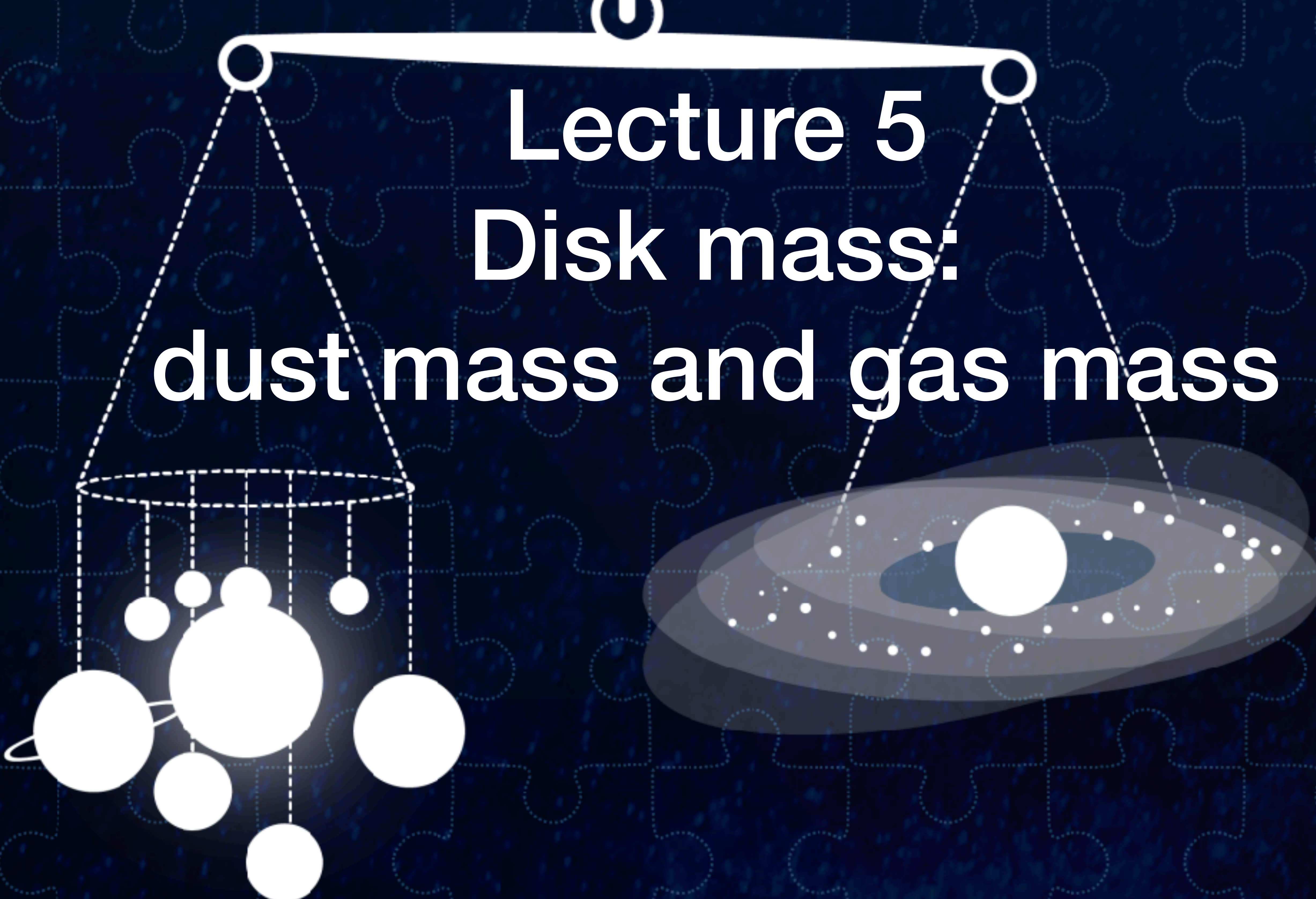
Lecture 5
Disk mass:
dust mass and gas mass



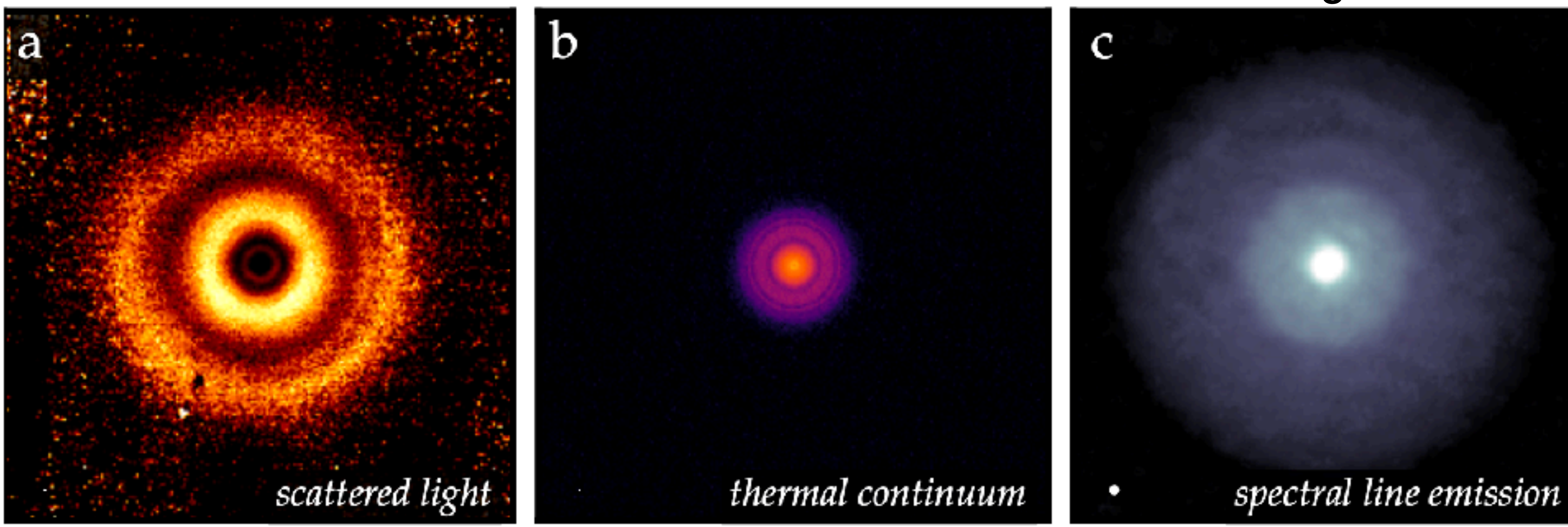
AstroTwin Colombia School 2022
Planet formation and ALMA
dr. Nienke van der Marel
Leiden Observatory

Graphic credits: Miotello

Contents

Recall: gas vs dust

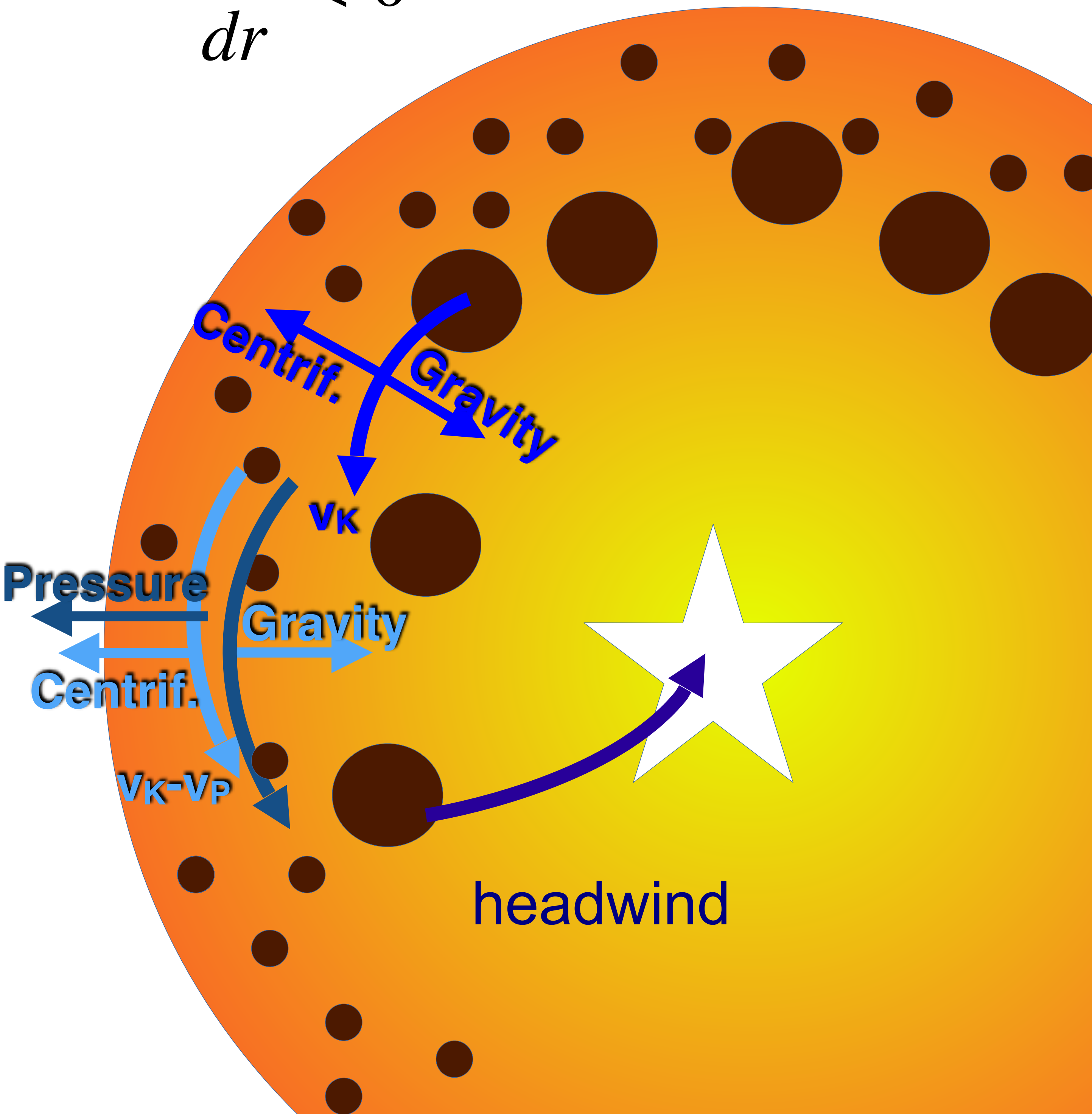
NIR | **ALMA mm continuum** | **ALMA integrated ^{12}CO**



Andrews 2020

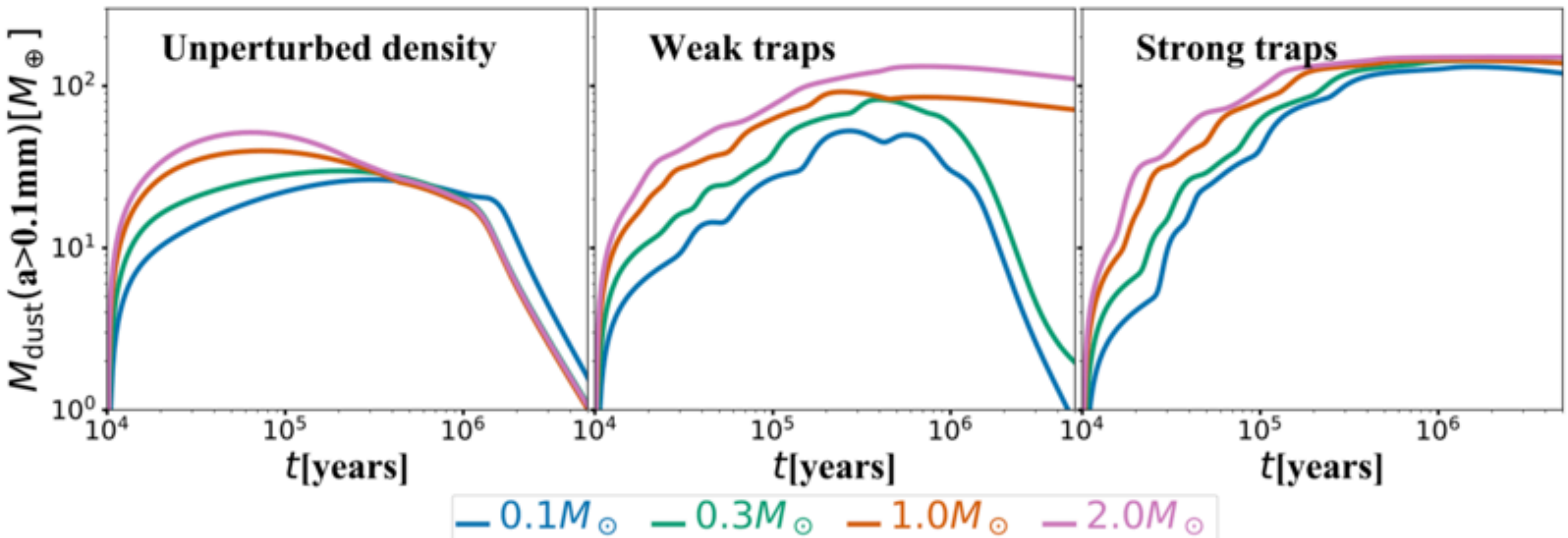
Recall: dust evolution

- Gas disk has a pressure gradient $\frac{dp}{dr} < 0$
  - Radial inward <u>drift</u> dust

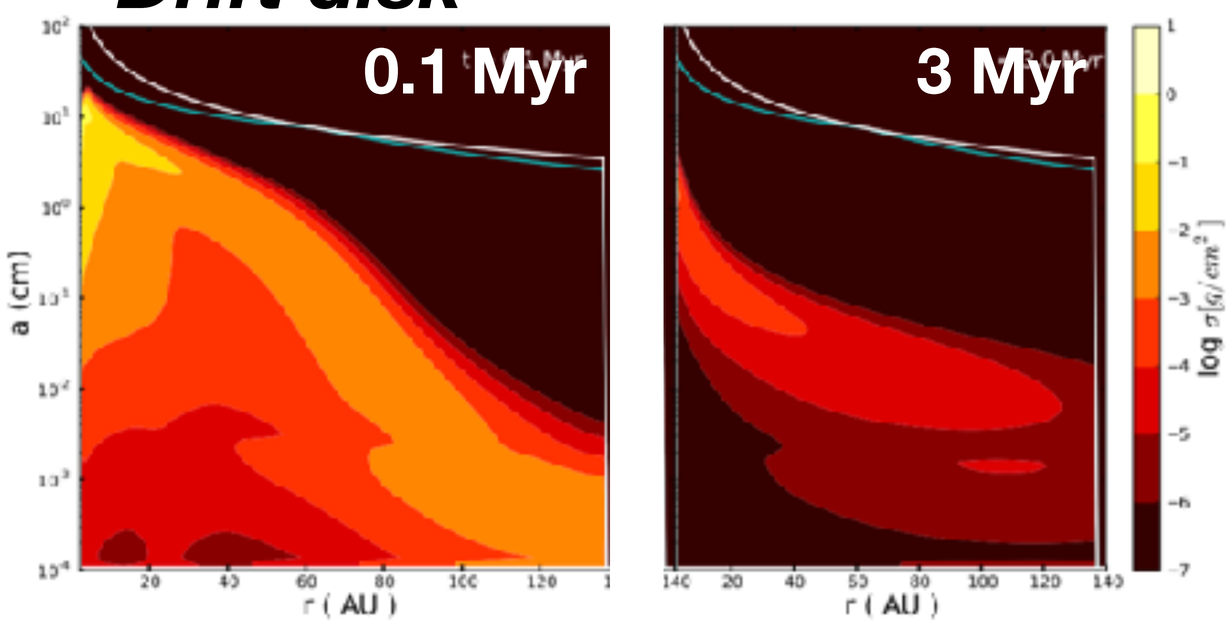


Weidenschilling 1977

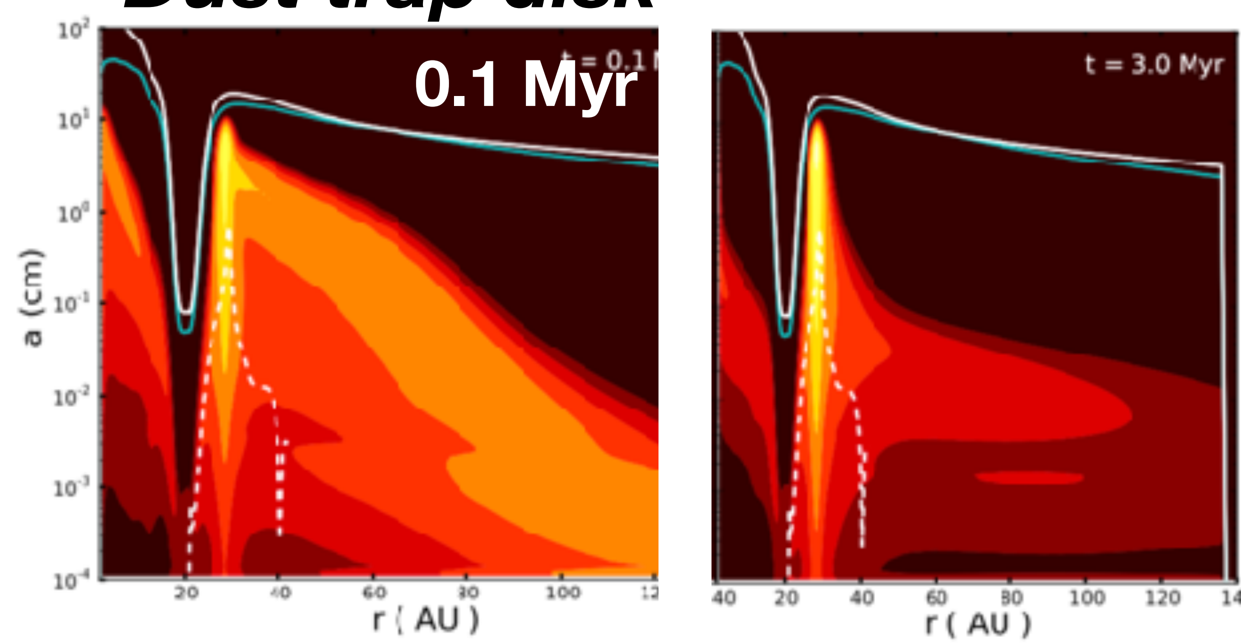
Recall: dust evolution



Drift disk



Dust trap disk

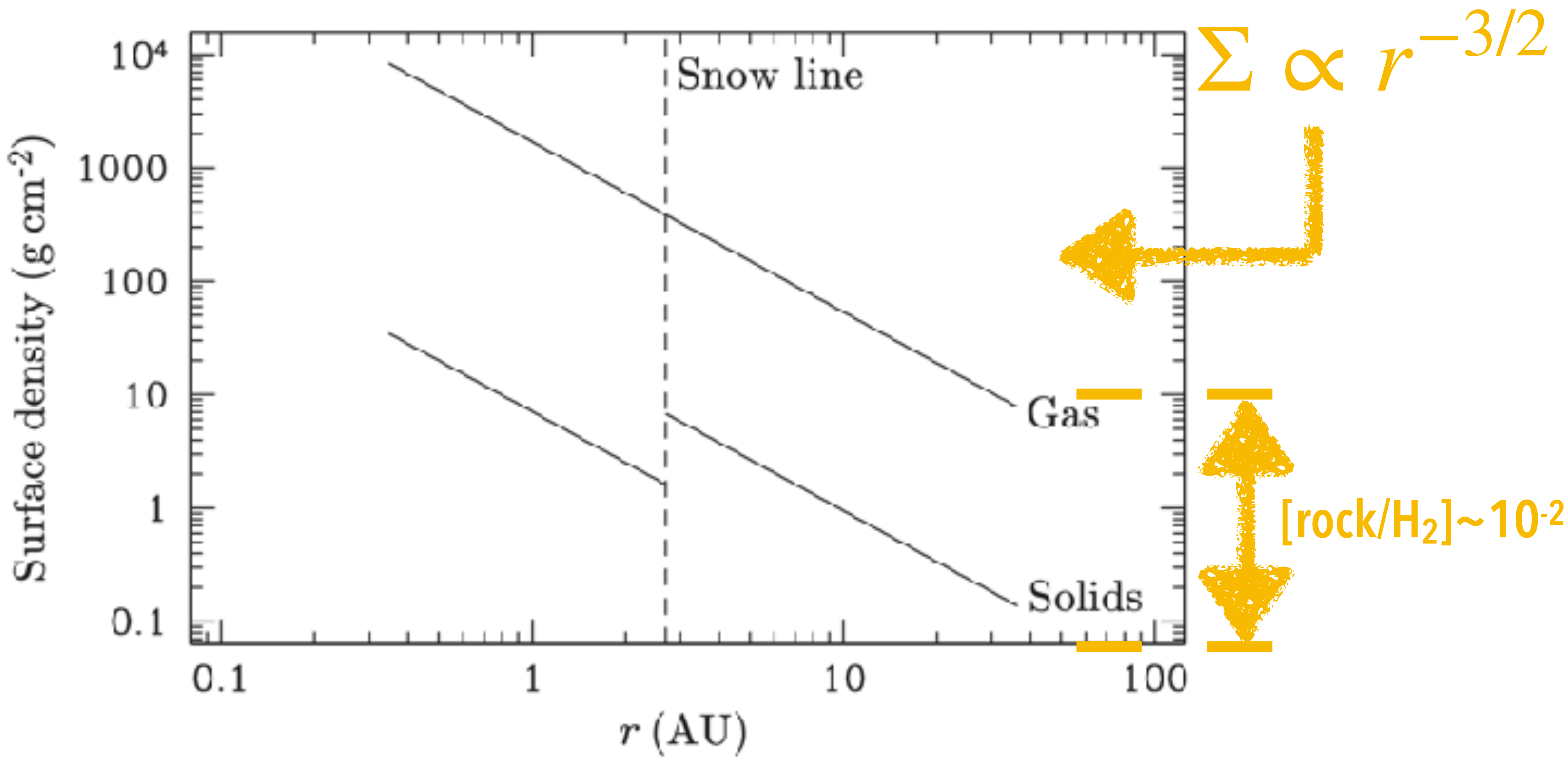


Pinilla et al. 2012, 2020

Dust mass: solid reservoir for planet formation

Solar System: cannot go back in time and measure disk mass, but can estimate the minimum amount of material needed: The Minimum Mass Solar Nebula

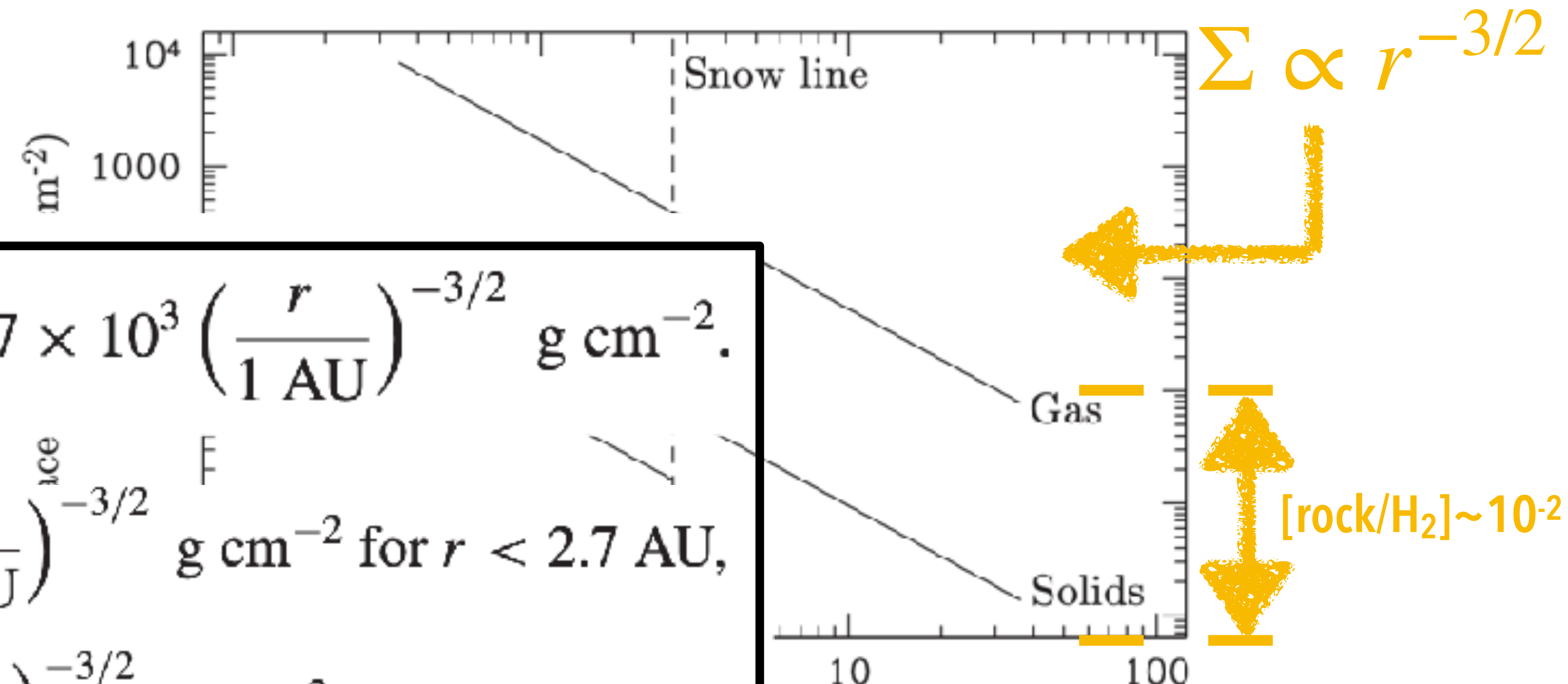
1. **Take amount of solid mass per planet and multiply by Solar composition**
2. **Divide in annuli and distribute mass across each planet orbit: gas surface density**
3. **Compute the solid surface density considering the H_2O snowline**



Weidenschilling 1977
Hayashi 1981

Dust mass: solid reservoir for planet formation

Solar System: cannot go back in time and measure disk mass, but can estimate the minimum amount of material needed: The Minimum Mass Solar Nebula



$$\Sigma(r) = 1.7 \times 10^3 \left(\frac{r}{1\ \mathrm{AU}}\right)^{-3/2} \mathrm{g\ cm^{-2}}.$$

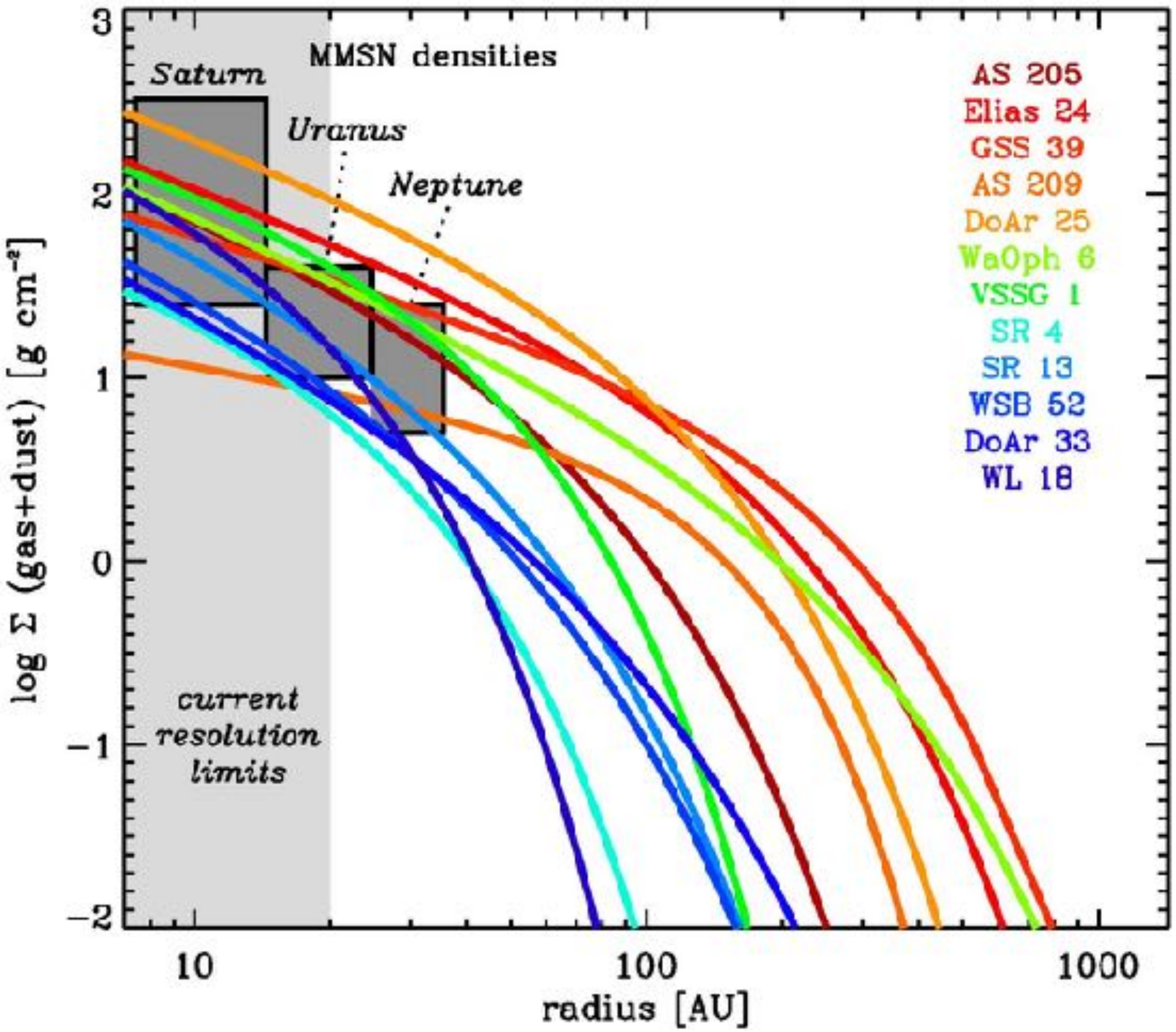
$$\Sigma_s(\mathrm{rock}) = 7.1 \left(\frac{r}{1\ \mathrm{AU}}\right)^{-3/2} \mathrm{g\ cm^{-2}}\ \text{for}\ r < 2.7\ \mathrm{AU},$$

$$\Sigma_s(\mathrm{rock/ice}) = 30 \left(\frac{r}{1\ \mathrm{AU}}\right)^{-3/2} \mathrm{g\ cm^{-2}}\ \text{for}\ r > 2.7\ \mathrm{AU}.$$

Weidenschilling 1977
Hayashi 1981

MMSN compared to disks

MMSN profile seems to be pretty consistent with early disk measurements

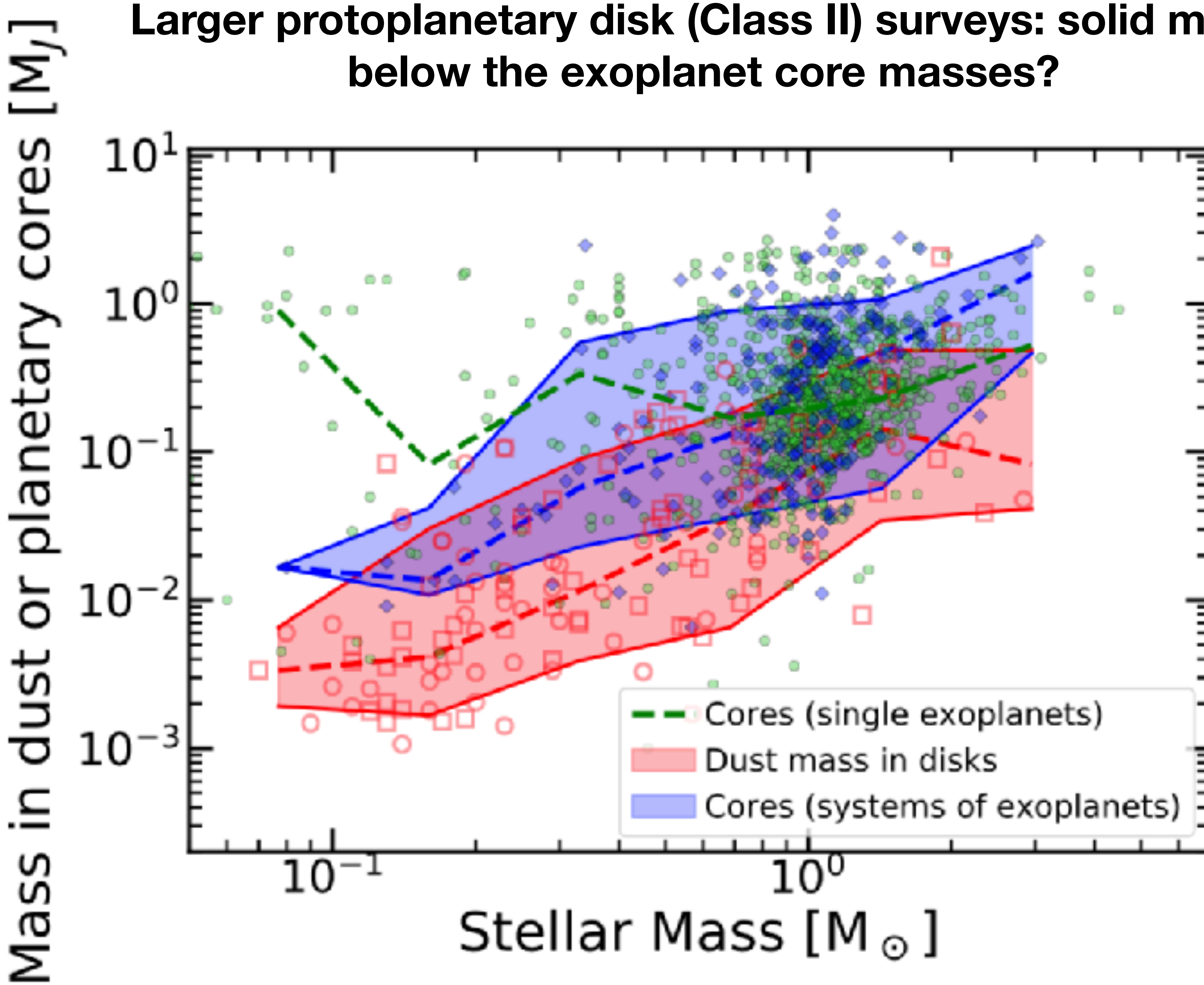


(But these are brightest, most massive disks!)

Williams & Cieza 2011

Dust mass budget in disks

Larger protoplanetary disk (Class II) surveys: solid mass below the exoplanet core masses?

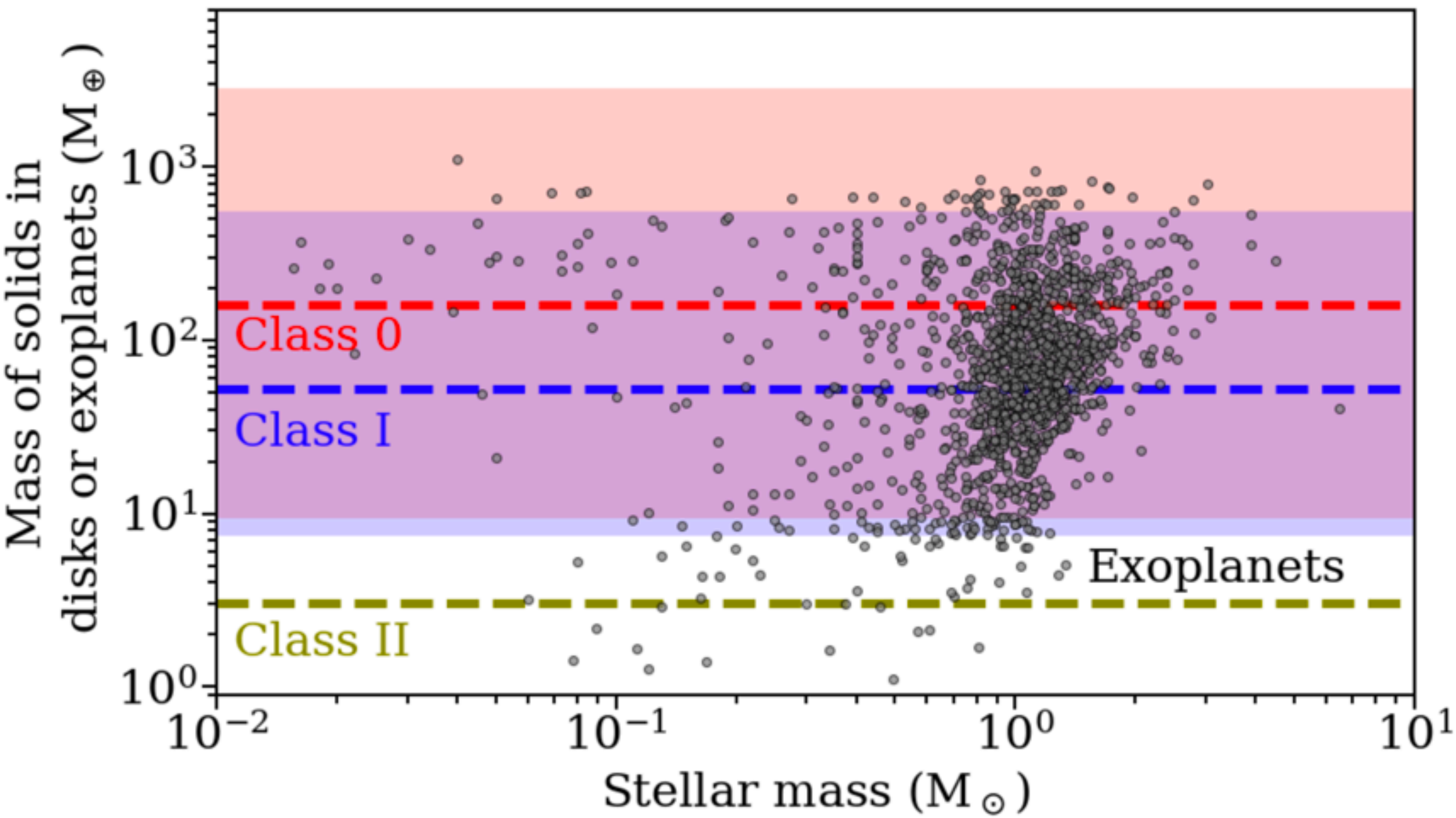


Exoplanets already formed in Class II stage?

Manara et al. 2018

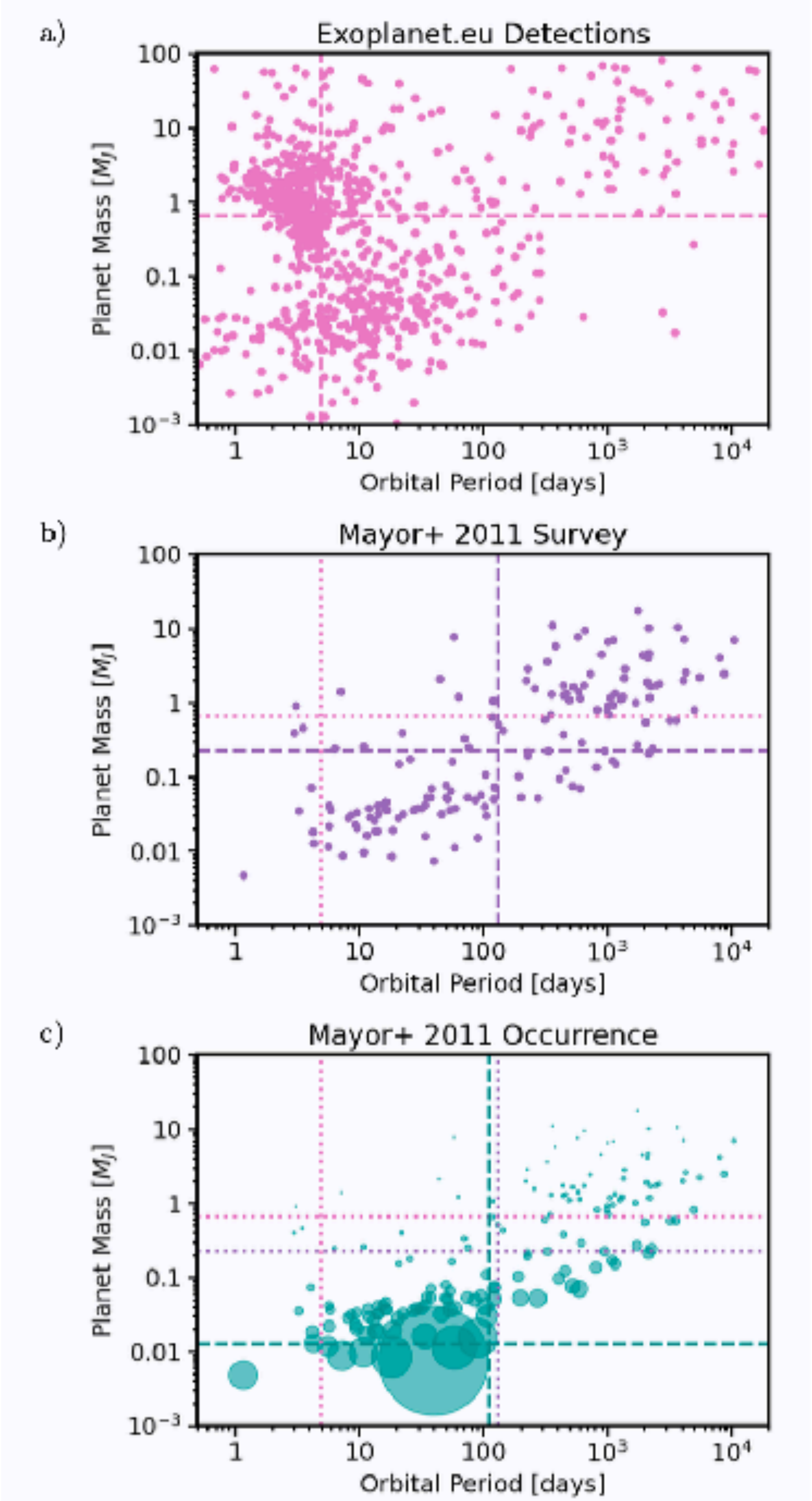
Dust mass budget in disks

Looking at the mass budget in Class 0 and I stage: more similar to exoplanet solid mass => evidence early formation?

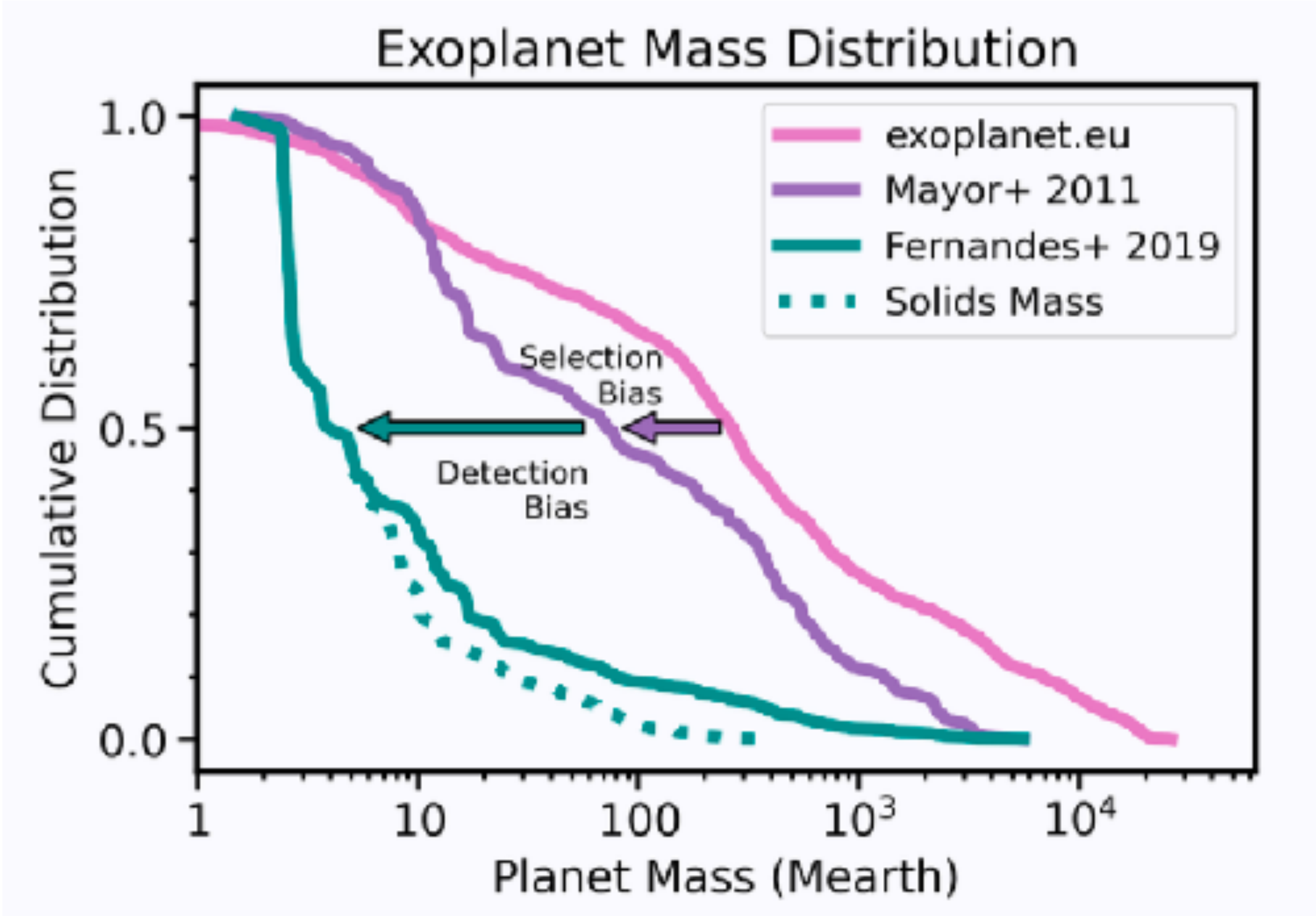


Tychoniec et al. 2020

Revised: dust mass budget



Careful! Exoplanet detection catalog is not a complete or unbiased survey

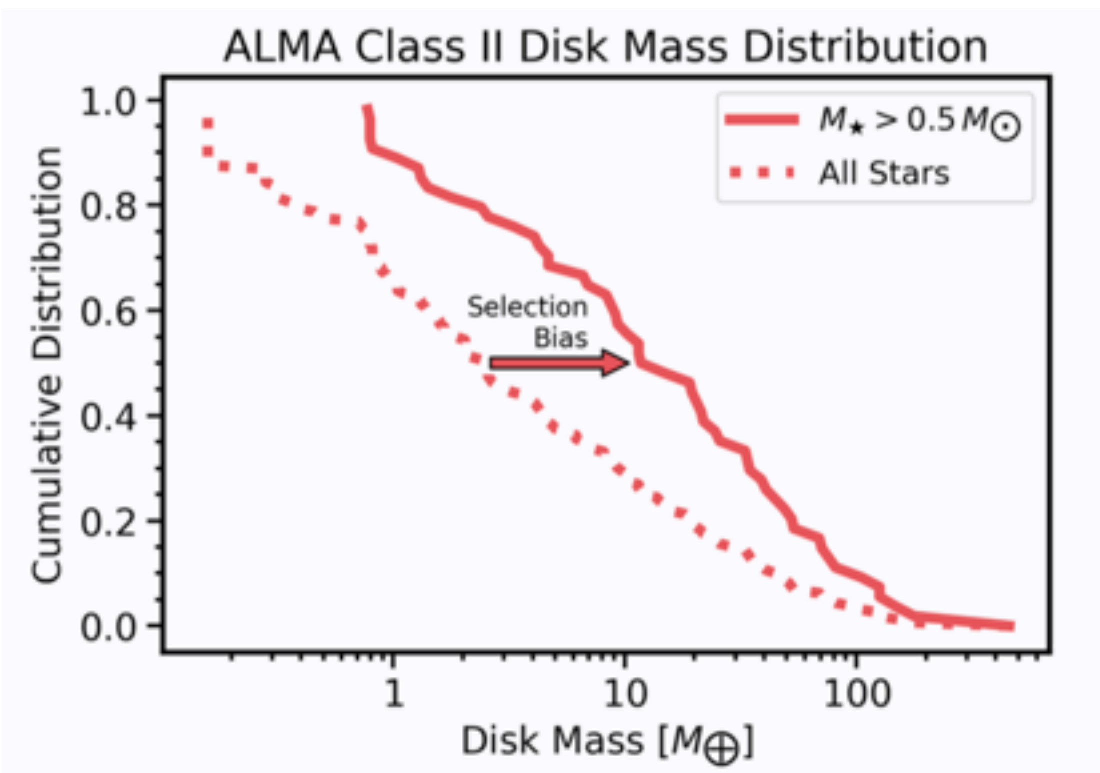


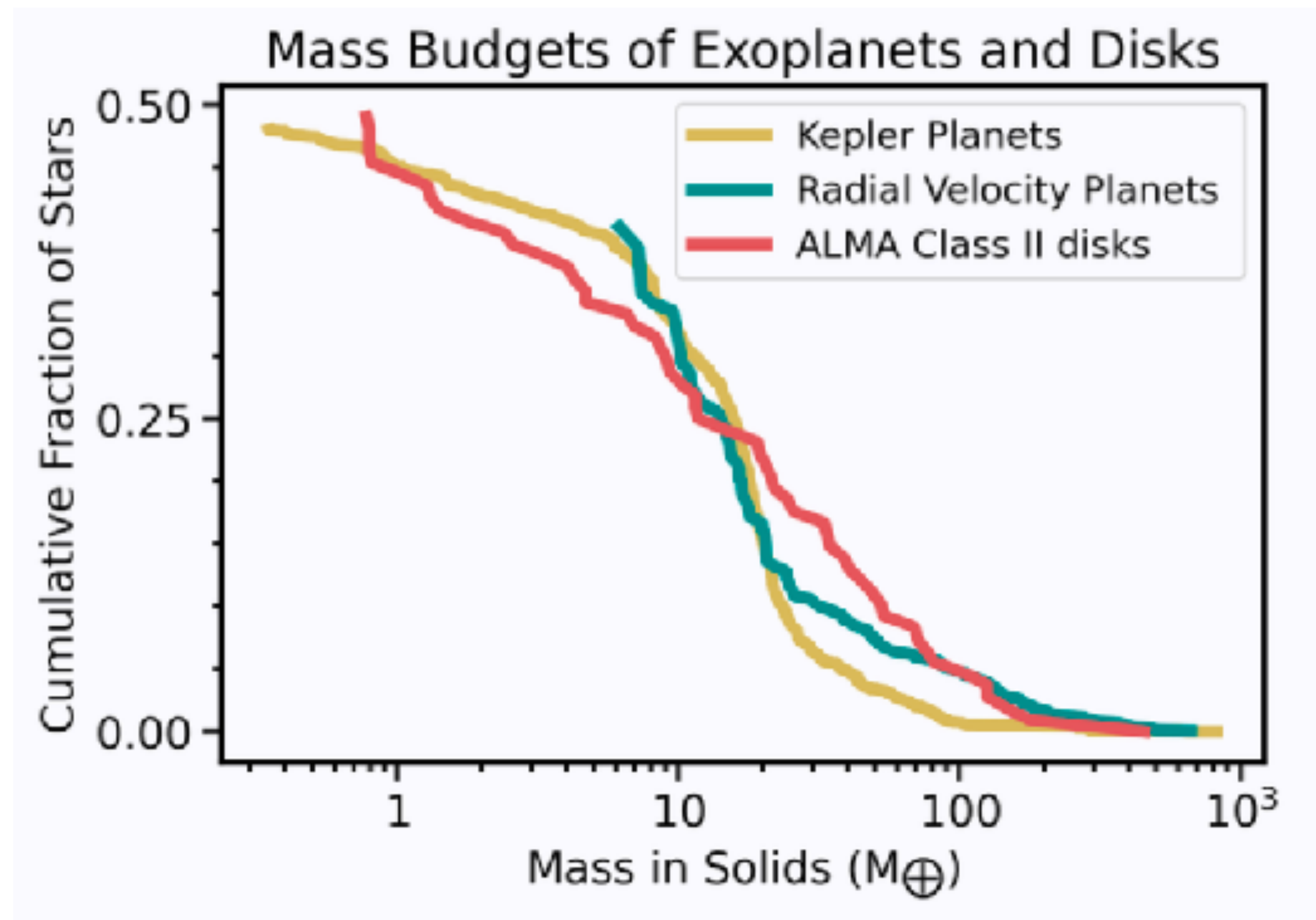
Need to correct for selection and detection biases to get the 'true' exoplanet mass budget

Mulders et al. 2021

Revised: dust mass budget

For disks, correct for selection bias as well: most exoplanets studies around Solar mass stars





So the solid mass is actually comparable between exoplanets and Class II disks:
this would still imply an (unrealistic) 100% planet formation efficiency, but it's not as bad as previously stated

Mulders et al. 2021

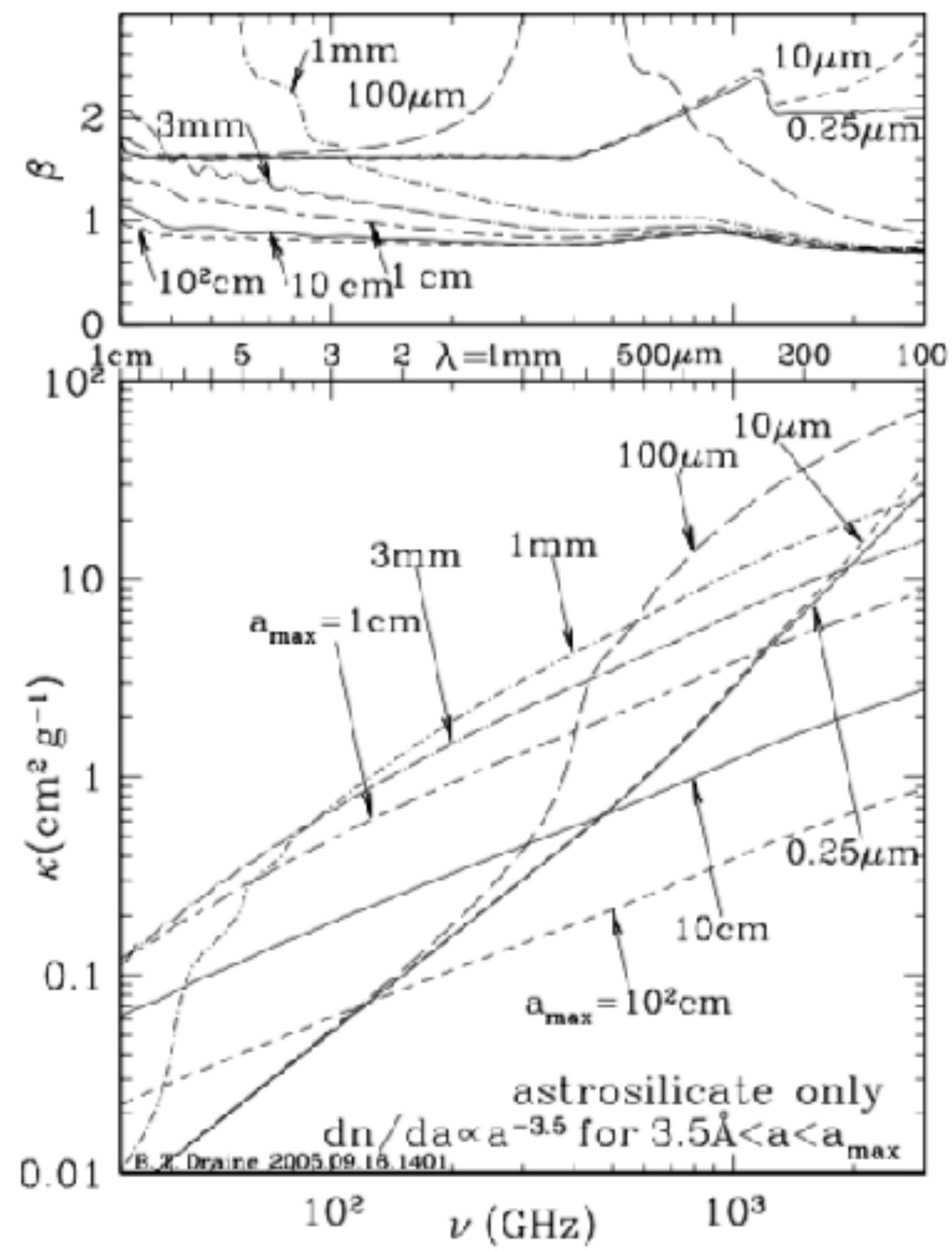
How do we compute the dust mass?

Dust

- Flux density (Jansky = erg s^{-1} cm^{-2} Hz^{-1}) $$F_\nu = \int I_\nu d\Omega$$
- Specific intensity (erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}) $$I_\nu = B_\nu(T)(1 - e^{-\tau_\nu})$$
- Planck function $$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}$$
- Optical depth $$\tau_\nu = \frac{\kappa_\nu \Sigma_{dust}}{\cos i}$$
- Dust opacity $$\kappa_\nu \sim \nu^\beta$$

$$\kappa_\nu \sim n(a) \propto a^{-p}, a_{max}, a_{min}$$

+ composition



Draine 2006

Dust opacity wavelength dependence: at wavelength λ you are sensitive to grains up to size ~3 λ

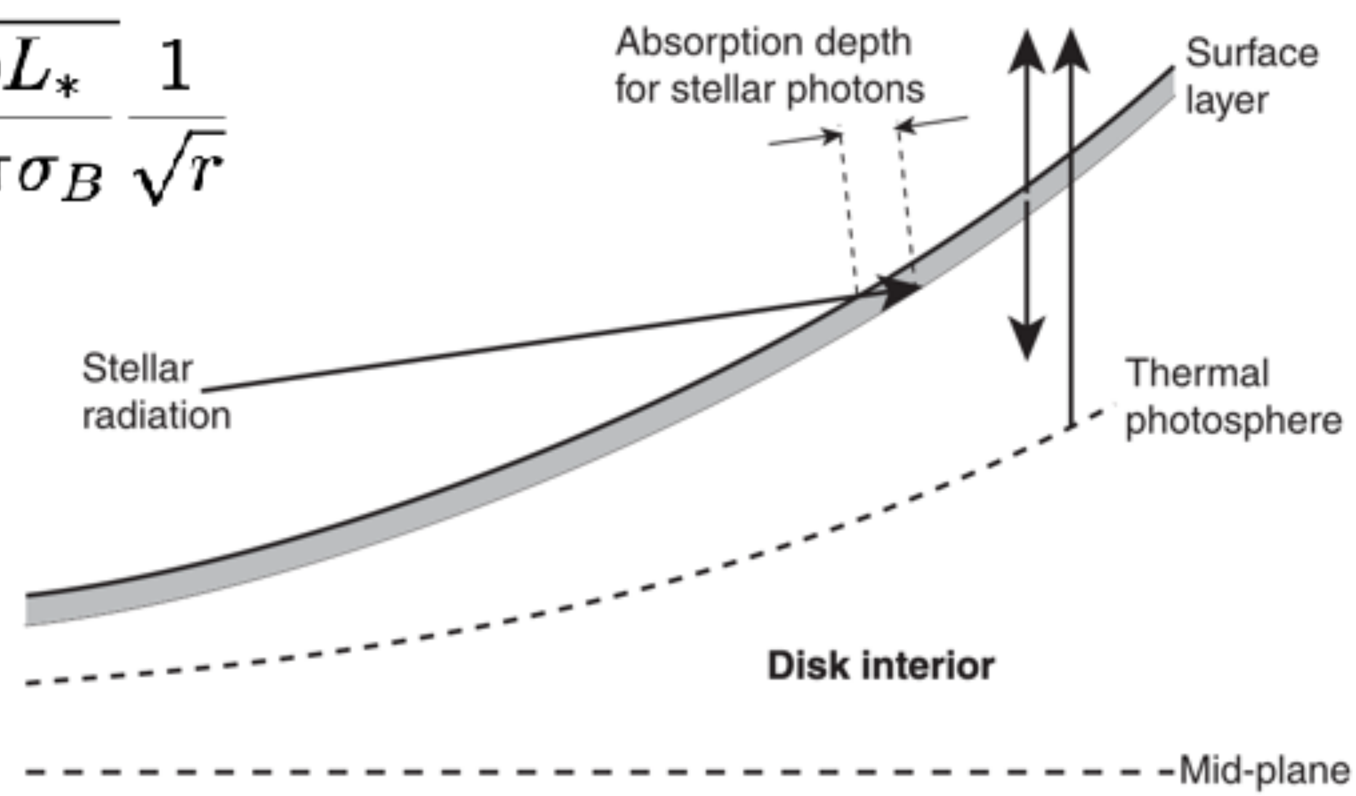
Dust temperature

Disk temperature generally depends on infalling stellar radiation

Passively heated, flared disk in radiative equilibrium has the following temperature:

$$T(r) = \left(\frac{\phi L_*}{8\pi\sigma_B r^2}\right)^{1/4} = \sqrt[4]{\frac{\phi L_*}{8\pi\sigma_B}}\frac{1}{\sqrt{r}}$$

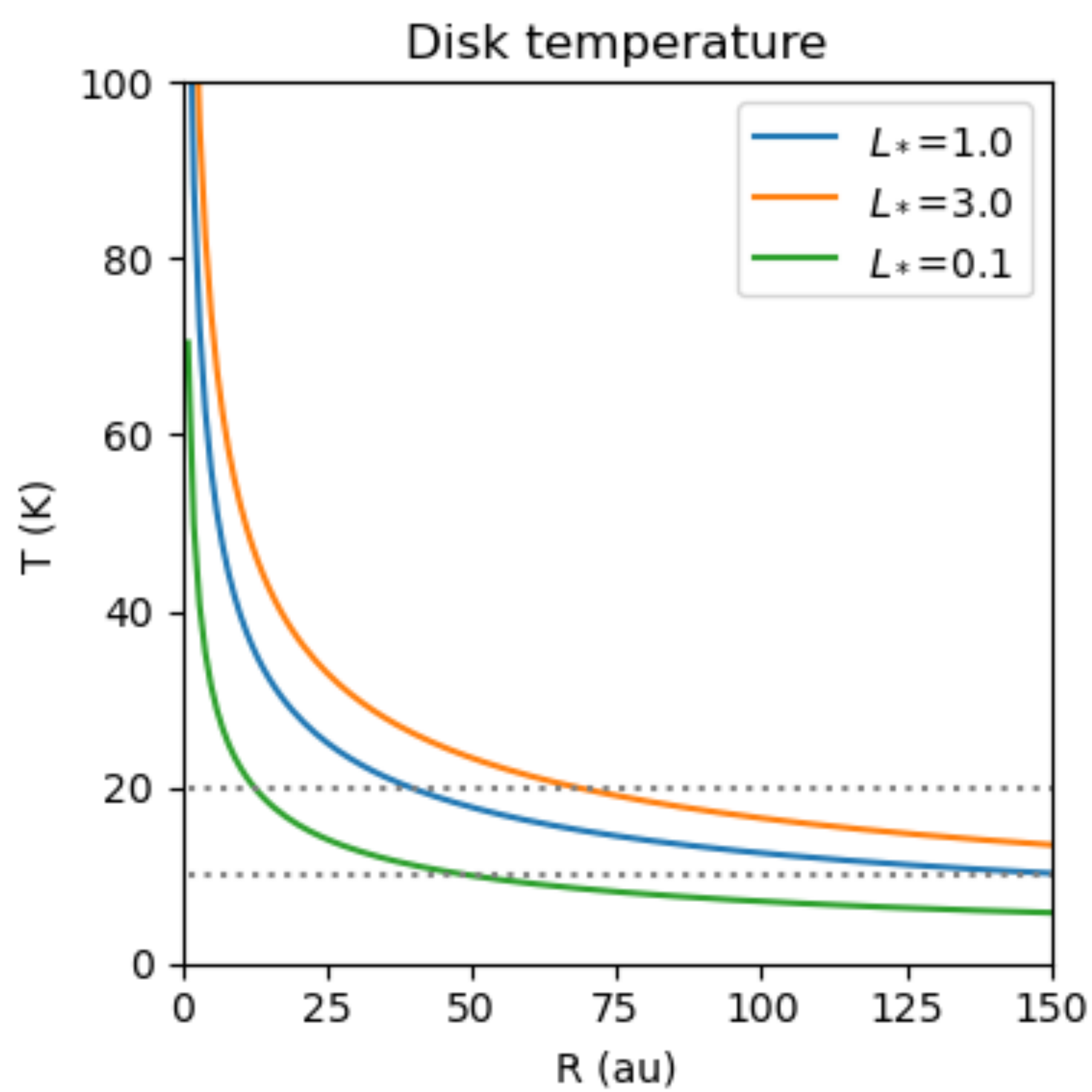
With phi the flaring angle (generally taken as 0.02 for the midplane)



Chiang & Goldreich 1997
Dullemond et al. 2001

Dust temperature

$$T(r) = \left(\frac{\phi L_*}{8\pi\sigma_B r^2}\right)^{1/4} = \sqrt[4]{\frac{\phi L_*}{8\pi\sigma_B}}\frac{1}{\sqrt{r}}$$



Bulk of the disk (50-150 au, where most of the mass is) is between 10 and 20 K:

General assumption:
use average temperature to compute dust mass (usually 20 K)

How do we compute the dust mass?

Dust

Optically thin: $\tau_\nu << 1$:

Power-law surface density: $\Sigma_d(r) = \Sigma_c(\frac{r}{r_c})^{-1}$

Dust mass: $M_{dust} = \int \Sigma(r) 2\pi r dr$

$$F_\nu = \int I_\nu d\Omega$$

$$I_\nu = B_\nu(T)(1 - e^{-\tau_\nu})$$

$$\tau_\nu = \frac{\kappa_\nu \Sigma_{dust}}{\cos i}$$

Compute M_{dust} and F_ν in optically thin regime

How do we compute the dust mass?

Dust

Optically thin: $\tau_\nu << 1$:

$$F_\nu = \frac{B_\nu(T)\kappa_\nu M_{dust}}{d^2}$$

Commonly used to derive disk dust masses with T=20 K

In practice:

- Dust opacity can be computed using Mie-theory: many tables available online (see later)
- Computation dust mass:
  - Either integrated flux (entire disk) conversion to mass
    OR
  - Full radiative transfer: compute dust temperatures throughout the disk based on a stellar radiation field and dust density structure, and compute SED and images at various wavelengths and compare with data
- Flux density is function of frequency/wavelength: remember: superposition blackbodies and opacities

Rayleigh-Jeans approximation

Rayleigh-Jeans: $$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}$$

Approximation: $h\nu \ll k_{\mathrm{B}} T$ (Valid in mm wavelengths)

Compute B(T) in RJ approximation

Rayleigh-Jeans approximation

Rayleigh-Jeans: $B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$

Approximation: $h\nu \ll k_B T$ (Valid in mm wavelengths)

$$B_\nu(T(r)) = \frac{2\nu^2 k_B T(r)}{c^2} \longrightarrow B_\nu(T) \sim \nu^2$$

Remember: $\kappa_\nu \sim \nu^\beta$

Rayleigh-Jeans approximation

Rayleigh-Jeans: $B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$

Approximation: $h\nu \ll k_\mathrm{B}T$

$$B_\nu(T(r)) = \frac{2\nu^2 k_B T(r)}{c^2} \longrightarrow B_\nu(T) \sim \nu^2$$

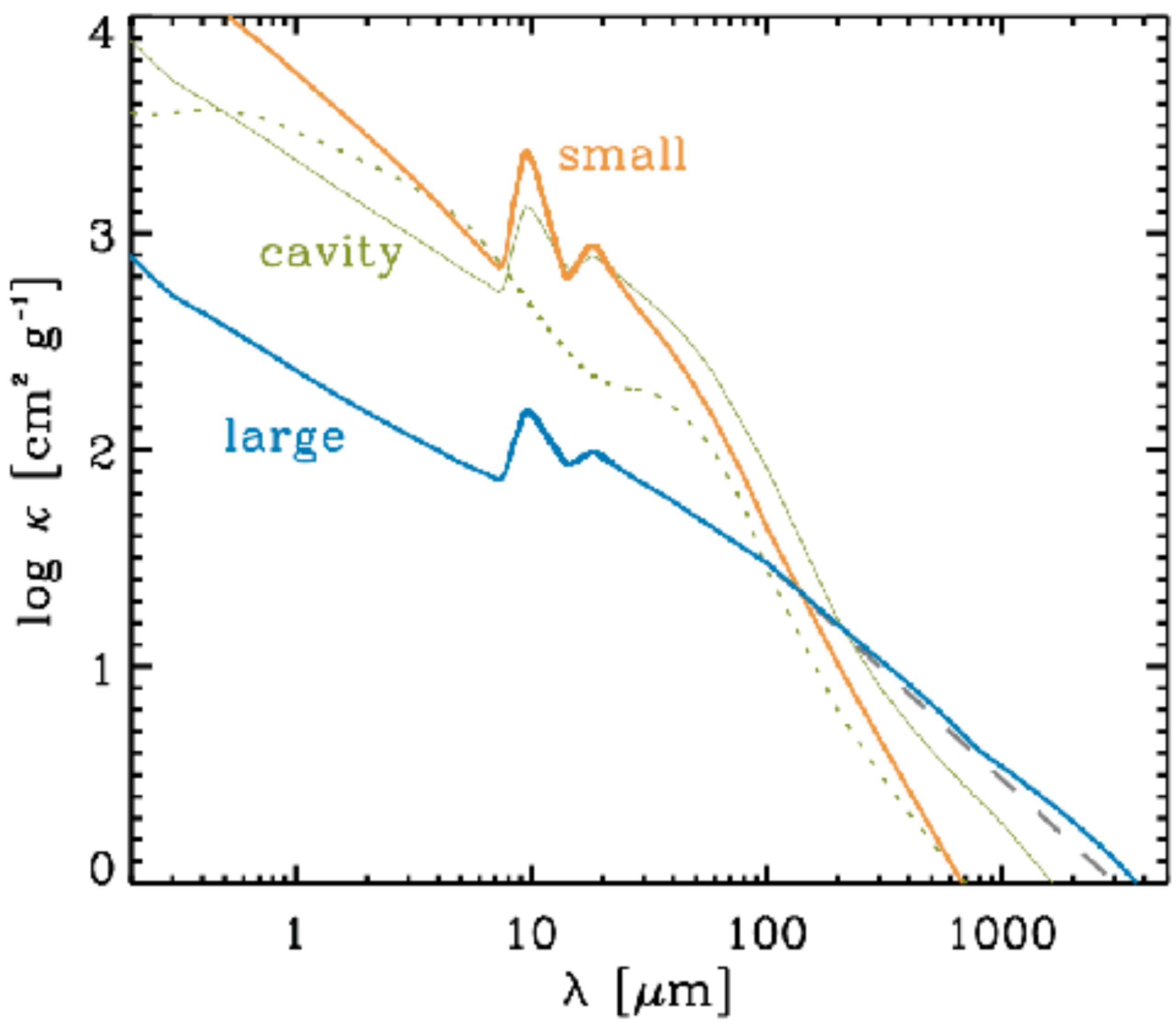
Remember: $\kappa_\nu \sim \nu^\beta$

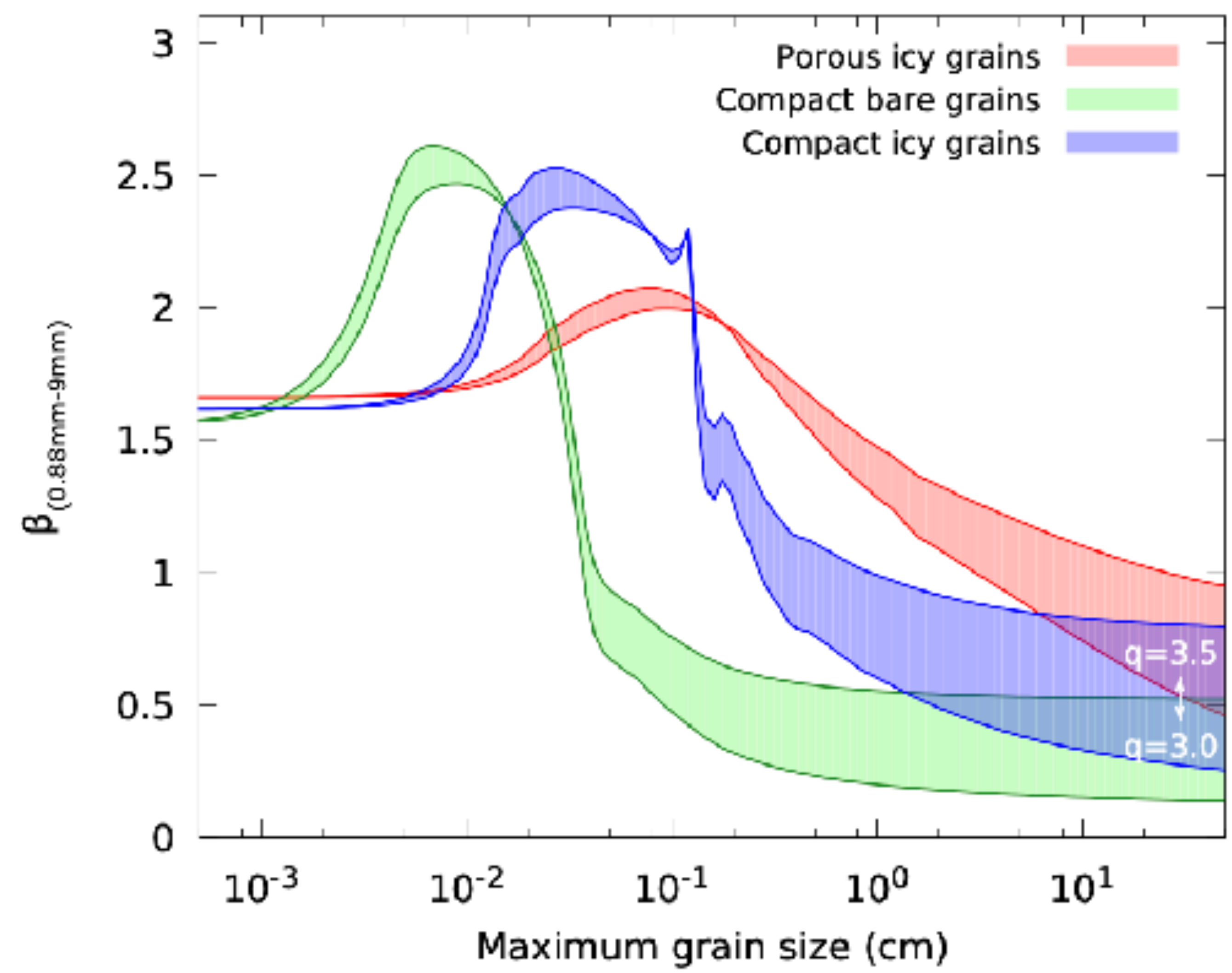
Rayleigh-Jeans + Opt thin regime: $F_\nu = \frac{B_\nu(T)\kappa_\nu M_{dust}}{d^2} \longrightarrow F_\nu \sim \nu^2\kappa_\nu \sim \nu^{2+\beta} \sim \nu^\alpha$

So the spectral index alpha can provide us the dust opacity β in the assumption of opt. thin emission

Dust opacity

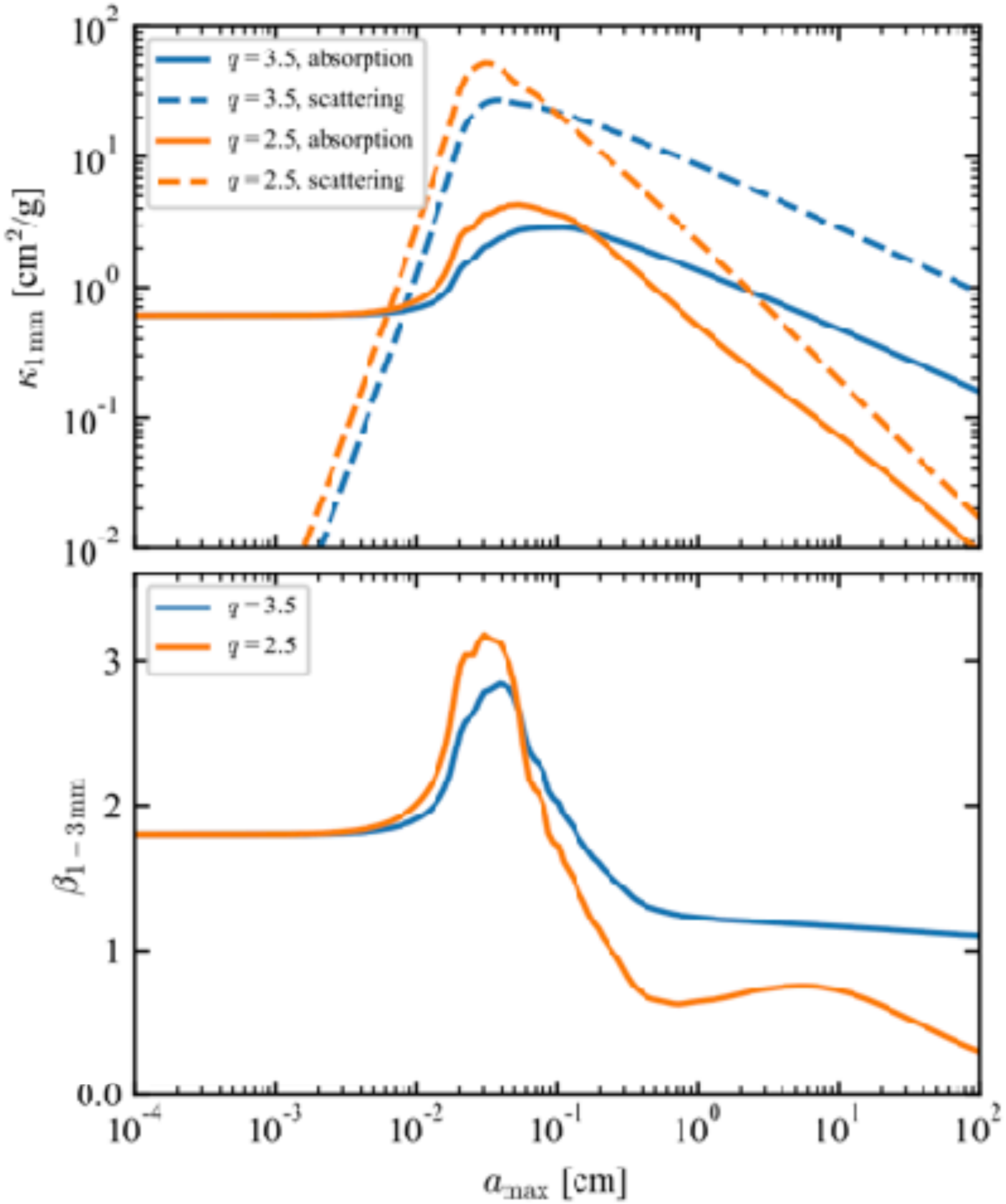
Dust opacity $\kappa_\nu \sim \nu^\beta$



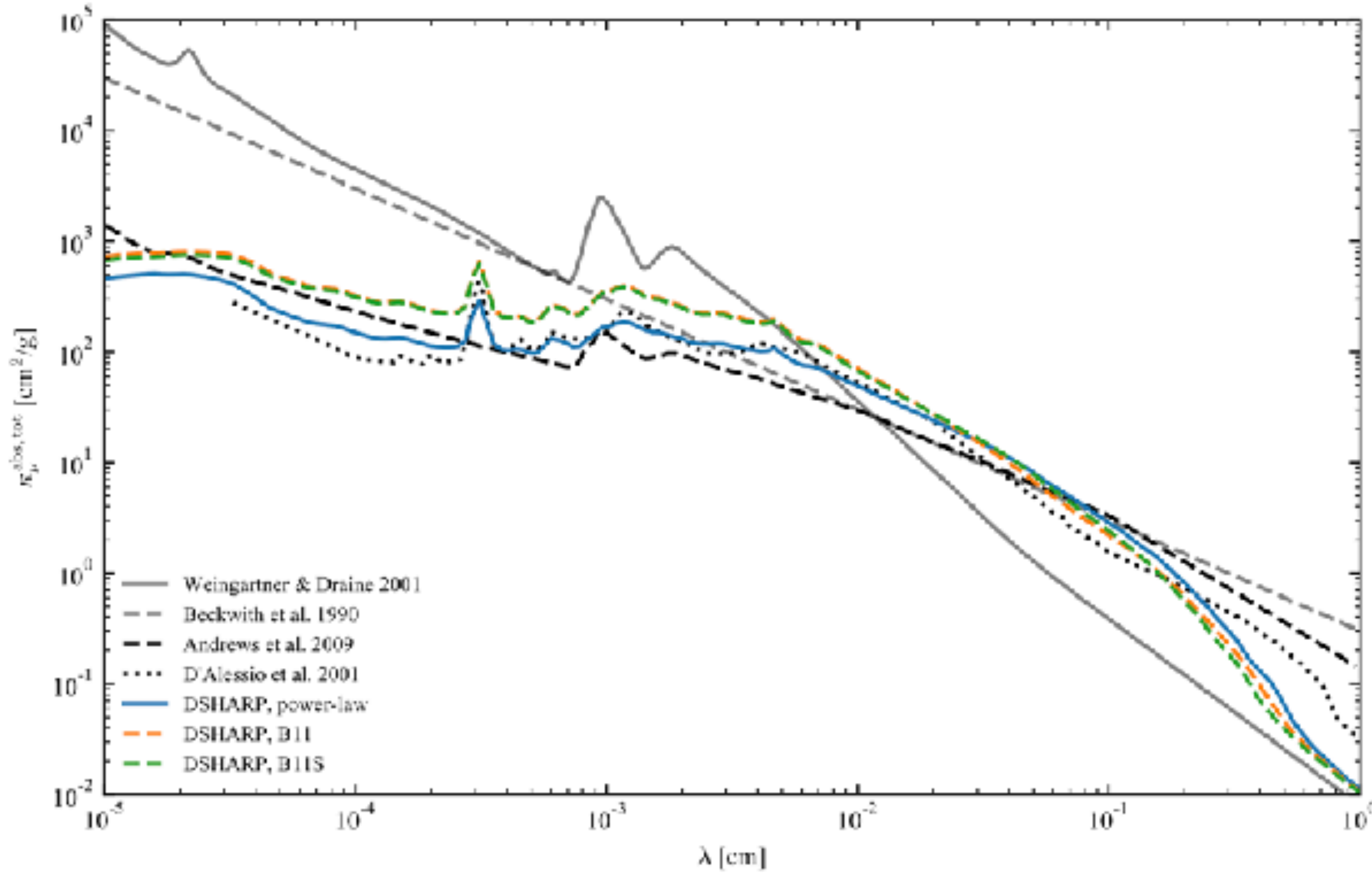


Testi et al. 2014
Andrews et al. 2011

Dust opacity



Dust opacity depends on assumed grain properties: generate table at https://github.com/birnstiel/dsharp_opac



Assumed dust opacity will have a major impact on the derived dust mass

Dust opacity $\kappa_\nu \sim \nu^\beta$

Birnstiel et al. 2018

What if dust is optically thick?

$$F_\nu = \int I_\nu d\Omega$$

$$I_\nu = B_\nu(T)(1 - e^{-\tau_\nu}) \;\; = B_\nu(T)$$

$$F_\nu \sim \nu^2 \cancel{\kappa_\nu} \sim \cancel{\nu^{2+\beta}} \sim \nu^\alpha$$

Spectral index α no longer represents the dust opacity and the dust mass is underestimated

Check optical depth?

If emission is spatially resolved, we can check if the emission is optically thick by comparing the emission with the local temperature

If optically thick:

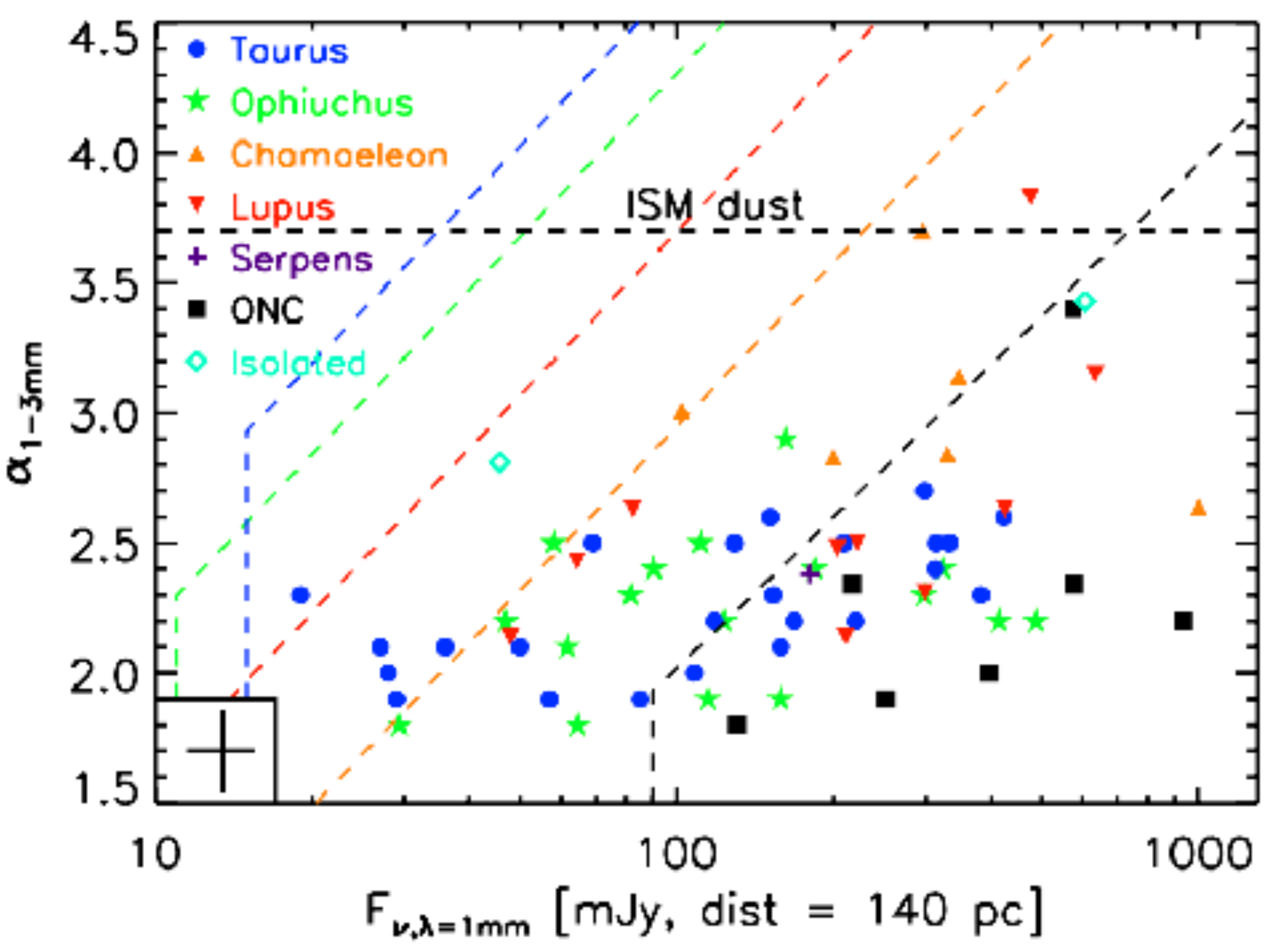
$$F_\nu(r) = B_\nu(r, T) \approx \frac{2\nu^2 k_B T(r)}{c^2} \propto T(r)$$

Compute the 'brightness temperature' T_b from the measured flux and compare with the physical temperature at that location: if comparable, the emission is likely optically thick

Multi-wavelength observations

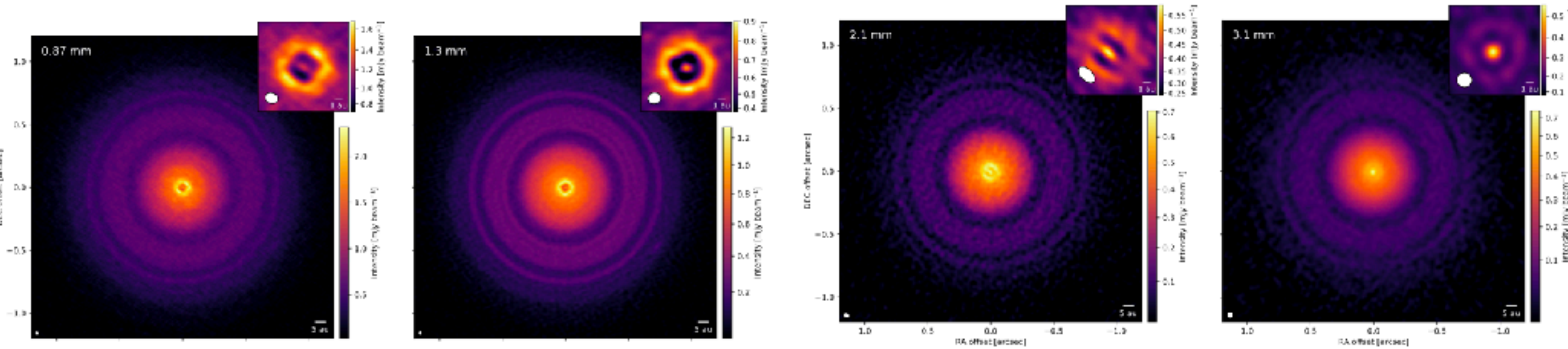
- Multi-wavelength observations: derive spectral index alpha
- Rule of thumb: spectral index $alpha_{mm}$ is:
    - 3.7 (ISM)
    - 2.0-3.0 (mm-grains/opt. thick)
    - (<)2.0 (optically thick)
    - -1 < 0 < 1 (free-free emission, non-thermal)
- If 3 or more wavelengths available: fit opacity (grain size), temperature and surface density independently!

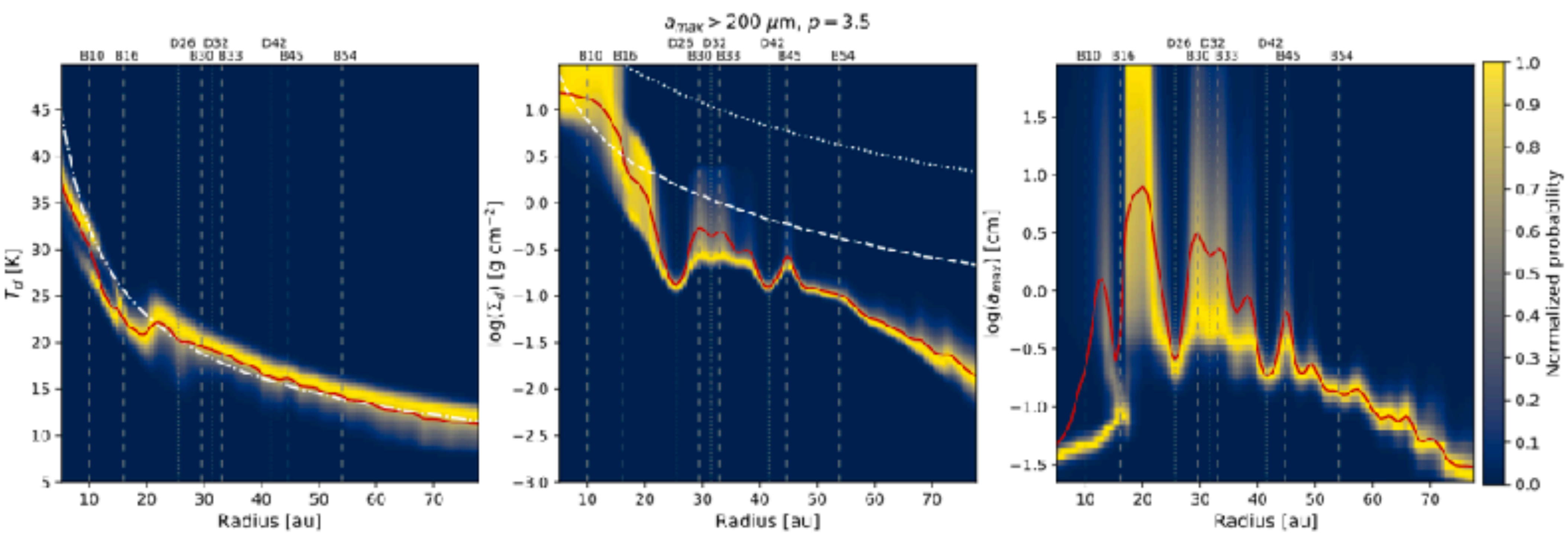
$$F_\nu \sim \nu^2 \kappa_\nu \sim \nu^{2+\beta} \sim \nu^\alpha$$



Testi et al. 2014 (PPVI)

Multi-wavelength observations

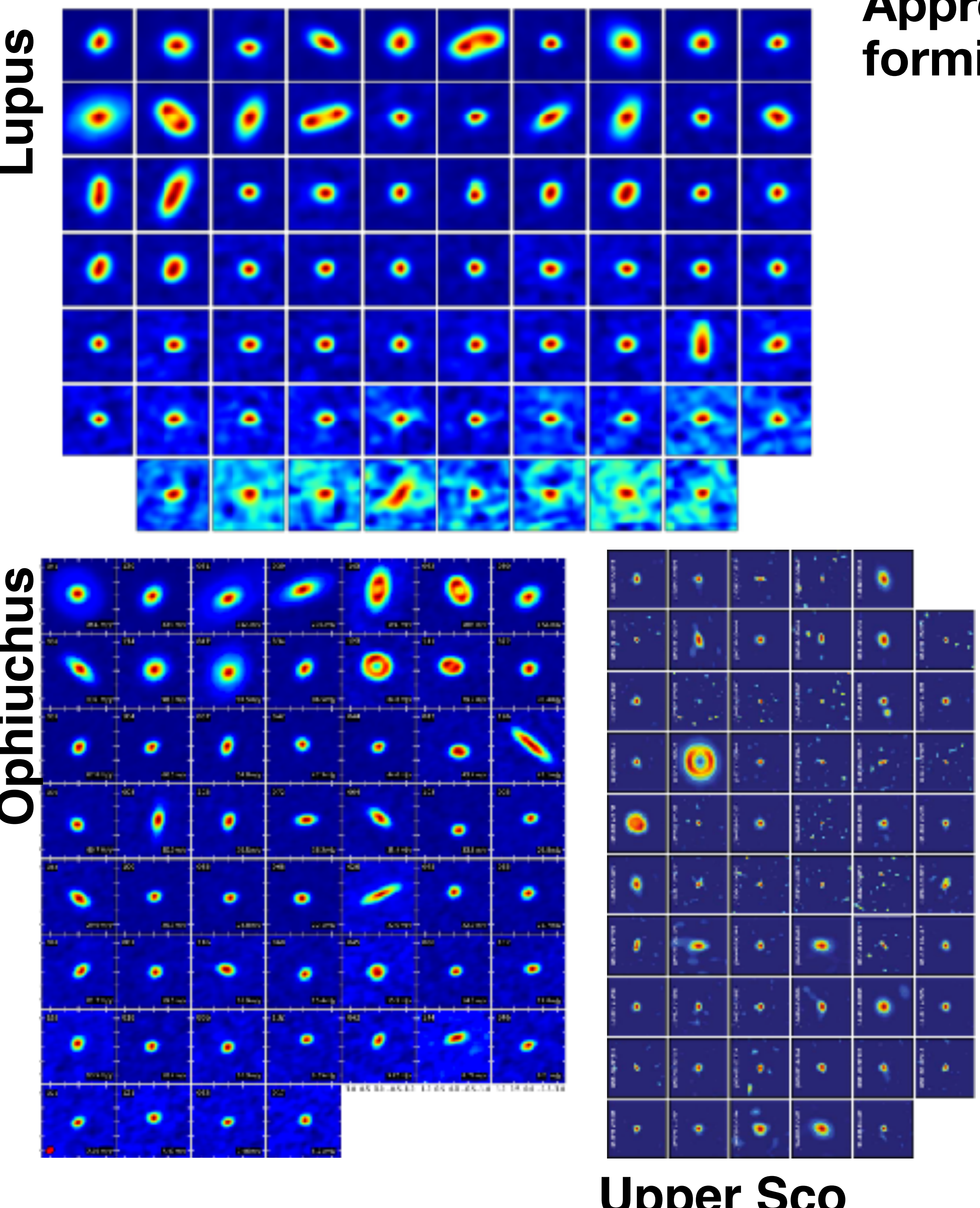




So dust masses may be underestimated somewhat (in inner part), but not by a factor 10

Carrasco-Gonzalez et al. 2019
Macias et al. 2021
Sierra et al. 2021 (MAPS)

Disk dust mass evolution



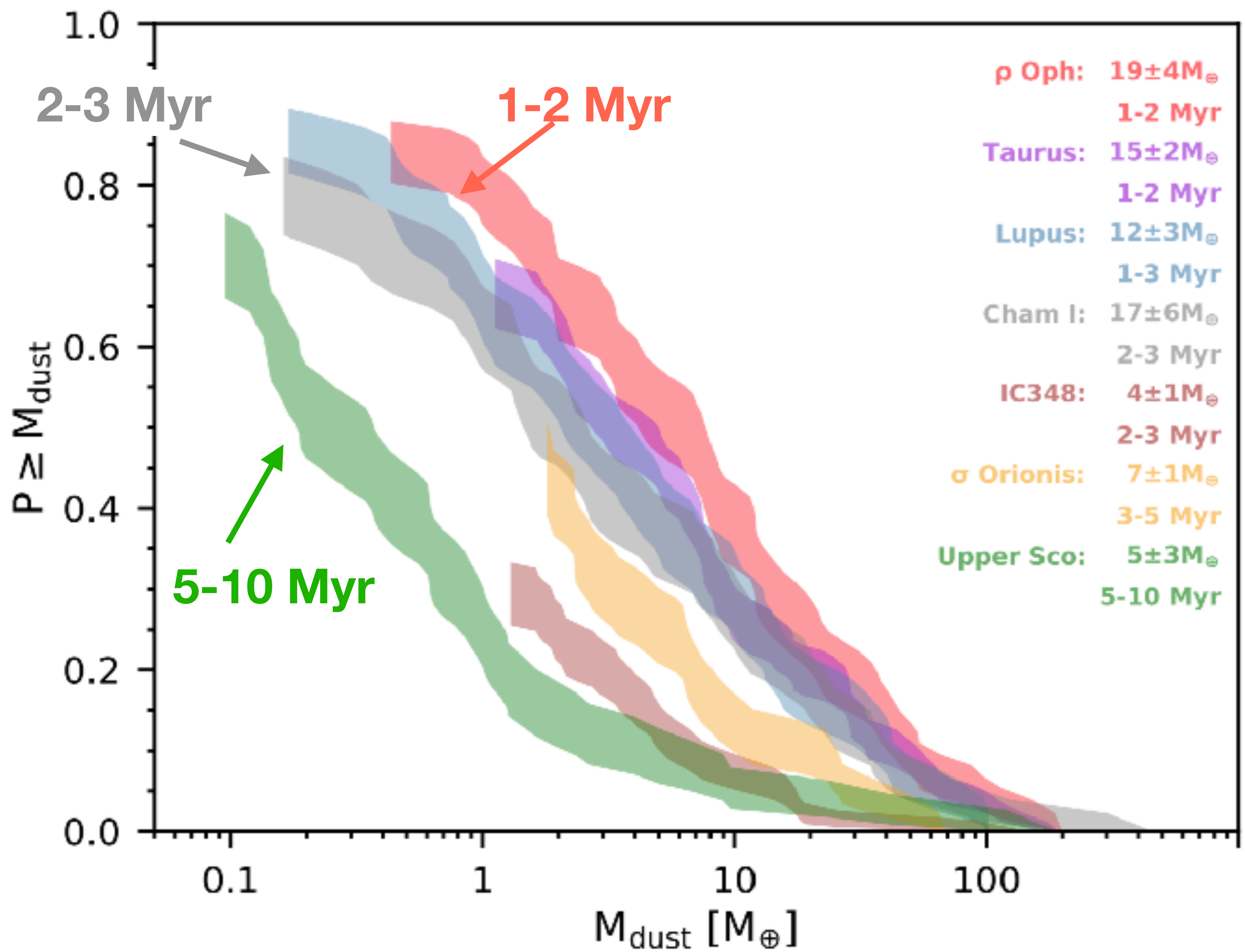
Approach: map all Class II disks in nearby star-forming regions at low resolution 0.25" with ALMA

- Snapshot surveys of 1-2 min/source
- Hundreds of disks in SF regions
- Regions of 1-10 Myr old
- Continuum flux provides disk dust mass

=> Statistics of disk dust mass and evolution!

Ansdell et al. 2016, 2018
Barenfeld et al. 2016
Cieza et al. 2018

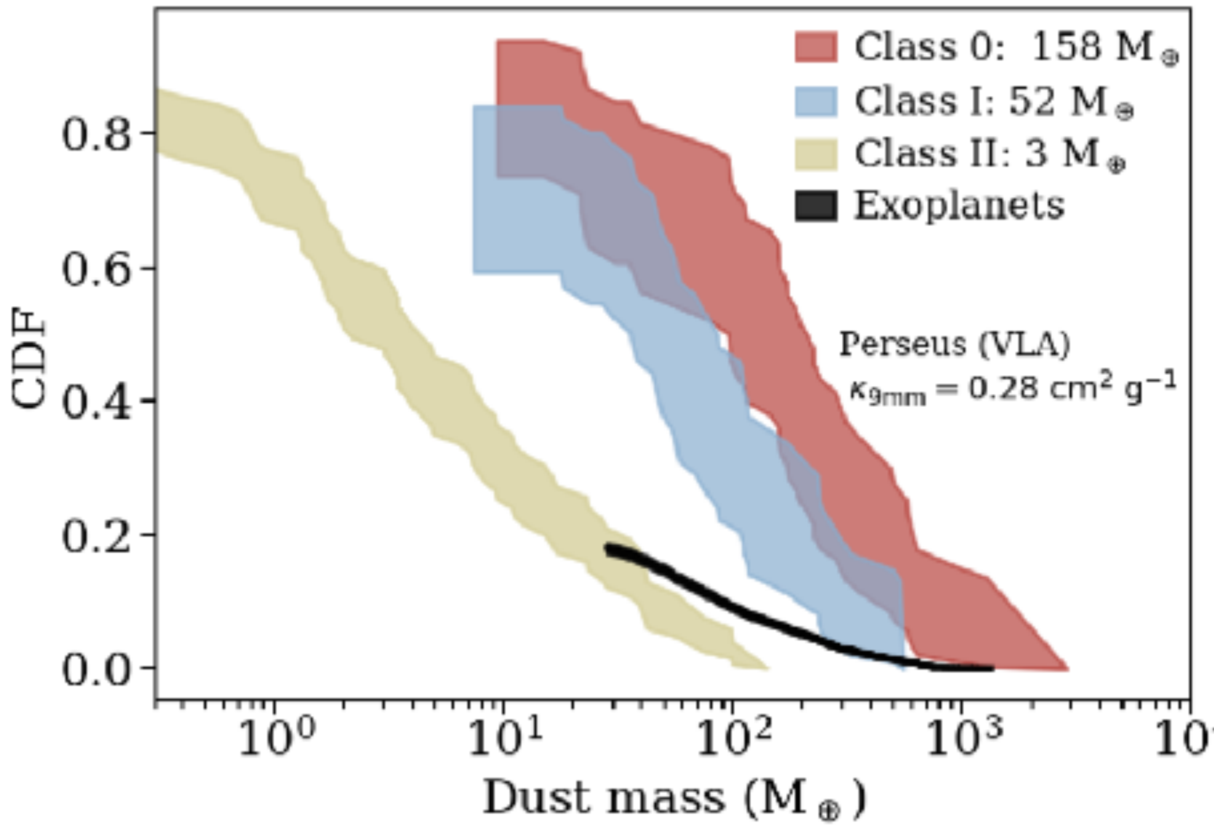
Disk dust mass evolution

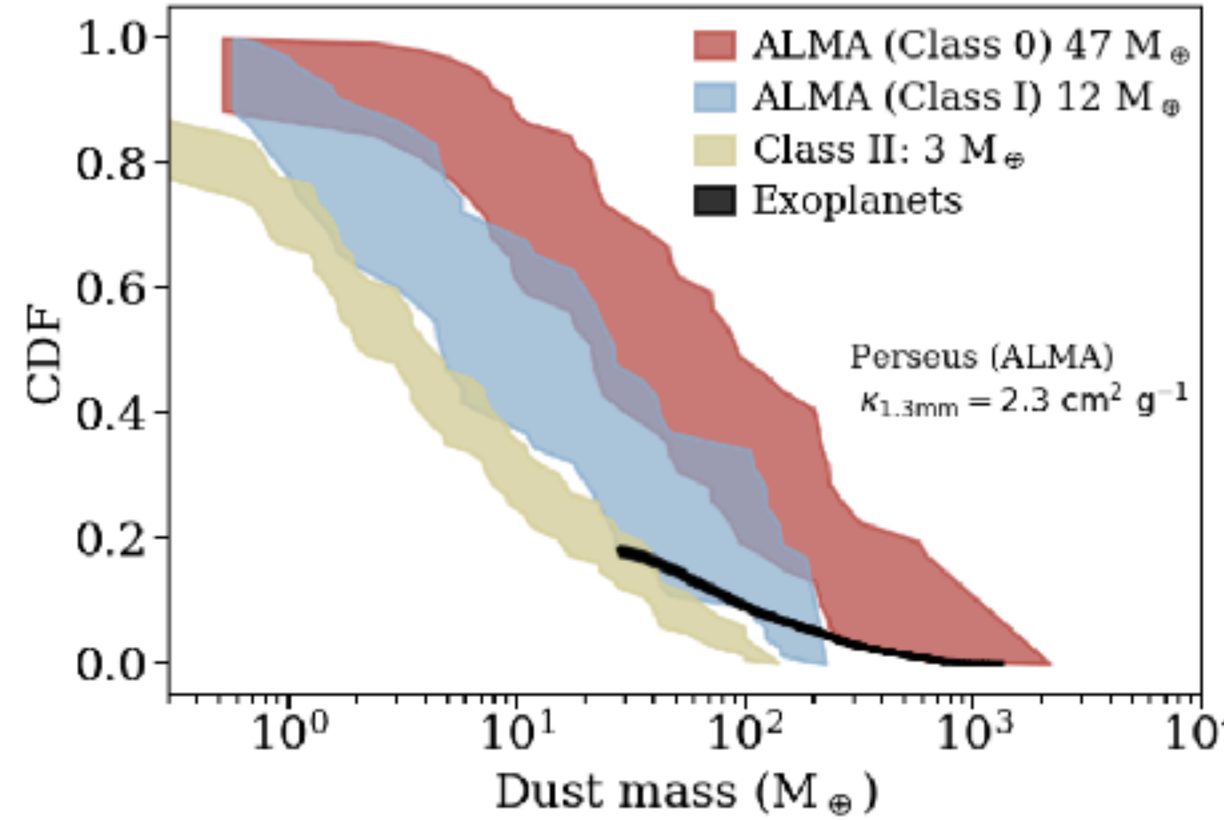


Observed dust mass decreases with age:
decrease of mm-dust grains or change in opacity (grain properties)?

Ansdell et al. 2016, 2017
Cieza et al. 2018

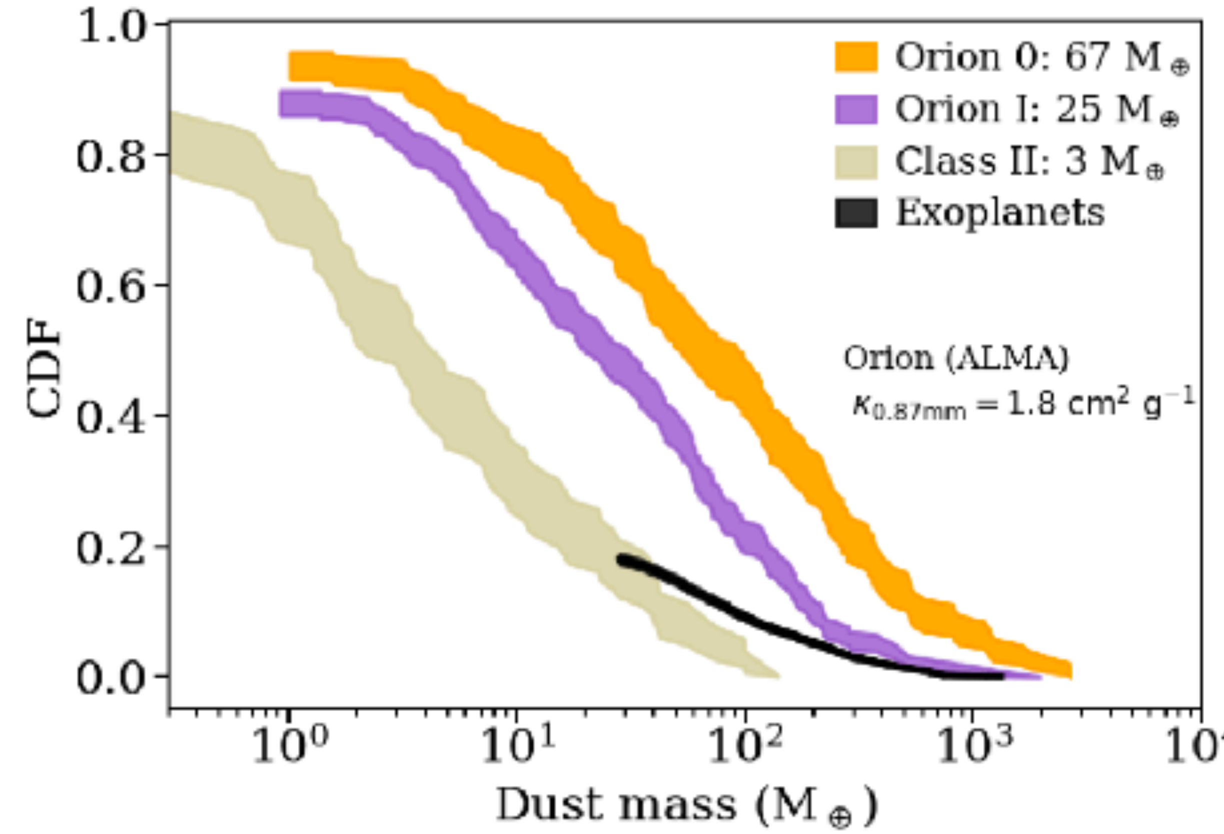
Disk dust mass evolution





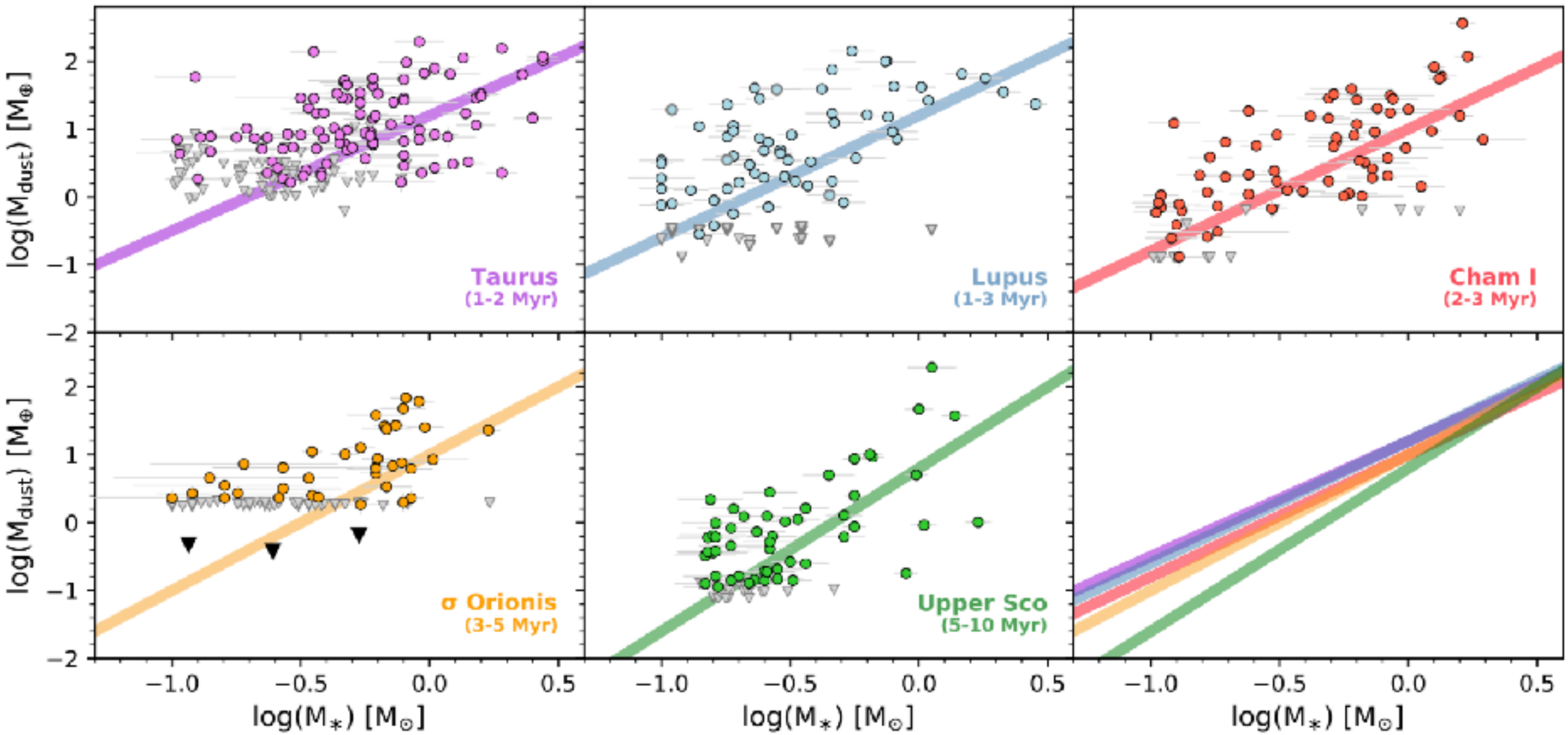
Decrease in dust mass already seen from Class 0 to Class II stage, even at longer wavelengths:

not just dust opacity change!



Tobin et al. 2020
Tychoniec et al. 2020

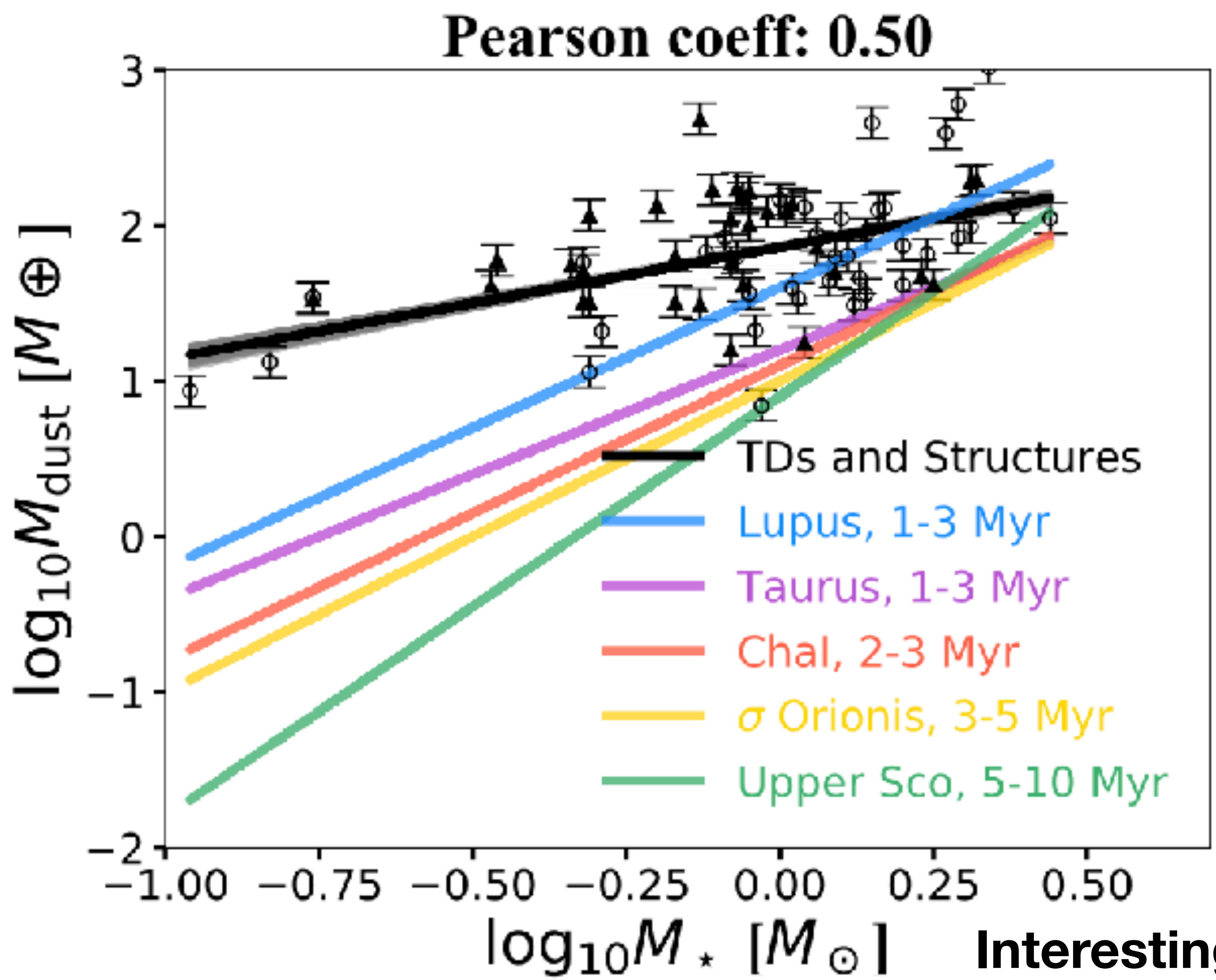
Disk dust mass evolution



Disk dust mass scales with stellar mass
and decrease with age is stronger for low-mass

Ansdell et al. 2016, 2017

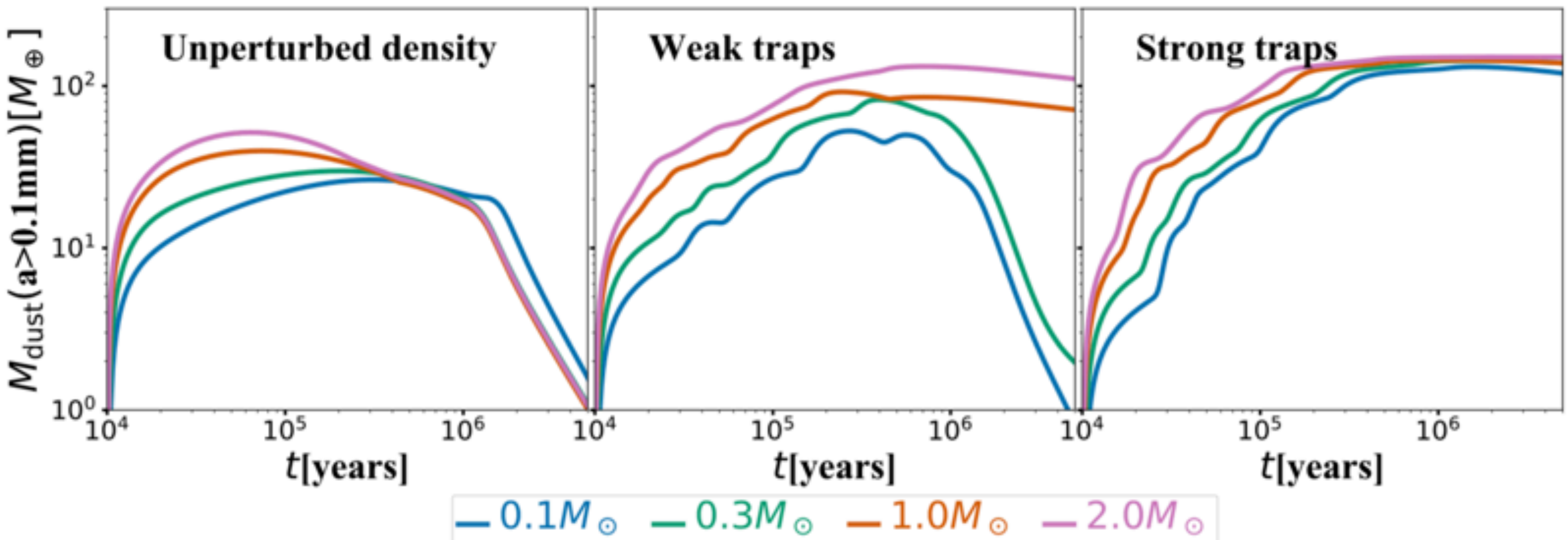
Disk dust mass evolution

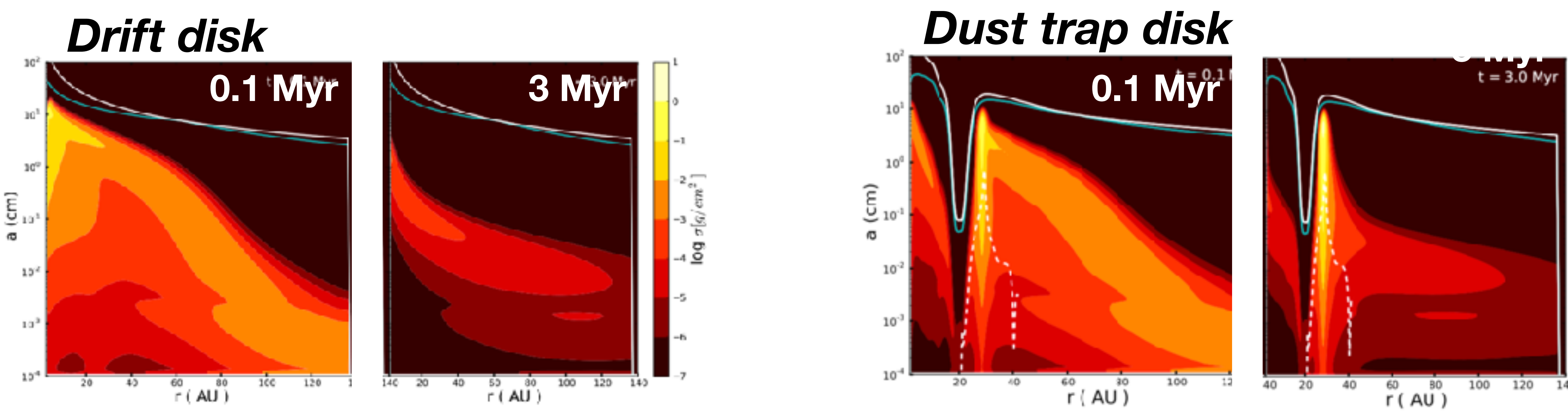


Interesting phenomenon: gapped disks (transition and ring disks) do not follow the trend of the bulk of the disk population

Pinilla et al. 2020

Recall: 2 options dust evolution



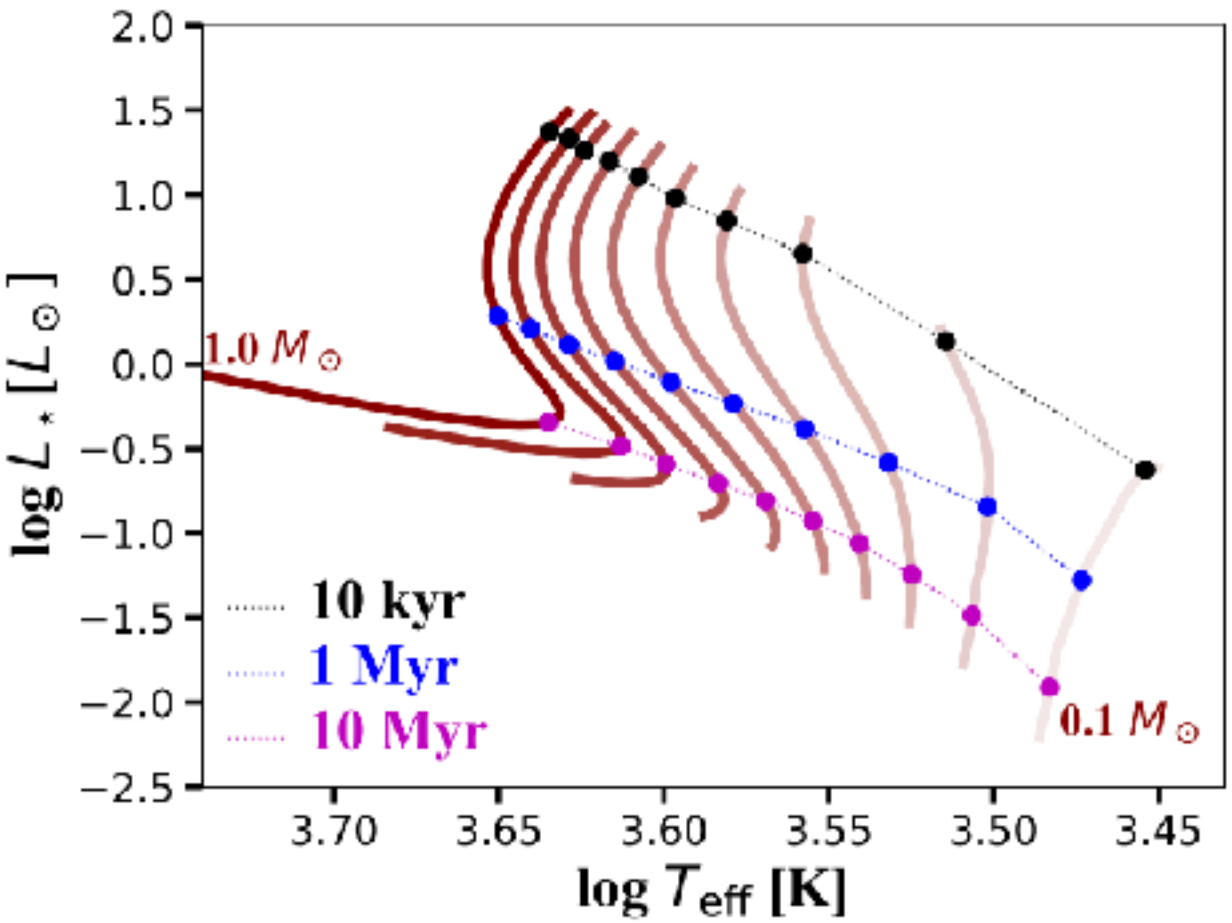


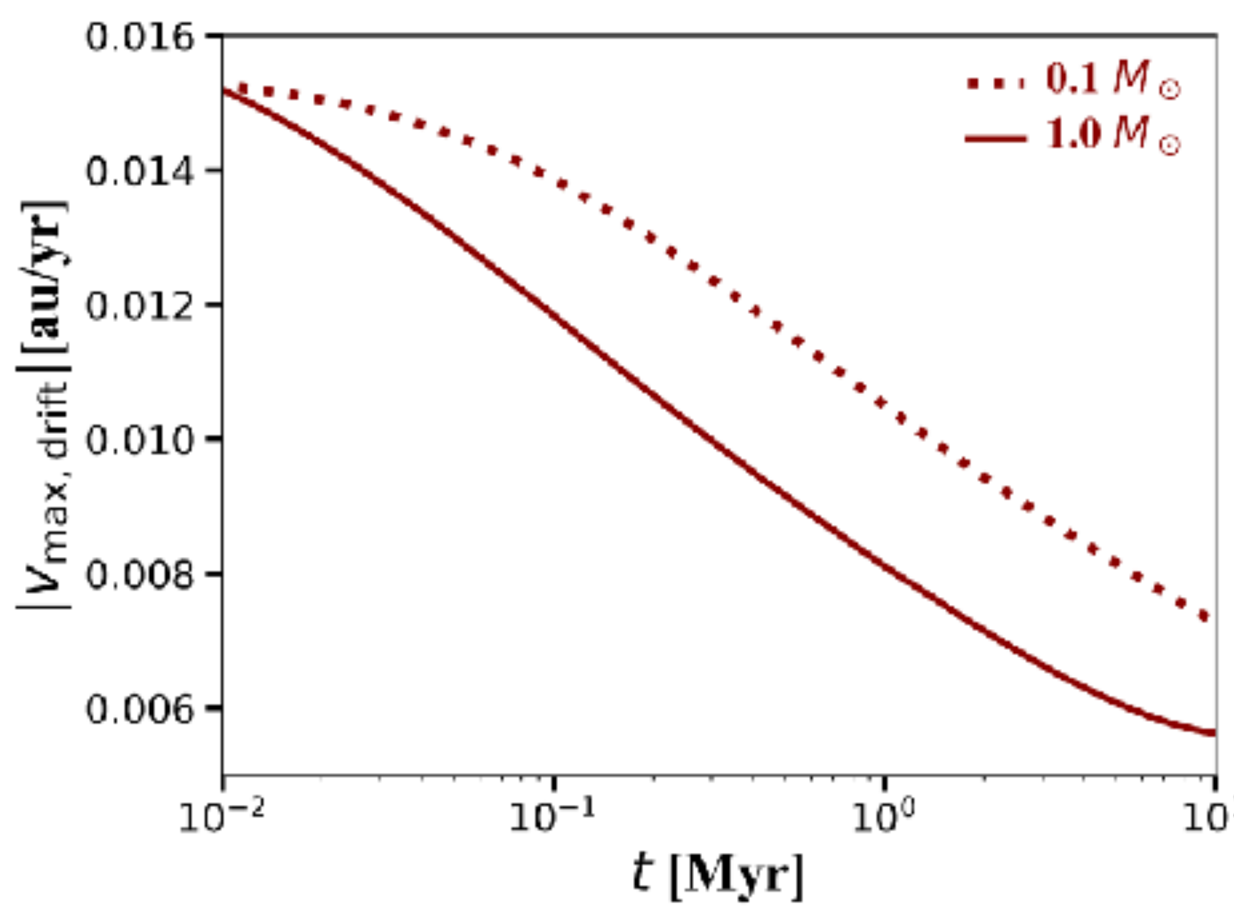
Pinilla et al. 2012, 2020

Also: radial drift more efficient around low-mass stars

$$v_{\rm drift} \propto L_\star^{1/4}/\sqrt{M_\star}$$

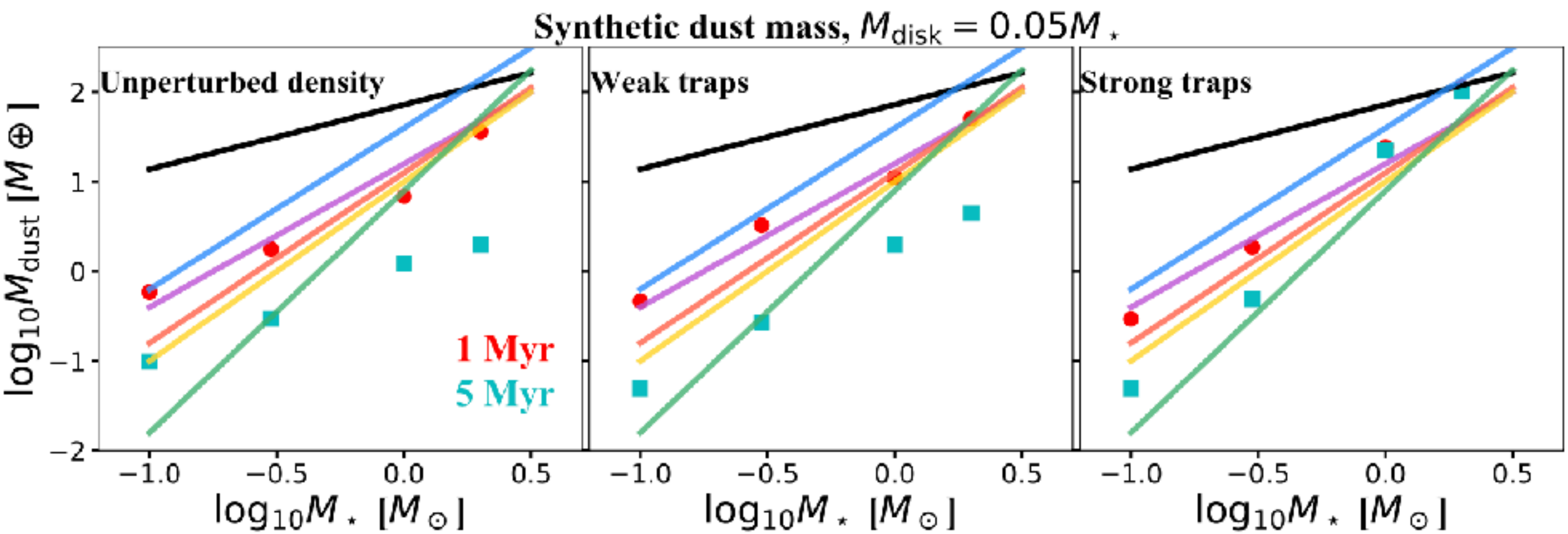
$$a_{\rm frag} = \frac{2}{3\pi}\frac{\Sigma}{\rho_{\rm s}\alpha_{\rm turb}}\frac{v_{\rm frag}^2}{c_{\rm s}^2}.$$





Pinilla et al. 2013, 2022

Resulting dust evolution

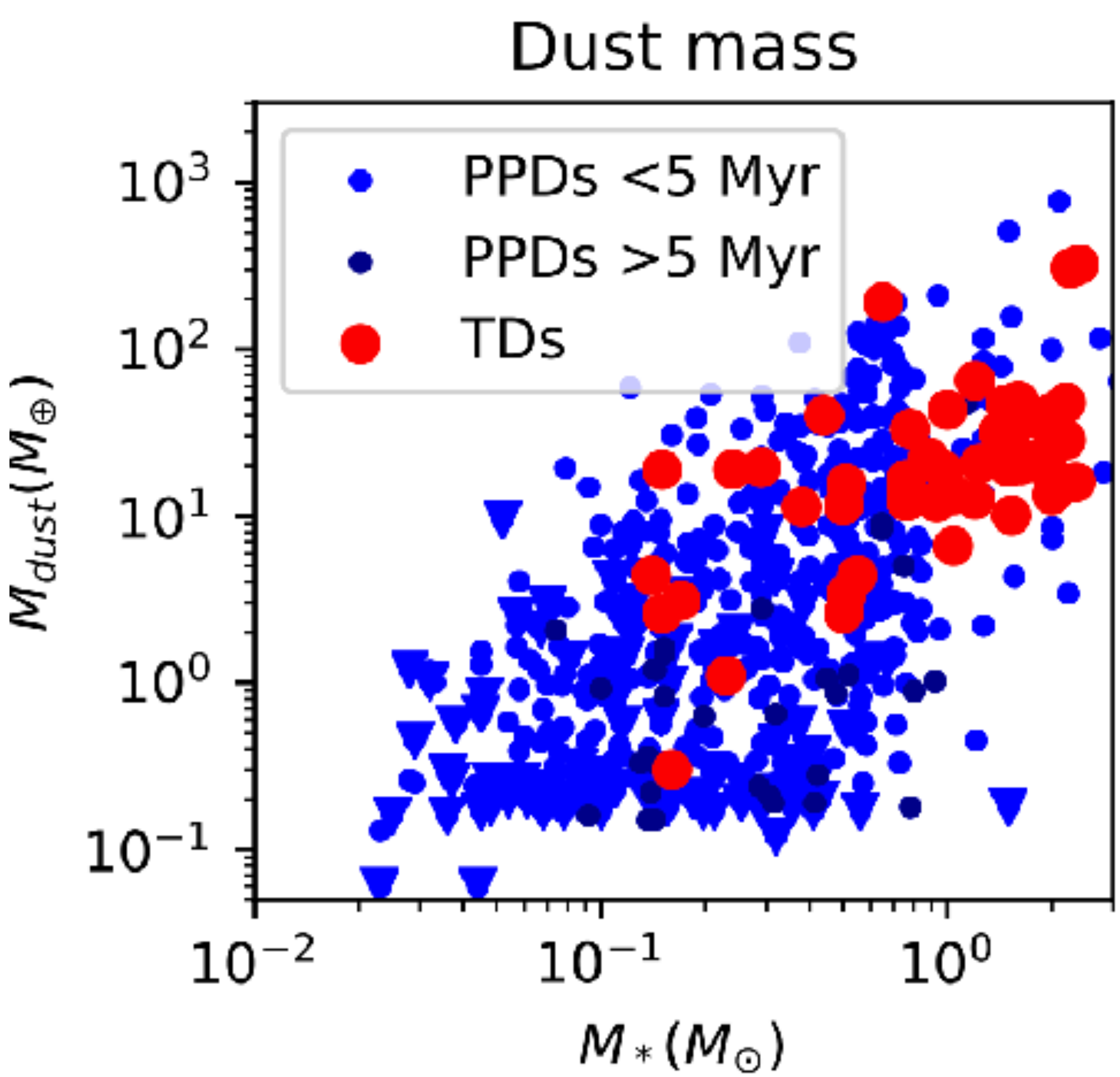


Trends remain unclear: flat slope not reproduced

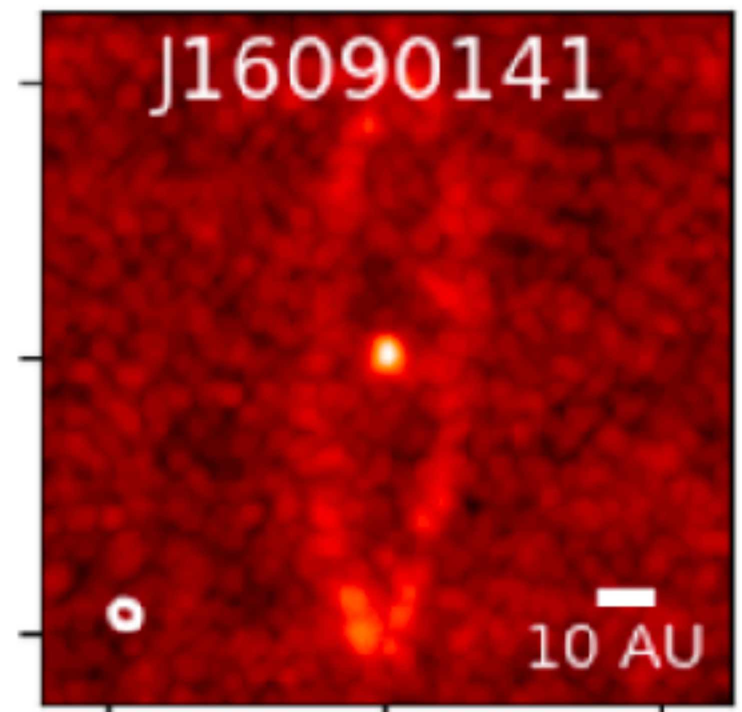
In the dust traps around low-mass stars, the mm-sized particles grow to boulders: decrease observable mm-dust mass. Dust mass maintained for Solar mass stars.

Pinilla et al. 2020

Is the slope really flat?



Larger sample of transition disks around low-mass stars, including fainter ones: slope of TDs is now comparable with that of PPDs, consistent with dust evolution models with boulder growth

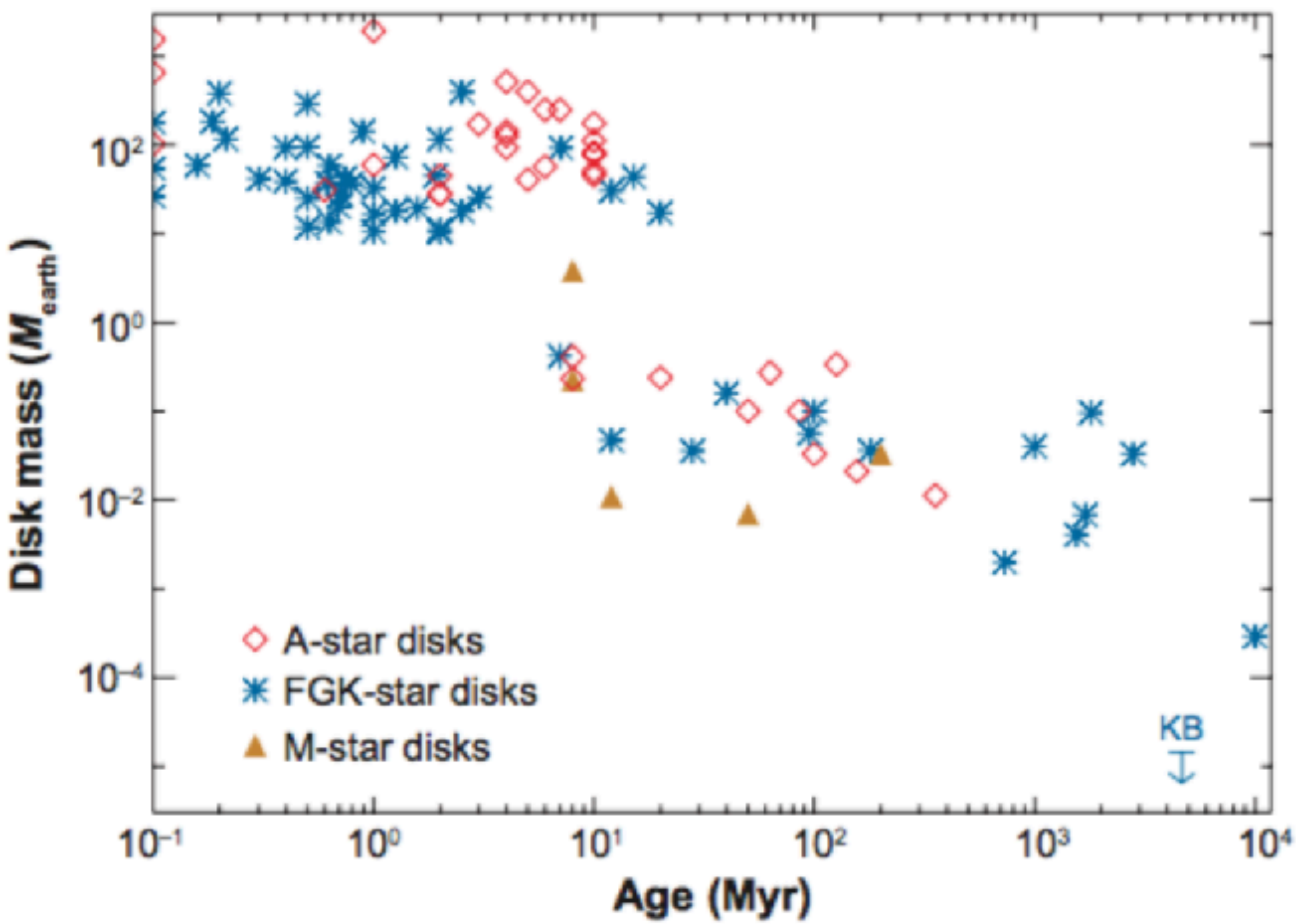


Faint transition disk

Van der Marel 2022 (review)
van der Marel et al. 2022, in rev.

Disk dust mass evolution

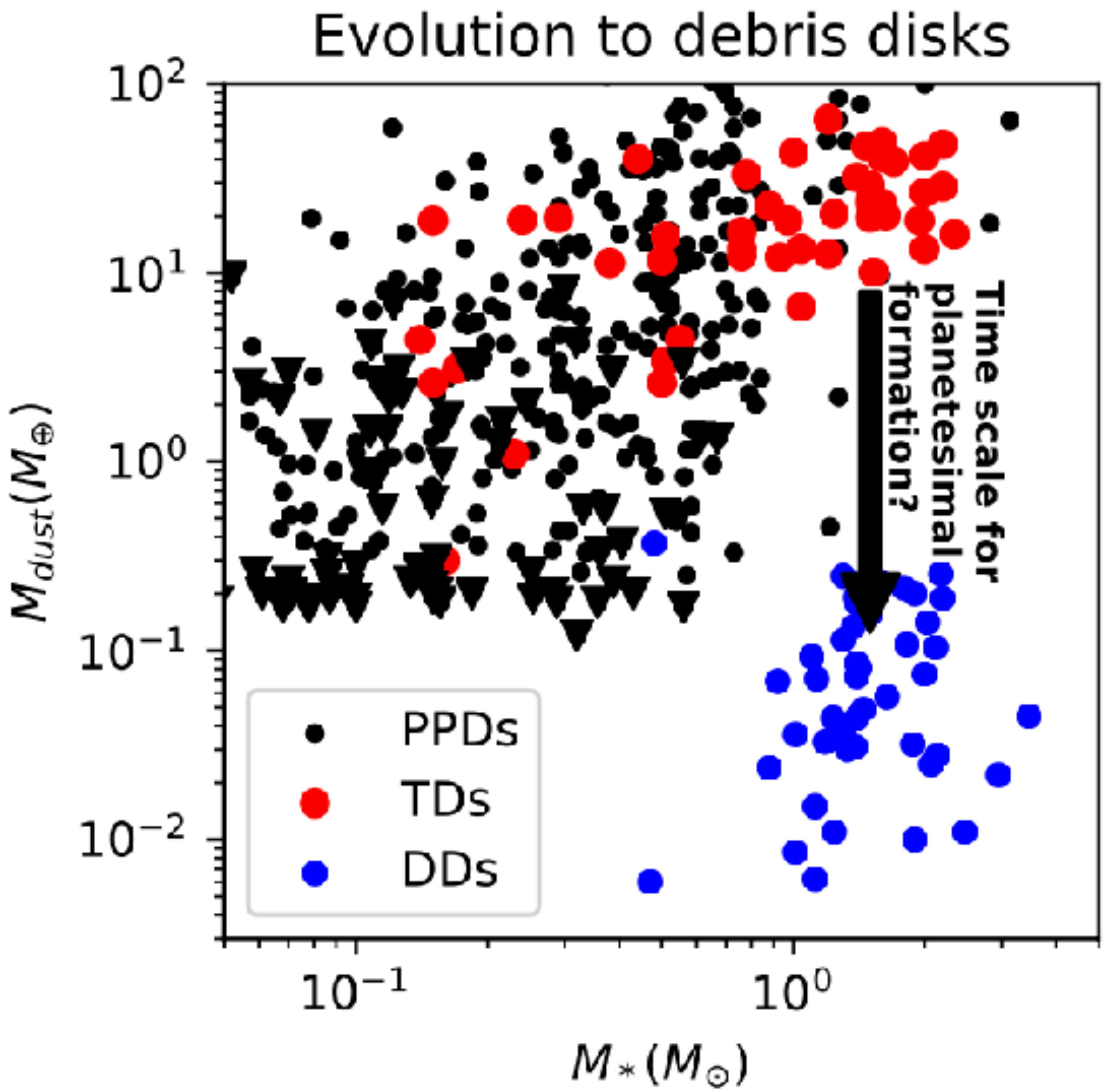
Disk dust mass decreases rapidly between protoplanetary disks and debris disks (note: incomplete/biased samples)



How can we explain this trend if debris disks have large planetesimal belts?

Wyatt et al. 2008

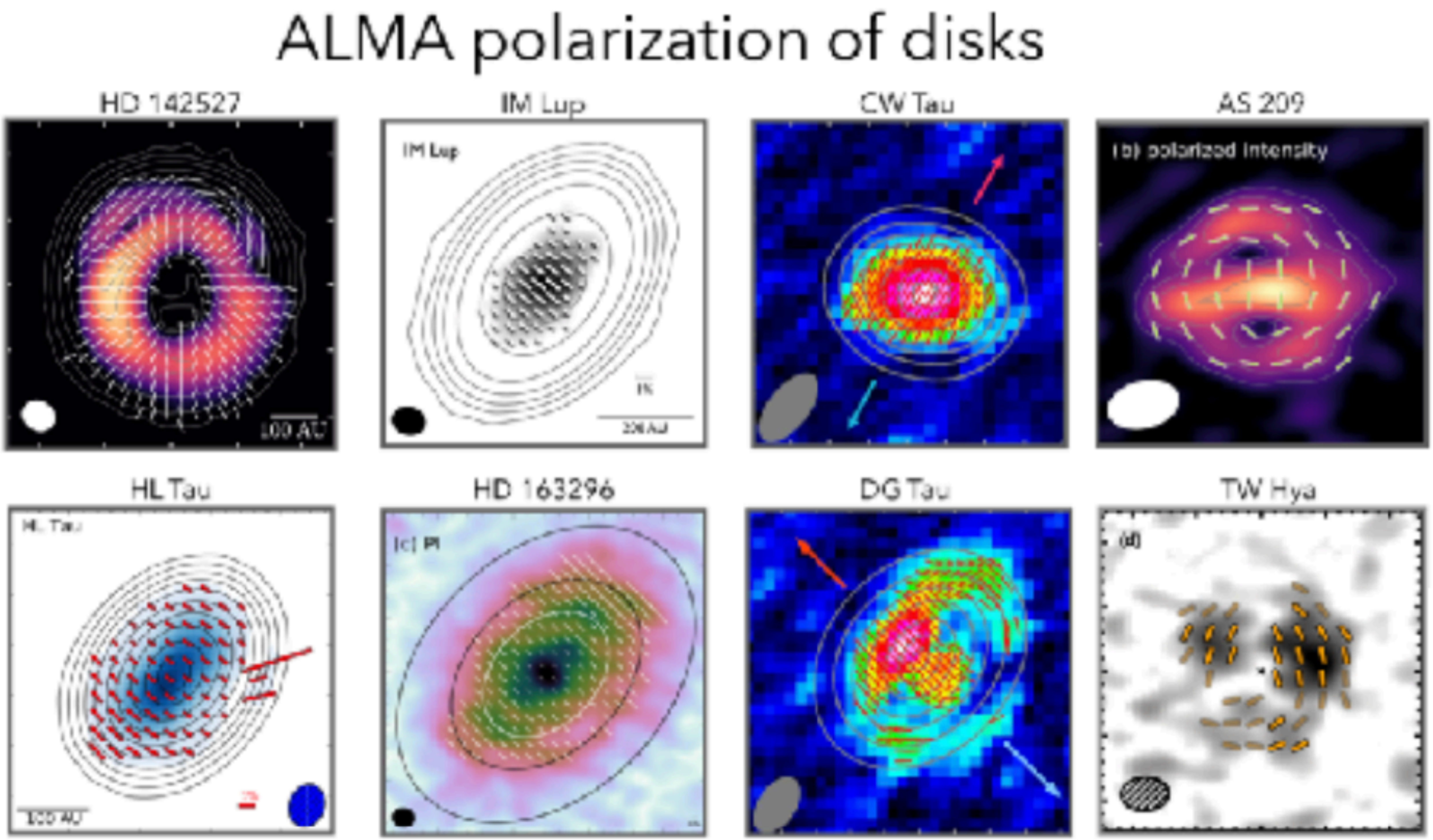
Disk dust mass evolution



Hypothesis: only the disks with dust traps which are most commonly found around super Solar mass stars, become observable debris disks

Najita et al. 2022
Van der Marel 2022 (review)

Polarisation

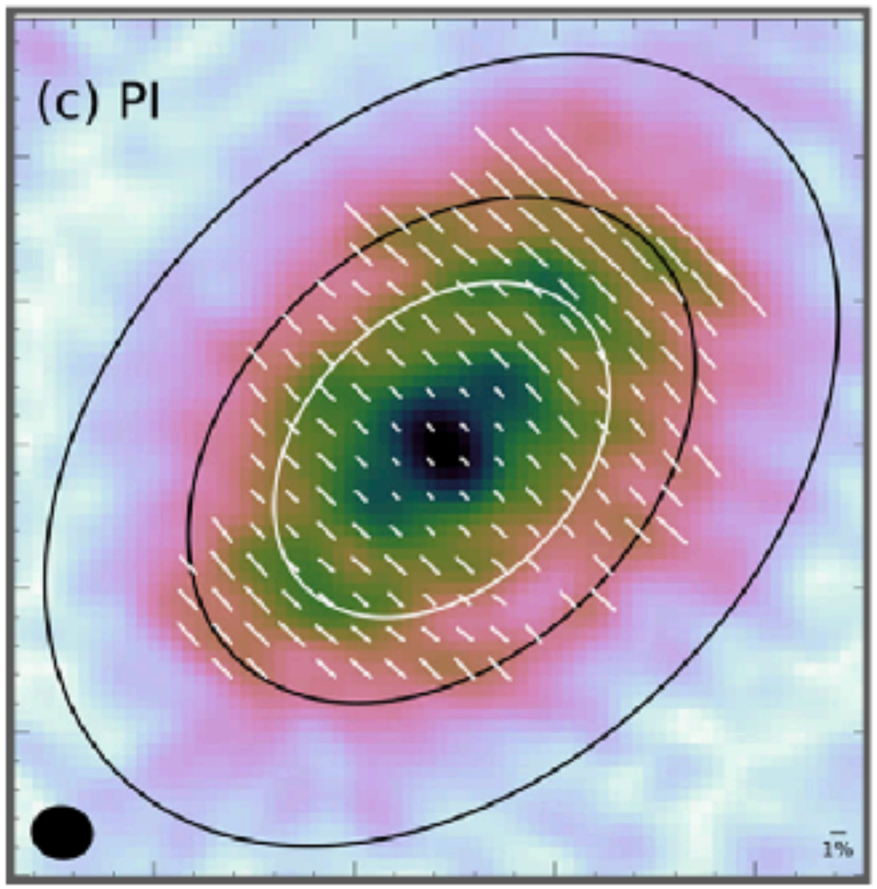


Kataoka et al. 2015

Polarisation

Parallel to the minor axis

HD 163296 (0.9 mm)

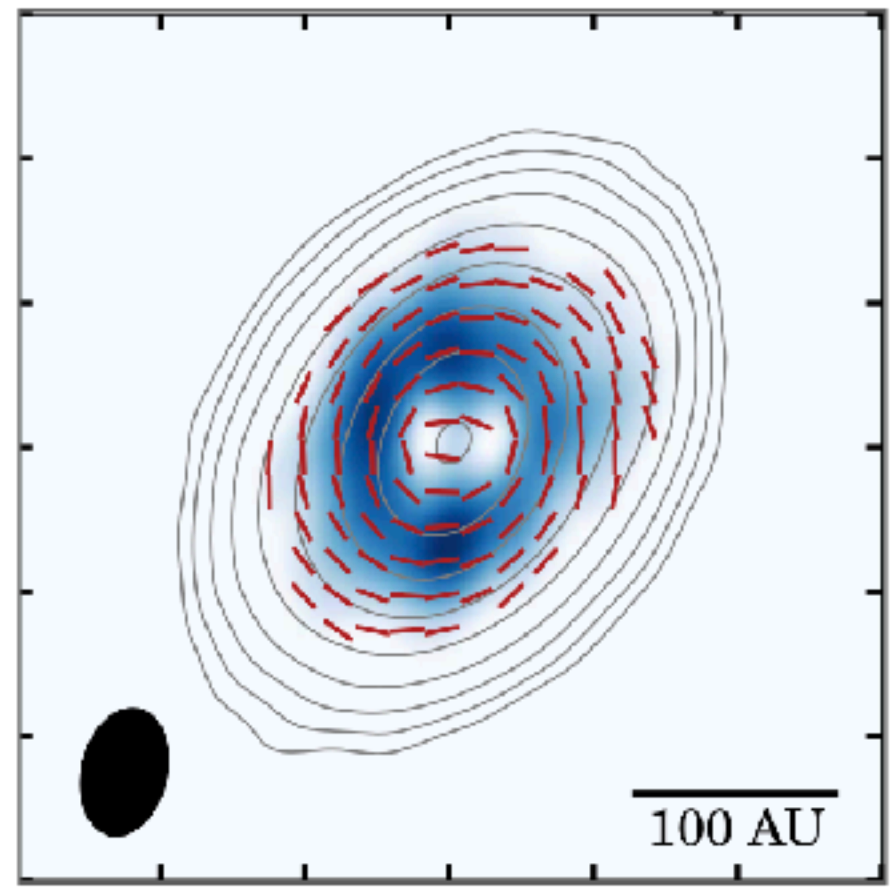


Dent et al. 2019

Self-scattering

Azimuthal

HL Tau (3 mm)

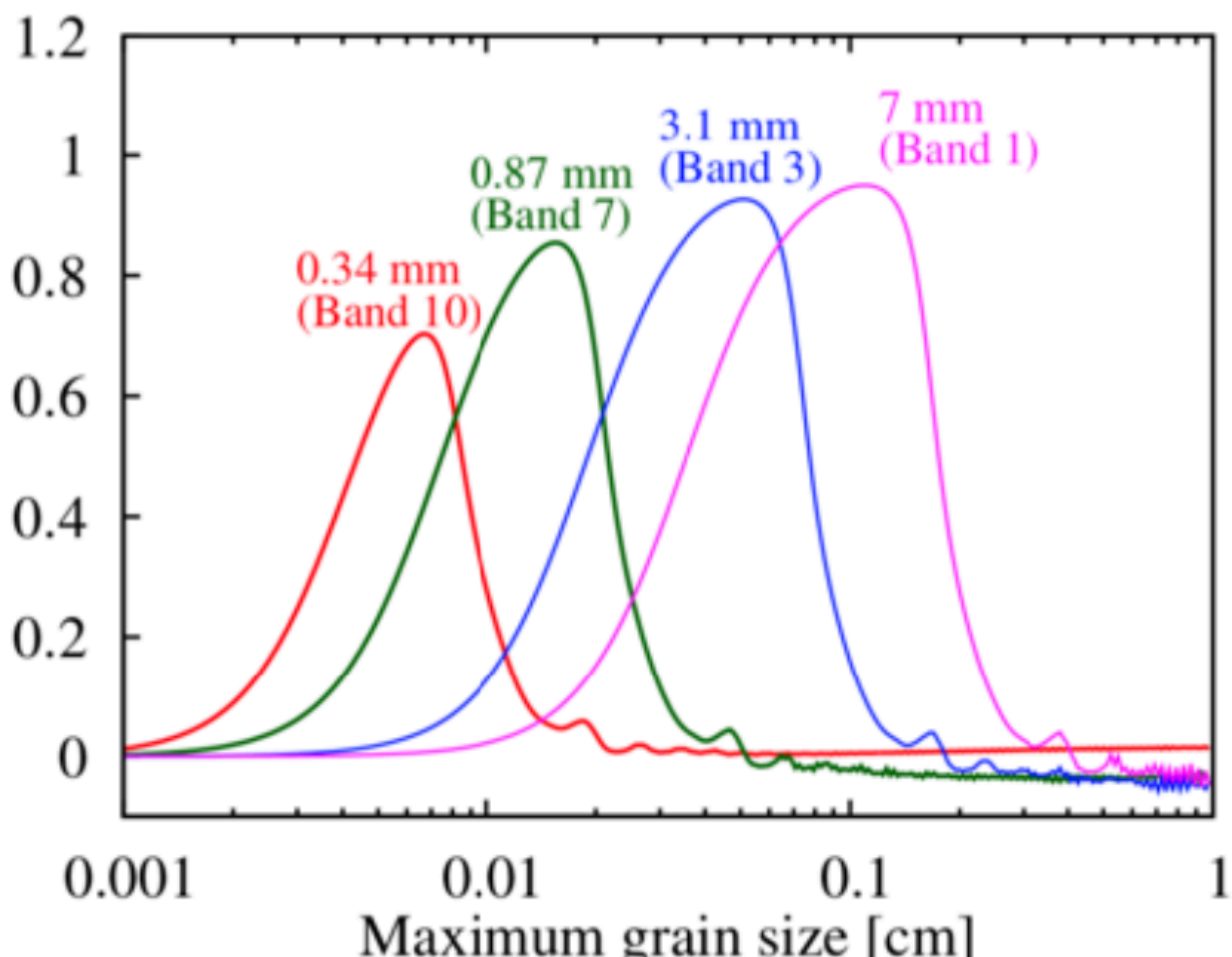


Kataoka et al. 2017

Intrinsic polarization of aligned dust grains

Polarisation

- Polarization due to scattering: only detectable when a ~ λ/2π

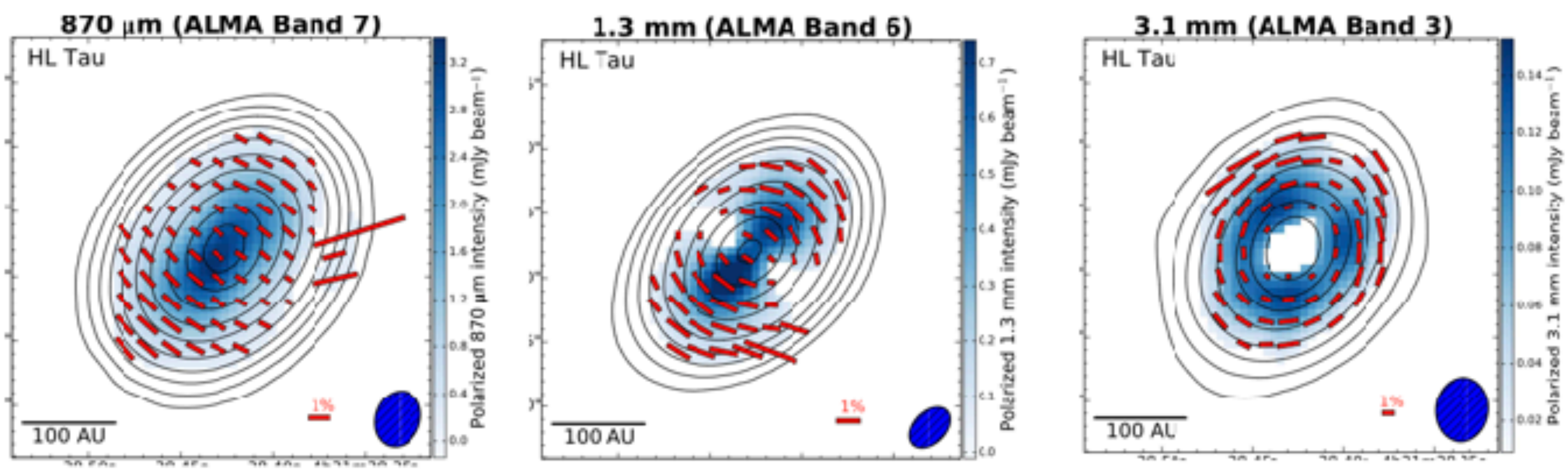


Kataoka et al. 2015

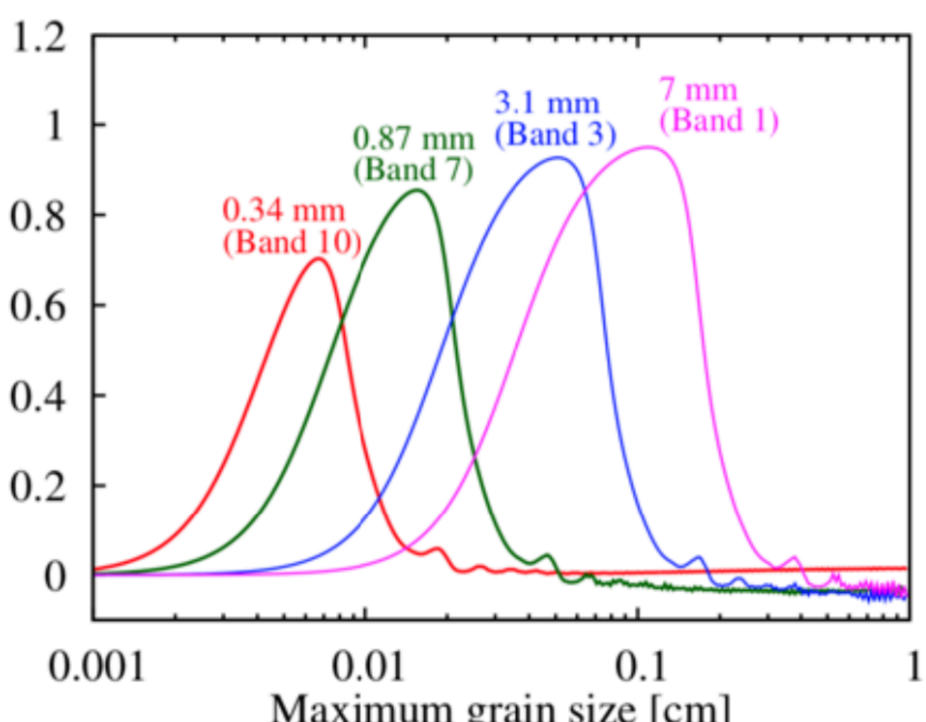
Polarisation

Measure polarisation in multiple wavelengths: transition from self-scattering to intrinsic polarisation by dust alignment

HL Tau



Self-scattering + Intrinsic polarization of aligned dust grains



Self-scattering visible in Band 7, not in Band 6/3 => maximum grain size must be <100 micron!

Kataoka et al. 2017

How large are the dust grains in disks?

Debate is still on-going!

From MIAPP meeting 2021

Summary dust

- Disk dust mass usually calculated using simple assumptions (optically thin, mm-grains)
- Disk dust mass changes in evolutionary plots can be interpreted in multiple ways
- Multi-wavelength observations can help to disentangle dust opacity effects
- Maximum dust grain size remains unknown

Disk gas mass

- Fundamental disk property
  (planet formation, disk processes, etc.)

- Problem: many uncertainties depending on method

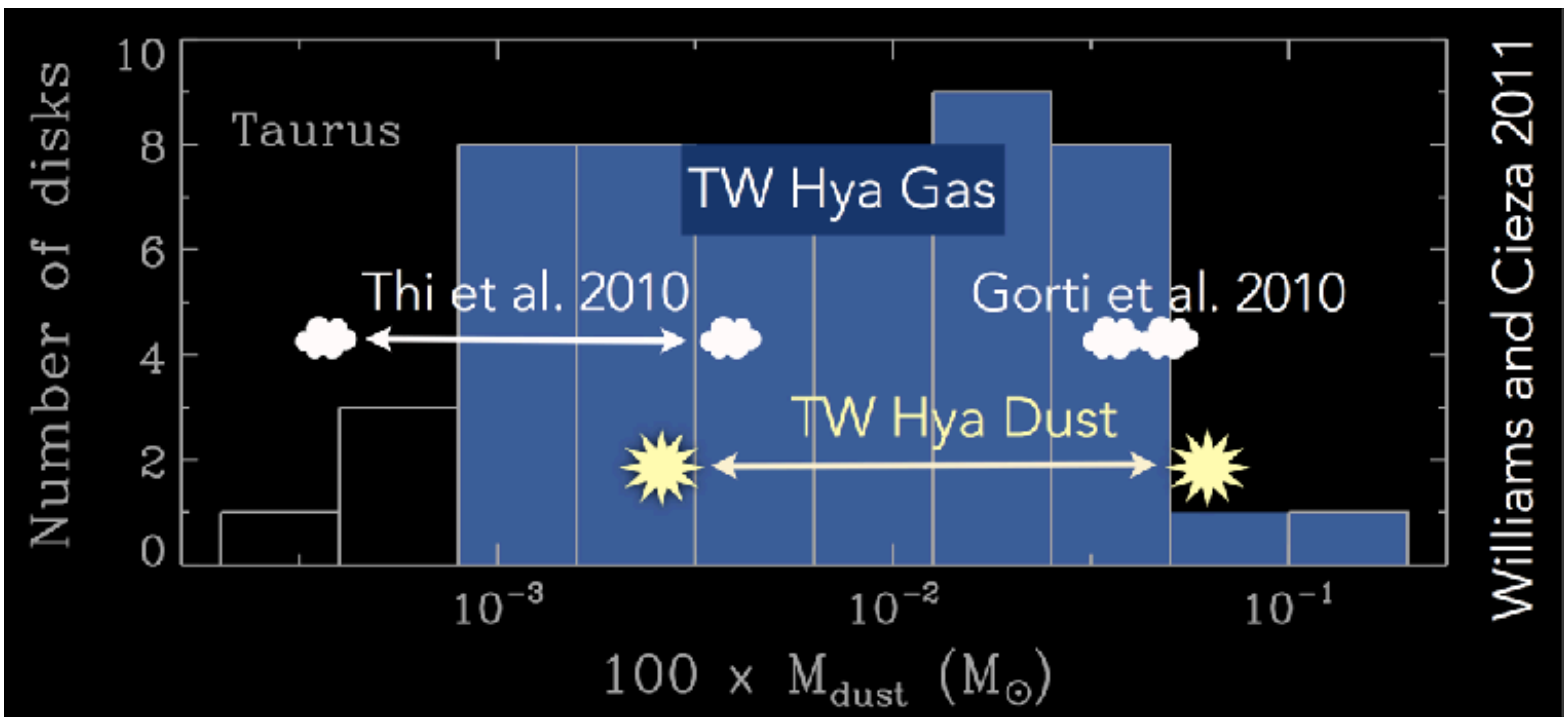


figure by Ted Bergin

Disk gas mass

- Methods
  - Dust mass x 100 (ISM)
  - CO isotopologues
  - HD
  - Self-gravity

Dust mass x 100 (ISM):
- **Dust follows gas?**
- **ISM ratio?**
- **Dust mass accurate?**

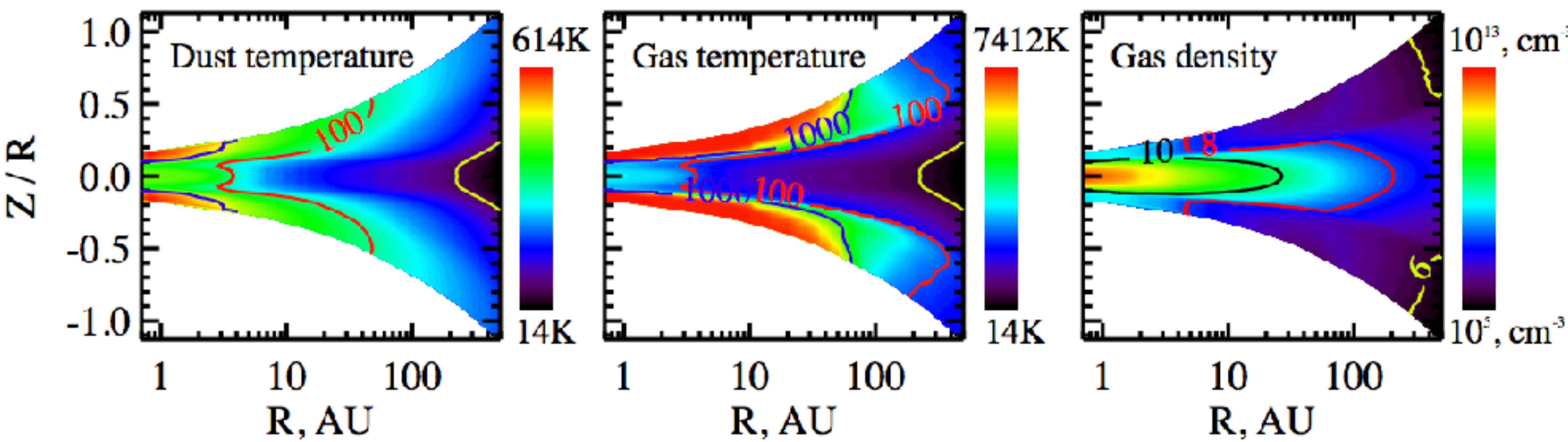
CO isotopologues:
- **CO optical depth?**
- **CO/H_2 ratio?**
- **Depletion?**

HD:
- **Dependence on vertical structure**
- **FIR: inaccessible**

Self-gravity:
- **Need very good kinematic data**

Using molecules

In order to use molecular line emission as a tracer of mass, we need to understand the density and temperature structure of the disk



Gas temperature is decoupled from dust temperature (additional heating mechanisms in surface layers) and large gradients in density and temperature which impact the molecular abundances

Using molecules

Bulk of the molecular gas structure in the disk (side view)

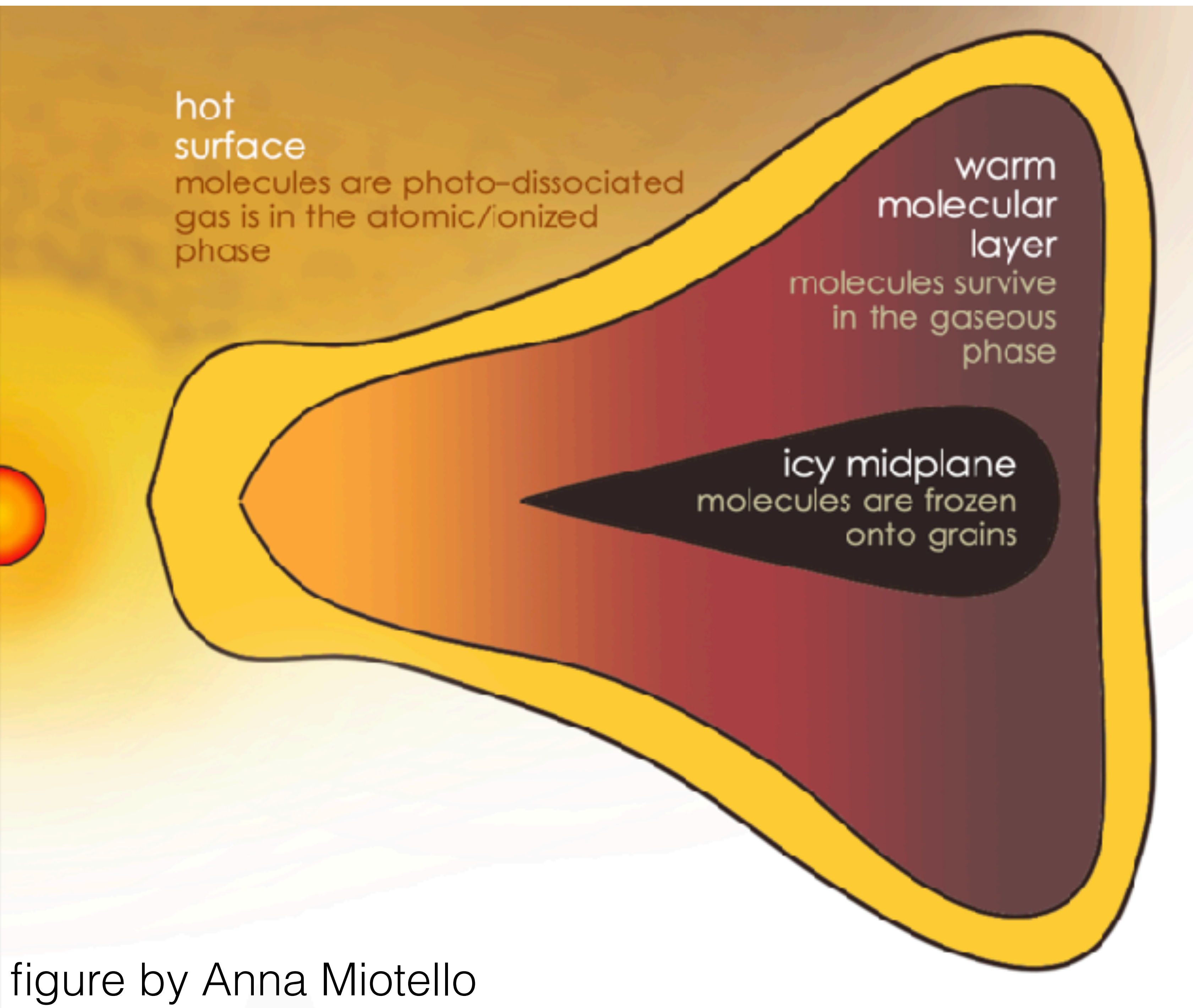


figure by Anna Miotello

<u>Main molecules:</u>

<u>H_2</u>

- most abundant constituent
- no permanent electric dipole moment:
  very weak rotational and vibrational lines
- However, isotopologue HD has dipole moment and is observable in FIR

<u>CO</u>

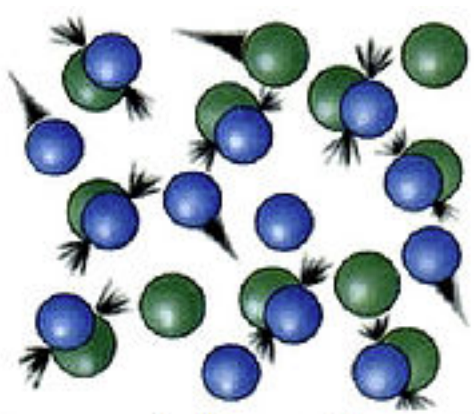
- second in abundance to H2 ($CO/H_2 \sim 10^{-4}$ in ISM)
- very well studied chemistry

readily detectable pure rotational lines at mm wavelength

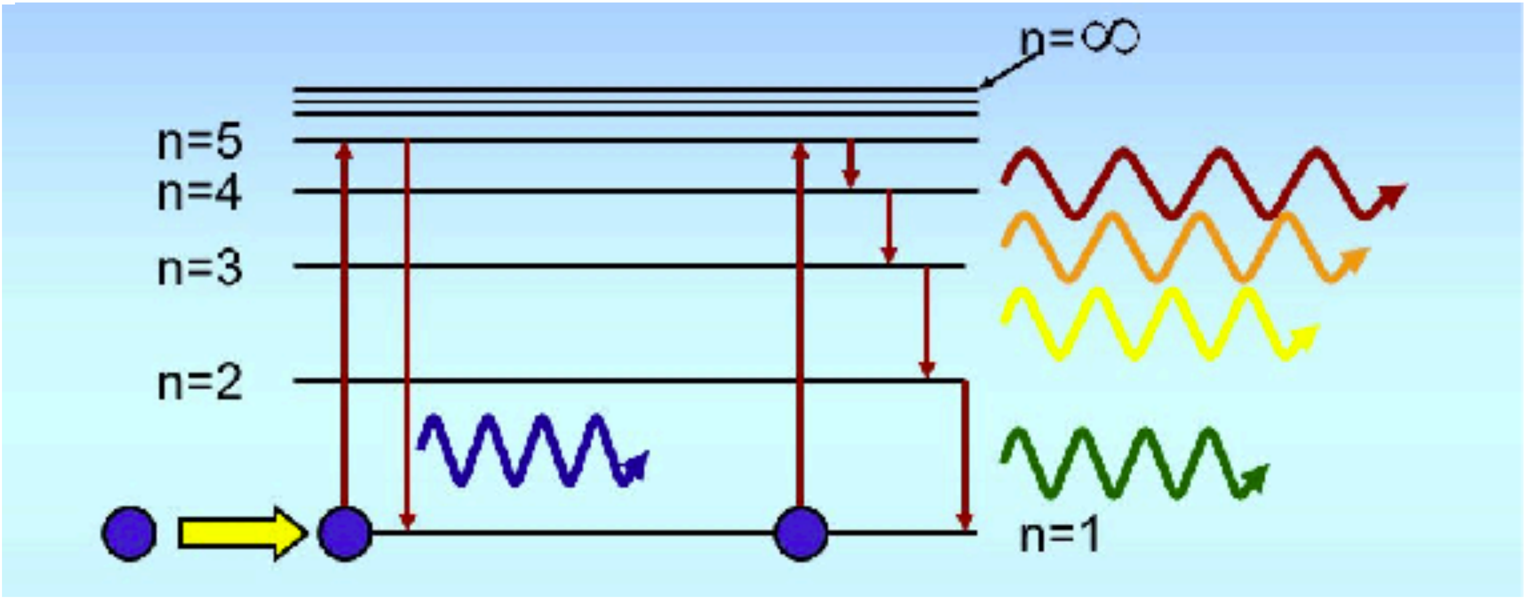
More on chemistry and line excitation in Lecture 6

Using molecules

What sets the emission strength of a line?

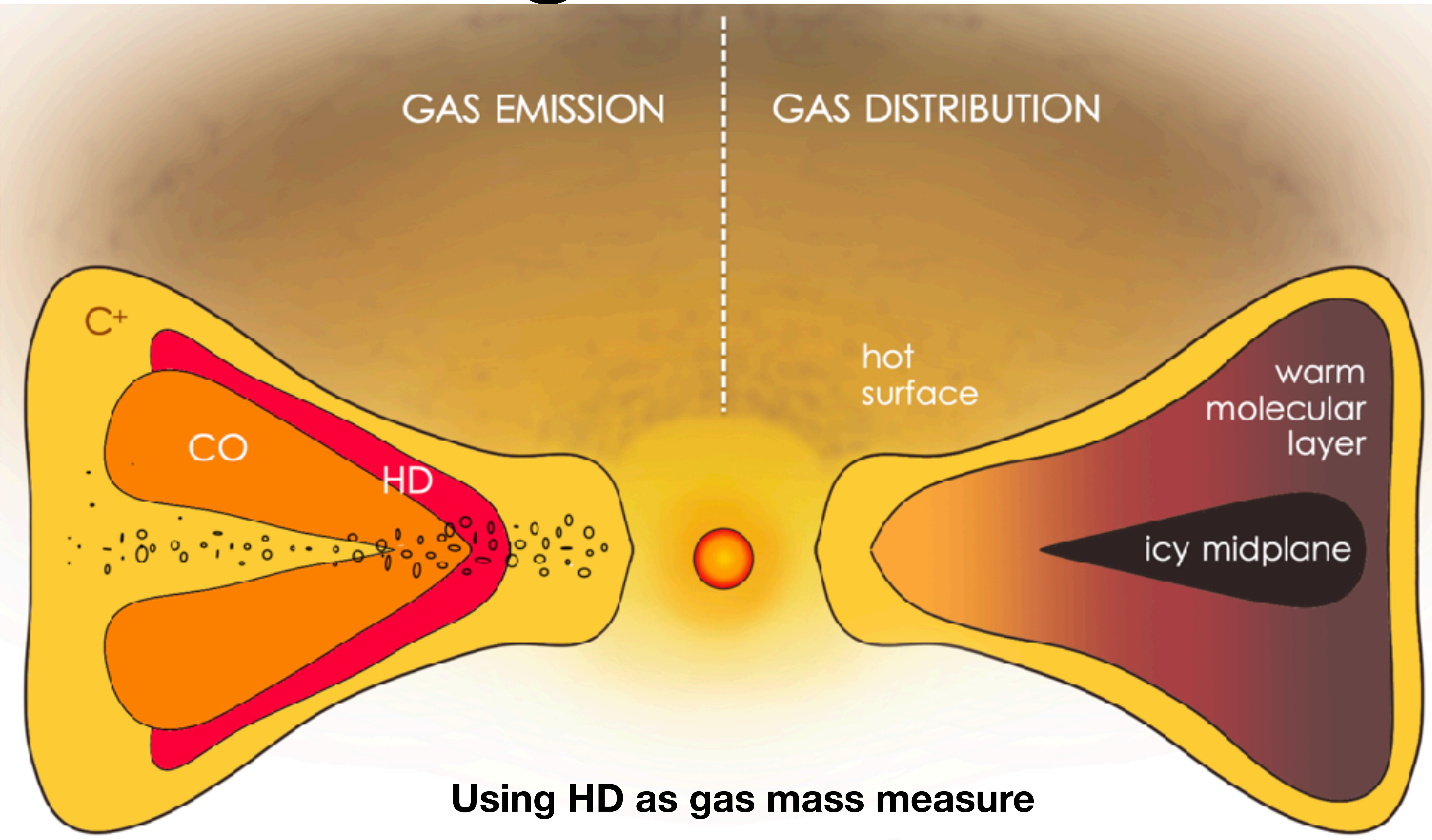


Molecules move around randomly and occasionally collide



A collision brings a molecule in a higher energetic state

Using molecules



Using HD as gas mass measure

figure by Anna Miotello

Using CO

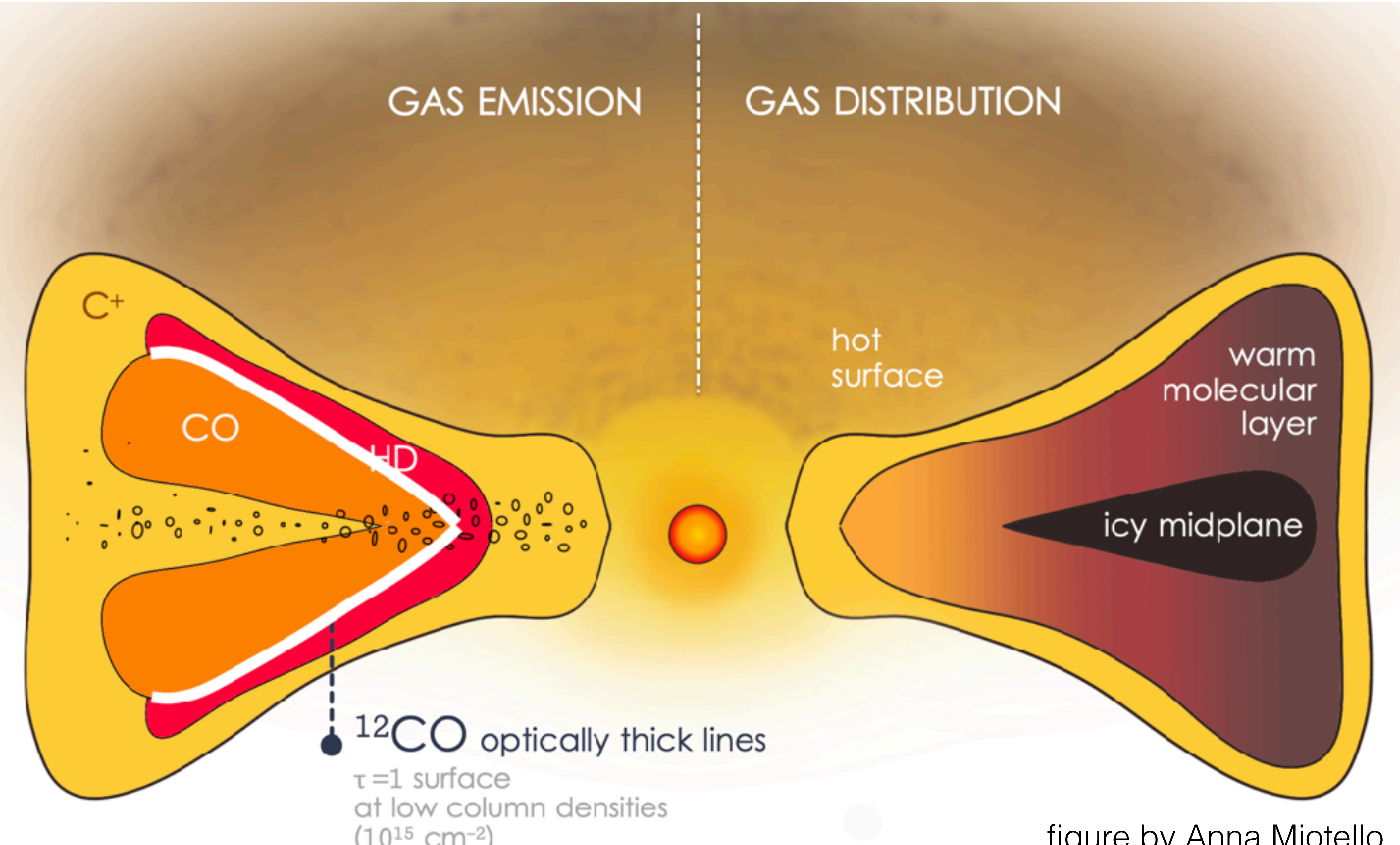


figure by Anna Miotello

Using CO isotopologues

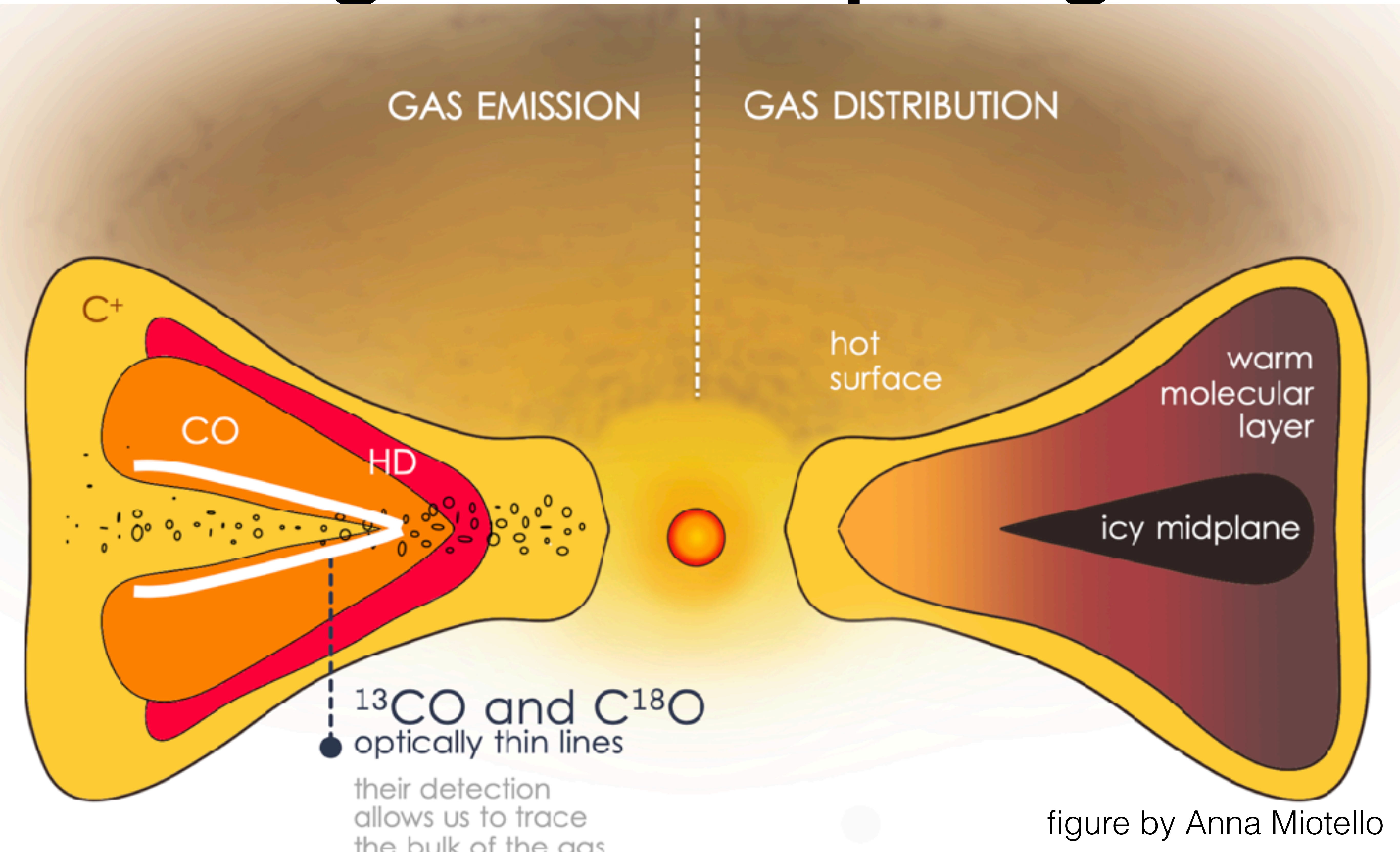
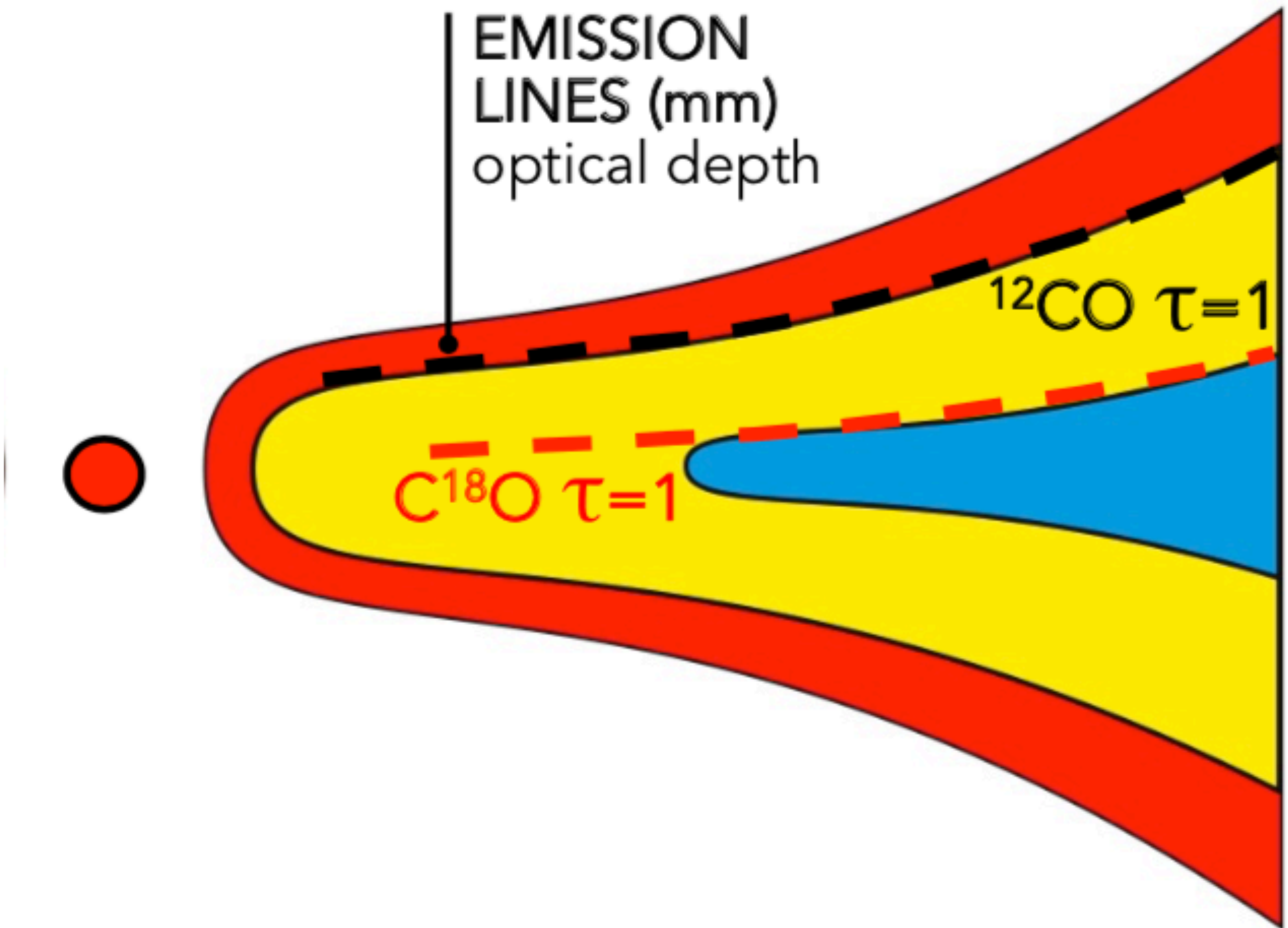


figure by Anna Miotello

CO optical depth

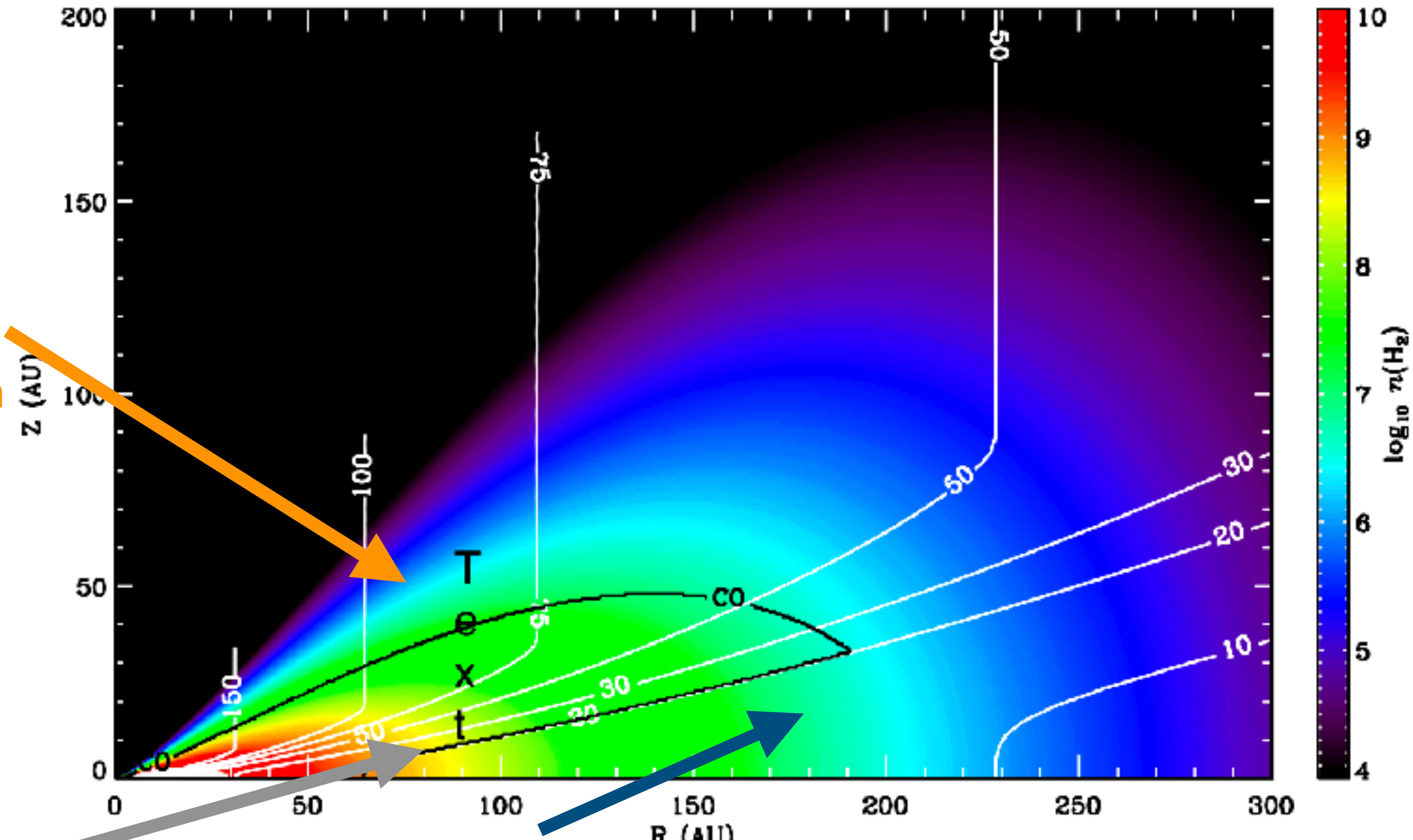


- ^{12}CO	1
- ^{13}CO	1/68
- C^{18}O	1/560

Parametrised structure

CO abundance and gas temperature are parametrised, followed by raytracing of the line

CO/H_2 set to 0 due to photodissociation (n_H threshold)

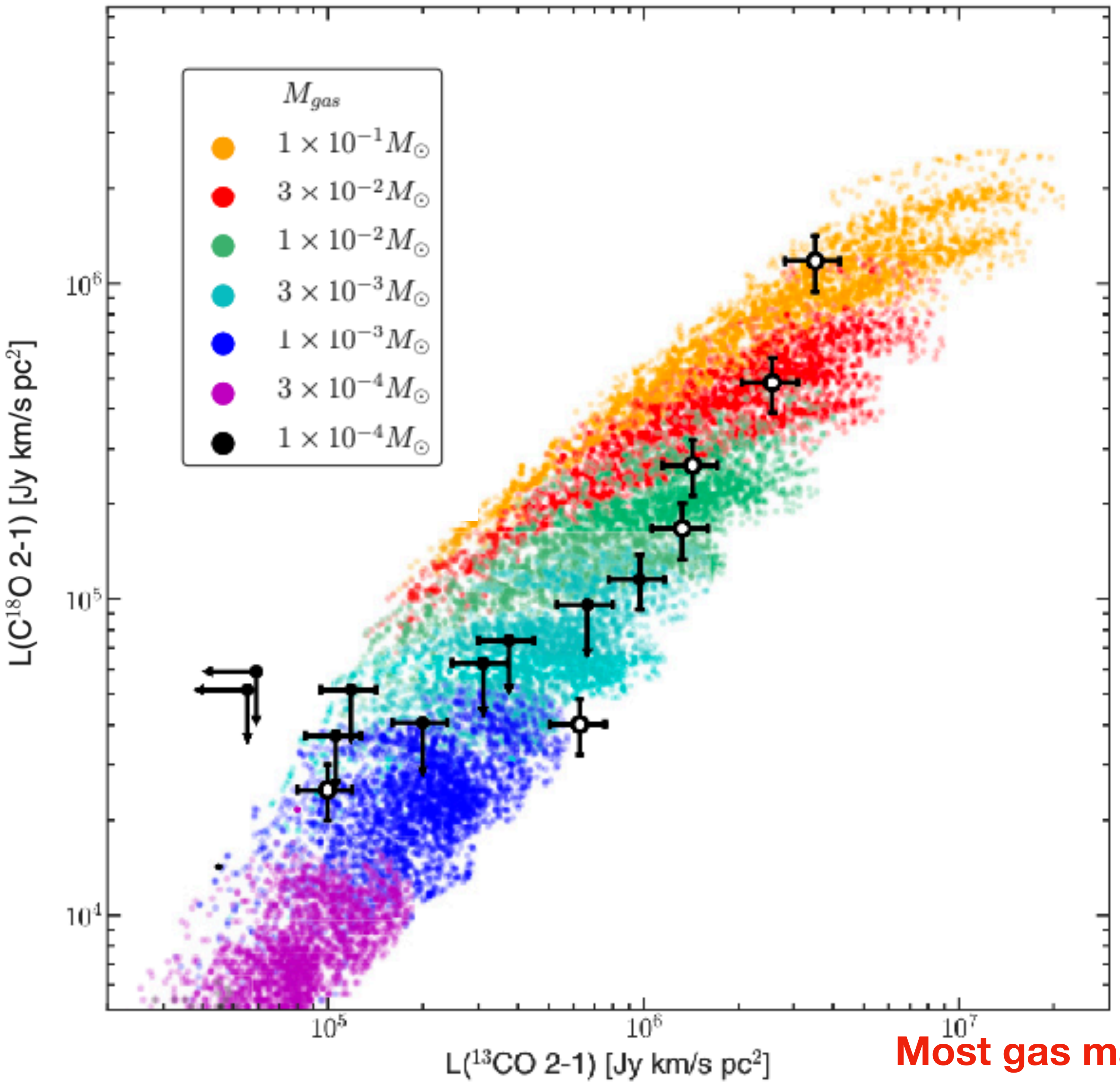


CO/H_2 set to 10^{-4}

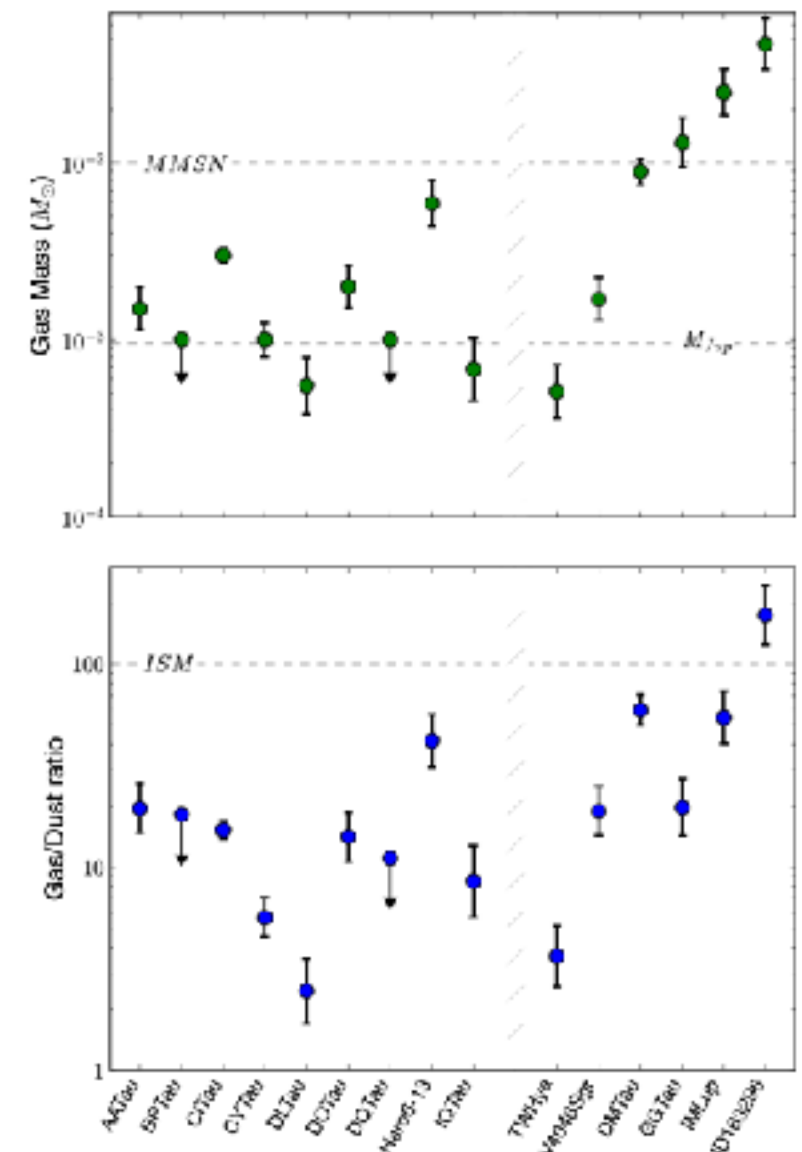
CO/H_2 set to 0 due to freeze-out (T<20 K)

Williams & Best 2014

Parametrised structure



Creating a large grid of models with a range of disk masses, stellar masses and other properties, we have estimates of combined line strength of ^{13}CO and C^{18}O 2-1 to compare with observed line fluxes

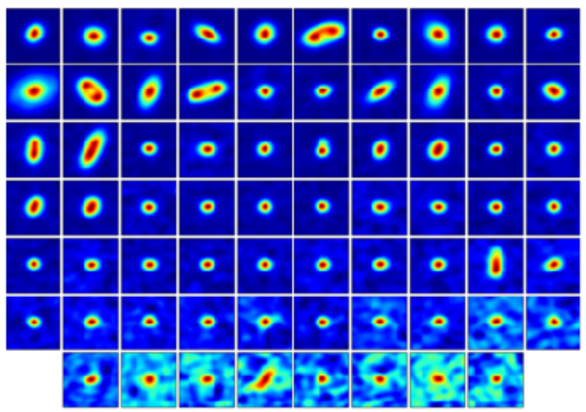


Most gas masses < MMSN and gas-to-dust ratio ~ 10!

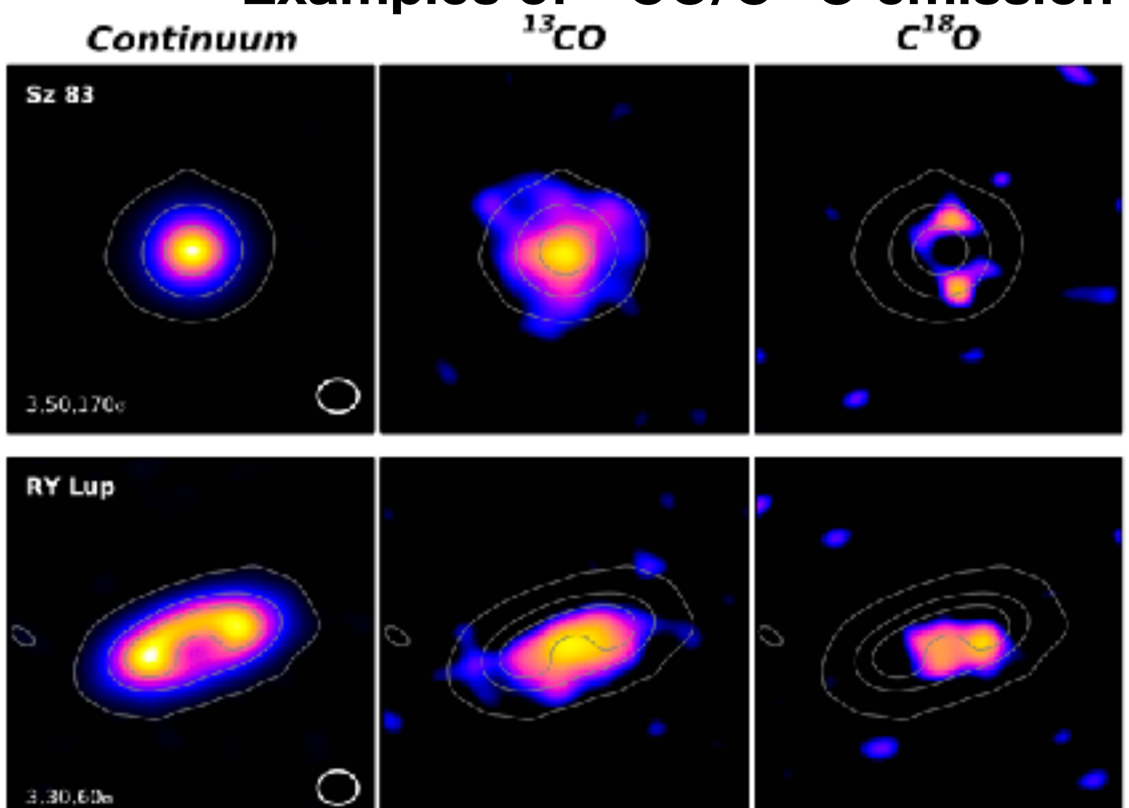
Williams & Best 2014

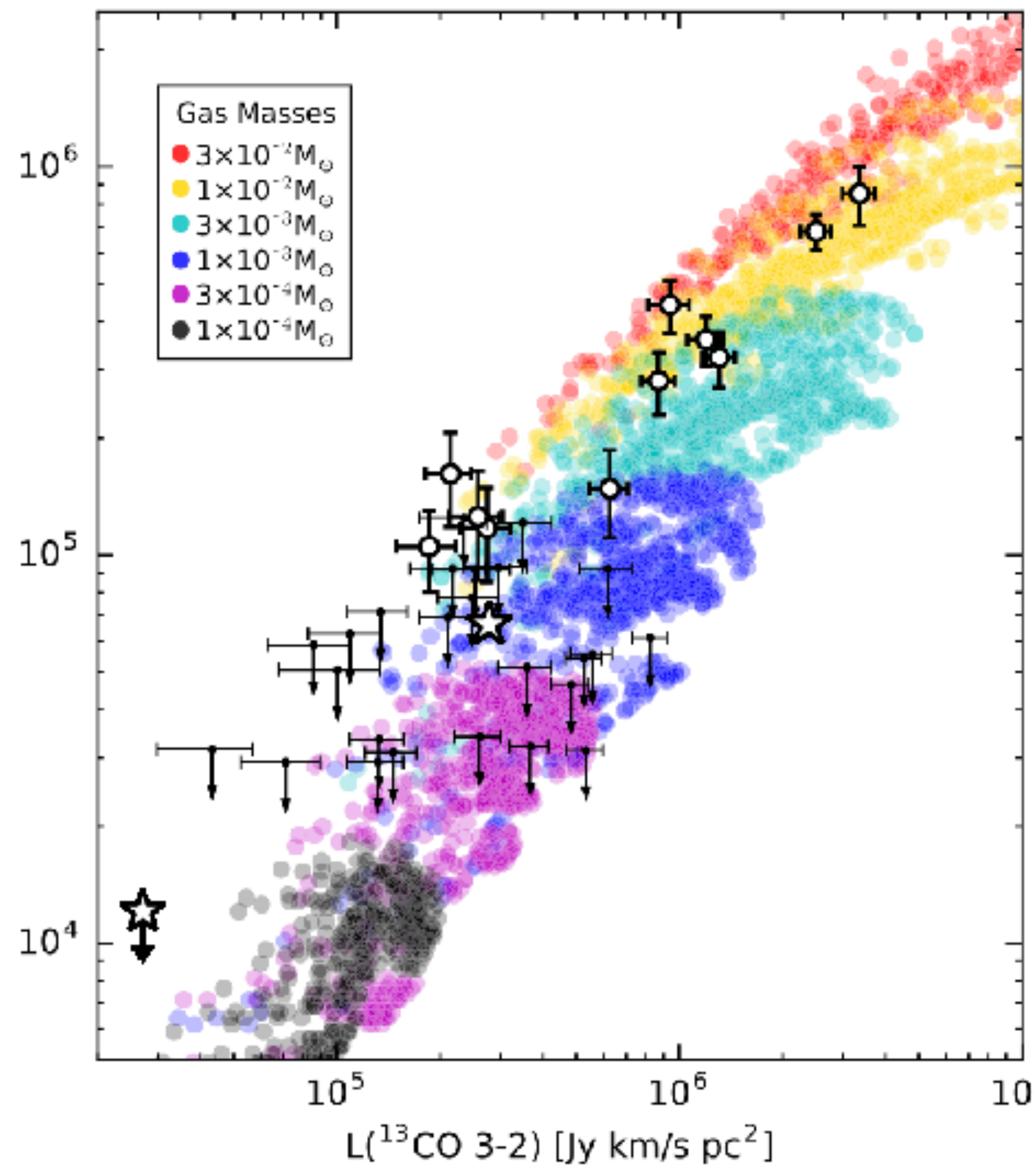
Parametrised structure

However, this was a biased sample towards very bright disks (detectable with SMA)
What about the Lupus survey?



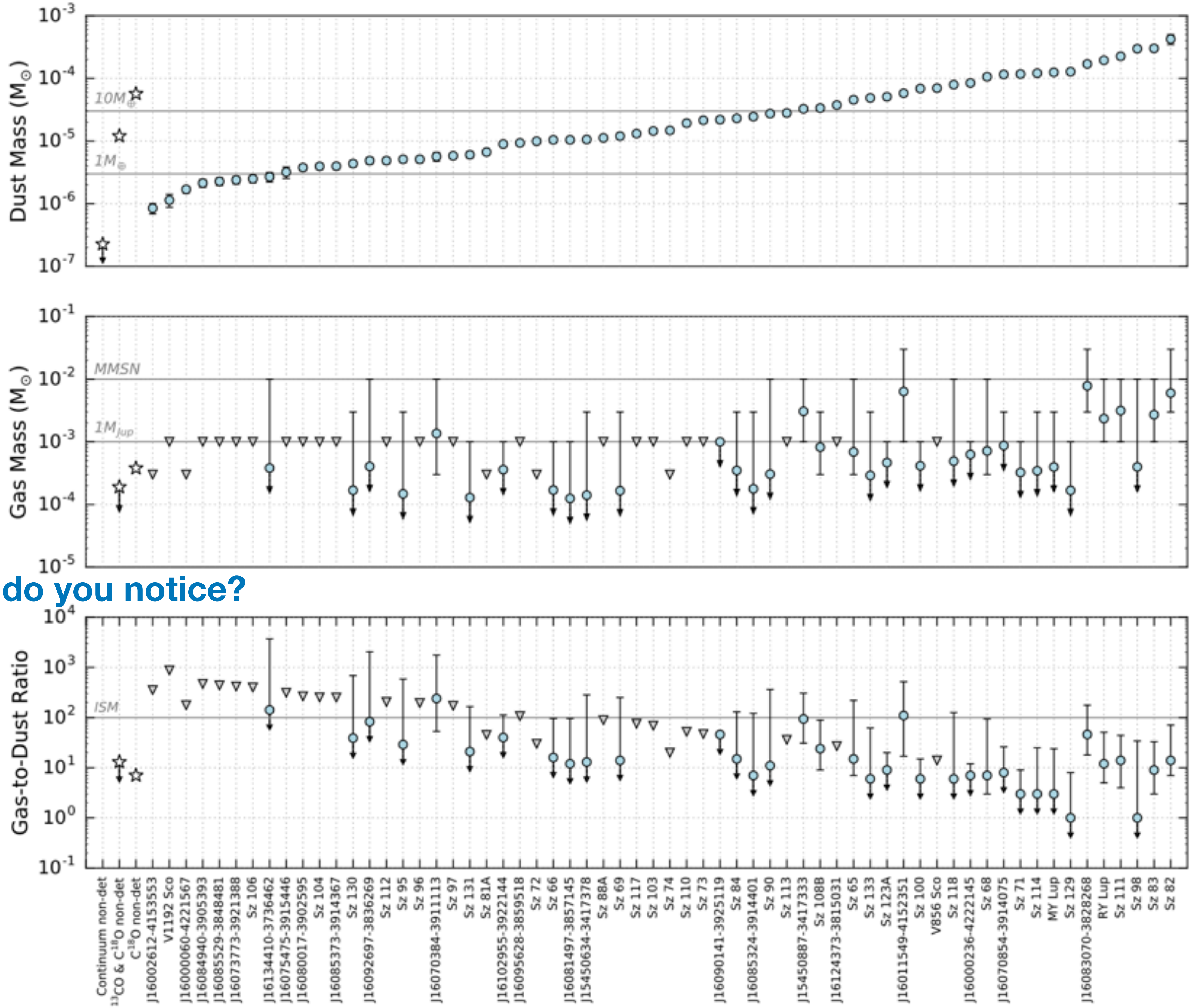
Examples of $^{13}CO/C^{18}O$ emission





Ansdell et al. 2016

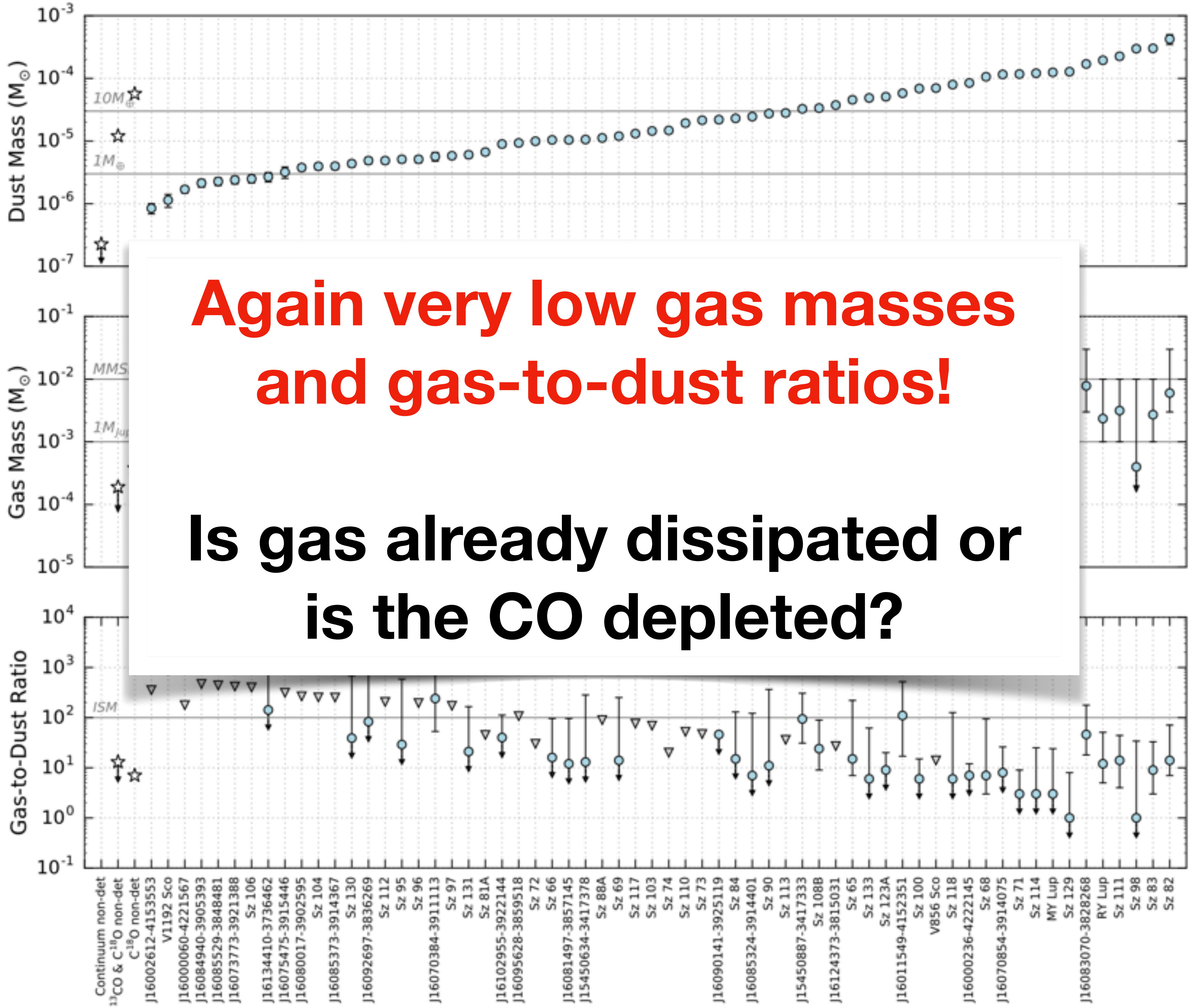
Parametrised structure



What do you notice?

Ansdell et al. 2016

Parametrised structure



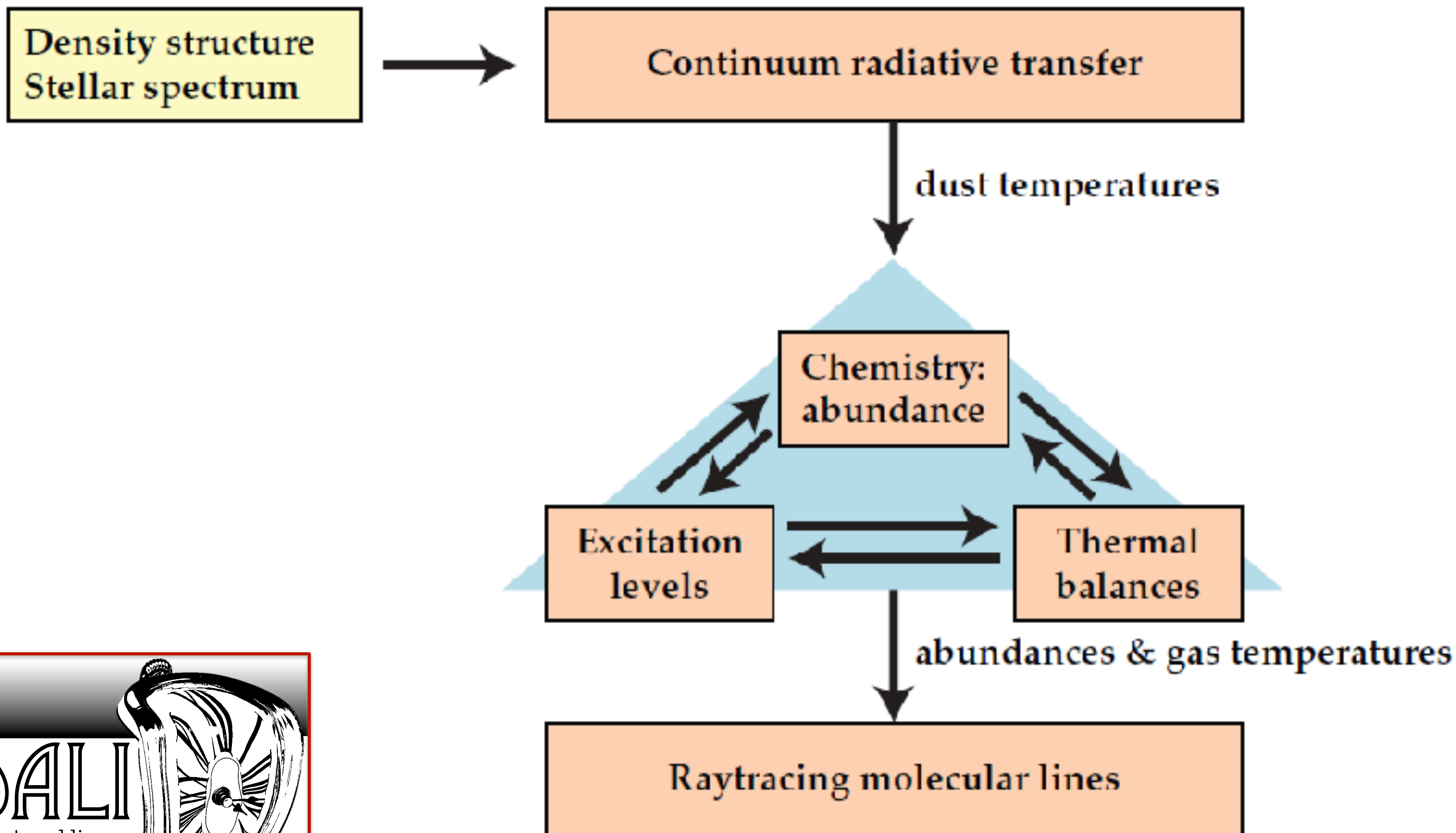
Again very low gas masses and gas-to-dust ratios!

Is gas already dissipated or is the CO depleted?

Ansdell et al. 2016

Full thermo-chemical model CO

More on chemistry and line excitation in Lecture 6

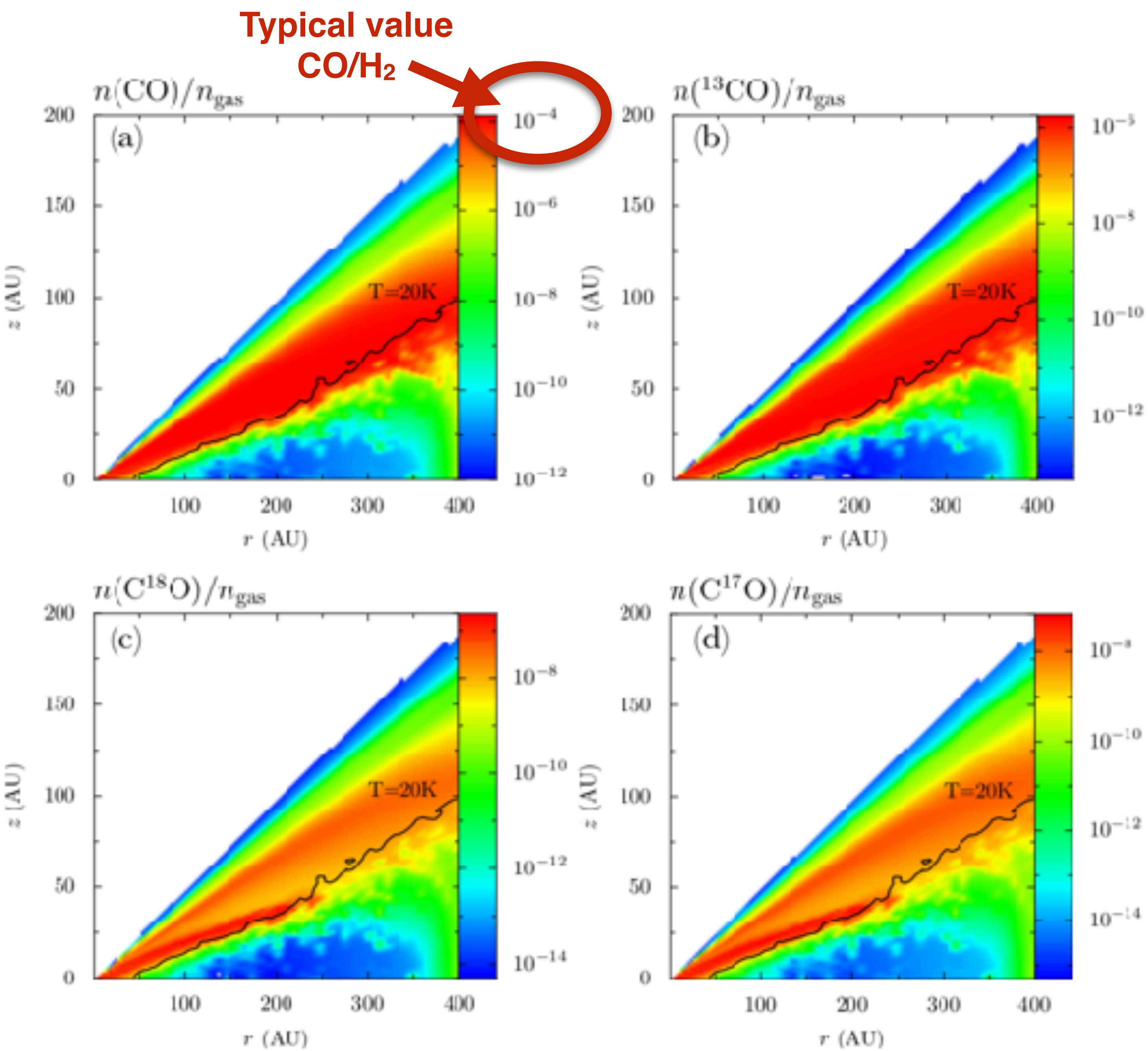


DALI
dust and lines

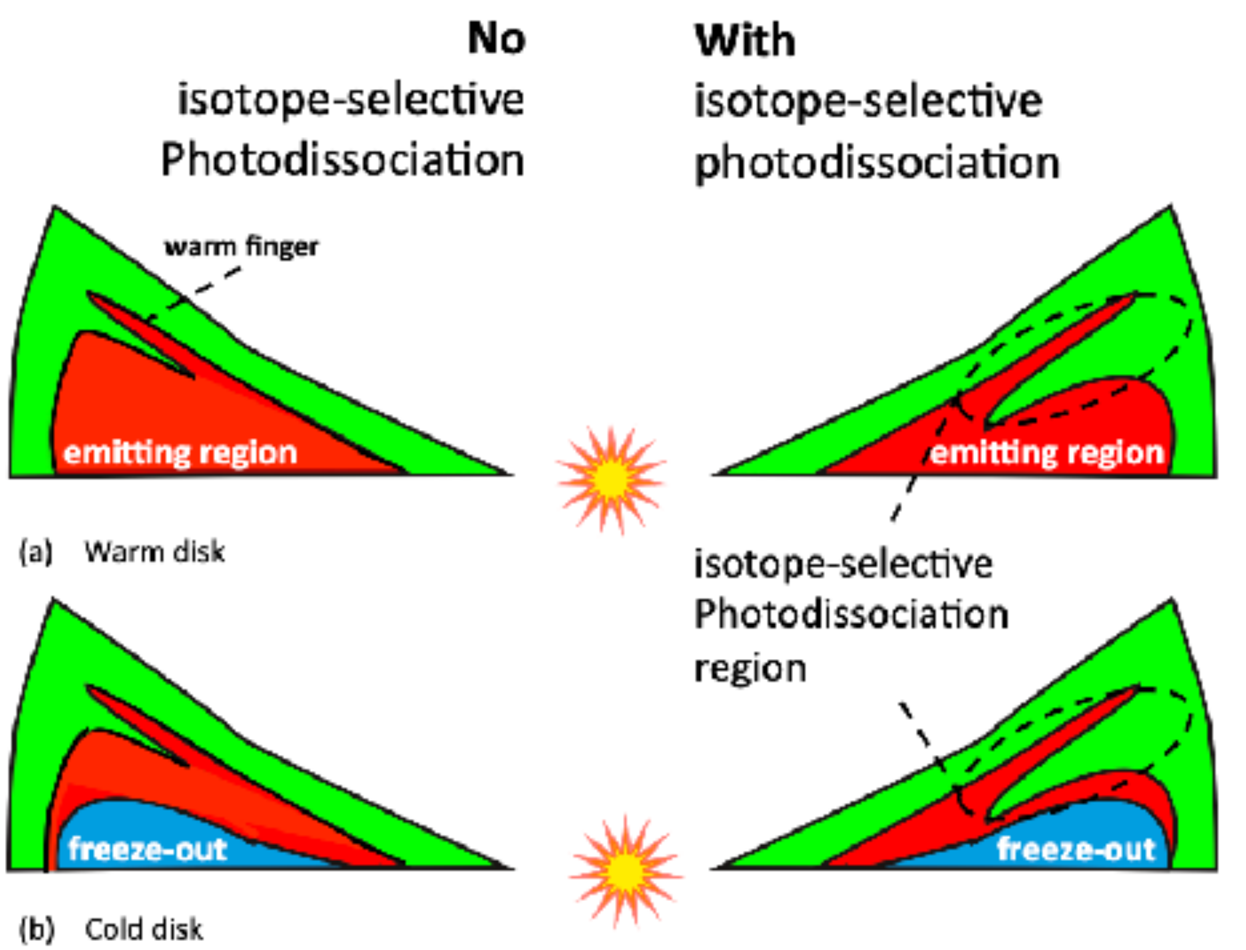
Compute abundances and temperatures, considering freeze-out, photodissociation, chemistry….

Bruderer et al. 2012, 2013, 2014
Van der Marel 2015

Compute molecular abundances of CO isotopologues



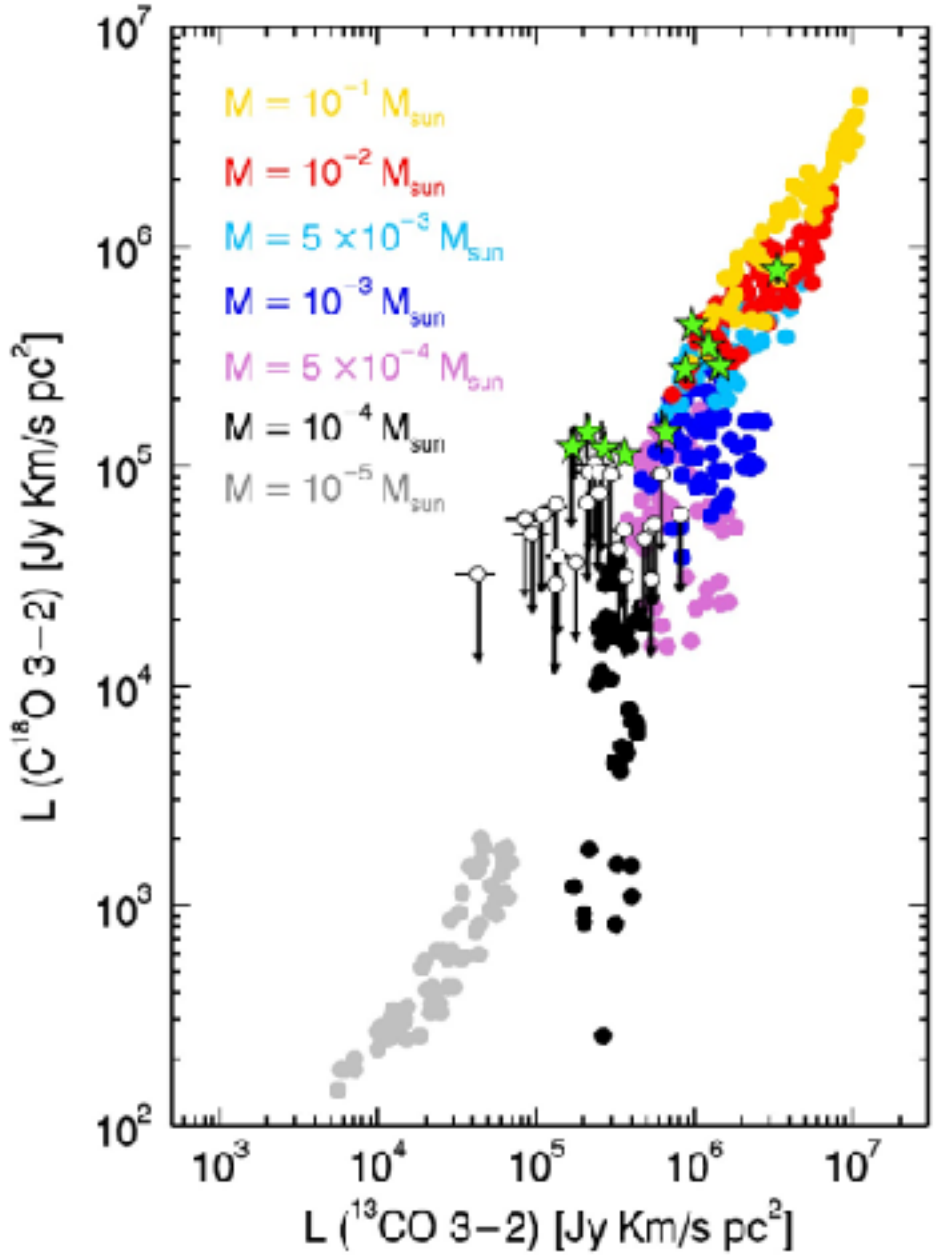
Isotope-selective photodissociation: photodissociation deeper into the disk surface for rarer isotopologues

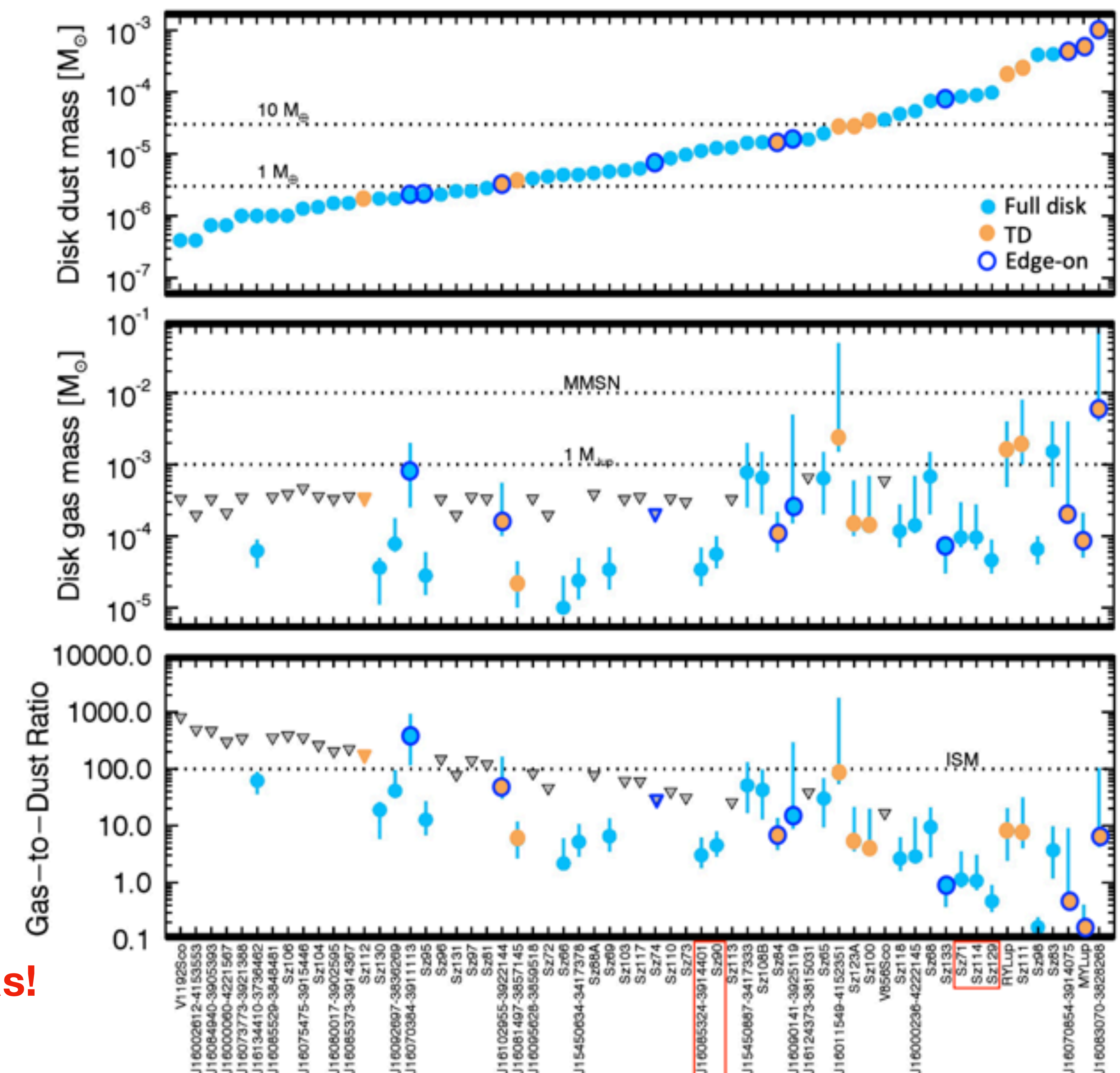


Again, grid of models to be compared with the Lupus data…

Miotello et al. 2014, 2016

Gas masses in Lupus



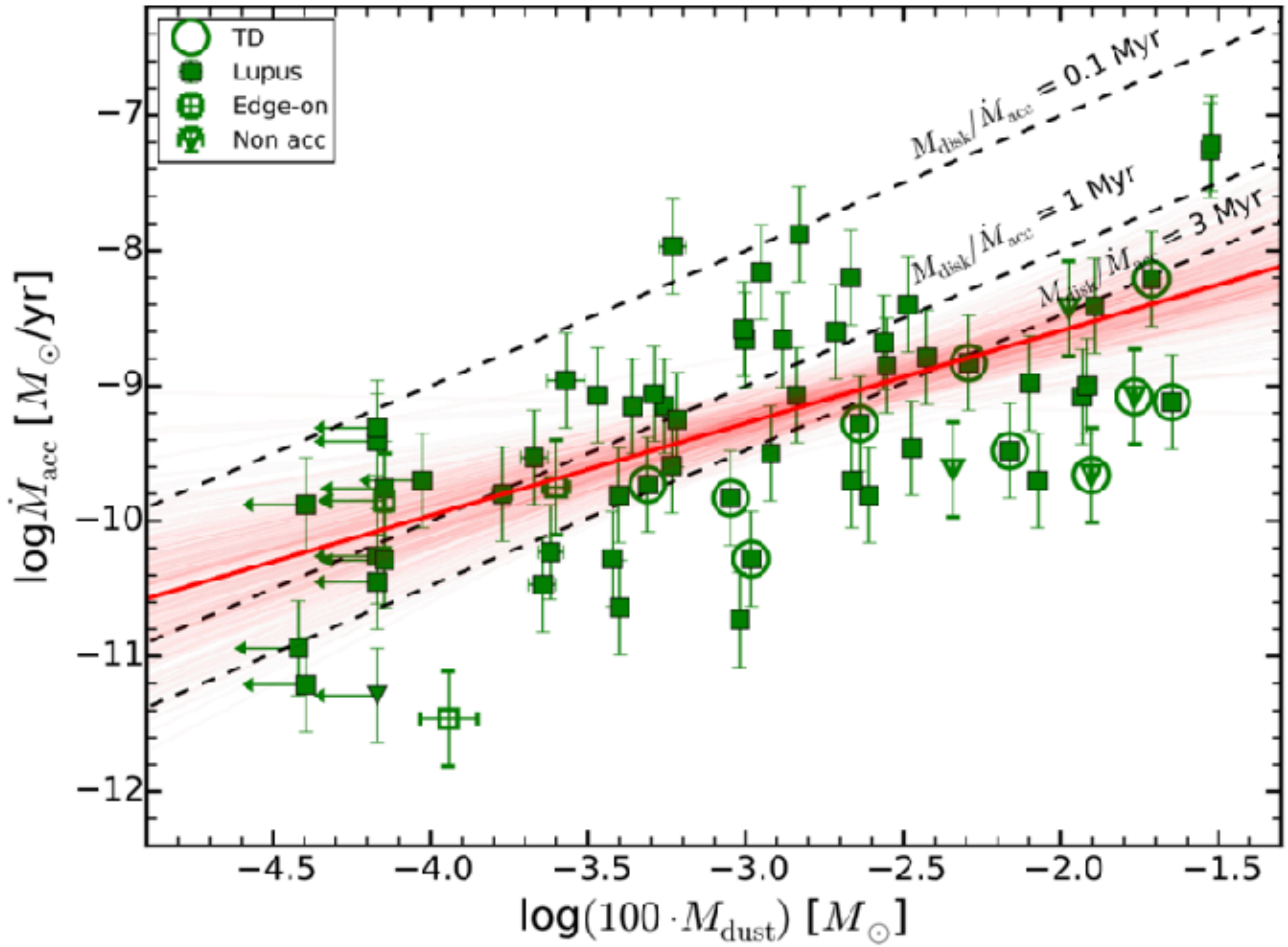


Still low gas masses and GDRs!

Miotello et al. 2017

Gas dissipation?

Rapid gas dissipation in Lupus disks is unlikely with the observed accretion rates, which are consistent with a few Myr of evolution



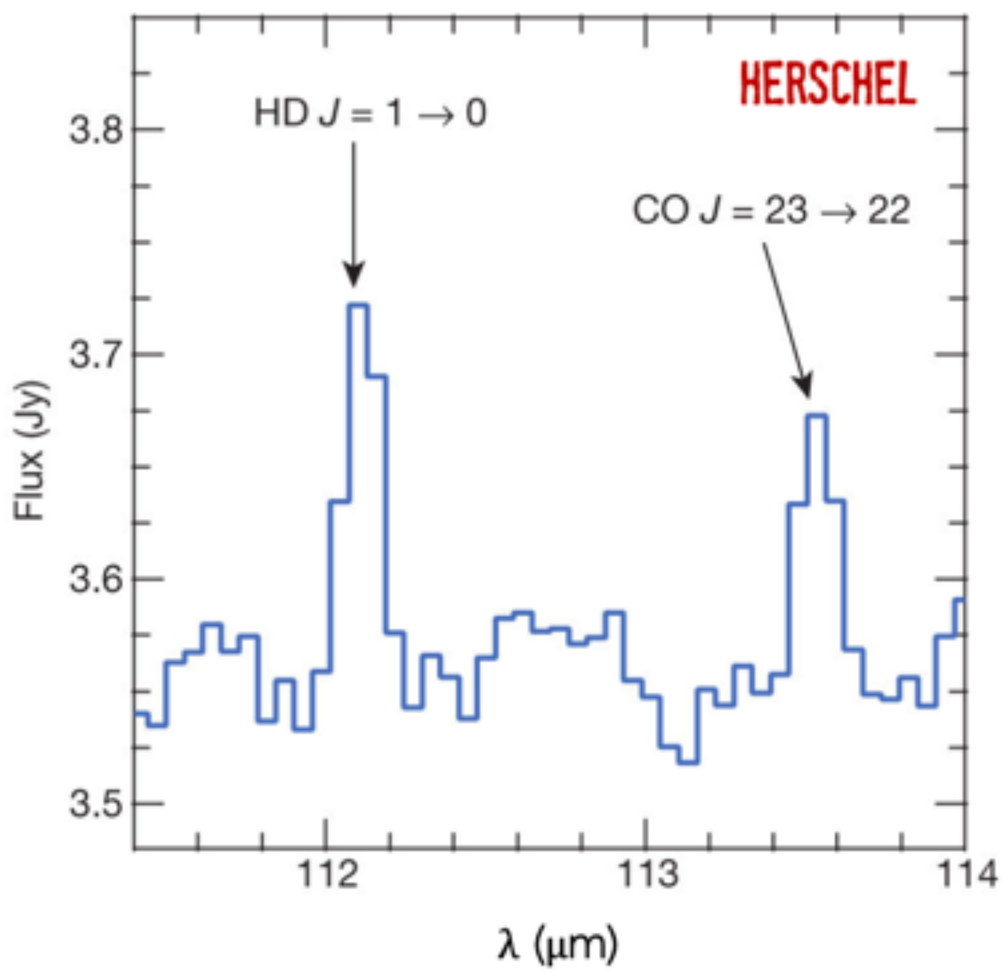
So something else must deplete the CO?

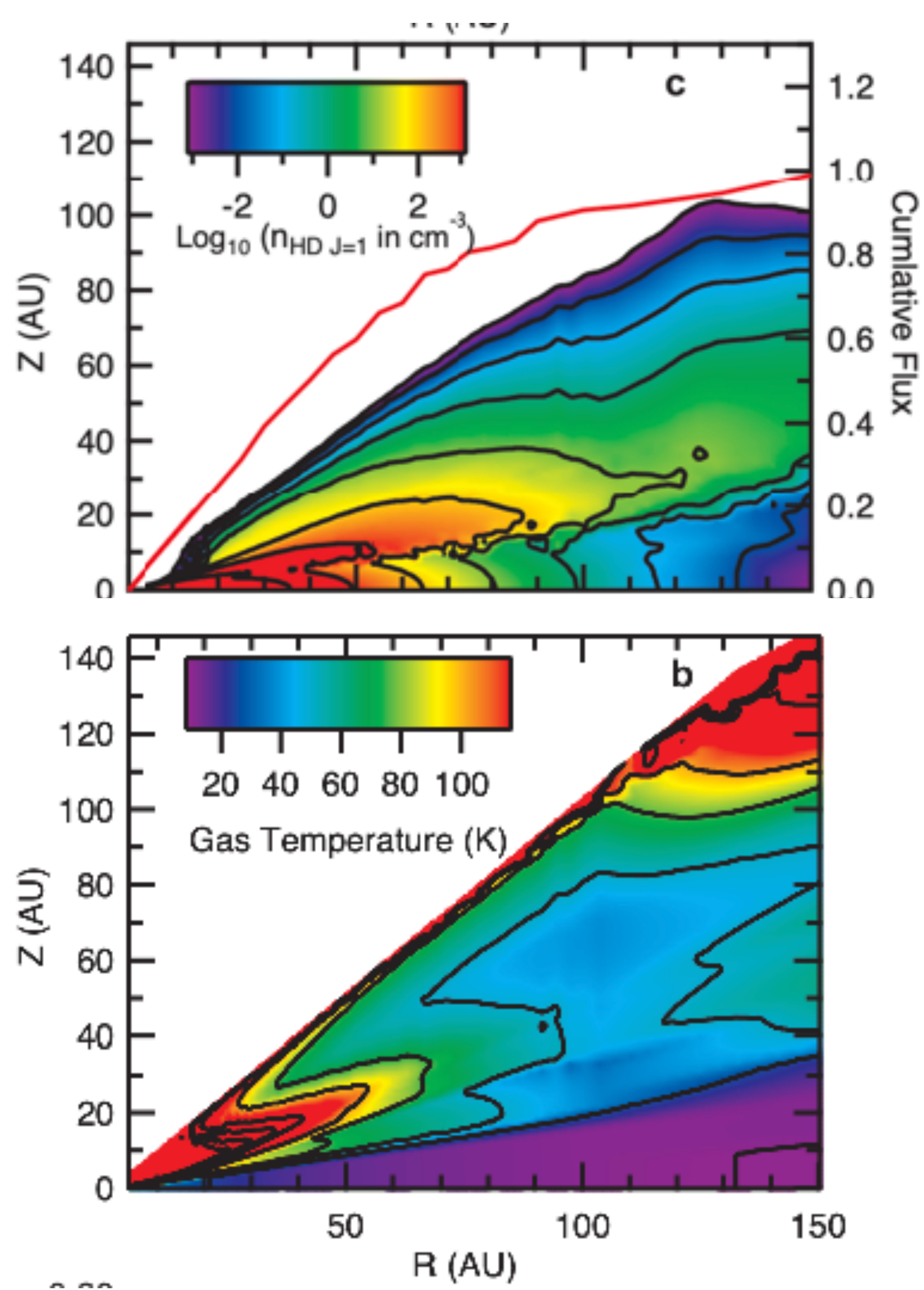
Manara et al. 2016

Using HD

$HD/H_2 = 3.10^{-5}$

FIR HD 1-0 line (Herschel-PACS) at 112 micron detected in TW Hya



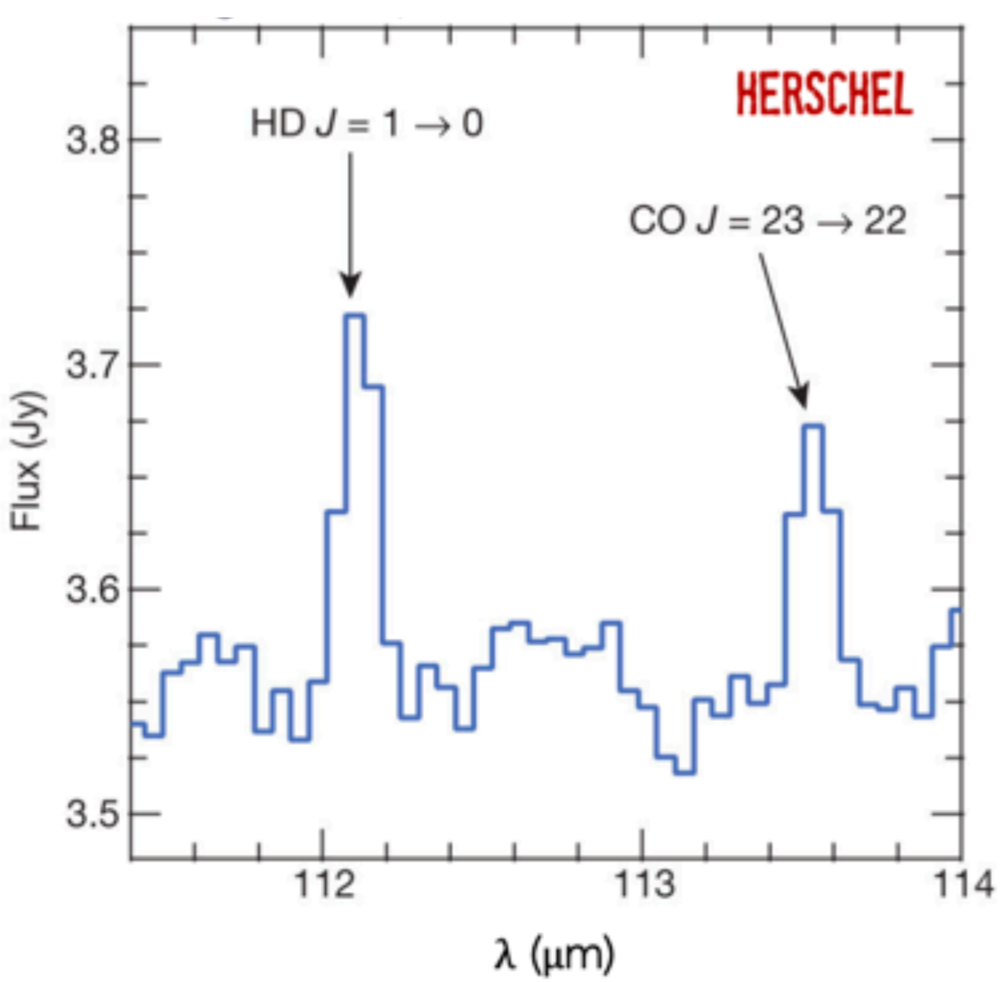


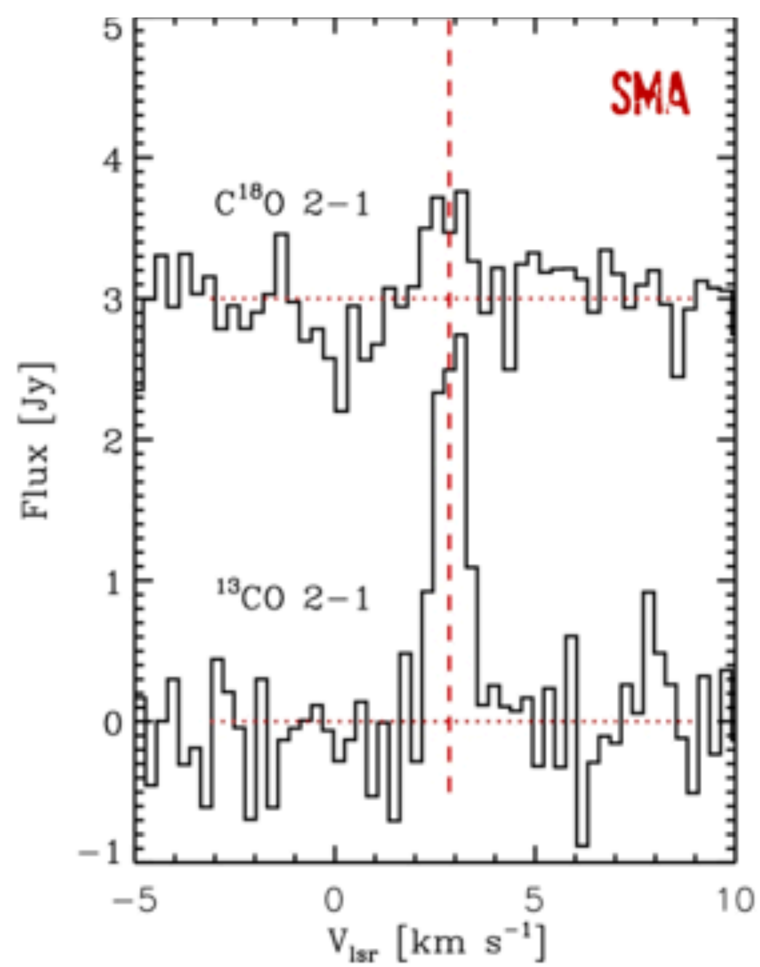
Using a thermo-chemical model: gas mass of >0.05 M_{sun} (MMSN) and gas-to-dust ratio of ??

Bergin et al. 2013

Comparison with CO

Gas mass derived from $C^{18}O$ emission is only 0.005 M_{sun}!!

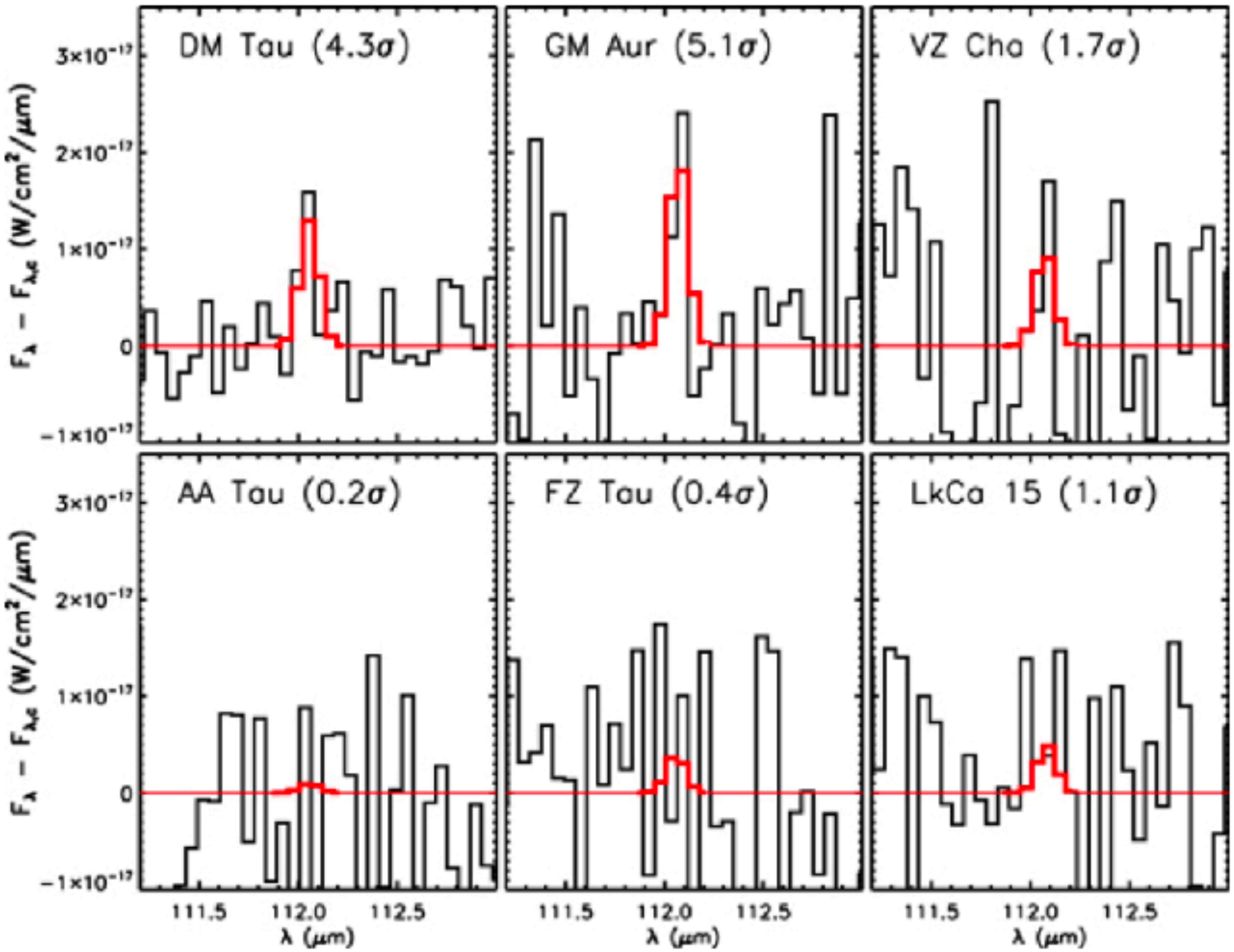




Implication: CO depleted by a factor 100?

Bergin et al. 2013
Favre et al. 2013

Other HD measurements



Only two more significant detections:

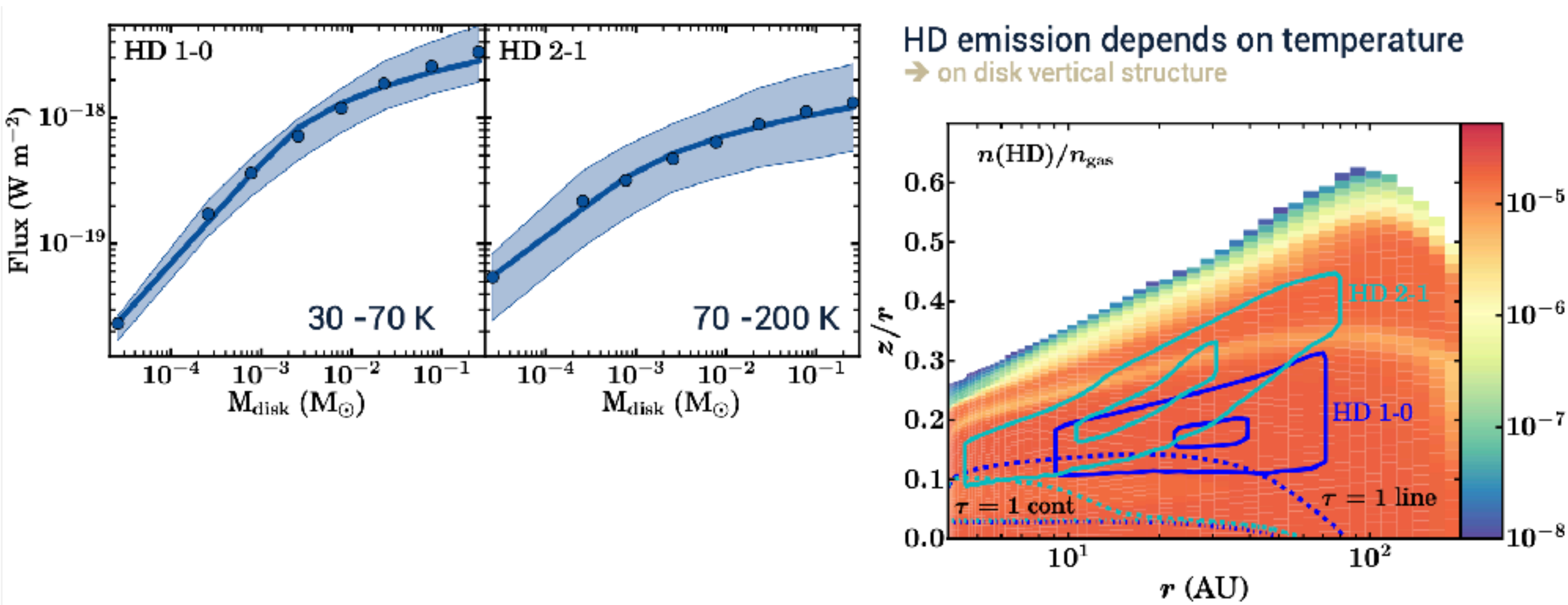
M_{gas} estimates of 0.01-0.05 and 0.02-0.20 M_{sun} or gas-to-dust ratios of 35-140 (~ISM!)

Large uncertainty: strong dependence on temperature (vertical) structure

McClure et al. 2016

HD measurements

HD emission depends strongly on disk temperature

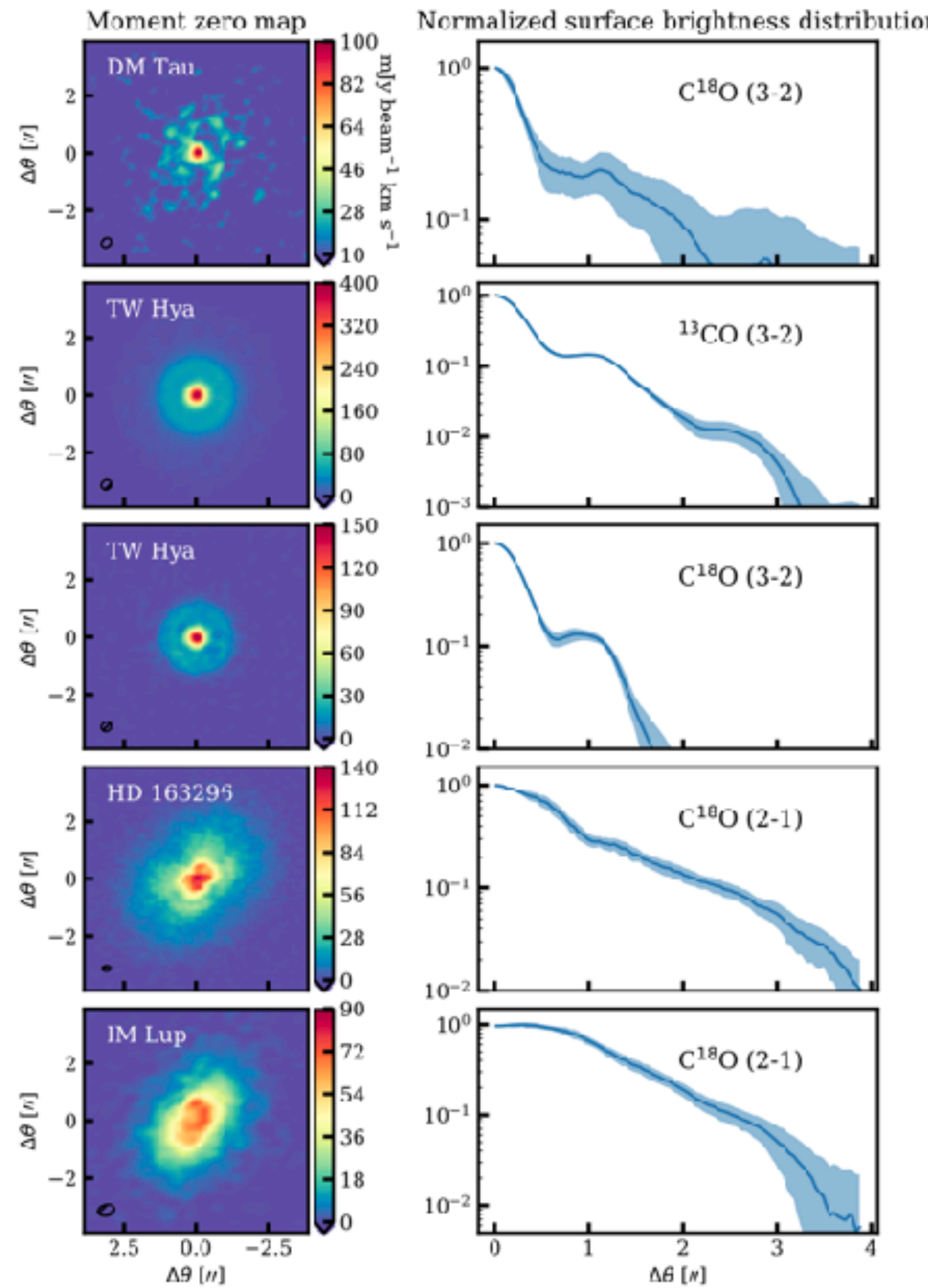


Why are there no other HD observations since then?

Trapman et al. 2017

CO depletion?

Starting from the assumption of M_{gas} =100x M_{dust}, it is possible to derive the CO depletion w.r.t. the ISM $CO/H_2 \sim 10^{-4}$ from $C^{18}O$ observations

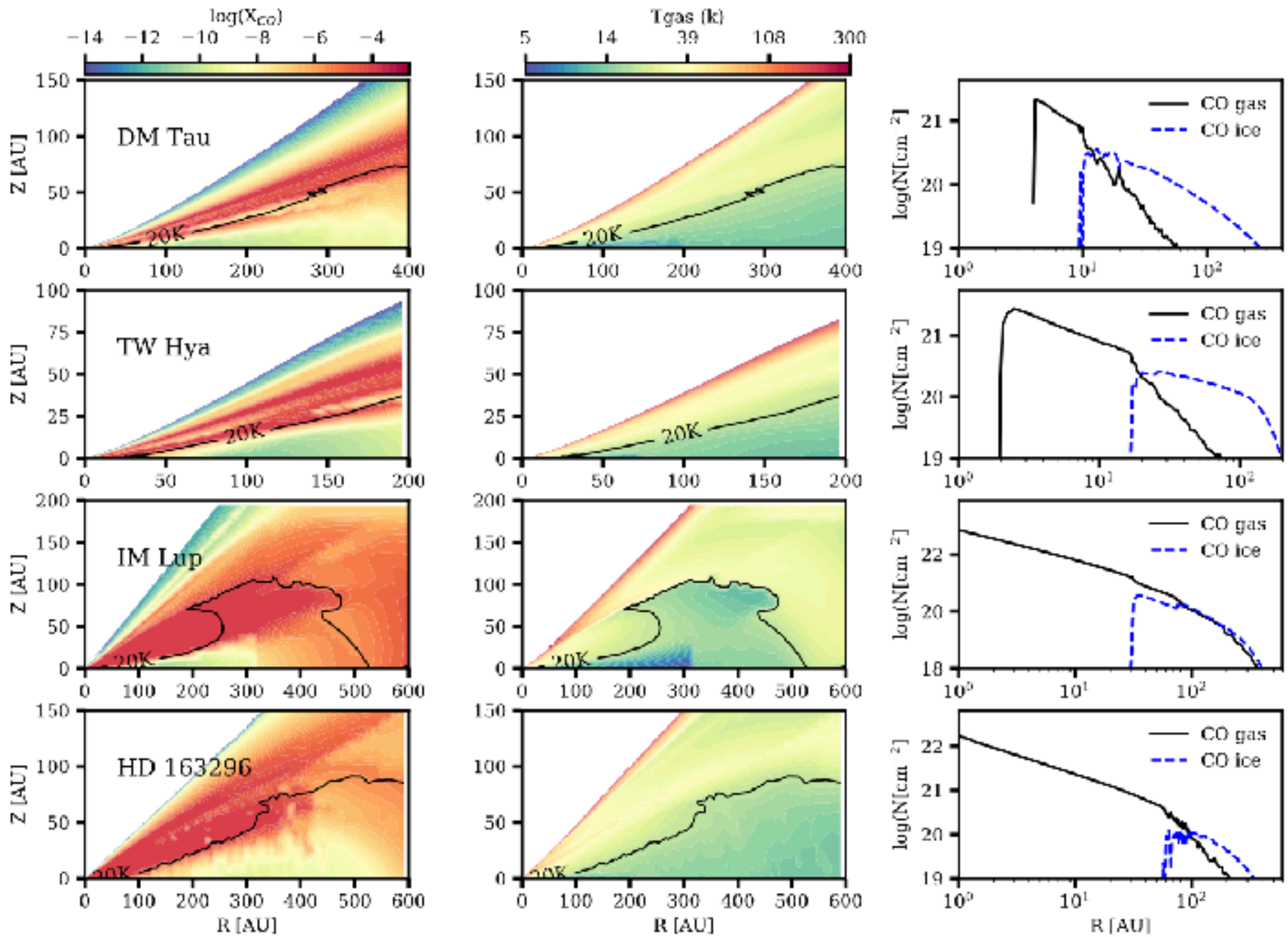


1. Derive the intensity profiles of the integrated (^{13}CO and) $C^{18}O$ line

Zhang et al. 2020a

CO depletion?

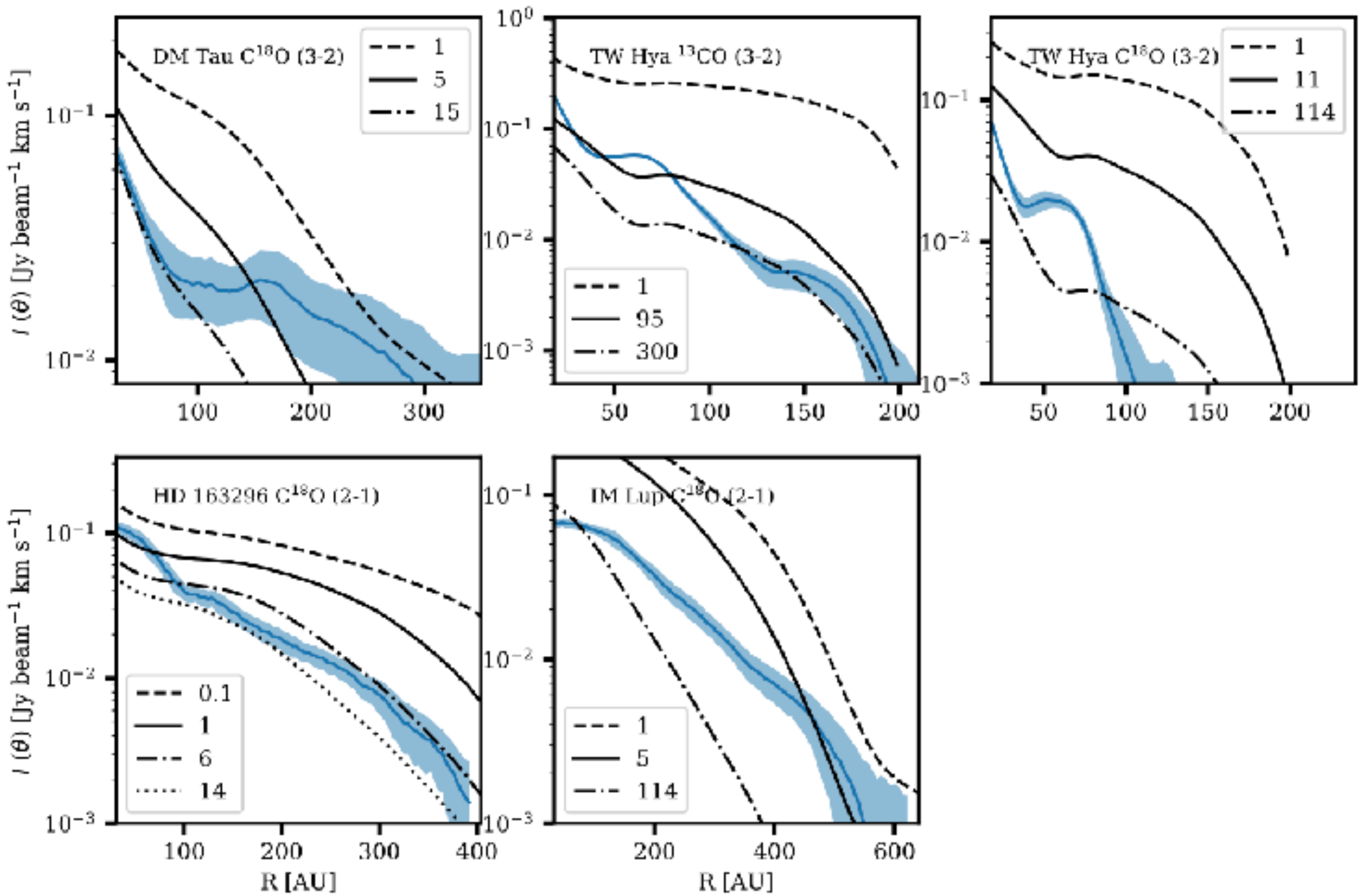
2. Run a thermal-chemical model using a gas mass that is 100 times the dust mass and compute the CO abundances and resulting ^{13}CO and $C^{18}O$ emission, for a number of depletion factors in CO w.r.t. the ISM ratio of 10^{-4}



Zhang et al. 2020a

CO depletion?

3. Compare the resulting integrated ^{13}CO and $C^{18}O$ radial profiles with the data for different depletions



Zhang et al. 2020a

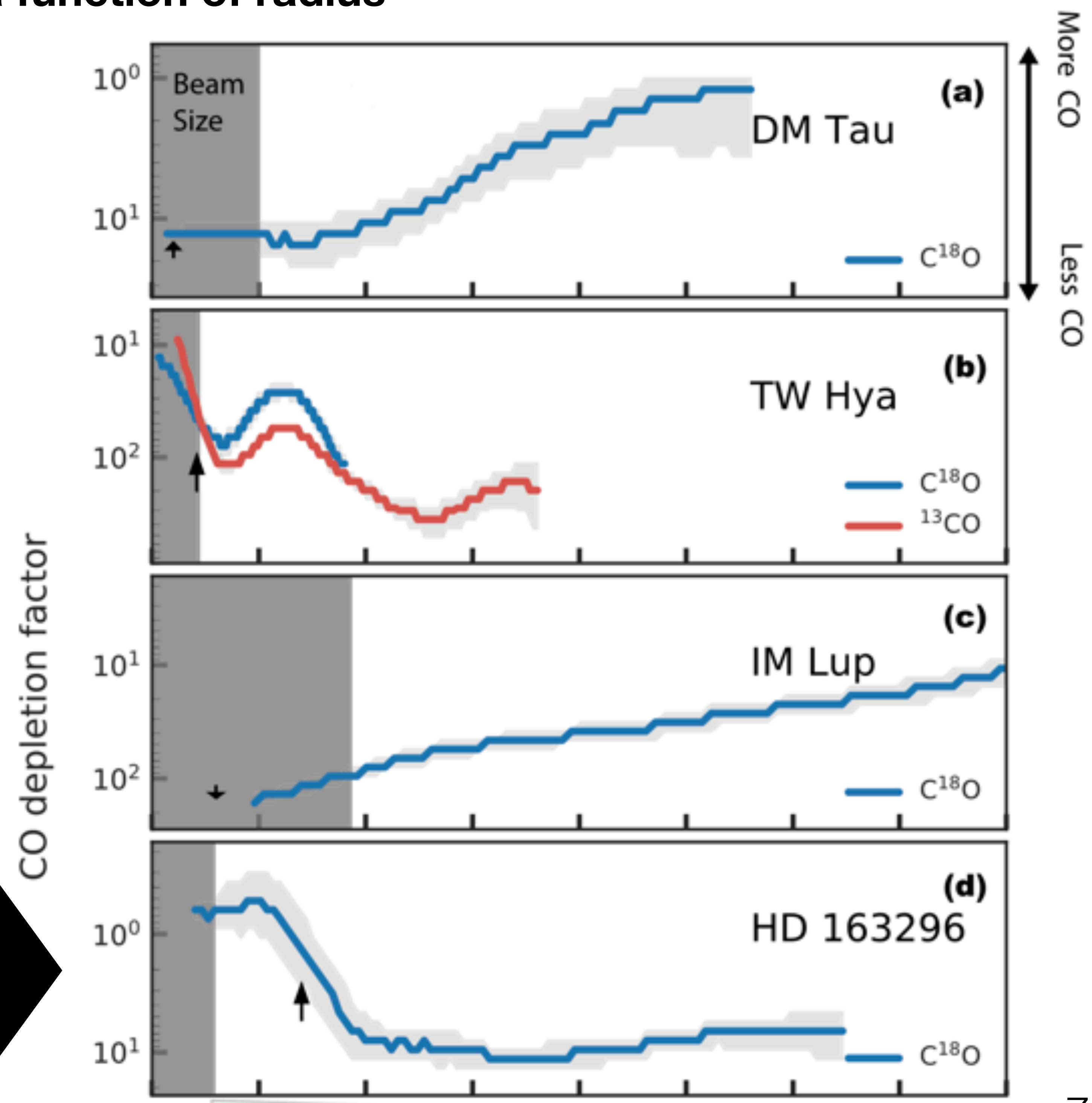
CO depletion?

4. Compute the depletion as a function of radius

Depletion factor is a factor 10-100 for all four disks!

Something is happening around the CO snowline in HD163296…

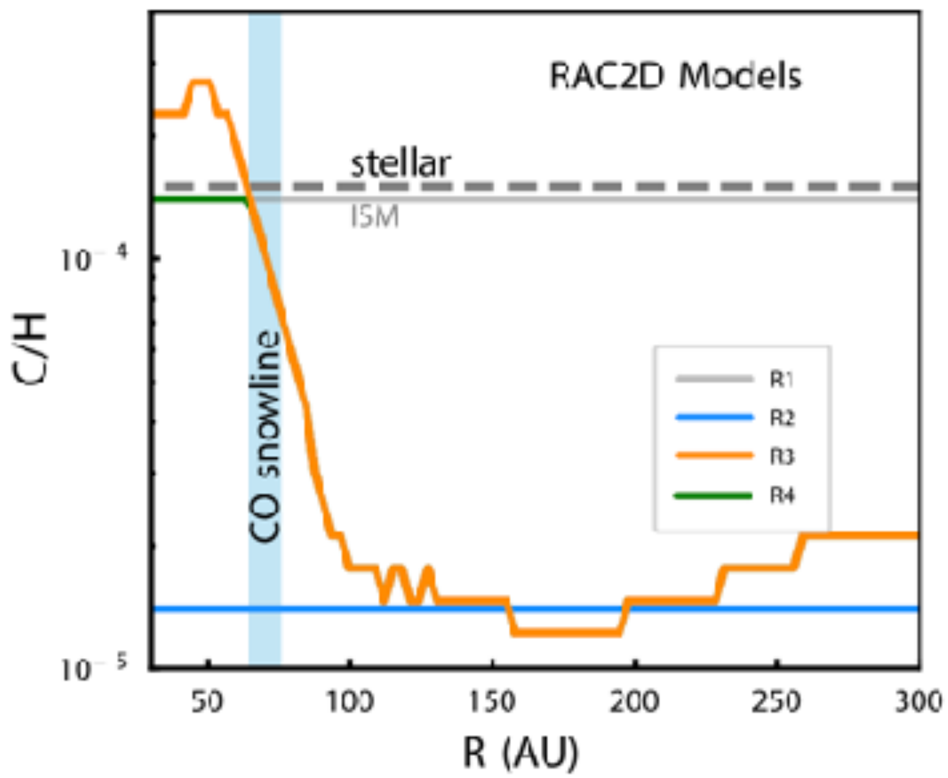
What is the CO snowline?



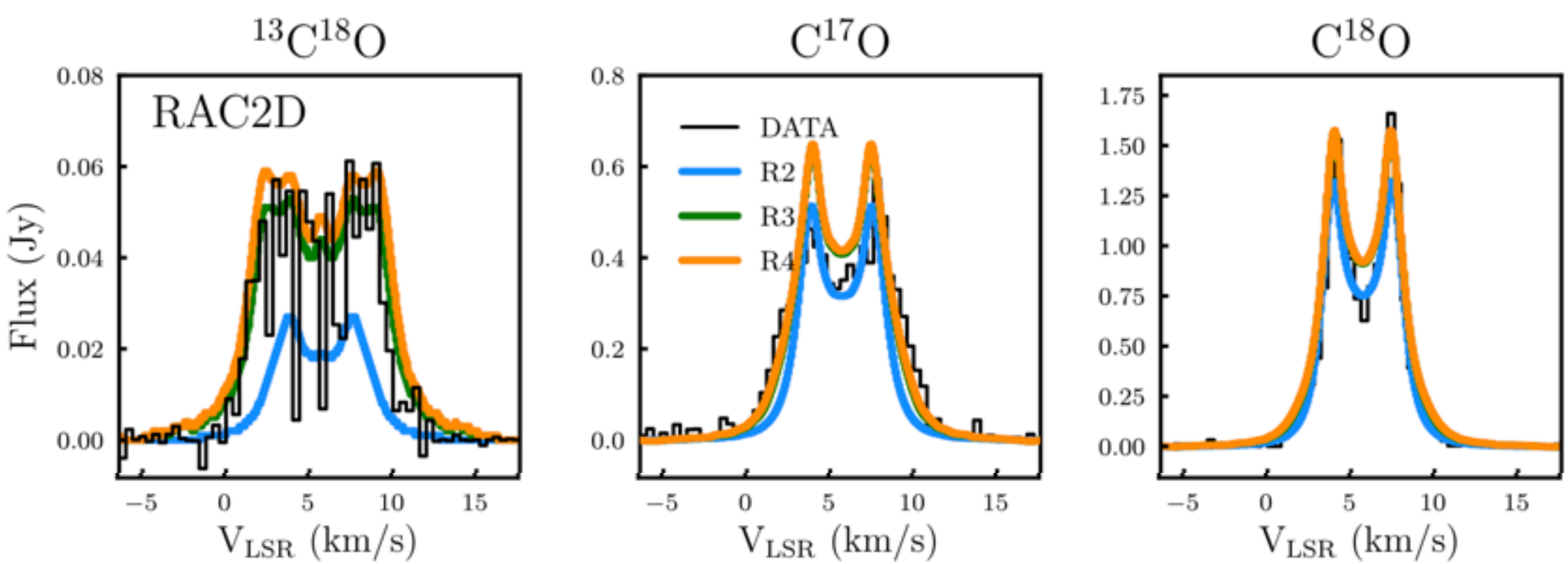
Zhang et al. 2020a

CO depletion?

Separate study varying the C/H across the snowline in HD163296 and comparison with even more optically thin CO isotopologues

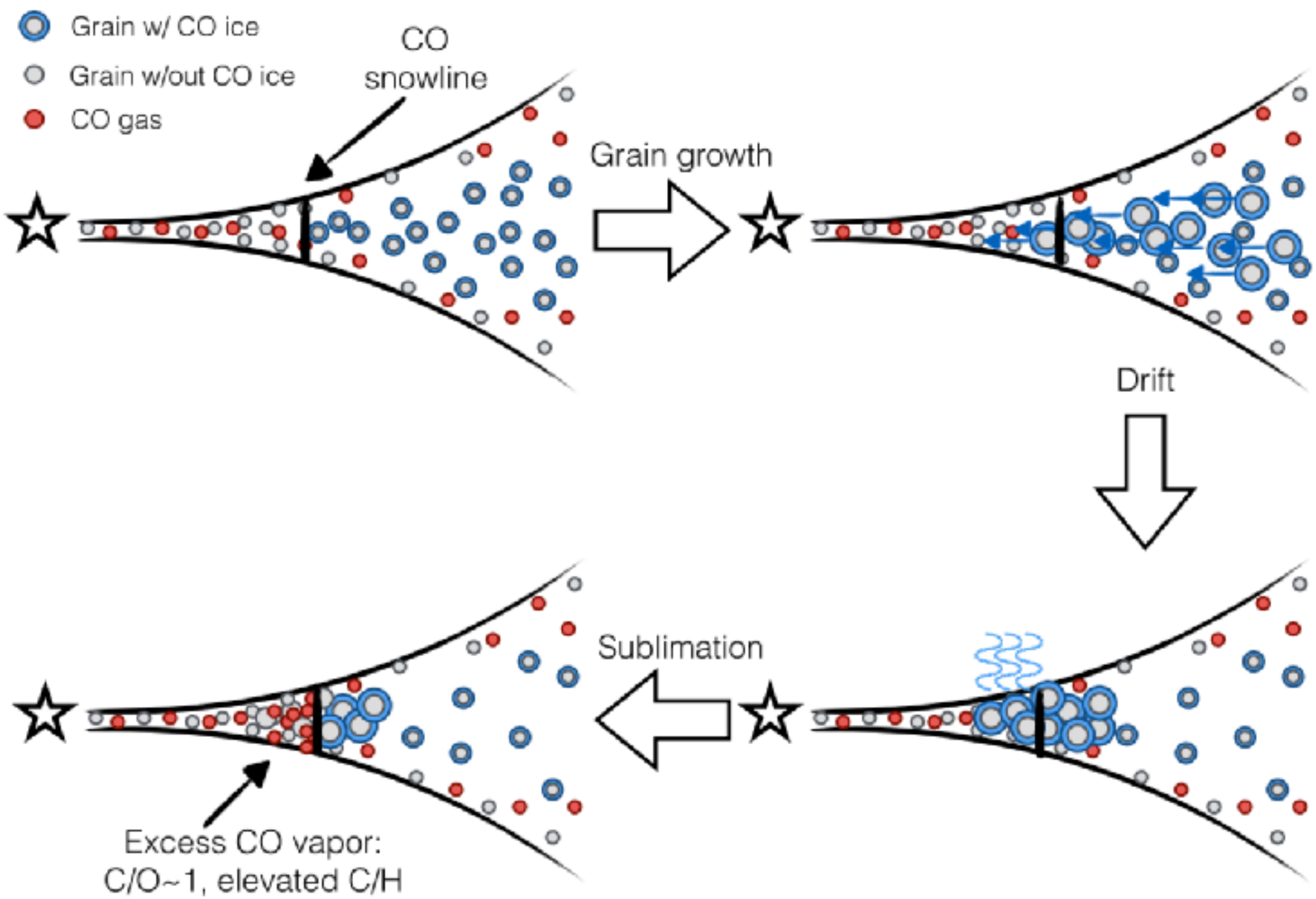


What do you see?
Can you think why?



Zhang et al. 2020b

CO depletion

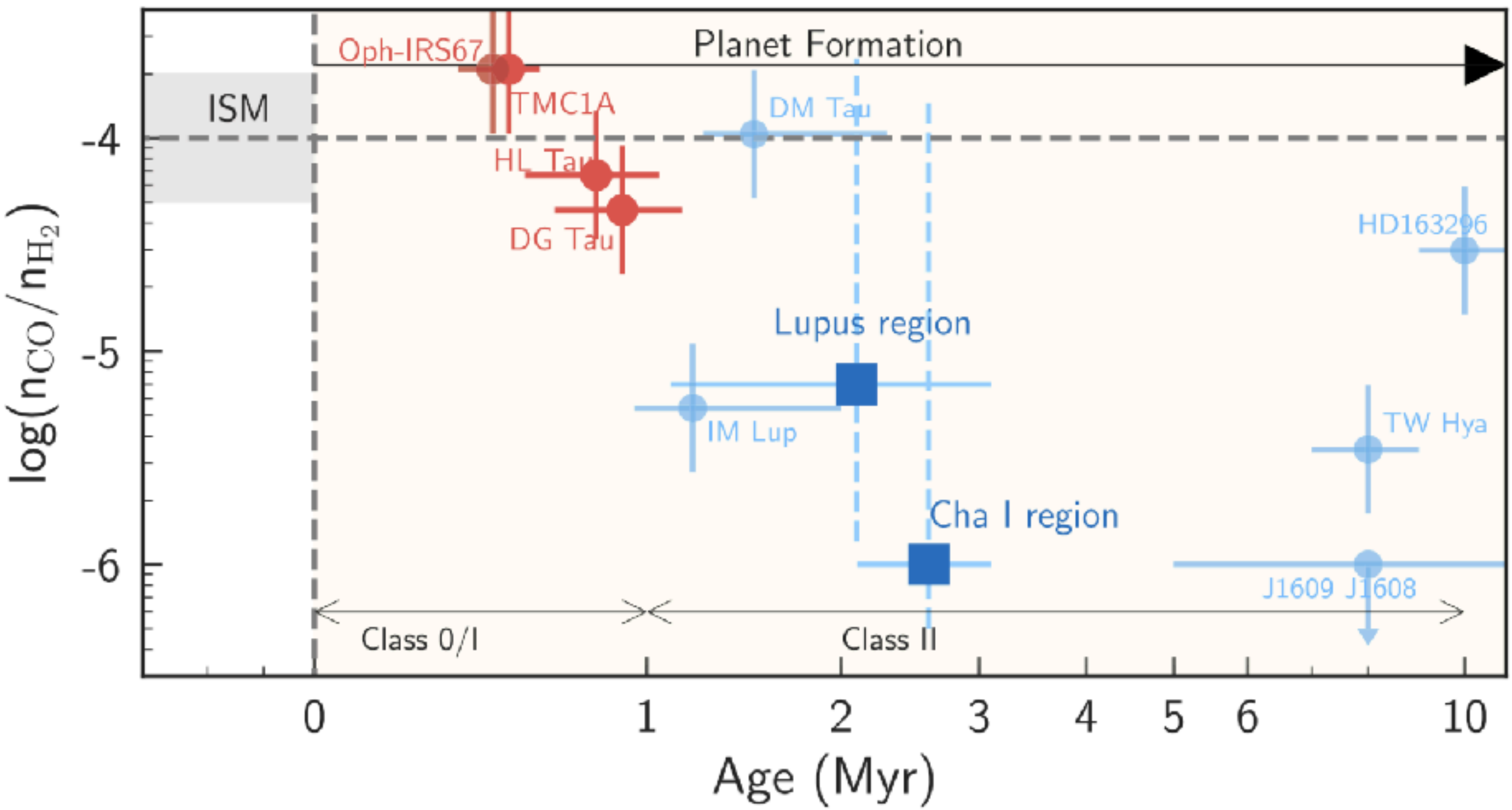


Dust pebble drift can cause CO depletion as the CO-icy pebbles drift inwards, depleting the outer disk of molecular CO

Oberg et al. 2016
Booth & Ilee 2019
Krijt et al. 2018, 2020

CO depletion

Similar study now as function of age

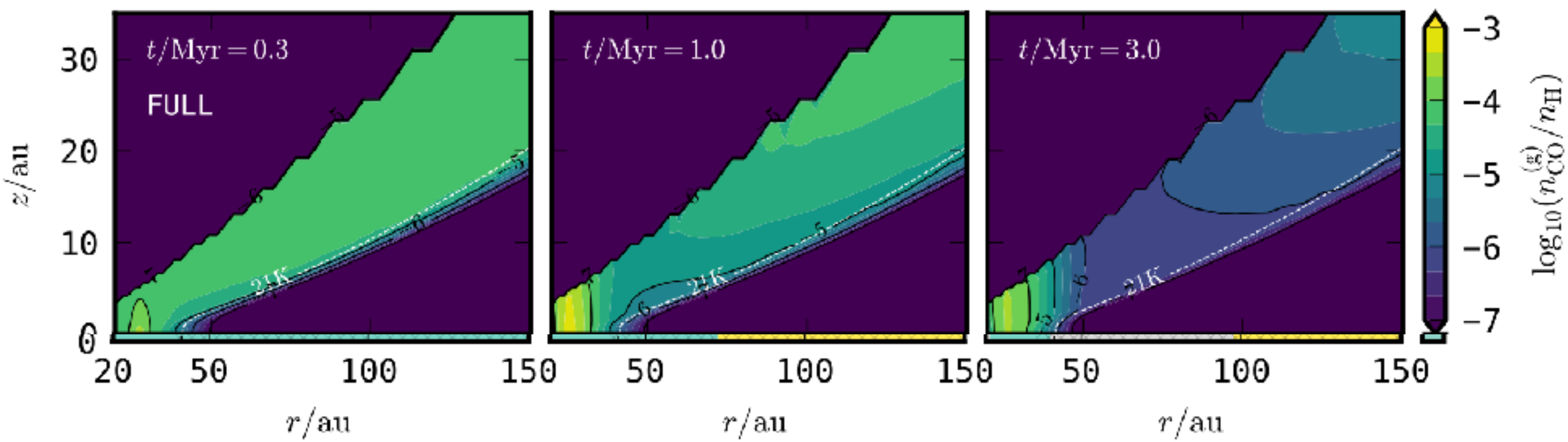


CO depletion is an evolutionary dust transport effect: ~ 1 Myr

Zhang et al. 2020
Bergner et al. 2020
Miotello et al. 2022 (PPVII)

CO depletion

Full modeling: studying effects dust evolution, chemical network and turbulent diffusion to test how to achieve strong CO depletion

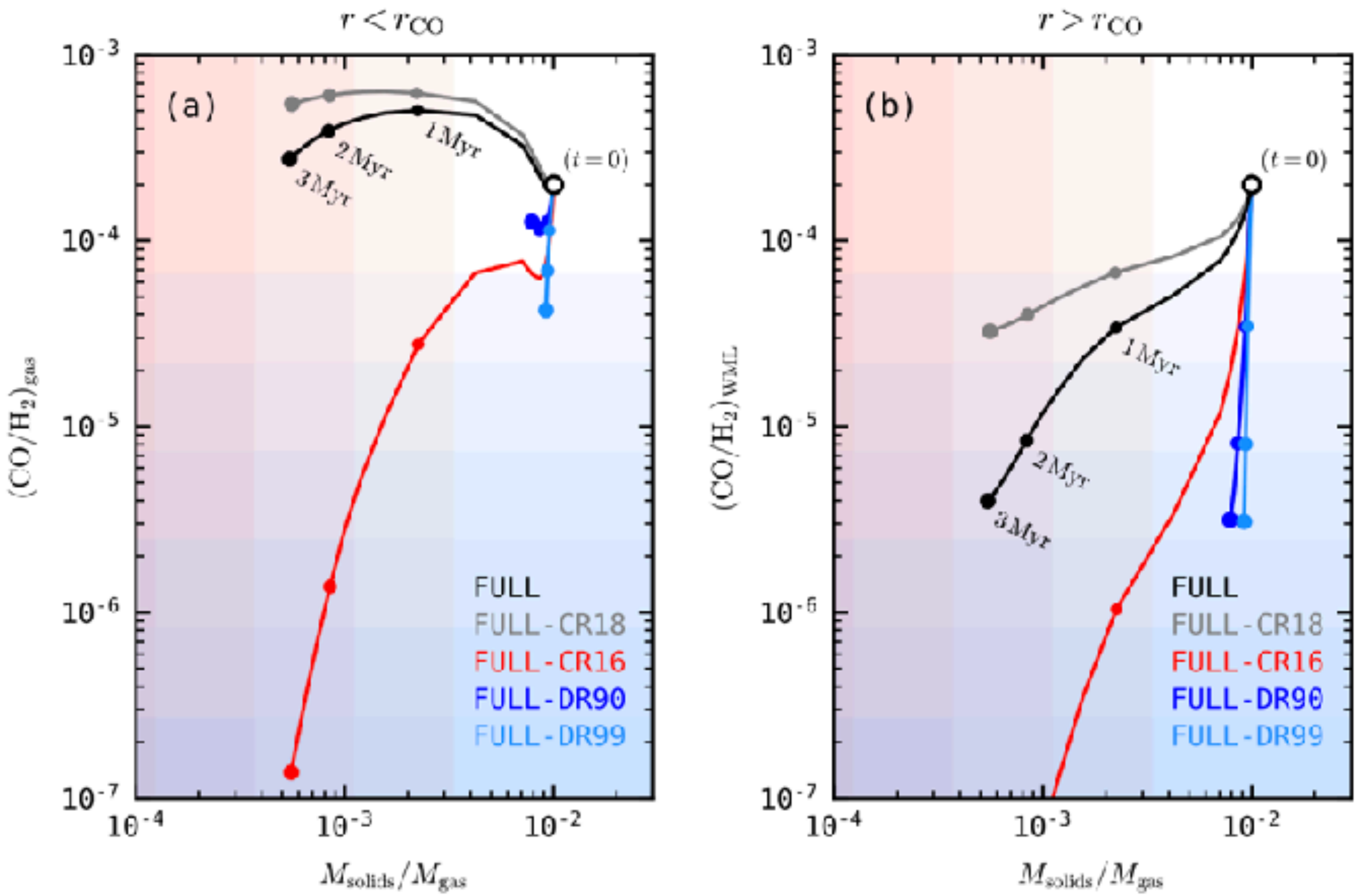


Modeling shows that CO is depleted by 2 orders of magnitude in the outer disk within 3 Myr, when all effects are combined

Krijt et al. 2018, 2020

CO depletion

CO depletion strongly depends on time, but also on cosmic rays. When drift is reduced (DR) only moderate depletion



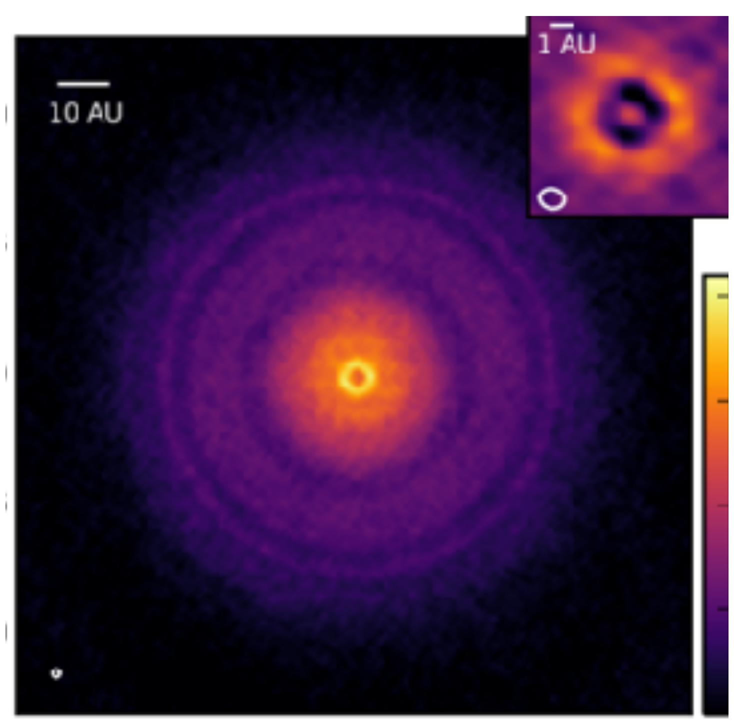
Icy pebble drift model can explain the basic effects, but still requires fine-tuning. Suggests that CO isotopologues can be used to derive gas disk masses!

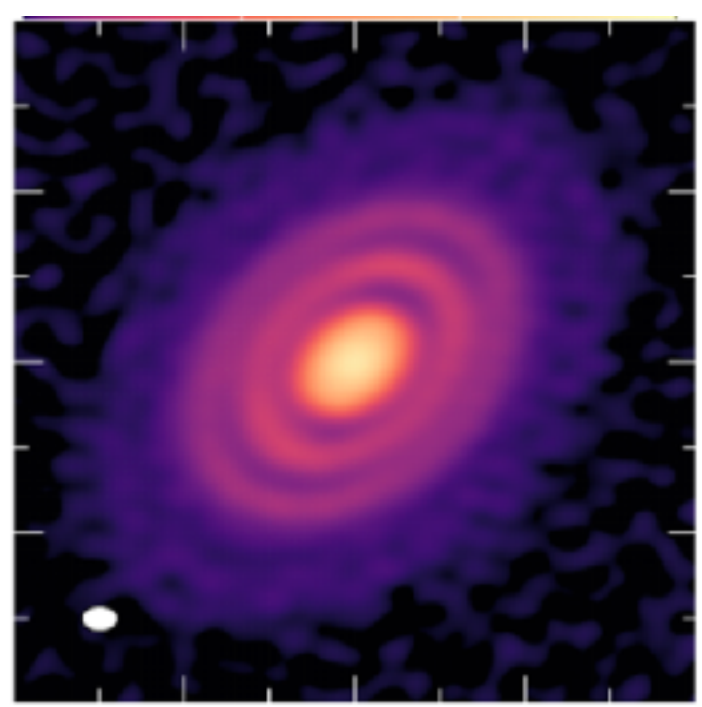
Krijt et al. 2020

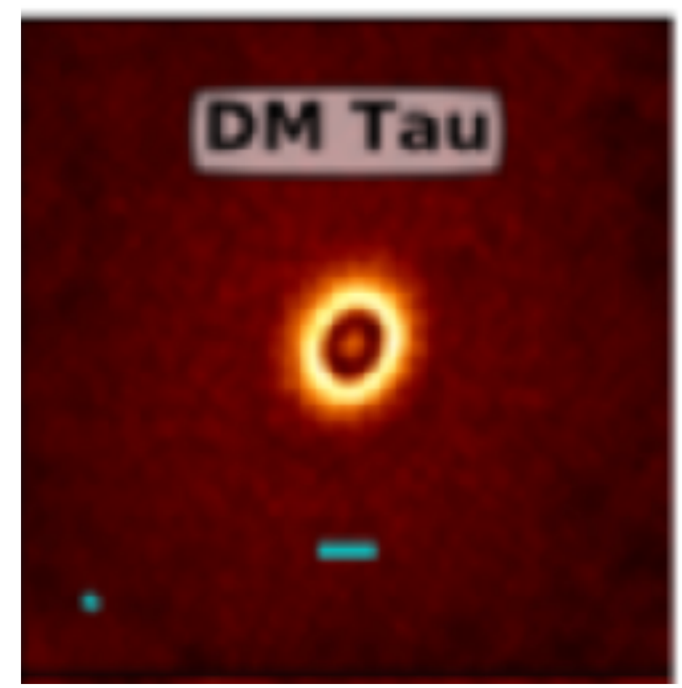
Issue CO depletion through pebble drift

Current data suggest the icy pebble drift scenario to explain the high CO depletion, assuming that the gas-to-dust ratio of 100 is correct (also for HD).

Problem: CO depletion models assume drift all the way in, inside the CO snowline, but most of the disks where CO depletion was measured have dust traps: there is no drift all the way in, CO-icy pebbles remain trapped: what happens to the CO abundance inside snowline?

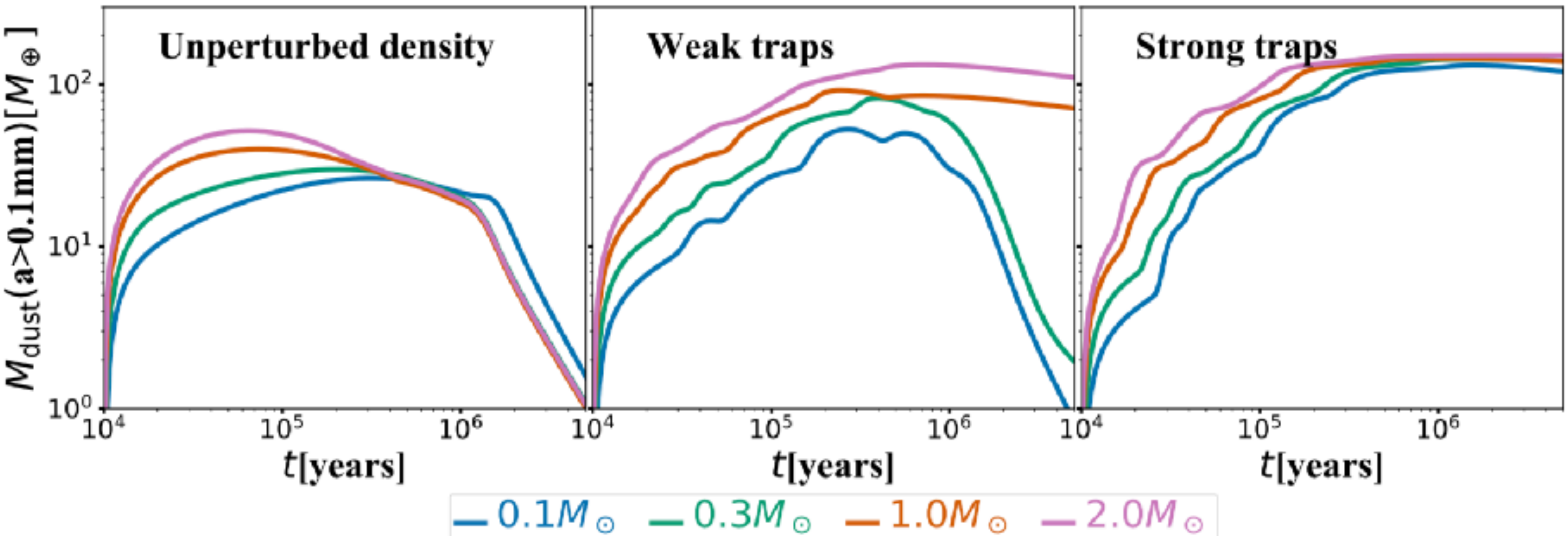






Second issue: what happens with dust mass in drift disks without traps?

Issue CO depletion through pebble drift



The dust mass drops quickly in absence of dust traps: the observed dust mass is NOT representative for the gas mass and ISM ratio of 100 cannot be used

Problem of bias towards brighter disks in ALMA studies: all strong dust traps!

Pinilla et al. 2020

Another method: self-gravity

Small perturbations in the velocity field due to disk self-gravity would directly probe the disk mass.

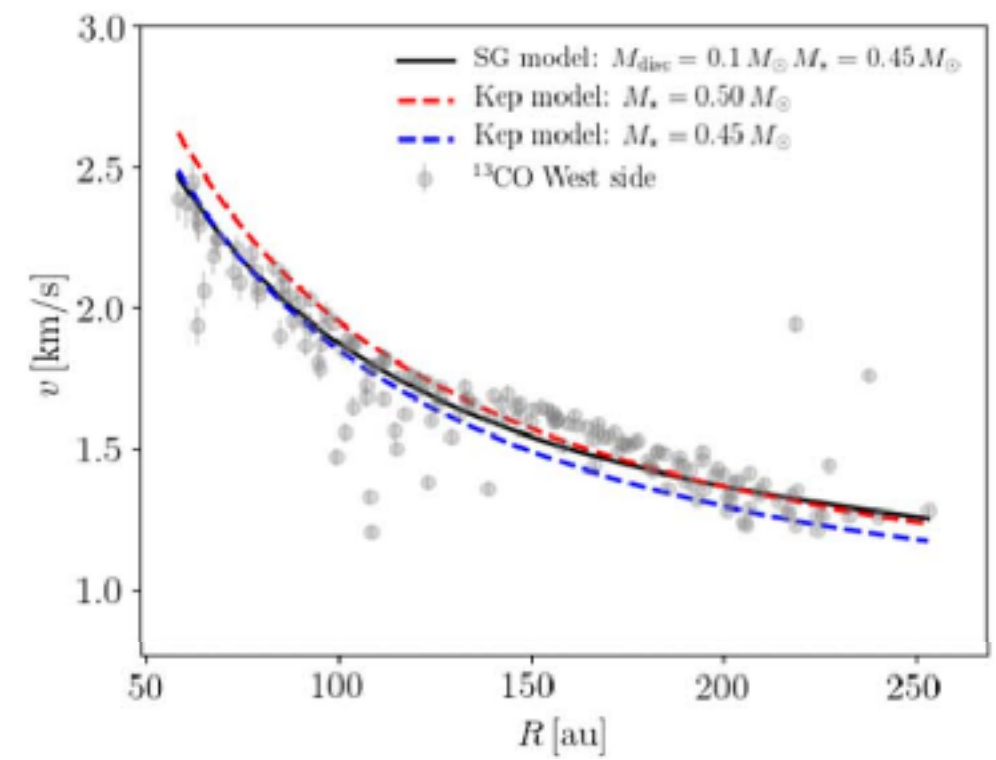
Self gravity
of the disk leads to super Keplerian velocity → marginal contribution

$$\frac{v^2}{r} = \frac{GM_* r}{(r^2+z^2)^{3/2}} + \frac{1}{\rho_{\rm gas}}\frac{\partial P_{\rm gas}}{\partial r} + \frac{\partial \phi_{\rm gas}}{\partial r}$$

Keplerian velocity
due to stellar gravity

Pressure gradient
leads ro sub-Keplerian velocities

One application: tentative evidence for SG disk, gas-to-dust ratio of 80



Rosenfeld, et al., 2013
Pinte et al., 2018a; 2018b
Teague et al., 2018a,b
Veronesi et al. 2021

Summary

- Determine the disk gas mass has been a long-standing issue in protoplanetary disk studies
- The gas-to-dust ratio of the ISM of 100 may be true,
at least for some disks
- HD measurements may be most accurate, but temperature-dependent and not observable any more
- CO isotopologues underestimate gas masses with the assumption of $CO/H_2 = 10^{-4}$
- CO depletion can be explained (and somewhat quantified) using icy pebble drift models

Questions?

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