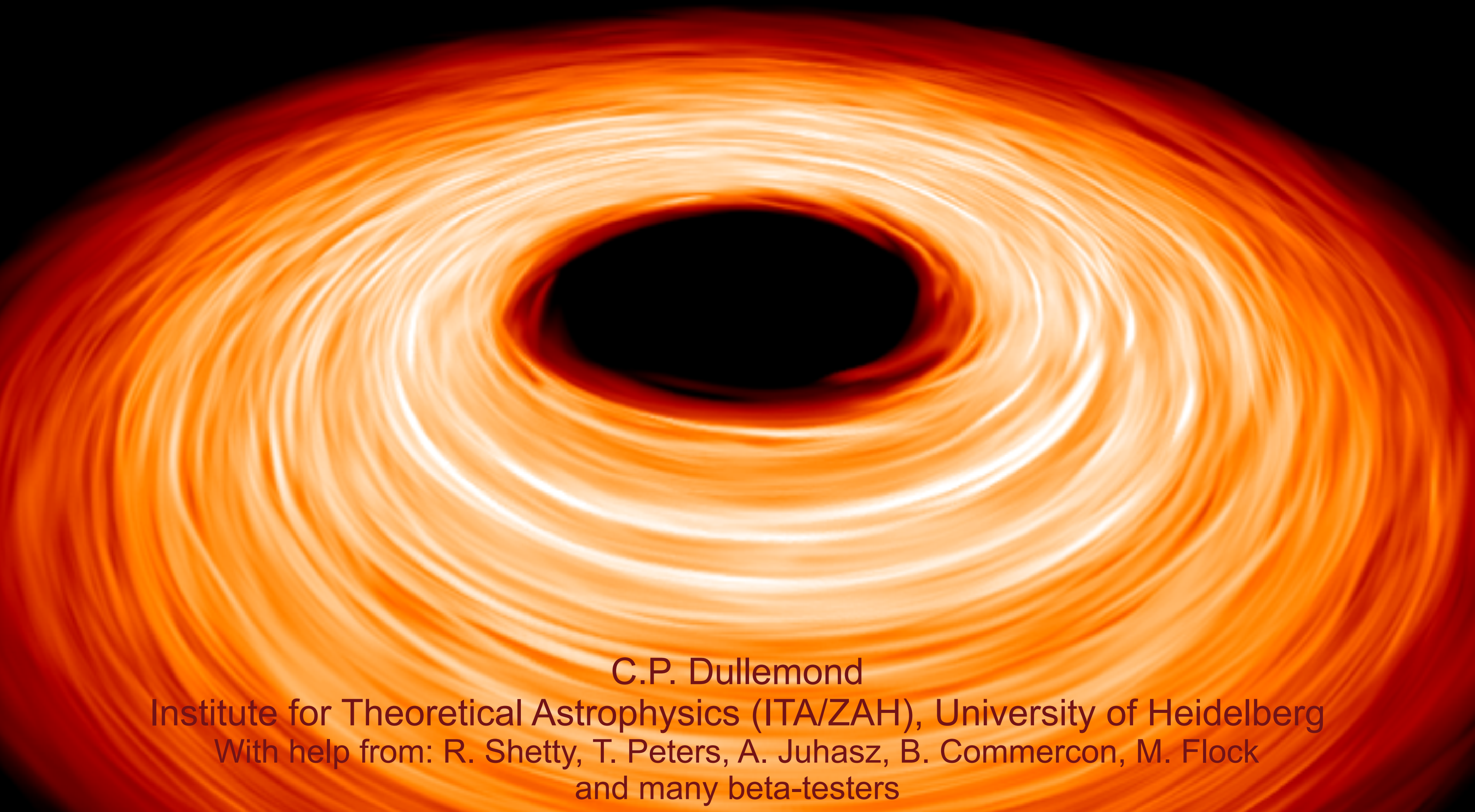
RADMC-3D

A publicly available radiative transfer program



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With help from: R. Shetty, T. Peters, A. Juhasz, B. Commercon, M. Flock
and many beta-testers

Two „kinds“ of radiative transfer

- In dynamic models:
  - Must be extremely fast (RT=bottle neck)
  - High accuracy not feasible (not really necessary)
  - Using mean opacities, flux lim diffusion, simplex-style
  - Must be as parallellizable as hydro
  - Complex on MPI

- Post-processing, for comparison to observations:
  - Must be very accurate, and frequency dependent
  - Must include complex radiative physics (lines,dust)
  - Must not necessarily be extremely fast
  - Can often be done on shared-memory machines

RADMC-3D Goals

- Compute synthetic observations from models:
  - Images
  - Spectra
  - ...and their combination: PV Diagrams etc
- Processes currently included:
  - Dust thermal emission, extinction, scattering
  - Line emission, extinction: LTE / simple non-LTE
- What it will *not* do:
  - Add noise, simulate instrument response

RADMC-3D philosophy

- Publicly available without strings attached
- Very flexible...
  - Any density distribution (1D,2D,3D) provided as:
    - List of numbers at grid points provided as input file
    - User-defined analytic function
  - Various coordinates: Cartesian / Spherical
  - Various grid-types: Regular / AMR / Patches
  - Various emission processes: Dust, Lines, User-defined
- ...yet relatively easy to use:
  - Well-documented (extensive manual)
  - Many simple example models
  - Out-of-the-box compilation and installation
  - Graphical User Interface for image-production

A short review of radiative transfer

Radiative transfer: A short review

Radiative transfer equation:

$$\frac{dI_\nu}{ds} = \rho\kappa_\nu (S_\nu - I_\nu)$$

Over length scales larger than $1/\rho\kappa_\nu$ intensity I tends to approach source function S.

Photon mean free path:

$$l_{\text{free},\nu} = \frac{1}{\rho\kappa_\nu}$$

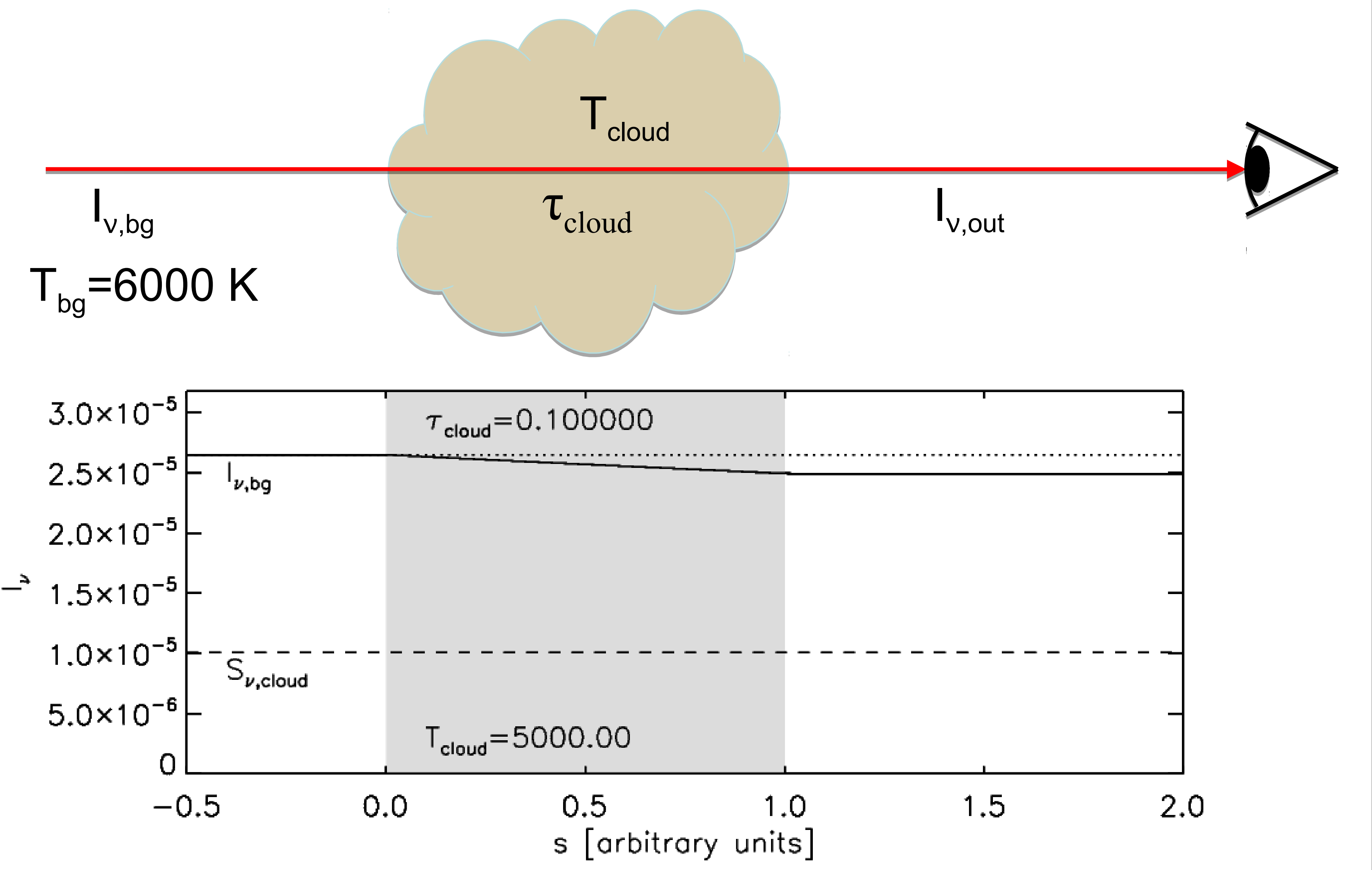
Optical depth of a cloud of size L:

$$\tau_\nu = \frac{L}{l_{\text{free},\nu}} = L\rho\kappa_\nu$$

In case of local thermodynamic equilibrium: S is Planck function:

$$S_\nu = B_\nu(T)$$

Rad. trans. through a cloud of fixed T



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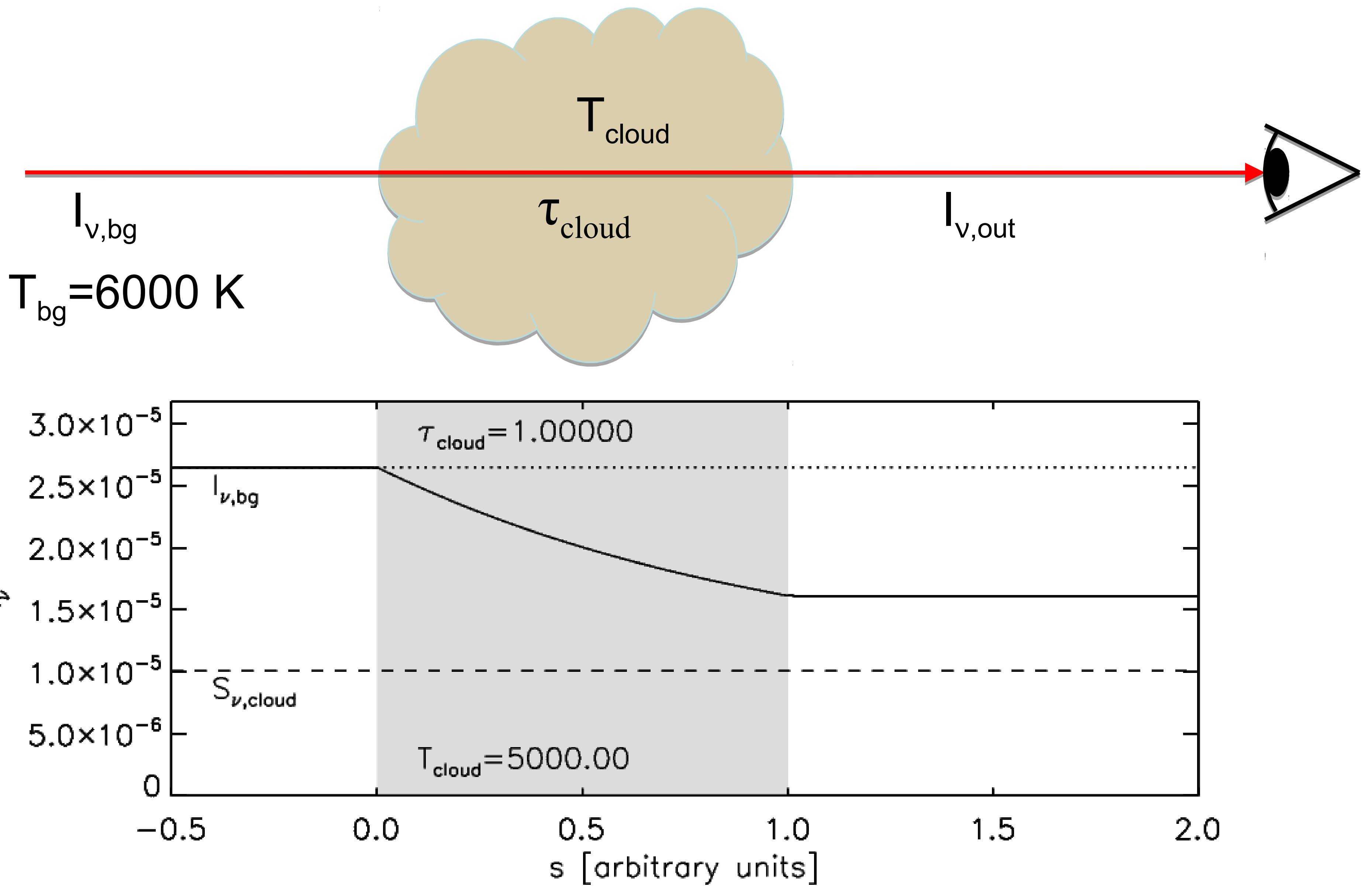

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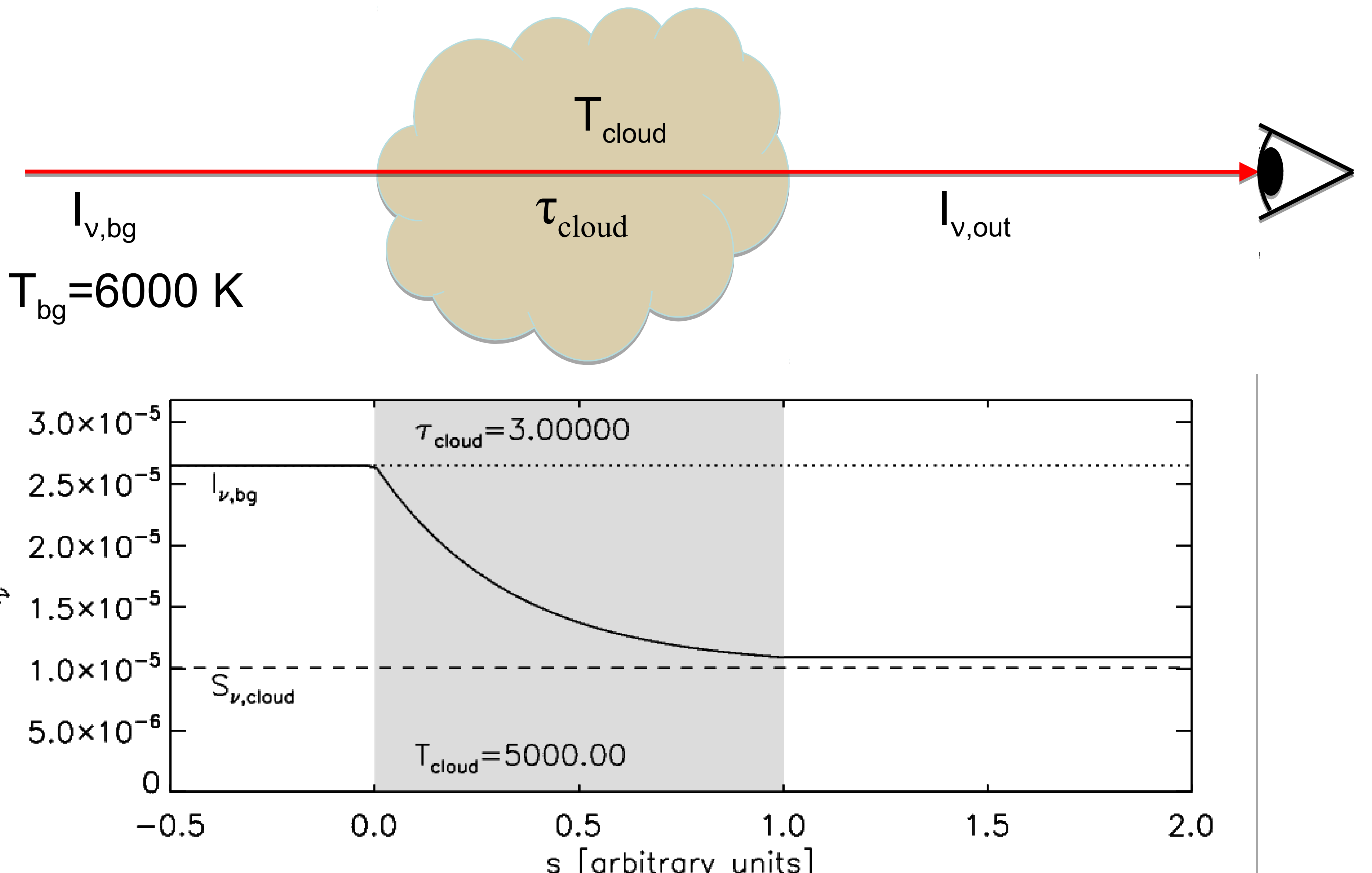

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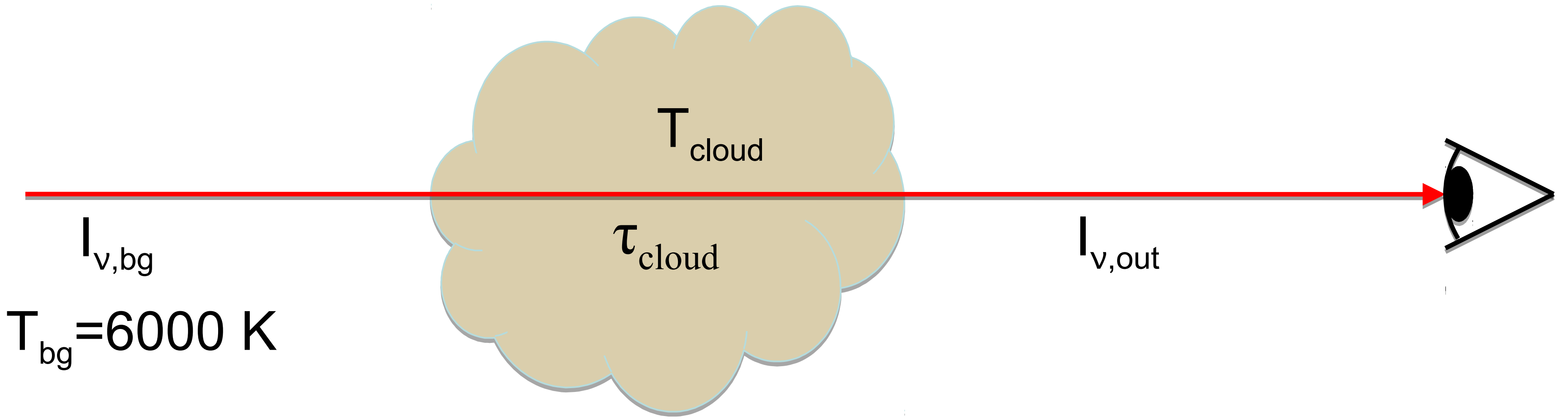

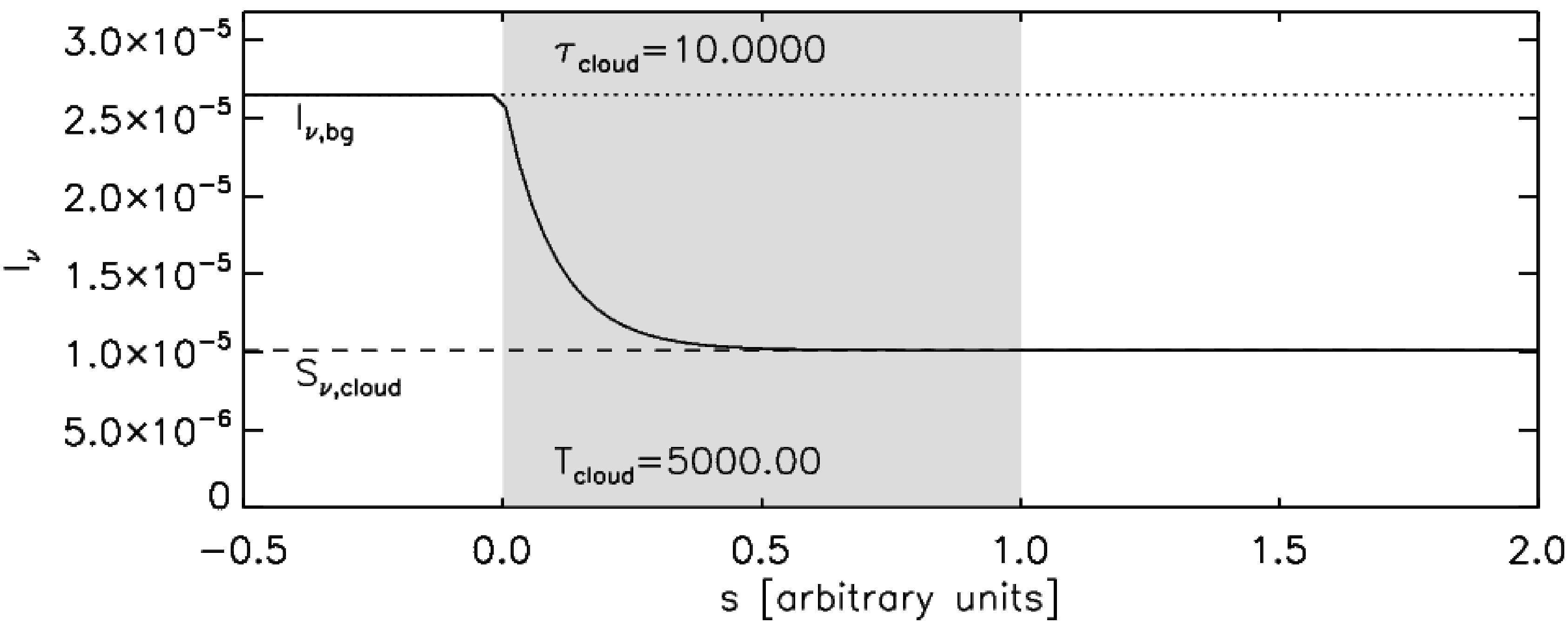

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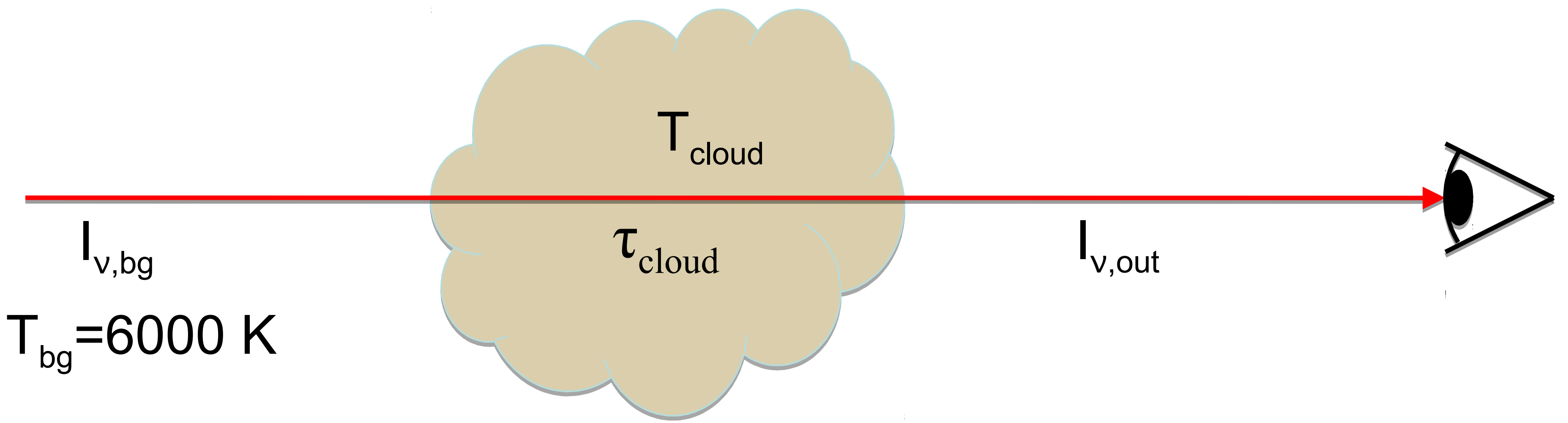
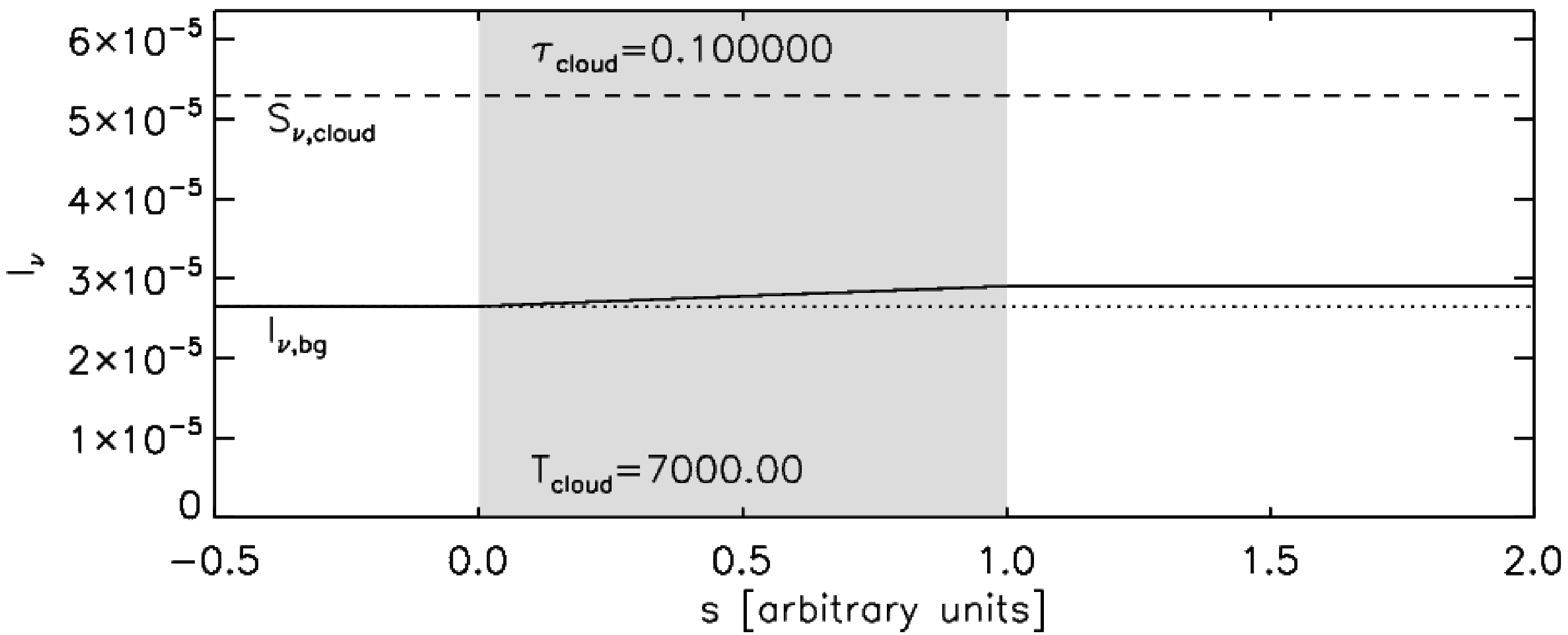
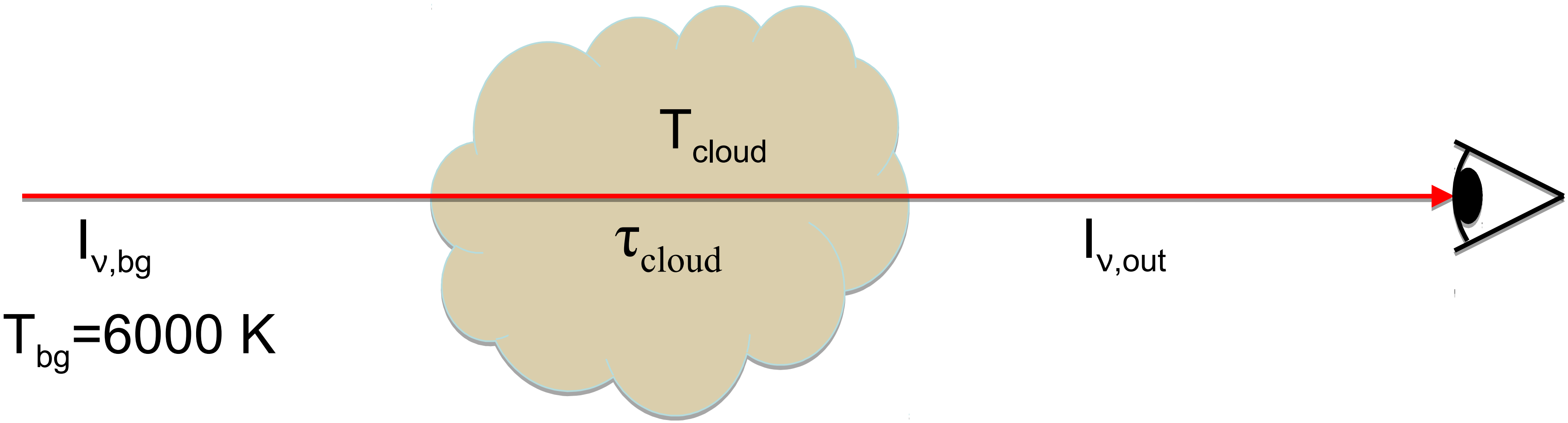
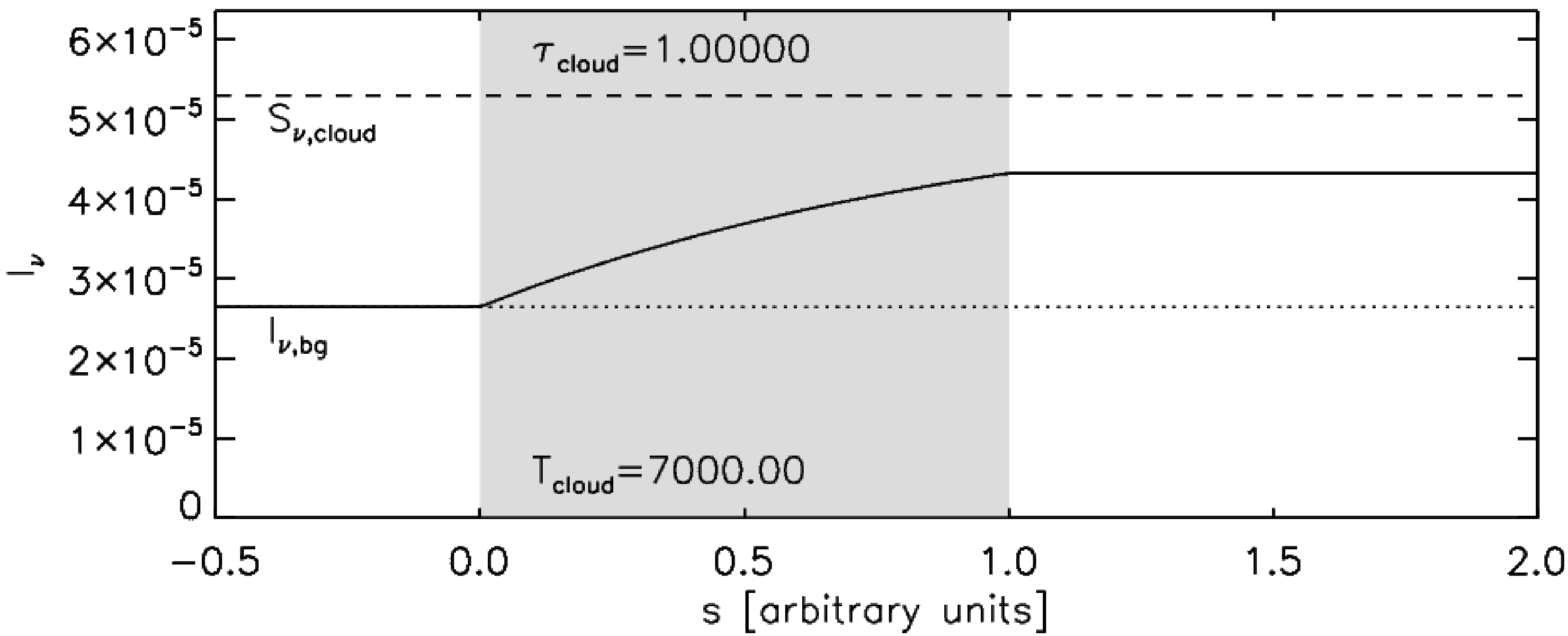




Rad. trans. through a cloud of fixed T





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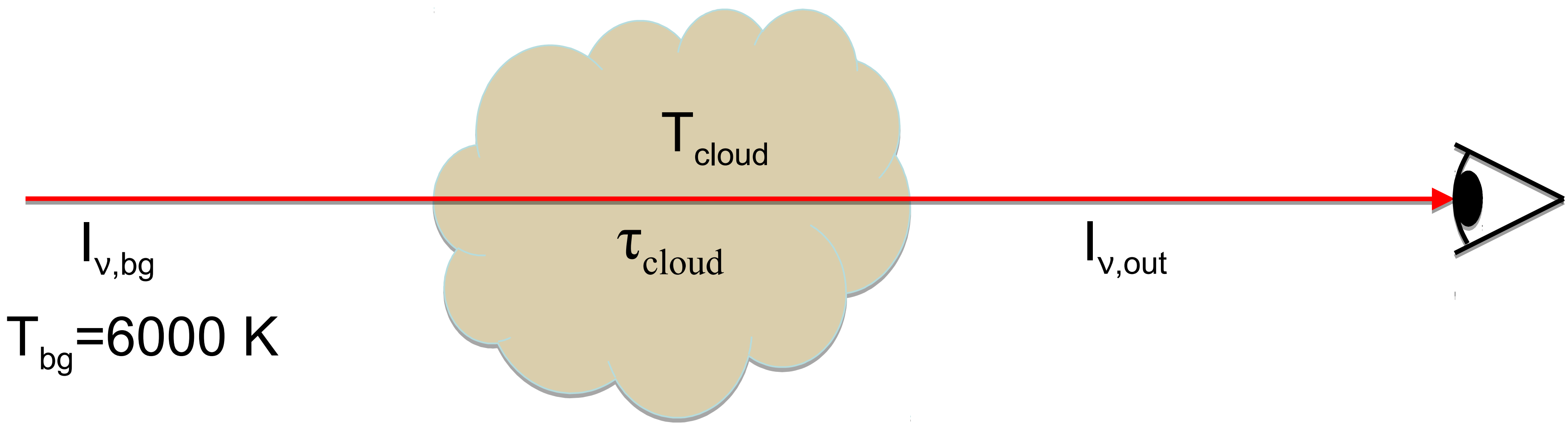

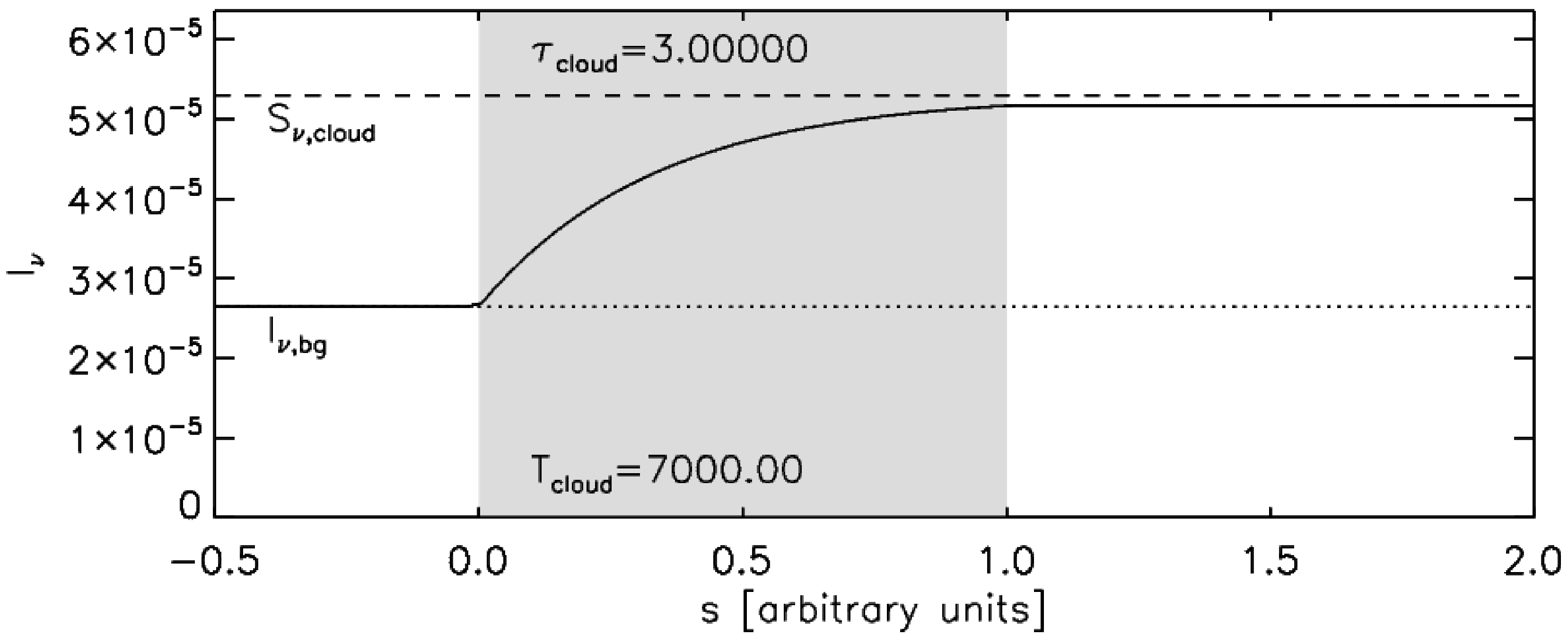

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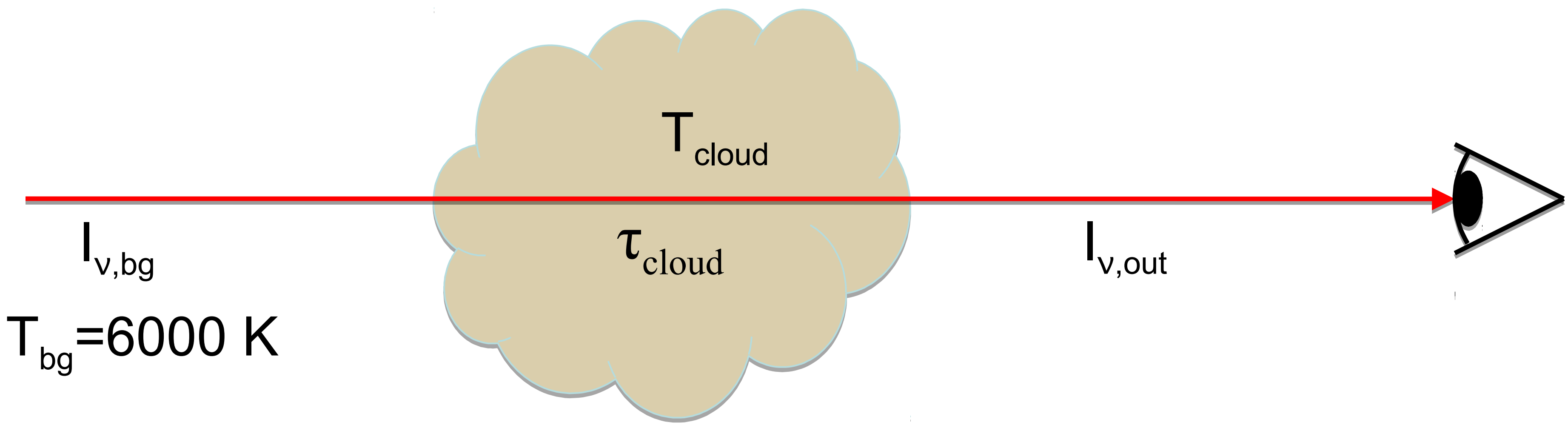
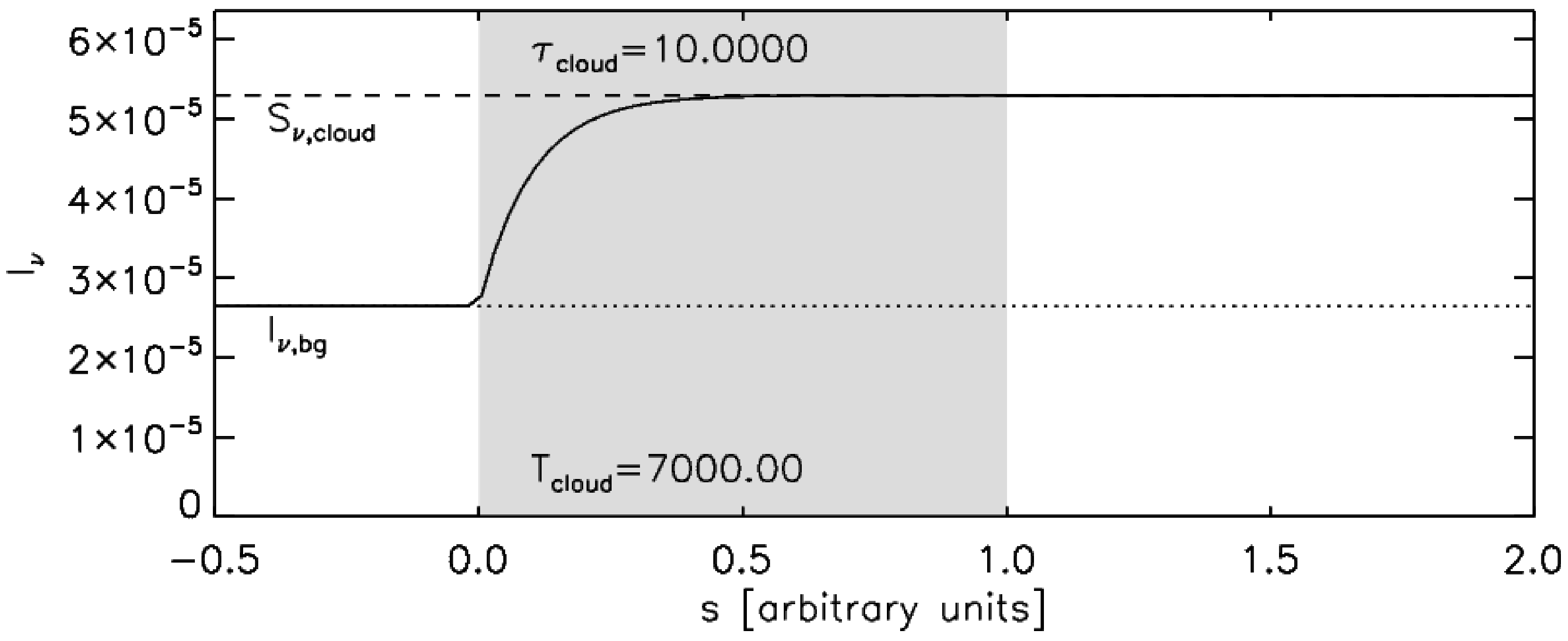




Formal radiative transfer solution

Radiative transfer equation again:

$$\frac{dI_\nu}{ds} = \rho\kappa_\nu (S_\nu - I_\nu)$$

Observed flux from single-temperature slab:

$$I_\nu^{\mathrm{obs}} = I_\nu^0 e^{-\tau_\nu} + (1 - e^{-\tau_\nu})\, B_\nu(T)$$

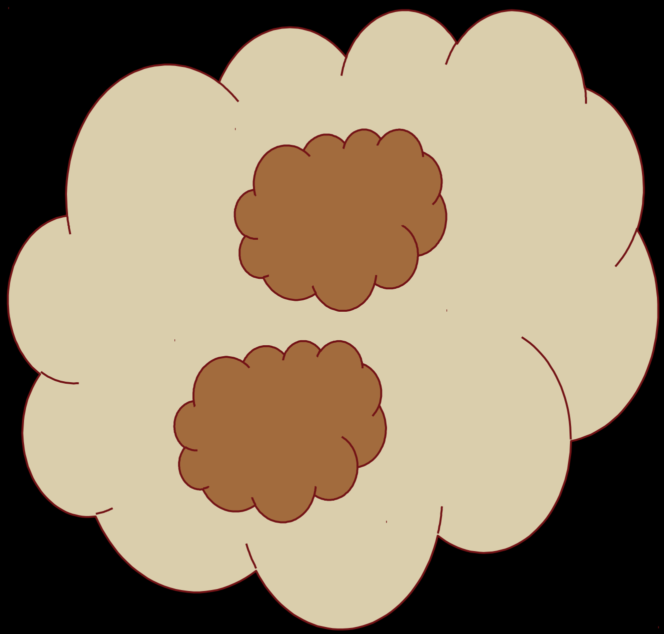
$$\tau_\nu = L\rho\kappa_\nu$$

$$\approx \tau_\nu B_\nu(T)$$

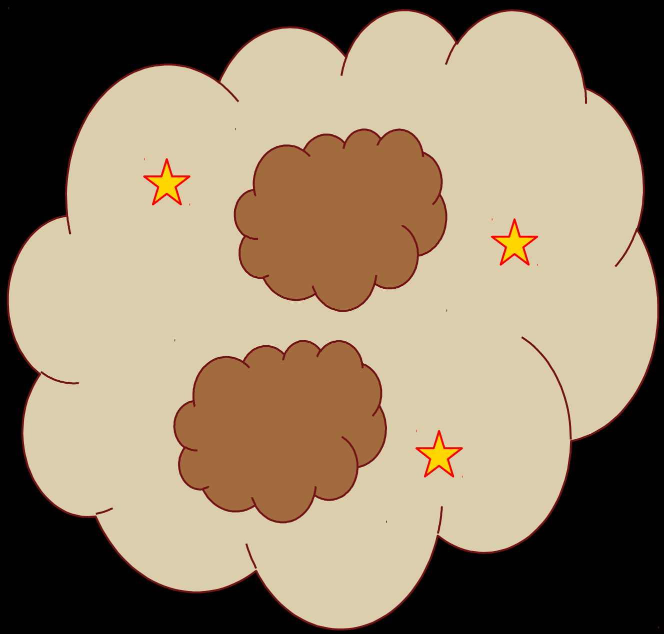
for $\tau_\nu << 1$ and $I_\nu^0 = 0$

How RADMC-3D is used

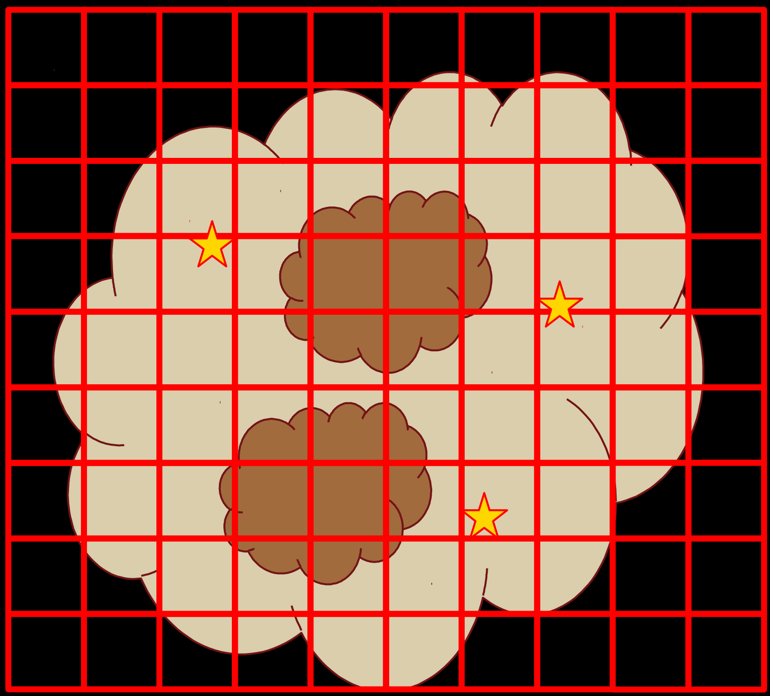
A model begins with a density distribution...



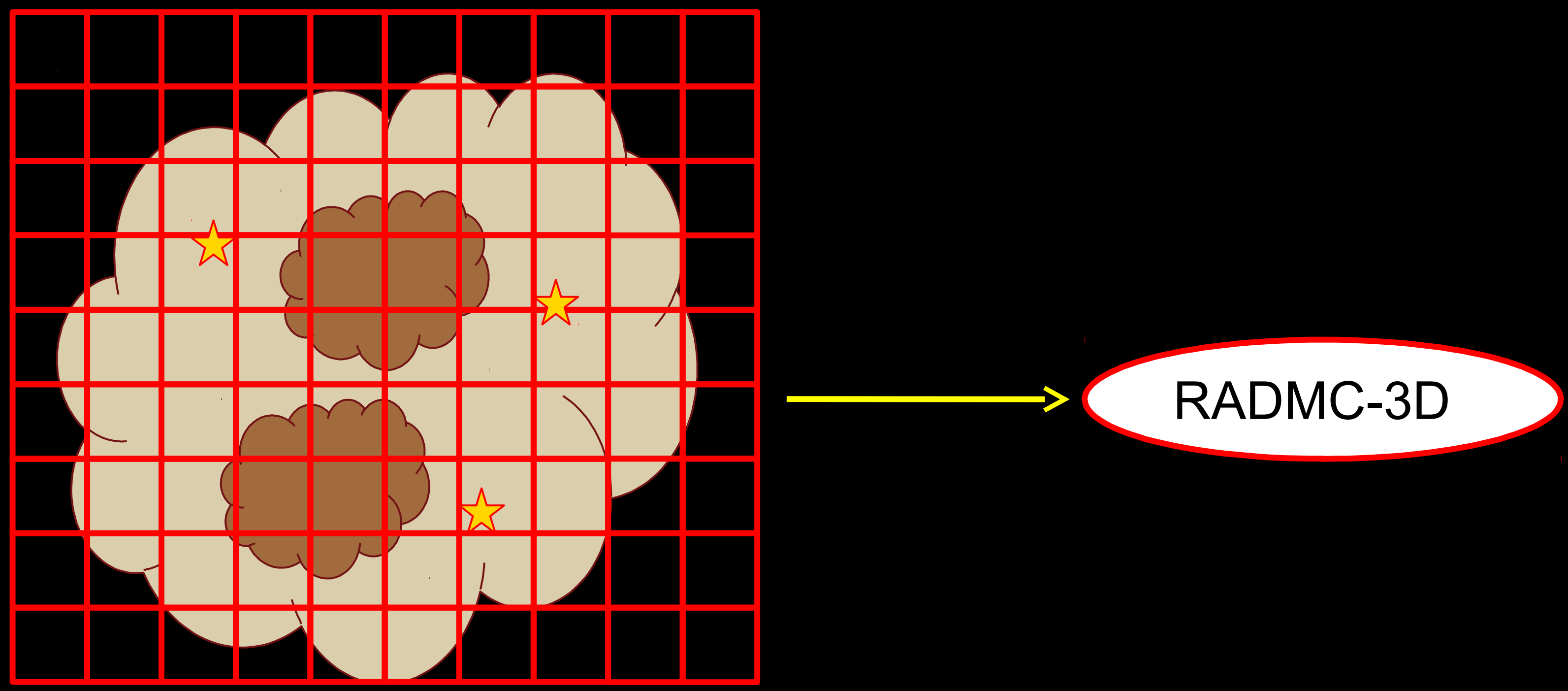
Add stars...



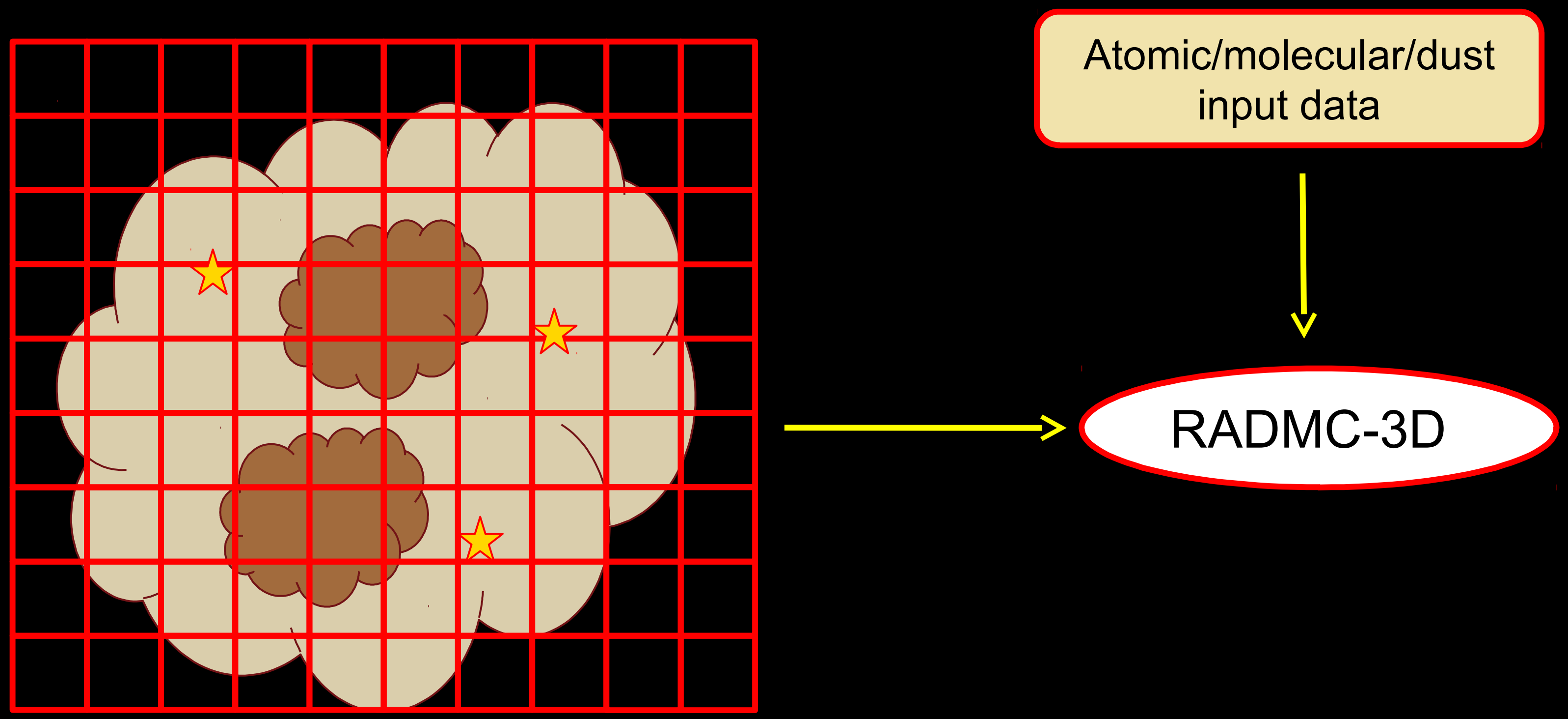
Map the density on a grid...



Pass these numbers to RADMC-3D...

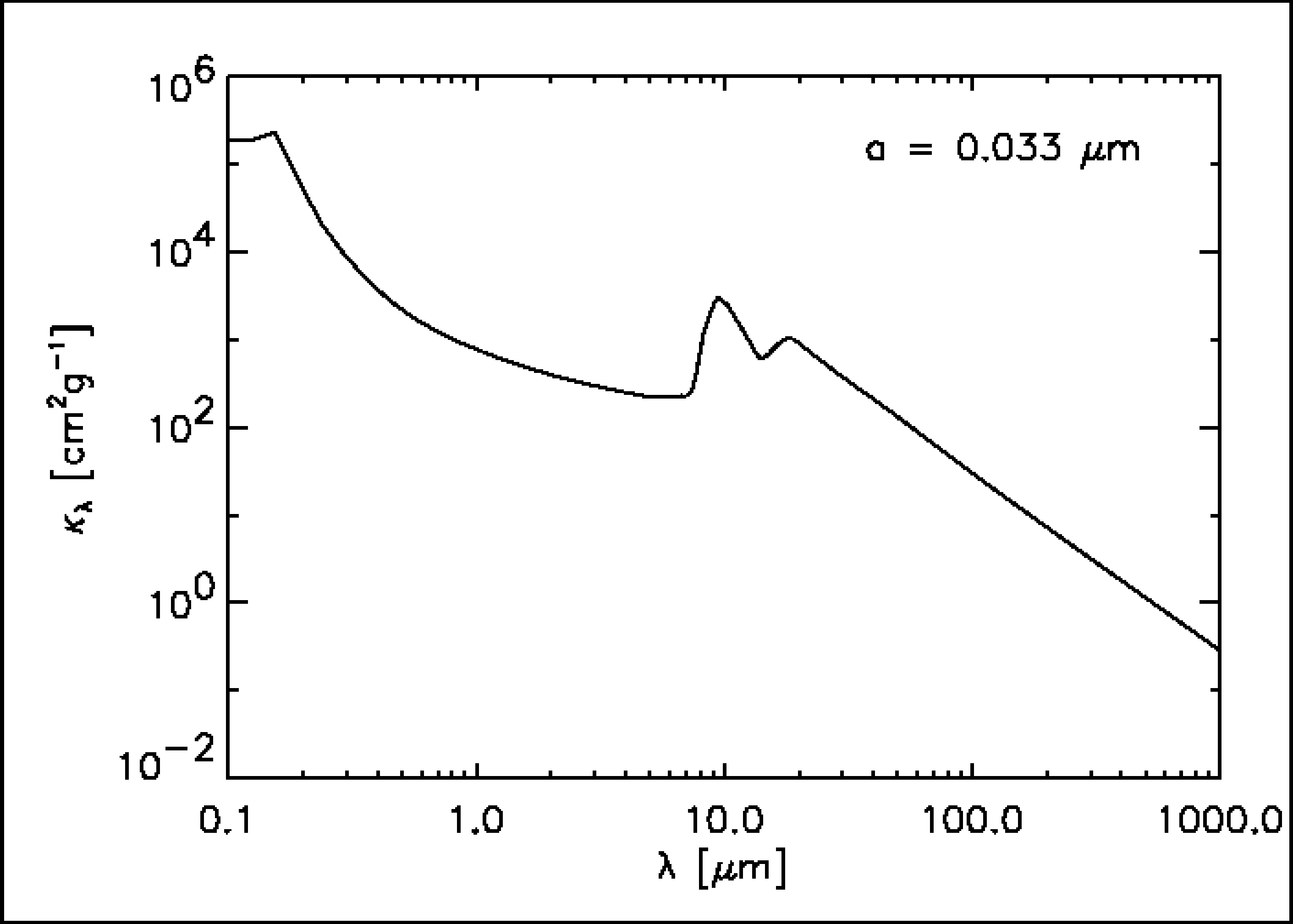


Also give RADMC-3D physical data...



Input: Dust opacity

Opacity of amorphous silicate

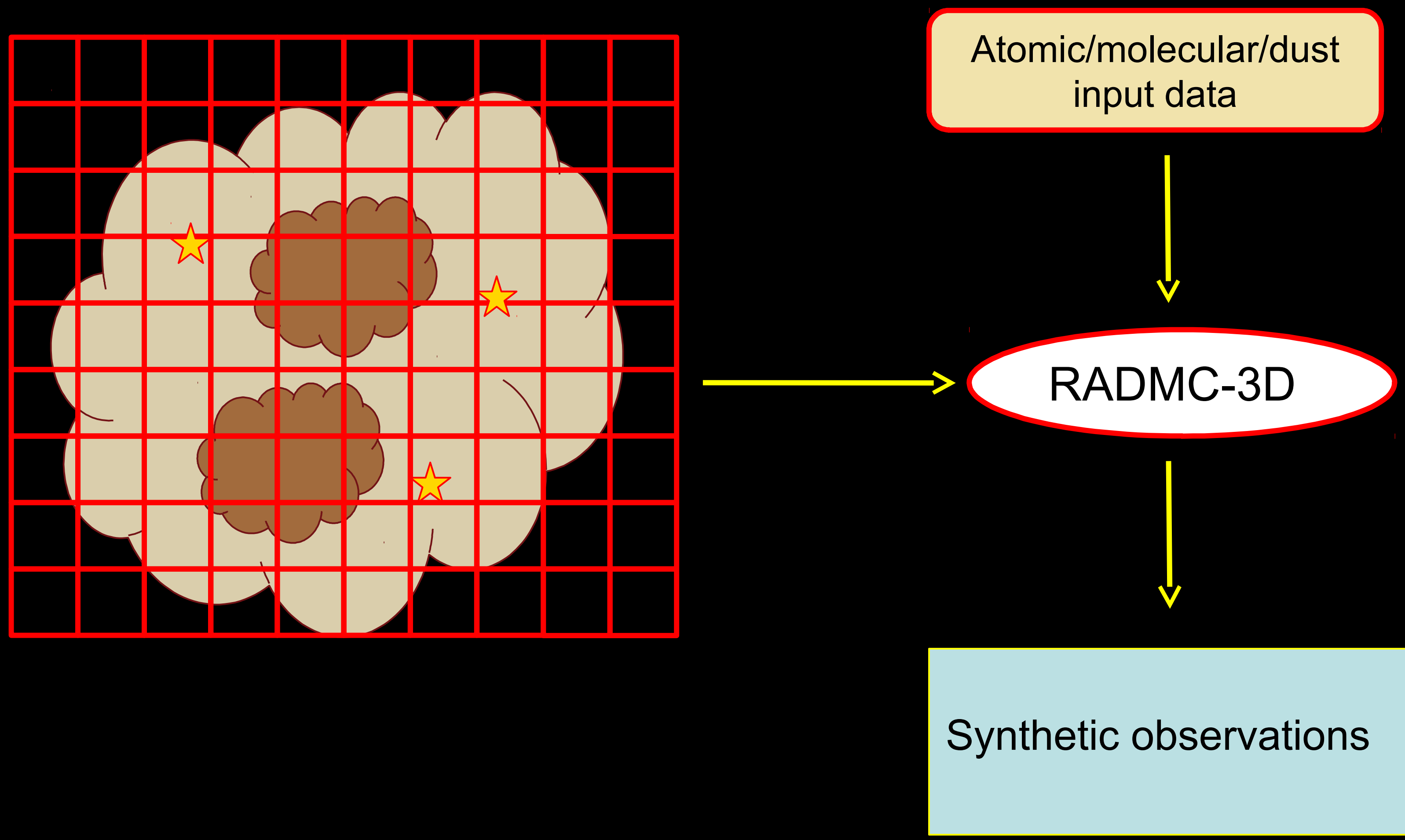


Input: Line data

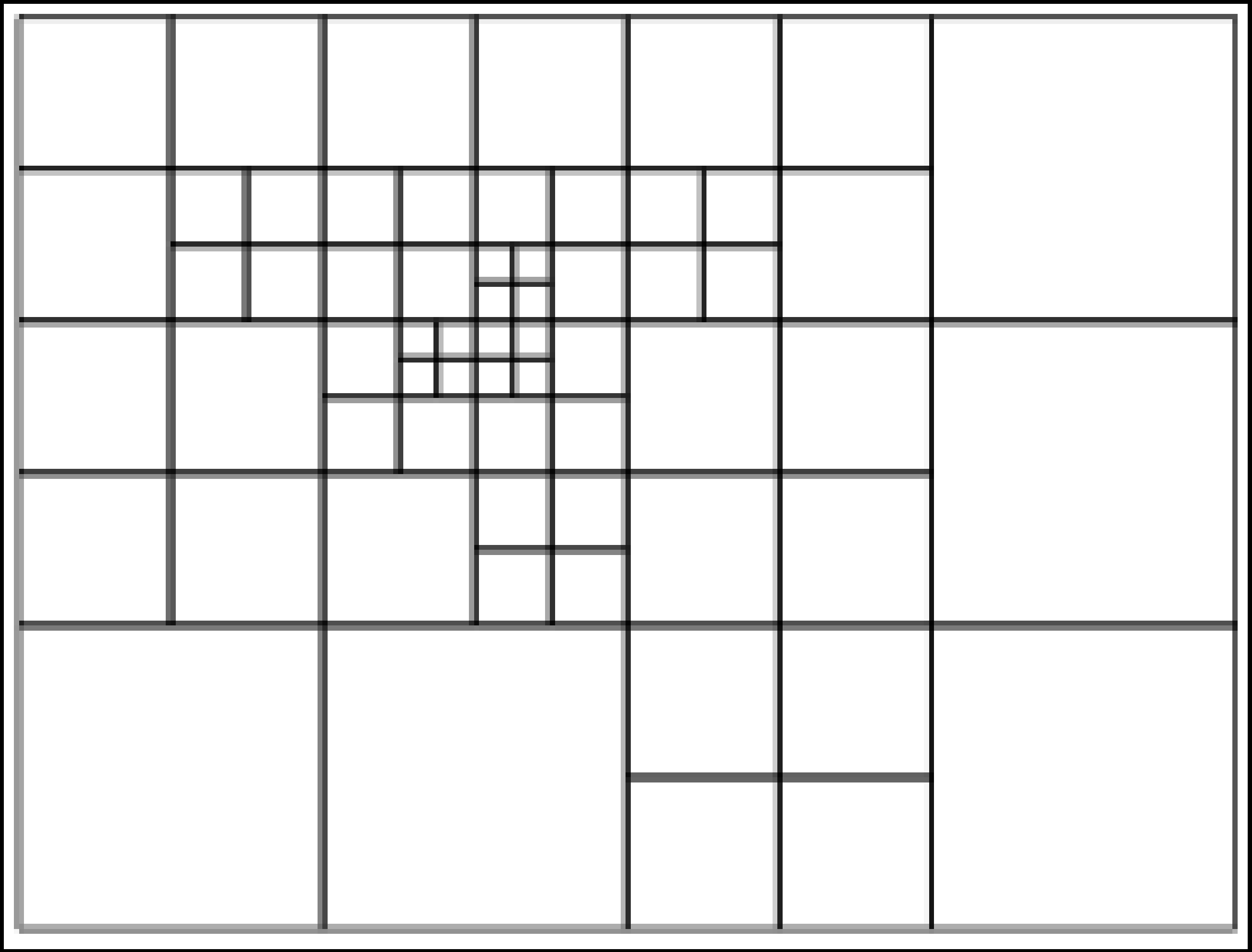
- Levels: Energies, degeneracies
- Transitions: A-coefficients
- Collisional data

- Various databases now readable:
  - Leiden
  - HITRAN (linelist)
  - ...

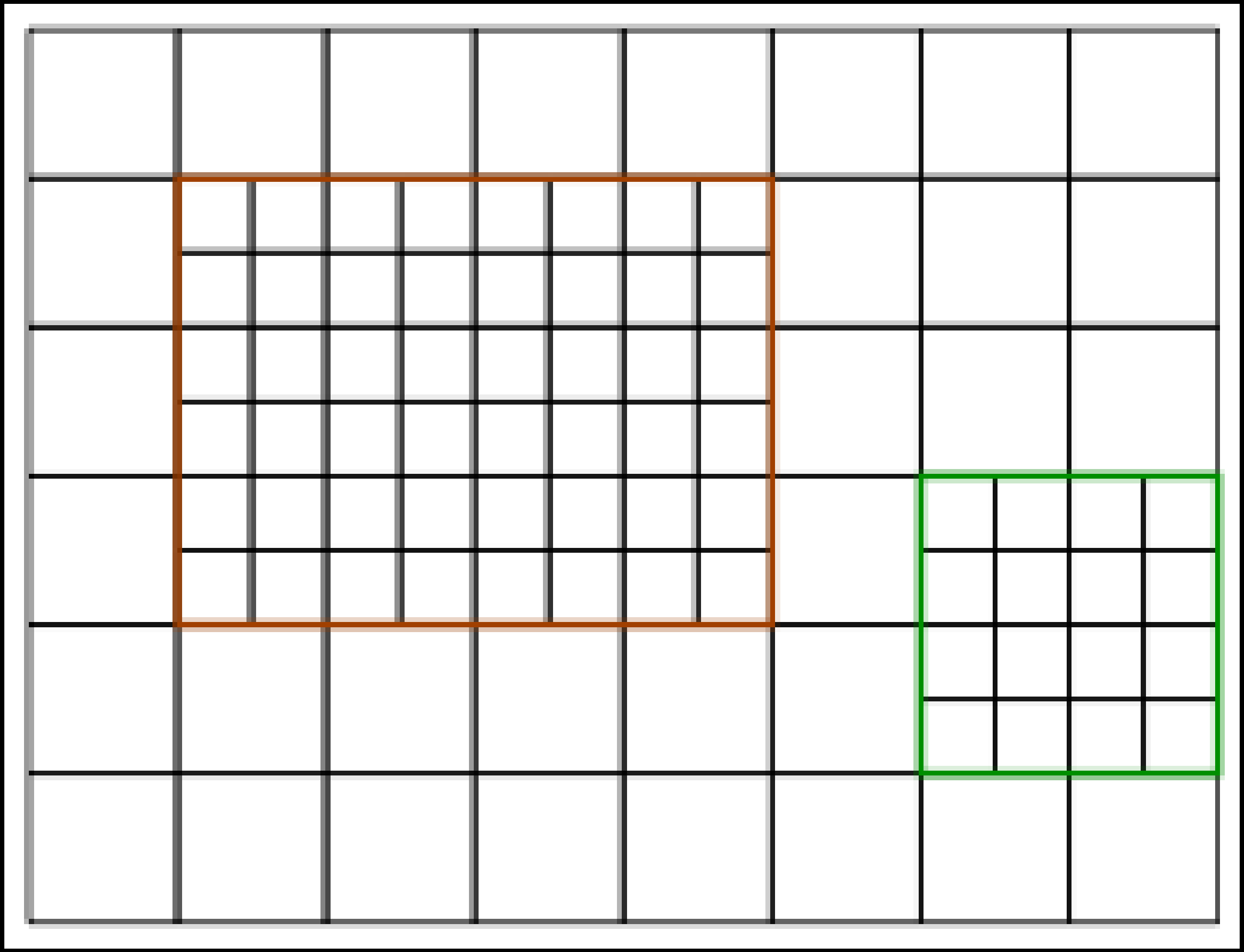
Now it can produce synthetic observations...



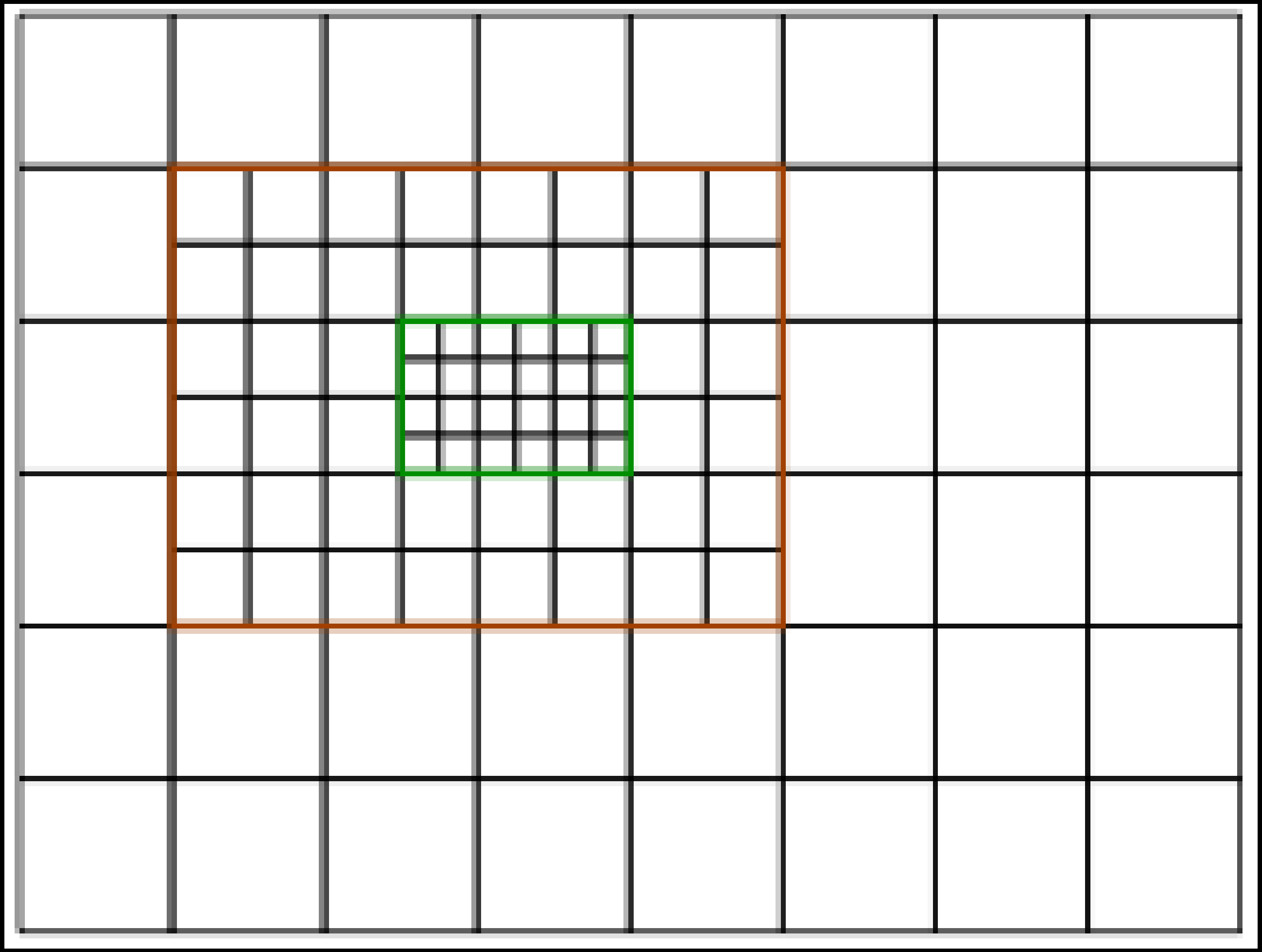
AMR Grid Structure: Oct tree



AMR Grid Structure: Patch-based



AMR: Patch-based, recursive



Coordinates

- Cartesian: 3D
- Spherical: 1D, 2D, 3D

- In all these coordinate systems the AMR is possible.

Interfaces from well-known codes

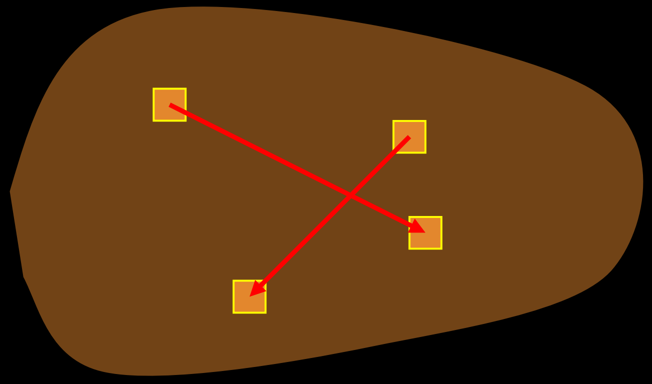
- FLASH
- RAMSES
- PLUTO
- ZEUS

Dust continuum radiative transfer

Difficulty of dust radiative transfer

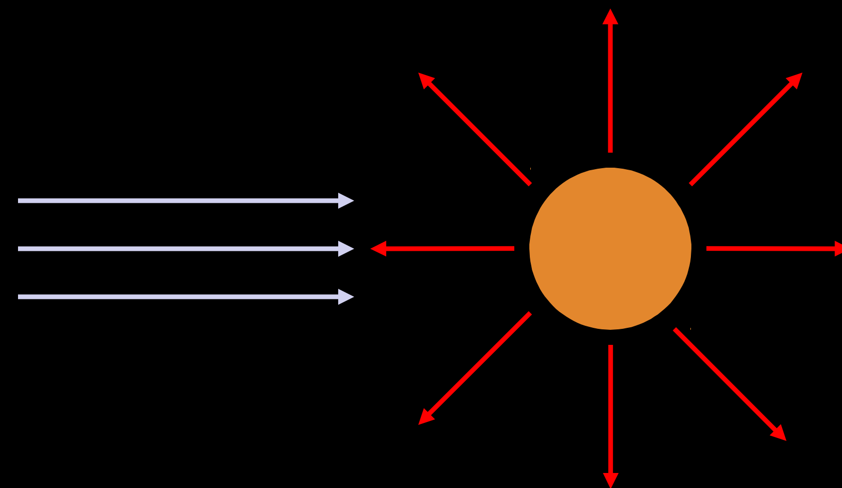
I. The thermal equilibrium problem

- If temperature of dust is given (ignoring scattering for the moment), then radiative transfer is a mere integral along a ray: i.e. easy.
- Problem: dust temperature is affected by radiation, even the radiation it emits itself.
- Therefore: must solve radiative transfer and thermal balance simultaneously.
- Difficulty: each point in cloud can heat (and receive heat from) each other point.



Thermal balance of dust grains

<u>Optically thin case:</u>



Heating:

$$Q_+ = \pi a^2 \int F_\nu \, \varepsilon_\nu \, d\nu$$

a = radius of grain

ε_ν= absorption efficiency (=1 for perfect black sphere)

Cooling:

$$Q_- = 4\pi a^2 \int \pi B_\nu(T) \, \varepsilon_\nu \, d\nu$$

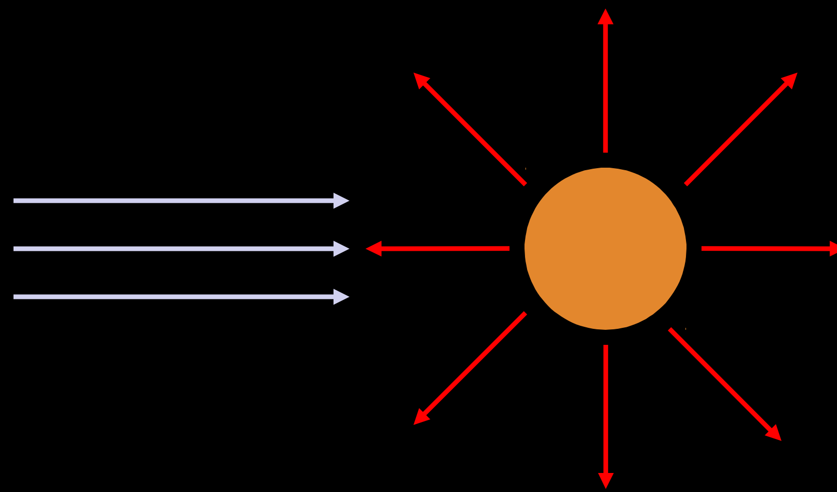
$$\kappa_\nu = \frac{\pi a^2 \varepsilon_\nu}{m}$$

Thermal balance:

$$4\pi a^2 \int \pi B_\nu(T) \, \varepsilon_\nu \, d\nu = \pi a^2 \int F_\nu \, \varepsilon_\nu \, d\nu$$

Thermal balance of dust grains

<u>Optically thin case:</u>



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$$\kappa_\nu = \frac{\pi a^2 \varepsilon_\nu}{m}$$

Thermal balance:

$$\int B_\nu(T) \kappa_\nu \, d\nu = \frac{1}{\pi} \int F_\nu \kappa_\nu \, d\nu$$

Optically thick case

Additional radiation field: diffuse infrared radiation from the grains

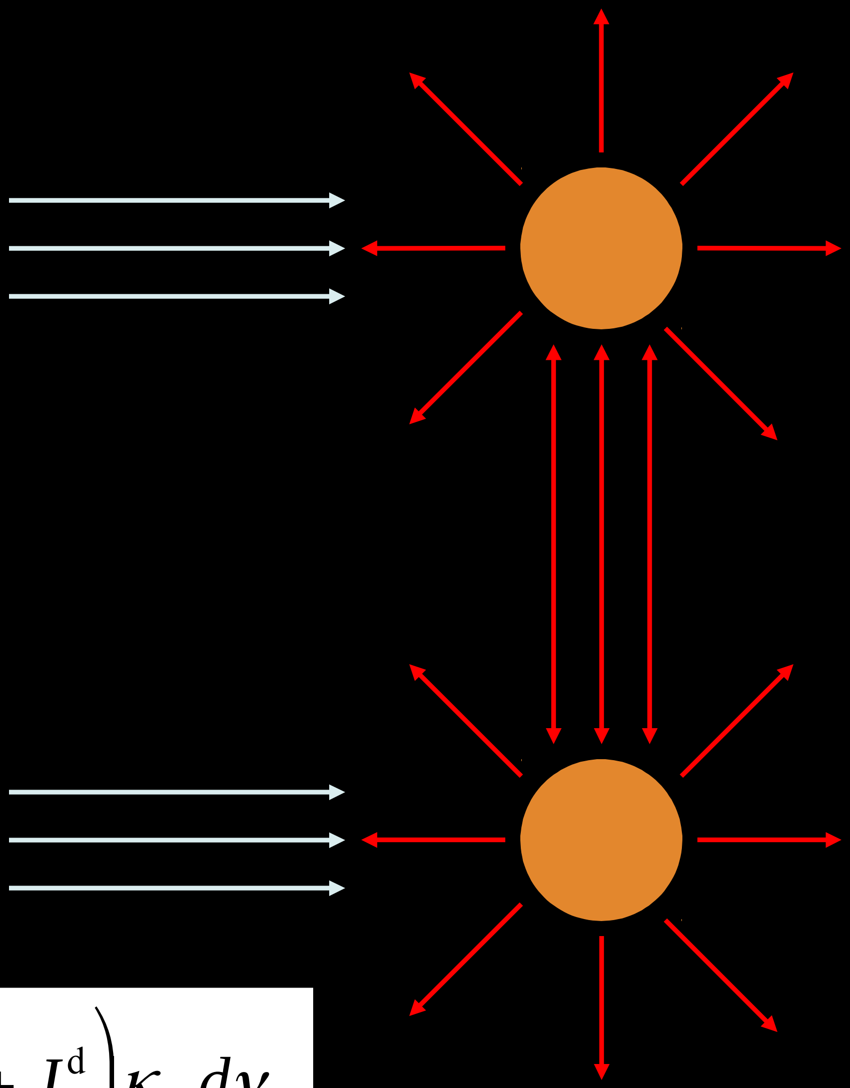
$$J_\nu^{\rm d} = \frac{1}{4\pi}\oint I_\nu^{\rm d}\, d\Omega$$

Intensity obeys tranfer equation along all possible rays:

$$\frac{dI_\nu^{\rm d}}{ds} = \rho\kappa_\nu\left(B_\nu(T) - I_\nu^{\rm d}\right)$$

Thermal balance:

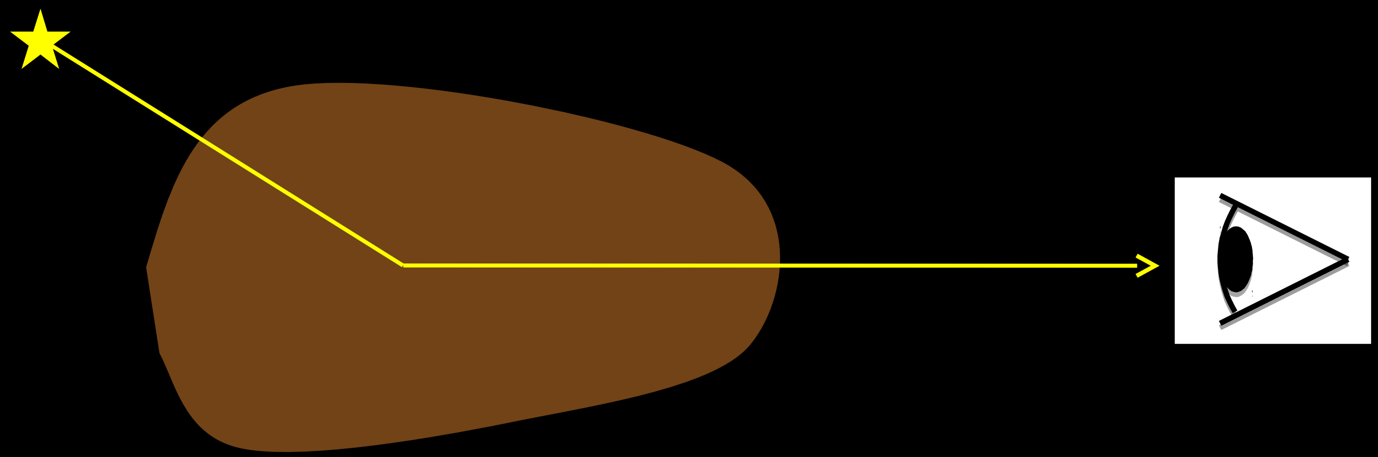
$$\int B_\nu(T)\kappa_\nu\, d\nu = \int\left(\frac{1}{\pi}F_\nu e^{-\tau_\nu} + J_\nu^{\rm d}\right)\kappa_\nu\, d\nu$$



Difficulty of dust radiative transfer

II. The scattering problem

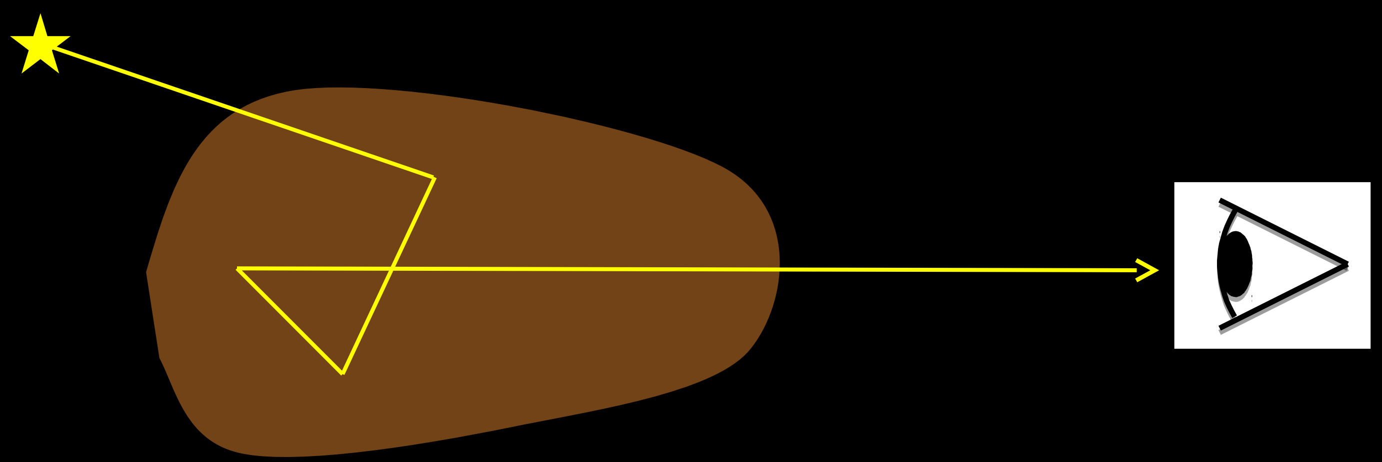
- Light from a star, or even from other regions of the cloud can scatter into the line of sight:



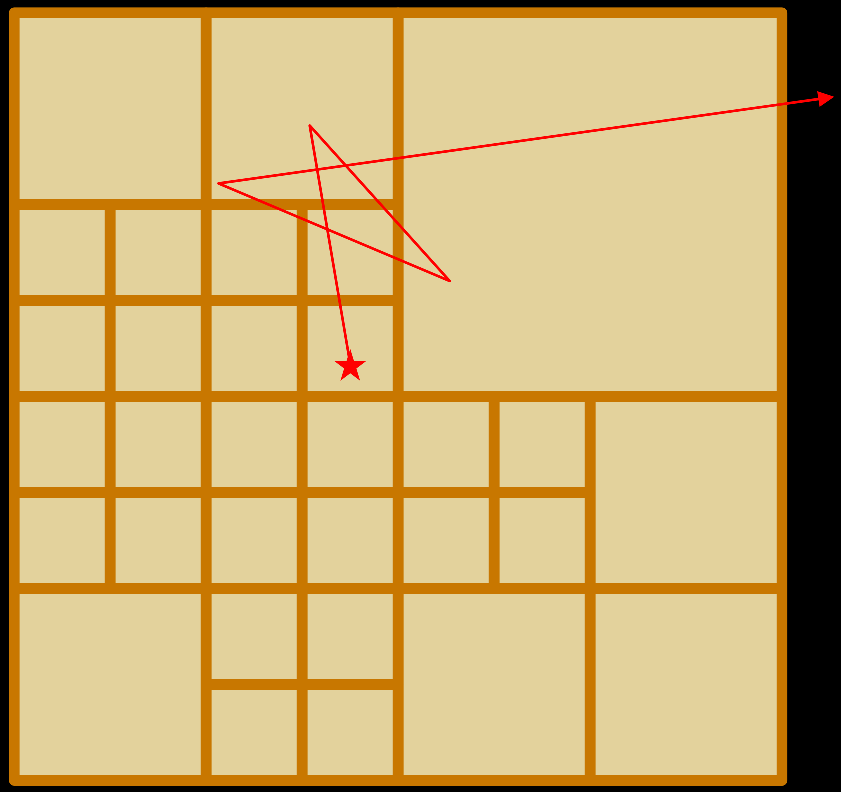
Difficulty of dust radiative transfer

II. The scattering problem

- Light from a star, or even from other regions of the cloud can scatter into the line of sight.
- Multiple scattering can happen:



Stage 1: Monte Carlo Dust Temperature



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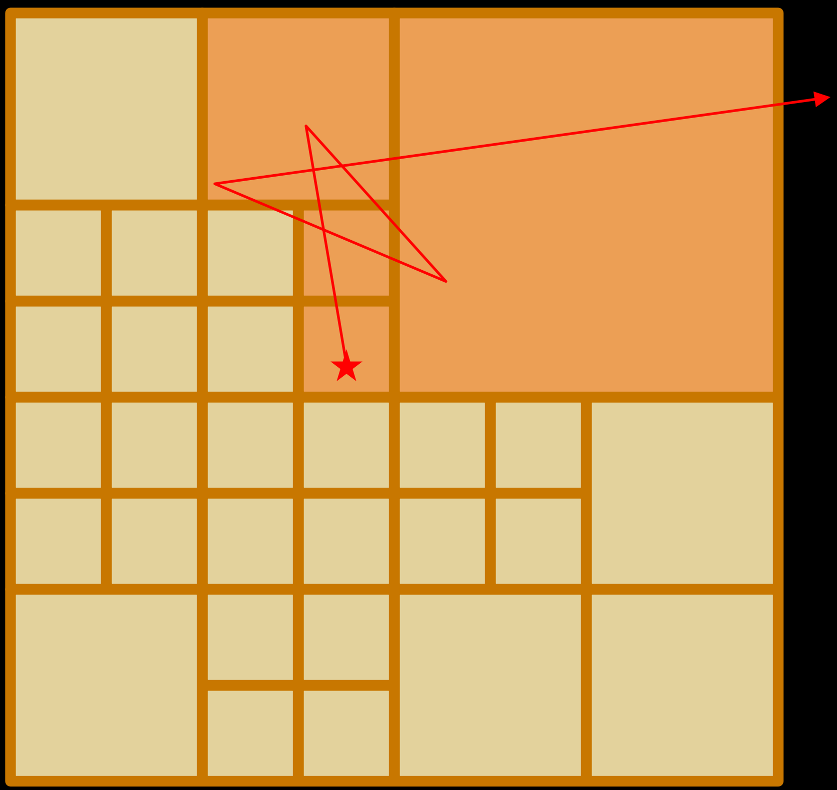

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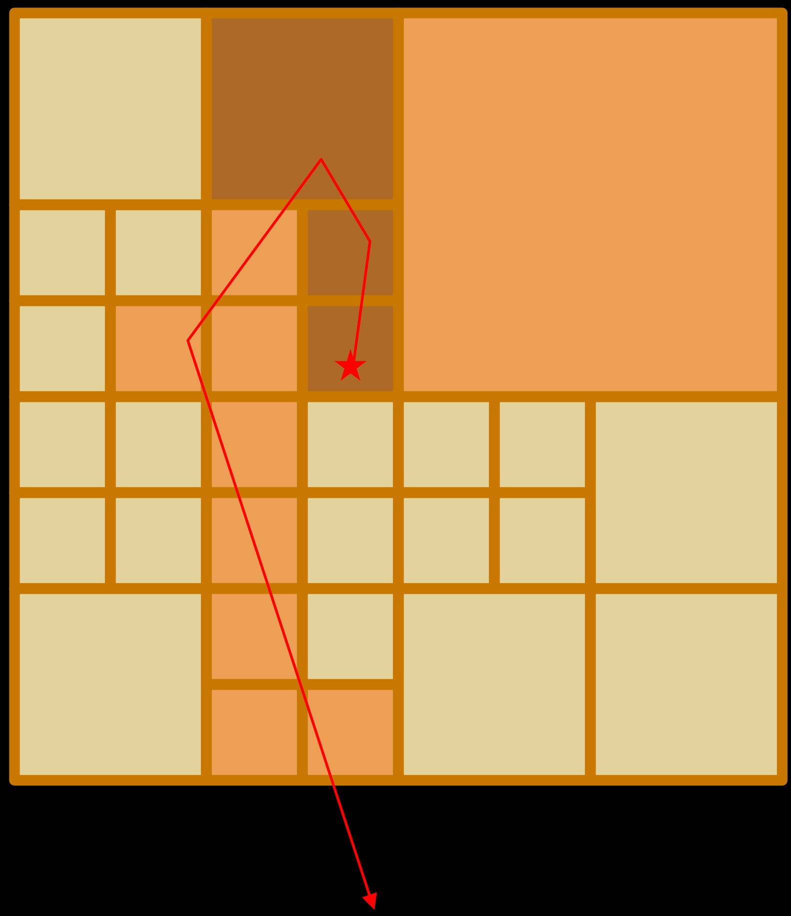
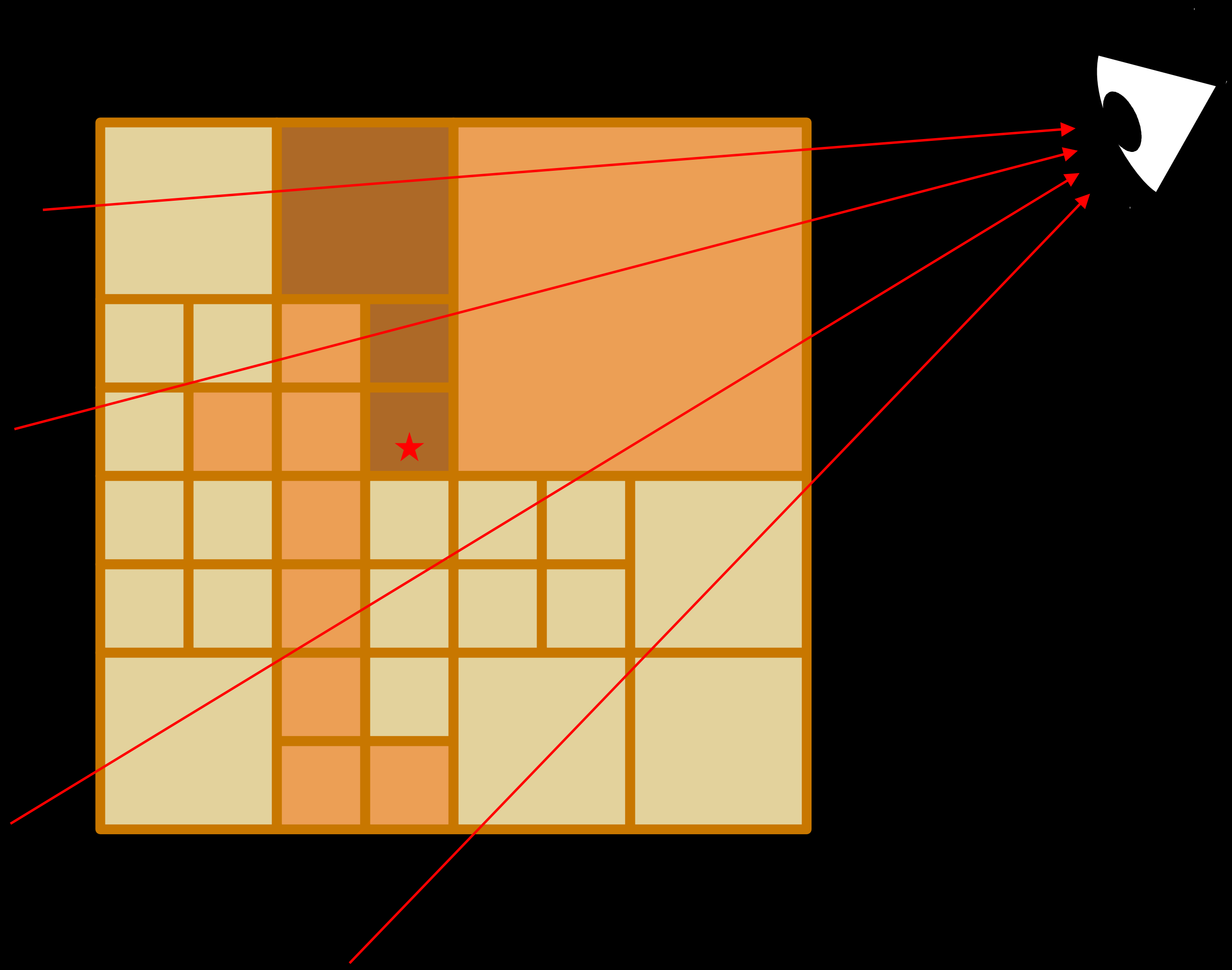
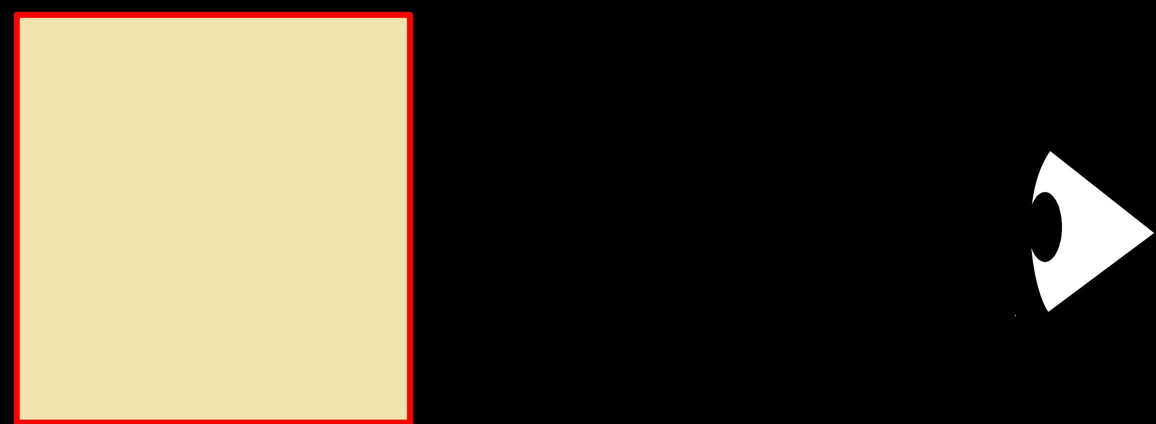


Stage 2: Ray tracing



Treatment of scattering off dust grains

Using a scattering source function



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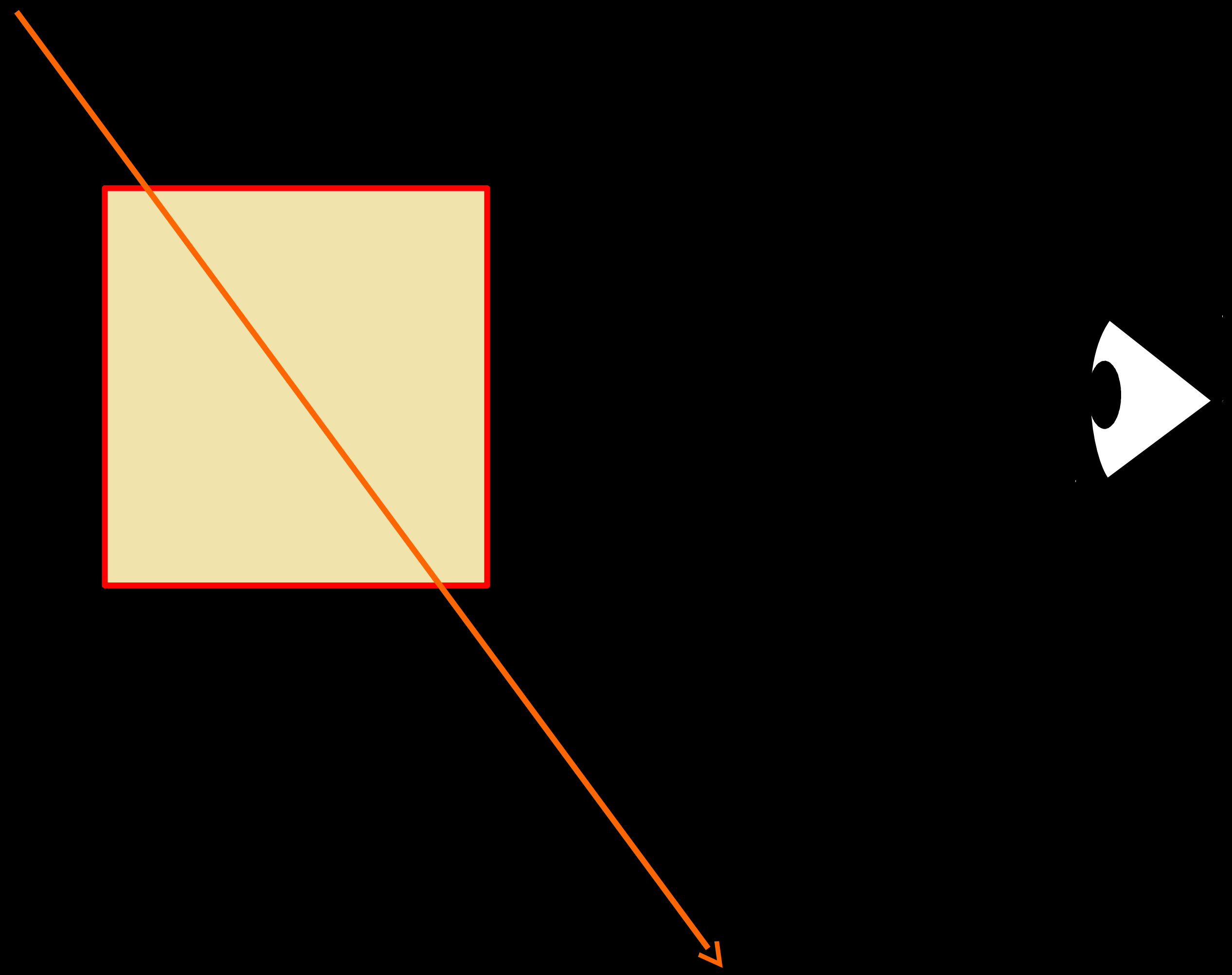
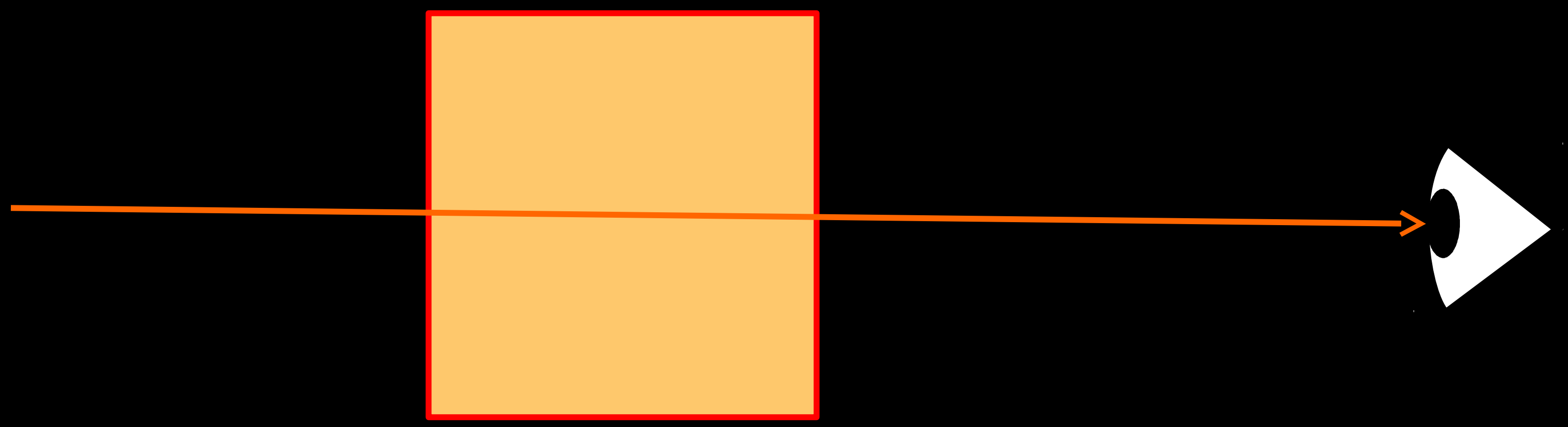


Treatment of scattering off dust grains

Using a scattering source function

Treatment of scattering off dust grains

Using a scattering source function



RADMC-3D Method of Dust RT

- First do an *all-frequency* Monte Carlo calculation for the dust temperature
- Then do ray-tracing for the images/spectra
  - Before each image (i.e. at each wavelength): do a *monochromatic* Monte Carlo calculation for the scattering source function.

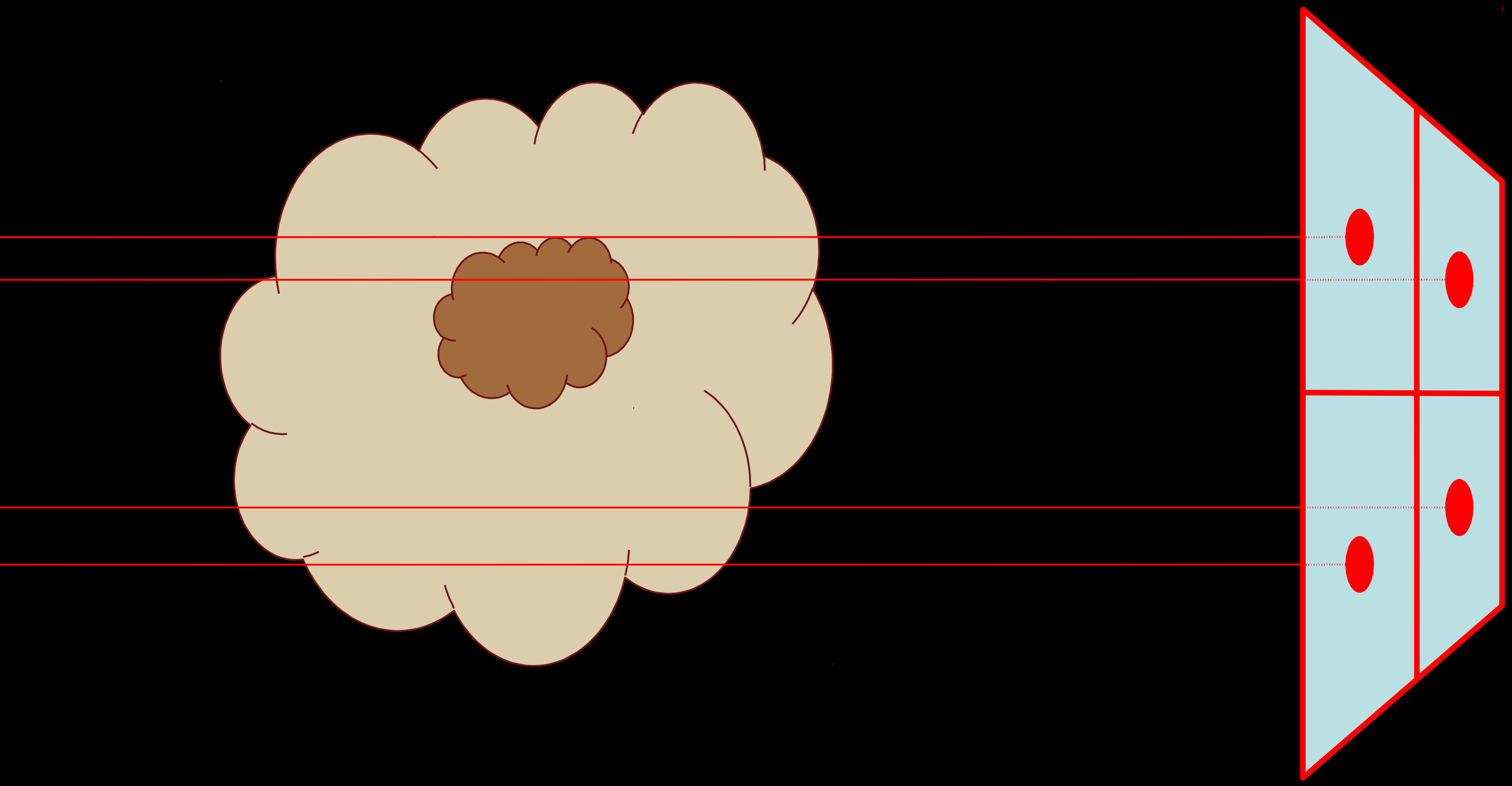
Line radiative transfer

Line transfer with RADMC-3D

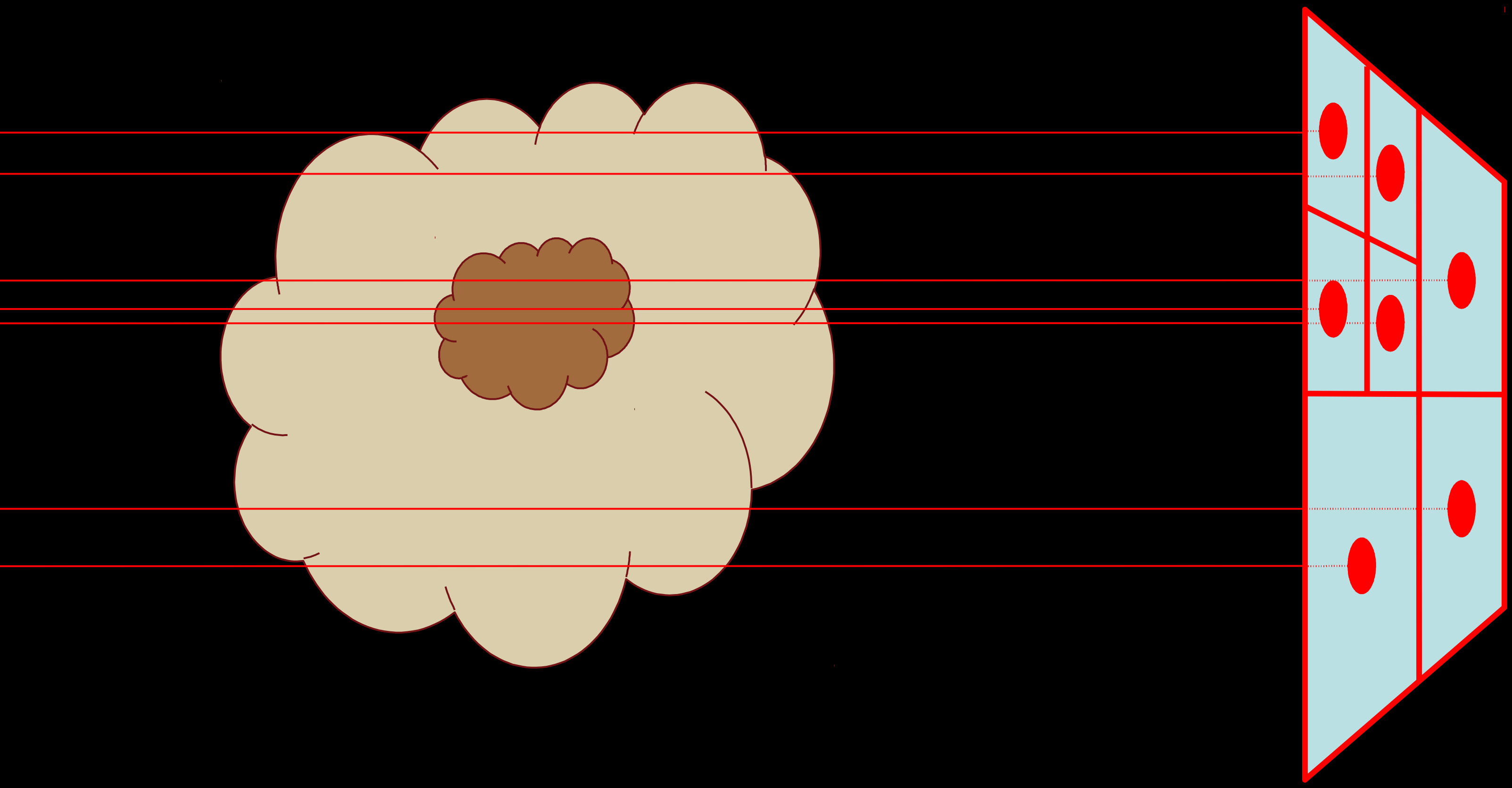
- At the moment the following modes are possible:
  - LTE
  - LVG (Sobolev)
  - Optically thin populations
- Full non-LTE not yet possible
- But:
  - Lines and dust continuum can be combined
  - Velocities included

The pitfalls of raytracing...

Recursive sub-pixeling of images



Recursive sub-pixeling of images



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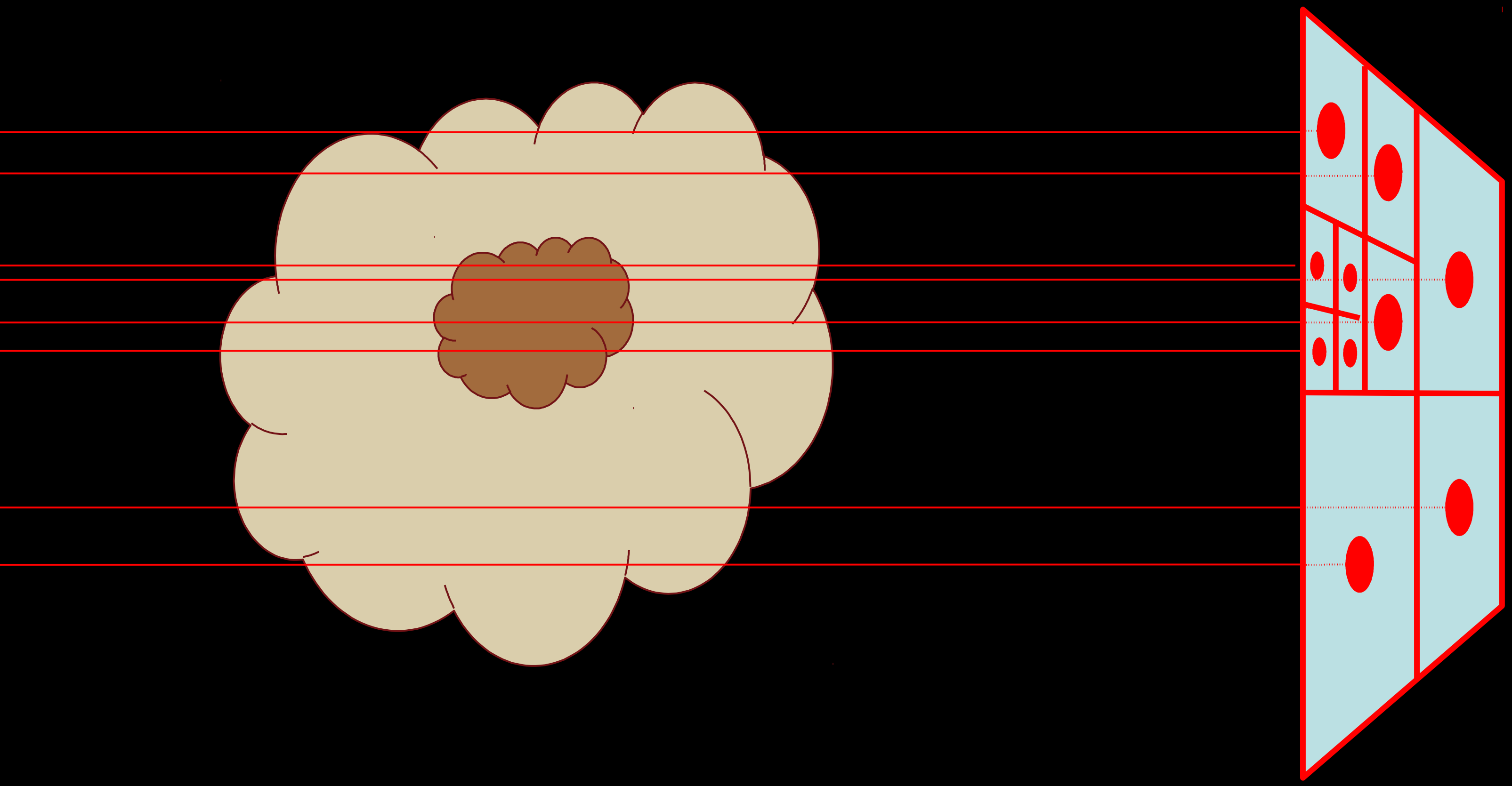
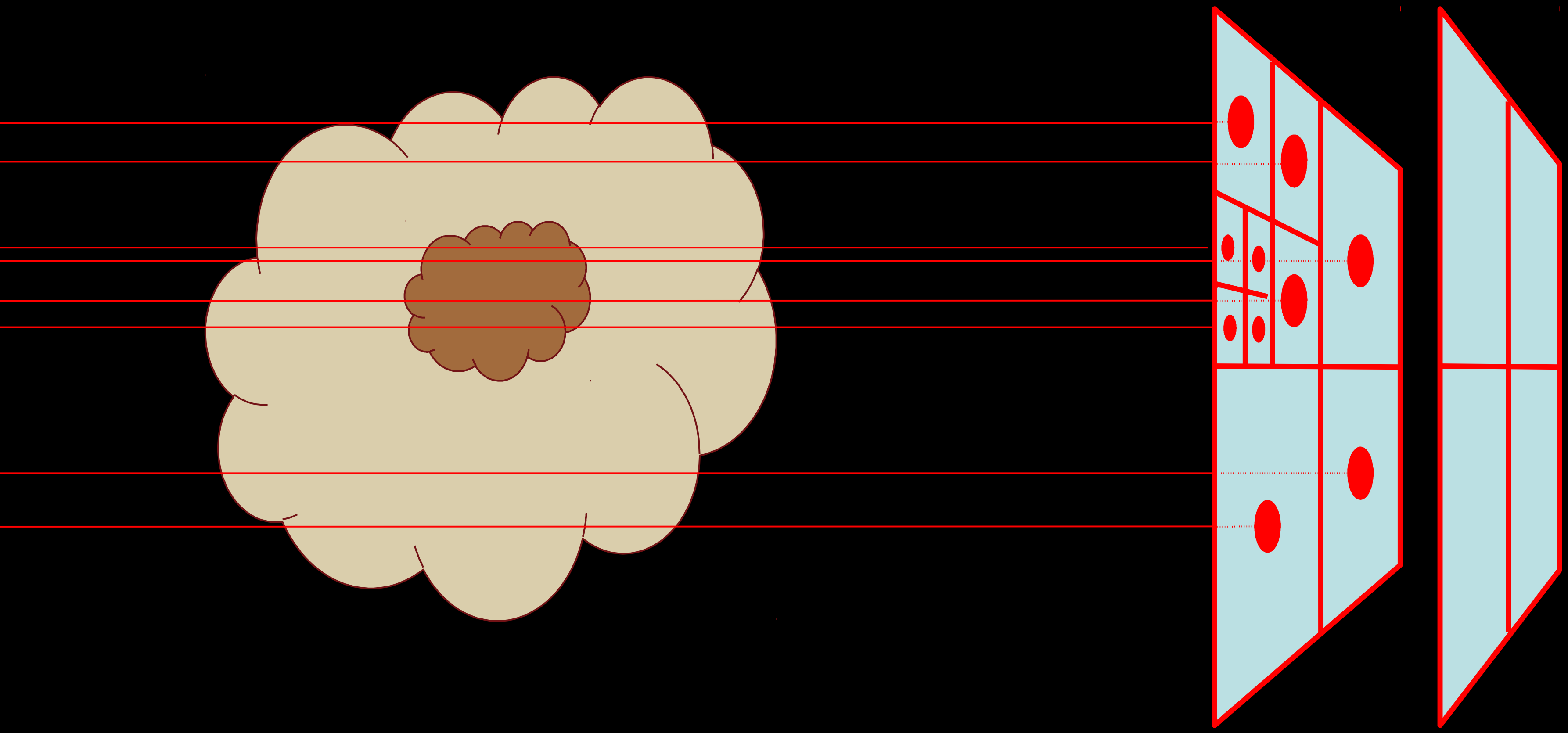


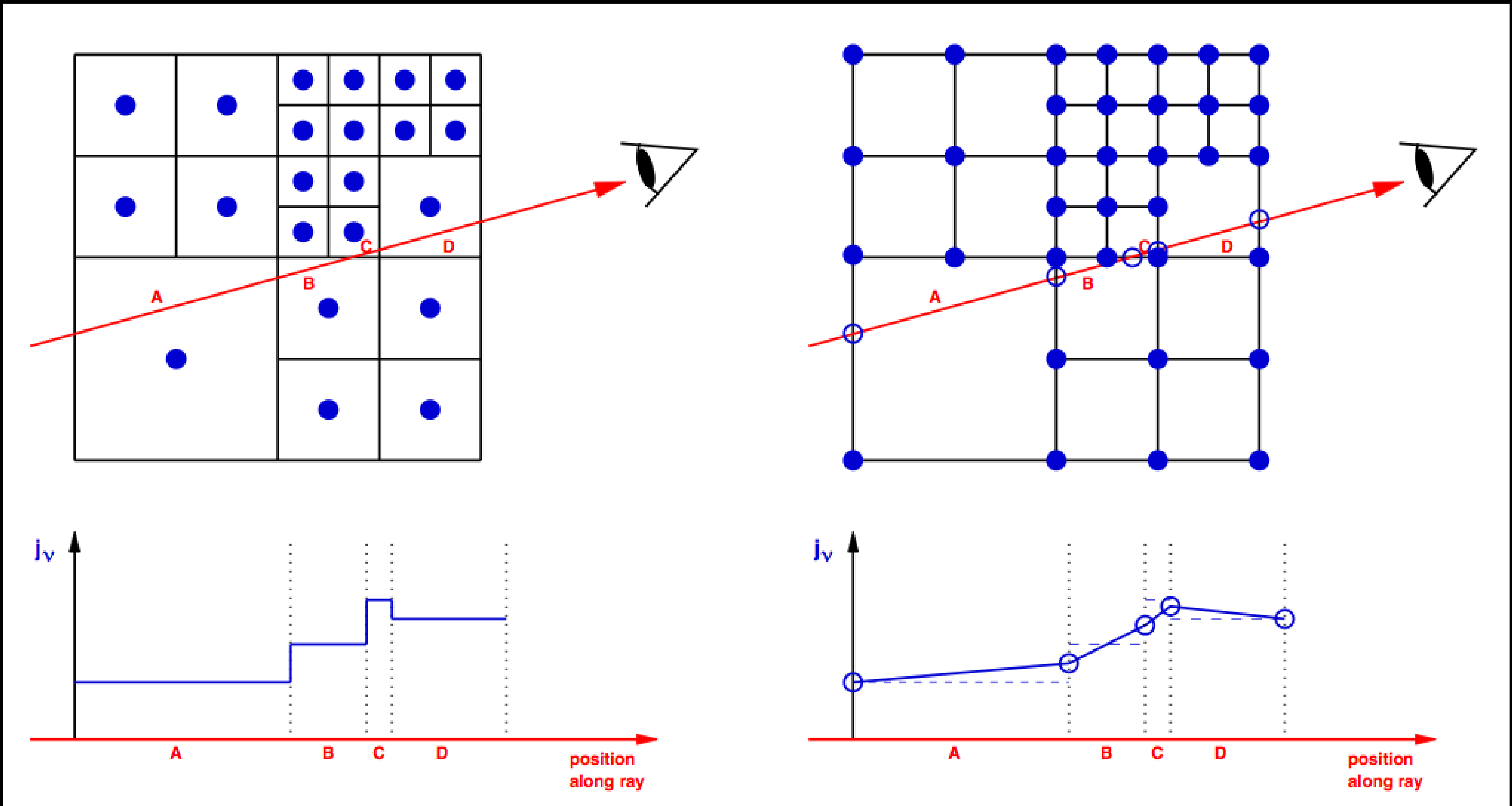
Necessary for obtaining the correct flux

Recursive sub-pixeling of images



Necessary for obtaining the correct flux

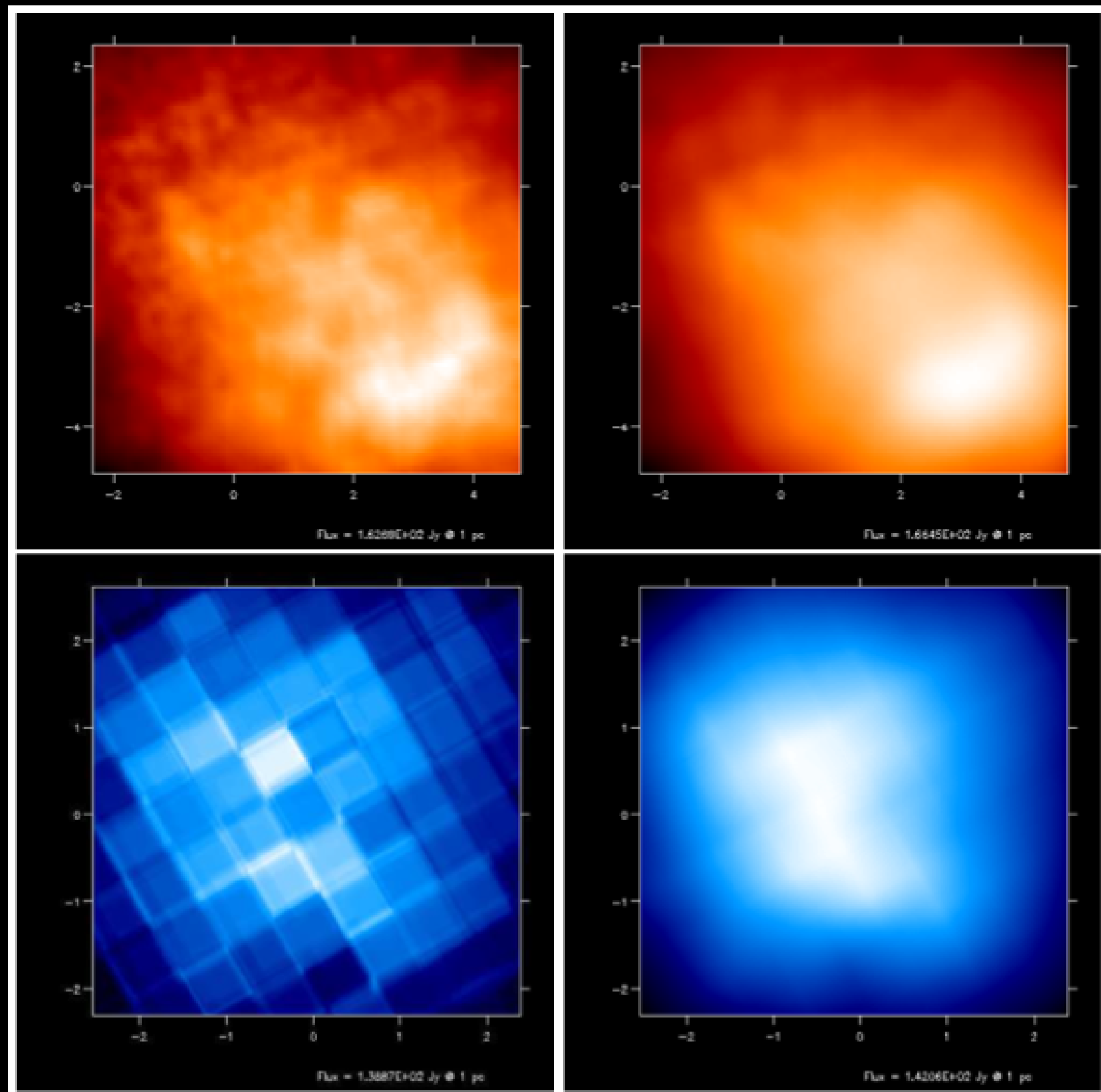
Second order ray-tracing



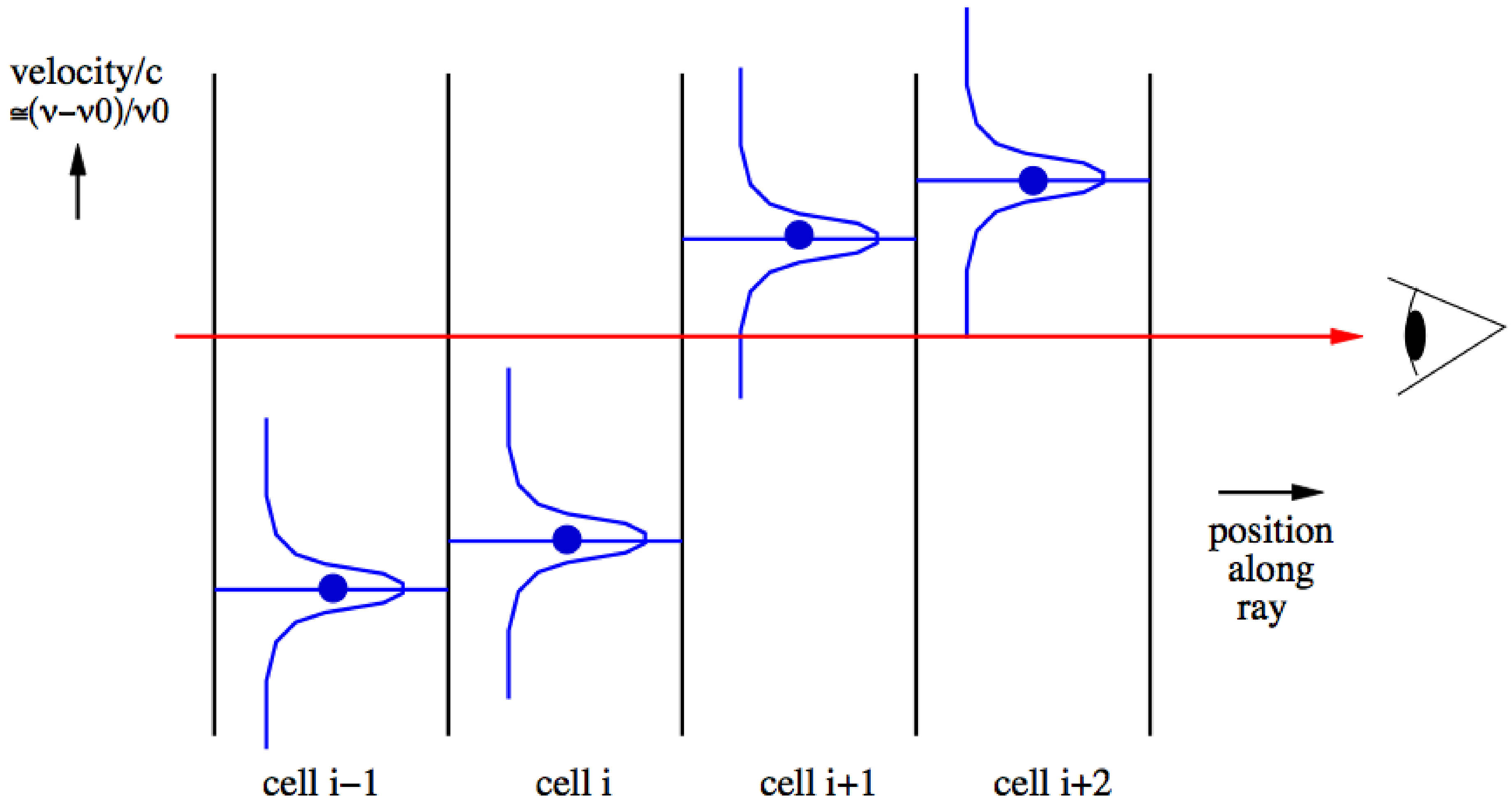
Useful for obtaining smoother images

Second order ray-tracing

First order integration: Second order integration:



Line transfer: Doppler Catching...



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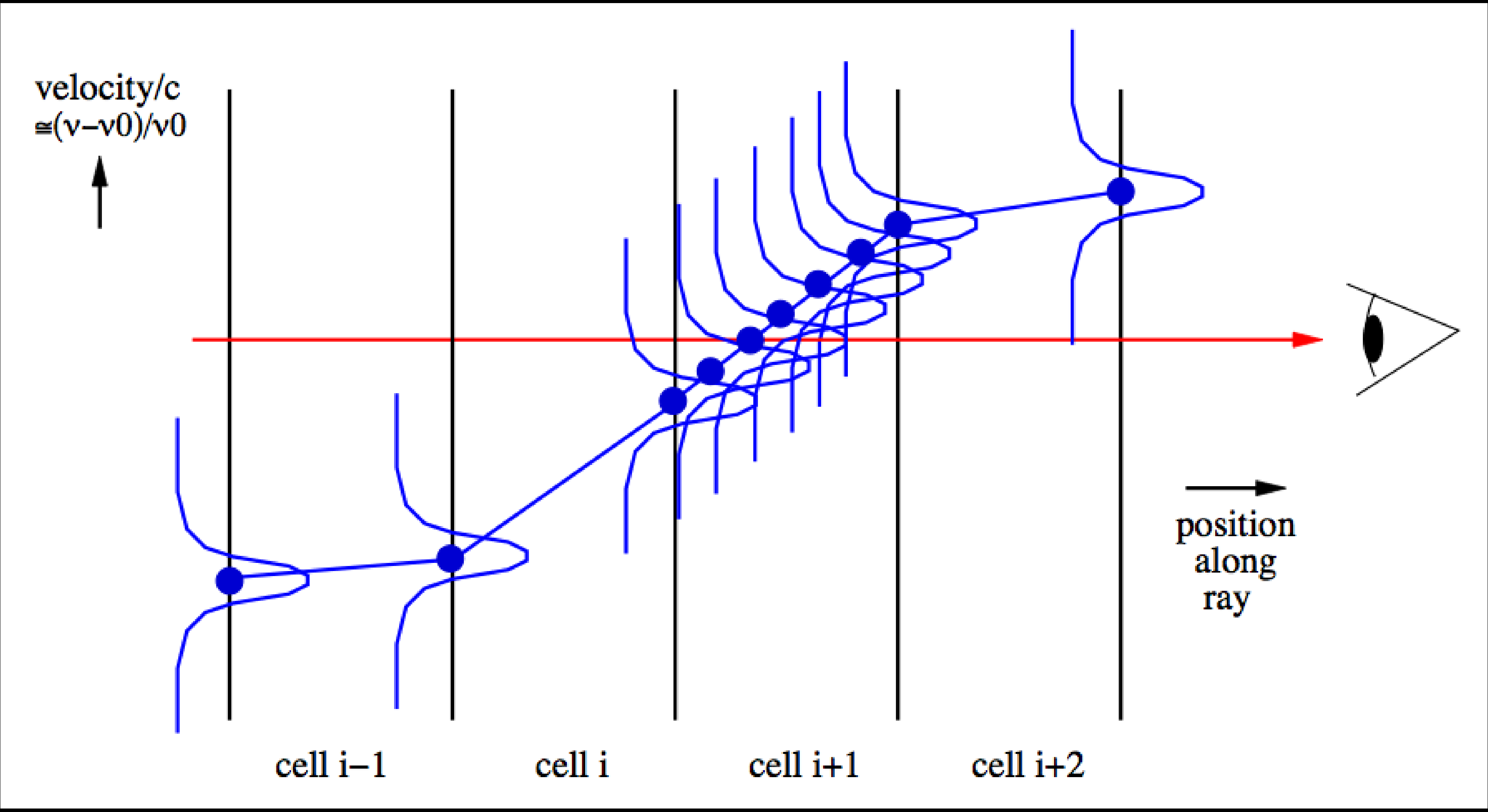


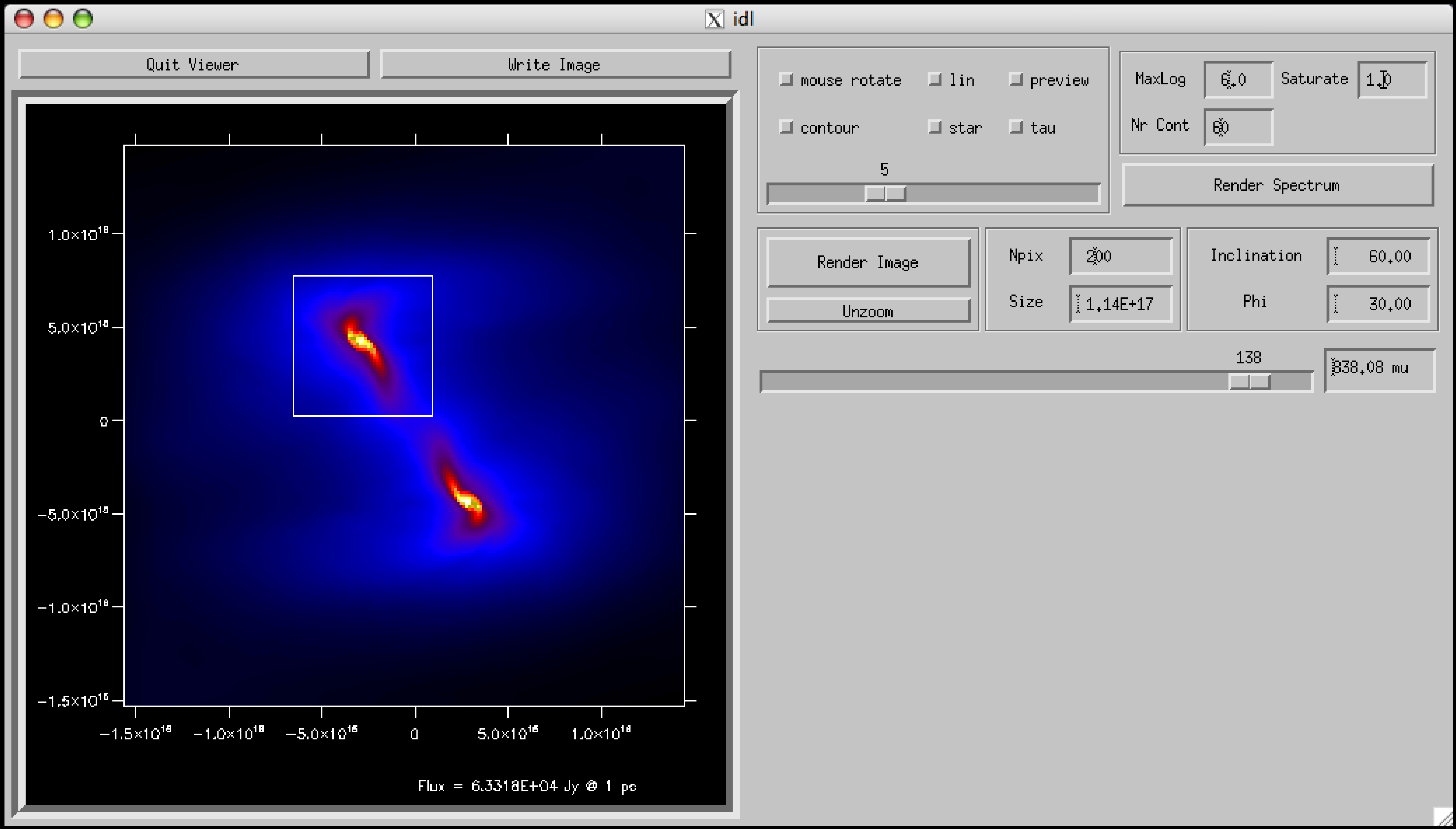
Necessary when there are strong velocity gradients

Some useful features of RADMC-3D

Add your own components

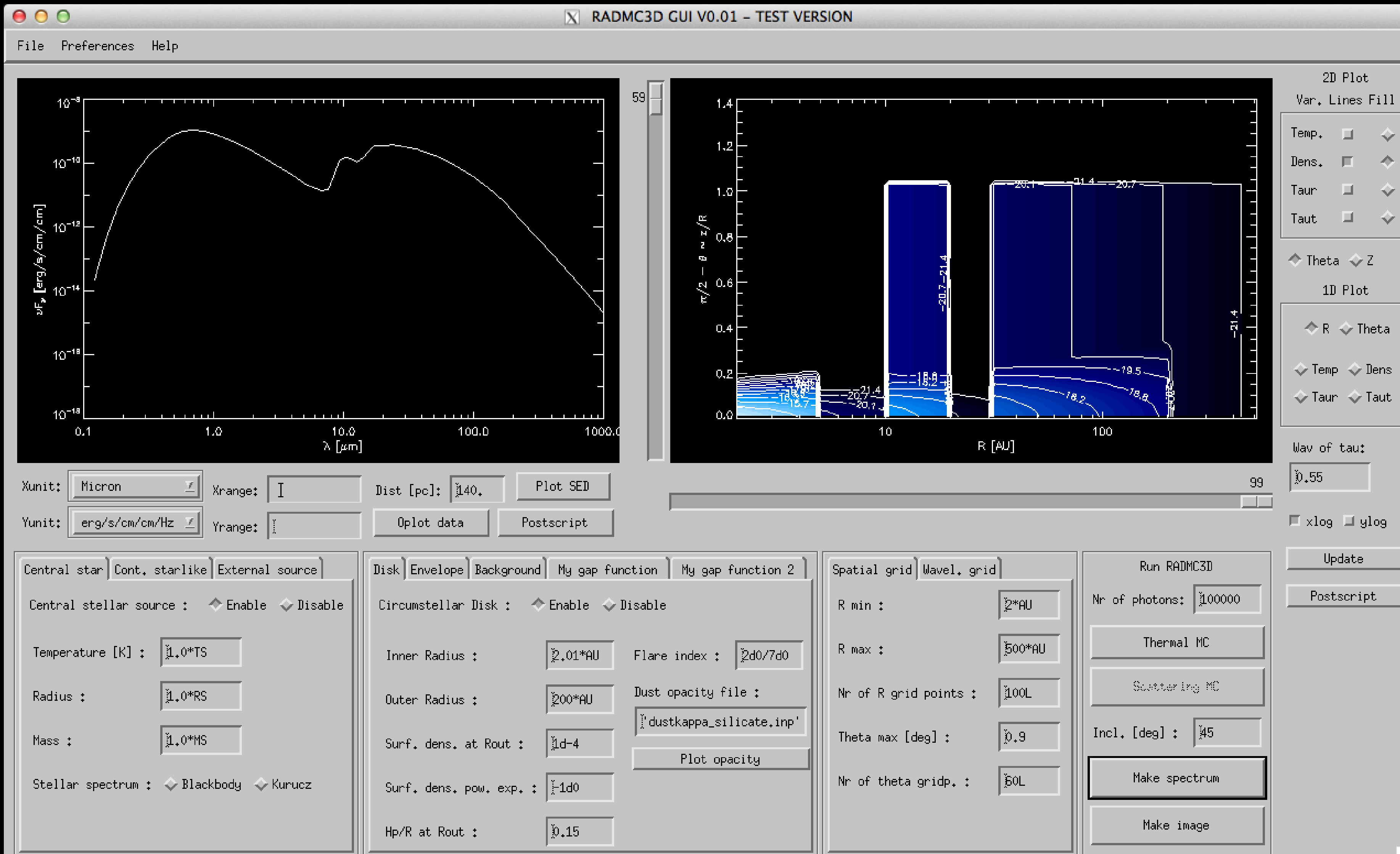
- RADMC-3D has a userdef_module.f90 module
  - Allows you to add physics and special-purpose modes into the code without the need for editing the main code!
  - This module is in your local model directory, all the rest of the code remains in main directory.

Graphical User Interface for Images



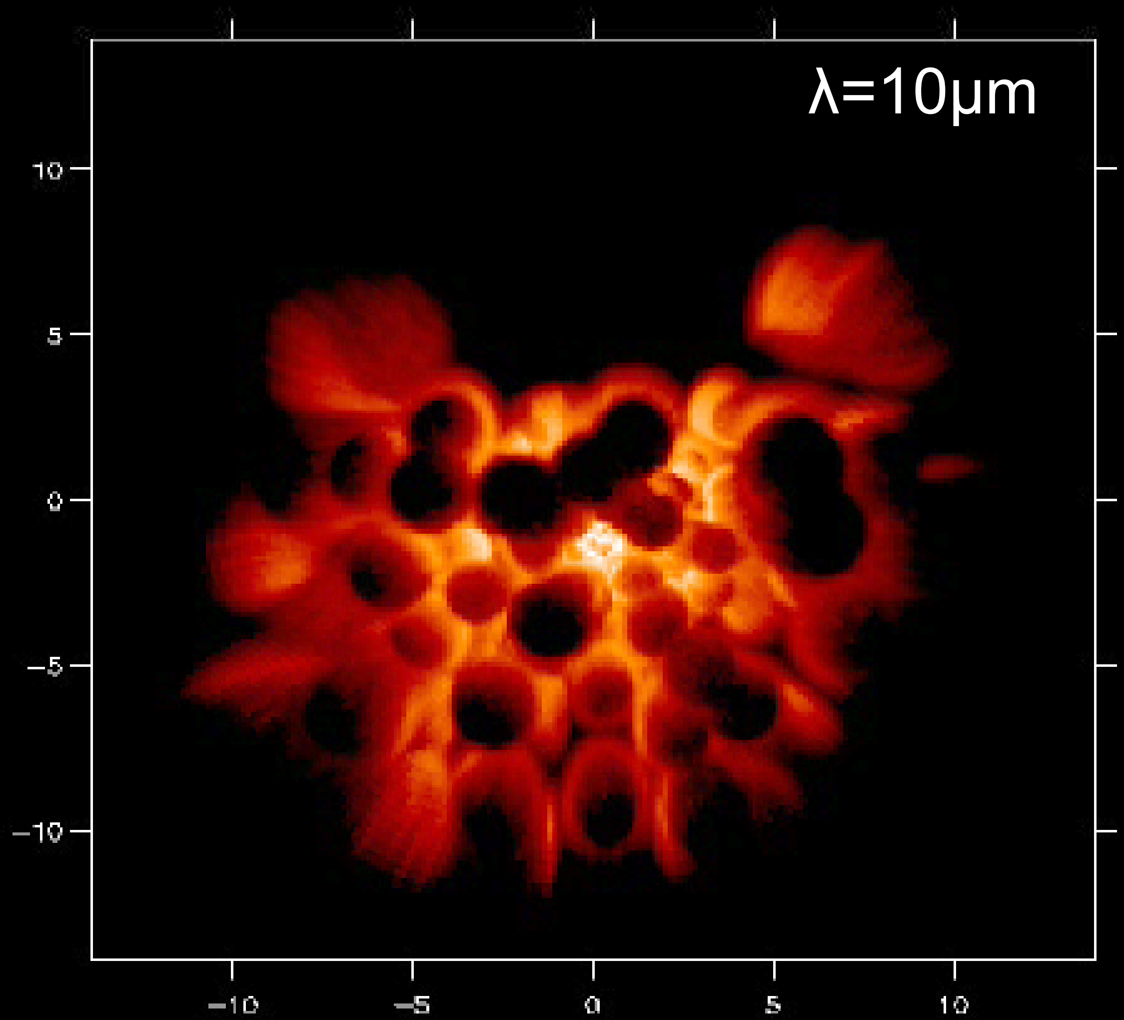
Graphical User Interface for Disk Models

By Attila Juhasz (IoA Cambridge)

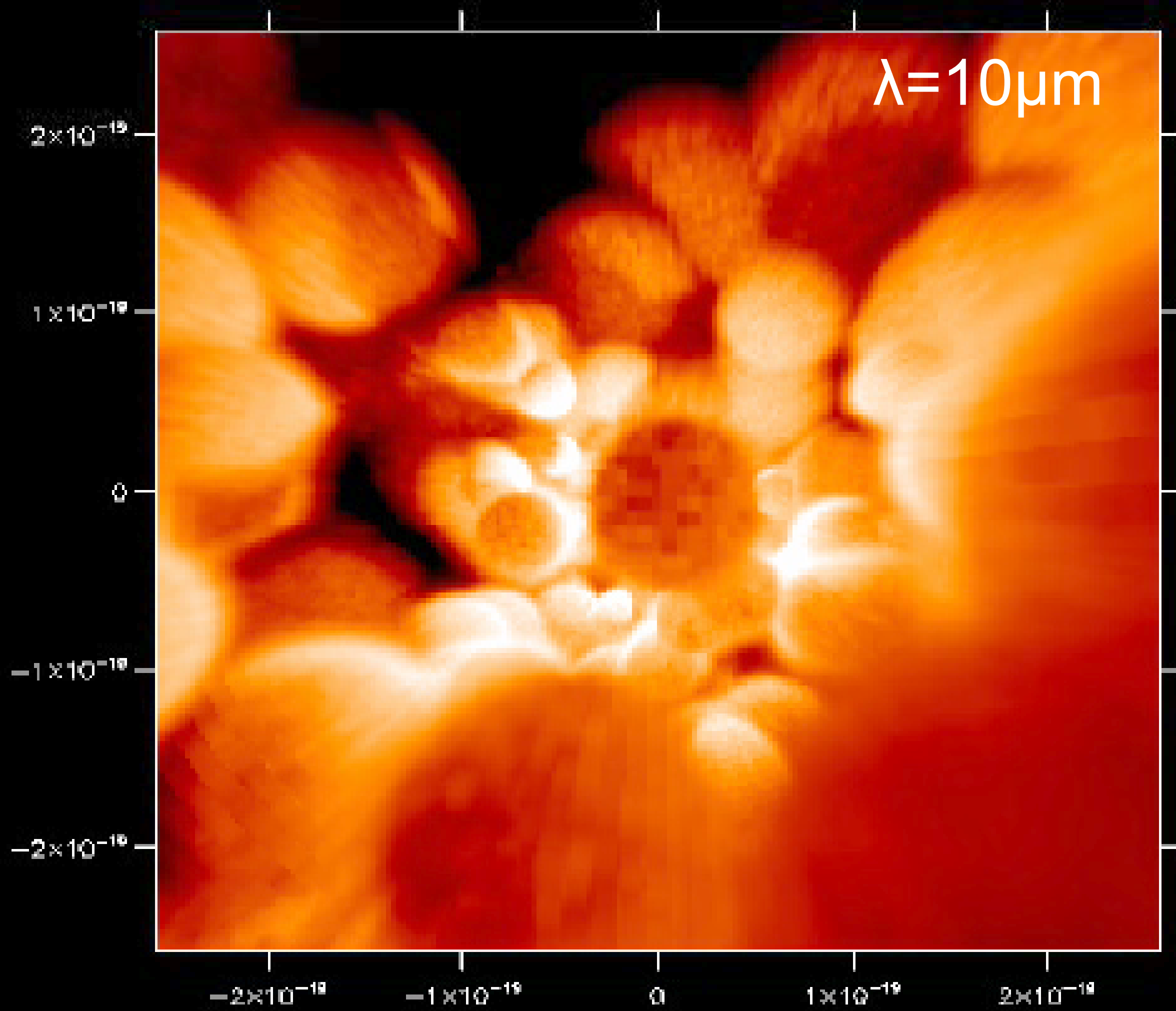


Examples

Example: Clumpy AGN torus model

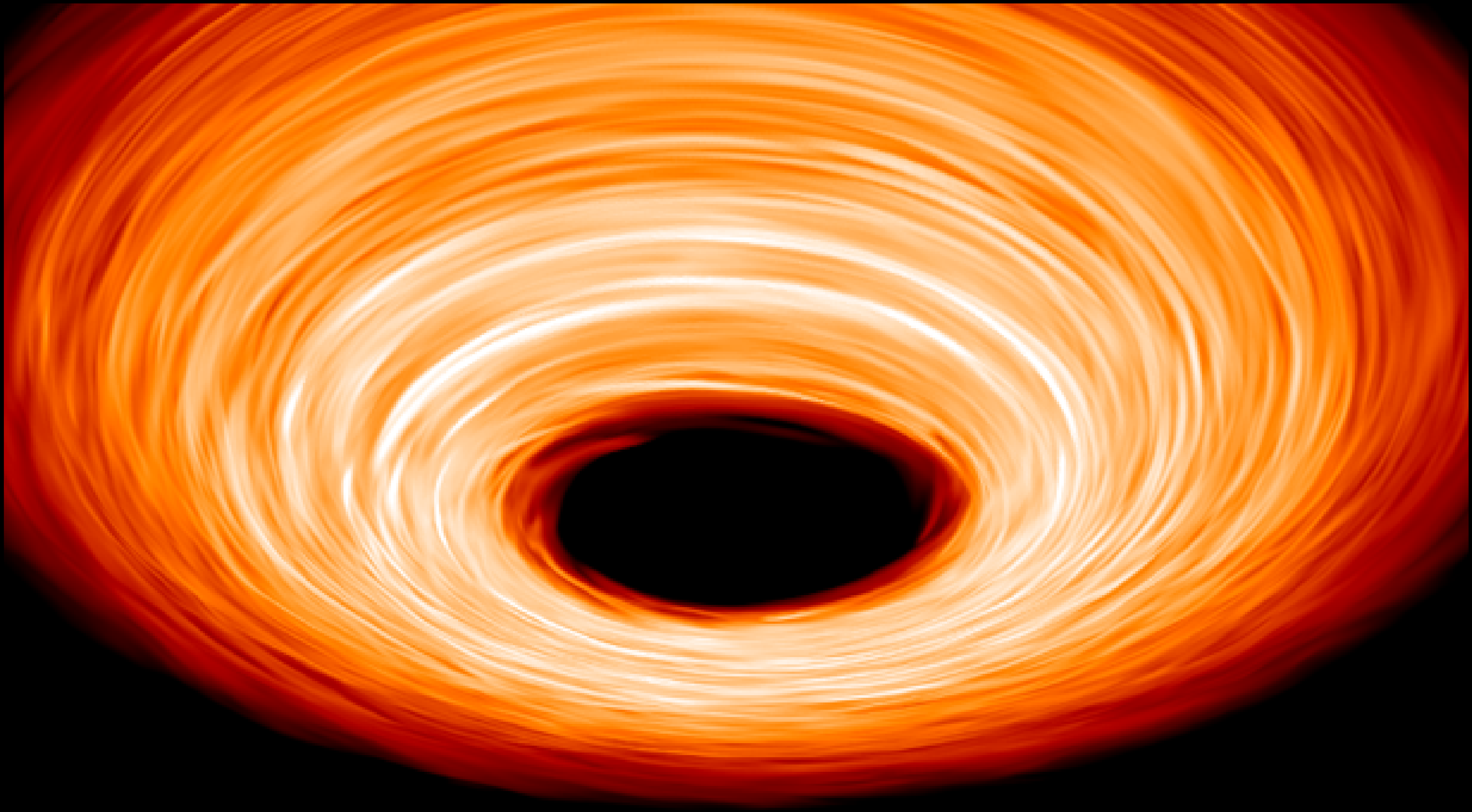


For public outreach: Travel through...



For public outreach: Travel through...

OMNIMAX Dome projection (fish eye)



Using RADMC-3D as volume renderer

- If you have 3-D models, there are free packages for 3-D volume rendering visualization: e.g. VisIt.
- However, these packages are often limited:
  - Limited grid options, Limited coordinate options
  - Limited opacity options
- RADMC-3D can act as fancy volume renderer:
  - You can (using userdef_module.f90) determine any complicated opacity and emissivity function.
  - Full rendering+gridding capabilities of RADMC-3D can be used.
  - Is often even faster than VisIt and more accurate

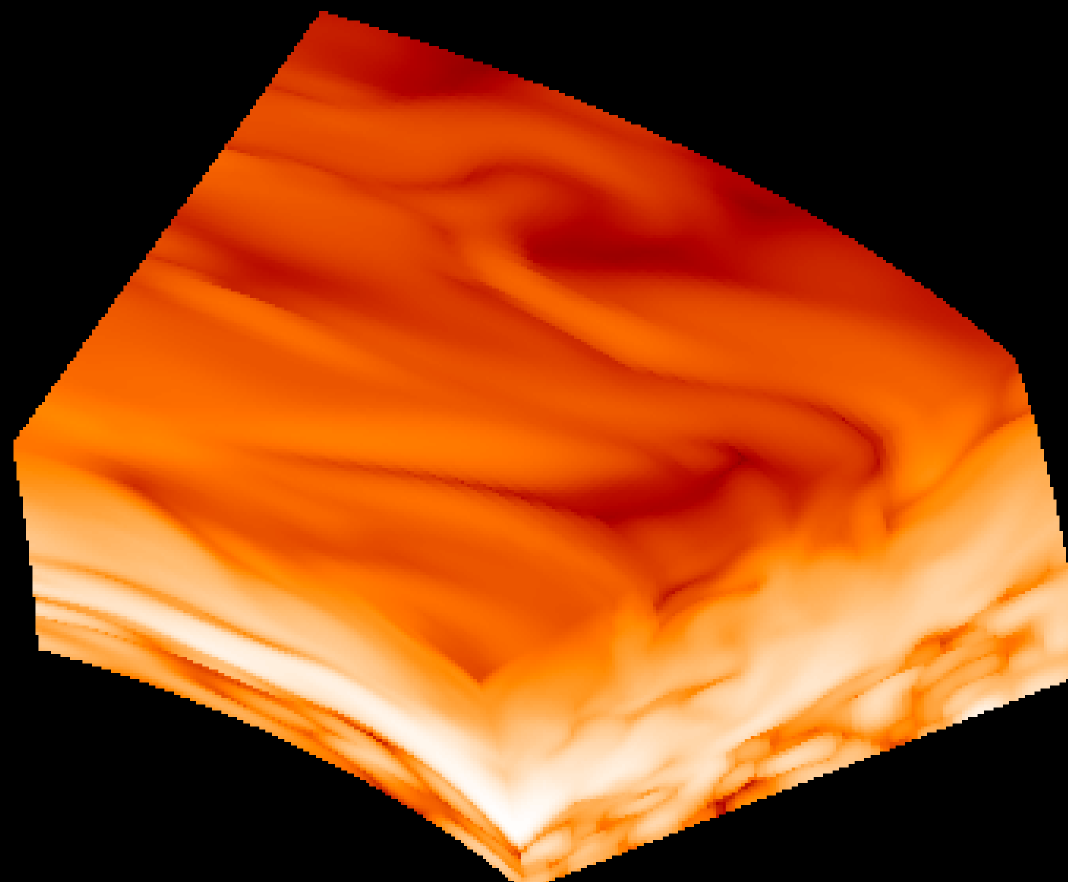
Using RADMC-3D as volume renderer

Example: 3-D MHD model of a protoplanetary disk with magnetorotational turbulence.

Model by Mario Flock (MPIA) made with the PLUTO code.

Shown here: magnetic pressure B^2

Method of visualization:
- Emissivity ~ B^4
- Opacity ~ B^2



Highest opacity (only surface visible)

Using RADMC-3D as volume renderer

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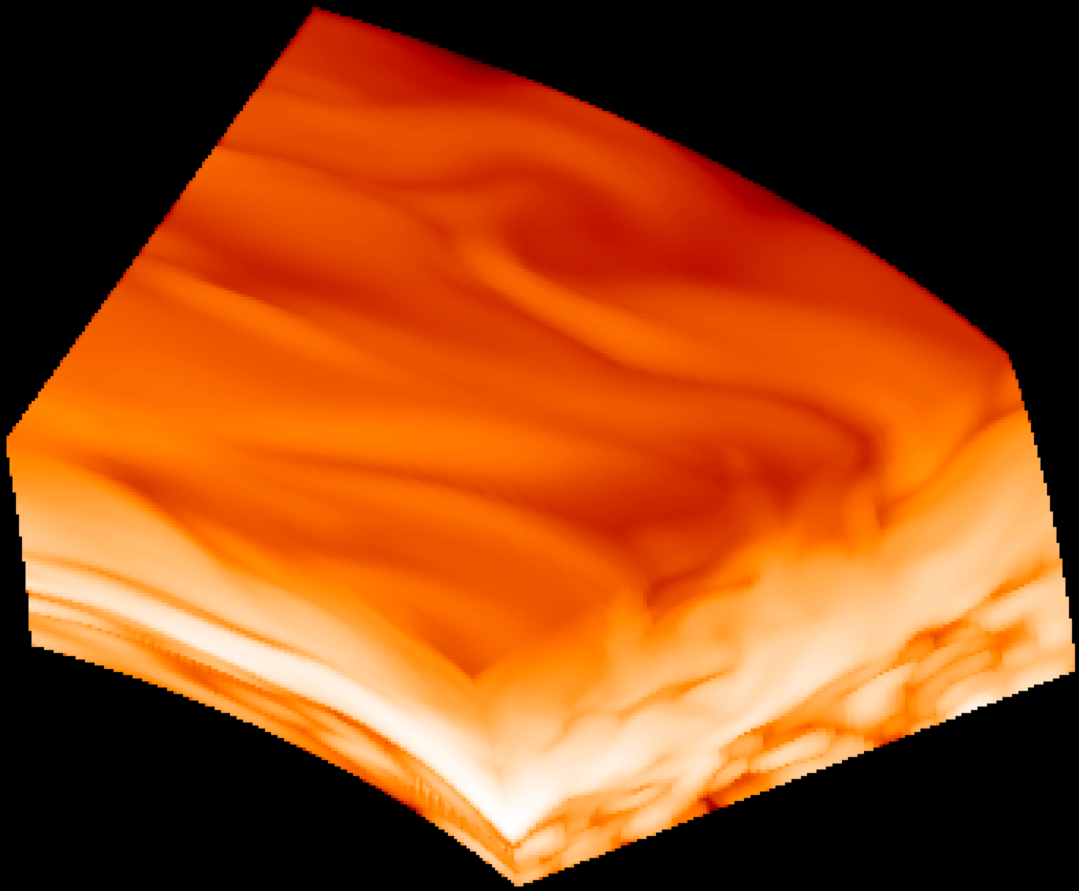


Lowering the opacity...

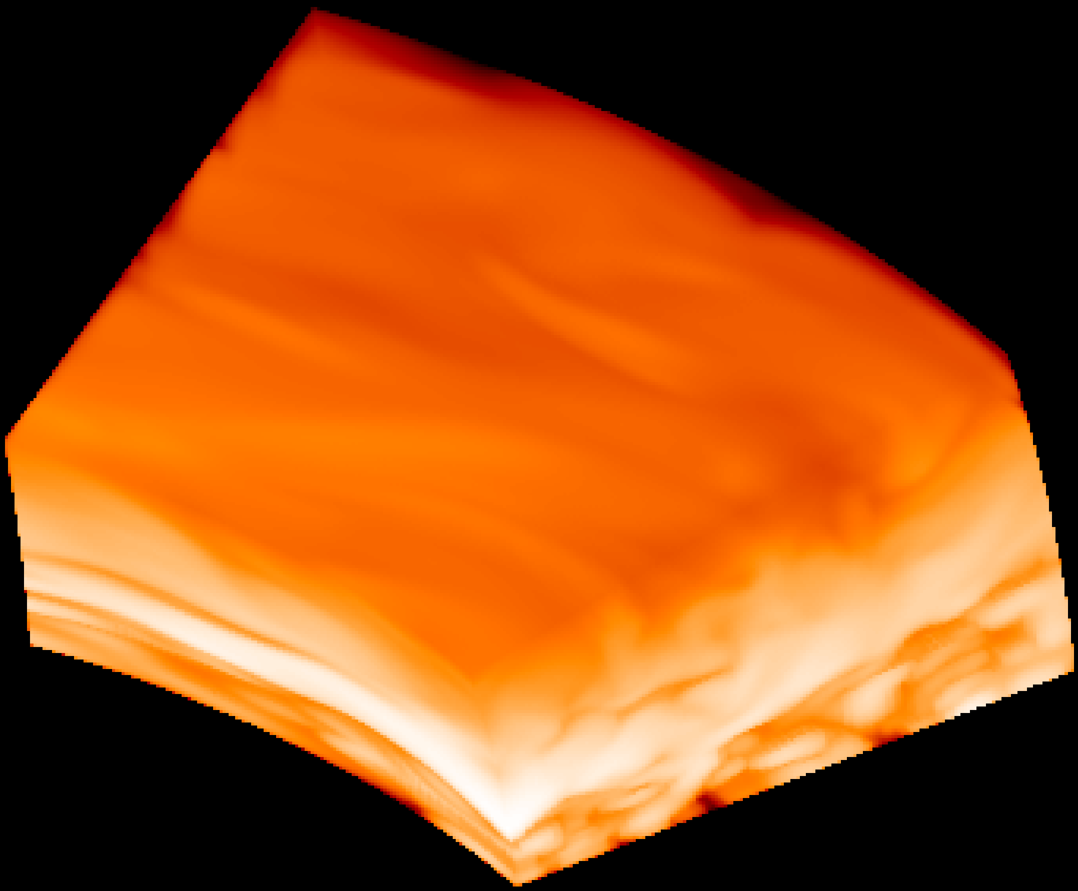
Using RADMC-3D as volume renderer

Example: 3-D MHD model of a protoplanetary disk with magnetorotational turbulence.

Model by Mario Flock (MPIA) made with the PLUTO code.

Shown here: magnetic pressure B^2

Method of visualization:
- Emissivity ~ B^4
- Opacity ~ B^2



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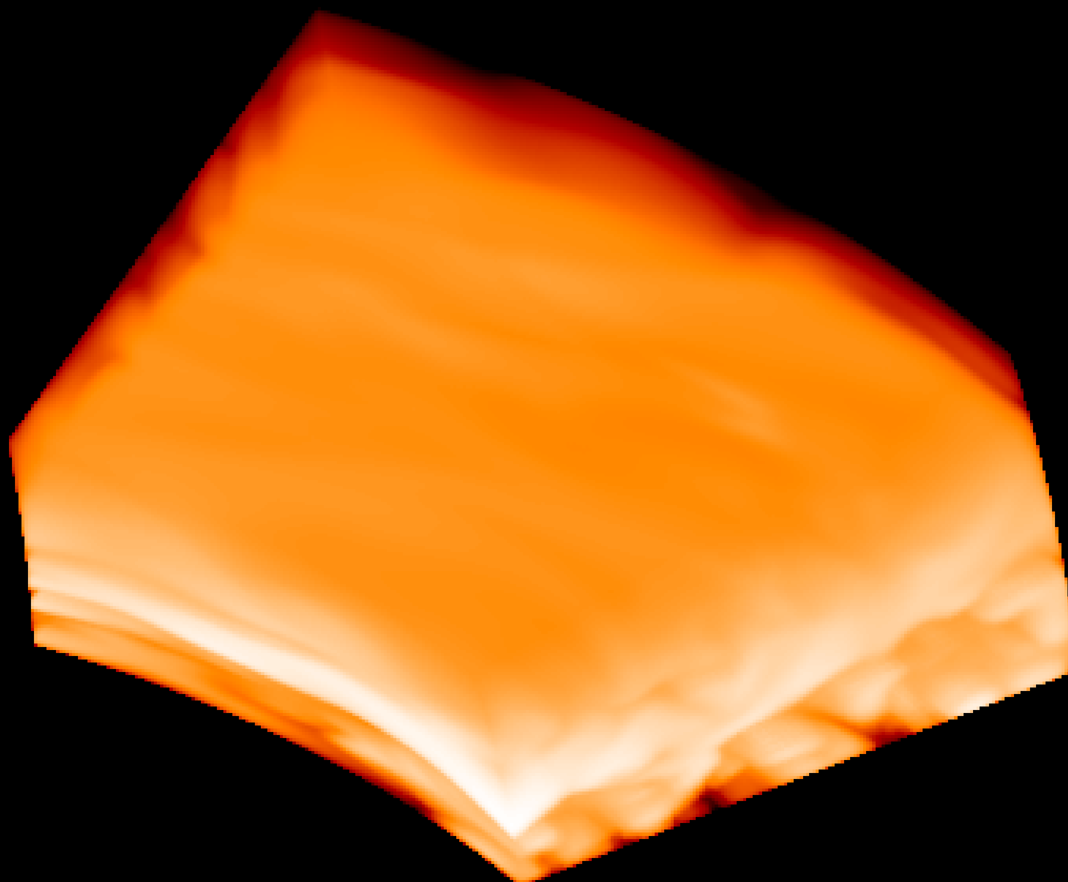

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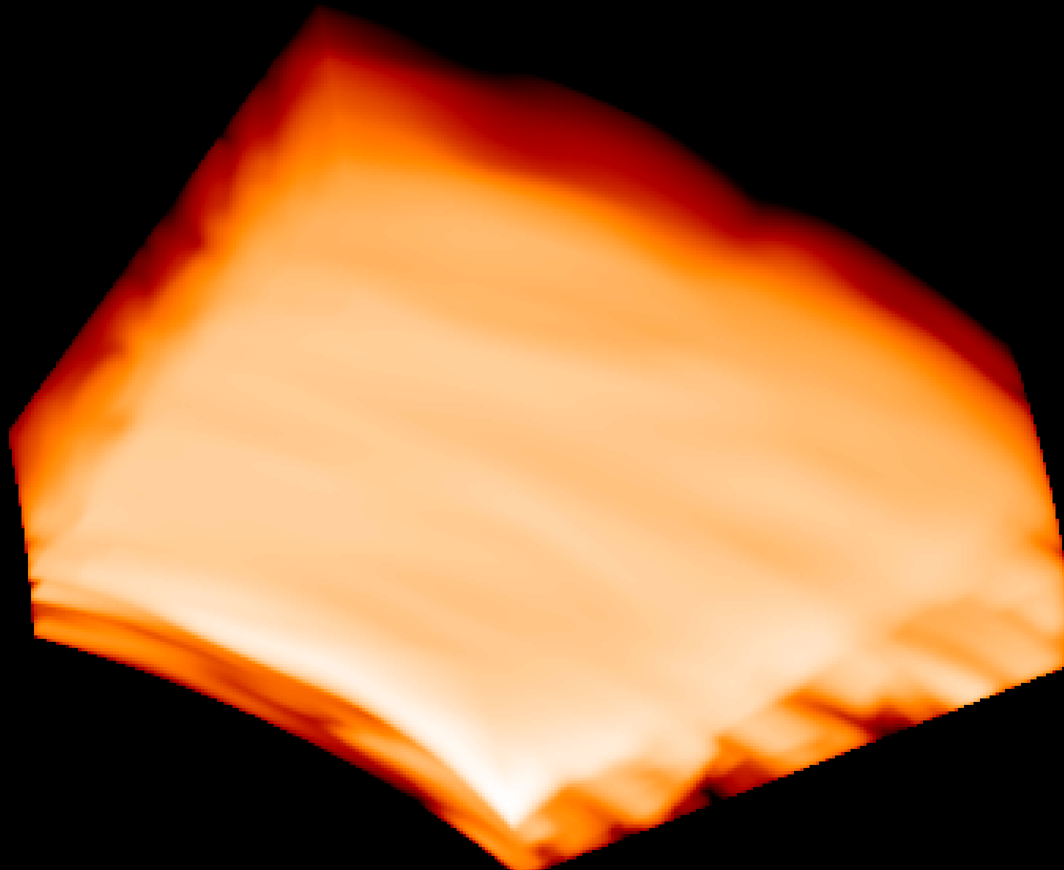
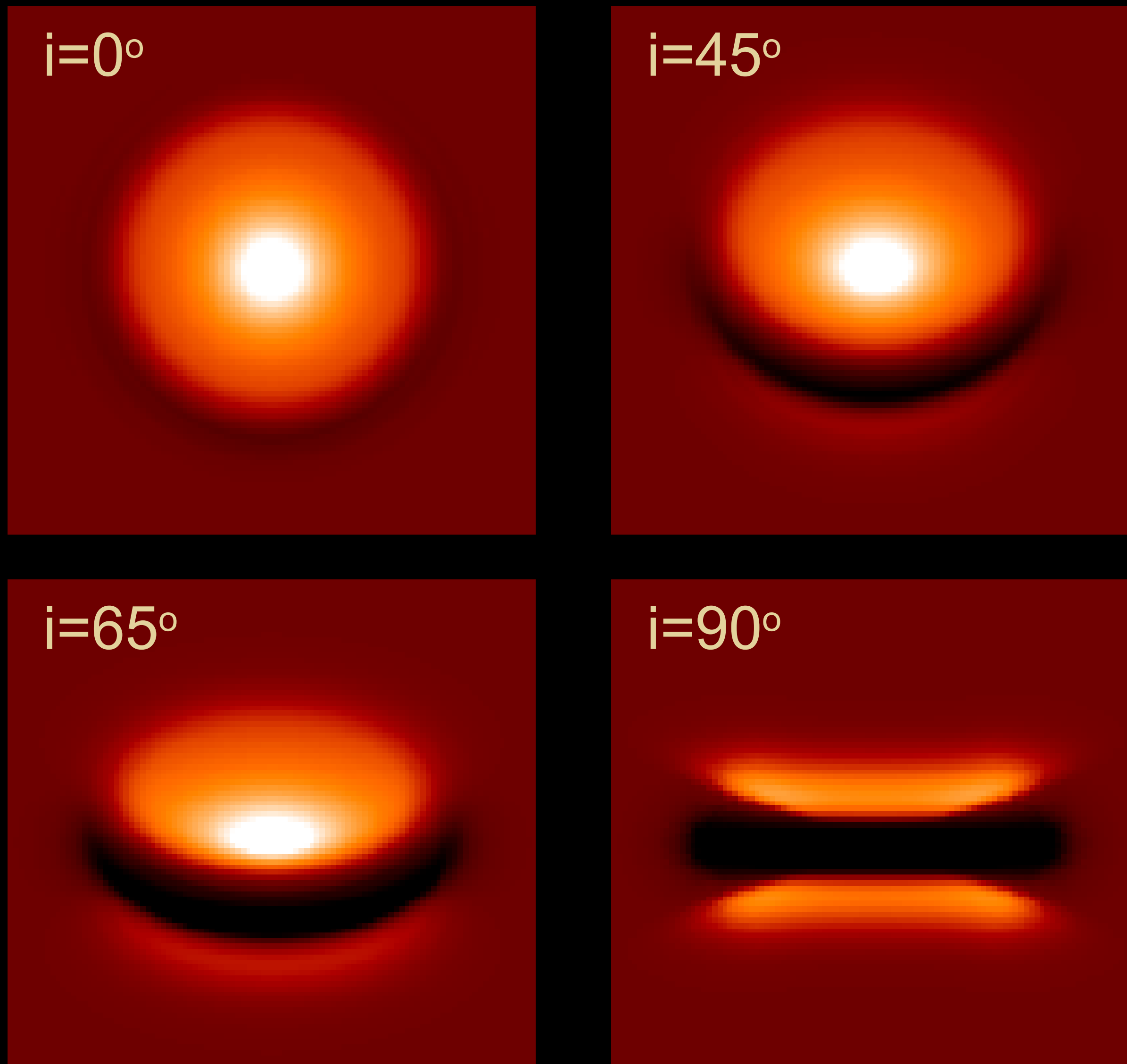


Lowest opacity (optically thin)

Example: Protoplanetary Disk

Done with RADMC-2D (predecessor to RADMC-3D)



Dullemond & Dominik 2004

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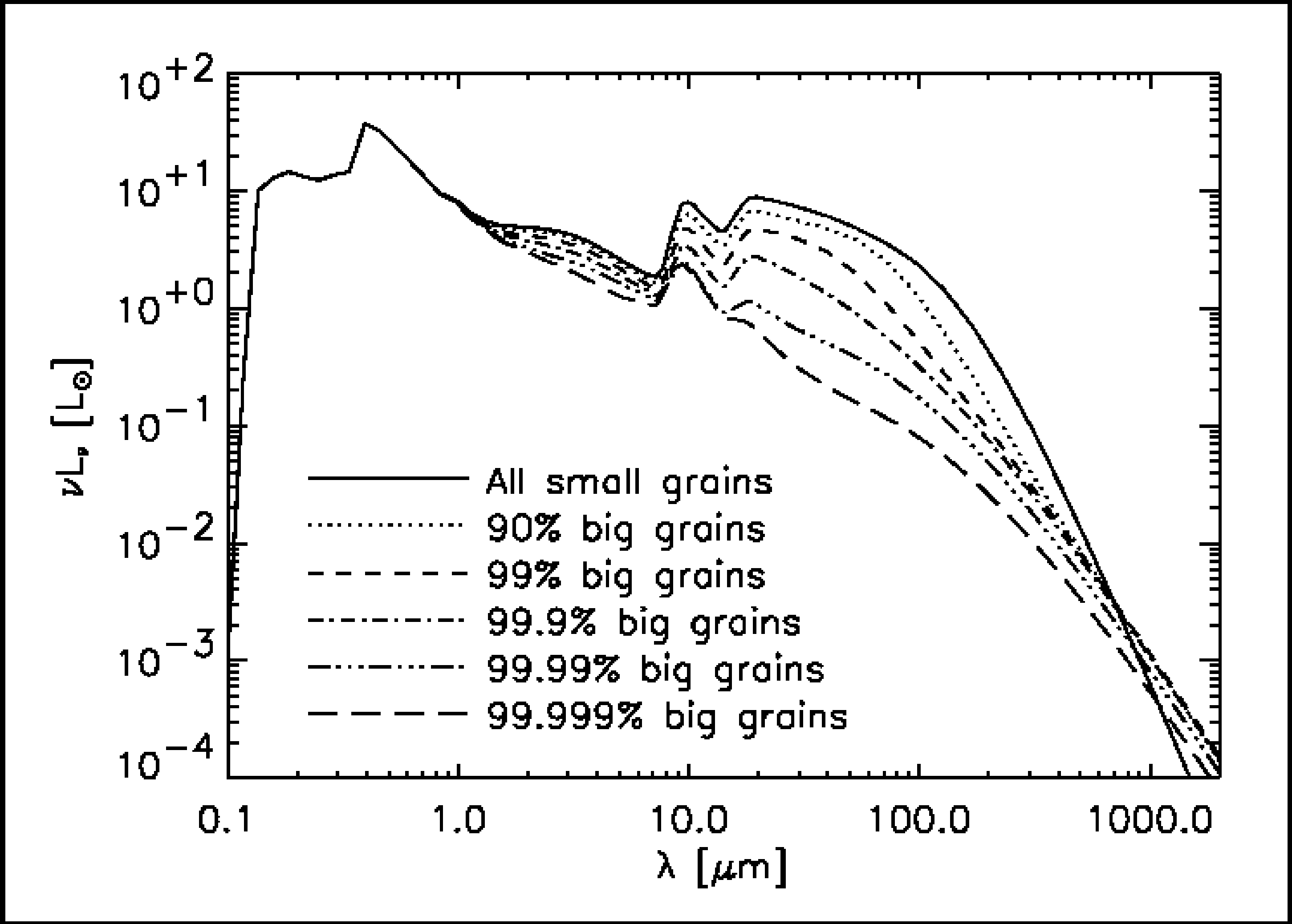

Dullemond & Dominik 2004

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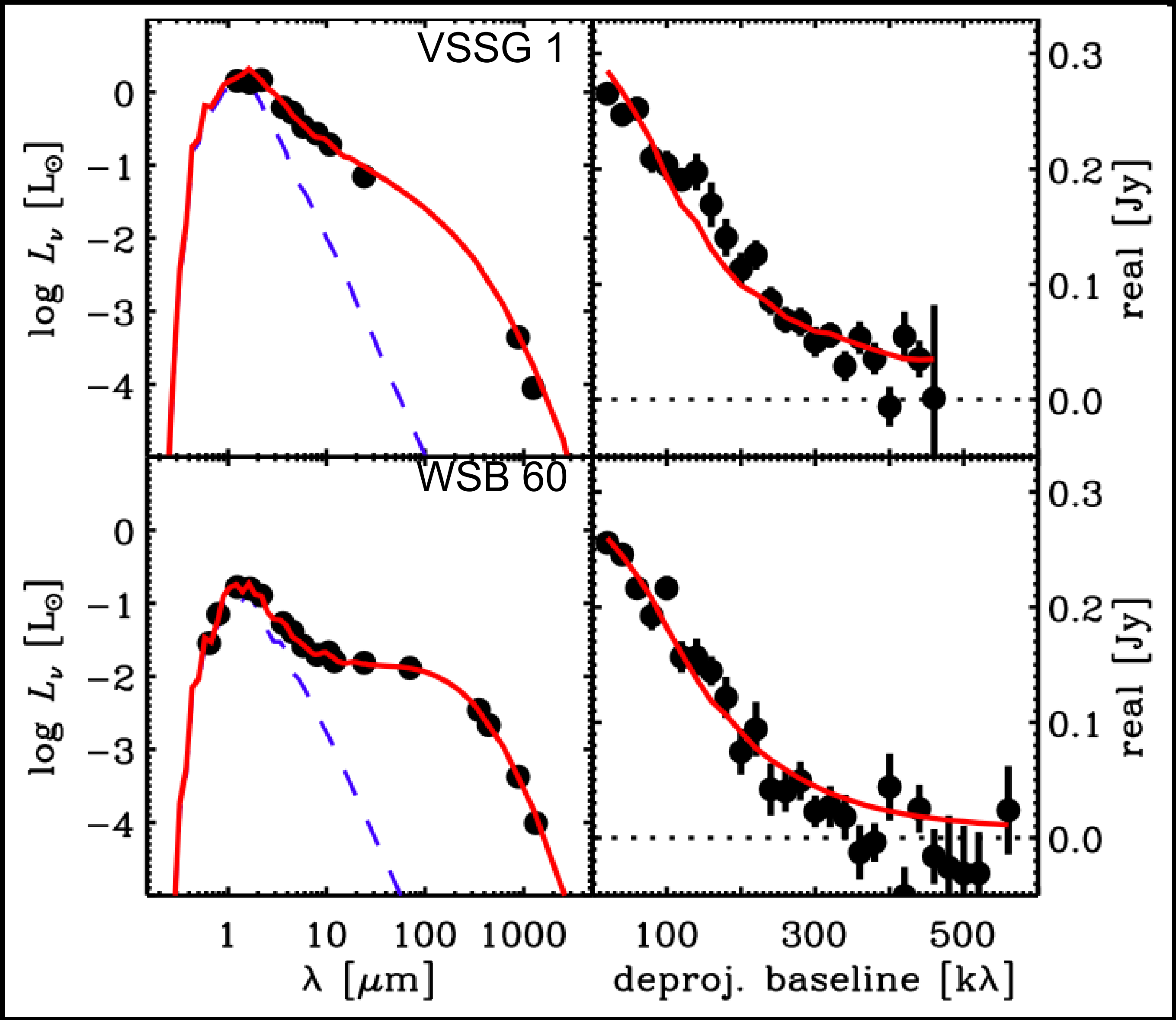
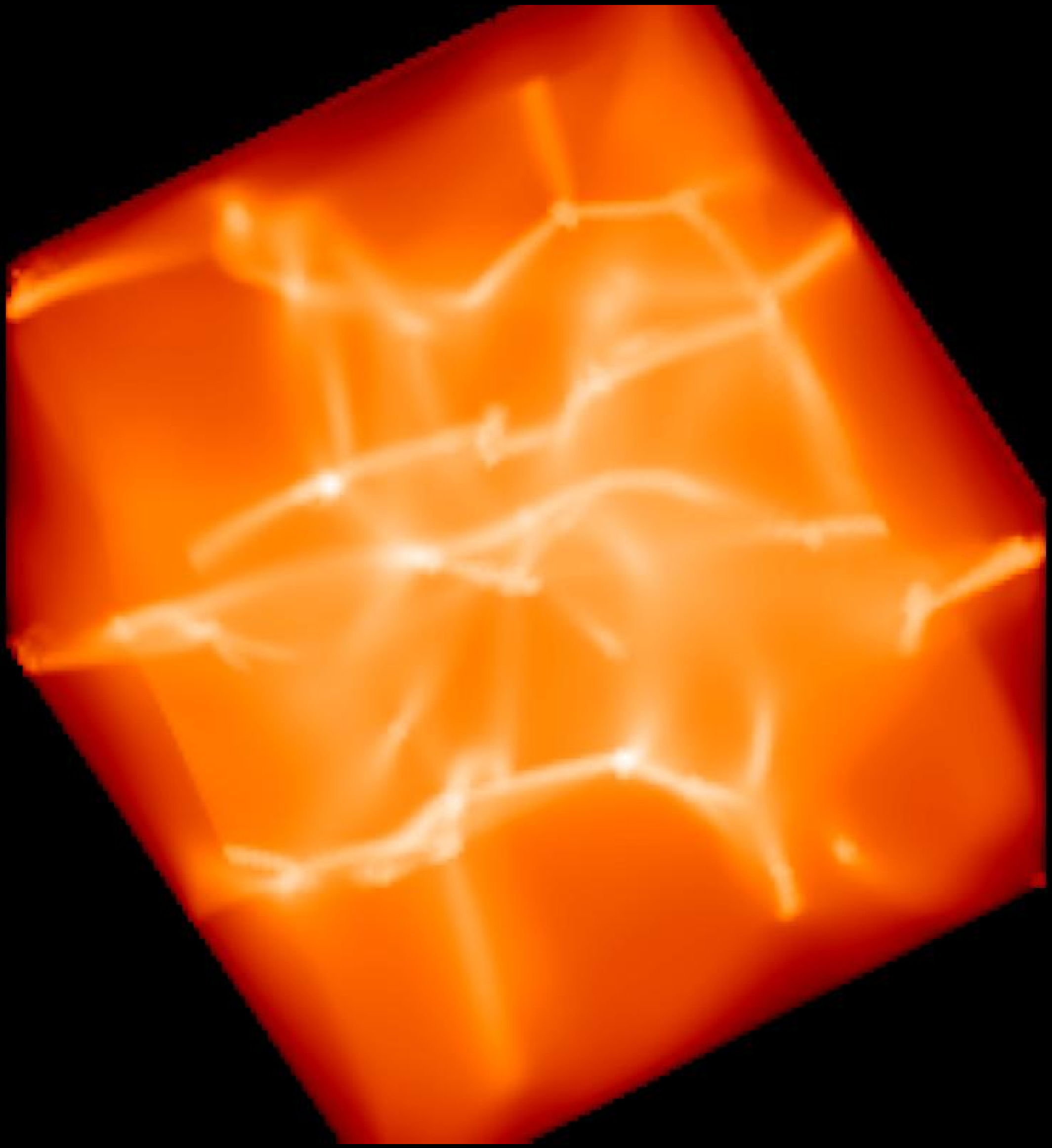


SED + millimeter resolved maps (=visibility values)

Andrews et al. 2009

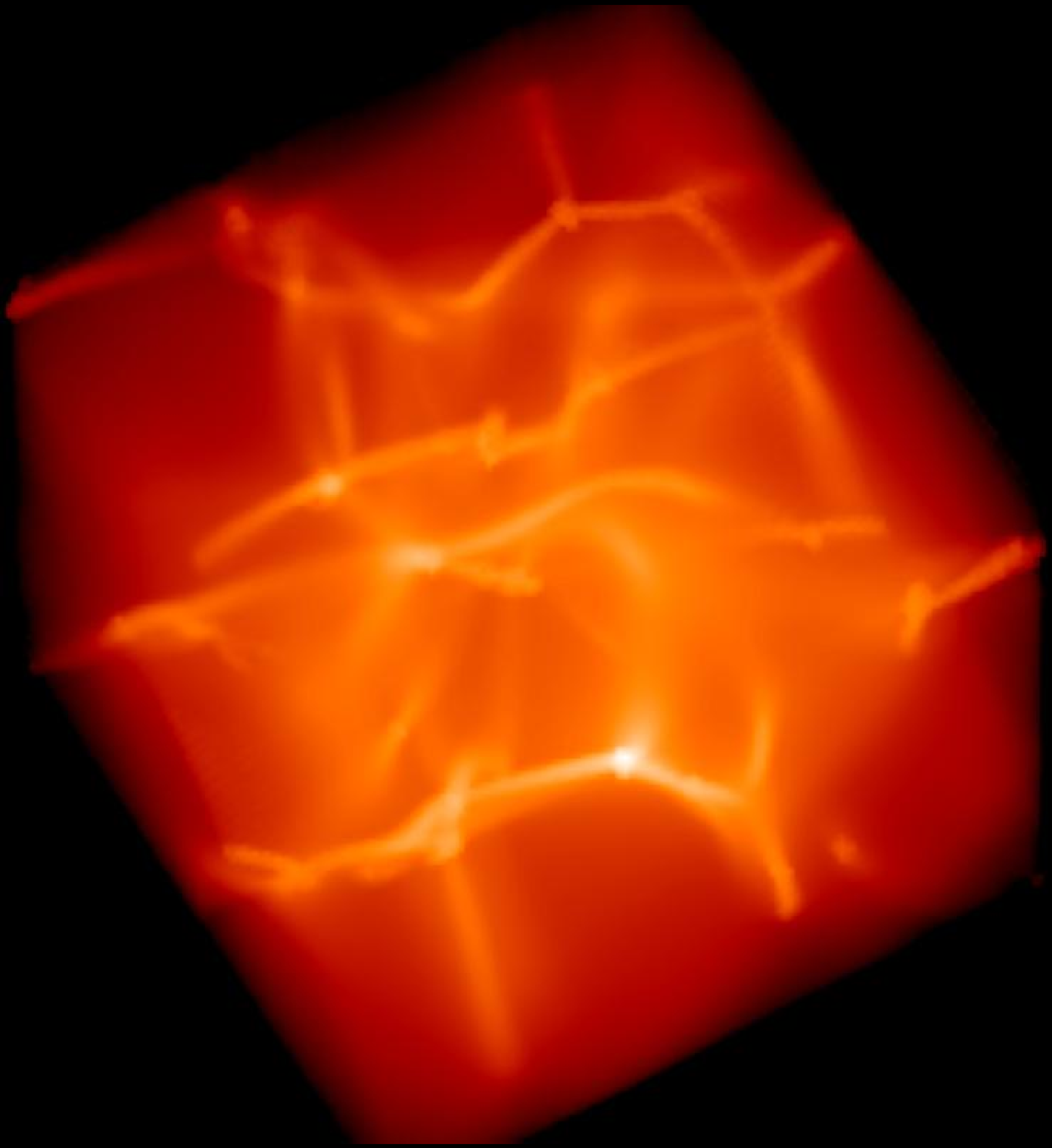
Example: Dust emissivity from SF region

λ=1000 μm



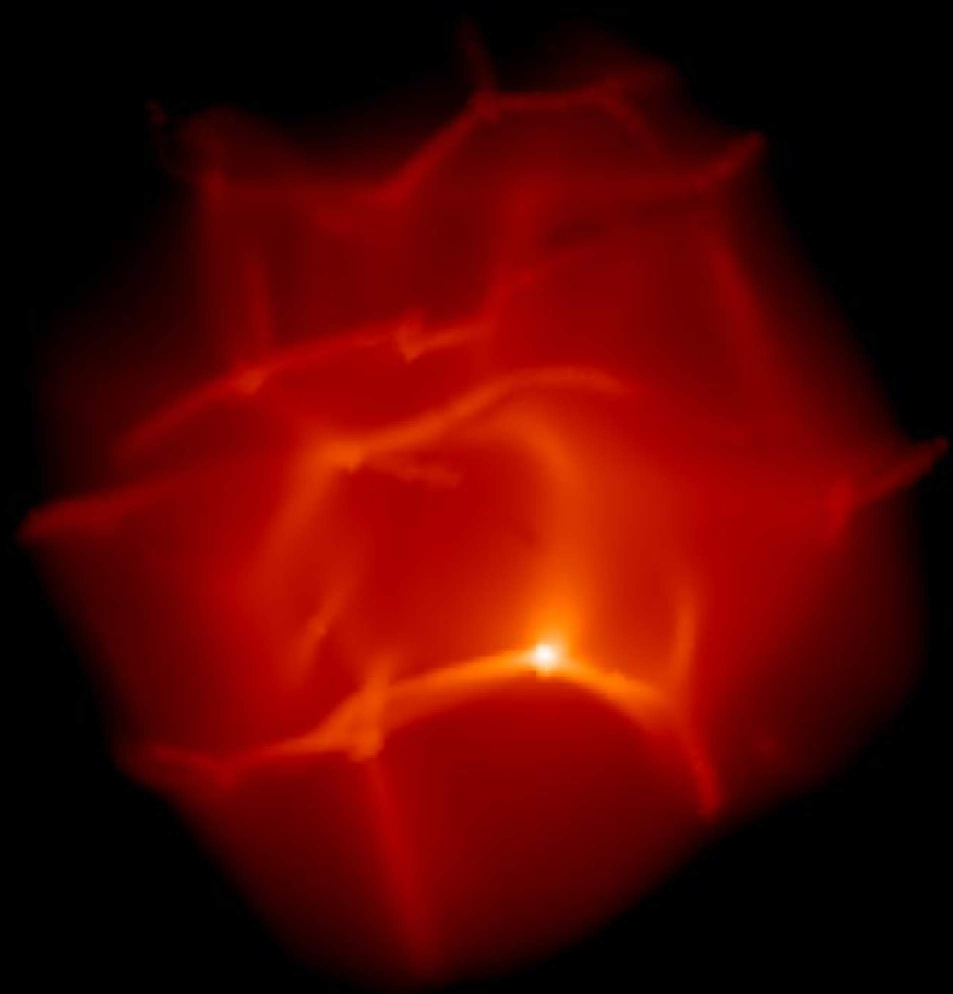
Example: Dust emissivity from SF region

$\lambda=100\ \mu m$



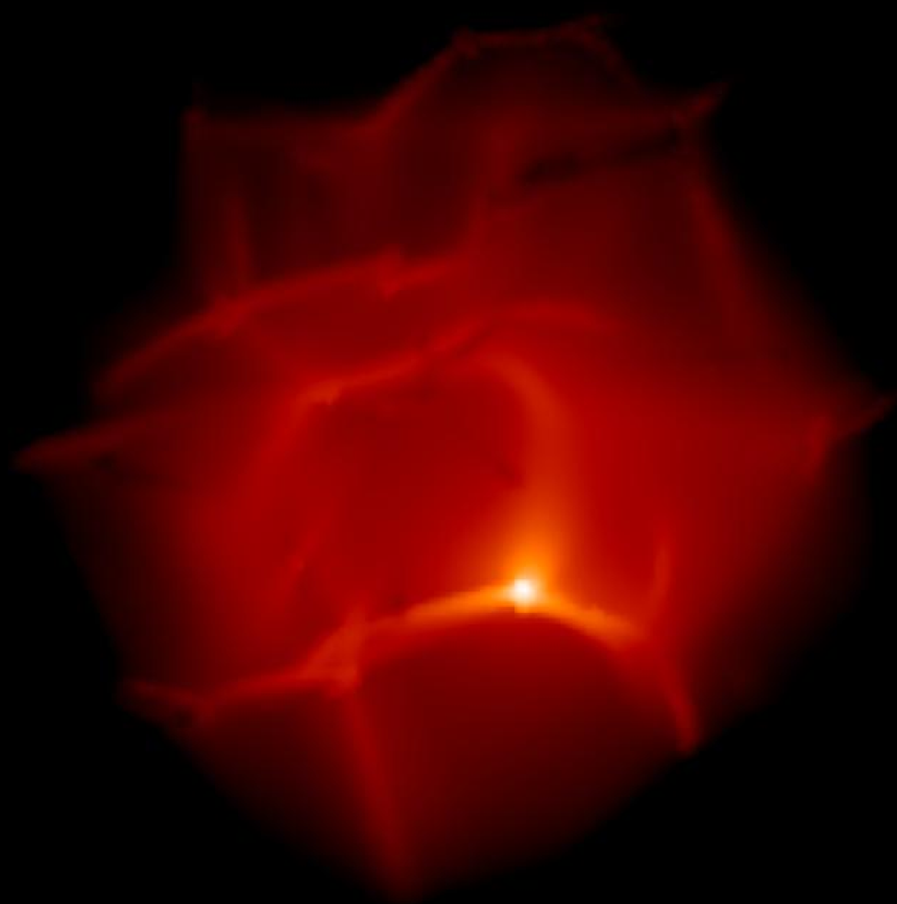
Example: Dust emissivity from SF region

λ=50 μm



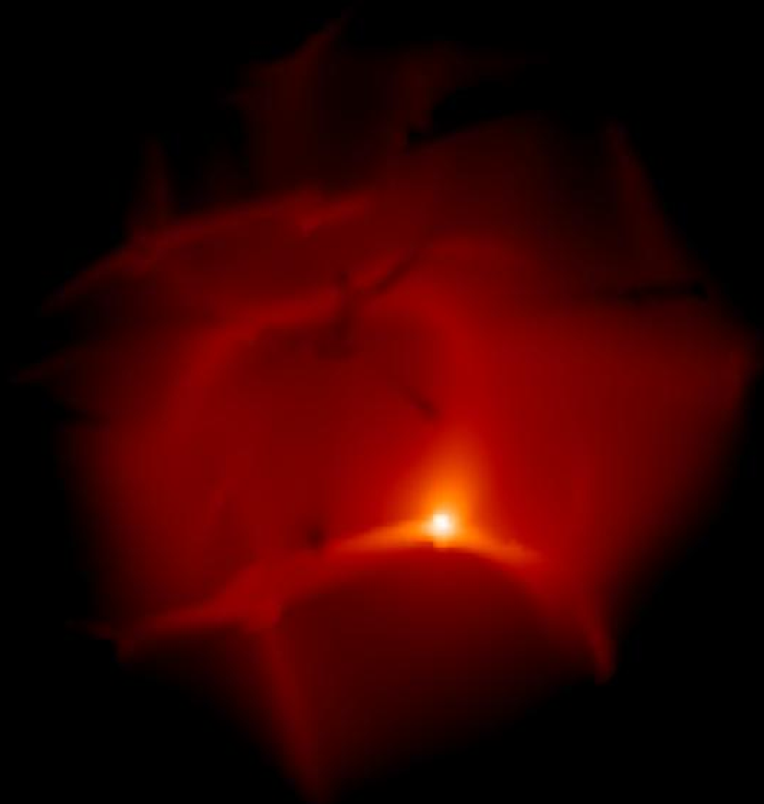
Example: Dust emissivity from SF region

λ=40 μm



Example: Dust emissivity from SF region

λ=30 µm

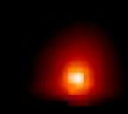


Example: Dust emissivity from SF region

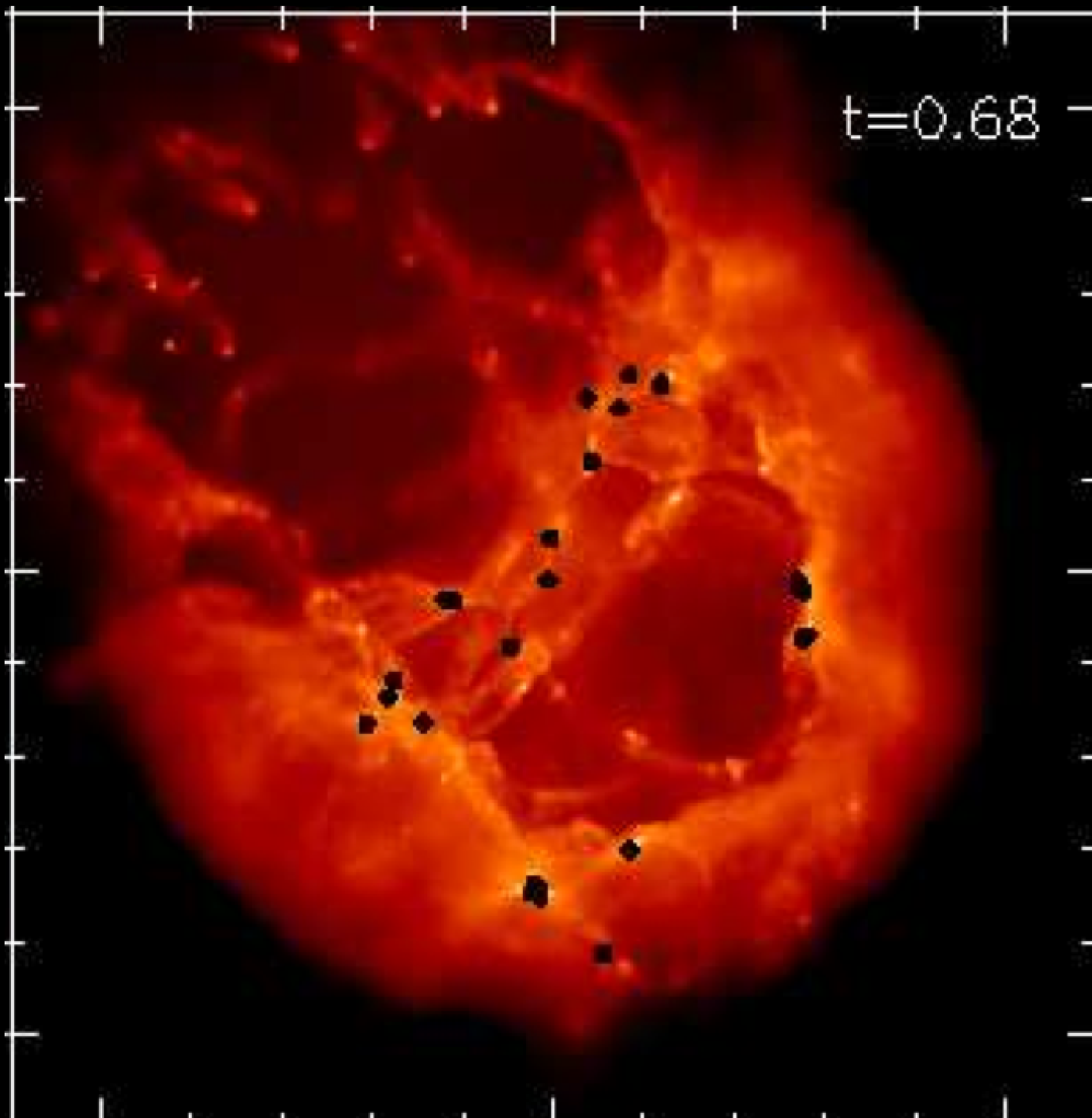
λ=20 μm

Example: Dust emissivity from SF region

λ=10 μm



Example: Models of HII regions



SPH Model of a star forming region with an HII bubble ripping the cloud apart.

Credit: Stefanie Walch
Cardiff and MPA-Garching

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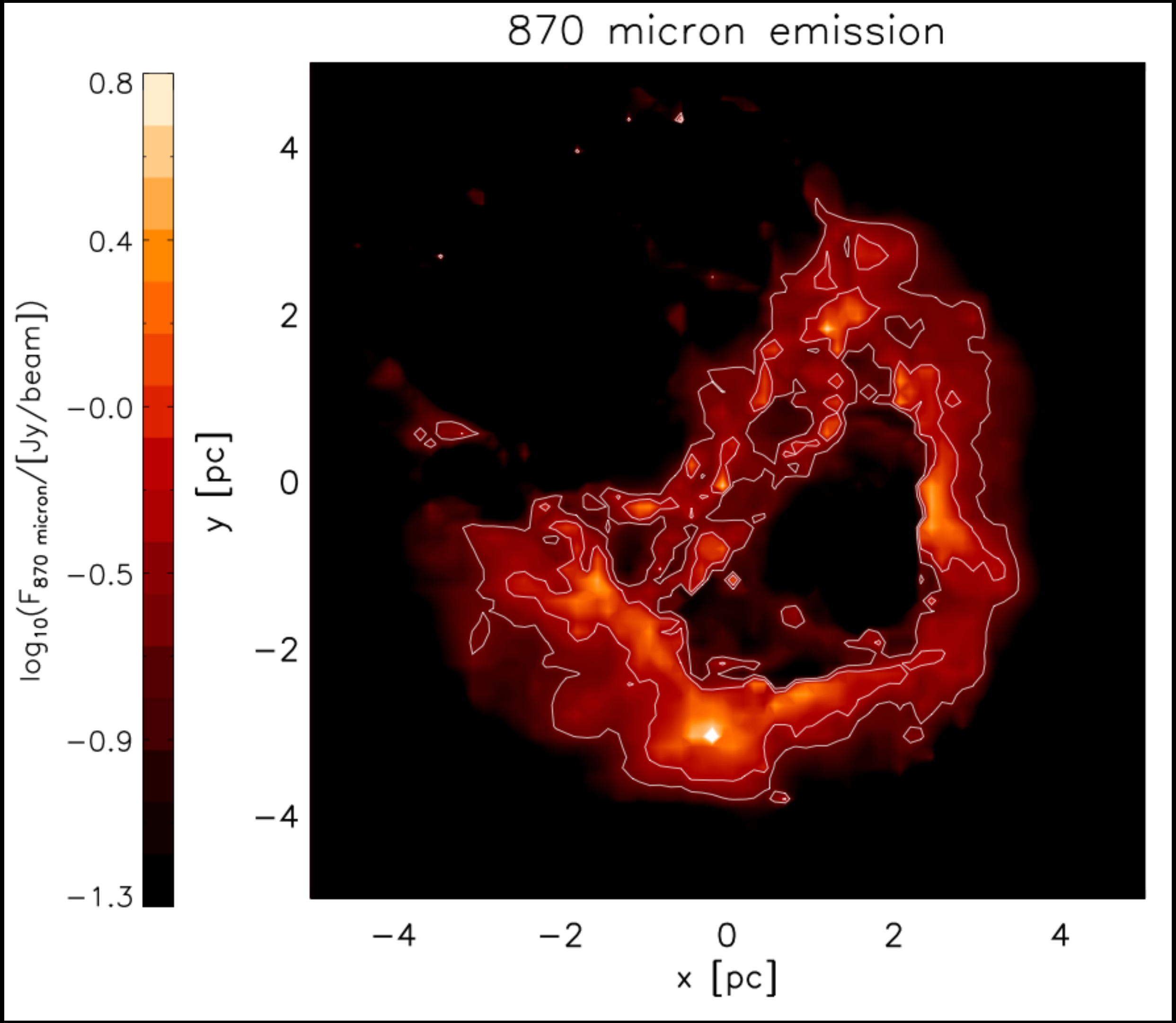

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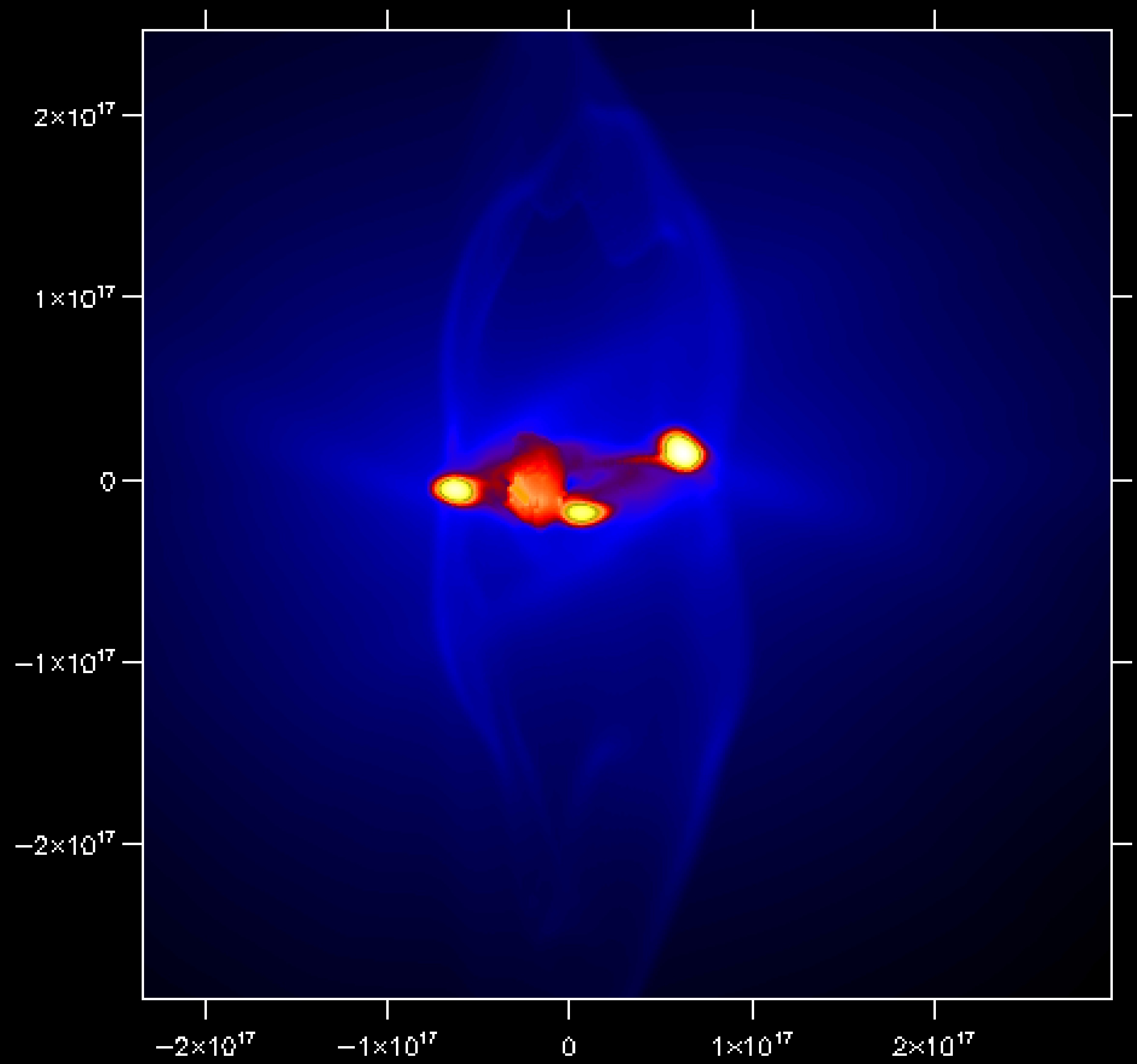
Viewing perspective of compact HII regions

Peters et al. 2010



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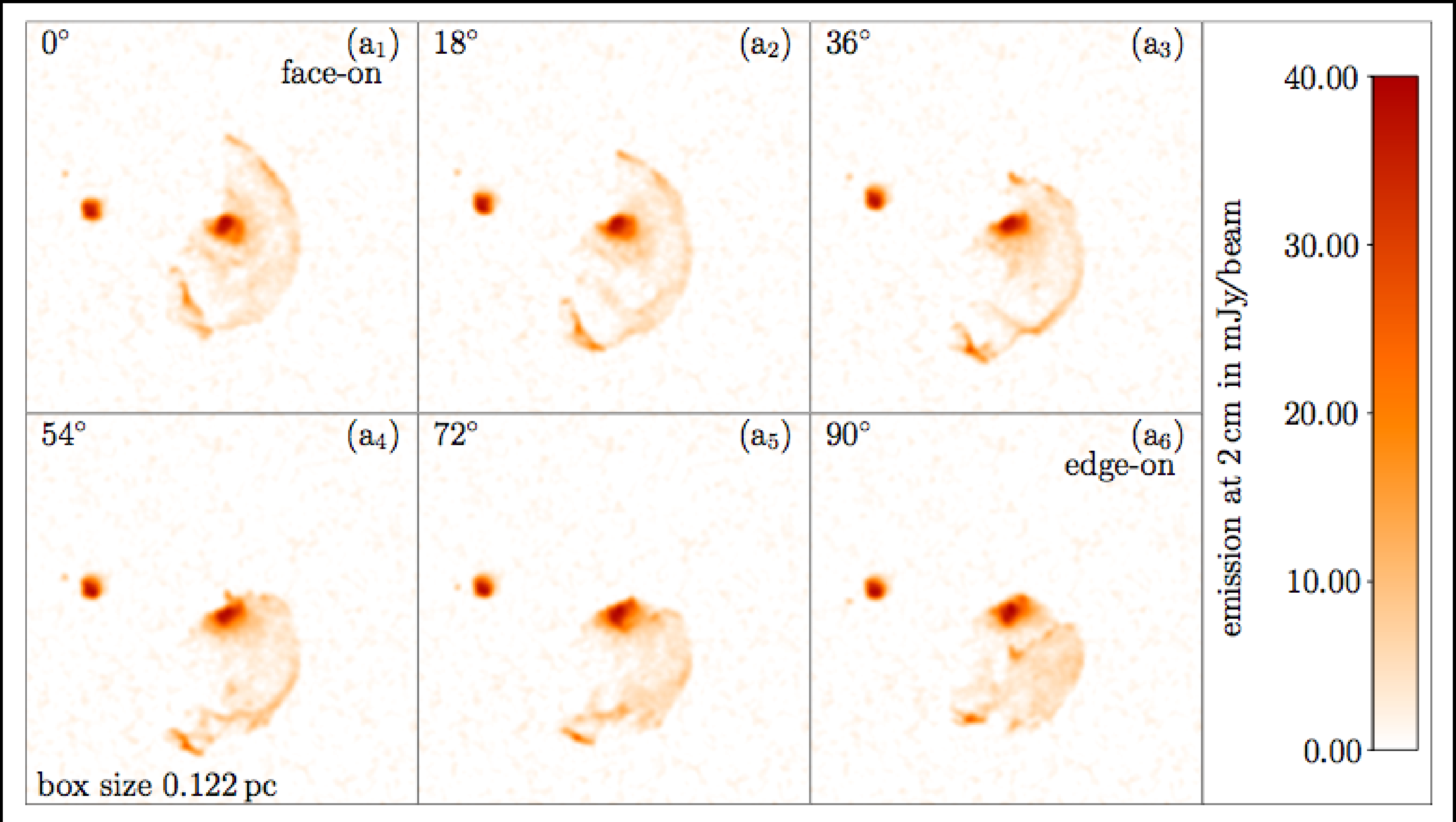
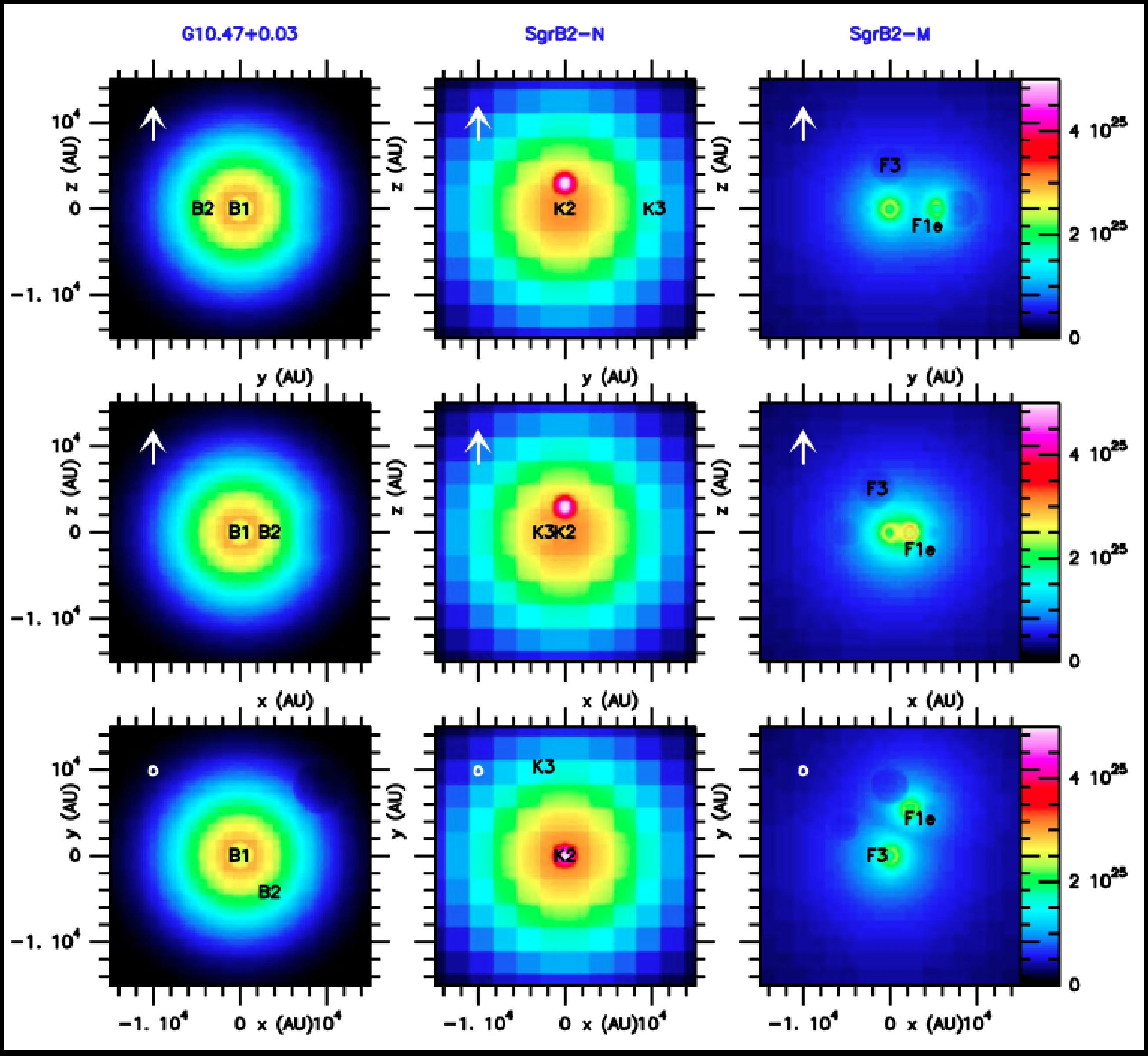


Example: Line transfer in SF regions

Model of HCN emission around young massive stars.



Rolffs, Schilke et al. 2011

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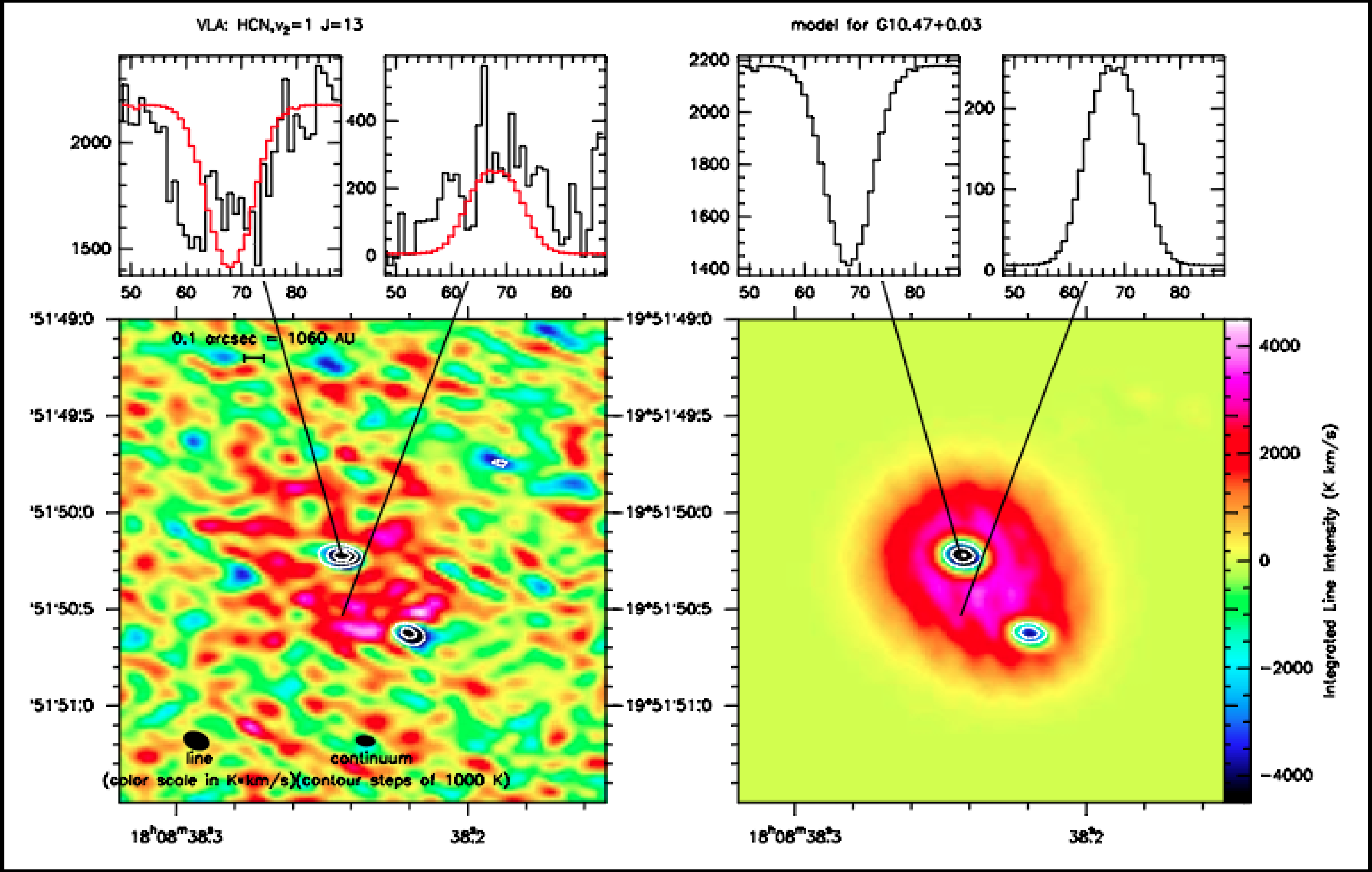
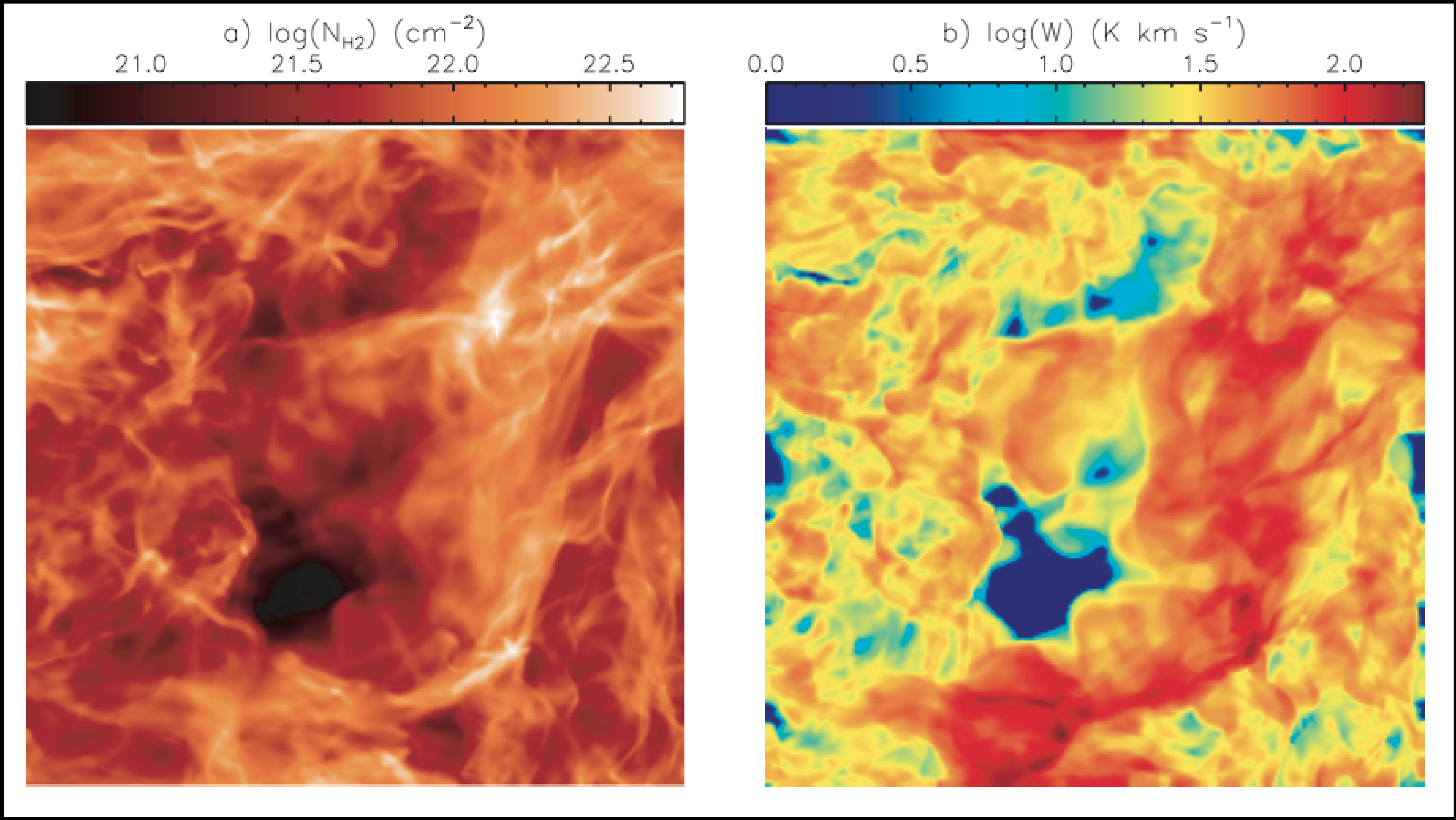


Rolffs, Schilke et al. 2011

The CO X-factor in the turbulent ISM

Shetty et al. 2011a/b



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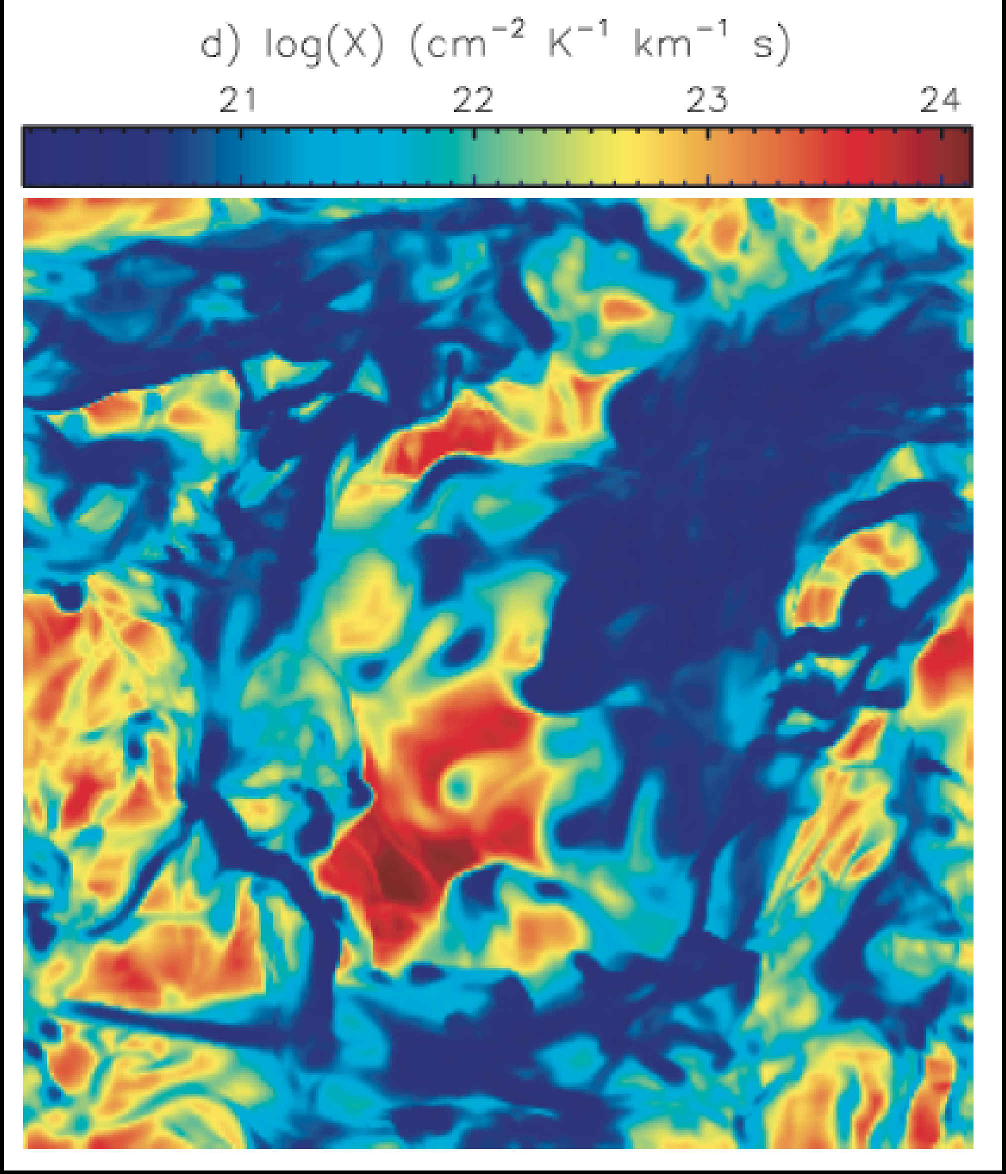
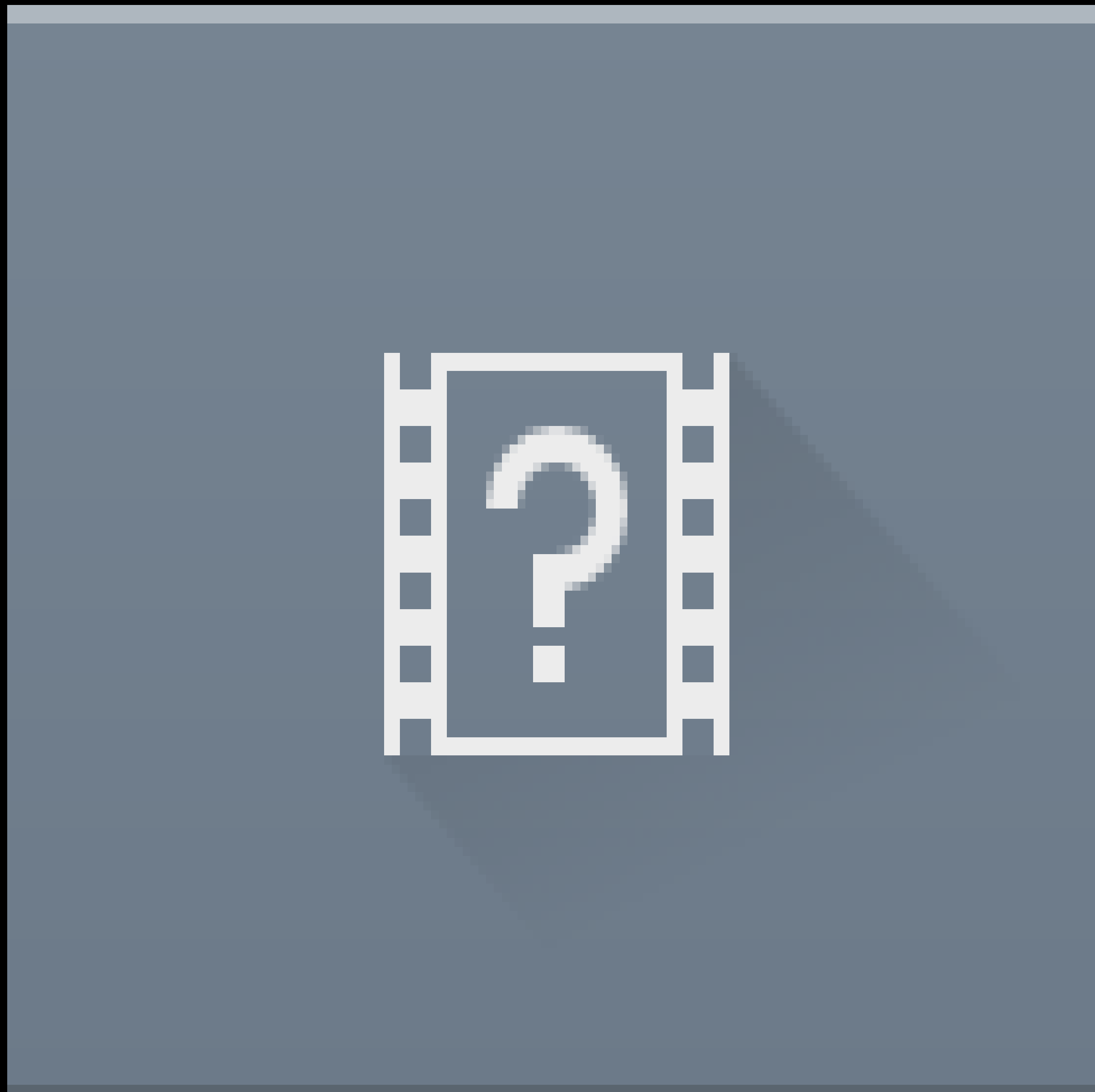


Example of AGN model



K. Wada, M. Schartmann and R. Meijerink (2016) ApJ, 828, L19

Issues of parallelization

- Currently RADMC-3D = OpenMP
- MPI distributed memory is hard. But a simple trick is possible:
  - Each node has FULL grid (possibly memory issue for large models)
  - Partly “embarrassingly parallel”:
    - Let 8 cores do MC for 5 minutes
    - Then add all cell-energies (gather)
    - Redistribute (broadcast)
    - Recompute the new temperatures
    - Do another 5 minutes etc.

Availability

- URL: http://www.ita.uni-heidelberg.de/~dullemond/radtrans/radmc-3d/
- Current version: 0.41
- Publically available
- For your convenience:
  - Extensive manual
  - Several simplistic example setups
  - Several more complex examples
  - Forum (PHPBB)
- GOAL:
  - Easy to use in simple way (complexities hidden)...
  - ...but if you want: Lots of flexibility + possibilities