Protoplanetary Disks

(the dirty job part II)

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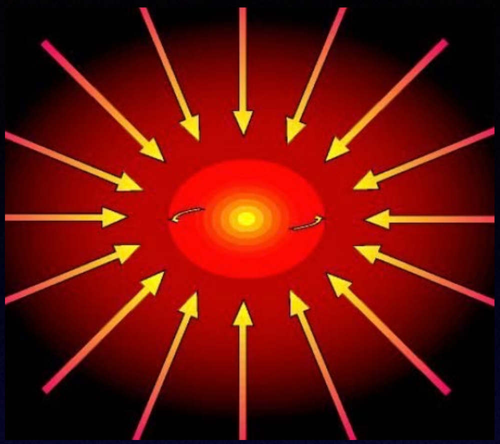
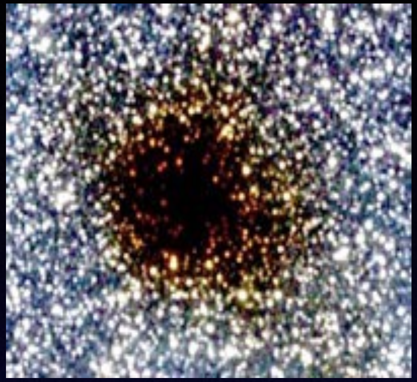
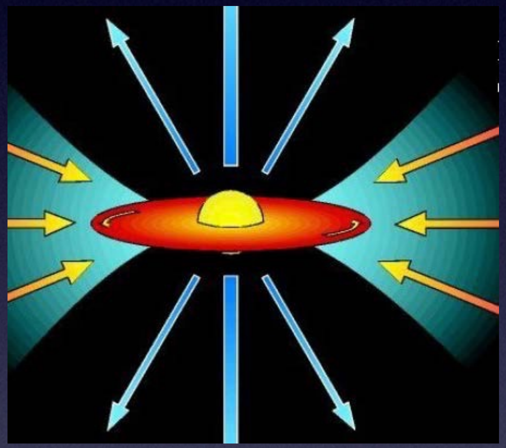
- Most of the focus will be on Class II disks
- How we determine the key properties of these systems
- Stellar masses and ages
- Disk physical parameters
- Evolution of the disk and its constituents

From Cores to Planetary Systems

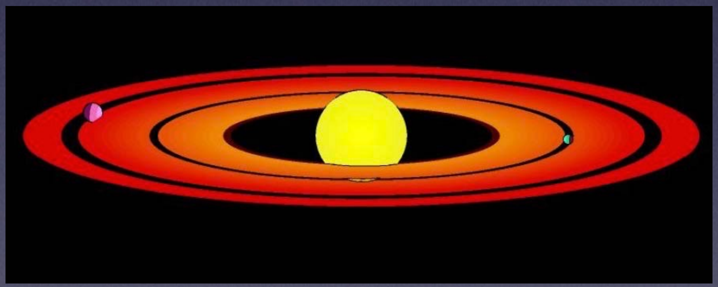


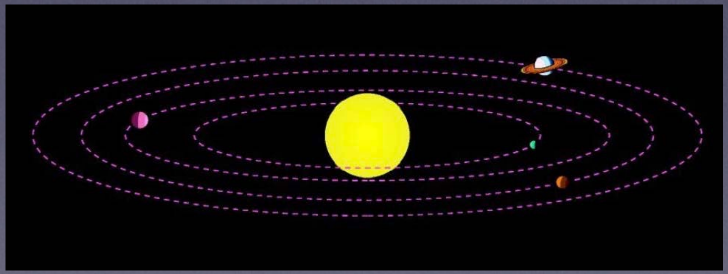


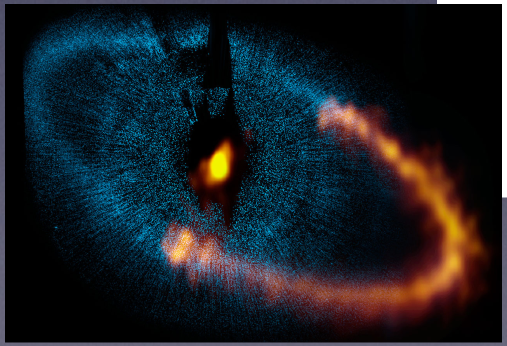
Core



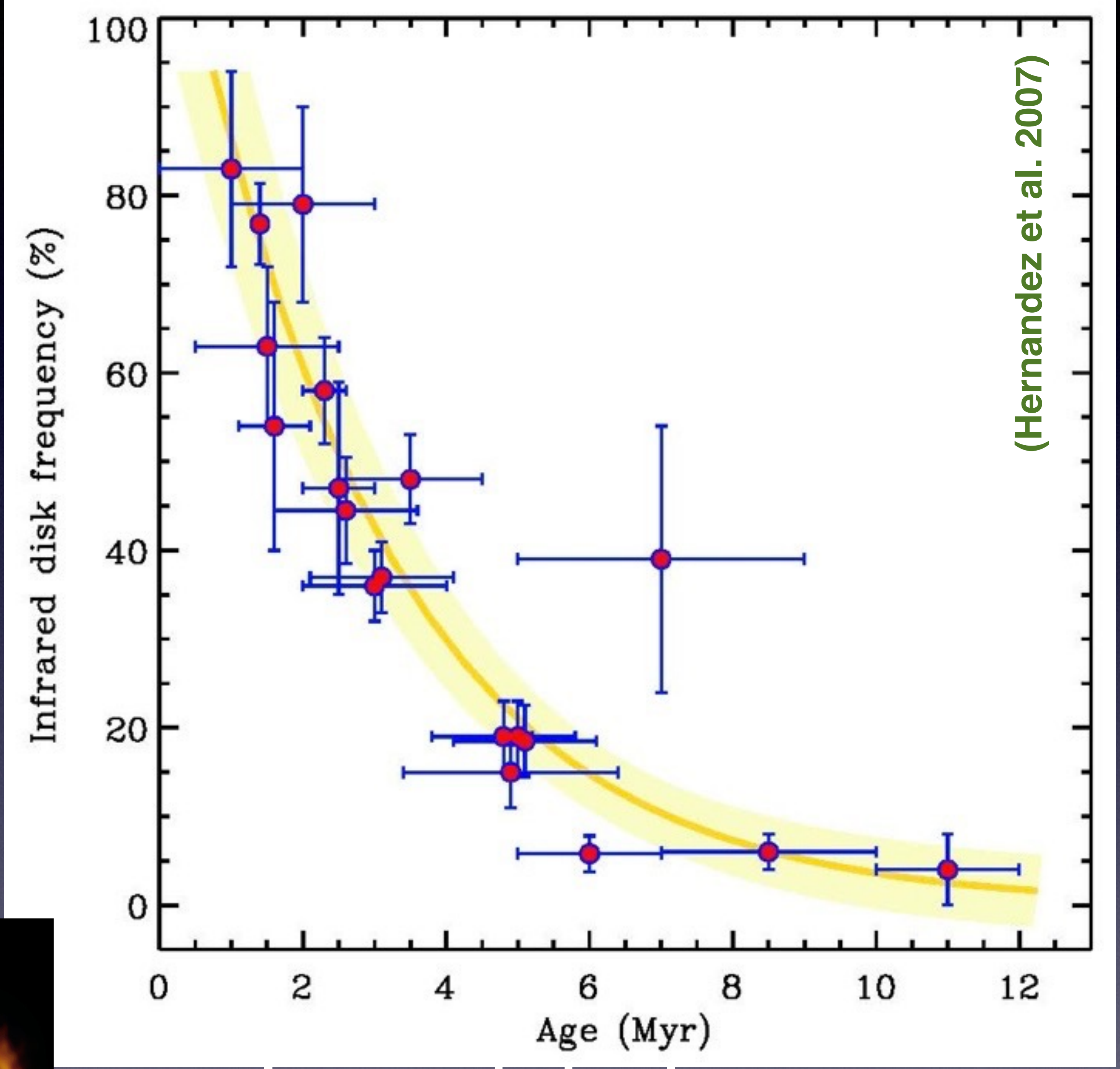
Disk







Debris Disk



(Hernandez et al. 2007)

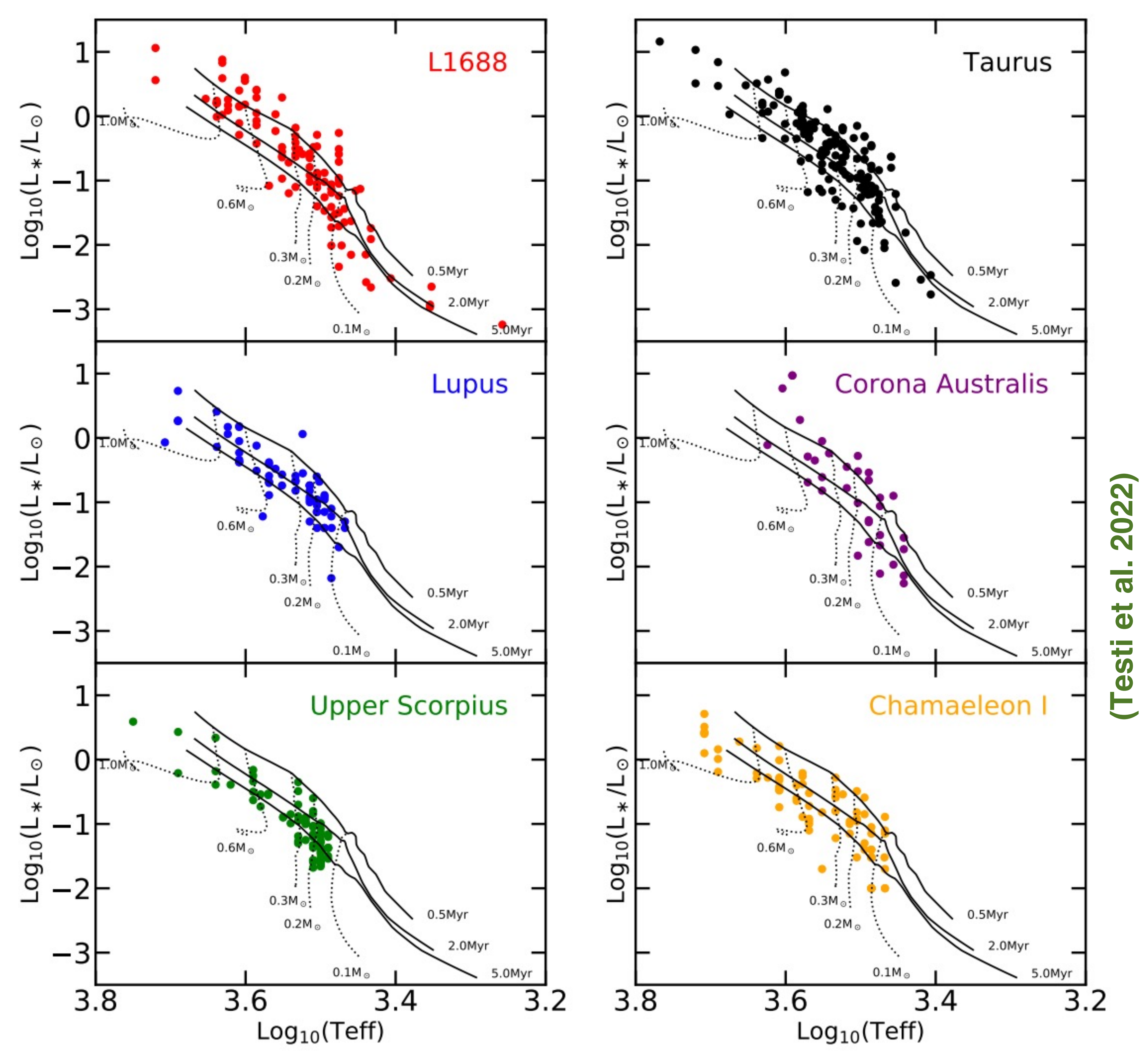
Inner disk clearing:
e-folding time t~2-3 Myr

Stellar parameters

~1Myr

~2Myr

~5Myr



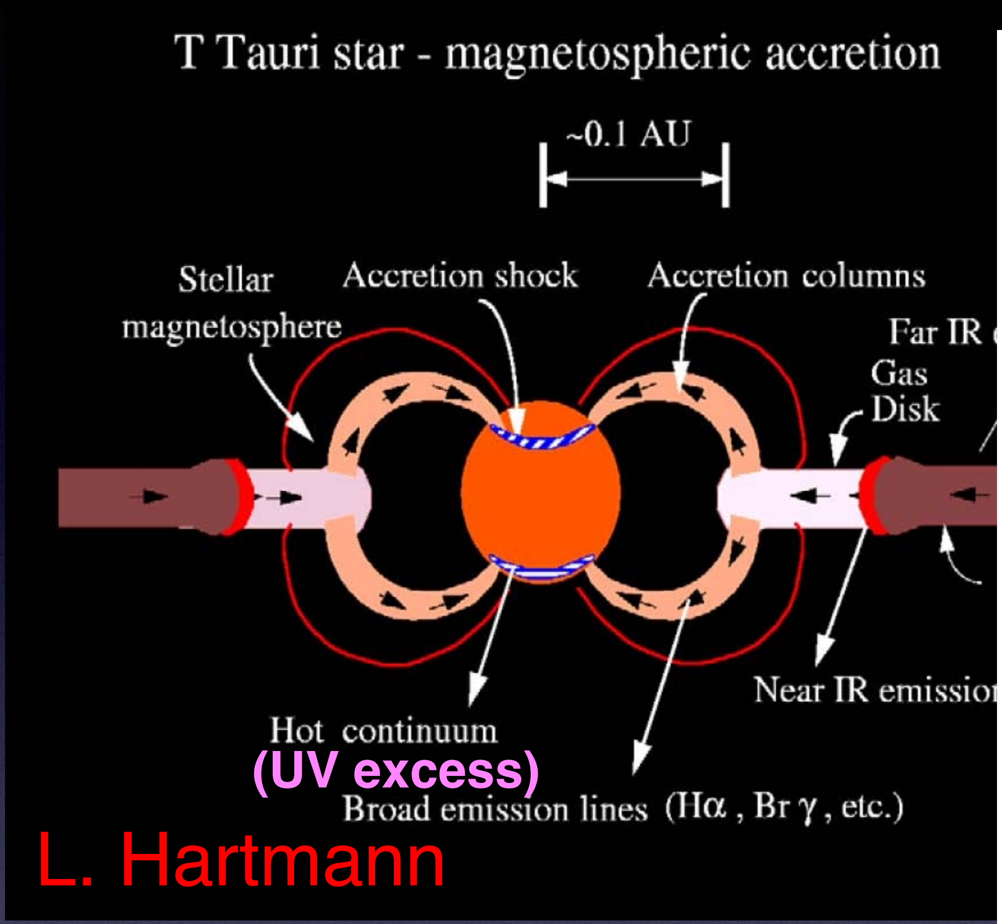
(Testi et al. 2022)

~0.9Myr

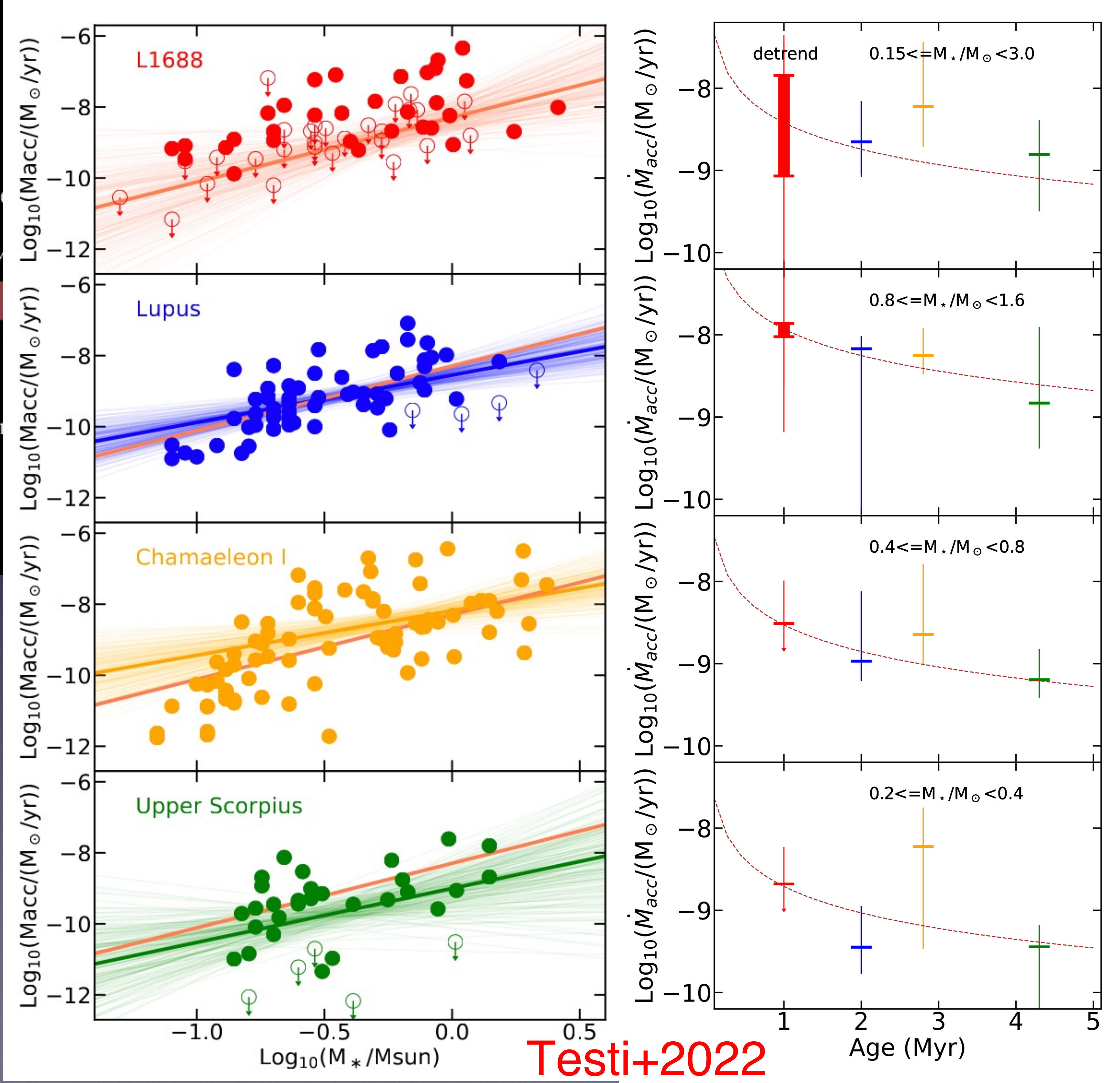
~0.6Myr

~3Myr

Accretion



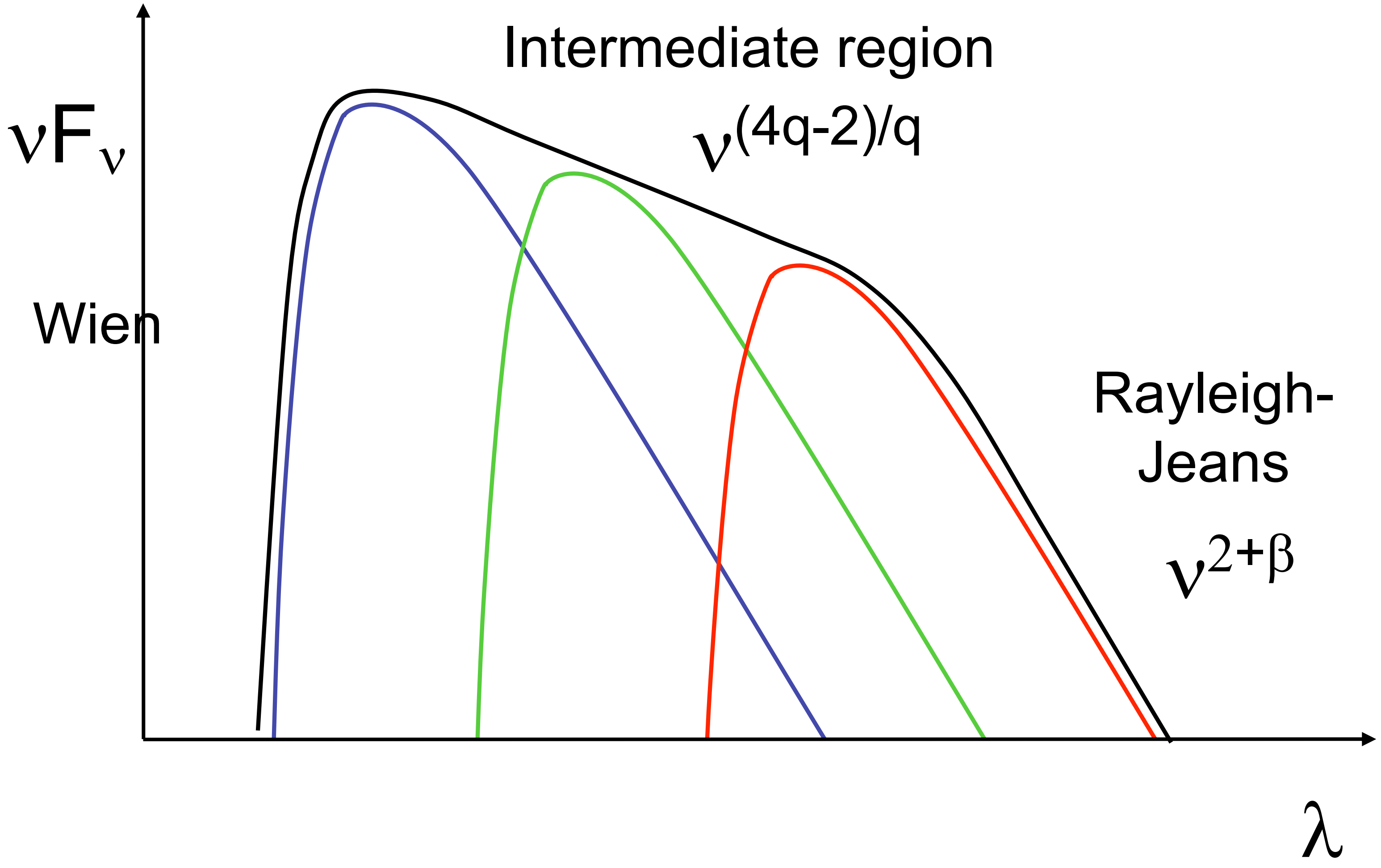
L. Hartmann

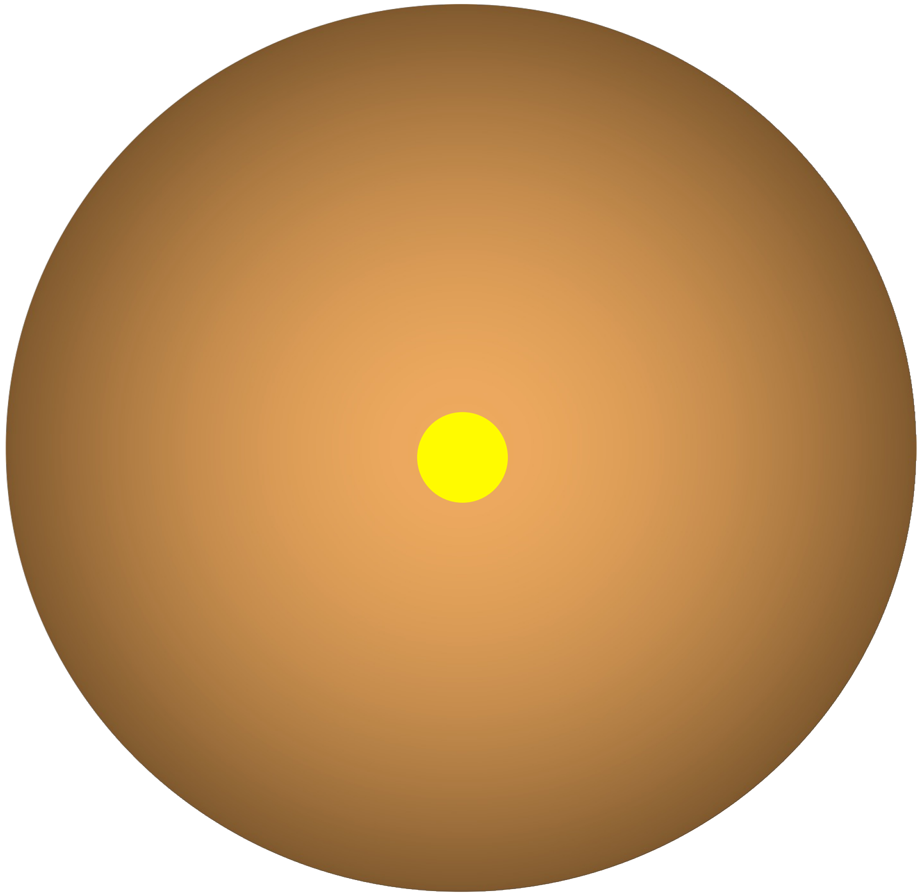


Testi+2022

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

SED for a locally isothermal disk





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

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

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

$\tau_\nu << 1$

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

$T_d \sim$ const.

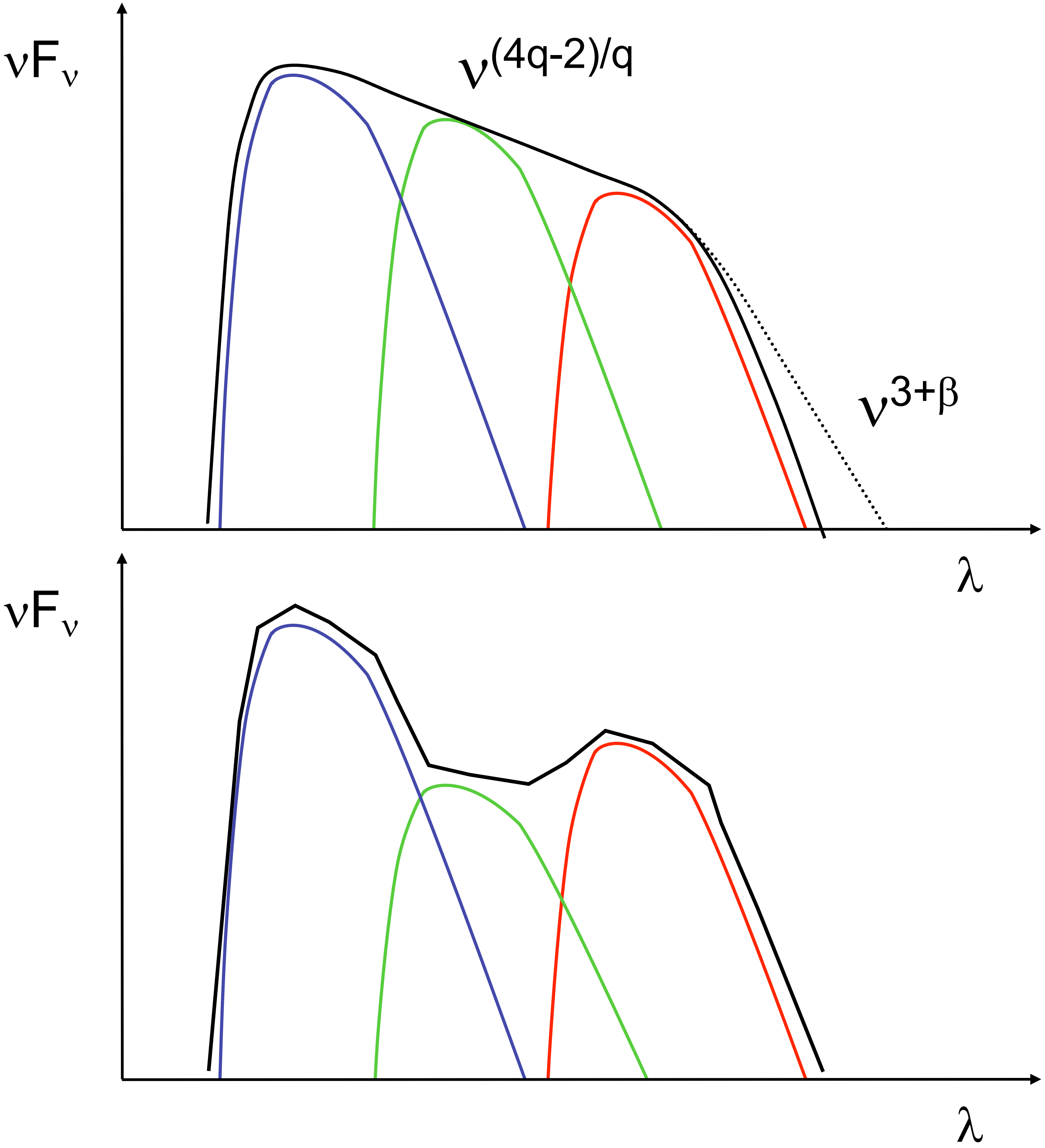
If $\tau_\nu \ll 1$:

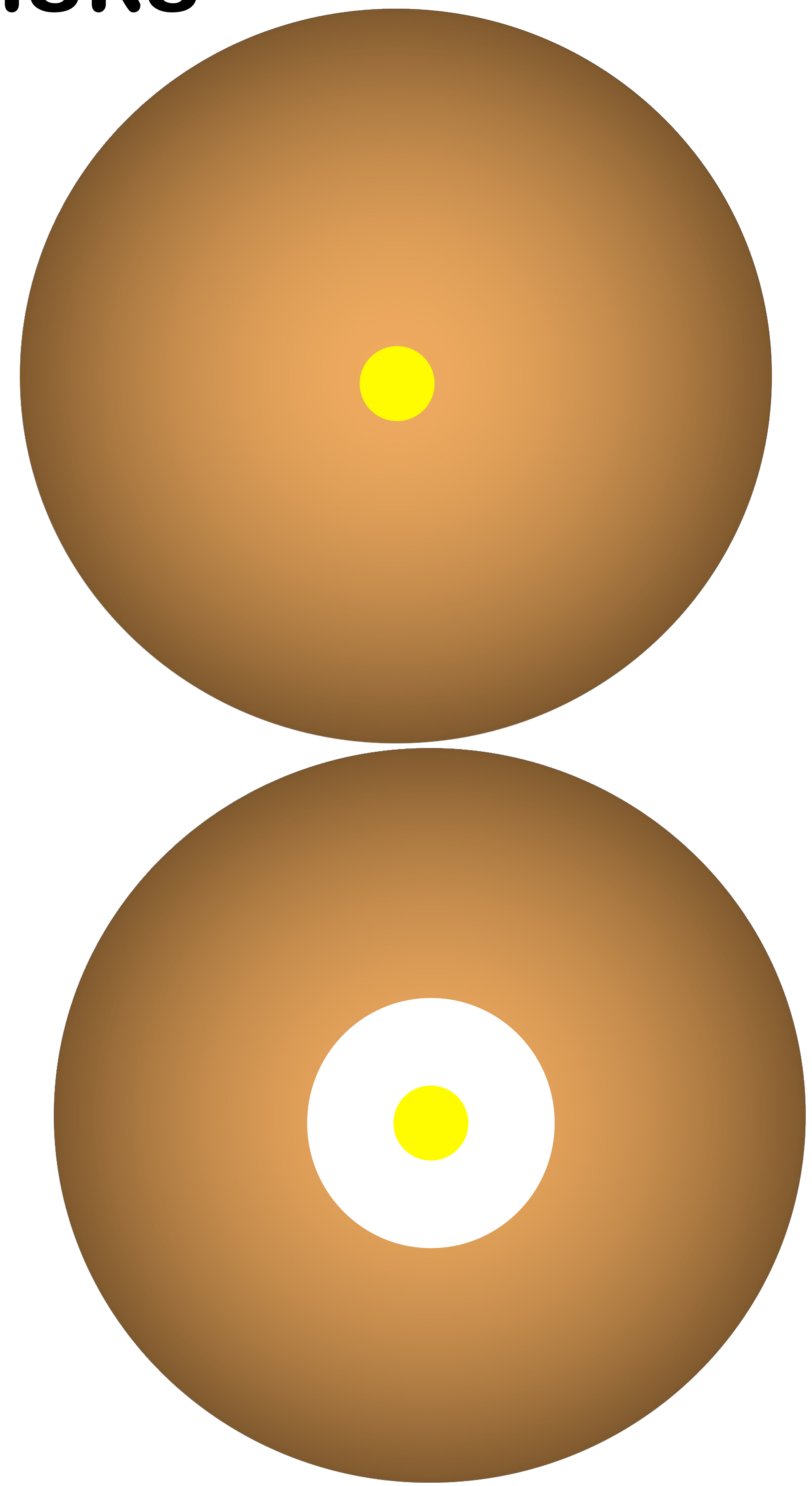
$$F_\nu \propto \kappa_\nu \times B_\nu(T_d) \times M_d$$

If $\tau_\nu \gg 1$:

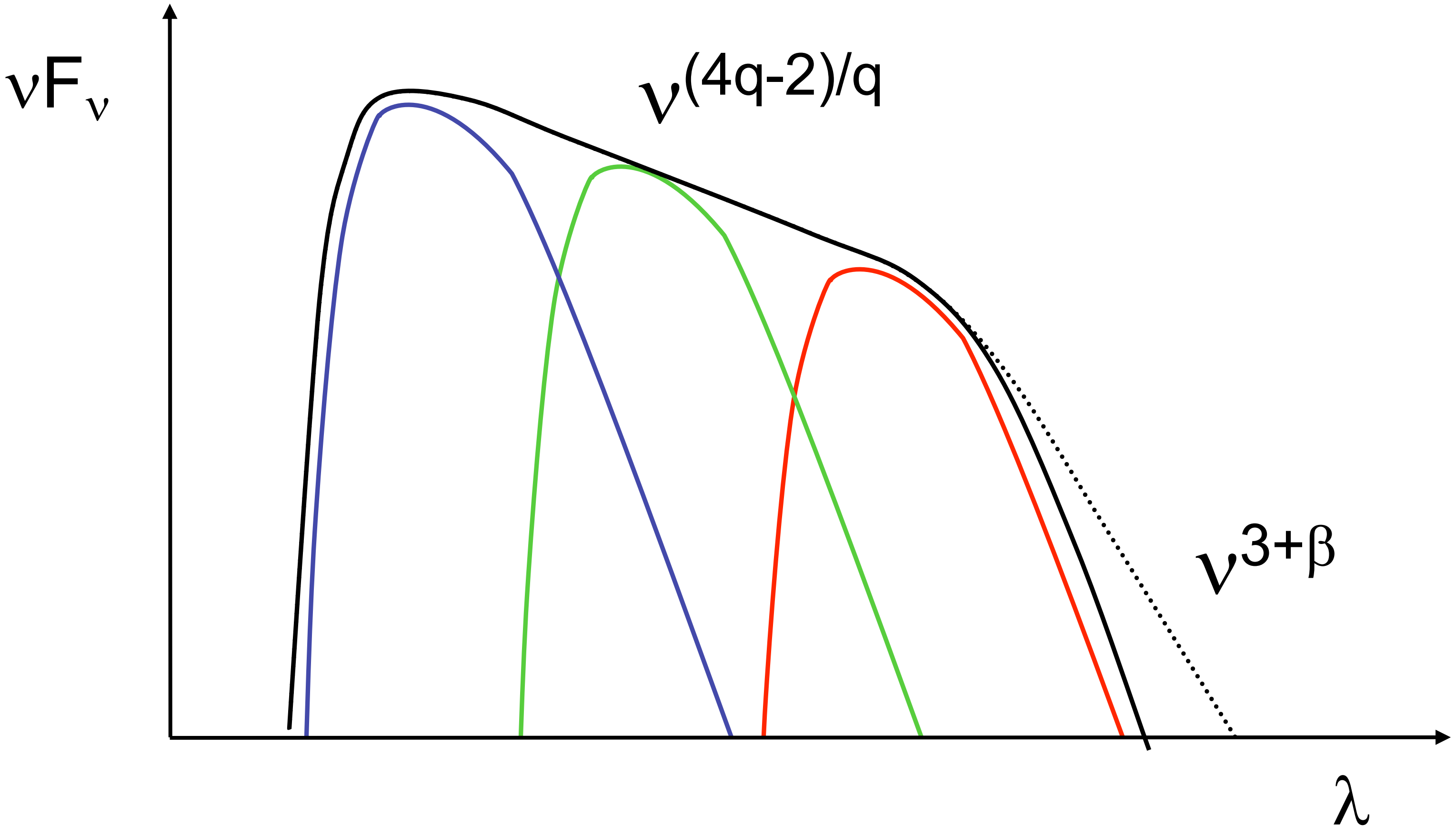
$$F_\nu \propto B_\nu(T_d) \times Area$$

Consequence: SED signature for Transition Disks





SED of a locally isothermal disk



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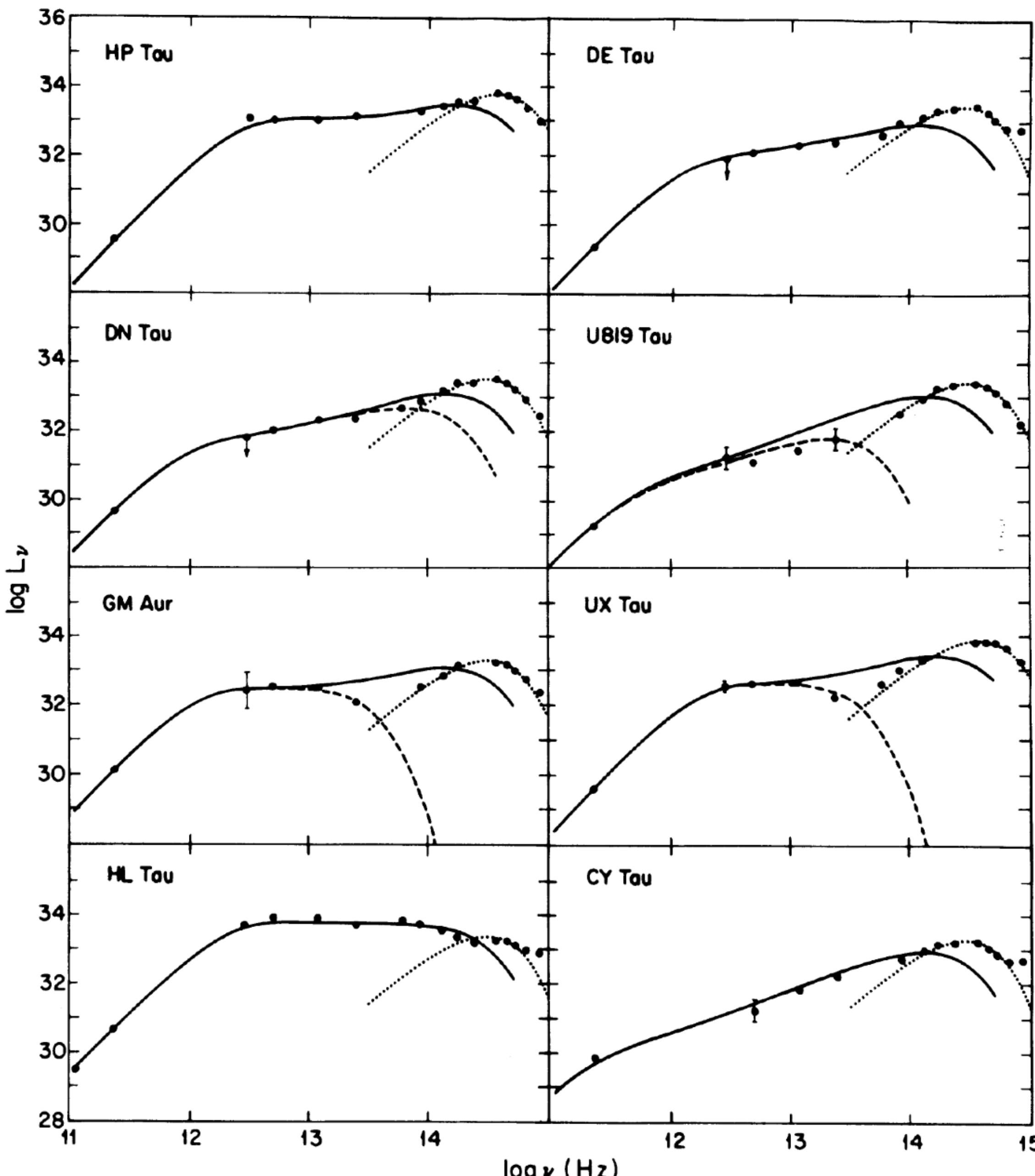
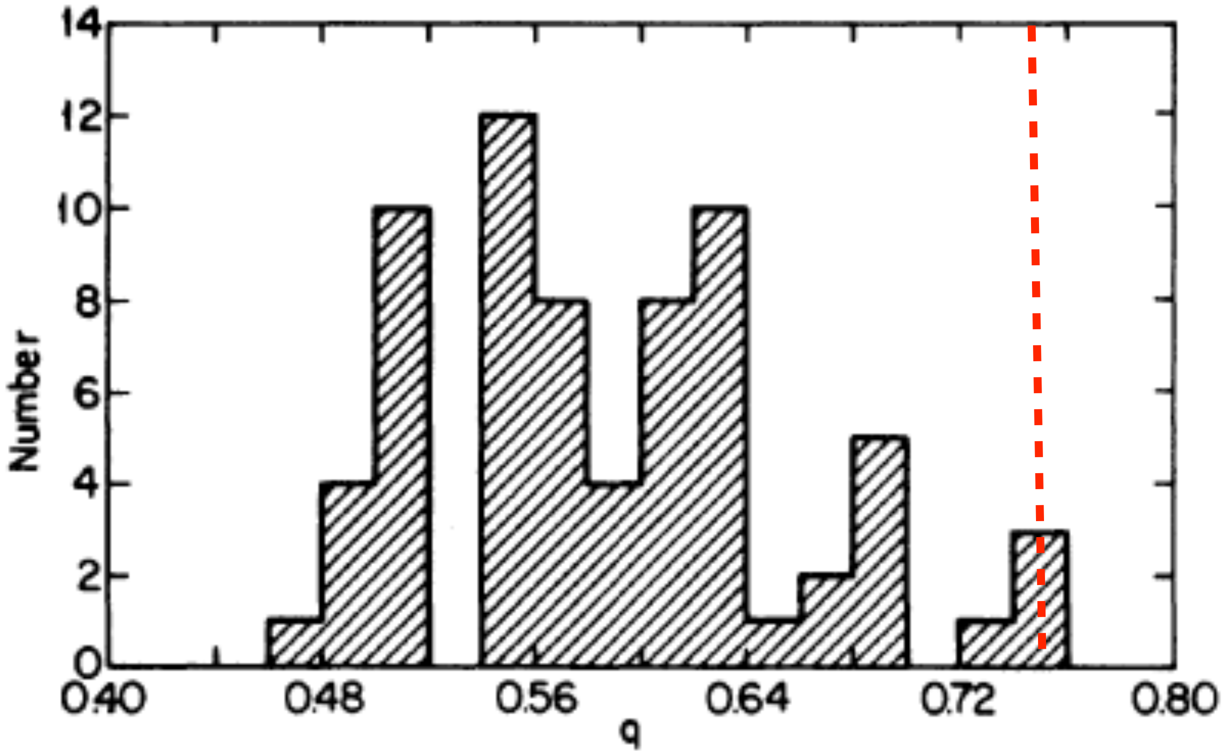
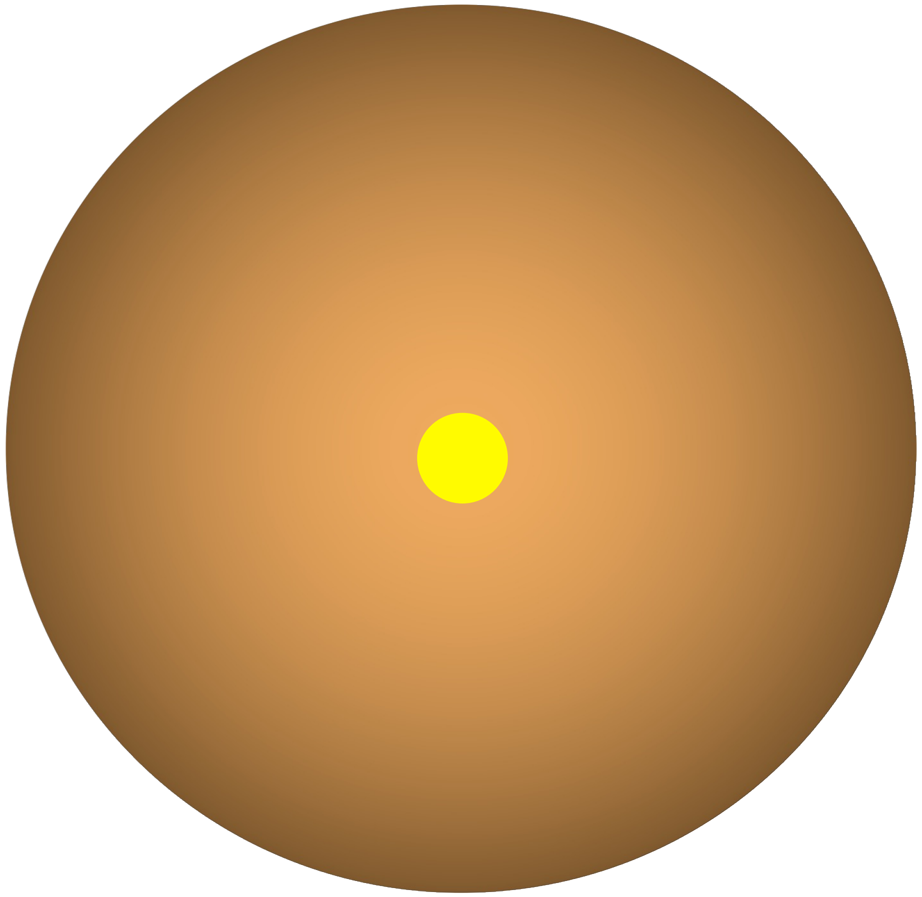
Beckwith+ 1991



SED for a locally isothermal disk



Beckwith et al. (1991)



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

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

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

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:

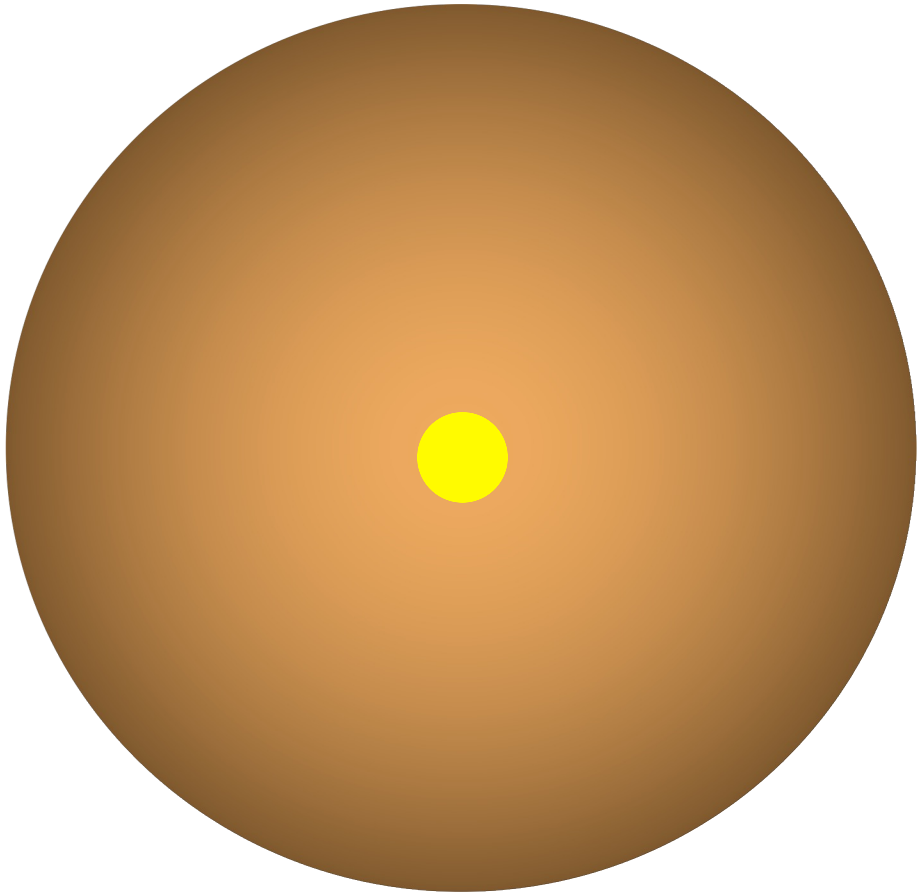
$$F_{\text{irr}} = \alpha \frac{L_*}{4\pi r^2}$$

The flaring angle:

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

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

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



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

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

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“flared” passive disk

Irradiation flux:

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

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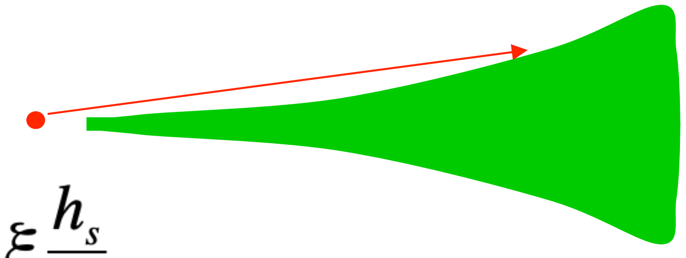
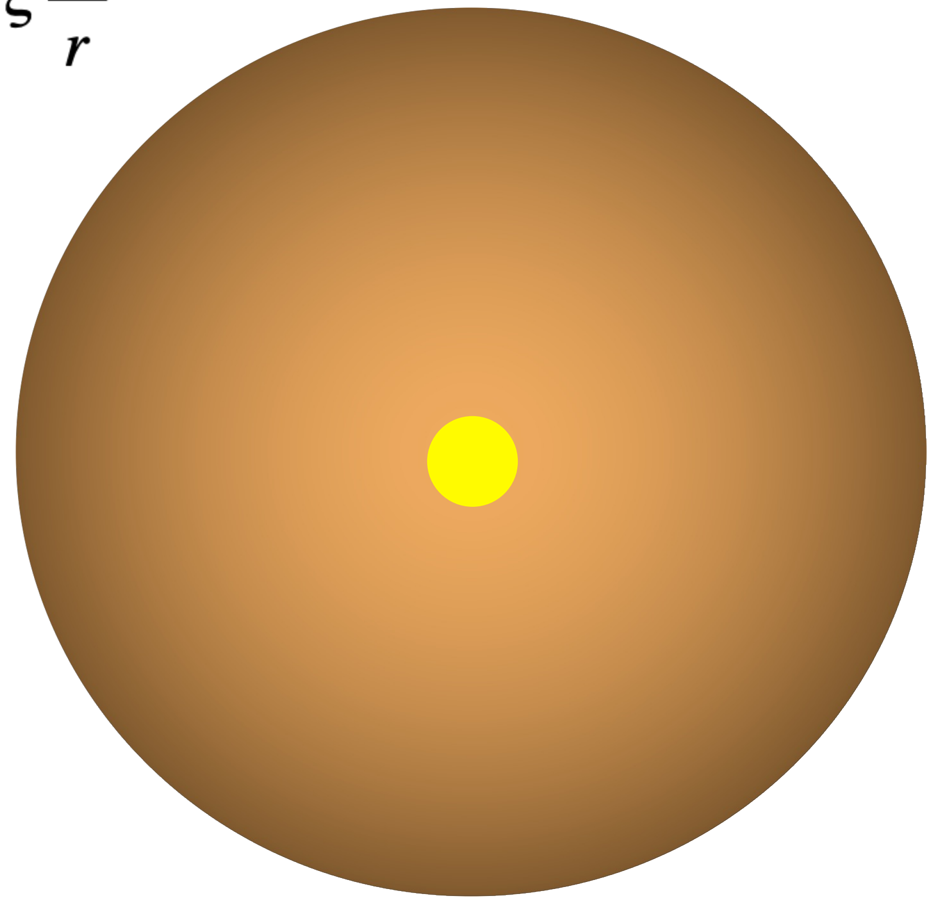


$$\alpha = r\frac{\partial}{\partial r}\left(\frac{h_s}{r}\right) \rightarrow \xi \frac{h_s}{r}$$

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

$$h_s = \chi h$$



Can work…

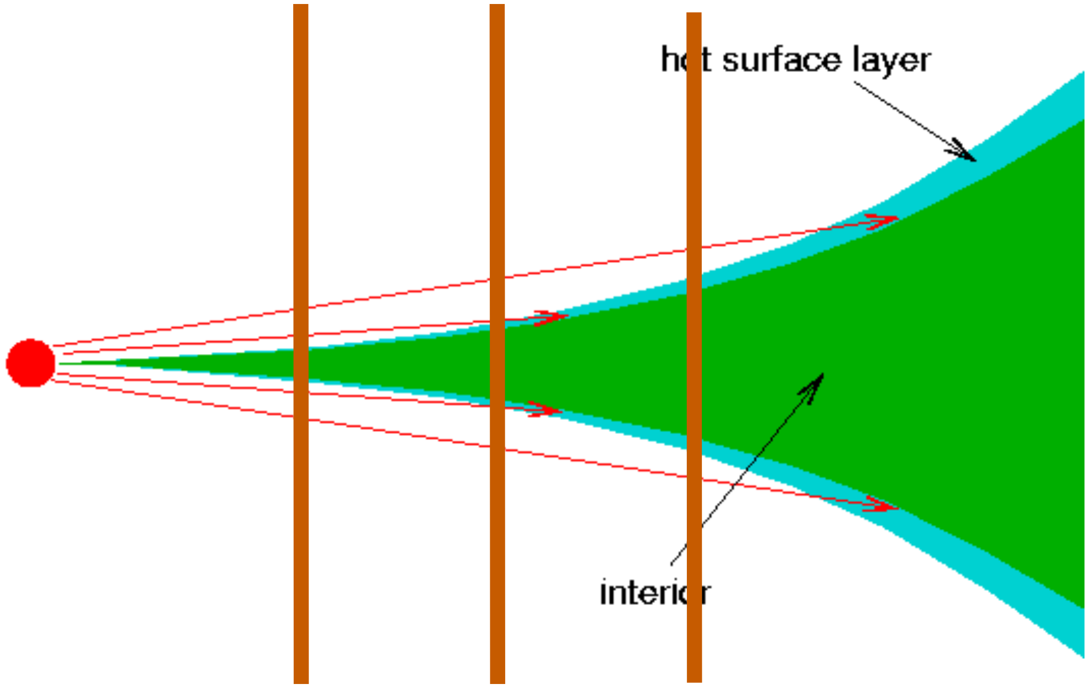
…depending on $h_s(r)$

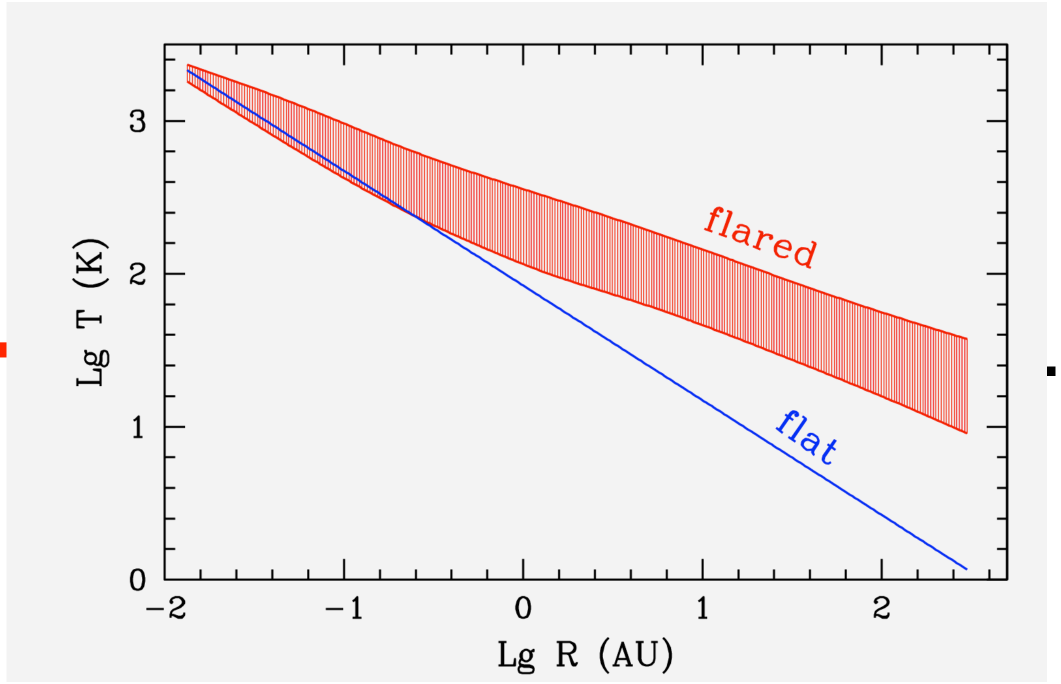
$$F_\nu = \frac{cos\theta}{D^2}\int_{r_i}^{r_o} B_\nu(T_d)(1-e^{-\tau_\nu})2\pi r dr$$

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

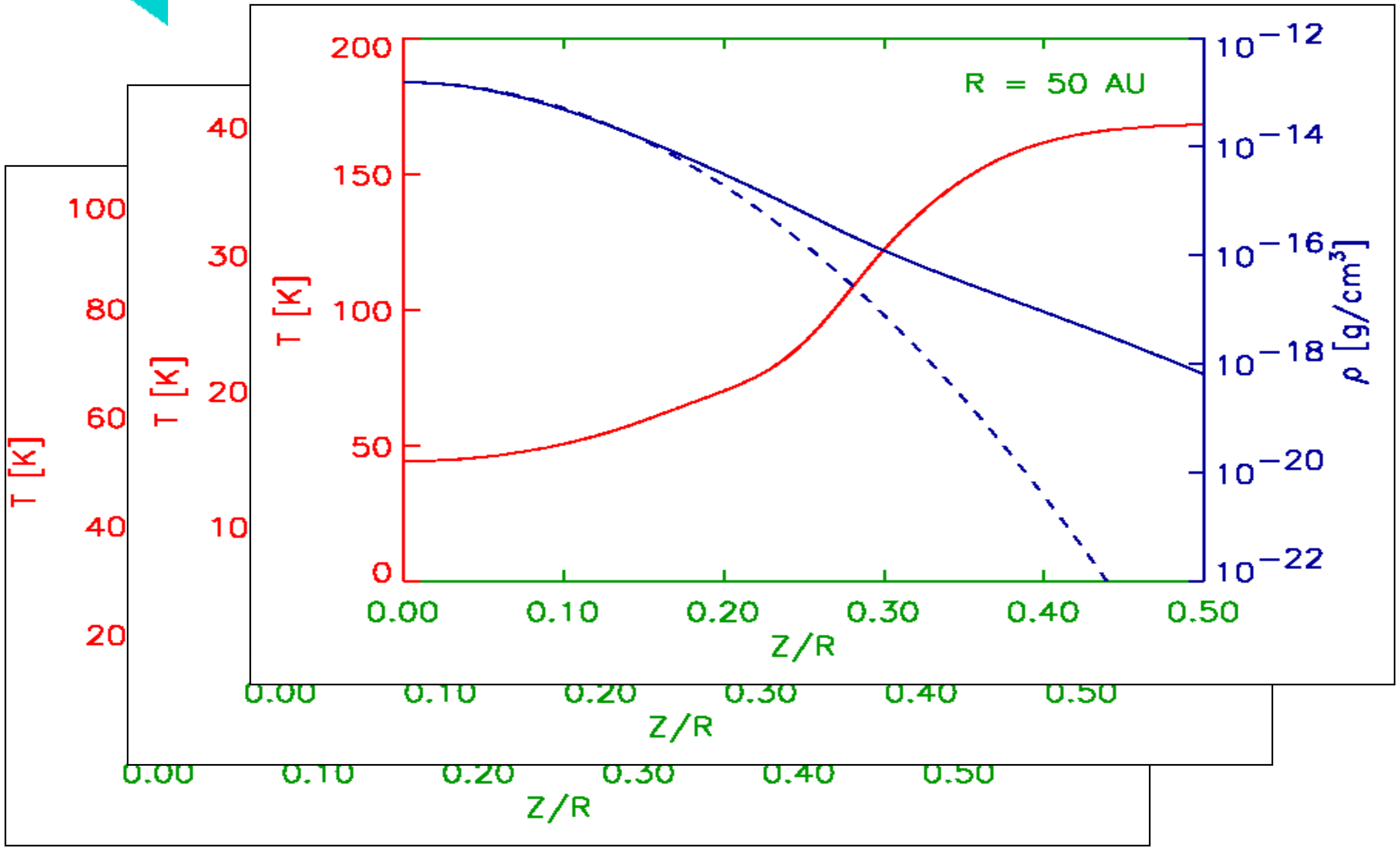
$\tau_\nu \propto \Sigma(r)\kappa_\nu$ $\Sigma(r) \propto r^{-p}$ $\kappa_\nu \propto \kappa_o \nu^\beta$

Flared disks: detailed models



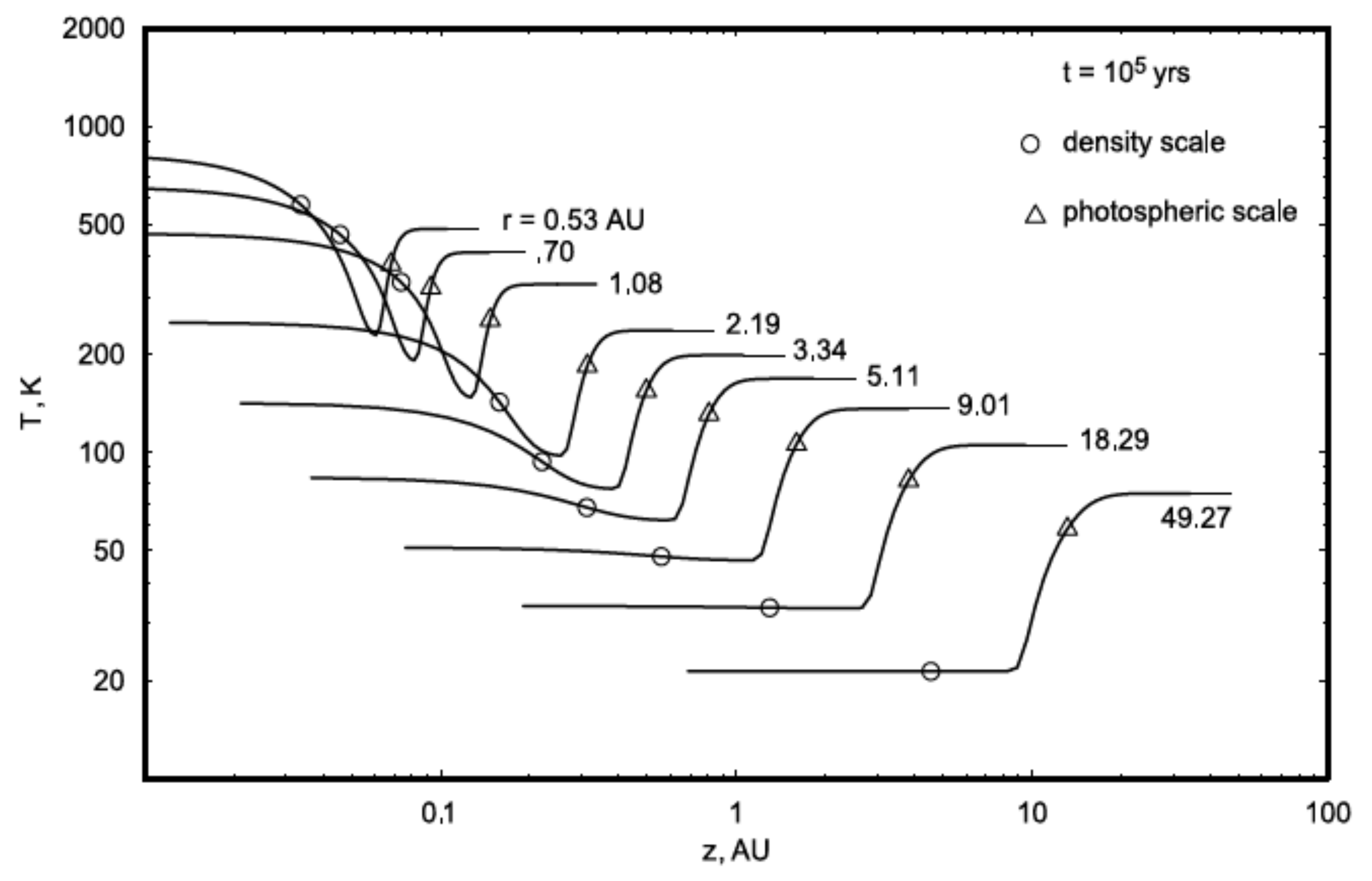


... consists of vertical slices, each forming a 1D problem. All slices are independent from each other.

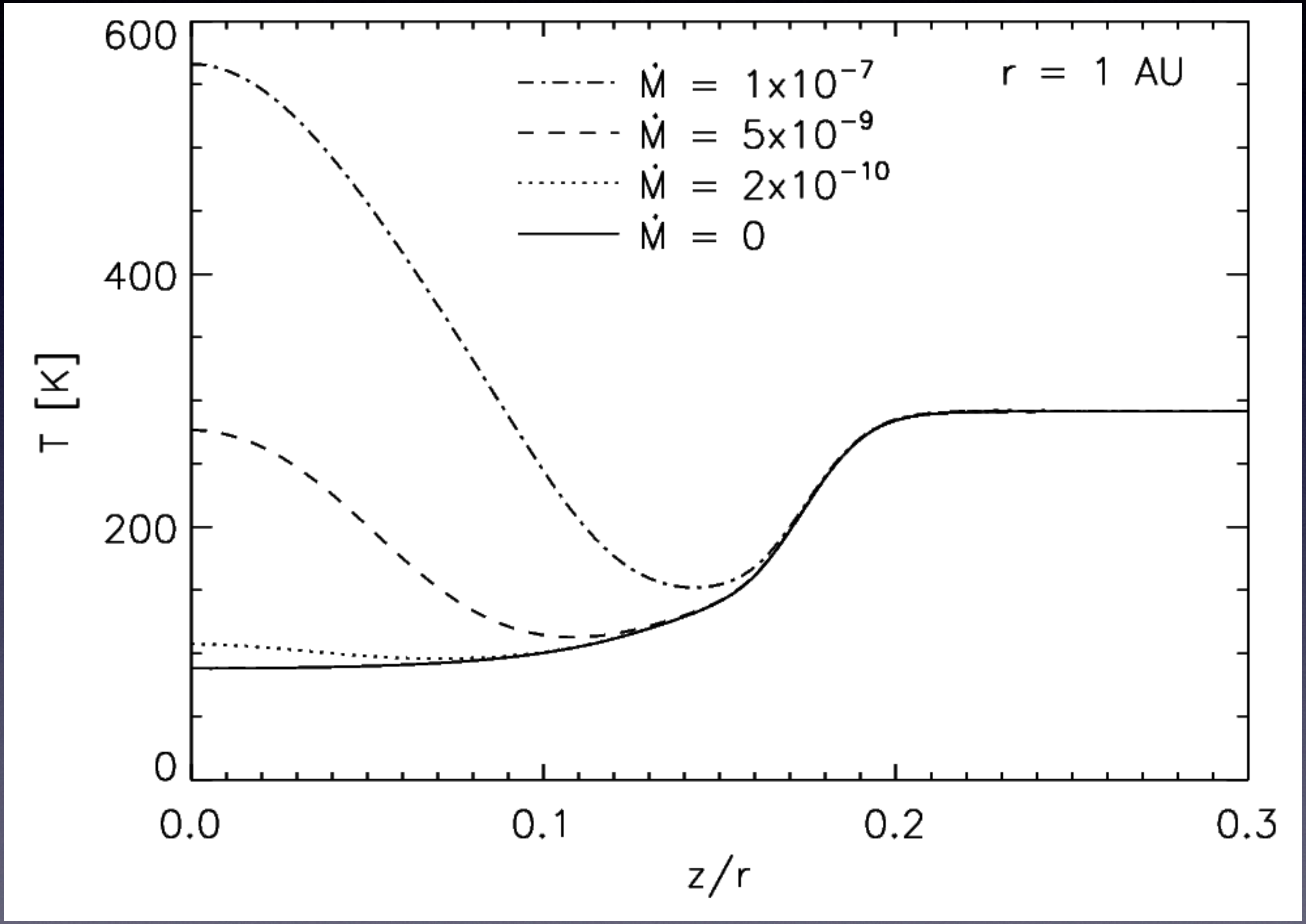


[K. Dullemond]

Including viscous heating



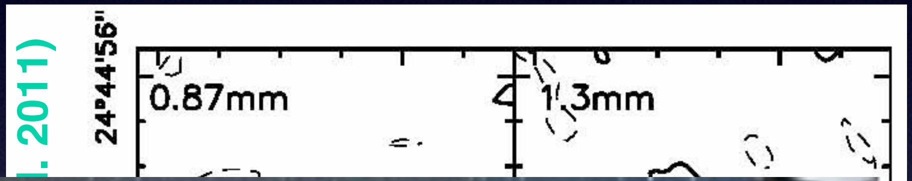
Including viscous heating



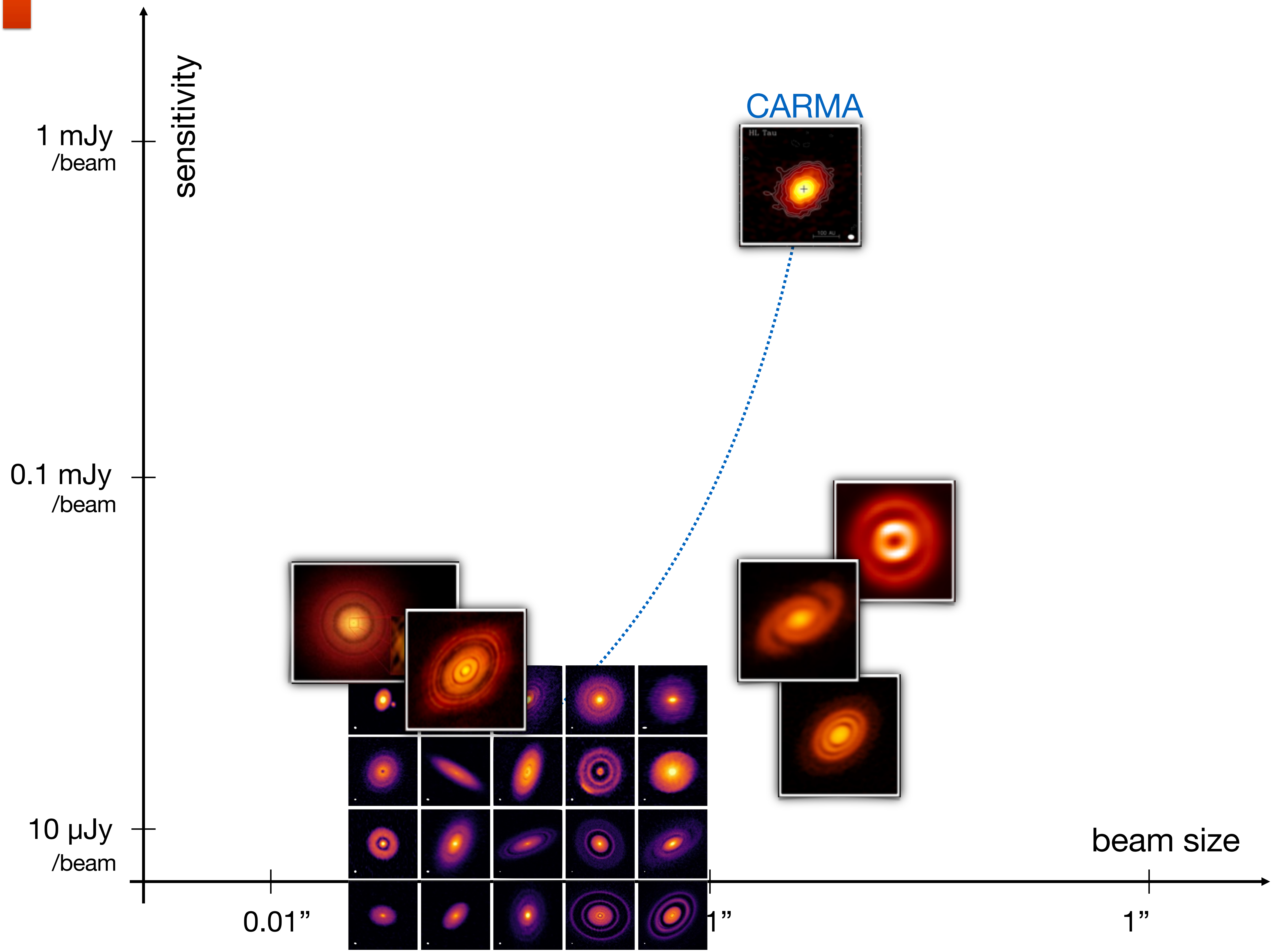
(M_{acc}~10^{-8} M_{sun}/yr @ 1 Myr)

Resolving disk structure

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

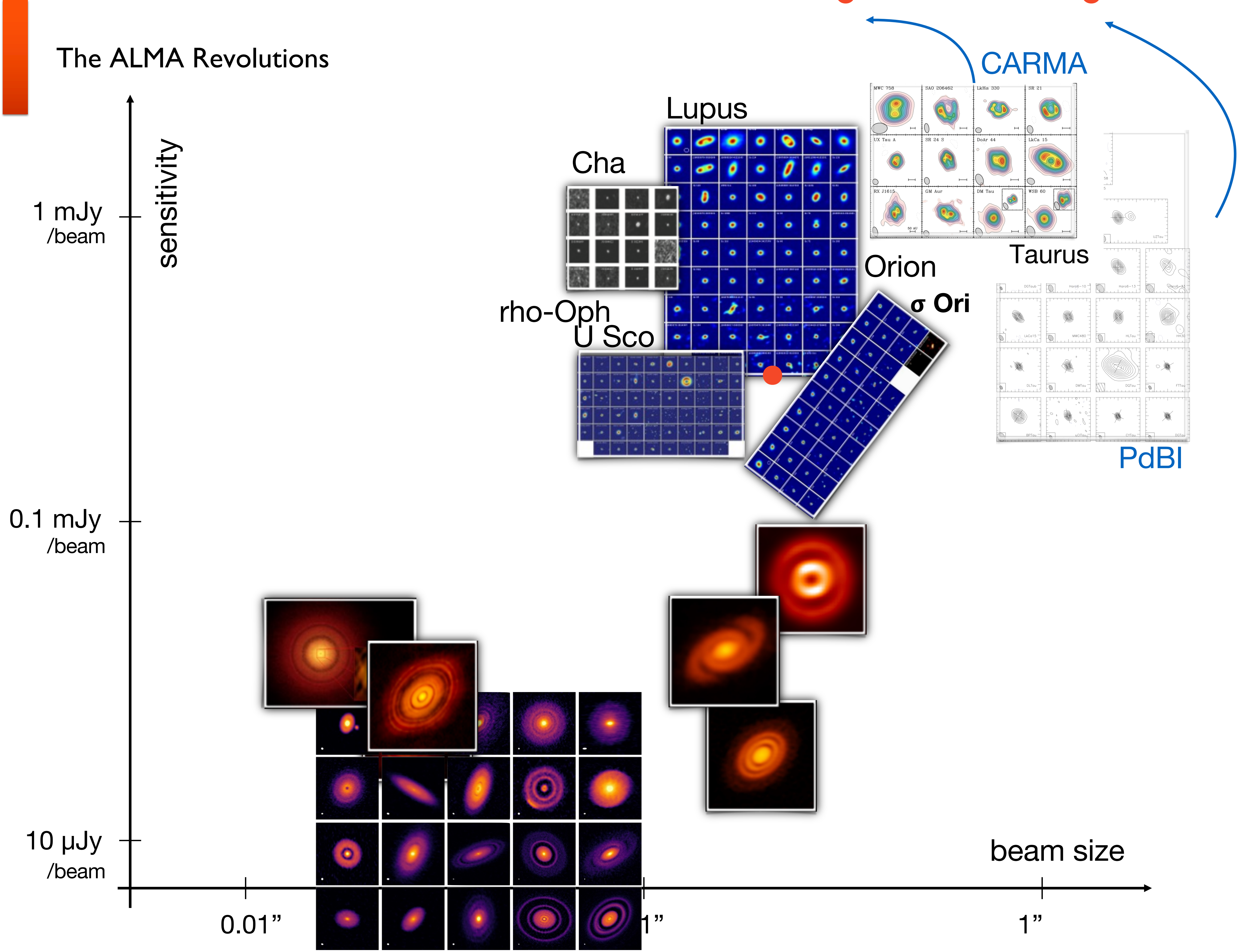


The ALMA Revolutions



(slide thanks to M. Tazzari)

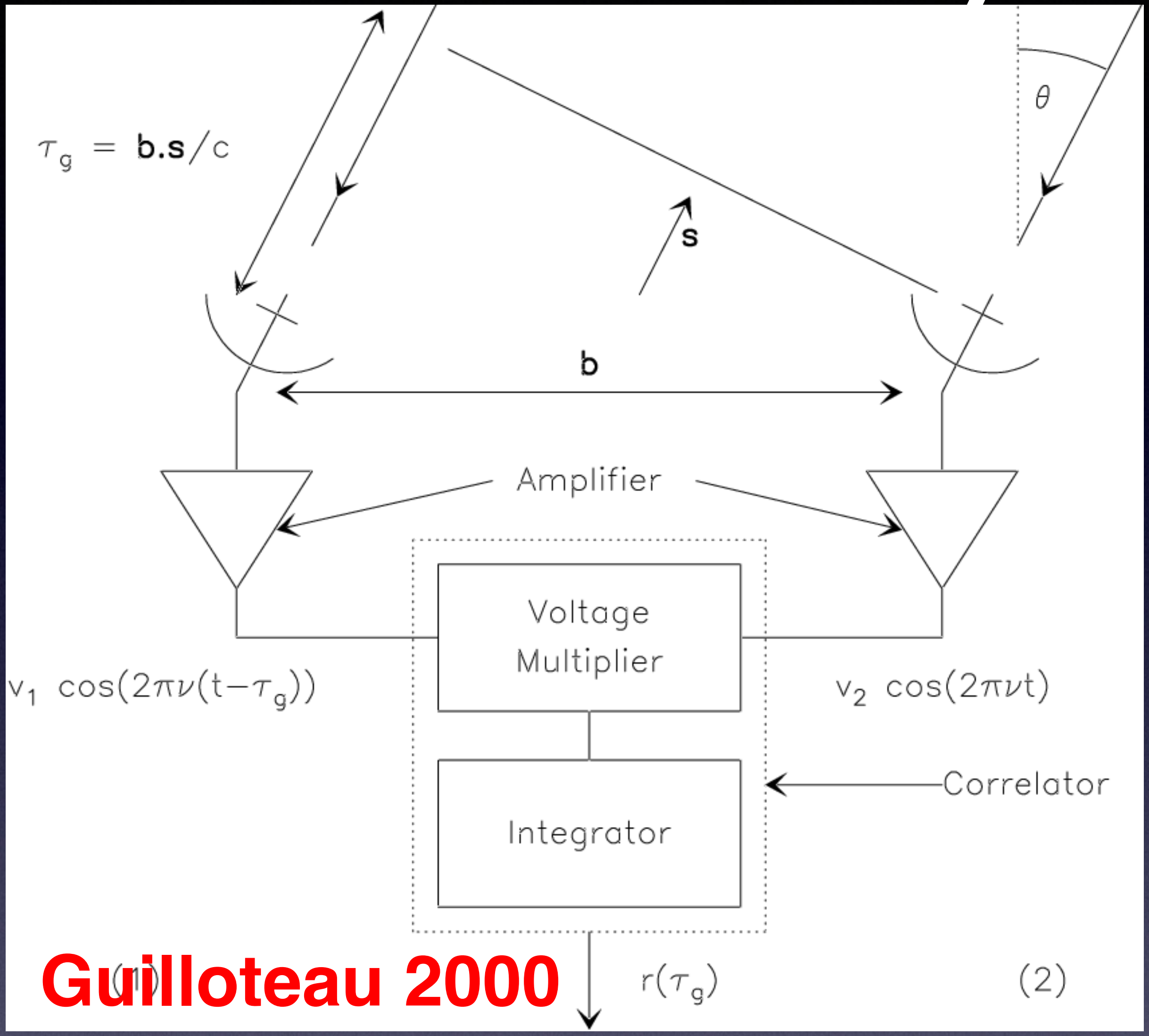
The ALMA Revolutions



(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)



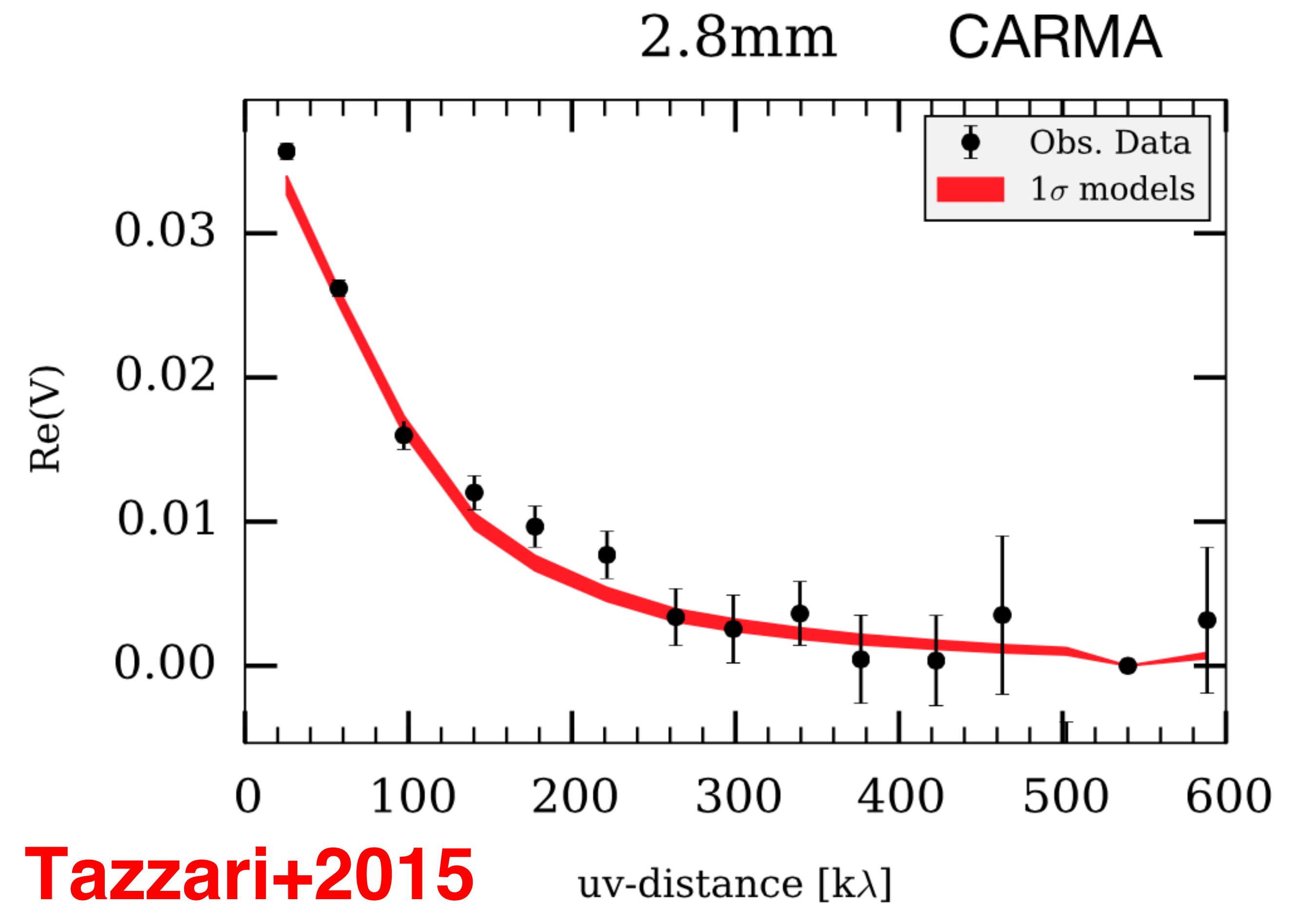
Guilloteau 2000

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

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

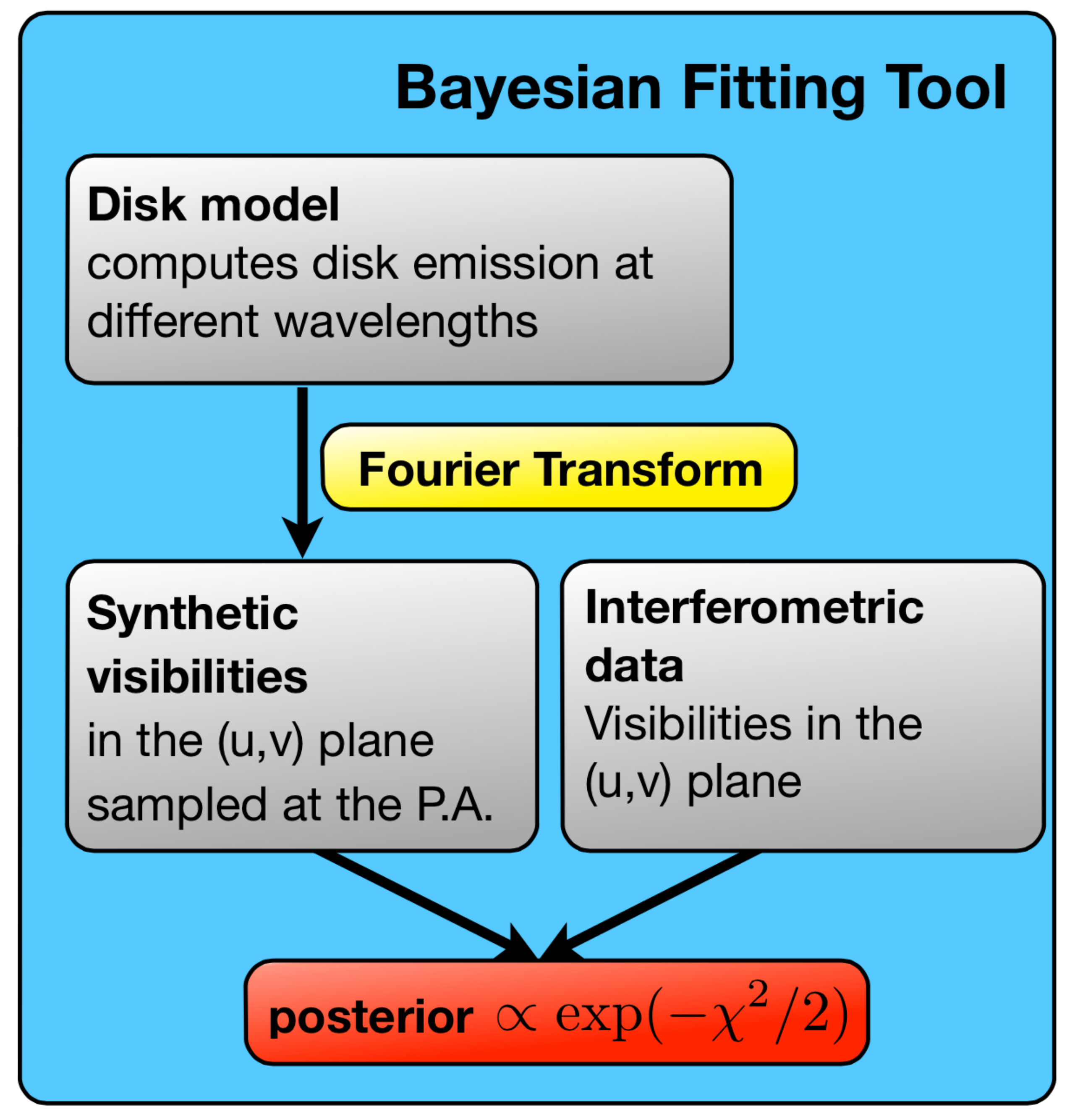
P(x,y)=Antenna power pattern I(x,y)=Brightness distribution on Sky

Analysis of interferometric data



Tazzari+2015

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



Bayesian Fitting Tool

Disk model
computes disk emission at different wavelengths

Fourier Transform

Synthetic visibilities
in the (u,v) plane sampled at the P.A.

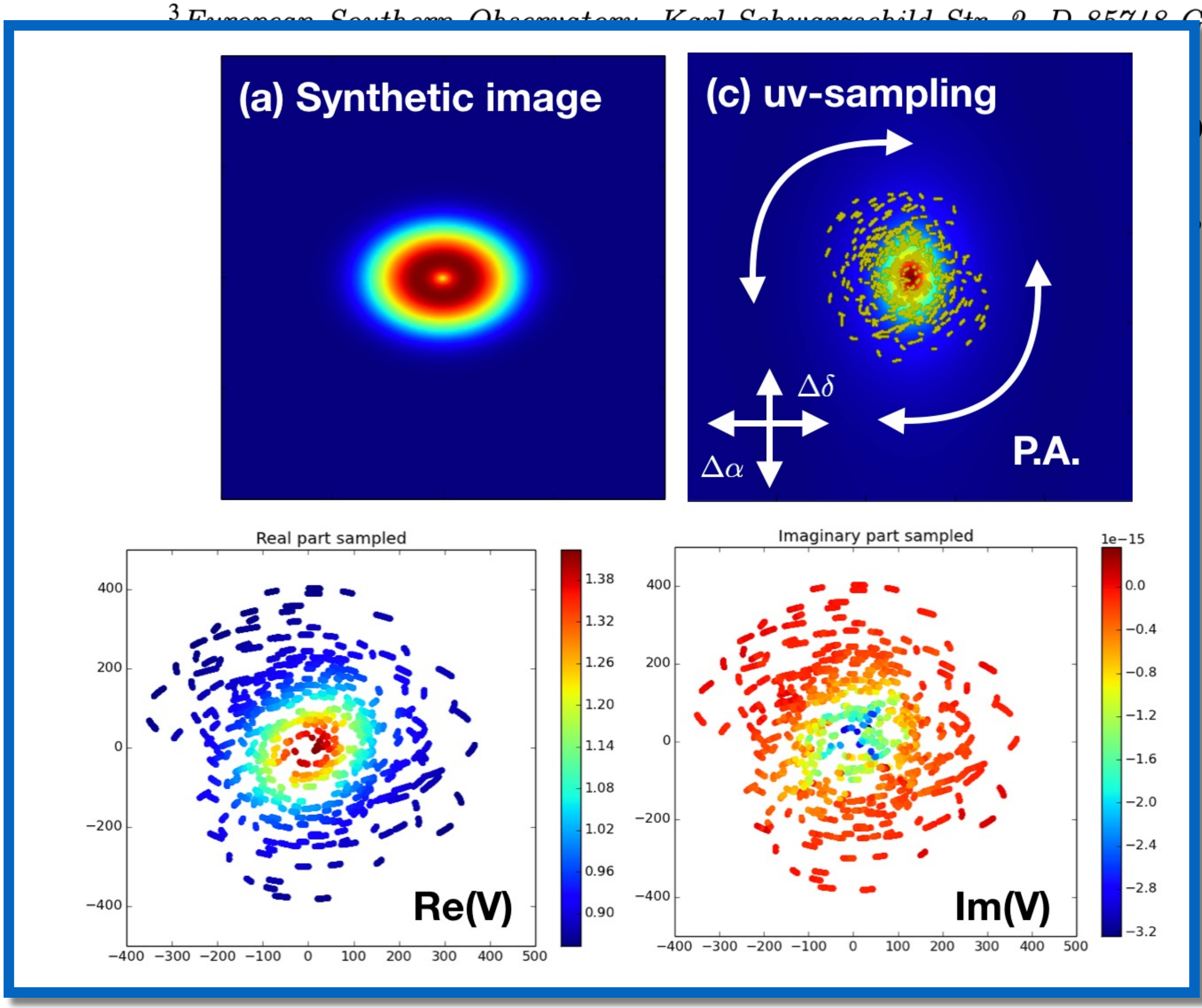
Interferometric data
Visibilities in the (u,v) plane

posterior $\propto \exp(-\chi^2/2)$

- 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

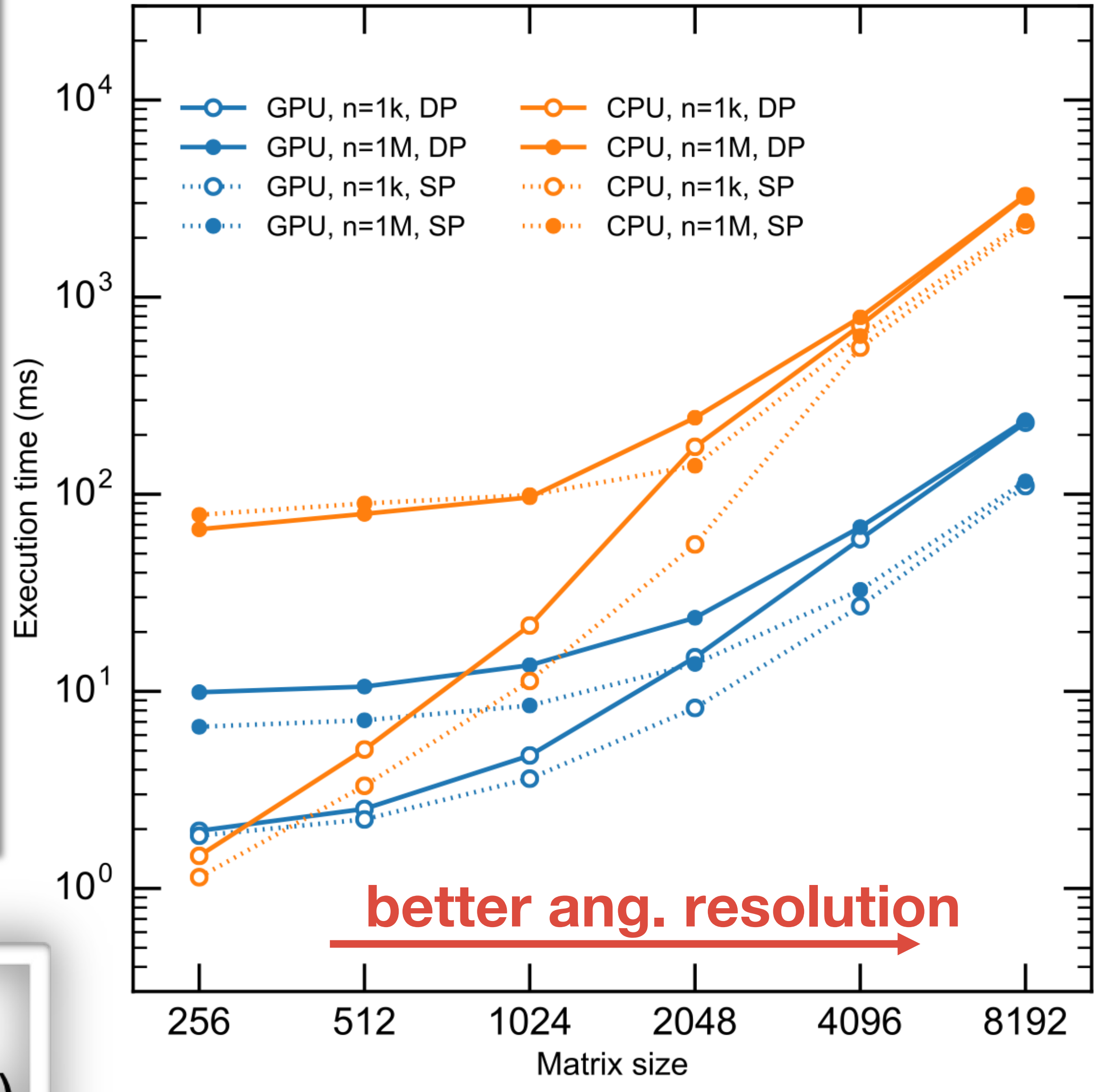
Marco Tazzari[1]⋆, Frederik Beaujean[2] and Leonardo Testi[2,3]
[1] Institute of Astronomy, University of Cambridge, Madingley Road, CB3 0HA, Cambridge, UK
[2] Excellence Cluster Universe, Boltzmannstr. 2, D-85748 Garching, Germany
[3] European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748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

GALARIO

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

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:

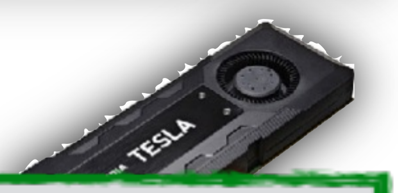
```
chi2 = chi2Image(image, dxy, u, v, ReV, ImV, w)
```

  - compute χ^2 from 1D profile:

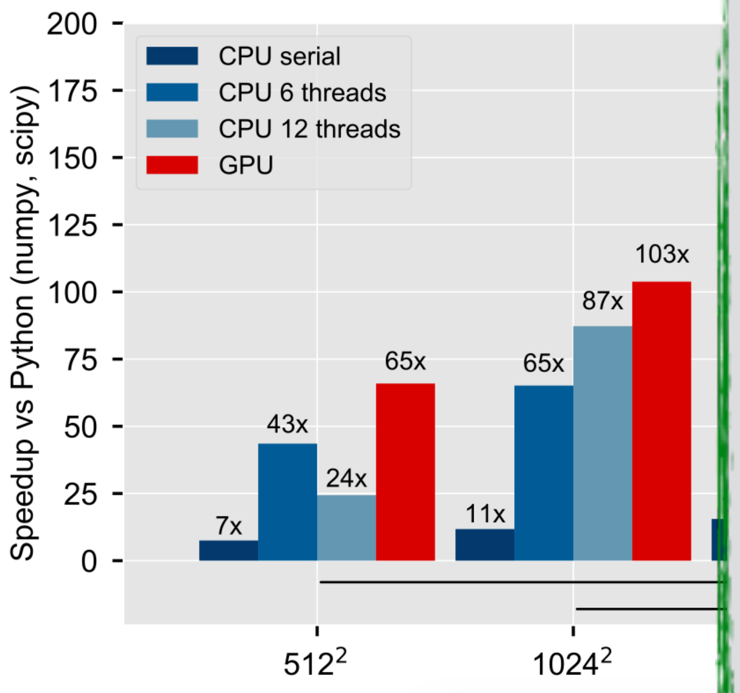
```
chi2 = chi2Profile(I, Rmin, dR, nxy, dxy, u, v, ReV, ImV, w)
```

- **Easy to install:**

```
conda install -c conda_forge galario
```



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



- **Simple switch to GPU:**

```
import galar
```

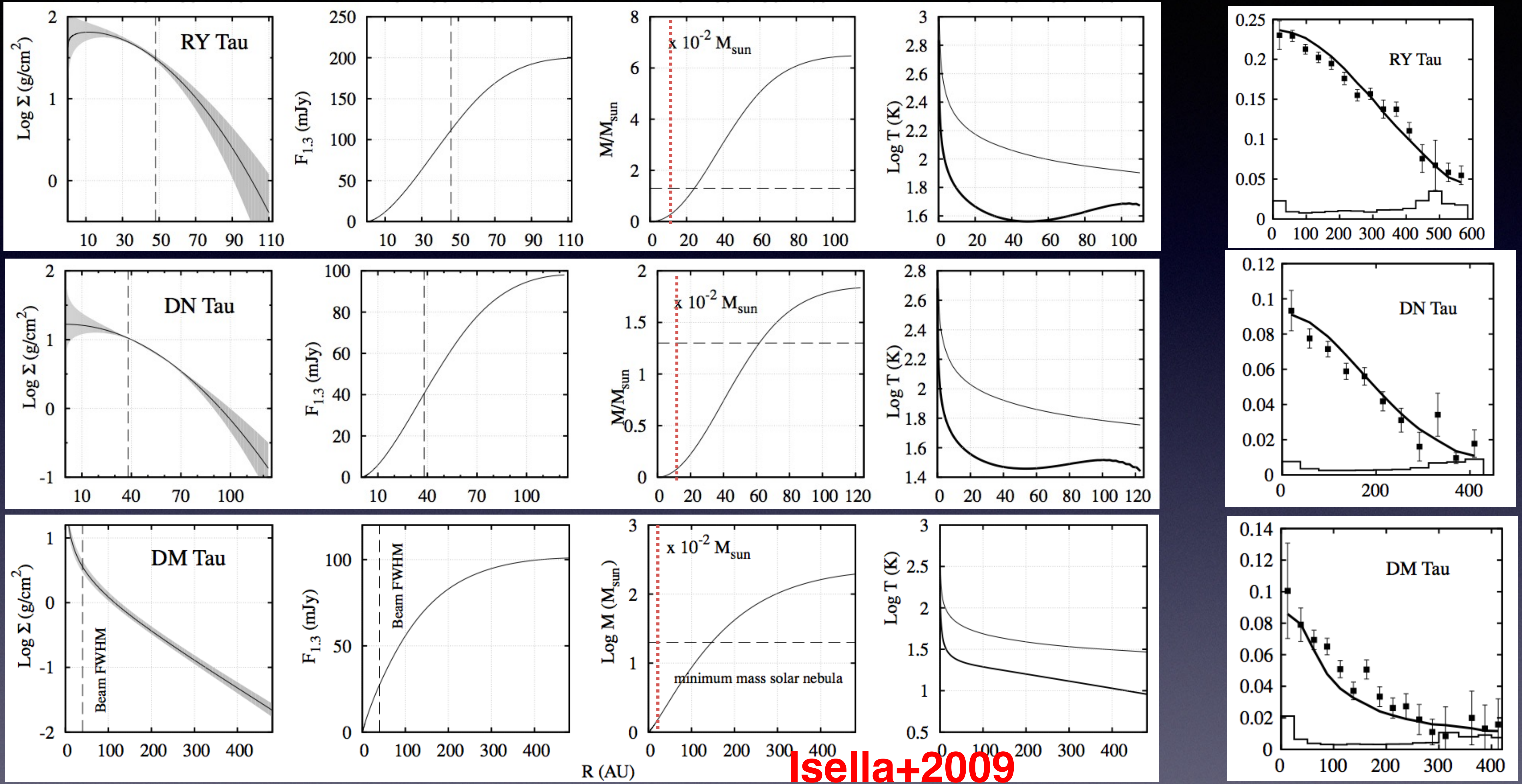
- **many applications:**
  - **protoplanetary** disks
  - **debris** disks
  - **high redshift** galaxies
  - **massive** stars cores

- **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

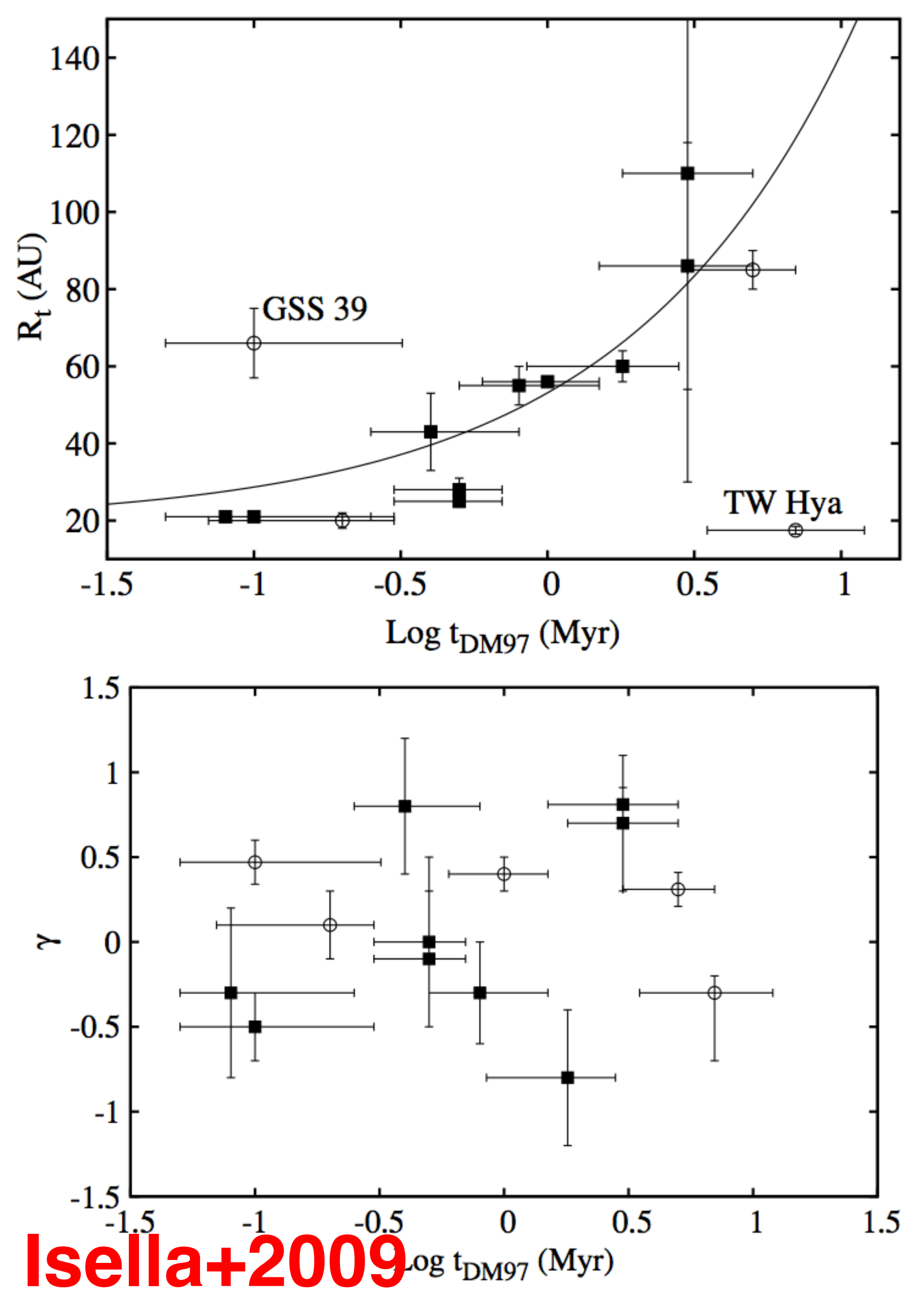


Isella+2009

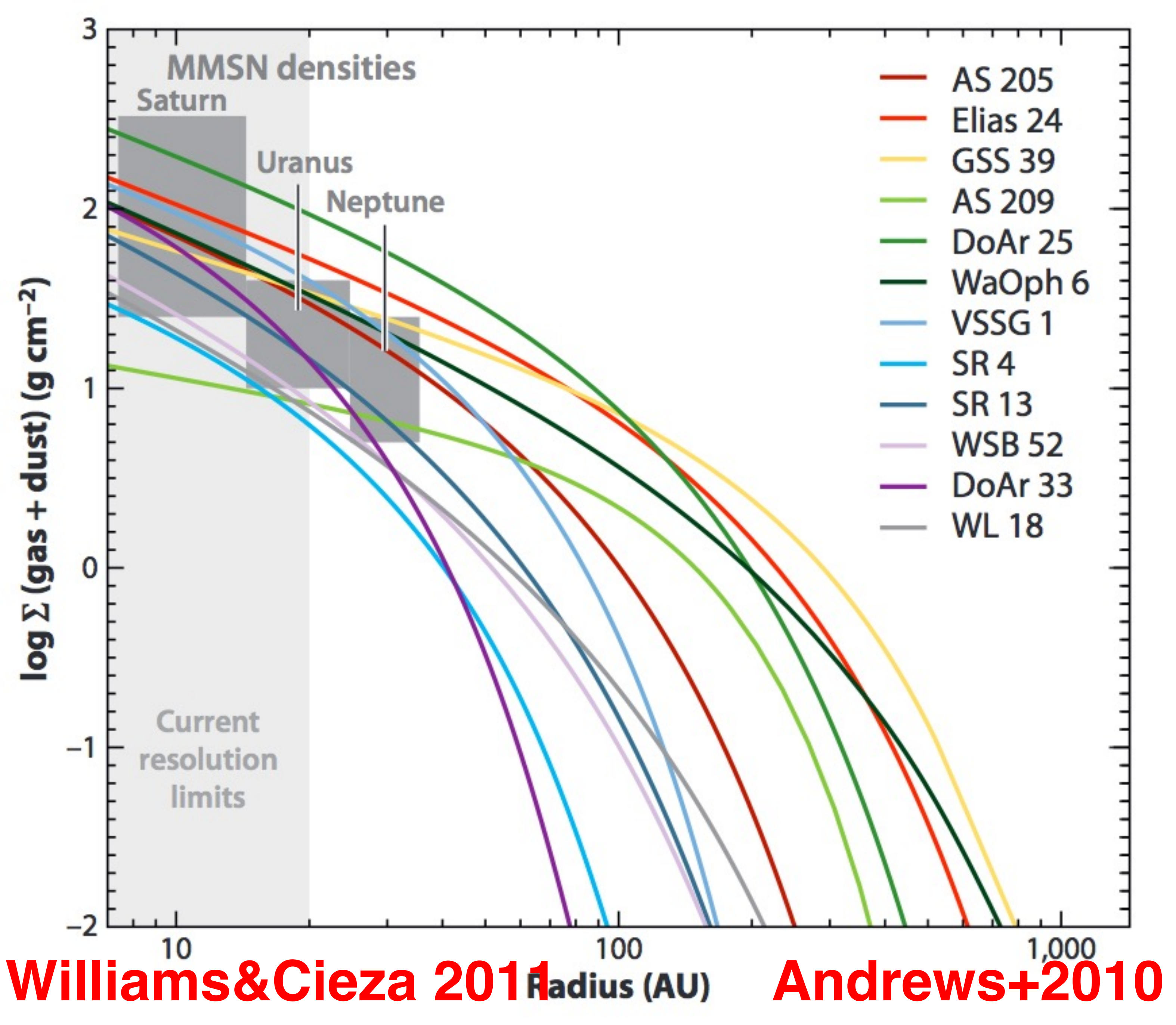
$$\Sigma(R,t) = \Sigma_t \left(\frac{R_t}{R}\right)^{\gamma} \times \exp\left\{-\frac{1}{2(2-\gamma)}\left[\left(\frac{R}{R_t}\right)^{(2-\gamma)} - 1\right]\right\}$$

- Data generally well described, note limited angular resolution

Examples of pre-ALMA results



Isella+2009

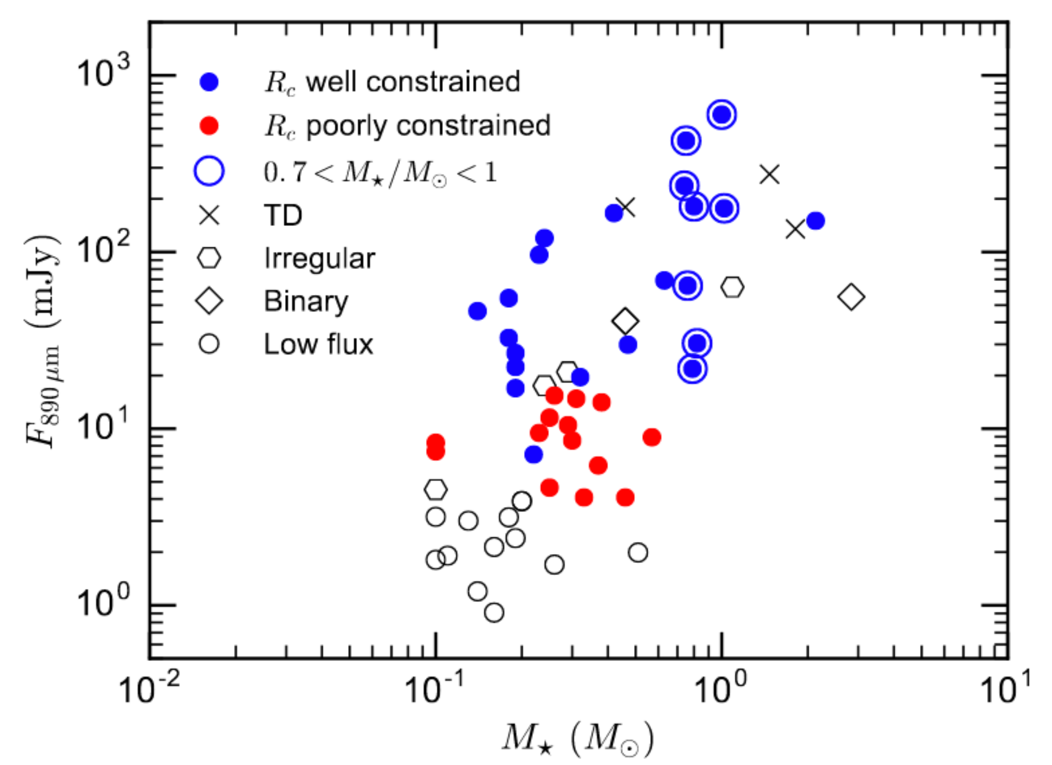


Williams&Cieza 2011 **Andrews+2010**

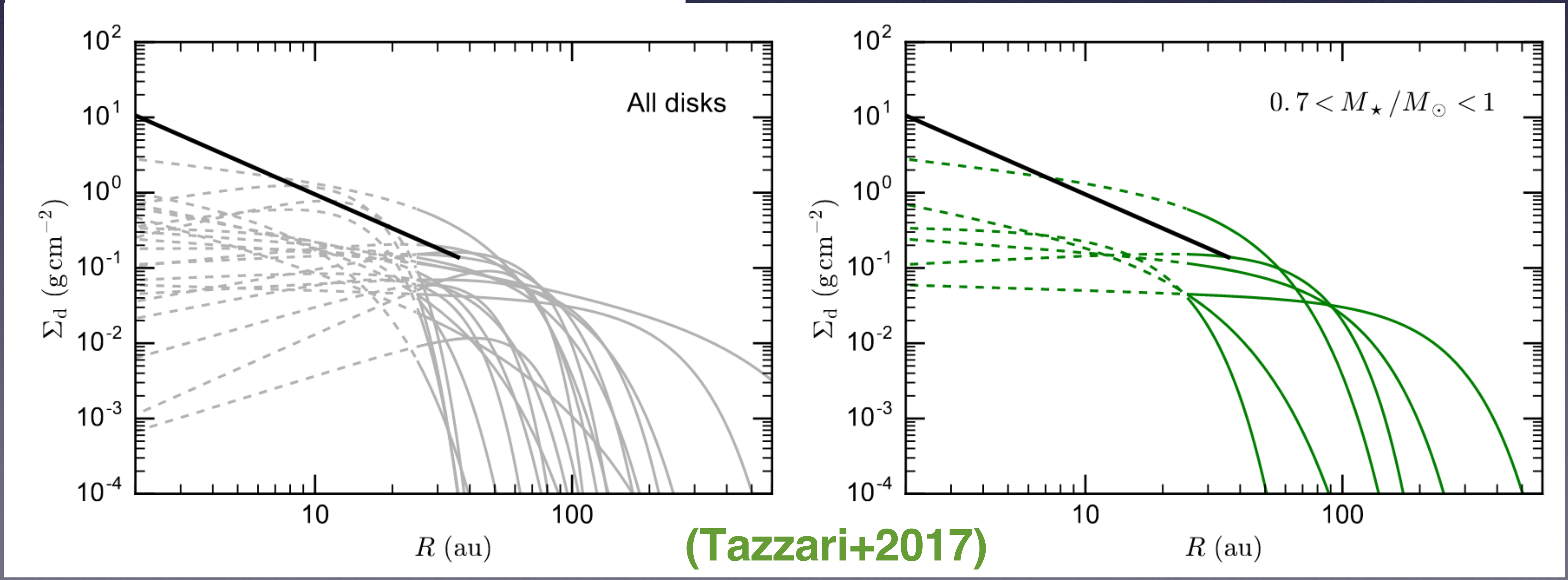
- Extract N random samples from “Taurus” applying the same selection biases as expected in the other region. Method first applied by Andrew+2013

Surface density distribution

Powered by Galario (Tazzari+2018)

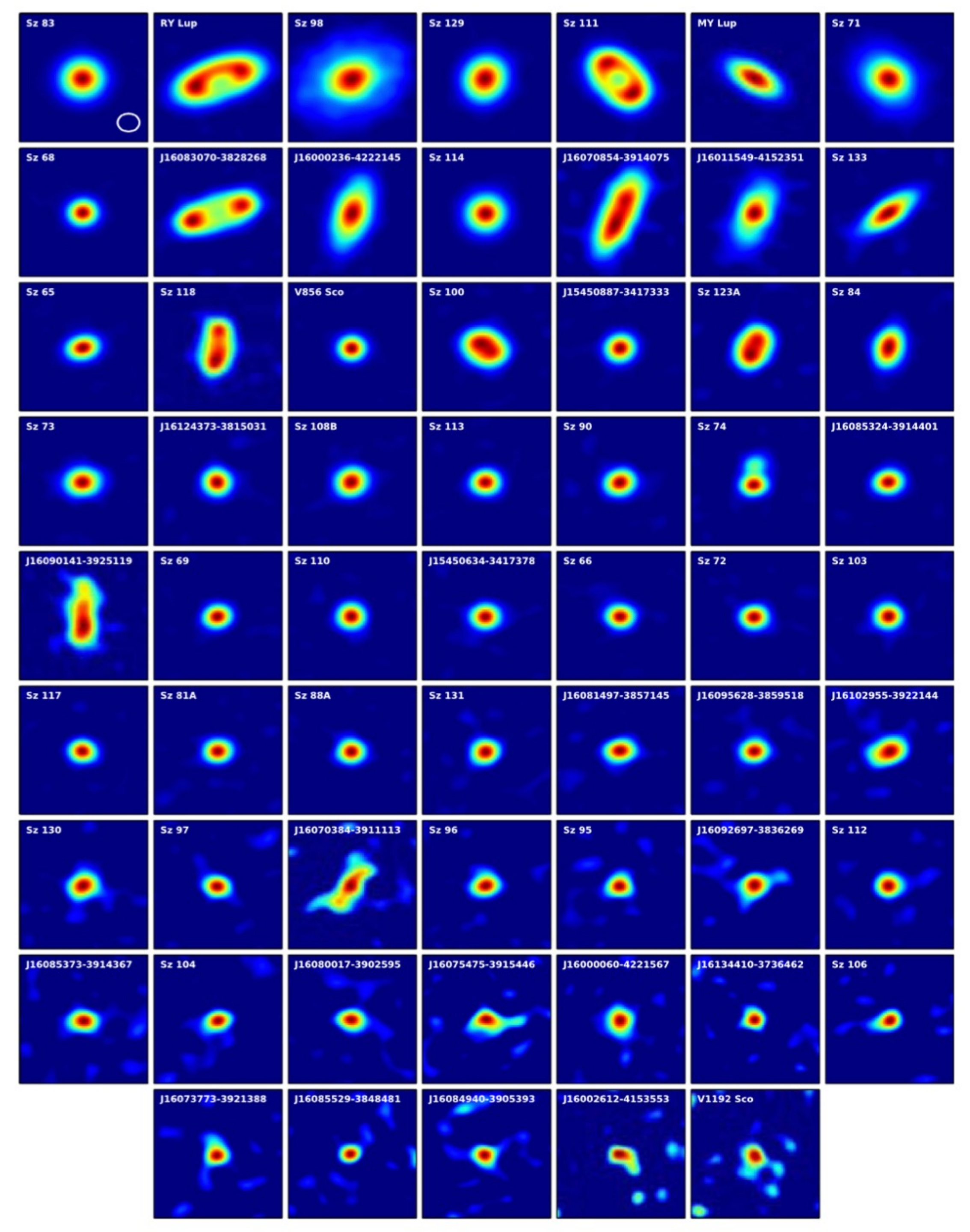


- First systematic/complete analysis of surface density distribution of solids in disks
- Compact disks (R<50AU) are up to ~30-40% of the population



(Tazzari+2017)

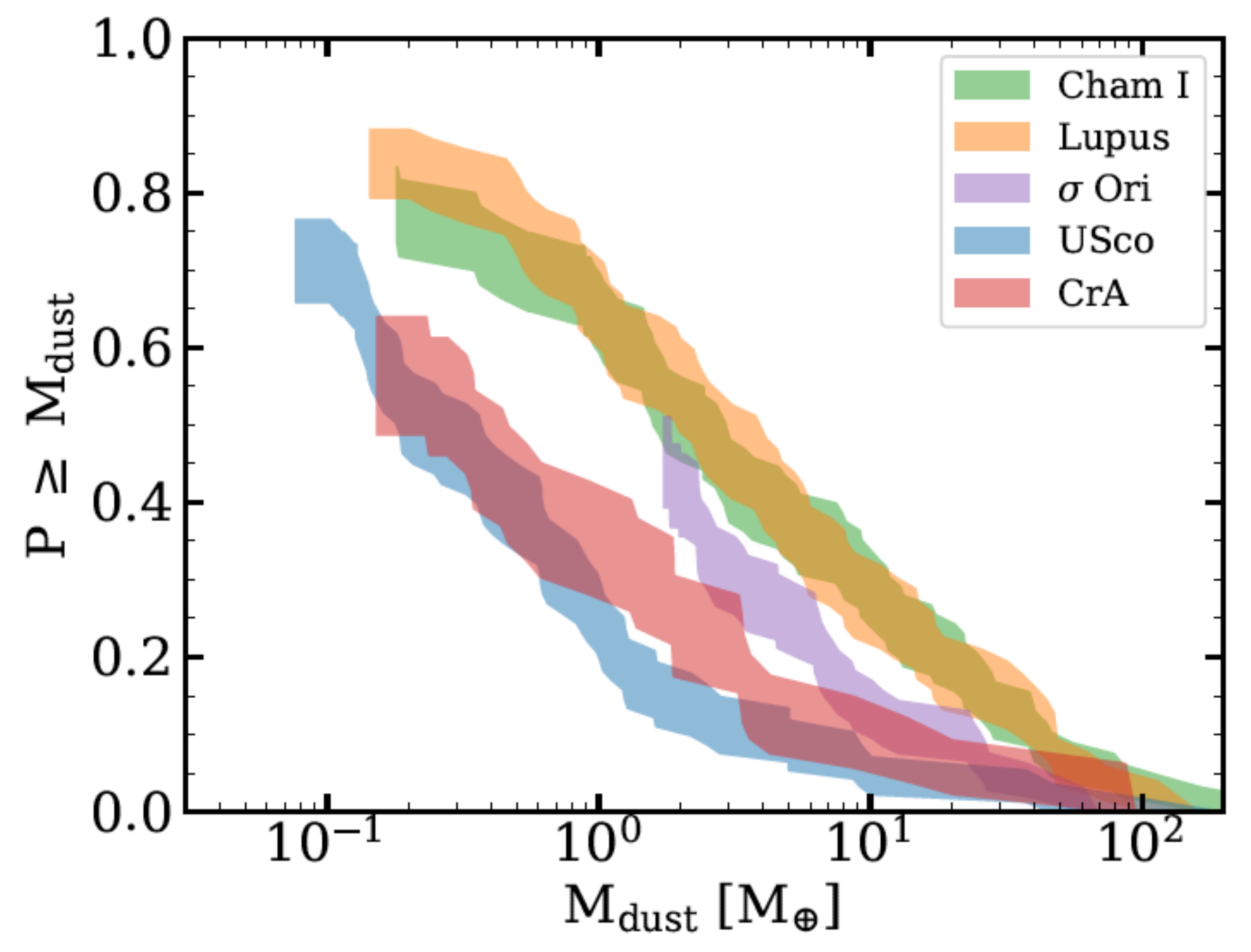
Full fit not always possible:
order of magnitude estimates technique



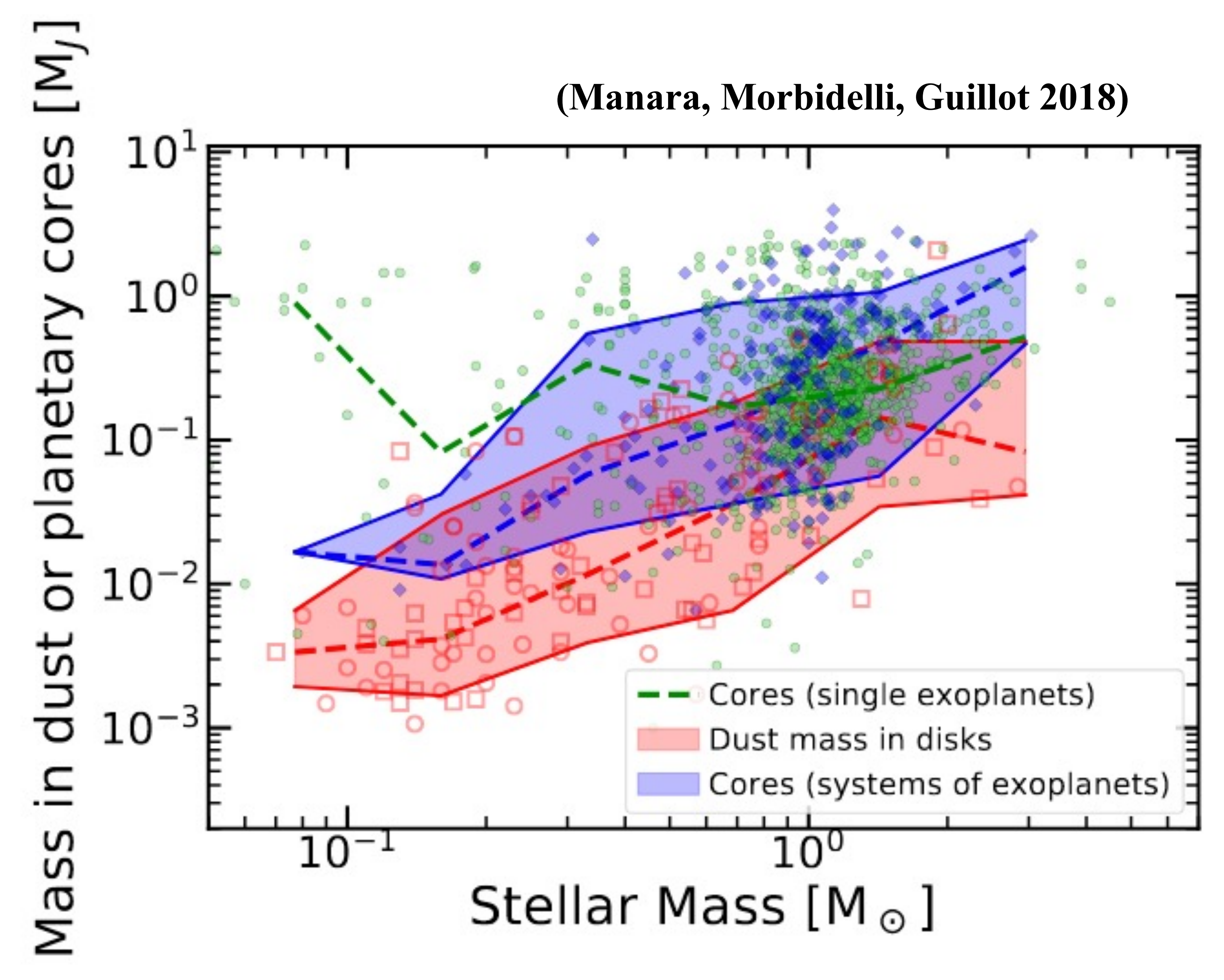
Ansdell+2016

(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



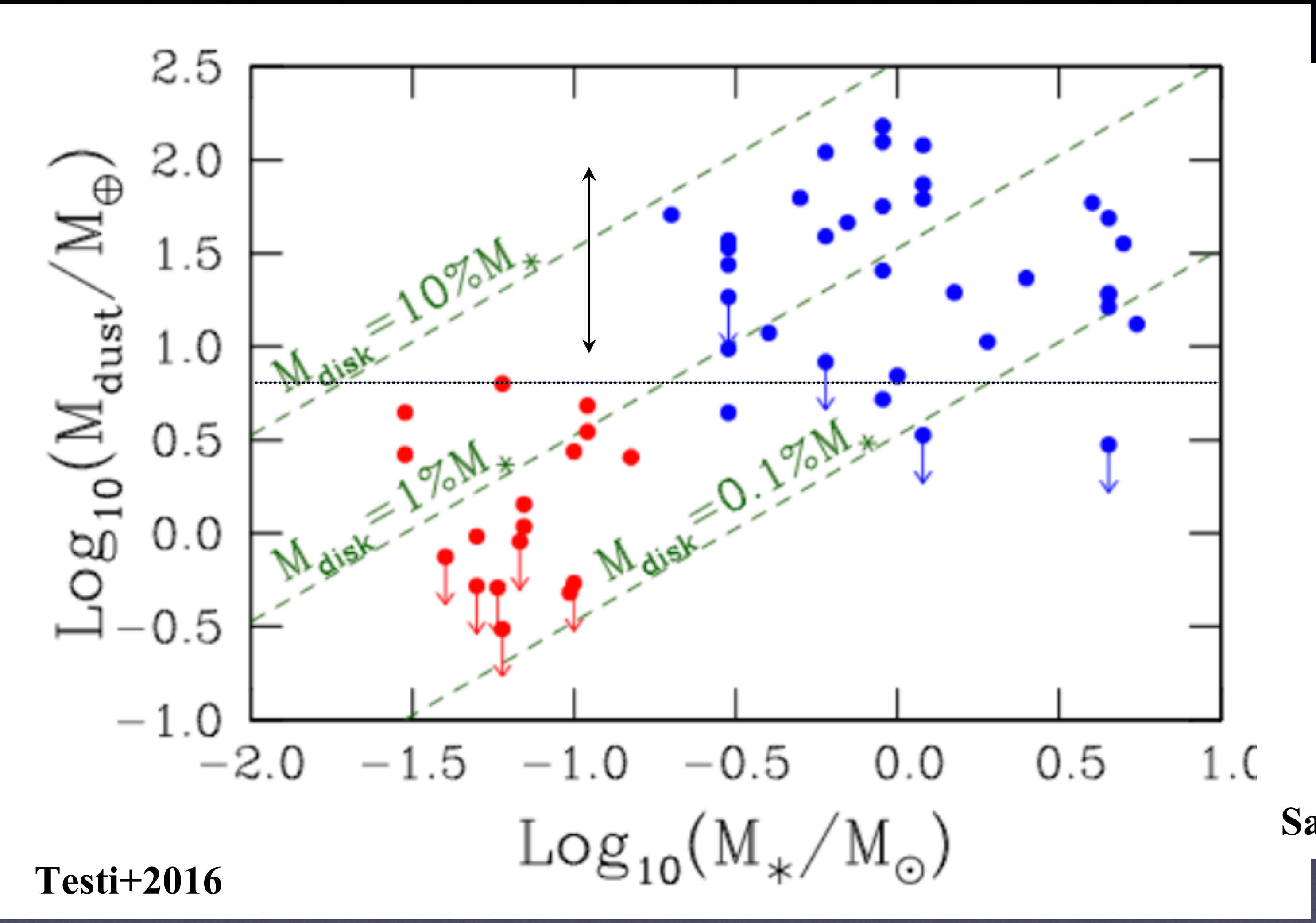
Solids in planets and disks



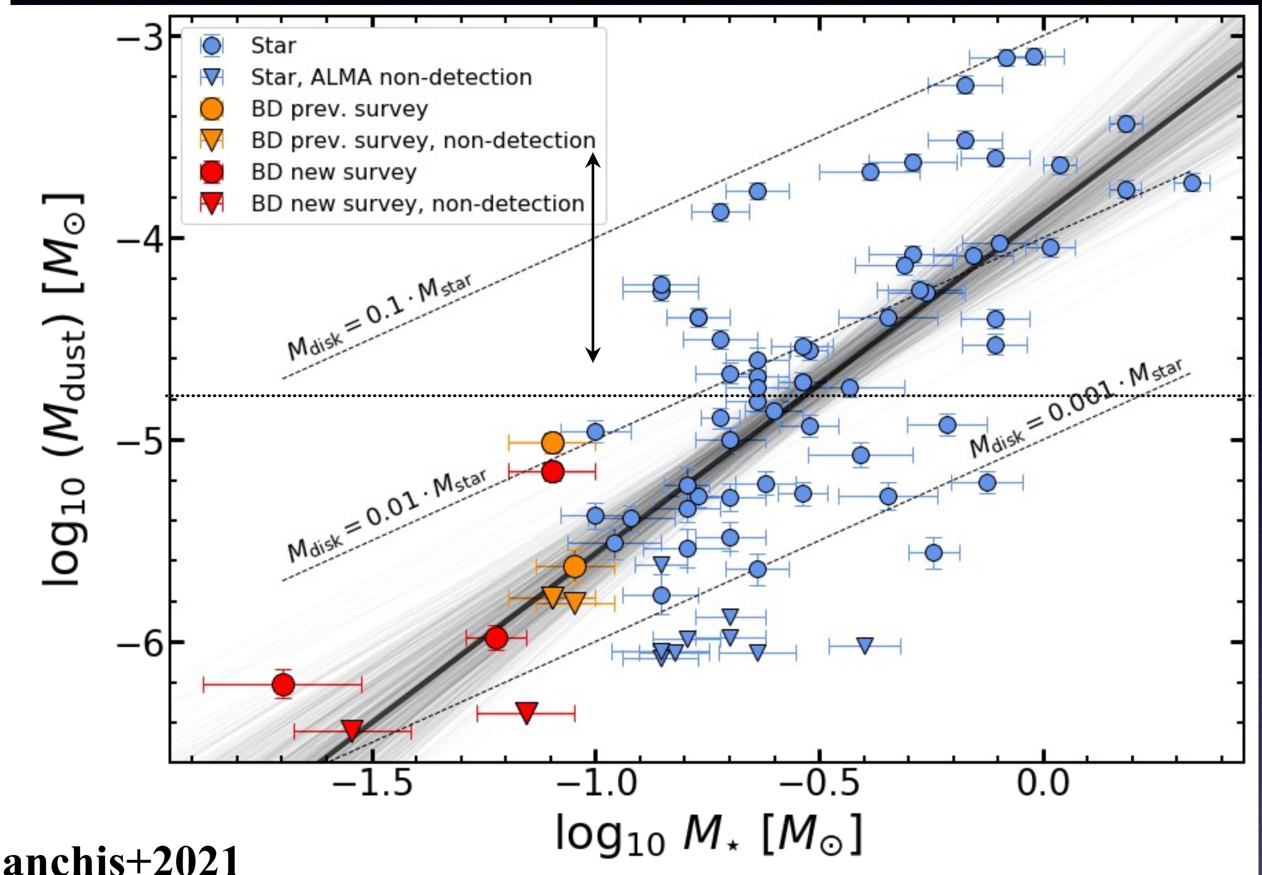
(Manara, Morbidelli, Guillot 2018)

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

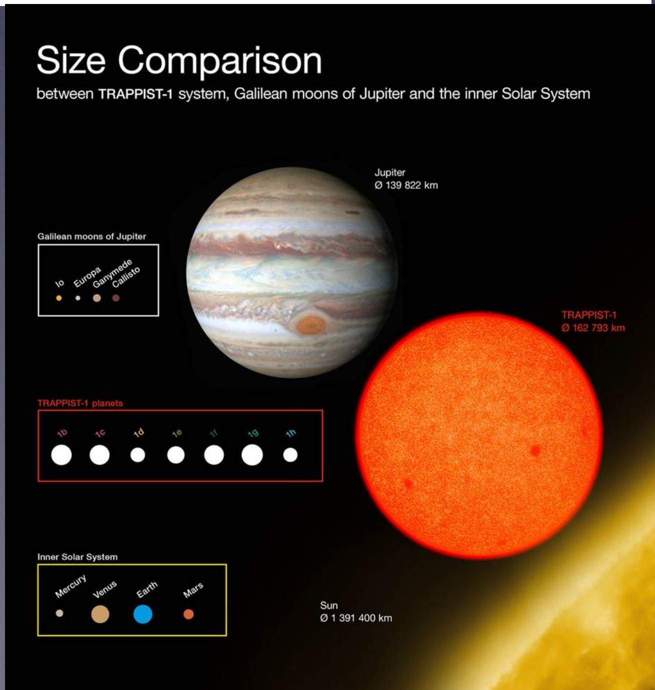
Deficit of solids in BD disks



Testi+2016

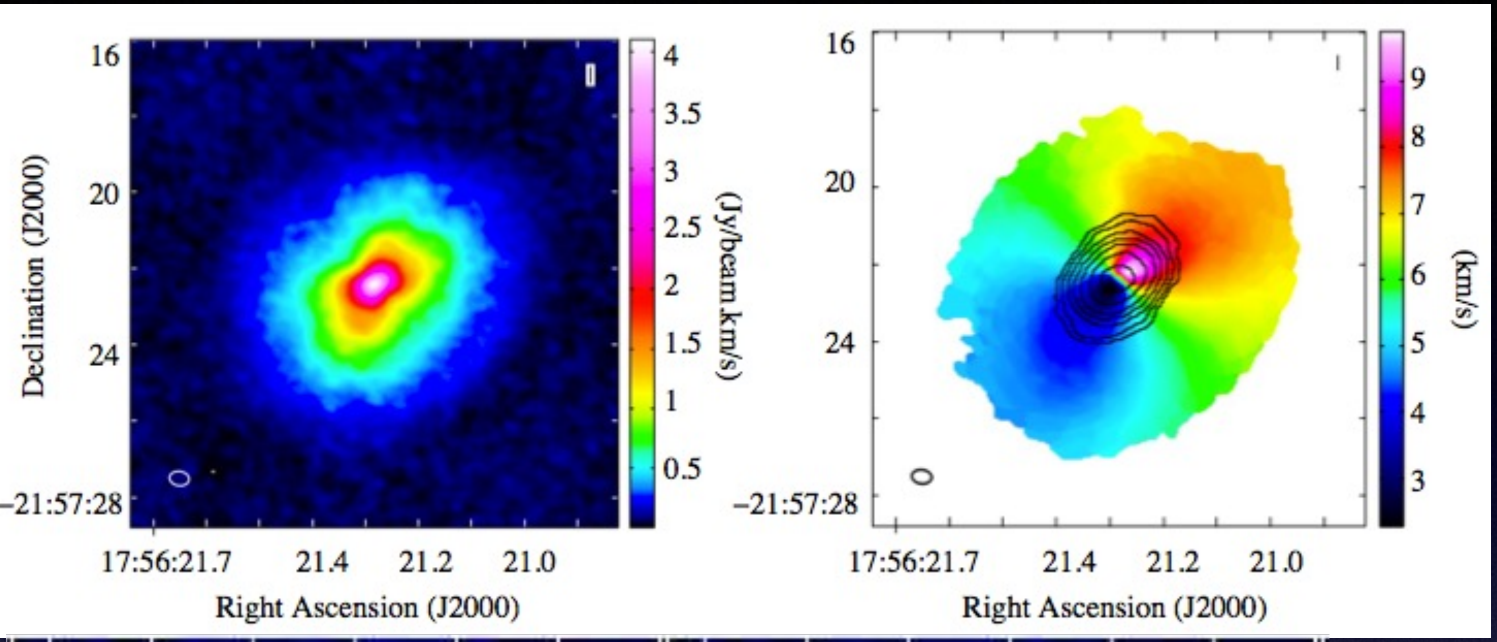


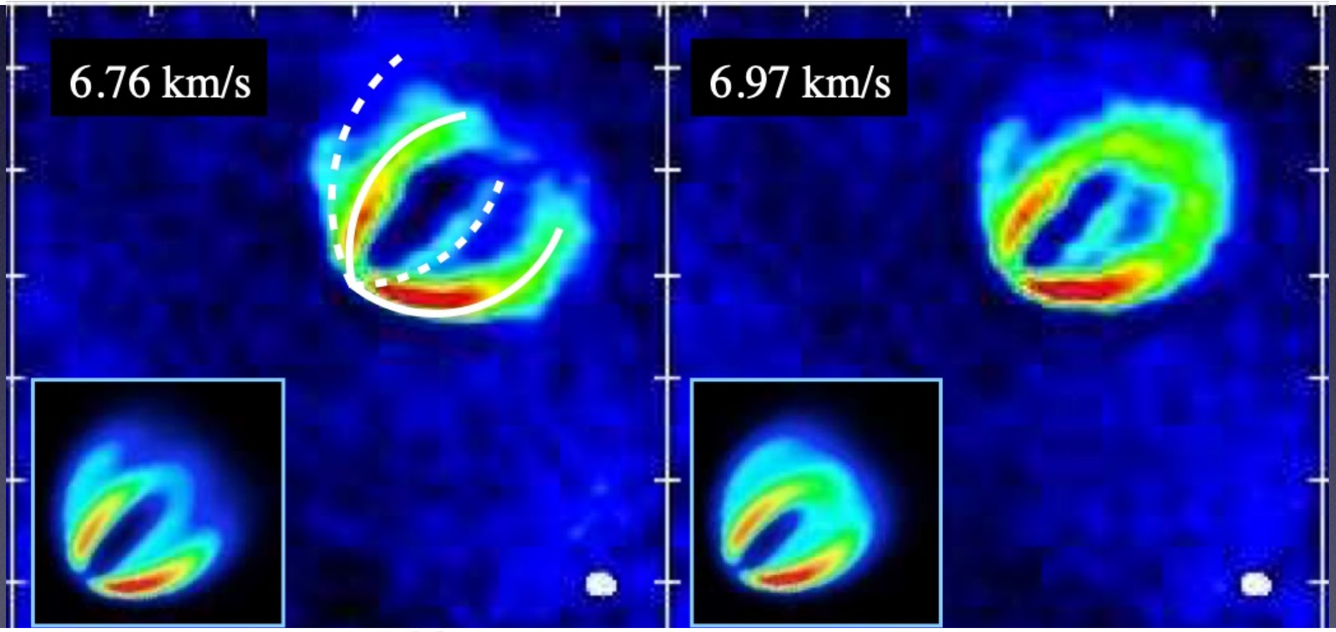
Sanchis+2021



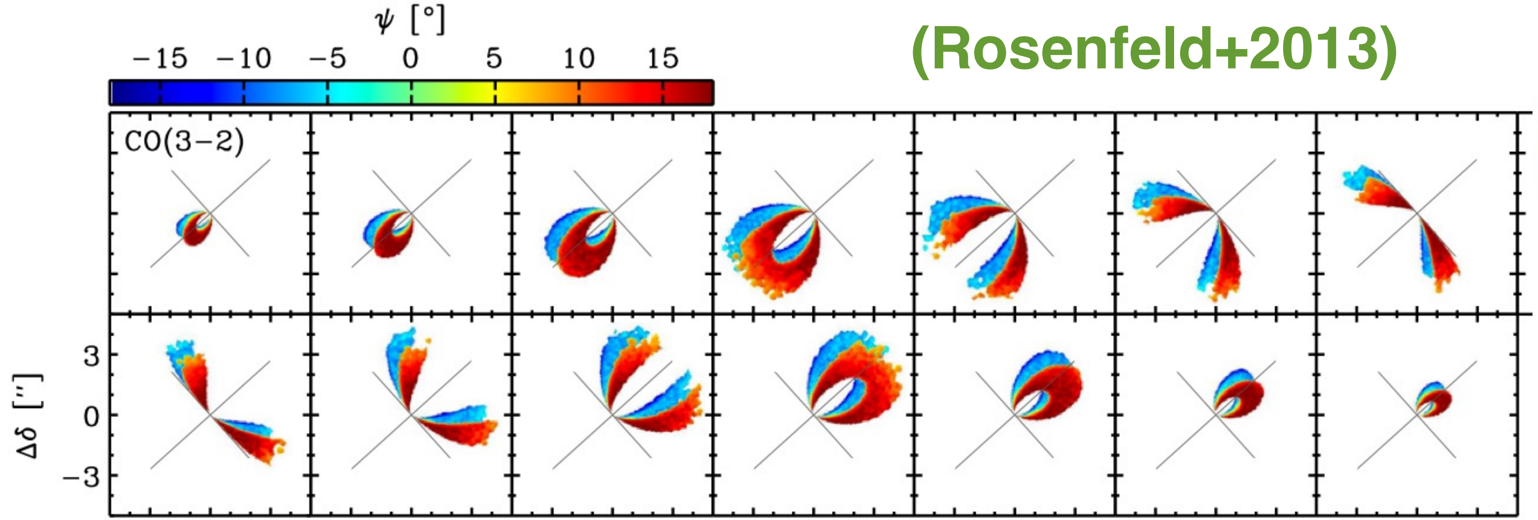
- Estimated solids mass in BD disks is too low to form the known exoplanets around BDs

HD163296 as seen by ALMA



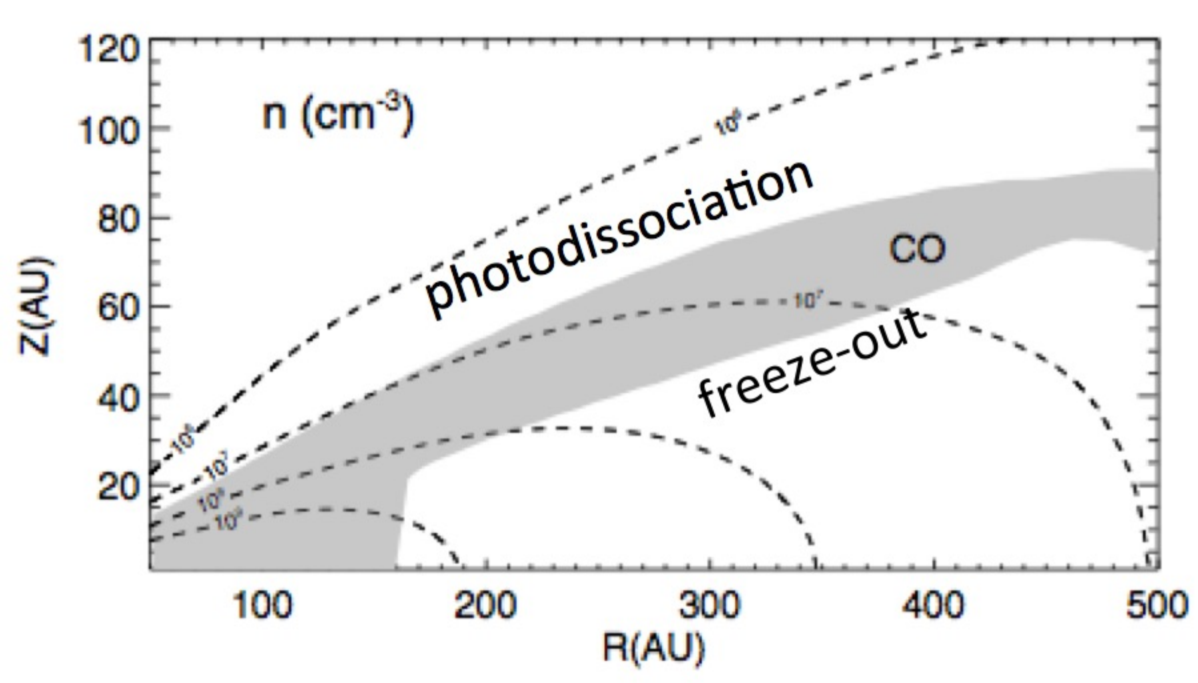


(deGregorio-Monsalvo+2013)

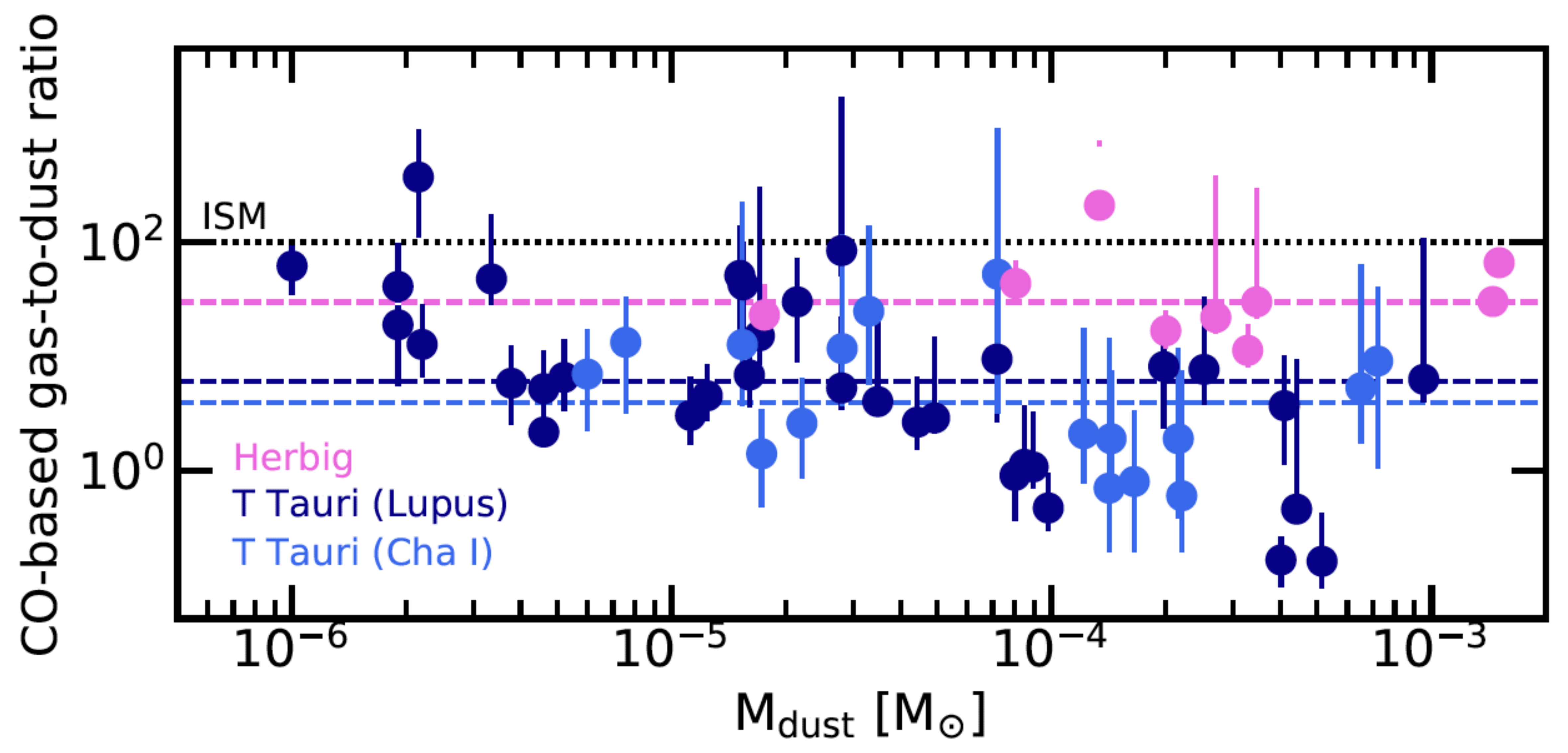


(Rosenfeld+2013)

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



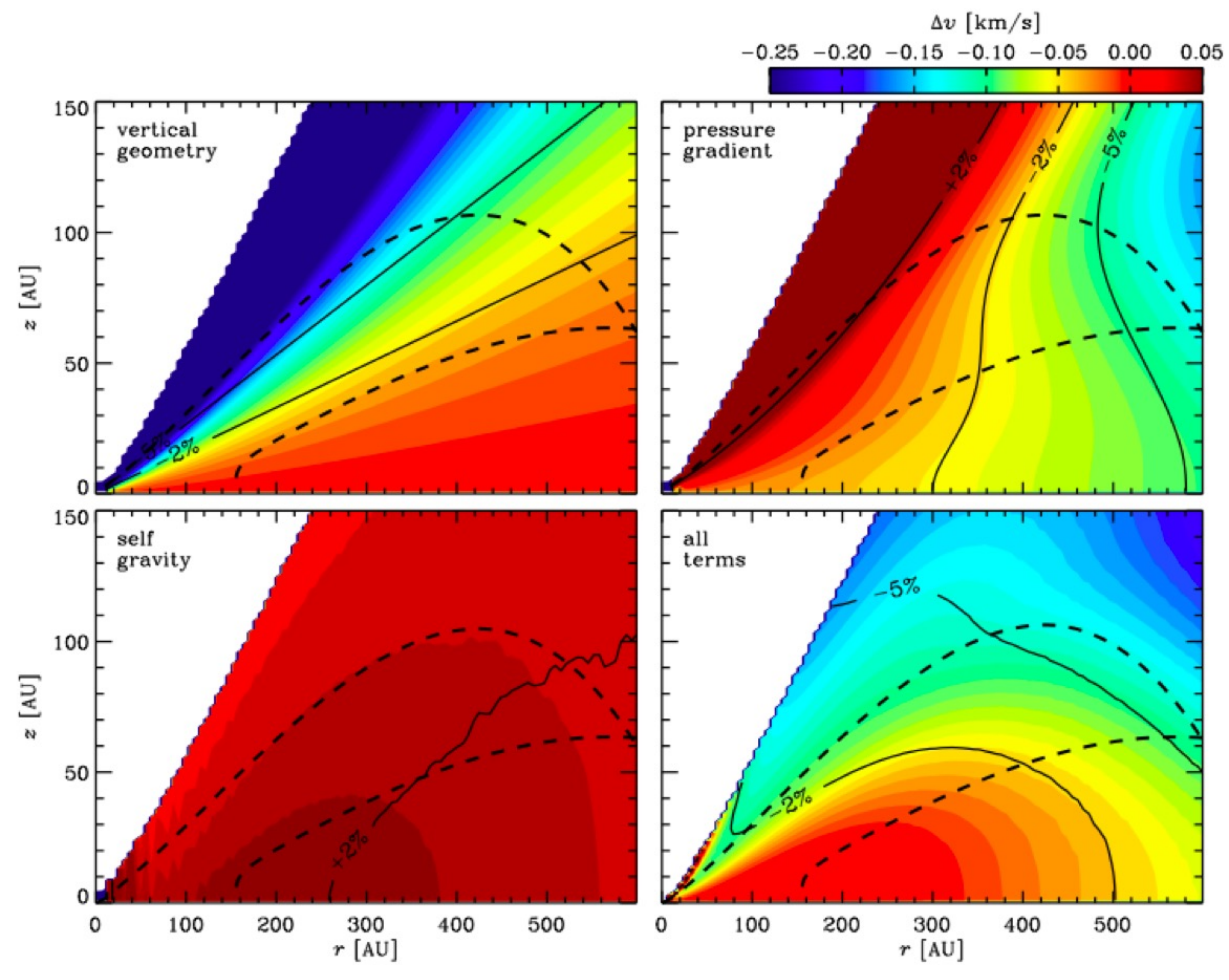
CO-based gas masses



(Miotello et al. 2022)

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

Gas kinematics



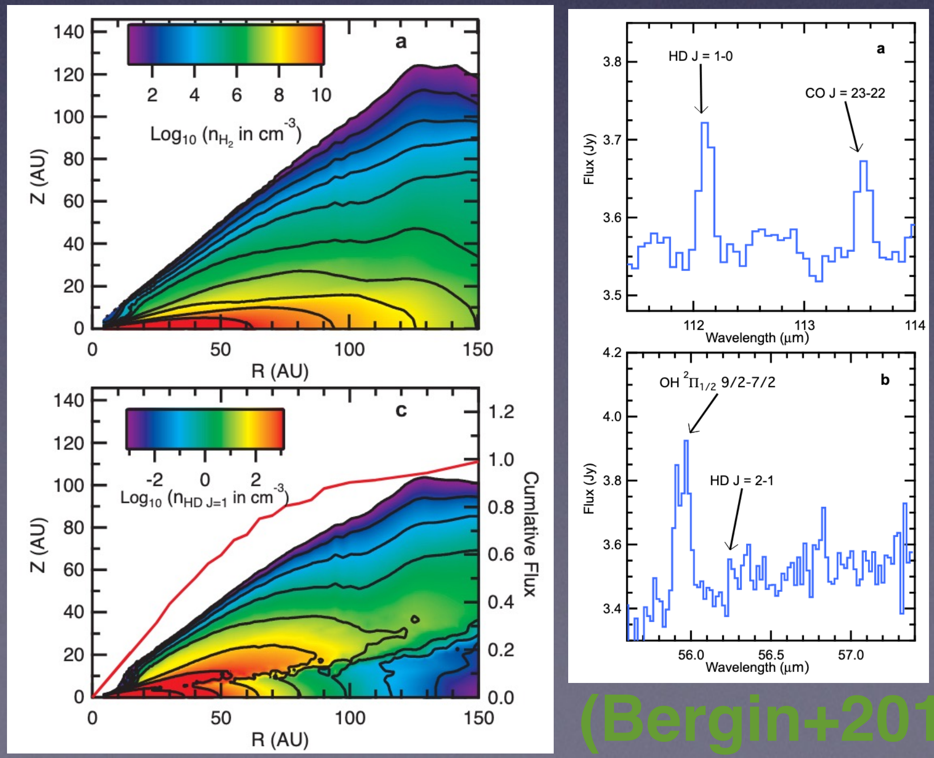
(Rosenfeld et al. 2013)

- Potentially a direct measurement of the disk self-gravity

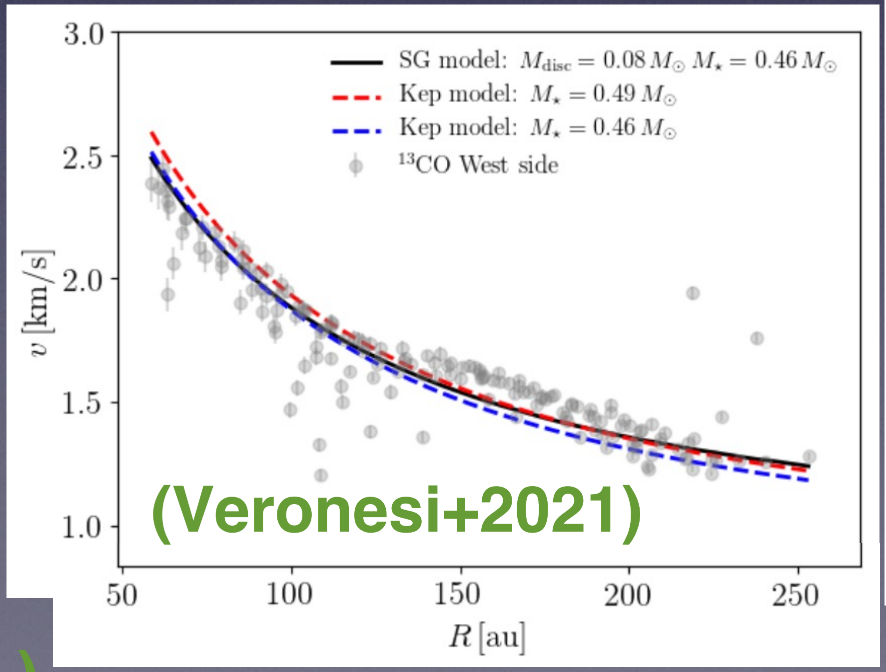
- Not exactly Keplerian
- Largest effect is the pressure term 5%, self gravity 0.1-0.5%

Dust mass and disk mass

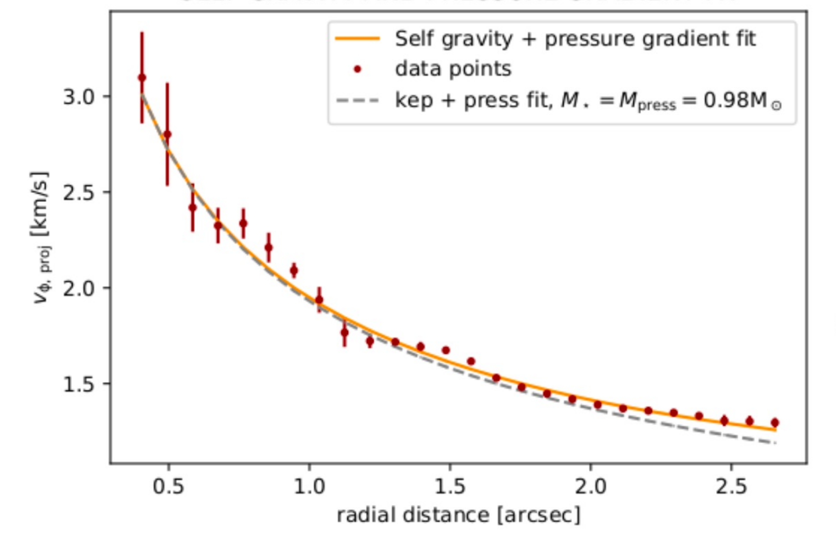
- Dust emission traces approx 0.01 of the H_2 mass
  - (by comparison, gas-phase CO emission traces <<<<1e-5, depending on how much of the CO mass is in solids and on the details of chemistry and photodissociation)
- Carefully estimated dust masses are within a factor 2-3 of "robust" disk mass estimates



(Bergin+2013)

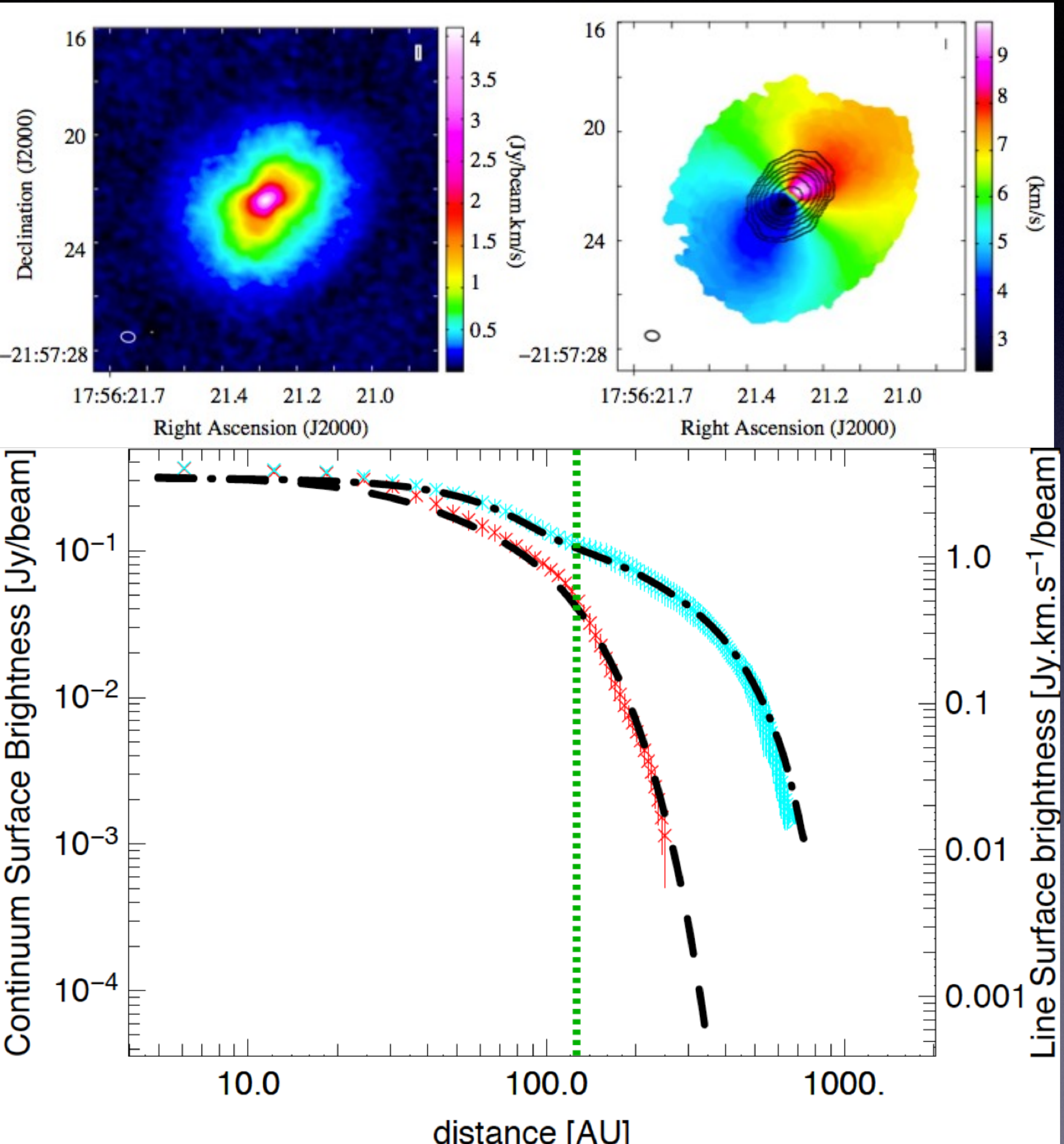


(Veronesi+2021)



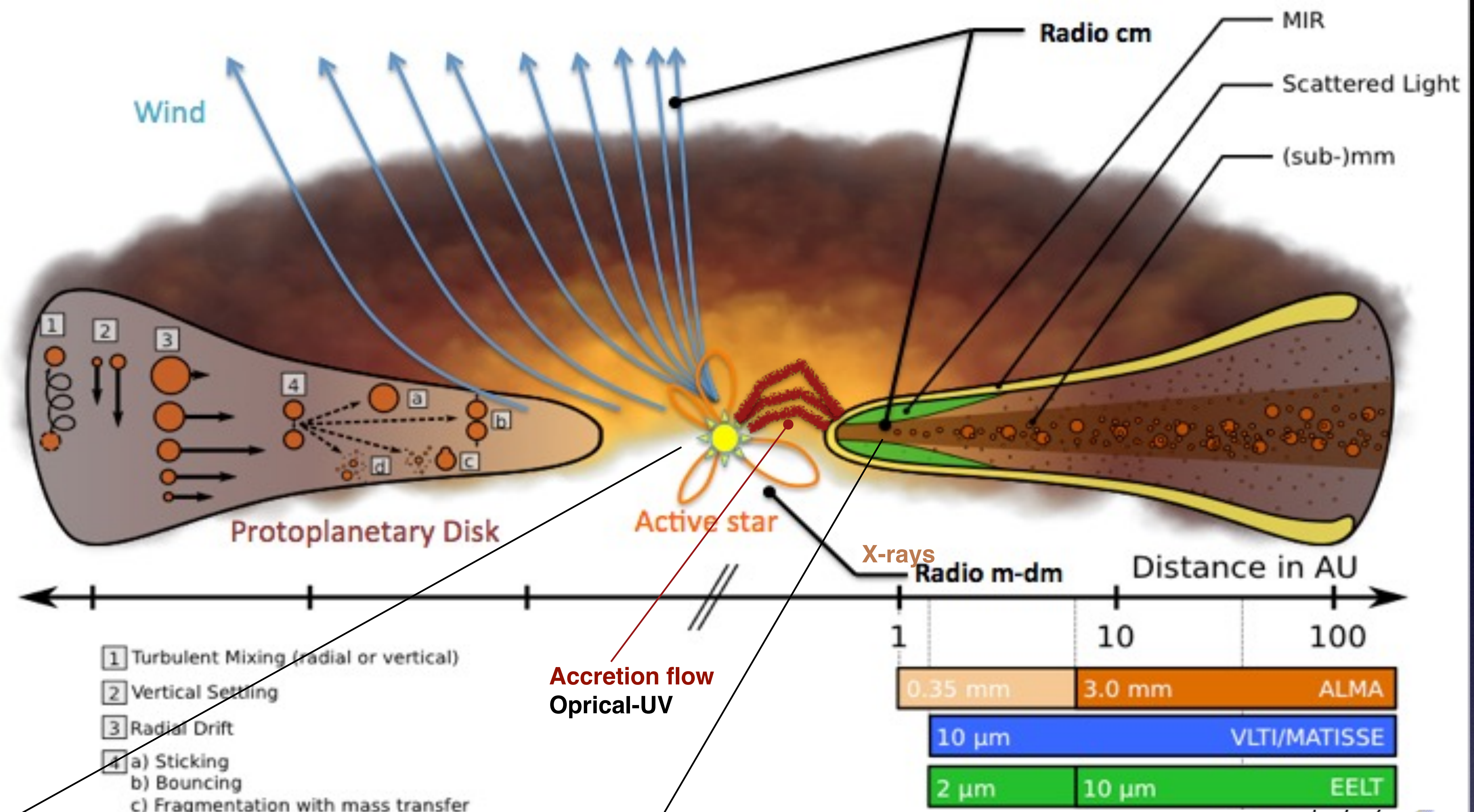
(Rampinelli+2022)

HD163296 as seen by ALMA



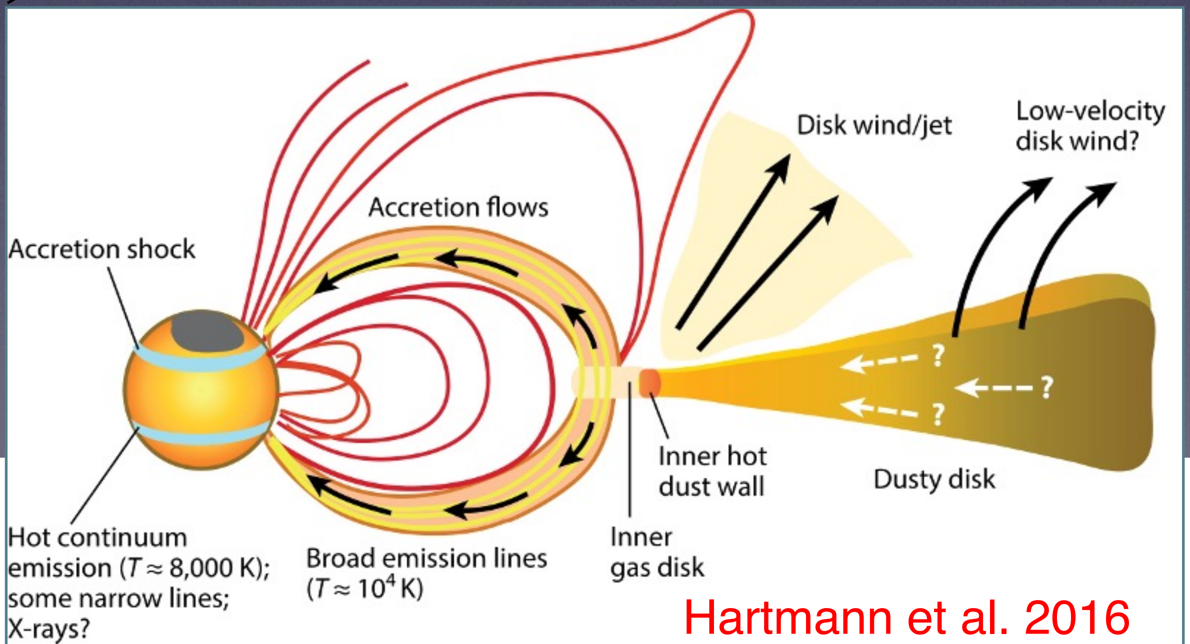
- Extent of the CO disk is much larger than that of the mm-grains disk
- Qualitative behaviour as expected from viscous spreading and migration of the larger grains

(deGregorio-Monsalvo+2013)

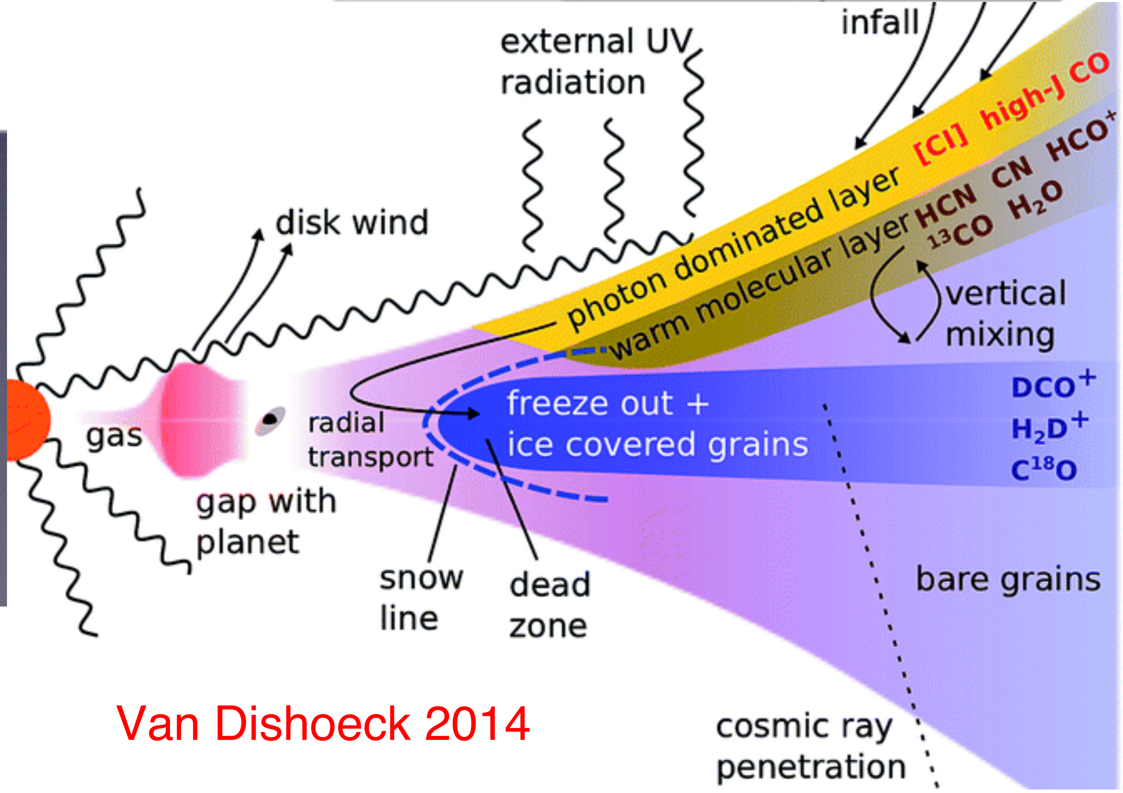


Accretion flow
Oprical-UV

Testi et al. 2014/15



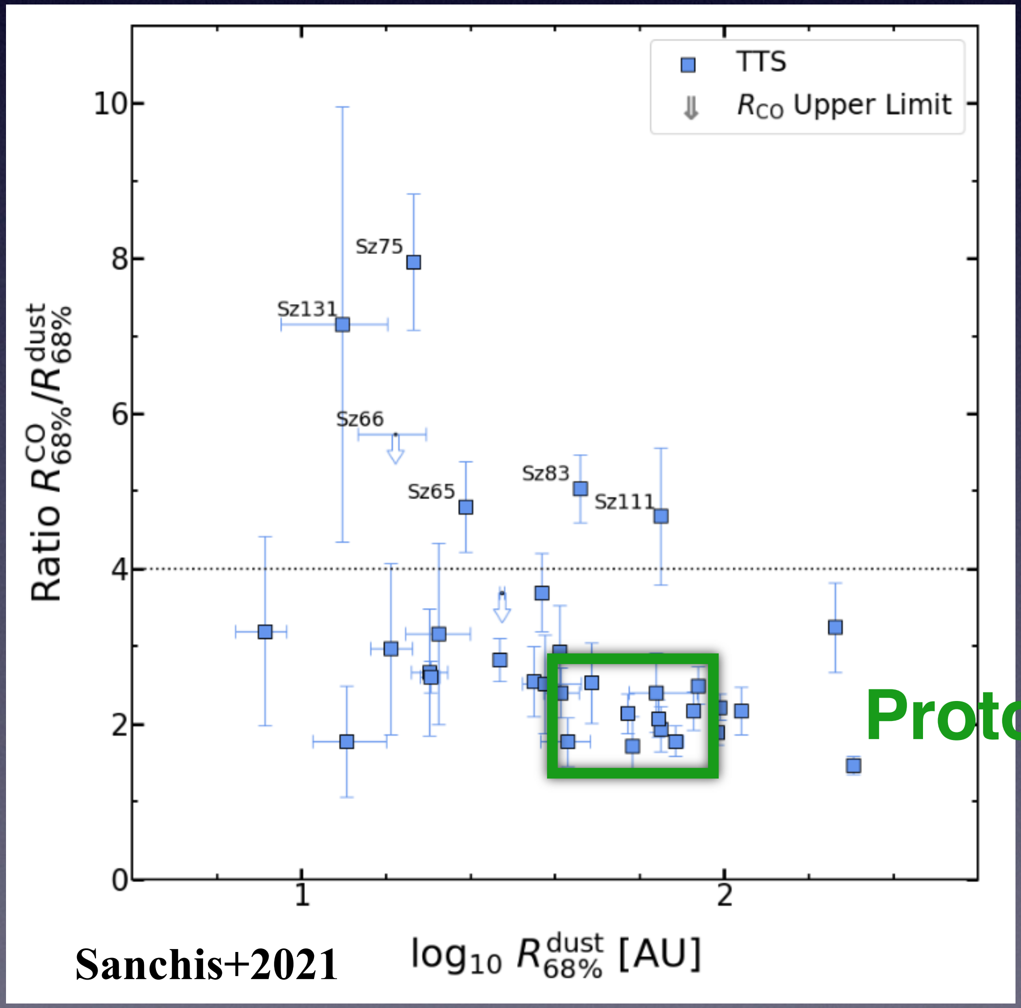
Hartmann et al. 2016



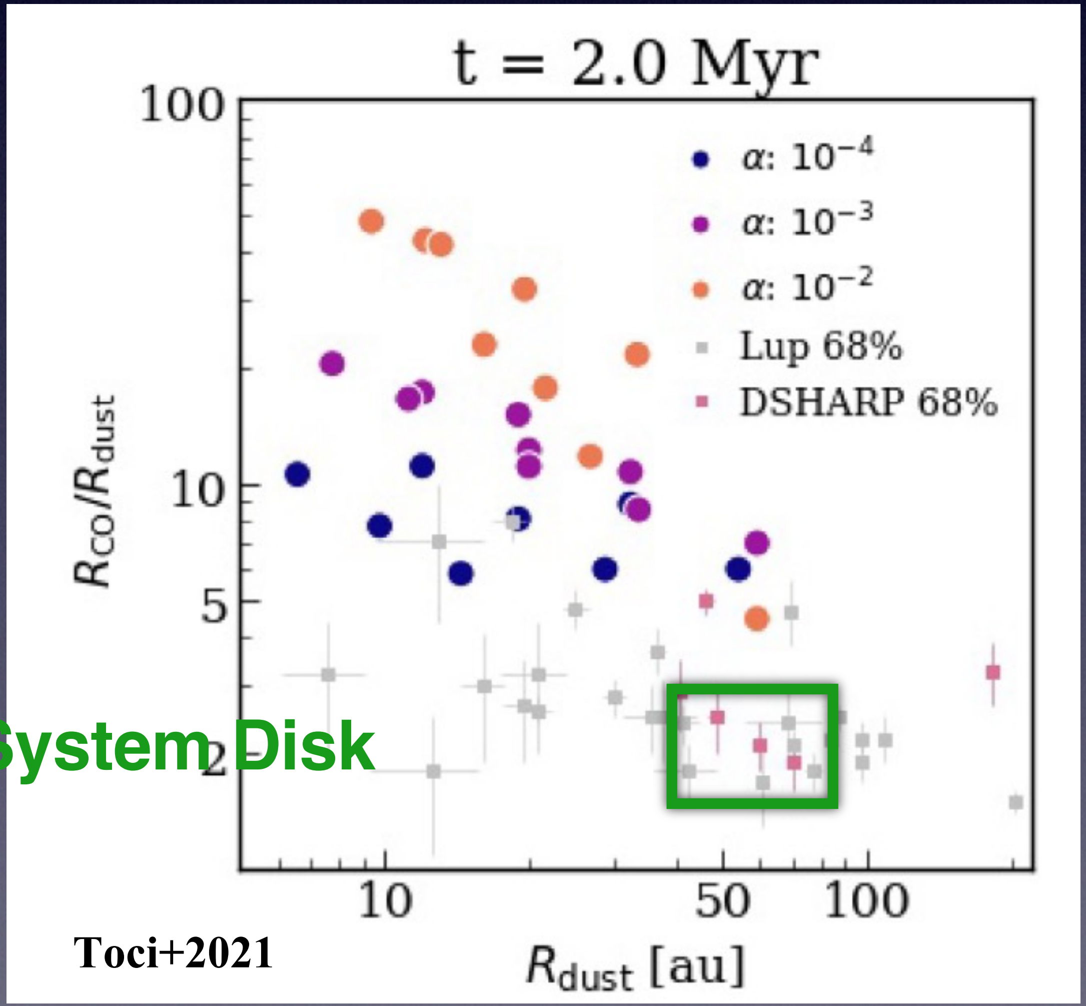
Van Dishoeck 2014

Gas and dust

- Continuum vs. Gas radii show surprisingly tight correlation
- This is surprising and needs to be better understood



Sanchis+2021



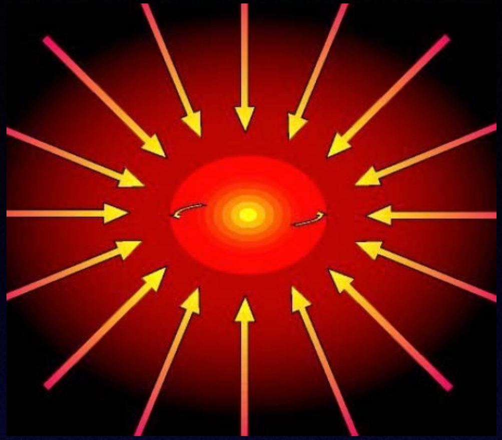
Toci+2021

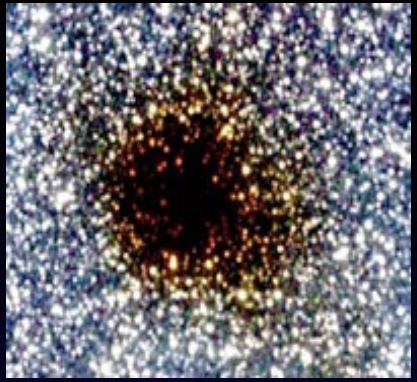
Proto Solar System Disk

- R_{CO}~2 R_{dust}

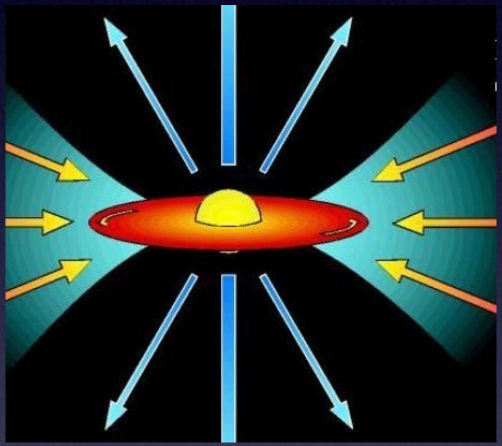
- Not consistent with steady viscous evolution

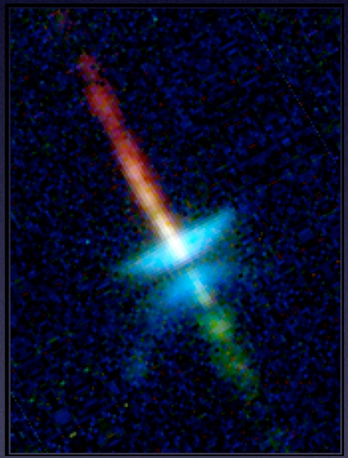
From Cores to Planetary Systems



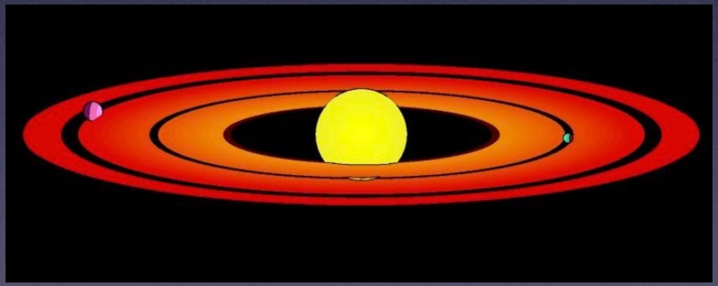


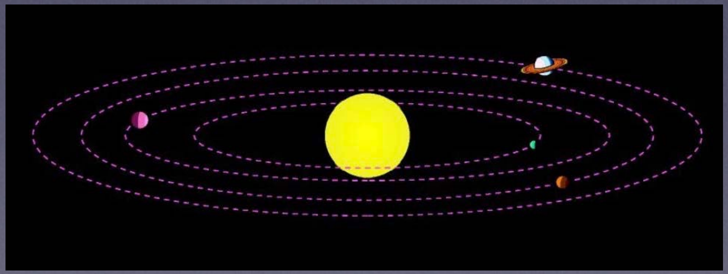
Core

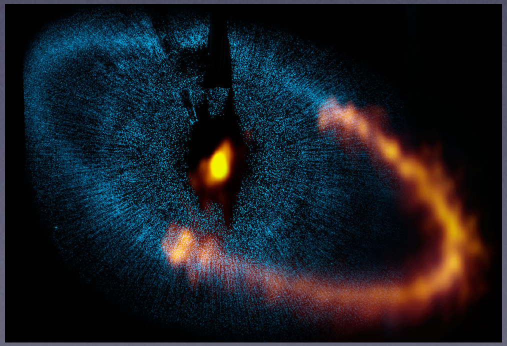




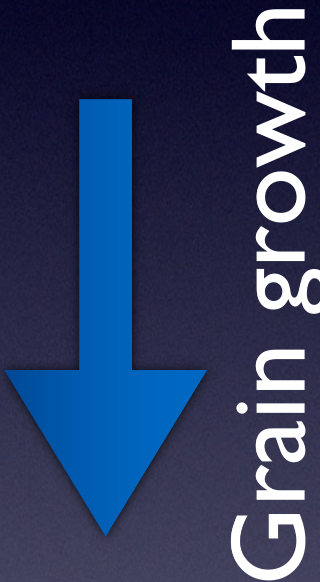
Disk







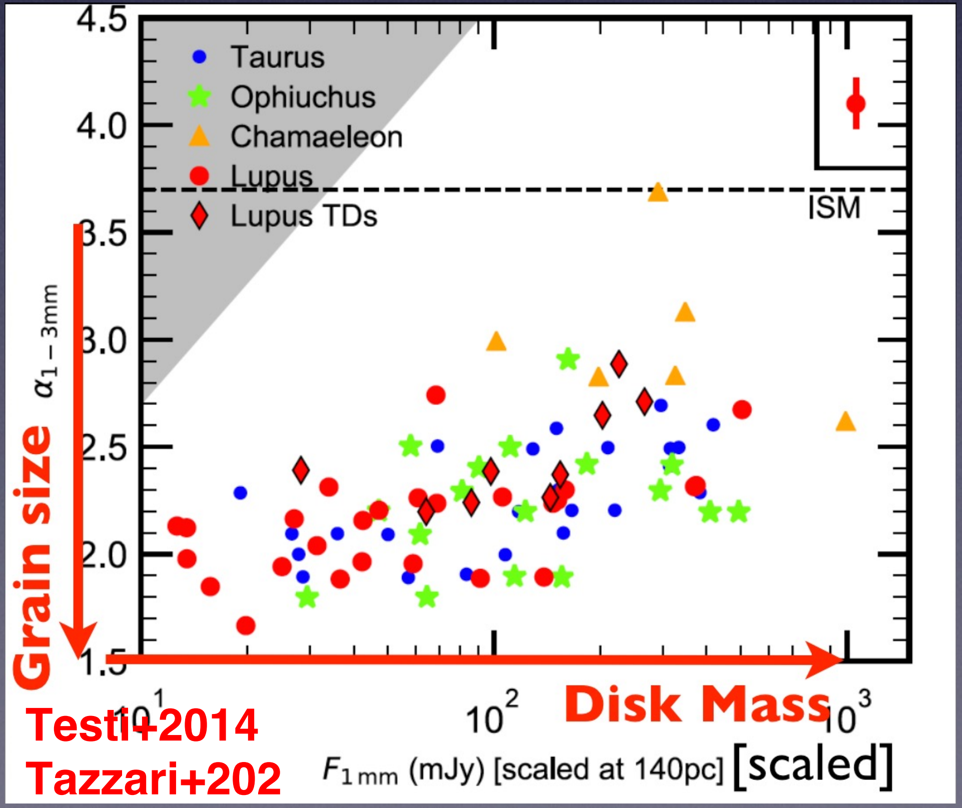
Debris Disk



Very difficult to grow beyond 10-100 um
(Ossenkopf & Henning 1994; Ormel et al. 2009)

Evidence for growth to micron-size grains
(Pagani et al. 2010)

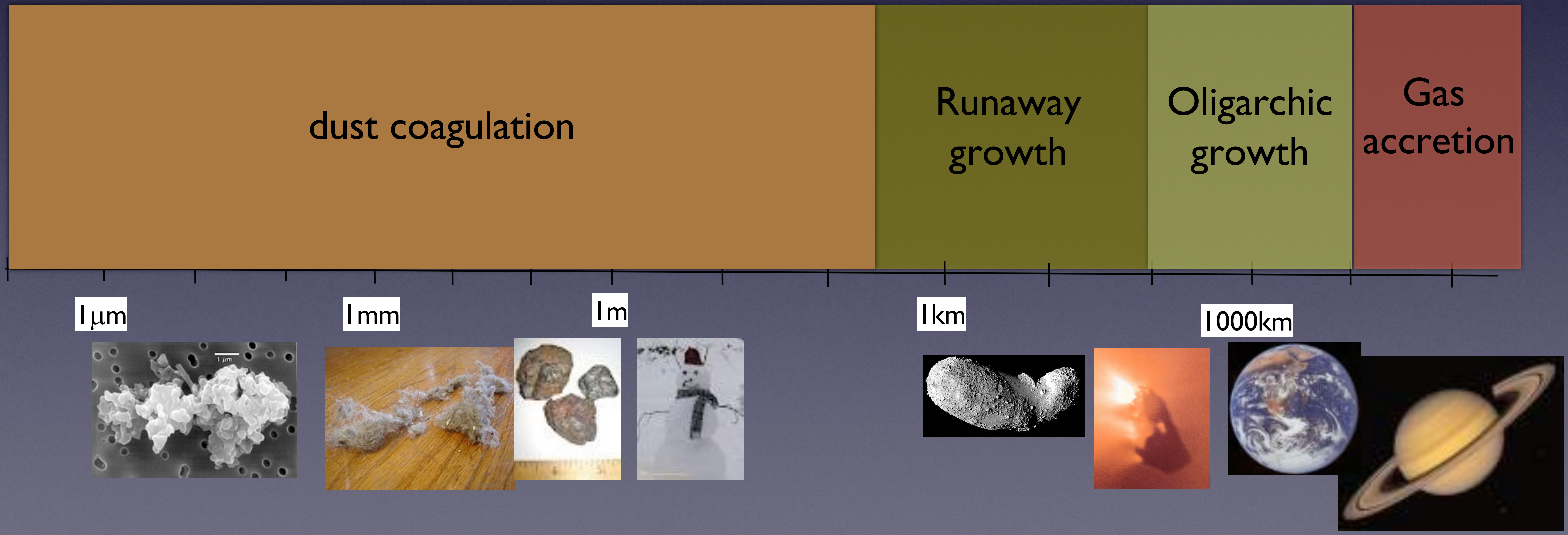
Observational evidence for large grains
(Beckwith & Sargent 1991)
(Testi et al. 2003, Natta et al. 2007, Testi et al. 2014)



Testi+2014
Tazzari+2021

Dust evolution

- The core-accretion scenario
  - Dust growth and planetesimals formation
  - Formation of rocky cores
  - Gas accretion from disk



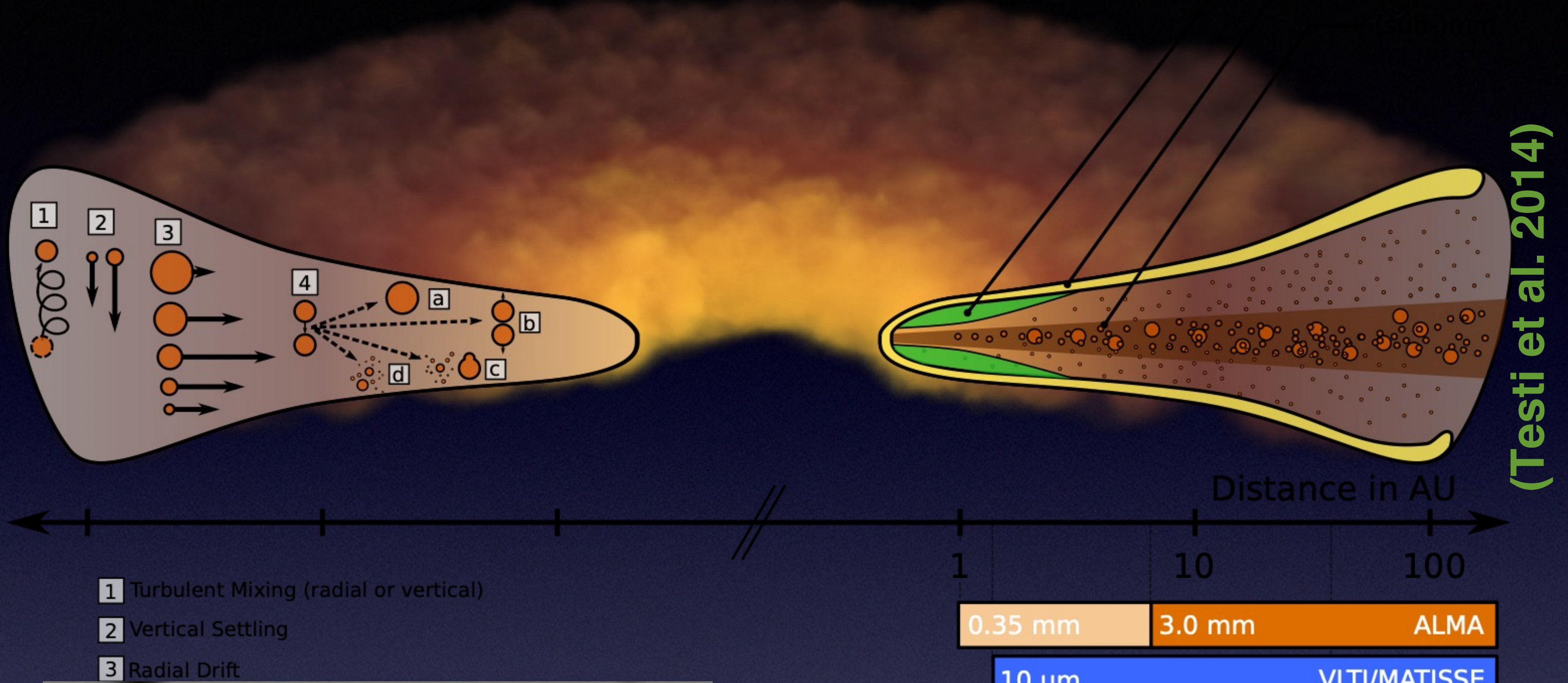
dust coagulation

Runaway growth

Oligarchic growth

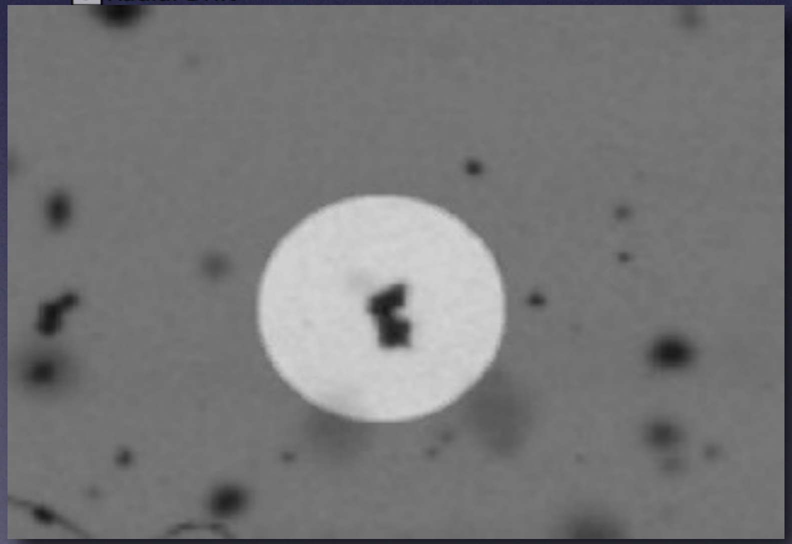
Gas accretion

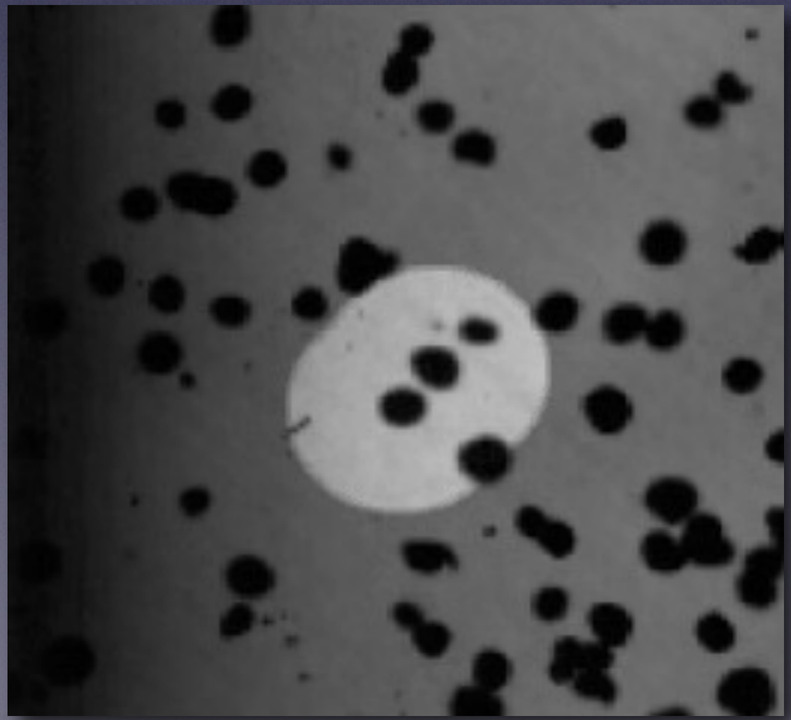
Dust evolution: grain growth processes



0.35 mm	3.0 mm ALMA
10 µm VLTI/MATISSE	
2 µm	10 µm EELT
	JWST/MIRI

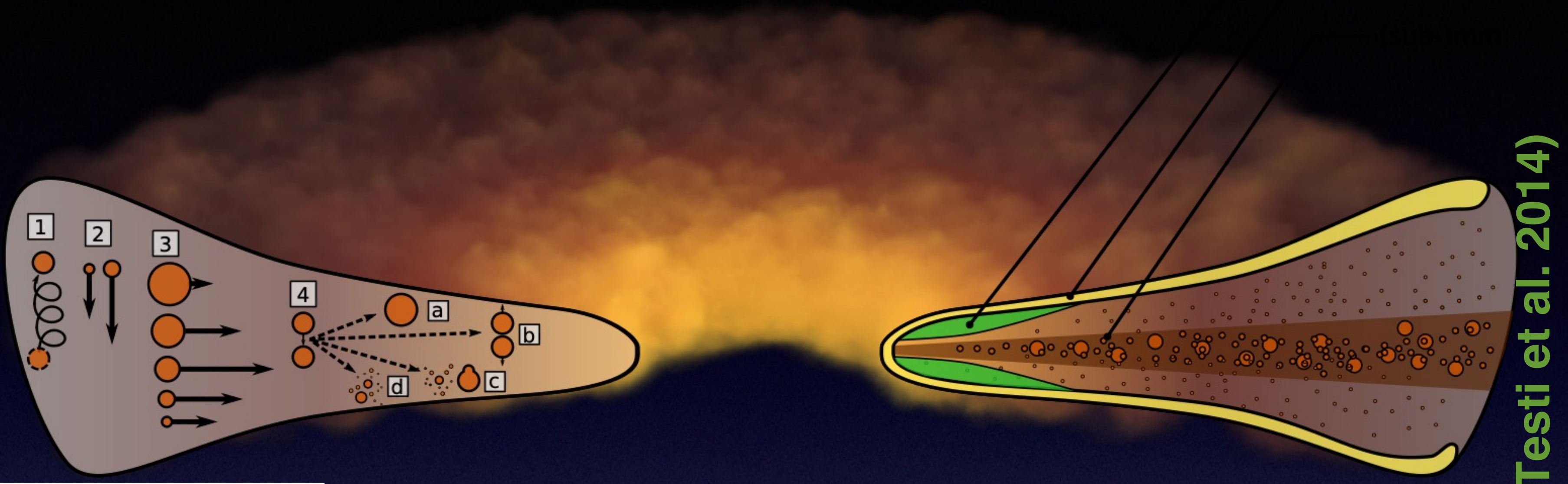
(Testi et al. 2014)

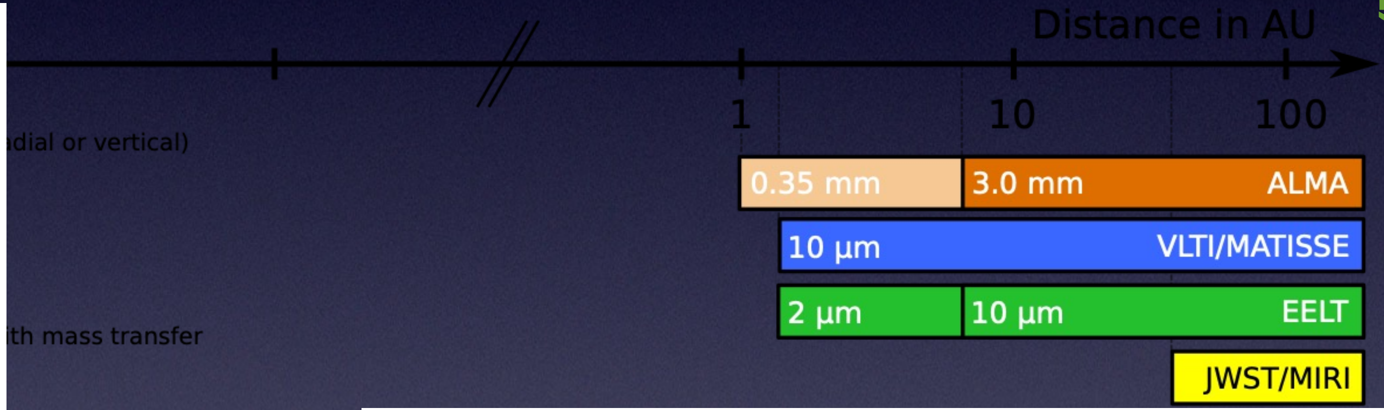




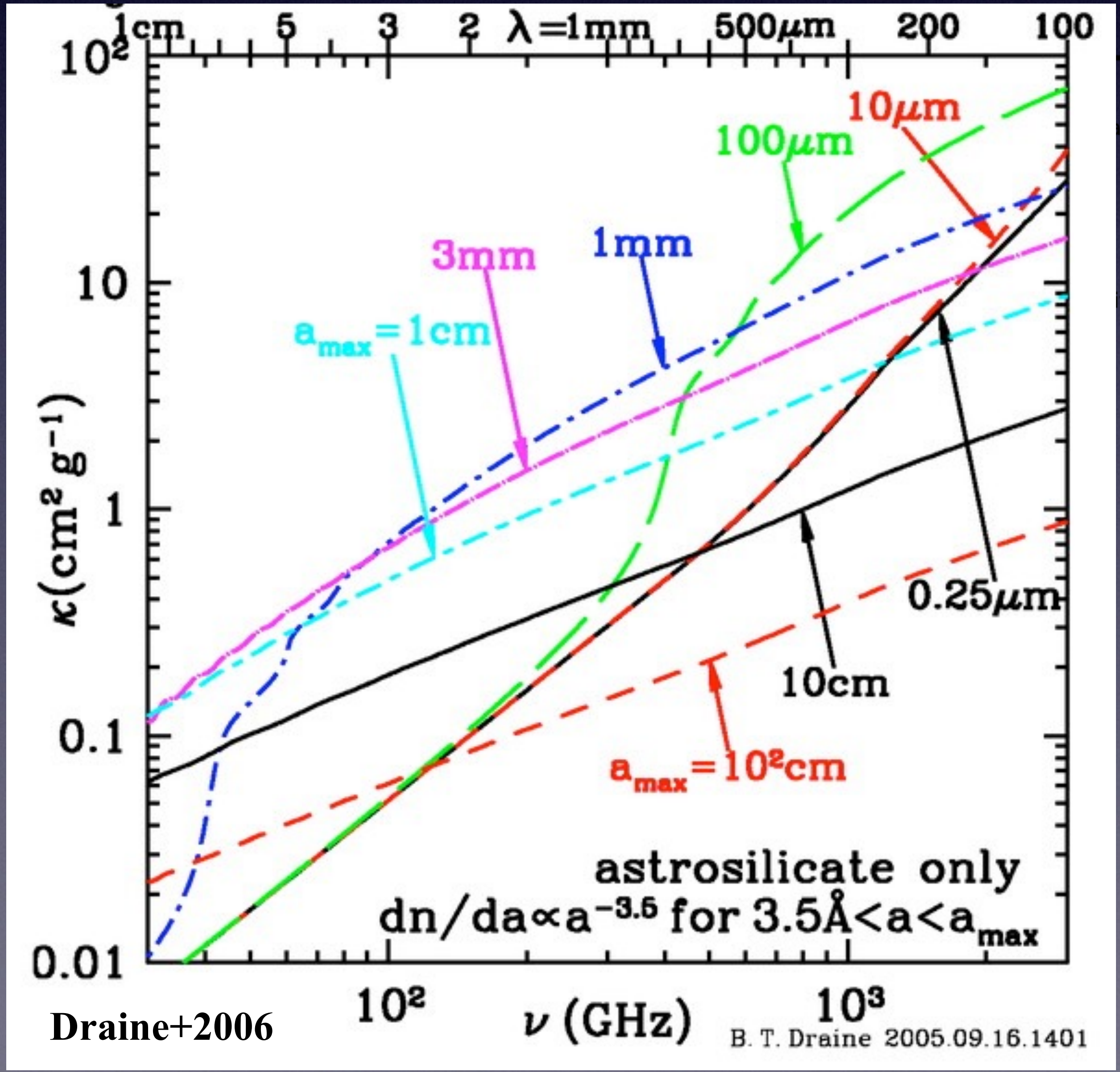
Movies from J. Blum and collaborators:
Weidling et al. 2012
Schraepler et a. 2012
Guettler et al. 2010

Dust evolution: grain growth processes



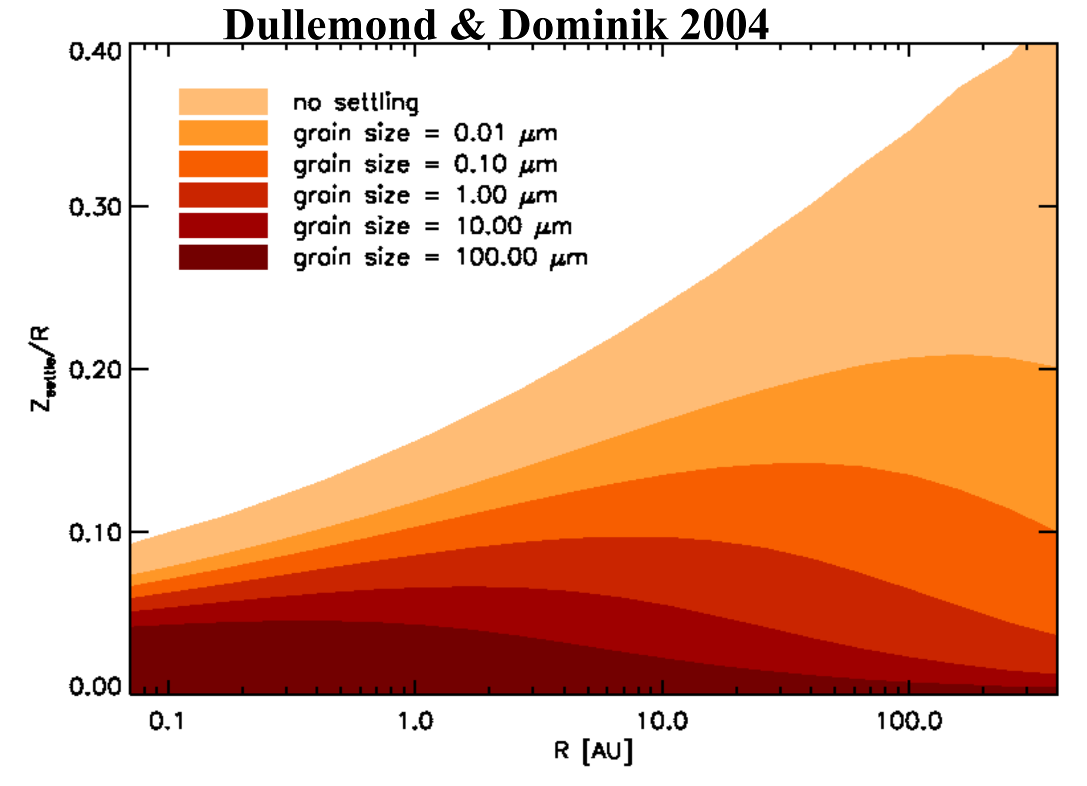


(Testi et al. 2014)

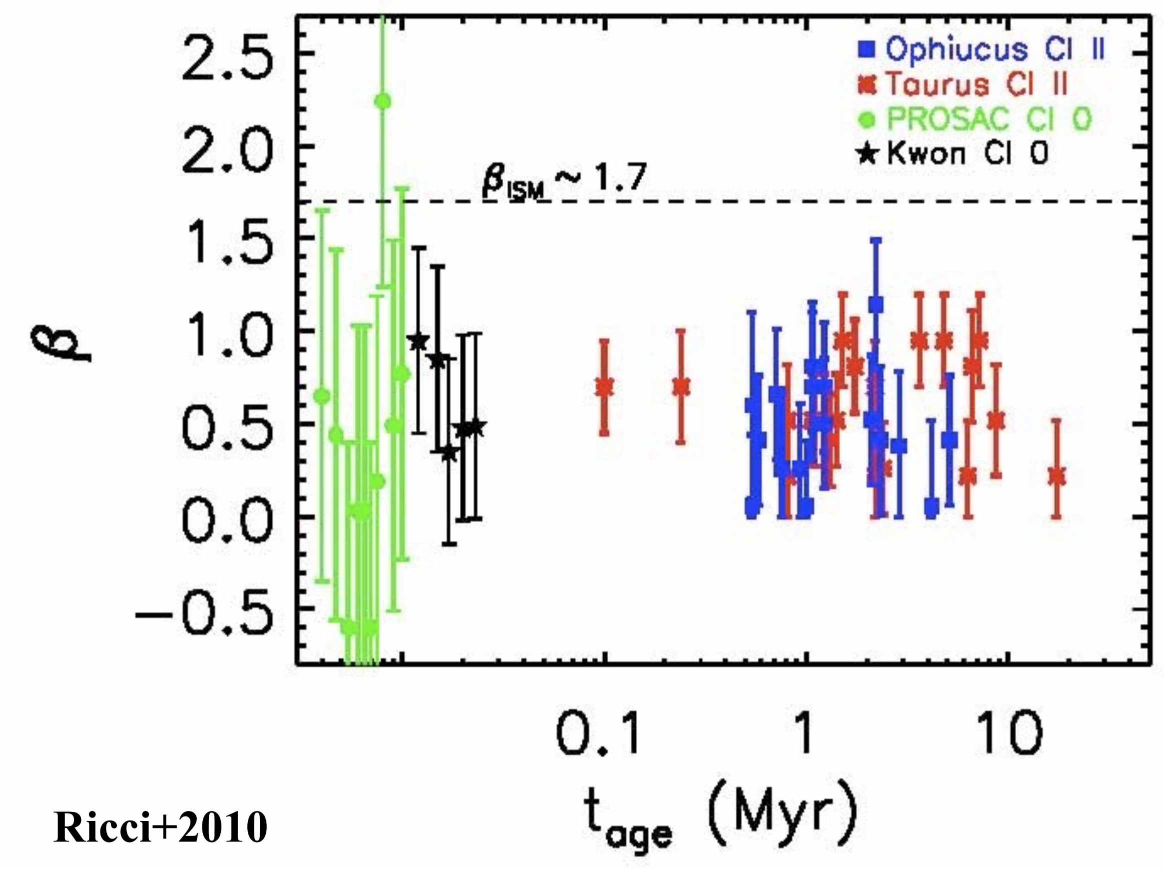


Draine+2006

Dullemond & Dominik 2004

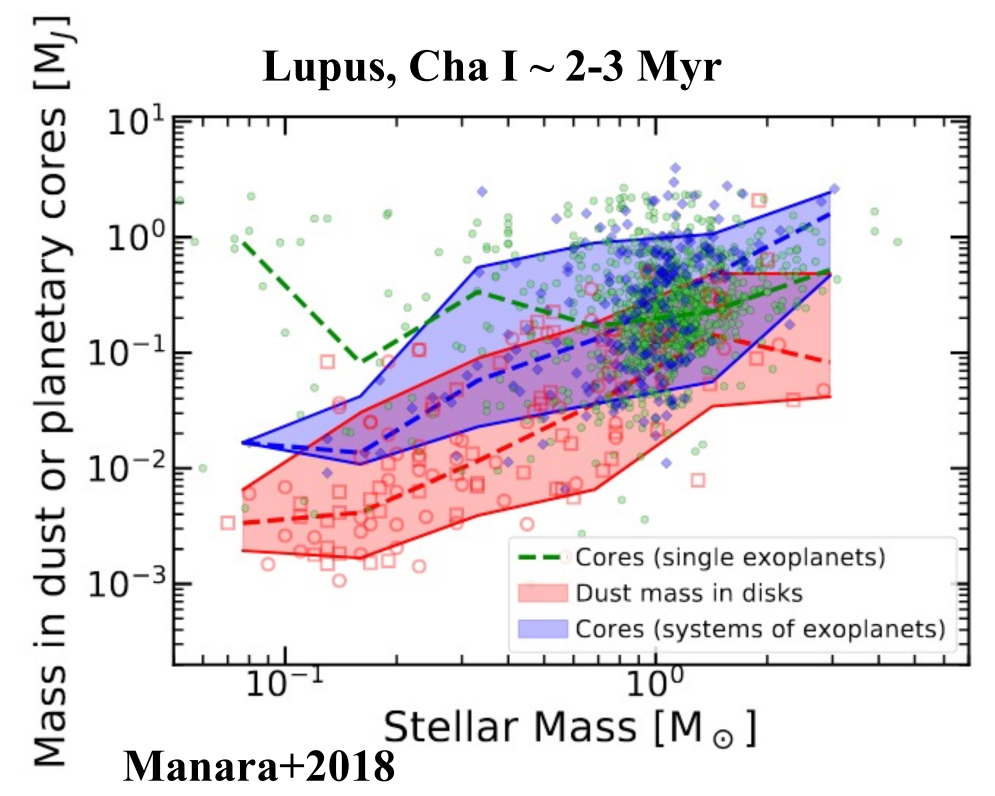


Annoying alarms



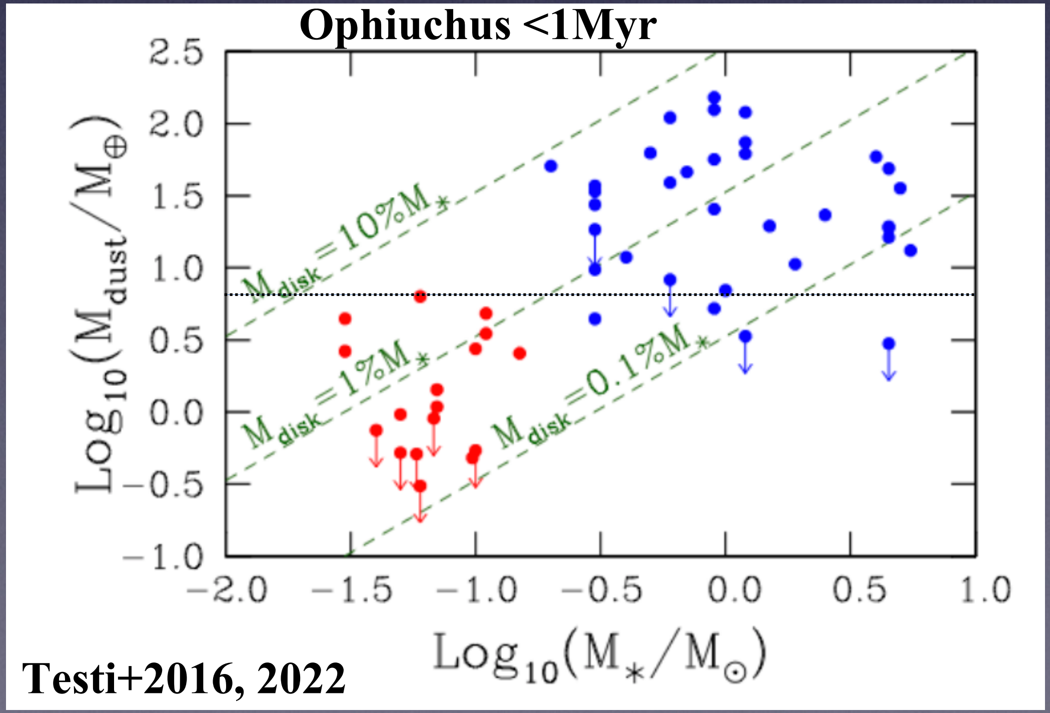
Ricci+2010

- Evidence for dust evolution in young protostars
- No evidence for evolution from small to large dust grains
- 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
- Already at 1Myr disks seem to contain too little dust to form planets



Lupus, Cha I ~ 2-3 Myr

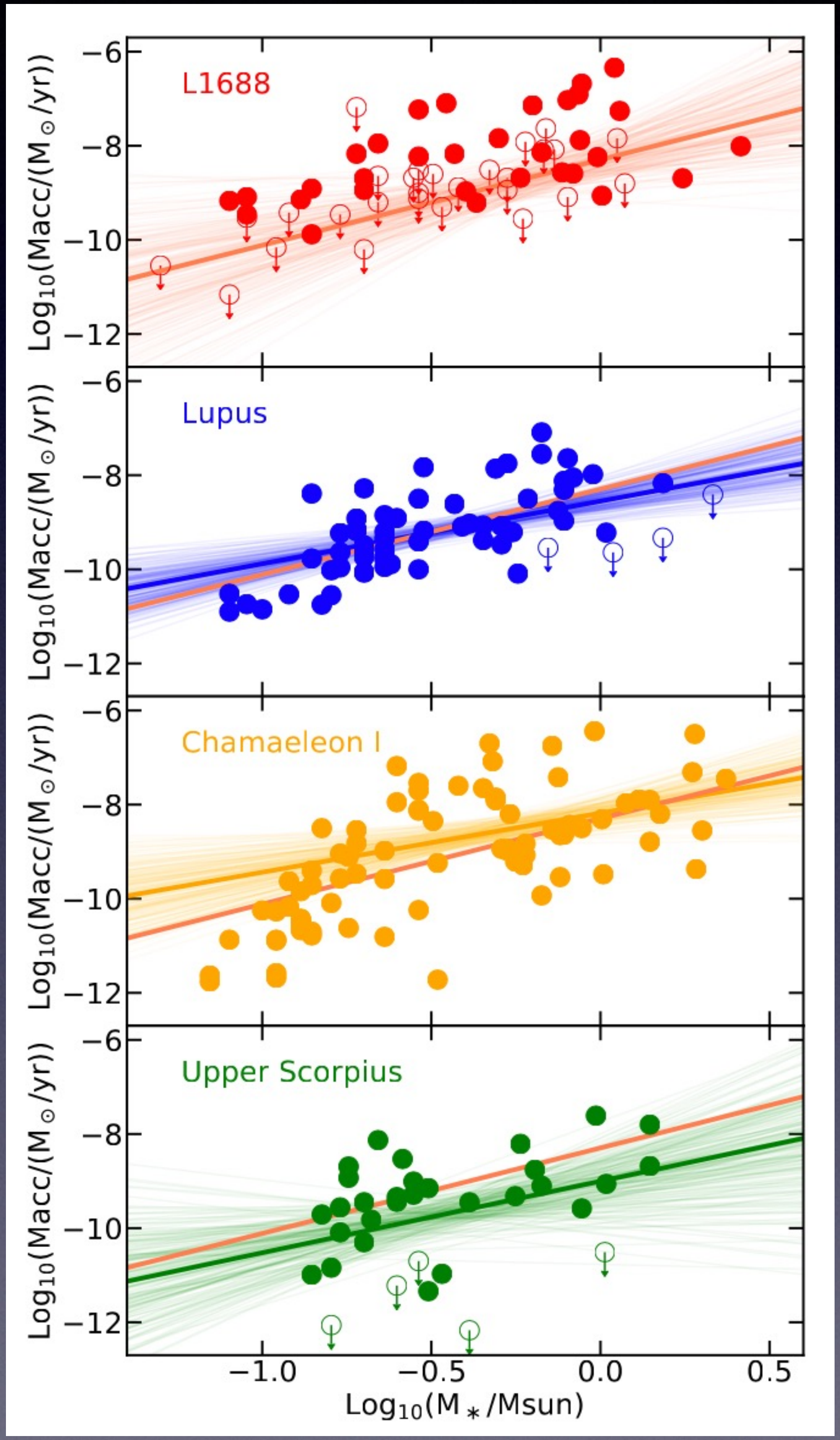
Manara+2018

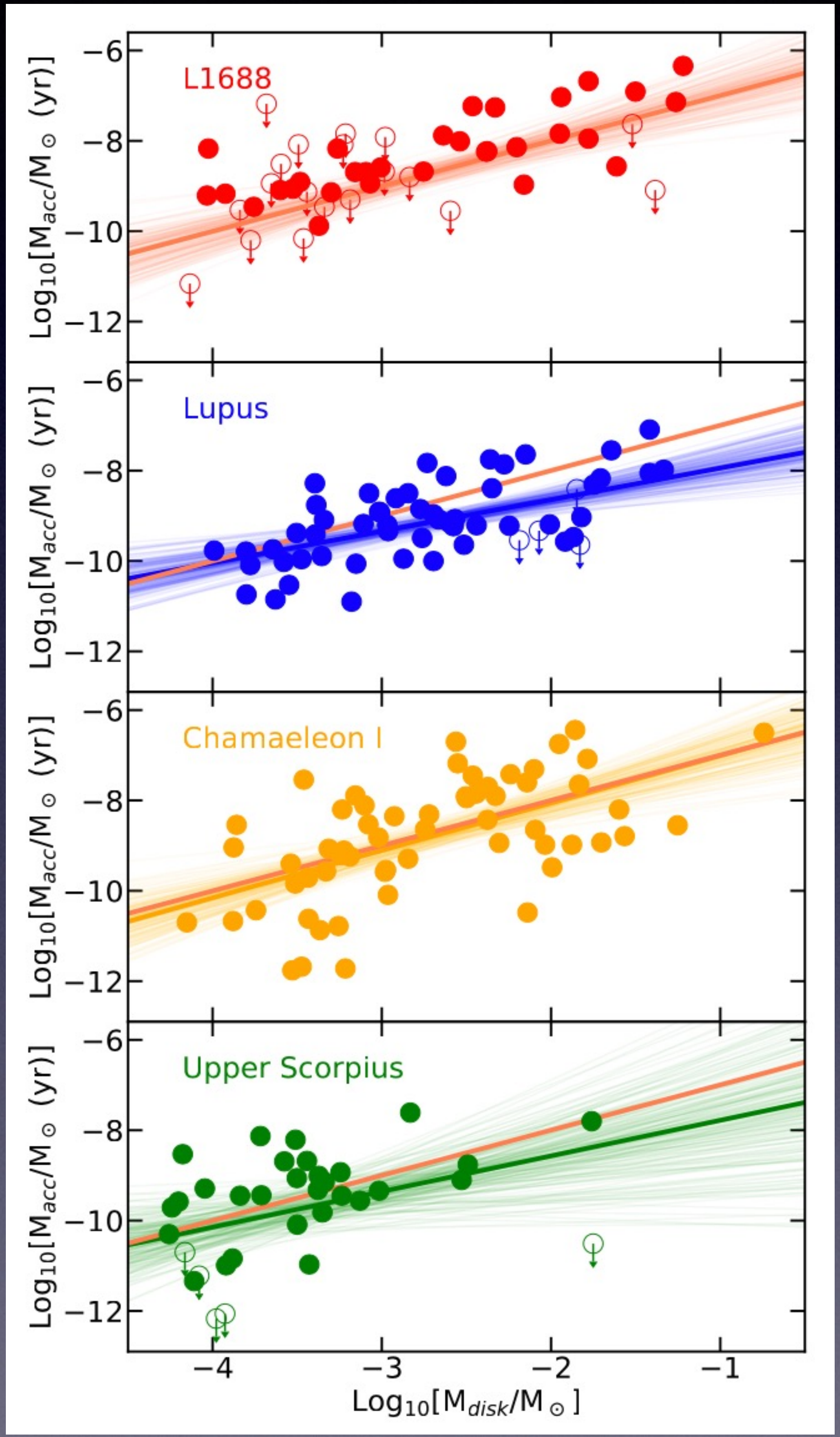


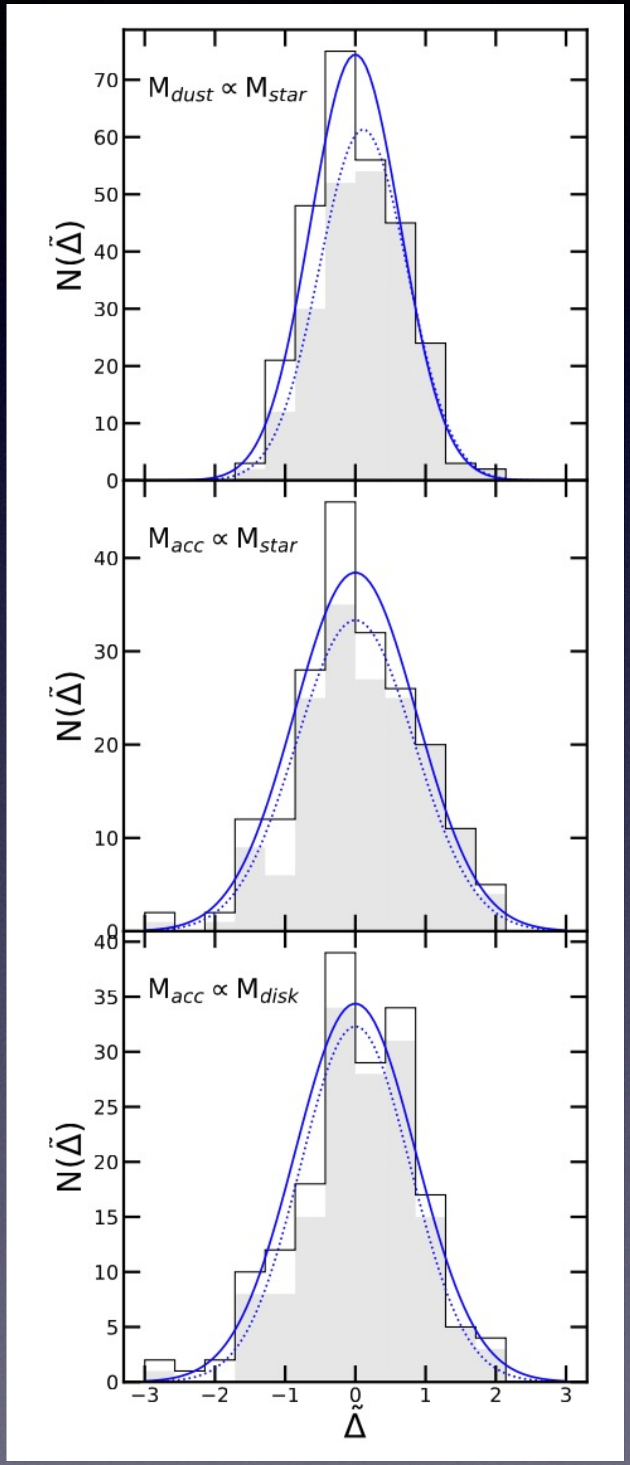
Ophiuchus <1Myr

Testi+2016, 2022

Evolution of disk properties

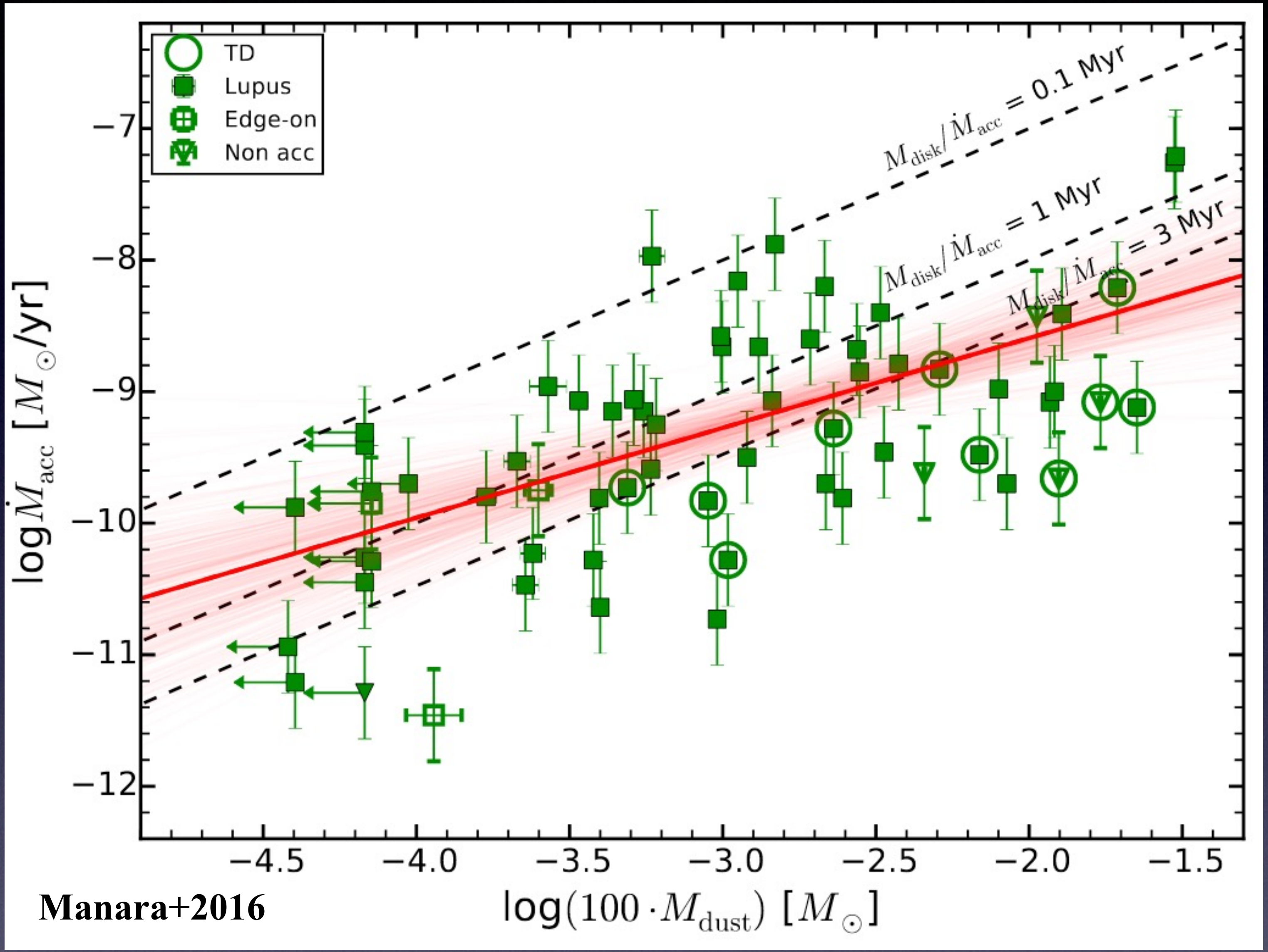




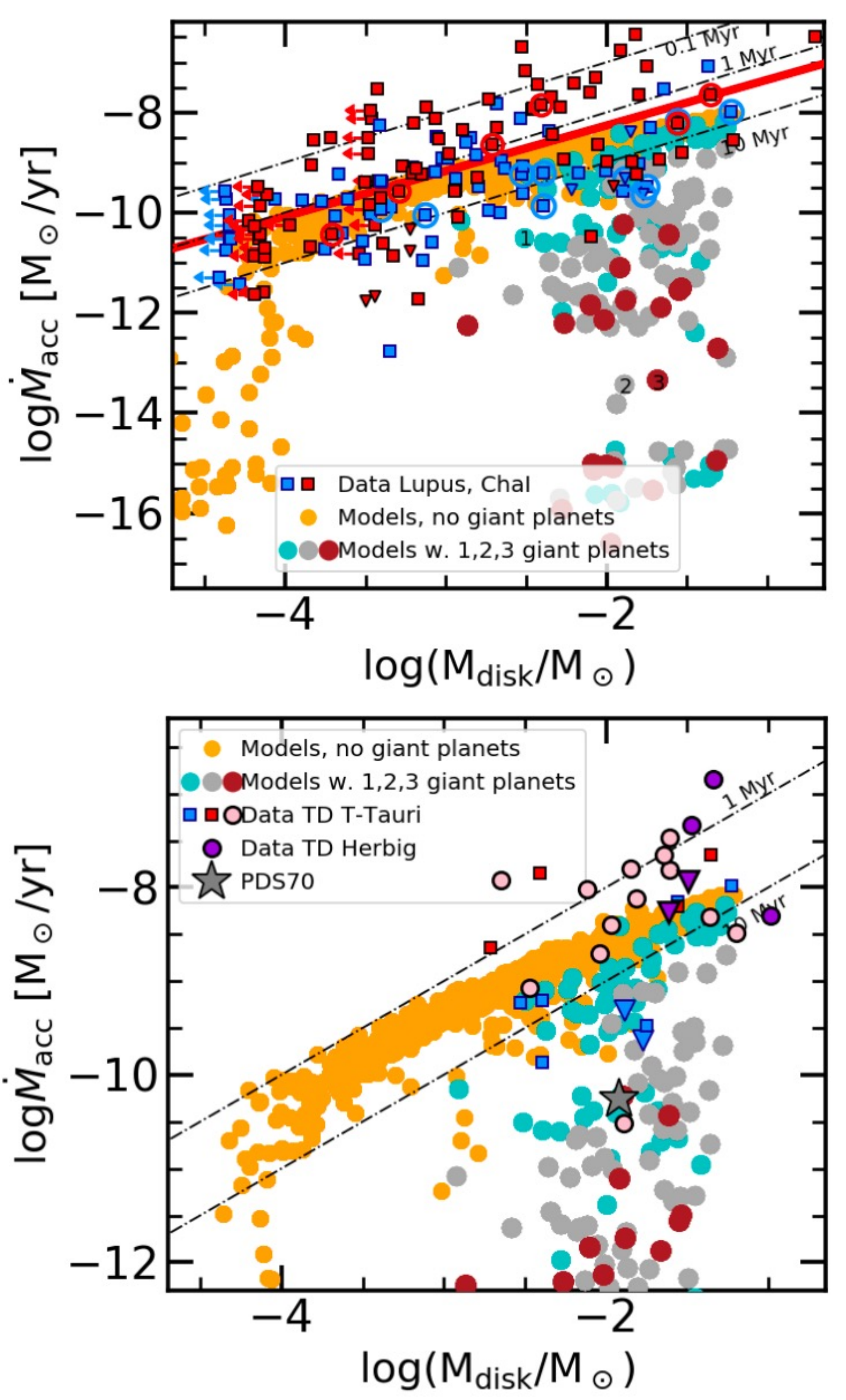


(Testi et al. 2022; see also Manara+2022)
Data from ALMA, XShooter, etc.

Long term disk evolution



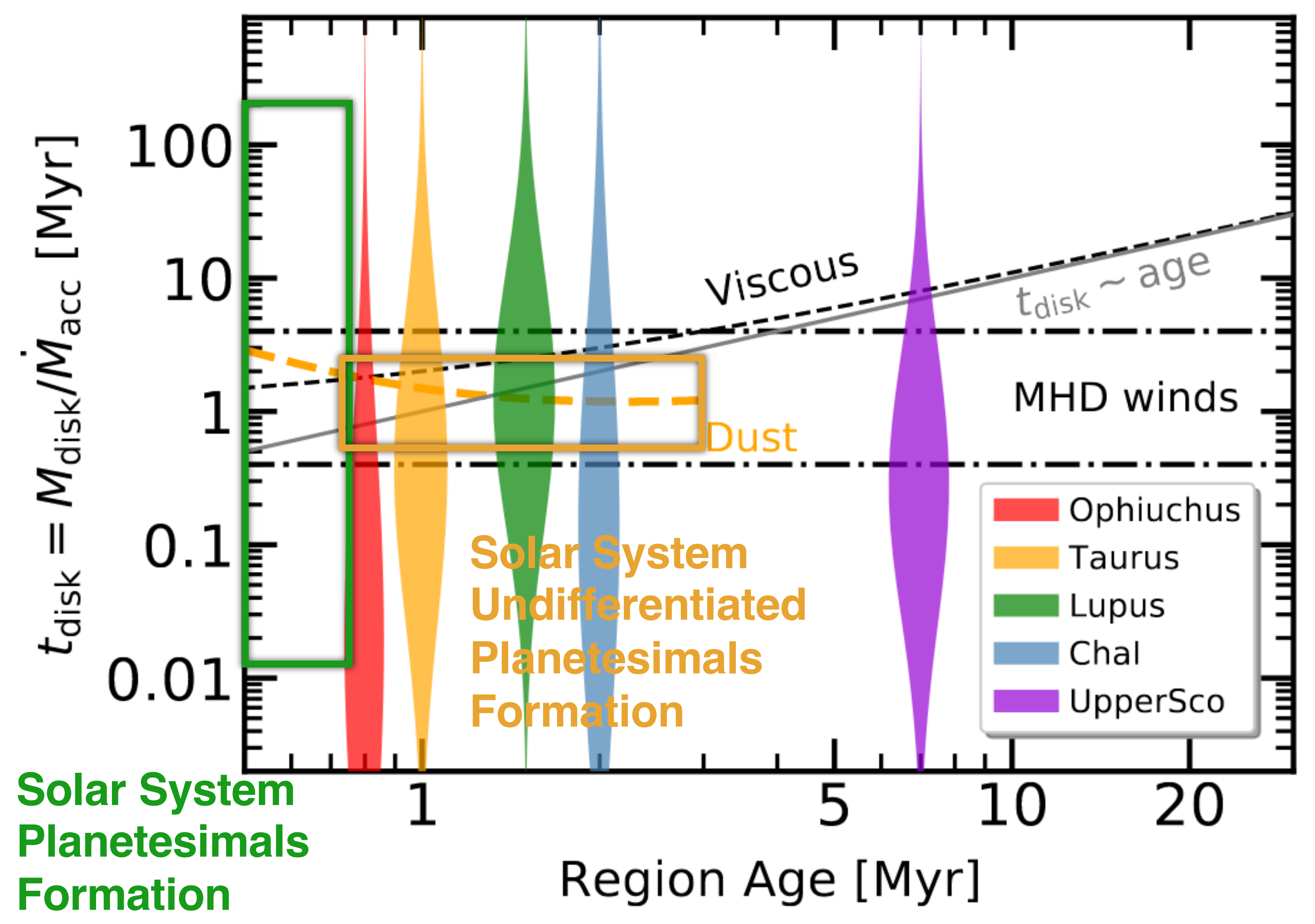
Manara+2016



Manara, Mordasini, Testi, et al. 2019

- Almost as predicted by viscous evolution… but not quite!

Evolution of disk properties



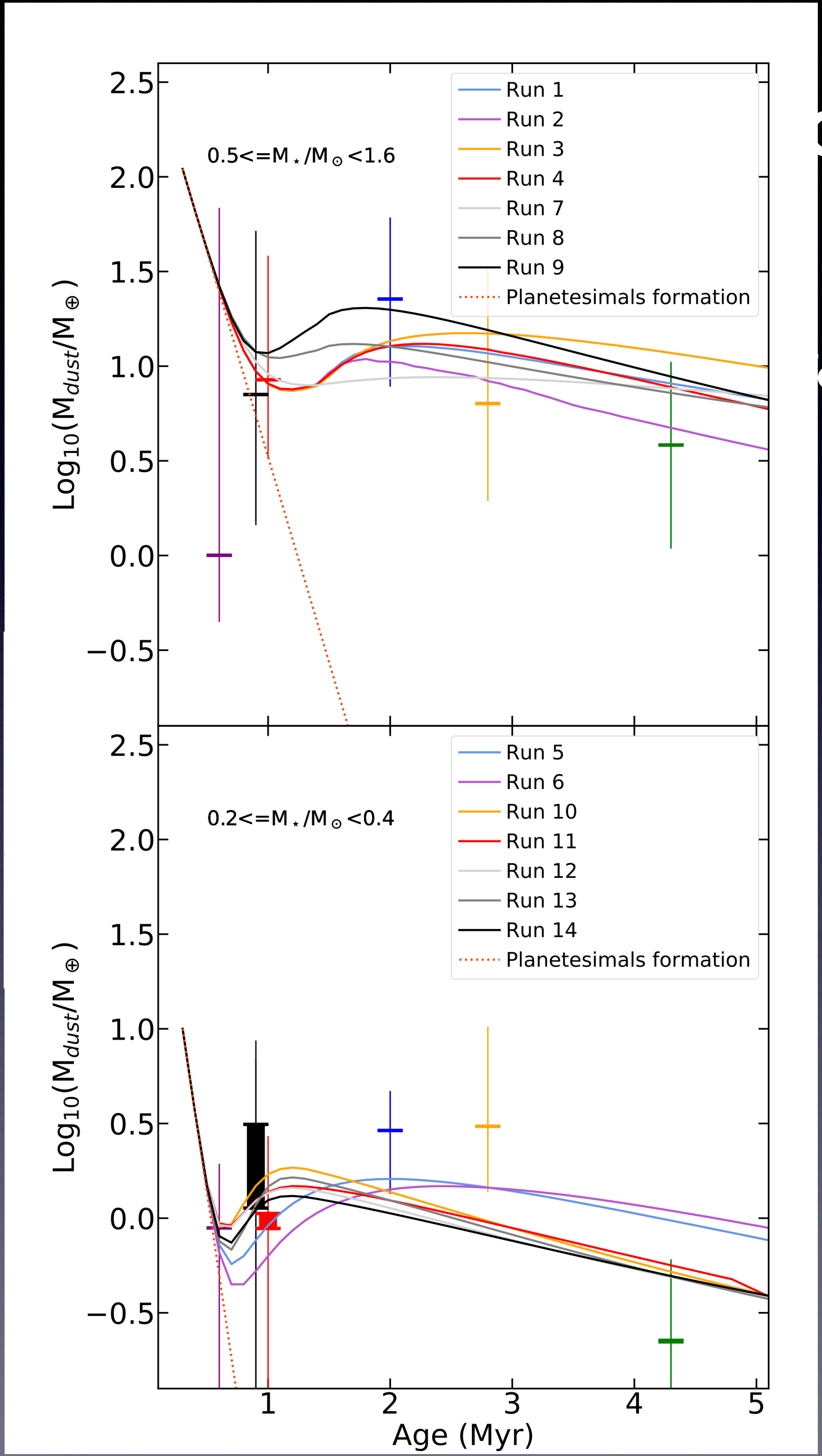
Solar System Undifferentiated Planetesimals Formation

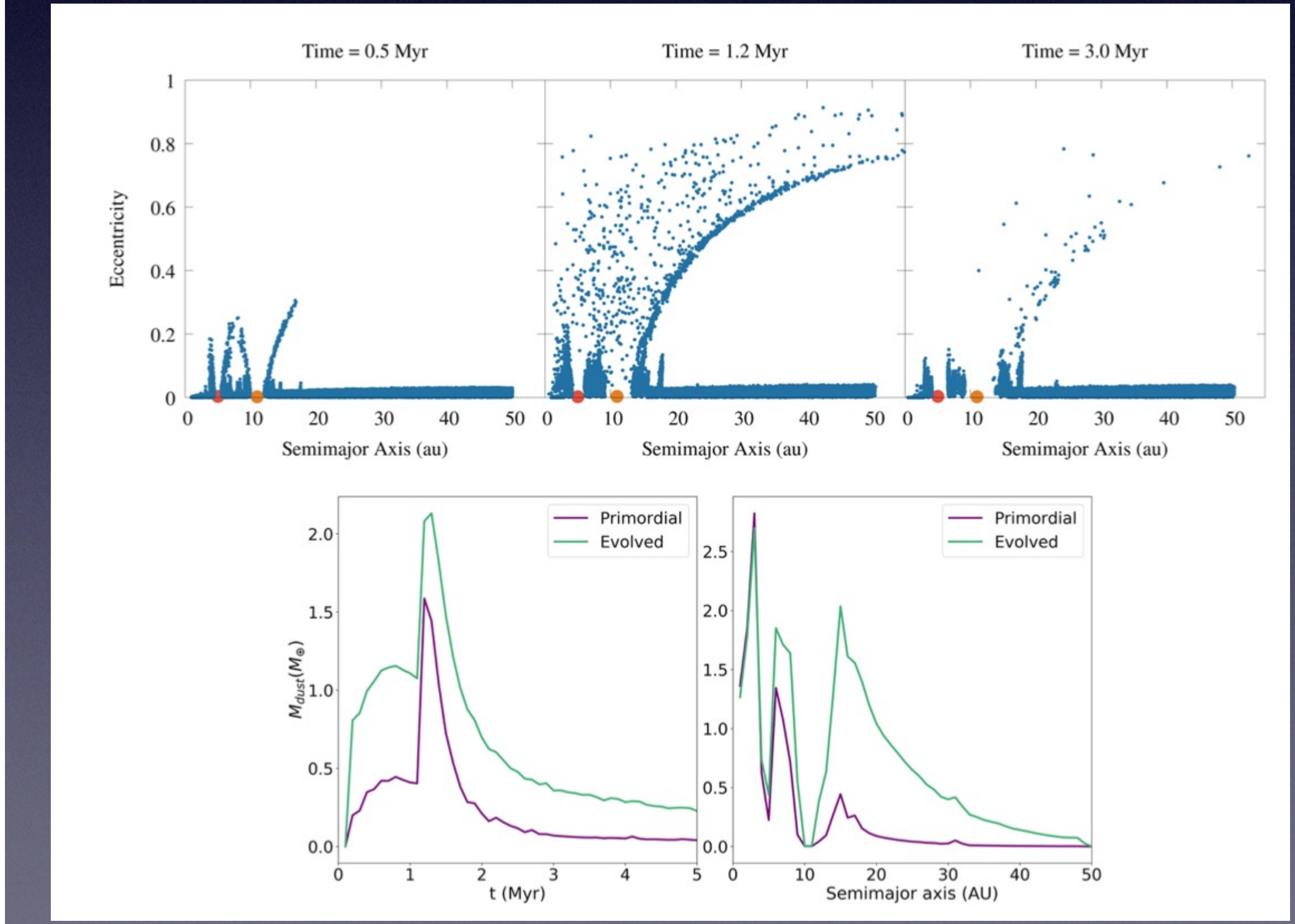
Solar System Planetesimals Formation

(Manara+2023)

cit explanations

ormation

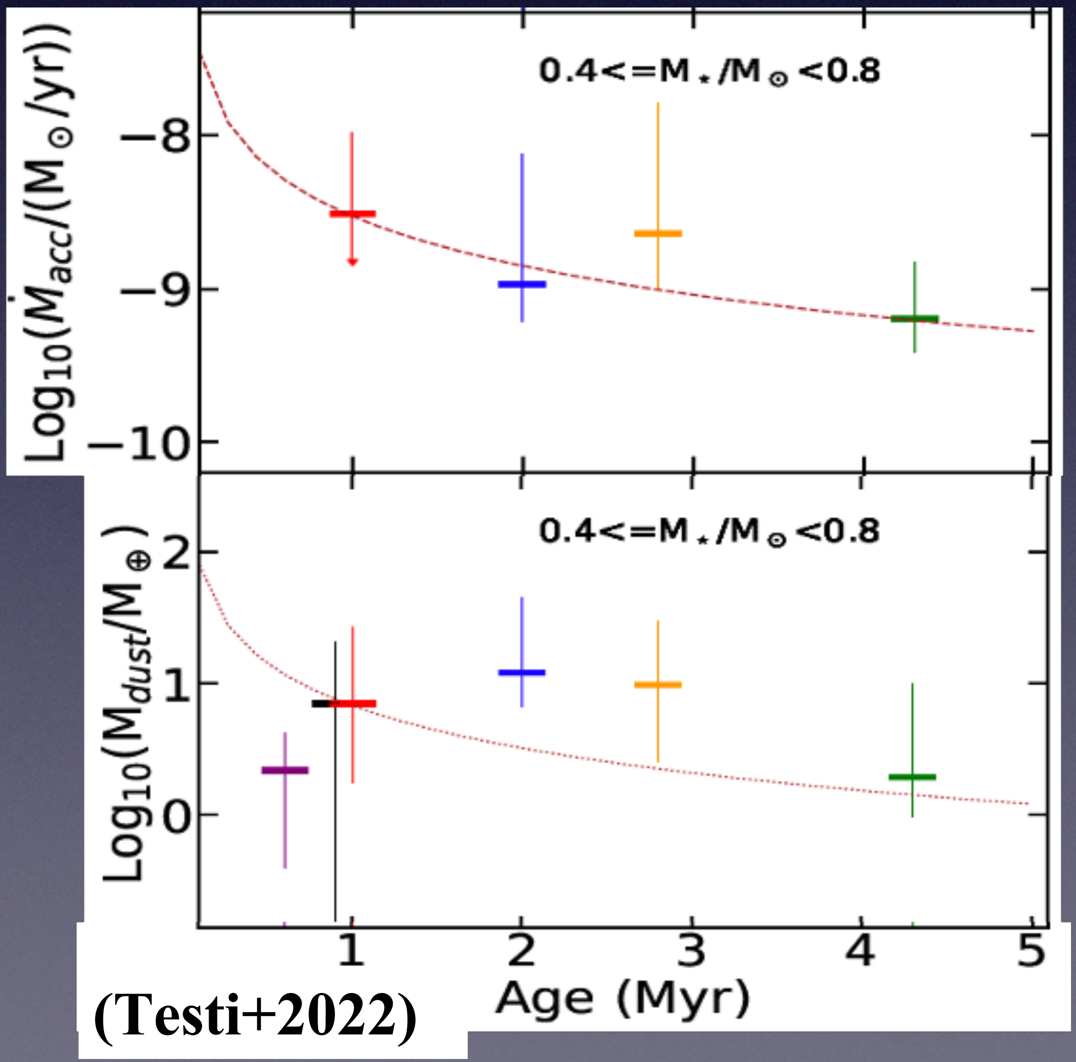




(Turrini+2019, Bernabo+2022)

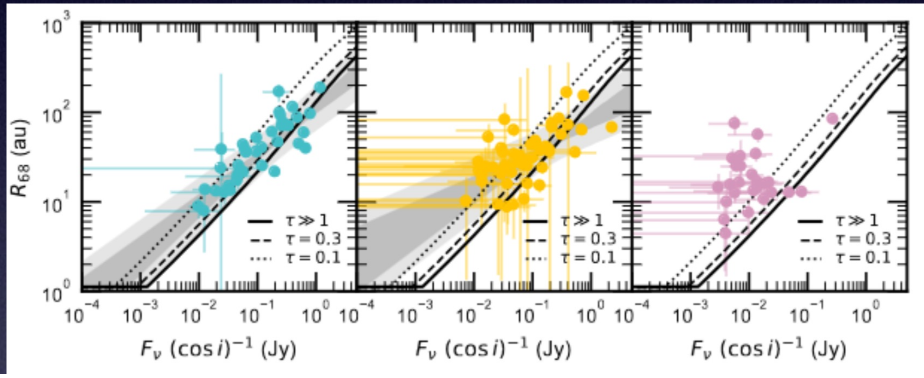
Mass deficit explanations

- Early planetesimals and planet formation
- Optical depth effects



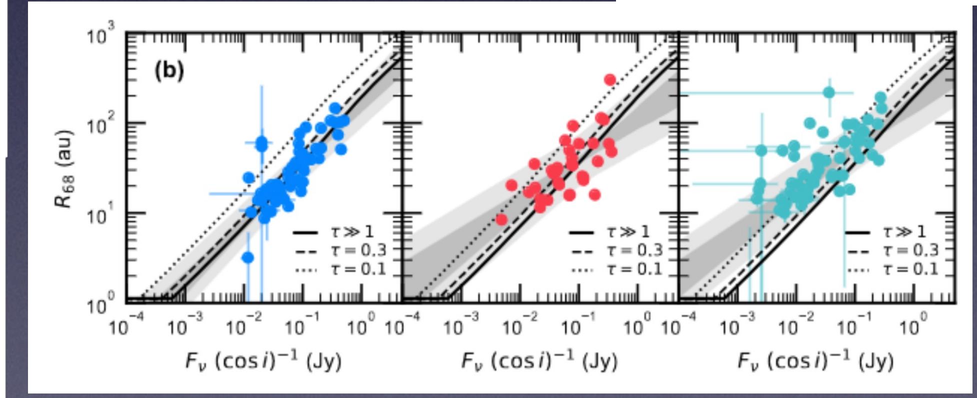
(Testi+2022)

0.9mm



(Tazzari+2023)

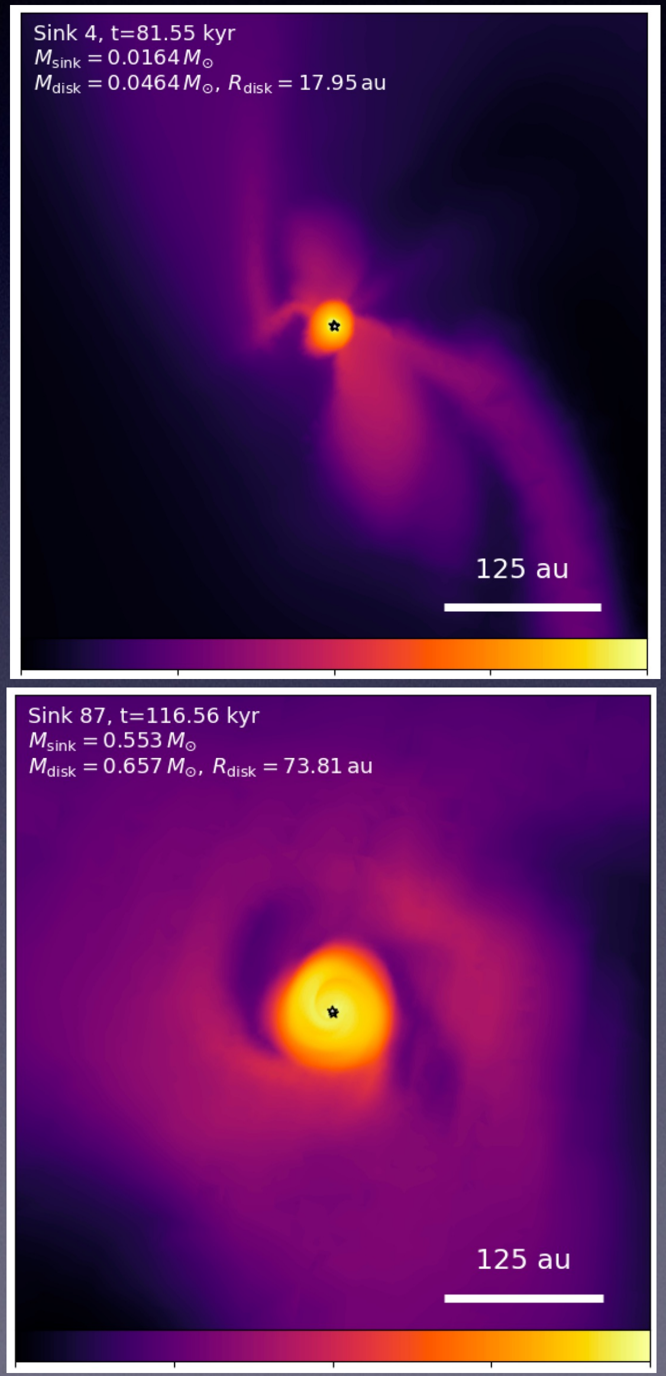
1.3mm



0.5Myr 1Myr 2Myr 3Myr 5-8Myr

Optical depth

Next generation population synthesis



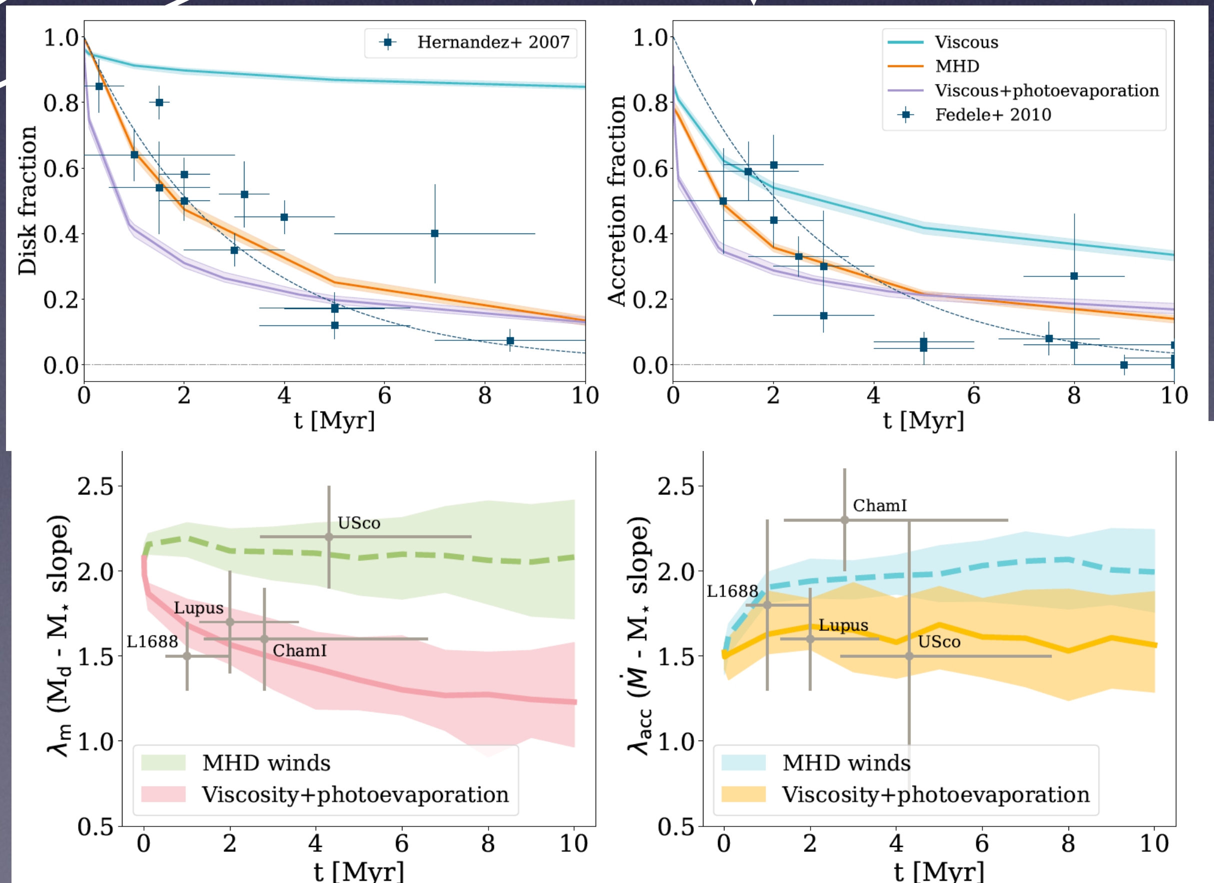
Initial conditions

Simplified 1D prescriptions

Diskpop
Population synthesis of planet forming disks

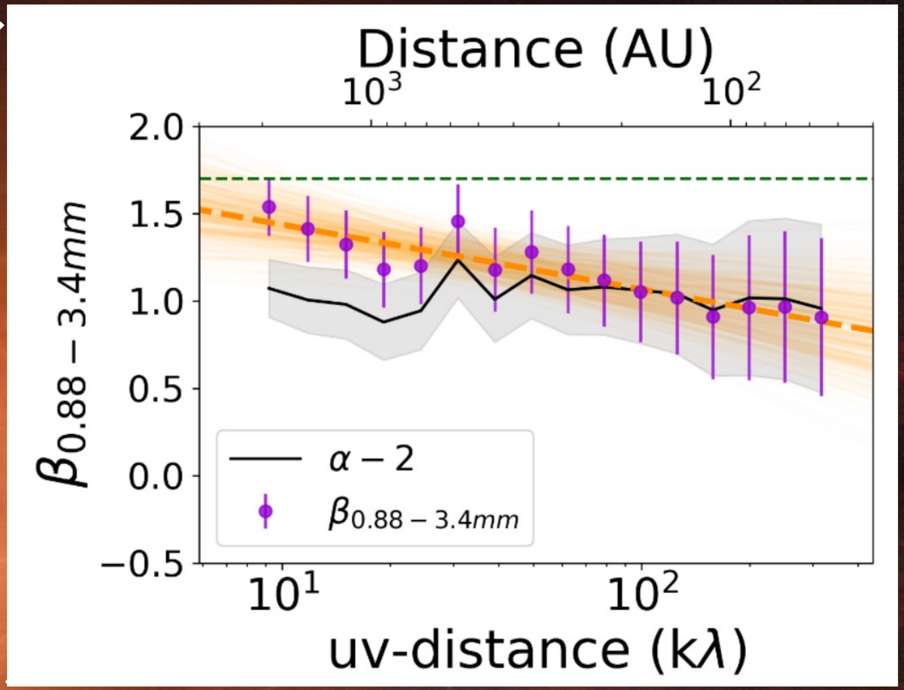
Missing ingredients:
Planet formation
Chemical evolution

Population observables

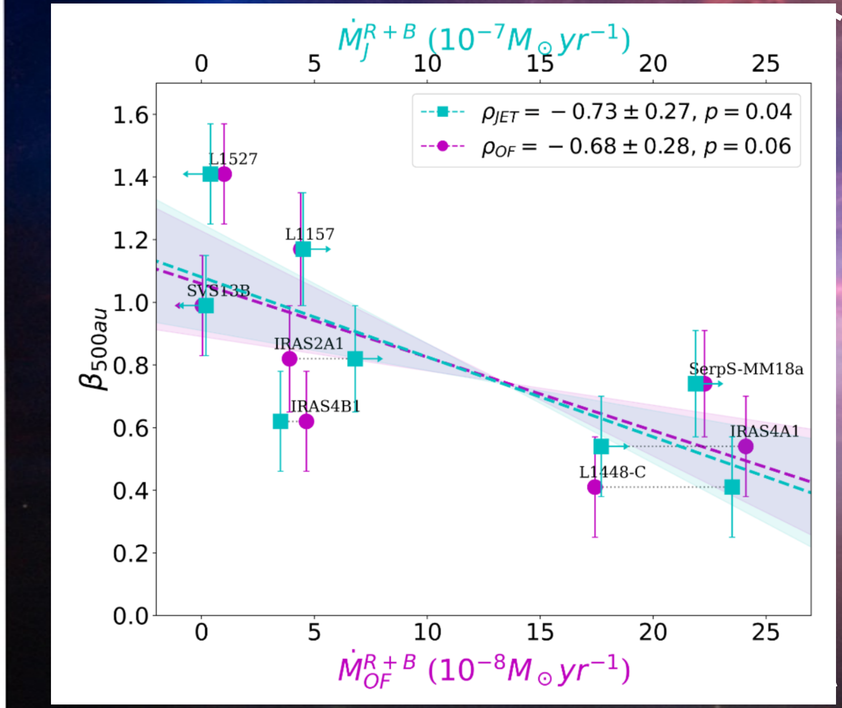


Are grains growing already in Class 0/I envelopes? Are they transported therein ?

Luca Cacciapuoti



Cacciapuoti, L. et al. 2023a, A&

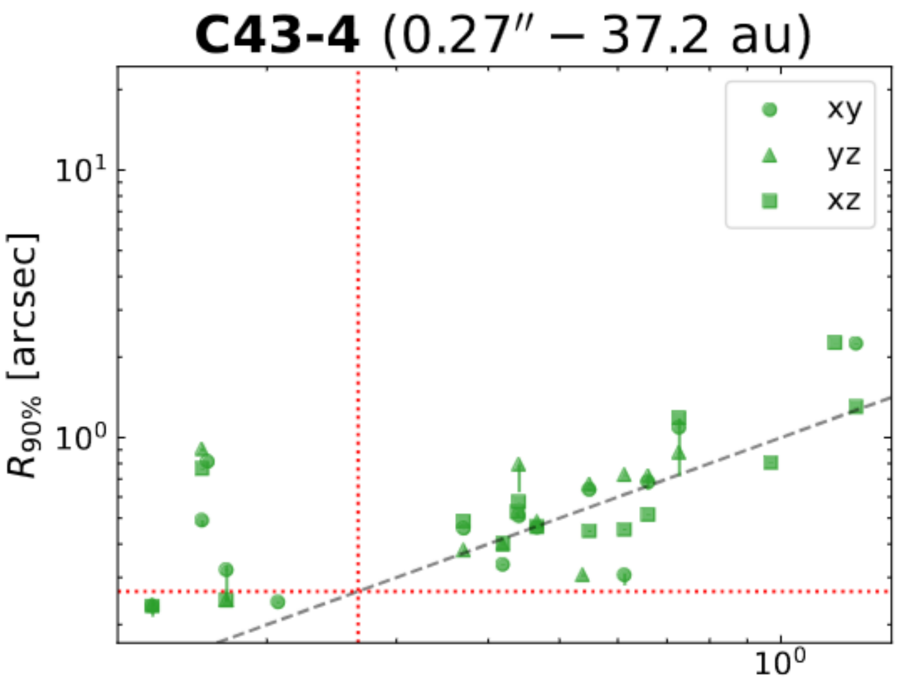


acciapuoti, L. et al. subm.

ALMA Band 4 archival data overlaid o
JWST NIRCam view of L1527 IRS, Taur
Credits: NASA, CSA, ESA, STScI

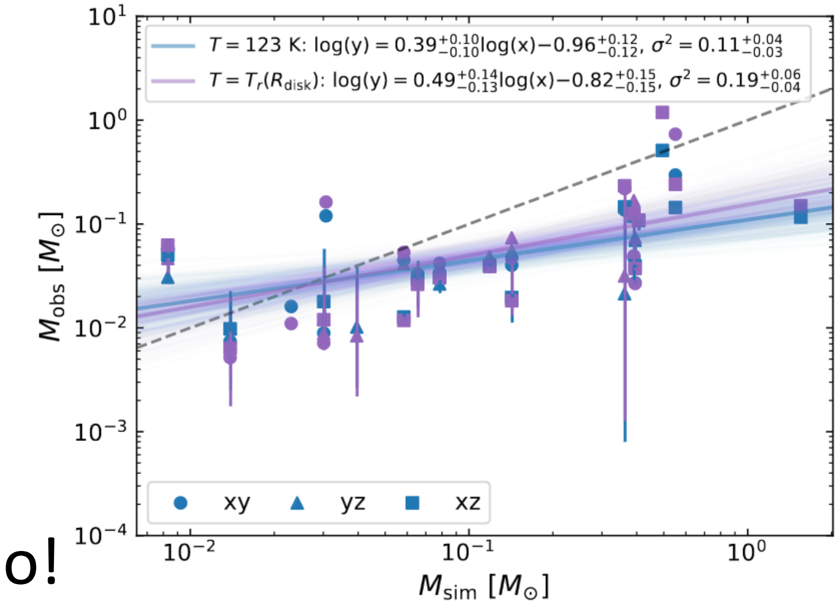
Definition of the observables

- Key conclusions: comparison not trivial, quick and dirty approach not meaningful to extract the physics
- Importance of going to longer wavelengths

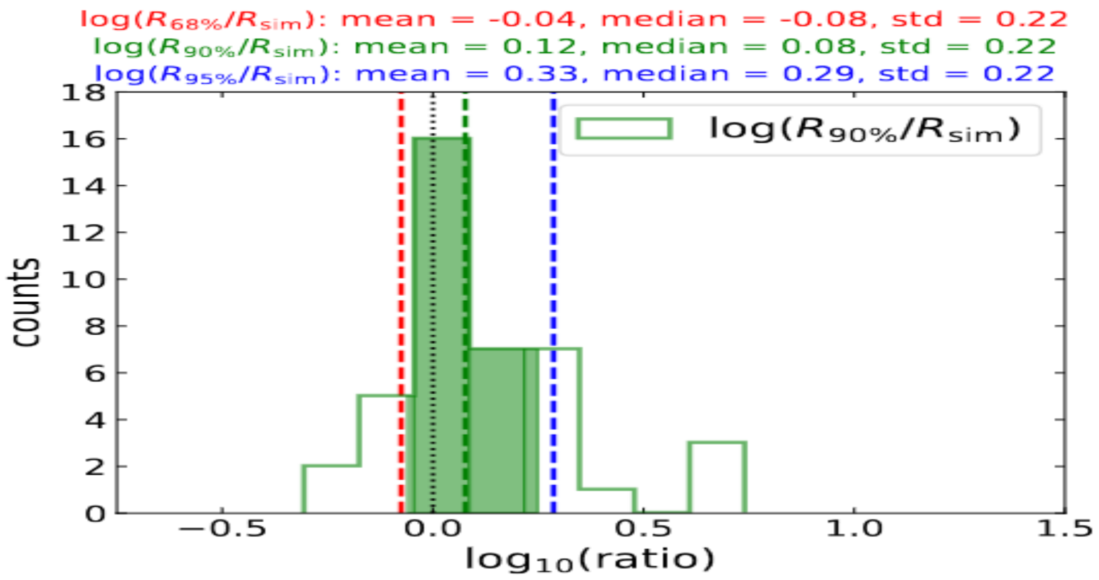


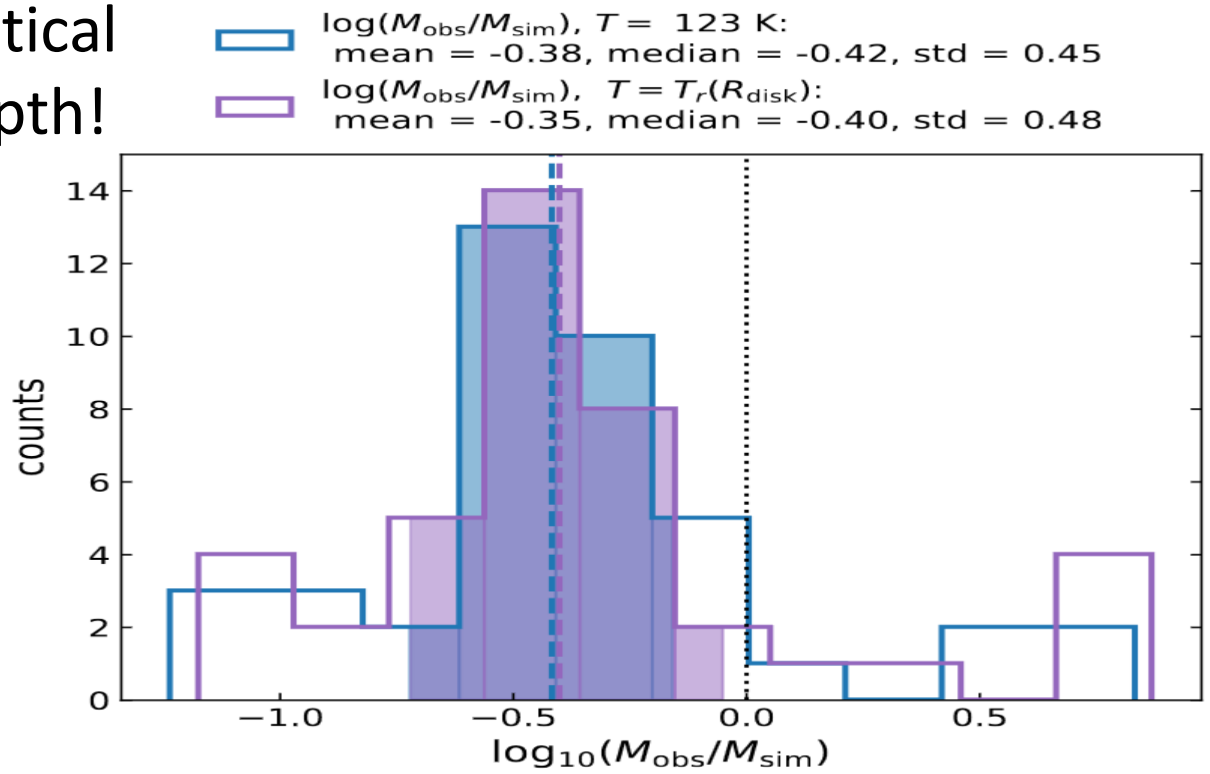
(Ngo et al. 2024)

Disk radii - Ok



Disk mass – No! Optical depth!

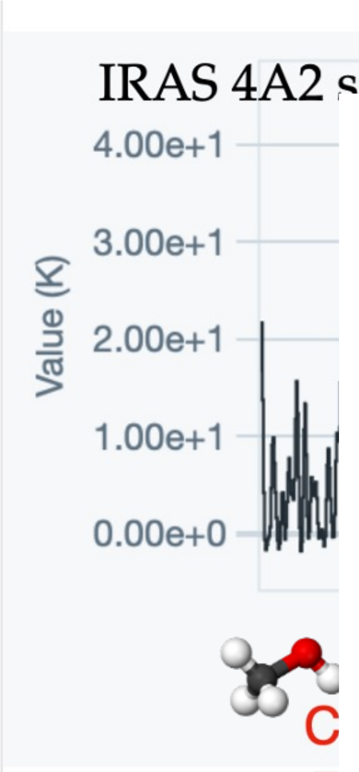


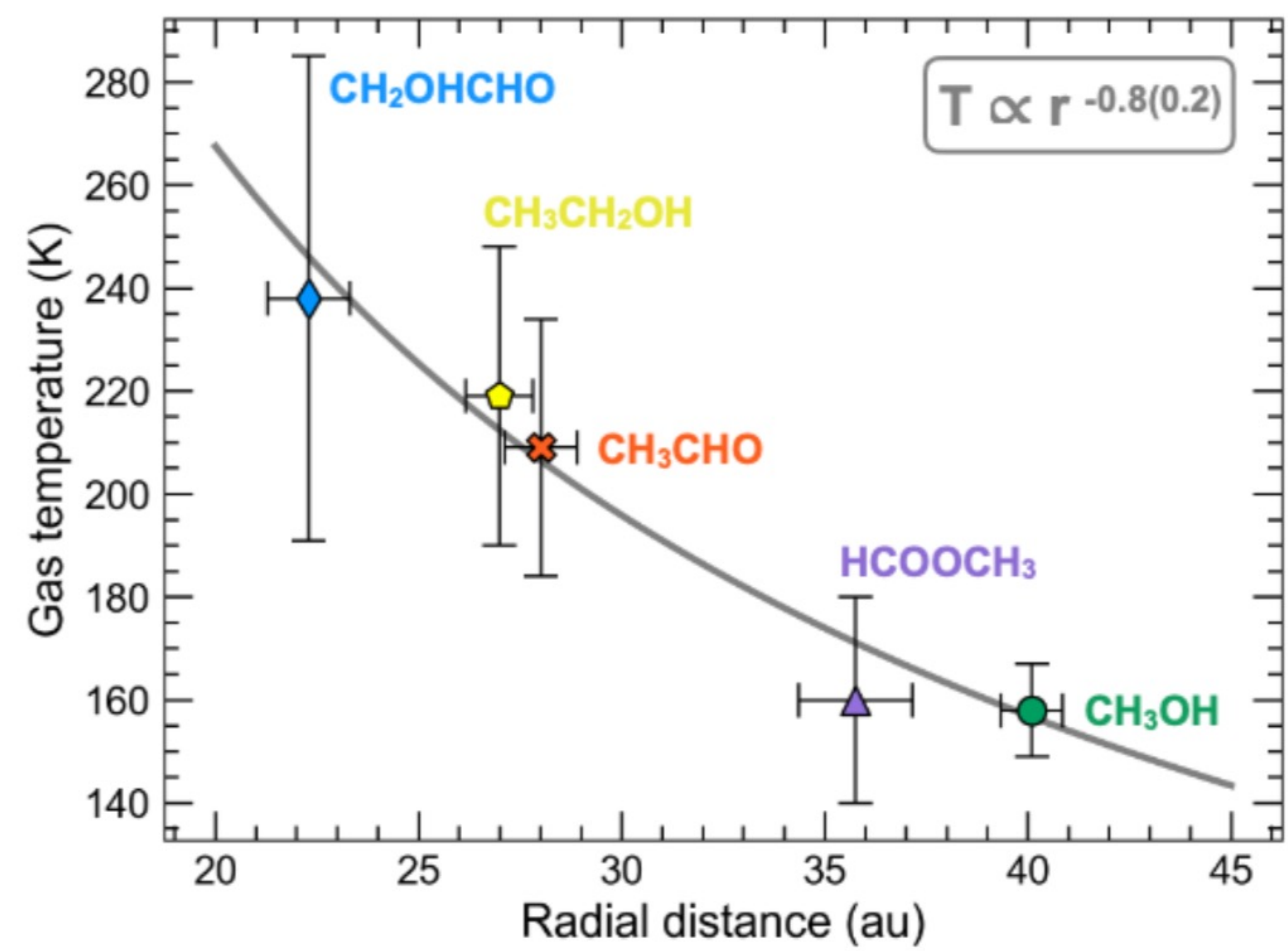


iCOMs: interstellar Complex Organic Molecules

Molecular lines identification in IRAS 4A2 spectrum

Jenny Frediani





Estimatec

- Methanc
- Acetald
- Methyl f
- Formam
- Glycolal