Protoplanetary Disks
(the dirty job part 1)

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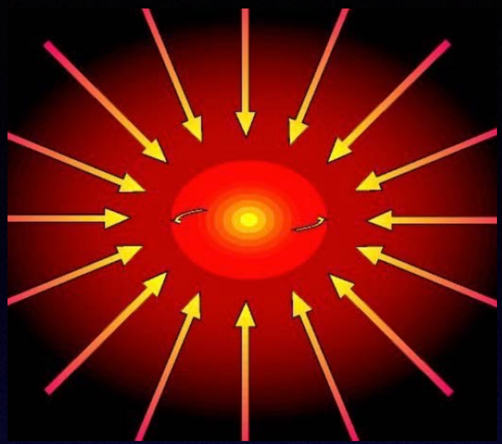
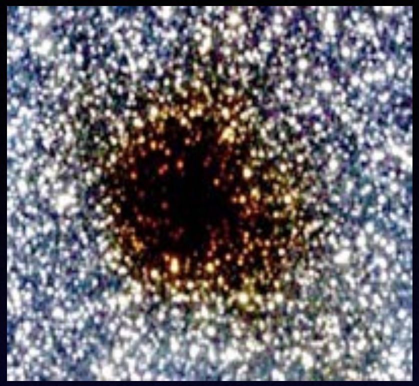
- Most of the focus will be on Class II disks
- How we determine the key properties of these systems
- Stellar masses and ages
- Disk physical parameters
- Evolution of the disk and its constituents

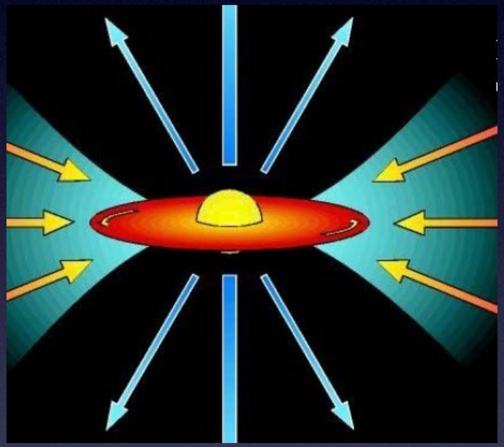
ECOGAL
erc

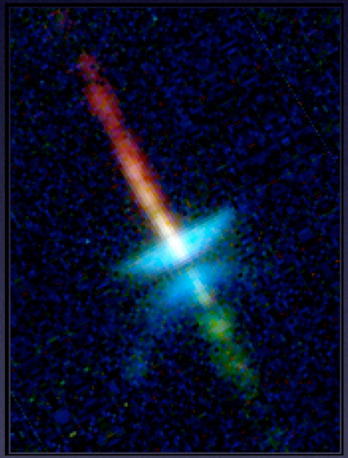
From Cores to Planetary Systems



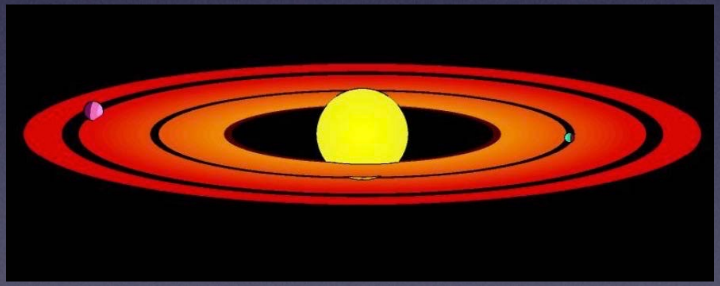


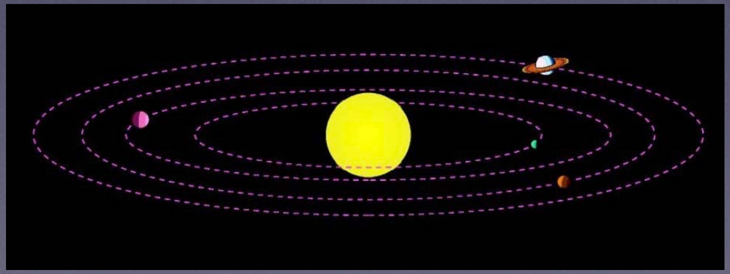
Core

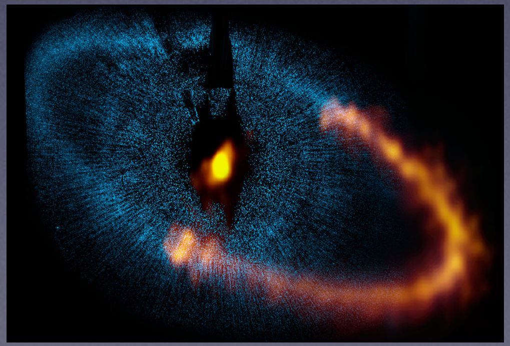




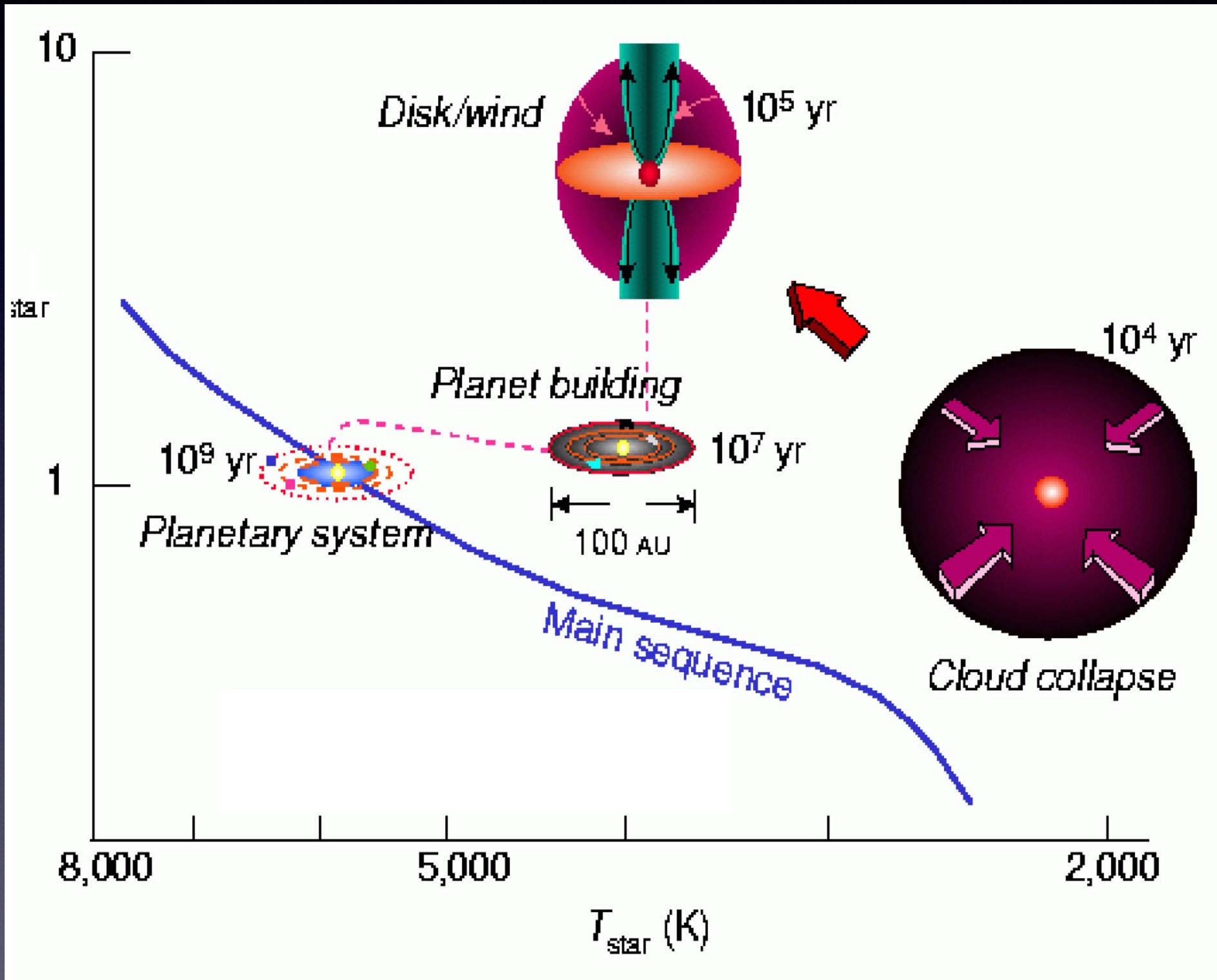
Disk



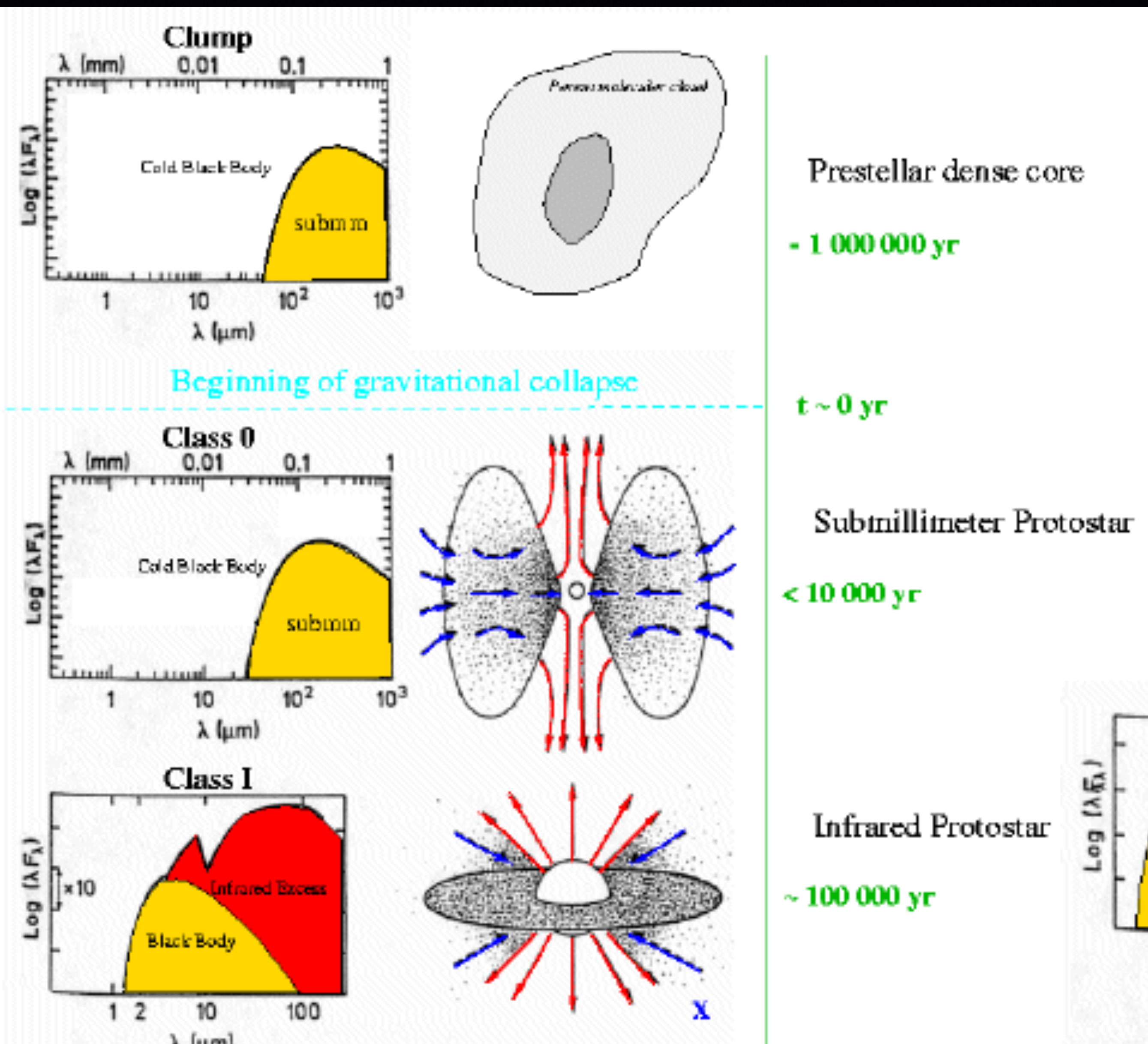




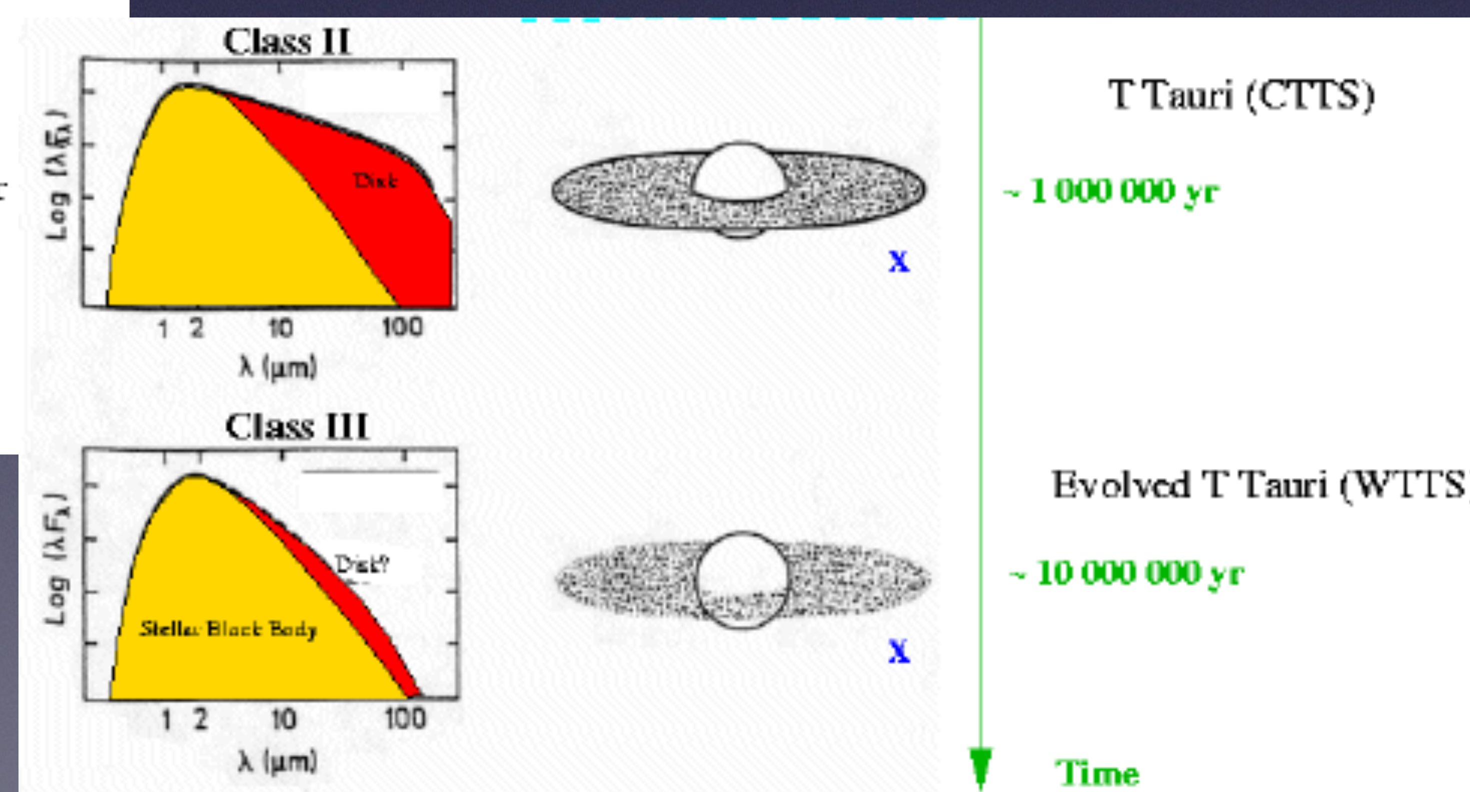
Debris Disk



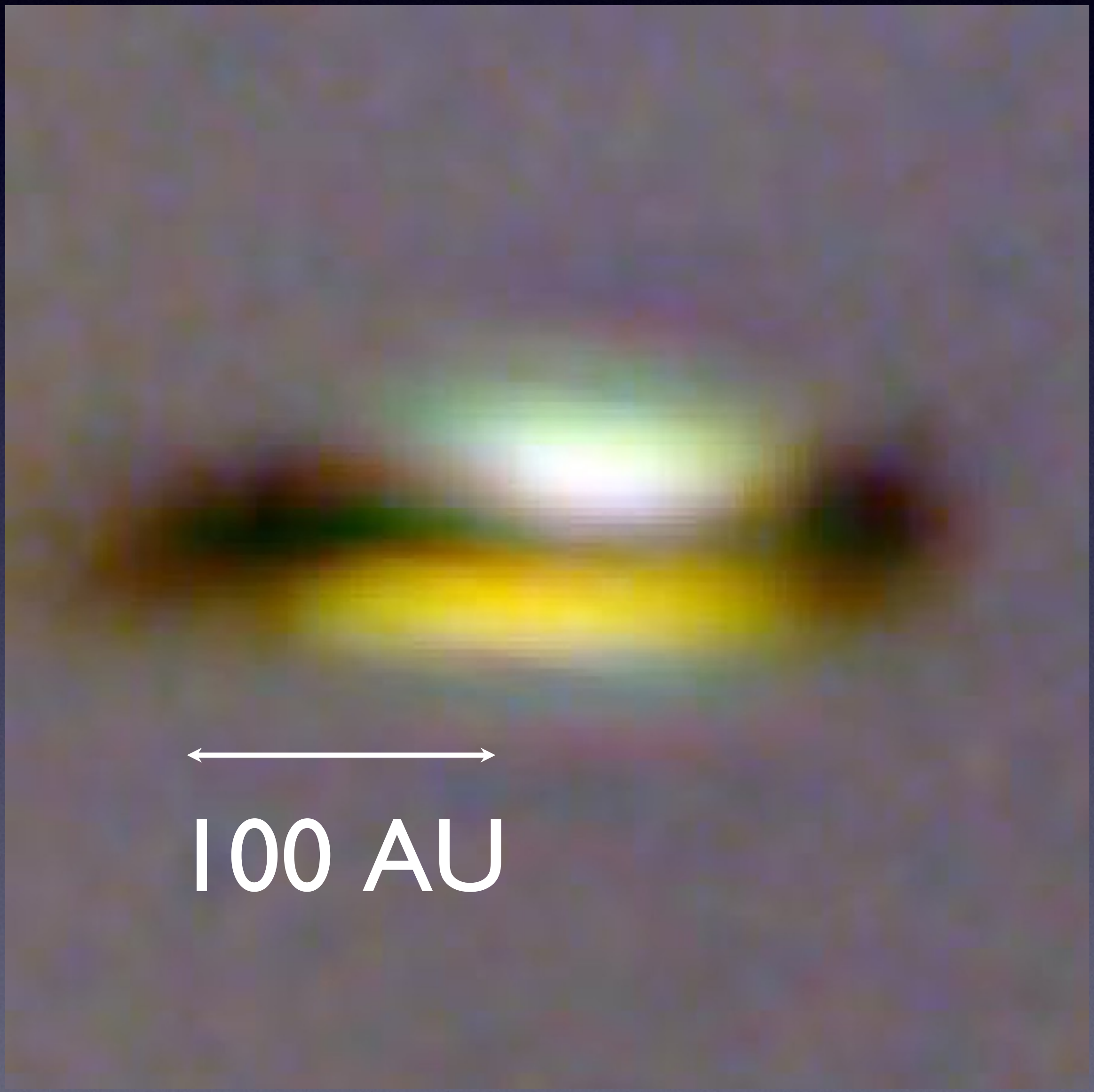
YSO SED classification

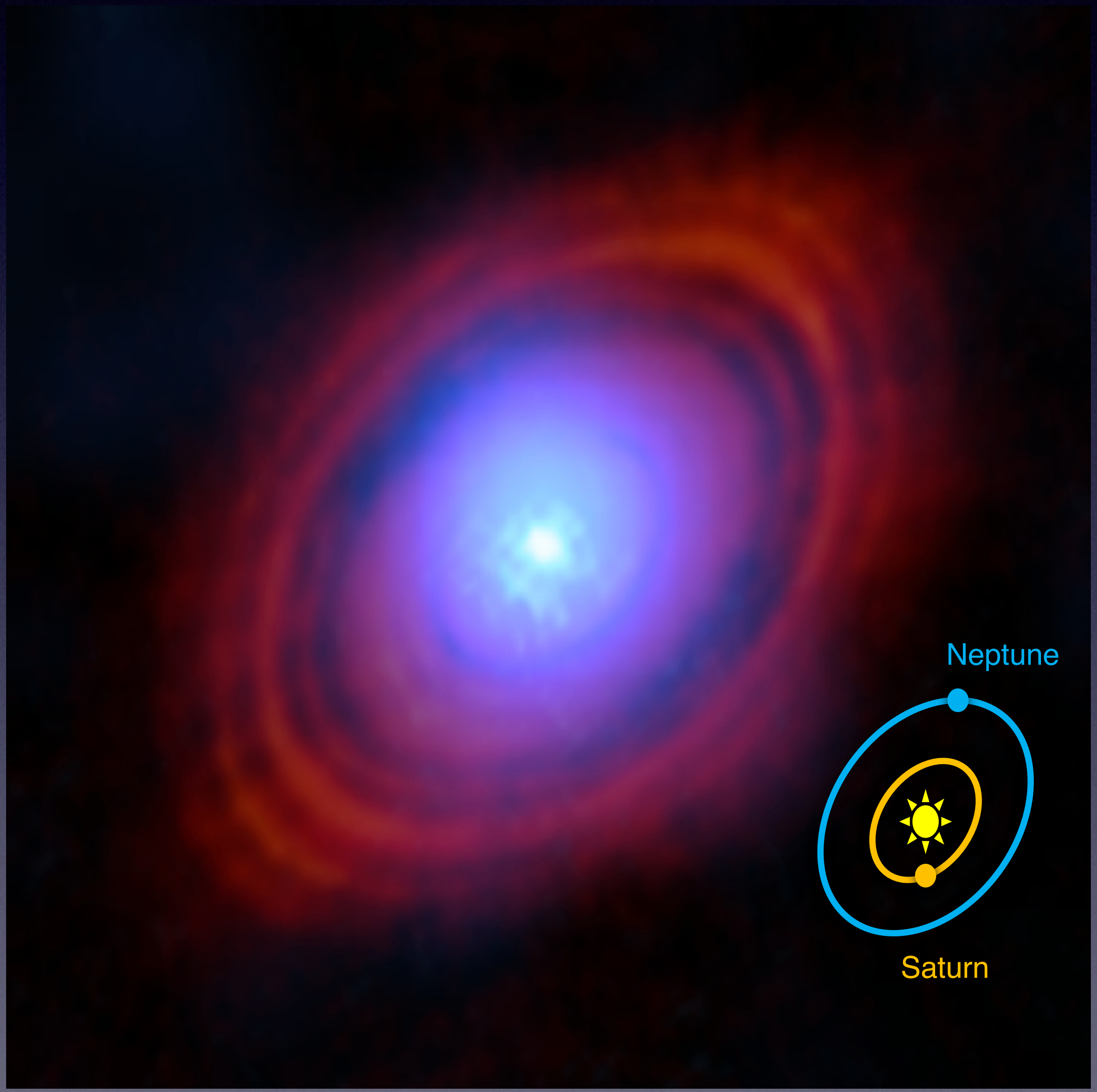


- Original classification I-II-II based on IR spectral index
- Class 0 based on FIR-submm
- Many caveats, but still a useful classification scheme

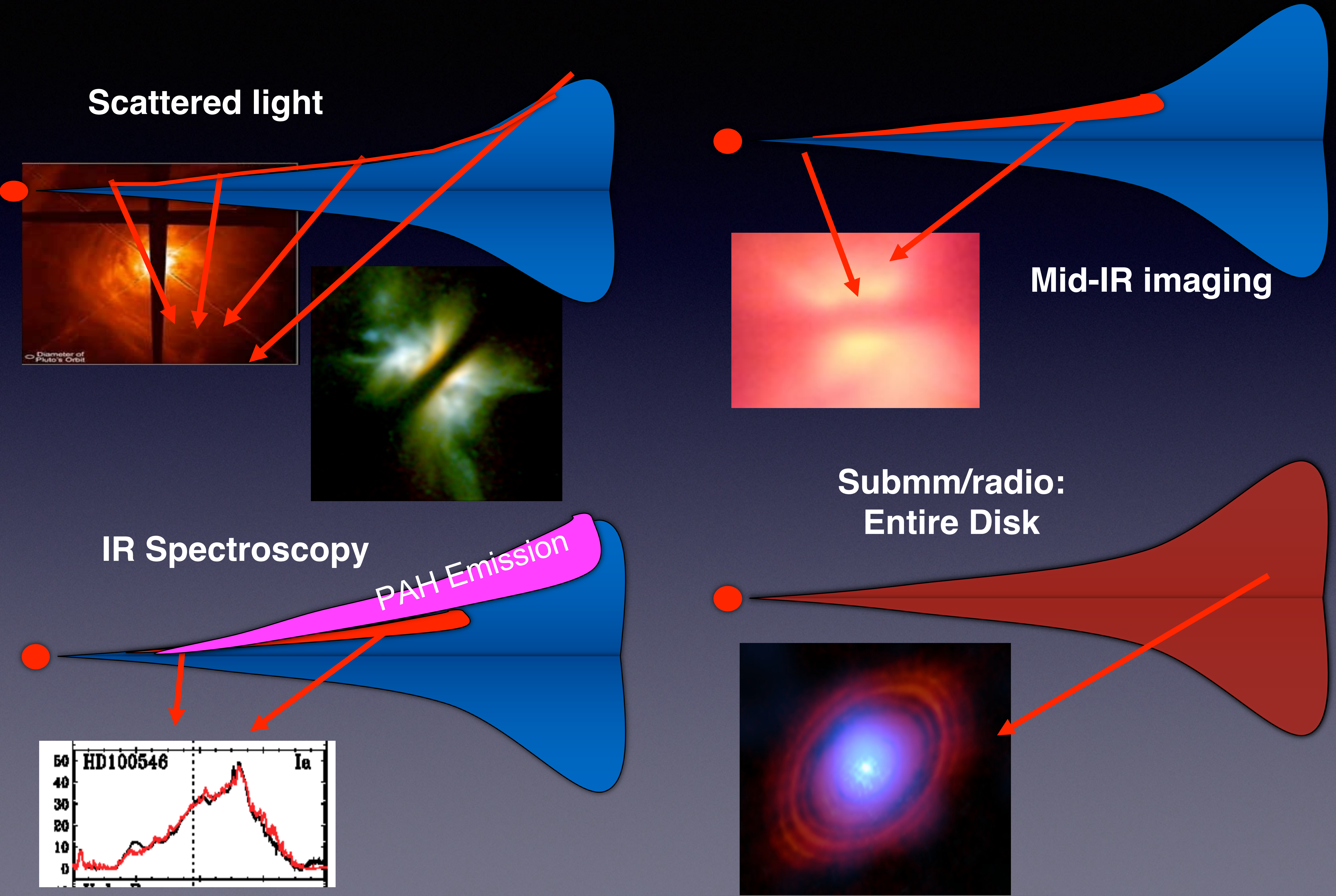


Protoplanetary disks



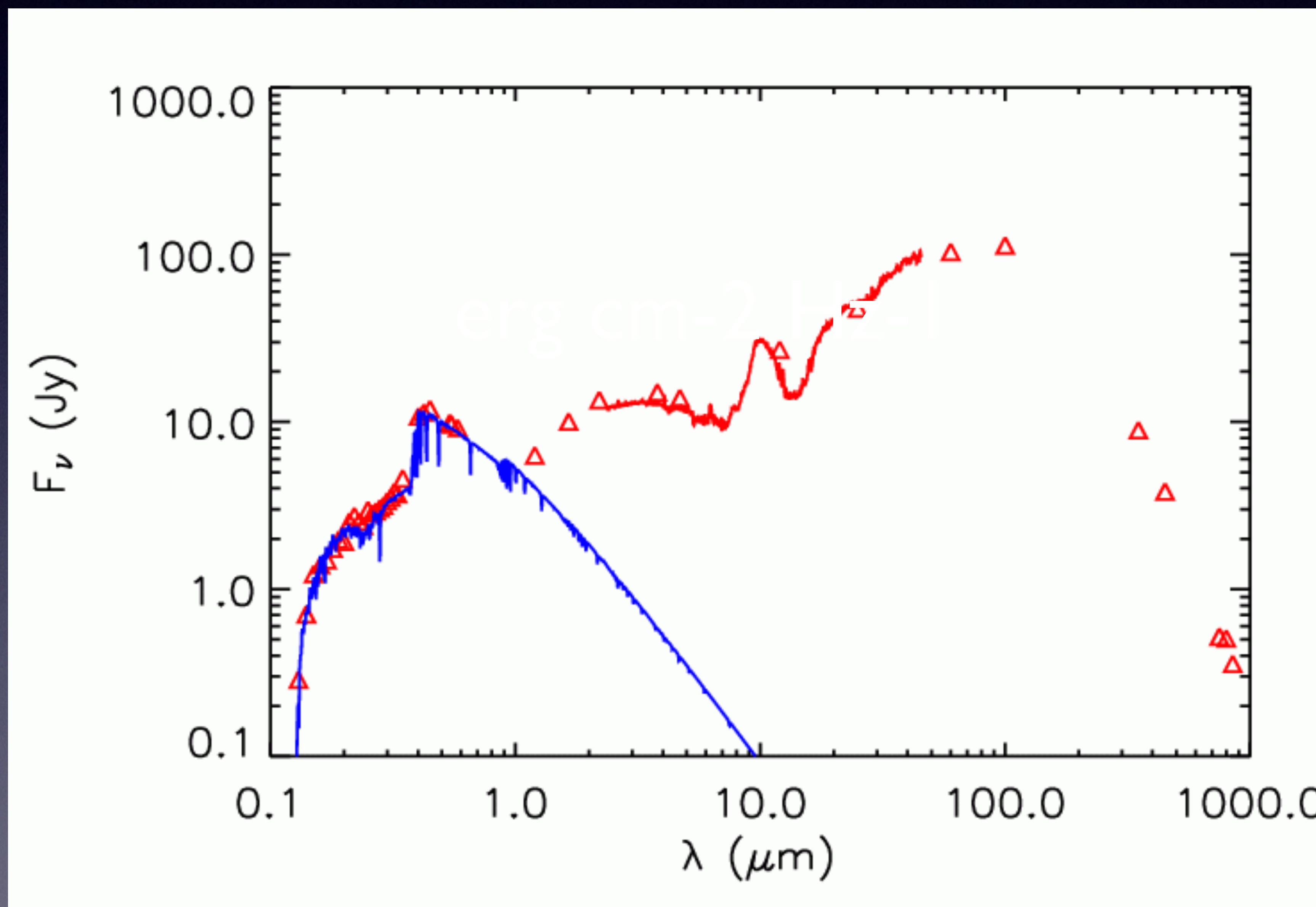


Flared disks: which observations probe what?



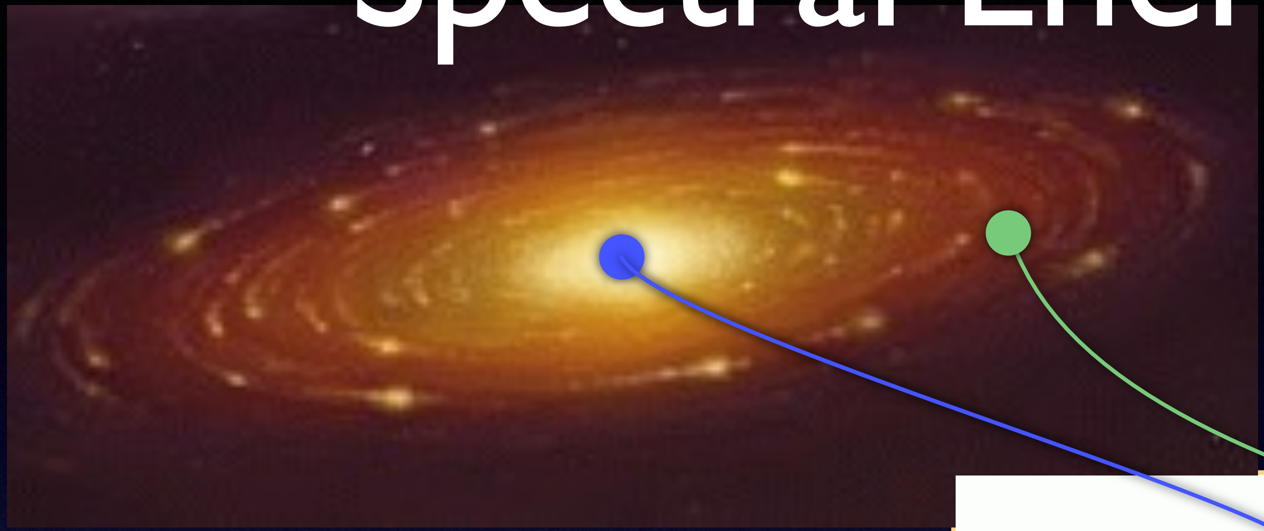
Spectral Energy Distributions (SEDs)

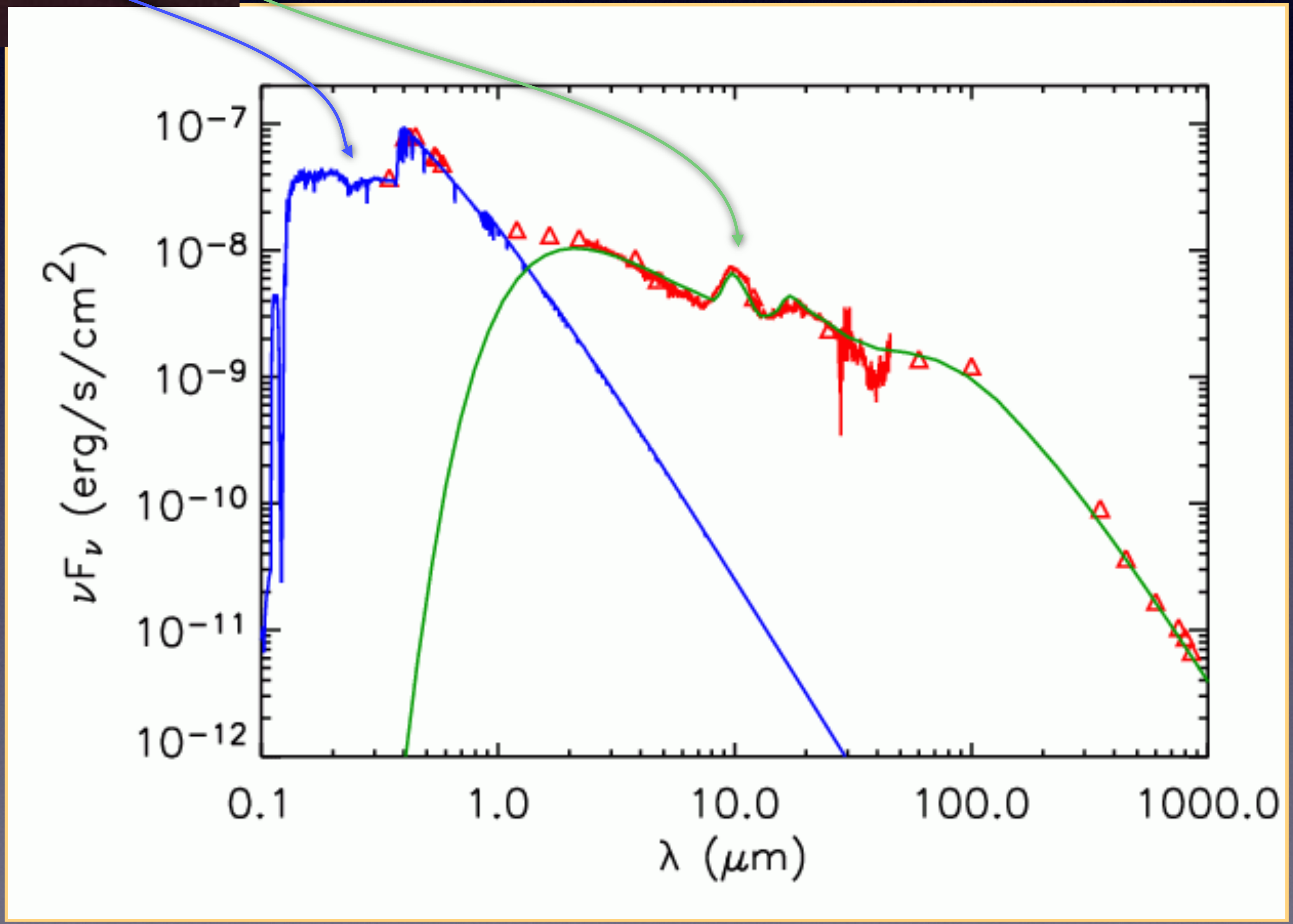
The SED shows the energy emitted per logarithmic wavelength interval. Plotting just the flux may be misleading:



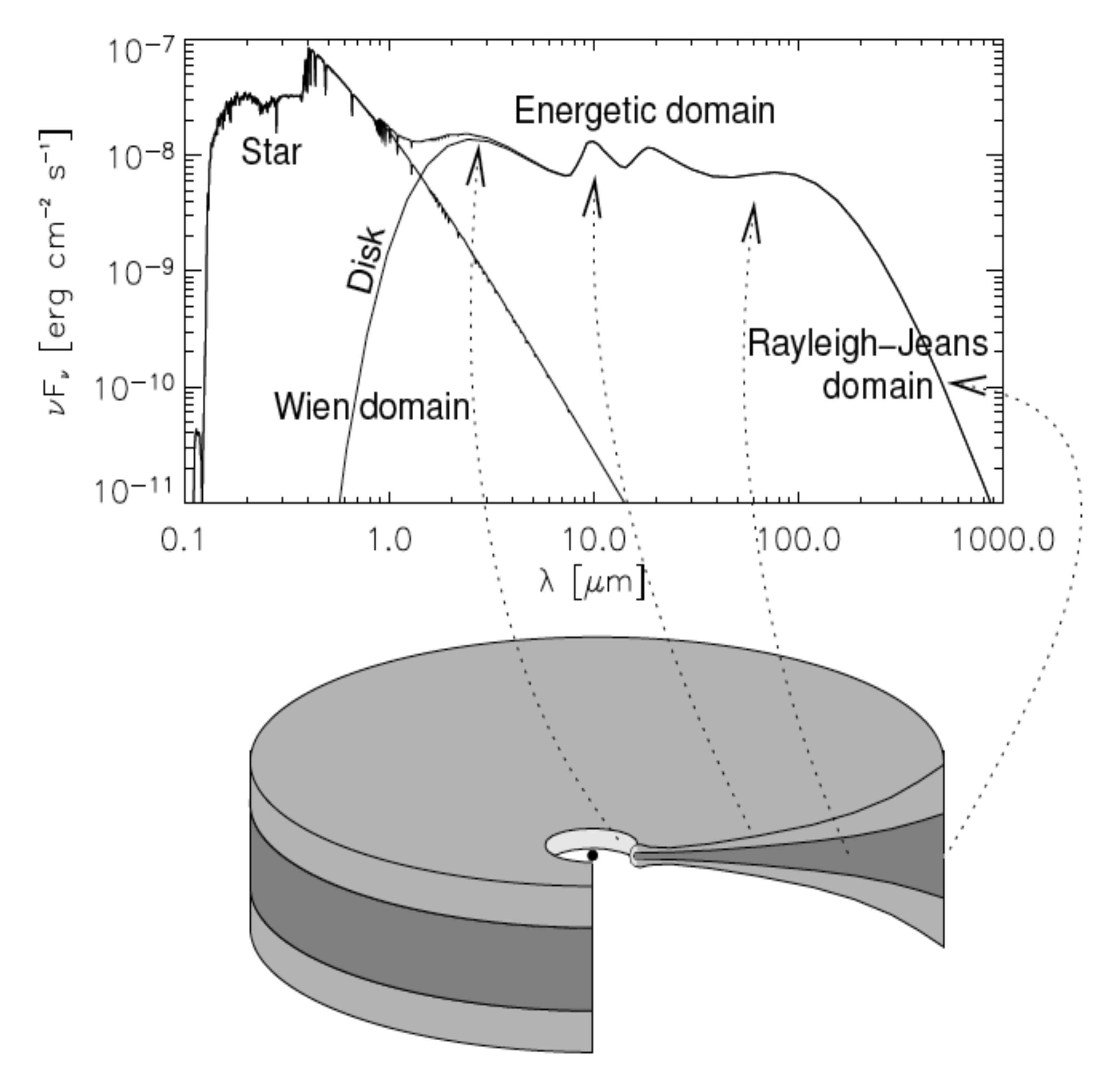
Energy: $F_\nu \, d\nu = F_\nu \, \Delta\nu$

Spectral Energy Distribution

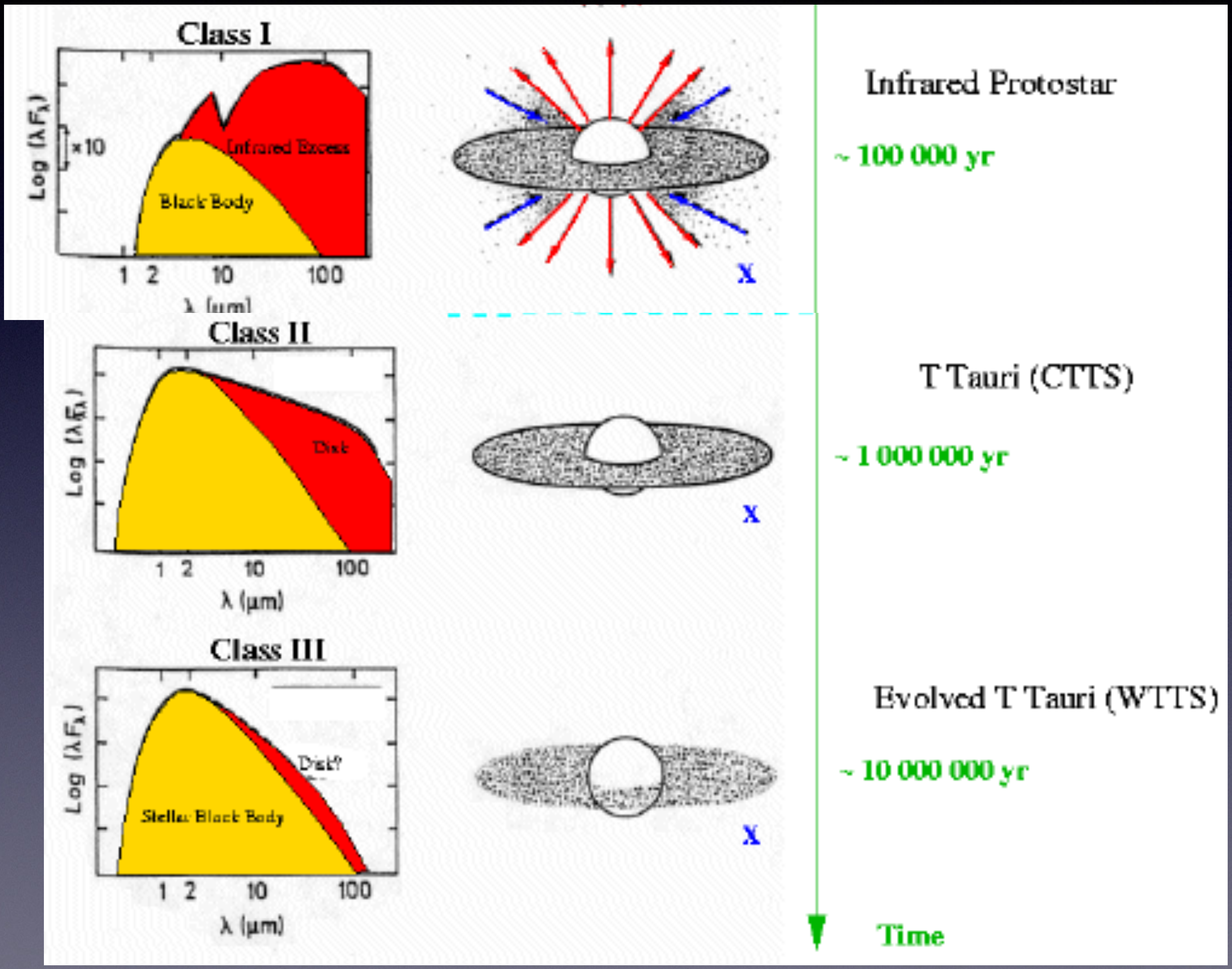




“flared” disk emission

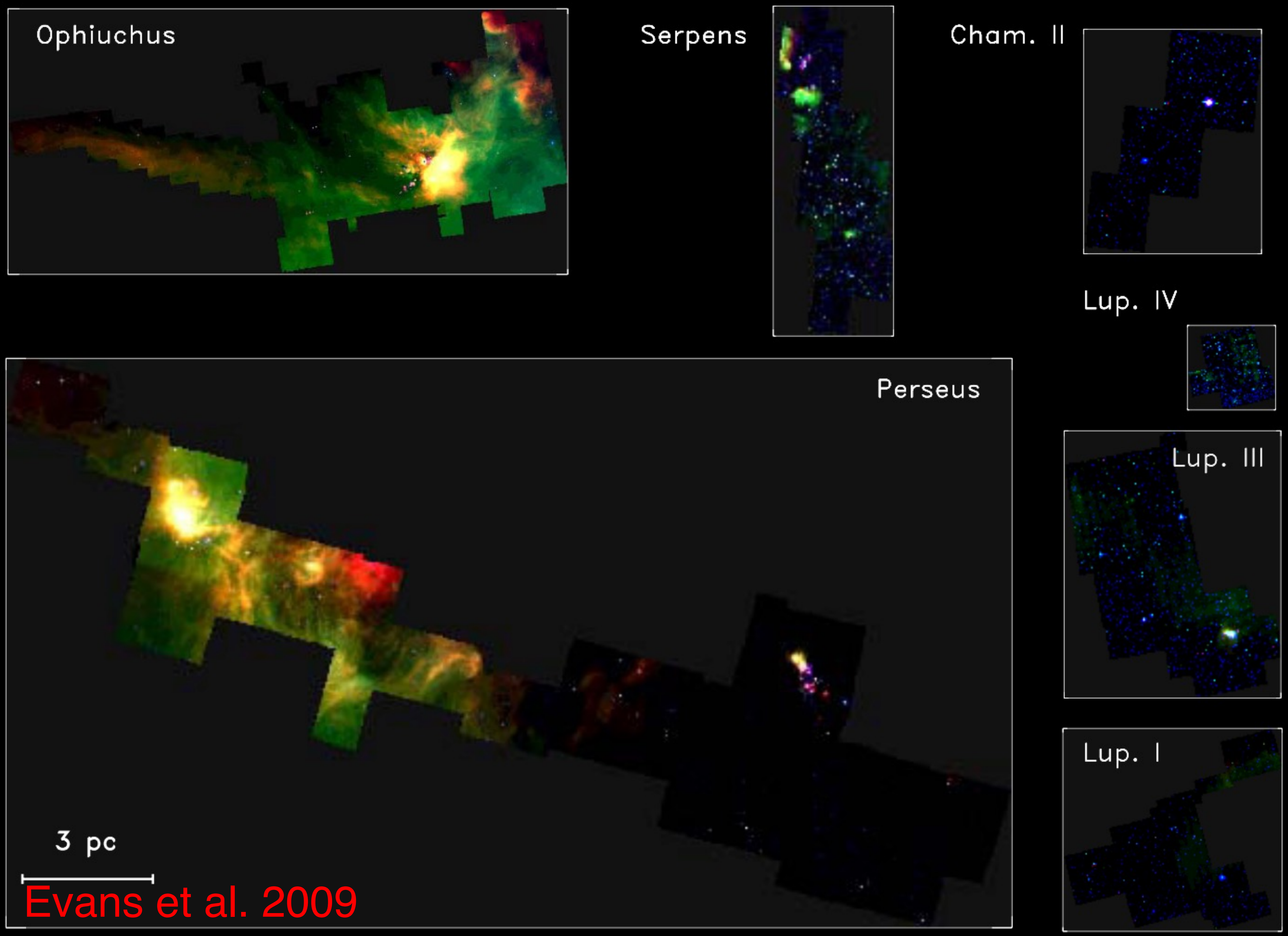


IR SED slope

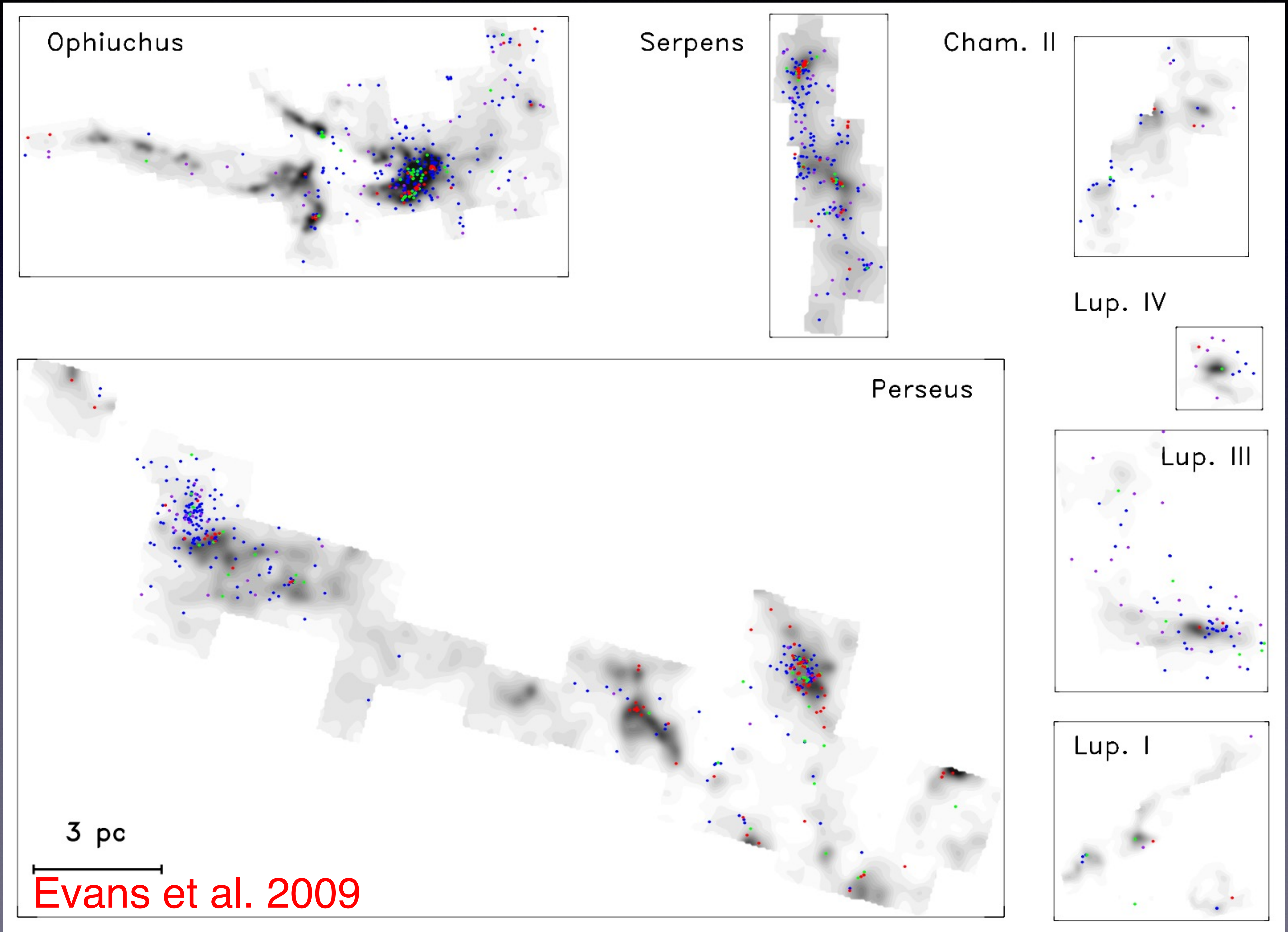


Class I
Log (λF_λ)
×10
Infrared Excess
Black Body
1 2 10 100
λ (μm)
Infrared Protostar
~ 100 000 yr
Class II
Log (λF_λ)
Disk
1 2 10 100
λ (μm)
T Tauri (CTTS)
~ 1 000 000 yr
Class III
Log (λF_λ)
Disk?
Stellar Black Body
1 2 10 100
λ (μm)
Evolved T Tauri (WTTS)
~ 10 000 000 yr
X
X
X
Time

Statistics and timescales



Statistics and timescales



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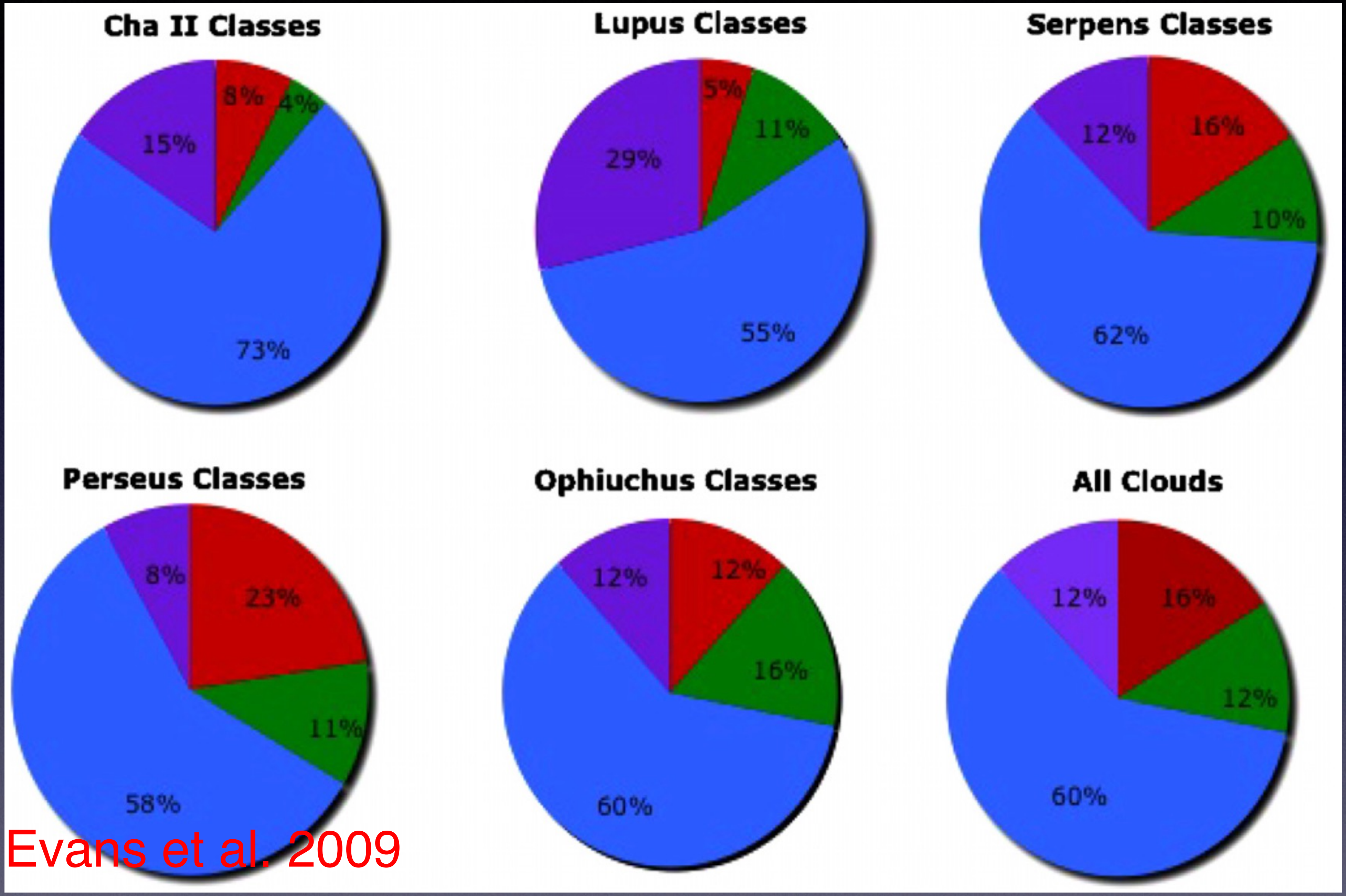
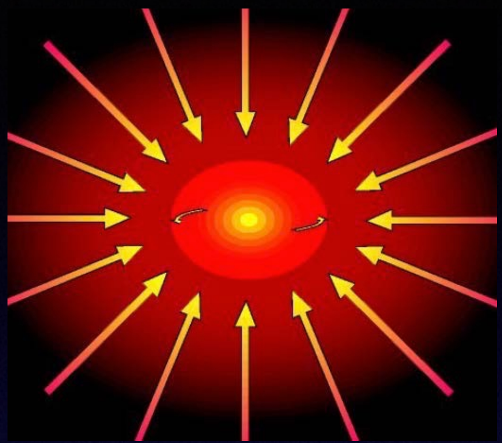
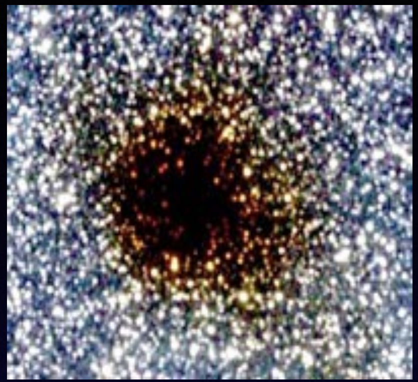


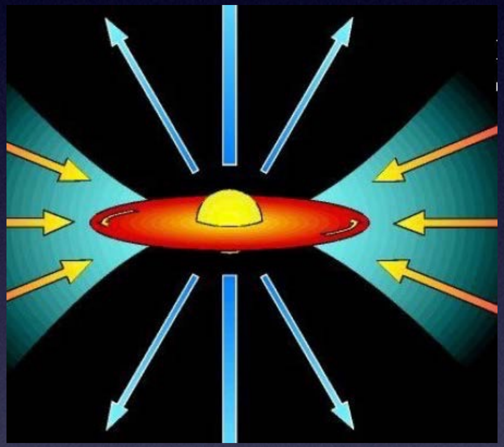
- In nearby star forming regions, we can estimate:
- very roughly $t_{II} \sim$ 5-10 $t_I \sim$ 5-10 t_0 or $\sim 10^6$ yr : $\sim 10^5$ yr : $\sim 10^4$ yr

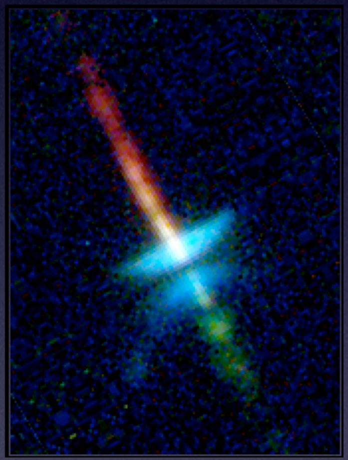
From Cores to Planetary Systems



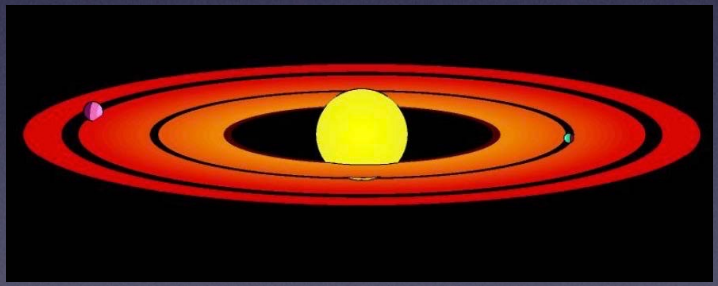


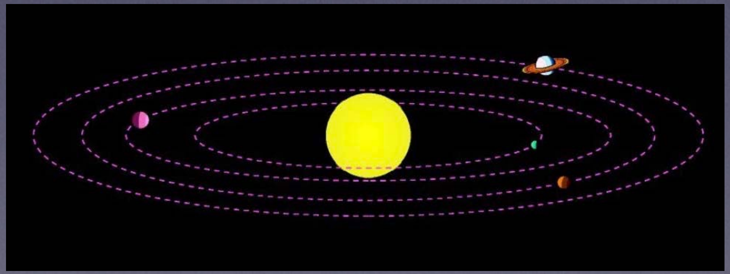
Core

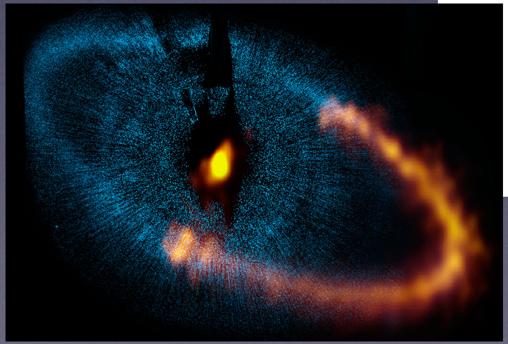




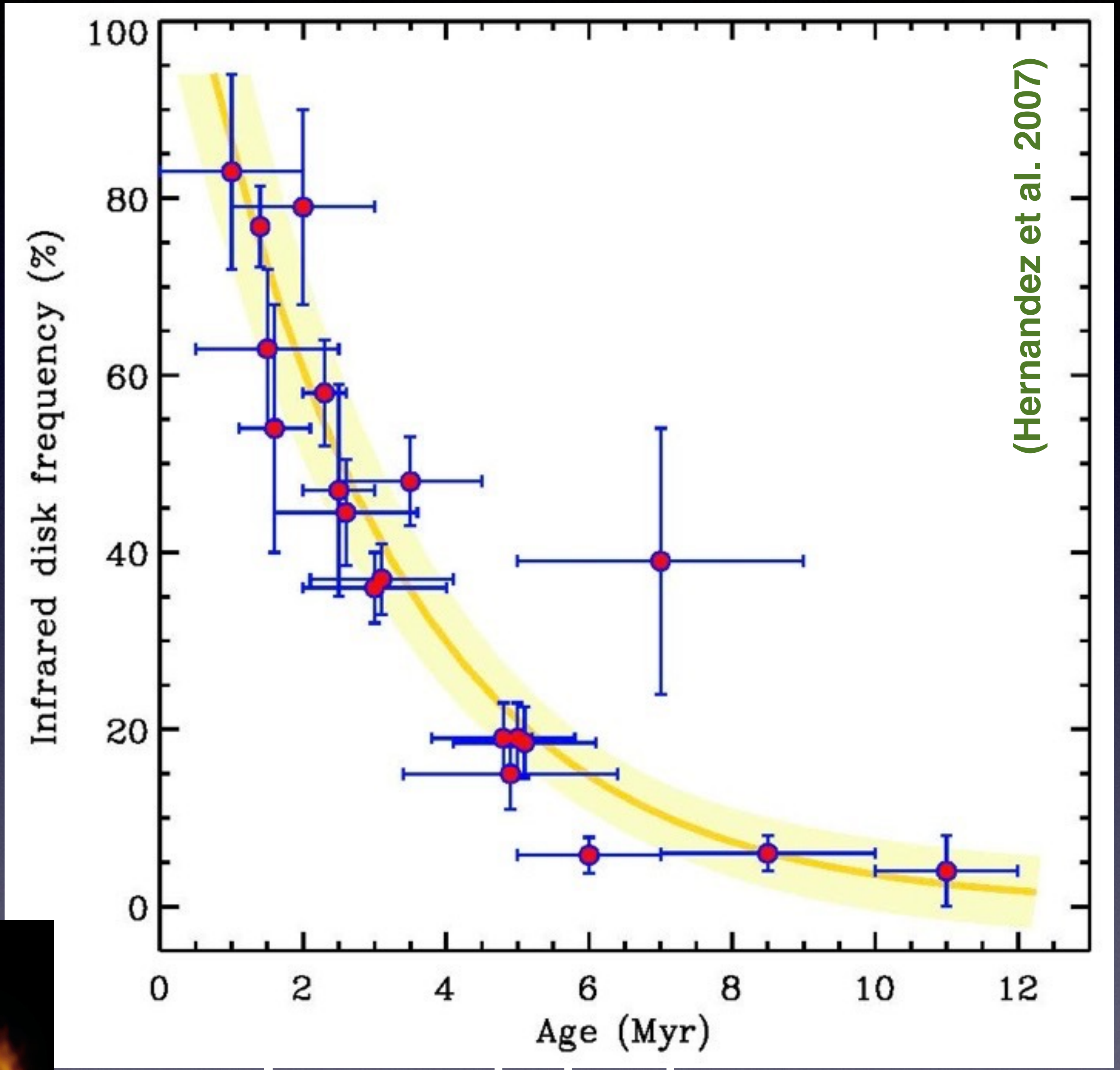
Disk





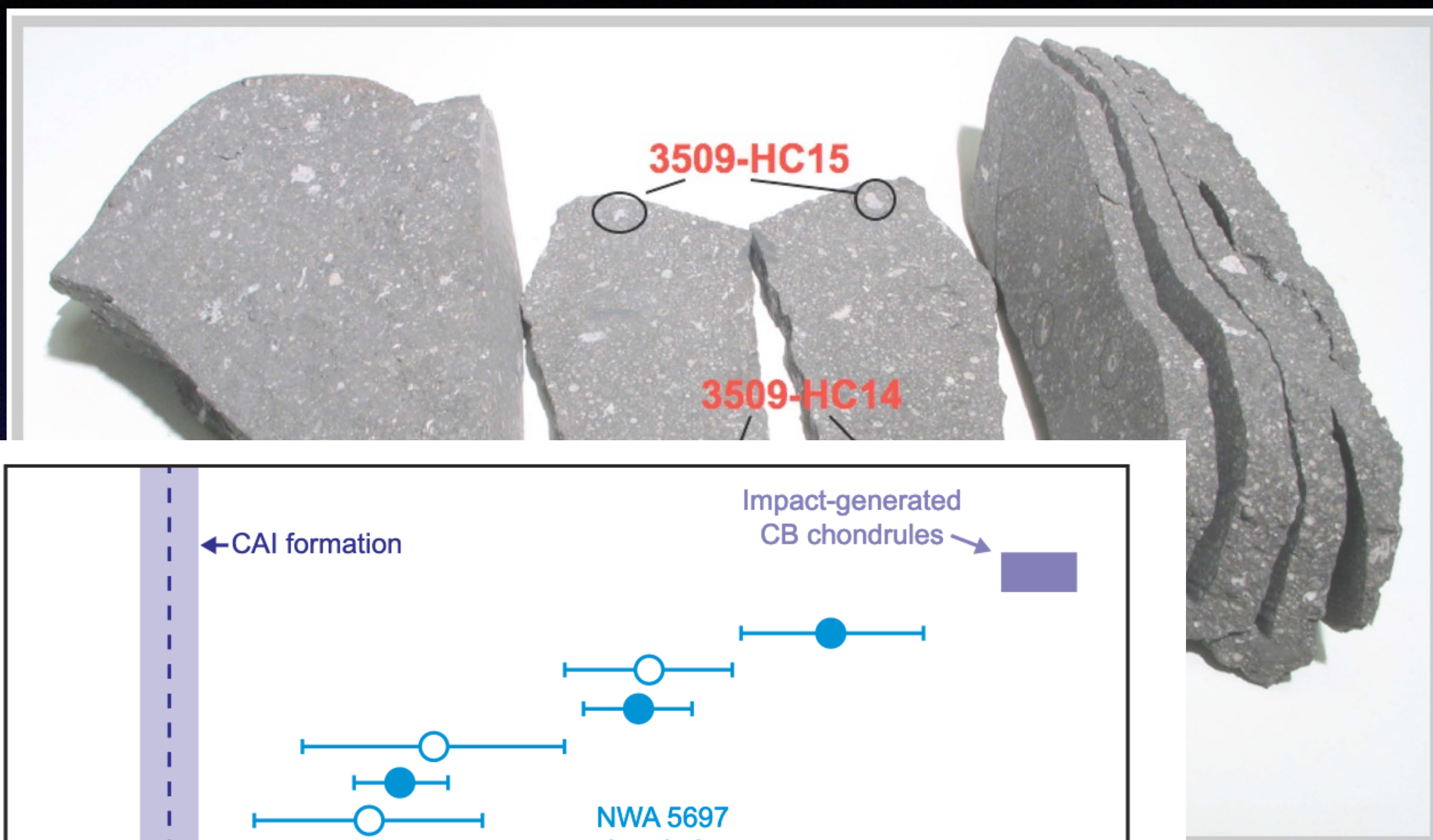


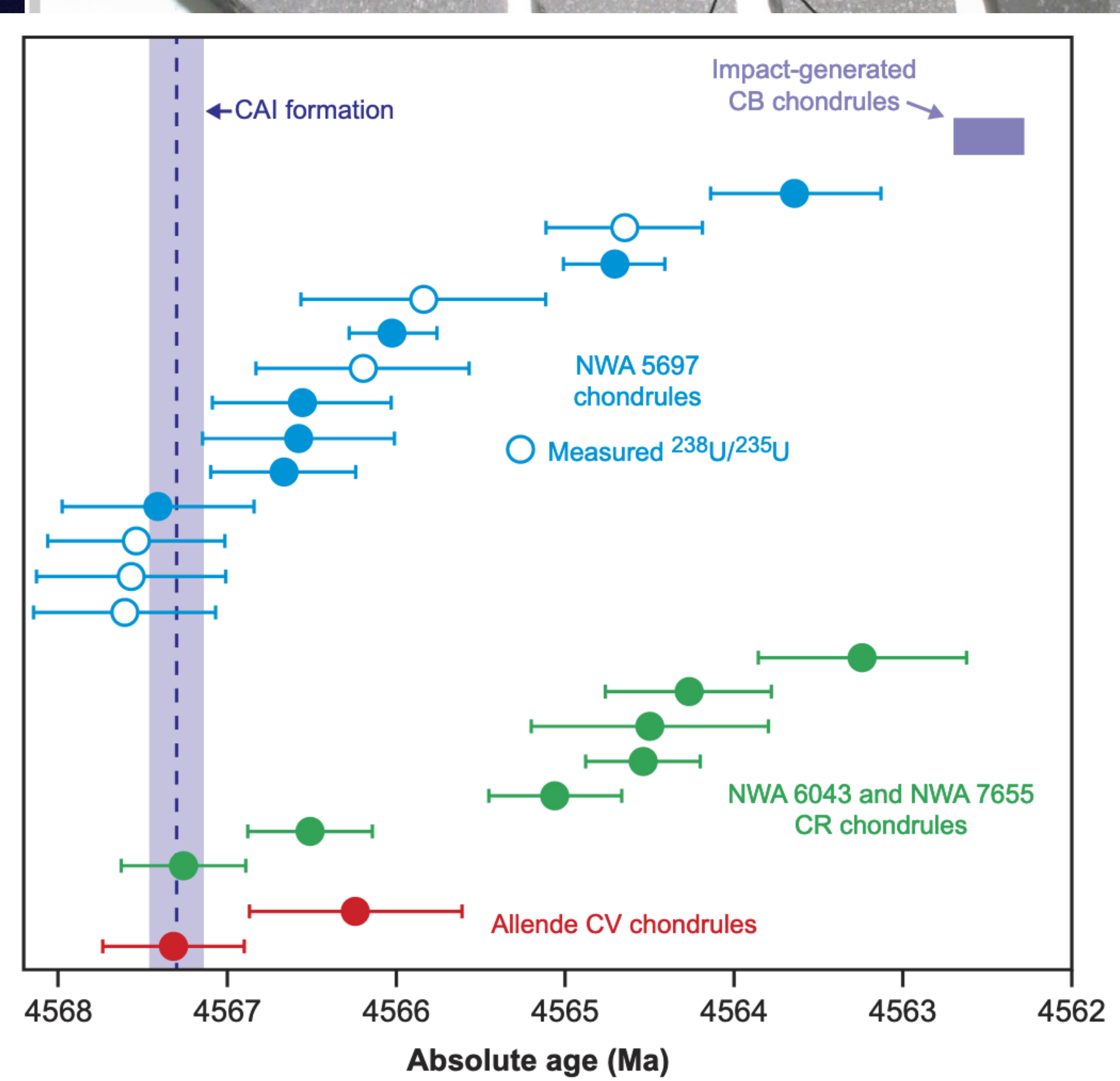
Debris Disk



Inner disk clearing:
e-folding time t~2-3 Myr

Allende meteorite





Mexico
8 Feb 1969

Calcium-Aluminum Inclusions (CAI)

- Oldest, high-T (>~1700K) processing, short formation phase (<~3x10^5 yr)

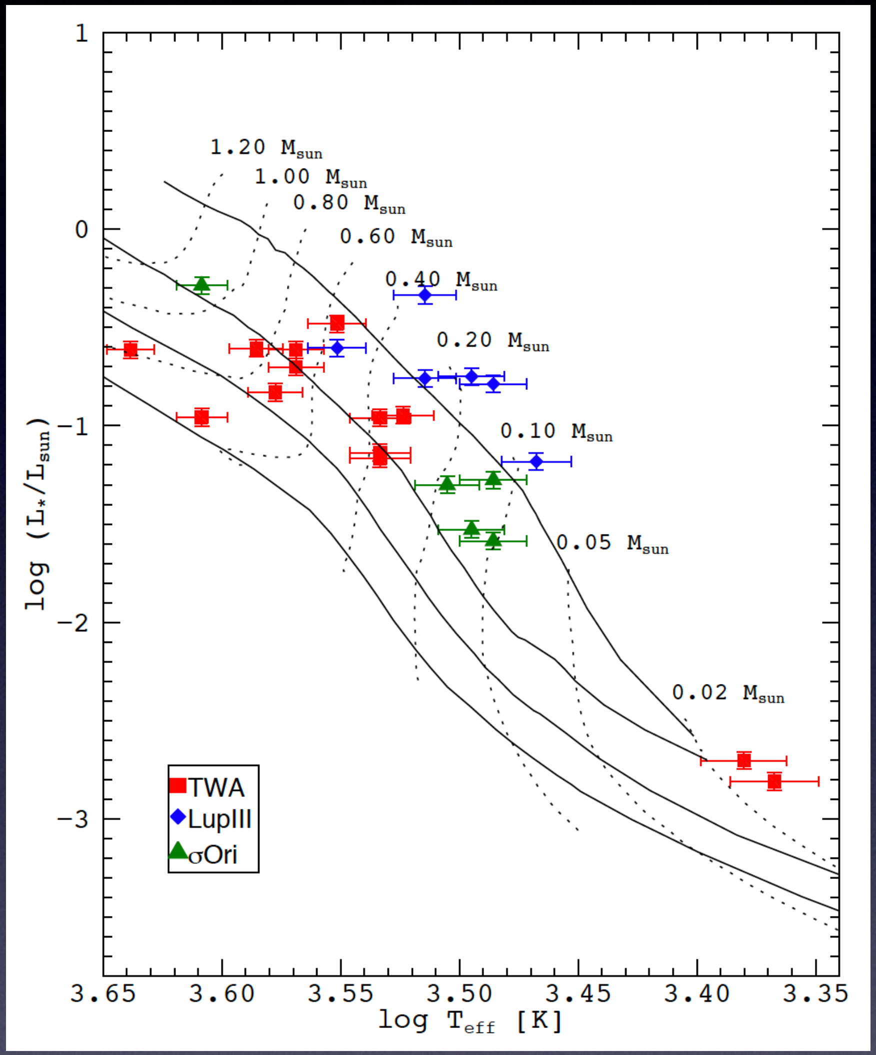
Chondrules

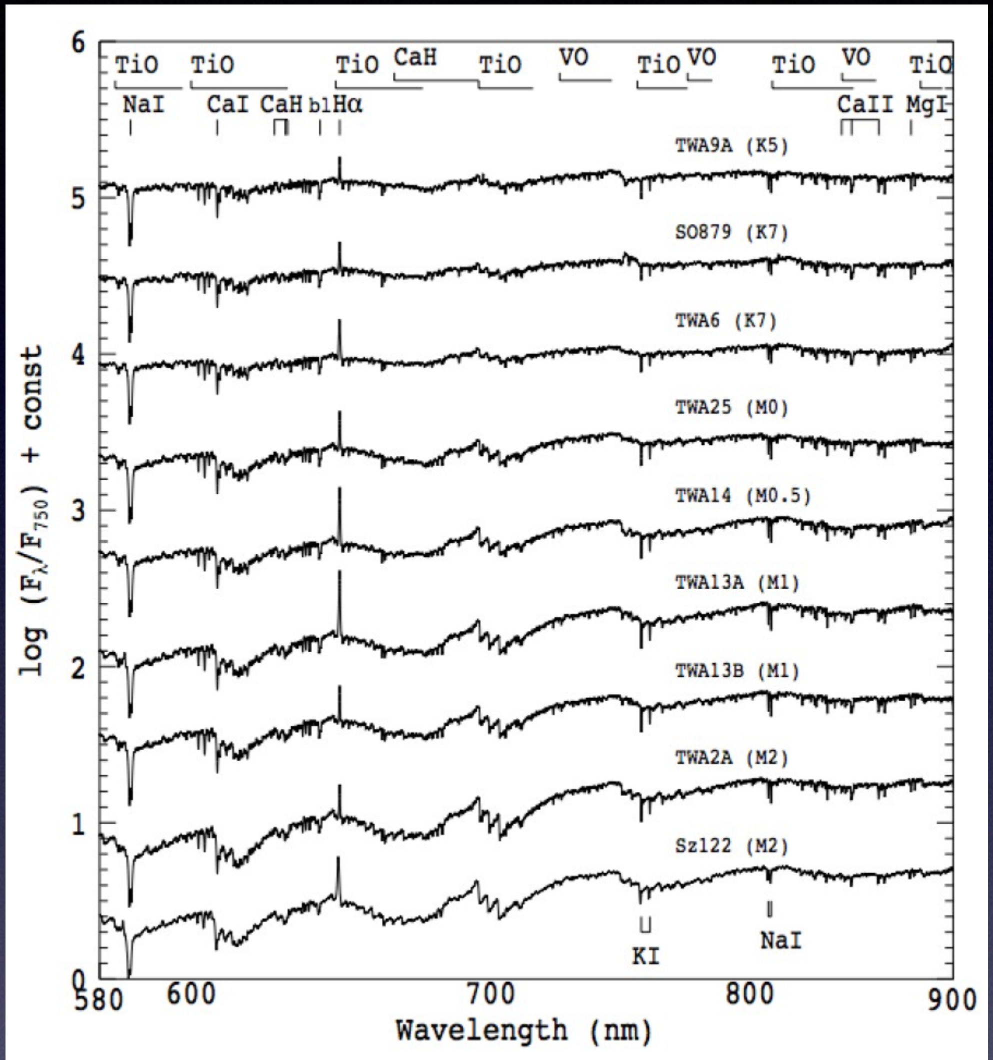
- Formed after CAI, high-T (~2000K) few Myr age dispersion

Matrix

- sub-um particles, glue together the material

Stellar parameters





(Manara et al. 2013)

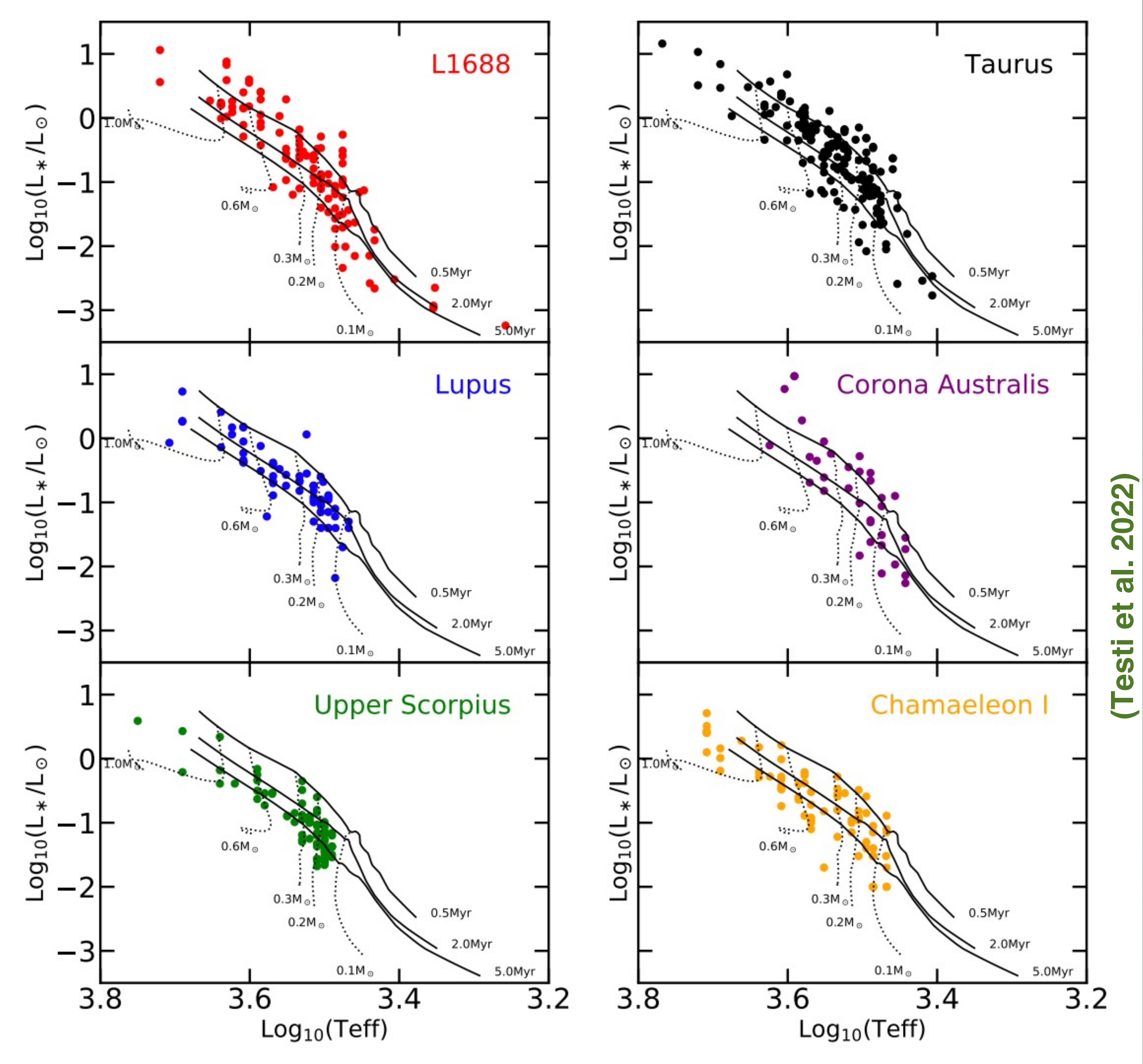
- Place star on HR-diagram using Teff and Lstar to read off masses and ages (hoping that the tracks are accurate…)
  - Teff from spectral typing
  - Lstar from magnitudes and extinction

Stellar parameters

~1Myr

~2Myr

~5Myr



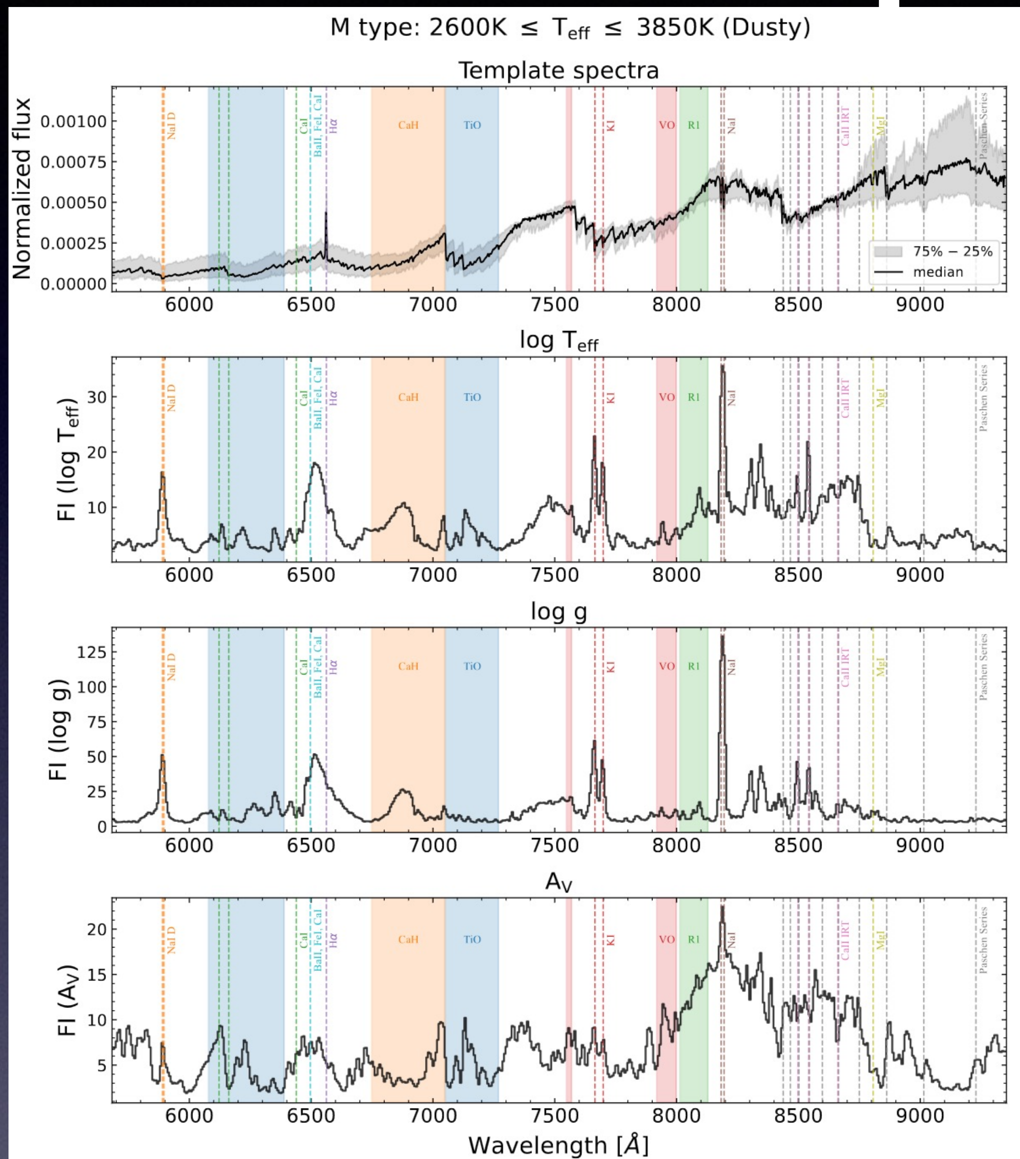
~0.9Myr

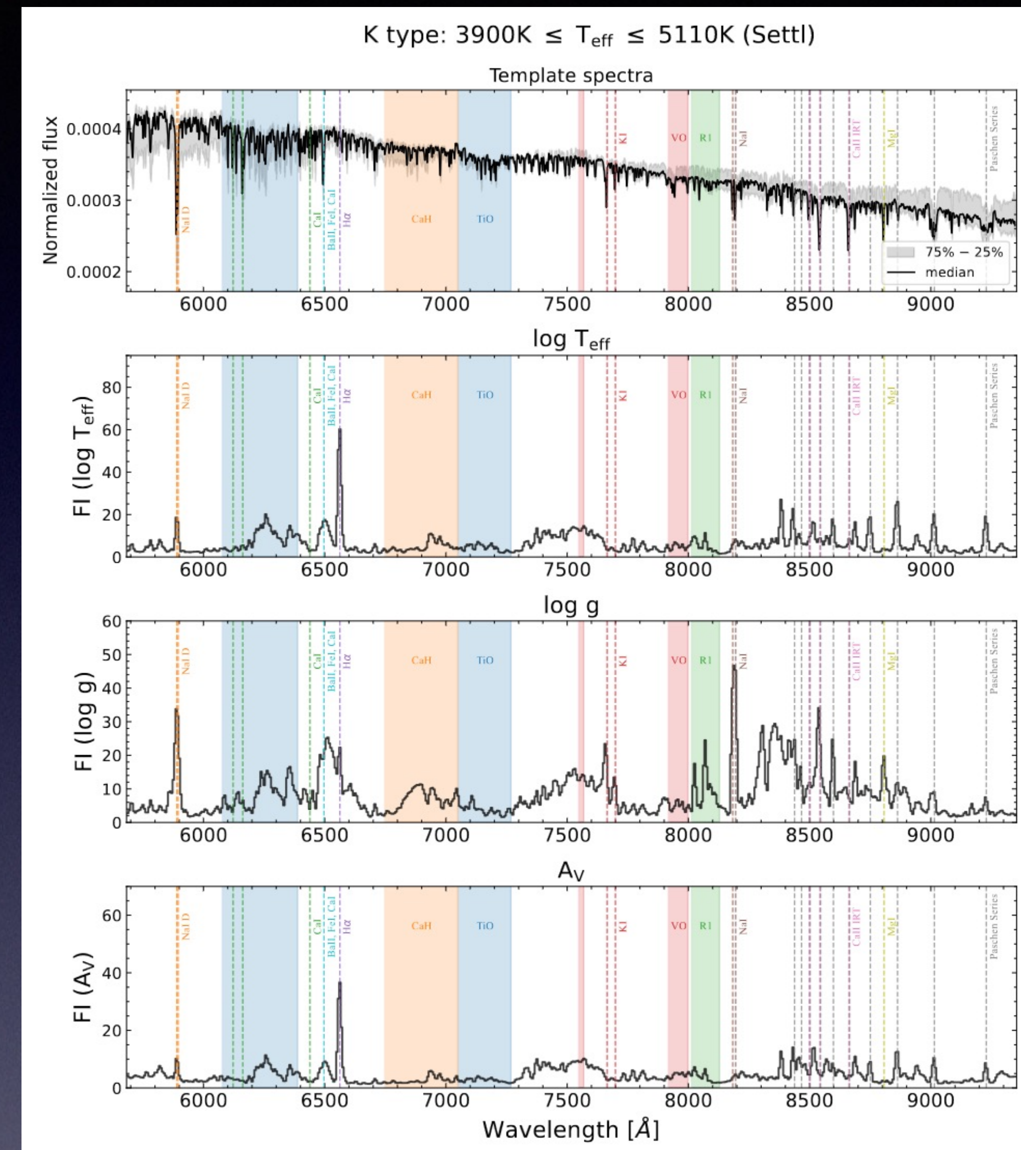
~0.6Myr

~3Myr

(Testi et al. 2022)

Stellar parameters





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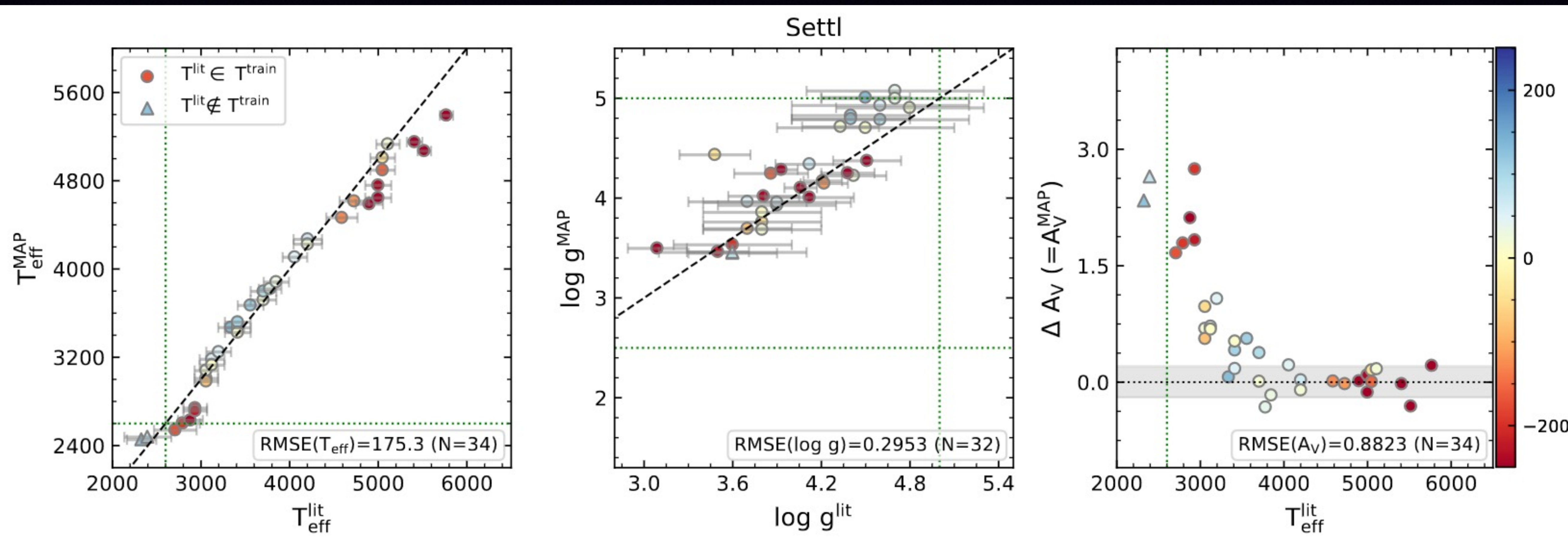
Stellar parameters



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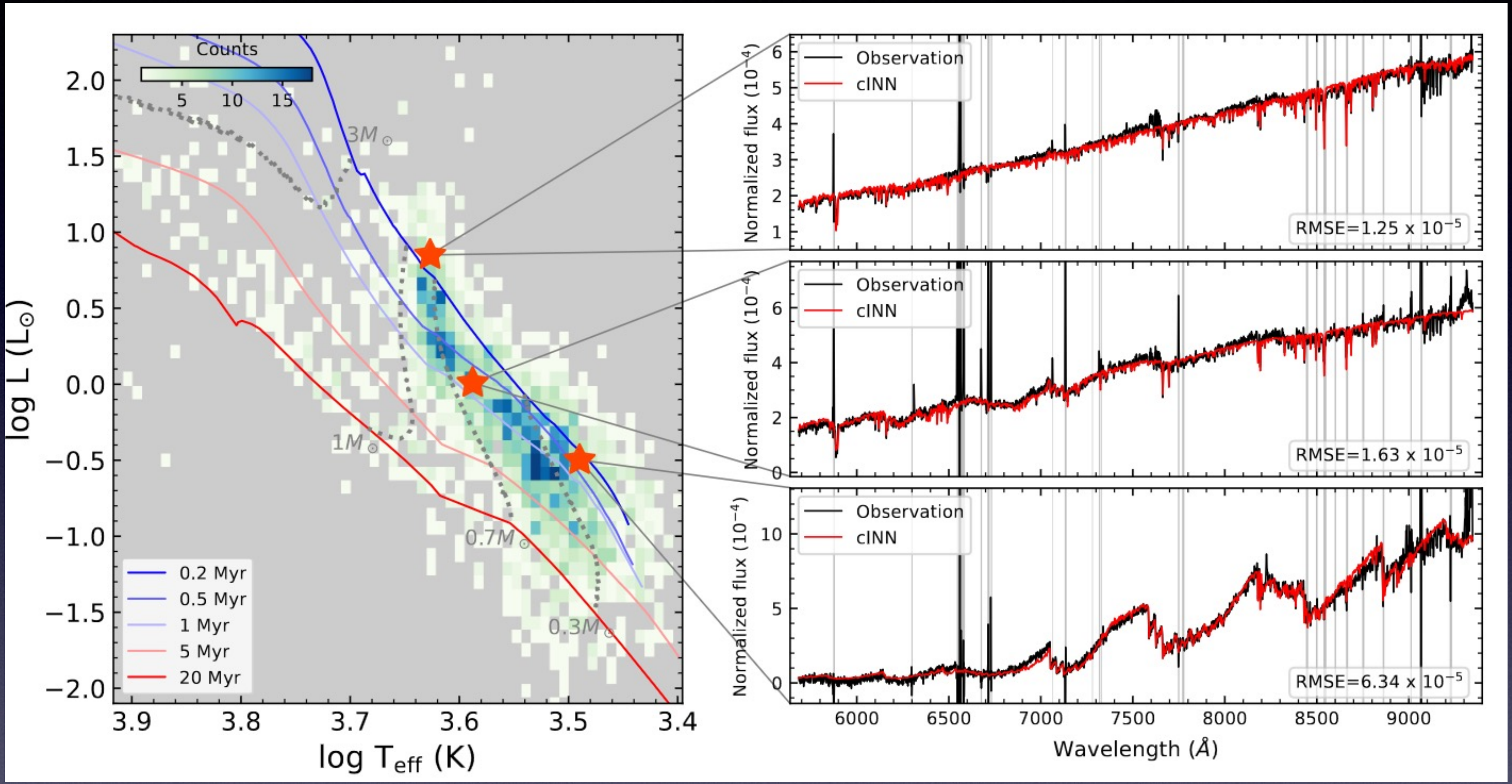

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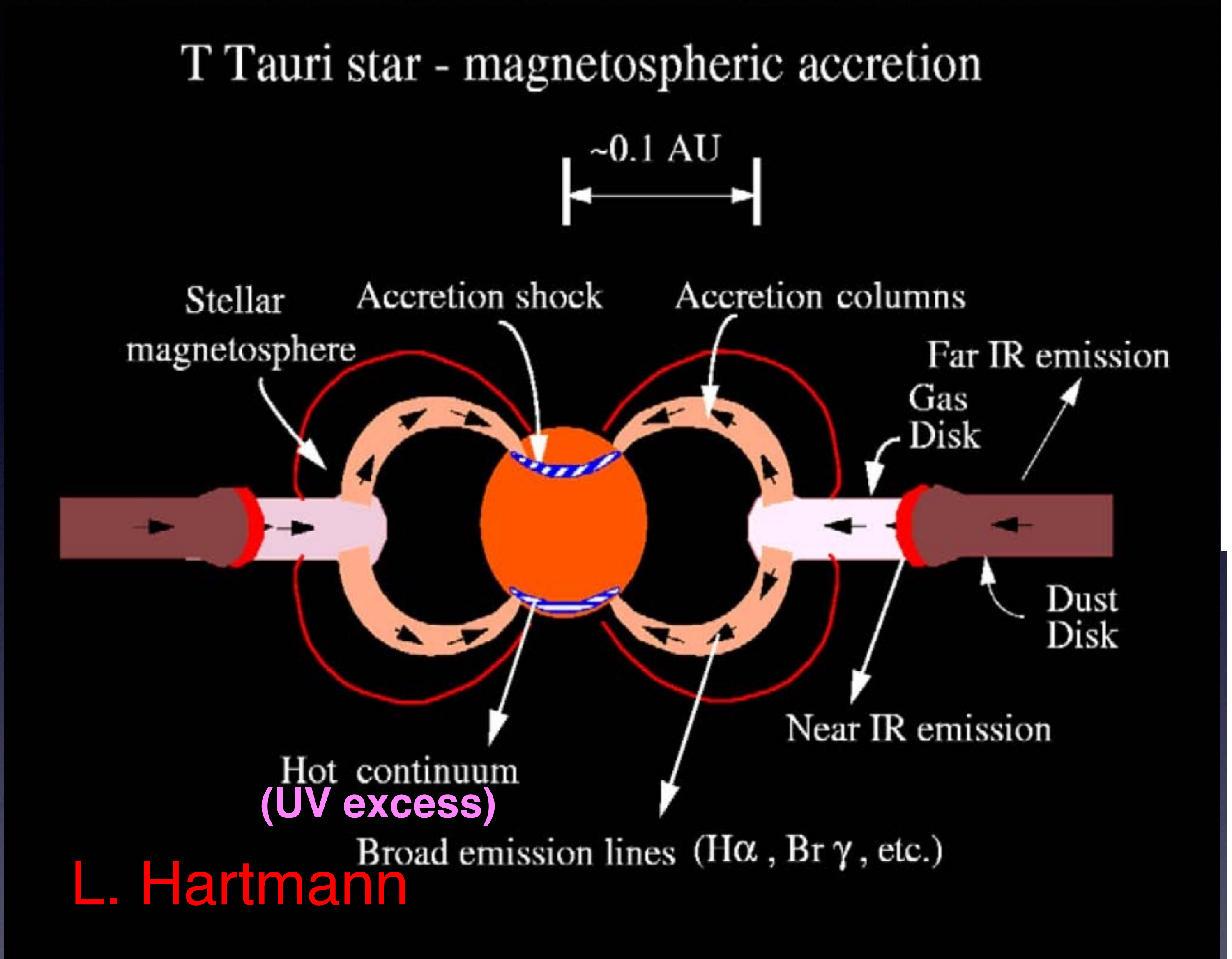
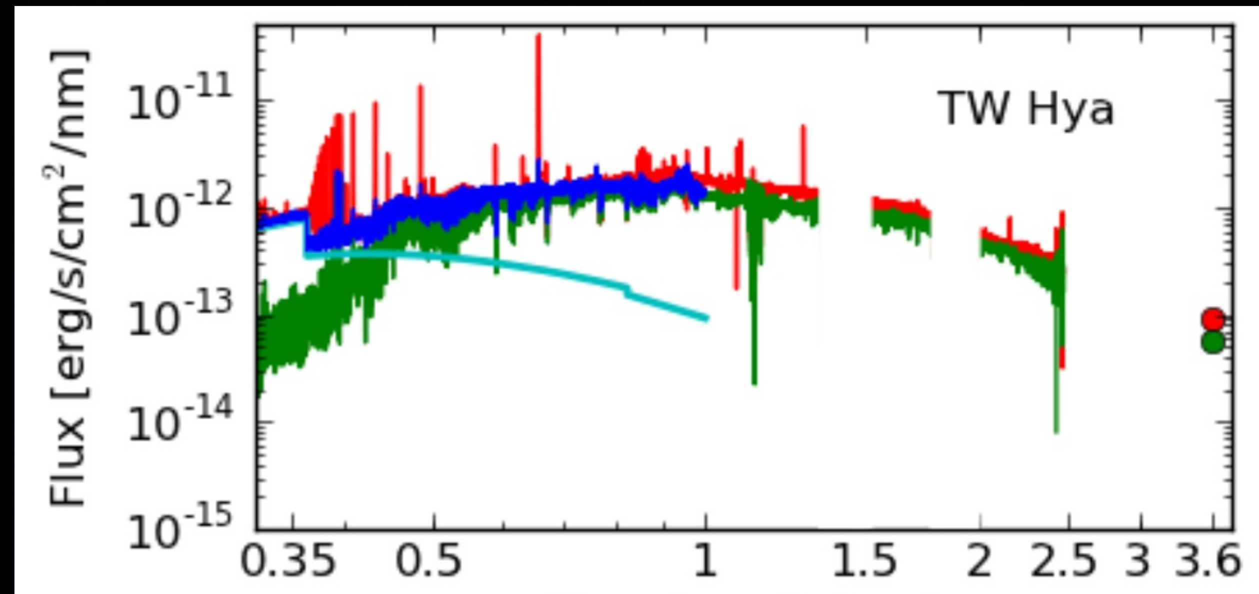
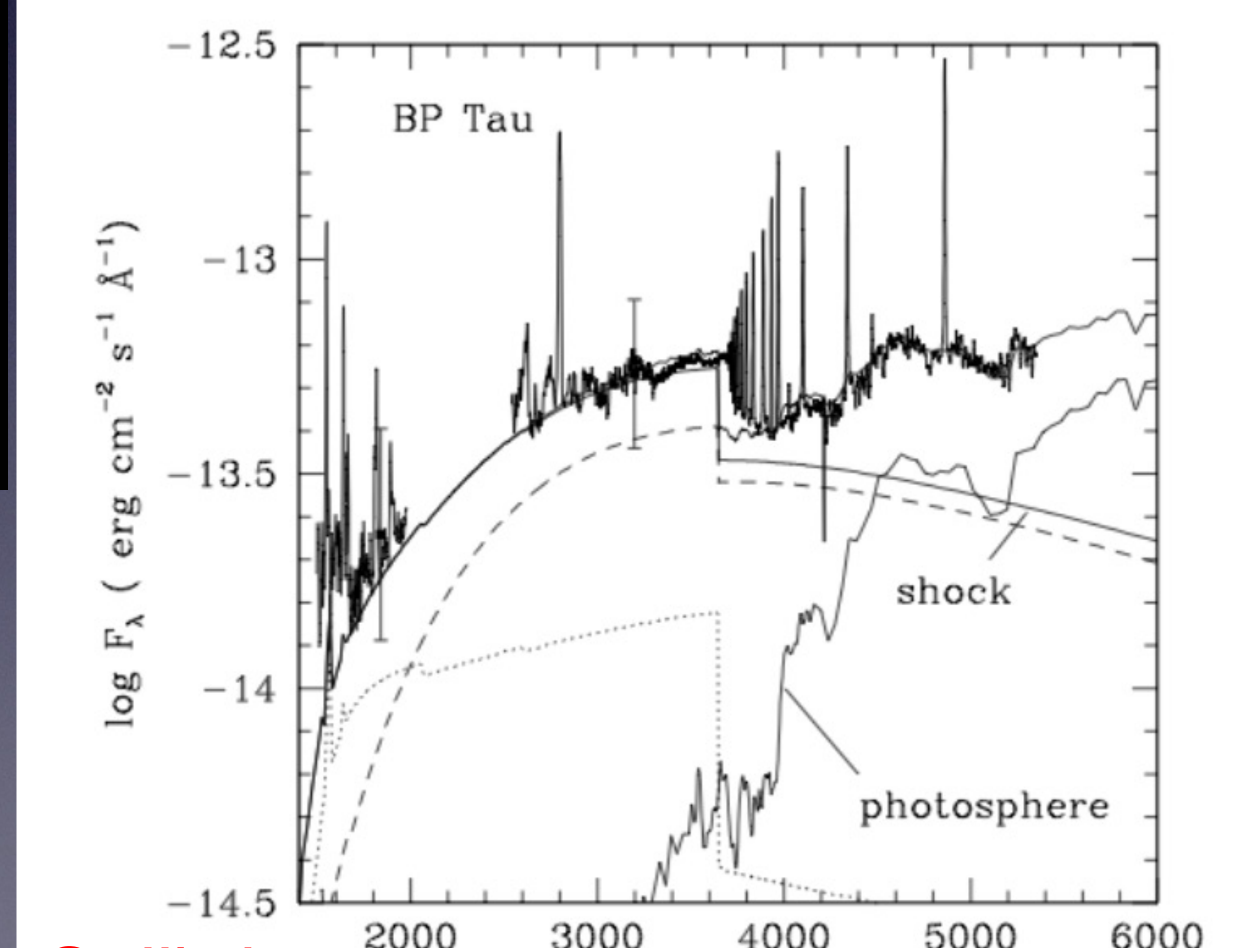
Accretion



L. Hartmann



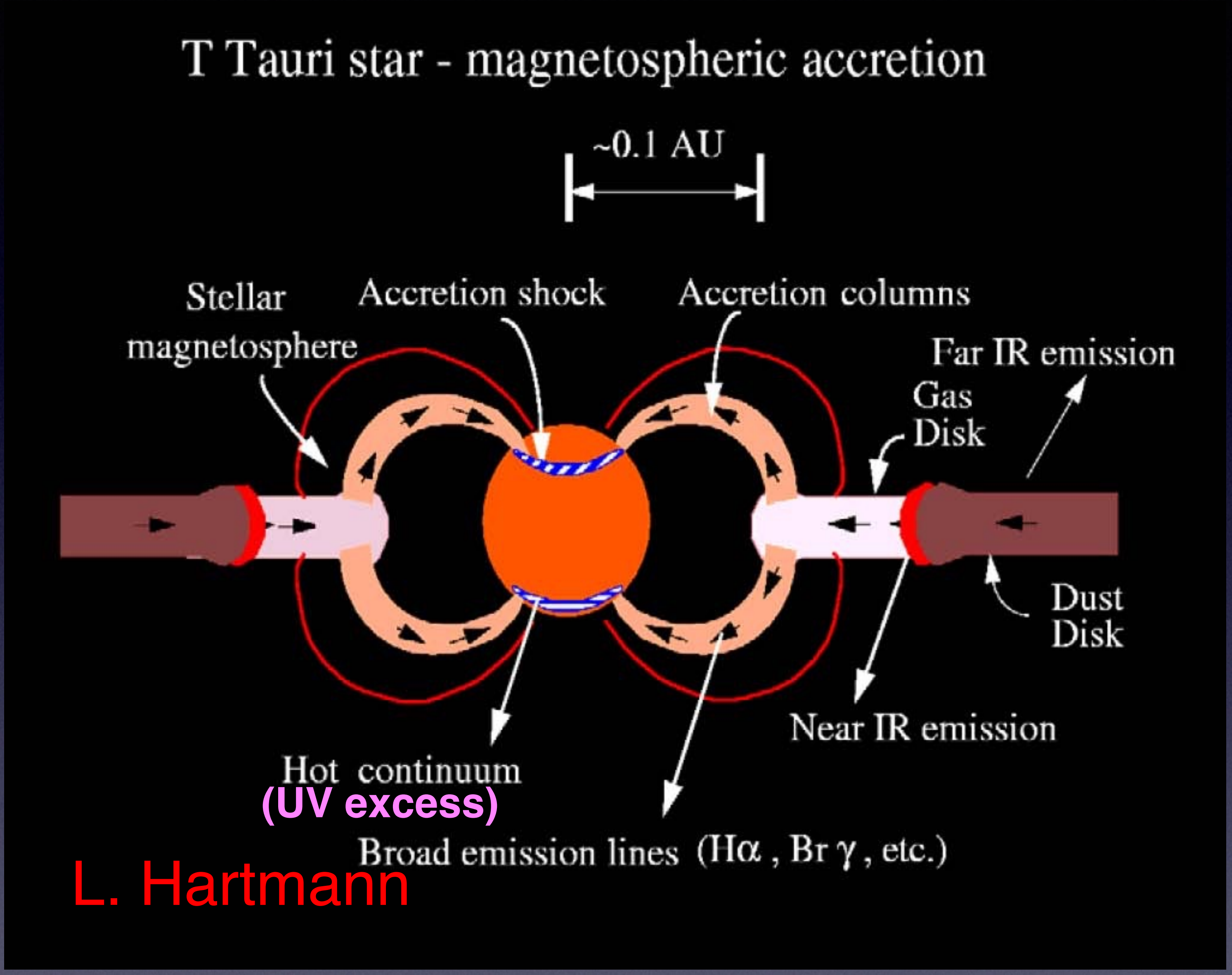
Manara+2014

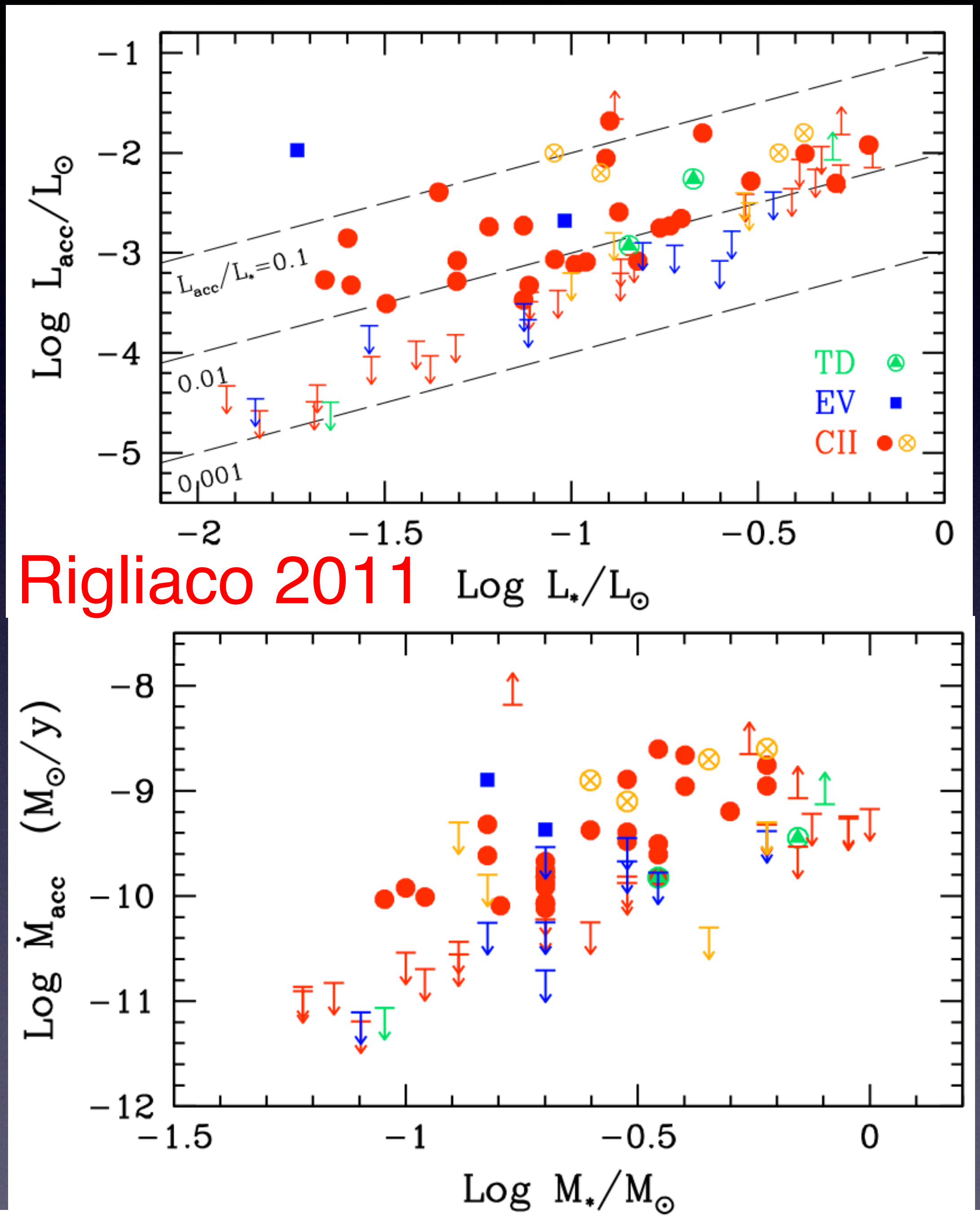


Gullbring+2000

- Direct measurement of accretion: energy released in the collision
- Indirect measurement: emission lines from accretion columns

Accretion





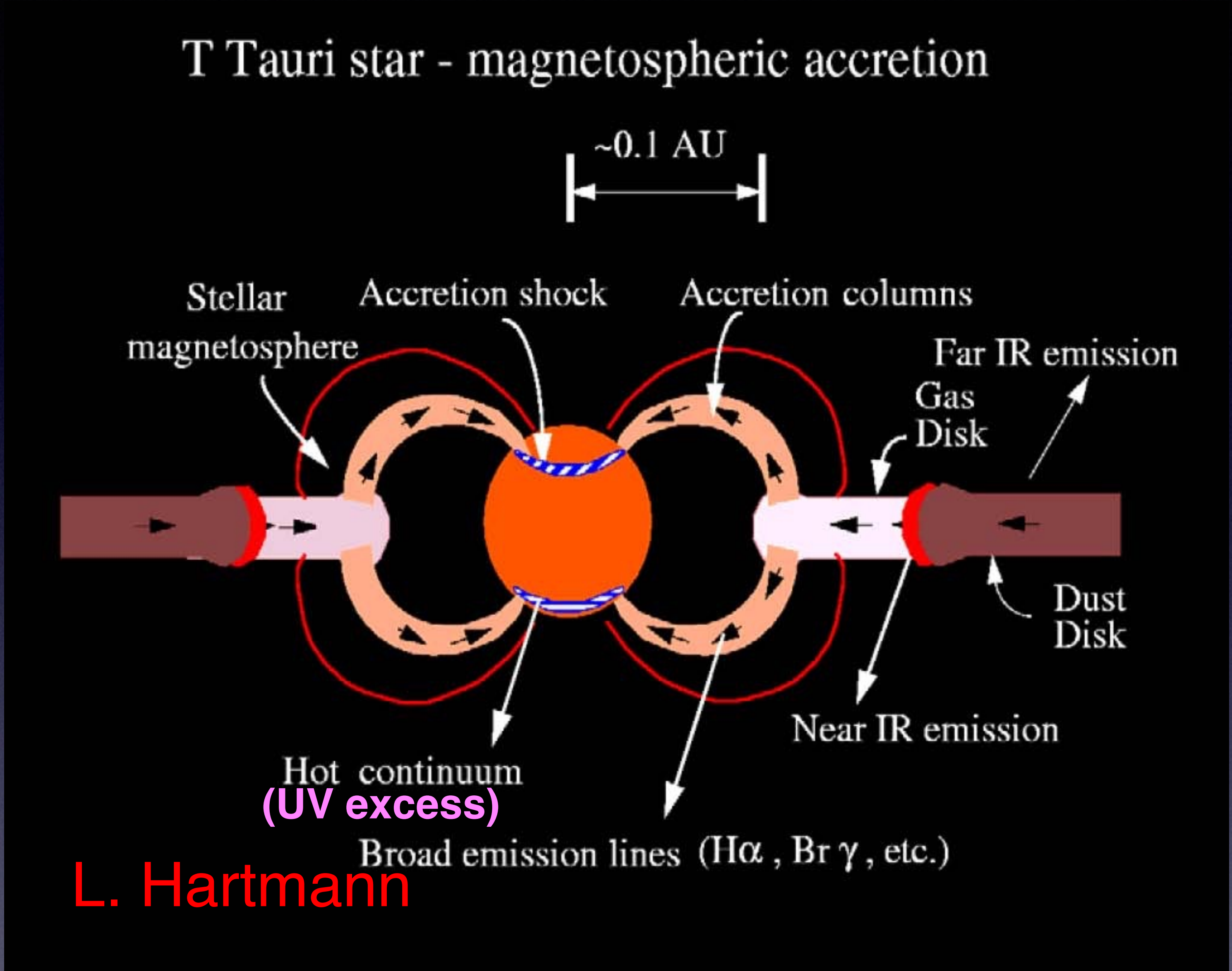
- L_{acc} measured directly from the UV excess luminosity (with a correction factor for FUV/EUV

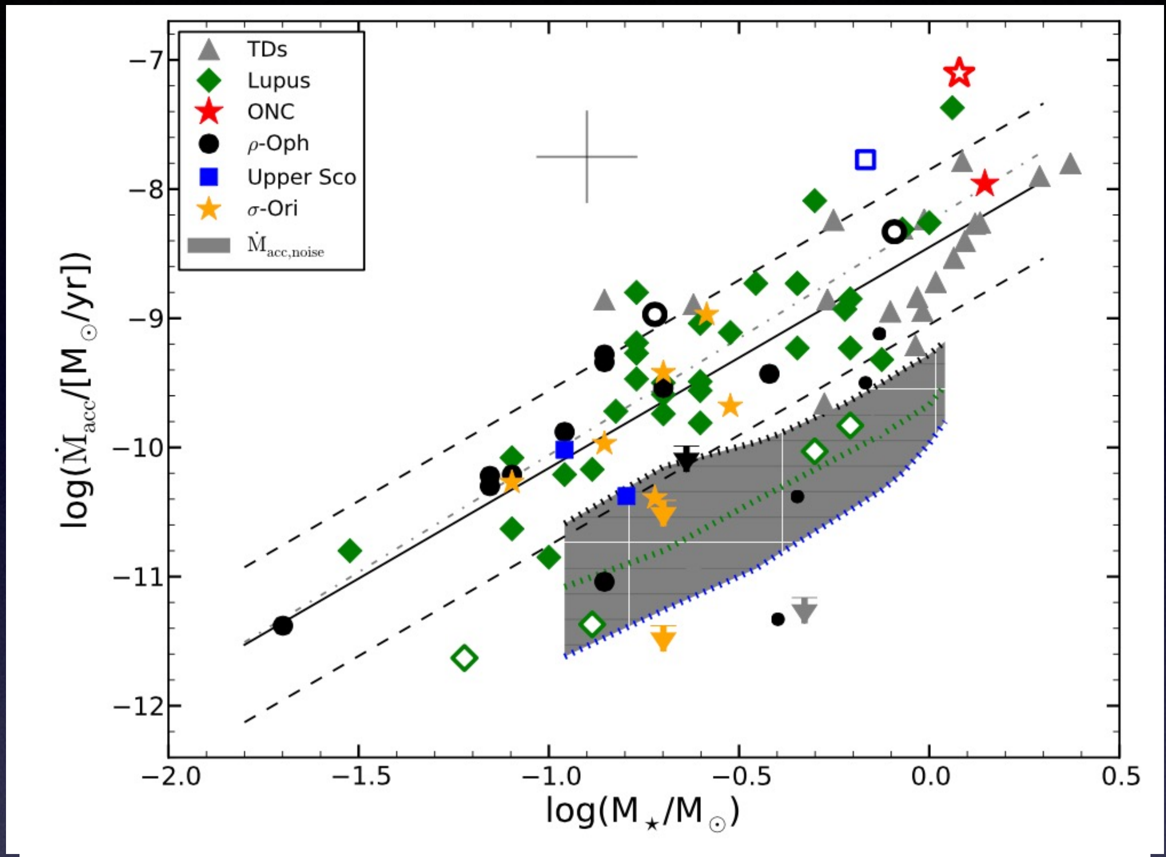
Gullbring 1998

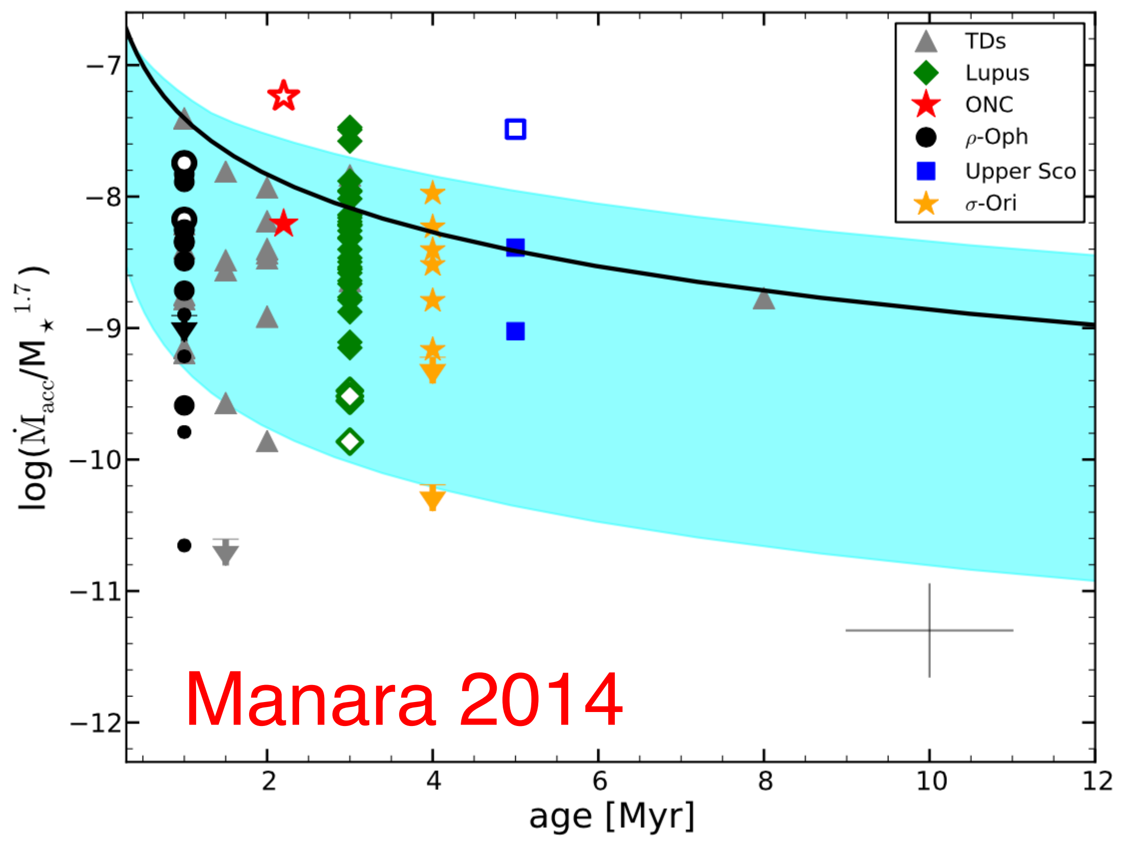
$$\dot{M}_{acc} = \left(1 - \frac{R_\star}{R_m}\right)^{-1} \frac{L_{acc} R_\star}{G M_\star} = \frac{L_{acc} R_\star}{0.8 G M_\star}$$

$R_m \sim 5\ R_{star}$

Accretion

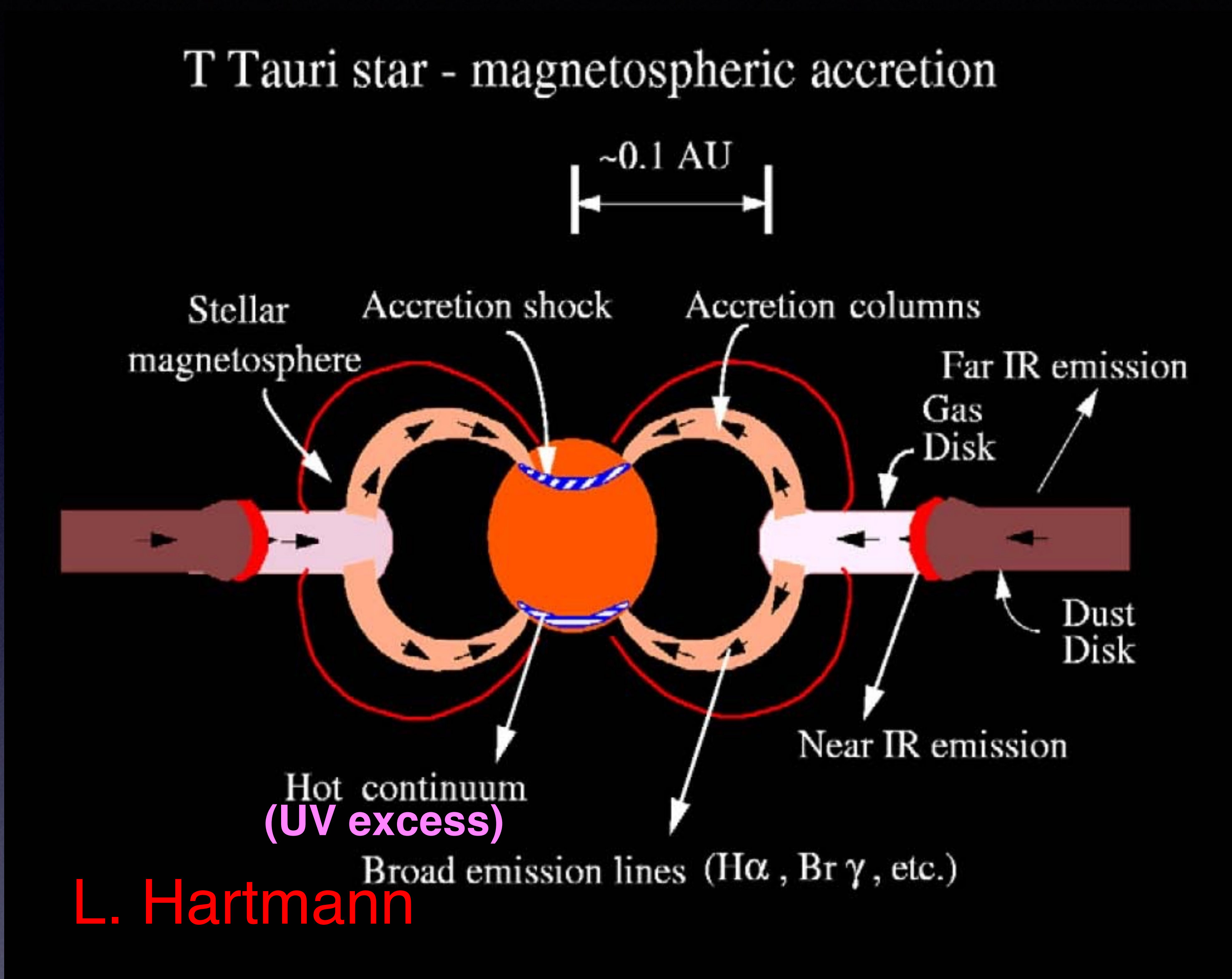


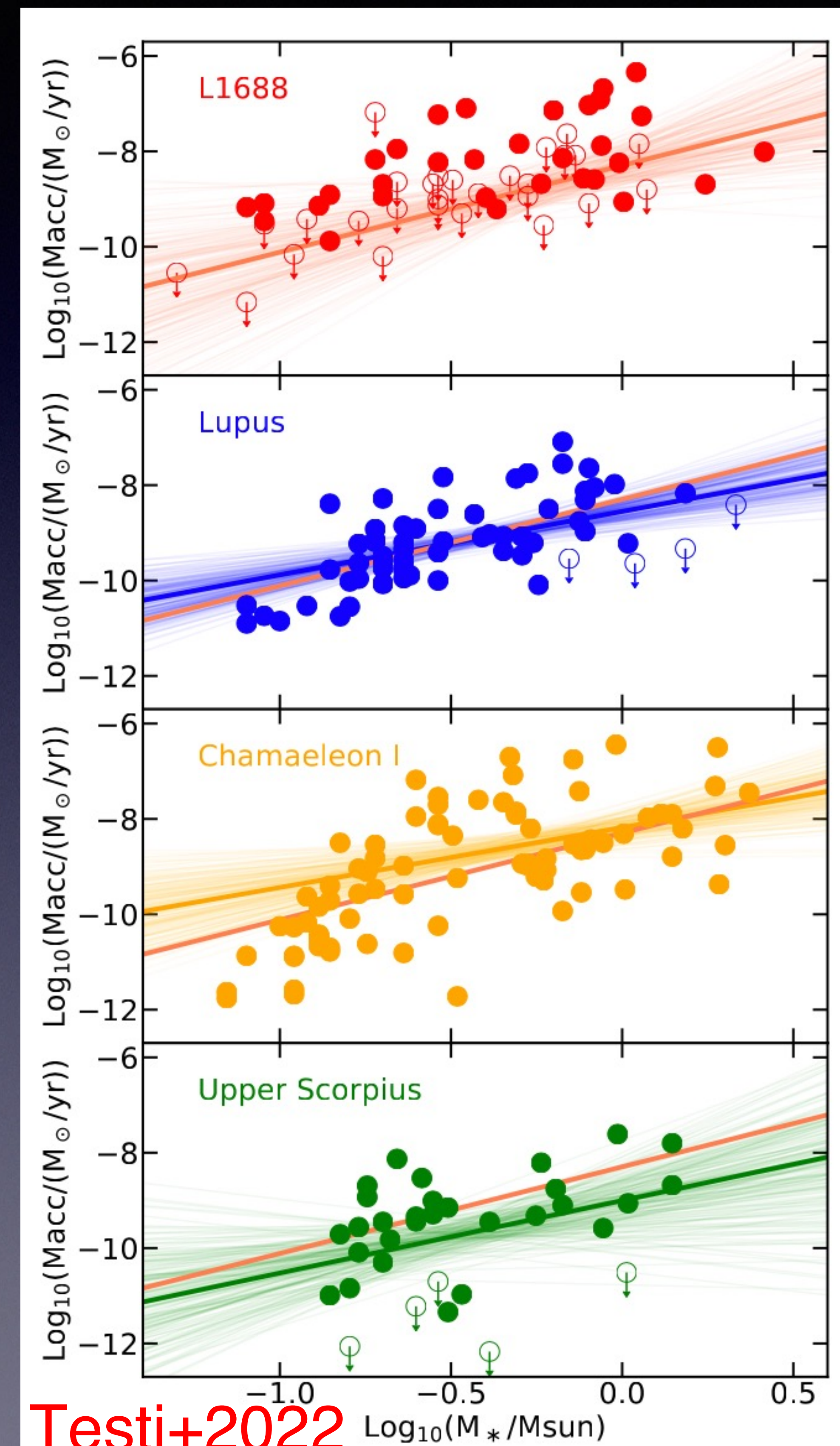




- Accretion rates fall "more or less" where predicted
- Evolution still hard to constrain (need better age/acc measurements)

Accretion





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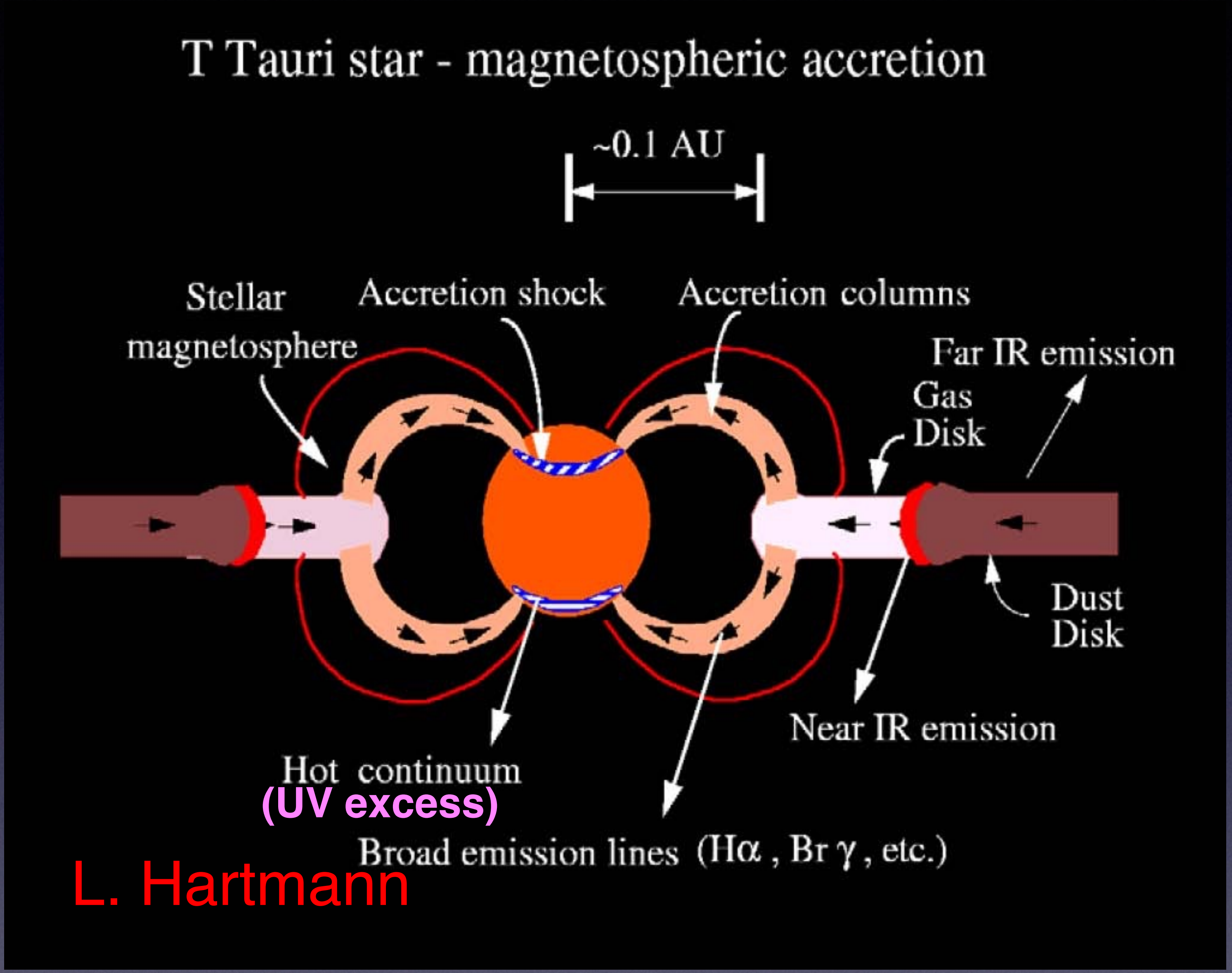

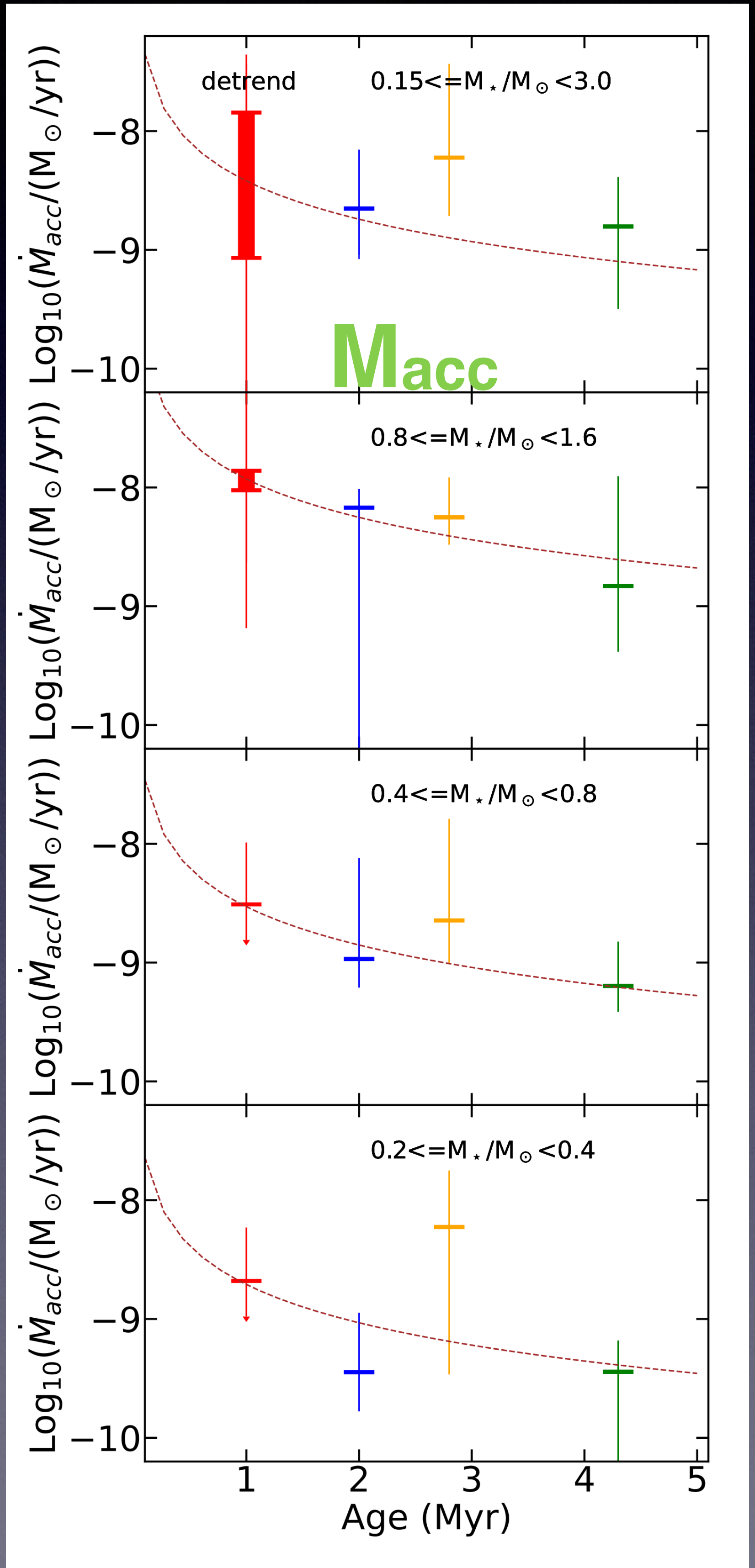

Testi+2022, see also Manara et al. 2023

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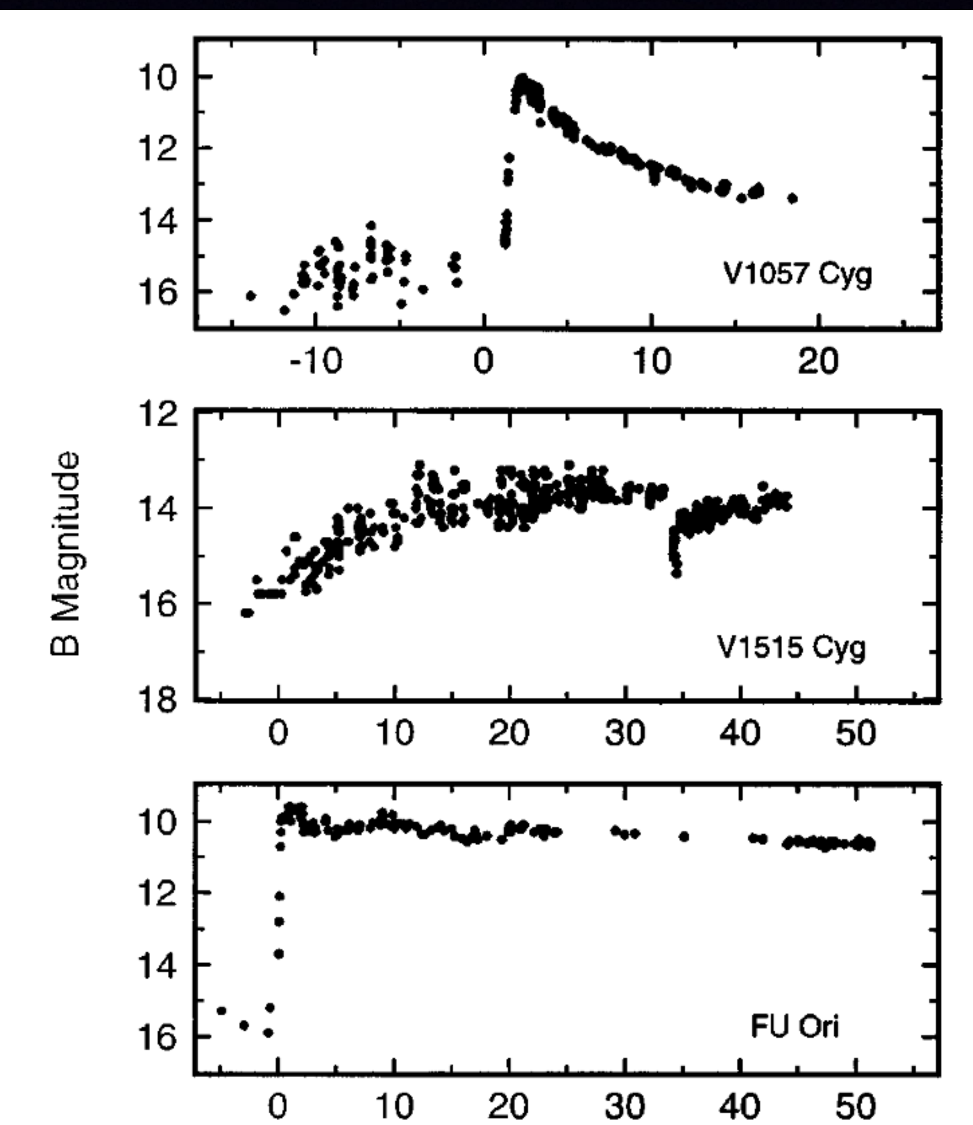
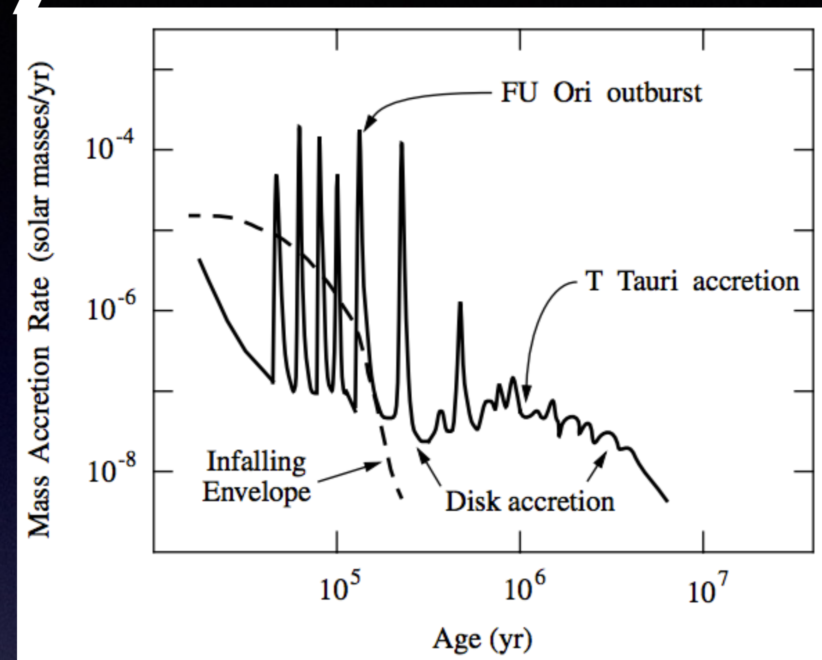
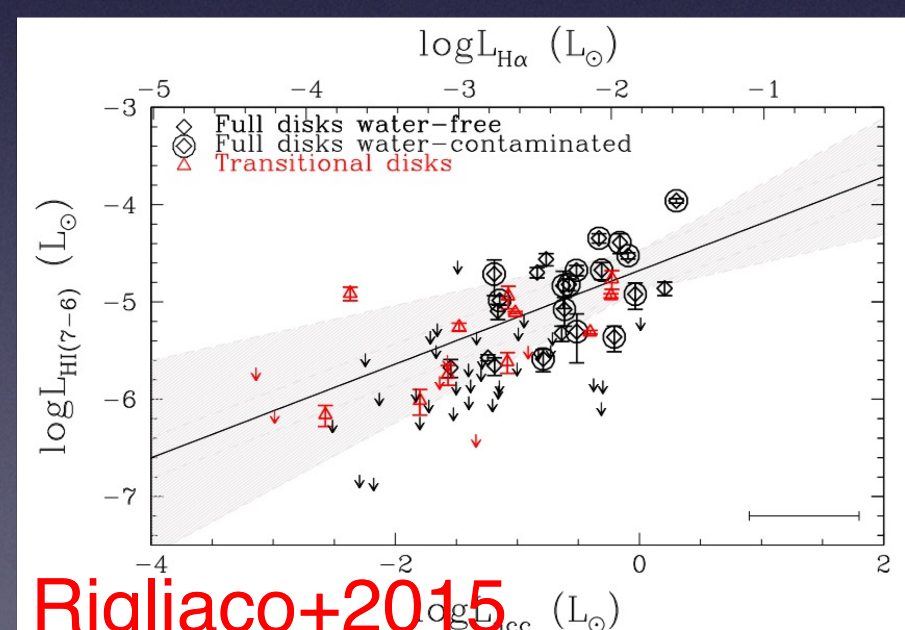
Early accretion



Hartmann & Kenyon 1996

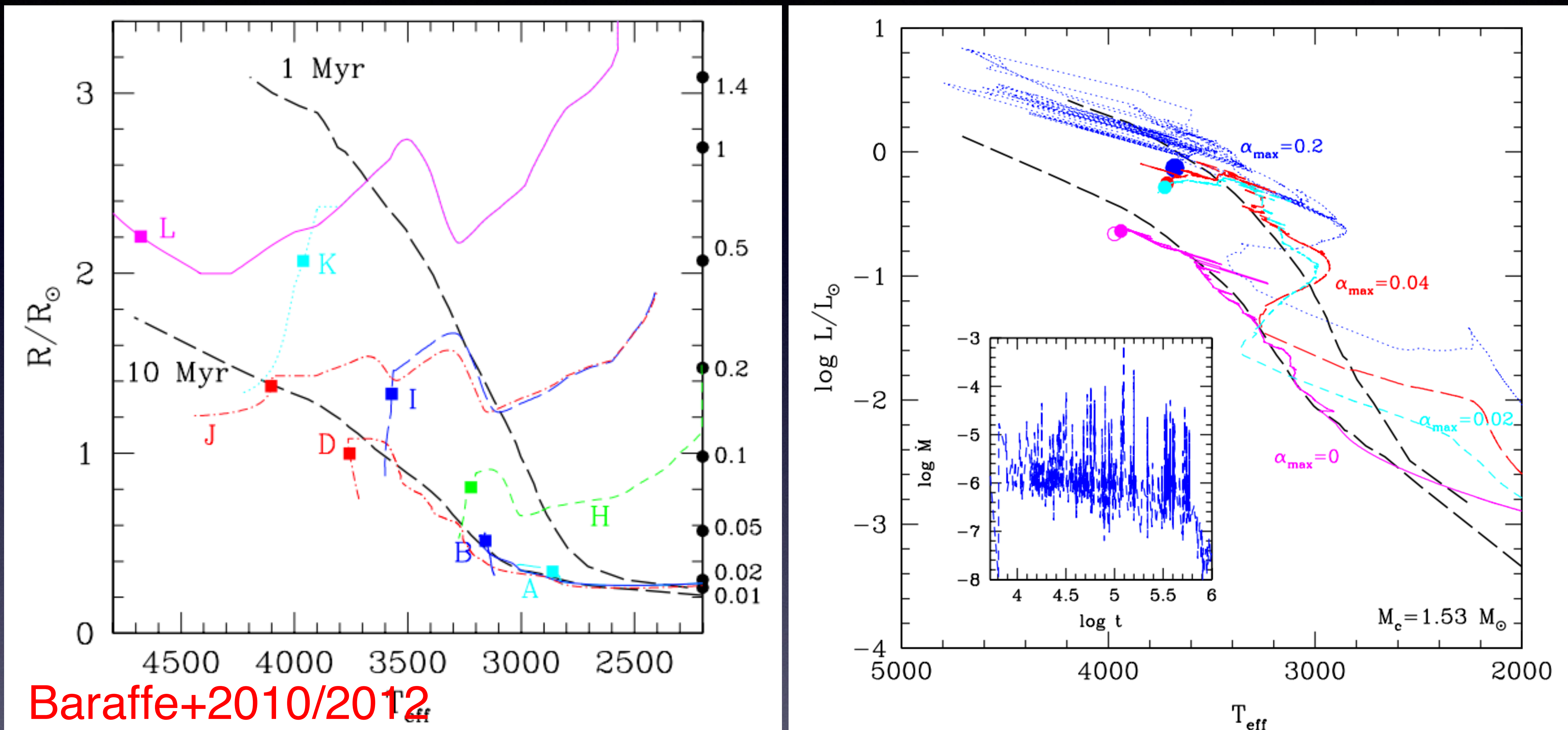




Rigliaco+2015

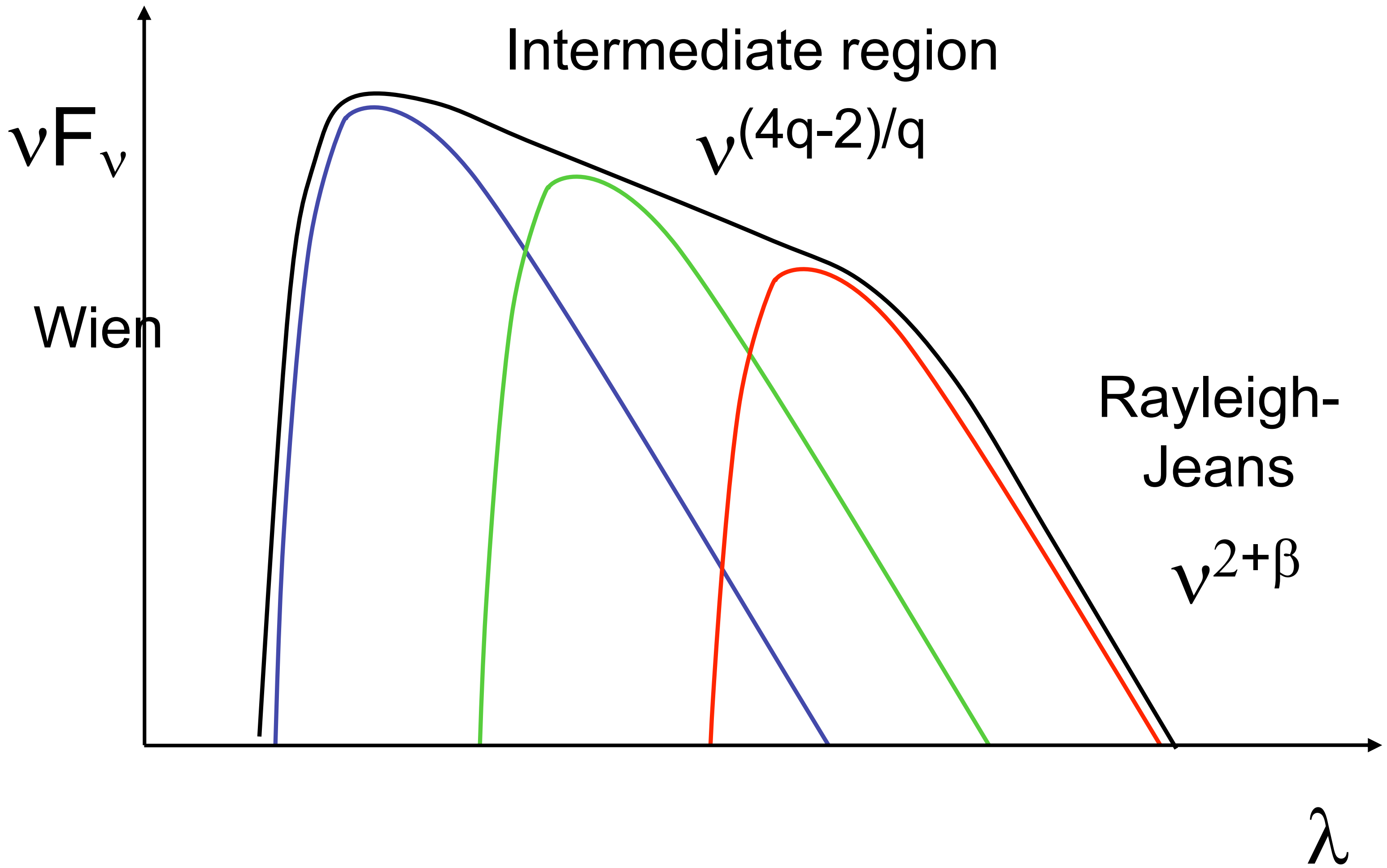
- Accretion highly variable in the early phases of disk evolution
- Hard to measure directly: hope from infrared lines

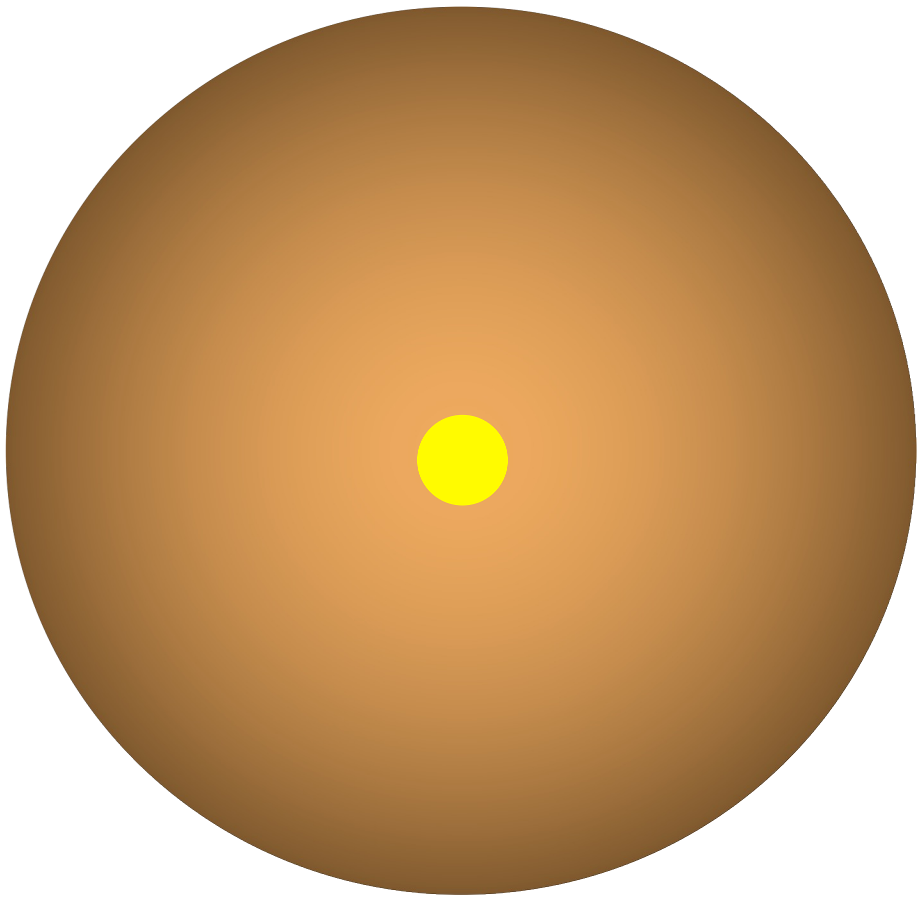
Young stars ages



- Uncertainty from stellar accretion history
- Do we know "relative" ages?
- Early accretion history very uncertain, but potentially critical

SED for a locally isothermal disk





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

$T_d \sim r^{-q}$

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

$\tau_\nu << 1$

$F_\nu \propto \Sigma(r) B_\nu(T_d(r))\, \kappa_\nu$

T_d~const.

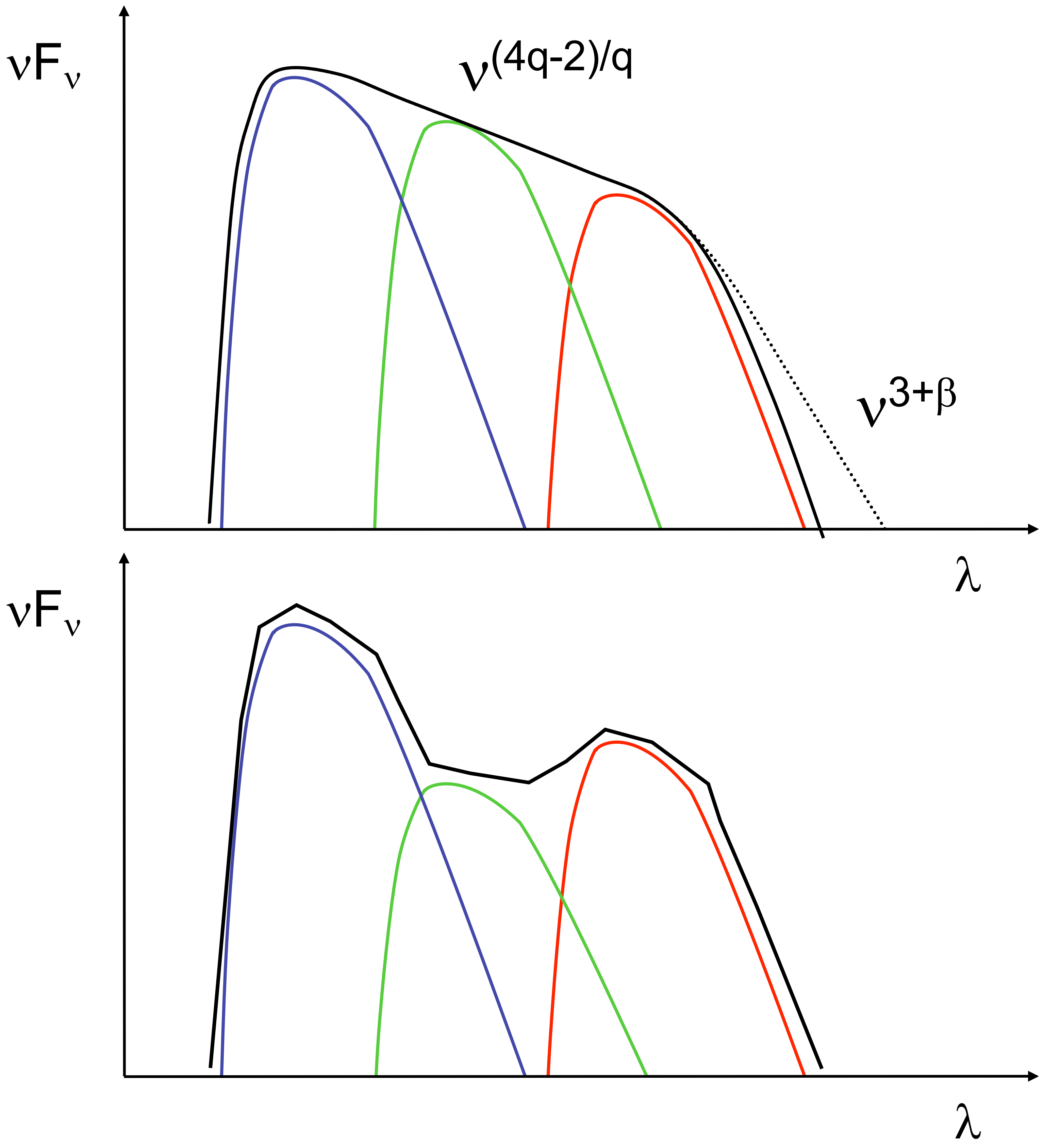
If $\tau_\nu \ll 1$:

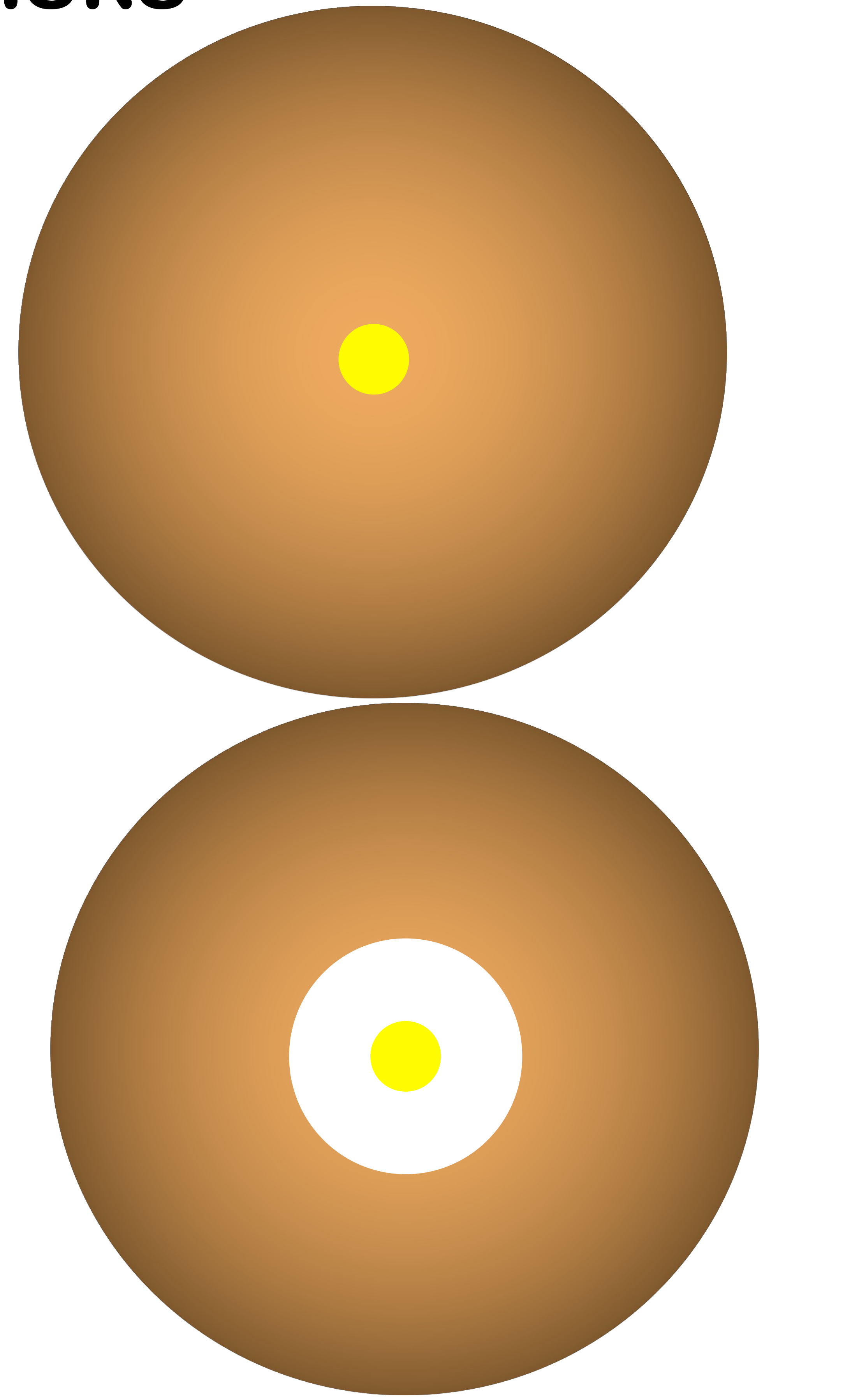
$$F_\nu \propto \kappa_\nu \times B_\nu(T_d) \times M_d$$

If $\tau_\nu \gg 1$:

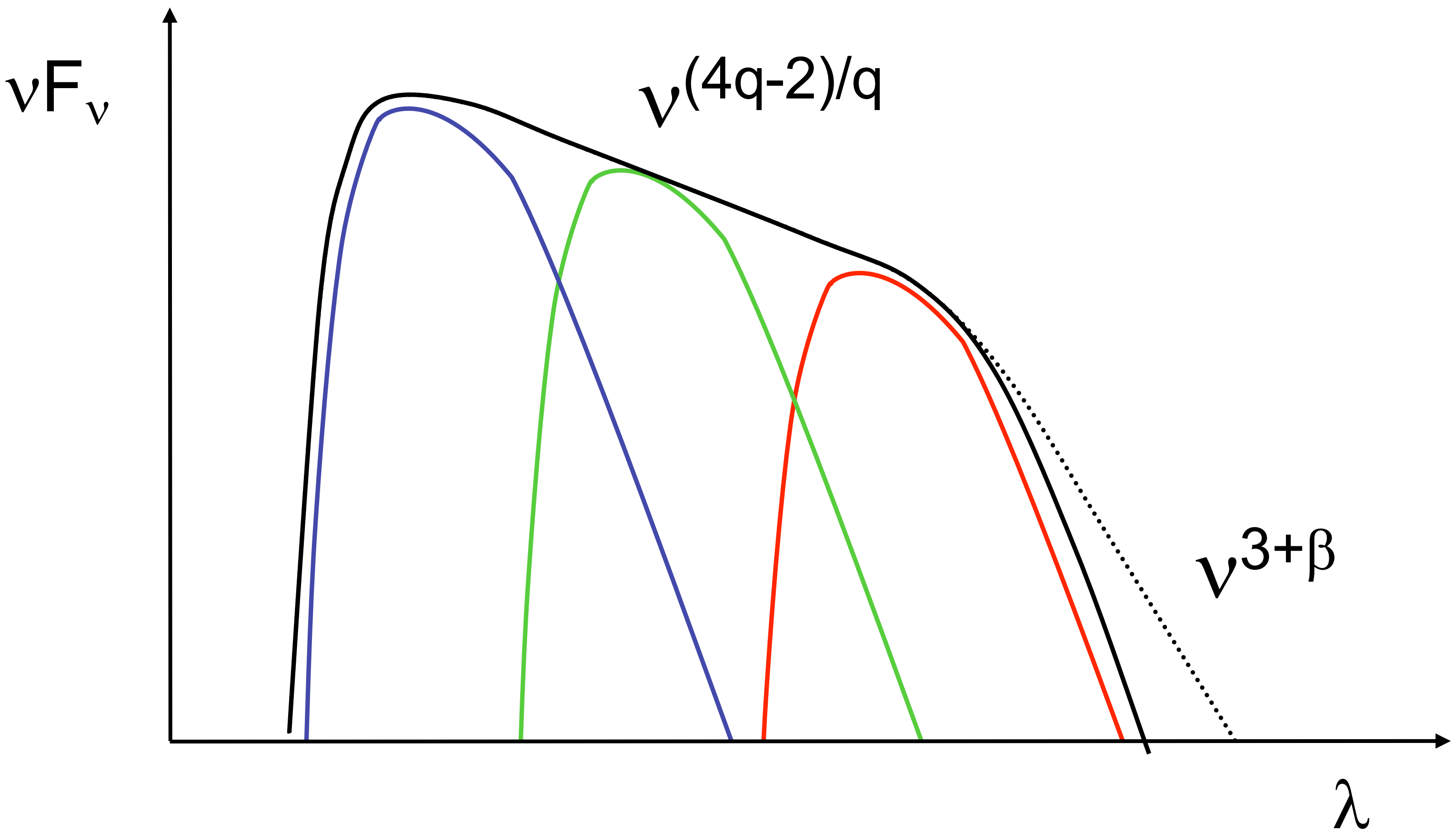
$$F_\nu \propto B_\nu(T_d) \times Area$$

Consequence: SED signature for Transition Disks





SED of a locally isothermal disk



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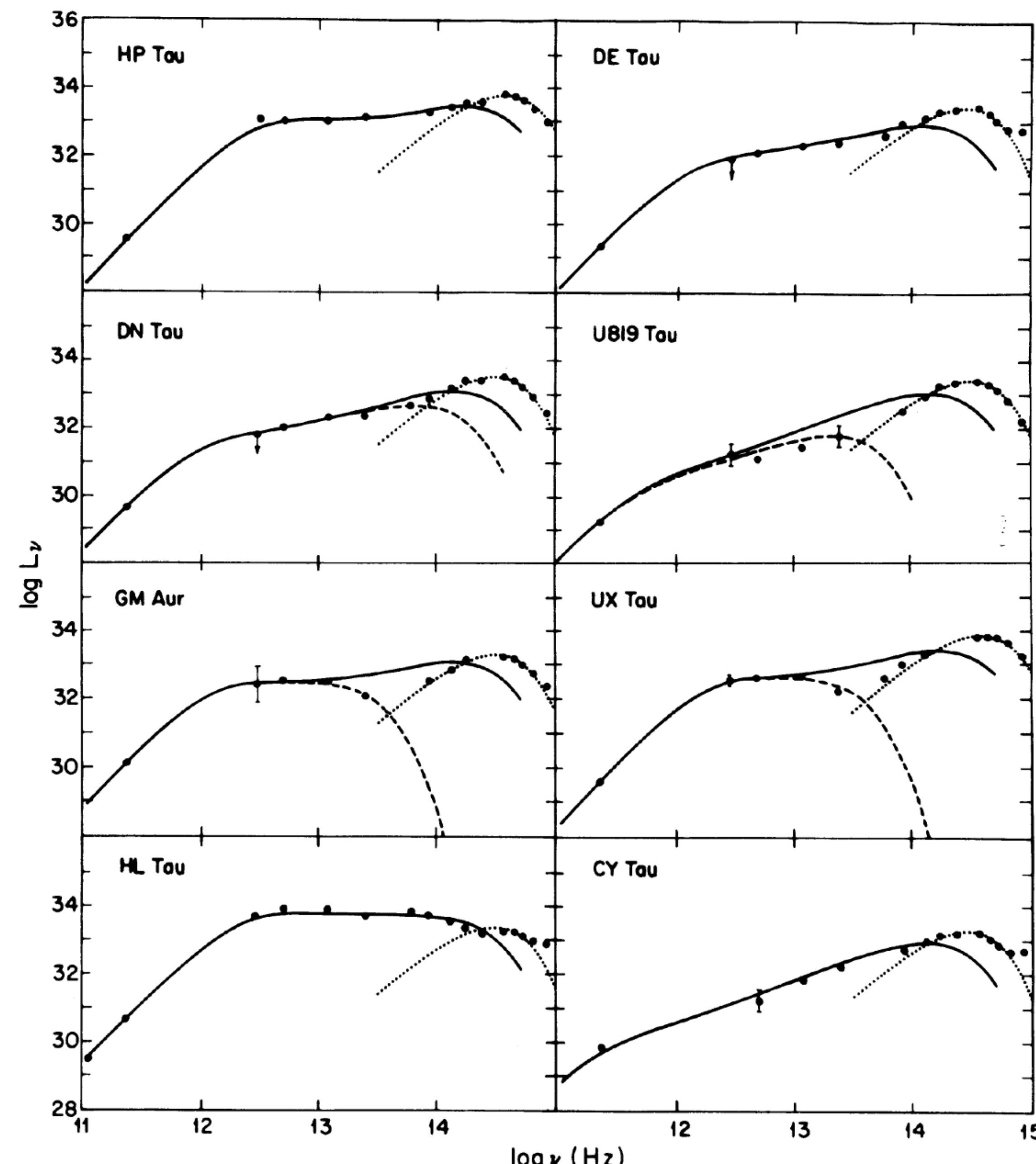
Beckwith+ 1991



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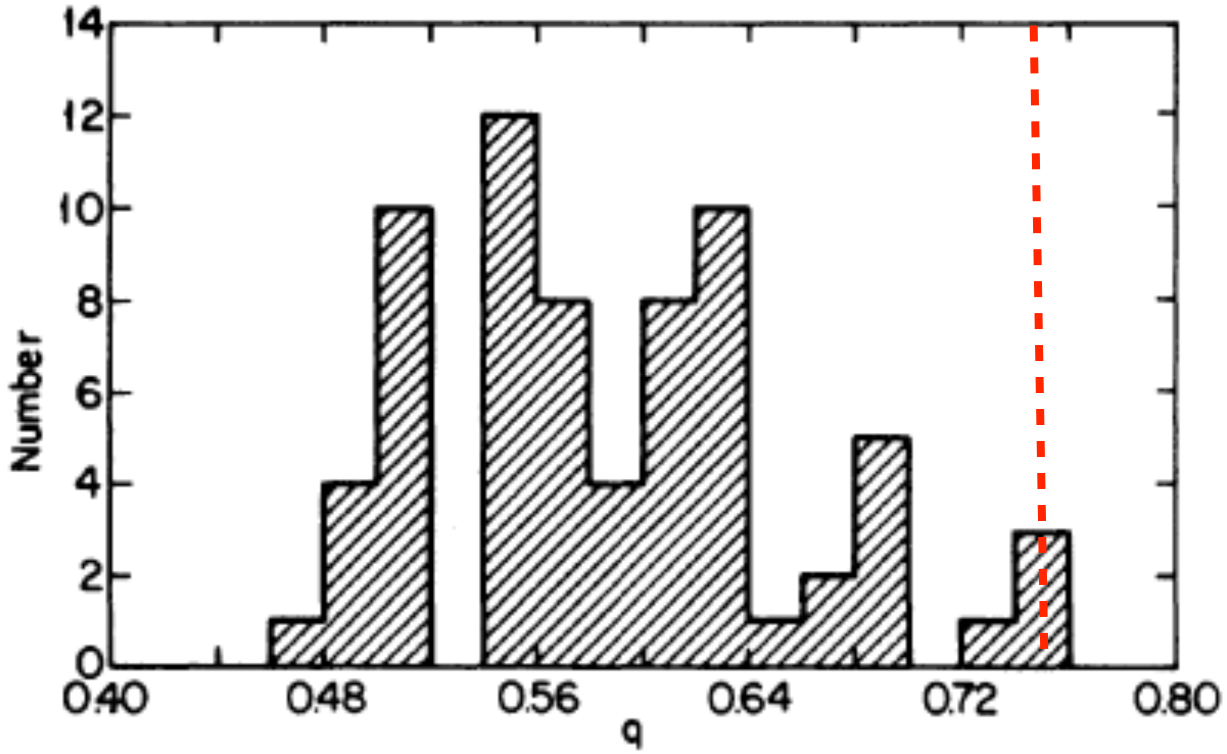
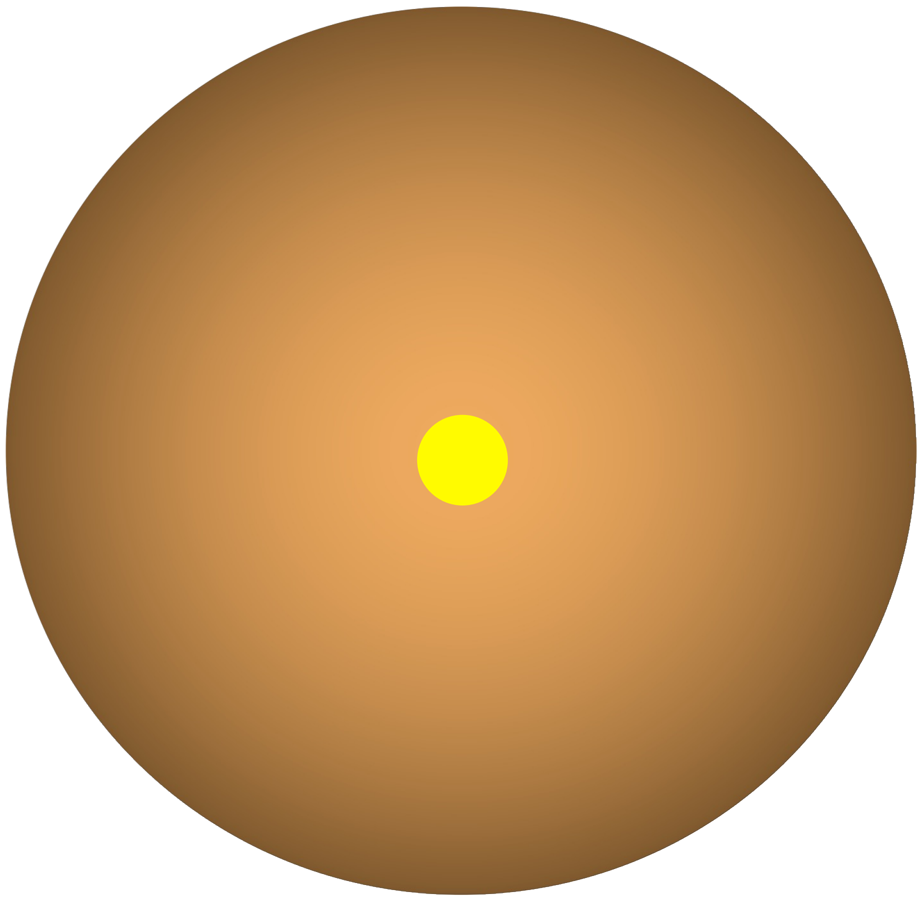


Beckwith et al. (1991)



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

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

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

Viscous heating provides a poor fit of protoplanetary disc temperature: real disks are warmer than expected in the outer regions!

"flat" passive disk

Irradiation flux:

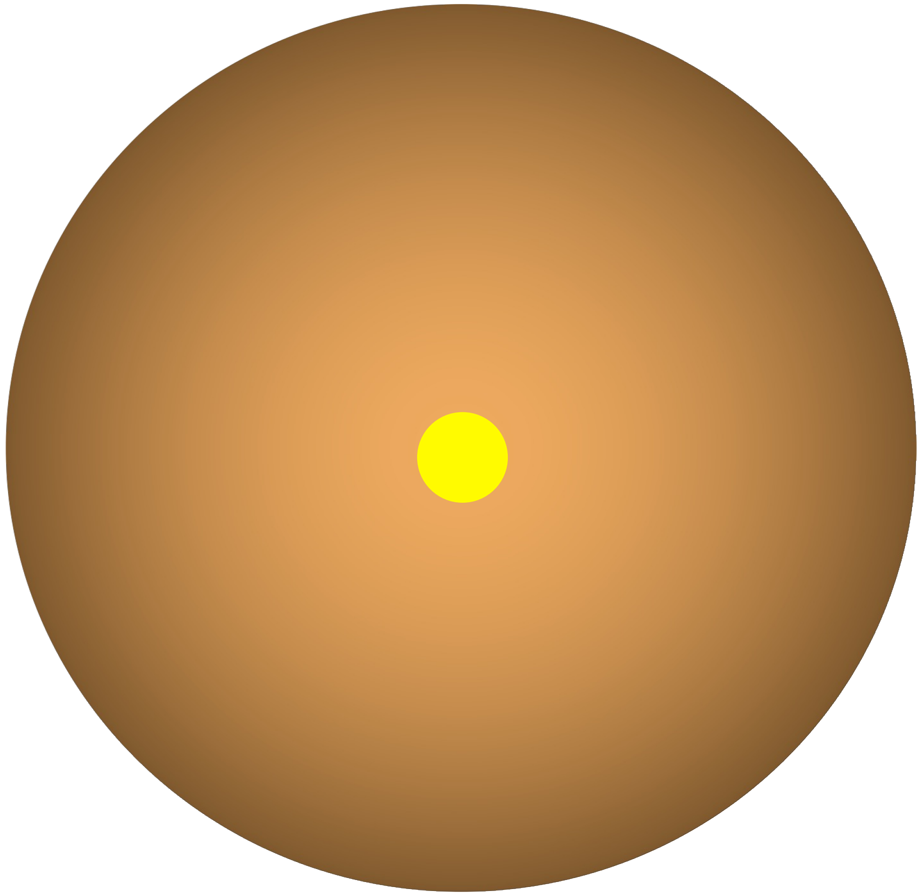
$$F_{\rm irr} = \alpha \frac{L_*}{4\pi r^2}$$

The flaring angle:

$$\alpha \cong \frac{0.4\, r_*}{r}$$

$$T = \left(\frac{0.4\, r_* L_*}{4\pi\sigma r^3} \right)^{1/4}$$

$$T \propto r^{-3/4}$$



Coincidentally, same profile as an viscously heated disk : not good!

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

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

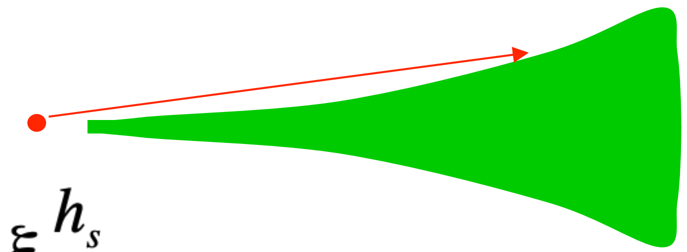
$\tau_\nu \propto \Sigma(\mathrm{r}) \kappa_\nu$ $\Sigma(\mathrm{r}) \propto \mathrm{r}^{-p}$ $\kappa_\nu \propto \kappa_o \nu^\beta$

“flared” passive disk

Irradiation flux:

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

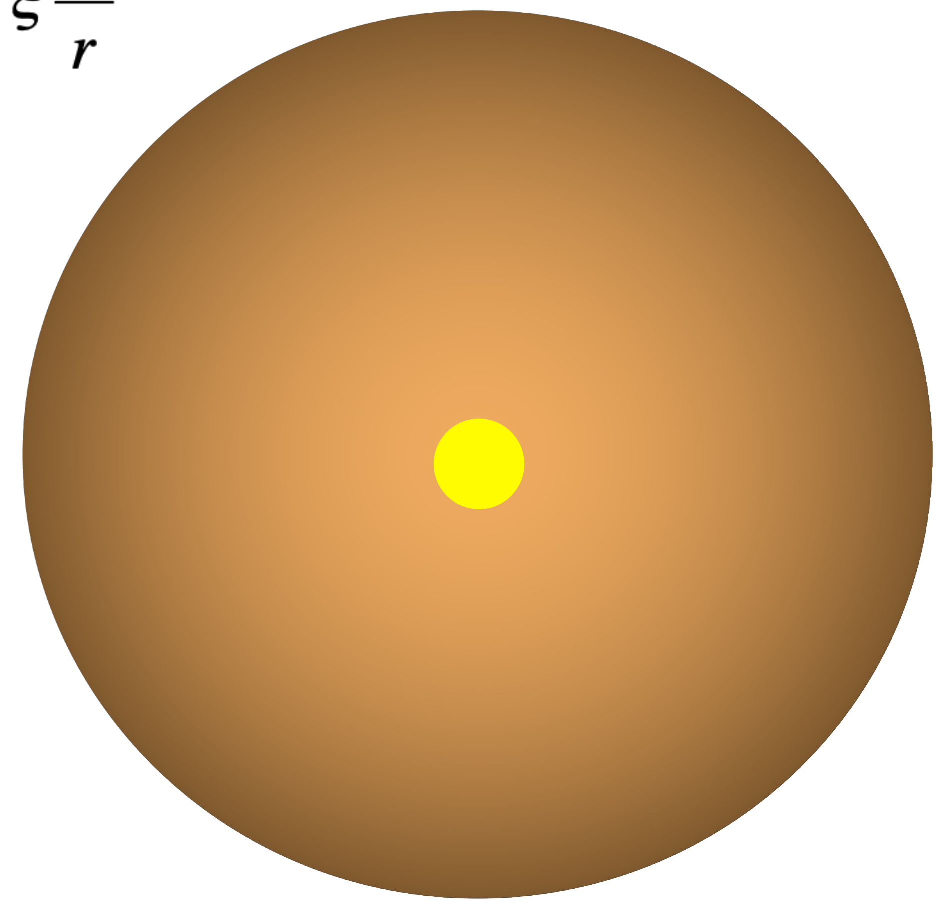
The flaring angle:



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

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

$$h_s = \chi h$$



Can work…

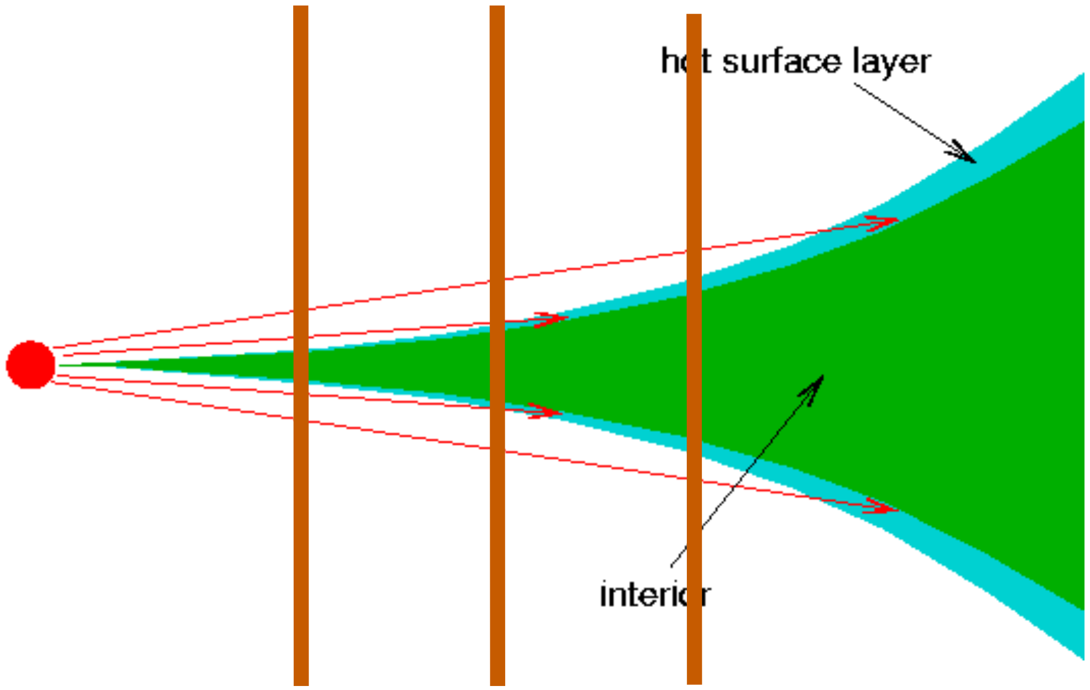
…depending on $h_s(r)$

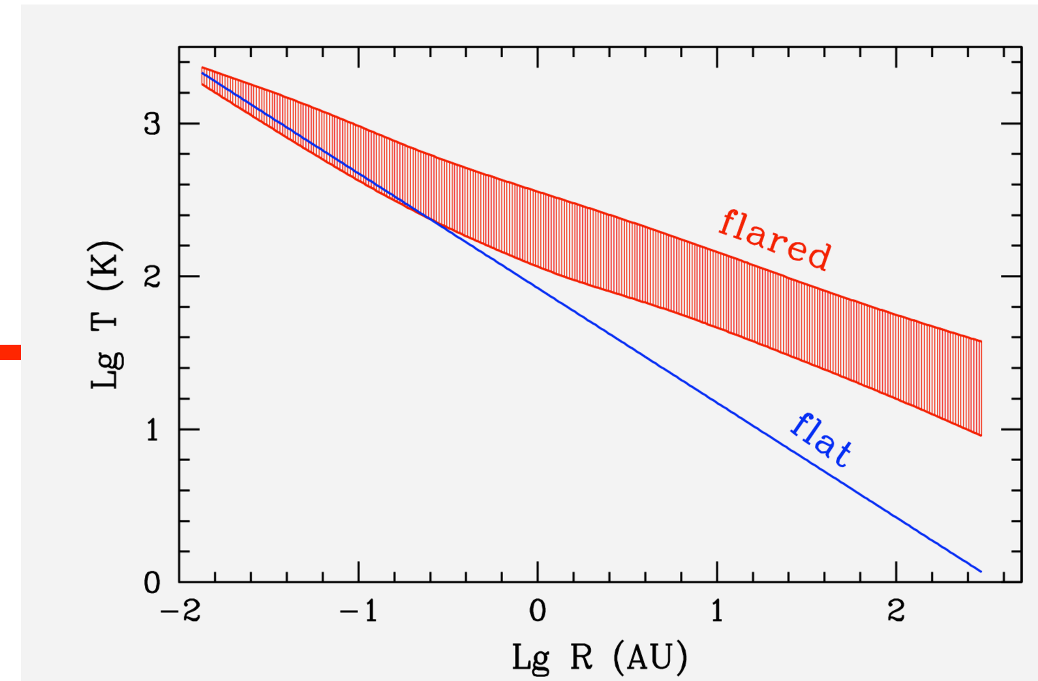
$$F_\nu = \frac{cos\theta}{D^2}\int_{r_i}^{r_o} B_\nu(T_d)(1 - e^{-\tau_\nu})2\pi r dr$$

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

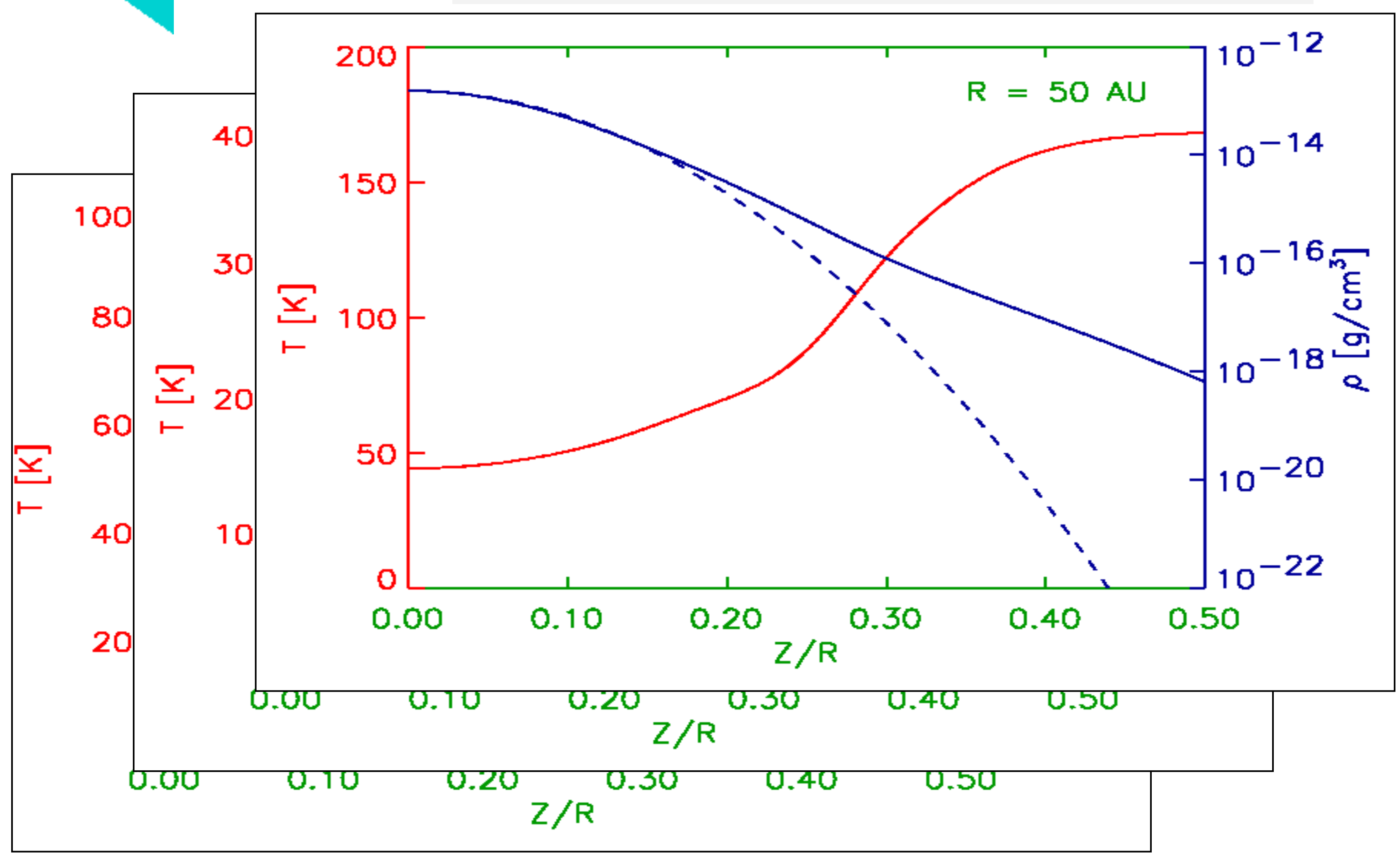
$\tau_\nu \propto \Sigma(r)\kappa_\nu$ $\Sigma(r) \propto r^{-p}$ $\kappa_\nu \propto \kappa_o \nu^\beta$

Flared disks: detailed models



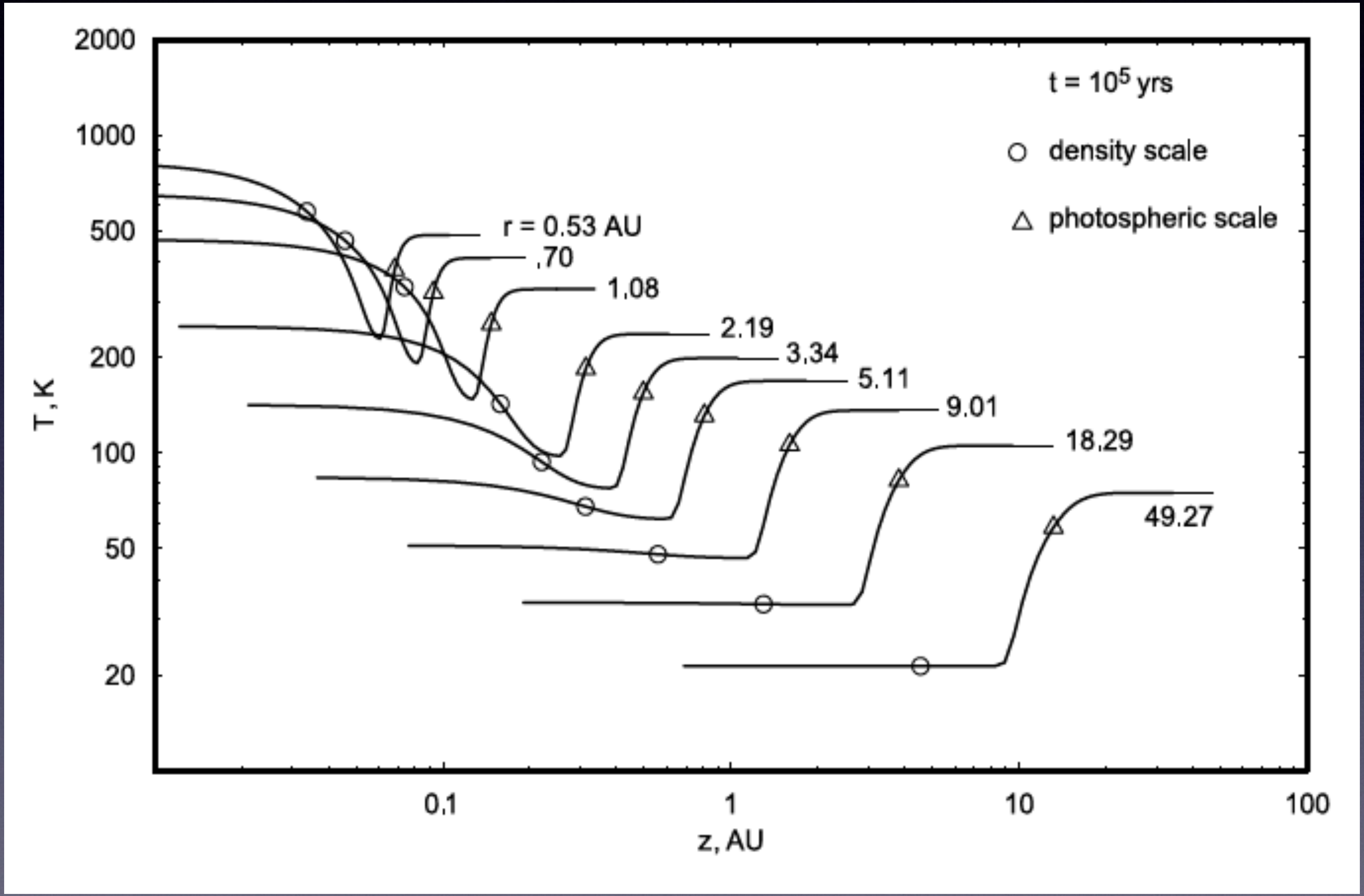


... consists of vertical slices, each forming a 1D problem. All slices are independent from each other.

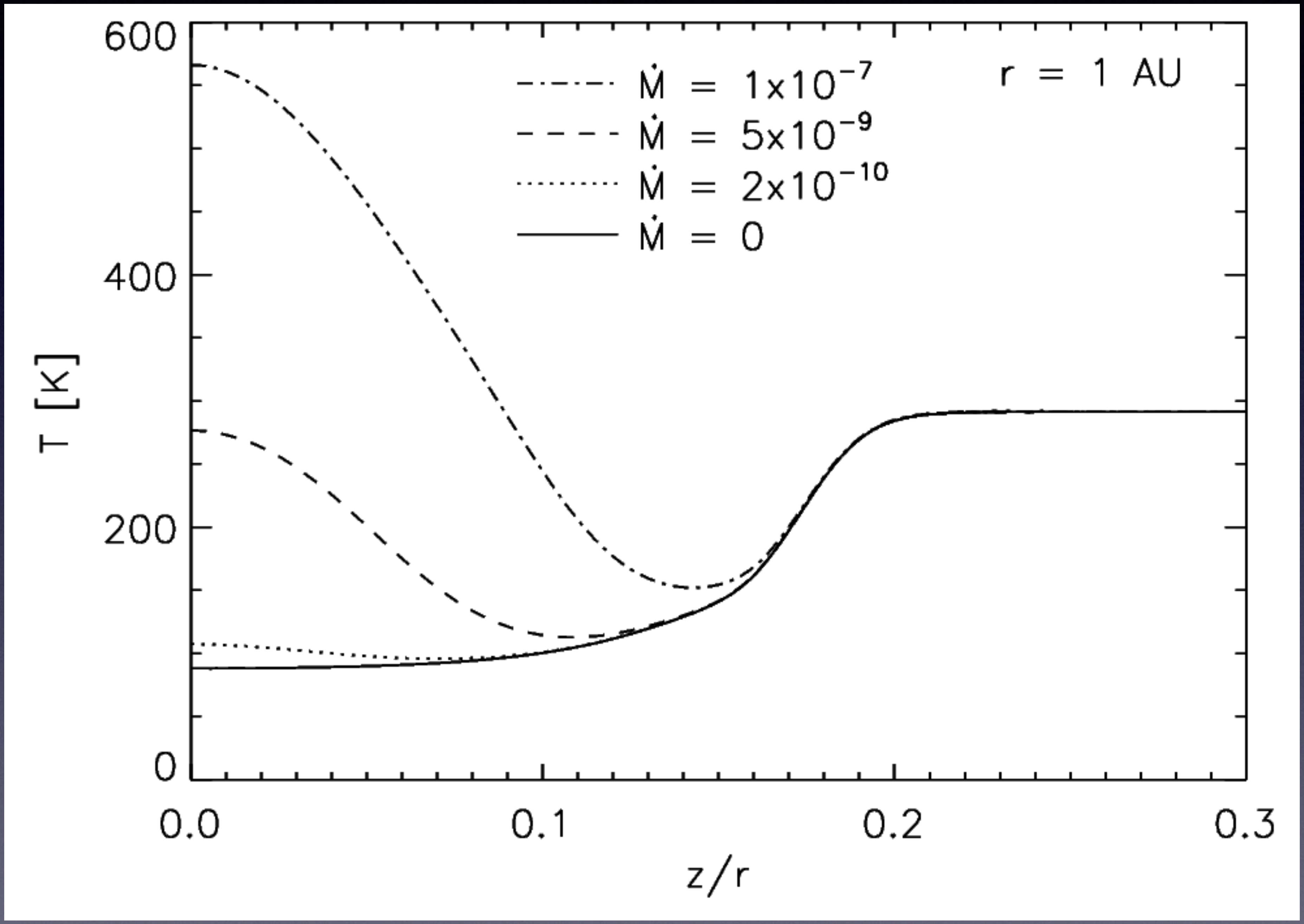


[K. Dullemond]

Including viscous heating



Including viscous heating

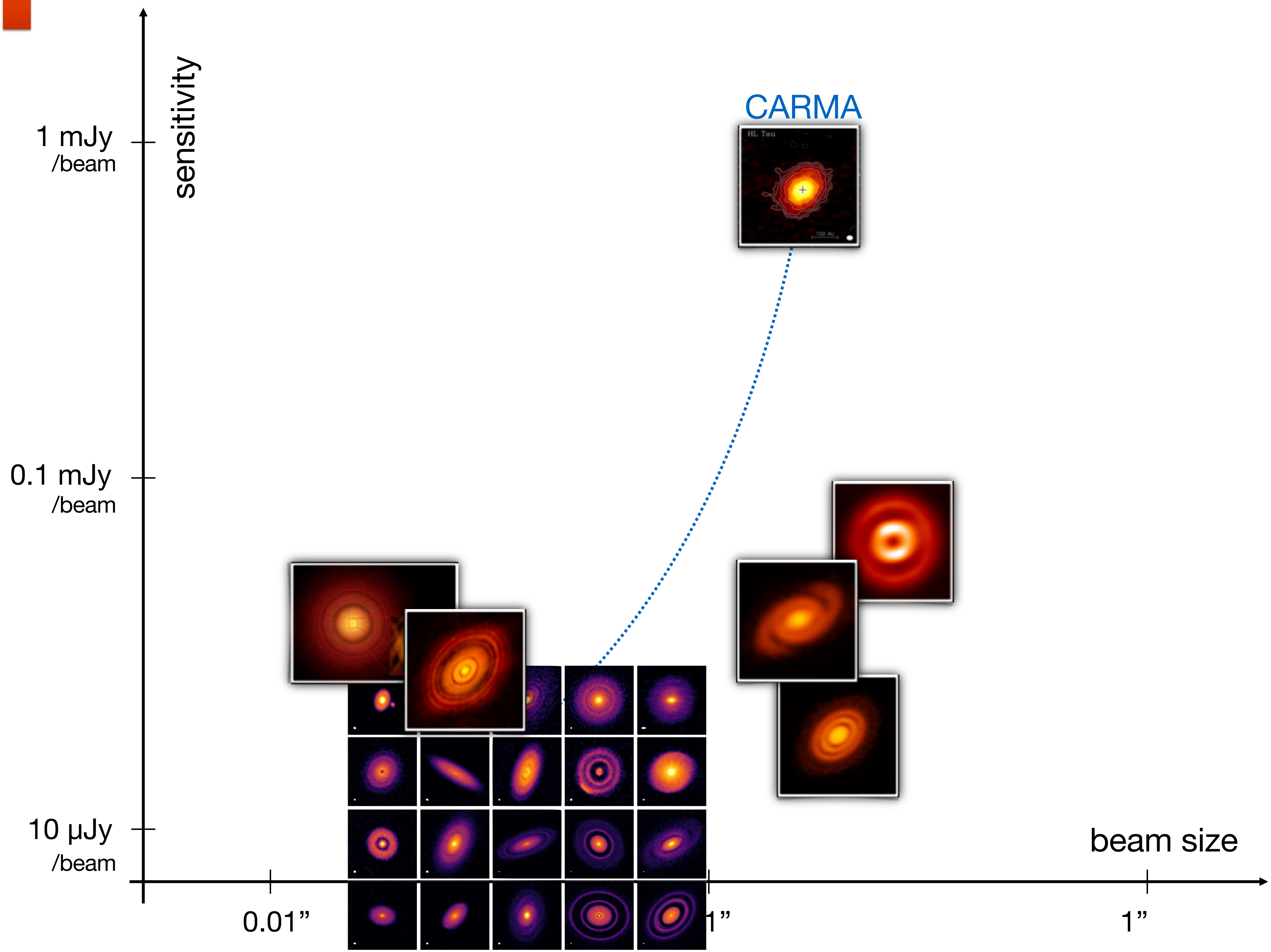


(M_{acc}~10^{-8} M_{sun}/yr @ 1 Myr)

Resolving disk structure

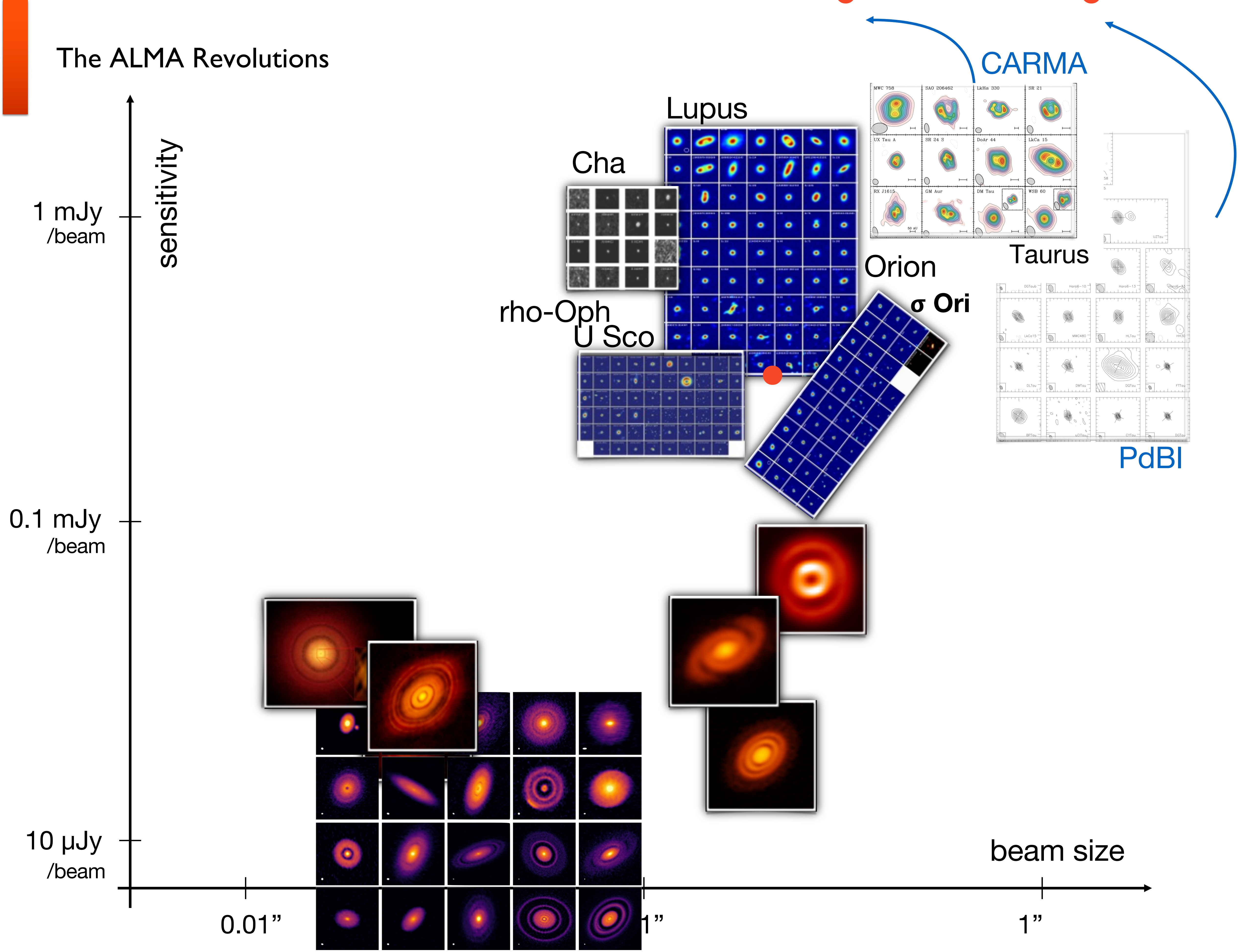
- 10AU@140pc=0.14 arcsec
- Diffraction: 0.14arcsec@1mm => 1.5km
- Need to use interferometry

The ALMA Revolutions



(slide thanks to M. Tazzari)

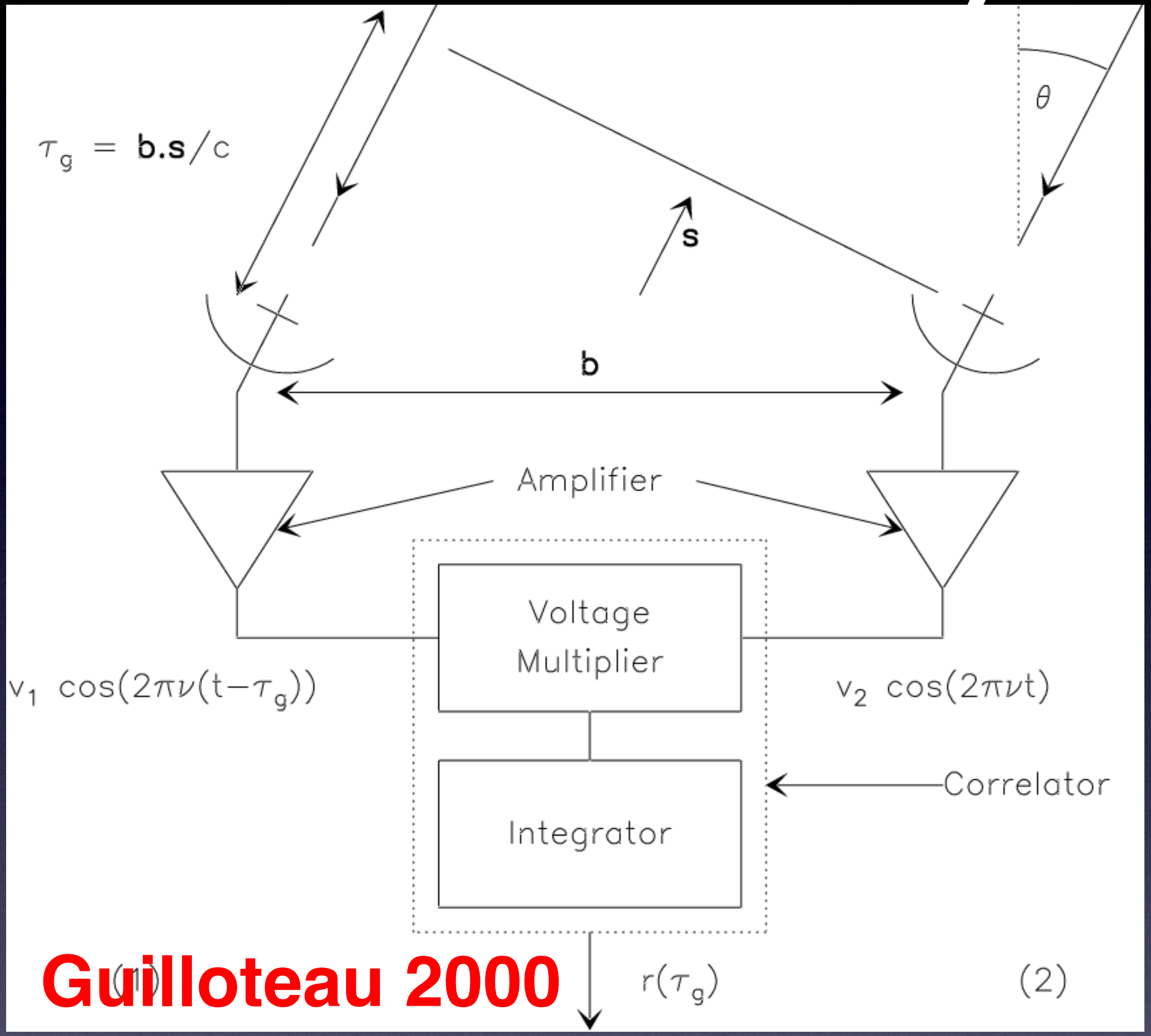
The ALMA Revolutions



(slide thanks to M. Tazzari)

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)

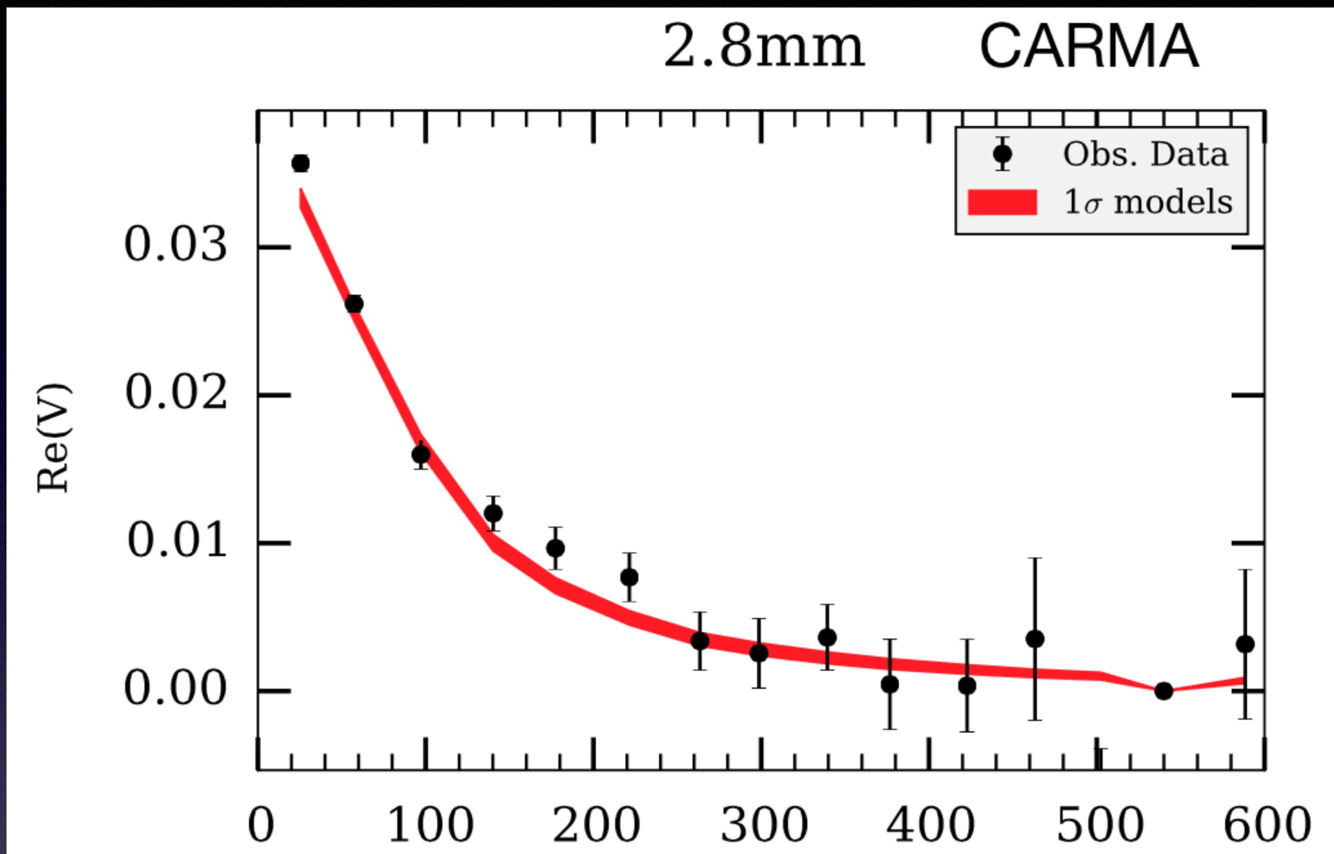


$$V(u, v) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} P(x, y) I(x, y) \exp(-2i\pi(ux + vy)) dxdy$$

(x,y)=Sky (u,v)=baselines plane V(u,v)=Measured visibility

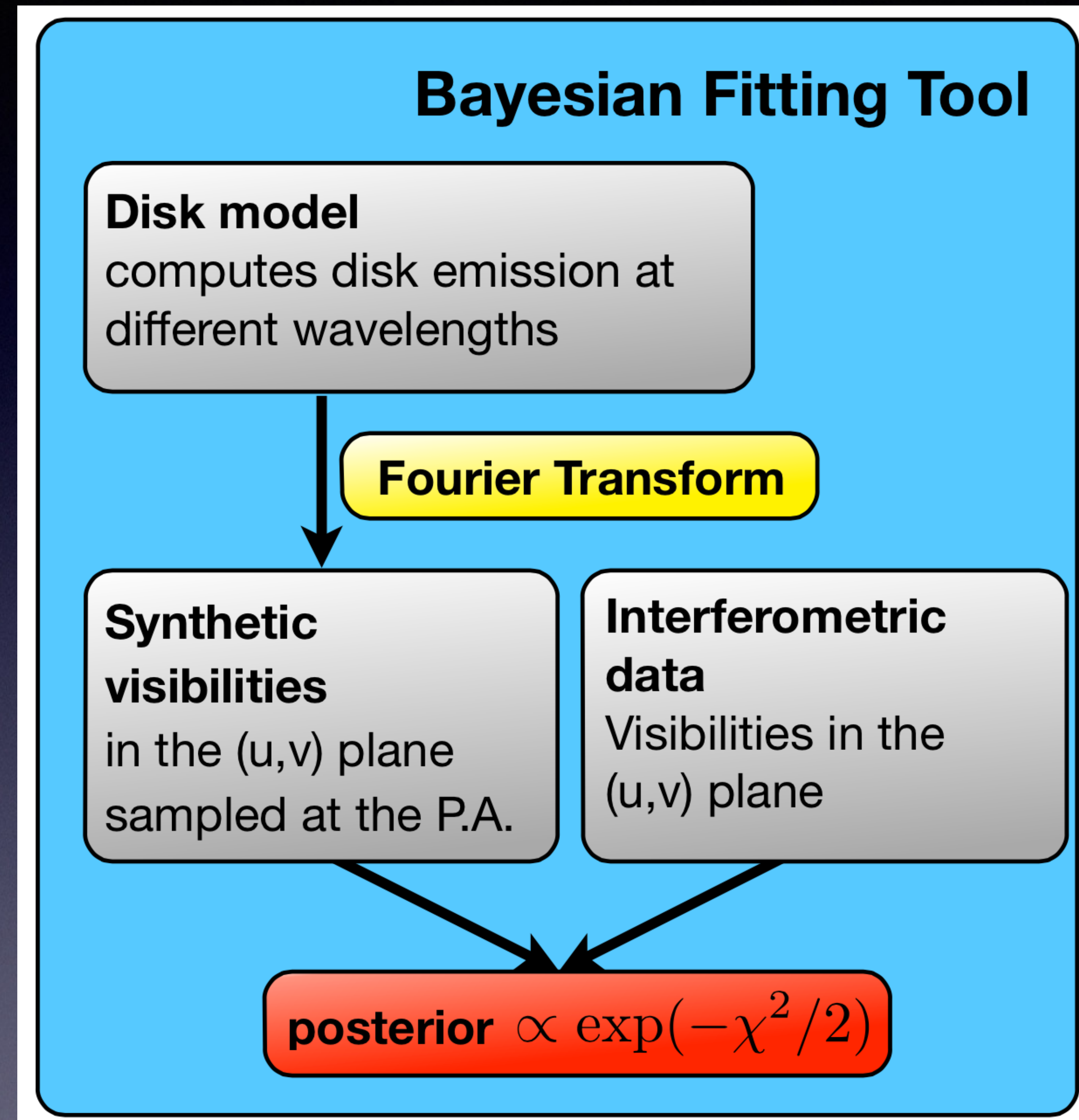
P(x,y)=Antenna power pattern I(x,y)=Brightness distribution on Sky

Analysis of interferometric data



Tazzari+2015

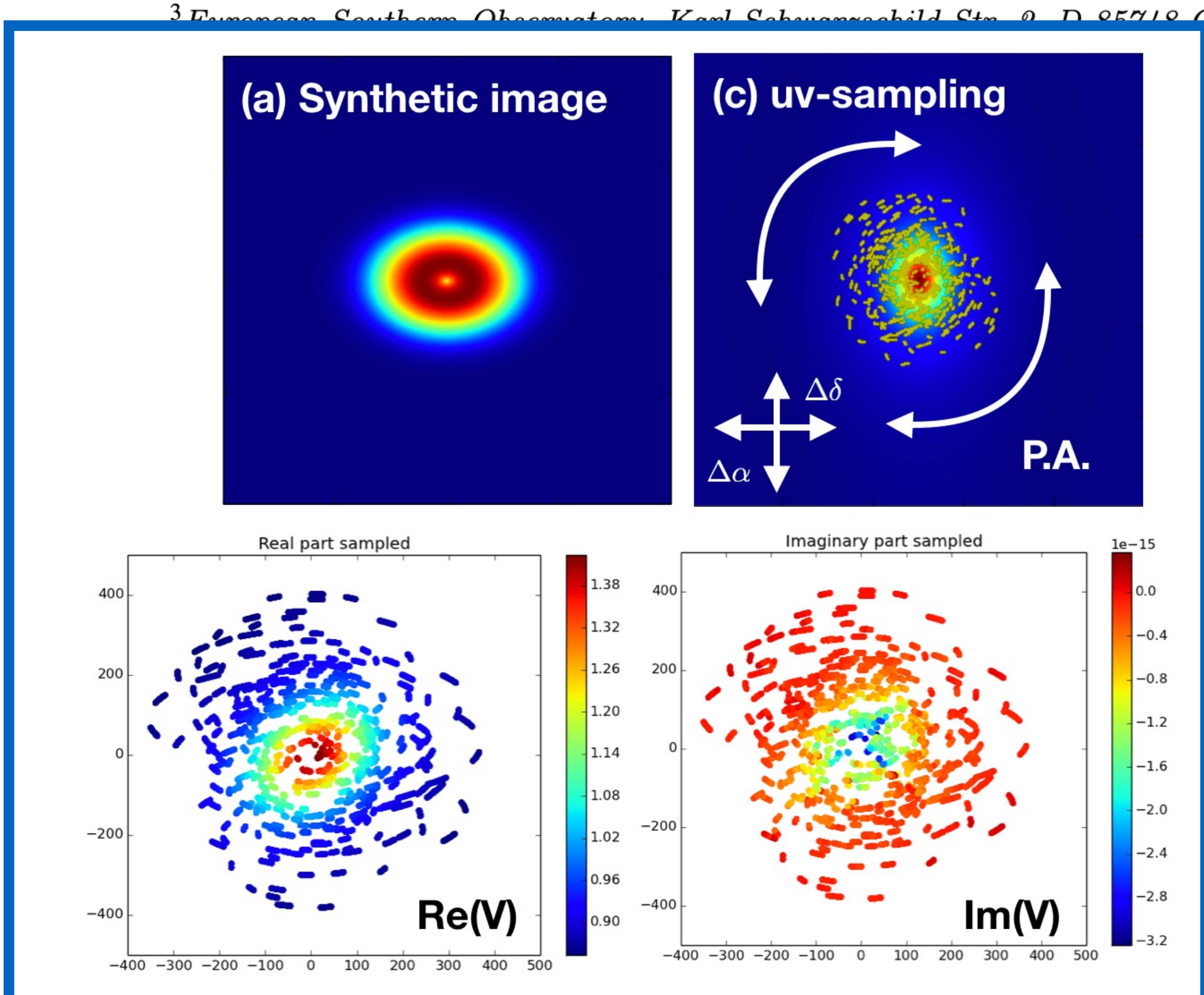
$$\Sigma(R,t) = \Sigma_t \left(\frac{R_t}{R}\right)^{\gamma} \times \exp\left\{-\frac{1}{2(2-\gamma)}\left[\left(\frac{R}{R_t}\right)^{(2-\gamma)} - 1\right]\right\}$$



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

galario: a Gpu Accelerated Library for Analysing Radio Interferometry Observations

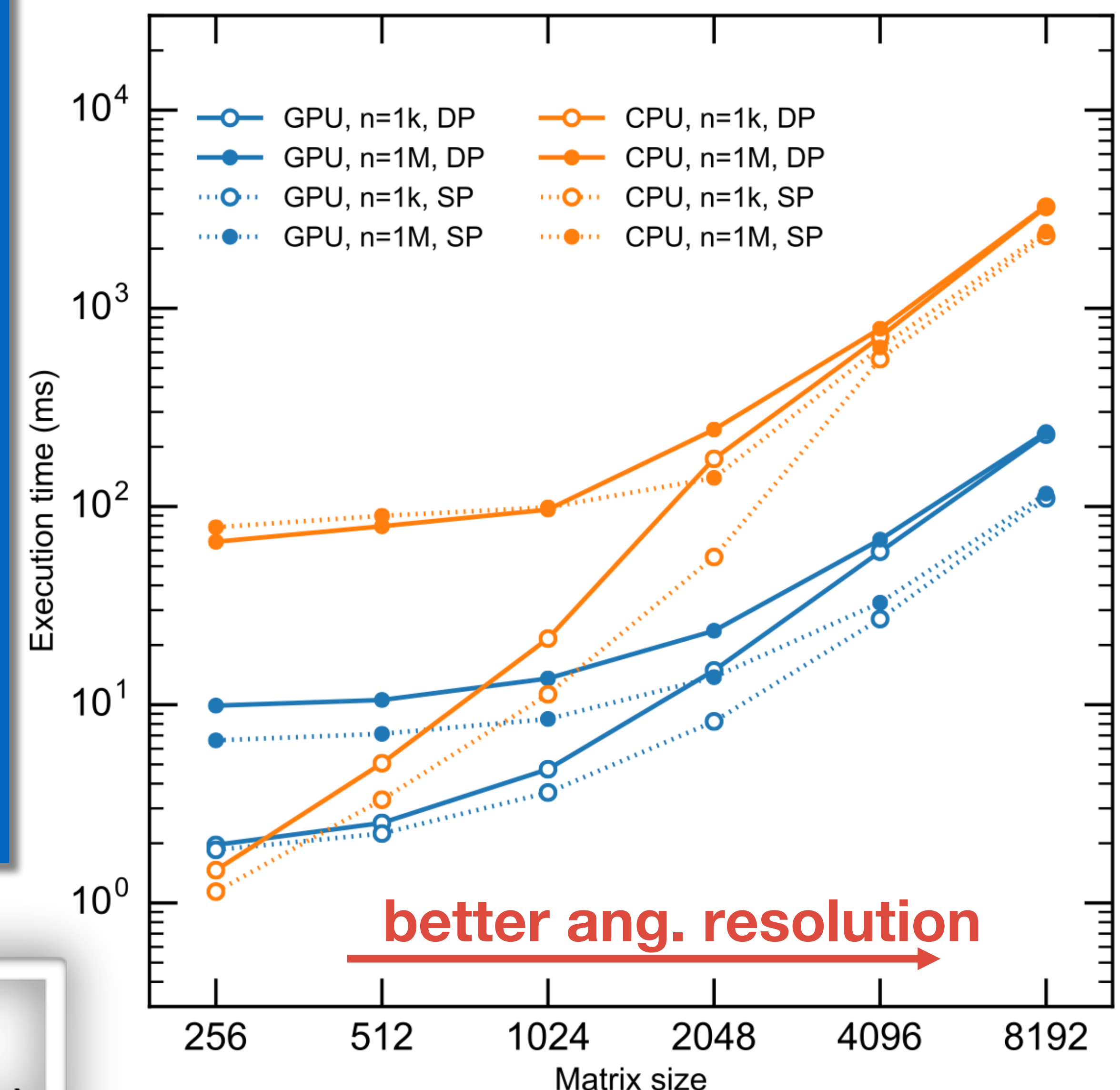
Marco Tazzari[1]★, Frederik Beaujean[2] and Leonardo Testi[2,3]
[1] Institute of Astronomy, University of Cambridge, Madingley Road, CB3 0HA, Cambridge, UK
[2] Excellence Cluster Universe, Boltzmannstr. 2, D-85748 Garching, Germany
[3] European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany



ility sampling)

is tools

https://github.com/mtazzari/galario



- example:

```
from galario import double_cuda, single_cuda
double_cuda.chi2(image, d_alpha, d_delta, uv, obs_vis)
```

GALARIO: a GPU Accelerated Library for Analysing Radio Interferometry Observations

Marco Tazzari[1★], Frederik Beaujean[2] and Leonardo Testi[2,3]

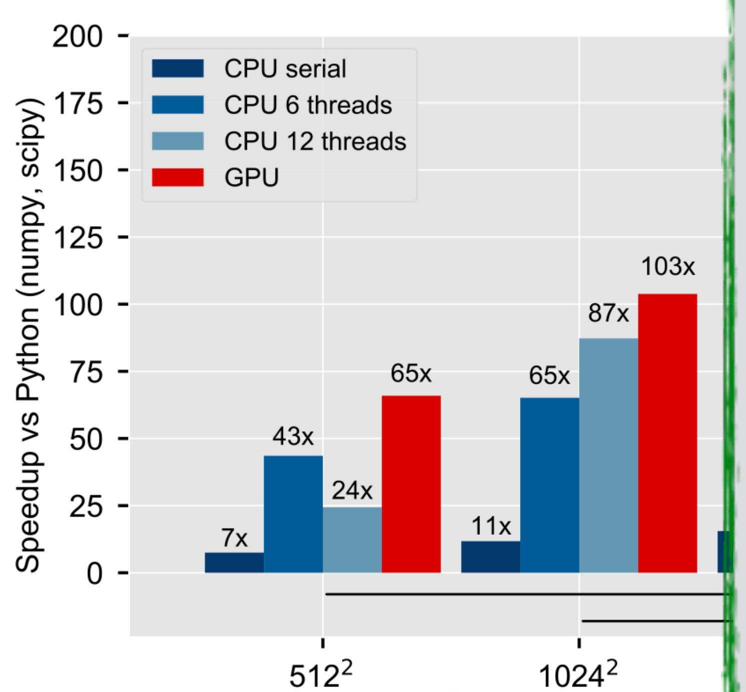
GALARIO

https://github.com/mtazzari/galario

- **Easy to use:**
  - compute **visibilities** from 2D image:
    `V_mod = sampleImage(image, dxy, u, v)`
  - compute χ^2 from 2D image:
    `chi2 = chi2Image(image, dxy, u, v, ReV, ImV, w)`
  - compute χ^2 from 1D profile:
    `chi2 = chi2Profile(I, Rmin, dR, nxy, dxy, u, v, ReV, ImV, w)`

- **Easy to install:** `conda install -c conda_forge galario`

- ***Fouriously* fast:** up to 150x faster than



- **Simple switch to GPU:** `import galar`

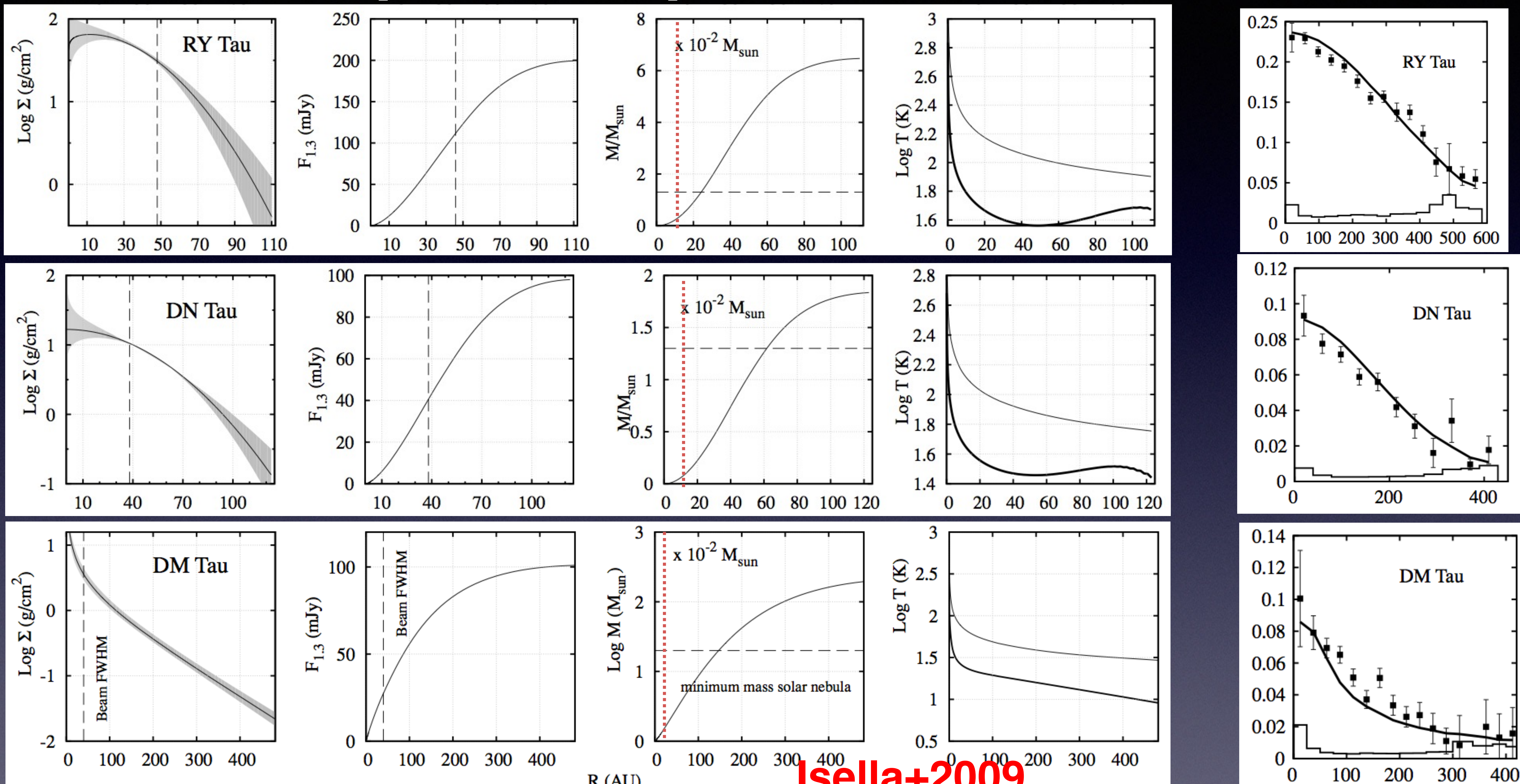
- **many applications:**
  - **protoplanetary** disks
  - **debris** disks
  - **high redshift** galaxies
  - **massive** stars cores

- **ready to exploit the ALMA wavelength coverage:**
  - **single**-wavelength continuum
  - **multi**-wavelength continuum
  - gas emission **spectral cubes**

- **single or multiple sources in the FOV**

- **fast enough for survey analysis**

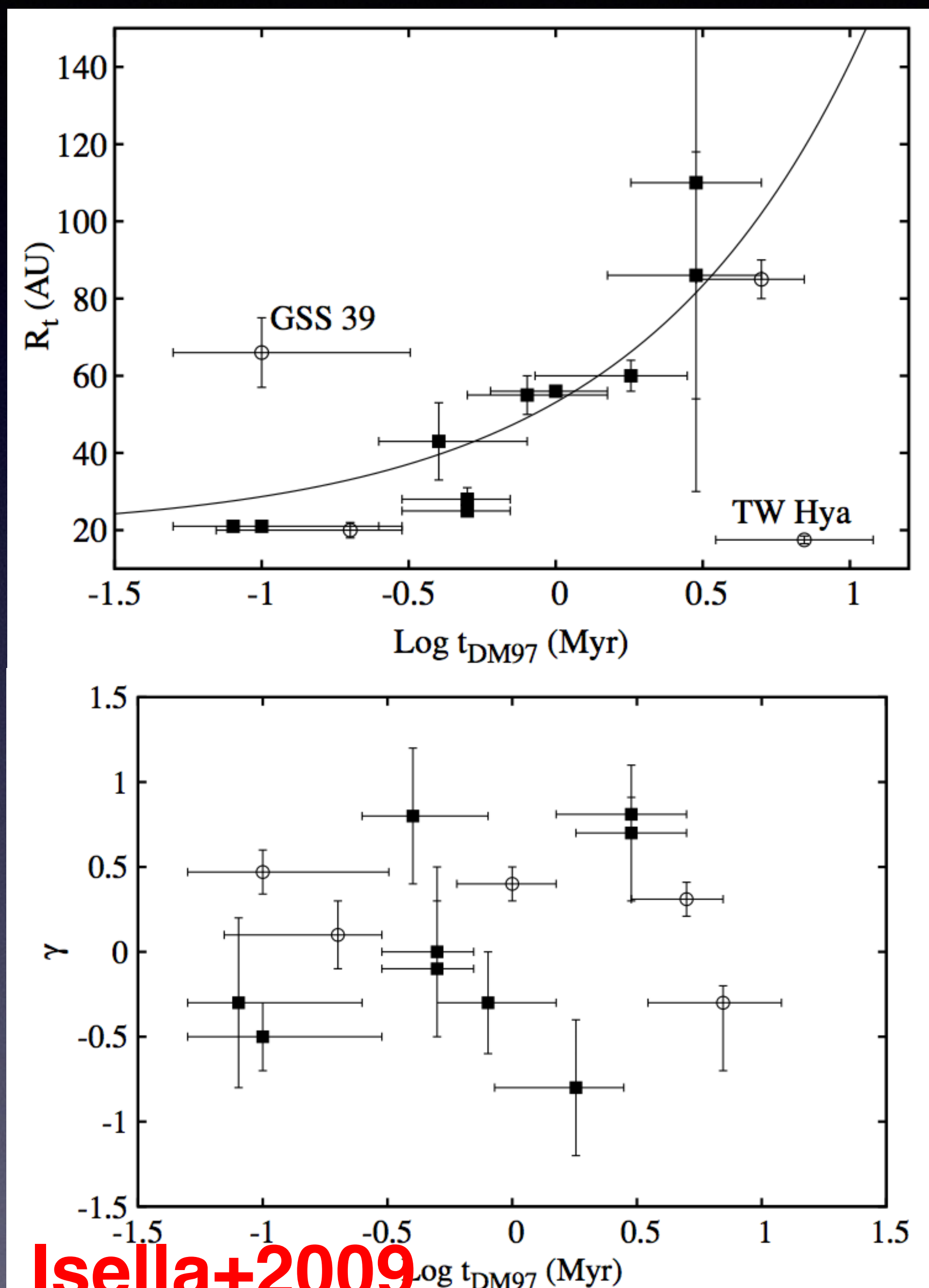
Examples of pre-ALMA results

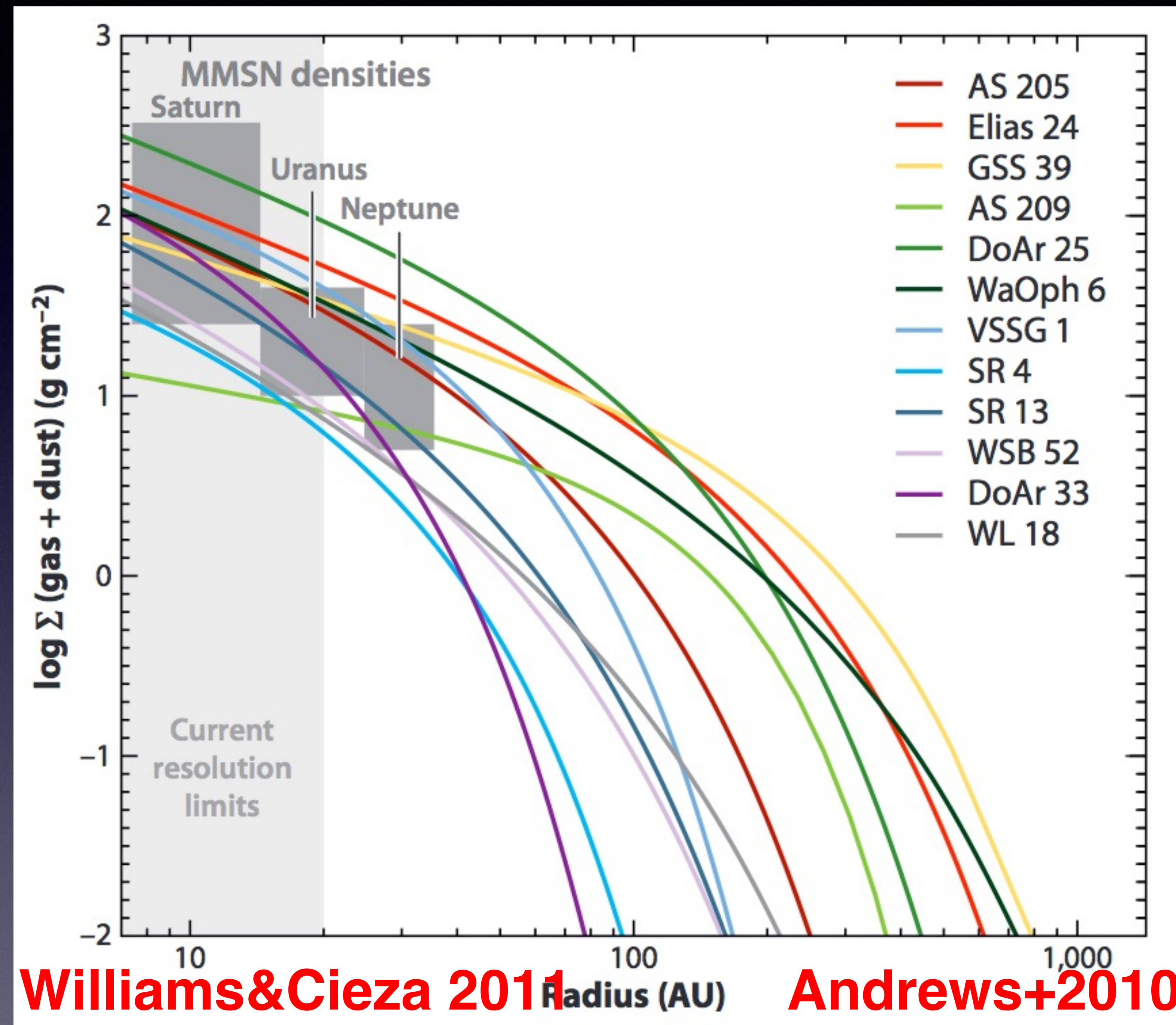


$$\Sigma(R,t) = \Sigma_t \left(\frac{R_t}{R}\right)^{\gamma} \times \exp\left\{-\frac{1}{2(2-\gamma)}\left[\left(\frac{R}{R_t}\right)^{(2-\gamma)} - 1\right]\right\}$$

- Data generally well described, note limited angular resolution

Examples of pre-ALMA results

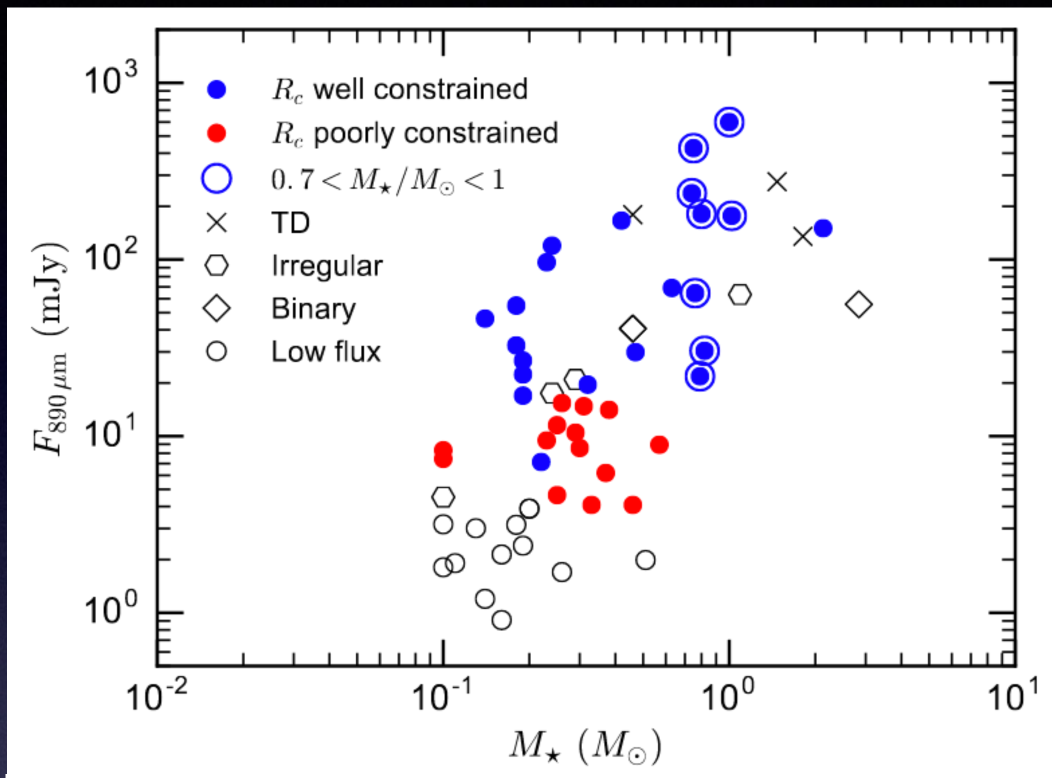




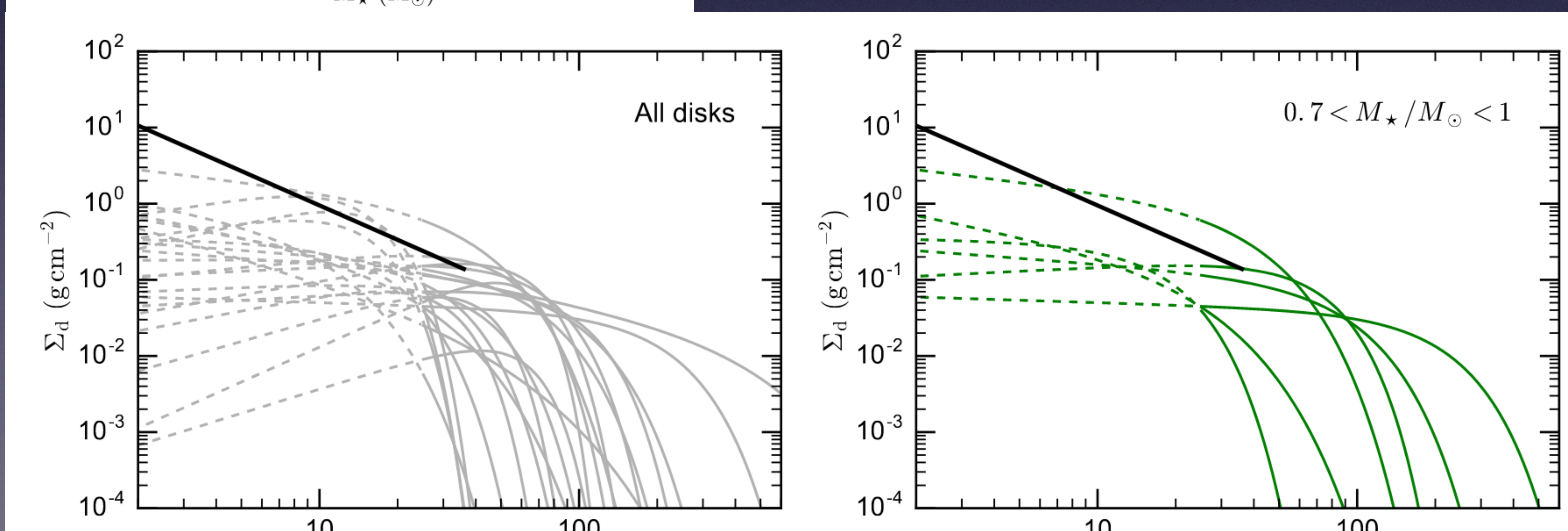
- Extract N random samples from "Taurus" applying the same selection biases as expected in the other region. Method first applied by Andrew+2013

Surface density distribution

Powered by Galario (Tazzari+2018)

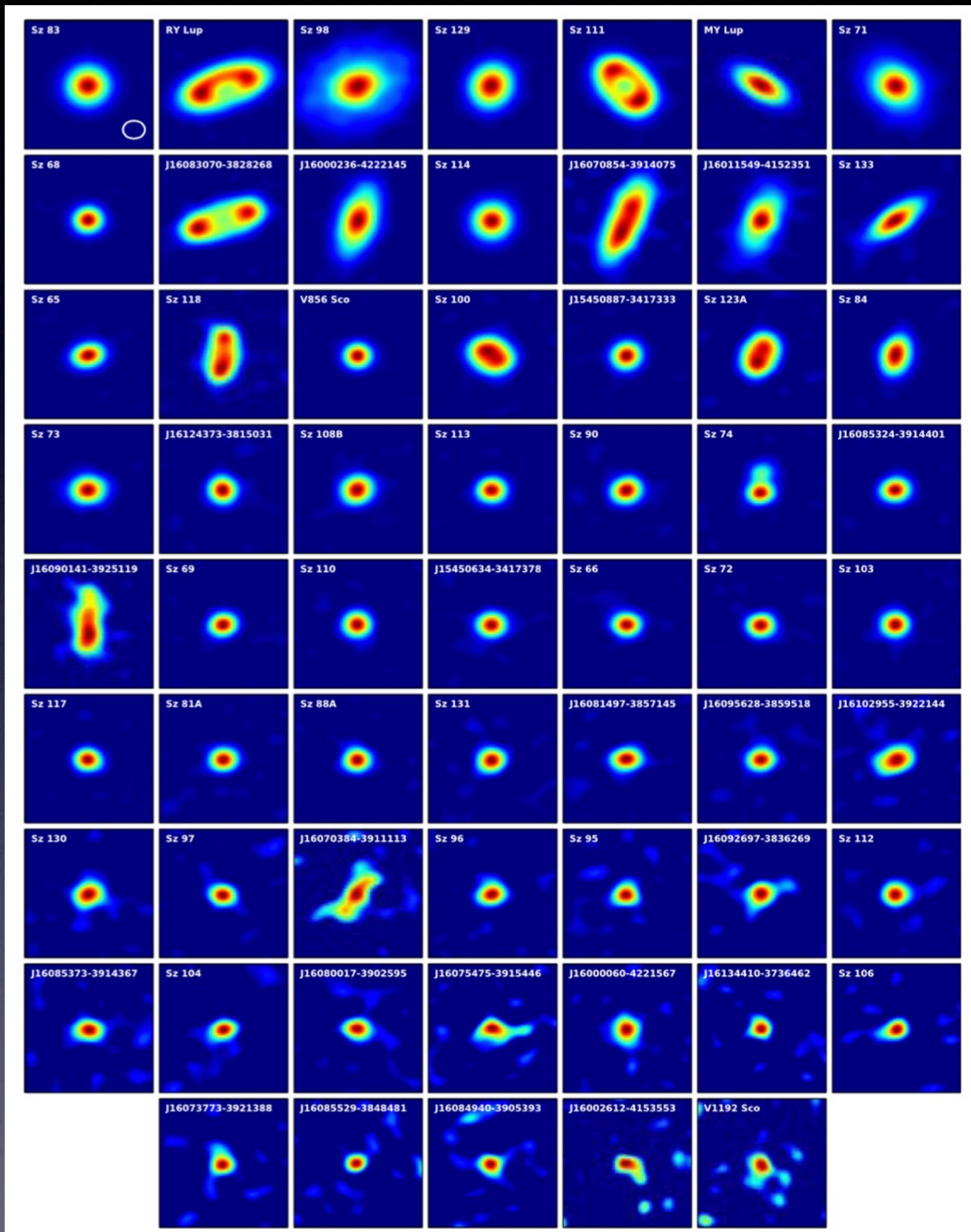


- First systematic/complete analysis of surface density distribution of solids in disks
- Compact disks (R<50AU) are up to ~30-40% of the population



(Tazzari+2017)

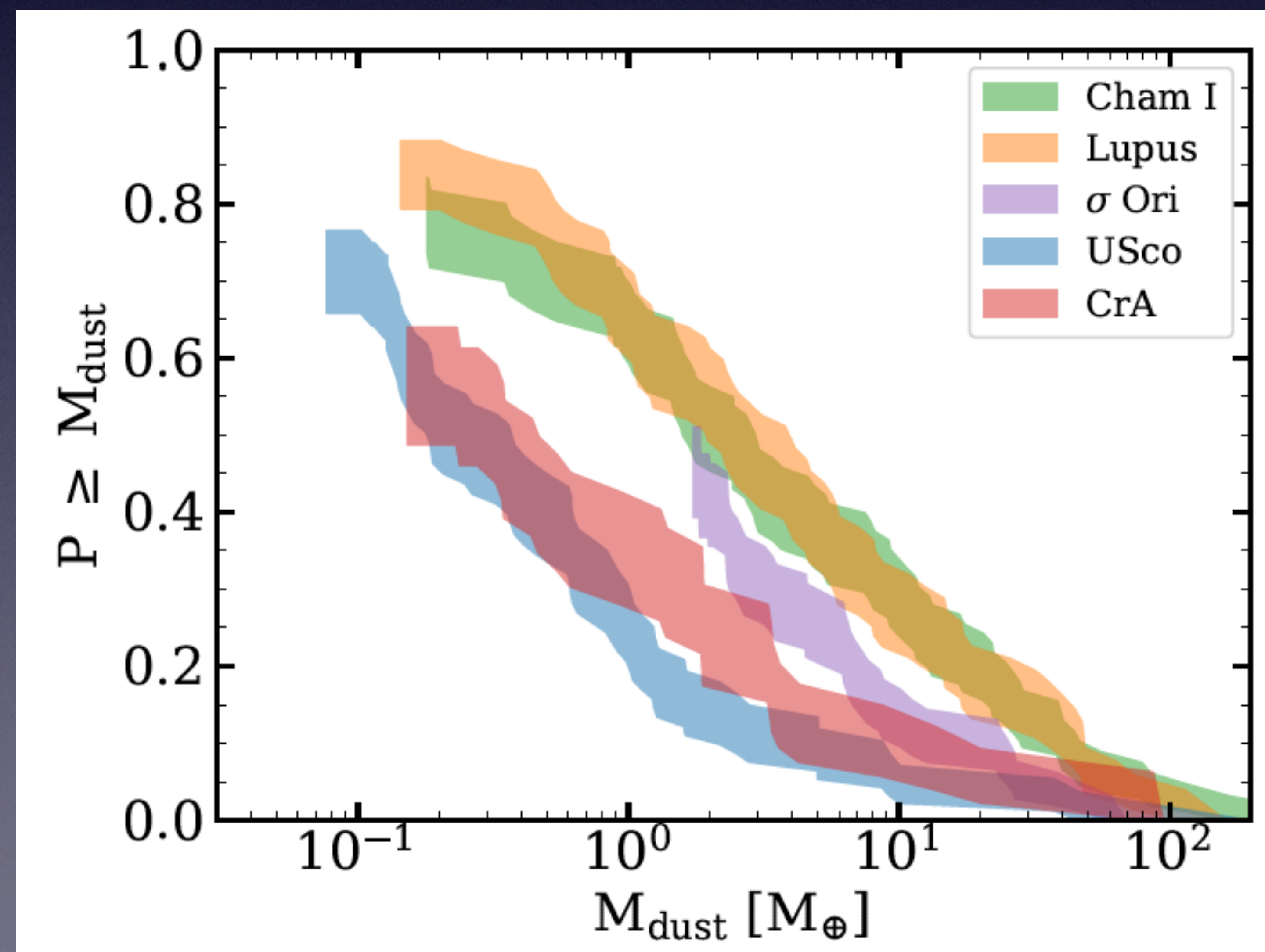
Full fit not always possible: order of magnitude estimates technique



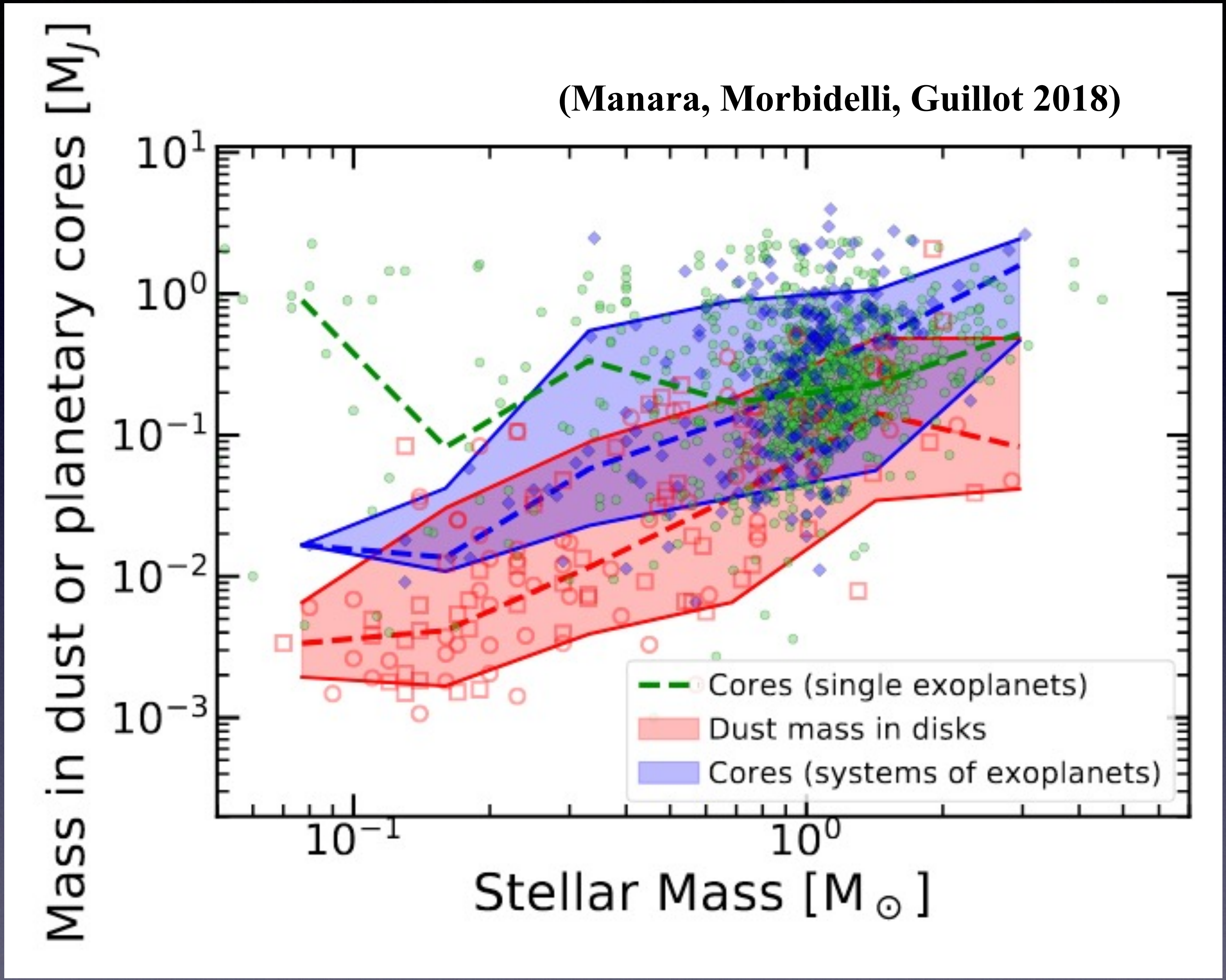
Ansdell+2016

(see also Pascucci+2016, Ansdell+2017, Barenfeld+2016, Cazzoletti+2019, Williams+2019, Testi+2022)

- Initial surveys revealed a gradual decay (factor ~4 in ~5Myr)
- Dust content is relatively low
- Estimates rely on simple assumption on temperature structure and dust opacity

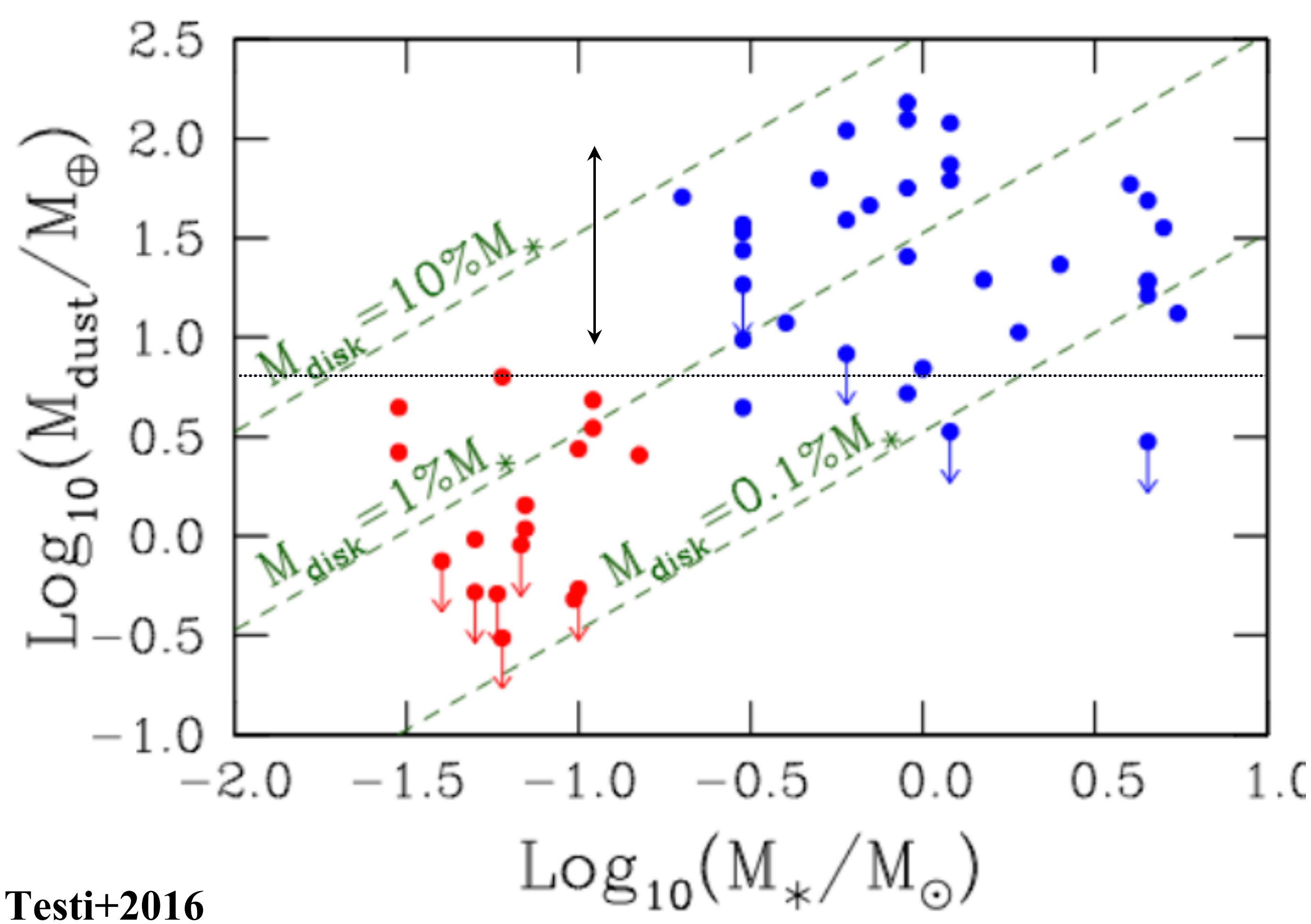


Solids in planets and disks

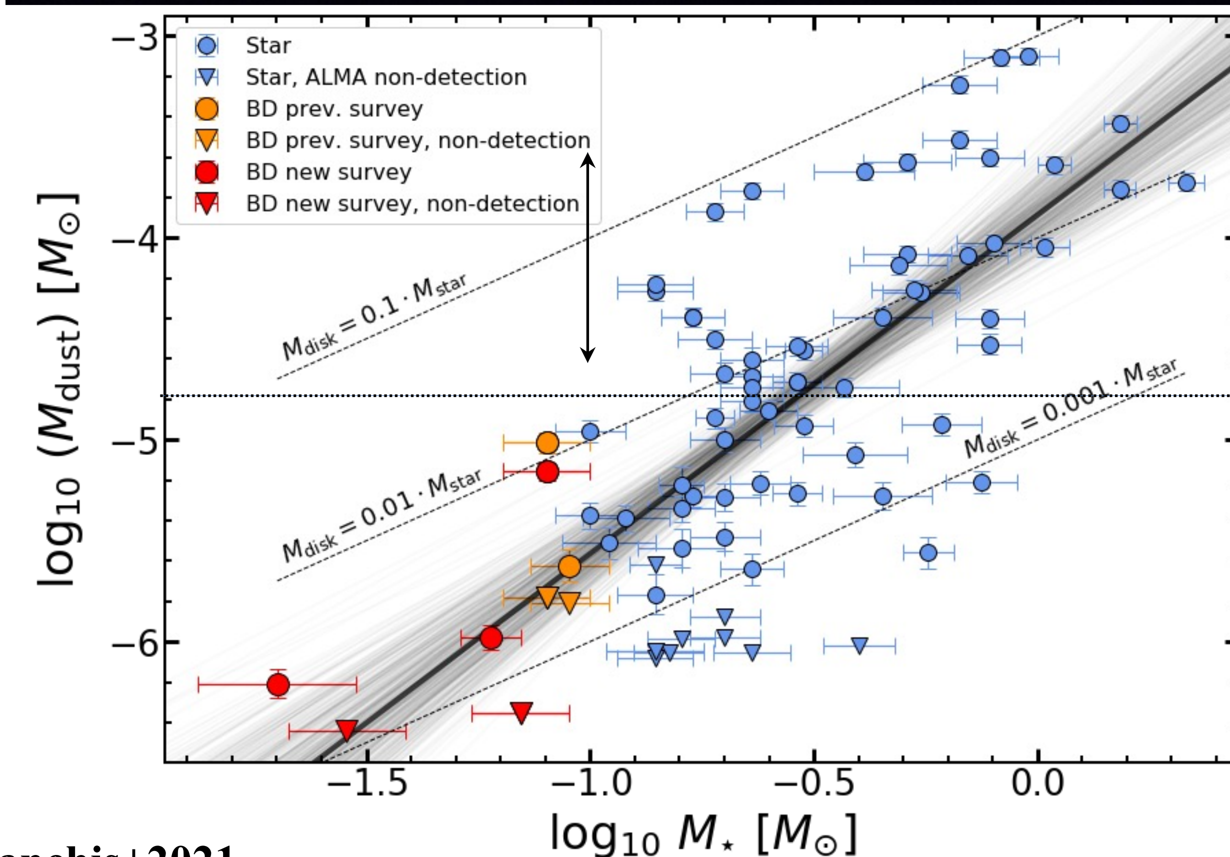


- 1-2Myr old disks do not contain enough solids
  - Consistent with the latest suggestions of Jupiter core growth (Kruijer+2017)

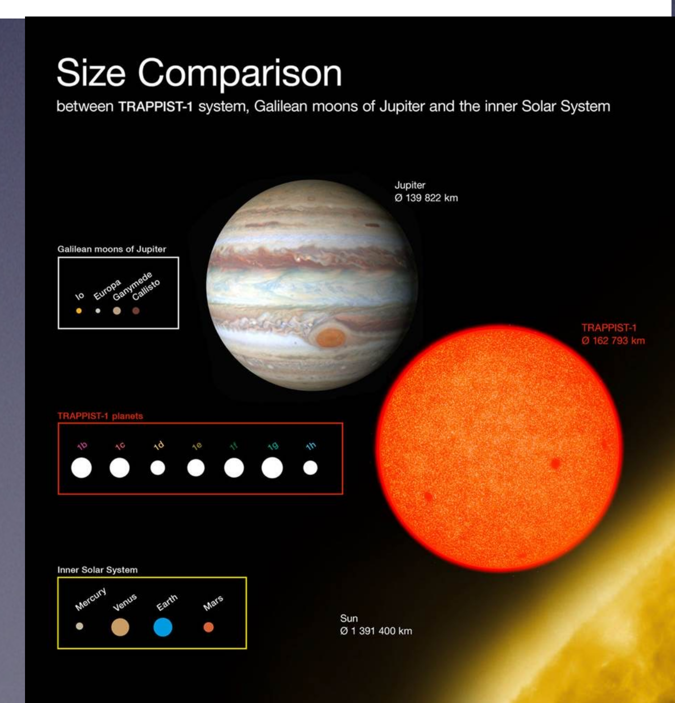
Deficit of solids in BD disks



Testi+2016

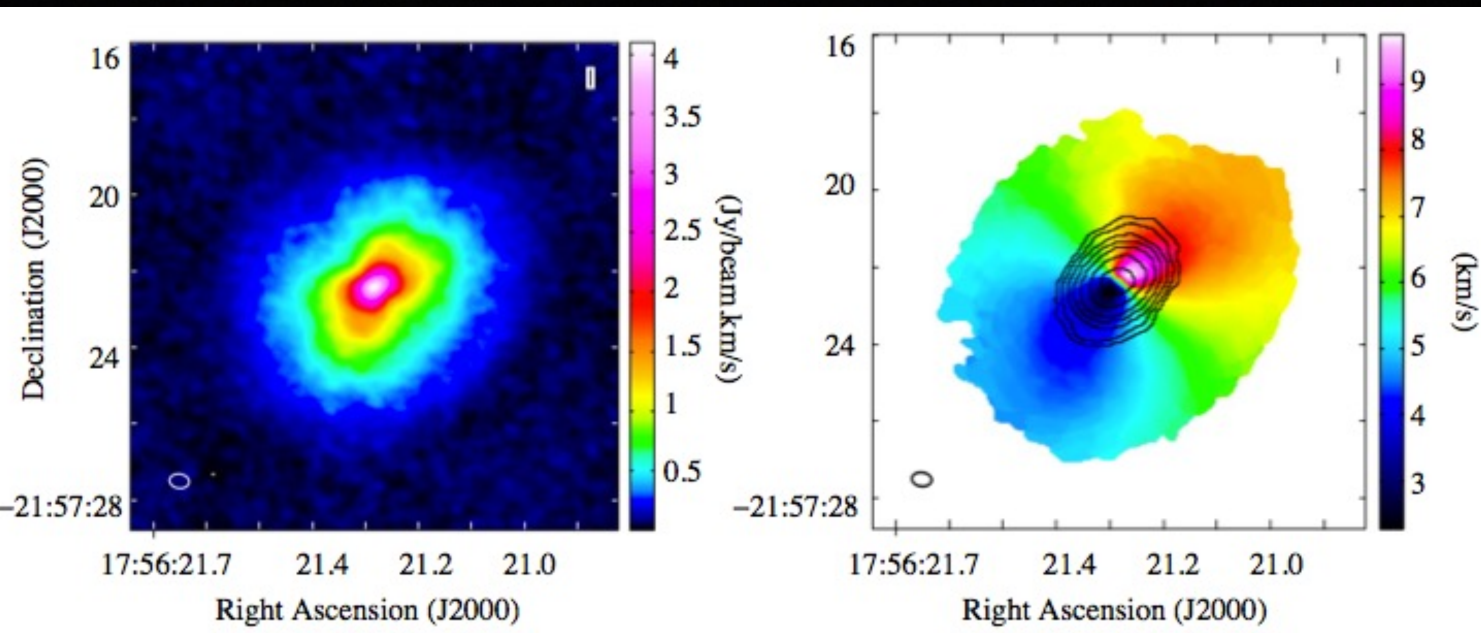


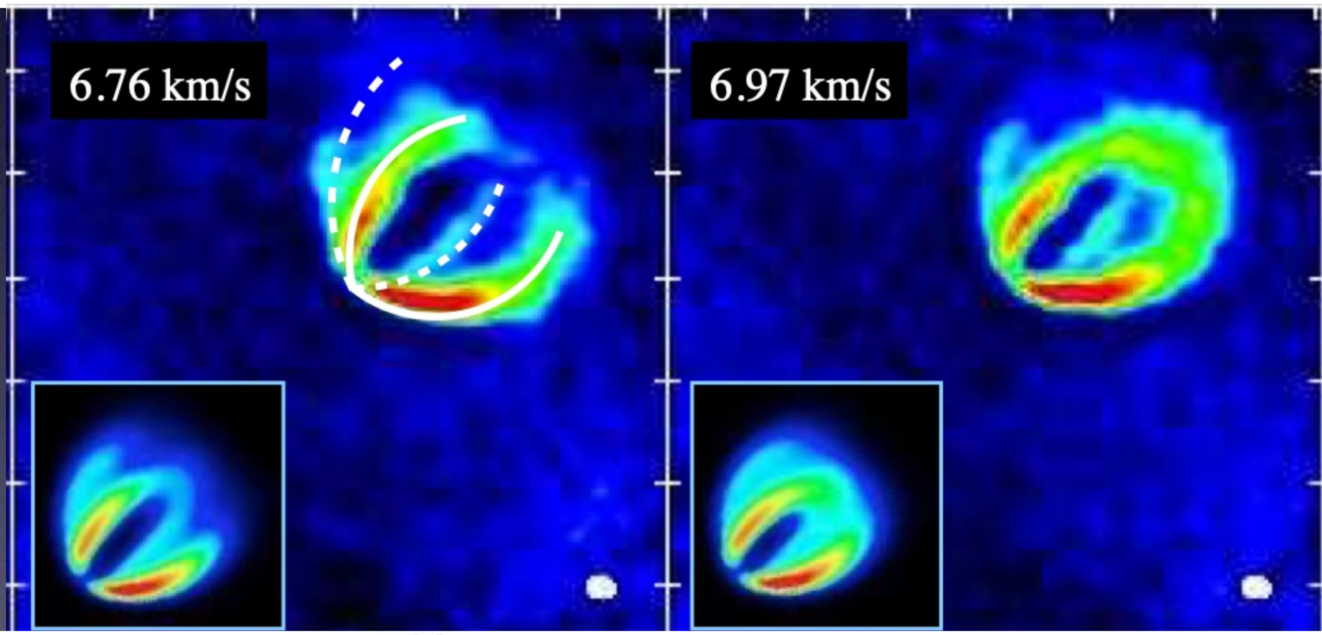
Sanchis+2021



- Estimated solids mass in BD disks is too low to form the known exoplanets around BDs

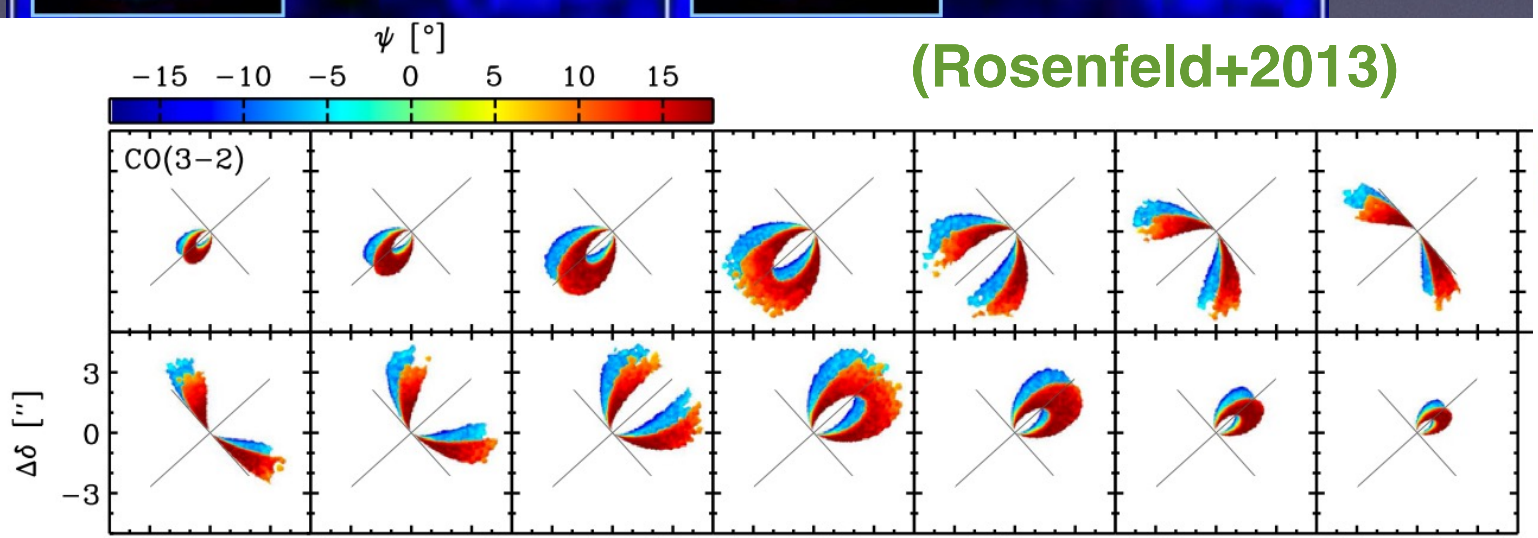
HD163296 as seen by ALMA



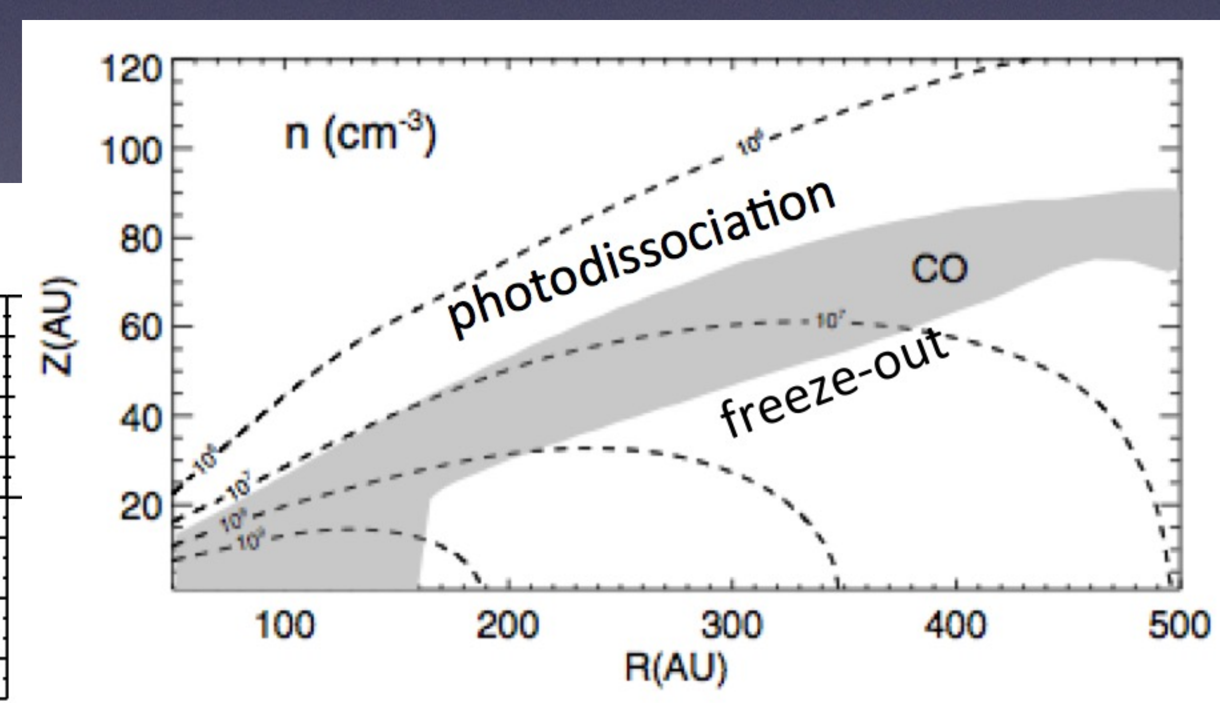


(deGregorio-Monsalvo+2013)

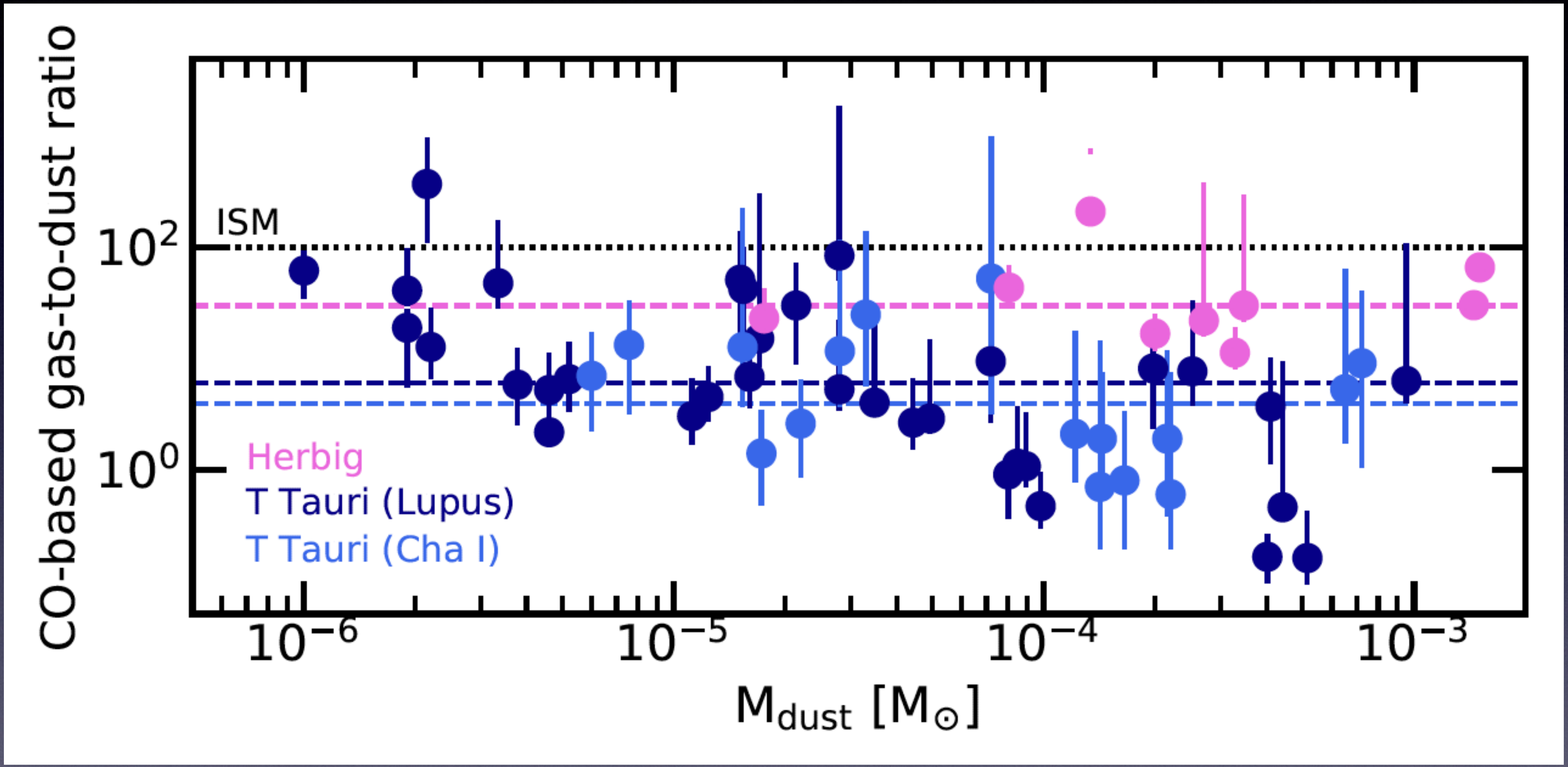
- Direct measurement of disk flaring and CO depletion on the mid plane



(Rosenfeld+2013)



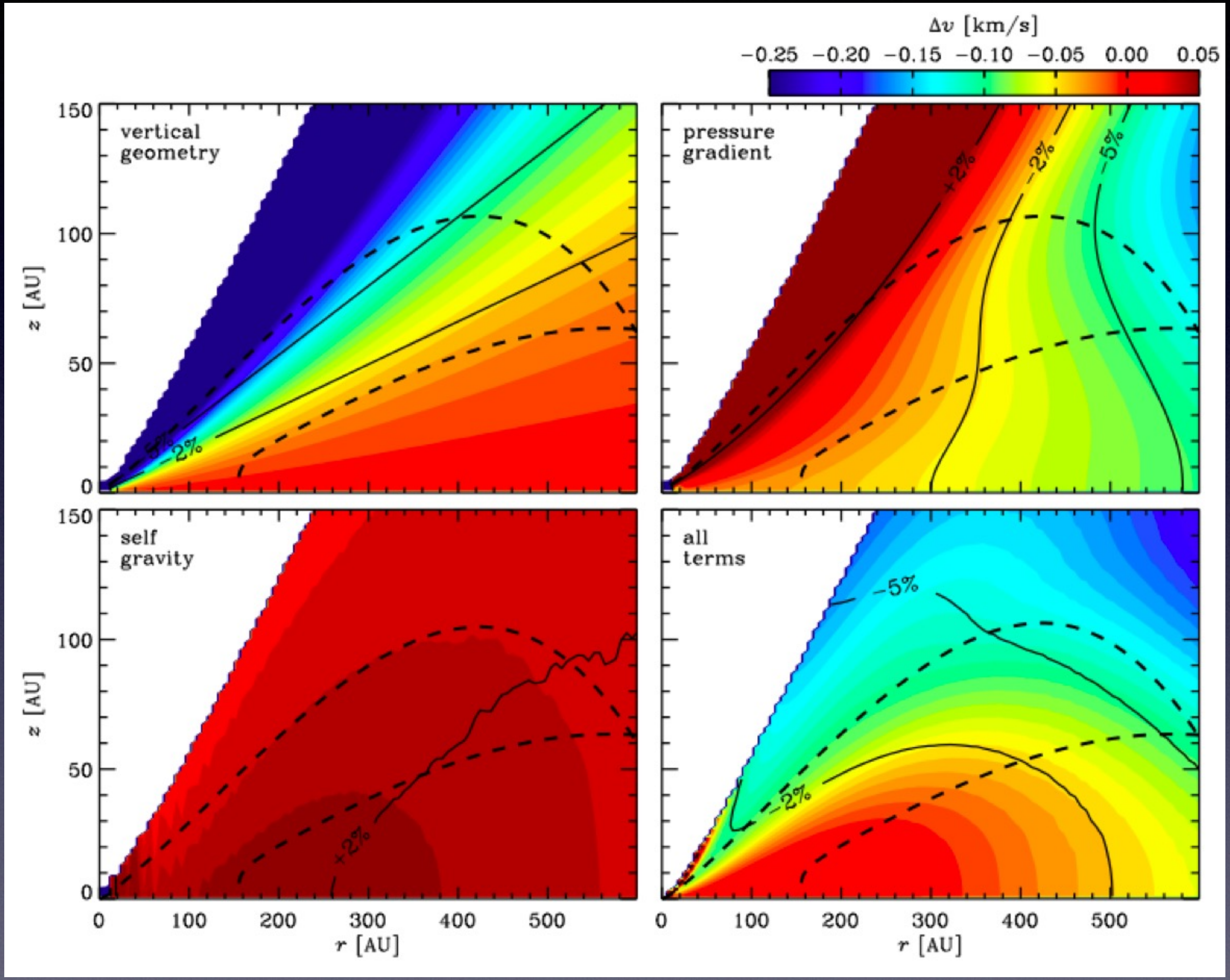
CO-based gas masses



(Miotello et al. 2022)

- Based on disk thermochemical modelling
- Truly low gas masses or “chemical” model deficit?

Gas kinematics

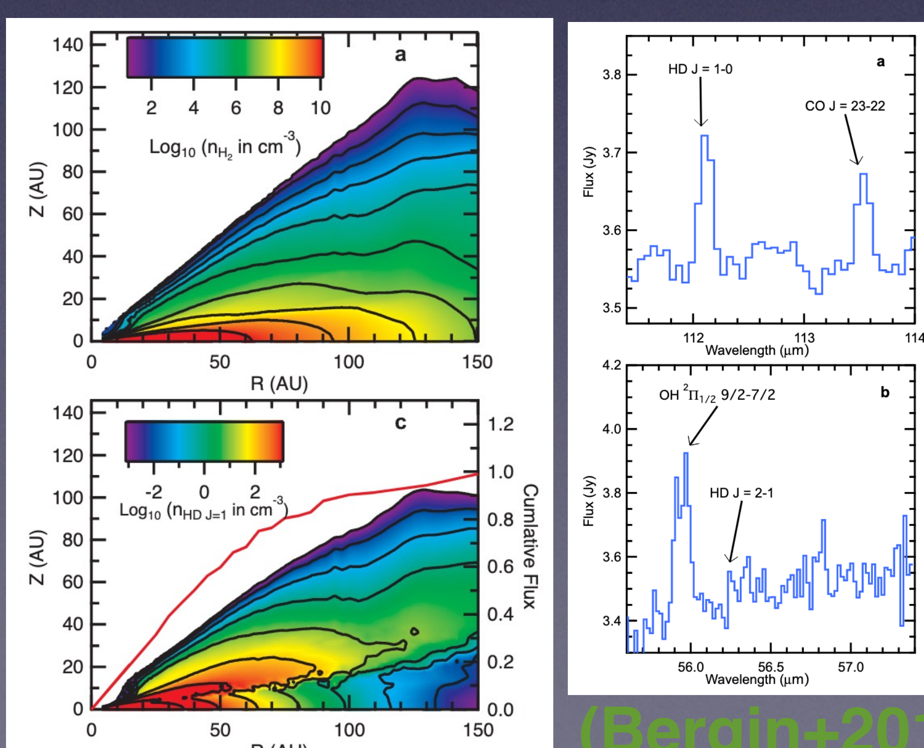


(Rosenfeld et al. 2013)

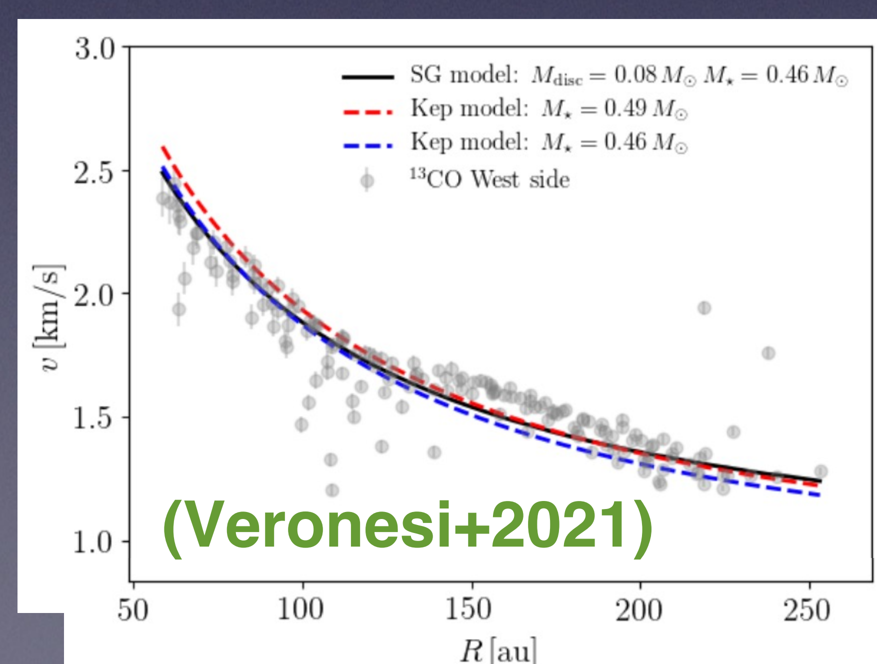
- Potentially a direct measurement of the disk self-gravity
- Not exactly Keplerian
- Largest effect is the pressure term 5%, self gravity 0.1-0.5%

Dust mass and disk mass

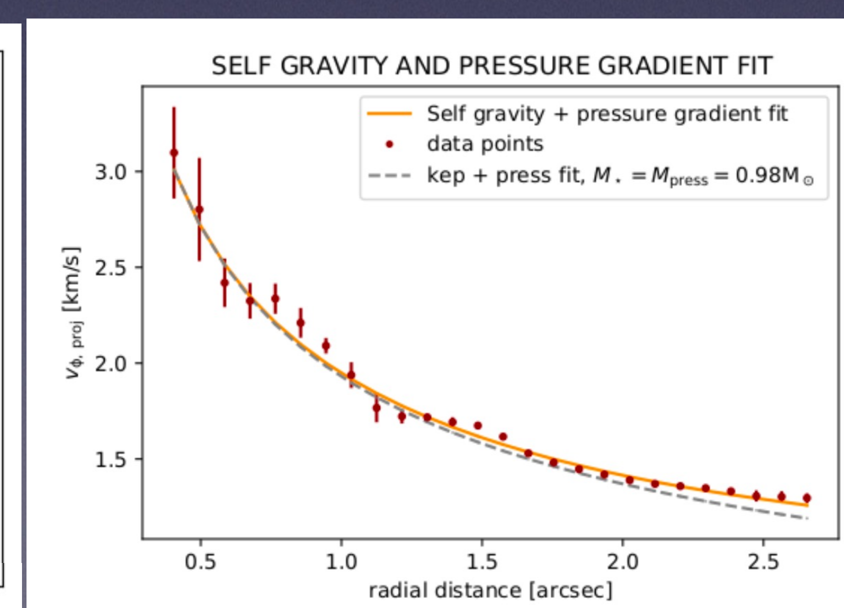
- Dust emission traces approx 0.01 of the H_2 mass
  - (by comparison, gas-phase CO emission traces <<<<1e-5, depending on how much of the CO mass is in solids and on the details of chemistry and photodissociation)
- Carefully estimated dust masses are within a factor 2-3 of "robust" disk mass estimates



(Bergin+2013)

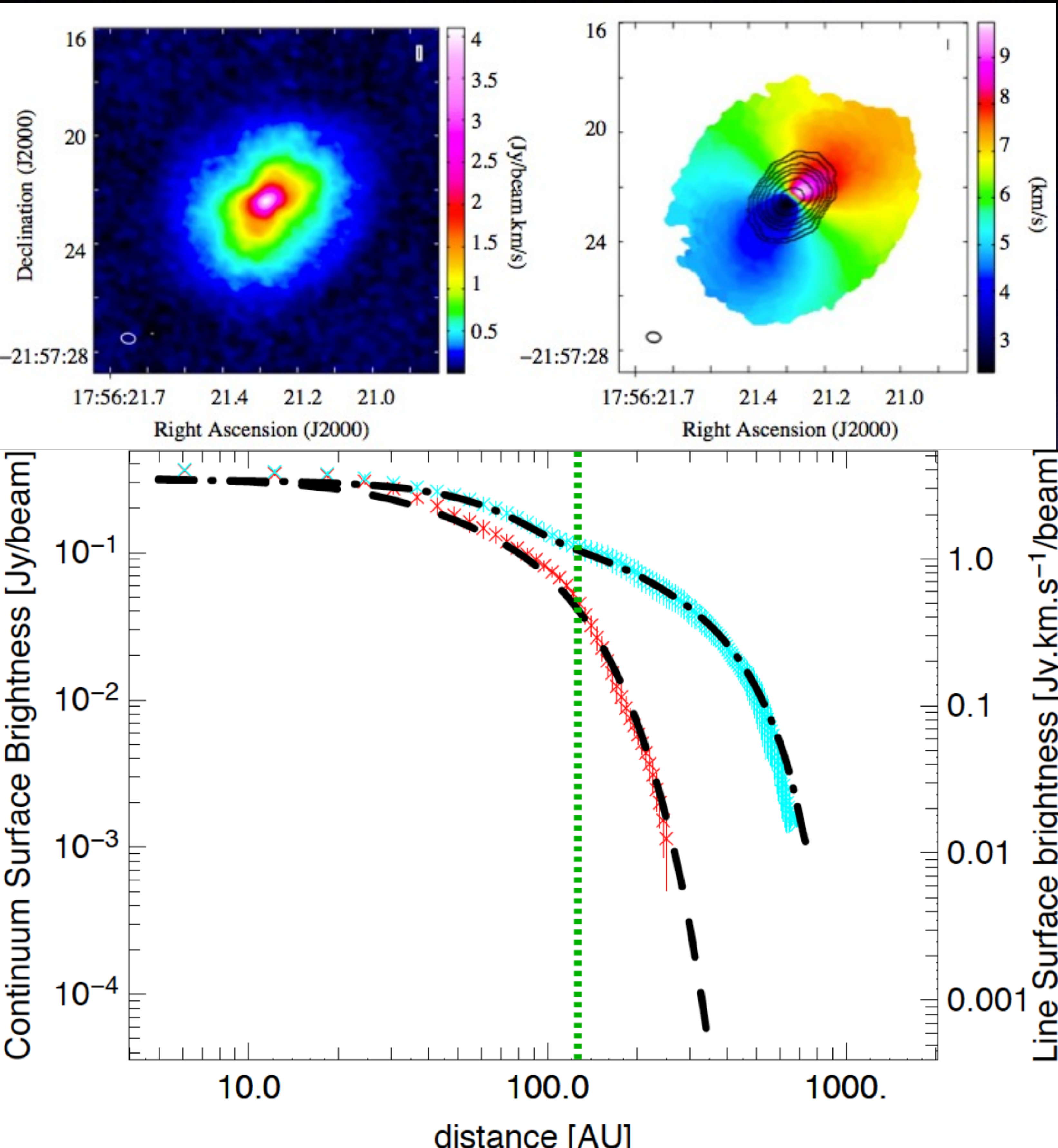


(Veronesi+2021)



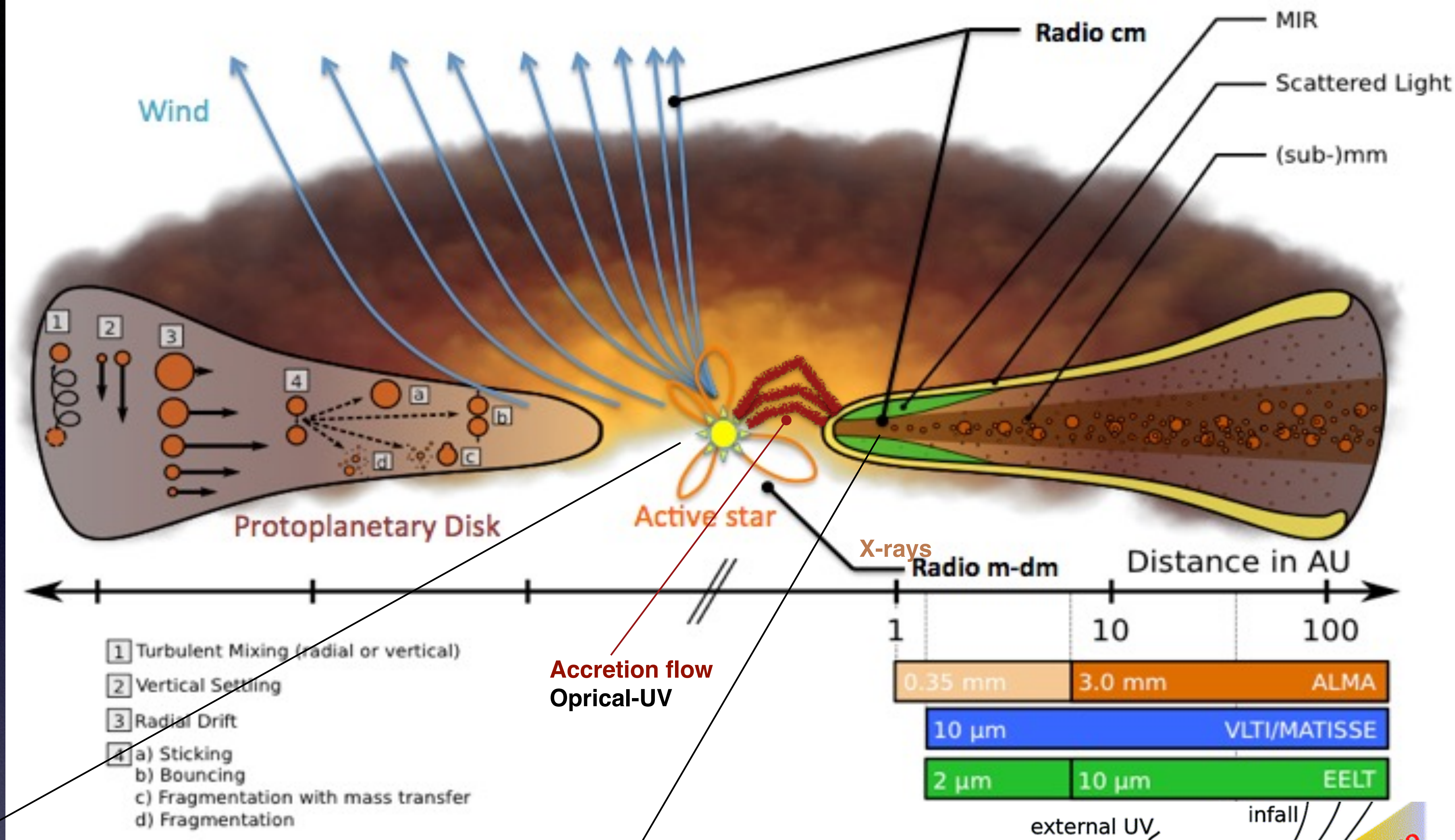
(Rampinelli+2022)

HD163296 as seen by ALMA

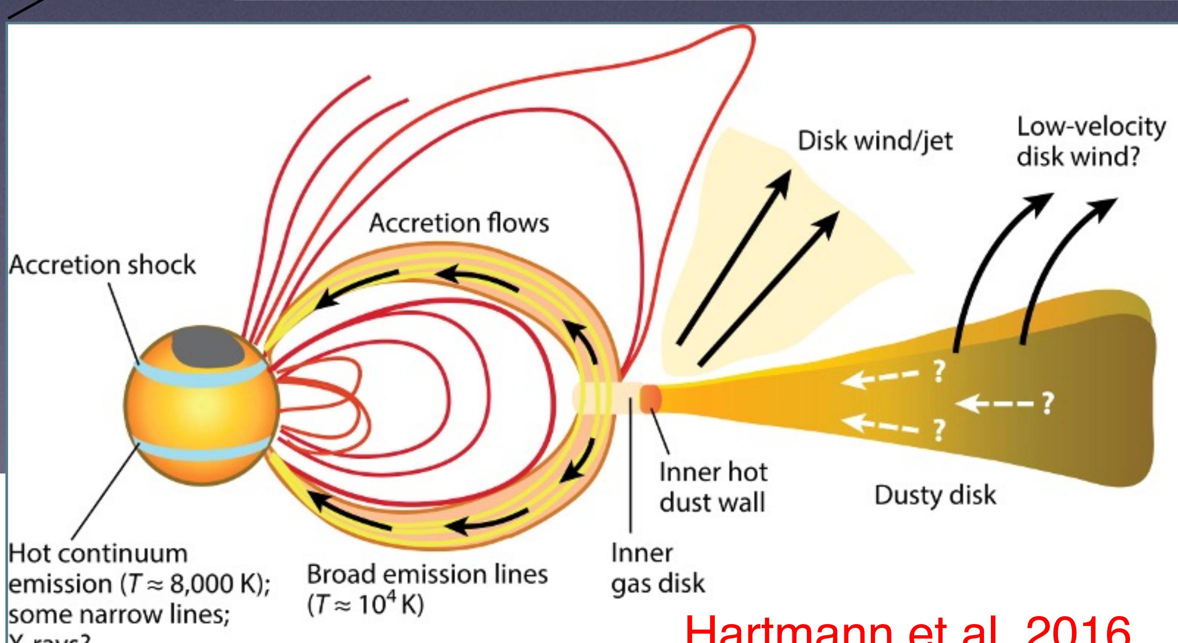


- Extent of the CO disk is much larger than that of the mm-grains disk
- Qualitative behaviour as expected from viscous spreading and migration of the larger grains

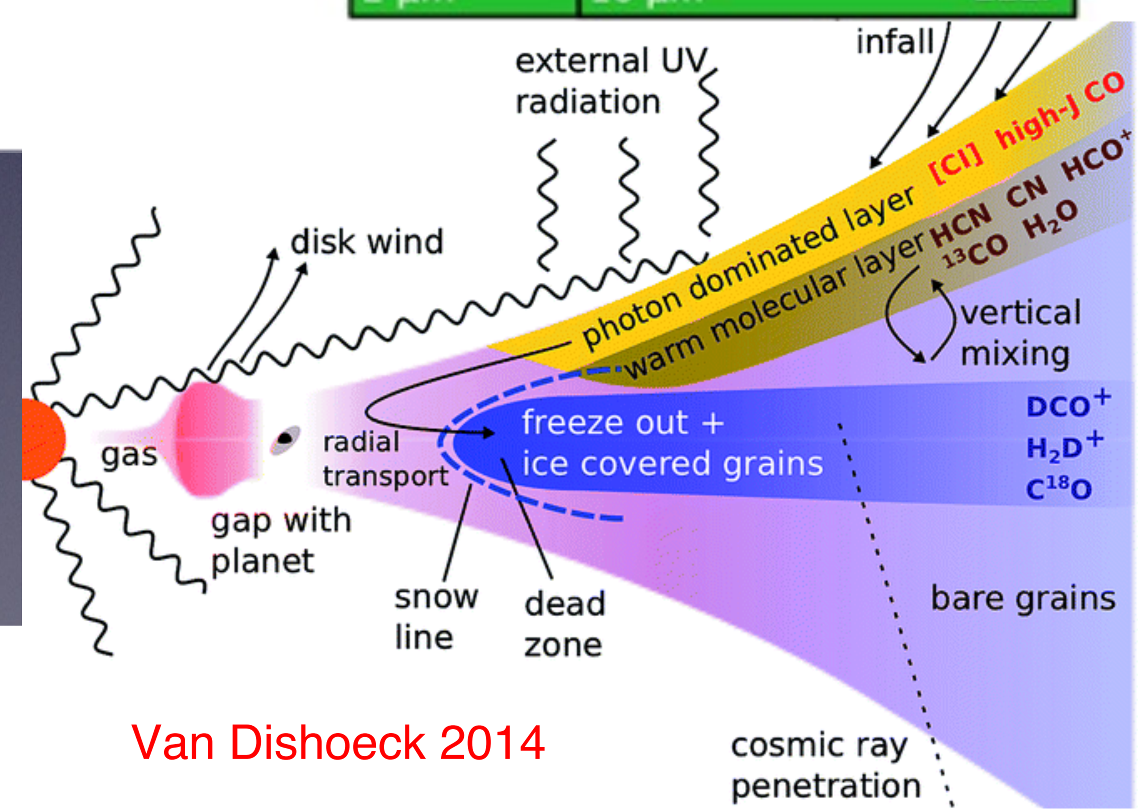
(deGregorio-Monsalvo+2013)



Testi et al. 2014/15



Hartmann et al. 2016



Van Dishoeck 2014