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Photons' in Relativistic Plasma with Velocity Shear: A novel mechanism for power law spectra at high energies

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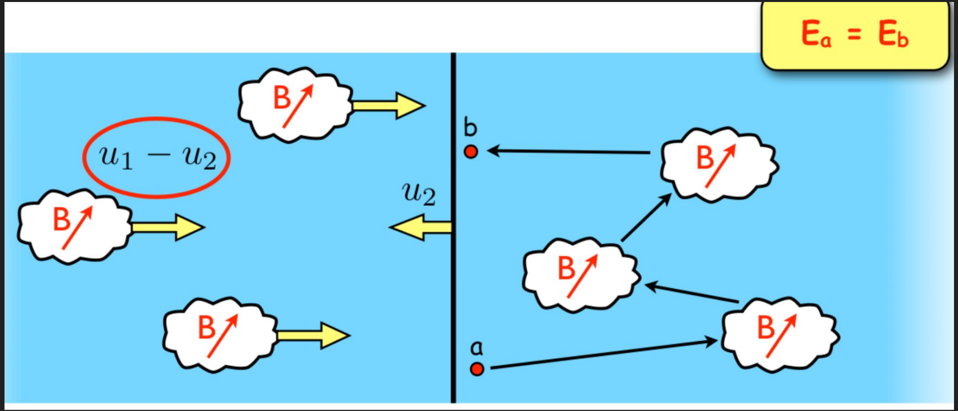
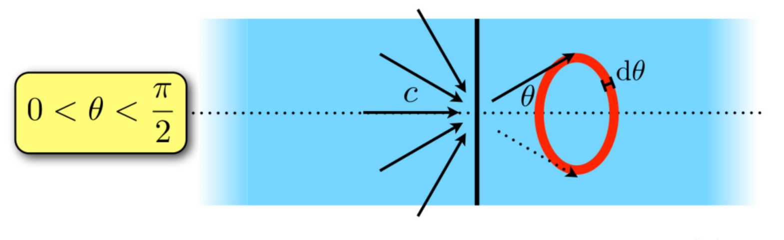
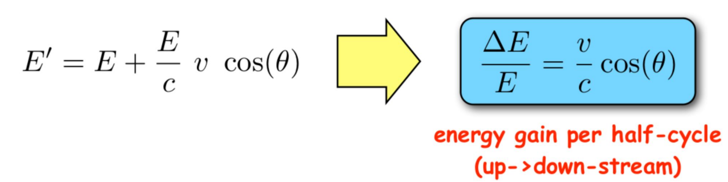
Overview

- **Introduction** : Fermi acceleration and photon energy gain in shearing flows
- **Physical mechanism** of photon energy gain
- Generation of power law spectrum at high energies
- **Results** : Comparison of estimated spectral slopes with Monte Carlo Simulations
- **Conclusions** : Significance of the work

First order Fermi acceleration:
Shock acceleration of charged particles





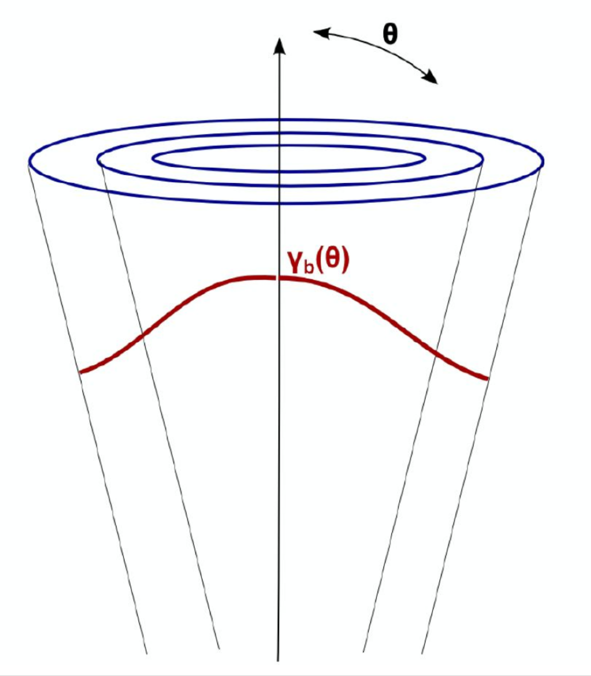


$$E' = E + \frac{E}{c}\, v\, \cos(\theta) \Longrightarrow \boxed{\frac{\Delta E}{E} = \frac{v}{c}\cos(\theta)}$$

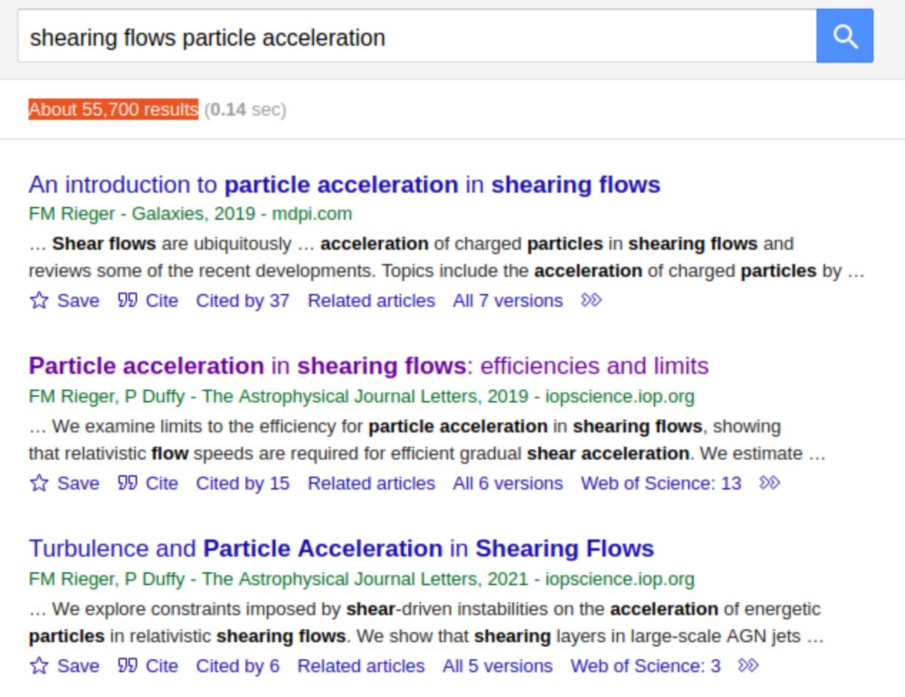
energy gain per half-cycle
(up->down-stream)

Electrons gain energy and produce a power law spectrum when they interact with regions having different speeds in the plasma

Particle acceleration in shearing flows



Rieger Galaxies ***2019****, 7(3)*



shearing flows particle acceleration

About 55,700 results (0.14 sec)

An introduction to **particle acceleration** in **shearing flows**
FM Rieger - Galaxies, 2019 - mdpi.com
… **Shear flows** are ubiquitously … **acceleration** of charged **particles** in **shearing flows** and reviews some of the recent developments. Topics include the **acceleration** of charged **particles** by …
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Particle acceleration in **shearing flows**: efficiencies and limits
FM Rieger, P Duffy - The Astrophysical Journal Letters, 2019 - iopscience.iop.org
… We examine limits to the efficiency for **particle acceleration** in **shearing flows**, showing that relativistic **flow** speeds are required for efficient gradual **shear acceleration**. We estimate …
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Turbulence and **Particle Acceleration** in **Shearing Flows**
FM Rieger, P Duffy - The Astrophysical Journal Letters, 2021 - iopscience.iop.org
… We explore constraints imposed by **shear**-driven instabilities on the **acceleration** of energetic **particles** in relativistic **shearing flows**. We show that **shearing** layers in large-scale AGN jets …
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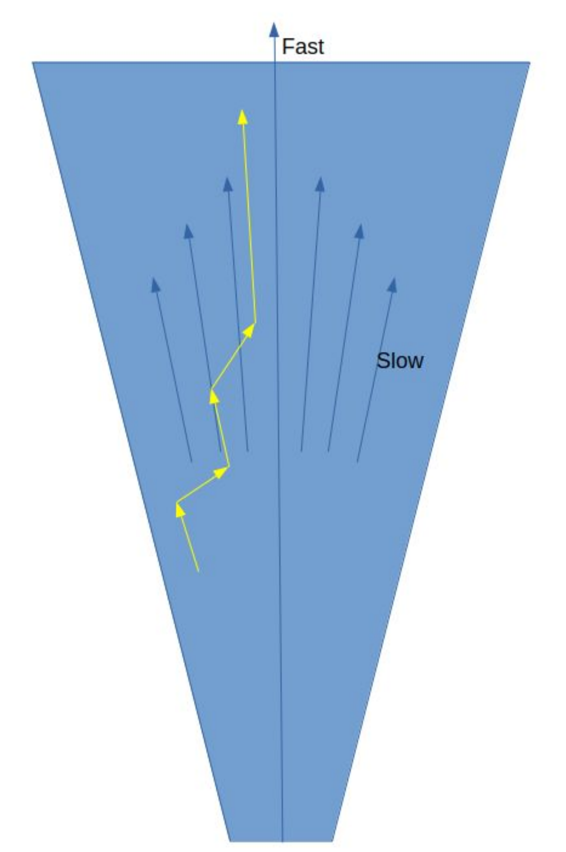
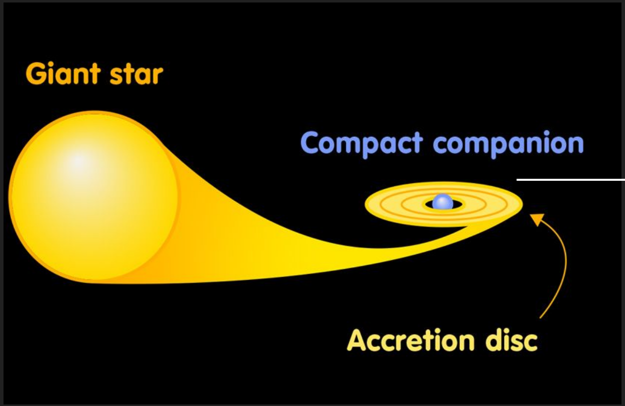
But what about a photon, trapped and escapes from shearing scatters??
We need investigation and a clear picture of this process.

Photon energy gain In shearing flows: the concept and motivation

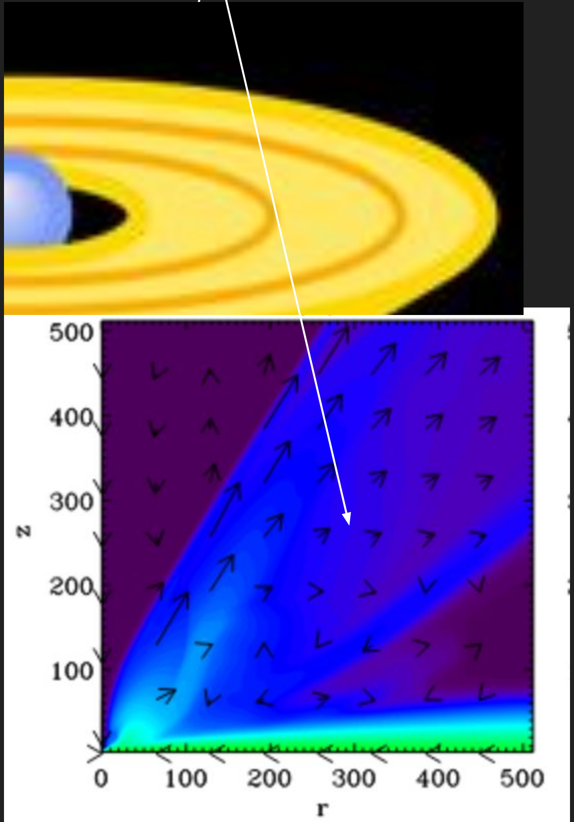
Any relativistic flow with a presence of
(i) Shear,
(ii) High optical depth
would lead to net photon energy gain producing a power law emission of spectra



Generation of power law due to Velocity shear in the plasma

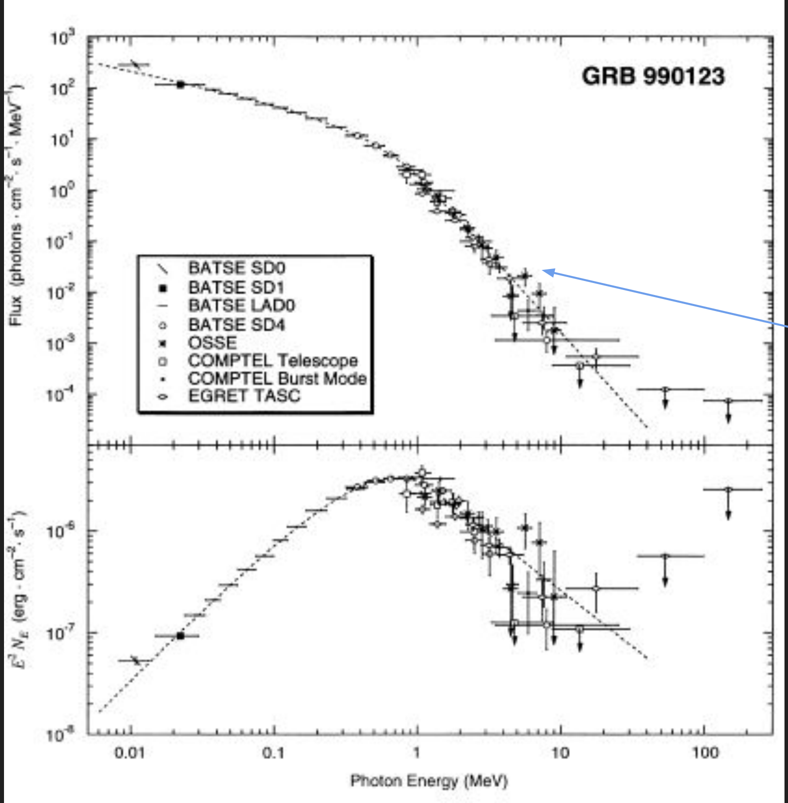


Physical picture



Simulations of radiation-driven winds from Keplerian discs (Raychaudhuri, Vyas & Chattopadhyay, 2021)

Attempts to explain high energy power law



Synchrotron shock model

Tavani 1996; Cohen et. el 1997; Panaitescu et. al. 1999; Frontera et al. 2000

Backscattering dominated emission

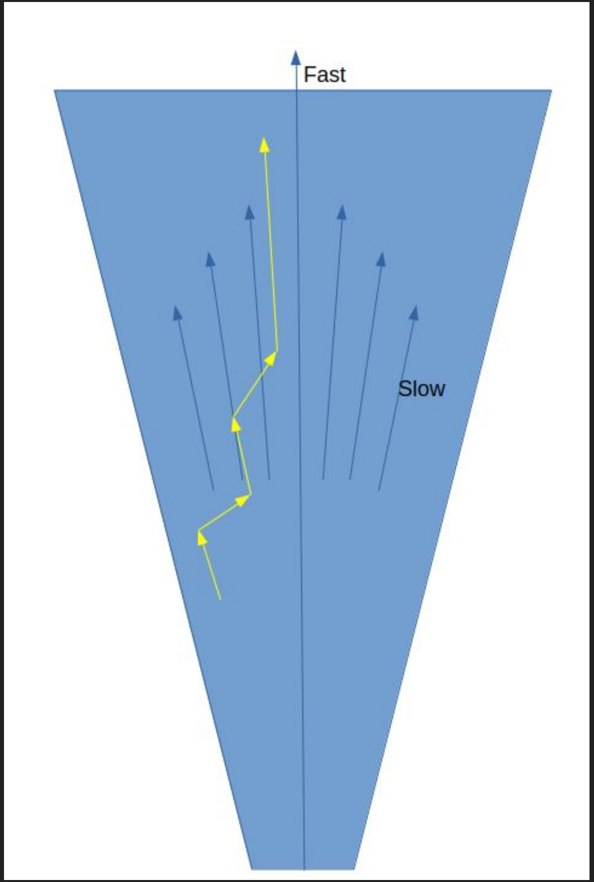
Eichler & Manis (2007, 08), Eichler 2004, Vyas et al. (2020, 2021)

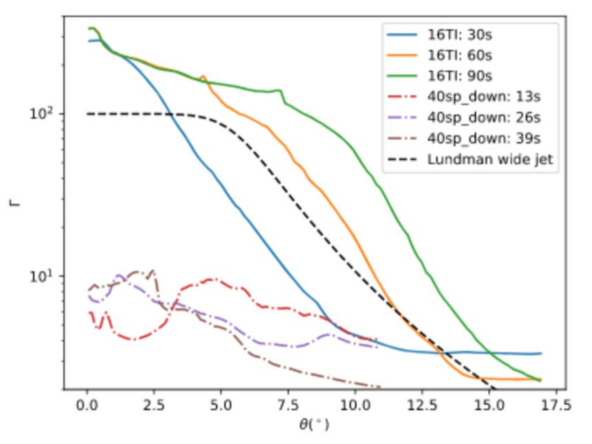
Bulk Comptonization from structured jets with photospheric emission :

Lundman et al. 2013, ***Vyas & Pe'er 2022 (current work)***

Piron, Comptes Rendus Physique 17, no. 6 (2016): 617-631

Photon energy gain from relativistic jets with structured Lorentz factor profile





Tyler Parsotan et al 2020 ApJ ***896*** *139*

$$\Gamma(\theta) = \Gamma_{\min} + \frac{\Gamma_0}{\sqrt{\left(\frac{\theta}{\theta_j}\right)^{2p} + 1}}$$

Lorentz factor (Γ) as a function of θ

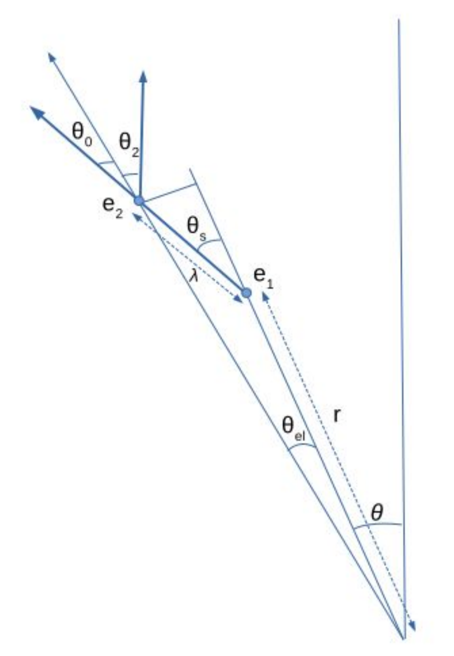
Zhang et al. 2003, ApJ, 586

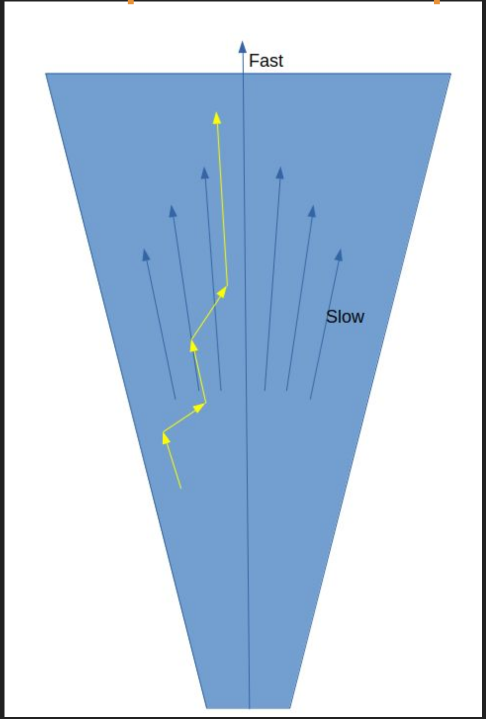
Lundman et al. 2013, 428-3, 2430

Lundman et. al. 2014, MNRAS ***440*** *3292*

Case of GRB jets : Energy gain in scattering process

1. Analytic estimates of spectral slopes





$$g = \frac{\varepsilon_2}{\varepsilon} = \frac{1 - \beta_2 \cos(\theta_s - \theta_{el})}{1 - \beta_2 \cos(\theta_2)}$$

$$\frac{\Gamma_2}{\Gamma} = 1 + \frac{\delta\Gamma}{\Gamma} = 1 + \sum \frac{\partial \log \Gamma}{\partial x^i} \delta x^i$$

Energy gain in scattering process

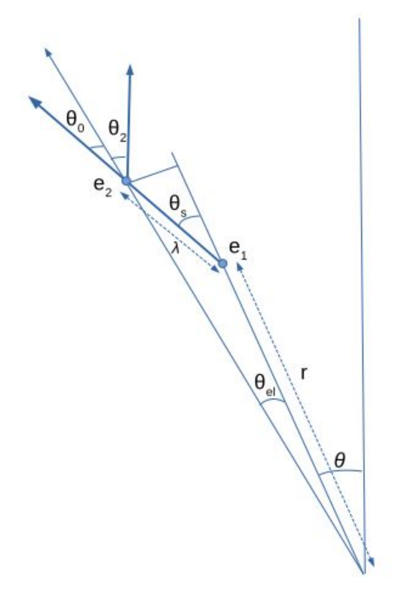
If the local mean free path measured in the lab frame is λ(r, θ), then

$$\tan\theta_{\rm el} = \frac{\lambda\sin\theta_{\rm s}}{r+\lambda\cos\theta_{\rm s}} = \frac{a\theta_{\rm s}}{1+a\cos\theta_{\rm s}}$$

Taylor expansion allows us to estimate the gain as:

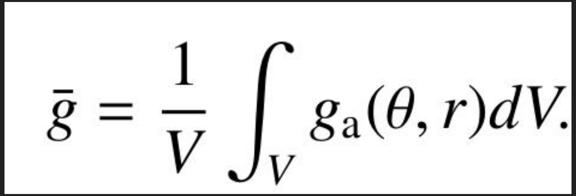
$$g(r,\theta) \approx \frac{1}{2}\left[1+\left[1+\sum\frac{\partial\log\Gamma}{\partial x^i}\delta x^i\right]^2\frac{1}{(1+a)^2}\right]$$

$$a \equiv \lambda/r$$



Averaged gain over all scatterings

The expectation value of the photon energy gain in the plasma is evaluated by integrating the average gain over the entire region of scattering



$$\bar{g} = \frac{1}{V} \int_V g_{\mathrm{a}}(\theta, r) dV.$$

Escape probabilities for the photon from accelerating region

$$P_{\mathrm{e}}(r,\theta) = \exp[-\tau(r,\theta)]$$

Escape probability at location *r, θ*

$$\tau_1 = r_{ph}/r$$

Photospheric optical depth

$$\tau_2 = \int_0^{s_0} \Gamma(1 - v\cos\theta_{\mathrm{s}}) n'_{\mathrm{e}} \sigma ds.$$

Angular optical depth

$$\tau_2 = \frac{2r_{ph}}{\beta r \cos\theta_s}\left[1 - \frac{1}{(\theta-\theta_j)\gamma\cos\theta_s + 1}\right]$$

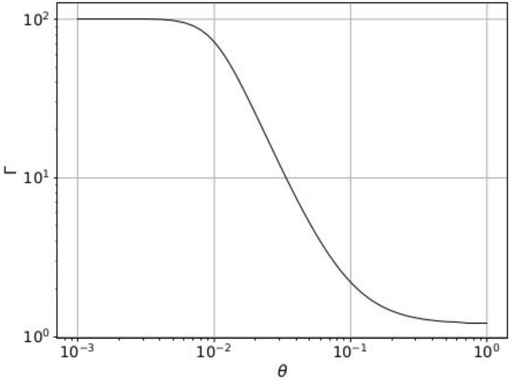


Figure 2. Lorentz factor (Γ) profile of the jet characterized by equation 13 with parameters $p = 2.0$, $\theta_{\mathrm{j}} = 0.01$ rad, $\Gamma_0 = 100$ and $\Gamma_{\min} = 1.2$. $\theta_{\mathrm{e}} = \theta_{\mathrm{j}}\Gamma_0^{1/p}$. The inner jet region is for $\theta < \theta_{\mathrm{j}}$ while outer region extends beyond θ_{e}. The region bounded within $\theta_{\mathrm{j}} - \theta_{\mathrm{e}}$ harbours an effective velocity shear leading to photon energy gain.

$$\tau = \min(\tau_1, \tau_2) \longrightarrow P(r,\theta) = 1 - \exp[-\tau(r,\theta)]$$

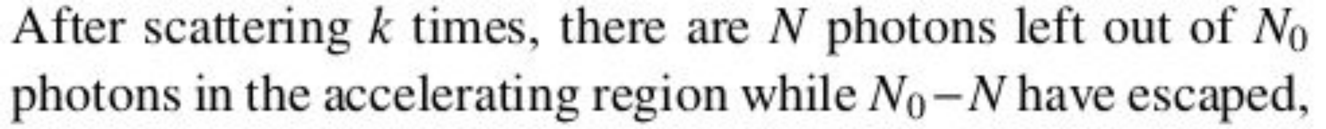
Probability for next scattering at location *r, θ without escape*

Averaged probabilities from the accelerating region

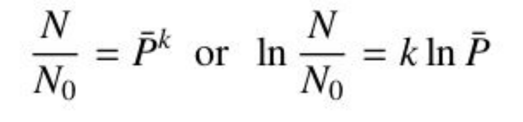
The average probability of the photon to have a scattering without escape within the jet is the probability P(r, θ) averaged over the available volume V of scattering where velocity shear is present, i.e.,

$$\bar{P} = \frac{1}{V} \int_{V} P(r, \theta) dV.$$

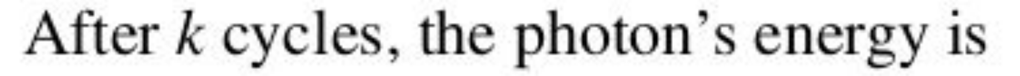
Generation of power law spectrum at high energies



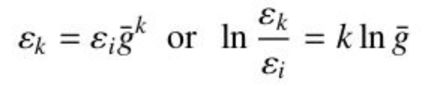
After scattering k times, there are N photons left out of N_0 photons in the accelerating region while $N_0 - N$ have escaped,



$$\frac{N}{N_0} = \bar{P}^k \quad \text{or} \quad \ln \frac{N}{N_0} = k \ln \bar{P}$$



After k cycles, the photon's energy is



$$\varepsilon_k = \varepsilon_i \bar{g}^k \quad \text{or} \quad \ln \frac{\varepsilon_k}{\varepsilon_i} = k \ln \bar{g}$$

Generation of power-law shaped spectra at high energies

$$\ln \frac{N}{N_0} = \ln \frac{\varepsilon_k}{\varepsilon_i} \cdot \frac{\ln \bar{P}}{\ln \bar{g}}$$

$$\frac{N}{N_0} = \left(\frac{\varepsilon_k}{\varepsilon_i}\right)^{\beta'}$$

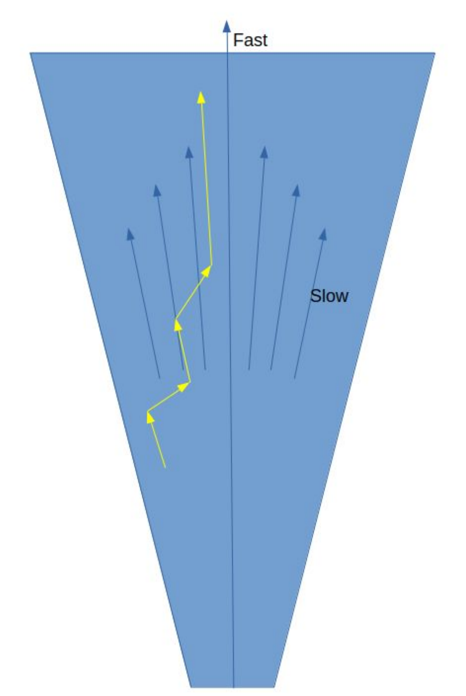
$$\beta' = \frac{\ln \bar{P}}{\ln \bar{g}}$$

$$\longrightarrow \quad \frac{dN}{d\varepsilon_1} = N_0 \beta' \varepsilon_1^{\beta' - 1}$$

$$\beta = \beta' - 1 = \frac{\ln \bar{P}}{\ln \bar{g}} - 1$$

We supply *P* and *g* for calculating the spectral slopes at high energies.

2. Numerical simulations

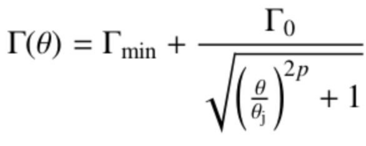


Numerical Code:

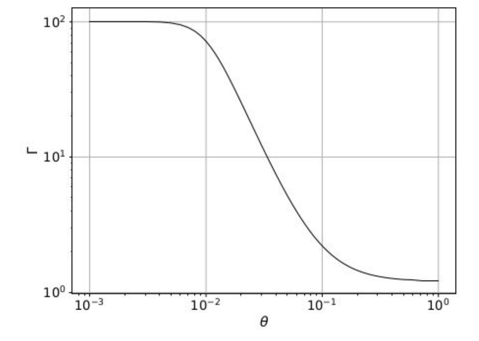
- The numerical simulations are based upon Monte Carlo method
- We inject around 6 million photons deep inside the jet. Each of the photon goes through multiple scattering within the shear layers before it escapes.
- The escaped photons' population is distributed then into bins of observing angles as well as energies
- These binned photons produce the observed light curves as well as the spectrum for the given parameters

Results: Simulated spectrum

(On axis observer)



$$\Gamma(\theta) = \Gamma_{\rm min} + \frac{\Gamma_0}{\sqrt{\left(\frac{\theta}{\theta_{\rm j}}\right)^{2p} + 1}}$$



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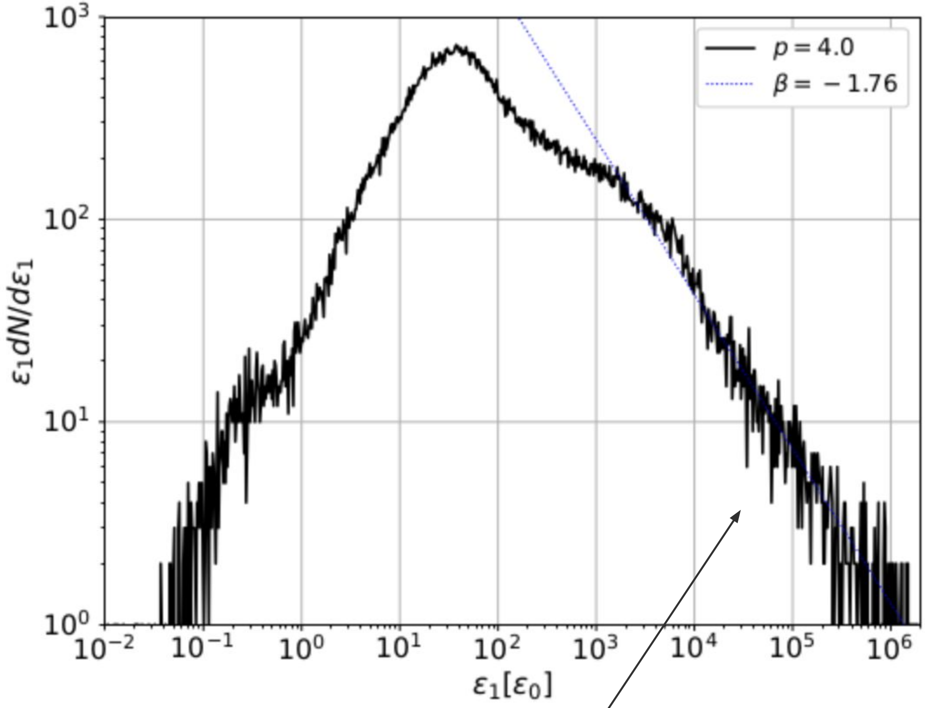
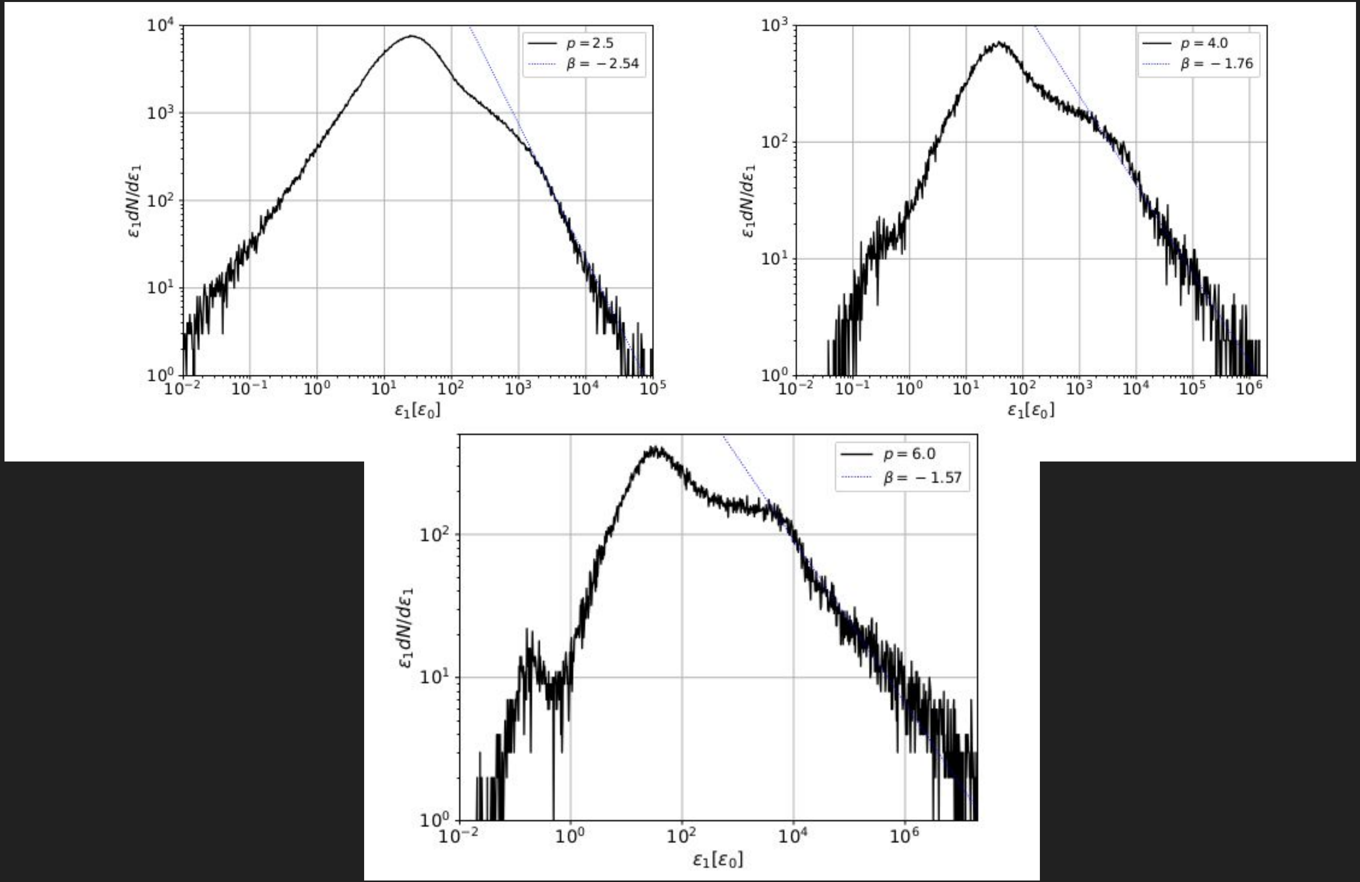


High energy tail produced by scattering within the shear layers

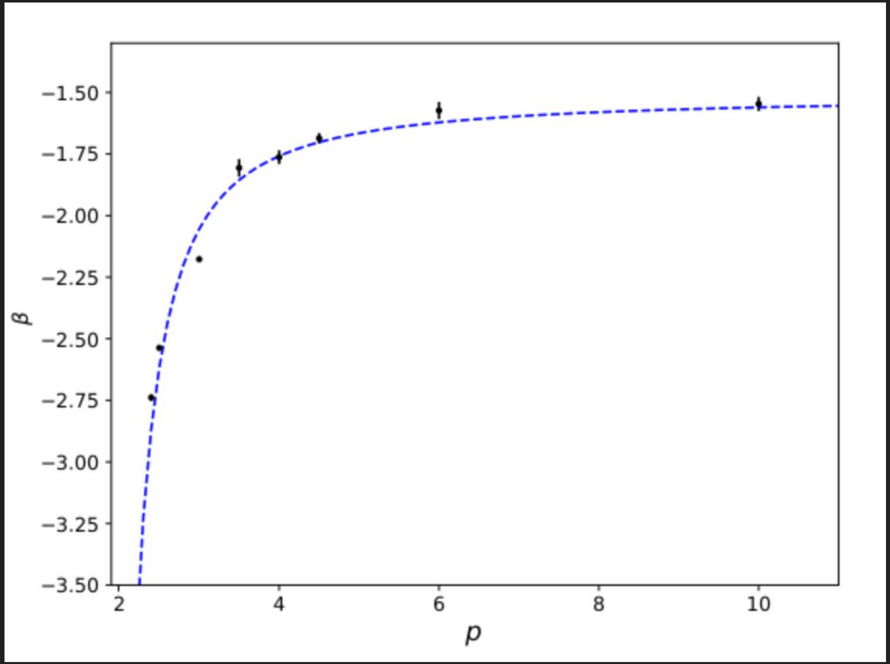
Simulated Spectra : Continued



Results : Analytic slopes and comparison with Monte Carlo Simulations

$$\beta = \beta' - 1 = \frac{\ln \bar{P}}{\ln \bar{g}} - 1$$

- Asymptotic slopes reach at -1.5 as p -> ∞
- For small and finite values of p (<2), the spectra vanishes due to geometric expansion of the jet
- The obtained range of **β is compatible with the observed values**



There are several other possible cases where such mechanism takes place

- A fast rotating star and its layers at the outskirts
- Relativistic turbulent plasma where there is a sharp velocity gradient in the turbulent eddies
- Sharply accelerating or decelerating relativistic jets/winds
- Corotating atmosphere of neutron stars (*Hanawa, ApJ, 1991*)

Summary : Conclusions and Significance

“Photons' Scattering in Relativistic Plasma with Velocity Shear: Generation of High Energy Power-law Spectra”
Vyas and Pe’er, ApJL 943-1, L3, 7

Such power laws are capable of explaining high energy tails observed in GRB prompt phase spectra where β ranges between −3 and −1.5. We found the theoretical range $-\infty$ to −1.5.

Inversely, we show that using the observed values of β, we can directly constraint the jet structure of the these bursts.

The mechanism is important for emission from other such objects like AGNs or X ray binary jets, fast spinning compact stars, accretion discs with velocity gradient etc. We will explore these possibilities in future.