The radiative transfer code POLARIS

Introduction and examples

Robert Brauer

July 2-4, 2019

An introduction to radiative transfer &
application in astrophysics and plasma physics

École Doctorale « Sciences physique et de l'ingénieur »

What is POLARIS?

Radiative transfer simulation code

- Numerical approaches to solve the RT equation
  - **Monte-Carlo** (temperature and scattering)
  - **Raytracing** (continuum and line emission)
- Analytical models and (M)HD simulations
- Emission maps and spectral energy distributions

Development

- C++ (main code) and Python (optional toolkit)
- By Stefan Reissl and Robert Brauer

History of POLARIS

Apr., 1999	MC3D in version 1 (basis for POLARIS, Wolf et al. 1999)
Feb., 2003	MC3D in version 2 (basis for POLARIS, Wolf 2003)
2010	MC3D in version 4 (basis for POLARIS)
2014	**Start of POLARIS development** (version 1.0)
June, 2014	⇒ Reissl et al. (2014)
July, 2015	Mol3D (basis for line RT in POLARIS version 2.0, Ober et al. 2015)
Apr., 2016	⇒ Brauer et al. (2016)
Sept., 2016	⇒ Reissl et al. (2016)
2017	Final merge of MC3D and Mol3D into POLARIS (version 3.0)
Sept., 2017	**First POLARIS workshop** (in Heidelberg)
May, 2017	⇒ Brauer et al. (2017a)
July, 2017	⇒ Reissl et al. (2017)
Nov., 2017	⇒ Brauer et al. (2017b)
Mai, 2018	⇒ Reissl et al. (2018)
Aug., 2018	**First public release of POLARIS** (version 4.0)
Jan., 2019	⇒ Seifried et al. (2019)
Jul., 2019	**Current stable release version 4.05.**

Installation of POLARIS

Download from our homepage

- `www1.astrophysik.uni-kiel.de/~polaris`
- Execute `./polaris.run` to start installation

Installation of POLARIS

Download from our homepage

- `www1.astrophysik.uni-kiel.de/~polaris`
- Execute `./polaris.run` to start installation

Download from our GitHub repository

- `https://github.com/robertbrauer1988/Polaris.git`
- Use `git clone` to download the POLARIS repository
- Execute `./install_polaris.sh` to start installation

Installation of POLARIS

Download from our homepage

- `www1.astrophysik.uni-kiel.de/~polaris`
- Execute `./polaris.run` to start installation

Download from our GitHub repository

- `https://github.com/robertbrauer1988/Polaris.git`
- Use `git clone` to download the POLARIS repository
- Execute `./install_polaris.sh` to start installation

$\Rightarrow$ **Already installed on your training PCs**

Using POLARIS

ASCII command files

- Most fundamental way of using POLARIS
- Files in UML-like script language to start simulation
- First choice when using (M)HD simulations

Using POLARIS

ASCII command files

- Most fundamental way of using POLARIS
- Files in UML-like script language to start simulation
- First choice when using (M)HD simulations

PolarisTools (Python scripts)

- Create grids, start simulations, and plot results
- Needs Python and other modules (e.g. numpy, matplotlib)
- First choice when using analytical models

Using POLARIS

ASCII command files

- Most fundamental way of using POLARIS
- Files in UML-like script language to start simulation
- First choice when using (M)HD simulations

PolarisTools (Python scripts)

- Create grids, start simulations, and plot results
- Needs Python and other modules (e.g. numpy, matplotlib)
- First choice when using analytical models

⇒ **The following exercises are based on PolarisTools**

PolarisTools (Python scripts)

polaris-gen

- Generates binary files that contain the grid/model

polaris-run

- Executes POLARIS simulations

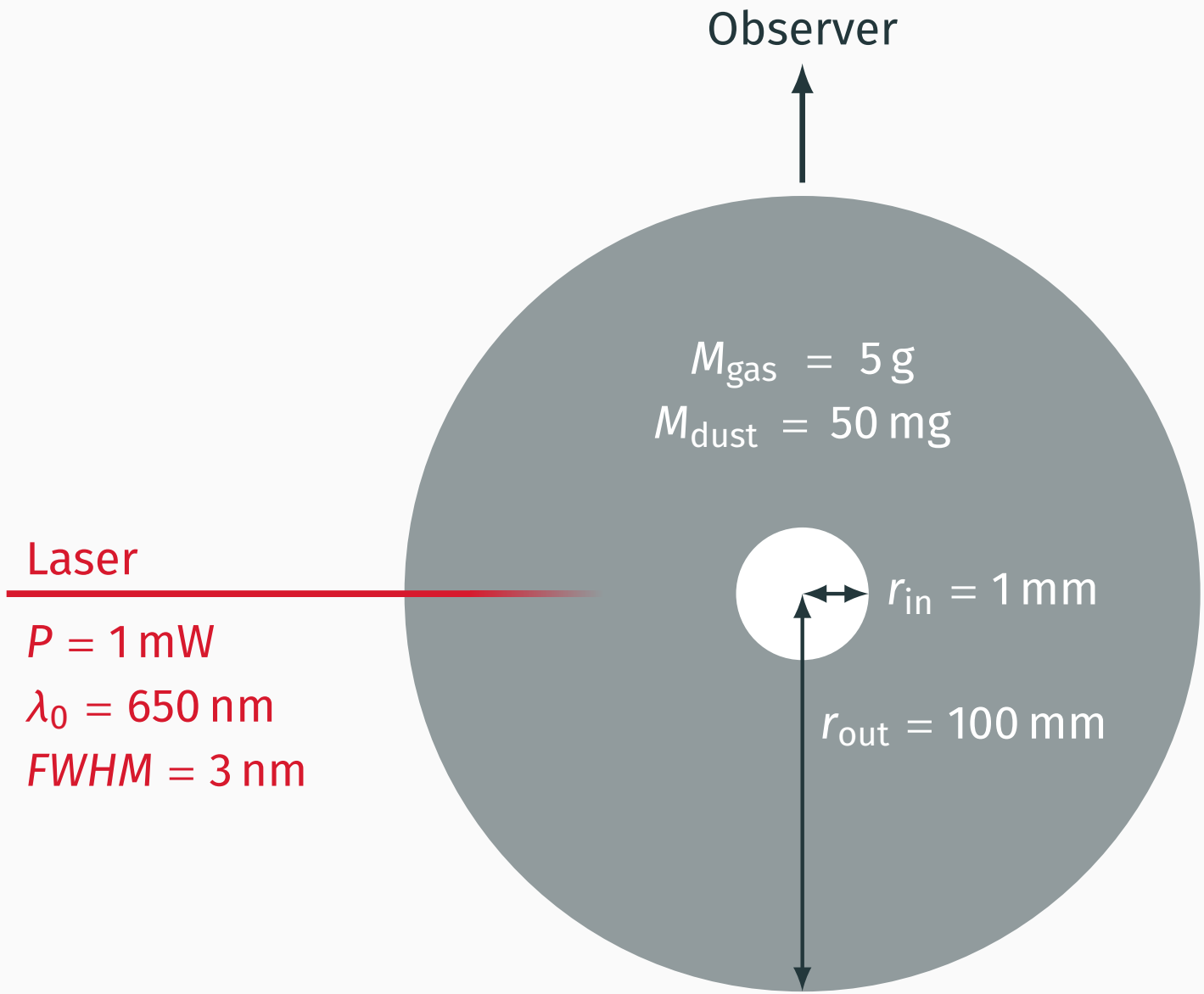
polaris-plot

- Creates plots of POLARIS results

⇒ **Use the option `--help` for more information**

Continuum radiative transfer

Exercise I: Laser directed at a sphere



Exercise I: Laser directed at a sphere

Create the grid

- `polaris-gen sphere grid1.dat`
  `↪ --inner_radius 1mm --outer_radius 100mm`
  `↪ --gas_mass 5g`

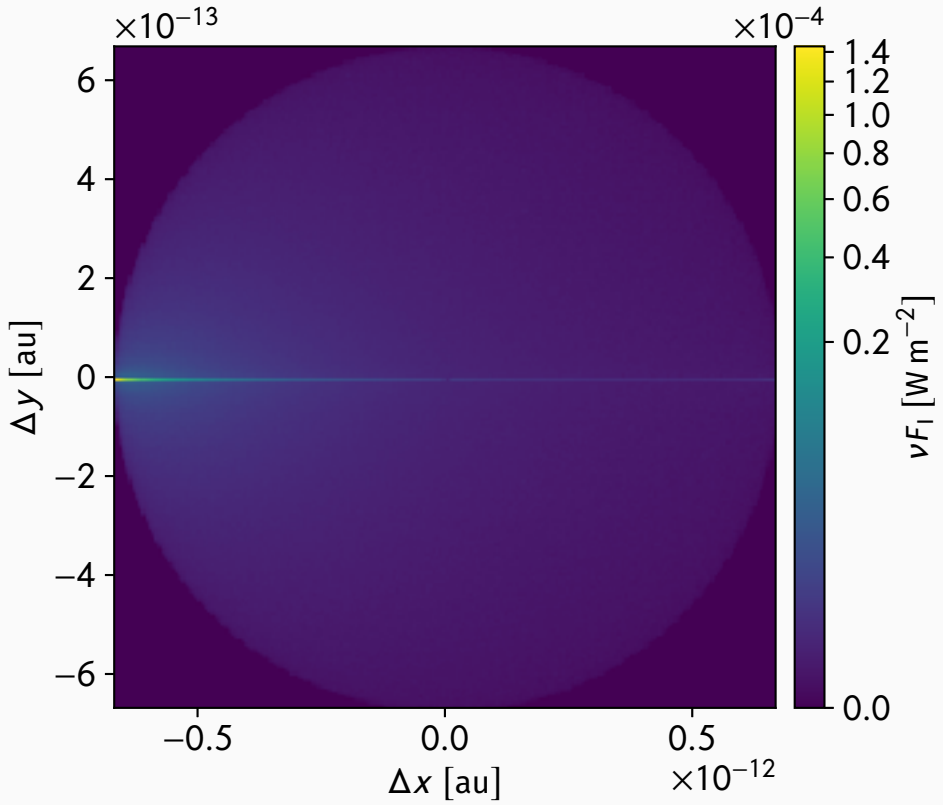
Simulate the scattered light (dust_mc → Monte-Carlo)

- `polaris-run sphere exercise_1 dust_mc`
  `↪ --grid grid1.dat --wavelength 650nm`
  `↪ --distance 1m --source laser`
  `↪ --source_position ' -100mm' 0 0`
  `↪ --source_direction 1 0 0 --source_power 1mW`
  `↪ --source_center_wl 650nm --source_fwhm 3nm`
  `↪ --rot_1 0 --rot_axis_1 1 0 0`

Exercise I: Laser directed at a sphere

Plot the emission map

- `polaris-plot sphere exercise_1 dust_mc map 1`
  `↪ --cmap_unit nuF --cmap_scaling power 0.3 -v`



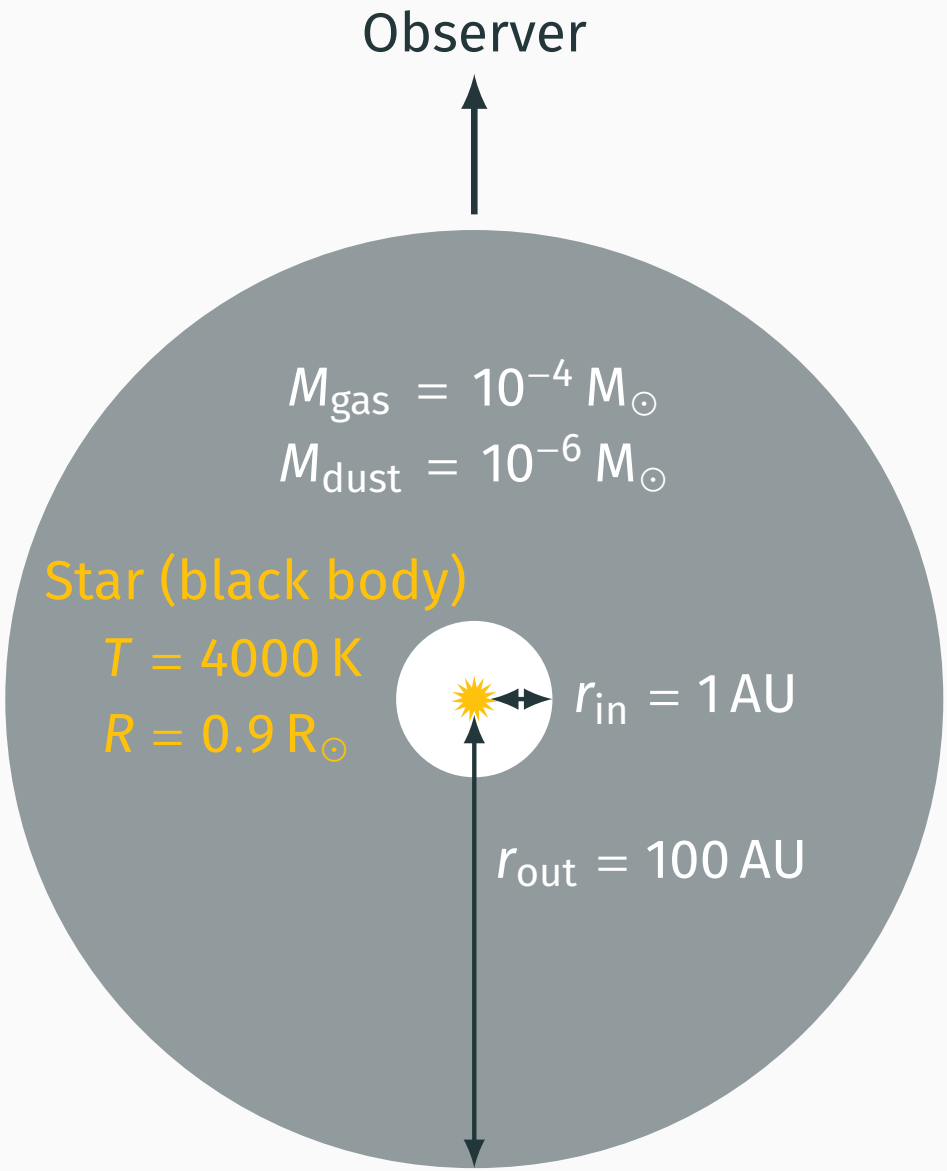
Continuum emission.

Exercise I: Questions

What will happen if the...

- Total mass is lower or higher?
- Wavelength is shorter or longer?
- Observer looks at a different angle or distance?
- Laser has more power?
- Laser has a broader beam (spectrum)?
+ *Own ideas*

Exercise II: Star with envelope



Exercise II: Star with envelope

Create the grid

- `polaris-gen sphere grid2.dat`
  `↪ --inner_radius 1au --outer_radius 100au`
  `↪ --gas_mass 1e-4M_sun`

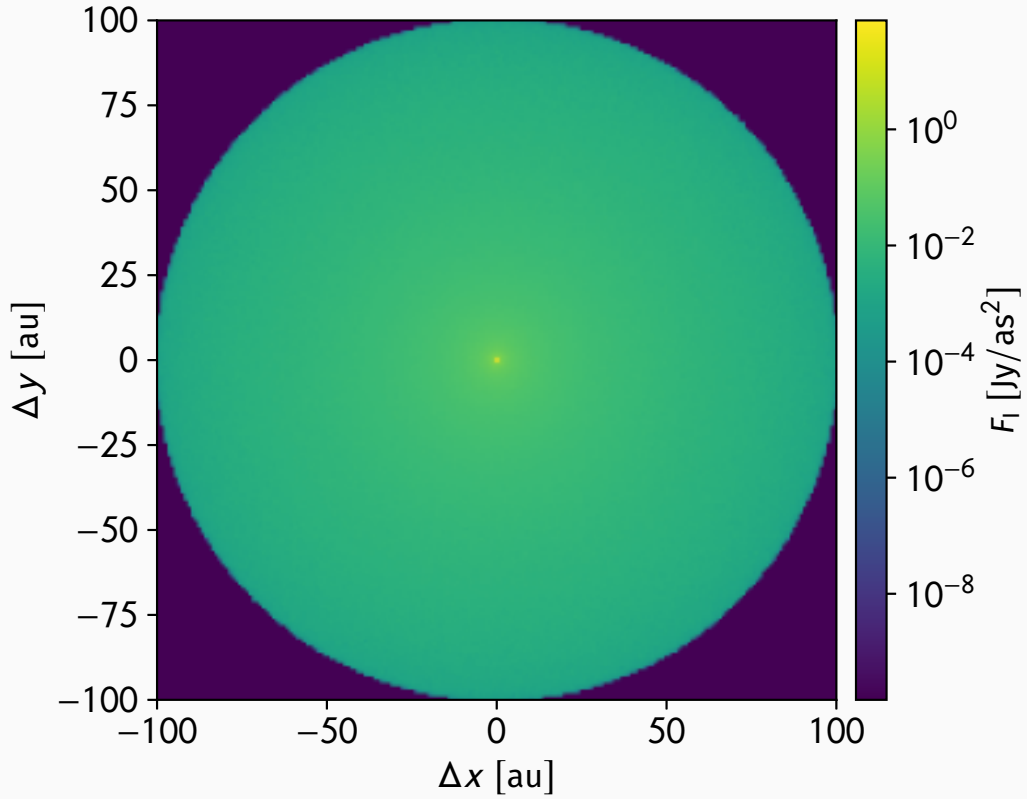
Simulate the scattered light (dust_mc → Monte-Carlo)

- `polaris-run sphere exercise_2 dust_mc`
  `↪ --grid grid2.dat --wavelength 1microns`
  `↪ --source t_tauri --source_position 0 0 0`
  `↪ --source_temperature 4000`
  `↪ --source_radius 0.9R_sun --distance 140pc`
  `↪ --dust_size 5nm 250nm --photons 1e6`

Exercise II: Star with envelope

Plot the emission map

- `polaris-plot sphere exercise_2 dust_mc map 1`
  `↪ --cmap_scaling log -v`



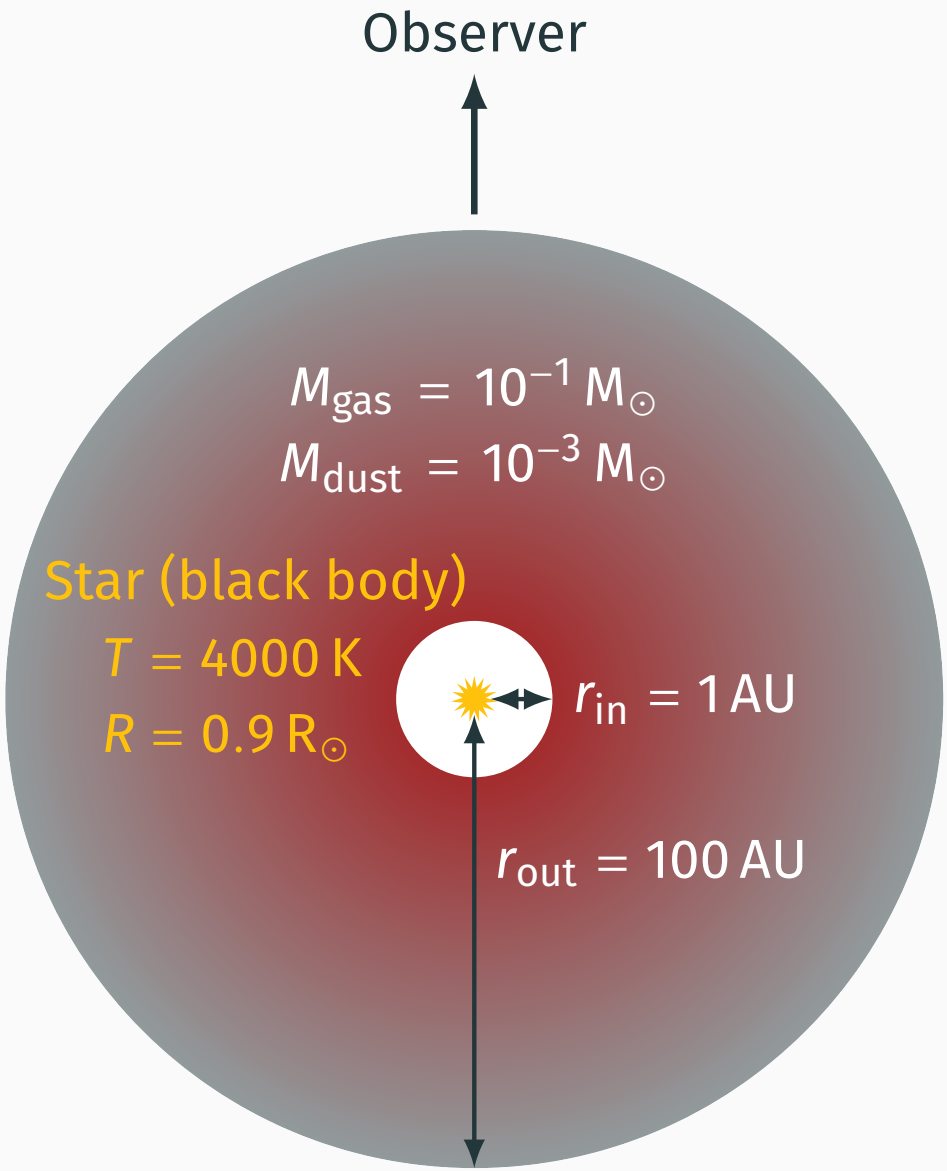
Continuum emission.

Exercise II: Questions

What will happen if the...

- Star is smaller or larger?
- Star is colder or hotter?
- Dust grains are smaller or larger?
- Sphere has a smaller or larger inner radius?
- Number of photons is lower or higher?
- \+ *Previous questions and own ideas*

Exercise III: Thermal emission of an envelope



Exercise III: Thermal emission of an envelope

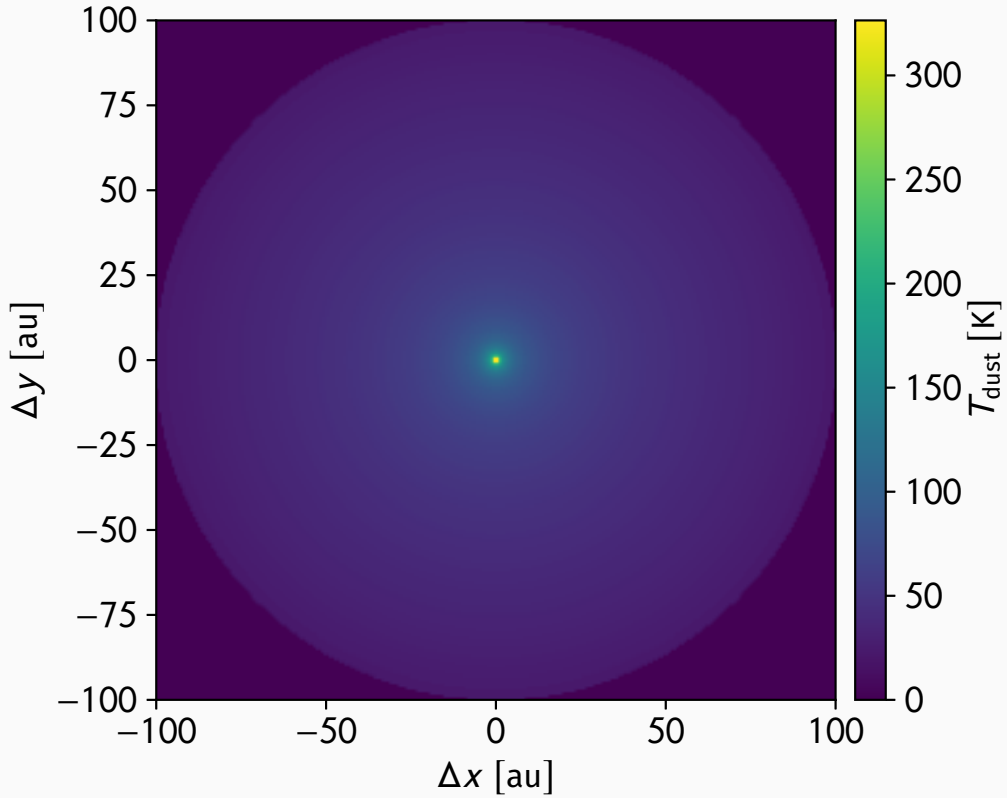
Simulate the heating of dust grains (Monte-Carlo)

- `polaris-run sphere exercise_3 temp`
  `↪ --grid grid2.dat --conv_dens 1e3`
  `↪ --dust_size 5nm 1mm`
  `↪ --source t_tauri --source_position 0 0 0`
  `↪ --source_temperature 4000`
  `↪ --source_radius 0.9R_sun`
  `↪ --photons 1e6`

Exercise III: Thermal emission of an envelope

Plot the temperature distribution

- `polaris-plot sphere exercise_3 temp midplane`
  `↪ output dust_temperature xy -v`



Temperature distribution in a horizontal cut through the model.

Exercise III: Thermal emission of an envelope

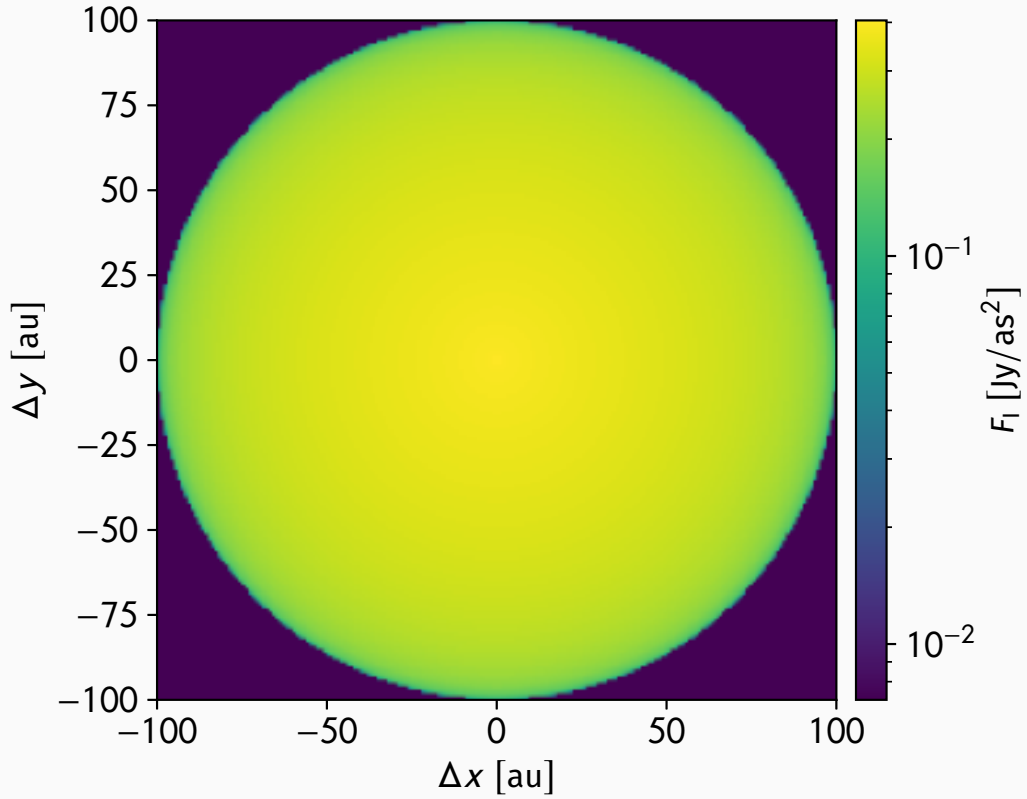
Simulate the thermal emission (Raytracing)

- `polaris-run sphere exercise_3 dust`
  `↪ --wavelength 1mm --dust_size 5nm 1mm`
  `↪ --source t_tauri --source_position 0 0 0`
  `↪ --source_temperature 4000`
  `↪ --source_radius 0.9R_sun`
  `↪ --pixel 201`

Exercise III: Thermal emission of an envelope

Plot the emission map

- `polaris-plot sphere exercise_3 dust map 1 --cmap_scaling log -v`



Continuum emission.

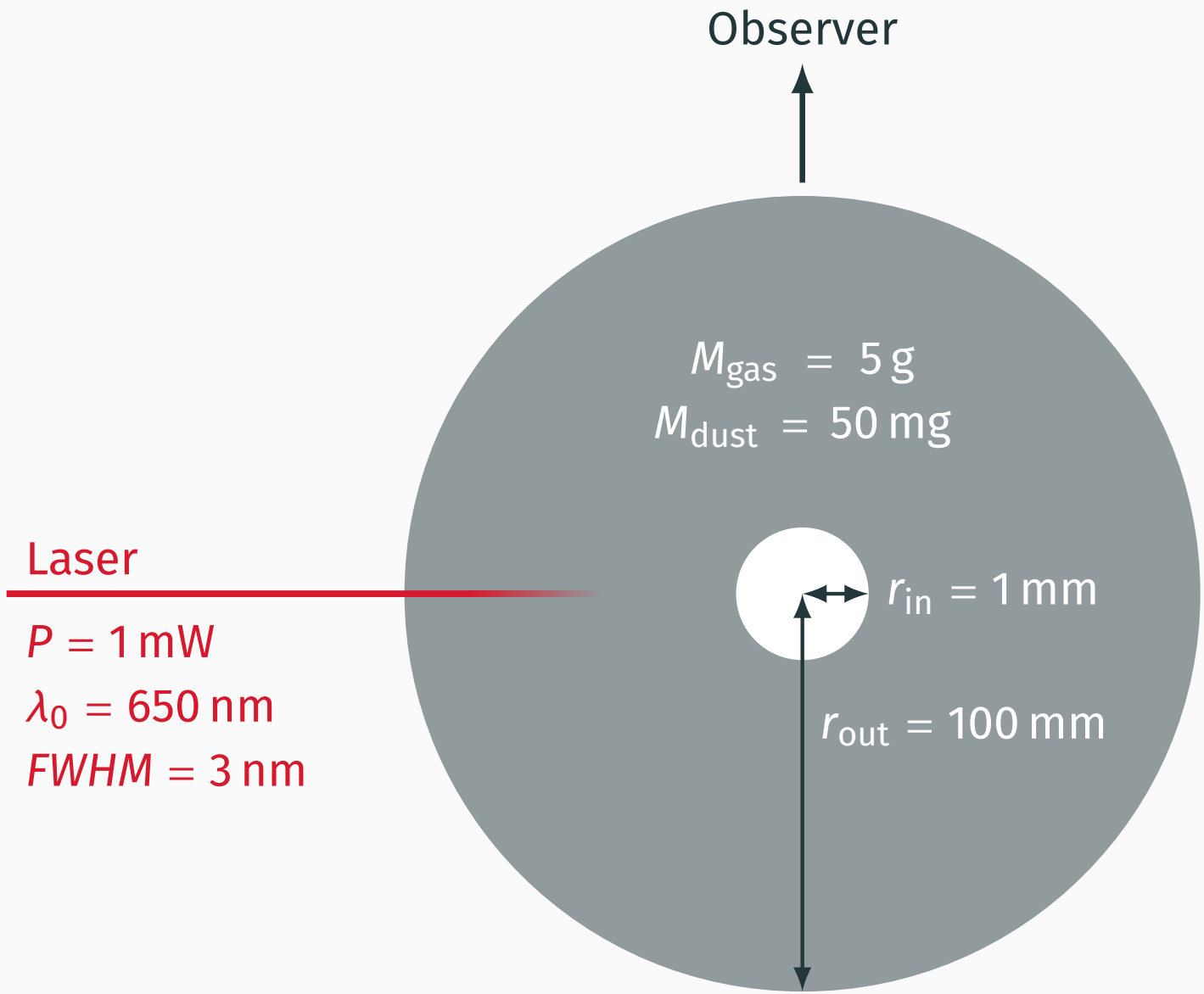
Exercise III: Questions

What will happen if the...

- Dust is colder or hotter?
- Emission map has less or more pixel?
- Temperature midplane cut has less or more pixel?
- \+ *Previous questions and own ideas*

Polarized continuum RT

Exercise I: Laser directed at a sphere



Exercise I: Laser directed at a sphere

Create the grid

- `polaris-gen sphere grid1.dat`
  `↪ --inner_radius 1mm --outer_radius 100mm`
  `↪ --gas_mass 5g`

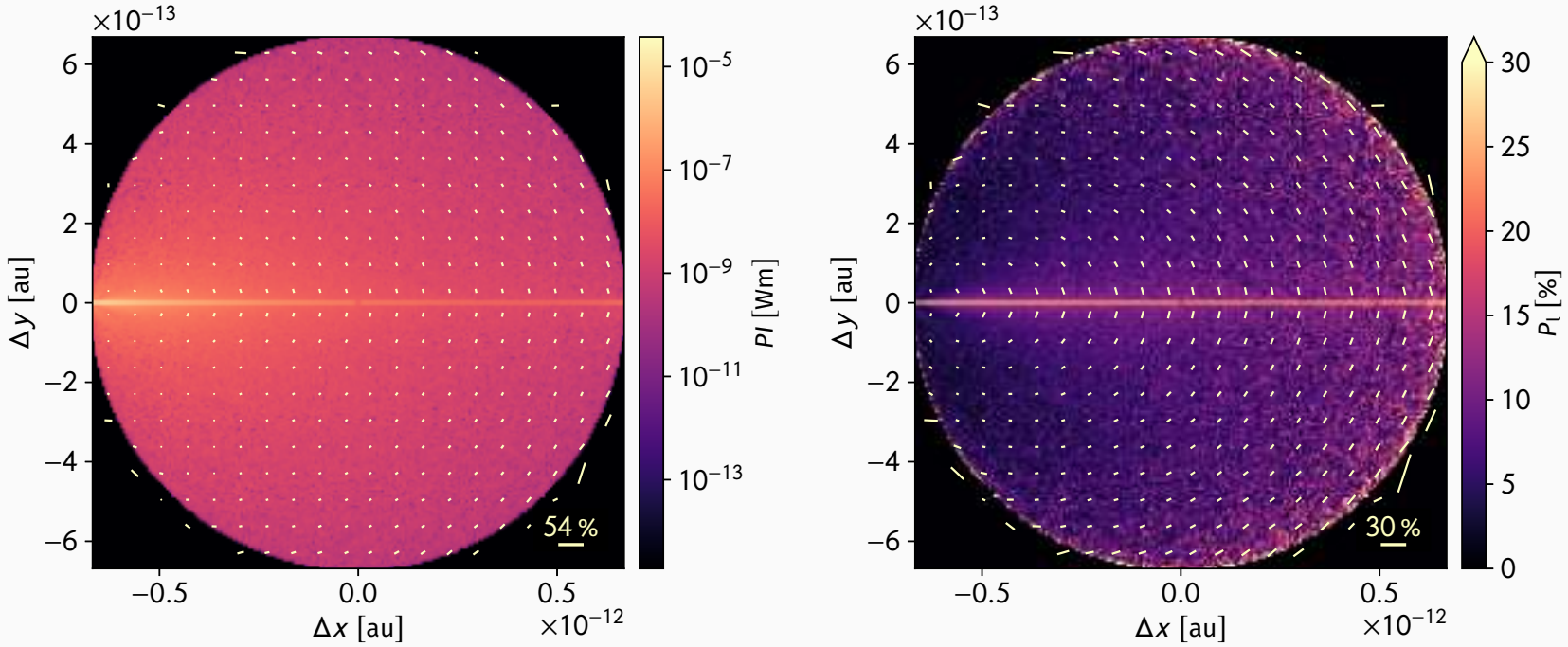
Simulate the scattered light (dust_mc → Monte-Carlo)

- `polaris-run sphere exercise_1 dust_mc`
  `↪ --grid grid1.dat --wavelength 650nm`
  `↪ --distance 1m --source laser`
  `↪ --source_position ' -100mm' 0 0`
  `↪ --source_direction 1 0 0 --source_power 1mW`
  `↪ --source_center_wl 650nm --source_fwhm 3nm`
  `↪ --rot_1 0 --rot_axis_1 1 0 0`

Exercise I: Laser directed at a sphere

Plot the polarized emission maps

- `polaris-plot sphere exercise_1 dust_mc map 1`
  `↪ --cmap_unit nuF --cmap_scaling log -v`



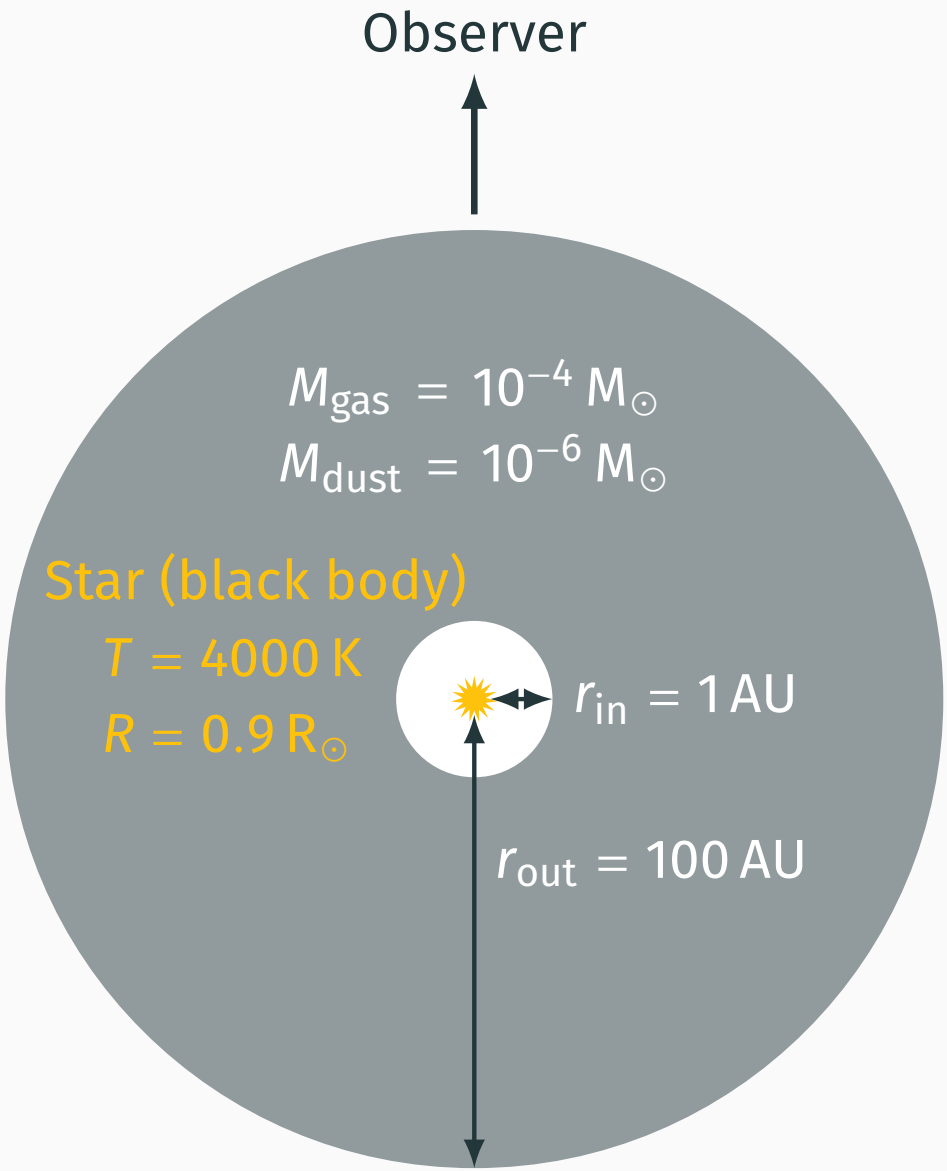
Left: Polarized emission. *Right:* Degree of polarization.

Exercise I: Questions

What will happen if the...

- Total mass is lower or higher?
- Wavelength is shorter or longer?
- Observer looks at a different angle or distance?
- Dust grains are smaller or larger?
+ *Previous questions and own ideas*

Exercise II: Star with envelope



Exercise II: Star with envelope

Create the grid

- `polaris-gen sphere grid2.dat`
  `↪ --inner_radius 1au --outer_radius 100au`
  `↪ --gas_mass 1e-4M_sun`

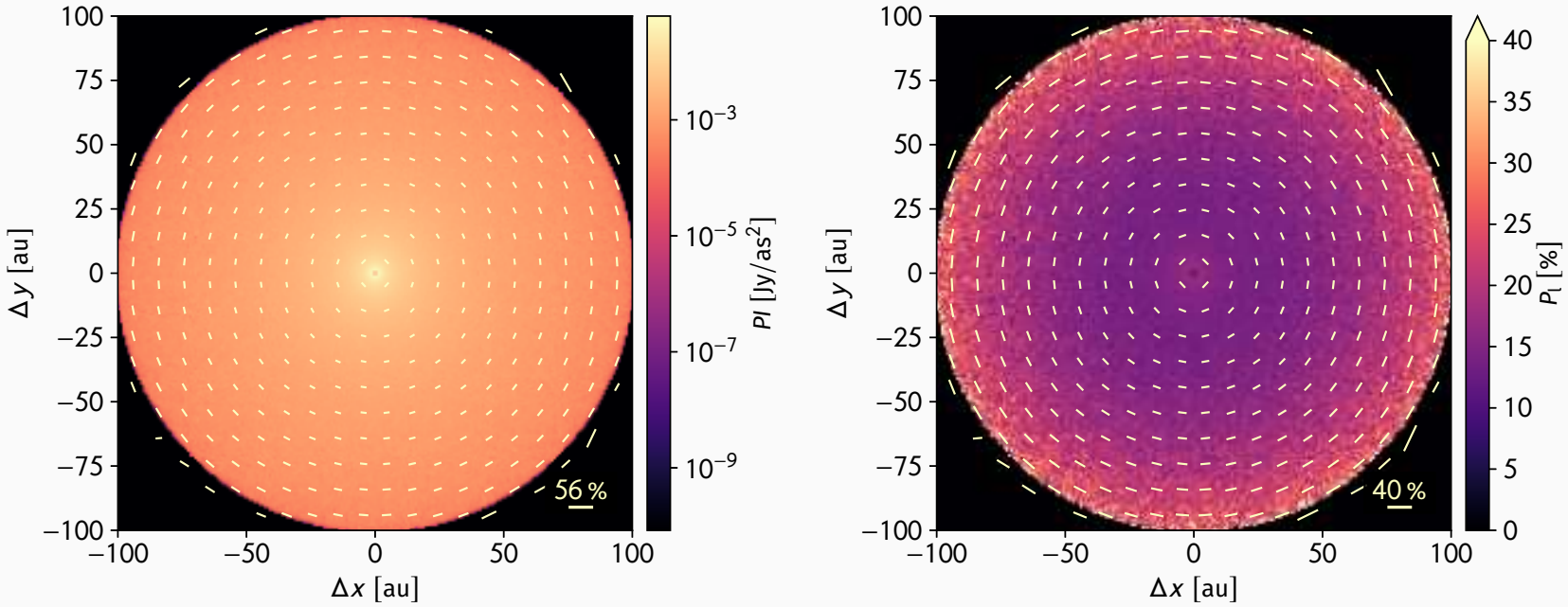
Simulate the scattered light (dust_mc → Monte-Carlo)

- `polaris-run sphere exercise_2 dust_mc`
  `↪ --grid grid2.dat --wavelength 1microns`
  `↪ --source t_tauri --source_position 0 0 0`
  `↪ --source_temperature 4000`
  `↪ --source_radius 0.9R_sun --distance 140pc`
  `↪ --dust_size 5nm 250nm --photons 1e6`

Exercise II: Star with envelope

Plot the polarized emission maps

- `polaris-plot sphere exercise_2 dust_mc map 1`
  `↪ --cmap_scaling log -v`



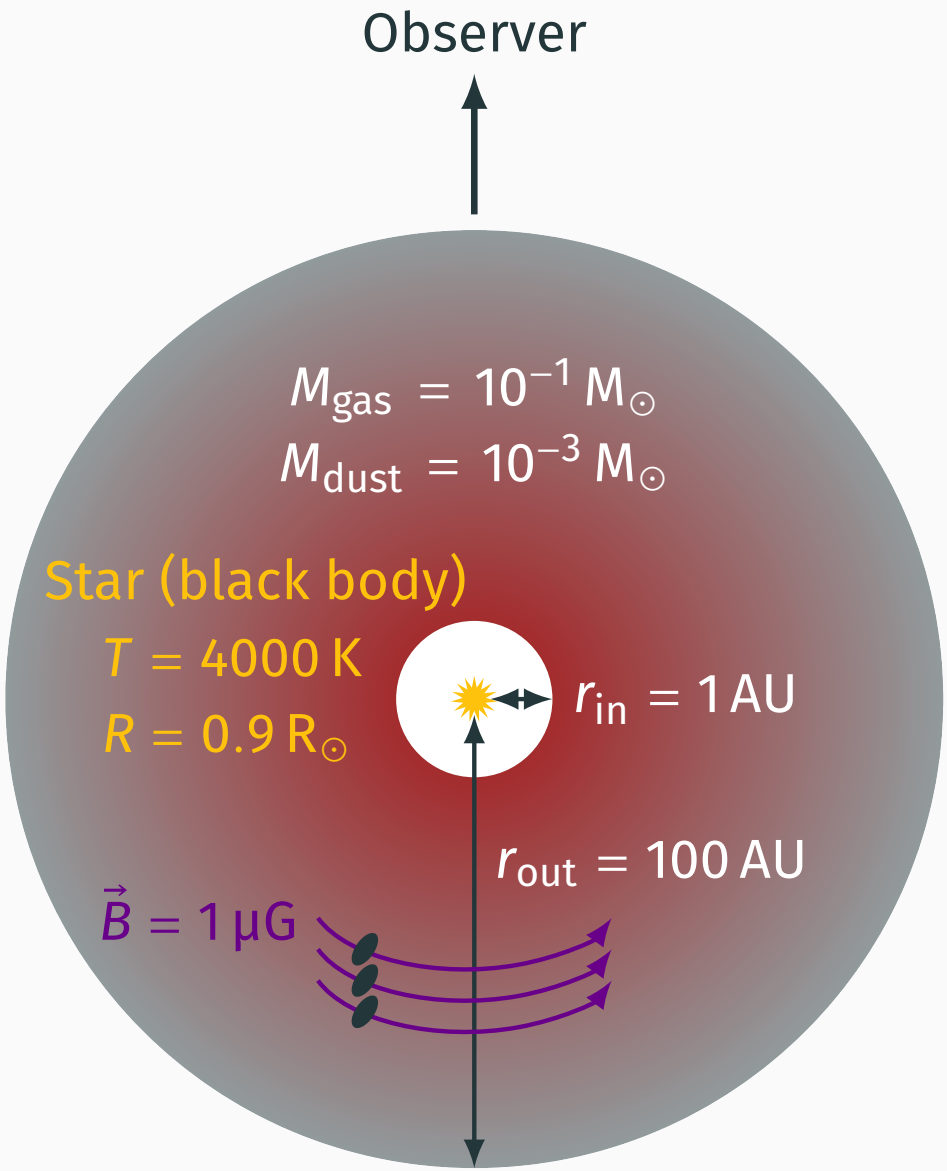
Left: Polarized emission. *Right:* Degree of polarization.

Exercise II: Questions

What will happen if the...

- Total mass is lower or higher?
- Wavelength is shorter or longer?
- Observer looks at a different angle or distance?
- Dust grains are smaller or larger?
- + *Previous questions and own ideas*

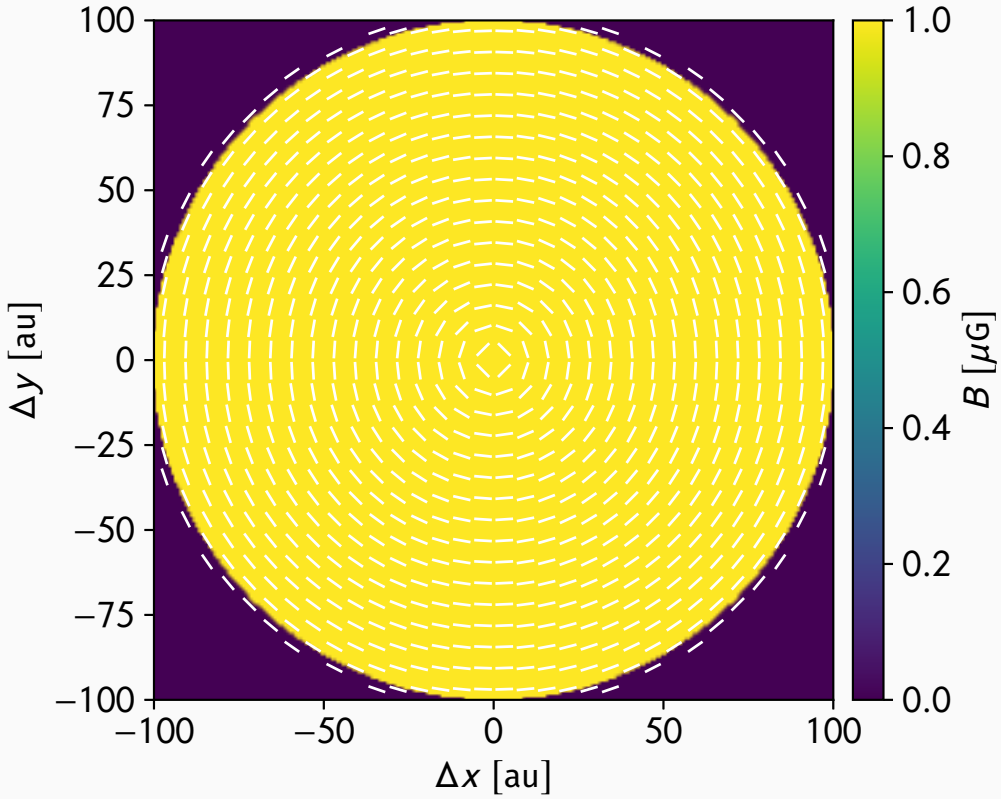
Exercise III: Thermal emission of an envelope



Exercise III: Thermal emission of an envelope

Plot the magnetic field

- `polaris-plot sphere exercise_3 temp midplane`
  `↪ input mag_field xy -v`



Magnetic field in a horizontal cut through the model.

Exercise III: Thermal emission of an envelope

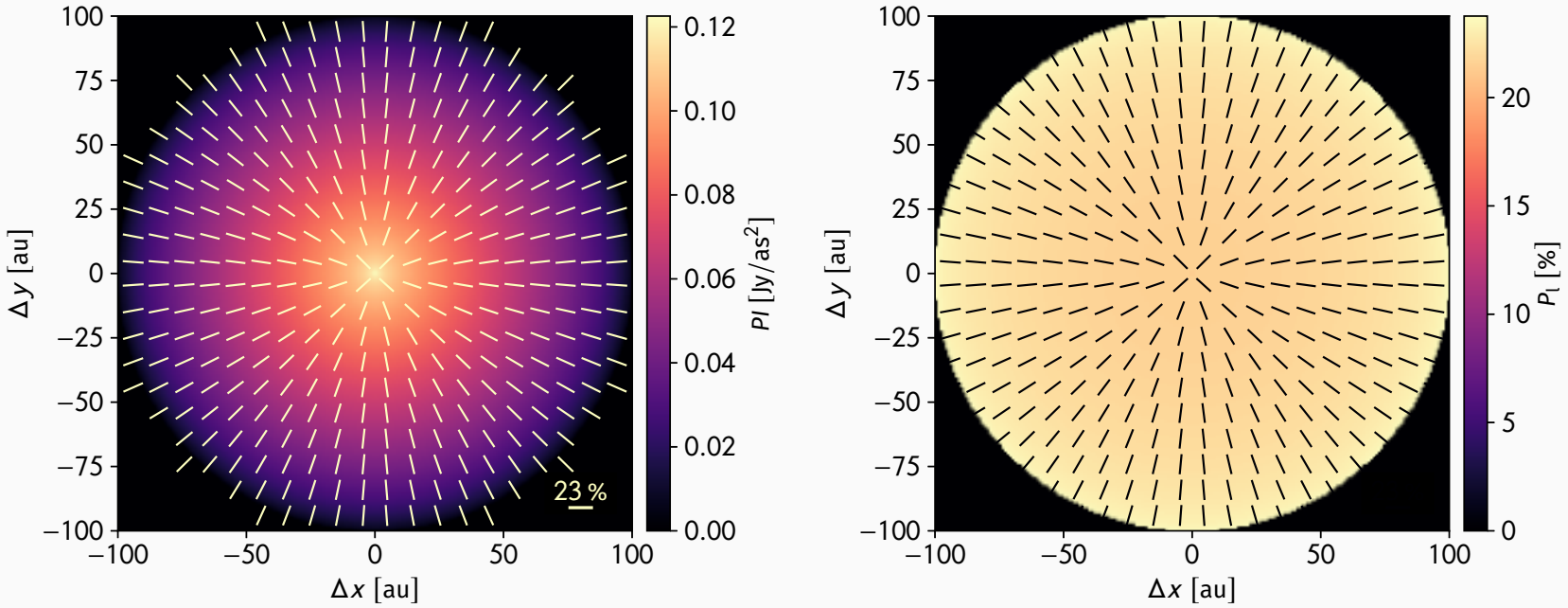
Simulate the polarized thermal emission (Raytracing, dust_pa → perfect alignment)

- `polaris-run sphere exercise_3 dust_pa`
  `↪ --wavelength 1mm --dust mrn_oblate`
  `↪ --source t_tauri --source_position 0 0 0`
  `↪ --source_temperature 4000`
  `↪ --source_radius 0.9R_sun`
  `↪ --dust_size 5nm 250nm`

Exercise III: Thermal emission of an envelope

Plot the polarized emission maps

- `polaris-plot sphere exercise_3 dust_pa map 1 -v`



Left: Polarized emission. *Right:* Degree of polarization.

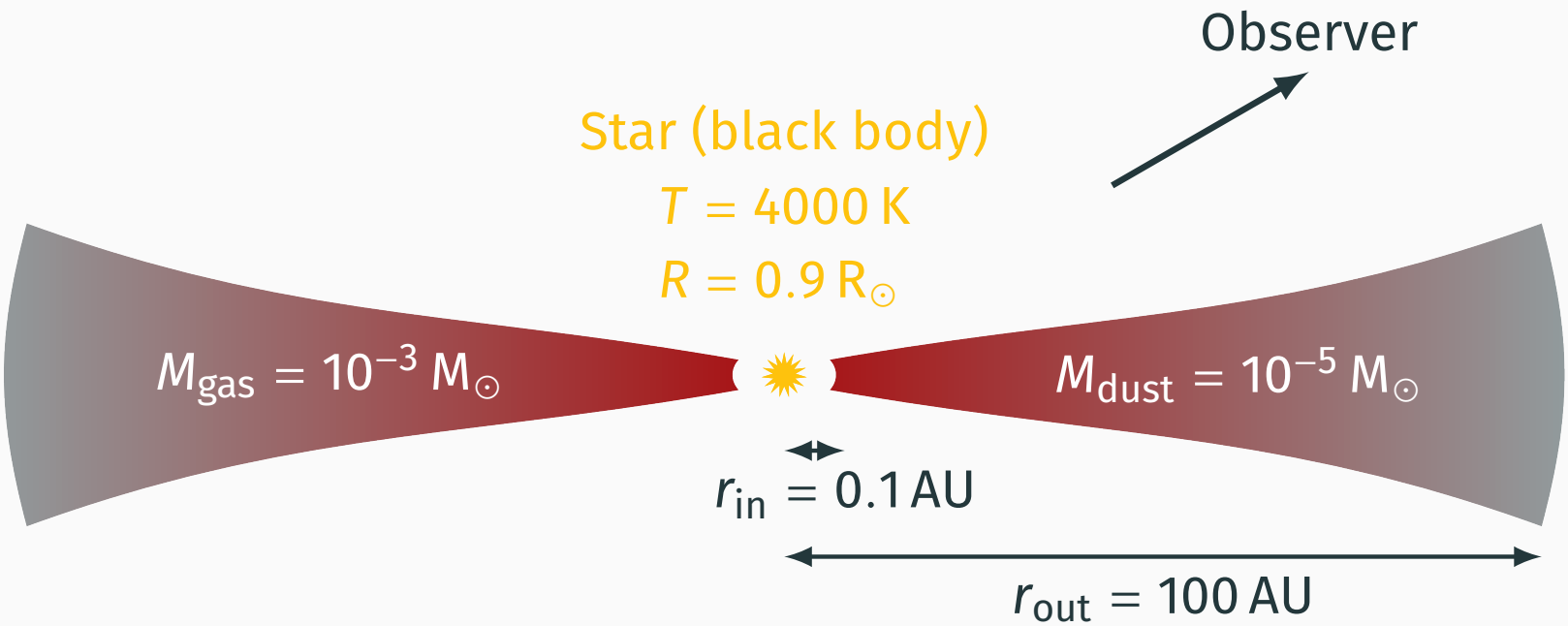
Exercise III: Questions

What will happen if the...

- Total mass is lower or higher?
- Wavelength is shorter or longer?
- Observer looks at a different angle or distance?
- Dust grains are smaller or larger?
- + *Previous questions and own ideas*

Circumstellar disks

Exercise IV: Circumstellar disk continuum emission



Exercise IV: Circumstellar disk continuum emission

Create the grid

- `polaris-gen disk grid.dat`
  `↪ --inner_radius 0.1au --outer_radius 100au`
  `↪ --gas_mass 1e-3M_sun`

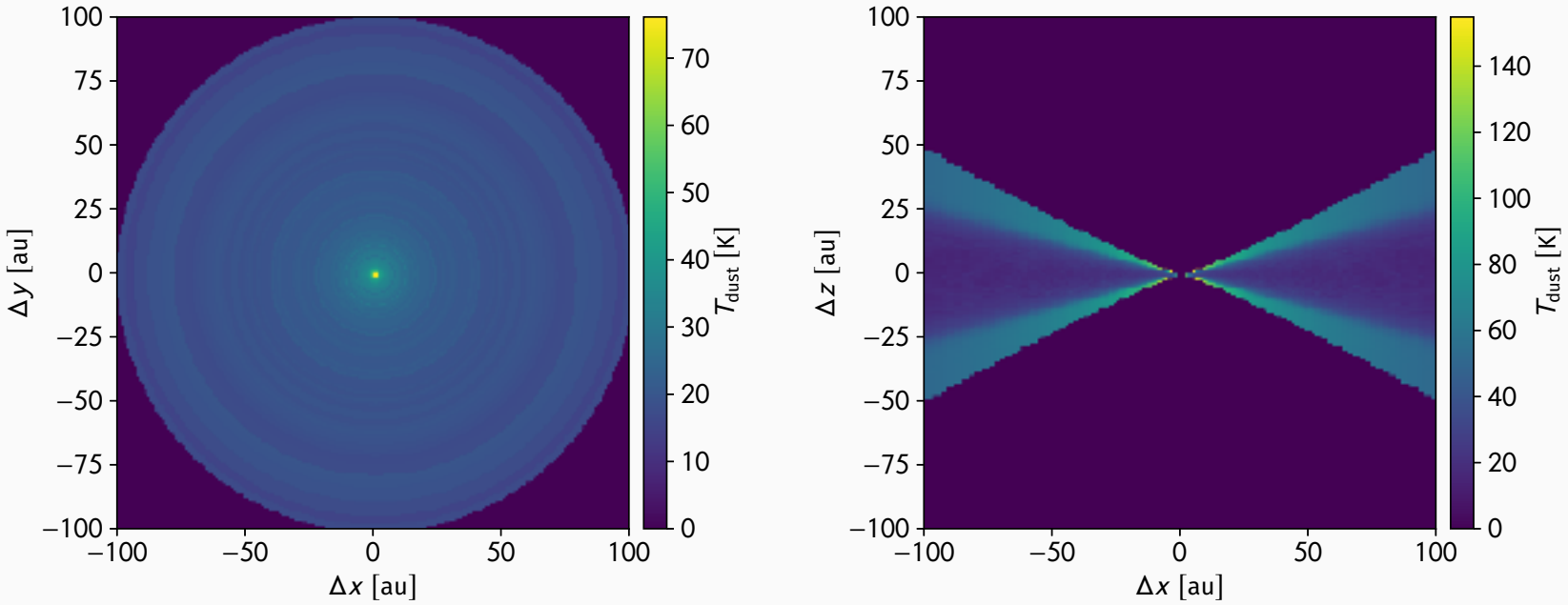
Simulate the heating of dust grains (Monte-Carlo)

- `polaris-run disk exercise_4 temp`
  `↪ --grid grid.dat`
  `↪ --source t_tauri --source_position 0 0 0`
  `↪ --source_temperature 4000`
  `↪ --source_radius 0.9R_sun`
  `↪ --dust_size 5nm 250nm --photons 1e6`

Exercise IV: Circumstellar disk continuum emission

Plot the temperature distributions

- `polaris-plot disk exercise_4 temp midplane`
  `↪ output dust_temperature xy -v`



Temperature distribution in a horizontal (*left*) or vertical (*right*) cut through the model.

Exercise IV: Circumstellar disk continuum emission

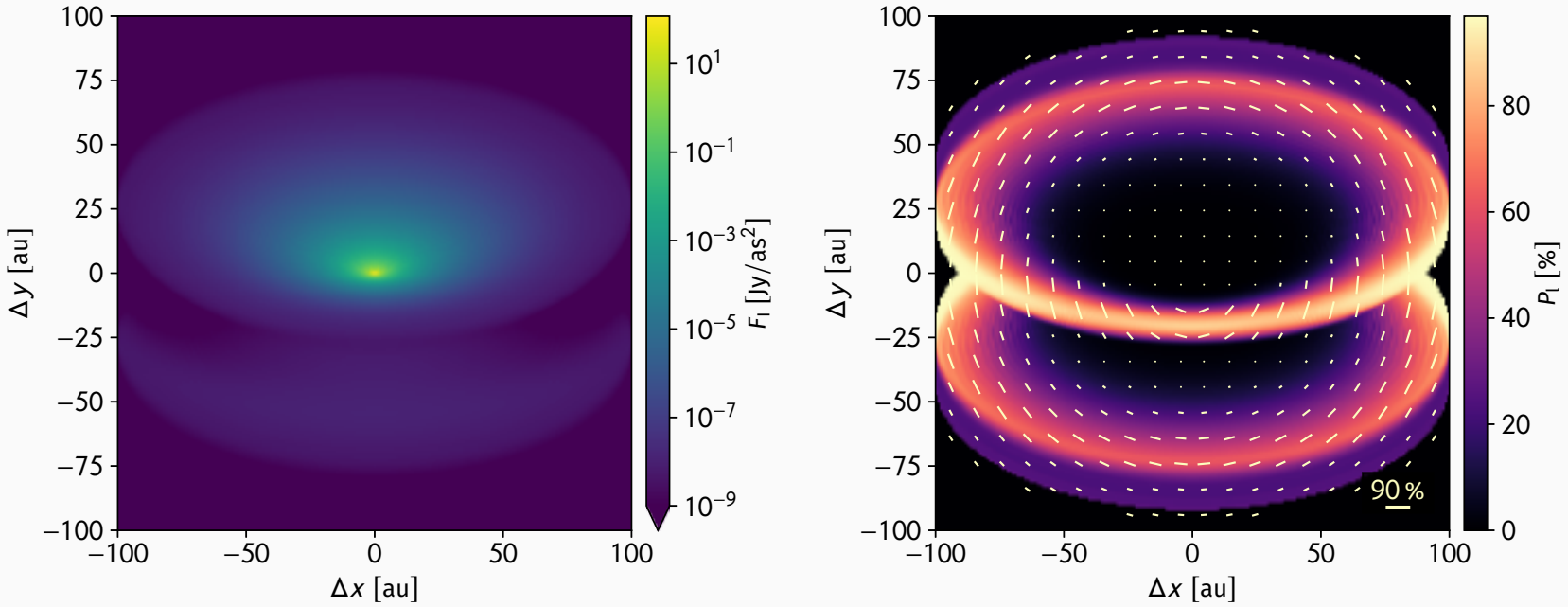
Simulate the full emission (Raytracing)

- `polaris-run disk exercise_4 dust`
  `↪ --wavelength 10microns --rot_1 60`
  `↪ --source t_tauri --source_position 0 0 0`
  `↪ --source_temperature 4000`
  `↪ --source_radius 0.9R_sun --distance 140pc`
  `↪ --dust_size 5nm 250nm`

Exercise IV: Circumstellar disk continuum emission

Plot the polarized emission maps

- `polaris-plot disk exercise_4 dust map 1`
  `↪ --cmap_scaling log --vmin 1e-9 -v`



Left: Continuum emission. *Right:* Degree of polarization.

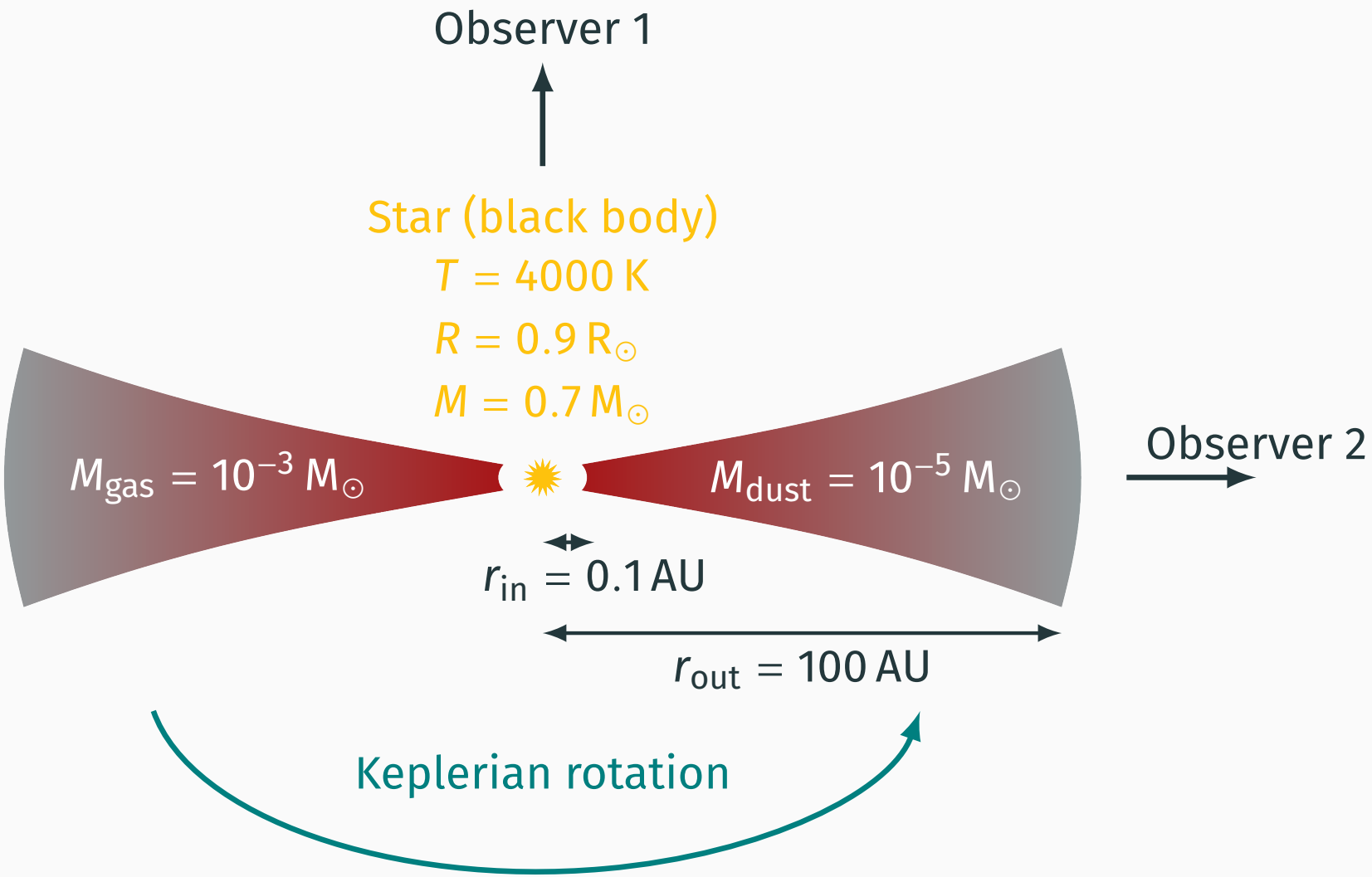
Exercise IV: Questions

What will happen if the...

- Star is at a different position?
- Total mass is lower or higher?
- Wavelength is shorter or longer?
- Observer looks at a different angle or distance?
- Dust grains are smaller or larger?
+ *Previous questions and own ideas*

Spectral line RT

Exercise V: Circumstellar disk line emission



Exercise V: Circumstellar disk line emission

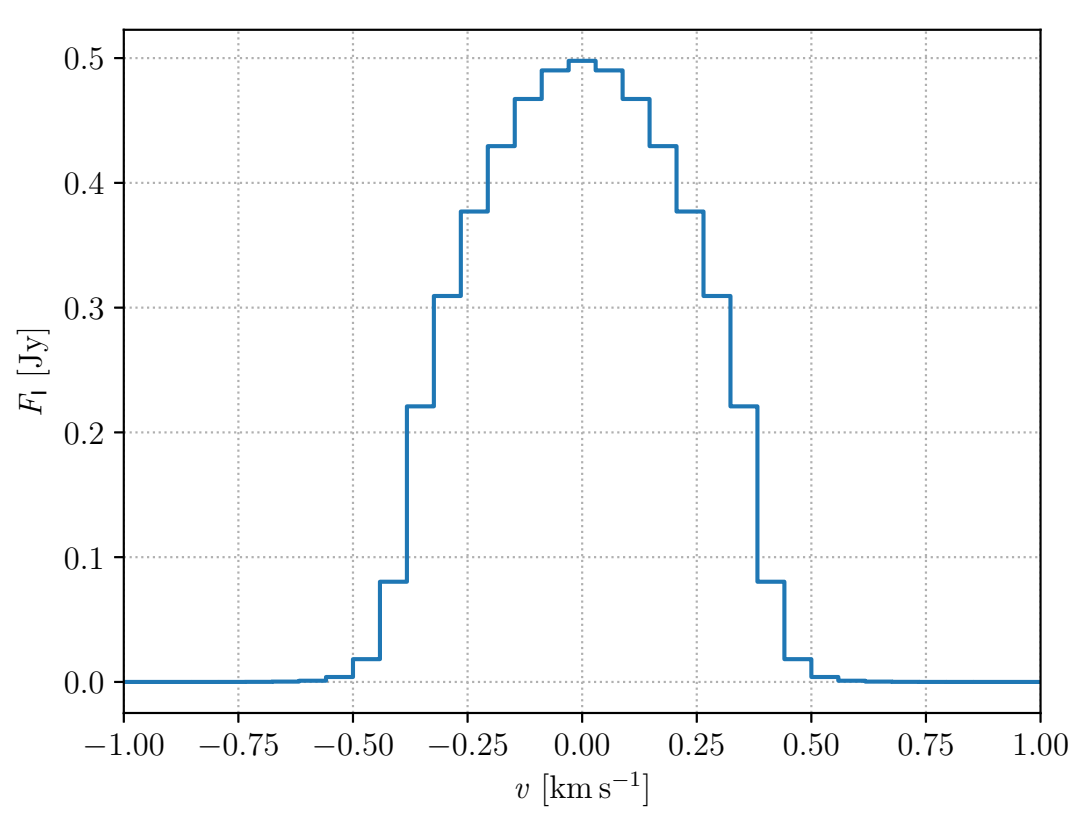
Simulate the spectral line emission (Raytracing)

- `polaris-run disk exercise_4 line`
  `↪ --max_vel 1km/s`
  `↪ --gas c18o --transition 1 --channels 35`
  `↪ --abundance 2e-7 --lvl_pop LTE`
  `↪ --turbulence 100`

Exercise V: Circumstellar disk line emission

Plot the spectrum

- `polaris-plot disk exercise_4 line spectrum 1 -v`

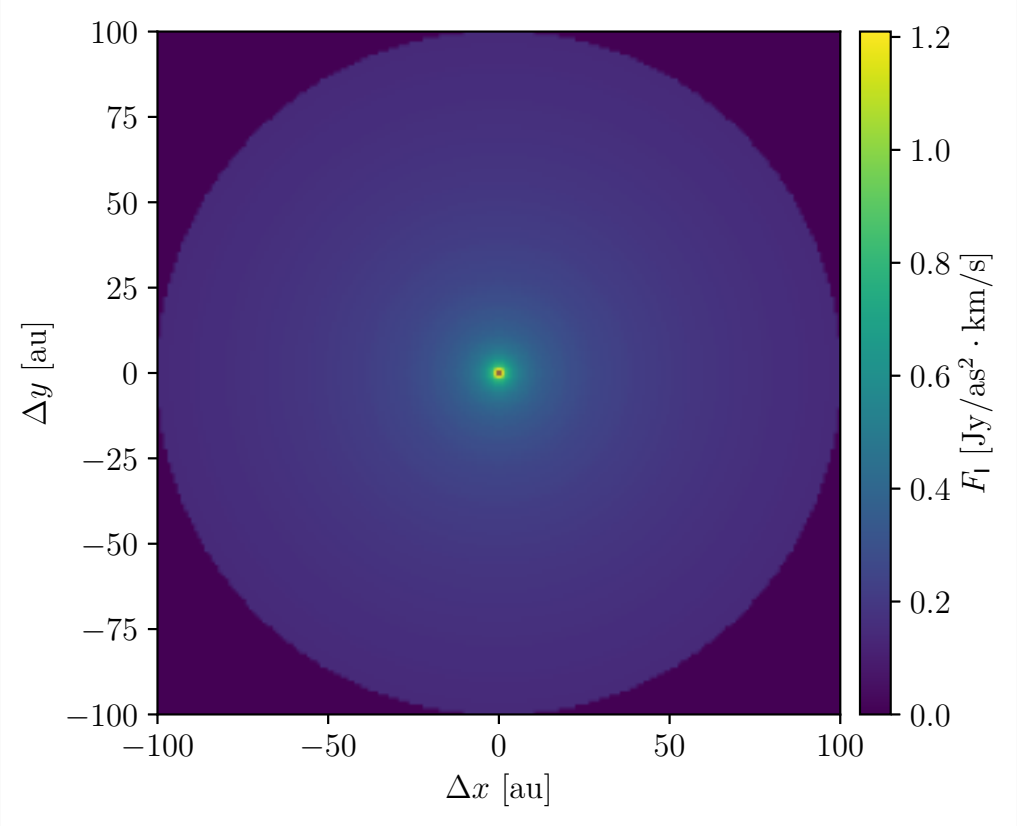


Spectral line profile

Exercise V: Circumstellar disk line emission

Plot the integrated velocity channel map

- `polaris-plot disk exercise_4 line int_map 1 -v`

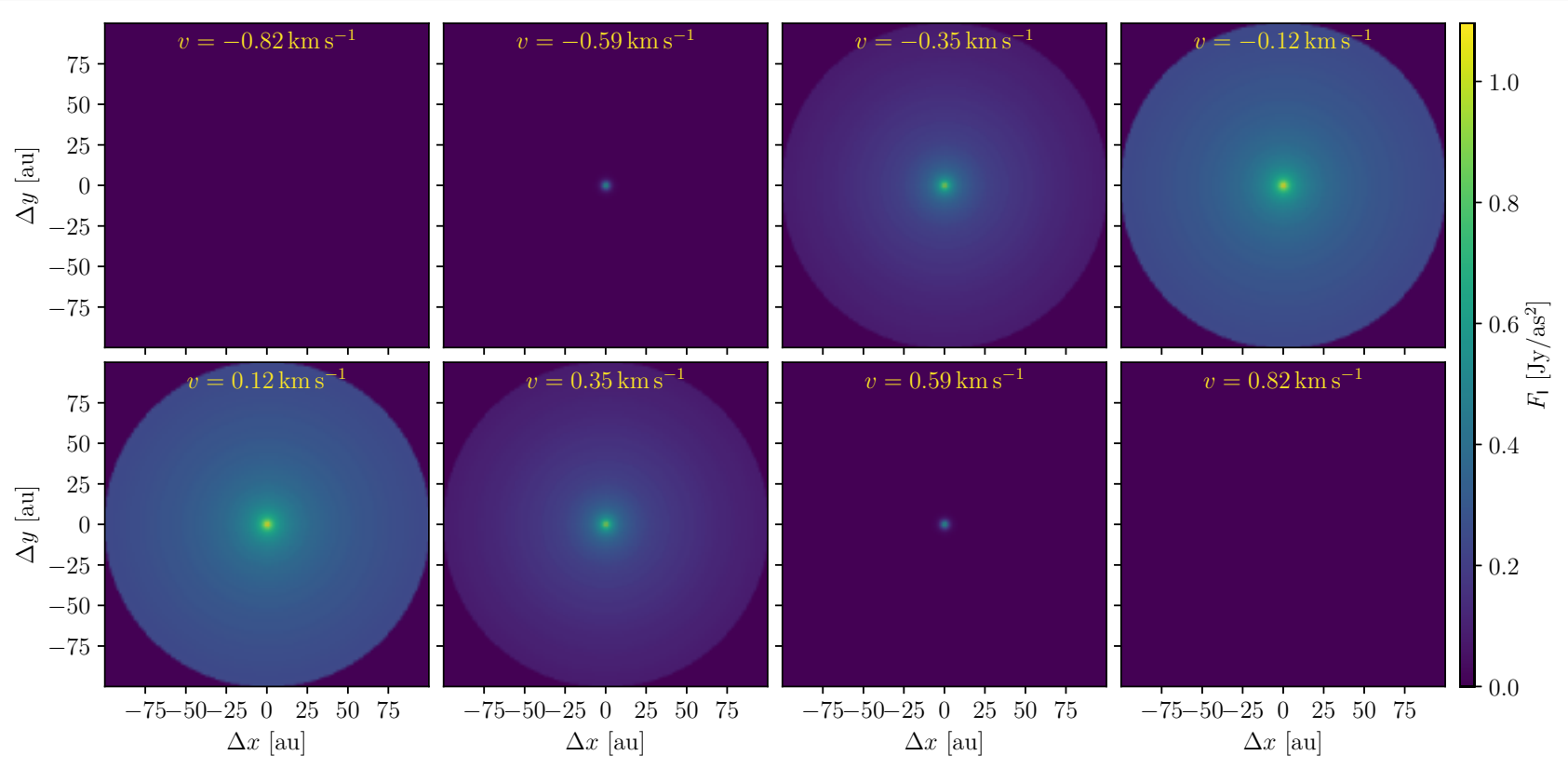


Integrated velocity channel map

Exercise V: Circumstellar disk line emission

Plot the velocity channels maps

- `polaris-plot disk exercise_4 line vel_map 1 -v`



Velocity channels maps

Exercise V: Circumstellar disk line emission

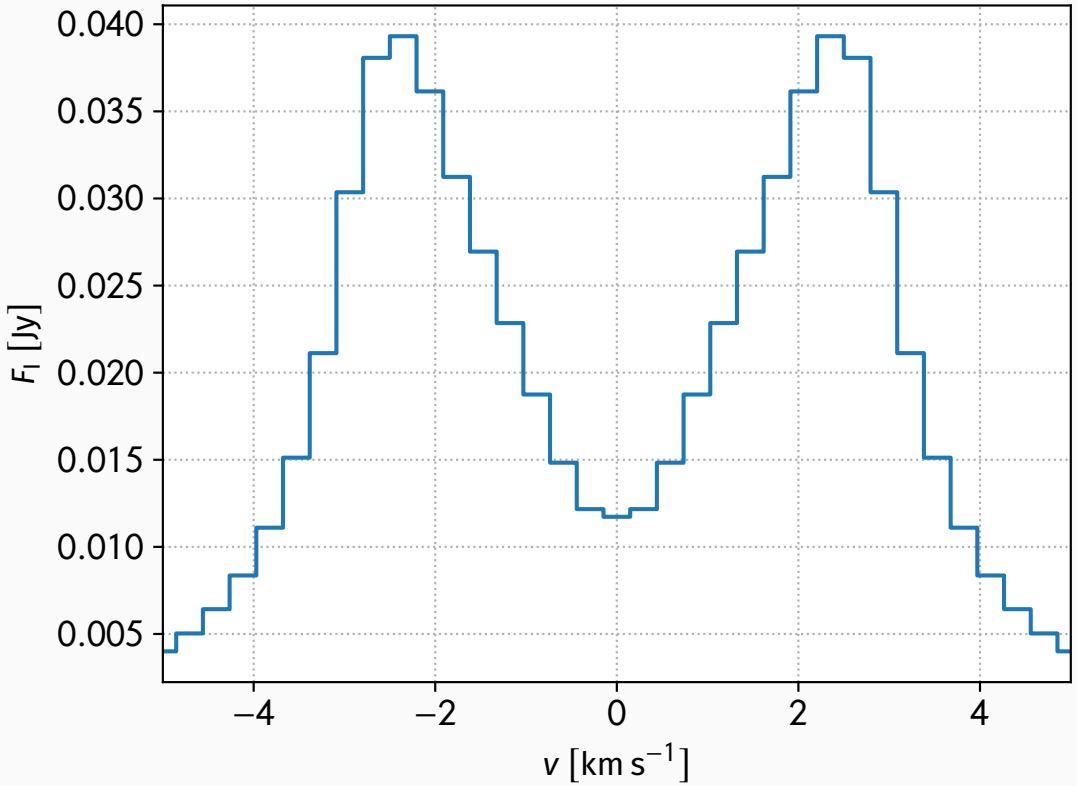
Simulate the spectral line emission (Raytracing)

- `polaris-run disk exercise_4 line`
  `↪ --rot_1 90 --kepler --max_vel 5km/s`
  `↪  --gas c18o --transition 1 --channels 35`
  `↪  --abundance 2e-7 --lvl_pop LTE`
  `↪  --turbulence 100 --source_mass 0.7M_sun`

Exercise V: Circumstellar disk line emission

Plot the spectrum

- `polaris-plot disk exercise_4 line spectrum 1 -v`

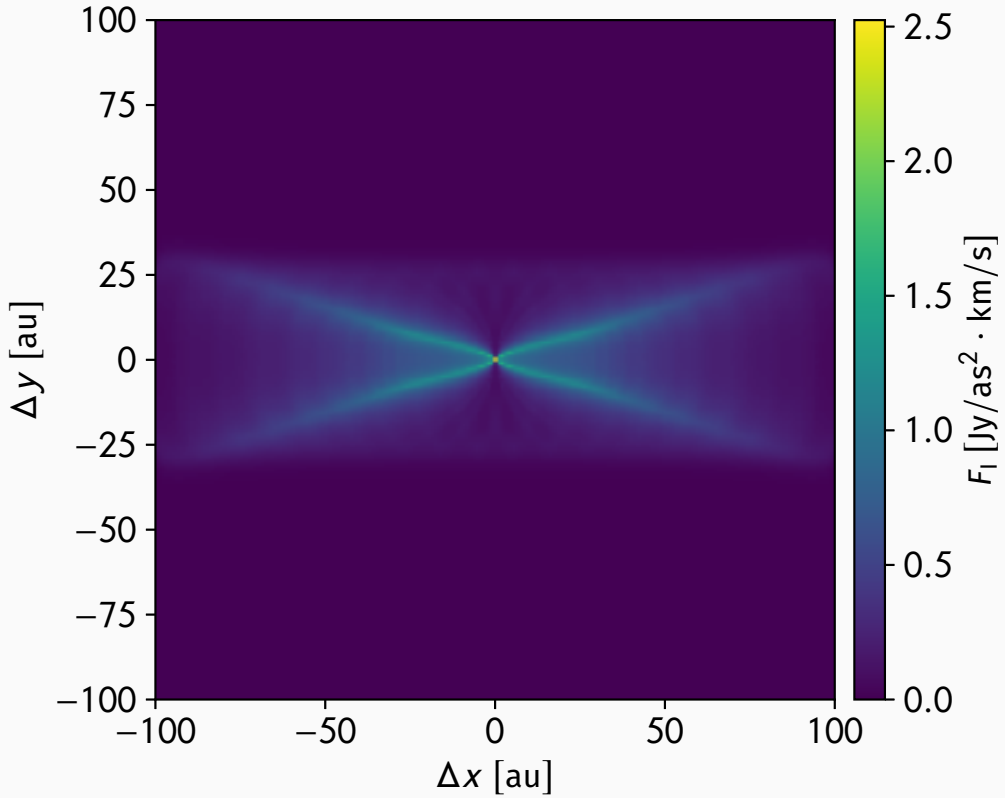


Spectral line profile

Exercise V: Circumstellar disk line emission

Plot the integrated velocity channel map

- `polaris-plot disk exercise_4 line int_map 1 -v`

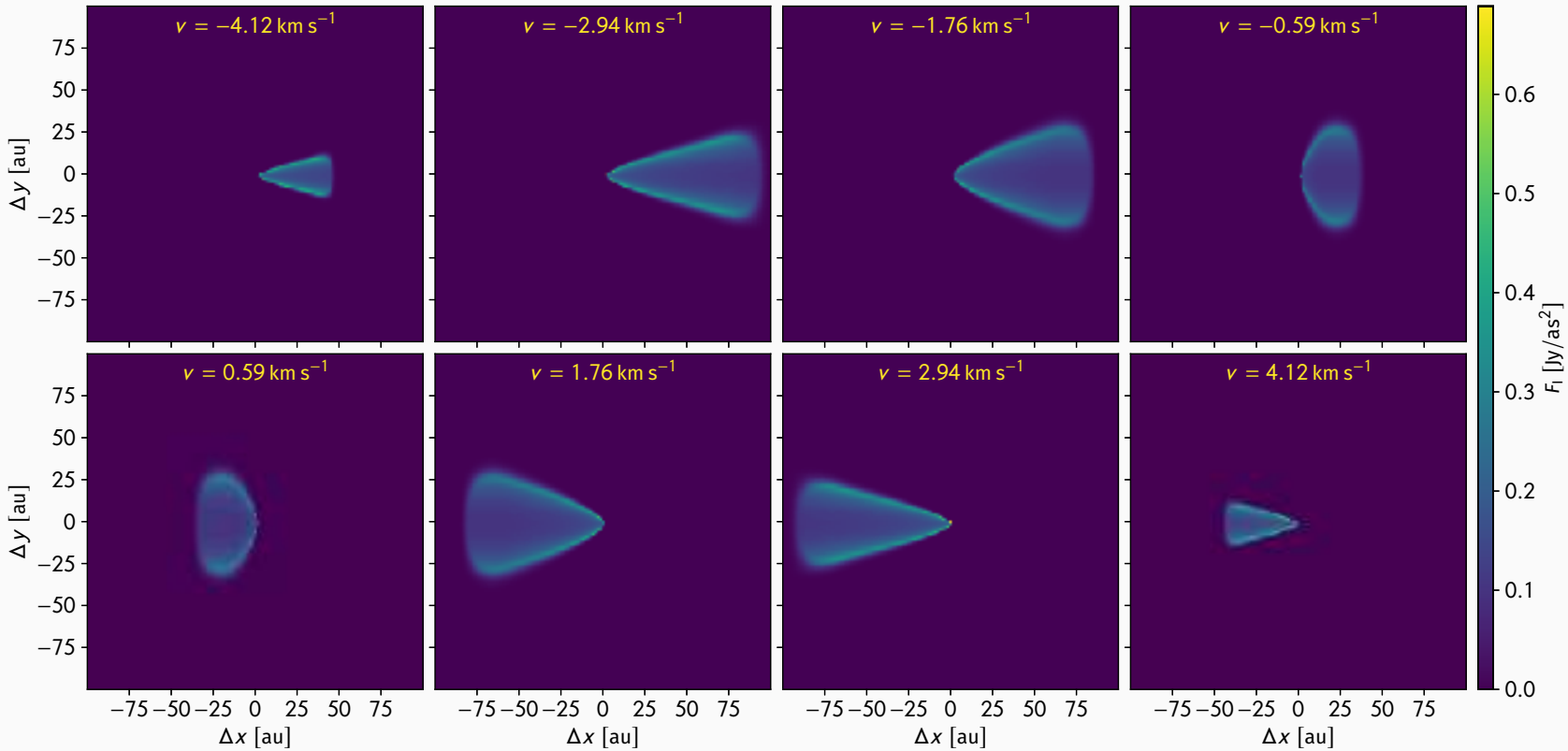


Integrated velocity channel map

Exercise V: Circumstellar disk line emission

Plot the velocity channels maps

- `polaris-plot disk exercise_4 line vel_map 1 -v`



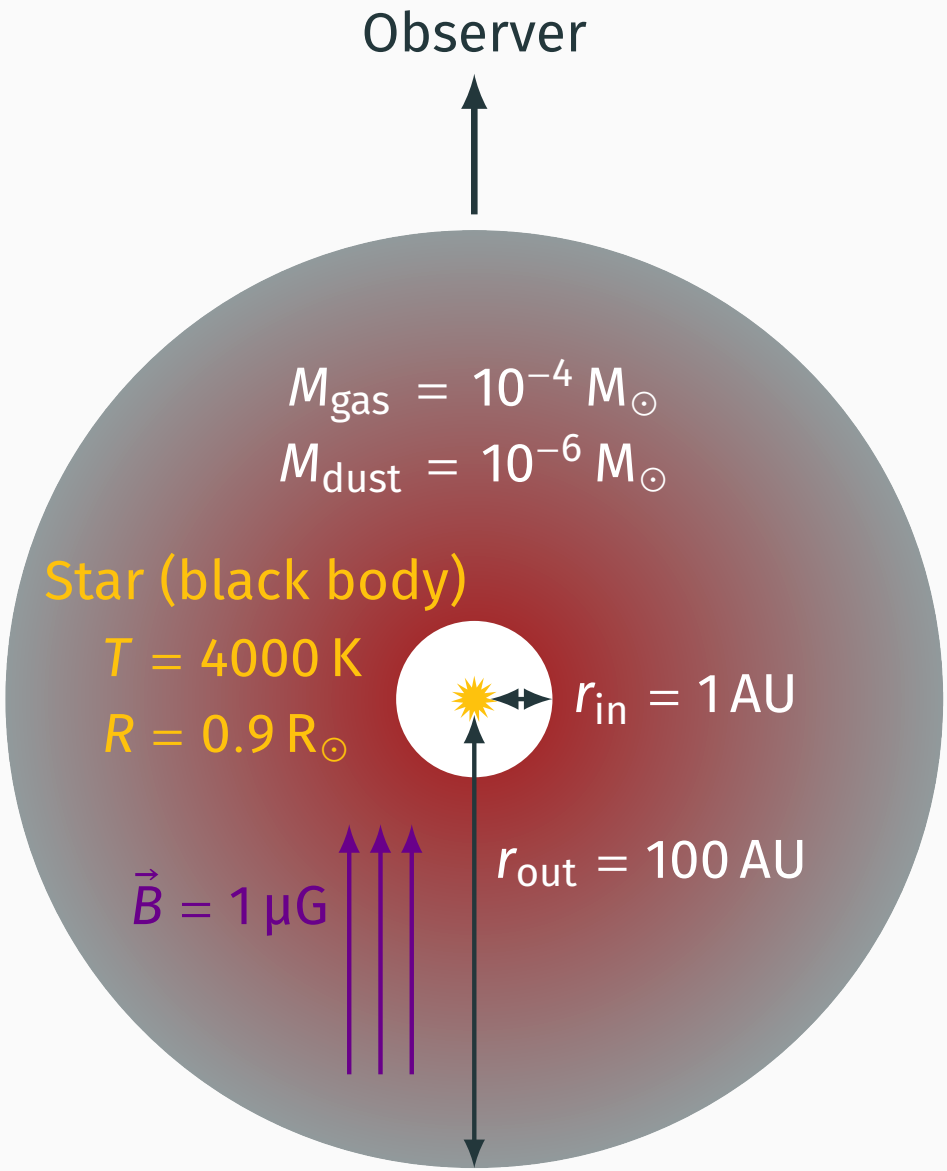
Velocity channels maps

Exercise V: Questions

What will happen if the...

- Line transition is different?
- Maximum velocity is lower or higher?
- Number of channels is lower or higher?
- Level population is calculated differently?
- Turbulence is weaker or stronger?
- Mass of the star is lower or higher?
+ *Previous questions and own ideas*

Exercise VI: Zeeman line emission of an envelope



Exercise VI: Zeeman line emission of an envelope

Create the grid

- `polaris-gen sphere grid3.dat`
  `↪ --extra vertical_mag_field`
  `↪ --inner_radius 1au --outer_radius 100au`
  `↪ --gas_mass 1e-4M_sun`

Simulate the heating of dust grains (Monte-Carlo)

- `polaris-run sphere exercise_5 temp`
  `↪ --grid grid3.dat`
  `↪ --source t_tauri --source_position 0 0 0`
  `↪ --source_temperature 4000`
  `↪ --source_radius 0.9R_sun`
  `↪ --photons 1e6`

Exercise VI: Zeeman line emission of an envelope

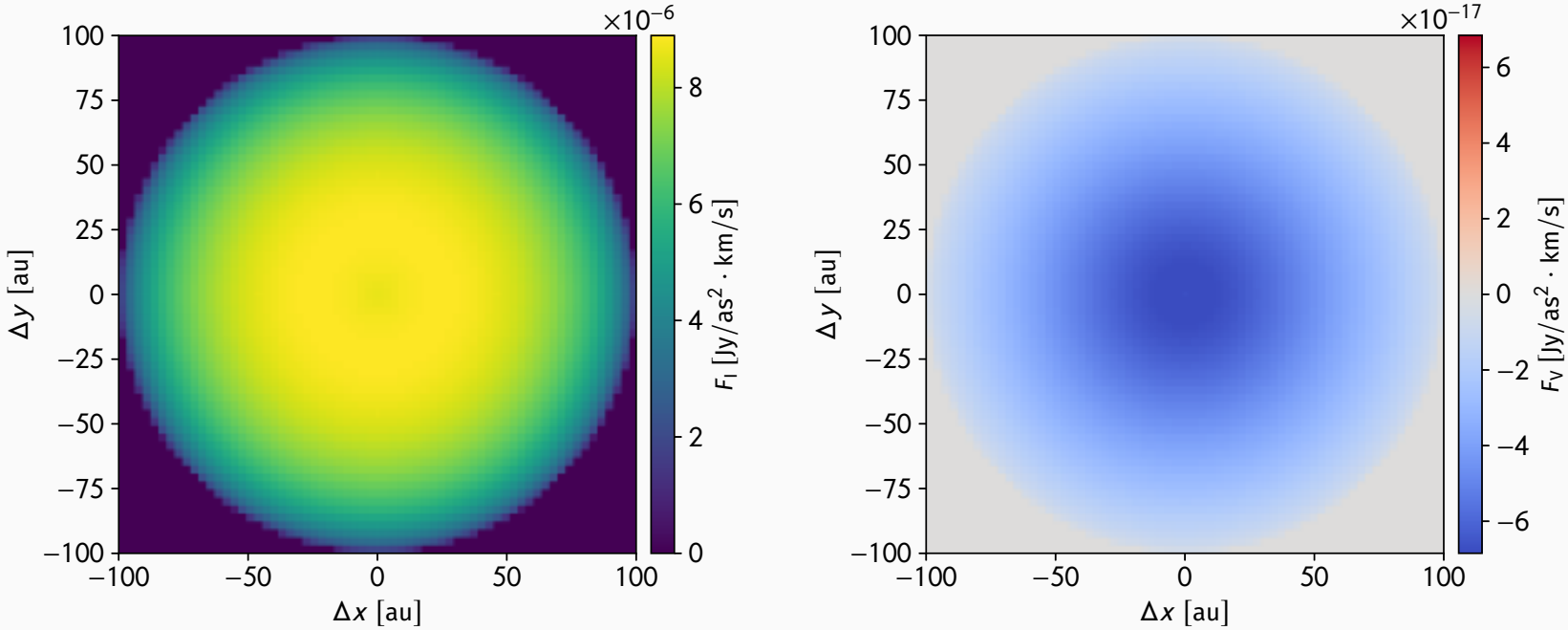
Simulate the polarized spectral line emission (Raytracing)

- `polaris-run sphere exercise_5 zeeman --gas oh`
  `↪ --transition 2 --max_vel 1km/s --pixel 65`
  `↪ --channels 35 --abundance 1e-07`
  `↪ --lvl_pop LTE --turbulence 100`

Exercise VI: Zeeman line emission of an envelope

Plot the integrated velocity channel map

- `polaris-plot sphere exercise_5 zeeman`
  `↪ int_map 1 -v`

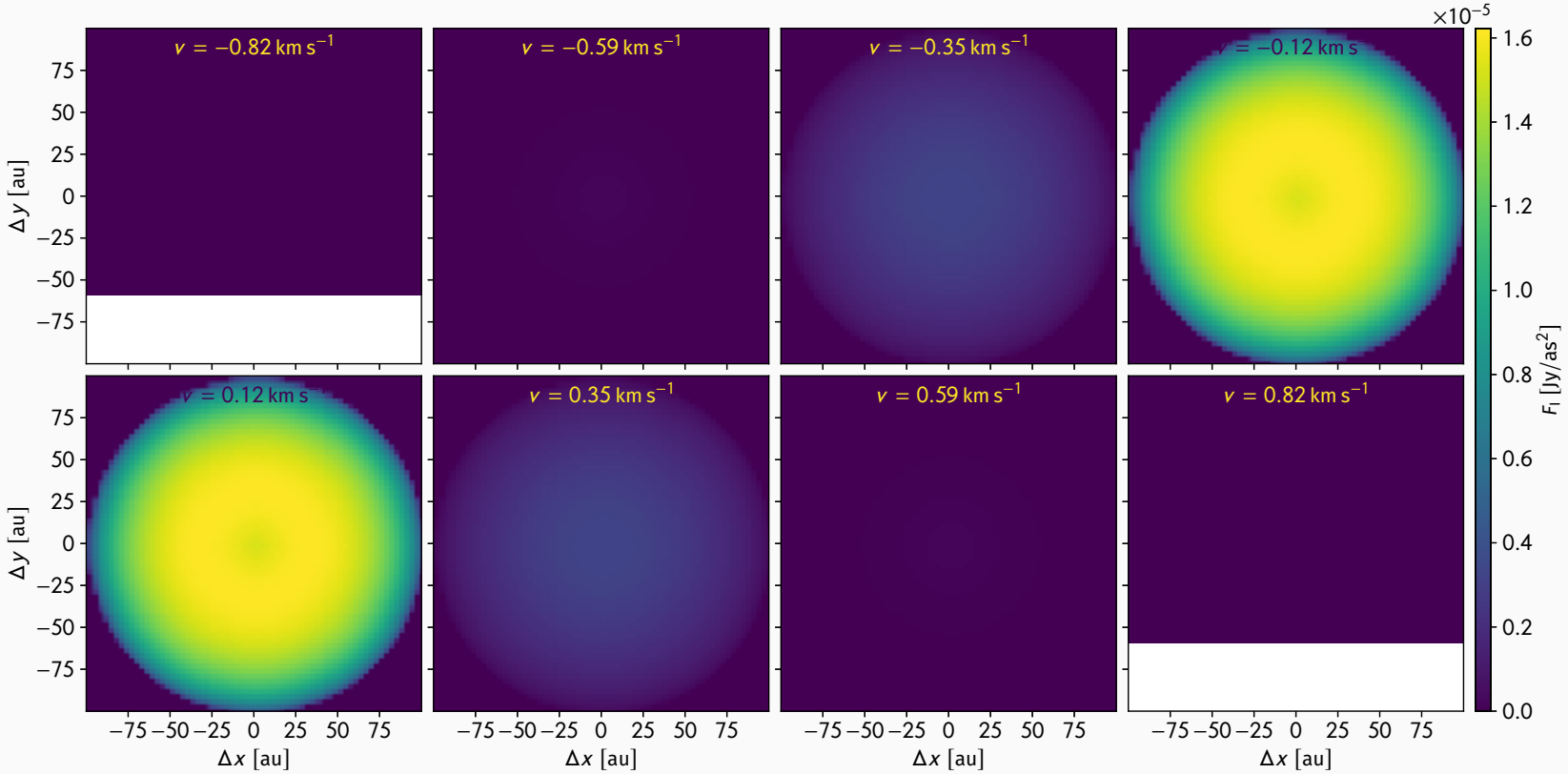


Spectral line intensity (*left*) and circular polarization *(right)* integrated velocity channel map.

Exercise VI: Zeeman line emission of an envelope

Plot the velocity channel maps

- `polaris-plot sphere exercise_5 zeeman`
  `↪ vel_map 1 -v`

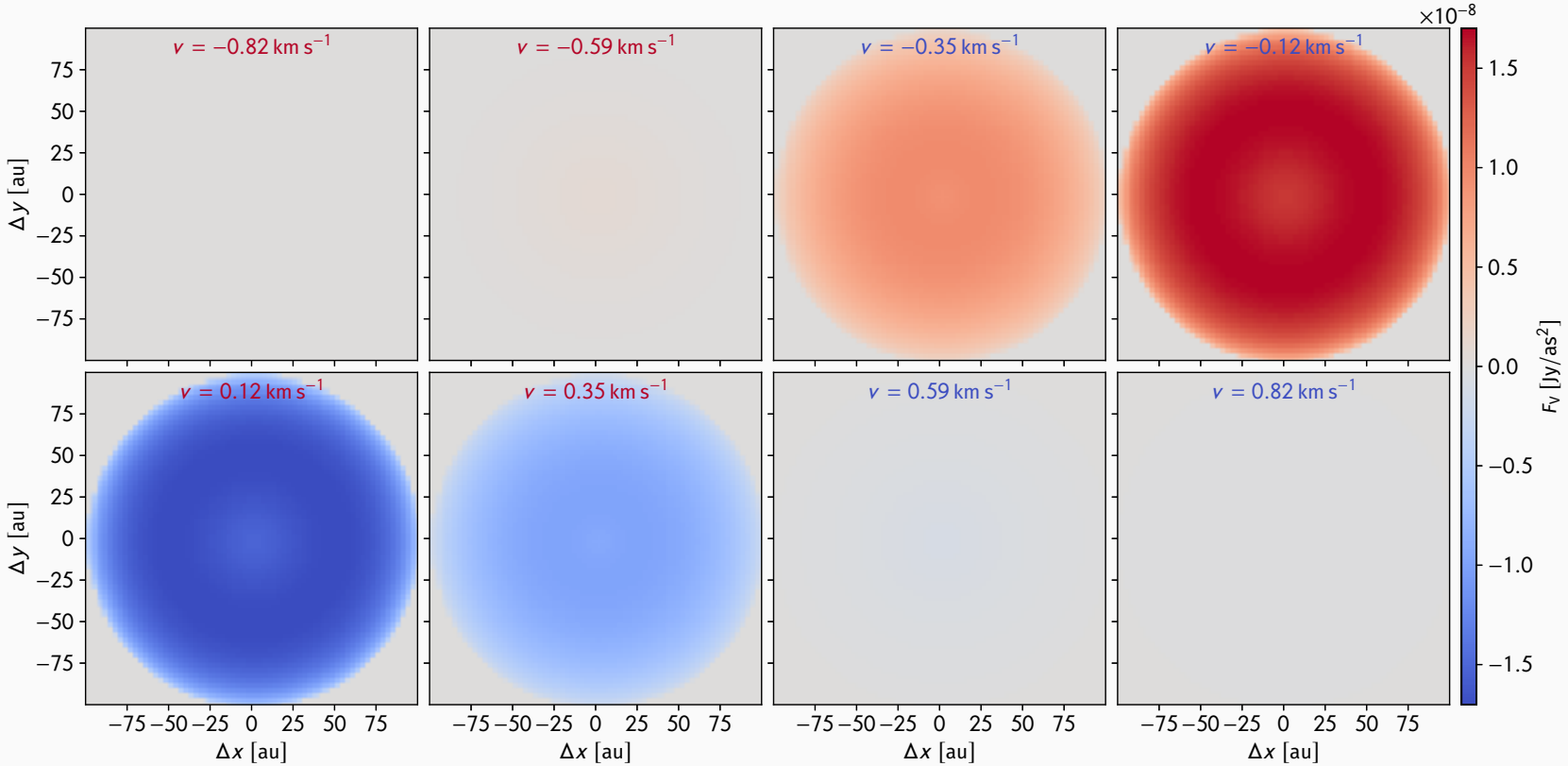


Spectral line intensity velocity channel maps.

Exercise VI: Zeeman line emission of an envelope

Plot the velocity channel maps

- `polaris-plot sphere exercise_5 zeeman`
  `↪ vel_map 1 -v`

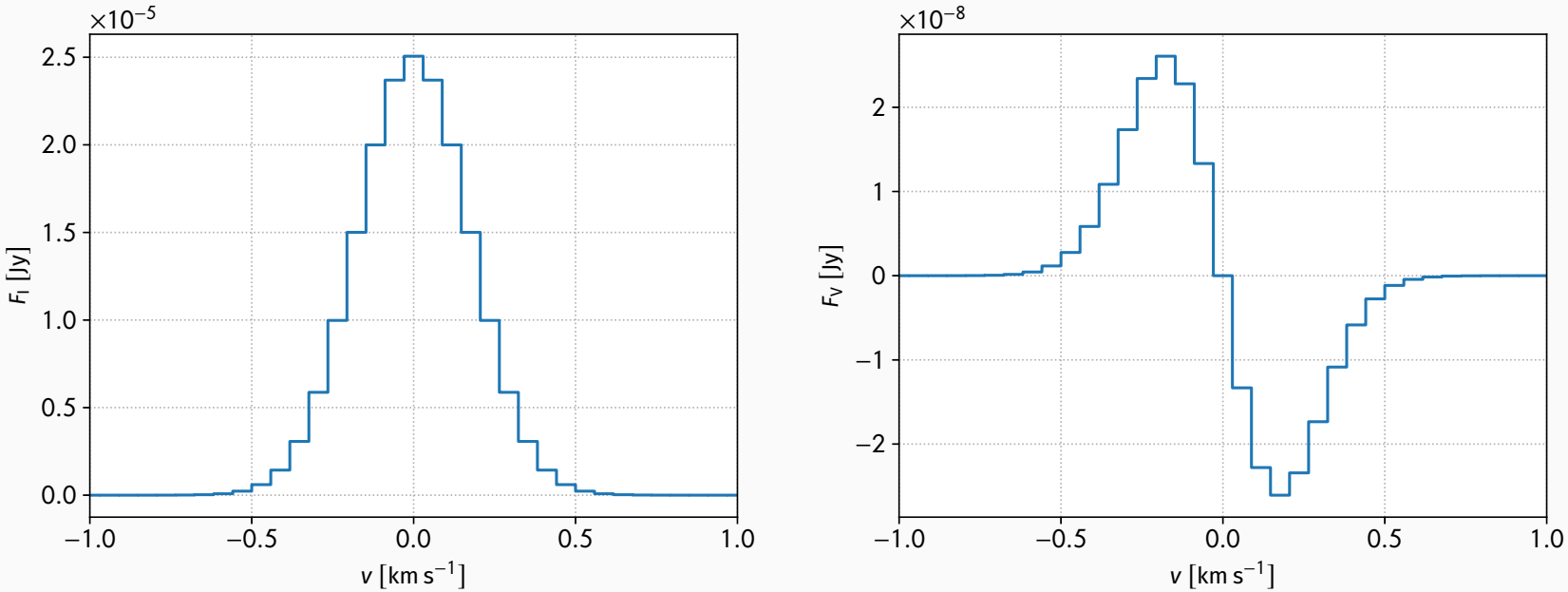


Spectral line circular polarization velocity channel maps.

Exercise VI: Zeeman line emission of an envelope

Plot the spectrum

- `polaris-plot sphere exercise_5 zeeman`
  `↪ spectrum 1 -v`

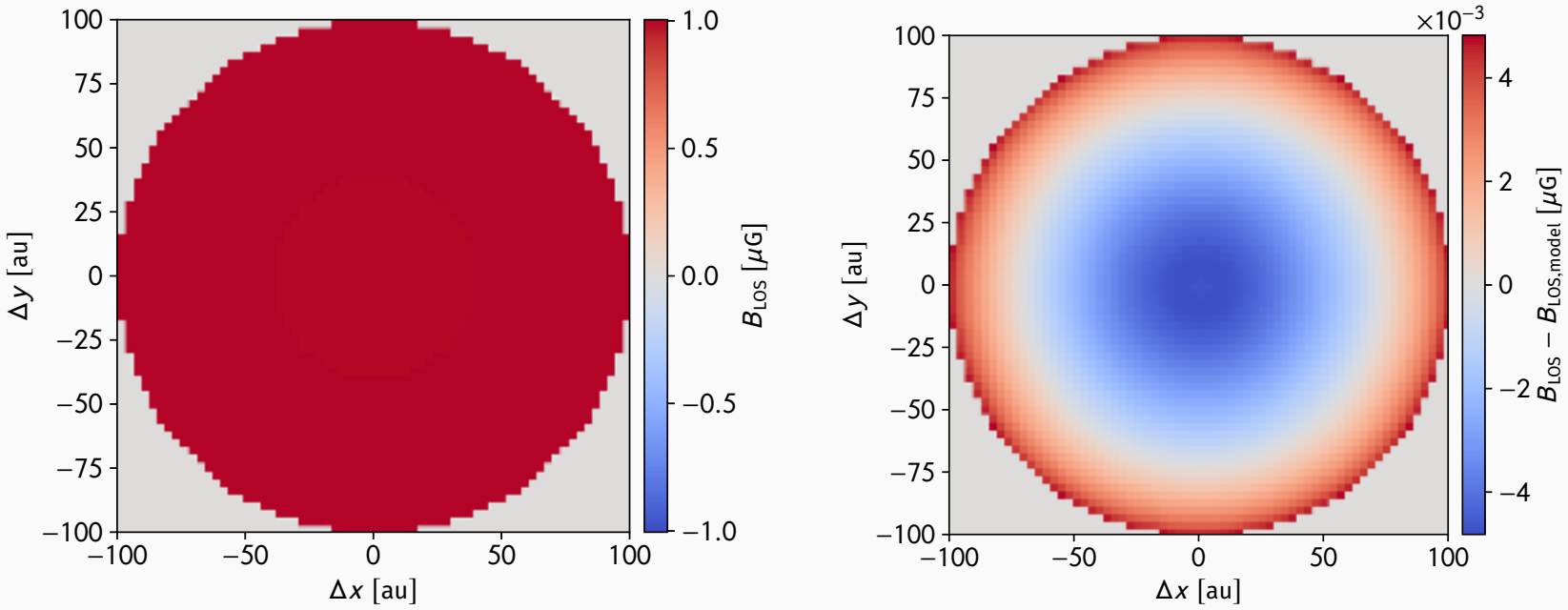


Spectral line intensity (*left*) and circular polarization *(right)* profiles.

Exercise VI: Zeeman line emission of an envelope

Plot the LOS magnetic field strength

- `polaris-plot sphere exercise_5 zeeman`
  `↪ mag_field 1 -v`



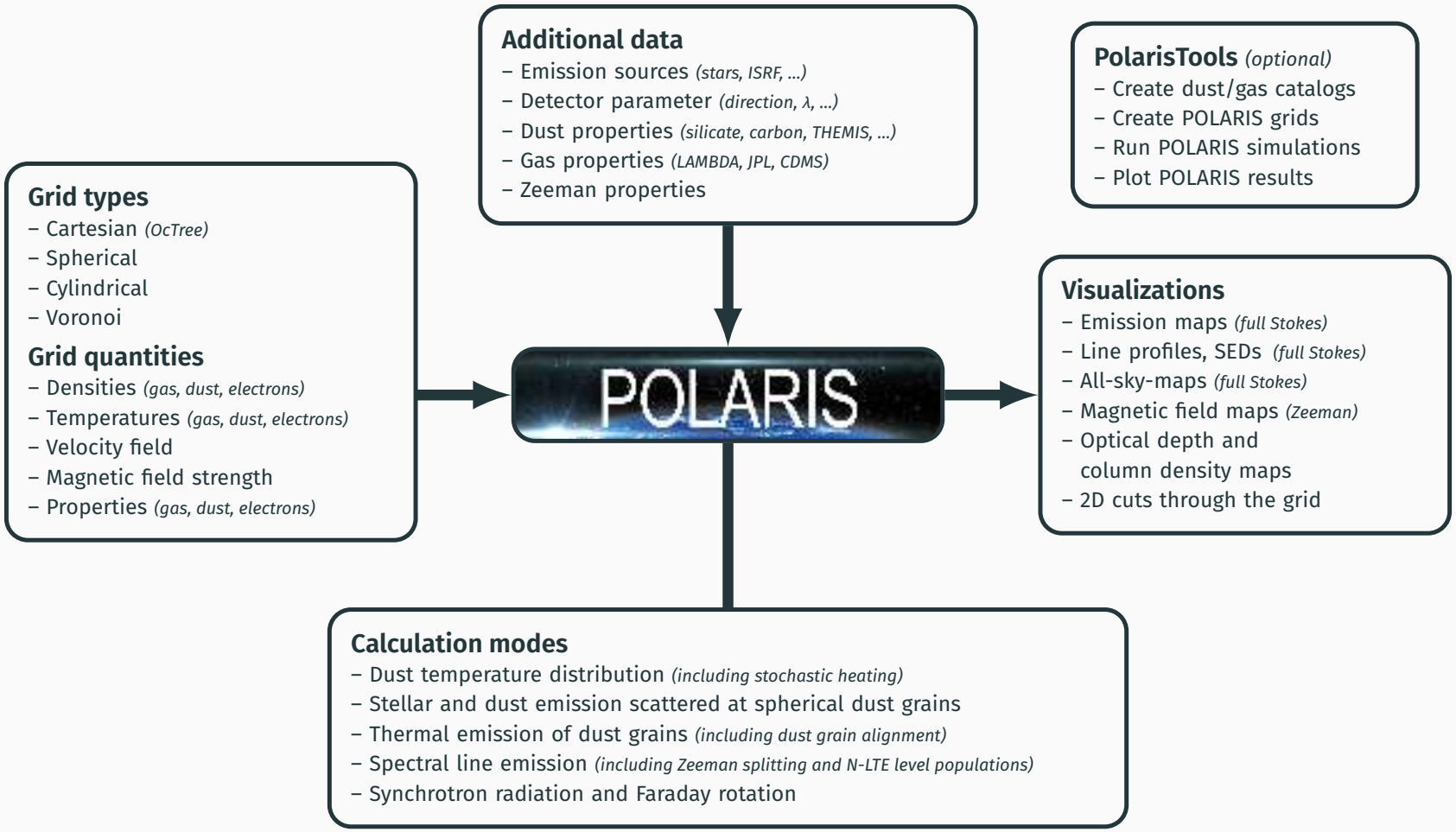
Derived LOS magnetic field strength (*left*) and difference to model value *(right)*.

Exercise VI: Questions

What will happen if the...

- Magnetic field if weaker or stronger?
- Line transition is different?
- Number of channels is lower or higher?
- Maximum velocity is lower or higher?
- *Previous questions and own ideas*

Overview of POLARIS



Thank you all for your participation!