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

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What are CRs

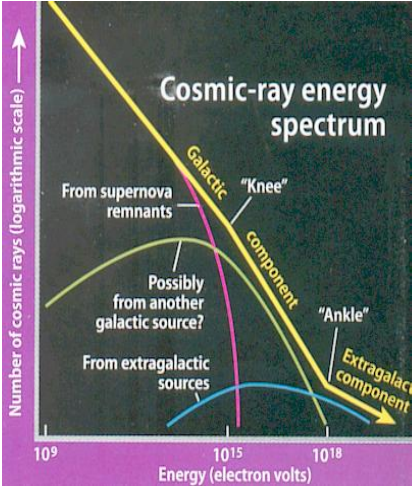


Figure: CR spectral: figure from universe-review.ca

- 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

Previous study

- In 2011, 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 comfirmed this break.

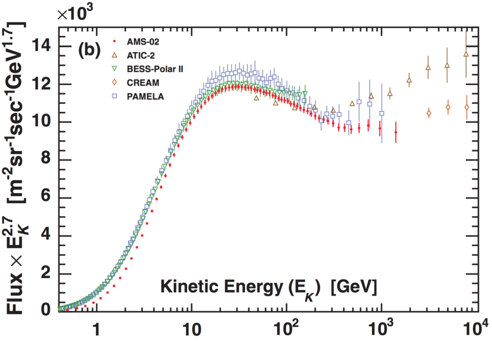
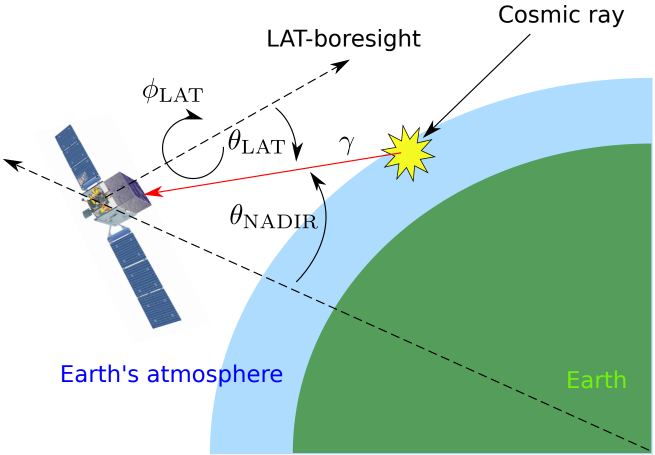


Figure: CR proton flux from Aguilar, et al., (2015)

Objective

- To measure CR proton spectrum between 60 GV - 2 TV using Earth's γ-ray data from *Fermi*-LAT through Kachelrieβ 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



Data selection

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

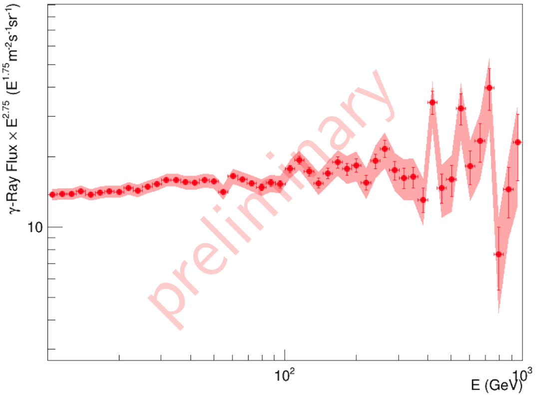
Flux calculation method

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

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

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)

$$\frac{dN}{dR} = R_0 R^{-\gamma} \tag{2}$$

Broken power law (BPL)

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

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

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

$$\frac{dN_\gamma}{dE_\gamma} \propto \sum_{E_i'} \left[\frac{E_i'}{E_\gamma} \Delta(\ln E_i') \right] \left[f_{pp} \frac{dN_p}{dE_i'} \left\{ 1 + \frac{\sigma_{\text{HeN}}}{\sigma pN} \left(\frac{dN_p}{dR} \right)^{-1} \frac{dN_{\text{He}}}{dR} \frac{dR_{\text{He}}}{dR_p} \right\} \right] \tag{4}$$

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

[1] T. W. Atwater (2015)

Poisson likelihood function

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

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

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

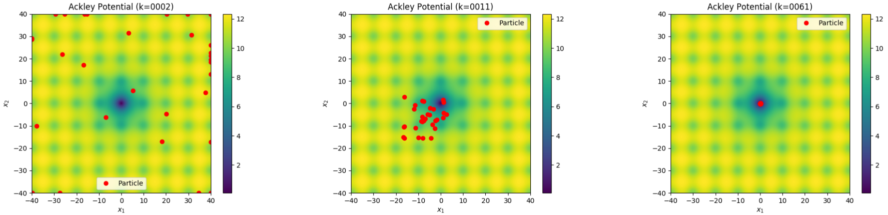


Figure: Example of particles in parameter space of Ackley potential

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 $c^B = 0.3$

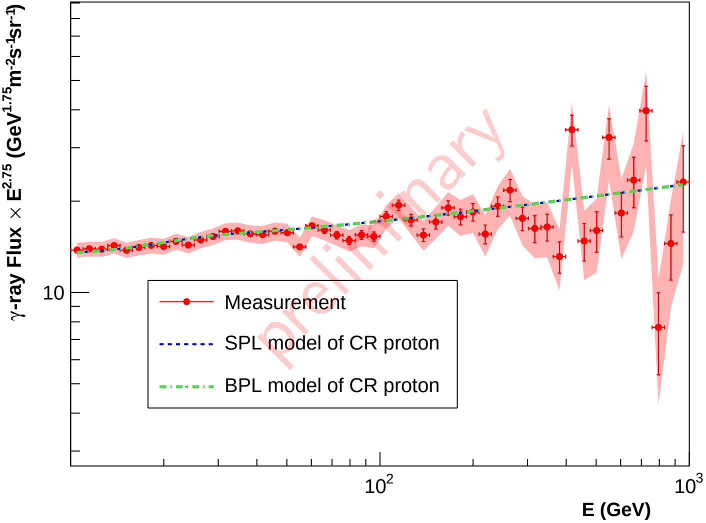
The iteration process would stop when standard deviation of fitness over any partilcle less than 0.1

Results

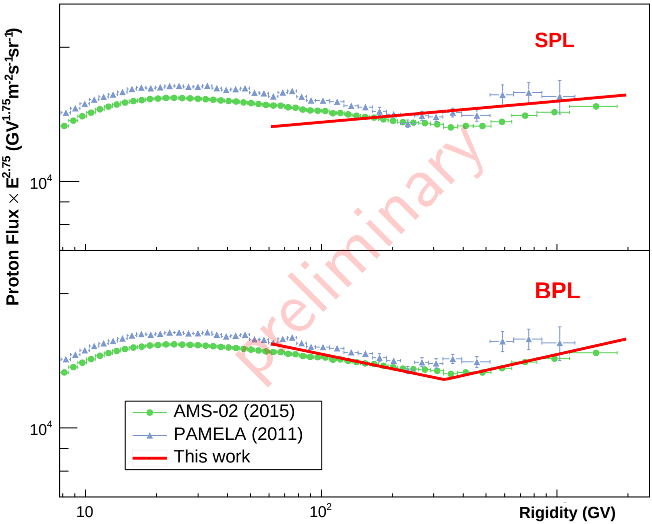
Best fits	γ_1	γ_2	E_{Break} (GeV)
SPL	2.70	-	-
BPL	2.86	2.63	333

Table: Optimization results

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



Proton spectrum



The normalization of this work is fitted AMS-02 data

Future work

- 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

References

[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)

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Backup slide

Power law in energy

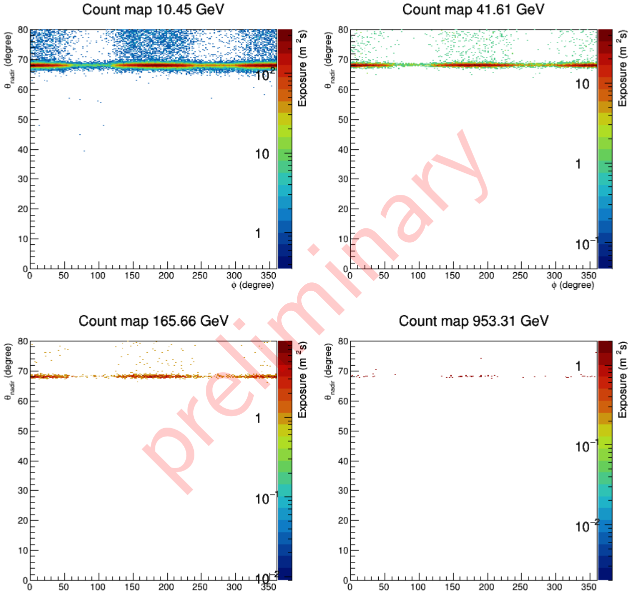
Converting the power law in rigidity to energy, we obtain **Single power law (SPL)**

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

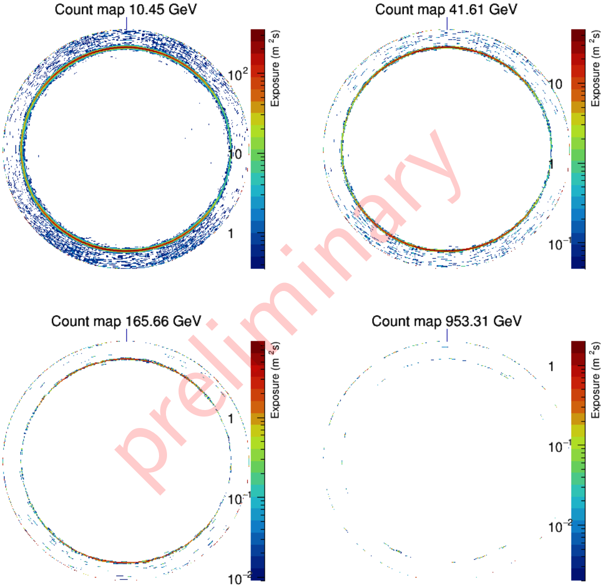
Broken power law (BPL)

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

Count map


Count map 10.45 GeV
Count map 41.61 GeV
Count map 165.66 GeV
Count map 953.31 GeV
θ_{nadir} (degree)
ϕ (degree)
Exposure ($m^2 s$)
preliminary

Count maps



Count map 10.45 GeV
Count map 41.61 GeV
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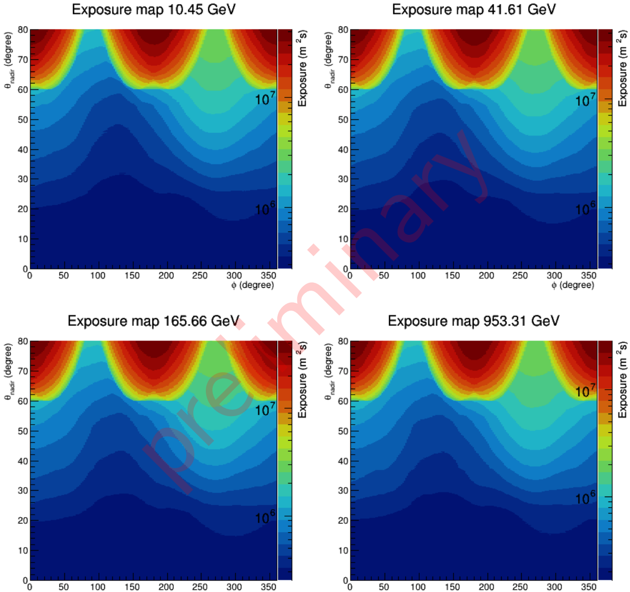
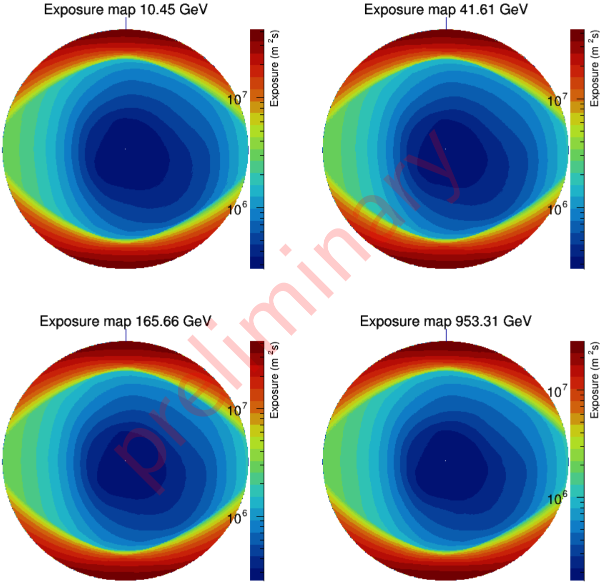
Exposure (m ^{2}s)
preliminary

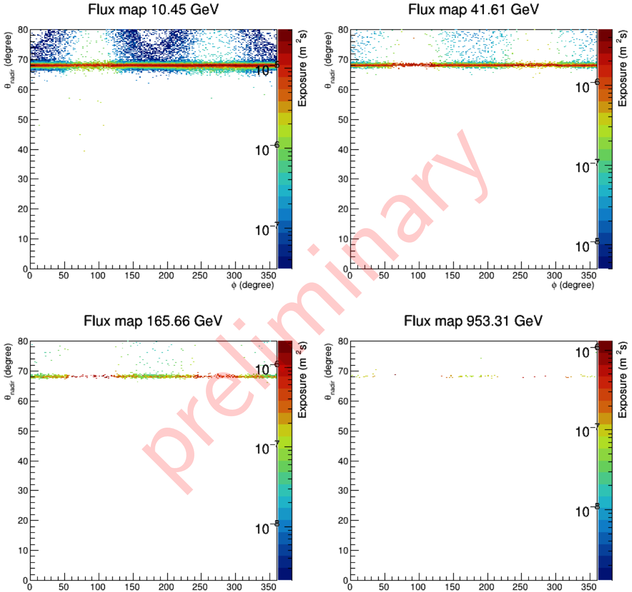
Exposure maps



Exposure maps



Flux maps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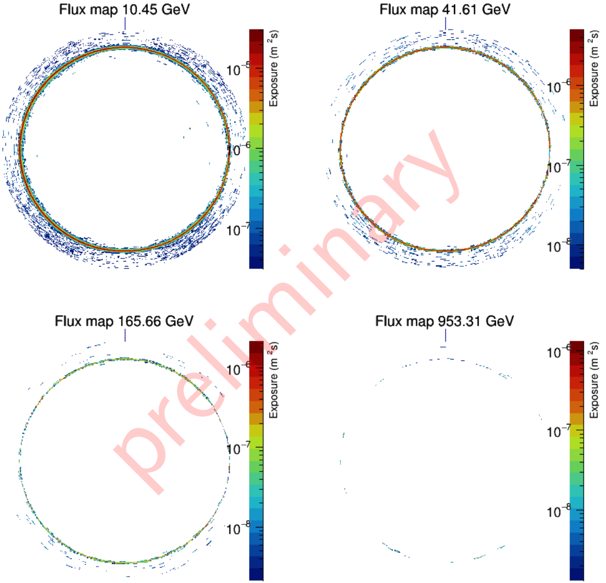

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