High-energy gamma-ray emission from Clusters of Galaxies

Why do we think of gamma-rays in galaxy clusters?
or: *the link from radio & X-rays observations*

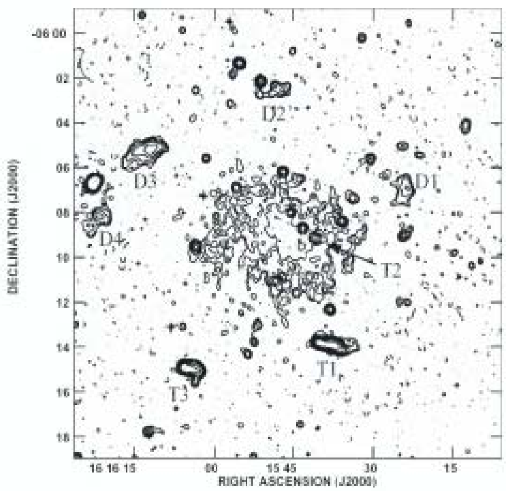
The present situation in gamma-rays
or: *claims on the way towards an unambiguous detection*

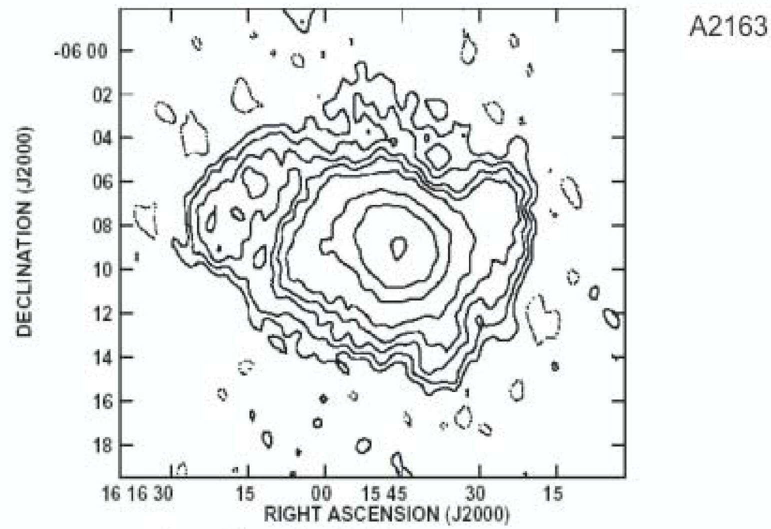
Ask the EGRET data once and for all!
- *a sample of individual clusters*
- *a collective study*

Beyond CGRO?

Hints from radio and X-ray observations

a few galaxy clusters exhibit a diffuse radio halo:





Feretti et al. 2001

only ~ 5 % of the X-ray brightest galaxy clusters show diffuse radio emission ("halos" "relics")

common: high T: kT > 7 keV & high Lx > 5 x 10^{44} erg s^{-1} (0.1 - 2.4 keV),

often: presence of merger processes & large core radii & absence of cooling flows

origin: nonthermal electrons interacting with a magnetic field
- in-situ acc. during merger processes
- diffusion of rel. electrons out of radio galaxies in the cluster
- secondary particle production by hadronic interactions of rel. p with ICM
- ... decay of dark matter annihilation products ...

Hints from radio and X-ray observations

EUV-excess emission: (not the common phenomenon of diffuse EUV emission)
unambiguous evidence only for Virgo and Coma
claims vs. anti-claims: A 2199, A1795, A4095, Fornax ...

hard X-ray emission: nonthermal = power-law component
detected in Coma, A2199, A2256 <-> Virgo!

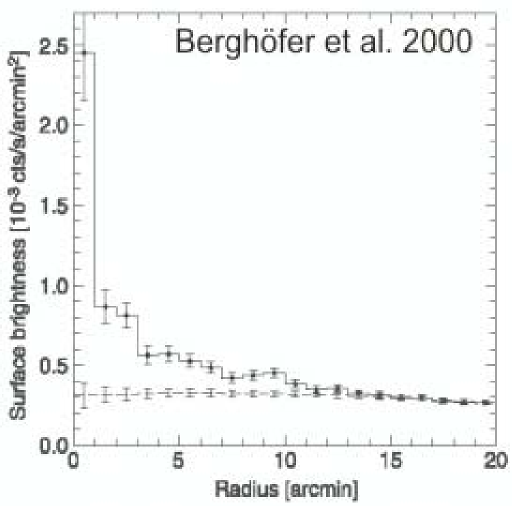
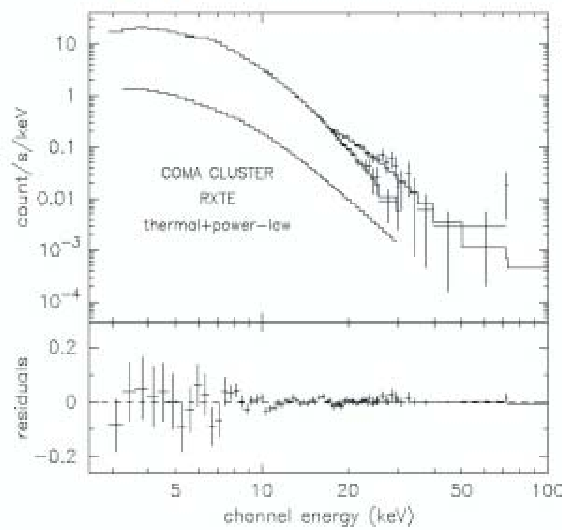


FIG. 1.—Azimuthally averaged radial intensity profile of the EUV emission in the central part of Virgo (centered on M87), shown as a solid line. The dashed line is the vignetted background. There is no EUV emission beyond $r \approx 13'$.



Rephaeli 2000

Figure 1. RXTE spectrum of the Coma cluster. Data and folded Raymond-Smith ($kT \simeq 7.51$ keV), and power-law (index = 2.34) models are shown in the upper frame;

Consequences from radio and X-ray observations

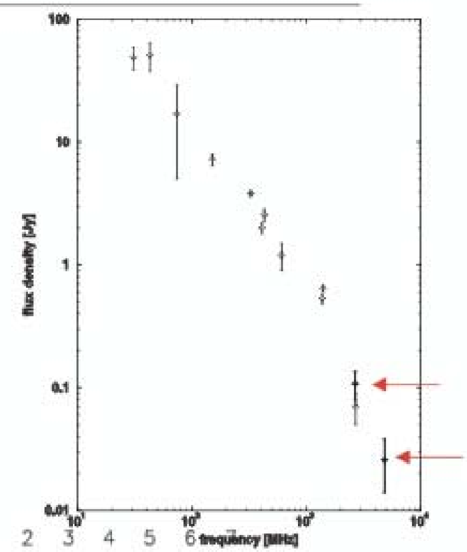
X-ray emission is *IC scattering* of the *radio producing electrons by the CMB*:
- power-law with index simply related to the index of radio emission
- matching spatial profiles in X-rays and radio images
  (of course, only *if* this is one and the same electron population)

if electron spectrum extend to energies both below and above the range deduced from the radio measurements:
low energy supra-thermal or trans-relativistic electrons
-> nonthermal bremsstrahlung: *also* power-law X-ray emission

Some models require a *second* distinct relativistic electron population!

What about p? (i) if π_o decay is detected in gamma-rays, YES!
(ii) if radio & X-ray detected electrons are secondaries from charged pion decays

Now put together the various bits of observational evidence in *multifrequency models* ...



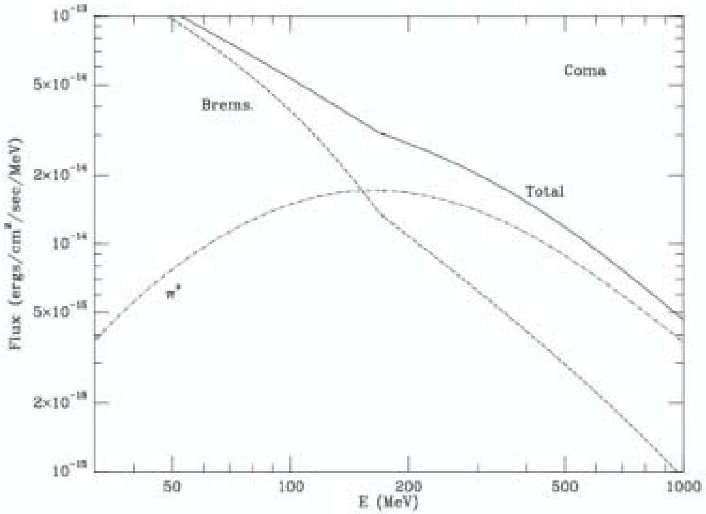


Fig. 7. The predicted gamma-ray spectrum of the Coma cluster in the region around 100 MeV. The emission is mainly the result of bremsstrahlung by relativistic electrons and π^o decay due to relativistic ions. The electron population was de-

Sarazin 1999

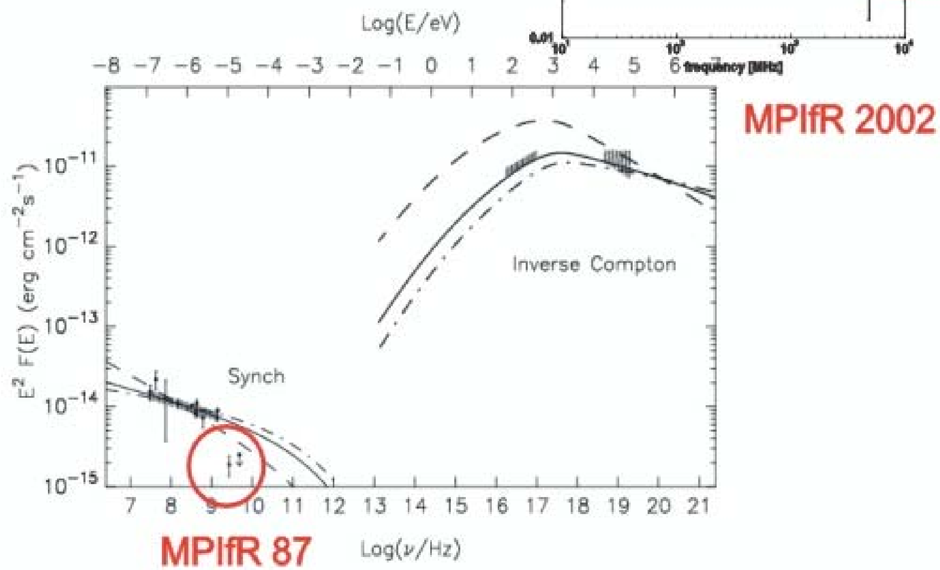


Fig. 1. The synchrotron and IC fluxes calculated for the magnetic field in Coma cluster $B = 0.12\,\mu$G, assuming station-

Atoyan & Völk 1999

... and constraints from OSSE and EGRET (Coma):

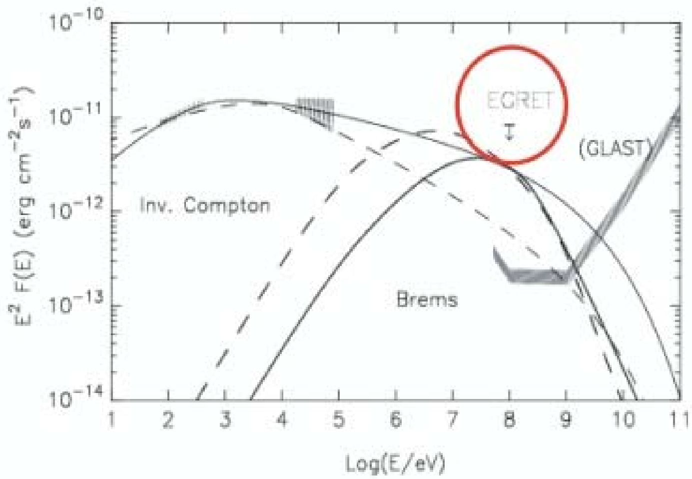


Fig. 2. The bremsstrahlung and IC radiation fluxes calculated in the case of injection of relativistic electrons with $\alpha_{\rm inj} = 2.3$ during the last $\Delta t_{\rm inj} = 3\,{\rm Gyr}$ assuming $B = 0.1\,\mu{\rm G}$ (solid curves), and $\alpha_{\rm inj} = 2.6$, $\Delta t_{\rm inj} = 1\,{\rm Gyr}$ assuming $B = 0.15\,\mu{\rm G}$ (dashed curves). A mean gas density $n_{\rm g} = 10^{-3}\,{\rm cm}^{-3}$ in the ICM is assumed. In the γ-ray region, the expected flux sensitivity of the GLAST detector (from Bloom 1996) and the upper flux limit of EGRET (Sreekumar et al 1996) are also shown.

Atoyan & Völk 2000

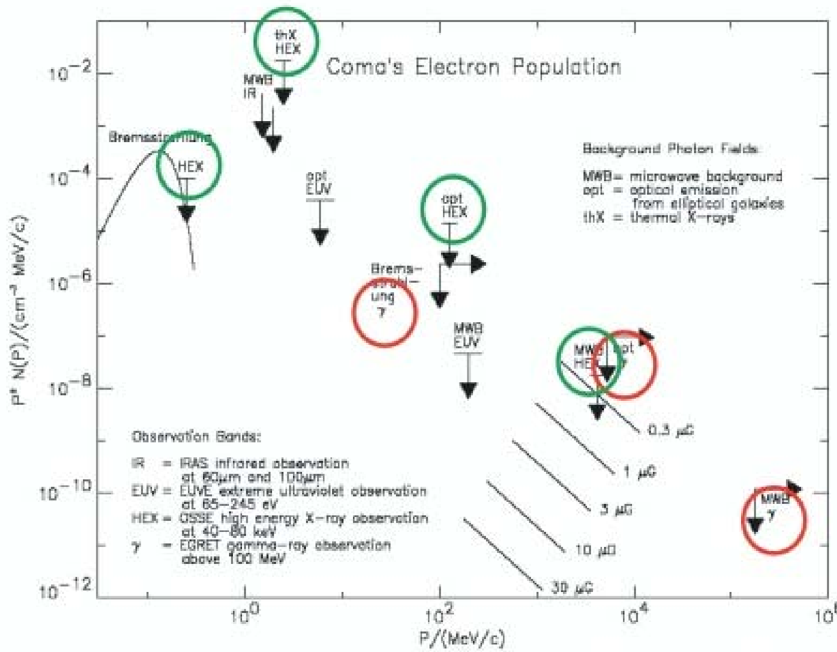
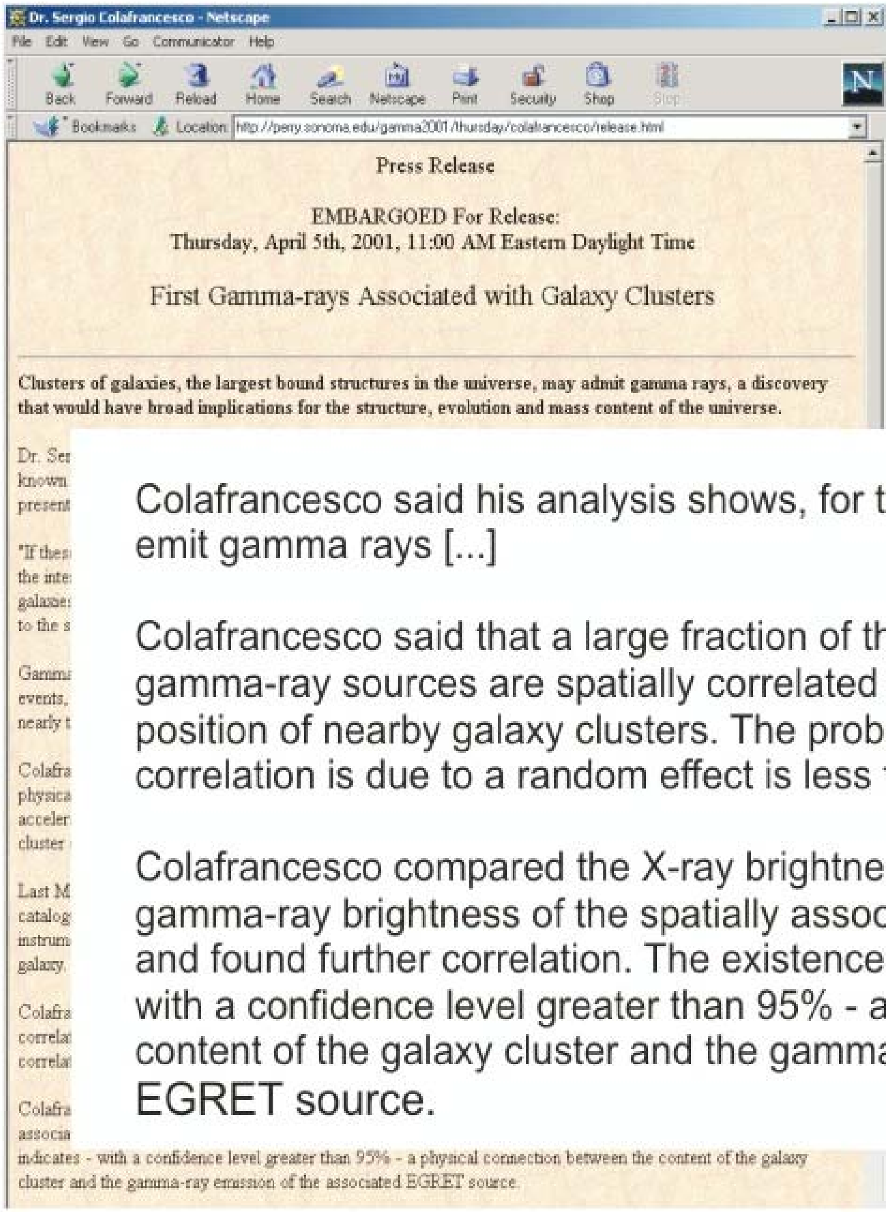


Figure 2. The electron spectrum in the center of the Coma cluster (from Enßlin & Biermann 1998). The solid line below 1 MeV/c is the thermal electron spectrum and the lines around 1 GeV/c give the radio emitting electrons for several magnetic field strength. The upper limits result from several upper limits to possible IC and bremsstrahlung processes.

Enßlin & Biermann 1999


Dr. Sergio Colafrancesco - Netscape

File Edit View Go Communicator Help

Location: http://perry.sonoma.edu/gamma2001/thursday/colafrancesco/release.html

Press Release

EMBARGOED For Release:
Thursday, April 5th, 2001, 11:00 AM Eastern Daylight Time

First Gamma-rays Associated with Galaxy Clusters

Clusters of galaxies, the largest bound structures in the universe, may admit gamma rays, a discovery that would have broad implications for the structure, evolution and mass content of the universe.

indicates - with a confidence level greater than 95% - a physical connection between the content of the galaxy cluster and the gamma-ray emission of the associated EGRET source.

Gamma2001, Baltimore April 2001

Colafrancesco said his analysis shows, for the first time, that galaxy clusters can emit gamma rays [...]

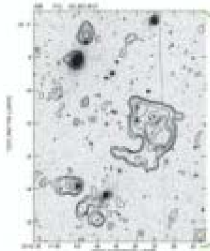
Colafrancesco said that a large fraction of these unidentified, extragalactic gamma-ray sources are spatially correlated - within one degree - with the position of nearby galaxy clusters. The probability that such a spatial correlation is due to a random effect is less than 0.5%.

Colafrancesco compared the X-ray brightness of a given cluster with the gamma-ray brightness of the spatially associated unidentified gamma-ray source and found further correlation. The existence of such a correlation indicates - with a confidence level greater than 95% - a physical connection between the content of the galaxy cluster and the gamma-ray emission of the associated EGRET source.

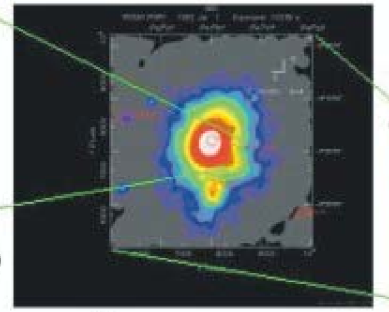
Abell 85

from Colafrancesco's talk Baltimore 2001

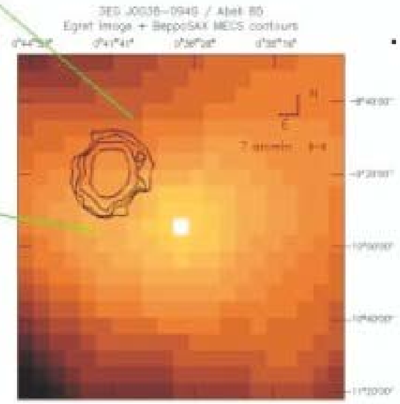
... paper accepted (A&A)



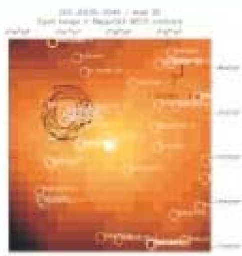
Radio halo/relic map (VLA – 327 MHz)



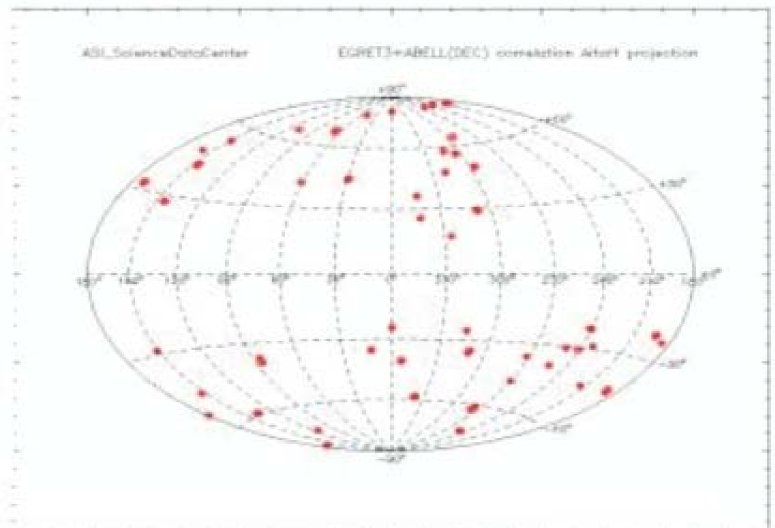
X-ray source (ROSAT PSPC)



EGRET source + SAX contours



NVSS radio sources in the field



50 EGRET sources associated with galaxy clusters within 1 deg radius.

($P_{random} < 5\ 10^{-3}$)

astro-ph/0108309:

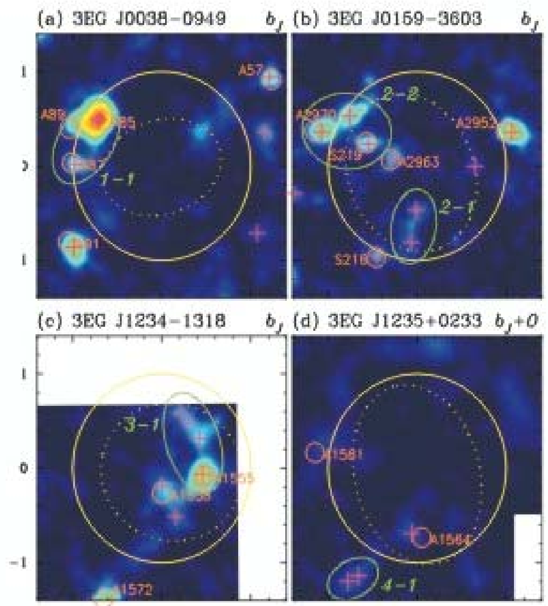
STRONG CORRELATION BETWEEN THE HIGH-LATITUDE STEADY UNIDENTIFIED GAMMA-RAY SOURCES AND POSSIBLY MERGING CLUSTERS OF GALAXIES

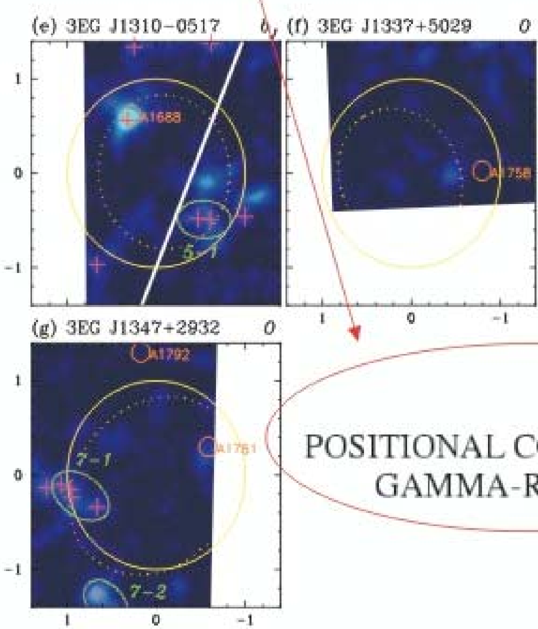
WATARU KAWASAKI[1,2] AND TOMONORI TOTANI[3,4]

Submitted 2001 Aug 18

ABSTRACT

We report an evidence for the first time that merging clusters of galaxies are a promising candidate for the origin of high galactic-latitude, steady unidentified EGRET gamma-ray sources. We made a matched-filter survey of galaxy clusters over $4^\circ \times 4^\circ$ areas around seven steady unidentified EGRET sources at $|b| > 45^\circ$ together with a 100 □° area near the South Galactic Pole as a control field. In total, 154 Abell-like cluster candidates with $z_{est} \leq 0.15$ and 18 close pairs/groups of these clusters, expected to be possibly merging clusters, were identified.





ApJ 2002:

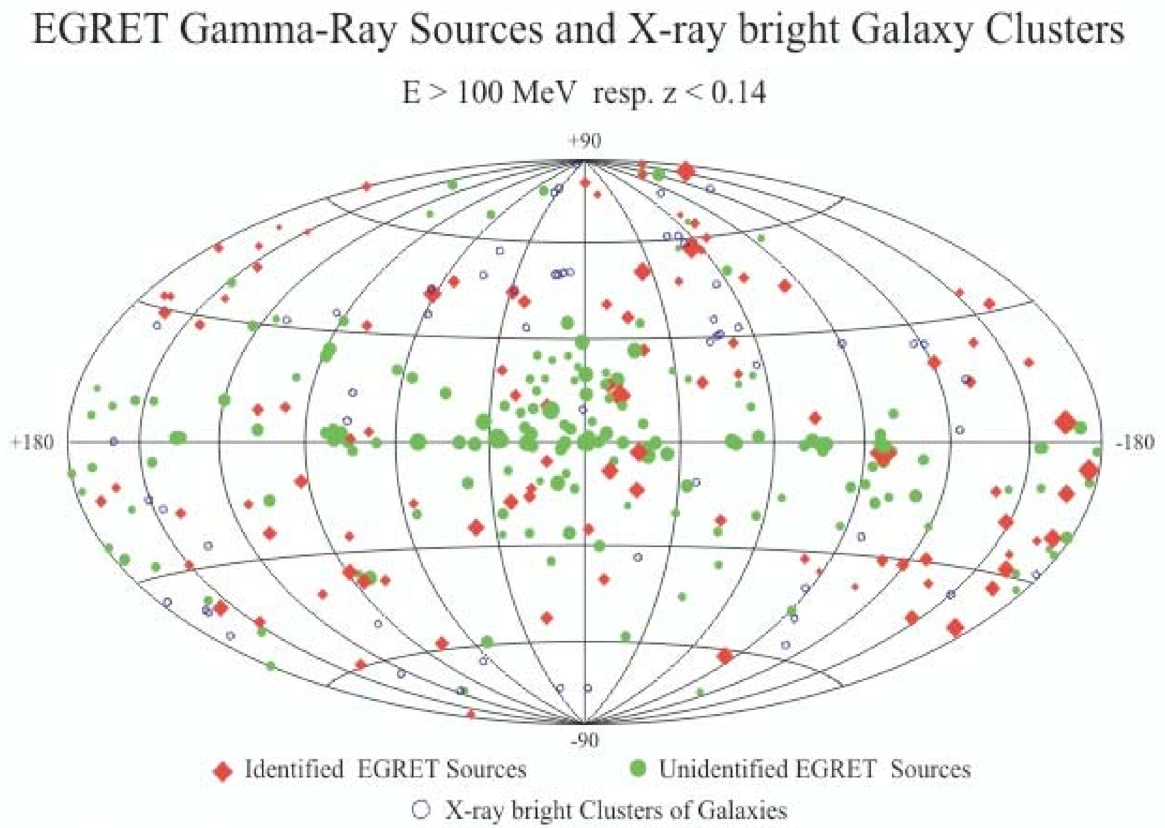
POSITIONAL COINCIDENCE BETWEEN THE HIGH-LATITUDE STEADY UNIDENTIFIED GAMMA-RAY SOURCES AND POSSIBLY MERGING CLUSTERS OF GALAXIES

WATARU KAWASAKI[1,2,3] AND TOMONORI TOTANI[4,5]

Ask the EGRET data once and for all again!

starting in 1999, a sample of 58 of the X-ray brightest clusters has been analyzed ($z < 0.14$), individually as well as in superposition

- *naturally* included: all those *flashy* clusters (EUV excess; hard X-ray emission; most of the radio halo clusters; Perseus, Coma, Virgo)



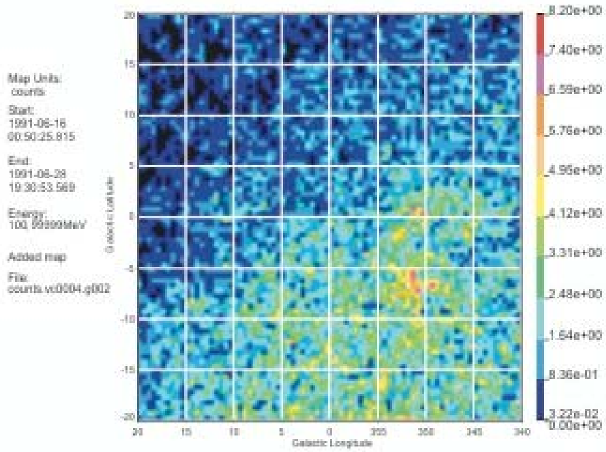
typical procedure for the individual cluster:

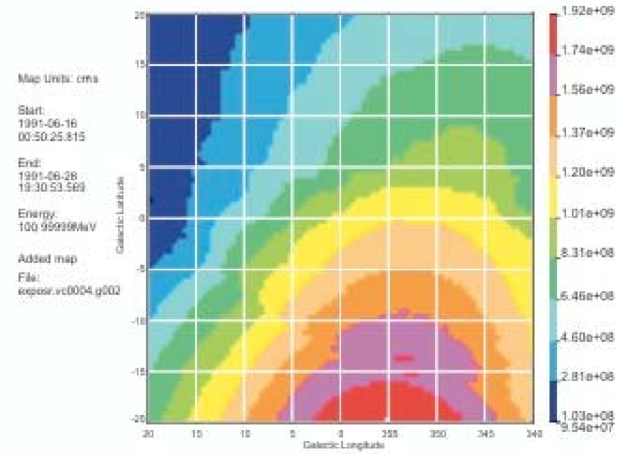
-> superpositioning of count/exposure files from individual viewing periods
(1999: 3EG P1-4, 2001: all available data for r < 25° from cluster center, individually stacked)
-> max lh algorithm (discrimination of excesses above diffuse gamma-ray background)
-> determination of flux at position centered of X-ray emission maximum

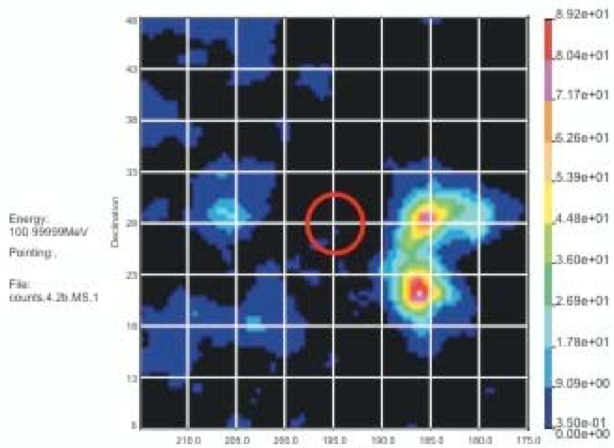
Table 1. EGRET Observations towards X-ray selected Galaxy Clusters

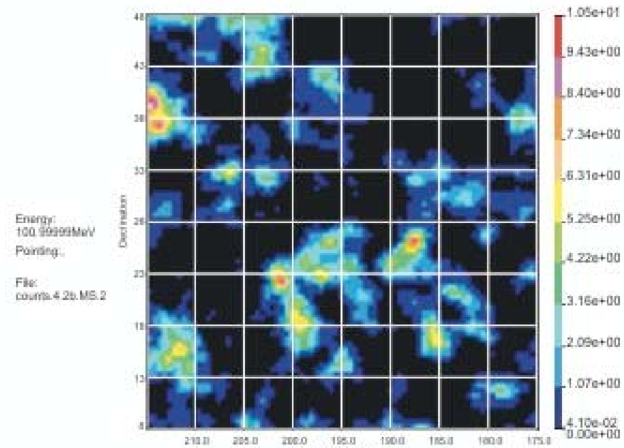
#	Name	l [°]	b [°]	r_{VTP} [arcmin]	z	flux (>100 MeV) [10^{-8} cm^{-2} s^{-1}]	viewing periods
1	A426 (PER Cluster)	150.58	-13.26	33.3	0.0184	< 3.72	0150,0310,0360,0365,0390,2110,3250,4270,7287,7289
2	OPH Cluster	0.56	9.27	–	0.028	< 5.00	0050,0160,0270,2100,2140,2190,2230,2260,2290,2295, 2320,3023,3230,3240,3300,3320,3340,3365,4210,4220, 4230,4235,4290,5080,5295,6250,6151
3	VIR Cluster	282.08	75.20	7.5	0.0038	< 2.18	0030,0040,0110,2040,2050,2060,3040,3050,3060,3070, 3080,3086,3110,3116,3120,3130,4050,4060,4070,4080, 5110,6105,6215,8065,8067,9100,9111
4	COMA Cluster	58.13	88.01	16.5	0.0238	< 3.81	0030,0040,0110,2040,2050,2060,2180,2220,3040,3050, 3070,3080,3086,3110,3116,3120,3130,4060,4070,4180, 5150,7155
5	A2319	75.68	13.50	17.6	0.056	< 3.79	0020,0071,2010,2020,2030,2120,3020,3032,3034,3037, 3181,3280,3310,3315,3330,7100,7110
6	A3571	316.31	28.54	13.9	0.04	< 6.34	0120,0230,0320,2070,2080,2150,2170,3160,4050,4080, 4240
7	A3526 (CEN Cluster)	302.40	21.55	23.5	0.0109	< 5.31	0120,0140,0230,0320,2070,2080,2150,2170,3030,3140, 3150,3160,4020,4025,4240
8	TRA Cluster	324.36	-11.38	–	0.051	< 8.13	0230,0270,0350,0380,2320,3140,3150,3365,4020,4025
9	3C129 (3A 0446+449)	160.39	0.13	–	0.021	< 5.29	0002,0005,0150,0310,0360,0365,0390,2130,2210,3211, 3215,3195,3250,4120,4260,4270

Example: Coma









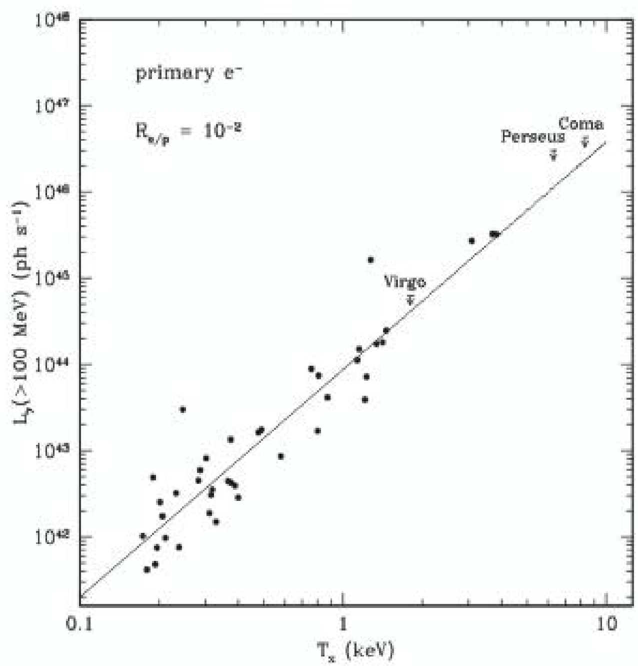
Comparison with predictions from the literature:

Cluster	F_γ this measurement (ph cm^{-2} s^{-1})	F_γ from Enßlin et al.(1997) (ph cm^{-2} s^{-1})	F_γ from Dar & Shaviv (1995) (ph cm^{-2} s^{-1})
A426 (Perseus)	$< 3.7 \times 10^{-8}$	12×10^{-8}	10×10^{-8}
Ophiuchus	$< 5 \times 10^{-8}$	9×10^{-8}	...
A1656 (Coma)	$< 3.8 \times 10^{-8}$	6×10^{-8}	5×10^{-8}
M87 (Virgo)	$< 2.2 \times 10^{-8}$	3×10^{-8}	22×10^{-8}

but not in conflict with other studies:

Colafrancesco & Blasi 1998:
A426 < 1.1 x 10^{-8} cm^{-2} s^{-1}
A1656 < 0.8 x 10^{-8} cm^{-2} s^{-1}

Miniati 2002:

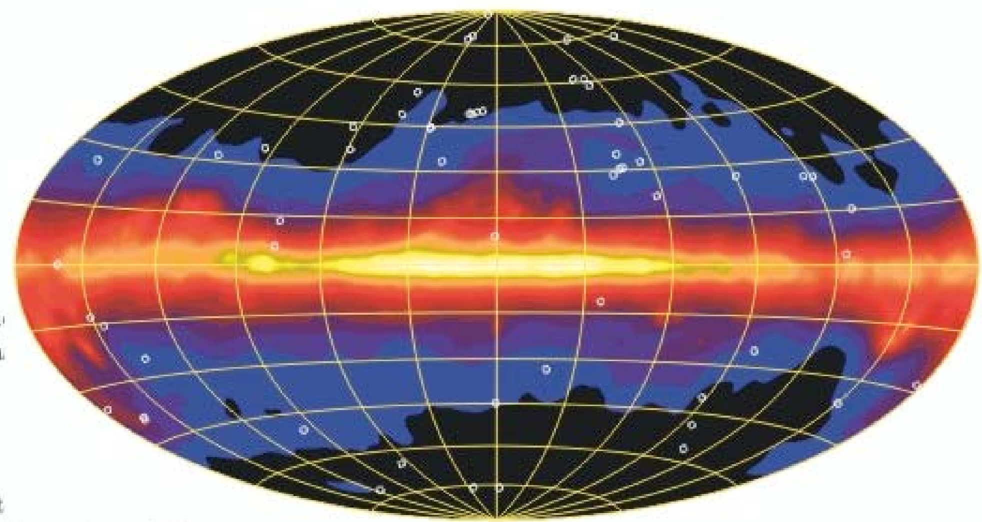


population study: a highly non-standard approach

-> superpositioning of data of all individually analyzed clusters
(~ 650 indiv. vp's!!! = most data extensive EGRET likelihood analysis ever carried out)
-> deterimantion of appropriate diffuse background model for *this* problem
-> subsequent equalizing to comparable exposures
-> max lh algorithm
-> determination of flux at image center

EGRET Galactic Diffuse Emission Model and Locations of X-ray bright Galaxy Clusters

E > 100 MeV resp. Z < 0.14



stacked images, an exposure weight ω_i has been introduced:

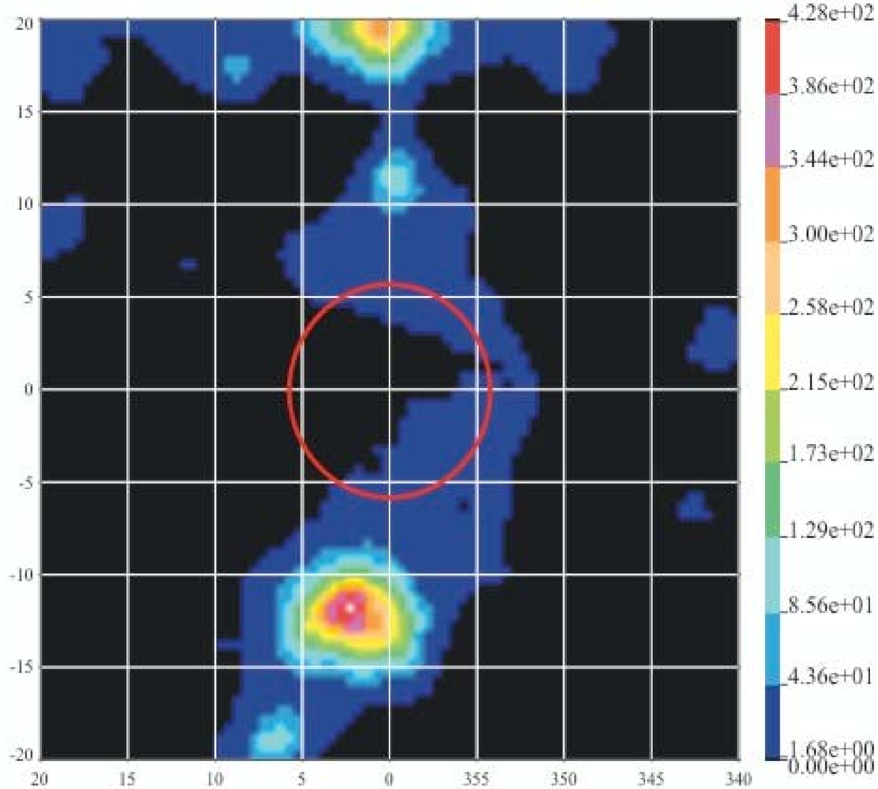
$$\omega_i = \frac{\bar{\varepsilon}_i}{\sum \varepsilon_i},$$

where $\sum \varepsilon_i$ is the total exposure of the galaxy cluster sample and $\bar{\varepsilon}$ is th
central bins in the individual exposure map in cluster–centered coordin

$$\bar{\varepsilon} = \sum_{j=1}^{4} \frac{\varepsilon_j}{4}$$

Thus, the corresponding galactic diffuse background model for a cumulat
clusters is the sum of the product of the individual diffuse background map dbg_i and the exposure weight:

$$dbg = \sum_{\#cluster} \omega_i dbg_i$$



our results: *still* **NO** detection !!

combined exposure: 3.5 x 10^{10} cm^2 s

upper limit (50 cluster sample): 5.9 x 10^{-9} cm^{-2} s^{-1}

What's wrong here?

sample right?

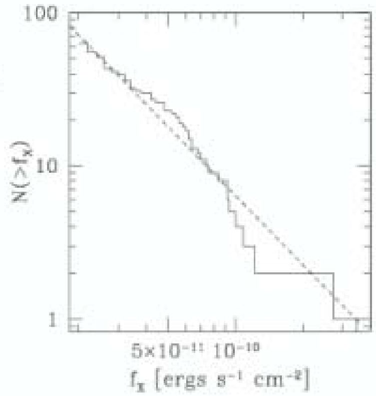


Fig. 8.— log $N(> f_X)$–log f_X diagram. Fluxes are measured in the ROSAT energy band (0.1 – 2.4 keV). The

Lx - M - relation right?

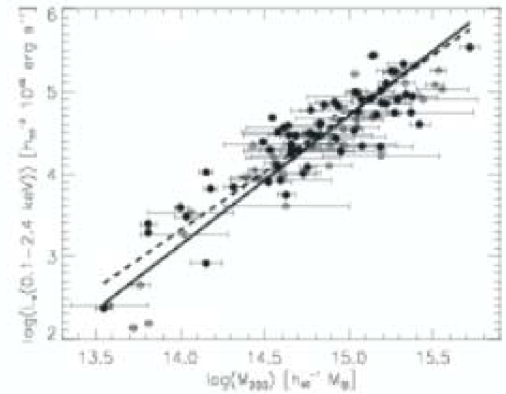


Fig. 6.— Gravitational mass–X-ray luminosity relation (solid line) for the extended sample of 106 galaxy clus-

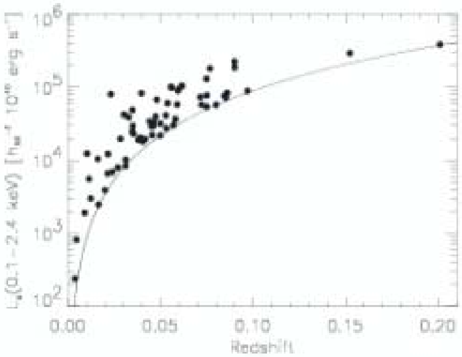
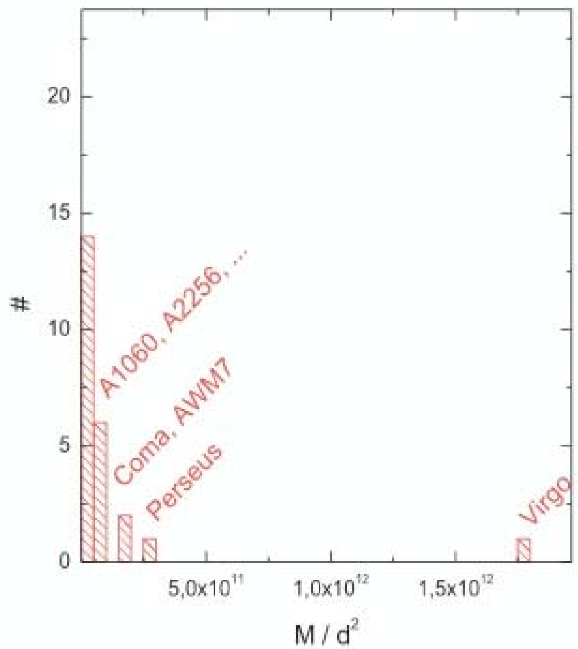


Fig. 9.— X-ray luminosity as a function of redshift. The flux limit is shown as a solid line.

z < 0.14 appropriate?



Problems with Colafrancesco's claim and Kawasaki & Totani's result ?

YES, unfortunately! ****It's all about number statistics!****

Colafranceso: |b|> 20° : 3979 Abell cluster <-> 128 EGRET sources

2.96 σ **corr. claim** (1°roi): 70 Abell cluster <> 50 EGRET

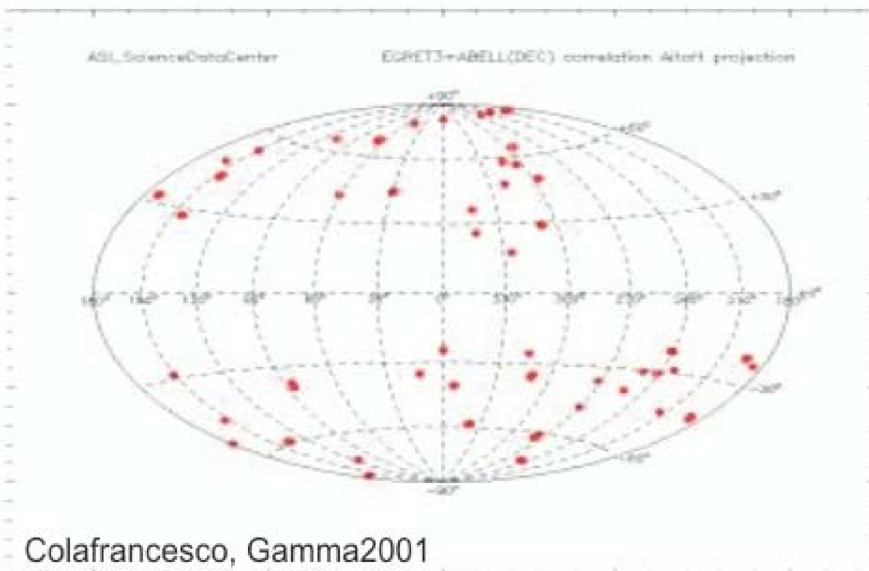
33 of it by chance

a) wrong statistics: correct yield: 56.6 Abell <> 40.7 EGRET by chance

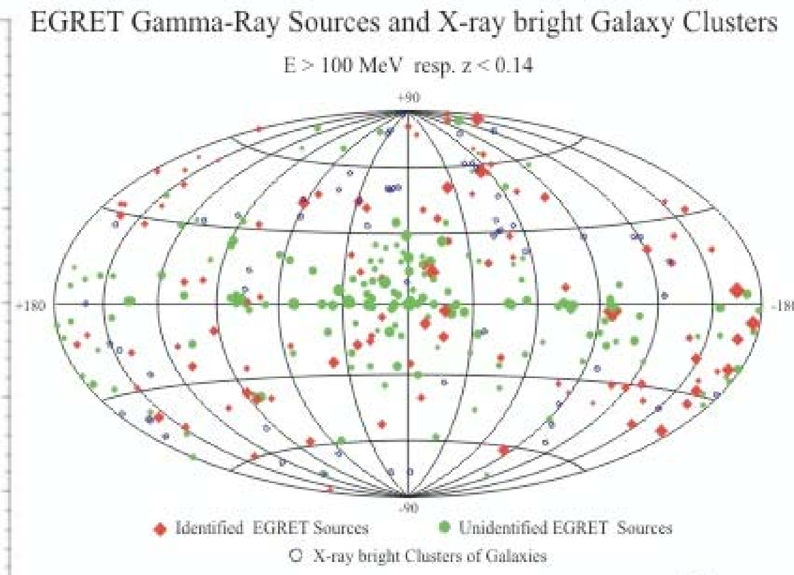
poissonian: 59.3 Abell <> 47.2 EGRET by chance

b) meaningless comparison, anyway:

identified gamma-ray blazars in sample !!



Colafrancesco, Gamma2001



Problems with Colafrancesco's claim ? (Part II)

Colafranceso: |b|> 20° : 3979 Abell cluster <-> 59 unid. EGRET sources

2.55 σ **corr. claim** (Θ_{95}: ~0.75°): 24 Abell cluster <> 18 EGRET

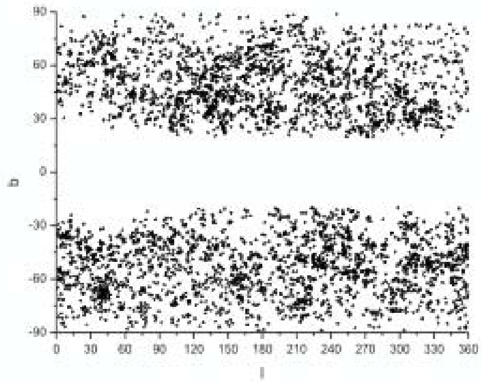
12 of it by chance

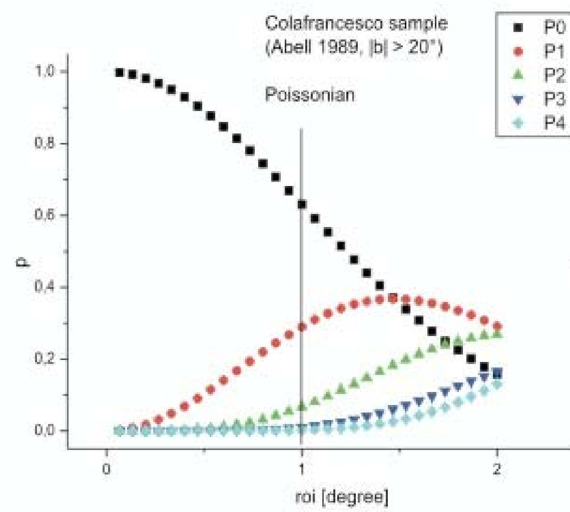
autocorrelation: $\omega(\Theta)$ "angular two-point correlation" (-> literature)

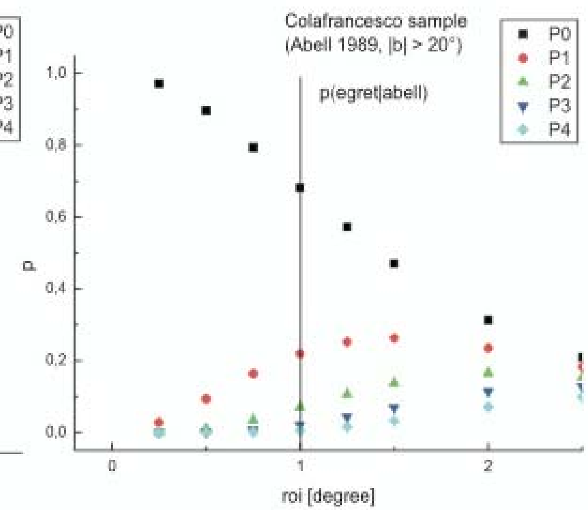
here: derive exactly for |b|>20°: p(iso|Abell) -> p(EGRET|Abell)

correctly yield: 15.1 Abell <> 12.1 EGRET

poissonian: 15.3 Abell <> 13.5 EGRET







Conflict with Kawasaki & Totani's result ?

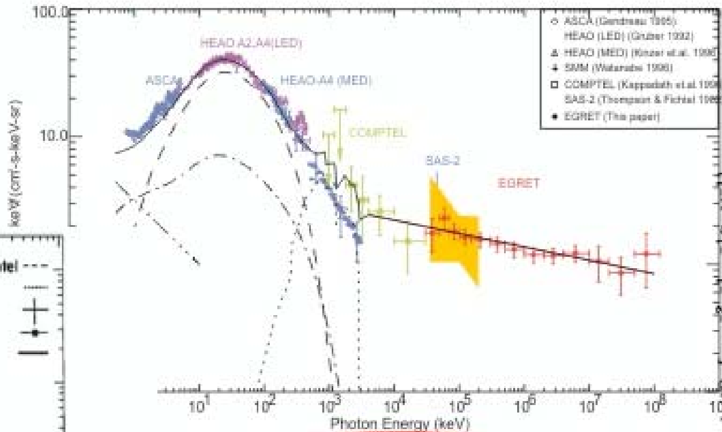
Not really! Kawasaki & Totani: 7 unidentified EGRET sources studied

if one considers one more observable: *gamma-ray flux variability*

-> 2 highly variable, 2 uncertain (statistical limits)

left: 3 candidates -> sufficient deep optical observation in 3°x3° field
-> *counterparts* -> classification ("*possible merging clusters*" t.b.d.)
-> statistics (no significant result from reduced sample)
-> inappropriate for a population study

Contribution to the extragalactic diffuse gamma-ray background



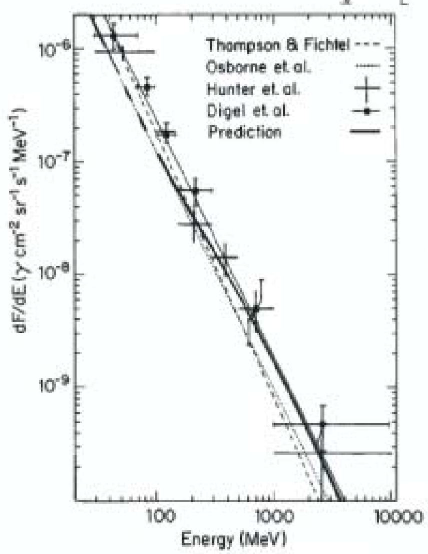
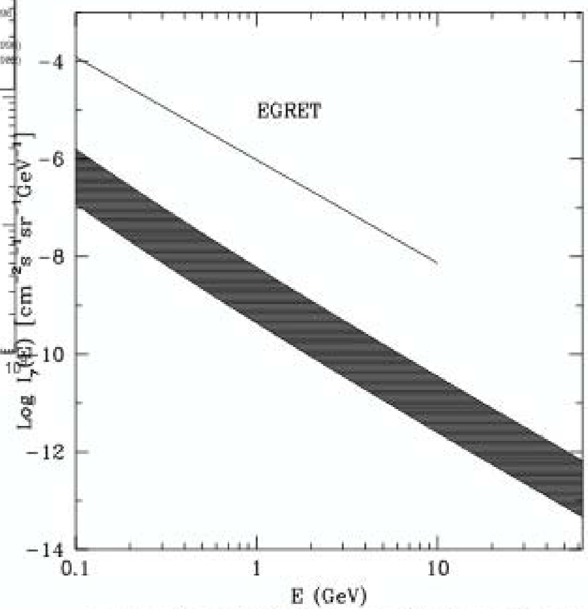
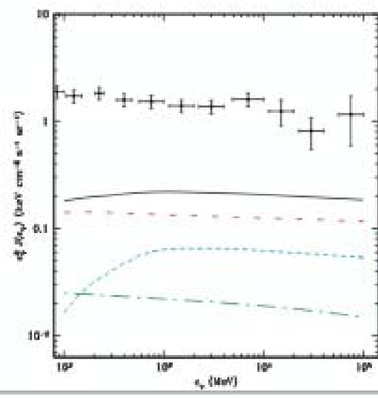


FIG. 1. Comparison between the predicted (thick line) extragalactic GBR produced by a universal MW-like cosmic ray flux in groups and clusters [Eq. (6)] and the observed high-energy GBR. The dashed, dotted, and full lines are the spectrum of the extragalactic GBR derived by Fichtel, Simpson, and Thompson [1] from SAS-2 observations, by Osborne *et al.* [3] from phase I of EGRET observations on CGRO, and by Digel *et al.* [5] from EGRET/CGRO observations of the Orion region, respectively. The actual data points of the measured GBR by Hunter *et al.* [4] and by Digel *et al.* [5] from EGRET/CGRO observations of the Ophiuchus and Orion regions, respectively, are also displayed.

Dar & Shaviv 1995



expected EGDB from Galaxy clusters, considering theoretical uncertainties in cluster modelling
Colafrancesco & Blasi 1998



IC from shock acc. CR electrons
π_0 from p-p inelastic
IC secondary electrons
Miniati 2002

We still have to await the detection of a galaxy cluster in gamma-rays!

But what's next (observationally) on galaxy clusters?
Which are the decicive measurements?

short term: hard X-ray observations (imaging?), high frequency radio observations
- resolve/discriminate, spectrum, composition!
- Jem-X, but INTEGRAL as a gamma-ray instrument ?
  - coded mask ideally suited best for point sources, arcmin resolution
  - moderate continuum sensitivity
  - pointing strategy, narrow FoV -> exposure on high-latitude sources
  - lines, perhaps ?

long term: GLAST!
- detect individual cluster as (extended?) gamma-ray sources
- verify estimates of contribution to EGDB

a *real* ACT!
- tackle hard X-ray/soft gamma