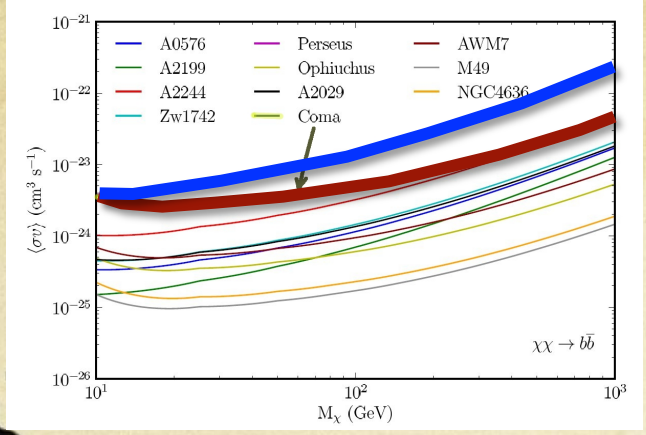
Gamma-Ray (Limits) & the physics of intracluster plasmas

Lawrence Rudnick
Minnesota Institute for Astrophysics

Gamma-Ray Sky 13



Storm, Jeltema, Profumo & Rudnick

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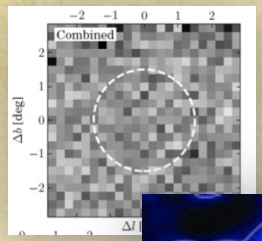
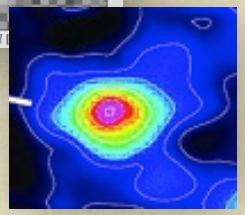




Lessons learned

- γ - rays are inevitable consequence of the encounter between CRs and keV plasma in clusters
- γ - rays provide unique diagnostic of physical conditions (magnetic field strength & profile, CR acceleration & transport) in clusters, which themselves carry imprint of cluster assembly
- Current limits on cluster γ - rays (require) strong fields and reacceleration of CRs
- We really want some detections!

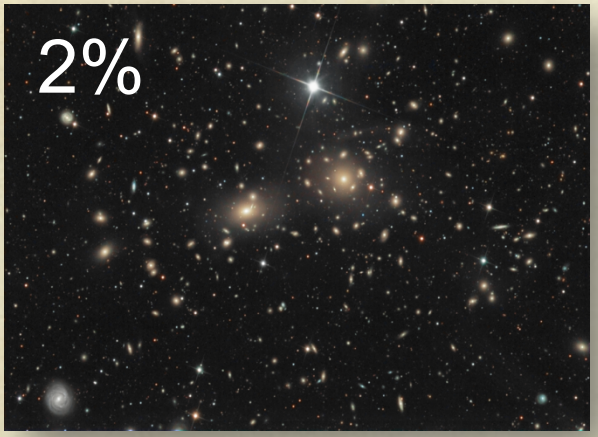
Outline

- What's in a Galaxy Cluster ?
- Why do we care about cluster γ −rays ?
- Making γ s and synchrotron
- Coma Cluster – no problems yet
- Coma – pushing the limits

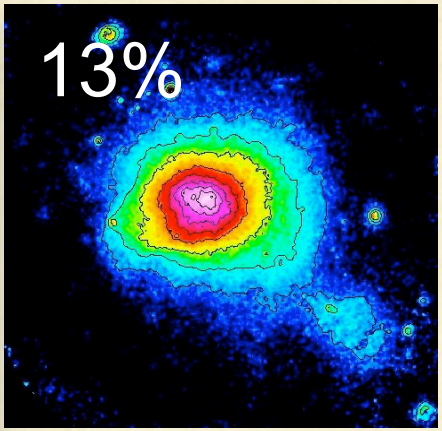
Collaborators:
Shea Brown U of Iowa
Gianfranco Brunetti, CNR, Italy
P. Blasi, A. Bonafede, O. Reimer,
Planck Collaboration

- **What's in a Galaxy Cluster ?**
- Why do we care about cluster γ−rays ?
- Making γ s and synchrotron
- Coma Cluster: no problem yet
- Coma we have a problem

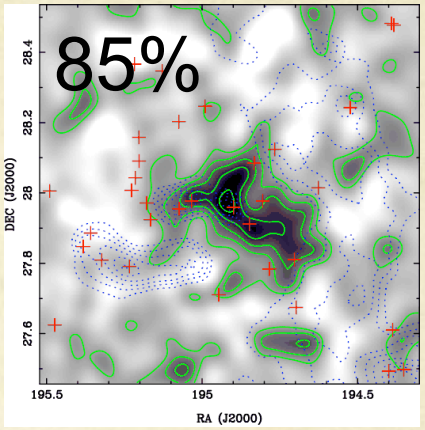
What's in a Galaxy Cluster? (mass budget)



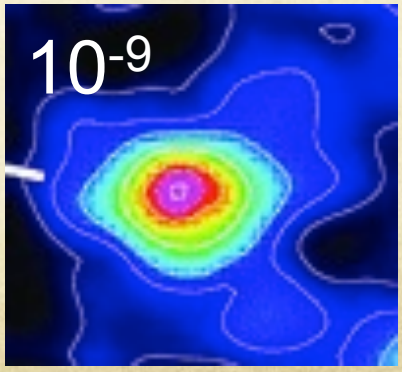
STARS



keV PLASMA



DARK MATTER



COSMIC RAYS

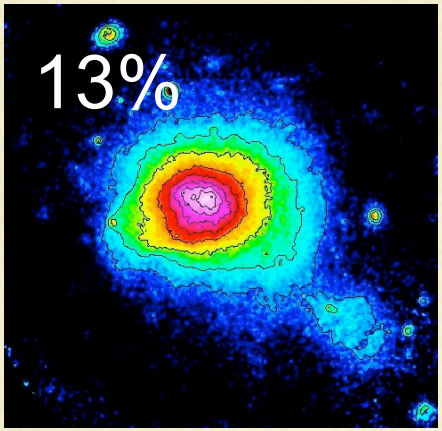
- What's in a Galaxy Cluster ?
- **Why do we care about cluster γ−rays ?**
- Making γ s and synchrotron
- Coma Cluster: no problem yet
- Coma : pushing the limits

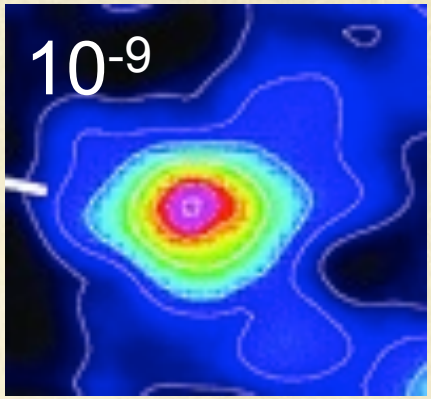
Why do we care about γs?

keV PLASMA

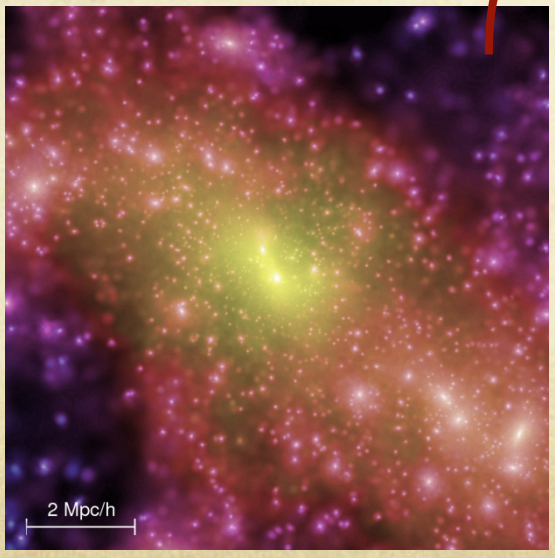
COSMIC RAYS

Coma Cluster

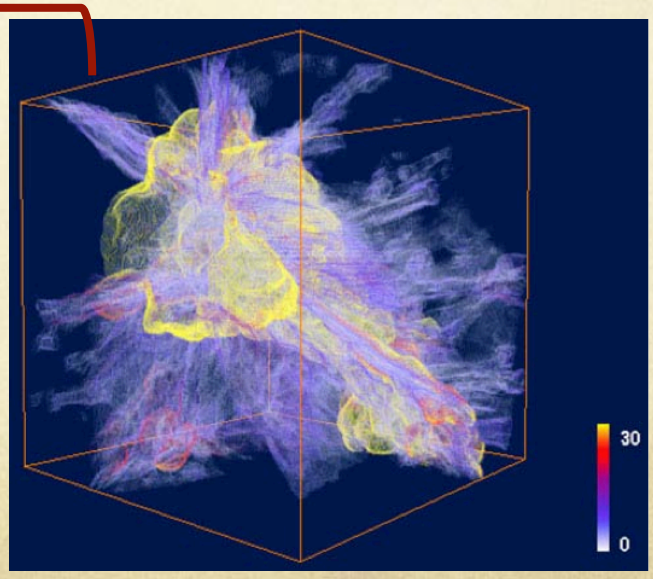




Simulations

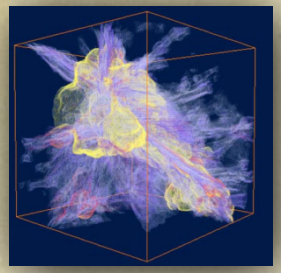


Millenium Simulation

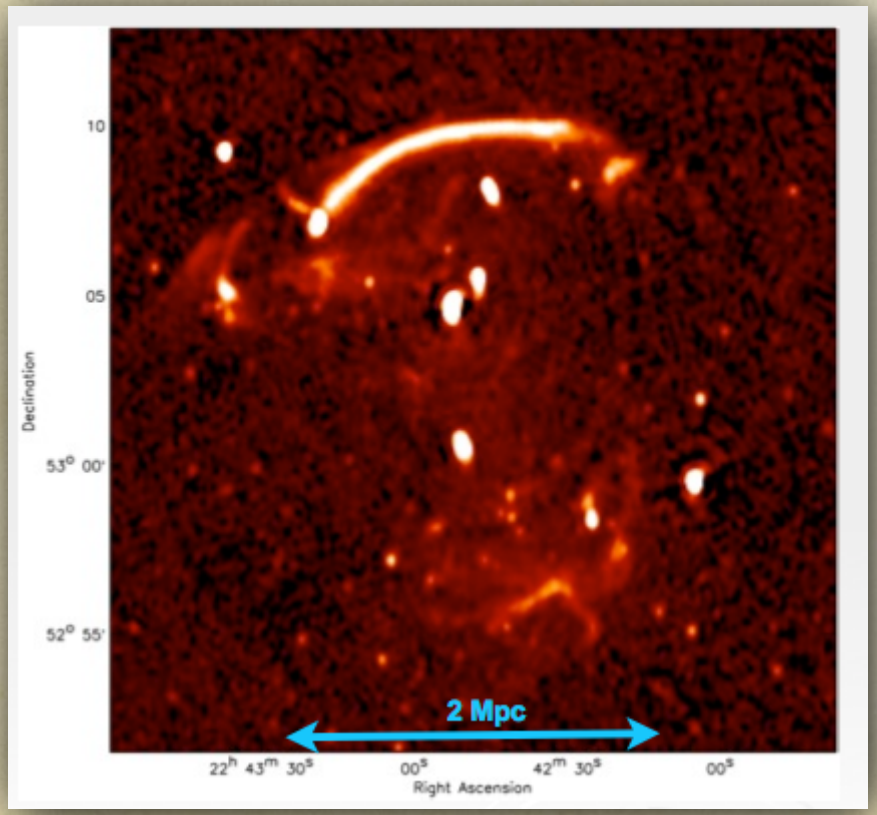


Ryu, Kang, Hallman, Jones 2003

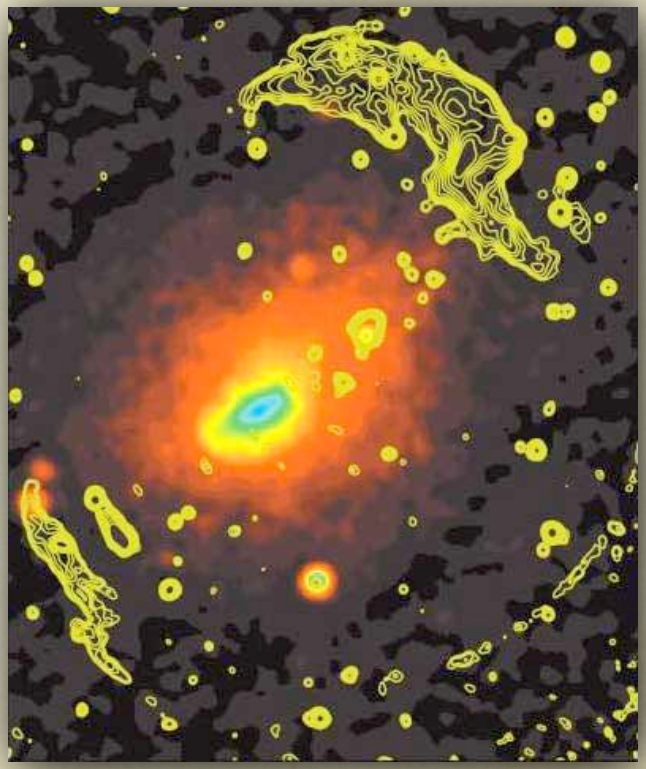
Mach number distribution of shocks around the cluster complex



Shocks on cluster edges

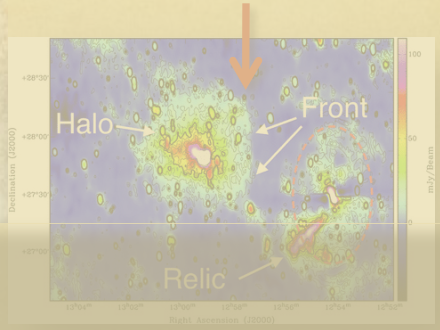


Van Weeren +

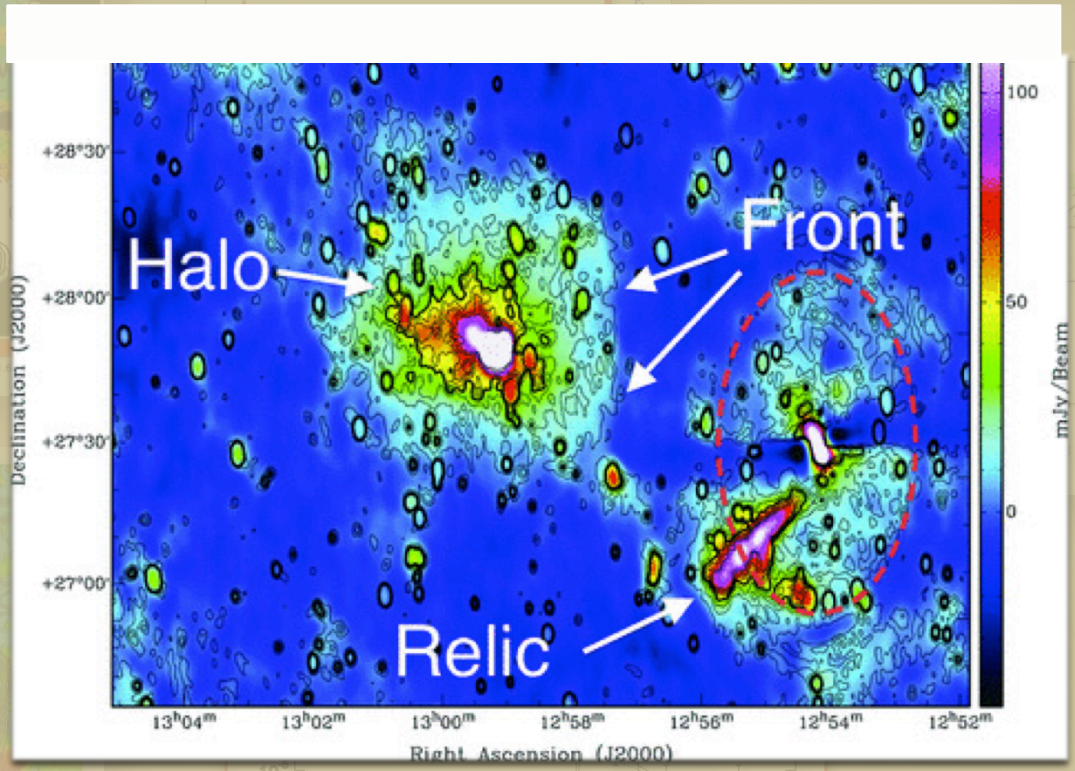


Johnston-Hollit +

...turbulence & shocks inside clusters



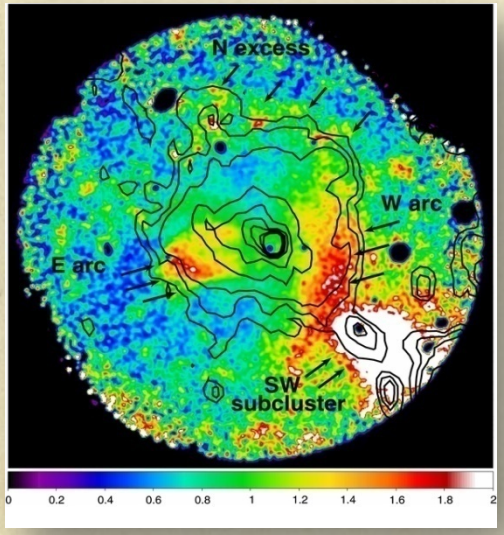
Thermodynamics of the Coma Cluster Outskirts
A. Simionescu et al. 2013 ApJ 775 4



Brown S , and Rudnick L MNRAS 2011;412:2-12

Planck intermediate results. X. Physics of the hot gas in the Coma cluster, 2013

...turbulence & shocks inside clusters



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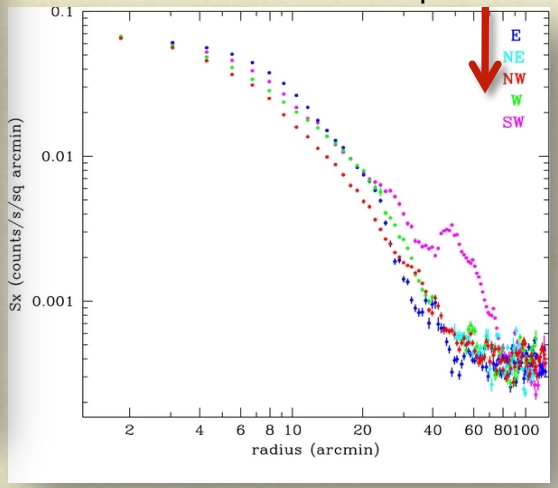

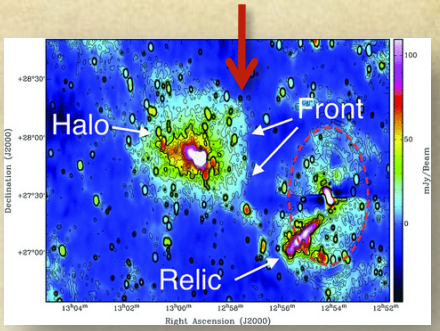

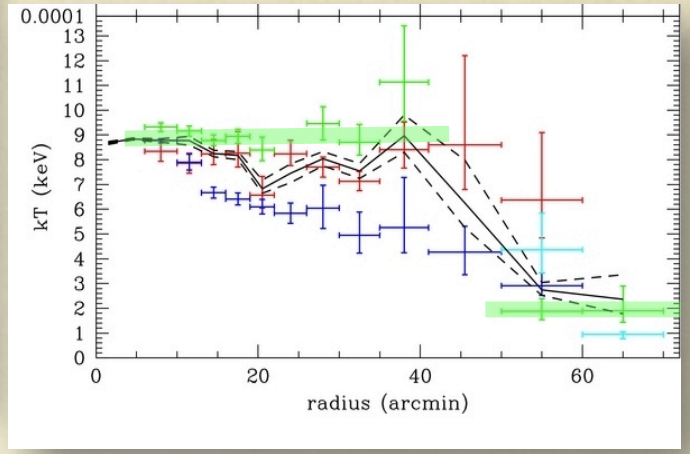

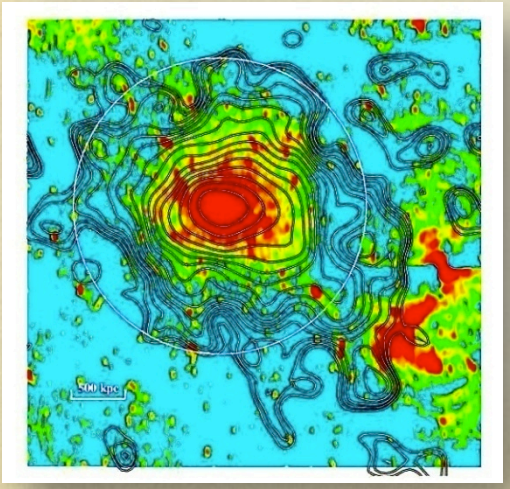

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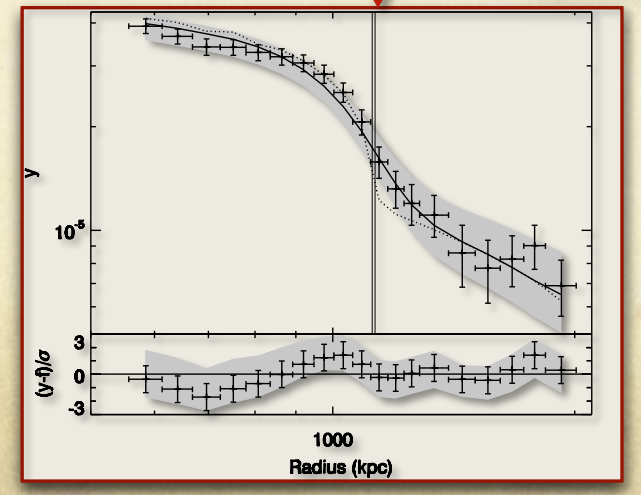
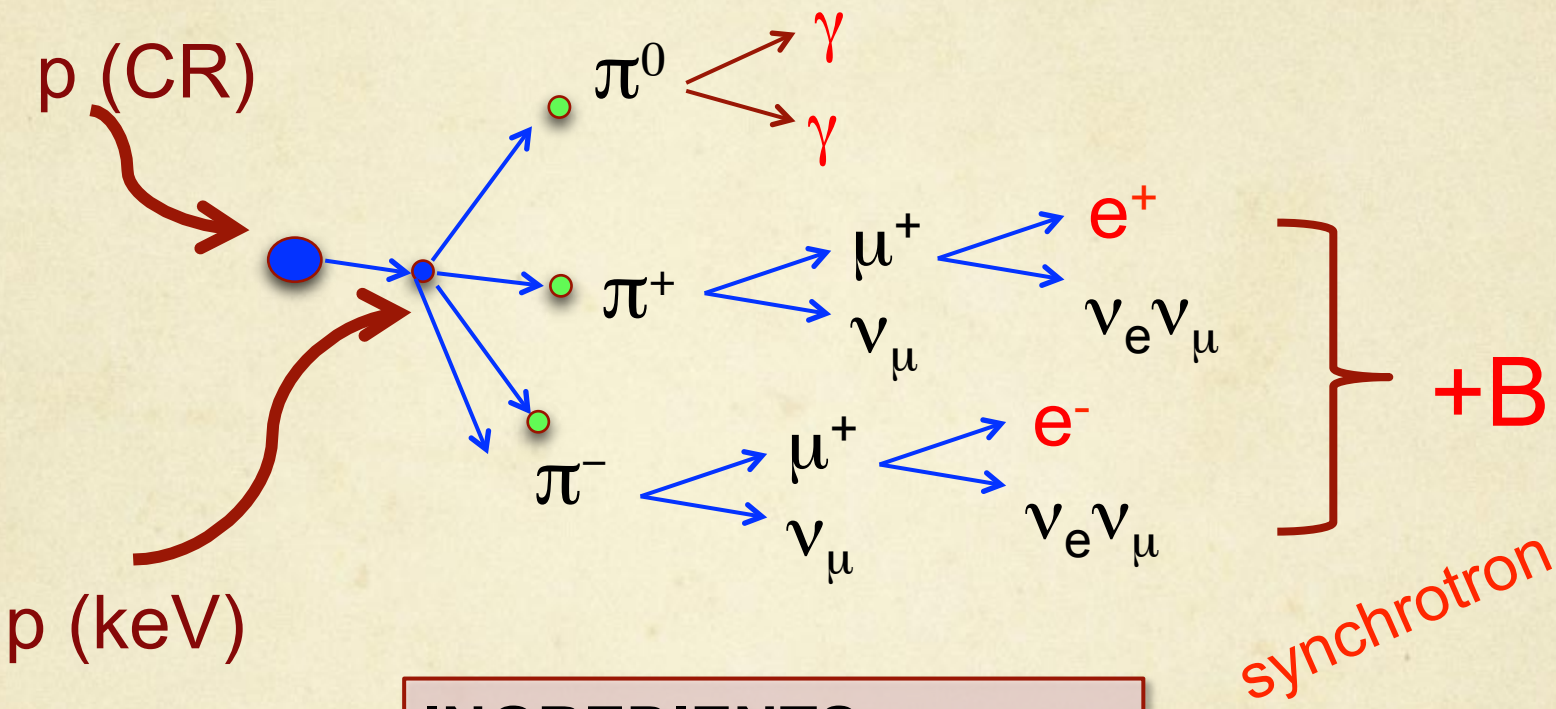


Making γs and synchrotron



INGREDIENTS:

keV plasma (X-rays)
source of CR protons
magnetic field

Making γs and synchrotron

INGREDIENTS:

keV plasma (X-rays)

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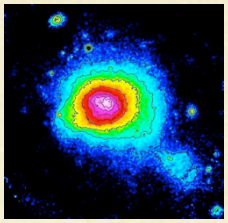
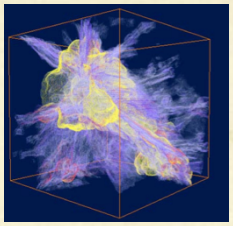
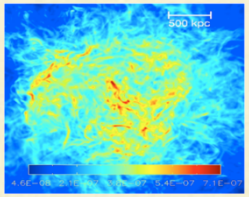






Ctr. for magnetic Self-organization

CHALLENGES

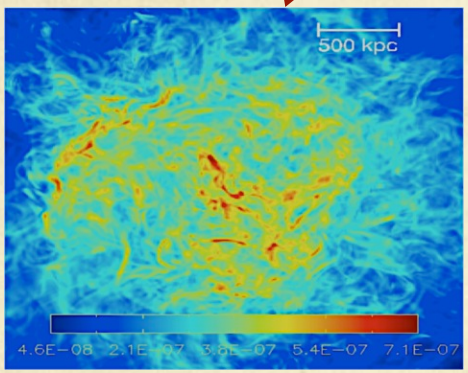
- A. Keeping CRe energized
- B. Strength and profile of B

- What's in a Galaxy Cluster ?
- Why do we care about cluster γ−rays ?
- **Making γ s and synchrotron**
- Coma Cluster: no problem yet
- Coma : pushing the limits

B. Why do we need B?

INGREDIENTS:

keV plasma (X-rays)
source of CR protons
magnetic field



Ctr. for magnetic
Self-organization

- Need **# of CRp** to produce γ
- Synchrotron → $N_{CR}{}^{*}\ B^{(1+\alpha)}$
- **so… how estimate B ?**

- Minimum energy B <~ 1 μG

→ too many γ

- Faraday rotation $\Phi = \int nB\,dl$

- What's in a Galaxy Cluster ?
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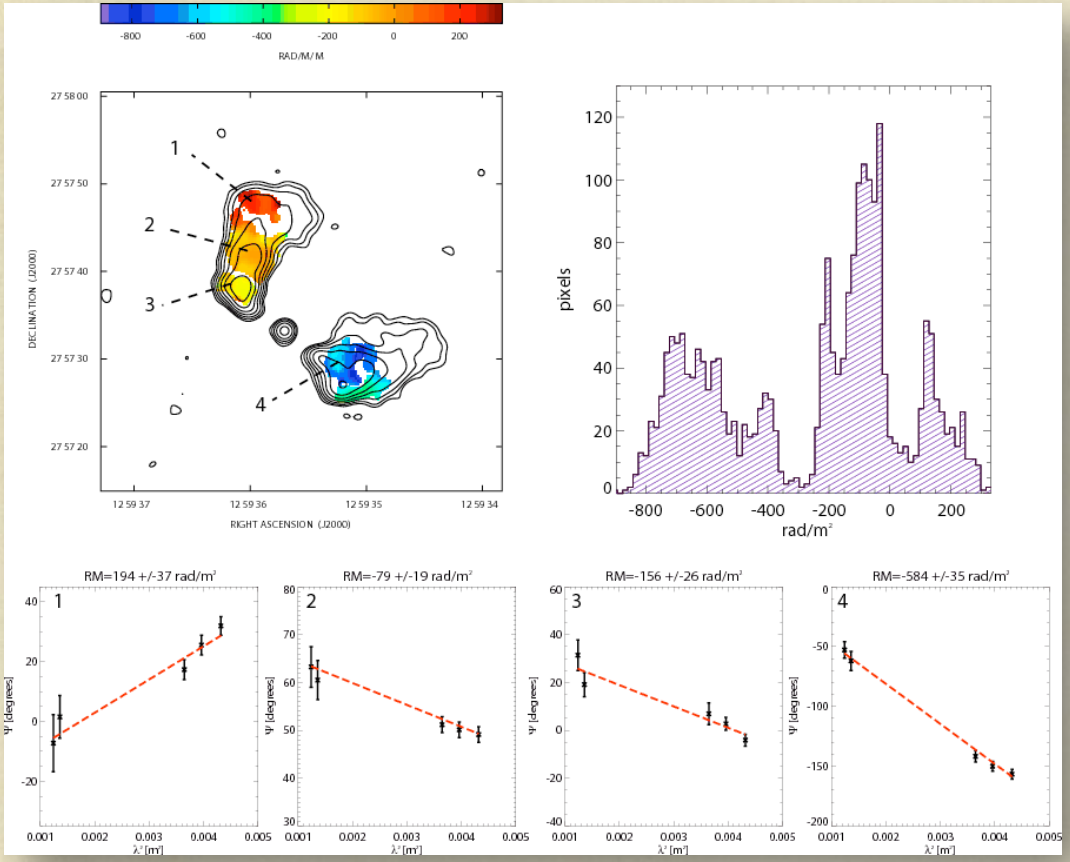
B from Faraday rotation



$$\Phi = \int nB\,dl$$

Bonafede+ 2010

- What's in a Galaxy Cluster ?
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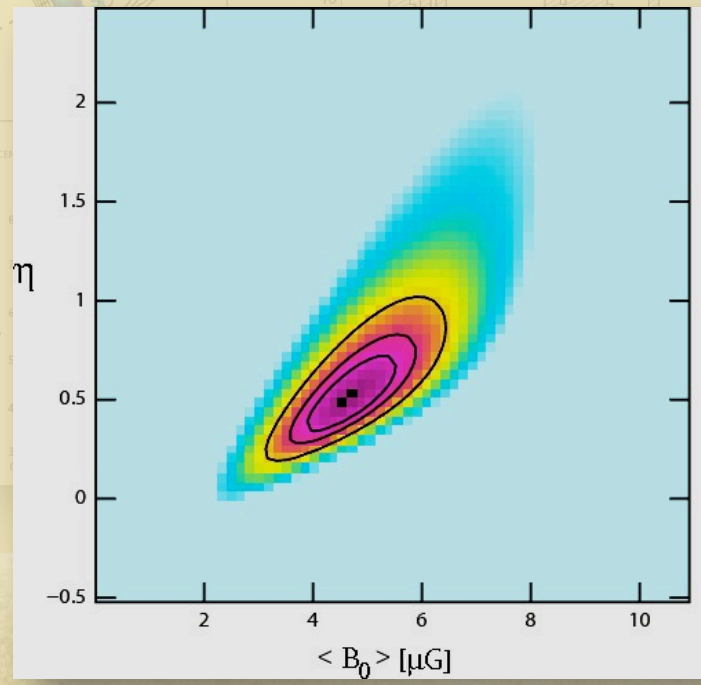
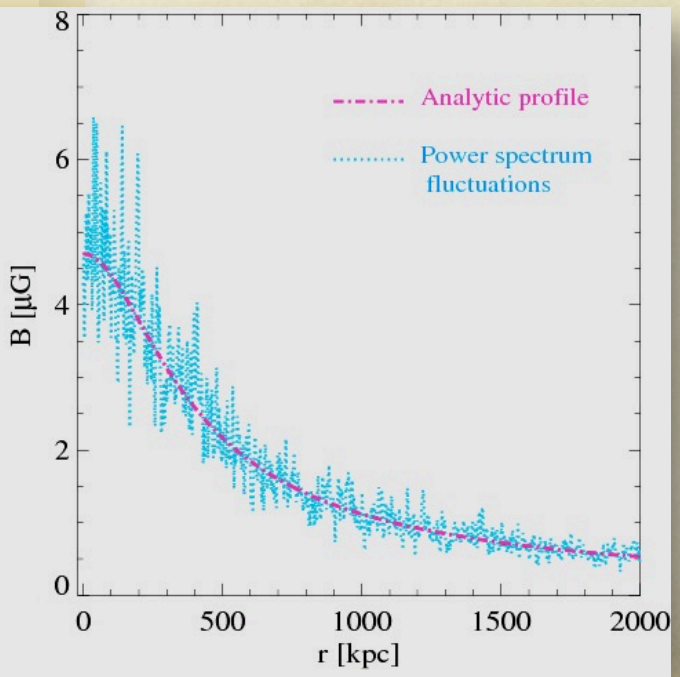
B from Faraday rotation

$$\langle \boldsymbol{B} \rangle(r) = \langle \boldsymbol{B}_0 \rangle \left(\frac{n_e(r)}{n_0} \right)^{\eta}$$





Bonafede+ 2010

- What's in a Galaxy Cluster ?
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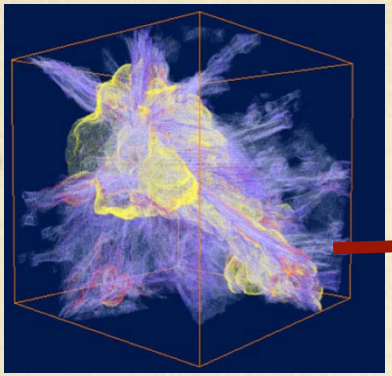
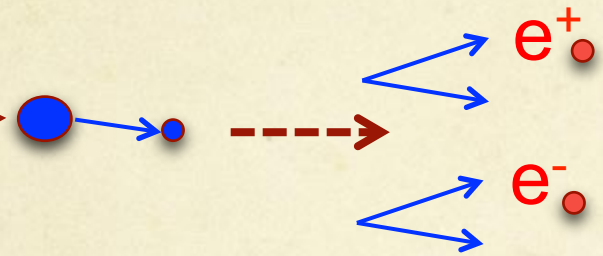
Keeping electrons energized

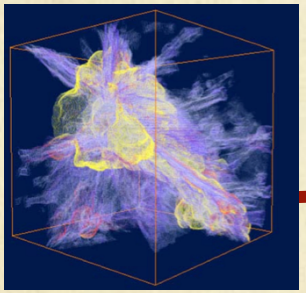
CRe lifetimes ~ 10^8 y

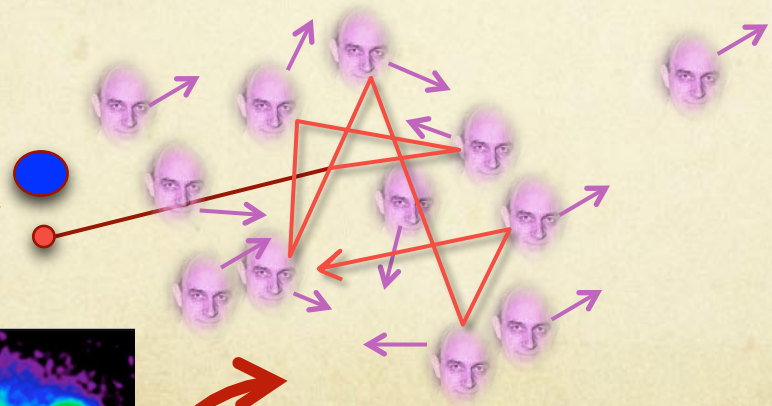
CRe diffusion times ~ 10^{10} y





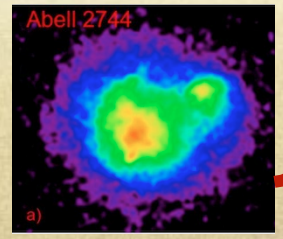
Secondary / Hadronic





Primary

W. Couch
M. Owers



Merger-driven turbulence

- What's in a Galaxy Cluster ?
- Why do we care about cluster γ−rays ?
- **Making γ s and synchrotron**
- Coma Cluster: no problem yet
- Coma : pushing the limits

Parametrizing our Ignorance

- CR / kev scaling: $\epsilon_{CR} \propto \epsilon_{ICM}^{1+f}$
- B keV scaling: $B(r) = B_0[\epsilon_{ICM}(r)/\epsilon_{ICM}(0)]^{\eta}$
- CR normalization, spectrum: $N(p) = K_p p^{-(2\alpha+1)}$

$$J_{syn}(\nu) \propto n_{th}^{2+f} T^{1+f} \frac{(n_{th}T)^{\eta(1+\alpha)}}{C_B^2 (n_{th}T)^{2\eta} + B_{cmb}^2}$$

- What's in a Galaxy Cluster ?
- Why do we care about cluster γ−rays ?
- Making γ s and synchrotron
- **Coma Cluster: no problem yet**
- Coma: pushing the limits

Coma: no problem yet…

The Astrophysical Journal, 728:53 (7pp), 2011 February 10 doi:10.1088/0004-637

IMPLICATIONS OF *FERMI* OBSERVATIONS FOR HADRONIC MODELS OF RADIO HALOS IN CLUSTERS OF GALAXIES

Tesla E. Jeltema[1] and Stefano Profumo[2]

Table 2
Hadronic Model Results

Cluster	α_p	$B_{0,\min}$ (μG)	*Fermi* Band (GeV)	Ratio of $F_{\gamma,\min}$ to *Fermi* Up. Lim.	Minimal γ-ray Flux (10^{-9} ph cm^{-2} s^{-1})	Maximum $\epsilon_{CR}/\epsilon_{th}$
A1656	2.70	1.70	1–10	0.040	0.186	0.018
A1914	3.76	7.40	0.2–1	0.077	0.181	0.684
A2029	2.70	0.37	0.2–1	0.001	0.006	0.052
A2142	3.01	0.65	0.2–1	0.002	0.010	0.091
A2163	2.05	0.37	0.2–1	0.004	0.011	0.131
A2256	3.25	2.70	0.2–1	0.037	0.099	0.138
A2319	2.57	1.40	0.2–1	0.040	0.046	0.010
A2744	2.01	0.26	1–10	0.004	0.004	1.396
1E 0657-56	2.60	0.77	1–10	0.005	0.018	0.508

Notes. Column 2 lists the cosmic-ray proton injection spectral index implied by the radio spectrum for a magnetic field strength of $B = 1\ \mu$G. Column 3 indicates the minimum average magnetic field required [illegible] radio-halo flux with secondary electrons without overproducing [illegible] Column 5 gives the ratio of the minim[illegible] to very large magnetic fie[illegible] Columns 3 and 5 are calculated for the most constra[illegible]ermann et al. (2010b), which is in turn noted in Column 4. Column 6, instead, gives [illegible] integrated gamma-ray flux between 0.2 and 100 GeV predicted in the hadronic scenario. The final column lists the maximum allowed ratio of the energy density in cosmic rays to the cluster thermal energy density implied by the *Fermi* limits given the proton spectral index implied by the radio spectrum and assuming that the cosmic-ray density traces the thermal gas density.

Modest B, hadronic OK, <2% CR pressure

Coma: no problem yet…

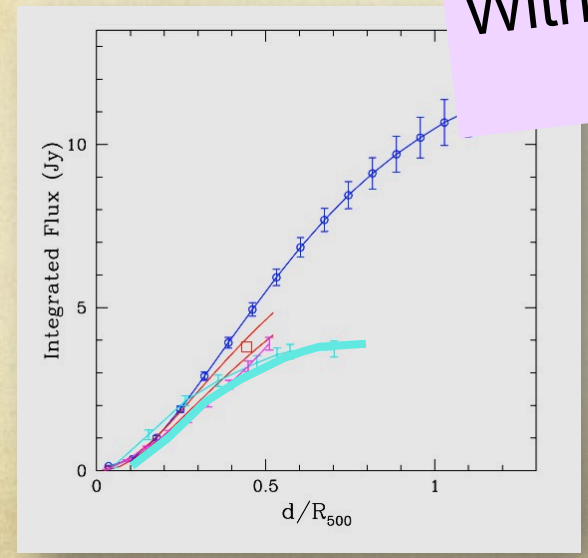
THE ASTROPHYSICAL JOURNAL, 757:123 (14pp), 2012 October 1 doi:10.1088/0004-637X/757/2/12

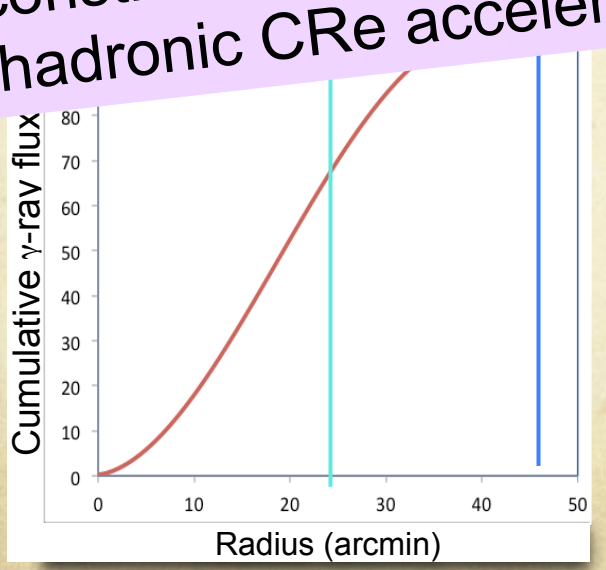
CONSTRAINTS ON COSMIC RAYS, MAGNETIC FIELDS, AND DARK MATTER FROM GAMMA-RAY OBSERVATIONS OF THE COMA CLUSTER OF GALAXIES WITH VERITAS AND *FERMI*

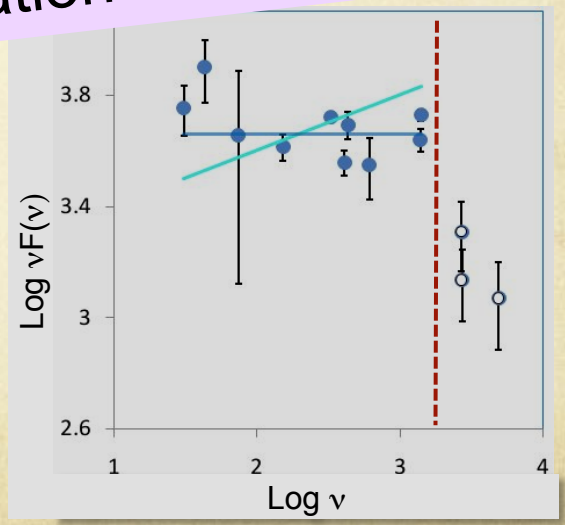
< $(2–5) \times 10^{-8}$ photons $m^{-2} s^{-1}$ (VERITAS, >220 GeV)

< $\sim 2 \times 10^{-6}$ photons $m^{-2} s^{-1}$ (*Fermi*, 1–3 GeV)

With constraints on f, η, α –
hadronic CRe acceleration OK, but…

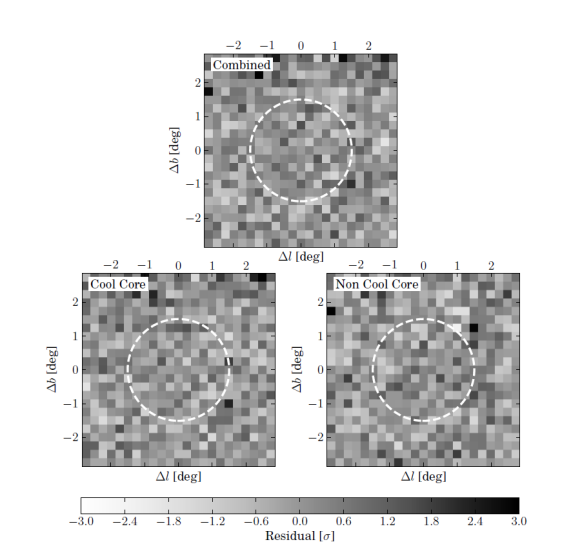






Coma (et al.) : tightening up…

Stacking (50) clusters [4 years]



- Exclude strong-shock hadronic acceleration efficiencies > 25%
- CR pressure ratios < 1%

[not using synchrotron constraints]

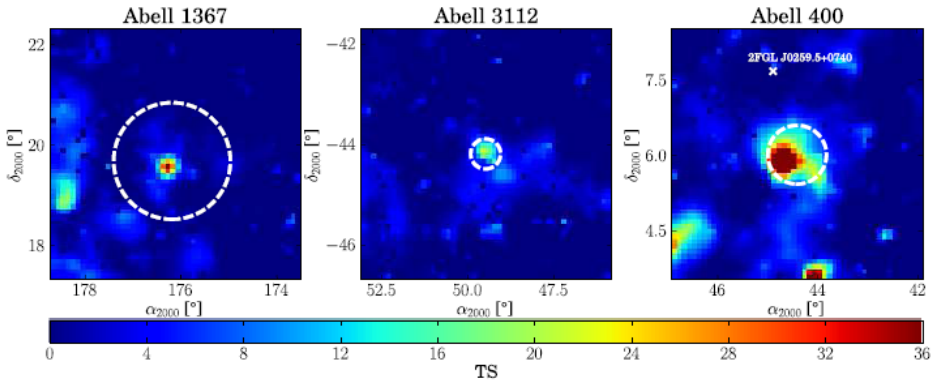
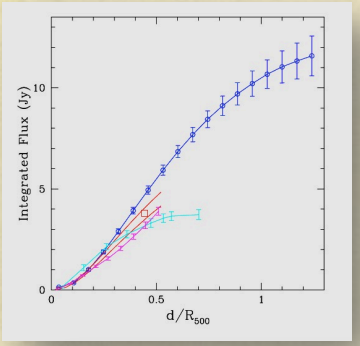


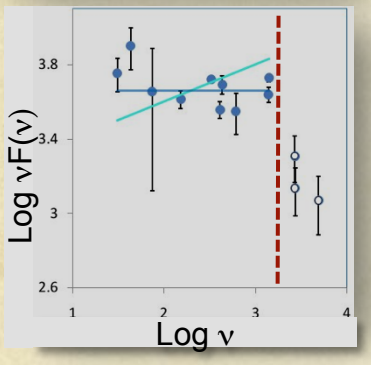
Fig. 7.— (color online) TS maps from an unbinned search in a 5° × 5° region centered on each of our notable clusters, Abell 1367, Abell 3112 and Abell 400. All excesses are found within the assumed cluster virial radius (dashed white circle), albeit marginally offset from the respective cluster centers (0.3° for both Abell 400 and Abell 1367 and 0.1° for Abell 3112). Each pixel has a width of 0.1°. The white × indicates the best-fit position of a previously detected 2FGL point source.

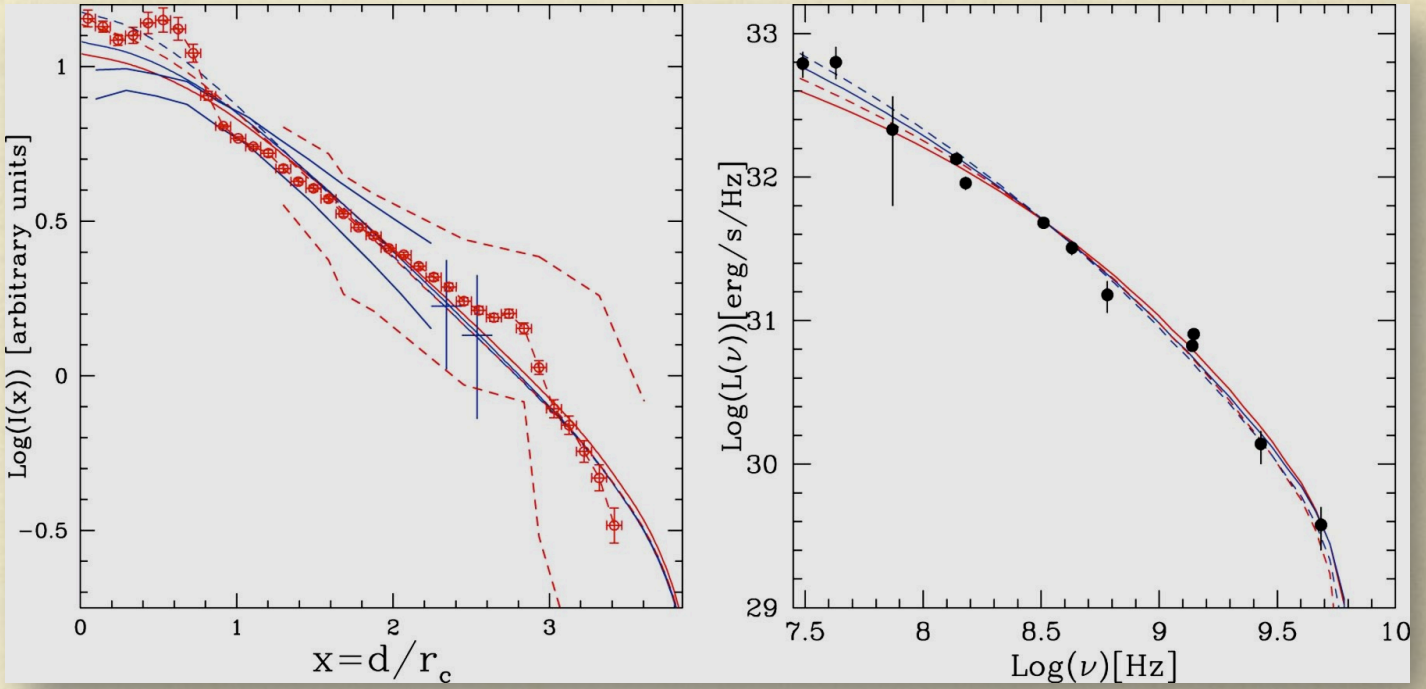
Fermi-LAT Collaboration arXiv:1308.5654

- What's in a Galaxy Cluster ?
- Why do we care about cluster γ−rays ?
- Making γ s – the models
- The optimists look at the Coma Cluster
- **Coma – pushing the limits**

Coma – synch+keV → pushing the limits

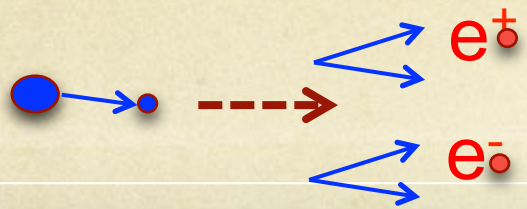


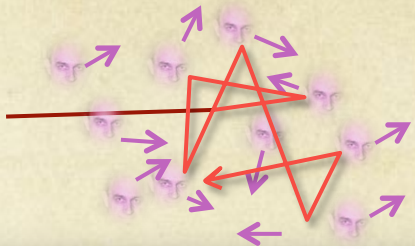


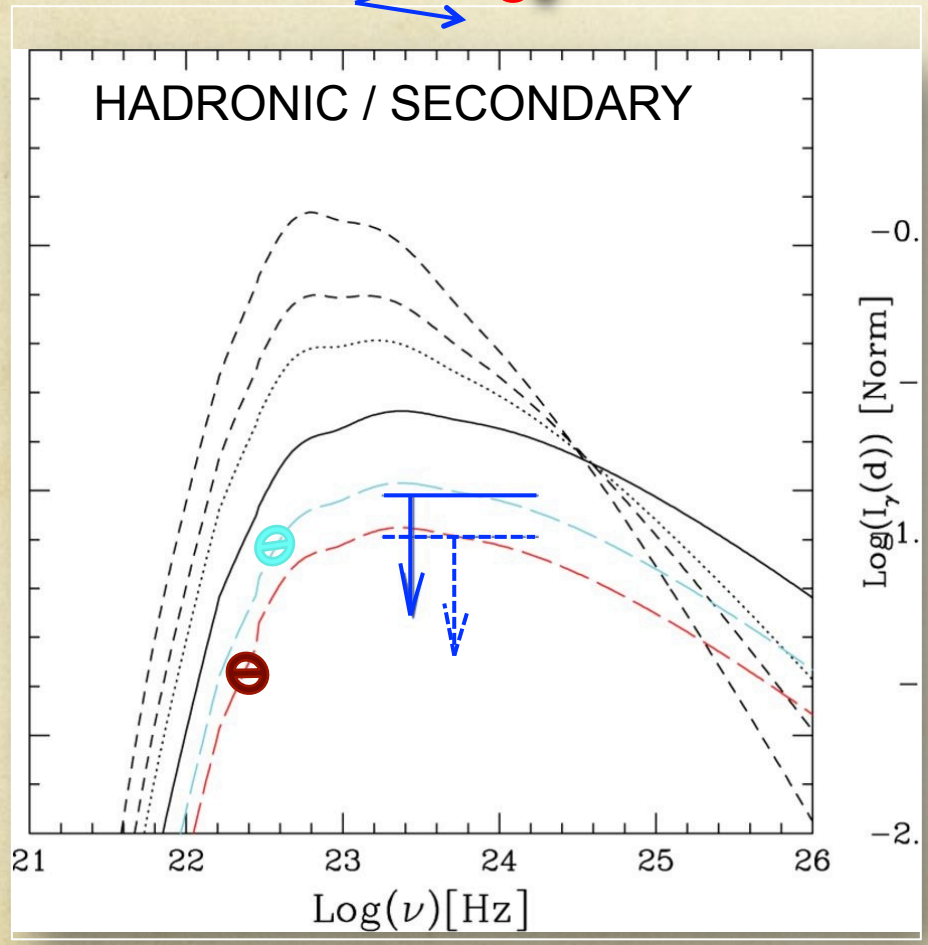


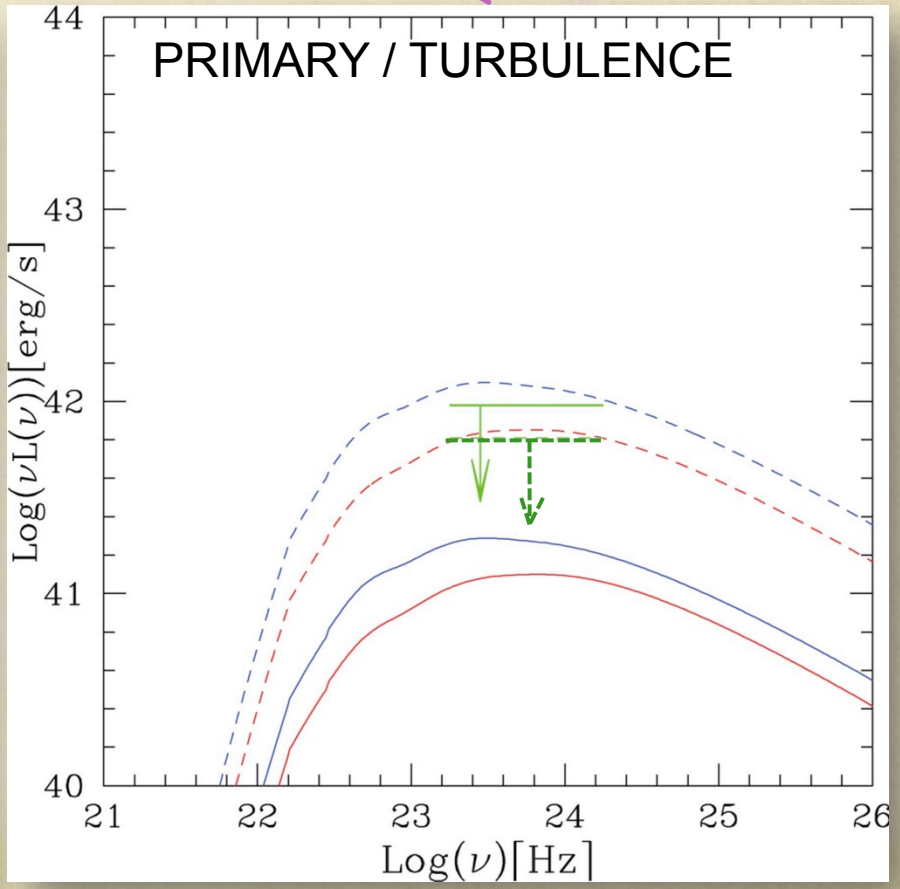
Brunetti, Blasi, Reimer, Rudnick, Bonafede, Shea Brown: MNRAS 2012;426:956-968

Pushing the limits in Coma: Model γ-ray spectra



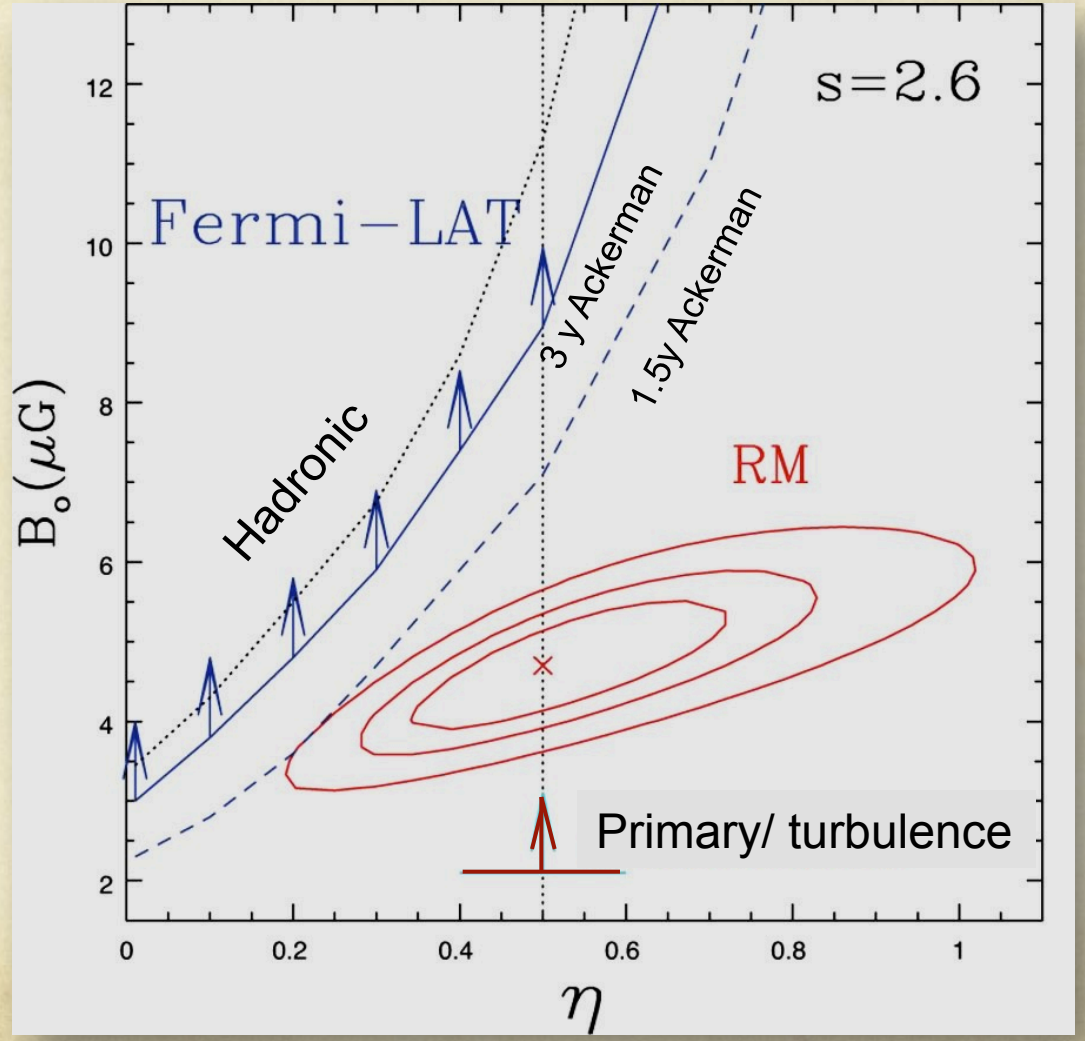




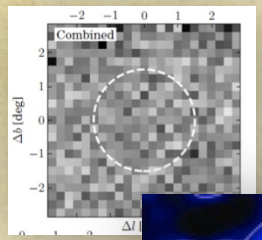


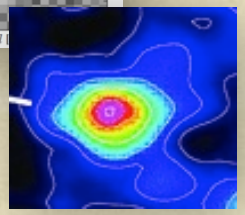
Brunetti G et al. MNRAS 2012;426:956-968

Coma: Pushing the limits



Brunetti G et al. MNRAS 2012;426:956-968





Lessons learned

- γ - rays are inevitable consequence of the encounter between CRs and keV plasma in clusters
- γ - rays provide unique diagnostic of physical conditions (magnetic field strength & profile, CR acceleration & transport) in clusters, which themselves carry imprint of cluster assembly
- Current limits on cluster γ - rays (require) strong fields and reacceleration of CRs
- We really want some detections!