

Tenth International Fermi Symposium

9th-15th October 2022



Generation of High Energy Power-law Spectra by Repeated Scattering in Jet's Velocity Shear

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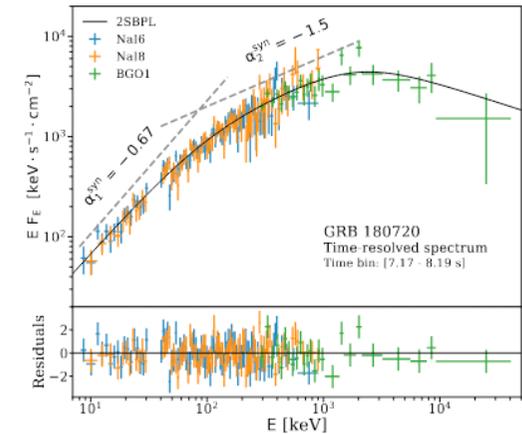
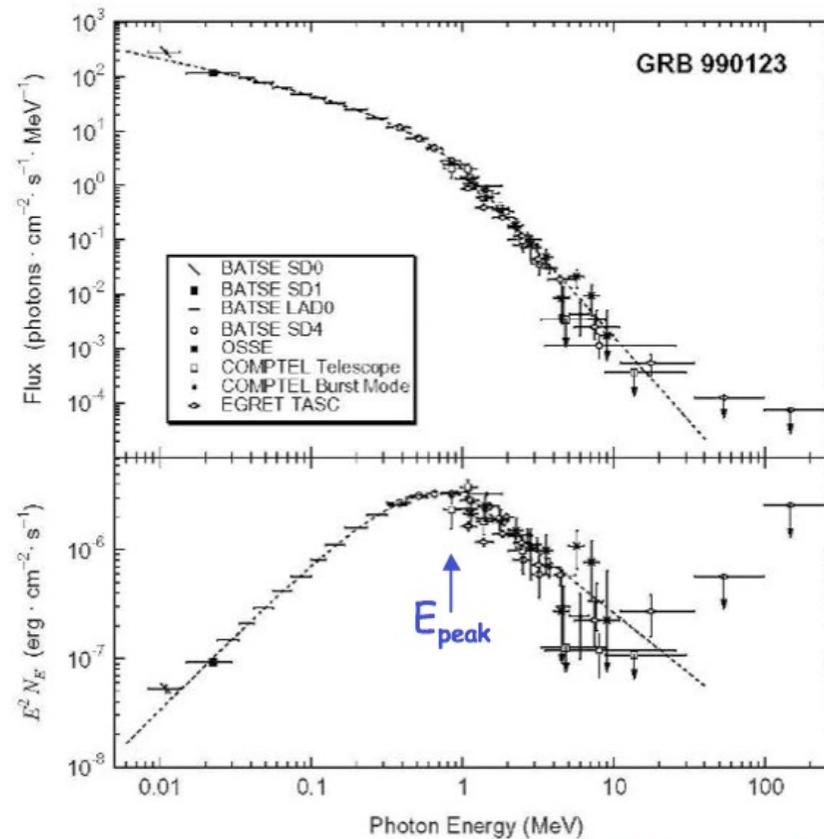
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The "Band" spectral fit

Pro's:

- ✓ Simple (4 parameters)
- ✓ 'Good fit to the data'
- ✓ Mathematical

Band et. al., 1993



Ravasio + 2019, A&A

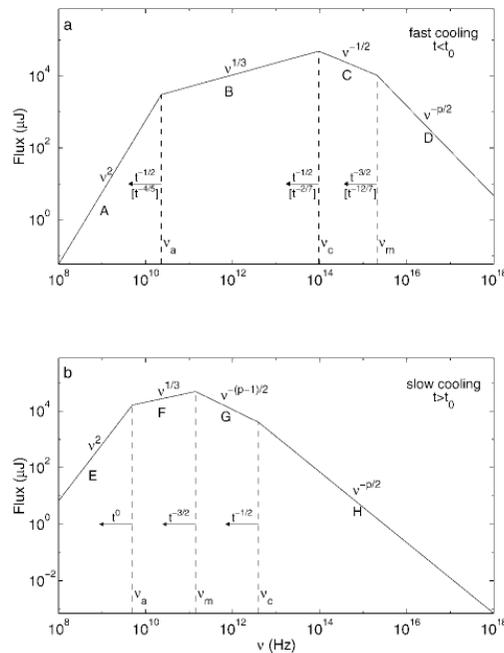
Briggs et al. 1999

Broken power law interpretation: synchrotron ?

- ◆ Getting a power law spectrum is straightforward - “only” need power law distribution of electrons: $N_{el}(\gamma) d\gamma \sim \gamma^{-p}$; $p > \sim 2.0$
- ◆ In (very) good agreement with late **Afterglow** observations

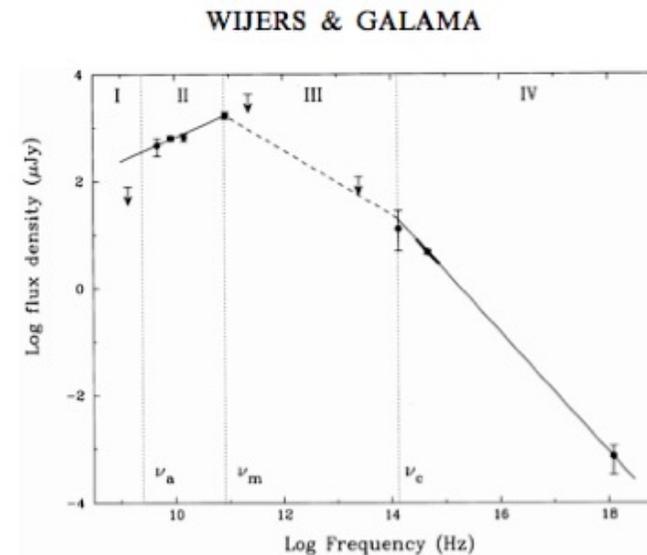
Theory

(Sari, Piran & Narayan, 1998)

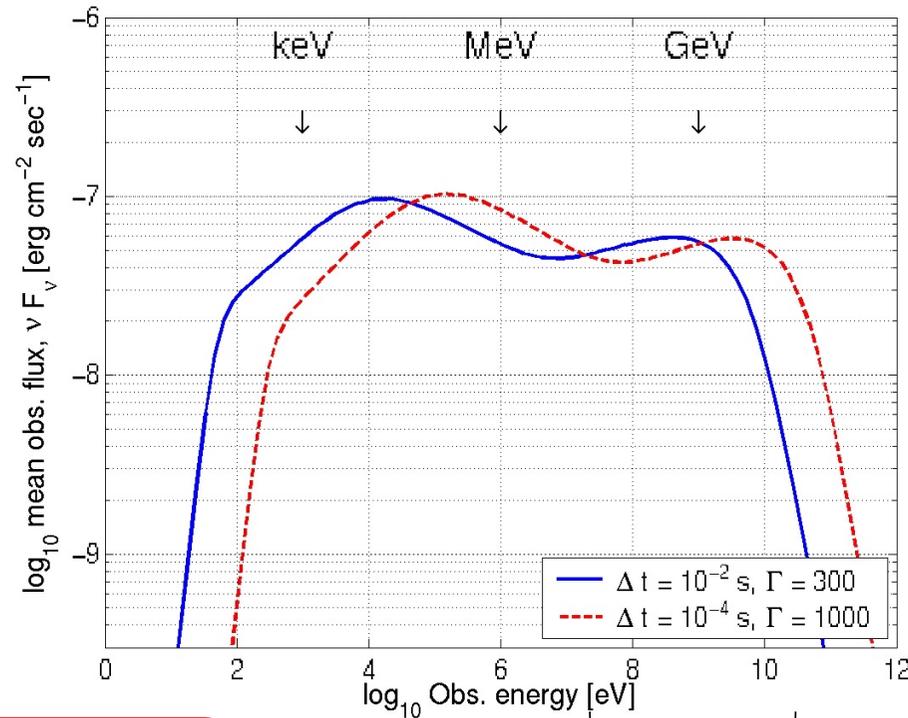


Afterglow observations

(Wijers & Galama, 1998)



Example of expected spectrum: optically thin case



For ≥ 25 years,
Synchrotron = leading model

Synchrotron
component

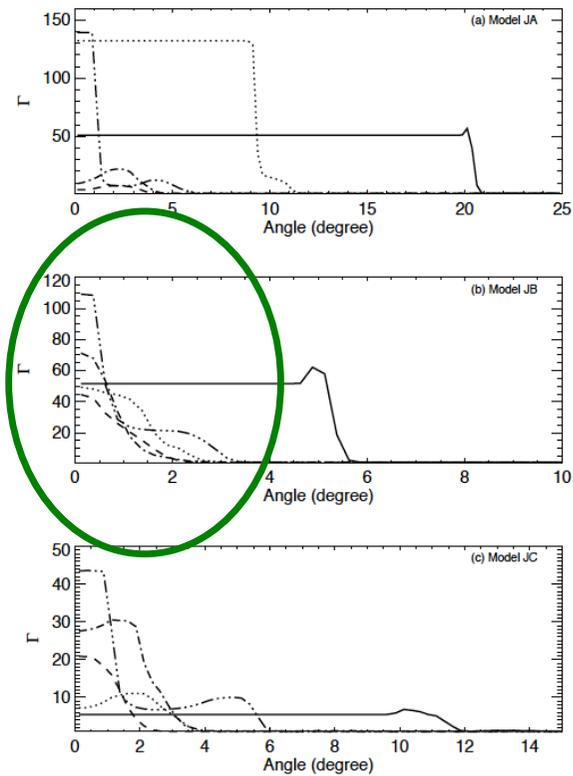
Inverse-Compton
Component

Pe'er & Waxman, 2004

Is there an alternative ? "reality": by definition, $\Gamma = \Gamma(\theta)$

No. 1, 2003

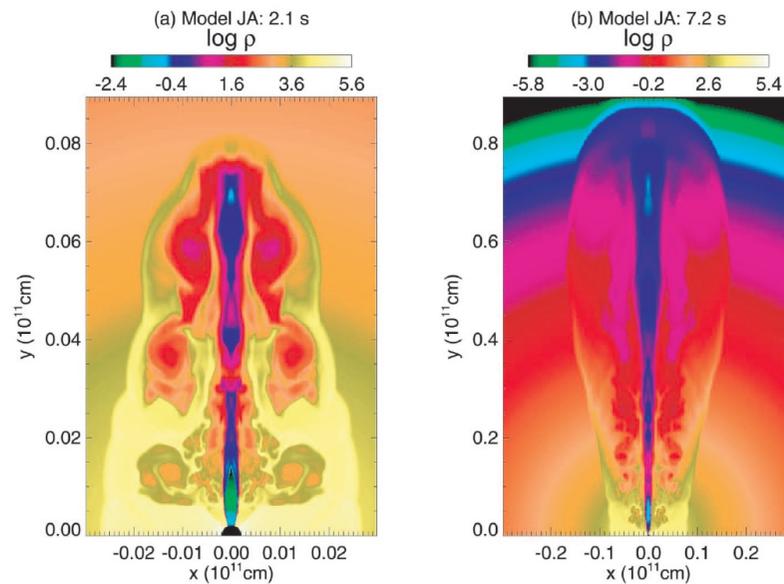
RELATIVISTIC JET



No. 1, 2003

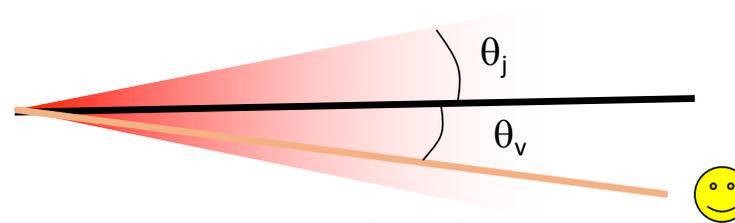
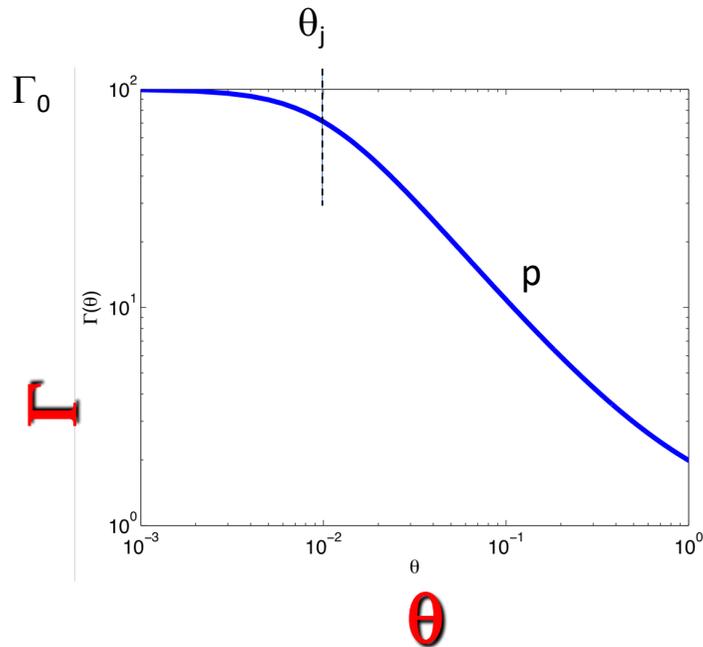
RELATIVISTIC JETS IN COLLAPSARS

359



(Zhang, Woosley & MacFadyen, 03)

Photospheric emission: 'realistic' jet velocity profile



4 free parameters:

$$\left\{ \begin{array}{c} \Gamma_0 \\ \theta_j \\ \theta_v \\ p \end{array} \right\}$$

Lundman, AP & Ryde 2013

$$[\Gamma(\theta) - 1]^2 = \frac{[\Gamma_0 - 1]^2}{1 + \left(\frac{\theta}{\theta_j}\right)^{2p}}$$

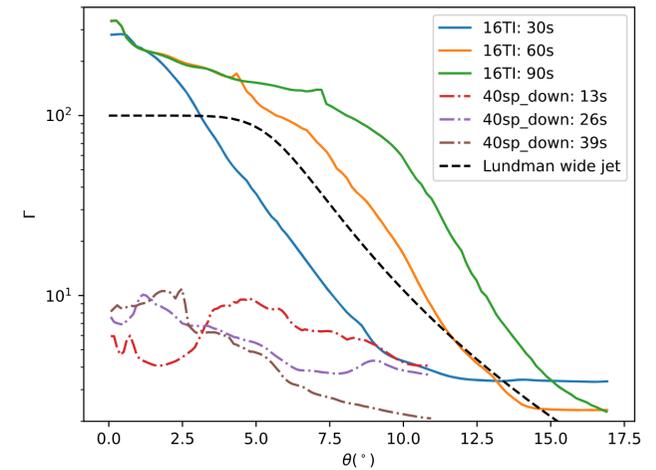
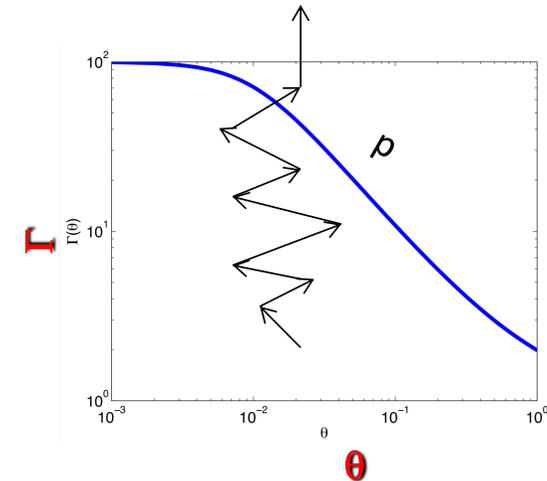
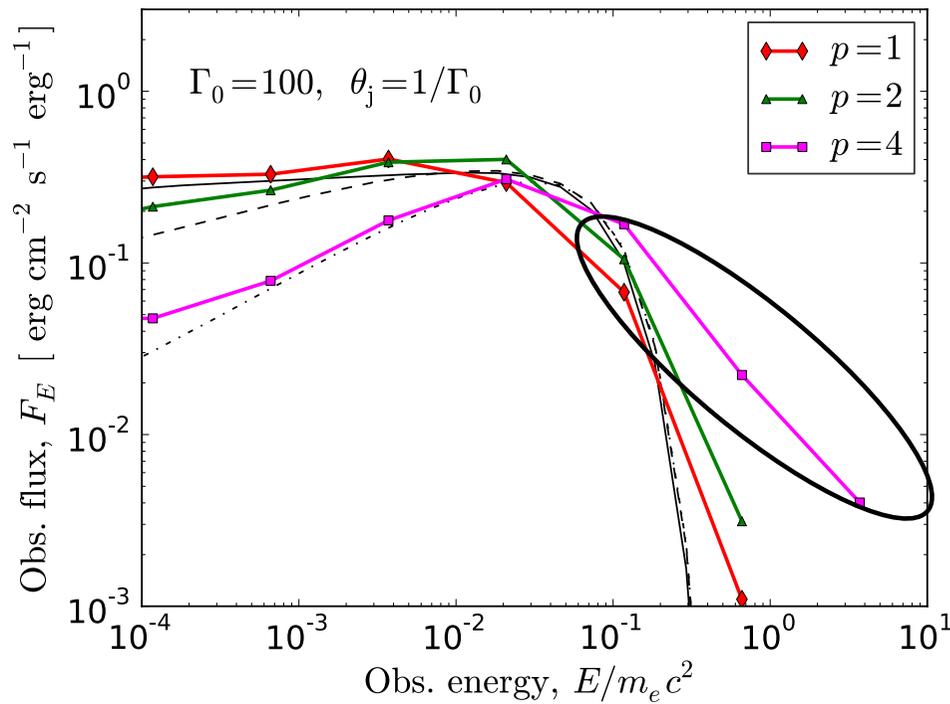


Figure 3. Plot of the Lorentz factor, Γ , of the synthetic *16TI* and *40sp_down*

Parsotan et. al., 2020

Photon up-scattering by Fermi-like mechanism



$$\left\langle \frac{v_{out,1}}{v_{in,2}} \right\rangle \approx \frac{1}{2} \left(1 + \left(\frac{\Gamma_2}{\Gamma_1} \right)^2 \right)$$

1 → 2 → 1

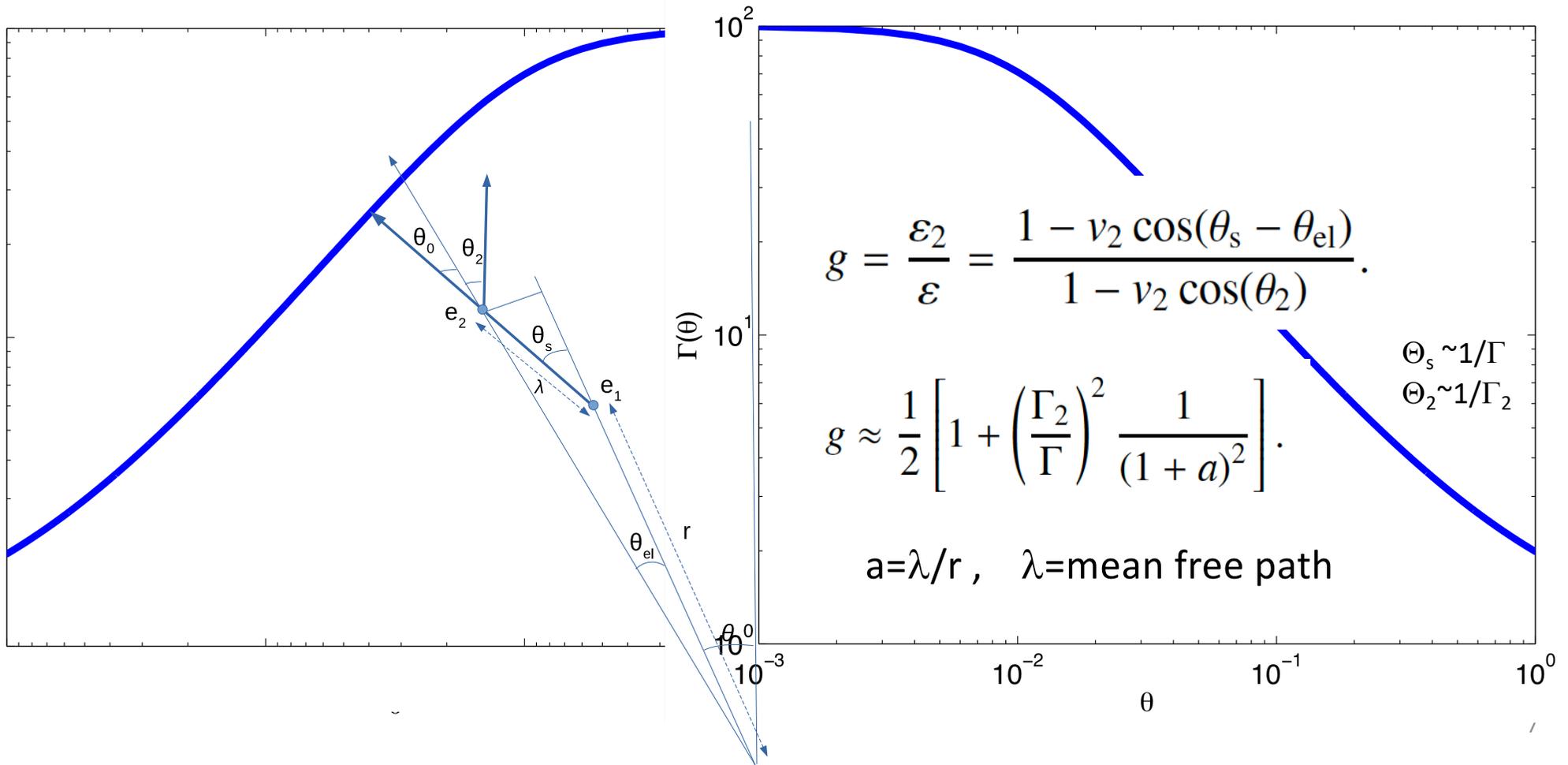
$$\left\langle \frac{v_{out}}{v_{in}} \right\rangle \approx \frac{1}{4} \left(1 + \left(\frac{\Gamma_2}{\Gamma_1} \right)^2 \right) \left(1 + \left(\frac{\Gamma_1}{\Gamma_2} \right)^2 \right) > 1$$

Repeated scattering between regions of different Γ , causes photon energy increase.

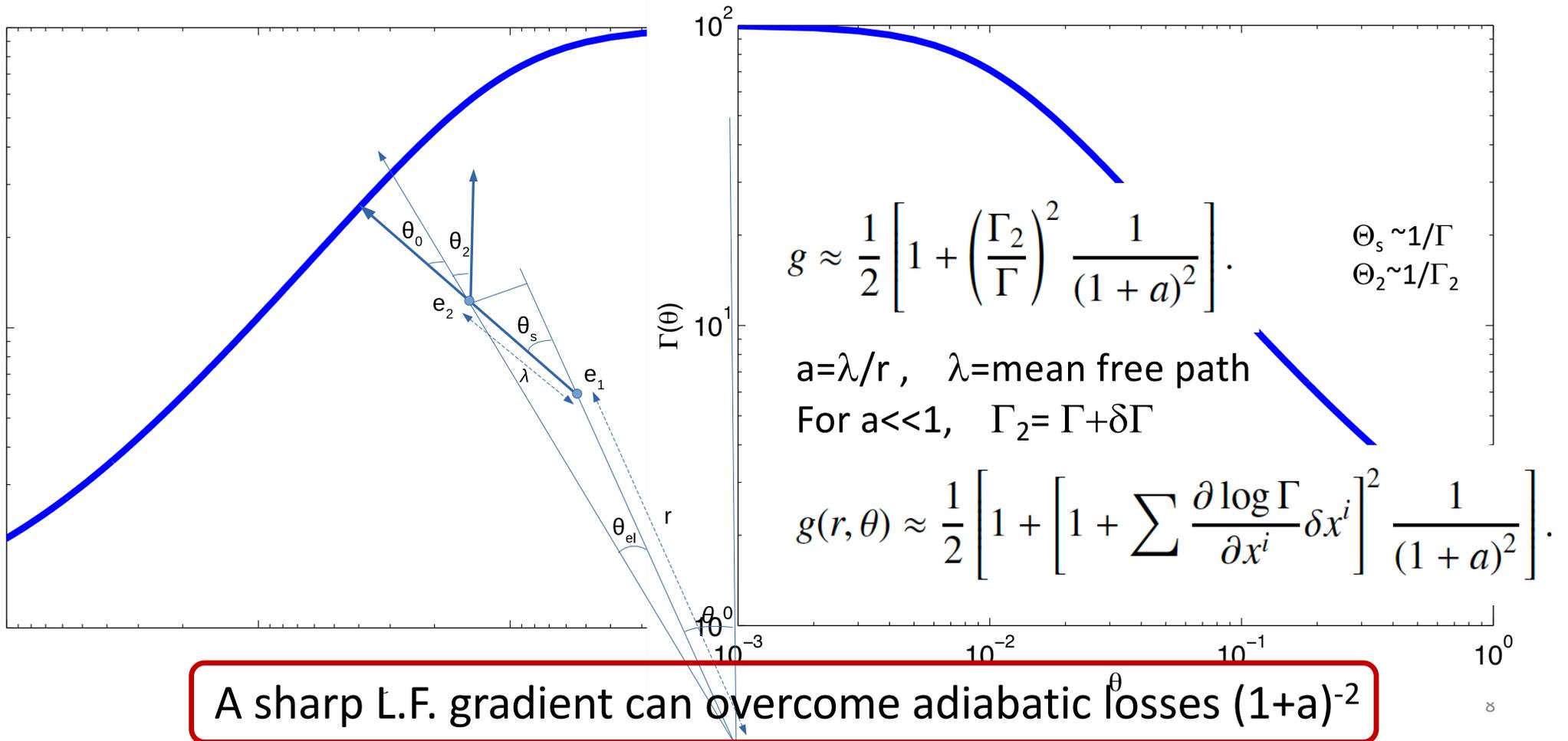
Lundman, AP & Ryde (2013, 2014); Ito.. Pe'er et. al. (2013)

Full calc. >>

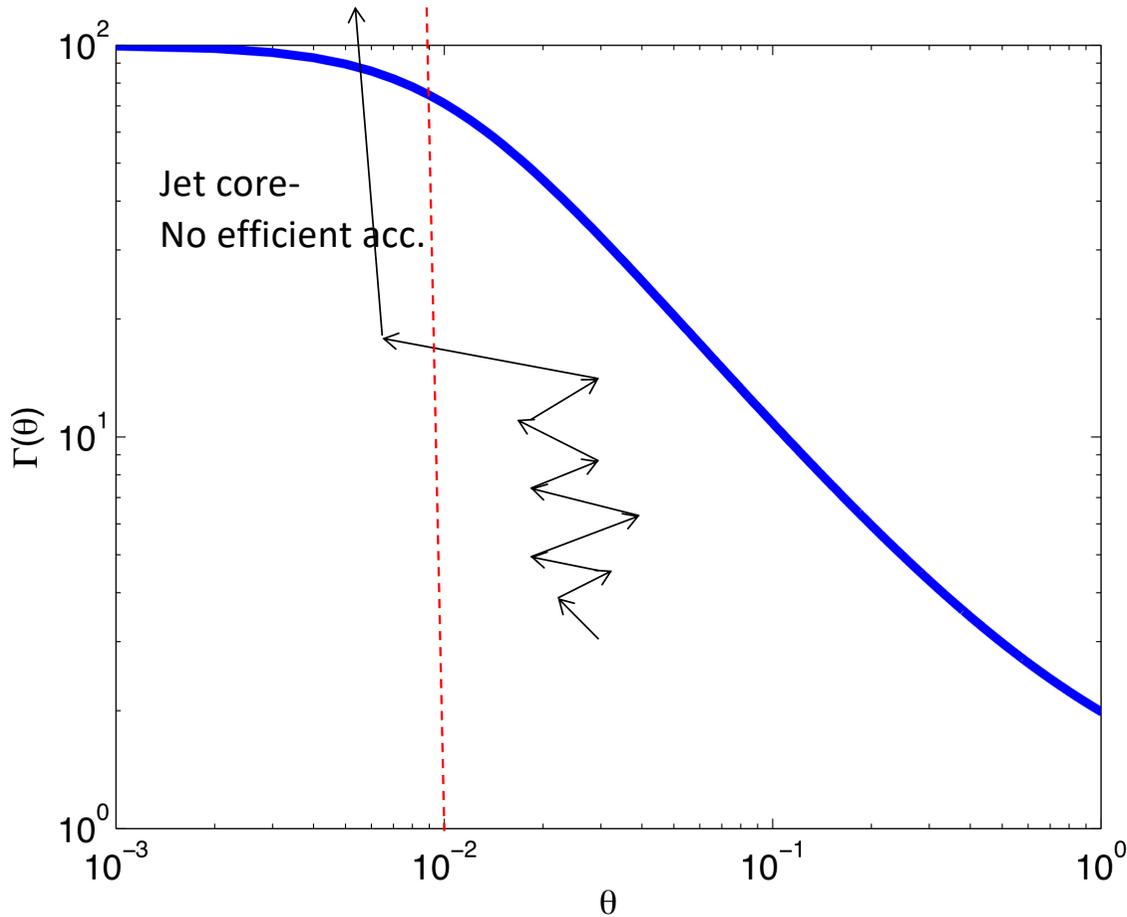
Photon energy gain: basic idea



Photon energy gain: basic idea



Multiple scattering: obtaining a power law



Expectation value of photon energy gain:

$$\bar{g} = \frac{1}{V} \int dV g(r, \theta)$$

Prob. of staying in the shear region:

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

$$P(r, \theta) = 1 - e^{-\tau(r, \theta)}$$

After k scattering photon energy is ε_k

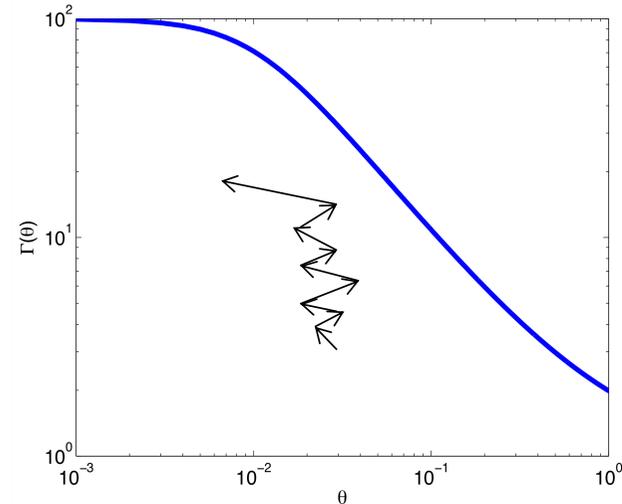
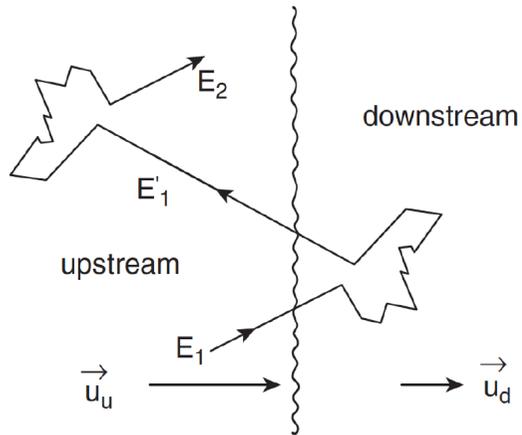
$$N = N_0 \bar{P}^k$$

$$\frac{N}{N_0} = \left(\frac{\varepsilon_k}{\varepsilon_0} \right)^{\beta'}$$

Obs. Photon index

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

1st order Fermi acceleration vs. photon energy gain



❖ g, p avg. over scattering angle, θ

❖ Electrons escape downstream

❖ Local isotropy

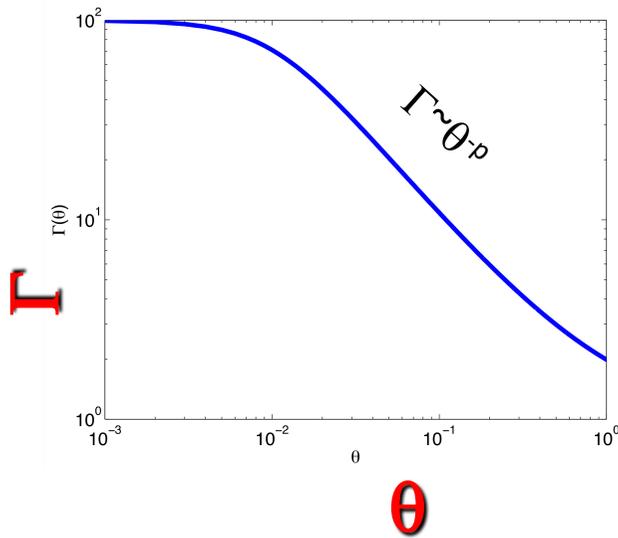
❖ g depends on both θ and \vec{r}
→ Need to avg. over entire scattering region

❖ Photons escape mainly into the inner jet
(some at the photosphere)

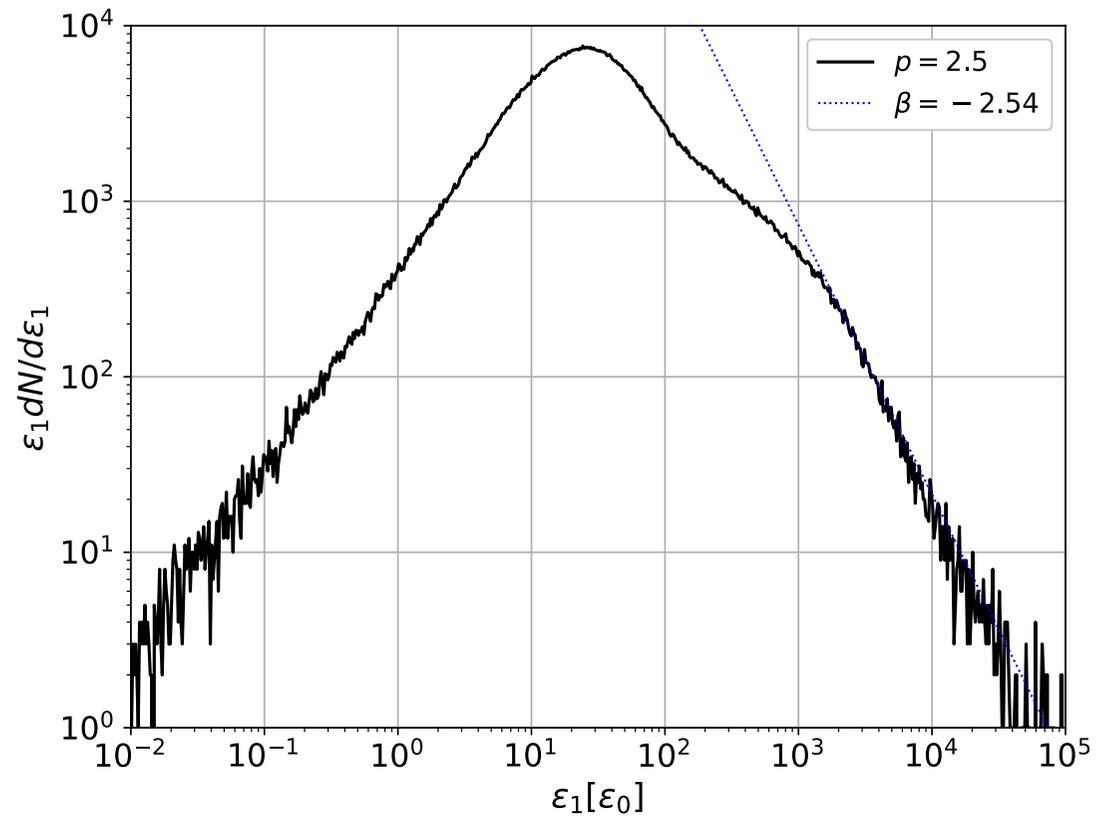
❖ → process is unisotropic

Results: Monte-Carlo simulation

$N_\gamma = 10^{6.5}$, $\Gamma_0 = 100$, $\theta_j = 0.01$, $\varepsilon_0 = 10^{-6} m_e c^2$

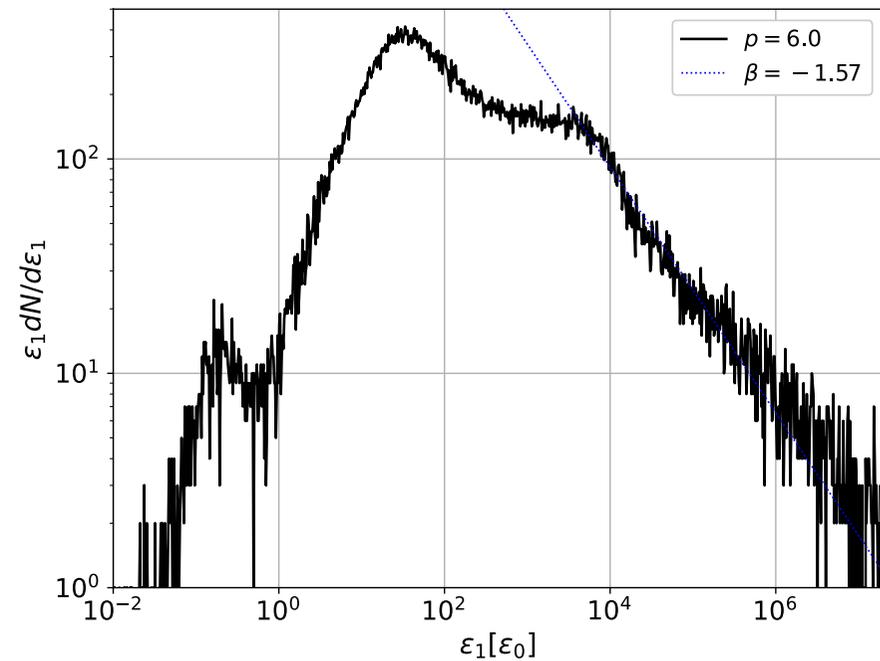
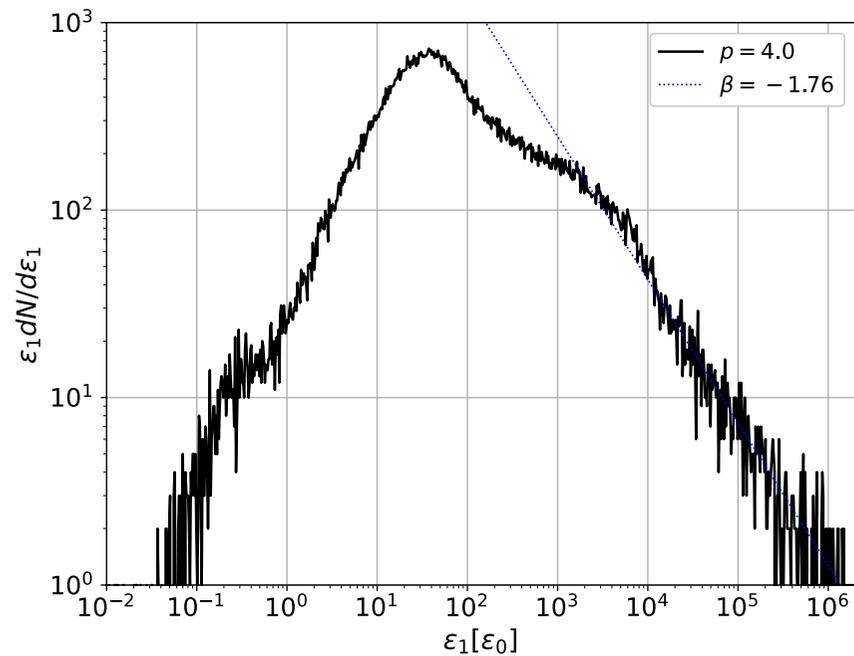


$$[\Gamma(\theta) - 1]^2 = \frac{[\Gamma_0 - 1]^2}{1 + \left(\frac{\theta}{\theta_j}\right)^{2p}}$$



Confirm analytic estimate: High energy power law; spectral slope $\beta = -2.54$

Results: slope dependence on p (jet structure)



Larger jet gradient (p) --- more efficient H.E. power law production (lower β)

Semi-analytic expression of the spectral slope

Asymptotic expression:

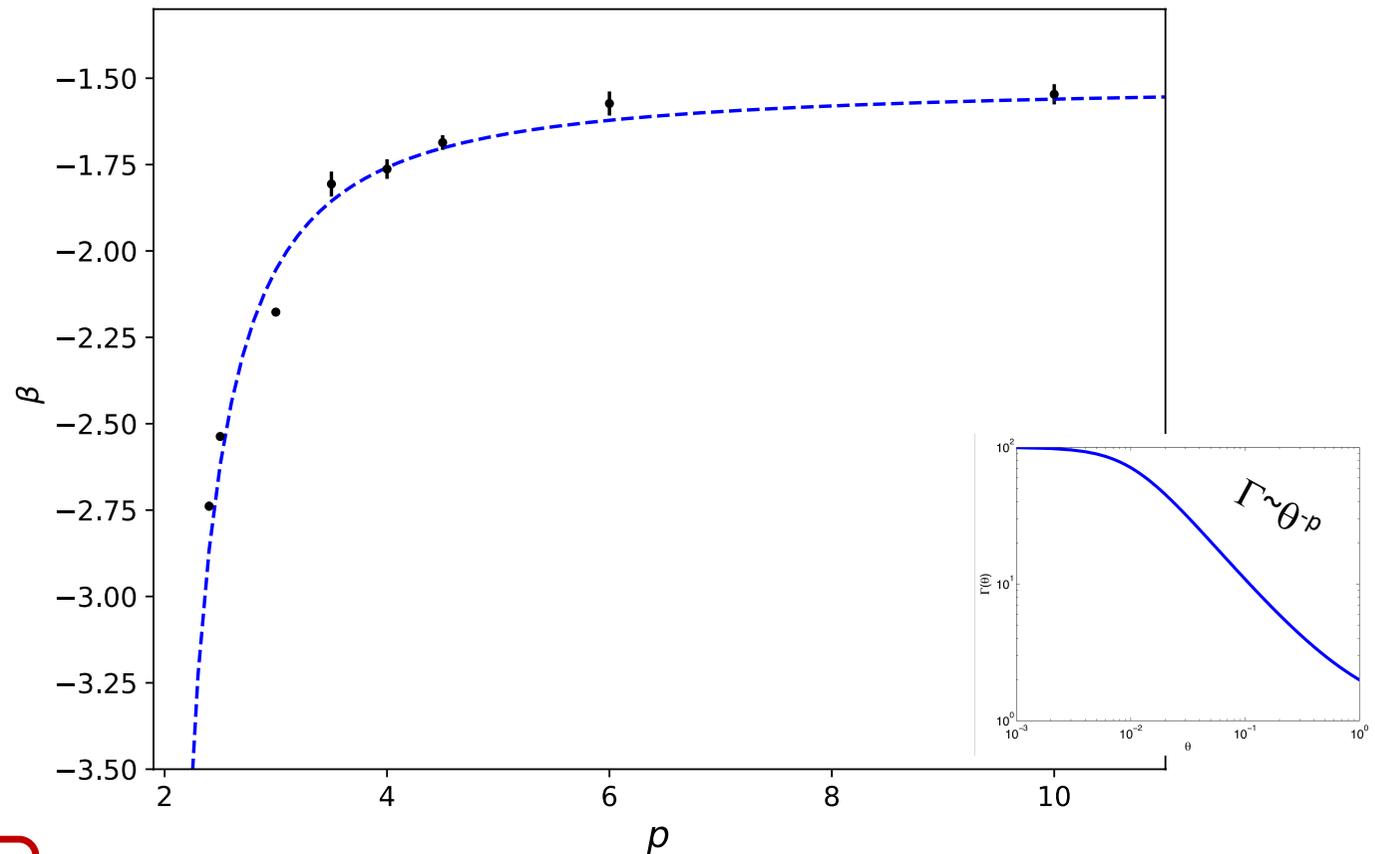
$$\tau \ll 1 \rightarrow P(r, \theta) \sim \tau$$

$$\langle g \rangle \sim p^2 ; p = \text{power law}$$

$$\langle P \rangle \sim \Gamma_0^{(1/p) - 1}$$

$$\beta = \frac{\ln \bar{P}}{\ln \bar{g}} - 1 \rightarrow -1.5$$

Prediction ! $\beta \leq -1.5$



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Summary

- Jets have angular structure.
- Repeated scattering in regions of velocity shear **produces a power law.**
- Similarity to 1st order Fermi acceleration.
- **Valid alternative to synchrotron emission** from power law distributed electrons
- Semi-analytic expression for the high energy slope β as a function of the jet gradient is derived.

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