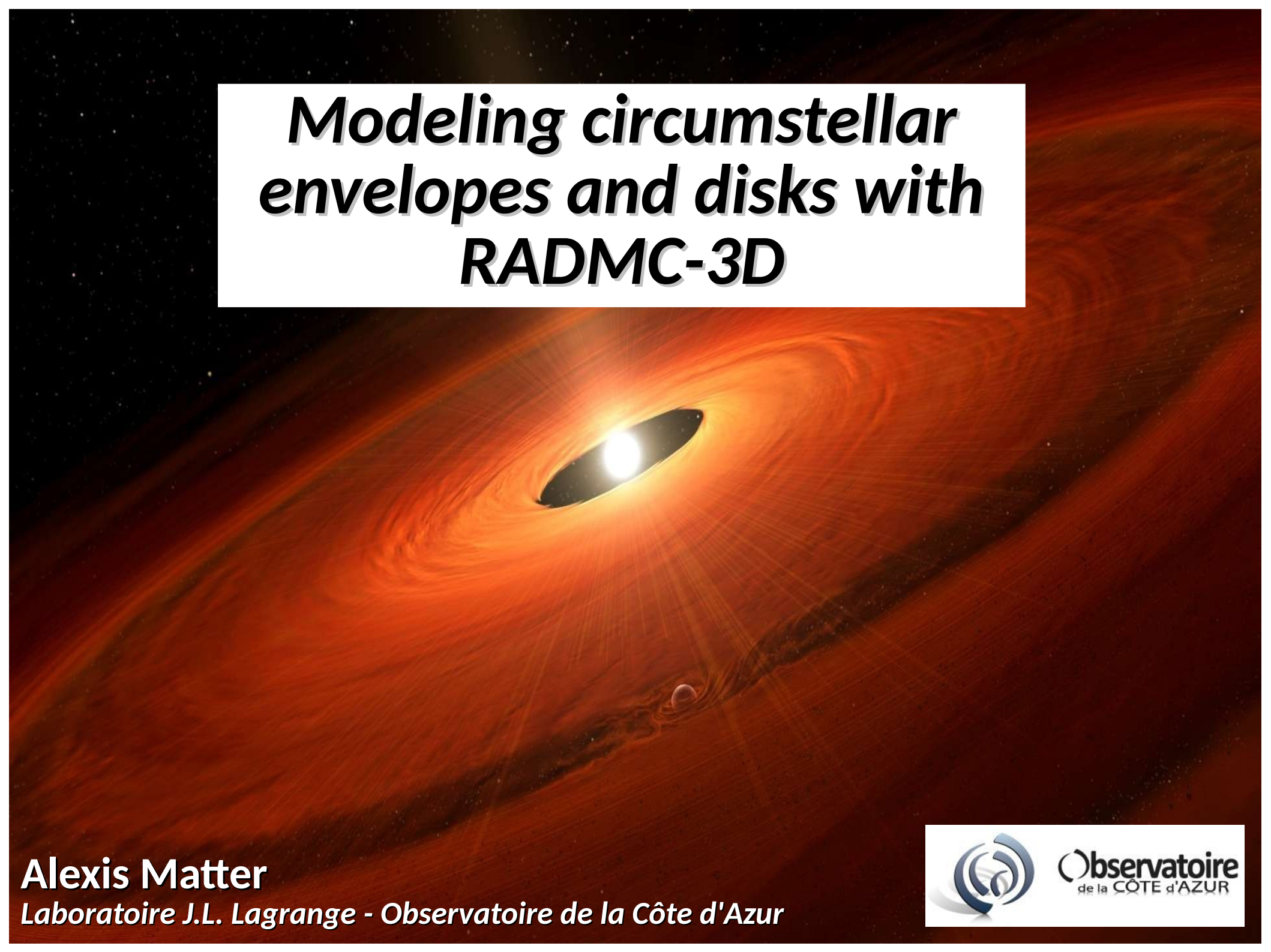
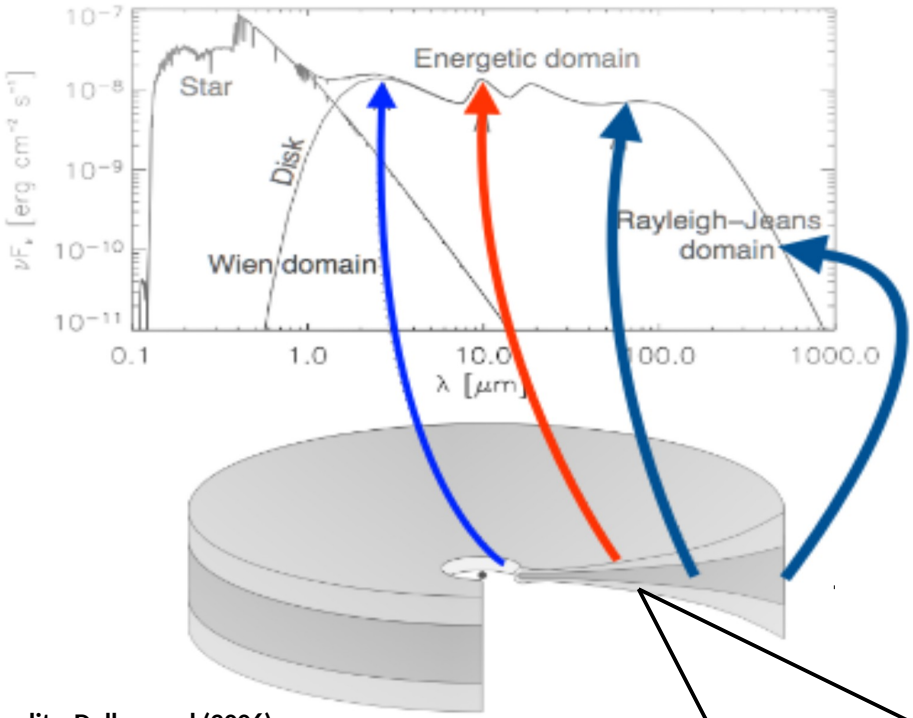
Modeling circumstellar envelopes and disks with RADMC-3D



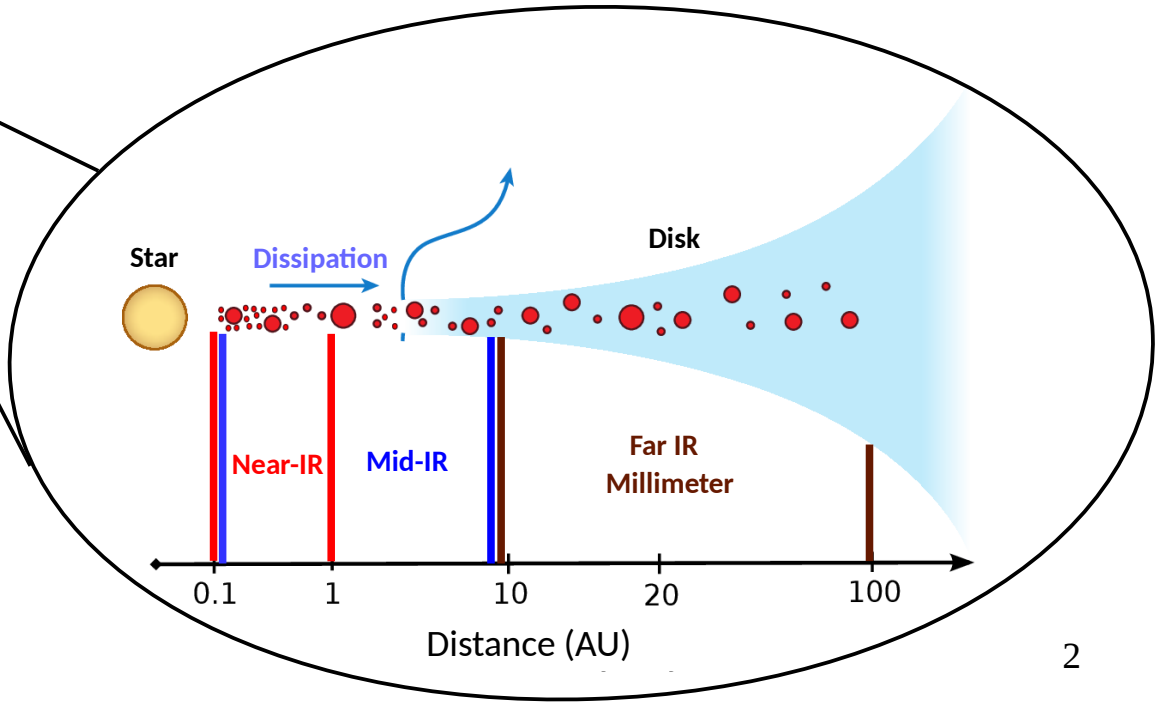
Alexis Matter
Laboratoire J.L. Lagrange - Observatoire de la Côte d'Azur

Circumstellar disks – Spatial distribution and emission

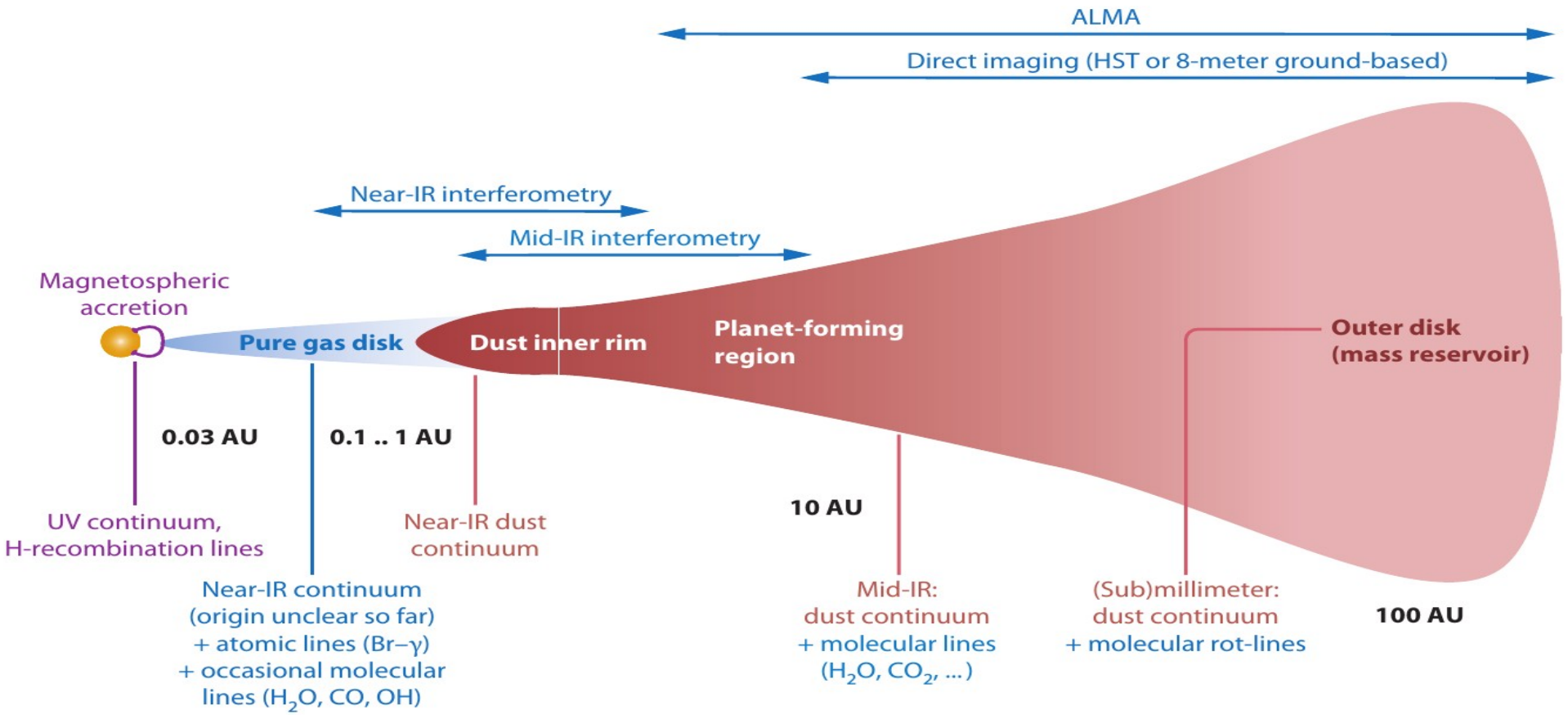
Spectral energy distribution of a young star (< 10 Myr)



Credit : Dullemond (2006)



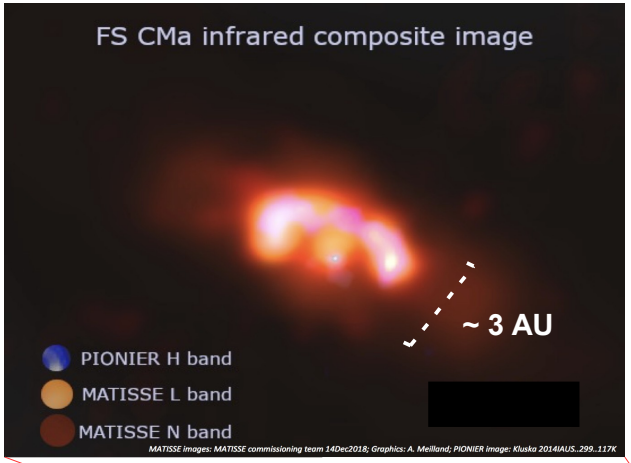
Circumstellar disks – Spatial distribution and emission



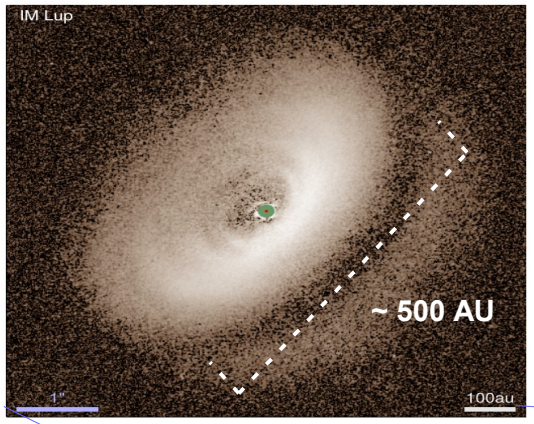
Taken from Dullemond & Monnier (2010)

Circumstellar disks – Spatial distribution and emission

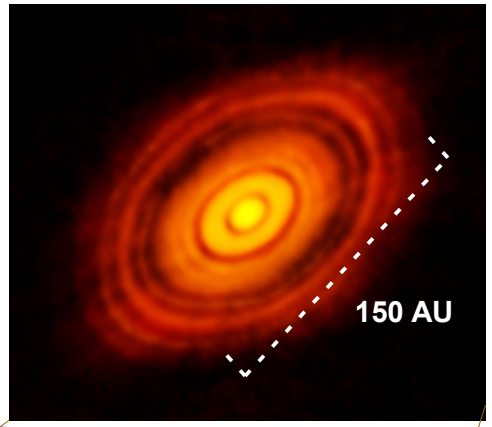
IR interferometry
(PIONIER, MATISSE)

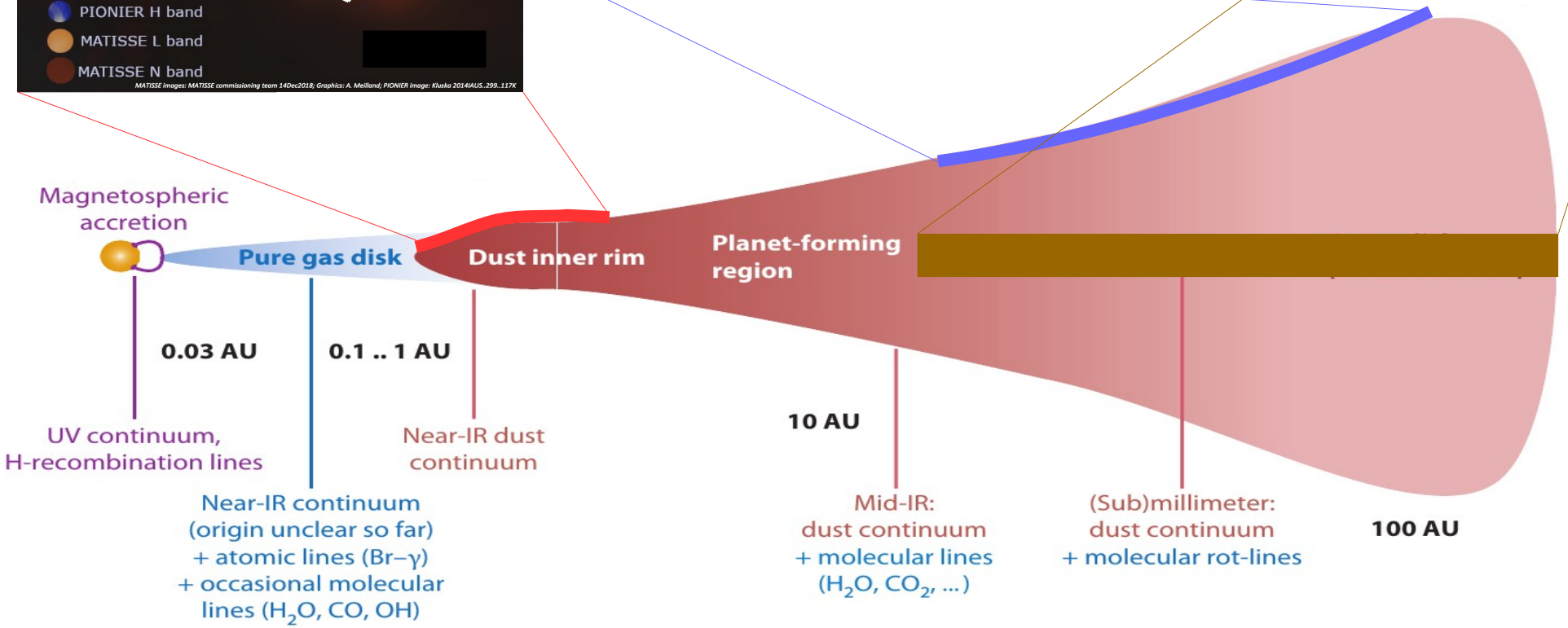


VLT/SPHERE
(Avenhaus et al., 2018)



ALMA interferometer
(Brogan et al., 2015)

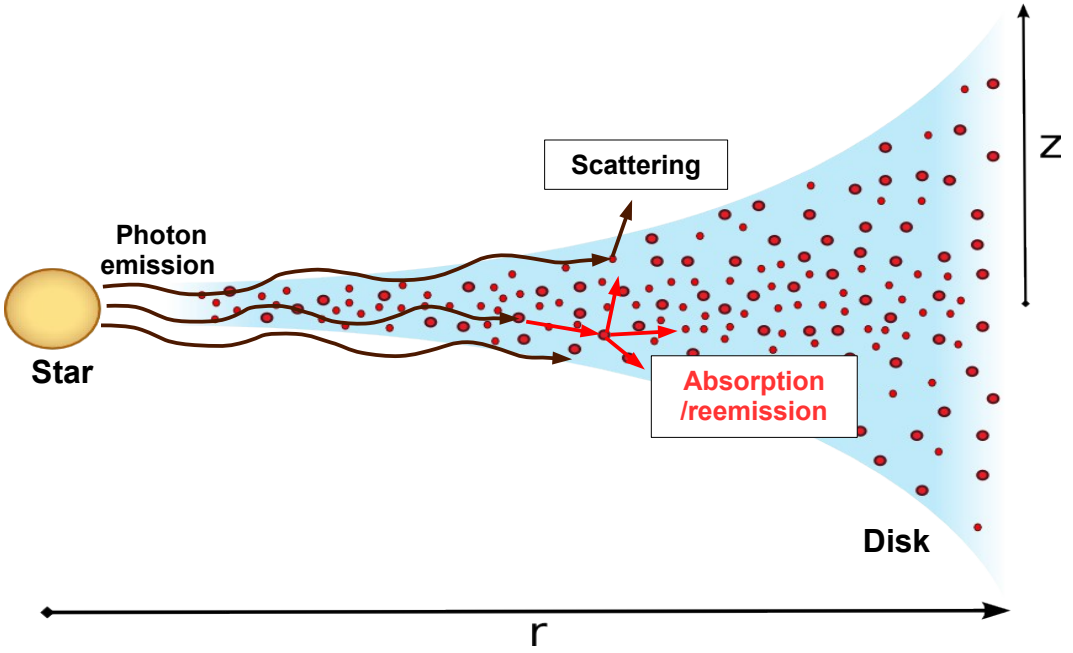




Taken from Dullemond & Monnier (2010)

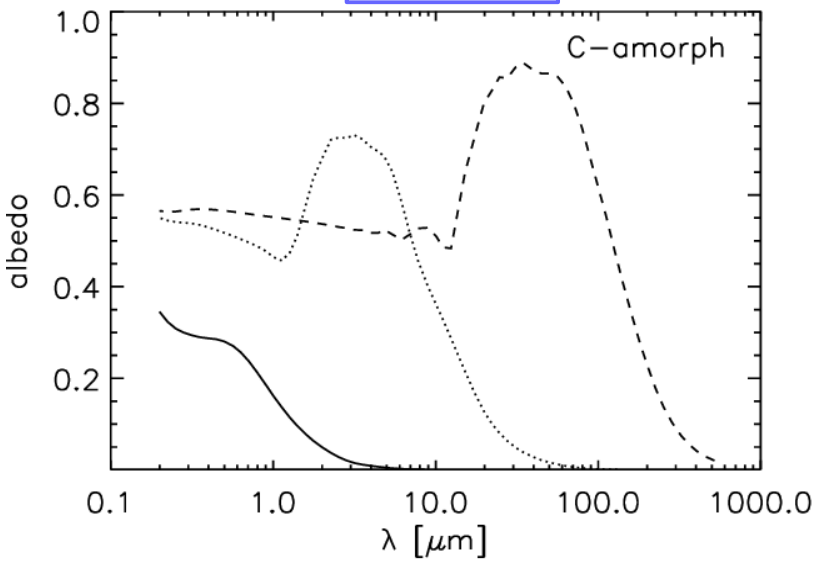
Circumstellar disks – Grain size regime and opacity

matter/radiation interaction

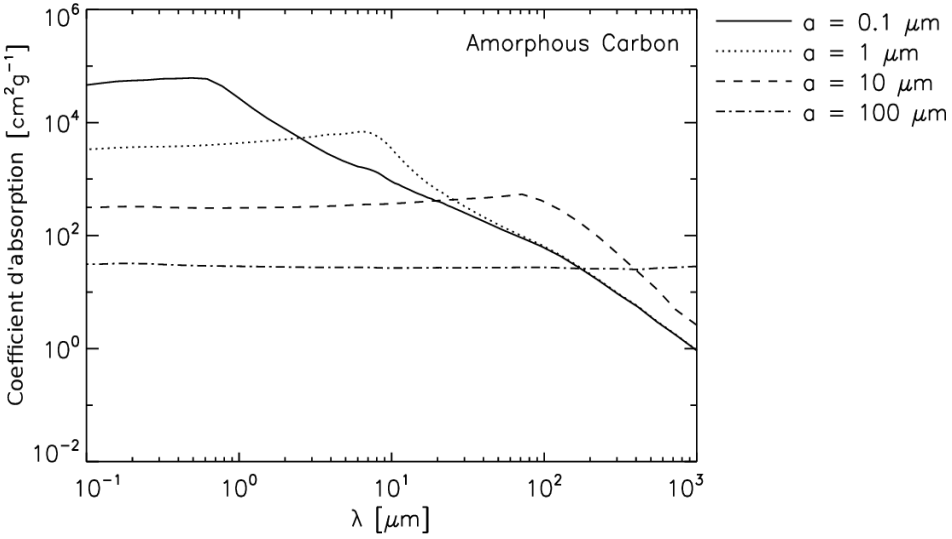


Dependence wavelength / dust grain size

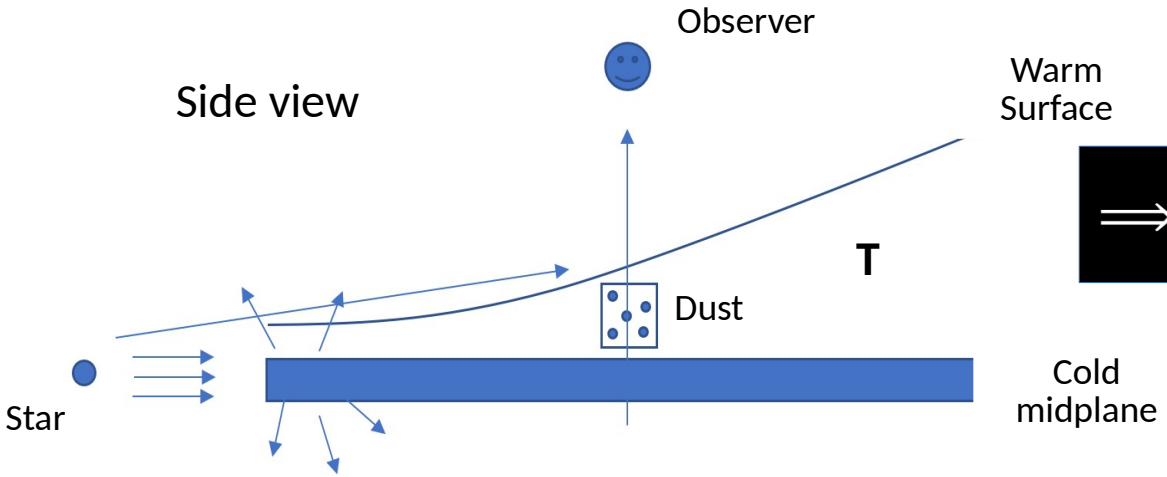
Scattering



Absorption

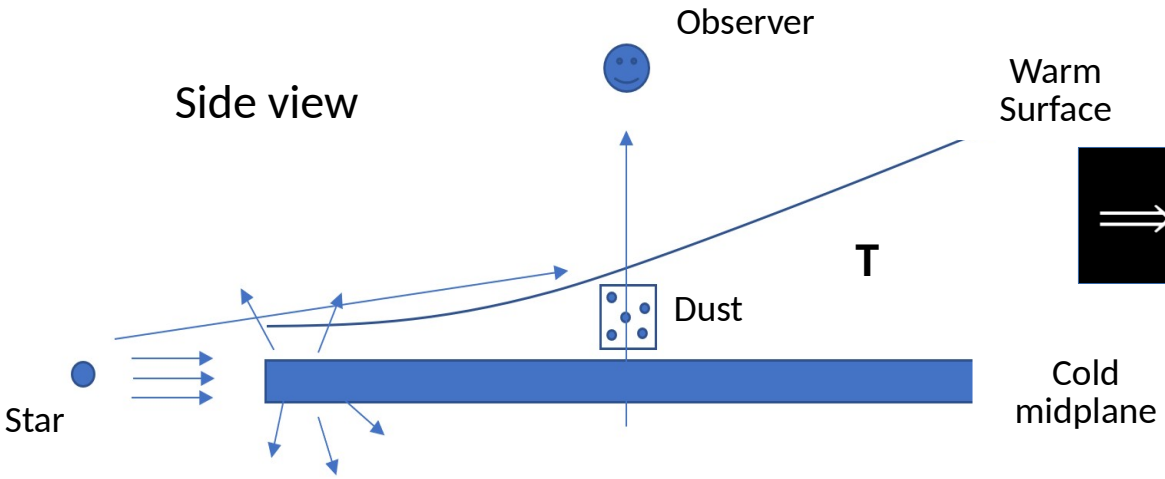


Analytical modeling ?



$$\Longrightarrow I_{disque} = B_\lambda(T) * (1 - e^{-\tau_\lambda})$$

Analytical modeling ?

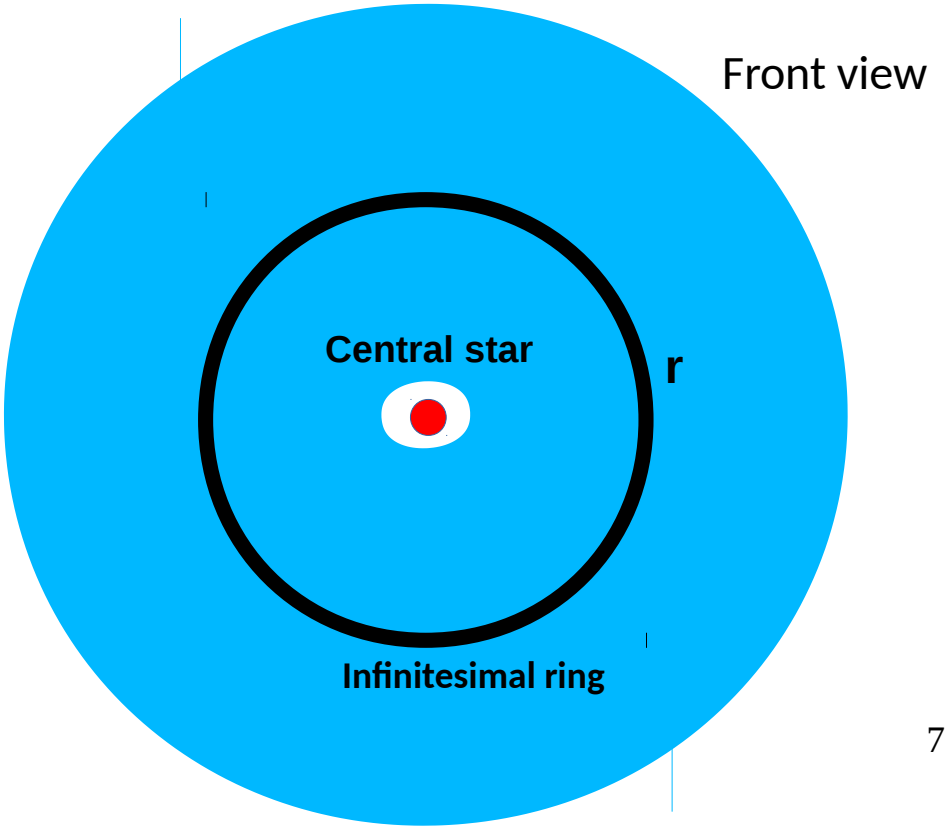


$$\Longrightarrow I_{disque} = B_\lambda(T) * (1 - e^{-\tau_\lambda})$$

Temperature-gradient model

$T_r = T_0 r^{-q}$ — **Temperature radial profile**

$\Sigma_r = \Sigma_0 r^{-p}$ — **Surface density profile**

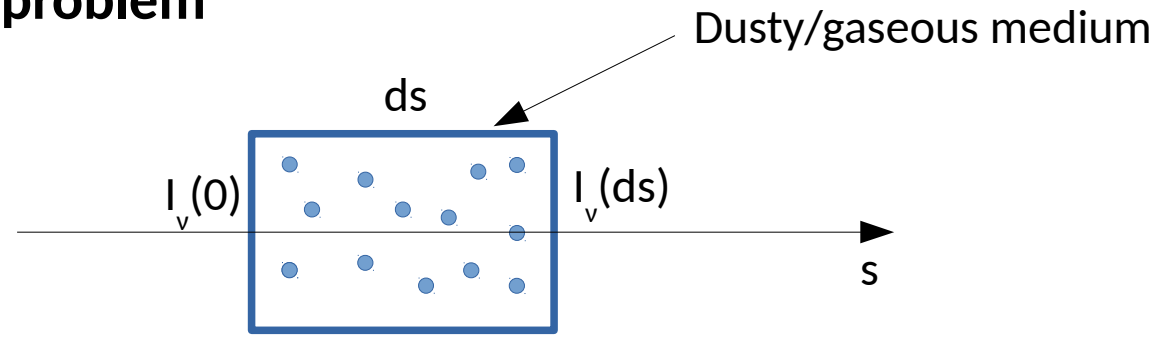


Radiative transfer modeling with RADMC-3D

Introduction

RADMC-3D is a software package for astrophysical radiative transfer calculations in arbitrary 1-D, 2-D or 3-D geometries. It is mainly written for continuum radiative transfer in dusty media, but also includes modules for gas line transfer and gas continuum transfer.

The radiative transfer problem



$$\frac{dI_\nu}{ds} = j_\nu^{\rm therm} + j_\nu^{\rm scat} - (\alpha_\nu^{\rm abs} + \alpha_\nu^{\rm scat}) I_\nu$$

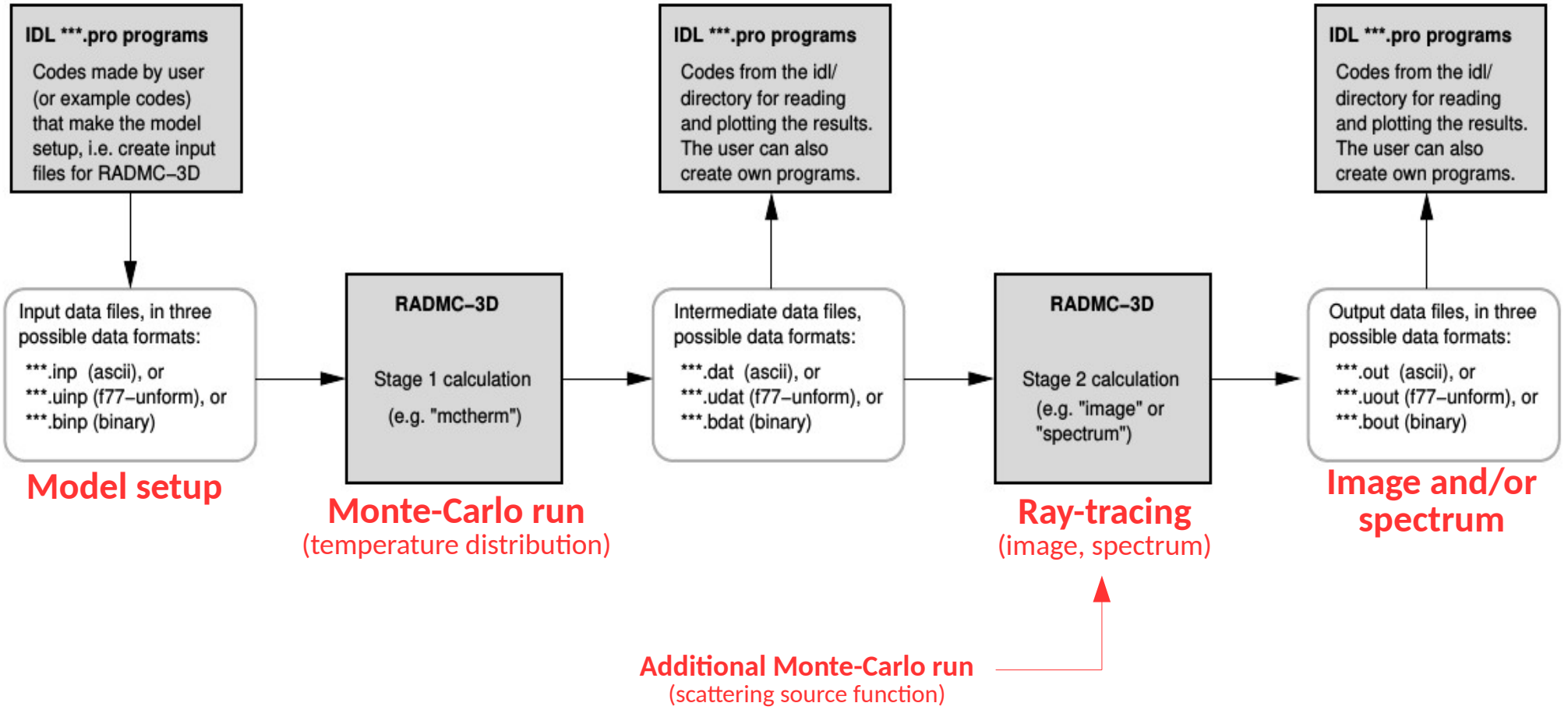
Thermal 'source' function

scattering 'source' function

Source term
(add energy to that ray)

Extinction term
(remove energy from that ray)

RADMC-3D dataflow



RADMC-3D – model setup

Which spatial distribution of dust/gas do i want for my model ?

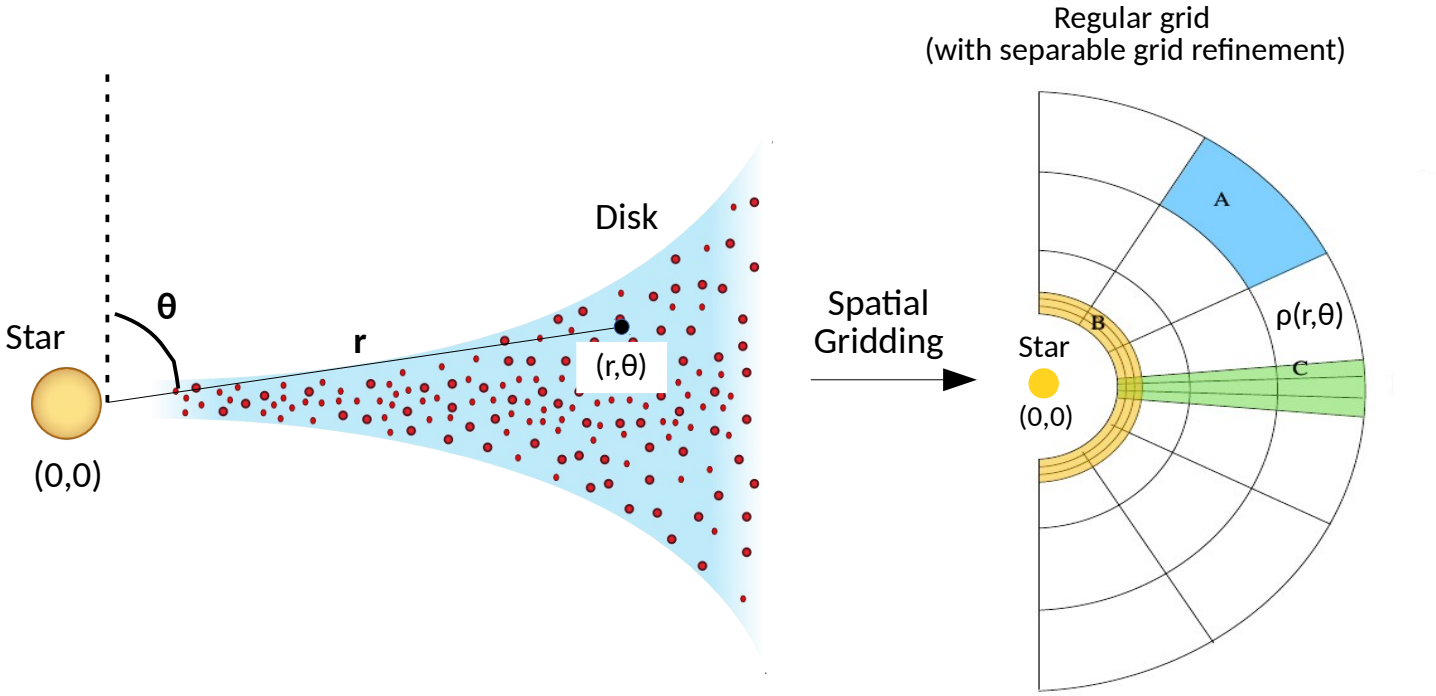
- Coordinate system = cartesian (x,y,z) or spherical (r,θ,φ)
- Spatial grid = 1D (spherical), 2D (spherical), or 3D (spherical or cartesian)

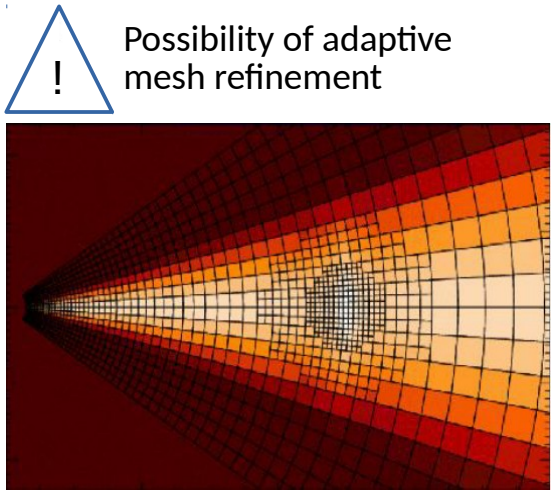
RADMC-3D – model setup

Which spatial distribution of dust/gas do i want for my model ?

- Coordinate system = cartesian (x,y,z) or spherical (r,θ,φ)
- Spatial grid = 1D (spherical), 2D (spherical), or 3D (spherical or cartesian)

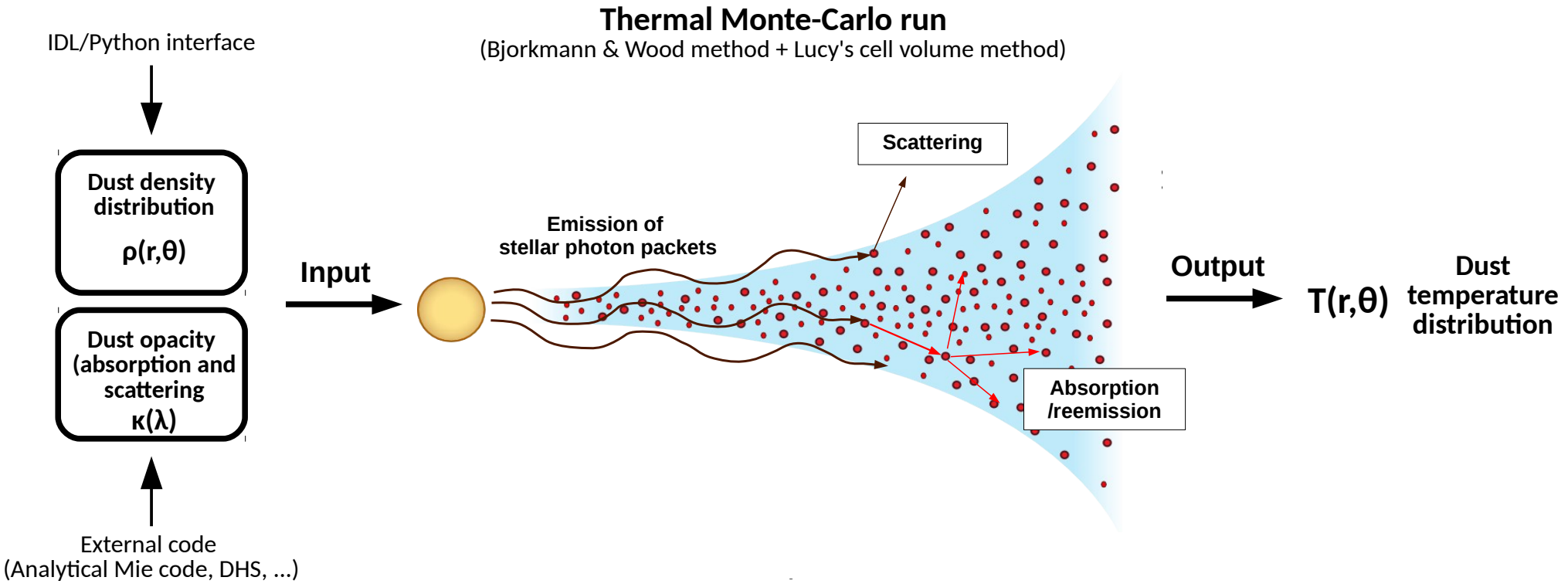
Example : 2D model (axial symmetry)





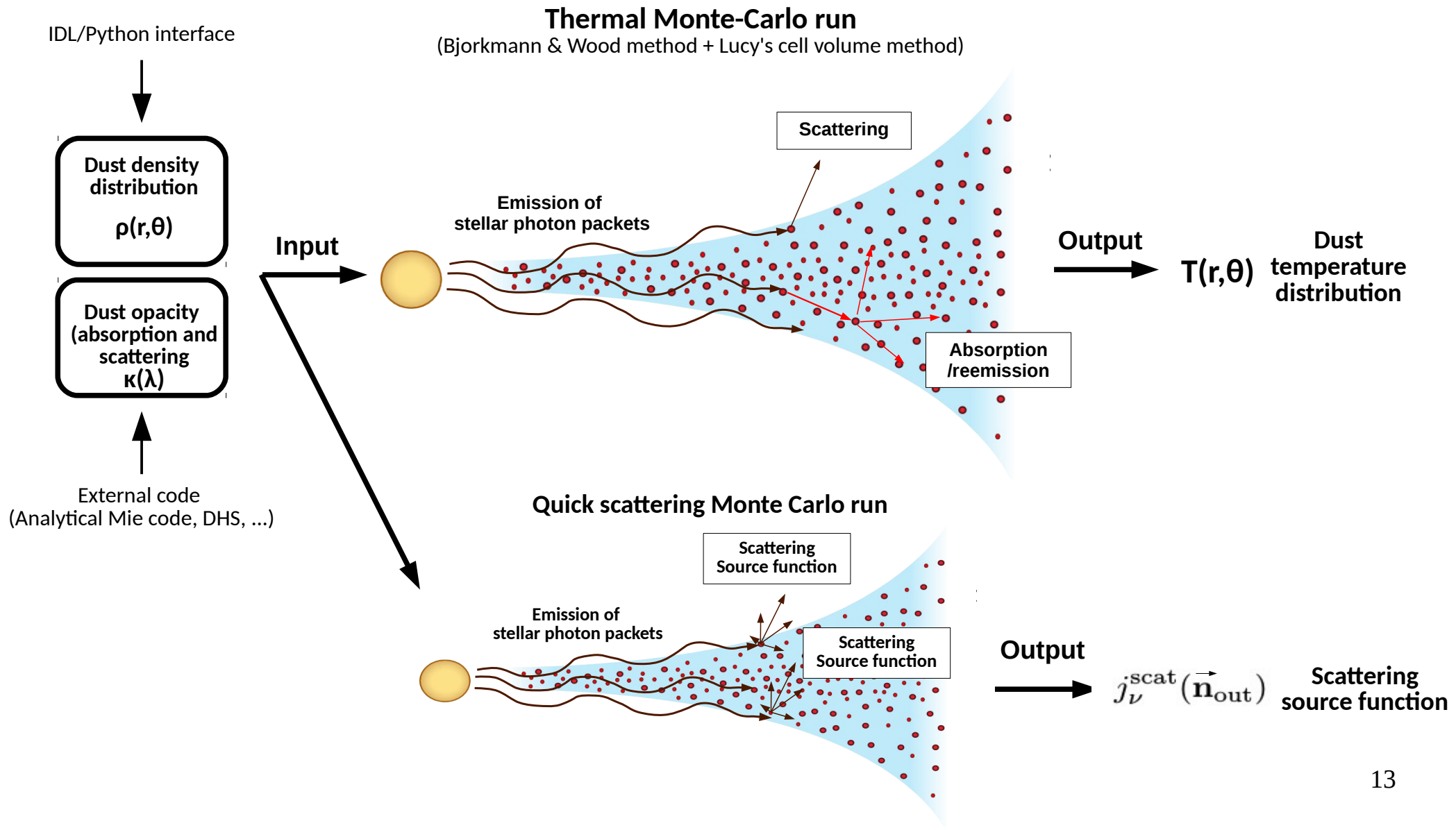
RADMC-3D – Monte Carlo run

Then, what is the dust EQUILIBRIUM temperature everywhere in the object ?



RADMC-3D – Monte Carlo run

Then, what is the scattering source function everywhere in the object ?



RADMC-3D – Making images and SED

Finally, how will my object look like ? What is the I(λ,x,y) ?

Thermal Monte Carlo run

Temperature distribution

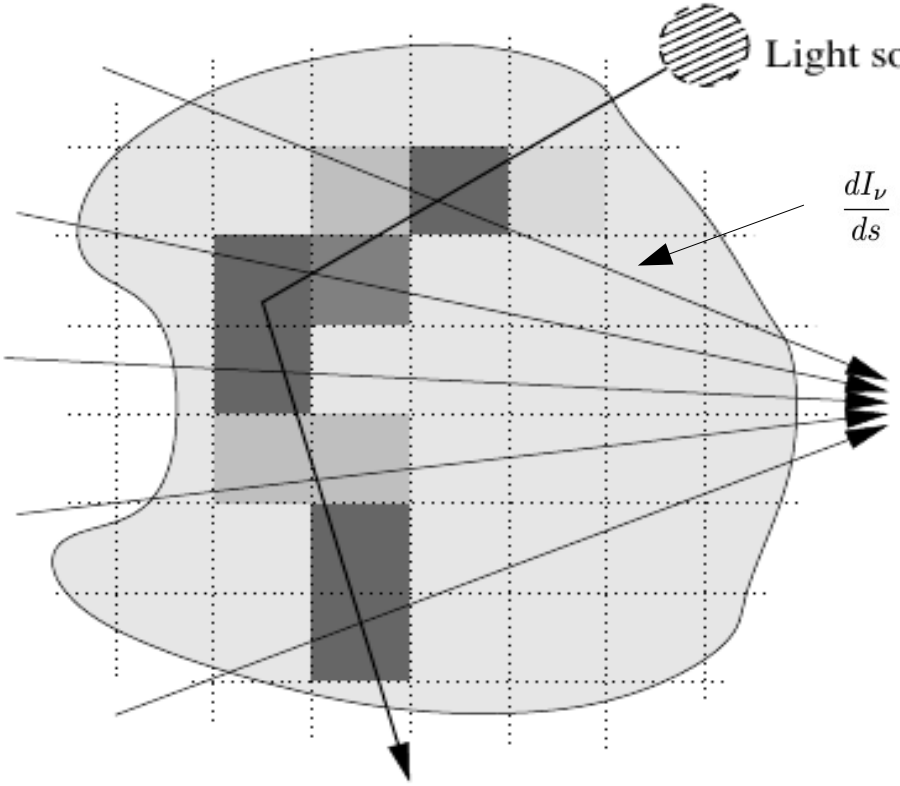
T(r,θ)

Scattering source function

Additional Monte Carlo run

Input

Ray-tracing (at each wavelength)

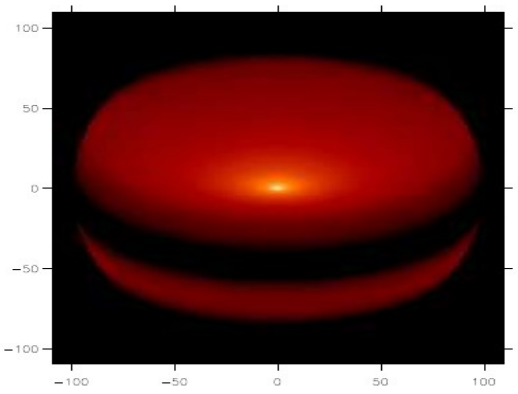


Integration along the ray

$$\frac{dI_\nu}{ds} = j_\nu^{\rm therm} + j_\nu^{\rm scat} - (\alpha_\nu^{\rm abs} + \alpha_\nu^{\rm scat}) I_\nu$$

Output

I(λ,x,y)



RADMC-3D – additional features

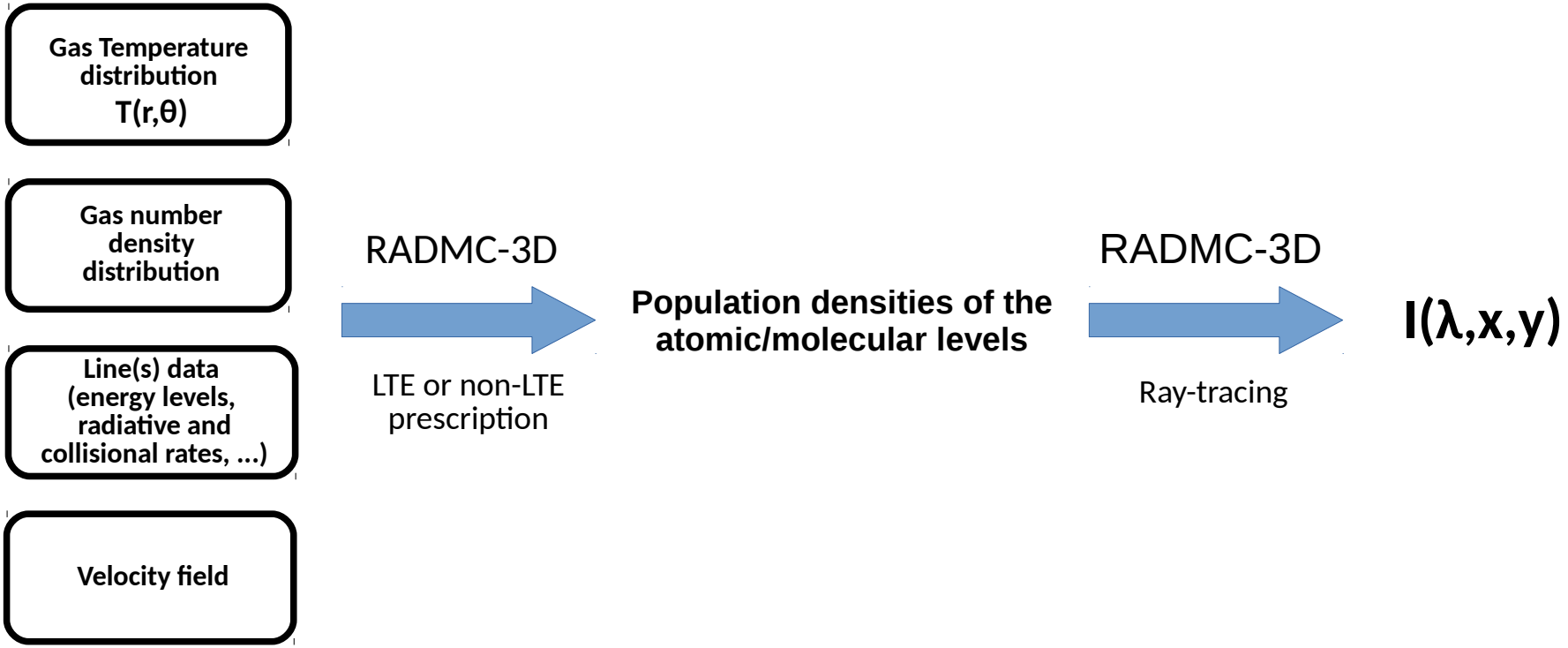
Modes of dust scattering

- ✔ No scattering
- ✔ Isotropic scattering
- ✔ Anisotropic scattering using the Henyey-Greenstein parameter g=<cosθ>
- ✔ Anisotropic scattering using tabulated phase function
- ✔ Anisotropic scattering with polarization for last scattering (requires scattering matrix)
- ✔ Anisotropic scattering with polarization, full treatment (requires scattering matrix)

The input opacity file must contain all the scattering information (scattering opacity, g parameter, scattering matrix, ...)

RADMC-3D – additional features

Computation of spectra/images in gas lines (channel maps)



Gas continuum radiative transfer

✔ Gas free/free absorption/emission (under testing)

✔ Gas bound/free absorption/emission (under development)

RADMC-3D – last but not least

Parallelization
✔ Monte Carlo runs → OpenMP parallelized version

Availability of the code
✔ Publicly available and free of charge
✔ Package downloadable at : **http://www.ita.uni-heidelberg.de/ dullemond/software/radmc-3d/**

User support
✔ Detailed manual included in the package
✔ Mailing list for updates and bug reports

Not included yet
✔ Radiative transfer computation for quantum heated grains (PAHs, VSGs)
✔ No self-consistent computation of the disk vertical structure (hydrostatic equilibrium)
✔ No dust/gas dynamics considered ('static' models)