On the role of neutral particles in generation of cosmic rays

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What limits acceleration?

Particle escape from the accelerator

Degradation of particles' energy

- Sinchrotron radiation
- Inelastic collisions
- Inverse Compton losses (for electrons)
- Photomeson interactions and creation of e^-e^+ pairs (for protons and nuclei)

The probability of photon-induced reaction is usually small, $\ll 1$

How small has to be “small” to become dynamically negligible?

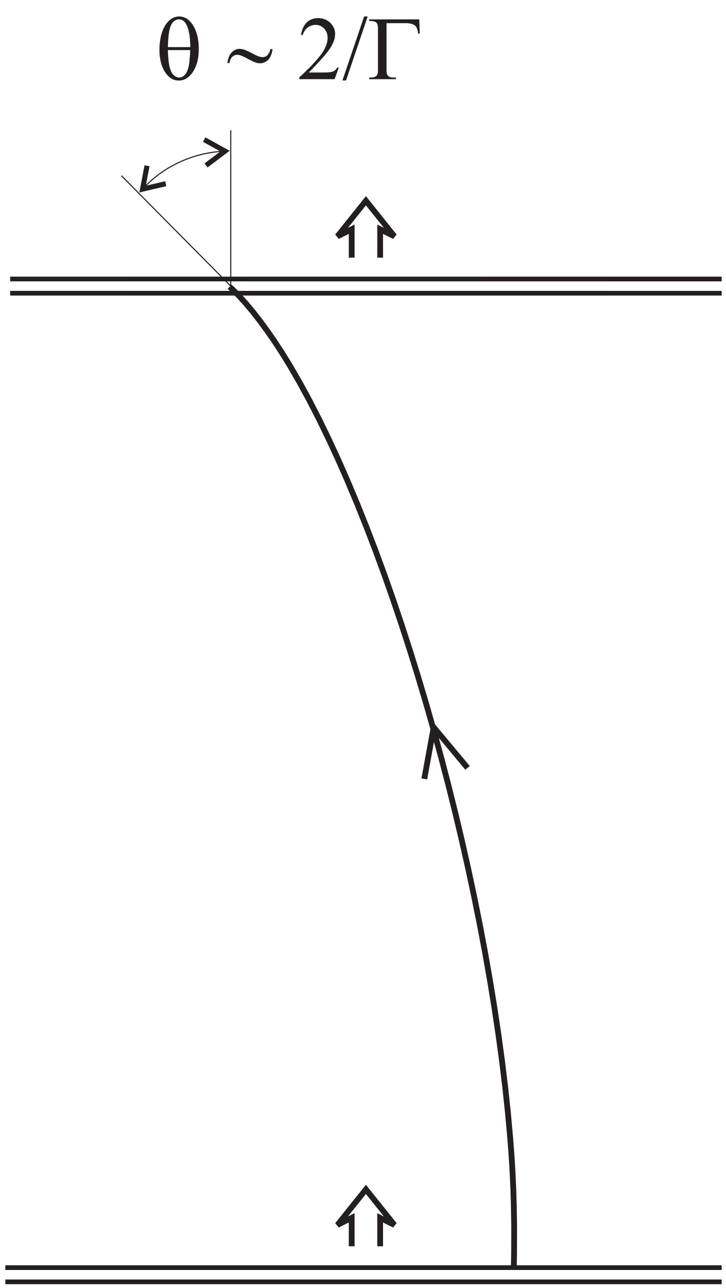
For a non-relativistic shock, a probability $\ll 1$ is always small

For a relativistic flow, the answer is either $\ll 1$ or $\ll 1/\Gamma^2$, depending on what you are talking about

If some energy leaks from downstream to upstream and mixes up with the upstream particles, we feed back to the shock Γ^2 times the initial energy!

Γ is the Lorentz factor of the flow

When "small" is large (standard acceleration)



The distribution of accelerated particles remains highly collimated.

The energy gain factor $g = (1/2)\,(\Gamma\theta)^2 \simeq 2$

The probability of particle injection back to upstream must be ~ 1 to get efficient acceleration. The actual probability depends on the (unknown) magnetic field geometry.

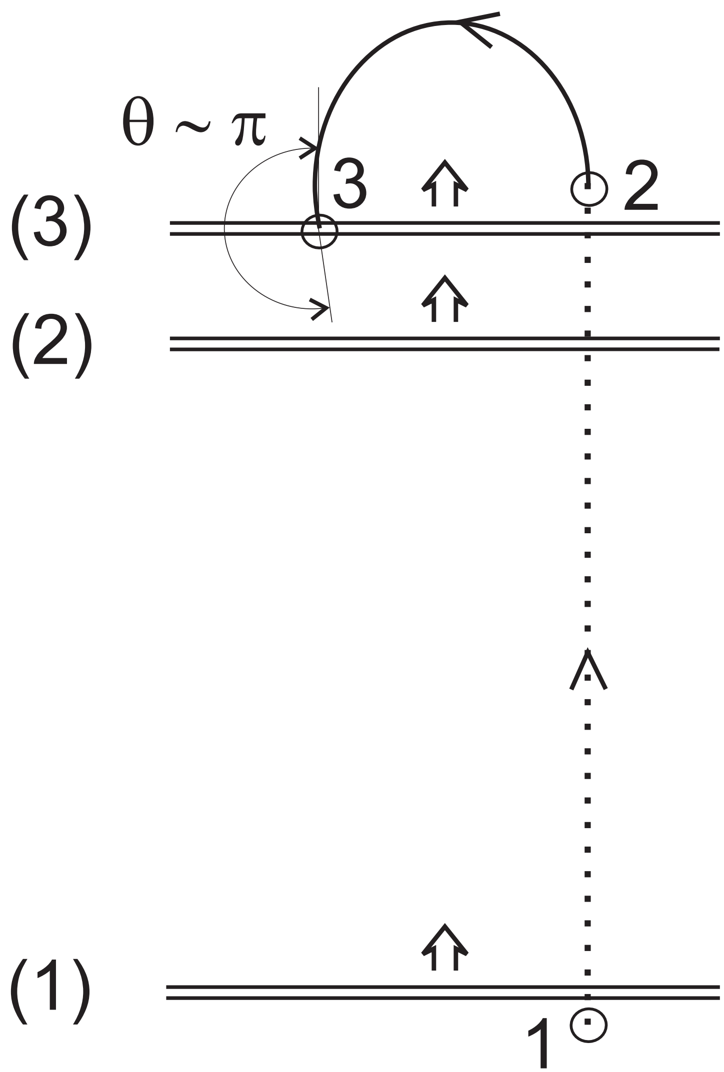
Favorable geometry gives, e.g., $\frac{\mathrm{d}N}{\mathrm{d}\varepsilon} \propto \varepsilon^{-\frac{22}{9}}$

(Keshet & Waxman, PRL 2005)

"Realistic" geometry leads to very soft particle distributions, with energy concentrated near $\Gamma^2 mc^2$

(Niemiec & Ostrowski, ApJ 2006;
Lemoine, Pelletier & Revenu, ApJ 2006)

When "small" is REALLY small



Full isotropization in the upstream ($\theta \sim 1$) gives the energy gain factor $g = \frac{1}{2}(\Gamma\theta)^2 \sim \Gamma^2$ in each shock-crossing cycle

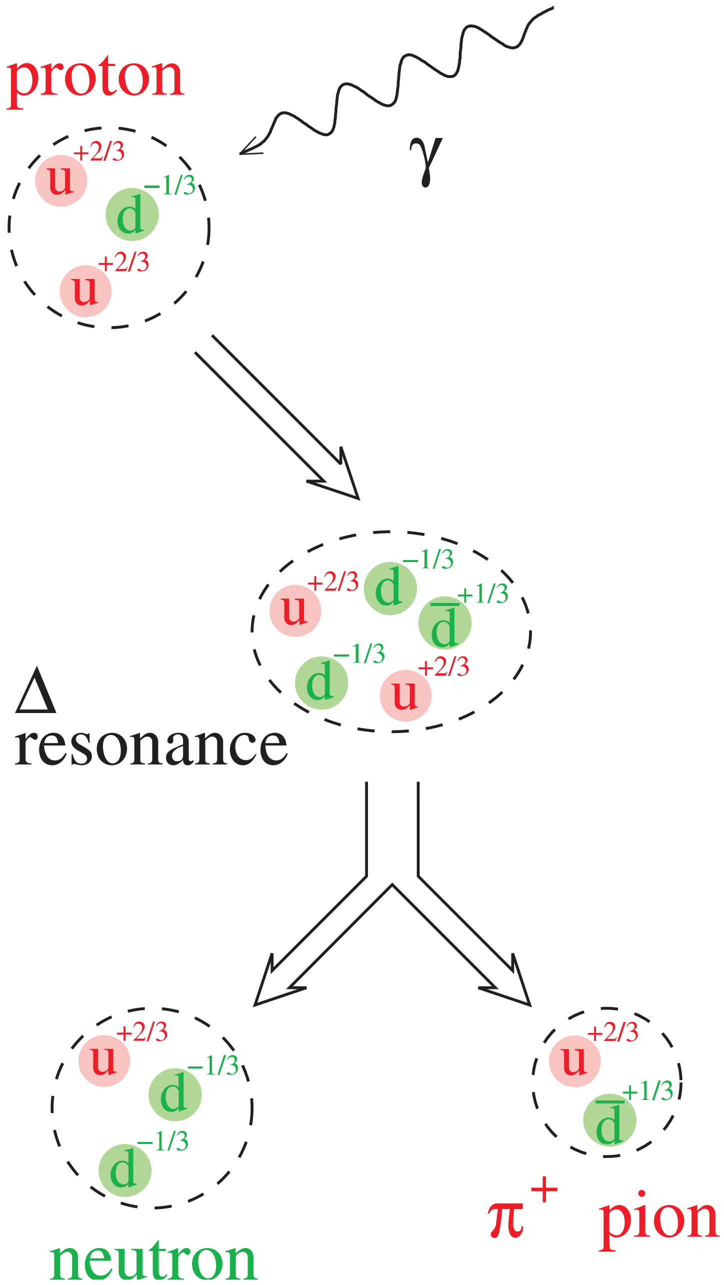
Photon-induced reactions reversibly "convert" accelerated particles to neutrals

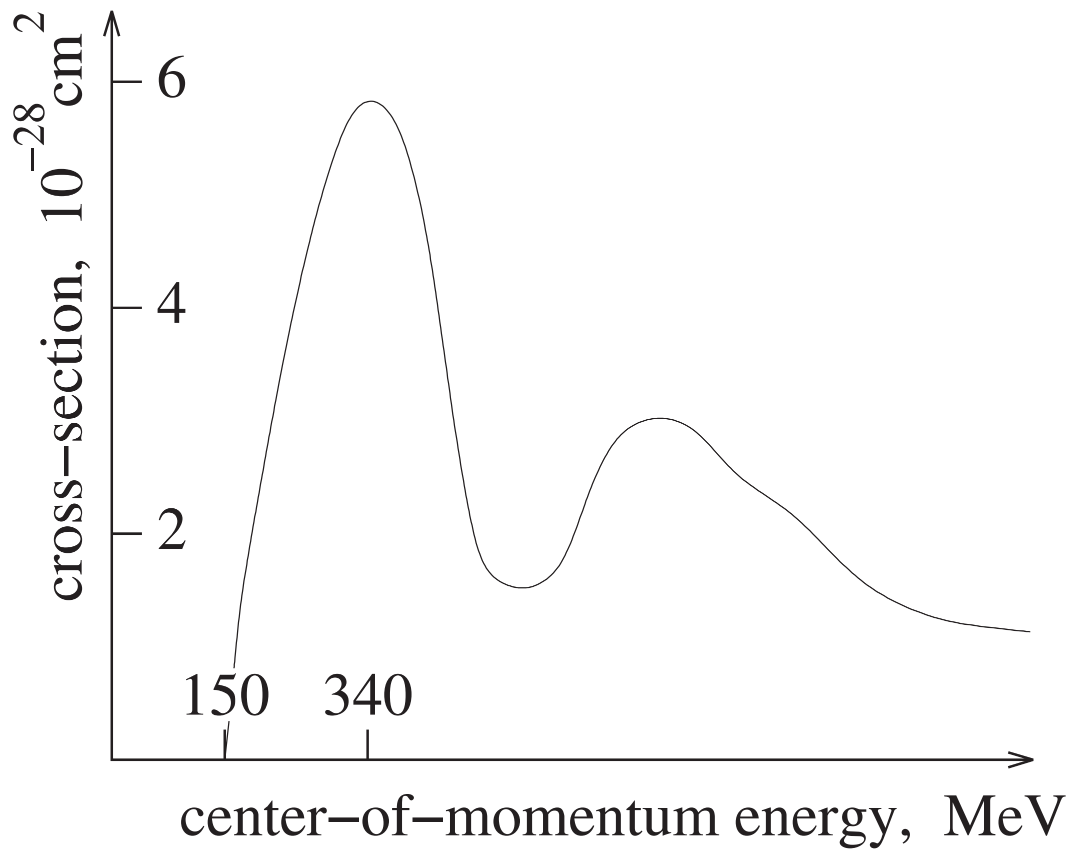
$\Rightarrow$ **Converter acceleration mechanism**

Derishev, Aharonian, Kocharovsky & Kocharovsky, PRD 2003;

Stern, MNRAS 2003

Conversion to neutrals for protons

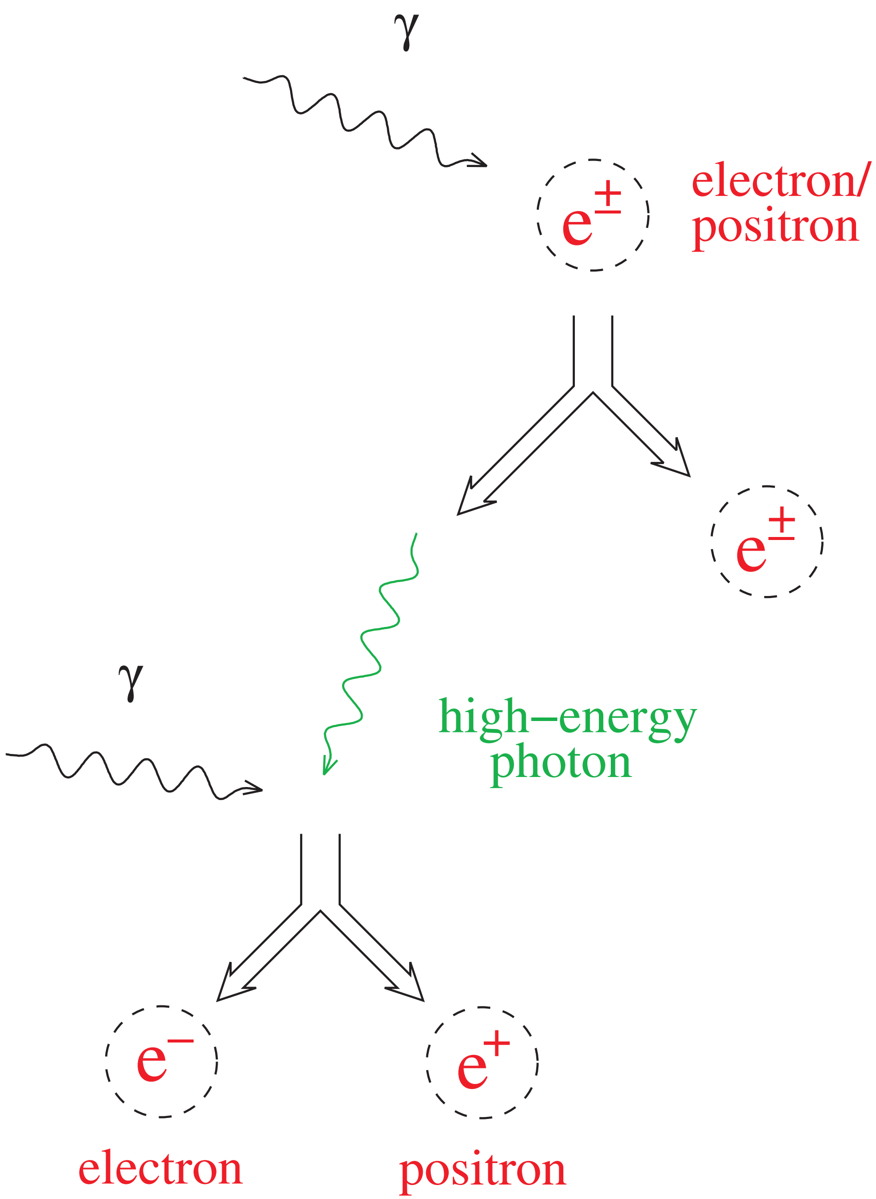


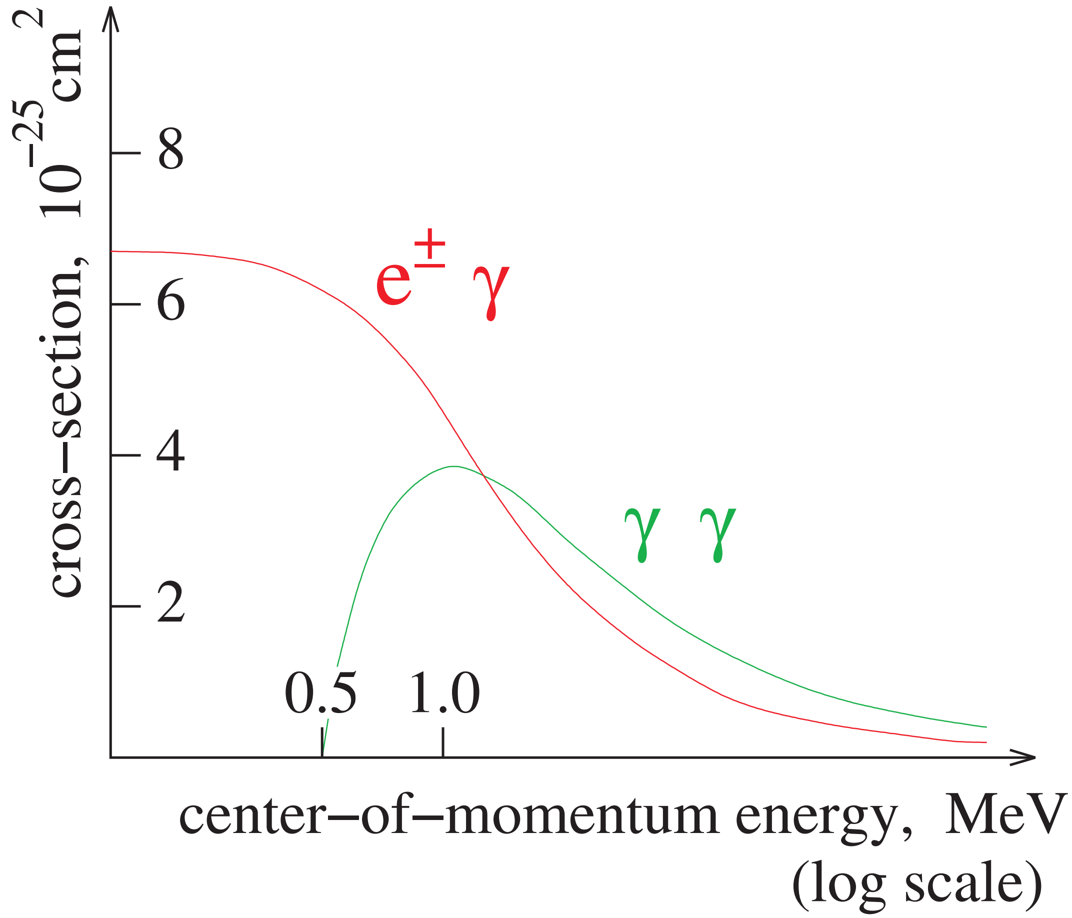


The proton cycle

- Requires presence of dense photon field or dense baryonic matter
- Operates down to mildly relativistic bulk velocities
- Accompanied by powerful neutrino emission
- If efficient, quenches the electron cycle

Conversion to neutrals for electrons/positrons





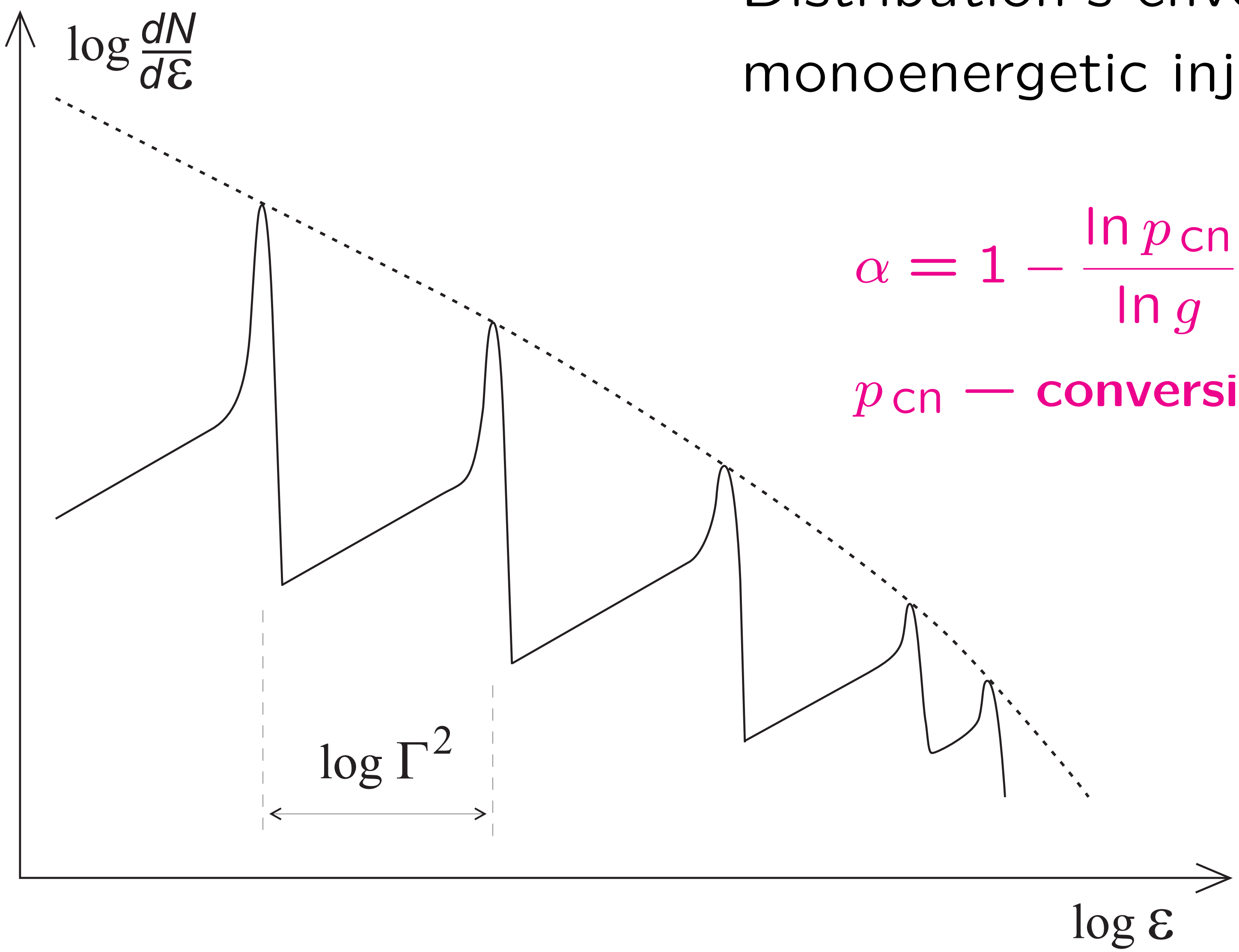
The electron cycle

- Operates in relatively week photon fields

- Usually requires bulk Lorentz factor in excess of a few

- Has two regimes: externally pumped cascade and acceleration

Emerging particle distribution



Distribution's envelope for monoenergetic injection: $\frac{\mathrm{d}N}{\mathrm{d}\varepsilon} \propto \varepsilon^{-\alpha}$

$\alpha = 1 - \frac{\ln p_{\mathrm{cn}}}{\ln g}$ — **spectral index**

p_{cn} — **conversion probability**

Estimations of the conversion probability

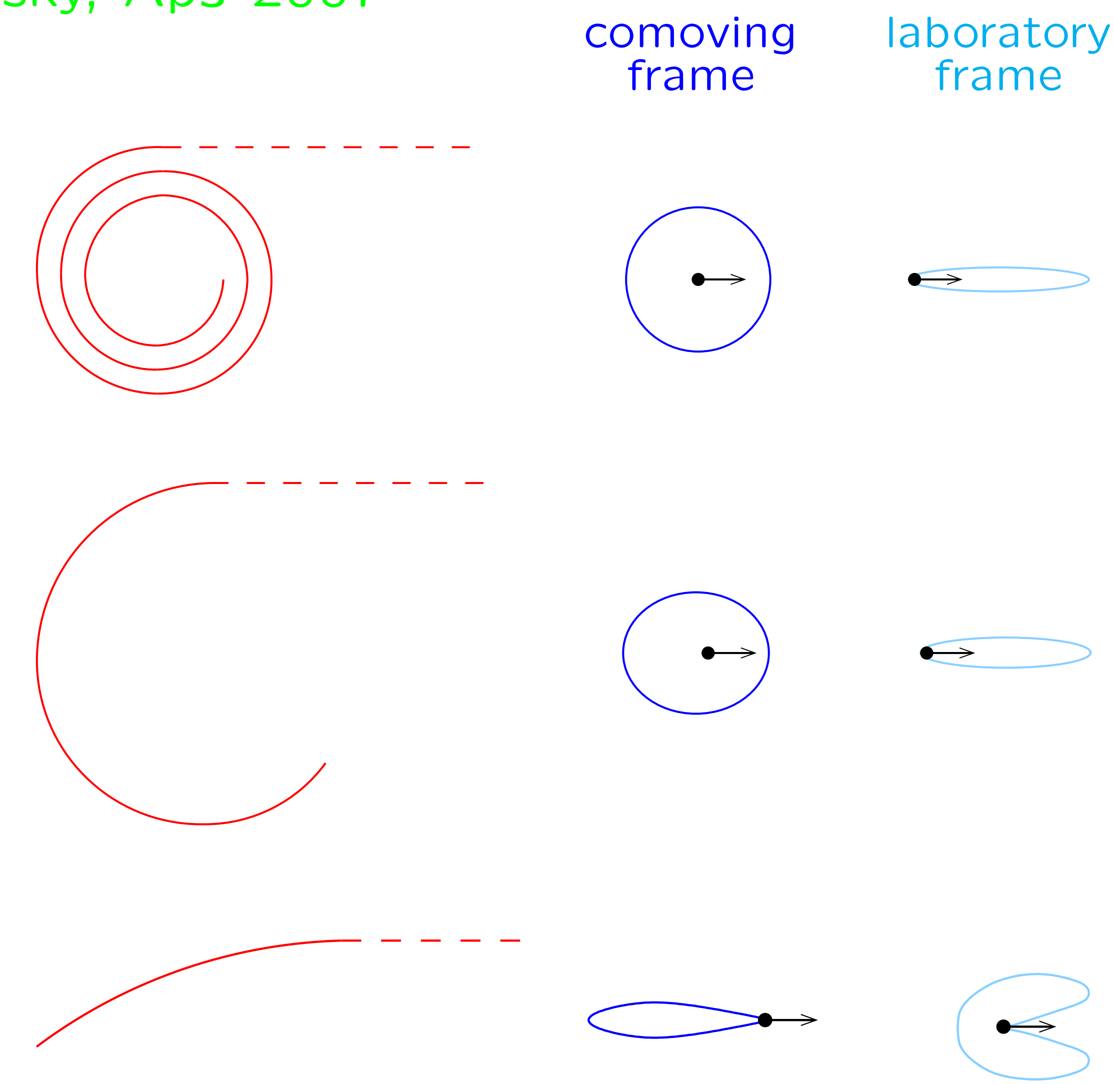
	Active Galactic Nuclei	Gamma-Ray Bursts
Luminosity/ Energy release	$L_{\rm BLR} \sim 10^{44}$ erg/s	$E_{\rm Xray} \sim 10^{52}$ erg
Distance	$R \sim 3 \times 10^{17}$ cm	$R \sim 3 \times 10^{16}$ cm
Avrg. photon energy	$\varepsilon_* \sim 6$ eV	$\varepsilon_* \sim 600$ keV
Conversion threshold	$\varepsilon \sim 10^{15}$ eV	$\varepsilon \sim 10^{12}$ eV
Optical depth: $\dfrac{\sigma_{p\gamma} L}{\pi R c \varepsilon_*}$ or $\dfrac{\sigma_{p\gamma} E}{4\pi R^2 \varepsilon_*}$	$\tau \sim 0.07$	$\tau \sim 2 \times 10^{-4}$

$L_{\rm BLR}$ – luminosity of the broad-line region

$E_{\rm Xray}$ – energy released in the form of hard X-rays

Changes in the beam-pattern

Derishev, Aharonian & Kocharovsky, ApJ 2007



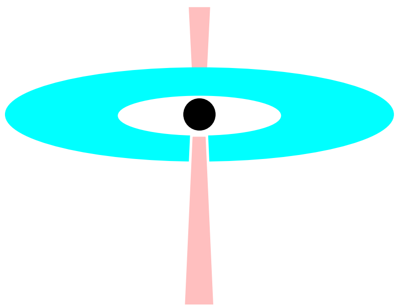
- **Low-energy particles**
  $\varepsilon \ll \varepsilon_{\rm cr}$

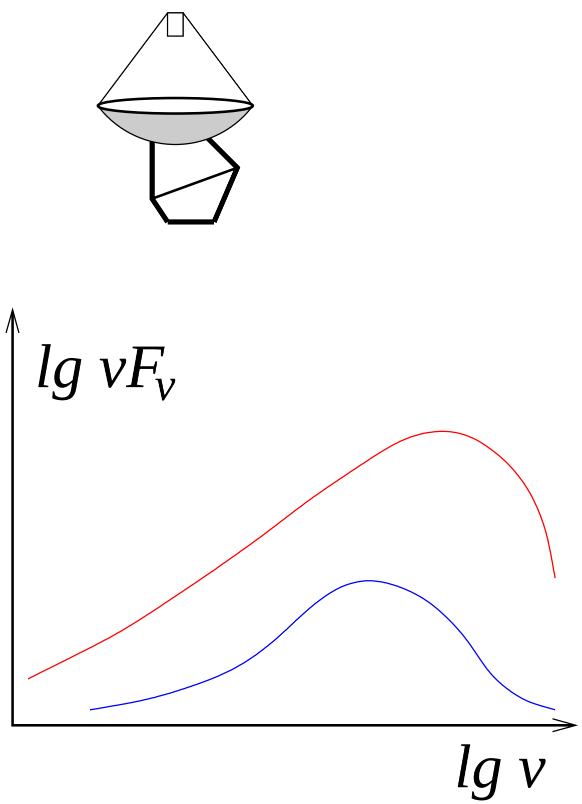
- **Critical-energy particles**
  $\varepsilon \simeq \varepsilon_{\rm cr}$

- **High-energy particles**
  $\varepsilon \gg \varepsilon_{\rm cr}$

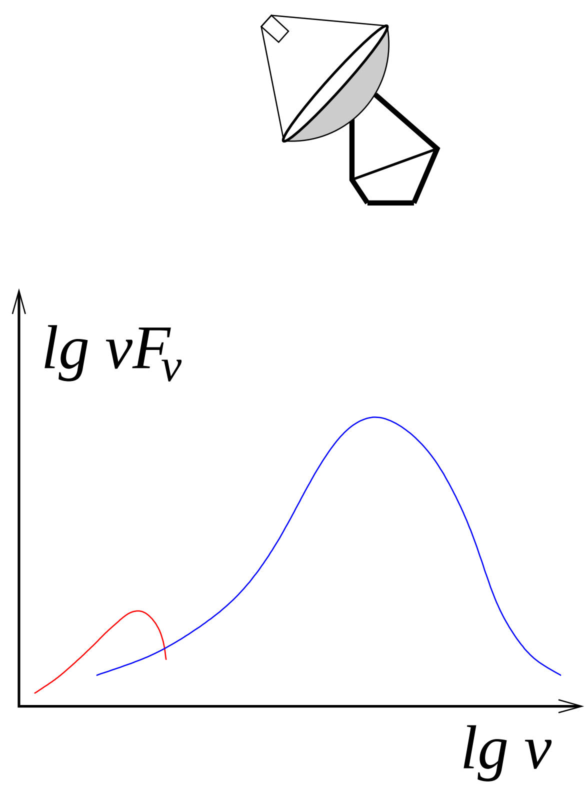
$\varepsilon_{\rm cr} = \frac{3}{2}\frac{\left(m_e c^2\right)^2}{e^{3/2}B^{1/2}}$; $h\nu \sim 100 \times \Gamma$ MeV — for synchrotron losses

Gamma-ray sources without a counterpart





on-axis view



off-axis view

Distinctive features of the converter mechanism

- Protons are accelerated, but not nuclei

- Accelerated particles reach supercritical energies, so that the spectrum of their synchrotron emission extends to much higher frequencies (up to Γ^2 times higher compared to diffusive shock acceleration mechanism)

Distinctive features of the converter mechanism

- **Emerging particle distribution is not universal, but instead depends on the source parameters**

Good for explaining the whole variety of spectra?

- **Broadening of beam pattern (up to becoming nearly isotropic) for high-energy emission in the sub-GeV − TeV range with possible applications to:**

high-latitude unidentified EGRET sources = off-axis blazars?

prolonged GeV emission from Gamma-Ray Bursts =
geometrically retarded off-axis emission?

Diffusive shock acceleration	Converter acceleration
Probability of injection is sensitive to the magnetic field geometry	Injection is equally easy at any point in the downstream
Acceleration efficiency is sensitive to the magnetic field geometry	Acceleration does not depend on the magnetic field geometry
Smoothing out sharp discontinuities progressively decreases efficiency	Efficiently works even in absence of any discontinuities
Acceleration starts from thermal ion energy	Acceleration is efficient only past certain energy threshold
Does not depend on presence of photon fields	Requires intense photon fields
Works for both relativistic and non-relativistic outflows	Requires relativistic hydrodynamical velocities