Circumstellar disks

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Artwork: Griatch-art / Deviant Art

Outline

- Why circumstellar disks?
- Observational evidence
- Accretion processes (angular momentum, energy)
- Disk Spectral Energy Distribution (SED)
- Disk structure & evolution
- Debris disks
- Current and future research

Why circumstellar disks?

- Inevitable consequence of star formation
- They are observed
- Set the stage for planet formation
- Observable planet/disk interaction
- Constrain planet formation end result

Inevitable consequence?

I. Kant 1755

Allgemeine Naturgeschichte und Theorie des Himmels

P.S. Laplace 1796, 1799

Exposition du systeme du monde Mechanique celeste

Inevitable consequence?

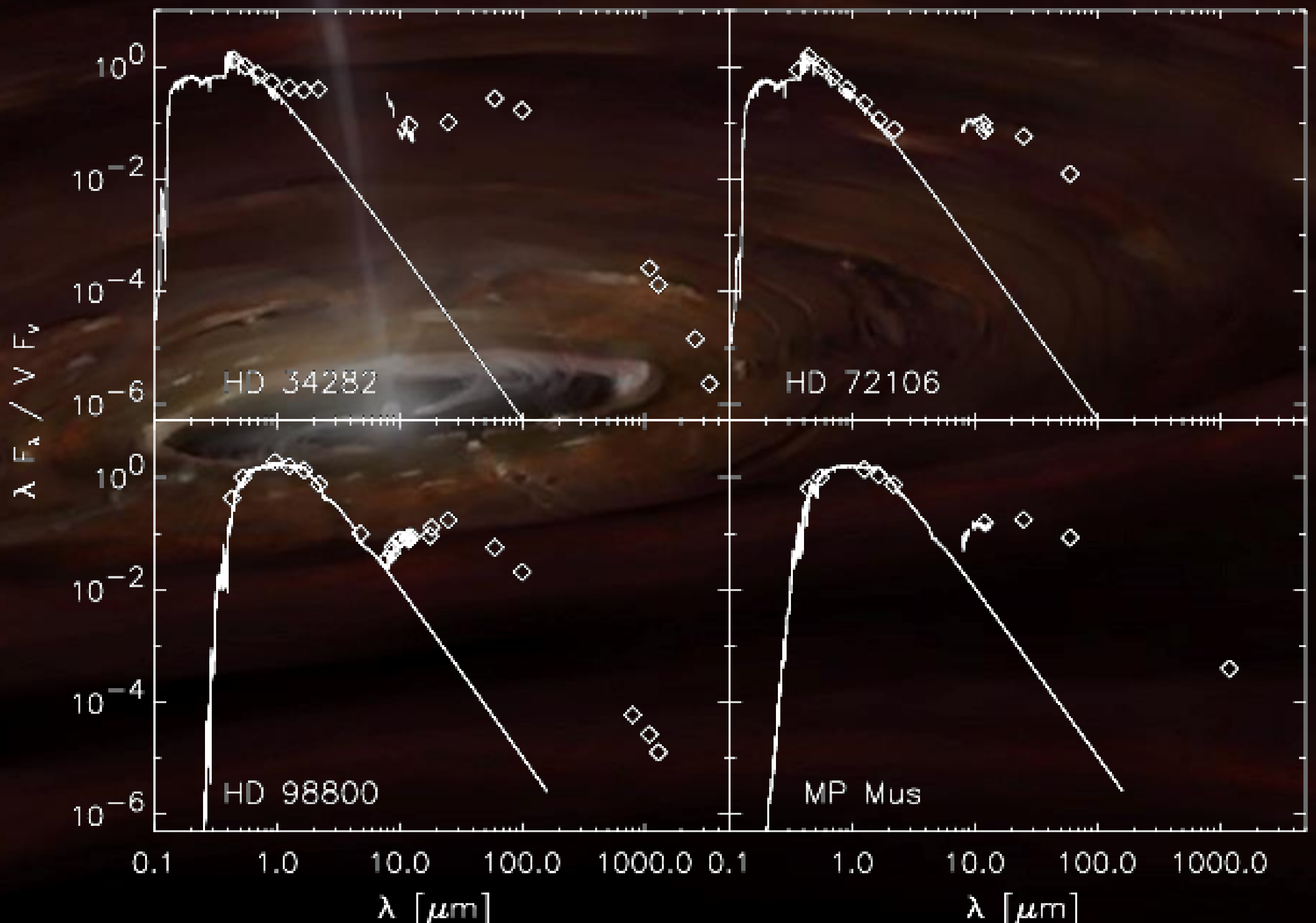
- *Conservation of angular momentum*:

$$\Omega_1 r_1^2 = L_1 = L_0 = \Omega_0 r_0^2$$

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

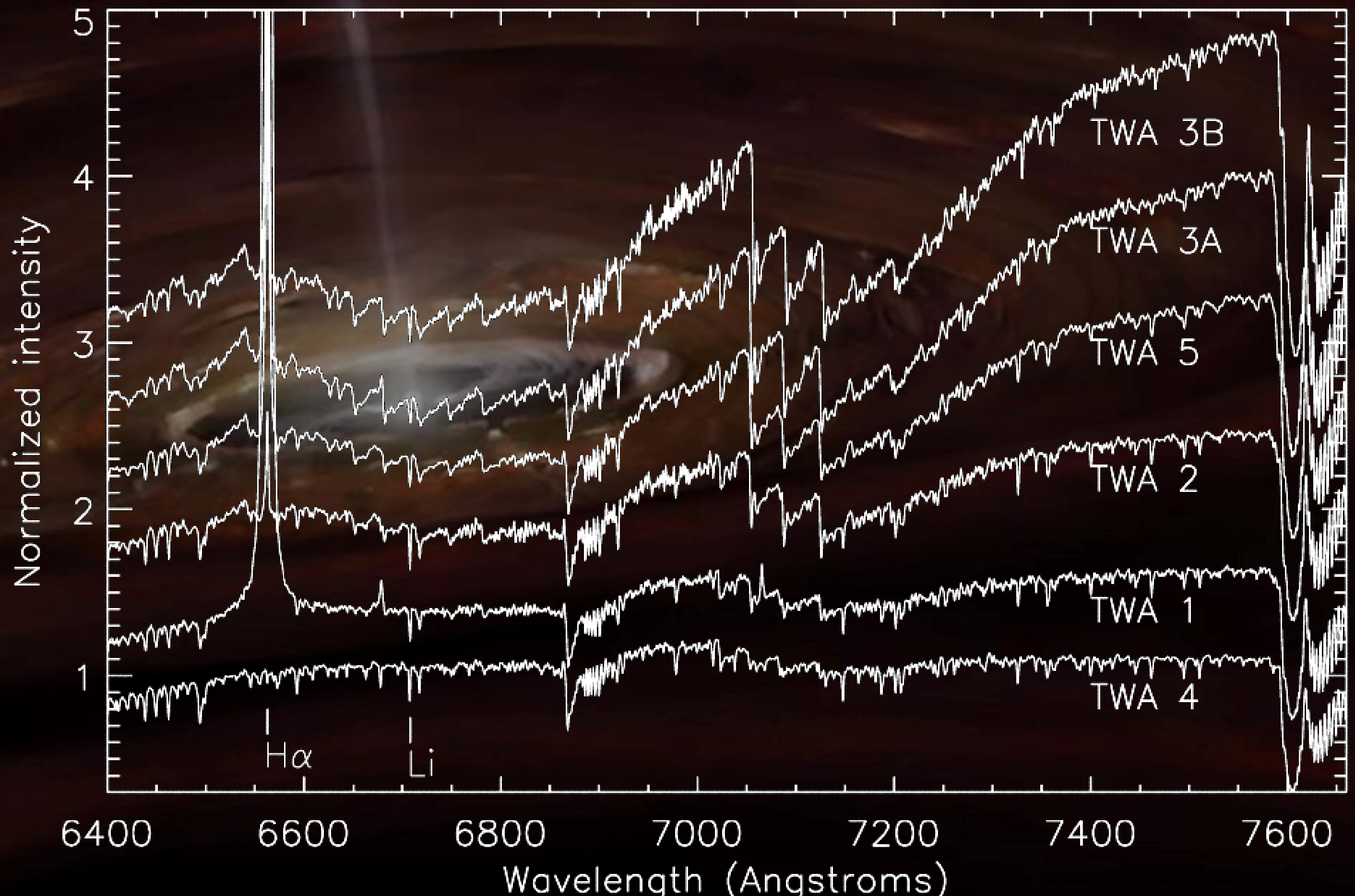
- Collapse compresses scale r from $r_0 \approx 0.2$ pc = 40000 AU to $r_0 \approx R_{sol} = 0.005$ AU $\rightarrow r_0/r_1 \approx 10^7$ and $\Omega_1 \approx 10^{14}\,\Omega_0$

Observation 1: IR excess



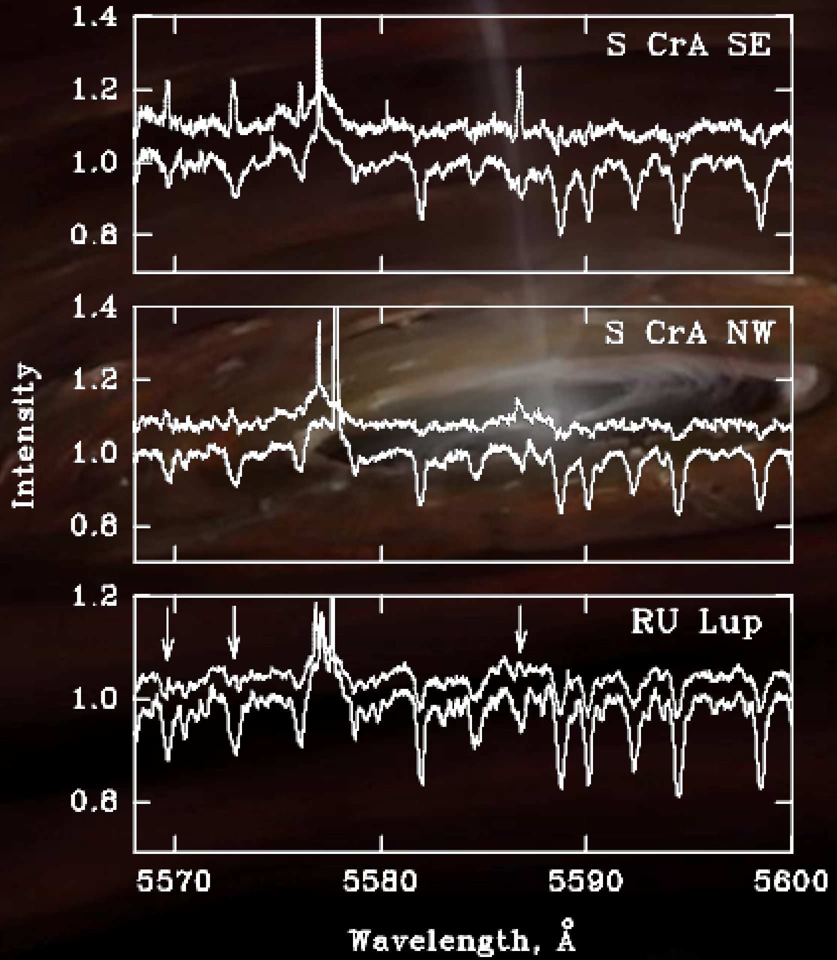
Schütz, Meeus & Sterzik (2005)

Observation 2: **Strong emission lines**



Webb et al. (1999)

Observation 3: **Veiling**



Gahm et al. (2008)

And more:

- UV excess
- X-ray activity
- Li abundance
- Variability
- …

Predictions of disks

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

Keplerian Disk

Differential Rotation
+
Viscosity

Mass Transport Inwards
Angular Momentum Transport Outwards

Disk accretion

Angular momentum:

$$L = m_1 v_1 r_1 + m_2 v_2 r_2$$

$$v = \sqrt{\frac{GM}{r}} \Rightarrow$$

$$L = (GM)^{1/2}\left(m_1 r_1^{1/2} + m_2 r_2^{1/2}\right)$$

Lee Hartmann (2008)

Disk accretion

Introduce small perturbation Δr:

$$r_i' = r_i + \Delta r_i$$

Use $(r+\Delta r)^{1/2} \approx r^{1/2}\left(1+\frac{\Delta r}{2r}\right)$

and that $L = L'$:

$$(GM)^{1/2}\left(m_1 r_1^{1/2} + m_2 r_2^{1/2}\right) =$$
$$(GM)^{1/2}\left[m_1 (r_1+\Delta r_1)^{1/2} + m_2 (r_2+\Delta r_2)^{1/2}\right]$$

or

$$m_1 r_1^{-1/2} \Delta r_1 = -m_2 r_2^{-1/2} \Delta r_2$$

Disk accretion

Energy:

$$E = -\frac{GM}{2}\left(\frac{m_1}{r_1} + \frac{m_2}{r_2}\right)$$

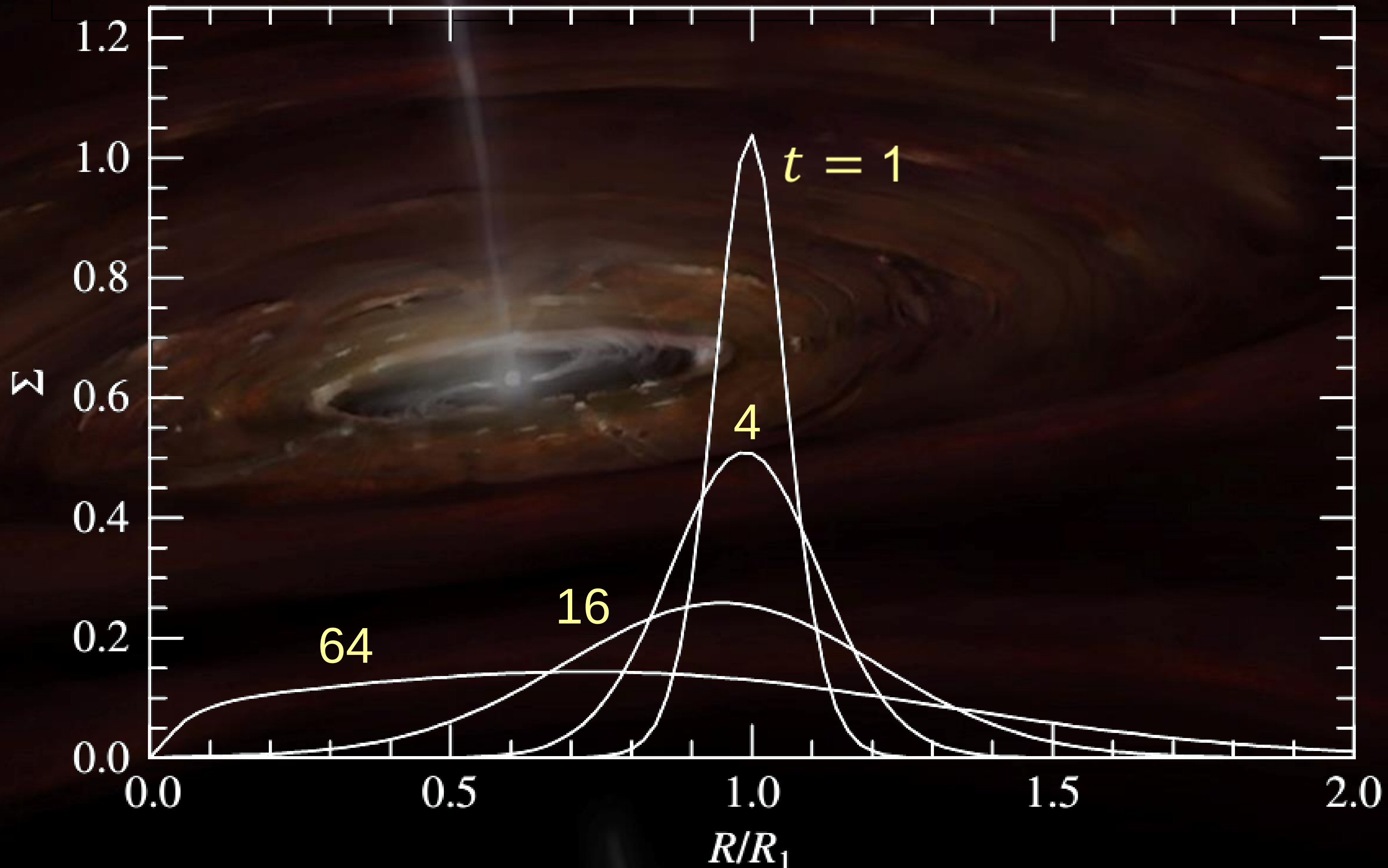
With

$$\frac{1}{r + \Delta r} \approx r^{-1}\left(1 - \frac{\Delta r}{r}\right)$$

we get

$$\Delta E = -\frac{GMm_1\Delta r_1}{2r_1^2}\left[\left(\frac{r_1}{r_2}\right)^{3/2} - 1\right]$$

Disk accretion



Sources of viscosity

- Viscous gas
- Turbulent motions
- Gravitational torques
- Magnetic fields
  - Magneto-rotational instability (MRI, “Balbus-Hawley”)

Disk temperature: accretion

$$\frac{GM_*\dot{M}}{2R}\frac{\Delta R}{R} \sim 2 \times 2\pi R \Delta R \sigma T_{\mathrm{d}}^4$$

$$T_{\mathrm{d}} \sim \left(\frac{GM_*\dot{M}}{8\pi\sigma R^3}\right)^{1/4}$$

Disk temperature: irradiation

$$\frac{L_*}{4\pi R^2}\langle\cos\gamma\rangle \sim \sigma T_{\mathrm{d}}^4$$

$$\langle\cos\gamma\rangle \sim \frac{R_*}{R}$$

$$T_d \sim \left(\frac{L_* R_*}{4\pi\sigma R^3}\right)^{1/4}$$

Disk temperature

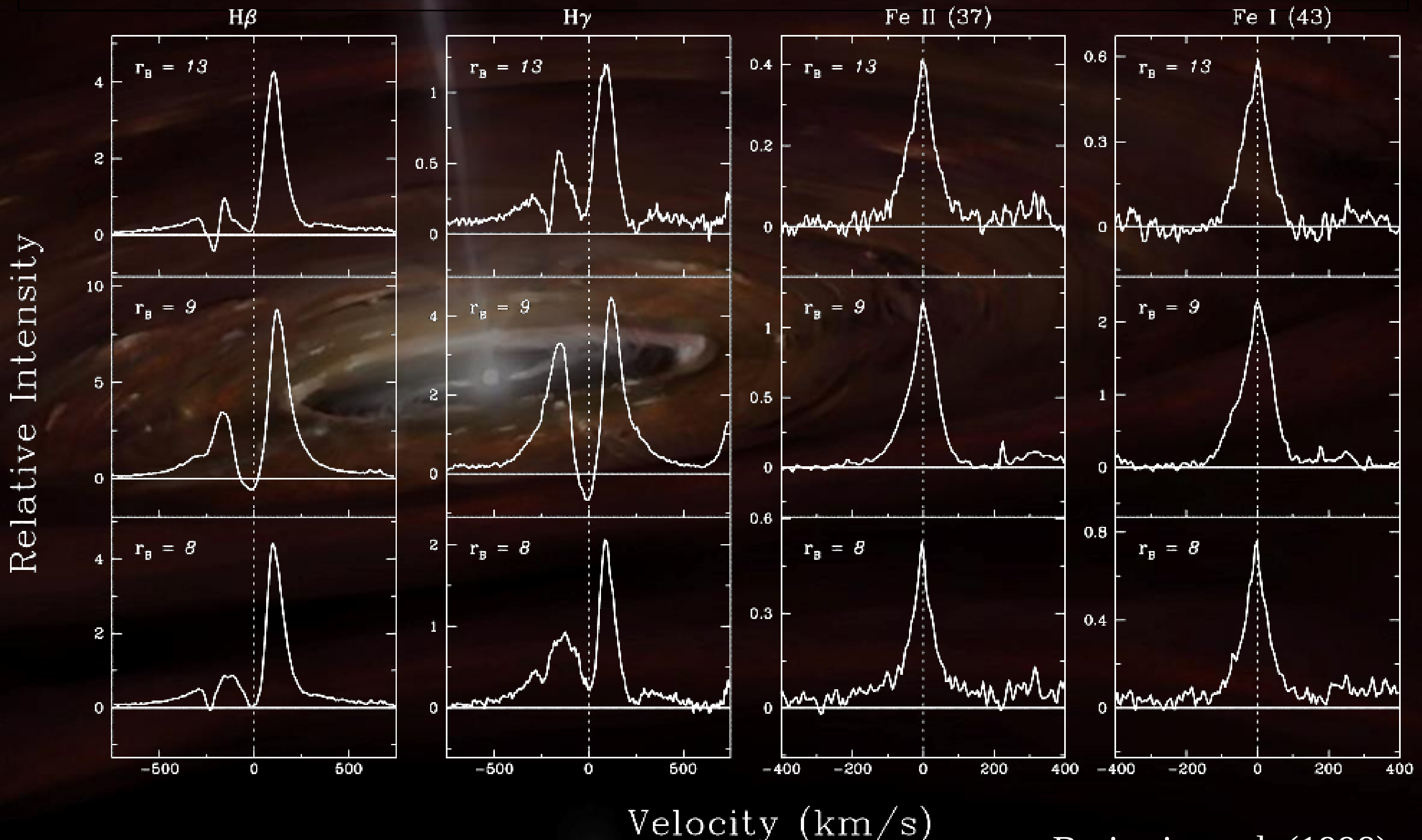
Accretion dominating when

$$\frac{GM_*\dot{M}}{R_*} > L_*$$

Example: for solar-like star, this happens when

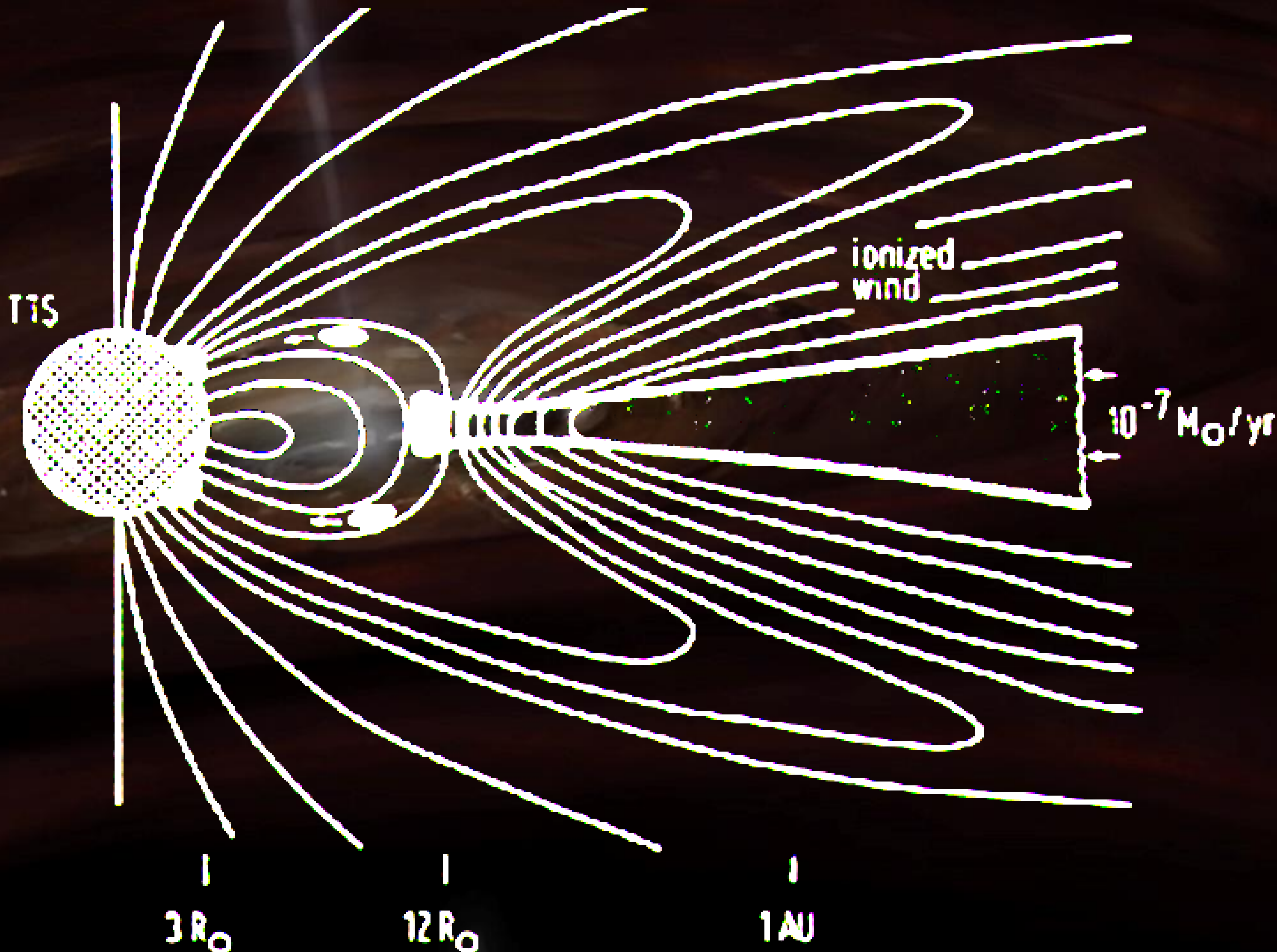
$$\dot{M} > 3 \times 10^{-8} M_* \mathrm{yr}^{-1}$$

Line variability



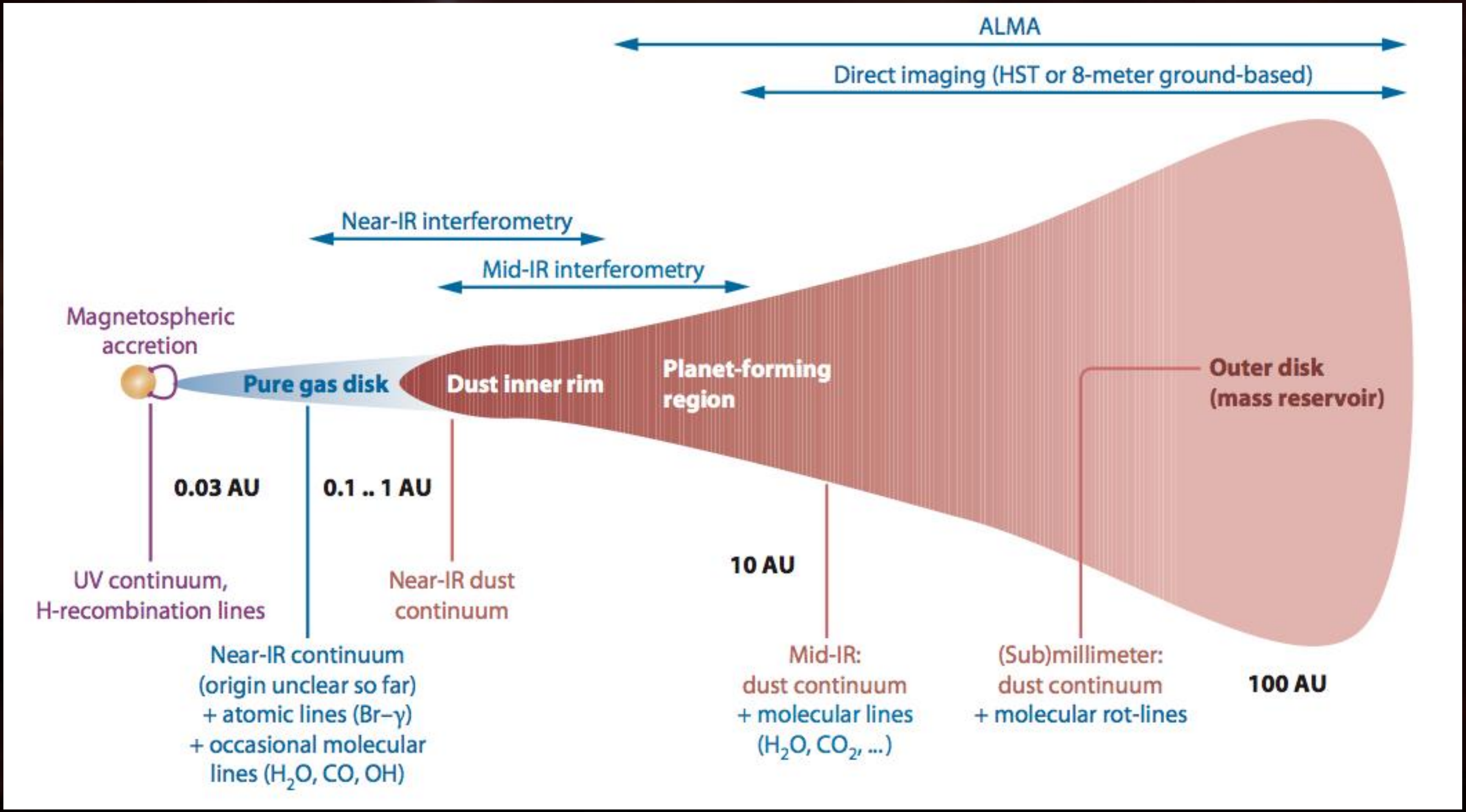
Beristain et al. (1998)

Accretion signatures



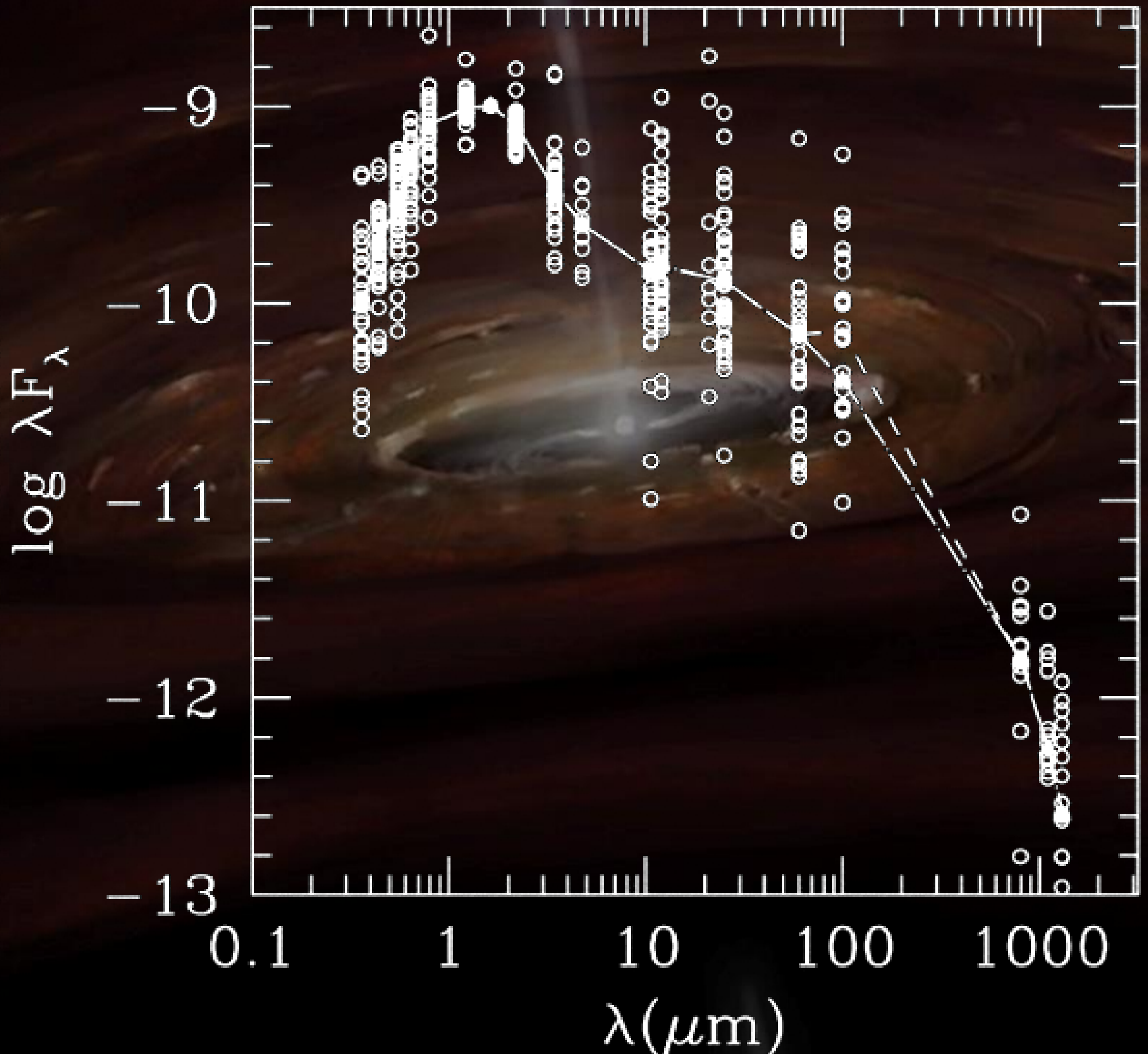
From Camenzind (1990)

Disk structure

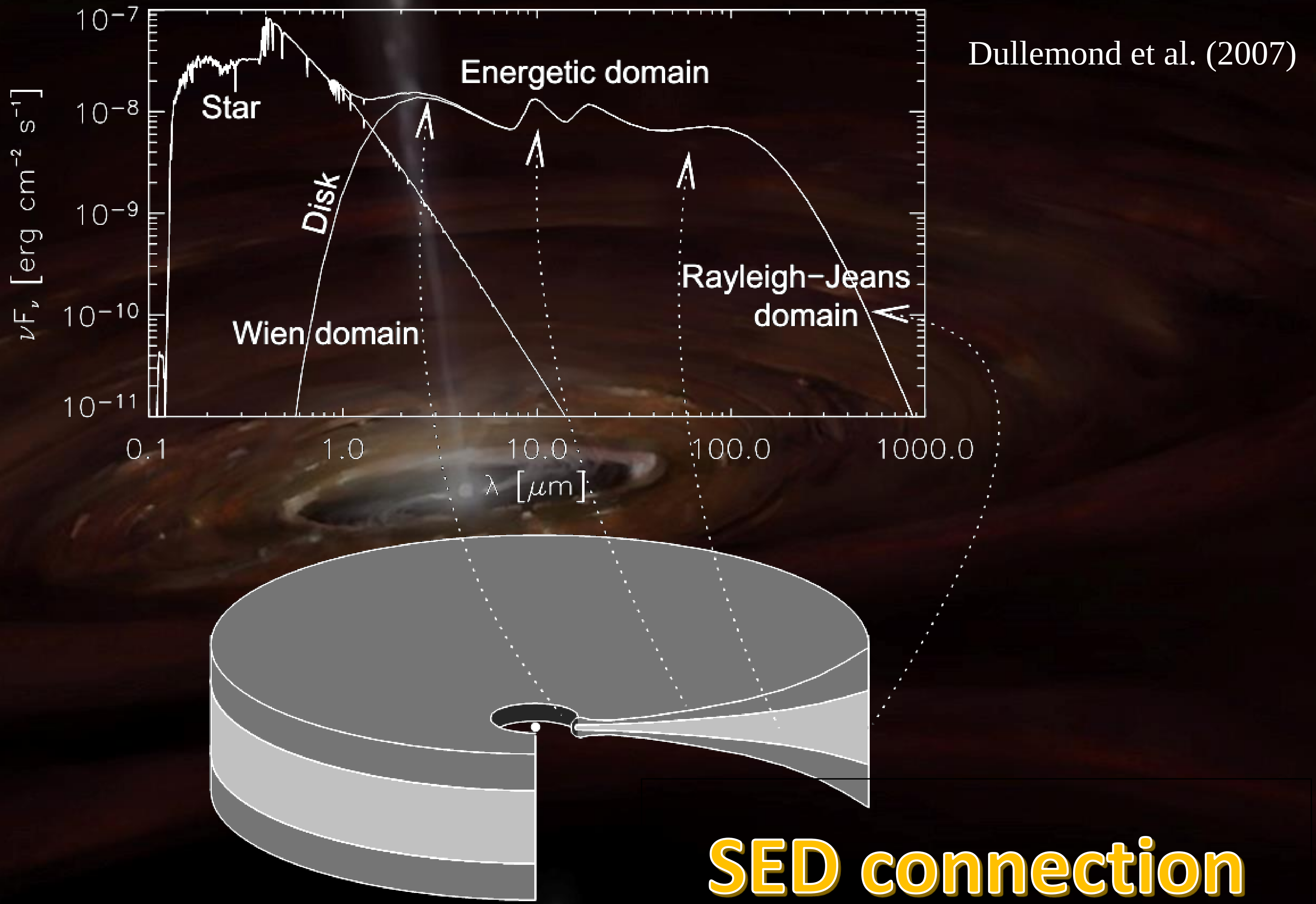


Dullemond & Monnier (2010)

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

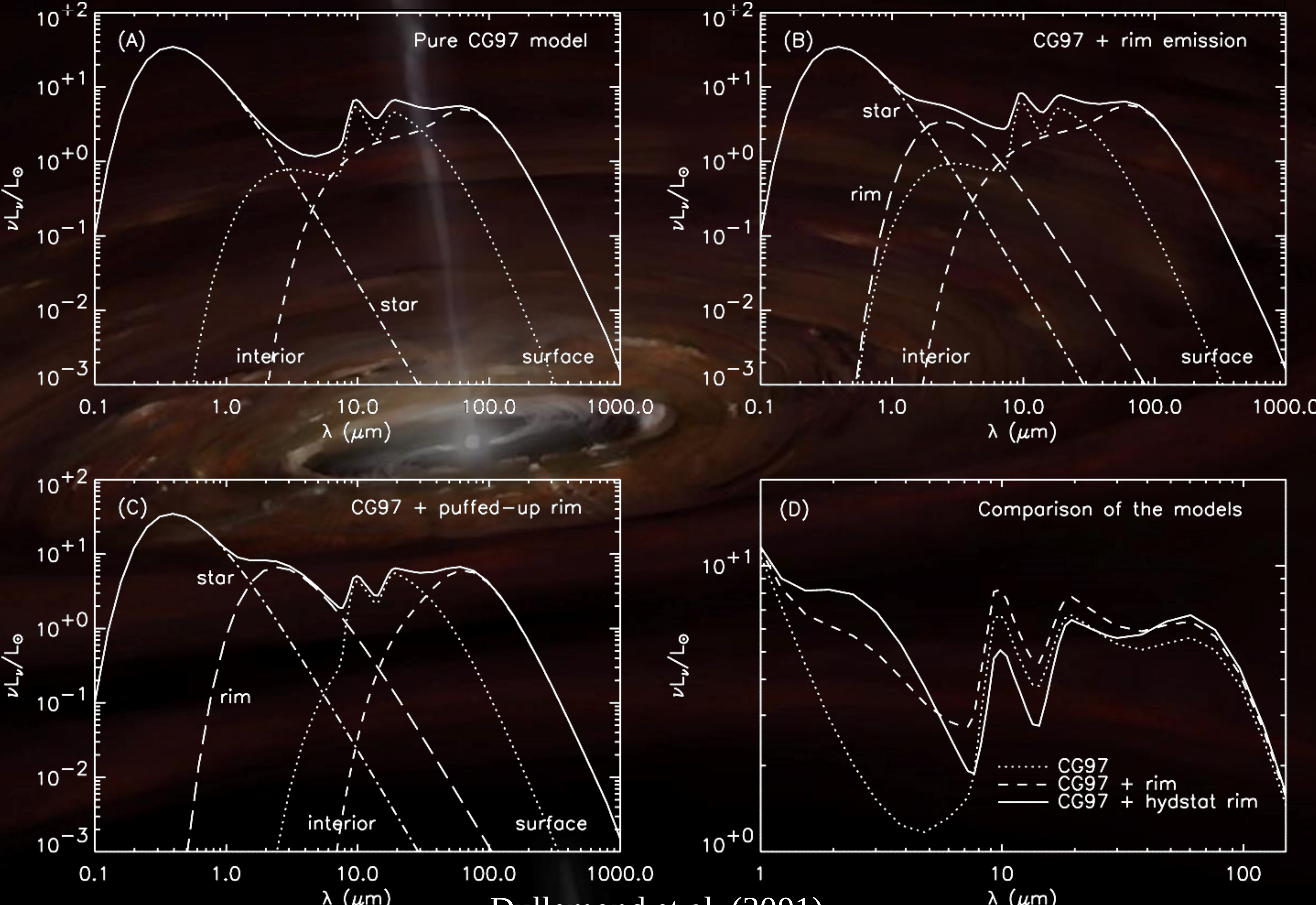


HABE Disk Structure:
Dullemond & Dominik 2004
D´Alessio et al. 1999



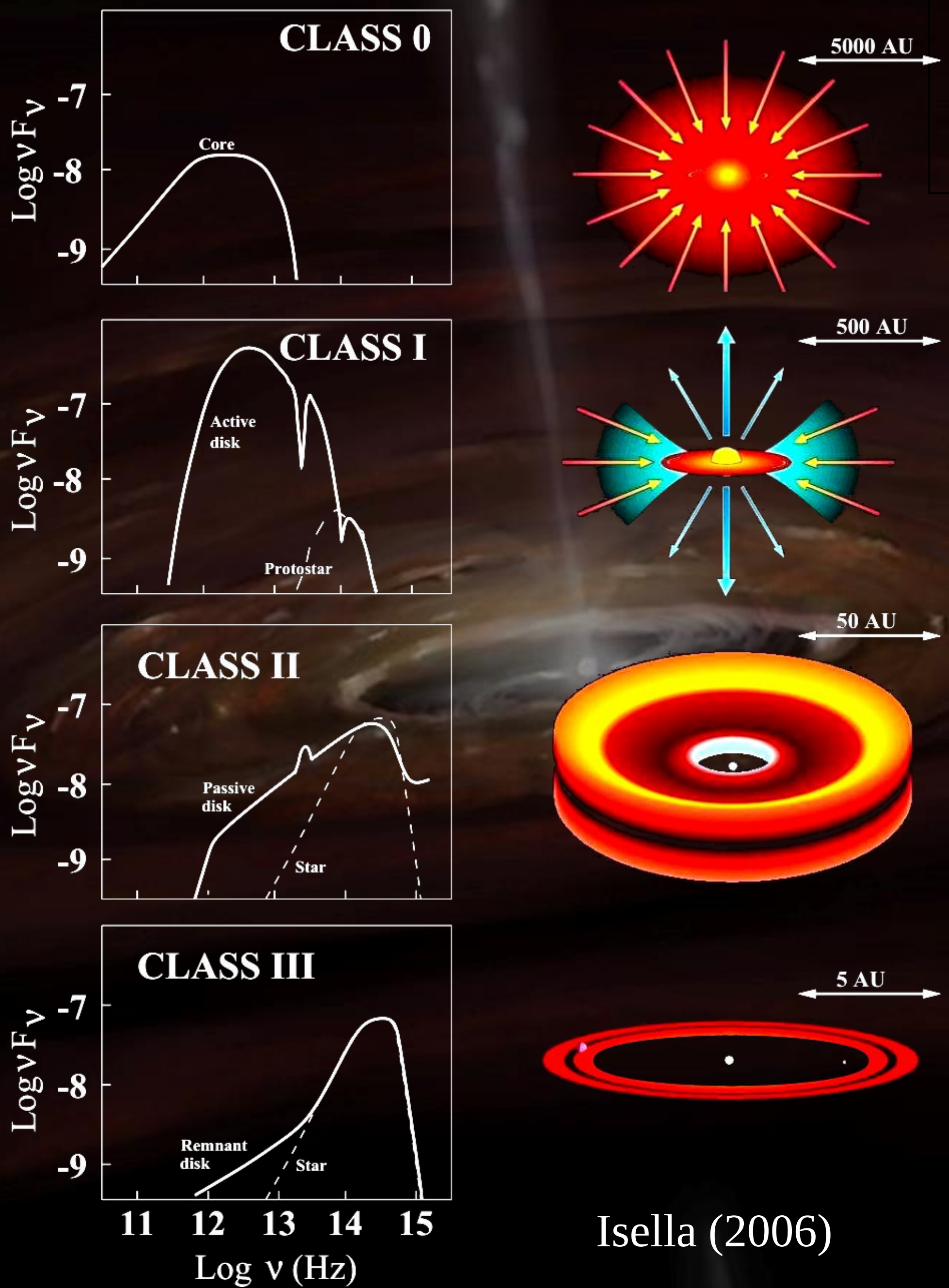
SED connection

SED connection



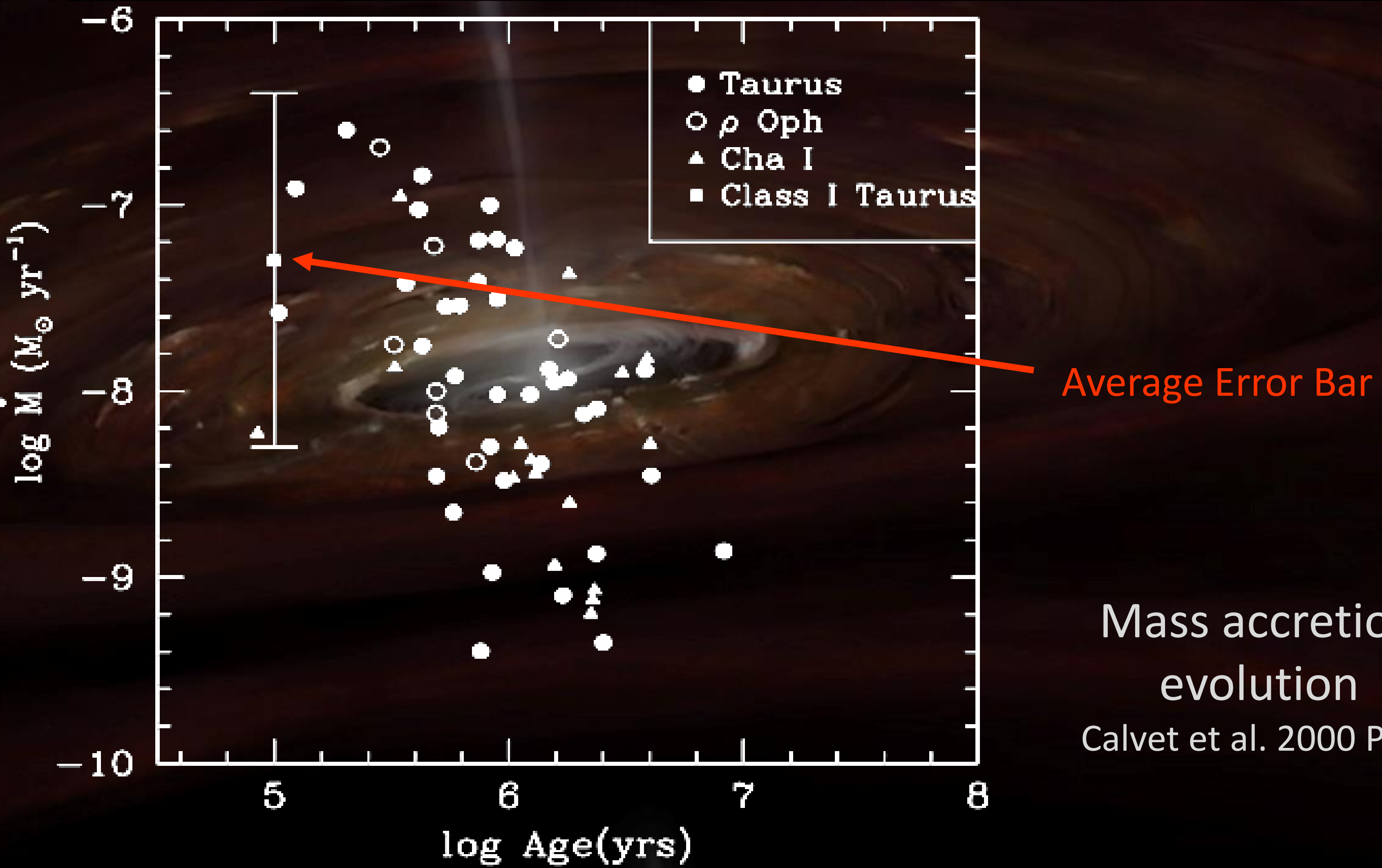
Dullemond et al. (2001)

Classification



Isella (2006)

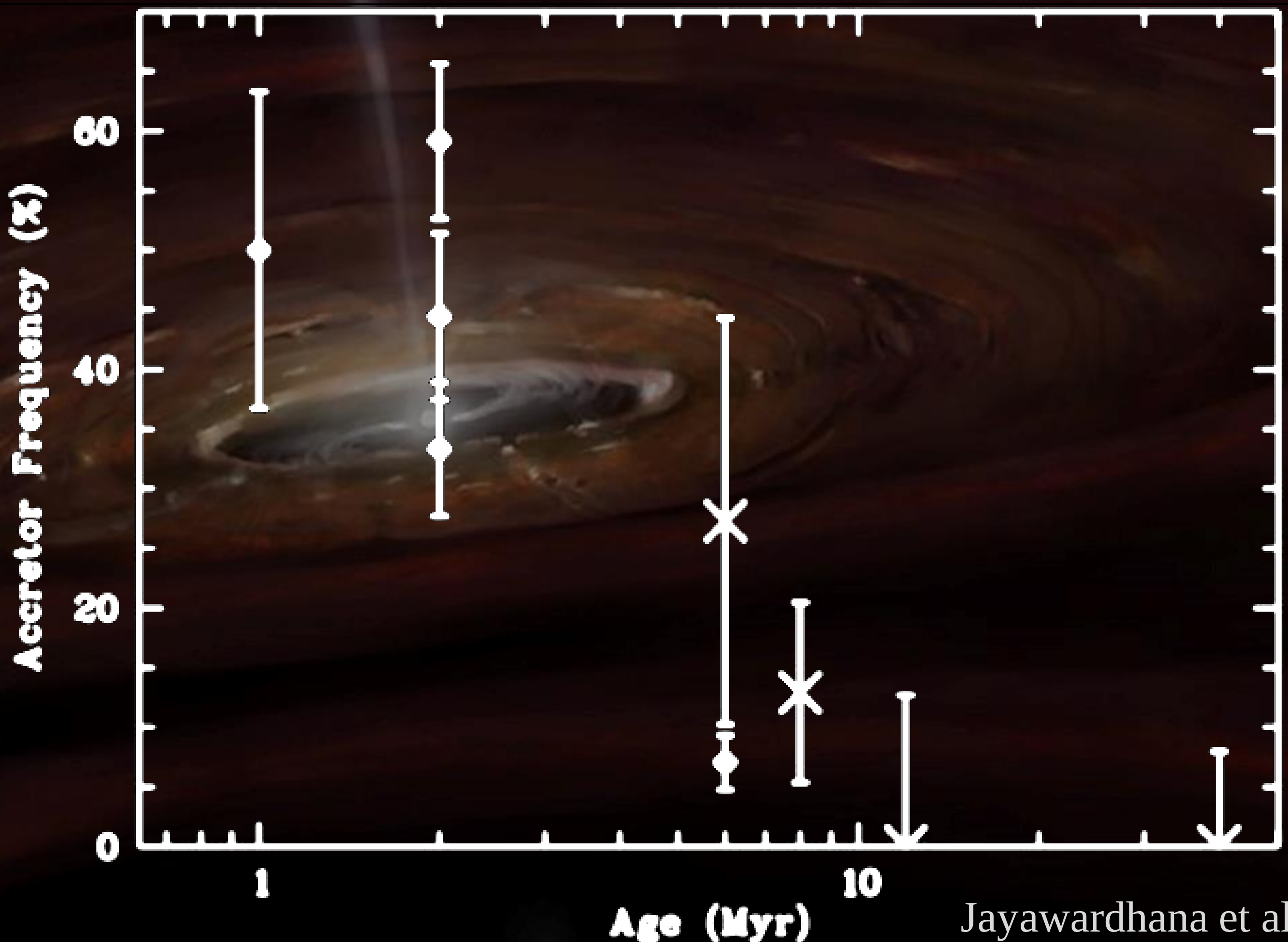
Disk lifetimes



Mass accretion evolution

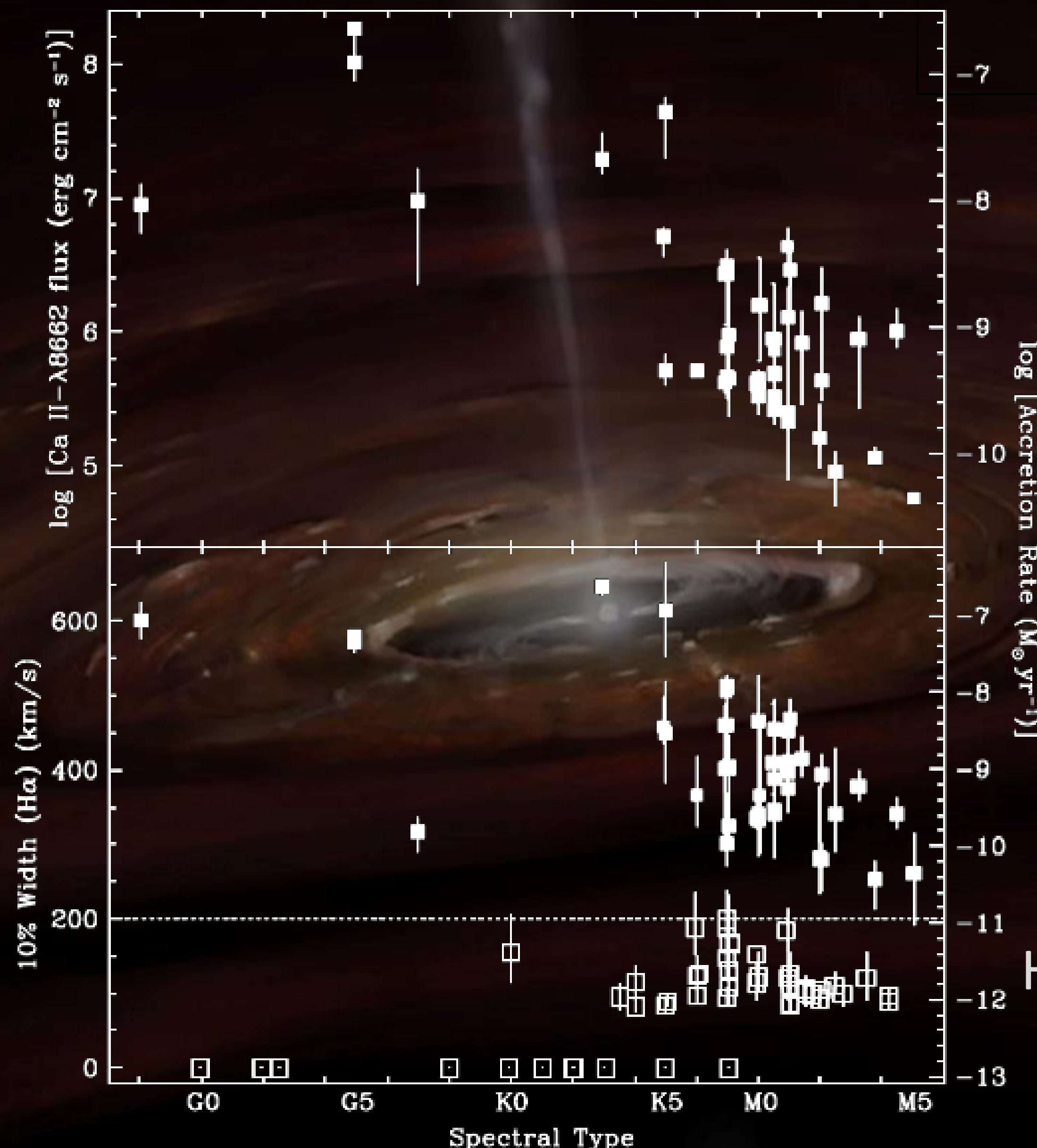
Calvet et al. 2000 PPIV

Disk lifetimes



Jayawardhana et al. (2006)

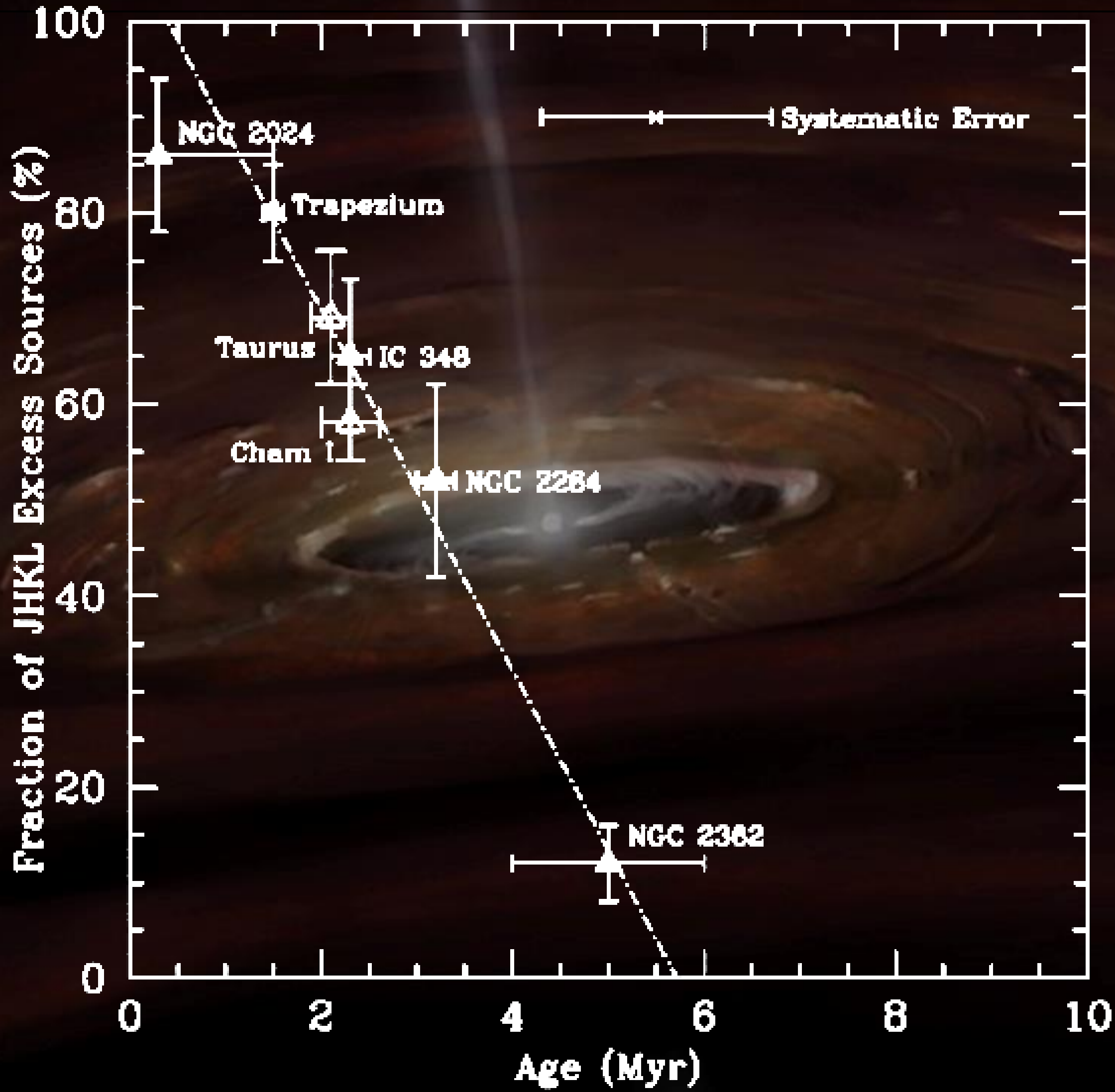
Disk lifetimes



How variable is accretion in young stars?

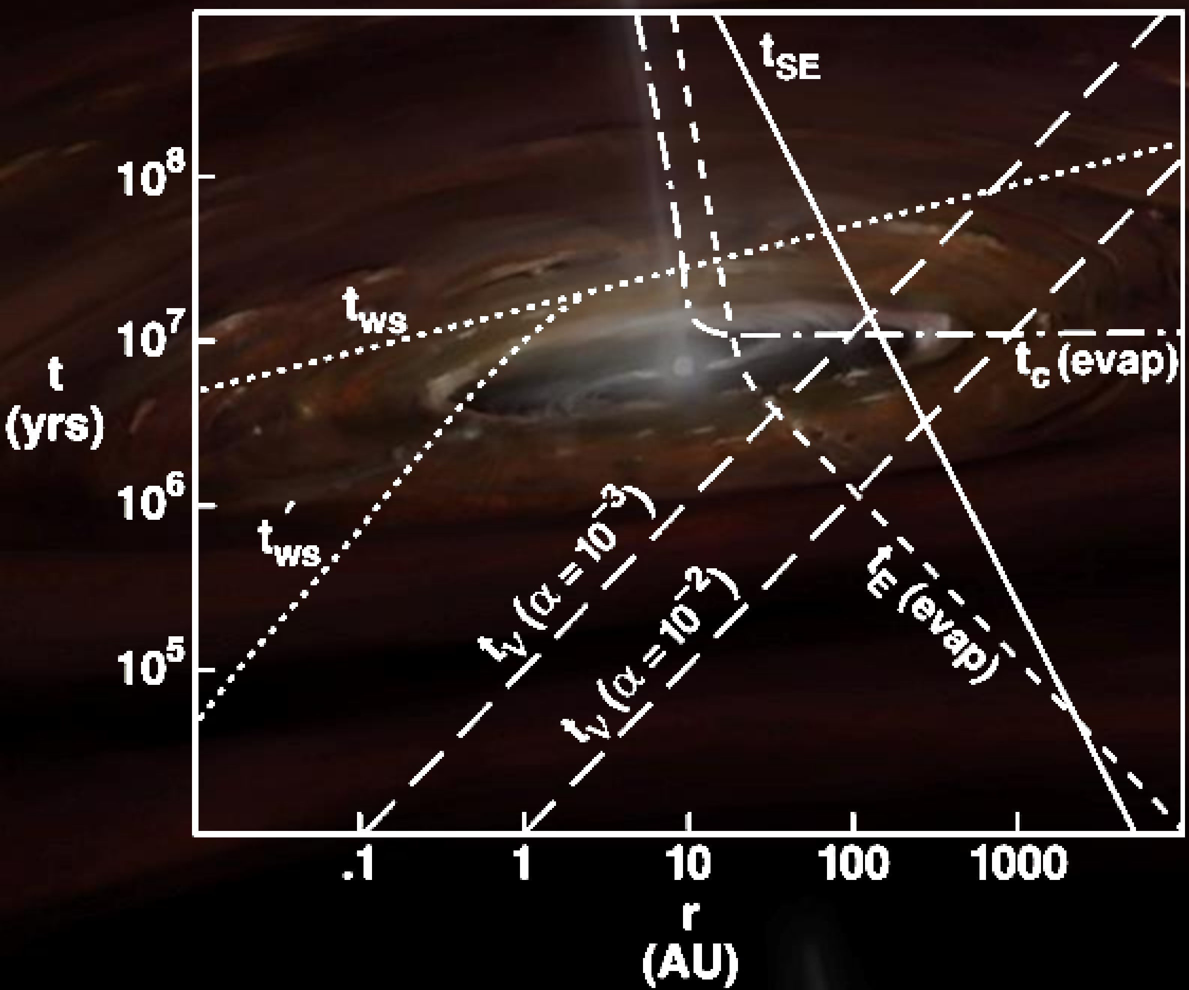
Nguyen et al. (2009)

Frequency of disks



Haisch, Lada & Lada (2001)

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

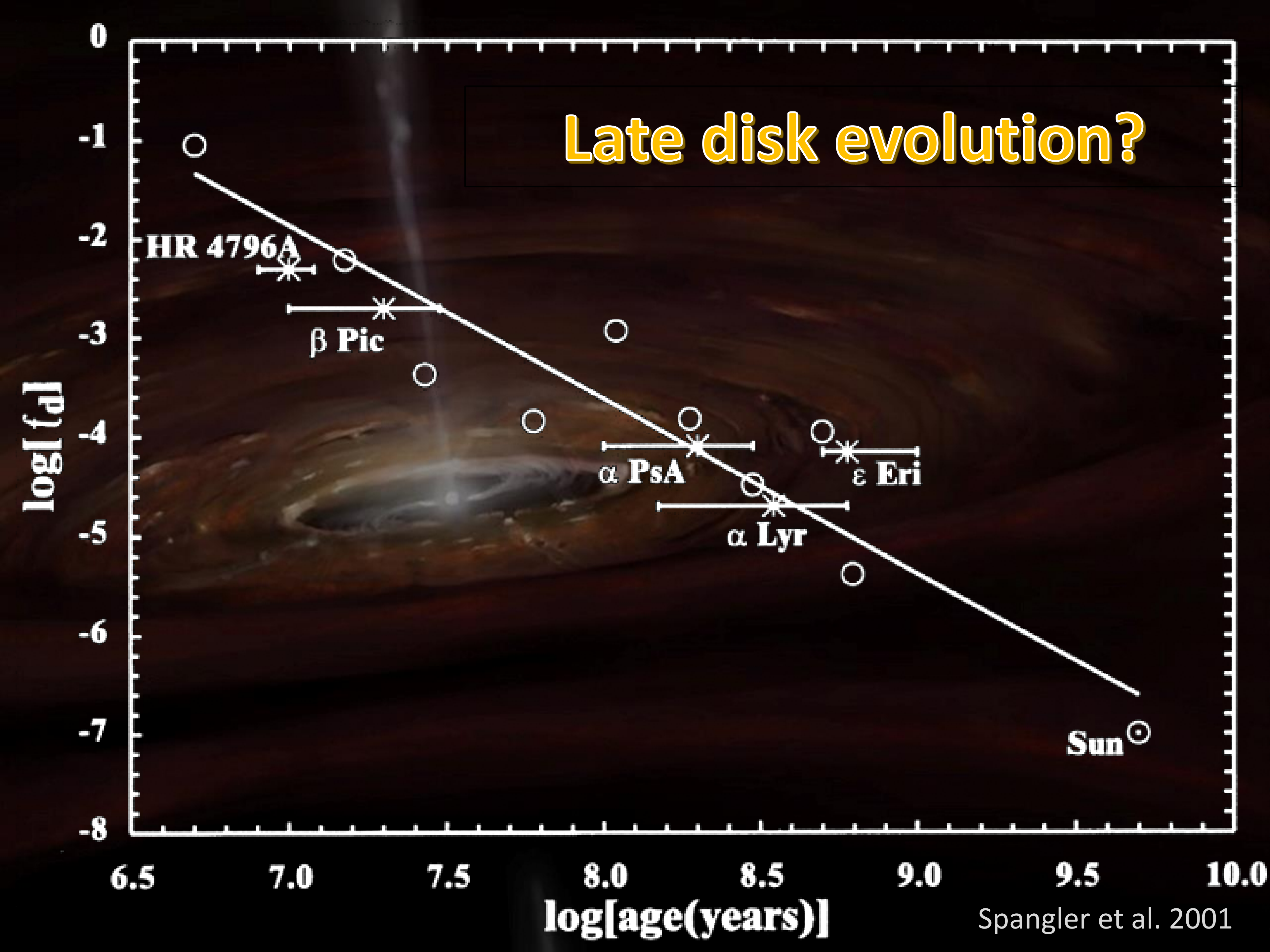
Physical Mechanisms
Hollenbach et al. 2000 PPIV

Gas rich to gas poor evolution?

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

(F)IR - excess

Stellar luminosity
(bolometric)


Late disk evolution?
HR 4796A
β Pic
α PsA
ε Eri
α Lyr
Sun
log[f_d]
log[age(years)]
0
-1
-2
-3
-4
-5
-6
-7
-8
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
Spangler et al. 2001

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

Observed disk sizes

T Tauri/HABE disks

50 – 100 AU Dust: mm-continuum interferometry

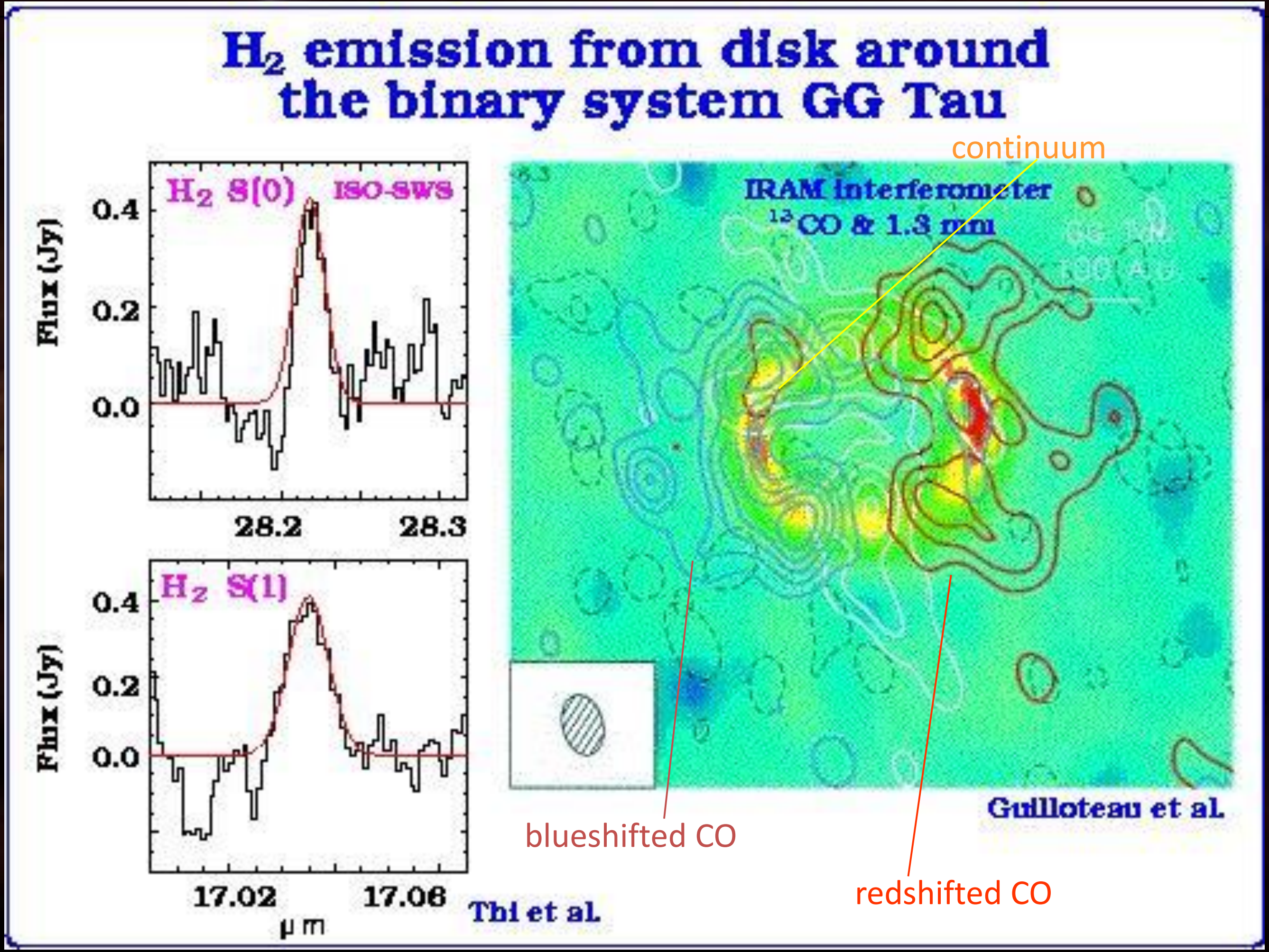
100 – 300 AU Dust: scattered stellar light

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

Silhouette disks (``proplyds ´´)

up to 1000 AU Dust: scattered stellar light

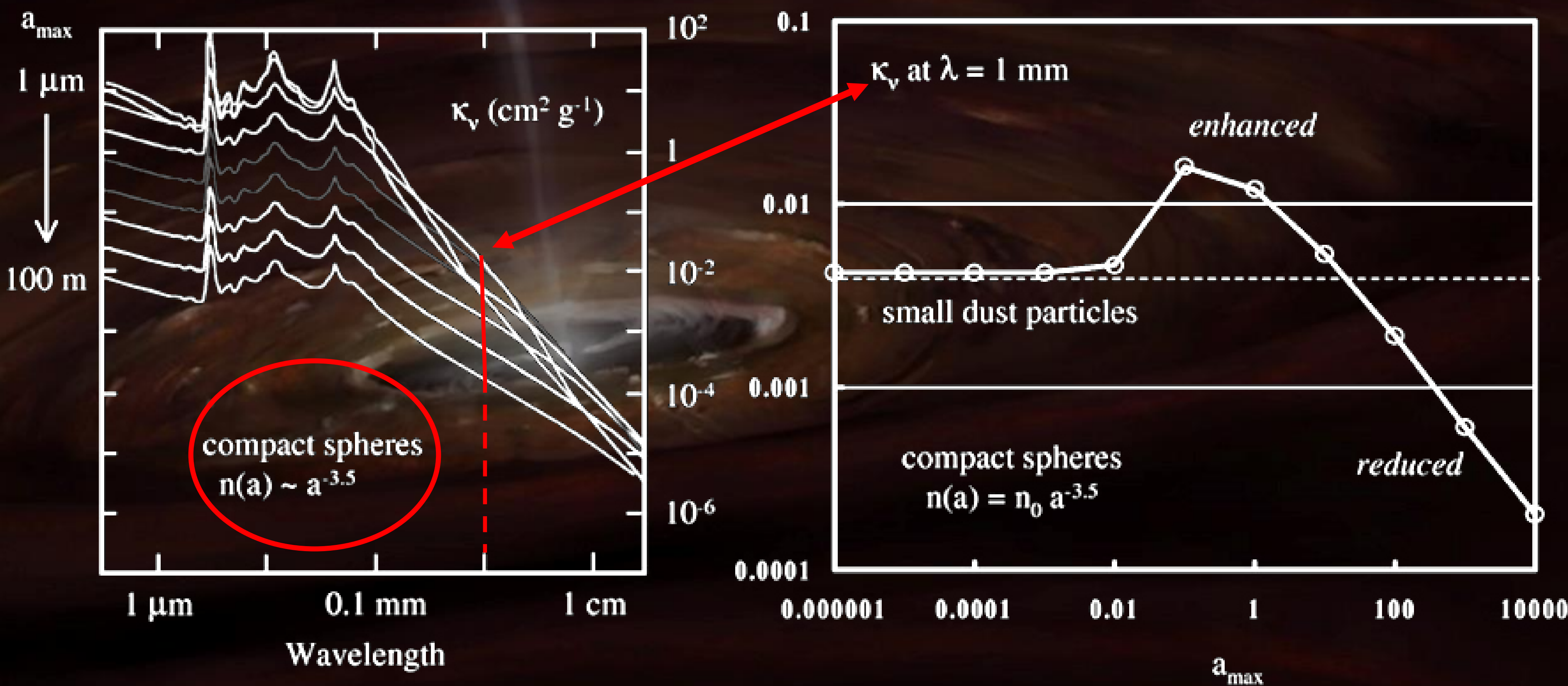
Observing disk masses



H_2
Gas
Directly

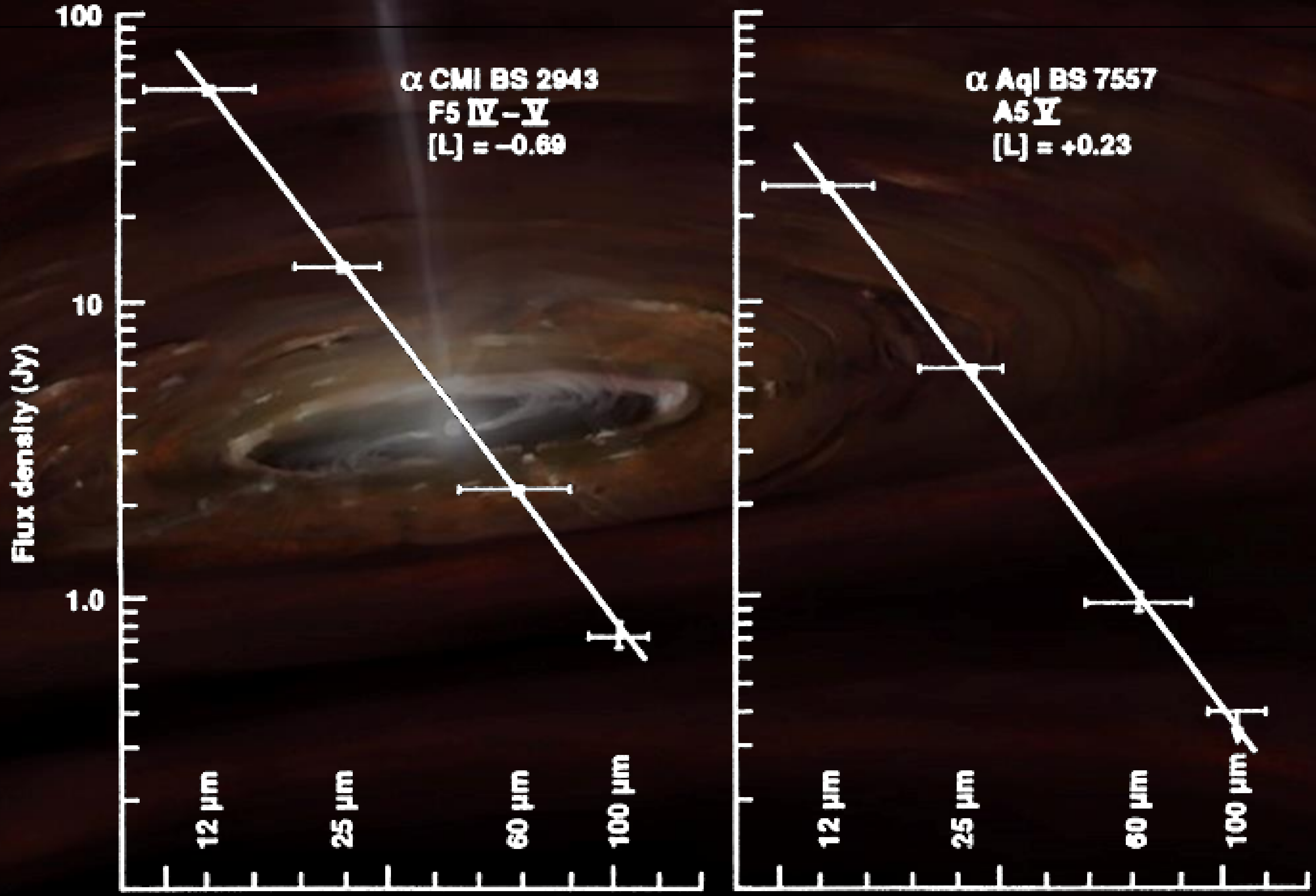
CO
and
Dust

Dust grain opacities



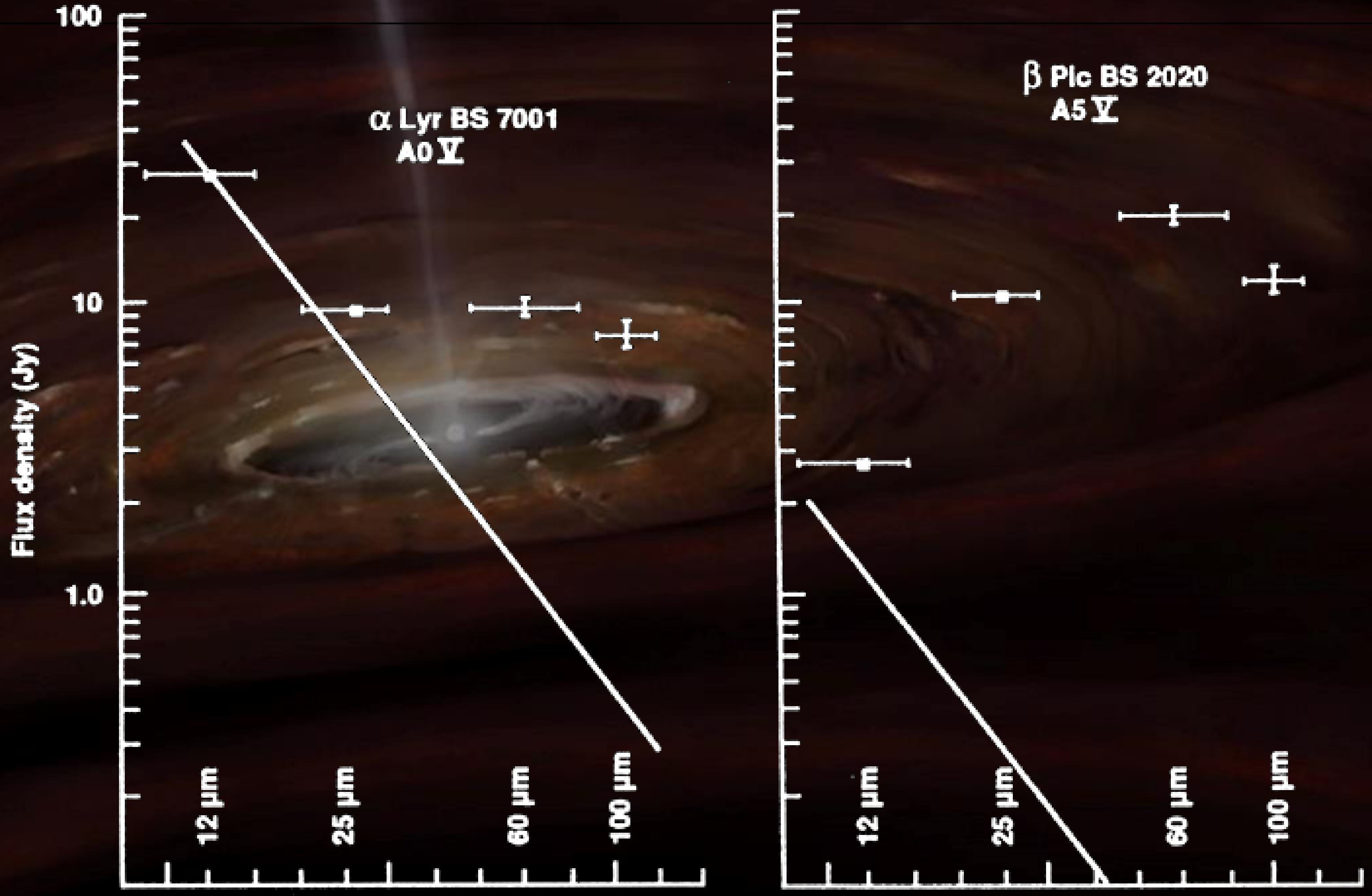
Beckwith et al. 2000, PP IV

The first resolved circumstellar disk



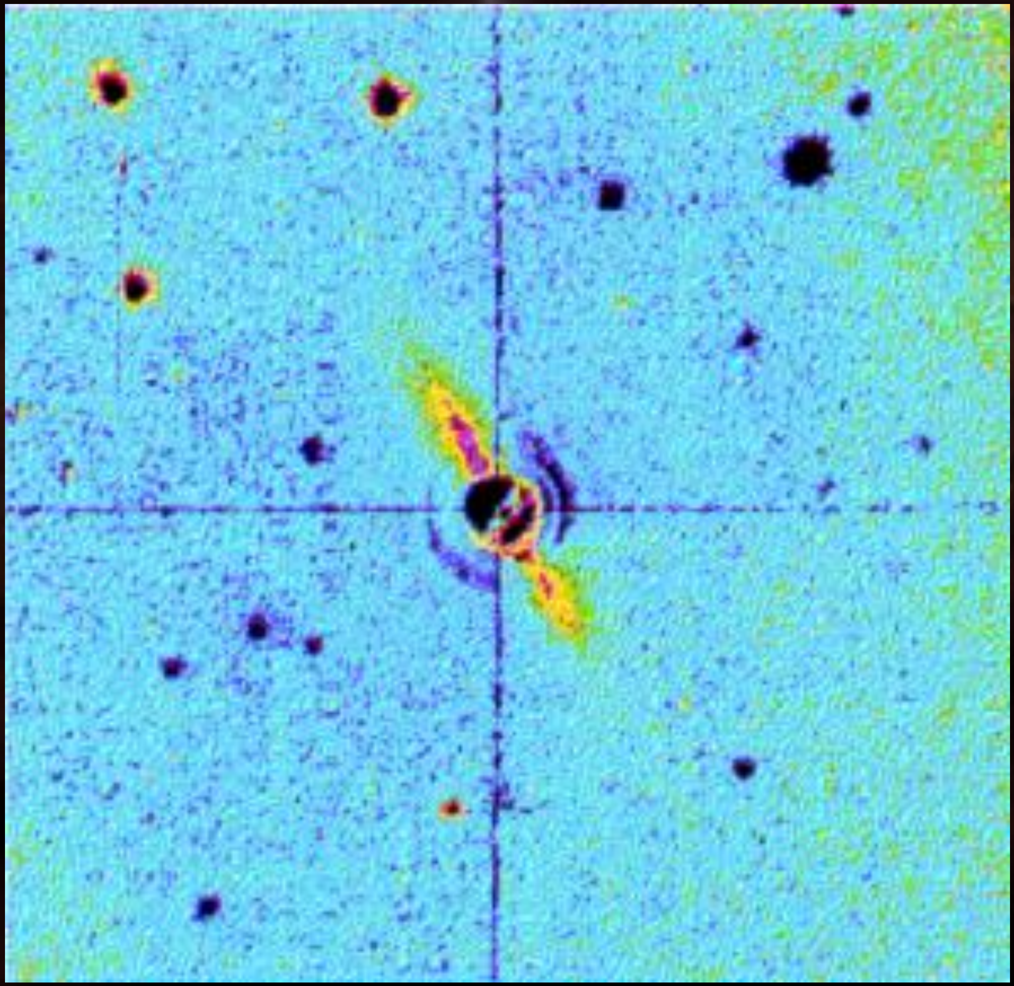
Backman & Parece 1993, PPIII, 1253

The first resolved circumstellar disk



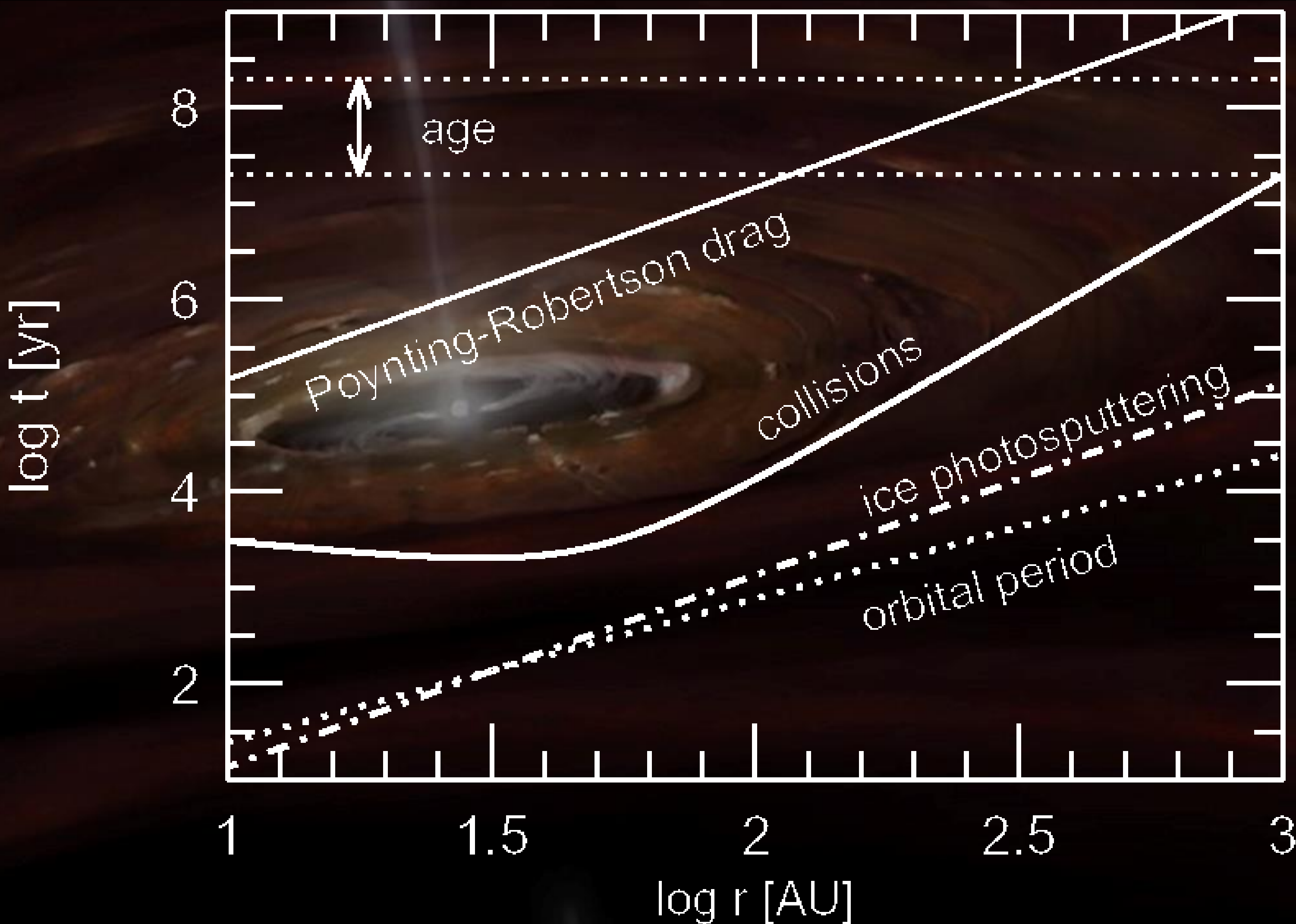
Backman & Parece 1993, PPIII, 1253

β Pictoris

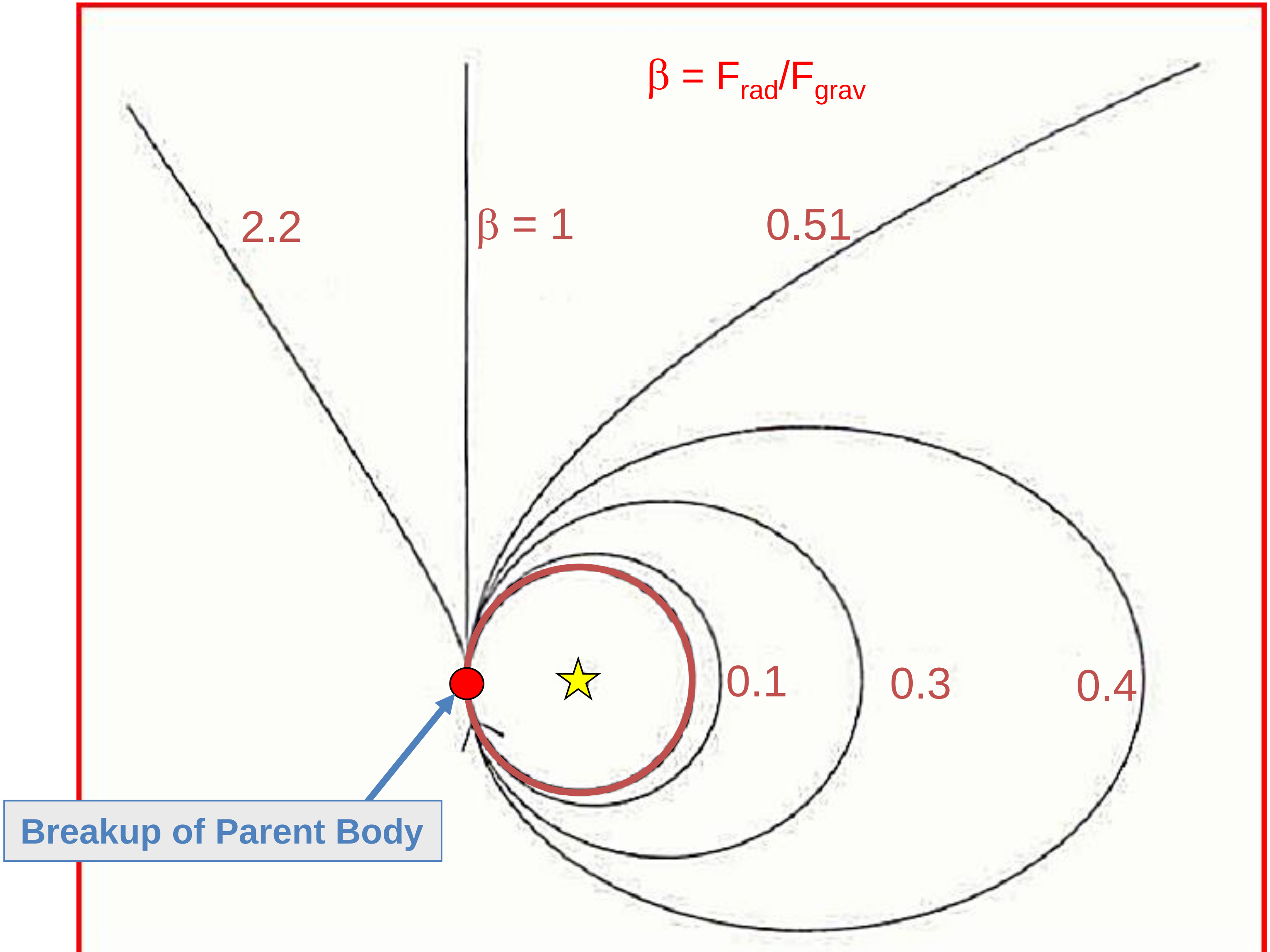


Discovery image by
Smith & Terrile 1984
(Sci. 226, 1421)

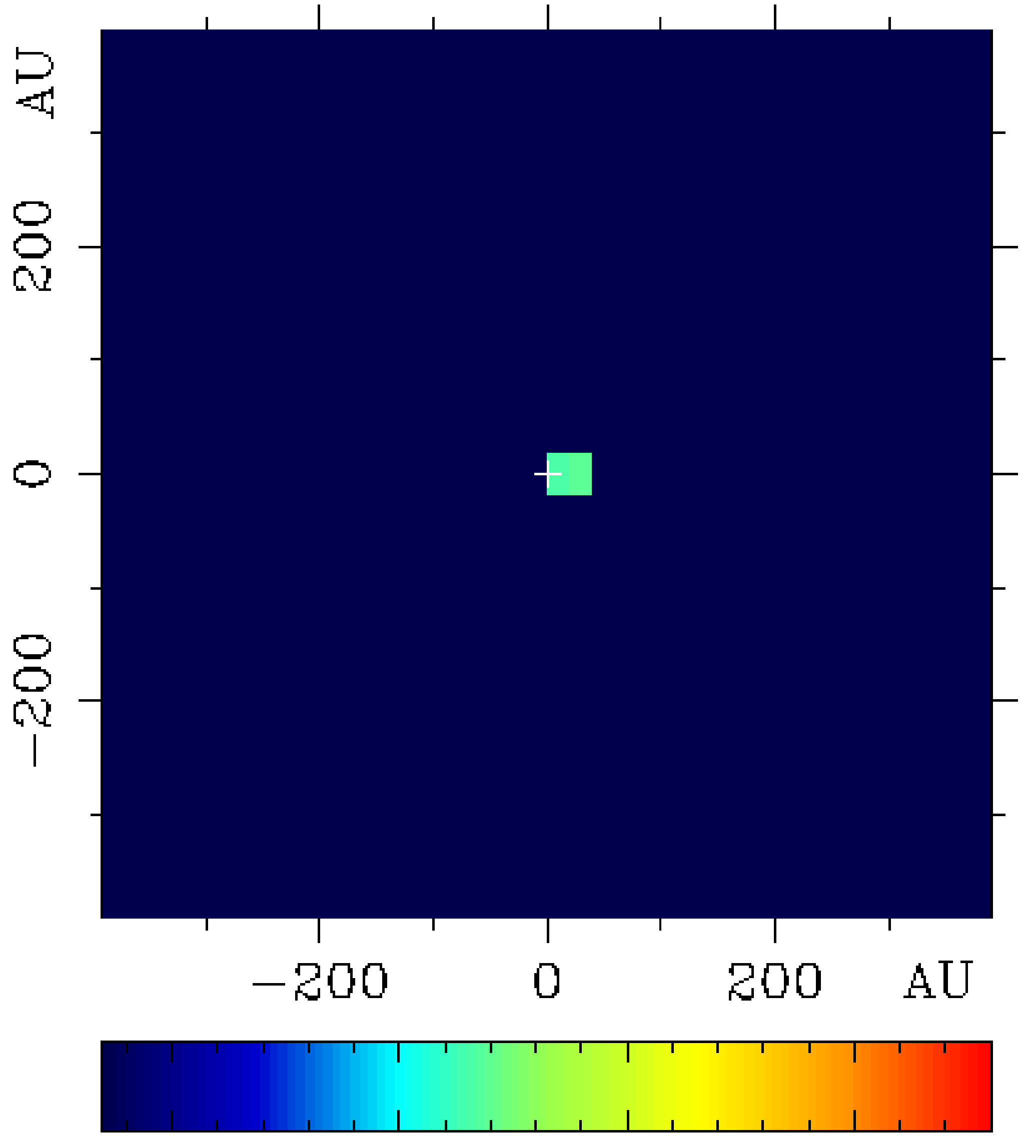
Why “debris”?



From Artymowicz 1997, AR 25:175


β = F_rad/F_grav
2.2
β = 1
0.51
0.1
0.3
0.4
Breakup of Parent Body

Dust producers: collisions



Grigorieva, Artymowicz & Thebault (2006)

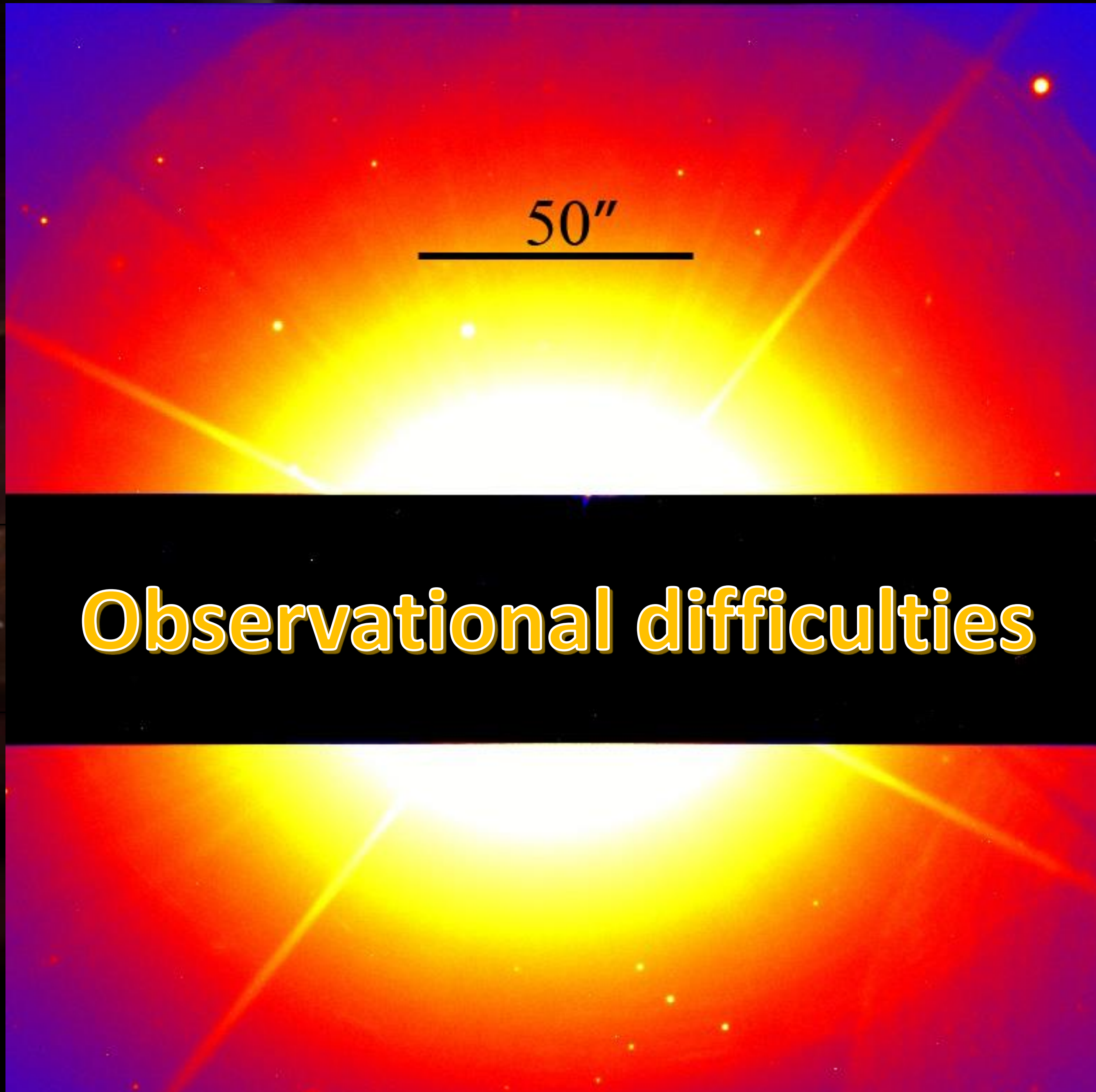
(Courtesy Philippe Thébault)

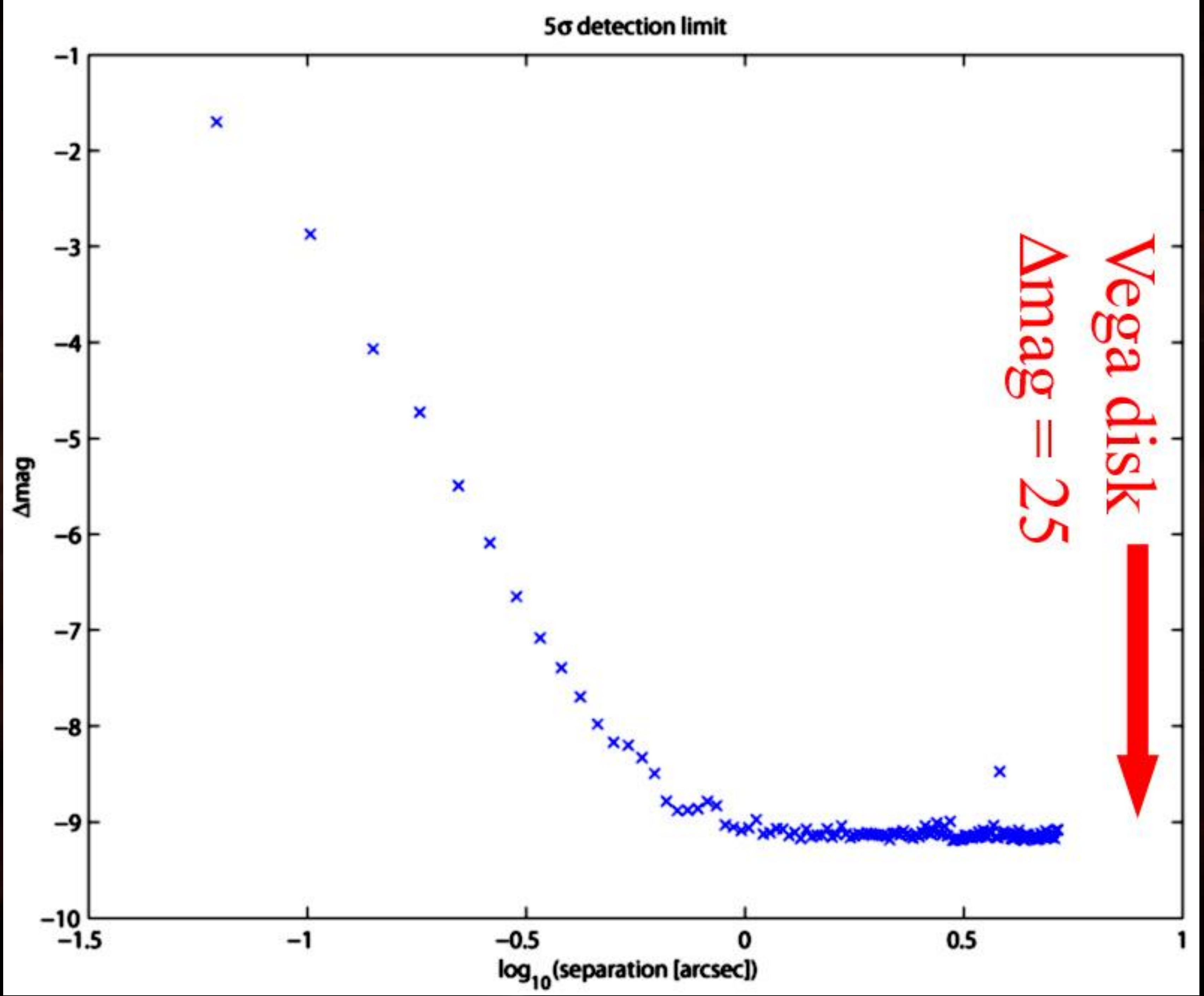
Collisional cascade after planetesimal/cometary breakup

Debris disk properties

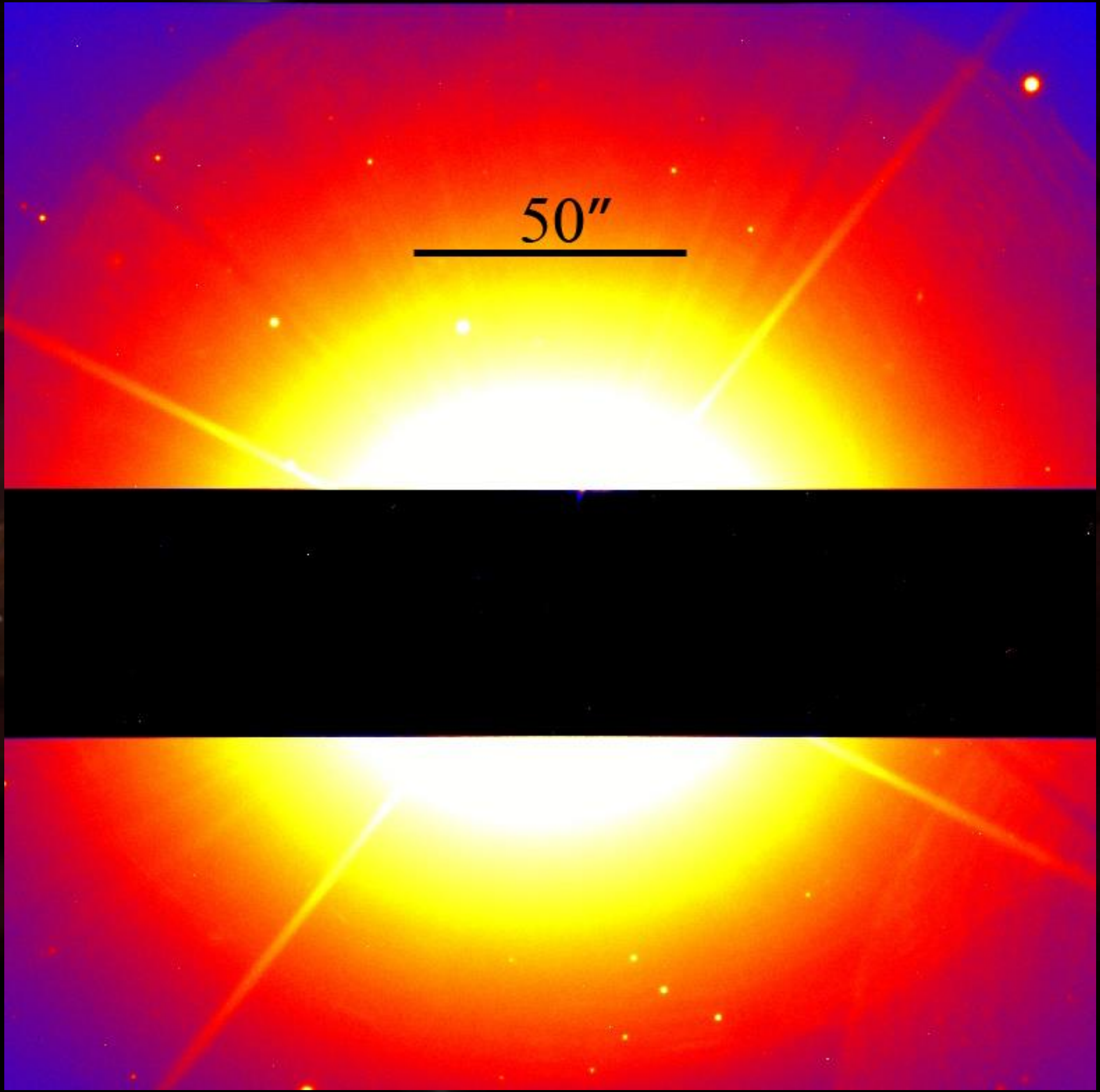
- Large (up to 1000 AU) dusty disks found around young main-sequence stars ~ 10 Myr – 1 Gyr
- Dust disk mass $M \sim 10^{-3}$ to a few M_{Earth}.
- Essentially free of gas
- Cold; typically 30 – 300 K
- Dominating dust emission from μm to mm sized grains

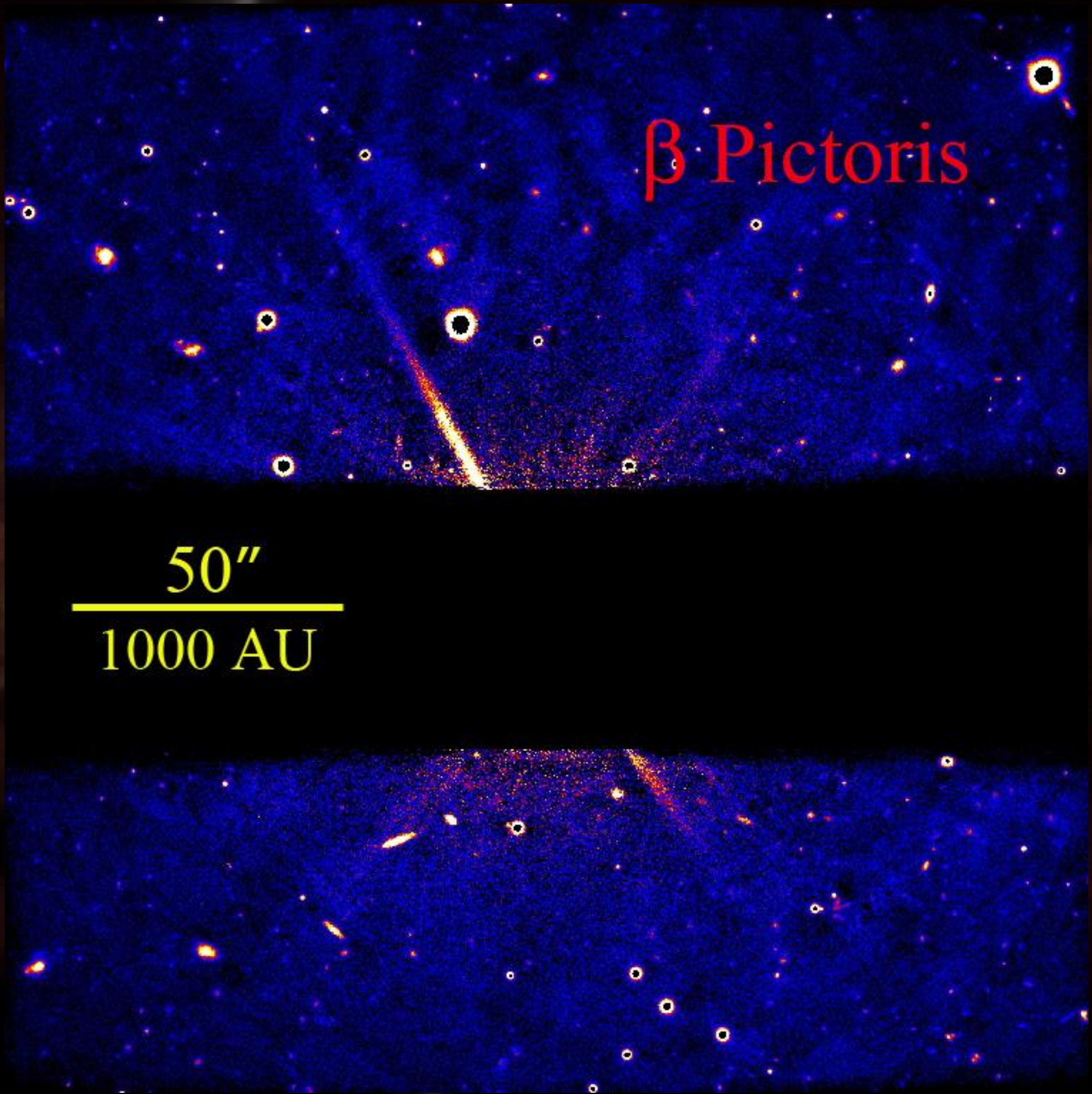
Observational difficulties

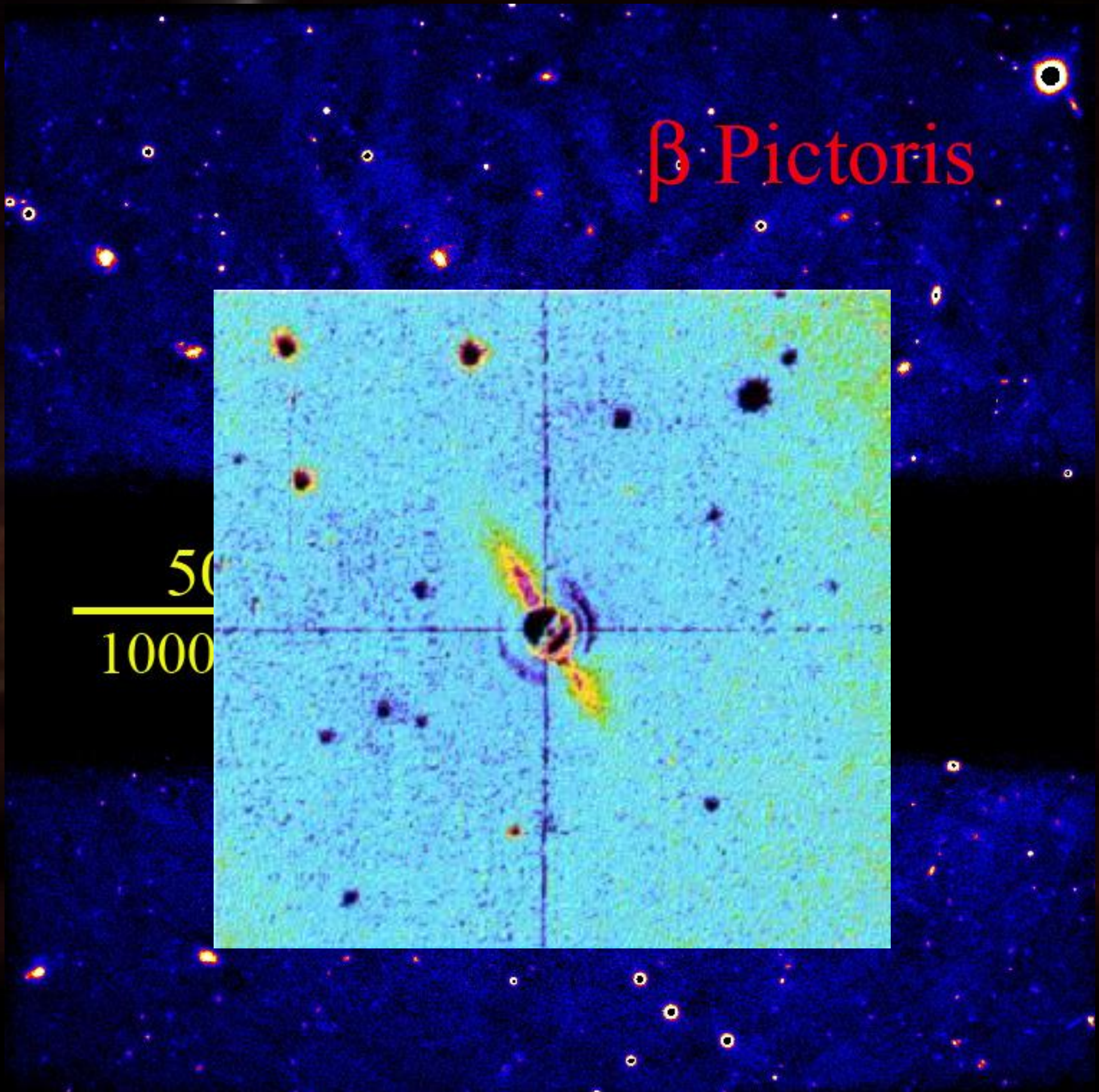




5σ detection limit
Δmag
log10(separation [arcsec])
Vega disk
Δmag = 25

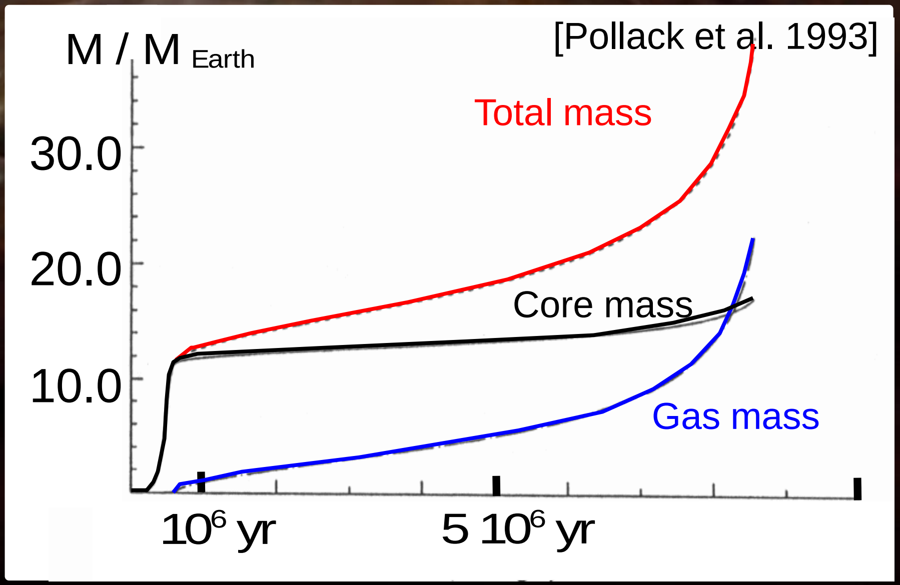

50″


β Pictoris
50″
1000 AU

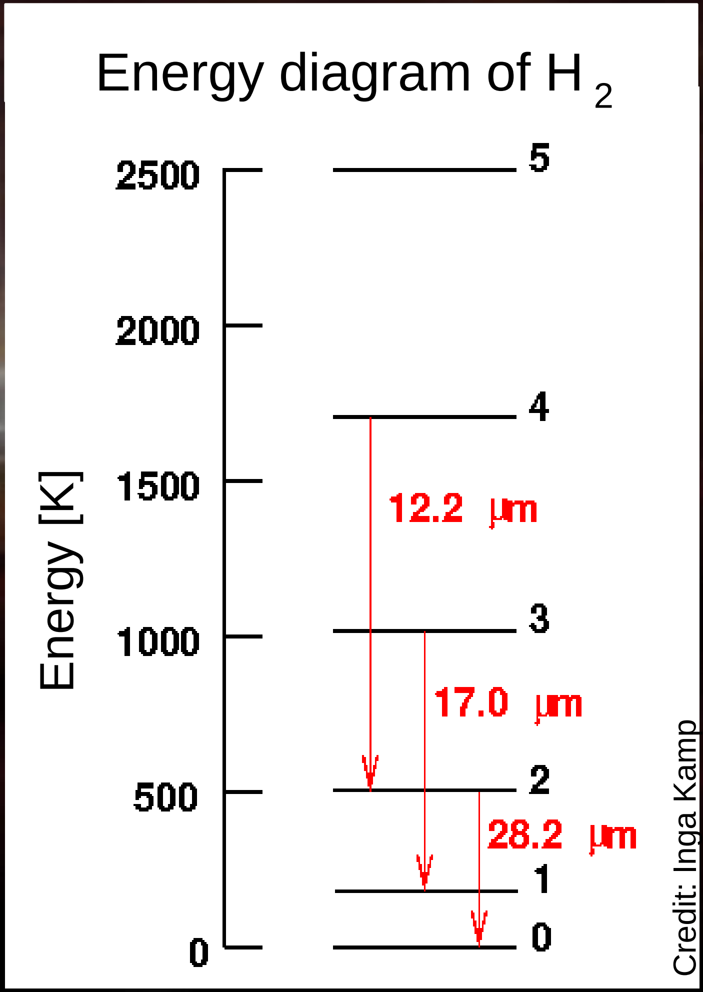

β Pictoris
5(
1000

Late gas disk evolution?

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

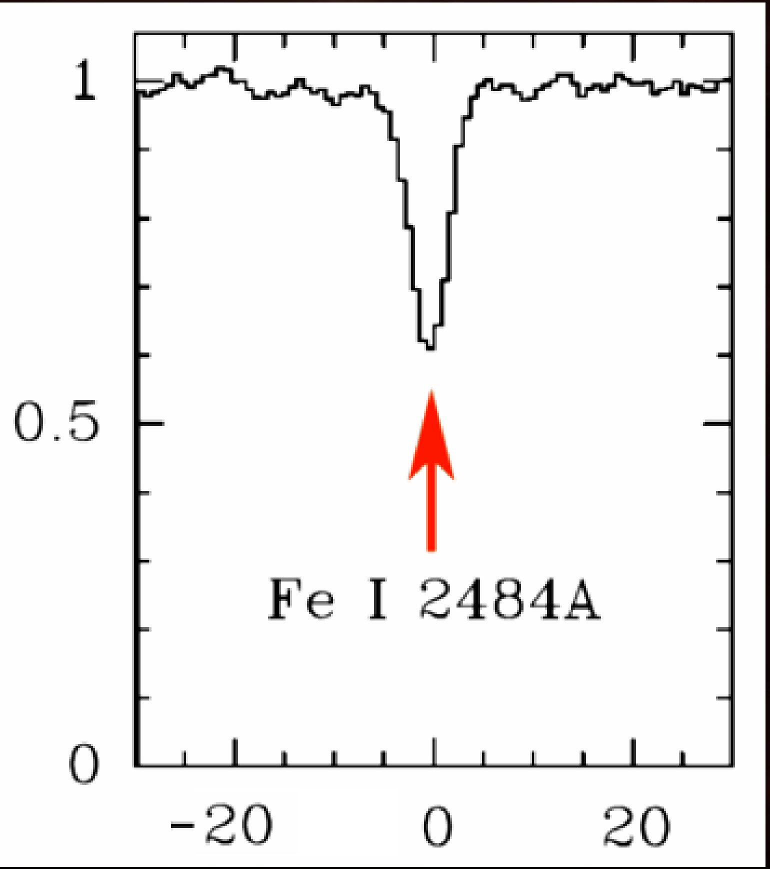


More observational difficulties



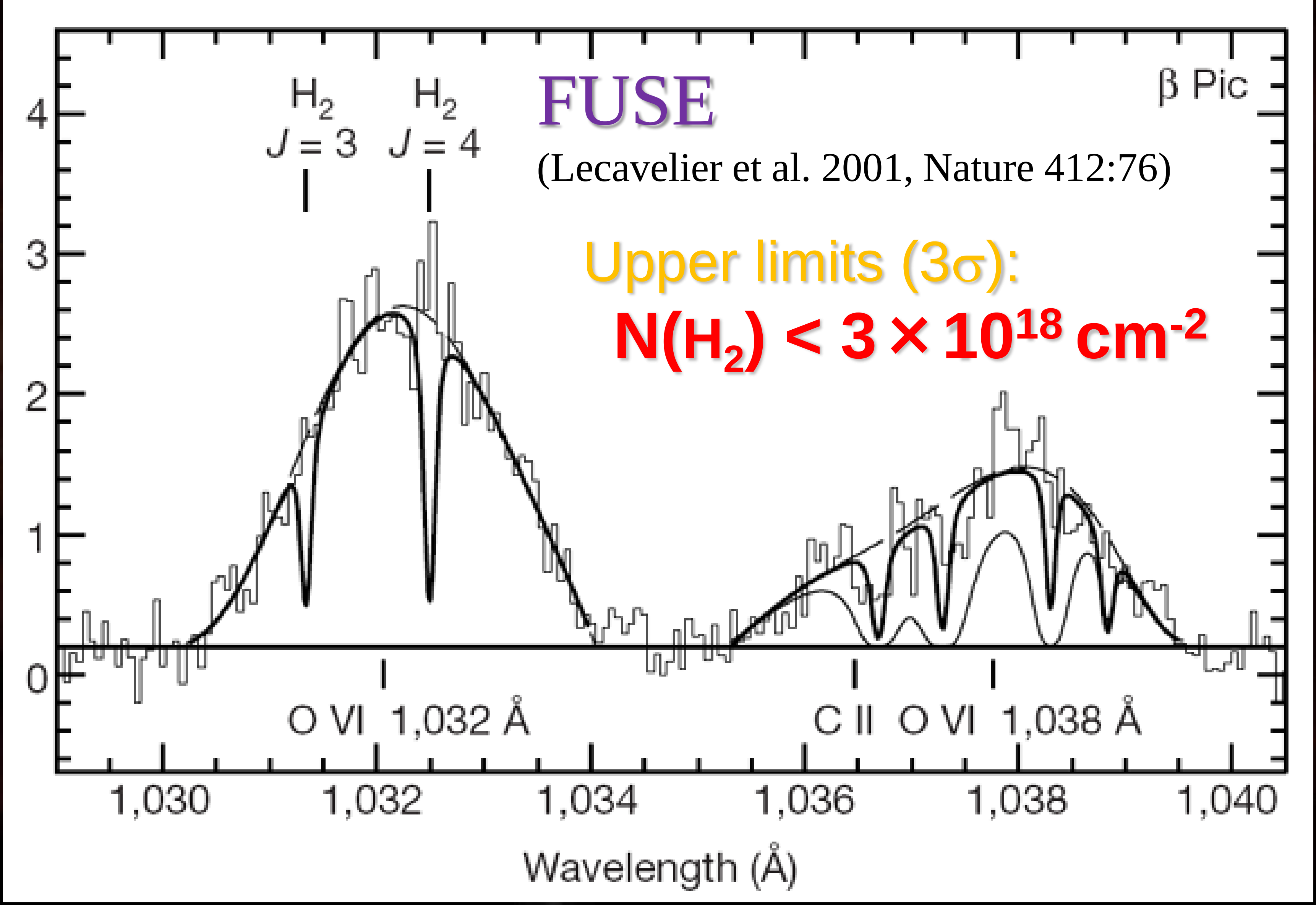
Favourable case: β Pictoris

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

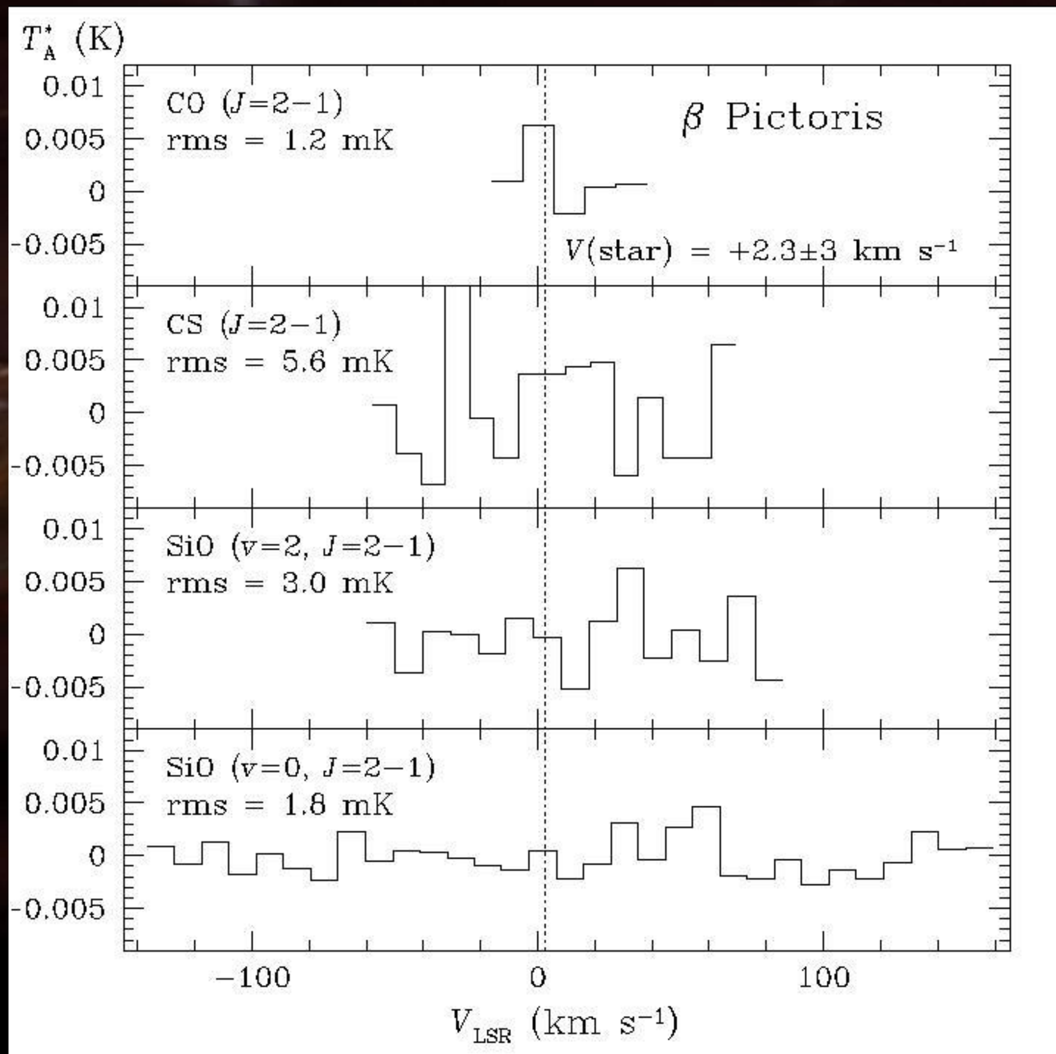


Lagrange et al. 1998, A&A 330:1091

Favourable case: β Pictoris

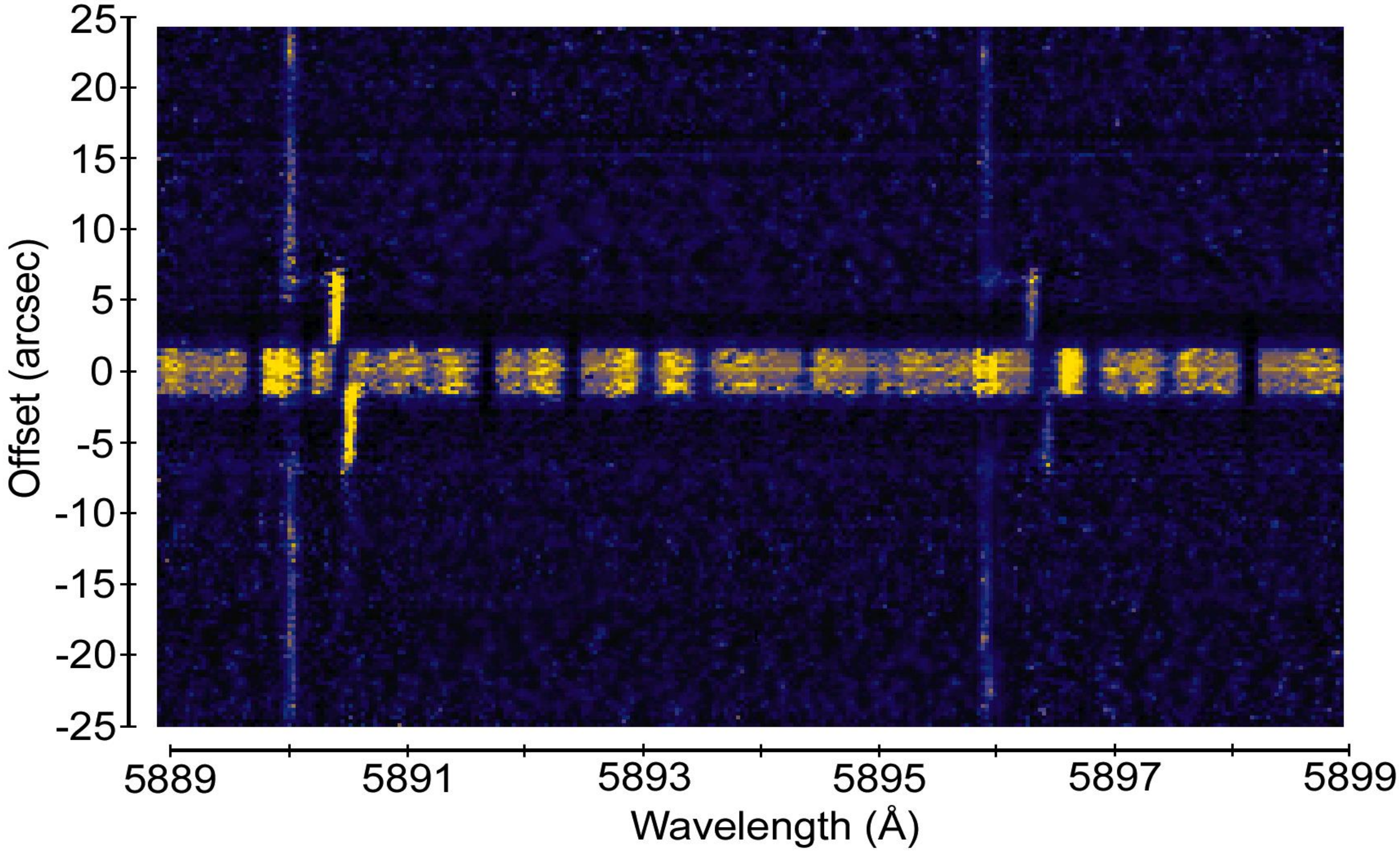


mm/submm observations

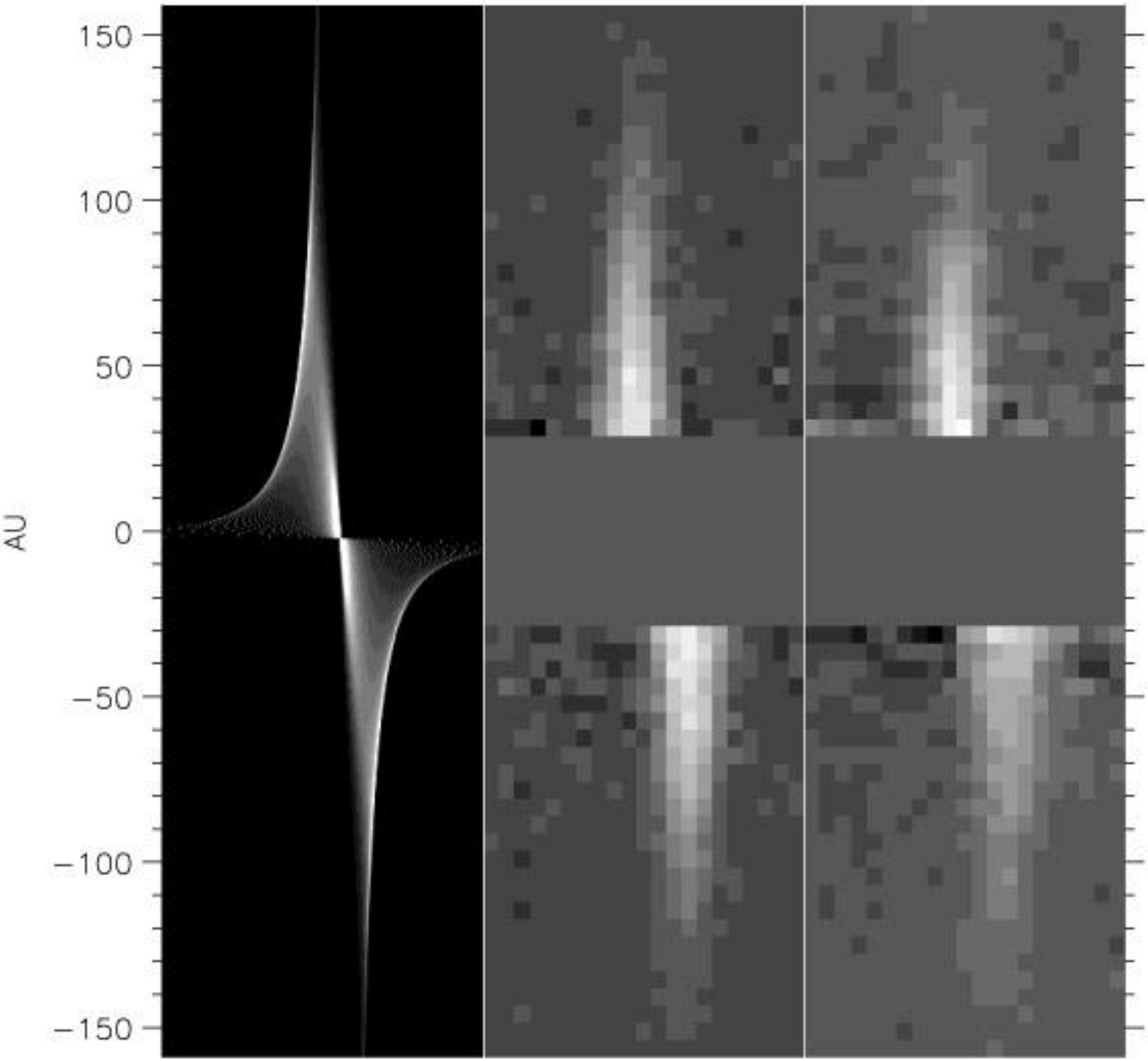


SEST Liseau & Artymowicz 1998, A&A 335, 935

Gas in emission

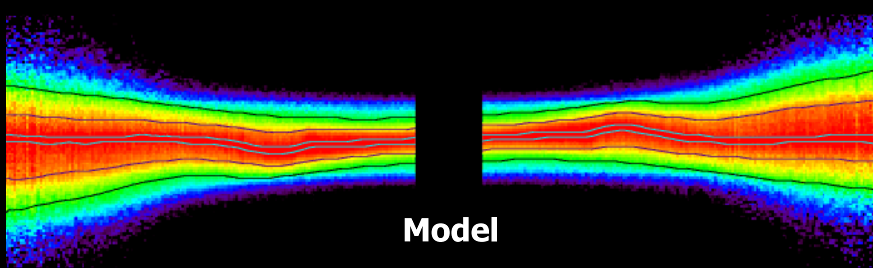


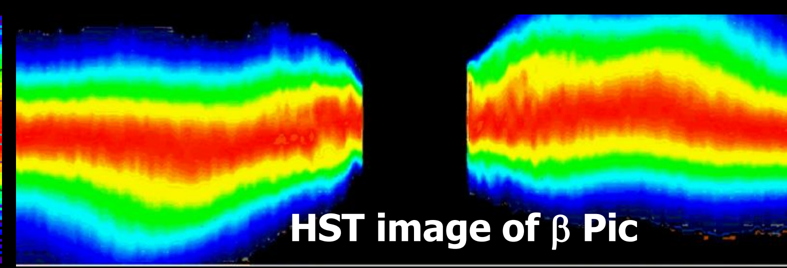
Olofsson, Liseau & Brandeker 2001, ApJL 563



150
100
50
0
−50
−100
−150
AU

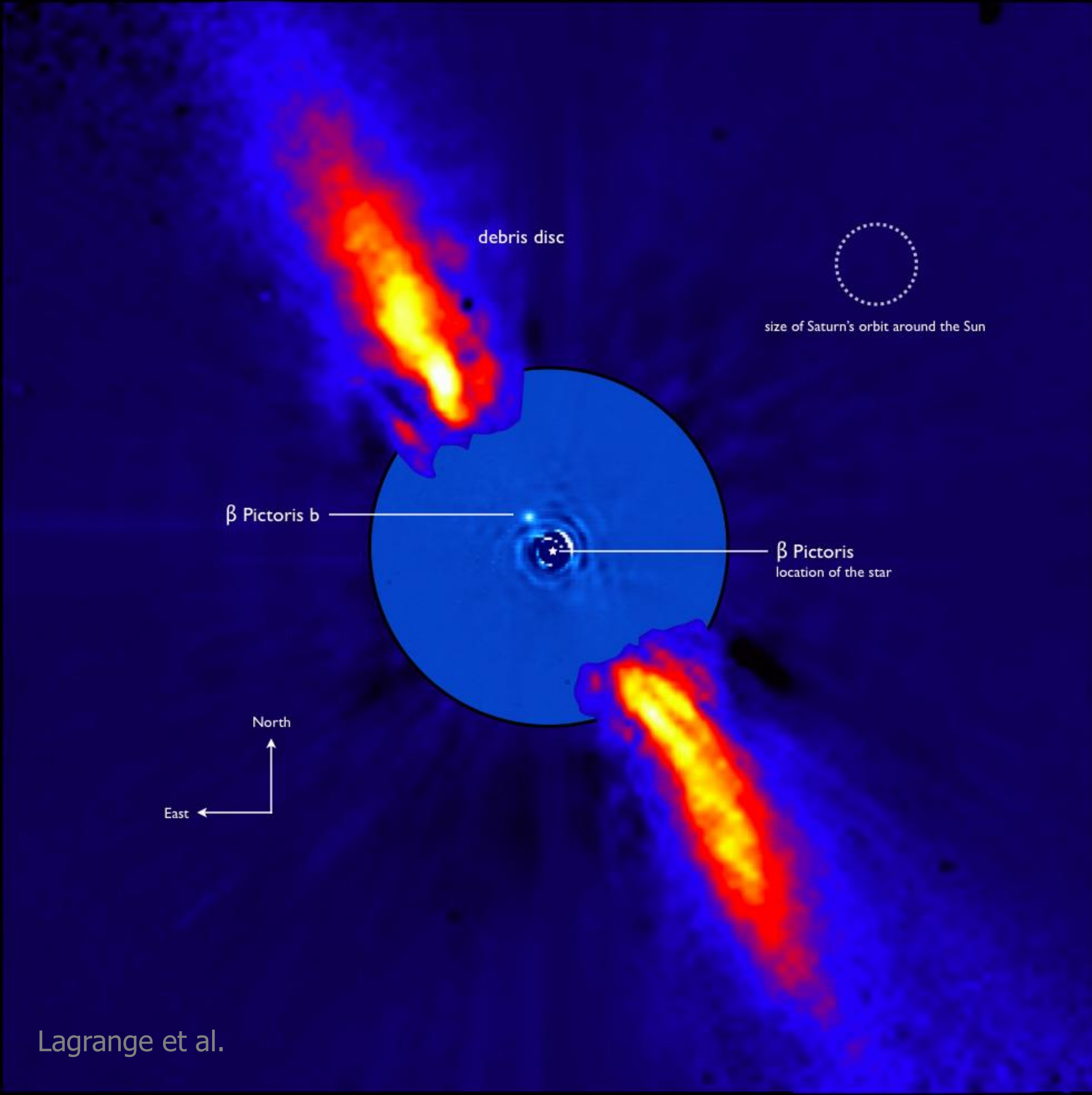
Planet-disk interaction



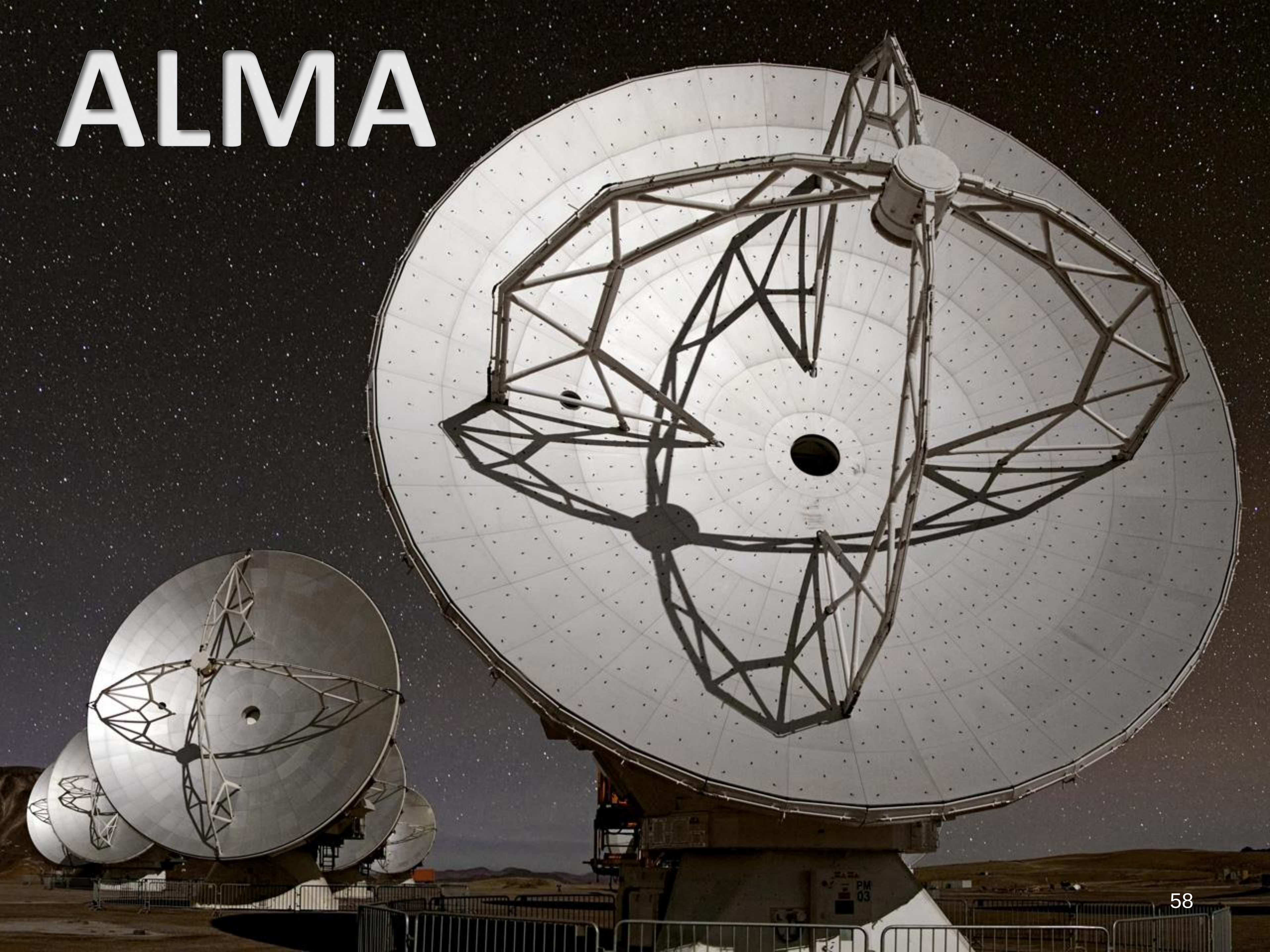


(Courtesy Philippe Thébault)

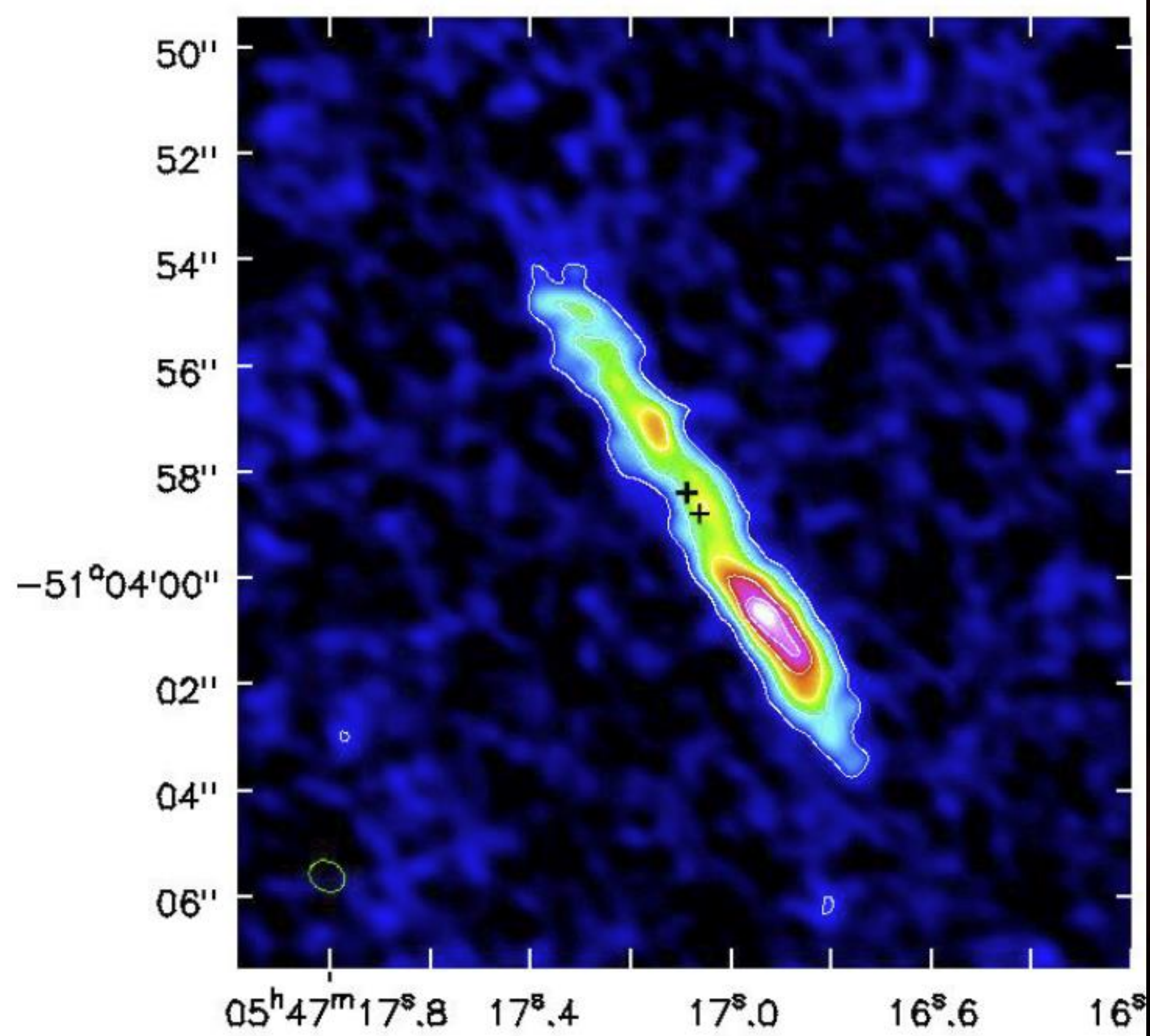
Planet-disk interaction



ALMA

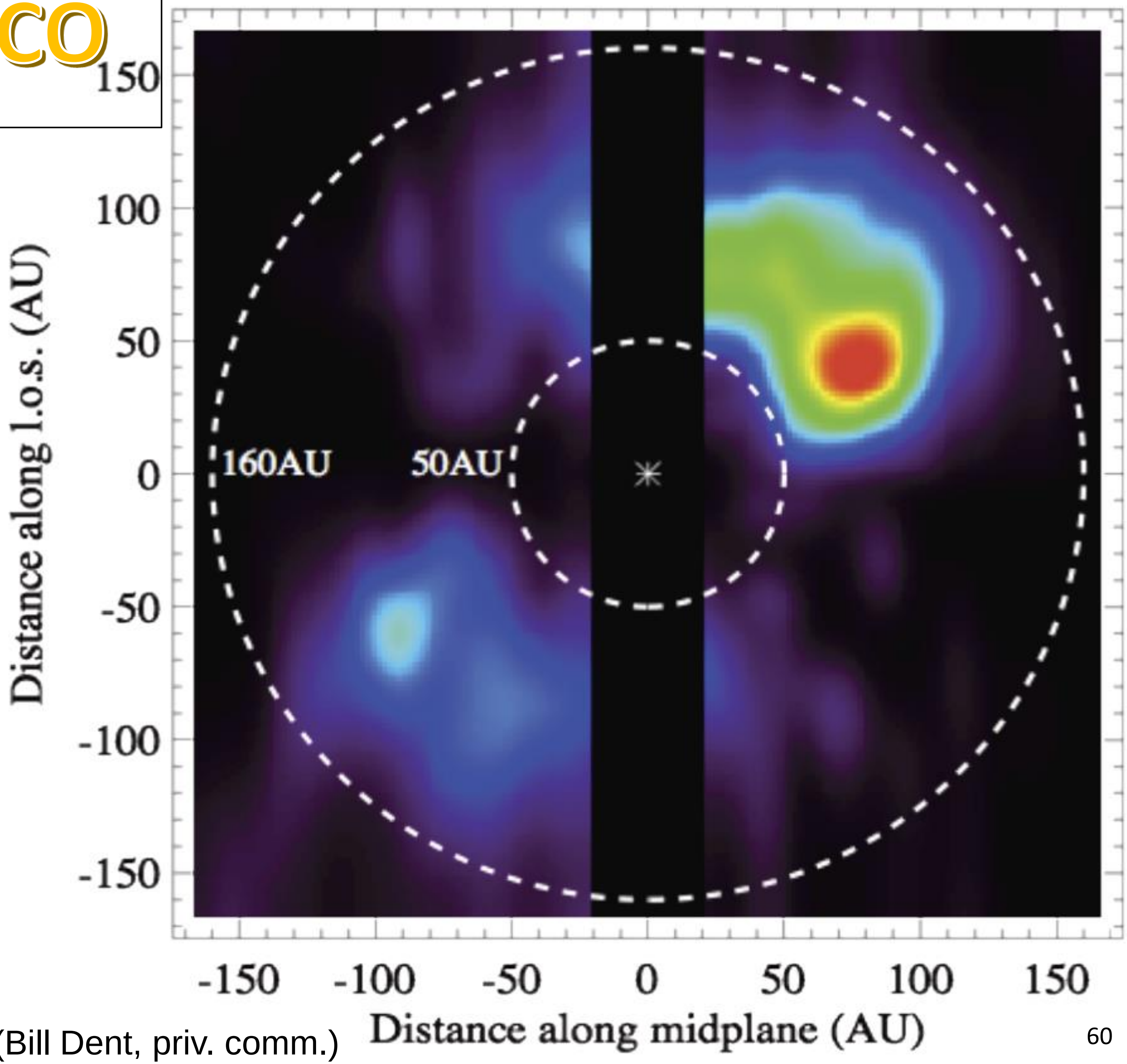


ALMA: CO



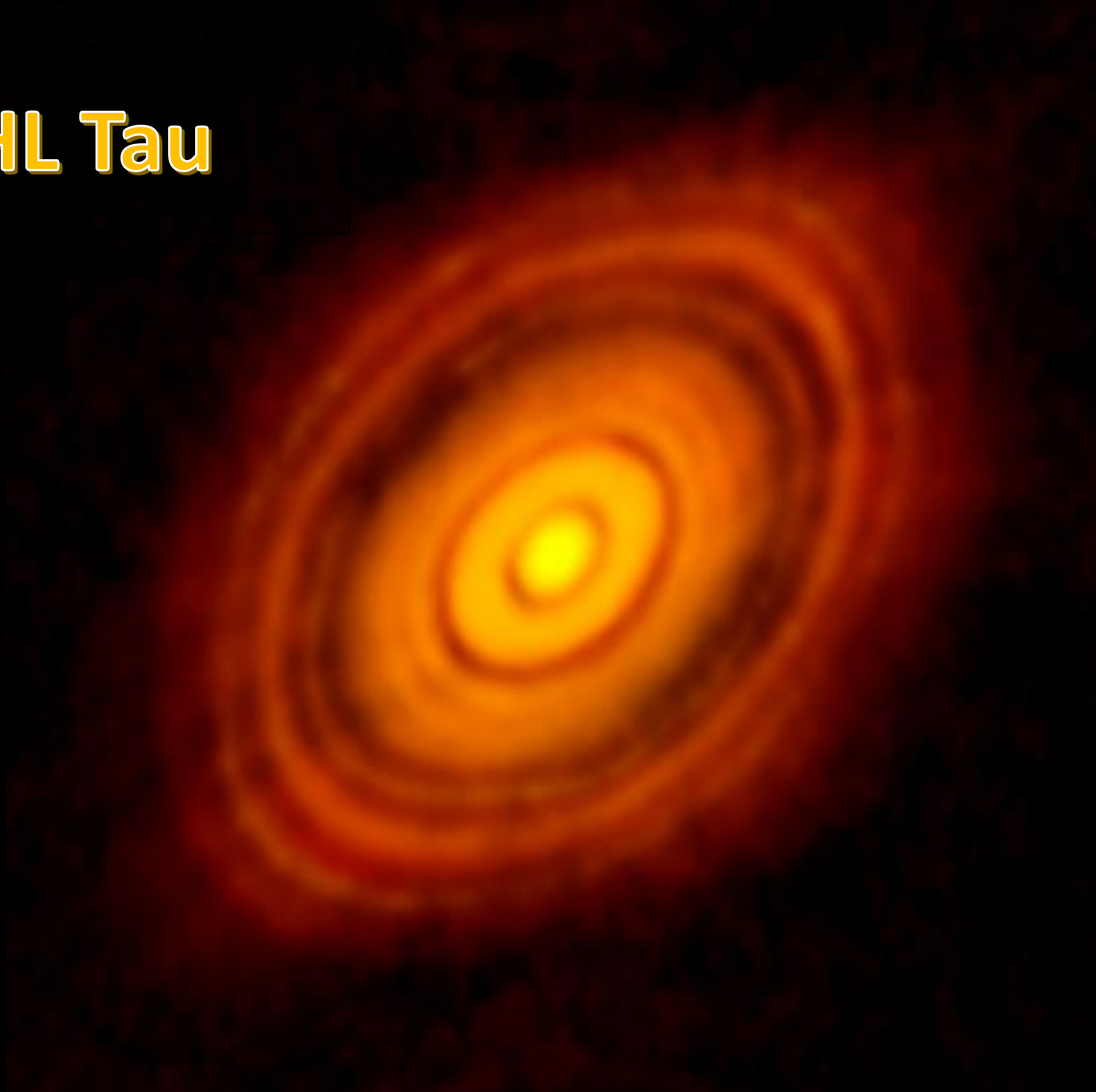
(Bill Dent, priv. comm.)

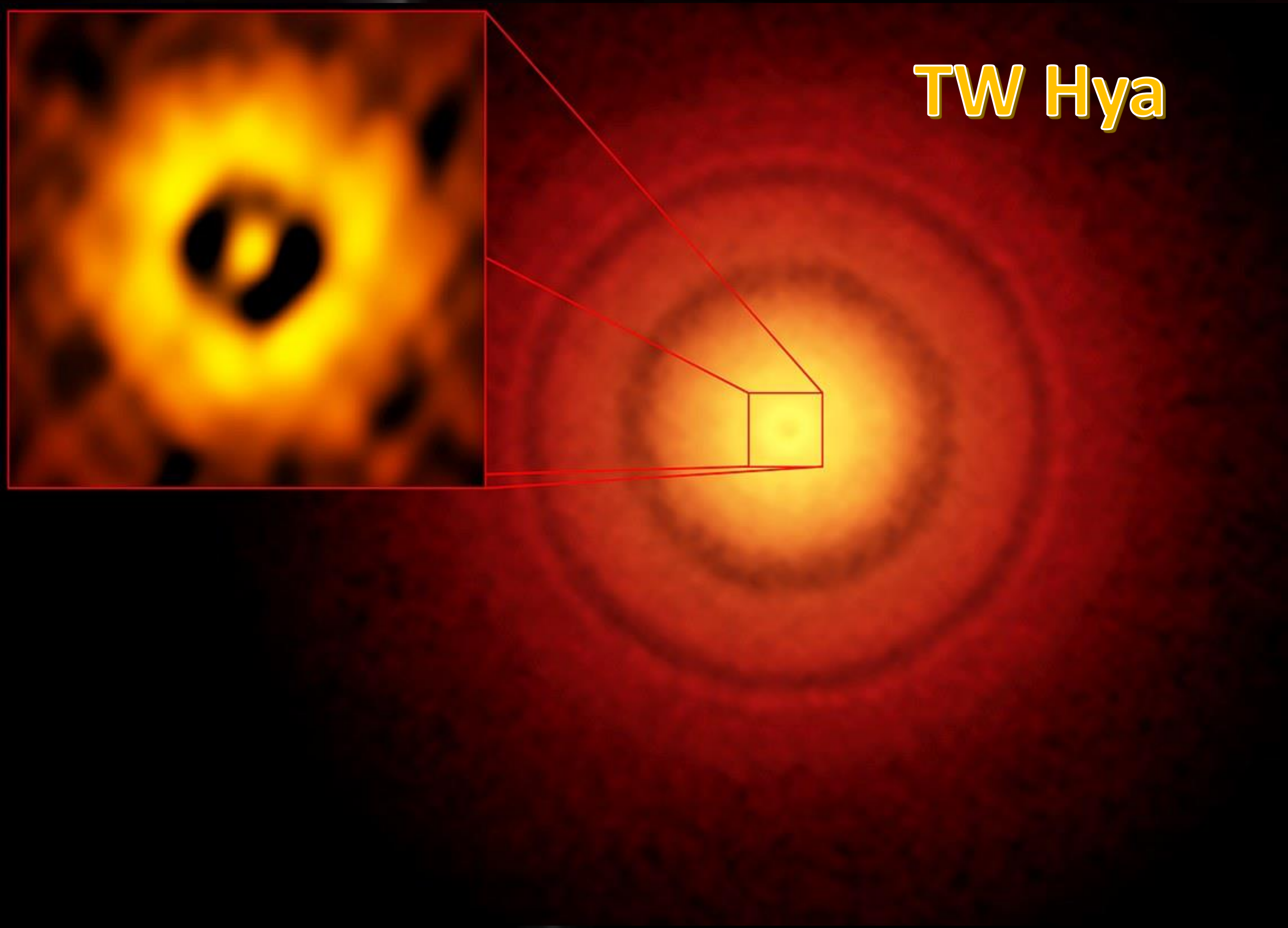
ALMA: CO



(Bill Dent, priv. comm.)

HL Tau




TW Hya

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
- ALMA is revolutionising the field!