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Study of GRB Emission Process by Coupled Computation of Radiation Transfer with Relativistic Hydrodynamics

Ayako Ishii
D3, Aerospace Engineering, Tohoku University


http://www.astroarts.co.jp/news/2013/08/08grb/index-j.shtml

Naofumi Ohnishi (Tohoku Univ.)
Hiroki Nagakura (Caltech)
Hirotaka Ito (RIKEN)
Shoichi Yamada (Waseda Univ.)

Outline

- Introduction
  - Models for GRB prompt emission
  - Numerical reproduction of GRB spectra
  - Coupled computation of radiation with hydrodynamics
- Method
  - Monte Carlo radiative transfer
- Results
  - Spectra computed on modeling flowfield
  - Spectra computed with hydrodynamical flowfield
- Summary

Introduction

Gamma-ray burst (GRB)

- GRB is the most energetic explosion in the universe
  (E_{iso} = $10^{49\text{-}55}$ erg $\leftrightarrow M_{\odot}c^2$ ~ 2 ×10^{54} erg)

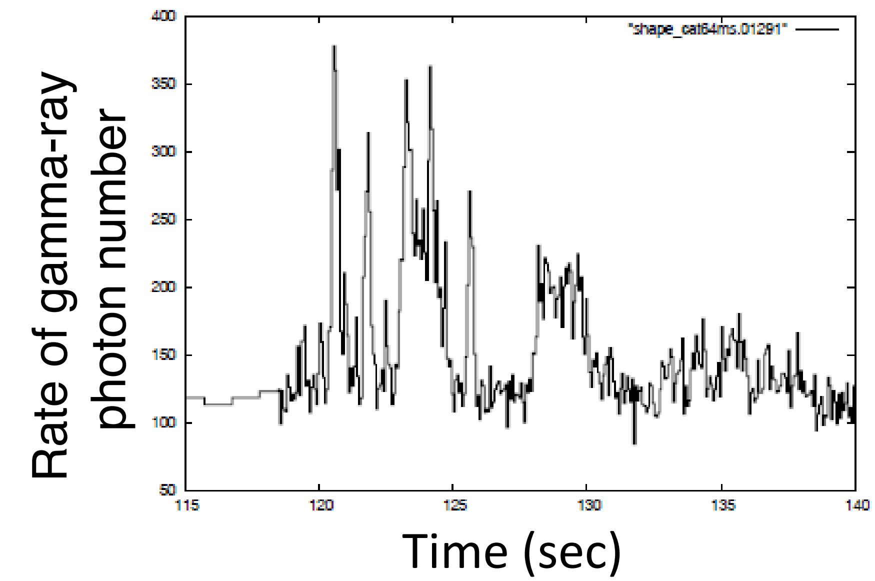
- A few GRBs are observed per day

- GRBs are classified depending on gamma-ray emission time

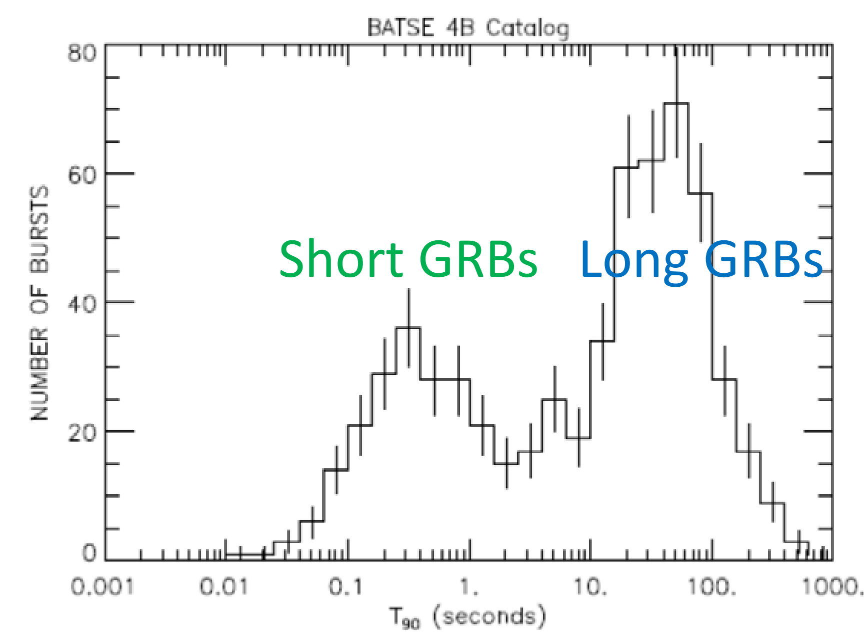
  ✓ Short GRB ($\lesssim$ 2 s)
    → Compact star binary merger

  ✓ Long GRB ($\gtrsim$ 2 s)
    → Collapsing massive star
    → A part of GRBs accompany with SNe

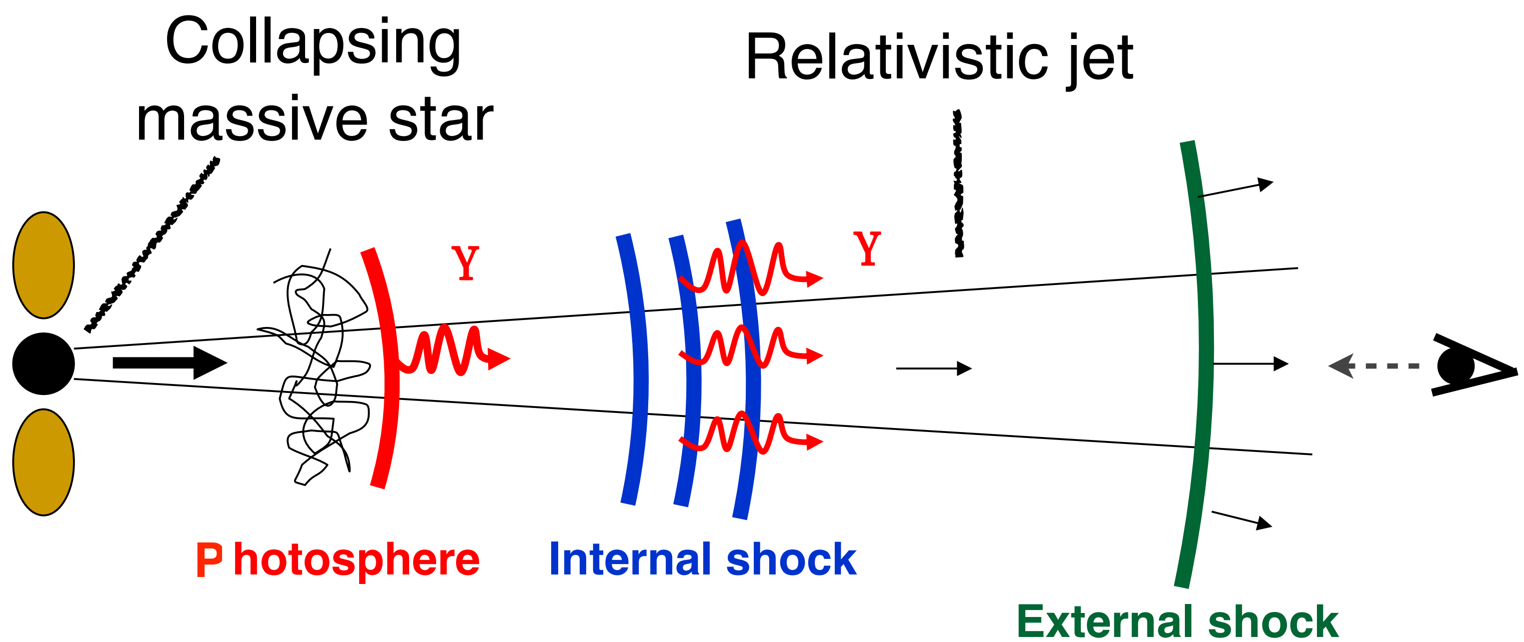
Light curve of a burst

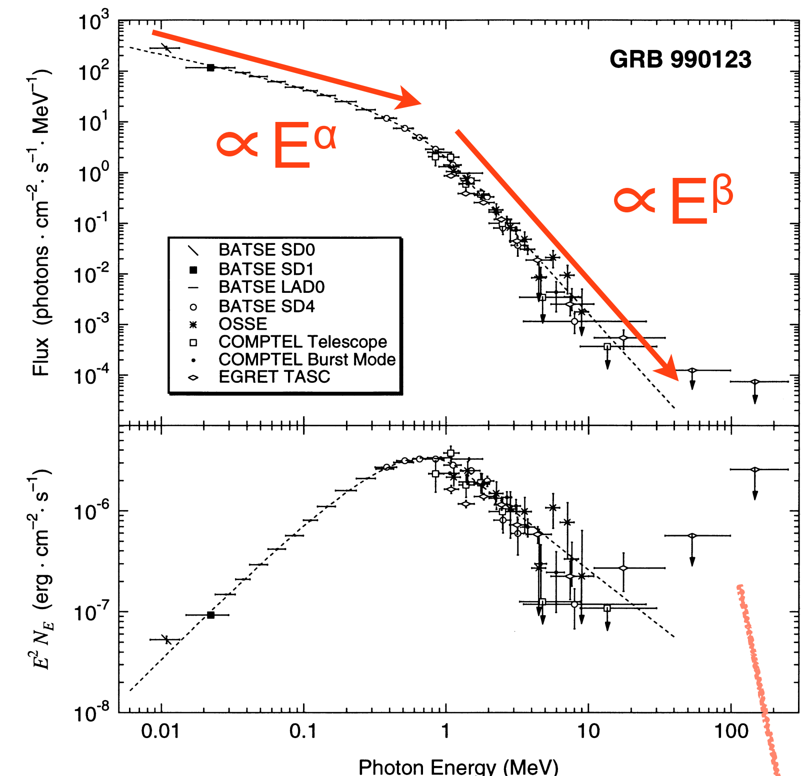


Distribution for duration of bursts



GRB emission mechanism





Briggs et al. 1999

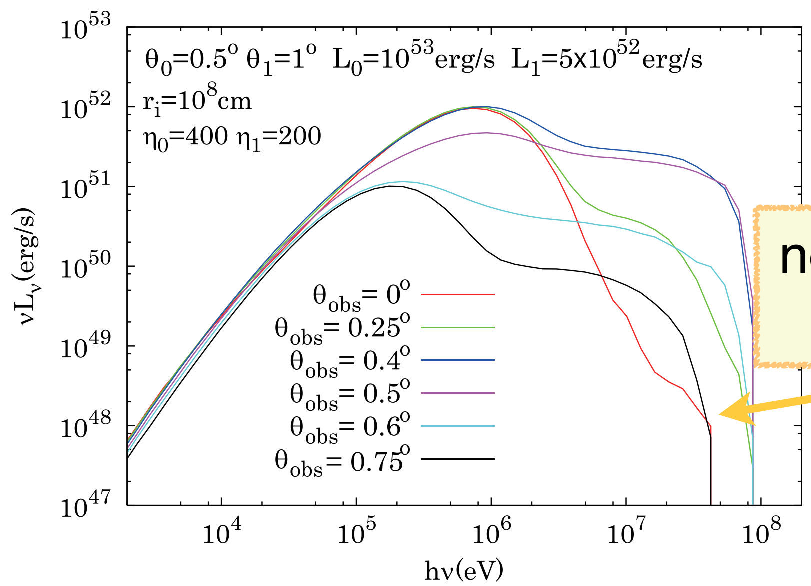
$\alpha \sim -1$
$\beta \sim -2.5$

Band et al. 1993

- GRBs originate from a relativistic jet formed around a collapsing massive star
- A specific broken power law is observed
- Detailed emission mechanism is unknown

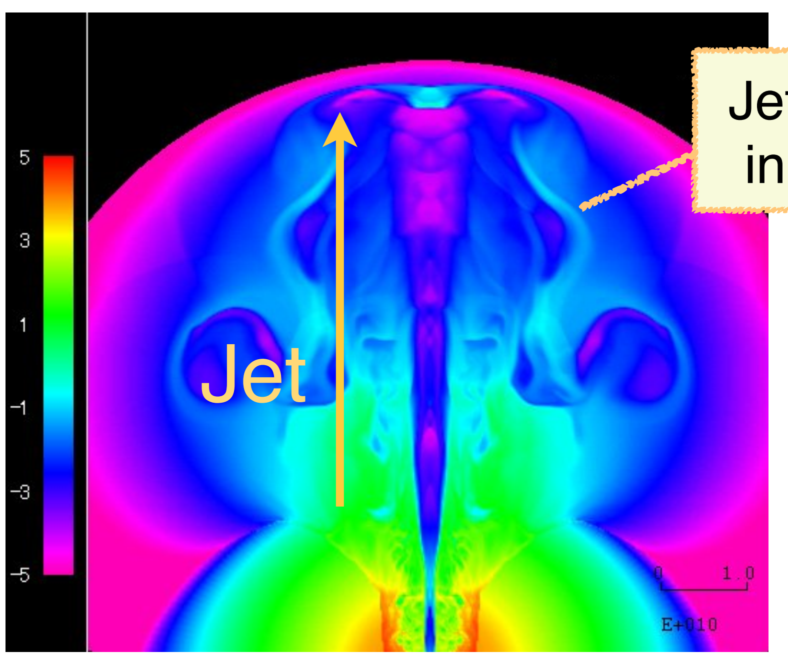
✓ Internal shock model → Radiation efficiency is low
✓ Photospheric model → Radiation efficiency is high

Numerical reproduction of GRB spectrum



Ito et al. 2013

non-thermal spectra were produced



Jet structure varies inhomogeneously

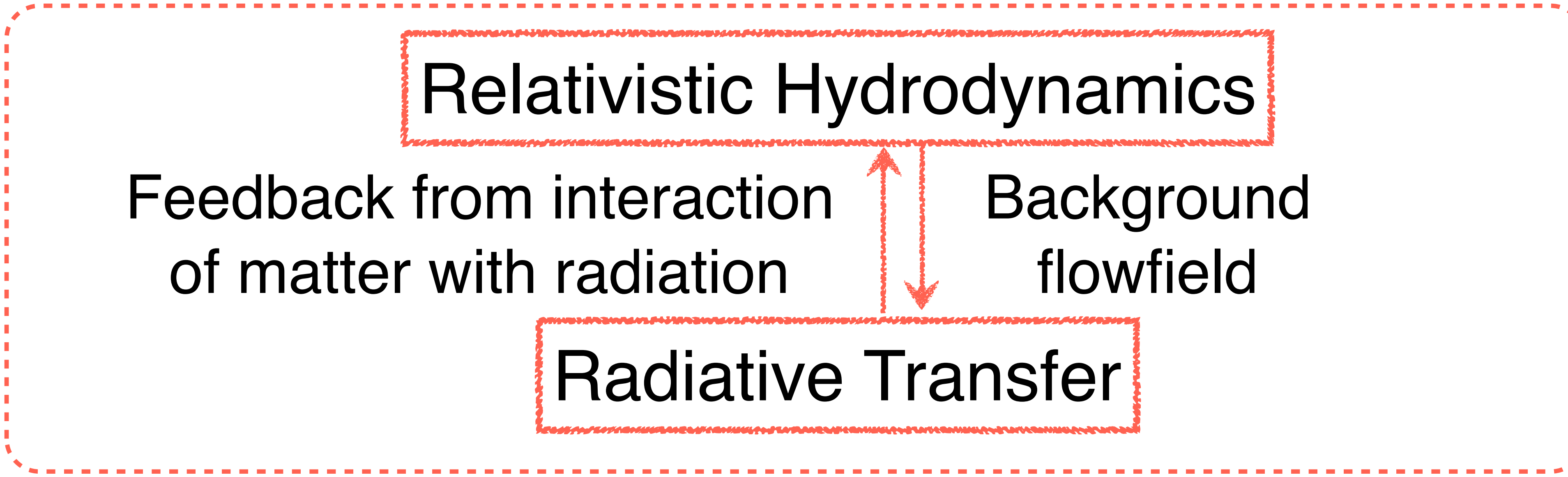
- Radiative transfer computations were implemented on steady modeling flowfield
  (Pe'er 2011, Ito 2014, Shibata 2014)

- Jet structure can affect on the observed spectrum
  (Aloy 2000, Mizuta 2006, Nagakura 2011)

Radiative transfer computation should be implemented on unsteady background

Coupled computation of radiative transfer with relativistic hydrodynamics

Coupled computation



Requirements for coupled computation in GRB

- Ultra-relativistic flow velocity (Lorentz factor $\Gamma \gtrsim 100$)
- Strongly anisotropic radiation
- Radiation mediated shock (A. Levinson 2008, R. Budnik 2010)

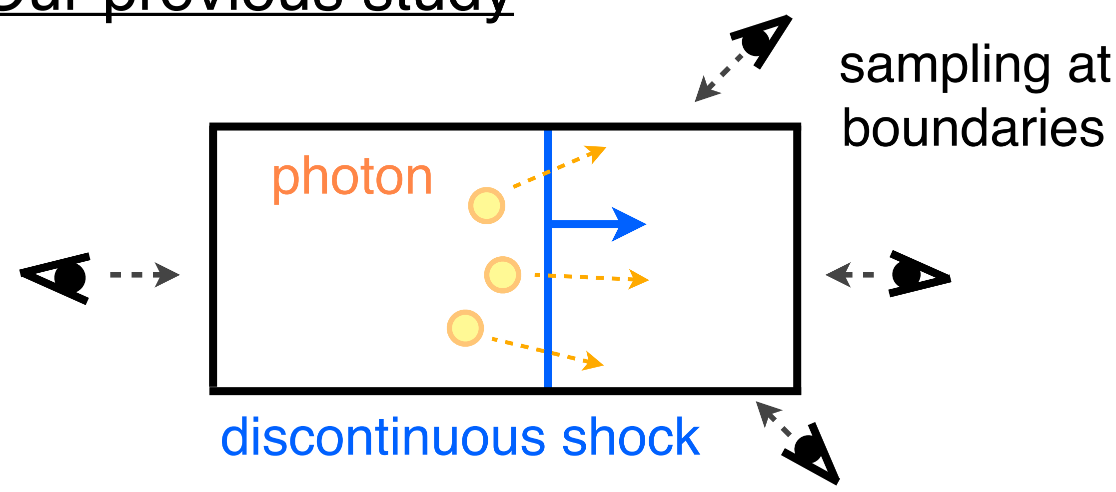
<u>Such coupled computation has not been performed yet</u>

Preliminary for coupled computation

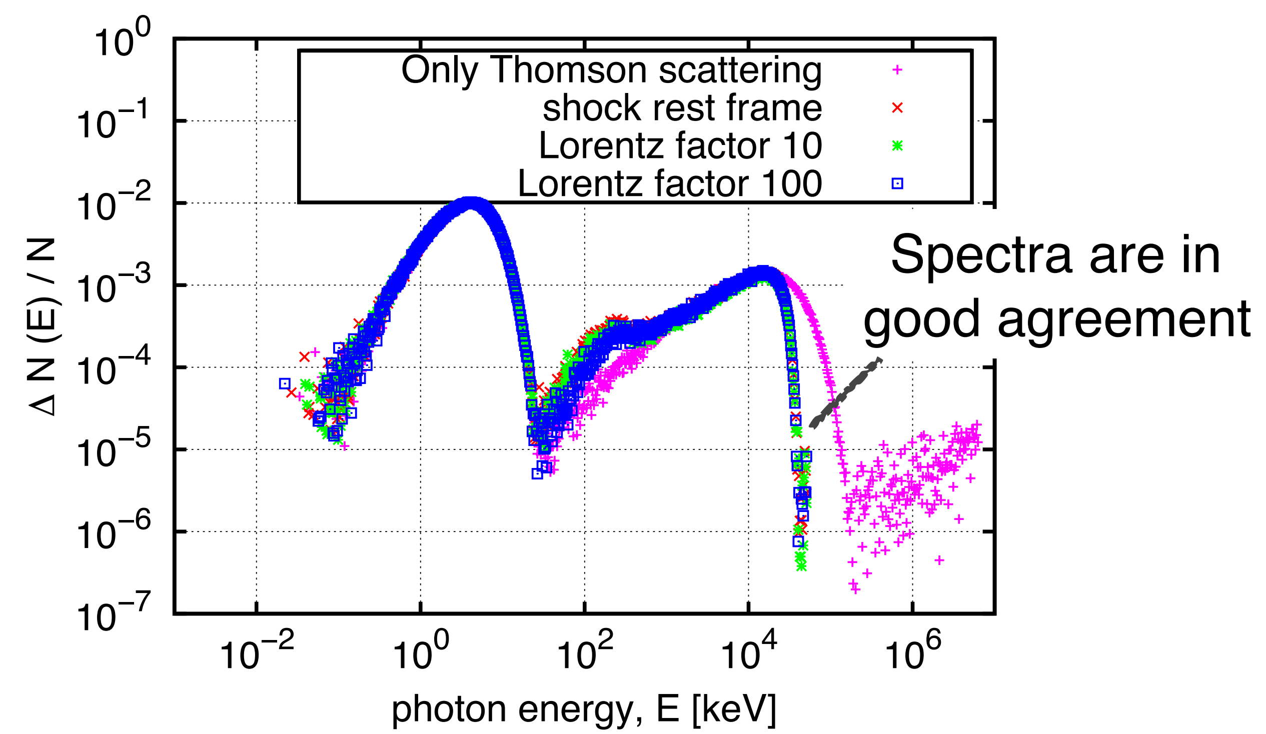
- Validation of photon transport with a discontinuous shock wave has been performed
- Shock wave front is smeared in a hydrodynamical simulation due to numerical diffusion

Radiative transport with a smeared shock wave should be implemented

Our previous study



Comparing among 3 different inertial frames



Objectives

Goal

Reproducing GRBs originated from relativistic jets by coupled computation

Preliminary for coupled computation

Examining the effect of shock structure of relativistic background flowfield on radiative transfer computation

- Performing photon transport in a modeling flowfield with a discontinuous and smeared shock wave
- Conducting photon transport in 1D hydrodynamical flowfield without interaction of radiation with fluid matter
- Estimating the effect of shock structure on the emission spectra

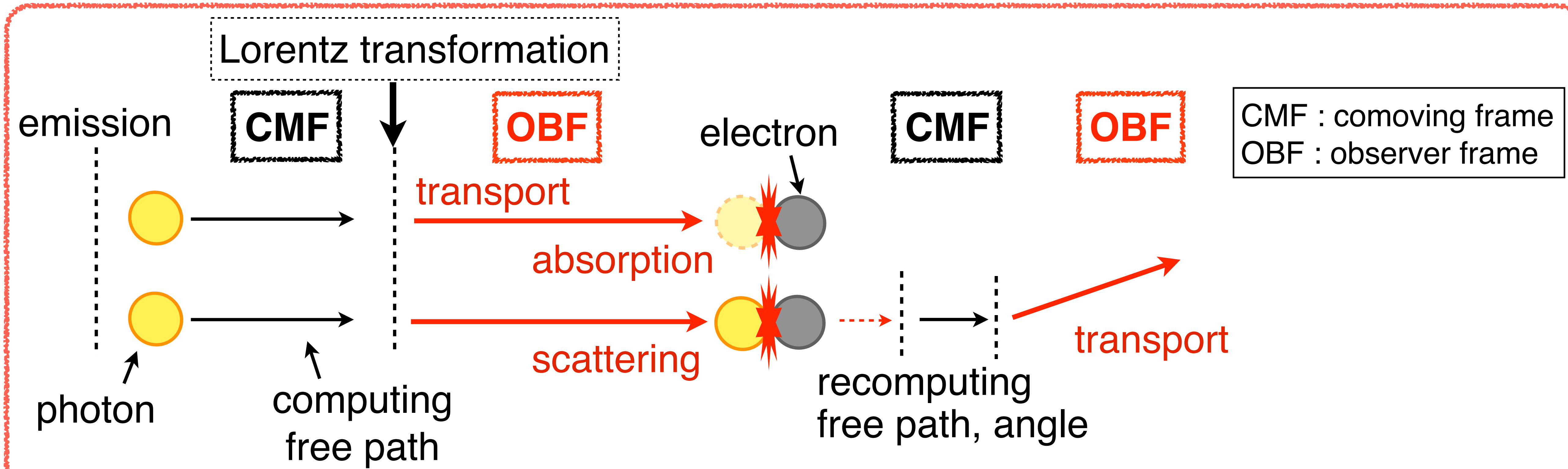
Method

Numerical method

Radiative transfer equation including scattering

$$\left(\frac{1}{c}\frac{\partial}{\partial t} + \boldsymbol{\Omega}\cdot\nabla\right) I = j + \frac{\rho}{4\pi}\int\int \sigma I \phi \, d\nu' d\boldsymbol{\Omega}' - [k+\sigma]\,\rho I$$

Computed in comoving frame

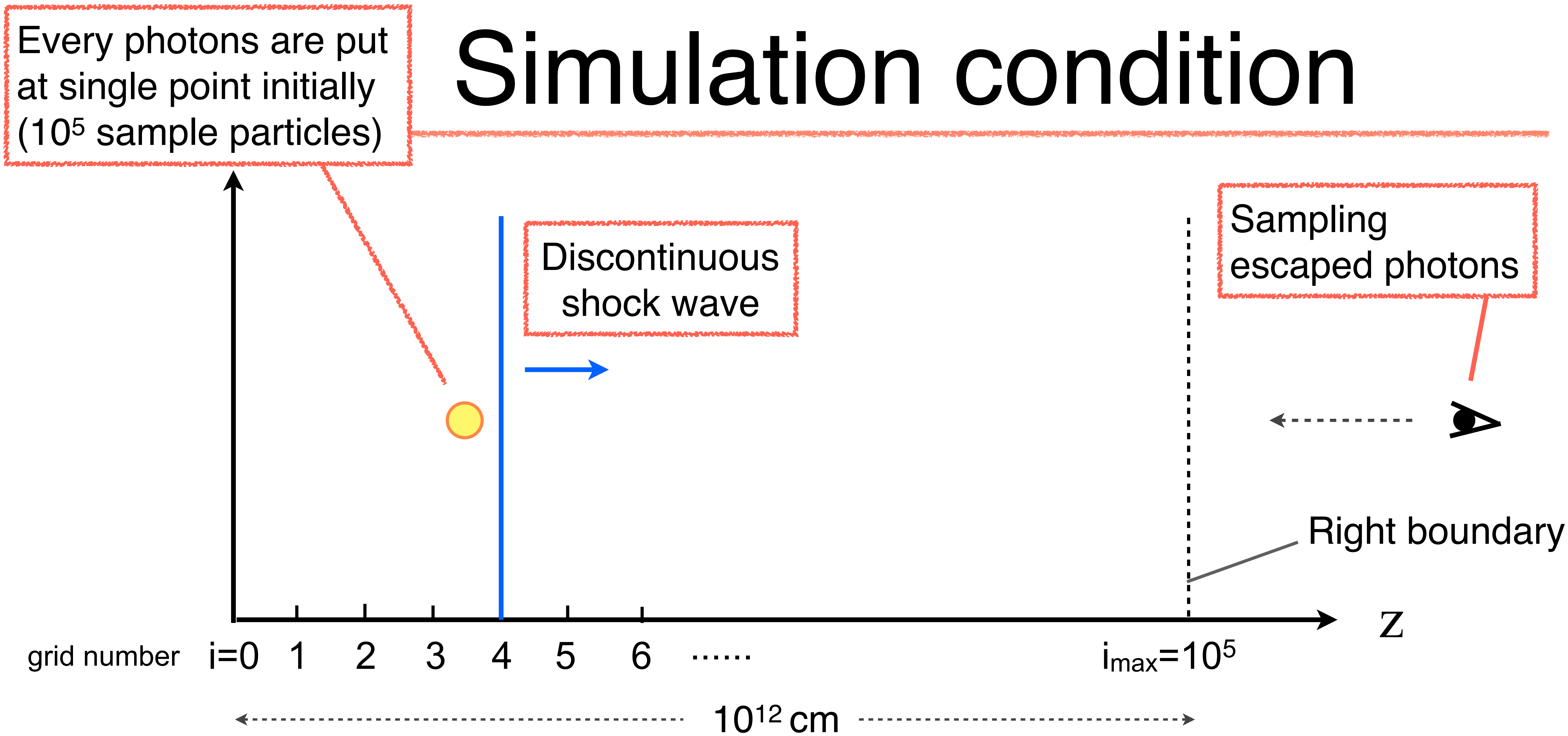


Monte Carlo method

No absorption

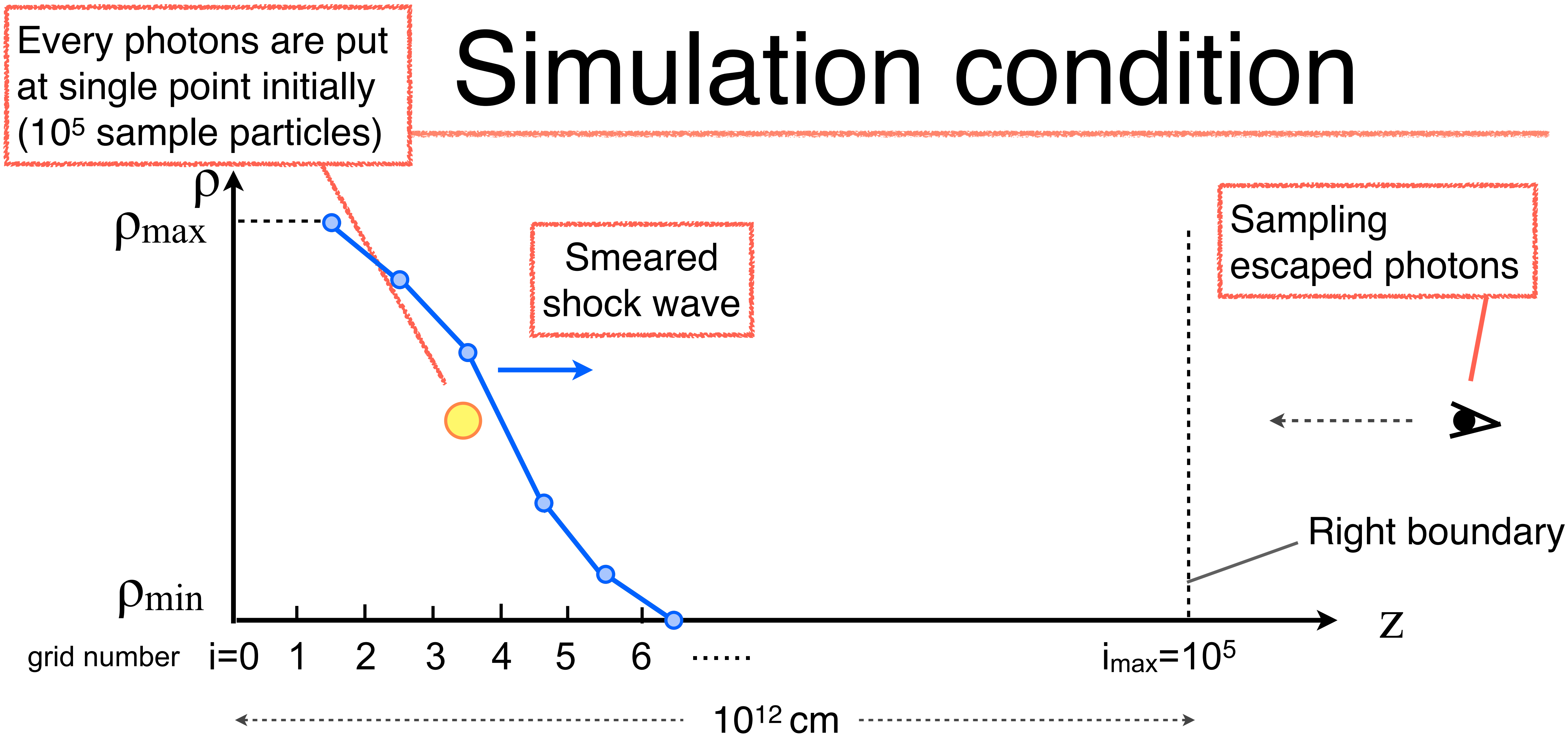
Including Thomson and Compton scatterings

Simulation condition



- Photons are tracked with a moving discontinuous and smeared shock wave, and sampled at right boundary
- Density distribution is artificially smeared in shock front (ρ_{max} and ρ_{min} satisfy Rankine-Hugoniot relations)
- Flow velocity is determined by the equation of continuity

Simulation condition



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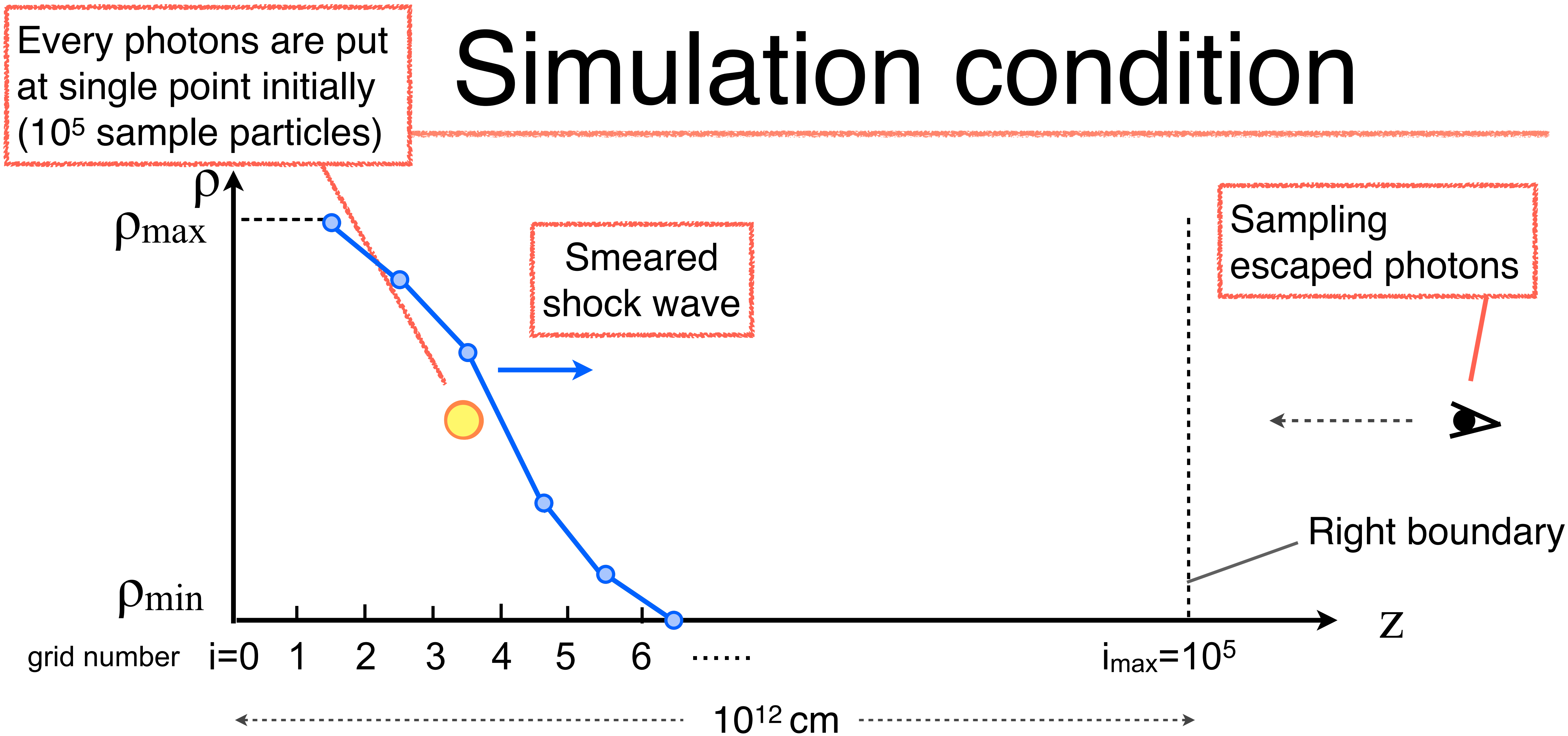

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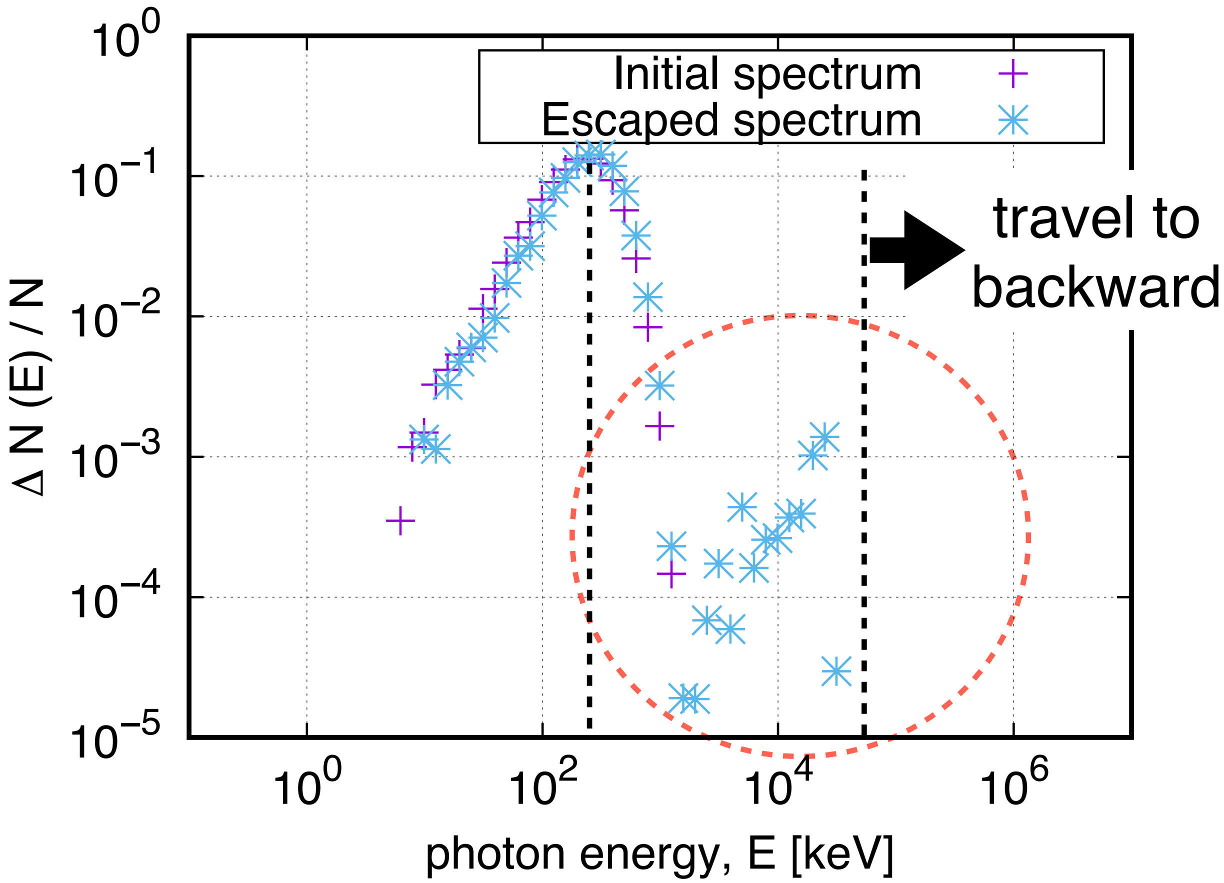
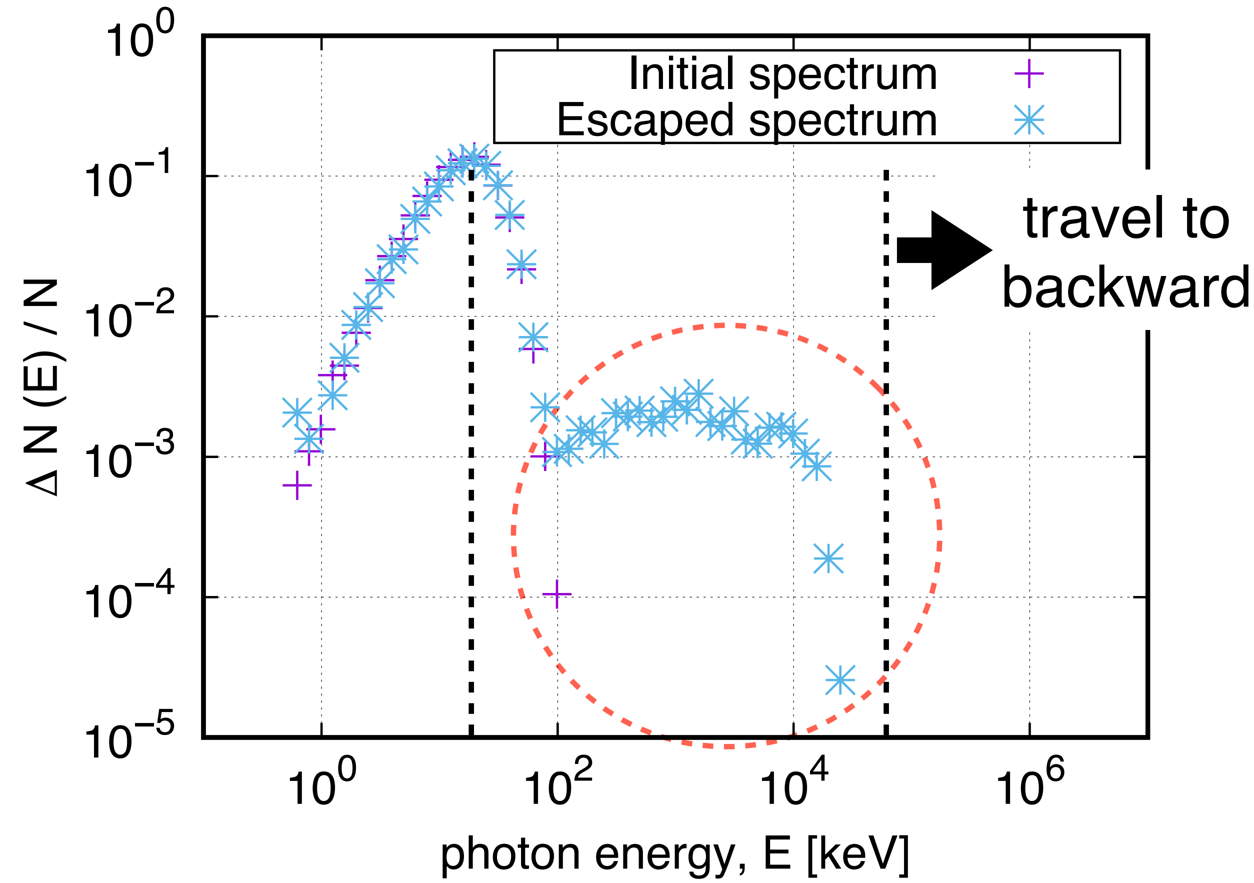
Spectra with modeling flowfield

Spectra with different shock width

With discontinuous shock wave

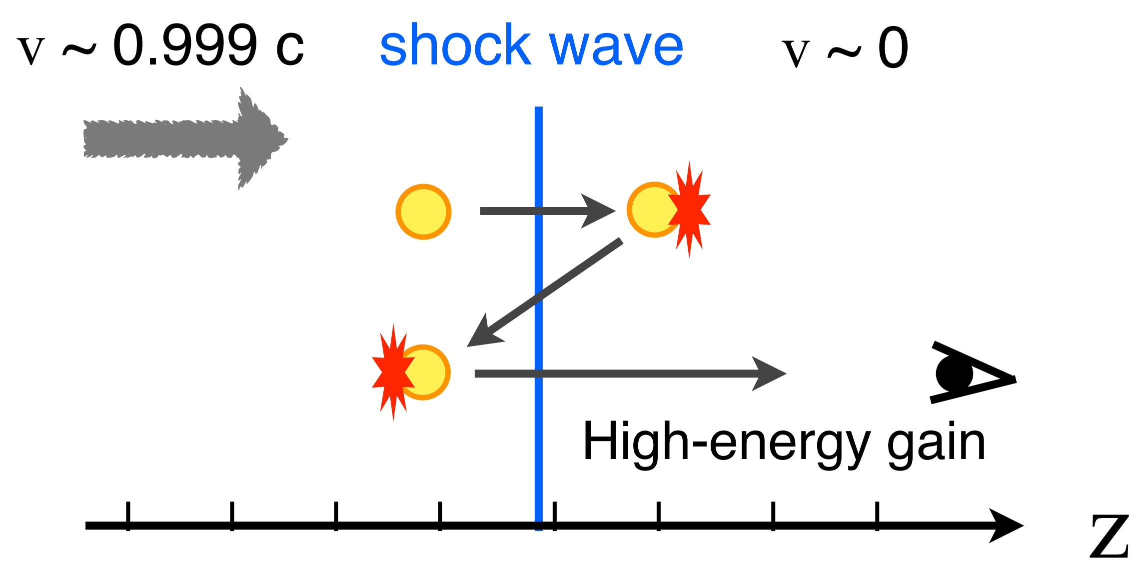


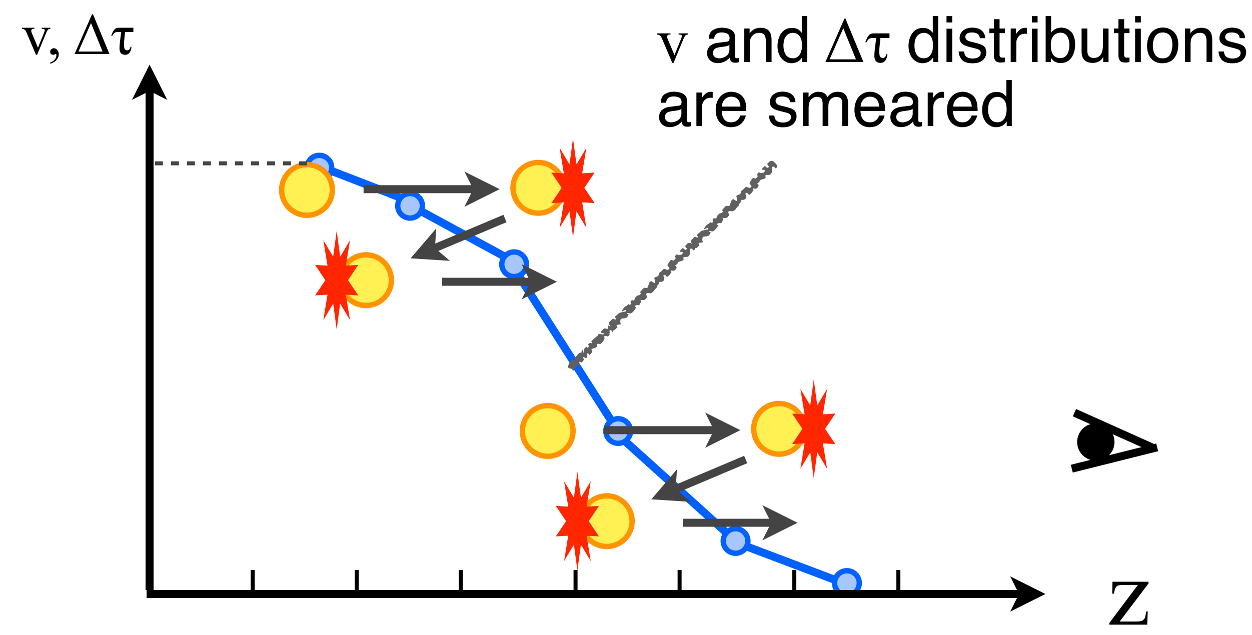
With 10-cell smeared shock wave



- Peak energy position is different depending on flow velocity of initial photon position
- High-energy photons (~10^5 KeV) are absent because they travel to backward direction
- Shape in high-energy side varies with shock width

Cause for shape difference of spectra





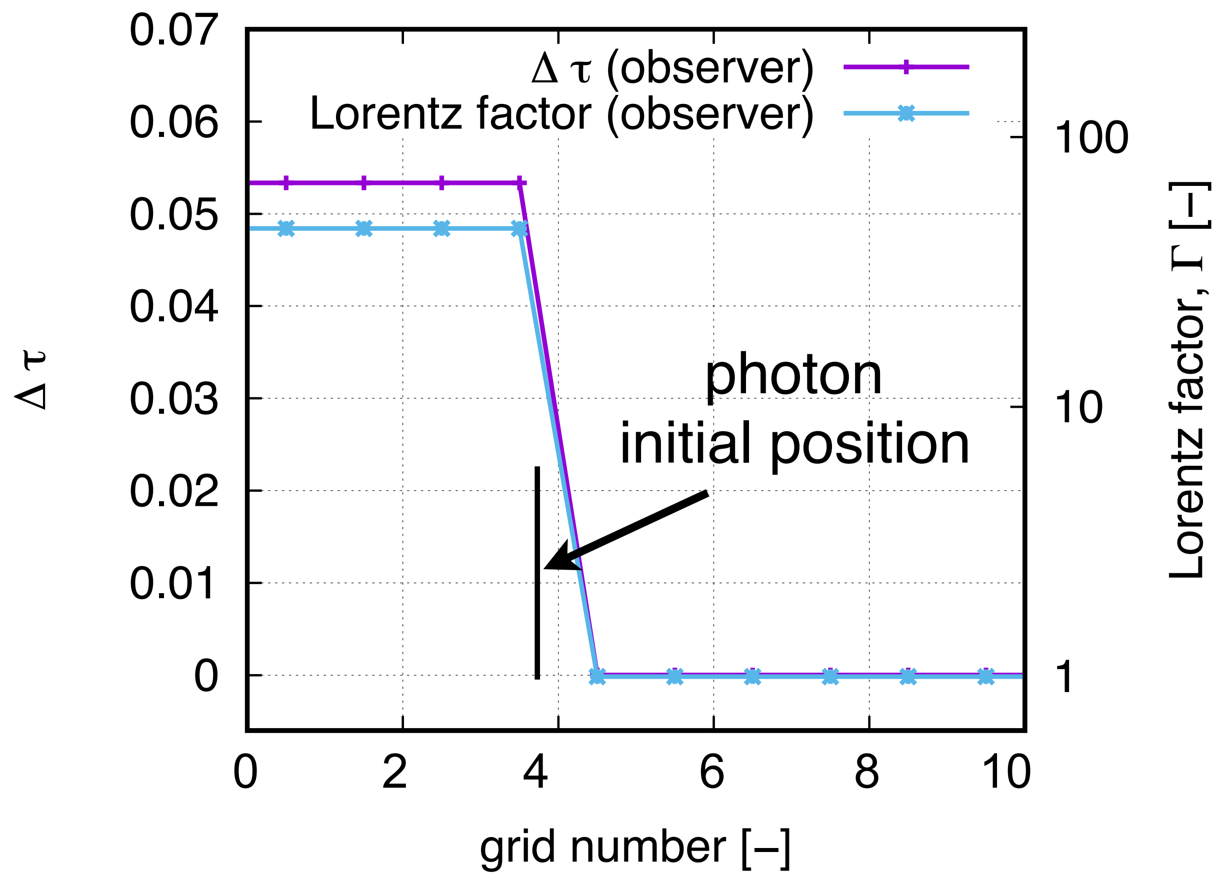
- High-energy photons are produced by bulk-Compton scattering
- Probability of scattering and energy gain vary due to a smeared shock wave

Probability of scattering	→ Optical depth per 1 cell, $\Delta\tau$
Energy gain by bulk-Compton	→ Flow velocity, v

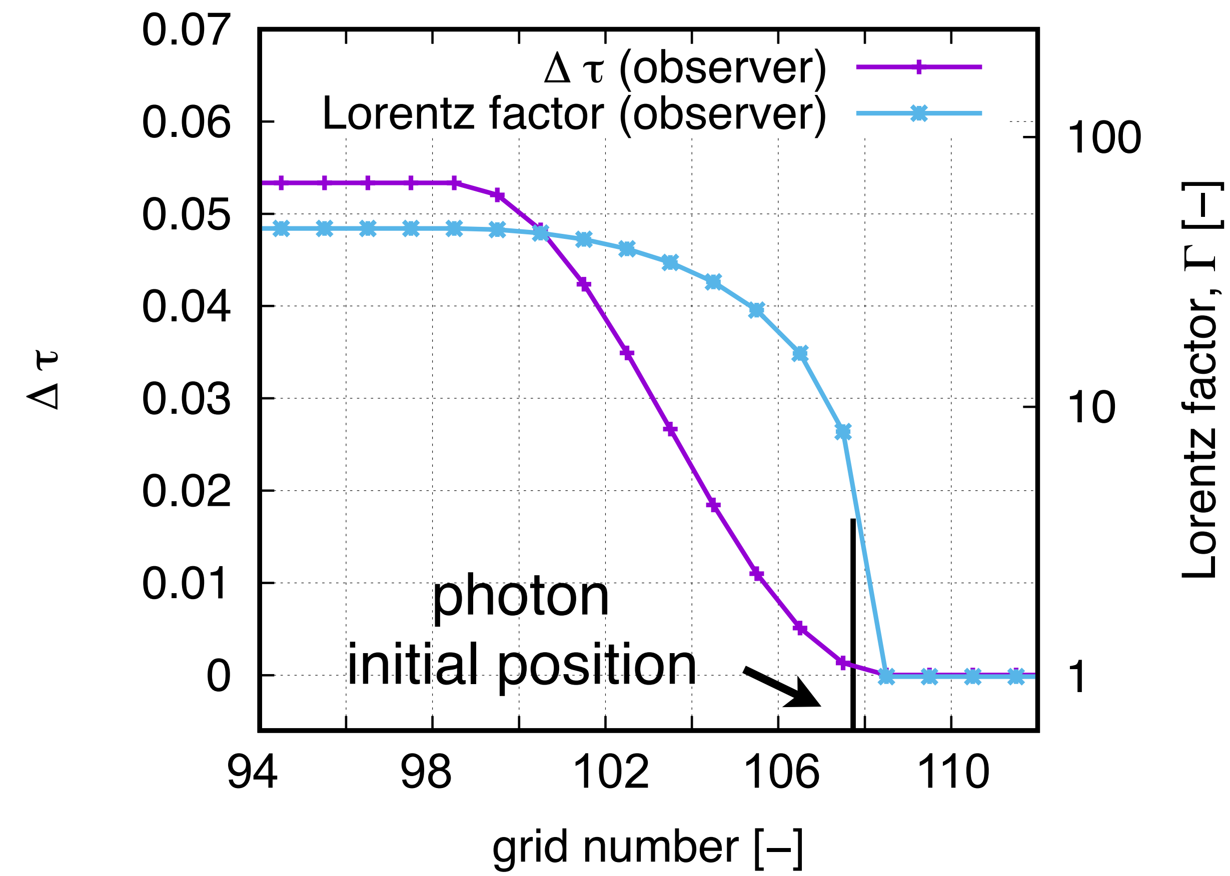
- The difference of the shape of spectra in high-energy side is interpreted by $\Delta\tau$ and v distributions around shock wave front

Δτ and v distributions around shock wave

With discontinuous shock wave

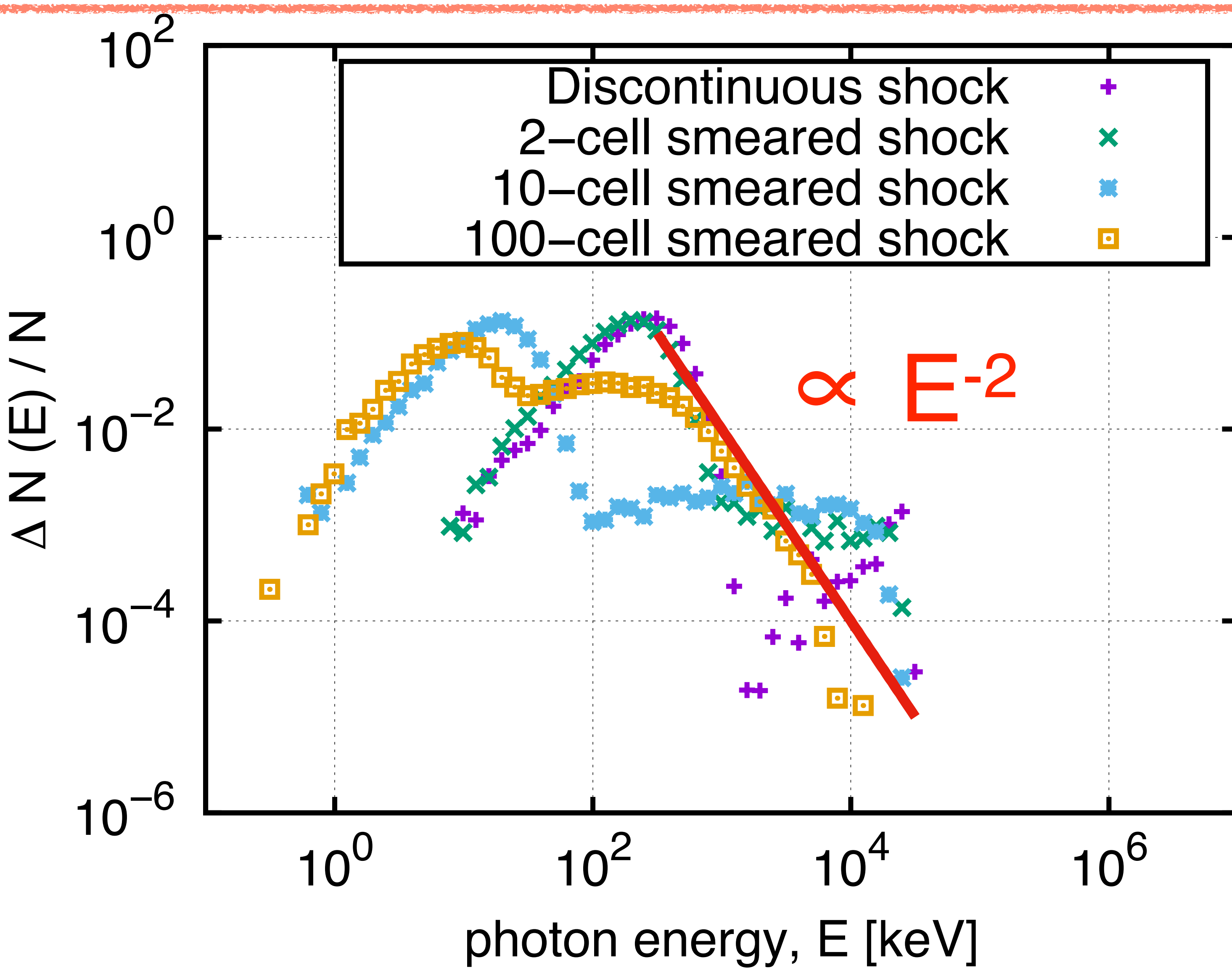


With smeared shock wave



- High-energy shape in spectra with smeared shock wave is formed by multiple small velocity jumps
- The shock structure can affect on the shape of spectra in one-dimensional shock wave

Comparing among various shock width



- Shape in high-energy side varies depending on shock width
- High-energy slope in 100-cell smeared shock → $\beta \sim -2$
- Appropriate β value may come from numerical diffusion

Summary

Effect of shock structure on radiative transfer computation has been examined

- Radiative transfer simulations were implemented on the flowfield with a discontinuous and smeared shock wave
- Shape in the high-energy side for the two cases were different due to the effect of bulk-Compton scattering
- Appropriate β value may come from numerical diffusion
- Similar feature appears in both of modeling and hydrodynamical computations
- The shock structure affects on the escaped spectra in one-dimensional computation

Future works

Goal

Reproducing observed GRB spectra by coupled computation of radiative transfer with relativistic hydrodynamics

- Introducing electron energy distribution
- Considering pair production and annihilation
- Selecting proper emission position
- Examining the effect of space resolution on emitted spectra
- Performing coupled computation with interaction between radiation and matter

Thank you for your attention !