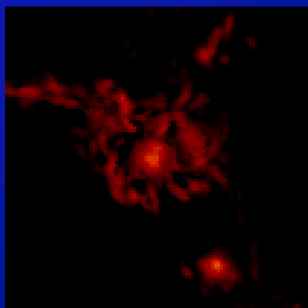
Investigating Galaxy Clusters through γ-rays



Francesco Miniati
MPA, Garching
Sept. 27 2002, Kashiwa

Outline

- **Observational evidence for CRs in the ICM**
- **Properties of IGM shocks**
- **Novel numerical scheme to follow CRs evolution**
- **CR ionic pressure component in ICM**
- **Numerical model of γ-ray emission from GCs**
- **Contribution of cosmological CRs to the CGB**
- **Conclusions**

Observations

Extended radio emission (eg Giovannini & Feretti 2000)
Halos: un-polarized, x-ray like morphology
Relics: polarized, peripheral

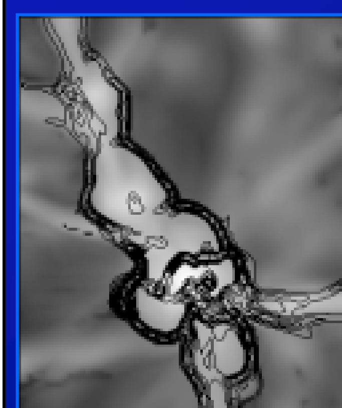
$L_{1.4GHz} \propto T^{\alpha}$ with $4 \leq \alpha \leq 5$ Liang et al. (2000)

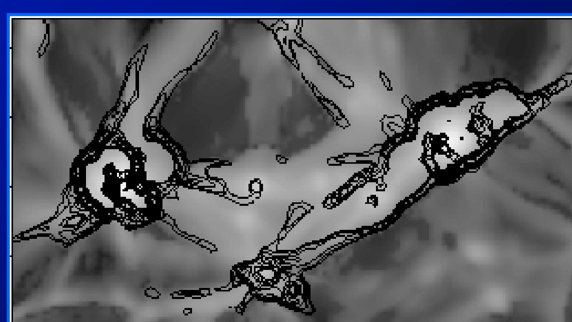
Radiation in excess to what expected from thermal emission of the intra-cluster medium:

Hard X-rays (Fusco-Femiano et al. 1999, Kaastra et al. 1999)

Extreme-UV (Lieu et al. 1996a,b; Bowyer et al. 1996,1999)

Properties of cosmic shocks





Miniati, Ryu, Kang, Jones, Cen & Ostriker (2000, ApJ 542, 608)

Nbody+Hydro TVD cosmological code (Ryu et al. 1993)

Simulate LSS formation: gas + dark matter + B-field

+

COSMOCR:Cosmic Ray Code for Cosmological Applications (Miniati 2001, CPC 141, 17)

•The code allows an *explicit treatment* of the CR component.

injection at shocks

acceleration + losses

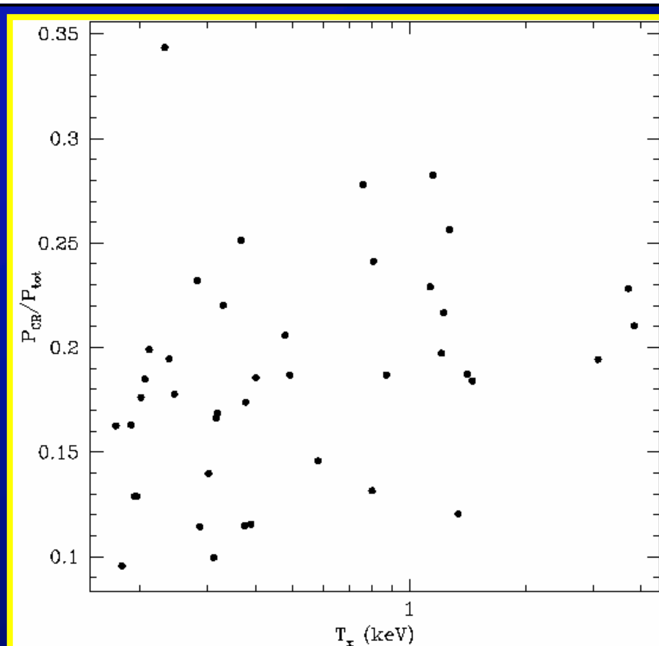
transport

⇒ spatial & spectral CR distribution

•Includes: ions, primary e^- and secondary $e^{\pm}$

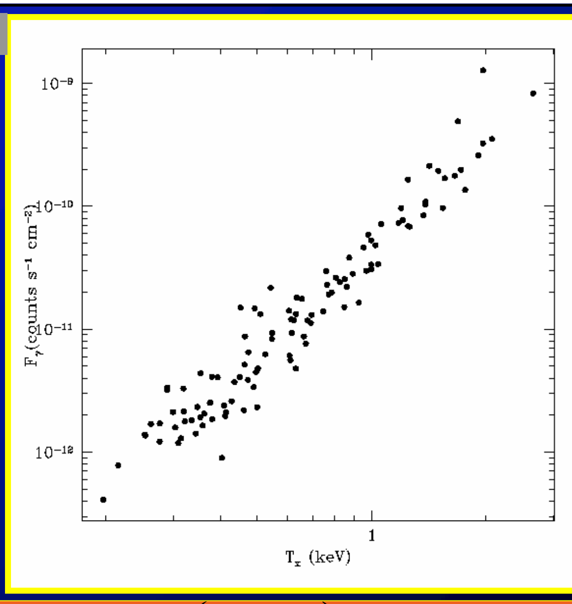
Ratio of CR to thermal pressure vs cluster temperature

ΛCDM
$N=512^3$
$\sigma_8=0.9$
$\Omega_\Lambda=0.7$
$\Omega_b=0.04$
$n_s=1$

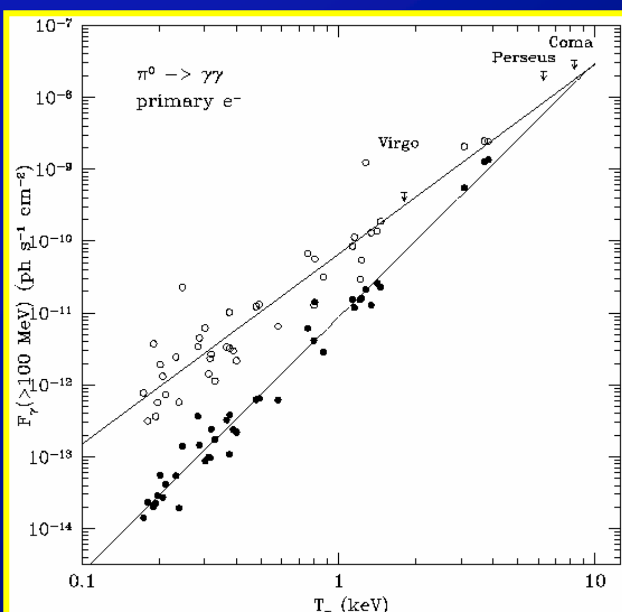


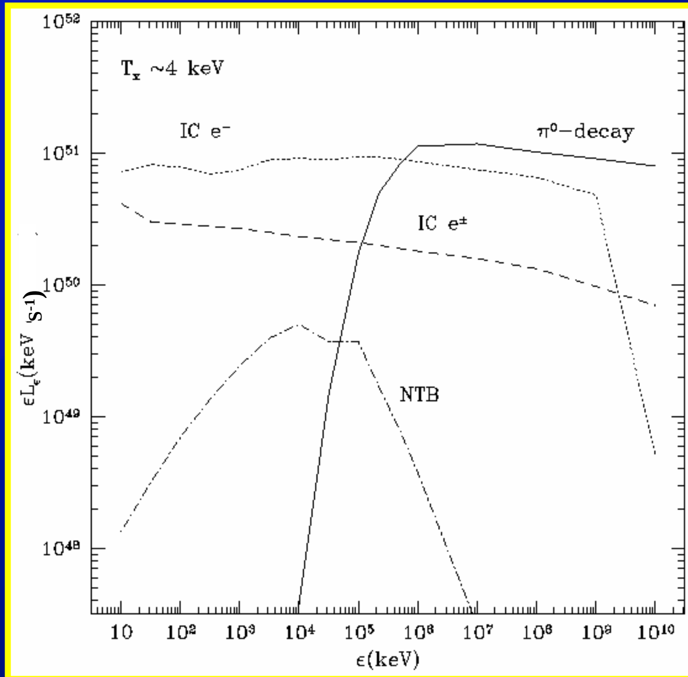
Miniati et al. 2001, ApJ 559, 59

γ-ray flux from $\pi^0 \rightarrow 2\gamma$ decay vs cluster temperature



$$F_\gamma(>100MeV) = 7.4\ 10^{-9} \times \left(\frac{T_x}{6.7keV}\right)^3 \text{ counts s}^{-1}\text{ cm}^{-2}$$

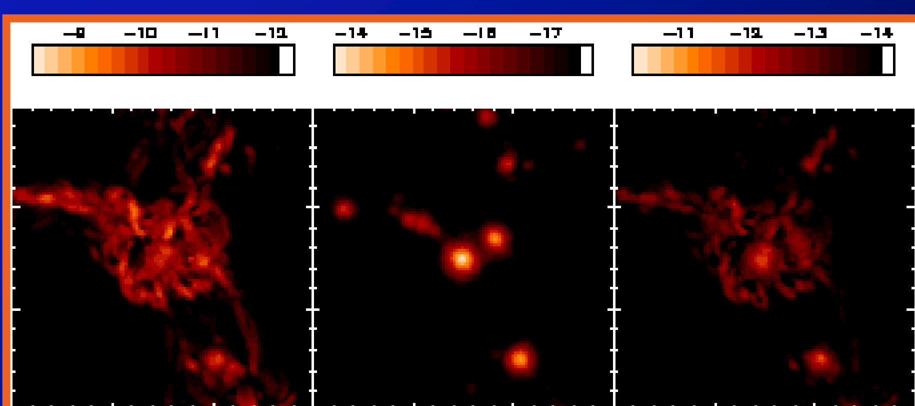




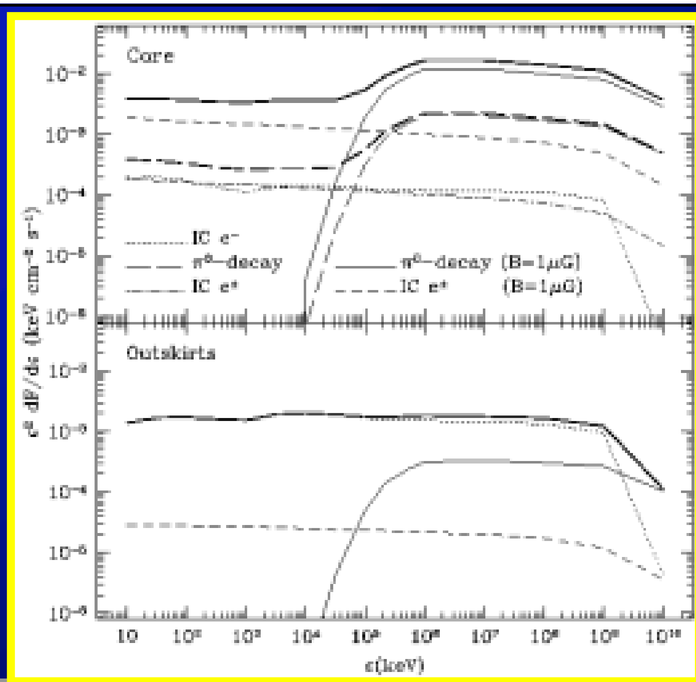
Hard X-ray
F(>100 keV)

Thermal X-ray

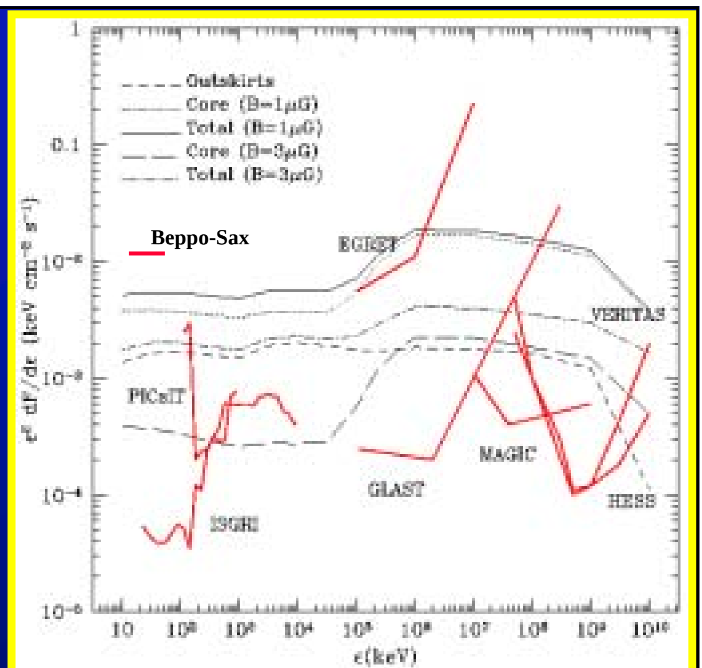
γ-ray
F(>100 MeV)



Miniati 2002, MN subm.



Miniati 2002, MN subm.

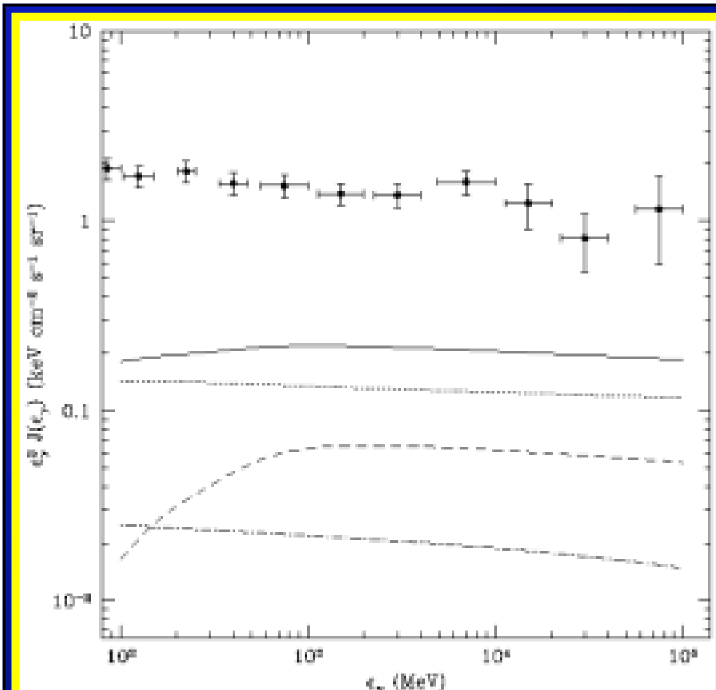


Miniati 2002, MN subm.

Cosmic γ-ray Background

$\varepsilon^{2} J(\varepsilon) \approx 5.4\,(\varepsilon/\mathrm{keV})^{-0.1}$ keV cm^{-2} s^{-1} sr^{-1} (Sreekumar et al. 1998)

- Identified EGRET balzars …… 7% (Mukherjee & Chiang 99)
- Undetected γ-ray loud blazars .. 100% (Padovani et al. 93, Steker & Salomon 96)
- Undetected γ-ray loud blazars …25% (Chiang & Mukherjee 98)
- IGM shock accelerated CR e$^-$ ... 75% (Loeb & Waxman 00)



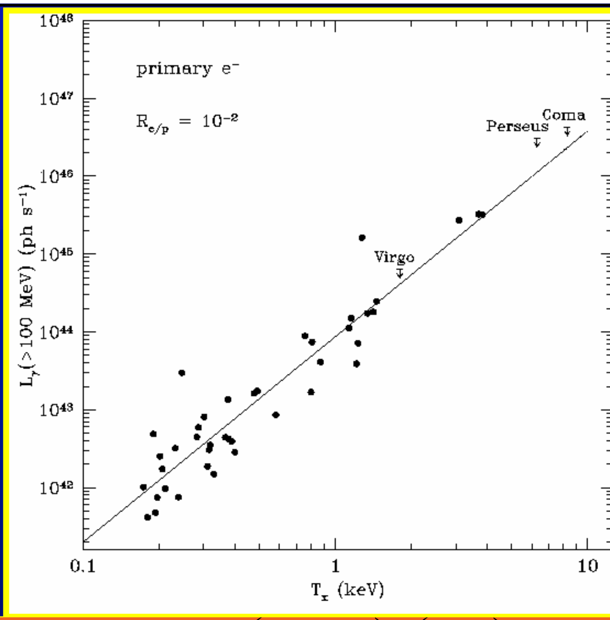
Data
(Sreekumar et al. 98)

Total
IC e$^-$
π^0-decay

IC e$^\pm$

Miniati 2002, MN
(astro-ph/0203014)

Miniati 2002, MN in press (astro-ph/0203014)



Upper limits from EGRET experiment (Reimer 1999; Sreekumar et al. 1996)

$$L_\gamma(>100\text{MeV}) = 8.7\times10^{43}\cdot\left(\frac{\eta}{4\times10^{-3}}\right)\cdot\left(\frac{T_x}{\text{keV}}\right)^{2.6}\ \text{ph s}^{-1}$$

Summary

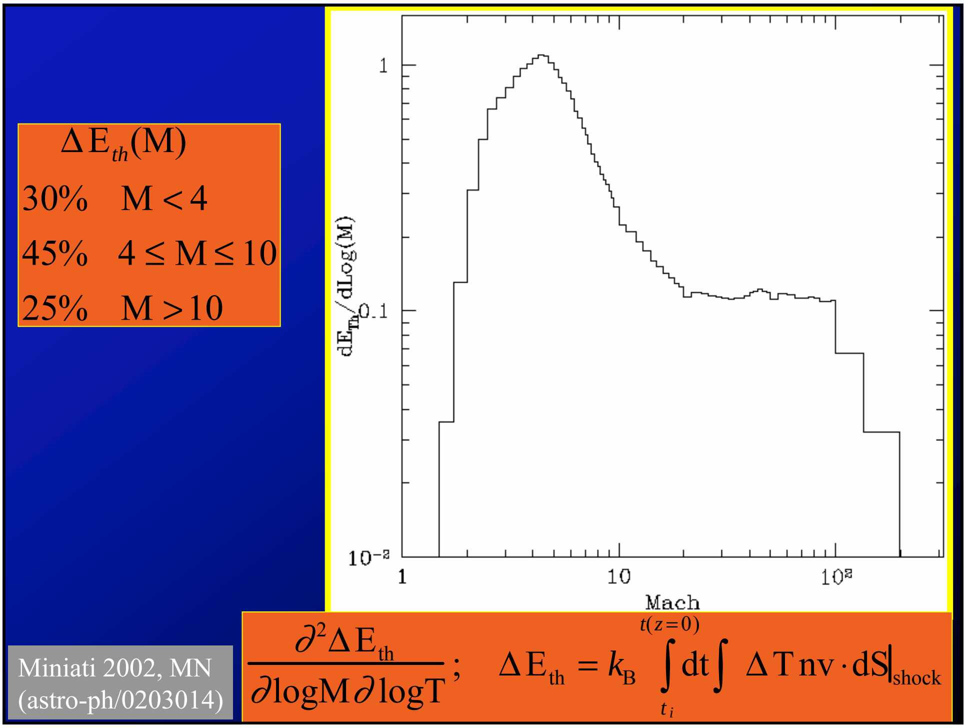
• Most effective shocks have 4<M<10 or so

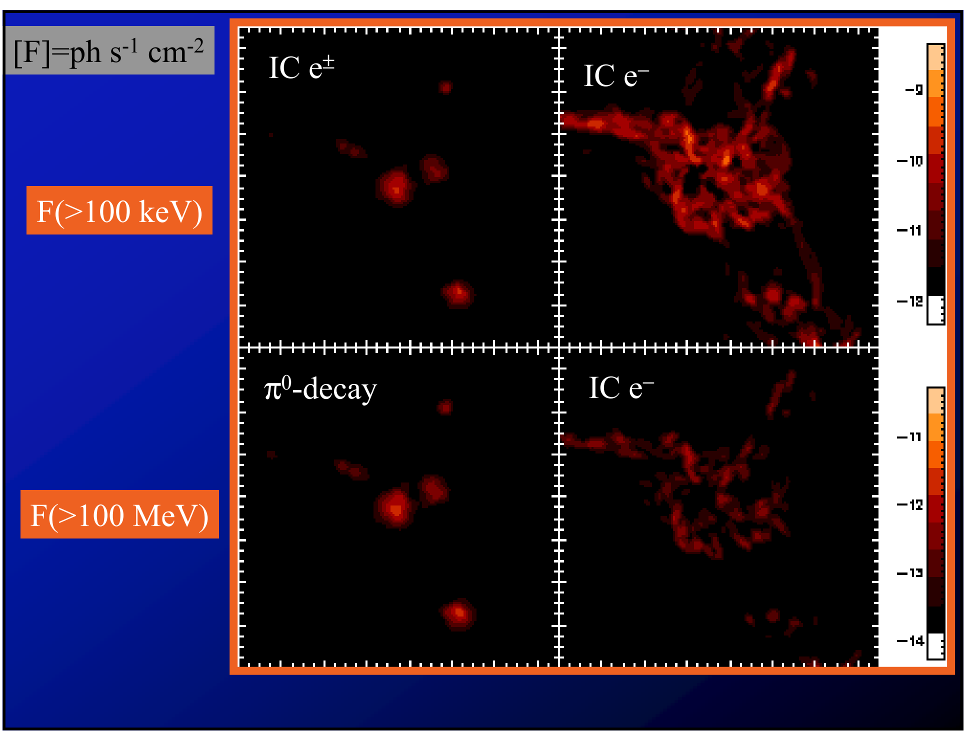
• CR ions might be dynamically important in the ICM

• HXR and γ-ray observations will help us better understand ICM physics but imaging capability is very important for a correct interpretation of the observational results.

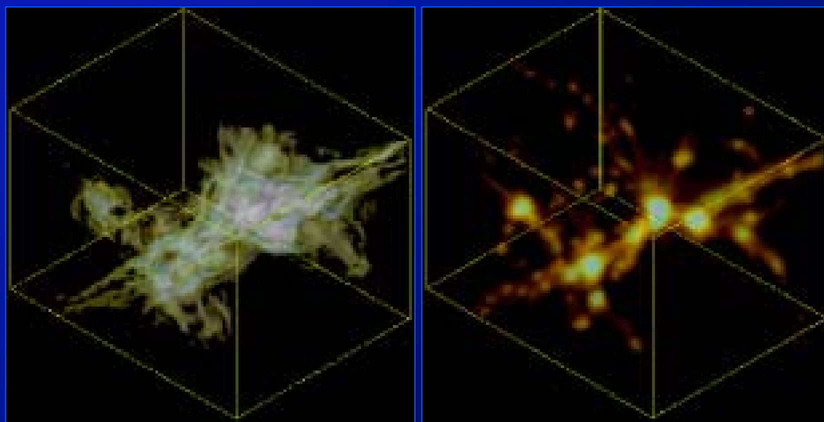
• EGRET experiment implies: $\eta_e \equiv \frac{P_{cre}}{\rho v_s^2} \leq 0.01$

• Cosmological CRs might contribute ~ 25% of the CGB (70% from CR e^- and 30% from CR p + $e^{\pm}$)


$\Delta E_{th}(M)$
30% $M < 4$
45% $4 \le M \le 10$
25% $M > 10$
$dE_{th}/dLog(M)$
1
0.1
10^{-2}
1
10
10^{2}
Mach
Miniati 2002, MN
(astro-ph/0203014)
$\frac{\partial^2 \Delta E_{th}}{\partial \log M \, \partial \log T}; \quad \Delta E_{th} = k_B \int_{t_i}^{t(z=0)} dt \int \Delta T \, nv \cdot dS|_{shock}$

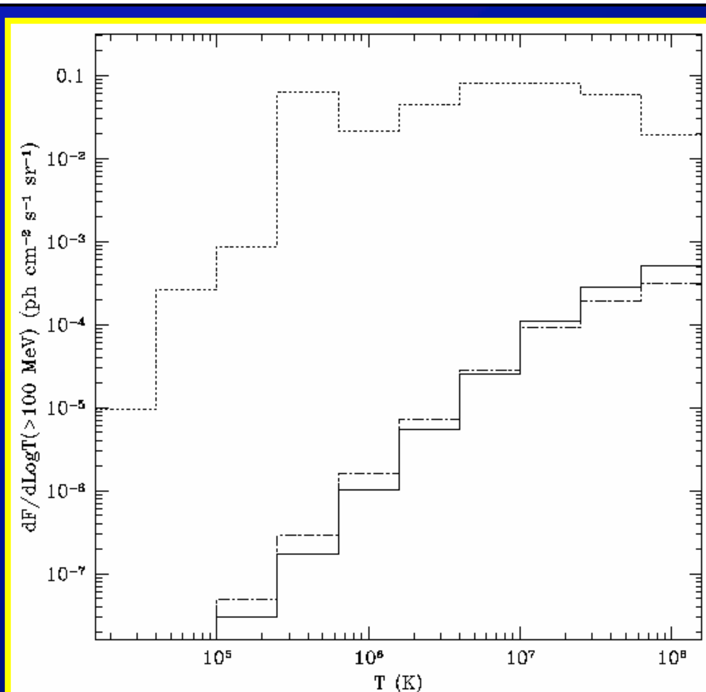

$[F]$=ph s^{-1} cm^{-2}
F(>100 keV)
F(>100 MeV)
IC $e^{\pm}$
IC e^{-}
π^0-decay
IC e^{-}
−9
−10
−11
−12
−11
−12
−13
−14

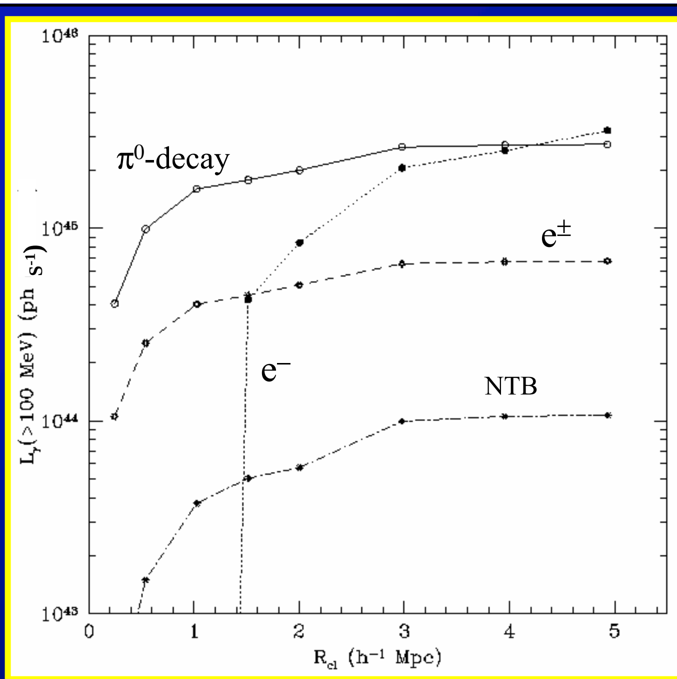
Properties of cosmic shocks

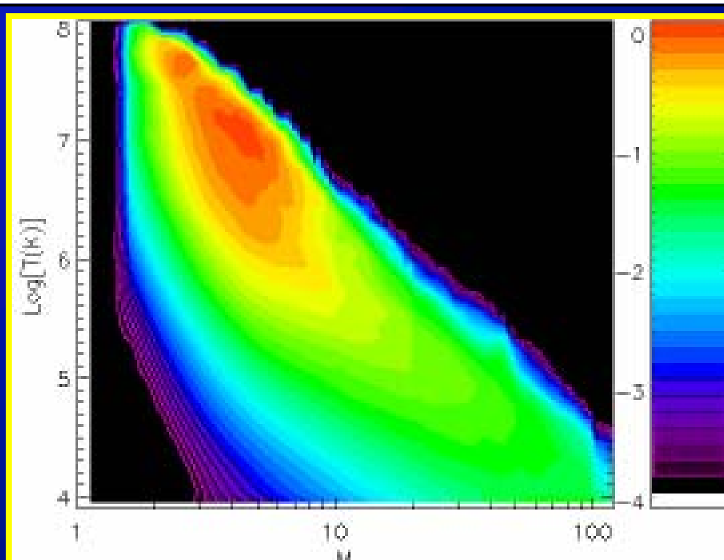


SCDM, L=80 Mpc, σ_8=1.05, n=1, N=270^3

Miniati, Ryu, Jones, Kang, Cen & Ostriker (2000, ApJ 542, 608)



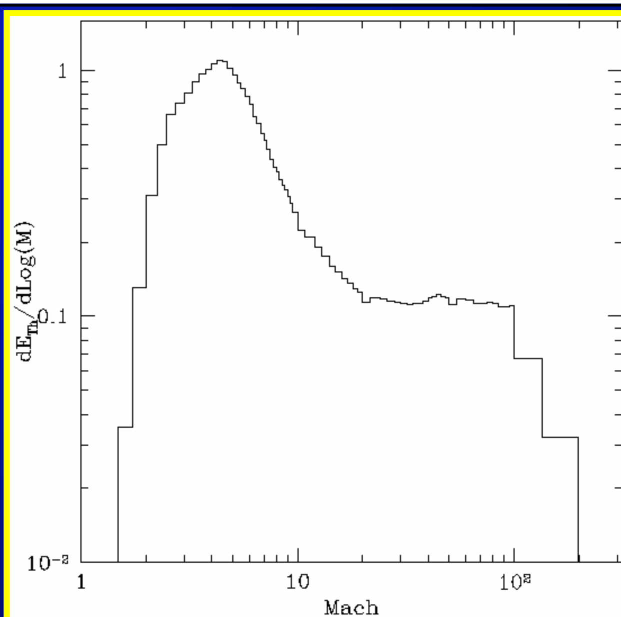




$$\frac{\partial^2 \Delta E_{th}}{\partial \log M \, \partial \log T}; \quad \Delta E_{th} = k_B \int_{t_i}^{t(z=0)} dt \int \Delta T \, nv \cdot dS \Big|_{shock}$$

Miniati 2002, MN
(astro-ph/0203014)

$\Delta E_{th}(M)$	
30%	$M < 4$
45%	$4 \le M \le 10$
25%	$M > 10$



$$\frac{\Delta T}{T} = \frac{[2\gamma_{gas}M^2 - (\gamma_{gas}-1)][(\gamma_{gas}-1)M^2+2]}{(\gamma_{gas}+1)^2 M^2} - 1$$

Injection

Based on the thermal leakage model of Kang & Jones (1995)

The post-shock gas is assumed to have nearly thermalized to a Maxwellian distribution with temperature T_{shock}
Then those particles with momentum above a threshold Value p_{inj} are injected in the acceleration mechanism

$$p \ge p_{inj} \equiv c_1 2\sqrt{m_p k_B T_{shock}}$$

$$c_1 \approx 2.6$$

…injection

$$\eta \equiv \frac{n_{inj}}{n_2} \cong 8\sqrt{2/\pi}\, c_1^3 e^{-2c_1^2} \approx 10^{-4}$$

The particles are injected as a power-law distribution in accord to the diffusive shock acceleration theory.

$$f(p) = f_{maxwell}(p_{inj})\left(\frac{p}{p_{inj}}\right)^{-q} \quad q = \frac{3r}{r-1} = \frac{4}{1-\frac{1}{M^2}}$$

$$\frac{P_{cr}}{\rho_1 u_1^2} \approx 10 - 30\ \% \quad \text{and} \leq 40\ \%$$

Motivation

Shock heating is an important process in cosmic structure formation.

•Most of the baryons in the local universe have been shock-heated to 10^5-10^7 K

•LSS most prominent in thermal X-ray from hot ICM

Astrophysical shocks are collision-less and can generate cosmic-ray (CR) distributions via 1st order Fermi acceleration mechanism (Axford et al. 1977, Krimsky 1977, Bell 1978a,b, Blandford & Ostriker 1978).

$$f(p) \propto p^{-q}; \quad q = \frac{3r}{r-1} = \frac{4}{1-\frac{1}{M^2}}$$

Test particle limit

e.g. ISM hosts copious CRs

- γ-ray emission across the disc + $e^{\pm}$
- Galactic radio halo from synchrotron emission
- CRs in rough equipartion with thermal and magnetic energy

$$F_{IC}^{\pm} \propto N_{e^{\pm}} \propto \frac{S_{syn}}{\langle B \rangle^{1+\alpha}}$$

$$N_{e^{\pm}} \propto \frac{N_{CRI} \langle \rho \rangle_{gas}}{1 + U_B / U_{CMB}}$$

$$F_{\pi^0 \to \gamma\gamma} \propto N_{CRI} \langle \rho \rangle_{gas} \propto S_{syn} \frac{1 + U_B / U_{CMB}}{\langle B \rangle^{1+\alpha}}$$

Time-scale for energy losses

$$\tau_{Coul} \approx 5\times10^{9}\left(\frac{\hat{p}}{0.1}\right)\left(\frac{n}{10^{-3}\,\mathrm{cm}^{-3}}\right)^{-1}\ \mathrm{yr}$$

$$\tau_{p-p} \approx 5.5\times10^{10}\left(\frac{n}{10^{-3}\,\mathrm{cm}^{-3}}\right)^{-1}\ \mathrm{yr}$$

Time-scale for diffusive escape

$$\tau_{esc} \approx 9\times10^{9}\left(\frac{\mathrm{R_{cl}}}{2\ \mathrm{Mpc}}\right)^{2}\left(\frac{E}{10^{15}\,\mathrm{eV}}\right)^{-1/3}\ \mathrm{yr}$$

…electrons injection

$$\frac{\mathrm{P_{cr}}}{\rho_1 \mathrm{u}_1^2} \le 40\ \%;\ \mathrm{R_{e/p}} = 10^{-2}$$

$$f(p) = f_{\mathrm{maxwell}}(p_{inj})\left(\frac{p}{p_{inj}}\right)^{-\mathrm{q}} \qquad \mathrm{q} = \frac{3\mathrm{r}}{\mathrm{r}-1} = \frac{4}{1-\frac{1}{\mathrm{M}^2}}$$

γ-ray background

$$\varepsilon^2 J(\varepsilon) = \frac{\varepsilon c}{4\pi \mathrm{H}_0}\int_0^{z_{\max}} \frac{e^{-\tau_{\gamma\gamma}}}{[\Omega_m(1+z)^3+\Omega_\Lambda]^{1/2}}\,\frac{j[\varepsilon(1+z),z]}{(1+z)^4}\,dz$$