Proton acceleration and emission in galaxy clusters

Giulia Vannoni

(F. Aharonian[1,2], S. Gabici[1], S. Kelner[2,3], A. Prosekin[2,3])

1) DIAS-Dublin
2) MPIK-Heidelberg
3) Moskow Institute of Engineering Physics

5th Korean Astrophysics Workshop November 20th, 2009

Outline

- Galaxy Clusters as UHE-CR sources.
- A theoretical model for acceleration: diffusive shock acceleration.
- Energy losses and the maximum energy: including energy losses into shock acceleration self-consistently.
- p-γ interactions: primary protons → secondary electrons → non-thermal radiation.
- Conclusions.

Galaxy Clusters As Non-thermal Sources

Radio: ~1/3 of rich clusters ($M \sim 10^{15}\ M_\odot$) synchrotron halos (e.g. Govoni & Feretti, 2004).

Non-thermal X-ray diffuse: excess at the level 10^{-11} erg $cm^{-2}s^{-1}$ in the range 10-100 keV (e.g. Fusco-Femiano, 1999; Eckert et al., 2008).

Gamma-rays: no detection → upper limits on CR content (Reimer et al., 2003; Aharonian et al., 2009; Aleksic et al., 2009).

⇨ Radio + X-ray (assuming same population of electrons): B ~ 0.1-1 μG
Gamma: constraints on CR energy budget ~ few % thermal. For Coma $E_{CR} \leq 10^{62}$ erg.

Particle Acceleration in Clusters

The ingredients:

- Formation of (strong) accretion shock at the virial radius (Bertschinger, 1985; Kang et al., 1994);
- Magnetic field of order 0.1-1 μG;
- Shock velocity, free fall velocity:

$$v_s \sim \sqrt{\frac{2\,G\,M_{cl}}{R_{cl}}} \simeq 2000 \left(\frac{M_{cl}}{10^{15}\,M_\odot}\right)^{1/2} \left(\frac{R_{cl}}{3\,Mpc}\right)^{-1/2} \text{km/s}$$

(Coma-like cluster)

- Acceleration time ~ Hubble time.
  High energy protons accumulate in the structure (Völk et al., 1996; Berezinsky et al., 1997).

⇒ Shock acceleration of protons possible to very high energies.

A Self-consistent Approach

(Vannoni, Gabici, Aharonian; 2009)

$$\frac{\partial f(x,p,t)}{\partial t}+u\frac{\partial f(x,p,t)}{\partial x}-\frac{\partial}{\partial x}\left(D\frac{\partial f(x,p,t)}{\partial x}\right)-\frac{p}{3}\frac{\partial u}{\partial x}\frac{\partial f(x,p,t)}{\partial p}\underbrace{+\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2L(x,p)f(x,p,t)\right)}_{\text{loss term}}=Q(x,p)$$

Numerical formulation kept general:

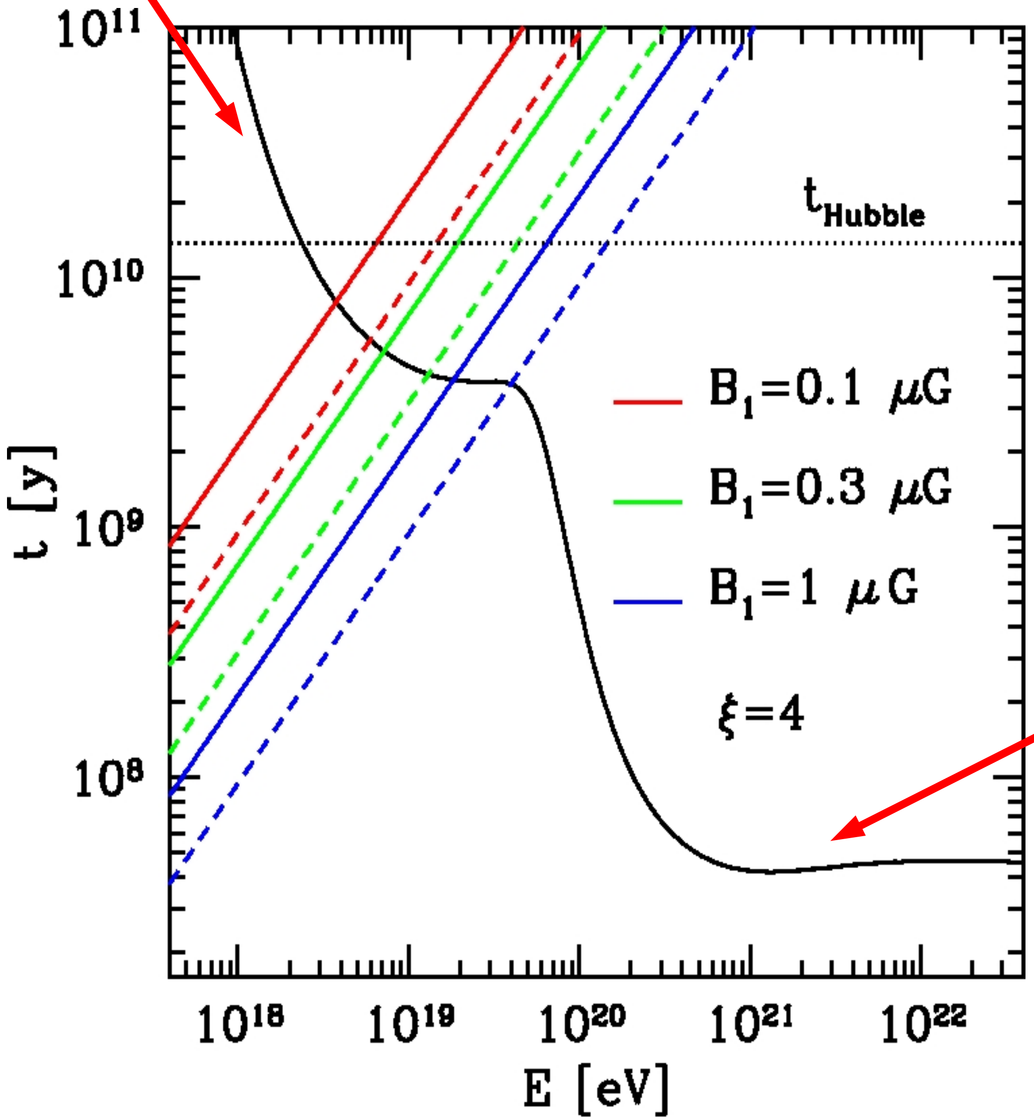
- protons or electrons
- general form of the loss term L(x,p)
- general form of the diffusion coefficient D(x,p)
- time evolution

Simplifying assumptions:

$Q(x,p)=Q_0\delta(x)\delta(p-p_0)$	injection at the shock
$D(p)=D_{.}\,p^{\beta}$	independent of x, Bohm: $D_0=\frac{c^2}{3eB}$, $\beta=1$
$L(x,p)=L(p)$	independent of x
$B_2=\xi B_1$	ξ=4, random magnetic field (Alfvén waves)

Proton Energy Losses

Assumption: Spherical accretion shock.



pair production

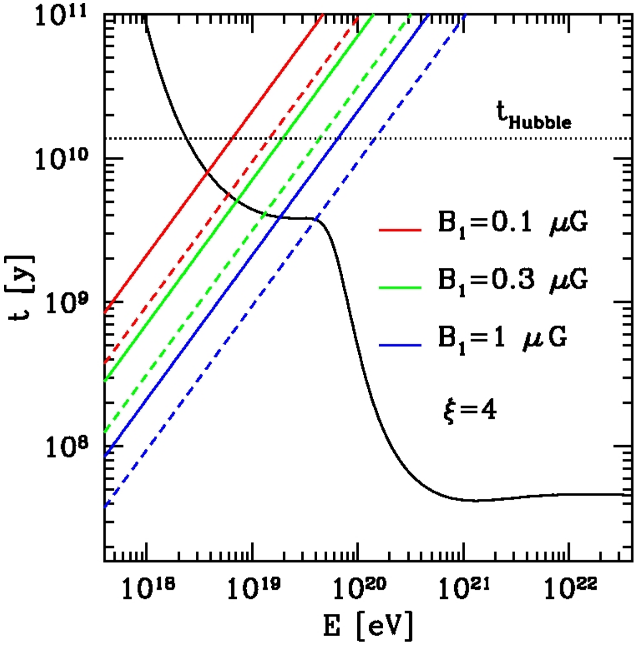
pion production

Interaction with the CMB can become the limiting mechanism (Norman et al., 1995; Kang et al., 1997).

Pair production dominant energy loss channel for all realistic sets of parameters.

Time dependent calculation needed.

Proton Spectrum



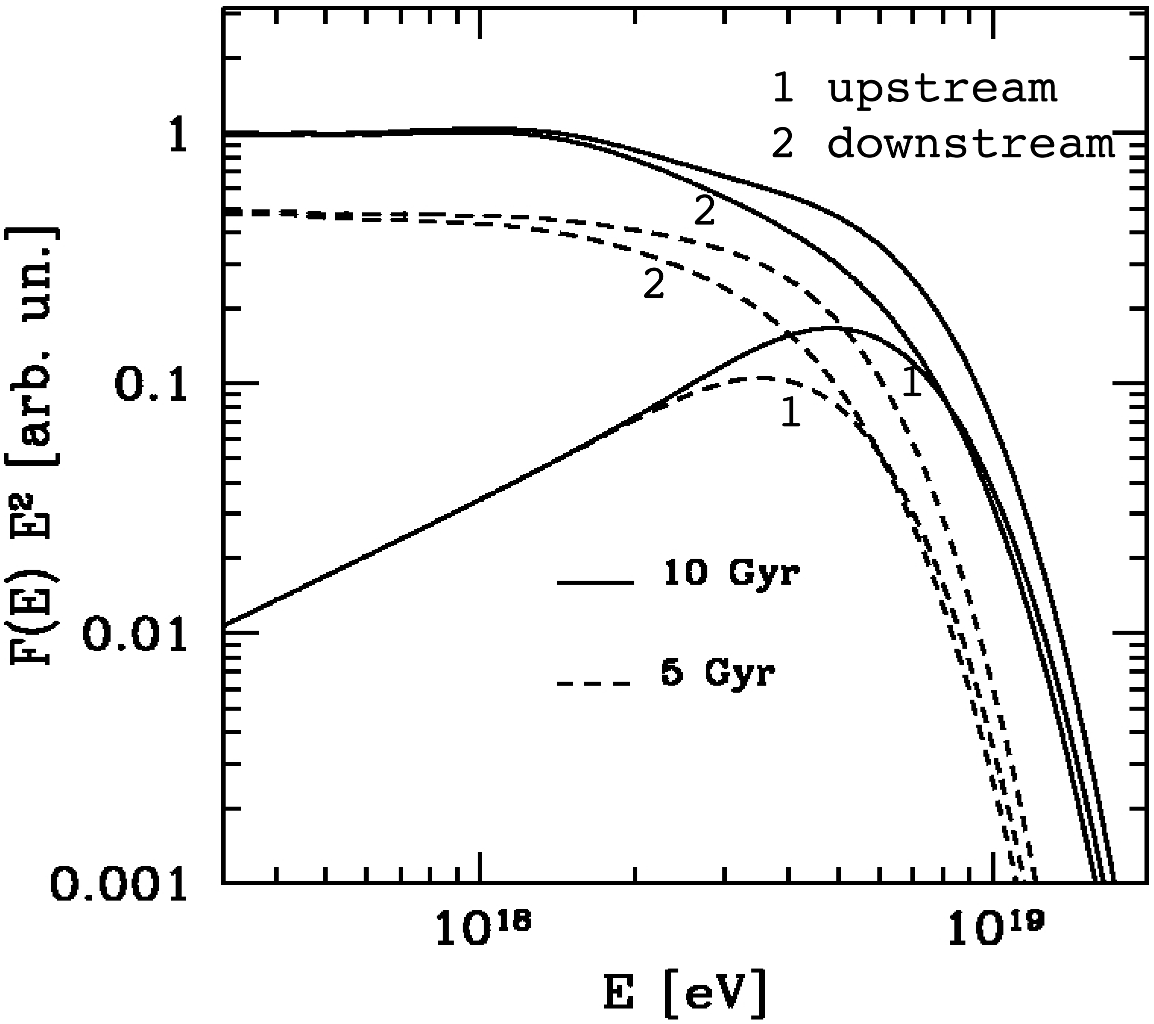
Pair production energy losses shape the proton spectrum around the cut-off:

small bump,
non-exponential cut-off

(Vannoni et al., arXiv0910.5715)

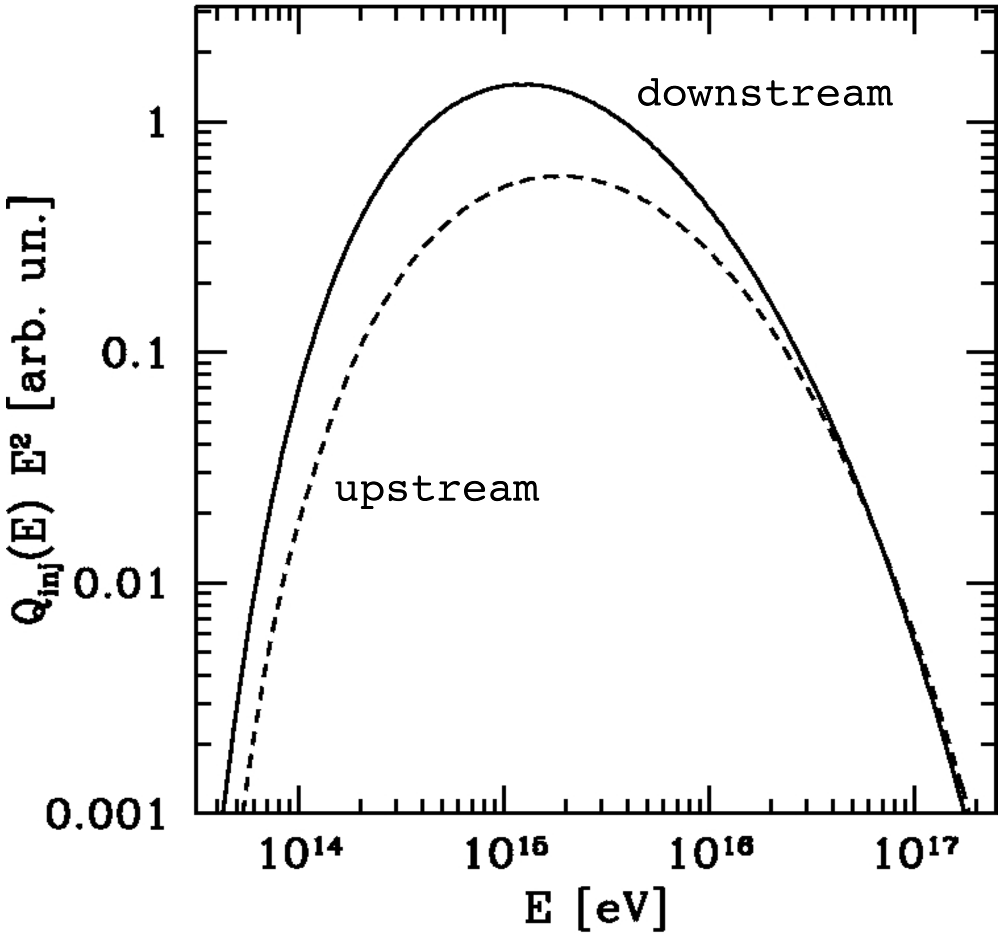
No steady state.

Cut-off energy ~$7\text{x}10^{18}$ eV



Production and Cooling of Secondary Electrons

τ_{acc}=5 Gyr.

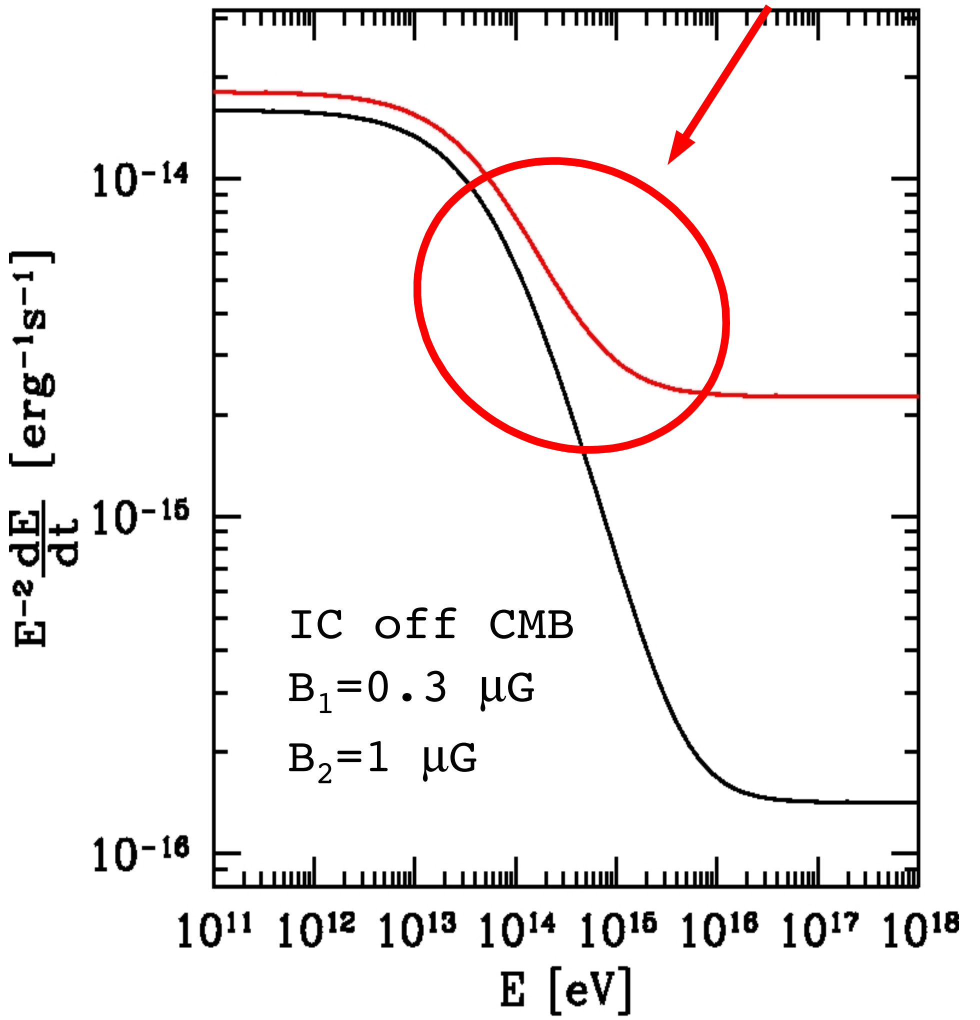


Photopair production: electrons production spectra – detailed numerical calculation

(Kelner & Aharonian, 2008).

Production and Cooling of Secondary Electrons

Electrons rapidly cool via synchrotron and IC.
IC cooling in Klein-Nishina regime.

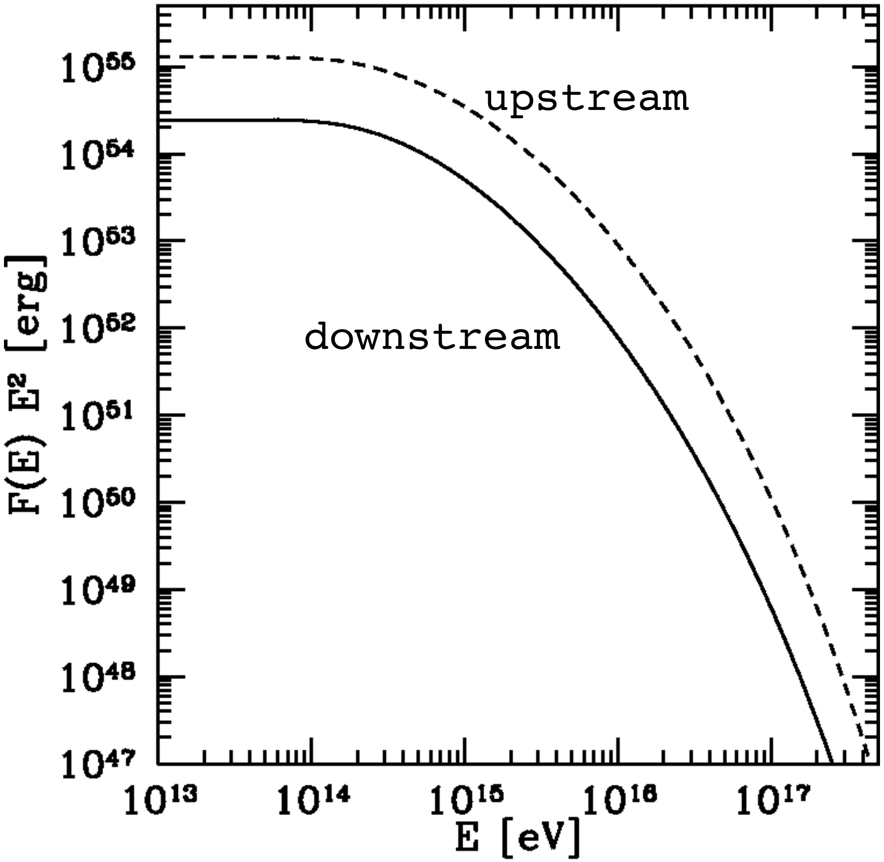


Cut-off in KN

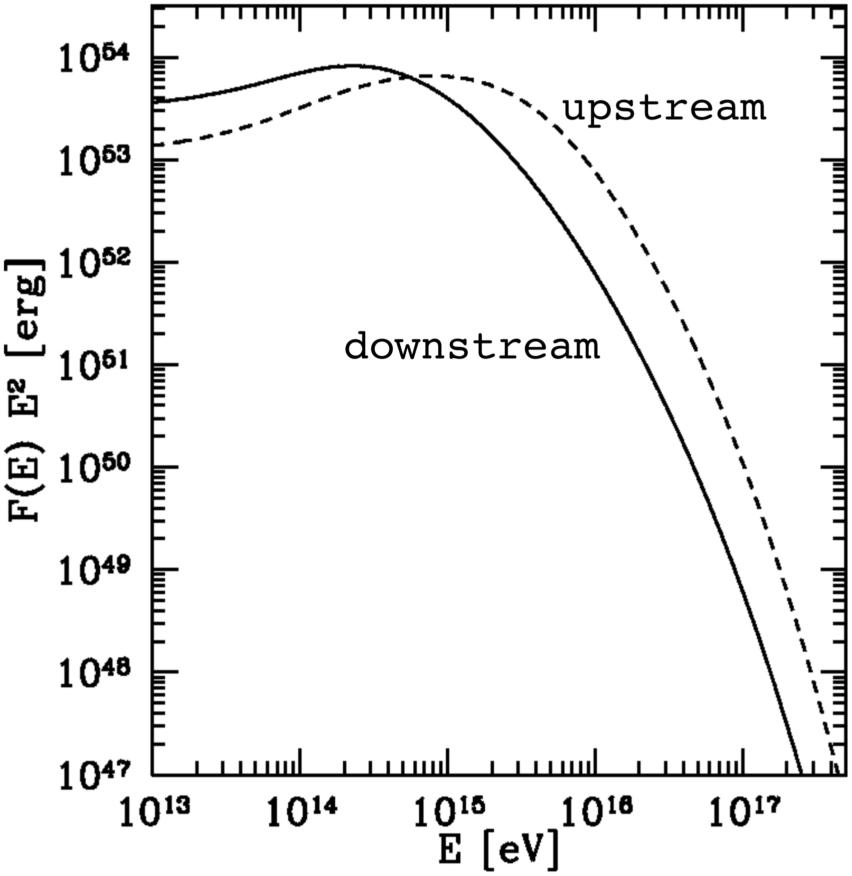
Cooling of Secondary Electrons

Normalisation: total proton energy budget 10^{62} erg

Pure synchrotron cooling



SY+IC in KN regime

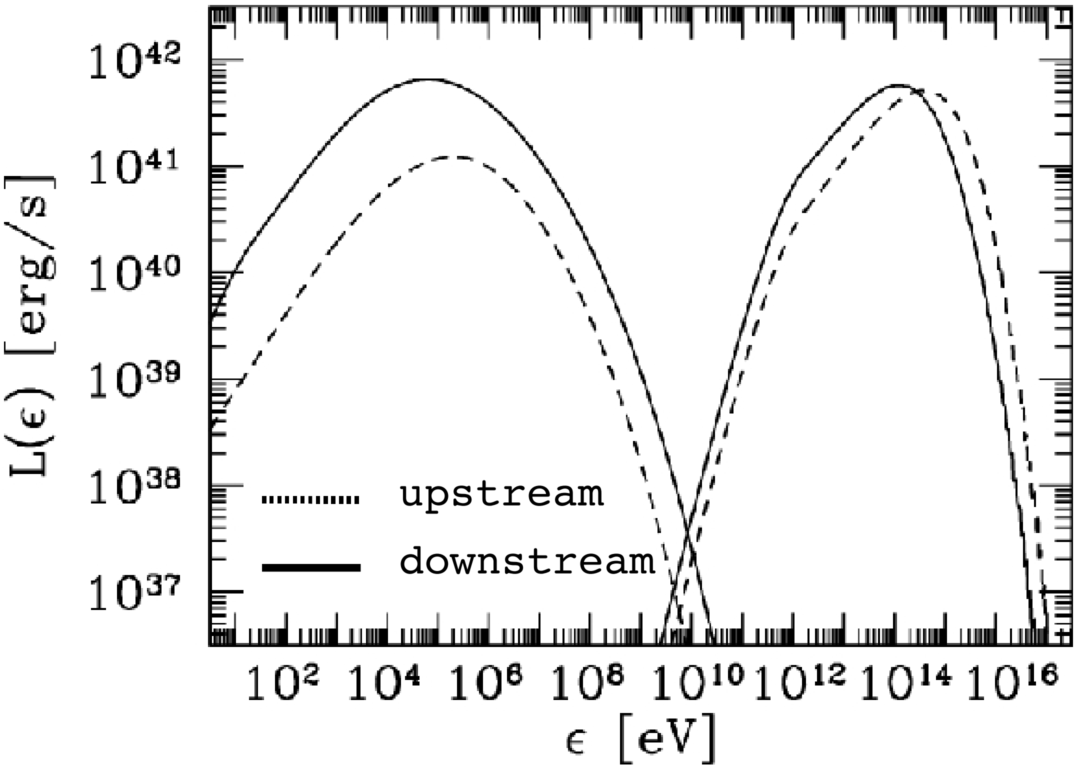


Assumption: no further acceleration $\left(F(E)=\frac{1}{\dot{E}}\int Q_{inj}(E)\,dE\right)$

Features in the cooled spectrum around the cut-off.

Upstream and downstream level comparable, shift in the cut-off energy.

Broadband SED, detectability



- Efficient proton acceleration up to 10^{18} eV.
- Efficient secondary electron production in p-photon interaction.
- Rapid electron cooling and energy transfer to non-thermal photons.

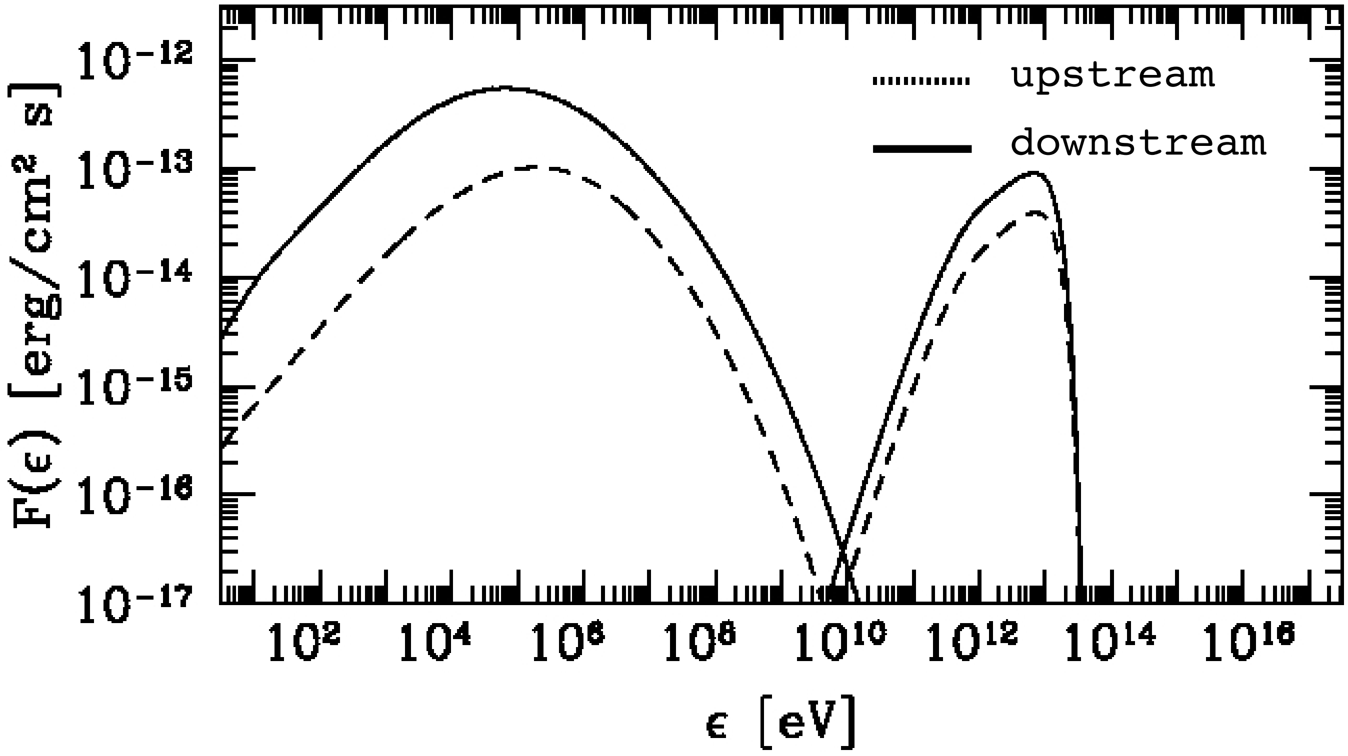
~100% of the energy lost by protons is found in non-thermal photons.

Broader cut-off, less steep than exponential.

Synchrotron: ~factor 10 enhancement downstream due to higher B. Peak energy ~100 keV.

Inverse Compton: same emission level up and downstream. Peak between 10 and 100 TeV, but absorption will reduce the gamma-ray flux.

Broadband SED, detectability



(Used EBL by Franceschini et al., 2008)

Peak luminosity L~10^{42} erg/s

Cluster at a distance 100 Mpc (Coma):

Flux at Earth=$L/(4\pi D\ )\sim10^{-12}$ erg $cm^{-2}s^{-1}$

(HESS PS sens.:~10^{-13} TeV^{-1} $cm^{-2}s^{-1}$ @1 TeV, 5σ in 25h, decreases linearly with source extension)

γ-rays from a source at 100 Mpc above 10 TeV effectively absorbed

Shock Modification

If acceleration is efficient, dynamical reaction of particles expected on the shock structure.

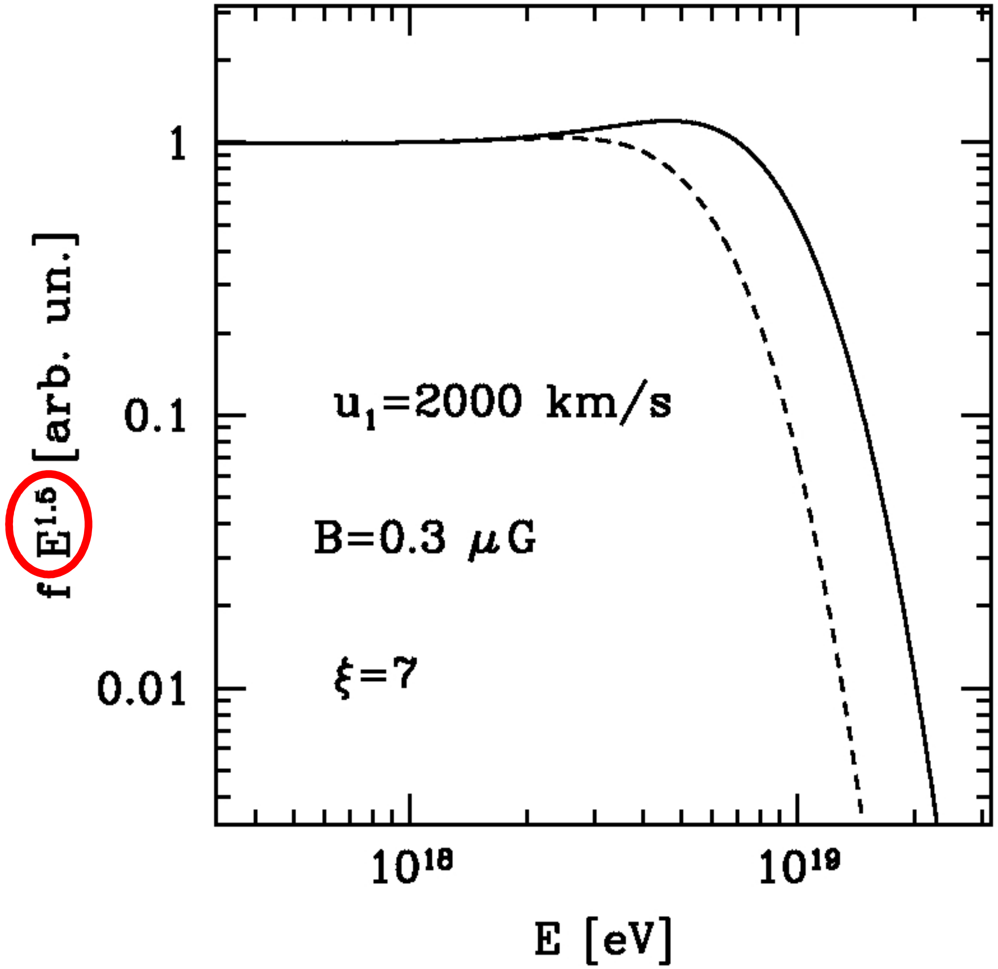
Non-linear shock acceleration theory:
(Drury & Völk 1981; Kang et al. 1996; Malkov 1997; Berezhko & Ellison 1999; Blasi 2002...)

- energy transferred by the shock to accelerated particles is accumulated at energies close to the cut-off.
- shock modification is expected to translate in an enhancement of the non-thermal luminosity of the system.

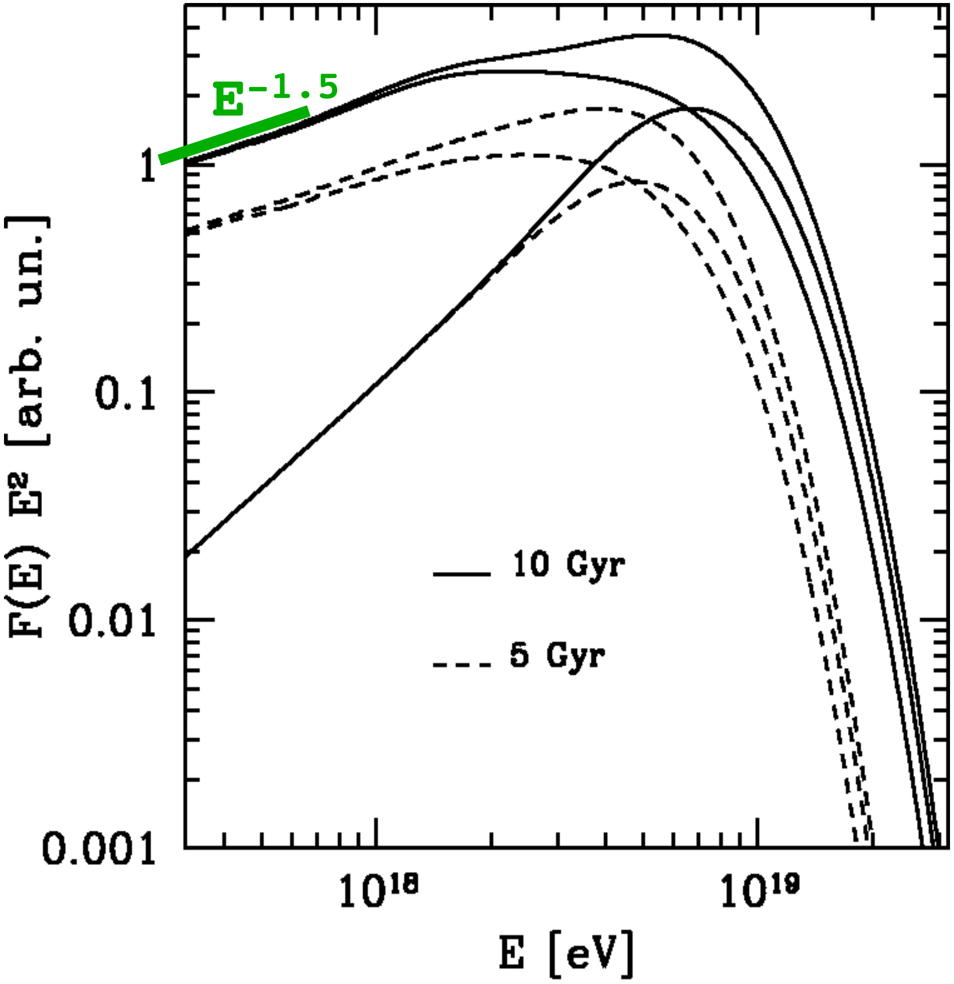
Approximation: $R=7$, $\xi=7$

Proton Spectrum

For R=7 ➔ expected energy spectrum $\propto E^{-1.5}$

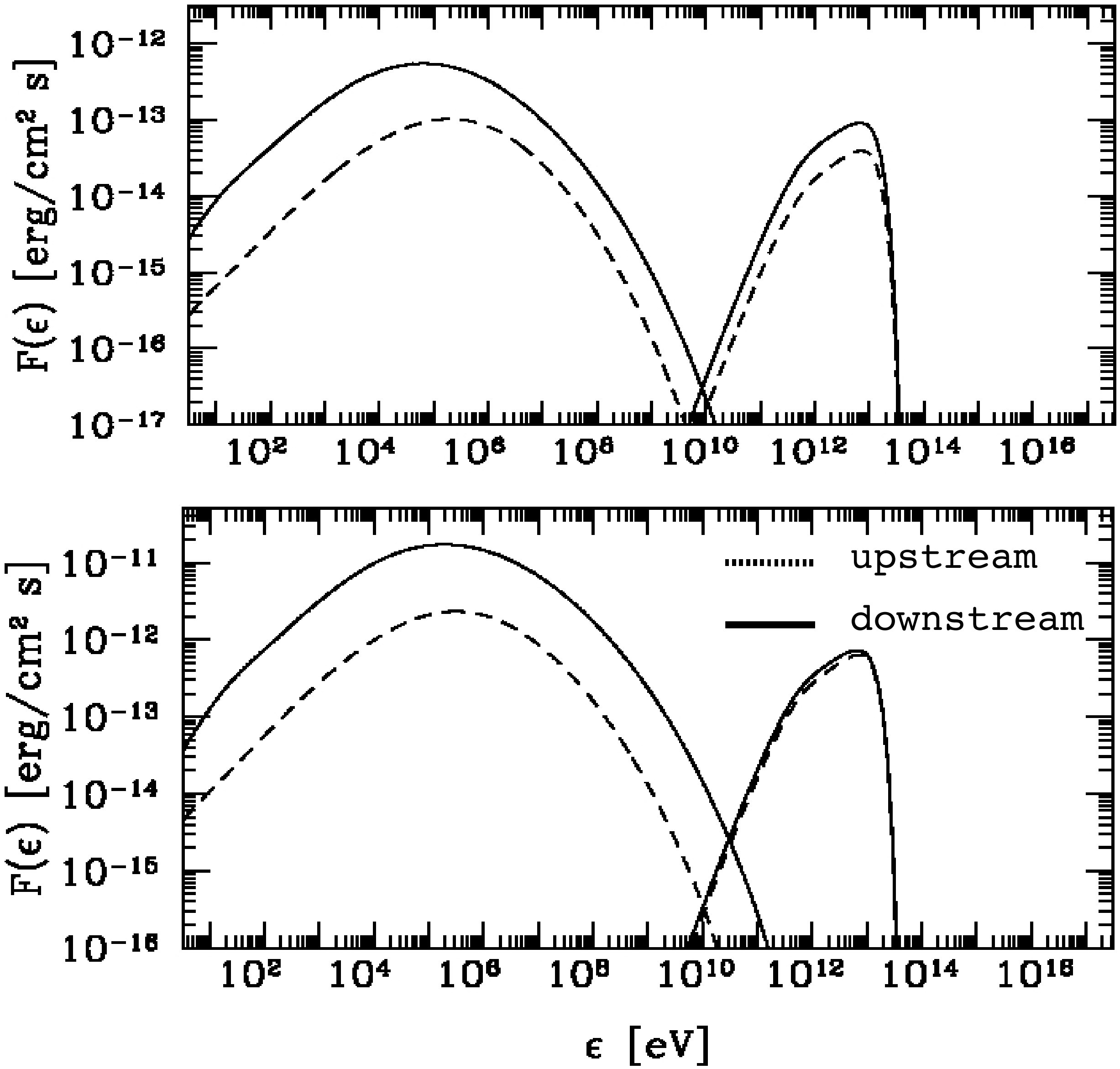


Spectrum at the shock:
feature around the cut-off



Integrated spectrum:
all energy transferred at E
around the cut-off

Broadband SED (Modified Shocks)



Linear
shock

Modified
shock

Emission enhanced by one order of magnitude
as a consequence of efficient acceleration.

Conclusions

- Self-consistent calculation of particle shock acceleration including energy losses regime – a very general method.
  - spectral shape not predictable a priori,
  - time dependent approach needed.
- Clusters of galaxies can efficiently accelerate CRs.
- Not EHE-CR sources: maximum energy determined by p-CMB interactions, Emax~10^{19} eV.
- Pair production is the dominant energy loss channel.
- Secondary electrons cool rapidly via SY and IC (in KN regime). All the energy lost by protons is found in non-thermal radiation
- For Coma-like parameters:
  X-ray flux ~10^{-12} erg cm^{-2} s^{-1} at ~100 keV
  γ-ray flux ~10^{-13} erg cm^{-2} s^{-1} at ~10 TeV, absorption at higher energies
- Possibility of enhanced emission if shocks are modified.

Detectable by next generation Cherenkov telescopes?