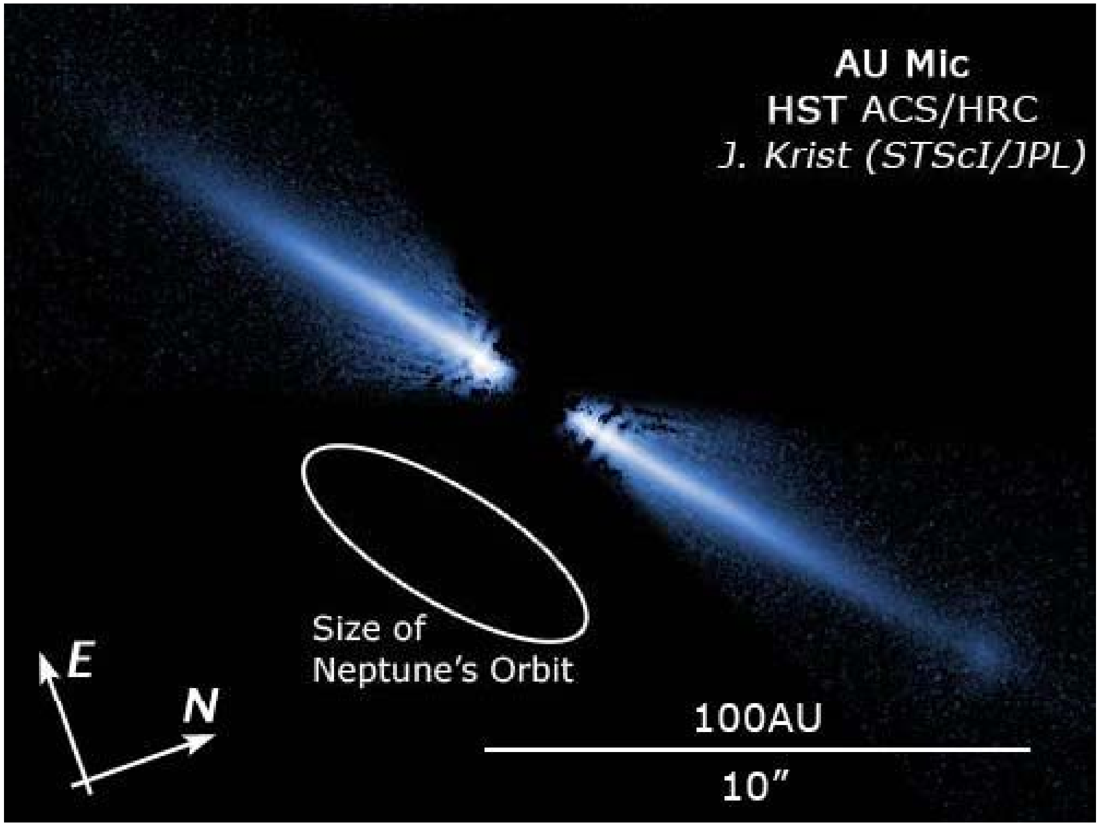
Part III

Early stages in stellar evolution



PhD course originally developed by René Liseau
Updated to Master level course by Alexis Brandeker

Early stages in stellar evolution

- L15 – General Overview / Pre-collapse phase I
- L16 – Pre-collapse phase II
- L17 – Collapse phase I
- L18 – Collapse phase II
- **L19 – Circumstellar disks I**
- L20 – Pre-main-sequence evolution
- L21 – Circumstellar disks II – debris disks

Circumstellar disks

- *Inevitable* consequence of star formation:

  $\Omega_1 r_1^2 = L_1 = L_0 = \Omega_0 r_0^2$
  $\rightarrow \; \Omega_1 = \Omega_0 (r_0/r_1)^2$

- Collapse compresses scale r from $r_0 \approx 0.2$ pc = 40000 AU to $r_0 \approx R_{sol} = 0.005$ AU $\rightarrow r_0/r_1 \approx 10^7$ and $\Omega_1 \approx 10^{14}\,\Omega_0$
- Assumes *conservation of angular momentum*

Magnetic braking

Stahler & Palla : the *centrifugal radius*

$$\varpi_{\rm cen} = 0.3\,{\rm AU}\left(\frac{T}{10\,{\rm K}}\right)^{\frac{1}{2}}\left(\frac{\Omega}{10^{-14}\,{\rm s}^{-1}}\right)^{2}\left(\frac{t}{10^{5}\,{\rm yr}}\right)^{3}$$

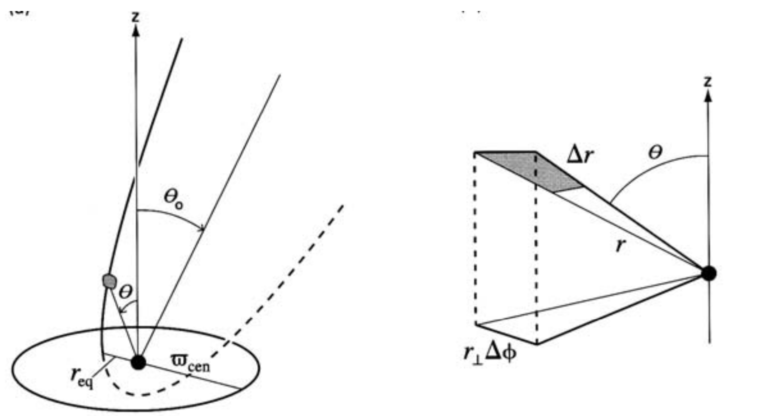


Figure 10.16 (a) Orientation of the orbital plane within a collapsing cloud. The plane is tilted from the rotation axis by the angle θ_o. A fluid element has the instantaneous polar angle θ relative to the axis and crosses the equatorial plane at a radial distance r_{eq}, less than the maximum value ϖ_{cen}. (b) Near the position of the fluid element, mass continually flows downward through the shaded patch.

Predictions of disks

P.S. Laplace 1796, 1799

Exposition du systeme du monde
Mechanique celeste

Kant

I. Kant 1755

Allgemeine Naturgeschichte
und Theorie des Himmels

Predictions of disks

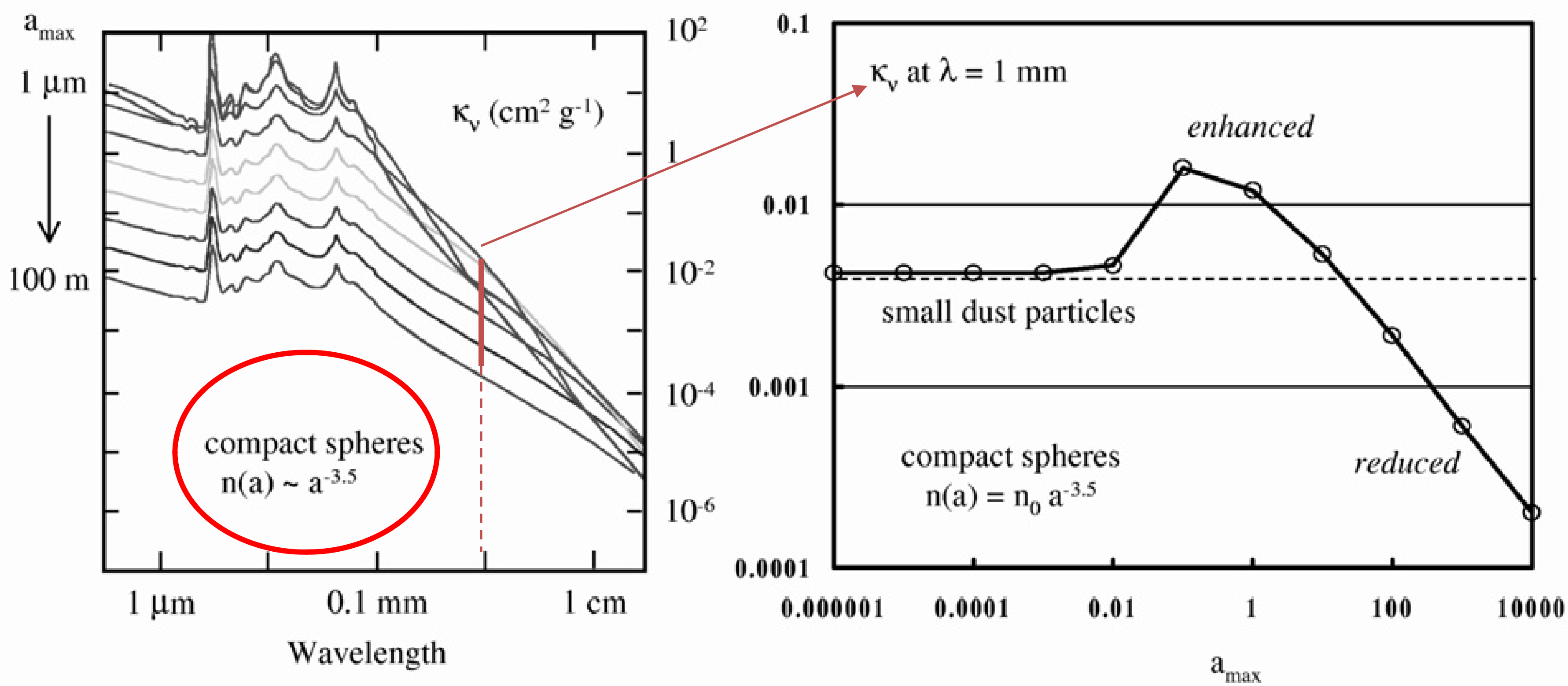
Lynden-Bell & Pringle 1974, MNRAS 168, 603:

Keplerian Disk

Differential Rotation
+
Viscosity

Mass Transport Inwards ←
Angular Momentum Transport Outwards →

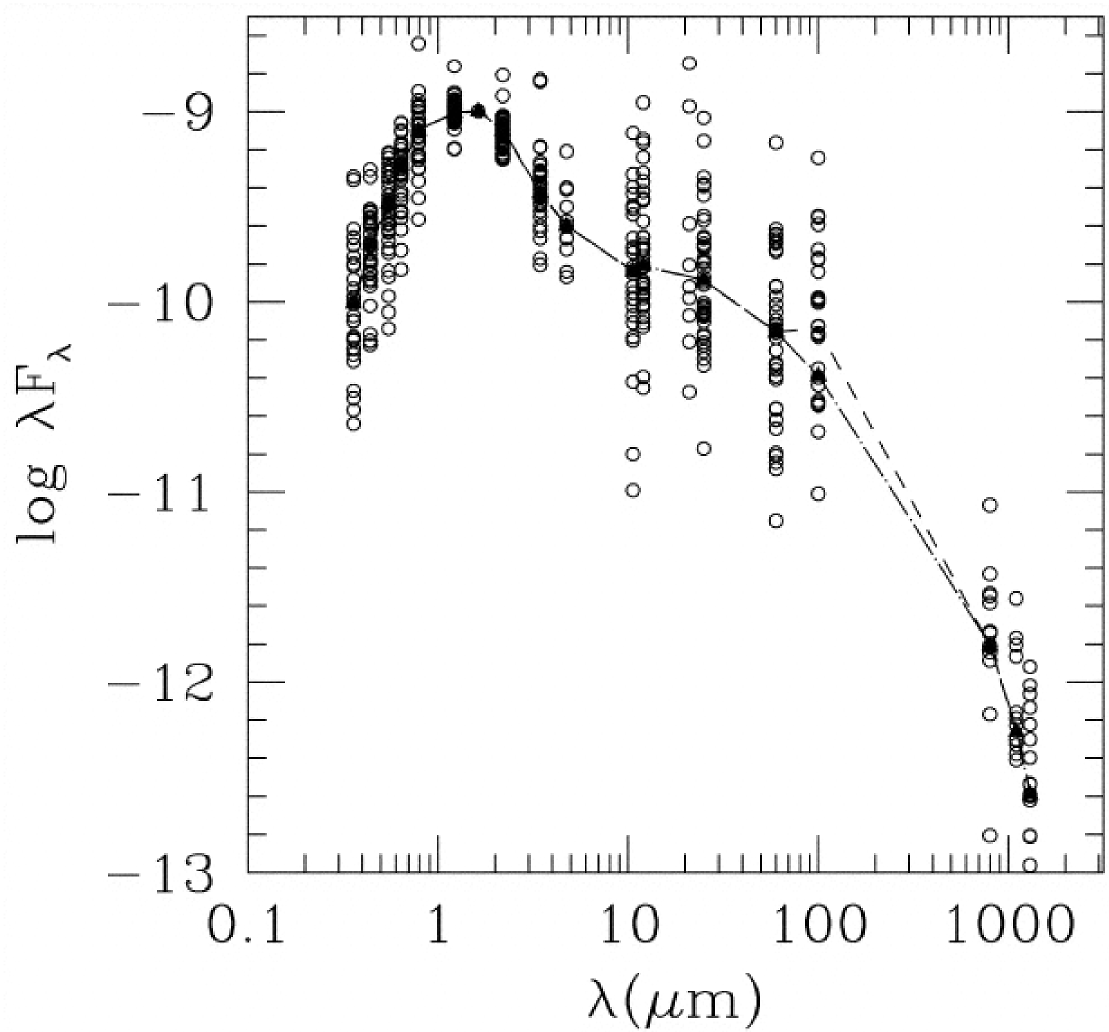
Dust grain opacities



See Ph. Thebault’s lecture

Beckwith et al. 2000, PP IV

40 observed SEDs of T Tauri Stars and \`mean model´ of star+disk



HABE Disk Structure:
Dullemond & Dominik 2004

D´Alessio et al. 1999

Gas Disks – Structure Models

Steady Disks around Single Stars

Boundary Conditions

R_{in} : boundary layer, magnetosphere, hole?
R_{out}: ad hoc? , interstellar turbulence?

Viscosity MHD/rotation (Hawley & Balbus 1995)

Opacity $\kappa = \kappa(\rho$, T, ..., XYZ, ..., ζ_0, ..., χ_ν ...)

Models Adams & Shu 1986 (flat)
[examples] Kenyon & Hartmann 1987 (flared)
Malbet & Bertout 1991 (vertical structure)
D´Allessio et al. 1998,... 2003
Aikawa & Herbst 1998 (chemistry)
Nomura 2002 (2D)
Wolf 2003 (3D)

Two categories of disks observed

T Tauri Disks: around young stars (0.1 - 10 Myr)
of half a solar mass (0.1 - 1 M_{sol})
at 150 pc distance (50 - 450 pc)
in and/or near molecular clouds
Accretion Disks

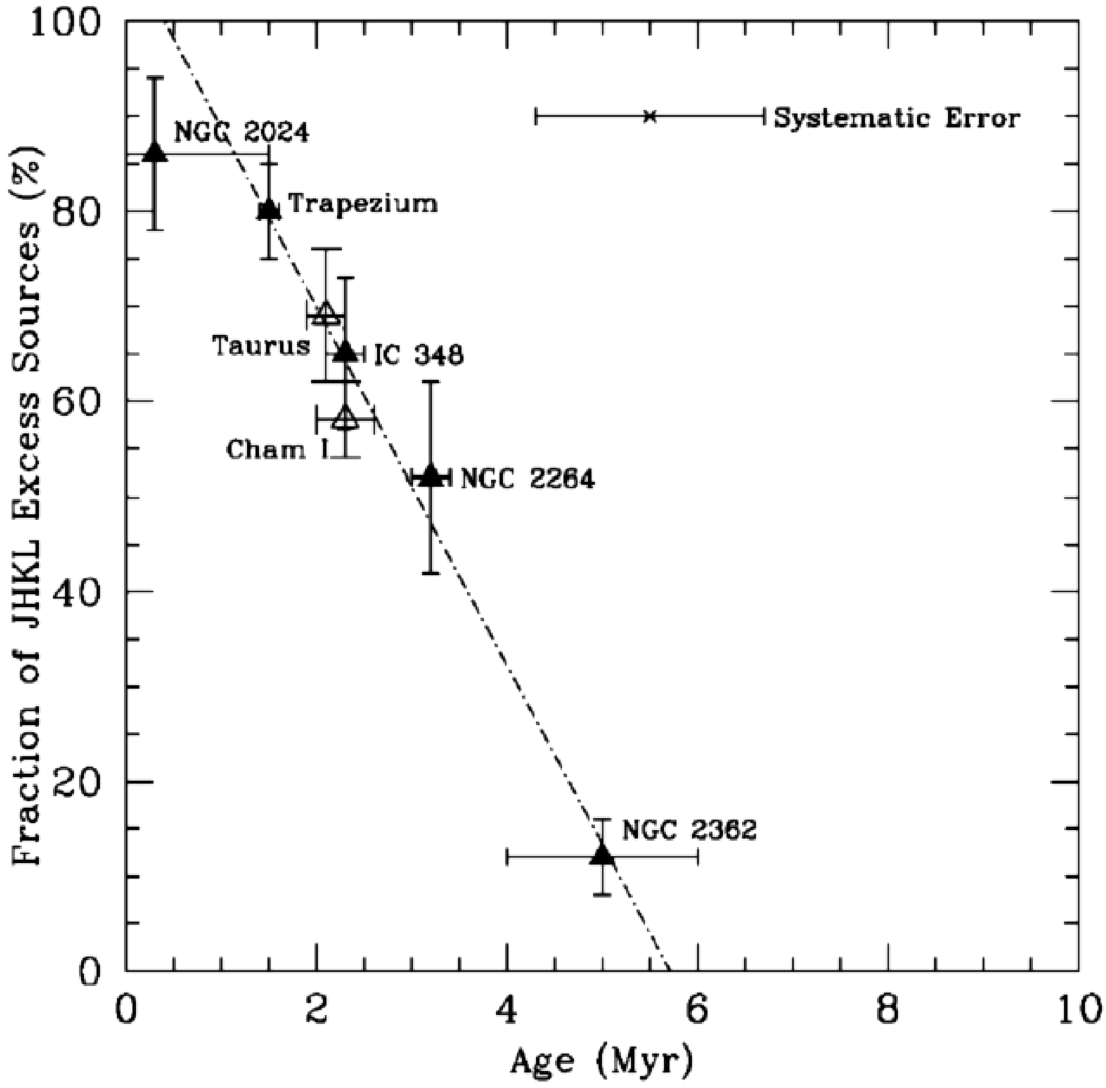
Debris Disks: around young ms-stars (10 - 400 Myr)
of about a solar mass (1 - 2 M_{sol})
at 20 pc distance (3 - 70 pc)
in the general field
Vega-excess stellar disks

Frequency of disks

High Rate of occurence around young stars

NGC 2024	86%
Trapezium cluster	80%
IC 348	65%

Frequency of disks



From Haisch, Lada & Lada 2001, ApJ, 553, 153

Observed disk sizes

T Tauri/HABE disks

50 – 100 AU Dust: mm-continuum interferometry

100 – 300 AU Dust: scattered stellar light

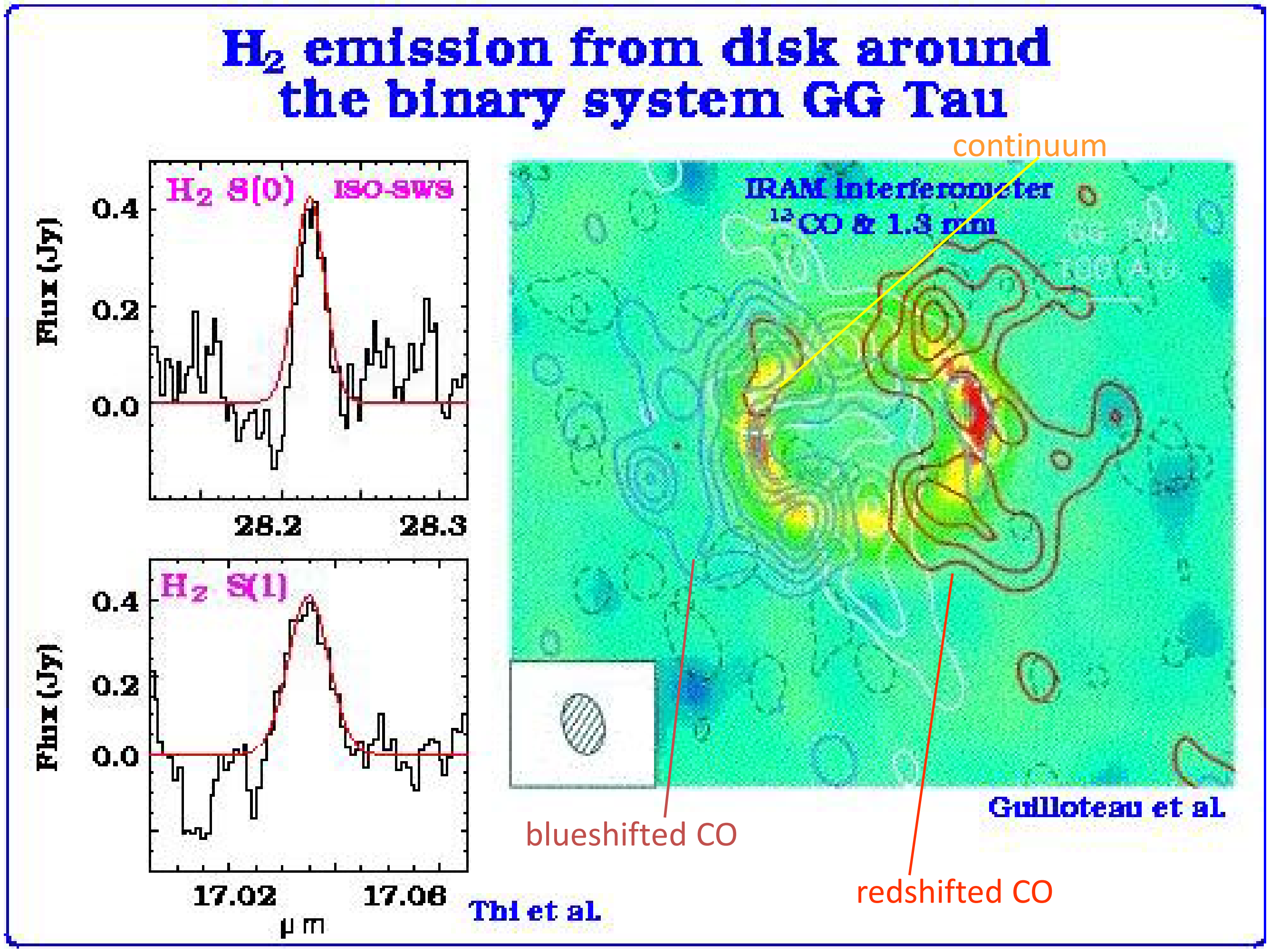
300 AU Gas: CO lines (evidence for Kepler rotation)

Silhouette disks (``proplyds´´)

up to 1000 AU Dust: scattered stellar light

Observing disk masses

H_2
Gas
Directly



CO
and
Dust

Gas disk evolution time scales

$$t_{\rm dyn} \sim \alpha\, t_{\rm therm} \sim \alpha\, (H/R)^2\, t_{\rm visc}$$

$t_{\rm dyn} \sim 1/\Omega_{\rm Kepler}$

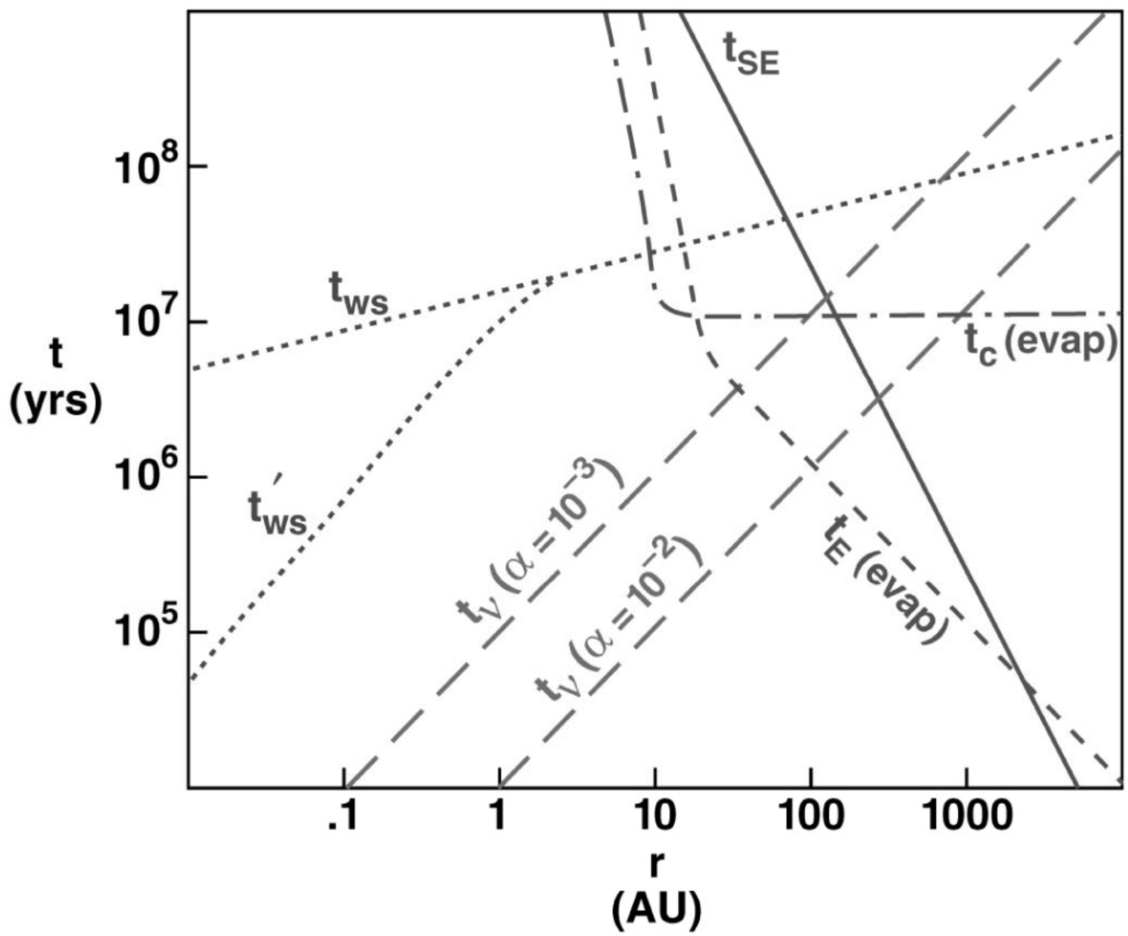
$\alpha \sim 10^{-3} - 10^{-2}$

$H/R \ll 1$

if $T \sim R^{-1/2}$, $t_{\rm visc} \sim R$

$t_{\rm visc} \sim 10^5$ yr $(\alpha/0.01)^{-1}$ $(R/10\ {\rm AU})$

Disk dispersal mechanisms

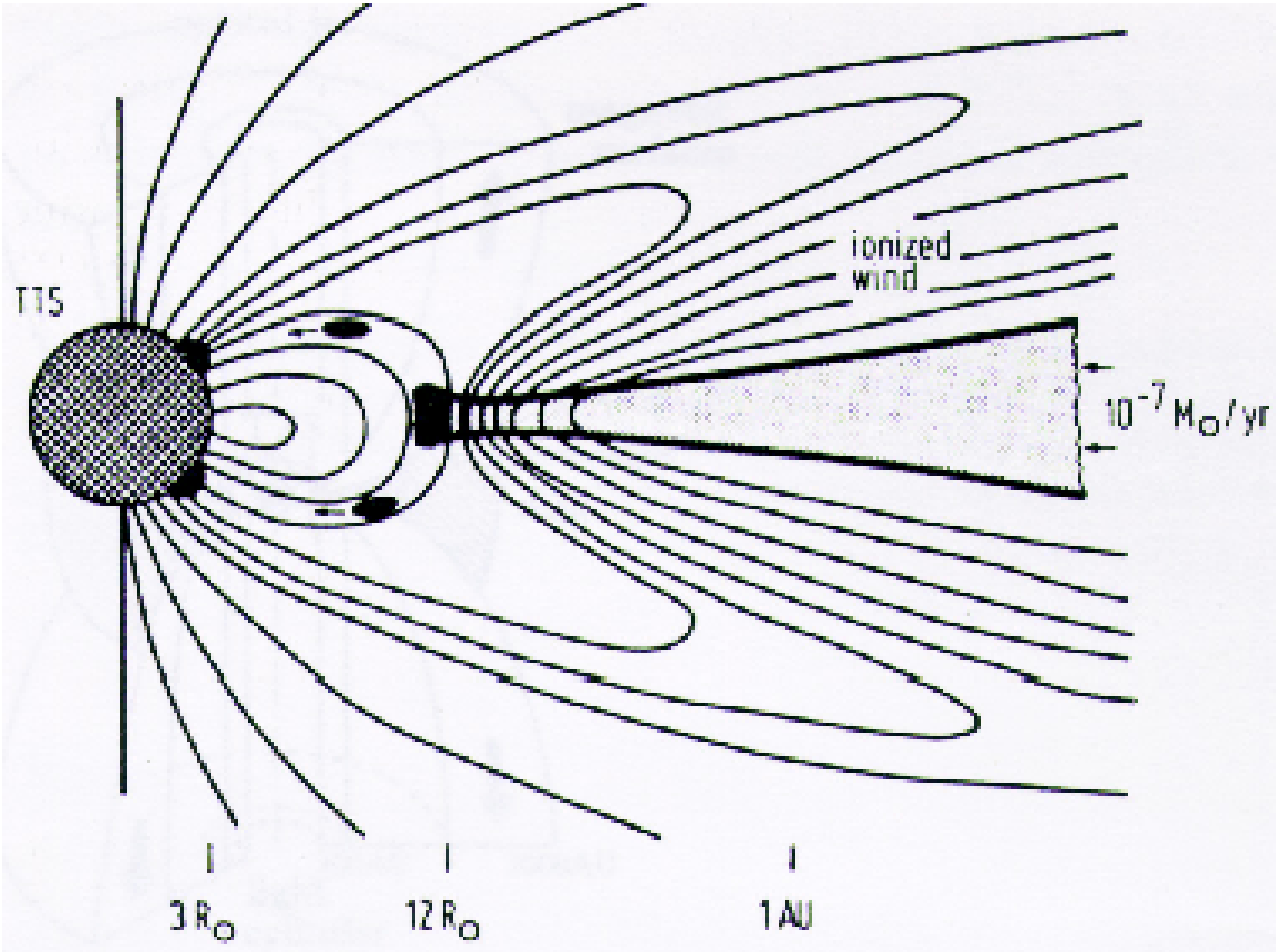


SE = Stellar Encounter (tidal stripping)
WS = Stellar wind stripping
evap E = photoevaporation external star
evap c = photoevaporation central star

All for Trapezium conditions

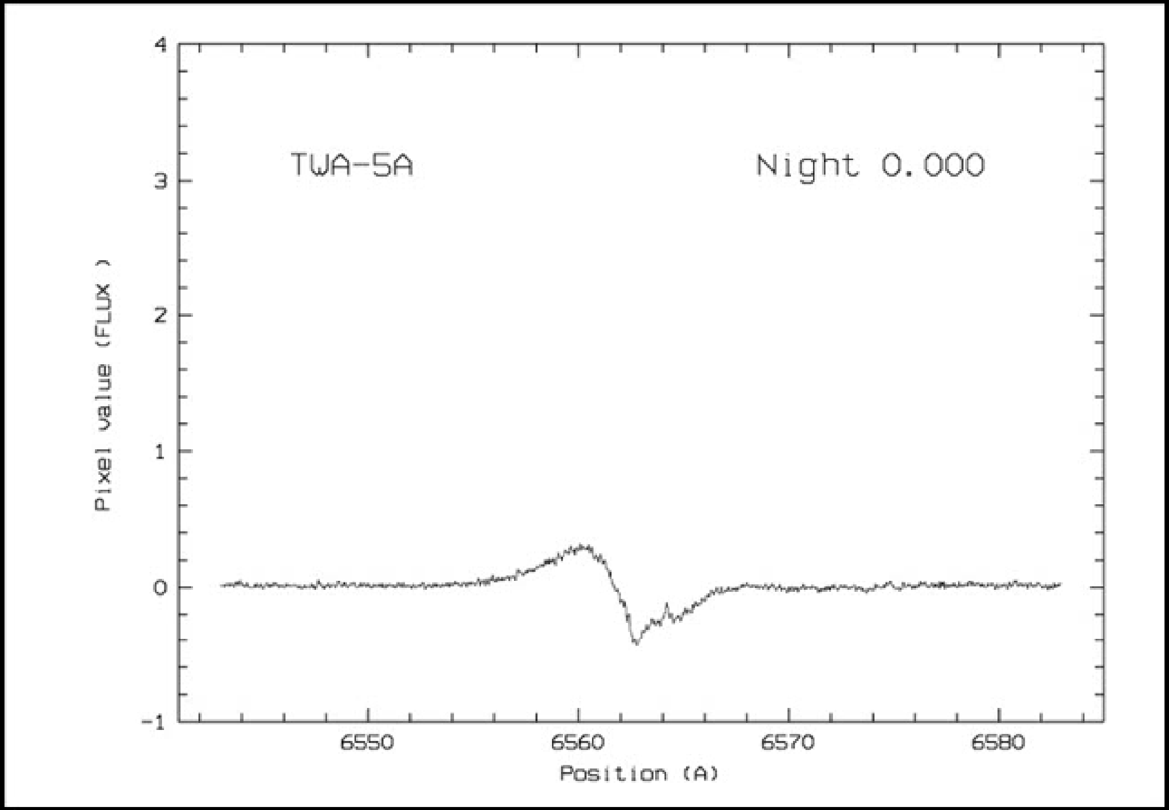
Physical Mechanisms
Hollenbach et al. 2000 PPIV

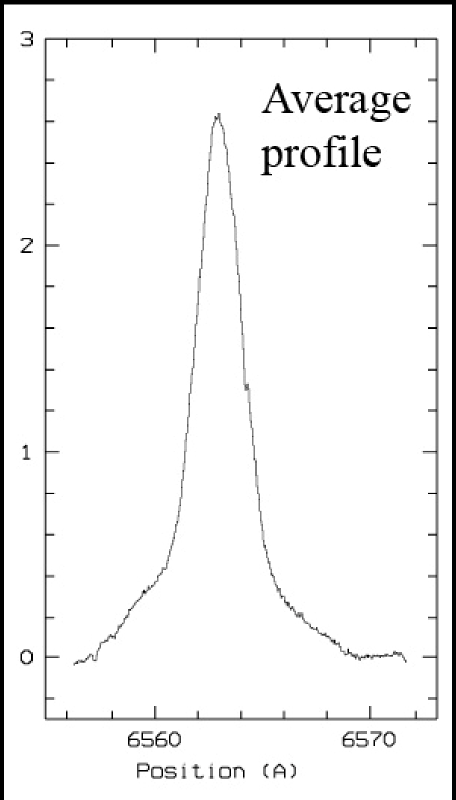
Accretion signatures



From Camenzind (1990)

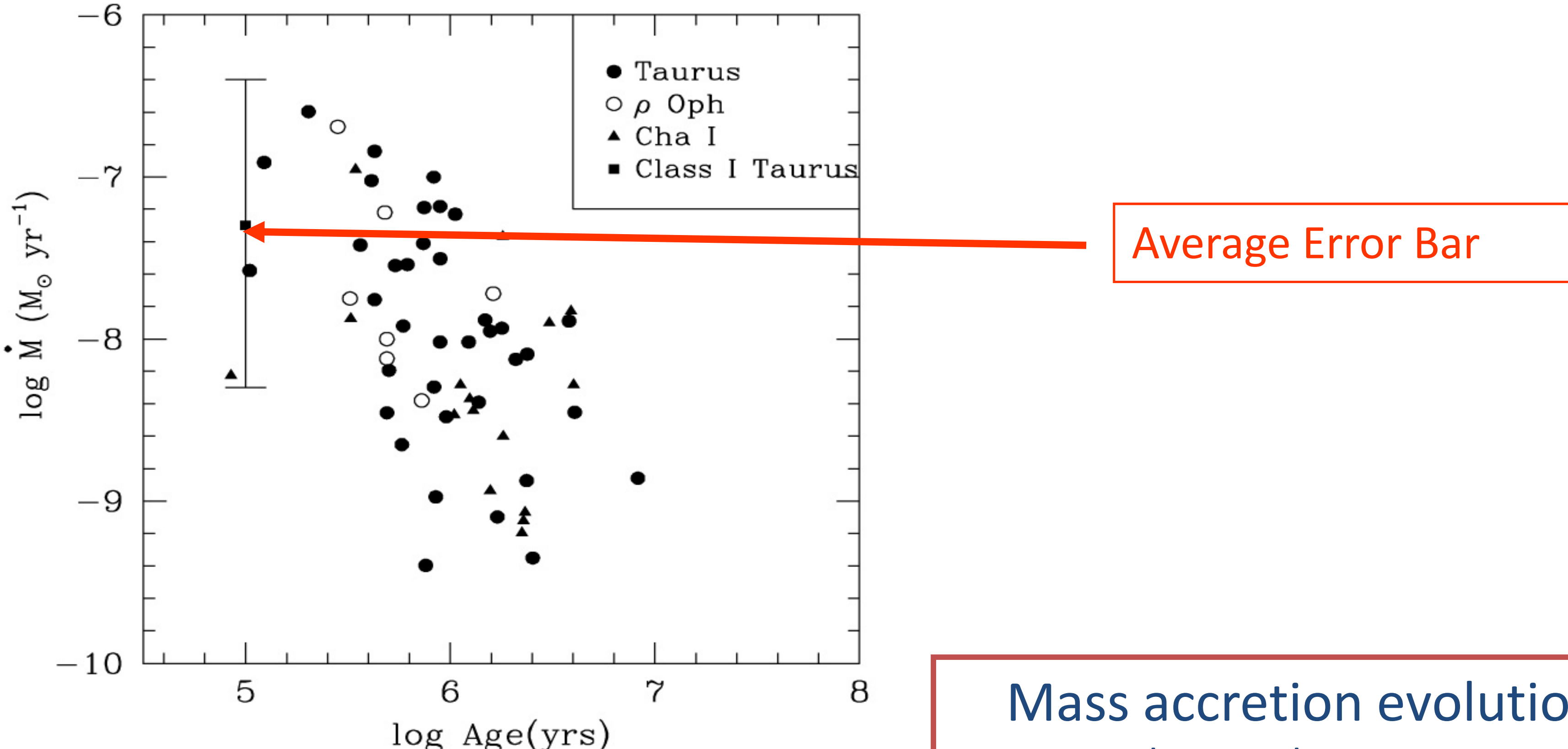
Accretion signatures





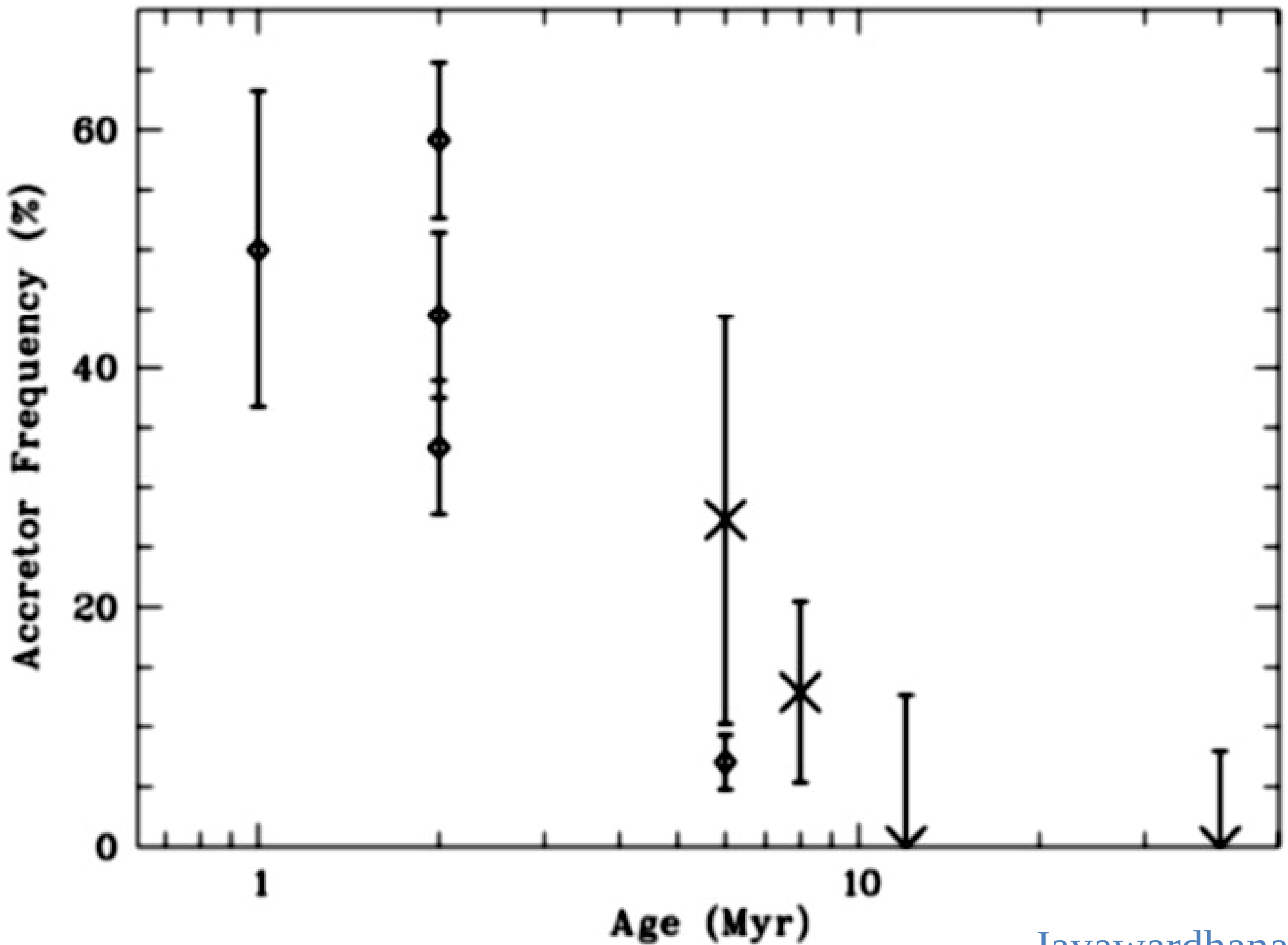
residual = profile - average

Disk lifetimes

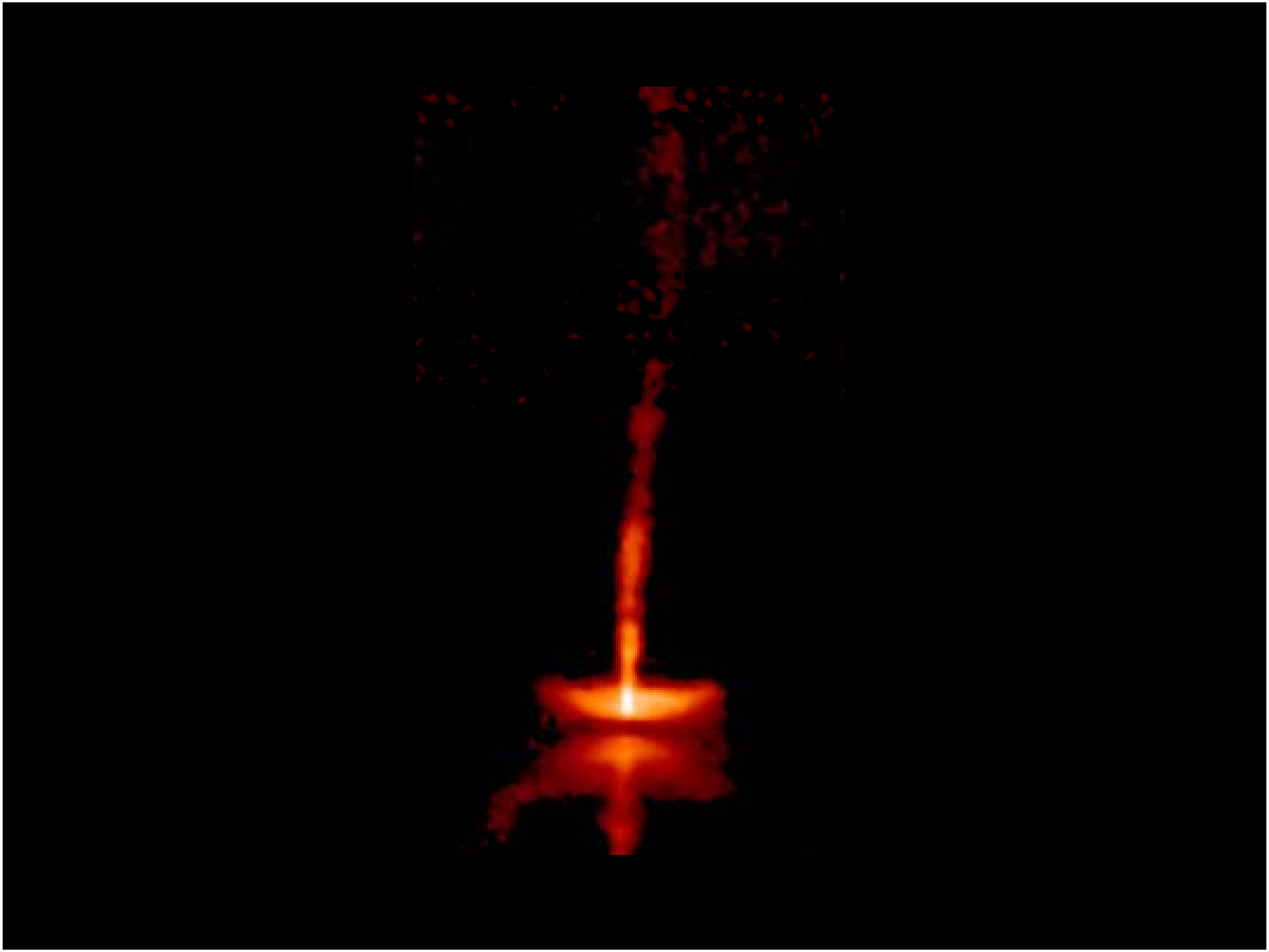


Mass accretion evolution
Calvet et al. 2000 PPIV

Disk lifetimes



Jayawardhana et al. (2006)



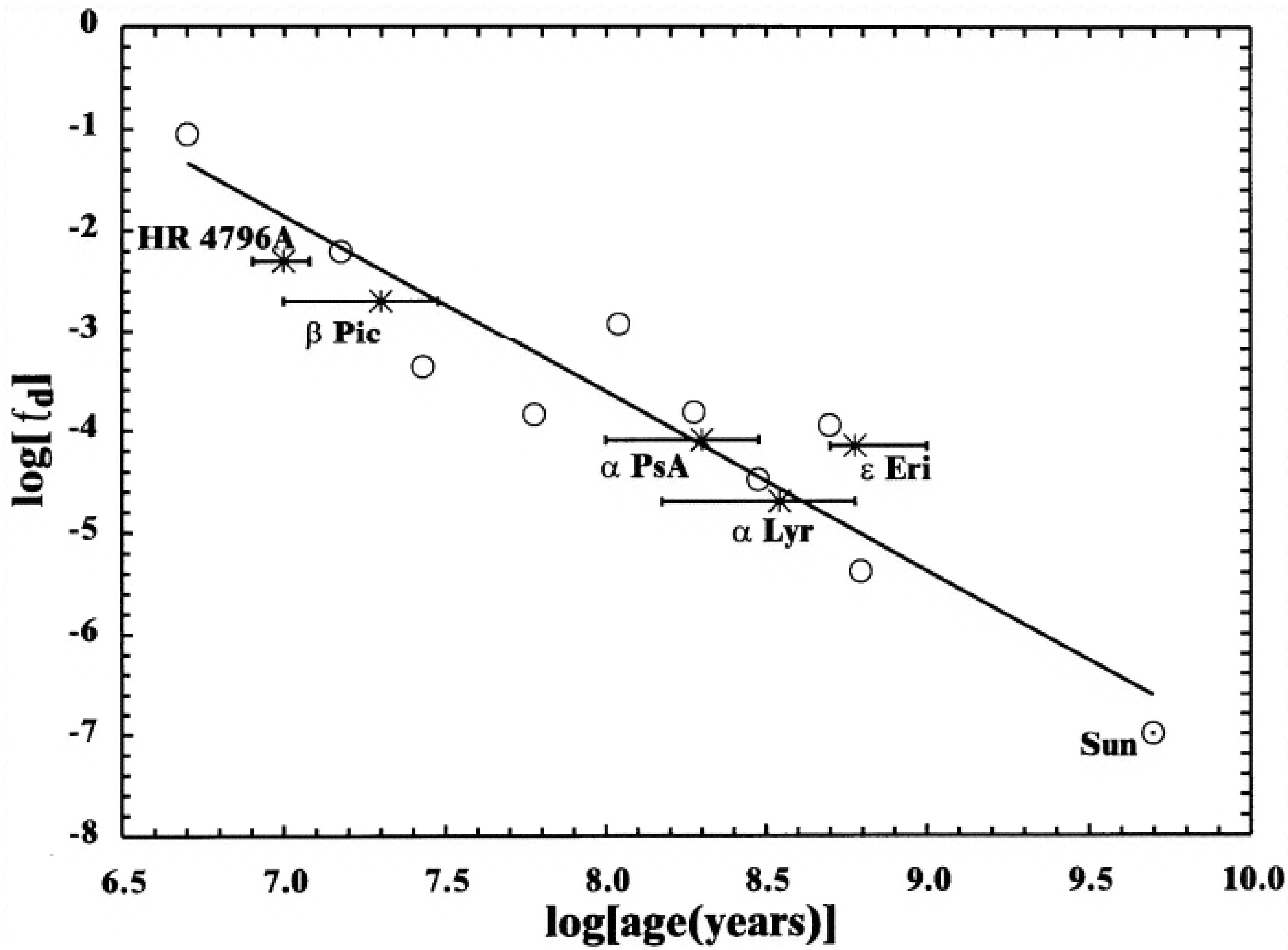
Gas rich to gas poor evolution?

$f_{\rm dust} = \Delta L_{\rm IR}/L$ vs stellar age

(F)IR - excess

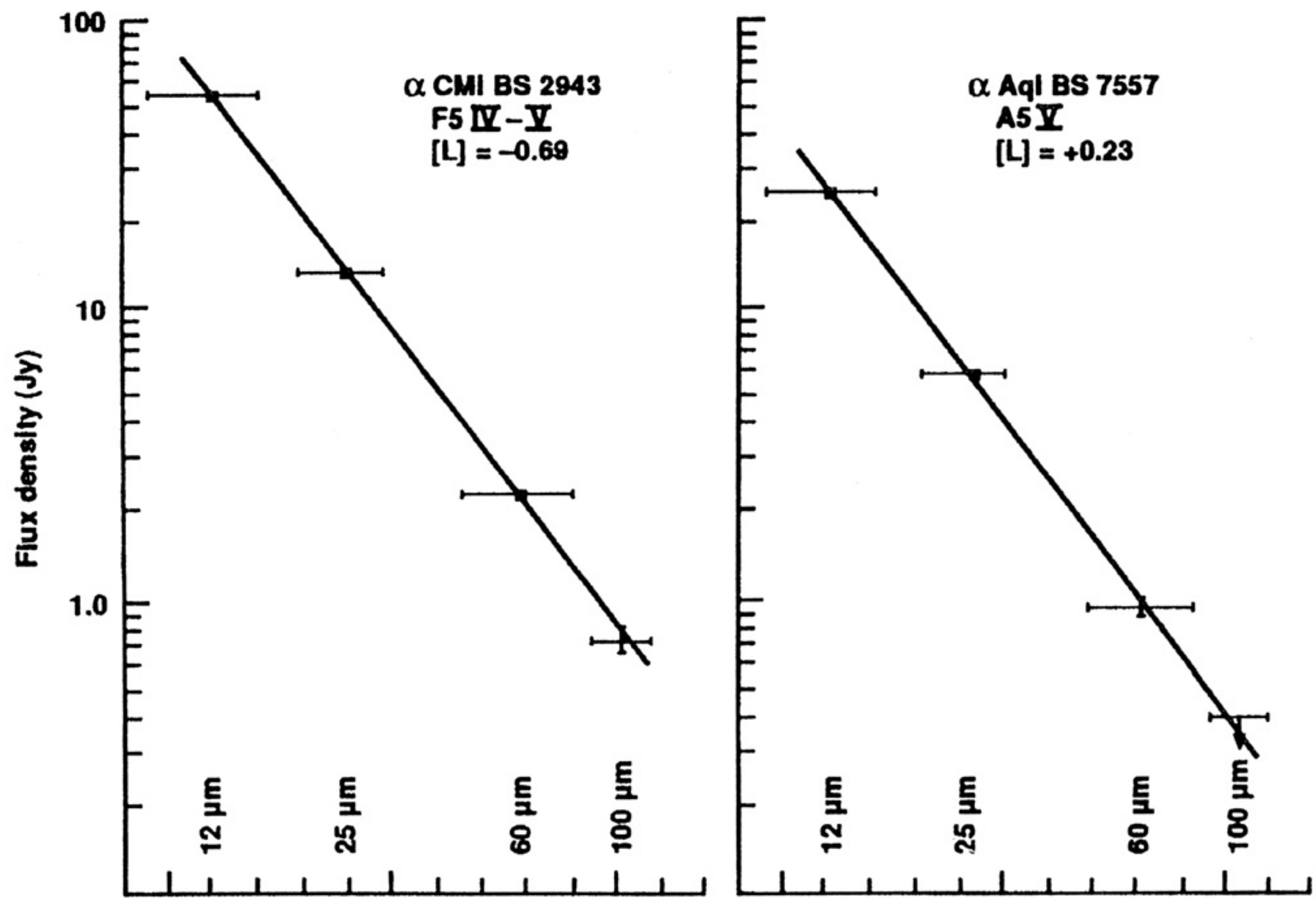
Stellar luminosity
(bolometric)

Disk evolution?



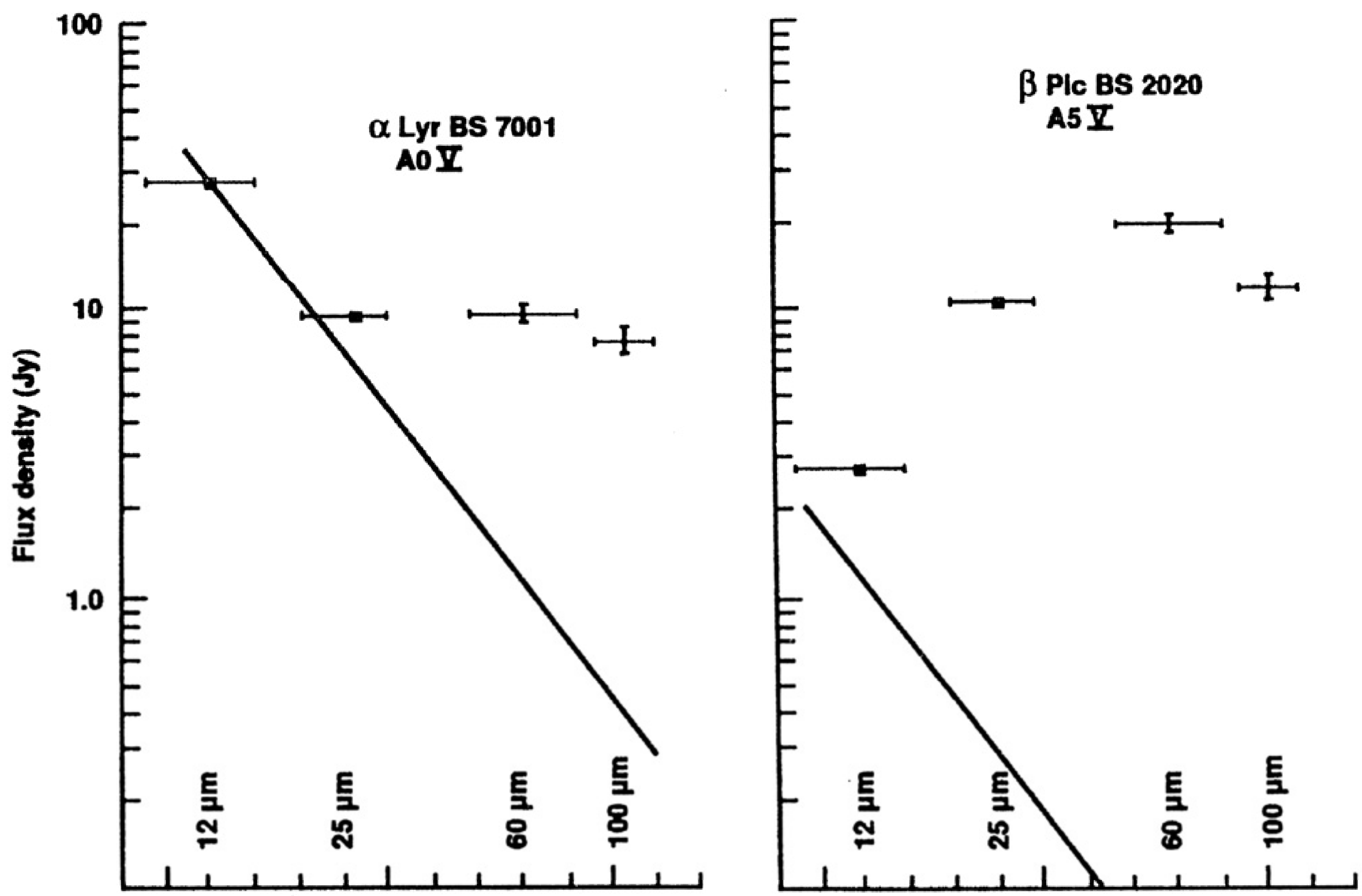
Spangler et al. 2001

Discovery of debris disks



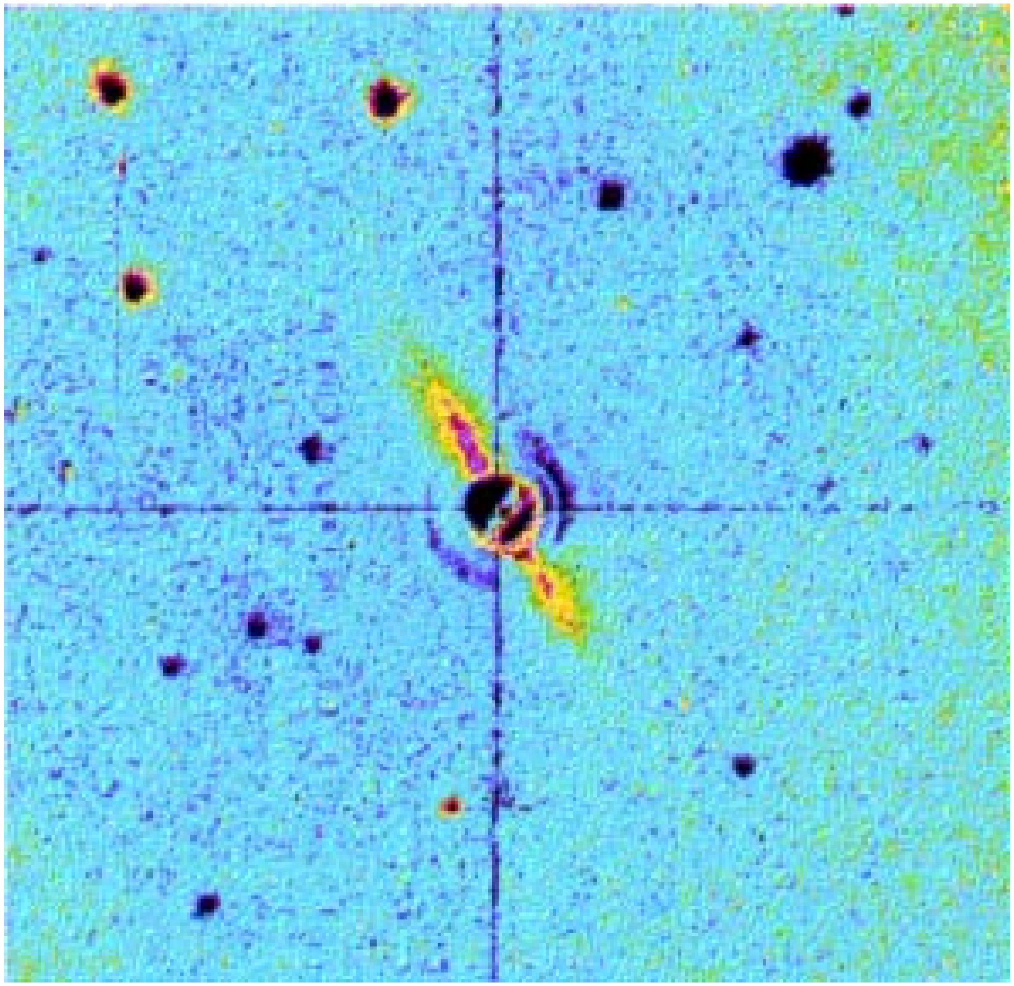
From Backman & Parece 1993, PPIII, 1253

Discovery of debris disks



From Backman & Parece 1993, PPIII, 1253

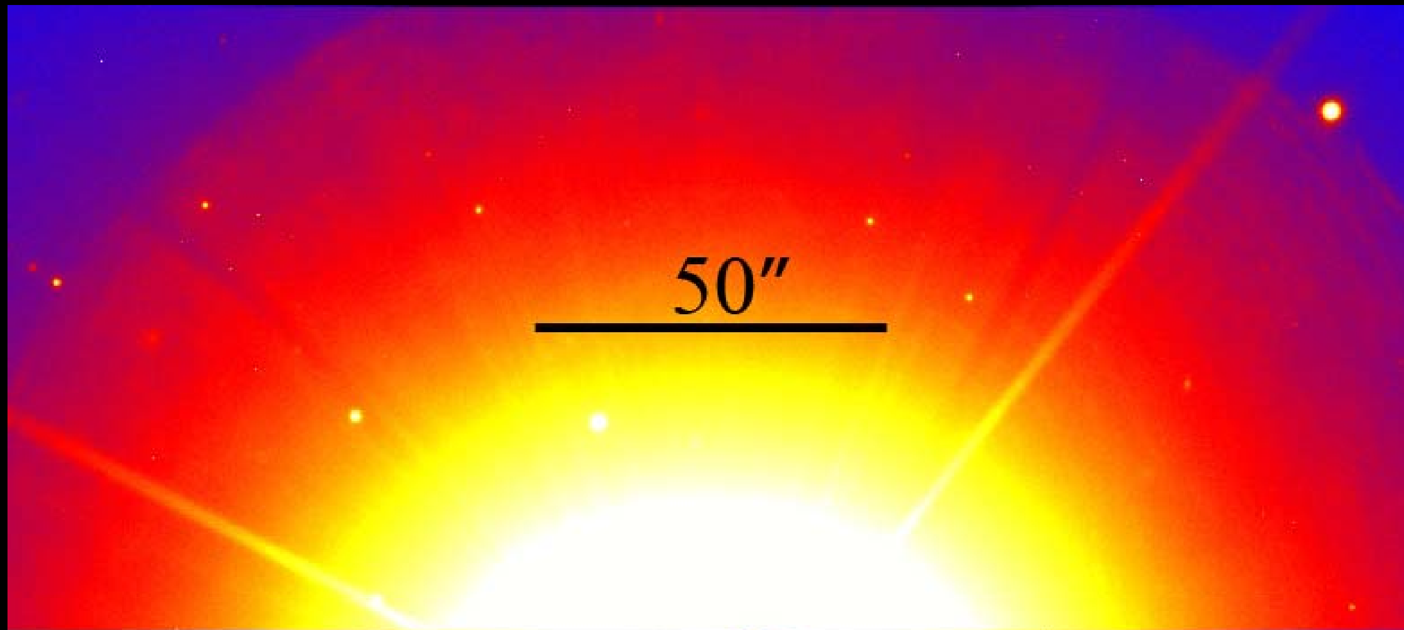
β Pictoris



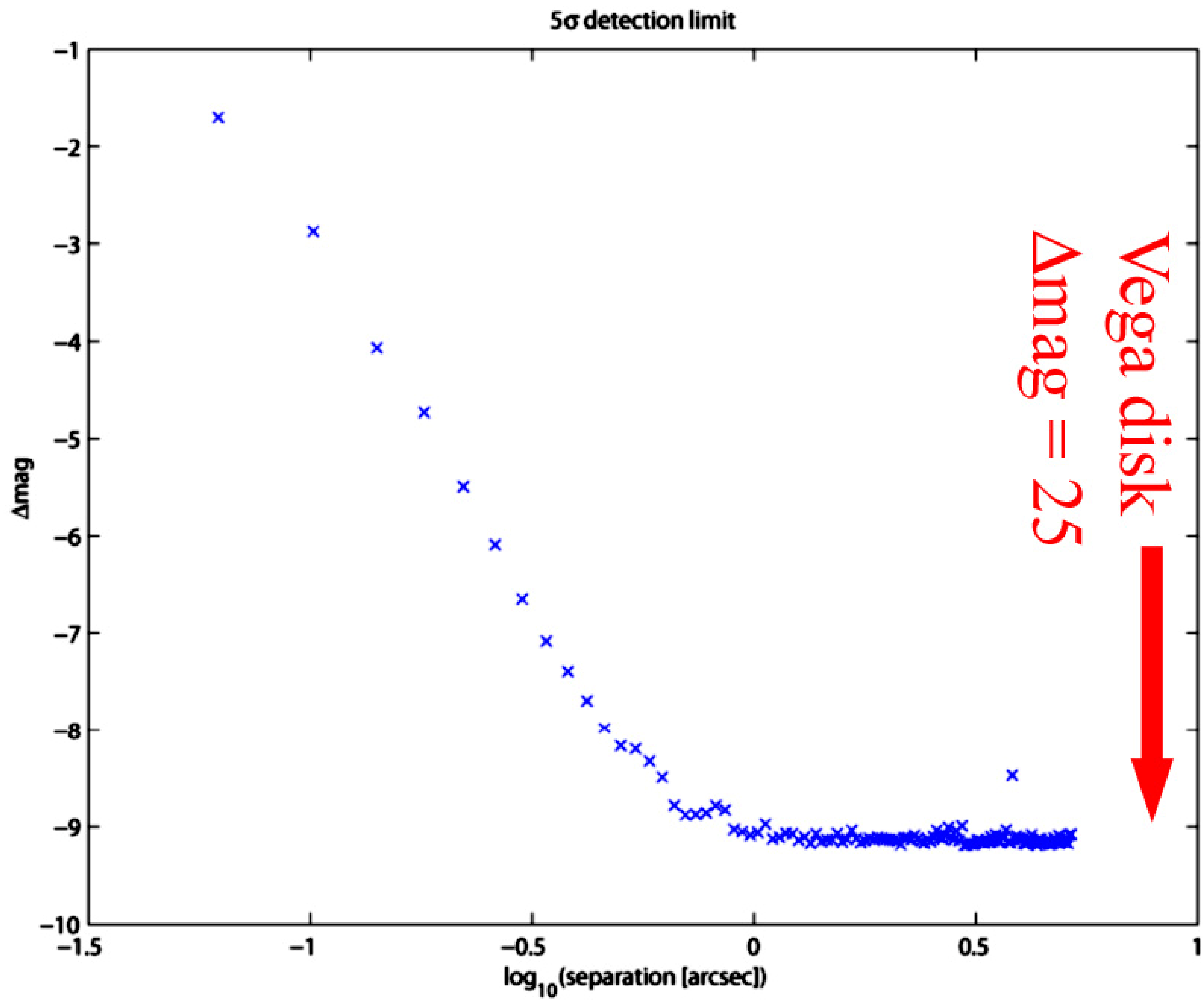
Discovery image by Smith & Terrile 1984
(Sci. 226, 1421)

Properties

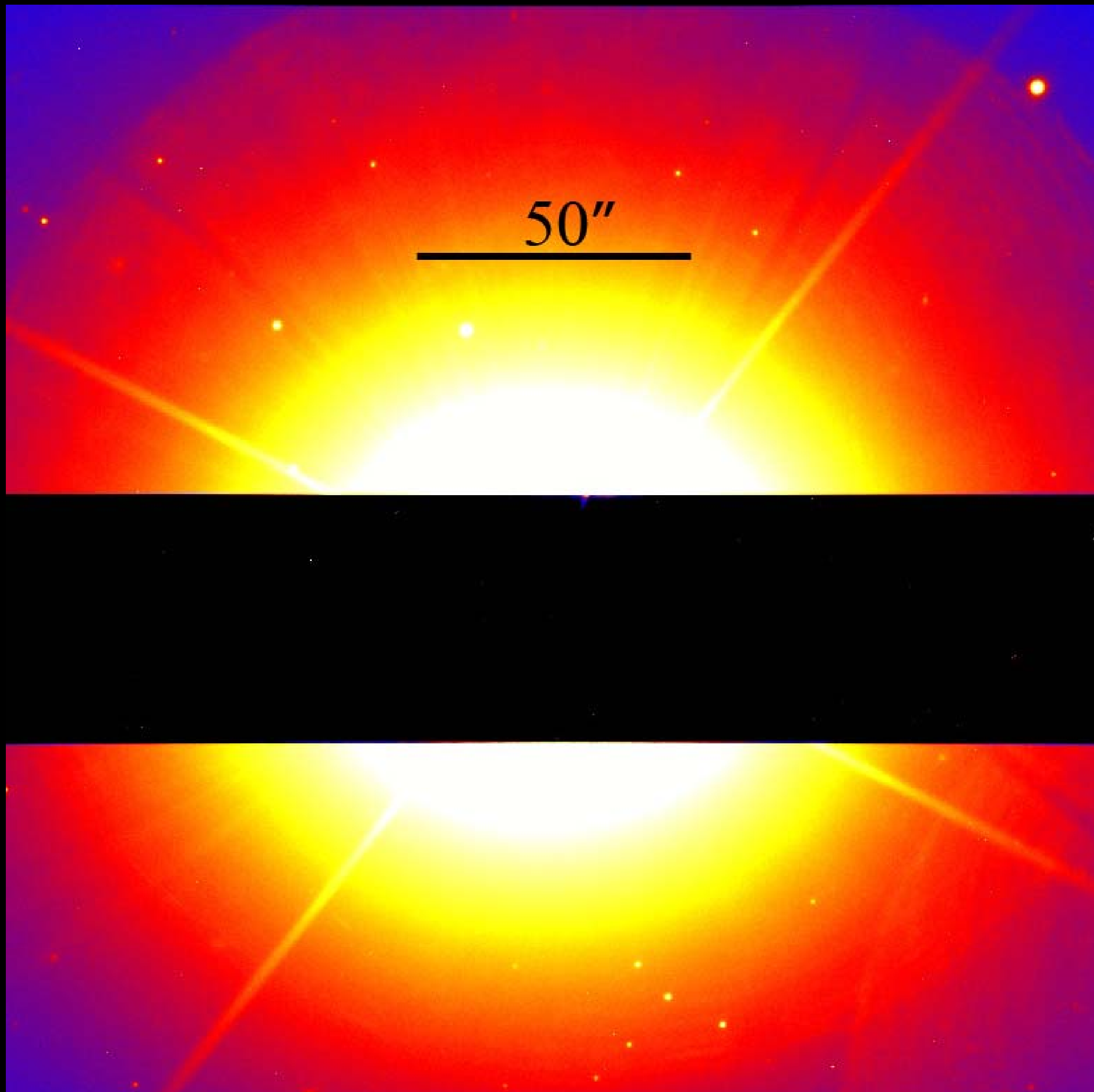
- Large (up to 1000 AU) dusty disks found around young main-sequence stars ~ 10 Myr – 1 Gyr
- Dust disk mass M ~ 10^{-3} to a few M_{Earth}.
- Essentially free of gas
- Cold; typically 30 – 300 K
- Dominating dust emission from μm to mm sized grains

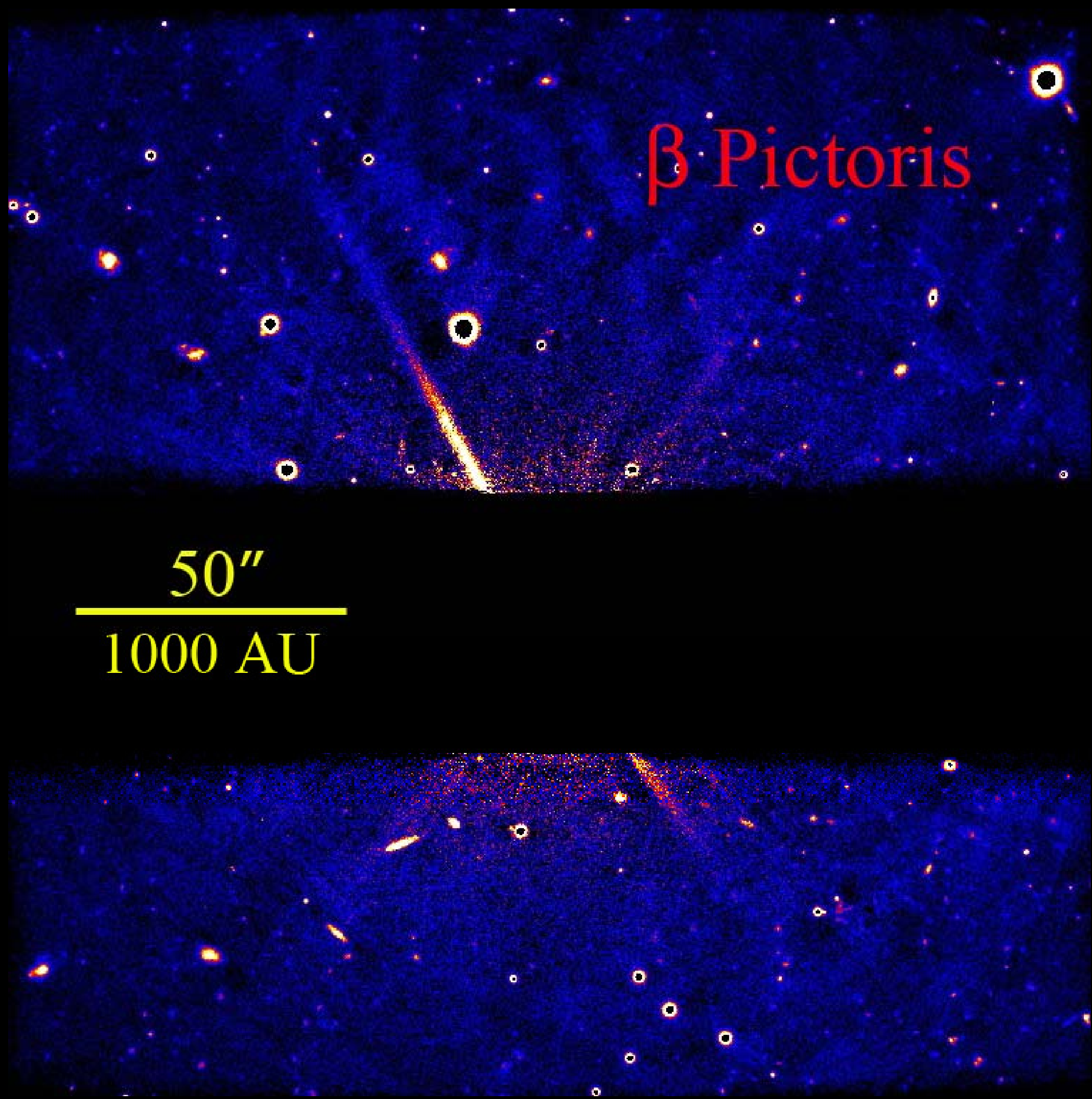


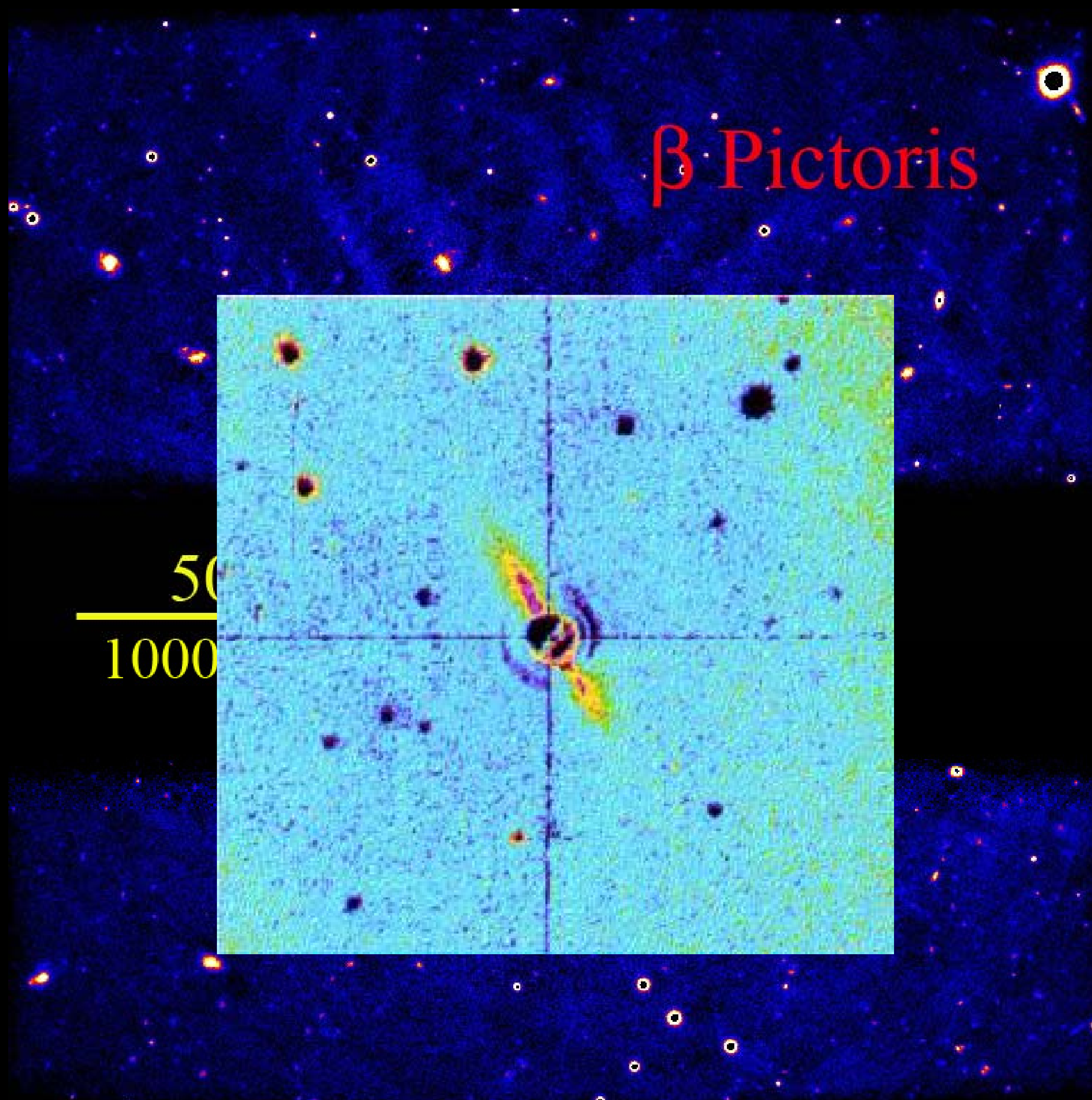
Observational difficulties



5σ detection limit
Δmag
log10(separation [arcsec])
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
−1.5
−1
−0.5
0
0.5
1
Vega disk
Δmag = 25

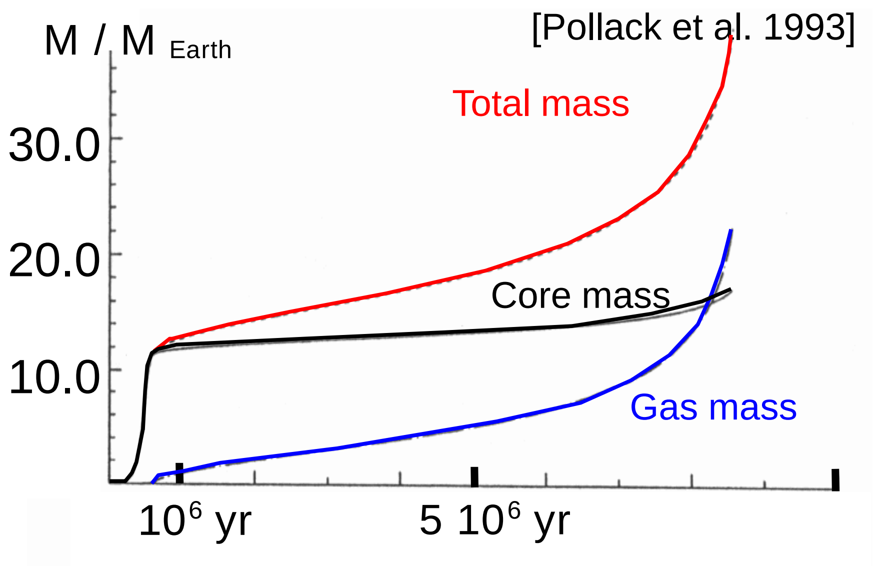

50″


β Pictoris
50″
1000 AU

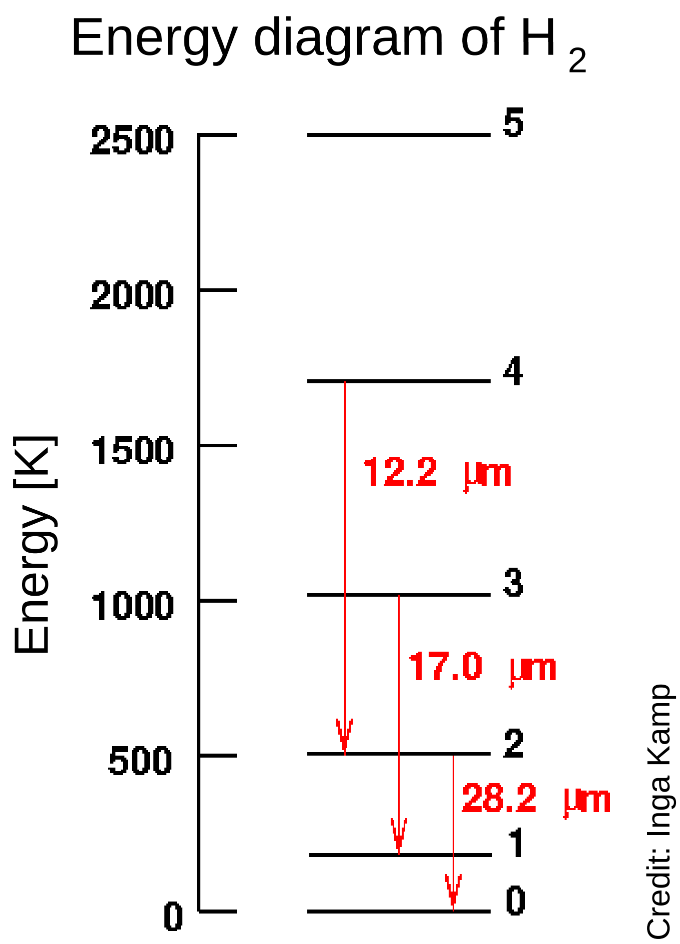

β Pictoris
50
1000

Late gas disk evolution?

- Young disks: gas/dust ~100 (?)
- Old disks: dust/gas ~100 (?)

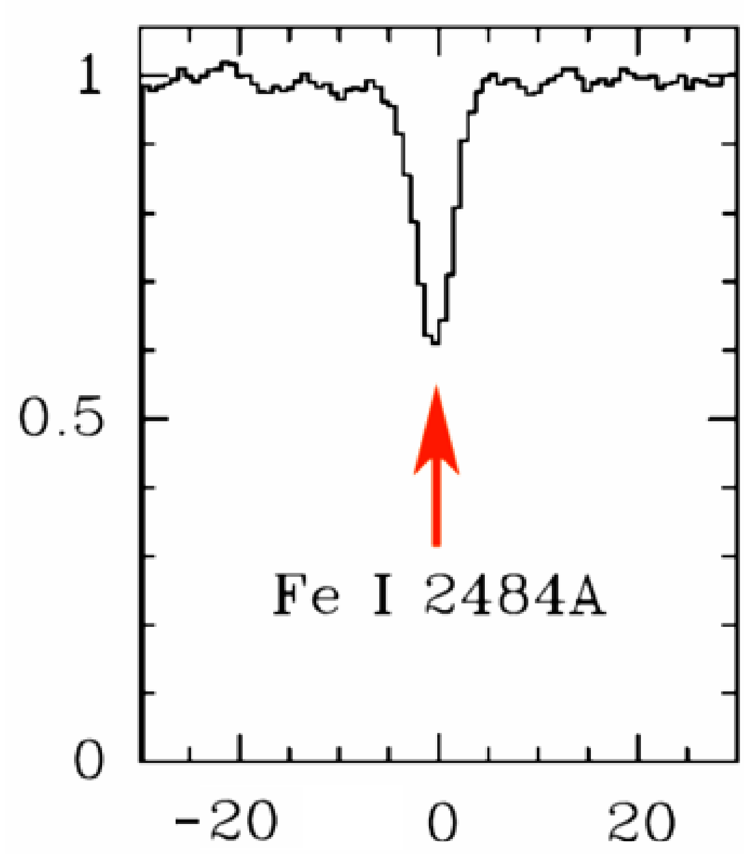


More observational difficulties



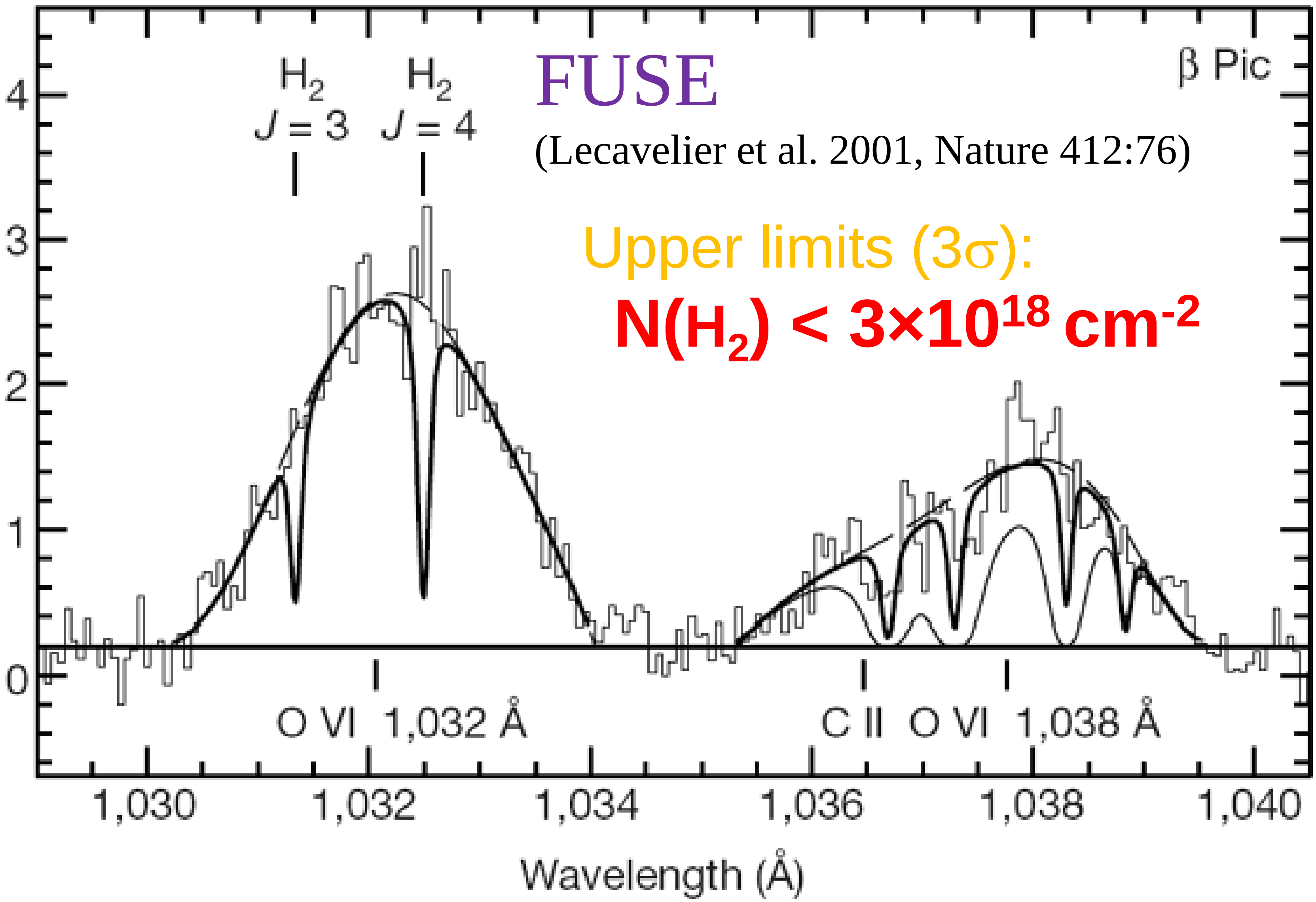
Favourable case: β Pictoris

- β Pictoris found to be “shell” star by Slettebak (1975, ApJ, 197:137)

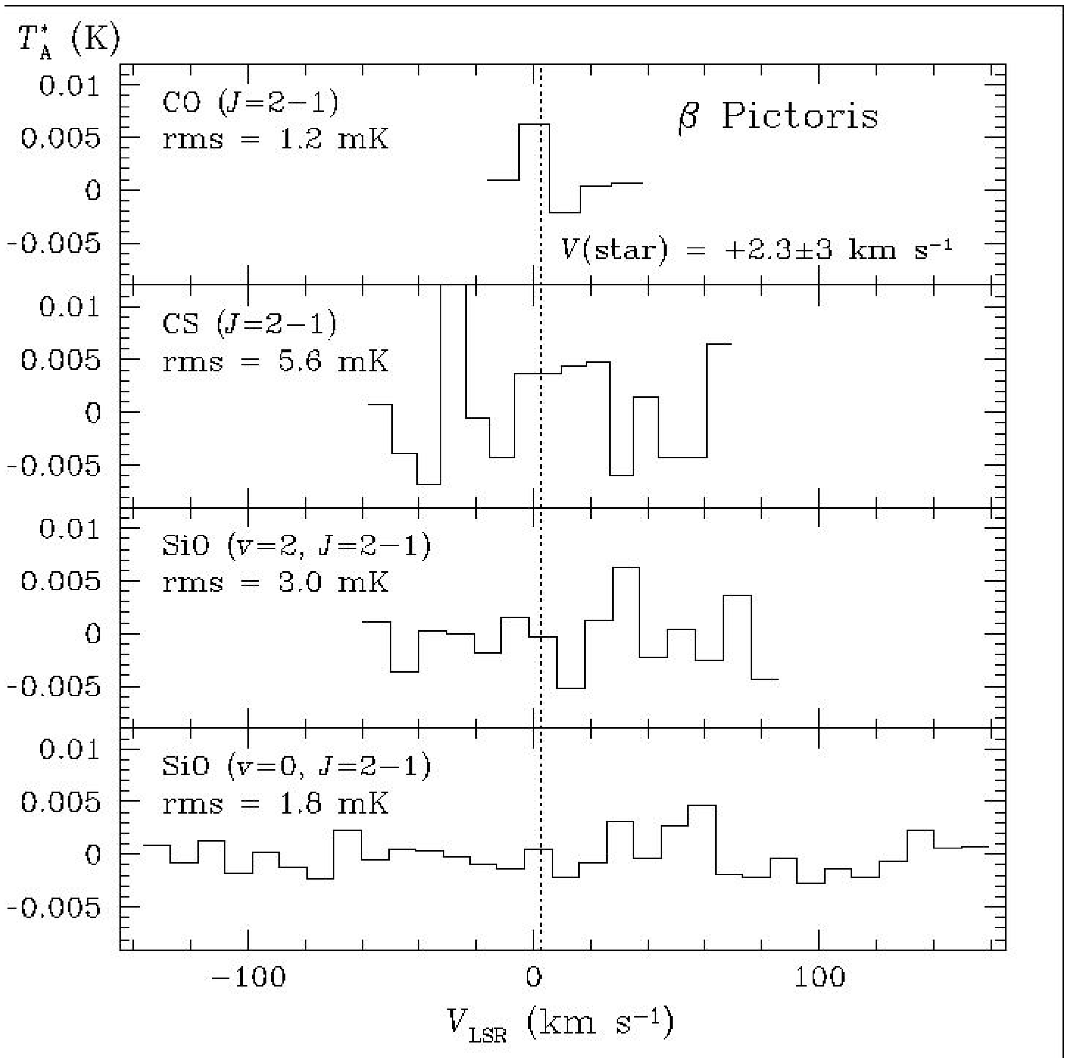


Lagrange et al. 1998, A&A 330:1091

Favourable case: β Pictoris

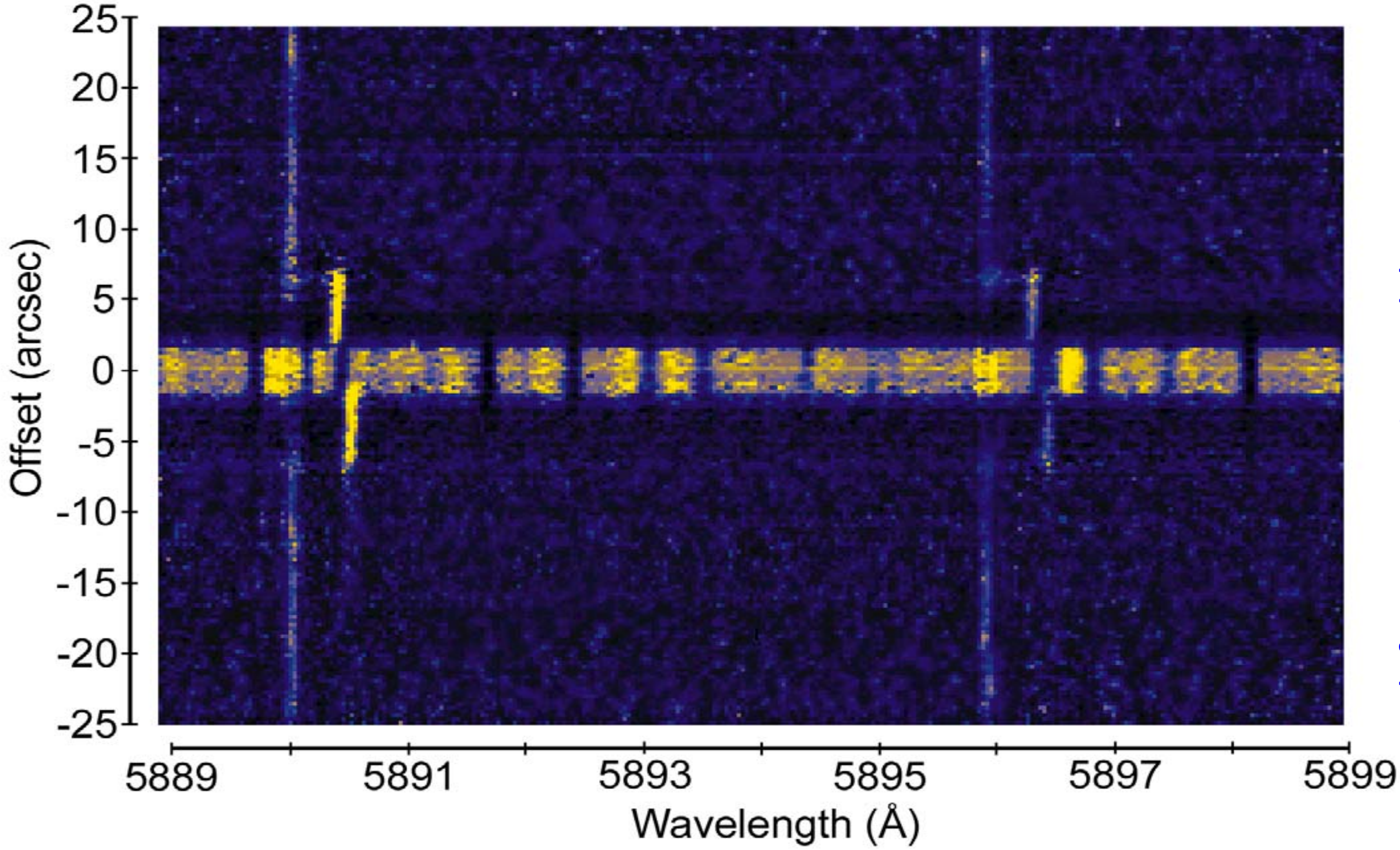


mm/submm observations



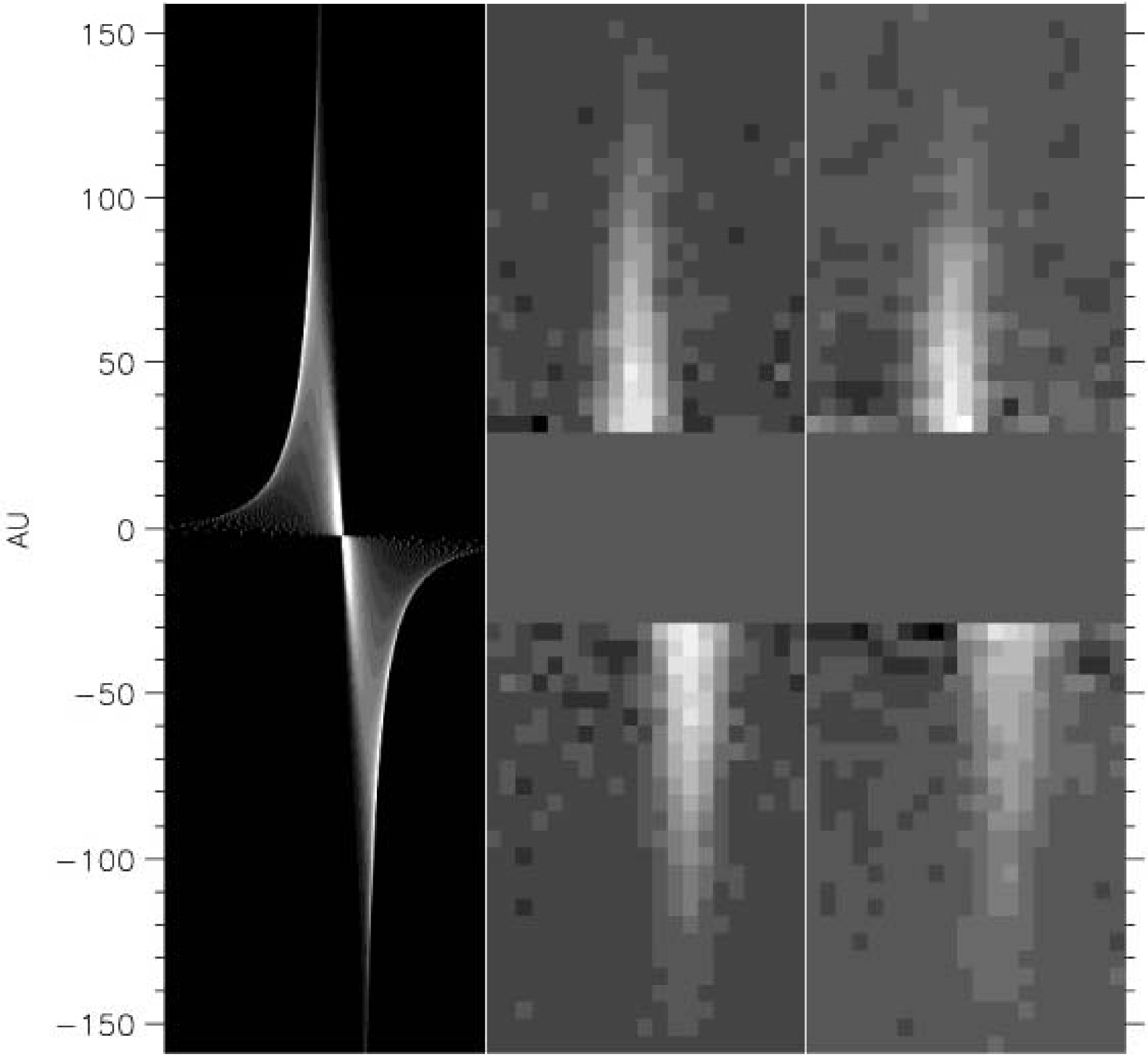
SEST Liseau & Artymowicz 1998, A&A 335, 935

Gas in emission



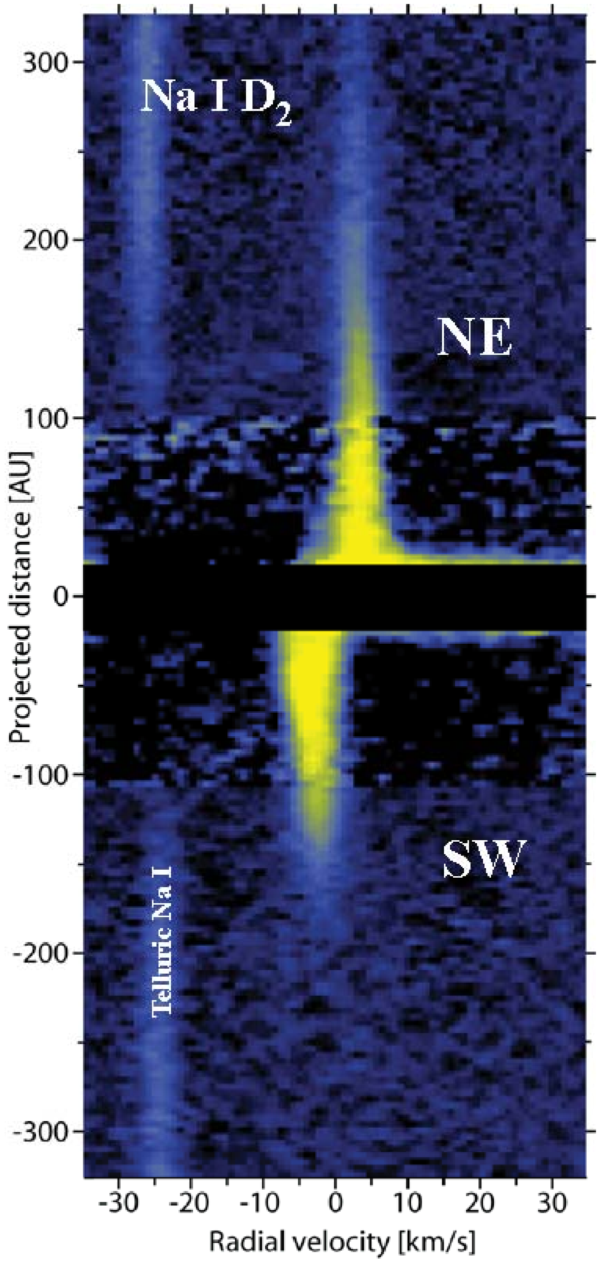
Olofsson, Liseau & Brandeker 2001, ApJL 563

Sodium D1/2 lines toward β Pictoris

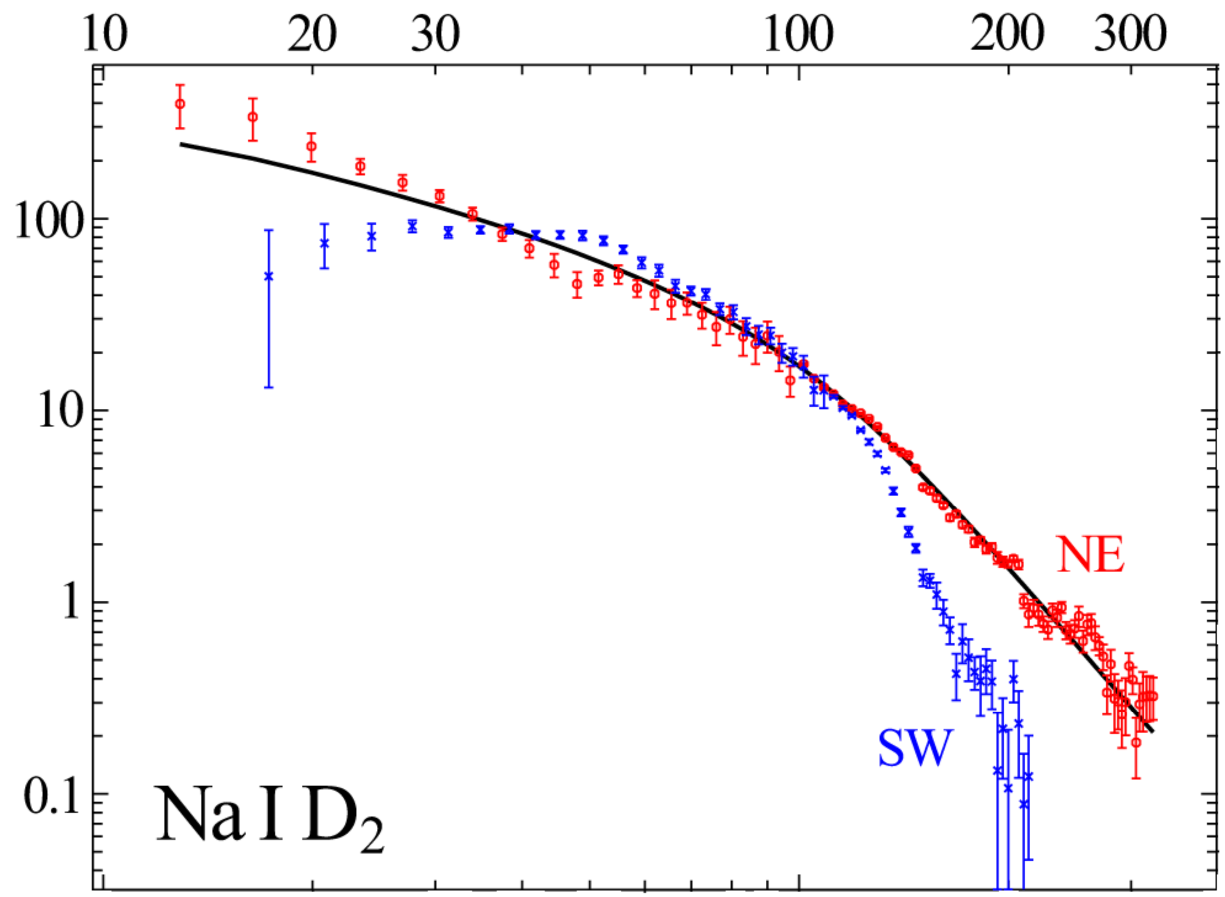


150
100
50
0
−50
−100
−150
AU

β Pictoris



Na I D2
NE
SW
Telluric Na I
300
200
100
0
-100
-200
-300
Projected distance [AU]
-30 -20 -10 0 10 20 30
Radial velocity [km/s]



10 20 30 100 200 300
100
10
1
0.1
NE
SW
Na I D2

Conclusions

- Circumstellar disks are a consequence of star formation
- Disks are the formation environments for planets
- Disk lifetimes dictate the timescale available for planet formation
- Disks start out gas rich and end up dust rich
- Accretion is intimately linked to outflow