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Facultad de Ciencias Exactas y Naturales

NIR SPECTRAL SIGNATURES OF THE CIRCUMPLANETARY DISK IN PDS 70 C

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AGENDA

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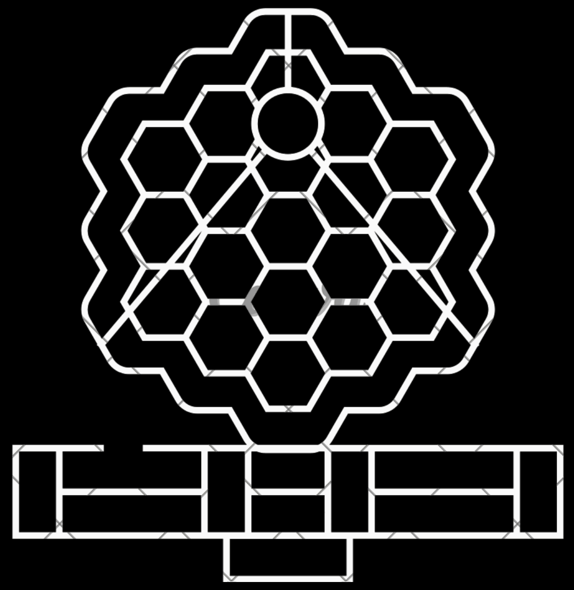
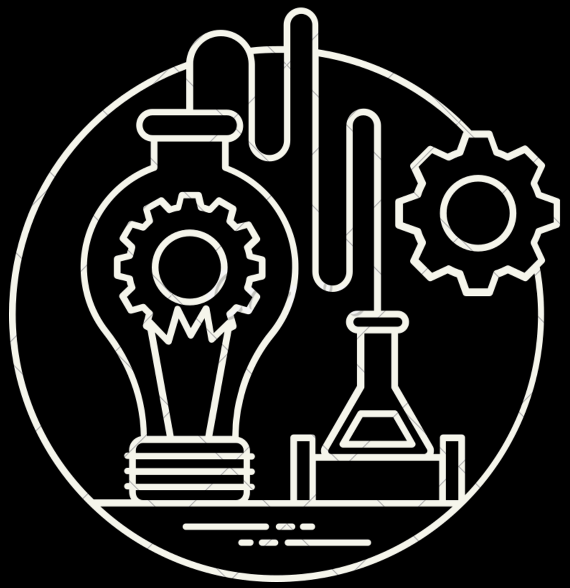
The Astrochemistry fundaments

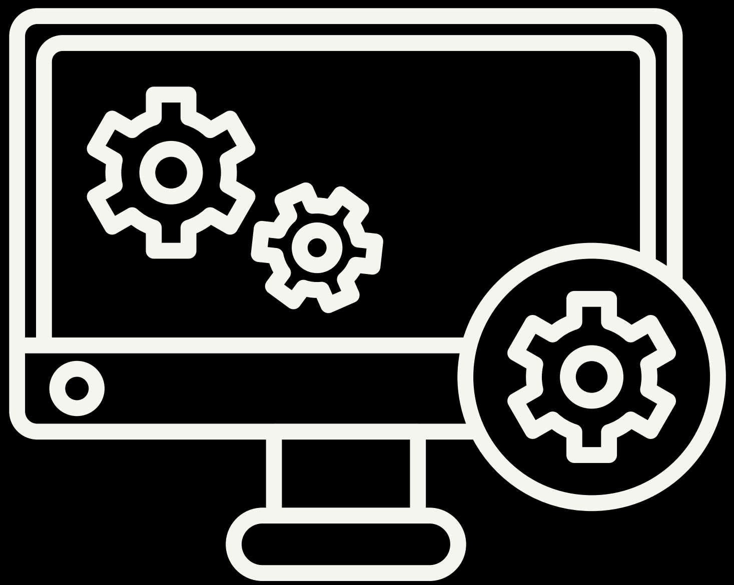


OBSERVATIONS



EXPERIMENTS

What can molecules tell about the environment in which they exist?



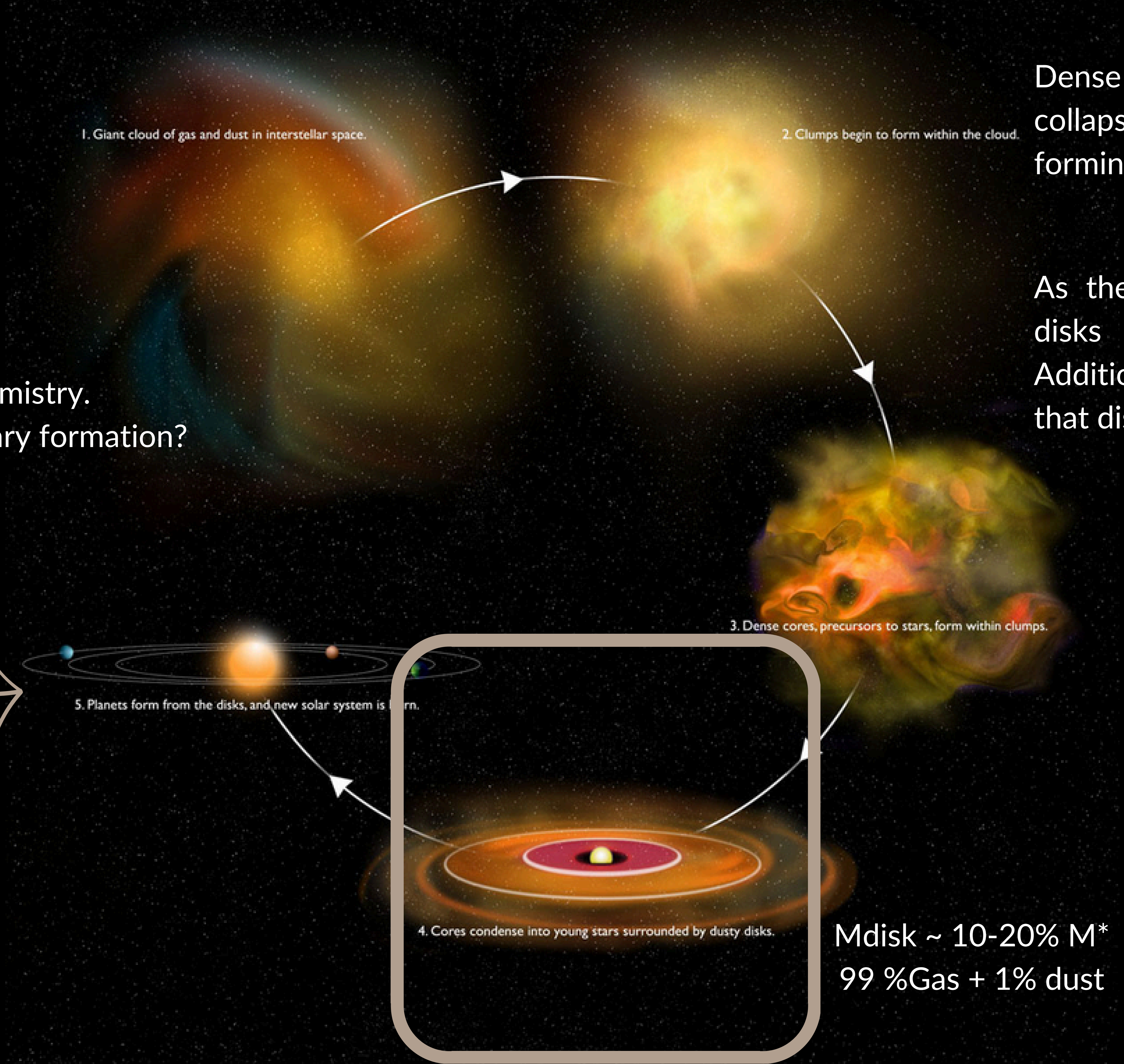
MODELS

Planetary Formation

Dense cores of molecular clouds collapse due to their own gravity, forming stars within them.

As the disks rotate, protoplanetary disks form around young stars. Additionally, young stars eject winds that disperse the parent cloud.

- It is a laboratory of astrochemistry.
- What is the origin of planetary formation?
- What is our origin?



Mdisk ~ 10-20% M*
99 %Gas + 1% dust

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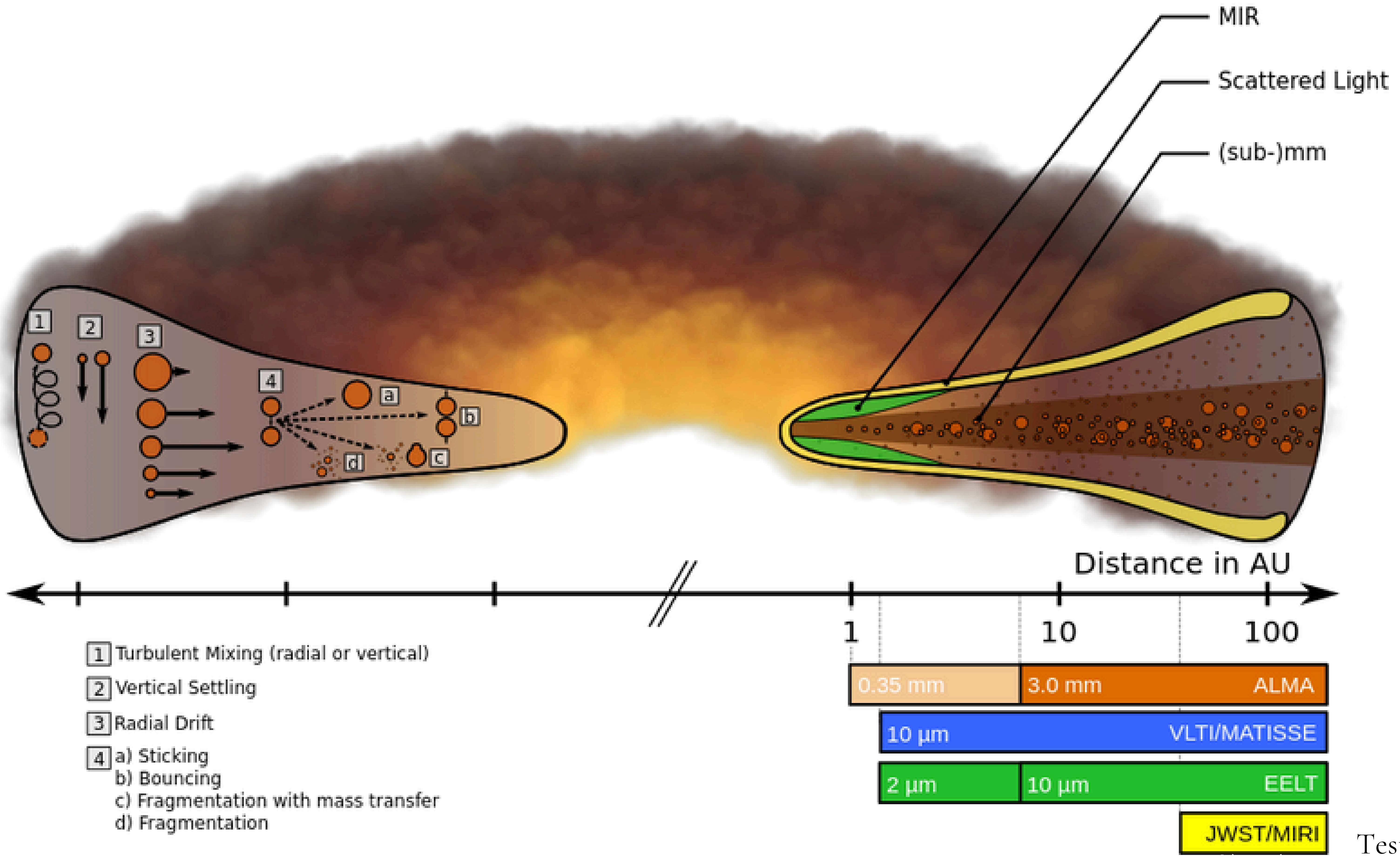
Dust settling and migration



Testi +2014

Hashimoto et al. (2020)
Wang et al. (2020)
Isella et. al (2019)

PDS 70

- *ALMA ~ 855 μm - Band 7*
- *T Tauri Star (near-IR)*
- *Distance: 370 light-years from Earth*
- *Age: ~5 Myr*
- *PDS 70 c has 5 Mjup*

When creating a model to attempt to reproduce the observed emission, it is possible to understand its density, temperature, and energy flux in order to determine its chemical components.

METHODOLOGY

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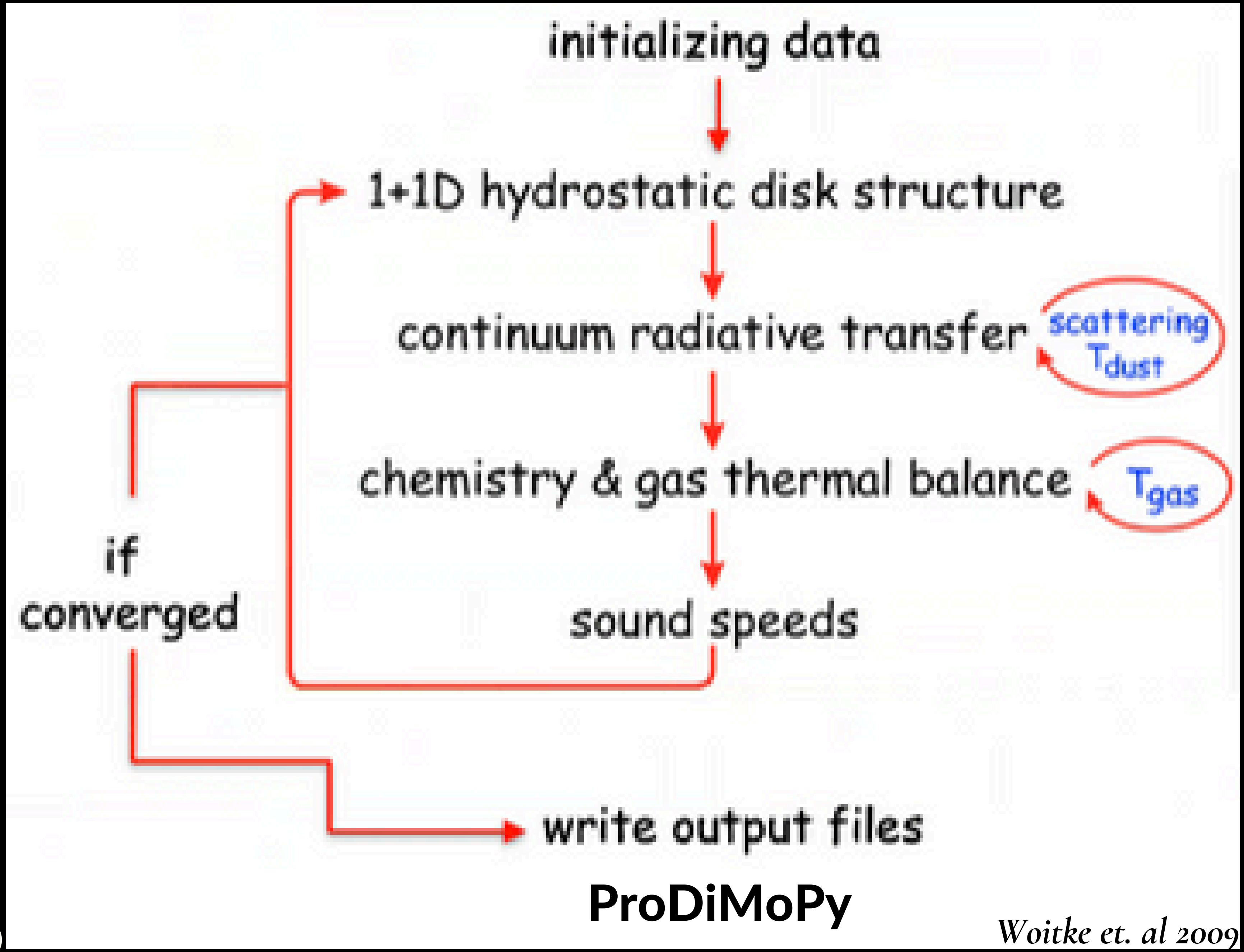
ProDiMo (Protoplanetary Disk Model)

A chemical-radiative code called ProDiMo is used to model protoplanetary disks (PPDs).

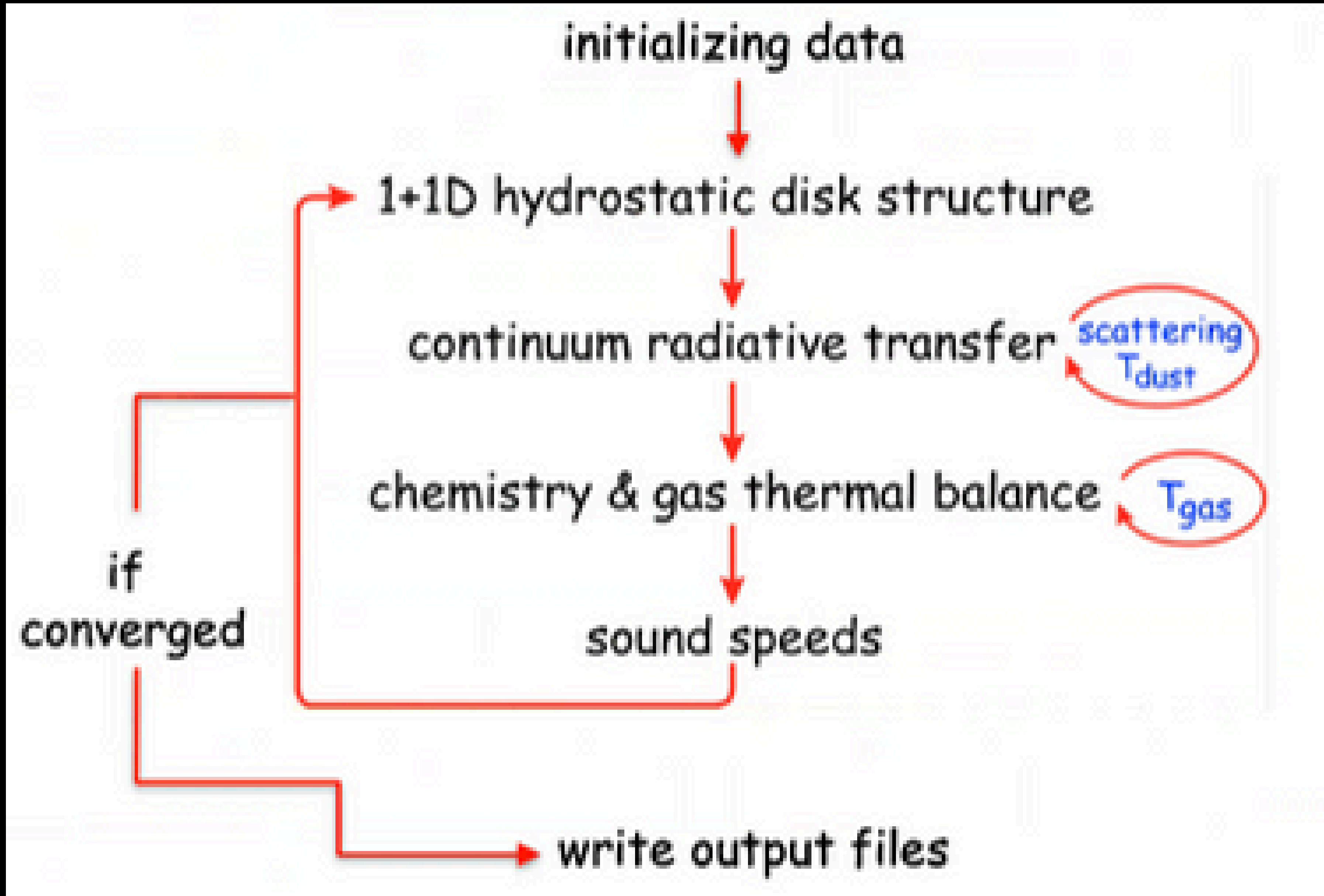



```
----- star and irradiation -----
0.76          ! Mstar       [Msun]   : stellar mass
0.35          ! Lstar       [Lsun]   : stellar luminosity
3972.0       ! Teff        [K]      : stellar effective temperature
0.00         ! fUV         [-]      : LUV/Lstar
1.3          ! pUV         [-]      : UV powerlaw exponent
.true.       ! Xrays       [-]      : use Xray chemistry and heating?
1.E+29       ! Xray_Lum    [erg/s]  : X-ray luminosity
2.E+7        ! Xray_Temp   [K]      : X-ray emission temperature
1.7E-17      ! CRI         [1/s]    : cosmic ray ionisation of H2
1.0          ! CHI_ISM     [-]      : strength of incident vertical UV

------ dust parameters ------
2.094          ! rho_gr      [g/cm^3]: dust grain material mass density
0.05           ! amin        [mic]   : minimum dust particle size
3000.0         ! amax        [mic]   : maximum dust particle size
3.9            ! apow        [-]     : dust size distr f(a)~a^-apow
2              ! settle_method       : dust settling (Dubrulle et al. 1995)
1.E-3          ! a_settle            : turbulence alpha
0.8            ! hollow_sphere       : max hollow volume ratio
dust_opacity_list2X.txt              ! dust_opacity_list_file
3              ! NDUST               : number of selected dust species
  0.60         Mg0.7Fe0.3SiO3[s]
  0.15         amC-Zubko[s]
  0.25         vacuum[s]
```

ProDiMo (Protoplanetary Disk Model)

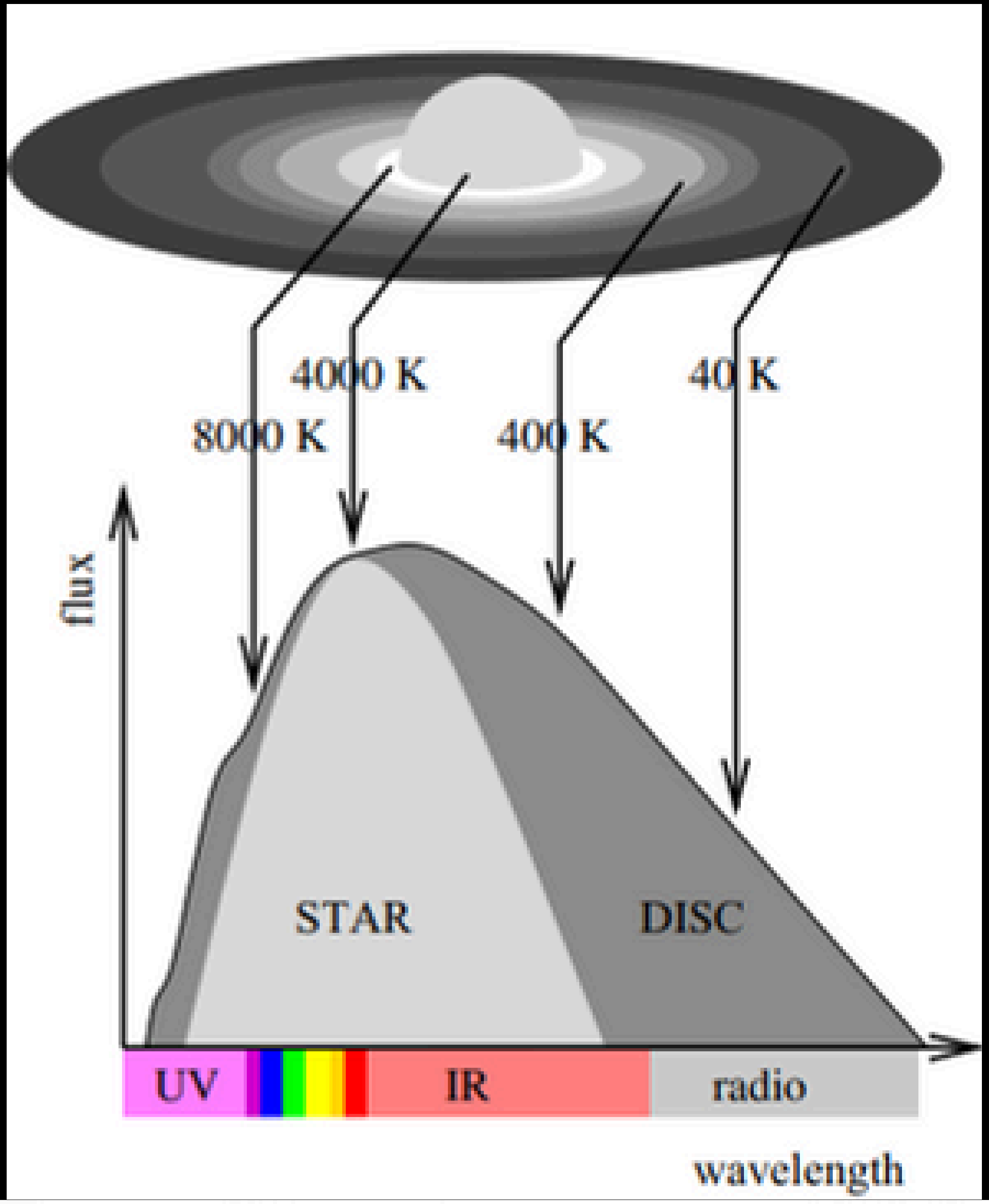
A chemical-radiative code called ProDiMo is used to model protoplanetary disks (PPDs).

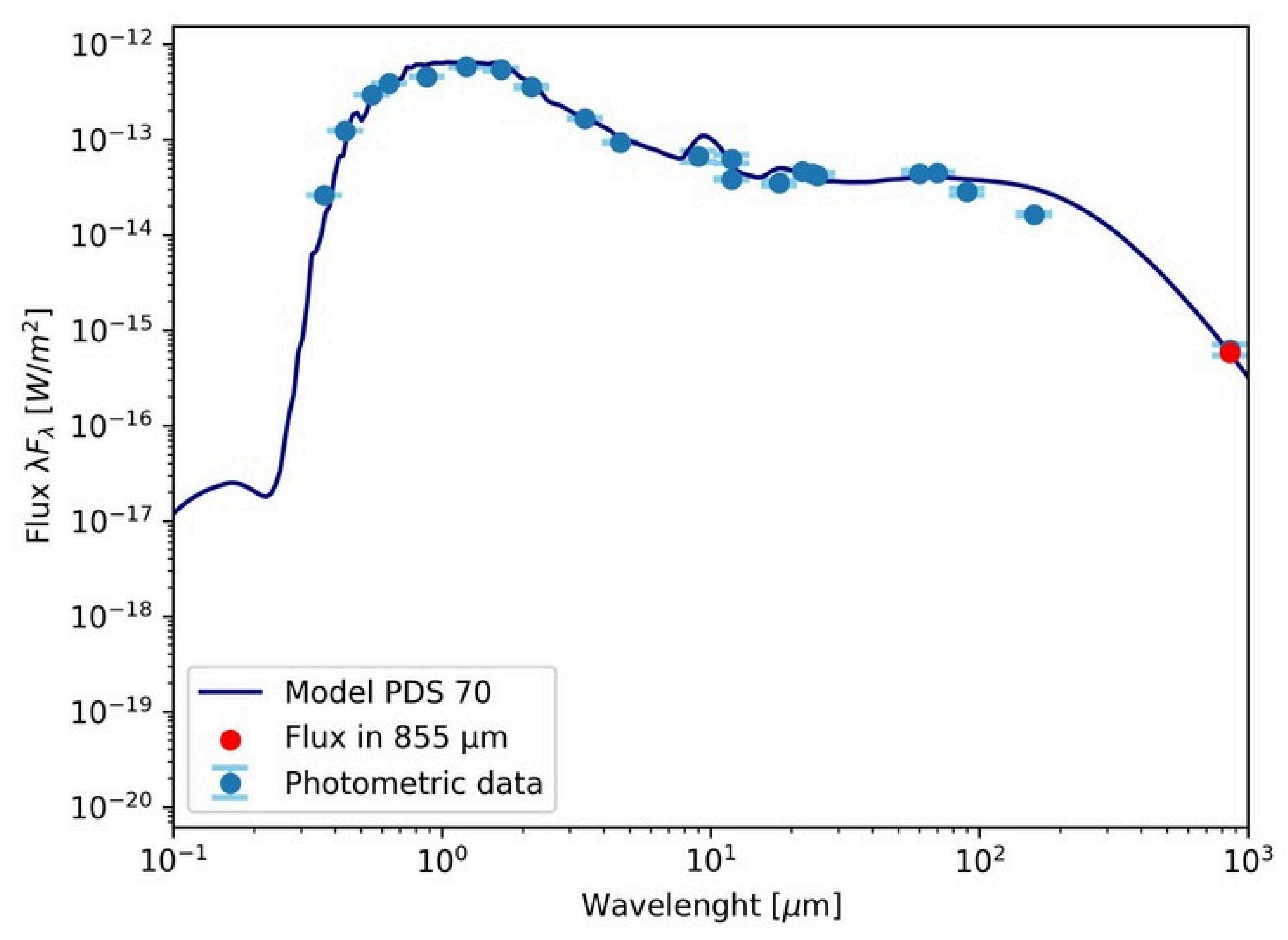


ProDiMoPy *Woitke et. al 2009*

```
------ outer zone -------
0.007        ! Mdisk        [Msun]  : disk mass
34.3         ! Rin          [AU]    : inner disk radius
100.0        ! Rtaper       [AU]    : tapering-off radius
130.0        ! Rout         [AU]    : outer disk radius
1.0          ! epsilon      [-]     : column density exponent
1.0          ! gtaper       [-]     : tapering-off exponent
10.0         ! MCFOST_H0    [AU]    : scale height ...
100.0        ! MCFOST_RREF  [AU]    : ... belonging to reference radius
1.15         ! MCFOST_BETA          : flaring power
0.01         ! dust_to_gas  [-]     : the dust-to-gas mass ratio
2.0          ! raduc
1.E-6        ! reduc
------ inner zone -------
1.E-5        ! M2disk       [Msun]  : disk mass
0.04         ! R2in         [AU]    : inner disk radius
22.0         ! R2out        [AU]    : outer disk radius
3000.0       ! a2max        [mic]
0.5          ! e2psilon     [-]     : column density exponent
0.015        ! MCFOST_H2    [AU]    : scale height ...
0.3          ! MCFOST_R2    [AU]    : ... belonging to reference radius
1.15         ! MCFOST_B2            : flaring power
0.1          ! d2ust_to_gas [-]     : the dust-to-gas mass ratio
1.E-8        ! r2educ
```

Spectral Energy Distribution (SED) for PDS 70



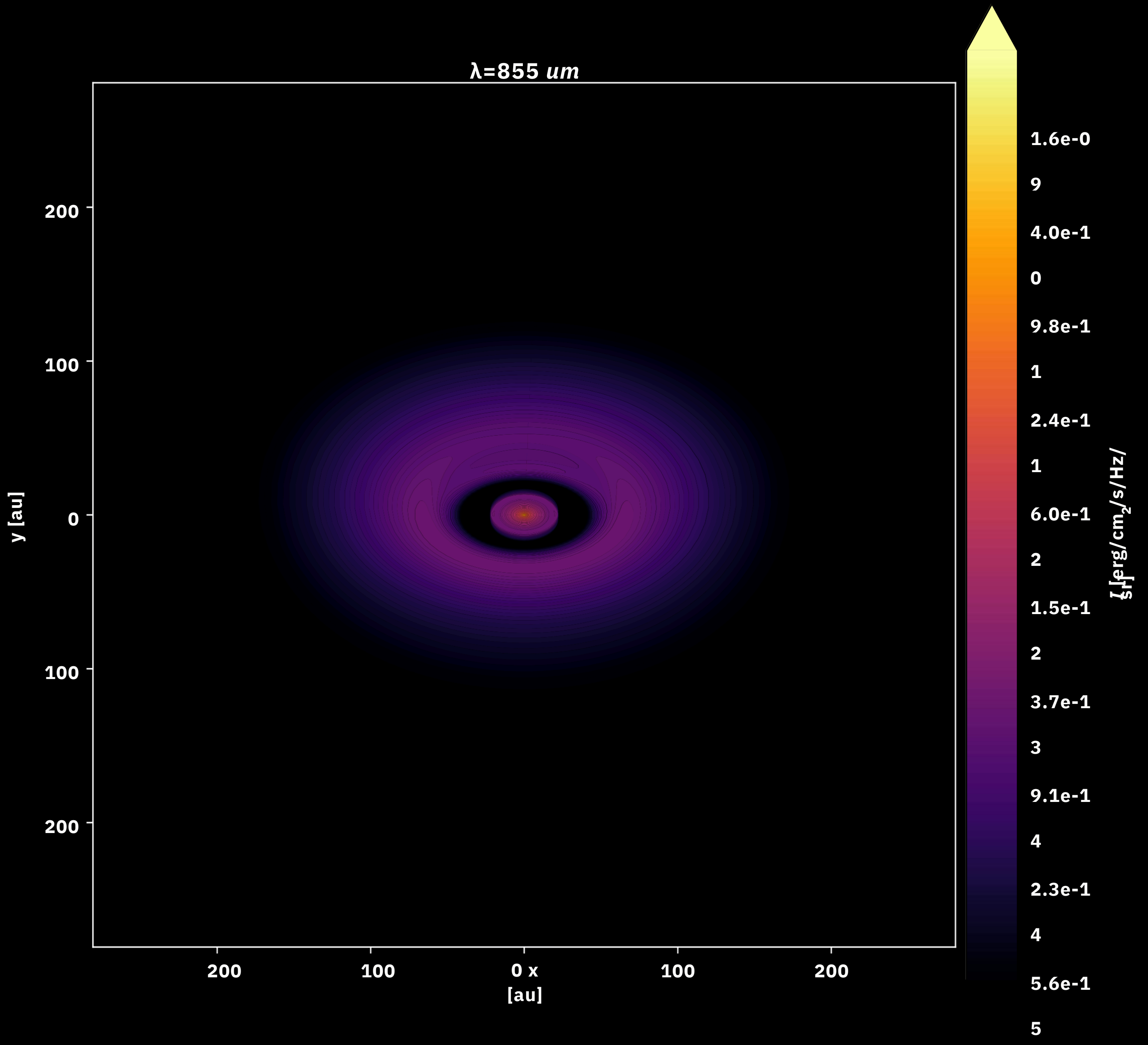


$$\frac{1}{\rho(\vec{r})}\frac{\partial I_\nu(\vec{r},\hat{k})}{\partial s} = -\kappa_\nu^{\rm ext} I_\nu(\vec{r},\hat{k}) + \kappa_\nu^{\rm abs} B_\nu(T(\vec{r})) + \kappa_\nu^{\rm sca} J_\nu(\vec{r})$$

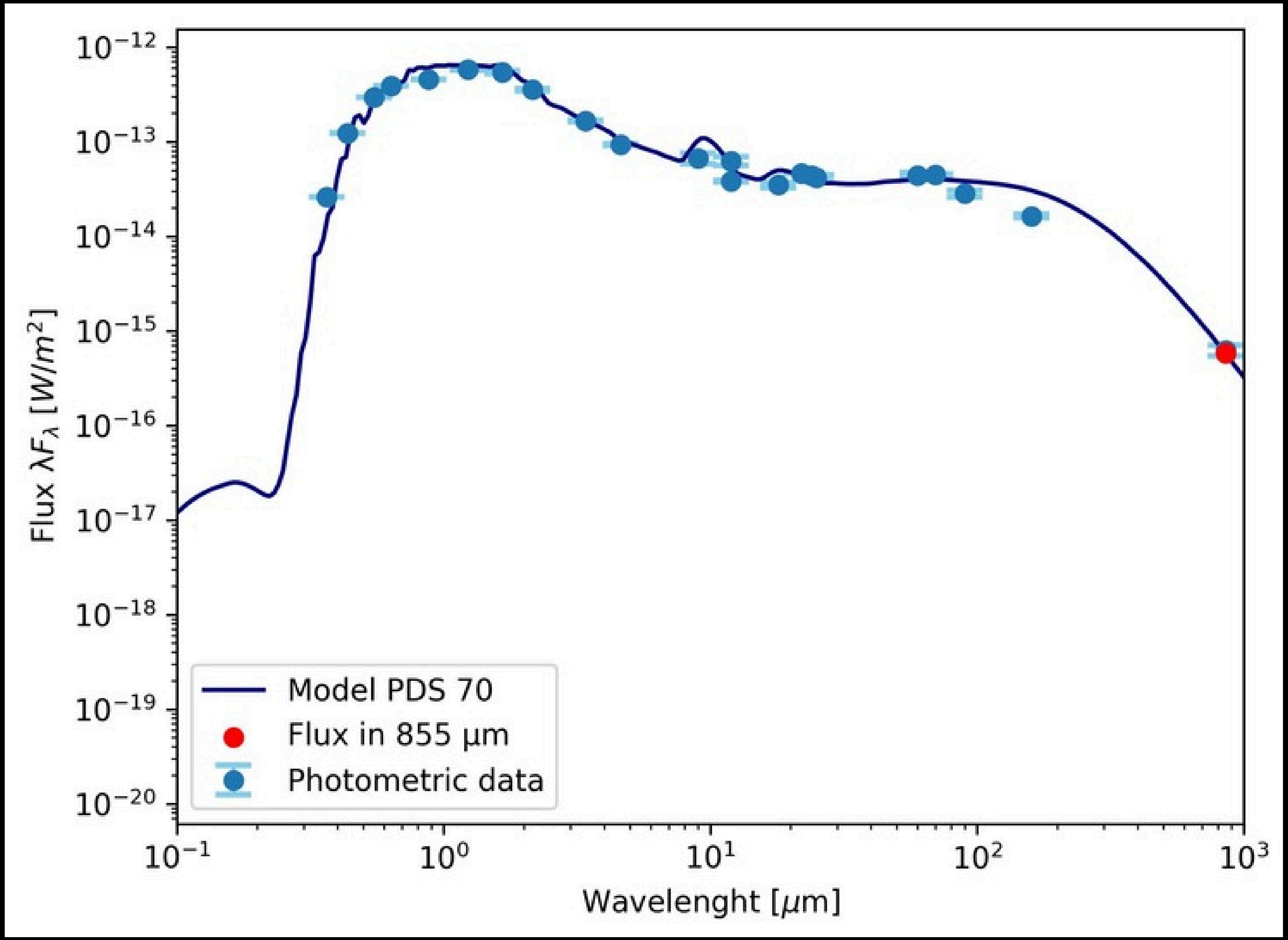
With Iv: Spectral intensity, Sv: Source function (radiation contributed by the disk), Bv: Planck function (blackbody approximation), Jv: Radiation field, and κv,abs, κv,sca, κv,ext {cm}^{-1} as the absorption, scattering, and extinction coefficients of the dust, respectively.

(Woitke et al. 2009, 2016; Kamp et al. 2010, 2017; Thi et al. 2011, 2020)

Spectral Energy Distribution (SED) for PDS 70



$$\frac{1}{\rho(\vec{r})}\frac{\partial I_\nu(\vec{r},\hat{k})}{\partial s} = -\kappa_\nu^{\mathrm{ext}} I_\nu(\vec{r},\hat{k}) + \kappa_\nu^{\mathrm{abs}} B_\nu(T(\vec{r})) + \kappa_\nu^{\mathrm{sca}} J_\nu(\vec{r}).$$



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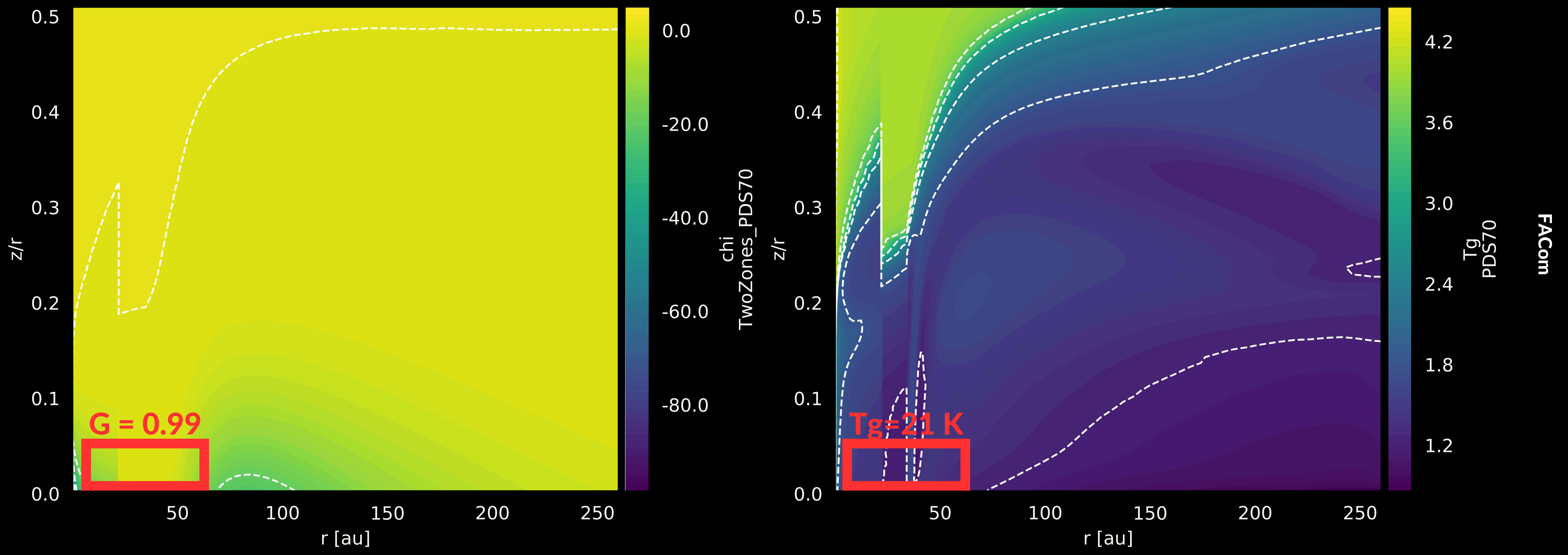
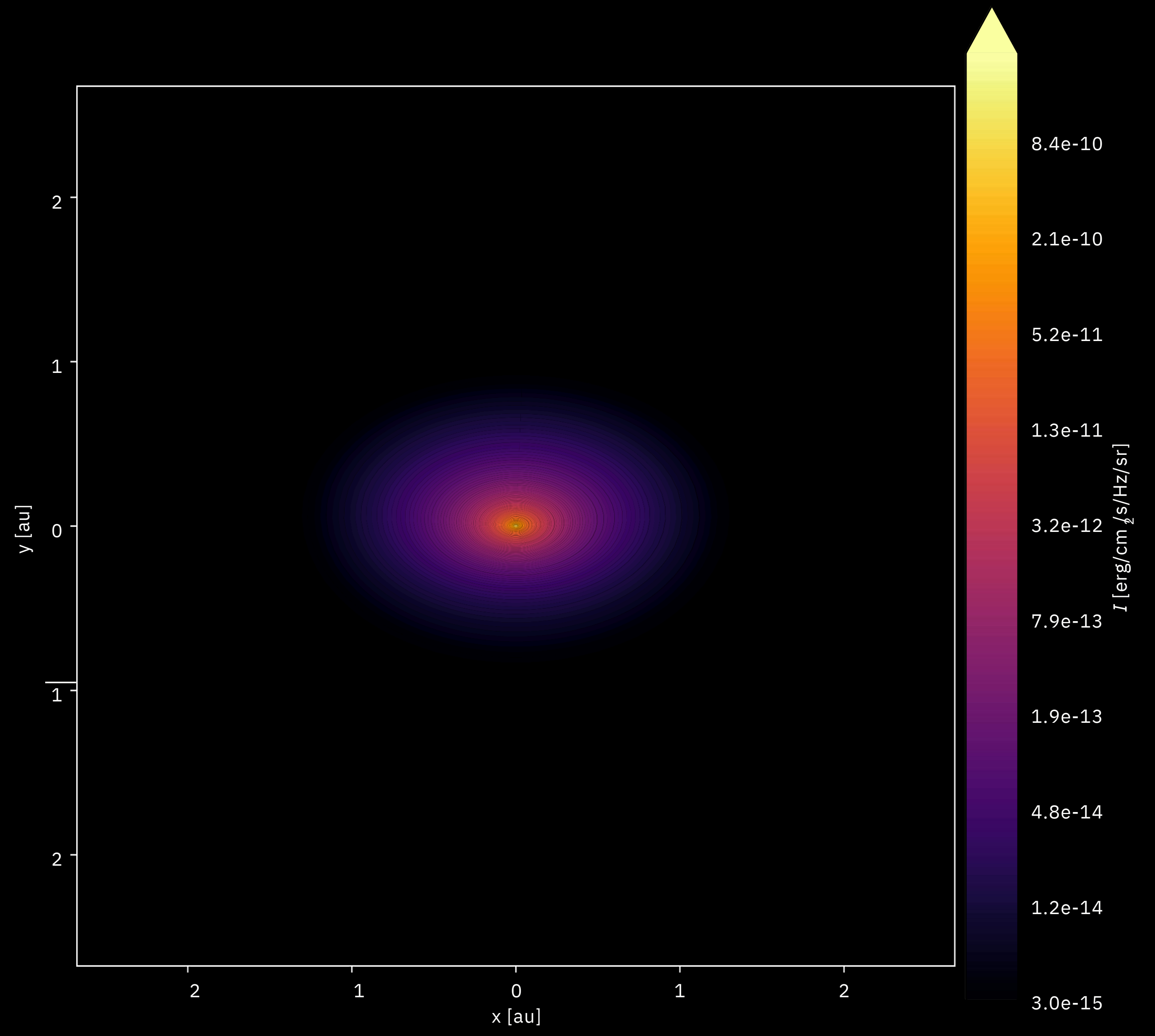
UV radiation field and Gas Temperature



ProDiMo (Protoplanetary Disk Model)

A chemical-radiative code called ProDiMo is used to model circumplanetary disks (CPDs) for a Brown Darf Model.

0.00764	!	Mstar	[Msun]
0.00016	!	Lstar	[Lsun]
1051.0	!	Teff	[K]
0.0	!	fUV	[-]
1.0	!	pUV	[-]
.true.	!	Xrays	[-]
1.E+29	!	Xray_Lum	[erg/s]
0.1	!	Xray_Emin	[keV]
2.2E+4	!	Xray_Temp	[K]
2.1E-6	!	Mdisk	[Msun]
0.01	!	dust_to_gas	[-]
0.01	!	fPAH	[-]
0.2	!	ChemHeatFac	[-]
1.3E-17	!	CRI	[1/s]
0.99	!	CHI_ISM	[-]
0.0	!	alpha_vis	[-]
0.15	!	v_turb	[km/s]



RESULTS

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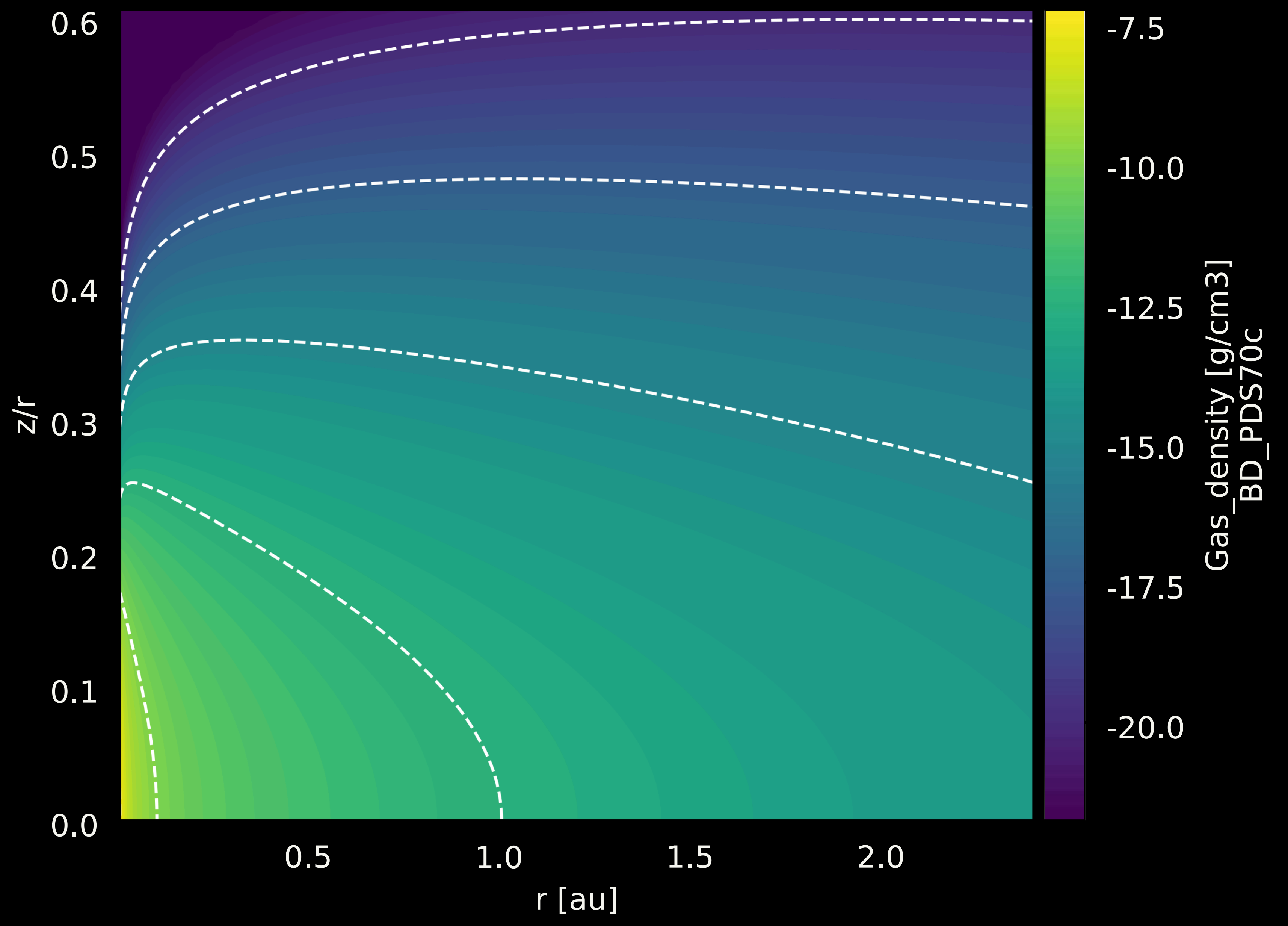
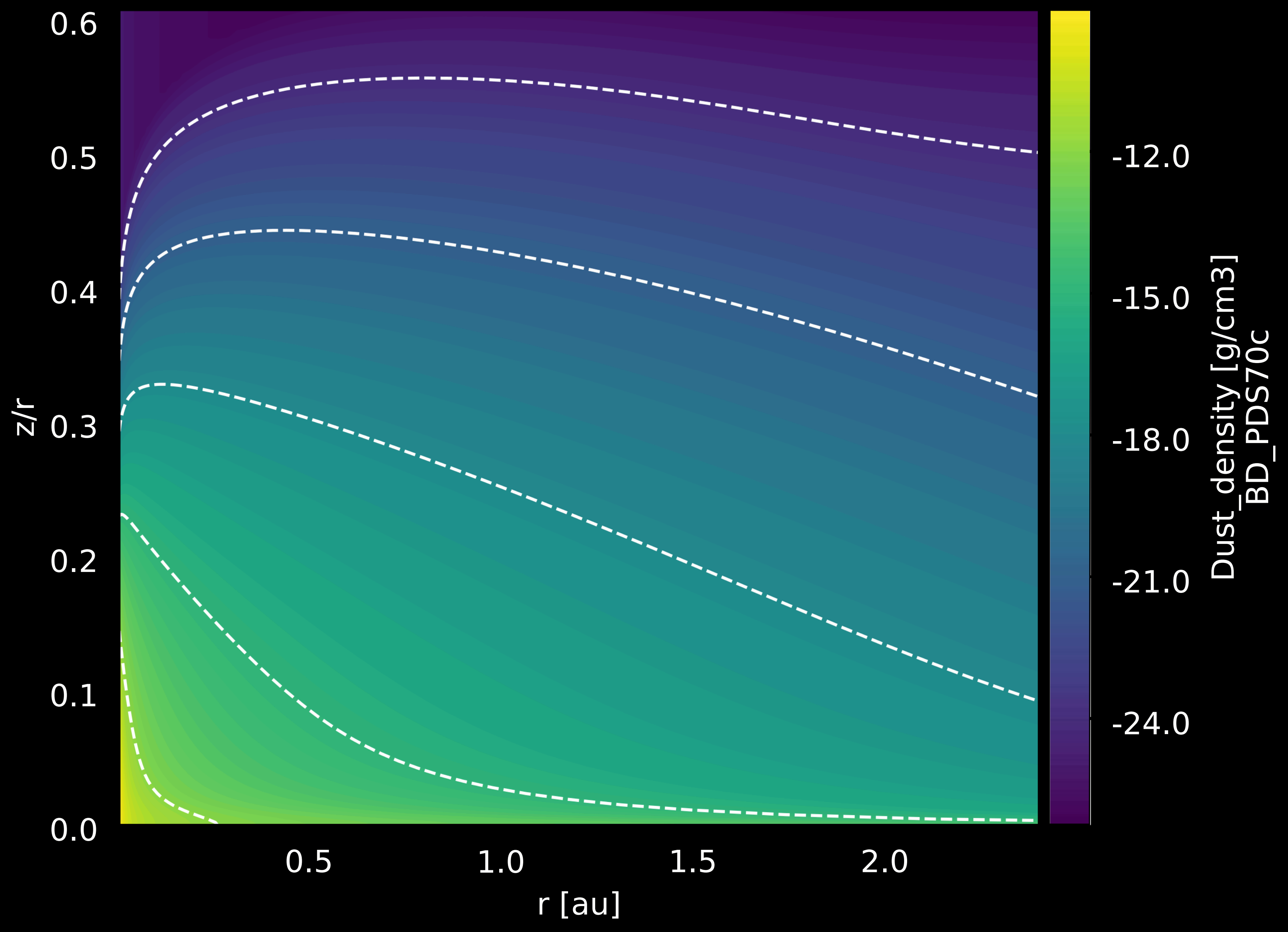
1. Disk Structure of PDS 70 c





$$\rho_g(r,z) = \frac{\Sigma(r)}{\sqrt{2\pi}\cdot h(r)} \exp\left(-\frac{z^2}{2h(r)^2}\right) \quad [\mathrm{g\,cm^{-3}}]$$

Σ(r): Surface density

h(r) :The disk scale height (gas pressure height) can be calculated using hydrostatic equilibrium.

For dust density, the gas-to-dust mass ratio is fixed at 1/100. The settling varies radially, depending on the grain size.

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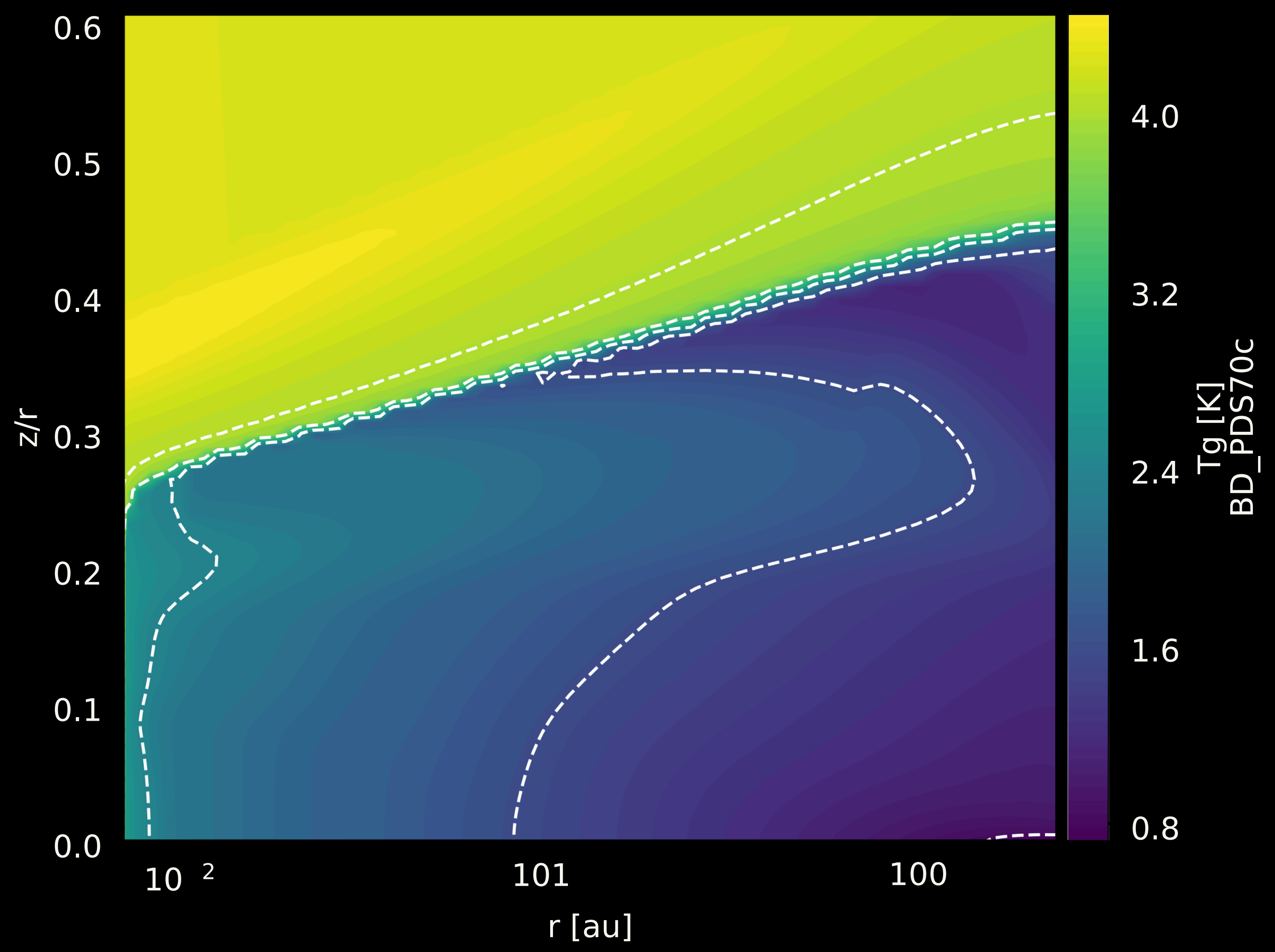
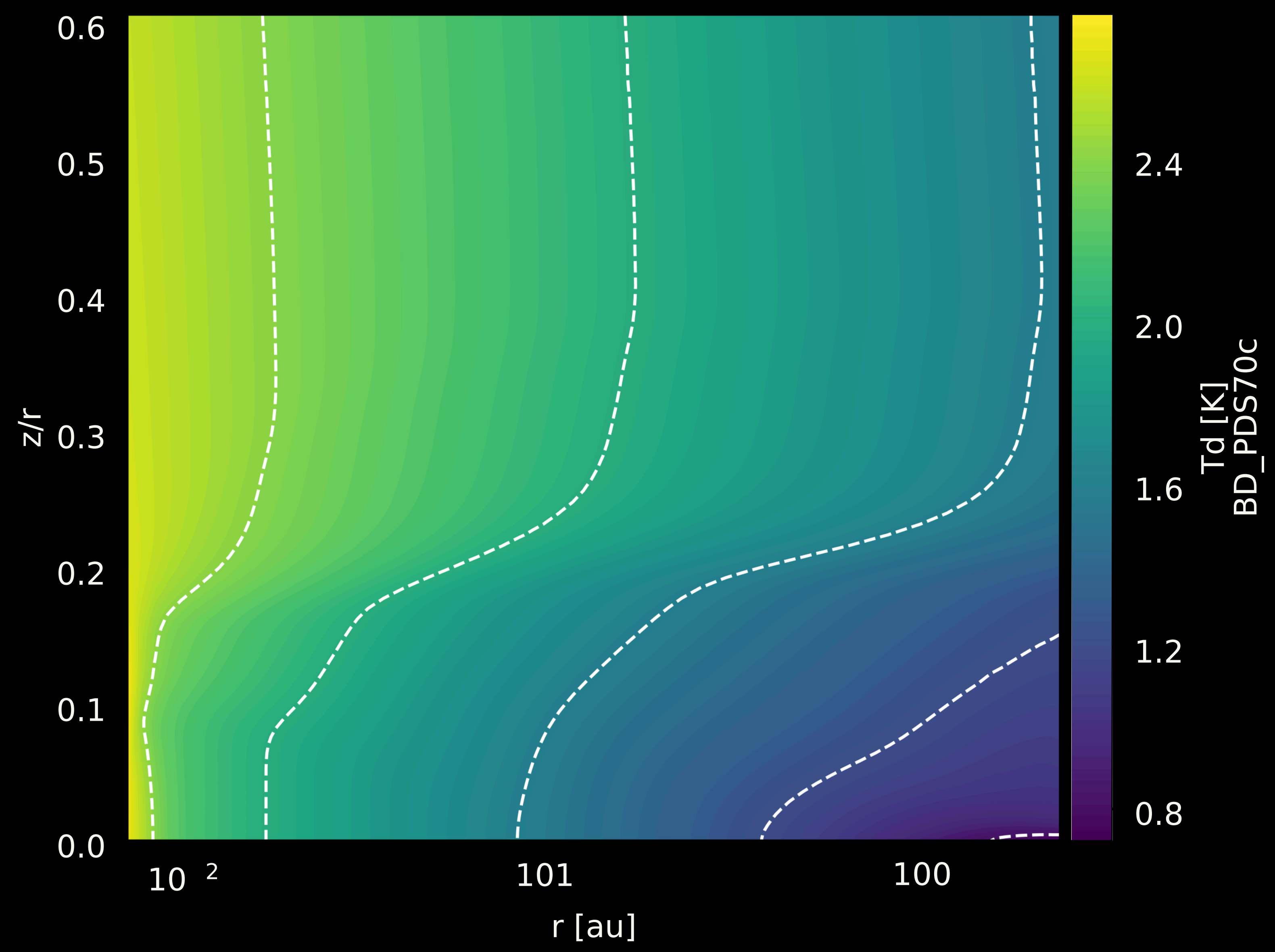
2. Thermal Balance of PDS 70 c





The net gain of thermal kinetic energy:

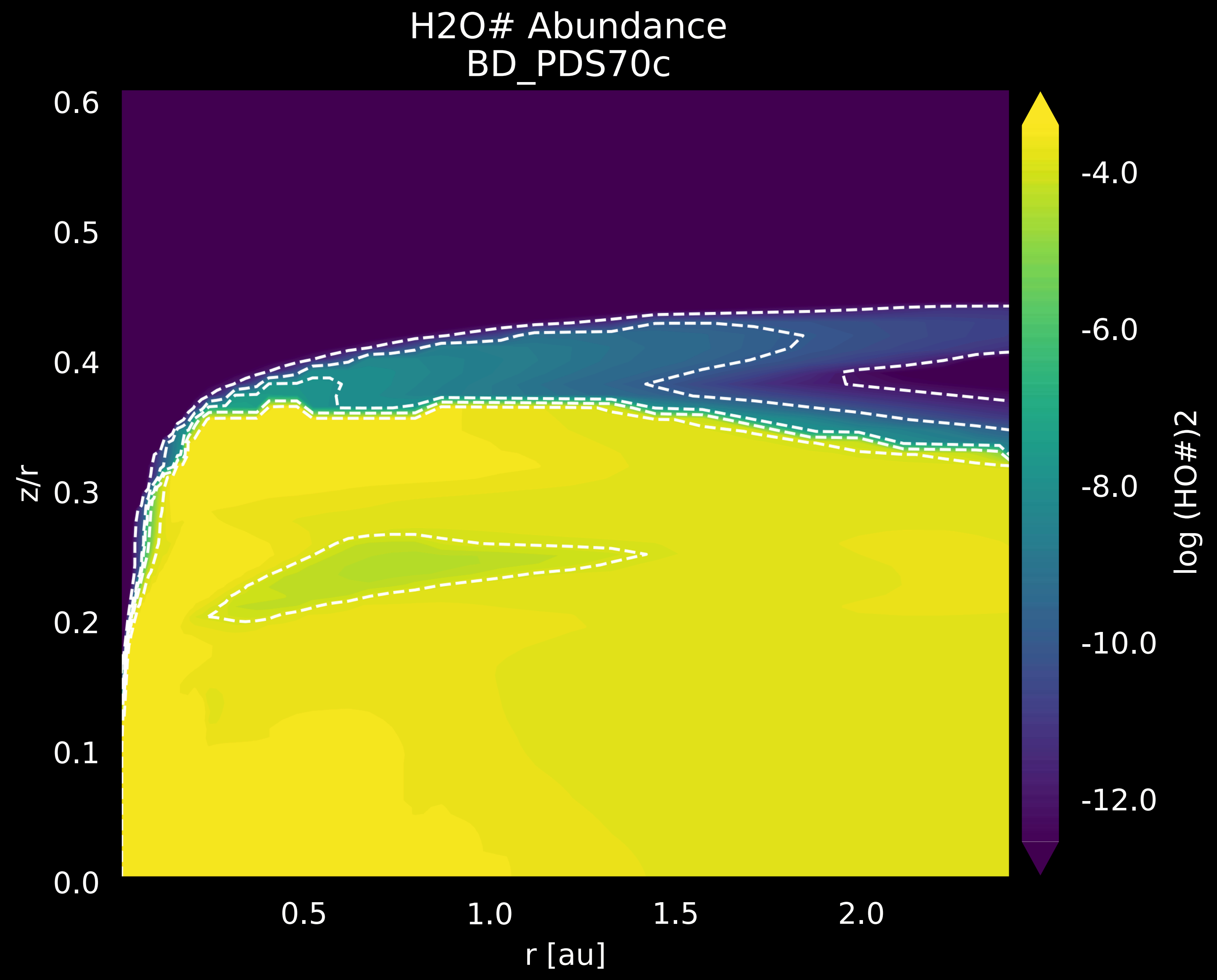
$$\frac{de}{dt} = \sum_k \Gamma_k(T_g, n_{sp}) - \sum_k \Lambda_k(T_g, n_{sp})$$

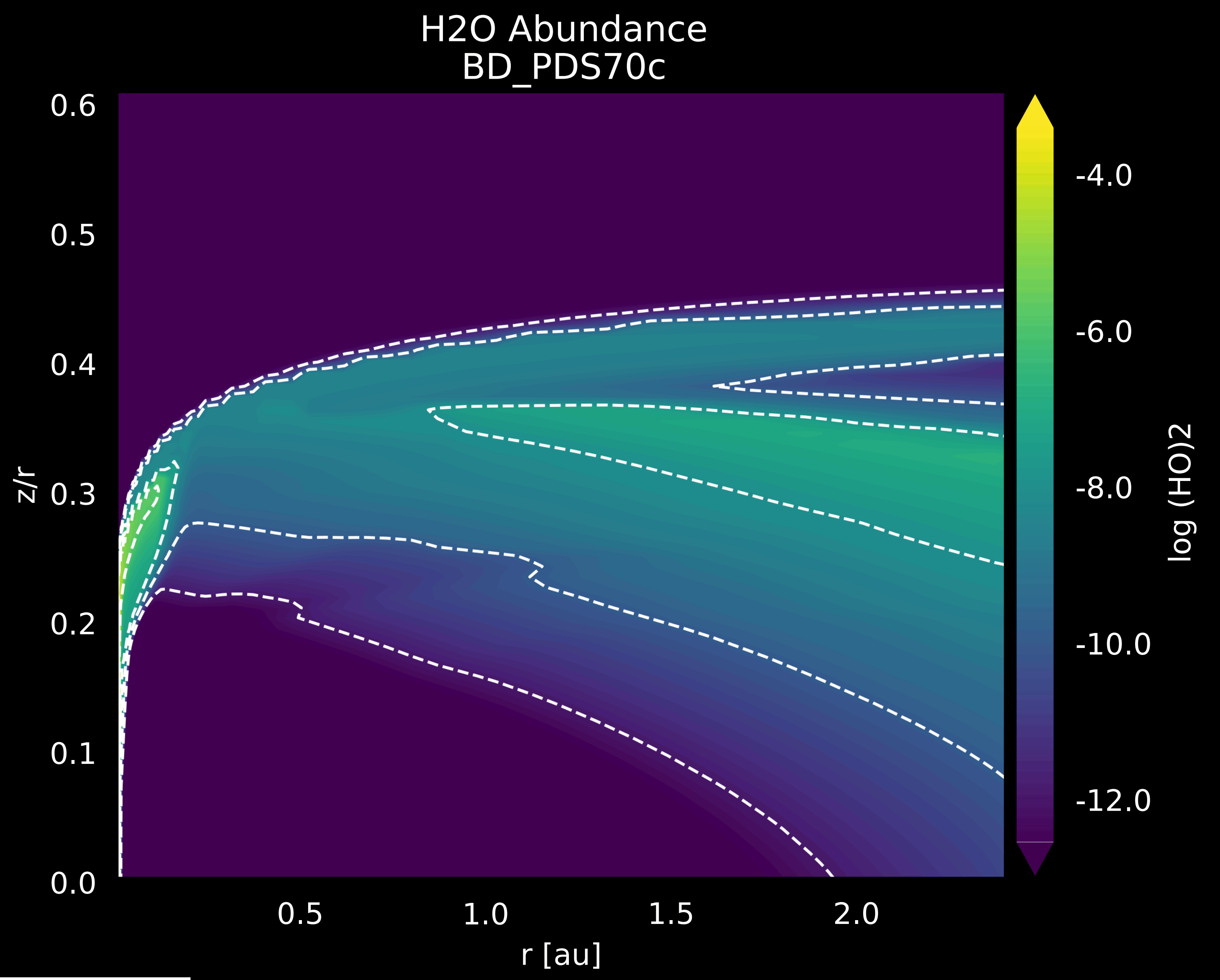
(Woitke et al. 2009, 2016; Kamp et al. 2010, 2017; Thi et al. 2011, 2020)

We can obtain population levels of molecules, flow lines, emission lines, heating-cooling levels, and population levels of species abundances

Con Γk y Λk: These are the different heating and cooling rates [erg cm^{-3}s^{-1}], and nsp: abundances.

3. Chemical Balance of PDS 70 and PDS 70c





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Equation of the formation and destruction rate -> Species densities: $n_{\rm sp}(r,z)$

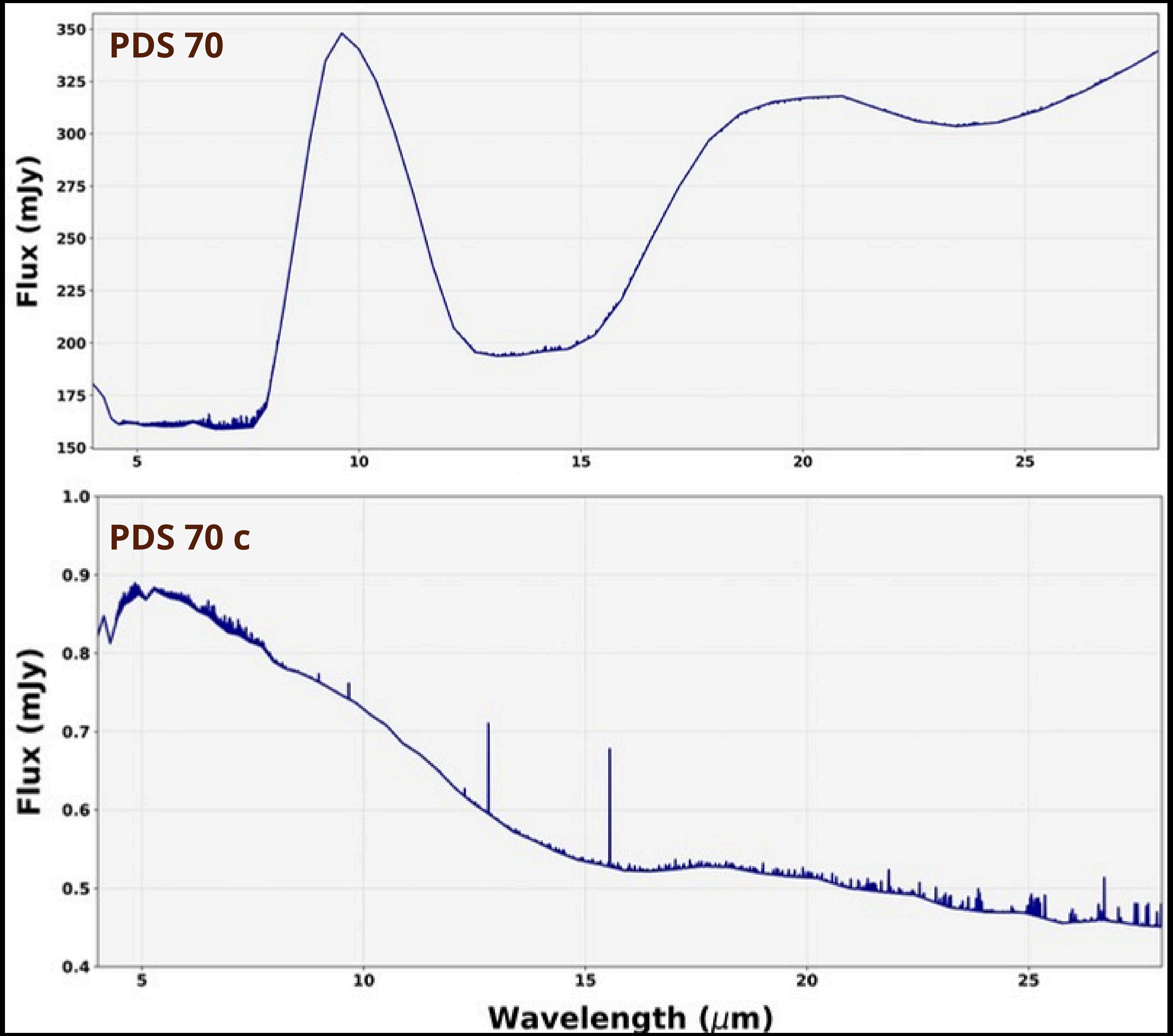
$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = \sum_{jk\ell} R_{jk\to i\ell}(T_{\rm g})\, n_j n_k + \sum_{j\ell}\left(R^{\rm ph}_{j\to i\ell} + R^{\rm cr}_{j\to i\ell}\right) n_j - n_i\left(\sum_{jk\ell} R_{i\ell\to jk}\, n_\ell + \sum_{jk}\left(R^{\rm ph}_{i\to jk} + R^{\rm cr}_{i\to jk}\right)\right)$$

(Woitke et al. 2009, 2016; Kamp et al. 2010, 2017; Thi et al. 2011, 2020)

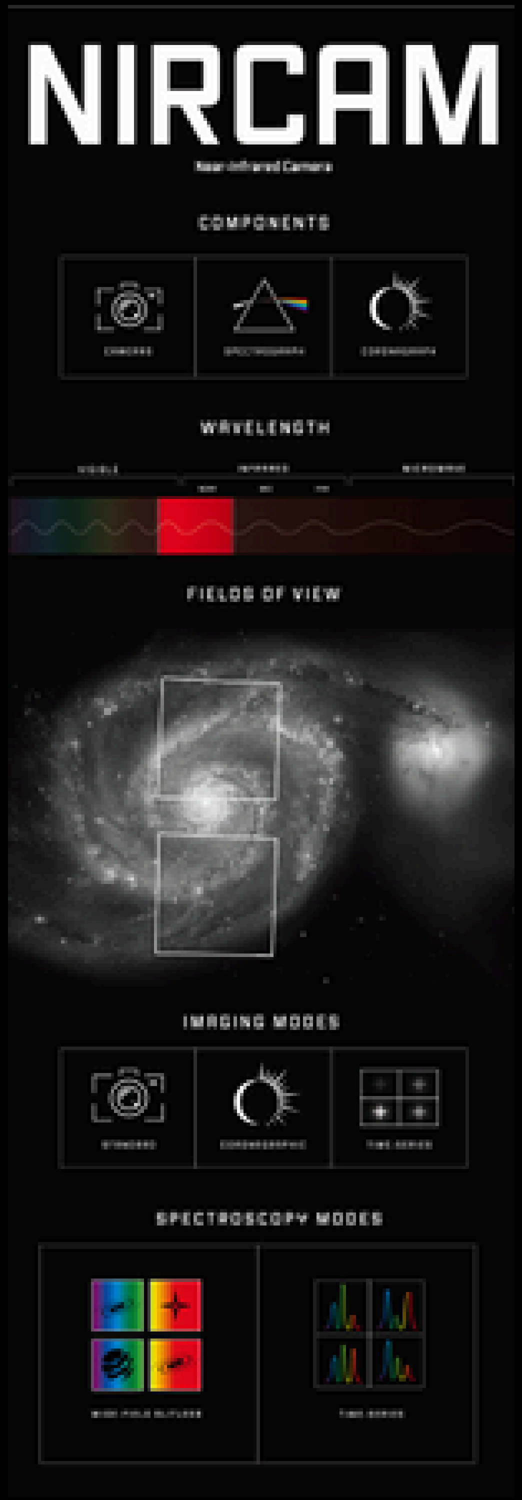
Chemical rates, absorption energies, species masses are required. UMIST, KIDA.

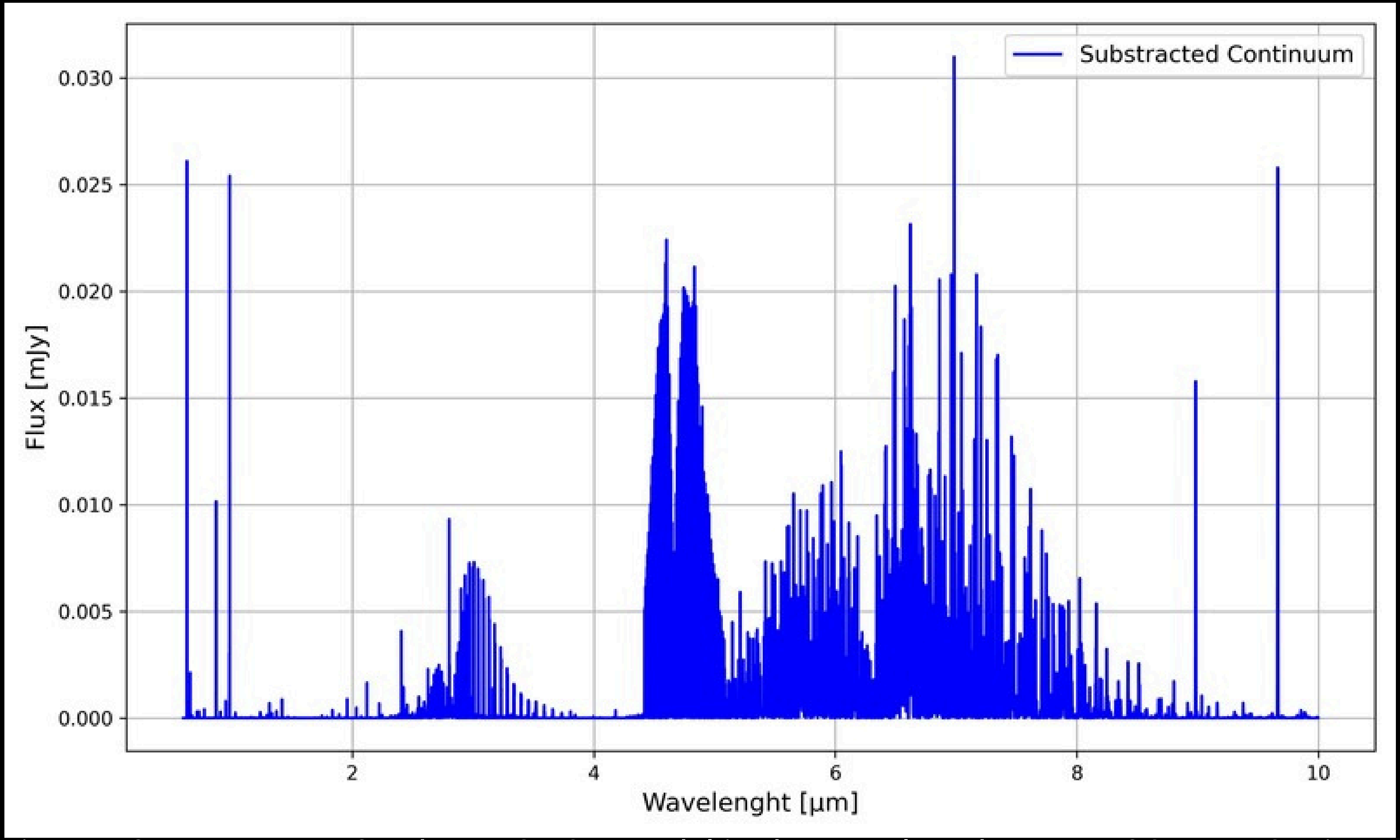
Synthetic spectrum of PDS 70 and PDS 70c

- Synthetic spectral fluxes in mJy, modeled over the range from 0.6 to 28 µm, corresponding to the near-infrared (NIR) and mid-infrared (MIR) regimes for the PDS 70 system (top) and PDS 70c (bottom). The peaks in PDS 70c, they are likely associated with molecular features from species such as H_2O, CH_4, and CO. This wavelength range is crucial for comparison with James Webb Space Telescope (JWST) observations, which are highly sensitive in the NIR and MIR, allowing for detailed analysis of the chemical composition and structure of these environments.



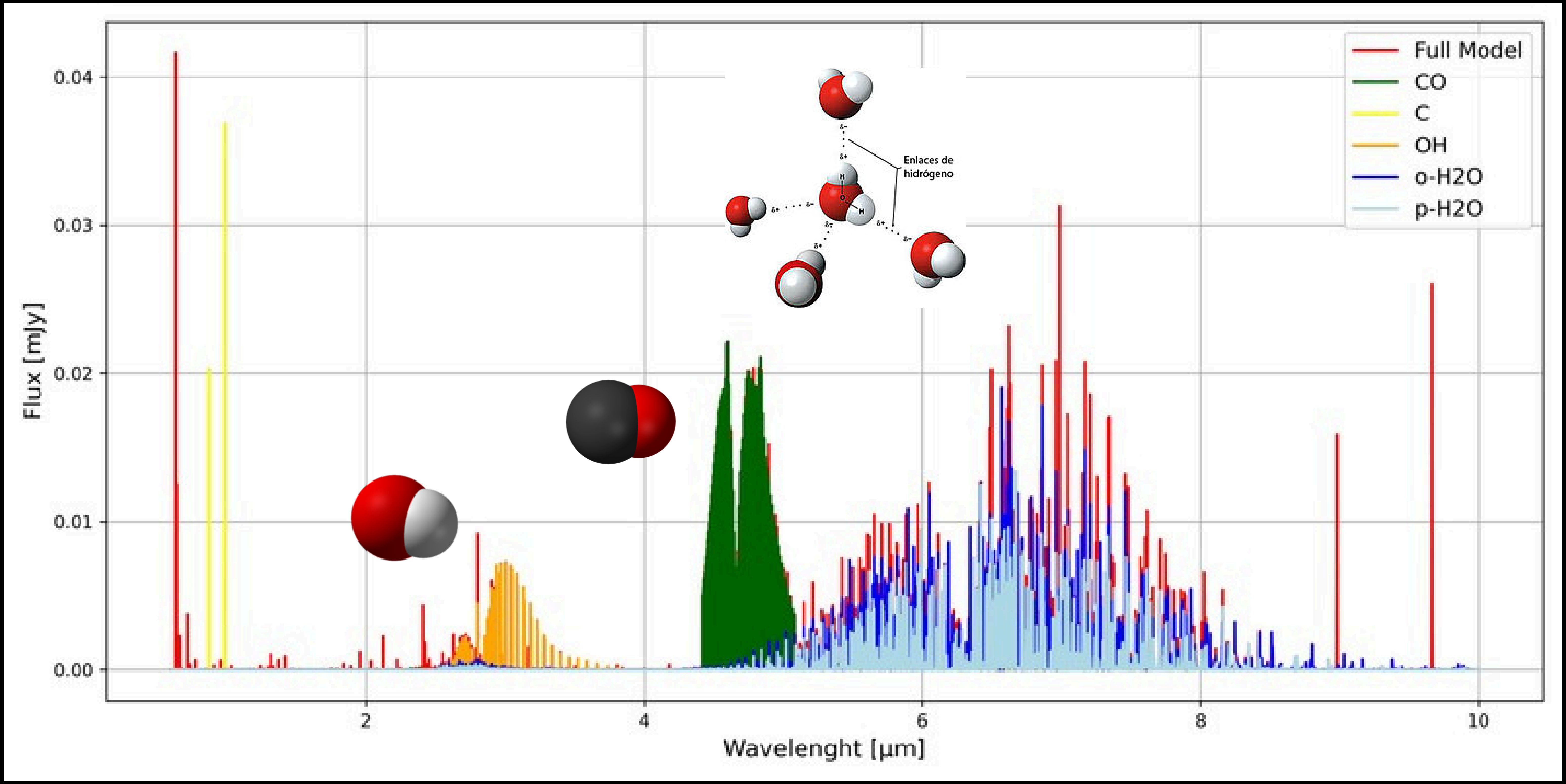
Synthetic spectrum without continuum





This figure shows the continuum-free spectrum for the PDS 70 c model in the wavelength range of 0.6 to 10 microns. The blue curve represents the flux (in mJy) as a function of wavelength, highlighting various spectral features. The spectrum reveals prominent peaks in the mid-infrared, indicating the presence of specific molecular transitions.

Synthetic spectrum without continuum



This figure presents the synthetic spectrum without the continuum for a protoplanetary disk, highlighting the emission lines of various chemical species such as CO, C, OH, ortho-H2O (o-H2O), and para-H2O (p-H2O) within the wavelength range of 0.6 to 10 microns. Each emission line is represented with distinct colors (e.g., CO in red, OH in yellow, etc.), showcasing their individual contributions to the overall spectrum.

Conclusions

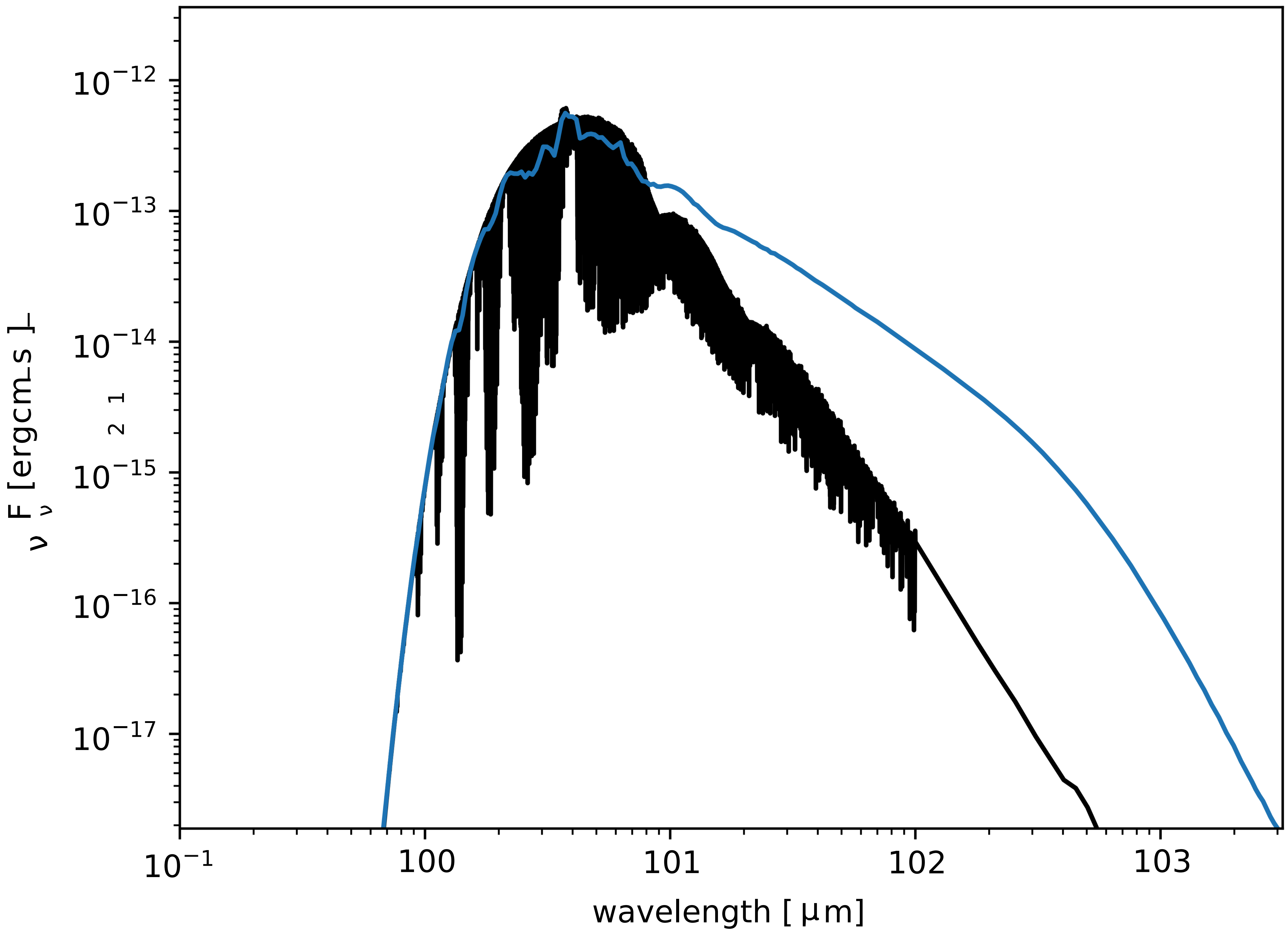
1.The **ProDiMo** modeling accurately reproduces the thermal structure, gas density, and spectral energy distribution (SED) of the PDS 70 and PDS 70 c disks. The SED, particularly at 855 µm, shows strong agreement with observational data, offering crucial constraints for the physical and chemical properties of circumplanetary and protoplanetary disks.

2.The flow of molecular emission lines in PDS 70c, alongside key compounds like H2O and CO, is essential for understanding the chemical pathways and thermal balance in the disk. These insights are fundamental for studying how circumplanetary environments influence moon formation and the overall composition of these emerging bodies.

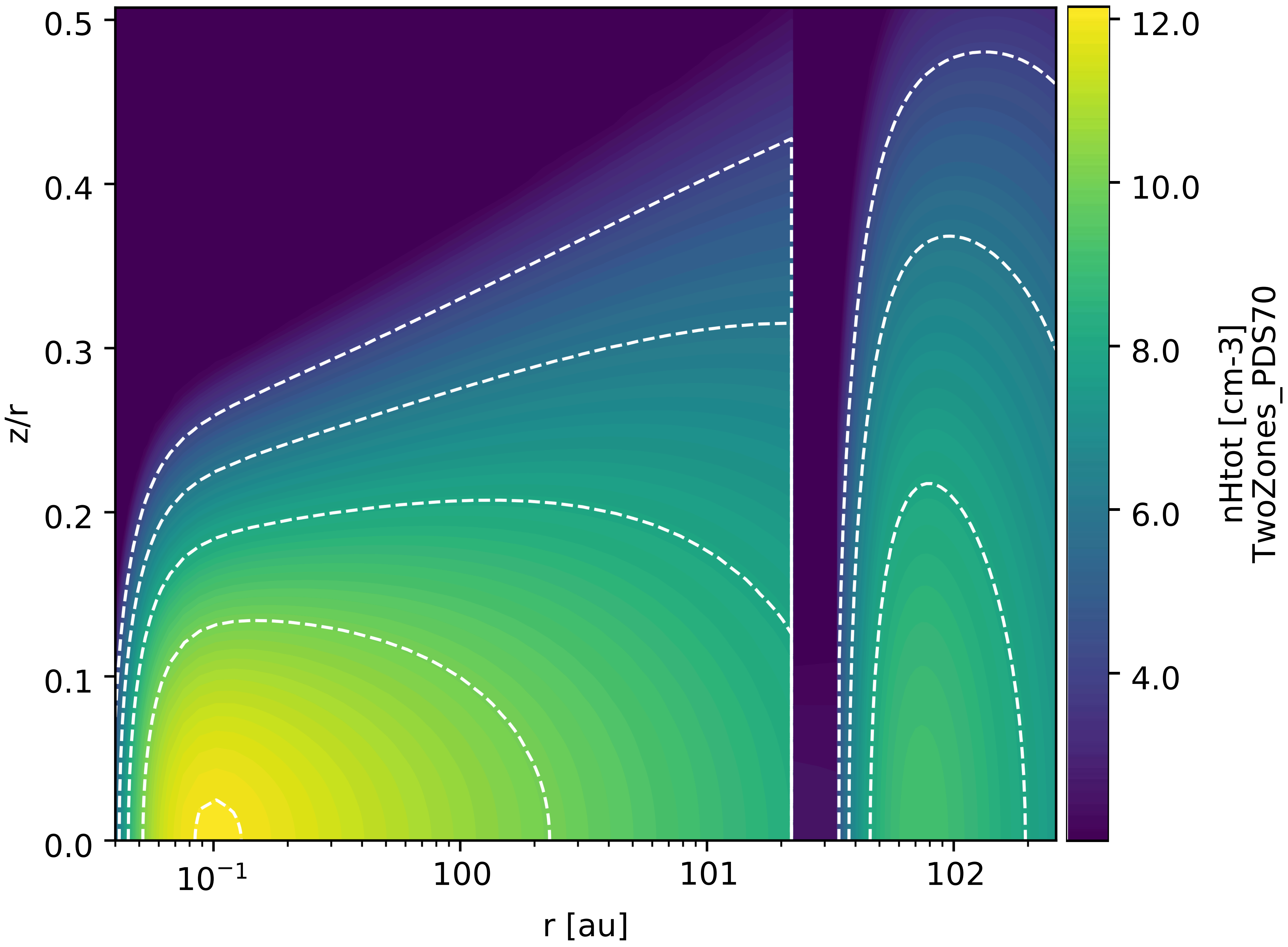
3. Future work will focus on using the **PSyCo** code to model the **formation of moons** within the PDS 70c circumplanetary disk. This will enable a deeper understanding of the disk's evolution and the formation of secondary bodies, advancing our knowledge of satellite systems.

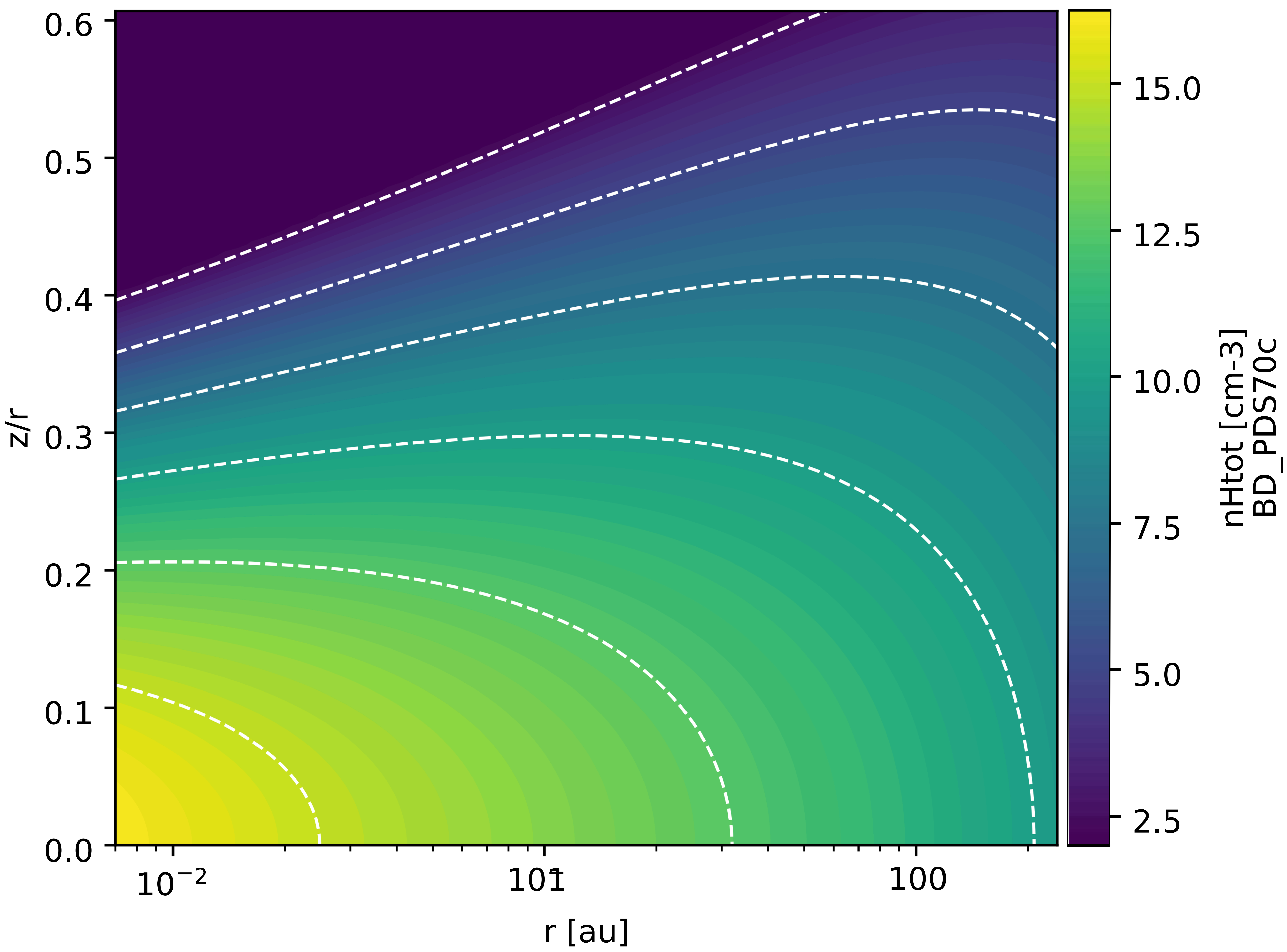
Thank you!

Anexos

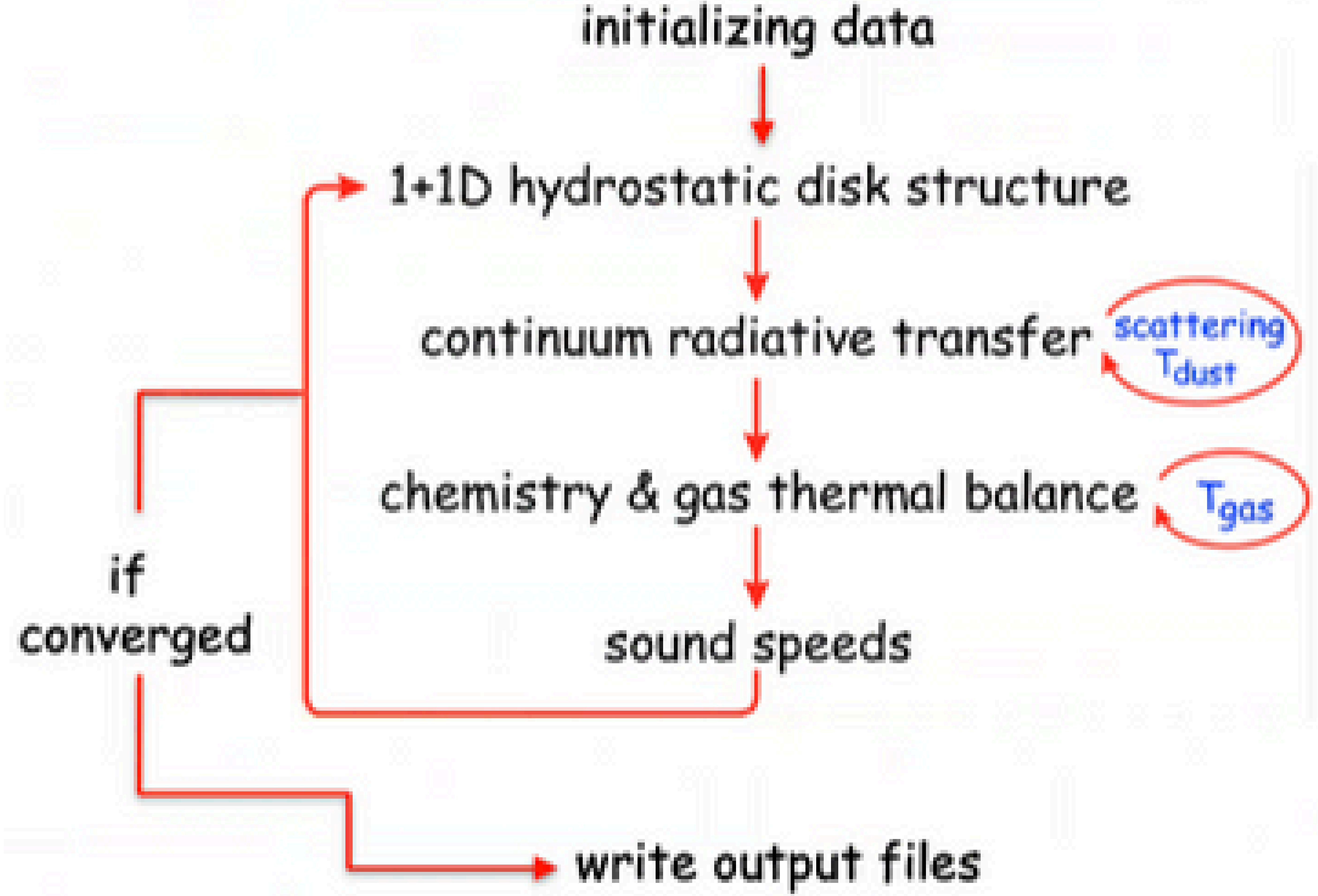


νF_ν [erg cm^{-2} s^{-1}]
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-1}
100
101
102
103
wavelength [μm]


0.5
0.4
0.3
0.2
0.1
0.0
z/r
10^{-1}
100
101
102
r [au]
12.0
10.0
8.0
6.0
4.0
nHtot [cm-3]
TwoZones_PDS70



0.6
0.5
0.4
0.3
0.2
0.1
0.0
z/r
10^{-2}
10^{1}
100
r [au]
15.0
12.5
10.0
7.5
5.0
2.5
nHtot [cm-3]
BD_PDS70c



ProDiMoPy

Woitke et. al 2009