

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

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Siam Physics Congress 2020  
June 2020

# Overview

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- Schematics of the Earth's  $\gamma$ -ray production

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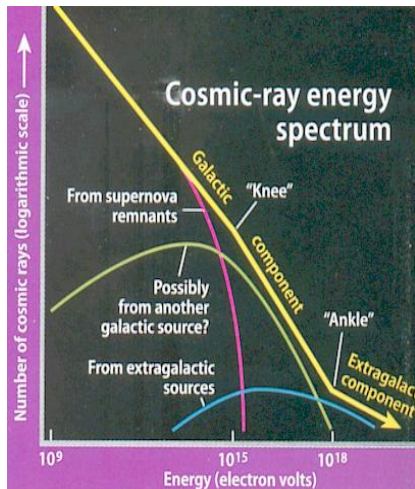
- Power-law spectrum
- Kachelrie $\beta$  and Ostapchenko proton-proton  $\rightarrow \gamma$  model
- Optimization

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# 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 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 confirmed this break.

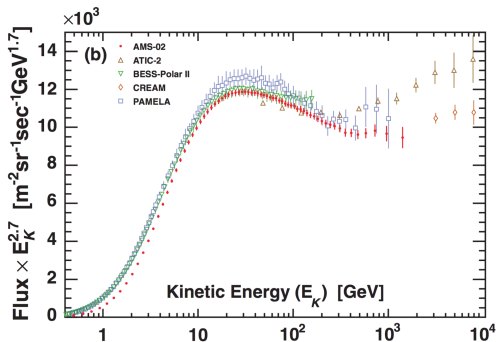
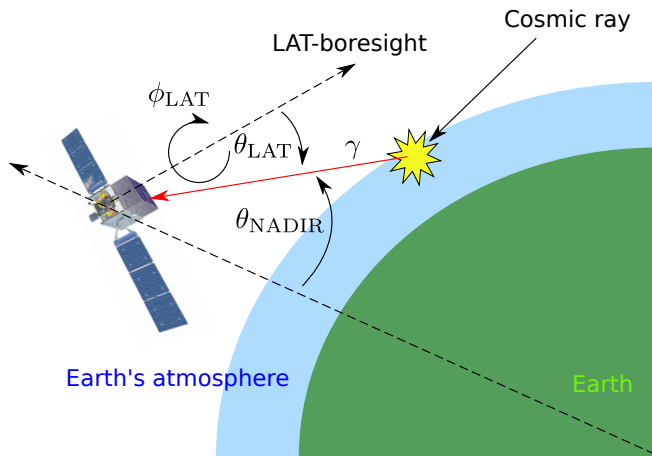


Figure: CR proton flux from Aguilar, et al., (2015)

# Objective

- To measure CR proton spectrum between 60 GV - 2 TV using Earth's  $\gamma$ -ray data from *Fermi*-LAT through Kachelrie $\beta$  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 $\gamma$ -ray production



- 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
- $\theta_{\text{NADIR}} \in 68.4^\circ - 70^\circ$  (Earth's limb)
- Use  $\theta_{\text{LAT}} < 70^\circ$

# Flux calculation method

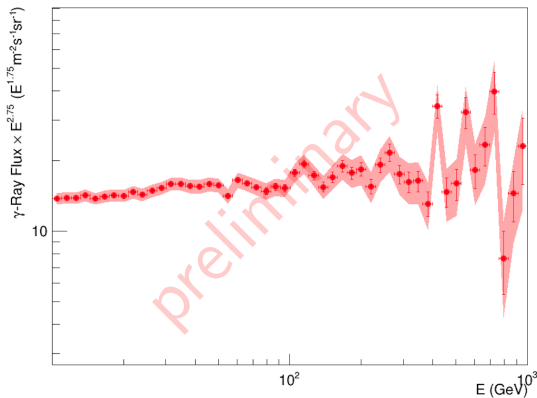
- 1 Make 2D histograms with 25 bins per decade of energy
- 2 Select photon data and fill in the 2D histograms
- 3 Calculate exposure maps which include the effective area and livetime of the LAT as it observed the Earth

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

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



# Earth's limb $\gamma$ -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  $\gamma$ -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  $\gamma$ -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 ( $\approx 1.6$ )<sup>1</sup>

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<sup>1</sup>T. W. Atwater (2015)

# Poisson likelihood function

We determine the incident proton spectrum that best fits the  $\gamma$ -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  $P_{\text{pois}}$  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

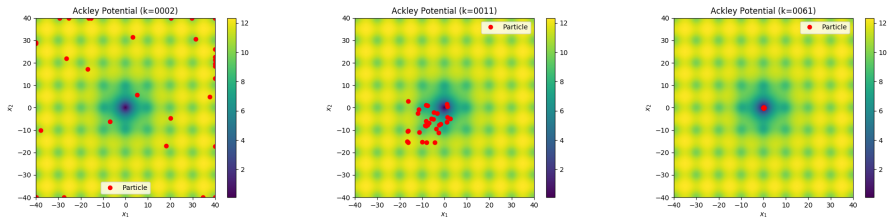


Figure: Example of particles in parameter space of Ackley potential

# 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  $c^B = 0.3$

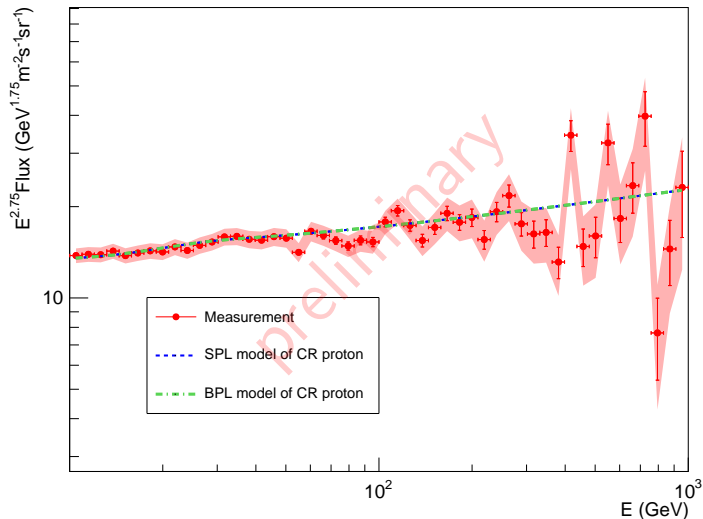
The iteration process would stop when standard deviation of fitness over any particle less than 0.1

# Results

Best fits	$\gamma_1$	$\gamma_2$	$E_{\text{Break}}$ (GeV)
SPL	2.70	-	-
BPL	2.86	2.63	333

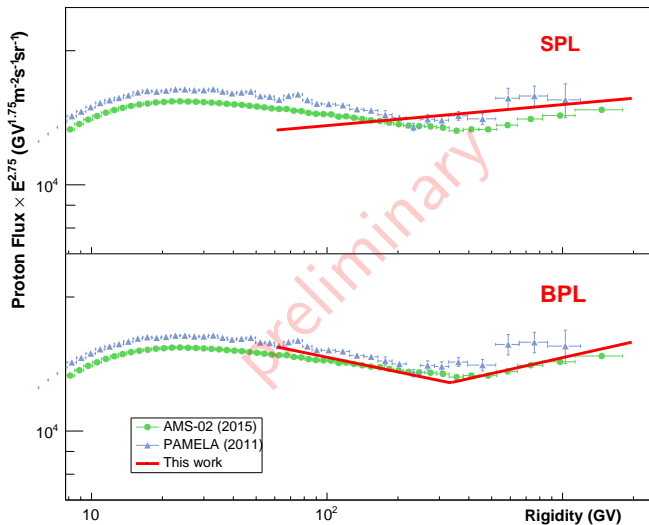
Table: Optimization results

# Earth's limb $\gamma$ -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  $\gamma$ -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

- Dr. Francesca Spada  
University of Pisa, Italy
- People in the Space Physics Laboratory at Mahidol University and the *Fermi*-LAT research group at the University of Pisa
- Development and Promotion of Science and Technology Talents Project (DPST)
- Partially supported by the Thailand Science Research and Innovation (RTA6280002)

# Backup slide

# Power law in energy

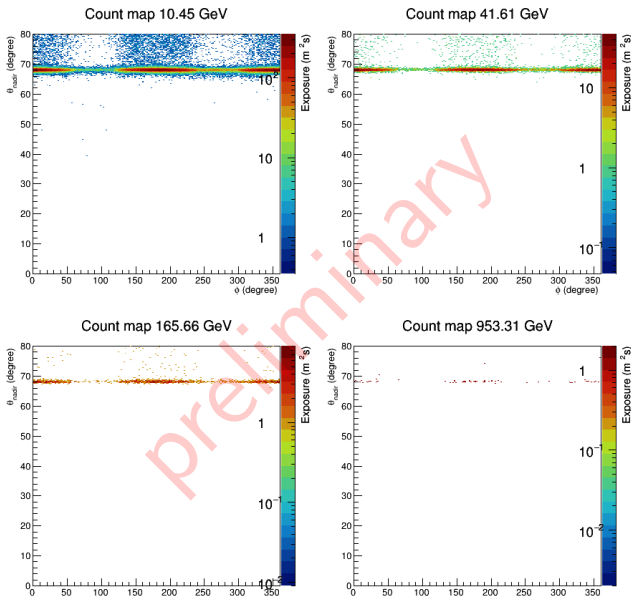
Converting the power law in rigidity to energy, we obtain **Single power law (SPL)**

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

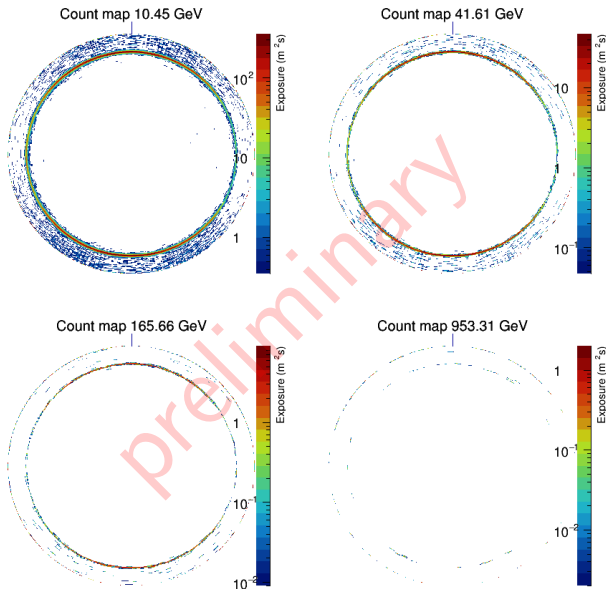
**Broken power law (BPL)**

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

# Count map



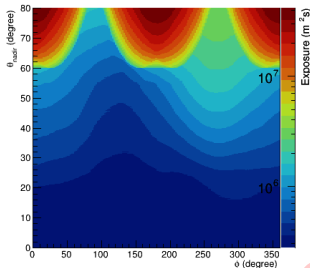
# Count maps



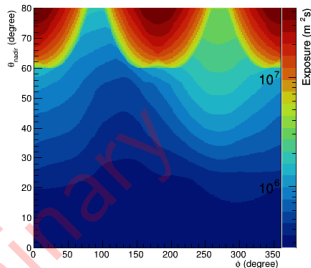


# Exposure maps

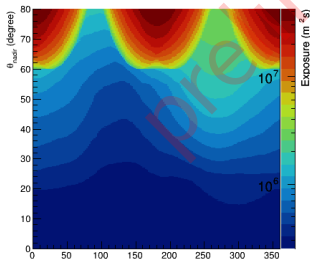
Exposure map 10.45 GeV



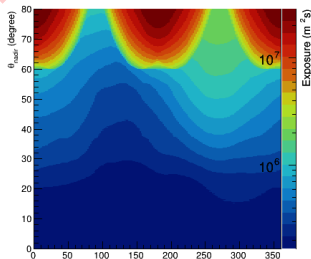
Exposure map 41.61 GeV



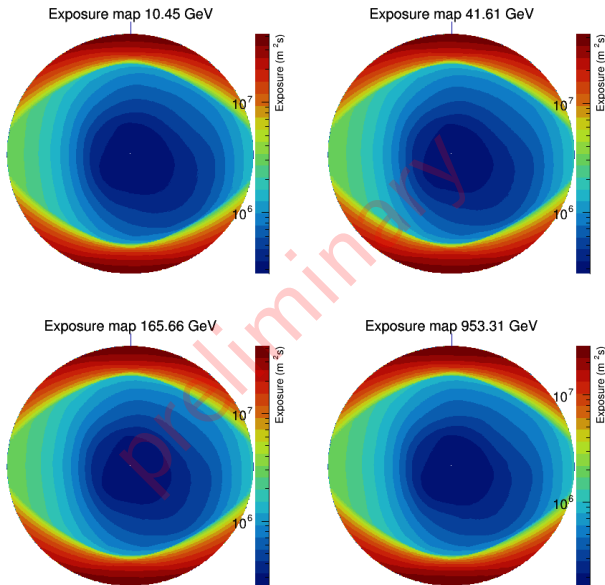
Exposure map 165.66 GeV



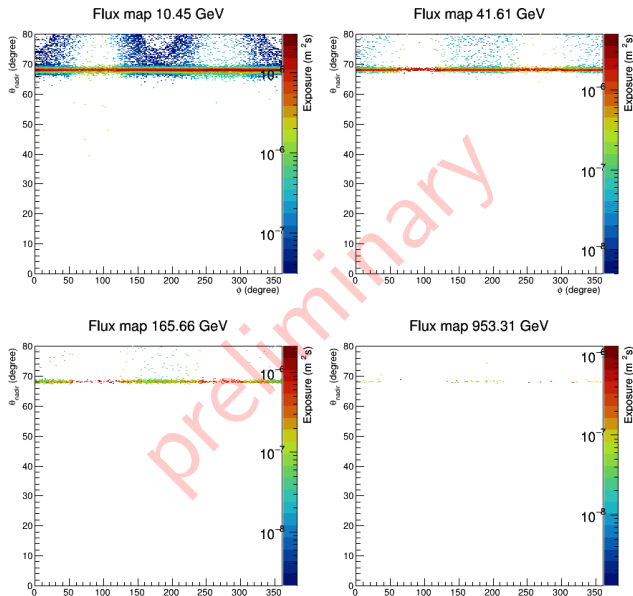
Exposure map 953.31 GeV



# Exposure maps



# Flux maps



# Flux maps

