Magnetic Fields, Relativistic particles and Nonthermal Emission in Galaxy Clusters

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11.4.2011

arXiv:astro-ph/09032271

arXiv:astro-ph/09032275

arXiv:astro-ph/09051950

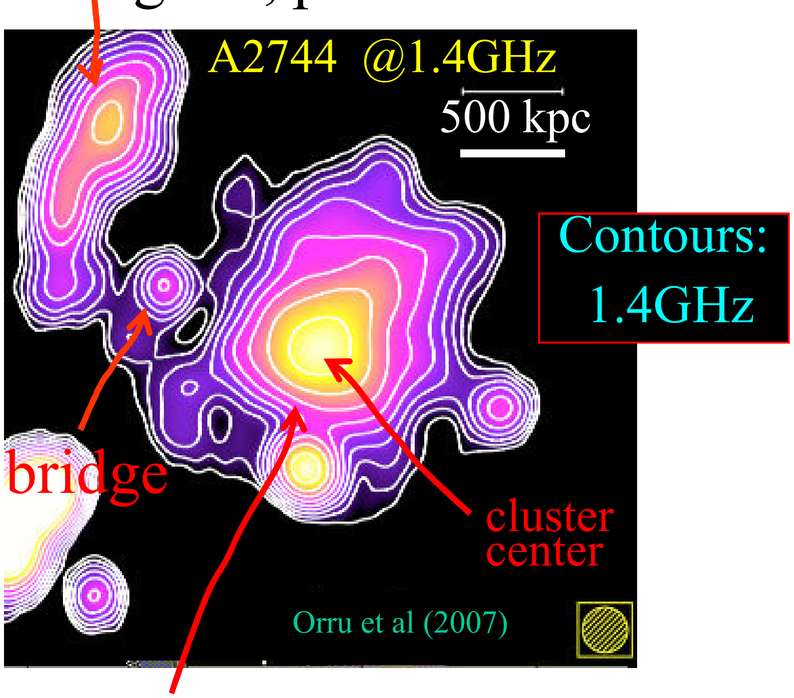
Related work:

arXiv:1003.1133 (Keshet & Loeb)

arXiv1011.0729 (Keshet)

A detailed view (Keshet 2011)

Relics : Peripheral, irregular, polarized



Contours: 1.4GHz

Giant Halos (GHs): Central, regular, unpolarised, R_ν~Mpc
$\alpha\approx$-(1.0-1.5) (flat); -(1.5-2) (steep)

$$I_\nu \propto \nu^\alpha$$

Also: Mini Halos (MHs): Central, regular, unpolarized, R_ν~100 kpc (~cooling region)

Reviews: Feretti et al. (2005), Ferrari et al. (2008)

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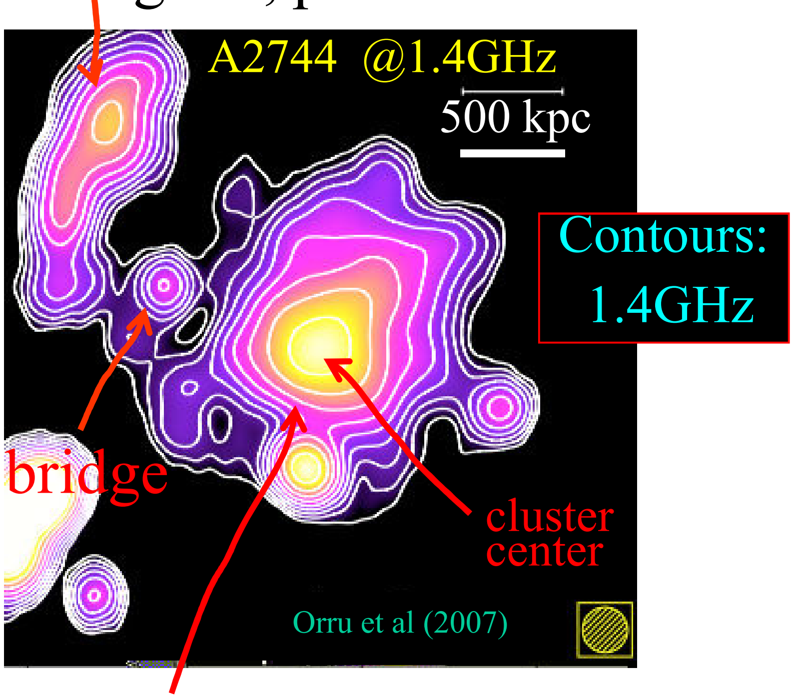

Orru et al (2007)

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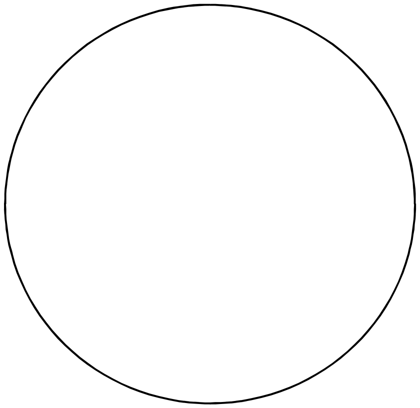
This talk

A galaxy cluster



A detailed view (Keshet 2011)

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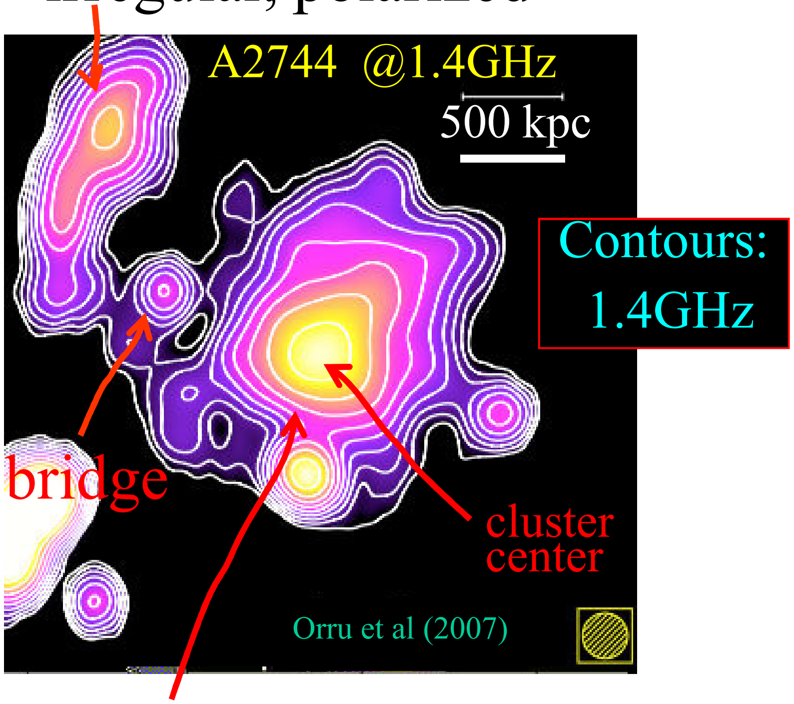

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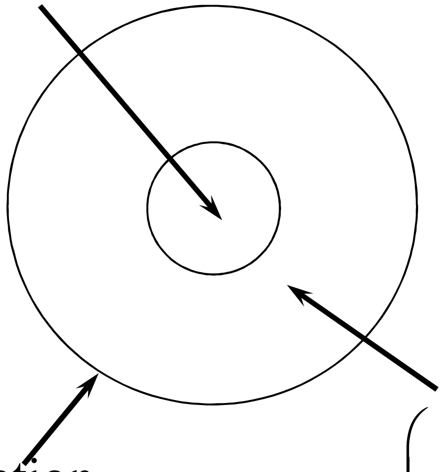
This talk

Massive GCs$\approx 10^{15}M_0$, $T\approx$10 keV

Core, $r_c\approx$300 kpc, $n\approx 10^{-3}$ cm^{-3}



LSS formation models: Virial shock @ ≈few×Mpc, high M

$$n \propto \left(1+\left(\frac{r}{r_c}\right)^2\right)^{-1}$$

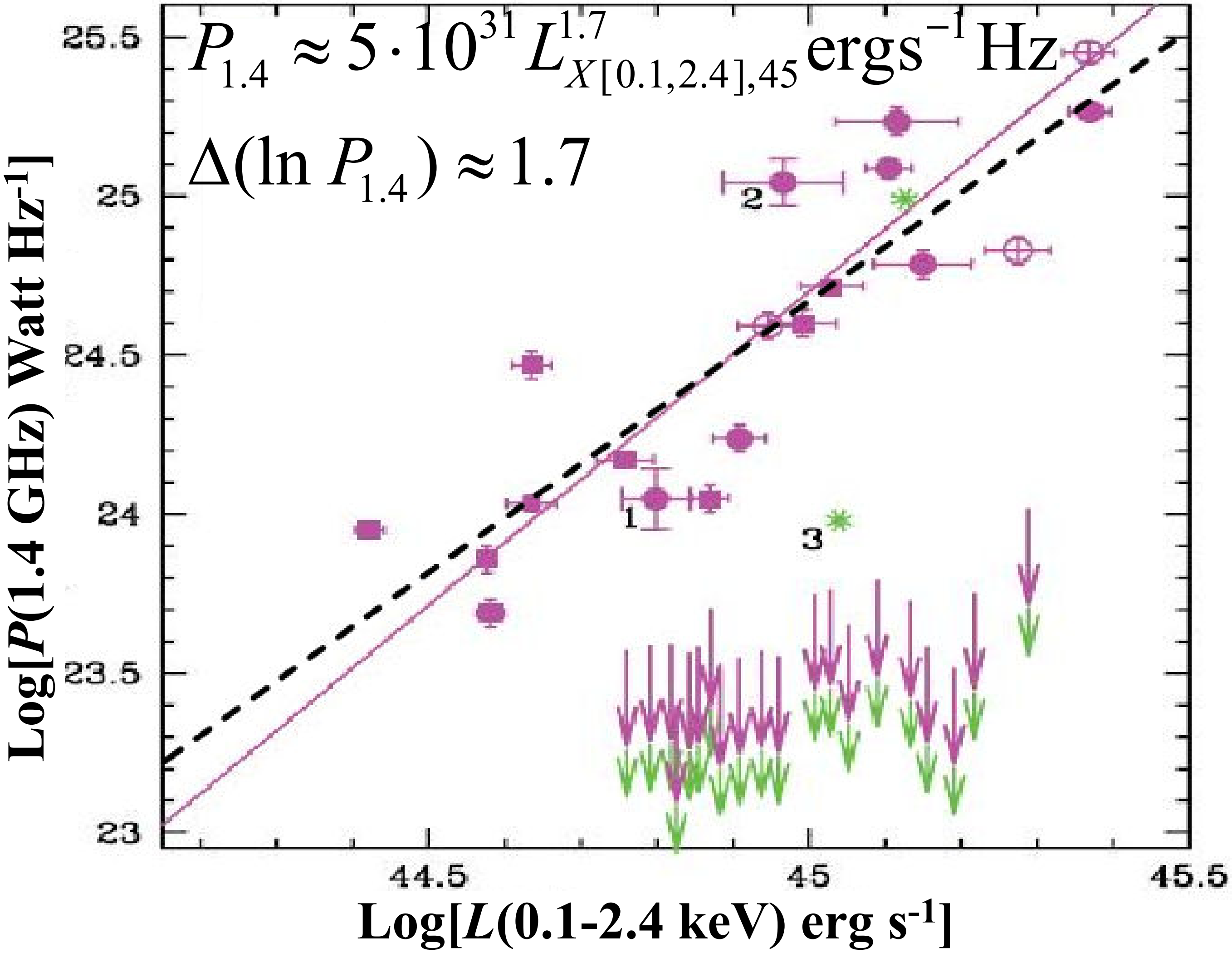
CC: cooling flow, relaxed

NCC, merging: distortion + low M shocks

Concentrate on flat GHs.

MHs: Keshet & Loeb 2010, Relics: Keshet 2010

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

Radio-*X*-ray Correlation: Observational Constraints

- $\beta_{\mathrm{core}} \equiv (\varepsilon^2 dn/d\varepsilon)/\varepsilon_{th} \sim 10^{-4}$

- β_{core} values + small scatter are naturally explained by CR production in 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.

A Simple Model

Ionized Hydrogen Plasma: $n,\ T$

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

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

Thermal *X*-ray bremsstrahlung

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

Energy production rate of secondaries per logarithmic secondary energy interval

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

Secondaries lose all energy to synchrotron radio emission

$$\Rightarrow \frac{\nu L_\nu^{\rm sync}}{L_X} \approx 10^{-5} \beta_{{\rm core},-4} T_1^{1/2}, \qquad \beta_{-4} \equiv \beta/10^{-4}, \quad T_1 \equiv T/10\,{\rm keV}$$

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

Model Vs. Observations

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

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

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

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

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 ∝ $\rho^{1/3}$

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

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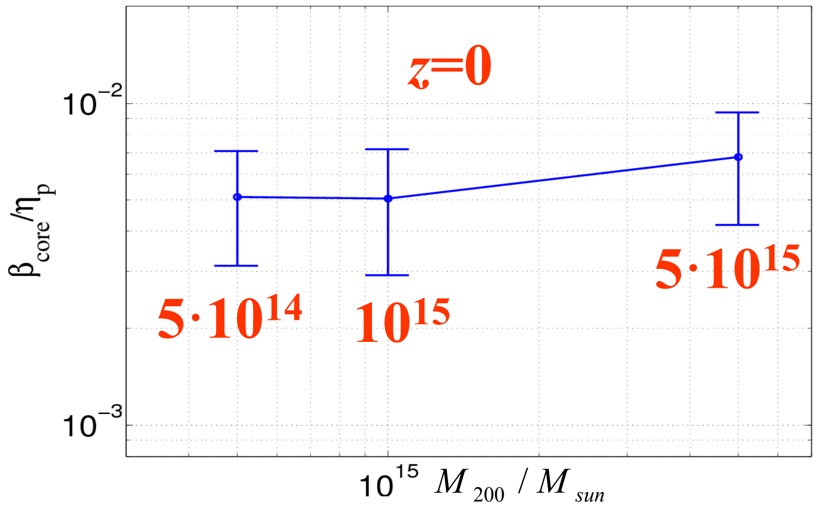
2. Small scatter



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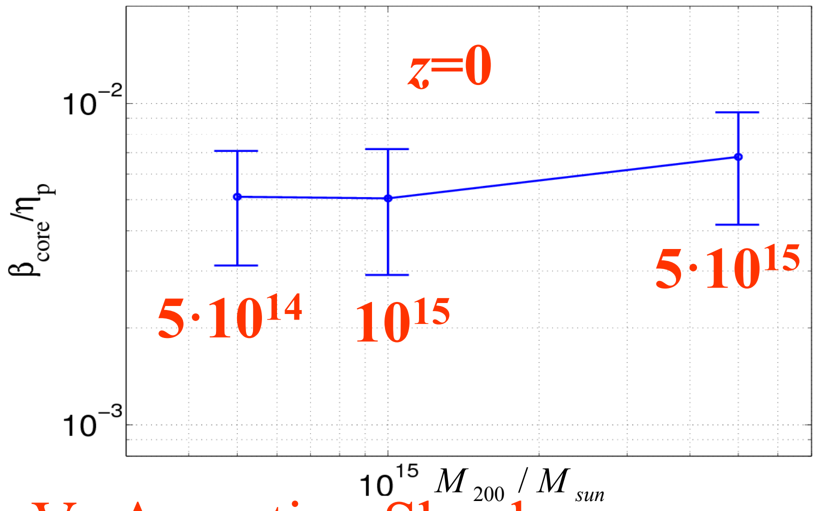


3. CR source : SNe Vs Accretion Shocks

$$\frac{\beta_{\rm core}^{\rm SN}}{\beta_{\rm core}^{\rm acc}} \approx 1.6\,\frac{\beta_{\rm CR}^{\rm SN}}{\beta_{\rm CR}^{\rm acc}}\,F_{\rm cool}\left(\frac{E_{\rm SN}}{10^{51}\ {\rm erg}}\right)\left(\frac{\delta M_{Fe}}{0.1 M_{\rm sun}}\right)^{-1} T_1^{-1}$$

Radio-*X*-ray Correlation: Observational Constraints

☑ $\beta_{\rm core} \equiv (\varepsilon^2 dn/d\varepsilon)/\varepsilon_{th} \sim 10^{-4}$

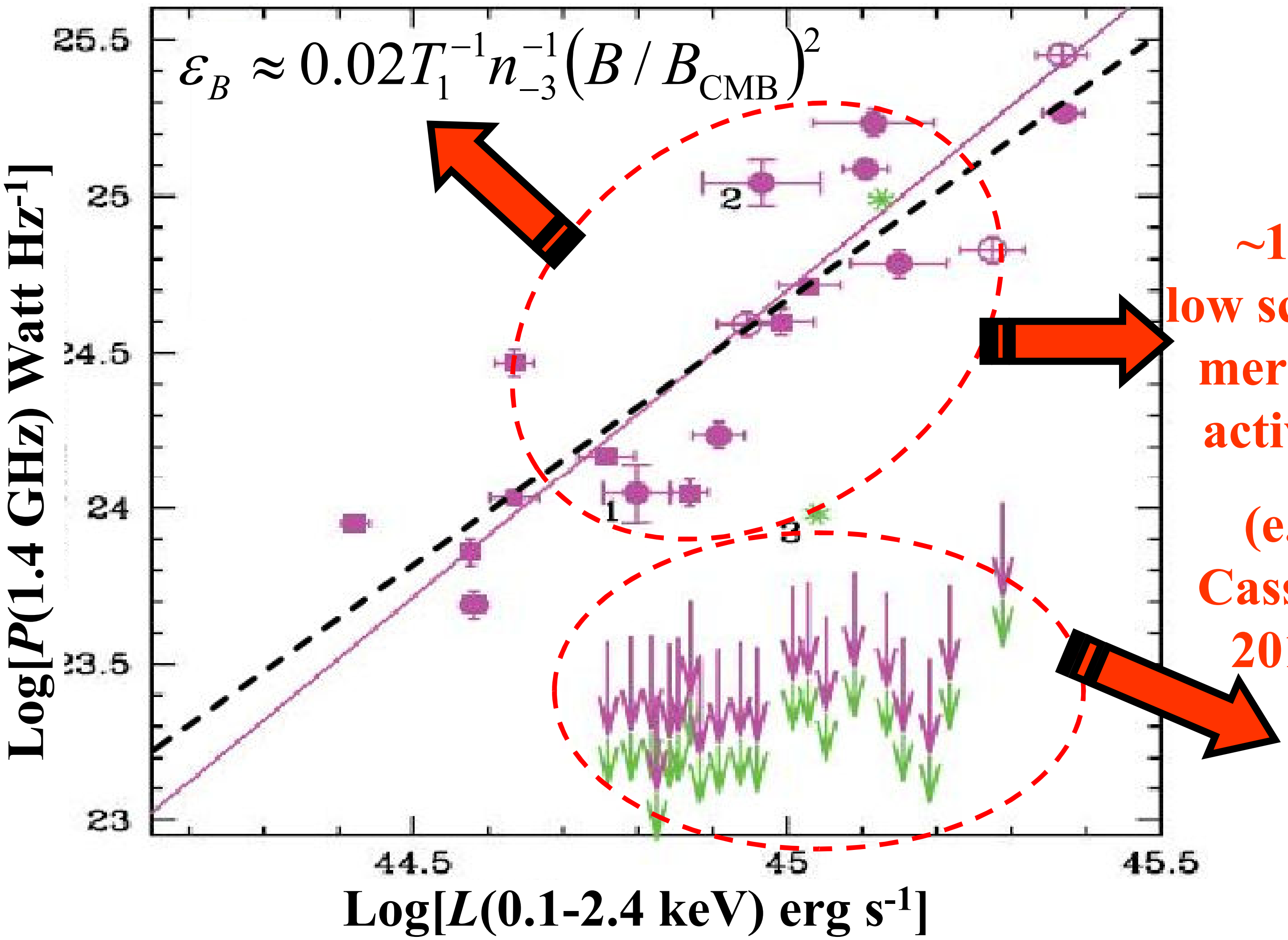
☑ $\beta_{\rm core}$ values + small scatter are naturally explained by CR production in accretion shocks

☑ $\eta_p \sim$ 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.

Radio Vs. *X*-ray Correlation - Bimodality



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

~1/3,
low scatter,
merging
activity,

(e.g.
Cassano
2011)

~2/3

Brunetti et al, ApJ, 670, L5

Radio-*X*-ray Correlation: Observational Constraints

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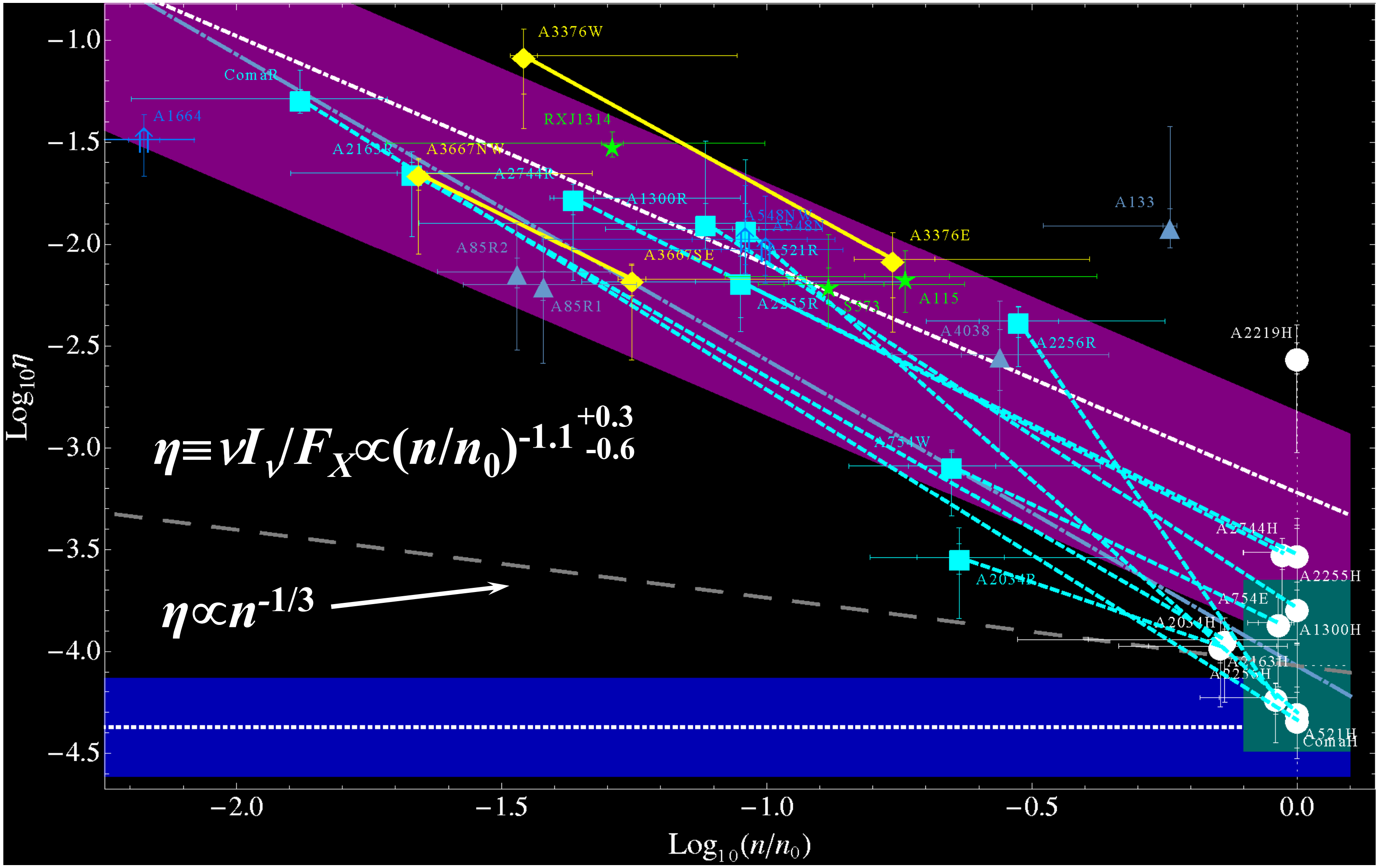
Extension to MHs and relics (Keshet 2010)



All radio emission is due to secondaries in a strong magnetic field.

Homogeneous CRs distribution? (ASCA data, local enhancement, scatter)

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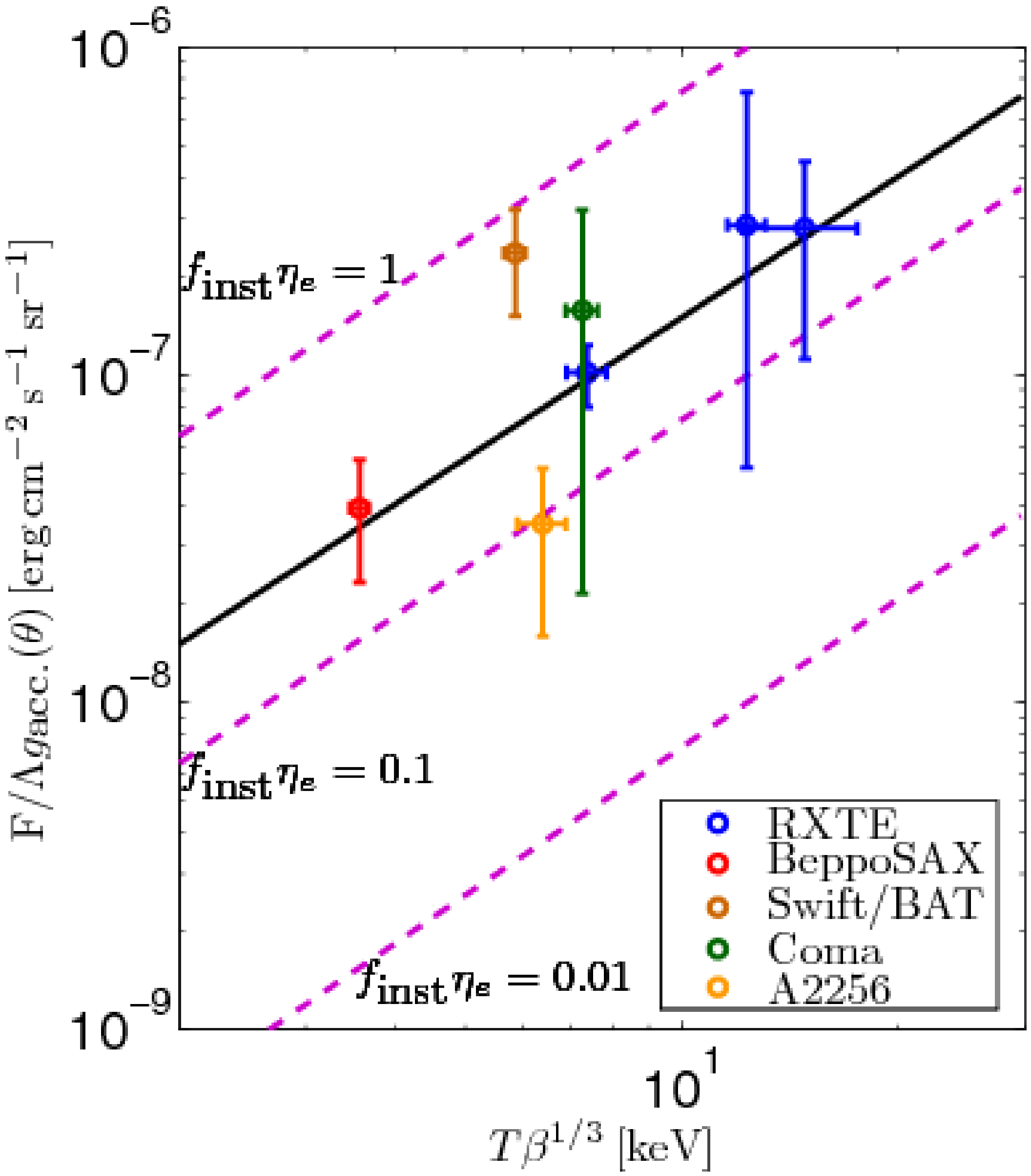
$$\frac{S}{\Lambda} \propto \frac{\nu L_\nu^{\mathrm{shock}}}{r_{200}^2} \propto f_{\mathrm{inst}} \eta_e T^{3/2}$$

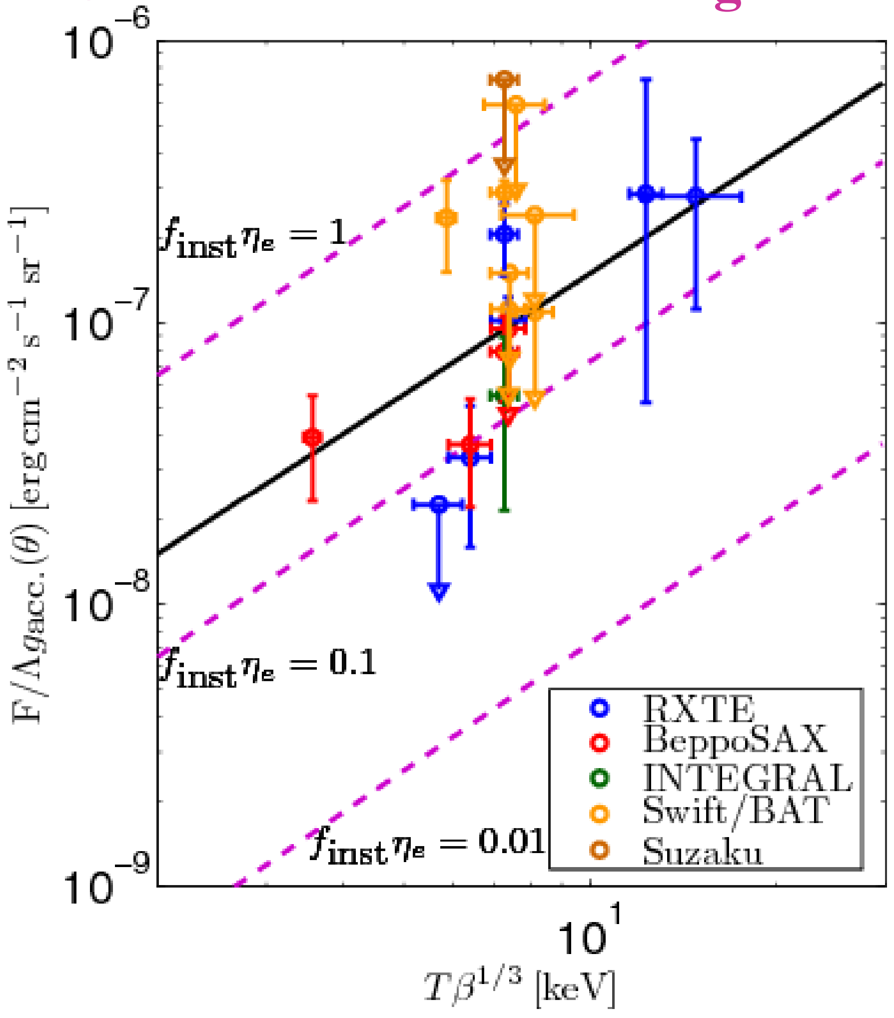
$$\Rightarrow f_{\mathrm{inst}} \eta_e \sim 10\%$$



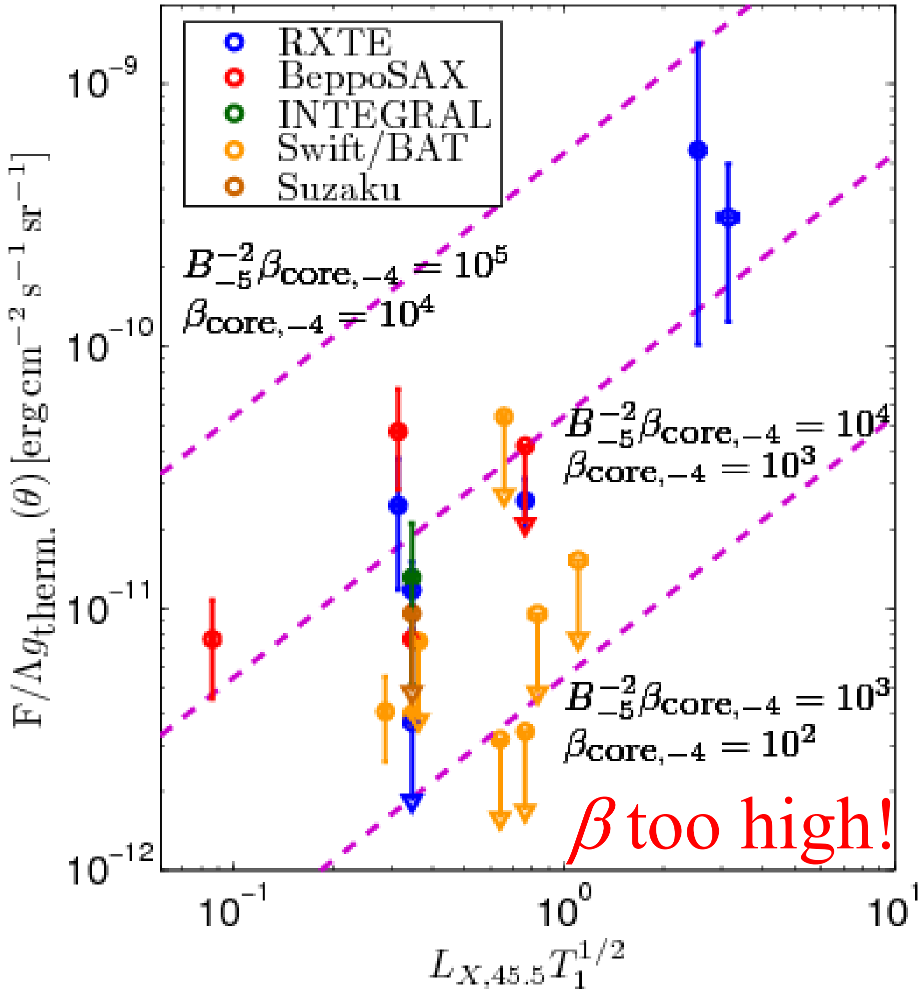
HXR : Primary e^- from accretion shocks

All HXR observations - comparing instruments with different FOV

Our model - ≈uniform brightness



Secondary models - core dominated



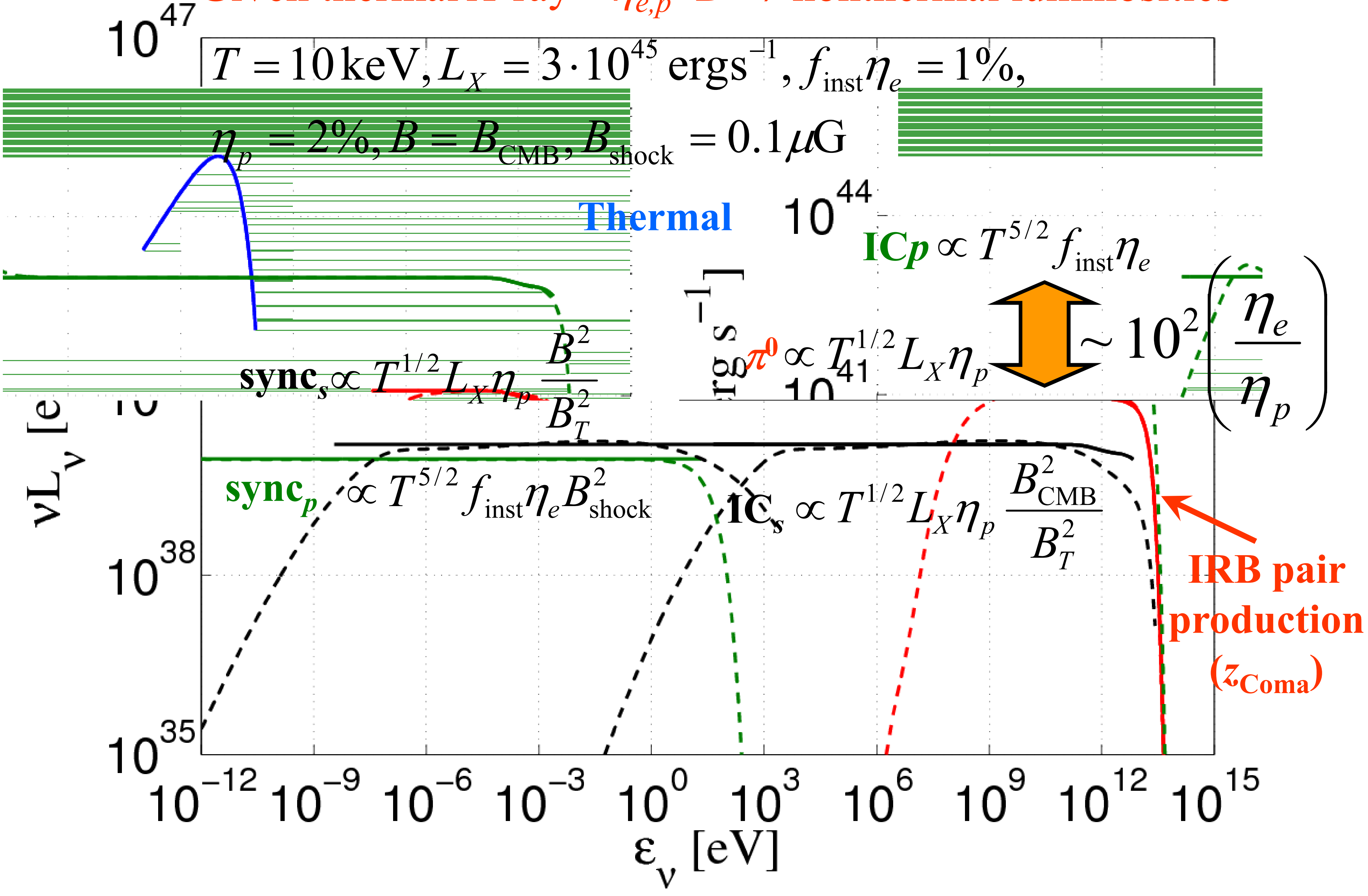
β too high!

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

Also confirmed for Coma by Wik et al 2011 (but accretion shock not detected by Swift)

Predictions

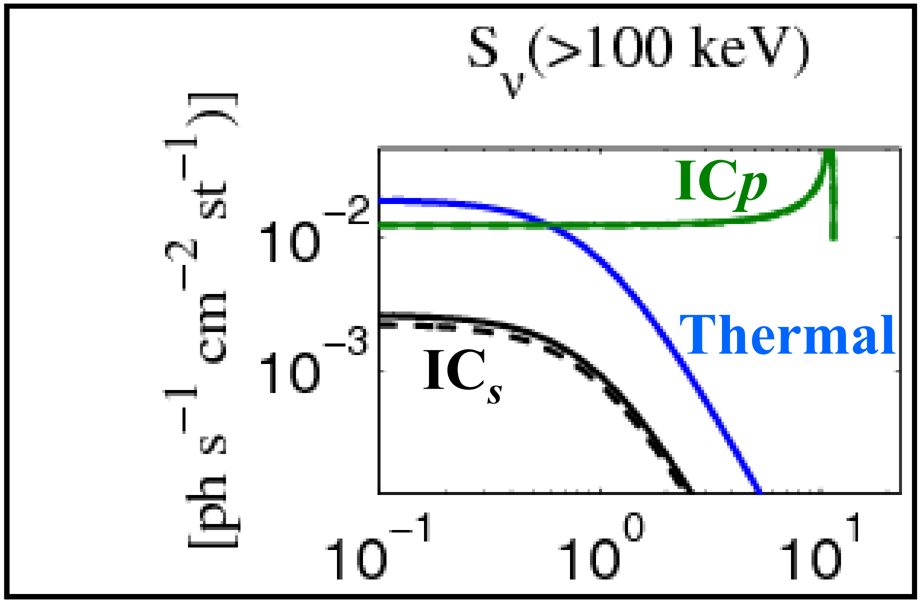
Given thermal X-ray+ $\eta_{e,p}$+$B \Rightarrow$ nonthermal luminosities

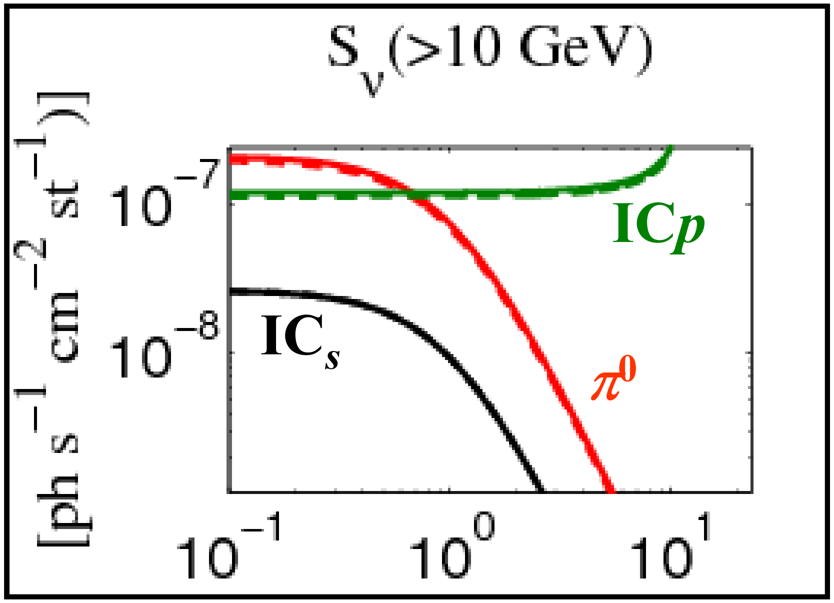


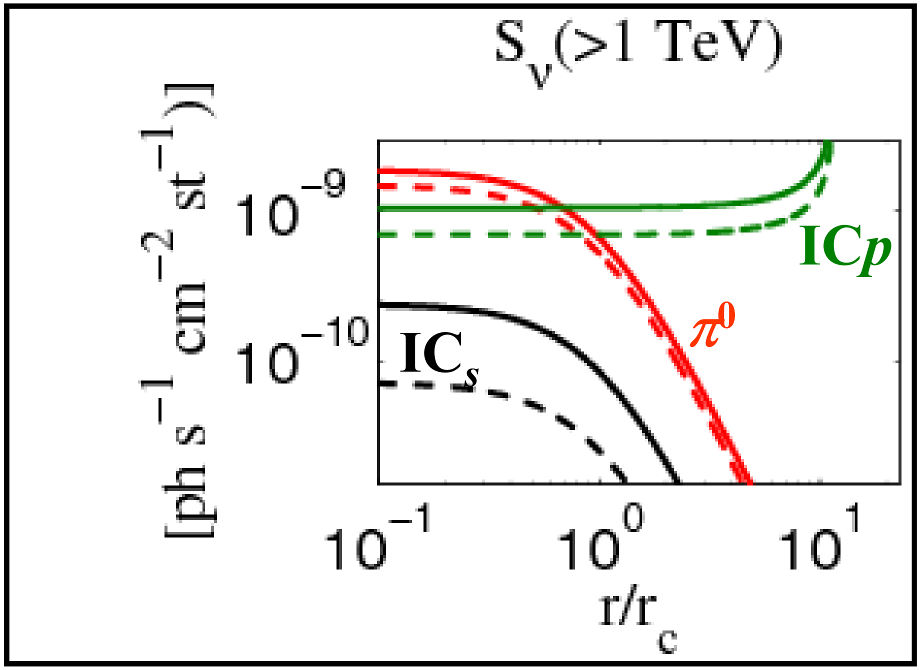
$T = 10\,\mathrm{keV}, L_X = 3\cdot 10^{45}\,\mathrm{erg\,s^{-1}}, f_{\mathrm{inst}}\eta_e = 1\%,$

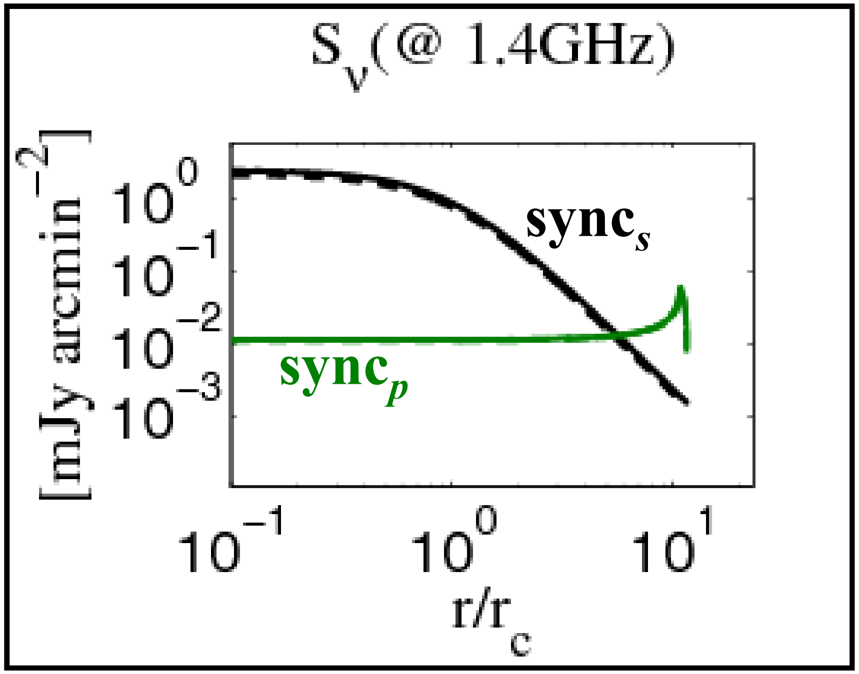
$\eta_p = 2\%, B = B_{\mathrm{CMB}}, B_{\mathrm{shock}} = 0.1\mu\mathrm{G}$

Predictions - Surface Brightness


S_ν(>100 keV)

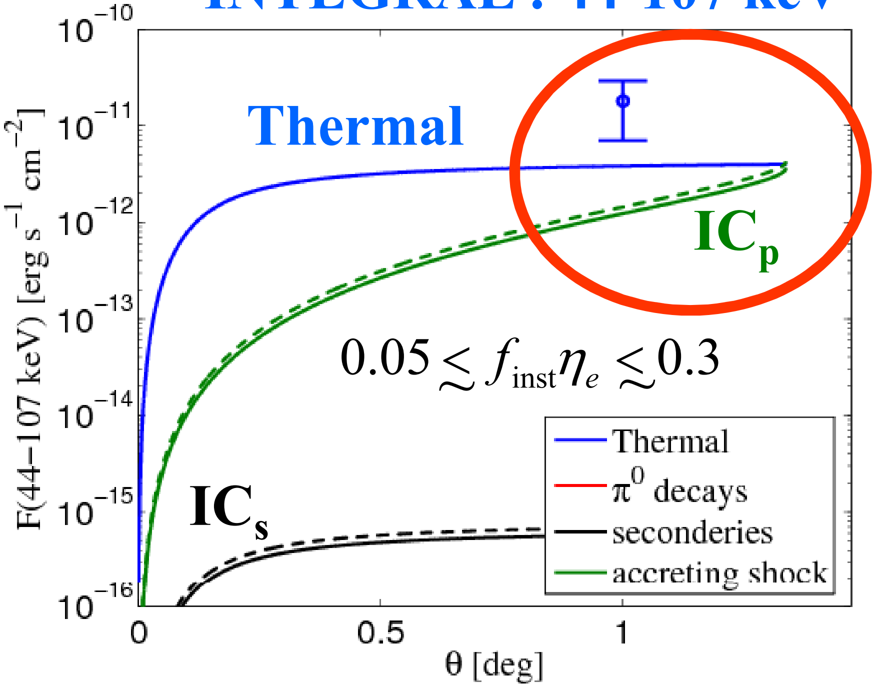

S_ν(>10 GeV)


S_ν(>1 TeV)


S_ν(@ 1.4GHz)

Model prediction Vs. Coma Observations

INTEGRAL : 44-107 keV



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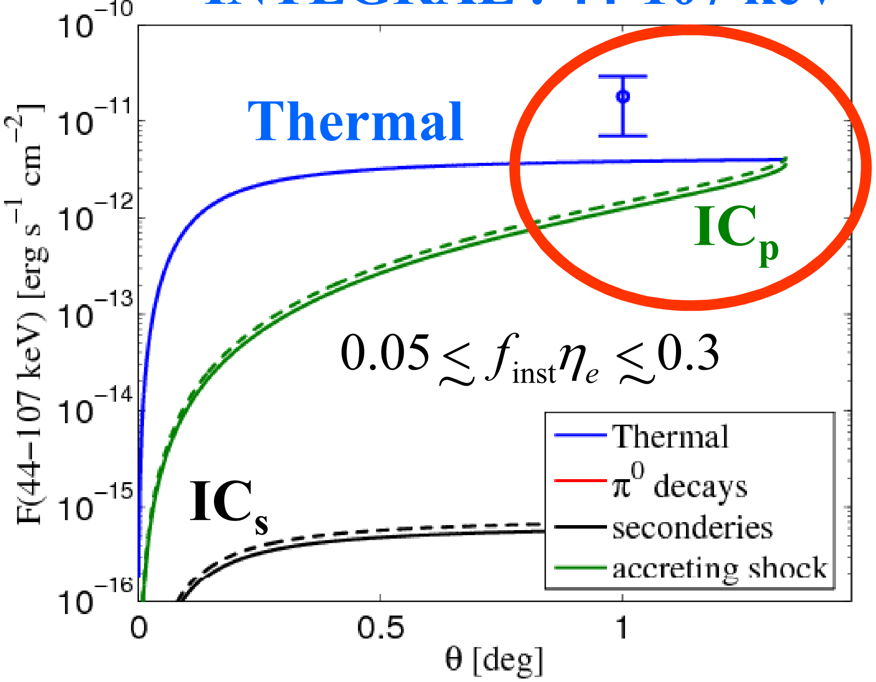
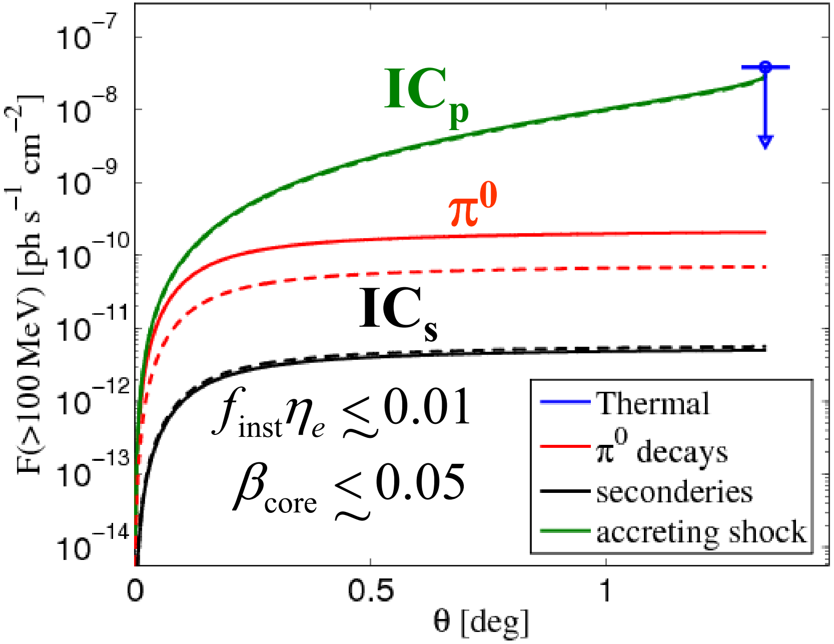


EGRET : > 100 MeV



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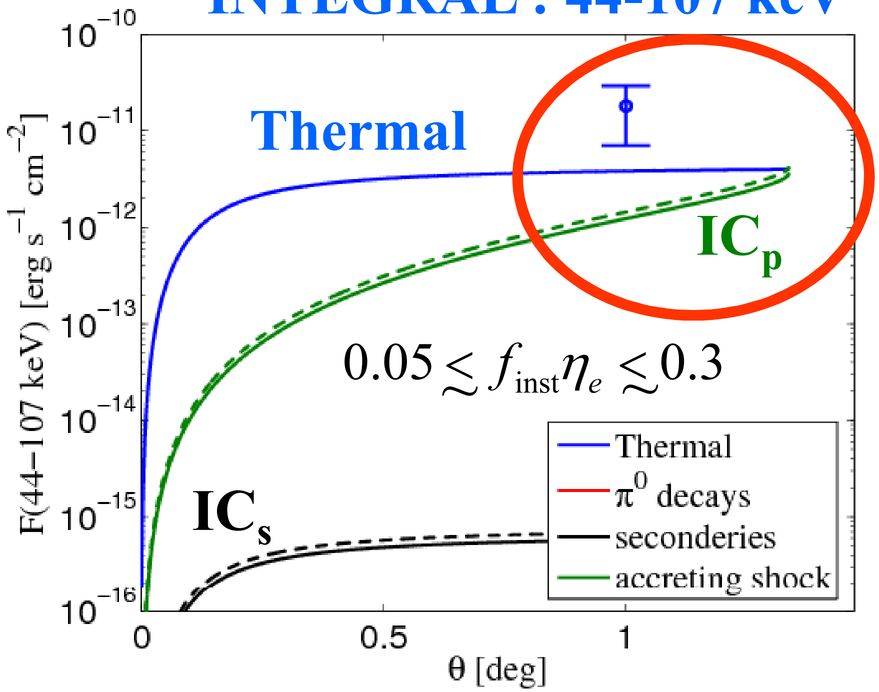

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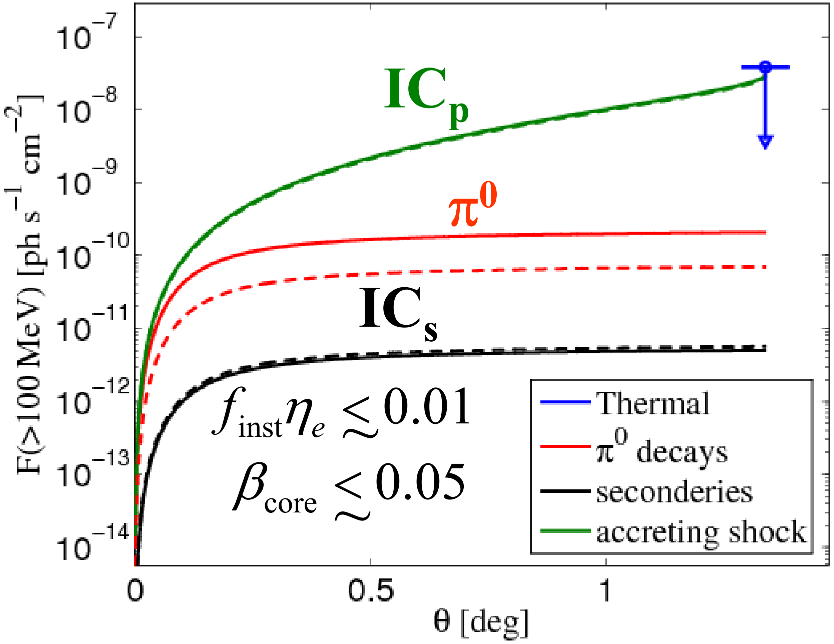

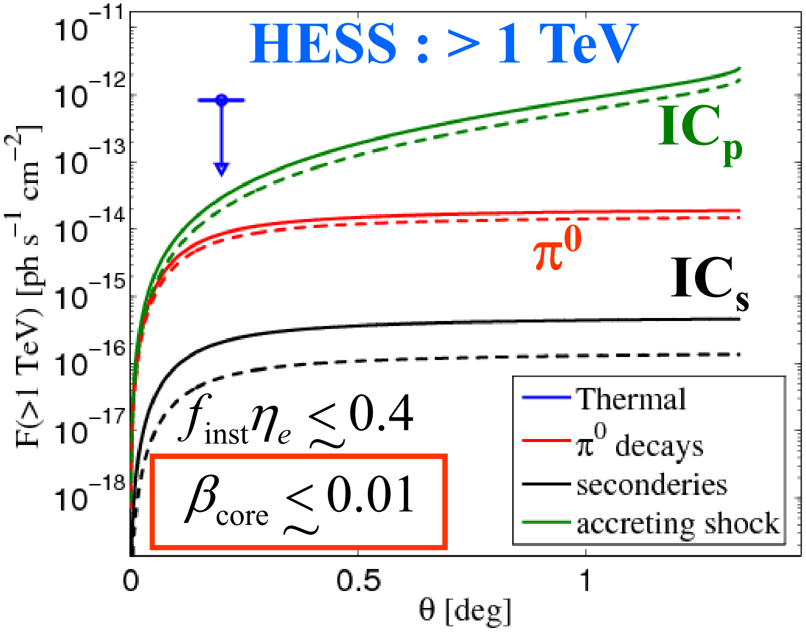

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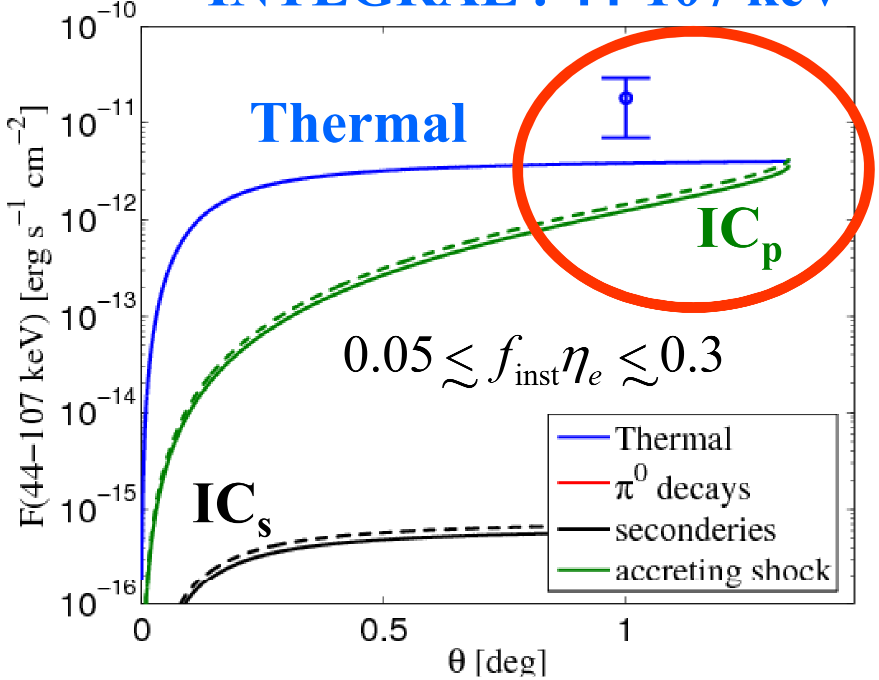

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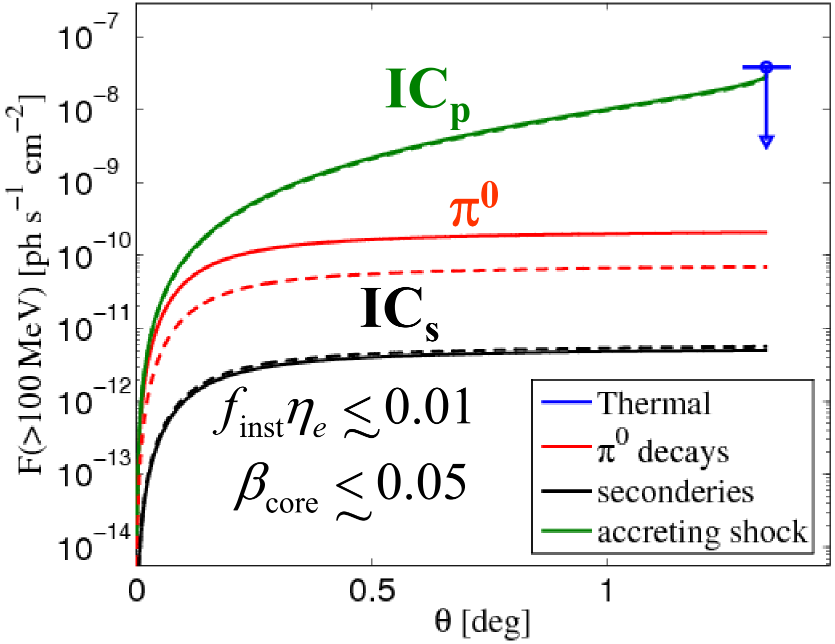

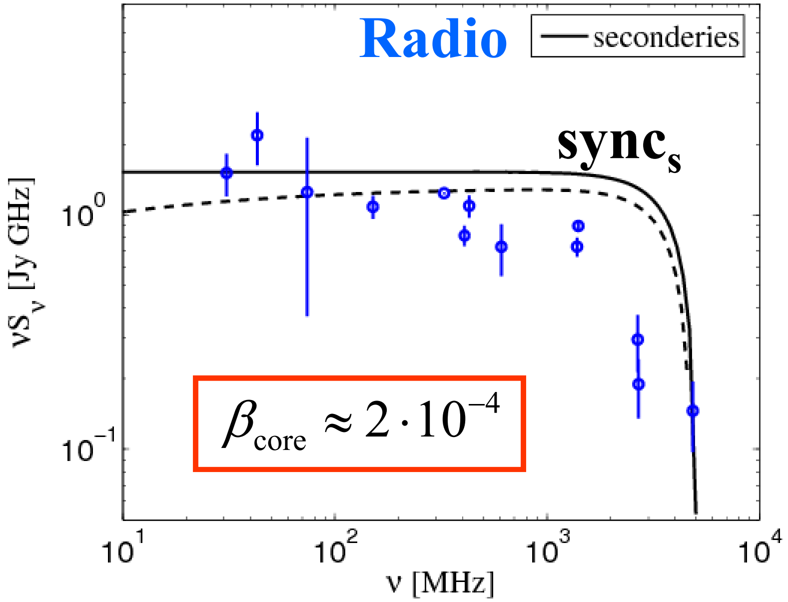

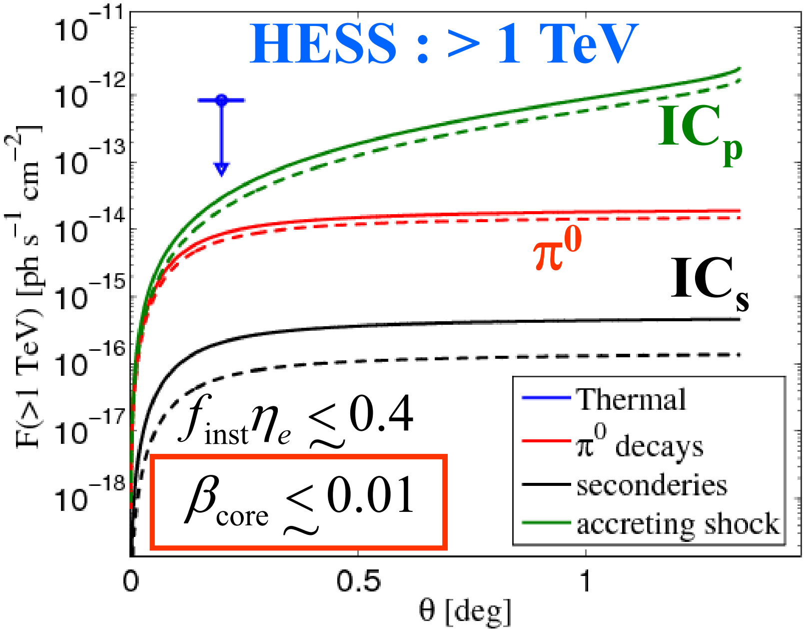

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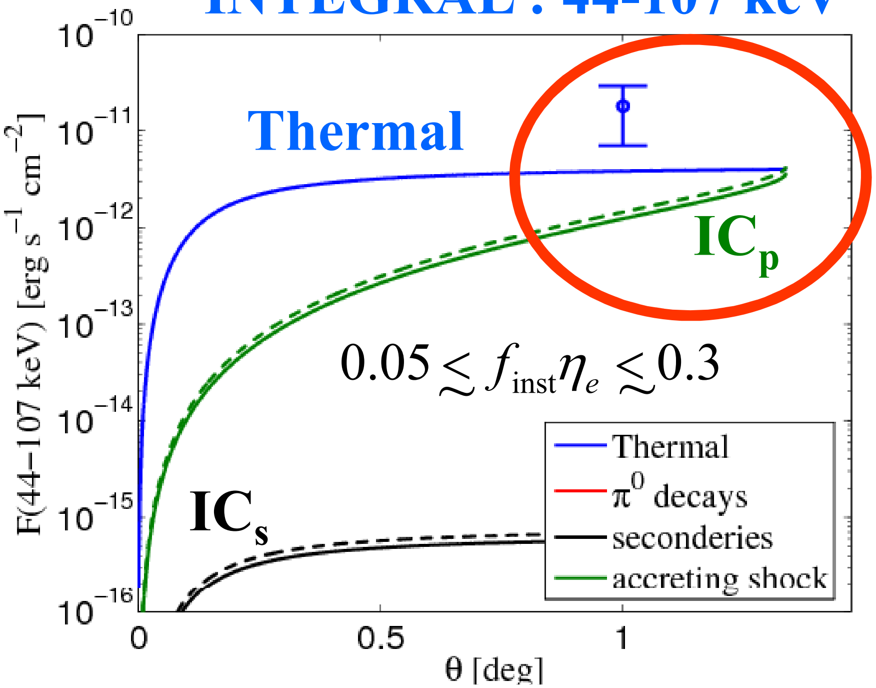

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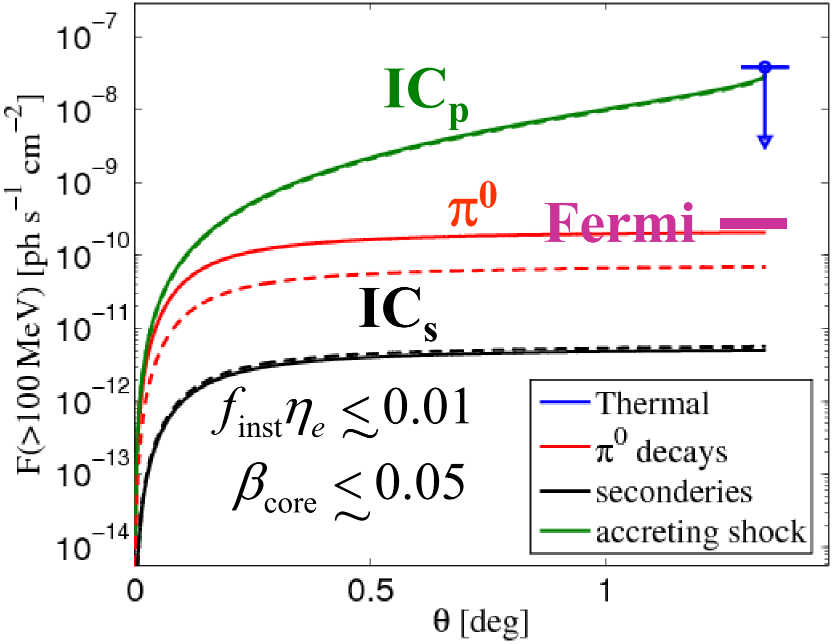
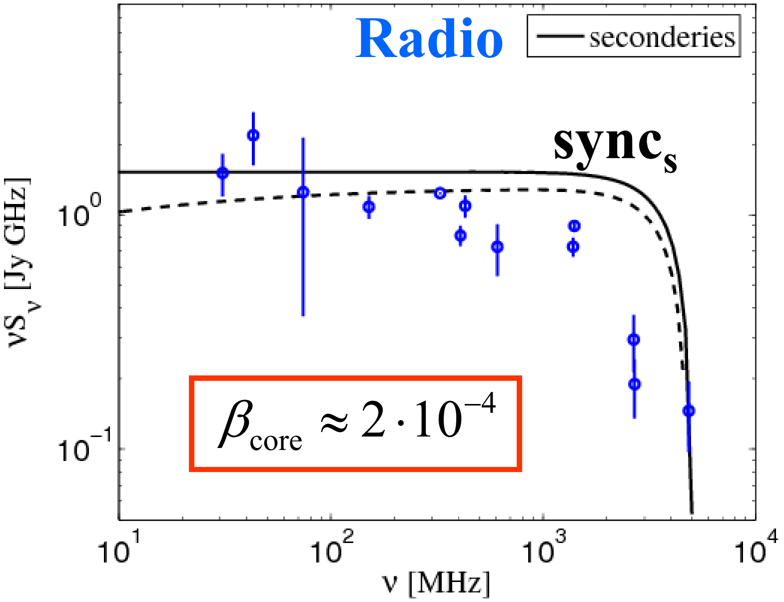
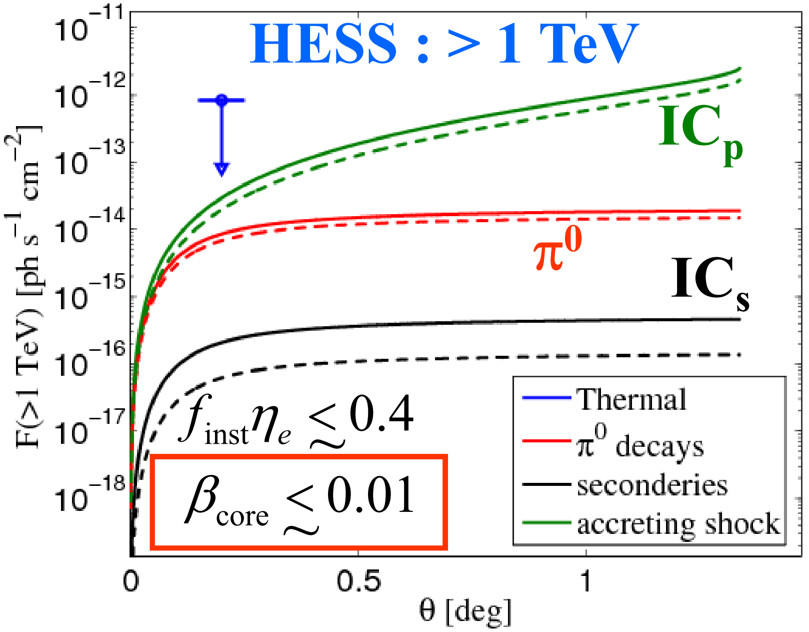



Radio


HESS : > 1 TeV

Predictions

All predictions depend on the values of $\eta_{e(p)}$

radio+HXR suggest $\eta_{e(p)}$~few %. In this case:

- High E nonthermal radiation dominated by accretion shock e^- IC
- extended emission, follows LSS.
- different from earlier work (π^0 and IC_s dominated, core dominated)

To be tested by:

- HXR: $IC_p/IC_s \approx 500(\eta_e/\eta_p) \Rightarrow$ NuStar, Simbol-X + resolve single sources
- 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

To detect radiation from π^0 decays:

- Target special objects (Perseus, A3526, NGC 4636)
- Subtract IC_p using high resolution HXR measurements.

Cocnclusion

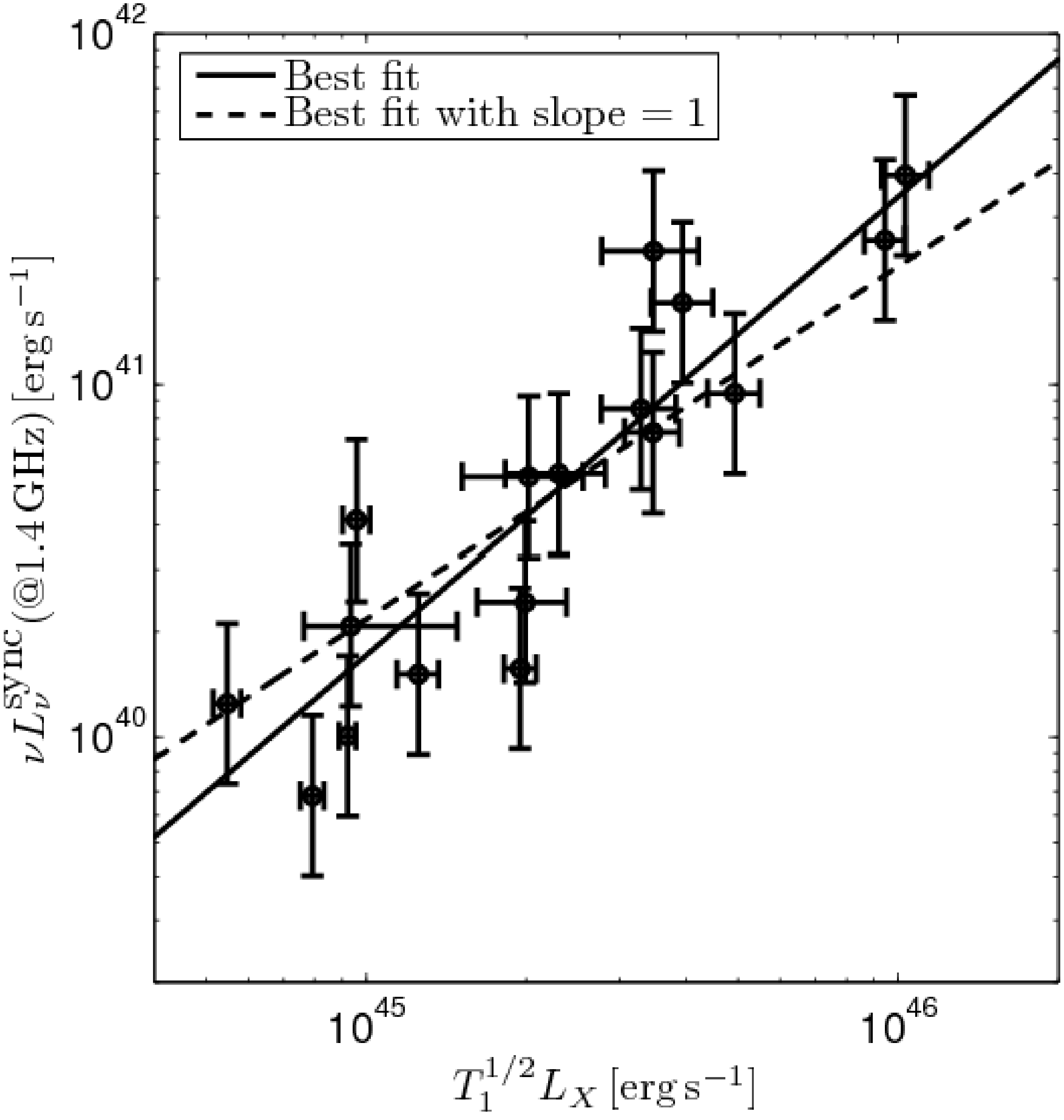
- Radio-X-ray correlation explained by a simple model with $\beta_{\rm core} \equiv (\varepsilon^2 dn/d\varepsilon)/\varepsilon_{th} \sim 10^{-4}$ and small scatter.

- $B > B_{\rm CMB}$ is required: Cluster magnetic fields are probably enhanced by mergers to ≥ 1% of EP (with gas) & Decay (to < 1 μG) on 1 Gyr time scale (possibly to EP with CRs).

- Both of $\beta_{\rm core}$ properties are naturally explained by CR production in accretion shocks with $\eta_p \sim$ few %

- HXR consistent with accretion shocks CR origin + $\eta_e \sim$ few %.

- Predictions - High E nonthermal radiation dominated by accretion shock e^- IC: extended emission, follows LSS, different from earlier work. To be tested by future HXR, γ-ray, VHE observations.


Best fit
Best fit with slope = 1
10^{42}
10^{41}
10^{40}
$\nu L_\nu^{\rm sync}(@1.4\,{\rm GHz})\,[{\rm erg\,s^{-1}}]$
10^{45}
10^{46}
$T_1^{1/2} L_X\,[{\rm erg\,s^{-1}}]$