Fermi ガンマ線衛星による
暗黒物質探査

Mar. 2, 2012@IPMU
(Workshop on Particle Physics of the Dark Universe)
T. Mizuno
(広島大学 宇宙科学センター)
On behalf of the Fermi-LAT collaboration
Fermi Gamma-ray Space Telescope

- Fermi = LAT + GBM
- LAT surveys Gamma-ray Sky (20 MeV ~ >300 GeV)

2008.06 launch
2008.08 Sci. Operation

Cape Canaveral, Florida
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1873 sources
Nolan+, ApJS accepted
arXiv:1108.1435
Gamma-ray Sky

- GeV gamma-ray sky
  = astrophysical objects + Galactic Diffuse + unresolved sources + others

![Fermi-LAT 1 year all-sky map](image)
• Gamma-rays may encrypt the DM signal

\[
\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \frac{<\sigma v_{\text{ann}} \rho^2(r,l,\phi') dl(r,\phi')}{2m_{\text{WIMP}}^2} \sum_f \frac{dN_f^\gamma}{dE_\gamma} B_f \times \int_{\Delta\Omega(\phi, \theta)} d\Omega' \int_{\text{los}} \rho^2(r(l, \phi')) dl(r, \phi')
\]
• Gamma-rays may encrypt the DM signal

\[ \frac{d\Phi_{\gamma}}{dE_{\gamma}}(E_{\gamma}, \phi, \theta) = \frac{1}{4\pi} \frac{<\sigma v>}{2m^2_{WIMP}} \sum_j \frac{dN_j^{\gamma}}{dE_{\gamma}} B_j \times \int\int_{\Delta \Omega(\phi, \theta)} \int_{\text{los}} \rho^2(r(l, \phi')) dl(r, \phi') \]

**Gamma Ray Flux**
(measured by Fermi-LAT)

**Particle Physics**
(photons per annihilation)

\[ <\sigma v> \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]

to reproduce the matter density

**DM Distribution**
(line-of-sight integral)

indirect search of a DM signal is complementary to direct detection (e.g., distribution of DM)

NFW profile is usually assumed

\[ \rho(r) = \rho_0 \frac{r_0}{r} \frac{1 + (r_0 / a_0)^2}{1 + (r / a_0)^2} \]

\( r_0 = 0.3 \text{ GeV cm}^{-3}, a_0 = 20 \text{ kpc}, r_0 = 8.5 \text{ kpc for the MW} \)
DM Search Strategies

**Satellites:**
Pros: Low BG and good source id
Cons: low statistics

**Galactic Center:**
Pros: Good statistics
Cons: confusion, diffuse BG

**MW halo:**
Pros: very good statistics
Cons: diffuse BG

**Baltz+08**

**Clusters:**
Pros: low BG and good source id
Cons: low statistics, astrophysical uncertainties

**Extragalactic:**
Pros: very good statistics
Cons: diffuse BG, astrophysical uncertainties

**Spectral lines:**
Pros: no astrophysical uncertainty (Smoking gun)
Cons: low statistics

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DM Search Strategies

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DM rich system

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Cluster of Galaxies

- Cluster of Galaxies are attractive targets for a DM signal search
  - Most massive structures, known to be DM dominated (X-ray)
- However, they are distant and suffer from (possible) astrophysical background
  - AGN, CR protons and electrons
- No positive detection yet by Fermi-LAT
  - place limits on DM models

**Perseus Cluster**

- Optical
- X-ray

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Fermi-LAT Search for a DM Signal

- Cluster of Galaxies are attractive targets for a DM signal search
- No positive detection by Fermi-LAT yet
  - place limits on DM models
- Select X-ray bright clusters excluding Perseus (AGN) and Ophiuchus and Norma (close to Galactic center or plane)

$\gamma$-ray flux Upper Limit (>0.1GeV)

<table>
<thead>
<tr>
<th>Cluster</th>
<th>RA</th>
<th>Dec</th>
<th>$z$</th>
<th>$J \times 10^{17}$ GeV$^2$ cm$^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWM 7</td>
<td>43.6229</td>
<td>41.5781</td>
<td>0.0172</td>
<td>$1.4^{+0.1}_{-0.1}$</td>
</tr>
<tr>
<td>Fornax</td>
<td>54.6686</td>
<td>-35.3103</td>
<td>0.0046</td>
<td>$6.8^{+1.0}_{-0.9}$</td>
</tr>
<tr>
<td>M49</td>
<td>187.4437</td>
<td>7.9956</td>
<td>0.0033</td>
<td>$4.4^{+0.2}_{-0.1}$</td>
</tr>
<tr>
<td>NGC 4636</td>
<td>190.7084</td>
<td>2.6880</td>
<td>0.0031</td>
<td>$4.1^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>Centaurus (A3526)</td>
<td>192.1995</td>
<td>-41.3087</td>
<td>0.0114</td>
<td>$2.7^{+0.1}_{-0.1}$</td>
</tr>
<tr>
<td>Coma</td>
<td>194.9468</td>
<td>27.9388</td>
<td>0.0231</td>
<td>$1.7^{+0.1}_{-0.1}$</td>
</tr>
</tbody>
</table>

line-of-sight integral of DM density squared
Cluster of Galaxies are attractive targets for a DM signal search

No positive detection by Fermi-LAT yet
  - place limits on DM models

For $b\bar{b}$ final state, the limit is looser than that by dwarf spheroidals (next)
(though LAT gives a strong limit on a $\mu^+\mu^-$ final state model favored by Pamela $e^+/e^-$ and Fermi electrons)
Search for a Galactic DM Substructure

• In the standard cosmological model, structures form from bottom up. Numerical simulations predict that the MW should be surrounded by smaller structures.

• Optically observed Dwarf Spheroidal (dSph) galaxies are the most attractive candidate subhalo objects
  – relatively nearby
  – known position and mass (stellar velocity dispersion)
  – very high M/L ratio (>=100 Msun/Lsun)
  – low astrophysical gamma-ray background

![Image of Ursa Minor](Credit: Mischa Schirmer)
Fermi-LAT Study of dSph

- Select 10 dSphs with relatively large “astrophysical factor” \( J \) (8 for individual study; +2 for stacking analysis)
Fermi-LAT Study of dSphs

- Select 10 dSphs with relatively large “astrophysical factor” $J$ (8 for study of individual; +2 for stacking analysis)

\(\gamma\)-ray flux Upper Limit (>0.1GeV)

<table>
<thead>
<tr>
<th>Name</th>
<th>$\rho_{NFW}^{\text{NFW}}$ (10^{19} \text{ GeV}^2 \text{ cm}^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ursa Major II</td>
<td>0.58^{+0.91}_{-0.35}</td>
</tr>
<tr>
<td>Coma Berenices</td>
<td>0.16^{+0.22}_{-0.08}</td>
</tr>
<tr>
<td>Bootes I</td>
<td>0.16^{+0.35}_{-0.13}</td>
</tr>
<tr>
<td>Usra Minor</td>
<td>0.64^{+0.25}_{-0.18}</td>
</tr>
<tr>
<td>Sculptor</td>
<td>0.24^{+0.06}_{-0.06}</td>
</tr>
<tr>
<td>Draco</td>
<td>1.20^{+0.31}_{-0.25}</td>
</tr>
<tr>
<td>Sextans</td>
<td>0.06^{+0.03}_{-0.02}</td>
</tr>
<tr>
<td>Fornax</td>
<td>0.06^{+0.03}_{-0.03}</td>
</tr>
</tbody>
</table>

\(b\bar{b}\) final state
(Flux limit comparable to that for clusters)

Limits on DM Models

- Select 10 dSphs with relatively large “astrophysical factor” $J$ (8 for study of individual; +2 for stacking analysis)

  \[
  \sigma v \approx 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}
  \]

  no structure (“boost factor”) assumed

  Gives stronger constraints on DM annihilation cross section than cluster galaxies for $b\bar{b}$ final state

Stacking Analysis

- Stacking analysis using 10 dSphs and 2 years data
  - conservative limit on DM cross section (no “boost factor”)

\[ \sigma_v = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]

Ackermann+11, PRL 107, 241302

\[ M_{\text{wimp}} \geq 20 \text{ GeV to satisfy } \langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]

Rule out models with generic cross section using γ-rays for the first time

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Predictions for DM Limit

• Future dwarf spheroidal limits:
  – Increased observation time
  – Discovery of new dwarfs
  – Gains at high energy

• The canonical 100 GeV WIMP appears to be within reach

2yr, 10 dSphs
2yr, 30 dSphs
10yr, 10 dSphs

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Summary

- γ-ray observation is a powerful probe to investigate the DM property
- No signal has been detected yet
  - (need better understanding of Galactic diffuse emission to investigate GC/MW halo)
  - Constraints on the nature of DM have been placed
- Among several search strategies, DM substructures (dSphs) are good targets
  - Start to reach thermal-relic cross section

Thank you for your Attention
Backup Slides
Current Upper Limit

- Dwarf spheroidals give stronger limits for $\bar{b}b$ final state
  - Combined analysis starts to reach to canonical $<\sigma v>$
- Clusters and dSphs are complementary for constraining $\mu^+\mu^-$ final state models
Example of DM signal (for extragalactic gamma-ray background)

- $1.2 \text{ TeV} \mu^+\mu^-$
- $1.2 \times 10^{-23} \text{ cm}^3/\text{s}$
- $200 \text{ GeV } b\bar{b}$
- $2.5 \times 10^{-26} \text{ cm}^3/\text{s}$
- $180 \text{ GeV } \gamma\gamma$
- $5 \times 10^{-25} \text{ cm}^3/\text{s}$

Abdo+10, JCAP 4, 14
(CA: Conrad, Gustafsson, Sellerholm, Zaharijas)
• $b\bar{b}$ final state

(not to exceed EGB only by DM signal)

(blazar/starburst included)

Abdo+10, JCAP 4, 14

(CA: Conrad, Gustafsson, Sellerholm, Zaharijas)
Limit on Cosmological DM(2)

- $\mu^+\mu^-$ final state

(Not to exceed EGB only by DM signal)

(blazar/starburst included)

Abdo+10, JCAP 4, 14
(CA: Conrad, Gustafsson, Sellerholm, Zaharijas)
2FGL: Second Source Catalog

- 1873 sources (~4\(\sigma\) significance)
  - 127 firm identifications and 1170 reliable associations
  - 576 unassociated with known \(\gamma\)-ray source class
    please pay attention to flags (e.g., 126 possibly confused with diffuse emission)

Abdo+, ApJS submitted
arXiv:1108.1435
EGRET GeV Excess

- EGRET observed an all-sky excess compared to “conventional” predictions
  - lots of interpretations including DM annihilation

EGRET Inner Galaxy Spectrum
(de Boer+05)
Fermi-LAT Performance

- New Dataset and Response (Pass7)
  - Improved Aeff in low Energy
  - In-orbit calibration of PSF

http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

1 year Integral Sensitivity (>10 GeV): ~0.05 Crab (Atwood+09)
Limit on DM models

- Cluster of Galaxies are attractive targets for a DM signal search
- No positive detection by Fermi-LAT yet
  - place limits on DM models

For $bb$ final state, the limit is looser than that by dwarf spheroidals (next) (though LAT gives a strong limit on a $\mu^+\mu^-$ final state model favored by Pamela $e^+/e^-$ and Fermi electrons)

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• PAMELA $e^+/e^-$ is not compatible with a standard scenario (secondary production)
  – Additional $e^-/e^+$ sources (astrophysical or exotic) can provide a good fit to Fermi CRE and PAMELA $e^+/(e^- + e^+)$

Example of an additional component

Adriani+09
Nature 458, 607

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Ackermann+10
PRD 82, 092004