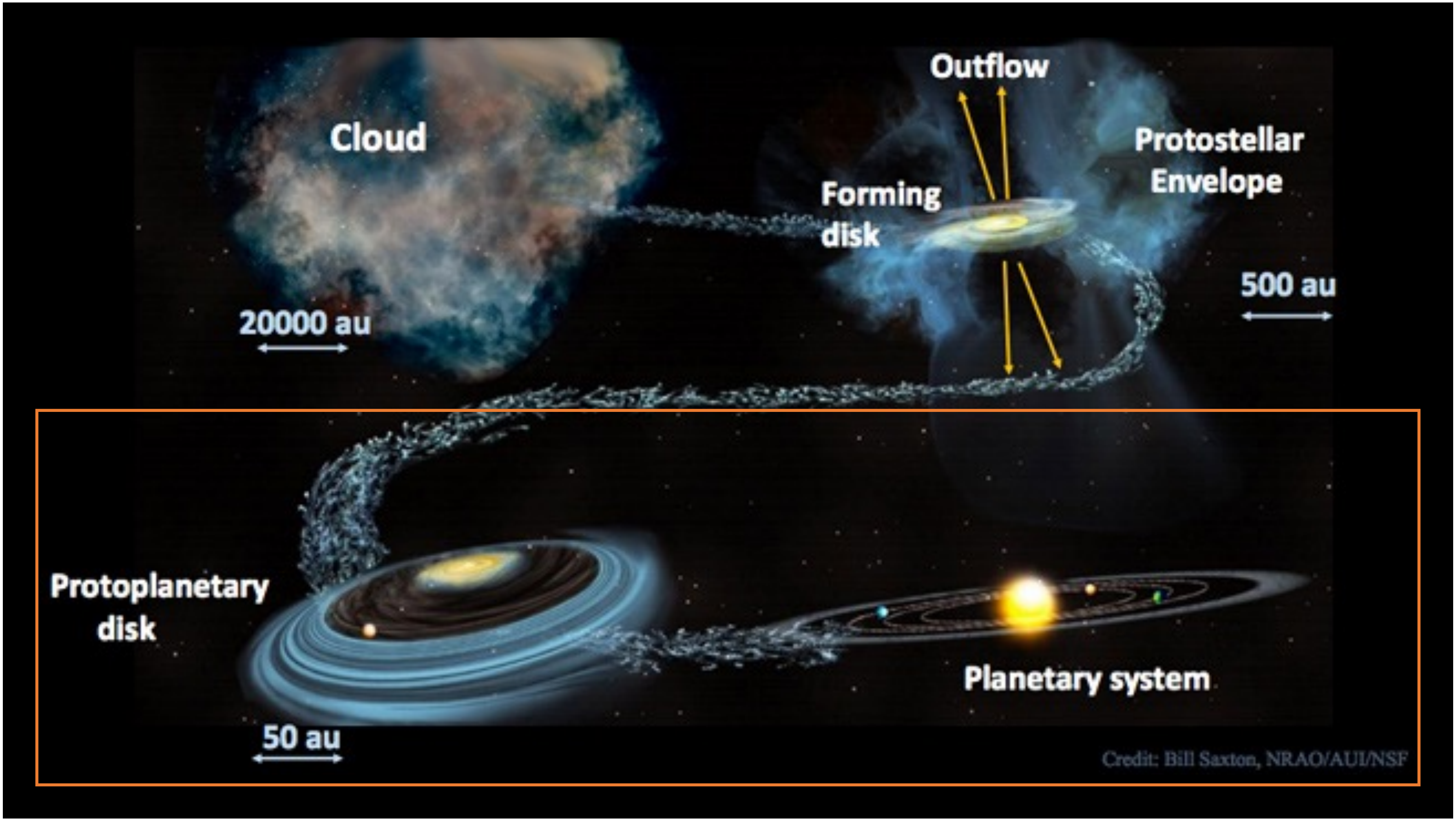
Regular lectures Tools and methods Advanced topics & project intro

	Mon	Tue	Wed	Thu	Fri
Time	July 22	July 23	July 24	July 25	July 26
9:20-10:40		Disk Observations I	Disk dynamics and evolution	Planet Formation III (Formation of planets + pop synthesis)	Disk Observations II
11:00-12:20	Protoplanetary disk overview	Radiative transfer process	Planet Formation II (Accretion of planetesimal/pebble)	Planet Formation IV (Disk-Planet Interactions)	Special topics
12:20-14:00	lunch	lunch	lunch	lunch	lunch
14:00-15:20	Hydrodynamics	Grid-based method for gas and dust dynamics	N-body method	GPU computing	SPH/meshless method
15:40-17:00 (regular and advanced topics)	Planet formation I (dust coagulation & dynamics)	Magneto-hydrodynamics	Disk microphysics	Project introduction 1	Project introduction 2
		open discussion	open discussion	open discussion	open discussion

Lecture: Protoplanetary Disk Basics

- References
  - [Astrophysics of Planet Formation] by Philip J. Armitage, Chapter 2
  - Miotello+23 PPVII reviews, https://ui.adsabs.harvard.edu/abs/2023ASPC..534..501M/abstract
- A basic overview of protoplanetary disks
  - What is it
  - How does it look like
  - What is it made of
  - How is material distributed
- **There are no stupid questions.** If you find anything confusing, please ask questions.


Outflow
Cloud
Protostellar
Envelope
Forming
disk
500 au
20000 au
Protoplanetary
disk
Planetary system
50 au
Credit: Bill Saxton, NRAO/AUI/NSF

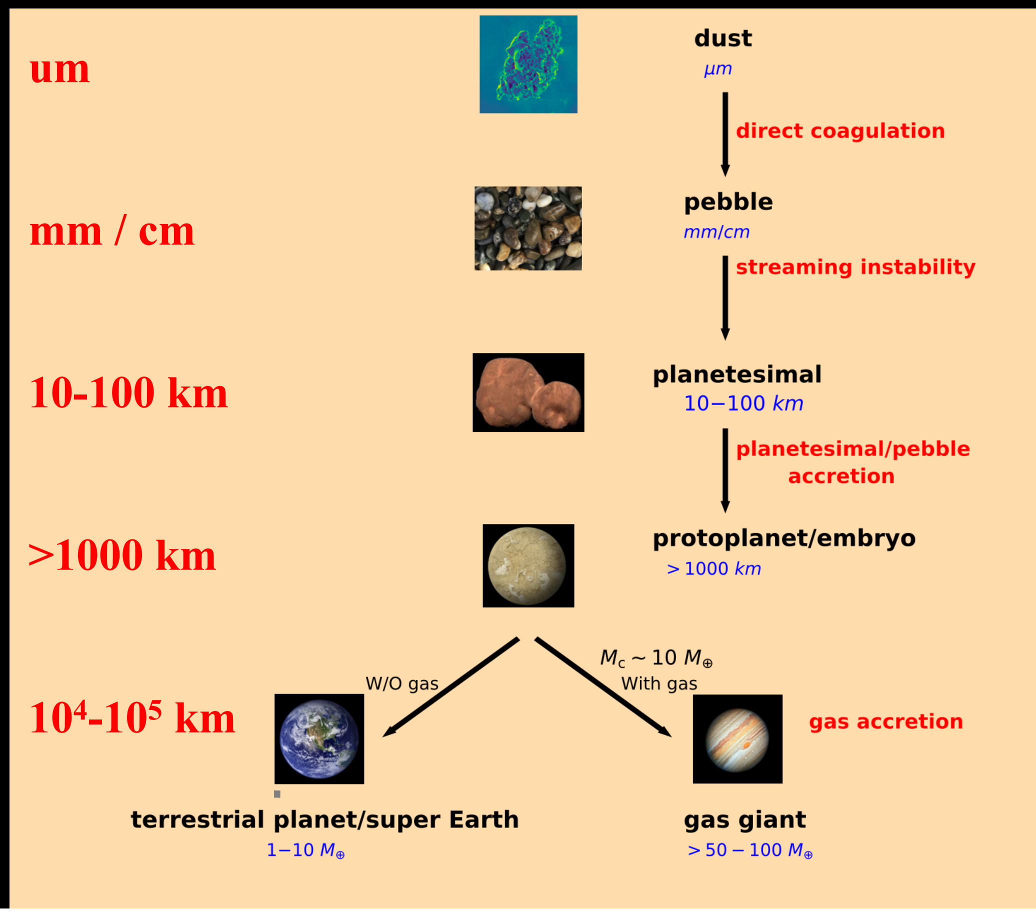
Planet Formation

Initial Conditions

Final Products

Two Main Avenues of Planet Formation

I: Core Accretion (Bottom-Up)

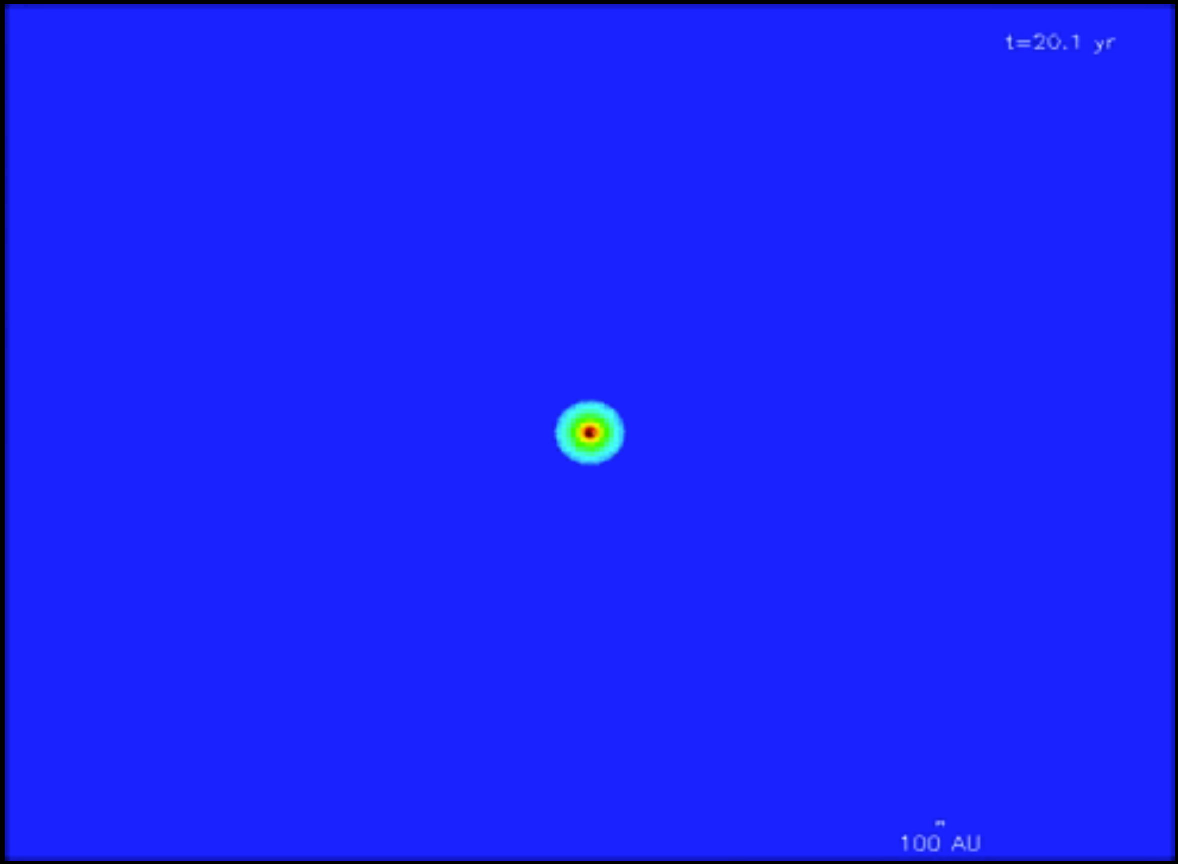


Liu & Ji 2020

Core Accretion

Two Main Avenues of Planet Formation

II: Gravitational Instability (Top-Down)



Stamatellos & Whitworth

Planet Formation

Initial Conditions

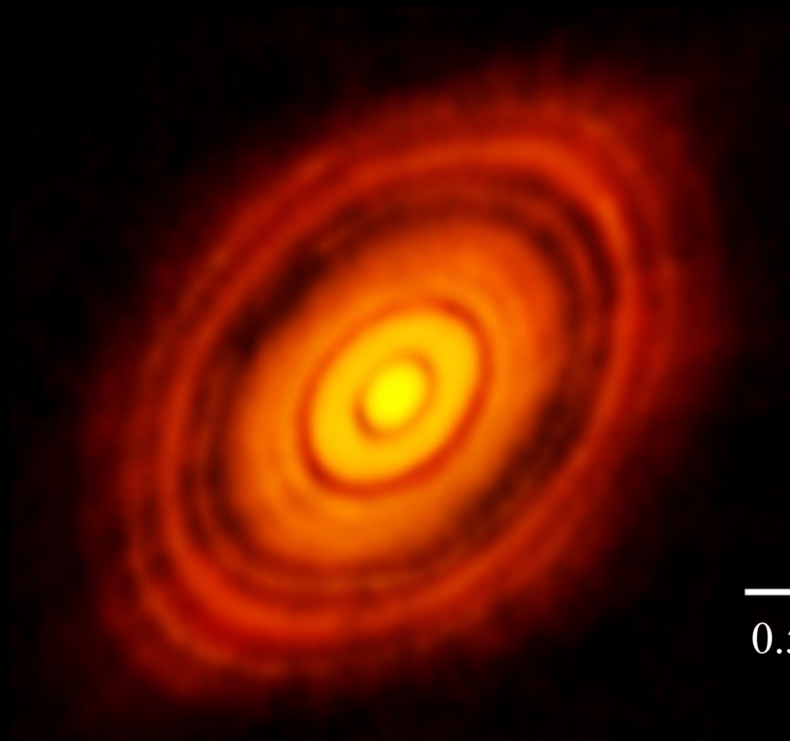
Final Products

Credit: Bill Saxton, NRAC

HL Tau

Dust Thermal Emission at 1 mm

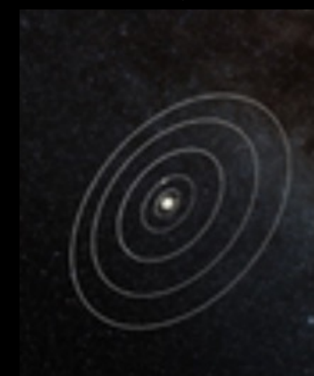
Atacama Large Millimeter / submillimeter Array (ALMA)



Min Max

Flux

Solar System

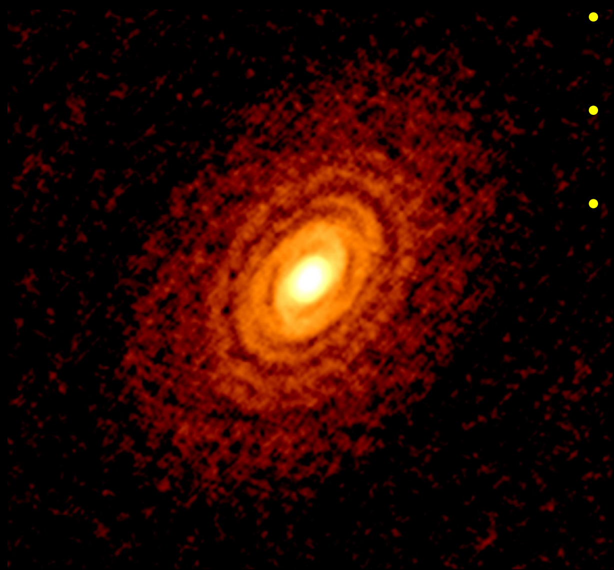


0.5" = 70 au

ALMA Partnership, Brogan et al. 2015

IM Lup

~1 mm

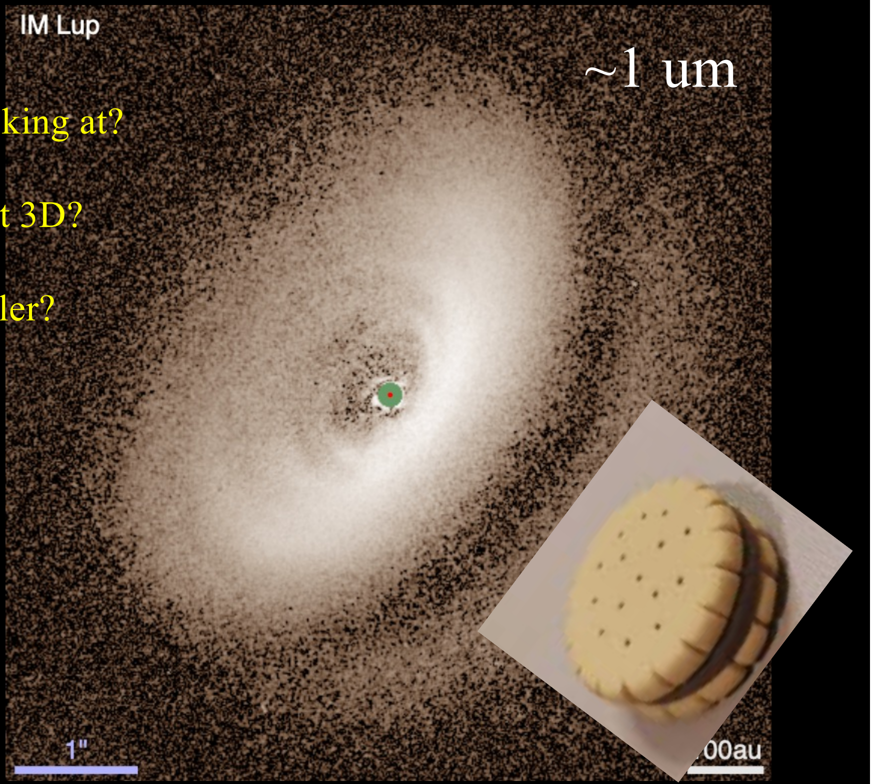


Millimeter Dust Emission / ALMA (Andrews+18)

- What are we looking at?
- Left 2D but right 3D?
- Left image smaller?

Inclination: 48 degree

~1 um



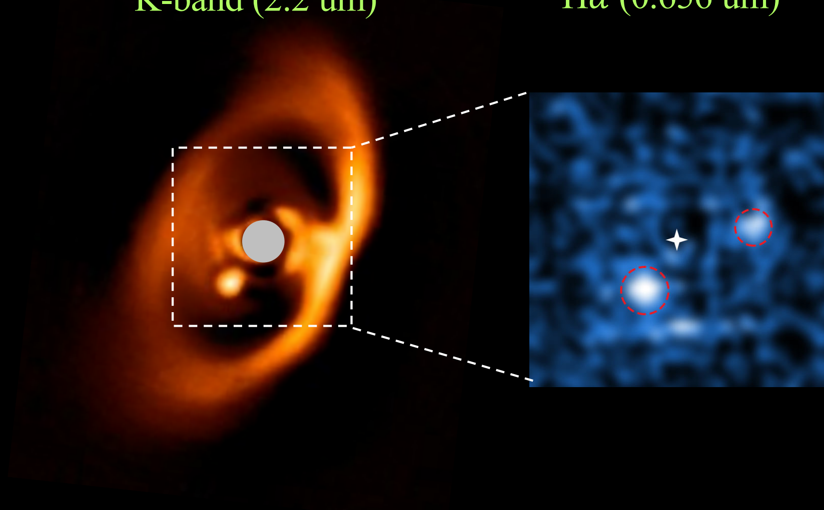
Near-Infrared Scattered light / SPHERE (Avenhaus+18)

Imaged Planets in Protoplanetary Disks

VLT/SPHERE
K-band (2.2 um)

VLT/MUSE
Hα (0.656 um)

ALMA
Band 7 (0.9 mm)

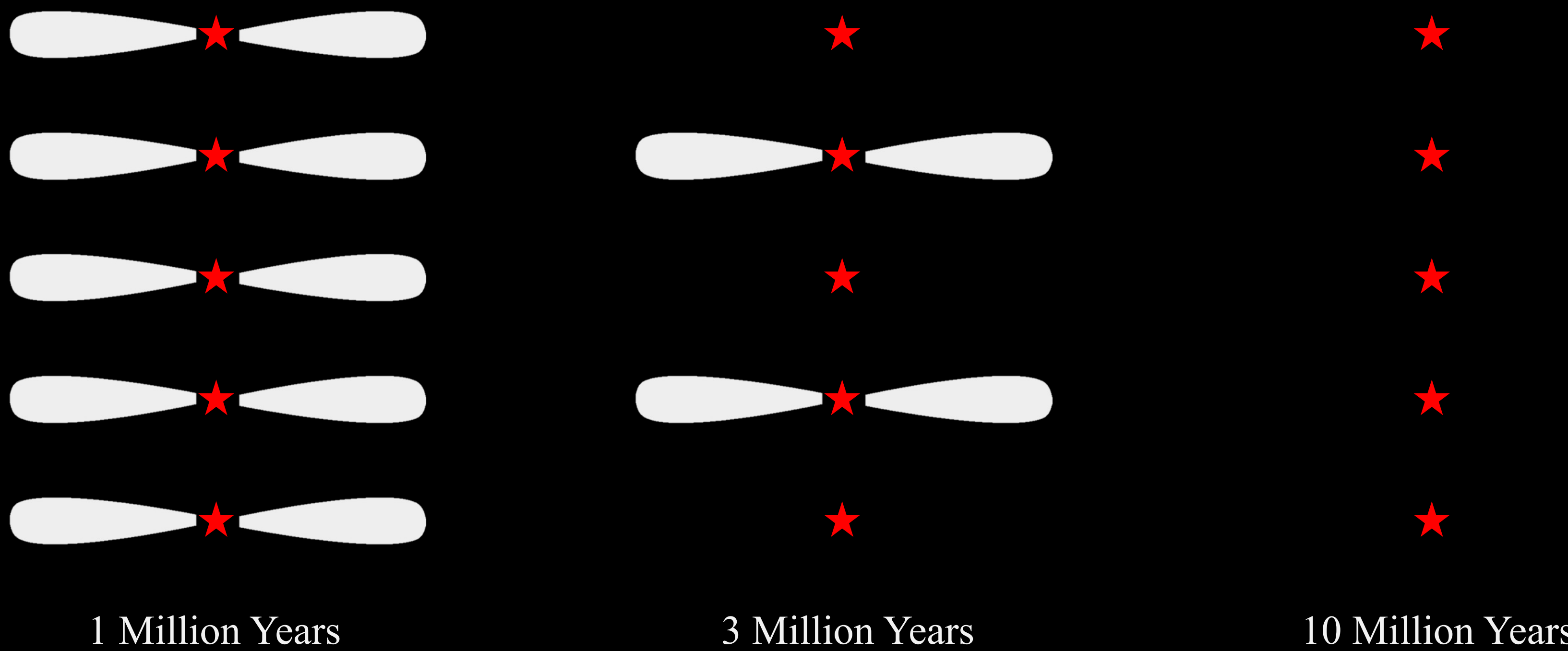


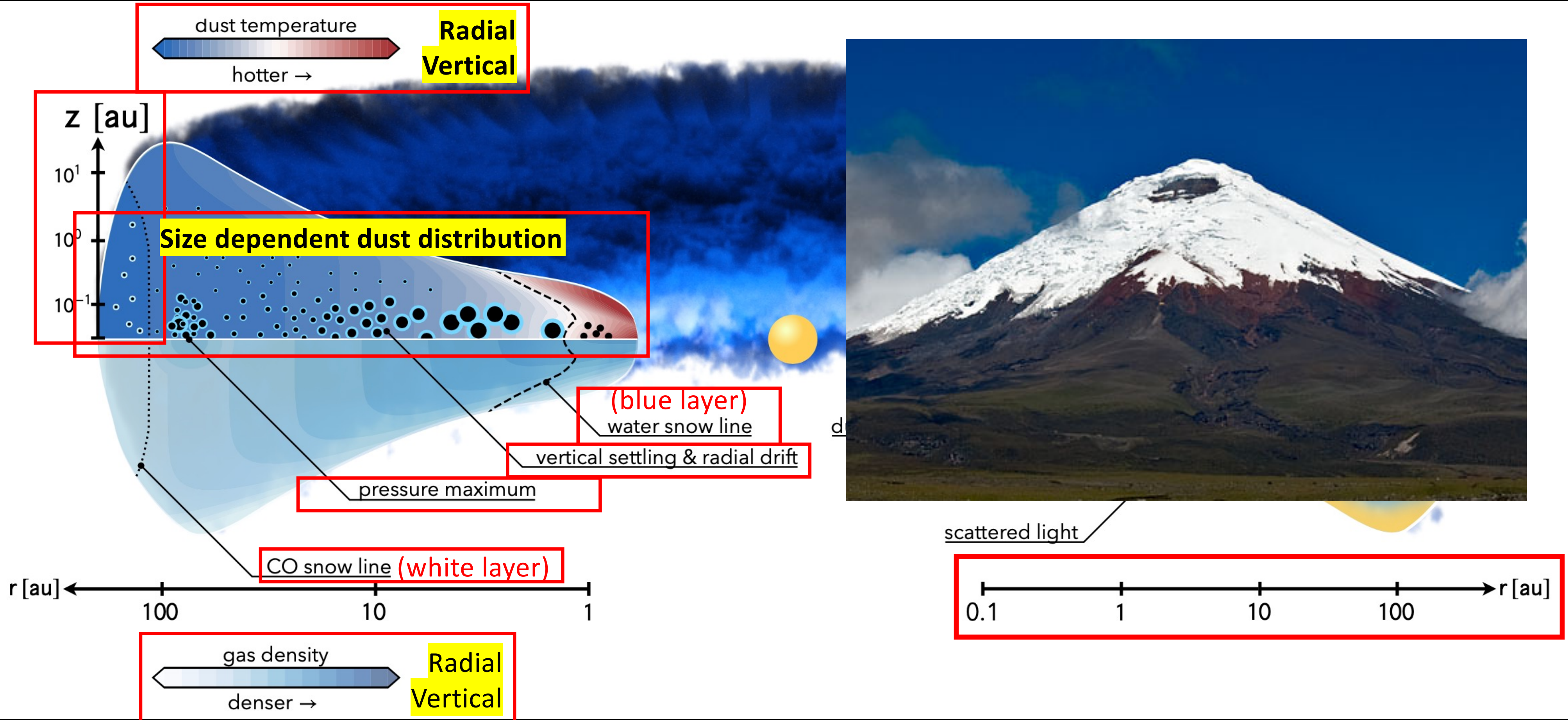
Keppler et al. 2018
Muller et al. 2018

Wagner et al. 2018
Haffert et al. 2019
Hashimoto et al. 2020

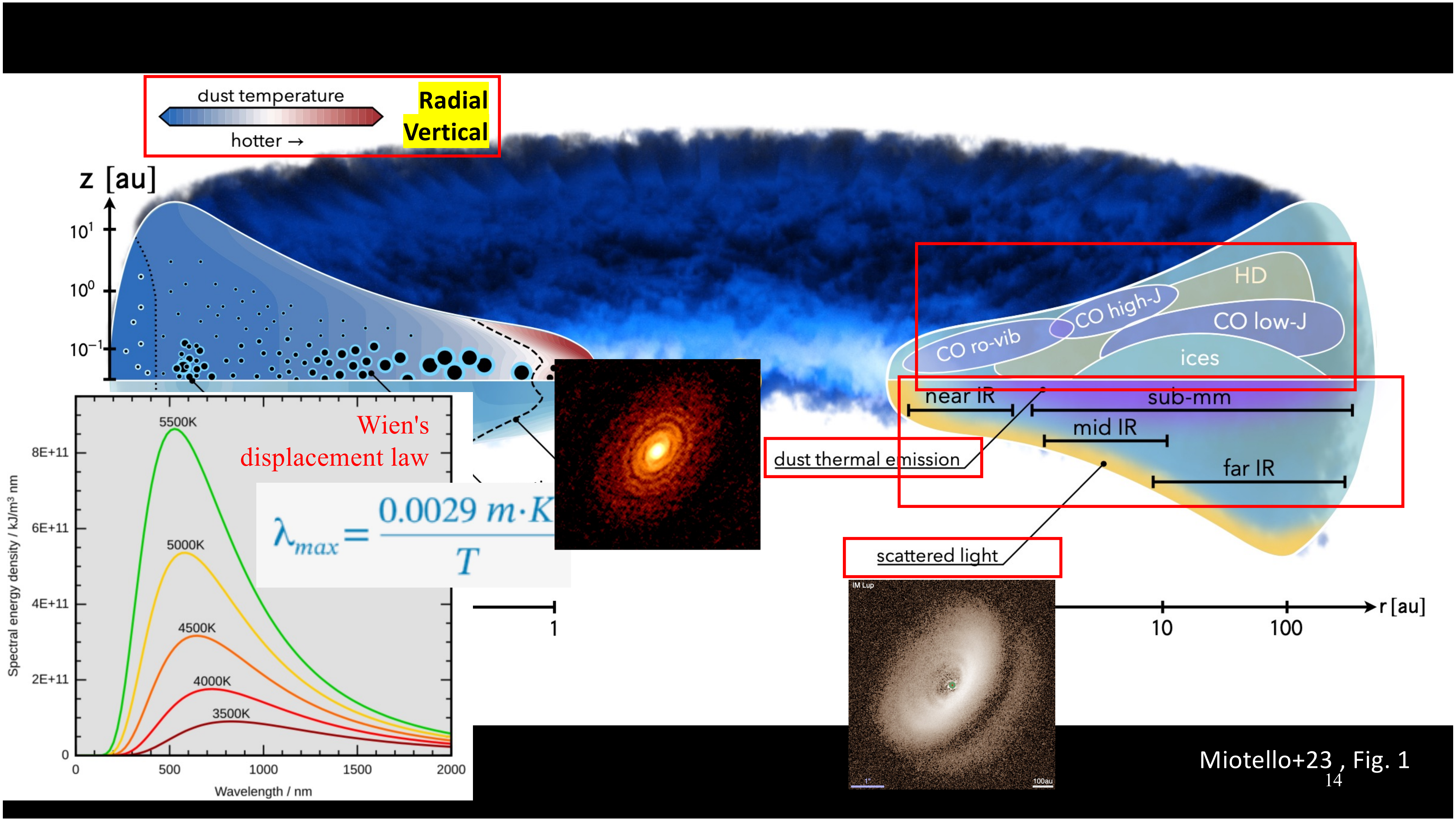
Benisty et al. 2021
Isella et al. 2019

Protoplanetary Disks Dissipate in a few Million Years





Miotello+23 , Fig. 1


dust temperature
hotter →
Radial
Vertical
z [au]
10^1
10^0
10^{-1}
HD
CO high-J
CO low-J
CO ro-vib
ices
near IR
sub-mm
mid IR
far IR
dust thermal emission
scattered light
1
10
100
r [au]
Wien's
displacement law
$\lambda_{max} = \frac{0.0029\ m\cdot K}{T}$
5500K
5000K
4500K
4000K
3500K
Spectral energy density / kJ/m³ nm
8E+11
6E+11
4E+11
2E+11
0
0
500
1000
1500
2000
Wavelength / nm
IM Lup
100au
Miotello+23 , Fig. 1

What Are Disks Made of?

- Gas: ~99% of the mass; (almost) transparent
  - H_2 + He: 98% of the gas
  - CO, H_2O, etc: ~1%
  - Gas opacity
- Dust: ~1% of the mass; main source of opacity*
  - Different size, composition, porosity, etc
- Magnetic field
- Planetesimals / planets

Ten most common elements in the Milky Way Galaxy estimated spectroscopically[3]

Z	Element	Mass fraction (ppm)
1	Hydrogen	739,000
2	Helium	240,000
8	Oxygen	10,400
6	Carbon	4,600
10	Neon	1,340
26	Iron	1,090
7	Nitrogen	960

Table 2
Condensation Temperatures of the Major Volatiles in Disks

Species	T^a_{cond} (K)	E_b (K)	Cometary Abundance % of H_2O	References
H_2O	128–155	5165	100	1, 5
CO	23–28	890	0.4–30	1, 5
CO_2	60–72	2605	2–30	1, 5
CH_4	26–32	1000	0.4–1.6	2, 5
CH_3OH	94–110	4355	0.2–7	1, 5
N_2	12–15	520	…	2, 5
NH_3	74–86	2965	0.2–1.4	1, 5
HCN	100–120	4170	0.1–0.6	3, 5
H_2S	45–52	1800	0.1–0.6	4, 5
$NH_3 \cdot H_2O$	78–81	…	…	6
$H_2S^\star$	77–80	…	…	6
$CH_4^\star$	55–56 (69–72)	…	…	6, 7
$CO^\star$	45–46 (58–61)	…	…	6, 7
$N_2^\star$	41–43 (55–57)	…	…	6

* https://en.wikipedia.org/wiki/Opacity

Zhang et al. 2015

Fundamental Properties of Protoplanetary Disks

1. Total disk mass (gas / dust)
2. Disk size
3. Material distribution (radial / vertical / gas / dust)
4. Temperature structure (radial / vertical)

Total Dust Mass

Flux to dust mass conversion assuming optically thin disks

$$F_\nu = \frac{B_\nu(\bar{T}_\mathrm{d})\,\bar{\kappa}}{d^2} M_\mathrm{dust},$$

Tychoniec+20

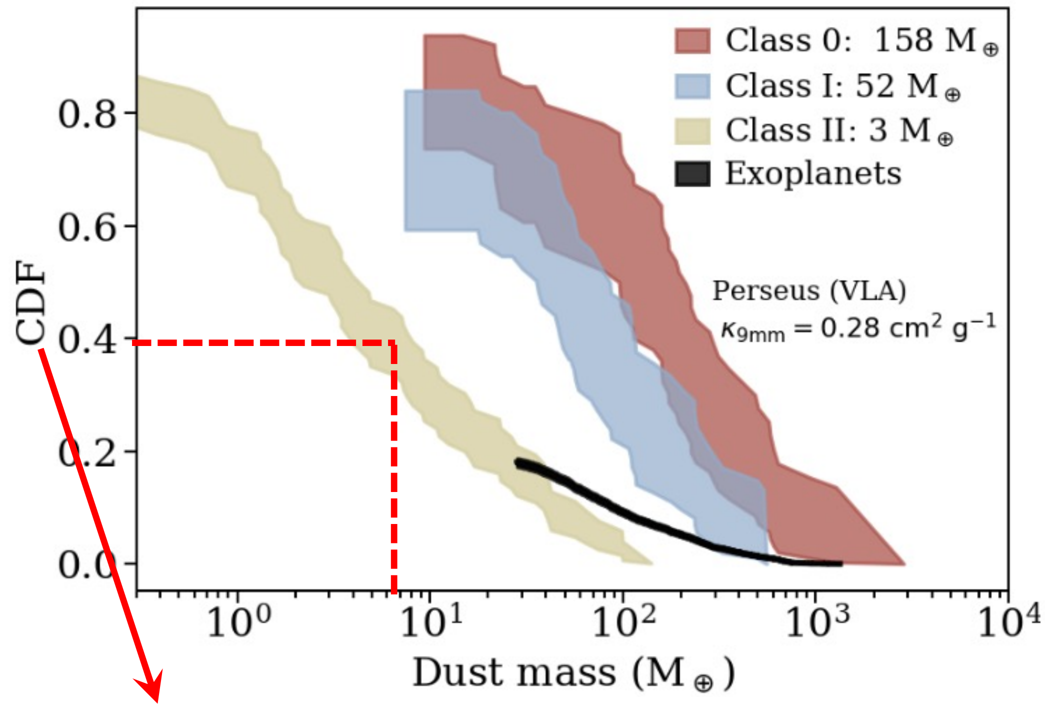


Fig. 4: Cumulative distribution function of dust disk masses and solid content of exoplanets. *Top*: Cumulative distribution function of dust masses for Class 0 (red) and Class I (blue) disks in Perseus and Class II disks (yellow) in Lupus measured with ALMA (Ansdell et al. 2016). In black, the masses of the exoplanet systems are normalized to the fraction of the gaseous planets (Cumming et al. 2008). Perseus disk masses calculated with $\kappa_{9\mathrm{mm}} = 0.28$ cm^2 g^{-1} from the VLA fluxes. Medians are indicated in the labels. *Bottom*: Zoom-in to the ranges where ex-

Total Gas Mass

- H_2: (Almost) No emission in protoplanetary disks
- He: similar

Sternberg 1989

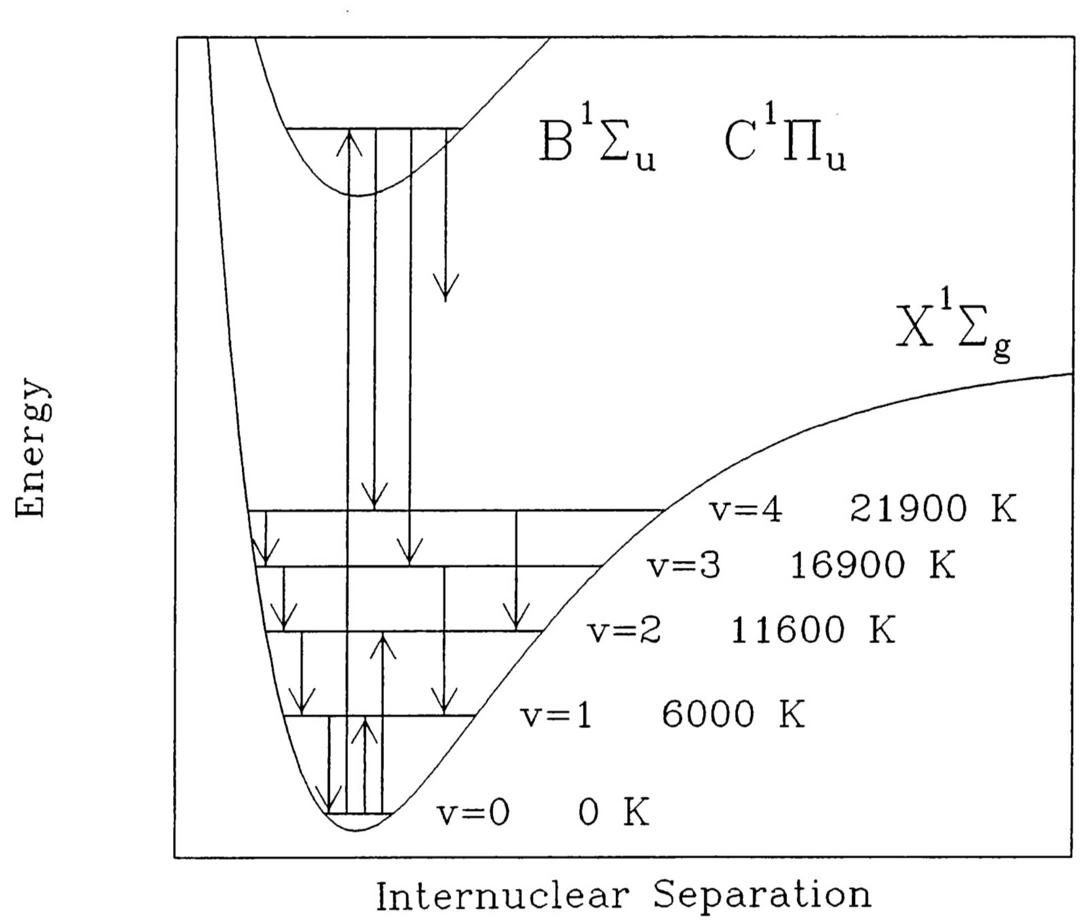
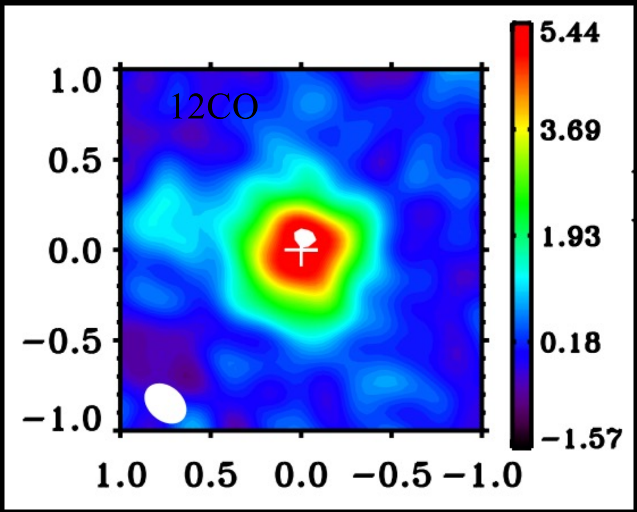
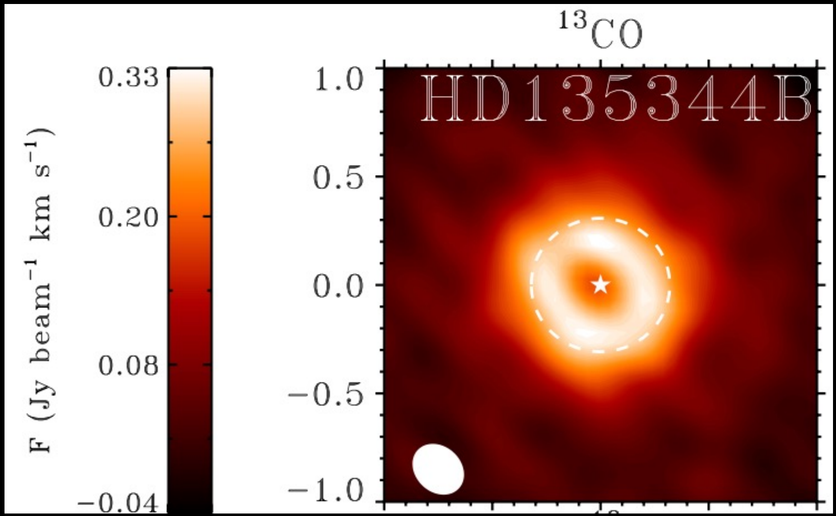


Fig. 1 Schematic energy level diagram (not to scale) of molecular hydrogen. Five of the fifteen vibrational levels of the ground $X^1\Sigma_g^+$ electronic state are displayed. The UV pumping mechanism via the $B^1\Sigma_u^+$ and $C^1\Pi_u$ excited electronic states is illustrated.

Total Gas Mass – *Tracer / (Tracer / Gas)*

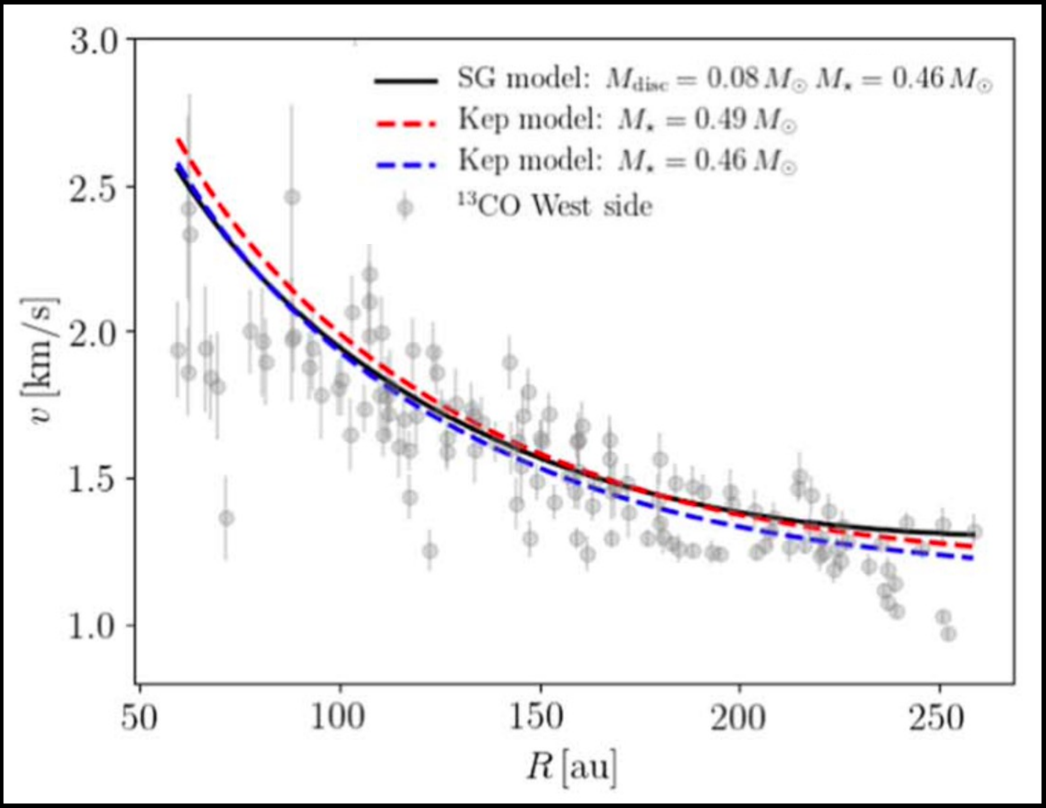
- CO and isotopologues (CO / H_2 : ~ 10^{-4})
  - Pro: high abundance; easy access (many lines at mm wavelengths)
  - Cons: conversion factor uncertain due to freeze out, photodissociation, chemical reaction, and dust processing
  - 12CO often optically thick; need optically thin tracers





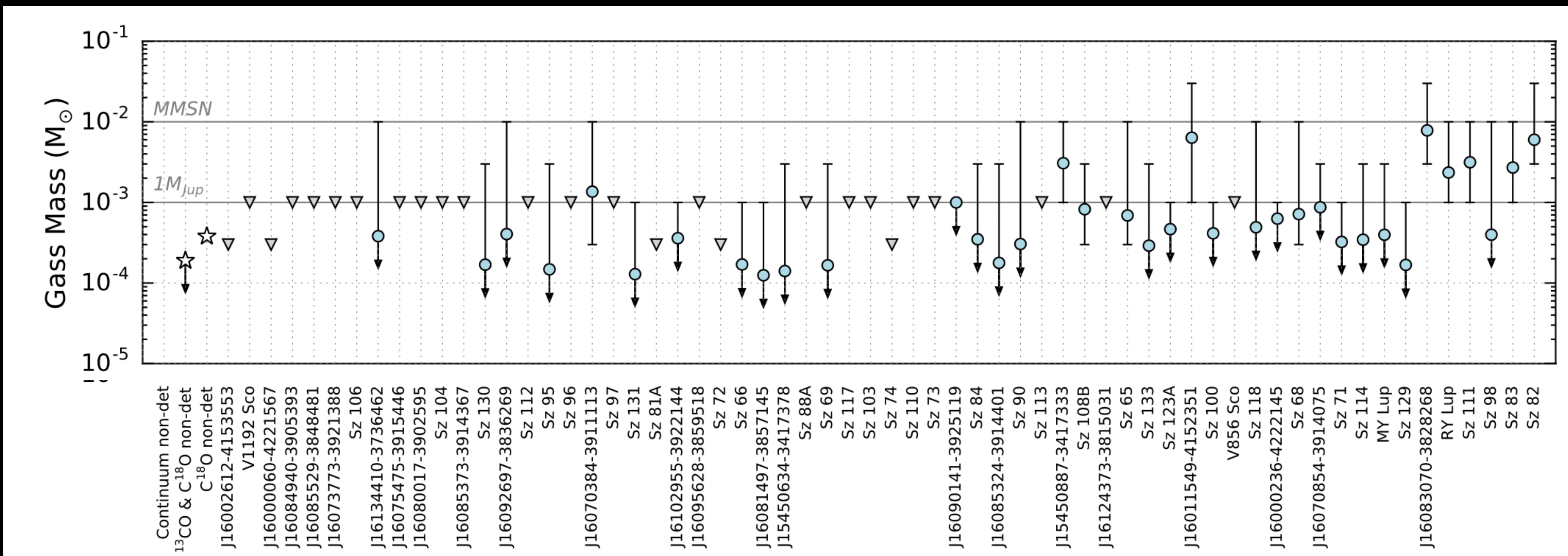
van der Marel + 15, 16

Total Gas Mass – Dynamical Mass Constraints



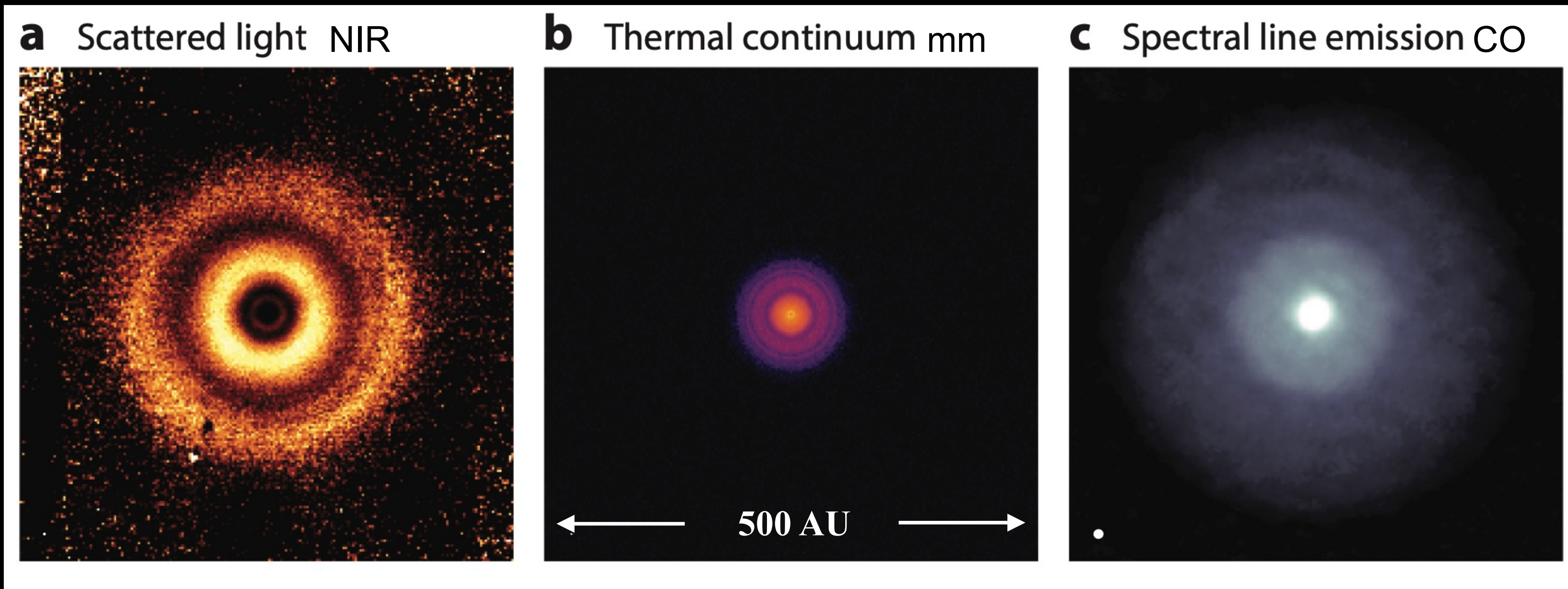
Veronesi et al. (2021)

Total Gas Mass



Ansdell+16

Disk Size



Small dust (micron-sized) Big dust (mm-sized) Gas (CO)

TW Hya, Andrews + 20

Disk size distribution, mm continuum emission

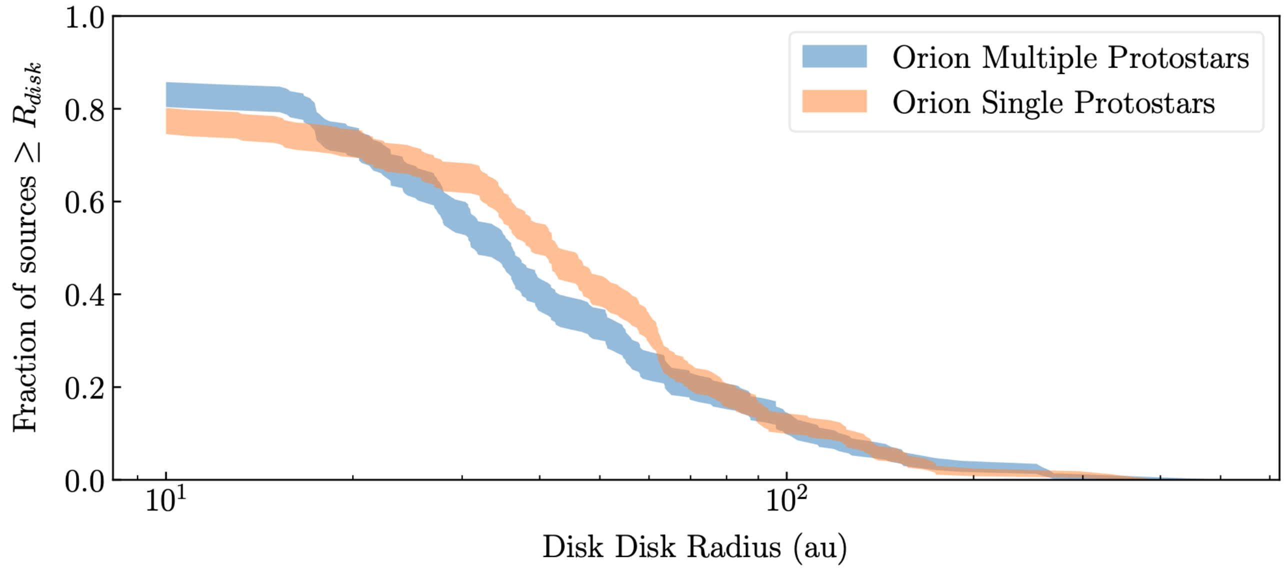


Figure 10: Cumulative distributions of dust disk radii, as measured by the deconvolved major axis of a two-dimensional Gaussian fit to each source, for protostars in Orion, split between single protostars and multiples.

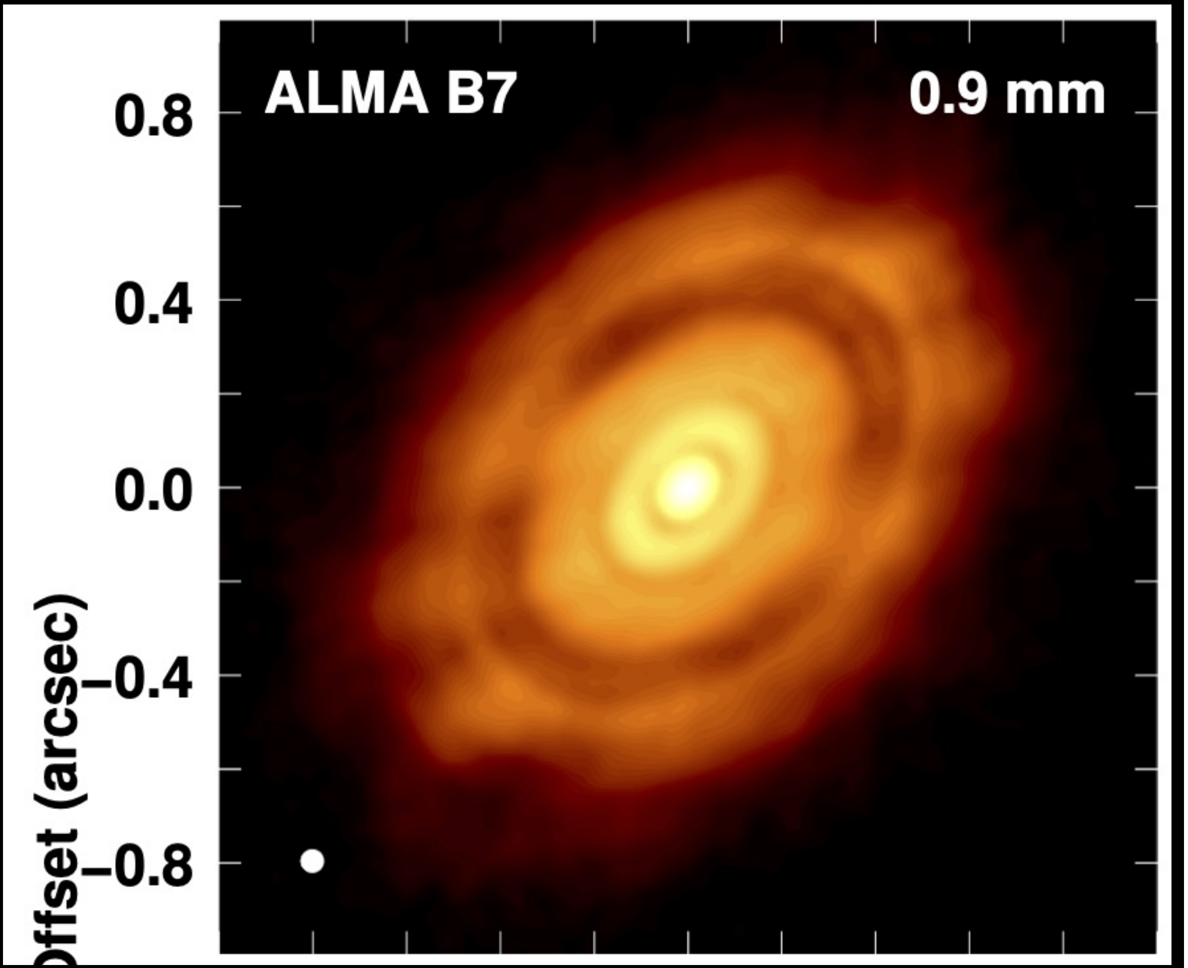
Tobin & Sheehan 2024

Radial Distribution of Material: Dust

$$I_\nu = B_\nu(T_{\rm dust})\left(1 - e^{-\tau_\nu}\right),$$
$$\tau_\nu = \Sigma_{\rm d}\,\kappa_{\rm abs}$$

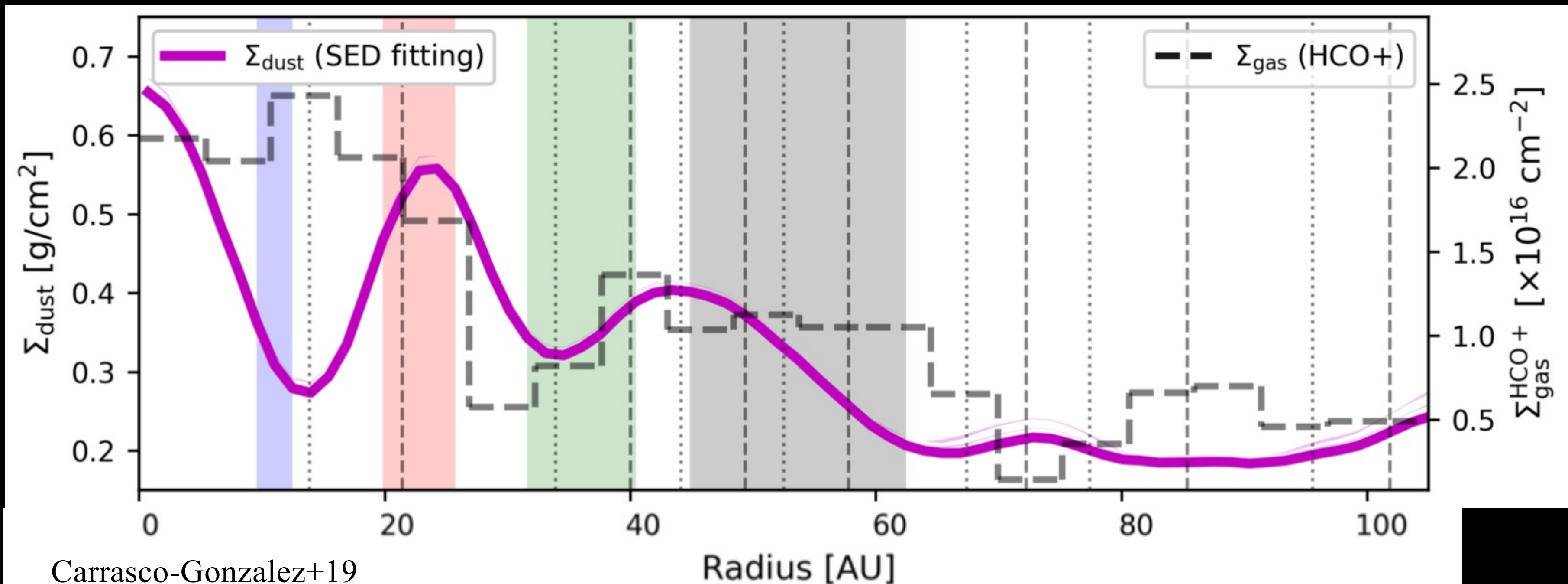
Assuming optical depth $\tau_\nu << 1$

$$I_\nu = B_\nu(T)\,\tau_\nu = B_\nu(T)\,\Sigma_{\rm d}\,\kappa_{\rm abs}.$$



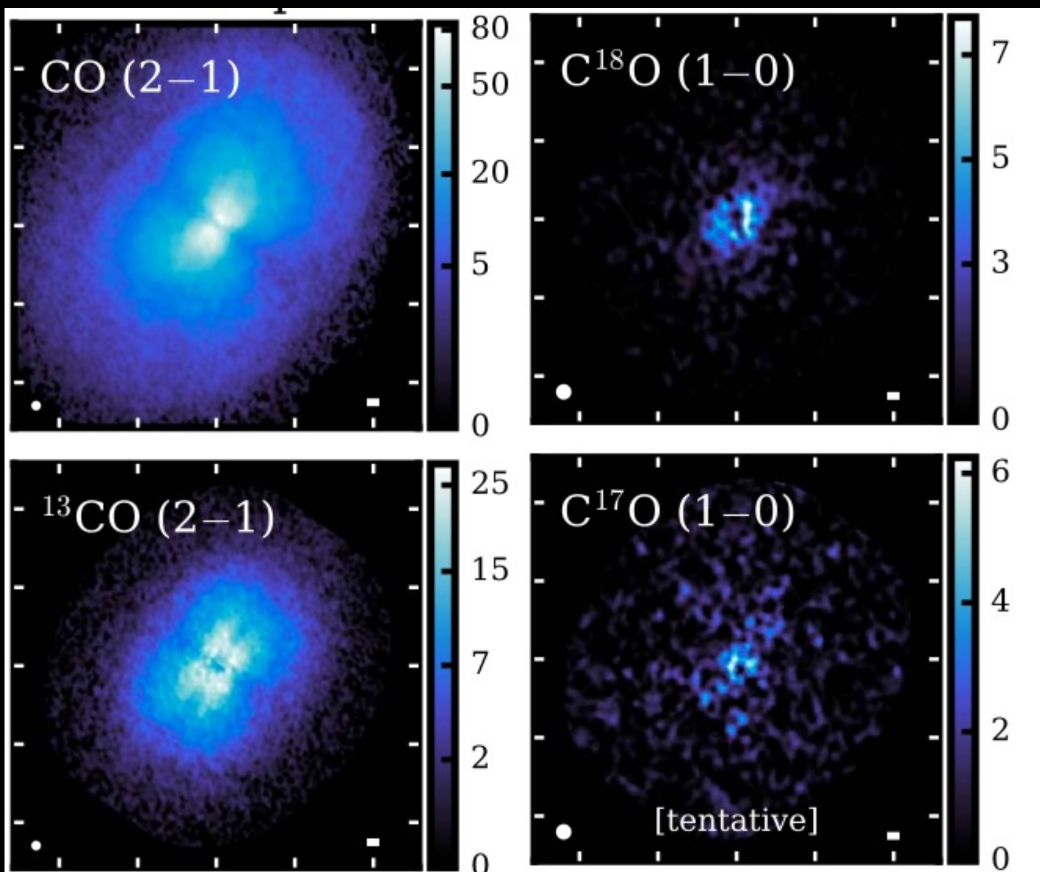
HL Tau Carrasco-Gonzalez+19

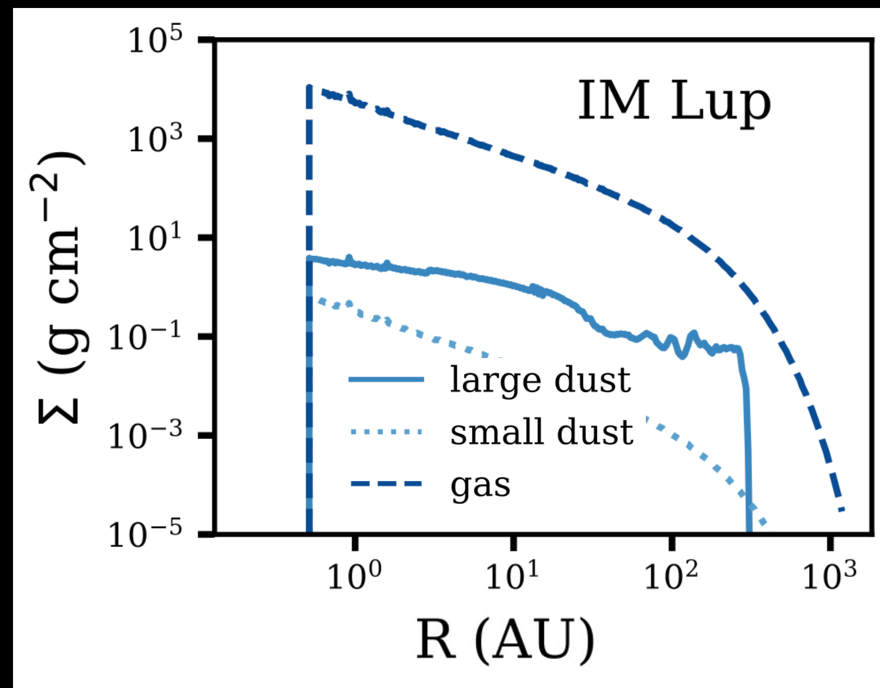
Radial Distribution of Material: Dust (HD 163296)



Carrasco-Gonzalez+19

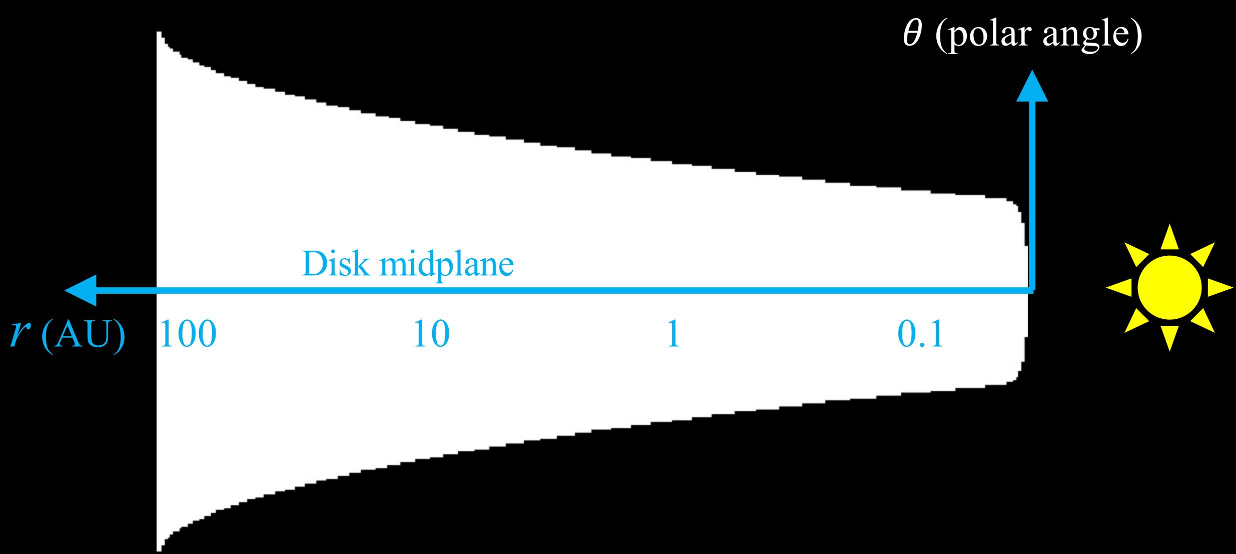
Radial Distribution of Material: Gas (IM Lup)

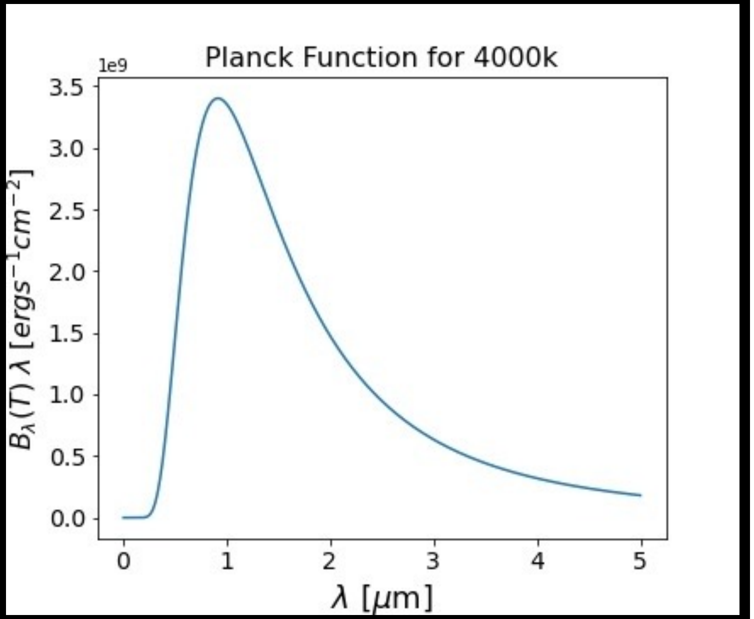




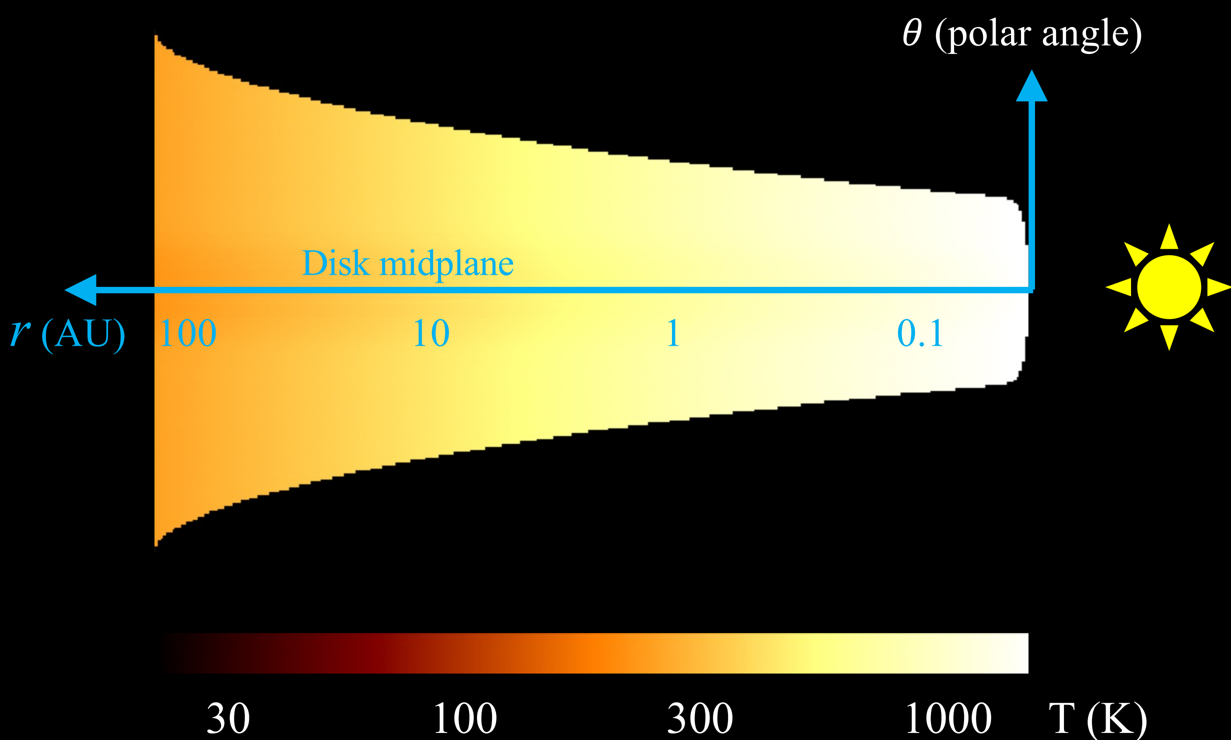
Zhang+21

Temperature Structure in Protoplanetary Disks





Temperature Structure in Protoplanetary Disks

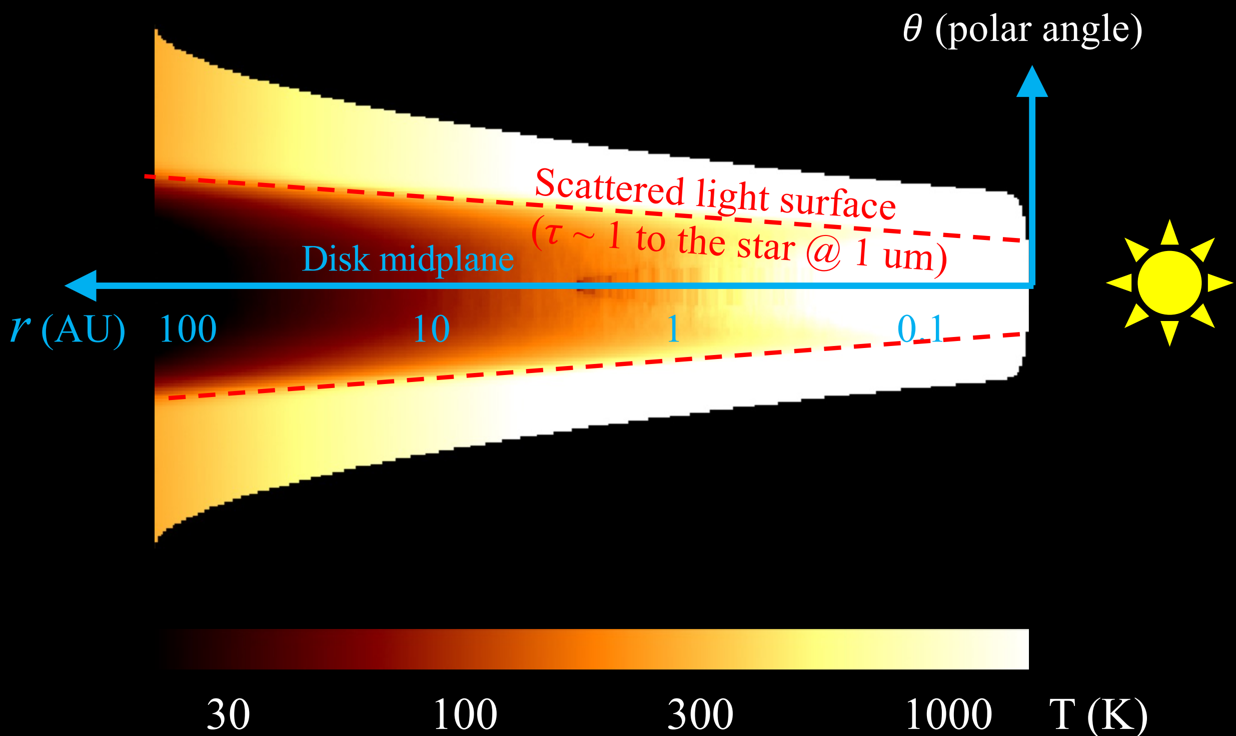


Optically thin disk

Every dust particle directly sees the star

Good approximation for debris disks

Temperature Structure in Protoplanetary Disks



Optically **thick** disk

Only dust particles at the surface sees the star

(notice the contribution from accretion at small radii)