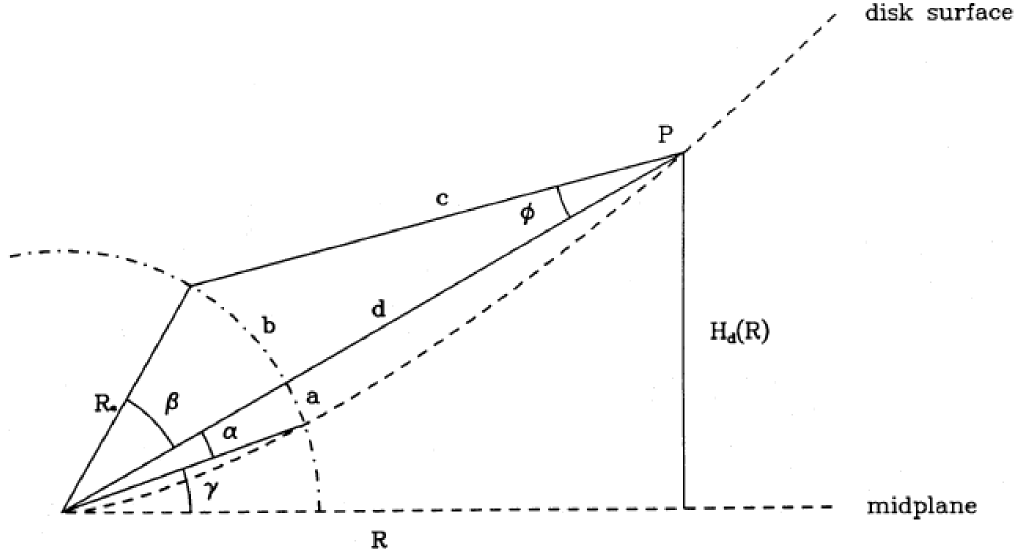
⇒ 50% L_* reprocessed

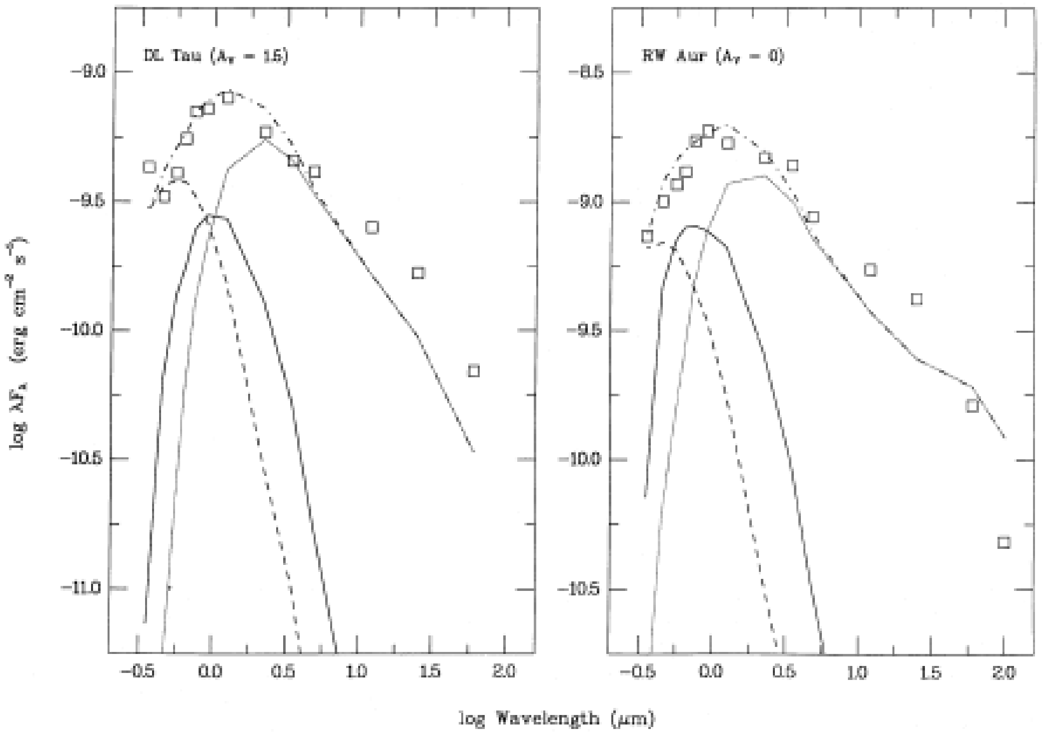
– Dust + gas well mixed and thermally coupled

⇒Main source heating: stellar radiation

– Passive disk (no accretion)

– Fits the SED of CTTS

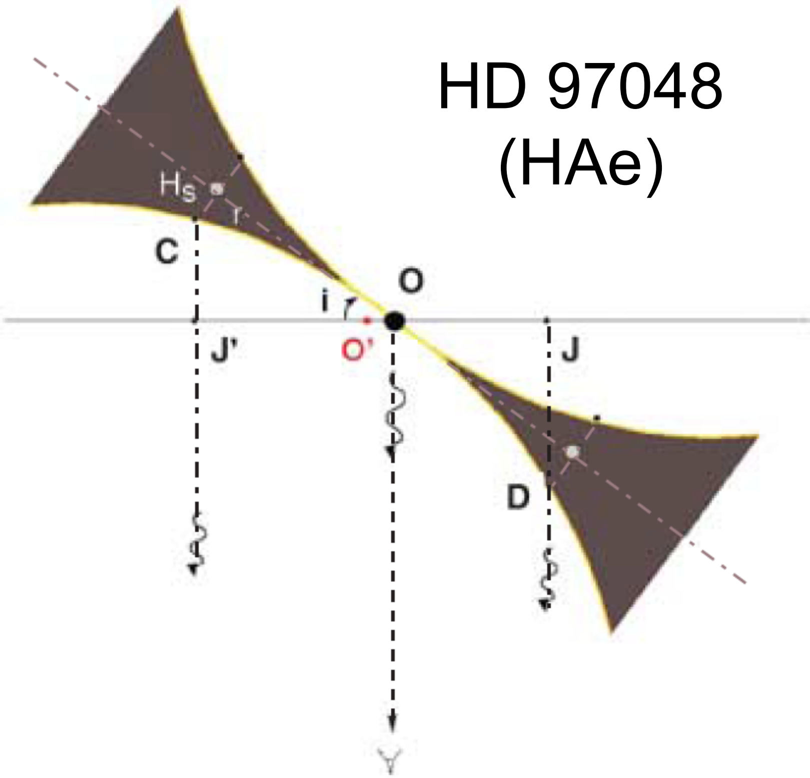




Kenyon & Hartmann (1987)

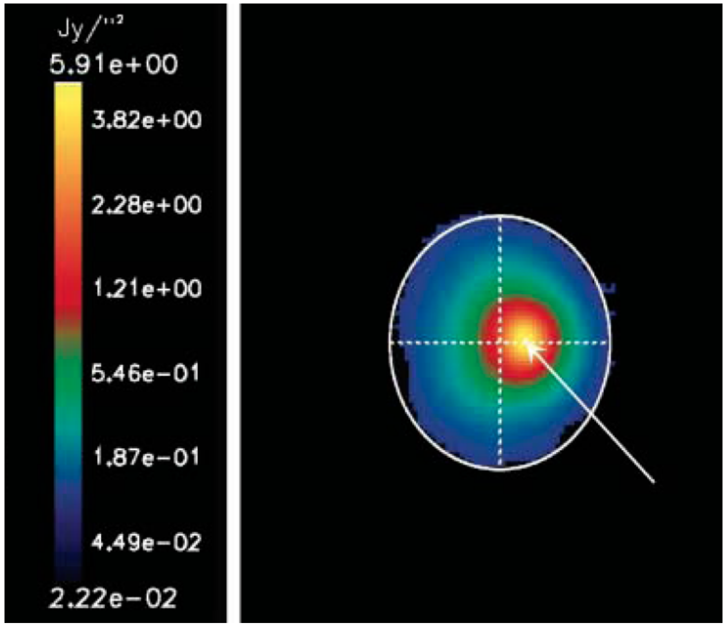
The flared disk

- Lagage et al. 2006, flared disk observed by the offset of the brightness center and the geometrical center



HD 97048 (HAe)

VISIR (VLT) - IR-interferometry

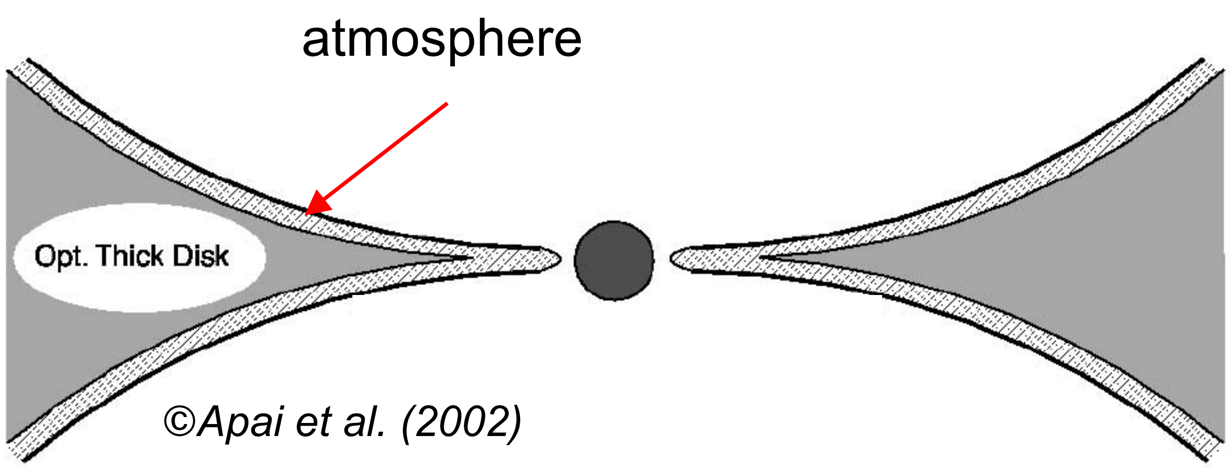


Also for HD 200775 (HBe), Okamoto et al. 2009, but flatter than HD 97048

Confirmed also by IR-polarimetry (Hales et al. 2006)

The two layer model

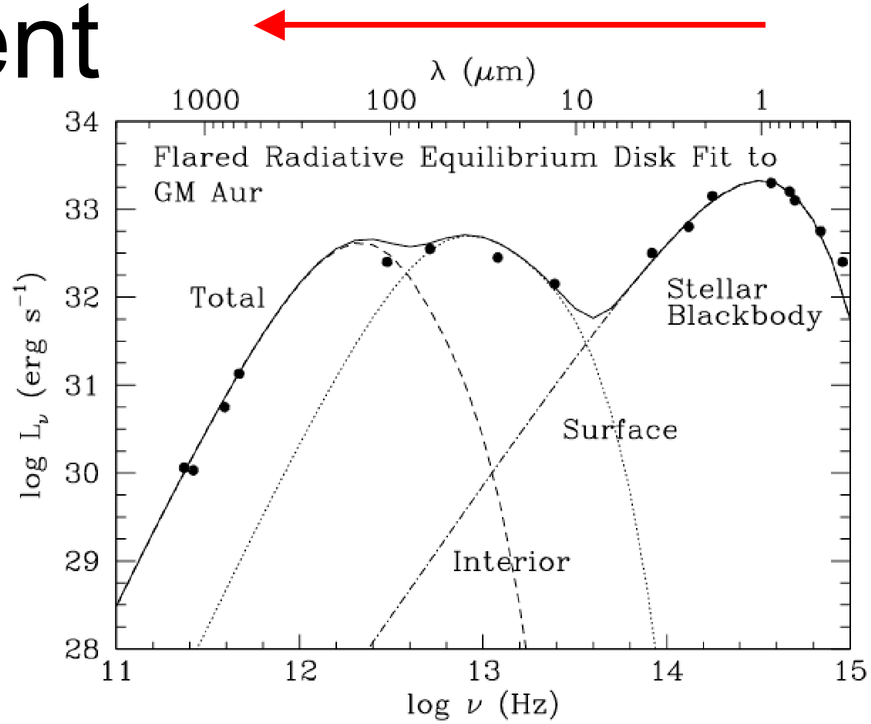
- Steady, viscous, geometrically thin, optically thick flared accretion disk
- Outer layers form an atmosphere
- Irradiation from the central star:
  - A fraction of it is reemitted as a black body
  - The other fraction is scattered
- T(atm) from:
  - the viscous energy interior
  - the stellar flux absorbed as it travels down the atmosphere
- Conspicuous features: H_2O, CO, TiO, silicate feature at 10 μm => determine the flaring, the mass accretion rate
- Need of high-resolution IR spectra

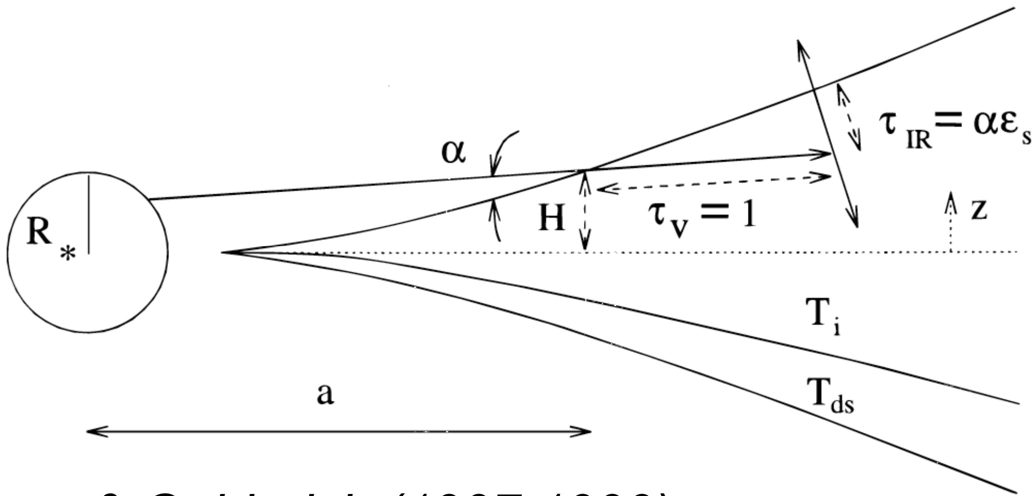


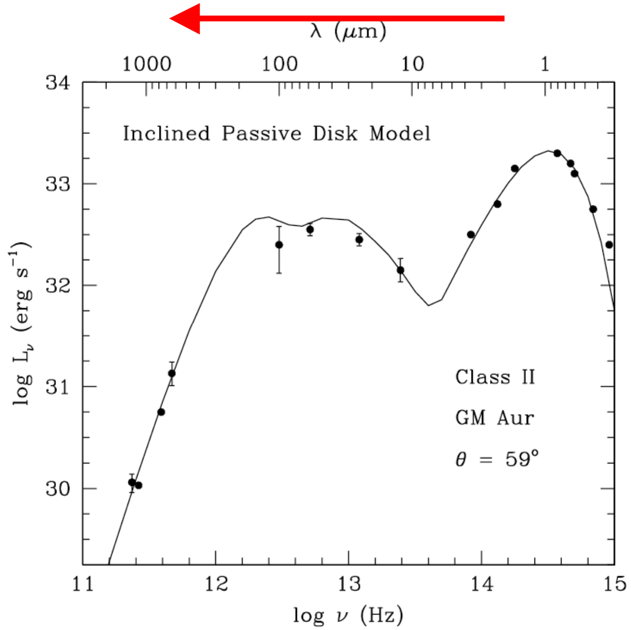
Calvet et al. (1991,1992)

The gap requirement

– Passive disk in hydrostatic and radiative equilibrium
– Stellar radiation strikes the surface
– The dust in the surface is superheated
– Half of it is reemitted as a black body
– The other half heat the interior
– Inner gap of few AU



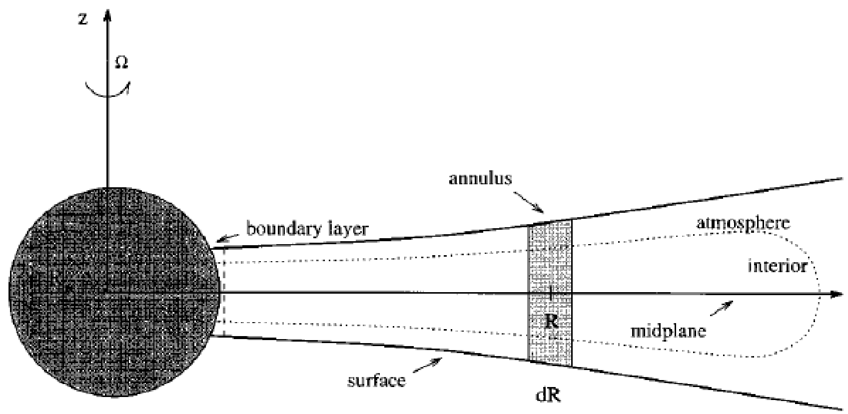


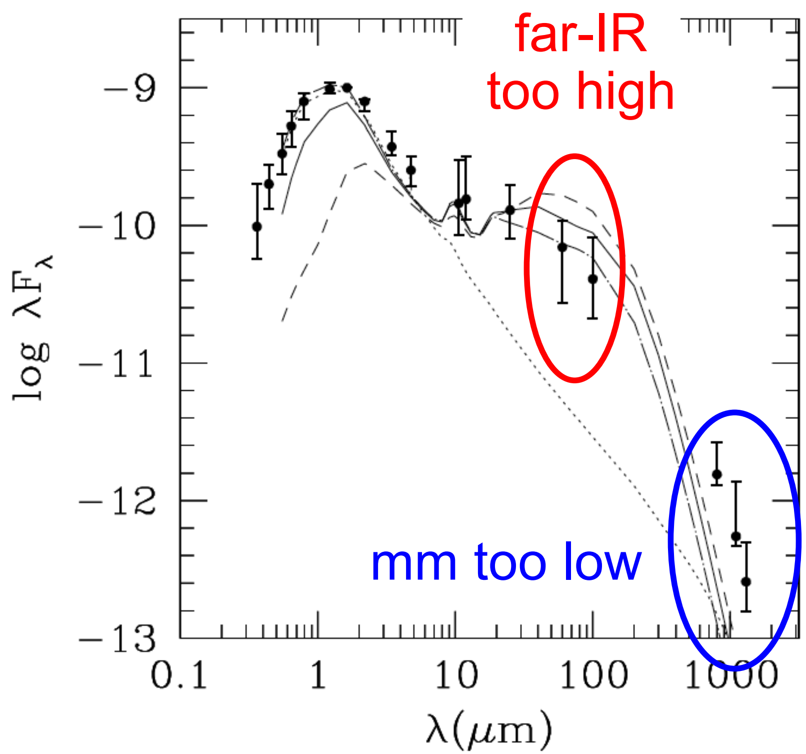


Chiang & Goldreich (1997,1999)

Evidence of grain growth

- Disk steady and optically thin
- Main heating sources: viscous dissipation and irradiation from the star + cosmic rays + radioactive decay
- => Irradiation is the main heating agent except in the innermost regions (< 2 AU)
- Gas and dust disk are well-mixed and thermally coupled
- Models too geometrically thick at large radii => dust settling





D'Alessio et al. (1998,1999)

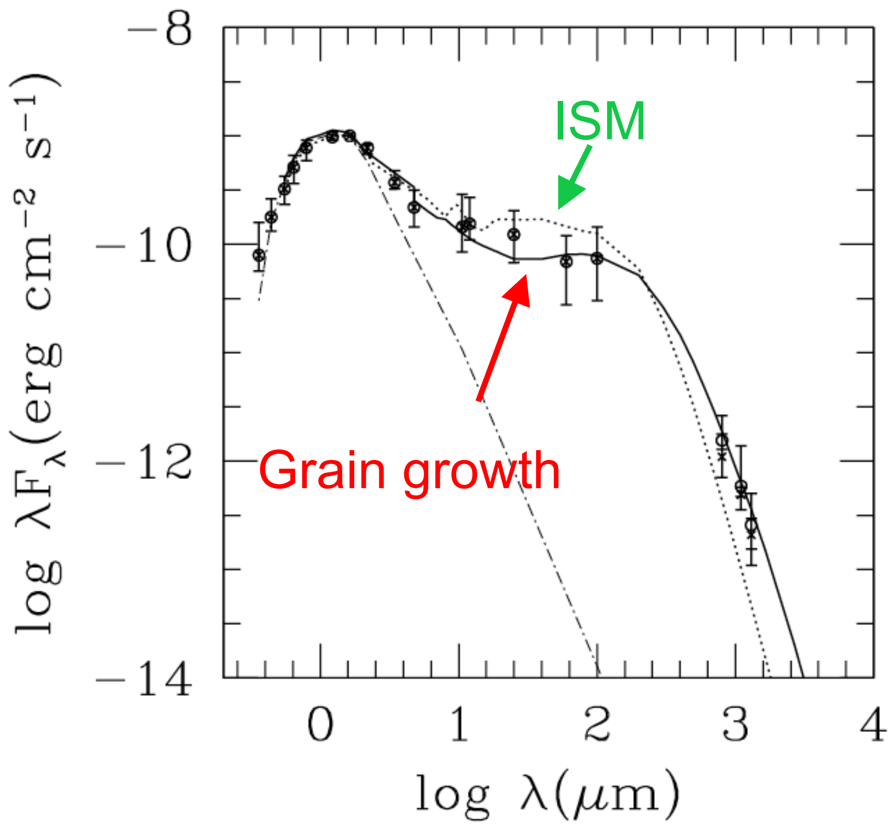
Evidence of grain growth

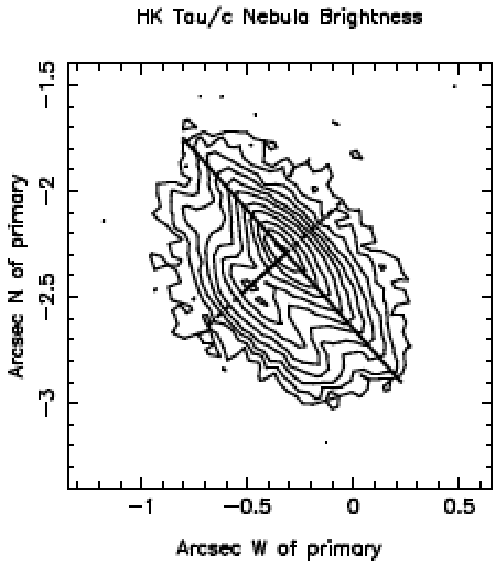
Power law distribution : $n(a) = n_0 a^{-p}$

Max size ~ 1 mm, p ~ 2.3 - 3.5

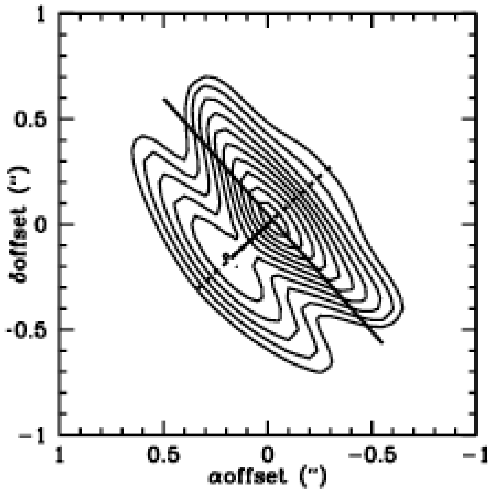
⇒median + quartile in Taurus reproduced

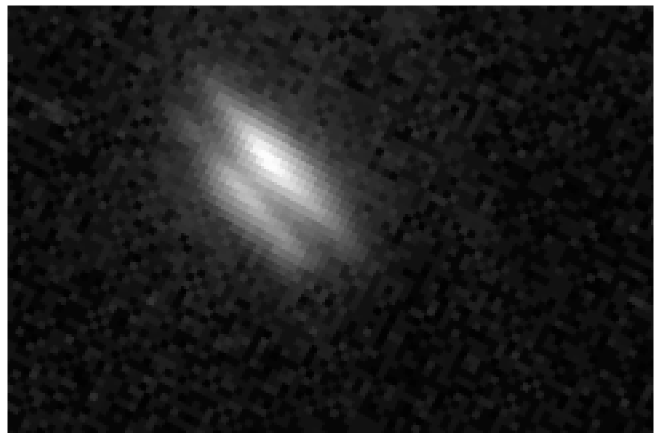
⇒HST image of HK Tau/c reproduced





HK Tau/c

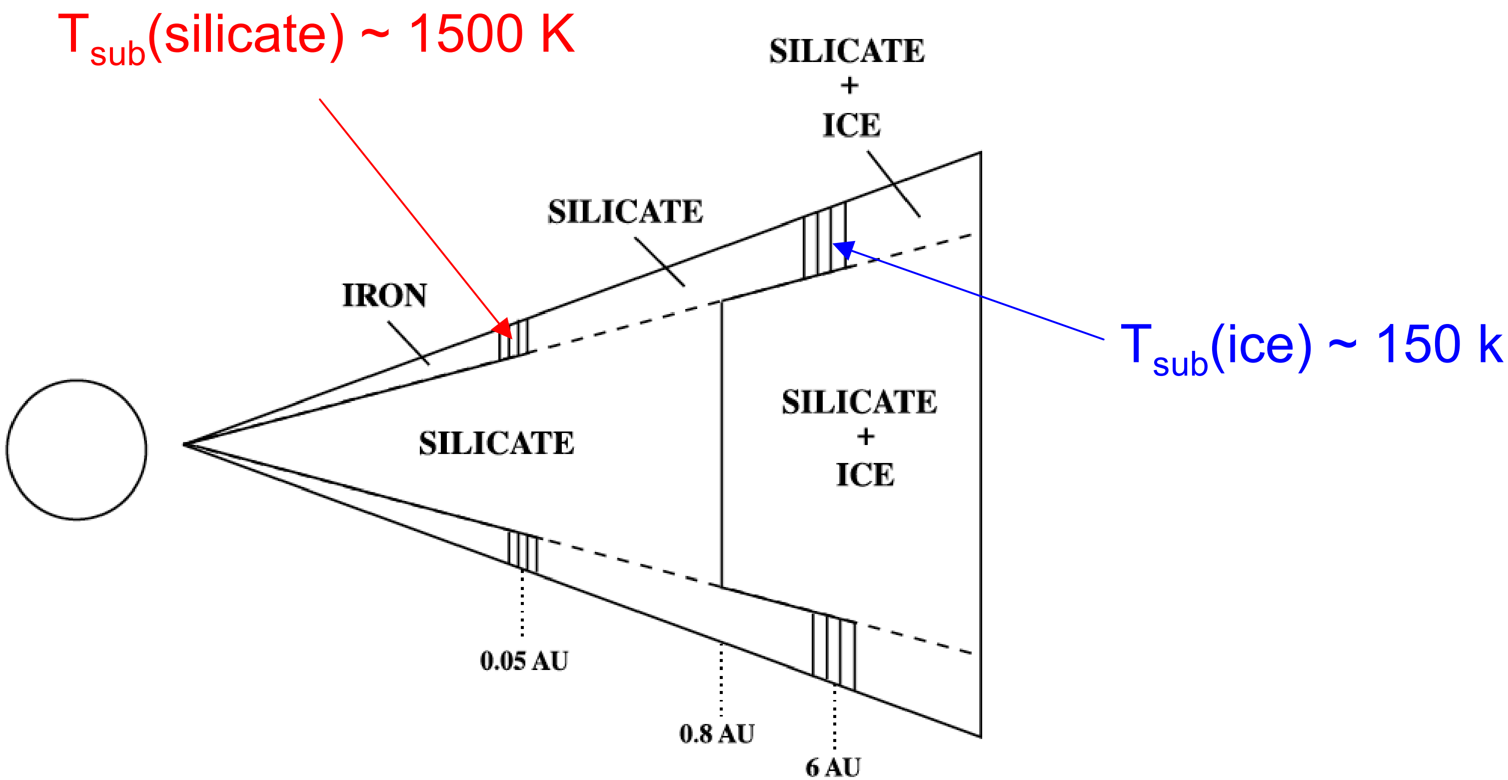




D'Alessio et al. (2001)

Dust composition

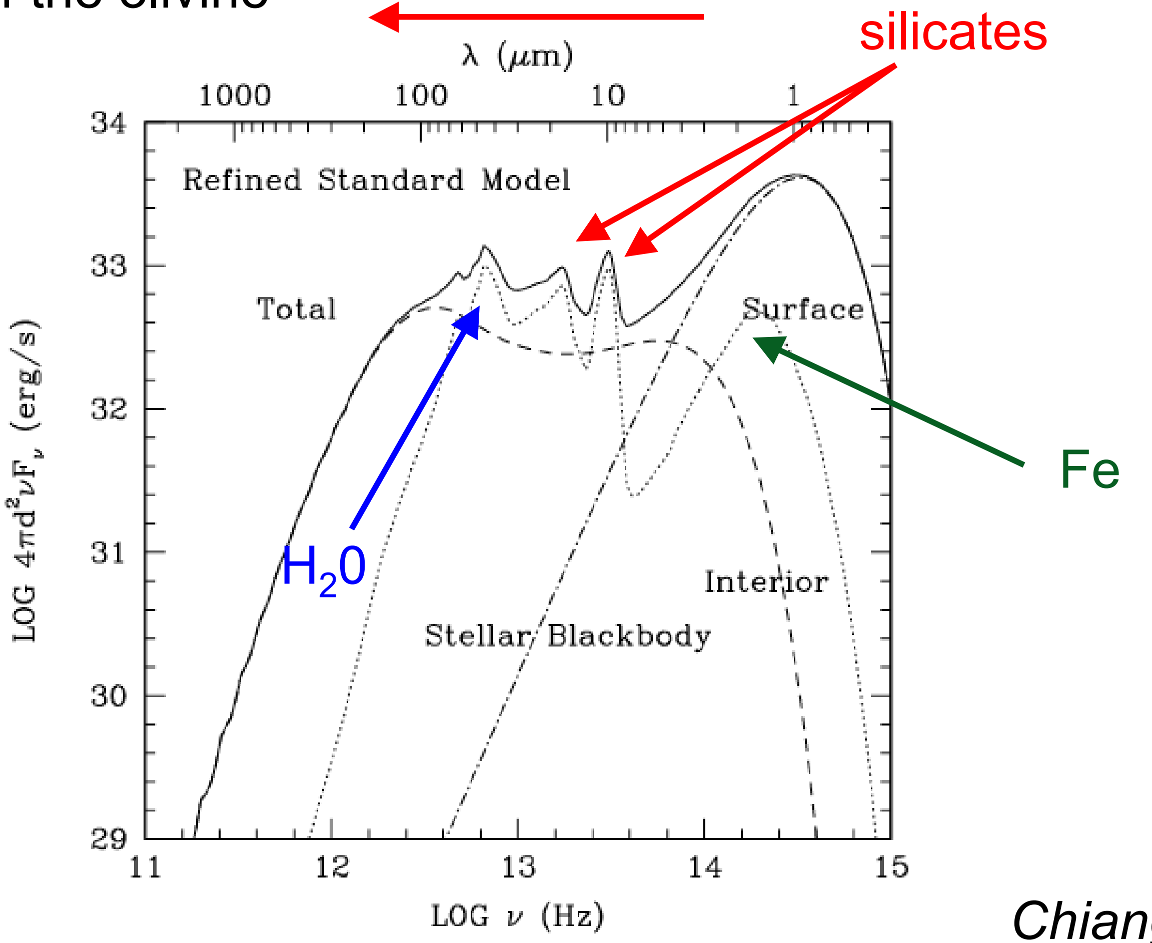
- Radiative, hydrostatic equilibrium models of passive circumstellar disks
- An account for particle sizes



Chiang et al. (2001)

Dust composition

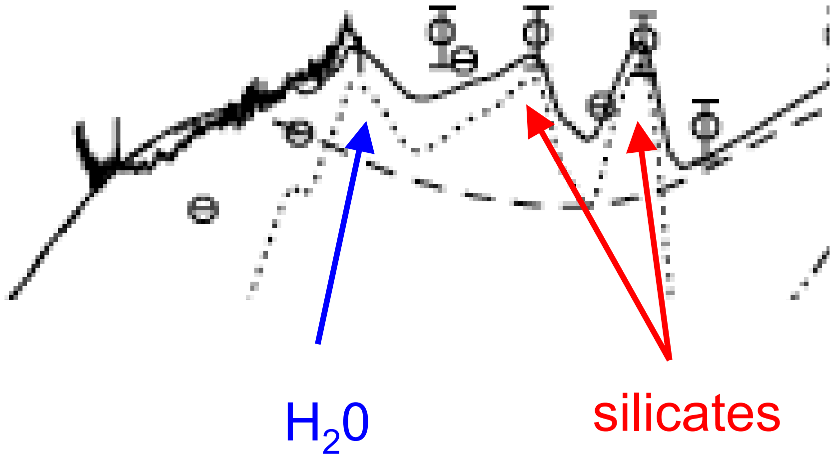
– No ice in disk within 6 AU (< 10 μm)
– No emission within 2 - 8 μm(silicates have r < 1 μm and therefore transparent)
– Emission around 1.5 μm arises from pure iron particles, and iron impurities of the olivine

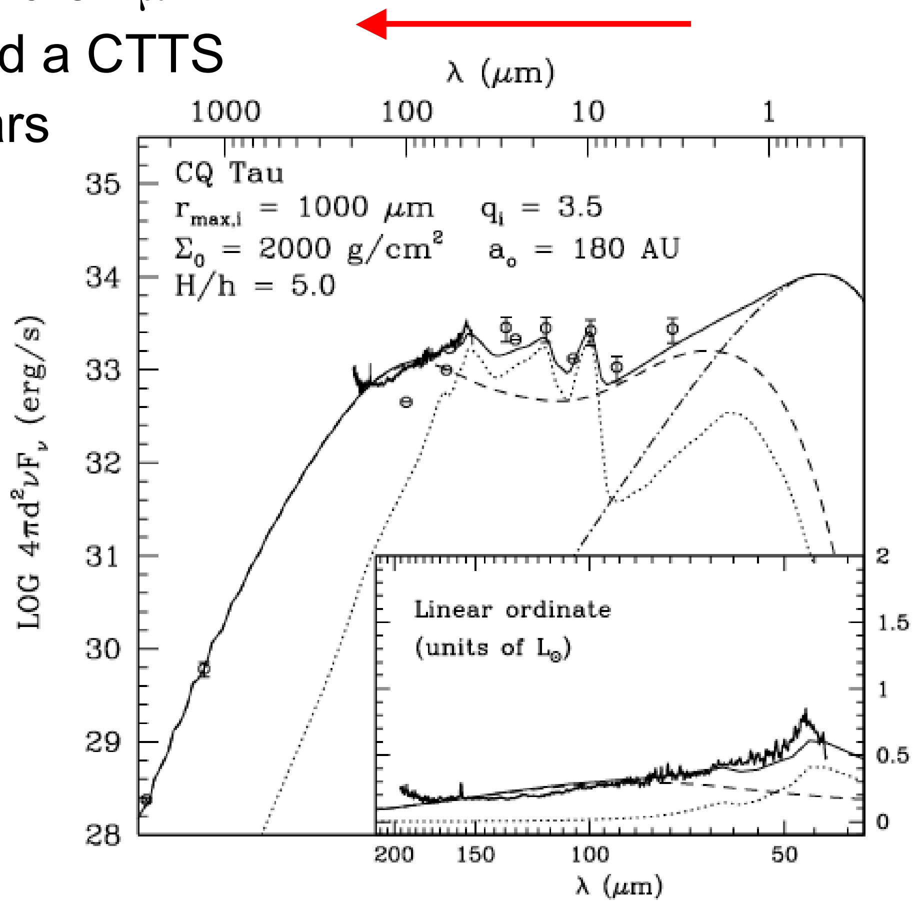


Chiang et al. (2001)

Dust composition

- ISO spectra (LWS) + IRAS + ground photometry of HAe and CTTS
- Prediction and detection of
  - vibrational modes in silicate at 10 μm and 18 μm
  - Transitional modes at 45 μm and 62 μm
- Water detected in one HAe (F3) and a CTTS
- No water in the two hottest HAe stars

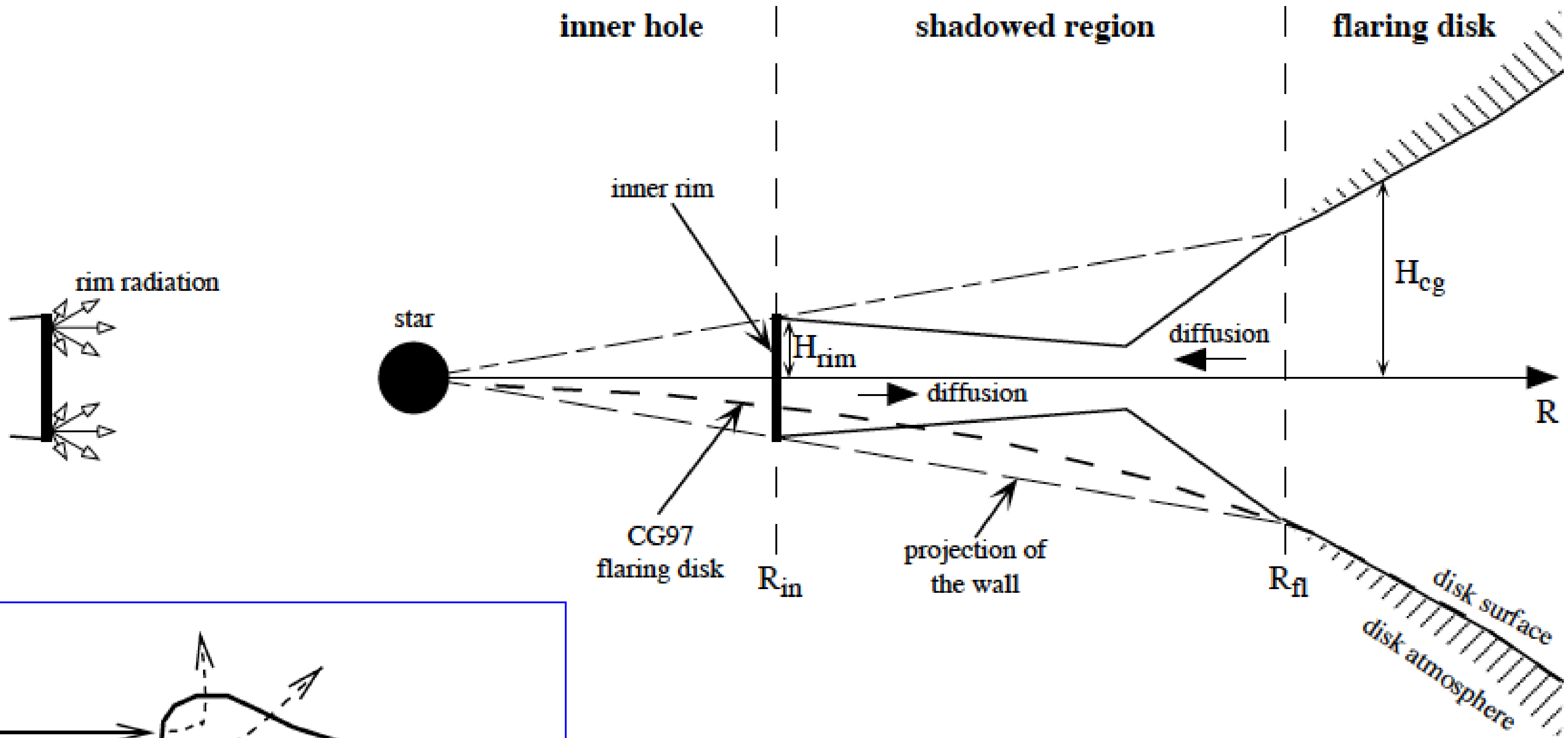


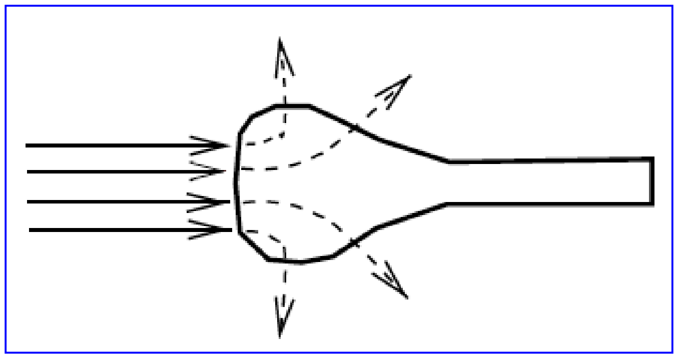


Chiang et al. (2001)

The puffed-up inner rim

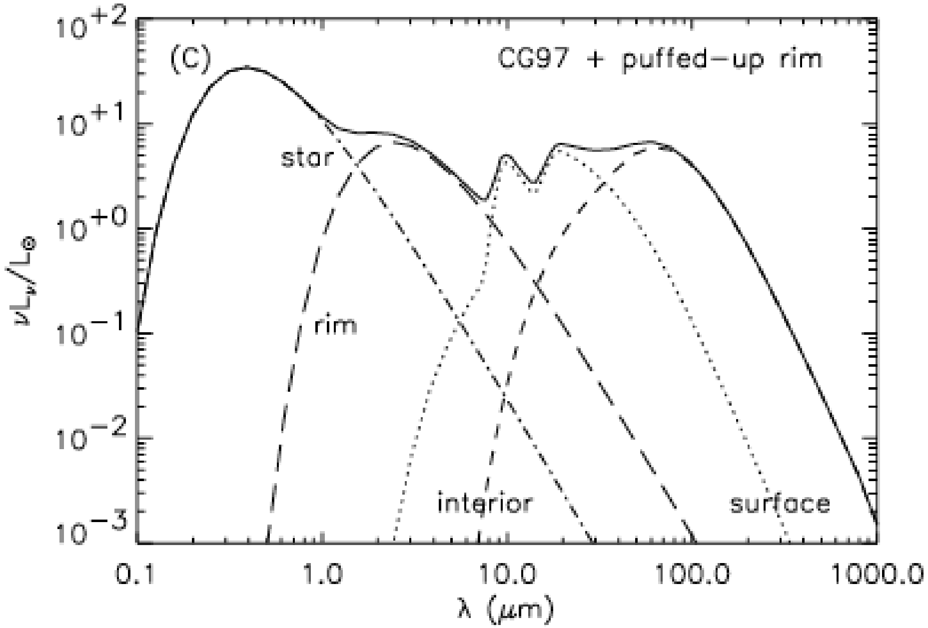
- Dusk truncated by dust evaporation
- Direct illumination of the inner rim => hotter than the flaring disk

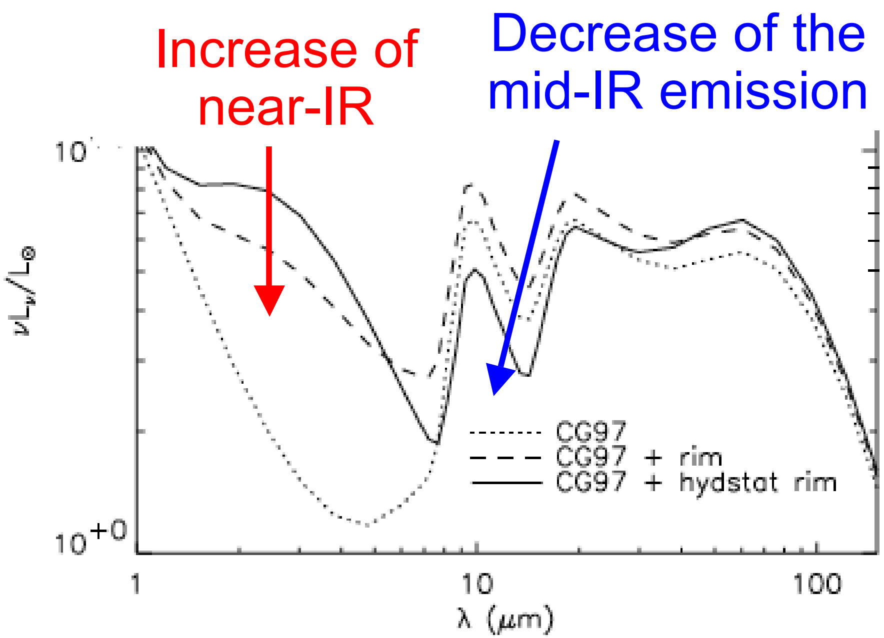


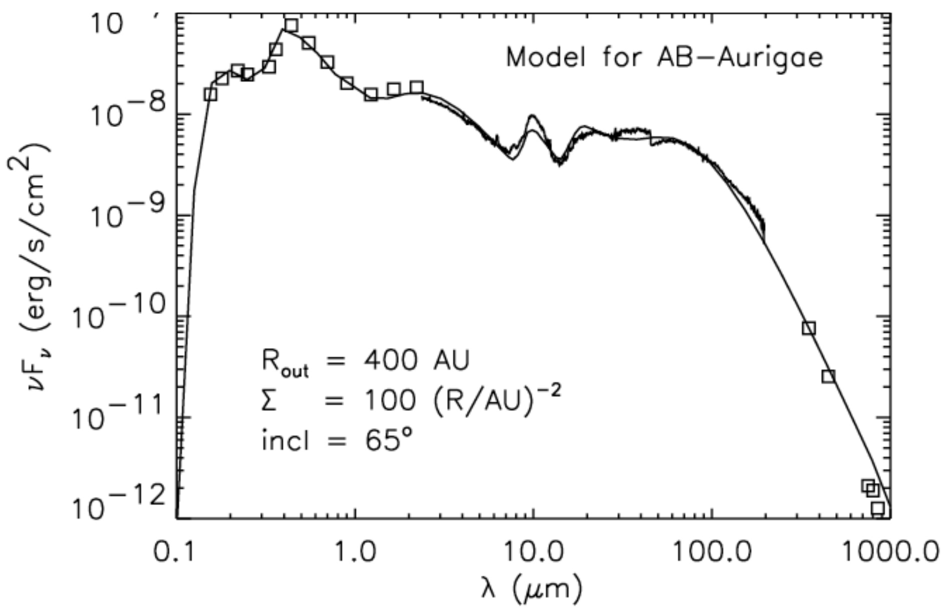


Dullemond et al. (2001,2002)

The puffed-up inner rim (HAe stars)





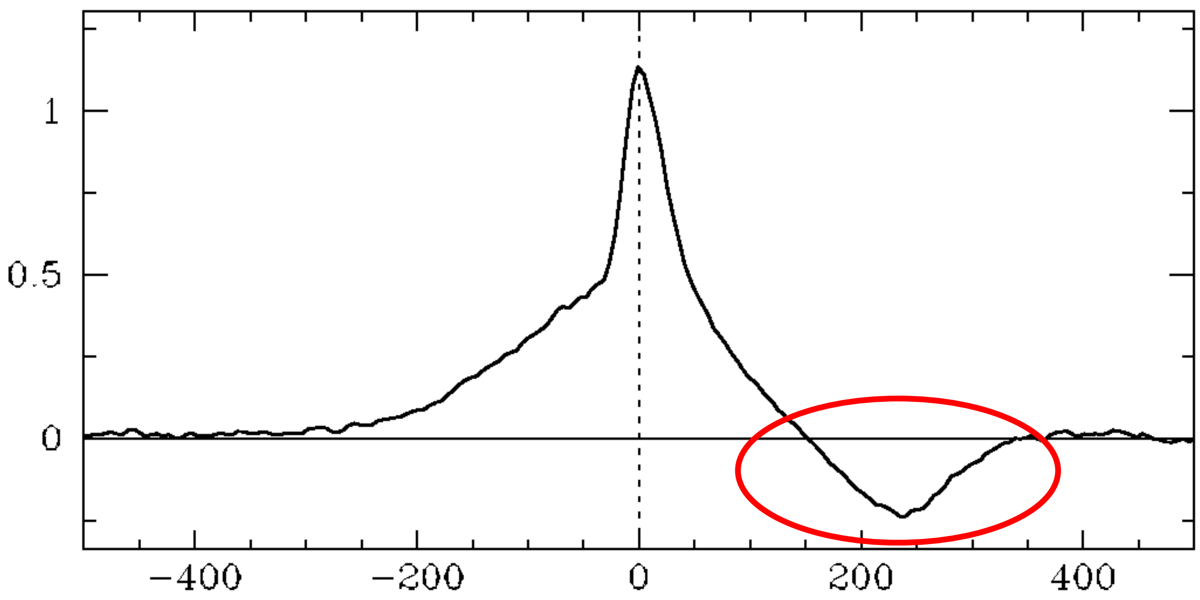


Puffed-up rim if the inner part of the disk is optically thin => observed inner holes (e.g. Grady et al. 2005, Monnier et al. 2005), and low mass accretion rate (Garcia Lopez et al. 2006) agree

Dullemond et al. (2001,2002)

The inner part of the CTTS disks

- Dullemond et al. (2001, 2002) => puffed-up inner rim for HAeBes
- Require optically thin inner gap
- In the case of CTTS: strong accretion to high-velocity ~ ff-velocity => magnetospheric accretion

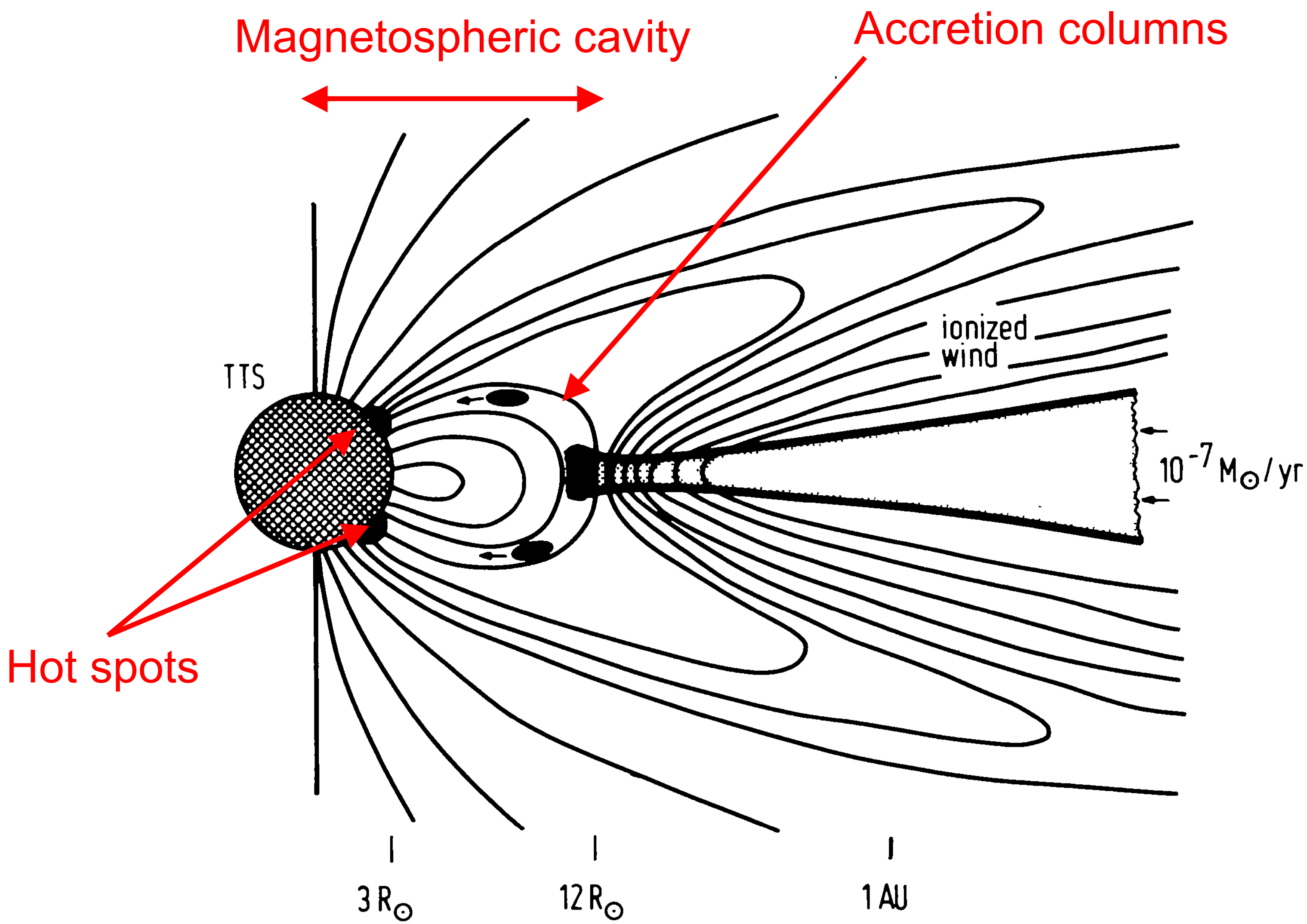


He I 5875

DR Tau

Edwards (1997)

Magnetospheric accretion in CTTS

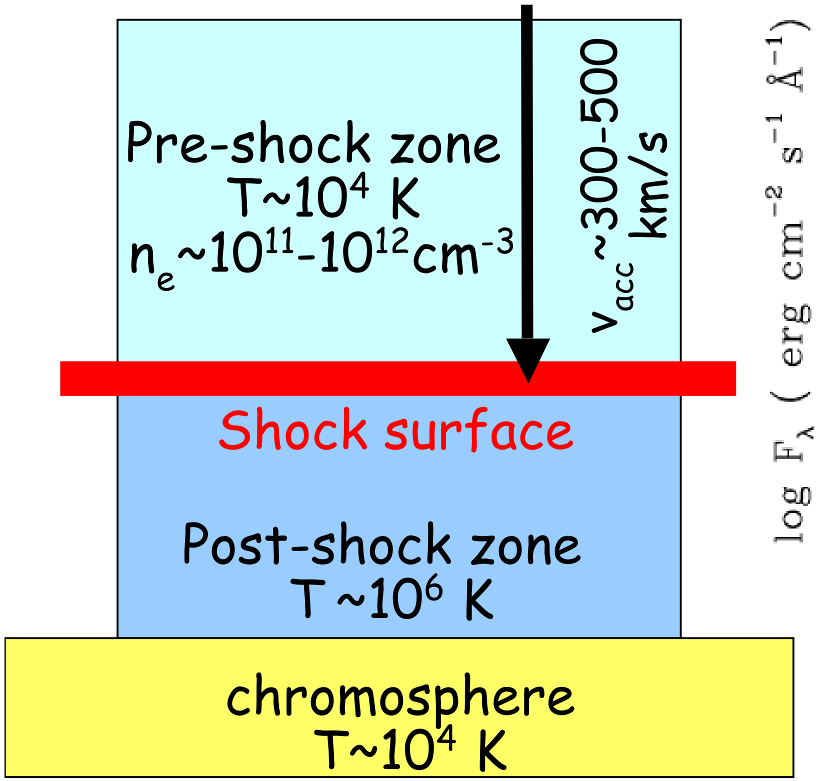


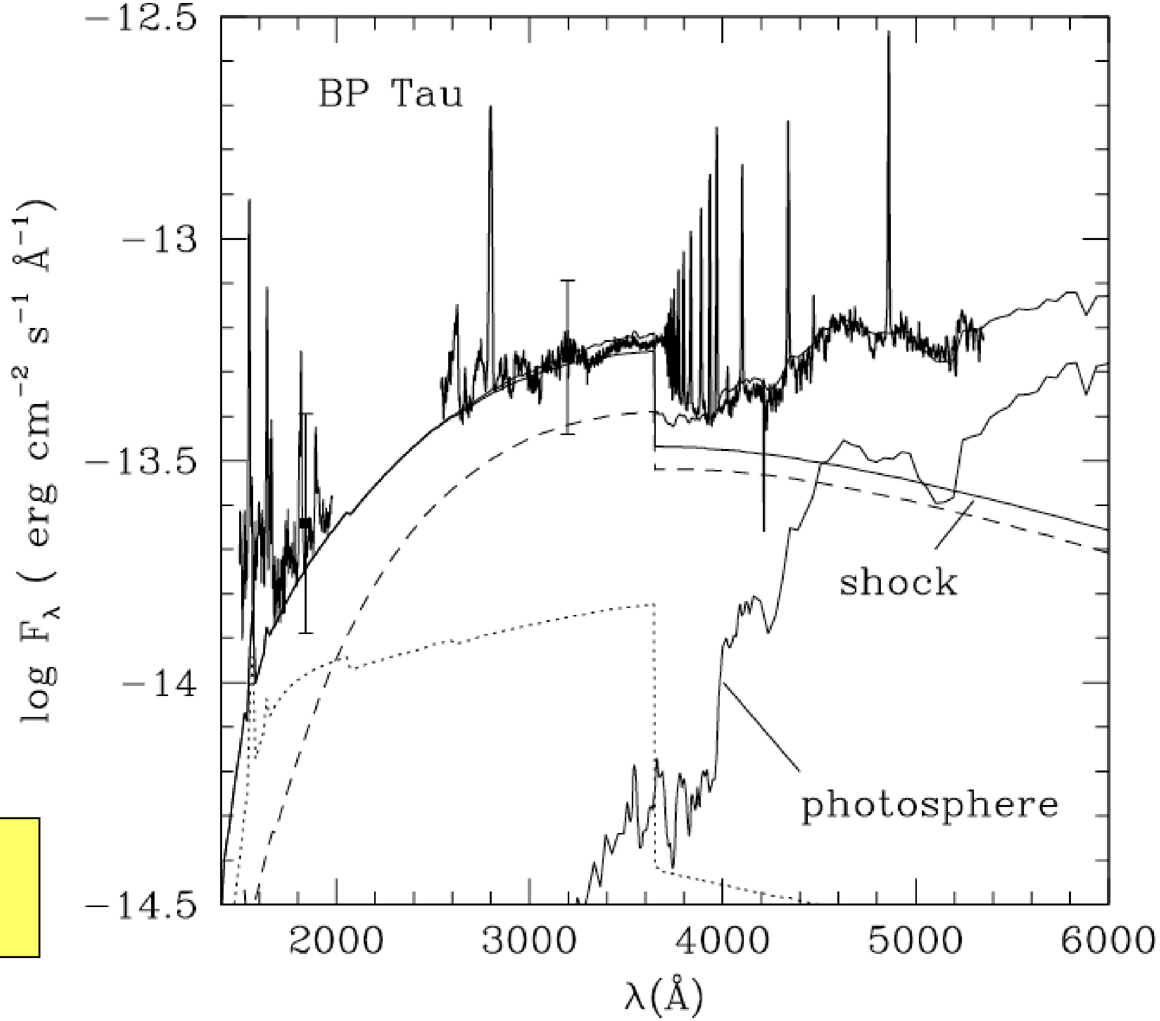
See also, e.g., Konigl (1991), Muzerolle et al. (2001)

Camenzind (1990)

Accretion shock models

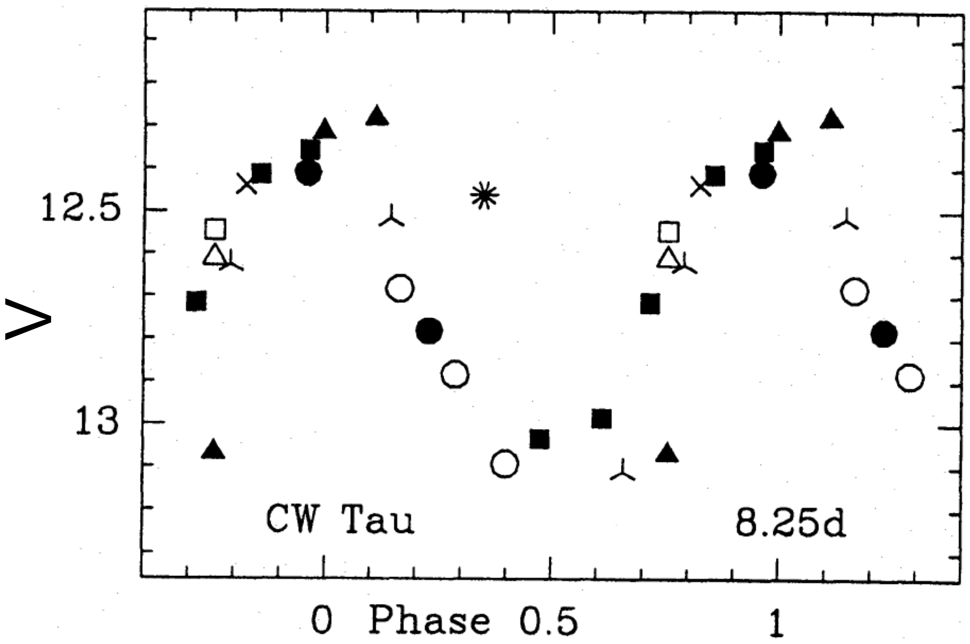
Shock emission =
postshock +
preshock +
heated photosphere



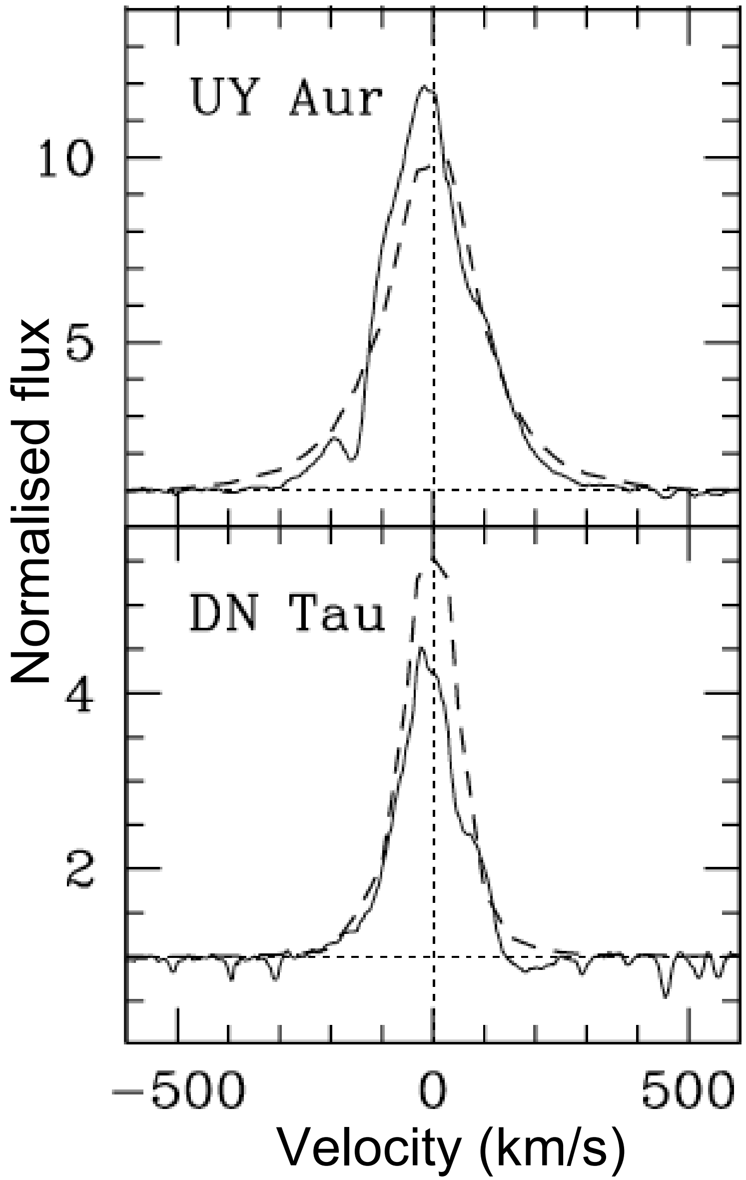


Calvet & Gullbring (1998), Gullbring et al. 2000

Rotational modulations + Magnetsopheric accretion models

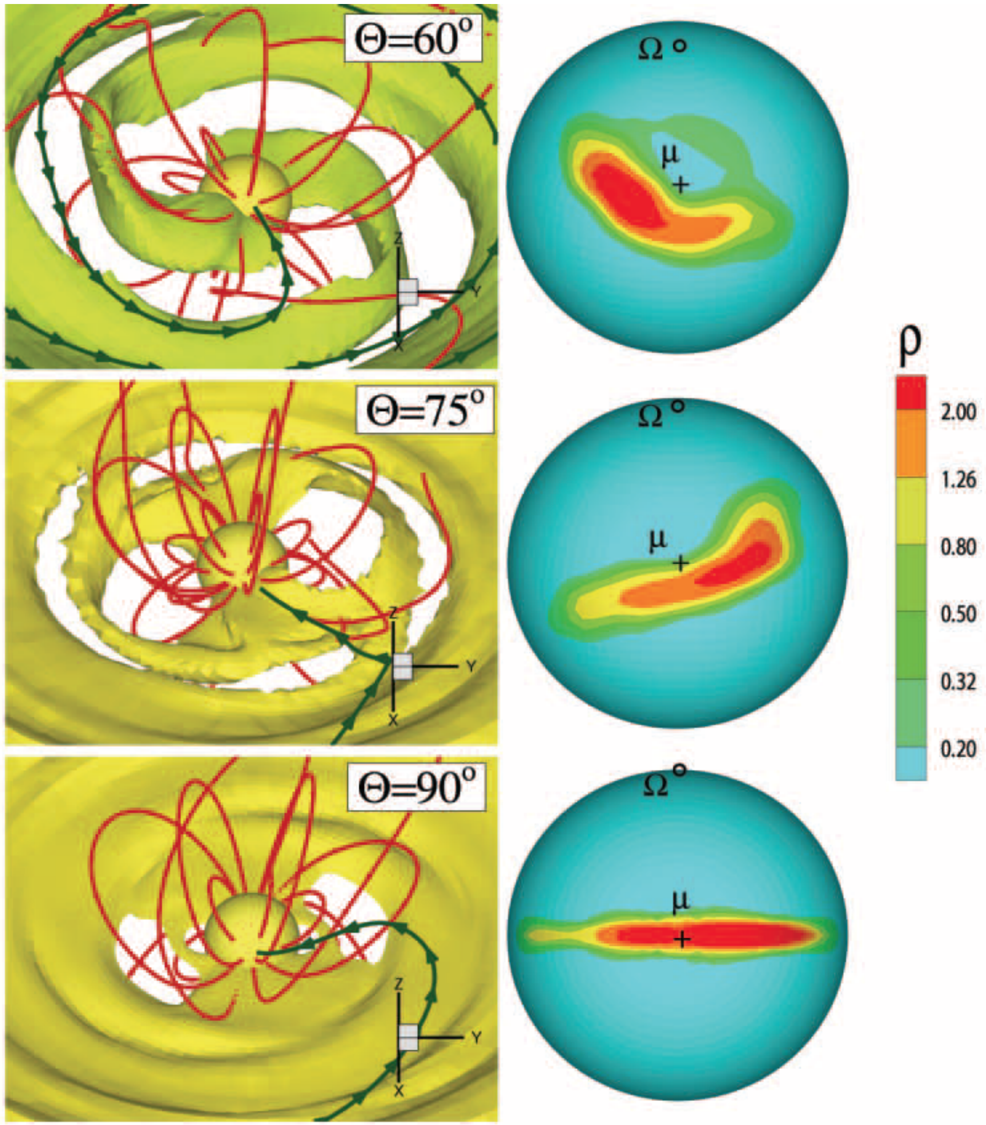


Bouvier et al. (1995)



Muzerolle et al. (2001)

3D models of magnetospheric accretion

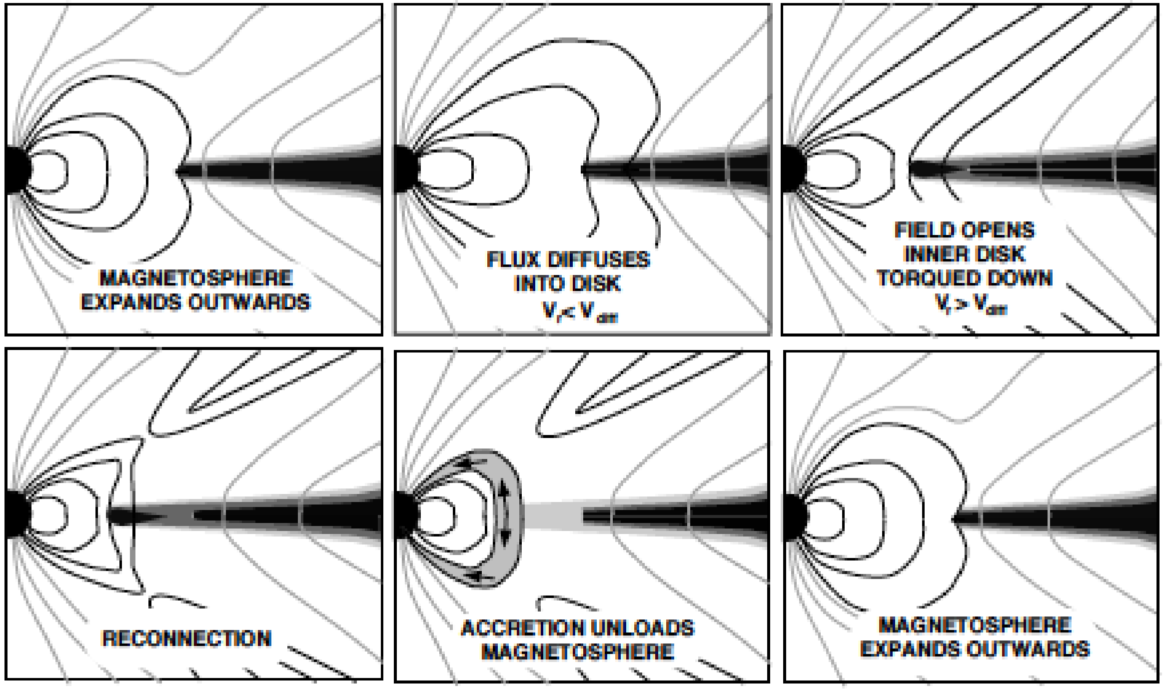


Accretion occurs through two or more funnel streams

Shape and characteristics of the spots reflects those of the funnel streams

Romanova et al. (2004)

A dynamical interaction between the disk and stellar magnetosphere



Model predictions: differential rotations along the field lines leads to their expension, opening, reconnection

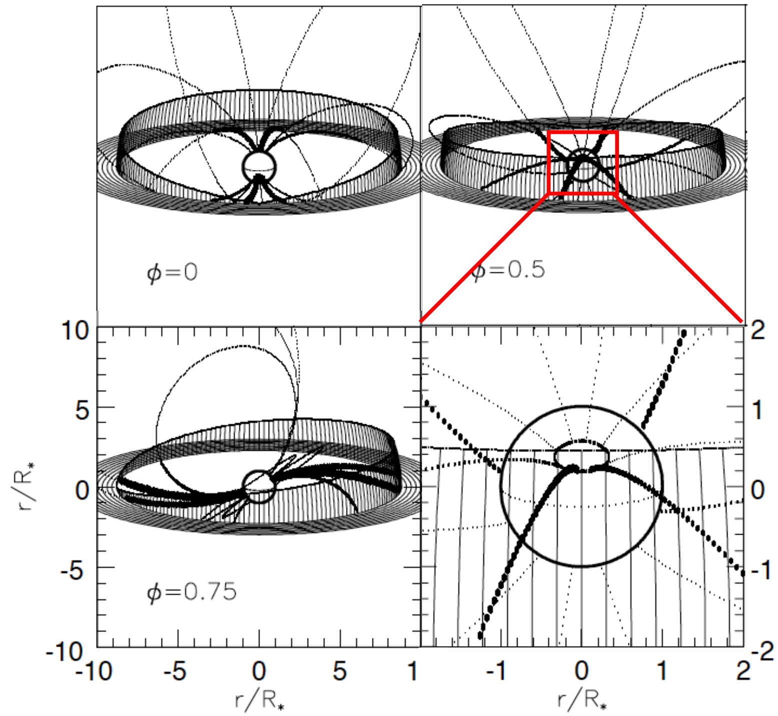
Restoration of the initial magnetospheric configuration

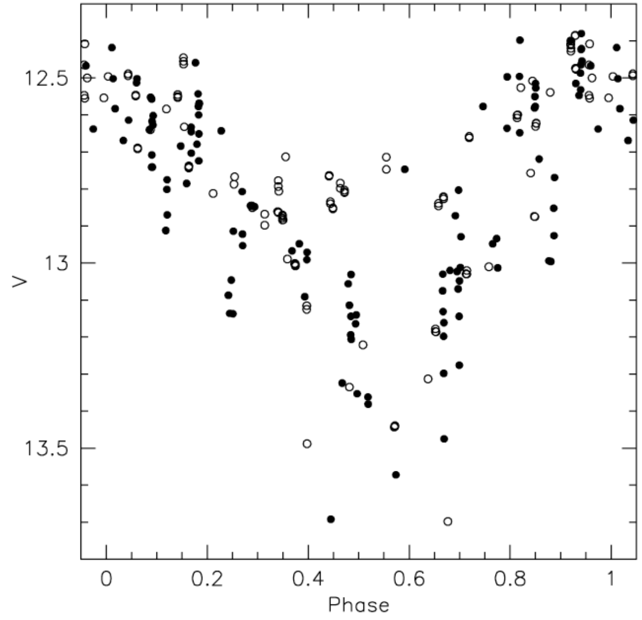
Timescale of a few rotation periods

adapted from S. Alencar

Goodson et al. (1999)

The photometric variability of AA Tau-type stars

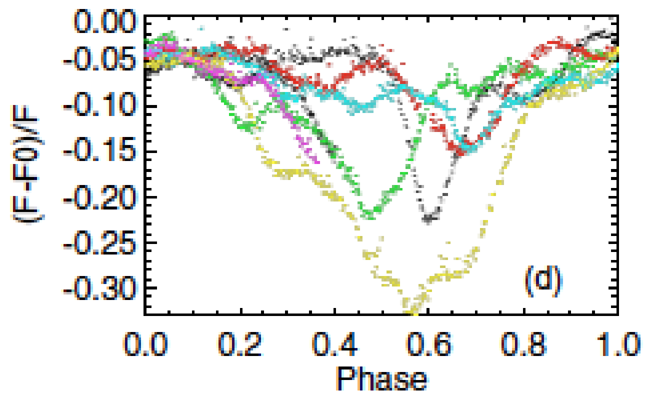




Bouvier et al. (1999,2003,2006)

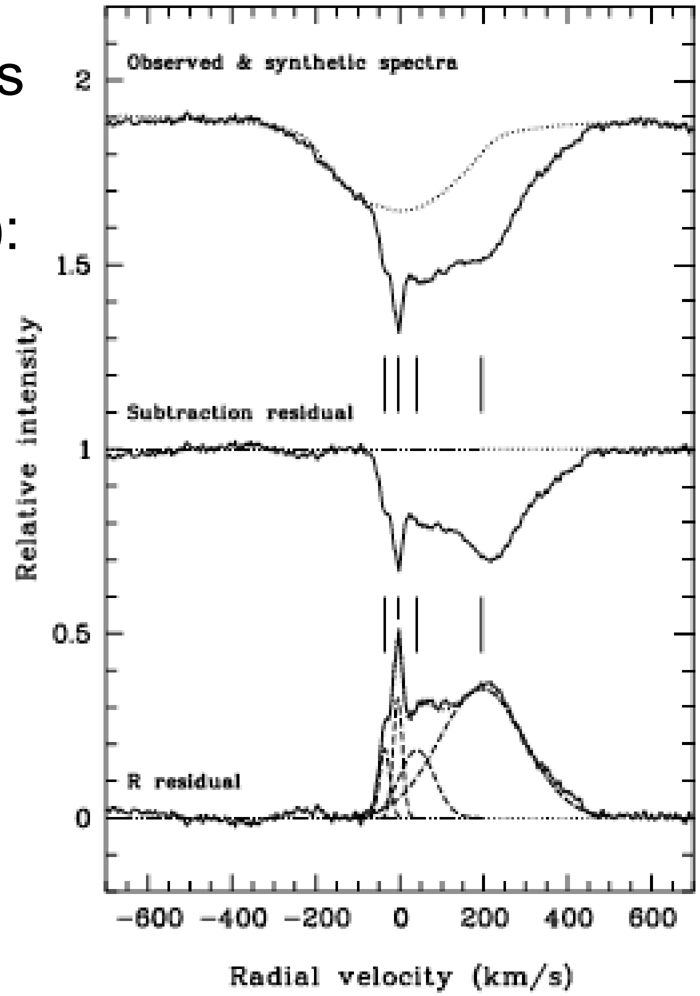
Dynamical interaction between the disk and stellar magnetosphere
=> variational warp in the inner disk of AA Tau

Other AA Tau-type light curves have been recently discovered with CoRoT in NGC 2264 (*Alencar et al. 2010*)



Clumpiness of the near-stellar HAe dust

- UXORs = the highly-photometric variables HAe stars
- Transient absorption components (TACs):
  - In Balmer and many metallic lines
  - Either on the blue side or on the red side
  - No change in velocity dispersion
  - No change in shape
  - Can last up to 6 days
- Blobs preserving their geometrical and physical properties, accelerating and decelerating
- Solar composition ? (WW Vul)
- Evaporation of gaseous bodies ? Magnetospheric accretion ? Occulting screen ?



Mora et al. (2002)

See also Rodgers et al. (2002), Beust et al. (2001), Mora et al. (2004)

Towards better constrained models

– Improved instrumentation: Spitzer, HST imaging, SMA mm, Herschel

– Development of sophisticated 2D, then 3D model, e.g.:

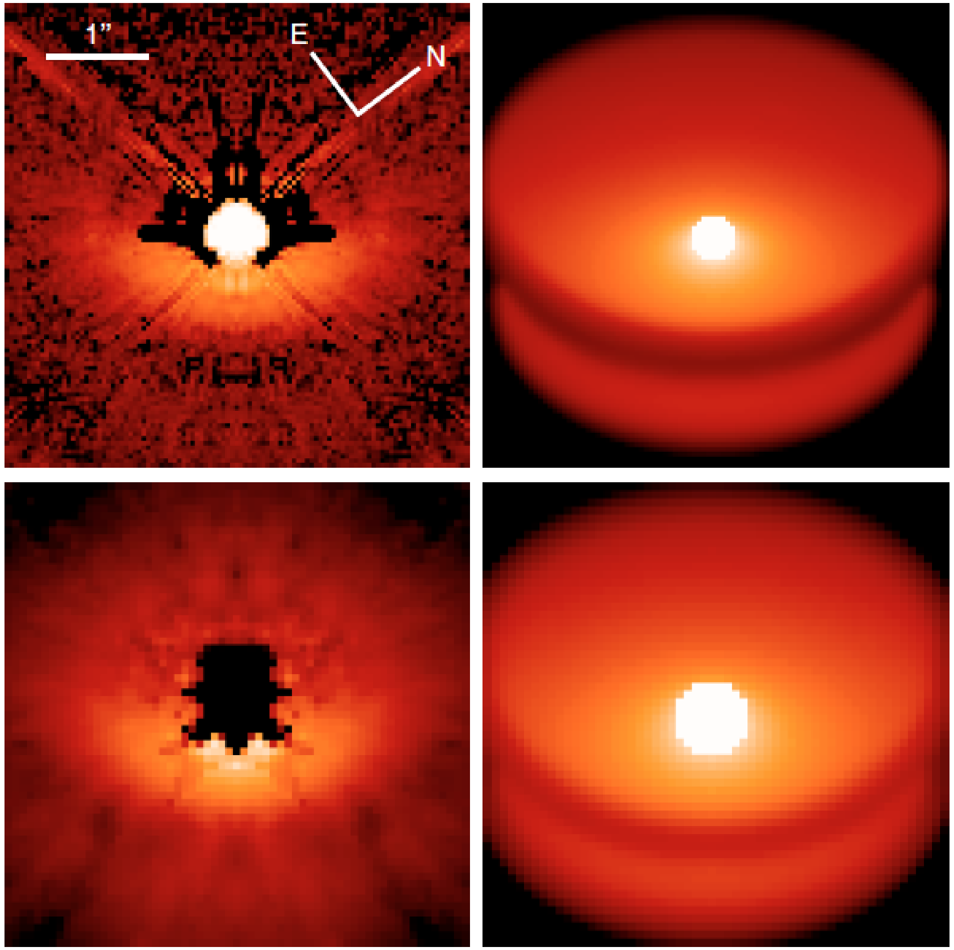
– MCFOST (Pinte et al. 2006):
passive dust heating
radiative equilibrium
continuum thermal re-emission
multiple scattering

$\Rightarrow$SED computation
$\Rightarrow$Imaging in different bands

$\Rightarrow$Evidence of dust evolution in the disk:
- grain growth
- μm grains close to the surface
- larger grains towards mid-plane
- fluffy aggregates or ice mantle around grains

– See the works of Dullemond et al. (2003, 2005, 2007), Perez-Becker & Chiang (2011), …

IM Lup CTTS

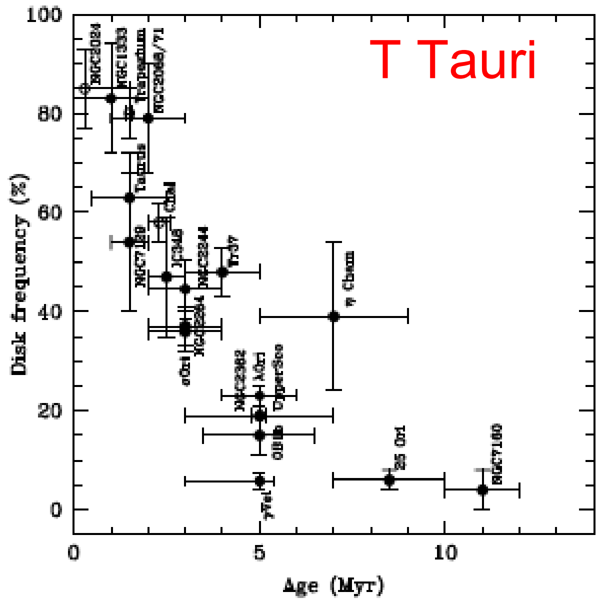


Pinte et al. (2008)

The disk evolution

The disk evolution

Hernandez et al. (2007a, 2007b)



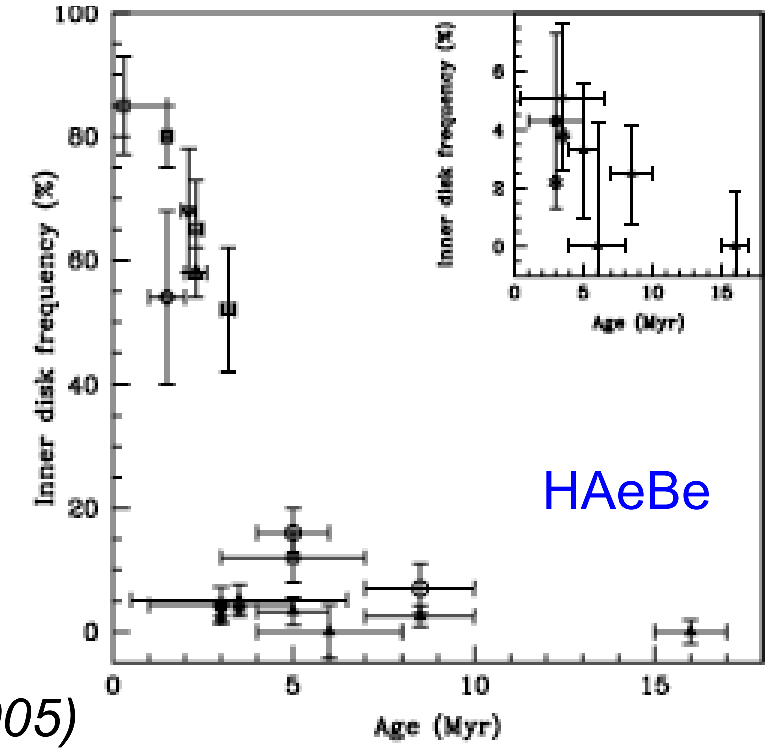
- Disk frequency decreases with age
- IR emission decreases with age
- Accretion rate is a function of age
- The amount of gas decreases with age (Pascucci et al. 2006, Carmona et al. 2007)

⇒ Disk around T Tauri stars dissipate mostly within 10 Myr, starting from the inner disk

- Disk frequency decreases with age faster in HAeBe stars (within 5 Myr), and the inner disk within 3 Myr

⇒ More efficient mechanism for disk dispersal ?

- Gaseous disk size decreases with age (Dent et al. 2005)



Hernandez et al. (2005)

The disk clearing mechanisms

– Dust growing/settling / planetary formation

e.g. Lommen et al. (2010), Rice et al. (2003), Varnière et al. (2006)

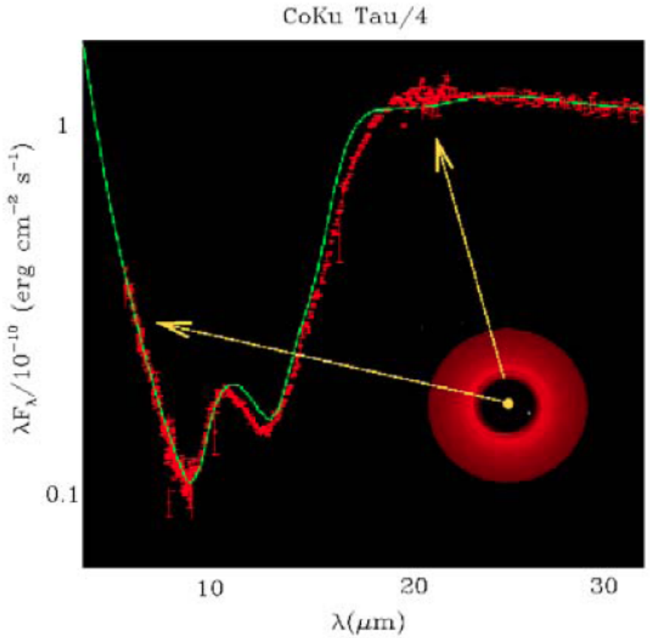
– Magnetorotational Instability (MRI, e.g. Suzuki & Inutsuka 2009)
  – Coronal X-rays ionising the CS disk
  – A surface layer is formed and well coupled with the magnetic fields of the disk, amplifying the disk magnetic field by MRI
  – With differential rotation, a disc wind is launched depleting the disc mass

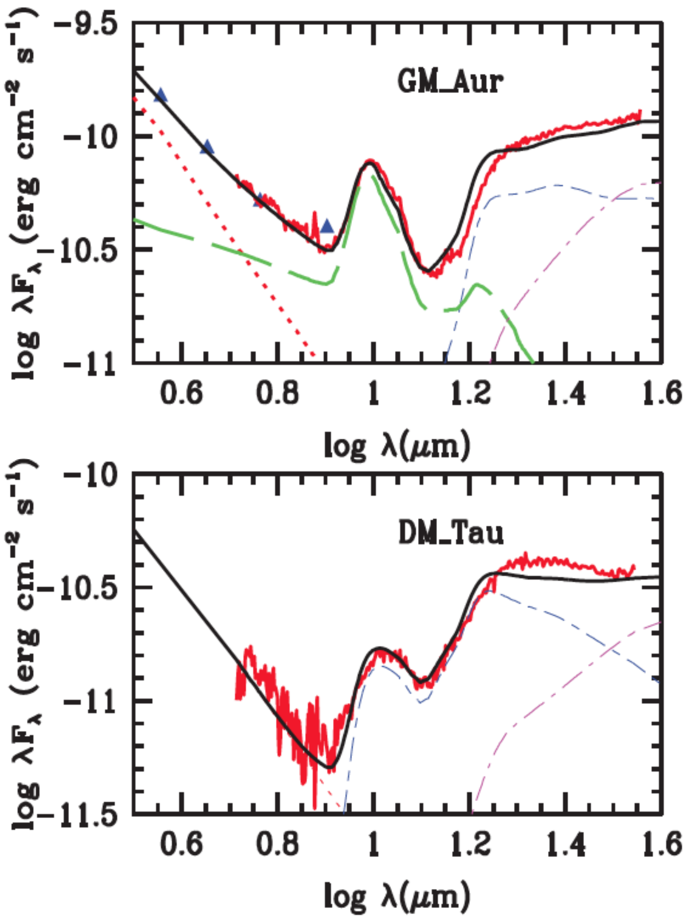
– Photoevaporation (e.g. Alexander et al. 2006)
  – Ionising radiation => evaporative wind at large radii (> R_g)
  – When dM_{wind} > dM_{accr} => depriving the disk of resupply within R_g, evaporating the disk within 10^5 yr
  – Two-time-scale behaviour for T Tauri stars

Transitional TT disks

– Lack of near- and mid-IR, but same SED at far-IR than CTTS
  – Removal of hot dust close to the star => inner hole
  – From class II to class III stars

R_{in} ~ 10 AU



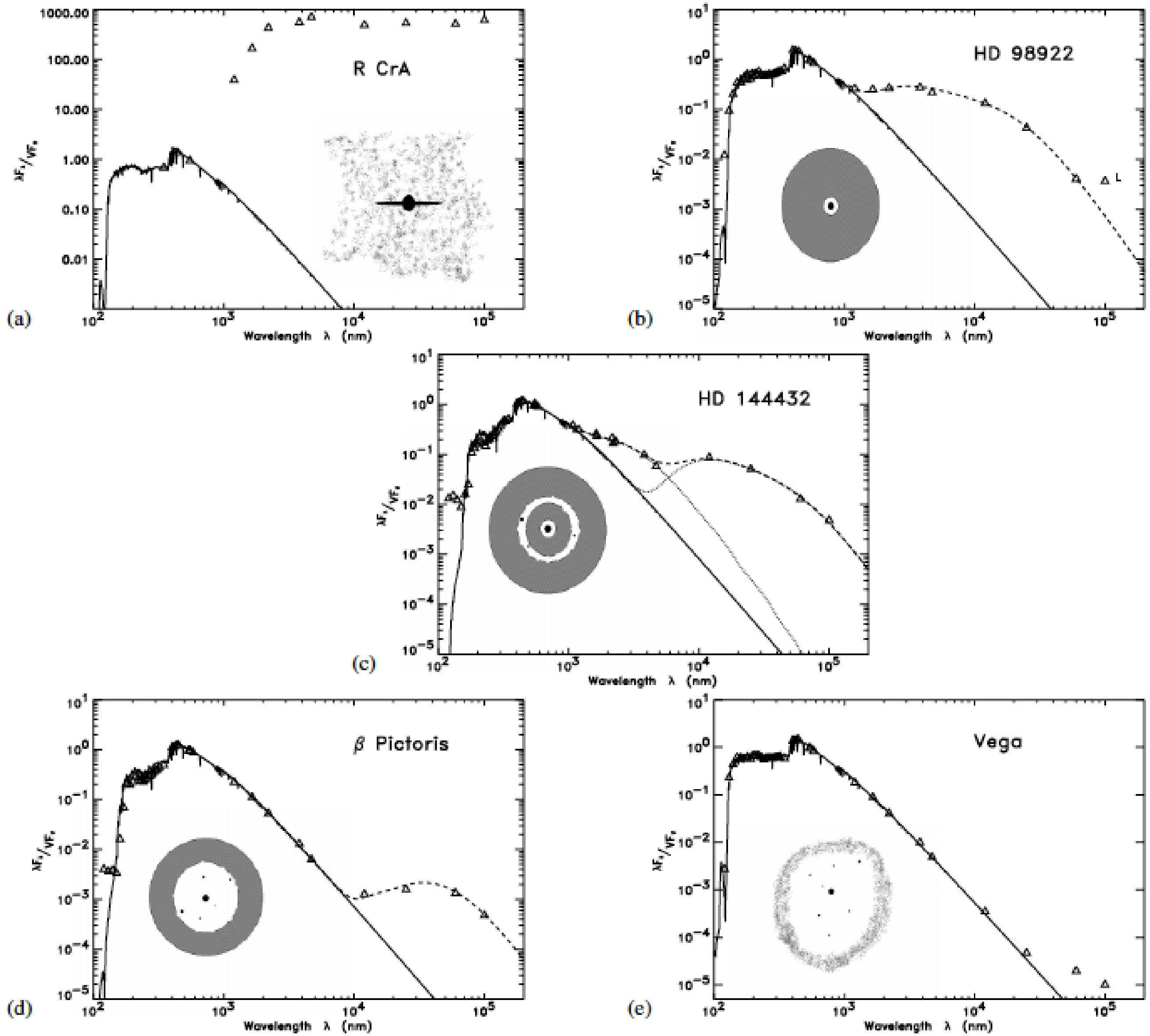


R_{in} ~ 24 AU

R_{in} ~ 3 AU

Espaillat (2009)

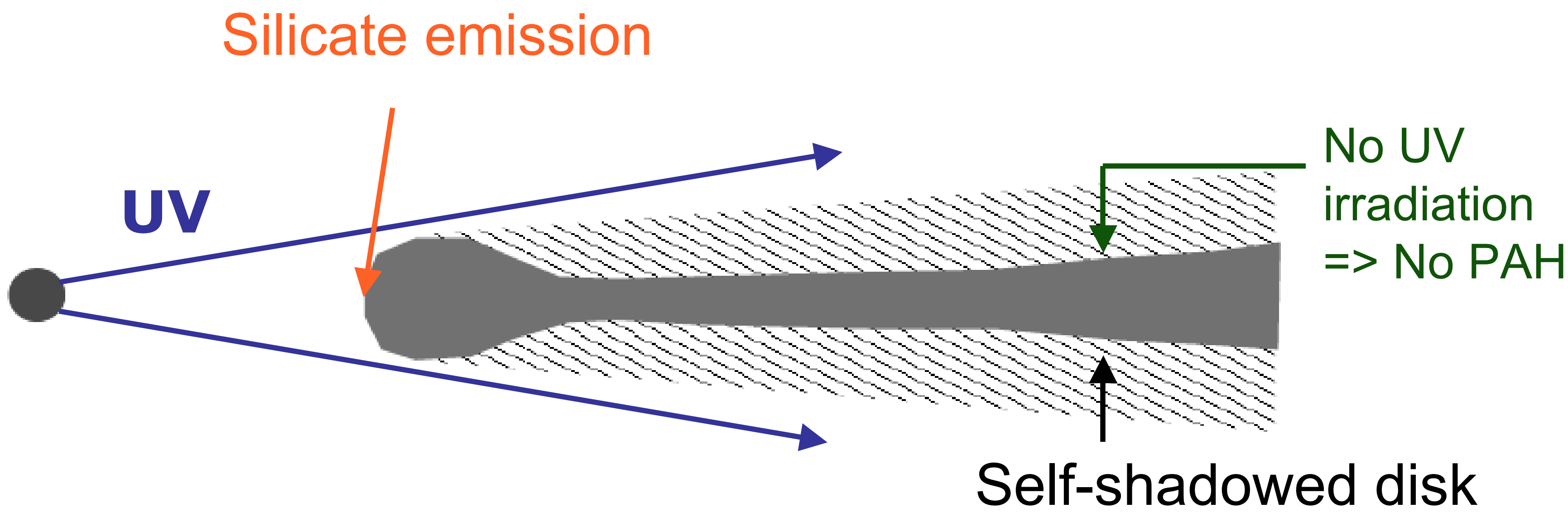
HAe disks evolutionary scenario



Malfait et al. (1998)

HBes: photoevaporation

- Okamoto et al. 2009: photoevaporation tracer in the IR spectrum of HD 200775
- Alonso Albi et al. 2009: disk mass of the HBes are smaller
- Lack of ionised PAH only in HBes => photoevaporation of the flared part of the disk => Shadowed disk might already dominate in Hbes due to photoevaporation



Conclusion

- Disk are present around CTTS, HAeBe
- Flared passive disk, mostly accepted
- Irradiation from the central star is the main heating mechanism
- Accretion ?
  - Magnetospherique for CTTS
  - For HAeBe ?
- Typical disk parameter:
  - R_{in} ~ 0.5 to few AU (depending M_*, age)
  - R_{out} ~ 300 - 1000 AU(depending M_*, age)
  - Dust disk mass ~ 10^{-8} - 10^{-4} $M_{\odot}$
  - M_{gas} / M_{dust} ~ 100 but might be lower
  - Minimum size grains ~ 0.003 - 0.1 μm
  - Maximum size grain ~ 1mm - 1cm
- Evidence of grains growing and settling
- Dust disk are clearing from inside out
- Origin of the clearing mechanism still open issue


Thank you