

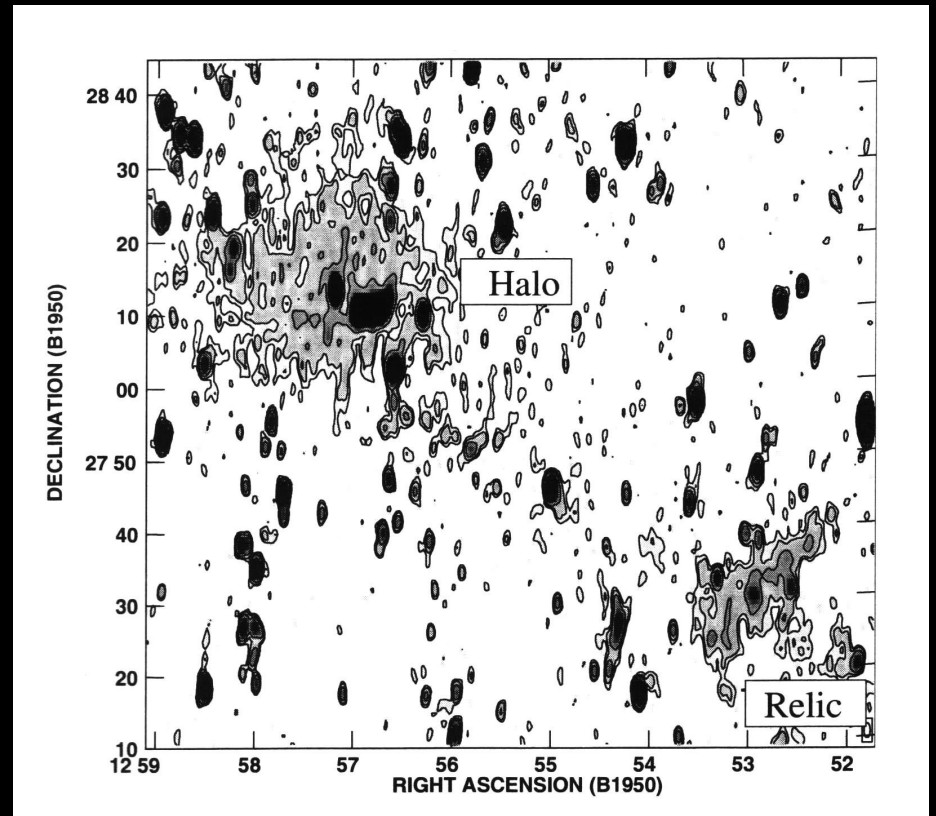
Particle reacceleration in the Coma Cluster*

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* Brunetti, Setti, Feretti, and Giovannini 2001

Radio Halo

- Radio Halo – existence of cluster magnetic fields and relativistic electrons.
- Relatively recent
 - Lifetime of relativistic electrons (due to Inverse Compton (IC) losses) – 10^{7-8} years
- Either freshly injected or reaccelerated electrons



Radio Emission of Coma C

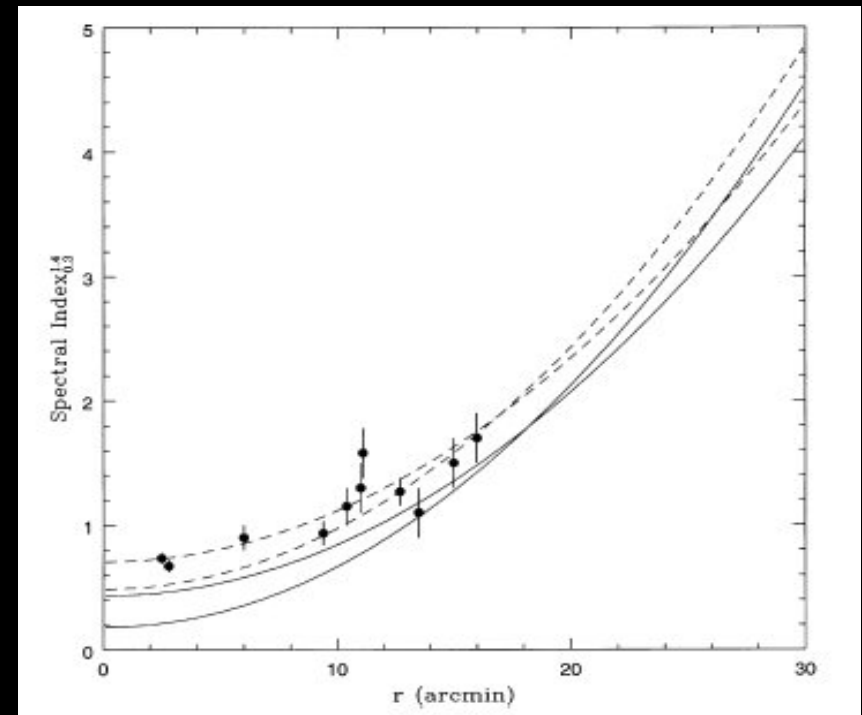
- Radio emission (at low frequencies) extends to ~ 30 - 40 arcmin from center
- Total radio spectrum is steep $\alpha \sim 1.2$ and it steepens rapidly from the center
 - Continuous injection of electrons may explain the total spectrum, but not the steepening with increasing radius.

Paper Objective

- Look at a two phase model to investigate:
 - Explain steepening with increasing radius
 - Effects of energy losses and reacceleration gains on energy distribution of the relativistic electrons
 - Obtain radial trend of magnetic field strength
 - Compare the derived IC emission with hard X-ray flux measured by BeppoSAX

Radio Spectral Steepening

- Solid lines – intrinsic
- Dashed lines – predicted observed
 - From Deiss et al. 1997
- Dots are from Giovannini et al. 1993 spectral map
- Steepening occurs at a distance from the center



Phase 1: Injection

- Injection in the past could be do to:
 - Starburst activity and violent galactic winds
 - AGN activity
- Both would create and inject relativistic electrons
- Also the ICM's high temperature could be do to a major merger, which could create shocks that heat the ICM and accelerate particles

Injection

- Start with kinetic equation to solve for particle energy distribution (N)

$$\frac{\partial N(\gamma, \theta, t)}{\partial t} = - \frac{\partial}{\partial \gamma} \left[\frac{d\gamma}{dt} N(\gamma, \theta, t) \right] + Q_{inj}(\gamma, \theta, t),$$

- Q is injection function
- Assume cooling is dominated by Coulomb(ξ) and radiation losses (ignoring relativistic bremsstrahlung).
- Cooling:
$$\frac{d\gamma}{dt} = -\xi - \beta(\theta, z)\gamma^2.$$

Injection

- Coulomb losses (depend on ICM density)

$$\xi \approx 1.2 \times 10^{-12} n \left[1 + \frac{\ln(\gamma/n)}{75} \right] \sim 1.4 \times 10^{-12} n \text{ s}^{-1},$$

- Radiation losses Coefficient($\beta(\theta, z)$)

$$\beta(\theta, z) = 1.9 \times 10^{-9} [B^2 \sin^2 \theta + B_{\text{IC}}^2(z)] \text{ s}^{-1},$$

Injection

- Assuming a time independent injection function $Q_{inj} = K_e \gamma^{-\delta}$

$$N(\gamma, \theta) = \frac{K_e}{\beta(\theta)(\delta - 1)} \gamma^{-\delta+1} \left[\gamma^2 + \frac{\xi}{\beta(\theta)} \right]^{-1},$$

- Goes as $\gamma^{-\delta+1}$ when dominated by Coulomb losses (low energies) and $\gamma^{-\delta-1}$ when dominated by radiation losses (higher energies)

Second Phase: Reacceleration

- When the injection of fresh particles stops the energy distribution rapidly steepens, and there are less high energy radio-emitting electrons.
- They assume reacceleration starts shortly after injection stops
- Could have been reaccelerated by merger (there have been mergers in Coma C history)

Reacceleration

- They calculate a typical break energy of γ_b of $10^4(B_{\mu\text{G}})^{-1/2}$ and a radiative lifetime T of $5 \times 10^{15} (B_{\mu\text{G}})^{1/2}$ for relatively weak magnetic fields.
- Reacceleration should balance radiation losses, giving a reacceleration efficiency:

$$\chi \sim 1/T \sim 2 \times 10^{-16} / \sqrt{B_{\mu\text{G}}} \text{ s}^{-1}$$

Evolution of Electrons and Synchrotron Spectra

- The time evolution of the electron energies:

$$\frac{d\gamma}{dt} = -\beta(\theta)\gamma^2 - \xi + \chi\gamma - \eta(\gamma)\gamma,$$

- They decide to ignore the bremsstrahlung losses since they are about 100 time less at typical cluster densities.

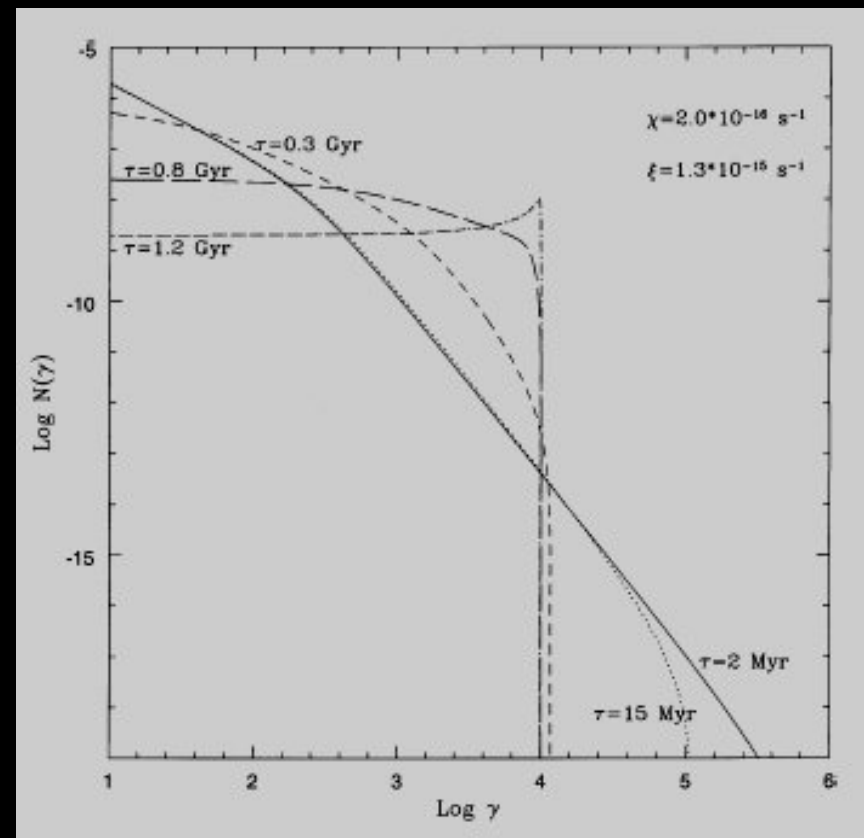
Ummm ok here it is

- The solution:

$$\begin{aligned} N(\gamma, \tau, \theta) &= \frac{K_e q(\theta)}{\delta - 1} \frac{[1 - \tanh^2(\tau\sqrt{q}/2)]\gamma^{-\delta+1}}{[2\gamma_b(\tau, \theta) \tanh(\tau\sqrt{q}/2)]^2 \beta^3(\theta)} \\ &\times \left[1 - \frac{\gamma}{\gamma_b(\tau, \theta)}\right]^{\delta-3} \left[1 + \frac{\xi\gamma^{-1} - \chi}{\gamma_b(\tau, \theta)\beta(\theta)}\right]^{-\delta+1} \\ &\times \left[\gamma^2 \left\{ \frac{1 + (\xi\gamma^{-1} - \chi)[\gamma_b(\tau, \theta)\beta(\theta)]^{-1}}{1 - \gamma/\gamma_b(\tau, \theta)} \right\}^2 + \frac{\xi}{\beta(\theta)}\right]^{-1}, \end{aligned}$$

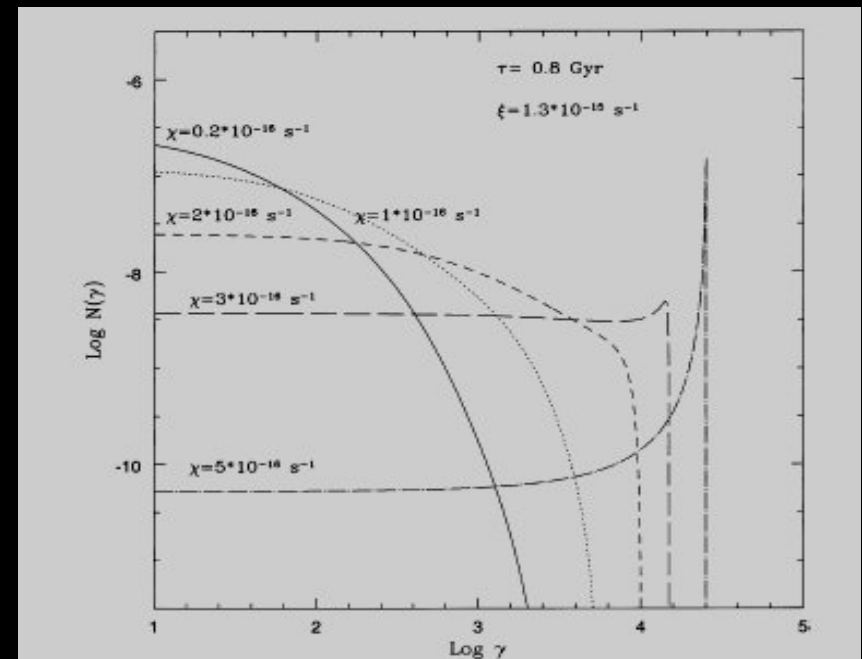
Energy Distribution evolution with time

- $\tau = t - t_i$
- Energy distribution vs. energy for 5 different times
- For a reacceleration efficiency $2.0 \times 10^{-16} \text{ s}^{-1}$ (reacceleration time of $1.6 \times 10^8 \text{ yrs}$)
- As time becomes larger than reacceleration time, the energy distribution flattens



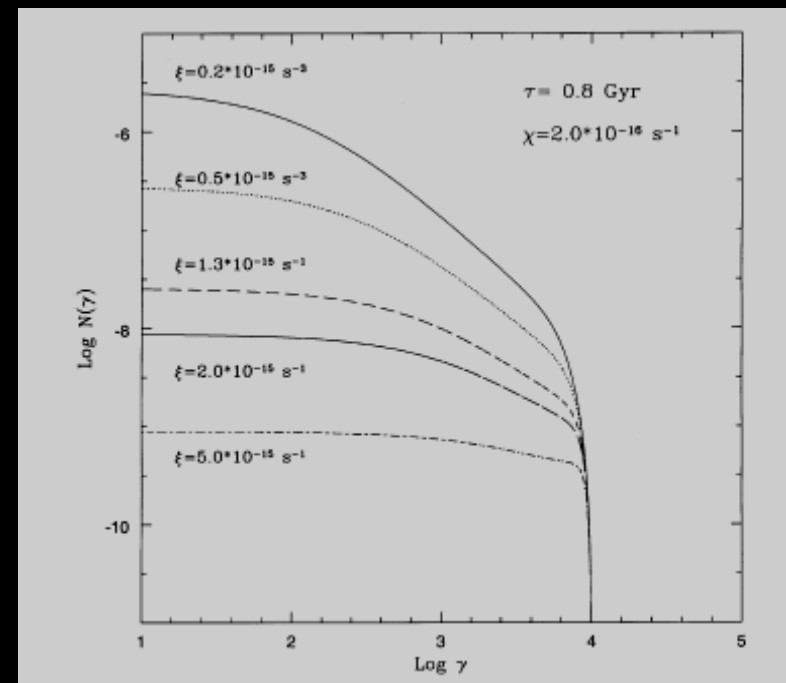
Reacceleration Efficiencies

- For $\tau=0.8\text{Gyr}$ 5 different reacceleration efficiencies
- Energy distribution flattens with increased reacceleration
- Also higher energy breaks



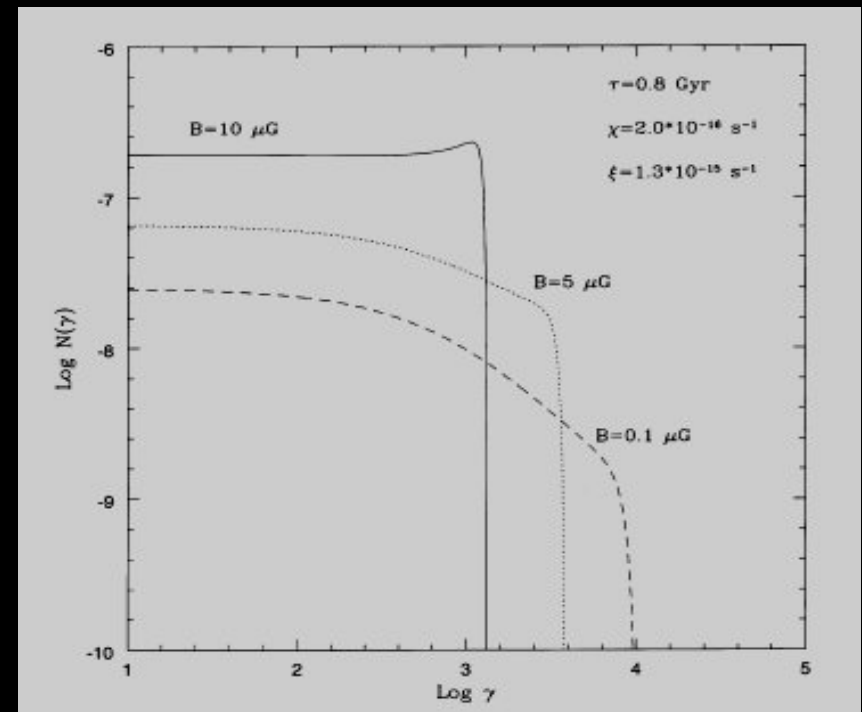
Coulomb Losses

- Increasing ξ is like increasing ICM density
- Increased ICM density/Coulomb losses causes greater flattening
- Since ICM density decreases with distance from center, the energy distribution is flatter near center



Magnetic Field

- Energy distribution flattens with increased B
- Lower energy breaks



More once again

■ Emissivity:

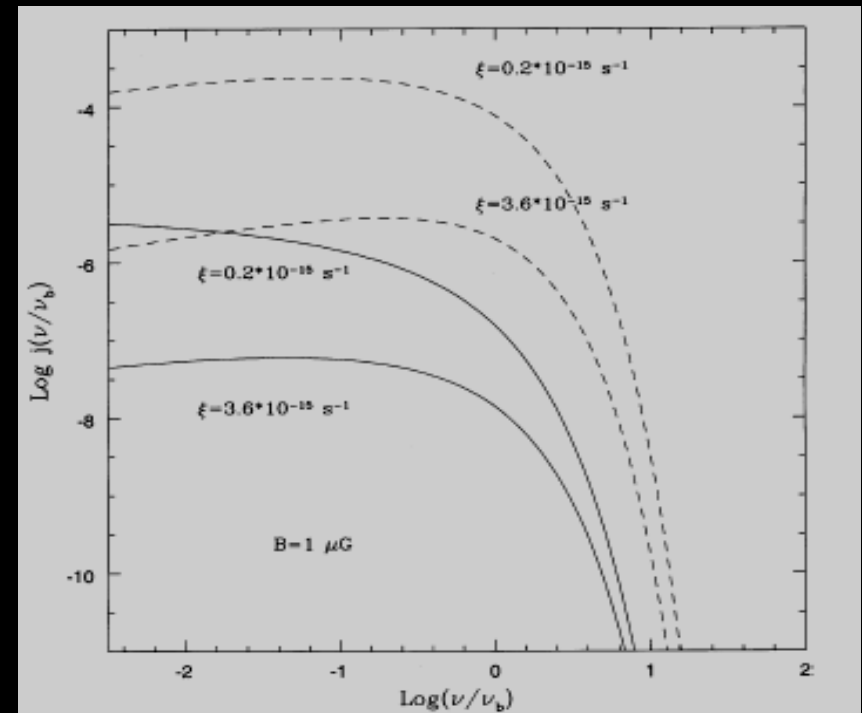
$$\begin{aligned} j\left(\frac{\nu}{\nu_b}, \tau\right) &= \frac{K_e}{\delta - 1} \frac{\sqrt{3}}{4} \frac{e^3}{mc^2} B \int_0^{\pi/2} d\theta \sin^2 \theta \phi(\theta) \\ &\times \int_0^1 du F\left(\frac{\nu/\nu_b}{u^2 \sin \theta}\right) (1 - u)^{\delta-3} u^{-\delta+1} \\ &\times \left[1 + \frac{\xi u^{-1} - \chi \gamma_b(\theta)}{\beta(\theta) \gamma_b^2(\theta)} \right]^{-\delta+1} \\ &\times \left[u^2 \left\{ \frac{1 + [\xi u^{-1} - \chi \gamma_b(\theta)] / [\gamma_b^2(\theta) \beta(\theta)]}{1 - u} \right\}^2 \right. \\ &\left. + \frac{\xi}{\beta(\theta) \gamma_b^2(\theta)} \right]^{-1} \end{aligned}$$

Importance of Radius from Center

- IC losses are constant throughout cluster
- Magnetic Field lessens with r
- Coulomb losses also depend on r
- This means the energy distribution also varies with r

Synchrotron Spectrum

- Used $B = 1 \mu\text{G}$ and $\tau = 0.8 \text{ Gyr}$, which are typical for Coma Cluster center
- Solid lines are for $\chi = 2.5 \times 10^{-16} \text{ s}^{-1}$
- Dashed lines are $\chi = 4.2 \times 10^{-16} \text{ s}^{-1}$



More Equations

- β -model for Coulomb losses:

$$\xi(r) = 4.2 \times 10^{-15} \left[1 + \left(\frac{r}{R_C} \right)^2 \right]^{-3\beta/2}$$

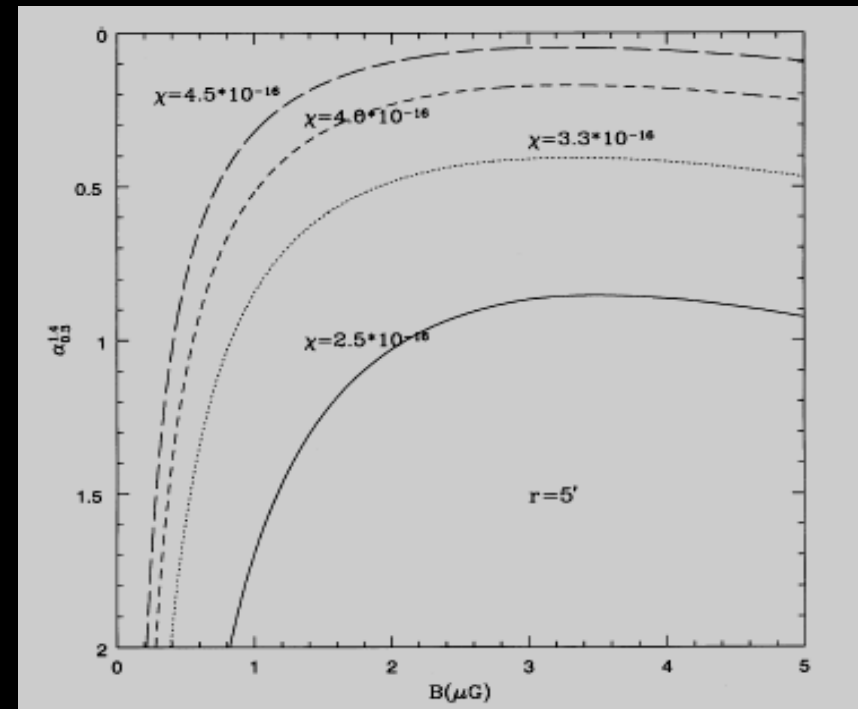
- For Coma $R_C=10.5$ arcmin and $\beta=0.75$
- Reacceleration efficiency is sum of large scale and small scale components:

$$\chi(r) = \chi_{LS} + \chi_{G0} \left[1 + \left(\frac{r}{R_G} \right)^2 \right]^{-\alpha_G/3}$$

- $R_G=5.5$ arcmin and $\alpha_G=0.8$

Spectral Index

- Calculated intrinsic spectral index as a function of magnetic field for different reacceleration efficiencies
- Small magnetic fields have steep spectral index
- Near center magnetic field depends on both χ_{LS} and χ_G , but further away from center it only depends on χ_{LS}

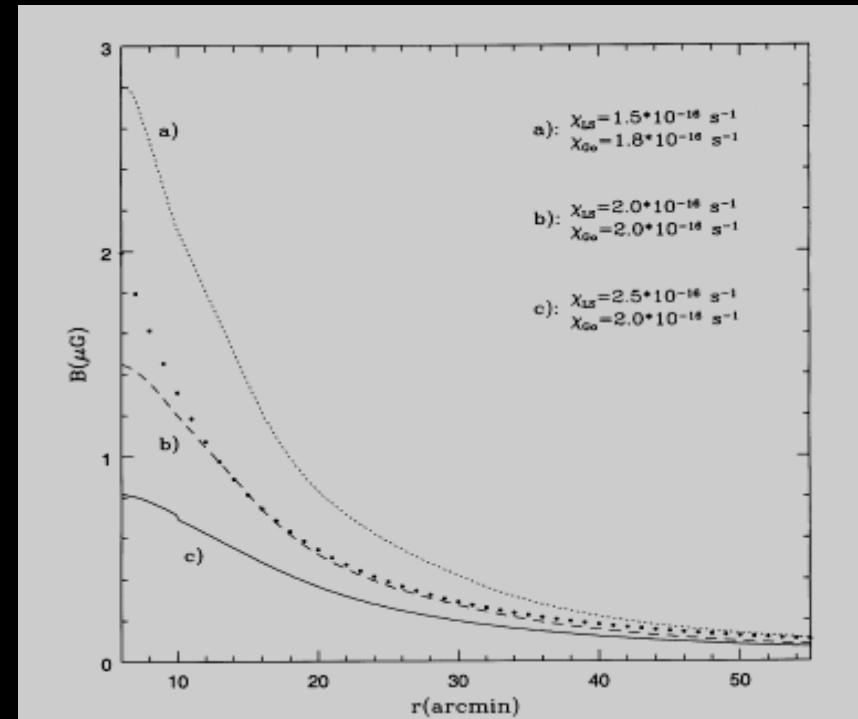


Some Bounds

- For a spectral index of 0.5:
 - Lower bound of reacceleration efficiency:
 - $\chi(0) = 3.3 \times 10^{-16} \text{ s}^{-1}$
 - Upper magnetic field:
 - $B(0) \sim 3 \mu\text{G}$
 - Some other measurements:
 - Kim et al. 1990 : $B = (1.7 \pm 0.9) \mu\text{G}$ in center
 - Feretti et al. 1995 $B \sim 6 \mu\text{G}$ near NGC 4869

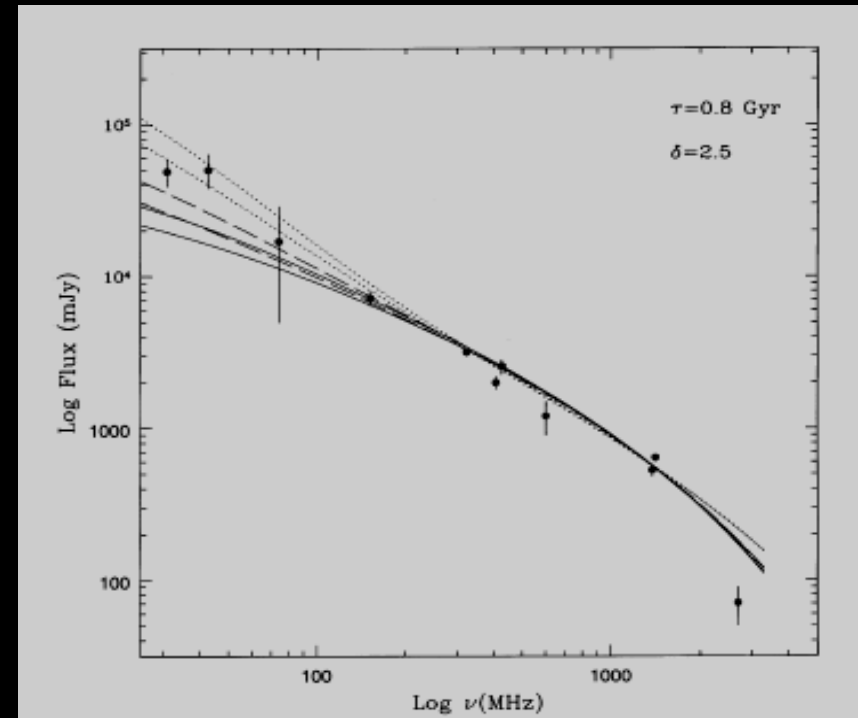
Magnetic Fields

- B distribution required to match spectral observations in model
- Dots are predictions by Jaffe 1980.
- At large distance only χ_{LS} matters



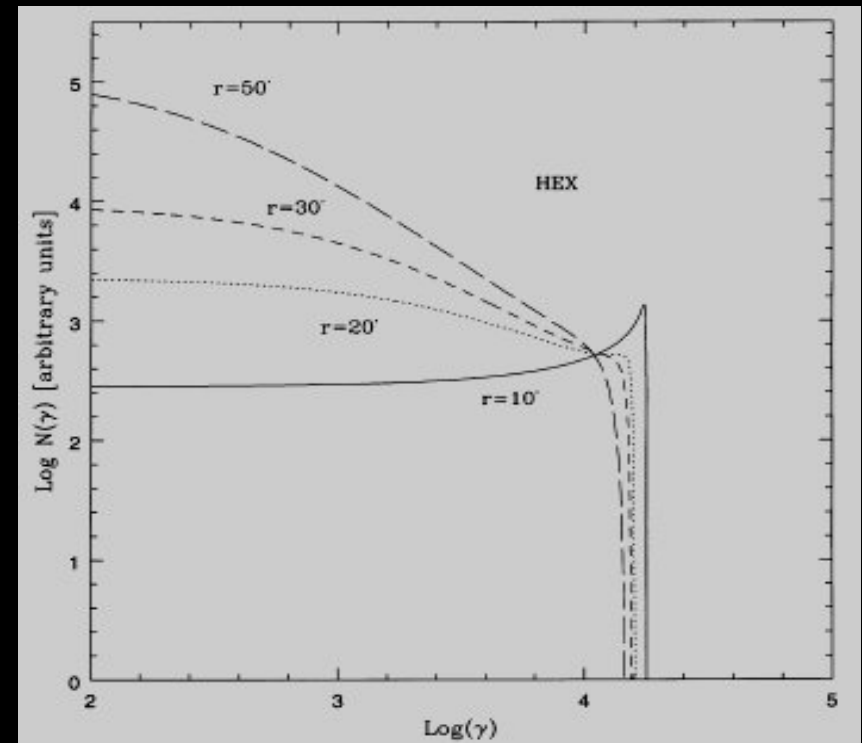
Synchrotron spectrum

- They integrated the synchrotron emissivity, considering those parameters that vary with r
- For different models from previous figure, compared to the data for total synchrotron emission



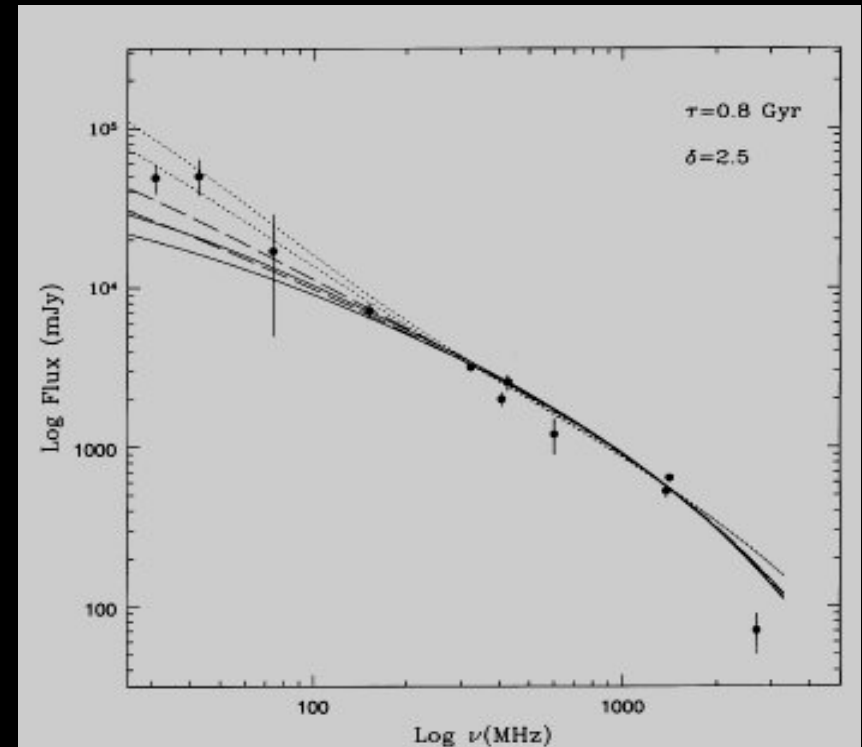
Effect of Radius

- Energy distribution at different radii from the cluster center
- More flattened and higher break energy closer to the center



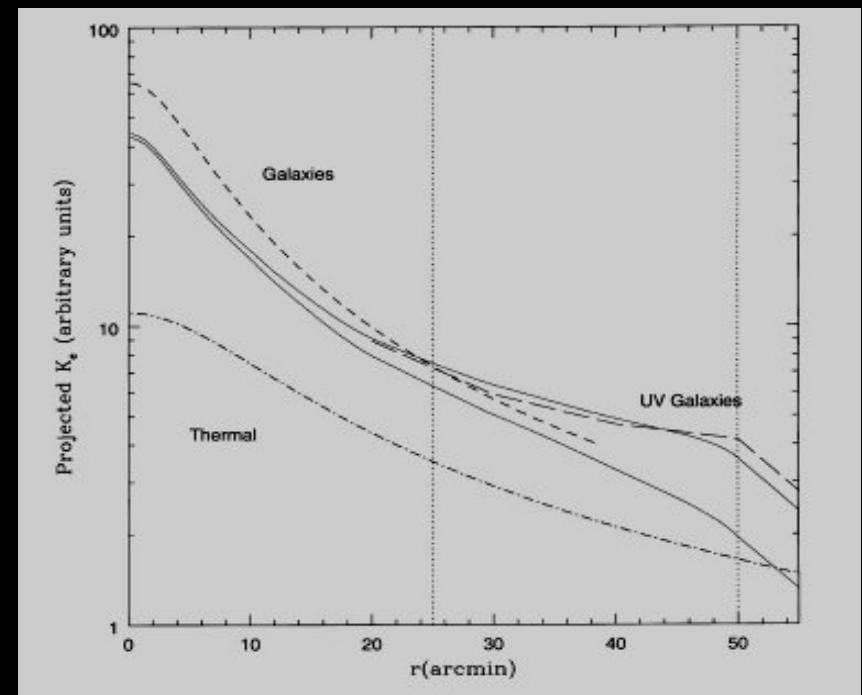
Bounding Reacceleration Efficiency

- For the dotted lines (model a) they overpredict observations and model c, solid lines, underpredict.
- So a good range for the large scale reacceleration efficiency is :
- $1.5 \times 10^{-16} < \chi < 3.0 \times 10^{-16}$



Injection Rate

- The shape of the injection rate of the relic electron population ($K_e(r)$)
- For the first phase = solid lines (for model c)
- Vertical dotted lines bound region where 80-90% of IC Xray flux from second phase occurs
- Dashed lines are predicts from Girardi et al. 1995



Total Energy

- For $\chi = 3.0 \times 10^{-16} \text{ s}^{-1}$ the total energy of relativistic electrons is 10^{59} erg.
- This is smaller (by about 10) than other models
- The flat electron energy spectrum is more efficient in emitting synchrotron radiation at radio wavelengths.

Hard X-Ray Tail

- BeppoSAX found a hard X-ray tail, in the range of 20-80 keV, which was confirmed by RXTE.
- Origin is not well established
 - Could be IC scattering of radio-emitting electrons with CMB photons
 - Also could be relativistic bremsstrahlung
 - Or thermal emission of a modified Maxwellian distribution of hot ICM induced by acceleration
- IC origin could allow a measurement of magnetic field strengths, but their model doesn't allow for this (cant use for whole volume because of reliance on r)

IC Scattering

- Since IC scattering is only sensitive to number of electrons, the majority of the scattering will be at $r > 30$ arcmin
- Models with a relatively high reacceleration efficiency can account for most or all of the X-ray flux.

Review

- Two-phase model can explain the observed radio properties of Coma C
 - Injection of electrons continuously at first
 - Reaccelerated for a typical duration of ~ 1 Gyr
- Reacceleration efficiency should be about $2 \times 10^{-16} \text{ s}^{-1}$ for a reacceleration time of about 0.6 Gyr

Assumptions

- Assumptions used in the model:
 - The brightness distributions at 327 and 1400 MHz are describe as the sum of two Gaussians
 - The Coulomb losses are fixed by a β model
 - Reacceleration efficiency is sum of a large scale and small scale part
 - The relic electron population is allowed to evolve, subject to radiation and Coulomb losses for 0.8 Gyr

Results

- The electron energy distribution depends on r
 - Higher energy break and flatter near center
 - Higher B and χ near center as well
- Using spectral index of 0.5
 - $B \sim 3 \mu\text{G}$
 - Lower bound $\chi = 3.3 \times 10^{-16} \text{ s}^{-1}$

Results

- At center, if B is at least $1\mu\text{G}$ upper limit to reacceleration efficiency at $5 \times 10^{-16} \text{ s}^{-1}$
- Magnetic field goes from $1\text{-}3\mu\text{G}$ at cent to $0.05 - 0.1 \mu\text{G}$ at $r \sim 50$ arcmin from center
- X-rays produced by IC scattering can account for hard X-ray Tail

Want more equations?

- Check out the appendix

$$\begin{aligned}
 N(\gamma, \tau, \theta) &= \frac{q(\theta)K_e}{4} \frac{1 - \tanh^{-2}(x)}{\beta^3(\theta)\gamma_b^2(\theta)} \frac{1 + \tan^2[\sqrt{\beta(\theta)}\xi\Delta t]}{\delta - 1} \\
 &\times \left[1 - \frac{\gamma\mathcal{L}(\theta)}{\gamma_{b,1}} \right]^{\delta-1} \\
 &\times \left\{ 1 + \left[\frac{1 - \gamma\mathcal{L}(\theta)/\gamma_{b,1}}{\gamma\mathcal{L}(\theta) + \frac{\xi}{\beta(\theta)\gamma_{b,1}}} \right]^2 \frac{\xi}{\beta(\theta)} \right\}^{-1} \\
 &\times \left[\gamma\mathcal{L}(\theta) + \frac{\xi}{\beta(\theta)\gamma_{b,1}} \right]^{-(\delta+1)} [1 - \gamma/\gamma_b(\theta)]^{-2},
 \end{aligned}$$

$$\tau = \begin{cases} q < 0 \Rightarrow \\ \frac{2}{\sqrt{-q}} \left[\tan^{-1} \frac{\chi - 2\xi\gamma(\tau)}{\sqrt{-q}} - \tan^{-1} \frac{\chi - 2\xi\gamma(\Delta t)}{\sqrt{-q}} \right] \\ q > 0 \Rightarrow \\ \frac{-2}{\sqrt{q}} \left[\tanh^{-1} \frac{\chi - 2\xi\gamma(\tau)}{\sqrt{q}} - \tanh^{-1} \frac{\chi - 2\xi\gamma(\Delta t)}{\sqrt{q}} \right], \end{cases}$$

$$\gamma_b(\tau, \theta) = \begin{cases} q < 0 \Rightarrow \\ \sqrt{-q} [2\xi \tan(x)]^{-1} + \chi/2\xi \\ q > 0 \Rightarrow \\ [\chi + \sqrt{q}/\tanh(x)][2\beta(\theta)]^{-1}. \end{cases}$$