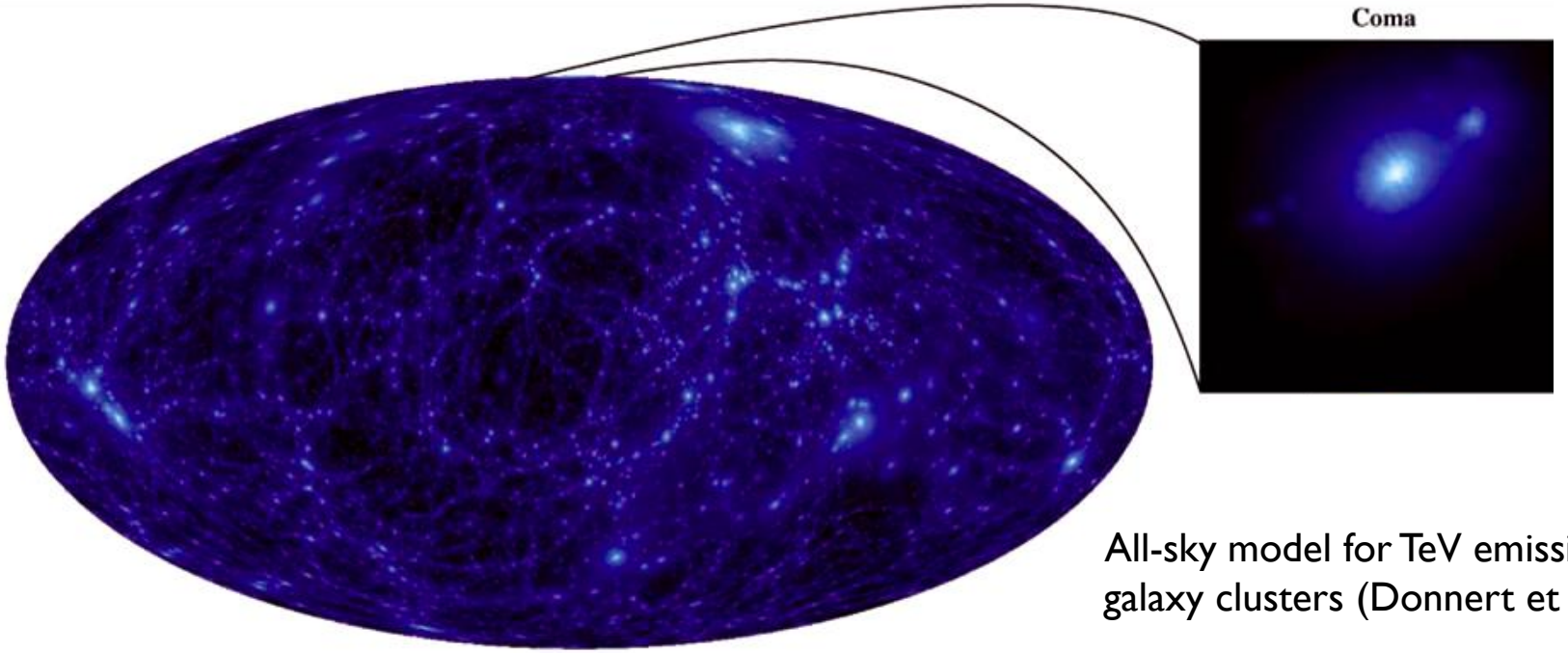


All-sky model for TeV emission from galaxy clusters (Donnert et al. 2010)

Gamma-ray Observations of Galaxy Clusters: A Brief Review

Keith Bechtol for the *Fermi*-LAT Collaboration

TeVPA / IDM, 23 June 2014

Kavli Institute
for Cosmological Physics
at The University of Chicago

Fermi
Gamma-ray
Space Telescope

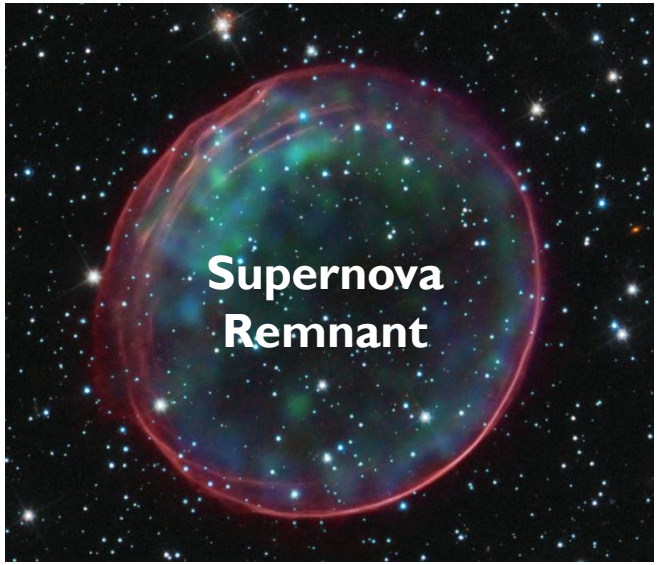
Topics

- No compelling detection of high-energy emission from the intracluster medium (ICM) yet
  - keV, GeV, and TeV observations
  - Constraints on CR energy density and B-fields

- Multiwavelength progress and opportunities

- Dark matter ⇨ see talk by Stephan Zimmer

Unique CR Accelerators



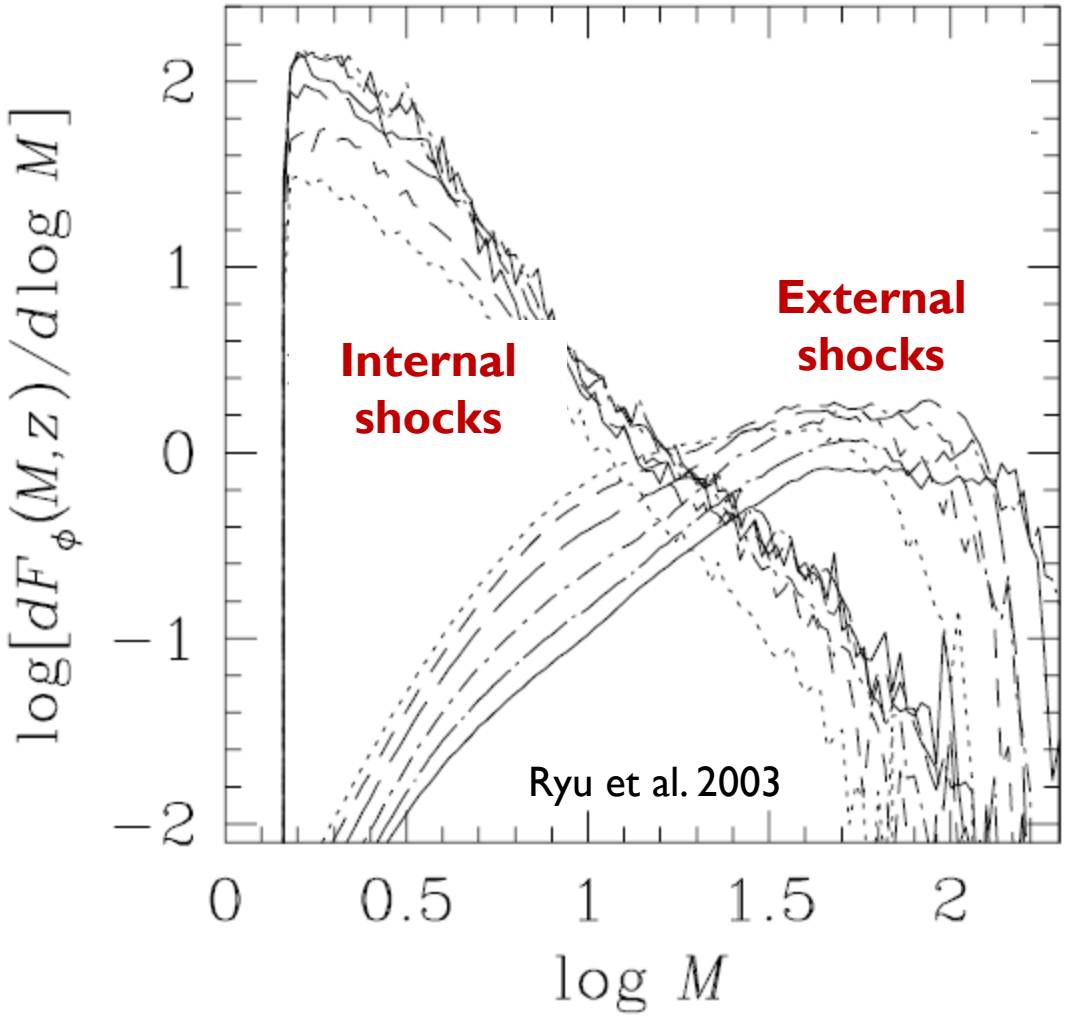
- Mpc-scale
- High beta-plasma
- Weak (M ~ 2 - 4)
- **CR efficiency ??**

- Pc-scale
- Low beta-plasma
- Strong (M ~ 1000)
- CR efficiency ~ 10%

$$\beta_{pl} = P_{gas} / P_B$$

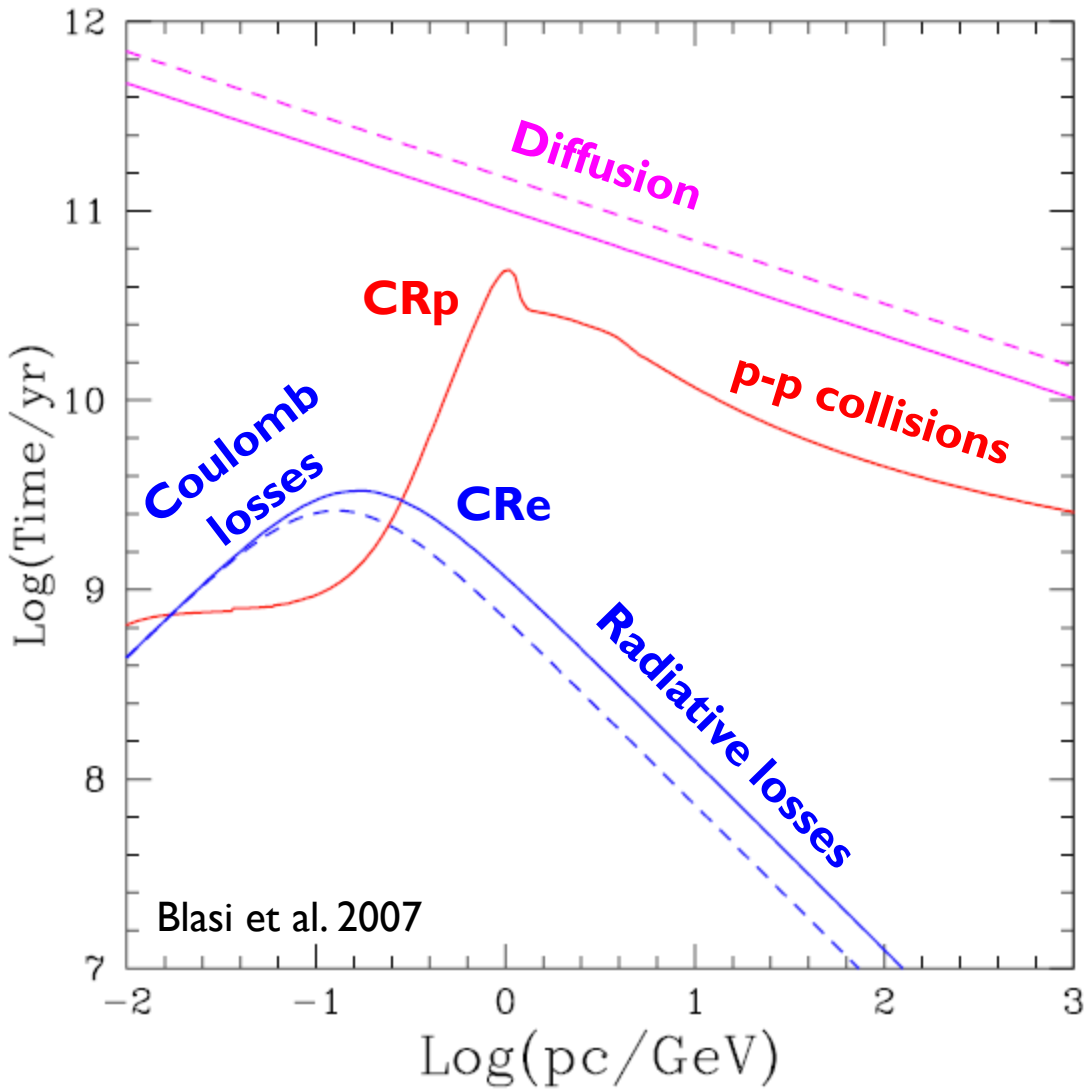
Large-Scale Shocks

- **Enormous energies** associated with merger events (10^{63} – 10^{64} erg)
- Majority of energy dissipated in **weak shocks** (M ~ 2 - 4)
- Also CR injection by galaxies and AGN which may be reaccelerated



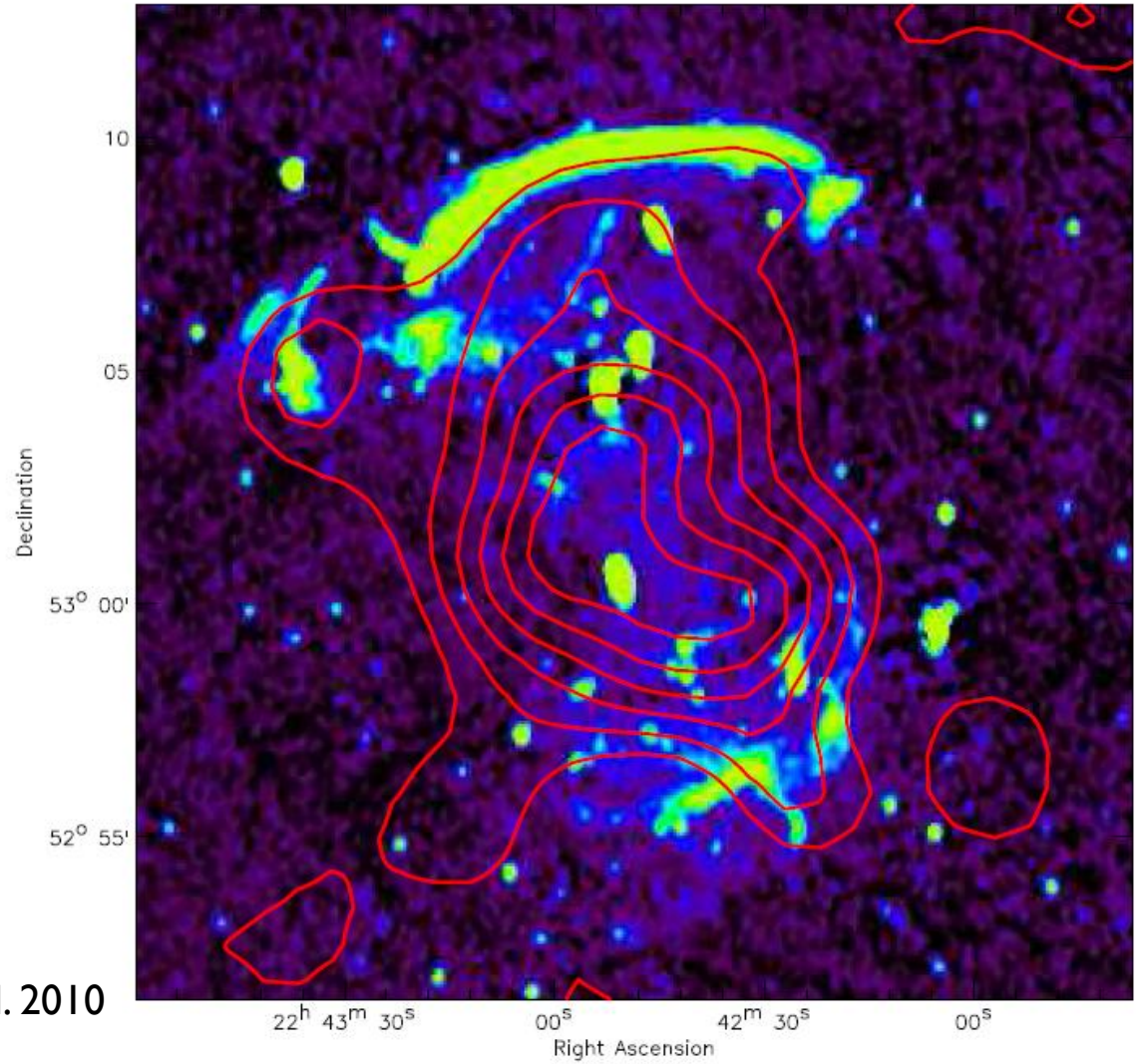
Unique CR Reservoirs

- CR electrons responsible for GHz emission must be constantly replenished
- CR protons accumulate in ICM over Gyrs
- CR protons encode integrated non-thermal history of large-scale structure formation



Mpc-scale Radio Features

- Relics
- Halos

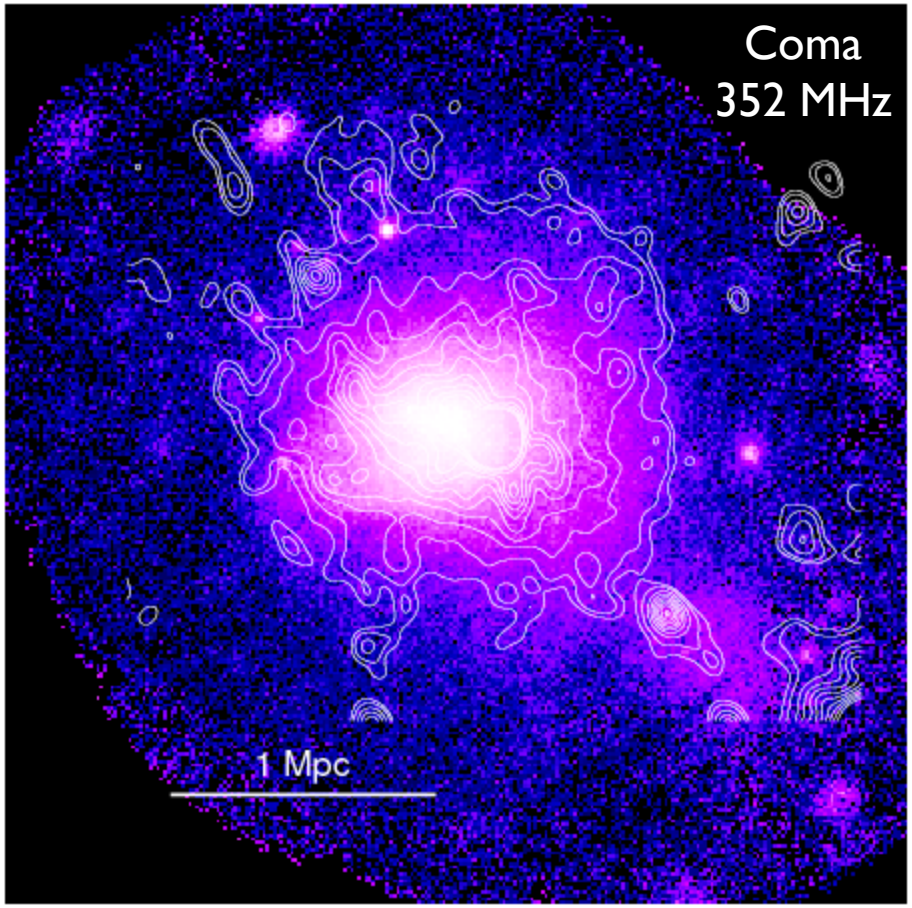


Van Weeren et al. 2010

Mpc-scale Radio Features

- Relics
- Halos

Only ~1/3 clusters host giant radio halos, and only merging systems

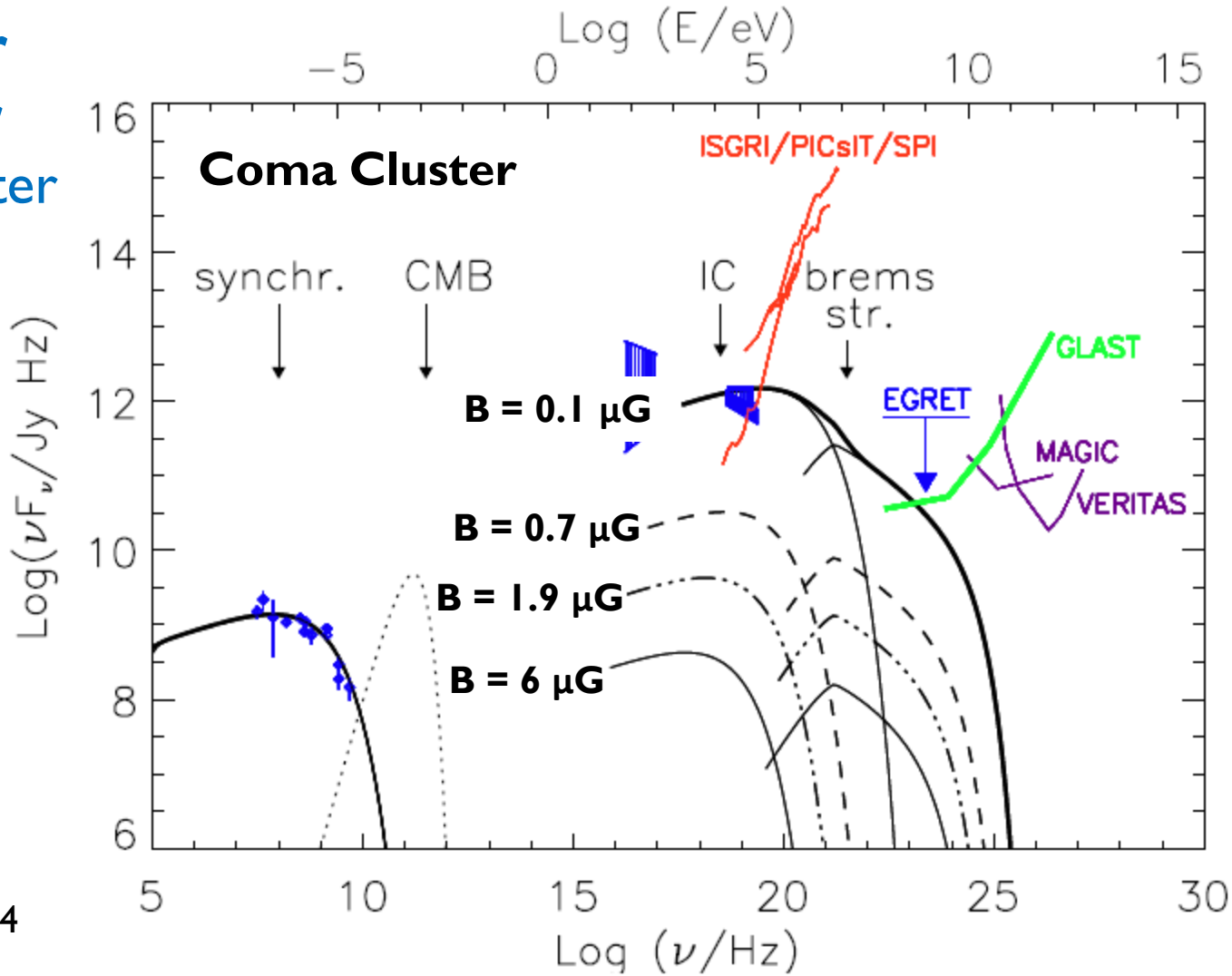


Brown & Rudnick 2011, Markevitch 2010

Are radio halos secondary in origin?

Broadband Non-thermal Spectra

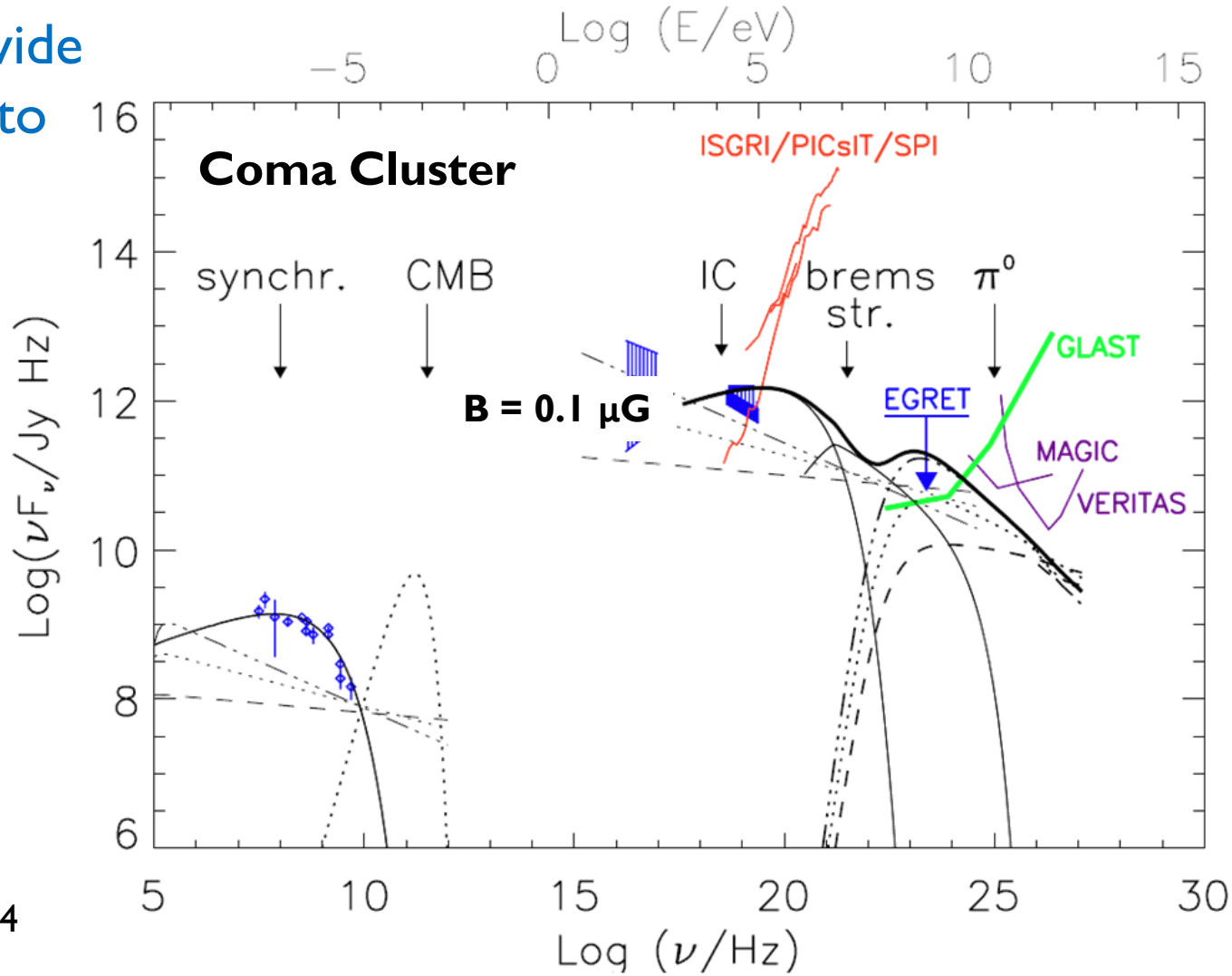
High-energy **upper limits** imply **lower limits** on intracluster magnetic field



Reimer et al. 2004

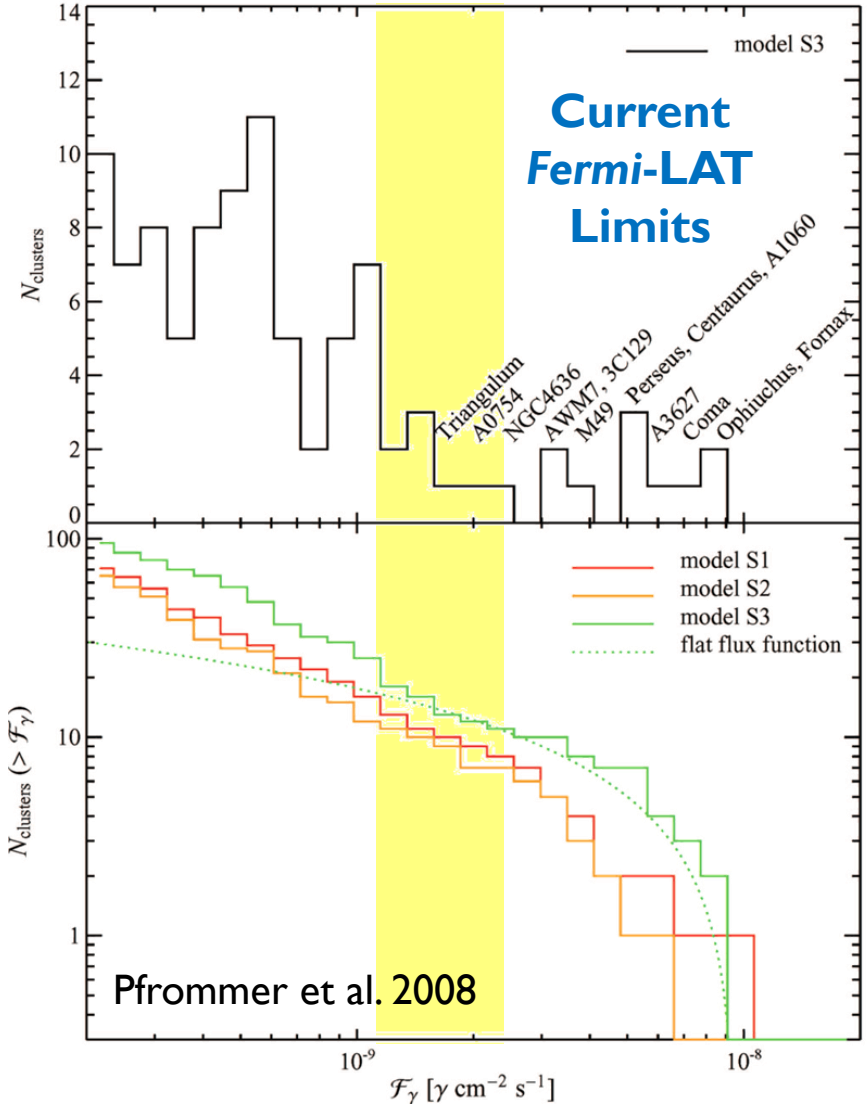
Broadband Non-thermal Spectra

Gamma rays provide most direct access to **CR protons**



Reimer et al. 2004

Gamma-ray Predictions pre-*Fermi*

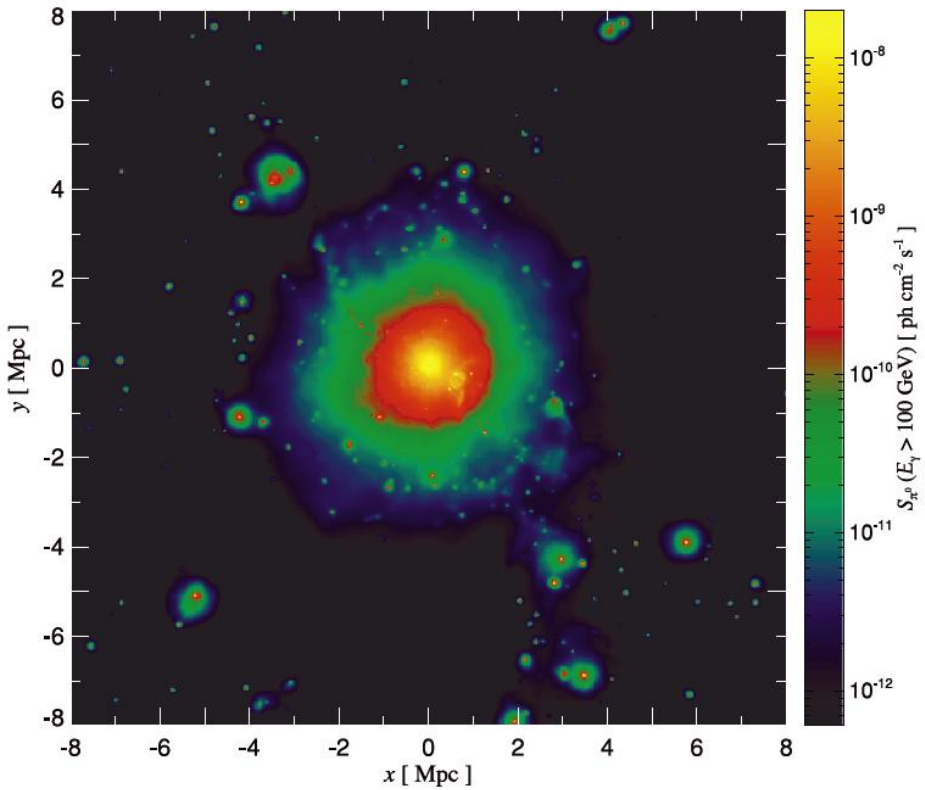


- Several groups anticipated that ~10 clusters might be detectable with *Fermi* LAT
- Predicated on uncertain acceleration efficiencies, especially for low Mach number (i.e., weak) shocks

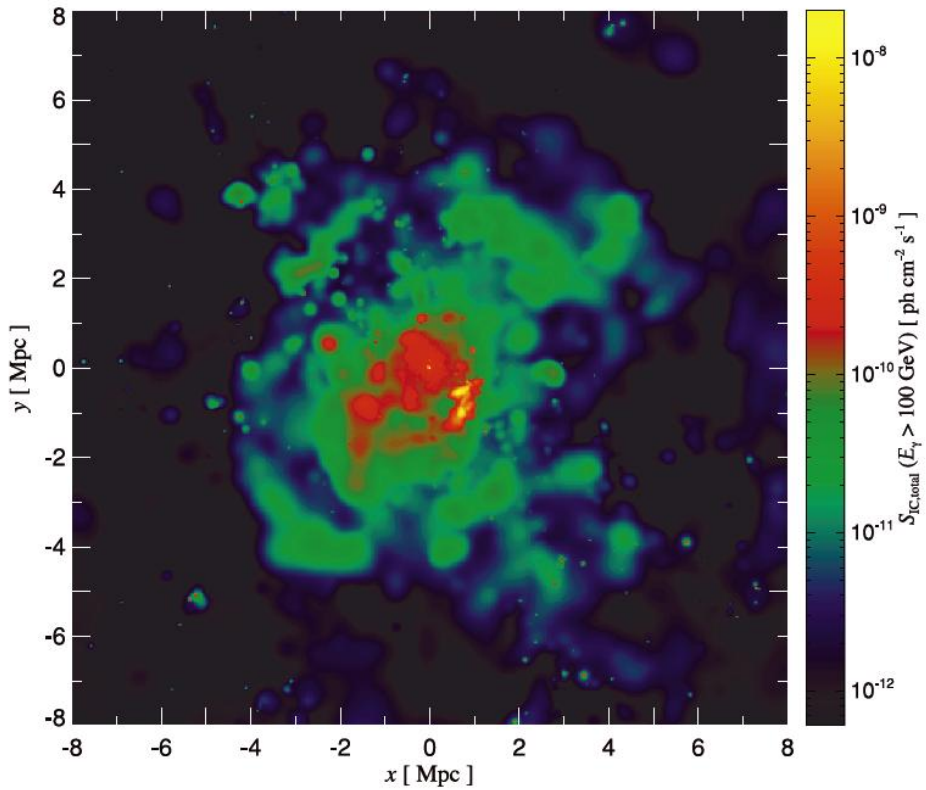
See also Miniati et al. 2003, Blasi et al. 2007, …

Gamma-ray Morphology from Numerical Simulations

Hadronic
>100 MeV



IC
>100 MeV

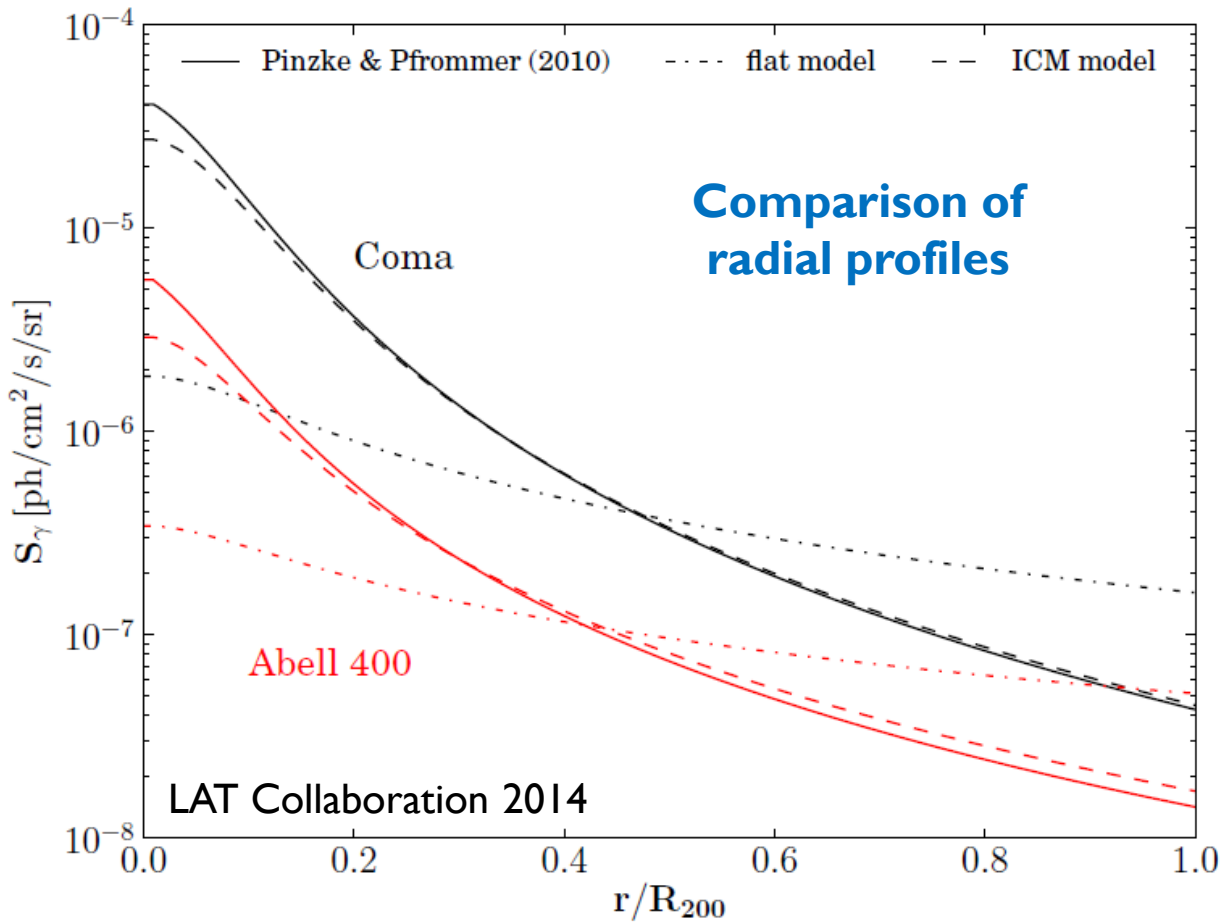


Pinzke & Pfrommer 2010

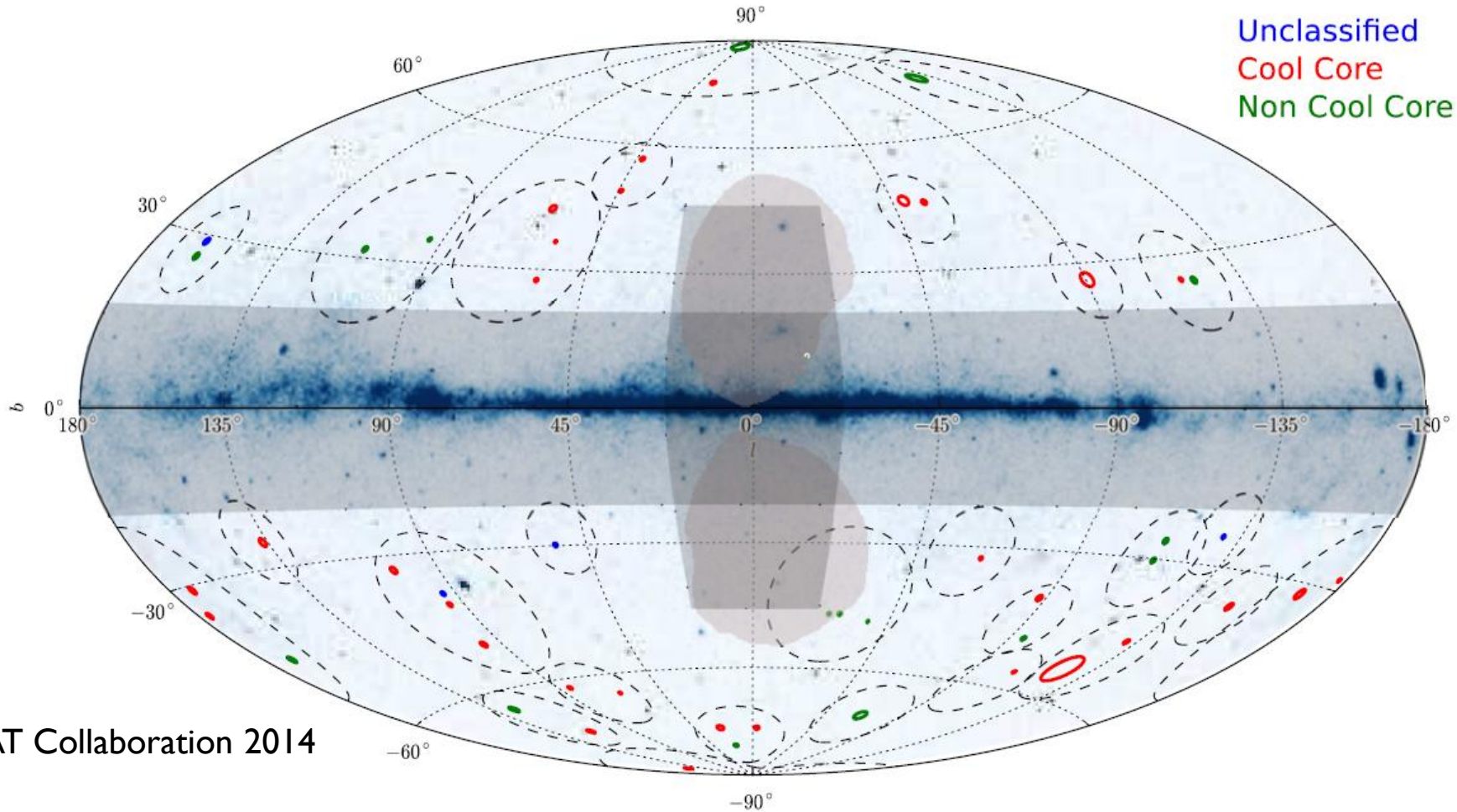
Fermi-LAT: Joint Likelihood Analysis

- If underlying physics is shared among clusters, can derive joint constraints on "universal" scale factor ⇨ proxy for CR proton efficiency

- Spatial and spectral model for CR distribution (Pinzke & Pfrommer 2010)



Fermi-LAT: Joint Likelihood Analysis

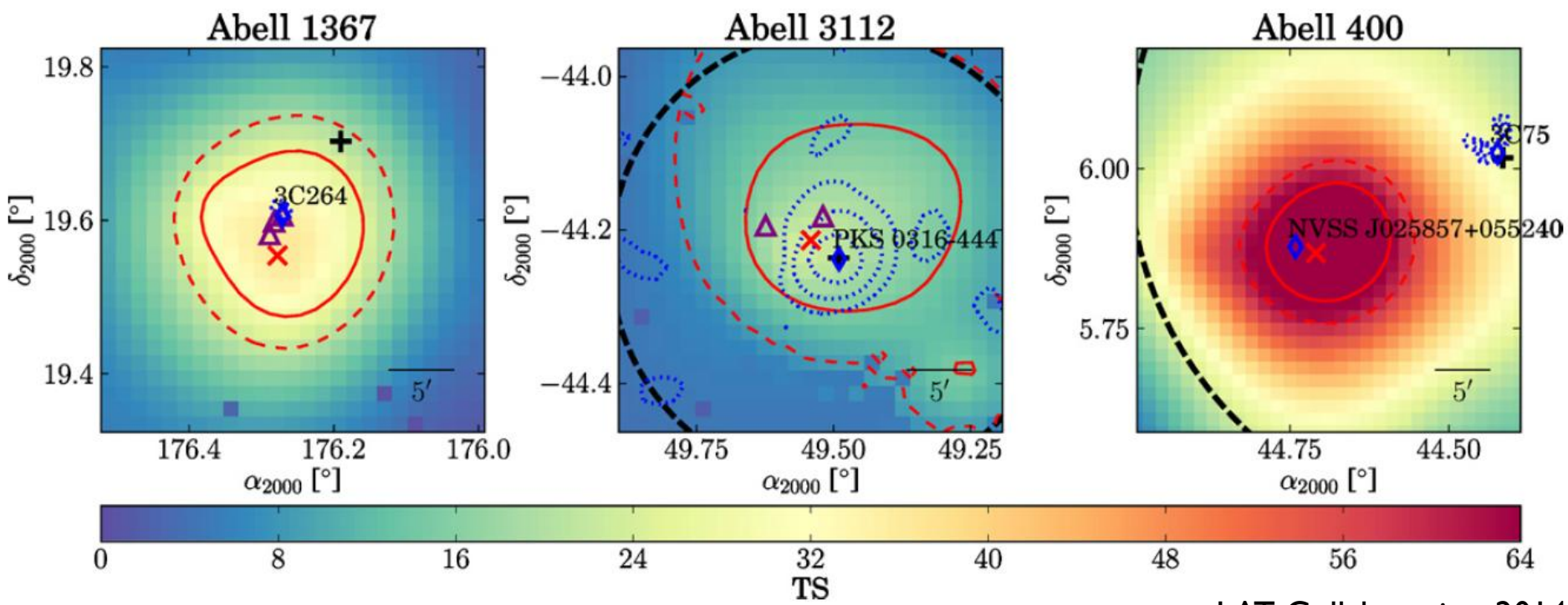


LAT Collaboration 2014

Positions of 50 clusters analyzed in 4 years of LAT data, >500 MeV

Fermi-LAT: Joint Likelihood Analysis

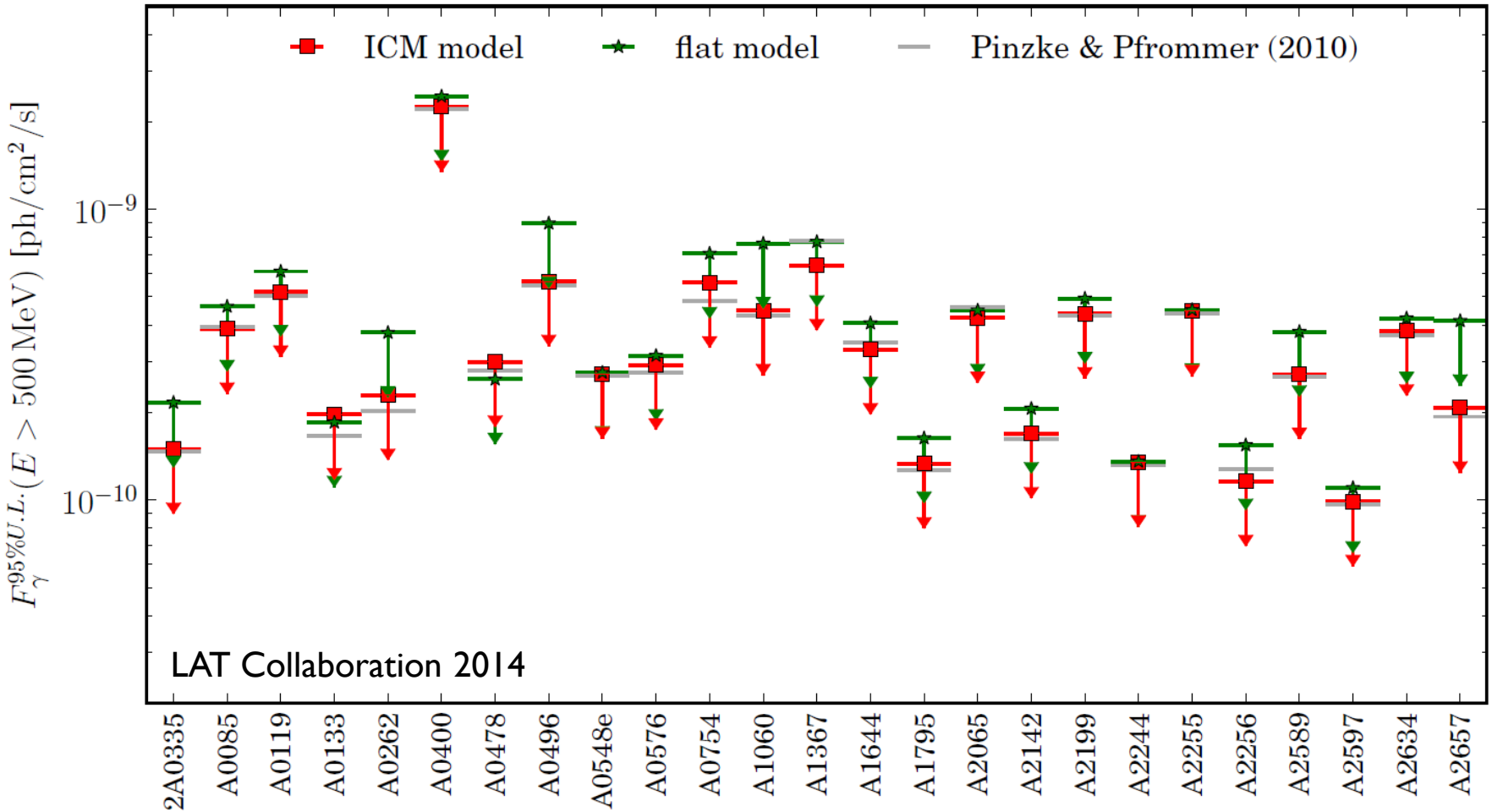
- 3 clusters with significant excess, **but unlikely associated with ICM**
- Either spatially offset, hard spectra, inferred normalization larger than other clusters, plausible radio counterparts



LAT Collaboration 2014

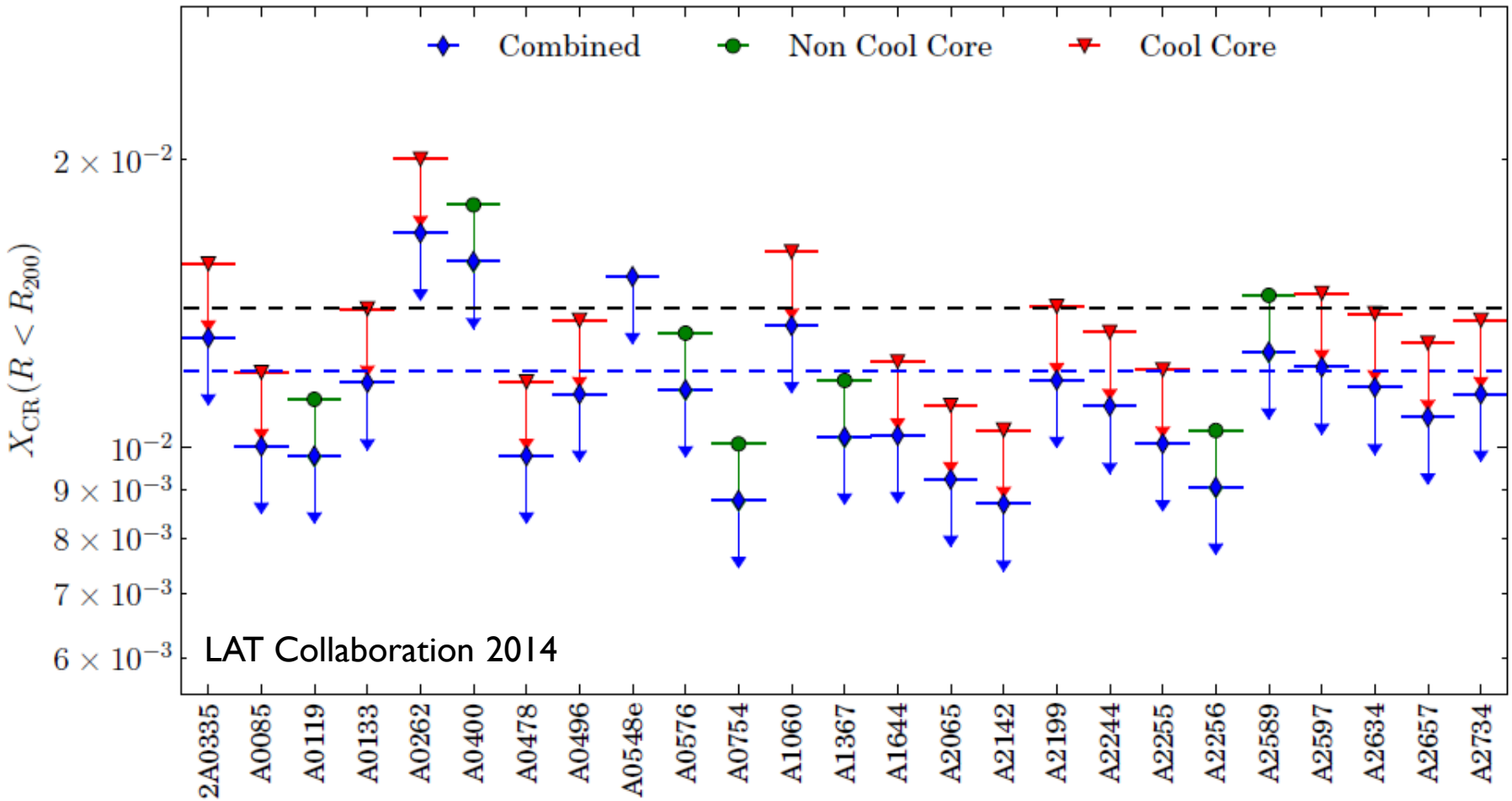
Fermi-LAT: Joint Likelihood Analysis

Representative collection of flux upper limits derived for individual clusters



Fermi-LAT: Joint Likelihood Analysis

Jointly derived upper limit on scale factor propagated to corresponding CR energy density limits for individual clusters



Fermi-LAT: Joint Likelihood Analysis

- Joint likelihood analysis yields most stringent GeV constraints for CR protons to date

- Volume-averaged CR energy density less than ~1% of thermal ICM gas

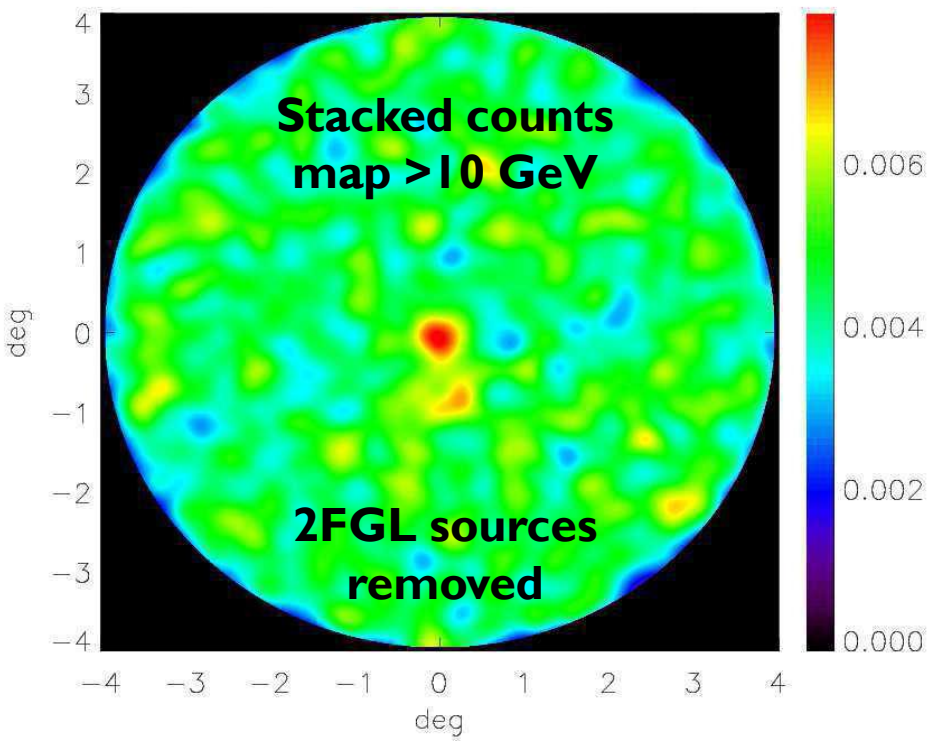
- CR proton acceleration efficiency for intermediate shocks (M ~ 3 – 4) less than ~25%

Full details:
Ackermann et al. 2014, ApJ, 787, 18

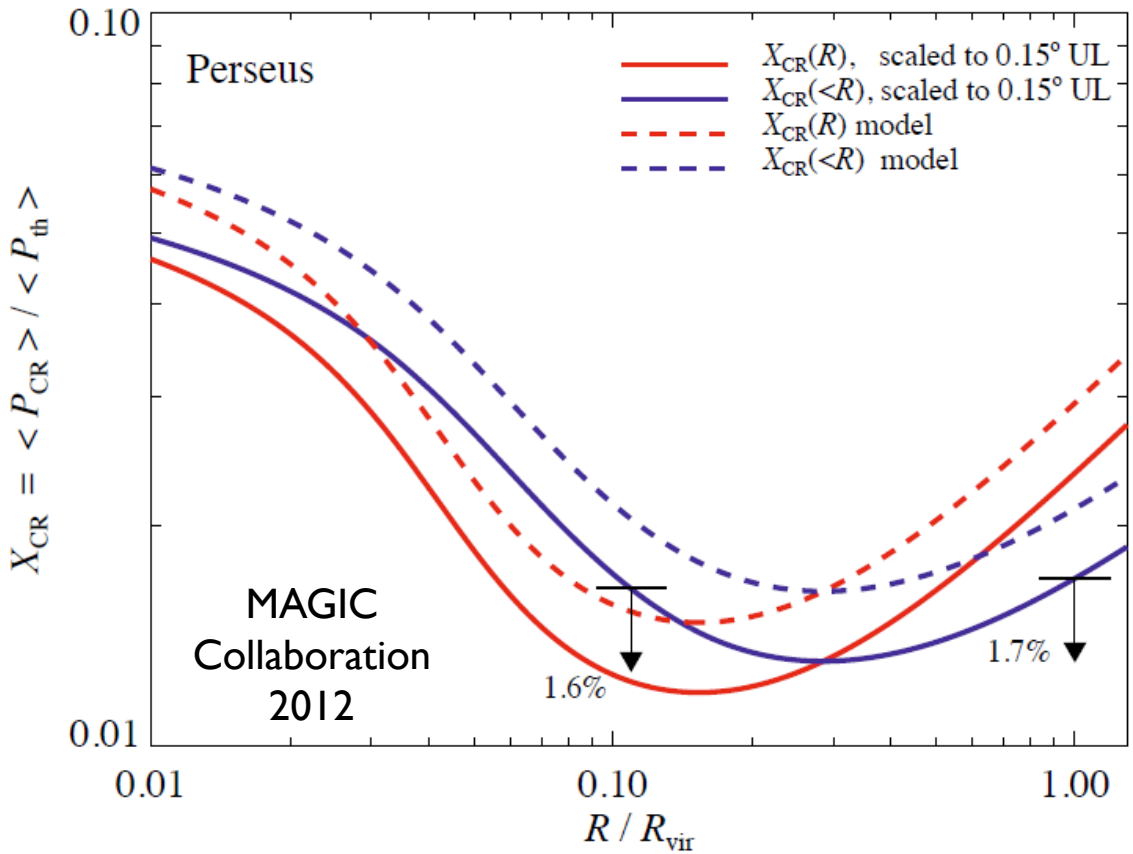
See also Huber et al. 2013

Fermi-LAT: Photon Counting Analysis

- Stacking search at energies >10 GeV using 55 high X-ray flux clusters (Prokhorov & Churazov 2014)
- Significant excess, **but unlikely to be from ICM**
  - Hints of variability
  - Fitted spectrum harder than expected from hadronic CR models
  - Significance of excess reduced when weighting clusters by X-ray flux



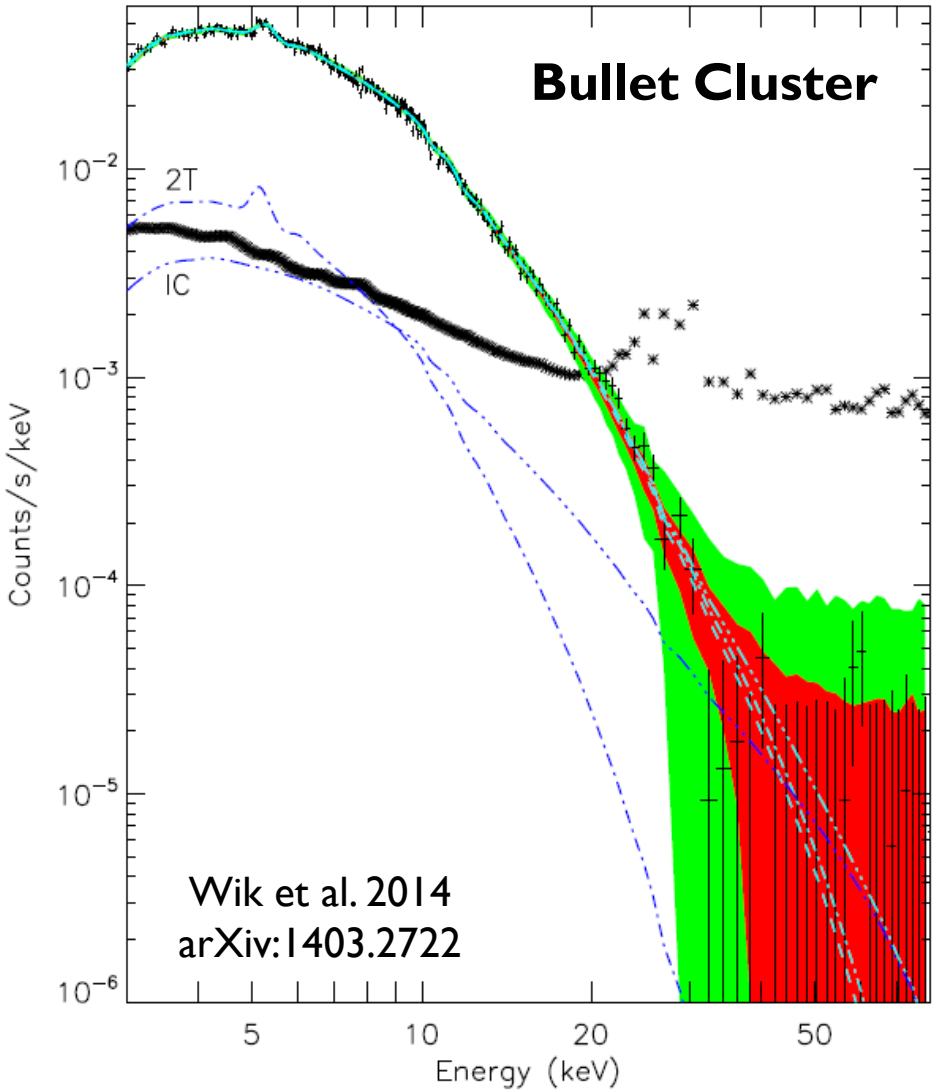
MAGIC:
TeV Upper Limits for Perseus



- Deep TeV observations (85 hrs)
- Emission from NGC 1275 vanishes above 630 GeV (clean search)
- Comparable upper limits on CR proton energetics as derived from *Fermi*-LAT data

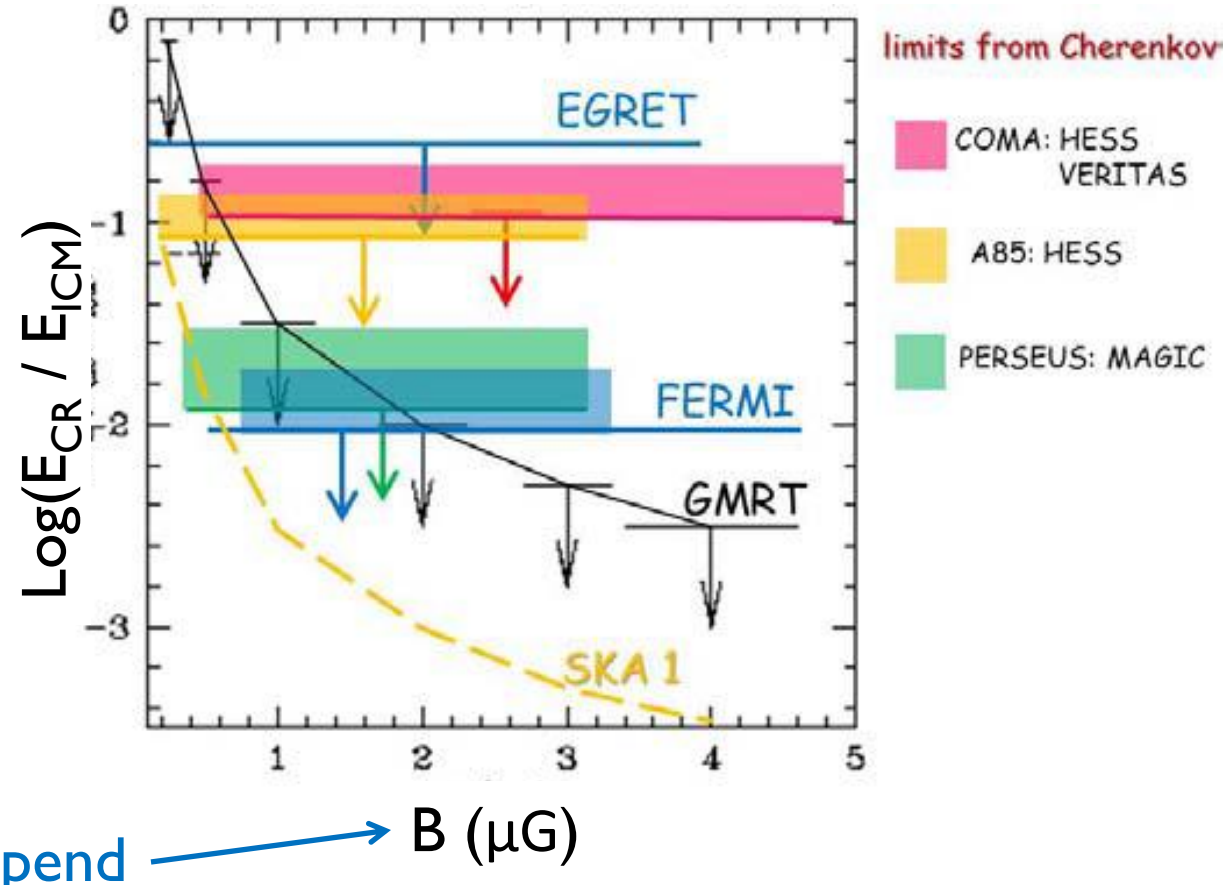
NuSTAR:
Hard X-ray Limits for Bullet

- First focusing hard X-ray (3-80 keV) optics
- **No IC component needed to fit spectrum**
- Limited by instrumental backgrounds > 30 keV
- Infer B > 0.2 μG



Current Observational Status

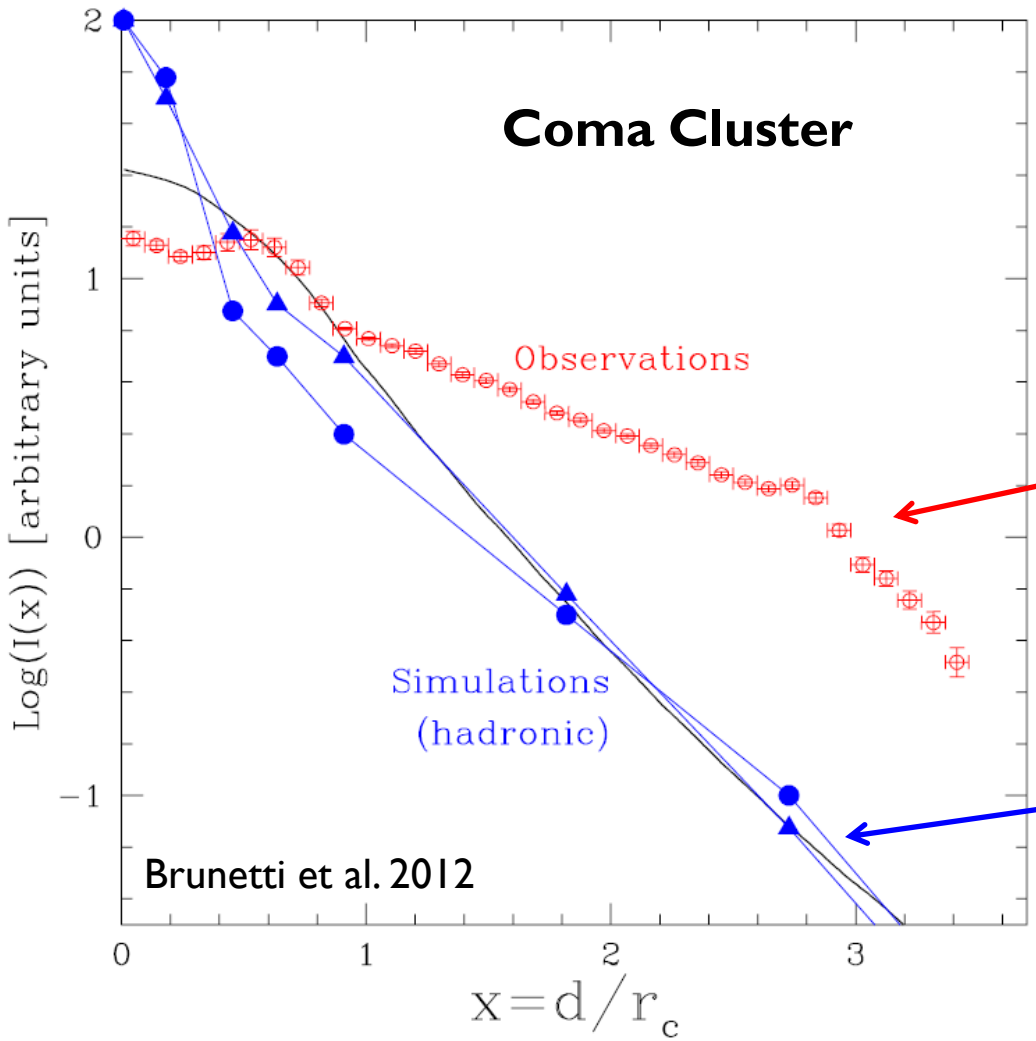
Radio observations constrain **CR protons** via the **secondary electrons** inevitably produced through interactions with ICM



Radio constraints depend on B-field (few μG)

Reviewed by Brunetti & Jones 2014

Spatial + Spectral Synthesis: Coma Cluster

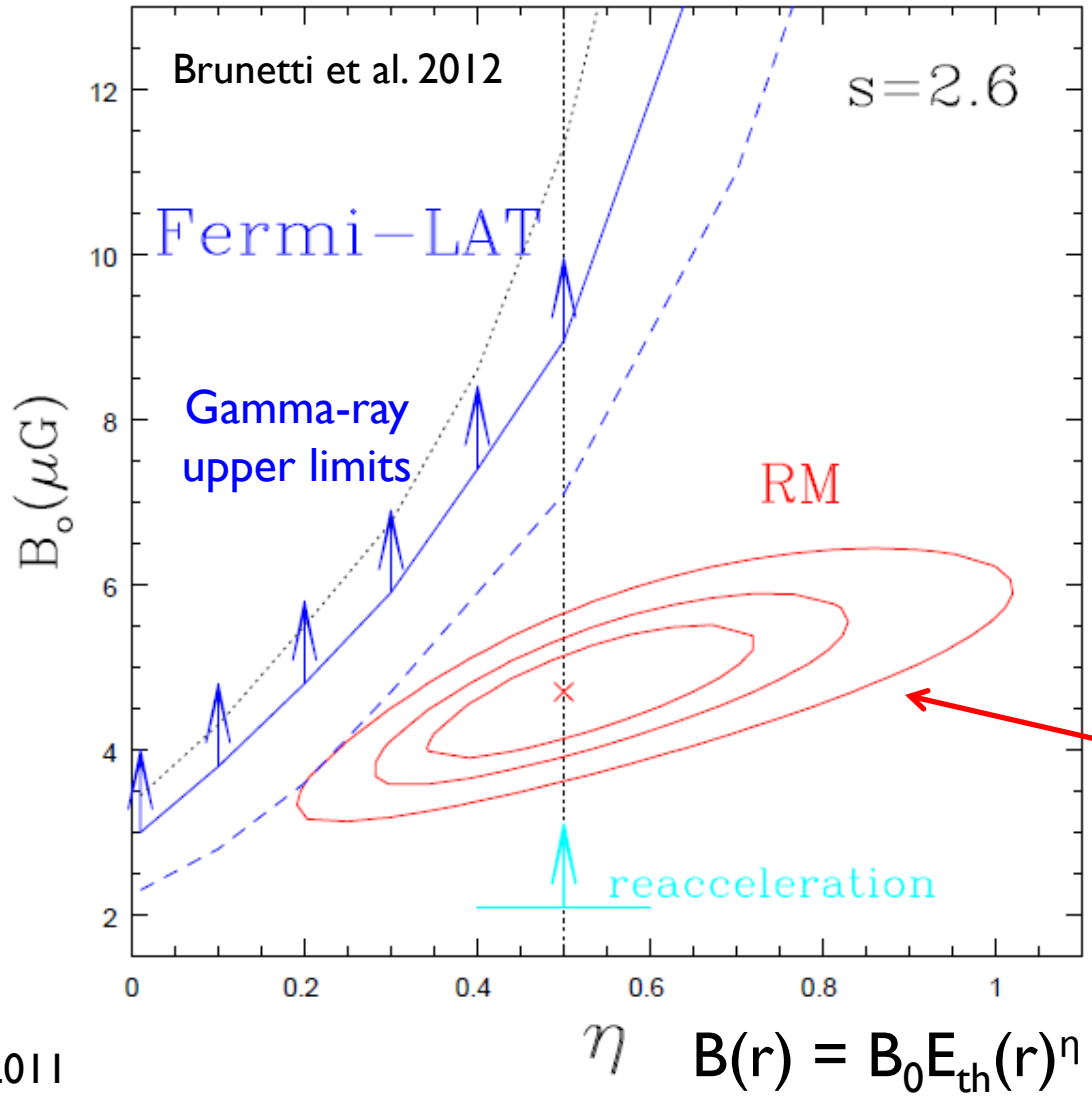


Pure hadronic secondary explanation of radio halo strongly disfavored

Observed broad radio profile

Numerical simulation compatible with *Fermi*-LAT limits (Pinzke & Pfrommer 2010)

Spatial + Spectral Synthesis: Coma Cluster



Coma Cluster

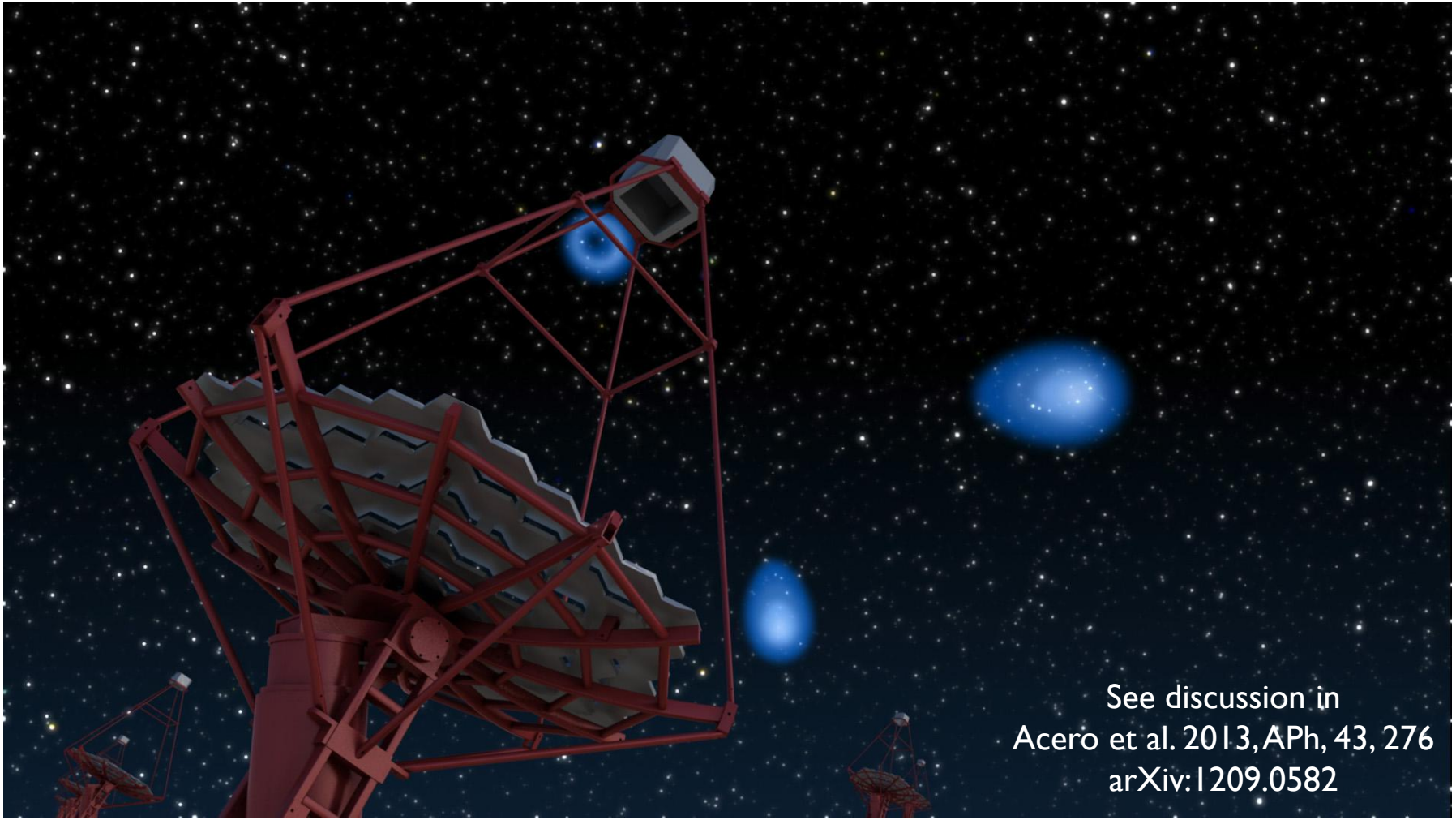
Faraday rotation measure constraints Bonafede et al. 2010

$B(r) = B_0 E_{th}(r)^{\eta}$

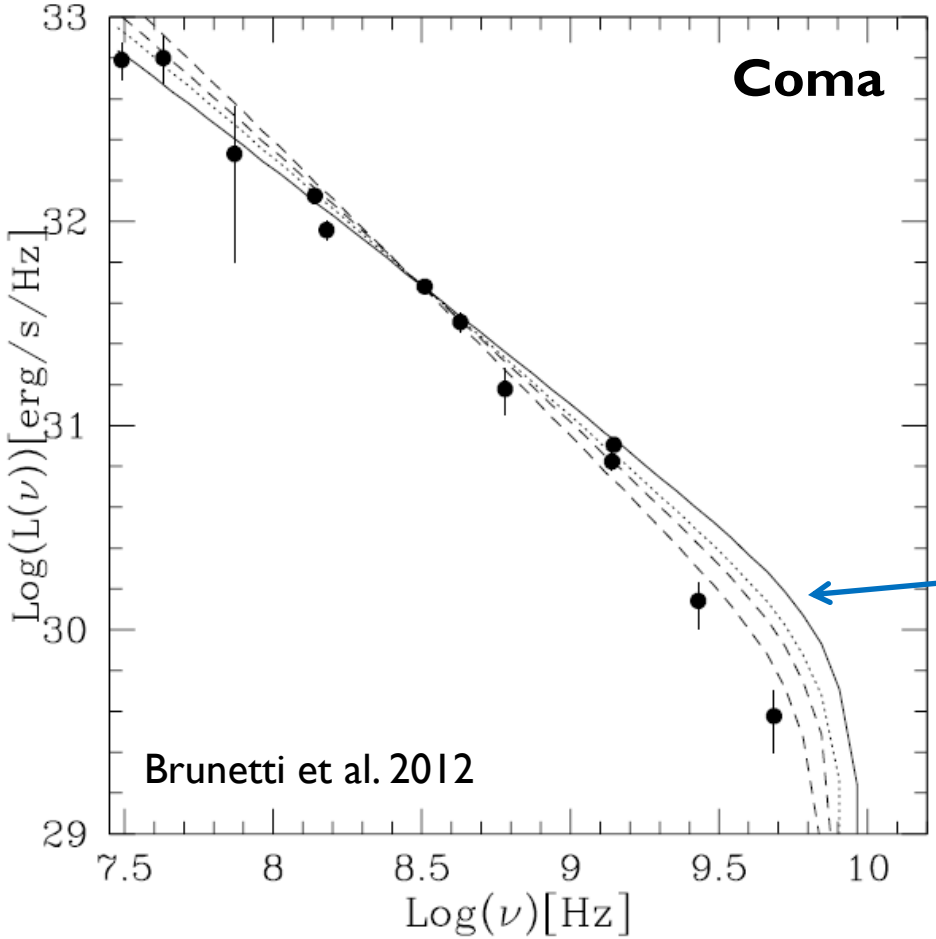
See also
Donnert et al. 2010
Jeltema & Profumo 2011

Multiwavelength Outlook

CTA has great **discovery** potential for CR protons in ICM



Multiwavelength Outlook



Upcoming radio observations (JVLA, LOFAR, SKA + pathfinders) have increased frequency coverage, sensitivity, and dynamic range

Hadronic models for radio halo overshoot data above break at ~1 GHz

Broad frequency coverage currently unique to Coma

Take-home Points

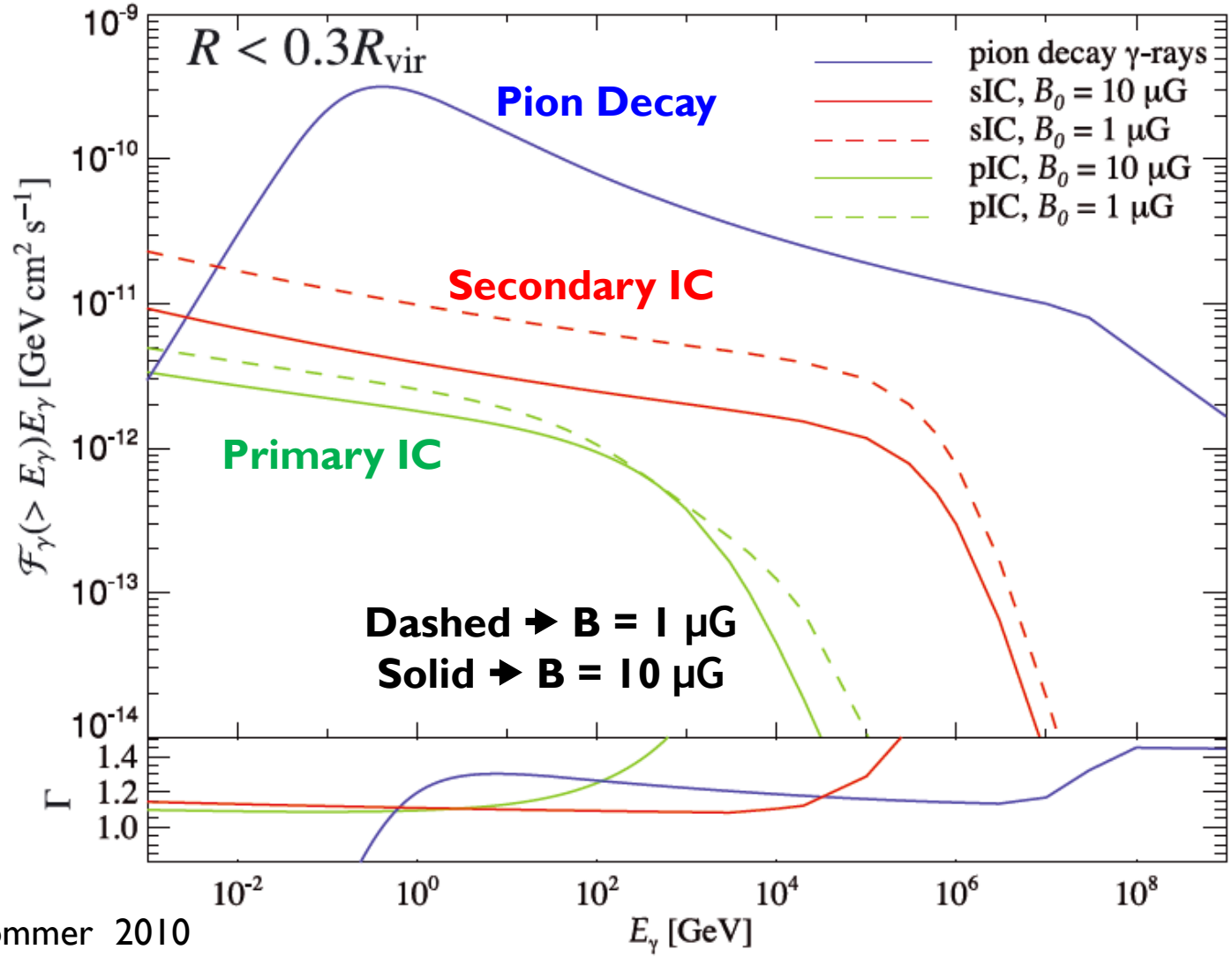
- Simplest hadronic secondary models to explain radio halos severely challenged by combination of gamma-ray non-detections and precision radio observations

- Energy density of CRs < 1 % of thermal ICM

- CTA has outstanding discovery potential, and keep in mind power of current and future radio arrays to constrain CR protons via their secondaries

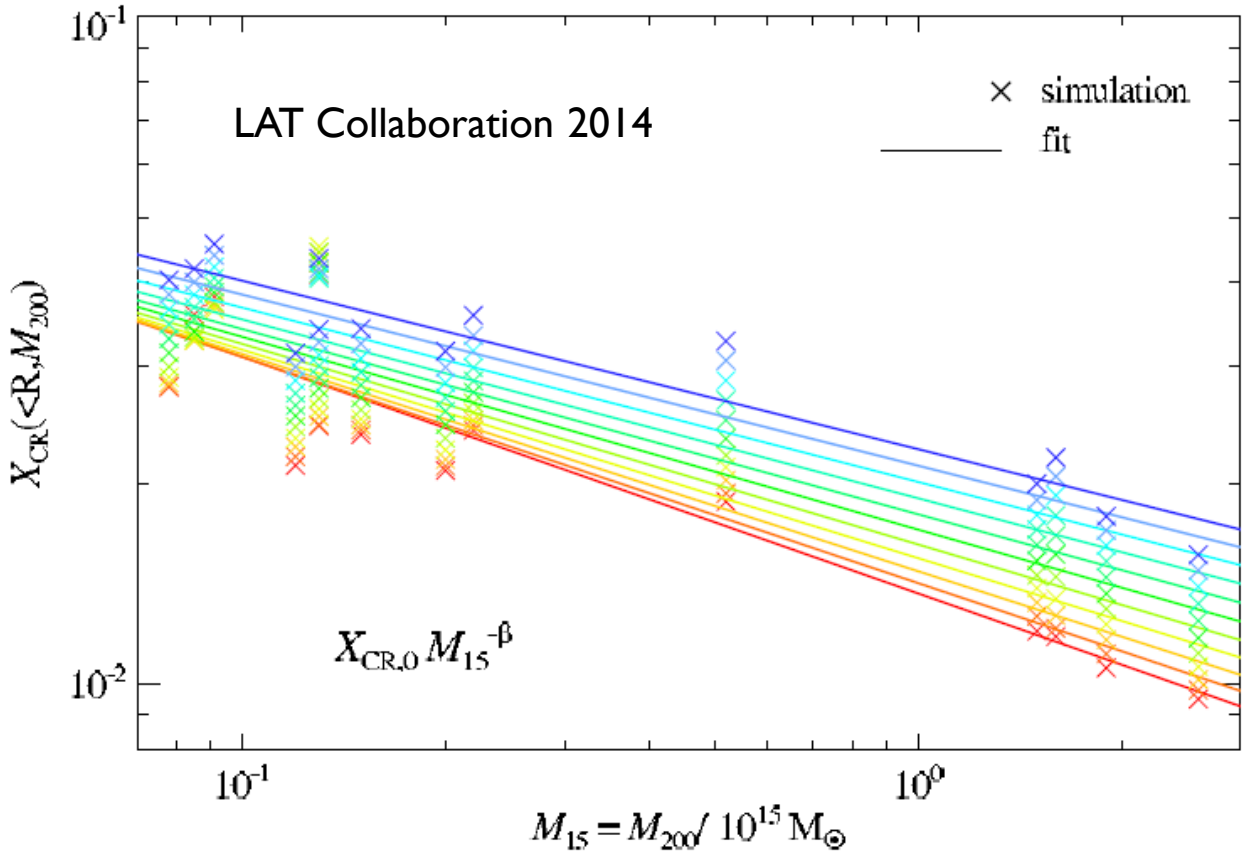
Extras

Gamma-ray Spectra from Numerical Simulations



Pinzke & Pfrommer 2010

CR to Thermal Pressure Ratio



Fitted formula

$$X_{CR} = 0.023 A_\gamma \left(\frac{R}{R_{200}}\right)^{0.369} \left(\frac{M_{200}}{10^{15} M_\odot}\right)^{-0.239\left(\frac{R}{R_{200}}\right)^{-0.258}}$$