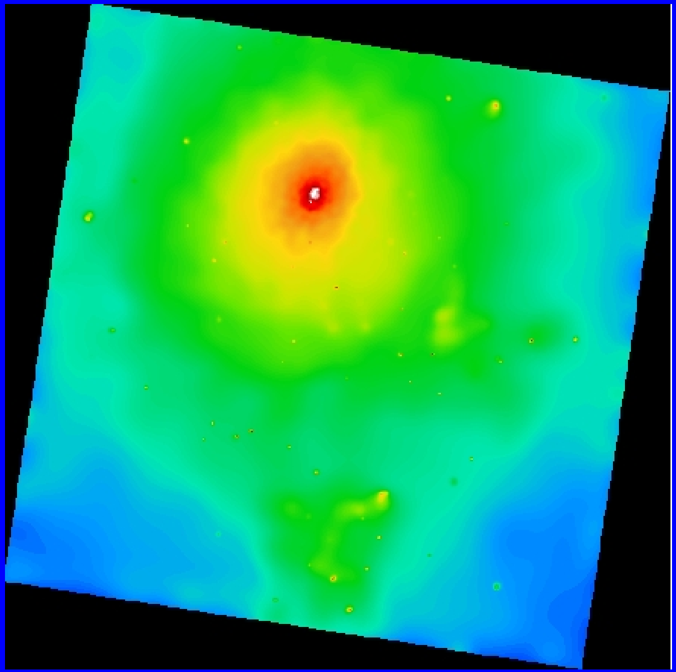
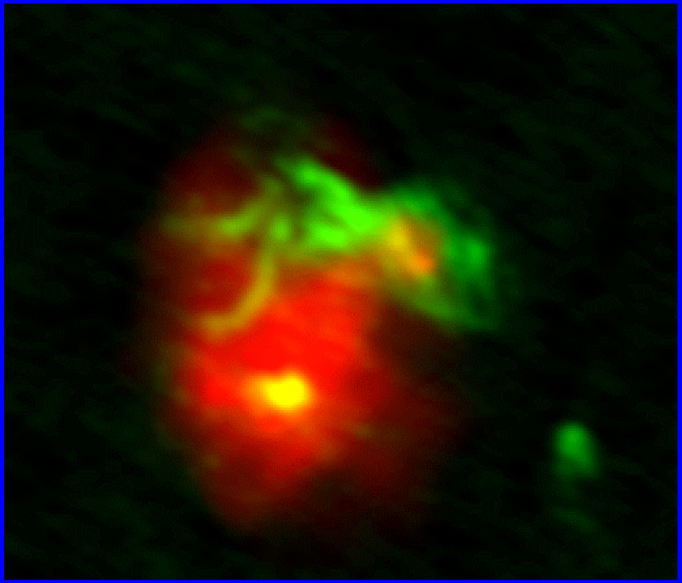
Mergers and Non-Thermal Processes in Clusters of Galaxies



A85 Chandra

Craig Sarazin
University of Virginia



A133 Chandra and VLA

Collaborators

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Paul Ricker (U. Ill.)

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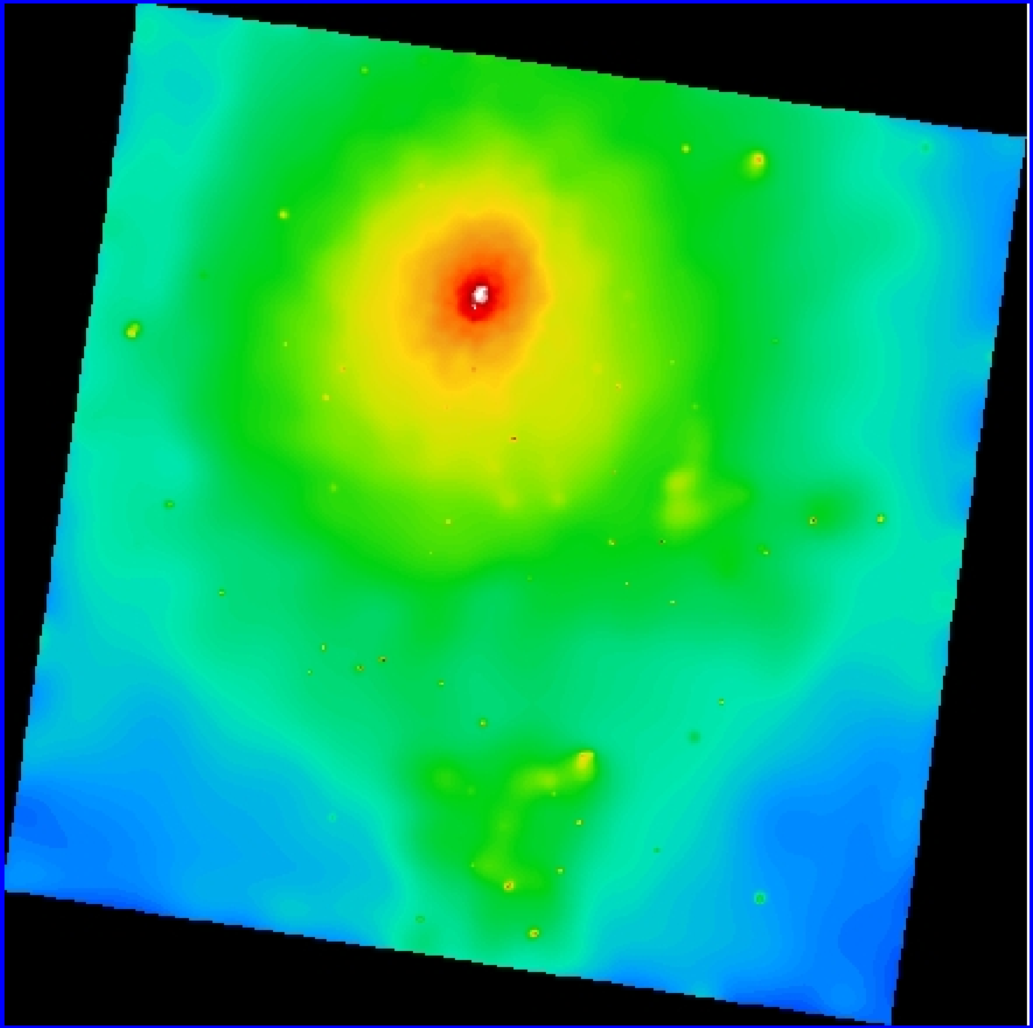
Cluster Mergers

- Clusters form hierarchically

→ Major cluster mergers are most energetic events in Universe since Big Bang

- Major cluster mergers, two subclusters, $\sim 10^{15}\ M_{\odot}$ collide at ~ 2000 km/s
- E (merger) ~ 2×10^{64} ergs
- E (shocks in gas) ~ 3×10^{63} ergs

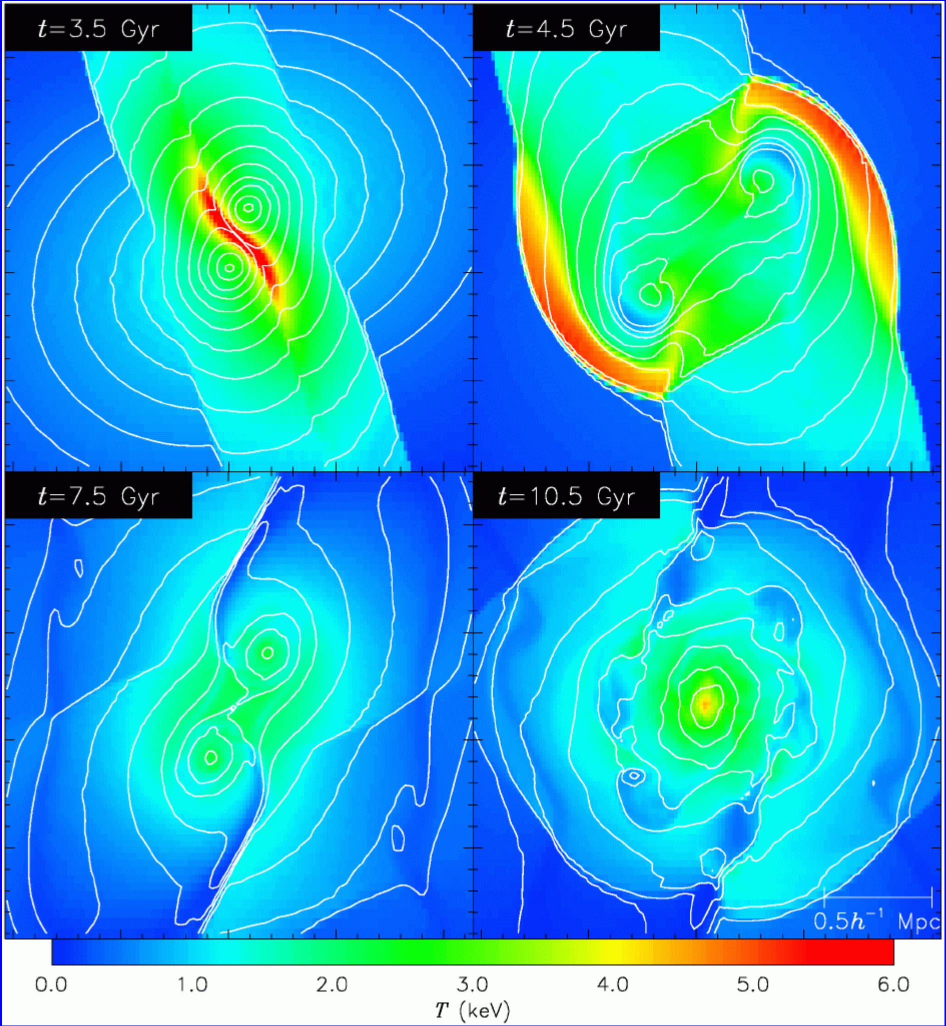
Abell 85 Merger



Chandra X-ray Image
Kempner et al.

Merger Shocks

- Typical shock velocity 2000 km/s
- E (shock) ~ 3 x 10^{63} ergs
- Main heating mechanism of intracluster gas



Ricker & Sarazin

Thermal Effects of Mergers

- Heat and compress ICM
- Increase entropy of gas
- Increase X-ray luminosity, temperature, SZ effect
- Mix gas
- Disrupt cool cores
- Provide diagnostics of merger kinematics

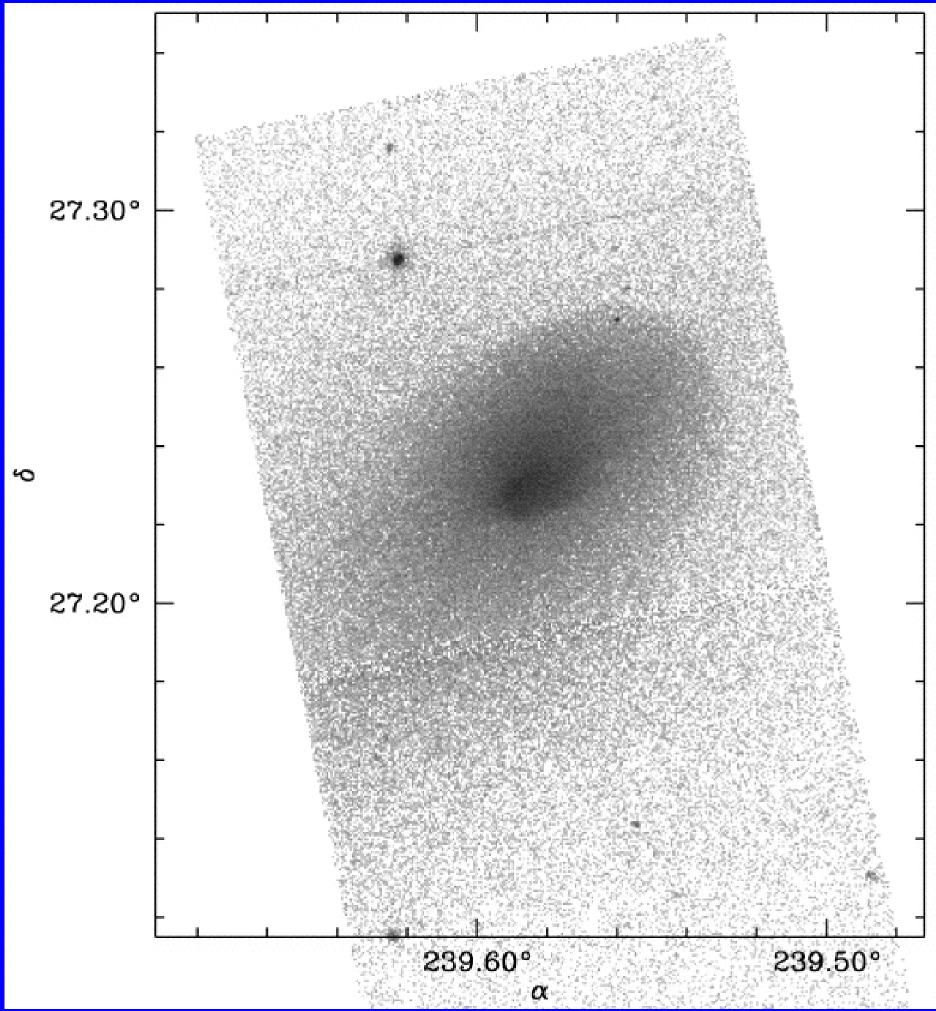
Chandra
"Cold Fronts" in Mergers

Merger shocks?

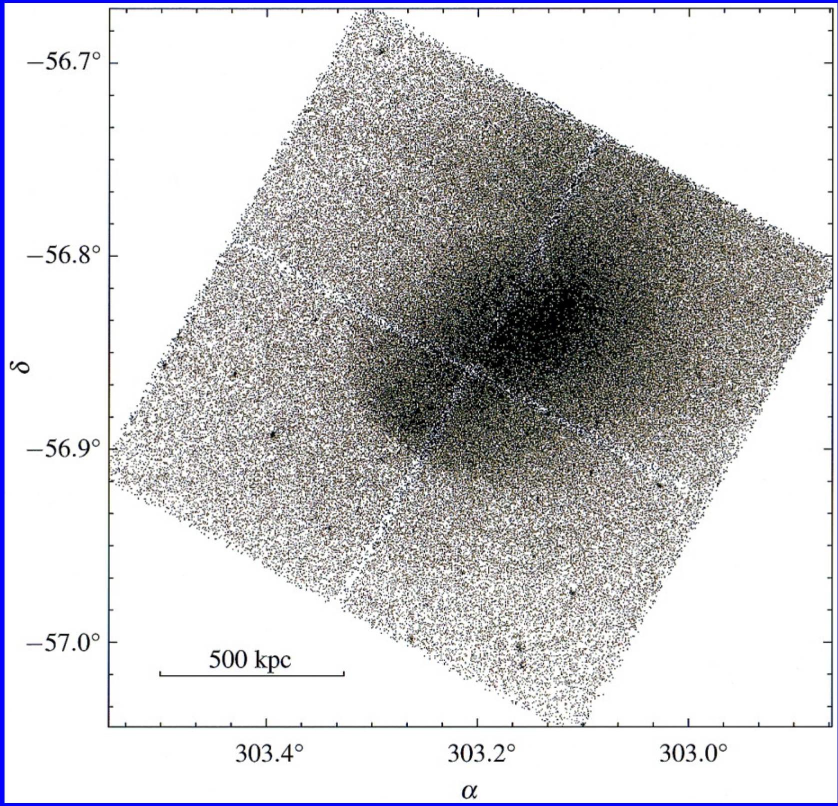
No: Dense gas is cooler, lower entropy, same pressure as lower density gas

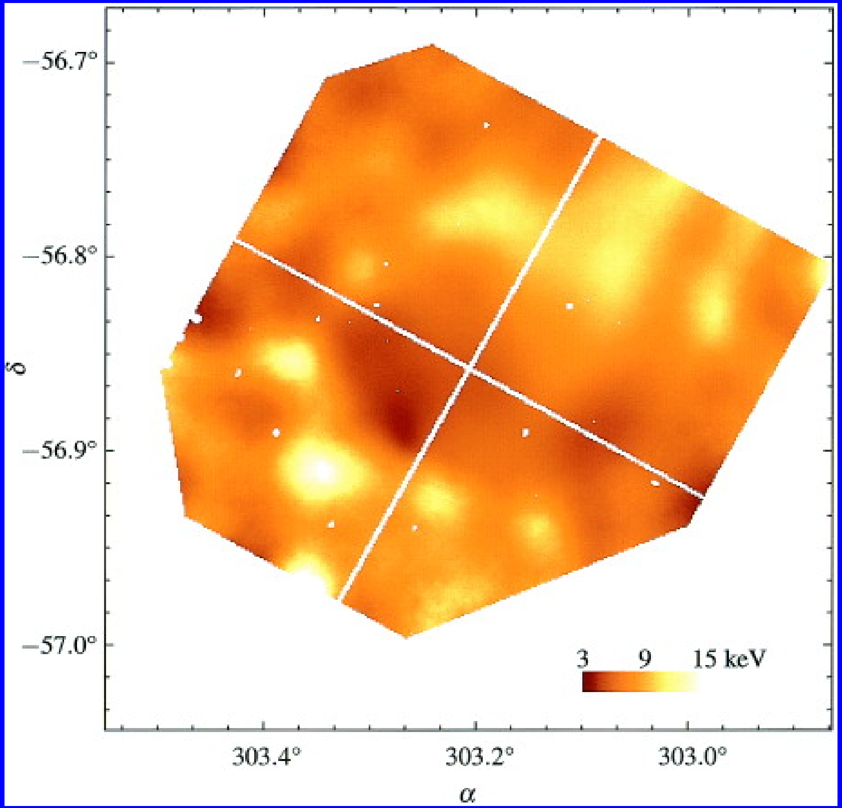
Abell 2142

Markevitch et al.



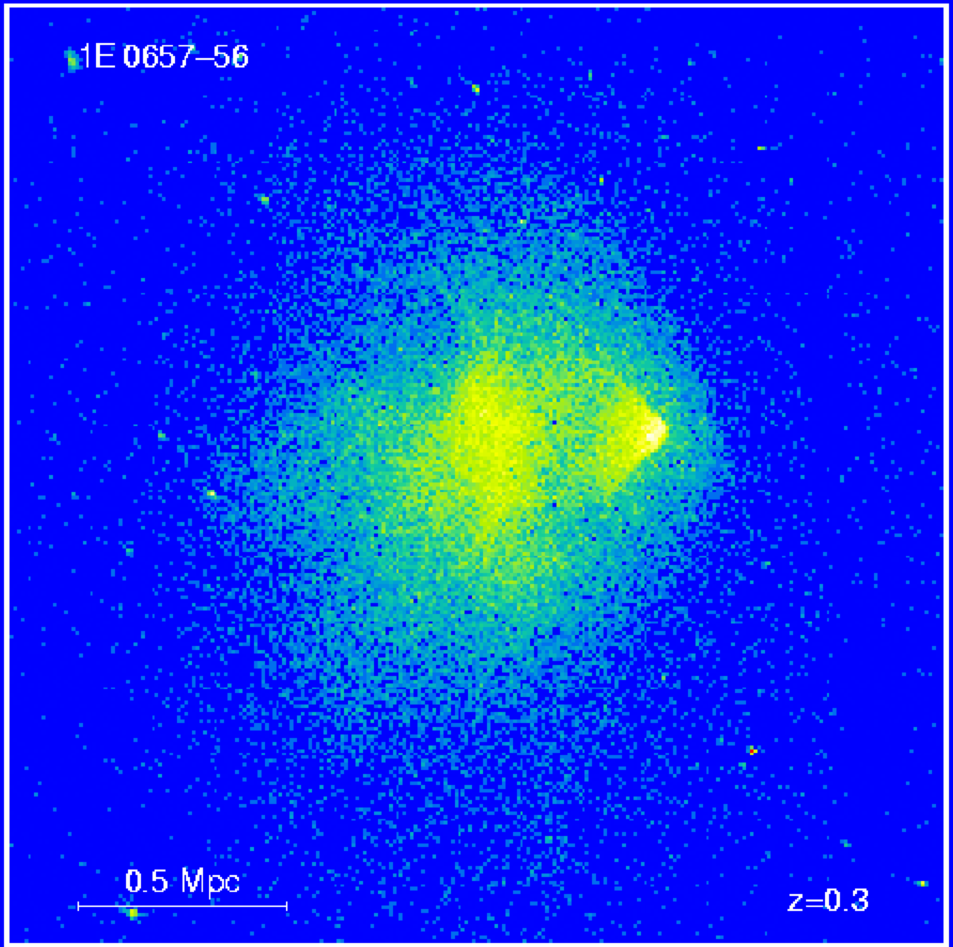
Abell 3667





Contact discontinuity, cool cluster cores plowing through hot shocked gas Vikhlinin et al.

Cold Front with Merger Bow Shock



Markevitch et al.

1E0657-56

Merger Kinematic Diagnostics

$\mathcal{M} \equiv$ Mach number of Cold Front motion

Stagnation Point Condition: (Vikhlinin, Markevitch, & Murray 2001)

$$\frac{P_{\rm st}}{P_1} = \begin{cases} \left(1 + \frac{\gamma-1}{2}\mathcal{M}^2\right)^{\frac{\gamma}{\gamma-1}}, & \mathcal{M} \le 1, \\ \mathcal{M}^2 \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}} \left(\gamma - \frac{\gamma-1}{2\mathcal{M}^2}\right)^{-\frac{1}{\gamma-1}}, & \mathcal{M} > 1. \end{cases} \quad (1)$$

$\gamma = 5/3$.

Rankine–Hugoniot Shock Jump Condition: (Markevitch, Sarazin, & Vikhlinin 1999)

$$\frac{1}{C} = \frac{2}{\gamma+1}\frac{1}{\mathcal{M}^2} + \frac{\gamma-1}{\gamma+1}, \quad (2)$$

$C \equiv \rho_2/\rho_1 \equiv$ shock compression

Mach Angle: (Sarazin 2002)

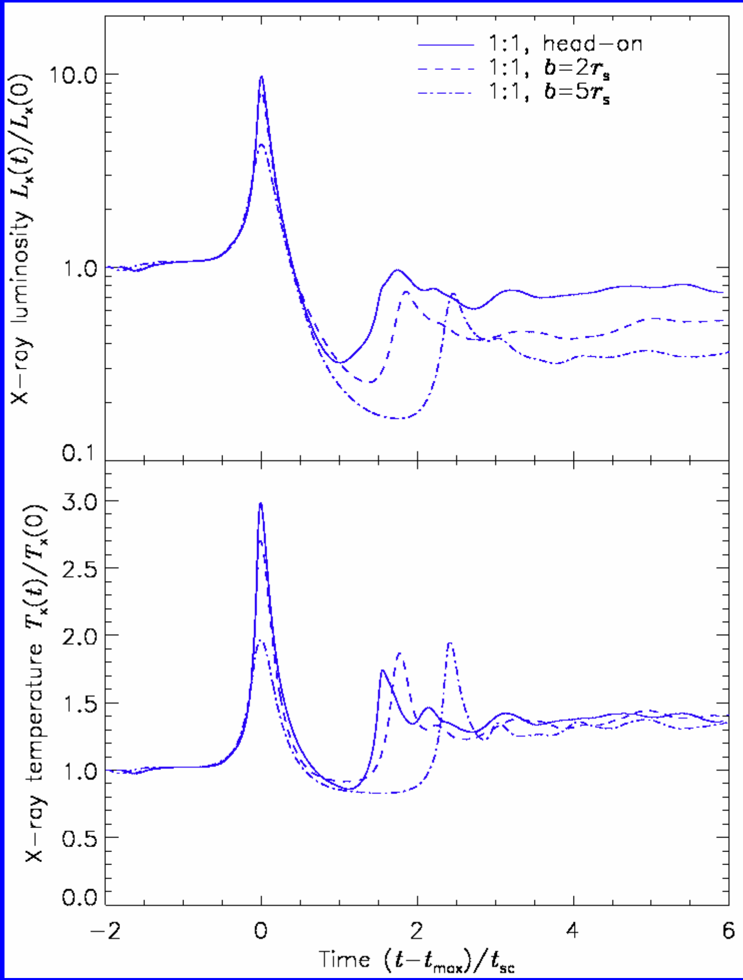
$$\theta_M \equiv \csc^{-1}(\mathcal{M}) \quad (3)$$

Shock Stand-Off Distance: (Vikhlinin et al. 2001; Sarazin 2002)

Find $\mathcal{M} \approx 1.5$, shock velocity ≈ 2000 km/s

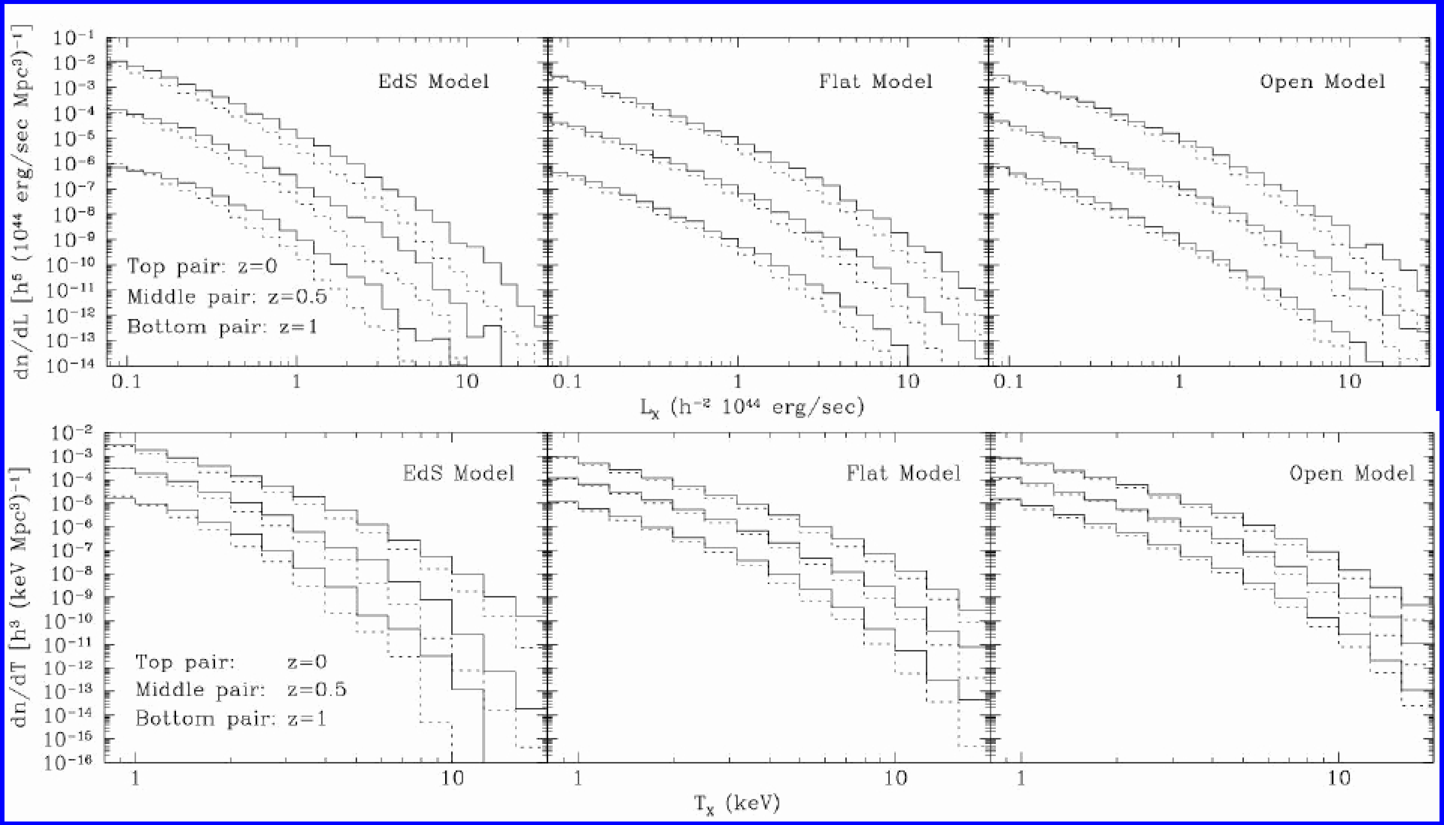
Merger Boosts to L_X & T_X

- Mergers temporarily boost
  - X-ray luminosity (factor of ≲ 10)
  - Temperature (factor of ≲ 3)
- Are the most luminous, hottest clusters mainly mergers?



Ricker & Sarazin

Merger Boosts (cont.)



→ The most luminous, hottest clusters should mainly be mergers. Affects values of Ω_M and σ_8 from luminous clusters. Randall et al.

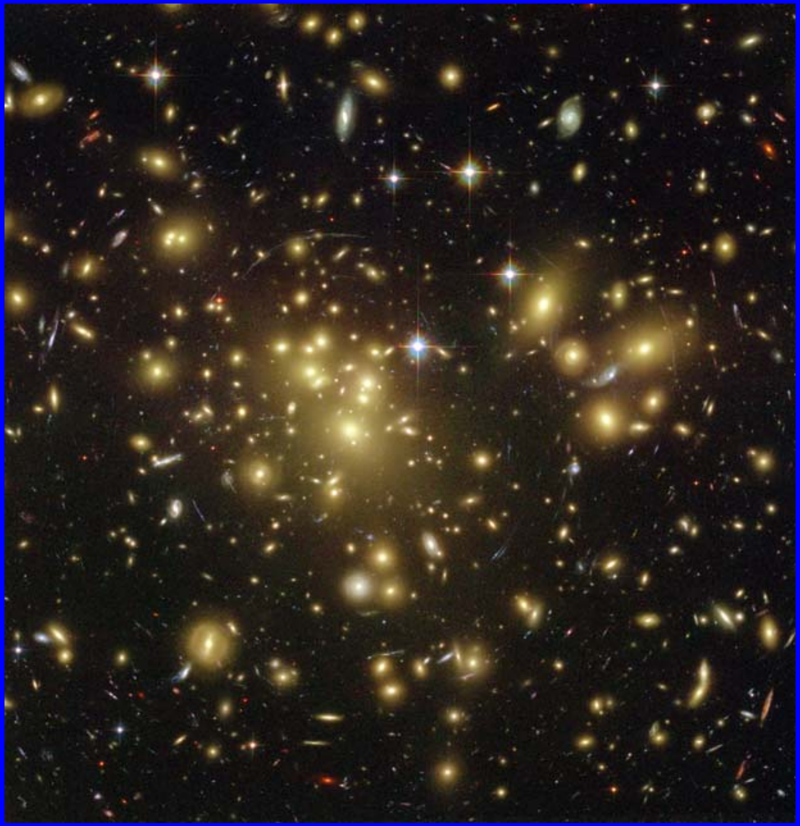
Merger Boosts (cont.)

Lensing studies of masses of most luminous, hottest clusters confirm merger boosts L_X & T_x Smith et al.

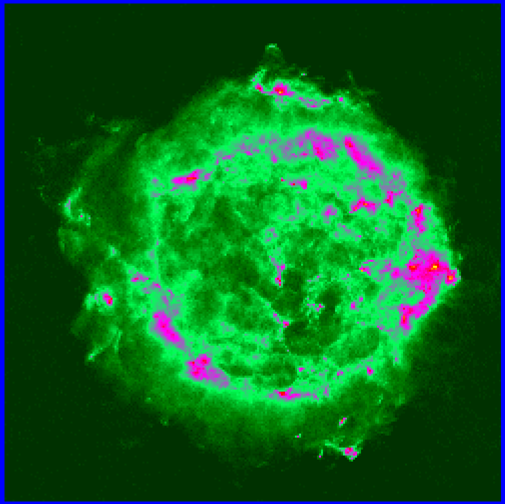
Mergers probably boost S-Z effect

Mergers also appear to boost probability of strong lensing

Meneghetti et al., Randall et al.

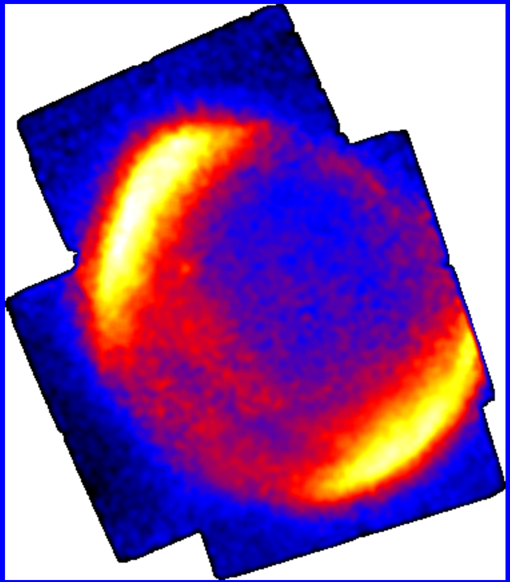


Nonthermal Effects of Mergers: Particle Acceleration



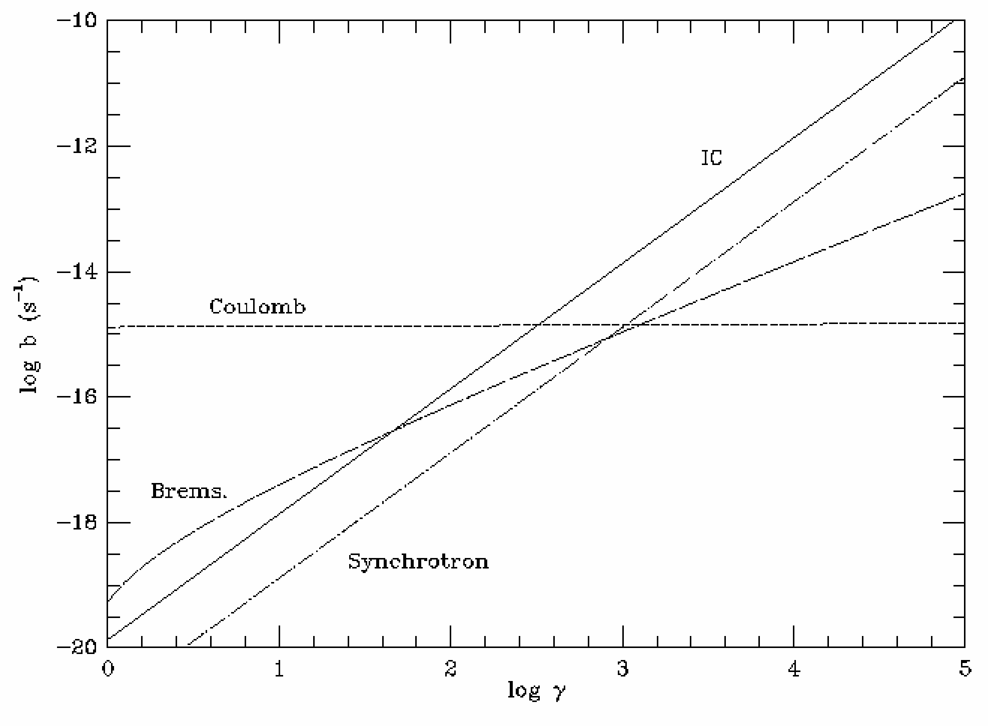
Supernova remnants: shocks at
$\gtrsim$ 1000 km/s →
$\gtrsim$ few % of shock energy →
cosmic ray electrons

→ $E_{CR,e} \gtrsim 10^{62}$ ergs
$E_{CR,ion} \gtrsim E_{CR,e}$
} Clusters



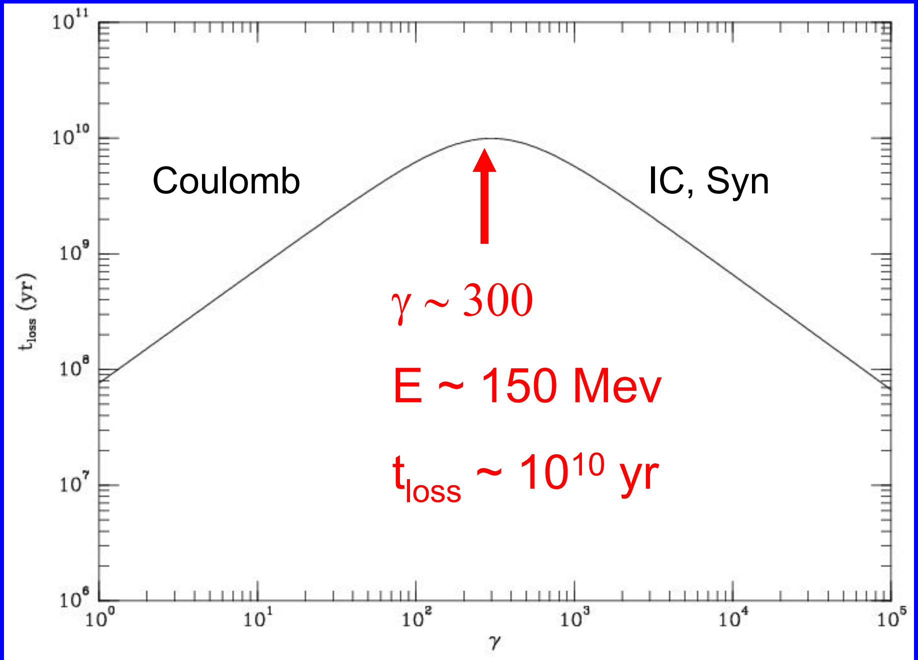
Energy Losses: Cosmic Ray e's

- Coulomb losses to thermal plasma at low energies ($\gamma \lesssim 300$, $E \lesssim 150$ MeV)
- IC, Synchrotron at high energies



Clusters: Cosmic Ray Store Houses?

- Strong gravity, ICM, B hold CRs
- Large → long diffusion times ≫ 10^{10} yr
- Low gas, radiation densities → losses low



Primary vs. Secondary Electrons

- Primary → electrons directly accelerated
- Secondary → Large population of protons

  Relativistic protons collide with thermal protons, make pions

  $$p + p \rightarrow p + p + n\,\pi$$

  Electrons produced by pion decays

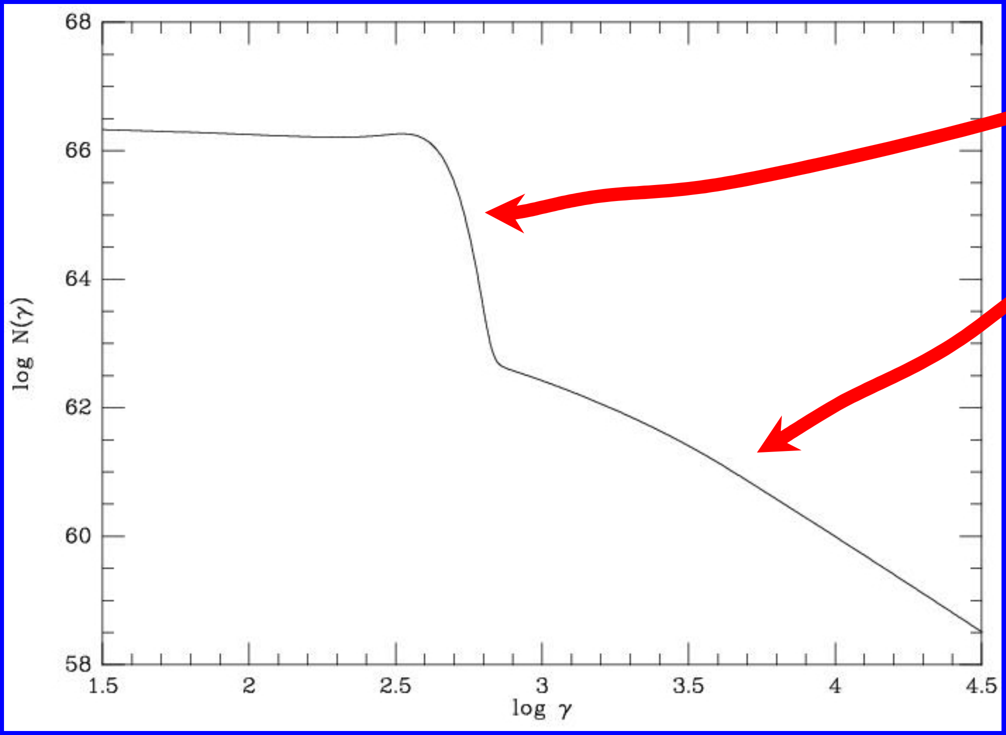
  $$\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$$

Shock vs. Turbulent Acceleration

- Radio relics → shock (re)acceleration (?)
- Radio halos → turbulent (re)acceleration
  following shock passage (?)

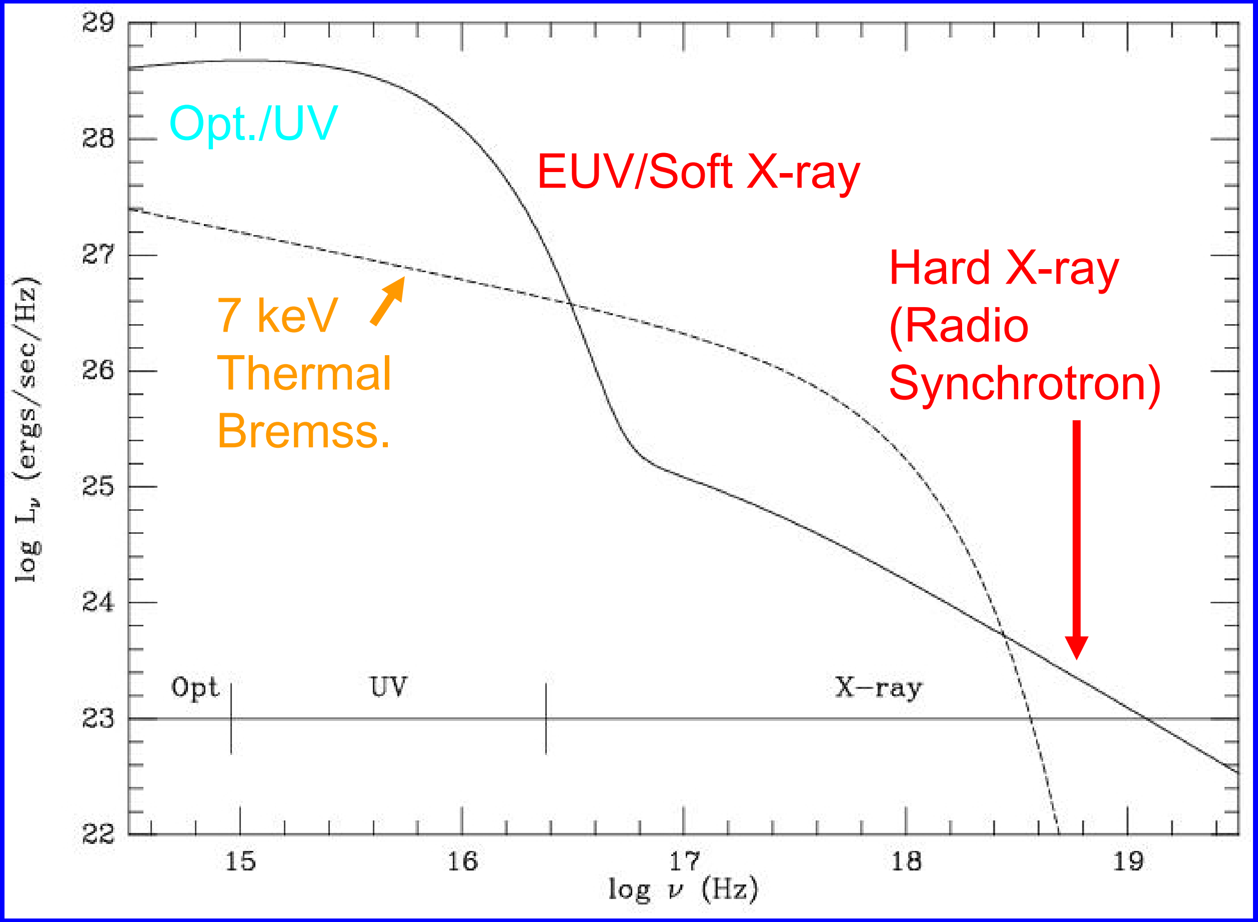
Typical CR Electron Distribution

- Lots of low energy e's ($\gamma \sim 300$, $E \sim 150$ MeV) from previous acceleration
- Tail of high E electrons from current merger acceleration (and small number of secondary electrons)



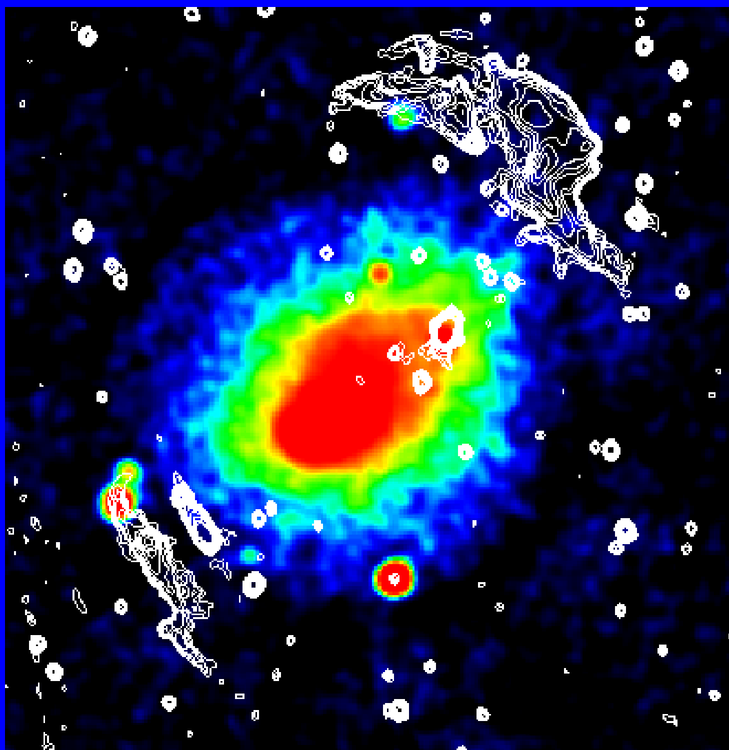
Typical IC Emission Spectrum

- EUV/Soft X-rays
- Hard X-ray Tail (Radio Synchrotron from similar electrons) – Only in clusters with current merger



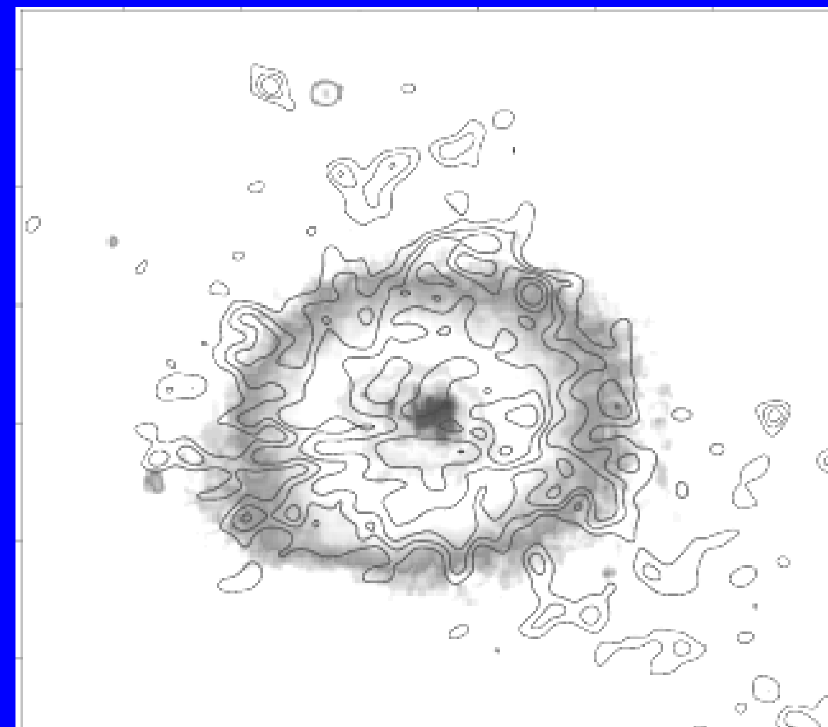
Cluster Radio Halos and Relics

Radio Relics
(shock acceleration?)



Abell 3667
Röttgering et al.

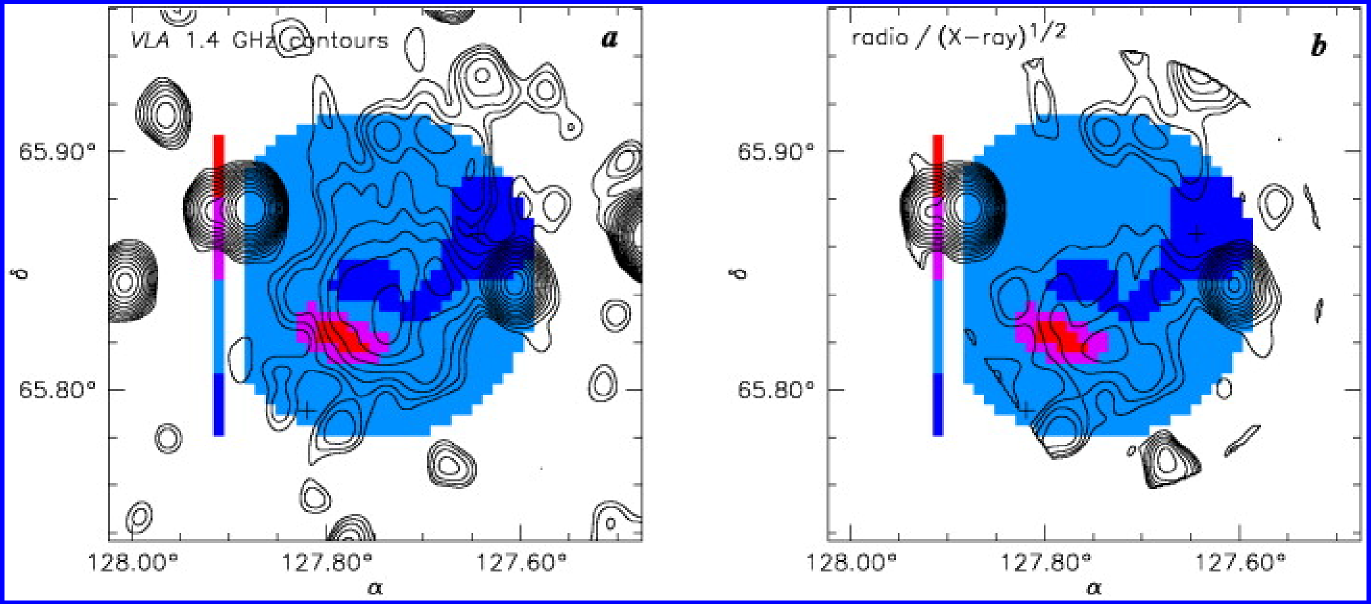
Radio Halo
(turbulent acceleration?)



Coma
Govoni et al.

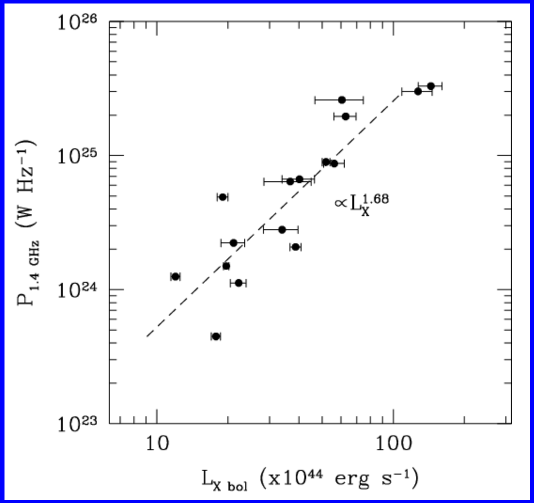
Merger Shocks and Diffuse Radio Emission

A665



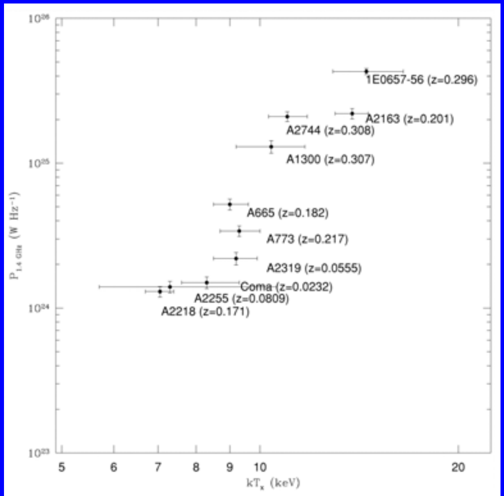
Chandra → Radio Emission at and behind merger shocks (Markevitch & Vikhlinin)

Radio Halo Power vs. L_X & T_X



Bacchi et al 2003

Liang et al 2000



- Mergers shocks → turbulent acceleration of electrons?
- Merger boosts to L_X & T_X

➡ Strong P_{radio} vs. L_X & T_X correlation?

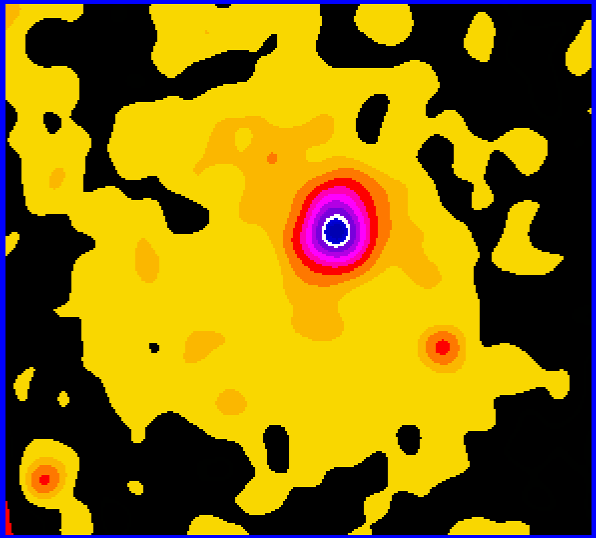
(Randall & Sarazin)

EUV/Soft X-ray Emission from Clusters

Possible detections of EUV/soft X-ray excess emission in many nearby clusters with EUVE, ROSAT, XMM/Newton

- Detections controversial
- Source of emission uncertain:

  thermal or nonthermal?



A1795 EUVE

Mittaz et al.

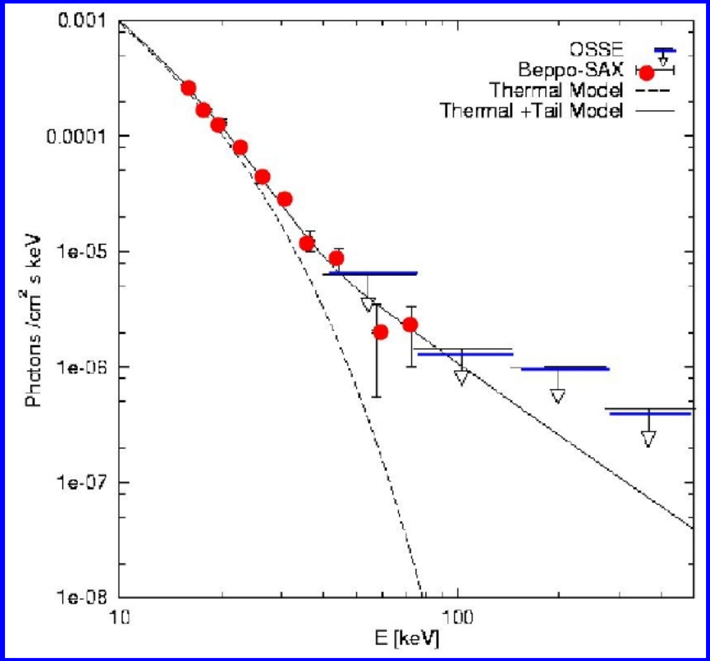
Nonthermal Hard X-ray Emission

Possible detections of hard X-ray excesses from clusters with BeppoSAX & RXTE

Coma, A2319, A2256, …

B ≈ 0.2 μG if IC
Surprising low?

- Detections weak ~ 4 σ
- Must be in excess of BG and thermal emission



Coma HXR
BeppoSAX
Fusco-Femiano et al.

Caution: IC Detections are Weak and Controversial

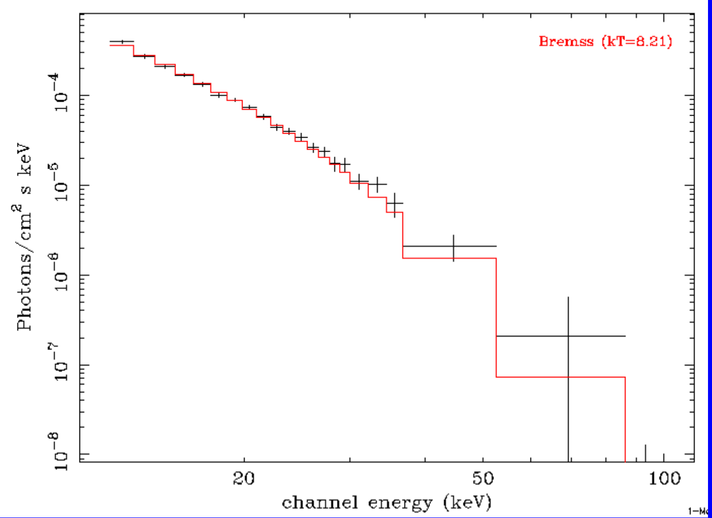
Longer (222 ksec) exposure on Coma with BeppoSAX (2000)

Rossetti & Molendi 2004:

Hard X-ray excess not detected

Fusco-Femiano et al. 2004:

Hard X-ray excess confirmed



Nonthermal Hard X-ray Emission from Groups?

Difficult to see IC Hard X-ray excess against luminous cluster hard X-ray thermal emission

→ Look at groups with radio halos?

(Hudson & Henriksen 2003)

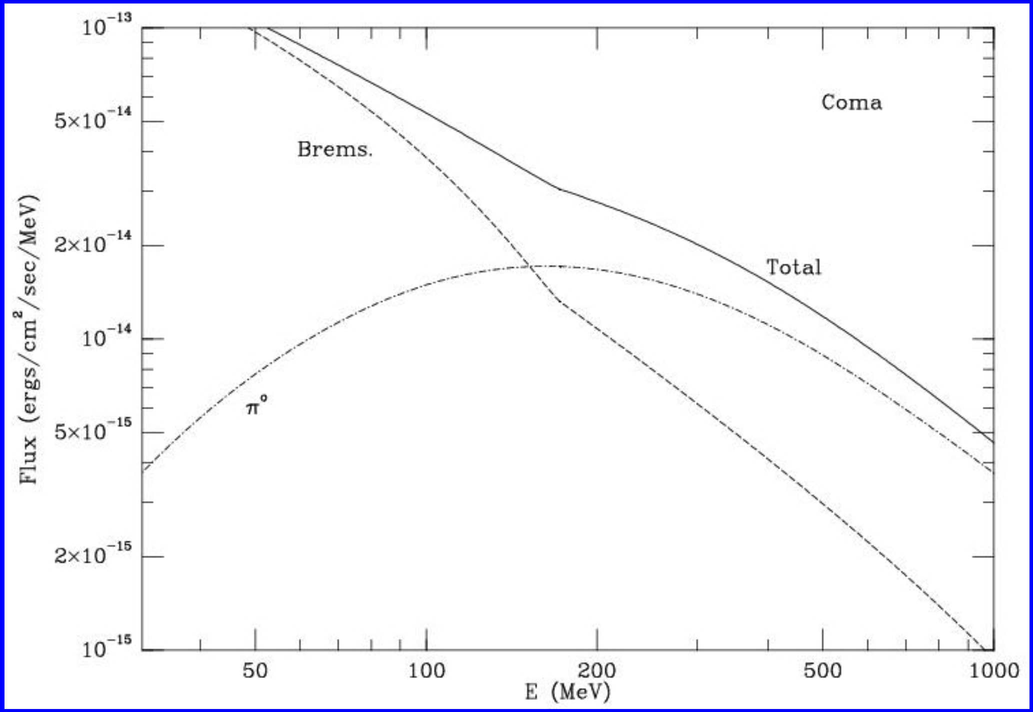
Cooler thermal gas → easier to see?

Gamma-ray Emission

Predict strong γ-ray emission at ~100 MeV

Detect both electron (bremss) and ions (π^o decay)

→ Detectable with GLAST & AGILE in ~40 clusters



Sarazin;
Gabici & Blasi

Conclusions

- Cluster mergers are the most energetic events in the Universe since the Big Bang, $E \sim 10^{64}$ ergs
- Cluster mergers boost L_X & T_X → the most luminous, hottest clusters may mainly be mergers
- Chandra has detected beautiful cold fronts and shocks in mergers → provide diagnostics of kinematics and cluster physics
- Merger shocks and turbulence → particle acceleration → nonthermal radio, EUV/soft X-ray, & hard X-rays.
- GLAST should detect ~40 clusters in ~100 MeV gamma-rays