Computer Simulations of Nonthermal Particle and Photon Spectra from Merging Clusters of Galaxies

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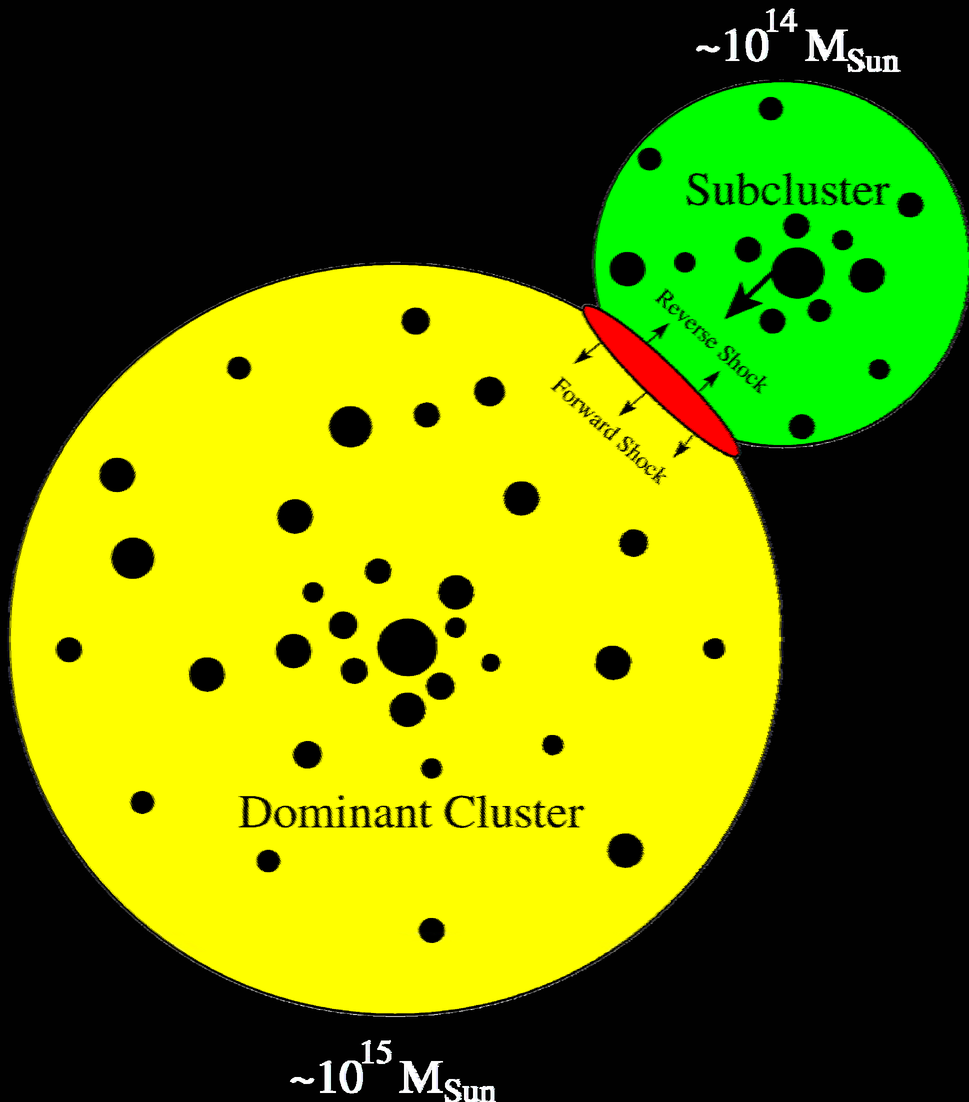
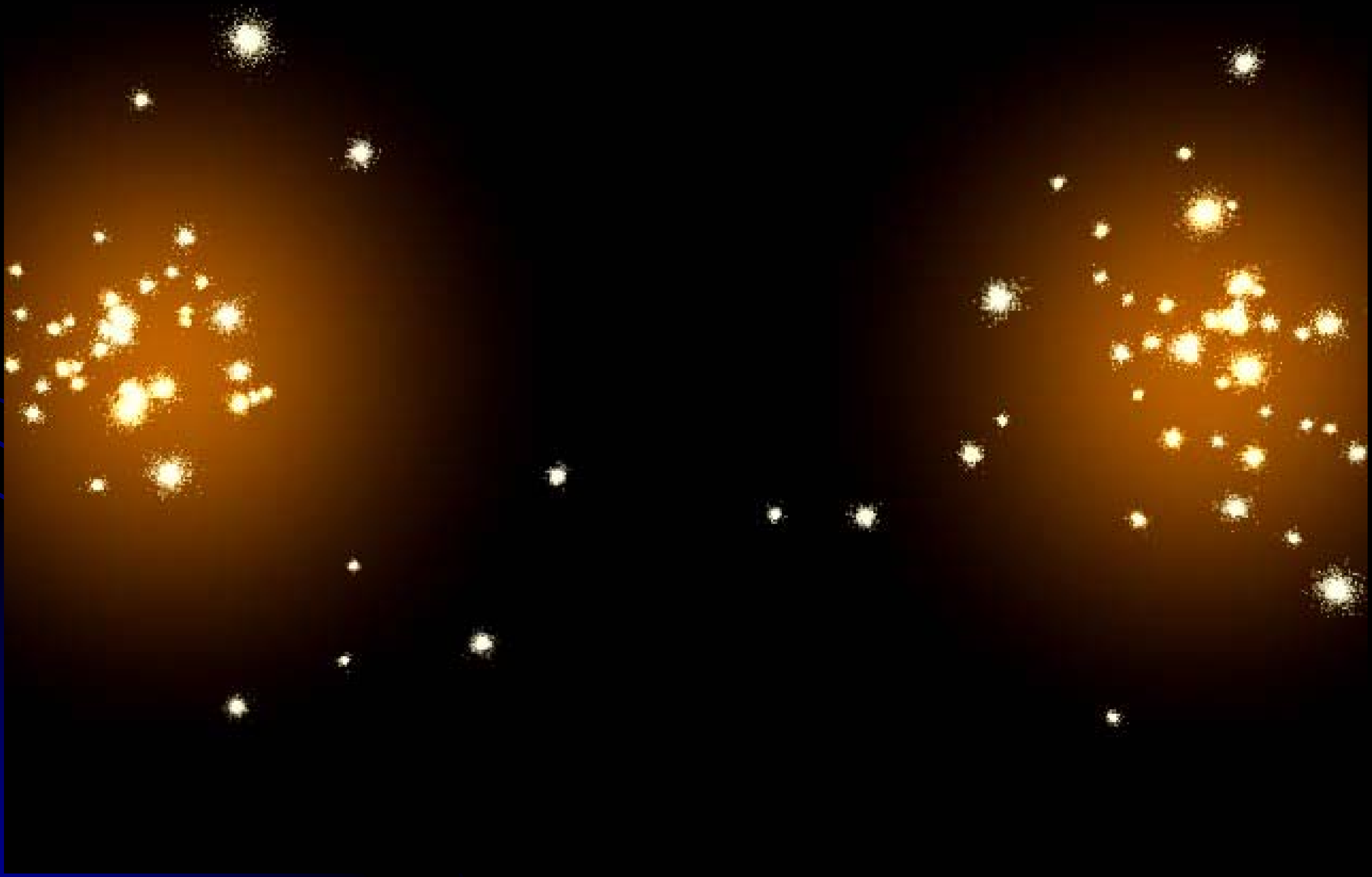
The Merging Cluster Scenario

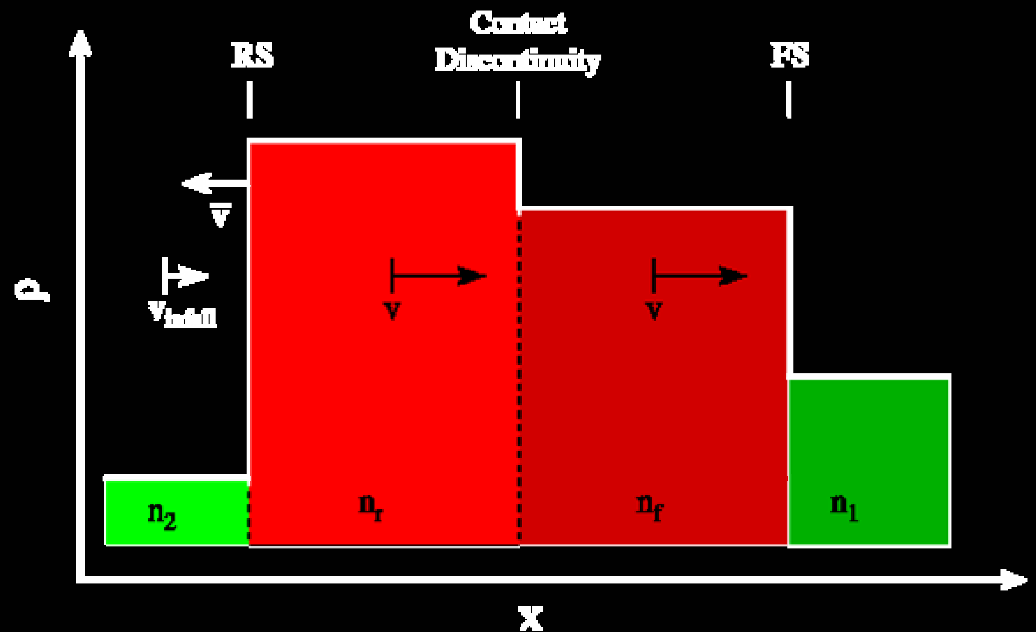
- Rich clusters form by accreting poor clusters
  - Shocks form in ICM at boundary
    - if v_s exceeds sound speed of ICM
  - Thermal particles swept up in shock
    - Accelerated via first-order Fermi
    - Sizes: ~1 Mpc are possible
  - May also reaccelerate particles
    - Head-tail radio galaxies nearby



Cluster Merger



Shock Dynamics



- Shocked fluid velocities

$$\frac{\mu_1 n_1(t)}{\mu_2 n_2(t)} = \frac{1+3M_1^{-2}(t)}{1+3M_2^{-2}(t)}\left(\frac{v_{\text{infall}}(t)-v(t)}{v(t)}\right)^2$$

Shock Dynamics

- Shock speed
  - Forward and reverse mach numbers:

$$M_1(t) = \frac{2v}{3c_1}\left(1+\sqrt{1+\frac{9c_1^2}{4v^2}}\right), \text{ and } M_2(t) = \frac{2\left(v_{\text{infall}}(t)-v\right)}{3c_2}\left(1+\sqrt{1+\frac{9c_2^2}{4\left(v_{\text{infall}}(t)-v\right)^2}}\right)$$

  - Compression ratio: $r_{1,2}(t) = \dfrac{\Gamma+1}{\Gamma-1+2\mathrm{M}_{1,2}^{-2}(t)}$
  - Γ = 5/3 is the ratio of specific heats for an ideal gas

Shock Dynamics

Forward Shock

Reverse Shock

Temporal Particle Evolution

- Fokker-Plank equation

$$\frac{\partial N(E,t)}{\partial t} = \frac{1}{2}\frac{\partial^2}{\partial E^2}\left[D(E,t)\,N(E,t)\right] - \frac{\partial}{\partial E}\left[\dot{E}(E,t)\,N(E,t)\right] + Q(E,t) - \sum_{i=pp,p\gamma,d}\frac{N(E,t)}{\tau_i(E,t)}$$

Coulomb diffusion term

Energy loss rate

Source term

Catastrophic loss from p-p, p-γ, and diffusion out of the system

Particle Injection

- Power law distribution with exponential cutoff

$$Q_{e,p}(E,t) = Q_{e,p}^{0}\left[\frac{(pc)^{-\alpha}}{\beta}\right]\exp\left[-\frac{E}{E_{\max}(t)}\right]$$

- Normalization

$$\int_{E_{\min}}^{E_{\max}} E_{e,p}Q_{e,p}(E,t)\,dE = \eta_{e,p}\left(\frac{1}{2}\langle n_{\mathrm{ICM}}\rangle \eta_{\mathrm{He}}^{e} m_p v_s^2\right)(A_s v_s)$$

  - Where $\eta_{e,p}$ is an efficiency factor, and is set to 5%.
  - Typical values are $E_{tot} \approx 10^{63\text{-}64}$ ergs

Particle Injection

- Maximum particle energy
  - Acceleration time constraint

$$\dot{E}_{\max,1} = \frac{100 B_{\mathrm{ICM}} v_s^2}{f r_J}\ \mathrm{MeV\ s^{-1}} \Rightarrow E_{\max,1} = \int_0^t dt\, \dot{E}_{\max,1}$$

  - Energy loss constraint
    - for electrons

$$E_{\max,2,e} = 2.8\times 10^4 \frac{v_s[\mathrm{km}]}{\sqrt{f r_J}} \sqrt{B_{\mathrm{ICM}}[\mu\mathrm{G}] \Big/ (1+z)^4 + 10^{-1} B_{\mathrm{ICM}}^2[\mu\mathrm{G}]}\ \mathrm{MeV}$$

    - for protons

$$E_{\max,2,p} = 2\times 10^{12} \frac{v_s[\mathrm{km}]}{\sqrt{0.1\, f r_J\, B_{\mathrm{ICM}}[\mu\mathrm{G}]}}\ \mathrm{MeV}$$

  - Size scale limitation

$$E_{\max,3} = \frac{10^{14}}{f}\left(\frac{B}{\mu\mathrm{G}}\right)\left(\frac{\lambda_{\max}}{\mathrm{Mpc}}\right)\mathrm{MeV}$$

Nonthermal Photon Spectra

Nonthermal Particle Luminosity

LOFAR

- Estimated Sensitivities (1 hour exposure)
  - ~1.6 mJy at 15 MHz with resolution of ~12”
  - ~40 µJy at 120 MHz with resolution of ~2.4”
- Detection limit
  - ~2000 Mpc at 15 MHz
  - ~700 Mpc at 120 MHz

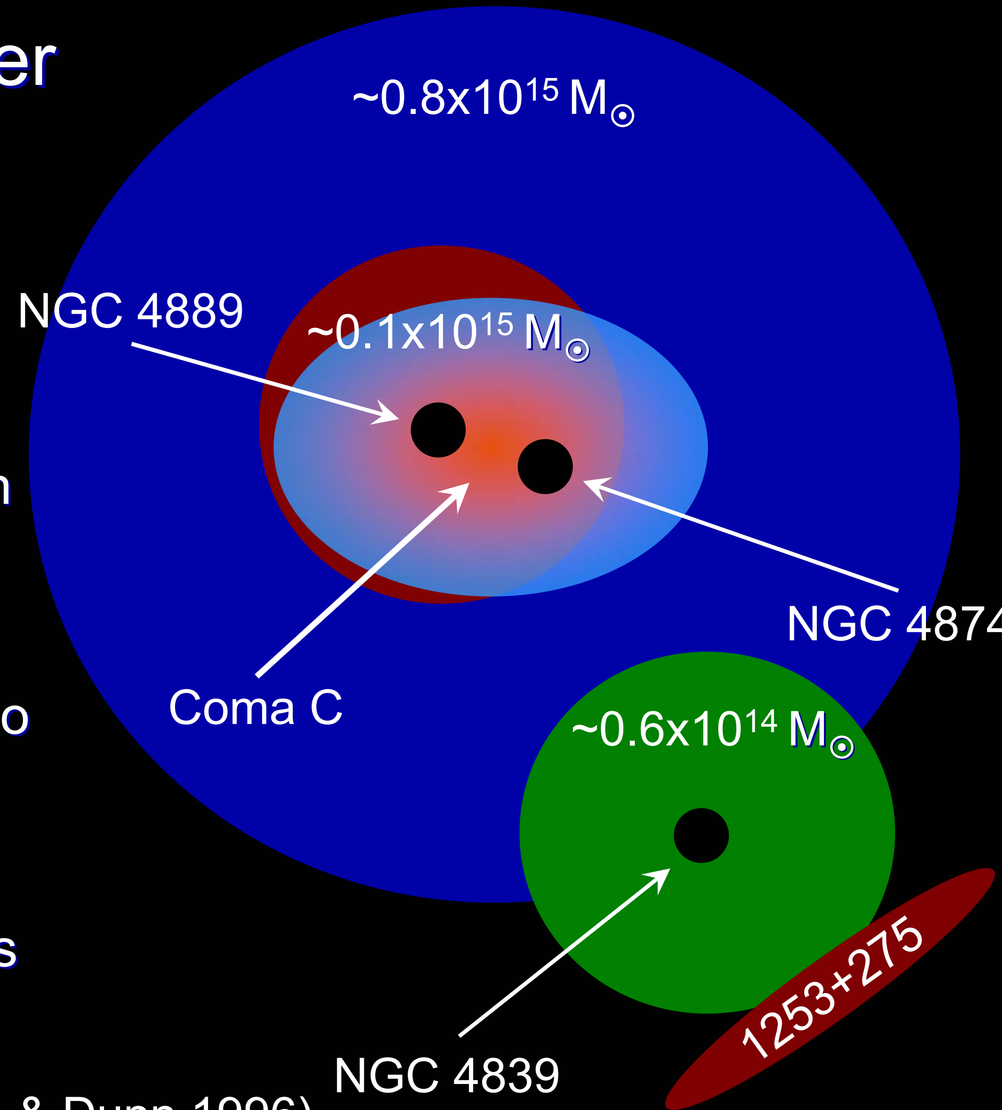
Diffuse Extragalactic γ-ray Background

- Our simulations show spectral indicies of ~2.2-2.4 for average density profile
  - DEGB power-law slope of 2.10 ± 0.03
  - Central cusps in dark matter profiles will lower spectral indicies
- Pion bump not observed
- Probably not a dominant contributor

Minimum Spectral Index

Modeling the Coma Cluster

- Likely a 3 body merger
  - NGC 4839
    - Inbound orbit
    - Mass ~ $0.6 \times 10^{14}\ M_\odot$
  - NGC 4889
    - Near collision time with main cluster
    - Mass ~ $0.1 \times 10^{15}\ M_\odot$
    - Probable cause of radio halo
  - NGC 4874
    - Main Cluster with Mass ~ $0.8 \times 10^{15}\ M_\odot$



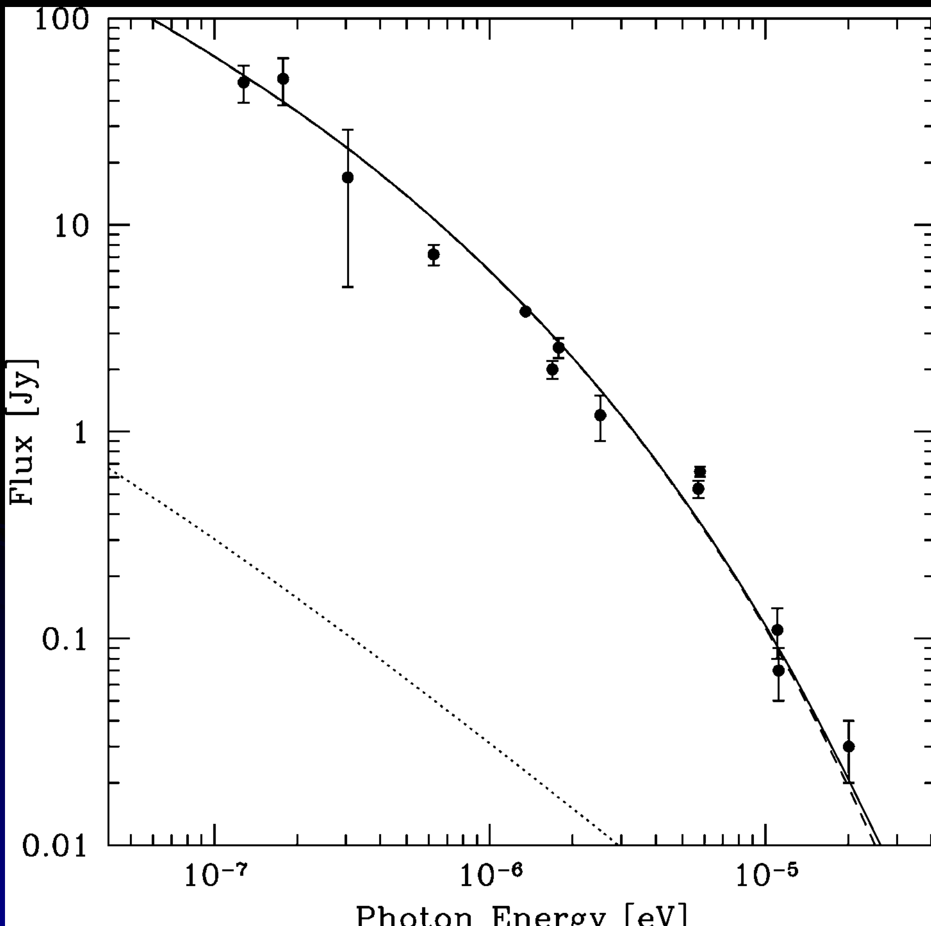
(Colless & Dunn 1996)

Parameters for Coma Cluster

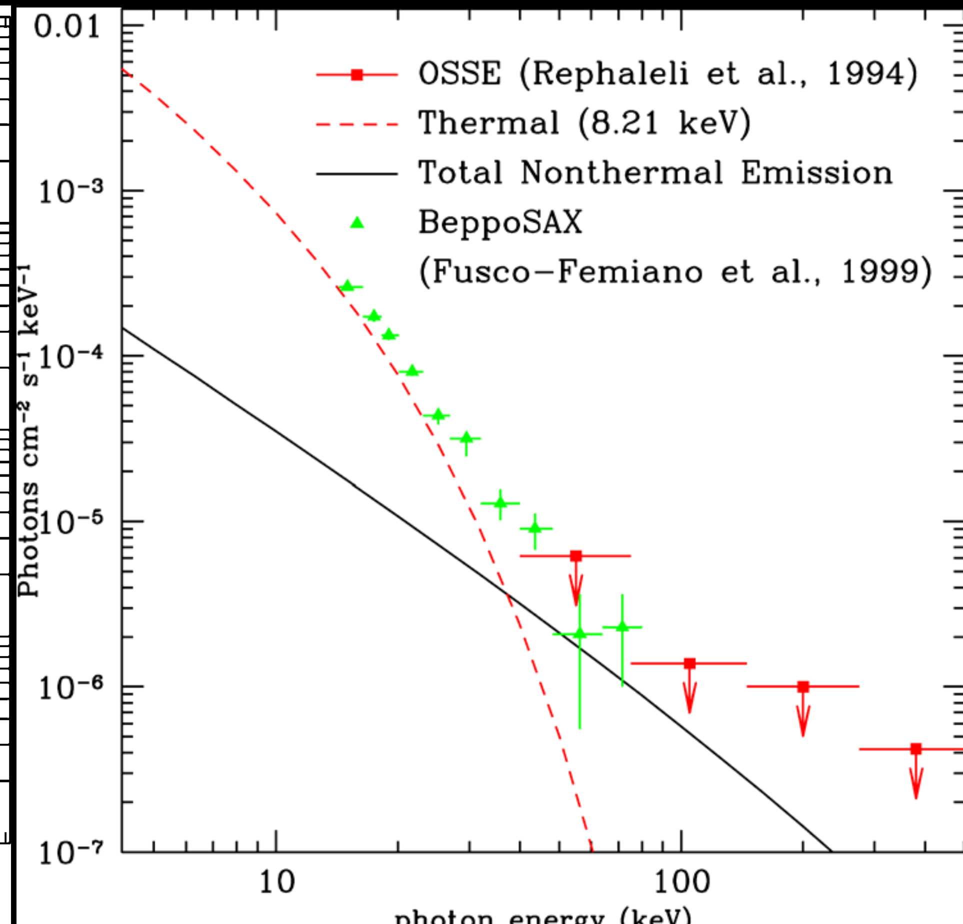
- Assuming H_0=70 km s^{-1} Mpc^{-1}, $(\Omega_0, \Omega_R, \Omega_\Lambda) = (0.3, 0.0, 0.7)$
  - $n_0 = 3.12 \times 10^{-3}\ cm^{-3}$
  - $\beta = 0.705$
  - $r_c = 257$ kpc
  - $\eta_{e,p} = 1\%$
  - $t_{age} = 9.7 \times 10^8$ yrs, $t_{coll} \approx 1.0 \times 10^9$ yrs
  - $B = 0.22\ \mu G$
  - $M_1 = 0.8 \times 10^{15}\ M_\odot$ and $M_2 = 0.1 \times 10^{15}\ M_\odot$

(Mohr, Mathiesen, & Evrard 1999) [applies to n_0, β, r_c]

Coma Cluster

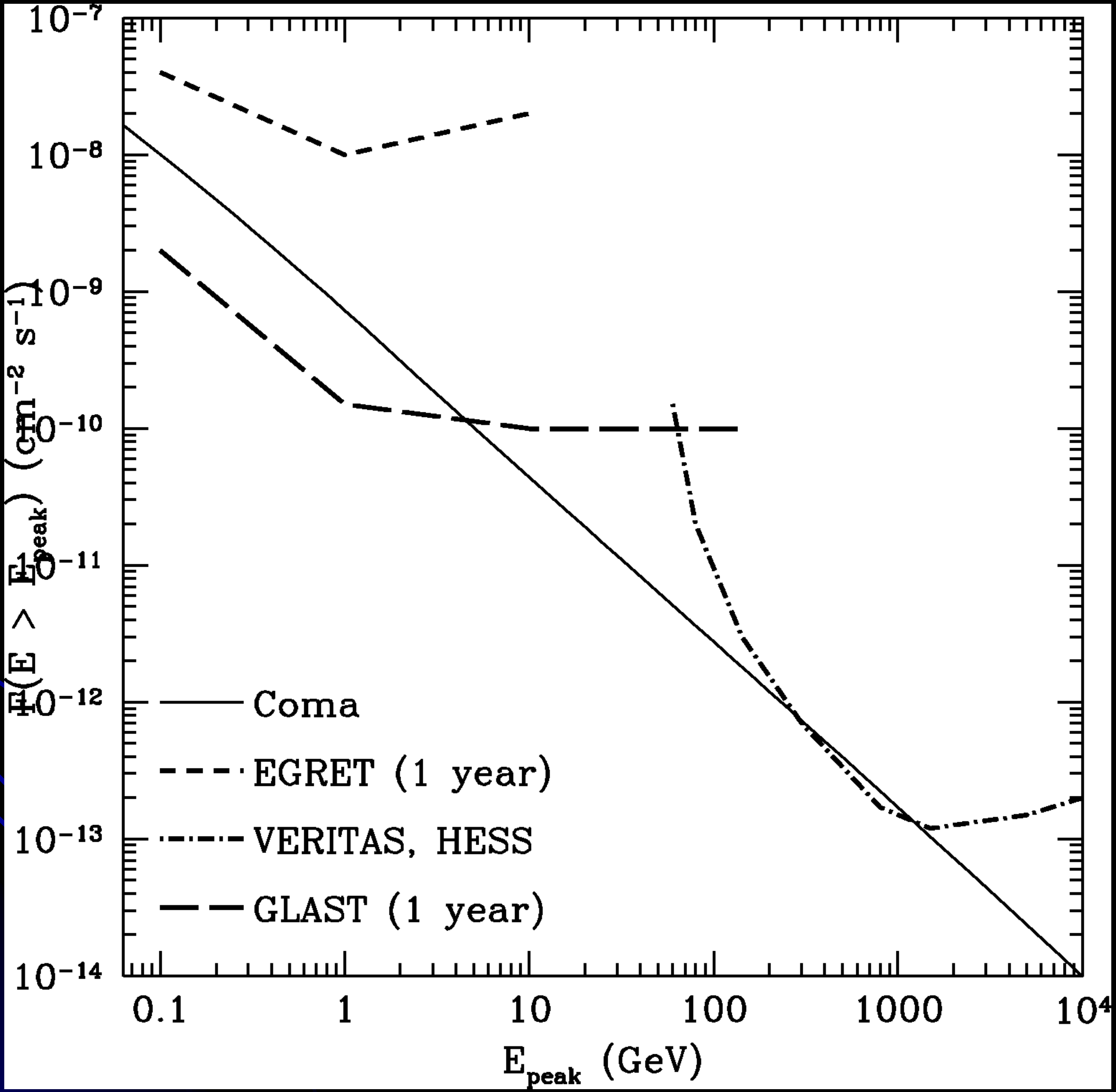


Radio



X-ray

Coma Cluster



Conclusions

- Radio halo and hard X-ray emission well fit by cluster merger model
- Difficult to account for the Diffuse Extragalacitc γ-ray Background
- Likely detection of the Coma Cluster by GLAST and marginal detection by VERITAS.