Indirect Searches for Dark Matter with the Fermi Large Area Telescope

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on behalf of  
The Fermi LAT Collaboration  

HEP Seminar  
University of Virginia  
12/05/12
Outline

• Dark Matter Overview

• The Fermi Large Area Telescope

• The Gamma-ray Sky

• Recent Dark Matter Results
  – Focus on spectral line search
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    – Focus on spectral line search
Astrophysical Evidence for Dark Matter

• Majority of mass in galaxies is *dark*
  – Coma Cluster + Virial Theorem
    F. Zwicky (1937)

• Dark Matter clumps in large halos around galaxies
  – Galactic Rotation Curves
    V. Rubin et al (1980)

• Dark Matter is virtually collisionless
  – The Bullet Cluster

• Dark Matter is non-baryonic
  – CMB Acoustic Oscillations
    WMAP (2010)
Astrophysical Evidence for Dark Matter

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    WMAP (2010)
WIMPs detectable by Fermi LAT

- Weakly Interacting Massive Particle (WIMP)
- GeV-TeV mass scale
- **Assume**: Can annihilate or decay into SM particles
- **Assume**: Accounts for measured DM density
- Ex) Neutralino
  - Predicted by many SUSY models
    - LHC experiments starting to put strong constraints on SUSY
  - Electrically neutral
  - LSP \(\rightarrow\) stable particles
  - GeV-TeV mass
WIMPs as a Thermal Relic

- If WIMP was a thermal relic, then it was in creation/annihilation equilibrium in early universe
- Once universe cools enough, amount of dark matter freezes out
  - No longer created, and expansion causes annihilation rate to drop to ~0
- Assume weak scale $\sigma_{\text{ann}} \rightarrow$ observed abundance (~23%)
  - $<\sigma v>_{\text{ann}} \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$ ($\sigma_{\text{ann}} \sim 3 \text{ pb}$)
  - $v_{\text{CDM}} \sim 0.3c$
- Virial theorem -> to form stable halos around galaxies, DM particle should be non-relativistic (cold dark matter)
How to Detect WIMPs

χ

Direct Detection (underground detectors)

Production (collider)

χ

Indirect Detection

χ

SM

SM

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• WIMP annihilation or decay can produce a variety of detectable SM particles

• Goal is to detect these particles and disentangle intrinsic WIMP properties
What we observe

\[ \Phi_{\chi}(E, \psi) = \frac{\langle \sigma \chi \nu \rangle}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi) \frac{1}{2} \frac{\rho(l)^2}{m_{\chi}^2} \]

DM Flux (events/cm^2/s)

Region of Interest (ROI)
(dwarf galaxy, the whole sky, etc)
WIMP Signatures (2)

Intrinsic Particle Properties

\[ \Phi_\chi(E, \psi) = \frac{\langle \sigma_\chi \nu \rangle}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi) \frac{1}{2} \frac{\rho(l)^2}{m_\chi^2} \]

Annihilation Cross Section * velocity
\( (\nu \sim 0.3c) \)
\( \langle \sigma \nu \rangle_{\text{ann}} \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \) \( (\sigma_{\text{ann}} \sim 3 \text{ pb}) \)

Note: large fraction of predicted gamma’s have \( E_\gamma < m_{\text{DM}} \)

Predicted gamma ray
\( dN/dE \) from various annihilation channels

Gustafsson et al. PRL 99.041301
WIMP Signatures (2)

\[ \Phi_\chi (E, \psi) = \langle \sigma_\chi \nu \rangle \sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi) \frac{1}{2} \frac{\rho(l)^2}{m_\chi^2} \]

Astrophysics

J-factor – Line of sight integral over a ROI

Dark matter density distribution
(example simulation)

Credit: Springel et al. (Virgo Consortium)

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WIMP Signatures (2)

\[ \Phi_\chi(E, \psi) = \frac{\langle \sigma_\chi \nu \rangle}{4\pi} \sum_f dN_f \frac{dE}{dE} B_f \int_{LOS} dl(\psi) \frac{1}{2} \frac{\rho(l)^2}{m_\chi^2} \]

Astrophysics

“J-factor” – Line of sight integral over a ROI

Various models for the smooth DM density as a function of distance from galactic center (r)
Derived from fits to N-body simulations
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Fermi Large Area Telescope (LAT)

- On board the Fermi Gamma-ray Space Telescope
  - Launched June 11, 2008
  - Started taking data Aug 2008
  - 5 year mission
  - Mission extended at least through 2016

Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs
20 MeV - 300 GeV - includes unexplored region between 10 - 100 GeV

Can go >300 GeV

Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV - 40 MeV
Gamma Ray Pair Conversion

Energy loss mechanisms

Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\alpha x)$, where $x$ is the path length in radiation lengths. (Review of Particle Properties, April 1990 edition).

Opening Angle

$$\theta_{\text{Open}} \approx \frac{4m_e}{E_\gamma}$$

At 100 MeV

$\theta_{\text{Open}} \sim 1^\circ$

NASA
Public Data Release: All $\gamma$-ray data made public within 24 hours (usually less)

Si-Strip Tracker: convert $\gamma \rightarrow e^+e^-$ reconstruct $\gamma$ direction EM v. hadron separation

Hodoscopic CsI Calorimeter: measure $\gamma$ energy image EM shower EM v. hadron separation

Trigger and Filter: Reduce data rate from $\sim 10$kHz to 300-500 Hz

Fermi LAT Collaboration: ~400 Scientific Members, NASA / DOE & International Contributions

Anti-Coincidence Detector: Charged particle separation
• < 100 MeV limited by 3 in-a-row trigger requirement & drop in pair production cross section (see slide 16)
• > 100 GeV limited by backsplash
• See arXiv:1206.1896 for more info on Fermi LAT performance/validation
Fermi LAT Point Spread Function (PSF)

- Limited by multiple scattering at low E
- Limited by strip pitch at high E (pitch = 228 µm)
- See arXiv:1206.1896 for more info on Fermi LAT performance/validation
• Limited by energy loss in tracker at low E
• Limited by leakage and CAL saturation at high E
• See arXiv:1206.1896 for more info on Fermi LAT performance/validation
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Daily Gamma-ray Sky

Northern Galactic Hemisphere

Southern Galactic Hemisphere

06-AUG-2008

05/12/2012

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• Sun is typically not the brightest gamma-ray source
  – Solar flares however…
Fermi LAT Gamma-ray Sky

1 year all sky map (E > 1 GeV)
Fermi LAT Gamma-ray Sky

4 year all sky map (E > 1 GeV)
Nature has given us a rich and complicated gamma-ray sky!

**Sources**
- Pulsars, AGN, SNR, etc

**Diffuse**
- complex gas structure
- Various CR interactions

**Isotropic**
- Extragalactic

**Galactic Plane**
- sources + diffuse

**Dark Matter?**
- Will be a small piece
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Dark Matter Searches with the Fermi LAT

DM Clumps in the Halo:
- Few Astro. Bkg
- Complicated by low statistics, unknown loc

Galactic Center:
- Large Statistics
- Complicated by Astrophysical Sources

Extragalactic:
- All galaxies
- Isotropic

Spectral Lines:
- Smoking Gun
- Small Stat.

Galactic Halo:
- Large Statistics
- Complicated by diffuse Y-rays from Cosmic Rays

Nearby Galaxies:
- dSph DM Enriched
- Known location
- Lower Statistics

Milky Way Halo simulated by Taylor & Babul (2005)
All-sky map of DM gamma ray emission (Baltz 2006)
• ATIC observed an unexpected bump in the CR e± spectrum

• Fermi observes a broader excess around the same energy

• This feature can be accounted for by adjusting the CR injection spectrum or nearby pulsars

• Can also be explained with leptophillic DM annihilation models
  – Requires large $<\sigma v>_{\text{ann}}$ to explain excess
Unexpected Rise in local CR Positron Fraction

- Fermi measures a rise in the local high-energy CR positron fraction, consistent with the PAMELA results
- No magnet on-board, so use Earth’s magnetic field
- Rise in local positron fraction disagrees with conventional model for cosmic rays
  - Local positrons are secondaries created by CR nuclei interactions (this should cause fraction to decrease)
- This can be explained with leptophilic annihilating/decaying DM
  - Requires large $<\sigma v>_{\text{ann}}$ to explain excess
  - Antiproton fraction does not rise; need to suppress hadronic modes
DM Constraints from the Milky Way Halo

- Look in 2 year diffuse from 1 – 100 GeV
  - Mask out known gamma-ray sources
- Region of Interest: two off-plane rectangles ($5^\circ<|b|<15^\circ$ & $|l|<80^\circ$)
  - Minimizes DM profile uncertainties (central cuspiness varies)
  - Limits astrophysical uncertainties (mask bright plane, avoid high latitude Fermi lobes and Loop I)
- This analysis focuses on setting limits on possible DM signals
  - See non-DM like residuals (e.g. not centrally peaked)
MW Halo Results - $b\bar{b}$

**Annihilation**

$\chi\chi \rightarrow b\bar{b},$ ISO

- $\sigma$ WIMP freeze-out
- $\sigma$ WIMP freeze-out (3σ, 5σ)
- w/o background modeling
- constrained free source fits

M. Ackermann et al (Fermi LAT Collaboration)

Accepted for publication in ApJ (arXiv:1205.6474)

**Decay**

$\chi \rightarrow b\bar{b},$ ISO

- 3σ
- 5σ
- w/o background modeling
- constrained free source fits

- $b\bar{b}$ annihilation spectrum is similar in shape to DM annihilations/decays producing heavy quarks and gauge bosons in this energy range

- Exclude canonical thermal relic WIMPs for masses below ~30 GeV in $b\bar{b}$
• Set limits assuming only Final State Radiation and FSR + Inverse Compton
  – Only FSR = only photons produced by taus (no electrons)
  – “FSR + IC” includes IC gamma rays from electrons produced via DM annihilation/decay
• Contours show 2σ and 3σ CL fits to PAMELA (purple) and Fermi (blue) positron fraction
  – DM interpretation of positron fraction strongly disfavored (for annihilating DM)
Constraints from dwarf galaxies

- Dwarf galaxies have a large mass-to-light ratio
- Good signal-to-noise for a DM search
Combined dSphs Results

• Joint likelihood analysis of 10 dwarf galaxies

• 4 years of data in energy range 100 MeV – 500 GeV

• Account for uncertainties in J-factor
  – DM distribution determined using observed stellar velocities

• 4 annihilation channels considered

• No DM seen
  – Exclude canonical thermal relic cross-section for masses less than ~10 GeV (in b bé and tau’s)

Comparison with Ground-based Telescopes (b bé)
Combined dSphs Results

- Joint likelihood analysis of 10 dwarf galaxies
- 4 years of data in energy range 100 MeV – 500 GeV
- Account for uncertainties in J-factor
  - DM distribution determined using observed stellar velocities
- 4 annihilation channels considered
- No DM seen
  - Exclude canonical thermal relic cross-section for masses less than \(~10\) GeV (in \(b\bar{b}\) and tau’s)
Projected Limit Improvement with dSphs

Predicted dSph Limits for $b\bar{b}$ Channel

- 2yr, 10 dSphs (Published)
- 2yr, 10 dSphs (Spatial Extension)
- 2yr, 30 dSphs
- 10yr, 10 dSphs
- 10yr, 30 dSphs (Spatial Extension)

$\langle \sigma v \rangle$ (cm$^3$ s$^{-1}$)

Mass (GeV)
• Han et al 2012 (arXiv 1201.1003) claimed ~4 sigma evidence from dark matter annihilation in the Virgo galaxy cluster
• Very extended DM annihilation profile (from substructure), majority of excess comes from inner 3 deg of the profile
Virgo Galaxy Cluster (2)

- **Excess is not in the cluster center (as expected from DM)**
- **Macias-Ramirez find 7 new candidate point sources that could explain excess**
  - Han et al 2012 (arXiv 1207.6749) find 4 new candidate point sources
- **Significance depends strongly on the interstellar emission model**
  - Requires a detailed study of systematic uncertainties especially of the interstellar emission model even for extragalactic regions
  - Virgo is at fairly low galactic latitude and in a challenging region for diffuse emission modeling.
Search for Gamma-ray Spectral Lines

- Annihilation/decay directly into $\gamma\gamma$ or $X\gamma$ ($X = Z^0, H^0, \ldots$)
- "Smoking Gun" channel
- Advantage: sharp, distinct feature
- Disadvantage: low predicted counts

Gustafsson et al. PRL 99.041301
The Fermi LAT Line Search

- 2 year analysis accepted for publication in PRD
  - Current analysis uses similar method
- 4 year analysis nearing completion
  - Use Reprocessed “Pass 7 Clean” data
    - Low cosmic-ray contamination
    - Reprocessing shifts energy scale by 1-4% to account for expected accumulation of radiation damage to calorimeter
  - Plan to submit paper to PRD end of December 2012
- Search for lines from 5 to 300 GeV
  - Maximum Likelihood Fit
  - Use sliding ±6σ_E windows
  - Fit for energies in σ_E steps
    - Perform finer 0.5σ_E scan near significant energies
  - Model bkg as single powerlaw
  - Γ_bkg and f_sig free in fit
Improved Model for LAT Response to a Line

- Use full detector simulation to get Fermi LAT energy dispersion
- Previously modeled line with a triple gaussian fit ("1D PDF")
- This analysis adds a 2nd dimension to line model: $P_E$
  - $P_E$ is the probability that measured energy is true energy
  - Labeled "CTBBestEnergyProb" in our extended data
    - "2D PDF" (a function of both energy and $P_E$)
- Break Line into 10 $P_E$ slices and do triple gaussian fit in each slice separately
  - Fit explicitly at 9 energies and interpolate parameters in each slice to produce lines at other energies
- Including $P_E \rightarrow \sim 15\%$ improvement to signal sensitivity (when there is signal) and counts upper limit (when there is no signal)
Region of Interest (ROI) Optimization

- Many have shown ROI optimization importance in line searches
  - e.g. C. Weniger JCAP 1208 (2012) 007
- Find $R_{GC}$ that optimizes $\text{sig}/\sqrt{\text{bkg}}$
  - ROI choices made a priori using MC
  - sig from J factor in that ROI
  - bkg from MC simulation of galactic diffuse model
  - [http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Model\_details/Pass7\_galactic.html](http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Model\_details/Pass7\_galactic.html)
- Search in 5 ROIs
  - R0 (12°×10° GC box)
  - R16 (Einasto Optimized)
  - R41 (NFW Optimized)
  - R90 (Isothermal Optimized)
  - R180 (2 year Analysis ROI)

Preliminary

E > 2.6 GeV

NFW Optimized ROI

12/05/2012 Andrea Albert (OSU)
No globally significant lines found
- Most significant fit was in R0 at 5 GeV, ~2σ (3.7σ local)

- Expected limits calculated from powerlaw-only pseudo-experiments
- No systematic errors applied
95% CL $<\sigma v>_{\gamma\gamma}$ Einasto Upper Limit R16

Expected limits calculated from powerlaw-only pseudo-experiments
No systematic errors applied
Line-like Feature near 135 GeV

- Our blind search does not find globally significant feature near 135 GeV
  - Reprocessing shifts feature from 130 GeV to 135 GeV
  - Most significant fit was in R0, 2.23σ local (<0.5σ global)

- Much interest after detection of line-like feature localized in the Galactic center at 130 GeV

- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of $P_E$)

**Note:** Fit in 4°x4° GC ROI
Not one of our a priori ROIs
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  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of $P_E$)
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of $P_E$)

Note: Fit in 4°x4° GC ROI
Not one of our a priori ROIs
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4.01σ (local) 1D fit at 130 GeV with 4 year unprocessed data
- Look in 4°x4° GC ROI
- Use 1D PDF (no use of $P_E$)

3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
- Look in 4°x4° GC ROI
- Use 1D PDF (no use of $P_E$)

3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data
- Look in 4°x4° GC ROI
- Use 2D PDF
  - $P_E$ in data → feature is slightly narrower than expected
  - <2σ global

Note: Fit in 4°x4° GC ROI
Not one of our a priori ROIs
Spatial Morphology of Features in Galactic Plane

- Fit in 4°x4° ROIs along the Galactic plane in 1° steps
  - Fit with “1D PDF”
    - To find where the counts are coming from
    - Allowed for negative fluctuations
- Find excess near ~135 GeV near GC
  - But find similar features at other energies along the GP
  - Some indication the 135 feature not smooth, but 2-3 smaller “hot spots”
  - Excess near 135 GeV is one of the largest and near GC, but is not otherwise unique
135 GeV in the Earth Limb spectrum (1)

- Earth Limb is a bright, well understood source
  - $\gamma$ rays from CR interactions in the atmosphere
    - Expected to be a smooth power-law
  - Can be used to study instrumental effects
    - Can see in loosest cuts $\rightarrow$ can study cut efficiencies
- Need to cut on times when the LAT was pointing at the limb
- Have made changes to increase our Limb dataset
  - Pole-pointed observations each week
  - Extended “targets of opportunity”
    - Trace limb while target is occulted
Dips in efficiency below and above 135 GeV
  - Appear to be related to CAL-TKR agreement
  - Could be artificially sculpting the energy spectrum

Line-like feature in the limb at 135 GeV
  - Appears when LAT is pointing at the Limb
  - Surprising since limb should be smooth
  - $S/N_{\text{limb}} \sim 18\%$, while $S/N_{\text{GC}} \sim 30\%$ - 66\% (depending on ROI choice)
    - Limb feature not large enough to explain all the GC signal
• Better event selection (higher signal efficiency at the same bkg level)
  – Expect a ~25% increase in high-energy effective area in the “standard” photon classes
• Better control over systematic uncertainties
• Extend both low and high energy reach
• Include calorimeter-only events (substantial effective area increase above 40 GeV)
• Better high-energy point spread function
Summary

• The Fermi LAT team has looked for indirect DM signals using a wide variety of different methods
  – So far no signals have been detected and strong constraints have been set

• Observed deviations from conventional models in e^+e^- spectrum
  – Confirm PAMELA e^+ fraction increase

• We do not see any globally significant spectral lines

• Uncovered some aspects of the 135 GeV line that require more study
  – Significance decreases with analysis improvements
  – Also present in the Earth limb
  – Too soon to draw firm conclusions, more data needed
    • More data + Pass 8 will give a more definitive answer in 1 year

• Current searches are already exploring interesting parts of WIMP phase space and will just keep getting more sensitive; stay tuned for more exciting Dark Matter results from the Fermi LAT!
For a list of Fermi LAT collaboration publications
  – see http://www-glast.stanford.edu/cgi-bin/pubpub
• “The Fermi Large Area Telescope On Orbit: Event Classification, Instrument Response Functions, and Calibration
• “Fermi LAT observations of cosmic-ray electrons from 7 GeV to 1 TeV”
  – arXiv: 1008.3999
• “Measurement of separate cosmic-ray electron and positron spectra with the Fermi Large Area Telescope”
  – arXiv: 1109.0521
• “Constraints on the Galactic Halo Dark Matter from Fermi-LAT Diffuse Measurements”
  – arXiv: 1205.6474
• “Constraining Dark Matter Models from a Combined Analysis of Milky Way Satellites with the Fermi Large Area Telescope”
  – arXiv: 1108.3546
• “Fermi LAT Search for Dark Matter in Gamma-ray Lines and the Inclusive Photon Spectrum”
  – arXiv: 1205.2739
• “Anisotropies in the diffuse gamma-ray background measured by the Fermi LAT”***
  – arXiv: 1202.2856
• Profumo and Linden, “Gamma-ray Lines in the Fermi Data: is it a Bubble?”***
  – arXiv: 1204.6047
• M.N. Mazziotta et al “A model-independent analysis of the Fermi Large Area Telescope gamma-ray data from the Milky Way dwarf galaxies and halo to constrain dark matter scenarios”***
  – arXiv:1203.6731
• M. Ajello et al (The Fermi LAT Collaboration) “Constraints on dark matter models from a Fermi LAT search for high-energy cosmic-ray electrons from the Sun”***
  – arXiv:1107.4272

***not discussed in this talk
BACKUP SLIDES
Halo Method I – “No-background” Limits

- Conservative
  - Method II w/detailed bkg modeling on next slide
- No non-DM background modeling
  - Robust to many uncertainties
- Expected DM counts \( n_{DM} \) compared to observed counts \( n_{data} \)
  and 3\( \sigma \) and 5\( \sigma \) upper limits are set using

\[
 n_{DM} - 3(5)\sqrt{n_{DM}} > n_{data}
\]

in at least one energy bin
Halo Method II – Limits + Bkg Modeling

- Profile likelihood fit combining several GALPROP diffusion models with DM
  - Derives DM limits marginalized over astrophysical uncertainties
- Allow several bkg parameters to vary
  - CRE injection index, diffuse halo height, gas (HI) to dust ratio, CR source distribution, local H$_2$ to CO factor, and isotropic normalization
- Distribution of CR sources is uncertain, so left free in radial Galactic bins.
  - To be conservative to DM constraints, CR source distribution set to zero in the inner 3 kpc
- Maps of each GALPROP + DM model are made and fit to the Fermi LAT data, incorporating both morphology and spectra
MW Halo Results - $\mu^+\mu^-$

- Set limits assuming only Final State Radiation and FSR + Inverse Compton
  - Only FSR = only photons produced by muons (no electrons)
  - “FSR + IC” includes IC gamma rays from electrons produced via DM annihilation/decay
- Contours show $2\sigma$ and $3\sigma$ CL fits to PAMELA (purple) and Fermi (blue) positron fraction
  - DM interpretation of positron fraction strongly disfavored (for annihilating DM)
Fractionally small, but significant deviations

- We see fractionally small, but significant fluctuations in the galactic data and limb spectrum at low energies
  - Fractional deviation $\approx$ or smaller than uncertainties in $A_{\text{eff}}$
  - See similar features in earth limb at low energies
    - See section 7.5 of Pass 7 performance paper
    - Need to consider both fit significance and fractional deviation

\[
\text{resid}_{\text{frac}} = \frac{(n_i - f_i)}{f_i} \\
\text{resid}_{\text{norm}} = \frac{(n_i - f_i)}{\sqrt{f_i}}
\]