Merging Clusters of Galaxies as Gamma Ray Sources

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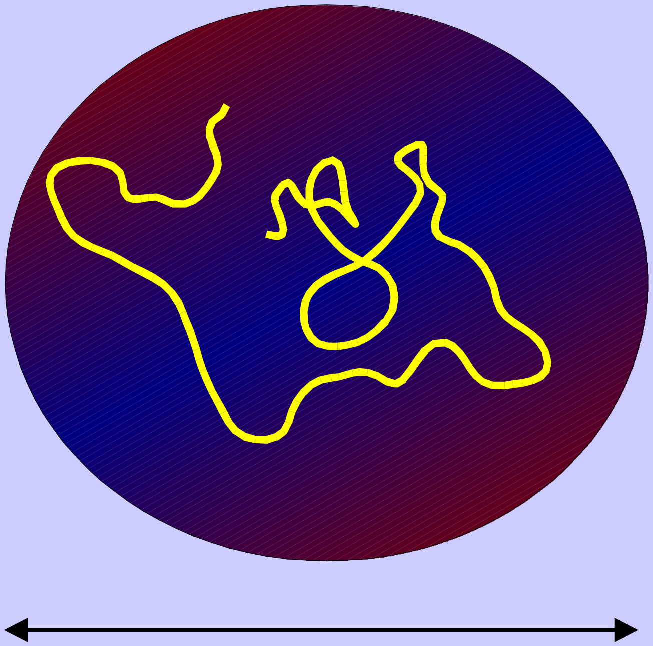
Layout of the talk

- Why do we expect gamma rays from clusters of galaxies?
  Cosmic Ray confinement
- Gamma rays, radio waves and hard X−rays from a cluster merger?
- Shocks in cluster mergers and particle acceleration/reacceleration
- Merger shocks versus accretion shocks
- The diffuse gamma ray background from accretion shocks
- Very high energy gamma rays from clusters...from GeV to TeV

Why γ – rays from Clusters of Galaxies:

Cosmic Ray Confinement



2Mpc

Magnetic fields in clusters in the ⑥G range have been detected (Clark and Kronberg's talks). In these fields the time for diffusion of cosmic rays out of a cluster is of order

$$T_{diff} = R^2/4D(E) >> \text{Age of cluster}$$

for the bulk of CR's (Berezinsky, PB & Ptuskin 1997, Volk et al. 1996).

Kolmogorov $2.3\ 10^{29}\ B_{\mu}^{-1/3} L_{20}^{2/3} E(GeV)^{1/3}$ cm^2/s $\rightarrow$ $E_{conf} = 30\ TeV\ B_{\mu}\ L_{20}^{-2}$

D(E)

Bohm $3.3\ 10^{22}\ B_{\mu}^{-1} E(GeV)$ cm^2/s $\rightarrow$ $E_{conf} = 2\ 10^5\ TeV\ B_{\mu}$

The main channel for energy losses of relativistic protons is pp scattering

$$\tau_{pp} = 1/(n_{gas}\sigma_{pp} c) >> \text{Age of cluster}$$

Long Diffusion time scales
Small energy losses
$\longrightarrow$
Accumulation of cosmic rays over cosmological times

Clusters of Galaxies behave like Storage Rooms for Cosmic Rays

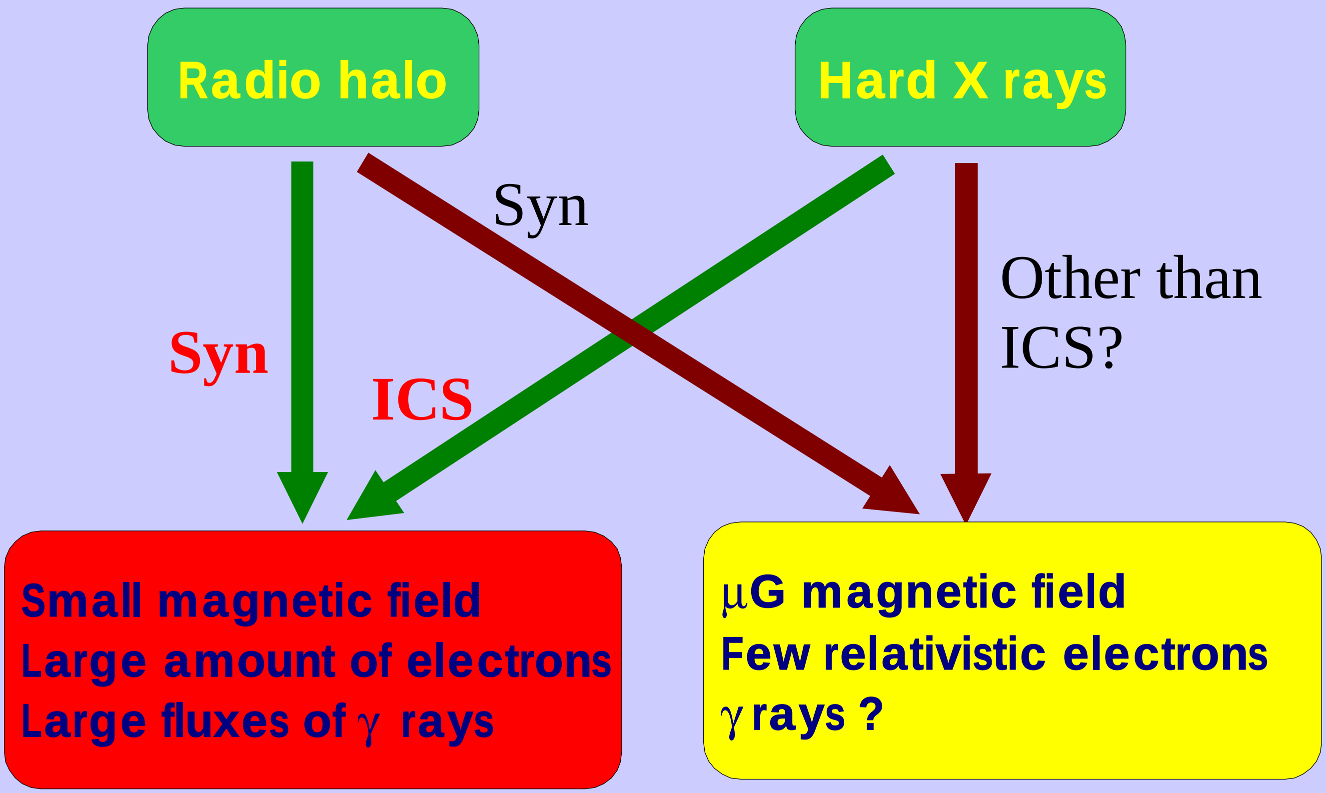
Gamma radiation is generated by production and decay of neutral pions. It is produced at *present* but it retains information about the *history of cosmic ray injection* in large scale structures.

Most lower frequency radiation is however produced by *electrons*

If they are freshly accelerated (*primaries*) they reflect only the recent past. If *secondaries*, we need to look at the cluster history.

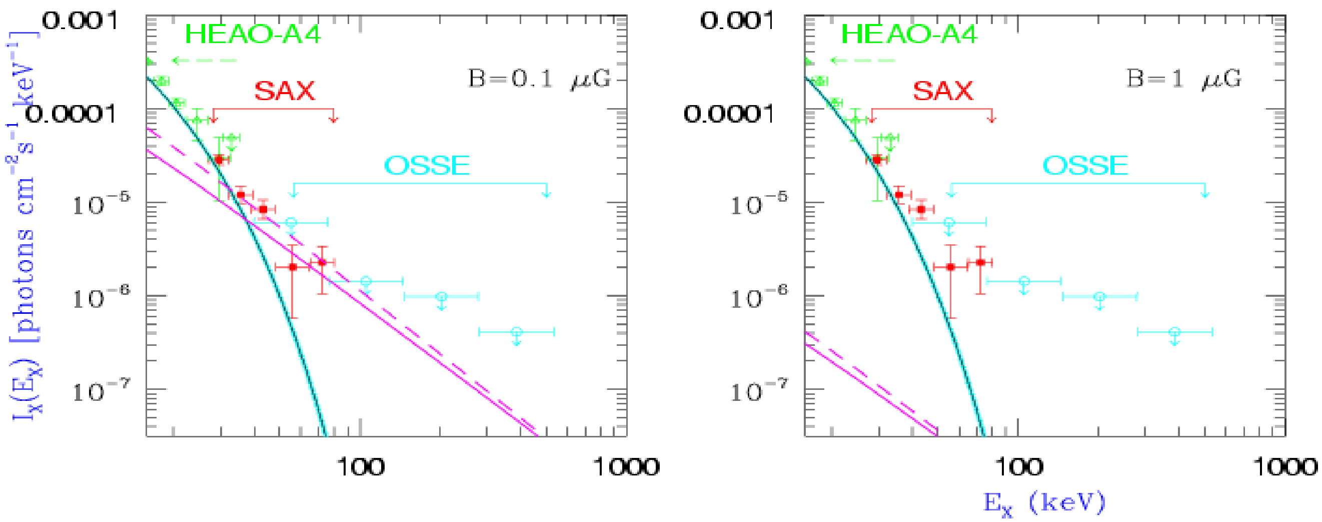
The Gamma ray option: when did it happen?

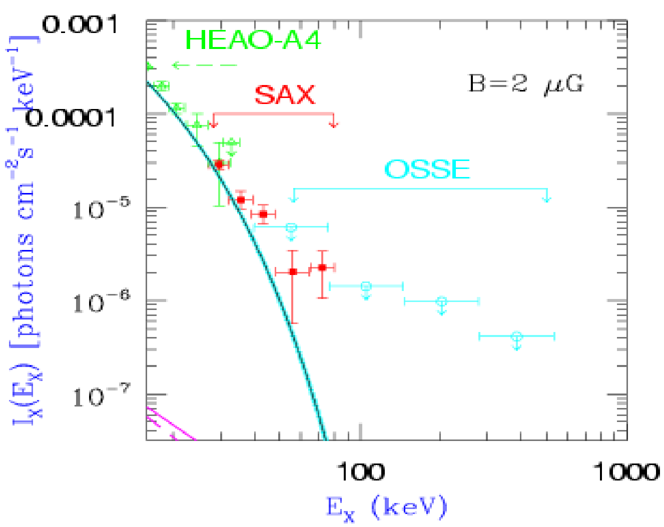
The possibility that gamma rays might be detected became real as a consequence of the first detection of an hard X–ray and a UV–soft X–ray excess in Coma and a few other clusters of galaxies.



Hard X-Rays

Why should there be gamma rays?





ICS can explain the hard X–ray fluxes only for low magnetic fields, of order 0.1 microGauss

Colafrancesco & PB, 1999

$p+p \rightarrow \pi^0+\pi^++\pi^- \blacklozenge X$

$\pi^0 \rightarrow \gamma\,\gamma$

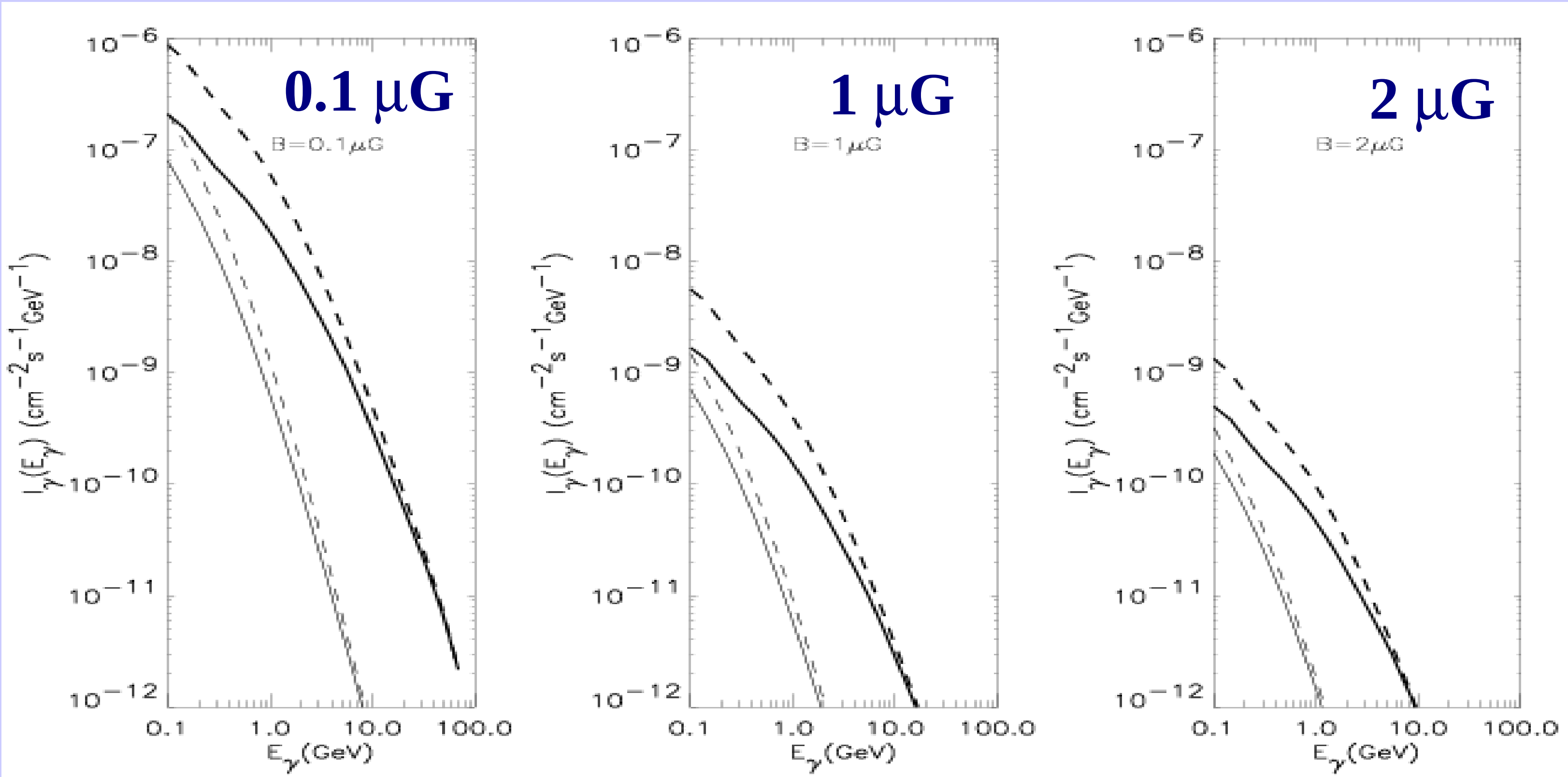
$\pi^\pm \rightarrow \mu\ \nu_\mu$

$\mu \rightarrow e\ \nu_e\ \nu_\mu$

Dennison 1980
Berezinsky, PB & Ptuskin 1997
Ensslin et al. 1998
Colafrancesco & PB 1998
PB & Colafrancesco 1999
Blasi 1999
Ensslin & Dolag 2001

Gamma Rays

The situation in secondary electron models



Colafrancesco & PB 1999

B_μ	γ	$\frac{L_p}{10^{44} ergs^{-1}}$	$\frac{F_\gamma(E_\gamma>100MeV)}{F_\gamma^{EGRET}(E_\gamma>100MeV)}$	$F_\gamma^{brem}/F_\gamma^{\pi^0}$
0.1	2.1	50	1.93	0.13
0.1	2.4	180	7.15	0.10
1	2.1	0.35	$1.8 \cdot 10^{-2}$	0.14
1	2.4	1	$4.5 \cdot 10^{-2}$	0.11
2	2.1	0.1	$5.3 \cdot 10^{-3}$	0.12
2	2.4	0.23	$1.1 \cdot 10^{-2}$	0.095

Primary electrons models

The flux of gamma rays in the cases where electrons are accelerated as primaries and it is *assumed* that there are no protons, is very model dependent. In fact the maximum energy of the accelerated electrons is typically not enough to be relevant for gamma ray emission.

When this energy is assumed to be high enough, the time dependence of the gamma ray emission is quite fast,and the radiation rapidly fades away.

This argument is in general true also when the electrons are accelerated by turbulence in the intracluster medium, where the maximum Lorentz factor is ~10000 (Brunetti).

A discussion of the multifrequency emission from primary electrons will be discussed later...

Hierarchical Scenario for Structure Formation

Bigger Structures are formed by merger of smaller structures formed at earlier times.

Clusters are also the result of this merging process. The heating of the gas is achieved by ***shock*** conversion of gravitational energy into heat

Cluster Mergers as CR accelerators?

Assuming that shocks are strong enough, part of the baryons (and electrons) crossing them may be diffusively accelerated by first order Fermi acceleration (Sarazin 2001)

For a ***Kolmogorov*** spectrum we obtain:

$$E_{e,max} = 118\, L_{20}^{-1/2} B_m^{1/4} v_8^{3/2} g(r)^{-3/4}\ \mathrm{GeV}$$

$$E_{p,max} = 9\ 10^7\, L_{20}^{-2} B_m v_8^{6} g(r)^{-1/2}\ \mathrm{GeV}$$

For ***Bohm*** diffusion:

$$E_{e,max} = 6.3\ 10^4\, B_m^{1/2} v_8\, g(r)^{-1/2}\ \mathrm{GeV}$$

$$E_{p,max} = 3\ 10^9\, B_m v_8^{2} g(r)^{-1}\ \mathrm{GeV}$$

Energetically, cluster mergers can clearly be responsible for the heating of the gas, and possibly for the production of non thermal particles.

The typical energy release during a cluster merger is of about

$$E_{merger} = G\, M_1\, M_2 / d \text{ » } 1.4\ 10^{64} \text{ erg}$$

$$\text{with } M_1 = M_2 = 5\ 10^{14}\ M_{sun} \text{ and } d = 1.5 \text{ Mpc}$$

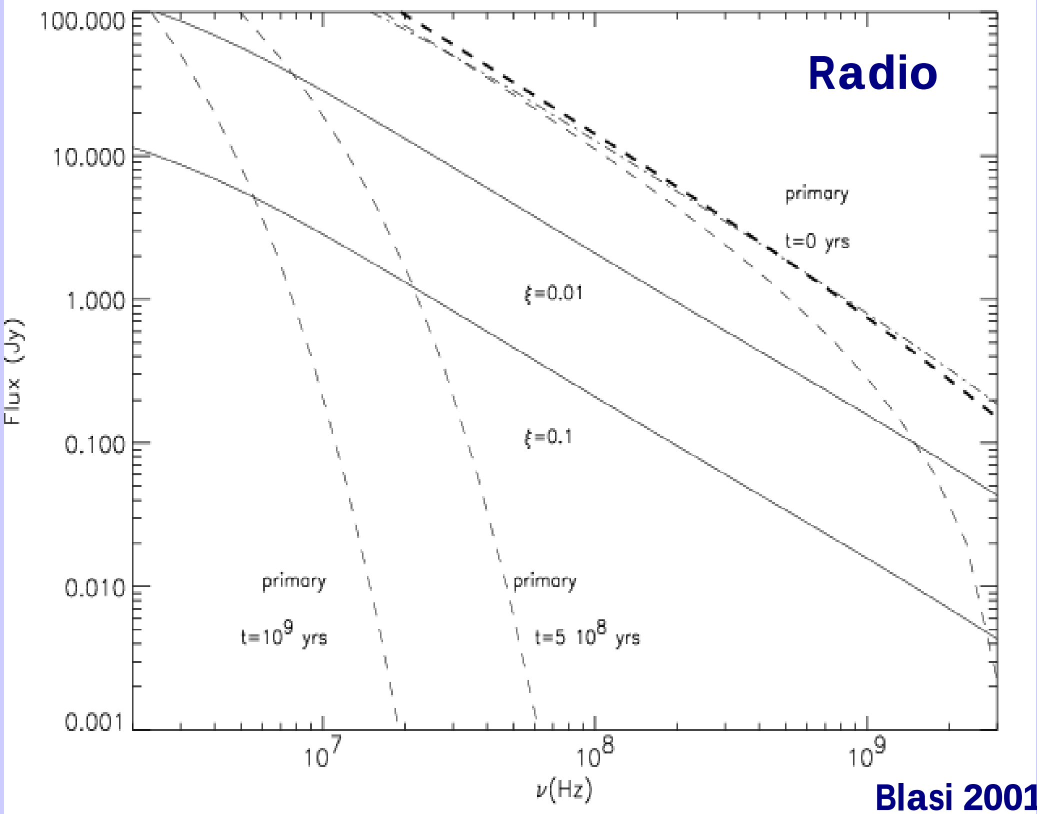
The fact that cosmic ray baryons are *efficiently confined* in the intracluster gas implies that each merger increases the CR content of the cluster.

Primary electrons in the energy region relevant for radio and hard X−ray emission are generated only at the last merger. Lower energy electrons (⓪○300) pile up on longer time scales.

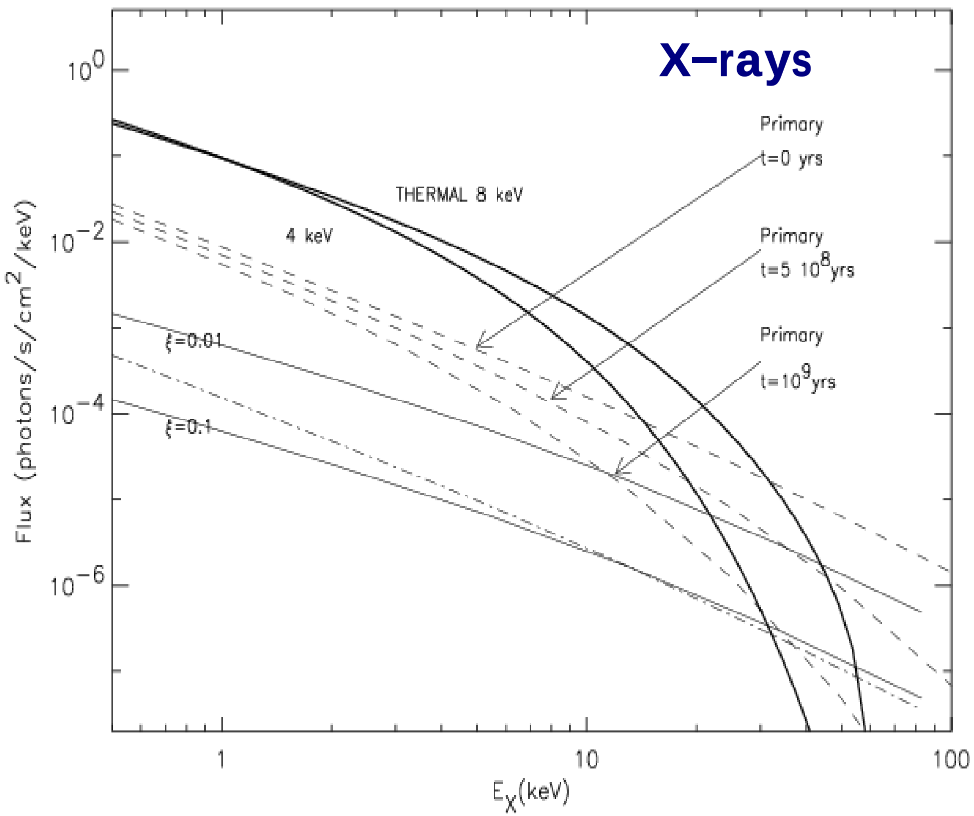
Realistic calculations involving mergers need to account for

1. **protons accumulated over cosmological time scales**
2. **electrons losing energy and piling up al low energy**
3. **newly accelerated particles**
4. **particles (electrons and positrons) generated as secondaries**
5. **particles re−energized by each shock**

The case of a single merger



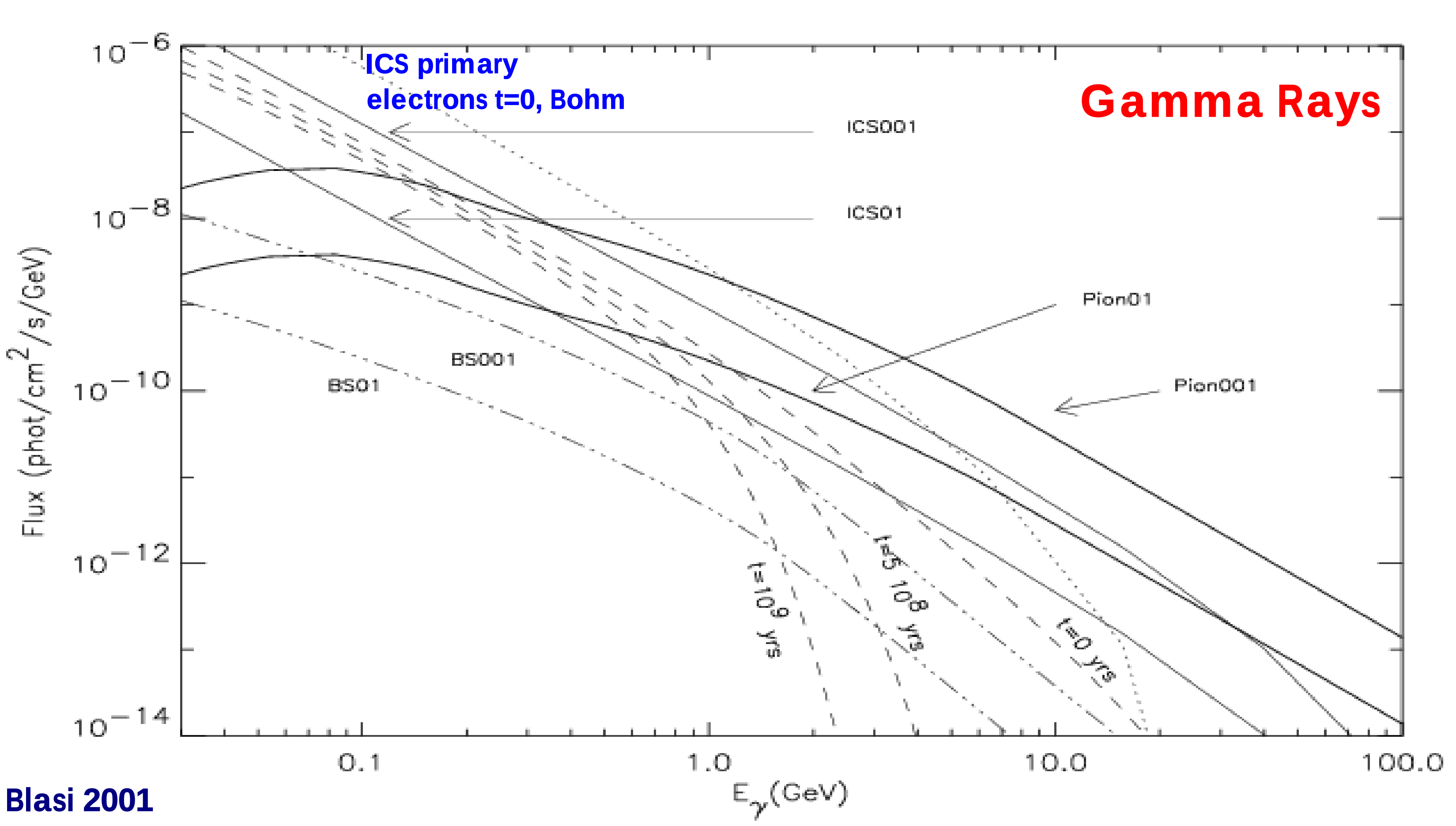
Blasi 2001



The radio flux due to synchrotron emission of primary electrons accelerated at the merger shock rapidly fades away after the end of the merger, due to fast energy losses. The hard X-rays also fade away in a time less than a billion years.

The contribution due to ICS of secondary electron-positron pairs remains basically unchanged, since the pairs are generated continuously by the confined protons.

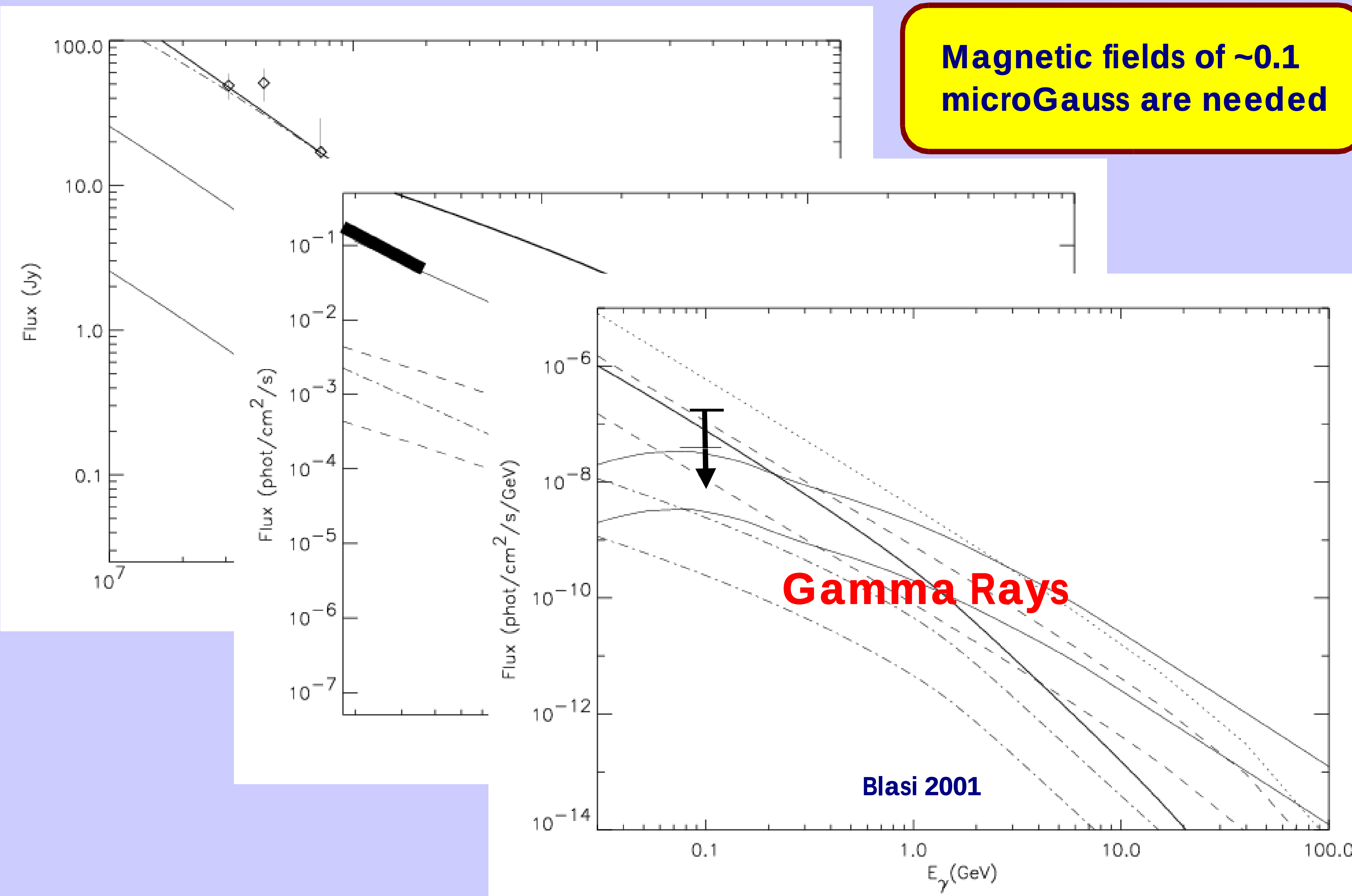
Gamma Rays from a single merger event



The contribution of ICS of primary electrons exists only for Bohm diffusion. In all other cases the maximum energy is too low to be relevant for gamma rays,
This contribution fades away rapidly with time, after the end of the merger process.
Note that the gamma rays from pion decay dominate over all other processes at E>a few GeV. This is a lower limit, because of protons previously trapped...
This is due to the flat spectra !

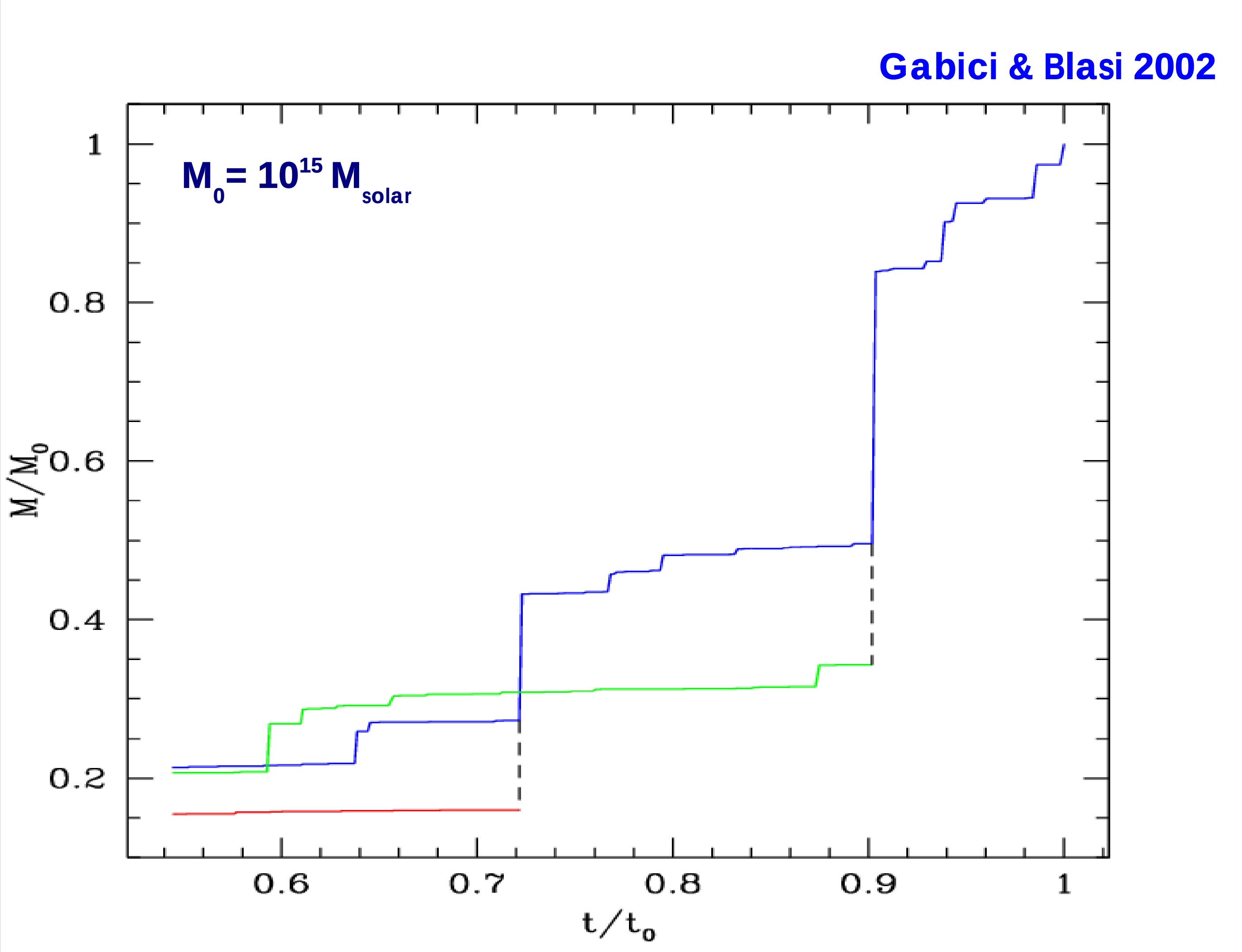
Gamma Rays from COMA

Magnetic fields of ~0.1 microGauss are needed

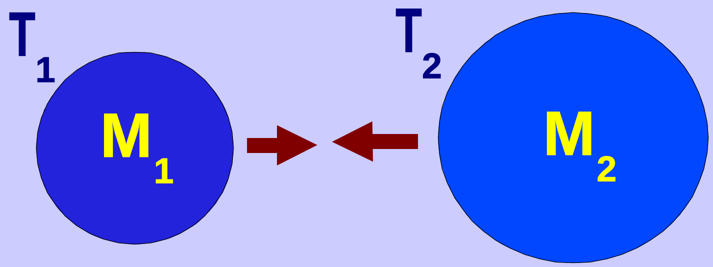


Cluster mergers: a cosmological view

Using a Press−Schchter model, it is possible to reconstruct the merger tree of a cluster that has today a fixed mass M (Fujita and Sarazin 2001; Lacey and Cole 1993).



Mach numbers and spectra of accelerated particles

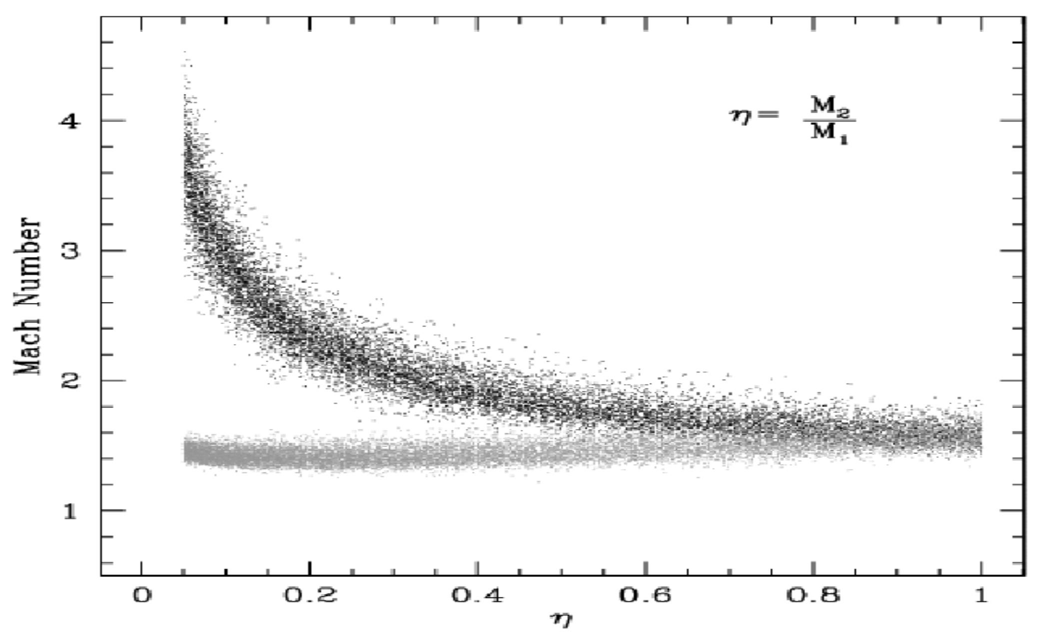


As a first approximation, the merger can be considered as a two body scattering between two sphere of radius and temperatures that equal their virial values. The relative velocity for the case of zero impact parameter can be easily calculated, and the Mach numbers derived from the scaling relations:

$$M_1^2 = \frac{18}{5}(1+\alpha)\left[\frac{1}{1+\alpha^{2/3}} - \frac{1}{4(1+\alpha)^{2/3}}\right]$$

$$M_2^2 = \alpha^{-1/2} M_1^2$$

Gabici & Blasi 2002

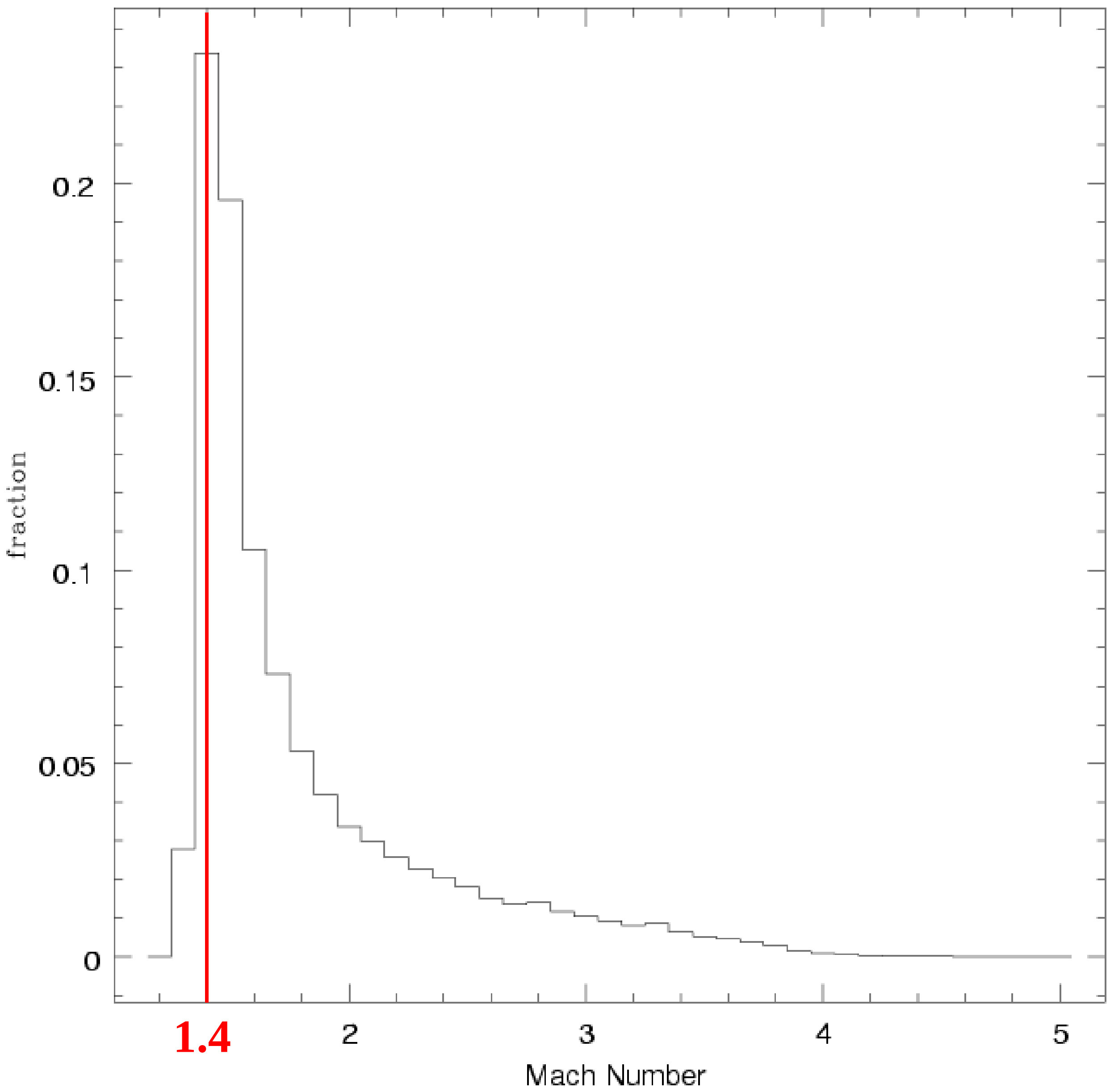


$$R \propto M^{2/3}$$

$$\rho \propto M^{-1}$$

$$T \propto M^{1/3}$$

STATISTICS OF MACH NUMBERS **Gabici & Blasi 2002**

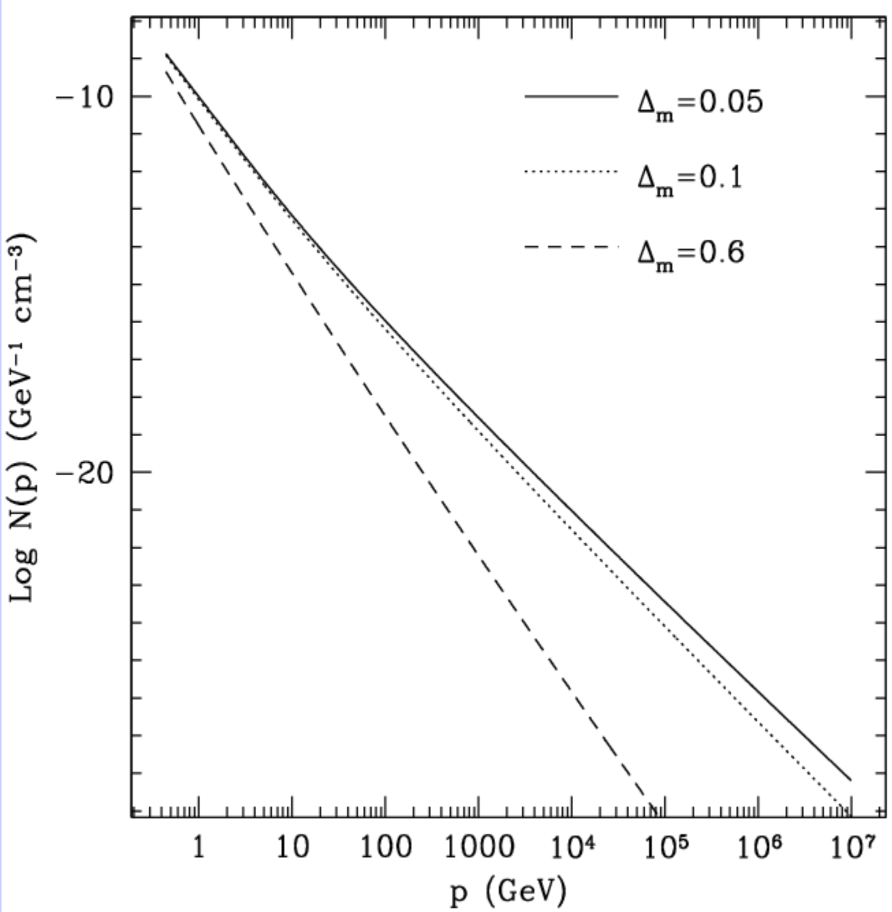


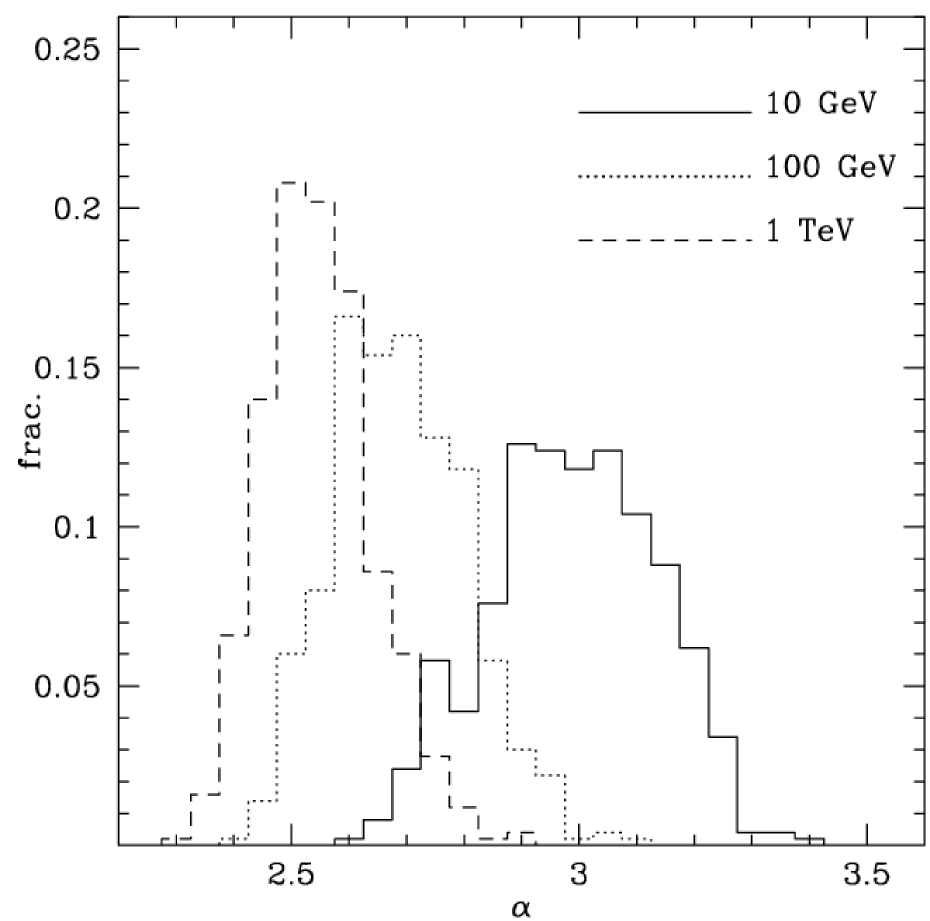
Spectra of accelerated particles

Running simulations of possible merging histories that produce the same final cluster, it is possible to calculate the spectra of the particles trapped in the cluster by diffusion.

For the case of primary electrons, only the last merger is important. For secondary electrons and for baryons all the cluster history must be followed.

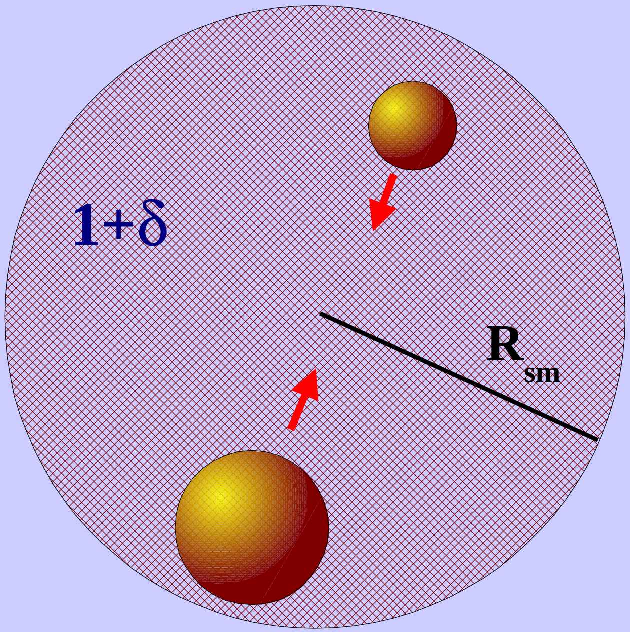
Gabici & Blasi 2002





Complications

Clusters may be falling onto one another in the potential well established by surrounding matter. In this case the relative velocity can be either smaller or larger than the value calculated for a two body collision.



$$\frac{4}{3}\pi R_{sm}^{3}\rho_{cr}\Omega_{m}(1+\delta)=\xi(M_{1}+M_{2})$$

$$(1+\delta)=2\,\xi\,M_{15}\,R_{10}^{-3}$$

$$v_{max}=2\sqrt{G\frac{M_{tot}}{R_{sm}}}=1.1\,10^{8}\,\xi^{1/2}M_{15}^{1/2}R_{10}^{-1/2}\,cm/s$$

$$(Mach)_{i,max}=1.25\,\xi^{1/2}R_{10}^{-1/2}M_{15}^{1/2}M_{i,15}^{-1/3}$$

Mach numbers >3 imply:

$$\boxed{(1+\delta)>11.6\,R_{10}^{-2}M_{i,15}^{2/3}}$$

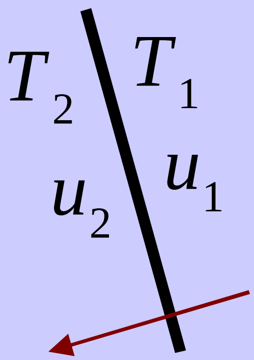
Kayo, Taruya & Suto 2001

$M_{i,15}$	R_{10}	$1+\delta$	$P(\delta)$
1	**0.8**	**18.1**	**$7\ 10^{-5}$**
1	**1.0**	**11.6**	**$9\ 10^{-5}$**
1	**1.2**	**8.1**	**10^{-4}**
0.5	**0.8**	**11.4**	**$5\ 10^{-4}$**
0.5	**1.0**	**7.3**	**10^{-3}**
0.5	**1.2**	**5.1**	**$2\ 10^{-3}$**
0.1	**0.8**	**3.9**	**$2\ 10^{-2}$**
0.1	**1.0**	**2.5**	**$5\ 10^{-2}$**
0.1	**1.2**	**1.7**	**0.12**

Gabici & Blasi 2002

A real case

A cluster merger has been observed in Cygnus A (z=0.057) with ASCA. Two subclusters with approximately similar masses are seen to merge. Following Markevitch, Sarazin & Vikhlinin (1999) we can write



$$\frac{1}{r}=\frac{u_2}{u_1}=\left[4\left(T_2/T_1-1\right)^2+T_2/T_1\right]^{1/2}-2\left(T_2/T_1-1\right)$$

T_1 = 4±1 keV **T_2 = 8^{+2}_{-1} keV**

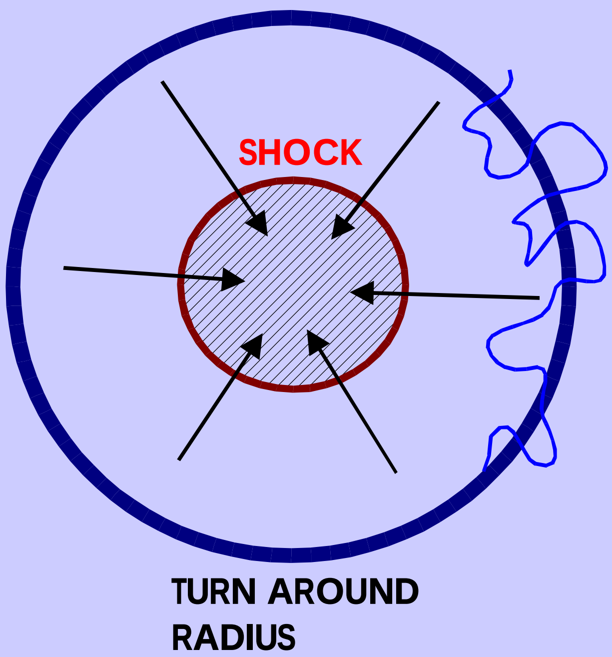
r=2.2 M=1.9

$\sigma=3.5$ **VERY STEEP SPECTRUM**

This result agrees fairly well with our theoretical prediction

The case of accretion

Accretion shocks occur in the outer regions of galaxy clusters and correspond to the propagation outwards of the information about the virialization of the inner regions.
A self−similar solution was found by Bertschinger (1985) in which a shock is formed at a fixed fraction $\lambda_s = 0.316$ of the turnaround radius R_{ta} (t) ~ $t^{8/9}$.



Energy crossing the shock and being adiabatically compressed ~

10^{63}−10^{64} erg

The shock propagates in a cold medium, so that it can reach very high Mach numbers. In particular, if the medium is at 10^4 K, the Mach number can be ~100−500. The Mach number is slightly smaller if the medium has been preheated to higher temperatures, but remains quite high.

Shocks with Mach numbers up to ~1000 are actually observed in numerical simulations (Miniati et al. 2001).

Cosmic rays accelerated at accretion shocks

The strength of the accretion shocks is determined by their large Mach numbers:

$$r = \frac{\frac{8}{3}M^2}{\frac{2}{3}M^2 + 2} \rightarrow 4 \;\; for\, M \gg 1$$

$$\sigma = \frac{r+2}{r-1} \rightarrow 2 \;\; for\, r \approx 4$$

Very Flat Spectra

In principle both protons and electrons can be accelerated at accretion shocks (with the usual problems for the electrons) but they behave in a crucially different way:

PRIMARY ELECTRONS

the acceleration time is dominated by the value of the magnetic field outside the shock. This can be very small! Moreover, the maximum energies are in the range relevant for gamma ray emission *only for Bohm diffusion*. The main energy loss channel is ICS off the CMB. After acceleretation they radiate fast, so that their *nonthermal radiation is in the outskirts of the clusters* (Miniati et al. 2001). These electrons are probably responsible for the so called *radio ghosts* (Ensslin & Brueggen 2001).

Clusters and the diffuse gamma ray background:

Dar & Shaviv (1995)	THE DIFFUSE EXTRAGALACTIC GAMMA RAY BACKGROUND MAY BE DUE TO PP COLLISIONS IN CLUSTERS
Berezinsky, Blasi & Ptuskin (1997)	THE FINDINGS OF D&S ARE NOT CONFIRMED AND ACTUALLY IT IS FOUND THAT ENERGETICALLY THE EDGRB CANNOT BE DUE TO CLUSTERS. COSMIC RAY CONFINEMENT IS FOUND.
Loeb & Waxman (2000)	THE EDGRB IS PRODUCED BY ICS OF ELECTRONS ACCELERATED AT MERGER SHOCKS WITH SPECTRUM $\sim E^{-2}$
Miniati (2002)	SIMULATIONS ARE USED TO CALCULATE THE EDGRB FROM CLUSTERS.
Gabici & Blasi (2002)	The EDGRB is hardly due to either cluster mergers or cluster accretion

PROTONS

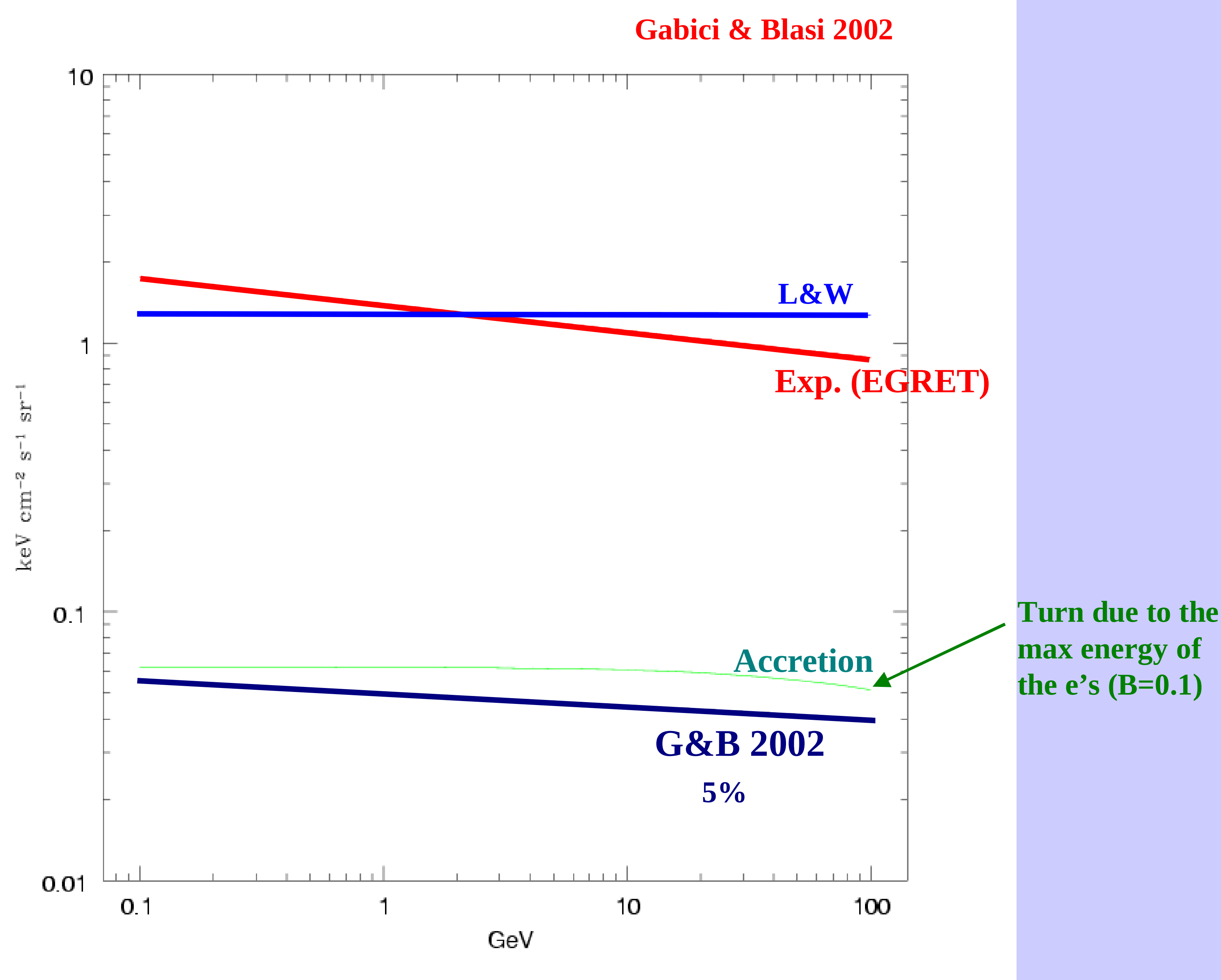
Accelerated protons also have very flat spectra. They do not lose their energy in situ, but are rather advected inside the accretion flow.

Most of the nonthermal radiation they generate is in the core of the cluster, where the target for pp scattering is. In other words this is an example of secondary electons model.

↓

LARGE GAMMA RAY FLUXES

Therefore this scenario would be testable by GLAST in the 0.1−100 GeV range.



Gabici & Blasi 2002
10
1
0.1
0.01
keV cm⁻² s⁻¹ sr⁻¹
0.1
1
10
100
GeV
L&W
Exp. (EGRET)
Accretion
G&B 2002
5%
Turn due to the max energy of the e's (B=0.1)

EGRET sources?

It has been recently claimed that there is "*a preliminary evidence of a possible association*" (Colafrancesco 2002) of some of the unidentified EGRET sources with the position of some clusters of galaxies. This idea has also appeared in Totani & Kitayama (2000) [see also next talk by Kawasaky]. In the catalog considered by Colafrancesco, all the clusters have a powerful radiogalaxy in the center, so that the possibility that the gamma radiation comes from the point source cannot be ruled out, and seems actually possible. Moreover, all the signals are just above the detection limit of EGRET.

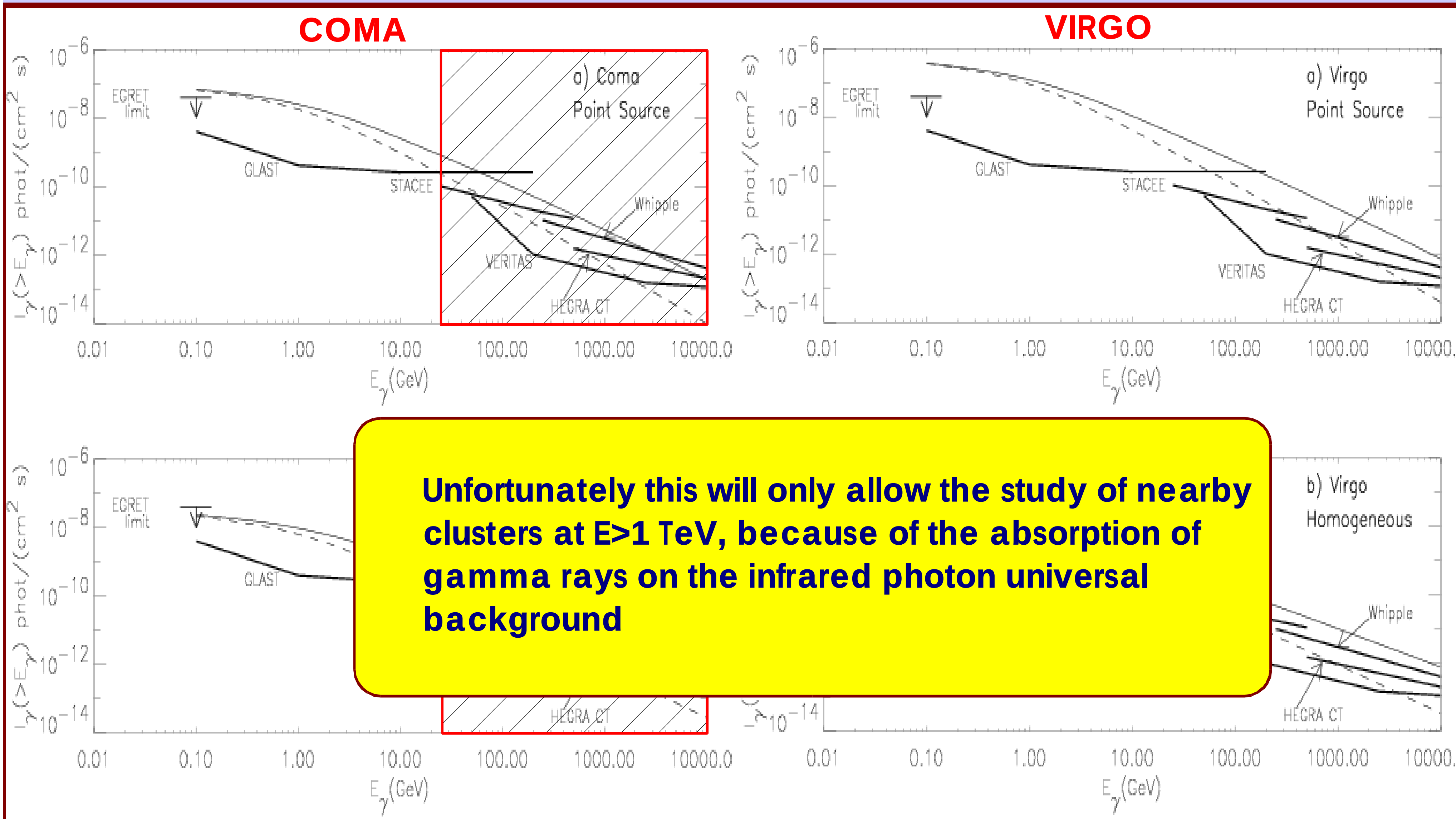
KEEP IN MIND: <u>for clusters with clear non thermal activity only upper limits are available from EGRET!</u>

The only thing to say is that if they are there they will show up in GLAST. Unfortunately EGRET is no longer there to carry out further observations.

In fact there may be another way to go:

From GeV to TeV

The spectra of gamma rays from neutral pion decays reproduces the spectrum of the parent protons and extends up to $E_{protons}^{max}$. On the other hand the ICS of electrons only extends to $2.4\,\mathrm{GeV}\ \gamma_6^2$



Unfortunately this will only allow the study of nearby clusters at E>1 TeV, because of the absorption of gamma rays on the infrared photon universal background

Blasi 1999

Conclusions

- Gamma rays are the best tool to look for CR confinement over cosmological time scales, in particular at E>10 GeV

- Gamma rays are the discriminant between models with secondary electrons (large gamma ray fluxes) and primary electrons.

- Mergers of galaxy clusters generate shocks, but these shocks are generally too weak to generate relevant populations of CR's

- Accretion shocks are strong (high Mach numbers) and may accelerate CR's with flat spectra. The electrons may radiate in situ and generate hard X–rays, while the proton component is advected toward the center and generate secondary $e^+ e^-$ pairs. The pairs may then generate radio and additional X–rays. It is plausible that the hard X–rays and radio radiation come from spatially different regions.

- The diffuse extragalacti gamma ray background is unlikely to be generated in cluster mergers and/or accretion.