Converter acceleration mechanism in GRB sources of extremely high-energy cosmic rays

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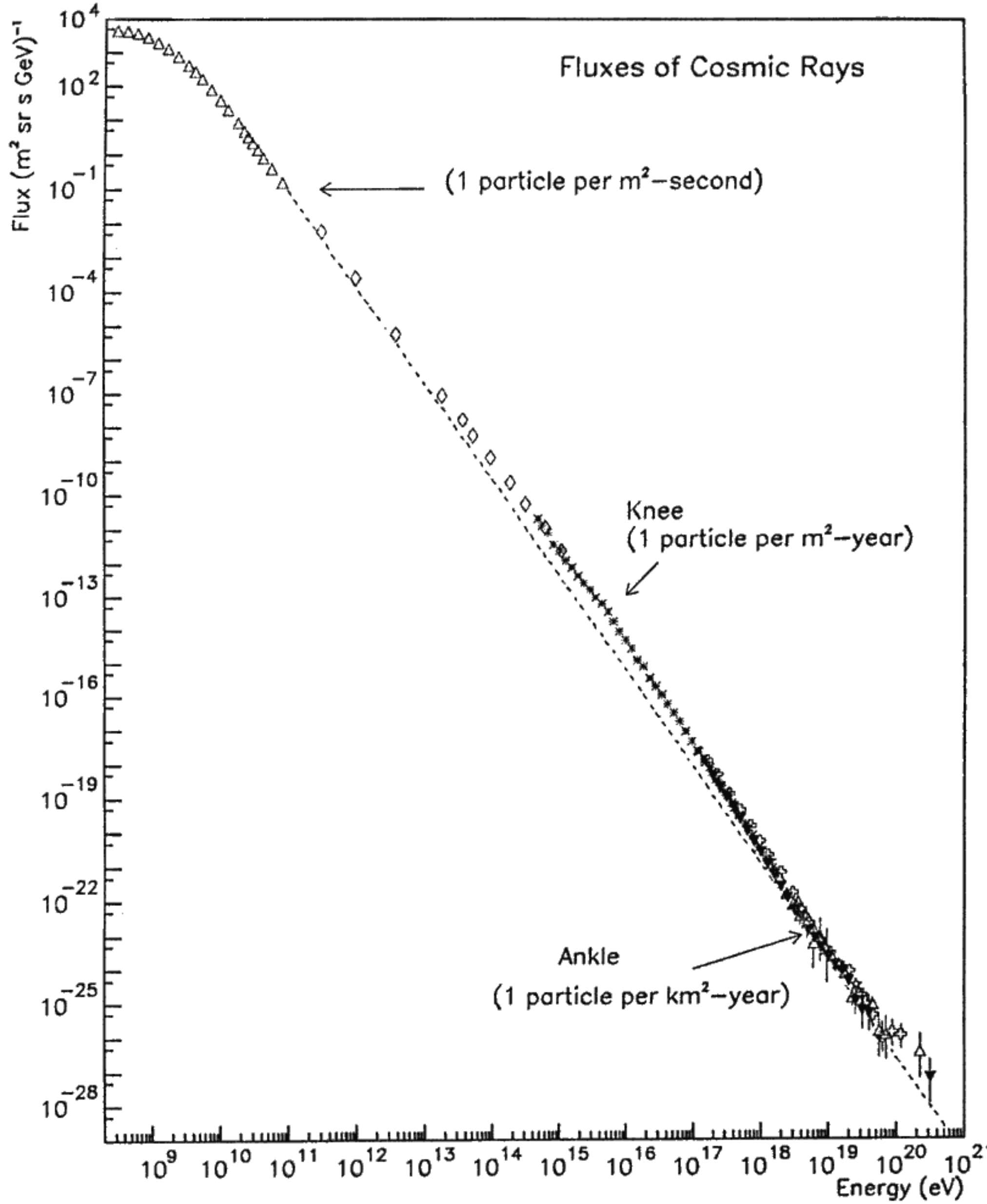


Fig. 1. The CR all particle spectrum [509]. Approximate integral fluxes are also shown.

Fermi-type acceleration

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

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

Diffusive shock acceleration

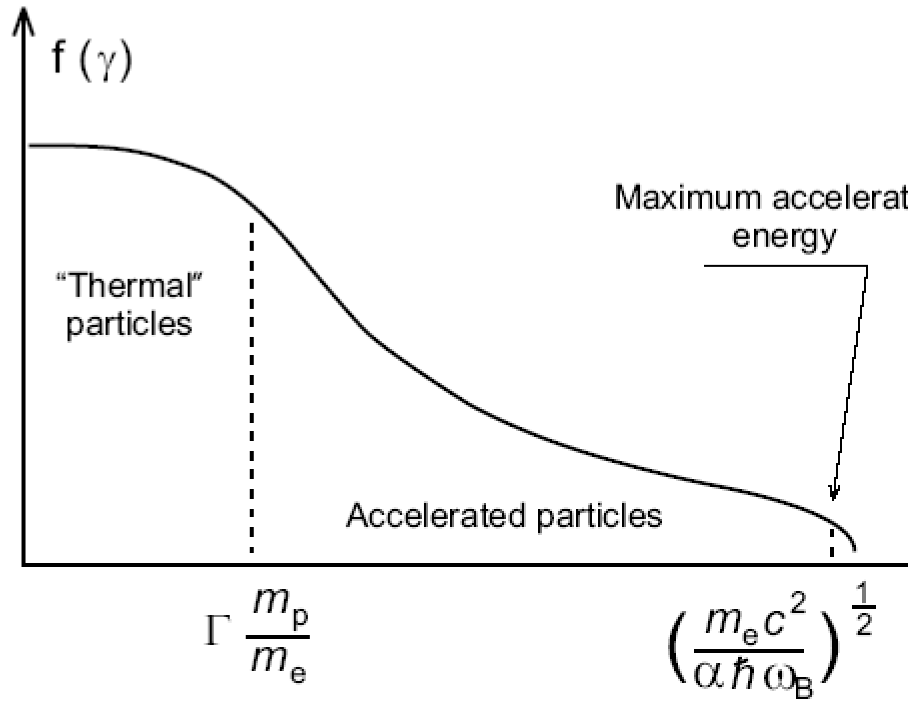
Γ – Lorentz-factor of the shock,

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

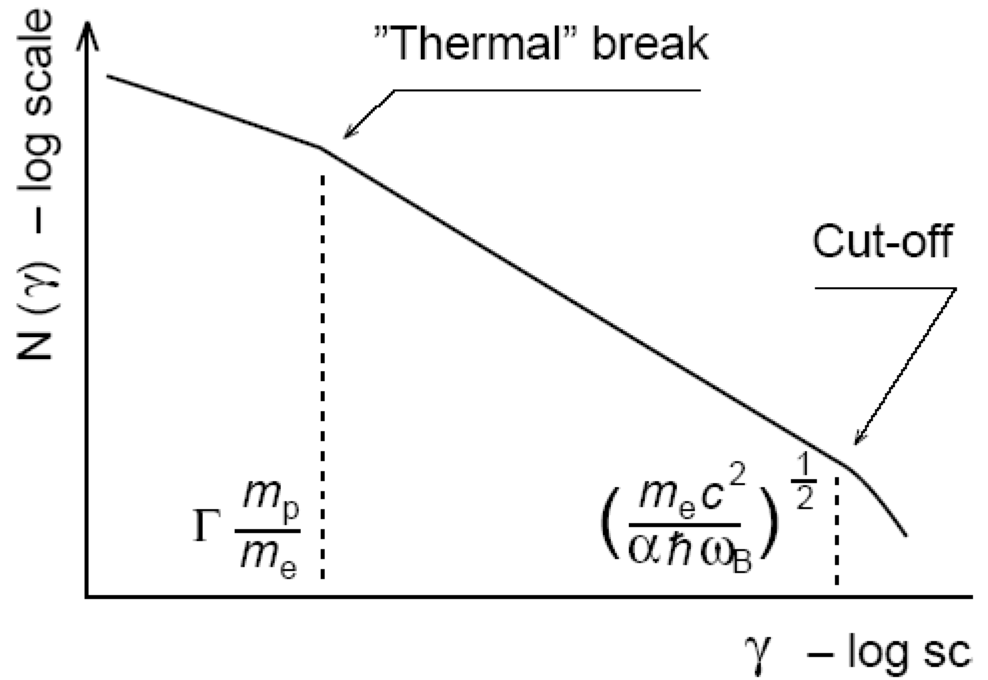
$N(\gamma)$ – electrons' distribution function

Continuity equation

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

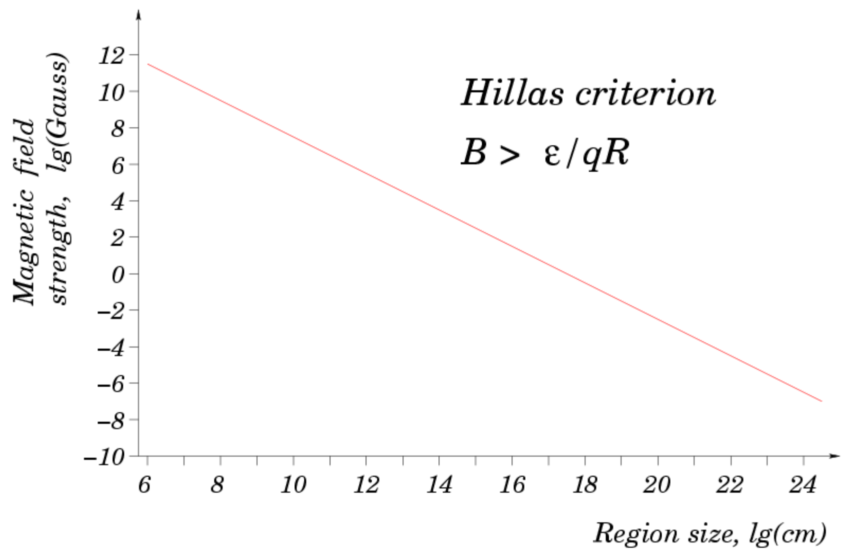
gives stationary solution

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

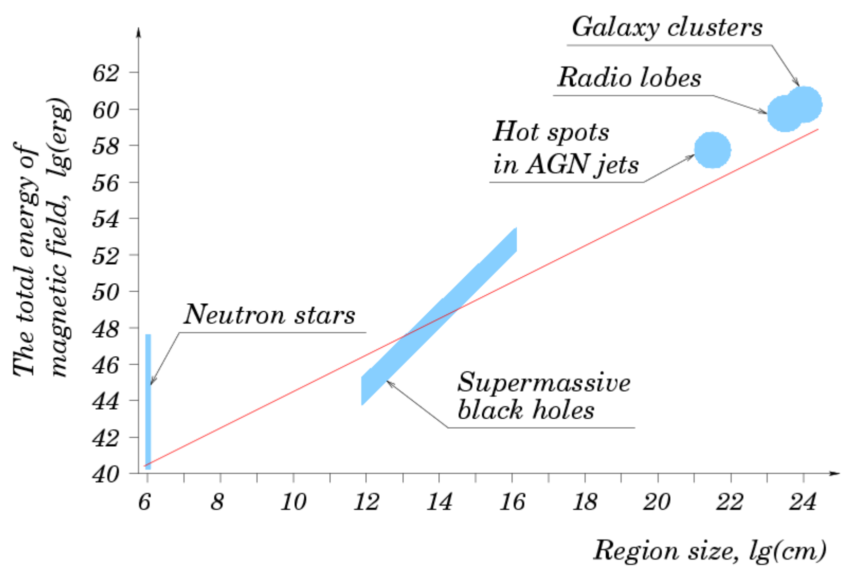


The corresponding spectrum (provided $\nu \propto \gamma^x$) is :

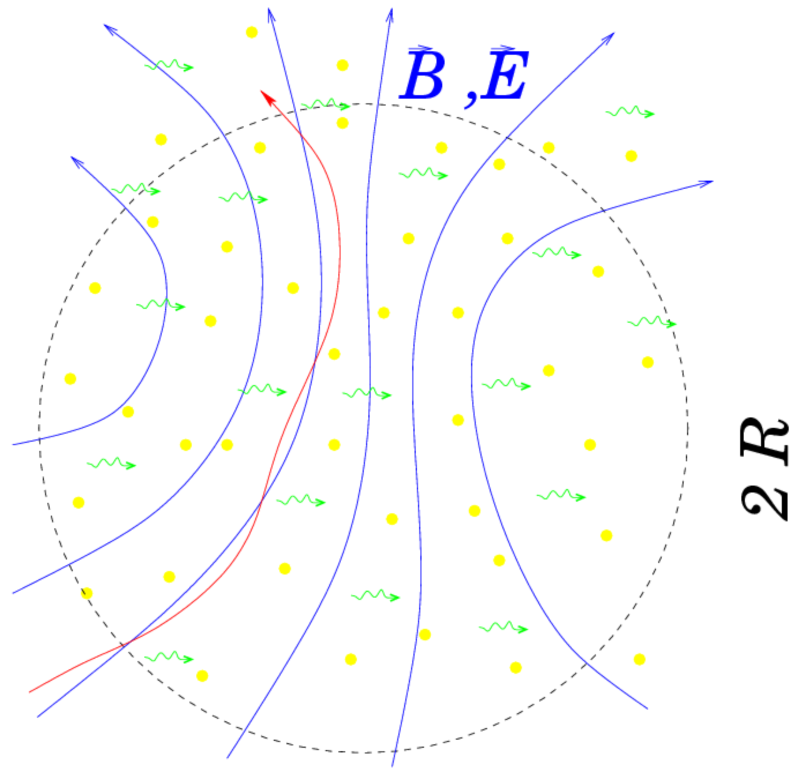
$$\nu F_\nu \propto \frac{dF}{d\ln\gamma} \propto \gamma\eta \int_{\gamma}^{\infty} f(\gamma')\, d\gamma'$$



Hillas criterion
B > ε/qR
Magnetic field strength, lg(Gauss)
12
10
8
6
4
2
0
−2
−4
−6
−8
−10
6
8
10
12
14
16
18
20
22
24
Region size, lg(cm)



Galaxy clusters
Radio lobes
Hot spots in AGN jets
Neutron stars
Supermassive black holes
The total energy of magnetic 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)



- *Collisions*
- *Cherenkov radiation in plasma*
- *Photomeson reactions*
- *Synchrotron & electrobremsstra 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)

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

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

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

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

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

for radiative-loss dominated regime and

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

for escape-dominated regime.

The optimal size is

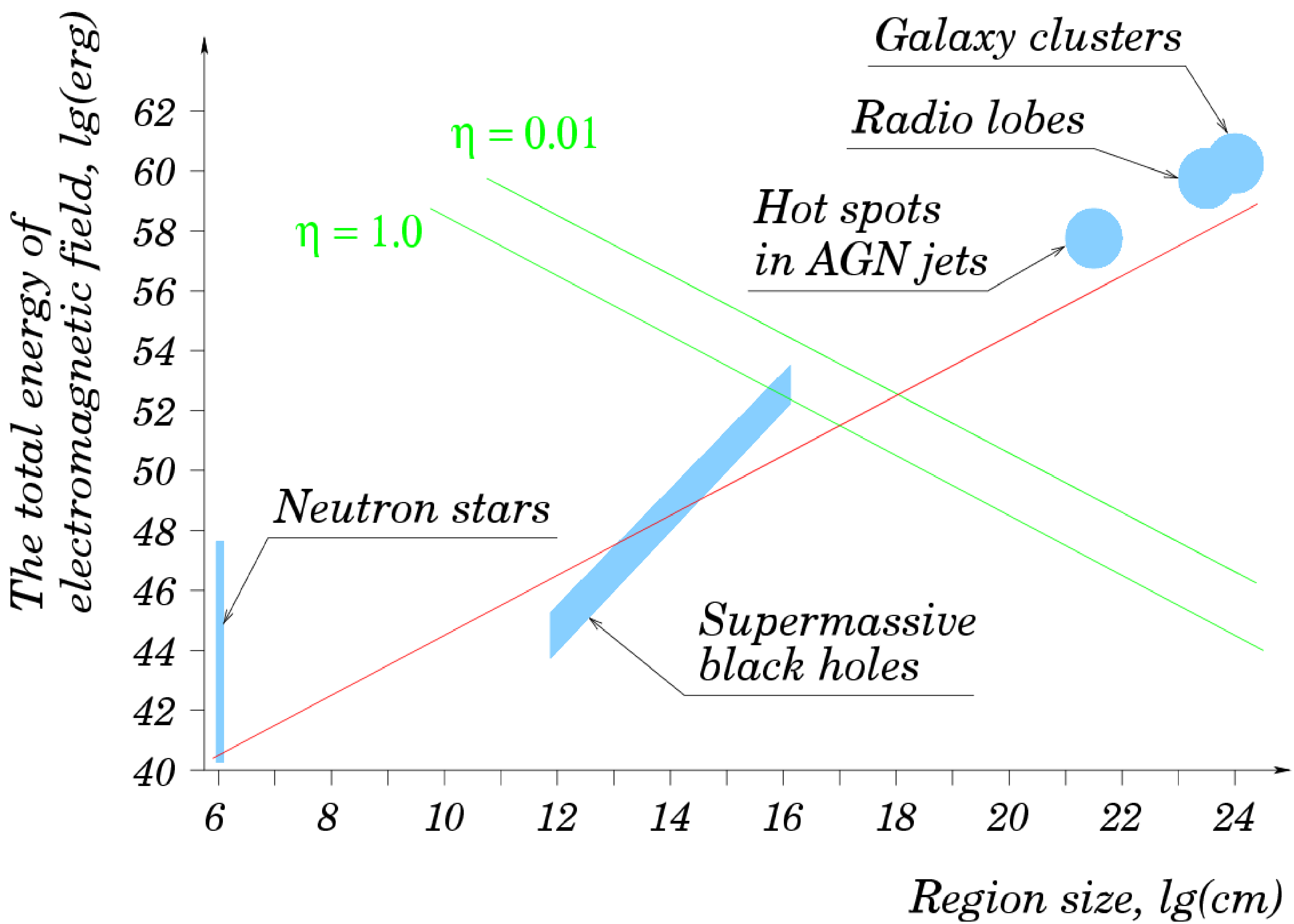
$$R^{(\rm opt)} \simeq \frac{2}{3}\frac{\sqrt{1+\eta^2}}{\eta}\frac{q^2\varepsilon_{\max}^3}{\left(mc^2\right)^4},$$

and the minimum required energy budget is

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

The corresponding optimal strength of the magnetic field:

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



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

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

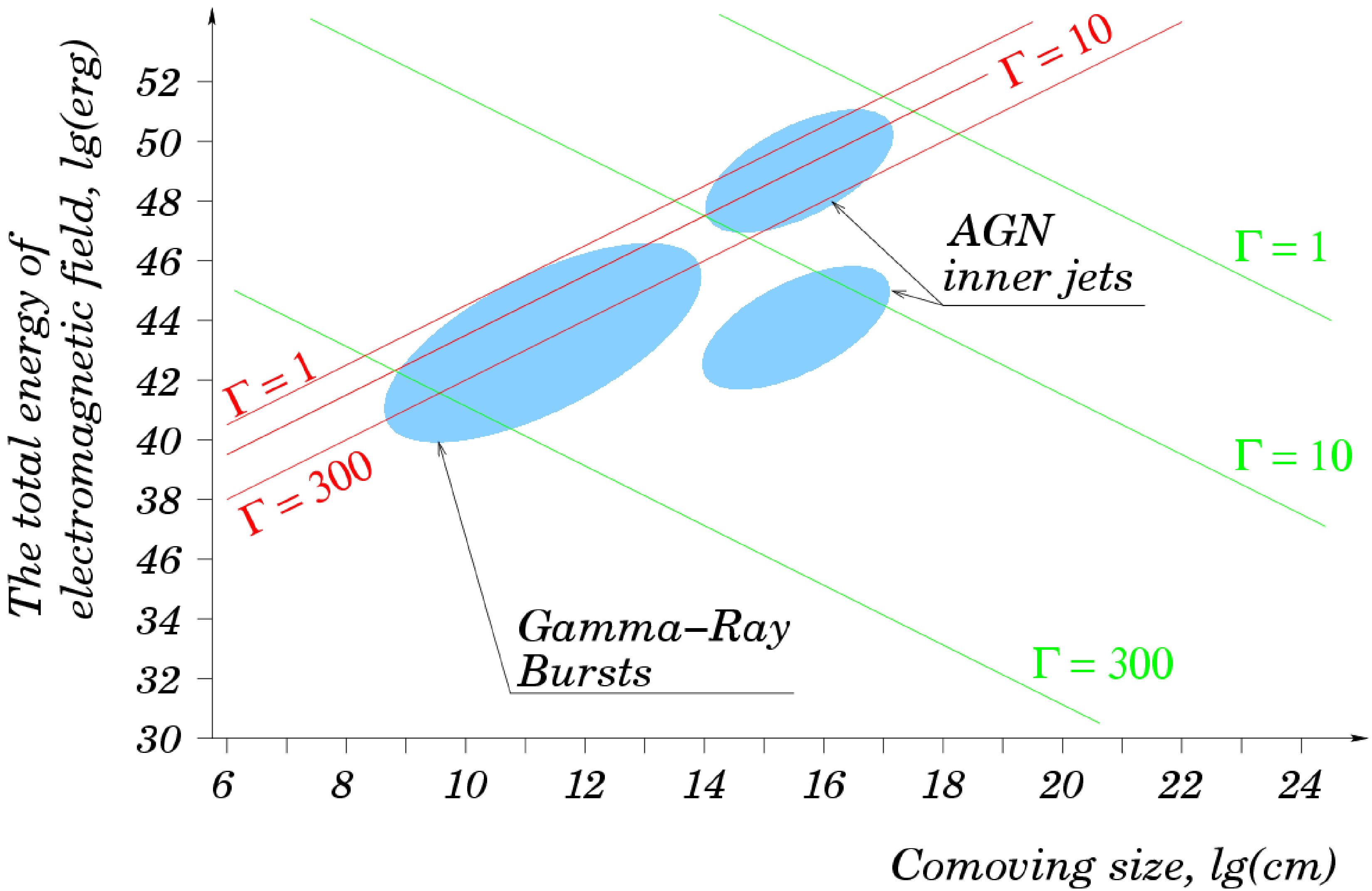
$$W_{\rm em}^{\rm (opt)} \simeq \frac{1}{9\,\Gamma^4}\frac{\sqrt{1+\eta^2}}{\eta}\frac{\varepsilon_{\rm max}^5}{\left(mc^2\right)^4},$$

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

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

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 = 1
Γ = 10
Γ = 300
Γ = 1
Γ = 10
Γ = 300
AGN inner jets
Gamma–Ray Bursts

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.

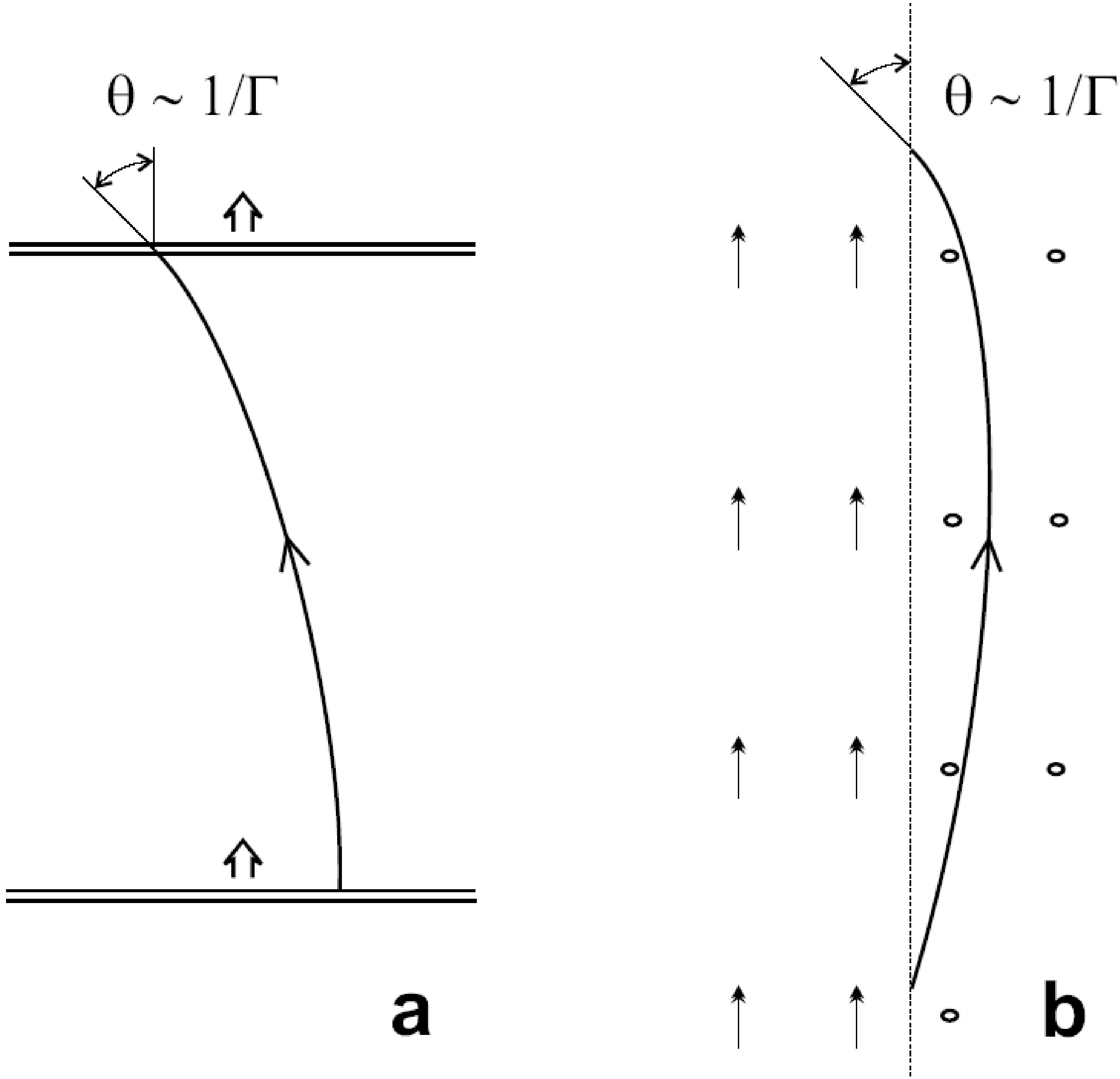
At least 50 per cent of the observed GRB energy has to be converted into EHECRs.

The attainable particle energy is

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

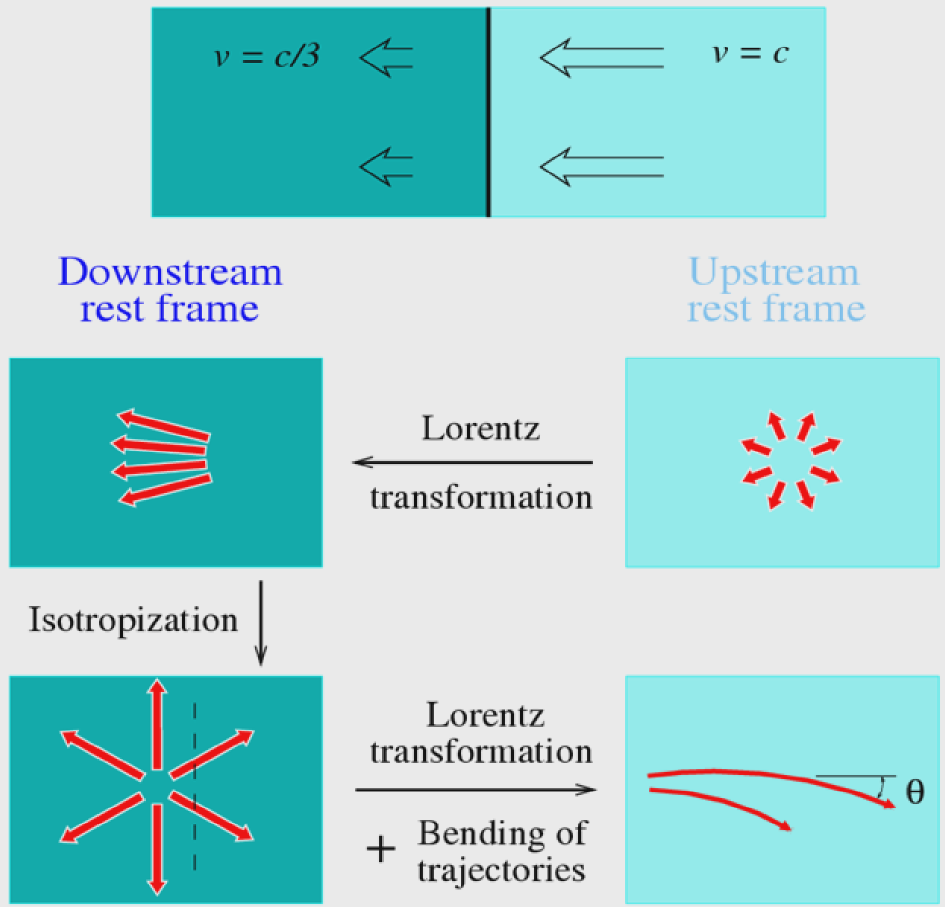
Explanation of some GRB properties requires $\Gamma > 100$, so that GRBs might be capable of accelerating protons well above 10^{20} eV.

Limitation of diffusive shock acceleration



Standard acceleration mechanism

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

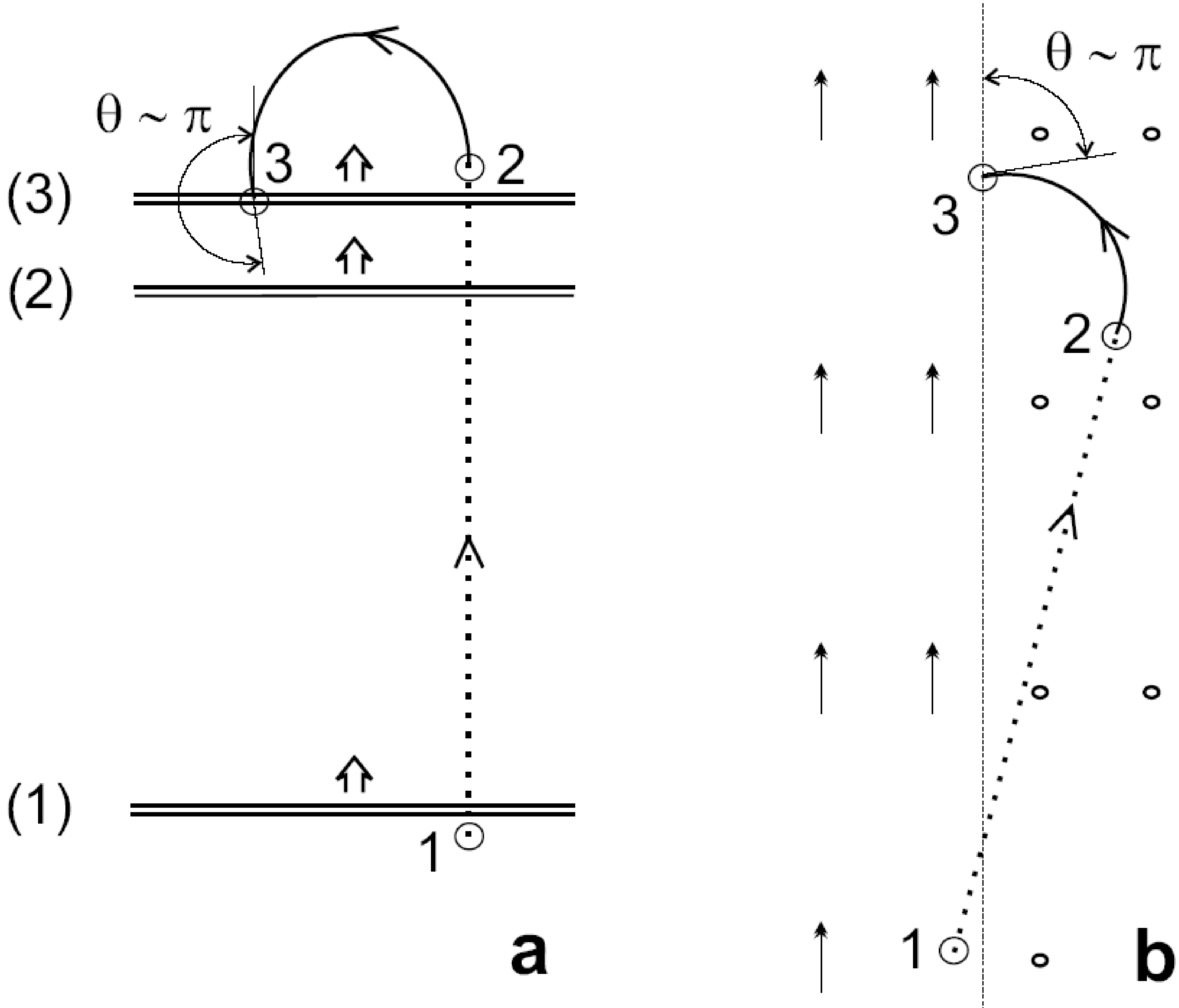


Energy gain is $g = (\Gamma\theta)^2/2$

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

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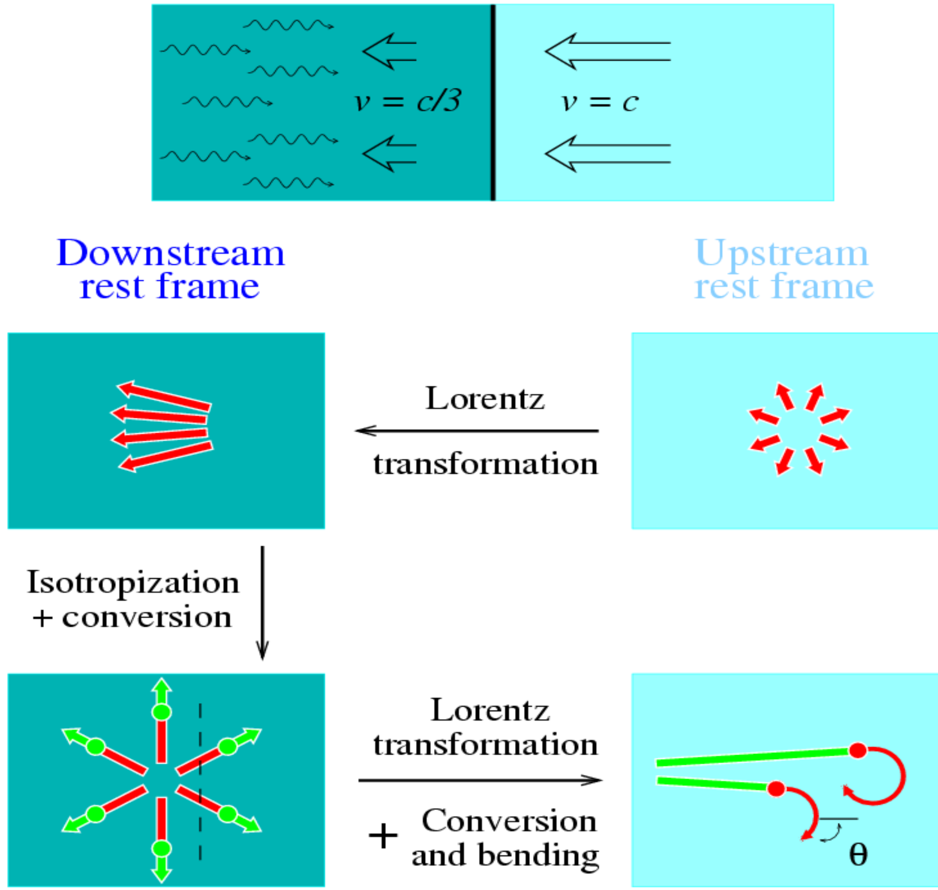
Phys. Rev. D **68**, 043003 (2003)

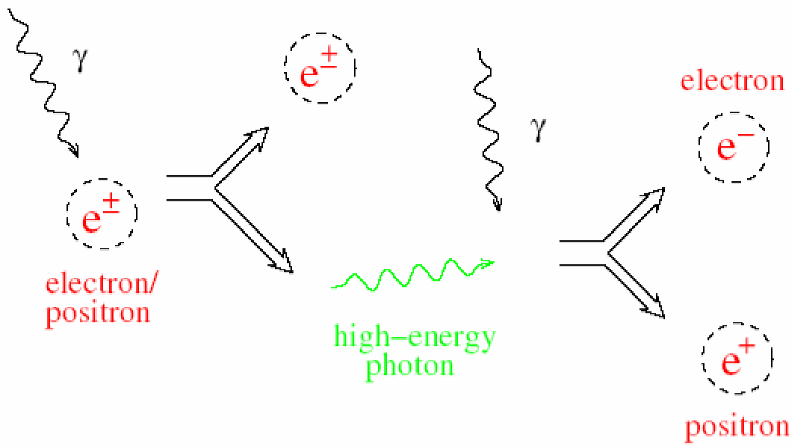


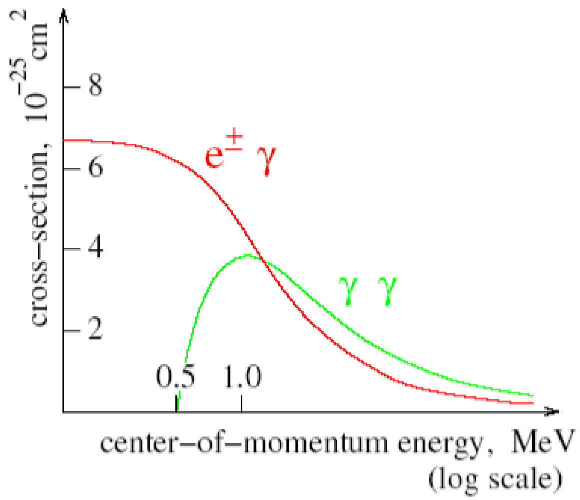
Energy gain is $g = (\Gamma\theta)^2/2$

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

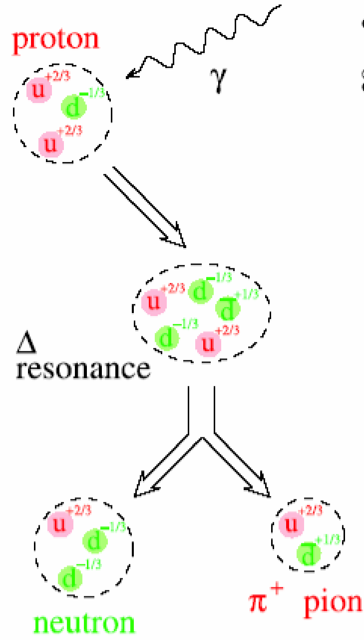
Particle distribution: $\dfrac{dN}{d\varepsilon} \propto \varepsilon^{-\alpha}$ with $\alpha = 1 - \dfrac{\ln p_{\rm cn}}{\ln g}$

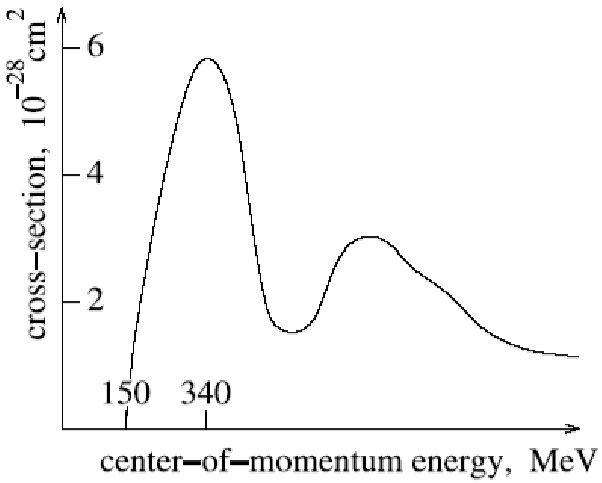
$e^-/e^+ - \gamma$ cycle





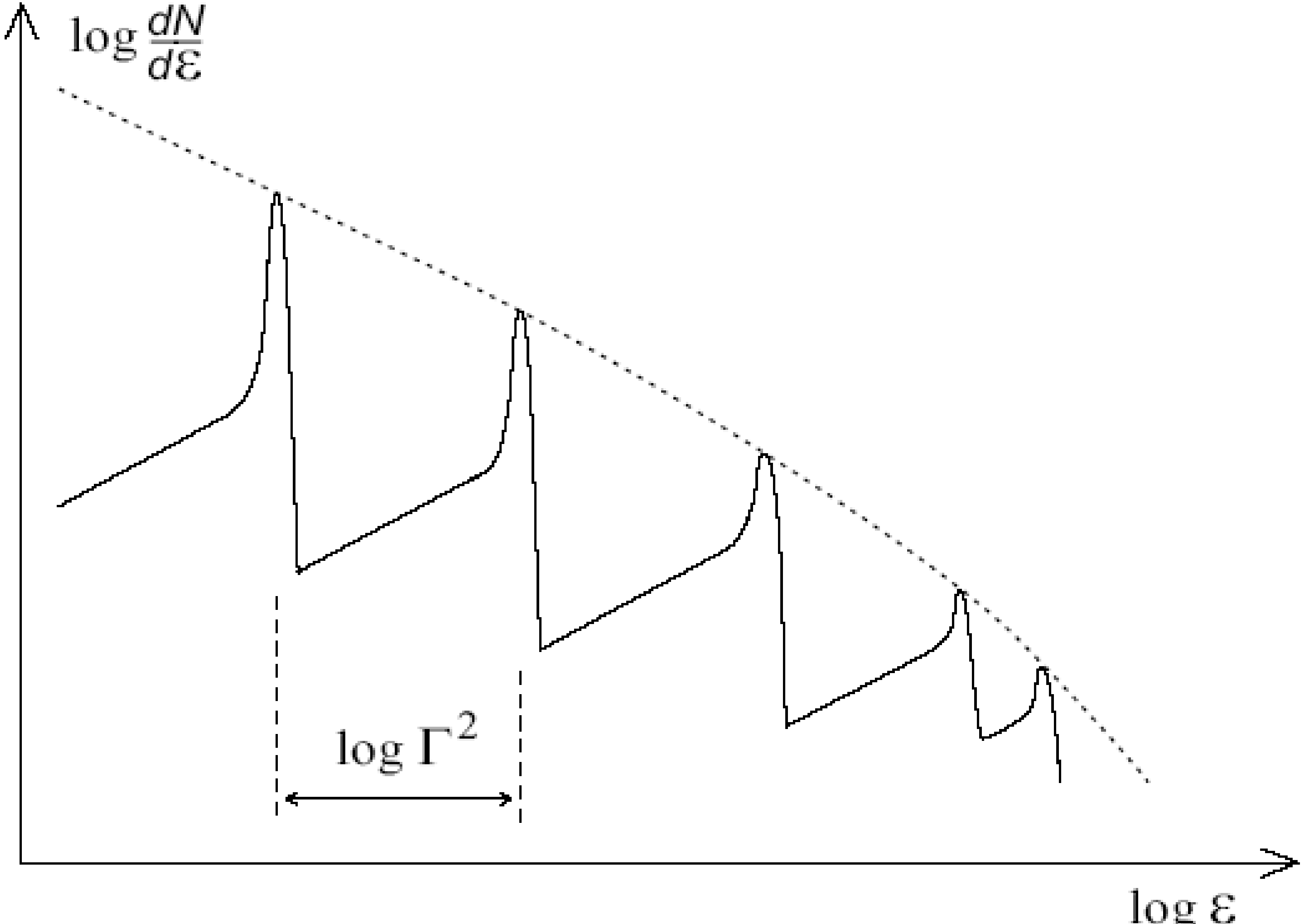
p - n cycle





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

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



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

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.

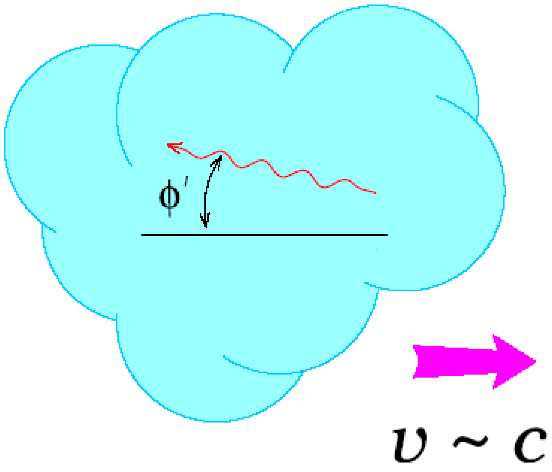
At the energies greater 10^{22}eV the cosmic ray primaries have to be heavy nuclei. In all the sources listed above the heavy nuclei are accelerated in the escape-limited regime, so that the attainable energy is roughly Z times more than for protons. However, the nuclei of such energy are fragmented 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 acceleration scenario.

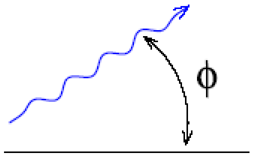
$$\cos\phi = \frac{\beta - \cos\phi'}{1 - \beta\cos\phi'}\ ; \qquad \cos\phi' = \frac{\beta - \cos\phi}{1 - \beta\cos\phi}$$

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

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

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



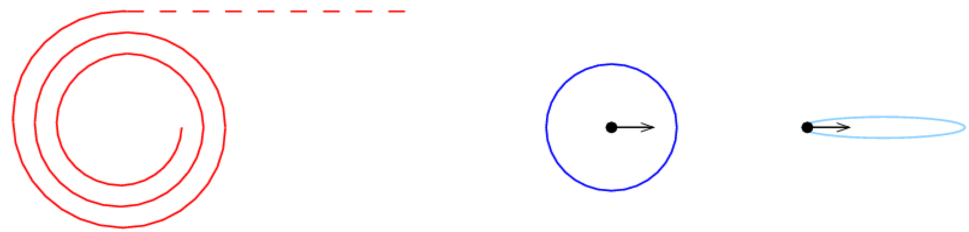


$$\phi \simeq \frac{2}{\sqrt{(\Gamma\phi')^2 + 1}} \quad и \quad \delta \simeq \frac{(\Gamma\phi')^2 + 1}{2\Gamma}$$

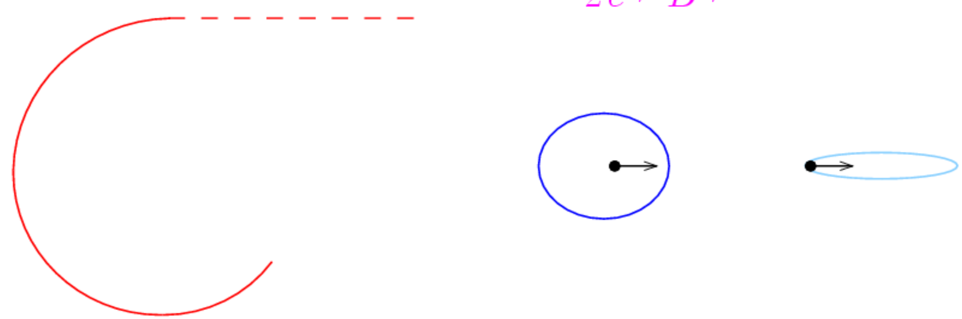
Changes in the emission beam-pattern

Downstream frame | Observer's frame

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



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



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

The synchrotron emission of the accelerated particles has two distinctive features. First, the maximum energy of synchrotron photons for the converter mechanism is Γ^2 times larger than for the standard one. Indeed, the acceleration cycle in the standard mechanism lasts $\sim r_g/c$ and the energy increment is $\sim \varepsilon$, which gives the acceleration rate $\dot{\varepsilon} \sim \varepsilon c/r_g$. The maximum admissible rate of synchrotron losses is just the same, so that the particle's energy is limited and so does the energy of synchrotron photons:

$$\varepsilon_{\rm sy}^{(\rm max)} \sim 0.5 \frac{\hbar e B}{mc} \left(\frac{\varepsilon}{mc^2}\right)^2 \sim \frac{\hbar c}{e^2} mc^2 \simeq 137\, mc^2 \,. \tag{18}$$

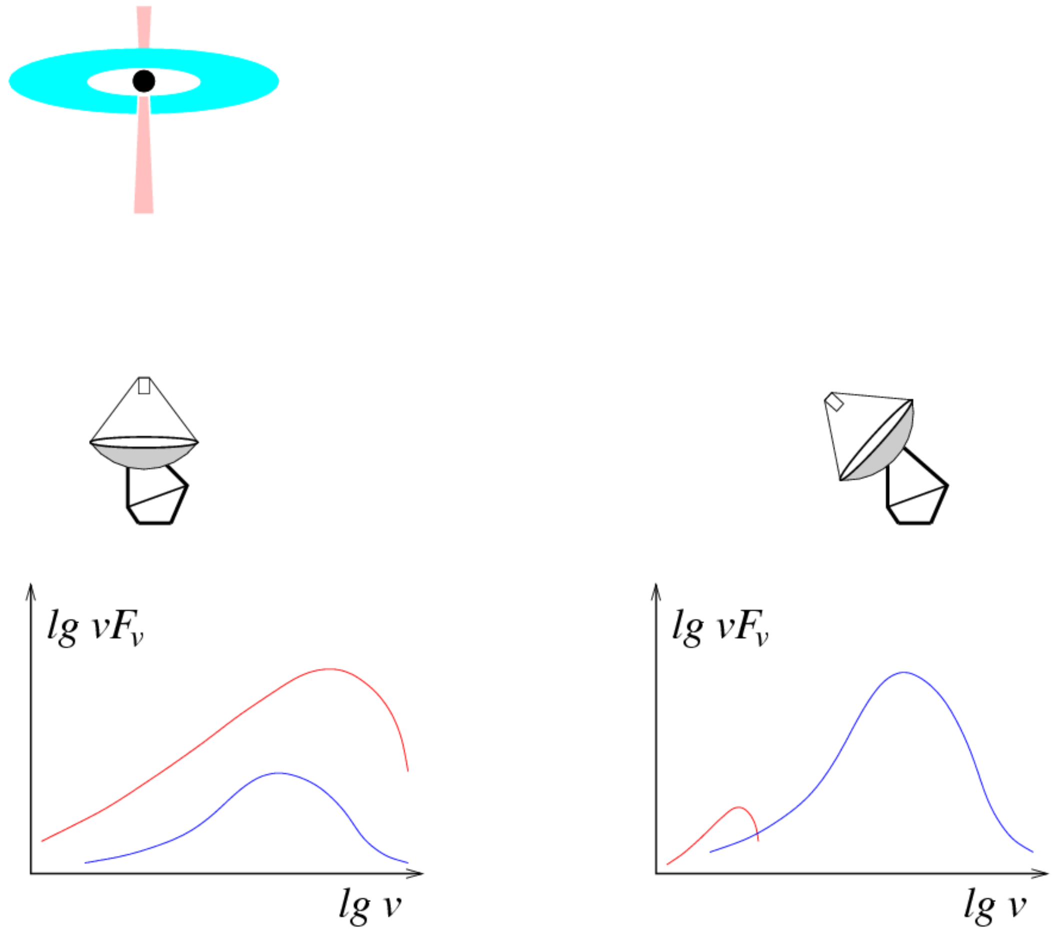
Doppler boosting gives additional factor Γ.

The same reasoning is valid for the converter mechanism, in which the cycle duration is $\geq r_g/c$ and the energy increment is $\leq \Gamma^2 \varepsilon$. This gives Γ^2 times larger limit for the energy of accelerated particle, which translates into factor Γ^4 in the expression for the energy of synchrotron photons. When the accelerated particle enters the relativistic flow being close to the limiting energy, the synchrotron emission is so efficient, that the particle loses almost all its energy before it is deflected by an angle $\sim 1/\Gamma$. Thus, the resulting synchrotron emission is beamed backwards in the flow comoving frame. In the laboratory frame it appears redshifted by the factor Γ, in contrast to the standard mechanism, in which the synchrotron emission is blueshifted by the same factor Γ.

Taking into account all factors, we find that for an observer resting in the laboratory frame, the maximum energy of synchrotron photons accompanying the converter-acceleration is by the factor of $\sim \Gamma^2$ larger than in the standard mechanism. Moreover, this highest-energy synchrotron radiation is quasi-isotropic in the laboratory frame, which is another distinctive feature of the converter mechanism.

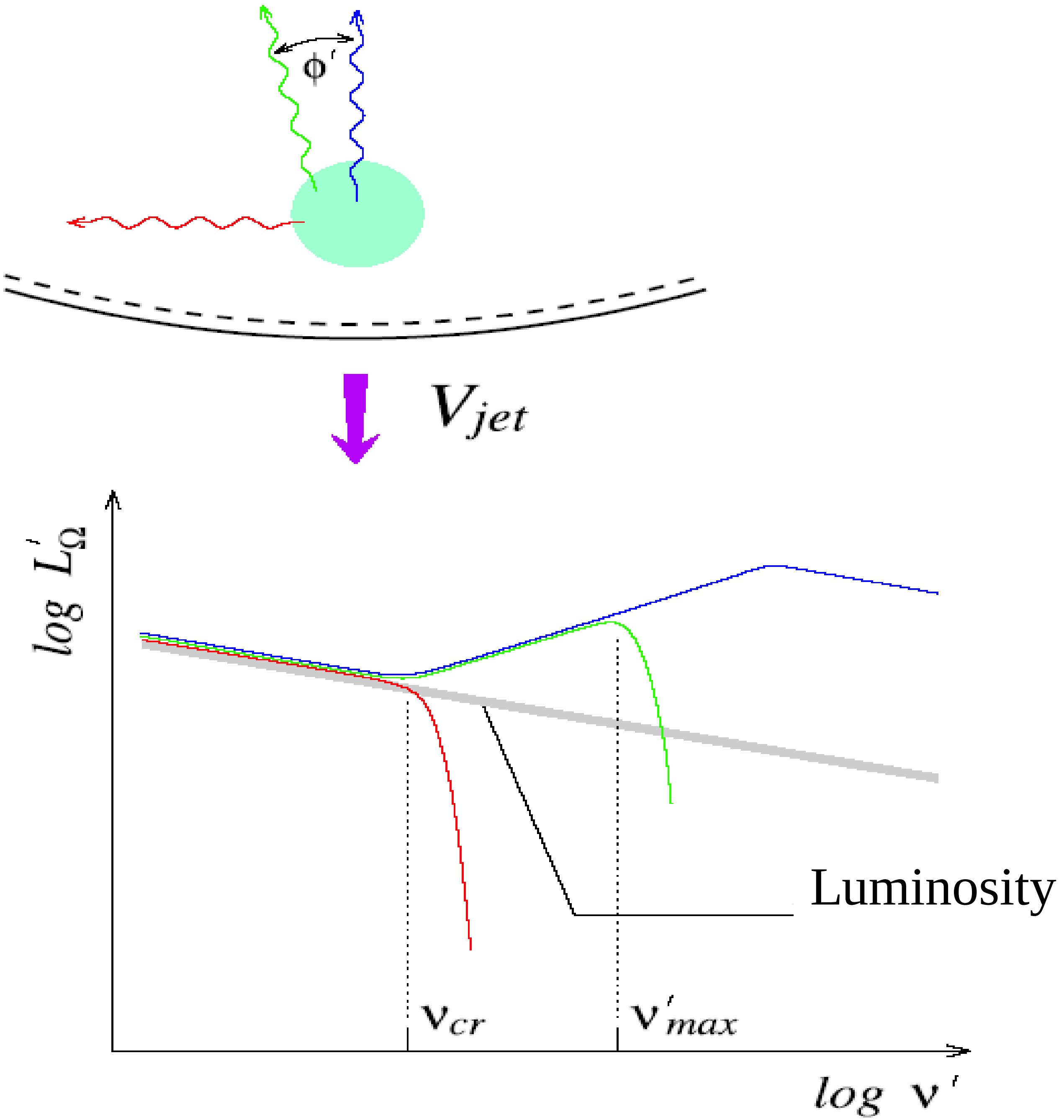
Generally speaking, the converter mechanism makes neutral beams of all kinds (photon, neutrino and neutron beams) broader than $1/\Gamma$, so that they can be seen even if the jet that produced them is not pointing towards the observer. The jet sources, which are observed off-axis owing to the effect of beam pattern broadening should exhibit very hard spectra. Indeed, the emission with broadened beam pattern is produced by high-energy particles which cool radiatively over a distance smaller than their gyroradius. For such particles the deflection angle (and hence the width of the beam pattern) is a function of their energy. An observer situated at a large angle to the jet axis effectively sees the particle distribution devoid of its low-energy part, whose emission can only be seen at smaller viewing angles. Therefore, the off-axis emission is the hardest possible – it is essentially as hard as the spectrum of an individual particle.

Dependence of γ-ray spectrum on the observation angle



On-axis view

Off-axis view



φ'
V_{jet}
log L'_{Ω}
Luminosity
ν_{cr}
ν'_{max}
log ν'

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.