Fermi ガンマ線衛星による
暗黒物質探査

Apr. 4, 2013@Tokyo
(2nd 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
Dark Matter Search with Fermi Large Area Telescope

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Dark Matter (DM) Search with $\gamma$-rays

- Gamma-rays may encrypt the DM signal

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

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \frac{<\sigma_{ann}v>}{2m_W^2} \sum_f \frac{dN_f^\gamma}{dE_\gamma} B_f$$

**Particle Physics**
(photons per annihilation)

**DM Distribution**
(line-of-sight integral)
Dark Matter (DM) Search with \(\gamma\)-rays

- Gamma-rays may encrypt the DM signal

\[
\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \frac{<\sigma_{ann}v>}{2m_{WIMP}^2} \sum_f \frac{dN_f}{dE_\gamma} B_f \times \int_{\Delta\Omega(\phi, \theta)} \int_{los} \rho^2(r(l, \phi')) dl(r, \phi')
\]

- Gamma Ray Flux (measured by Fermi-LAT)
- Particle Physics (photons per annihilation)
- \(<\sigma v> \approx 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}\)
  to reproduce the matter density

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

NFW profile is usually assumed

\(\rho_0 \approx 0.3 \text{ GeV cm}^{-3}, a_0 \approx 20 \text{ kpc},\)

\(r_0 = 8.5 \text{ kpc for the MW}\)

Indirect search of a DM signal is complementary to direct detection (e.g., distribution of DM)
Fermi Gamma-ray Space Telescope

- Fermi = LAT + GBM
- LAT = GeV Gamma-ray Space Telescope
  (20 MeV ~ >300 GeV; All-Sky Survey)

2008.06 launch
2008.08 Sci. Operation

Cape Canaveral, Florida

1873 sources
Fermi LAT

- Pair-conversion telescope
  - good background rejection due to “clear” $\gamma$-ray signature
  - (also sensitive to CR electrons)
- Tracker: pair conversion, tracking
  - angular resolution is dominated by multiple scattering below $\sim$GeV
- Calorimeter:
  - use shower profile to compensate for the leakage
- Anti-coincidence detector:
  - efficiency $>99.97$

energy band: 20MeV to $>300$ GeV
effective area: $>8000$ cm$^2$
FOV: $>2.4$ sr
angular resolution: 0.04-10deg
time measurement: 10-500ms
energy resolution: 5-10%

Si Tracker
70 m$^2$, 228 $\mu$m pitch
$\sim$0.9 million channels

(Japanese contribution)
Fermi-LAT Collaboration

- France
- Italy
  - Hiroshima Univ.
  - ISAS/JAXA
  - Tokyo Tech
  - Waseda Univ.
  - Kyoto Univ.
  - Nagoya Univ.
  - Aoyama Gakuin Univ.
  - Ibaraki Univ.
- Japan
- Sweden
- US

PI: Peter Michelson (Stanford)
~400 Scientific Members
Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.
Project managed at SLAC.
Gamma-ray Sky

• GeV gamma-ray sky

= astrophysical objects + Galactic Diffuse + unresolved sources + Extra Gal. Background + others
DM Search Strategies with $\gamma$-rays

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

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

**Galactic Center:**
- Pros: Good statistics
- Cons: Confusion, diffuse BG

**MW halo:**
- Pros: Very good statistics
- Cons: Diffuse BG

**Extragalactic:**
- Pros: Very good statistics
- Cons: Diffuse BG, astrophysical uncertainties

**Spectral lines:**
- Pros: No astrophysical uncertainty (Smoking gun)
- Cons: Low statistics

(Figure taken from Pieri+11)
DM Search Strategies with $\gamma$-rays

- In short, we search for DM signal in $\gamma$-rays by utilizing their spatial and/or spectral signatures.

\[
\text{Fermi-LAT data} = \text{Galactic Diffuse, Sources, isotropic} + \text{DM signal (e.g., MW halo)}?
\]

\[
\text{DM signal (e.g., line)?}
\]

Good understanding of Galactic diffuse emission and the instrument is crucial.

(Figure taken from Abdo+10, PRL 104, 091302)
DM Search Strategies with $\gamma$-rays

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

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

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

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

(Figure taken from Pieri+11)
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
Fermi-LAT Study of dSphs

- Select 10 dSphs with relatively large “astrophysical factor” $J$ (8 for individual study; +2 for stacking analysis)
Stacking Analysis with Old Response (Pass6)

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

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

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

Rule out models with generic cross section using \( \gamma \)-rays for the first time

Ackermann+11, PRL 107, 241302
(CA: Cohen-Tanugi, Conrad, Garde)
Stacking Analysis with Old Response (Pass6)

- Result also in outreach ([http://www-heaf.hepl.hiroshima-u.ac.jp/glast/glast-j.html](http://www-heaf.hepl.hiroshima-u.ac.jp/glast/glast-j.html))
Stacking Analysis with New Response (Pass7)

- Update analysis with Pass 7
  - take account of an improved understanding of the instrument

- Use new response (P6->P7) and redo the analysis

- This leads to a statistical reshuffling of γ-ray-classified events (only ~50% events are common in two dataset above 10 GeV)

- Two limits are statistically consistent

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

dSphs still constrain generic cross section for \( M_{\text{WIMP}} \leq 10 \text{ GeV} \) and will remain a prime target for DM search

• Another recent and complementary DM search for MW halo
  – Search for continuous emission from DM annihilation/decay in the smooth MW halo

  ![DM signal](image1)

  ![γ-ray map](image2)

• Analyze bands 5deg off the plane
  - decrease astrophysical BG
  - mitigate uncertainty from inner slope of DM density profile

• Two approaches:
  - 1) more conservative - assume all emission are from DM (no astrophysical BG)
  - 2) more accurate – fit DM source and astrophysical emission simultaneously

(CA: Conrad, Yang, Zaharijas, Cuoco)
DM Halo Search: Method I

- Assume all $\gamma$-rays are from DM and give upper limits
  - conservative, robust to uncertainty
- Expected DM counts ($n_{DM}$) compared to observed counts ($n_{data}$) and $3\sigma$ upper limit are set using (in at lease one energy bin)

$$n_{DM} - 3\sqrt{n_{DM}} \geq n_{data}$$
DM Halo Search: Method II

DM halo

Galactic diffuse emission
(CR interactions with the interstellar medium)
Inverse Compton
$\pi^0$-decay
Bremsstrahlung
allow several parameters to vary
(e.g., CRE injection spectrum, CR halo size and CR source distribution)

LAT sky, E>1 GeV, 4 years
Resolved point sources
Isotropic extragalactic diffuse emission

NFW and Isothermal
consider $b\bar{b}$, $\mu^+\mu^-$ and $\tau^+\tau^-$
(annihilation and decay)
DM Halo Search: Method II

- Disentangle DM signal from foreground by utilizing spatial and spectral shapes (good diffuse model is important)

\[
E = 10 \text{ GeV}
\]

**DM halo**

\[
|b| < 15^\circ, |b| > 5^\circ, |l| < 80^\circ
\]

**IC (astrophysical)**

\[
|b| < 15^\circ, |b| > 5^\circ, |l| < 80^\circ
\]

(CA: Conrad, Yang, Zaharijas, Cuoco)

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Constraints on DM Model

- Modeling the astrophysical emission improves DM constraints by a factor of ~5
- w/ astrophysical BG, the limit constrains the thermal relic cross section for WIMP with mass > 30 GeV (comparable to dSphs)

\[ \chi \rightarrow bb, \text{ NFW} \]

\[ \langle \sigma v \rangle \text{ cm}^2\text{s}^{-1} \]

\[ m [\text{GeV}] \]

\[ \tau [\text{s}] \]


(CA: Conrad, Yang, Zaharijas, Cuoco)
• Several groups (outside of Fermi-LAT collaboration) showed evidence for a narrow spectral feature at $\sim 130$ GeV near the Galactic Center (GC)

• Over $4\sigma$, S/N $>30\%$, up to $\sim 60\%$ in optimized region of interest

[Diagram showing statistical analysis and gamma-ray map]

$E_\gamma = 129.8$ GeV

Signal counts: $46.1$ ($4.36\sigma$)

$p$-value $= 0.37$, $\chi^2_{\text{red}} = 23.6/22$

Weniger+12
Improve the Model of Energy Dispersion

- Use full MC to get Fermi-LAT energy dispersion
- Previously modeled line with a triple Gaussians (1D PDF)
- Updated analysis add a 2nd dimension to line model $P_E$ (probability that measured energy is close to the true value)
- Including $P_E$ improves line sensitivity by ~15%

$E_t = 100$ GeV
$\chi^2$/dof = 32.9/32
p-value = 0.43
Containment windows
68% = (-0.086, 0.081)
95% = (-0.311, 0.188)
bias = 0.013

Ackermann+12, PRD 86, 022002
(CA: Bloom, Edmonds, Essig)
Evolution of line-like Feature near 135 GeV

- 1) 1D PDF, unreprocessed data (public data)
  - $4.1\sigma$ (local) 1D fit at 130 GeV
- 2) 1D PDF, reprocessed data (better energy calibration)
  - $3.7\sigma$ (local) at 135 GeV
- 3) 2D PDF, reprocessed data
  - $3.4\sigma$ (local) at 135 GeV (Energy dispersion in data is narrower than expected when $P_E$ is taken into account)
  - $<2\sigma$ global

4 year data
Look in 4x4deg$^2$ at GC

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Search 135 GeV in Earth Limb Data

- Earth Limb is bright and well understood
  - $\gamma$s are from CR interaction with atmosphere
  - Can be used to study instrumental effects
- Need to cut on time when the LAT was pointing at the limb
- Have made changes to increase our Limb dataset
  - Pole-pointed observation each week
  - Extended target of opportunity (tracing Limb while target is occulted)

- Excess is seen (likely due to dips in efficiency below/above 130 GeV)
- Not at the level of GC ($S/N_{\text{limb}} \sim 15\%$ while $S/N_{\text{GC}} = 30-60\%$)

unclear if the 135GeV signal (@GC) is physical or systematic

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Future Prospects

- Dwarfs will remain a prime target (MW halo analysis close match)
- Future dSphs limits:
  - increased observation time
  - discovery of new dwarfs
  - gains at high energy
- The canonical 100 GeV WIMP appears to be within reach
- Next generation Cherenkov Telescope (e.g., CTA) will give complementary limit on WIMP mass

![Graph showing expected limits on WIMP annihilation rates](CTA, MW halo (taen from Doro+ 13))
Summary

- $\gamma$-ray observation is a powerful probe to investigate the DM property
- Fermi-LAT data is still improving
  - from P6 to P7, P7 reprocessed (+ongoing effort for P8)
- No significant detection of the signal yet
  - (130GeV line not significant globally with reprocessed data and new Edisp model)
- Constraints on the nature of DM have been placed (dSphs, MW halo)
  - start to reach thermal-relic cross section
  - the canonical 100 GeV WIMP appears to be within reach

Thank you for your Attention
Backup Slides
Cosmic-ray Electrons/Positrons

- 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

Ackermann+10
PRD 82, 092004
DM Signal Example

• Example of DM signal (for extragalactic gamma-ray background)

Abdo+10, JCAP 4, 14
(CA: Conrad, Gustafsson, Sellerholm, Zaharijas)
Limit on Cosmological DM by EGB

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

DM interpretation challenged by EGB
(and dSphs, MW halo)

(not to exceed EGB only by DM signal)

(blazar/starburst included)

Abdo+10, JCAP 4, 14
(CA: Conrad, Gustafsson, Sellerholm, Zaharijas)
Measuring Efficiency with the Earth Limb

- The Earth Limb can be seen in the P7TRANSIENT class at high energies.
- This allows us to use it to measure efficiencies for tighter event classes as a function of energy.

E \([50,200]\) GeV
Sky Survey Data
Rocking angle cut reversed
ABS(ROCK_ANGLE)>52

Preliminary

Counts / 0.25°

\(\theta_z [°]\)
The efficiency at ~115 GeV is $0.57/0.75 = 75\%$ of the MC prediction. => 30\% boost in signal at 130 GeV relative to the prediction from nearby energy bins.
• Pass 8 is a comprehensive revision of the Fermi-LAT analysis chain

Preliminary background rejection =>
~25% increase in HE acceptance
~100% increase in LE acceptance
Pass7 Performance (EGB vs. BG)

- EGB vs. Background of P7

**P7SOURCE**

- Total residual CRs
- Primary CR protons
- Primary CR $e^{-} + e^{-}$
- Secondary CRs
- EGB

**P7CLEAN**

- Total residual CRs
- Primary CR protons
- Primary CR $e^{-} + e^{-}$
- Secondary CRs
- EGB

**P7ULTRACLEAN**

- Total residual CRs
- Primary CR protons
- Primary CR $e^{-} + e^{-}$
- Secondary CRs
- EGB

Ackermann+12, ApJS 203, 70

*(CA: Baldini, Charles, Rando)*
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

Porter+11