Fermi Observation of Clusters of Galaxies

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大阪大学大学院理学研究科宇宙地球科学専攻 宇宙進化グループセミナー
2010年2月10日
Hillas, 1984

\[ \left( \frac{E_{\text{max}}}{10^{18} \text{ eV}} \right) = \frac{\beta}{2Z} \left( \frac{R}{\text{kpc}} \right) \left( \frac{B}{\mu \text{G}} \right) \]

Two possible sites:

- Mergers
- Cluster accretion shocks
Model 1.

Hadronic emission: \( p+p \rightarrow \pi^0 \rightarrow \gamma+\gamma + X \)

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**Fig. 2.** Hadronic \( \gamma \)-ray fluxes expected from the Coma Cluster for a proton differential energy spectrum with spectral index \( \alpha_{CR} = 2.1 \) and cutoff energy \( E_c = 200 \) TeV. The solid and dashed curves show the \( \gamma \)-ray fluxes produced in \( pp \) interactions of CRs with \( E_{CR} = 3 \times 10^{52} \) ergs and \( E_{CR} = 3 \times 10^{51} \) ergs, respectively, in an ICM with \( n = 10^{-3} \) cm\(^{-3} \); the lower CR energy content might reflect a lower acceleration efficiency at the galactic wind termination shocks. Also, the EGRET upper limit is shown (Sreekumar et al. 1996). The heavy bar shows the 10% level of the TeV \( \gamma \)-ray flux from the Crab Nebula (e.g., Konopelko 1999). The light vertical bars show the limiting fluxes for a 100 hr observation time with the H.E.S.S. imaging atmospheric Cherenkov telescope (IACT) array of a 1° extended source (upper ends), on the one hand, and of a point source (lower ends) on the other (see Aharonian et al. 1997a, 1997b).
IC emission from high-energy electron interactions with the CMB

Fig. 3. Gamma ray emission in the 100 GeV–10 TeV region. The thick solid lines represent the sensitivities of a IACT for point sources (lower curve) and extended sources (upper curve). The predicted gamma ray fluxes from a Coma-like cluster at a distance of 100 Mpc with and without absorption of the infrared background are plotted as dashed and solid lines respectively.

From top to bottom:
(1) a merger between two clusters with masses $10^{15}M_\odot$ and $10^{13}M_\odot$;
(2) an accreting cluster with mass $10^{15}M_\odot$ with a magnetic field at the shock in the upstream region 0.1 $\mu$G;
(3) an accreting cluster with mass $10^{15}M_\odot$ with a magnetic field at the shock in the upstream region 0.01 $\mu$G.
Synchrotron and IC emission from secondary electron/positron pairs produced in $p-\gamma$ interactions with the CMB

\begin{figure}
\centering
\includegraphics[width=\textwidth]{spectrum.pdf}
\caption{Spectra of proton-induced emission from our fiducial cluster accretion shock, for $B_*=0.1$, 0.3 and 1\,\mu G. The p-p $\pi^0$ component has been multiplied by 10.}
\end{figure}
Simulation with a universal cosmic-ray spectrum and spatial distribution

Figure 19. Predicted $\gamma$-ray flux above 100 MeV in clusters and groups in the extended HIFLUGCS catalog to which we also add the Virgo cluster. The flux comes from the region within the Fermi angular resolution at 100 MeV, i.e. a circular region of radius 3.5 degree that contains 68 per cent of the PSF, but with the limit at $3 R_{\text{vir}}$ for each cluster and group. The black line refers to our optimistic model where we include the flux contribution from galaxies and the red line shows the flux without galaxies (cf. Table 5). We name the clusters and groups with $F_{\gamma}(E_\gamma > 100 \text{ MeV}) > 2 \times 10^{-9} \text{ ph cm}^{-2} \text{ s}^{-1}$ in our optimistic model which roughly corresponds to the sensitivity of the Fermi all-sky survey after two years of data taking.
EGRETによるGeV領域の上限

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>$l$ (deg)</th>
<th>$b$ (deg)</th>
<th>$z$</th>
<th>Flux ($&gt;100$ MeV) (10^{-8}$ cm$^{-2}$ s$^{-1}$)</th>
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<tbody>
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“58 nearby X-ray-bright galaxy clusters”
<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
<th>Redshift</th>
<th>Limit</th>
<th>Reference</th>
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<td>Perseus</td>
<td>(03h19m, 41° 30’)</td>
<td>0.018</td>
<td>&lt;13% Crab (&gt;400GeV, 0.3°)</td>
<td>Whipple (Perkins+ 2006)</td>
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<td>&lt;1-2% Crab (&gt;150GeV, point-like)</td>
<td>MAGIC (Aleksic+ 2009)</td>
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<td>Abell 2029</td>
<td>(15h10m, 05° 45’)</td>
<td>0.077</td>
<td>&lt;14% Crab (&gt;400GeV, 0.3°)</td>
<td>Whipple (Perkins+ 2006)</td>
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<td>Abell 496</td>
<td>(04h34m, -13° 16’)</td>
<td>0.033</td>
<td>&lt;5% Crab (&gt;0.57TeV, 0.6°)</td>
<td>H.E.S.S. (Aharonian+ 2008)</td>
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<td>Abell 85</td>
<td>(00h42m, -09° 21’)</td>
<td>0.055</td>
<td>&lt;2% Crab (&gt;0.46TeV, 0.49°)</td>
<td>H.E.S.S. (Aharonian+ 2008)</td>
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<tr>
<td>Coma</td>
<td>(12h59m, 27° 58’)</td>
<td>0.023</td>
<td>&lt;15% Crab (&gt;1TeV, 0.4°)</td>
<td>H.E.S.S. (Aharonian+ 2009)</td>
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<td>Abell 3667</td>
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<td>&lt;29% Crab (&gt;950GeV, 0.4°)</td>
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<td>Abell 4038</td>
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<td>0.029</td>
<td>&lt;12% Crab (&gt;750GeV, 0.25°)</td>
<td>CANGAROO-III (Kiuchi+ 2009)</td>
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</table>
Fermi Gamma-ray Space Telescope

General Dynamics clean room, standing are: Chip Meegan, NASA Marshall Space Flight Center, Huntsville, Ala.; Peter Michelson, Stanford University, Stanford, Calif.; Steve Ritz, from NASA Goddard Space Flight Center, Greenbelt, Md. Kneeling are: Bill Atwood, University of California at Santa Cruz, Calif.; Dan Blackwood, NASA Headquarters; Rick Harnden, NASA Headquarters, Washington; and Neil Johnson, Naval Research Laboratory, Washington. In the right corner, a technician checks the satellite. Credit: NASA and General Dynamics

2008年6月11日打ち上げ
Pair telescope for high-energy gamma-rays

Evans 1955

- OSO-3 (1967-1968)
- SAS-2 (1972-1973)
- COS B (1975-1982)
- AGILE (2007-)
- Fermi (2008-)
Fermi Gamma-ray Space Telescope: spéc

<table>
<thead>
<tr>
<th></th>
<th>Years</th>
<th>Ang. Res. (100 MeV)</th>
<th>Ang. Res. (10 GeV)</th>
<th>Eng. Rng. (GeV)</th>
<th>$A_{\text{eff}} \Omega$ (cm$^2$ sr)</th>
<th># γ-rays</th>
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<tr>
<td>EGRET</td>
<td>1991–00</td>
<td>5.8°</td>
<td>0.5°</td>
<td>0.03–10</td>
<td>750</td>
<td>1.4 × 10$^6$/yr</td>
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<tr>
<td>AGILE</td>
<td>2007–</td>
<td>4.7°</td>
<td>0.2°</td>
<td>0.03–50</td>
<td>1,500</td>
<td>4 × 10$^6$/yr</td>
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<tr>
<td><em>Fermi LAT</em></td>
<td>2008–</td>
<td>3.5°</td>
<td>0.1°</td>
<td>0.02–300</td>
<td>25,000</td>
<td>1 × 10$^8$/yr</td>
</tr>
</tbody>
</table>

- LAT has already surpassed EGRET and AGILE celestial gamma-ray totals.
- Unlike EGRET and AGILE, LAT is an effective All-Sky Monitor whole sky every ~3 hours.
Sample event display (1)
Sample event display (2)
Sample event display (3)
Sample event display (4)
Event class and effective area

Class = “Transient” “Source” “Diffuse”

Real event distribution

Fewer background

“Diffuse” class >100-200 MeV

Fig. 2. Effective area versus energy at normal incidence for Diffuse (dashed), Source (solid) and Transient (dotted) P6_V3 event classes.
Fermi First Source Catalog (1FGL)

2010年1月14日発表、1451天体 (1.1×10⁷ “Diffuse” events >100 MeV)

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/lyr_catalog/
Superimposed...
Superimposed... (linear scale)
Fermi count map
Fermi Galactic diffuse model
Fermi isotropic model
Point sources = Observed intensity – Diffuse model

- Observed
- Galactic diffuse
= Isotropic
= Sources
Sources = residuals

Heavily depends on diffuse model!
Galactic diffuse emission: components

Cosmic Rays and Diffuse Emission

Credit: Moskalenko

Troy A. Porter, Santa Cruz Institute for Particle Physics
TeV Particle Astrophysics, July 14th 2009
Galactic diffuse model: profile

- Latitude fit over factor 100 from plane to pole → IC at high latitudes, large halo?
- Unresolved sources not accounted for

Model Adjusted: Long/Lat Profile 1.2 GeV

Modified model = increased cosmic-ray intensities and corrections for residual gas → agreement with inner Galaxy is very good in spectrum and profile
Galactic diffuse model: spectrum

Inner Galaxy: keV to ~ 100 GeV

Porter et al. (2008) with LAT data

galdef ID 54_80Xvarh7S

INTEGRAL/SPI

COMPTEL

Fermi/LAT

\'isotropic\' = instrumental + astrophysical backgrounds
Skymap of 3EG and revised catalog


Red: EGR (Casandjian & Grenier, l.A.AA 489, 849 (2008))
Dark gas contribution

3EG catalog

“Extended” catalog
3EG / 1FGL sources
EGR / 1FGL sources
3EG / EGR / 1FGL sources
No good consistency around the Galactic center…
TeV / 1FGL

△ ○
>30GeV allsky map

+ TeV sources
Extragalactic diffuse emission

Comparison with EGRET results

- Considerably steeper than the EGRET spectrum by Sreekumar et al.
- No spectral features around a few GeV seen in re-analysis by Strong et al.

<table>
<thead>
<tr>
<th>LAT (this analysis)</th>
<th>Flux, E&gt;100 MeV</th>
<th>Spectral index</th>
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</thead>
<tbody>
<tr>
<td>EGRET (Sreekumar et al., 1998)</td>
<td>1.45 +/- 0.05</td>
<td>2.13 +/- 0.03</td>
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<tr>
<td>EGRET (Strong et al. 2004)</td>
<td>1.11 +/- 0.10</td>
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<tr>
<td>LAT + resolved sources below EGRET sensitivity</td>
<td>1.19 +/- 0.18</td>
<td>2.37 +/- 0.05</td>
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<tr>
<td></td>
<td>x 10^{-5} cm^2 s^{-1} sr^{-1}</td>
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</tbody>
</table>
Fermi analysis of point sources

Data extract
- FSSC website
- Specify position, period & energy

Data selection
- Event selection
- Time selection

Exposure calculation
- Livetime cube generation
- Exposure map generation

Source analysis
- Likelihood analysis
  - Unbinned / Binned

Platform: Scientific Linux 4/5, Mac OS 10.4/10.5

FITS files:
- Photon data
- Spacecraft data

Tools:
- gtselect
- gtmktime
- gtltcube
- gtexpmap
- gtlike

Catalog sources

Source model
- modeleditor

Data display
- ds9 / fv

See also “Fermi Data Analysis Workshop” presentations:

http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/
Allsky files are ready...

Mrk 501

START, 2009-09-30 00:00:00
Query Successfully Submitted

Your query has been successfully submitted to the search system.

The submitted query parameters for query ID=L100128025926E0D2F37E00 were:

- Search Center (RA,Dec)=(253.468,39.7602)
- Radius = 15 degrees
- Start Time (MET) = 239557417 seconds (2008-08-04T15:43:37)
- Stop Time (MET) = 275961600 seconds (2009-09-30T00:00:00)
- Minimum Energy = 100 MeV
- Maximum Energy = 300000 MeV

The estimated time until completion of the query is 82 seconds. The results of the query can be accessed at:

http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/QueryResults.cgi?id=L100128025926E0D2F37E00

If you would like to receive an e-mail notification when your query is complete, please submit your e-mail address in the form below.

Submit e-mail address

Click!
LAT Data Query Results

Welcome to the LAT Data Query Results page. This page provides access to the LAT data requested from the FSSC’s data servers.

The submitted query parameters for query ID=L100128025926E0D2F37E00 were:

- Search Center (RA,Dec)=(253.468,39.7602)
- Radius =15 degrees
- Start Time (MET)=239557417 seconds [2008-08-04T15:43:37]
- Stop Time (MET)=275961600 seconds [2008-09-30T00:00:00]
- Minimum Energy =100 MeV
- Maximum Energy =300000 MeV

Server | Position in Queue | Estimated Time Remaining
---|---|---
Photon Server | Query Completed | N/A
Spacecraft Server | Query Completed | N/A

The filenames of the result files consist of the Query ID string with an identifier appended to indicate which database the file came from. The identifiers are of the form: _DDNN where DO indicates the database and NN is the file number. The file number will generally be '00' unless the query resulted in a very large data return. In that case the data is broken up into multiple files. The values of the database field are:

- PH - Photon Database
- SC - Spacecraft Pointing, Livetime, and History Database
- EV - Extended Database

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<th>Number of Entries</th>
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To get the results from another query, enter the query ID string below:

Submit Reset

You may submit a new search at:
FERMI LAT Data Query Page
Data exploration

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<tbody>
<tr>
<td>Photon data</td>
<td>Spacecraft data</td>
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```
“gtselect”
```

Event data

```
“gtmktime”
```

Event data in GTI (good time interval)

```
“gtbin”
```

Count map

Count map viewed by “ds9”
Likelihood analysis

Maximize $L$ to get best fit:

The likelihood is the probability of the observed EGRET data for a specific model of high-energy $\gamma$-ray emission. It is the product of the probability for each pixel:

$$L = \prod_{ij} p_{ij},$$

where

$$p_{ij} = \frac{\theta_{ij} e^{-\theta_{ij}}}{n_{ij}!}$$

is the Poisson probability of observing $n_{ij}$ counts in pixel $ij$ when the number of counts predicted by the model is $\theta_{ij}$. The logarithm of the likelihood is more conveniently calculated

$$\ln L = \sum_{ij} n_{ij} \ln (\theta_{ij}) - \sum_{ij} \theta_{ij} - \sum n_{ij}.$$  \hspace{1cm} (5)

Because the last term is model independent, it is not useful for estimation or for the likelihood ratio test. Neglecting the last term,

$$\ln L = \sum_{ij} n_{ij} \ln (\theta_{ij}) - \sum_{ij} \theta_{ij}.$$  \hspace{1cm} (6)

Model = $K_1 \times$ (diffuse model) $+ K_2 \times$ (isotropic) $+ \sum_i F_i \times (PSF)_i$

Adjust $K_1$ & $K_2$ and seek for best fit with $F_i$. 

Likelihood fit with “gtlike”

Event data

Source model

modeleditor (GUI)

Catalog sources

Likelihood fit

Background

Galactic diffuse

Isotropic

Foreground

Point sources

Scaled in fitting

Resulting energy spectra

Least-square fitting routines: MINUIT etc.
Built-in spectral functions

- **PowerLaw** (see example XML Model Definition). This function has the form
  \[
  \frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^\gamma
  \]
  where the parameters in the XML definition have the following mappings:
  - Prefactor = \( N_0 \)
  - Index = \( \gamma \)
  - Scale = \( E_0 \)

- **BrokenPowerLaw** (see example XML Model Definition)
  \[
  \frac{dN}{dE} = N_0 \times \begin{cases} (E/E_b)^{\gamma_1} & \text{if } E < E_b \\ (E/E_b)^{\gamma_2} & \text{otherwise} \end{cases}
  \]
  where
  - Prefactor = \( N_0 \)
  - Index1 = \( \gamma_1 \)
  - Index2 = \( \gamma_2 \)
  - BreakValue = \( E_b \)

- **PowerLaw2** (see example XML Model Definition). This function uses the integrated flux as a free parameter rather than the Prefactor:
  \[
  \frac{dN}{dE} = \frac{N(\gamma + 1)E^\gamma}{E_{\text{max}}^{\gamma + 1} - E_{\text{min}}^{\gamma + 1}}
  \]
  where
  - Integral = \( N \)
  - Index = \( \gamma \)
  - LowerLimit = \( E_{\text{min}} \)
  - UpperLimit = \( E_{\text{max}} \)

  The UpperLimit and LowerLimit parameters are always treated as fixed, and as should be apparent from this definition, the flux given by the Integral parameter is over the range (LowerLimit, UpperLimit). Use of this model allows the errors on the integrated flux to be evaluated directly by likelihood, obviating the need to propagate the errors if one is using the PowerLaw form.

- **BrokenPowerLaw2** (see example XML Model Definition). Similar to PowerLaw2, the integral flux is the free parameter rather than the Prefactor:
  \[
  \frac{dN}{dE} = N_0(N, E_{\text{min}}, E_{\text{max}}, \gamma_1, \gamma_2) \times \begin{cases} (E/E_b)^{\gamma_1} & \text{if } E < E_b \\ (E/E_b)^{\gamma_2} & \text{otherwise} \end{cases}
  \]
  where
  - \( N_0(N, E_{\text{min}}, E_{\text{max}}, \gamma_1, \gamma_2) = N \times \)
    \[
    \int_{E_{\text{min}}}^{E_{\text{max}}} \left( \frac{E}{E_b} \right)^{\gamma_1} dE + \int_{E_{\text{min}}}^{E_b} \left( \frac{E}{E_b} \right)^{\gamma_2} dE
    \]
    \[
    \int_{E_{\text{min}}}^{E_{\text{max}}} \left( \frac{E}{E_b} \right)^{\gamma_1} dE - 1
    \]
    \[
    \int_{E_{\text{min}}}^{E_b} \left( \frac{E}{E_b} \right)^{\gamma_2} dE - 1
    \]
    \[
    E_{\text{max}} < E_b
    \]
    \[
    E_{\text{min}} > E_b
    \]
  and
  - Integral = \( N \)
  - Index1 = \( \gamma_1 \)
  - Index2 = \( \gamma_2 \)
  - BreakValue = \( E_b \)
  - LowerLimit = \( E_{\text{min}} \)
  - UpperLimit = \( E_{\text{max}} \)

Also available:
- LogPrabola
- BPLExpCutoff
- Gaussian
- ConstantValue
- BandFunction
- PLSuperExpCutoff
Modeleditor

XML-format file ... can be a part of the catalog XML file
Example session of “gtlike”

prompt> gtlike refit=yes plot=yes
Statistic to use (BINNED|UNBINNED) [UNBINNED]
Spacecraft file[none] spacecraft_data_file.fits
Event file[none] events_diffuse_filtered_gti.fits
Unbinned exposure map[none] expMap.fits
Event hypercube file[none] expCube.fits
Source model file[] src_model.xml
Response functions to use[P6_V3_DIFFUSE]
Optimizer (DRMNFB|NEWMINUIT|MINUIT|DRMNGB|LBFGS)
[DRMNFB] NEWMINUIT

(MORE OUTPUTS HERE...)

Computing TS values for each source (4 total)
....!

3C 273:
Prefactor: 10.7154 +/- 4.79318
Index: -2.39036 +/- 0.261339
Scale: 100
Npred: 28.651
ROI distance: 10.4409
TS value: 58.0328

(10.7 ± 4.8)×10^-9(E/100)^-2.39±0.26
TS=58

3C 279:
Prefactor: 8.97673 +/- 5.45668
Index: -2.8986 +/- 0.470354
Scale: 100
Npred: 13.8568
ROI distance: 0
TS value: 17.8267

EG_v02:
Normalization: 1.11606 +/- 0.234866
Npred: 278.964

GAL_v02:
Value: 1.161 +/- 0.328156
Npred: 199.892
WARNING: Fit may be bad in range [100, 146.235] (MeV)
WARNING: Fit may be bad in range [4472.14, 6539.83] (MeV)

Total number of observed counts: 521
Total number of model events: 521.364

-log(Likelihood): 5979.486023

Be patient…
Fermiによる銀河団の観測 (Bechtol+2009)

Cluster candidates

Monitor 15 clusters with highest predicted γ-ray flux [Pfrommer 2008]

1-month counts map

Coma
M49
A1367
NGC4636
NGC5846
Ophiuchus
Centaurus
Hydra
Norma
Triangulum
Fornax
A0754

Monitor cumulative significance at seed positions
Expect steady sources to accumulate significance ∝ sqrt(time)
Detailed analysis with 9-month dataset
Fermiによる銀河団の観測 (Bechtol+2009)

Non-detection -> Upper limits

**Flux upper limits**

**Event selection**
- \( E > 100 \text{ MeV} \)
- 9-month data set

**Assume**
- Point source spatial model
- Power law spectral model
  \( dN/dE \sim E^{-\Gamma} \)
- Photon index \( \Gamma = 2 \)

<table>
<thead>
<tr>
<th>Cluster</th>
<th>EGRET</th>
<th>Fermi 9-month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophiuchus</td>
<td>5.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Fornax</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Coma</td>
<td>3.8</td>
<td>0.6</td>
</tr>
<tr>
<td>A3627</td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>Perseus</td>
<td>3.7</td>
<td>19.9</td>
</tr>
<tr>
<td>A3526</td>
<td>5.3</td>
<td>2.5</td>
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<tr>
<td>A1060</td>
<td>14.9</td>
<td>2.3</td>
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<tr>
<td>M49</td>
<td>1.2</td>
<td>0.5</td>
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<tr>
<td>AWM7</td>
<td>3.5</td>
<td>0.9</td>
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<tr>
<td>3C129</td>
<td>5.3</td>
<td>3.2</td>
</tr>
<tr>
<td>NGC4636</td>
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<tr>
<td>A1367</td>
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<tr>
<td>A0754</td>
<td>8.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Triangulum</td>
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<td>1.4</td>
</tr>
<tr>
<td>NGC5846</td>
<td></td>
<td>0.6</td>
</tr>
</tbody>
</table>

Plan to address alternative spatial and spectral models in a 1-year publication

14 July 2009  
Keith Bechtol – Fermi LAT
Fermiによる銀河団の観測 (Bechtol+2009)

Fermi upper limits in context

Compare Fermi upper limits to EGRET and theoretical predictions

Improved sensitivity over EGRET for each cluster
Limits are comparable to theoretical predictions of brightest clusters
Fermi/LAT count map: Perseus

0.2-10 GeV
2008Aug-2009Sep

Ref: RASS (broad)
Fermi/LAT count map: Abell 2029

0.2-10 GeV
2008Aug-2009Sep

Ref: RASS (broad)
Fermi/LAT count map: Abell 496/85

Abell 496

Abell 85

0.2-10 GeV, 2008Aug-2009Oct

*: not 0FGL source
Fermi/LAT count map: Coma

0.2-10 GeV
2008Aug-2009Sep
*: not 0FGL source

Ref: RASS (broad)
Fermi/LAT count map: Abell 3667

0.2-10 GeV
2008Aug-2009Sep
*: not 0FGL source

Ref: RASS (broad)
Fermi/LAT count map: Abell 4038

0.2-10 GeV
2008Aug-2009Sep
*: not 0FGL source

Ref: RASS (broad)
### Upper limits

[Unit: $10^{-8}$cm$^{-2}$s$^{-1}$]

<table>
<thead>
<tr>
<th>Name</th>
<th>&gt;100MeV (95% C.L.)</th>
<th>&gt;200MeV (95% C.L.)</th>
<th>Bechtol et al. (&gt;100 MeV, TeVPA 2009)</th>
<th>EGRET (&gt;100MeV, Reimer+)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perseus</td>
<td>—</td>
<td>—</td>
<td>20</td>
<td>3.72</td>
<td>NGC1275 (point source)</td>
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<tr>
<td>Abell 2029</td>
<td>4.8</td>
<td>1.3</td>
<td>—</td>
<td>7.49</td>
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<tr>
<td>Abell 496</td>
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<td>0.61</td>
<td>—</td>
<td>7.11</td>
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<td>Abell 85</td>
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<tr>
<td>Coma</td>
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<tr>
<td>Abell 3667</td>
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<td>0.095</td>
<td>—</td>
<td>3.82</td>
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</tr>
<tr>
<td>Abell 4038</td>
<td>0.52</td>
<td>0.45</td>
<td>—</td>
<td>3.60</td>
<td></td>
</tr>
</tbody>
</table>

Fermi Science Tools v.9.15.2, gtlke (unbinned), point-like source, “PowerLaw2” model
Upper limits were calculated by Profile method.
Upper limits compared with model/TeV data (1)

Coma \((E^{-2} \text{ assumed}, \text{ HESS: } 0.4^\circ)\)

\[
\begin{align*}
\pi^0 \text{ model: } & \text{Völk & Atoyan, ApJ 541,88 (2000)} \\
\end{align*}
\]
Upper limits compared with model/TeV data (2)

Upper limits compared with model/TeV data (3)

Figure taken from Pinzke & Pfrommer, arXiv: 1001.5023 (2010)
Gamma-ray luminosity upper limit

$\Gamma$-ray luminosity upper limit

Graph showing the relationship between 100MeV luminosity [erg/s] and (Distance)$^2$ [Mpc$^2$]. The graph includes points for various galaxy clusters such as A2029, Perseus, Ophiuchus, Triangulum, A496, A4038, A3667, A754, A1367, AWM7, A3627, 3C129, A1060, and M49. The trend line is given by $L \propto D^2$. The logarithmic scale is used for both axes, ranging from $10^3$ to $10^5$ for the distance squared and from $10^{39}$ to $10^{45}$ for the luminosity.
X-ray vs gamma-ray luminosity

\[ L_{\gamma} = L_{X} \]

\[ L_{\gamma} = 0.01 L_{X} \]

Spectral energy distribution

Summary

- EGRETの結果より一桁厳しい上限値が6つの銀河団に対し得られた。[95% C.L., >100MeV, preliminary]
  - Perseus: ー
  - A2029: $0.78 \times 10^{-8}$cm$^{-2}$s$^{-1}$
  - A496: 0.43
  - A85: 0.020
  - Coma: 0.24
  - A3667: 0.13
  - A4038: 0.035

- 銀河団の高エネルギーガンマ線放射はX線放射量より少なく、上限値からは放射モデルに対する制限が得られた。