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Radiative Transfer Analysis for Coupled Computation with Relativistic Hydrodynamics


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

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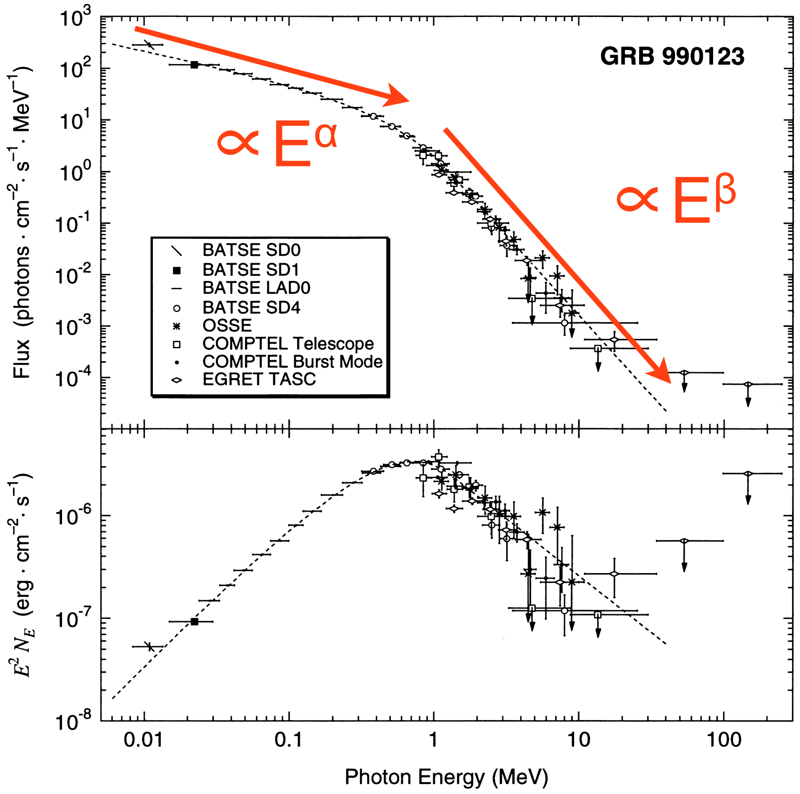
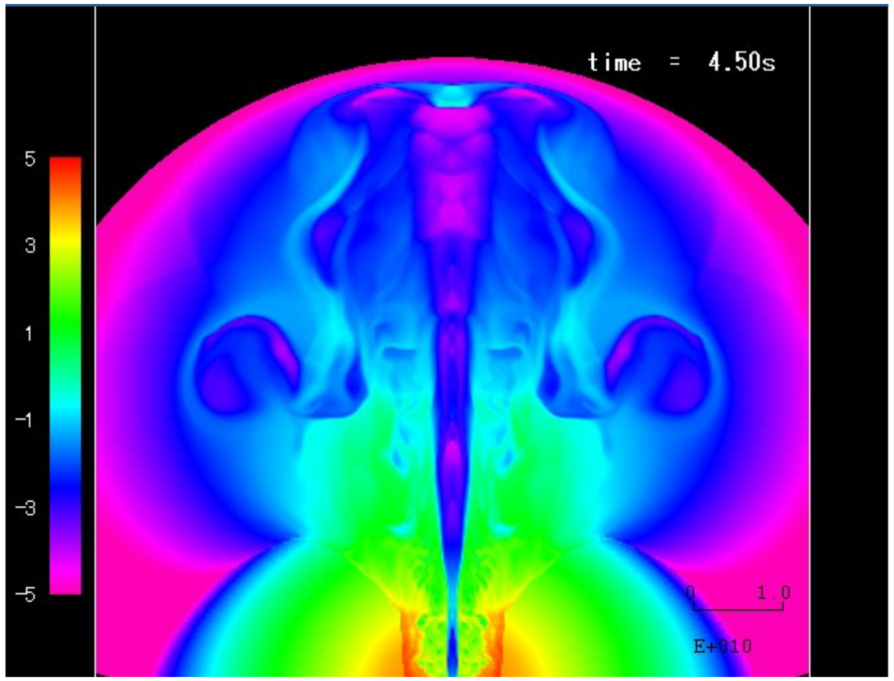
Numerical works of GRB



Briggs et al. 1999

reproduce observed spectra

- Some radiative transfer simulations on the steady background have been performed
- Jet structure can affect the observed spectrum (Mizuta 2006, Lazzati 2009, Nagakura 2011)
- Radiative transfer computation should be implemented on inhomogeneous background



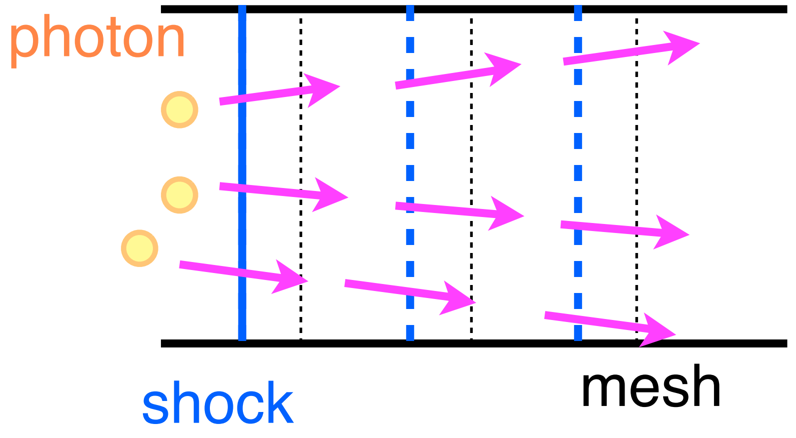
Radiative transfer computation on the unsteady fluid background is necessary

Coupled computation of radiative transfer with relativistic hydrodynamics

Preparation for coupled computation

Past study

- Relativistic hydrodynamics simulation of jets
  (Aloy 2000, Zhang 2003, Mizuta 2006, Morsony 2007, Nagakura 2011, Matsumoto 2013)
- Radiative transfer computation (Monte Carlo, photospheric emission) in a simple model
  (Pe’er 2011, Ito 2013, Ito 2014, Shibata 2014)



Flow velocity of jet → almost speed of light
(Lorentz factor $\Gamma \gtrsim 100$)

- Coupled computation with time-dependent ultrarelativistic flow has not been performed yet (Radiation hydrodynamics)
- Radiative transfer method on the ultrarelativistic background should be validated for a reliable computation

Objectives

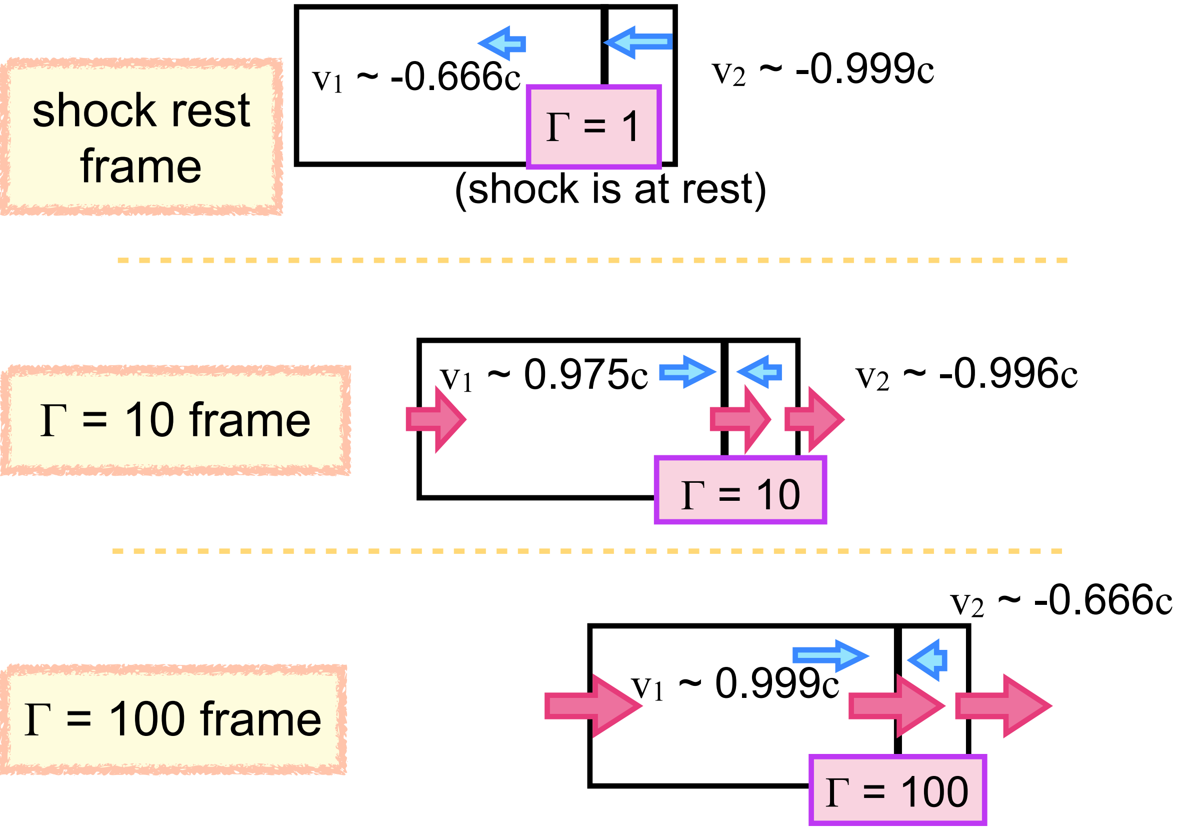
Goal

GRBs originated with relativistic jets by coupled computation

Preparation of coupled computation

Are simulation results in different inertial frames equivalent each other in computing radiative transfer on the ultrarelativistic background?

- Implementing radiative transfer simulation in the shock rest frame and the shock moving frame
- Comparing results in the same frame
- Performing photon transport with the shock moving on the computational grids



shock rest frame

$v_1 \sim -0.666c$

$v_2 \sim -0.999c$

$\Gamma = 1$

(shock is at rest)

$\Gamma = 10$ frame

$v_1 \sim 0.975c$

$v_2 \sim -0.996c$

$\Gamma = 10$

$\Gamma = 100$ frame

$v_1 \sim 0.999c$

$v_2 \sim -0.666c$

$\Gamma = 100$

Numerical method

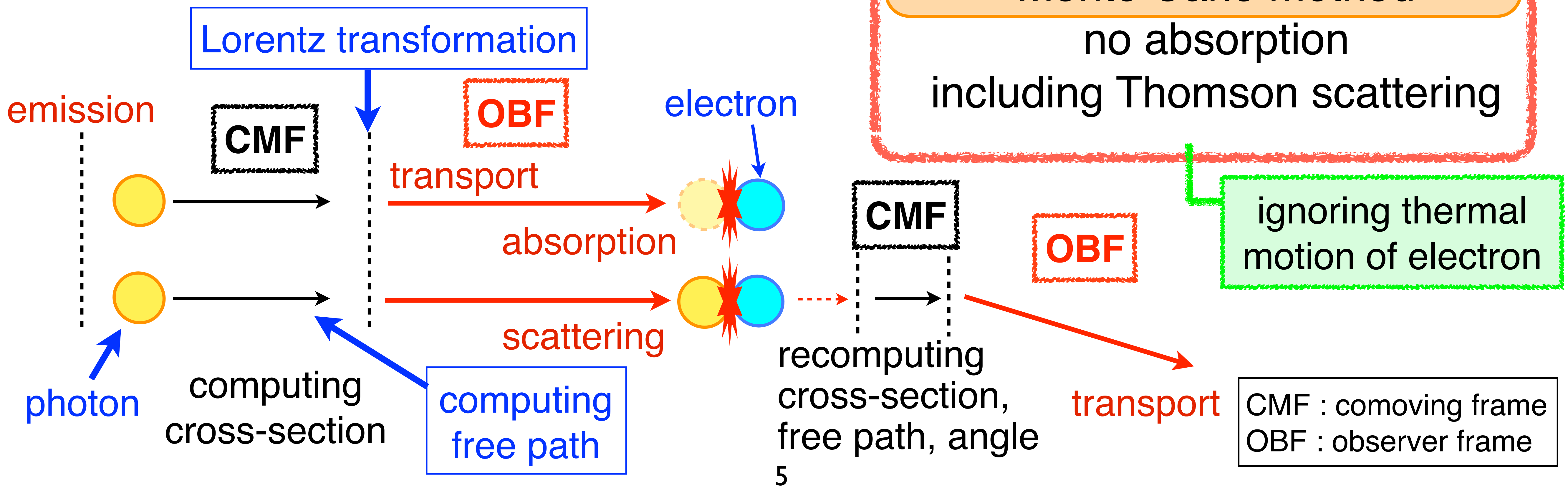
radiative transfer equation including scatterings

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

c : speed of light
t : time
$\boldsymbol{\Omega}'$: incident direction
$\boldsymbol{\Omega}$: scattered direction
I : specific intensity
j : emissivity
ν' : incident frequency
ν : scattered frequency
σ : scattering cross-section
ϕ : scattering kernel
k : absorption cross-section

computed in comoving frame

Monte Carlo method
no absorption
including Thomson scattering



ignoring thermal motion of electron

Lorentz transformation

emission

CMF

OBF

electron

transport

absorption

scattering

CMF

OBF

photon

computing cross-section

computing free path

recomputing cross-section, free path, angle

transport

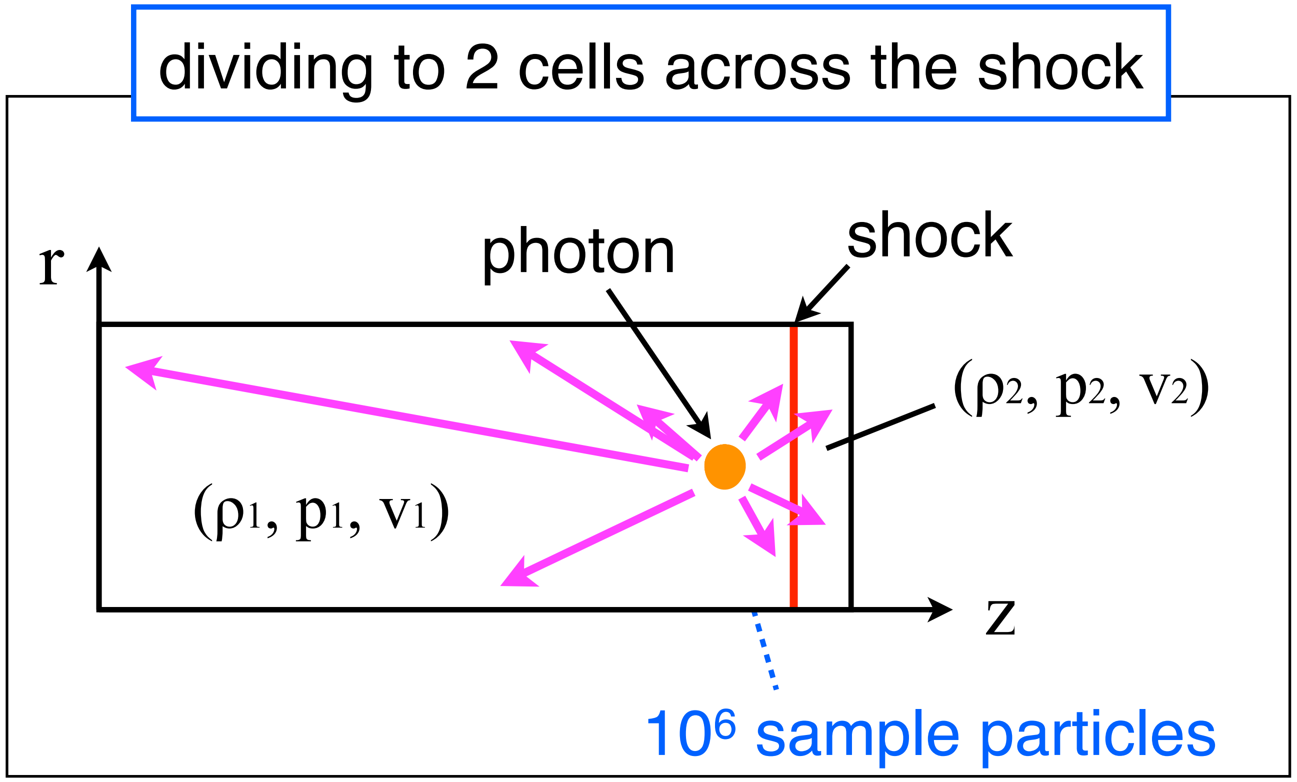
CMF : comoving frame
OBF : observer frame

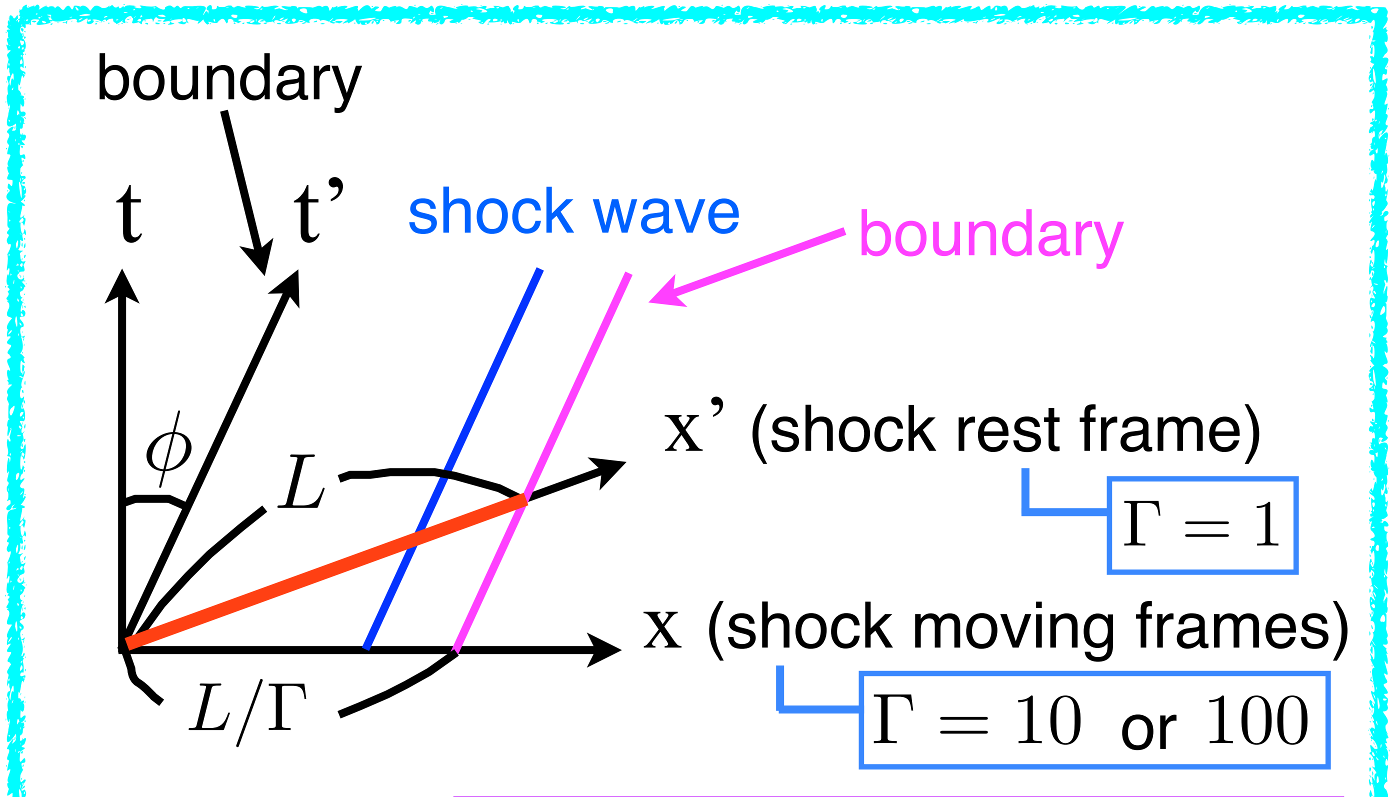
Computing in the different inertial frames

Simulation condition

- Setting of shock wave
  →relativistic Rankine-Hugoniot relations
- In the comoving frame, putting every photons at the single point initially
  (isotropic emission)
- Computing until all photons reach the boundary
- Simulating in shock rest frame and shock moving frames
  (Γ = 1, 10, 100)

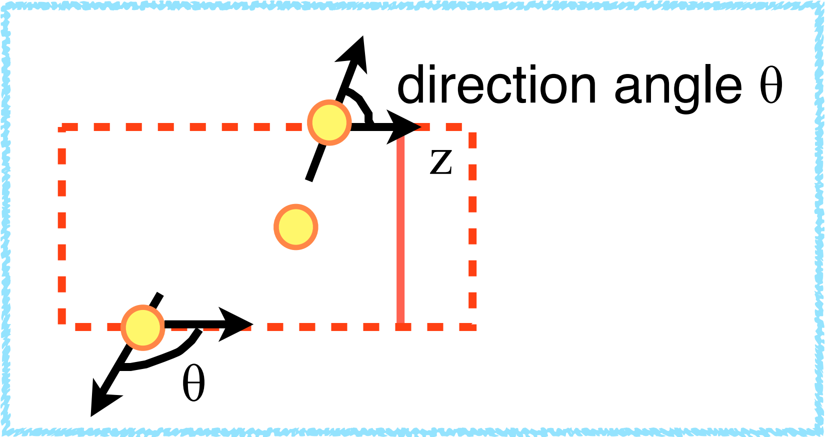
dividing to 2 cells across the shock





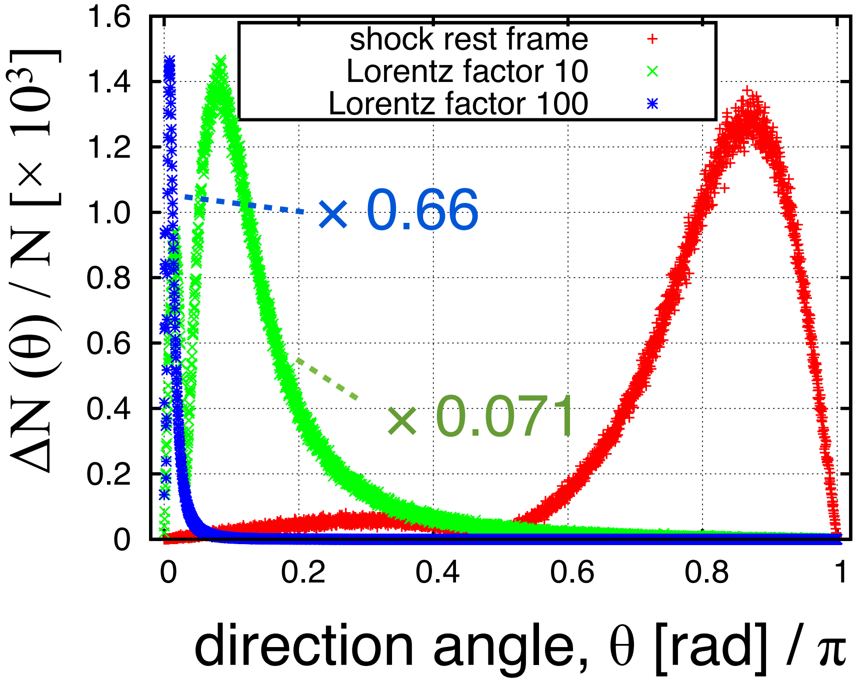
$\tan\phi = v$ (shock speed)

Directional distribution of the escaped photons

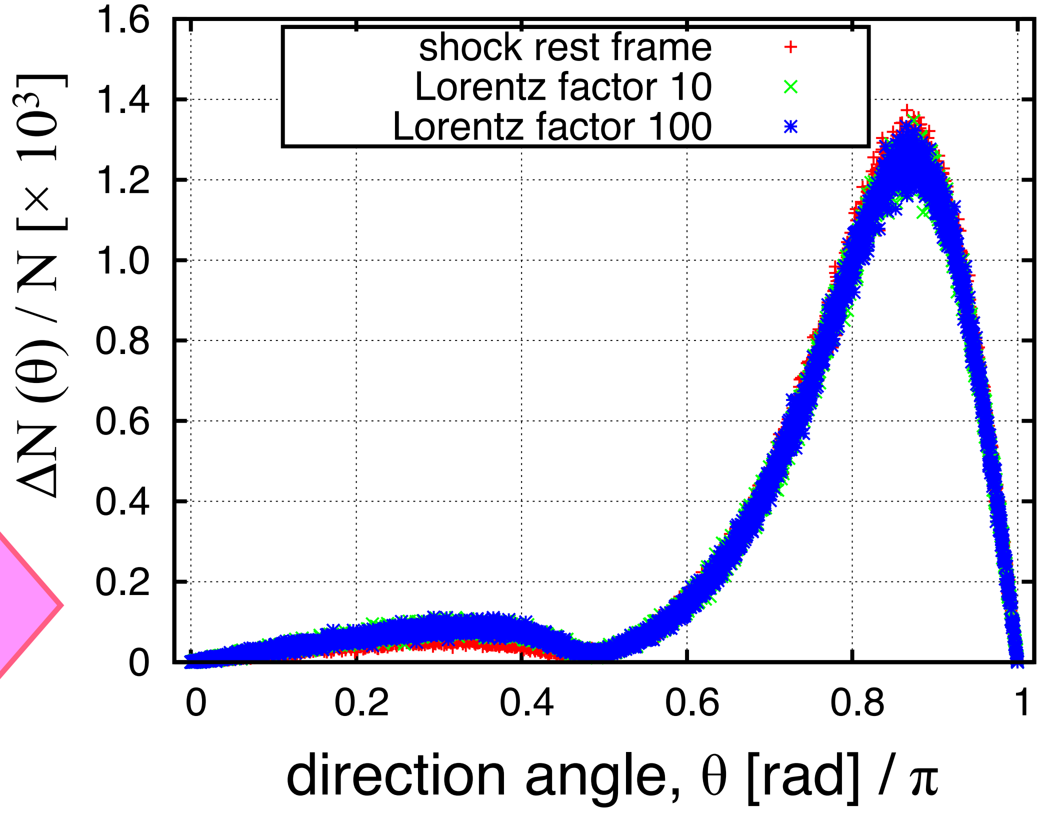


forward

←



after transforming to the shock rest frame



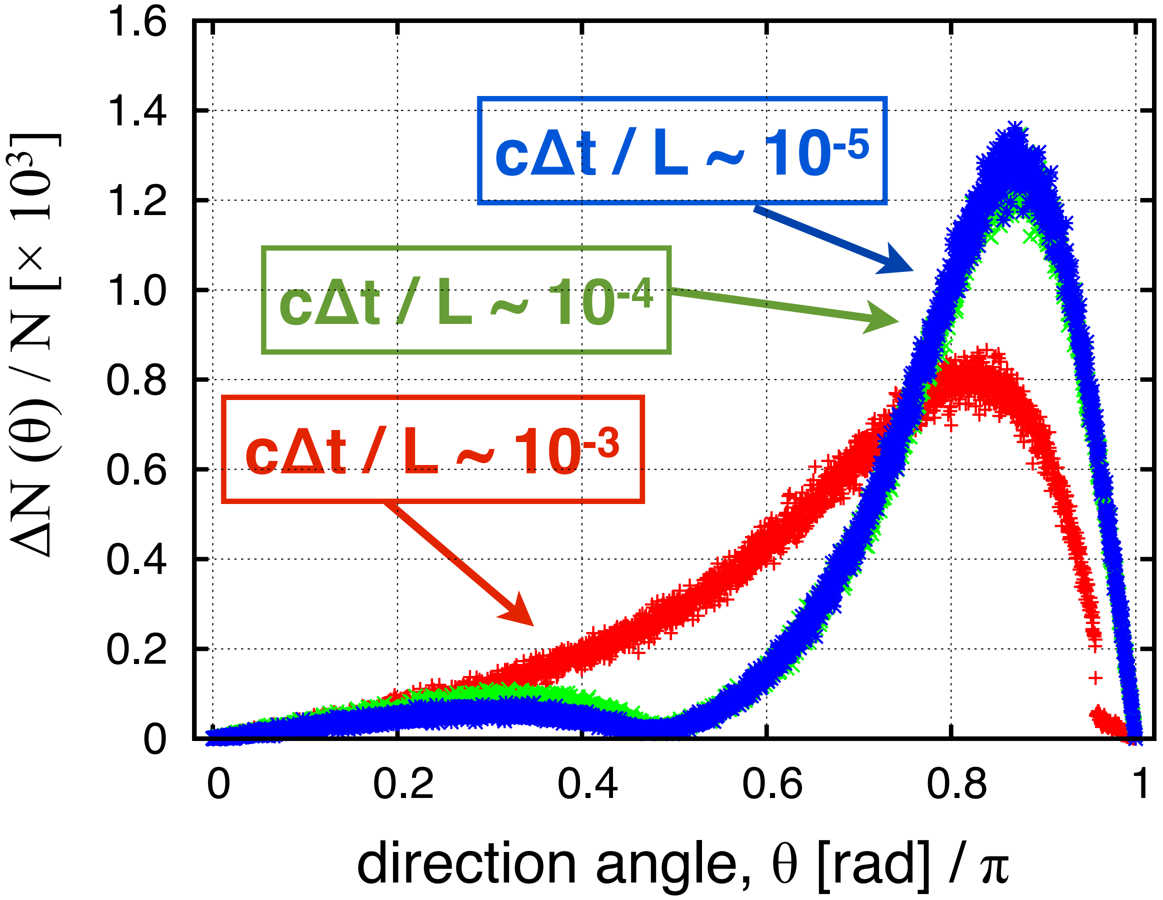
backward

→

- In the shock rest frame, photons are deflected backward because of flow velocity to the negative z-direction
- In the shock moving frames, photons are deflected forward in contrast
- After transformation, the profiles are identical in all frames

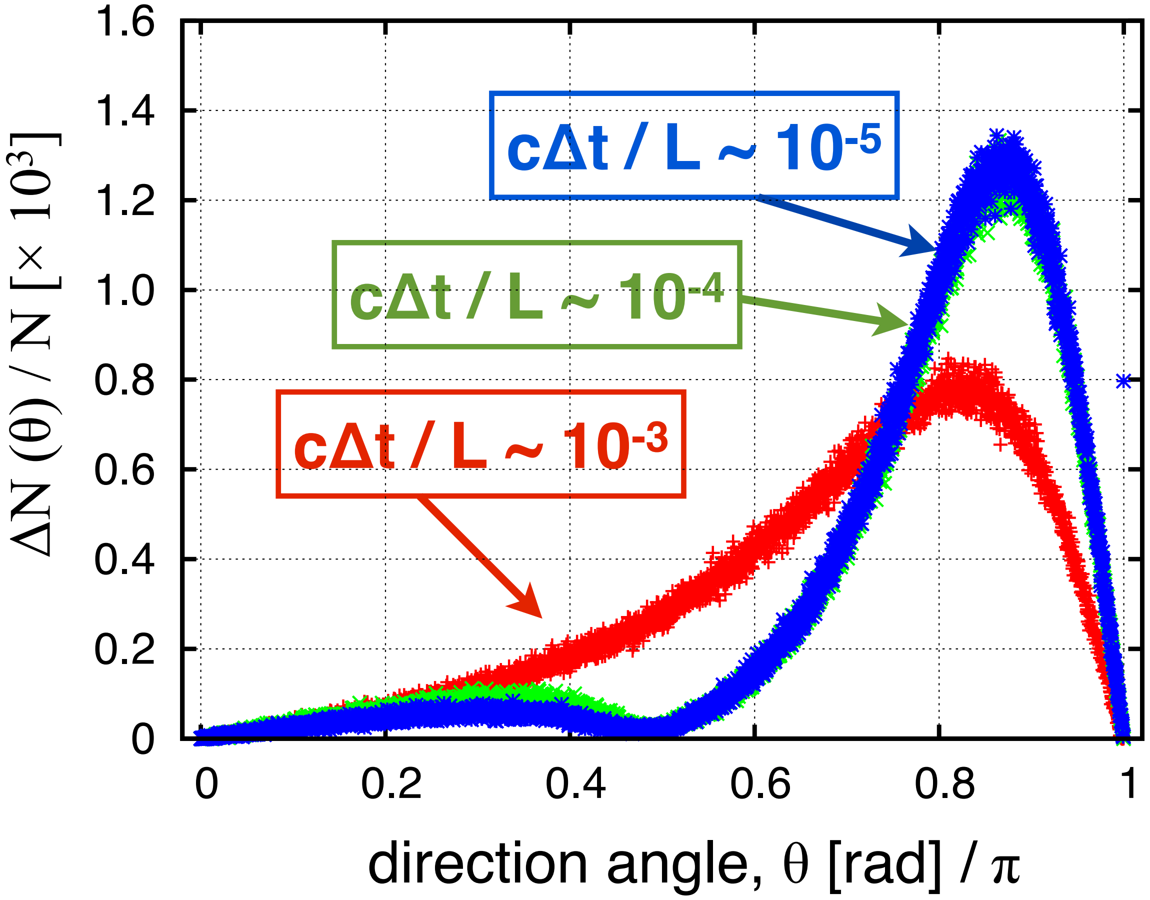
Difference due to time duration

Γ =10

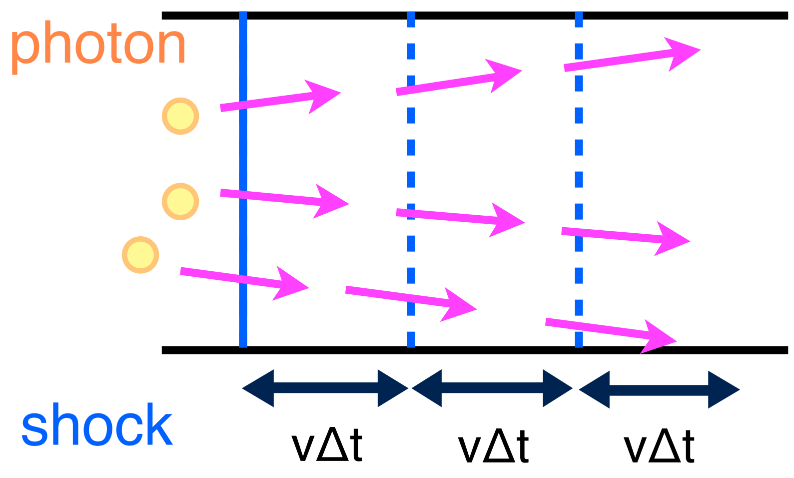


Γ =100

L : width of computational cell



- Computation with limited Δt should be performed for convergent result
- Shock speed (= boundary speed) is almost speed of light



Constraint for time duration

Relation of mean free path with Δt

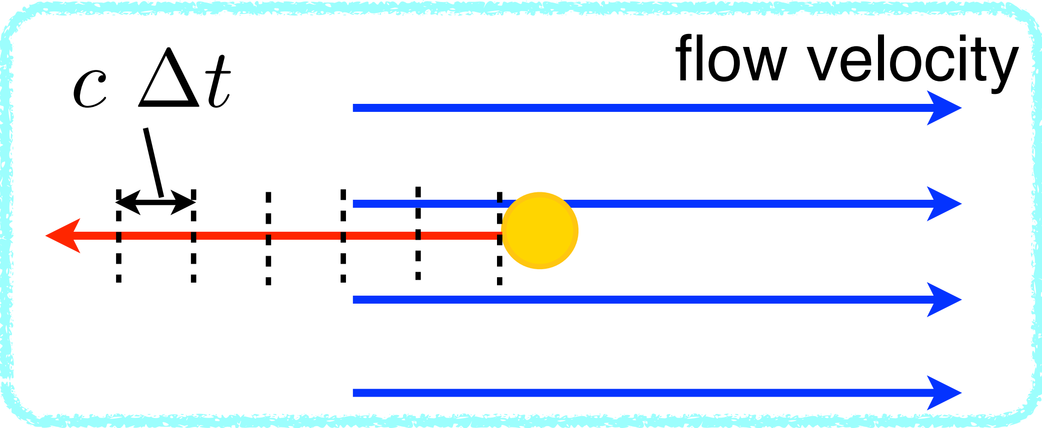
$$\alpha = \frac{c\Delta t}{s_{min}}$$

s_{min} : mean free path of photon traveling opposite to flow velocity

c : speed of light Δt : time duration

Γ =10 $$\frac{c\Delta t}{s_{min}} \sim 0.1931$$

Γ =100 $$\frac{c\Delta t}{s_{min}} \sim 0.1935$$



transformation of free path

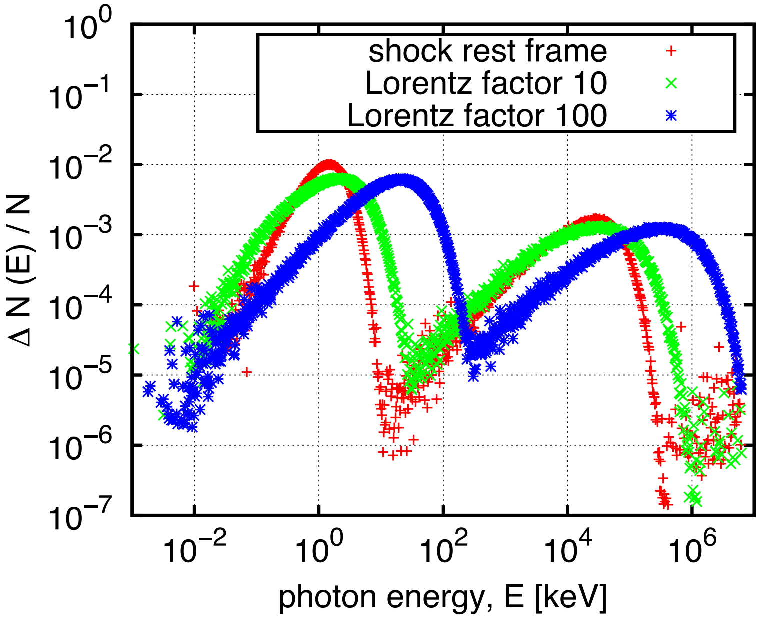
$$s_{min} = \frac{\sqrt{1-(v/c)^2}}{1+v/c} s_{cmf}$$

comoving frame

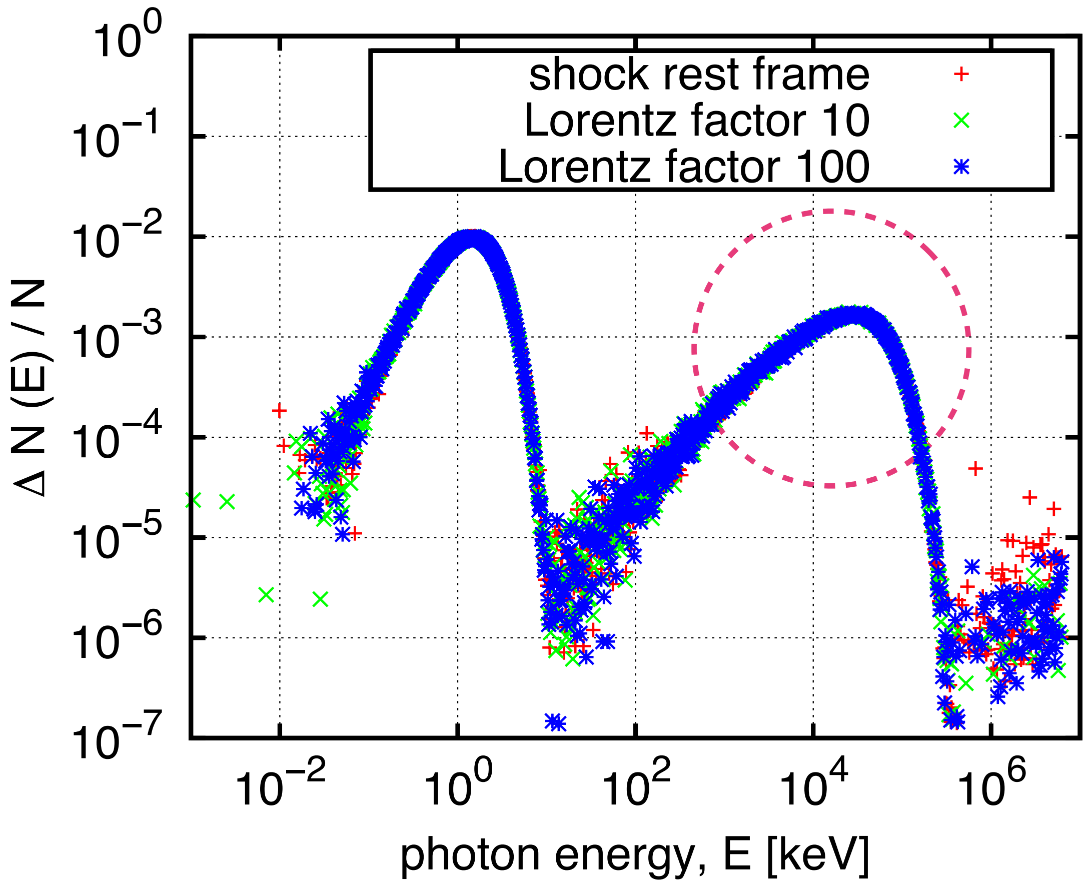
- α is almost 0.2
- We should adopt Δt that resolves the mean free path to five steps

Energy spectra of the escaped photons

in each frame



after transforming to the shock rest frame



- In each frame, the peak energy is shifted due to difference of flow velocity
- After transforming to the same frame, the profiles are identical each other
- Double peaks are found → bulk-Compton scattering

Summary

Radiative transfer computation in ultrarelativistic fluid background has been validated

- Simulation results in the differential frames were identical in the same frame
- Double peaks of energy spectrum were found due to bulk-Compton scattering
- In the Eulerian fluid background, no photon can catch up the shock front of $\Gamma \sim 220$
- Validation in more realistic situation should be performed

Future works

Goal

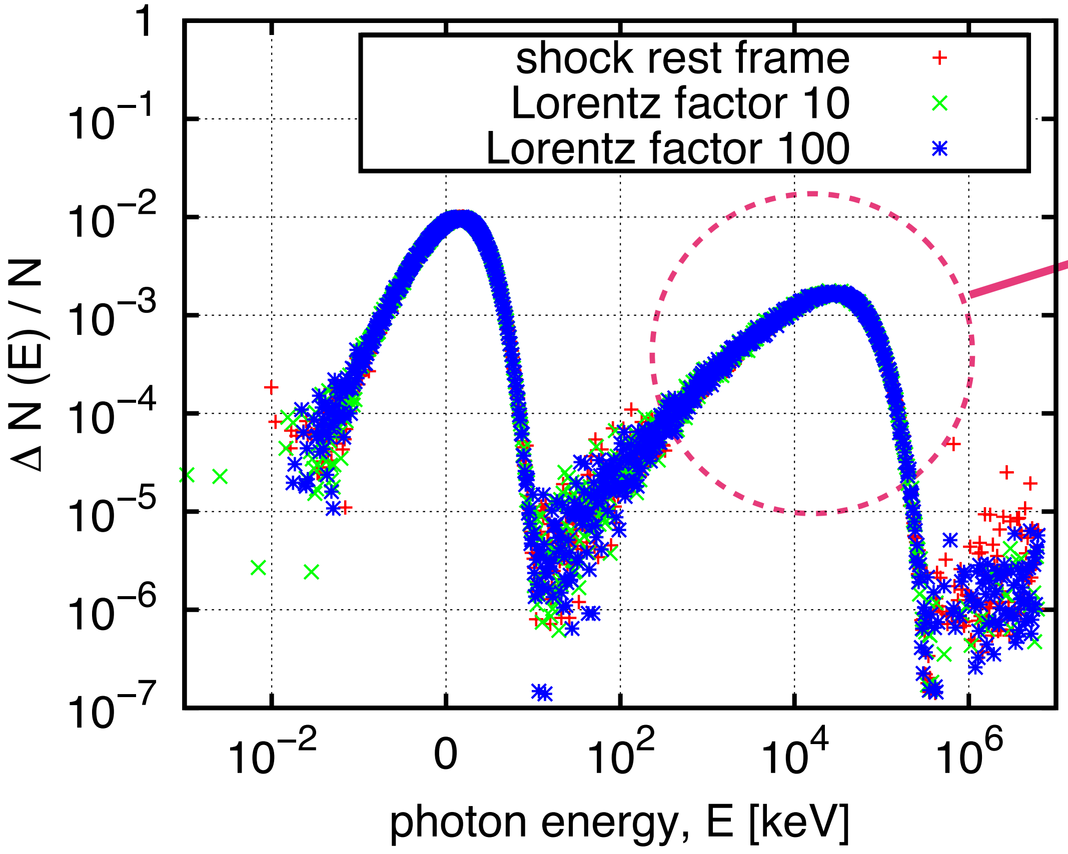
Reproducing observed high energy photons by coupled computation of radiative transfer with relativistic hydrodynamics

- Introducing electron energy distribution
- Selecting proper emission position
- Performing coupled computation with one-dimensional relativistic hydrodynamics

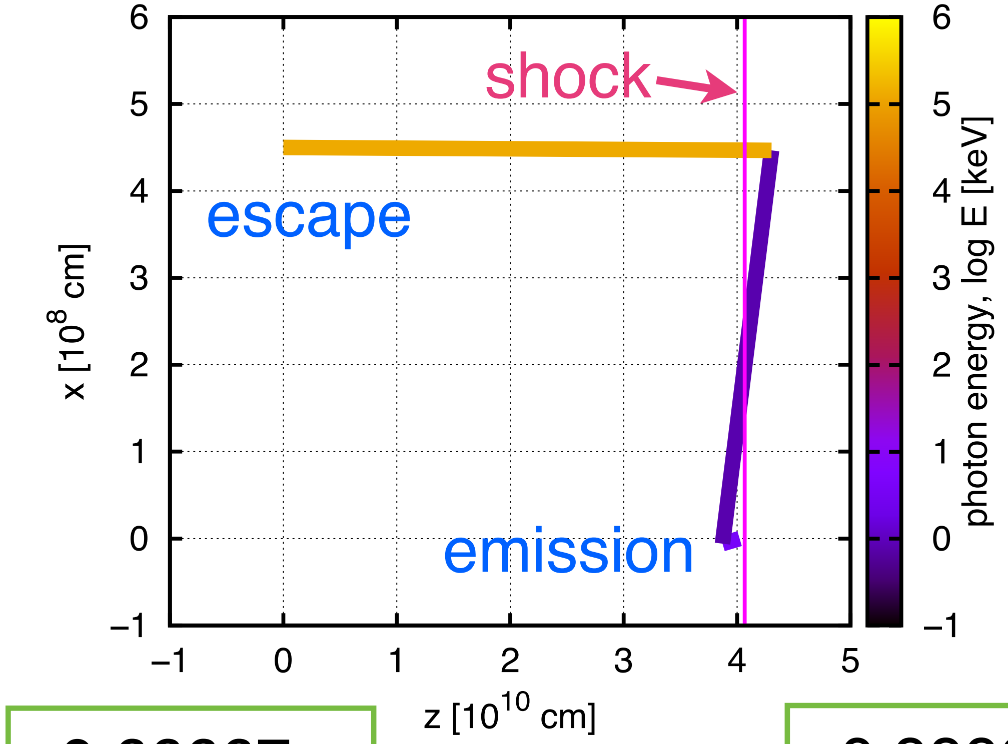
Thank you for your attention !

Bulk-Compton scattering

after transformation to the shock rest frame



Trajectory of high-energy photon



- 0.66667 c
$(\Gamma \sim 1.34)$

- 0.99999 c
$(\Gamma \sim 220)$

- Double peaks are found
- Bulk-Compton scattering occurs across the shock