Universiteit van Amsterdam
MSc Grid Computing

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Dust radiative transfer using Monte Carlo methods

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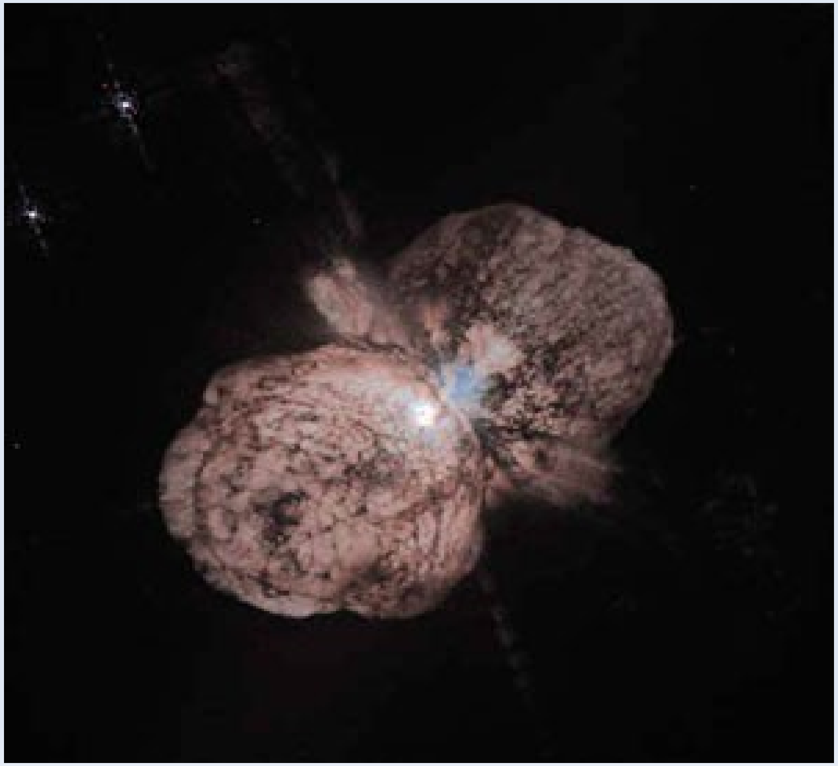
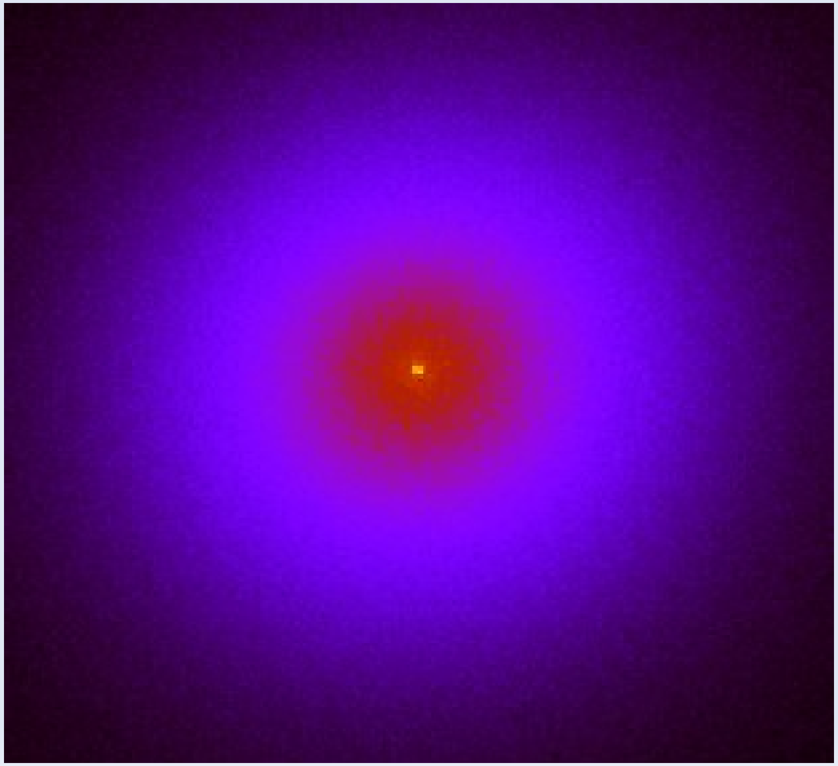
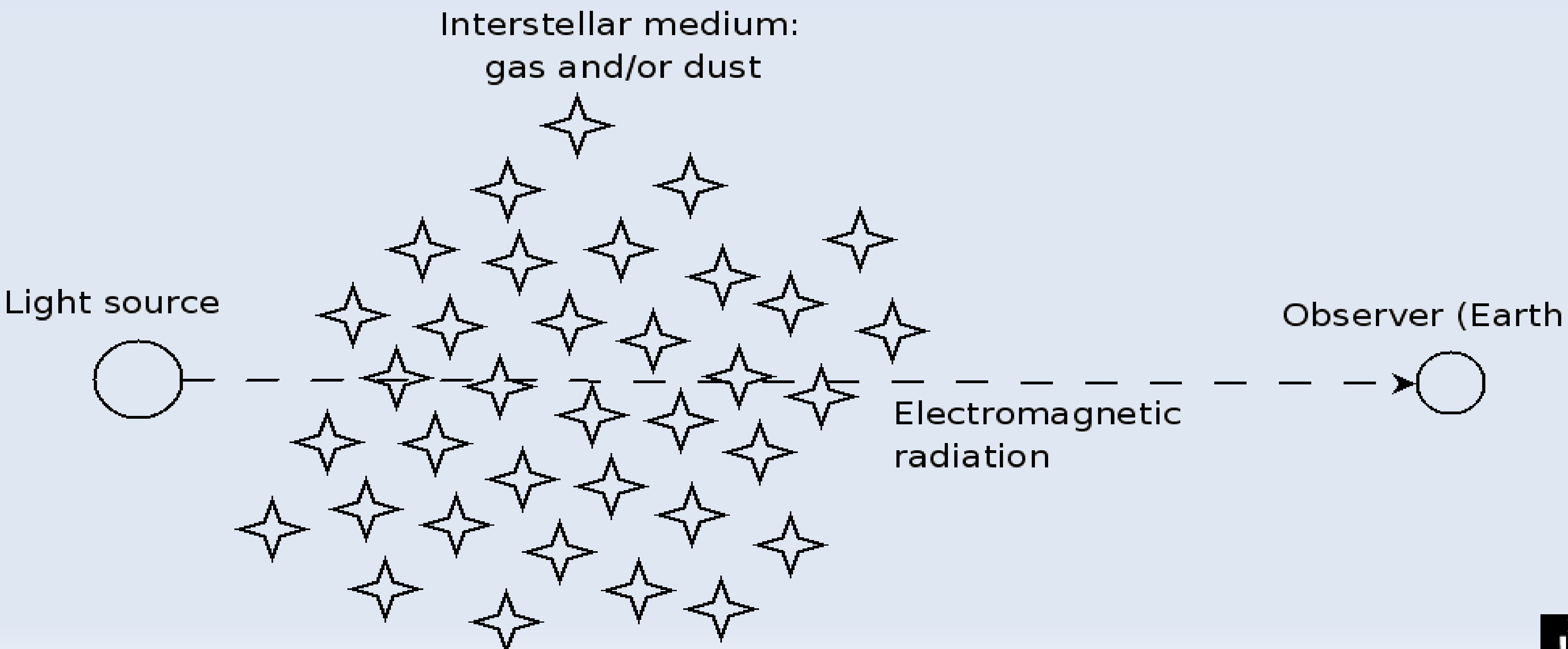




Radiative transfer in Astrophysics

Radiative transfer in astrophysics refers to the phenomena of energy transfer in the form of electromagnetic radiation between astrophysical objects.



RT: main applications

- Interpret high-resolution images produced by modern telescopes
- Understand the thermodinamical phenomena involved in an astrophysical system
- Study the physical structure of celestial bodies

Why Monte Carlo methods for RT

- Simple underlying idea
- Permit to simulate complex and inhomogeneous systems
- Under certain assumptions they are as accurate as their analytical counterparts
- Well known and widely used
- They particularly fit to the structure of the problem of RT

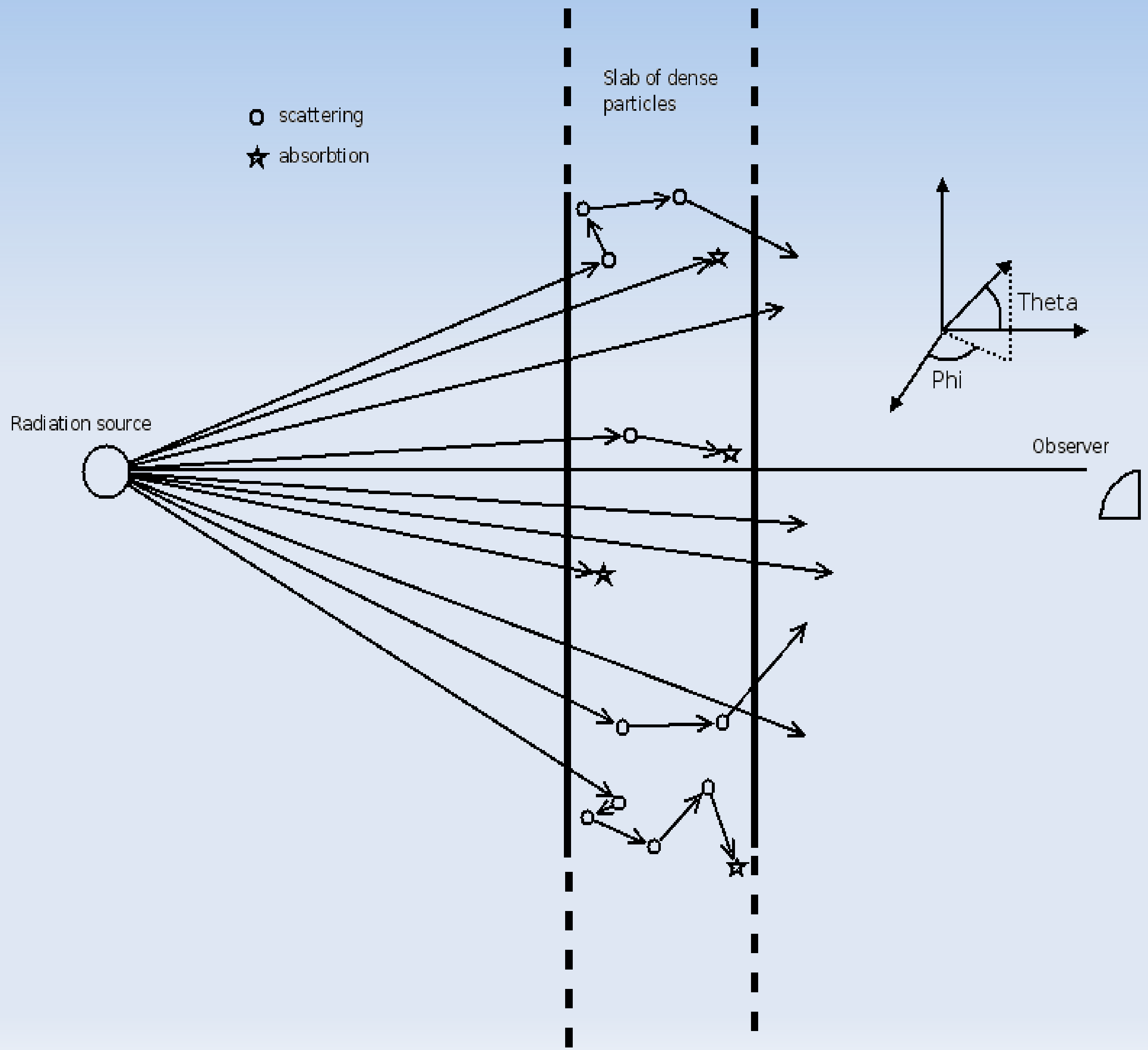
Monte Carlo RT: basics

- Photons are generated isotropically from a point source (a star)
- They travel across a defined interstellar medium (dust or gas)
- Along their path two main phenomena may happen due to their interaction with the matter:
  - *scattering*: the trajectory of the photon is deviated
  - *absorption*: the photon is absorbed by the medium
- The photons that exit the medium are projected into the observer's frame, producing images

RT theory: basics

- Intensity $$I_\nu = \frac{dE_\nu}{\cos(\theta)\, dA\, dt\, d\nu\, d\Omega}$$
- Flux $$F_\nu = \int I_\nu \cos(\theta)\, d\Omega$$
- Interaction probability $$P(L) = (1 - n\sigma\frac{L}{N})^N = e^{-n\sigma L} = e^{-\tau}$$
- Optical depth $$\tau = \int_0^L n\sigma\, dl$$
- Albedo $$a = \frac{n_s\sigma_s}{n_s\sigma_s + n_a\sigma_a}$$
- Density ρ and opacity κ $$\rho\kappa = n\sigma$$

The plane parallel semi-infinite slab



- infinite height
- infinite width
- finite depth (1.0)
- placed right in front of the source
- homogeneous density and opacity

The slab: MC algorithm

for a number of photons N {

generate a new photon from the source

do {

sample the interaction length L using: $L = -\frac{\ln(\xi)}{n\sigma}$

while photon is inside the slab {

if x[0,1] < albedo

scatter

else

absorb

compute thermodynamical measures

}

if photon exited the slab {

project it into the observer's plane

}

}

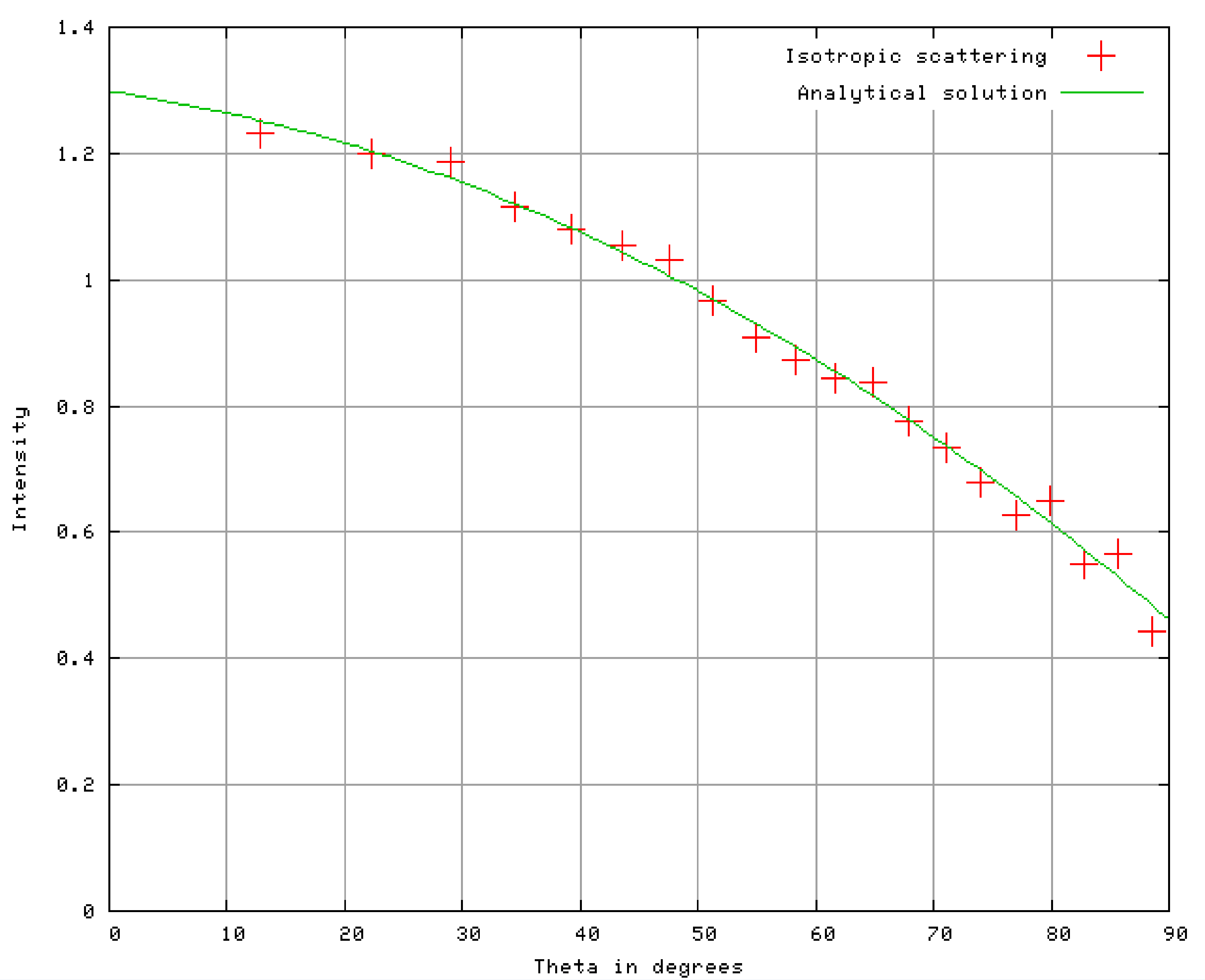
}

Isotropic scattering

The new direction of travel is picked uniformly from any possible direction

- Advantage: the analytical solution for this problem is known (Chandrasekhar 1960) and can be used for validation
- Disadvantage: it is a not enough accurate approximation for realistic gas or dust scattering

Isotropic scattering: validation

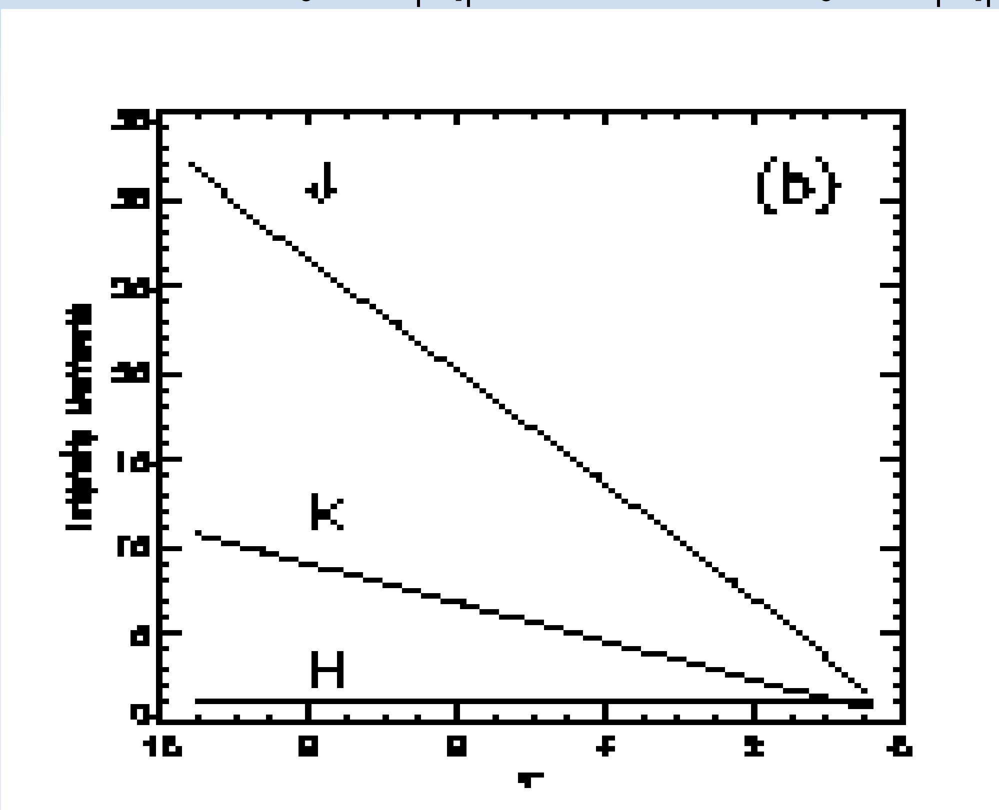


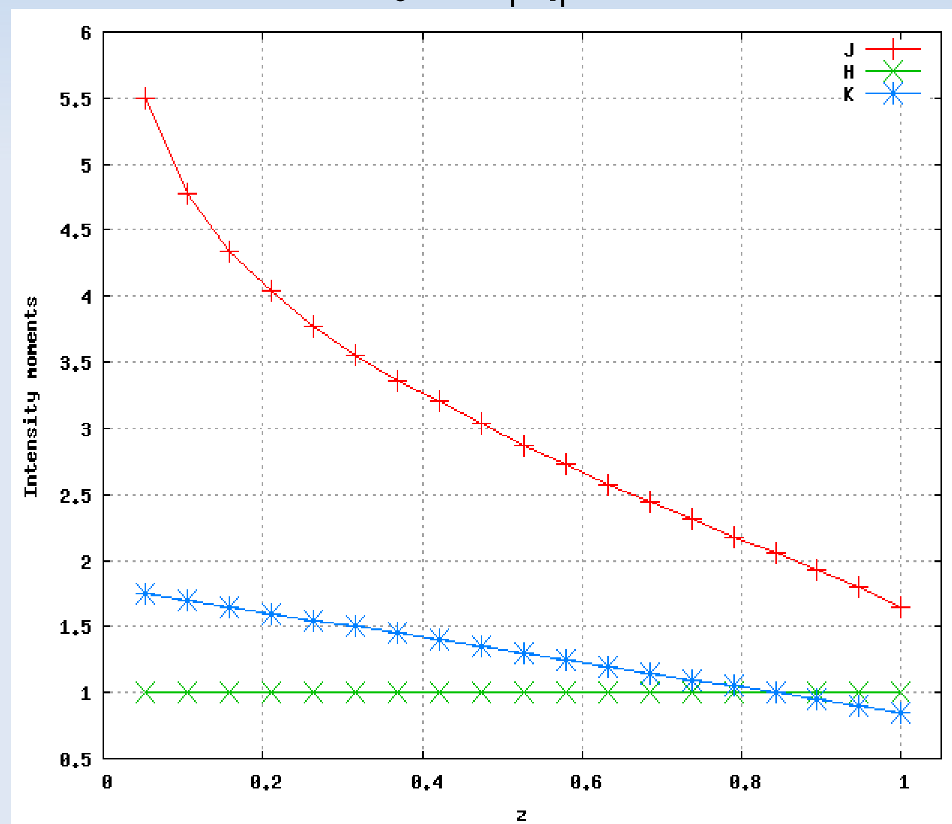
- optical depth = 10.0
- albedo = 1.0
- photons = 100,000

Isotropic scattering: moments

$$J=\frac{1}{4\pi}\int I\,d\Omega \qquad H=\frac{1}{4\pi}\int I\cos(\theta)\,d\Omega \qquad K=\frac{1}{4\pi}\int I\cos(\theta)^2\,d\Omega$$

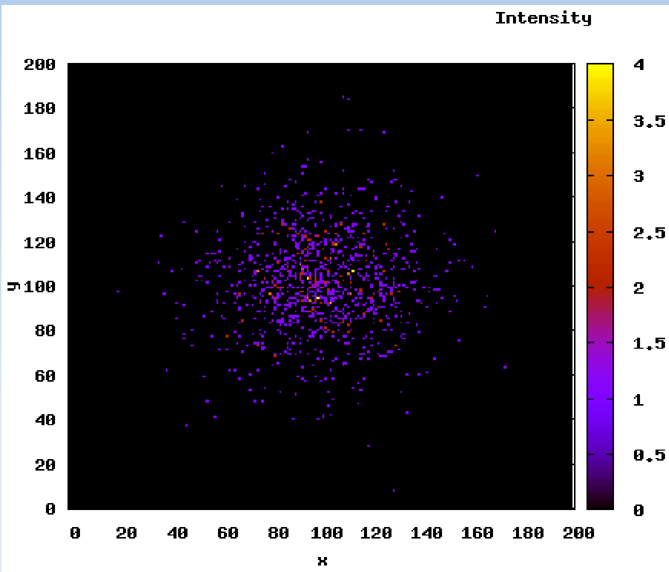
$$J=\frac{B_\nu}{4N_0}\sum_i\frac{1}{|\mu_i|} \qquad H=\frac{B_\nu}{4N_0}\sum_i\frac{\mu_i}{|\mu_i|} \qquad K=\frac{B_\nu}{4N_0}\sum_i\frac{\mu_i^2}{|\mu_i|} \qquad \mu=\cos(\theta)$$

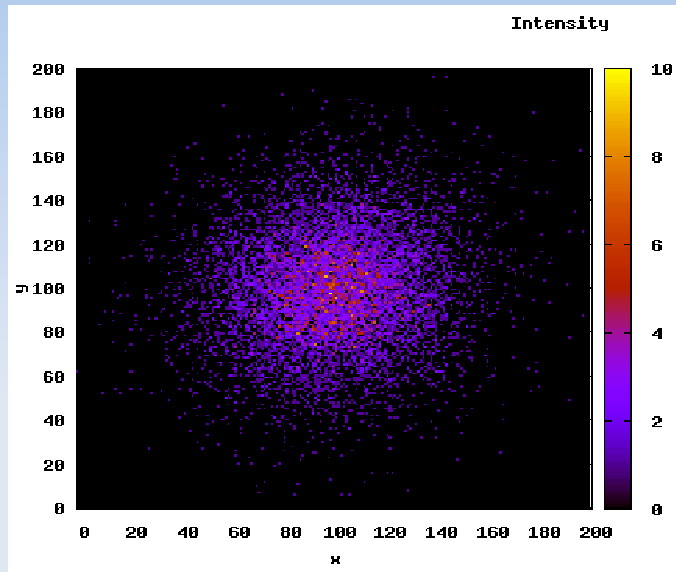


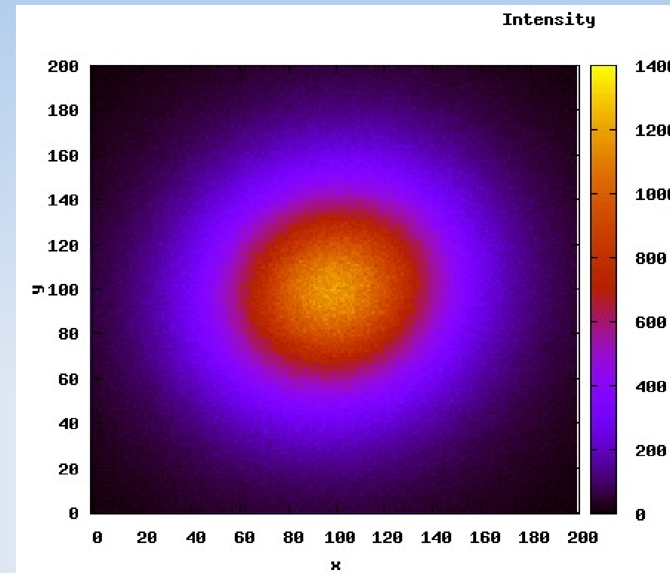


Isotropic scattering: results

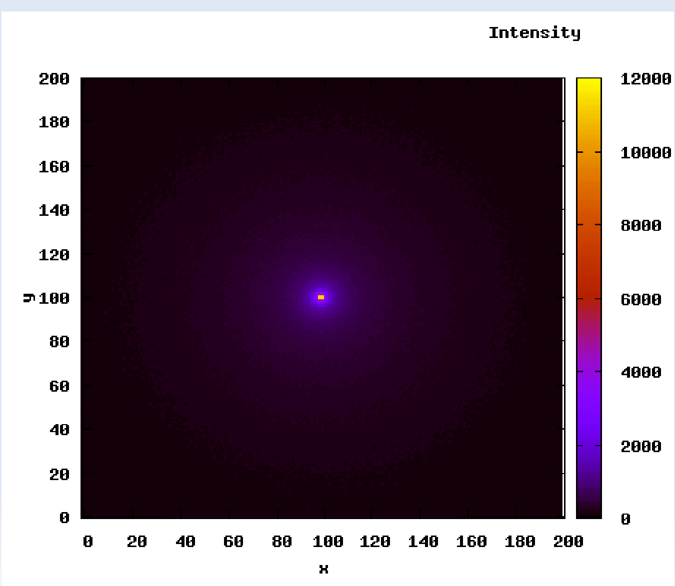
Intensity against albedo

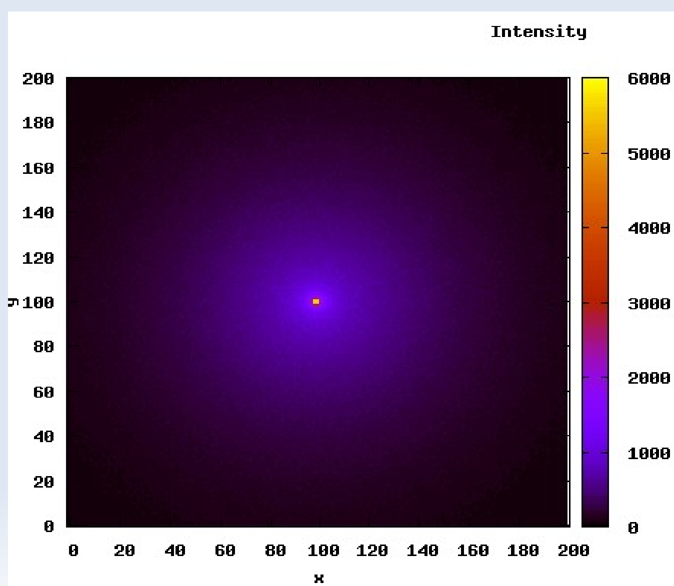


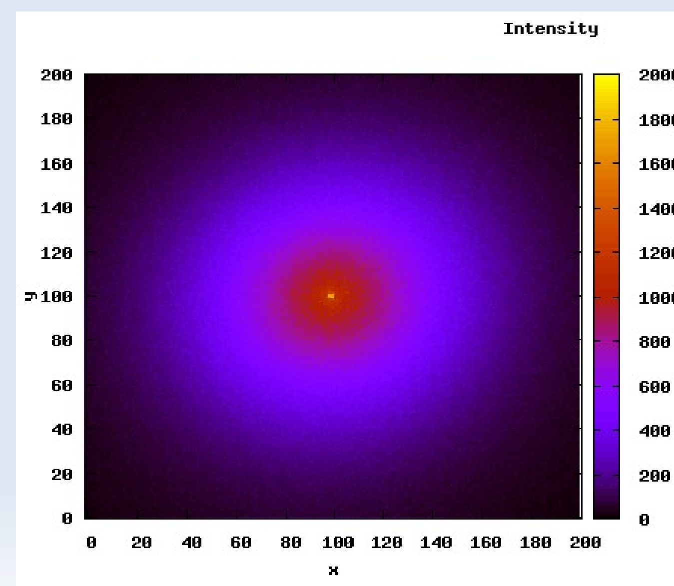




Intensity against optical depth

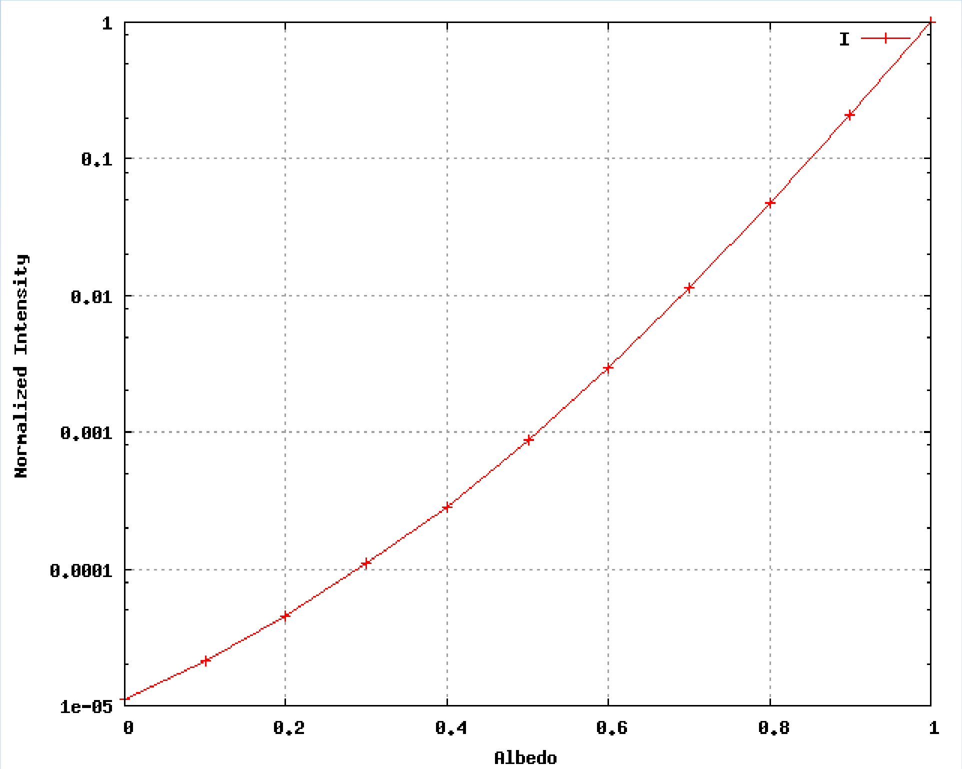




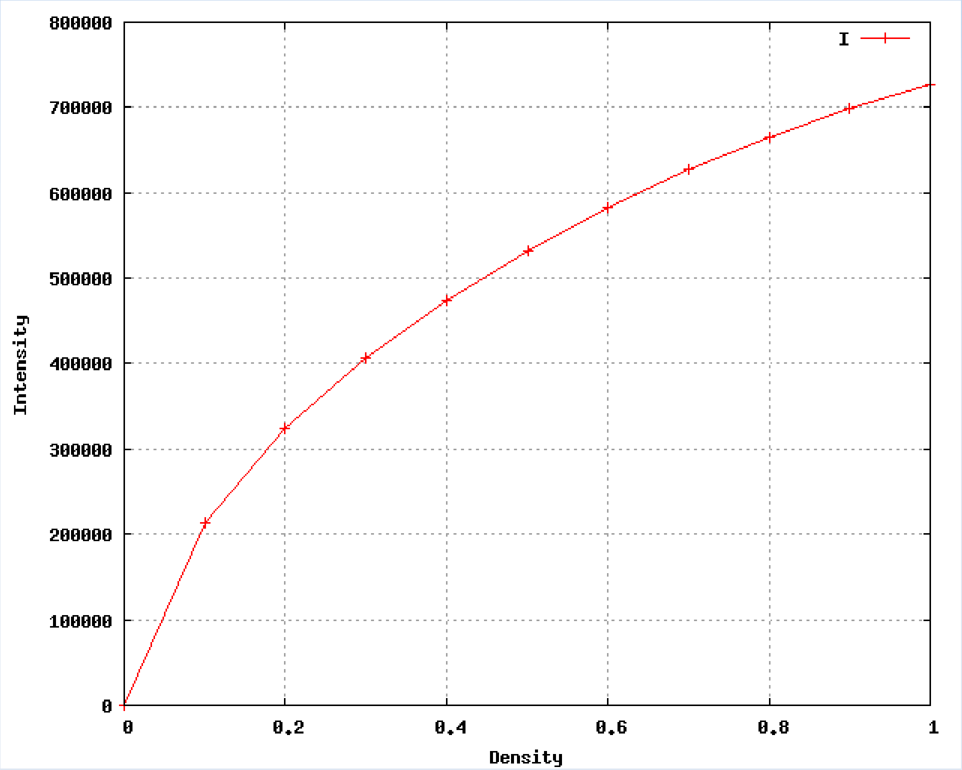


Isotropic scattering: results

Total intensity against albedo



Total intensity against optical depth



Anisotropic scattering

- Interstellar medium: gas and dust
- We want to simulate dust scattering (ex Nebulae and some cases of accretion disk)
- Anisotropic scattering using *Rayleigh* + *Henyey-Greenstein* function
- The scattering depends on the incident angle and on several other parameters
- Photons polarization is also modeled
- Simulation of dust or gas properties for different wavelengths is possible

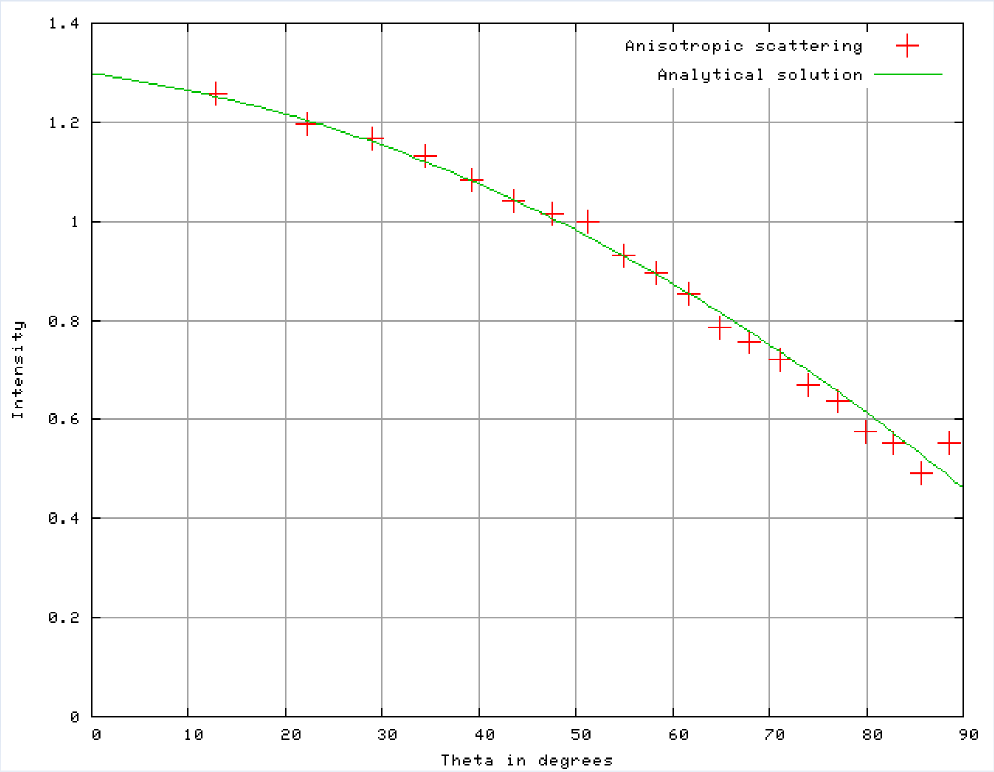
Anisotropic scattering: validation

Additional anisotropic scattering parameters:

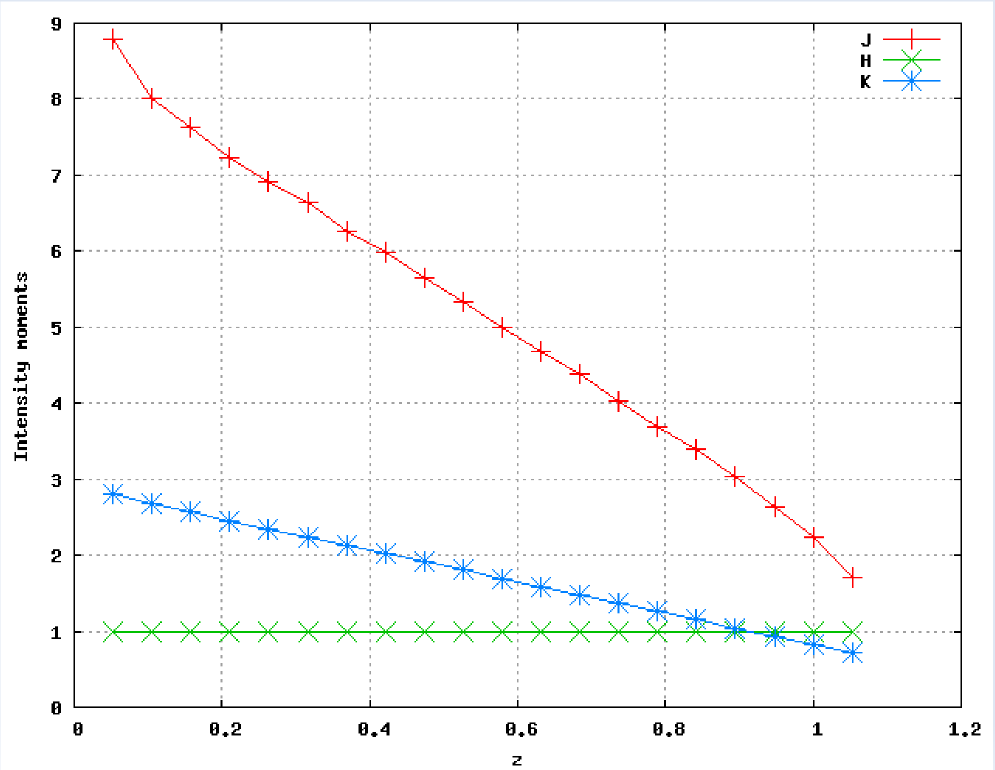
- **g**: scattering asymmetry parameter (0 = isotropic, 1 = forward-throwing)
- **pl**: peak linear polarization

We validated Anisotropic scattering using **g**=0

Intensity-cos(θ)

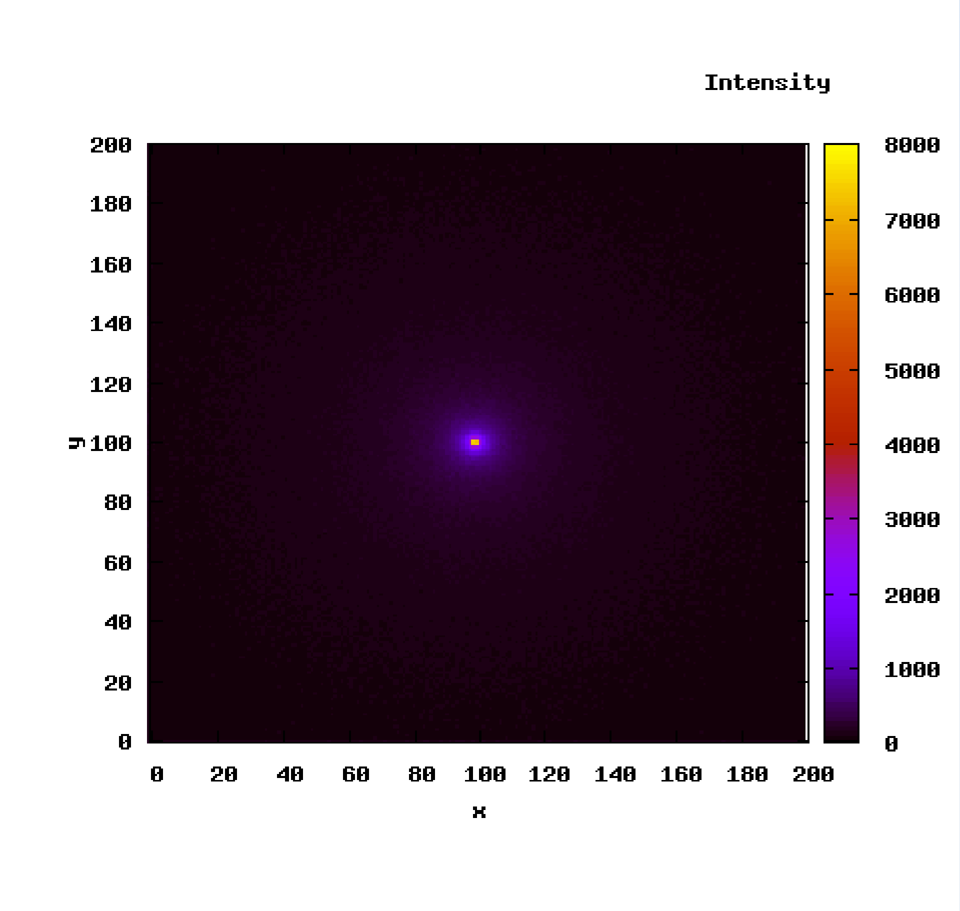


Intensity moments



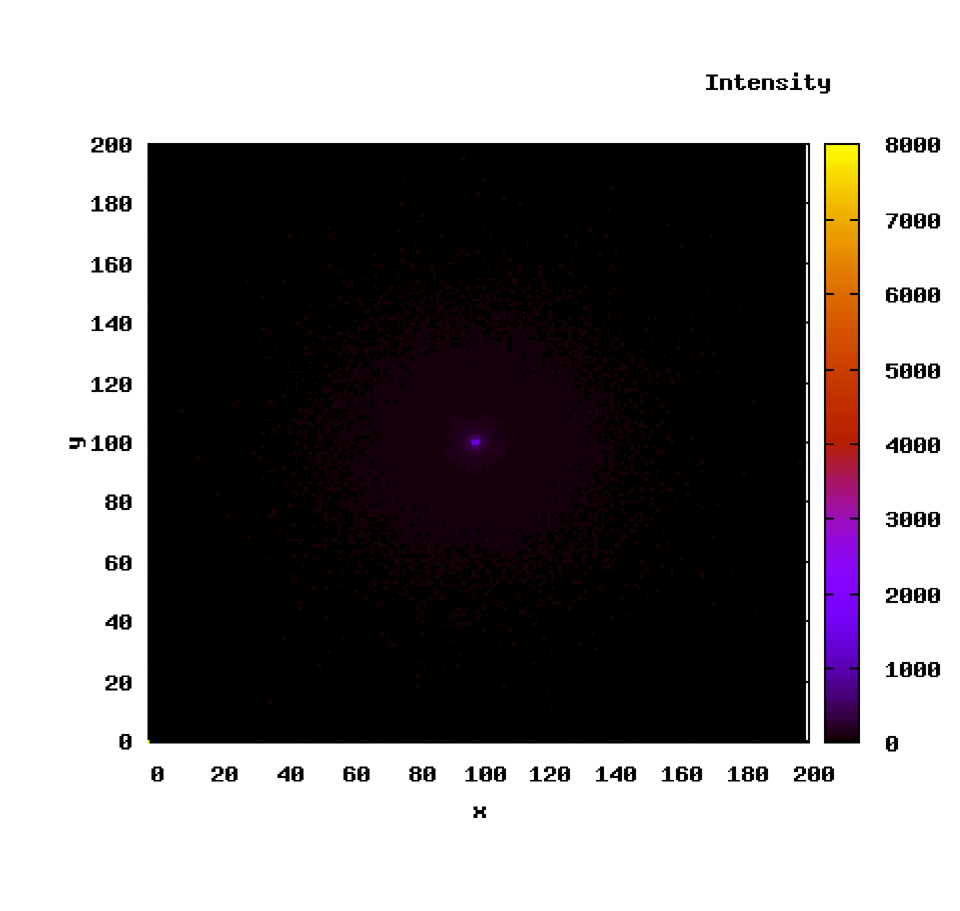
Anisotropic scattering: results

Ultraviolet band U (λ=0.34µm)



depth=1, albedo=0.54, kappa=360, g=0.48, pl=0.26

Infrared band K (λ=2.20µm)



depth=1, albedo=0.21, kappa=20, g=0.02, pl=0.93

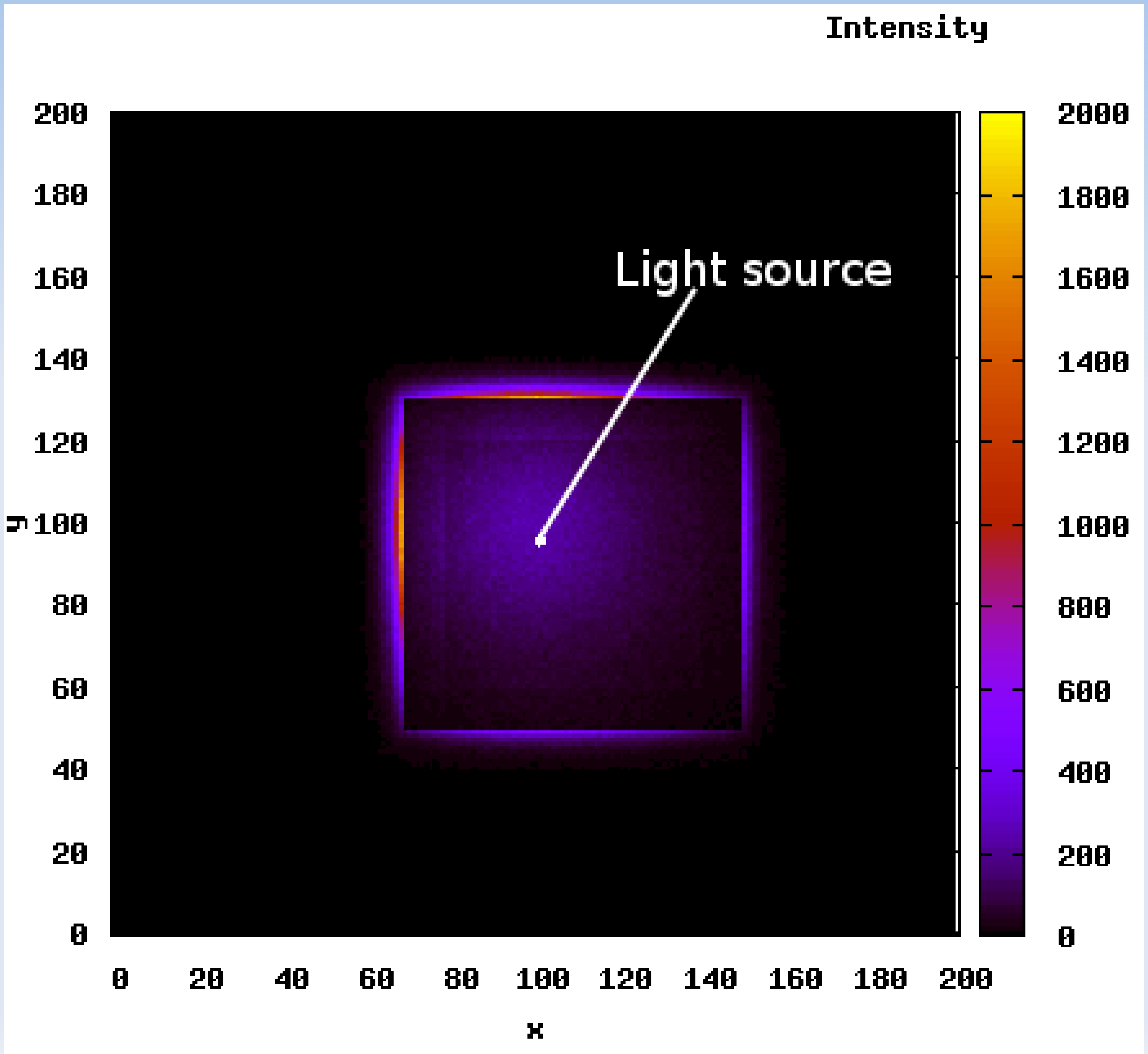
3D grid with dust scattering

- We build a 3D Cartesian grid to simulate inhomogeneous media
- Each point of the grid is associated to a a value of density ρ and opacity κ
- For every photon we have to compute the optical depth depending on the instant position and direction using:

$$\tau = \int_0^L n \sigma \, dl$$

- We can simulate totally arbitrary conditions

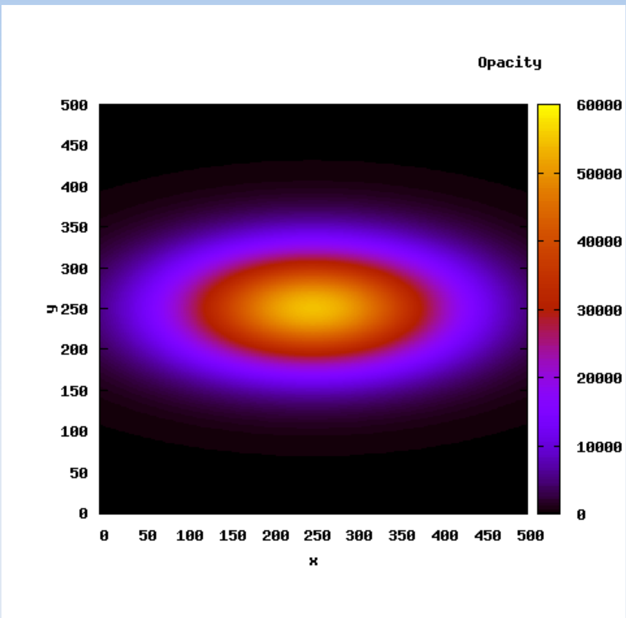
3D grid: a dust cube



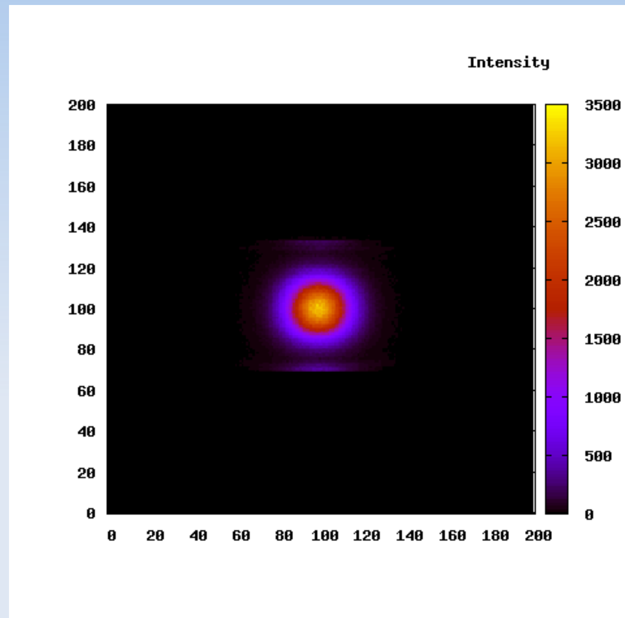
- Grid: 1.0x1.0x1.0 discretized to 200x200x200 points
- Dust cube: 10x10x10 grid points at position -7,7,100

3D grid: a dust spheroid

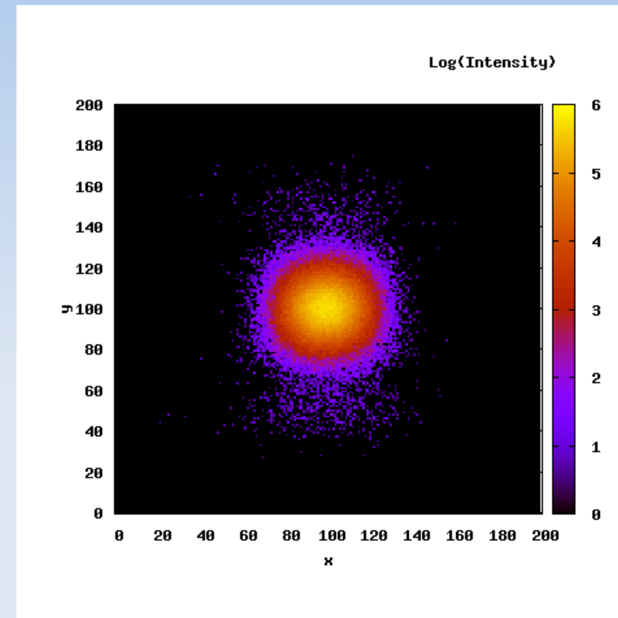
Opacity distribution



Intensity



Intensity (logarithmic scale)



Spheroid volume:

$$x^2+\frac{y^2}{c}+z^2=r$$

Spheroid opacity:

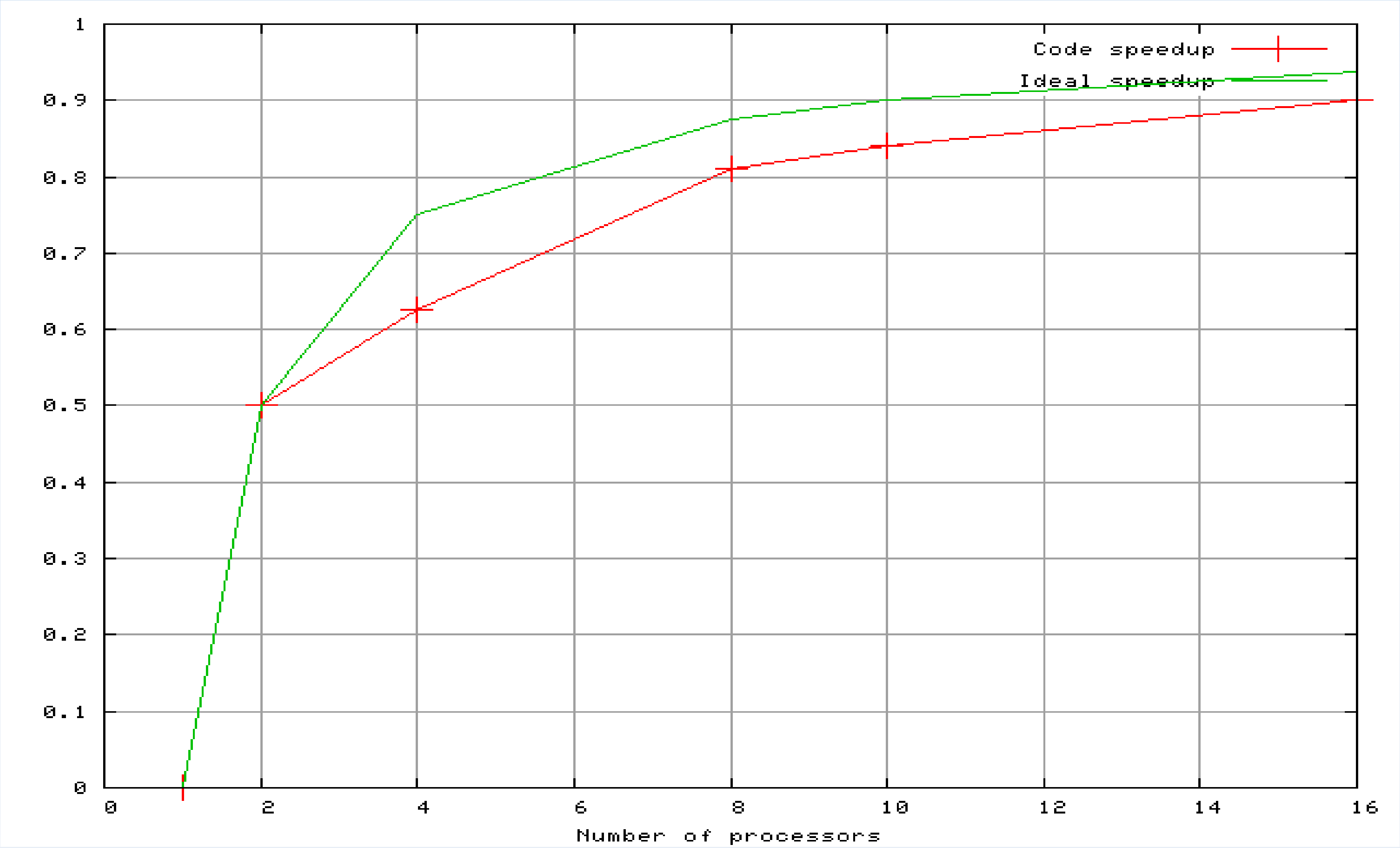
$$k=e^{-2r_i/r}$$

Parallelization using MPI

- We parallelize the simulation by decomposing the number of generated photons among the CPUs
- At the final step all the values are merged to the *root* processor
- High-efficiency and low communication overhead obtained
- Eventually for very big grids a spatial domain decomposition is also possible (in case of memory limits)

Parallelization: speedup

Results obtained using the DAS 3 cluster



Conclusions

- RT is a very complex process with several underlying aspects
- We studied and understood a considerable part of the theoretical background
- We implemented a MC simulation for dust RT
- We validated it for the plane parallel slab scenario, we did experiments and measurements on it
- We implemented a 3D grid for inhomogeneous media on which we also experimented
- We parallelized the simulation code using MPI