What’s Coming

• Dark matter candidates
• Overview of the Fermi LAT (Fermi LAT – Collaboration)
• The Milky Way as seen through the eyes of the Fermi-LAT (Fermi LAT Collaboration)
• Fermi Search for Dark Matter Update (Fermi LAT – Collaboration)
  – electrons and positrons
  – extra galactic background
  – Known and unknown dwarf galaxies
  – Gamma line search
  – The search for extra large dimensions (ADD)
• Future with CTA (Stefan Funk)
Particle Dark Matter?

- Most widely accepted assumption so far: dark matter is made out of particles.

- What data tell us about dark matter:
  - it interacts very weakly, and at least gravitationally, with ordinary matter.
  - it is cold, i.e. non-relativistic.
  - it is neutral.
  - it is stable (or it is very long-lived).

- However, no known particles are good candidates for dark matter!
Several beyond the Standard Model of particle physics scenarios have been proposed that naturally predict the existence of new particles that are excellent dark matter candidates.
Several beyond the Standard Model of particle physics scenarios have been proposed that naturally predict the existence of new particles that are excellent dark matter candidates.
For weak scale interactions between dark matter and SM particles, a *typical* thermal WIMP has:

- mass of order **100 GeV**
- annihilation cross section of order **3 x 10^{-26} cm^3 s^{-1}**

\[\sim\] three 100 GeV WIMPs per liter in the room

Many current and planned experiments are sensitive to a broad range of WIMP models.
Dark Matter WIMP Searches

DM  →  ?  →  SM

DM  →  SM
Dark Matter WIMP Searches

Collider Searches

Fermilab  LHC

DM  → ?  → SM  SM

DM  →
Dark Matter WIMP Searches

Collider Searches

Fermilab  LHC

Direct Searches

CDMS  XENON100
Dark Matter WIMP Searches

Collider Searches
- Fermilab
- LHC

Direct Searches
- CDMS
- XENON100

Indirect Searches
- IceCube
- Fermi-LAT
- PAMELA
Fermi Gamma Ray Space Telescope

Two Instruments:
- **LAT**: 20 MeV → 300 GeV
- **GBM**: 10 keV → 30 MeV

Launch: June 11, 2008

5-year mission (10-year goal)

LEO @ 565km, 25.6° orbit inclination

Gamma ray Burst Monitor (GBM)

spacecraft partner: General Dynamics
The LAT

Pair conversion telescope

Precision Si-strip Tracker:
precise measurement of photon direction, photon ID.
Si strip detectors, W conversion foils; 80 m² of Si active area. 1.5 radiation lengths on-axis.

Hodoscopic CsI Calorimeter:
measurement of photon energy, shower imaging.
Array of 1536 CsI(Tl) crystals in 8 layers. 8.6 radiation lengths on-axis.

Segmented Anti-Coincidence Detector (ACD):
charged particle veto (0.9997 average detection efficiency). Segmented design reduces self-veto at high energy.
89 plastic scintillator tiles and 8 ribbons.
Fermi-LAT as a Telescope

- Shh: *It isn’t one*
- However, it is an astounding machine – a massive particle physics detector in orbit
- 1.8 x 1.8 m², 3 metric tons, moving at 17,000 miles/hr
- Position knowledge to few m, attitude to ~10”, time to <10 µs
- FoV >120 deg across (20% of the sky)
- “It uses less power than a toaster and we talk to it over a telephone line.” (Bill Atwood)
- Cosmic-ray background is intense; onboard filtering is essential (~10⁻⁶ rejection of background for the cleanest photon classes).

Single Events classified as $\gamma$ rays
The Observatory

Large Area Telescope (LAT)
20 MeV - >300 GeV

Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 40 MeV

KEY FEATURES

• Huge field of view
  - LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours.
  - GBM: whole unocculted sky at any time.

• Huge energy range, including largely unexplored band 10 GeV - 100 GeV.
  Total of >7 energy decades!
FGST Prior to Fairing Installation
Sky Image is for Energies $> 1$ GeV

Fermi two-year all-sky map

Credit: NASA/DOE/Fermi/LAT Collaboration
The Fermi LAT 1FGL Source Catalog

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The new structure consists of enormous bubbles extending about 50° north and south of the Galactic center.

Su, Slatyer and Finkbeiner, 2010
Via Lactea – II
The Milky Way Dark Matter Halo
(viewed from far far far away)
**Dark Matter Distribution**

- The dark matter annihilation (or decay) signal strongly depends on the dark matter distribution.
- Cuspy profiles and clumpiness of the dark matter halo can provide large boost factors.

**NFW profile**

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

\[
\rho_0 = 0.3 \text{ GeV/cm}^3
\]

\[
a_0 = 20 \text{ kpc}, \quad r_0 = 8.5 \text{ kpc}
\]

- Via Lactea II predicts a cuspy profile, \(\rho(r) \propto r^{-1.2}\)
- Aquarius predicts a shallower than \(r^{-1}\) innermost profile.
Fermi Search Strategies

**Satellites:**
Low background and good source ID, but low statistics

**Galactic center:**
Good statistics but source confusion/diffuse background

**Milky Way halo:**
Large statistics but diffuse background

**Spectral lines:**
No astrophysical uncertainties, good source ID, but low statistics

**Galaxy clusters:**
Low background but low statistics

**Extragalactic:**
Large statistics, but astrophysics, Galactic diffuse background

All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

Fermi-LAT publications

- High-level papers (121 refereed publications since launch, i.e. 3.7 per month)

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Possibility to detect DM signatures not only in the gamma-rays but also in charged particles


Fermi’s

... Next step: Electron/Positron separation

Photons from WIMP Annihilation

\[
\frac{d\Phi}{dE}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \left( \frac{\langle \sigma_{\text{ann}} v \rangle}{2m^2} \sum_f \frac{dN_f}{dE} B_f \right) \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2 \left( \tilde{r}(l, \theta', \phi') \right) dl
\]

- Charged particles are more complicated (need to include propagation, energy losses)

Note: For a decaying DM particle

\[
\frac{\langle \sigma v \rangle}{2m^2} \rho^2 \rightarrow \frac{1}{m\tau} \rho
\]
Extragalactic diffuse emission

- Contains contribution from sub-threshold sources
- Global fit (Galactic diffuse, sources, isotropic)
- Softer than previously thought (smaller contribution to electron spectrum at TeV energies). Difference to EGRET can be explained by more resolved source
The extragalactic background diffuse emission (EGB)

For E> 100 GeV the limits are 95% upper limits and include a 20% uncertainty on the LAT effective area at high energies.

- >100 GeV the Fermi LAT Monte Carlo simulation of residual CR contamination was too statistically limited to allow an accurate subtraction of this background. Only upper limits on the EGB are shown.
- A more robust energy estimator is used above 100 GeV instead of the standard LAT reconstructed energy.
- E> 100 GeV we only use regions of the sky for which the EGB is the dominant component of the diffuse emission.
- Regions within 1.5 deg of LAT 1FGL catalog sources were cut.
Extragalactic diffuse emission

- Case A: be completely agnostic about the Fermi-LAT sky and assume that all of the extragalactic diffuse emission is generated by DM annihilation (i.e. only require that the DM annihilation channel is below the measurement)
Extragalactic diffuse emission

- Case B: Can do better by subtracting the known population contribution using $\log N - \log S$ to extrapolate below Fermi source detection flux values.
  - explains ~ 30% of extra galactic diffuse
  - additional contributions from star forming galaxies, GRBs, … dark matter.


All sources = 425 = Total
All blazars = $[\Sigma(\#\text{red})](1+\#\text{UnS}/\text{Total})$
Curves overlap $\Rightarrow$ UnS are mostly blazars.
Extragalactic diffuse emission

Figure 5. Cross section \(\langle \sigma v \rangle\) limits on dark matter annihilation into \(b\bar{b}\) final states. The blue regions mark the (90, 95, 99.999)% exclusion regions in the MSII-Sub1 \(\Delta^2(z)\) DM structure scenario (and for the other structure scenarios only 95% upper limit lines). The absorption model in Gilmore et al. [68] is used, and the relative effect if instead using the Stecker et al. [69] model is illustrated by the upper branching of the dash-dotted line in the MSII-Res case. Our conservative limits are shown on the left and the stringent limits on the right panel. The grey regions show a portions of the MSSM7 parameter space where the annihilation branching ratio into final states of \(b\bar{b}\) (or \(b\bar{b}\) like states) is > 80%. See main text for more details.
Comparison of the Extragalactic Diffuse $\gamma$–ray Background\(^1\) to Calculations of Contributions from Blazars\(^2\) + Star-forming Galaxies\(^3\)

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DM Subhalos

DM substructures: very low background targets for DM searches a “smoking gun” signal.

Optically observed dwarf spheroidal galaxies (dSph): largest clumps predicted by N-body simulation.

- Very large M/L ratio: 10 to ~ 1000 (M/L ~ 6-10 for Milky Way)
- More promising targets could be discovered by current and upcoming experiments! (SDSS, DES, PanSTARRS, ...)
- Great targets for gamma ray observations as most are expected to be free from other astrophysical gamma ray sources and have low content in dust/gas, very few stars

Never before observed DM substructures (DM satellites):
- Would significantly shine only in radiation produced by DM annihilation/decay
- Some of these satellites could be within a few kpc from the Sun (N-body simulations)
- All sky search for promising candidates with Fermi LAT
Fermi: Dwarf Spheroidals

Select promising dSph: less than 180 kpc from the Sun, more than 30° from the Galactic plane, stellar kinematic data.

- Ursa Major II
- Segue 2
- Willman 1
- Coma Berenices
- Bootes II
- Bootes I
- Ursa Minor
- Sculptor
- Draco
- Sextans
- Ursa Major I
- Hercules
- Fornax
- Leo IV
Fermi: Dwarf Spheroidals

- No detection by Fermi with 11 months of data.

Determine 95% flux upper limits for several possible annihilation final states

Combine with the DM density inferred from the stellar data to extract constraints on the annihilation cross section for a subset of 8 dSph (based on stellar kinematic data)

(Stellar data from the Keck observatory by Martinez, Bullock, Kaplinghat)

Annihilation into bottom quarks

Search For Spectral Lines

- Another Clean signal of dark matter with no astrophysical uncertainties!
- WIMP Annihilations (Decay) → γν, γγ, γZ, γH0, …
- The photon line signal is suppressed in SUSY as internal loops are needed in that case. However, the signal is enhanced in other models such as Inert Higgs, and some gravitino decays.

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<th>Particle</th>
<th>Branching Ratios</th>
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<tr>
<td>Neutralino</td>
<td>10^{-3} to 10^{-5}</td>
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<tr>
<td>Inert Higgs</td>
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<td>Gustafsson, Lundstrom, Bergstrom, Edsjo. March 2007</td>
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<td>Gravitino decay</td>
<td>0.66 (85 GeV)</td>
</tr>
<tr>
<td>Ibarra, Tran. Sept 2007</td>
<td>0.05 (150 GeV)</td>
</tr>
</tbody>
</table>
Theories with Enhanced Lines (BE)

M. Gustafsson et al. [astro-ph/0703512v1]

Inert Higgs

Gravitino Decay

A. Ibarra & D. Tran [astro-ph/0709.4593v1]

Radiative Corrections

T. Bringmann et al. [hep-ph/0710.3169v2]

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</tr>
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</table>
Photon Line Search Region of the Sky and Data Selection

- August 7, 2008 - June 30, 2010 – ~23 months of data
- Remove Galactic Plane except for GC: includes (|B|>10) | (|L|<10)
- LAT Profile Energy (fit shower profile assuming cylindrical symmetry) in range [4.8, 264] GeV (the profile energy is not public at this time).
  - Best results for line analysis, not so important for standard astrophysics analyses. Pass 7 coming this year solves the energy measurement issue.
- P6V3 Data Clean Cuts (now public) && (LAT frame theta) < 65° && (Earth zenith angle) < 105° && abs(LAT Rocking angle) < 52°
- Removed 1087 point sources, using 1FGL Catalog (1451 sources total).

✓ Cut Radius @ PSF 68% containment

✓ 6 point sources within a 2 deg by 2 deg square at the GC are not removed.

✓ Removes ~10% of photons

• This work is largely based on the thesis of Y. Edmonds of SLAC, Stanford University. She defended in early March.
Fermi LAT Inclusive Photon Spectrum from ROI 4.8 – 264 GeV

- Inclusive Photon Spectrum is featureless power-law, index $\sim 2.44$ (13 < $E$ < 264 GeV)
- Estimate background from charged particles to be < 5% for $E > 100$ GeV based on results from LAT Extragalactic Background results (Abdo et al. 2010), and MC of CR background spectrum yielding index $\sim 2.6$ after cuts (compared to our measured index of 2.44 for $\gamma$s). No additional CR subtraction is made based on this estimate at this time.

$E^2 \times \text{flux} [\text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$

P6V3 dataclean class

$\pm 20 \%$ Systematic error on effective area
Challenges some final state radiation models
“Decaying Dark Matter as a Probe of Unification and TeV Spectroscopy”,
Search for Spectral Lines

- The shape of the line is determined by the Fermi LAT resolution function for the profile energy determined via MC and checked with beam test results.
  - Resolution (68% containment) = -8% + 5% @ 7 GeV
  - Resolution (68% containment) = -10% +10% @ 200 GeV
  - Composite likelihood fits signal + background $S(E) = \text{signal pdf}$, $B(E) = \text{background pdf} = \text{power law}$, $f = \text{signal fraction}$
  - $f$ and $\Gamma$ free, $f \geq 0$ constraint
    \[
    L = \prod_{i=0}^{N} f \cdot S(E_i) + (1 - f) \cdot B(E_i, \Gamma)
    \]
- Fitting ranges in search are ±4σ wide on a grid of energies: 7, 10, 15, 20, 30, 40, 50, …, 200. (Control “look-elsewhere” effect.)
  - The fitting ranges overlap significantly
  - LAT team analysis shows a systematic effect that gives an enhanced signal at ~7 GeV that is mainly the result of analysis data cut in P6V3 (“CTBCORE”). This is being changed in future releases. Beware the smoking gun in P6V3! Solved with pass 7 to be released this year.
    - “CTBCORE” is a high level cut variable that influences the quality of the γ directional information.
  - The LAT team reports no lines observed, and gives upper limits. No detection at 95% CL.
Fermi LAT 23 Month Line search results
Flux Upper Limits, 7 GeV – 200 GeV

- ± 20 % overall scale systematic error (+20 % systematic for UL).
- Additional systematic on spectral structures with LAT resolution for E < 13.2 GeV of s/bg ~ 1%. 7 and 10 GeV bins use a modified event selection to reduce the systematic uncertainty associated with public IRFs.
- For E > 12 GeV no indication of a spectral structure systematic effect is seen.

95% Confidence Upper limits to flux from spectral lines
Fermi LAT 23 Month
\( \gamma\gamma \)-Cross-section upper limits
7 GeV – 200 GeV

- + 20 % overall scale systematic error (UL)
- Additional systematic on structure with LAT resolution for E < 13 GeV of s/bg ~ 1%.
- For E > 12 GeV no indication of a structure systematic effect is seen.
Fermi LAT 23 Month
g-Z-Cross-section limits
7 GeV – 200 GeV

- + 20% overall scale systematic error (UL)
- Additional systematic on structure with LAT resolution for E < 13 GeV of s/bg ~ 1%.
- For E > 12 GeV no indication of a structure systematic effect is seen.

Preliminary
Fermi LAT 23 Month
γZ-Cross-section limits
7 GeV – 200 GeV

- +20 % overall scale systematic error (UL)
- Additional systematic on structure with LAT resolution for $E < 13$ GeV of s/bg ~ 1%.
- For $E > 12$ GeV no indication of a structure systematic effect is seen.

Acharya, Kane, et al. (2011)
arXiv:1102.0556v1 [hep-ph]
D for Dirac fermion, M for Majorana, C for complex scalar, and R for real scalar and the number specifies the particular operator belonging to a given WIMP spin. Within each family, the earlier numbers refer to coupling to quark scalar bilinears (D1-4, M1-4, C1-2, and R1-2), the middle numbers to quark vector bilinears (D5-8, M5-6, and C3-4) and quark tensor bilinears (D9-10) and the largest numbers to coupling to gluons (D11-14, M7-10, C5-6, and R3-4). The WIMP electric and magnetic dipole moment operators are labeled D15 and D16.

Similar to early days of the study of weak interactions.

![Feynman diagram](image)

**TABLE I:** Operators coupling WIMPs to SM particles. The operator names beginning with D, M, C, R apply to WIMPs that are Dirac fermions, Majorana fermions, complex scalars or real scalars respectively.
Plots for the PRL line search, mapped into direct detection parameter space assuming an NFW profile. The two plots on left are for a scalar WIMP. The top right indirect detection plots are for a Majorana WIMP. (T. Tait Private communication)
The Fermi LAT Search for Large Extra Dimensions


• ADD postulated the existence of large extra dimensions as an explanation for the difference between the gravitational scale to electroweak scale (the hierarchy problem).
  – Planck scale: \( M_{P,4} = 1.22 \times 10^{16} \text{ TeV} \)
  – Electroweak scale: \( M_{EW} \sim 1 \text{ TeV} \)

• For a given number of extra dimensions \( n \), they considered compactified dimensions of the same size, \( R \), in this model.

• Due to the presence of extra dimensions, the effective Planck mass in \( n+4 \) dimensions, \( M_{P,n+4} \) would be brought closer to the electroweak scale (\( \sim 1 \text{ TeV} \)).

\[
\frac{M_{P,n+4}^2}{M_{P,4}^2} = (n+4) R^n
\]

• In this scenario, gravity in 4 dimensions is weak because it is diluted in a large space. Standard Model fields DO NOT propagate in the extra dimensions.
Limits on LED from Neutron Stars

• In the LED model by ADD, Kaluza-Klein (KK) gravitons (h) are produced via nucleon-nucleon gravi-bremsstrahlung in supernova cores (involves scattering process of nucleons)

\[ NN \rightarrow NNh \]

• h particles have masses \( \sim 100 \text{ MeV} \), lifetimes of \( \sim 10^9 \text{ yr} \), and decay into photons: \( h \rightarrow \gamma\gamma \)

• The first astrophysical bounds on LED were placed indirectly from SN1987A
  – based on neutrino signal precluding too much energy loss into the KK gravitons’ channel

• Restrictive limits on the size of extra dimensions can be placed from neutron star γ–ray emission originating from trapped h graviton decay.
  – For \( n<4 \), more stringent limits than can be probed by signatures of LED at colliders, about the same for \( n=4 \)
The Fermi LAT Search for Large Extra Dimensions

**Limits on LED from Neutron Stars**

• In this model, neutron stars (NS) will shine in \( \sim 100 \text{ MeV} \) \( \gamma \)-rays.
  - Previous results have no corrections for orbit, decay and absorption in B field.
  - Hannestad and, Raffelt (2003): used EGRET point source sensitivity as basis for results.
  - Cassé, Paul, Bertone, Sigl (2004): averaged over a population of \( \sim 10^9 \) NS in the galactic disk using EGRET data.
The Pulsing Gamma-ray Sky
As of December 2010

25 Gamma-ray pulsars found in a blind search of bright sources.

19 Millisecond gamma-ray pulsars

20 Millisecond radio pulsars found in a search of LAT source error boxes.

Pulses at 1/10\textsuperscript{th} true rate

Fermi Pulsar Detections

> 86 $\gamma$-ray pulsars are now known.
Data on Candidate Pulsar Sources

Criteria for selecting pulsar sources:

- \( t_{\text{age}} < 2 \times 10^8 \) yr (not too old)
- \( B_{\text{surf}} < 3 \times 10^{13} \) gauss (not too high field)
- \( |b| > 15^\circ \) (avoid galactic plane)
- Dist. < 0.4 kpc (sensitivity)
- Not Fermi-LAT source in 1FGL (gives bad limit)

This work is largely based on the thesis of Bijan Berenji of SLAC, Stanford University. He is defending in mid-April (and looking for a post doc job).

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(Data obtained from ATNF Catalog, NASA HEASARC mirror site.)
Fermi LAT Lower Limits on Unification Scale

- 95% CL Lower Limits on the \((n+4)\)-dimensional Planck Scale (TeV units),
  \[ M_D \equiv M_{P,n+4} \]
- Better than past collider limits (DØ, CDF, LEP) for \(n < 5\), LHC for \(n < 4\)
- Interpretation:
  - if unification occurs at around a TeV, \(n > 4\) LED are favored from our results
  - If unification occurs for \(n = 2\) or \(3\), the compactification topology is more complicated than a torus (e.g., warping, different sizes for different dimensions)

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<th>J0953+0755</th>
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Low-energy section
energy threshold
of 20-30 GeV
~24m telescopes

Medium Energies:
mCrab sensitivity
100 GeV–10 TeV
12m telescopes

High-energy section
10 km² area at
multi-TeV energies
4-6m telescopes
Example: Sensitivities for WIMP detection

- Cross-over mass for DM wimp at $\sim 500$ GeV (for $J = 10^{14} \text{ Mo}^{-2} \text{ kpc}^{-5}$)

CTA Collaboration Estimate
Complementarity direct and indirect detection methods

Dark Matter Array (DMA)
See Bergstrom et al. (2010)
CTA at high altitude (10 GeV threshold).

Indirect detection (annihilation $\gamma$'s)
Conclusions I

- No discovery... however promising constraints on the nature of DM have been placed.

- Our knowledge of the astrophysical background is uncertain. This is currently a big limitation in particular for the Galactic center and the Galactic halo which otherwise have huge potential in terms of discovery or setting constraints. It requires a dedicated effort.

- An another example of better understanding is our study of Fermi pulsar SEDs and how they can fake WIMP decay at lower mass (coming soon).

In addition, better understanding of the dark matter density distribution is essential in interpreting observations.

- Some analyses will further benefit from multi-wavelength observations (e.g. dSph and DM satellites.) And if a signal is observed elsewhere (e.g. LHC) it’s likely to make our job easier!

- If a signal is found, indirect detection will provide invaluable information on the distribution of dark matter and will offer a glimpse into the thermal relic hypothesis by measuring the annihilation cross section
Conclusions II

- Fermi is a 5 year mission, with a goal of 10 years.
- Even with current limits from Fermi $\gamma$-ray observations, Fermi LAT Collaboration results are challenging interesting parts of the theoretical phase space.
  - This is particularly the case for DM models that sprang-up to explain the ATIC, Pamela, and Fermi electron and positron results.
  - The photon line limits have a broader significance beyond specific models using an effective field theory formalism. Easy comparison with direct detection and accelerator DM results.
    - The limits on the search for ELD have excluded up to $d=3$ for the ADD model.
- Data analysis: Pass 7 will be a significant improvement over the current public data, Pass 6, and will be released this year. Pass 8 is in the works!
- For the longer term future CTA, perhaps a special indirect dark matter tuned version, DMA, has promise to dramatically improve the search space.

Thank You!
Extra Slides
LAT Collaboration

- France
  - CNRS/IN2P3, CEA/Saclay
- Italy
  - INFN, ASI, INAF
- Japan
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- Sweden
  - Royal Institute of Technology (KTH)
  - Stockholm University
- United States
  - Stanford University (SLAC and HEPL/Physics)
  - University of California, Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - The Ohio State University
  - University of Washington

PI: Peter Michelson
(Stanford)

~400 Scientific Members (including 96 Affiliated Scientists, plus 68 Postdocs and 105 Students)

Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

Project managed at SLAC.
25.6 Degree Orbit

Circular orbit, 565 km altitude (96 min period), 25.6 deg inclination

http://observatory.tamu.edu:8080/Trakker/
The extragalactic background diffuse emission (EGB) has an isotropic distribution on the sky, and is considered to be the superposition of different classes of unresolved sources (AGNs, star-forming galaxies, GRBs) and genuinely diffuse processes like the interaction of ultra-high energy cosmic rays with the extragalactic background light, structure formation shocks, and potential contributions from the decay or annihilation of dark matter.

Compilation of predictions of EGB contributions from different unresolved source classes and diffuse processes in comparison to the EGB measured by EGRET. This figure is adopted from Dermer 2007 (pre Fermi Launch prediction).
Comments below are from Marco Ajello, one of the lead authors on this paper:

- In our paper, the hypothesis that blazars can be represented by a power-law spectrum is discussed and showed not to introduce a strong bias. To show this we derived 3 independent logN-logS distributions in 3 contiguous energy bands (0.1-1 GeV, 1-10 GeV and 10-100 GeV). These can be integrated to derive the contribution to the background in those bands and this is what's reported as blue shaded areas in Fig. 18 and 19 of our paper. Certainly one can assume that spectra of blazars in a small energy band (e.g. 1 decade) can be successfully modeled as a power-law).

- Very recently Inoue & Totani (http://adsabs.harvard.edu/abs/2011ApJ...728...73I) who advanced the idea of the blazar sequence being coupled to the X-ray luminosity function published an erratum of their original paper (basically they found a bug in their code). Now their estimate of the contribution of blazars to the background comes to within ~2% (!!) of what we have published.
Why Use The Profile Energy for the LAT Line Search?

- P6V3 FT1 energy is not well suited to perform a line search.
  - FT1 energy has a number of structures at the few percent level that could be mistaken for photon lines from 5 GeV – 300 GeV. Impacts ULs.
- These structures don’t affect typical astrophysical analyses.
- The Energy measurement problem is corrected in Pass7, which will be released this year (2011).

![Image of energy vs. Enerav plot](image.png)
Examples of Profile Energy Line Energy Resolution Used for S(E) in Fit.

3-Gaussian Fits to MC
Energy Ranges for Fitting Line limits
Remove "CTBCORE" cut below 13.2 GeV, i.e. for 7 GeV (and 10) GeV fits.

- Using standard event selection below 13.2 GeV we estimate a systematic on spectral structures with LAT resolution for E < 13.2 GeV of s/b~3% by not only considering this ROI, but also the control region.

- Removing "CTBCORE" cut we see 1.2 $\sigma$ bump at 7 GeV.

Using standard event selection below 13.2 GeV we estimate a systematic on spectral structures with LAT resolution for E < 13.2 GeV of s/b~1%.

7 GeV signal fitting range
(bin center is 7 GeV.)

Residual = (#counts – model counts)/ $\sqrt{(#counts)}$
We consider a solution to the mu-problem within M theory on a G2-manifold. Our study is based upon the discrete symmetry proposed by Witten that forbids the mu-term and solves the doublet-triplet splitting problem. We point out that the symmetry must be broken by moduli stabilization, describing in detail how this can occur. The mu-term is generated via Kahler interactions after strong dynamics in the hidden sector generate a potential which stabilizes all moduli and breaks supersymmetry with $m_{3/2} \sim 20 - 30$ TeV. We show that mu is suppressed relative to the gravitino mass, by higher dimensional operators, $\mu \sim 0.1 m_{3/2} \sim 2$-3 TeV. This necessarily gives a Higgsino component to the (mostly Wino) LSP, and a small but non-negligible LSP-nucleon scattering cross-section. The maximum, spin-independent cross-sections are not within reach of the current XENON100 experiment, but are within reach of upcoming runs and upgrades.

“If we insist on a good description of the Pamela data plus consistent compactification including m, EWSB, etc, we find an LSP mass from about 140-155 GeV, and an annihilation cross section $2-3.5 \times 10^{-24}$ cm$^3$/s. The annihilation to $\gamma$-Z ranges from 0.7 to 1.2 $\times 10^{-26}$. ”
Old PRL Result 11 Months of Data

**Search for Spectral Lines**

- Smoking gun signal of dark matter.
- The line signal is generally suppressed, but enhanced in some models.
- The signal is the LAT line response function. The background is modeled by a power-law function and determined by the fit.
  - No astrophysical uncertainties.

- No line detection by Fermi with 11 months of data (30-200 GeV)

Example fit for a 40 GeV line

- Wino LSP γZ line (Kane 2009)
Relating Flux Measurements and Bounds on LED

The following equation relates gamma-ray SED from neutron star \( \frac{d\Phi}{dE} \), \( n \), and extra dimensions size \( R \):

\[
\frac{d\Phi_n}{dE} = k_n \left( \frac{d}{\text{kpc}} \right)^{-2} R^n \frac{dN_n}{dE} \quad \text{[cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}] 
\]

\[
k_n = \frac{1}{4\pi (3.086 \times 10^{21} \text{ cm/kpc})^2} (30 \text{MeV})^3 \times (3.17 \times 10^{-23} \text{ MeV}^{-3}\text{s}^{-1}) \left(1.52033 \times 10^{14}\right)^n N_{0,n} \times \frac{2}{3} \quad \text{(T/\hbar c)}^n
\]

2 photons per graviton

Spectrum after attenuation and decay (integral = \( N_{ev} \) in case of no attenuation, decay)

\( N_{ev} = \) [Number of events simulated]

 Distribution function shown on next slide

Extra dimension size (m)

Branching ratio \( \text{BR}(2\gamma) = 1/3 \)

Table of \( k_n \) values

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<th>( k_n )</th>
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\( T = 30 \text{ MeV} \) is the progenitor supernova core temperature
Determining the Distribution of $dN/dE_\gamma$

For a given $n$:

• Sample $\omega$ from the distribution: $f(\omega) = \frac{(\omega / T)^{n+2}}{1 + \exp(\omega / T)}$
  – Exponential term from detailed balancing

• Sample $\mu = 1/\gamma$ from the function $G_{n+3}(\mu) = \mu^{n+3}(1 - \mu^2)^{1/2}\left(\frac{19}{18} + \frac{11}{9} \mu^2 + \frac{2}{9} \mu^4\right)$
  – this is related to the initial distribution of $\mu$ from SN core

• The previous two steps determine the mass $m = \mu \omega$ of a simulated graviton in the MC simulation.

• Sample $r(t)$ from the radial distribution, determined by the KK graviton orbital trajectory, a function of $\mu$.
  – Approximate gravitational potential as Newtonian potential for neutron star
  – Radial trajectory for graviton orbits: Harmonic oscillator inside, radial Kepler equation outside
  – Initial condition on $\beta, \gamma$ derived from $G_{n+3}(\mu)$.

• Determine the velocity $\beta' c$ as a function of radius from $dr/dt$

• Photon energy:

\[
E_\gamma = \frac{1}{2} \gamma' m (1 + \beta' \cos \theta)
\]

$\theta$: angle between KK graviton and decay photon
Determining the Spectrum: Accounting for Decay

• Spectra for each source have been corrected for decay

\[ \sim \exp \left( - \frac{t_{\text{age}}}{\omega \tau(m)} \right), \quad \tau(m) = 1 \times 10^9 \text{ yr} \left( \frac{100 \text{ MeV}}{m} \right)^3 \]

• Attenuation of signal by decay:
  – Exponential decay: higher mass \( h \) decay more rapidly
  – Decay to photons, e\(^+\)e\(^-\), neutrinos in this mass range
  – Greater effect in older stars
Attenuation in the Magnetosphere

- **B-field attenuation:**
  - $\tau_{pp}$ is the pair production optical depth
    \[
    \sim e^{-\tau_{pp}(E_\gamma, \vec{B}(\vec{r}))}, \quad \tau_{pp}(E_\gamma, \vec{B}(\vec{r})) = \int_{\text{path}} \alpha \, ds
    \]
  - $\alpha$ is the pair production attenuation coefficient, integrated over the path of photon away from point of decay until $r = 7R_{\text{NS}}$ (little change after that).
    - Assume a dipole magnetic field for neutron star, no obliquity nor time dependence
    - Use formulas by Erber, Landau and Lifshitz for pair production
      - Used in models of curvature radiation emission by pulsars
    - Attenuation is a function of $\chi$, related to the product of photon energy and the B-field component perpendicular to photon direction
      \[
      \chi = \frac{E_\gamma}{m_e c^2} \frac{B_{\perp}}{B_{\text{cr}}} \quad \alpha(\chi) = 0.16 \frac{\alpha_{fs}}{\chi_e} \frac{B_{\perp}}{B_{\text{cr}}} \frac{1}{\chi} K_{1/3}^{2} \left( \frac{2}{3 \chi} \right) B_{\text{cr}} = 4.4E14 \, \text{G}
      \]
Table of Individual Upper Limits (1 year LAT data)

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