The Converter Acceleration Mechanism for Potential Sources of Ultra-High Energy Cosmic Rays

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For refs see an introductory review Physics-Uspekhi **50** (3), 308 (2007) and original papers Phys.Rev. D **66**, 023005 (2002); **68**, 043003 (2003); ASS **297**, 21 (2005); ApJ **655**, 980 (2007)

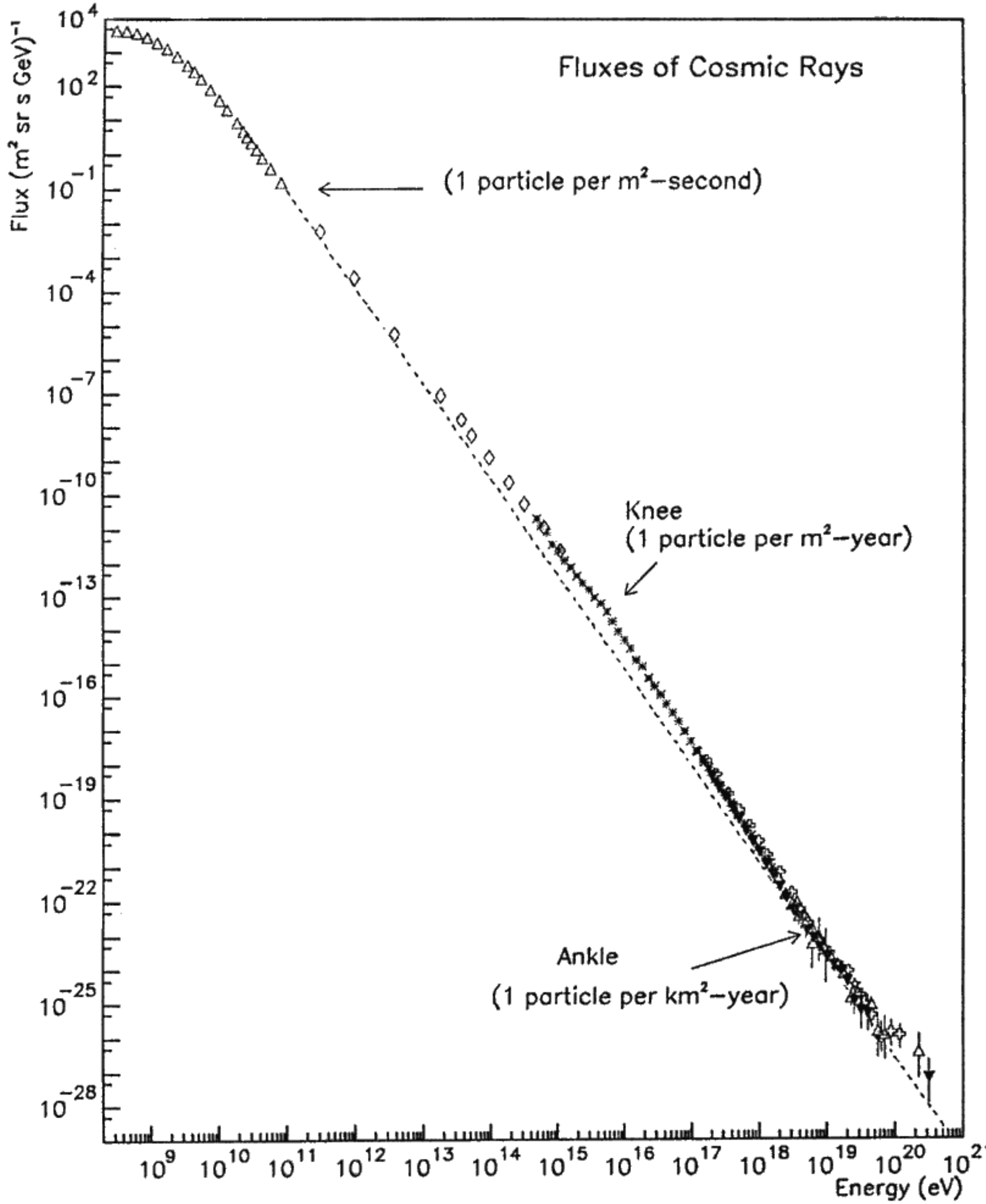
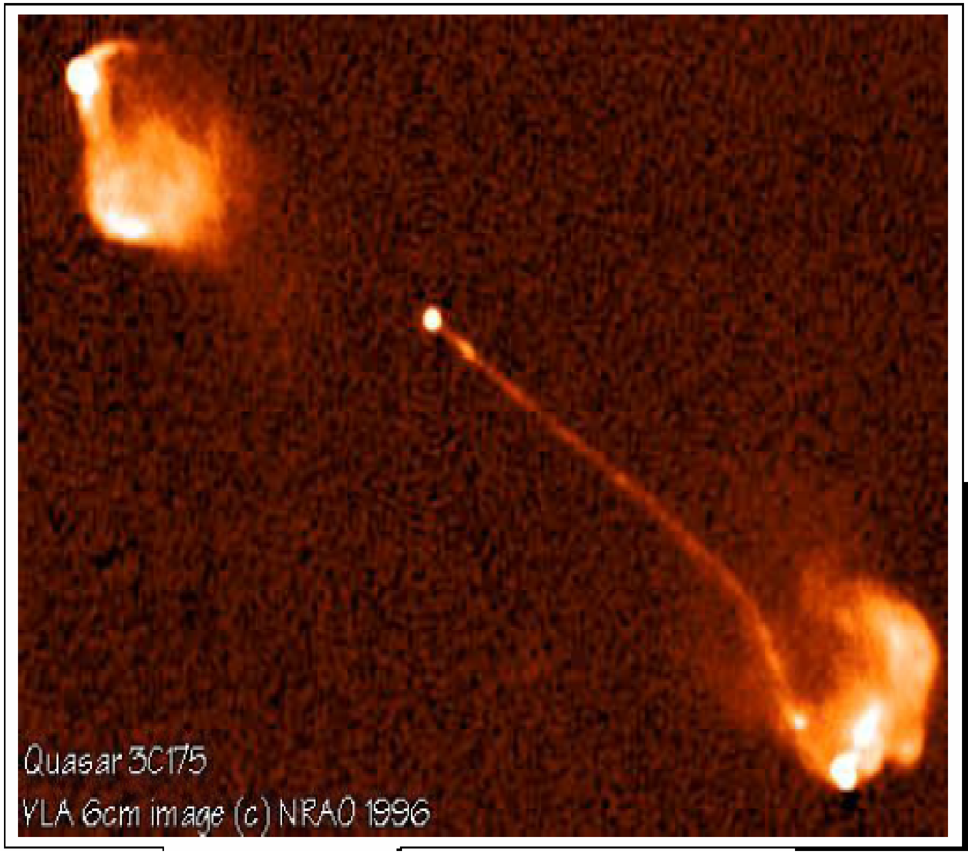


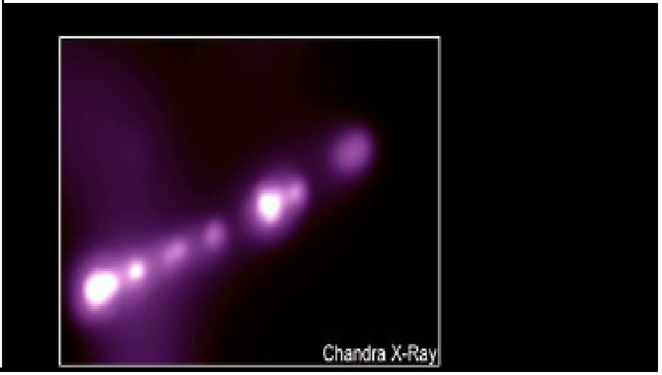
Fig. 1. The CR all particle spectrum [509]. Approximate integral fluxes are also shown.

Fermi-type acceleration

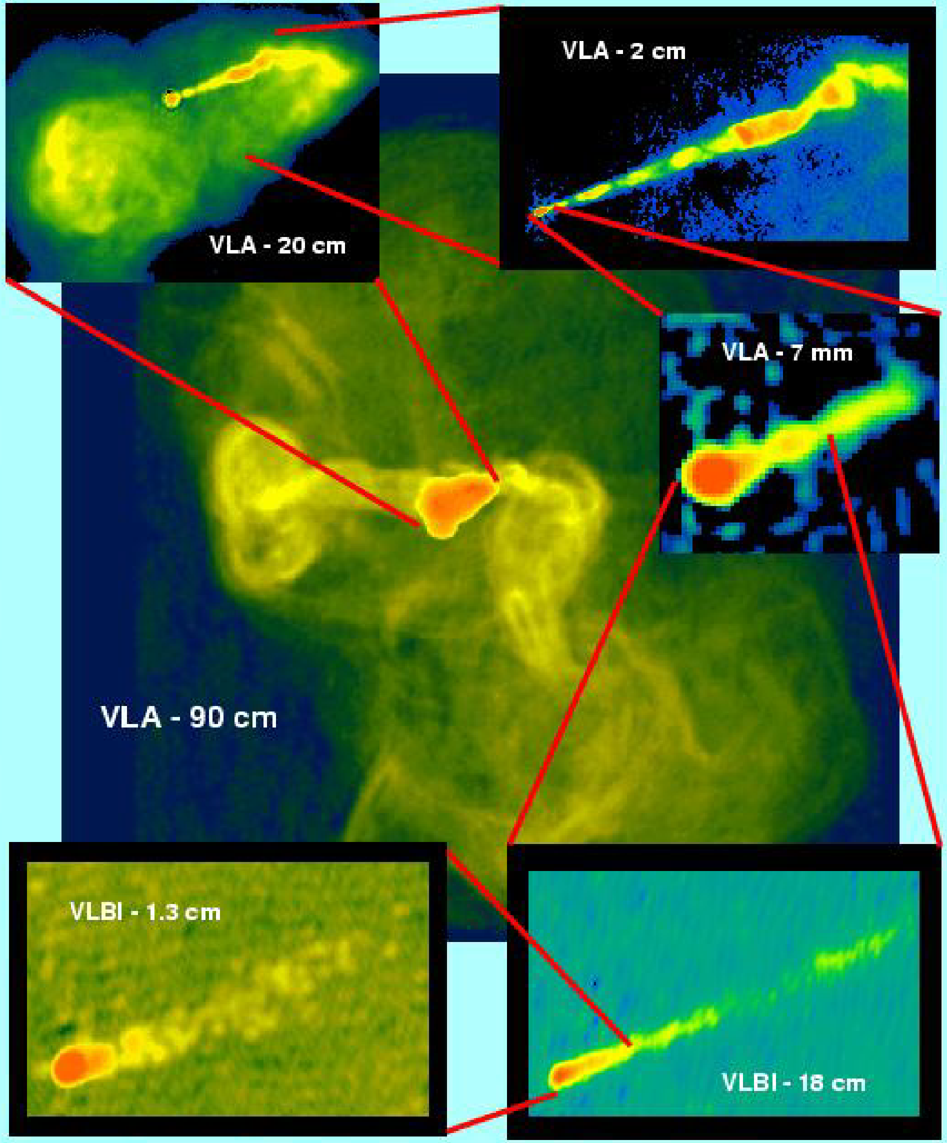
- I, II, and I & II
- Shocks and shear flow
- Supernovae
- Problems
- Relativistic flows

Examples of relativistic jets

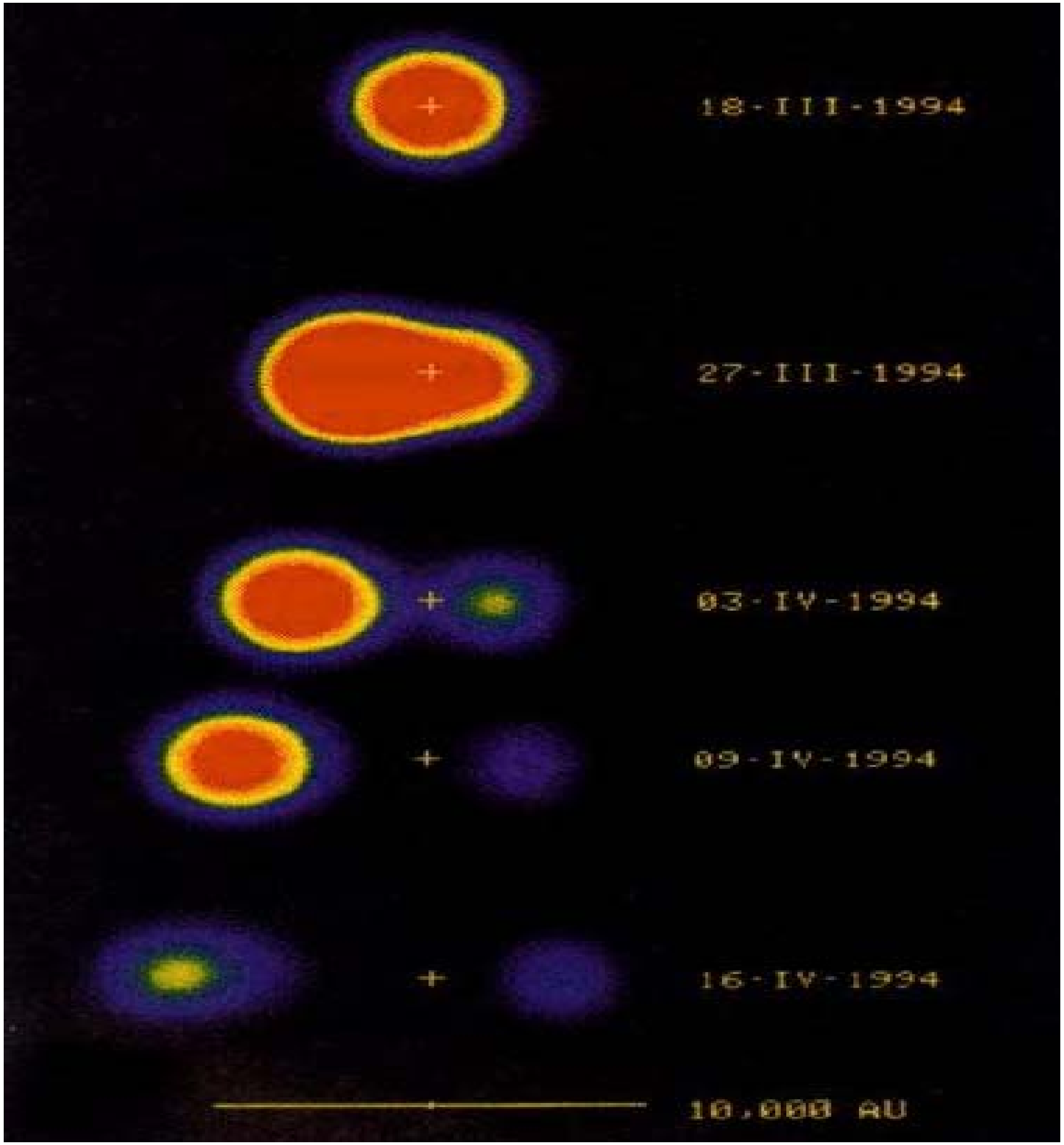




M87 -- From 200,000 Light-Years to 0.2 Light-Year



Credit: Frazer Owen (NRAO), John Biretta (STScI) and colleagues.
The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.



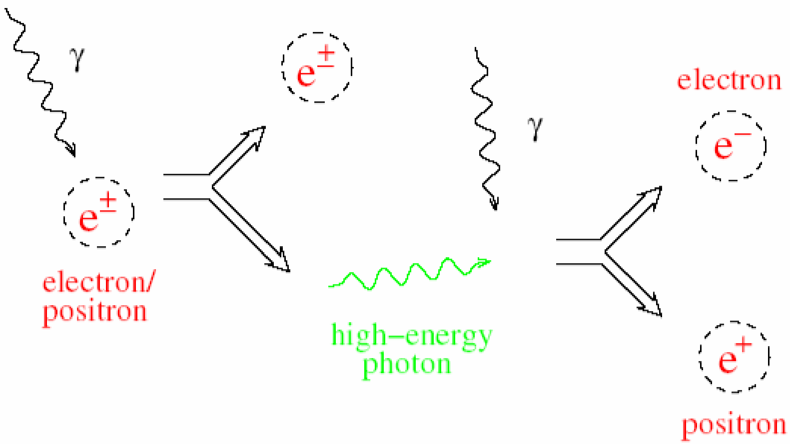
- Apparent superluminal motion in microquasars

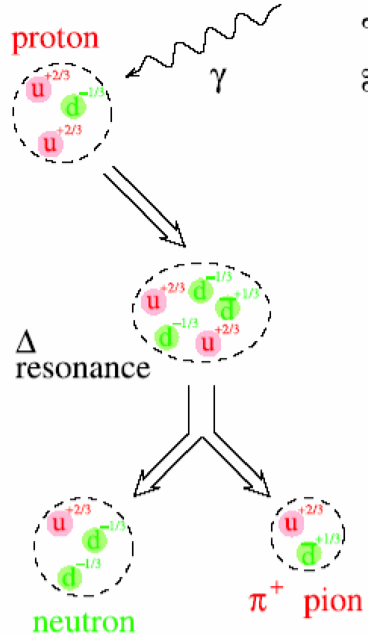
Relativistic outflows

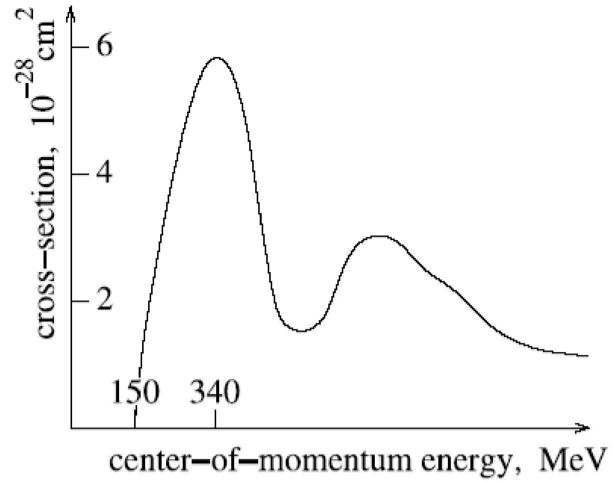
- Energy gain at each particle-shock encounter: Γ^2 vs. 2
- Particle conversion from charged into neutral state and back
- Radiative and photo-pion losses
- Acceleration efficiency and nonlinear phase
- Observation of acceleration sites

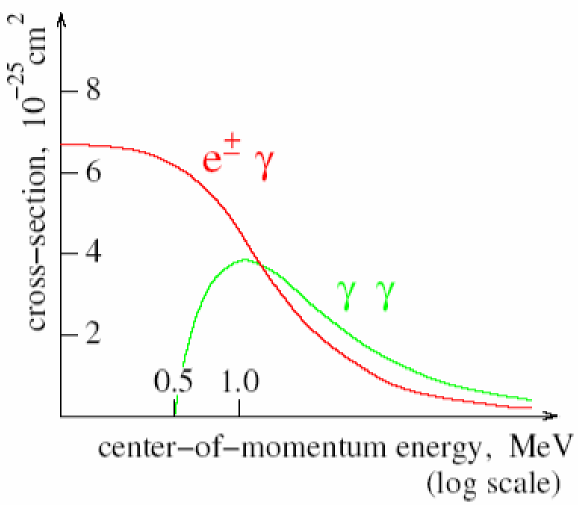
e^-/e^+ - γ cycle

p - n cycle









	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: $\frac{\sigma_{p\gamma} L}{\pi R c \varepsilon_*}$ or $\frac{\sigma_{p\gamma} E}{4\pi R^2 \varepsilon_*}$	$\tau \sim 0.07$	$\tau \sim 2 \times 10^{-4}$

Diffusive shock acceleration

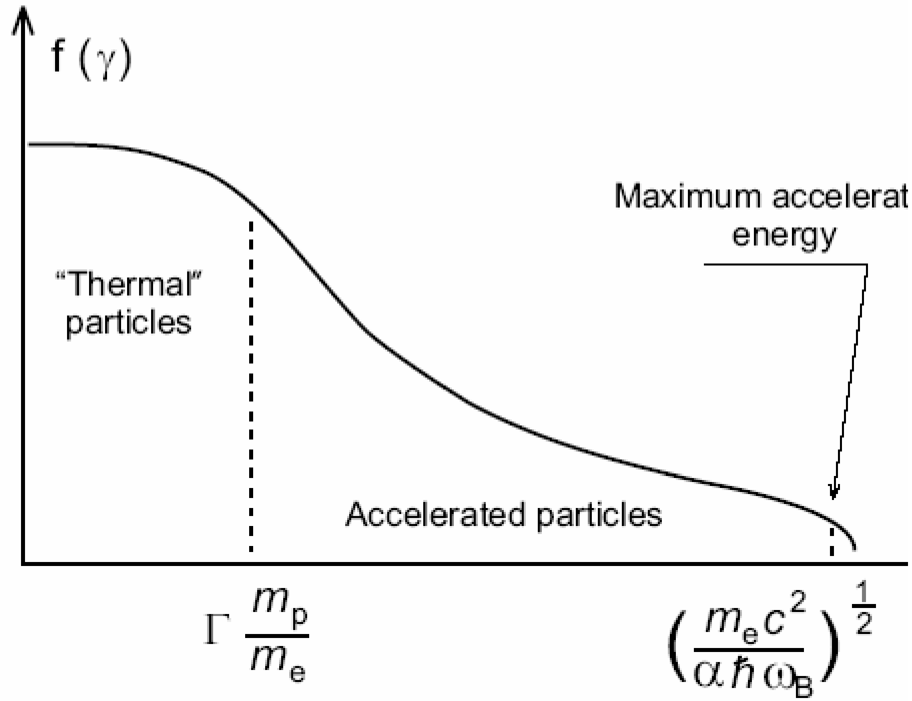
Γ – Lorentz-factor of the shock,

γ – Lorentz-factor of an electron,

$\omega_B = eB/m_e c$ – gyrofrequency,

α – fine structure constant,

$f(\gamma)$ – injection function



Diffusive shock acceleration gives $f(\gamma) \propto \gamma^{-s}$,

where $s \simeq 2.2$ (universal power-law)

Fast cooling regime

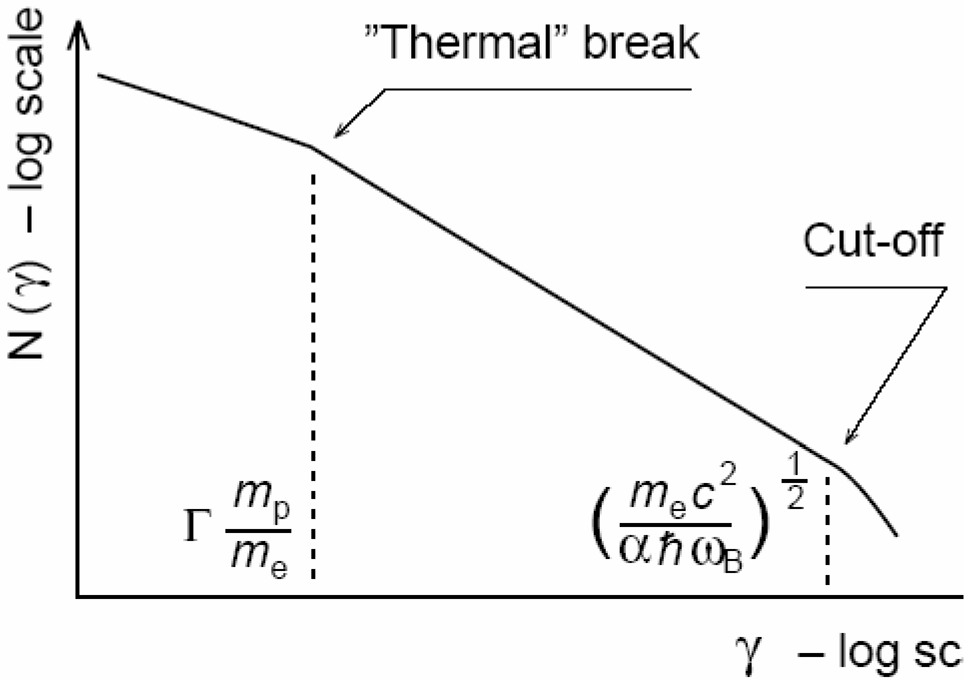
$N(\gamma)$ – electrons' distribution function

Continuity equation

$$\frac{\partial N}{\partial t} + \mathrm{div}\,(\dot{\gamma} N) = f(\gamma)$$

gives stationary solution

$$N(\gamma) = -\frac{1}{\dot{\gamma}} \int_{\gamma}^{\infty} f(\gamma')\, d\gamma'$$



The corresponding spectrum (provided $\nu \propto \gamma^x$) is :

$$\nu F_\nu \propto \frac{dF}{d\ln\gamma} \propto \gamma\eta \int_{\gamma}^{\infty} f(\gamma')\, d\gamma'$$

... – standard problems

- **Position of the peak is too sensitive to the shock Lorentz-factor**

  Photon energy at the peak in the comoving frame

$$\varepsilon'_{\mathrm{peak}} \sim \left(\Gamma \frac{m_p}{m_e}\right)^2 \frac{\hbar e B}{m_e c}$$

  in the laboratory frame $\varepsilon_{\mathrm{peak}} \propto \Gamma^4$ (since $B \propto \Gamma$)

- **The spectrum well above the peak frequency is universal and too hard**

$$N_\gamma \propto \gamma^{-3.2} \qquad \Rightarrow \qquad \nu F_\nu \propto \nu^{-0.1}$$

... – other problems

- **The synchrotron cut-off frequency is too high**

At the maximum energy, the scattering length (gyroradius) equals to the radiation length:

$$\eta \left(\frac{4}{3} \gamma \sigma_\mathrm{T} \frac{B^2}{8\pi} \right)^{-1} = \frac{\gamma m_e c^2}{eB}$$

So that $\gamma^2_\mathrm{max} \frac{\hbar e B}{m_e c} \simeq \eta \frac{m_e c^2}{\alpha}$ σ_T – Thomson cross-section

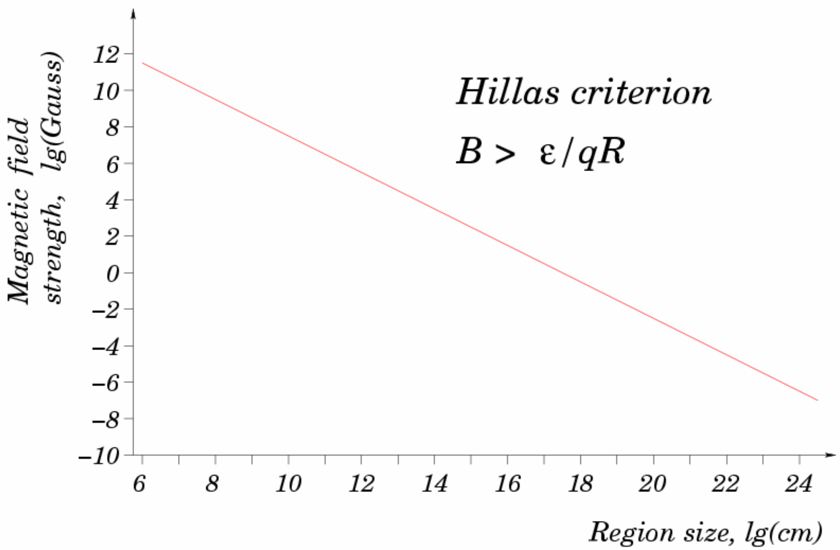
- **Low-frequency asymptotics in the fast-cooling regime is too soft**

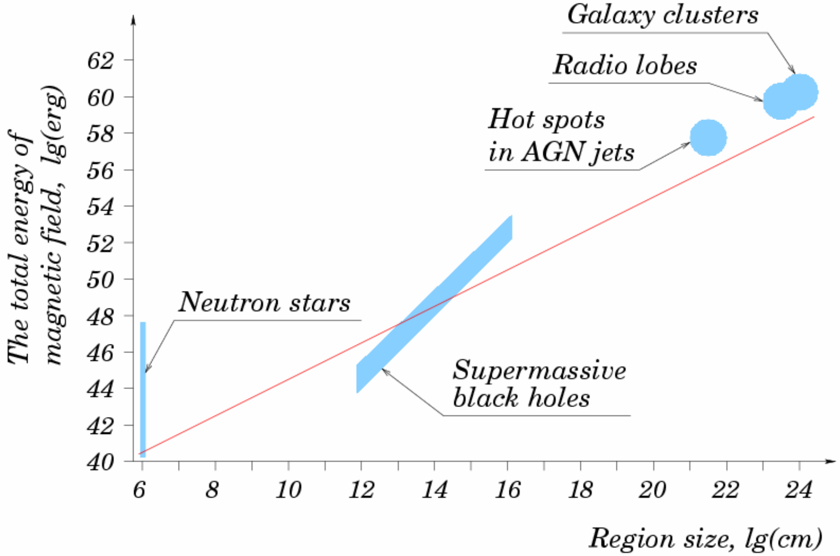
The hardest possible injection $f(\gamma) = \delta(\gamma - \gamma_0)$ gives

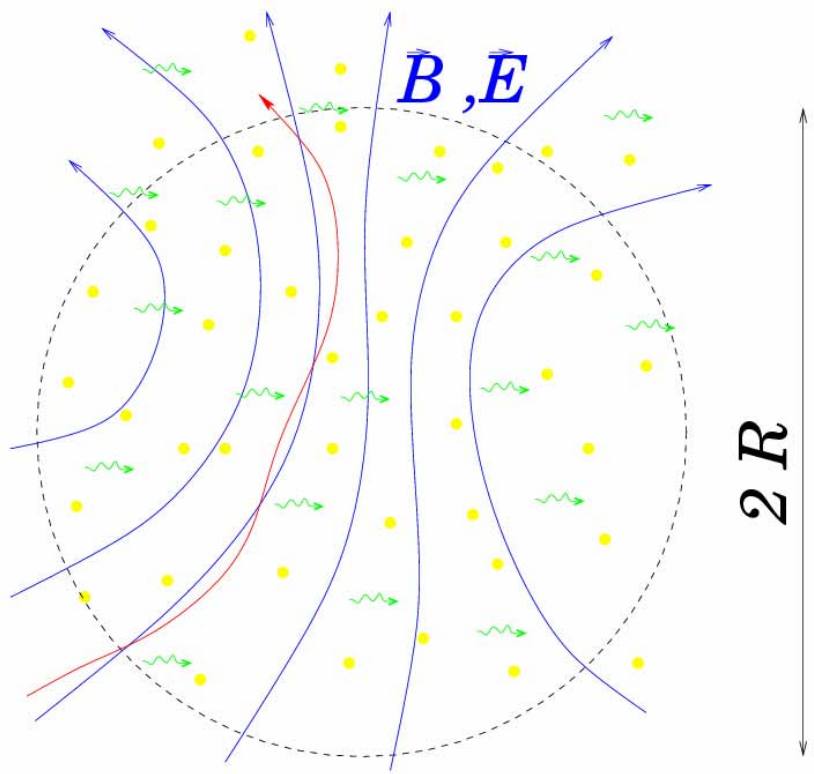
$\nu F_\nu \propto \gamma \eta$ for $\gamma < \gamma_0$;

$\Rightarrow$ $\nu F_\nu \propto \nu^{1/2}$, if $\eta = const$

Electrodynamic requirements







- *Collisions*
- *Cherenkov radiation in plasma*
- *Photomeson reactions*
- *Synchrotron & electrobremsstrahlung radiation*
- *Curvature radiation*

The particle acceleration rate is $\dot{\varepsilon} = \eta q B c$, where $\eta B = E_{\rm eff}$ is the effective electric field, q the particle's charge, and B the magnetic filed strength.

The particle can be accelerated up to the terminal energy which is the smallest of either the work done by accelerating force in a time it takes for a particle to escape from the acceleration region of size R, (the generalized Hillas criterion)

$$\varepsilon_{\max} < qR \max\{B, E_{\rm eff}\}.$$

or the energy at which radiative losses balance the acceleration. These losses are inevitable even for a particle moving along the field lines, due to the fact that the field lines are curved.

As long as the generalized Hillas criterion is satisfied, the curvature-radiation energy loss rate,

$$\dot{\varepsilon}_{\rm rad} = \frac{2}{3}\gamma^4 \frac{q^2}{R^2} c\,,$$

gives a more favorable estimate for the terminal particle energy. We assumed the curvature radius of field lines to be equal to the accelerator's size. Now we have

$$\varepsilon_{\max}^4 = \frac{3}{2}\left(mc^2\right)^4 \frac{\eta B R^2}{q}\,.$$

The overall energy of an electromagnetic field in a spherical region of radius R, capable of accelerating particles up to $\varepsilon_{\rm max}$, is $W_{\rm em} = R^3(B^2+E^2)/6$.

$$W_{\rm em} > \frac{2}{27}\frac{q^2}{R}\left(\frac{\varepsilon_{\rm max}}{mc^2}\right)^8 \frac{1+\eta^2}{\eta^2}$$

for radiative-loss dominated regime and

$$W_{\rm em} > \frac{R}{6}\left(\frac{\varepsilon_{\rm max}}{q}\right)^2$$

for escape-dominated regime.

The optimal size is

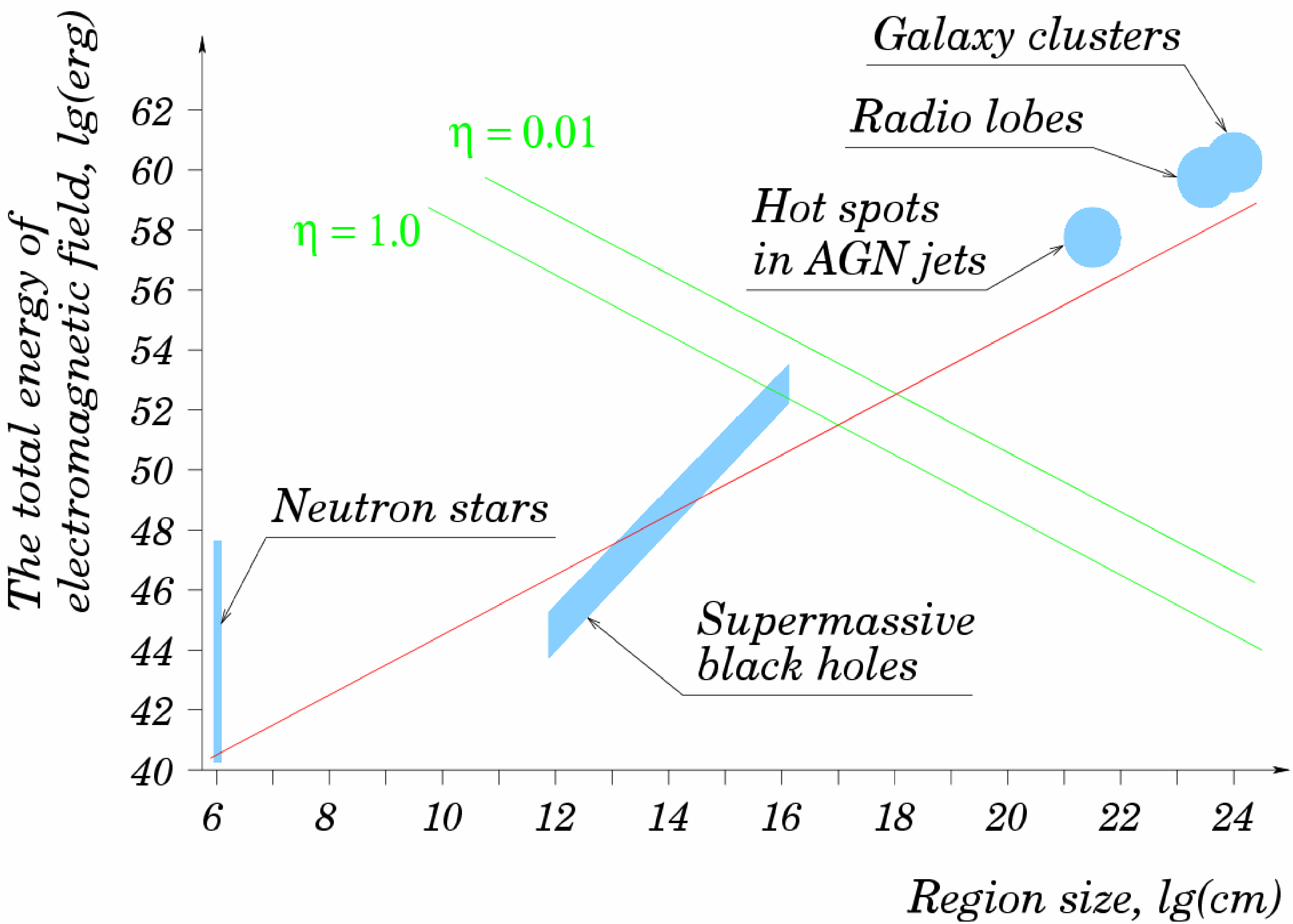
$$R^{\rm (opt)} \simeq \frac{2}{3}\frac{\sqrt{1+\eta^2}}{\eta}\frac{q^2\varepsilon_{\rm max}^3}{(mc^2)^4},$$

and the minimum required energy budget is

$$W_{\rm em}^{\rm (opt)} \simeq \frac{1}{9}\frac{\sqrt{1+\eta^2}}{\eta}\frac{\varepsilon_{\rm max}^5}{(mc^2)^4}.$$

The corresponding optimal strength of the magnetic field:

$$B^{\rm (opt)} \simeq \frac{3}{2}\frac{\eta}{1+\eta^2}\frac{(mc^2)^4}{q^3\varepsilon_{\rm max}^2}.$$



The total energy of electromagnetic field, lg(erg)
62
60
58
56
54
52
50
48
46
44
42
40
6
8
10
12
14
16
18
20
22
24
Region size, lg(cm)
η = 0.01
η = 1.0
Galaxy clusters
Radio lobes
Hot spots in AGN jets
Neutron stars
Supermassive black holes

All the above results are valid also for an accelerator that moves as a whole with the Lorentz-factor $\Gamma \gg 1$, if the quantities are measured in the comoving frame. However, a more conveniet form is

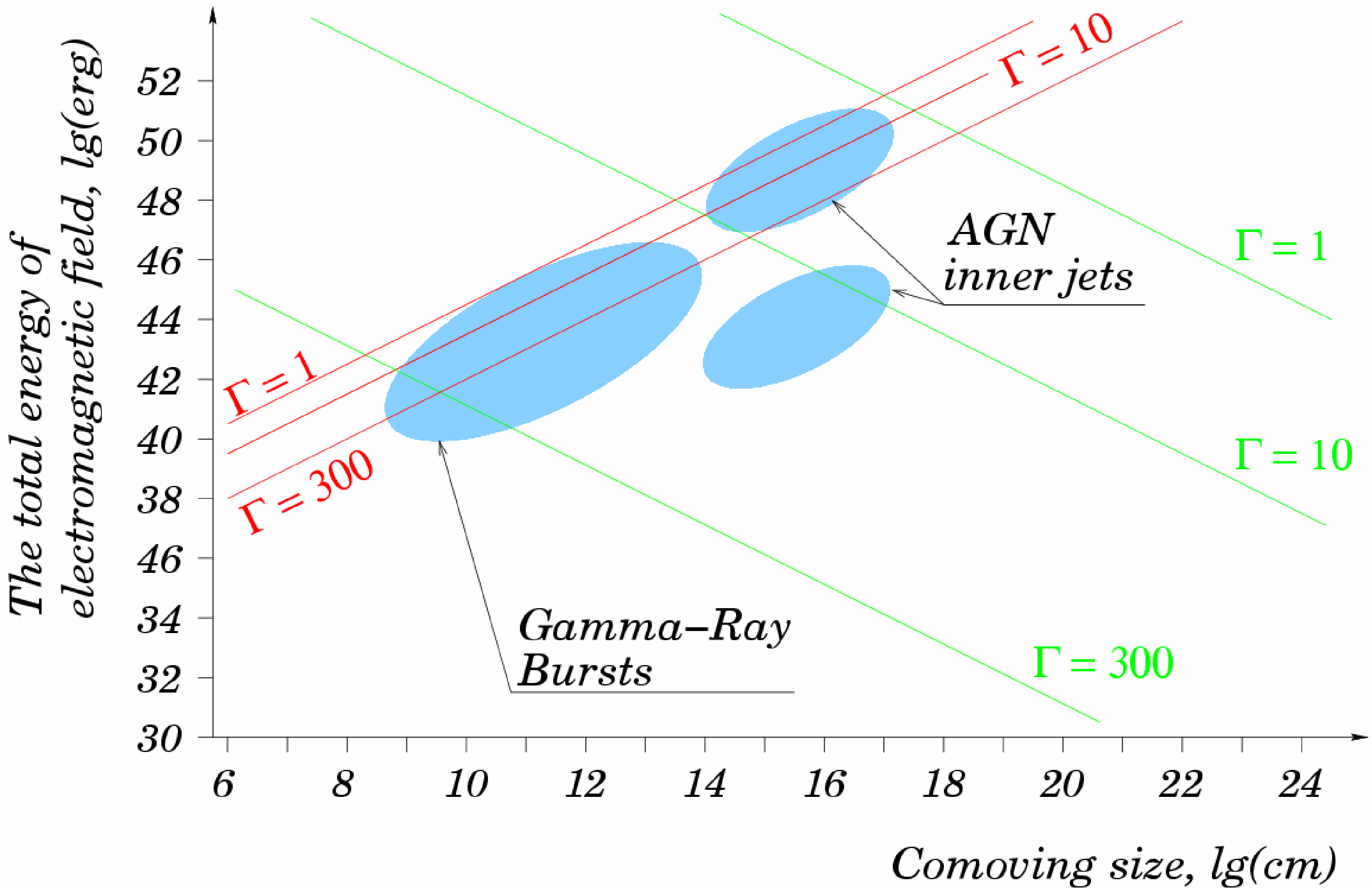
$$W_{\rm em}^{\rm (opt)} \simeq \frac{1}{9\,\Gamma^4}\frac{\sqrt{1+\eta^2}}{\eta}\frac{\varepsilon_{\rm max}^5}{\left(mc^2\right)^4},$$

$$R'^{\rm (opt)} \simeq \frac{2}{3\,\Gamma^3}\frac{\sqrt{1+\eta^2}}{\eta}\frac{q^2\varepsilon_{\rm max}^3}{\left(mc^2\right)^4},$$

$$B'^{\rm (opt)} \simeq \frac{3\,\Gamma^2}{2}\frac{\eta}{1+\eta^2}\frac{\left(mc^2\right)^4}{q^3\varepsilon_{\rm max}^2},$$

where the primed quantities are measured in the comoving frame and others – in the laboratory frame.

For wind-like relativistic flows the actual requirements are geometry-dependent. For the causality reasons, the acceleration region does not occupy the whole sphere of radius R, but rather extends to a distance $R' = R/\Gamma$ transverse to the radius and to a distance R'/Γ along it, so that the total energy within the volume of radius R is of $\sim \Gamma^4 W_{\rm em}$ for a wind with a broad beam pattern. Since the energy stored in the acceleration region, $W_{\rm em}$, is multiplied by Γ^4 in this case, one can only gain from a more favorable ratio $R'/R'^{\rm (opt)}$. A jet geometry is more favorable.



The total energy of electromagnetic field, lg(erg)
52
50
48
46
44
42
40
38
46
34
32
30
6
8
10
12
14
16
18
20
22
24
Comoving size, lg(cm)
Γ = 10
Γ = 1
Γ = 300
AGN
inner jets
Γ = 1
Γ = 10
Gamma–Ray
Bursts
Γ = 300

Accompanying radiation vs. diffuse γ-background

As a result of particle's acceleration, the following fraction of its terminal energy $\varepsilon_{\max}$ is lost for γ-radiation

$$\frac{E_{\rm rad}}{\varepsilon_{\max}} \gtrsim \begin{cases} R^{(\rm opt)}/R & \text{if} \quad R > R^{(\rm opt)} \\ 1 & \text{if} \quad R^{(\rm opt)} > R > \eta R^{(\rm opt)} \\ \eta R^{(\rm opt)}/\sqrt{1+\eta^2} R & \text{if} \quad R < \eta R^{(\rm opt)}. \end{cases}$$

The spectral energy distribution of the accompanying radiation has a maximum (in the source frame) around

$$\varepsilon_\gamma \sim \hbar \frac{\gamma^3 c}{R} \sim \eta \frac{R^{(\rm opt)}}{R} \frac{mc^2}{\alpha Z^2}, \qquad (1)$$

provided the accelerator size is less than $R^{(\rm opt)}$. Here $\alpha \simeq 1/137$ is the fine-structure constant and Z the nucleus charge ($Z = 1$ for protons).

The comparison of the diffuse background in 10 MeV - 100 GeV energy range with the observed flux of 10^{20} eV cosmic rays implies $L_\gamma/L_{\rm acc} \lesssim 5$ and hence $R/(\eta R^{(\rm opt)}) \gtrsim 1/5$. Since the spectral energy distribution of the γ-ray background is nearly constant in 10 MeV - 100 GeV range, the same limit applies for iron nuclei.

Neutron stars – ruled out.

1. The energy requirements to neutron star magnetospheres are unphysical: $\sim 10^{62}$ erg for protons and $\sim 10^{51}$ erg for iron nuclei. In addition, the luminosity in accompanying curvature γ-radiation is 5 to 6 orders of magnitude higher than in the produced EHECRs. Particles accelerated near the light cylinder produce less accompanying radiation, but the energy requirements rise in this case.

2. For ultrarelativistic pulsar winds the required Poynting-flux luminosity in the best case ($R' = R'^{(\mathrm{opt})}$ and $\eta = 1$) is $L_{\mathrm{em}} \simeq 10^{45}\Gamma^2$ erg/s for protons ($\Gamma \lesssim 600$) and $L_{\mathrm{em}} \simeq 1.5 \cdot 10^{42}\Gamma^2$ erg/s for iron nuclei ($\Gamma \lesssim 60$).

Black holes – nearly ruled out.

The required black hole size is

$$R_g > \left(\frac{2}{81\,\pi}\sigma_T \frac{1+\eta^2}{\eta^2} \frac{q^2 \varepsilon_{\mathrm{max}}^8}{(mc^2)^8\, m_p c^2} \right)^{1/3} \simeq 3 \times 10^{15} Z^{2/3} A^{-8/3}\,\mathrm{cm}.$$

If the accelerated particles are protons, then only super-massive black holes with $M > 10^{10} M_{\odot}$ can meet the above requirement. For iron nuclei $M > 2 \times 10^6 M_{\odot}$ is enough.

Active galactic nuclei (AGN) – possible.

The required magnetic field strength 100 G, like in the extreme hadronic models. The Poynting-flux luminosity must be higher than $\sim 10^{45}$ erg/s.

Large accelerators (hot spots in AGN jets, radio lobes and galaxy clusters) – possible.

Acceleration is escape-limited.

The required acceleration efficiency is $\eta \gtrsim 0.03$ if particles escape on the Bohm-diffusion timescale. Even if the diffusion is strongly suppressed, η must be larger than $\sim (0.3 - 1) \times 10^{-2}$ in radio lobes and galaxy clusters, and larger than few $\times 10^{-5}$ in the hot spots.

Gamma-Ray Bursts (GRBs) – still possible.

At least 50 per cent of the observed GRB energy has to be converted into EHECRs.

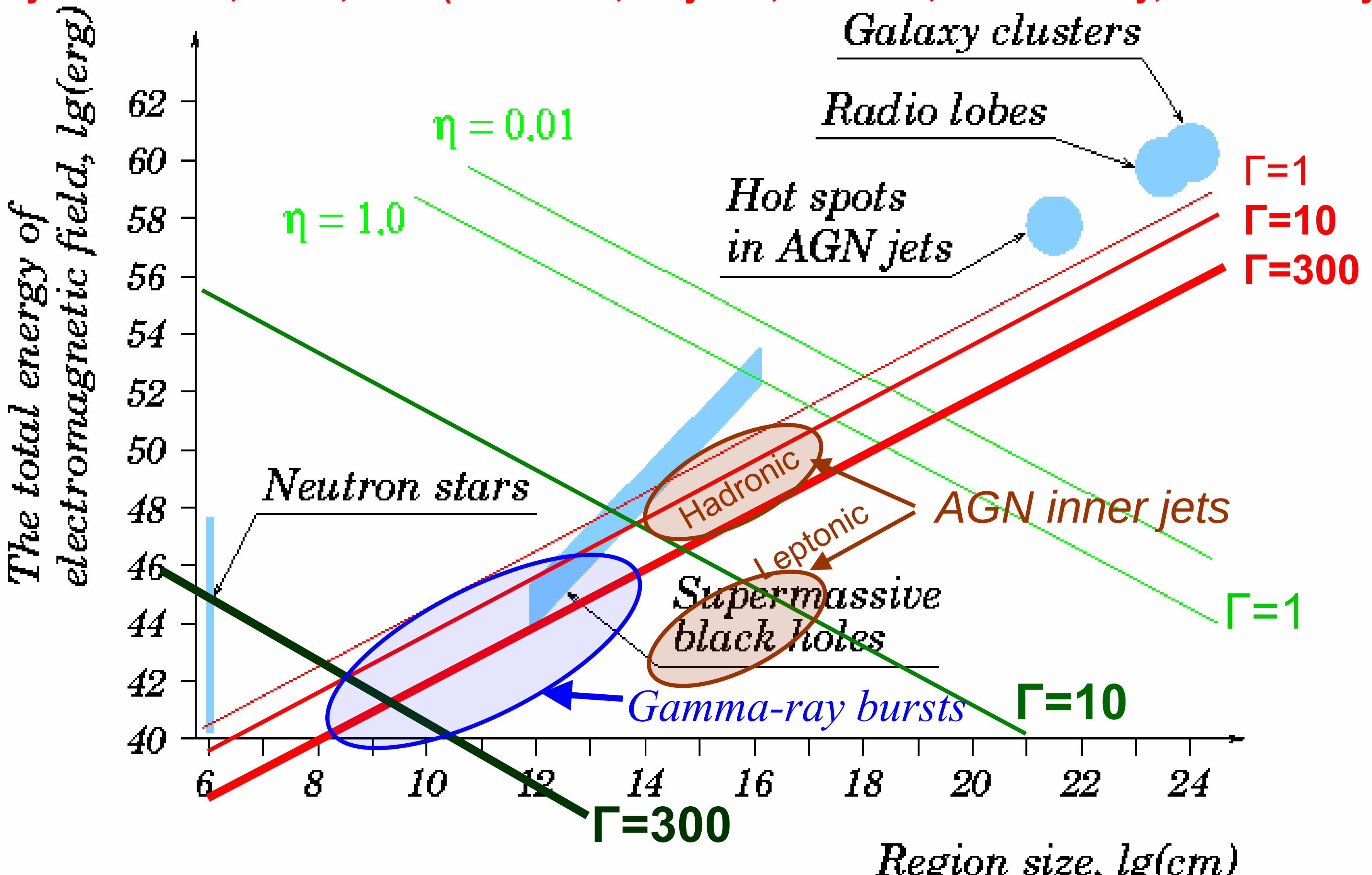
The attainable particle energy is

$$\varepsilon_{\max} = \Gamma \varepsilon'_{\max} = \frac{\eta \epsilon_m^{1/2}}{\Gamma} q \sqrt{\frac{2\,L}{c}} \sim \frac{2.5 \times 10^{23}\,\mathrm{eV}}{\Gamma}.$$

Explanation of some GRB properties requires $\Gamma > 100$, so that GRBs might be capable of accelerating protons well above 10^{20} eV.

Ultimate limits on the accelerators of extremely high-energy cosmic rays (10^{20} eV) set by electrodynamics (confinement and radiation losses)

Phys. Rev. D 66, 23005, 2002 (Aharonian, Belyanin, Derishev, Kocharovsky, Kocharovsky)



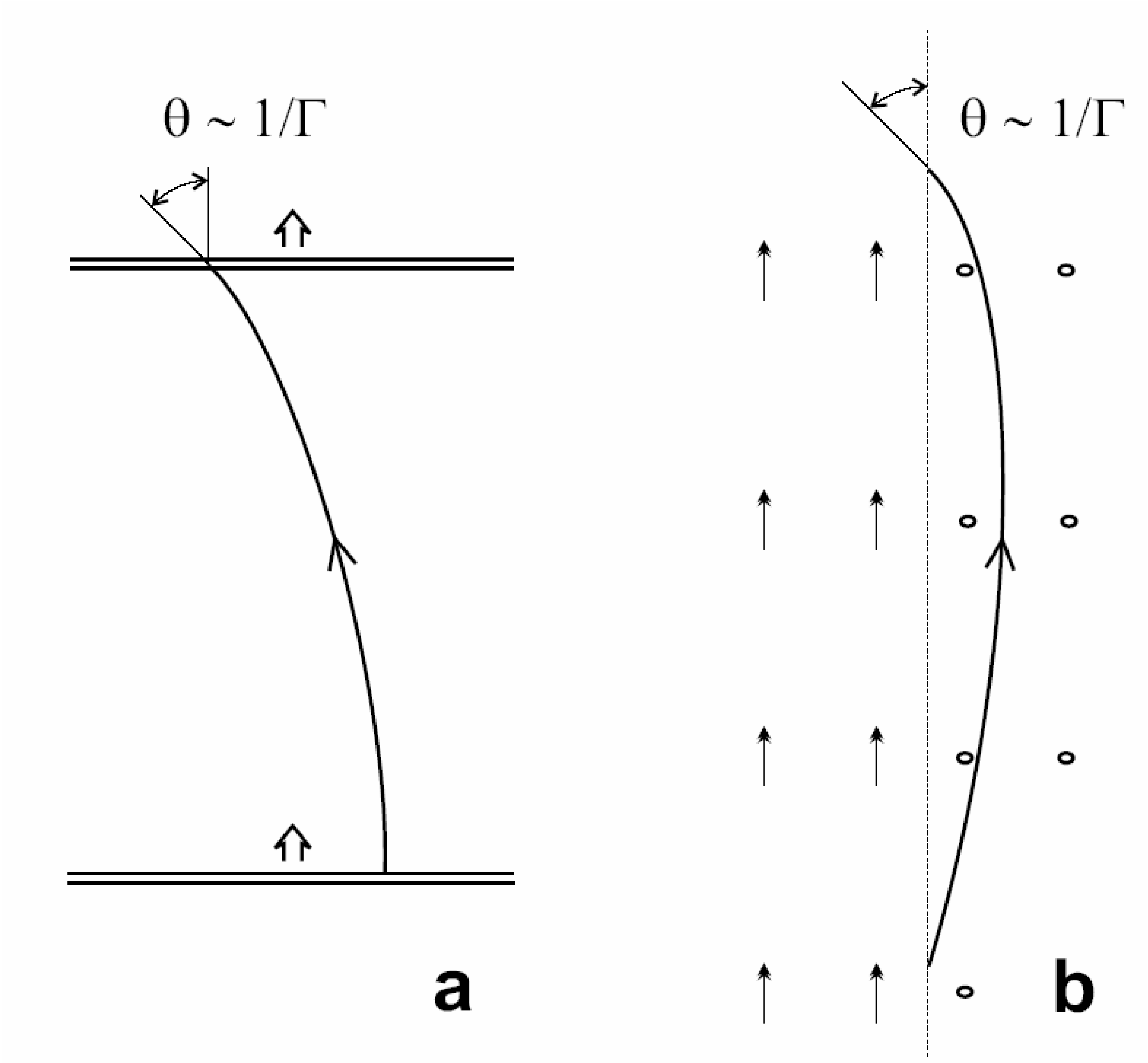
Energy requirements for protons of energy 10^{20} eV for different bulk Lorentz factors Γ=1, 10, 300

Maximum energy of cosmic-ray particles

One can see that in GRBs and AGN inner jets protons can in principle be accelerated up to 10^{21}eV. At such energies, acceleration is likely to be radiative-loss limited in both cases. Above 10^{21}eV GRBs fail because of their insufficient duration and AGN inner jets -- because of insufficient Poynting-flux luminosity. Hot spots, radio lobes and galaxy clusters can still work to $3\text{-}5 \cdot 10^{21}$eV under very speculative assumption that the magnetic field is ordered on all scales and the acceleration efficiency is about 1. In this case, acceleration is escape-limited.

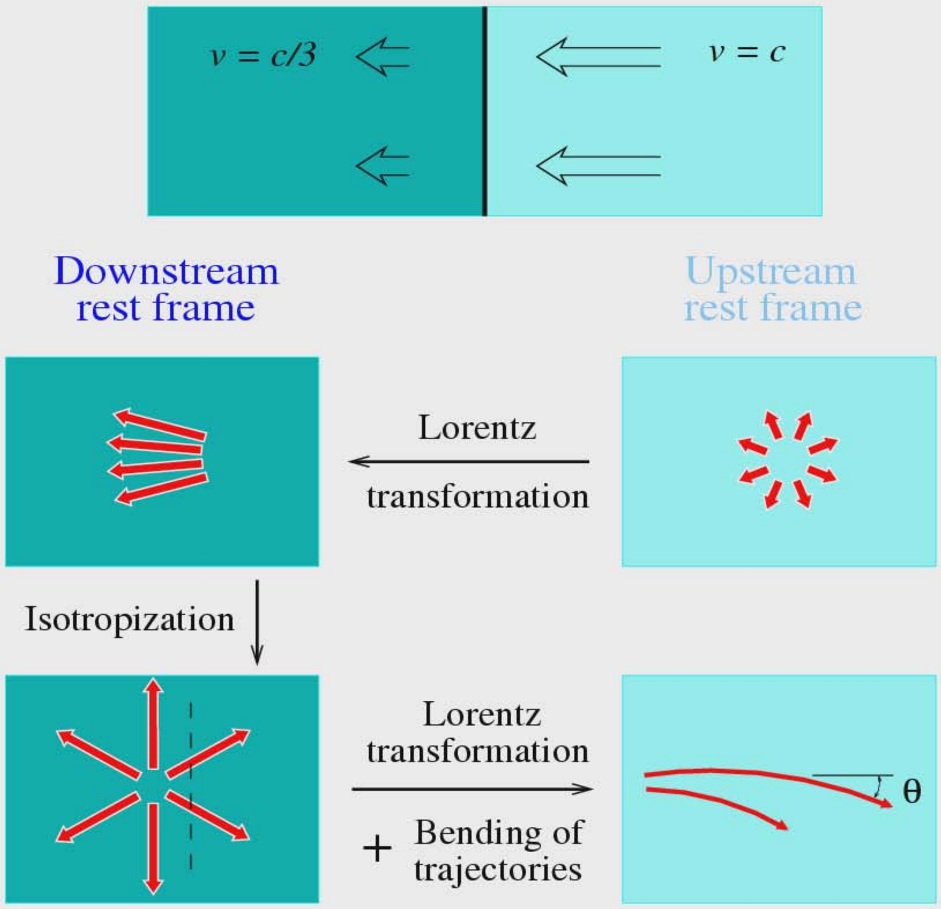
At the energies greater 10^{22}eV the cosmic ray primaries have to be heavy nuclei. In all the sources listed above the heavy nuclei are accelerated in the escape-limited regime, so that the attainable energy is roughly Z times more than for protons. However, the nuclei of such energy are fragmented through interaction with the microwave background photons after traveling a distance of less than 1Mpc, that means they must be produced within the local group of galaxies, and GRBs would be the only possibility to do this. Although the nuclei are easily fragmented in radiation-reach environments of GRBs, we have to conclude that formally the primaries with energy up to $2\text{-}3 \cdot 10^{22}$eV can be produced within the framework of pure electromagnetic acceleration scenario.

Limitation of diffusive shock acceleration



Standard acceleration mechanism

(Vietri 1995, Waxman 1995, cf. Achterberg *et al.* 2001)

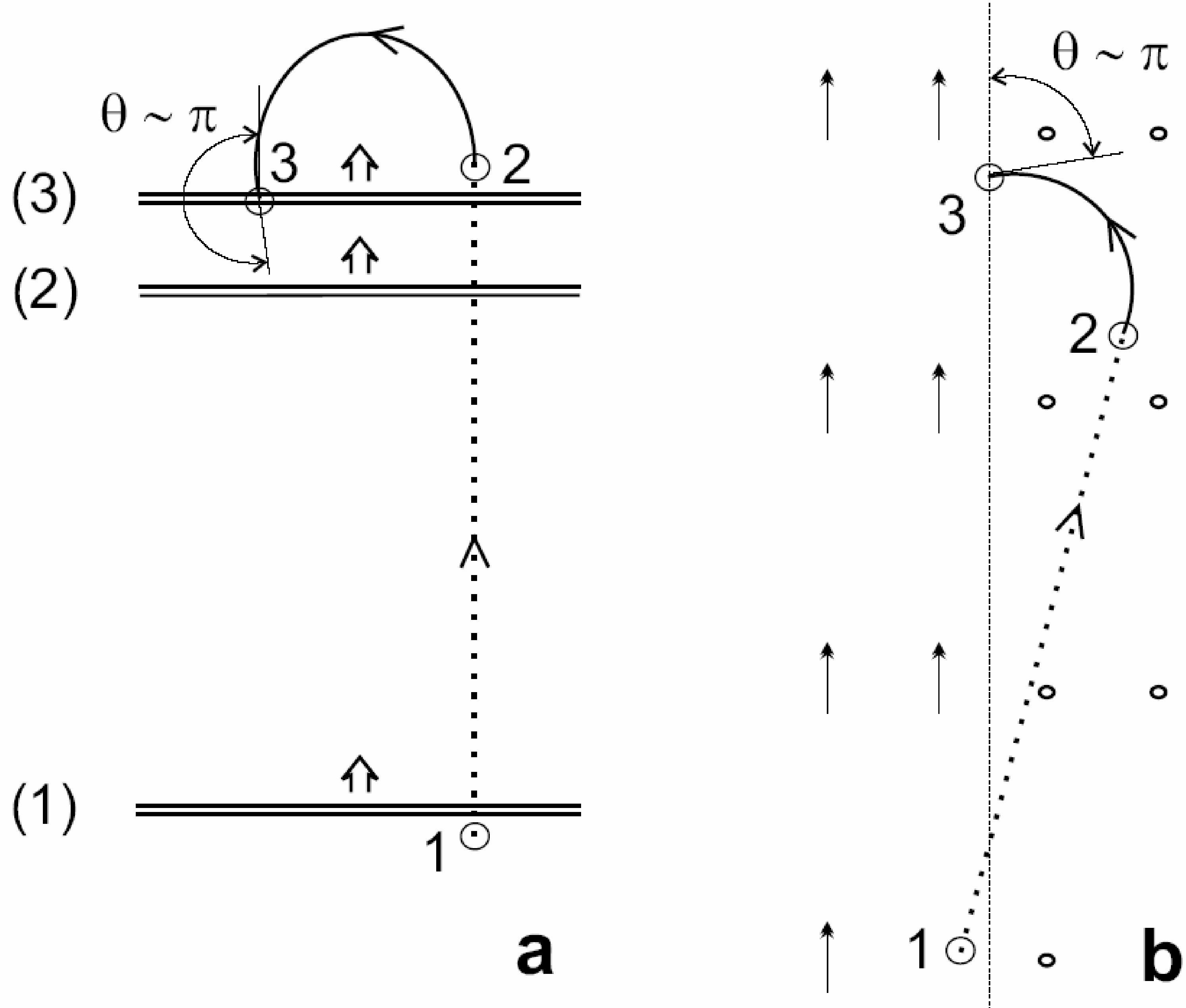


Energy gain is $g = (\Gamma\theta)^2/2$

Pick-up by the shock limits the deflection angle to $\theta \sim 2/\Gamma$

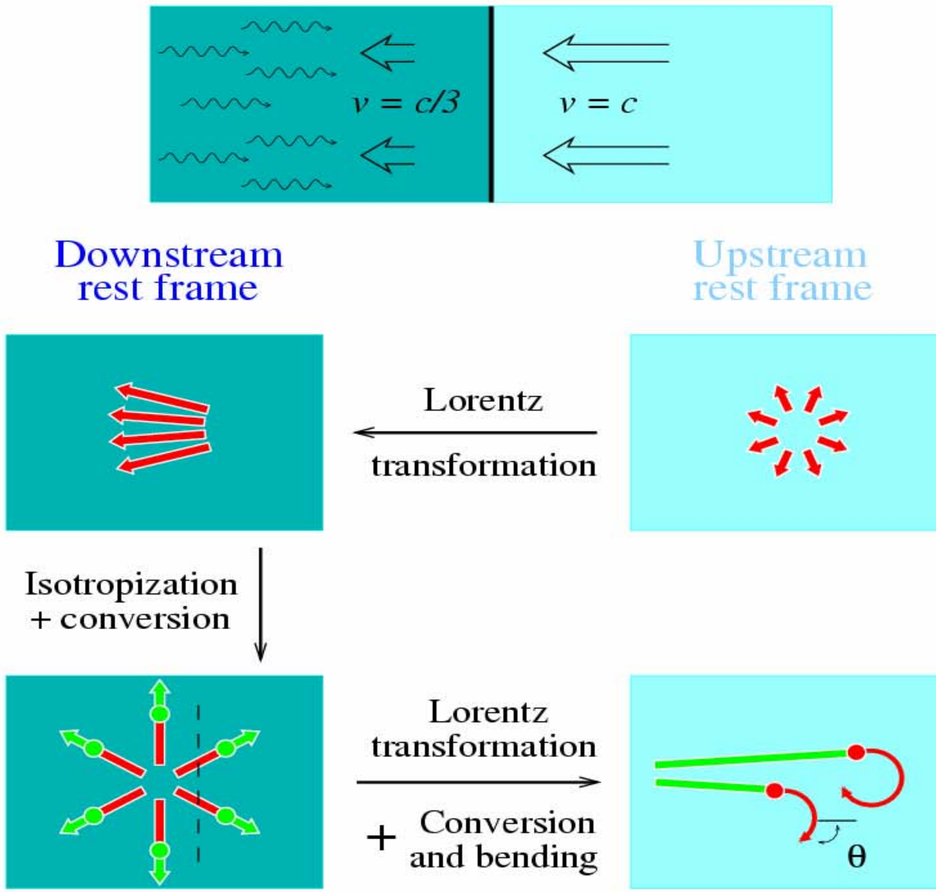
hence $g \sim 2$ in all but the first acceleration cycles.

Advantages of converter mechanism



Converter acceleration mechanism

E.V. Derishev, F.A. Aharonian, V.V. Kocharovsky, and Vl.V. Kocharovsky
Phys. Rev. D **68**, 043003 (2003)



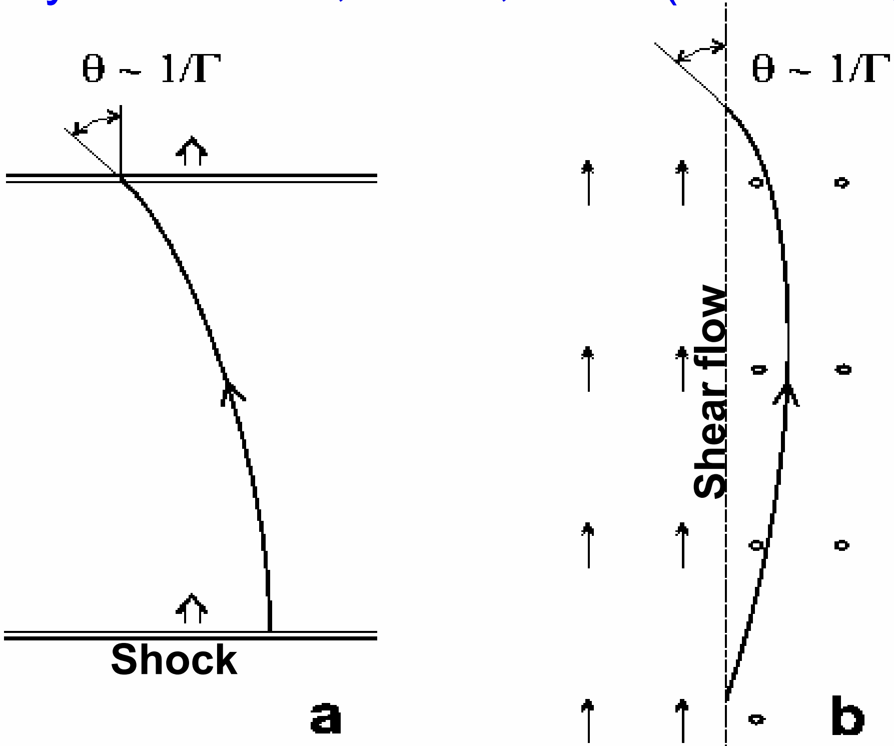
Energy gain is $g = (\Gamma\theta)^2/2$

Complete isotropization upstream results in $\theta \sim 1$
hence $g \sim \Gamma^2$ in every acceleration cycle.

Particle distribution: $\dfrac{\mathrm{d}N}{\mathrm{d}\varepsilon} \propto \varepsilon^{-\alpha}$ with $\alpha = 1 - \dfrac{\ln p_{\rm cn}}{\ln g}$

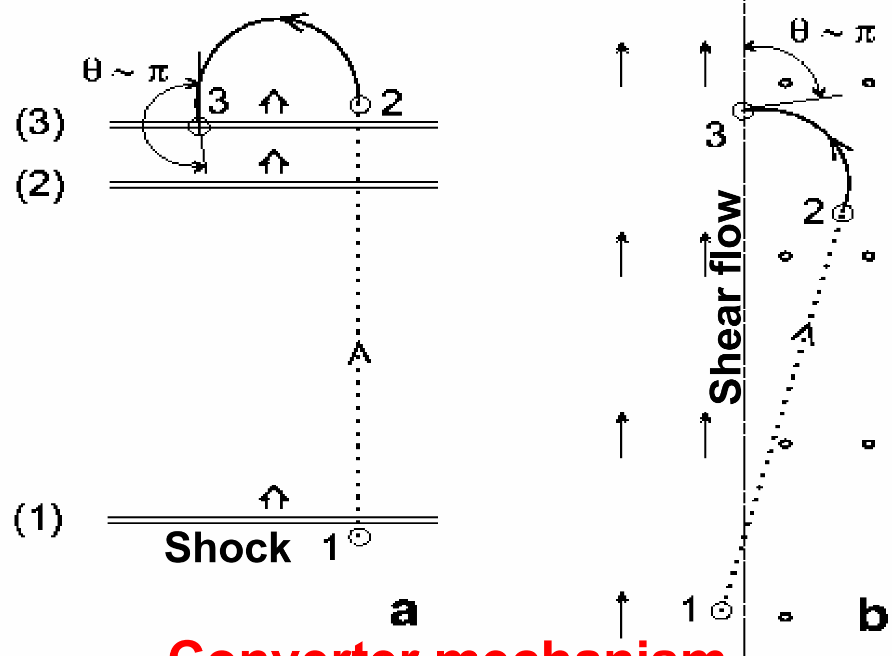
Converter acceleration mechanism for ultra-high energy cosmic rays

Phys. Rev.D**68**,43003, 2003 (Derishev, Aharonian, Kocharovsky, Kocharovsky)



Standard mechanism

Figure 1: The acceleration cycle in the standard mechanism for a shock (a) and for a shear flow (b). The thick solid line shows the particle's trajectory. The magnetic field is perpendicular to the picture plane. The locations of the shock at the moments of particle escape from the shock and subsequent catch-up are shown as double lines. The shear flow boundary is shown by thin dotted line.

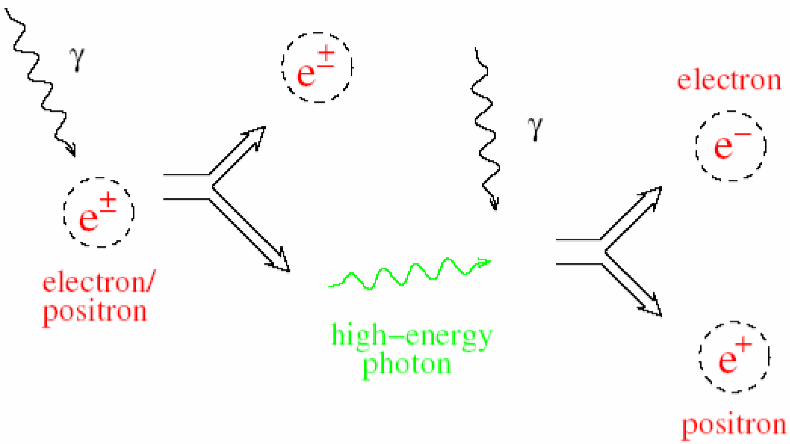


Converter mechanism

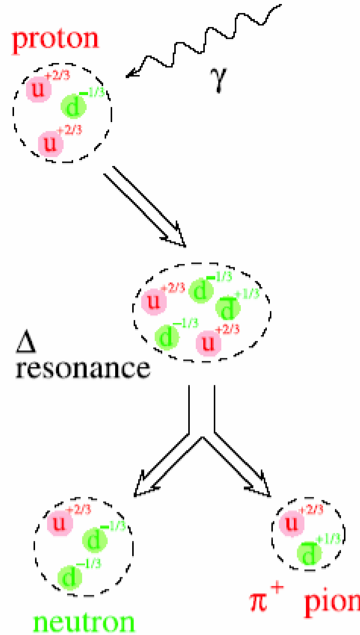
Figure 2: The acceleration cycle in the converter mechanism for a shock (a) and for a shear flow (b). The particle's trajectory is shown by thick dotted line (neutral state) and thick solid line (charged state). The magnetic field is perpendicular to the picture plane. Numbered are the moments of particle conversion into neutral state, transition from neutral to charged state, and subsequent return to the flow. The locations of the shock at the corresponding moments are shown by double lines. The shear flow boundary is shown by thin dotted line.

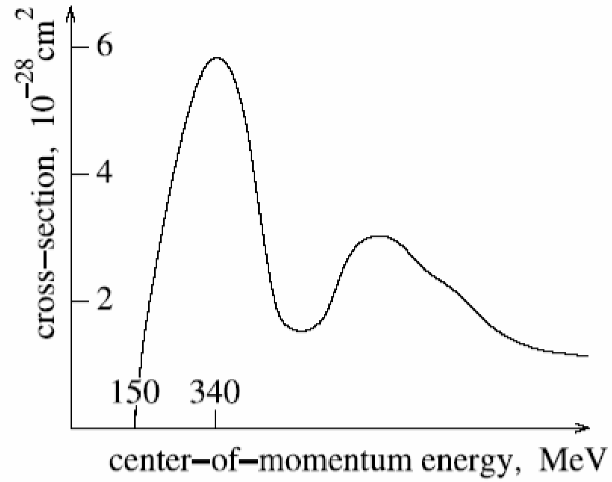
The mechanism operates via continuous conversion of accelerated particles from charged into neutral state and back. The energy gain per cycle is Γ^2>>1, instead of Fermi's ~2.

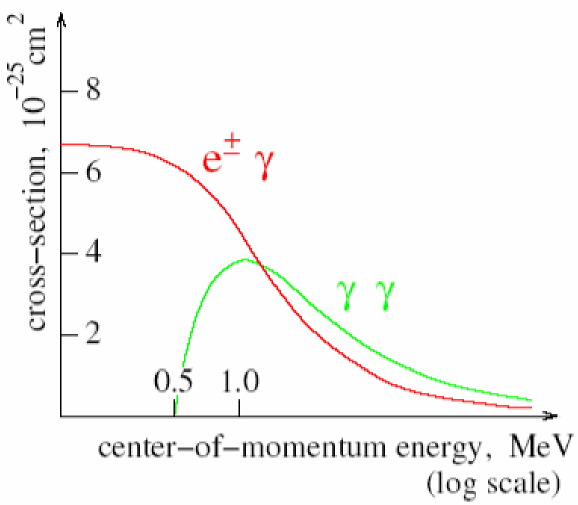
e^-/e^+ - γ cycle



p - n cycle







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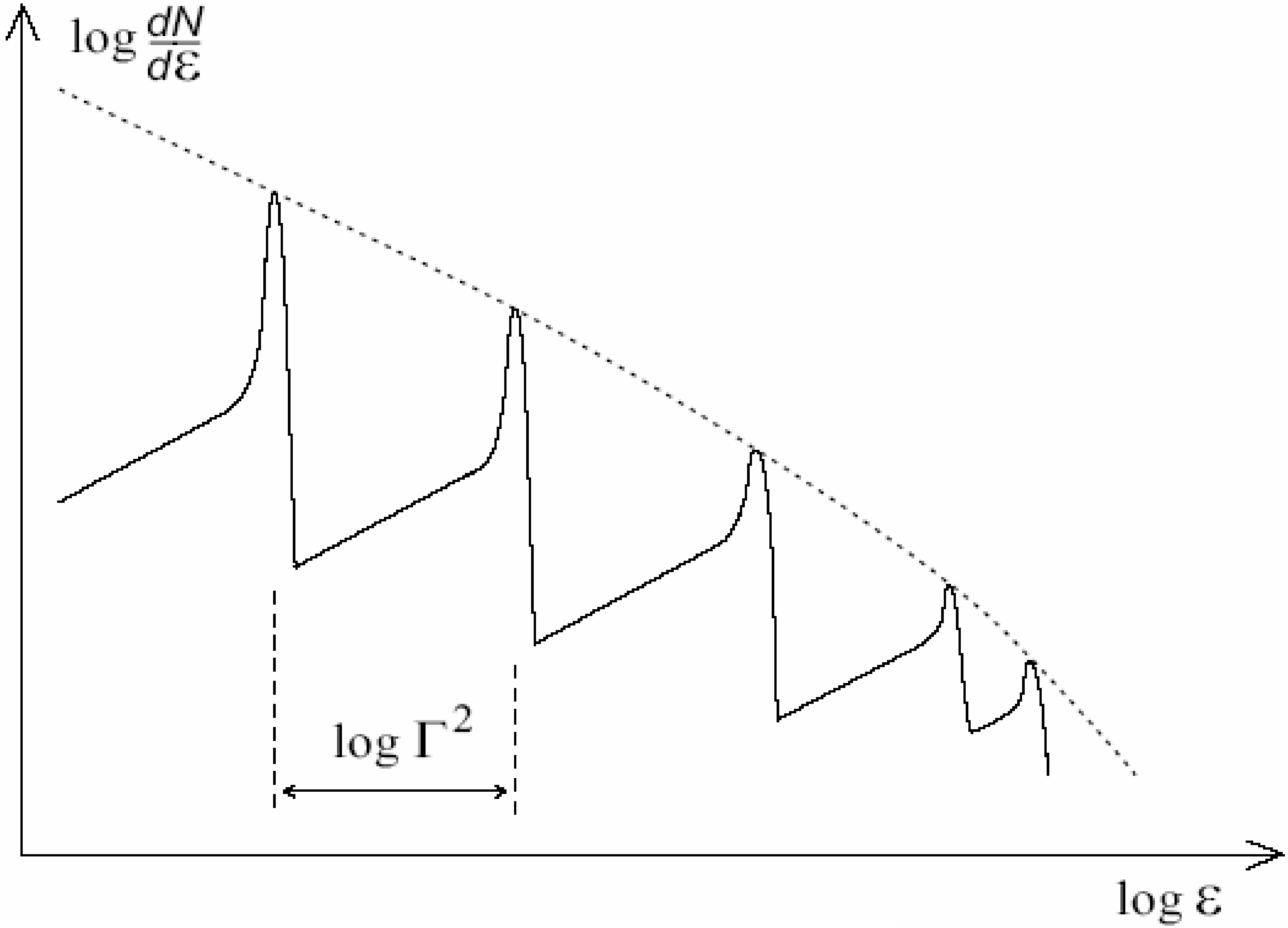
Deflection angles, critical energies	Shock wave	Shear flow
Homogeneous magnetic field	$\theta \sim (3l_0/r_g\Gamma^2)^{1/3}$ $\varepsilon_1 = \Gamma\varepsilon_2 = \Gamma eBR$	$\theta \sim (2l_0/r_g\Gamma^2)^{1/2}$ $\varepsilon_1 = \varepsilon_2 = \Gamma eBR$
Chaotic magnetic field	$\theta \sim (2l_c l_0/r_g{}^2\Gamma^2)^{1/4}$ $\varepsilon_1 = \varepsilon_2 = \Gamma eB(Rl_c)^{1/2}$	$\theta \sim (3l_c l_0/2r_g{}^2\Gamma)^{1/3}$ $\varepsilon_1 = \Gamma^{-1/2}\varepsilon_2 = \Gamma eB(Rl_c)^{1/2}$



$$\frac{\mathrm{d}N}{\mathrm{d}\varepsilon} \propto \varepsilon^{-\alpha}$$

Main features of the converter acceleration mechanism

•It produces much more ultra-high energy cosmic rays than the standard diffusive-type acceleration mechanism since the particle energy is attained in fewer steps, with many more particles surviving against downstream losses.
•It is efficient for acceleration of both protons and electrons (positrons), but not nuclei.
•It is capable of producing the highest-energy cosmic rays in GRBs and AGNs.
•The maximum attainable proton energy (~10^{21} eV for GRBs and AGNs) is larger than in the standard mechanism since the cut-off energy is less affected by the magnetic field turbulence and, in the case of a shear flow with chaotic ambient magnetic field, is additionally larger by the factor $\Gamma^{1/2} >> 1$.
•It is very efficient means of transferring the kinetic energy of bulk relativistic flow to the accompanying radiation in the regions of high optical thickness, which could explain the origin of GRB emission.
•It predicts the powerful neutrino emission at a level comparable to the power of the produced highest-energy cosmic rays.
•The converter mechanism makes neutral beams of all kinds (photon, neutrino and neutron beams) broader than $1/\Gamma$, so that they can be seen even if the jet that produced them is not pointing towards the observer. This opens an interesting possibility for observation of the off-axis blazars and GRBs.

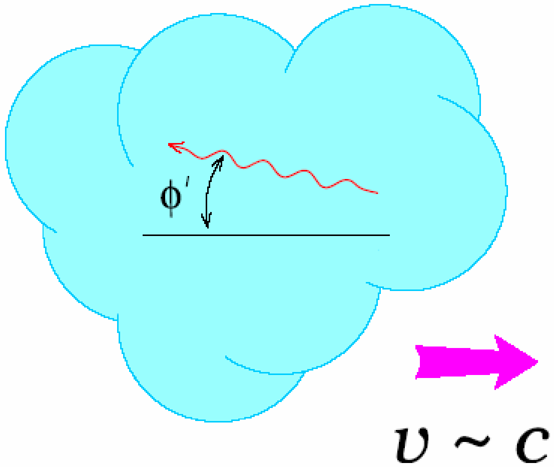
Accompanying radiation patterns and relativistic transformations

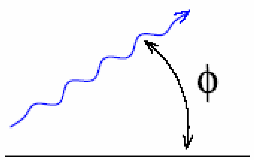
$$\cos\phi = \frac{\beta - \cos\phi'}{1 - \beta\cos\phi'} \; ; \qquad \cos\phi' = \frac{\beta - \cos\phi}{1 - \beta\cos\phi}$$

$$\nu L_\Omega(\nu) = \delta^3 \times \nu' L'_\Omega(\nu')$$

$$\nu = \delta \times \nu'$$

$\delta = \Gamma(1 - \beta\cos\phi')$ — see, e.g., ApJ **655**, 980 (2007)





$$\phi \simeq \frac{2}{\sqrt{(\Gamma\phi')^2 + 1}}$$ и $$\delta \simeq \frac{(\Gamma\phi')^2 + 1}{2\Gamma}$$

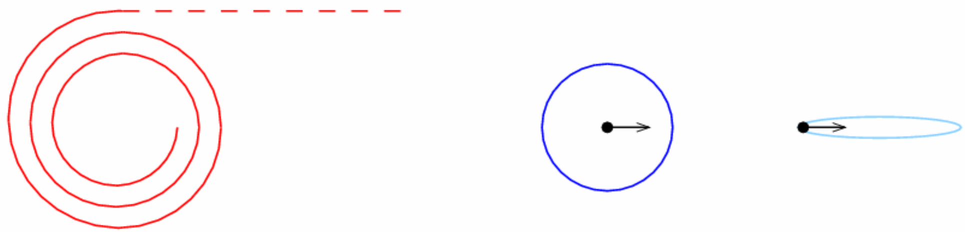
Synchrotron emission of particles accelerated via converter mechanism

- Maximum photon energy is Γ^2 times greater then that in the diffusive shock acceleration: $\Gamma^3 mc^2$ instead of Γmc^2
- Highest-energy radiation is quasi-isotropic in the observer frame contrary to beamed radiation below the critical energy
- Off-axis observation of relativistic jets in gamma- and hard X-rays above the critical energy

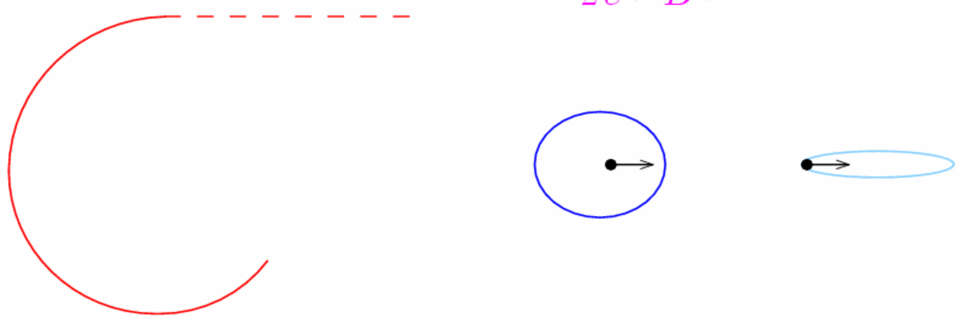
Changes in the emission beam-pattern

Downstream frame | Observer's frame

- Low-energy particles, $\varepsilon \ll \frac{3}{2}\frac{\left(mc^2\right)^2}{e^{3/2}B^{1/2}}$

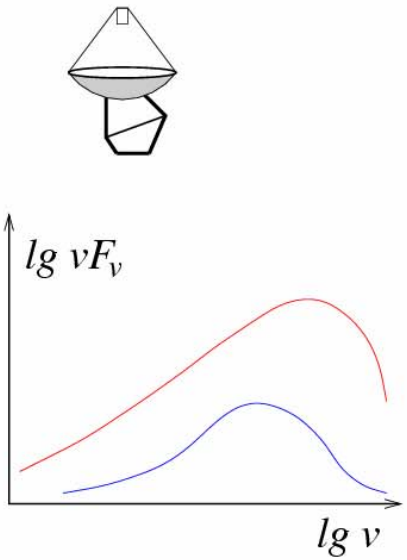


- Critical-energy particles, $\varepsilon \simeq \frac{3}{2}\frac{\left(mc^2\right)^2}{e^{3/2}B^{1/2}}$

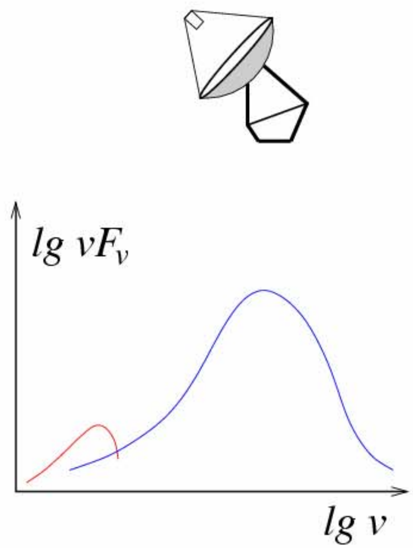


- High-energy particles, $\varepsilon \gg \frac{3}{2}\frac{\left(mc^2\right)^2}{e^{3/2}B^{1/2}}$

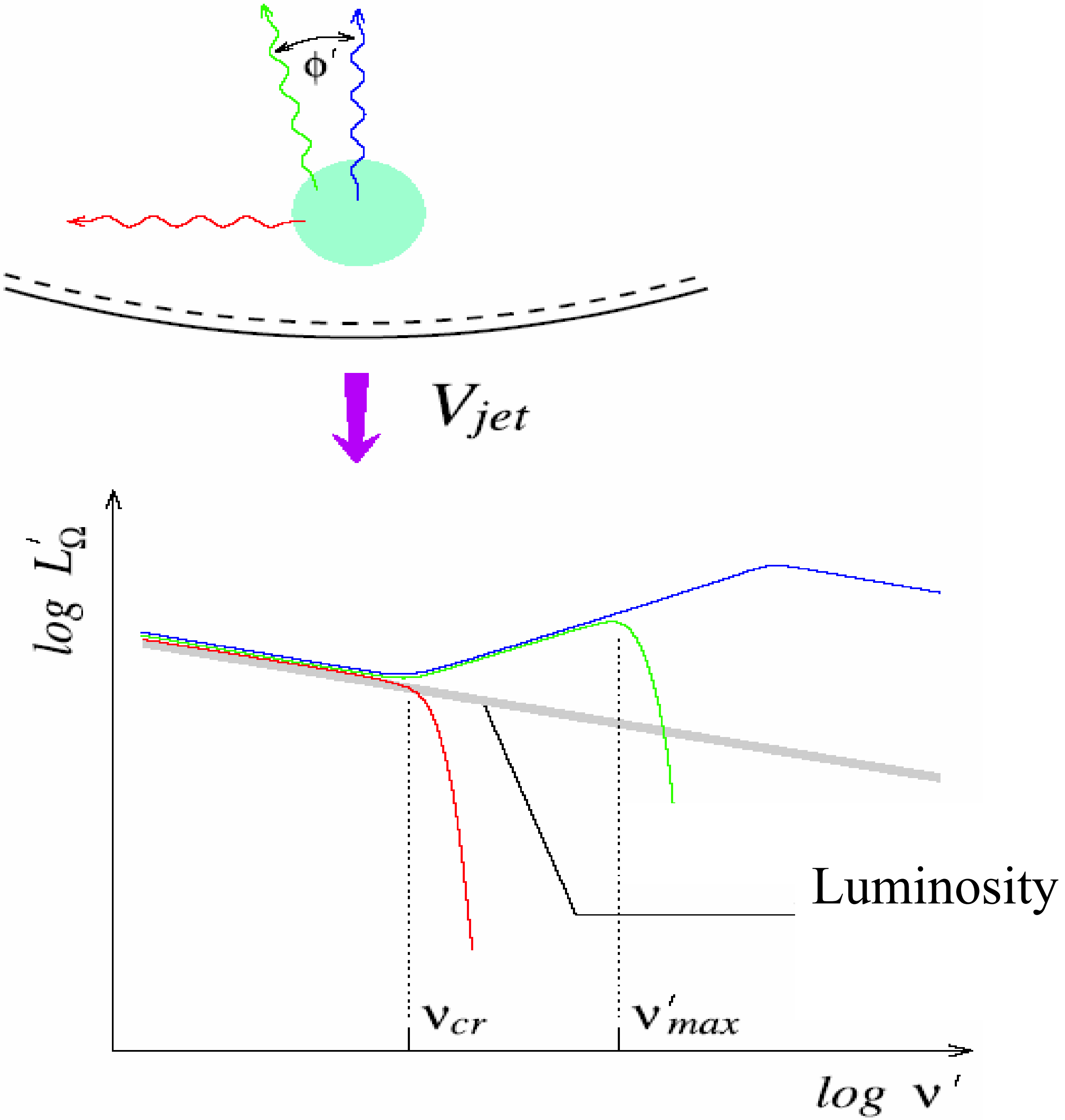
Dependence of γ-ray spectrum on the observation angle



On-axis view



Off-axis view



φ'
V_{jet}
$log\ L'_{\Omega}$
Luminosity
ν_{cr}
ν'_{max}
$log\ \nu'$

Conclusions

We compare different acceleration mechanisms and show that the converter mechanism, suggested recently, is the least sensitive to the geometry of the magnetic field in accelerators and can routinely operate up to cosmic-ray energies close to the fundamental limit. The converter mechanism utilizes multiple conversions of charged particles into neutral ones (protons to neutrons and electrons/positrons to photons) and back by means of photon-induced reactions or inelastic nucleon-nucleon collisions.

It works most efficiently in relativistic shocks or shear flows under the conditions typical for Active Galactic Nuclei, Gamma-Ray Bursts, and microquasars, where it outperforms the standard diffusive shock acceleration. The main advantages of the converter mechanism in such environments are that it greatly diminishes particle losses downstream and avoids the reduction in the energy gain factor, which normally takes place due to highly collimated distribution of accelerated particles.

We also analyze the properties of gamma-ray radiation, which accompanies acceleration of particles via the converter mechanism and can provide an evidence for the latter. In particular, we point out the fact that the opening angle of the radiation beam-pattern is different at different photon energies, which is relevant to the observability of the cosmic-ray sources as well as to their timing properties.