Radiative Transfer Calculasion for the Thermal Radiation from GRB Jets

✓ Sanshiro Shibata (Konan Univ.)

Collaborator: Nozomu Tominaga (Konan Univ., Kavli IPMU)

Outline

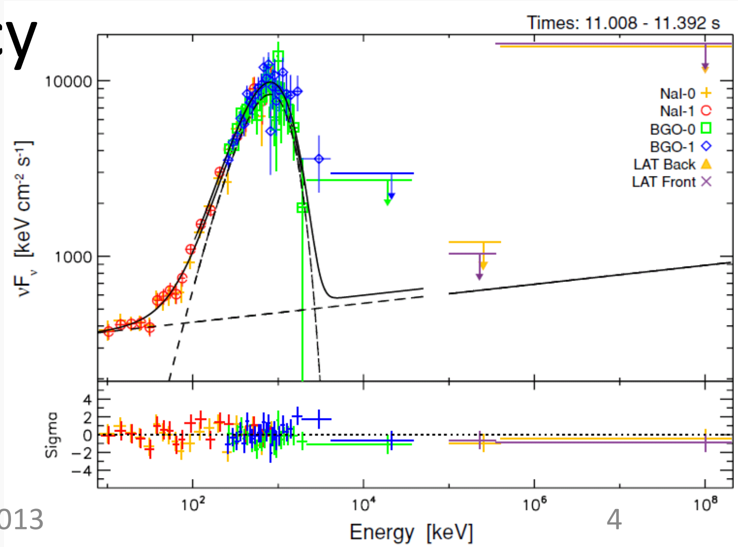
- Introduction
  - Models for the prompt emission
  - Thermal emission from GRB jet
- Method
  - Hydrodynamical simulation
  - Photosphere
  - Radiative transfer
- Results
- Summary

Introduction

Models for the prompt emission

- Internal shock model
  - A standard scenario for a long time.
  - Low Radiative efficiency, line of death problem
- Photospheric (thermal emission) model
  - Thermal emission from relativistic jets
  - (possibly) high radiative efficiency
  - Some GRBs exhibit blackbody like feature (e.g., GRB090902B).

(Ryde et al 2010)

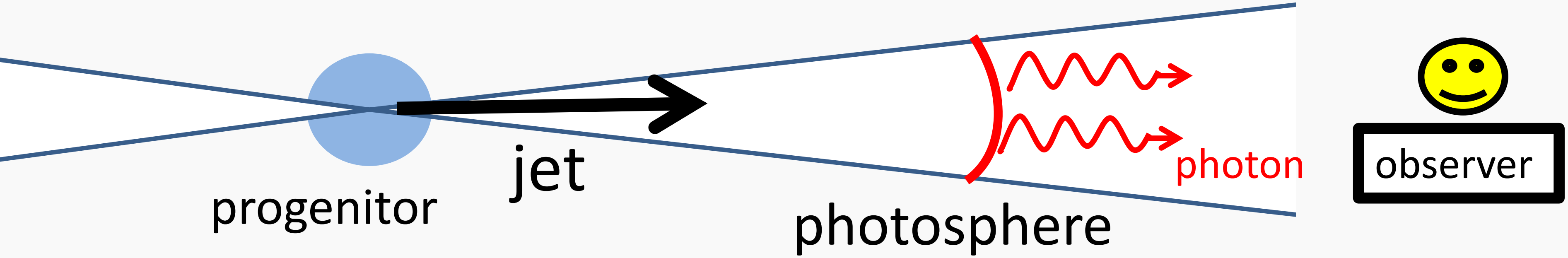


Thermal emission from GRB jets

- Thermal emission from GRB jets have been investigated by performing hydrodynamical simulations.

(Lazzati+2009, Mizuta+11, Nagakura+11)

- They calculated the light curves and spectra by superposing blackbody radiation emitted from the photosphere with $\tau=1$.



Thermal emission from GRB jets

However

- The observed photons should be generated in the inner layer with $\tau \gg 1$. (e.g., Beloborodov 13)
- Radiation intensity can be anisotropic even in the comoving frame at $\tau \sim 1$. (Beloborodov 11, Aksenov+ 13)

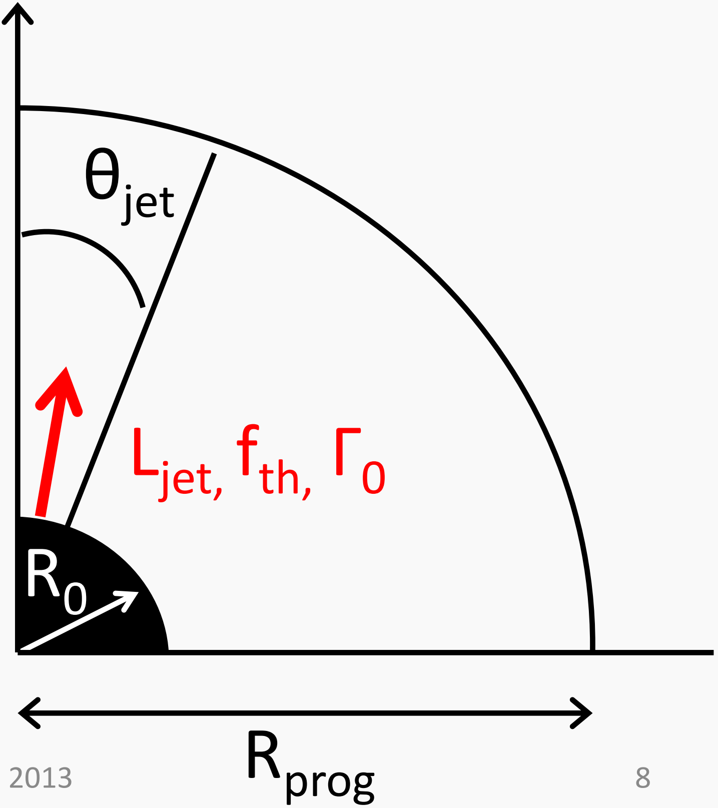
In order to treat the thermal radiation from GRB jets properly, both the radiative transfer in the jet and complex structure of the jet and cocoon should be taken into account.

We calculate the radiative transfer in the jet and cocoon.

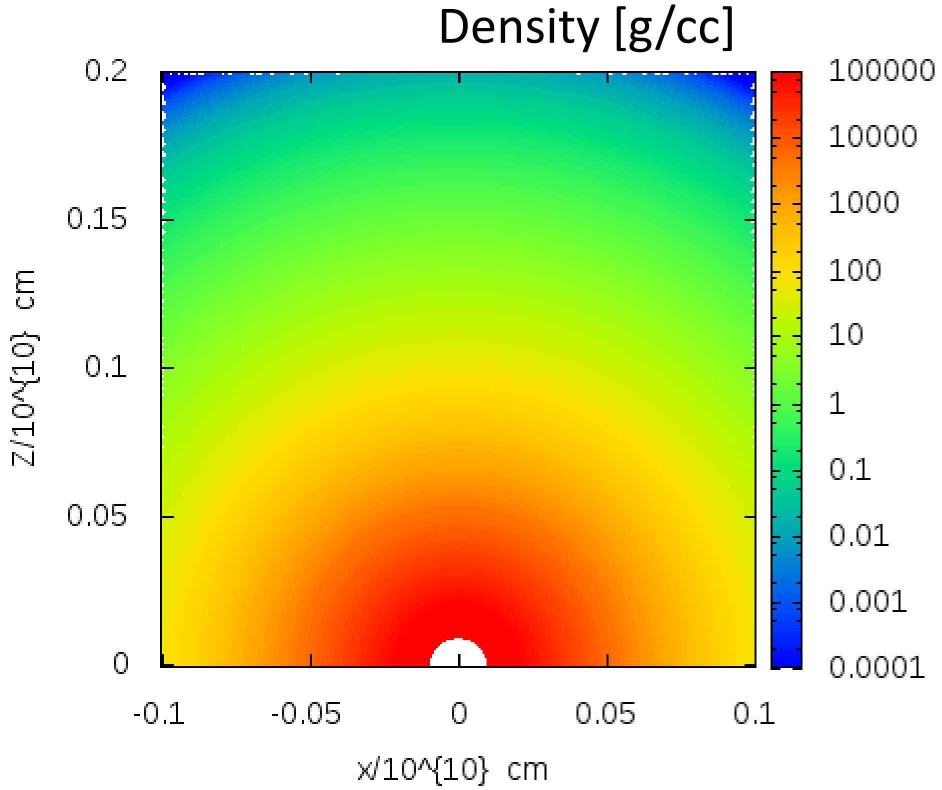
Method

Hydrodynamical simulation

- ✓ 2D relativistic hydrodynamics (Tominaga 2009)
- ✓ Setup
  - Progenitor: $15M_{sun}$ WR star ($R_{prog} \sim 2.3 \times 10^{10}$cm)
  - $\Gamma_0=5$
  - $\Theta_{jet}=10^\circ$
  - $L_{jet}=5.3 \times 10^{50}$ erg s^{-1}
  - $f_{th}=0.9925$ ($e_{int}/\rho c^2=80$)
  - (log r, θ) = (600, 150) grids from $R_0=10^9$cm



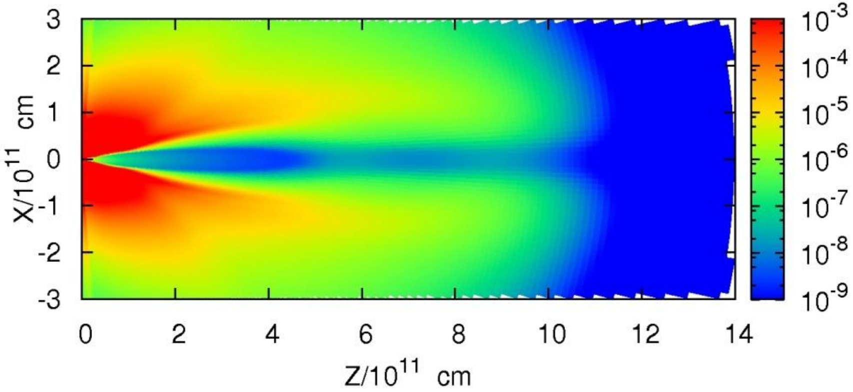
Hydrodynamical simulation



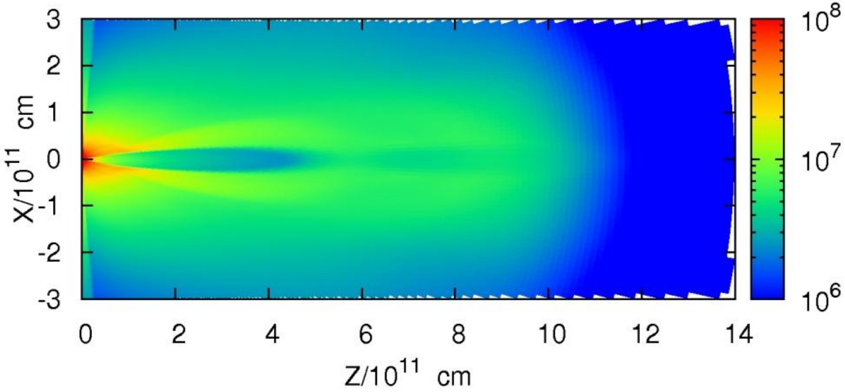
Snapshot at 40s

- We use a snapshot at 40s for the structures of the jet and cocoon.

Density ρ [g/cm^3]



Temperature T [K]



The site of photon production

- The effective optical depth τ_*

For the static medium (Rybicki & Lightman 79)

$$\tau_*^{\rm NR} \sim \sqrt{\tau_{\rm a}(\tau_{\rm a}+\tau_{\rm s})}$$

For the relativistic medium

$$\boxed{\tau_*^{\rm R} = \left\{\frac{\Gamma^2}{3}(\beta^2+3)+(\Gamma\beta)^2\frac{\tau_{\rm s}}{\tau_{\rm a}}\right\}^{-1/2} \frac{\sqrt{\tau_{\rm a}(\tau_{\rm a}+\tau_{\rm s})}}{\Gamma(1-\beta\cos\theta_{\rm v})}}$$

$\tau_{\rm a} = \Gamma(1-\beta\cos\theta_{\rm v})\alpha' L$, $\tau_{\rm s} = \Gamma(1-\beta\cos\theta_{\rm v})\sigma' L$

In the non-relativistic limit, $\tau_*^{\rm R} \rightarrow \tau_*^{\rm NR}$

In the relativistic limit, $\tau_*^{\rm R} \rightarrow 2\,\tau_{\rm a}$ for Θ=0

Absorption processes

$$\alpha'(x) = \alpha'_{\mathrm{ff}}(x) + \alpha'_{\mathrm{DC}}(x)$$

- Free-free absorption (e + p + γ → e + p)

$$\alpha'_{\mathrm{ff}}(x) = \frac{\alpha_{\mathrm{fin}} \lambda_{\mathrm{c}}^3 \sigma_{\mathrm{T}}}{\sqrt{6\pi}} \theta^{-1/2} Z^2 n_{\mathrm{e}} n_{\mathrm{i}} x^{-3} (1 - e^{-x/\theta}) g_{\mathrm{ff}}$$

(Rybicki&Lightman 79)

- Double Compton absorption (γ + γ + e → γ + e)

$$\alpha'_{\mathrm{DC}}(x) = \frac{2\alpha_{\mathrm{fin}} \lambda_{\mathrm{c}}^3 \sigma_{\mathrm{T}}}{\pi^2} \theta^2 n_{\mathrm{e}} n_{\gamma} x^{-3} (e^{x/\theta} - 1) g_{\mathrm{DC}}$$

(Svensson 84)

- We assume hν=kT

$$x = \frac{h\nu}{m_{\mathrm{e}} c^2} \qquad \theta = \frac{k_{\mathrm{B}} T}{m_{\mathrm{e}} c^2}$$

Photosphere

- τ_* to a radius R_*

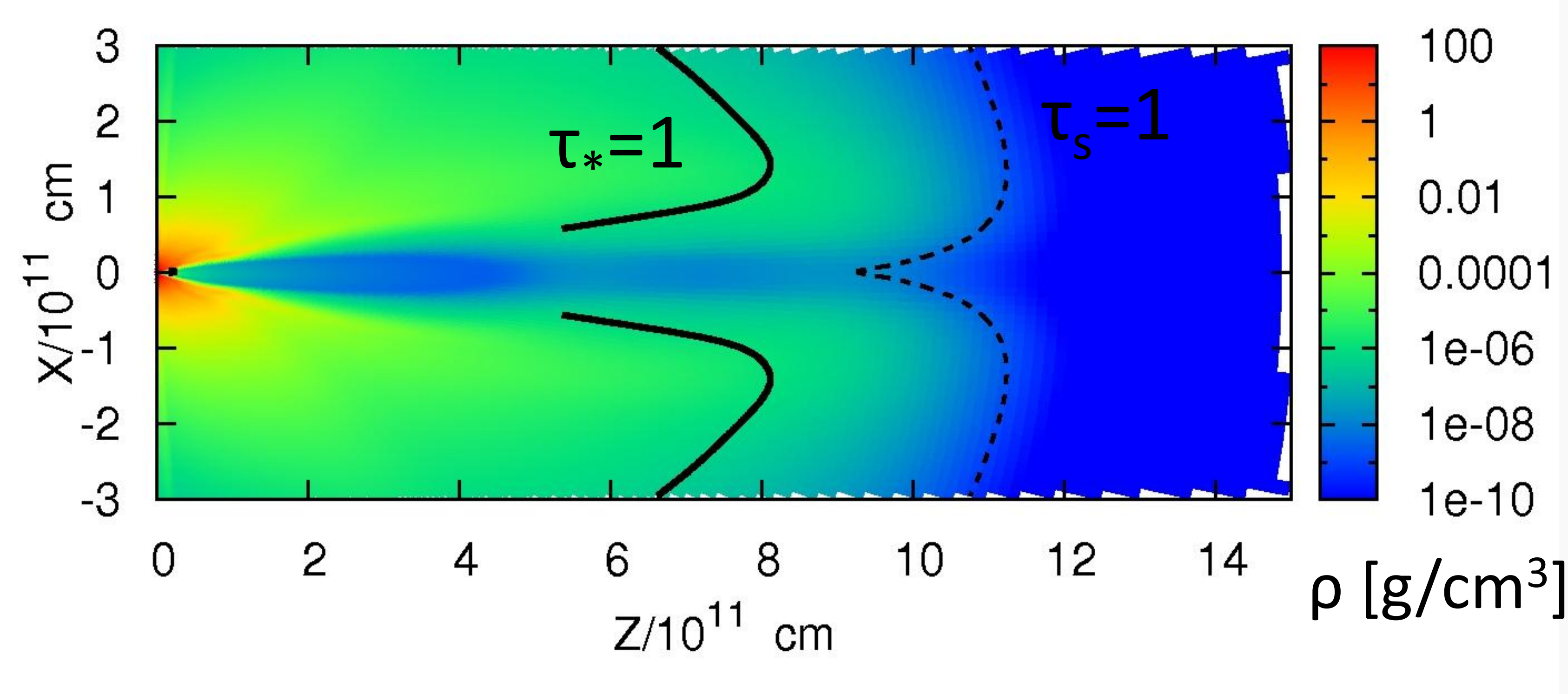
$$\tau_* = \int_{R_*}^{\infty} \left\{ \frac{\Gamma^2}{3}(\beta^2+3) + (\Gamma\beta)^2 \frac{\sigma'}{\alpha'} \right\}^{-1/2} \sqrt{\alpha'(\alpha'+\sigma')} dr$$

- $\sigma' = n_e \sigma_T$
- α' depends on n_e, n_γ, T.
- We assume

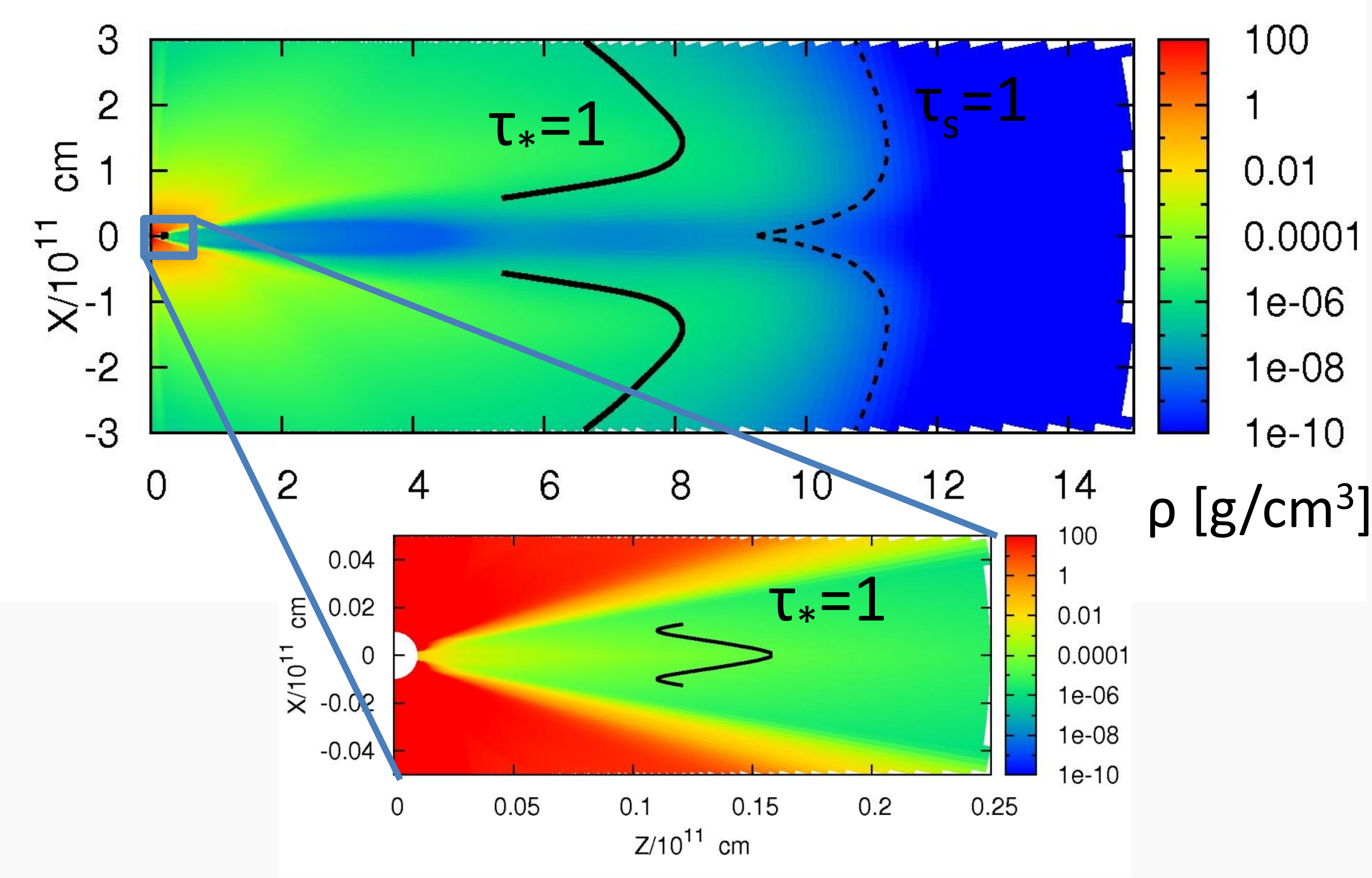
$$n_\gamma = n_{\gamma *} \left(\frac{R_*}{r} \right)^2$$ and $$n_{\gamma *} \equiv n_{\rm bb}(R_*)$$

We find the R_* which satisfies $\tau_* = 1$

Photosphere



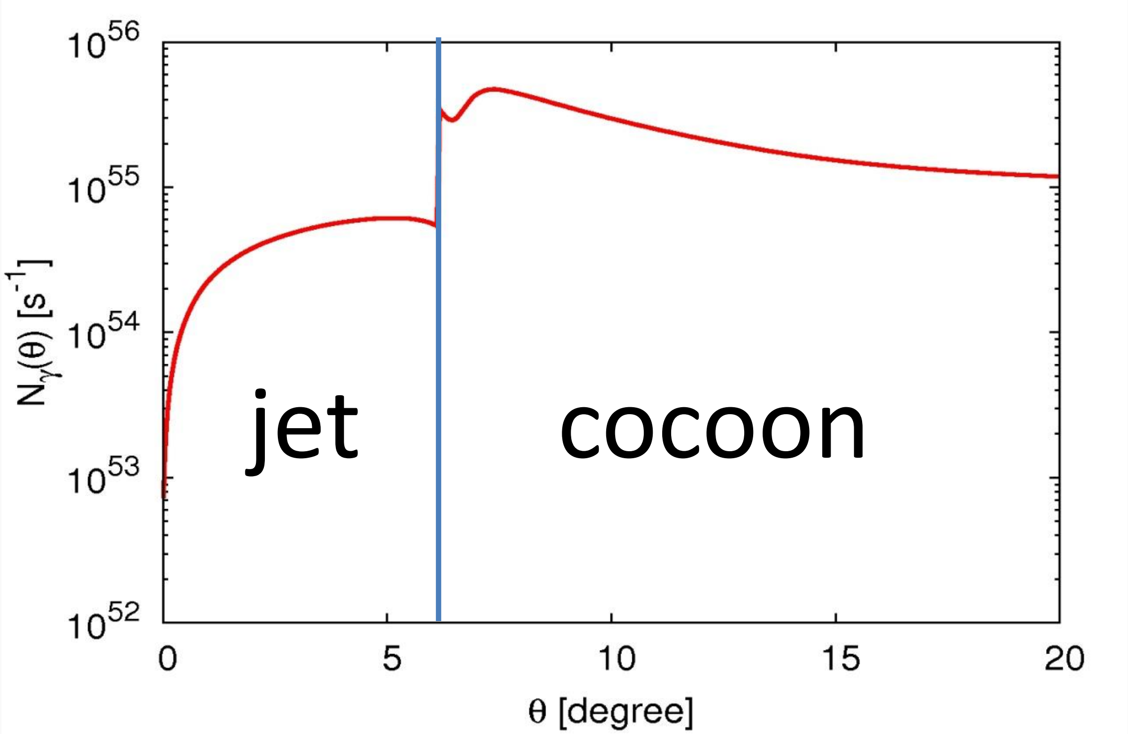
Photosphere



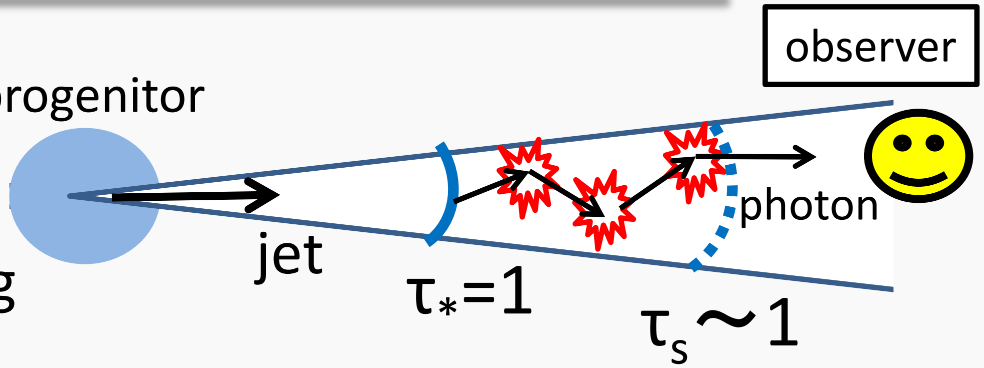
Photosphere

- The number of photons emitted at the photosphere:

$N_\gamma(\Theta)=16\pi^2\Gamma(3)\zeta(3)(kT_*/hc)^3R_*{}^2\sin\Theta_*$



Radiative transfer



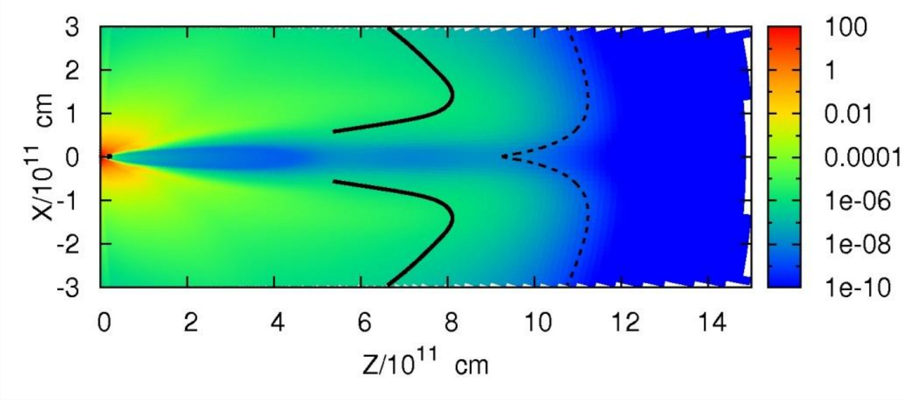
✓Numerical code

- Monte Carlo method
- Calculate Compton scattering
- Photons are injected at $\tau_*=1$

✓Photon injection

- Spatial distribution: $N_\gamma(\Theta)$
- Planck distribution with local plasma temperatures
- Isotropic in the comoving frame

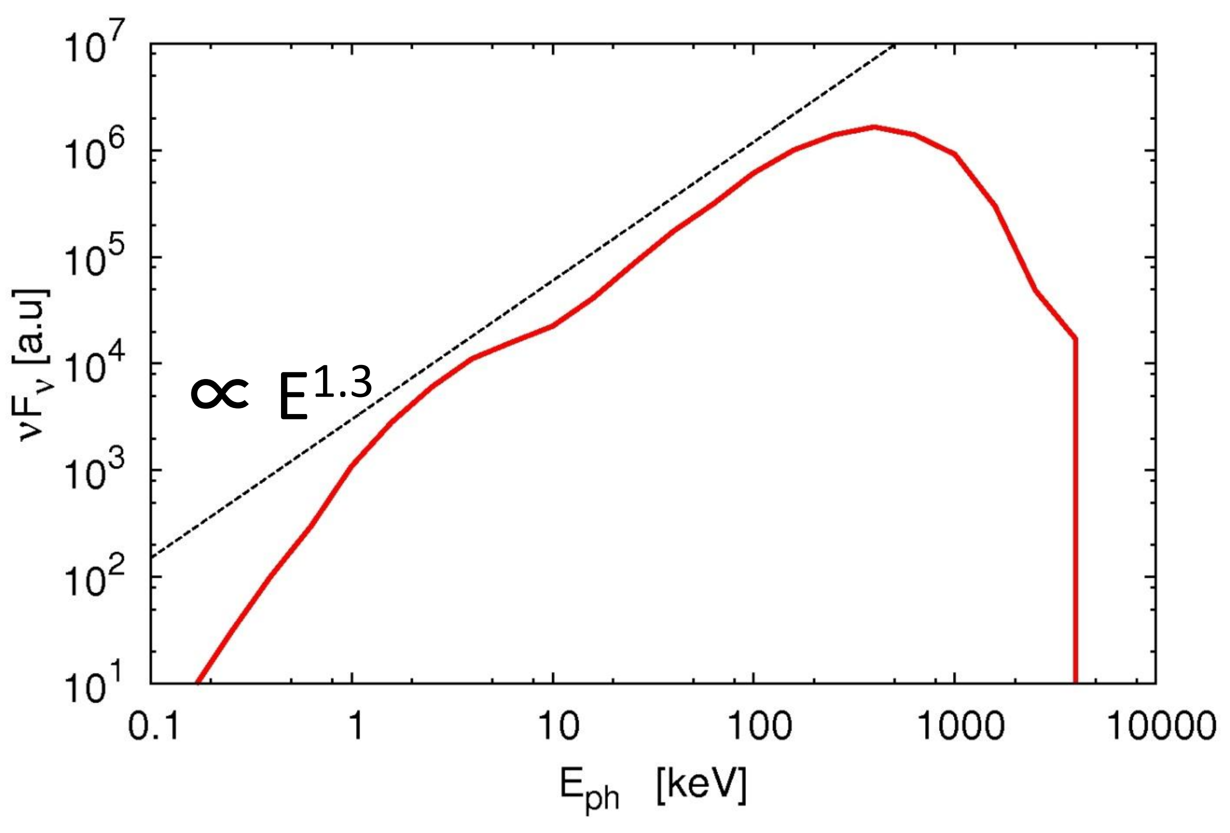
We use a snapshot at t=40s for the jet and cocoon structure.



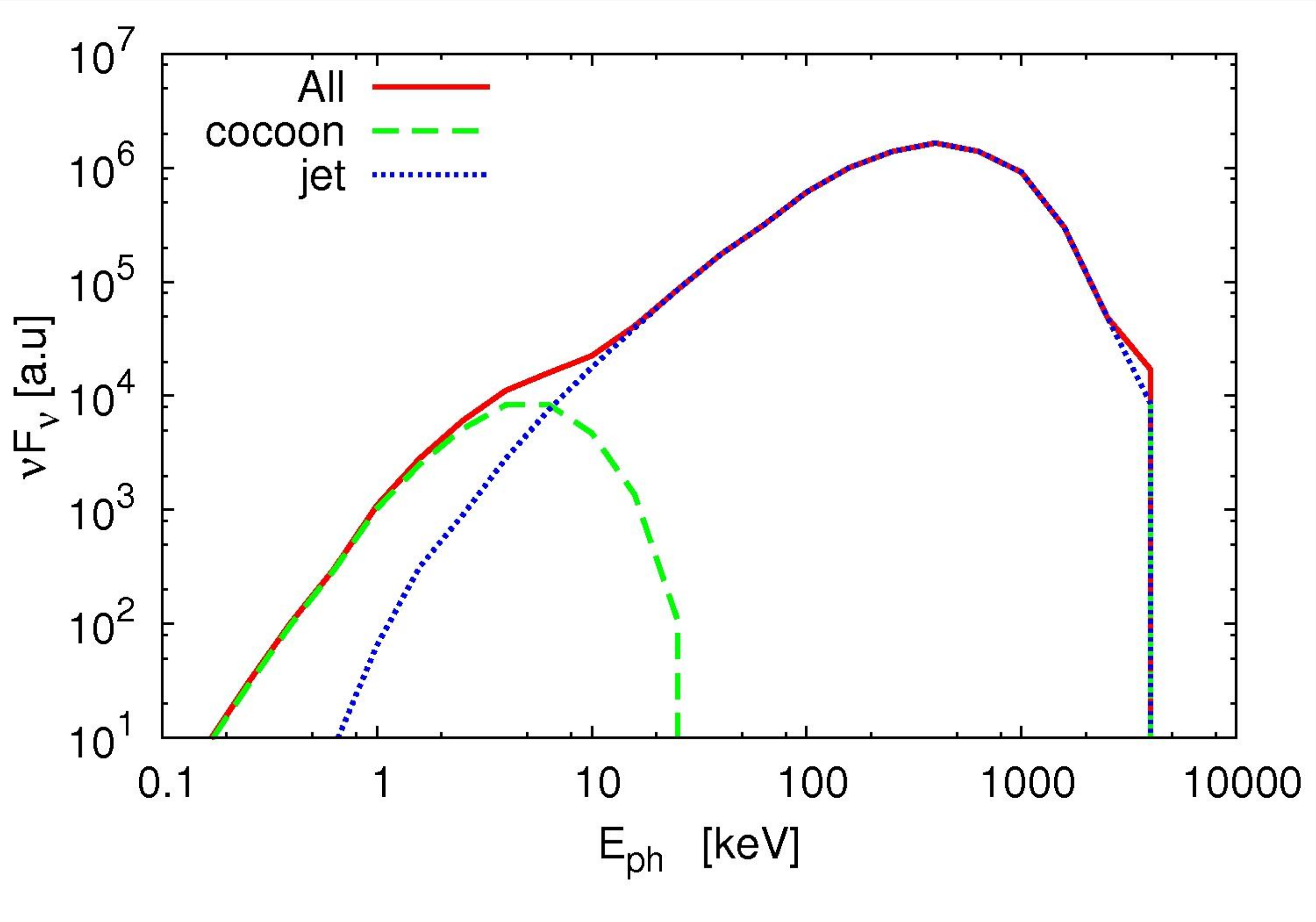
Results

Observed spectrum

- E_{peak}～450keV
- A bump like feature at low energies
- At the low energy, $\nu F_\nu \propto E^{1.3}$ $\rightarrow N_\nu \propto E^{-0.7}$
- No high energy PL

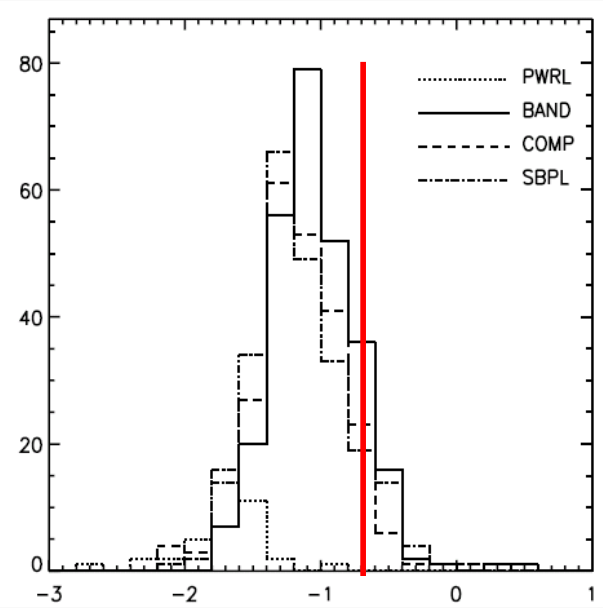


Origin of the bump?

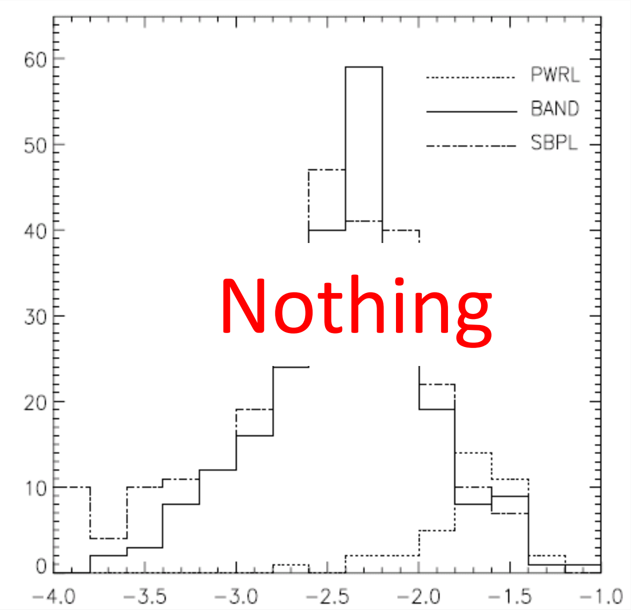


Comparison with the observations

Kaneko et al 2006

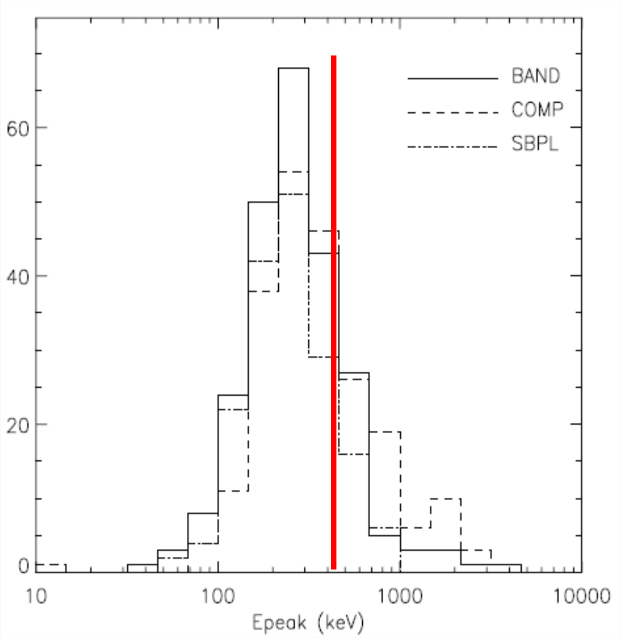


low energy index (α)



Nothing

high energy index (β)



peak energy (E_{peak})

Summary

Summary

- ✓ We calculate radiative transfer for the thermal radiaiton from GRB jet.
- ✓ Both the jet and cocoon components constitute the observed spectrum.
- ✓ The low energy index may be determined by the relative brightness of these two components.