Cosmic Rays and Dark Matter searches with Fermi

Luca Baldini
INFN–Pisa
luca.baldini@pi.infn.it

on behalf of the Fermi LAT collaboration

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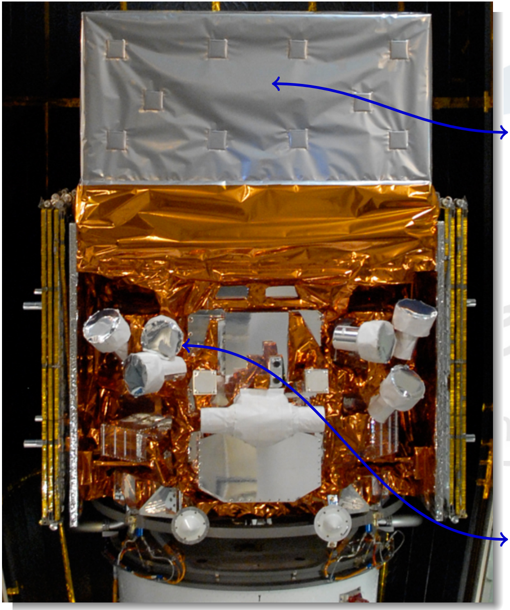
Outline

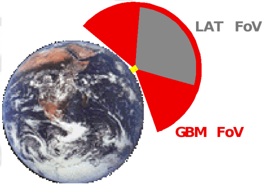
- Introduction
    - Description of the Fermi observatory, status
    - The Large Area Telescope (LAT)
- Direct measurements of Cosmic Rays
    - Cosmic-Ray Electron ($e^+ + e^-$) spectrum
    - Search for Cosmic-Ray Electron anisotropies
    - Future perspectives for direct cosmic-ray measurements with Fermi
- Dark matter searches in gamma-rays
    - Overview of the basic search strategies
    - Review of the most constraining results
- Conclusions

The Fermi observatory



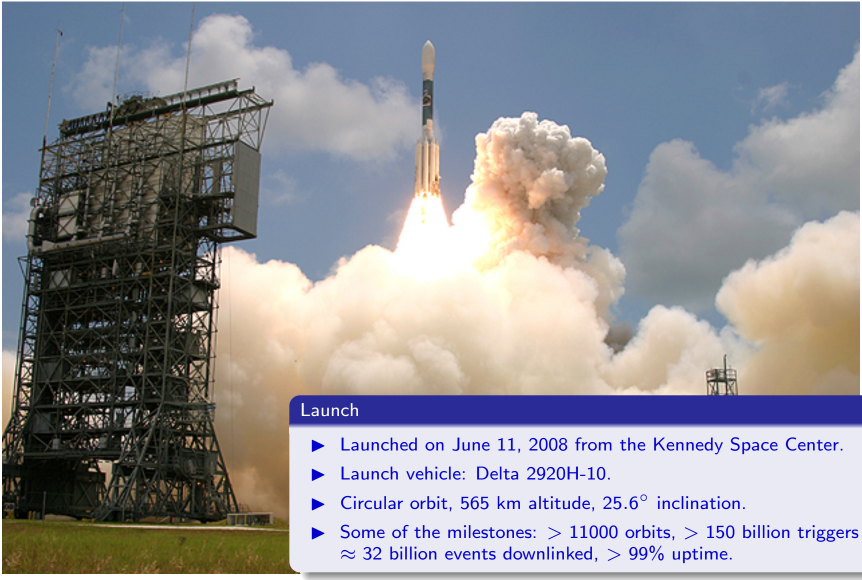
Large Area Telescope (LAT)

- Pair conversion telescope.
- Energy range: 20 MeV–> 300 GeV
- Large field of view ($\approx$ 2.4 sr): 20% of the sky at any time, all parts of the sky for 30 minutes every 3 hours.
- Long observation time: 5 years minimum lifetime, 10 years planned, 85% duty cycle.



Gamma-ray Burst Monitor (GBM)

- 12 NaI and 2 BGO detectors.
- Energy range: 8 keV–40 MeV.



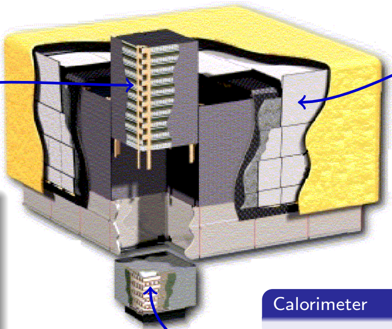
Launch

- Launched on June 11, 2008 from the Kennedy Space Center.
- Launch vehicle: Delta 2920H-10.
- Circular orbit, 565 km altitude, 25.6° inclination.
- Some of the milestones: $>$ 11000 orbits, $>$ 150 billion triggers $\approx$ 32 billion events downlinked, $>$ 99% uptime.

The Large Area Telescope

Large Area telescope

- Overall modular design.
- 4 × 4 array of identical towers (each one including a tracker and a calorimeter module).
- Tracker surrounded by and Anti-Coincidence Detector (ACD)



Tracker

- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis.
- 10k sensors, 80 m^2 of silicon active area, 1M readout channels.
- High-precision tracking, short dead time.

Anti-Coincidence Detector

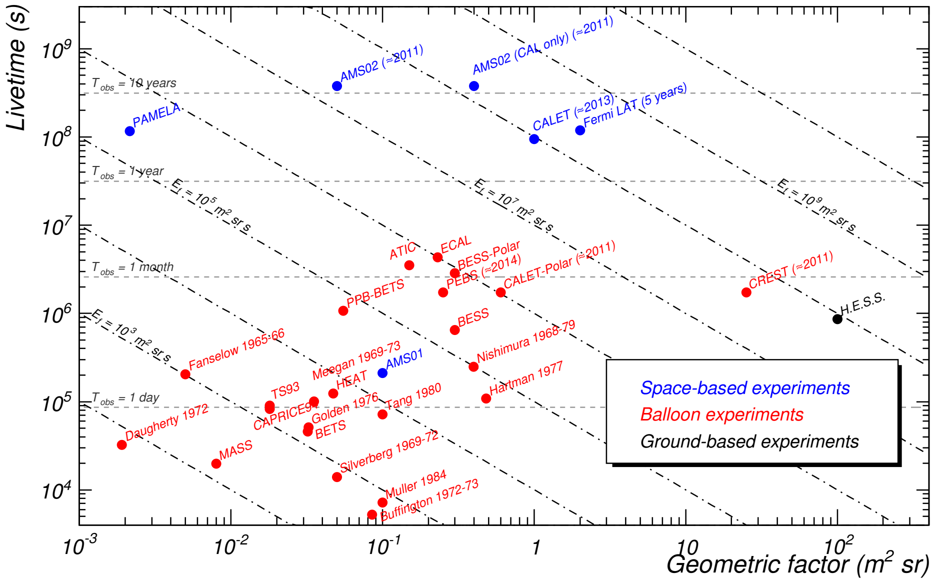
- Segmented (89 tiles) as to minimize self-veto at high energy.
- 0.9997 average detection efficiency.

Calorimeter

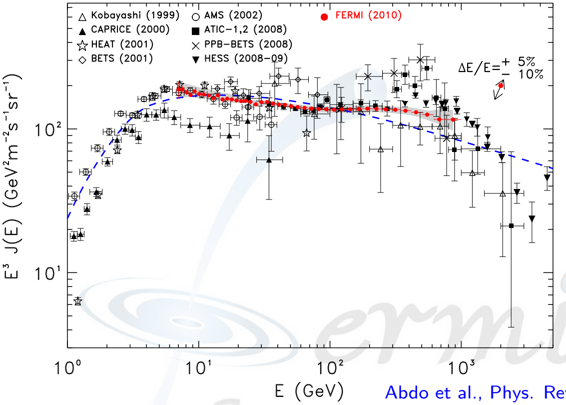
- 1536 CsI(Tl) crystal; 8.6 radiation lengths on-axis.
- Hodoscopic, 3D shower profile reconstruction for leakage correction.

Cosmic-Ray Electron analysis basics

- Trigger and onboard filter
  - All events depositing more than 20 GeV in the CAL downlinked
  - Prescaled (1/250) sample of all trigger types
- Event selection
  - All the three LAT subsystem contribute to the rejection of the hadronic (mainly protons) background
  - The measurement of the shower development in the calorimeter plays a prominent role
  - $\approx$ 20% estimated hadronic contamination after the electron cuts
- Energy reconstruction
  - Same algorithms used for the γ analysis.
  - 5–15% (20 GeV–1 TeV, 1 σ) for an isotropic flux, after the electron cuts.
  - Validated with electron beams at CERN; the excellent data/MC agreement gives us solid ground in extrapolating to 1 TeV.
- Peak geometry factor of $\approx 2.8\ m^2\ sr$ around 50 GeV
  - Large statistics, the *knowledge* of the effective geometry factor dominates the systematic uncertainties

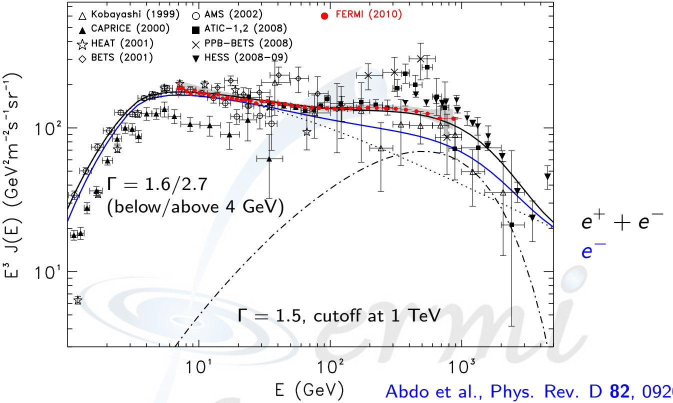

Livetime (s)
Geometric factor (m² sr)
10⁻³
10⁻²
10⁻¹
1
10
10²
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
T obs = 10 years
T obs = 1 year
T obs = 1 month
T obs = 1 day
E_f = 10³ m² sr s
E_f = 10⁵ m² sr s
E_f = 10⁷ m² sr s
E_f = 10⁹ m² sr s
PAMELA
AMS02 (≈2011)
AMS02 (CAL only) (≈2011)
CALET (≈2013)
Fermi LAT (5 years)
ATIC
ECAL
BESS-Polar
PEBS (≈2014)
CALET-Polar (≈2011)
CREST (≈2011)
H.E.S.S.
PPB-BETS
BESS
Nishimura 1968-79
Hartman 1977
Fanselow 1965-66
Meegan 1969-73
AMS01
HEAT
TS93
CAPRICE94
Golden 1976
Tang 1980
BETS
Daugherty 1972
MASS
Silverberg 1969-72
Muller 1984
Buffington 1972-73
Space-based experiments
Balloon experiments
Ground-based experiments

Cosmic-Ray Electron spectrum



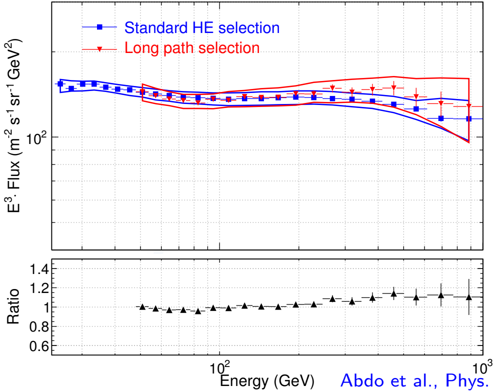
Abdo et al., Phys. Rev. D **82**, 092004 (2010)

- ≈ 8M electron candidates in the first year of operations
  - Follow up on Abdo et al., Phys. Rev. Lett. **102**, 181101 (2009)
  - No evidence for prominent spectral features (confirmed by H.E.S.S.)
  - The low-energy (7–20 GeV) data points exacerbate the tension with the hypothesis of a single power-law spectrum



Abdo et al., Phys. Rev. D **82**, 092004 (2010)

- Good fit possible with an additional high-energy component
  - If it's an e^+/e^- (e. g. nearby pulsars or dark matter), the Fermi spectrum and Pamela positron fraction can be simultaneously fitted
- However more *standard* explanations are possible
  - See Blasi, Phys. Rev. Lett. **103**, 051104 (2009)...
  - ...or Kats et al., MNRAS **405(3)**, 1458 (2010)

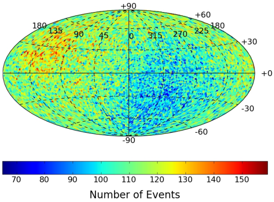


Abdo et al., Phys. Rev. D **82**, 092004 (2010)

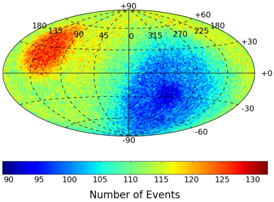
- Long path selection only optimized for energy resolution
  - Require at least 13 X0 in the calorimeter, shower contained in a single module (5% energy resolution up to 1 TeV)
  - More challenging in terms of systematics (5% of the full sample)
  - Really a cross check, not necessarily more accurate!
- The two spectra are consistent within the systematic errors

Search for anisotropies in the CRE flux

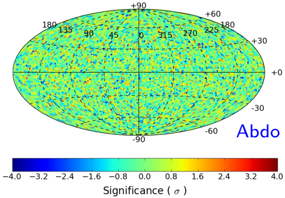
Count map ($E > 60$ GeV)



No-anisotropy map ($E > 60$ GeV)



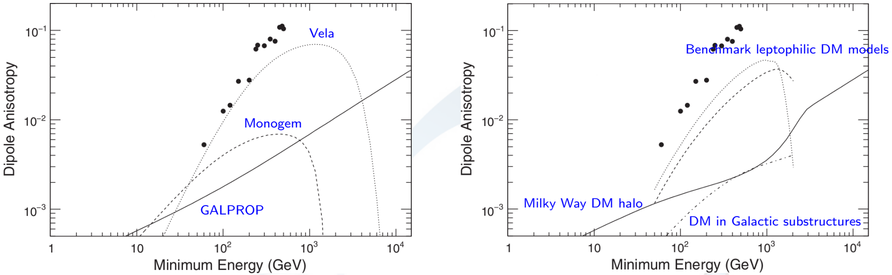
Significance map ($E > 60$ GeV)



Abdo et al., Phys. Rev. D **82**, 092003 (2010)

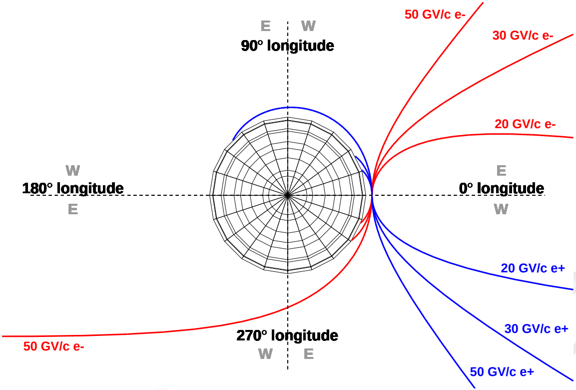
- Fermi offers a unique opportunity for the measurement of possible CRE anisotropies thanks to the large exposure factor
- The *no anisotropy* map accounts for non uniform exposure

Upper limits on anisotropies in the CRE flux



Abdo et al., Phys. Rev. D **82**, 092003 (2010)

- More than 1.6 M candidate electrons above 60 GeV in the first year of operation.
- Entire sky searched for anisotropies in Galactic coordinates
  - Direct bin-to-bin comparison
  - Integrated skymaps with different ROIs (10–90°)
  - Spherical harmonic analysis
- Upper limits for the dipole case ranging from ≈ 0.5% to ≈ 10%
  - Comparable to the values expected for a single nearby source dominating the high-energy electron spectrum



- Measurement of the positron fraction in CRs
  - The LAT is not a magnetic spectrometer
  - Use the Earth magnetic field to separate charges
  - Need a model of the field and particle-tracing code
- Measurement of the proton spectrum
  - Poor energy measurement is a challenge

Dark Matter search strategies

Galactic center

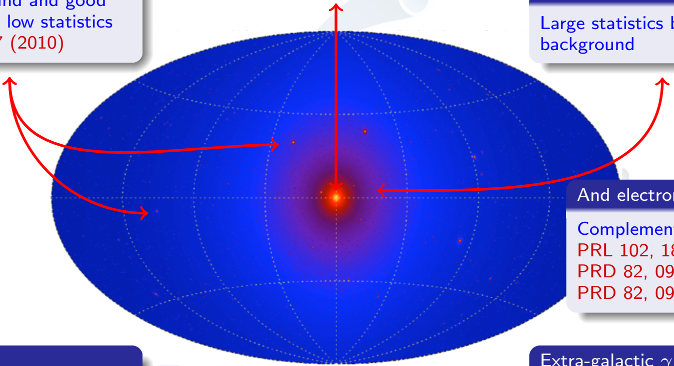
Good statistics but source confusion and diffuse background

Satellites

Low background and good source id, but low statistics
ApJ, 712, 147 (2010)

Milky Way halo

Large statistics but diffuse background



And electrons!

Complementary to γs
PRL 102, 181101 (2009)
PRD 82, 092004 (2010)
PRD 82, 092003 (2010)

Spectral lines

No astrophysical uncertainties, good source id but small branching ratio
PRL 104, 091302 (2010)

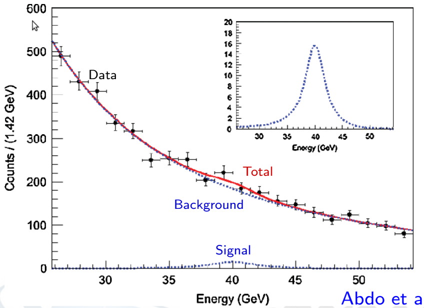
Galaxy clusters

Low background but low statistics
JCAP 05, 025 (2010)

Extra-galactic γ radiation

Large statistics, but astrophysics and galactic diffuse background
JCAP 04, 014 (2010)

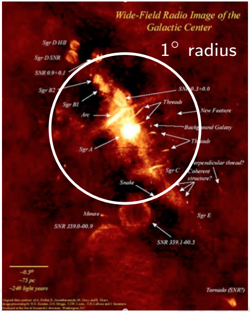
All-sky map of gamma-rays from DM annihilation from arXiv:0908.0195 (based on Via Lactea II simulation)



Abdo et al., PRL **104**, 091302 (2010)

- Dark matter particle annihilation or decay into $\gamma + X$ can produce monochromatic gamma-rays
  - Optimal energy resolution ($\approx$ 10% at 100 GeV) and calibration very important for this analysis
- No detection in the first 23 month of data between 7 and 200 GeV
  - High latitude ($|b| > 10^\circ$) plus 20° degrees around the Galactic center
- Model-dependent upper limits on DM cross section or lifetime
  - Limits on $\langle \sigma v \rangle$ too weak to constrain typical thermal WIMP models

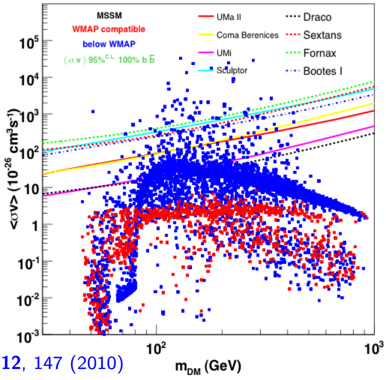
Galactic center



- Steep DM profiles, expect large DM annihilation signal
- Very complicated region, understanding of the astrophysical background is crucial to extract a potential DM signal
  - Source confusion, modeling of the Galactic diffuse emission
- Preliminary analysis of a $7^\circ \times 7^\circ$ centered at the Galactic center
  - Model generally reproduces data well within uncertainties
  - DM constraints have been derived under conservative assumptions
  - They can significantly improve only with a better understanding of the background and the detector response

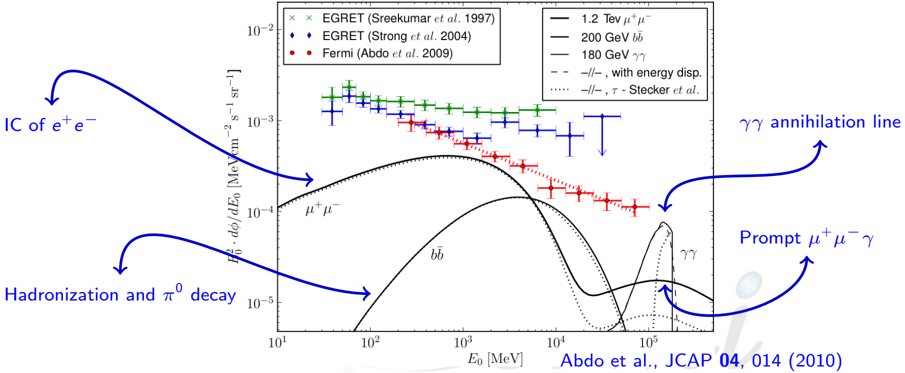
Dwarf spheroidal galaxies

- System with very large mass/luminosity ratio
  - 25 discovered so far, more will be by current/upcoming experiments
- Select most promising candidates for observations
  - Selection based on proximity (within 180 kpc from the Sun), latitude (more than 30° from the Galactic plane), stellar kinematic data
  - Most of them are expected to appear as point sources
- No detection by Fermi with 11 months of data
  - Determine flux upper limits for several possible annihilation final states
  - Combine with the DM density inferred from the stellar data to extract constraints on $\langle \sigma v \rangle$ vs WIMP mass
- Complementary systematic blind search for DM satellites



Abdo et al., ApJ **712**, 147 (2010)

Cosmological Dark Matter



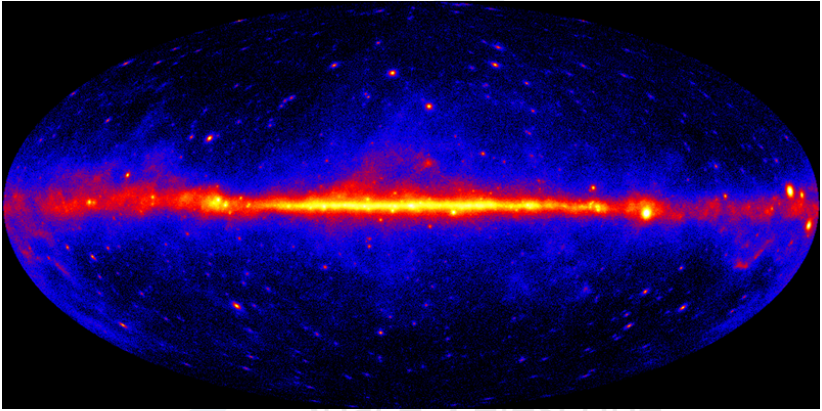
Abdo et al., JCAP **04**, 014 (2010)

- Search for a DM annihilation signal from all halos at all redshifts
- Limits based on Fermi measurement of the isotropic diffuse gamma-ray emission
  - Limits can be very constraining for many interesting models
  - Uncertainties on the evolution of the DM structures are large
  - Constraints will tighten as we assign some fraction of isotropic diffuse to unresolved point sources and push the measurement higher in energy

Conclusions

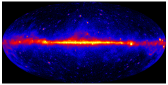
- Direct Cosmic-Ray measurements
  - First systematic-limited measurement of the Cosmic-Ray Electron spectrum up to 1 TeV
  - No evidence for anisotropies in the arrival directions of CREs above 60 GeV
  - Work in progress for the measurement of the Cosmic-Ray proton spectrum and positron fraction
- Dark matter searches
  - No discovery. . .
  - Important constraints set, in particular for some of the model invoked to explain the Cosmic-Ray electron *excesses*
  - The uncertainties in the knowledge of the astrophysical background is one of the current big limitations in terms of potential for discovery
- Fermi is a 5 to 10 years mission
  - There's much more to come!
  - More improvements are anticipated with better understanding of the detector response as we develop more control samples

Spare slides



- The γ-ray sky
  - Rate map (exposure corrected) of γ-candidates above 200 MeV collected during the first year of data taking.

Dissecting the gamma-ray sky



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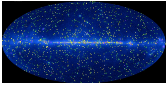
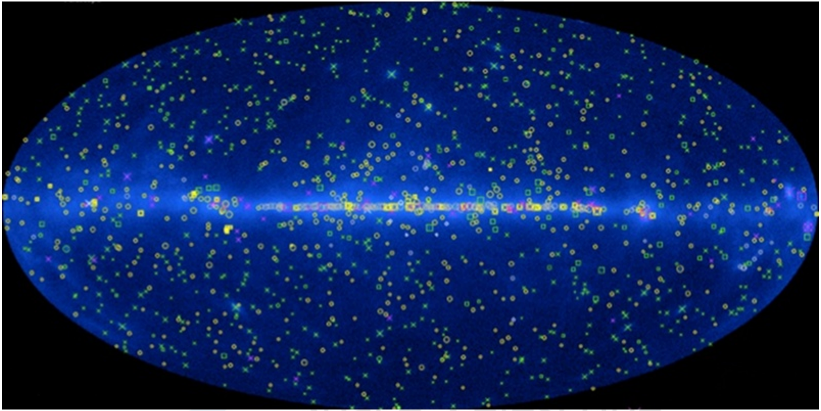
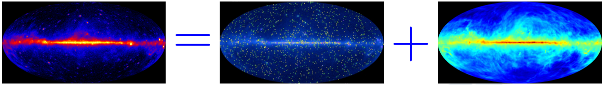
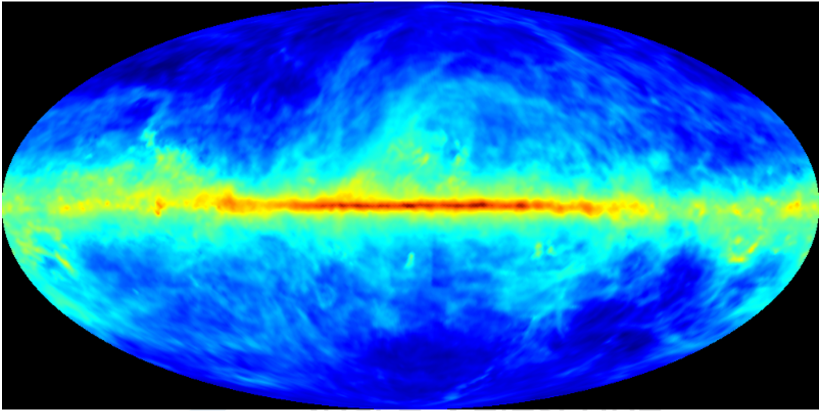




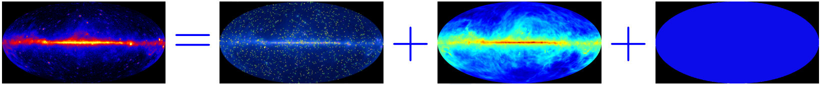
- Resolved point sources
  - 1451 sources above 100 MeV in the 1FGL catalog (arXiv:1002.2280).

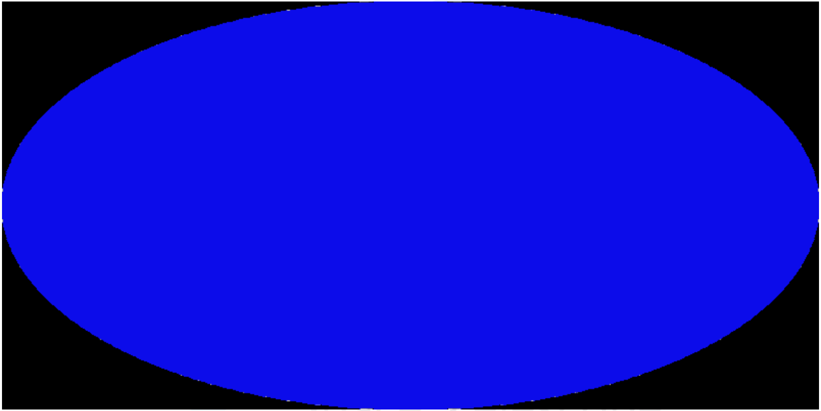




- Galactic diffuse radiation
  - Cosmic-ray interactions with the interstellar medium (Synchrotron, Inverse Compton, π^0 decay, Bremsstrahlung).

Dissecting the gamma-ray sky

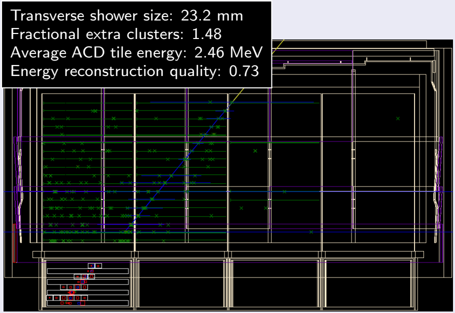




- Isotropic diffuse
  - Unresolved sources and truly diffuse (extragalactic) emission.
  - Residual cosmic-rays surviving background rejection filters.

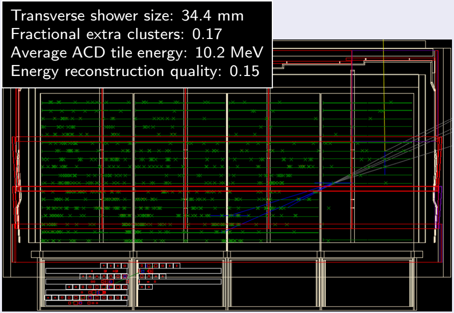
Flight event displays

Candidate electron
475 GeV raw energy, 834 GeV reconstructed



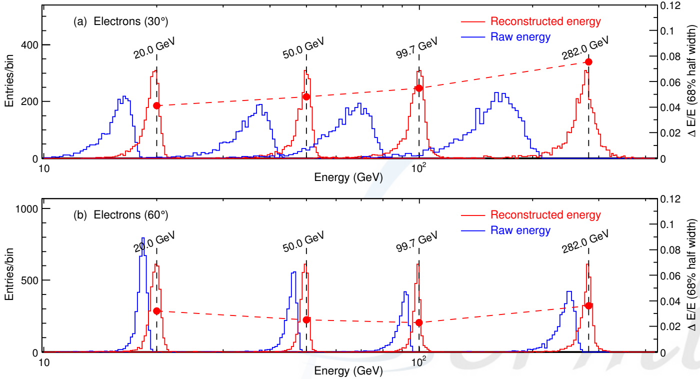
- Clean main track with extra clusters close to the track (note backsplash from the calorimeter).
- Relatively few ACD tile hits, mainly in conjunction with the track.
- Well defined (not fully contained) symmetric shower in the calorimeter.

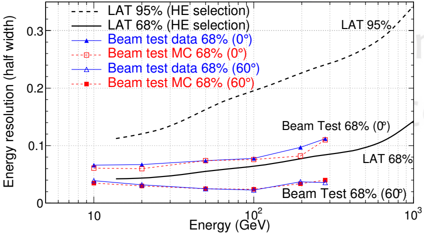
Candidate hadron
823 GeV raw energy, 1 TeV reconstructed



- Small number of extra clusters around main track, many clusters away from the track.
- Different backsplash topology, large energy deposit per ACD tile.
- Large and asymmetric shower profile in the calorimeter.

Energy reconstruction

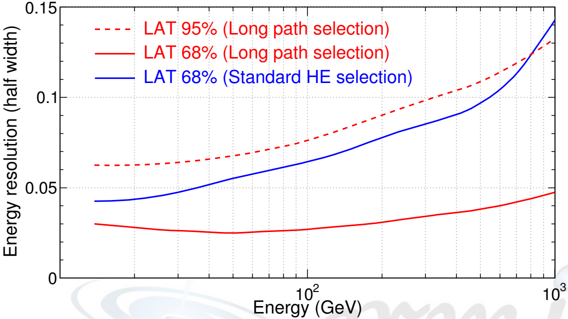




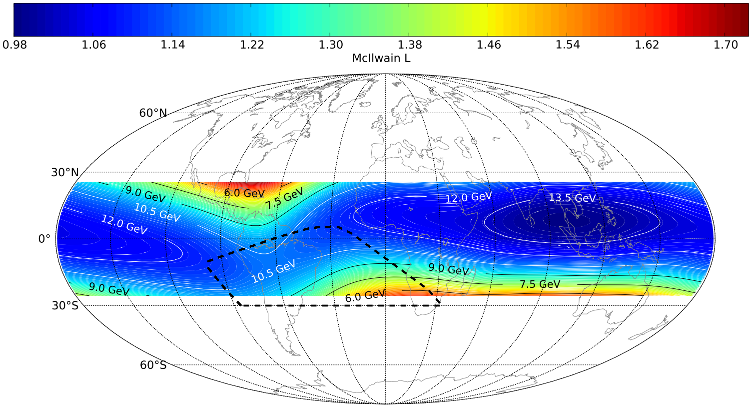
Energy reconstruction

- Same algorithms used for the γ analysis.
- Validated with electron beams at CERN.
- The excellent data/MC agreement gives us solid ground in extrapolating to 1 TeV.
- 5–15% (20 GeV–1 TeV, 1 σ) for an isotropic flux, after the electron cuts.

CRE spectrum and LAT energy resolution



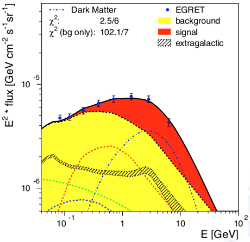
- Test possible systematic effects related to the energy resolution of the detector
- Events with long path (13 X_0 min, 16 X_0 average) in the instrument and contained in a single calorimeter module
  - Energy dispersion much narrower and more symmetric, energy resolution better than 5% (1σ) up to 1 TeV
  - Acceptance reduced to 5% of the *standard* one



- Need to take into account the effect of the Geomagnetic field
- Rigidity cutoff depends on the detector geomagnetic position
  - ≈ 7 GeV is the minimum energy accessible in the Fermi orbit

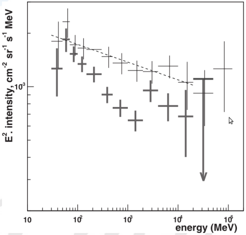
EGRET galactic diffuse

Hunter et al., ApJ **481**, 205 (1997)
de Boer et al., A&A **444**, 51 (2005)



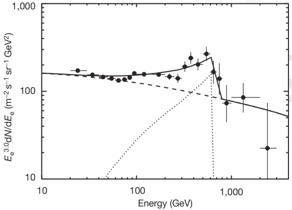
EGRET extra-galactic diffuse

Sreekumar et al., ApJ **494**, 523 (1998)
Strong et al., ApJ **613**, 956 (2004)



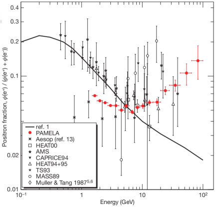
ATIC cosmic ray electrons

Chang et al., Nature **456**, 362 (2008)



Pamela positron fraction

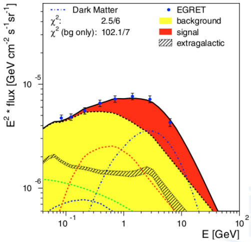
Adriani et al., Nature **458**, 607 (2009)



Features in gamma-ray/CRE spectra?

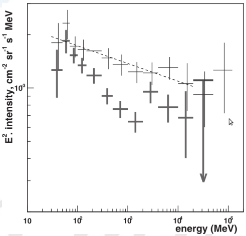
EGRET galactic diffuse

Hunter et al., ApJ **481**, 205 (1997)
de Boer et al., A&A **444**, 51 (2005)



EGRET extra-galactic diffuse

Sreekumar et al., ApJ **494**, 523 (1998)
Strong et al., ApJ **613**, 956 (2004)



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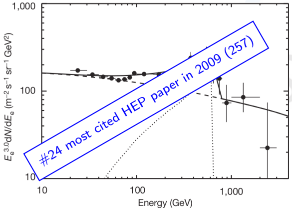
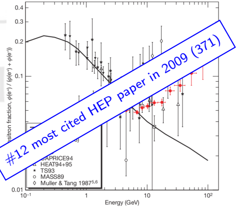
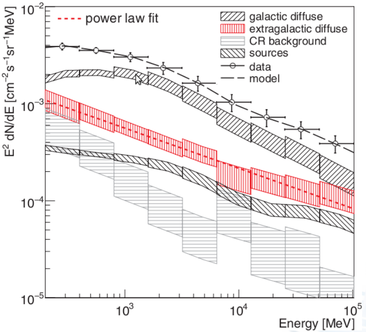
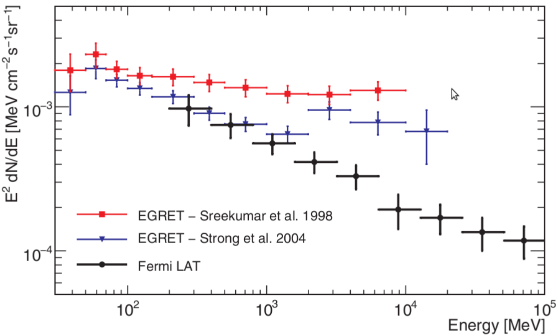


Pamela positron fraction

Adriani et al., Nature **458**, 607 (2009)







- Can be fitted with a single power law with $\gamma = 2.41 \pm 0.05$
  - Steeper than the EGRET spectrum by Sreekumar et al.
  - No spectral feature seen in re-analysis by Strong et al.
- Unresolved AGNs can account for up to 30% of the total
  - Based on Fermi measurements of the blazar luminosity function (Abdo et al., ApJ **720**, 435 (2010))
  - Depends on the LAT point source sensitivity (will decrease with time)

Particle physics

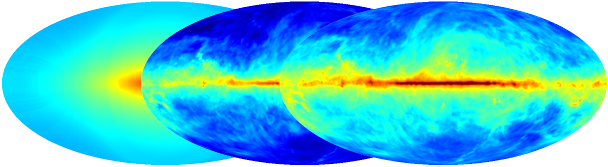
$$\frac{d\Phi}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}} v\rangle}{2m^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f$$

$$\times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\mathrm{l.o.s.}} \rho^2\left(r(l,\phi')\right) dl(r,\phi')$$

Dark Matter distribution

- For Dark Matter decay (rather than annihilation):
  - $\frac{\langle\sigma_{\mathrm{ann}} v\rangle}{2m^2} \rightarrow \frac{1}{\tau m}$
  - $\rho^2 \rightarrow \rho$

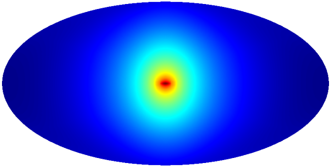
Galactic halo



Inverse Compton

Bremsstrahlung

π^0 decay



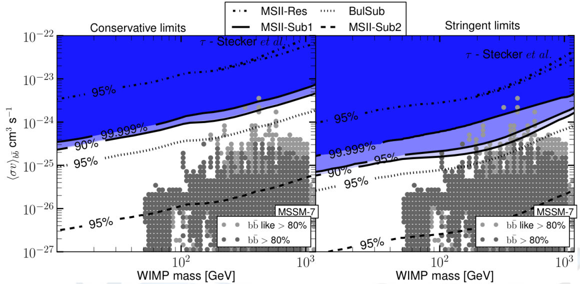
Prompt DM signal (annihilation into b-$\overline{b}$)

- Look for a signal from the entire halo
  - Advantage: lots of statistics
  - Challenge: large background from Galactic diffuse emission and large uncertainties in its modeling
- Exploit both spatial and spectral information to differentiate DM from astrophysical background
- Preliminary DM constraints have been obtained with a benchmark GDE model (consistent with CR data and Fermi gamma-rays)
  - Constraints very sensitive to the choice of the Galactic diffuse model

Search for Dark Matter satellites

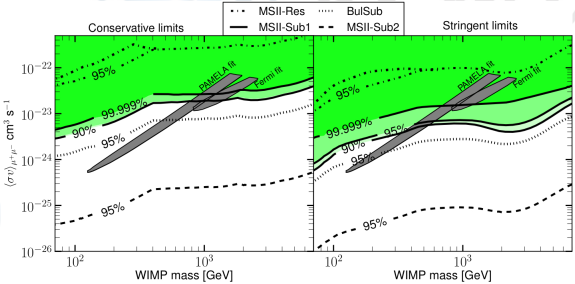
- DM substructures: very low background targets for DM searches
  - Predicted by N-body simulations
  - Some of them might be within a few kpc from the Sun
  - Their extension might be resolved by the LAT
- Systematic search on all the Fermi LAT sources; basic search criteria:
  - More than 10° from the Galactic plane
  - No counterpart at other wavelengths
  - Steady emission
  - Spatially extended
  - Spectrum determined by the underlying DM model (possibly search for more than one source with the same spectrum)
- No DM satellite candidates found in 10 months of data
  - Search for sources with more than 5σ significance between 200 MeV and 300 GeV
  - Consistent with sensitivity studies based on Via Lactea II predictions for a benchmark model
- Work ongoing to refine the analysis and quantify the implications in terms of different DM models

$b\bar{b}$



$\mu^+\mu^-$

Based on the measured isotropic flux alone



Contribution from unresolved point sources subtracted from the isotropic flux