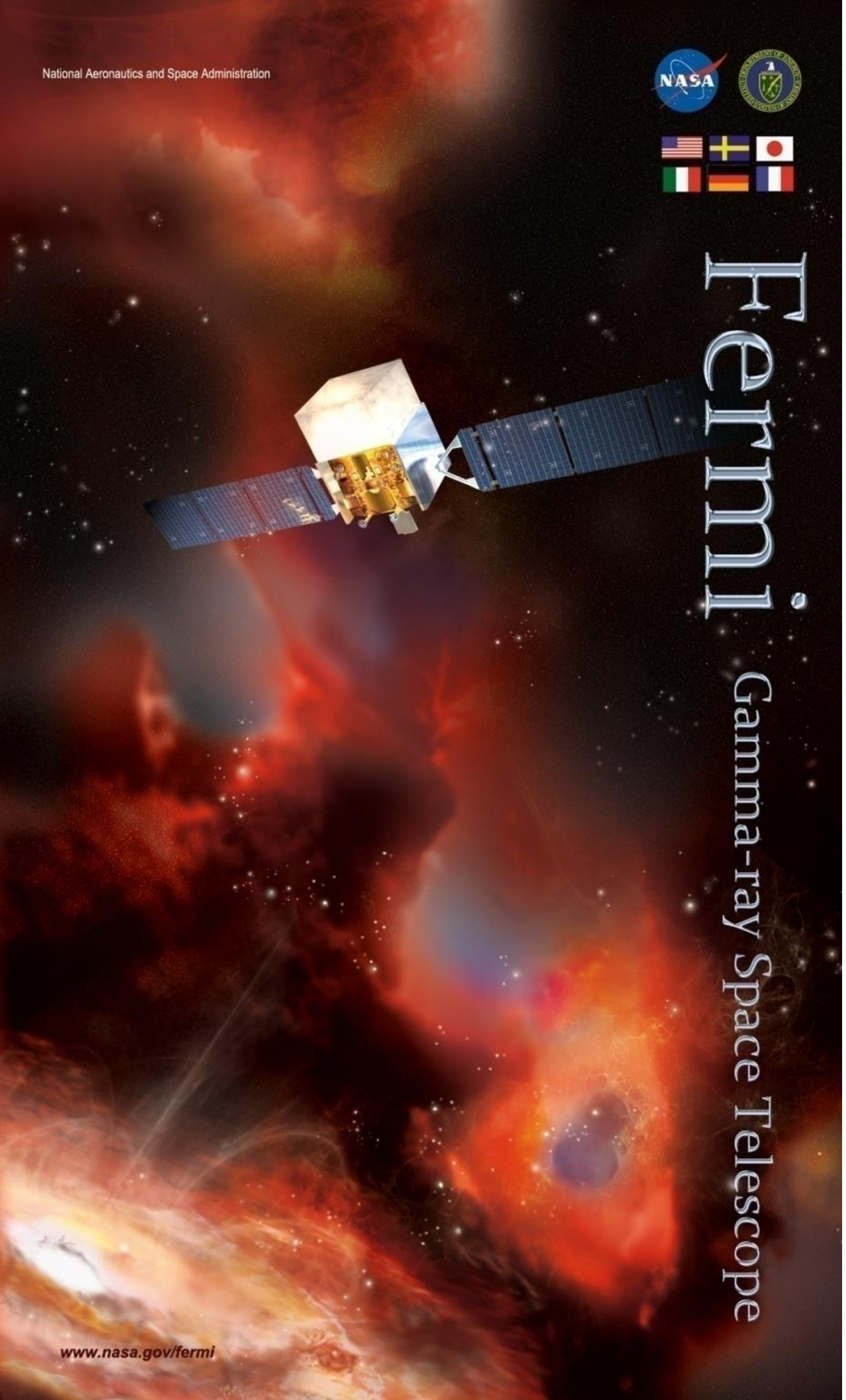

Measurement of the cosmic-ray electron and positron spectrum and anisotropies with the Fermi LAT

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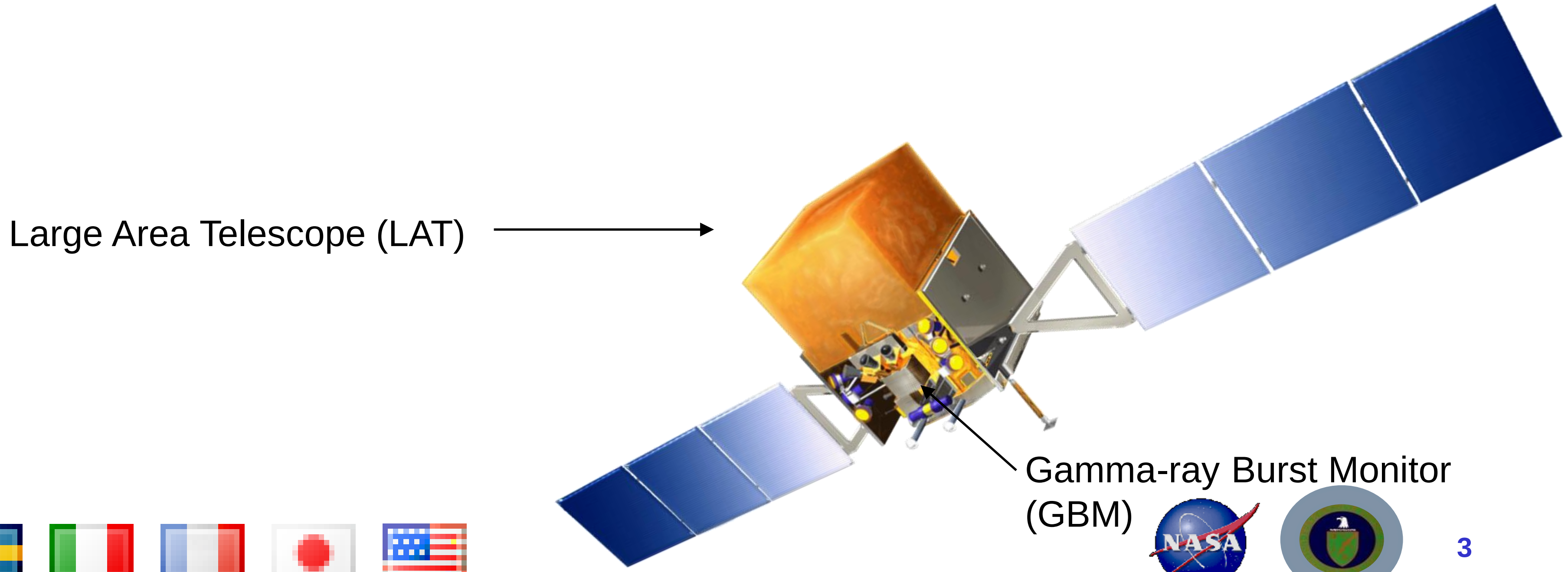
on behalf of the Fermi LAT Collaboration

The Fermi mission

- **Launched by NASA on 2008 June 11, from Cape Canaveral, Florida**
  - **Almost circular orbit, at 565 km altitude and 25.6° inclination**
- **Science mission started on August 2008**
- **Mission extended until 2018 after the NASA Senior Review in 2016**

The Fermi satellite

- **The Fermi Gamma-Ray Space Telescope is an international Science Mission exploring the gamma-ray sky by means of its two main instruments:**
  - **Gamma-ray Burst Monitor (GBM): 8 keV → 40 MeV**
  - **Large Area Telescope (LAT): 20 MeV → > 300 GeV**
- **Huge energy range: including largely unexplored band for a total of >7 energy decades!**



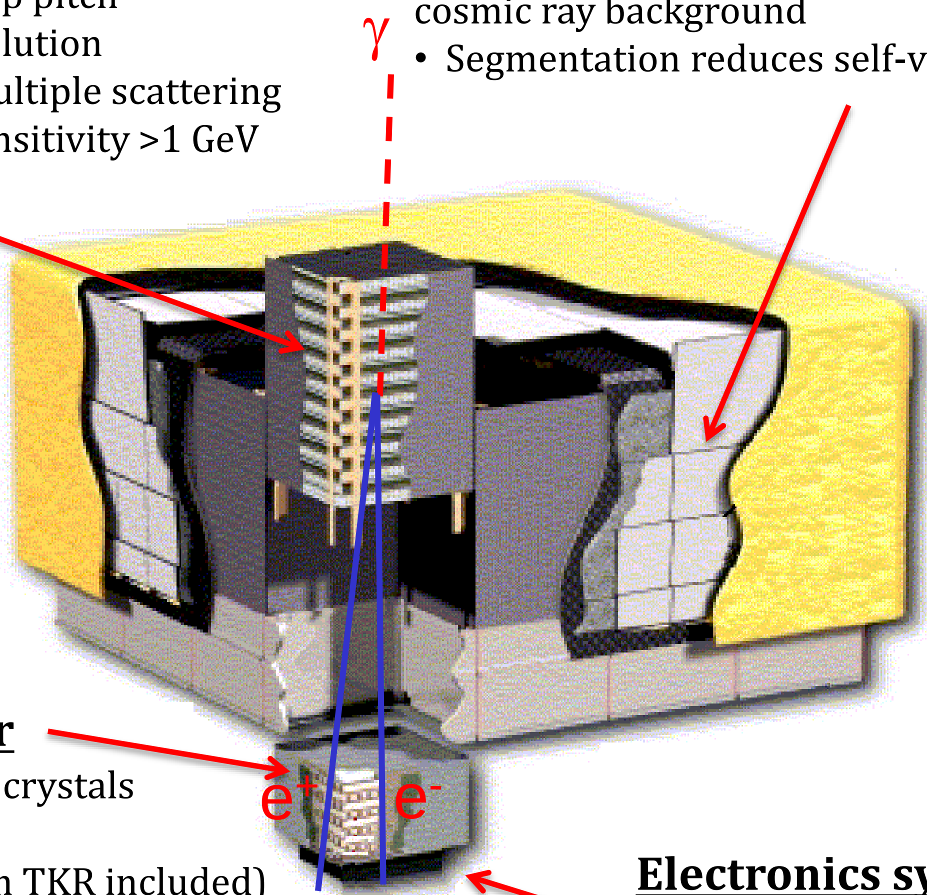
The Fermi LAT

Precision Si-strip Tracker (TKR)

- Measures incident γ-ray direction
- 18 XY tracking planes: 228 μm strip pitch
- High efficiency. Good position resolution
- 12x 0.03 X_0 front end → reduce multiple scattering
- 4x 0.18X_0 back-end → increase sensitivity >1 GeV

Anticoincidence Detector (ACD)

- 89 scintillator tiles
- First step in the reduction of large charged cosmic ray background
- Segmentation reduces self-veto at high energy



Hodoscopic CsI Calorimeter

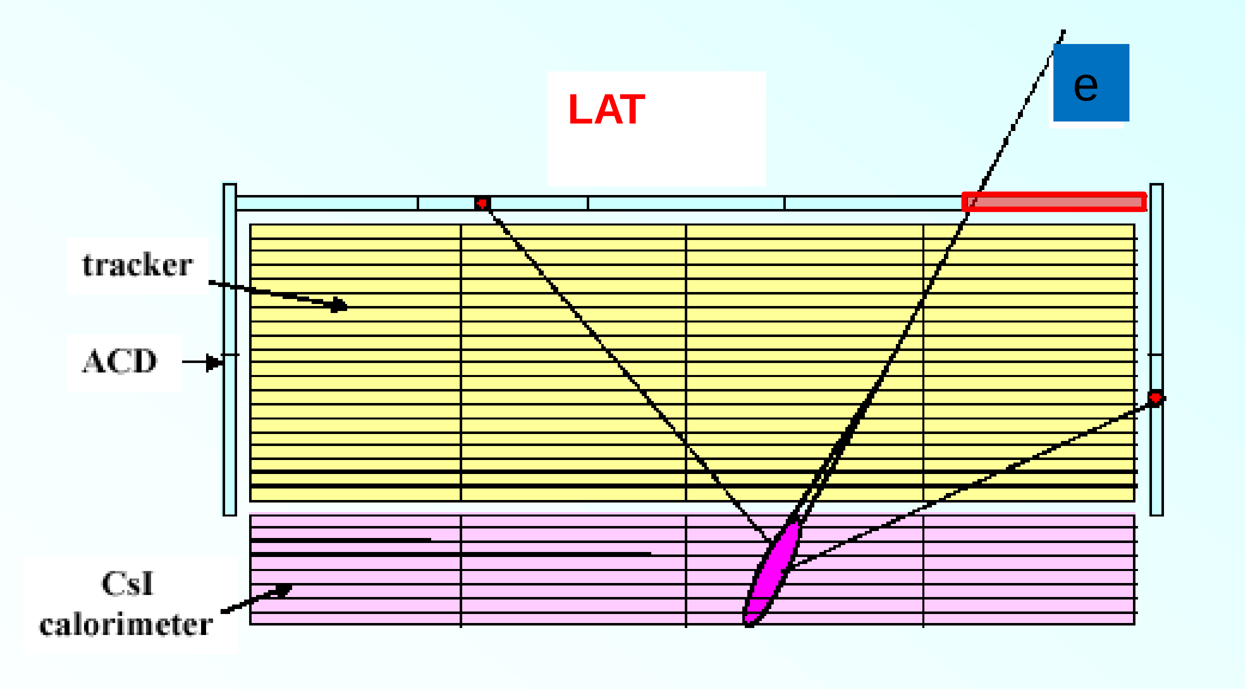
- Segmented array of 1536 CsI(Tl) crystals
- 8.6 X_0: shower max contained
  - ~ 200 GeV normal (1.5X_0 from TKR included)
  - ~ 1TeV @ 40° (CAL-only)
- Measures the incident γ-ray energy
- Rejects cosmic-ray background

Electronics system

- Includes flexible, highly efficient, multi-level trigger

The LAT as an e^+/e^- detector

- **Gamma-ray detection:**
  - **Look for an electromagnetic cascade**
  - **Reject incident charged particles ➔ACD**
- **Electron detection:**
  - **Also an electromagnetic cascade! (removed charge veto, tighten the other cuts)**
  - **The LAT does not distinguish between e^- and e^+, we use the word "electrons" to refer to both**



Onboard trigger and filtering

- Five hardware trigger primitives
  - TKR: 3 x + 3 y tracker planes hit in a row
  - CAL LO: single log with more than 100 MeV
  - CAL HI: single log with more than 1 GeV
  - ROI: MIP signal in a ACD tiles close to a triggering tower
  - CNO: heavy ion signal in the ACD
- Upon L1 trigger the entire detector is read out
- Need onboard filtering to fit the data volume within the allocated bandwidth
  - Gamma
    - Selects γ-ray candidates and events depositing >20 GeV in the CAL
    - High-energy events, including electrons, available for analysis on ground
  - Heavy Ions
    - Selects heavy ion candidates with large energy deposits in the ACD
  - MIP
    - Selects not showering charged particles (protons)
    - Disabled in standard science operations
  - Diagnostic
    - Selects an unbiased event sample for filter and background performance studies
    - The selected sample is prescaled of a factor 250

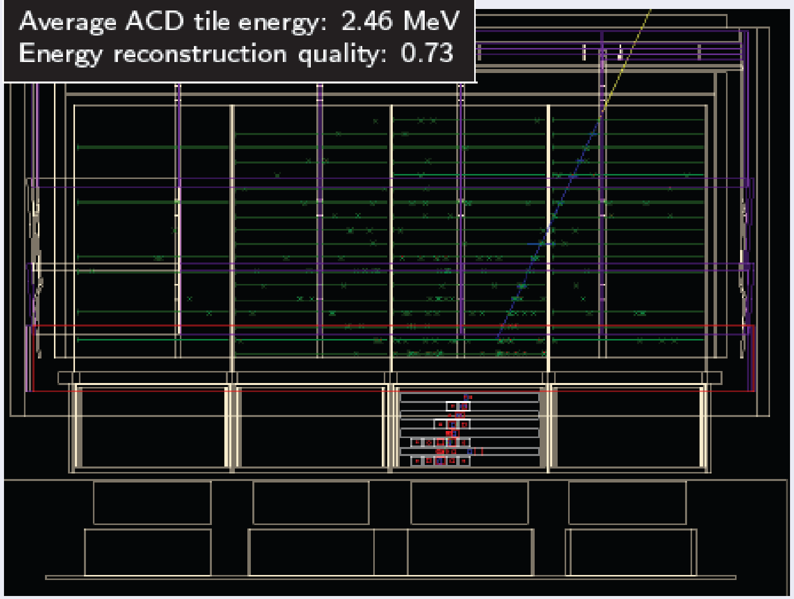
Event selection

- Data sample:
  - Data collected from Aug 4, 2008 to June 24, 2015 (~7 years)
  - ~4.7 years live time
- High-energy analysis (E > 42 GeV)
  - Events selected by the gamma filter
- Low-Energy analysis (7 GeV < E < 70 GeV)
  - Events selected by the diagnostic filter
    - The sample is prescaled by a factor 250
- Pre-cuts:
  - Events with a well reconstructed track
  - Path length through the CAL $>8X_0$
  - Angle of the track with respect to the LAT z-axis $<60^{\circ}$
  - Fit of the shower profile with $\chi^2/n.d.f. < 20$
  - Further cuts on the ACD signal and on the TKR time over threshold
    - These quantities are corrected taking path-length into account
    - Cuts needed to remove the residual contamination from heavy ions
  - Above 42 GeV the residual non-proton background after pre-cuts is negligible
- Further selection made using Boosted Decision Trees (BDTs)
  - Selection is based on topological information
  - BDTs are trained with Monte Carlo simulations

Event topologies: electron vs hadron

Candidate electron
475 GeV raw energy, 834 GeV reconstructed

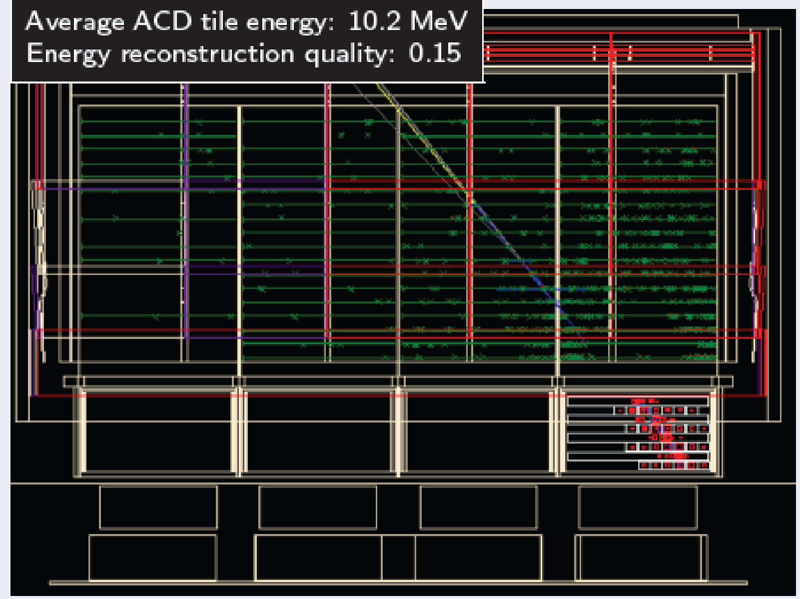
Tranverse shower size: 23.2 mm
Fractional extra clusters: 1.48
Average ACD tile energy: 2.46 MeV
Energy reconstruction quality: 0.73



- Well defined (not fully contained) symmetric shower in the calorimeter.
- 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.

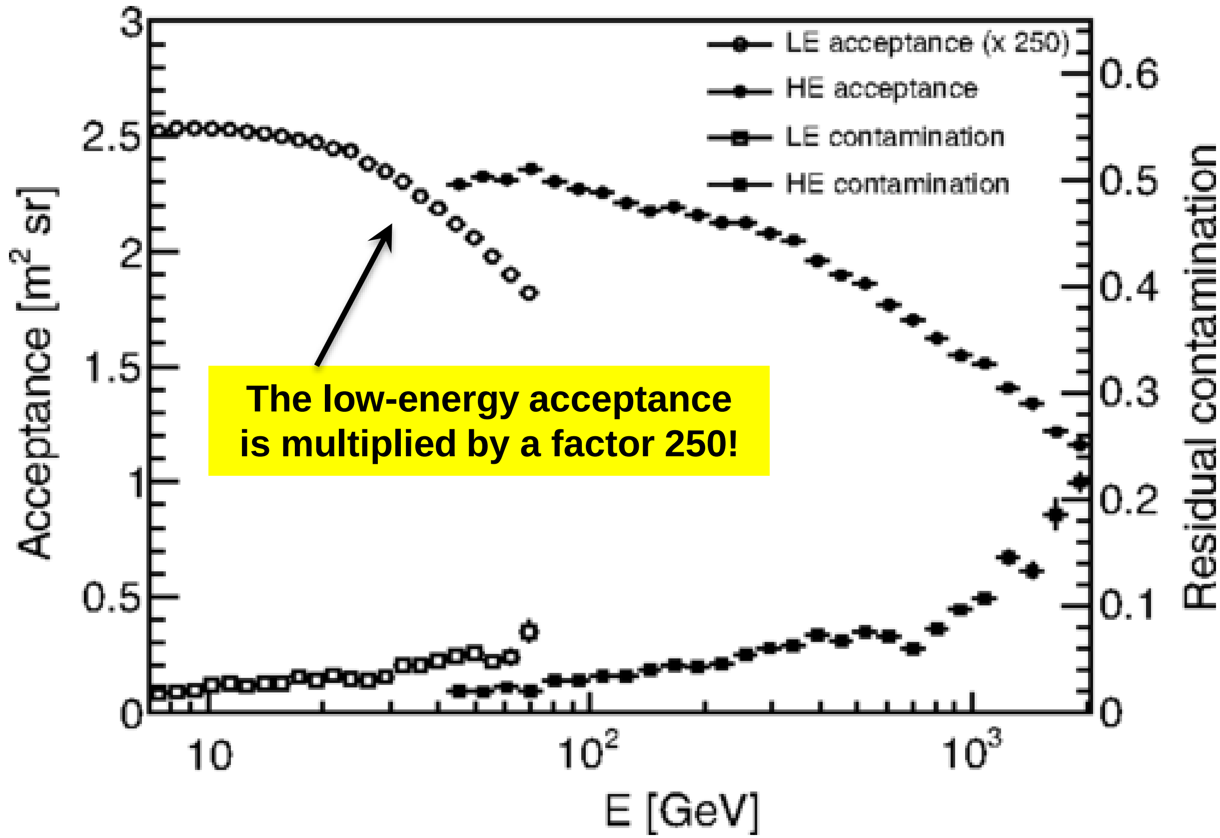
Candidate hadron
823 GeV raw energy, 1 TeV reconstructed

Tranverse shower size: 34.4 mm
Fractional extra clusters: 0.17
Average ACD tile energy: 10.2 MeV
Energy reconstruction quality: 0.15



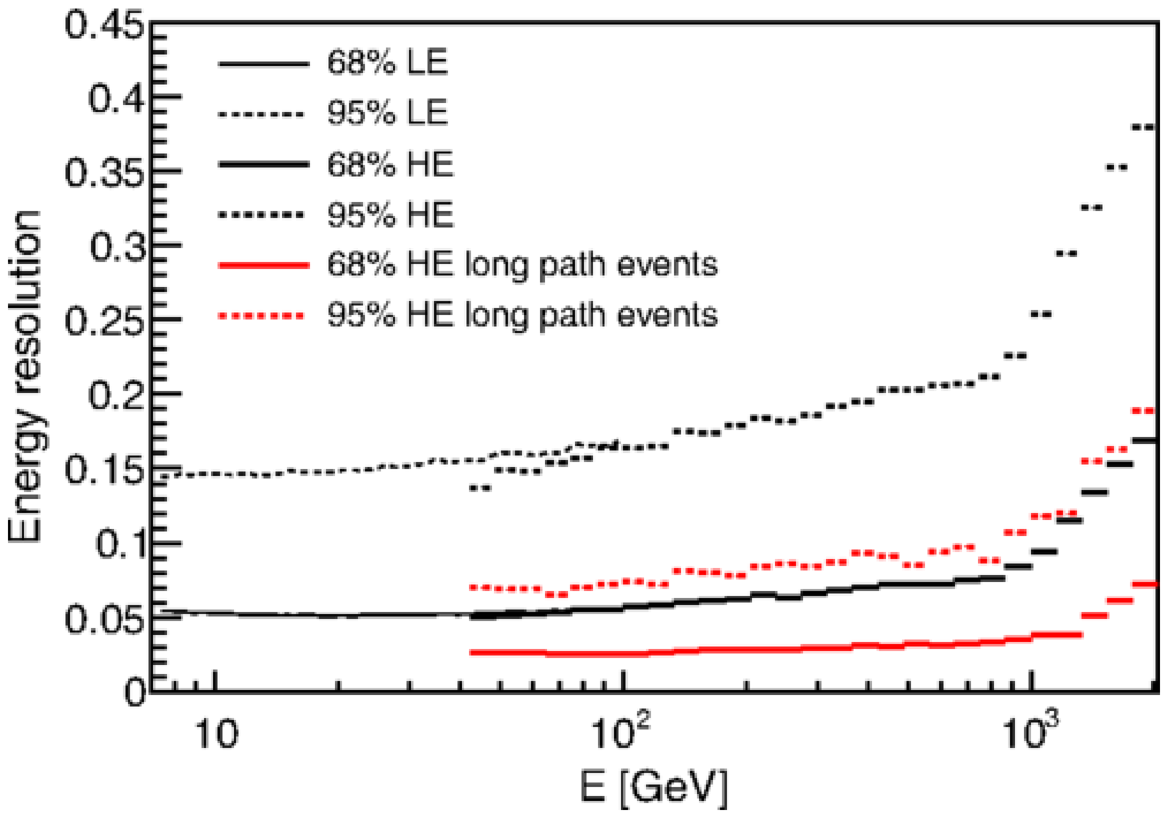
- Large and asymmetric shower profile in the calorimeter.
- Small number of extra clusters around main track, many clusters away from the track.
- Different backsplash topology, large energy deposit per ACD tile.

Acceptance and contamination



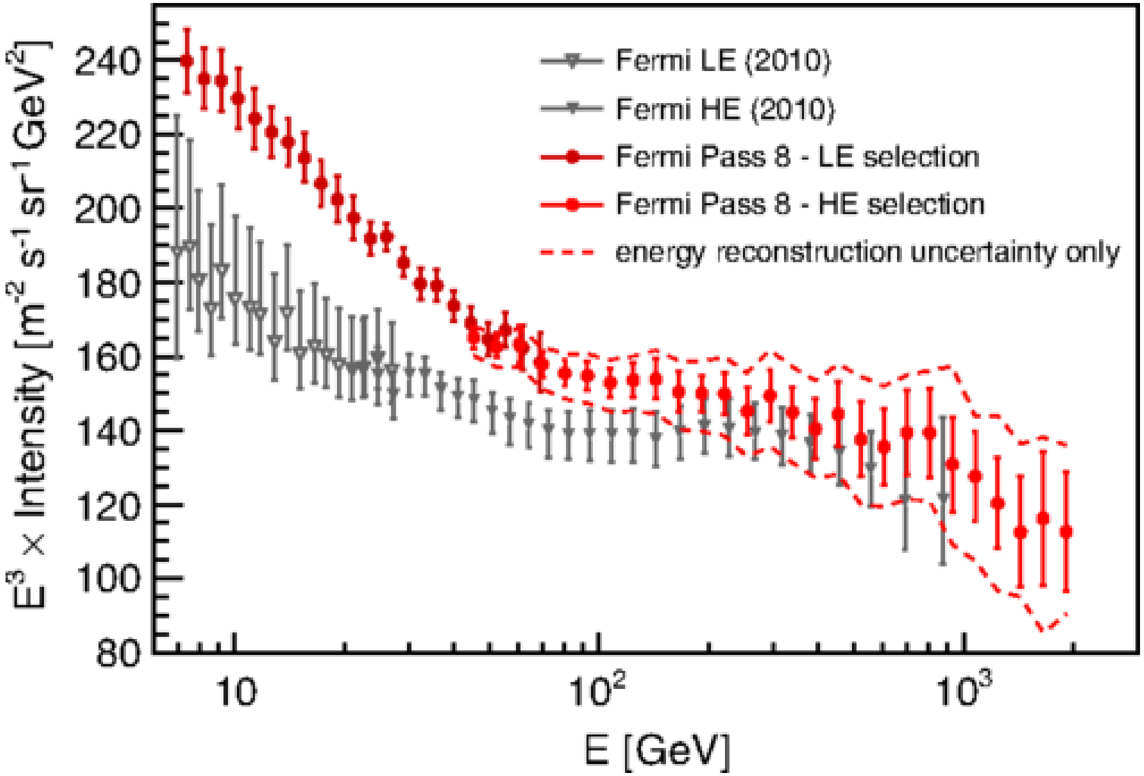
- For the high-energy analysis a pure proton MC background sample is used
- For the low-energy analysis the MC background sample consists of charged cosmic rays (both primaries and secondaries) and Earth limb photons

Energy resolution



- **Long path events are events with path length > 12 X_0 in the CAL**
  - **They correspond to ~15% of the dataset**
  - **These events are used to check systematics on the energy measurement**

The CRE energy spectrum



Differences up to 30% wrt previous results:

- **Below 30 GeV the previous analysis did not take into account the loss of CREs due to the geomagnetic field**
- **The previous analysis did not include "ghost events" in the MC simulation**

- **The spectrum is well fitted by a broken power law:**
  - **Break energy: 53±8 GeV**
  - **Spectral index below the break: 3.21±0.02**
  - **Spectral index above the break: 3.07±0.02**
- **An exponential cutoff lower than 1.8 TeV is excluded at 95% CL**

Search for anisotropies in the CRE arrival directions

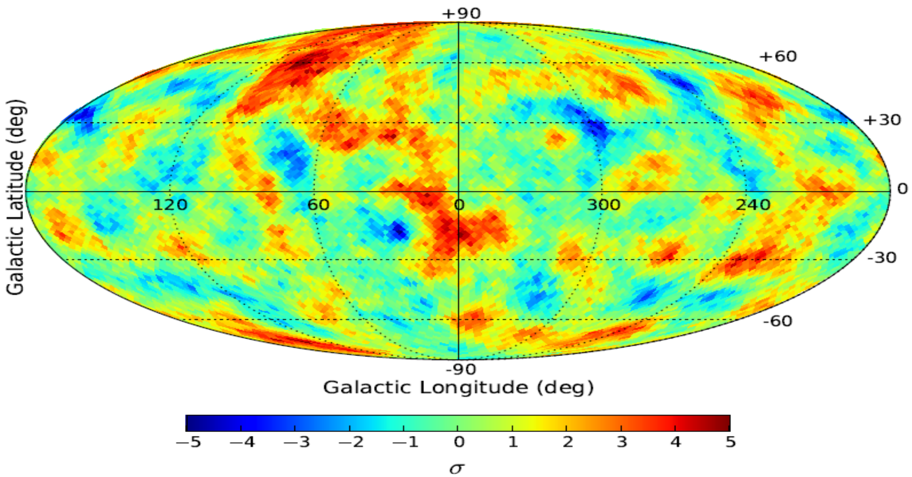
- The search is performed using the high-energy data sample
  - 9 energy bins between 42 GeV and 2 TeV
  - Energy dependent field of view to avoid distortions in the distribution of CRE arrival directions due to geomagnetic effects
- The observed sky map in each energy bin is compared with a reference (isotropic) sky map:
  - Direct pixel-to-pixel comparison
  - Comparison of integrated count maps
    - Each pixel is assigned the counts of all pixels within a circular region of given integration radius centered on the given pixel
    - Are used to search for anisotropies of the same angular scale as the integration radius
    - The counts in different pixels are correlated!
  - Spherical harmonic analysis of fluctuation maps
    - The auto-angular power spectra (APS) are evaluated
    - Each multipole coefficient C_l is sensitive to anisotropies at an angular scale $\sim 180°/l$
- The reference sky maps are built starting from observed data
  - The comparison of the actual sky maps with the reference sky maps avoids features which could arise from the calculation of the exposures

The reference maps

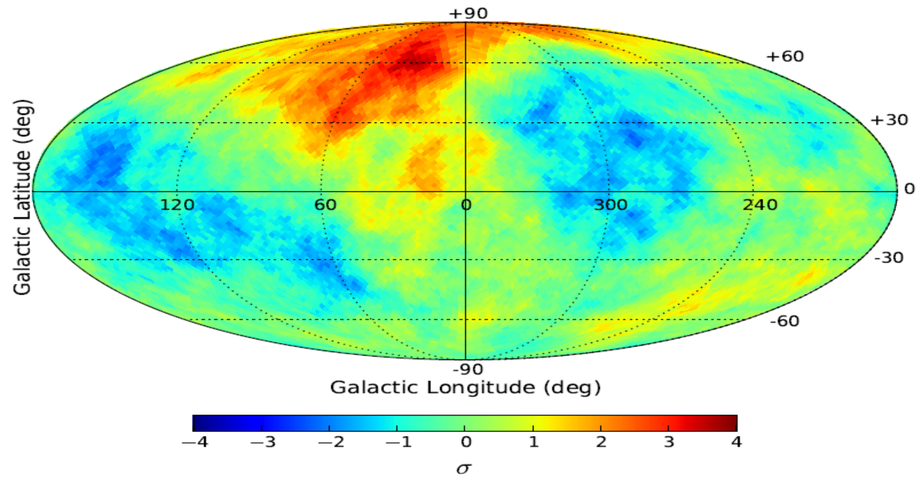
- **Two methods implemented to build the reference sky maps:**
  - **Method 1 ("shuffling" technique)**
    - **Event times taken from observed events**
    - **Event directions in the LAT taken from observed events**
  - **Method 2 ("event rate" technique)**
    - **Event times generated from an exponential distribution with the same average rate as in real data**
    - **Event directions in the LAT generated from the observed distribution $P(\vartheta, \varphi)$**
- **These methods have been validated with dedicated MC simulations**

Significance for integrated sky maps

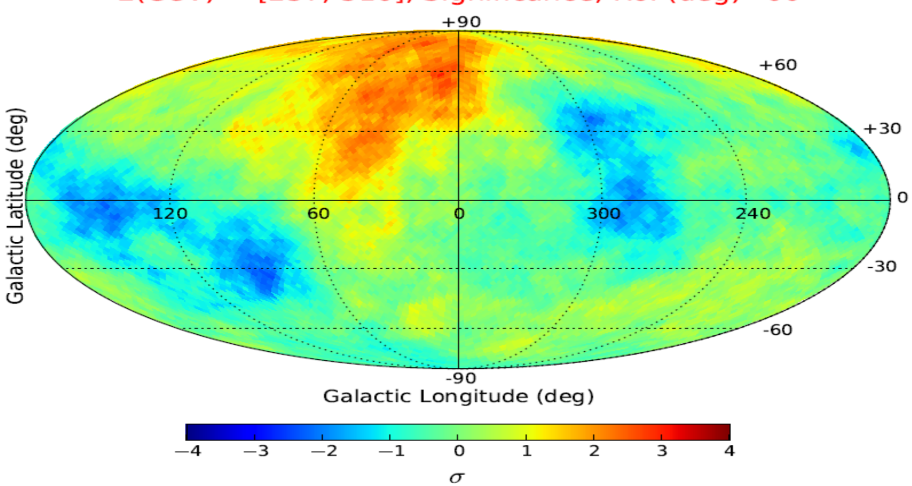
E(GeV) = [237, 316], Significance, RoI (deg)=10



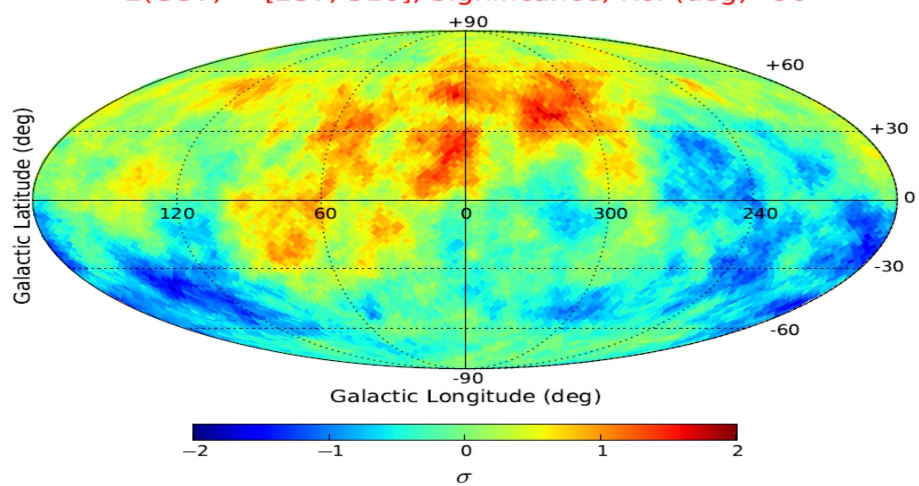
E(GeV) = [237, 316], Significance, RoI (deg)=45



E(GeV) = [237, 316], Significance, RoI (deg)=60

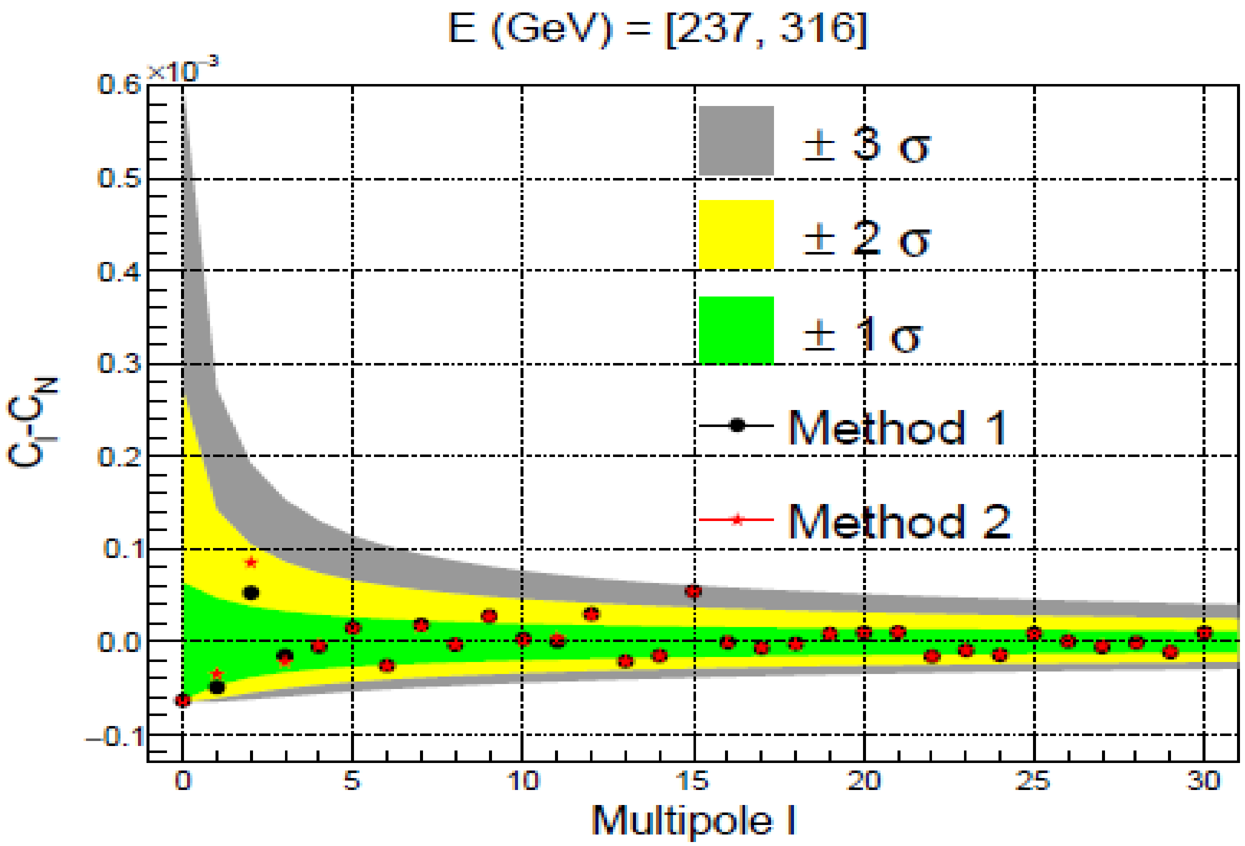


E(GeV) = [237, 316], Significance, RoI (deg)=90



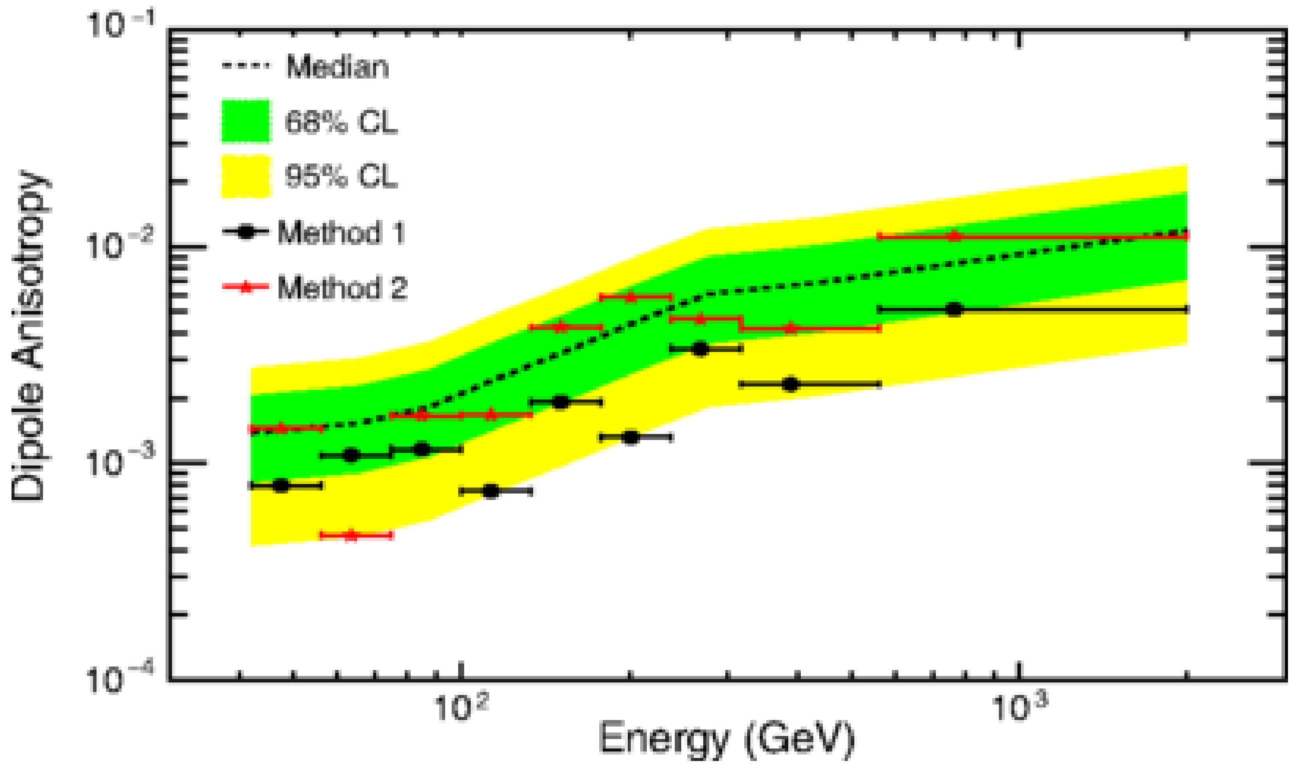
Significances shown in these plots are pre-trials!

Angular power spectra (APS)



- **The measured APS are consistent with the white noise APS in all the energy bins**

Dipole anisotropy

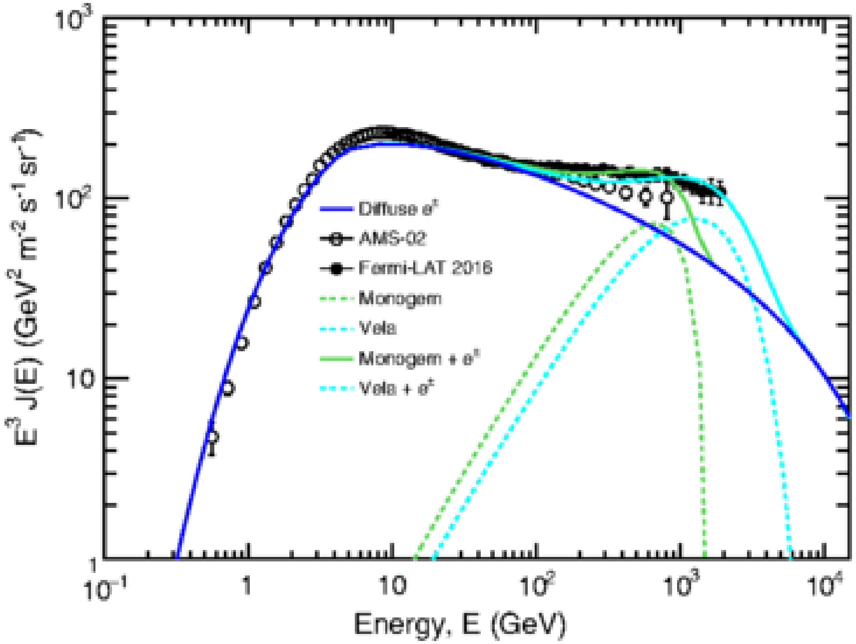


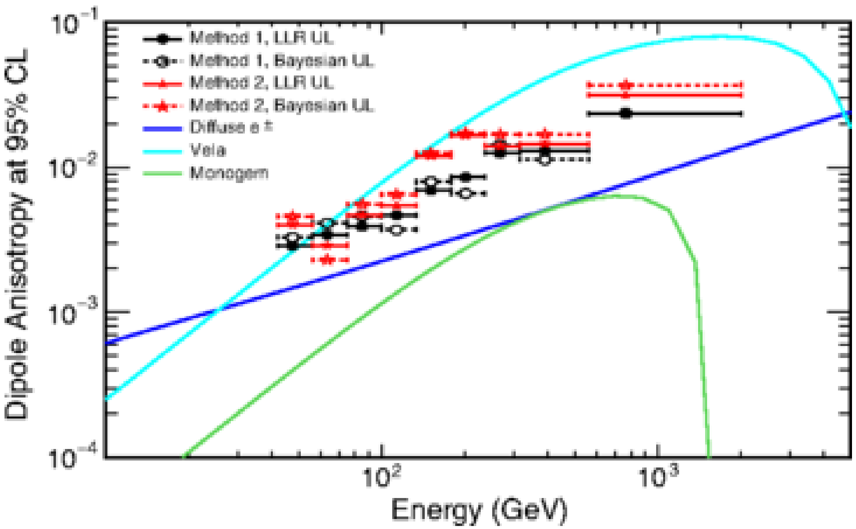
- **The dipole anisotropy is evaluated from the multipole coefficient C_1 of the APS:**

$$\delta = 3\sqrt{C_1/4\pi}$$

- **The measured values are consistent with those expected in the isotropic case**
- **Upper limits on C_1 are converted into upper limits on δ**

Interpretation of the results





- **The CRE spectrum can be reproduced assuming the presence of an additional high-energy source**
- **The Galactic CRE component is evaluated using a simulation based on the DRAGON propagation code**
- **We have evaluated the contributions from two possible sources:**
  - **Vela (d=290pc, T=10^4 yrs)**
  - **Monogem (d=300pc, T=10^5 yrs)**
  - **The injected luminosity of each source is such that the total flux is not higher than the one measured by the Fermi-LAT and AMS-02**
  - **The injection spectrum of both sources is a power law with spectral index 1.7 and cut-off energy at 1.1 TeV**
- **The anisotropy limits disfavor a scenario with a nearby young source**

Conclusions

- The Fermi LAT has measured the energy spectrum of CREs in the range 7 GeV – 2 TeV
  - The spectrum is well fitted by a broken power law with break at ~50 GeV and spectral index of 3.07 above 50 GeV
  - An exponential cutoff lower than 1.8 TeV is excluded at 95% CL
- A search for possible anisotropies in the arrival directions of CREs in the energy range 42 GeV – 2 TeV has been performed
  - No anisotropies detected
  - Upper limits on the dipole anisotropy <1% in the whole energy range
  - The constraints on the anisotropy data can probe the presence of nearby young or middle-aged CRE sources
- For further details:
  - S. Abdollahi et al., Phys. Rev. D 95, 082007 (2017)
  - S. Abdollahi et al., Phys. Rev.Lett. 118, 091003 (2017)