

Preliminary indirect measurement of cosmic-ray proton spectrum using Earth's γ -ray data from *Fermi* Large Area Telescope

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Overview

1 Introduction

- Background
- Objectives
- Schematics of the Earth's γ -ray production

2 Flux extraction

- Data set
- Flux calculation

3 Analysis

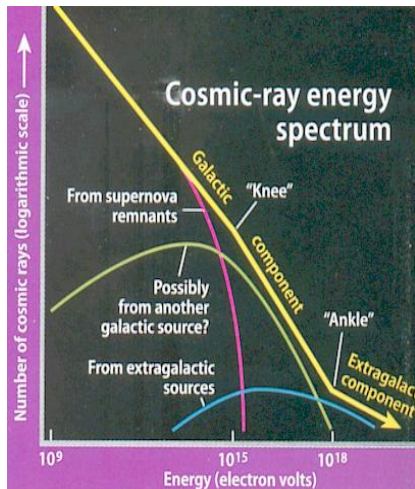
- Power-law spectrum
- Kachelrie β and Ostapchenko proton-proton $\rightarrow \gamma$ model
- Optimization

4 Results

5 Future work

6 Reference

What are CRs



- High energy particles in space
- **Criteria** : Here "flux" means differential flux
- **Feature** : CR rigidity spectrum can be described well by power-law
- Changes of power-law indices may come from superposition of different acceleration mechanisms

Figure: CR spectral: figure from universe-review.ca

Previous study

- In 2012, PAMELA claimed to discover a break in CR proton spectrum at around 300 GV.
- In 2014, *Fermi* LAT found some hint of this break though the results were inconclusive.
- In 2015, the AMS-02 confirmed this break.

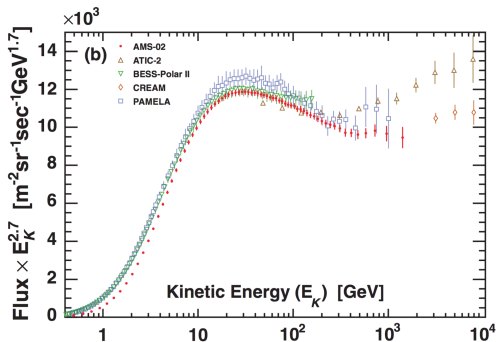
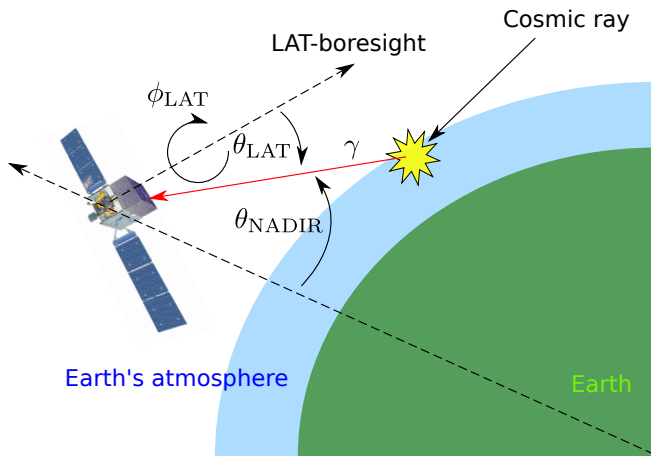


Figure: CR proton flux from Aguilar, et al., (2015)

Objective

- To measure CR proton spectrum between 60 GV - 2 TV using Earth's γ -ray data from *Fermi*-LAT through Kachelrie β and Ostapchenko model
- To test if we can use Fermi LAT data to confirm the spectral break at around 340 GV as observed by some experiments

Schematics of the Earth's γ -ray production



- P8R2_ULTRACLEANVETO_V6 data from 07/08/2008 to 17/10/2017 (~ 9 years)
- Photon energy range from 10 GeV up to 1 TeV
- $\theta_{\text{NADIR}} \in 68.4^\circ - 70^\circ$ (Earth's limb)
- Use $\theta_{\text{LAT}} < 70^\circ$

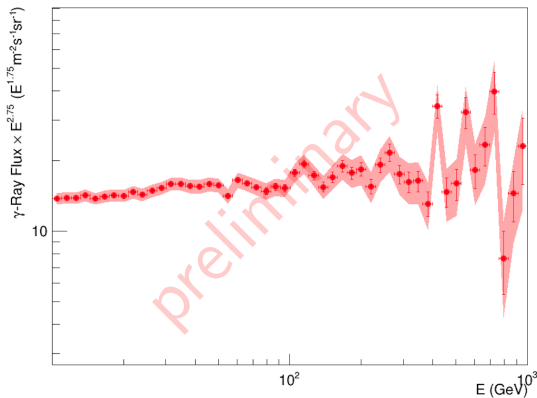
Flux calculation method

- 1 Make 2D histograms with 25 bins per decade of energy
- 2 Select photon data and fill in the 2D histograms
- 3 Calculate exposure maps which include the effective area and livetime of the LAT as it observed the Earth

$$\mathbf{Flux} \equiv \frac{dN_{\gamma}}{dE} = \frac{\int_{\text{Limb region}} (\text{Count map/Exposure map})}{\Delta\Omega\Delta E} \quad (1)$$

where $\Delta\Omega$ is the solid angle of the Earth's limb region and ΔE is the energy bin width

Earth's limb γ -ray spectrum from measurement



- Error bars show statistical uncertainties and red bands show total (statistical + systematic) uncertainties
- The amount of data in this work is about 2 times greater than previously published analysis by the LAT

Power-law models (in rigidity)

We use 2 models of CR proton to fit the γ -ray data:

Single power law (SPL)

$$\frac{dN}{dR} = R_0 R^{-\gamma} \quad (2)$$

Broken power law (BPL)

$$\frac{dN}{dR} = \begin{cases} R_0 R^{-\gamma_1} & : E < E_{\text{Break}} \\ R_0 [R(E_{\text{Break}})]^{\gamma_2 - \gamma_1} R^{-\gamma_2} & : E \geq E_{\text{Break}} \end{cases} \quad (3)$$

Rigidity is defined by $R \equiv P/q$ where P is the momentum and q is the absolute value of the charge (in unit of proton charge) of a particle

Kachelrieß and Ostapchenko model

This model can compute the γ -ray spectrum from a broad and smooth power-law spectrum of CR protons

$$\frac{dN_\gamma}{dE} \propto \sum_{E_{\text{inc},i}} \left[\frac{E_{\text{inc},i}}{E_{\gamma,i}} \Delta(E_{\text{inc},i}) \right] \left[f_{pp} \frac{dN_H}{dE_{\text{inc},i}} \left\{ 1 + \frac{\sigma_{\text{He}N}}{\sigma_{pN}} \left(\frac{dN_H}{dR} \right)^{-1} \frac{dN_{\text{He}}}{dR} \frac{dR_{\text{He}}}{dR_H} \right\} \right] \quad (4)$$

- Red color terms are for **incident proton spectrum**
- Blue color term is the He spectrum from AMS-02 (2015)
- $f_{pp} \equiv E_\gamma (d\sigma^{pp \rightarrow \gamma} / dE_\gamma)$ is the interaction cross section table in the K&O model
- The cross-section ratio $\sigma_{\text{He}N} / \sigma_{pN}$ at high energy ($> 10\text{GeV}$) is roughly constant (≈ 1.6)¹

¹T. W. Atwater (2015)

Poisson likelihood function

We determine the incident proton spectrum that best fits the γ -ray measurement using the maximum likelihood (or minimum log likelihood) method

$$\log \mathcal{L} \equiv \sum_{i=1}^N -\log P_{\text{pois}}(n_{i,\text{model}}, n_{i,\text{measurement}}) \quad (5)$$

where P_{pois} is the Poisson probability of measuring $n_{i,\text{measurement}}$ counts when the model predicts $n_{i,\text{model}}$ counts for N energy bins

Fitting algorithm: Particle Swarm Optimization

- Randomly initiate many particles in a given range of the parameter space
- Check global and local best particle from a defined profit function
- Rest of them move toward the global and local particles
- Iterate the process until most of them yield nearly the same profit

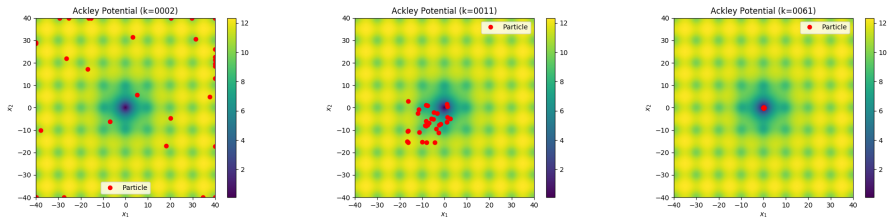


Figure: Example of particles in parameter space of Ackley potential

Particle Swarm Optimization

For every iteration k , particle i move with velocity v_k^i where

$$v_{k+1}^i = \omega v_k^i + c^b r_k^b [b_k^i - x_k^i] + c^B r_k^B [B_k^i - x_k^i] \quad (6)$$

Update the new state of particle i with

$$x_{k+1}^i = x_k^i + v_{k+1}^i \quad (7)$$

where

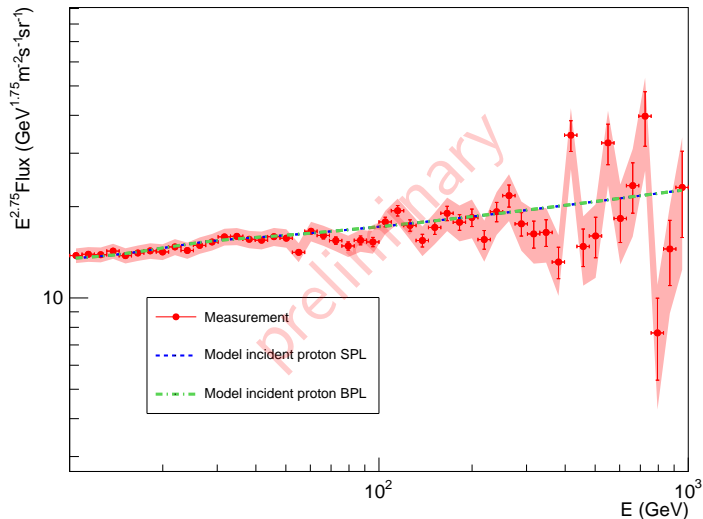
- x_k^i represent variable that particle i hold
- b and B are best local and global parameter sets along the optimization process
- Set $\omega = 0.2$, $c^b = 0.2$ and $c^B = 0.3$

The iteration process would stop when standard deviation of fitness over any particle less than 0.1

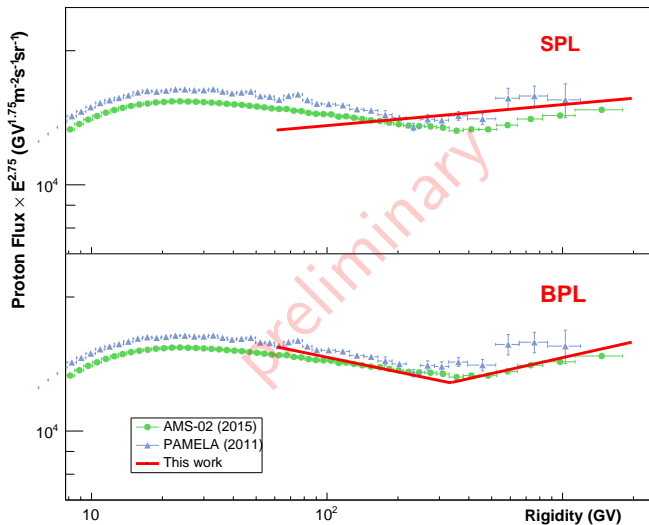
Best fits	γ_1	γ_2	E_{Break} (GeV)
SPL model of CR proton	2.70	-	-
BPL model of CR proton	2.86	2.63	333

Table: Optimization results

Earth's limb γ -ray spectra from best-fit models



Proton spectrum



The normalization of this work is fitted PAMELA data

- Calculate the errors of the fitted parameters for both the SPL and BPL models of CR proton spectrum
- Determine if the BPL model of CR proton spectrum fits the γ -ray data significantly better than the SPL model does

- [1] O. Adriani et al., Science 332, 69 (2011)
- [2] M. Ackermann et al. (*Fermi* LAT Collaboration), Phys. Rev. Lett. 112, 151103 (2015)
- [3] Kachelriess & Ostapchenko, Phys. Rev. D 86 (2012)
- [4] M. Aguilar et al. (AMS Collaboration), Phys. Rev. Lett. 115, 211101 (2015)
- [5] M. Aguilar et al. (AMS Collaboration), Phys. Rev. Lett. 114, 171103 (2015)

Acknowledgement

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- Development and Promotion of Science and Technology Talents Project (DPST)
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Backup slide

Power law in energy

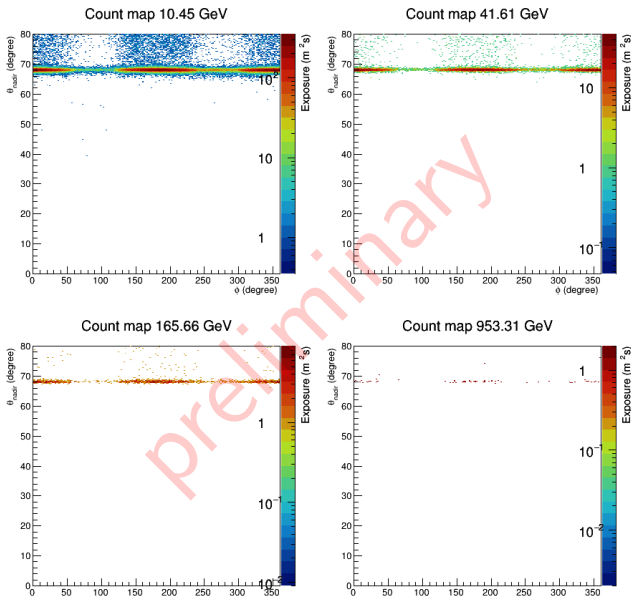
Converting the power law in rigidity to energy, we obtain **Single power law (SPL)**

$$\frac{dN}{dE} = N_0[E_k(E_k + 2m_p)]^{-\gamma/2} \left(\frac{E_k + m_p}{\sqrt{E_k(E_k + 2m_p)}} \right) \quad (8)$$

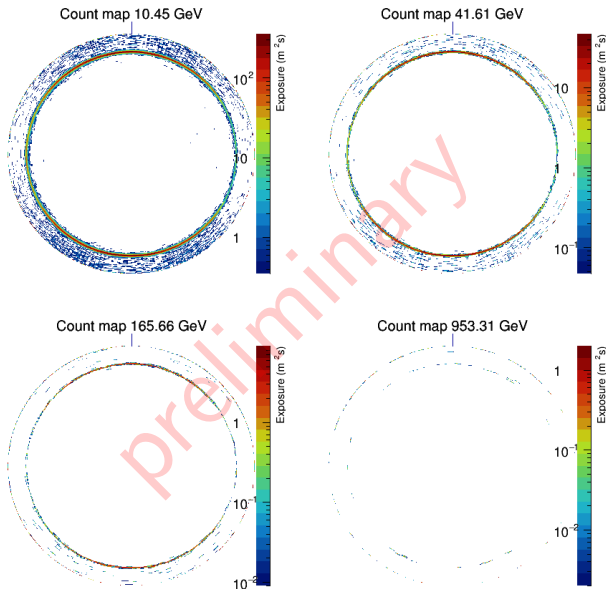
Broken power law (BPL)

$$\frac{dN}{dE} = \begin{cases} N_0[E_k(E_k + 2m_p)]^{-\gamma_1/2} \left(\frac{E_k + m_p}{\sqrt{E_k(E_k + 2m_p)}} \right) & : E < E_{\text{Break}} \\ N_0[E_b(E_b + 2m_p)]^{(\gamma_2 - \gamma_1)/2} [E_k(E_k + 2m_p)]^{-\gamma_2/2} \left(\frac{E_k + m_p}{\sqrt{E_k(E_k + 2m_p)}} \right) & : E \geq E_{\text{Break}} \end{cases} \quad (9)$$

Count map

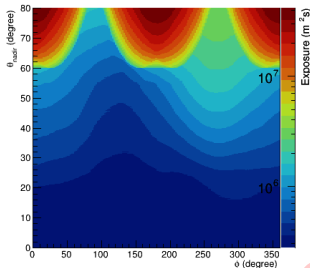


Count maps

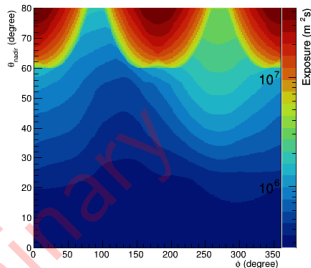


Exposure maps

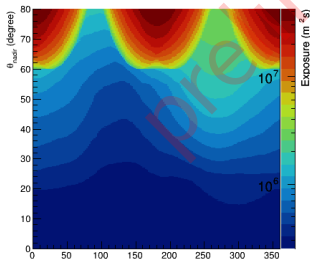
Exposure map 10.45 GeV



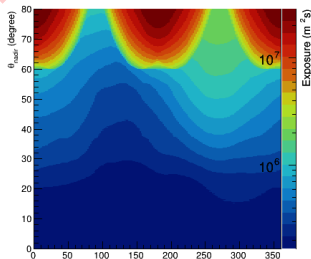
Exposure map 41.61 GeV



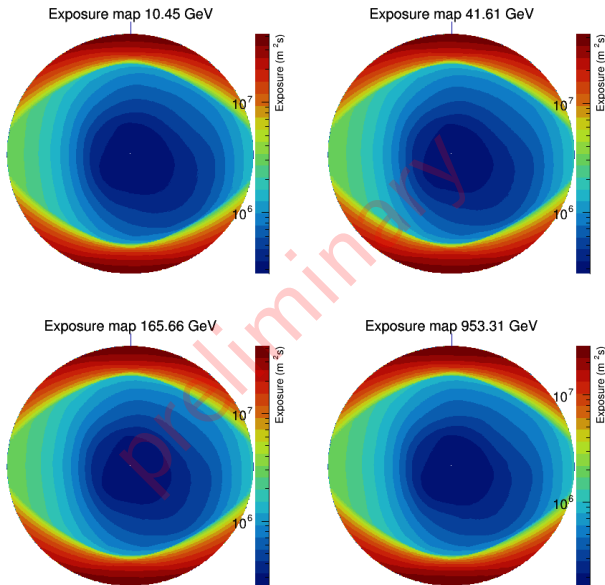
Exposure map 165.66 GeV



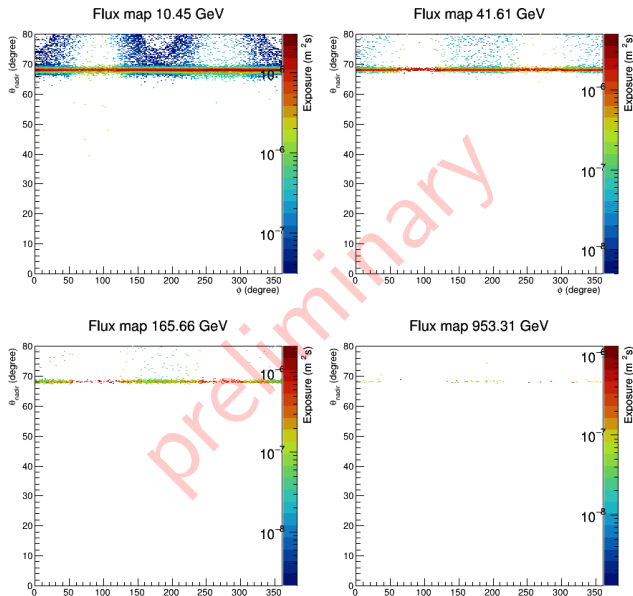
Exposure map 953.31 GeV



Exposure maps



Flux maps



Flux maps

