Magnetic Fields, Relativistic particles and Nonthermal Emission in Galaxy Clusters

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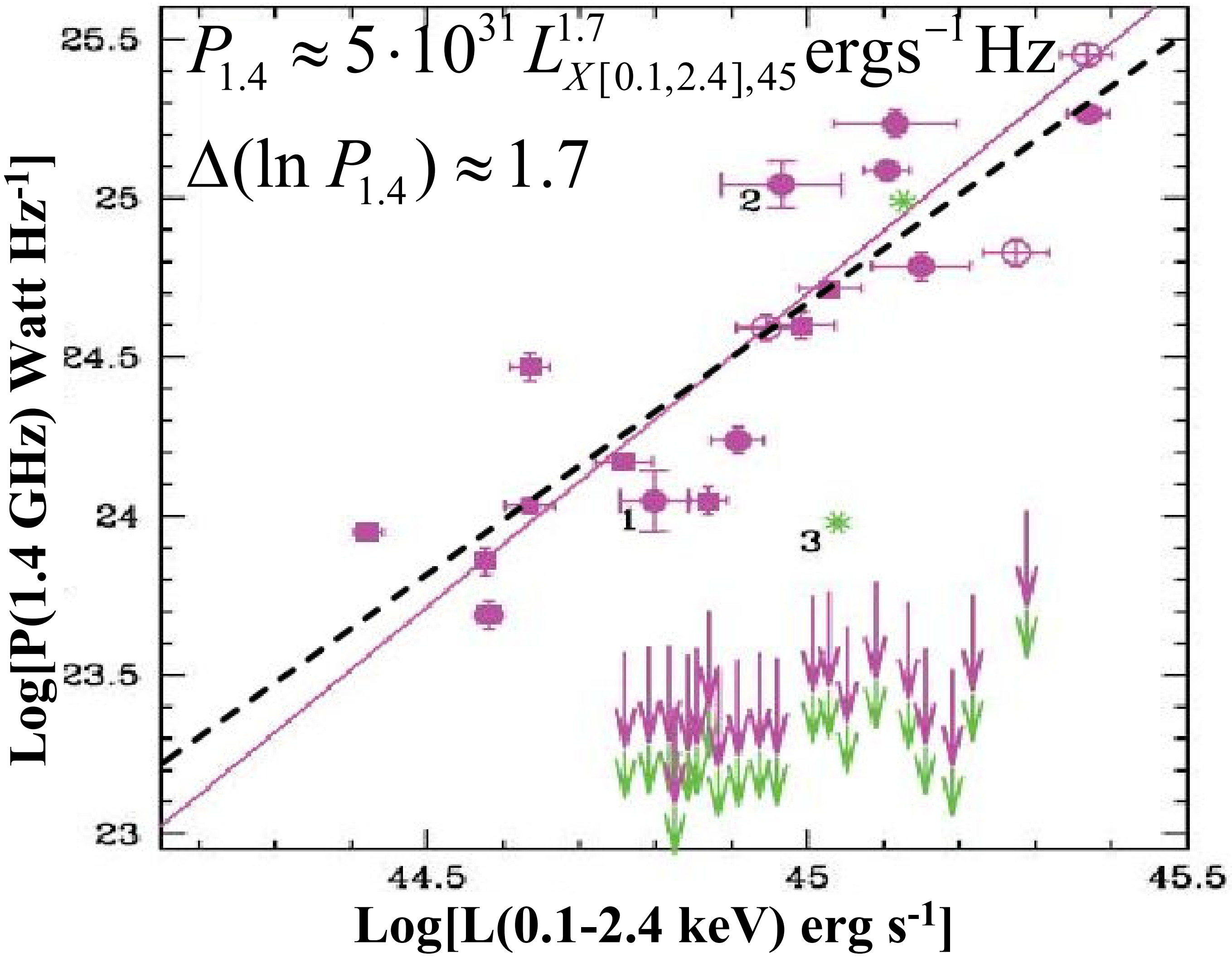
Radio Vs. X-ray Correlation



$$P_{1.4} \approx 5 \cdot 10^{31} L_{X[0.1,2.4],45}^{1.7} \mathrm{ergs}^{-1}\,\mathrm{Hz}$$

$$\Delta(\ln P_{1.4}) \approx 1.7$$

Brunetti et al, ApJ, 670, L5

A Simple Model

Ionized Hydrogen Plasma: n, T

Proton CR population: $\varepsilon^2 dn/d\varepsilon = \beta_{\mathrm{core}} 3nT/2$

A strong magnetic field: $B > B_{\mathrm{CMB}} \equiv (8\pi a T^4_{\mathrm{CMB}})^{1/2} \approx 3\ \mu\mathrm{G}$

Thermal X-ray bremsstrahlung

$$\propto T^{1/2} n^2$$

Energy production rate of secondaries per logarithmic secondary energy interval

$$\propto n\varepsilon^2 dn/d\varepsilon \propto \beta_{\mathrm{core}} T n^2$$

Secondaries lose all energy to synchrotron radio emission

$$\Rightarrow \frac{\nu L_\nu^{\mathrm{sync}}}{L_X} \approx 10^{-5} \beta_{\mathrm{core},-4} T_1^{1/2}$$

$$\Rightarrow P_{1.4} \approx 2.5 \cdot 10^{31} L_{X[0.1,2.4],45}^{1.6} \left(\frac{\beta_{\mathrm{core}}}{10^{-4}} \right) \mathrm{erg\,s}^{-1}\,\mathrm{Hz}^{-1}$$

Model Vs. Observations

Model: $P_{1.4} \approx 2.5 \cdot 10^{31} L^{1.6}_{X[0.1,2.4],45} \left(\frac{\beta_{\rm core}}{10^{-4}} \right) \mathrm{erg\,s^{-1}\,Hz^{-1}}$

Observations: $P_{1.4} \approx 5 \cdot 10^{31} L^{1.7}_{X[0.1,2.4],45} \mathrm{erg\,s^{-1}\,Hz}$

$$\Rightarrow \beta_{\rm core} \equiv \frac{\varepsilon^2 \partial n / \partial \varepsilon}{\varepsilon_{th}} \approx 2 \cdot 10^{-4}$$

$$\Delta(\ln \beta_{\rm core}) \approx 1.7$$

Source of cluster CRs must explain:

1. Small $\beta_{\rm core}$
2. Small scatter

Accretion Shocks - The Source of CRs

1. Small β_{core}

Behind the shock

$$\beta_{CR} \equiv \left(\frac{\varepsilon^2 \frac{dn}{d\varepsilon}}{\varepsilon_{th}} \right) \approx \frac{\eta_p}{\ln\left({}^{p_{\max}}\!\big/_{m_p c} \right)} \Rightarrow \frac{\beta_{shock}}{\eta_p} \approx \frac{1}{20}$$

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adiabatic losses $\propto \rho^{-1/3}$ ➡

$$\frac{\beta_{\text{core}}}{\eta_p} \approx \frac{1}{200} \Rightarrow \eta_p \sim \text{few}\,\%$$

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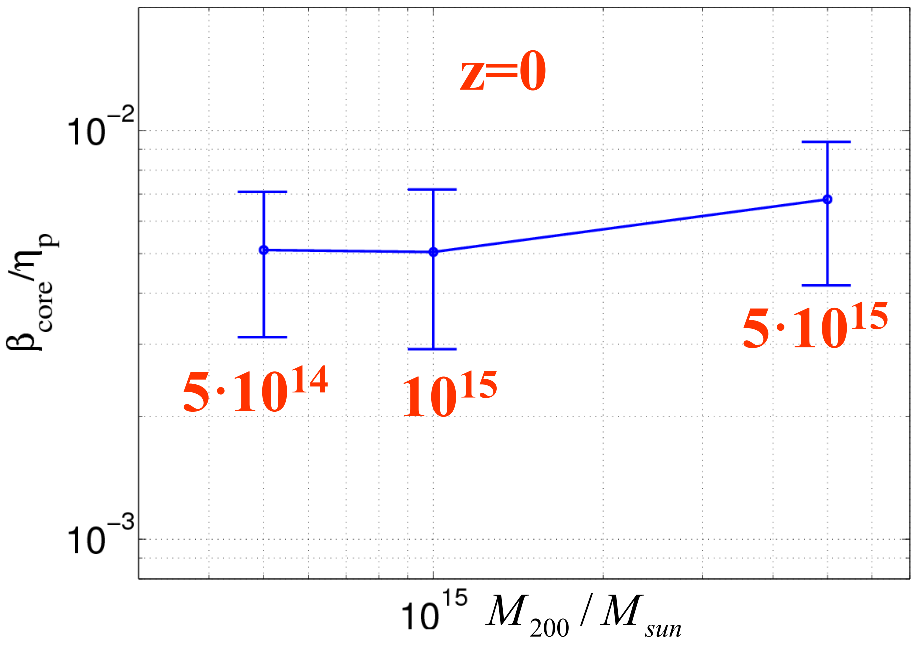
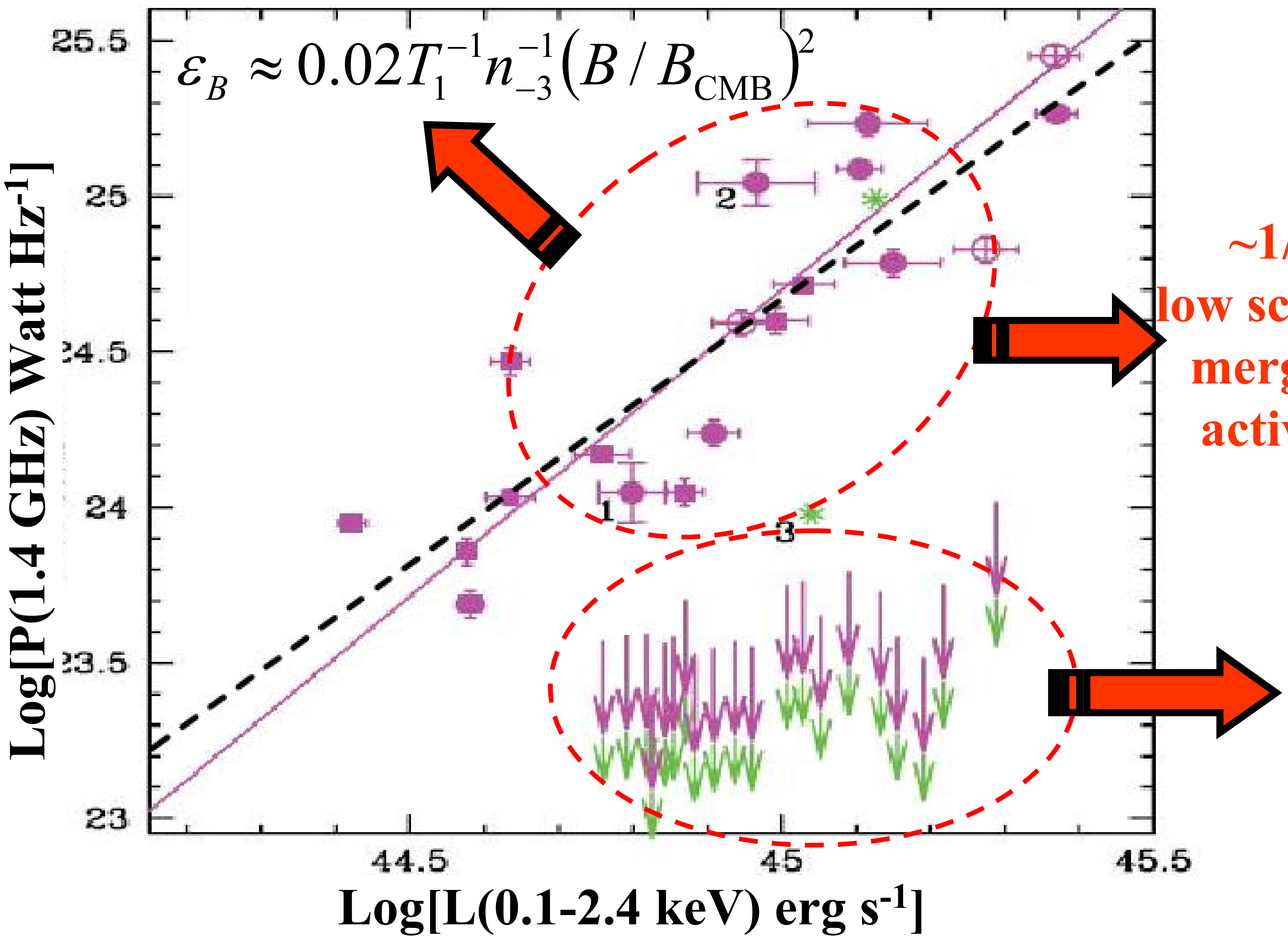
2. Small scatter



Radio Vs. X-ray Correlation - Bimodality



$$\varepsilon_B \approx 0.02 T_1^{-1} n_{-3}^{-1} \left(B / B_{\rm CMB} \right)^2$$

~1/3,
low scatter,
merging
activity

~2/3

Brunetti et al, ApJ, 670, L5

Radio-X-ray Correlation: Observational Constraints

- ☑ $\beta_{core} \equiv (\varepsilon^2 dn/d\varepsilon)/\varepsilon_{th} \sim 10^{-4}$
- ☑ Cluster CRs produced by accretion shocks
- ☑ $\eta_p \sim$ few %
- ☑ Diffusion time of 100 GeV CRs over scales ≥ 100 kpc is not short compared to t_H
- ☑ Cluster magnetic fields are enhanced by mergers to ≥ 1% of EP & Decay (to < 1 μG) on 1 Gyr time scale.

HXR : Primary e$^-$ from accretion shocks

Secondaries : Too Low !

$$\frac{\nu L_\nu^{\mathrm{IC}}}{L_X} \approx 10^{-5}\,\beta_{\mathrm{core},-4} T_1^{1/2}\,\frac{B_{\mathrm{CMB}}^2}{B^2}$$

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Primary e$^-$: Accretion rate:

$$\dot{M} = f_{\mathrm{inst}} M_{200} / t_H \propto f_{\mathrm{inst}} T^{3/2}$$

Luminosity:

$$\nu L_\nu^{\mathrm{shock}} \propto \eta_e T \dot{M} \propto f_{\mathrm{inst}} \eta_e T^{5/2}$$

Surface brightness:

$$\frac{S}{\Lambda} \propto \frac{\nu L_\nu^{\mathrm{shock}}}{r_{200}^2} \propto f_{\mathrm{inst}} \eta_e T^{3/2}$$

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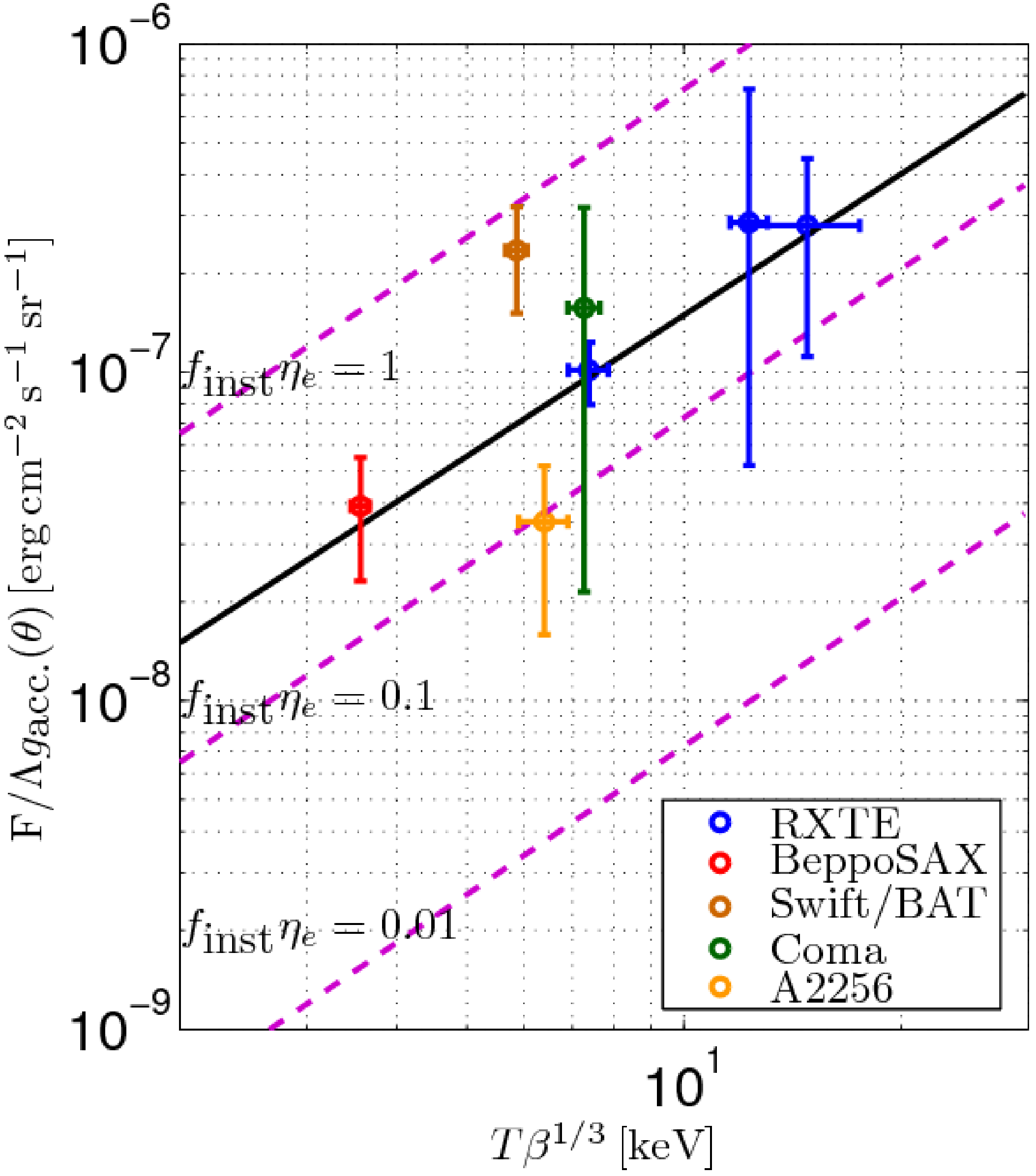
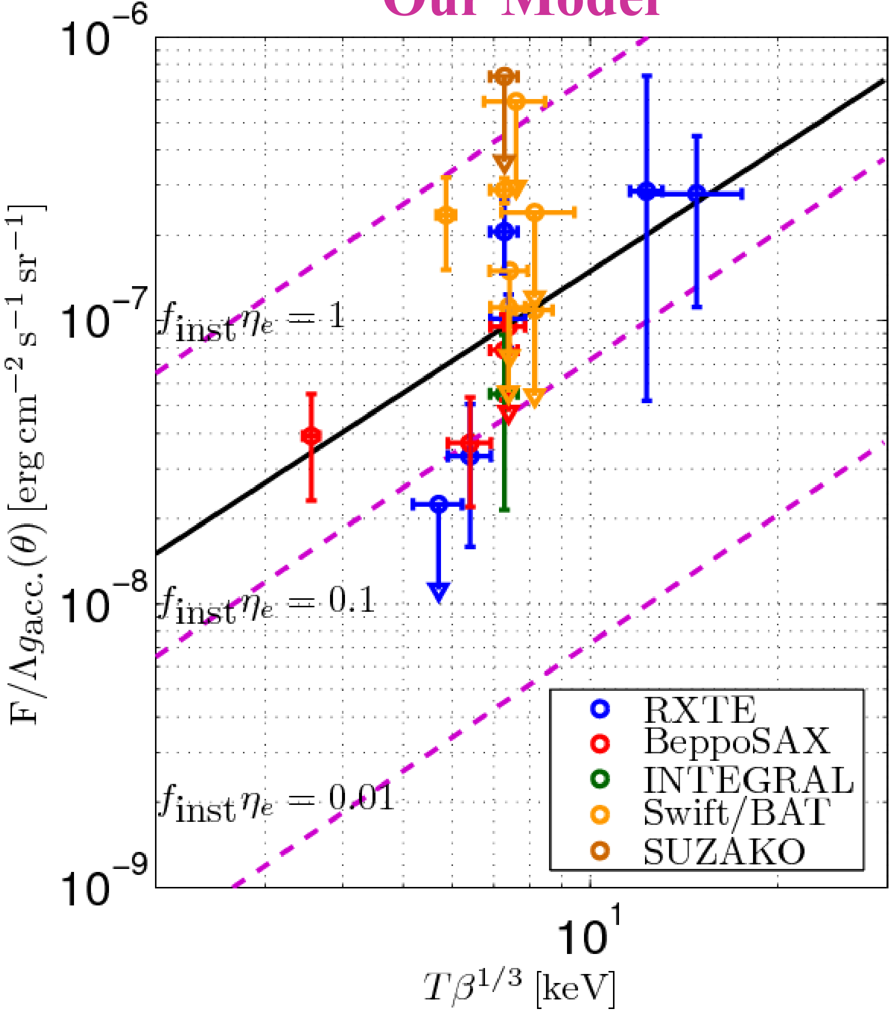
$\Rightarrow f_{\mathrm{inst}}\eta_e \sim 10\%$



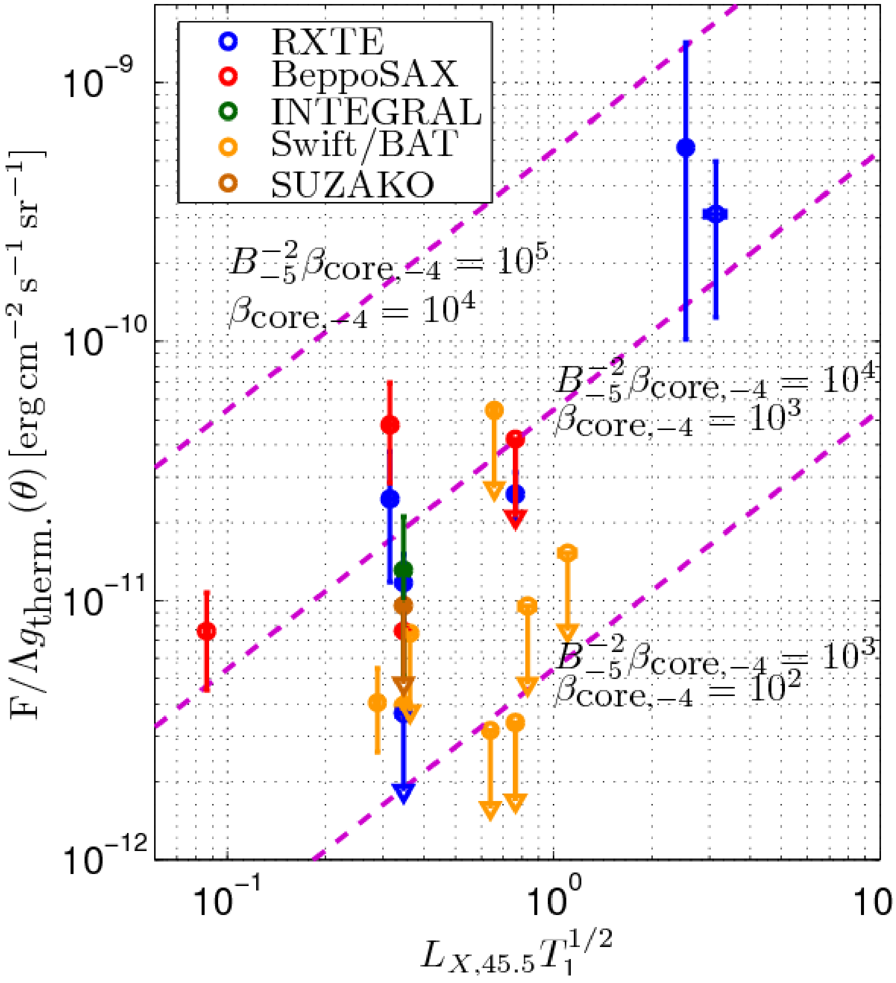
HXR : Primary e$^-$ from accretion shocks

All clusters with HXR observations

Our Model



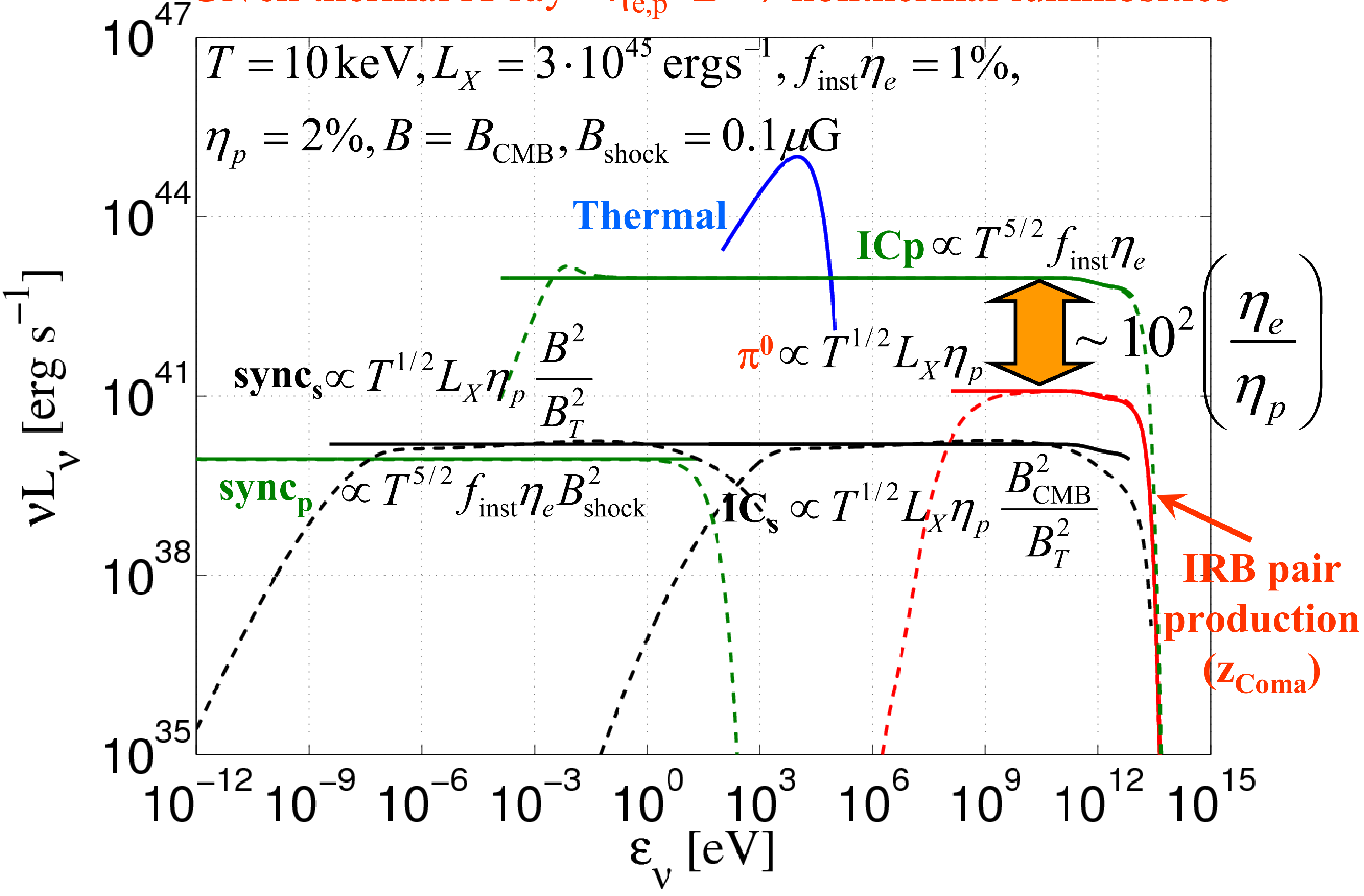
Secondary Models



⇒HXR is not dominated by emission from the cluster’s core

Predictions

Given thermal X-ray+ $\eta_{e,p}$+B ⇒ nonthermal luminosities



Conclusion

Radio-X-ray correlation + HXR consistent with accretion shocks CR origin + $\eta_{e,p}$~0.1.

Predictions

1. High E nonthermal radiation dominated by accretion shock e^- IC - extended emission, follows LSS, different from earlier work:
   - HXR: $IC_p/IC_s \approx 500(\eta_e/\eta_p) \Rightarrow$ NuStar, Simbol-X
   - γ-ray: $IC_p/\pi^0 \approx 150(\eta_e/\eta_p) \Rightarrow$ Fermi$\Rightarrow$ calibrate $\eta_{e,p}$
   - VHE: should lower threshold to ~100 GeV $\Rightarrow$ HESS, MAGIC, VERITAS
2. Single sources can be resolved by future HXR, γ-ray detectors: A2163, A1914, Ophiuchus, A3888, A0754
3. To detect radiation from π^0 decays:
   - Target special objects (Perseus, A3526, NGC 4636, 2A 0335)
   - Subtract IC_p using high resolution HXR measurements.
4. Low frequency radio (ALMA, LOFAR): uncertain extrapolation