Energetic Particles in Clusters of Galaxies and Starburst Galaxies

Heinz Völk, Max Planck Institute for Nuclear Physics
Heidelberg, Germany

Topics:

Production of Particles
Transport / Confinement
Observed Nonthermal Radiation
Interpretation
Future Gamma-Ray Perspectives

Starburst Galaxies:

External Galaxies should also produce CRs from sources similar to the Galaxy – **plus** possibly through other mechanisms, like overall accretion or an AGN.

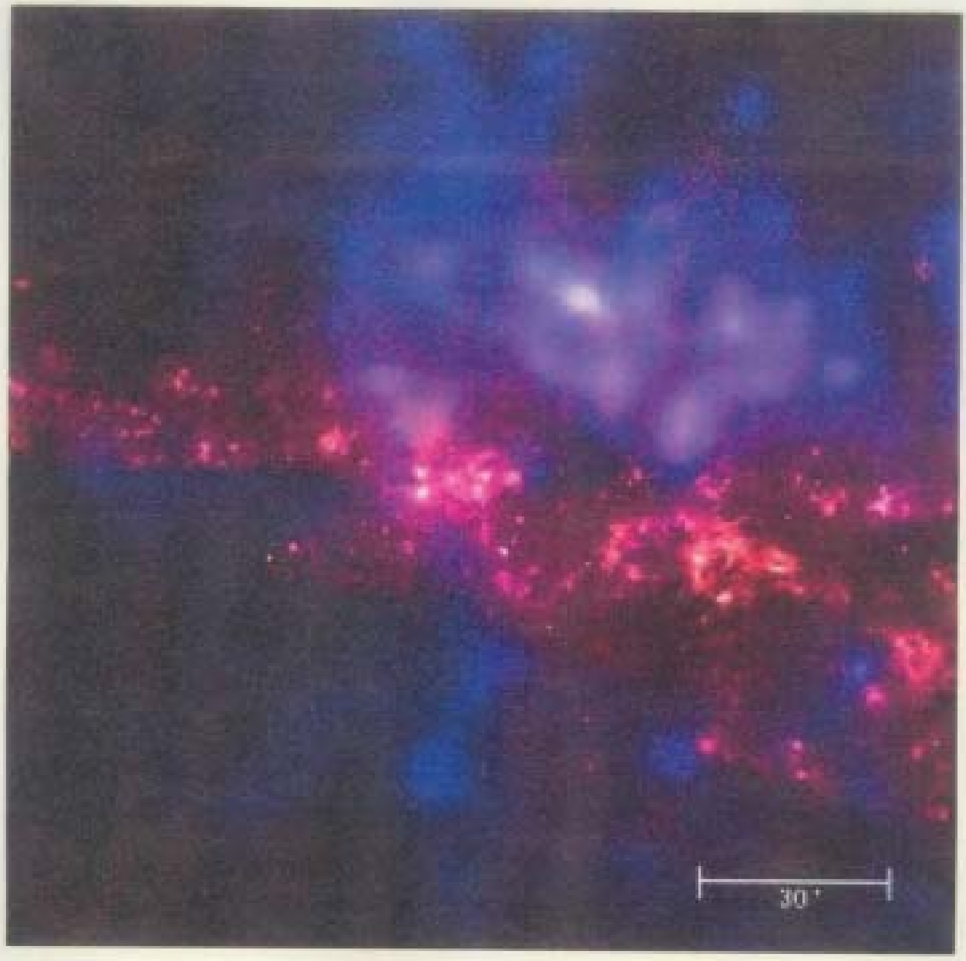
Starburst galaxies assumed to be **analogous** to Milky Way. **However**, significantly enhanced star formation rate (SFR). Assumed to result in higher CR production rate. Different form and strength of Galactic Wind.

Comparison with Galaxy important for:

1. **Contribution of recent SF** to CR production, compared to **other** processes (e.g. Central Black Hole, SN Ia [old stars], X-ray binaries from old component)

2. **CR propagation process** (convection vs. diffusion)

- **Universal CR origin ?** (Universal CR intensity ?)



Possible examples: M82 (North), NGC 253 (South)

Closest SB galaxies at distances of ~3.2 Mpc (M82), and ~2.5 Mpc (NGC 253).

NGC 253:

R.A.= 0h 47min 45.3sec

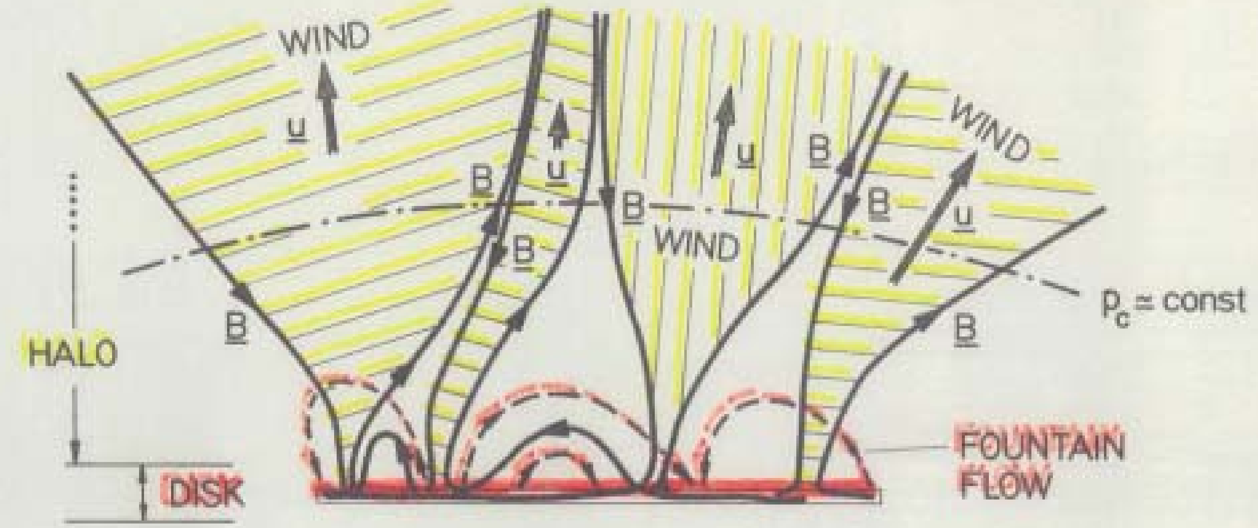
Declination = - 25 degrees 17' 18", for NGC 253

Projected optical size = 27.5' x 6.8' ➔ extended γ-ray source for < 6' resolution ? Starburst nucleus smaller.

SN rate: 0.1/yr to 0.3/yr; u_{CR} (NGC 253) ≅ 10 to 100 u_{CR} (Galaxy). Galactic Wind in thermal X-rays. High FIR flux.

(IC model: Goldshmidt & Rephaeli [1995, using LS wind model])

Analogous: IC 342, with R.A. 03h 42'; Dec. ~ 67 deg 56'; Incl'n ~ 25 deg?
(Böker et al. 1997)



75-90 MPI H

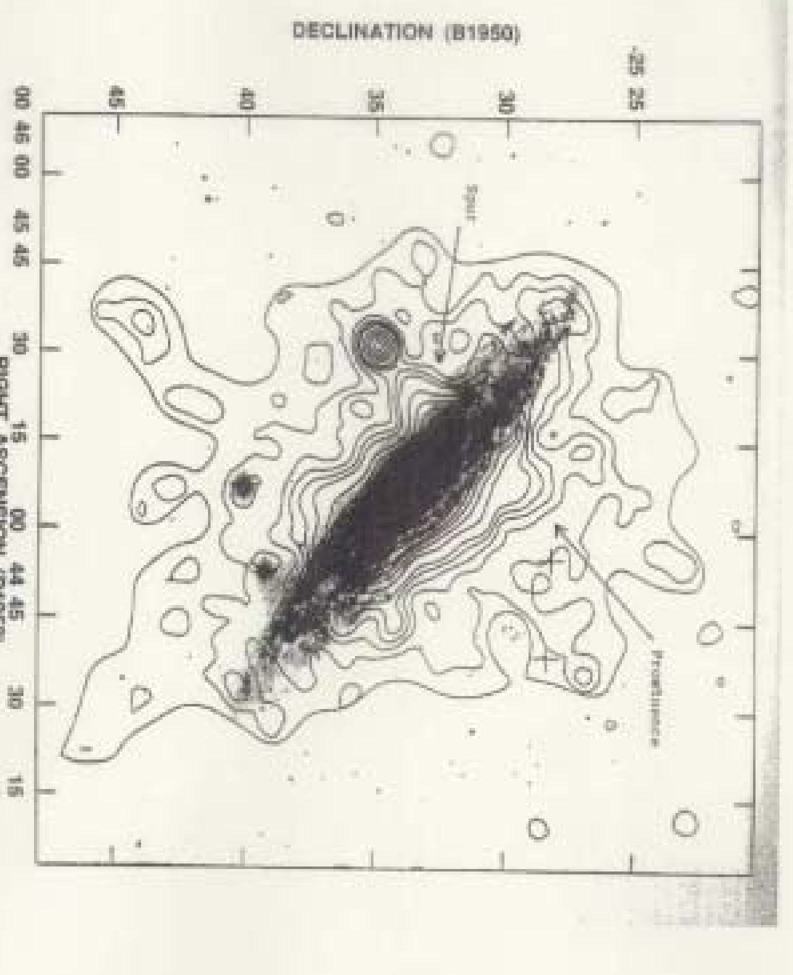
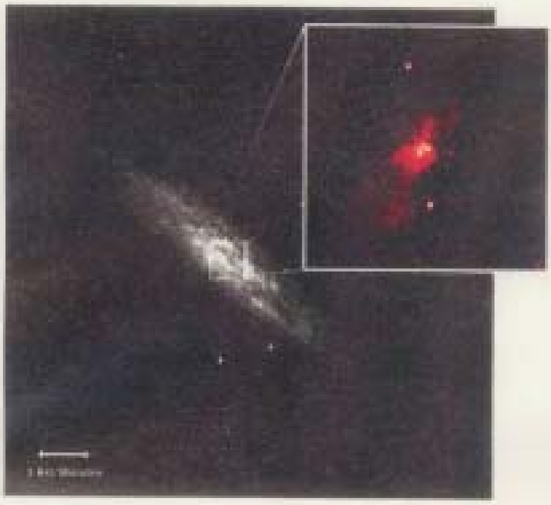


PLATE 13

CHANDRA pictures in hard X-rays

NGC 253



M82

M82:

High **radio synchrotron intensities** in central region (r = 300 pc; h = 100 pc). **Minimum energy** in CRs plus magnetic field ➔ CR energy density $u_{CR} \cong 80$ eV/cm^3 and $B^2/4\pi = u_B \cong 50$ μG. (Assumption e/p = 1/100)

100 times larger than in Galaxy (≅ 1 eV)

FIR radiation field (100 μm) equally strong: $u_{rad} \cong 200$ eV/cm^3 $\cong u_B$

Soft X-rays indicate fast wind v = few 1000 km/s

Mean (molecular) gas density in SB nucleus ≅ 140 H-atoms/cm^3

Supernova rate ≤ 1/(3 yr) ≤ 10 x Galactic SN rate ➔ **Convective escape, consistent with SNRs as sources for energetic particles:**
➔ **dE(CR)/dt = α ν(SN), α universal ?** (Völk et al. (1989)

Recently: Strong Chandra X-ray sources ! Slower wind ?

M82 in gamma rays ?

SB nucleus ≅ 40 arcsec (γ-ray point source)

Small hadronic γ-ray flux expected due to large distance (marginal for Northern instruments ?) :

$$F_\gamma (> 100 \text{ MeV}) = 1.3 \times 10^{-9} \text{ ph/cm}^2 \text{ sec;}$$

$$F_\gamma (>E) = 2.6 \times 10^{-13} (E / 1\text{TeV})^{-1.1} \text{ ph/cm}^2 \text{ sec}$$

Hard particle energy spectrum,at least towards cutoff, due to strongly convective transport (no escape softening) !

➔ IC flux perhaps higher: Even though both gas density (in SB nucleus) and target photon field ~ factor 100 larger than in Galaxy, larger IC emission volume in halo !

YET: Not detected by HEGRA CT-System in 35 hrs ! (< 0.02 Crab)

NGC 253 (Chandra)

Correlation of soft X-rays with Hα up to 10 kpc above disk: thermal wind ! dM/dt ~ 24 Solar masses
(Strickland et al. 2002)

Heavily absorbed source of hard X-rays in nuclear SB region (~300 pc radius; thickness ~ 150 pc). L(X) > L(Edd)[1.4 M(Sun)]
Intermediate mass BH ? Gamma-ray source? B ~ 0.3 mG
(Weaver et al. 2002)

NGC 253 in gamma rays ?

EGRET: Only upper limits (also M82)
OSSE (< 10 MeV): detected
TeV: Hadronic due to high B-field ?
But large halo volume!

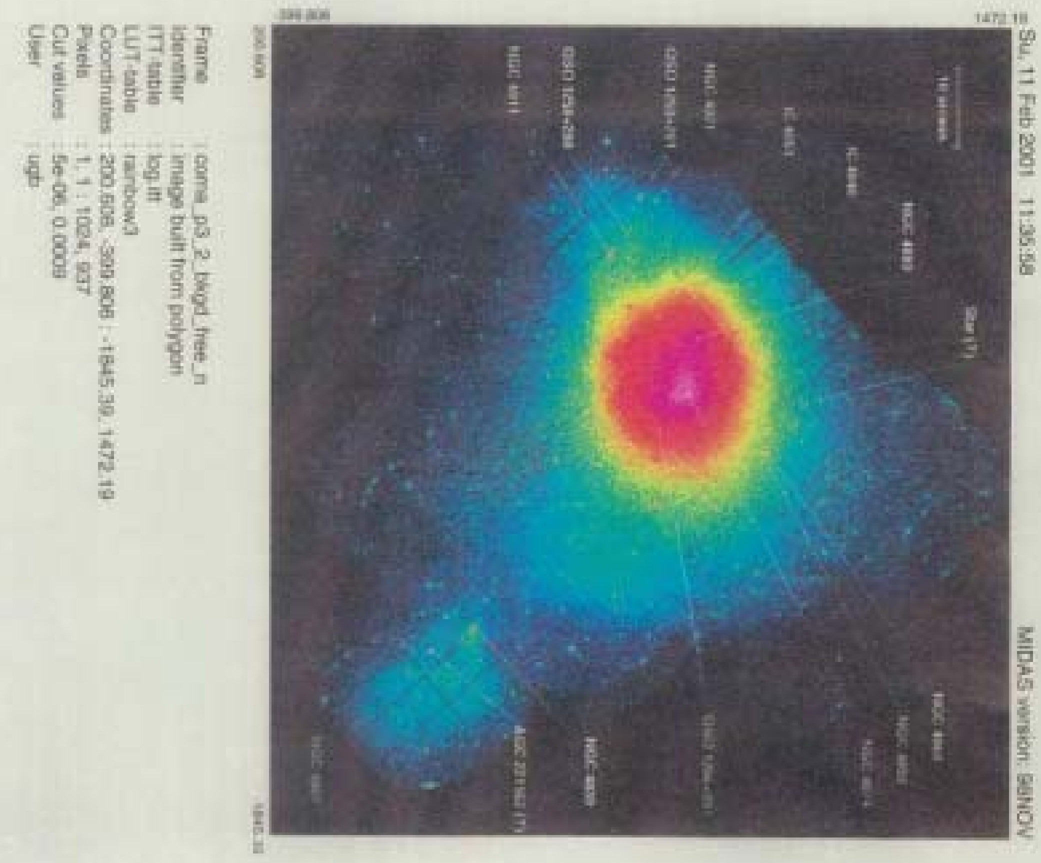
Clusters of Galaxies

- Largest gravitationally bound objects in the Universe. Mass dominated by the diffuse Intracluster gas by factor 3 to 5 compared to the galaxies (typically several 100 galaxies per cluster)
- Contain a representative sample of thermal matter in Universe ("Confinement")
  Typical gas temperatures = several keV.

Production of Particles; Transport / Confinement

Probably also confinement of nonthermal particles over a Hubble time ("Cosmological CRs") ➔ Entropy history of cluster formation.

From chemical abundances of IC gas (about 0.4 x Solar) huge amount of Star Formation/galaxy in clusters: must have happened in these constituent galaxies. Strong CR production in core collapse SNRs ? Removal and reacceleration in Galactic Winds to IC medium ?



Production of Particles, cont'd

Main particle energization is gravitational. Factor > 10

Extreme case: More or less mere adiabatic gravitational contraction after acceleration as a result of the SBs in galaxies (little additional entropy production). Unlikely, even though accretion shocks not strong!

Alternative: (Primary) particle acceleration also - or even dominantly - in (relatively weak) accretion shocks of subclusters onto the main cluster during ongoing cluster formation ?

Additionally: FRII-jet acceleration ?

Observed Nonthermal Radiation

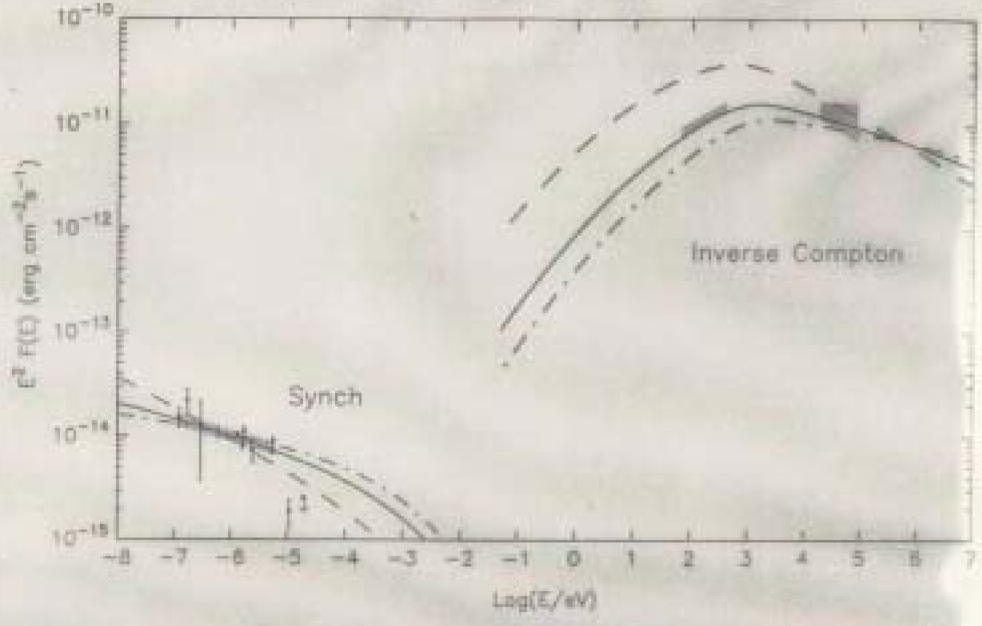
Observed low energy Synchrotron/IC emission testifies to recent acceleration: Radio "Halos", EUV excess, Nonthermal X-rays.

No high energy gamma-rays yet detected !

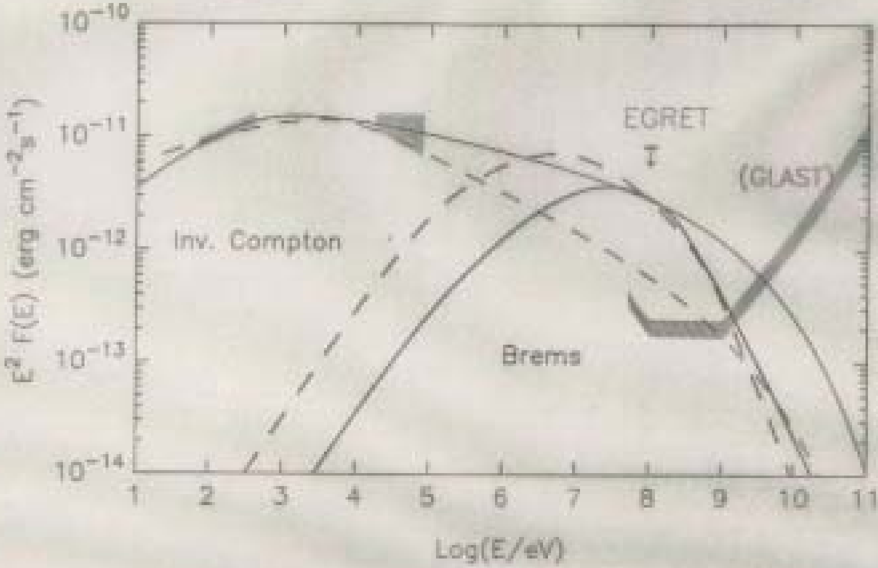
B-fields possibly large ~ microG, from galactic Winds ?
(Brecher & Burbidge 1972)

1) Radio synchrotron compatible with IC emission in radio and X - rays **for B ~ 0.1 microG**

Steady injection over last 3x10^9 yr.
Break between EUV and X-rays due to radiative losses



E² F(E) (erg cm⁻²s⁻¹)
Log(E/eV)
Synch
Inverse Compton



E² F(E) (erg cm⁻²s⁻¹)
Log(E/eV)
Inv. Compton
Brems
EGRET
(GLAST)

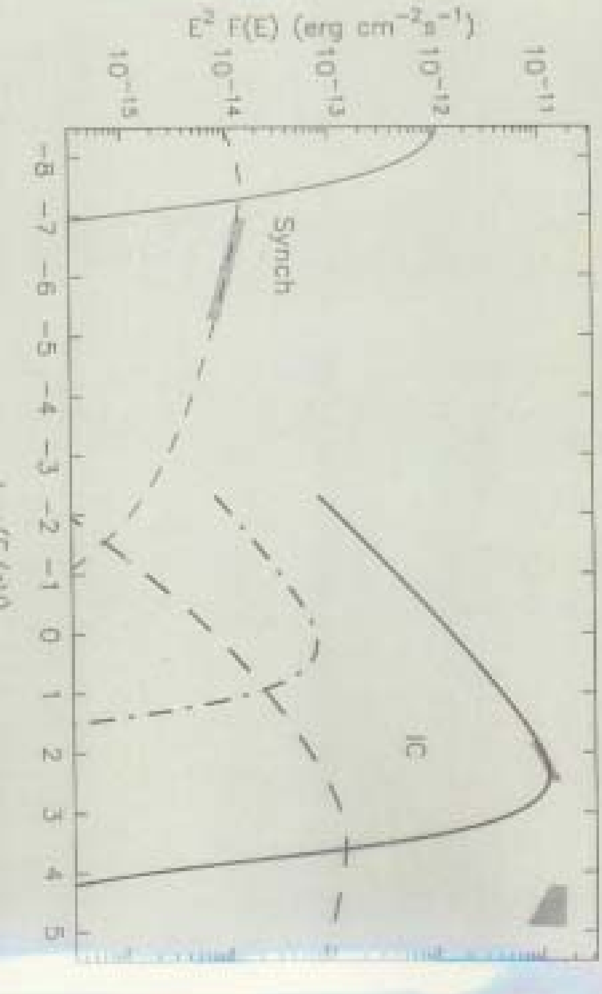
Observed Nonthermal Radiation, cont'd

2) Difficulty for high B-field ~ 1 microG:

No IC X-ray emission from radio electrons possible
(X-rays thermal (superhot component, Bremsstrahlung?)
(Sarazin & Lieu 1998; Atoyan & Völk 2000):

IC EUV possible from electron distribution with
γ(EUV) < γ(max) < γ (radio)

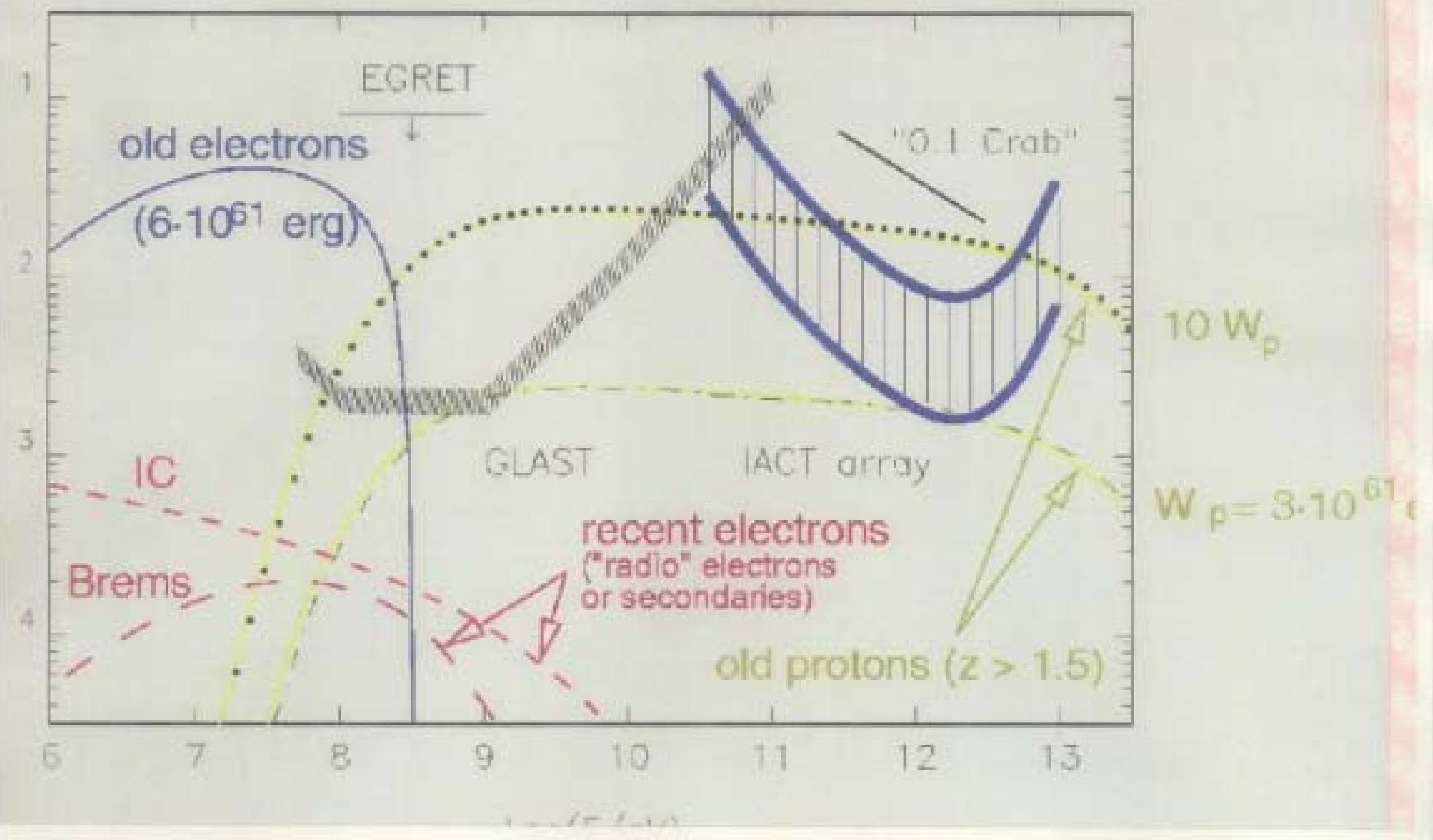
Due to "Old" electrons = cosmological electrons.
Sharp cutoff for E < 100 MeV.
Adiabatic compression during cluster contraction
Radio electrons separate component, continuously injected or due to secondaries.



Old electrons produce Bremsstrahlung up to 300 MeV.

Hadrons should contain large energy with hard spectrum (=source spectrum)

W(Protons) ~ 1/30 W (Gas) ~ 3x10^62 ergs



Future Gamma-Ray Perspectives

Depend strongly on source extension (> 1 degree extended)

Might be observable with GLAST (1yr)
HESS, CANGAROO, VERITAS, MAGIC in 50 h (5 sigma)

GLAST should see the "old" EUV electrons

Völk, Aharonian, Breitschwerdt (1996), Atoyan & Völk (2000), Miniati (2002)