Gamma Ray Emission from Galaxy Clusters
-an observational assessment-

Olaf Reimer

(i) Why do we consider galaxy clusters as candidate gamma-ray sources?

or: links from radio, EUV & X-ray observations and cosmological structure formation scenarios

(ii) Different ways to detect galaxy clusters in gamma rays

(iii) Characterizing our present standing in gamma rays

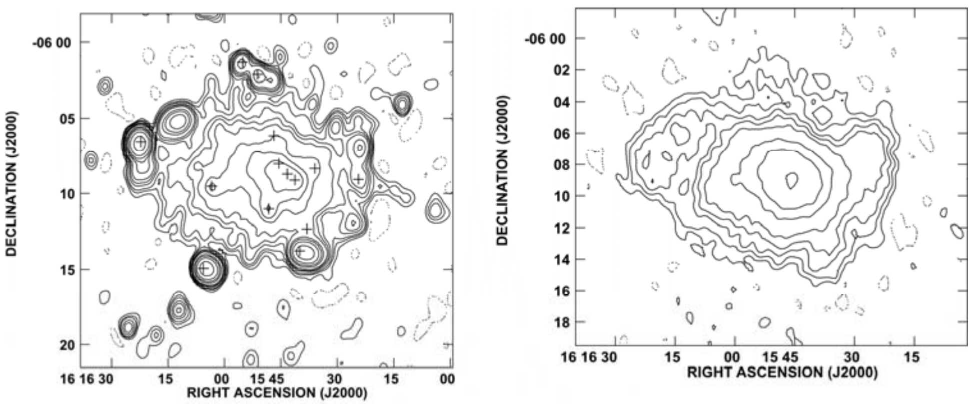
(iv) What's next ? A perspective

here: Coma, examplary for GLAST & IACTs

Why galaxy clusters at gamma-rays ?

Two general scenarios make us believe to consider clusters of galaxies as potential gamma-ray emitters:

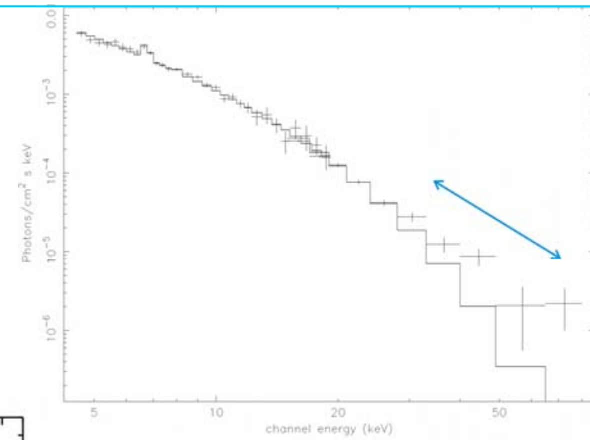
(1) Multifrequency evidence of nonthermal activity



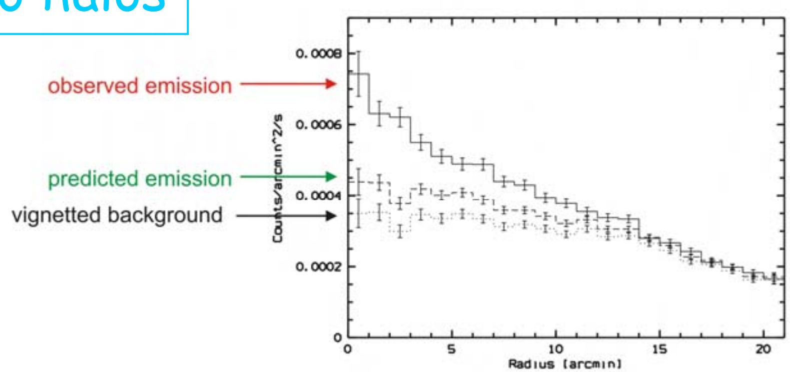
A2163 (Feretti et al. 2001)

diffuse radio halos

nonthermal X-ray emission



BeppoSAX Spectrum of the Coma cluster, fitted with kT = 8.2 keV.
(Rephaeli 2001)



Coma (Bowyer et al. 1999)

EUV excess emission

(2) Large-scale cosmological structure formation

Hierarchical merging scenarios of galaxy clusters:

Larger structures evolve from mergers of adjacent but smaller structures

↓

baryonic matter condenses in form of galaxy clusters

↓

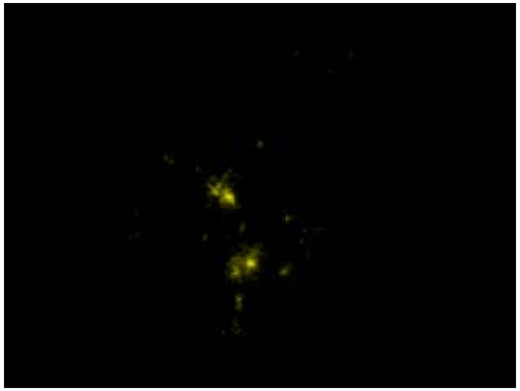
dark matter halos interact/merge

↓

1st order Fermi acceleration of particles at the shock fronts/ MHD turbulence

↓

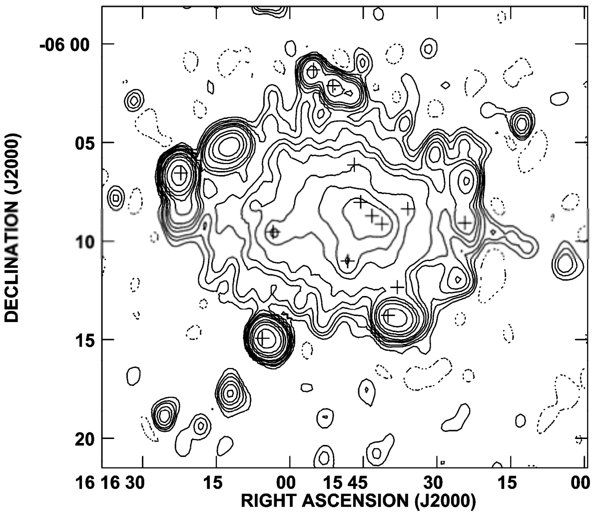
integral part of large scale structure formation codes ?!

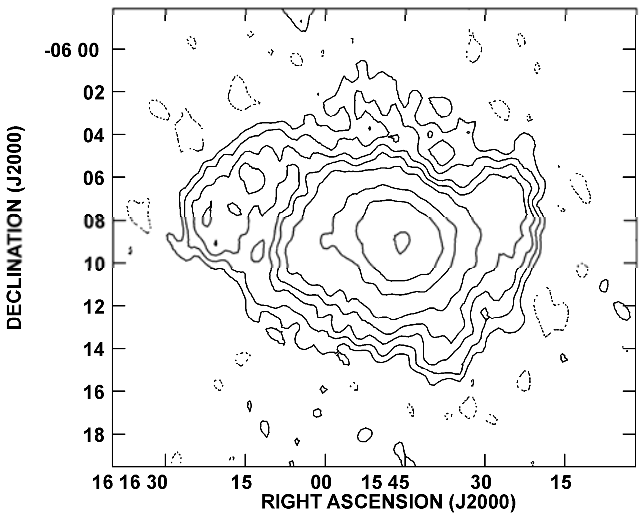


Formation of a galaxy cluster in the tCDM 3D simulation. (Starting z= 2.5) (from Jenkins et al. 1998)

Hints from multifrequency observations: radio

a few galaxy clusters exhibit **diffuse radio halos**:





A2163 (Feretti et al. 2001)

~ 30-35% of the X-ray luminous clusters ($L_x > 10^{45}$ erg/s)

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

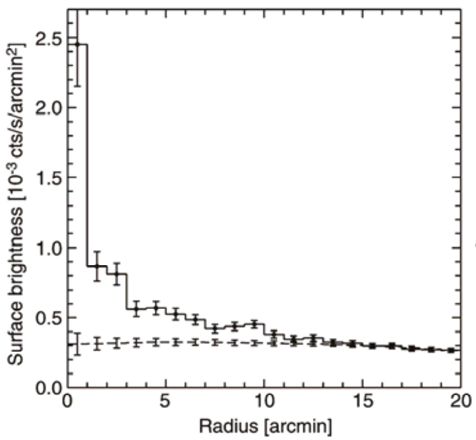
common: high T: kT > 7 keV & high Lx > 5 x 10^{44} erg s^{-1} (0.1 - 2.4 keV),
presence of merger processes & large core radii

origin: nonthermal electrons interacting with a magnetic field
in-situ acceleration during merger processes
diffusion of relativistic 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 ...

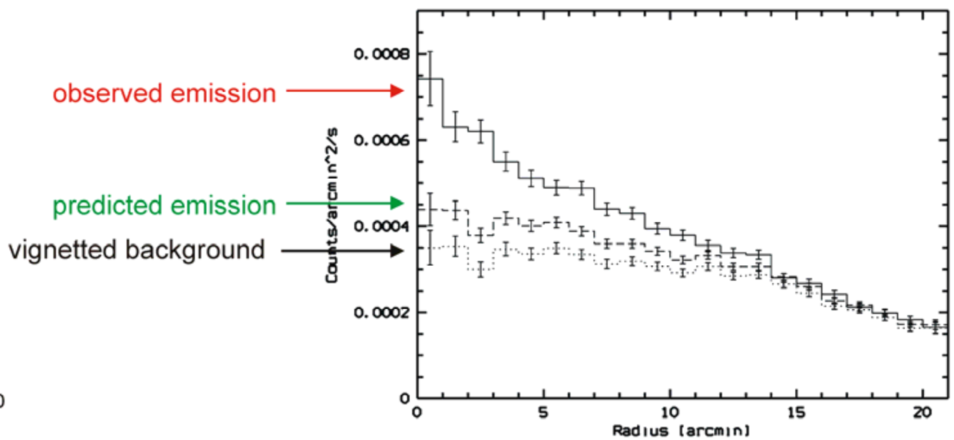
Hints from multifrequency observations: EUV

nonthermal emission from galaxy clusters?
EUV-excess emission ?

EUV-excess:(not the common phenomenon of diffuse EUV emission)
unambiguous evidence only for Virgo and Coma
claims vs. anti-claims: ~~A 2199~~, ~~A1795~~, ~~A4095~~, ~~Fornax~~ ...
... ongoing (i.e. Shapley-supercluster, EUV -> ... soft X-rays)



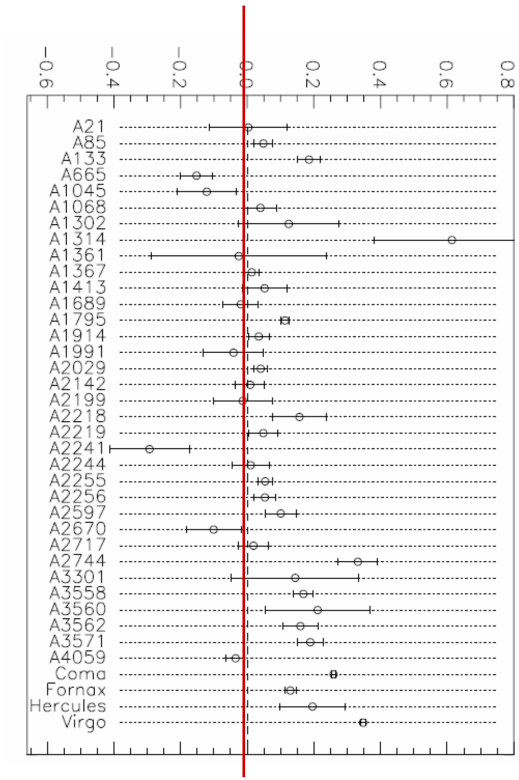
Virgo (Berghöfer et al. 2000)



Coma (Bowyer et al. 1999)

Hints from multifrequency observations: X-ray

Soft X-ray excess – a common feature?



Bonamente et al. 2002 (ROSAT PSPC)

Kaastra et al. 2003 (XMM EPIC)

Table 5. Power law fits to the soft excess. Luminosities of the power law (L_{PL}) and thermal plasma L_{th} are in the 0.2–10 keV band in the rest frame of the cluster.

Cluster	Γ	L_{PL} (10^{37} W)	L_{th} (10^{37} W)
Coma	$2.2^{+0.6}_{-0.4}$	1.0 ± 0.3	10.5
A 1795	$1.9^{+0.6}_{-0.2}$	4.8 ± 0.9	19.9
Sérsic 159–03	$2.6^{+0.5}_{-0.4}$	1.3 ± 0.2	4.5
MKW 3s	$2.1^{+0.3}_{-0.2}$	1.7 ± 0.2	4.0
A 2052	$2.1^{+0.4}_{-0.2}$	1.2 ± 0.1	3.0

Bregman & Lloyd-David 2006 – ApJL

On the Lack of a Soft X-Ray Excess from Clusters of Galaxies

- incorrect subtraction of the soft X-ray background -> soft X-ray excess largely disappears

--> thus not associated with the target clusters

- "redshifted" O VII lines (Kaastra et al.) correlated with solar system charge exchange emission

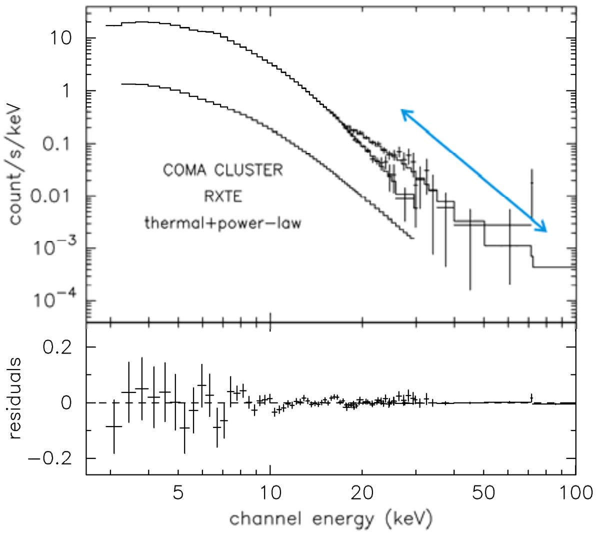
--> not extragalactic either.

Hints from multifrequency observations: X-ray

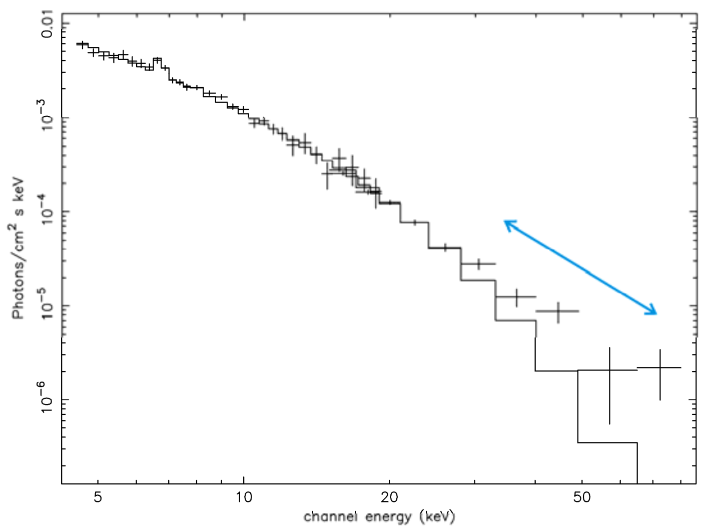
hard X-ray emission:

nonthermal = power-law component detected in Coma, A2199, A2256
A2319, … A 754, … (A2163, A119)

no imaging of the hard X-ray component yet



RXTE data and folded Raymond-Smith (kT = 7.51 keV), and power-law (index = 2.34)



BeppoSAX Spectrum of the Coma cluster, fitted with kT = 8.2 keV.

(Rephaeli 2001)

Galaxy Clusters contain significant populations of Cosmic Rays, stored over cosmological timescales
-> the largest non-thermal sources in the universe

Various scenarios appear to be able to energize the CRs
-> in merger or accretion shocks, through SN-driven winds, radio- or active galaxies within a cluster

Physical processes to be considered:

- p-p-interactions -> π^0 decay -> HE γ's
- TeV electrons -> IC photon upscattering on CMB -> HE γ's
- p-acceleration up to 10^{18} eV (?) -> CMB interaction /injection into ICM
  -> photomeson production: p-γ -> π^0, π's, ...
  -> Bethe-Heitler pair production: p-γ -> p, e^+, e^-
- secondary pair production through γ-γ-interactions of VHE gammas from AGN / IC CMB γ (UV/OPT: GeV, IR: TeV)

Consequences from radio and X-ray observations

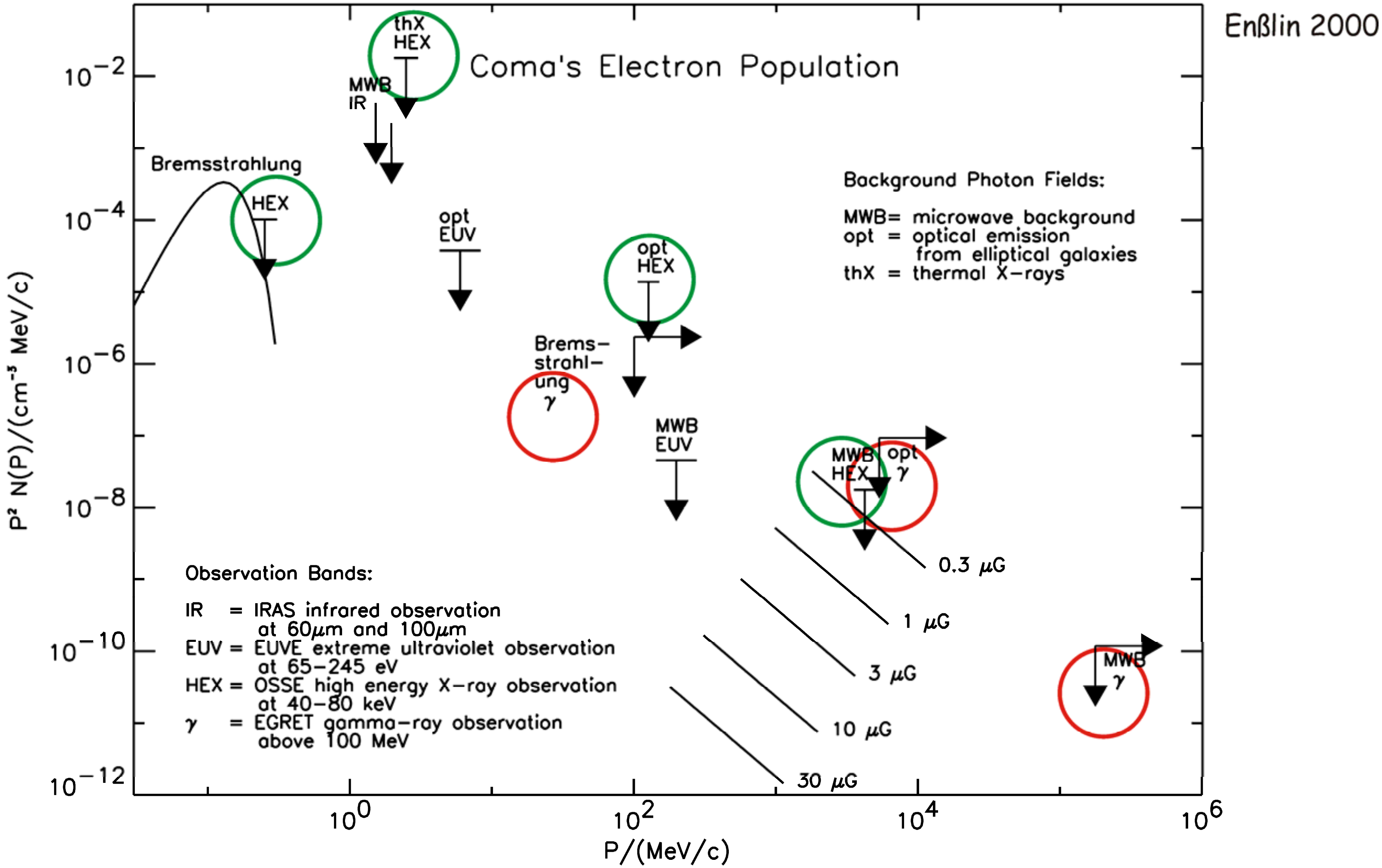
X-ray emission is IC scattering of the radio emission producing electrons by the CMB:
- power-law with index simply related to the index of radio emission
- matching spatial profiles in X-rays and radio images
(of course, only if this is one and the same electron population)

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

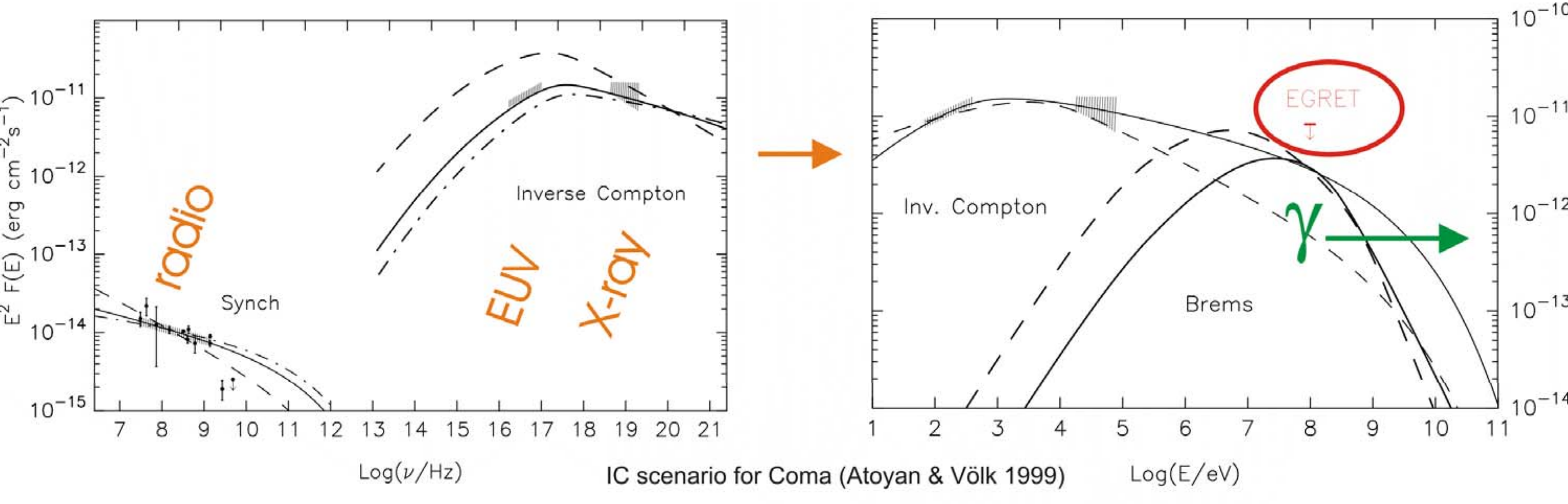
Some models require a second distinct relativistic electron population

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

... and therefore:



Multifrequency modeling



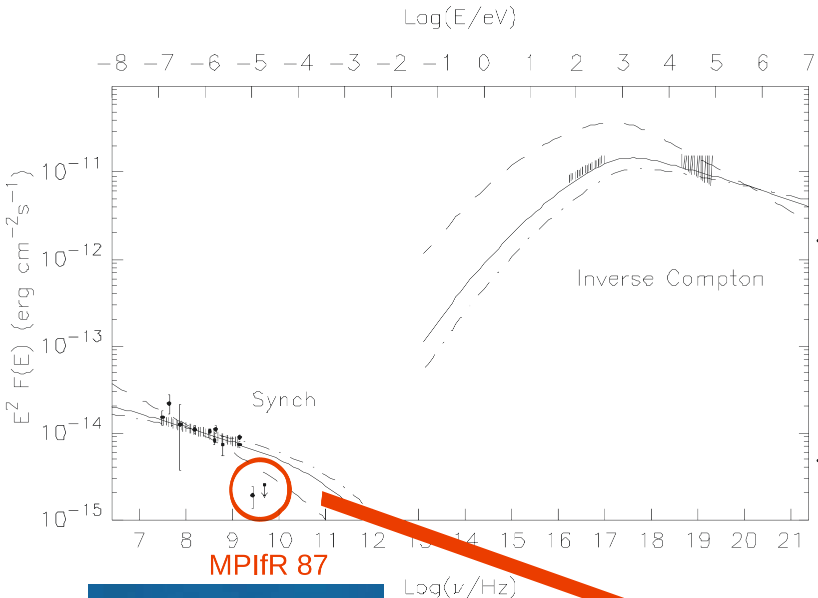
IC scenario for Coma (Atoyan & Völk 1999)

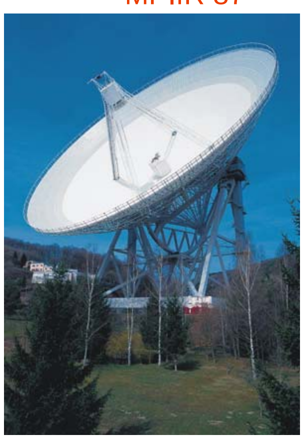
$\alpha_{inj} = 2.3\ \Delta t_{inj} = 3$ Gyr B = 0.1 μG

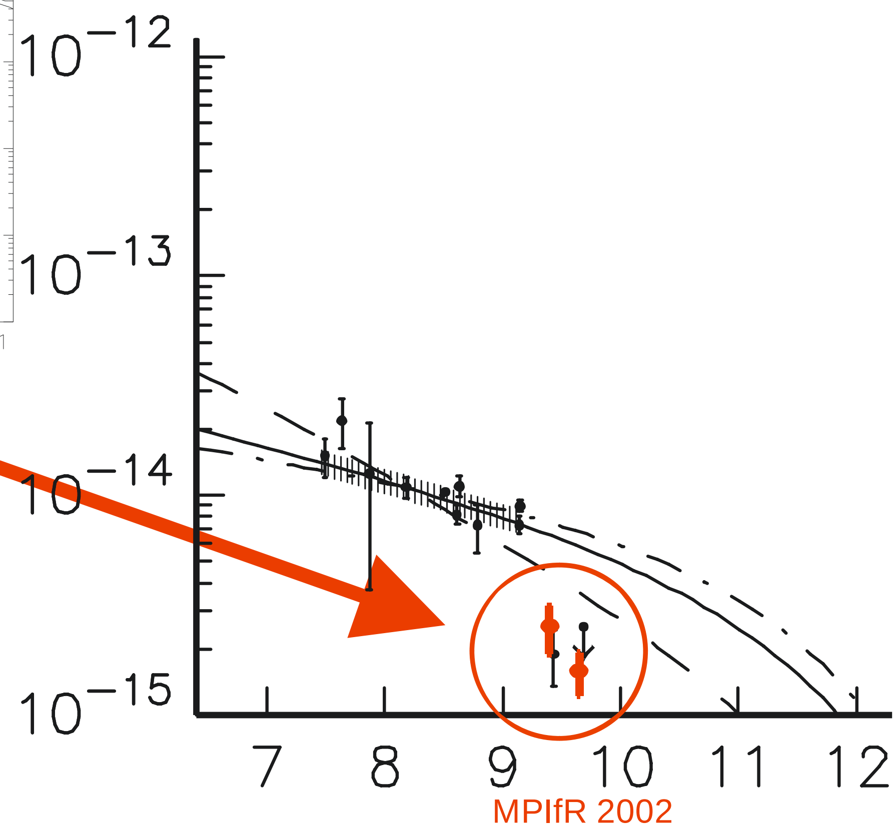
$\alpha_{inj} = 2.6\ \Delta t_{inj} = 1$ Gyr B = 0.15 μG

Continuing with observations at other wavebands…

Coma: Thierbach et al. 2003

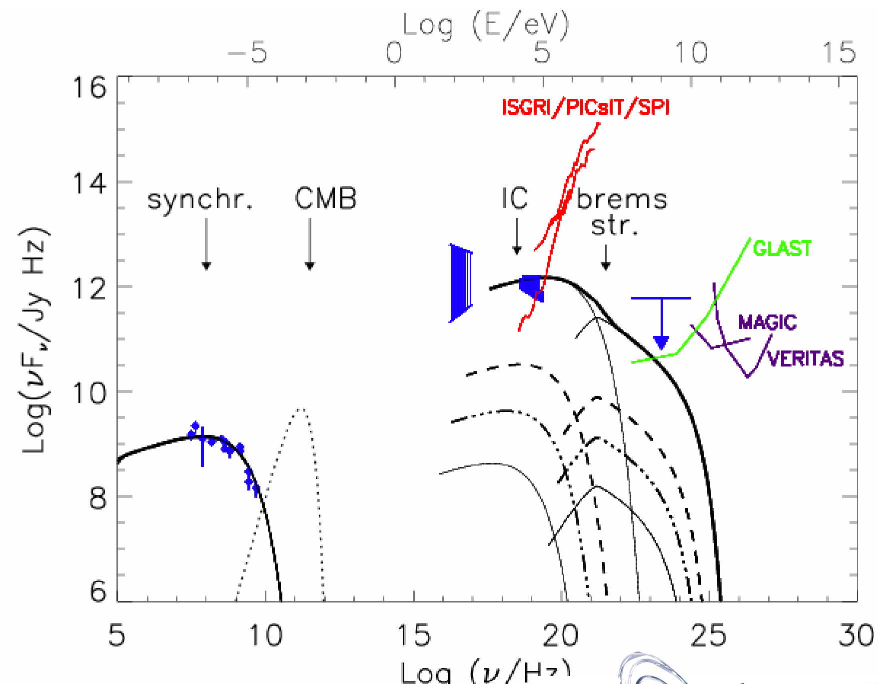


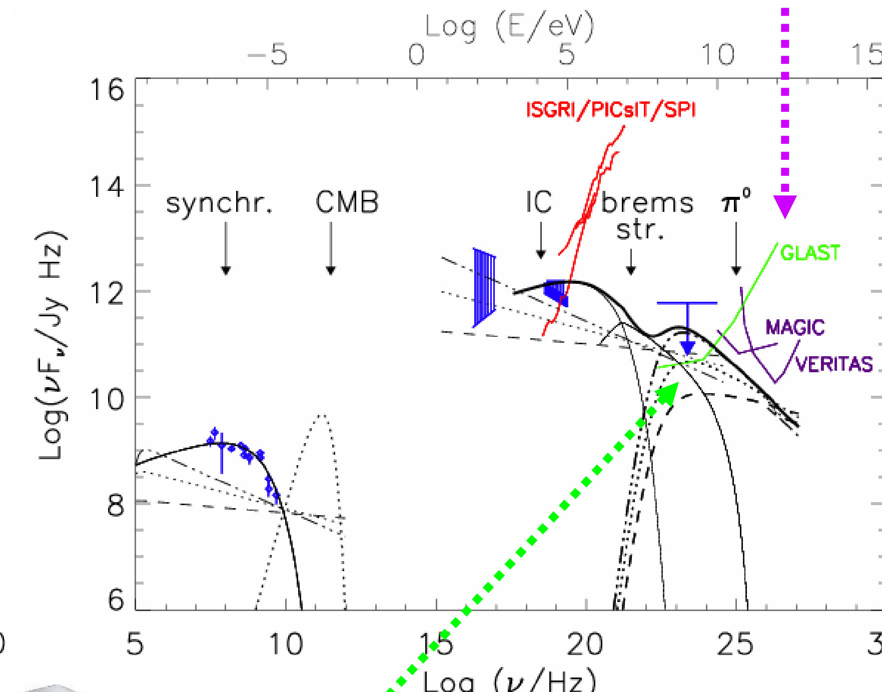




... lead to improve

Coma cluster (A.Reime



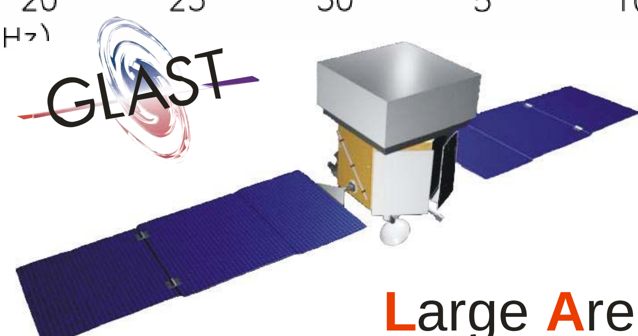


B= 0.1 μG

B= 0.7 μG

B= 1.9 μG

B= 6 μG



α = 2.1

α = 2.3

α = 2.5

Large Area Telescope

Three ways to detect galaxy clusters at gamma-rays

Direct detection of gamma-ray emission in unambiguous positional coincidence with one candidate galaxy cluster
-> „pointing“ approach

Spatial-statistical correlation between still unidentified gamma-ray sources and a candidate object population
-> „correlation study“

Unresolved gamma-ray emission excesses through localized enhancements in the extragalactic background
-> „background contribution studies“

Coma, Virgo & other clusters in the EGRET data?

McGlynn, Vestrand & Jennings (2nd Compton Symposium, 1993)

22 u.l.'s based on earliest CGRO observations

↓

Sreekumar et al. 1996 (ApJ 464)

sensitive u.l.'s for Coma & Virgo cluster

↓

Reimer et al. 2003 (ApJ 588)

58 of the X-ray brightest clusters, nearby ($z < 0.14$)

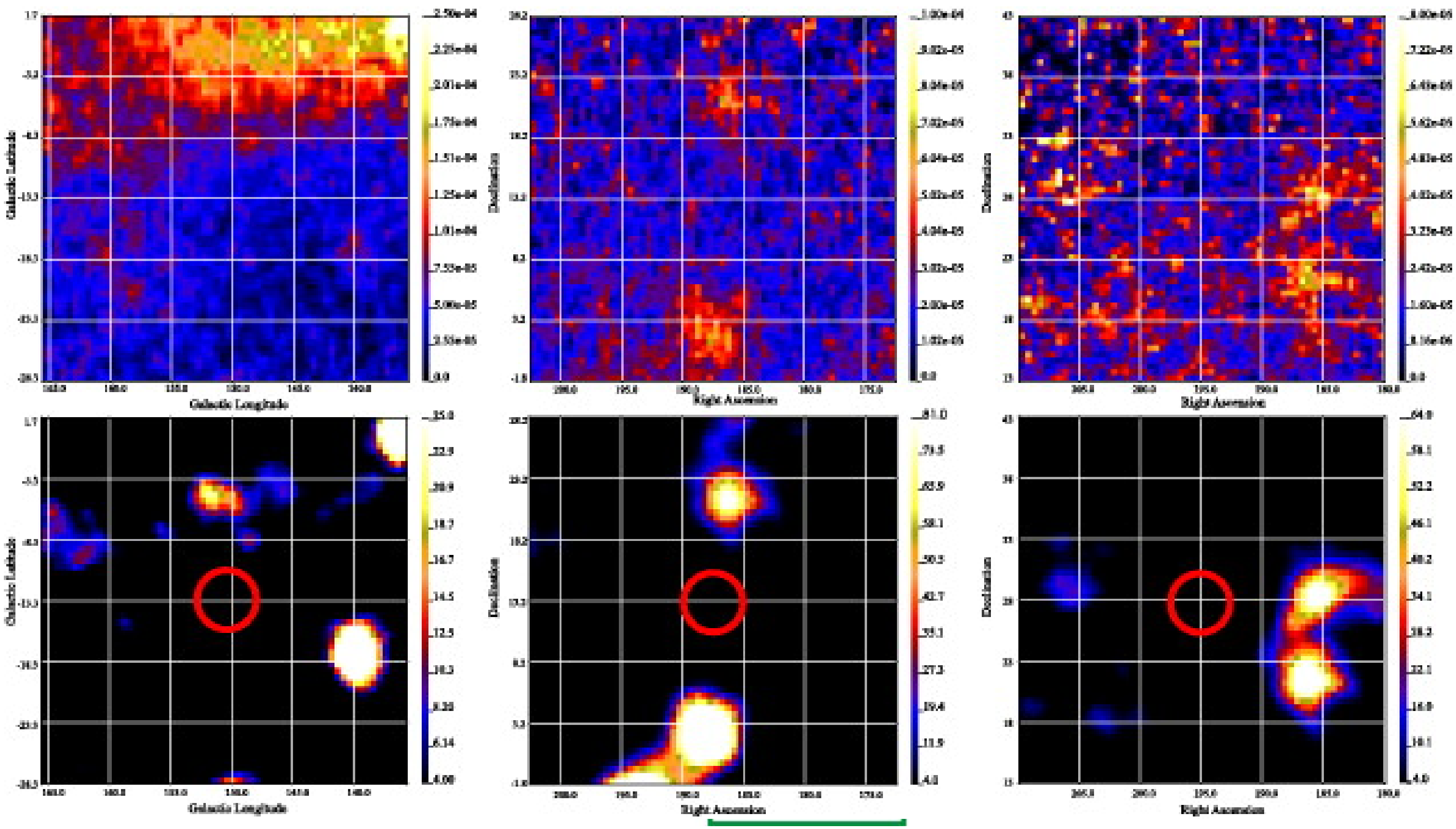
finalized EGRET data and instrumental response functions

Part I: **individually** analyzed clusters

naturally included := best-observed 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
-> max lh algorithm (discrimination of excesses above diffuse gamma-ray background)
-> determination of flux at the position of the X-ray emission maximum



Comparison with predicted gamma-ray fluxes

Cluster	this measuremnt	from Enßlin et al. (1997)	from Dar&Shaviv (1995)
A426 (Perseus)	< 3.7 x 1E-8	12 x 1E-8	10 x 1E-8
Ophiuchus	< 5.0 x 1E-8	9 x 1E-8	
A1656 (Coma)	< 3.8 x 1E-8	6 x 1E-8	5 x 1E-8
M87 (Virgo)	< 2.2 x 1E-8	3 x 1E-8	22 x 1E-8

Fluxes in units of ph/cm^{2}s

but not in conflict with other studies:

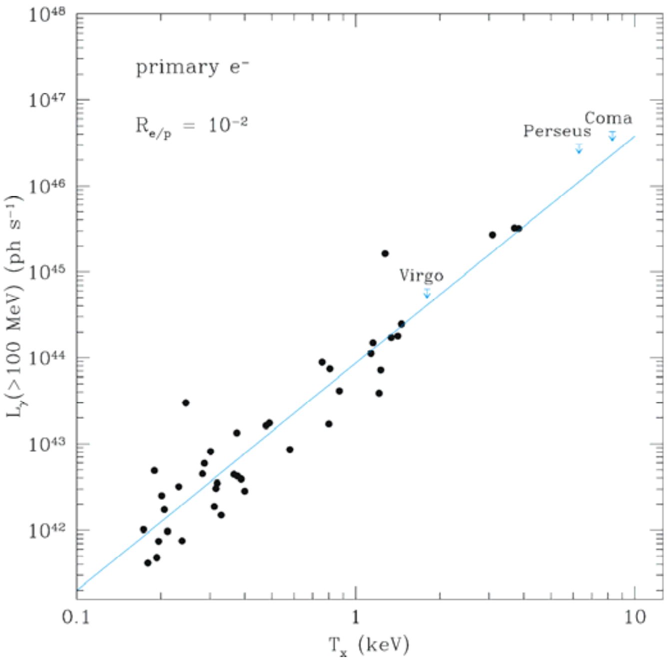
Colafrancesco & Blasi 1998:

A426 < 1.1×10^{-8} cm^{-2} s^{-1}

A1656 < 0.8×10^{-8} cm^{-2} s^{-1}

Miniati 2002:

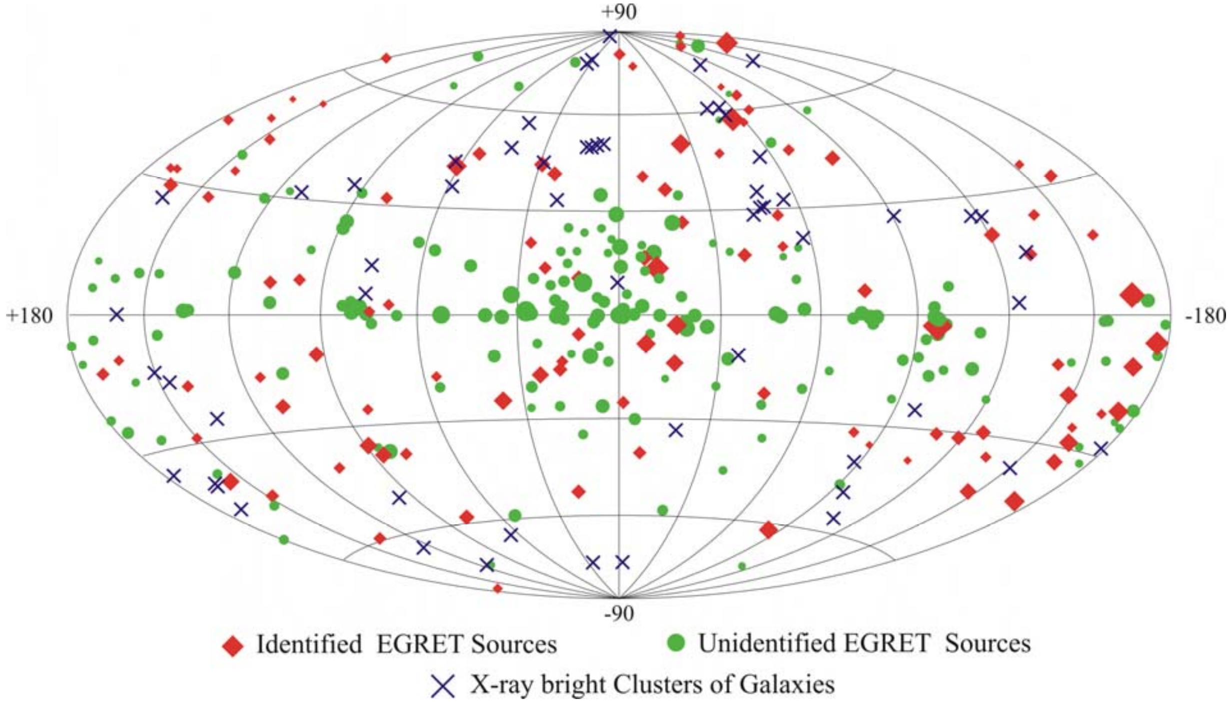
Predicted correlation between IC gamma-ray luminosity and cluster core temperature:



Reimer et al. 2003 (ApJ 588)

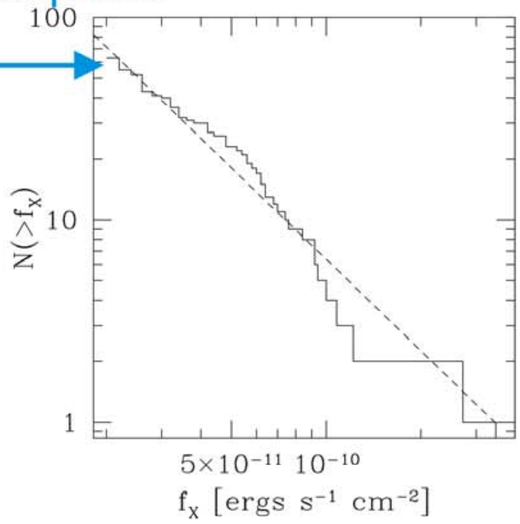
58 of the X-ray brightest clusters, nearby (z < 0.14)
(alternatives? **implicated source physics <-> sample size?**
mass rich? merger? non-thermal? nearby? supercluster? ...)

Part II: analyzed in **superposition**

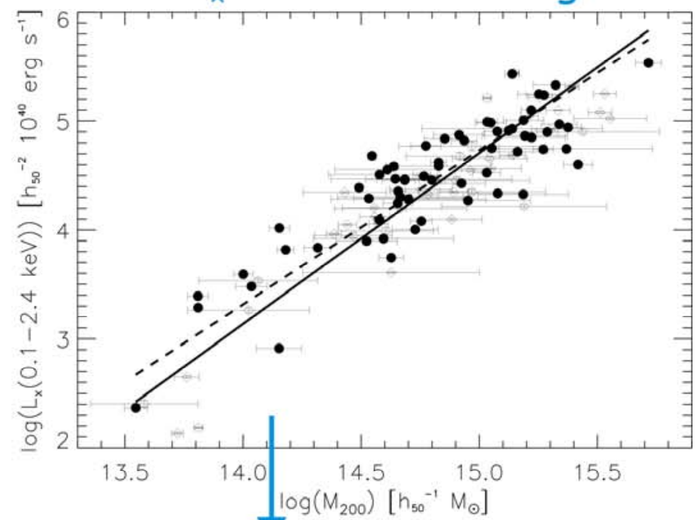


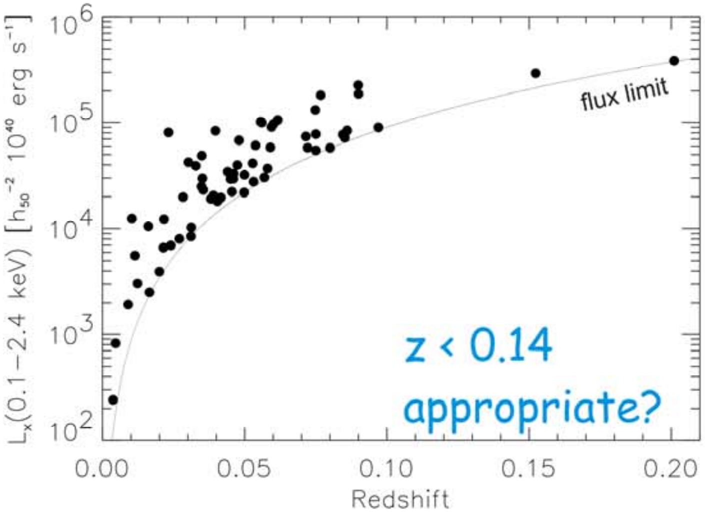
sample complete?

HIFLUGCS



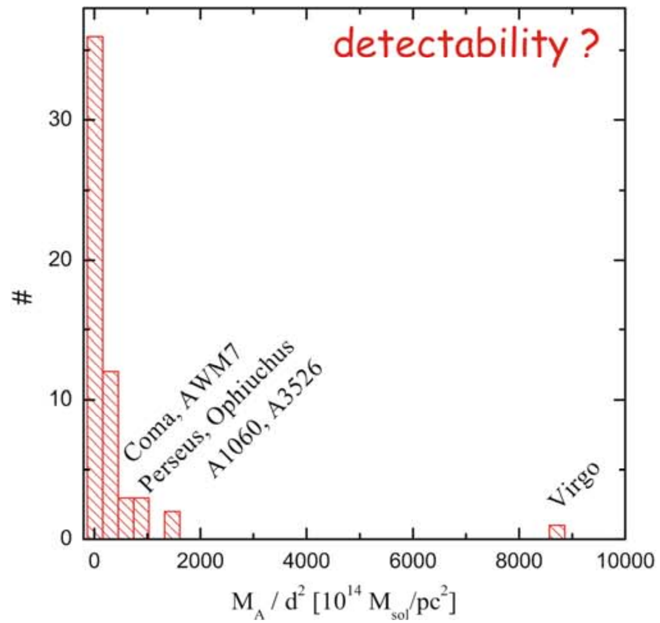
L_x - M - relation right?





z < 0.14 appropriate?

detectability ?



The superposition: a highly non-standard approach

(at least for treating EGRET observations)

-> stacking of data of all individually analyzed clusters
(~ 650 indiv. vp's) in cluster-centered coordinate system

-> usage of an galactic diffuse foreground prediction matching exactly *this* sample

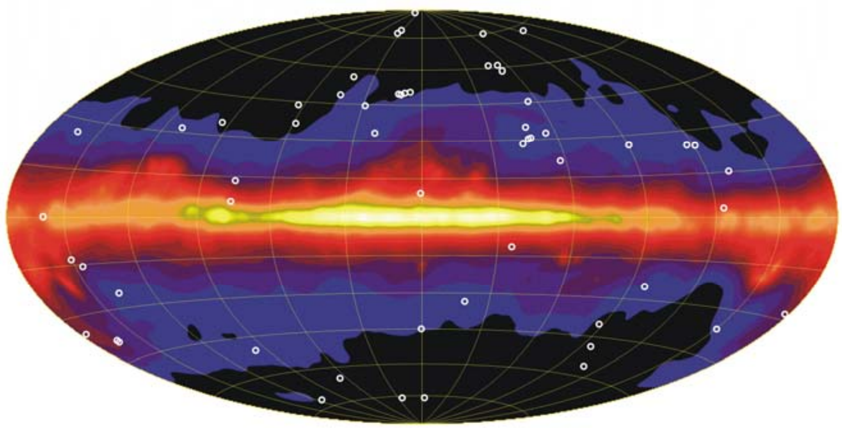
-> correction for different foreground expectations to account for unequal detectability conditions

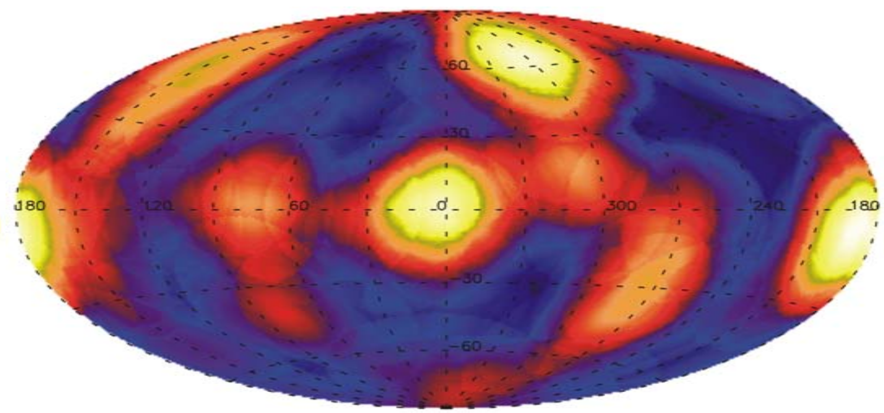
$$\mathrm{DF_{tot}} = \frac{1}{\varepsilon_{\mathrm{tot}}} \sum_i c_i = \frac{1}{\varepsilon_{\mathrm{tot}}} \sum_i \varepsilon_i \mathrm{DF}_i \ , \qquad \varepsilon_{\mathrm{tot}} = \sum_i \varepsilon_i \ .$$

counts diffuse emiss.   exposure   intensity diffuse emiss.

-> max lh algorithm

-> flux determination at image center





Galactic diffuse model as used in likelihood algorithm (Hunter et al. 1997)

here incl. positions of considered clusters; E > 100 MeV; gmult = 1, gbias = 0

-> different contributions at different cluster locations

Exposure from pointed observations 1991 – 2000:

-> better exposed -> more counts (source:hopefully / diffuse:obviously)

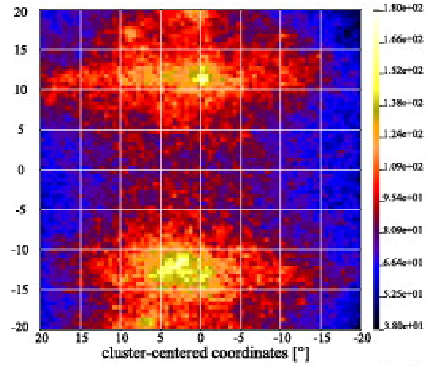
-> different treatment of uncertianties in diffuse forground expectation

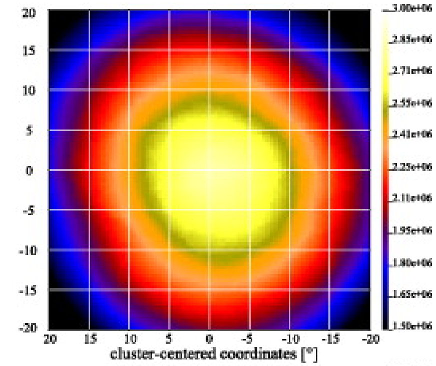
58 cluster sample minus 4 [prominent identified blazars nearby]

minus 4 [galactic plane near image center]

50 cluster sample

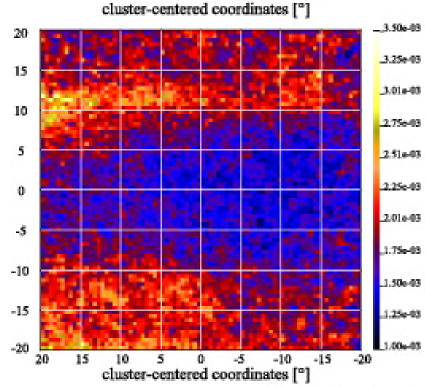
counts

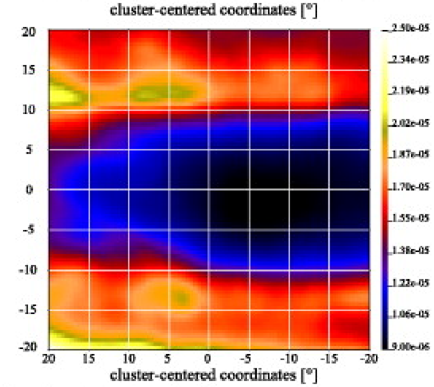




exposure

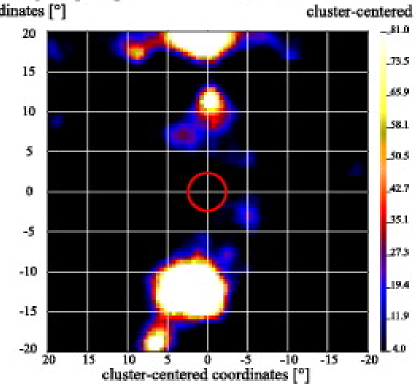
intensity

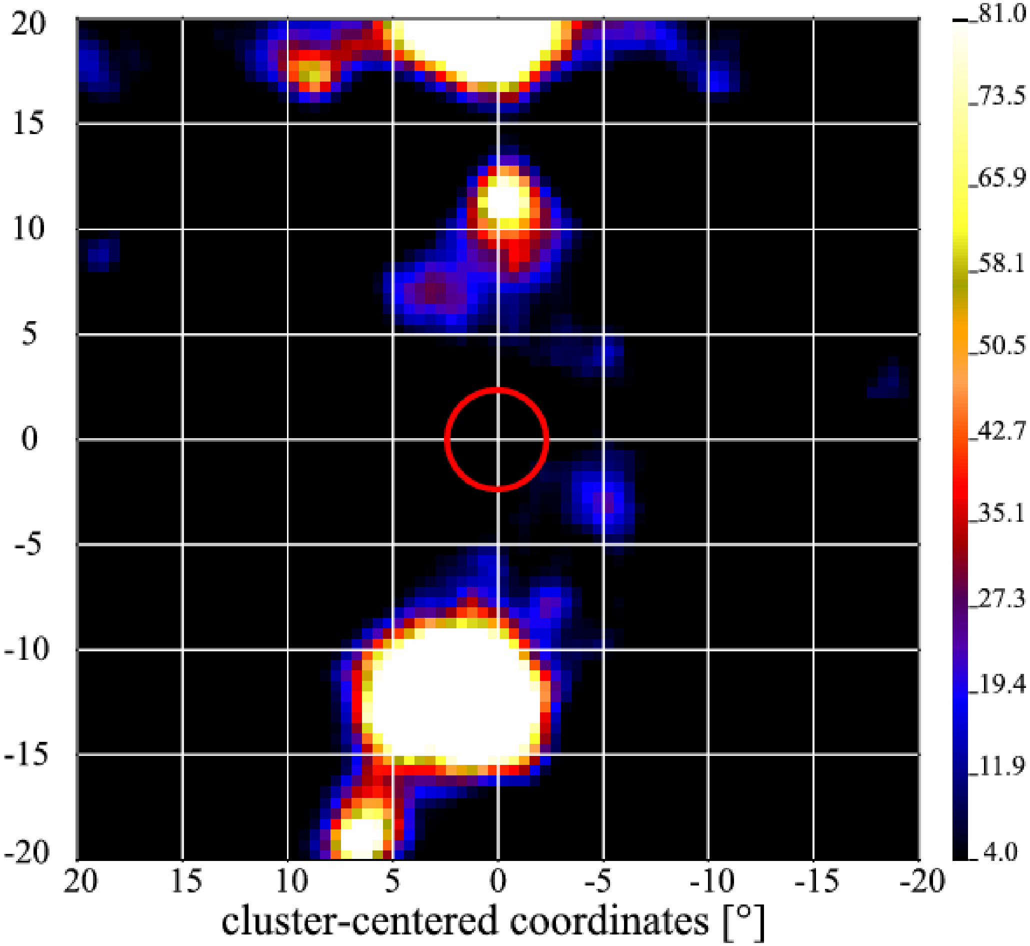




diffuse model

likelihood TS





RESULT:

NO DETECTION !

combined exposure: 3.5×10^{10} cm^2 s

upper limit: 5.9×10^{-9} cm^{-2} s^{-1}

Three ways to <u>detect</u> galaxy clusters at gamma-rays

Direct detection of gamma-ray emission in unambiguous positional coincidence with one candidate galaxy cluster
-> „pointing“ approach

Spatial-statistical correlation between still unidentified gamma-ray sources and a candidate object population
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Unresolved gamma-ray emission excesses through localized enhancements in the extragalactic background
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Three results obtained in correlation studies:

Kawasaki & Totani 2002:

analysis of optical survey data -> new cluster candidates

-> look for cataloged unidentified sources in positional coincidence

Colafrancesco 2002:

Abell cluster catalog -> look for cataloged unidentified sources in positional coincidence

Reimer et al. 2003:

nearby, X-ray brightest clusters, moderatly sized sample -> individually,

in superposition, re-analysis of correlation claims (incl. autocorr for large

cluster samples...)

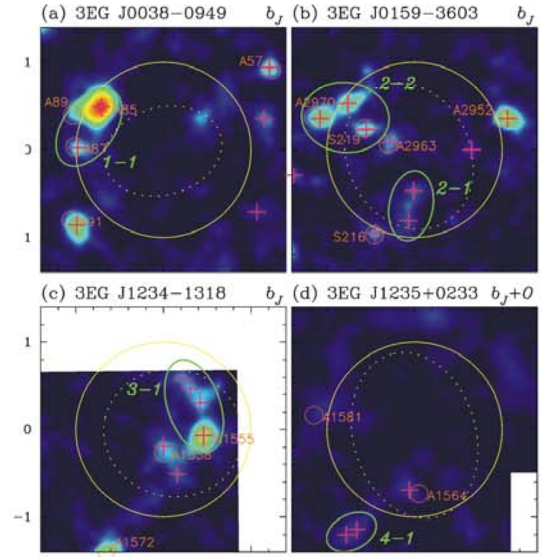
astro-ph/0108309:

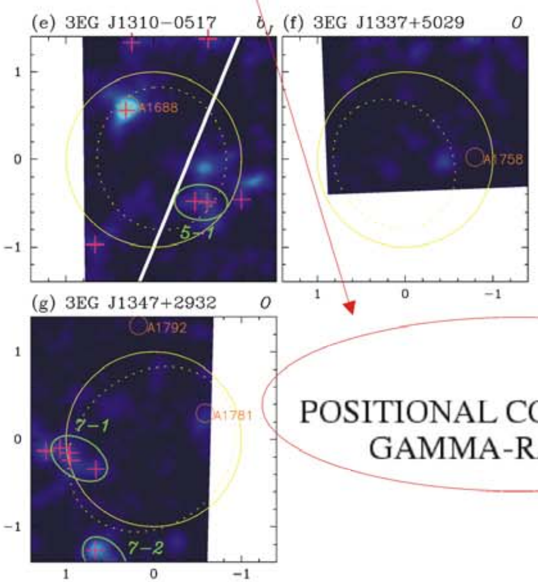
STRONG CORRELATION BETWEEN THE HIGH-LATITUDE STEADY UNIDENTIFIED GAMMA-RAY SOURCES AND POSSIBLY MERGING CLUSTERS OF GALAXIES

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 $4° \times 4°$ areas around seven steady unidentified EGRET sources at $|b| > 45°$ together with a 100 $\square°$ 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 576, Sep 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]

Discussion of Kawasaki & Totani's result:

7 unidentified EGRET sources studied

if one considers one additional observable: gamma-ray flux variability

-> 1 highly variable, 3 uncertain (statistical limits)

left (conservatively): 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

...individuals need to be investigated further!

Colafrancesco 2001, 2002

…

A large fraction of 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.

Problems with Colafrancesco's findings ?

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

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

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

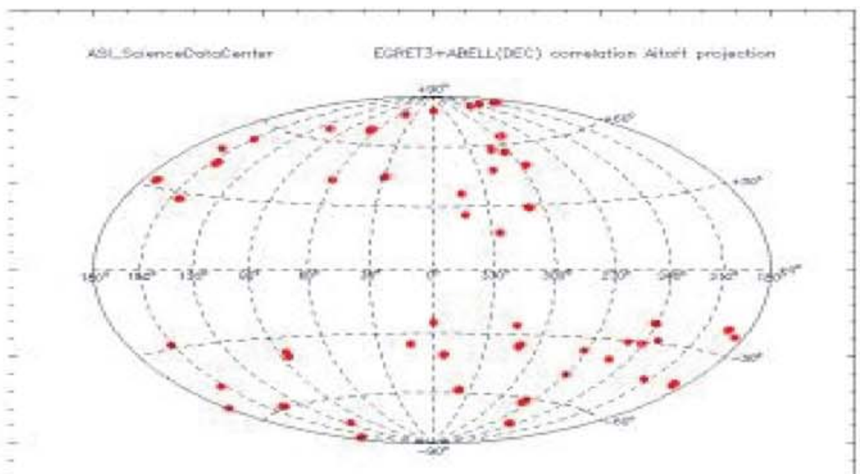
33 of it by chance

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:

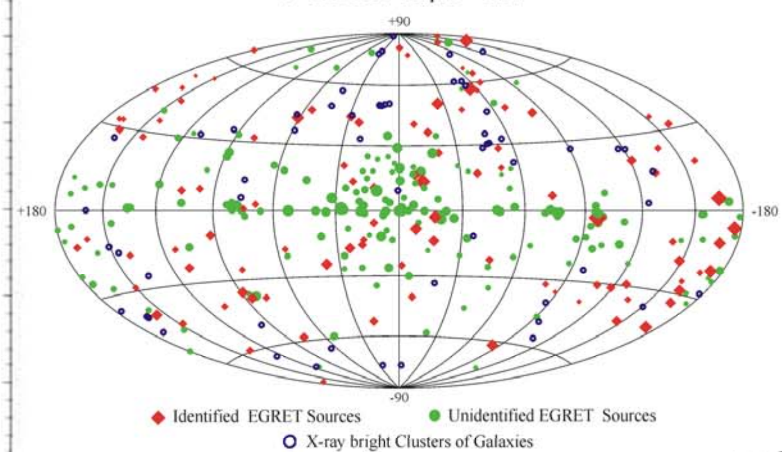
identified gamma-ray blazars in sample !!



Colafrancesco, Gamma2001

EGRET Gamma-Ray Sources and X-ray bright Galaxy Clusters

E > 100 MeV resp. z < 0.14



Problems with Colafrancesco's findings ?

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

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

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

incl. chance coinc.

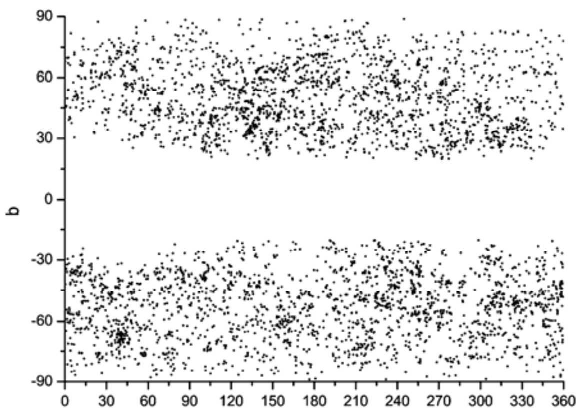
autocorrelation: $\omega(\Theta)$ "angular two-point correlation"

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

poissonian: 15.3 Abell <> 13.5 EGRET

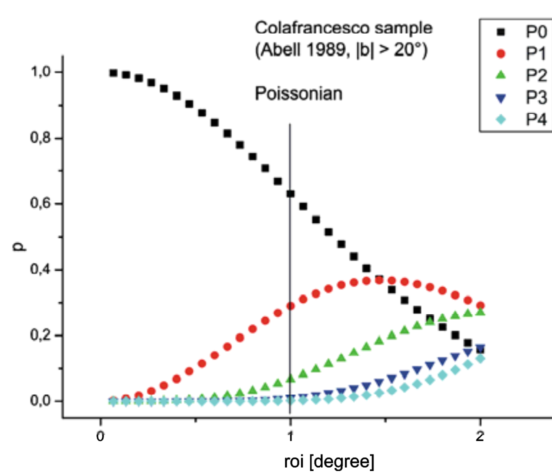
correct yield: 15.1 Abell <> 12.1 EGRET

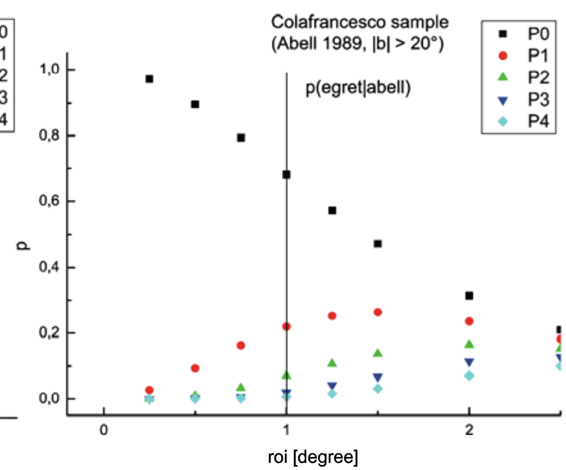
excess corresponds to only 1.7 s = INSIGNIFICANT!



Abell cluster catalog |b| > 20°

+ cumulative Poisson probability





Thanks, Dave Thompson!

"Believe-o-meter" unambiguous - - -> ambiguous

1. Periodicity – high significance
2. Correlated time variability with other wavelengths
3. Spatially-extended source
4. Large sample of well-defined, energetic object class spatially correlated with sources
5. SED with an unusual object at multiple wavelengths
6. Plausible class of objects with testable model predictions
7. Periodicity – lower significance
8. Sample of plausible objects correlated with sources and having testable predictions
9. One plausible object in a gamma-ray source error box
10. Hypothesized class of objects without testable predictions

plausible ?

Three ways to detect galaxy clusters at gamma-rays

Direct detection of gamma-ray emission in unambiguous positional coincidence with one candidate galaxy cluster
-> „pointing" approach

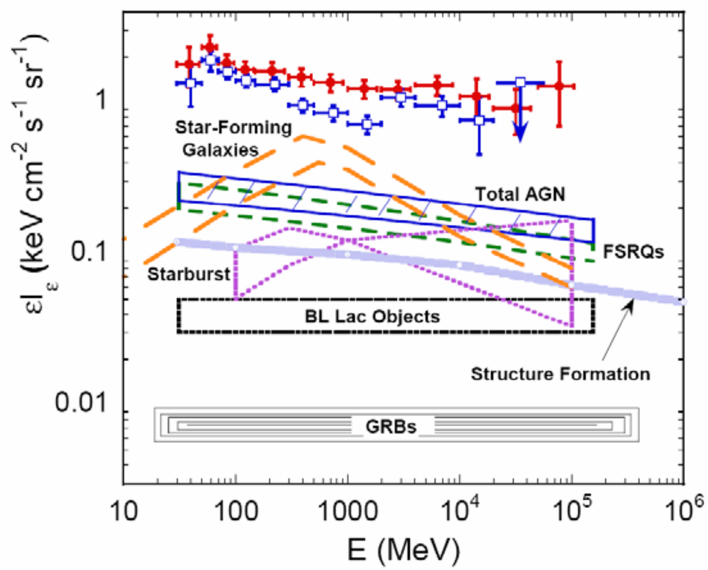
Spatial-statistical correlation between still unidentified gamma-ray sources and a candidate object population
-> „correlation study"

Unresolved gamma-ray emission excesses through localized enhancements in the extragalactic background
-> „background contribution studies"

The obvious case: unresolved AGN contribute to the extragalctic background !

deduced from the luminosity function of already detected AGN
(but at predictions ranging between 12% ... 100% - Sreekumar level)

The less obvious case: galaxy clusters as explanation of the extragalactic diffuse gamma-ray background



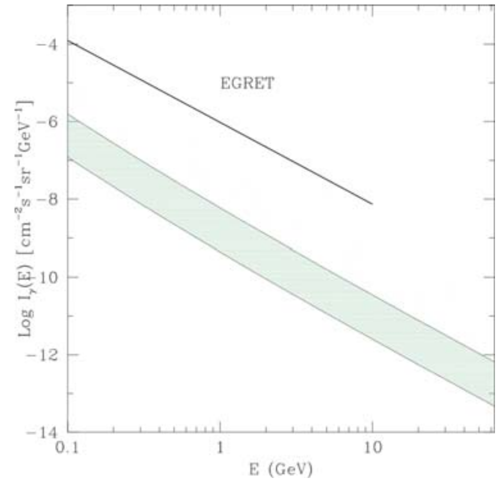
...yes, it's getting busy below the EGRET EGDB measurement(s)

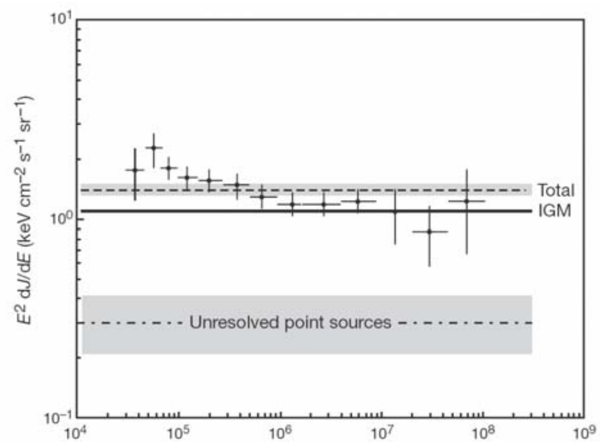
Dermer 2006

more recently:

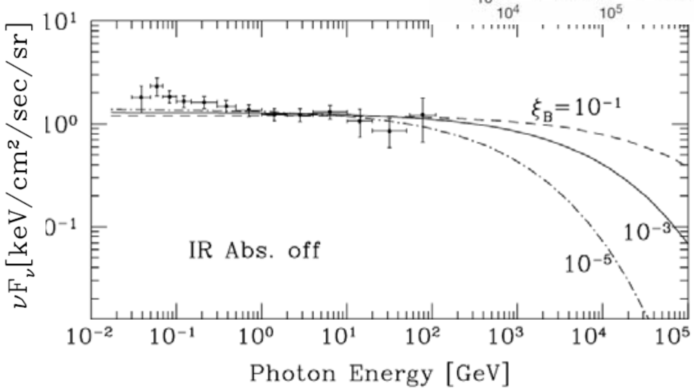
Berezinsky, Blasi & Ptuskin 1997 -> not detectable by current instrumentation

Colafrancesco & Blasi 1998 - - - - - - - - - ->





<- Waxman & Loeb 2000



<- Totani & Kitayama 2000

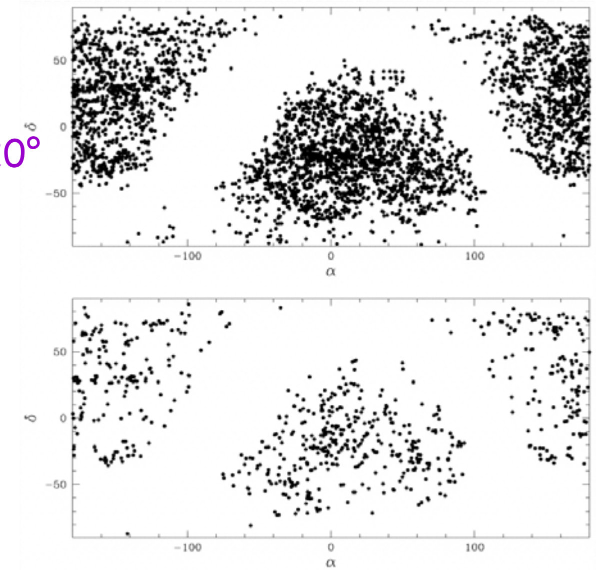
Statistical Detection of Galaxy clusters in EGRET data -> unresolved sources -> EGDB

Method: annular binning of EGRET intensity data

|b|> 45°, 2.7° cut around 100 identified EGRET sources

sample: positions of 2469 Abells, 447 Abell ($R \geq 2$), stacked out to 20°

average indiviudal cluster: **1.4 x 10^{-9} cm^{-2} s^{-1} (447)**



What does this mean?

sample size: |b|> 45°: 3.68 sr, - 0.69 sr source contribution: ~3 sr

$1/2\ \pi\ r^2$ ... $\pi\ r^2$:472 ...945 sr or 150 ... 300 x oversampling of a bin in EGRET intensity map

residuals in EGRET data:

sources below 3EG catalog detection threshold(s) exist

+ contributions of unidentified AGN (unIDs awaiting their AGN identification)

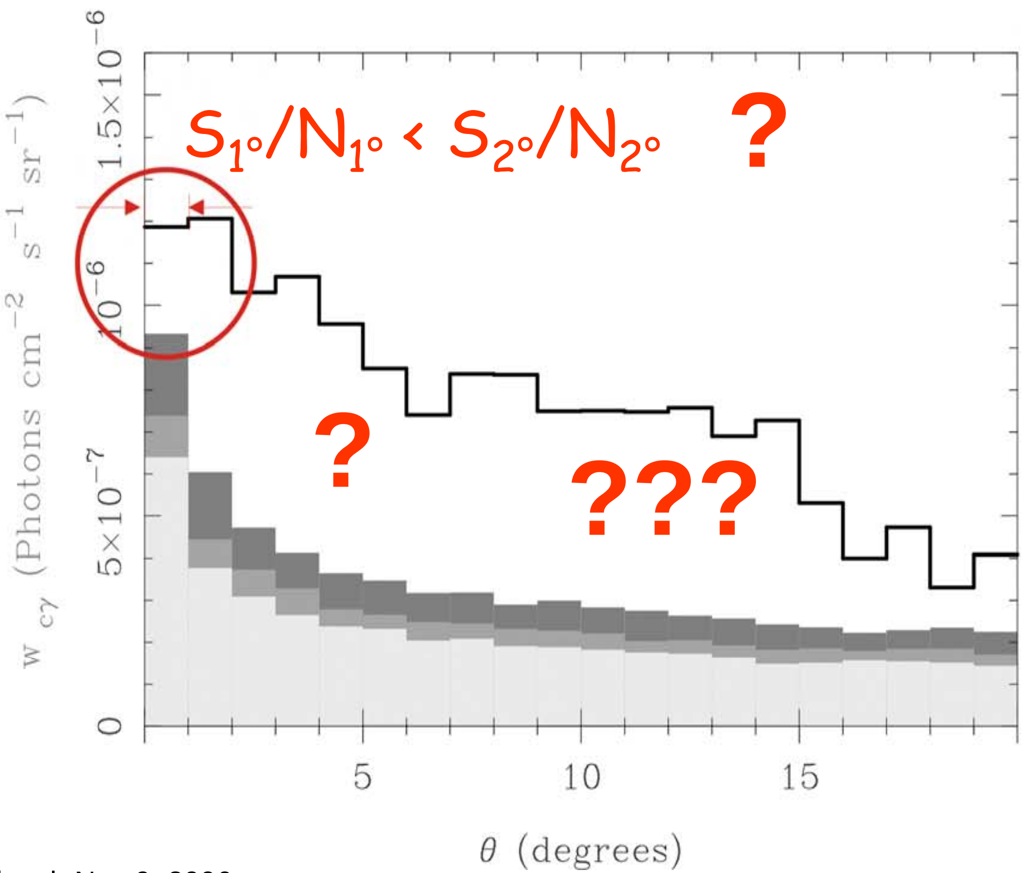
+ contributions of identified sources with psf-extension of > 2.7° (the psf tails!),

+ plain diffuse galactic foreground (unadapted GALDEF !)

energy averaged psf (E > 100 MeV) 6 **wrong** ure

68% in 3.1° aperture, 1° corresponds only 24% flux enclosure

	claim	recalc using correct psf	conclusion
r=1°:	1.14×10^{-9} cm^{-2}s^{-1}	4.7×10^{-9} cm^{-2}s^{-1}	marginally inconsistent
r=2° ?	9.6×10^{-9} cm^{-2}s^{-1}	our u.l.: 5.9×10^{-9} cm^{-2}s^{-1}	clearly inconsistent !!



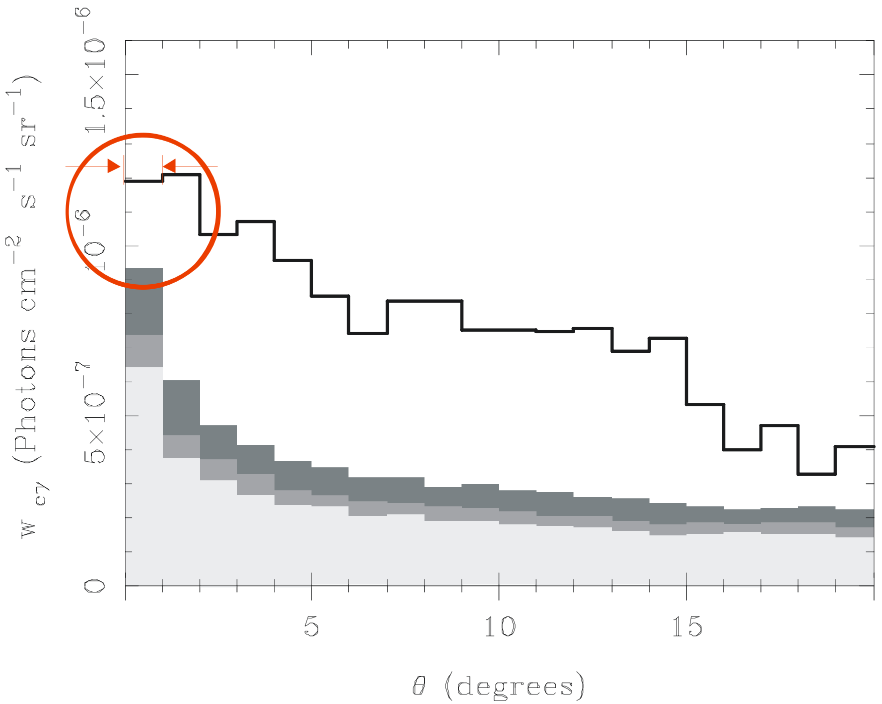
main result figure from S&M 2002

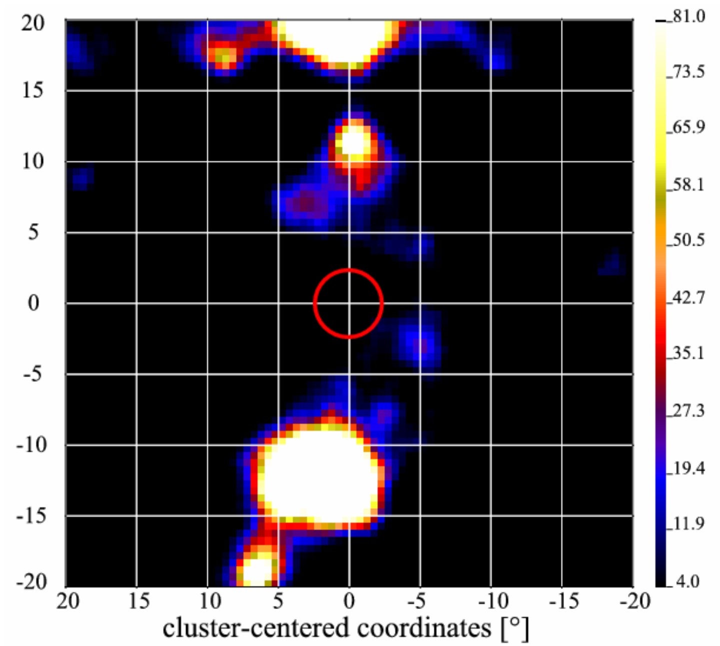
Statistical Detection of Galaxy clusters in EGRET -> unresolved sources -> EGDB !

(Scharf & Mukherjee 2002)

Likelihood source investigation -> individual and population -> upper limits only!

(Reimer et al. 2003)





Conclusions:

We still have to await the first detection of galaxy clusters at high-energy gamma rays.

Analysis requires precise handling of diffuse foreground, instrumental response, observational pecularities, and statistical assessments (noise expectations)
... but EGRET was not sensitive enough here

...as for Radio Galaxies & Seyferts (Cillis, Hartman & Bertsch 2004),
Starburst galaxies (Blom et al. 1999),
LIRGs & ULIRGs (Cilis, Torres & Reimer 2005),
and Normal Galaxies (Pavlidou & Fields 2001)

Conclusions 2:

When a cluster will be detected at gamma-rays, predictions will be more precisly determined/verified.

-> especially if regions will be spatially resolved (core/outskirts)

We were presumable close to the required instrumental sensitivity in EGRET, so it's a very appropriate science case for the coming generation of instruments: GLAST, perhaps a little more difficult for IACTs.

-> for best observed nonthermals, major uncertainty is B!

Magnetic field estimates derived from various methods for the galaxy cluster A3667

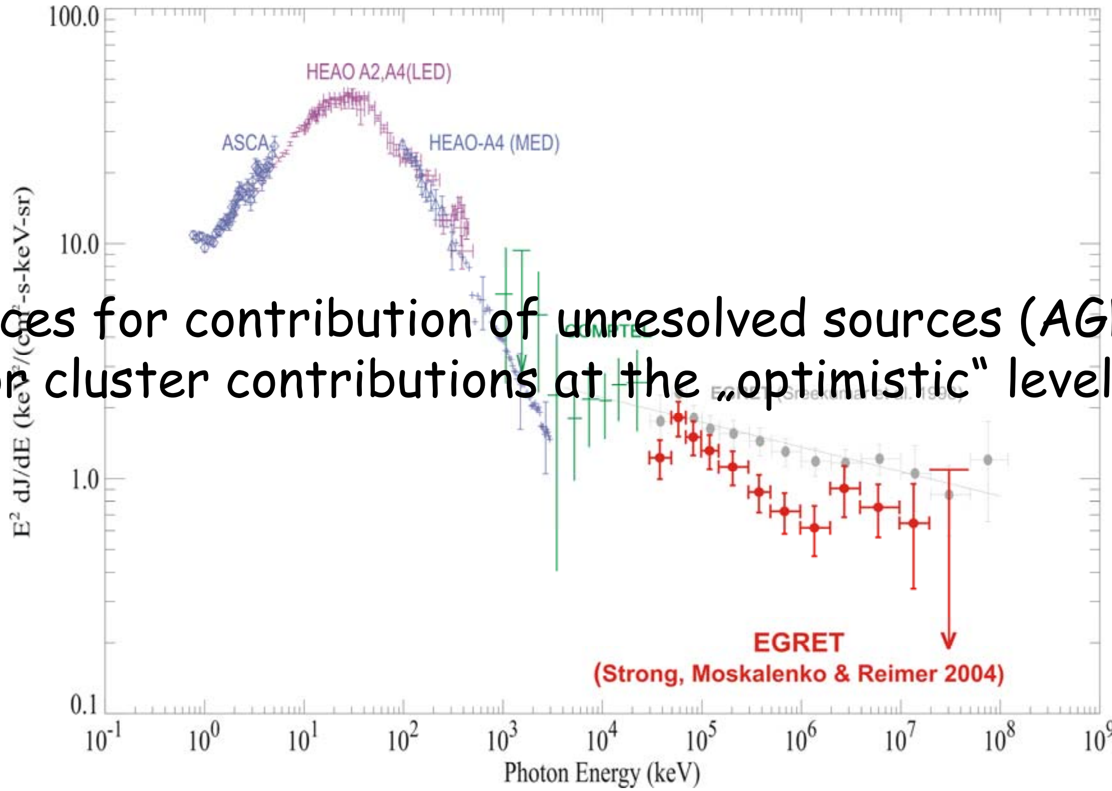
Method	Field estimate (μG)	Location in the cluster	Reference
Inverse Compton	$\geqslant 0.4$	Cluster core	Fusco-Femiano et al. (2001)
Kelvin–Helmholtz	7–16	Along the cold front	Vikhlinin et al. (2001)
Faraday rotation	1–2	Cluster core	Johnston-Hollitt (2003)
Faraday rotation	3–5	NW radio emission region	Johnston-Hollitt (2003)
Equipartition	1.5–2.5	NW radio emission region	Johnston-Hollitt (2003)

Conclusions 3:

The extragalactic diffuse background was reevaluated…

…and will be reevaluated again…

-> underestimation of diffuse galactic emision, hence overestimation of EGDB
-> improved modelling of high-latitude γ-rays based on IC halo emission



-> consequences for contribution of unresolved sources (AGN!)
but also for cluster contributions at the „optimistic" level (majority… 100%)