Placing Our Solar System in Context

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Why should planetologists *care* about circumstellar disks?

- initial conditions of planet formation.

- trace evolution of planetary systems.

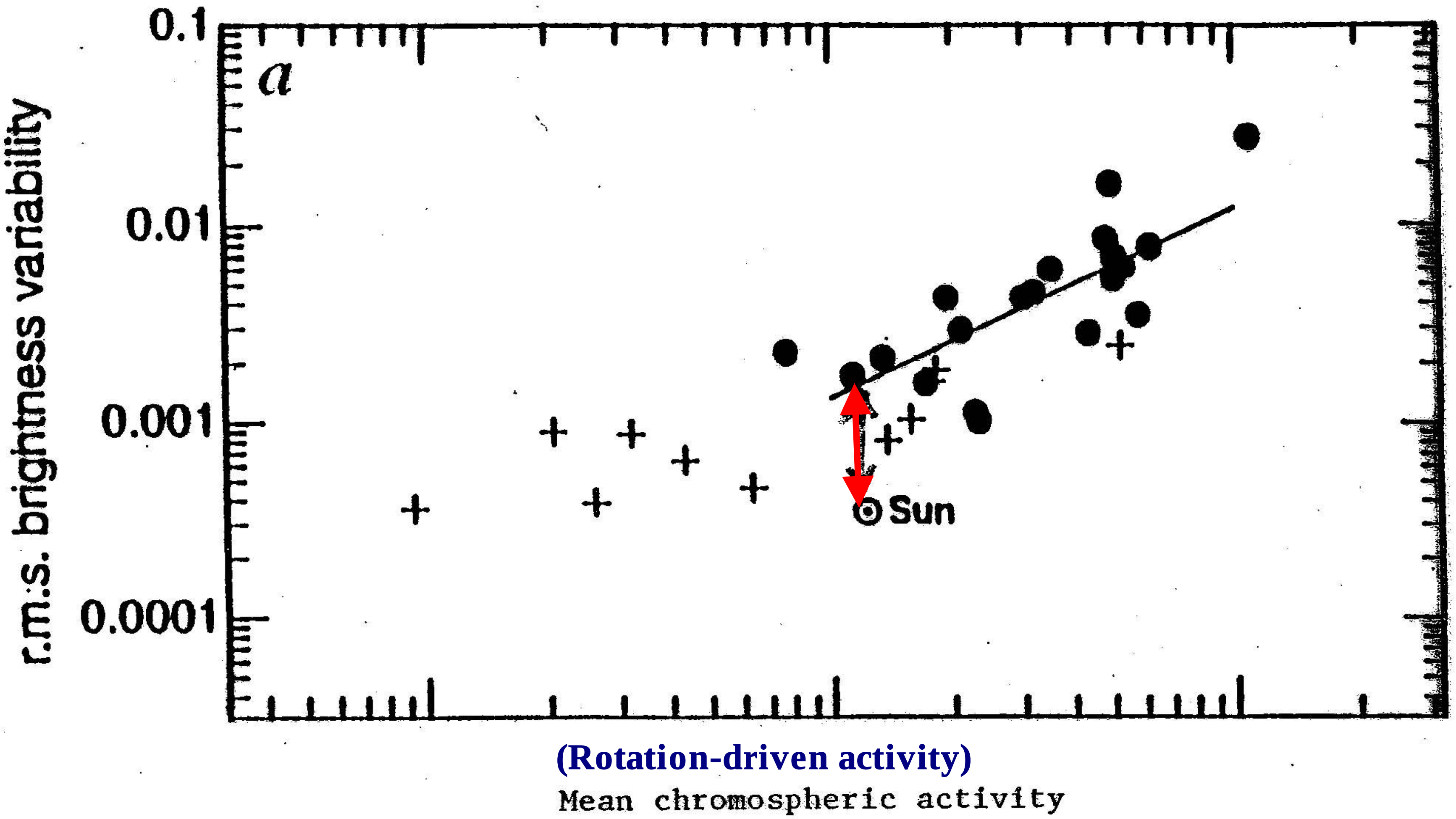
- attempt to place our solar system in context.

Problem #1:

Do you believe solar systems like our own are common or rare among sun-like stars in the disk of the Milky Way galaxy? Why?

Please write down your answer in a few sentences.

Is the Evolution of Our Sun `Normal'?

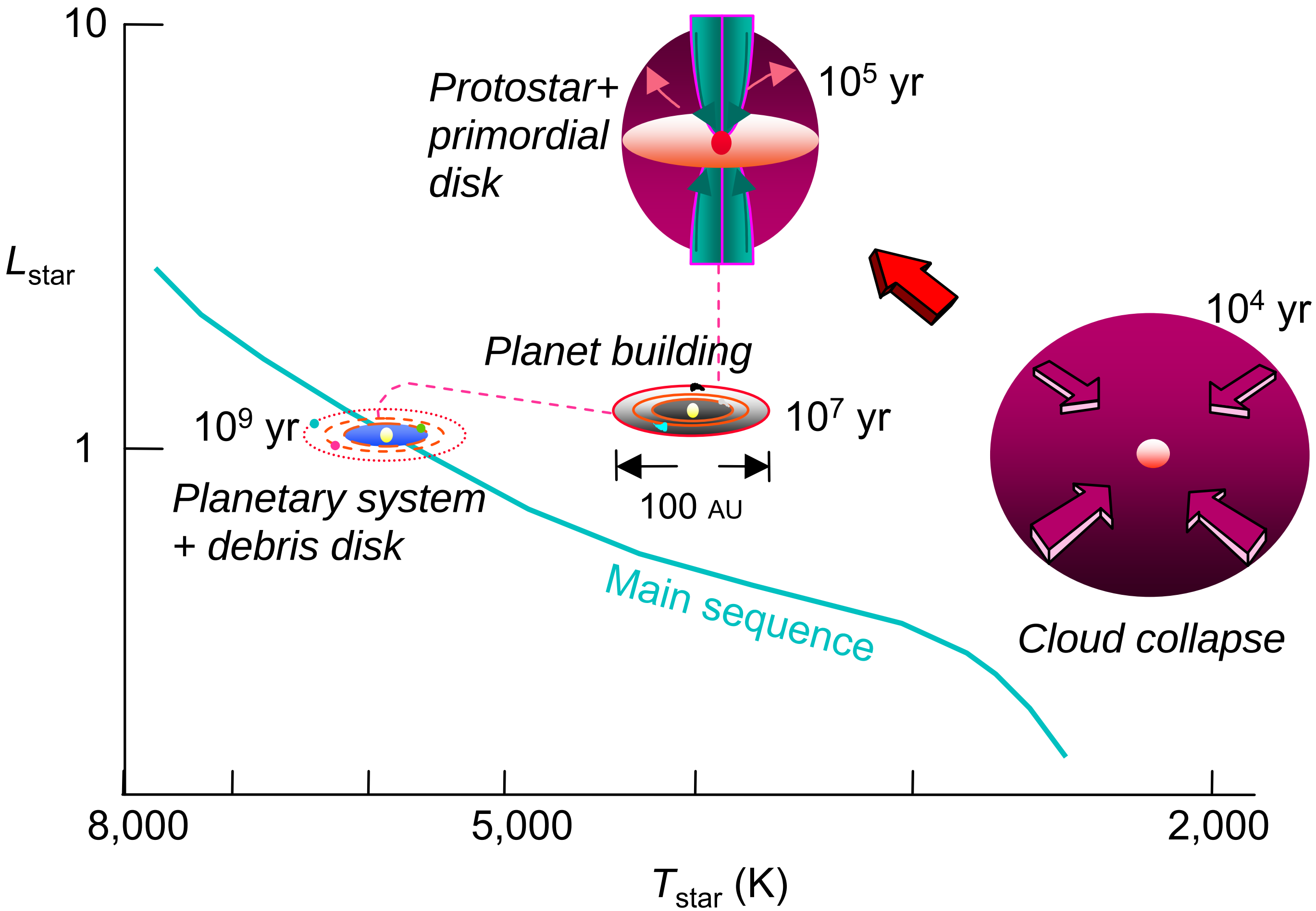


See review by Giampapa (2004).

Ways in which our solar system might be odd:
Properties of Planetary Systems?

- Frequency and location of gas giants.
- Frequency and location of terrestrial planets.
- Frequency and location of ice giants.
- Location and evolution of asteroid belts.
- Location and evolution of Kuiper belts.

Pre-main Sequence Evolution



Protostellar Disks (10^5-10^6 yrs):
Initial Conditions of Planet Formation

- **Standard model:**
  - » **Most of stellar mass passes through disk.**
- Limits on disk masses:
  - » < 10-25 % of central mass or disk is gravitationally unstable (Adams et al. 1990).
- Size of disk grows with time:
  - » R(cent) increases with specific angular momentum (Tereby et al. 1984).
- Mdot infall >> Mdot(accretion):
  - » Leads to disk instability and outburst (FU Ori stage).
- Outbursts decrease with time:
  - » The last one fixes initial conditions of remnant disk.

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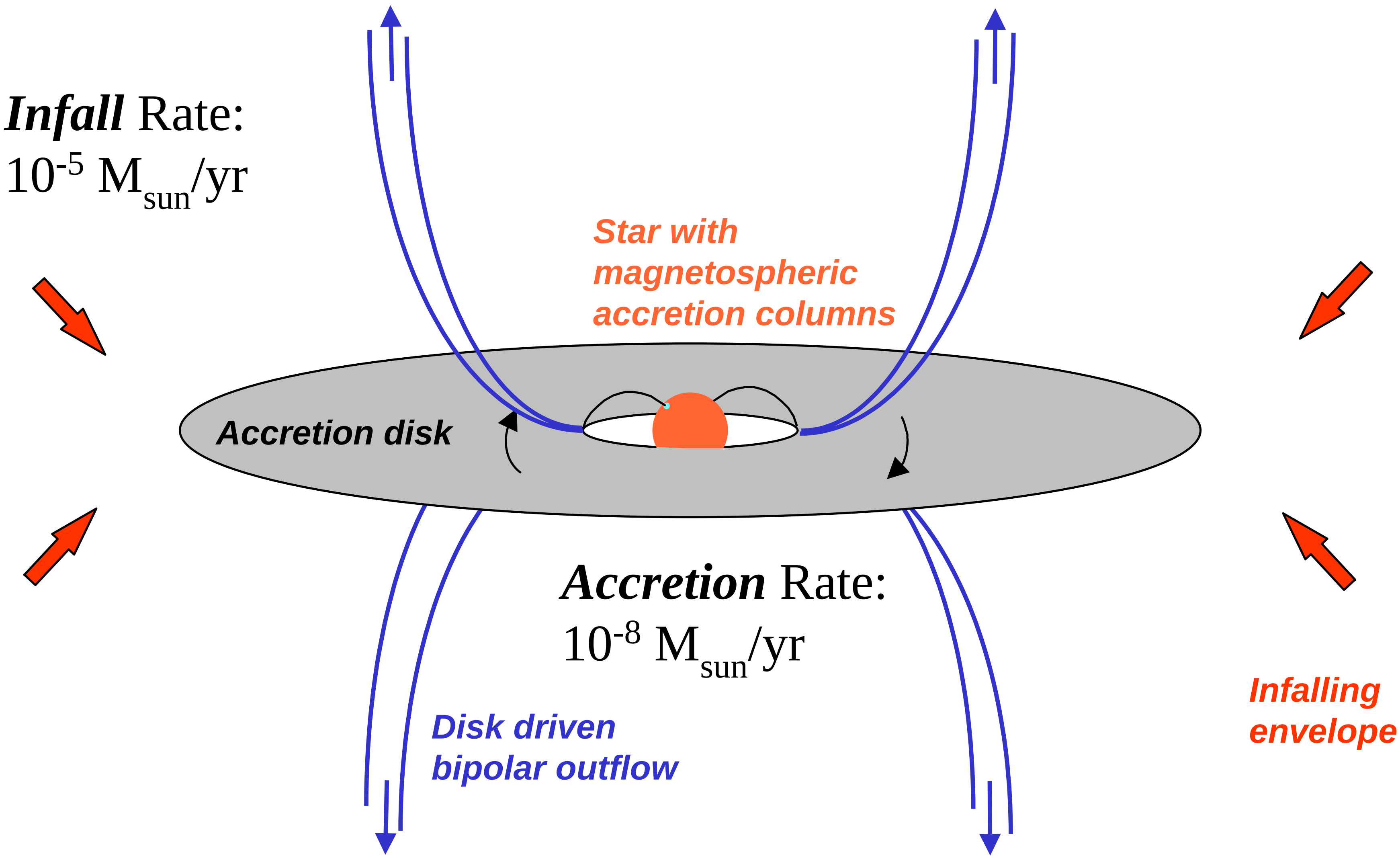
ırrent Paradigm:

Shu, Adams, & Lizano ***ARAA*** **(1987)**
Hartmann ***Cambridge Press*** **(1998)**

Infall Rate:
10^{-5} M_{sun}/yr



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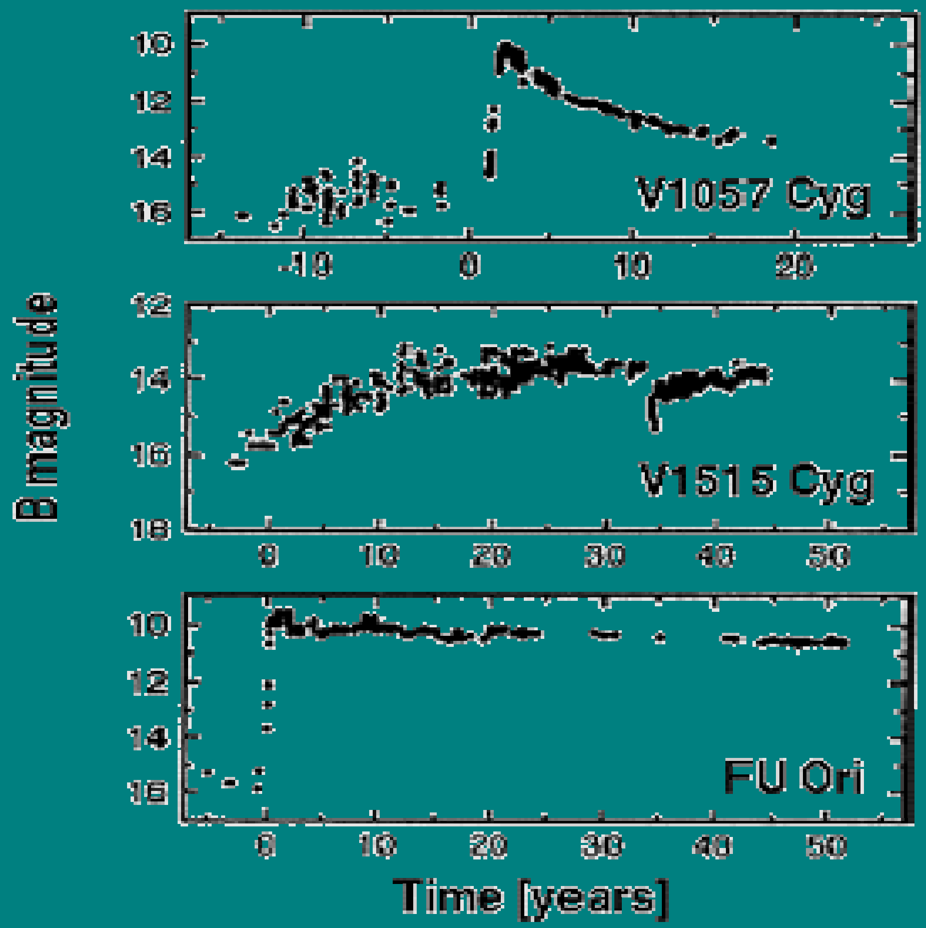
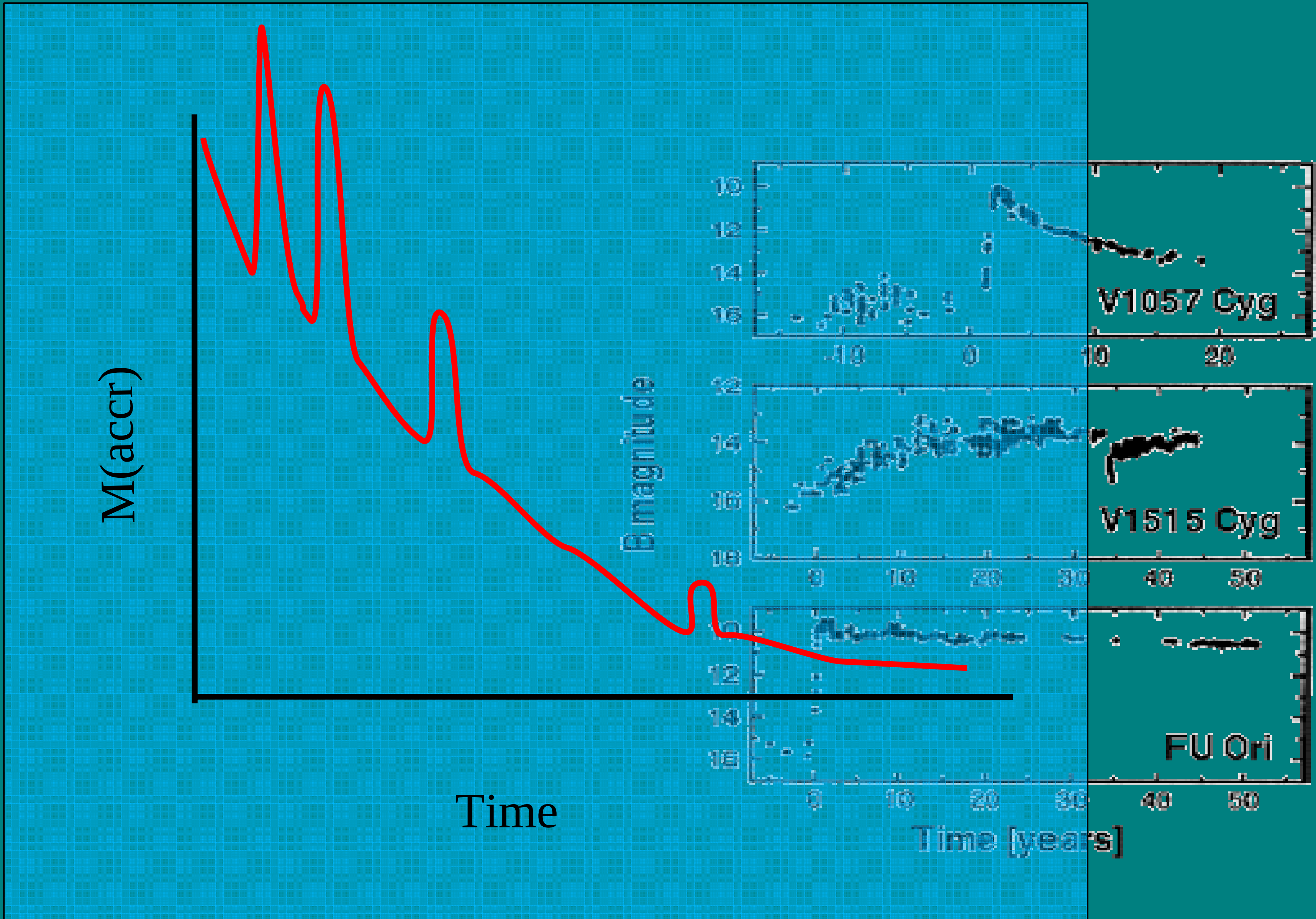


Kenyon & Hartmann (1995) Ann Rev Ast Astrophys.

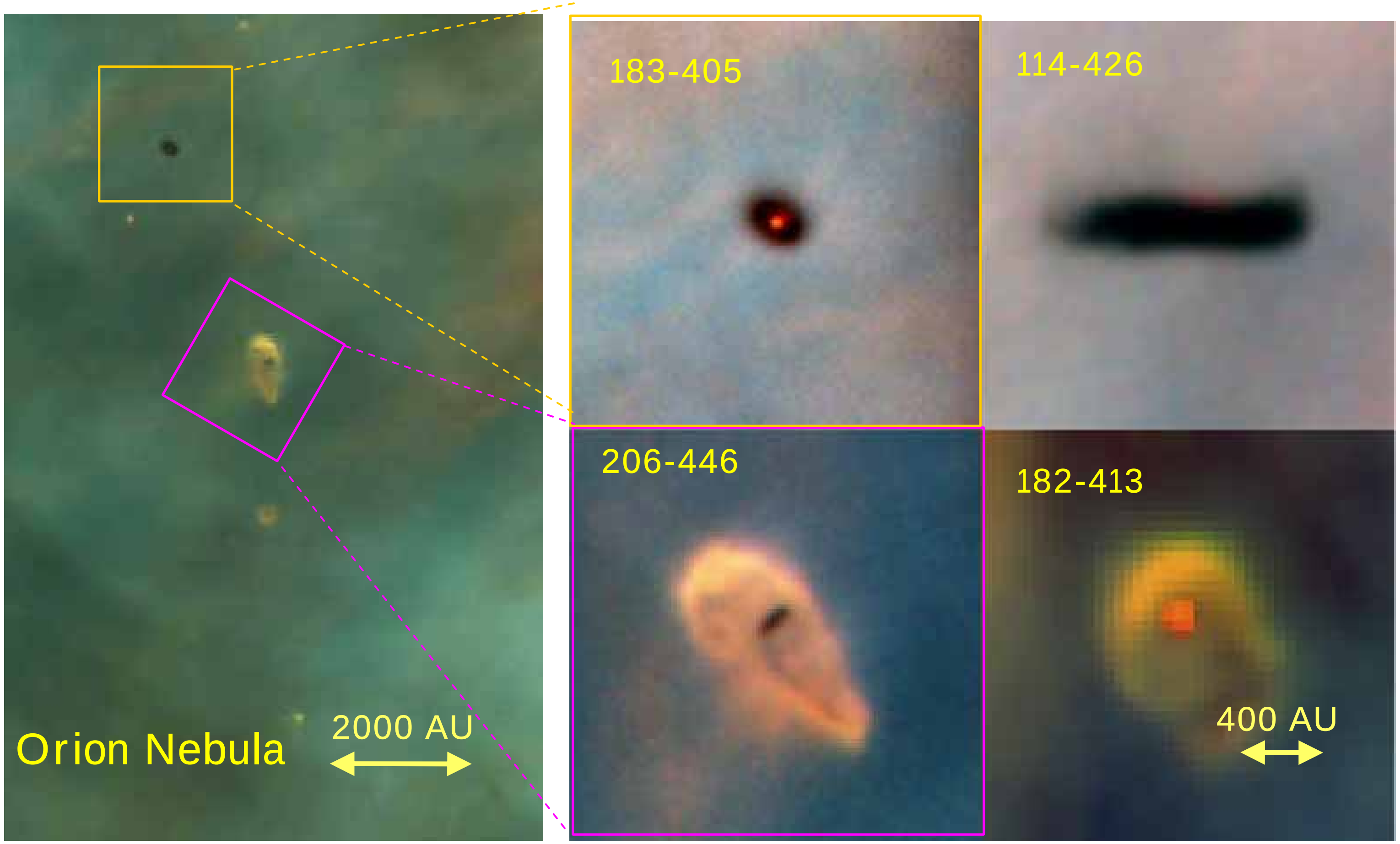


Kenyon & Hartmann (1995) Ann Rev Ast Astrophys.

Evidence for Disks Around Young Stars

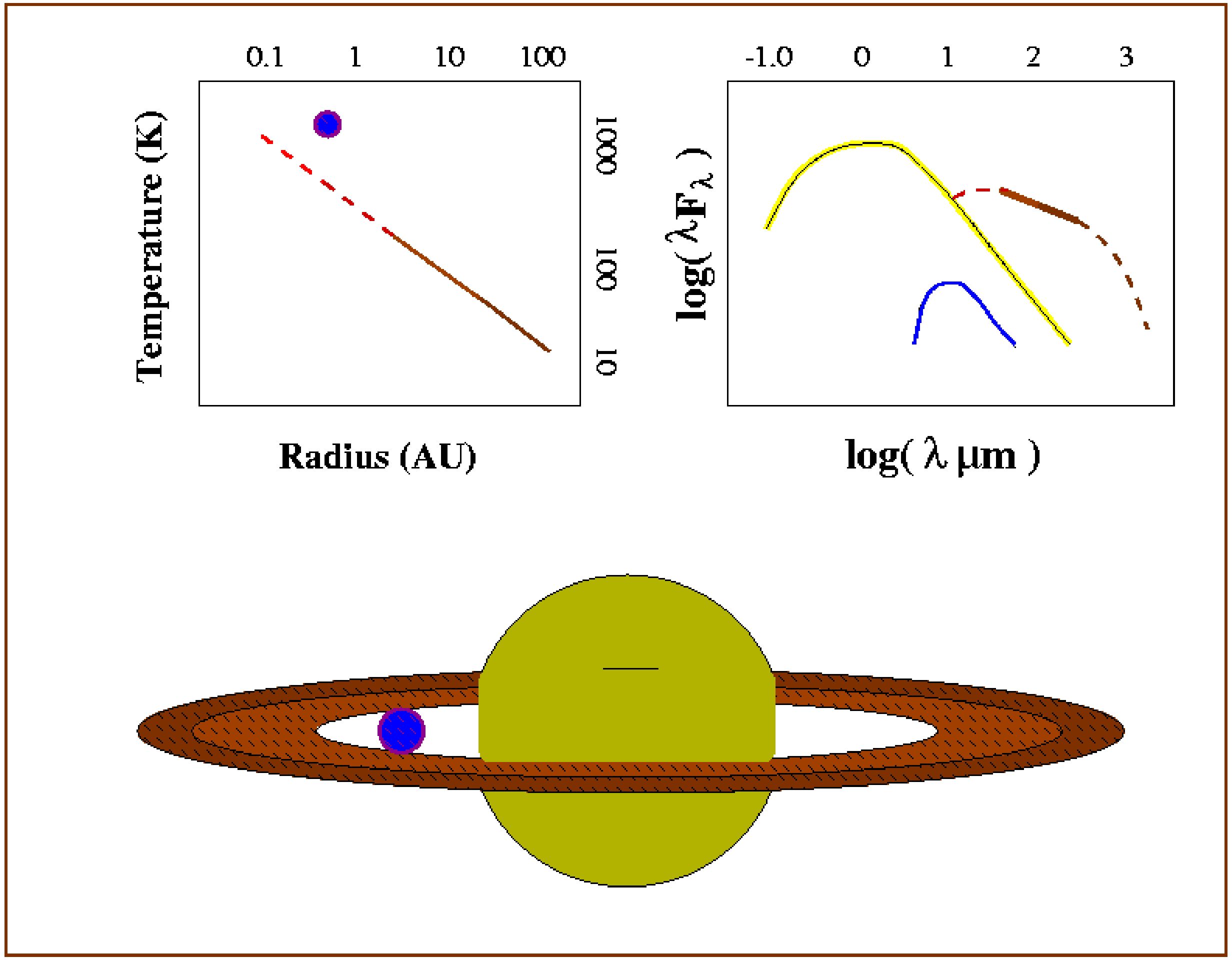
- Optical & near-IR polarization:
  - » Elsaesser & Staude (1978).
- mm and IR excess emission:
  - » Rucinski (1985) & Myers et al. (1987).
- blue-shifted mass-loss:
  - » Appenzeller et al. (1984) & Edwards et al. (1987).
- kinematic signatures of rotation:
  - » disk-dominated systems (Welty et al., 1989).
- direct images from HST:
  - » O'Dell & Wen (1992) ; McCaughrean & O'Dell (1996).

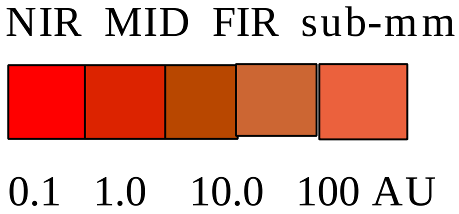
Direct Images of Circumstellar Disks



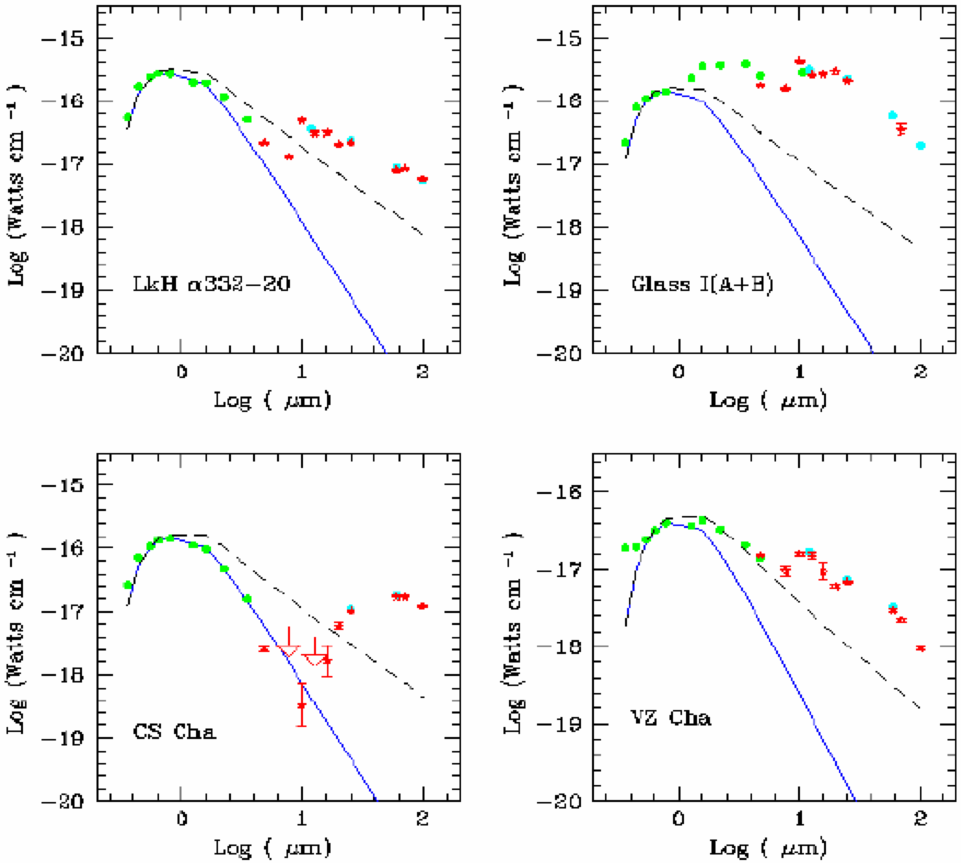
O’Dell & Wen 1992, *Ap.J.*, **387**, 229. McCaughrean & O’Dell 1996, *AJ*, **108**, 1382.

Blackbody Disk with Dynamically Cleared Gap





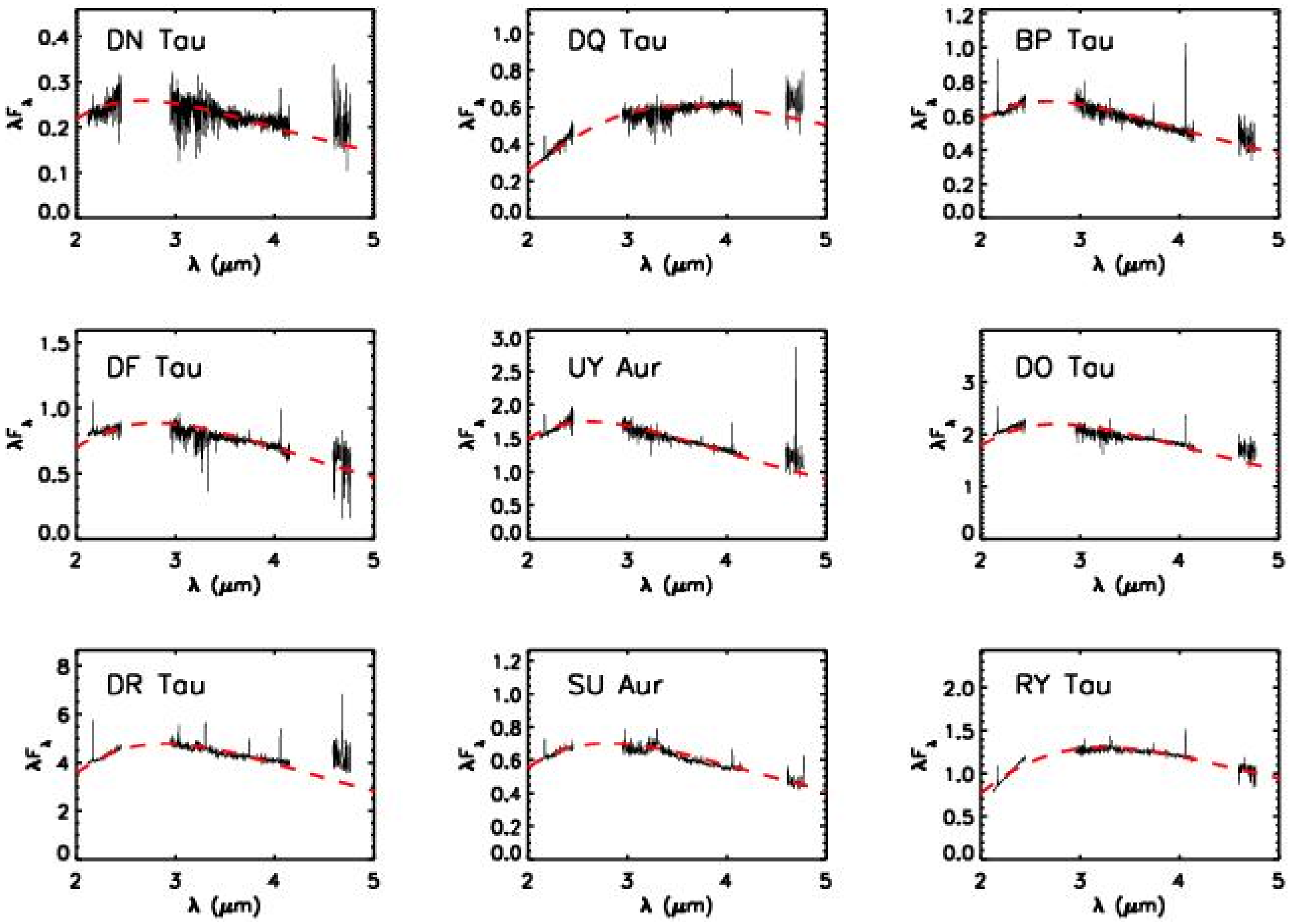
SEDs of T Tauri Stars in Chamaeleon



Robberto et al. (2003).

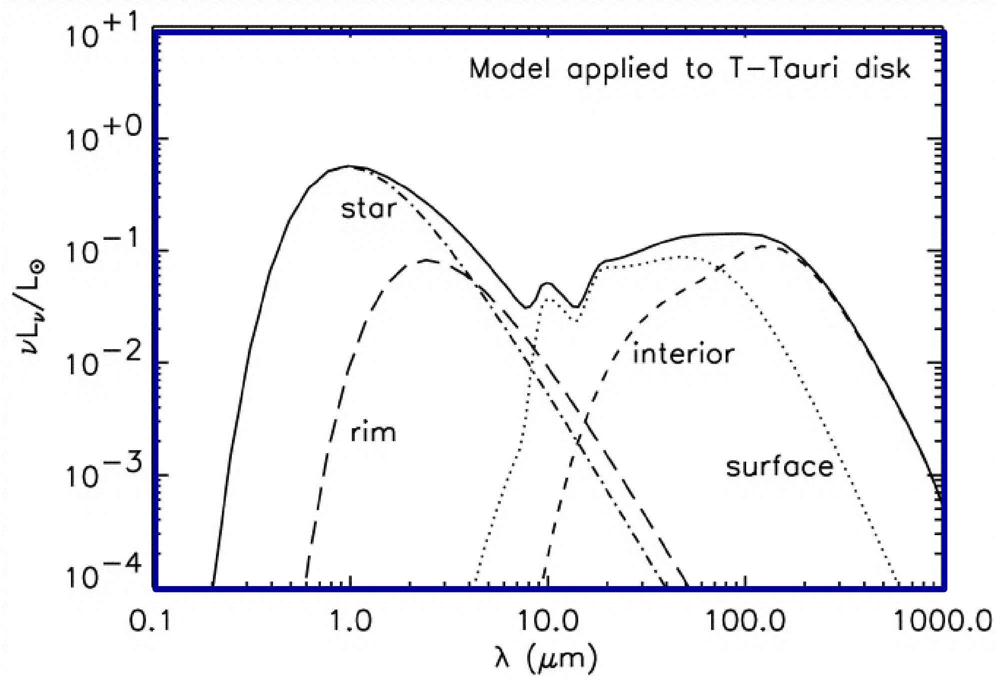
Near-IR Spectrophotometry of T Tauri Stars: Opacity Gap due to Dust Sublimation?

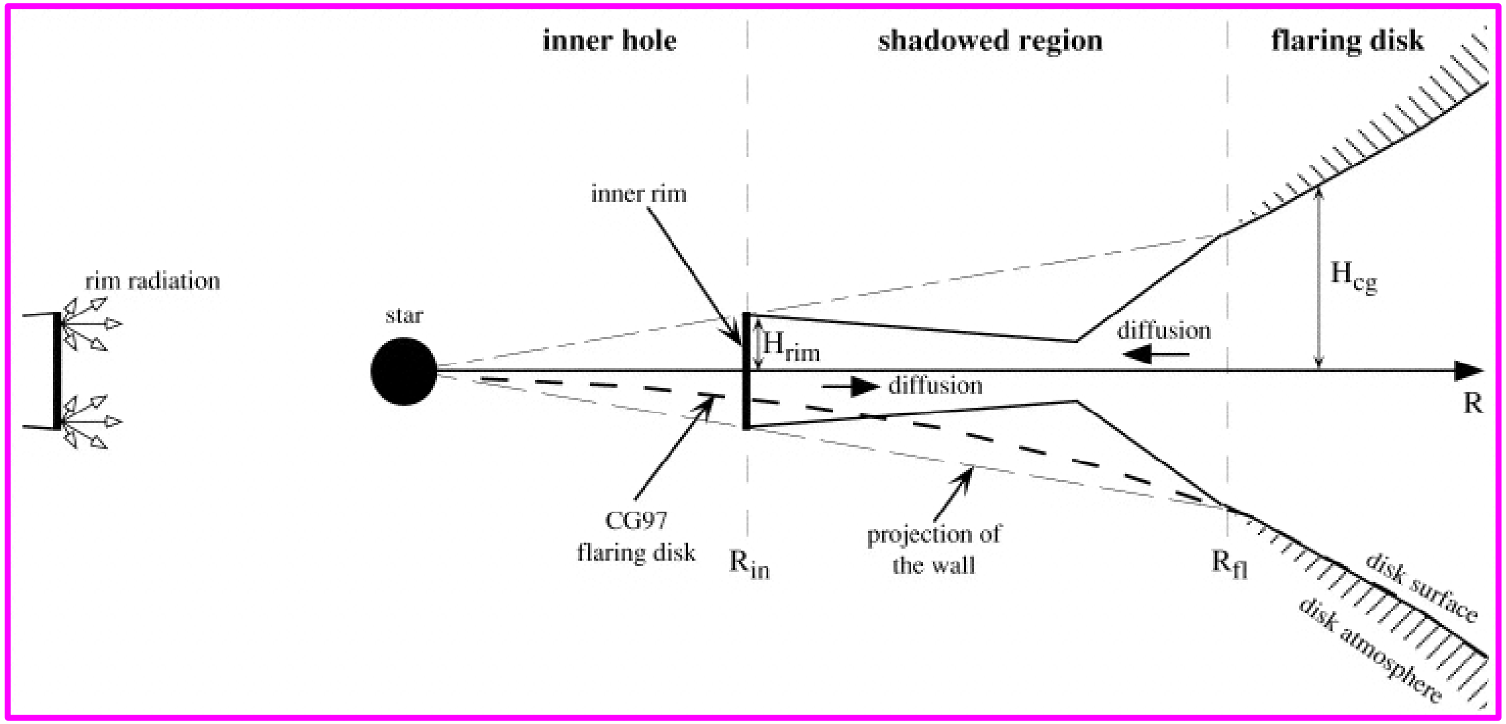
Muzerolle et al. (2003).



Chiang & Goldreich 1997;
Dullemond et al. 2001;
see also Calvet et al. 2003

SEDs of T Tauri Stars: A Consequence of Inner Holes?





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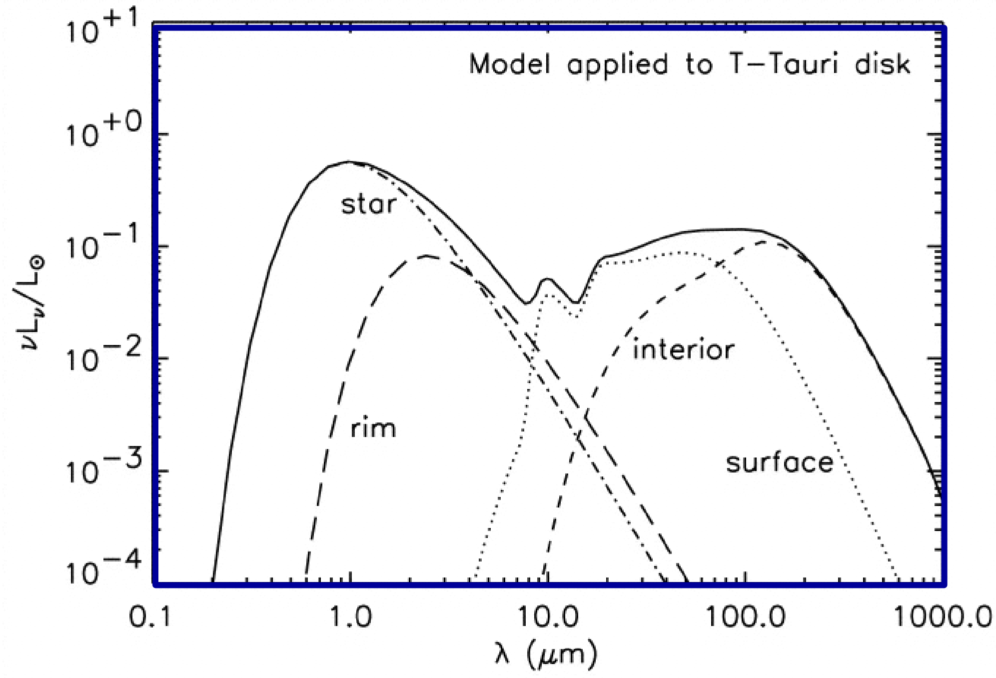

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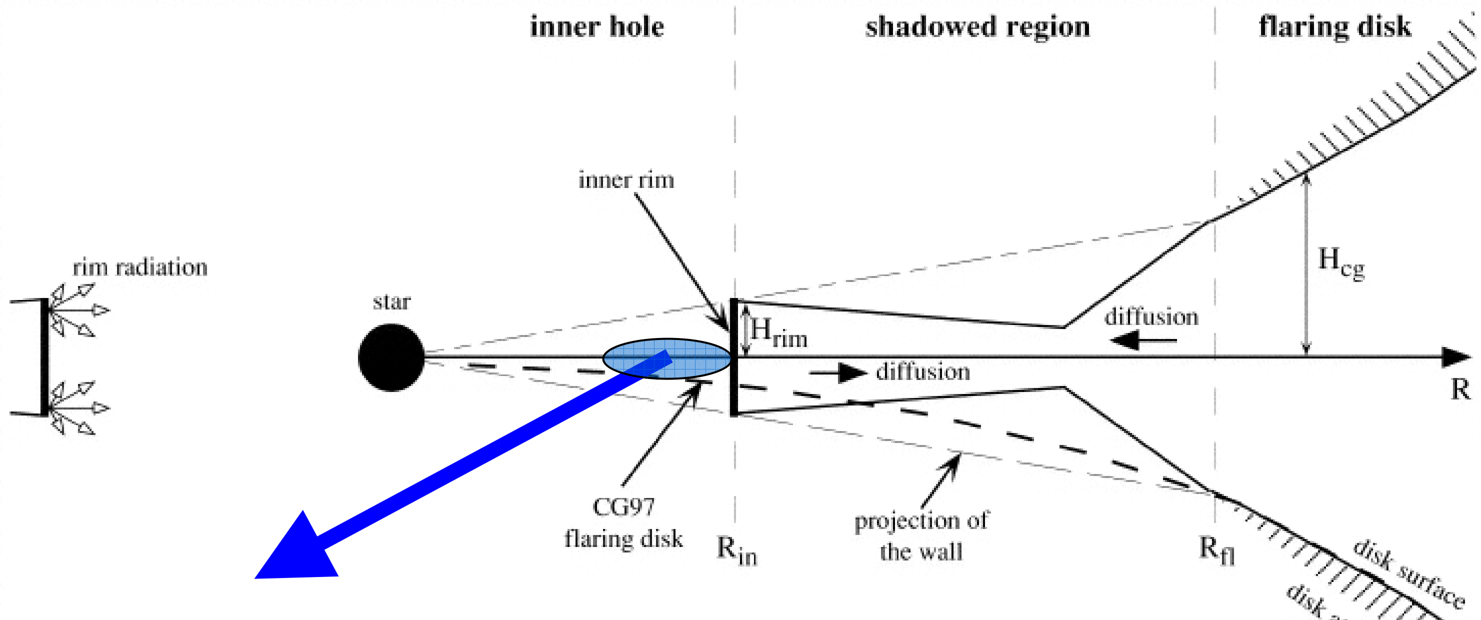
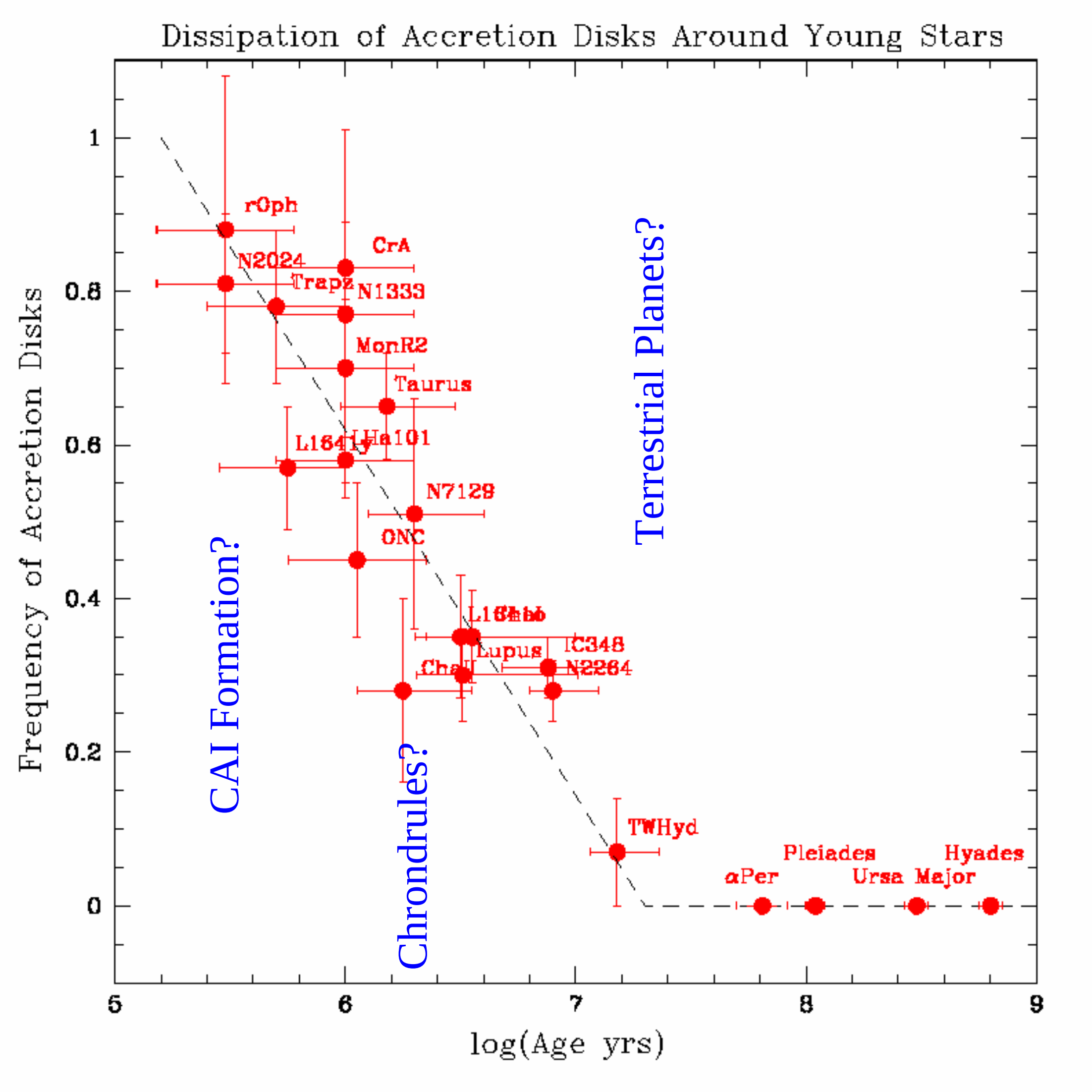


Gas inside R(dust)? **Yes! Najita et al. (2003)**

Evolution of Inner (< 0.1 AU) Accretion Disks

- **Near-IR Excess Fraction vs. Age:**
  - » **Accretion disks dissipate in 1-10 Myr.**
- Angular momentum regulation:
  - » inner disks coupled to stellar rotation.
- Accretion rates decrease with time.
  - » Evolution of α-disk.
- Transition objects are rare:
  - » Transition time << 1 Myr *P-R Drag Timescale? Viscous Timescale?*

NIR Excess Fraction (< 0.1 AU) vs. Cluster Age



Haisch etal. 2001; see also Hillenbrand, Meyer, and Carpenter (2002).

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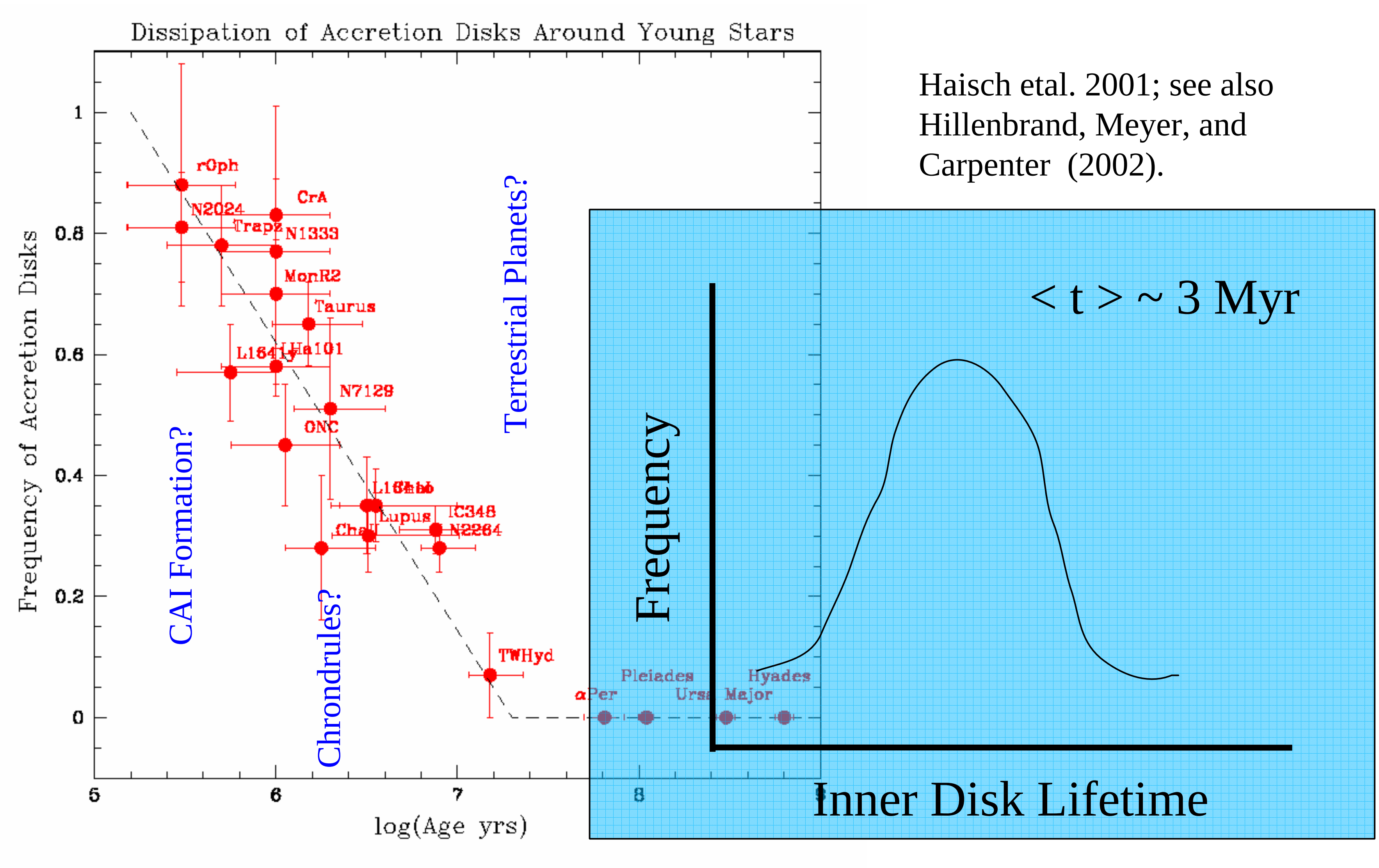

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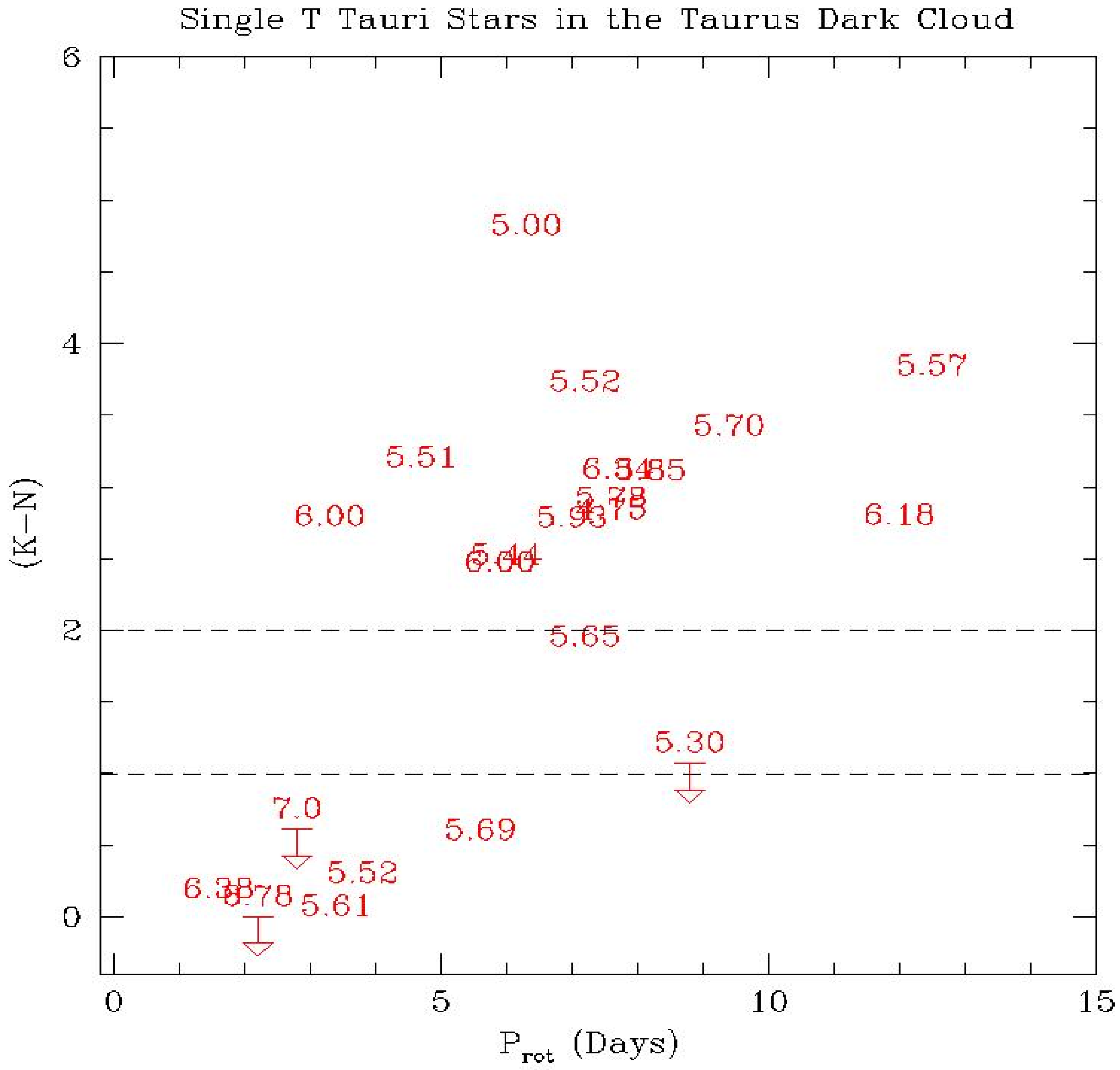
Angular Momentum Regulation?



cf. Edwards et al. 1993;
Bouvier et al. 1993;
Stassun et al. (2001).

Kundurthy, Meyer, Beckwith, Robberto, & Herbst (2005).

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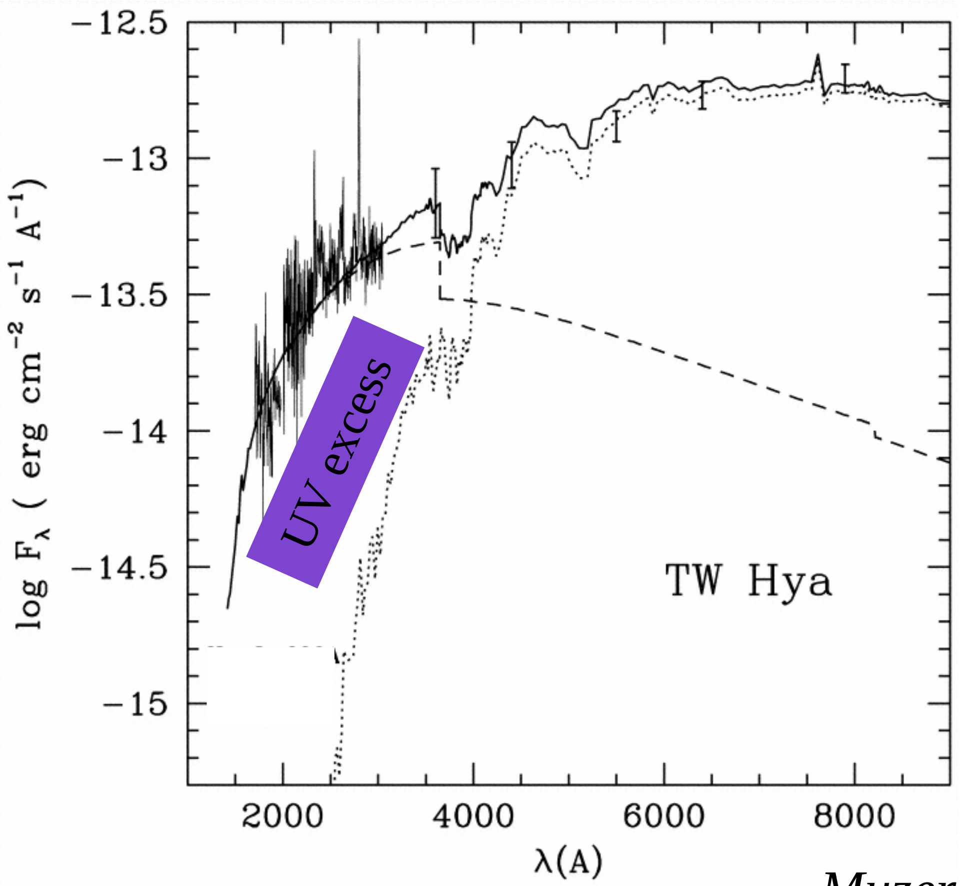
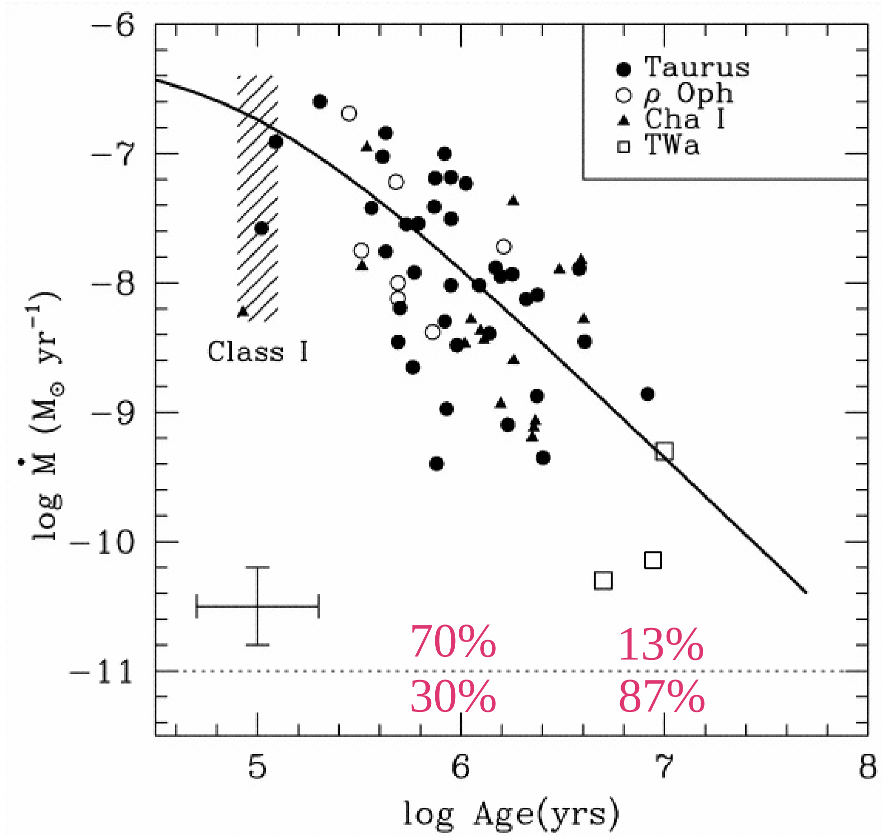
Accretion vs Stellar Age

Measuring disk accretion rates



Evolution of $\dot{M}_{accretion}$



Muzerolle et al. 2000

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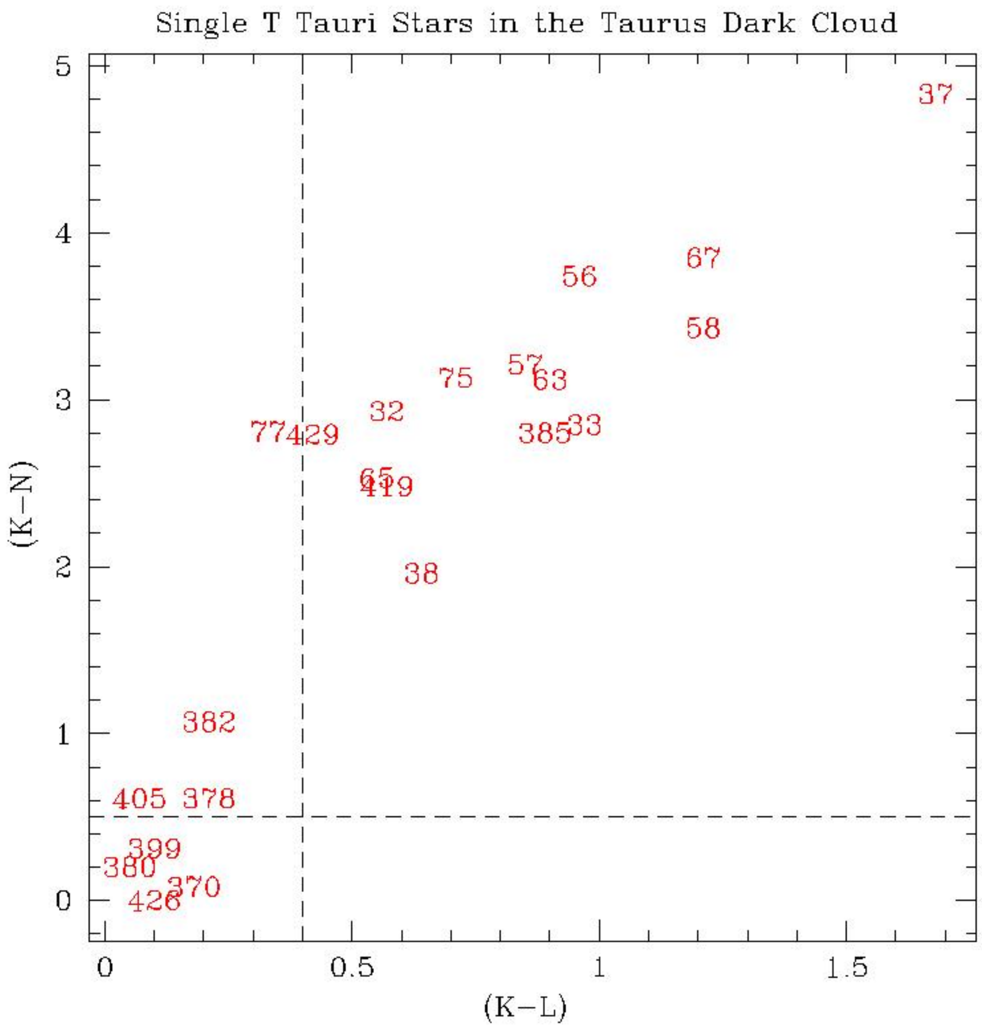
Transition Objects are Rare!



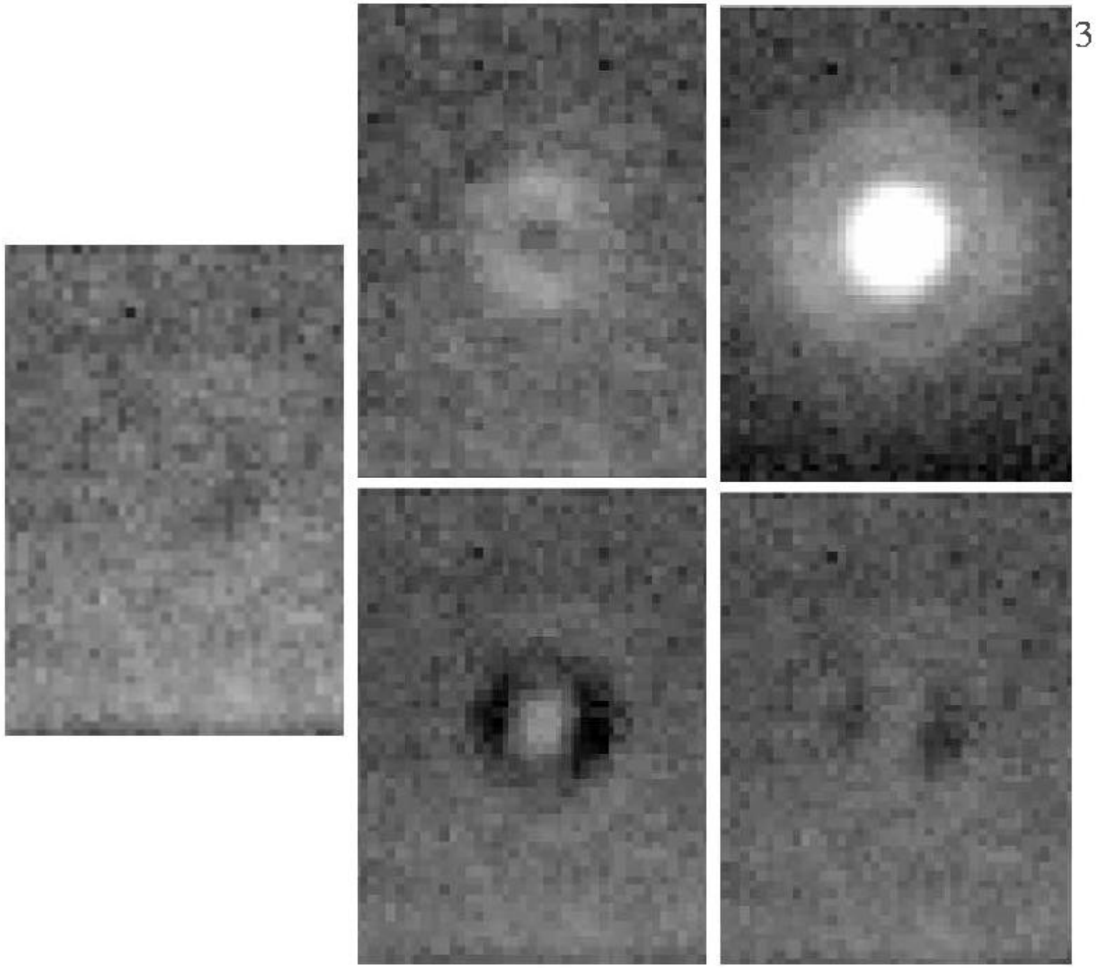
Skrutskie et al. 1990; Kenyon & Hartmann (1995); Wolk & Walter 1996;
See also Kundurthy, Meyer, Beckwith, Robberto, & Herbst (2005).

$$\frac{N(\text{trans. Obj.})}{N(\text{T Tauri stars})} \sim \frac{\tau}{1\ \text{Myr}}$$

suggests transition time τ optically-thick to thin (0.1-1 AU) << 1 Myr.

HD 100546: Inner Hole in Disk Caused by Proto-planet?

MIR



Resolved at 24.5 μm:
Inner hole < 30 AU devoid of dust.
Indirect evidence of planetary companion?

Liu, Hinz, Meyer, Hoffman, Mamajek, and Hora, ApJ L (2003)

Evolution of Primordial Disks: Some Answers?

- Collapse of rotating cloud cores set initial conditions.
- Disk instabilities occur during protostellar phase.
- 50 % of accretion disks (< 0.1 AU) dissipate < 3 Myr.
- Large dispersion (1-10 Myr) in accretion disk lifetimes.
- Stellar angular momentum tied to disk accretion.
- Disk accretion rates decrease with time.

The Transition between Thick & Thin:

- Primordial Disks:
  - » Opacity dominated by primordial grains.
- Debris Disks:
  - » Opacity dominated by grains produced through collisions of planetesimals.
- How can you tell the difference?
  - » Absence of gas (Gas/Dust < 0.1) argues for short dust lifetimes (blow-out/P-R drag).
  - » Dust processing through mineralogy?

1. How much *gas* is required for $\tau = 1$?

- M(accretion) > 10^{-7} M_{sun}/year?

2. How much *dust* is required for $\tau = 1$?

- Near-IR r < 0.1 AU: ~ 2-10 M(Ceres).
- Mid-IR 0.1-1.0 AU: ~ 0.1-2 M(Earth).
- FIR 1.0-10.0 AU: 0.1-10 M(Jupiter).

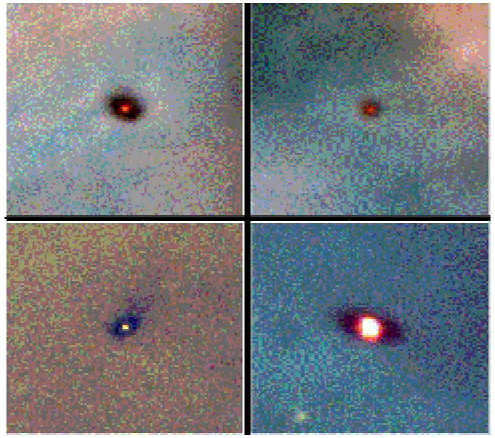
It is often assumed that optically-thin implies a ''debris'' disk rather than primordial disk, though this need not be the case.

Factors Influencing Disk Evolution

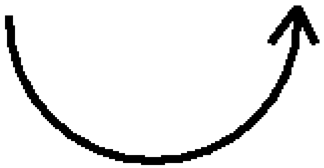
- Stellar mass:
  - » Do high mass stars lose disks quicker?
- Close companions:
  - » dynamical clearing of gaps
    (Jensen et al. 1995; 1997; Meyer et al. 1997b; Ghez et al. 1997; Prato et al. 1999; White et al. 2001).
- Formation environment:
  - » cluster versus isolated star formation
    (Hillenbrand et al. 1998; Kim et al. 2005; and Sicilia-Aguilar et al. 2004).

From Active Accretion to Planetary Debris Disks...

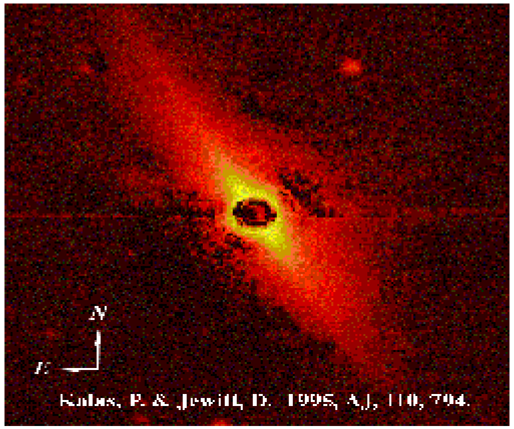
Images courtesy of M. McCaughrean, C.R. O'Dell, NASA, and P. Kalas.



Orion Disks 1 Myrs



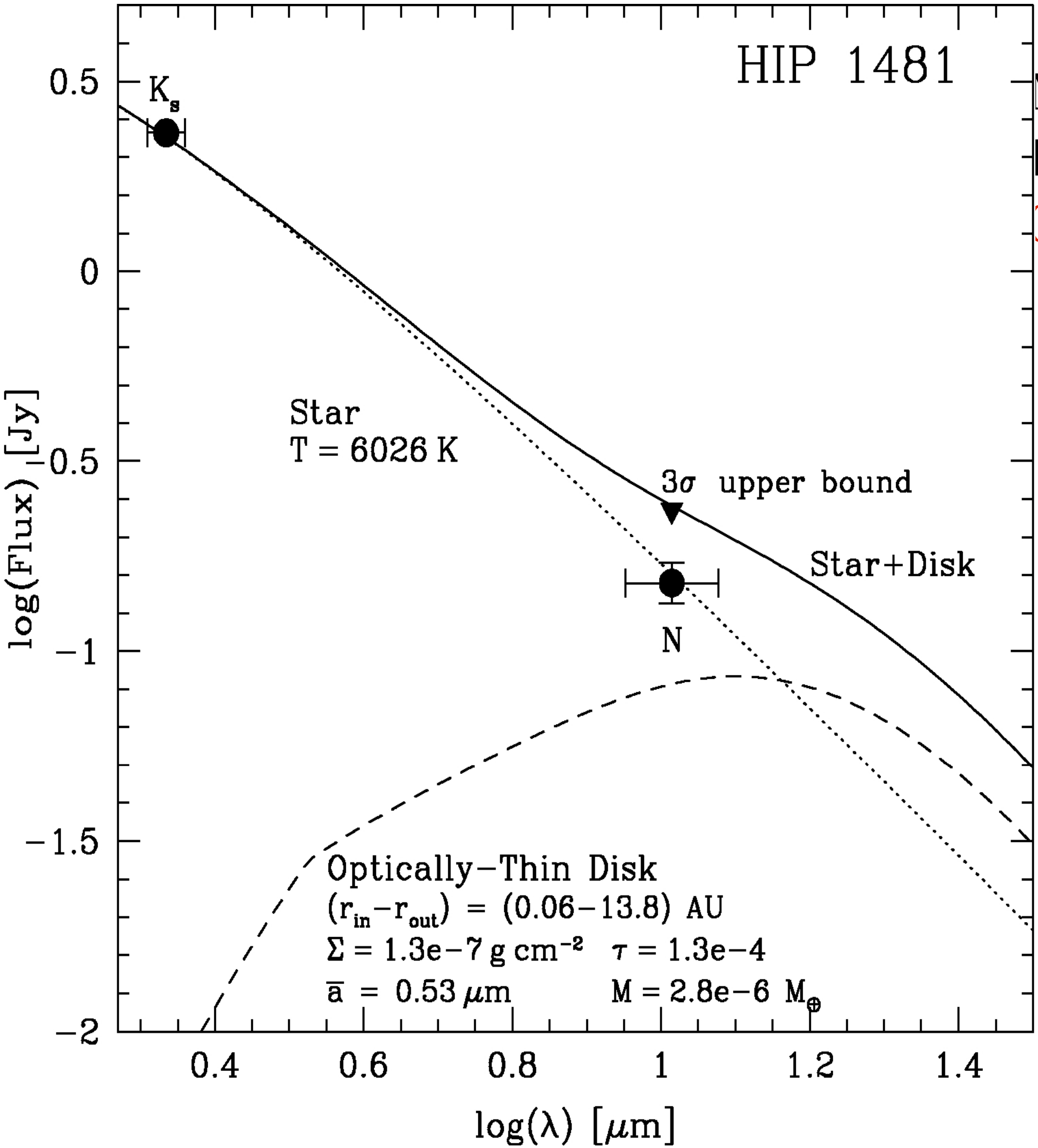
Zodiacal Dust 5 Gyrs



β Pic 20 Myrs

MIR

MIR Excess Emission:
Probing Remnant Disks
0.3-1 AU over time...

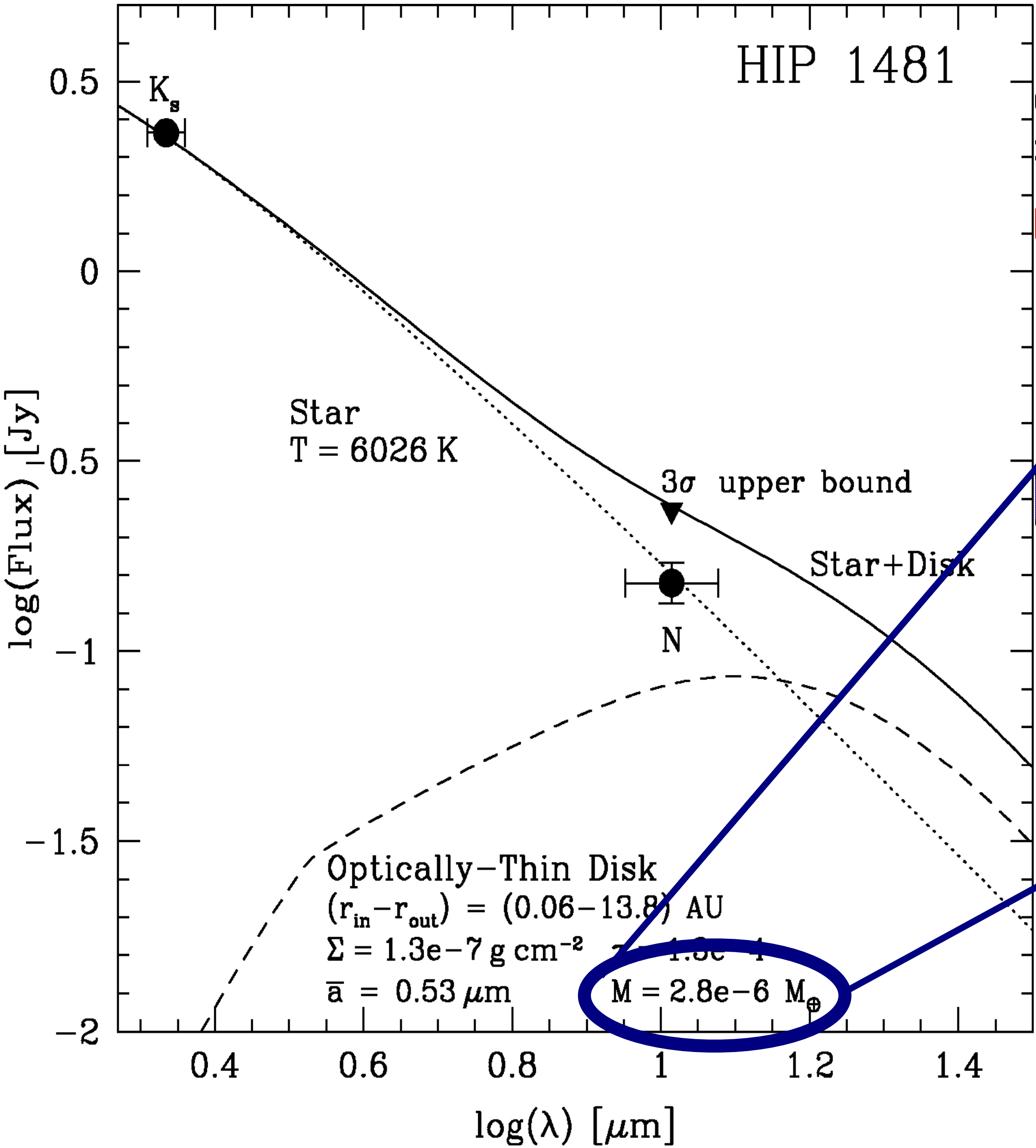


Upper limits correspond to optically-thin disks with very small dust masses.

Mamajek et al. 2004, ApJ.

MIR

MIR Excess Emission: Probing Remnant Disks 0.3-1 AU over time...

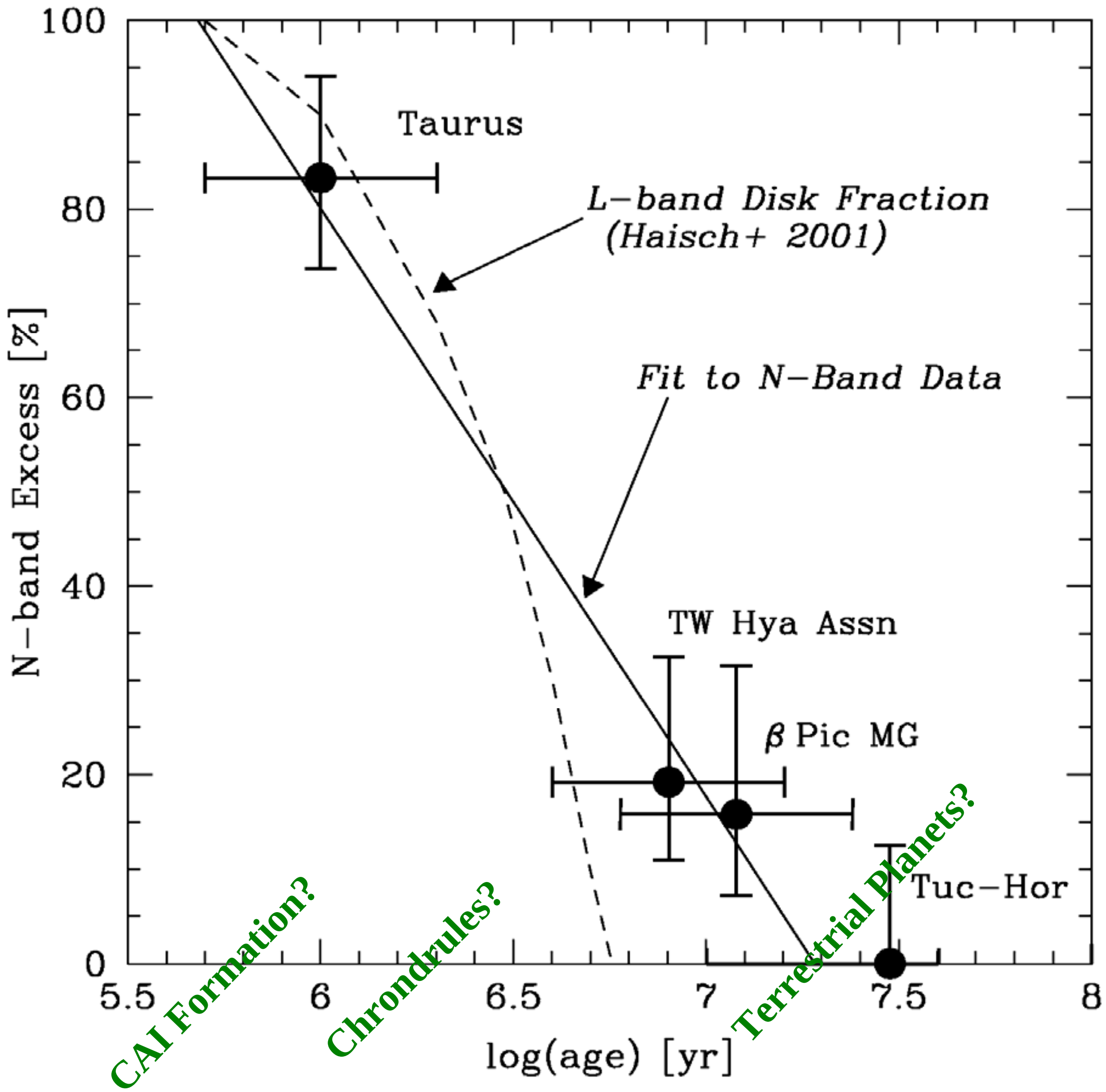


cf. 1000 x zodi => could detect solar system zodi before late-heavy bombardment!

Mamajek et al. 2004, ApJ.

MIR Excess (0.3-1.0 AU) vs. Cluster Age

MIR



Dust in terrestrial planet zone dissipates when accretion stops!

Mamajek et al 2004, ApJ.

Metchev, Hillenbrand, and Meyer, 2004, ApJ.

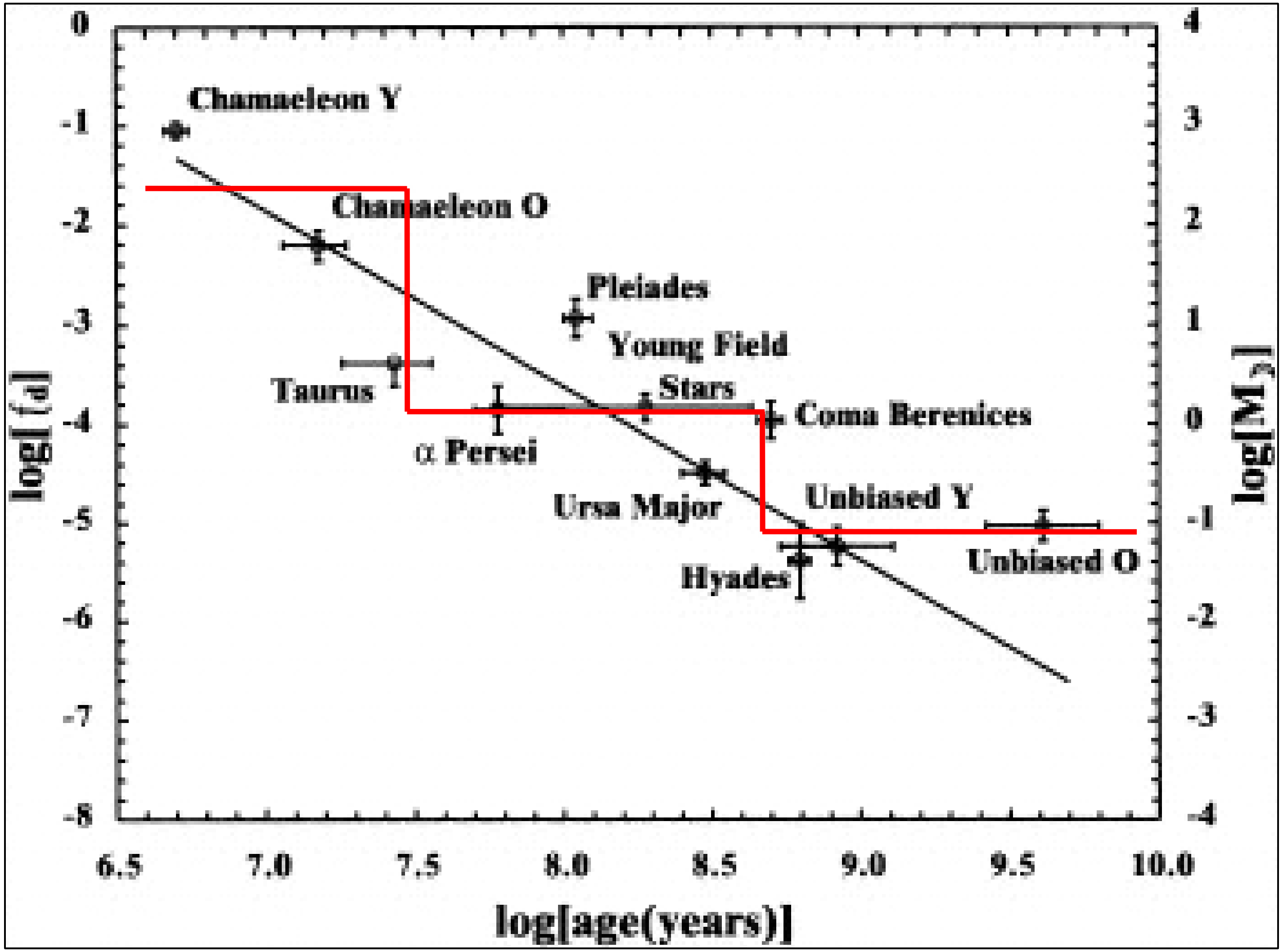
See also Low et al. (2005) as well as Chen et al. (2005).

FIR Outer Disks (1-10 AU) vs. Time

Classical Evolution or Punctuated Equilibrium?

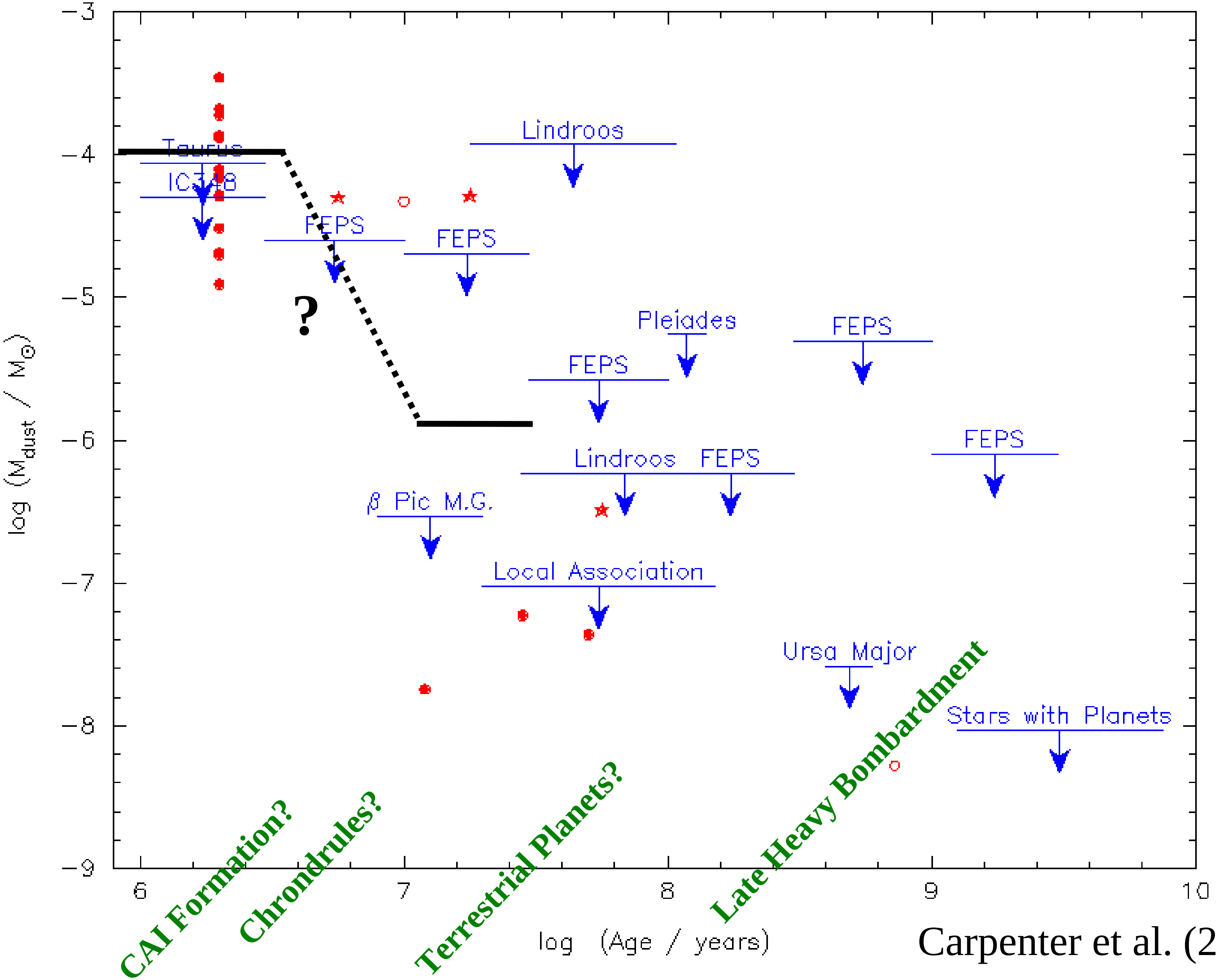
FIR

Habing et al. (1999)
Meyer et al. (2000)
Habing et al. (2001)
Spangler et al. (2001)



Sub-mm Photometry: Dust Mass over Time?

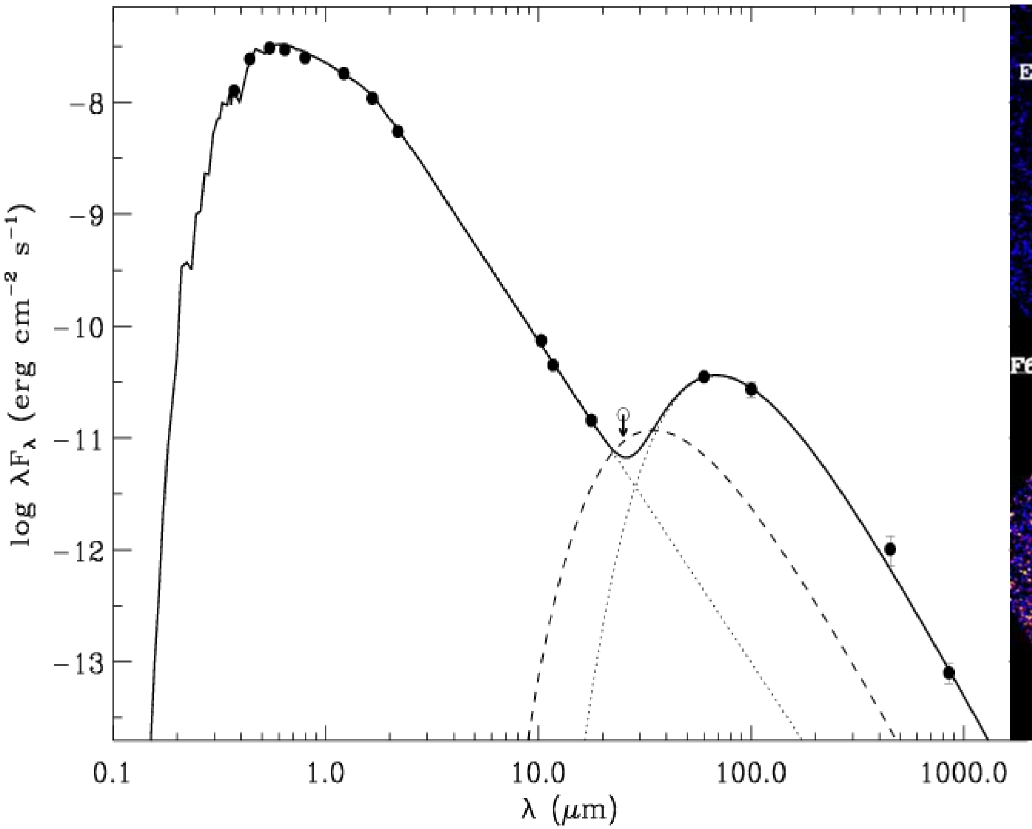
SMM

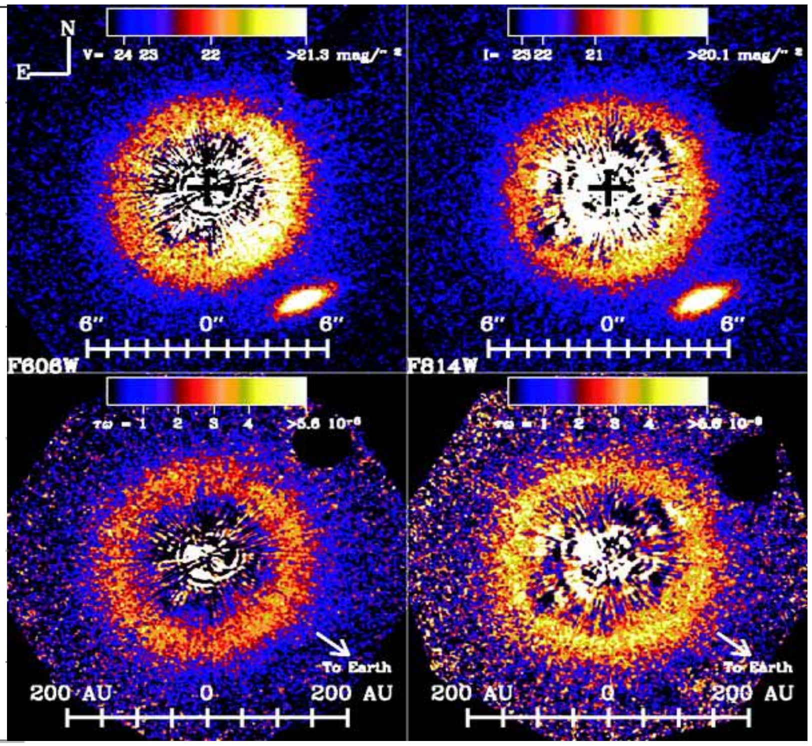


Carpenter et al. (2004)

HD 107146: Debris Disk Surrounding 100-300 Myr G star?

SMM





Williams et al. (2004) ApJL.

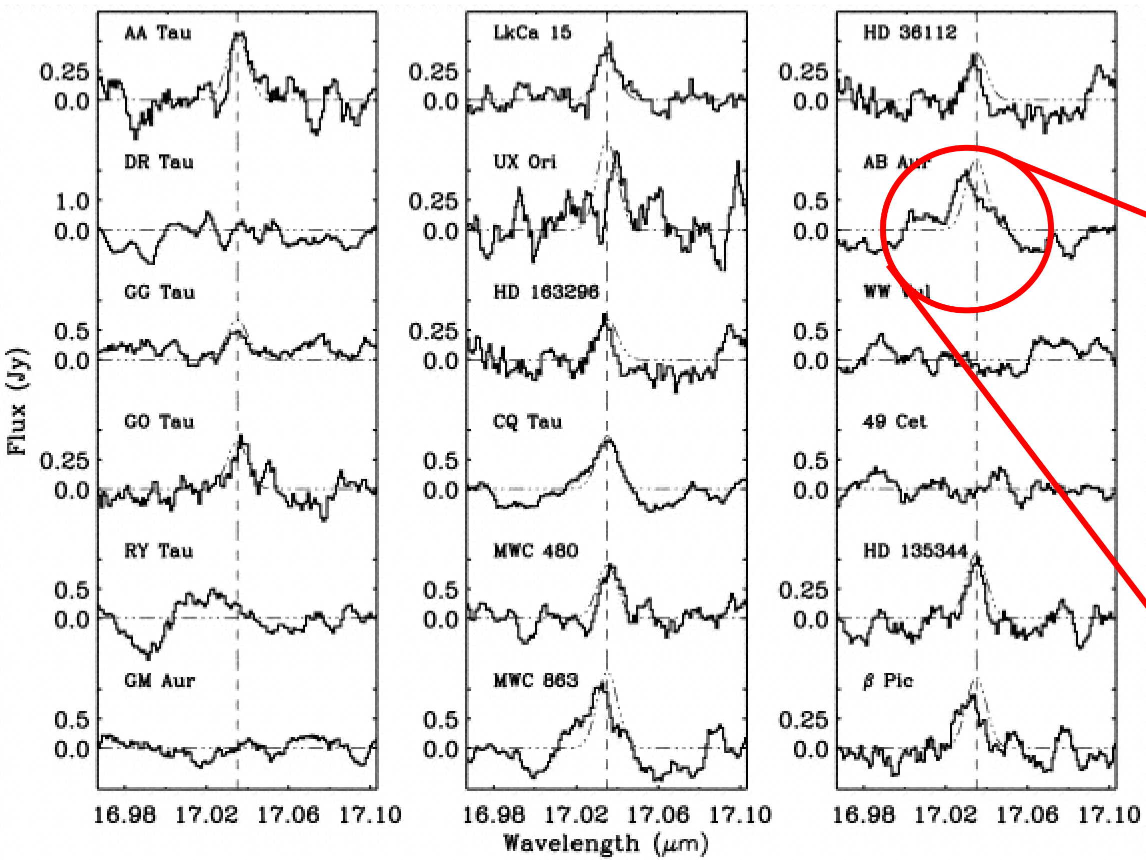
Ardila et al. (2005).

Theoretical Gas-Disk Dispersal Timescales

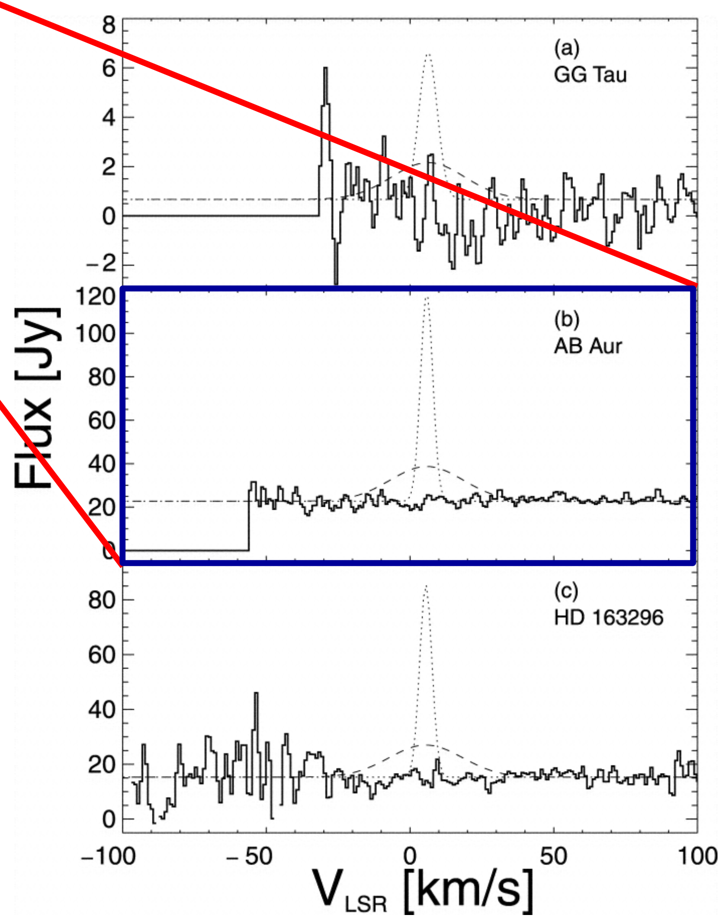
- Photo-evaporation:
  - » $R > 10$ AU => $T < 10$ Myr (Hollenbach et al., 2000)
- Viscous evolution:
  - » $T(\text{diff}) \sim R^2/[\alpha\, h\, _{cs}]$ Pringle (1986); Chiang (this school)
- Planet Formation:
  - » Gravitational fragmentation <<< 10^6 yrs.
  - » Core accretion 1-10 $\times 10^6$ yrs.

Where is the molecular gas???

GAS

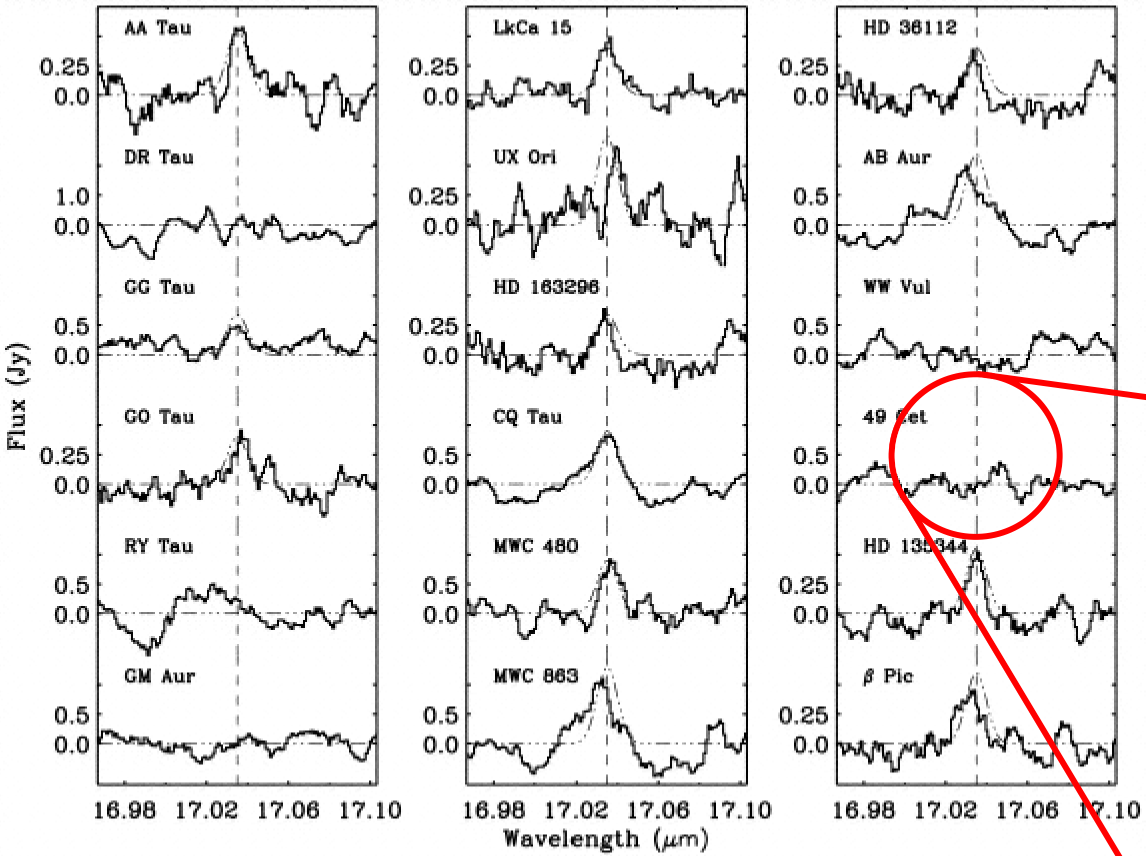


Thi et al. 2001

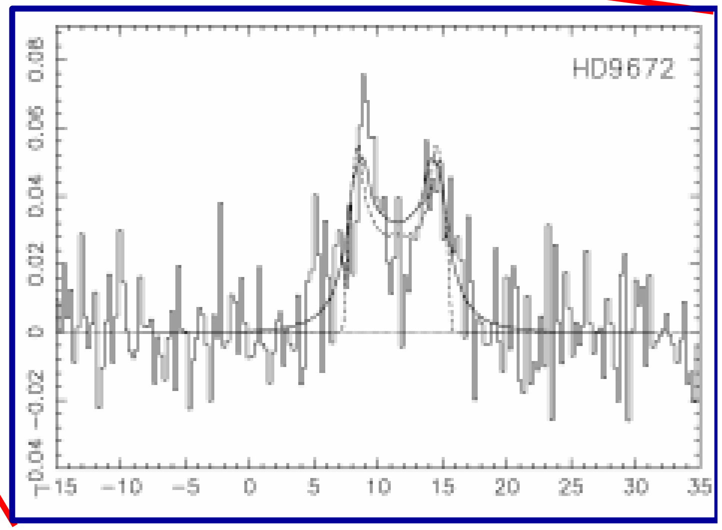


Ritcher et al. 2002

Where is the molecular gas???



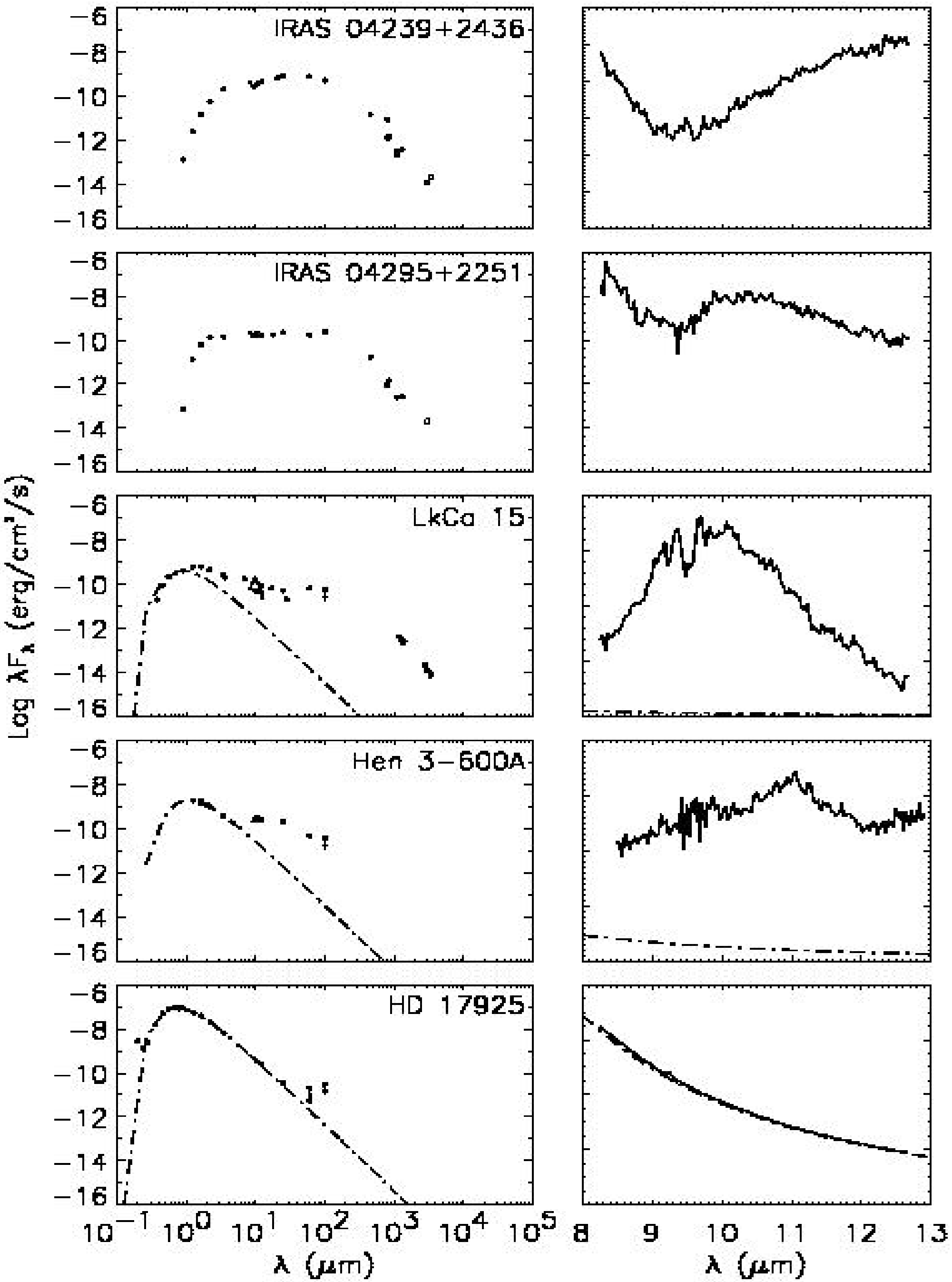
Thi et al. 2001



Dent et al. 2005

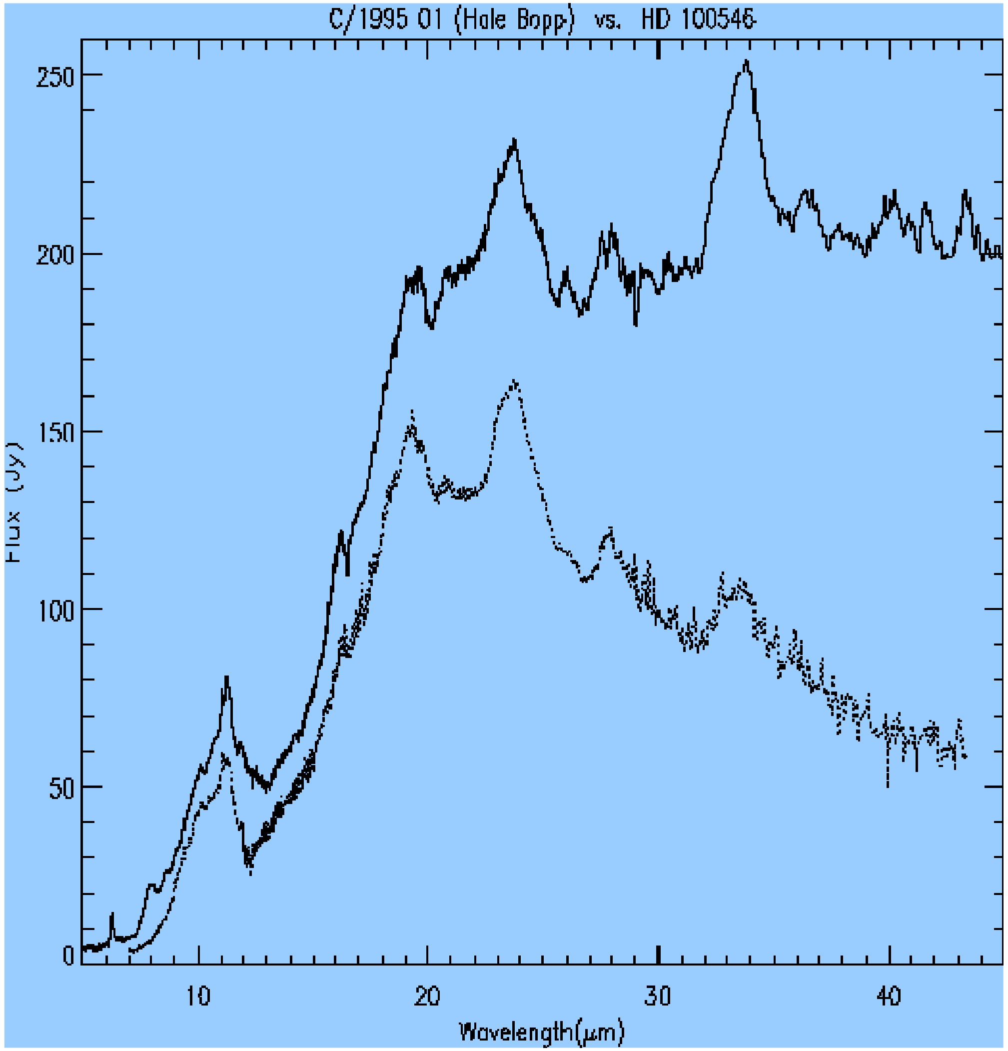
(See also Lecavelier des Etangs et al. 2001; Chen et al. 2005).

Silicate Evolution in T Tauri Disks?



Kessler, Hillenbrand, Blake, & Meyer (2005).

Silicate Emission: Effects of Mineralogy



Malfait et al. A&A 1999, 345, 181.
Malfait et al. A&A 1999, 332, L25.
Meeus et al. A&A 2001, 365, 476.

Herbig Ae/Be star survey:
~ 10 % of isolated targets
show crystalline silicates.

=> Because no crystalline
silicates in the diffuse ISM
this implies ***processing***!

Theoretical Dust Disk Dispersal Timescales

- **Radiation Pressure Blow-out:**
  - **T(BO) ~ 0.5 yrs $r(AU)^{3/2}/(M^*/Msun)^{1/2}$**
- Poynting-Robertson Effect:
  - T(P-R) ~ 720 yrs $a(\mu m) r(AU)^2 \rho(g/cm^3)/(L^*/Lsun)$

    σ(P-R) = constant (Chiang, this school)
- Collisional Timescale:
  - T(Coll) ~ P(orb)/σ ~ $r(AU)^{3/2}/[10(M^*/Msun)^{1/2}\sigma]$yrs

    –> f ~ L(IR)/L* ~ $\sigma / |2\alpha|$ where $\sigma \sim \sigma(r') (r/r')^{-\alpha}$
    - Backman & Paresce (1993)
    - Burns et al. (1979); Decin & Dominik (2003)

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    $\rightarrow$ $f \sim L(IR)/L^* \sim \sigma / |2\alpha|$ where $\sigma \sim \sigma(r') (r/r')^{-\alpha}$
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  - » $T(P\text{-}R) \sim 720$ yrs $a(\mu m) r(AU)^2 \rho(g/cm^3)/(L^*/Lsun)$

    $\sigma(P\text{-}R)$ = constant (Chiang, this school)
- **Collisional Timescale:**
  - » **$T(Coll) \sim P(orb)/\sigma \sim r(AU)^{3/2}/[10(M^*/Msun)^{1/2}\sigma]$yrs**
    - **–> $f \sim L(IR)/L^* \sim \sigma / |2\alpha|$ where $\sigma \sim \sigma(r') (r/r')^{-\alpha}$**
      - » Backman & Paresce (1993)
      - » Burns et al. (1979); Decin & Dominik (2003)

Physical Processes in Debris Disks

- **Critical gas-to-dust ratio:**
  - » **GDR ~ 100 ==> 0.1 for *radiation dominated***

    (Takeuchi & Artymowicz, 2001; Takeuchi & Lin, 2002)
- Blow-out size:
  - » a(SiO) ~ 0.52 μm L*/[M* T*] (Chiang, this school)
- Collisional size distribution:
  - » $dn/da \sim a^{-3.5}$ (Dohnanyi, JGR, 1969)
- Disk Asymmetries due to planets:
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Grain Temperature Distributions:

- **Small (ISM) Grains:** ***particles smaller than incident and emitted light***
  - » **$T \sim 636\ L_*^{2/11}\ R(AU)^{-4/11}\ (T_*/T_{sun})^{3/11}$ K**
- Intermediate Grains:

  particles larger than incident, smaller than emitted
  - » $T \sim 468\ L^{-1/5}\ R(AU)^{-2/5}\ \lambda_o^{-1/5}$ K

  $\xi = \lambda_{o/a}$ **= [1/2π,2π]=[weak,strong] absorption**
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$\sigma >= 1 / [7200 \times 2.5\, r(AU)^{1/2}\, a(\mu m)]$

$f > 1 / [7200 \times 2.5 \times 2\, r(AU)^{1/2}\, a(\mu m)] \sim 3 \times 10^{-5} / [r(AU)^{1/2}\, a(\mu m)]$

For r = 45 AU and a = 50 μm, and disk with $f > 10^{-7}$ would be collisionally dominated.

Problem #3:

For a debris disk with T(dust) = 40 K, f(IR/*) ~ 1 x 10^{-5}, surrounding a star like the sun, assuming generic silicate grains (ρ = 2.5 gm/cm^3), calculate: a) disk radius for 0.1 μm ISM grains; b) 5.0 μm grains; c) 250 μm blackbody grains; d) what is the blow-out size? e) For what combinations of particle size and radius in the disk is the collision timescale shorter than the P-R drag timescale?

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5.0 μm => R ~ 340 AU
250 μm => R ~ 48 AU

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λ (absorbed) ~ 0.5 μm while λ (emitted) ~ 3000/T ~ 75 μm

0.1 μm => R ~ 2000 AU!!!
5.0 μm => R ~ 340 AU
250 μm => R ~ 48 AU

Note blow-out size is ~ 0.5 μm. Under what conditions is the 'small grain' hypothesis reasonable?

Problem #3:

For a debris disk with T(dust) = 40 K, f(IR/*) ~ 4 x 10^{-4}, surrounding a star like the sun, assuming generic silicate grains (ρ = 2.5 gm/cm^3), calculate: a) disk radius for 0.1 μm ISM grains; b) 5.0 μm grains; c) 250 μm blackbody grains; d) what is the blow-out size? e) For what combinations of particle size and radius in the disk is the collision timescale x10 shorter than the P-R drag timescale?

$f \sim 1 \times 10^{-5} > 3 \times 10^{-4} / [r(AU)^{1/2}\, a(\mu m)]$

or $[r(AU)^{1/2}\, a(\mu m)] > 30$

For a = 0.1 μm, r > 90,000 AU != for T(r)
a = 5.0 μm, r > 36 AU

Properties of our Own Debris Disk

- Kuiper-belt dust:
  - » 30-50 AU => M(KB) ~ 1 x 10^{-10} Msun (Fixen & Dwek, 2002; Kelsall et al., 1998)
- Inner zodiacal dust:
  - » 0.1-3 AU => M(zodi) ~ 3 x 10^{-10} Msun (Hahn et al. 2001; Fixen & Dwek, 2002)
- Role of Comets?
  - » Sikes et al. (1990); Reach et al. (1997)
- Asymmetries due to planets:
  - » Dermott et al. (Earth); Moro-Martin (Neptune)

Problem #4:

Using the models of Wolf & Hillenbrand (2003) construct a model of the spectral energy distribution for the 30 Myr old solar mass star, HD 105. Determine: a) the mean particle size, b) temperature of the dust; c) the inner radius of the disk, d) the mass of the dust; d) summarize a physical model for the disk; and e) come up with an observational test of the hypothesis offered above.

Links to the transfer code, stellar models, and Spitzer data will be available at:

http://feps.as.arizona.edu