# Observational Properties of Protoplanetary Disks

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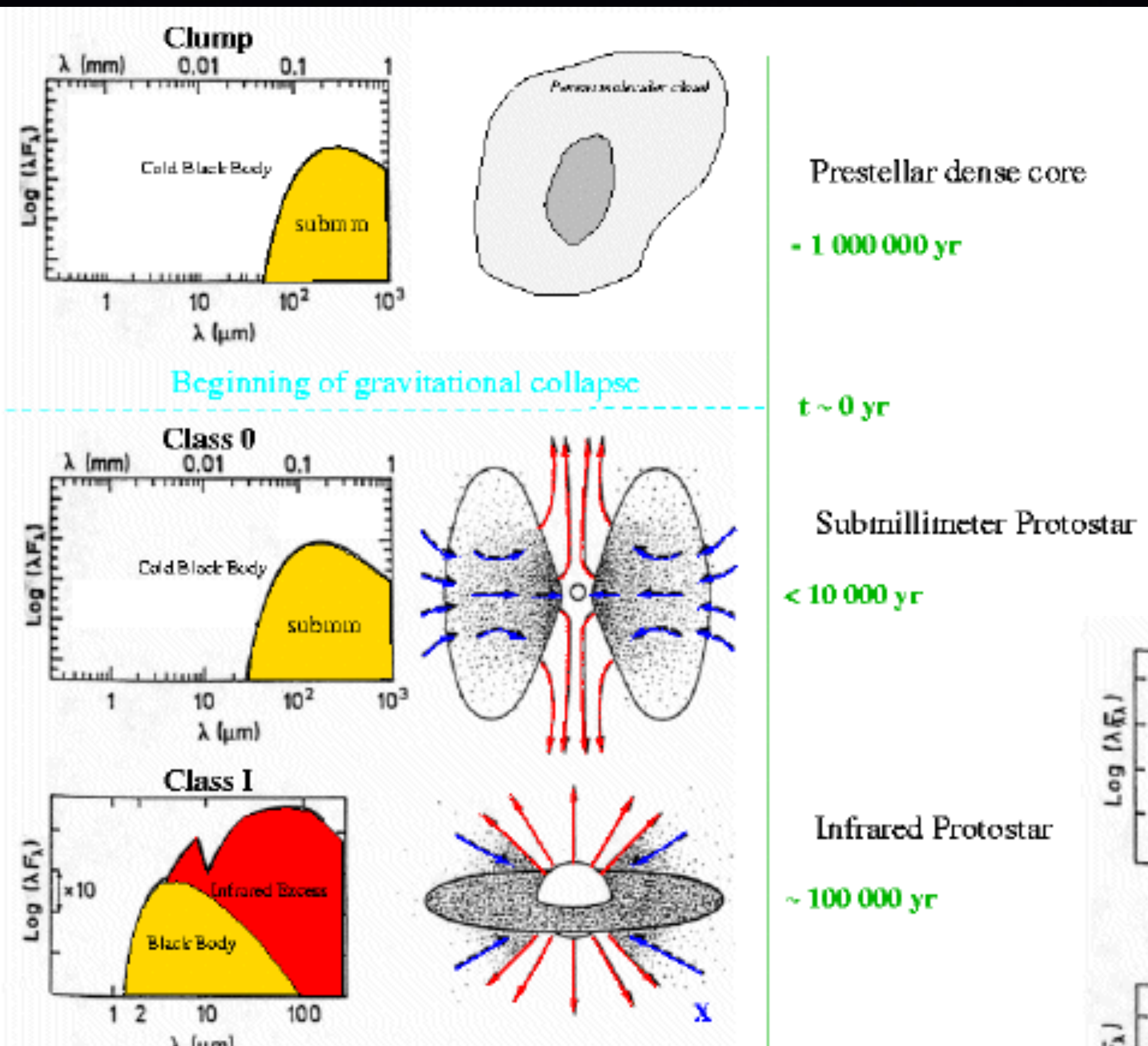
- Today:
    - Continuum emission from disks
    - Dust disk masses from mm observations
    - Interferometry

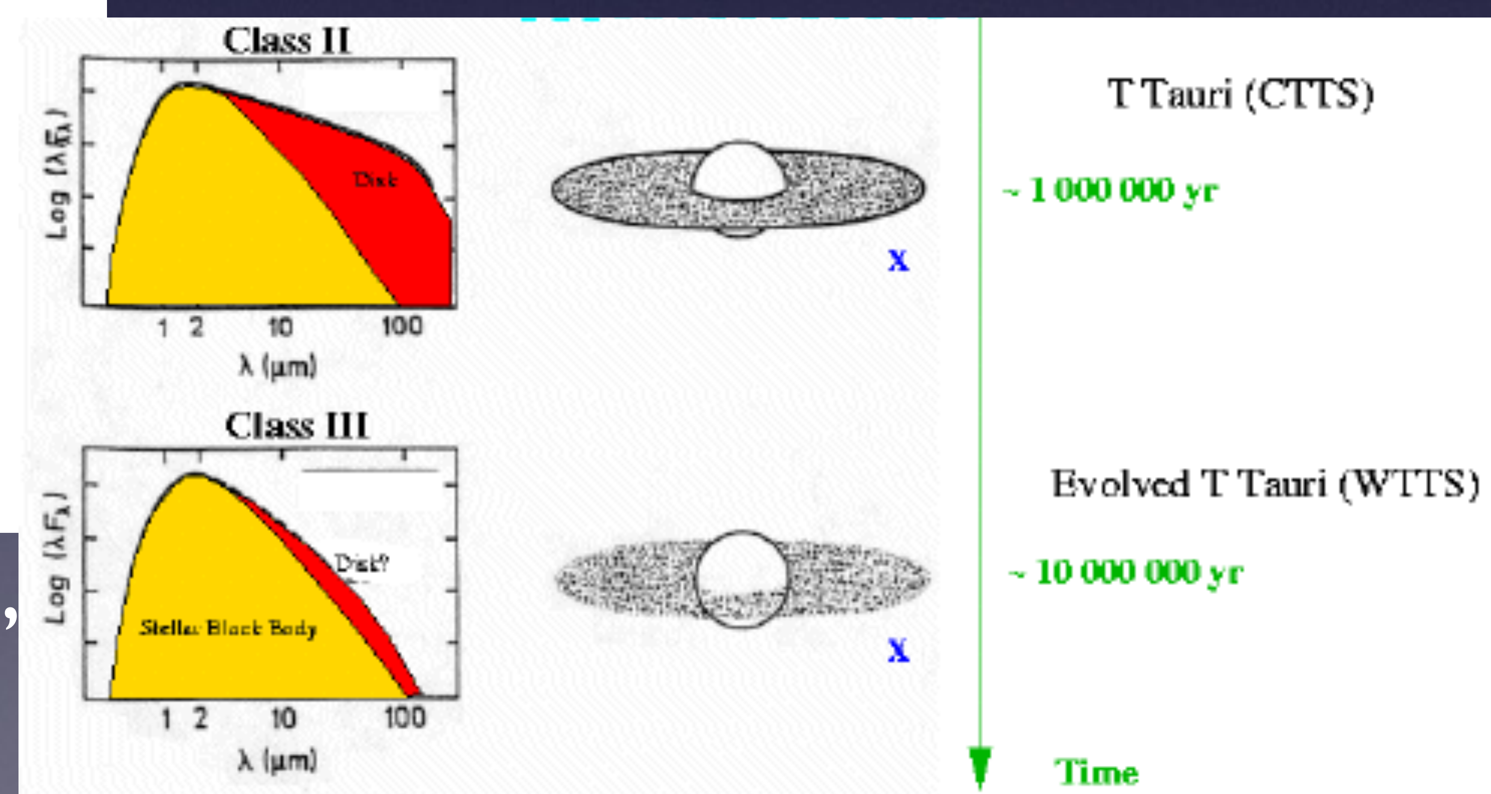
# Questions from yesterday

- Different classes of YSOs confusing
  - will revisit this in the next couple of slides

# YSOs Classification




- Originally based on the infrared Spectral Energy Distribution
- Class 0 added based on Sub-mm/FIR measurements

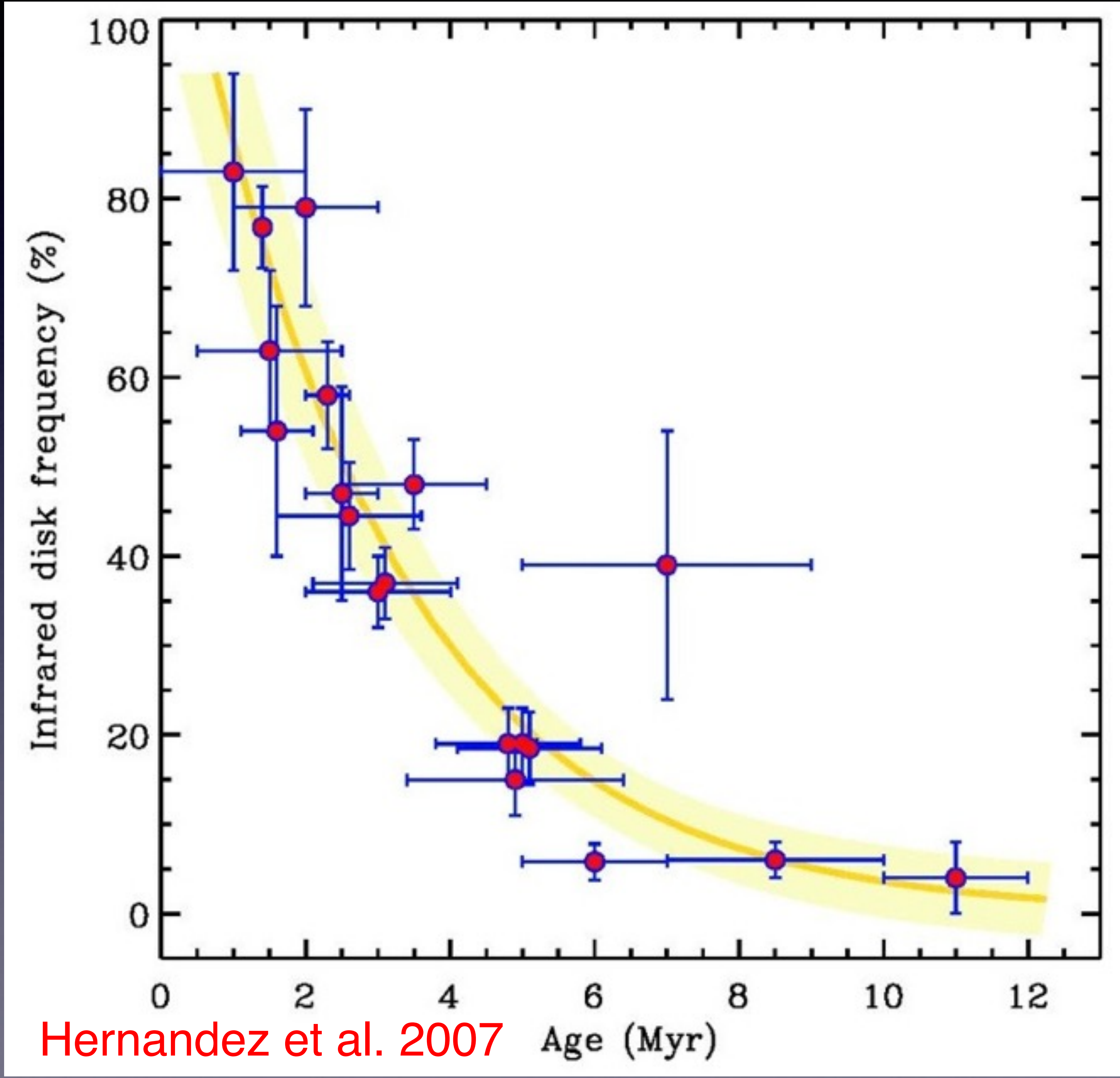



Protostars were the "Holy Grail" of IR astronomy, but were finally identified in the (sub)mm

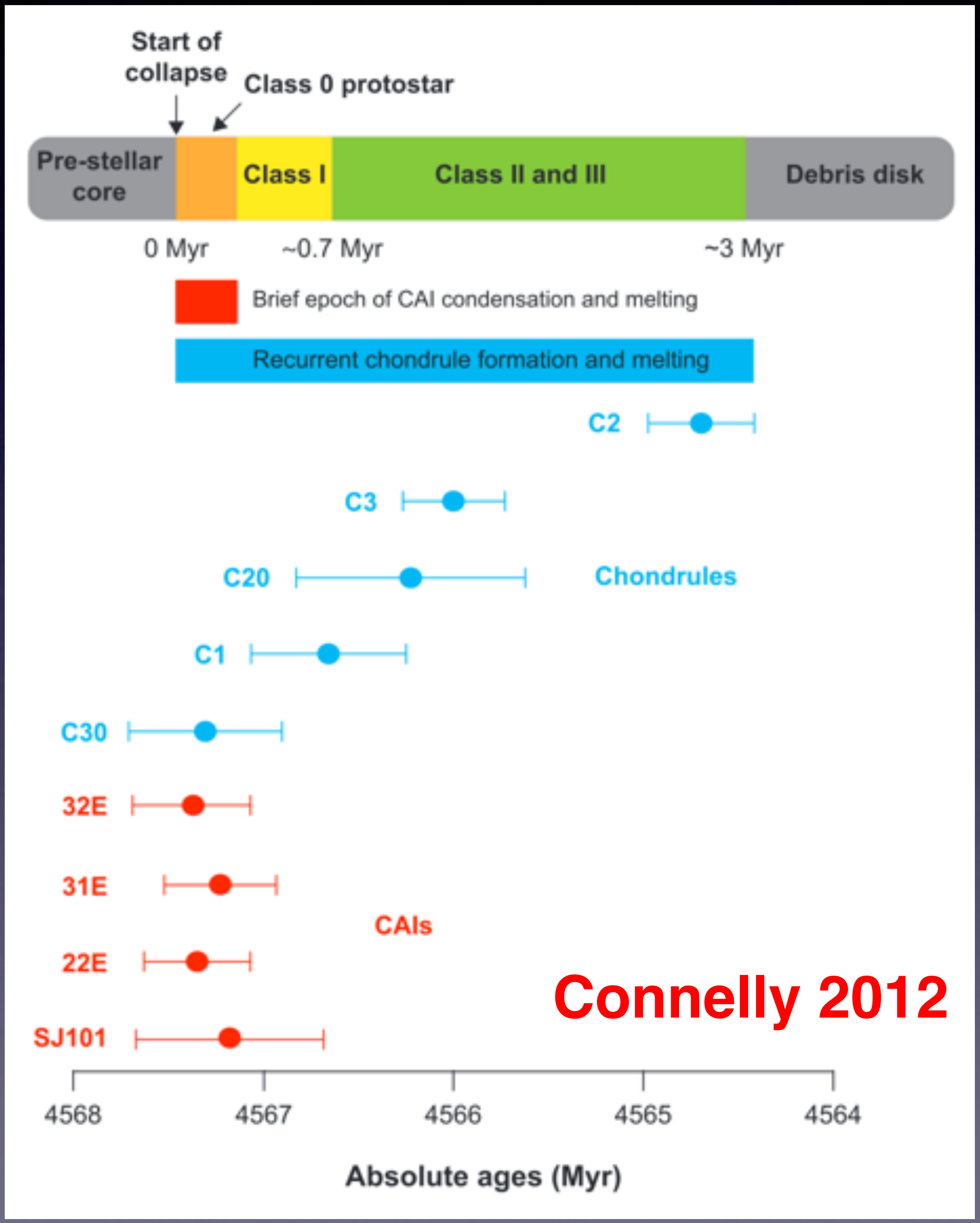
Shu+87, Lada 87, Wilking+89, Andre'+93

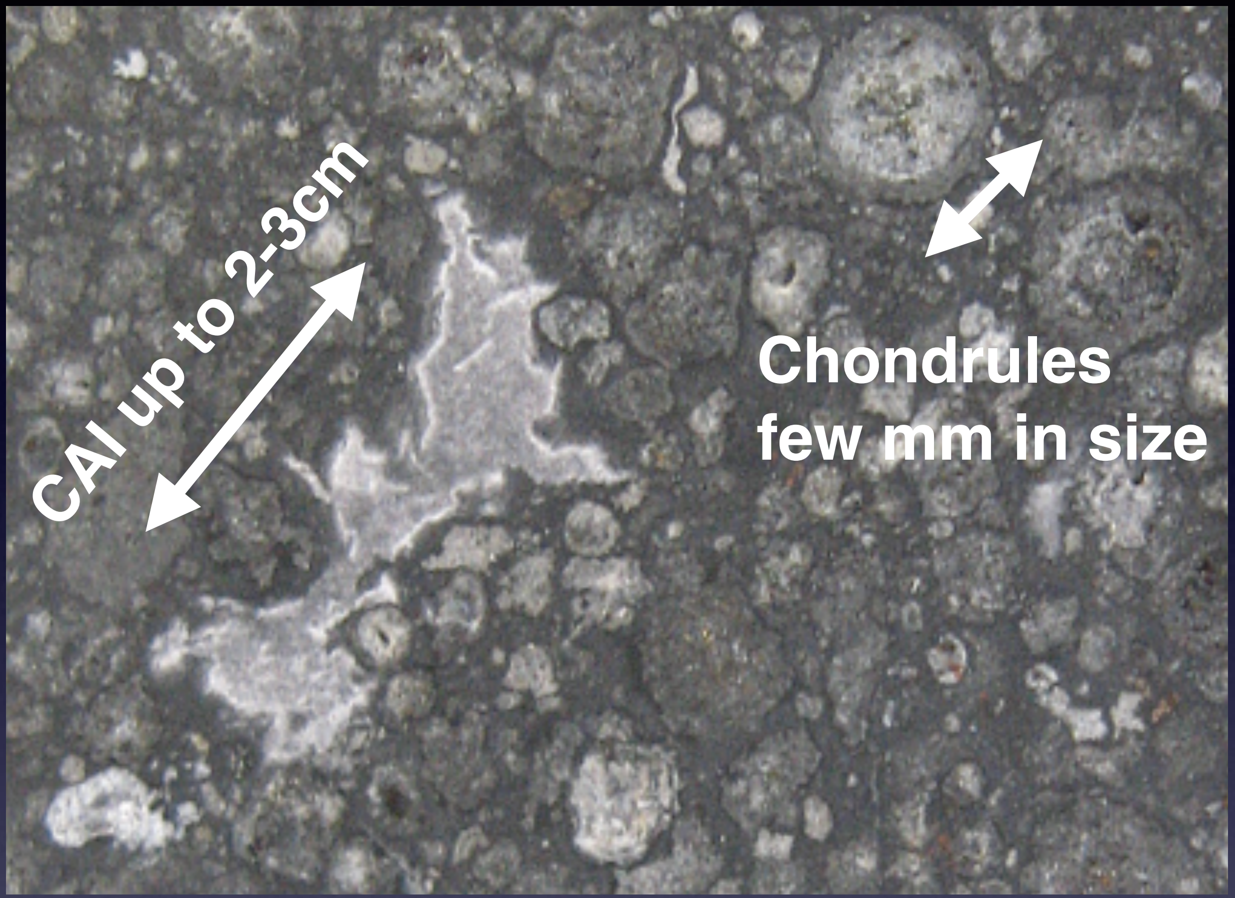
# Timescales for inner disk

- Mesuring the fraction of objects that show disk-like infrared excess
- Uncertainties:
  - ages (computed from pms-tracks
  - tracing only hot dust very close to the star
  - whole population is difficult to probe



# Comparison with Solar System




## Calcium-Aluminum Inclusions (CAI)

Oldest, high-T (>~1700K) processing,
short formation phase (<~3x$10^5$ yr)

## Chondrules

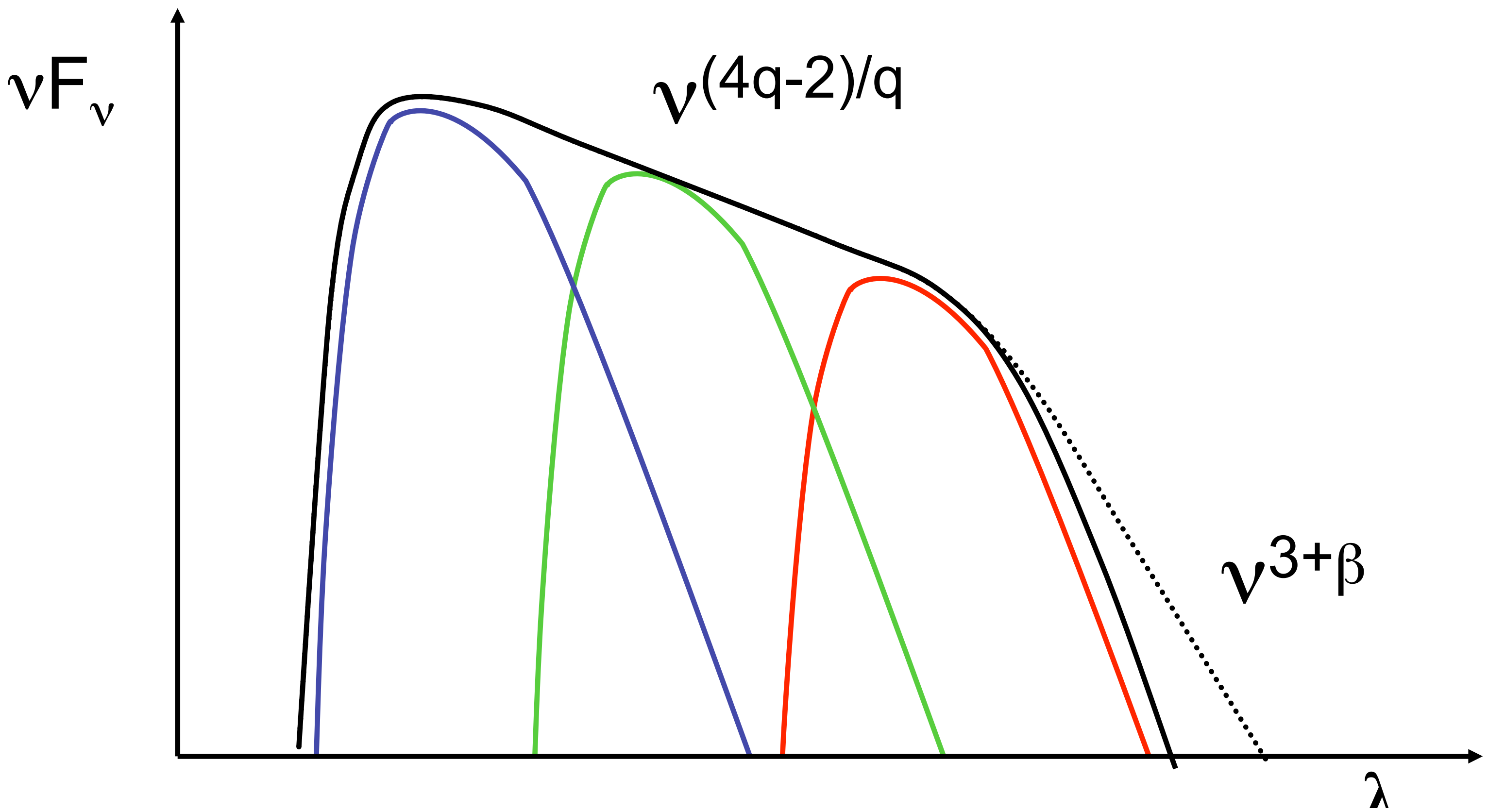
Formed for longer time than CAI, high-T (~2000K)
few Myr age dispersion

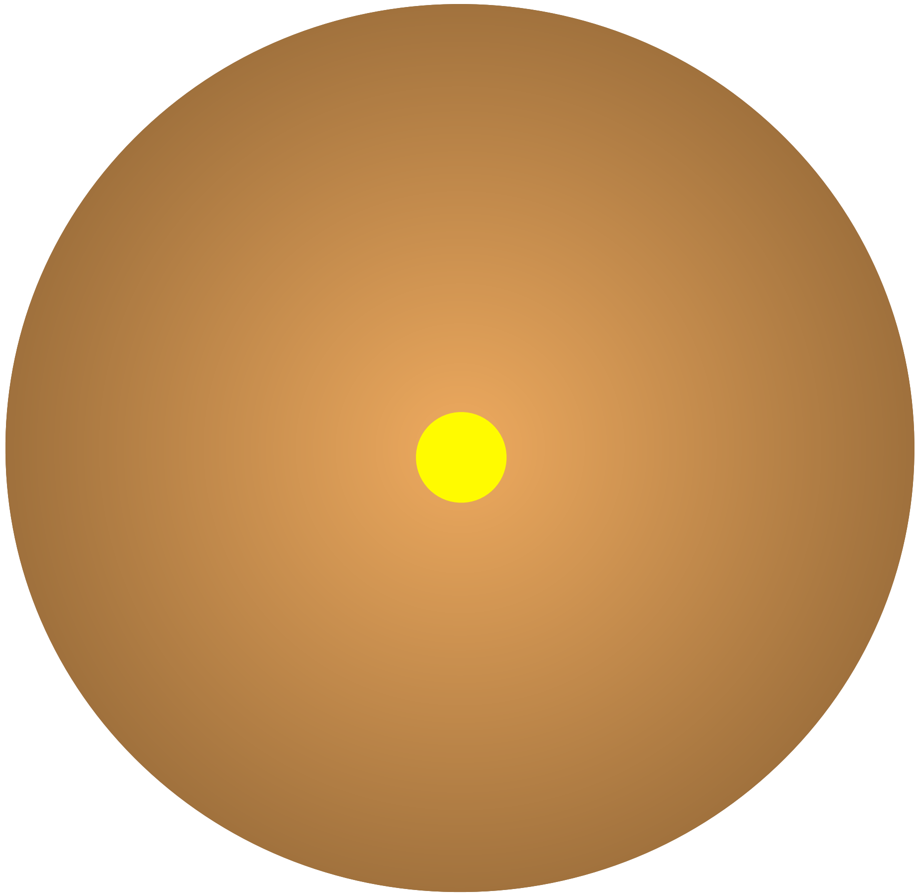
## Matrix

sub-um particles, glue all together

# Part VI
# Continuum emission from classical disks

# SED of a locally isothermal disk



$$F_\nu = \frac{cos\theta}{D^2}\int_{r_i}^{r_o} B_\nu(T_d)(1-e^{-\tau_\nu})2\pi r dr$$

$$\mathrm{T}_d \sim r^{-q}$$

$\tau_\nu \propto \Sigma(r)\kappa_\nu$ $\Sigma(r) \propto r^{-p}$ $\kappa_\nu \propto \kappa_o \nu^\beta$

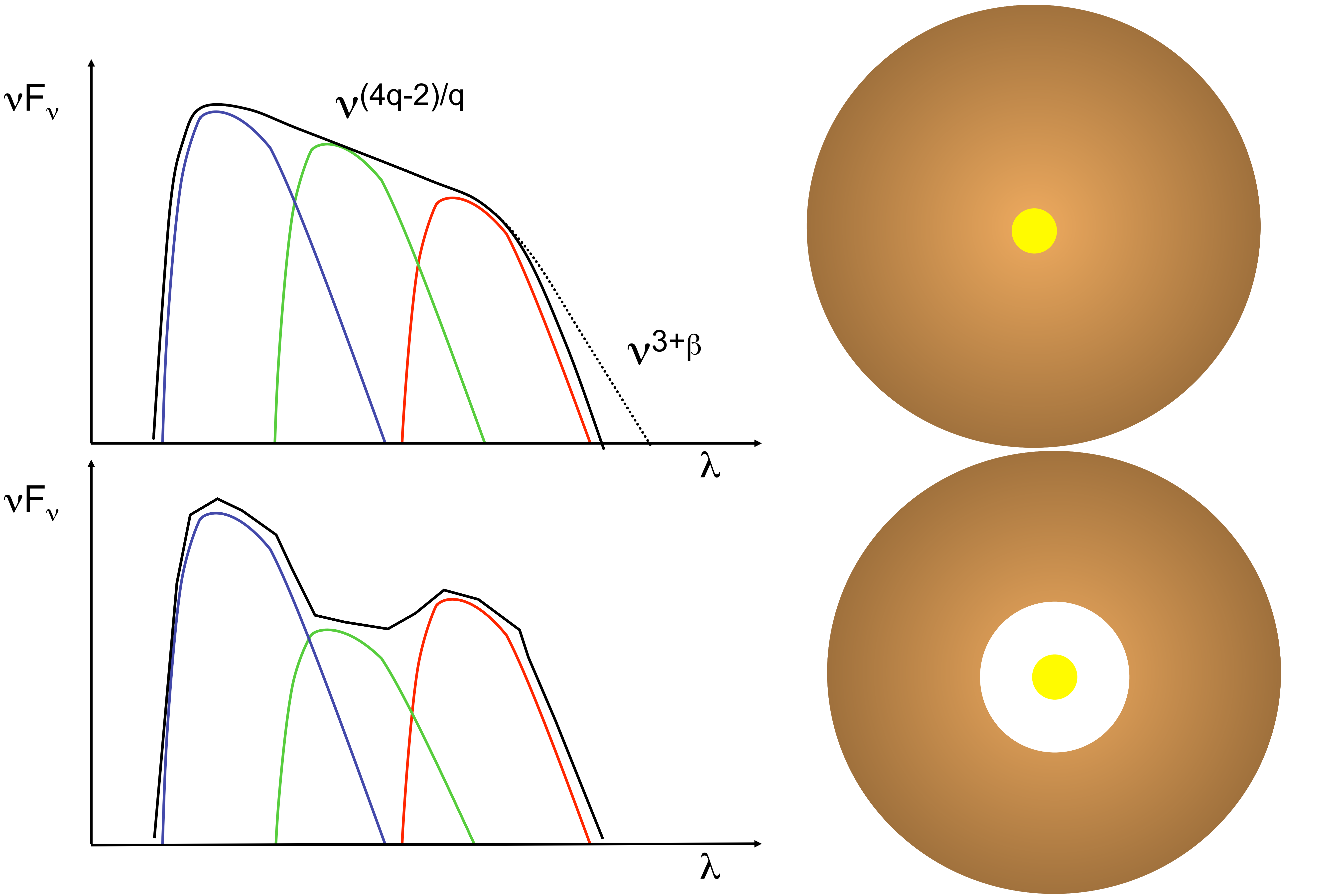
If $\tau_\nu \ll 1$:

$$F_\nu \propto \kappa_\nu \times B_\nu(T_d) \times M_d$$

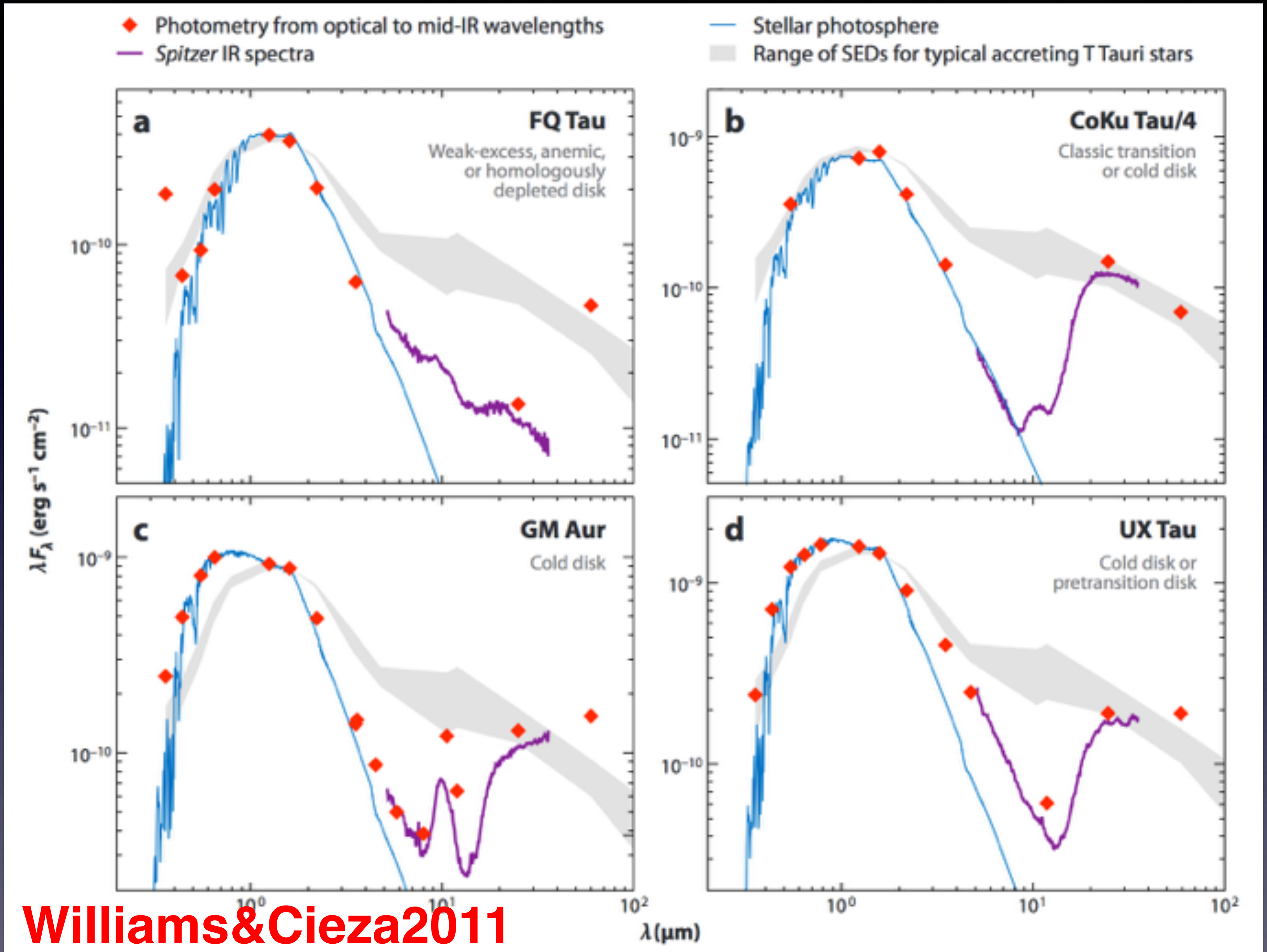
If $\tau_\nu \gg 1$:

$$F_\nu \propto B_\nu(T_d) \times Area$$

# What if we carve a hole?

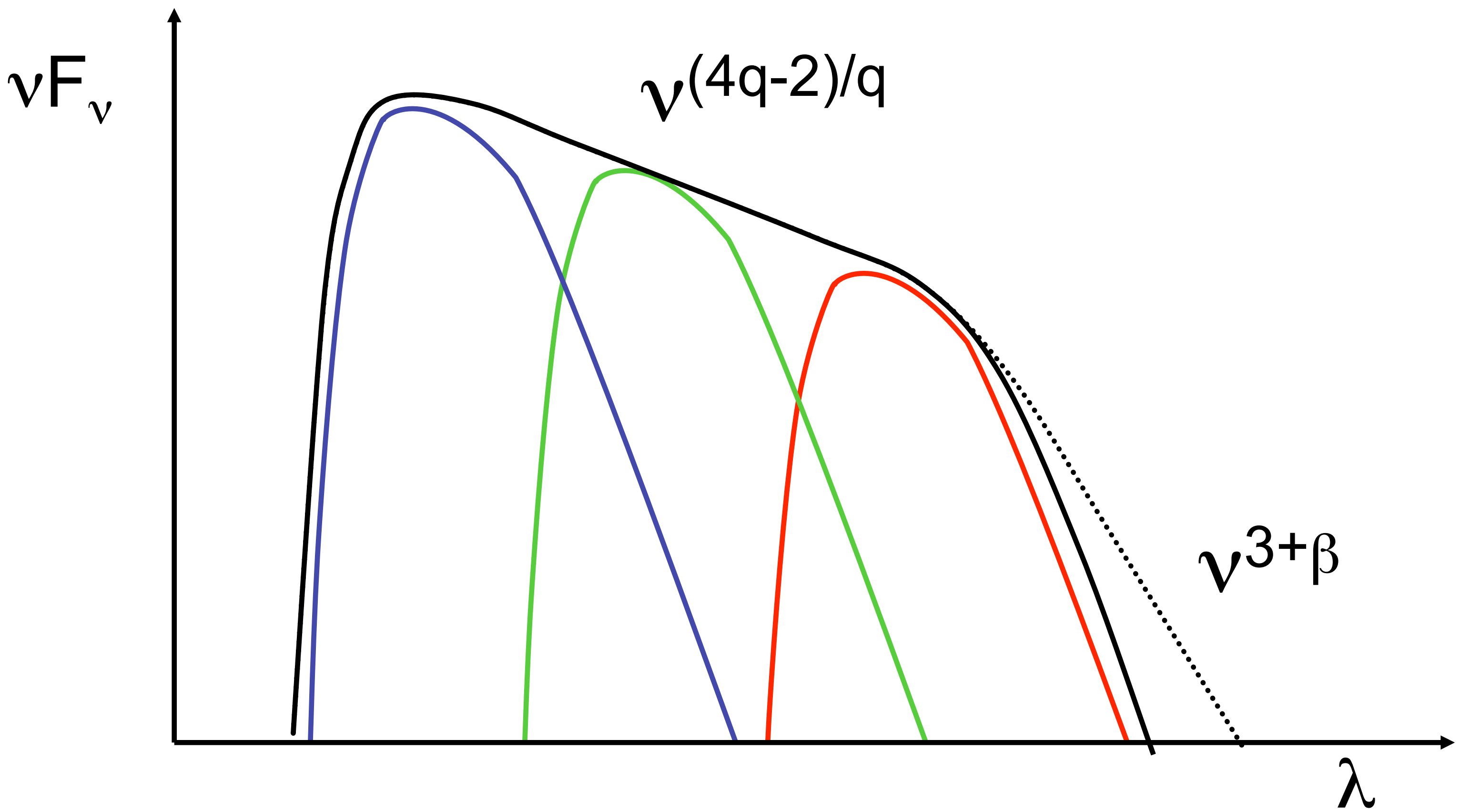


# Transition disks




- ~10-20% of disk population, likely represent a variety of evolutionary patterns
- We shall go back to these tomorrow

# SED of a locally isothermal disk




$$F_\nu = \frac{cos\theta}{D^2}\int_{r_i}^{r_o} B_\nu(T_d)(1-e^{-\tau_\nu})2\pi r dr$$

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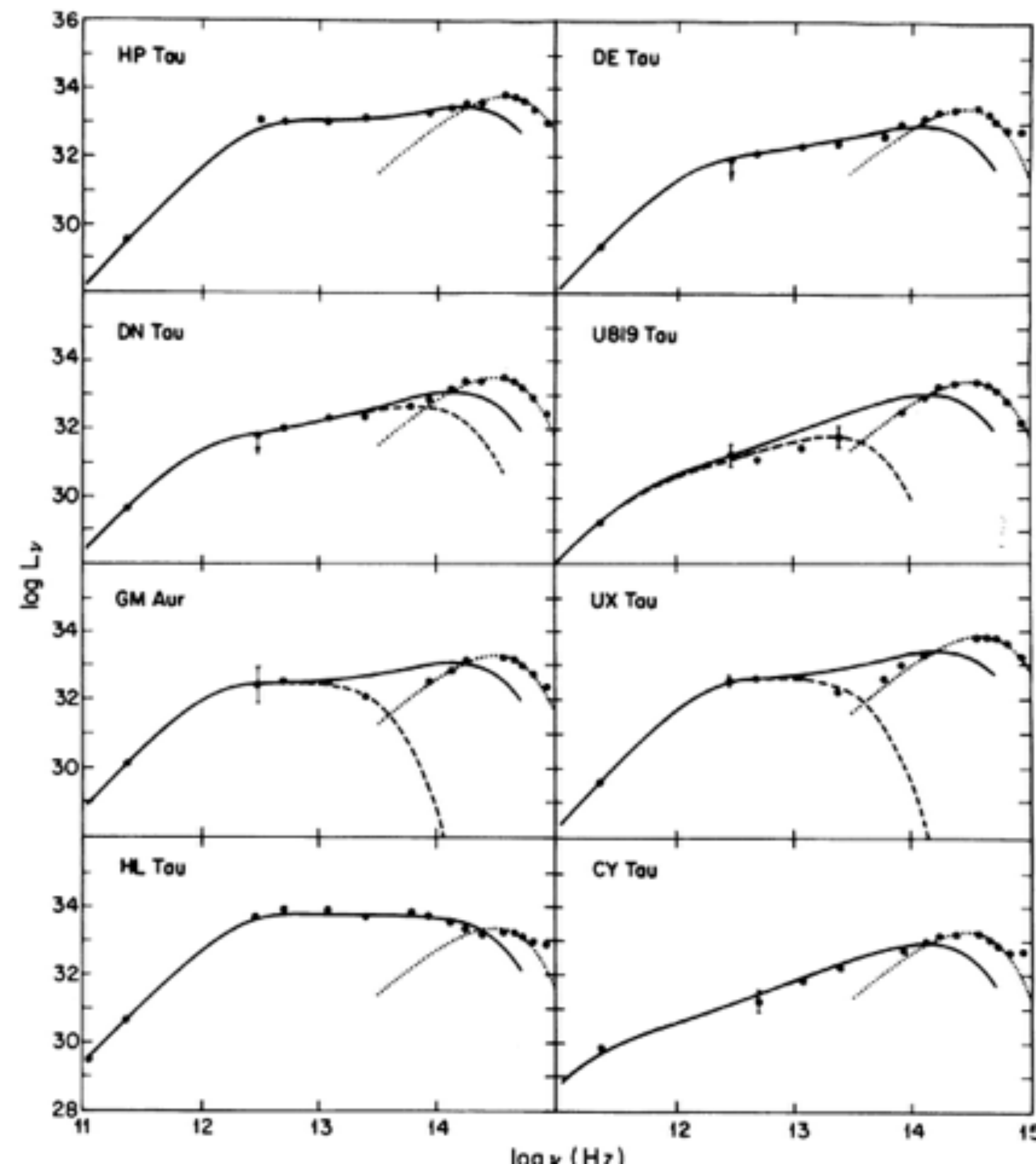
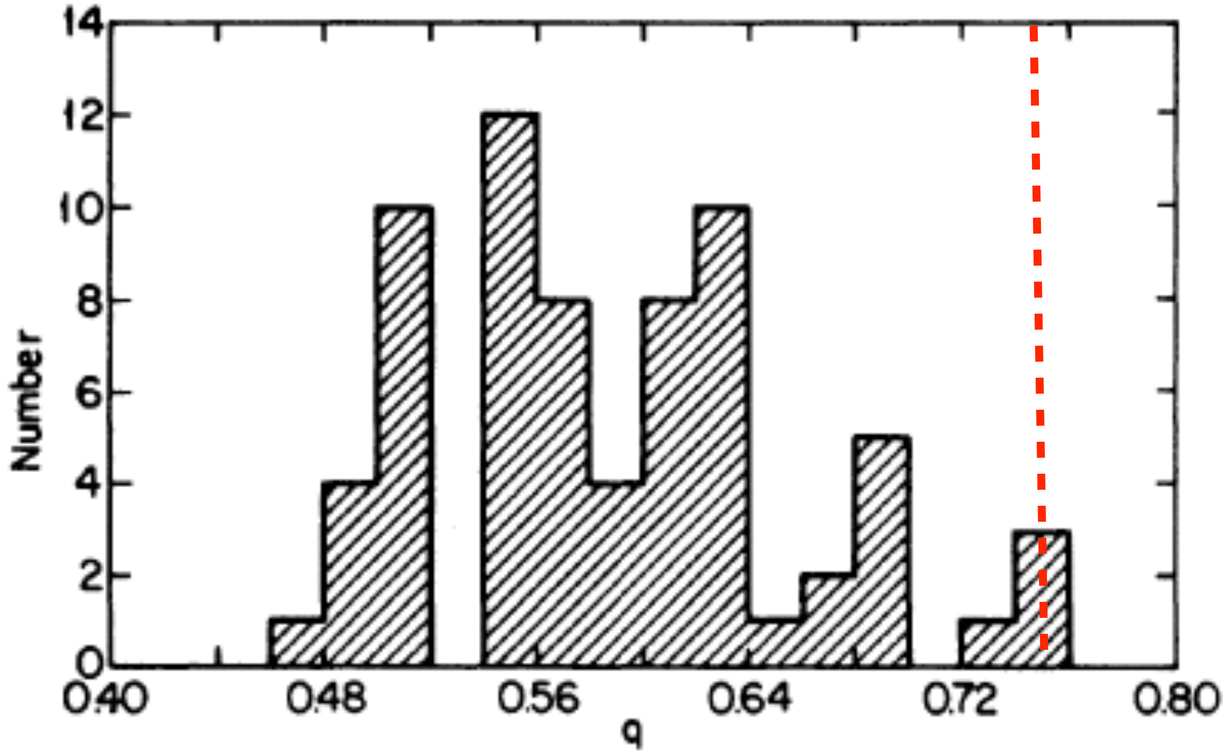
$\tau_\nu \propto \Sigma(r)\kappa_\nu$ $\Sigma(r) \propto r^{-p}$ $\kappa_\nu \propto \kappa_o \nu^\beta$

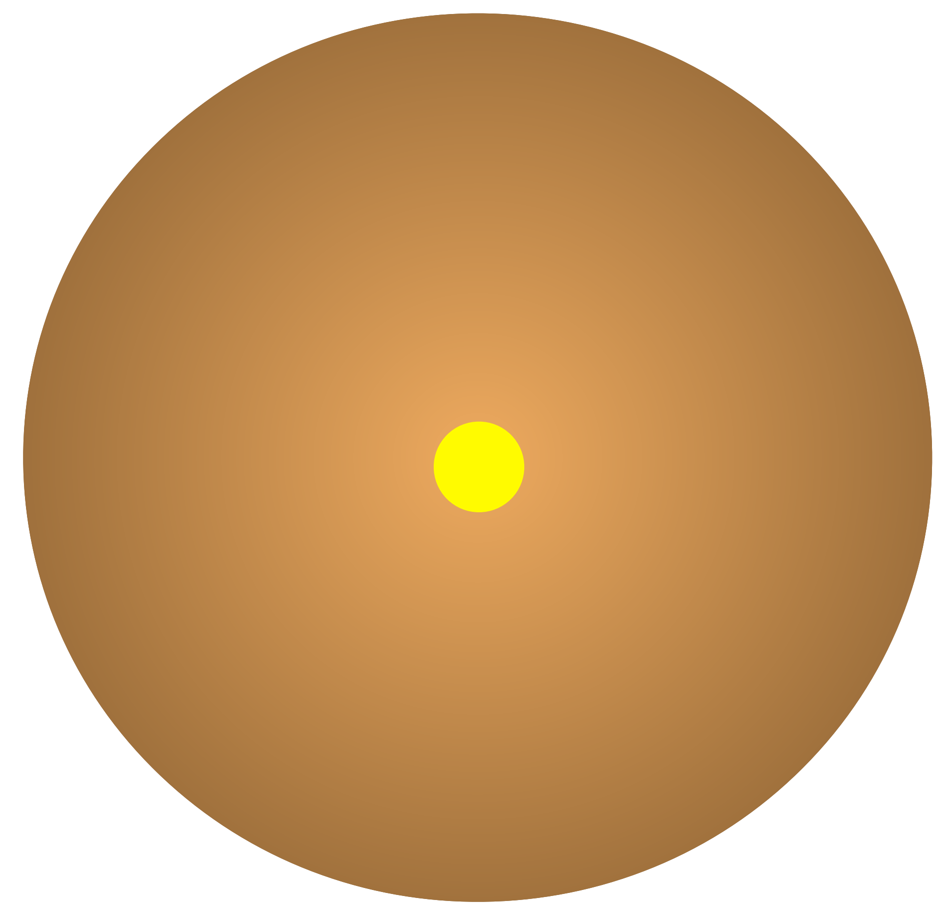
**Beckwith+ 1991**



# SED of a locally isothermal disk




Beckwith et al. (1991)



$$F_\nu = \frac{\cos\theta}{D^2} \int_{r_i}^{r_o} B_\nu(T_d)(1 - e^{-\tau_\nu}) 2\pi r dr$$

$$T_d \sim r^{-q}$$

$\tau_\nu \propto \Sigma(r)\kappa_\nu$ $\Sigma(r) \propto r^{-p}$ $\kappa_\nu \propto \kappa_o \nu^\beta$

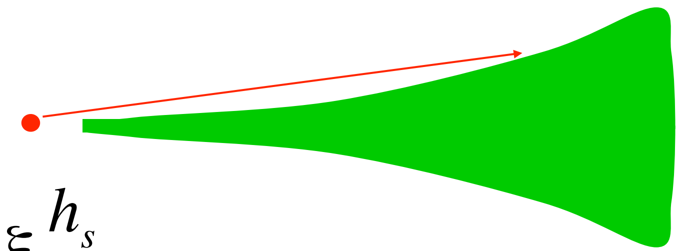
Viscous heating provides a poor fit of protoplanetary disc temperature: the outer disk would be too cool

# “flared” disk

Irradiation flux:

$$F_{\rm irr} = \alpha \frac{L_*}{4\pi r^2}$$

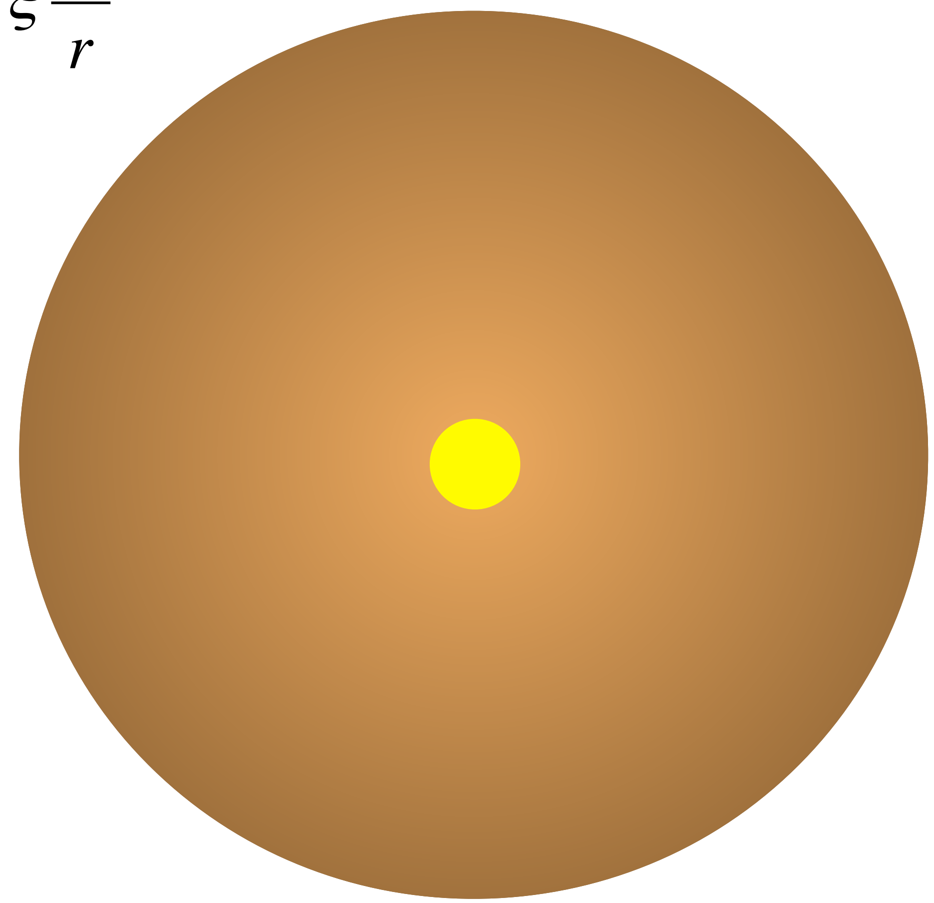
The flaring angle:



$$\alpha = r\frac{\partial}{\partial r}\left(\frac{h_s}{r}\right) \rightarrow \xi \frac{h_s}{r}$$

$$T^4 = \frac{\xi}{\sigma}\frac{h_s L_*}{4\pi r^3}$$

$$h_s = \chi h$$



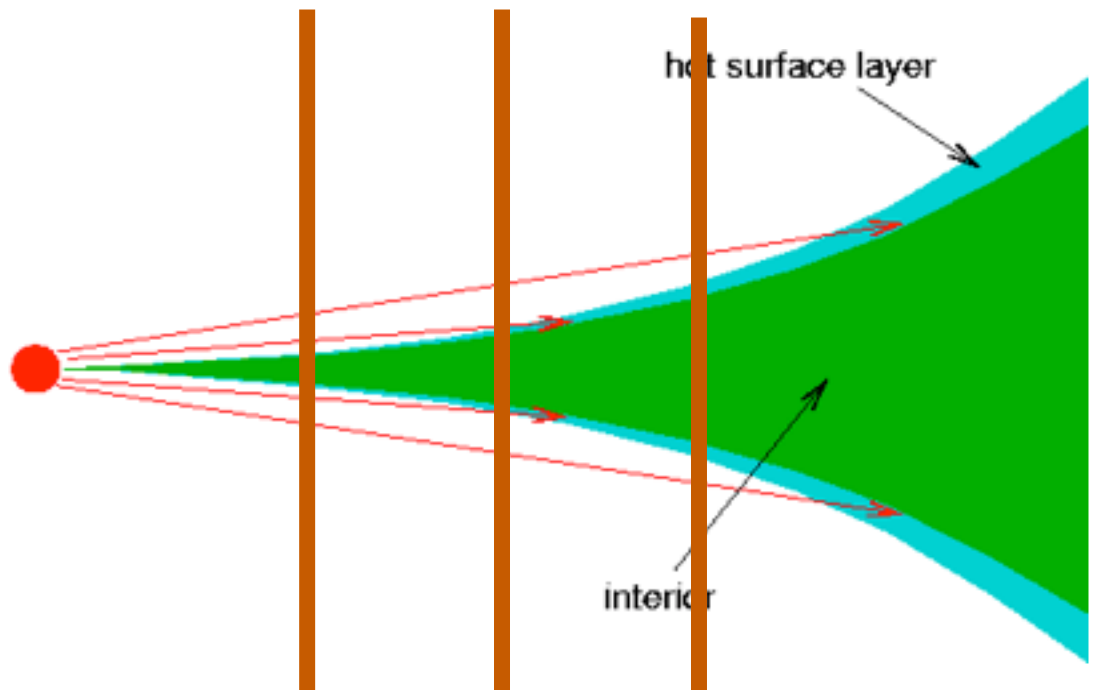
An increasing $h_s(r)$ allows to intercept more radiation warming the outer disk

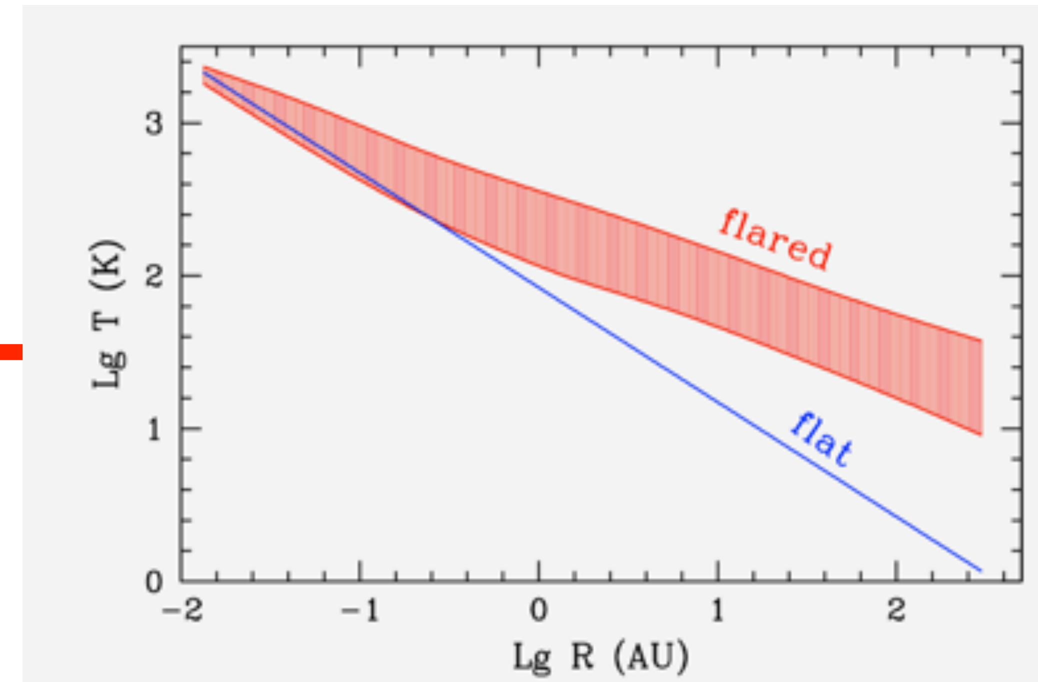
$$F_\nu = \frac{cos\theta}{D^2}\int_{r_i}^{r_o} B_\nu(T_d)(1-e^{-\tau_\nu})2\pi r dr$$

$$\mathrm{T}_d \sim r^{-q}$$

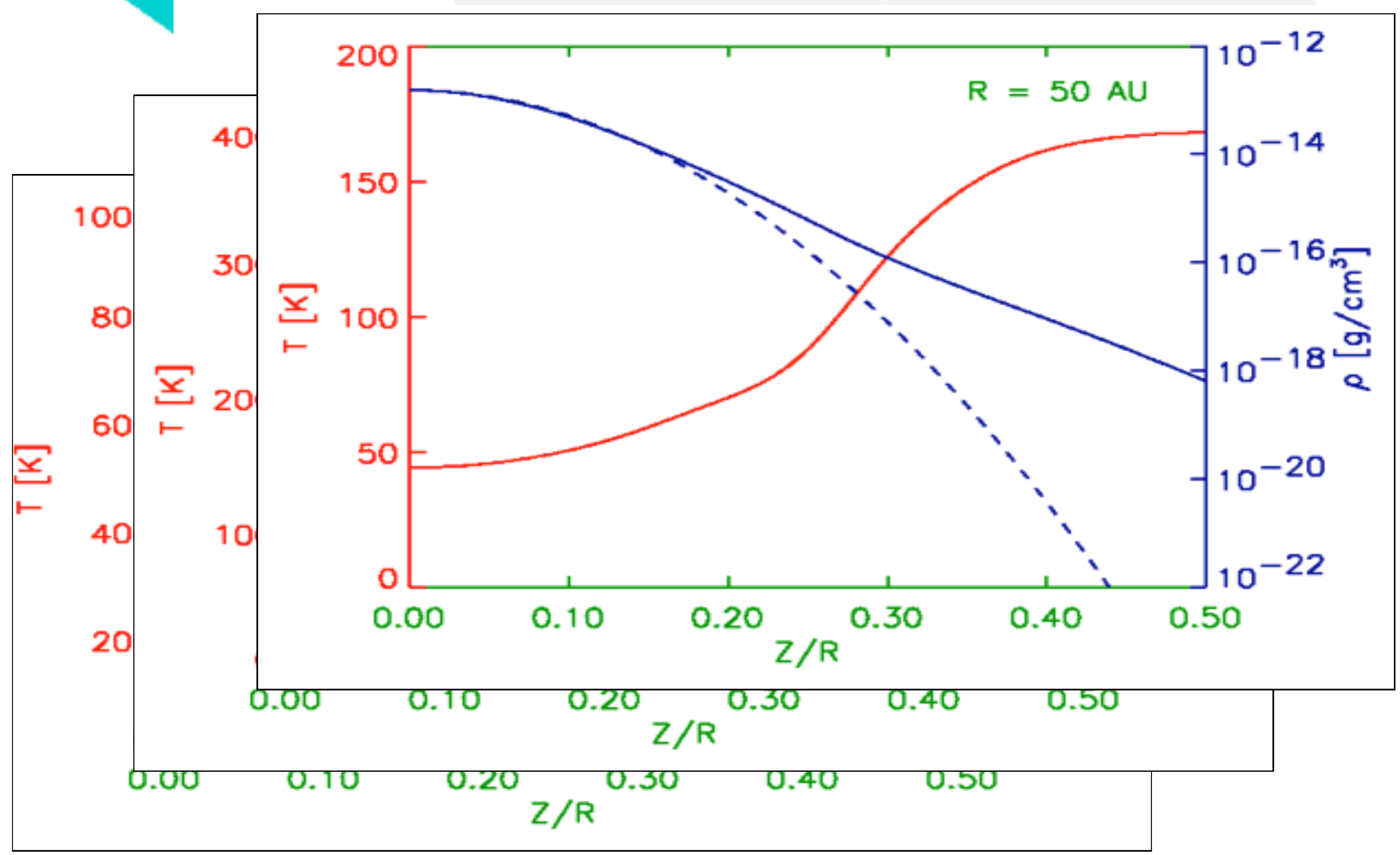
$\tau_\nu \propto \Sigma(r)\kappa_\nu$ $\quad$ $\Sigma(r) \propto r^{-p}$ $\quad$ $\kappa_\nu \propto \kappa_o \nu^\beta$

# Flared disks: detailed models



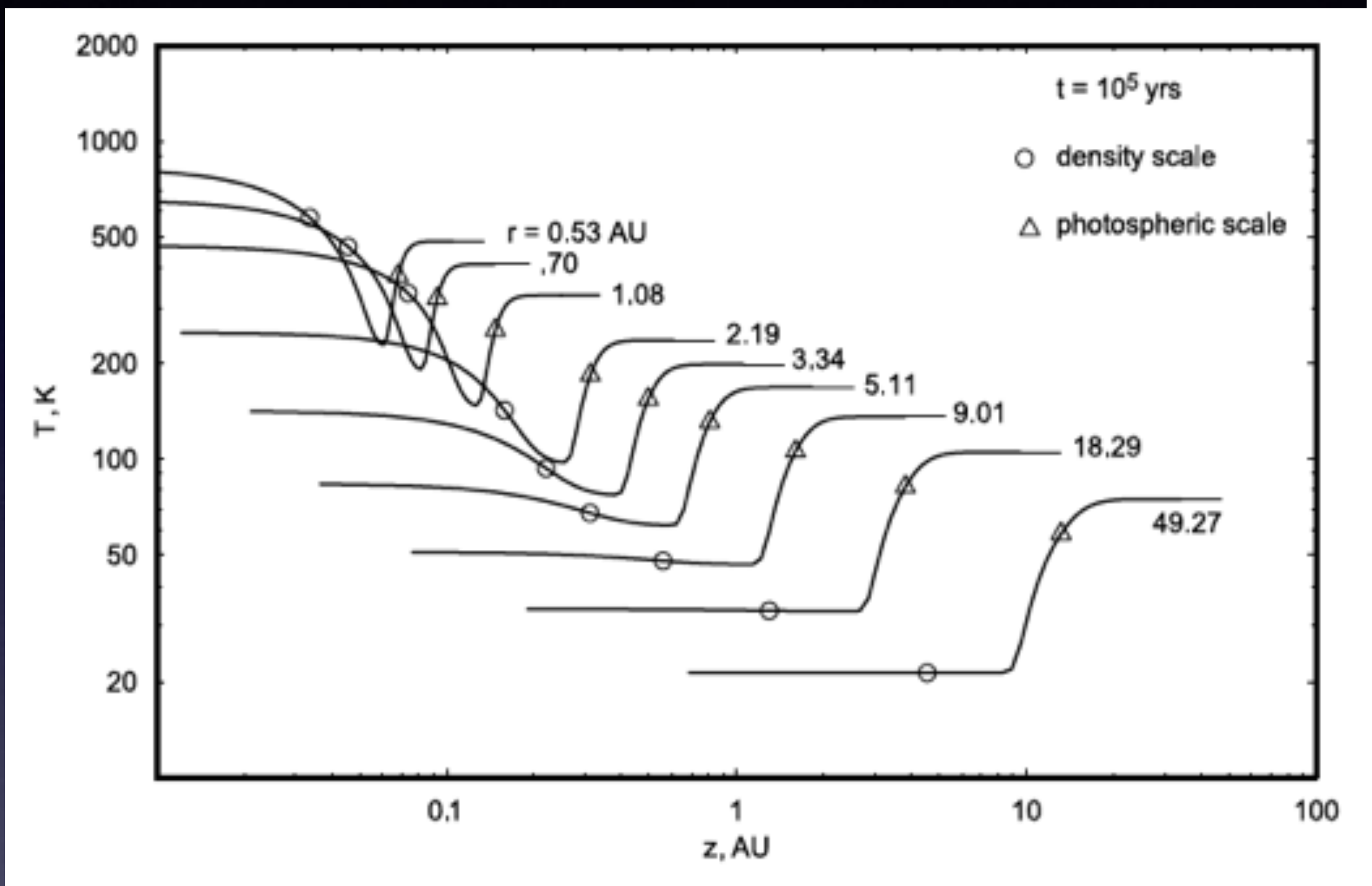


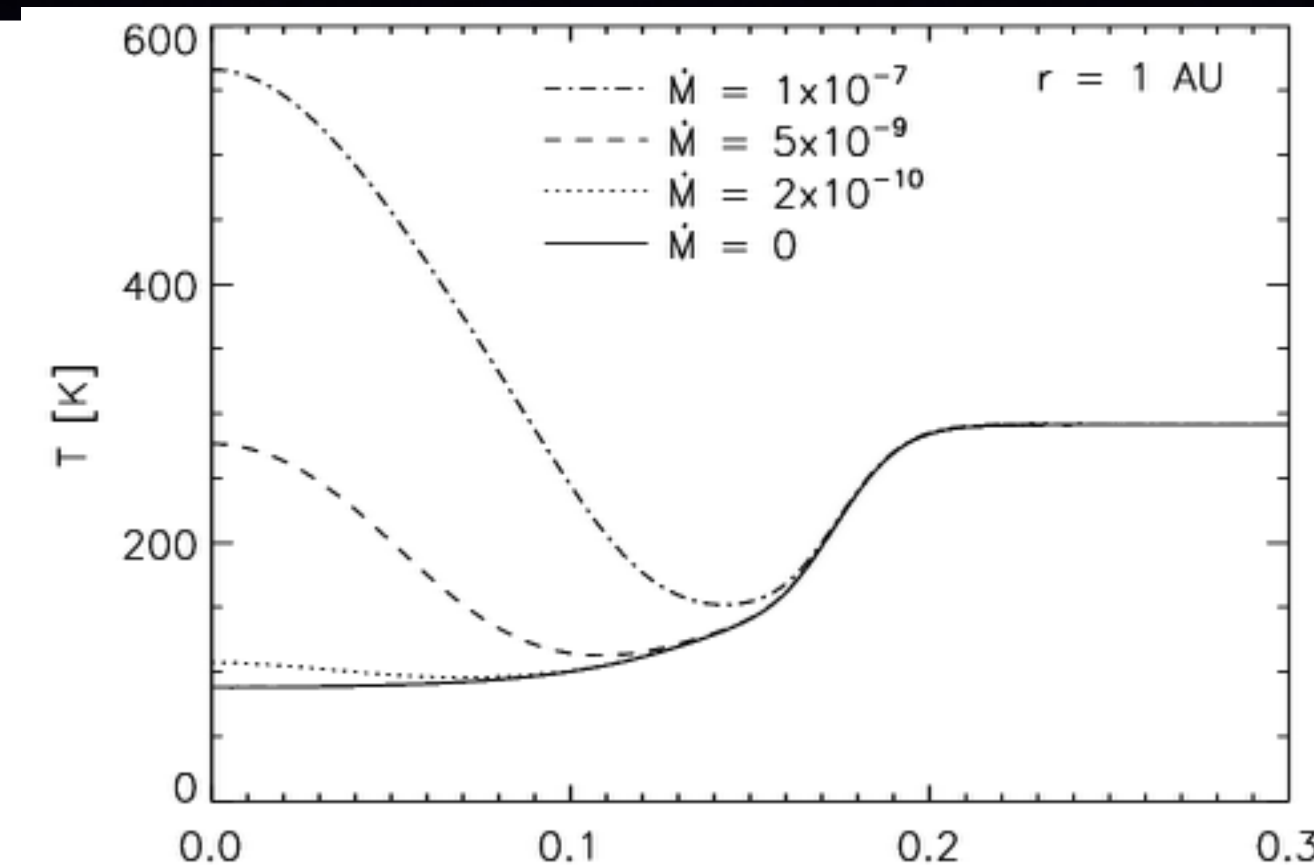

... consists of vertical slices, each forming a 1D problem. All slices are independent from each other.




[K. Dullemond]

# Including viscous heating



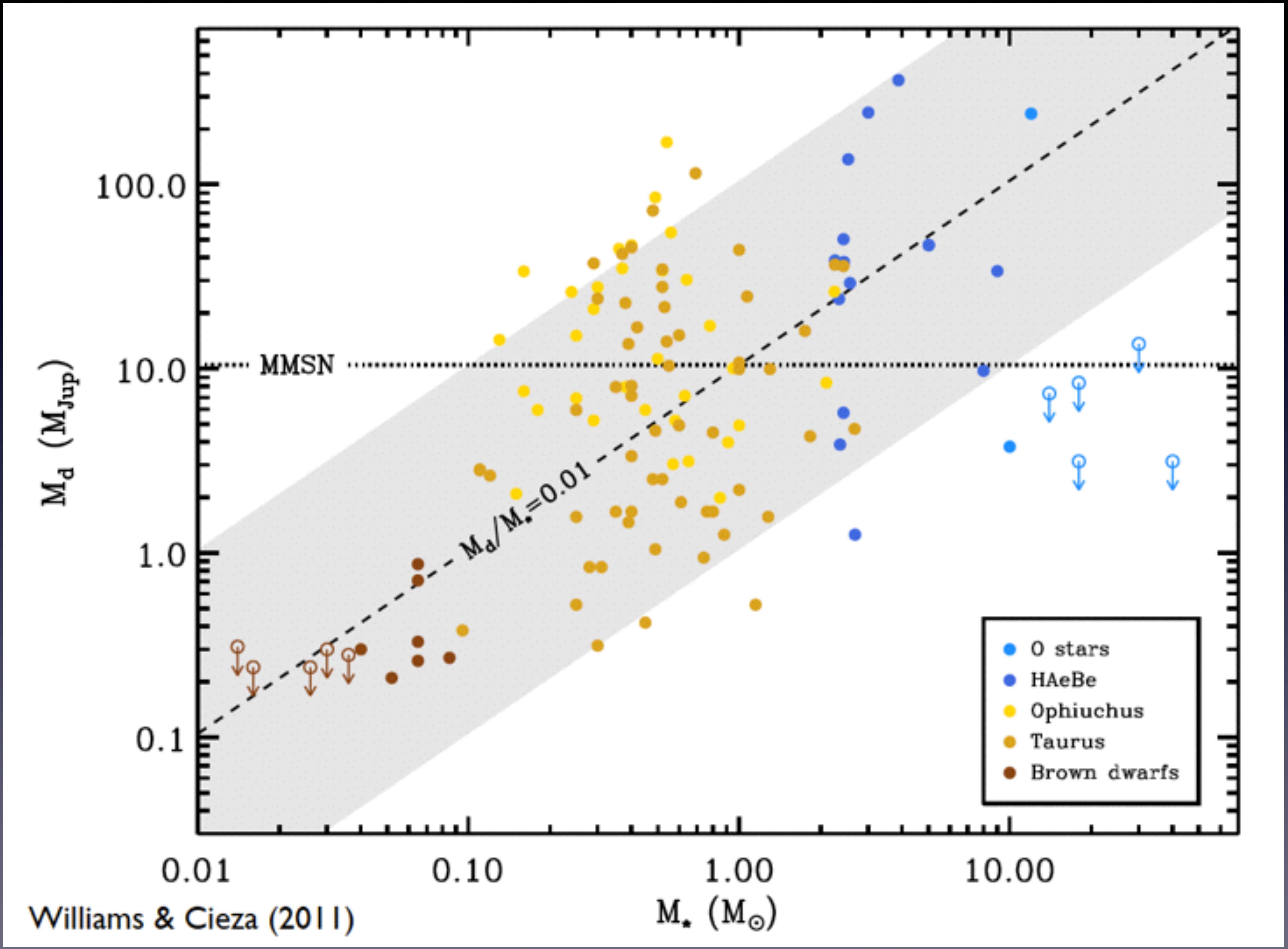




**Dullemond+2007**

- Stellar radiation heats the disc atmosphere
- viscosity heats the midplane, but only close to the central star

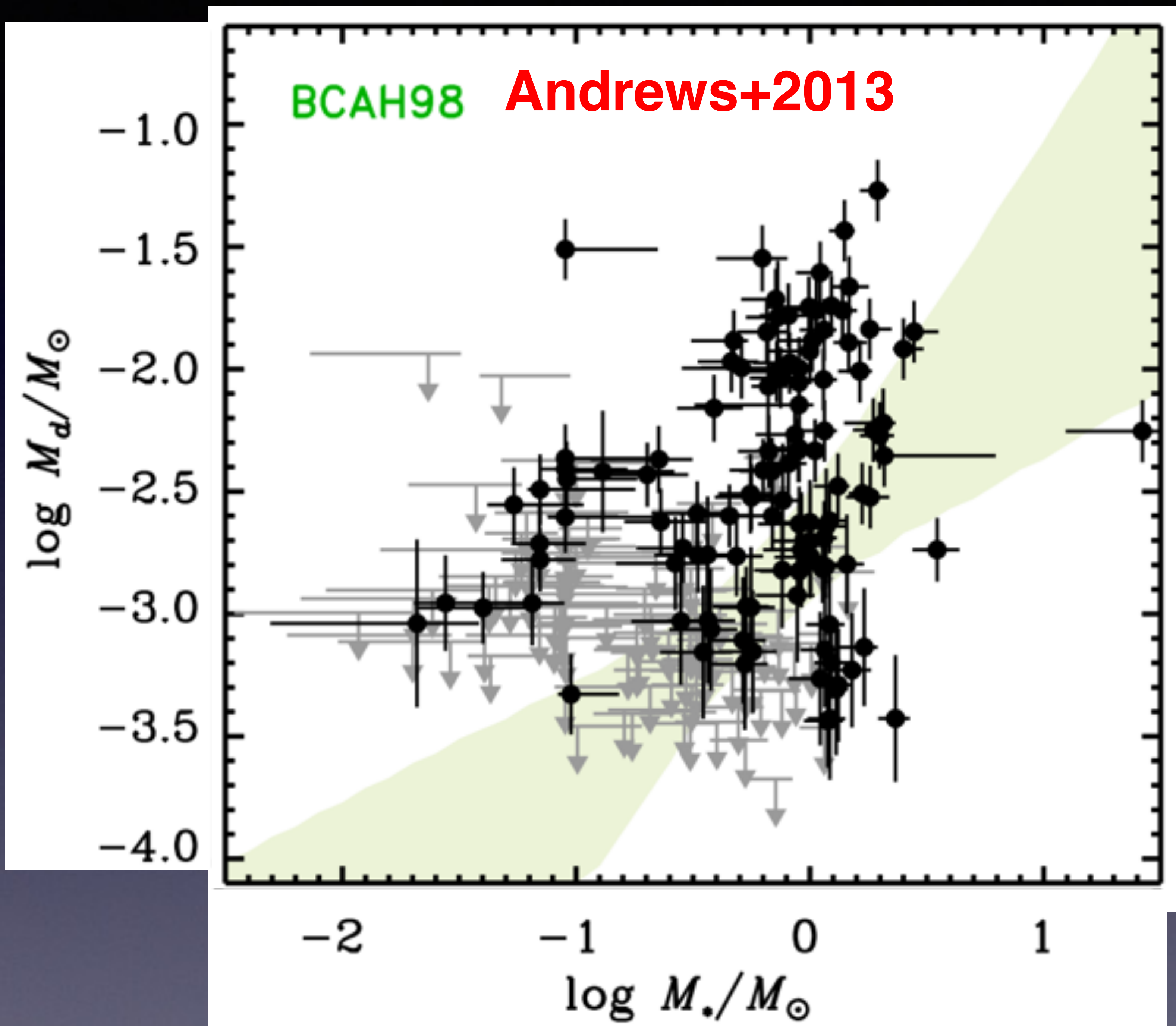
($M_{acc} \sim 10^{-8}\, M_{sun}$/yr @ 1 Myr)

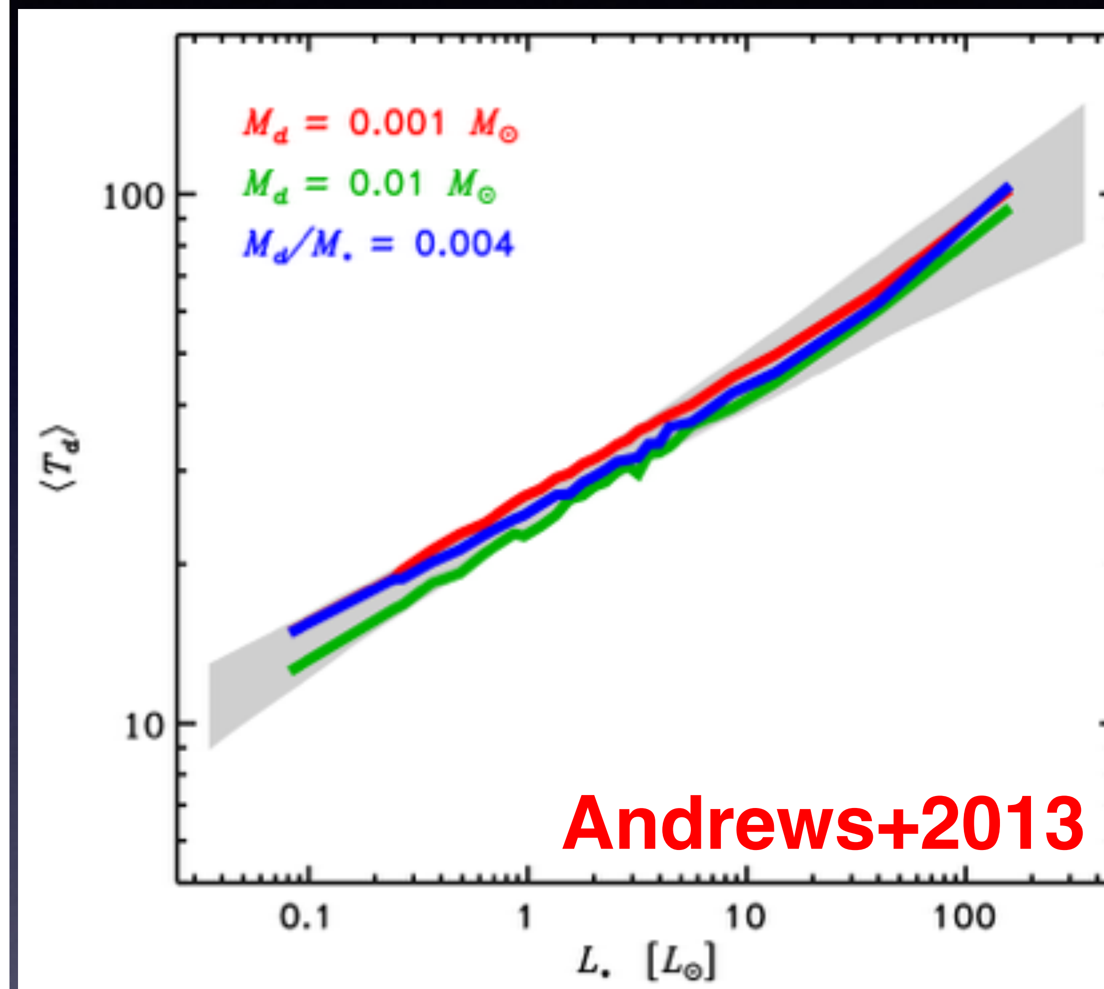
# Disk masses




- $F_{1mm} \sim B_\nu(T)\, k_{1mm}\, M_d$

# Disk masses - Taurus



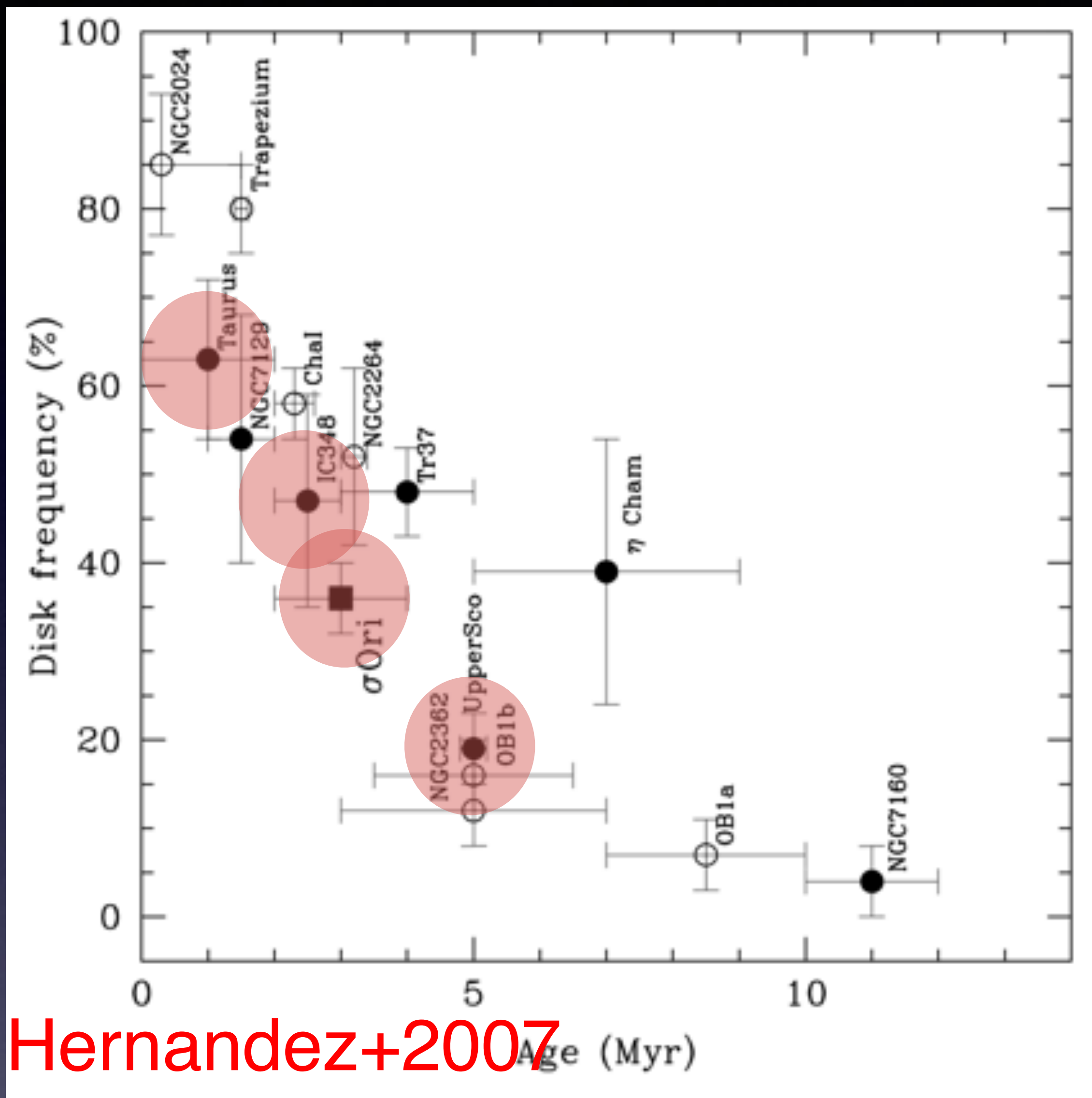

- Full Taurus survey, pre-ALMA: low detection rate $M_* < 0.3 M_{sun}$
- $F_{1mm} \sim B_\nu(T)\, k_{1mm}\, M_d$

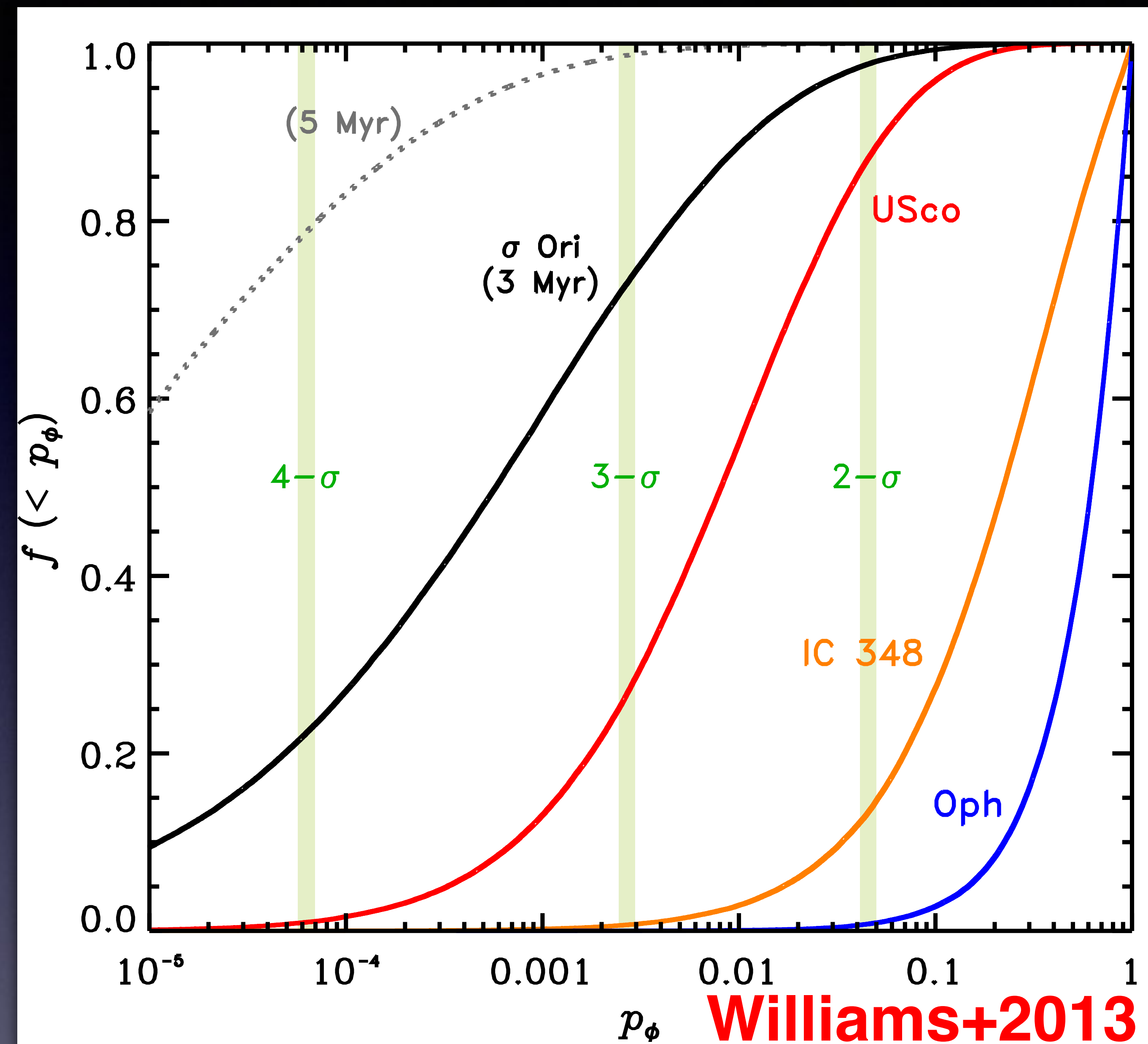
# 5 min pause

- mm traces the outer disk mass, NIR the inner disk, should they be related at all?

- Which disk parameter is relevant to follow disk evolution and planet formation?

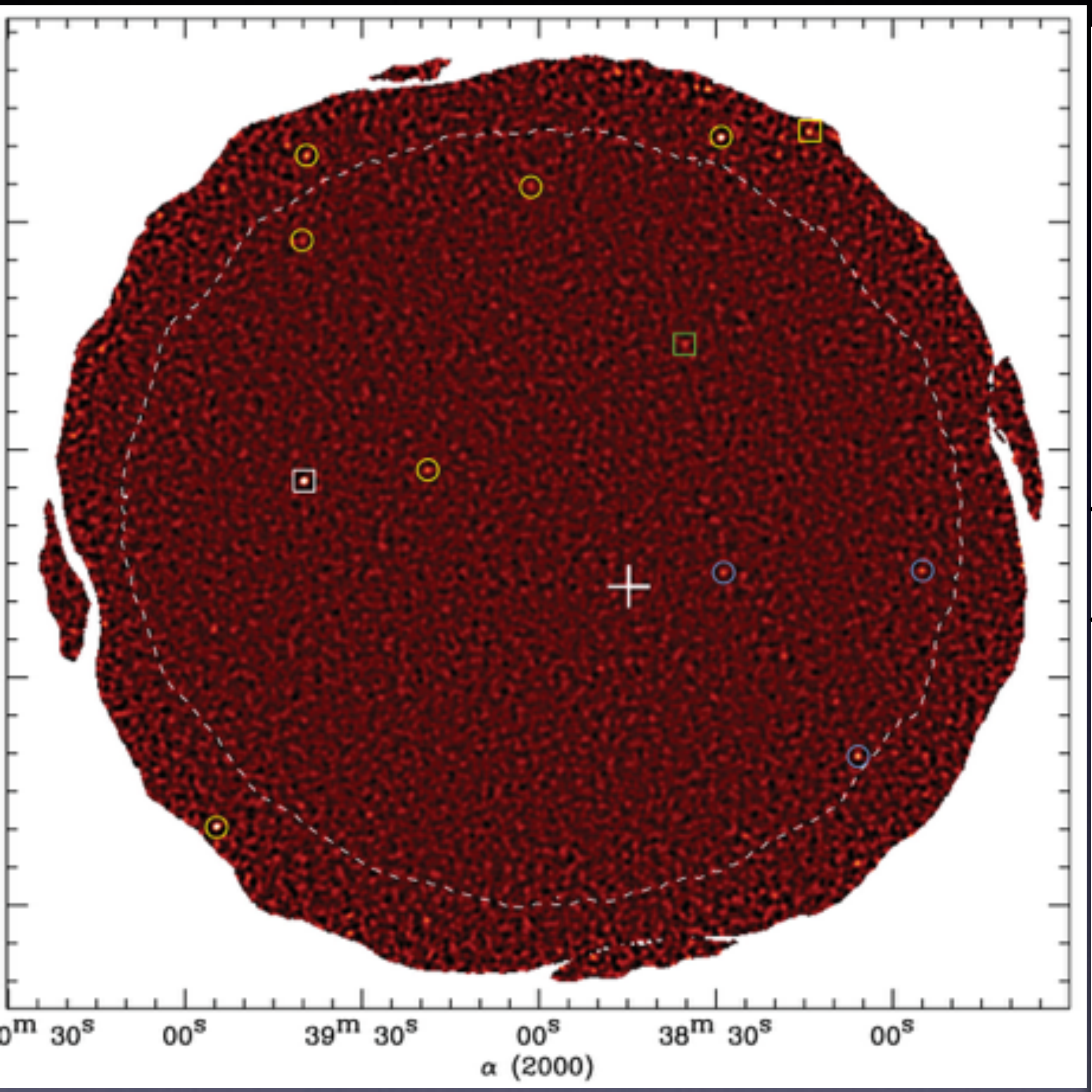
# Disk masses - Evolution

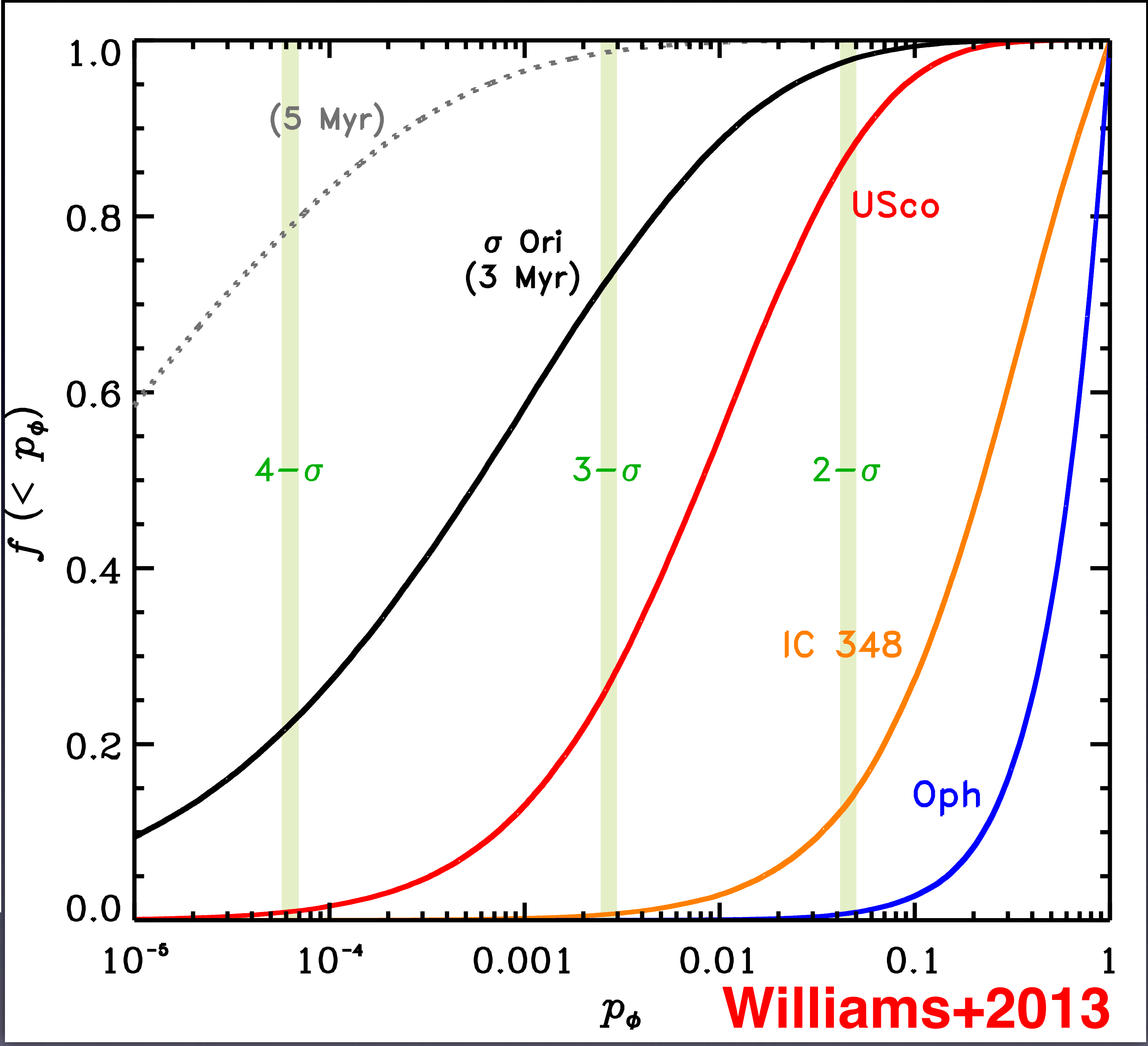



- mm tracks the amount of dust for the objects with NIR excess
- Comparison of mm luminosity functions taking into account observational biases

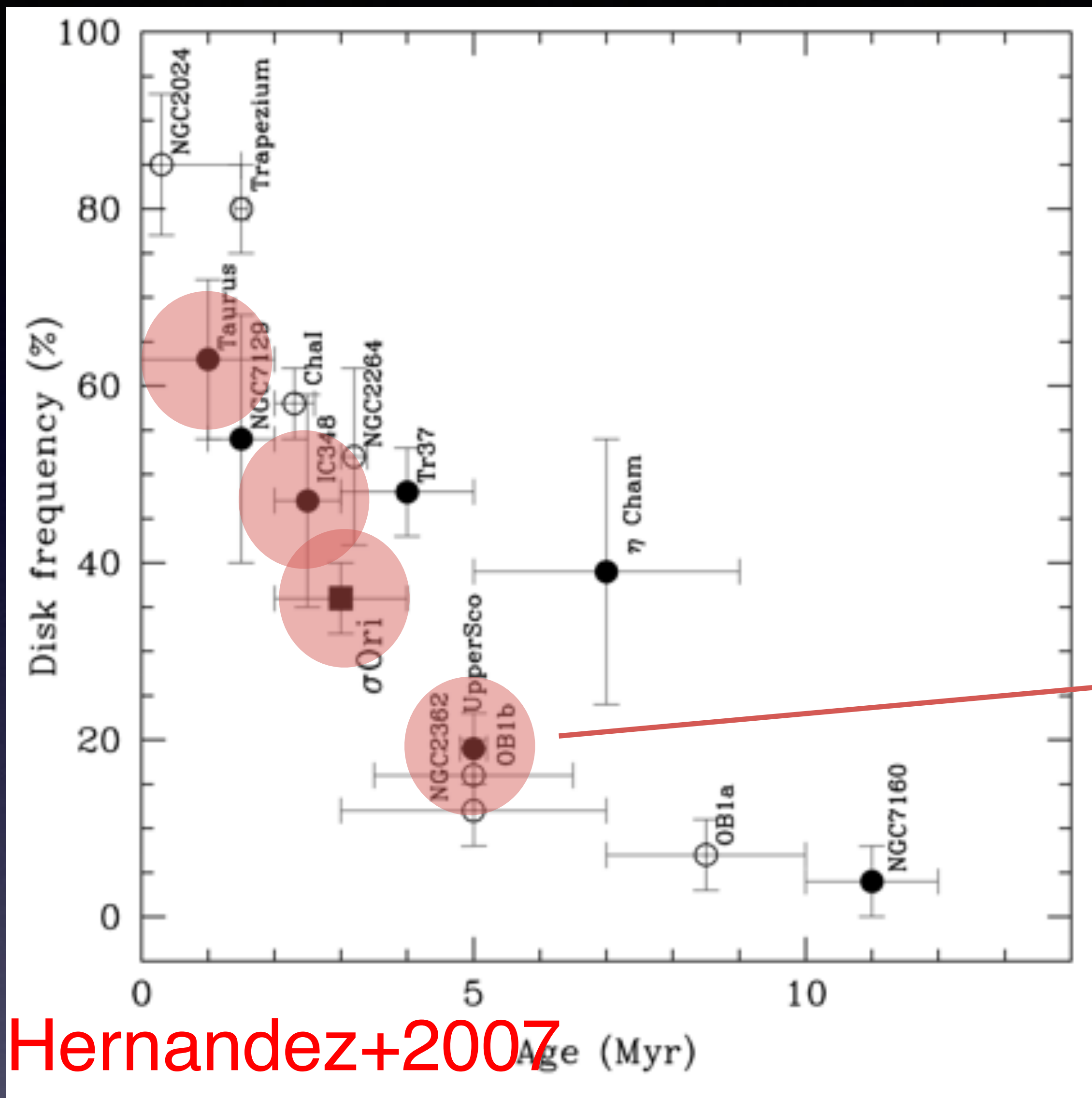
# Disk masses - Evolution

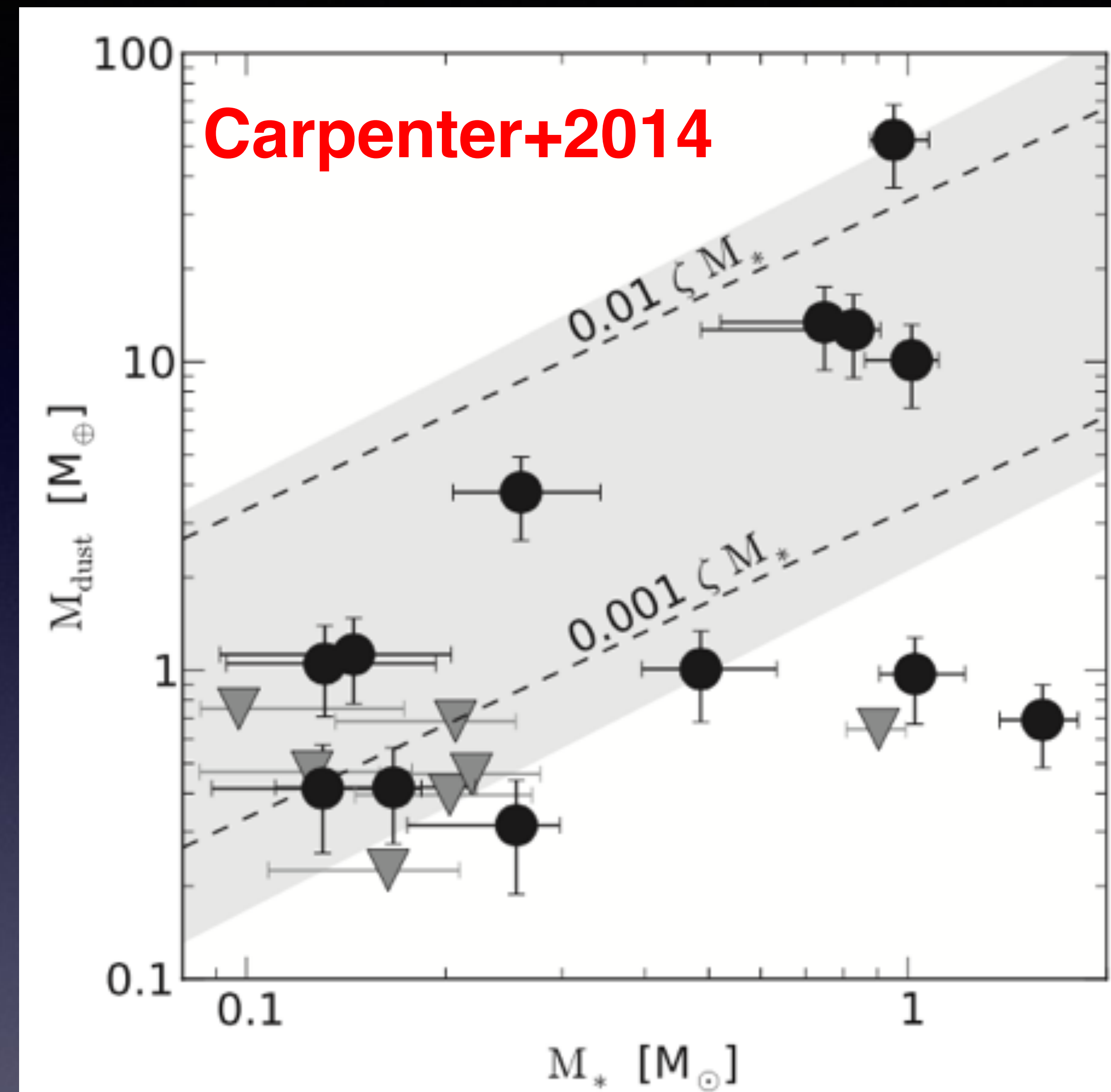



- Comparison of mm luminosity functions taking into account observational biases

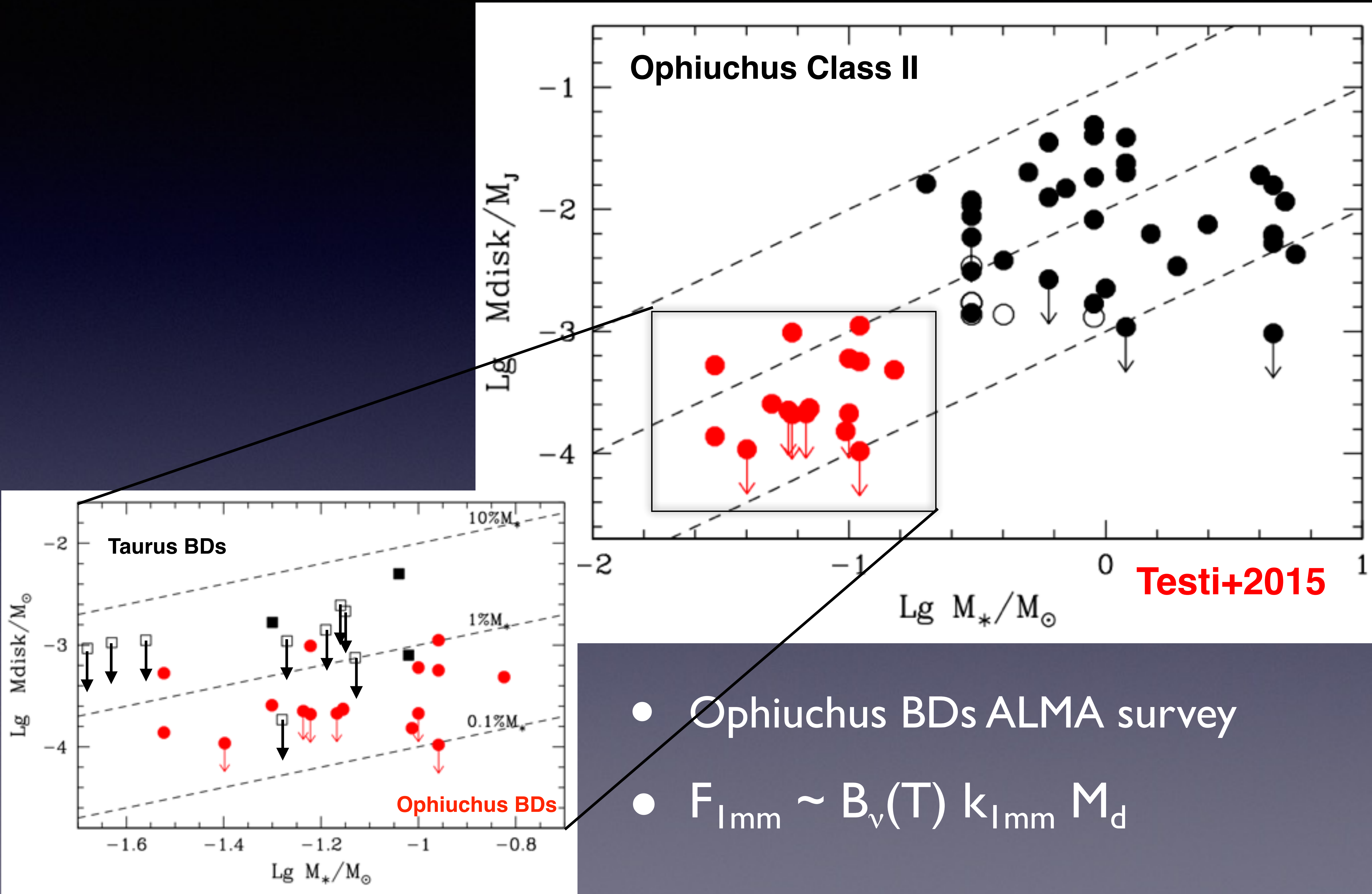
# Disk masses - Evolution




- Mass differences are not yet statistically significant (low number statistics)
- Comparison of mm luminosity functions taking into account observational biases

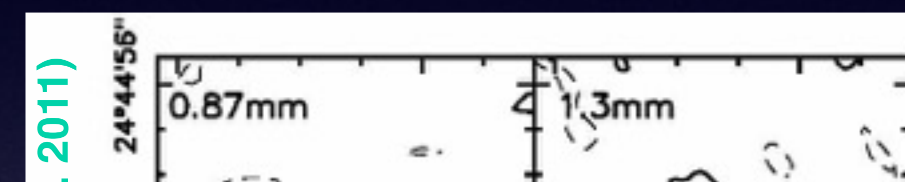
# Disk masses - Brown Dwarfs




- Ophiuchus BDs ALMA survey
- $F_{1mm} \sim B_\nu(T)\ k_{1mm}\ M_d$

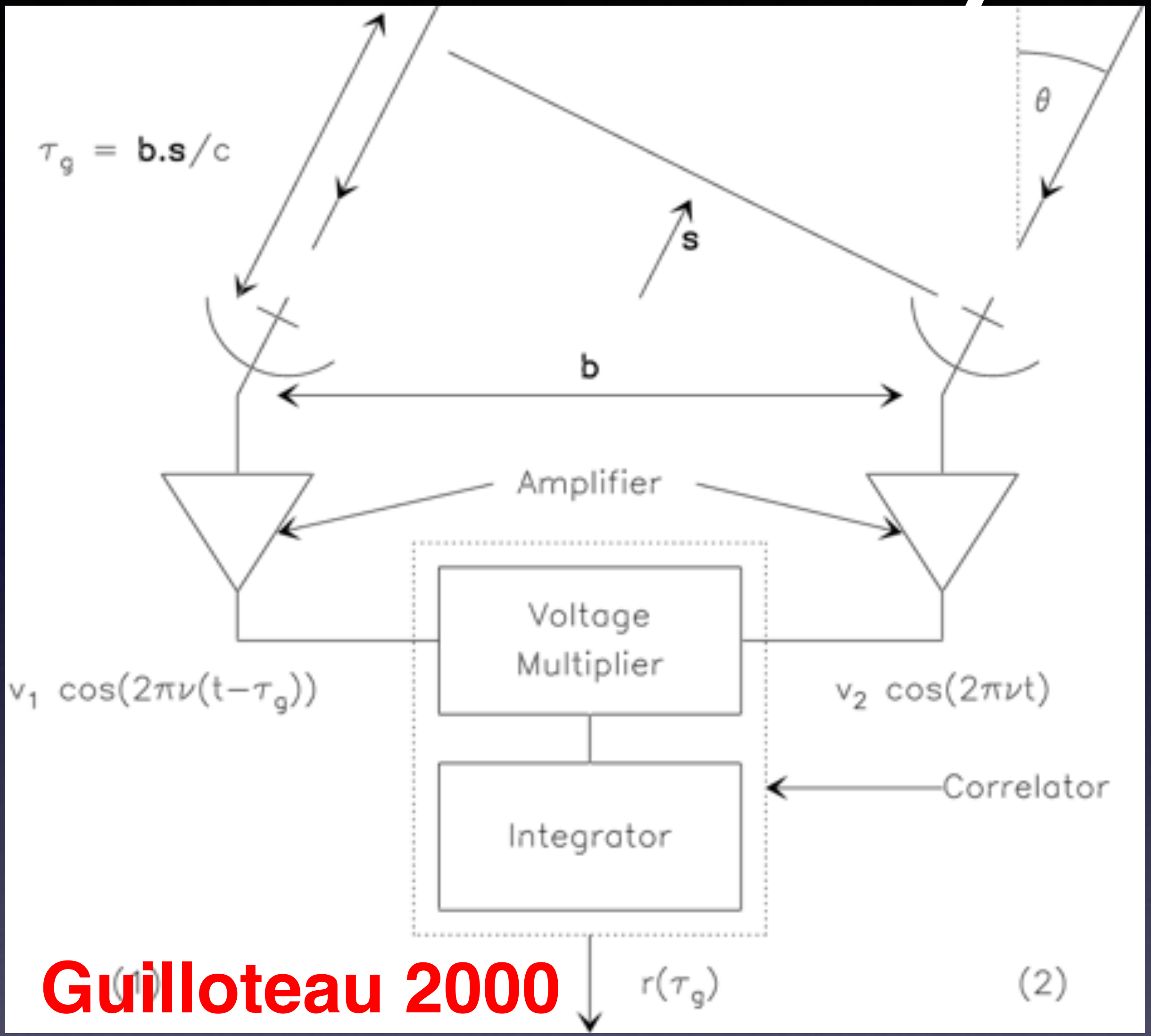
# Resolving disk structure

- 10AU@140pc=0.14 arcsec
- Diffraction: 0.14arcsec@1mm => 1.5km
- Need to use interferometry




# Small digression on interferometry

- Interference pattern of the signal from two antennas separated by a baseline b
- After correction for the optical path delay each pair of antennas measure the fringe visibility corresponding to the baseline b (as seen from the source

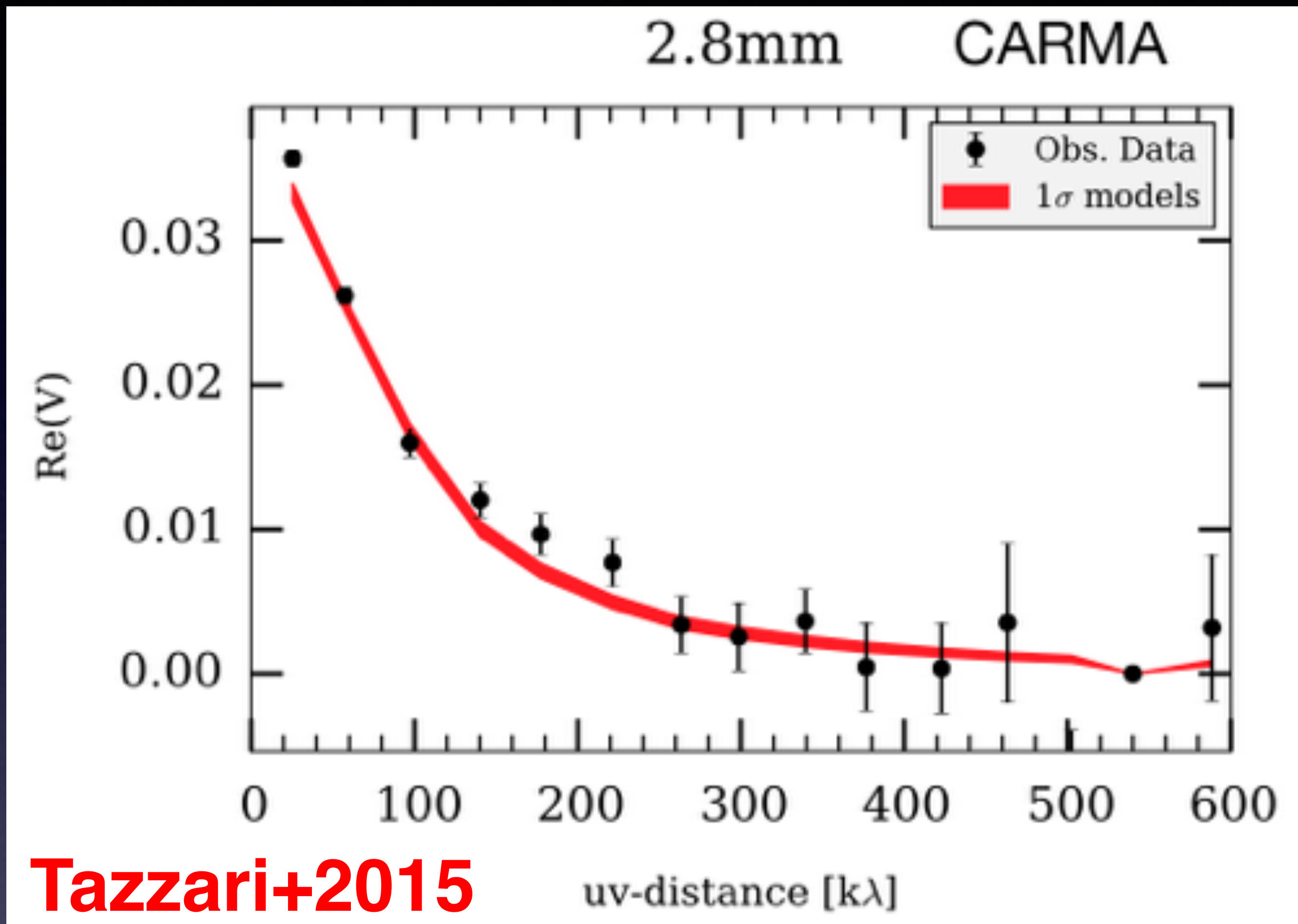


Guilloteau 2000

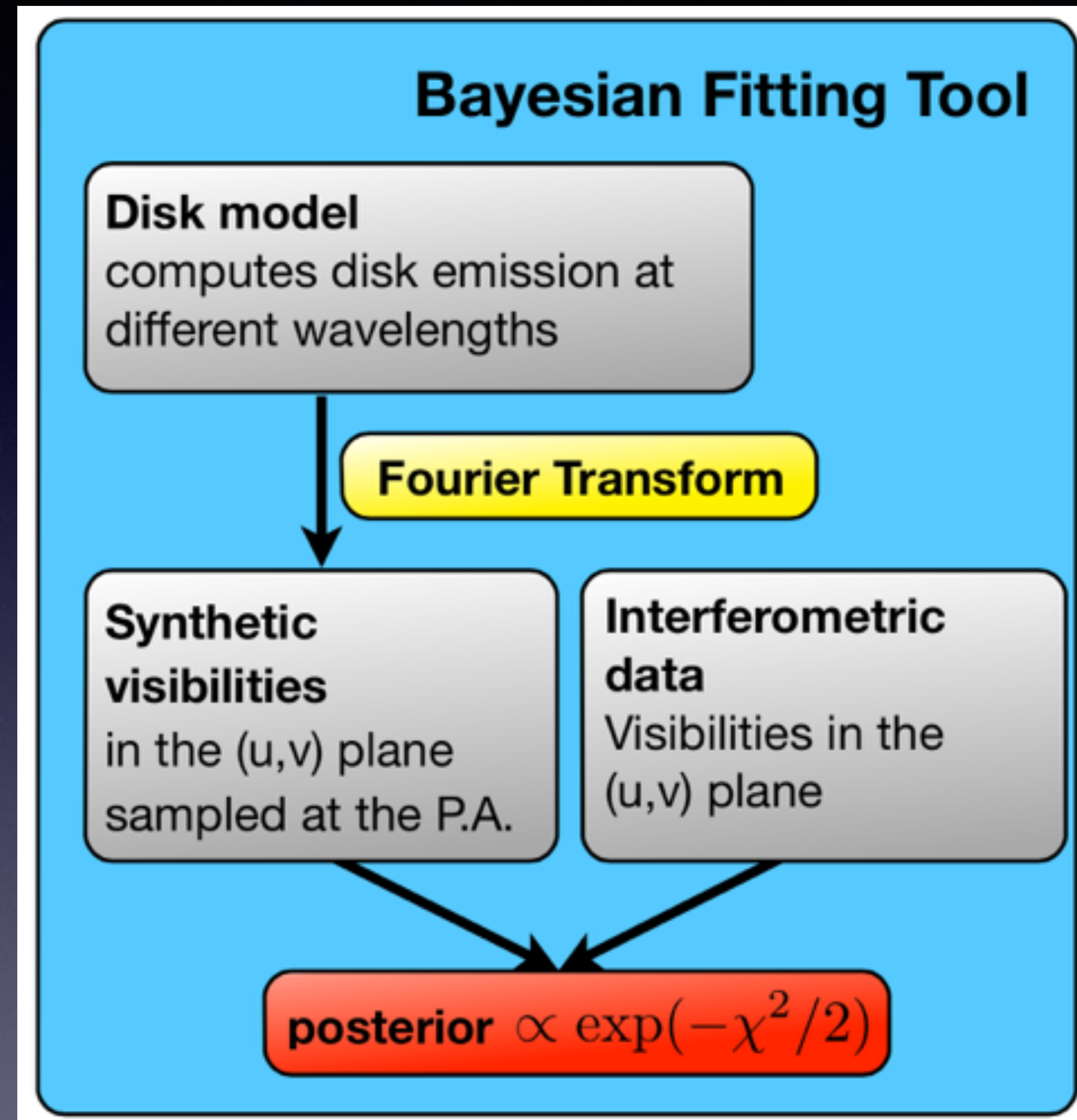
$$V(u,v) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} P(x,y) I(x,y) \exp(-2i\pi(ux+vy))\,dxdy$$

(x,y)=Sky (u,v)=baselines plane V(u,v)=Measured visibility
P(x,y)=Antenna power pattern I(x,y)=Brightness distribution on Sky

# Analysis of interferometric data




$$\Sigma(R,t) = \Sigma_t \left(\frac{R_t}{R}\right)^{\gamma} \times \exp\left\{-\frac{1}{2(2-\gamma)}\left[\left(\frac{R}{R_t}\right)^{(2-\gamma)} - 1\right]\right\}$$




- Models solve for the self consistent structure, given Sigma (and star)
- See also Isella+2007;2009

# Take home points

- Inner disk timescale consistent with SS dating
- Little evidence for mass evolution disks
  - Disk dissipation seems to be a fast process
- Resolving the disk structure requires high angular resolution (mm interferometry), and a lot of sensitivity…