Non Thermal Radiation and Particle Acceleration in Clusters of Galaxies

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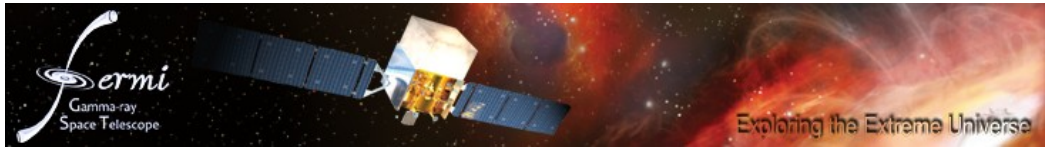


OUTLINE

I. Signatures of Non Thermal Activity

II. Radiative Processes

III. Particle Acceleration

I. Possible Signatures of Non Thermal Activity

1. Non Thermal Radiation

   Radio, EUV, Hard X-ray, Gamma-ray

2. Shocks, Turbulence, Magnetic Field

   Sharp Features, Line Widths, Faraday Rotation

3. Merger Activity and Substructures

   Structure of Hot Gas: e.g. Cold fronts

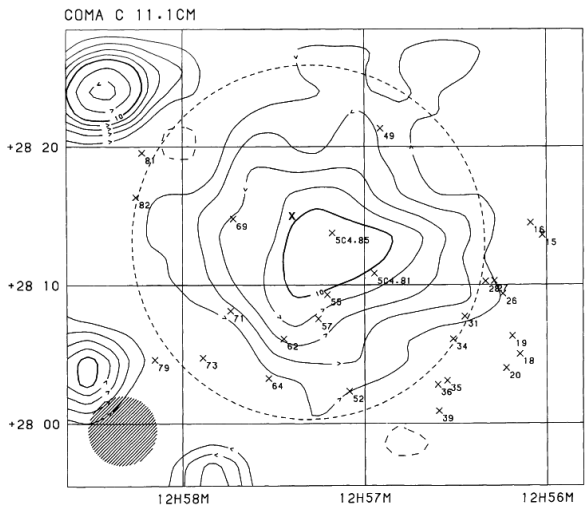
   Galaxy Velocity Dispersion

Radiative Signature: *Radio*

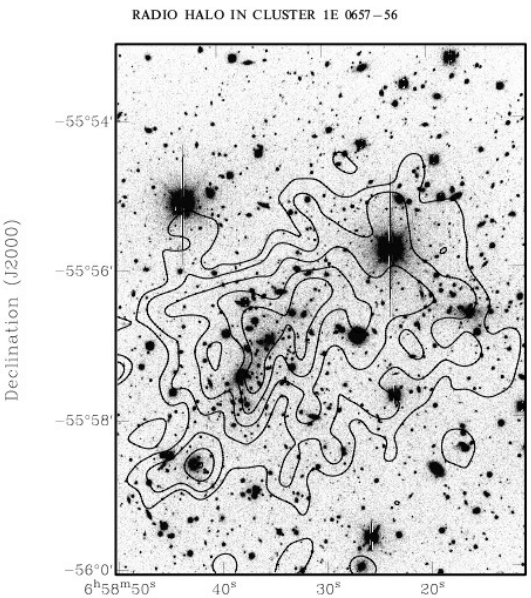
- First and Most Definite Signature

Diffuse Halo or Relic with steep spectrum synchrotron

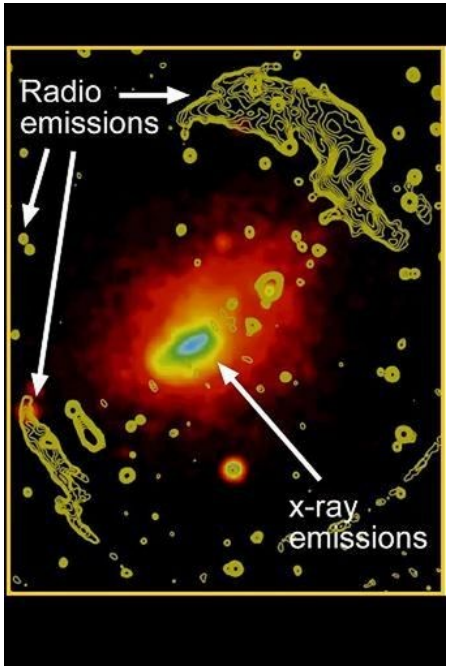
Coma Halo



Bullet Halo

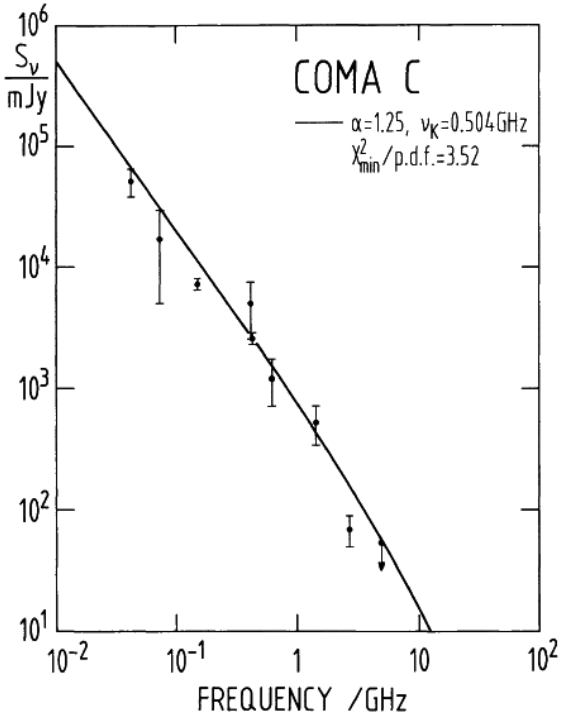


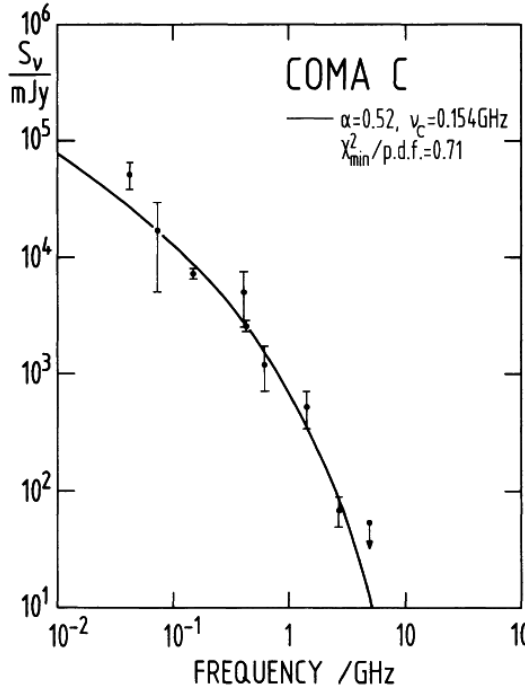
A 3667 Relic



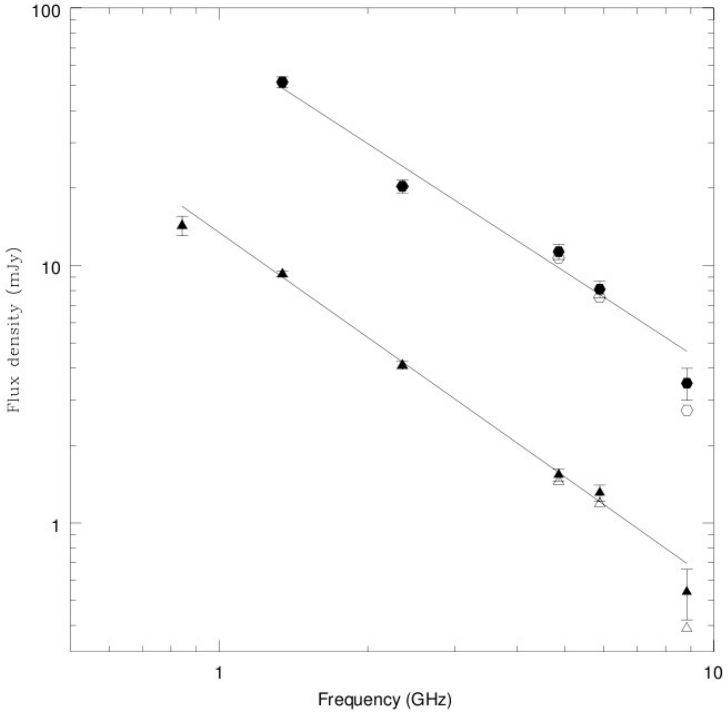
Radiative Signature: *Radio*

Coma and Two possible Fits

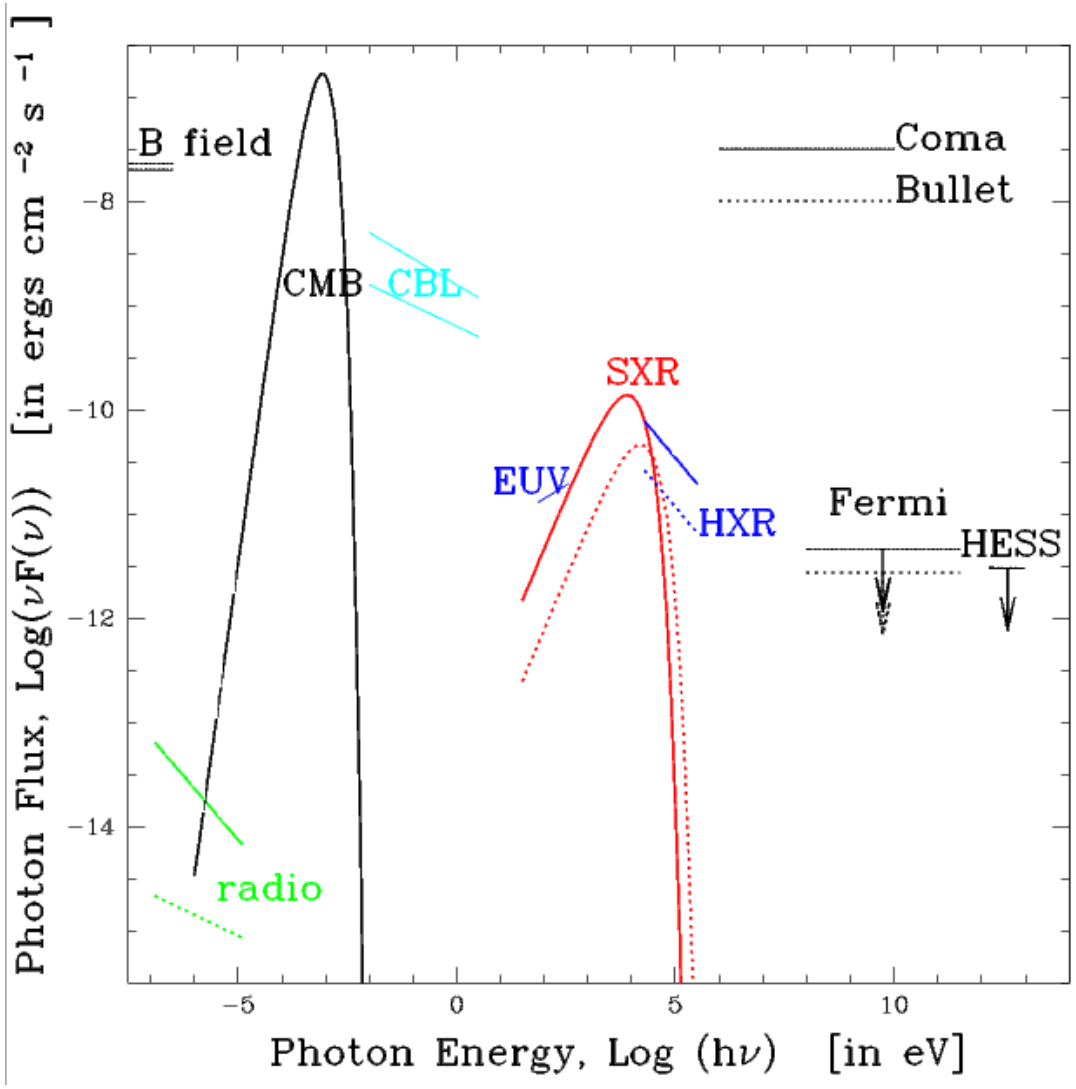




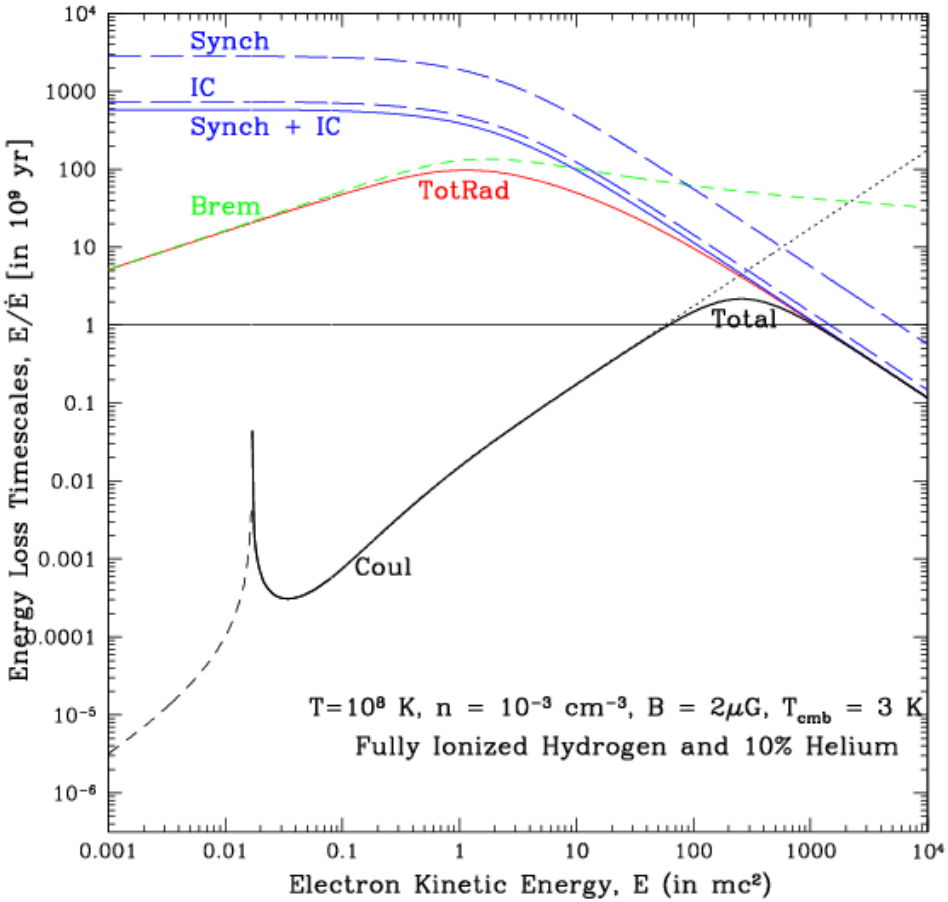
Bullet

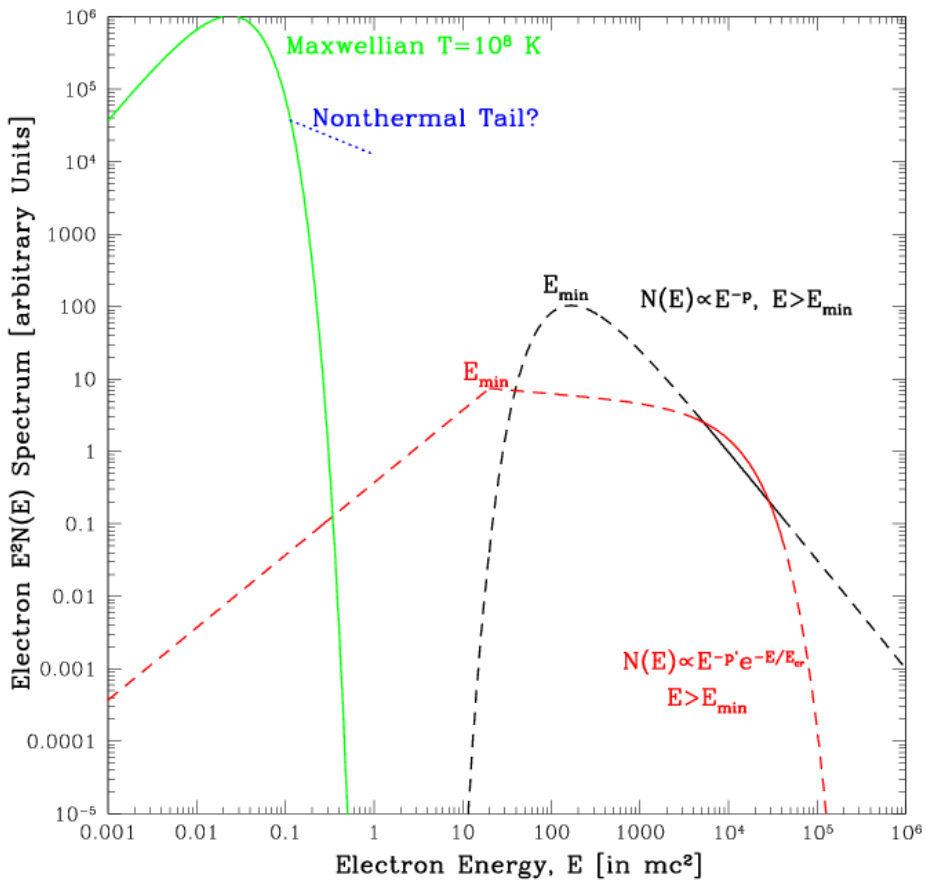


Total Electromagnetic Spectrum in Coma and Bullet



Possible Electron Spectra: *Coma*





II. Radiation Processes

1. Inverse Compton (IC), Nontherm. Brem. (NTB)

   By electrons of Energy $E > h\nu$ $F \propto \int N_e^{NT}\{n_p \text{ or } u_{\text{Soft}}\} dV/d^2$

2. Decay of pions from p-p interactions

   No observational evidence for CR p's $F \propto \int N_p^{CR} n_p dV/d^2$

3. Decay or Annihilation of Dark Matter

   Only if above processes do not work $F \propto \int n_{dm}^{(1 \text{ or } 2)} dV/d^2$

X- and Gamma-Rays From Radio Producing Electrons

1. Inverse Compton Scattering of soft photons:
   CMB, EBL, Starlight and Soft X-rays (*Klein-Nishina Regime*)

   a. Spectrum (simple power-law)

$$\epsilon_\gamma J(\epsilon_\gamma) = \pi r_0^2 c N_0 E_{\rm min}^p A(p) u_{\rm soft} (\epsilon_\gamma/\bar{\epsilon}_s)^{(3-p)/2}$$

   b. Normalization

$$\frac{\epsilon_\gamma J(\epsilon_\gamma)}{\nu F(\nu)} \propto g(p) u_{\rm soft} (\bar{\epsilon}_s)^{(p-3)/2} B^{-(p+1)/2}$$

1a. Inverse Compton Spectra Models: *Electron Spectra and B Field*

MODEL B:
- Low magnetization
- Electrons distributed within the whole cluster

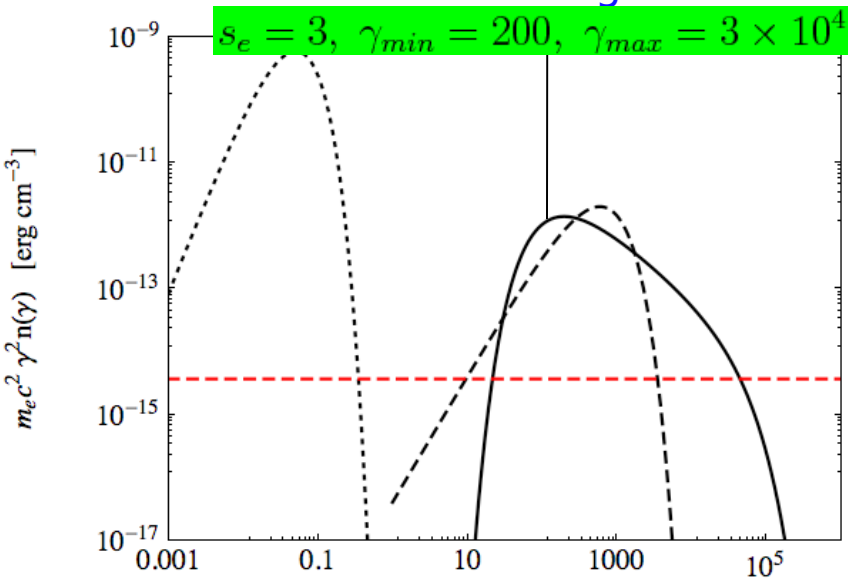
$$B_0 = 0.3\,\mu\mathrm{G},\ \ r_{e,max} = r_{vir}$$

MODEL C:
- High magnetization
- Electrons distributed within the cluster core

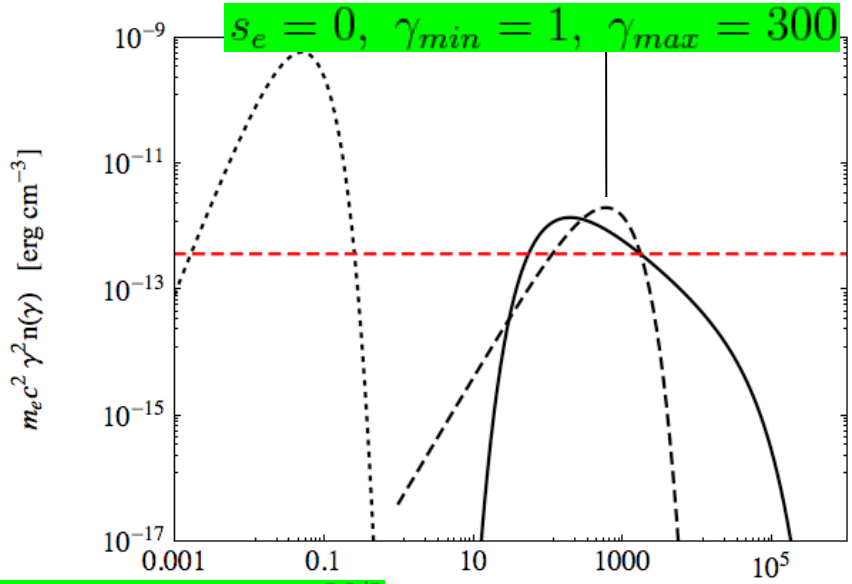
$$B_0 = 3\,\mu\mathrm{G},\ \ r_{e,max} = 0.1 r_{vir}$$

$$n_e(\gamma) \propto \gamma^{-s_e} \exp(-\gamma/\gamma_{max})$$

Young

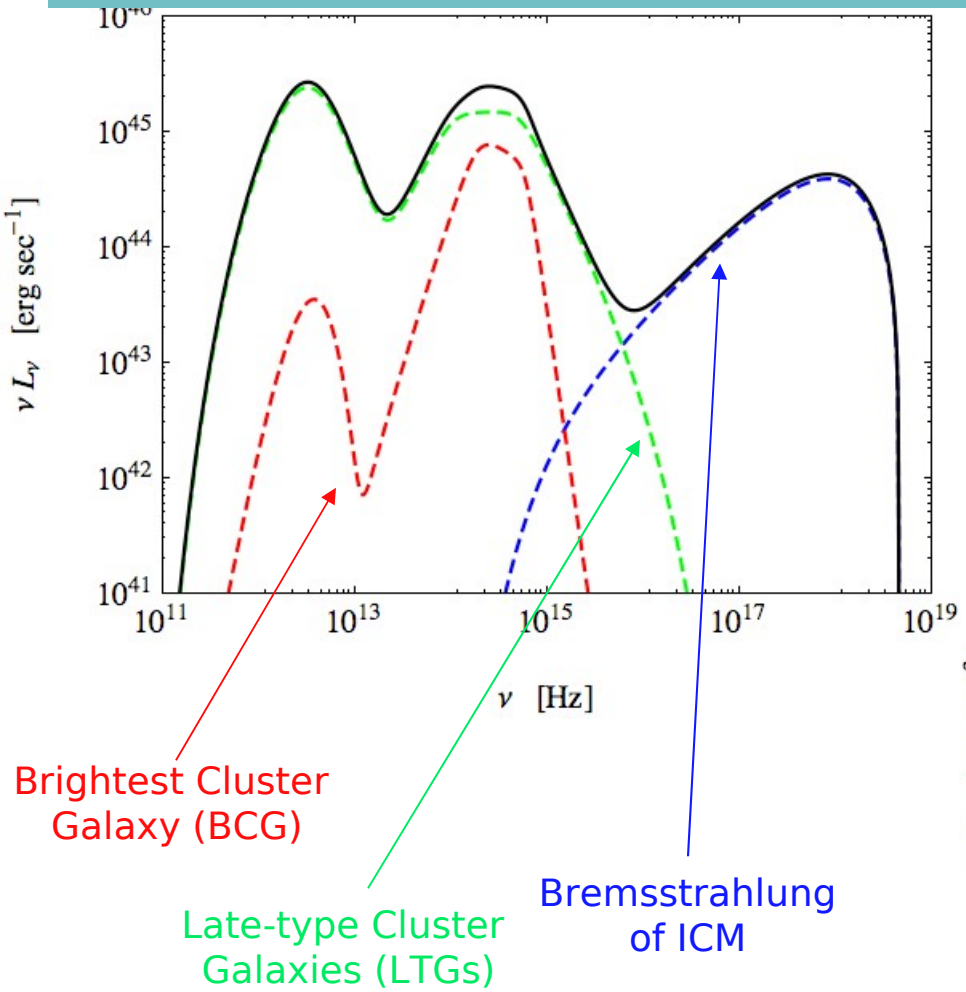


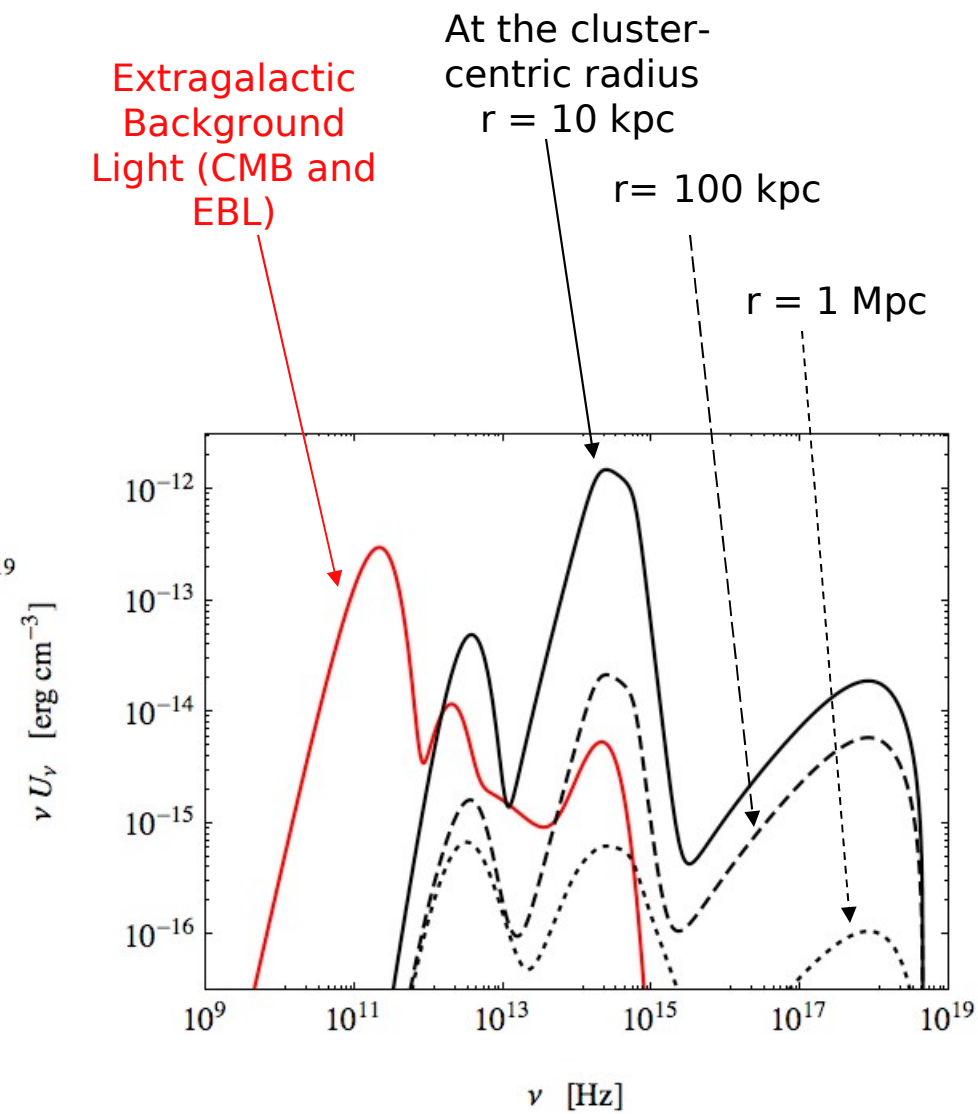
Evolved



$$\frac{n_{e,th}(r)}{n_0} = \left(\frac{B(r)}{B_0}\right)^2 = \left(1 + \left(\frac{r}{r_c}\right)^2\right)^{-3\beta/2}$$

Models: *Soft Photon Specs. and Dist.*

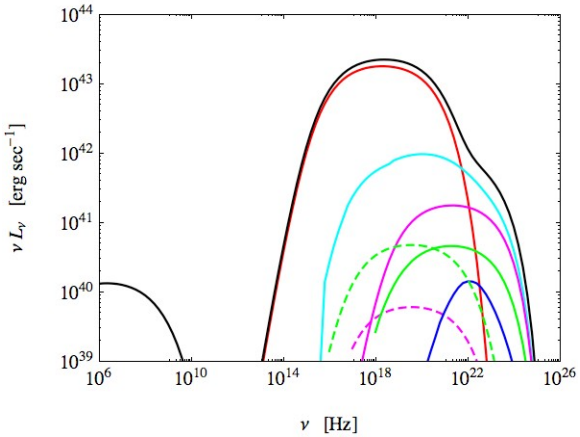


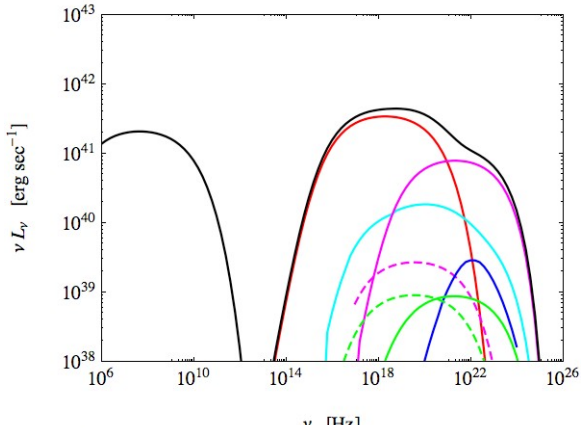


1a. Inverse Compton Spectra

MODEL B:
- Low magnetization
- Whole Electrons distrib.

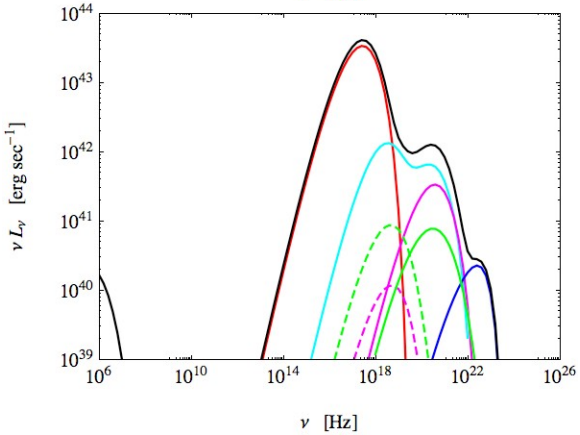
MODEL C:
- High magnetization
- Core Electrons distrib.

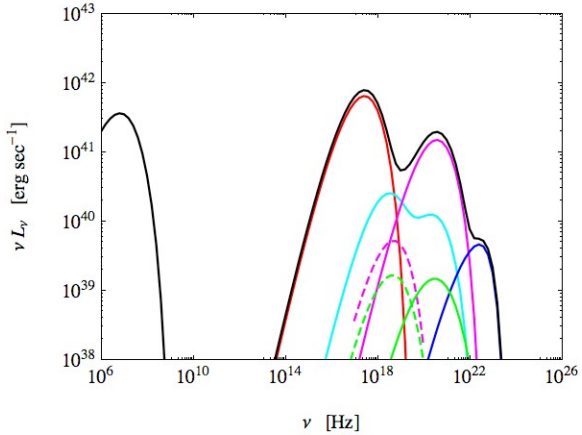




young electron population

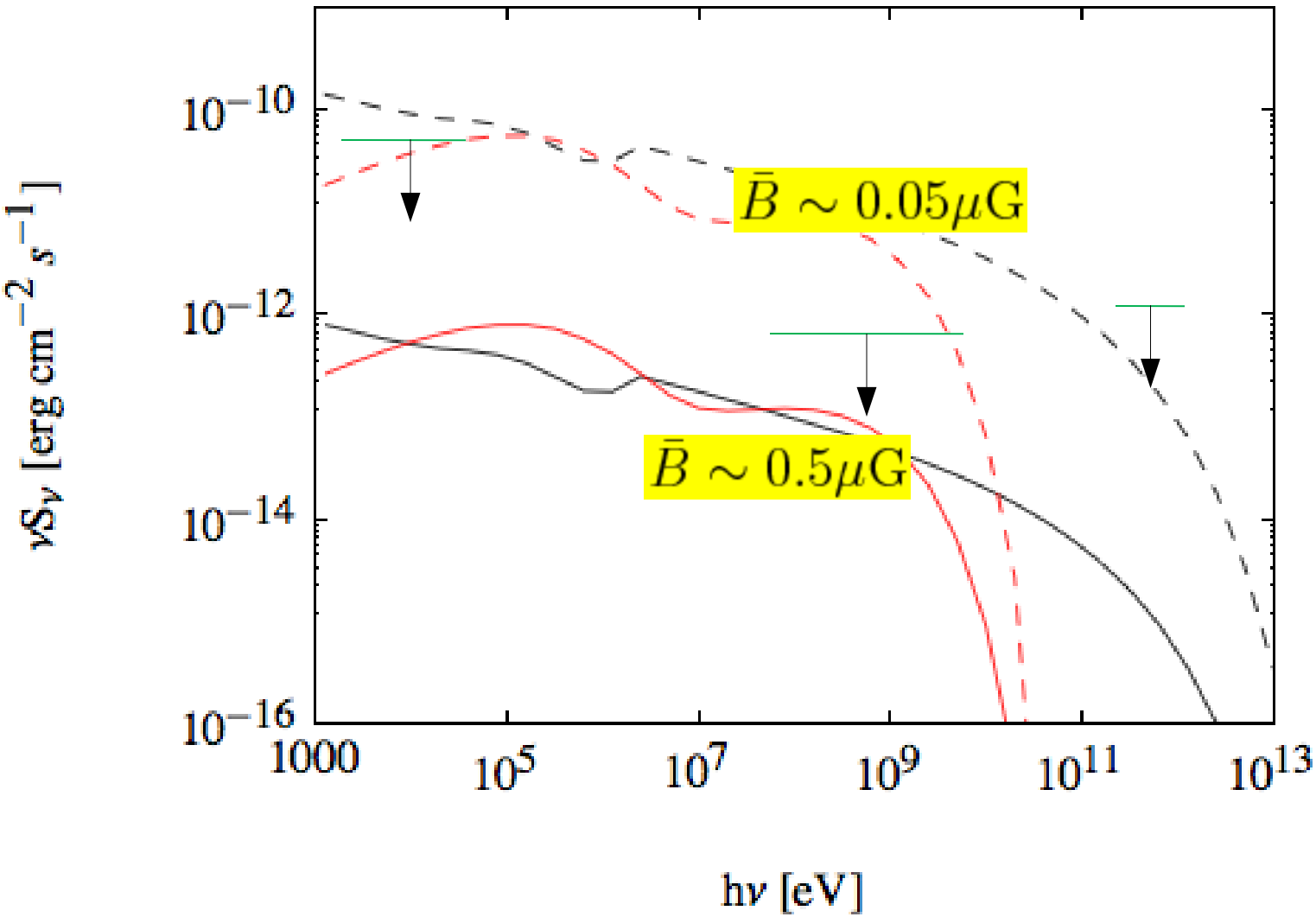
IC/CMB
IC/EBL
IC/BCG
IC/LTGs
IC/soft-X





evolved electron population

Comparison of IC Spectra with Observations



1b. Non-thermal Bremsstrahlung

From $e^{\pm} - p$ and $e^{\pm} - e$ interactions

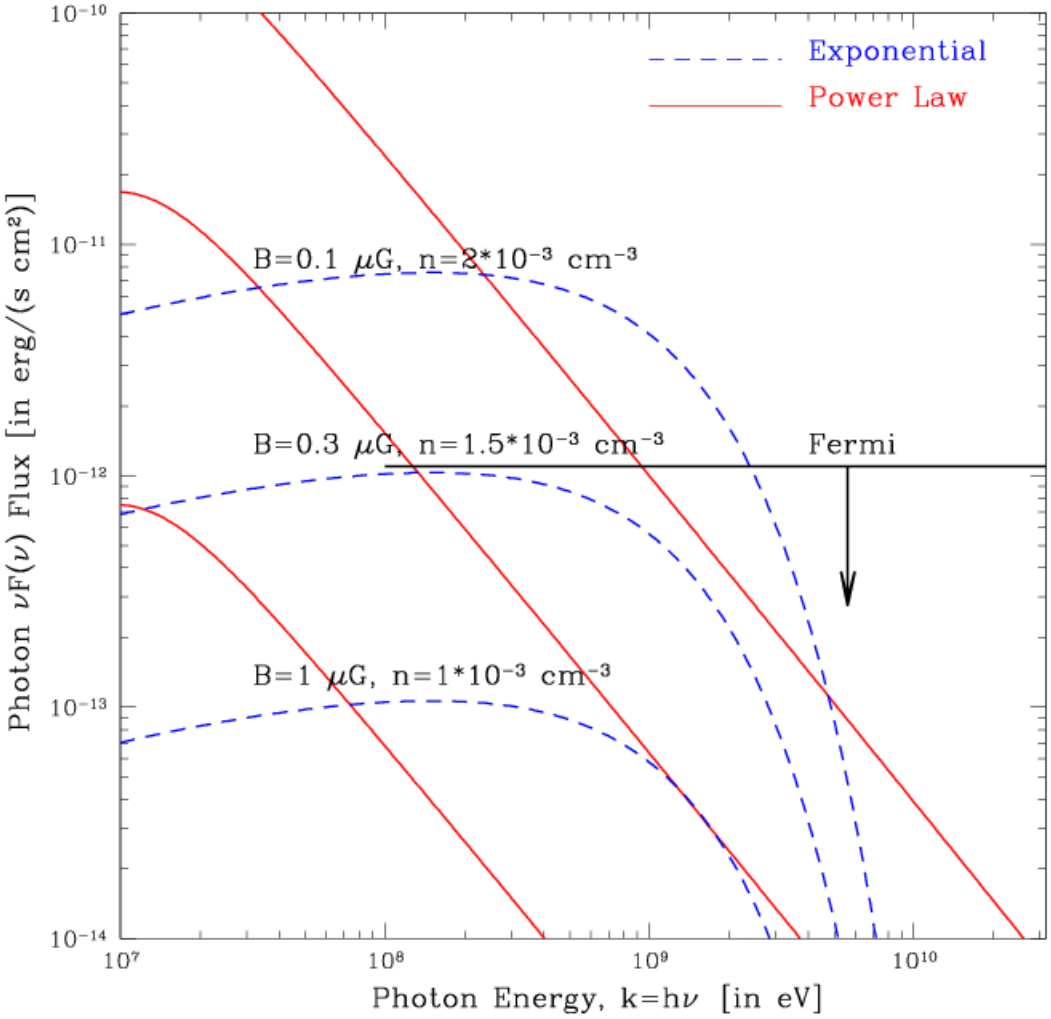
a. Photon Spectrum (simple power-law)

$$kJ(k) \propto k^{-p+2}(\ln k + a); \quad k = h\nu/m_e c^2$$

b. Normalization

$$R_{\mathrm{NTB}} = \frac{kJ(k)}{\nu f(\nu)} \propto \alpha \frac{n m_e c^2}{B^2} \sim 10 \left(\frac{n}{10^{-3}}\right) \left(\frac{1\mu\mathrm{G}}{B}\right)^2$$

Comparison with observations



2. X- and Gamma-Rays From CR Protons

a. Gamma-rays Primarily from pi-zero decays

$$kJ(k) = cn_p k^2 \int \sigma_{p-p}(E_p) N(E_p) f(k/E_p) dE_p/E_p \propto k^{-s+2}(a + \ln k)$$

Only unknown: *CR spectrum*

$$N(E_p) = N_0 E_p^{-s}$$

Usually expressed as the ratio

$$X_p = \frac{P_{\rm CR}}{P_{\rm gas}} = \frac{\int E_p N(E_p) dE_p/3}{2nkT/3}$$

b. X-rays (and radio) produced by secondary (e+e-) as above

Limits on CR protons *(Xp)* in Coma

Coma cluster:

Xp based on the full energy band flux limits (0.1-300 GeV) and assuming a point source.

alpha	Xp (beta=0)	Xp (beta=-0.5)	Xp (beta=1.0)
2.0	0.0642	0.0274	0.247
2.5	0.0313	0.0134	0.121
3.0	0.0391	0.0167	0.151

The Xp limits can be imporved by considering the flux limits in the 0.4-1.6 or 1.6-6.4 energy bands.
energy bands quoted in Table 1 as well as how these change if Coma is treated as an extended sc

energy range	Xp (point)	Xp (gauss=0.2 deg)	Xp (gauss=0.6deg)
0.1-300	0.0642	0.0590	0.0905
0.1-0.4	0.149	0.0797	0.0777
0.4-1.6	0.040	0.0368	**0.0396**
1.6-6.4	**0.0119**	**0.0149**	0.0446
6.4-25.6	0.0393	0.0961	0.653
25.6-102.4	0.123	0.997	4.91

Summary of Radiative Signatures

Upper limits on X- and gamma-ray fluxes can be used to set limits on

A. Magnetic Field (>0.3 microG)

B. Cosmic-Ray Protons (Xp<0.1)

C. Dark Matter Annihilation (not very constraining yet)

III. Acceleration: *1. Mechanisms*

1. Electric Fields || to Magnetic Fields

e.g. in reconnection process

But, unstable and leads to TURBULENCE

2. Fermi Acceleration

2nd order Stochastic Acceleration

1st order Shock Acceleration

Both need Plasma Waves-TURBULENCE

III. Acceleration: *2. Formalisms*

Fokker-Planck Kinetic Equation

$$\frac{\partial f}{\partial t}+v\mu\frac{\partial f}{\partial s}=\frac{1}{p^2}\frac{\partial}{\partial p}p^2\left[D_{pp}\frac{\partial f}{\partial p}+D_{p\mu}\frac{\partial f}{\partial \mu}\right]+\frac{\partial}{\partial \mu}\left[D_{\mu\mu}\frac{\partial f}{\partial \mu}+D_{\mu p}\frac{\partial f}{\partial p}\right]-\frac{1}{p^2}\frac{\partial}{\partial p}(p^2\dot{p}_L f)+\dot{S}$$

1. Isotropic if $D_{\mu\mu}\gg v/L$ and D_{pp}/p^2 Define $F(p,s,t)\equiv\frac{1}{2}\int_{-1}^{1}d\mu f(p,\mu,s,t)$ and $\dot{Q}(p,s,t)\equiv\frac{1}{2}\int_{-1}^{1}d\mu\dot{S}(p,\mu,s,t)$

$$\frac{\partial F}{\partial t}-\frac{\partial}{\partial s}\kappa_s\frac{\partial F}{\partial s}=\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^4\kappa_p\frac{\partial F}{\partial p}-p^2\dot{p}_L F\right)+\dot{Q}(p,s,t)+\frac{\partial}{\partial s}(.....),$$

Where $\kappa_s=\frac{v^2}{8}\int_{-1}^{1}d\mu\frac{(1-\mu^2)^2}{D_{\mu\mu}}$ and $\kappa_p=\frac{1}{2p^2}\int_{-1}^{1}d\mu(D_{pp}-D_{\mu p}^2/D_{\mu\mu})$

With acceleration and scattering times $\tau_{ac}=1/\kappa_p$ and $\tau_{sc}=8\kappa_s/v^2$

2. If $D_{pp}/p^2\gg D_{\mu\mu}$ then $\tau_{ac}=p^2/<D_{pp}>\ll\tau_{sc}$

III. Acceleration: *2. Formalisms*

3. If Homogeneous *(or spatially averaged)*

and defining $N(E)dE = 4\pi p^2 F(p)dp$ we get

$$\frac{\partial N(E)}{\partial t} = \frac{\partial^2}{\partial E^2}\left[D_{\mathrm{EE}}N(E)\right] - \frac{\partial}{\partial E}\left[\left(A(E) - \dot{E}_{\mathrm{L}}(E)\right)N(E)\right] - \frac{N(E)}{T_{\mathrm{esc}}(E)} + \dot{Q}(E)$$

Diffusion Accel. Loss Escape

$$D_{EE} = c^2\beta^2 D_{pp} \qquad A(E) = \frac{1}{p^2}\frac{d(c^2\beta^2 D_{pp})}{dp}$$

$$T_{\mathrm{esc}}(E) \simeq \tau_{\mathrm{cross}}(1 + \tau_{\mathrm{cross}}/\tau_{\mathrm{sc}})$$

$$\dot{E}_L = 4\pi r_0^2 \ln\Lambda mc^3 n/\beta + (4/9)r_0^2 c\beta^2\gamma^2 B^2$$

III. Acceleration: *2. Formalisms*

3. If Homogeneous *(or spatially averaged)*

and defining $N(E)dE = 4\pi p^2 F(p)dp$ we get

$$\frac{\partial N(E)}{\partial t} = \frac{\partial^2}{\partial E^2}\left[D_{\mathrm{EE}}N(E)\right] - \frac{\partial}{\partial E}\left[\left(A(E) - \dot{E}_{\mathrm{L}}(E)\right)N(E)\right] - \frac{N(E)}{T_{\mathrm{esc}}(E)} + \dot{Q}(E)$$

Diffusion Accel. Loss Escape

$$D_{EE} = c^2\beta^2 D_{pp} \qquad A(E) = \frac{1}{p^2}\frac{d(c^2\beta^2 D_{pp})}{dp} + A_{\mathrm{shock}}(E)$$

$$T_{\mathrm{esc}}(E) \simeq \tau_{\mathrm{cross}}(1 + \tau_{\mathrm{cross}}/\tau_{\mathrm{sc}})$$

$$\dot{E}_L = 4\pi r_0^2 \ln\Lambda mc^3 n/\beta + (4/9)r_0^2 c\beta^2\gamma^2 B^2$$

III. Acceleration: *Model Parameters*

We need the diffusion coefficients $D_{EE}(E)$ and $\bar{D}_{\mu\mu}(E)$

From which we can get $T_{\rm esc}(E)$ and $A(E)$

These depend on the

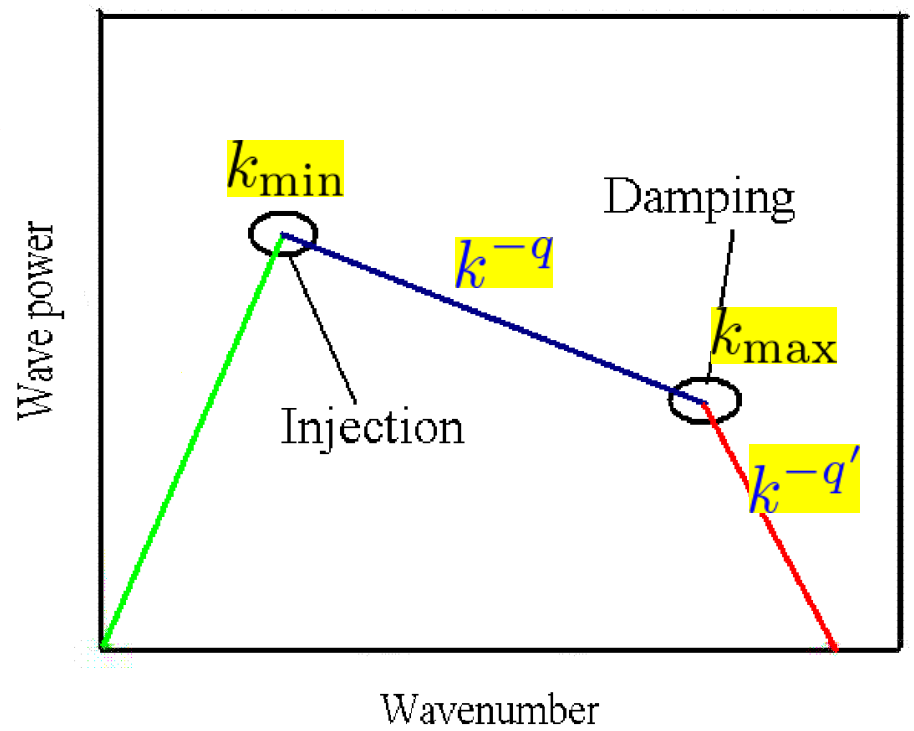
1. Turbulence parameters

$k_{\rm min}$, $k_{\rm max}$ and q

2. Plasma Parameters

$$\alpha = \left(\frac{\omega_{\rm pe}}{\Omega_e}\right) \propto \left(\frac{\sqrt{n}}{B}\right) \text{ and } u_{\rm turb} \sim 8\pi\delta B^2 \sim \rho v_{\rm turb}^2$$

$$\tau_p^{-1} = \left(\frac{\pi}{2}\right)\Omega_e \left(\frac{u_{\rm turb}}{B^2/8\pi}\right)(q-1)\left(\frac{ck_{\rm min}}{\Omega_e}\right)^{q-1}$$



TWO IMPORTANT ASPECTS

Define $R_1 = (D_{pp}/p^2)/D_{\mu\mu}$ and $R_2 = (D_{\mu p}/p)/D_{\mu\mu}$

In general

$$(D_{pp}/p^2) : (D_{\mu p}/p) : D_{\mu\mu} = [x_j^2] : [x_j(1-\mu x_j)] : [(1-\mu x_j)^2] \text{ with } x_j = (\beta_{ph,j}/\beta)^2$$

1. Thus when a Single Mode dominates The *Acceleration Rate* $\kappa_p = \frac{1}{2p^2}\int_{-1}^{1} d\mu (D_{pp} - D_{\mu p}^2/D_{\mu\mu}) \to 0$

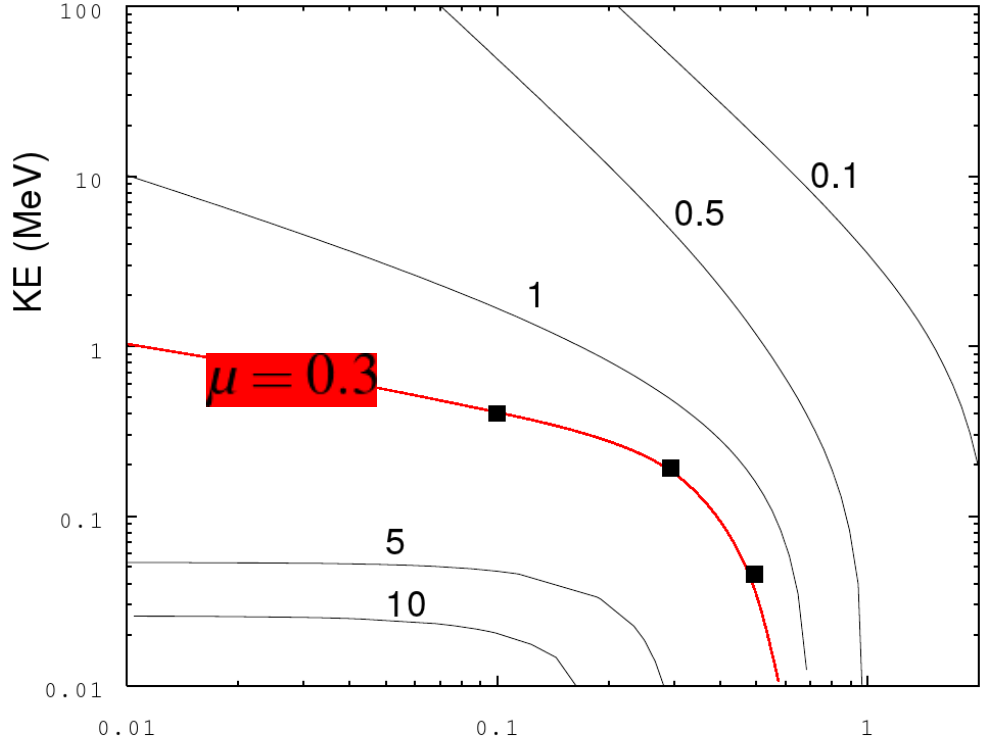
2. High Energy Protons and Relativistic Electrons

Alfven and Fast Mode $\beta_{ph} = (\omega/kc) = \beta_A$ and $R_1 = (\beta_A/\beta)^2 < 1$

But for highly magnetized plasmas or at low energies $R_1 > 1$ *And Acceleration more Efficient than Scattering*

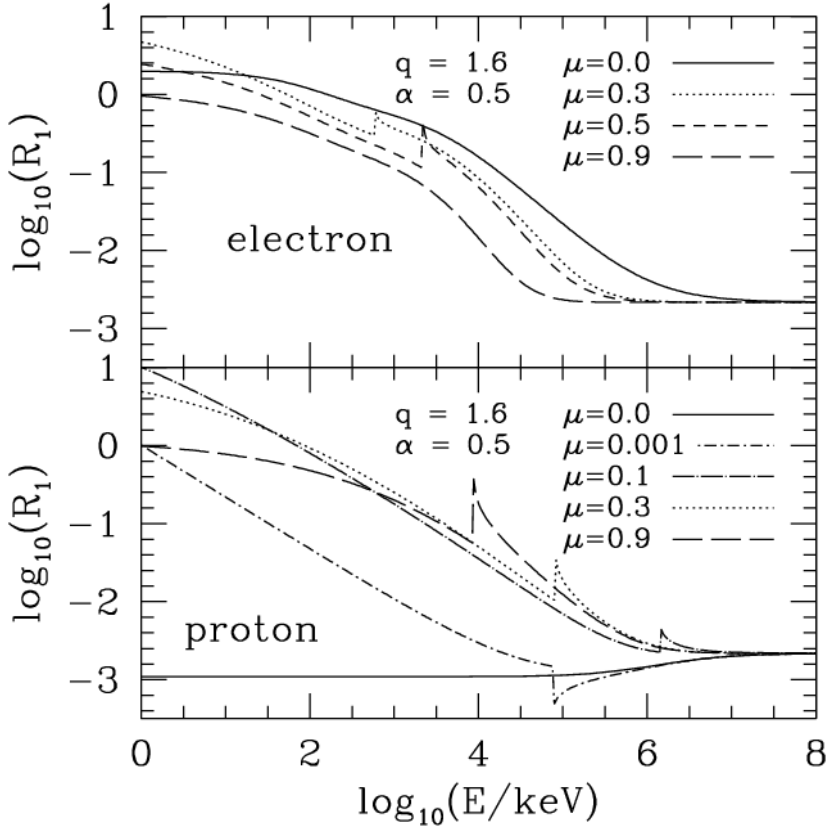
Accel/Scatt Ratio *R1*

R1 Contours (mu=0)



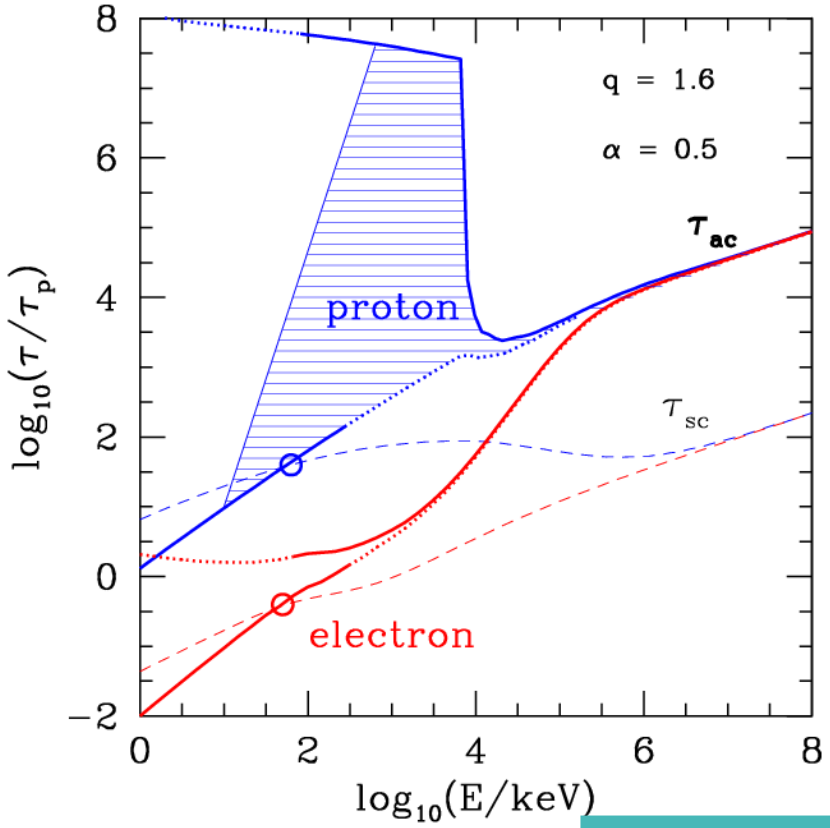
$$\alpha = (m_e/m_p)^{1/2}/\beta_A \propto n^{1/2}/B$$

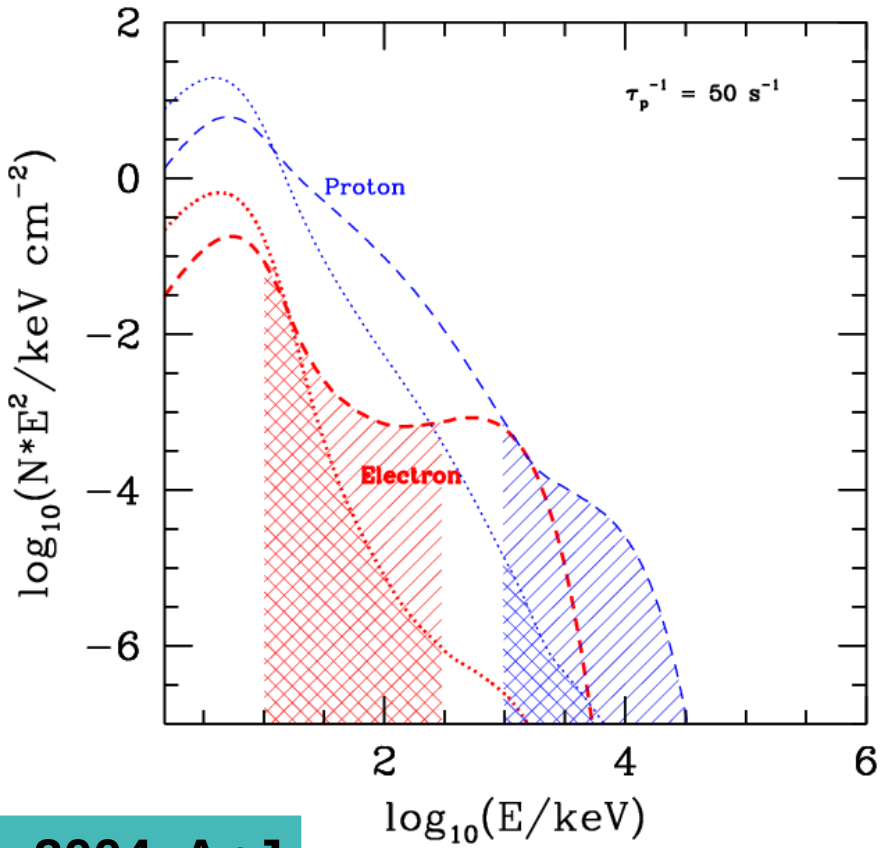
R1 values



III. Acceleration

Electron vs Proton Acceleration and Spectra



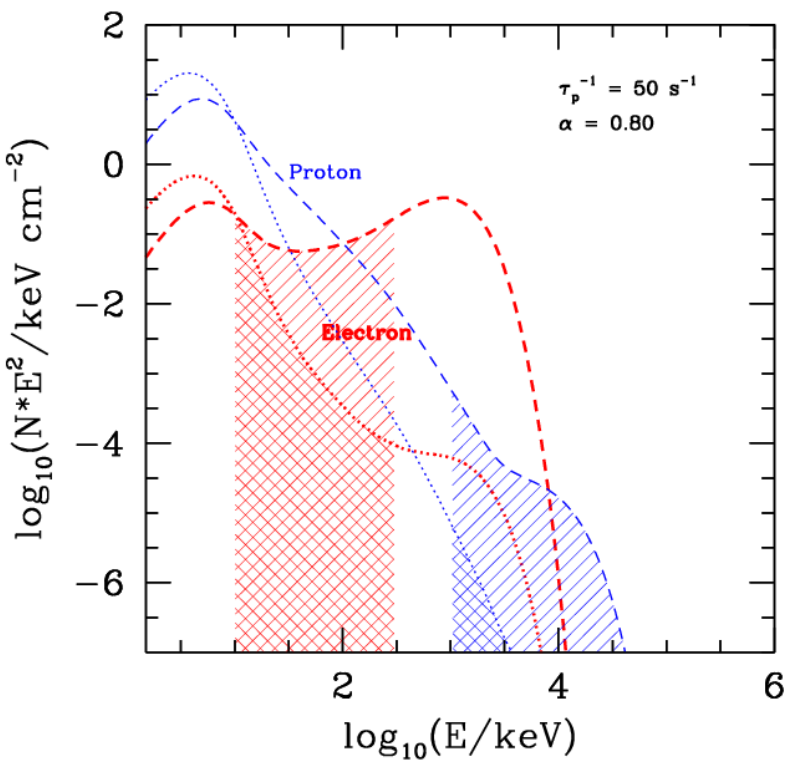


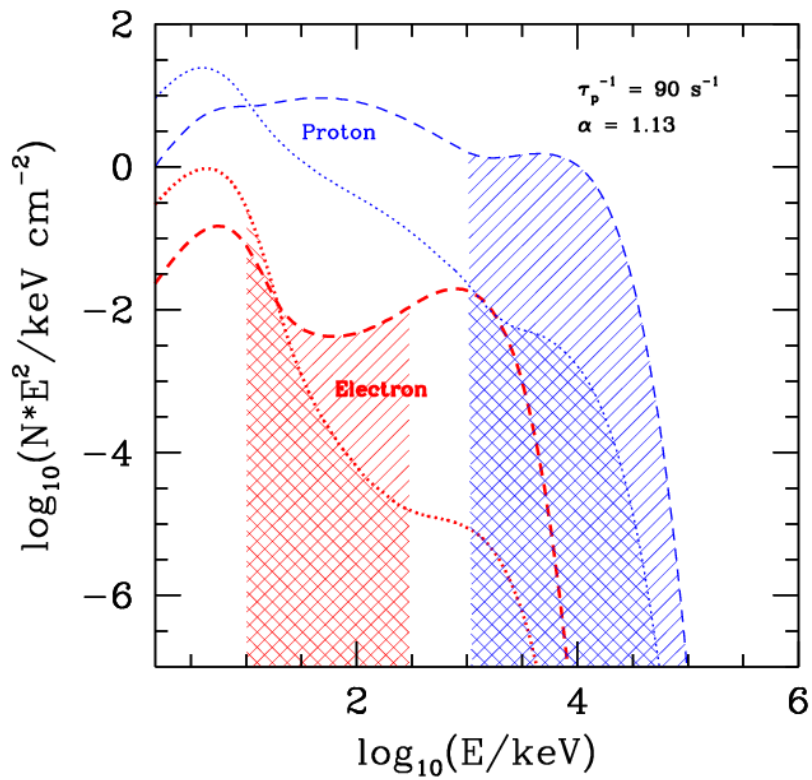
VP and Liu, 2004, ApJ

e vs p: Dependence on Magnetization

$$\alpha = (m_e/m_p)^{1/2}/\beta_A \propto n^{1/2}/B$$

$$\tau_p^{-1} = \left(\frac{\pi}{2}\right)\Omega_e\left(\frac{u_{\rm turb}}{B^2/8\pi}\right)(q-1)\left(\frac{ck_{\rm min}}{\Omega_e}\right)^{q-1}$$





III. Acceleration: *3. Sources of Particles*

1. Background Thermal Particles

Competition between acceleration and heating

2. Injected High Energy Particles

From AGN activity and escaping From galaxies

Need for a re-acceleration of electrons

Escape of Cosmic-rays from Galaxies
(No Acceleration Only Transport)

$$\frac{\partial n_e(E_e)}{\partial t} = -\frac{\partial}{\partial E_e}\left[\frac{E_e\, n_e(E_e)}{\tau_{rad}}\right] - \frac{n_e(E_e)}{\tau_{esc}} + \dot{Q}_e(E_e)$$

$$n_e(E_e) = \frac{\tau_{rad}(E_e)}{E_e}\int_{E_e}^{\infty} dE'_e\ \dot{Q}_e(E'_e)\ \exp\left[-\int_{E_e}^{E'_e}\frac{dE''_e}{E''_e}\ \frac{\tau_{rad}(E''_e)}{\tau_{esc}(E''_e)}\right]$$

$$\tau_{\rm rad} \ll \tau_{\rm esc} \qquad n_e(E_e) = \frac{\tau_{rad}(E_e)}{E_e}\int_{E_e}^{\infty} dE'_e\ \dot{Q}_e(E'_e)$$

$$\tau_{\rm rad} \gg \tau_{\rm esc} \qquad n_e(E_e) = \tau_{\rm esc} \times \dot{Q}_e(E_e)$$

ICM CRs from Galaxies

$$n_{\rm ICM}(E_P) = n_{\rm gal}(E_p) \times \frac{N_{\rm gal} V_{\rm gal}}{V_{\rm cl}} \times \frac{\tau_{\rm Hubble}}{\tau_{\rm esc}}, \quad E_p > 30{\rm GeV}$$

Filling factor

$$f = \frac{N_{\rm gal} V_{\rm gal}}{V_{\rm cl}} \sim 3 \times 10^{-3} \ \text{ and } \ \frac{\tau_{\rm Hubble}}{\tau_{\rm esc}} \sim 200 (E_p/{\rm GeV})^{1/3}$$

Spectrum and Pressure

$$n_{\rm ICM}(E_p) \sim 0.6 n_{\rm gal}(E_p) \propto E^{-2.42}$$

$$P_{\rm CR} \sim 0.01 {\rm eV cm}^{-3} \ \text{ and } \ X_p \sim 10^{-3}$$

III. Acceleration of Background Particles

In situ acceleration of thermal electrons and protons for production of a non-thermal tail that may explain the hard X-ray emission via

bremsstrahlung of electrons *(with E>100 keV)* *VP and W. East 2008*

inverse-bremsstrahlung of protons *(with E>200 MeV)* *VP and B. Kang 2011*

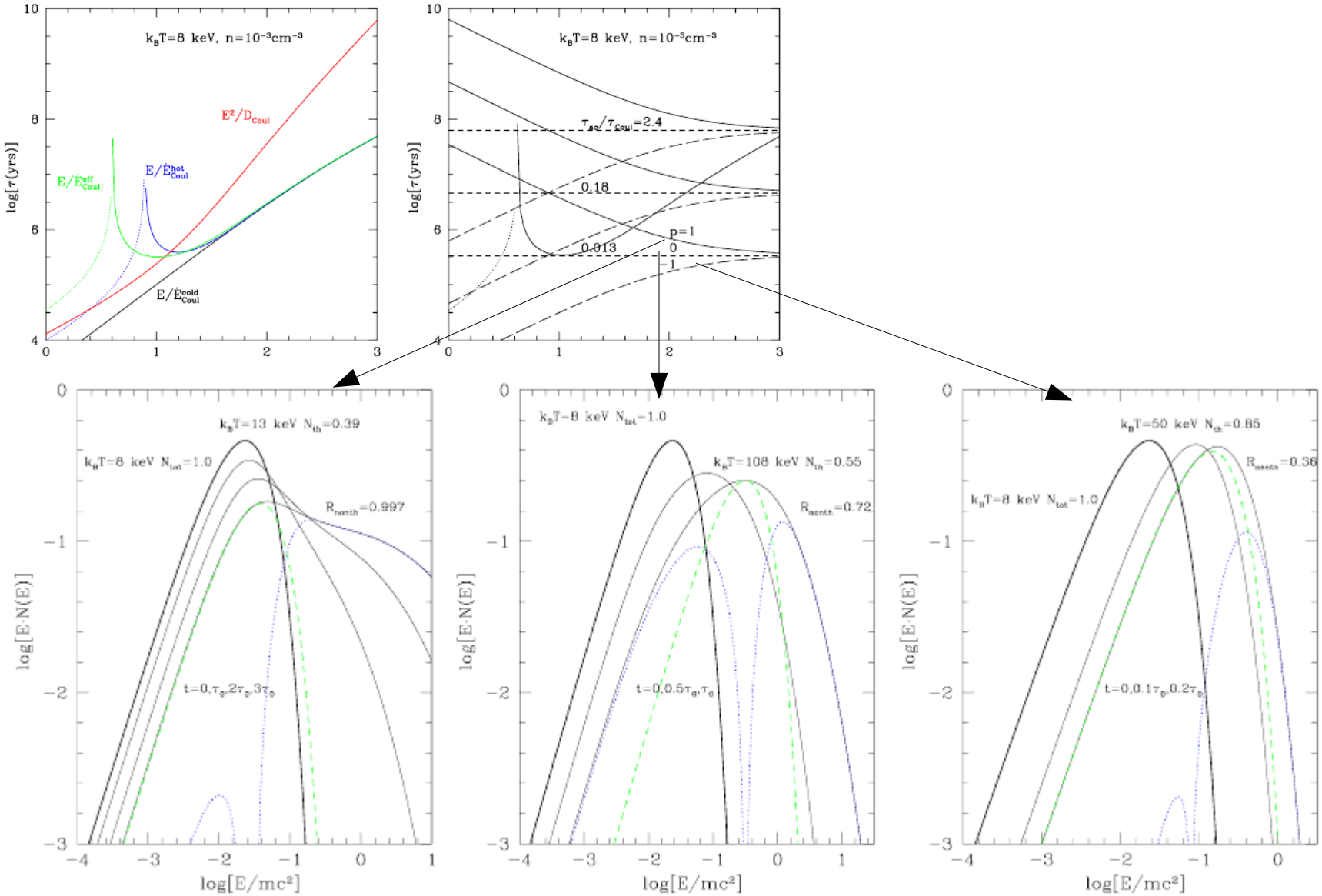
Simple Phenomenological Approach

Acceleration Timescale $\tau_{\rm acc} \equiv E/A(E) = \tau_0(1 + E_c/E)^p$

Transport Equation for $T_{\rm esc} \gg T_{\rm Hubble}$

$$\frac{\partial N}{\partial t} = \frac{\partial^2}{\partial E^2}[(D(E) + D_{\rm Coul}(E))N] - \frac{\partial}{\partial E}[(A(E) - \dot{E}_L)N].$$

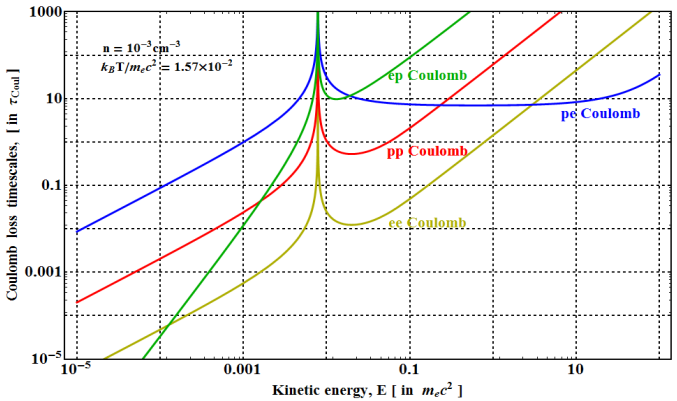
Acceleration and Heating of Electrons

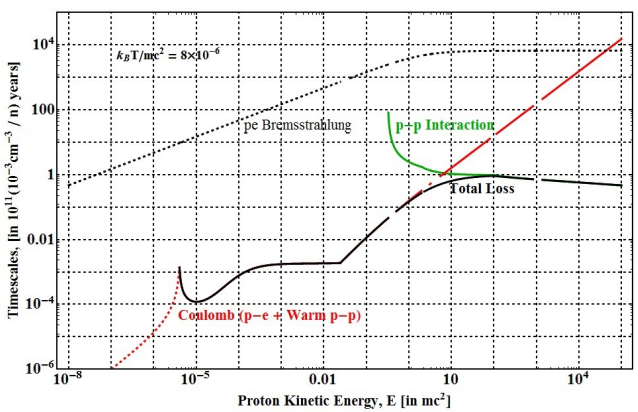


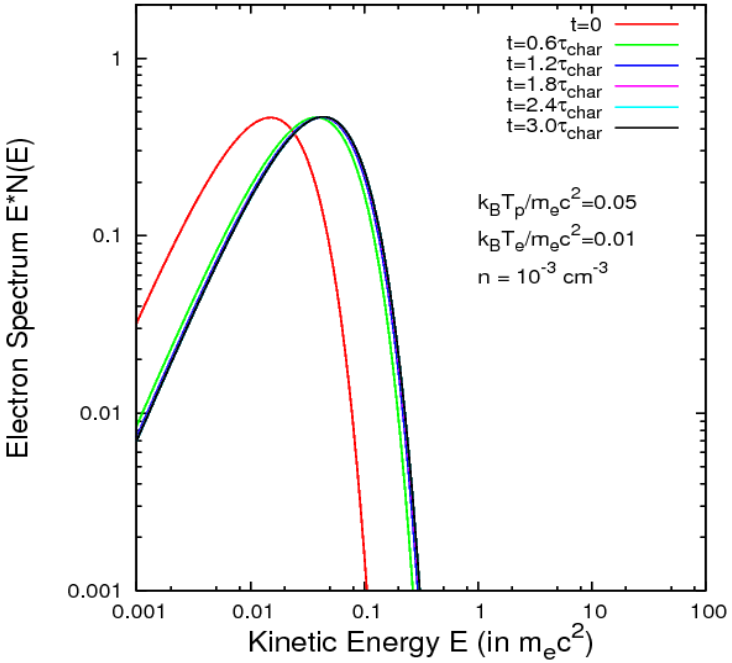
Acceleration of Thermal Protons

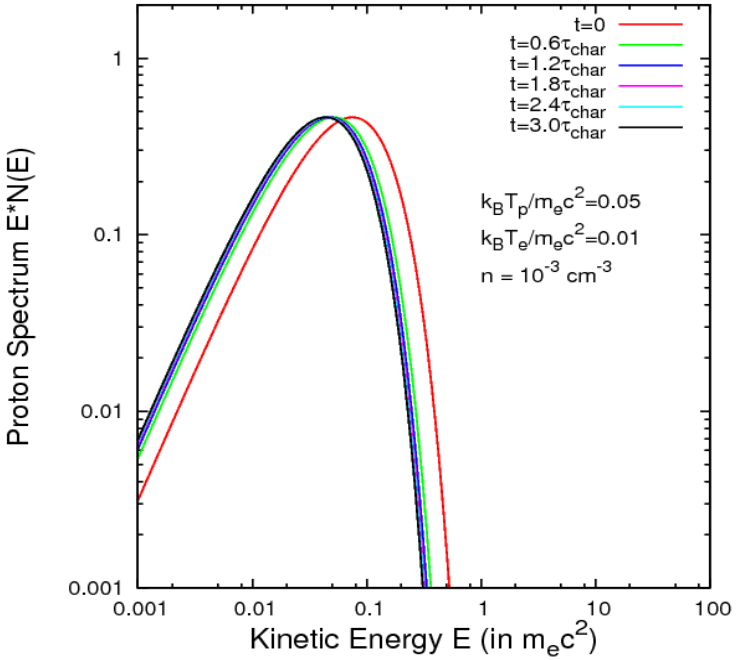
Coupled Electron and Proton Kinetic Equations

Thermalization of electrons and protons





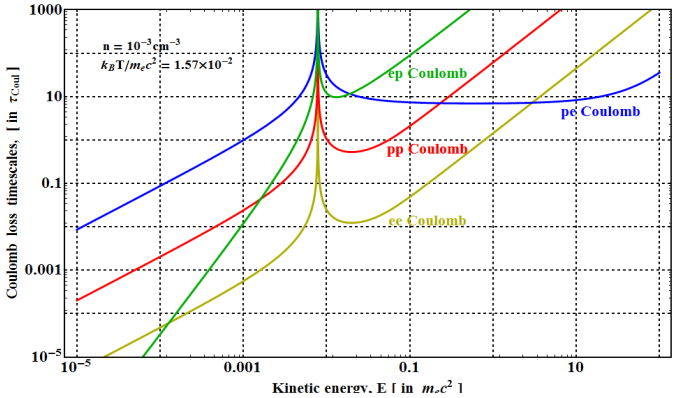


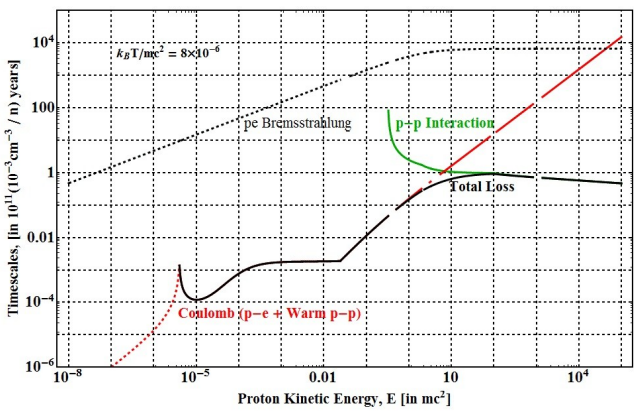


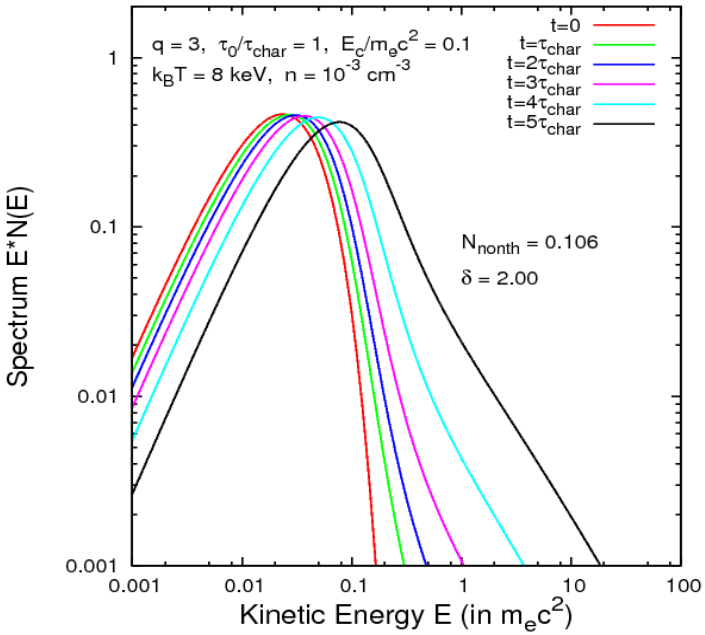
Acceleration of Thermal Protons

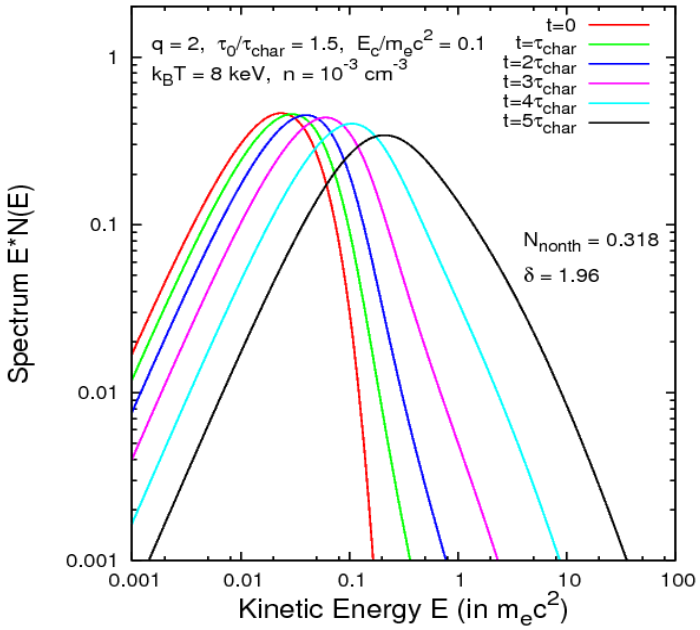
Coupled Electron and Proton Kinetic Equations

Proton Spectra









III. Acceleration of Background Particles

In summary: Attempts to accelerate thermal background particles

a. leads to rapid heating in addition to production of non thermal tails

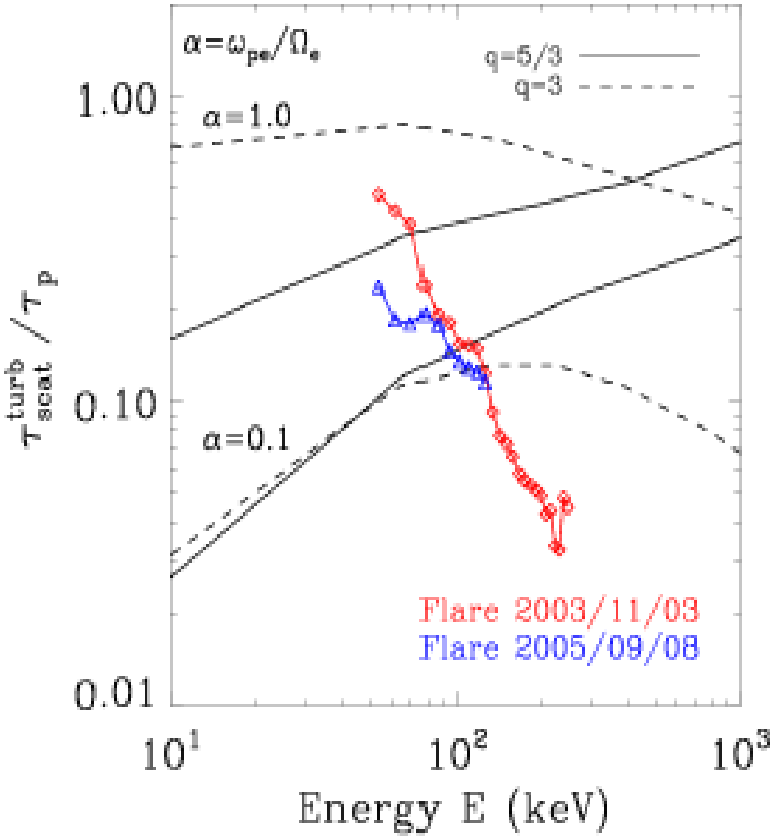
AND

b. requires a more efficient acceleration at higher energies

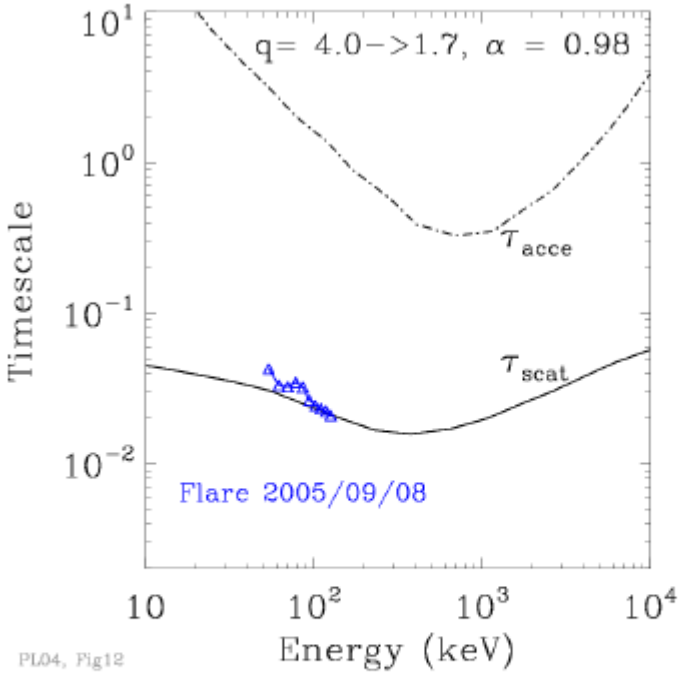
Acceleration and Heating of Electrons

We require rapidly decreasing time scales BUT

In the inertial range



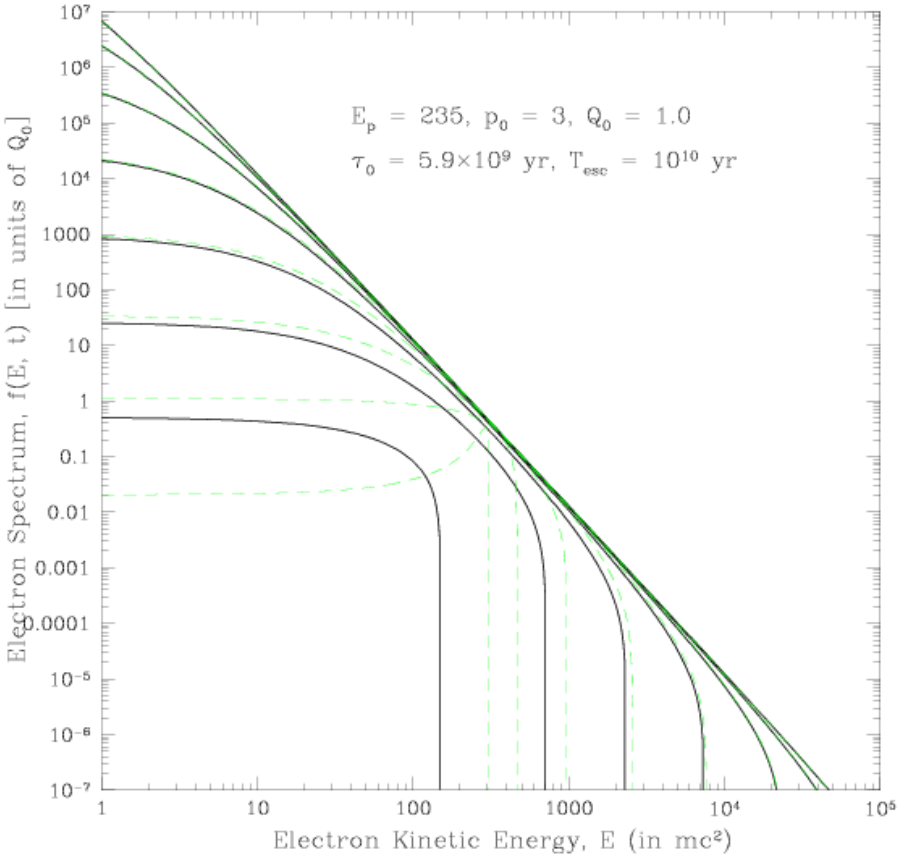
In the damping range



$$\alpha = \left(\frac{\omega_{pe}}{\Omega_e}\right) \propto \left(\frac{\sqrt{n}}{B}\right) \text{ and } u_{turb} \sim 8\pi\delta B^2 \sim \rho v_{turb}^2$$

Re-acceleration of Injected Electrons

1. Injection alone not sufficient



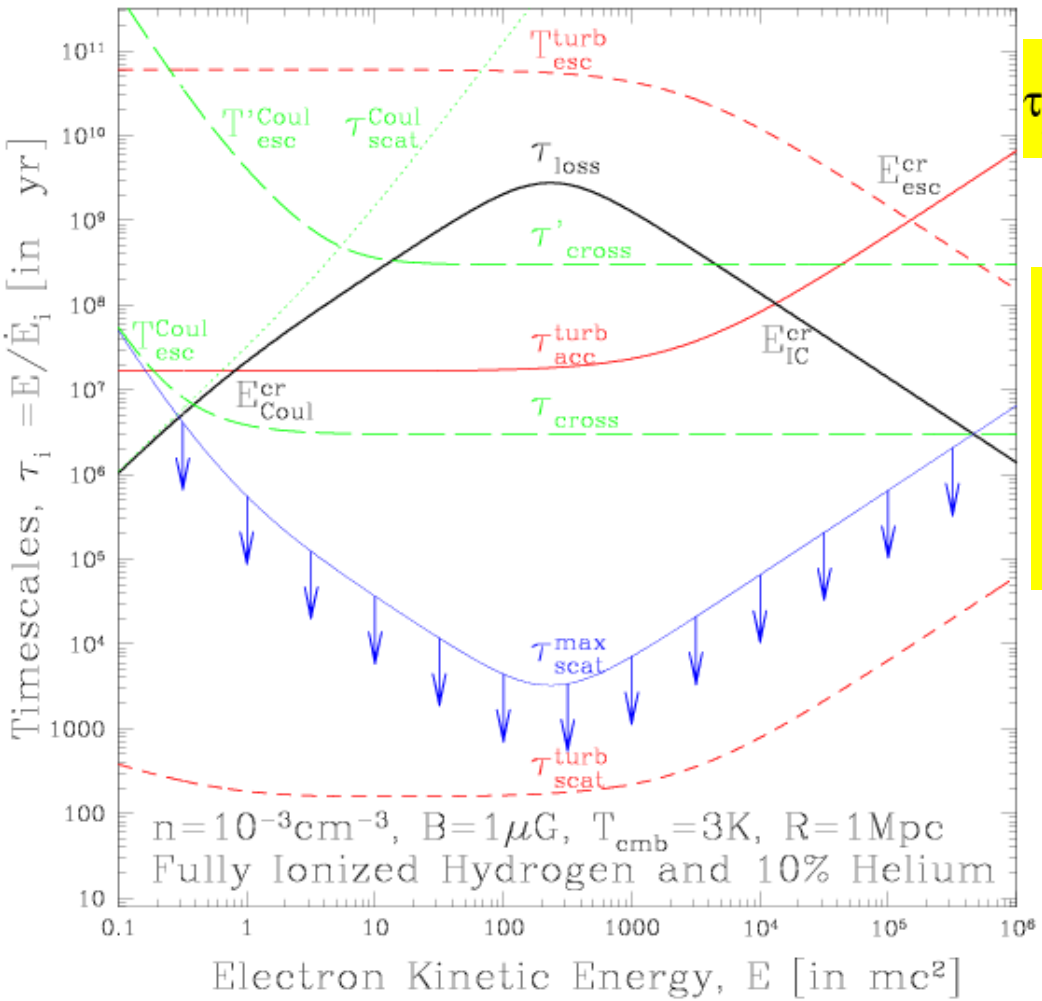
Re-acceleration of Injected Electrons

1. Injection alone not sufficient

Need re-acceleration: General requirements

$$T_{\rm esc} > \tau_{\rm loss} \ \text{ for all, and } \ \tau_{\rm acc} < \tau_{\rm loss} \ \text{ for relevant } E's$$

Loss, Scattering, Escape and Acceleration Times



$$\tau_p^{-1} = \left(\frac{\pi}{2}\right)\Omega_e \left(\frac{u_{\rm turb}}{B^2/8\pi}\right)(q-1)\left(\frac{ck_{\rm min}}{\Omega_e}\right)^{q-1}$$

$$\tau_{\rm scat} \sim 100 \times \tau_p$$

For the ICM n, B etc.

$$f_{\rm turb} = (\delta B/B)^2 \sim 10^{-2}$$

Re-acceleration of Injected Electrons

1. Injection alone not sufficient

Need re-acceleration: General requirements

$$T_{\rm esc} > \tau_{\rm loss} \ \text{ for all, and } \ \tau_{\rm acc} < \tau_{\rm loss} \ \text{ for relevant } E's$$

2. Steady State Acceleration

Acceleration of Injected NonThermal Electron

Injected Spectrum $Q(E) = Q_0 \delta(E - E_0)$

Example: Assume Parametric Forms

$$D(E) = \mathcal{D} E^{q'}, A(E) = a\mathcal{D} E^{q'-1}, \text{ and } T_{esc} = E^s/(\theta \mathcal{D}) \tag{2}$$

Special case of $s = 2 - q'$:

$$N(E) \propto Q_0 \begin{cases} (E/E_0)^{a-x+\sqrt{(x^2+\theta)}} & \text{if } E < E_0, \\ (E/E_0)^{a-x-\sqrt{(x^2+\theta)}} & \text{if } E > E_0, \end{cases} \tag{3}$$

$$x = (a - 1 + q')/2.$$

But we need

$$\theta \sim \tau_{ac}/T_{esc} \ll 1$$

So

$$N(E) \propto Q_0 \begin{cases} (E/E_0)^{a} & \text{if } E < E_0, \\ (E/E_0)^{-q'+1} & \text{if } E > E_0, \end{cases} \tag{4}$$

For $p = 3$ we need $q' = 4$!. For $q' < 2$, $p < 1$.
Too flat. Predicts HXR/EUV=200 while observed value is < 2.

Re-acceleration of Injected Electrons

1. Injection alone not sufficient

Need re-acceleration: General requirements

$$T_{\rm esc} > \tau_{\rm loss} \ \text{ for all, and } \ \tau_{\rm acc} < \tau_{\rm loss} \ \text{ for relevant } E's$$

2. Steady State Acceleration

Kolmogorov and inertial range too flat.

Need steep turb. spectrum: Damping range

3. Time Dependent or Episodic

TIME DEPENDENT MODELS

2. Acceleration Plus Transport

No Diffusion; $D(E) = 0$

For power law injection; $Q(E) = Q_0(E/E - p)^{-p_0}, \ p_0 > 2$

$$\dot{E}_L(E)/E_p = (1 + (E/E_p)^2 - b(E/E_p)^{q'-1})/\tau_0,$$

$$b = a\mathcal{D}\tau_0 E_p^{q'} = \tau_0/\tau_{ac}(E_p) \sim 10^2 \text{ or } 1$$

For shock and stochastic acceleration, respectively.

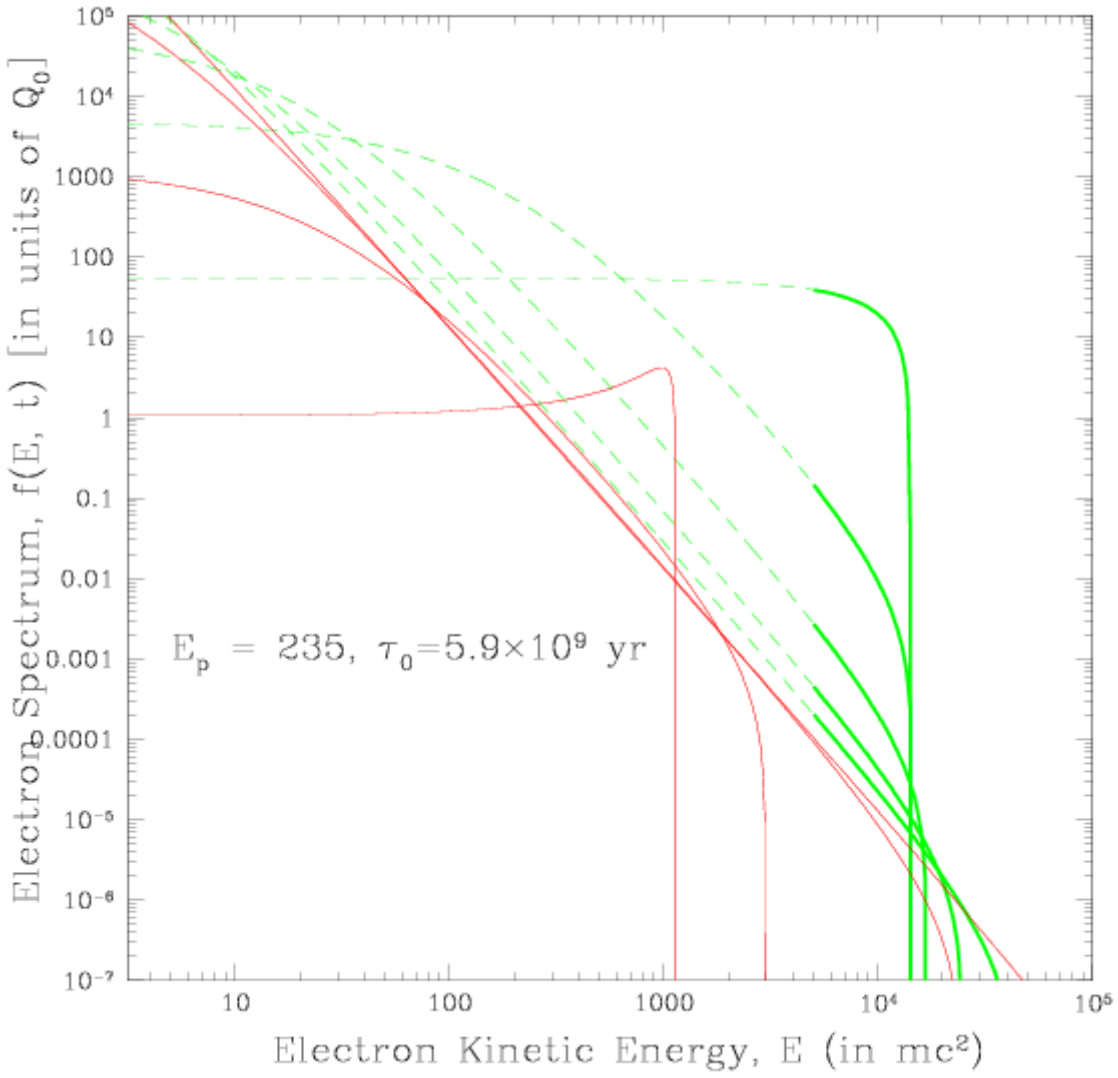
For $q' = 2$

$$f(E,t) = \exp\{-t/T_{esc}\} Q_0 \frac{[T_+ - (E/E_p)\tan(\delta t/\tau_0)/\delta]^{p_0-2}}{\cos^2(\delta t/\tau_0)[T_-(E/E_p) + \tan(\delta t/\tau_0)/\delta]^{p_0}},$$

$$\delta^2 = 1 - b^2/4 \text{ and } T_\pm = 1 \pm b\tan(\delta t/\tau_0)/(2\delta).$$

For $\delta = 0$ or $b = 2$

$$f(E,t) = \exp\{-t/T_{esc}\} Q_0 \frac{[1 - (E/E_p - 1)t/\tau_0]^{p_0-2}}{[E/E_p - (E/E_p - 1)t/\tau_0]^{p_0}}.$$


Electron Spectrum, f(E, t) [in units of Q_0]
Electron Kinetic Energy, E (in mc^2)
E_p = 235, τ_0=5.9×10⁹ yr
10⁵
10⁴
1000
100
10
1
0.1
0.01
0.001
0.0001
10⁻⁵
10⁻⁶
10⁻⁷
10
100
1000
10⁴
10⁵

Summary

1. There are multiple circumstantial evidence for NTA in ICM of many clusters
2. Radio halos and relics in many clusters and Hard X-ray emission from Bullet cluster are convincing
3. Synchrotron and IC and possibly NTB all provide radiative signatures for NTA
4. Stochastic re-acceleration by turbulence of (episodic) injected energetic electrons seem to be required
5. CR protons escaping star forming galaxies may not be sufficient

Acceleration of Thermal Electrons

The Source Term

$$Q(E) = (\sqrt{\pi}/2)n(kT/E)^{3/2}\sqrt{E}e^{-E/kT} \qquad (1)$$

Many Problems

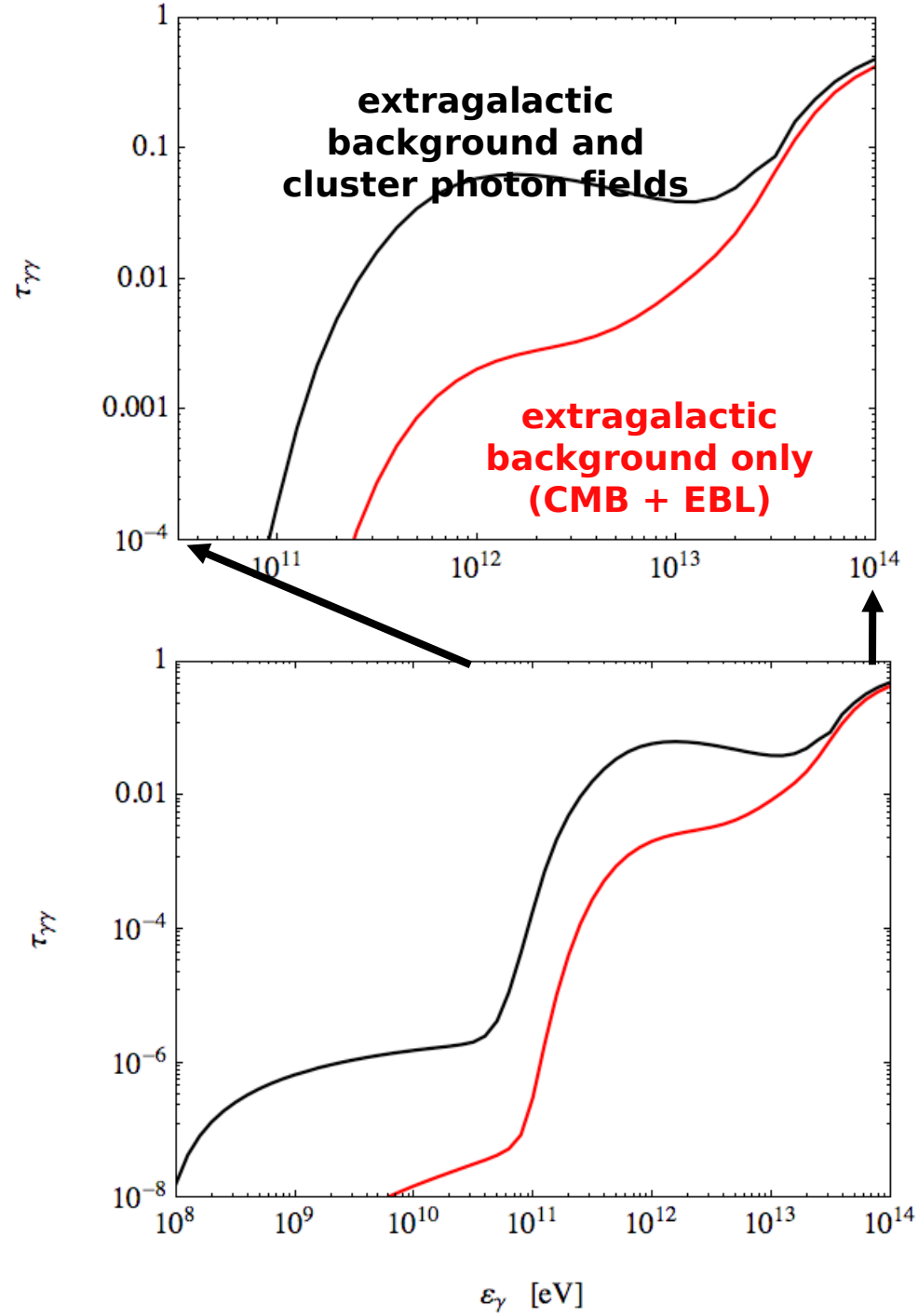
NEED	*OBSERVED*
$\beta_{Alfven} \sim 10^{-2}$	3×10^{-4}
$\lambda_{turb} \sim 10^{9}$ cm	few kpc
$\alpha = \omega_p/\Omega_e \sim 1$	2×10^{2}
$L_{input} \sim 10^{48}$	$< 10^{45}$

- Acceleration of protons more likely
- Too much heating unless shotrtlived

$$Duration < 10^{8} \text{ yrs.}$$

Optical depth for gamma-ray photons emitted at the cluster center, propagating through the ICM, and annihilating on the soft photon fields provided by the cluster starlight, dust emission, and bremsstrahlung.

Note that for example M87 in the Virgo cluster as well as NGC 1275 in the Perseu cluster are established gamma-ray emitters (Fermi/LAT, IACTs)!



ELECTRON ACCELERATION

$$\frac{\partial f}{\partial t} = \frac{\partial^2}{\partial E^2}[D(E)f] - \frac{\partial}{\partial E}[(A(E) - |\dot{E}_L|)f] - \frac{f}{T_{\rm esc}(E)} + Q(E,t).$$

TIME DEPENDENT MODELS

$$Q(E,t) = Q(E)\delta(t - t_0)$$

1. Transport Effects

$D = A = 0$; $T_{\rm esc}$ and $\dot{E}_L$ constants in time.

$$f(E,t) = \exp\{-t/T_{\rm esc}\}Q(E'(E,t))\dot{E}_L(E'(E,t))/\dot{E}_L(E),$$

$E'(E,t) = \tau^{\rm inv}(\tau(E) - t)$ and $\tau^{\rm inv}$ is the inverse function of

$$\tau(E) = \int_E^\infty dE/\dot{E}_L(E) = \pi/2 - \tan^{-1}(E/E_p), \quad \tau^{\rm inv}(x) = \coth x,$$

$$E'/E_p = (E/E_p + \tan(t/\tau_0))/(1 - (E/E_p)\tan(t/\tau_0)).$$

For power law injection; $Q(E) = Q_0(E/E - p)^{-p_0}$, $p_0 > 2$

$$f(E,t) = \exp\{-t/T_{\rm esc}\}Q_0\frac{[1 - (E/E_p)\tan(t/\tau_0)]^{p_0-2}}{\cos^2(t/\tau_0)[E/E_p + \tan(t/\tau_0)]^{p_0}}.$$