

# Study of cosmic-ray spectrum using $\gamma$ -ray data from *Fermi* Large Area Telescope (*Fermi*-LAT)

Patomporn Payoungkhamdee

Mahidol University

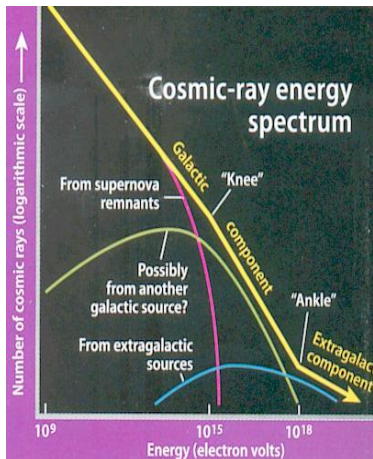
*patomporn.pay@gmail.com*

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# Overview

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# What are cosmic rays



- A high-energy particles that travelling through space
- **Criteria** : When we call flux it means differential flux
- **Feature** : CRs spectrum in rigidity follow power law
- Discontinuity in spectrum came from superposition of different acceleration mechanism

Figure: Cosmic ray feature :  
retrieved from [universe-review.ca](http://universe-review.ca)

# Trend in cosmic ray research

In 2015, the AMS collaboration claims that there is a broken in cosmic ray proton spectrum around 336 GV.

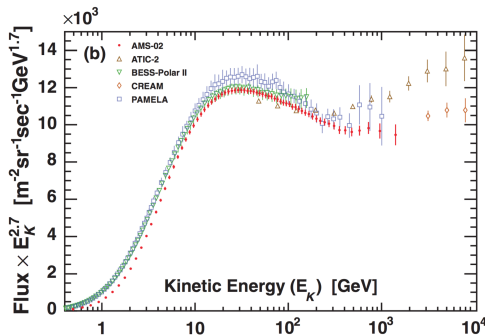
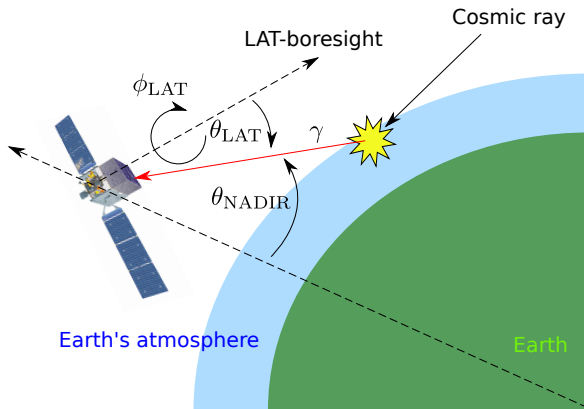


Figure: Cosmic rays proton flux : retrieved from M. Aguilar et al. (2015)

# Objective

- Want to **measure cosmic ray proton spectrum in range GV** by using  $\gamma$ -ray data from *Fermi*-LAT through Kachelrieβ and Ostapchenko model
- Some instruments claim that cosmic ray proton spectrum has discontinuity around 200-350 GV , then if our result agree with other instruments. Space **might have another acceleration mechanism that people did not know very well.**

# Schematics of limb $\gamma$ -ray production



# Data selection

- P8R2\_ULTRACLEANVETO\_V6 data from 07/08/2008 to 28/01/2015 ( $\sim 7$  years)
- Collect photon energy range from 10 GeV up to 1 TeV
- $\theta_{\text{NADIR}} \in 68.4^\circ - 70^\circ$  (Earth's limb)
- Use  $\theta_{\text{LAT}} < 70^\circ$

# Calculation method

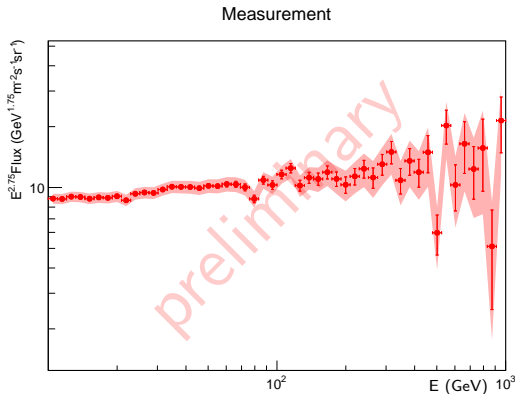
- ① Make 2D histogram as much as energy bin that we want
- ② Select photon data and fill in the 2D histogram
- ③ Calculate exposure maps which include effective area and time that LAT view can looking at Earth's limb

$$\text{Flux} = \frac{dF}{dE} = \frac{\int_{\text{Limb region}} (\text{Count map} / \text{Exposure map})}{\Delta\Omega\Delta E}$$

- ④ Divide every single grid of couple histogram (count map and exposure map)
- ⑤ Sum over limb region of this map then divided by solidangle and energy bin width
- ⑥ Now we got  $\gamma$ -ray flux



# $\gamma$ -ray spectrum from measurement



Notice that error bar came from statistics error and the red band already take into account instrument error

# Power law (in rigidity)

Typically, cosmic ray spectrum follow power law in rigidity as  
**Single power law (SPL)**

$$\frac{dN}{dR} = R_0 R^{-\gamma} \quad (1)$$

**Broken power law (BPL)**

$$\frac{dN}{dR} = \begin{cases} R_0 R^{-\gamma_1} & : E < E_{\text{Break}} \\ R_0 [R(E_{\text{Break}})]^{\gamma_2 - \gamma_1} R^{-\gamma_2} & : E \geq E_{\text{Break}} \end{cases} \quad (2)$$

Note for someone who not familiar with rigidity : it just defined by  
 $R \equiv P/q$  when  $P, q$  is a momentum and charge of particle

# Kachelrieβ and Ostapchenko model

Is the model which can compute spectrum of  $\gamma$ -ray from a known incident proton

$$\frac{dN_{\gamma}}{dE} \propto \sum_{E_{inc,i}} \left[ \frac{E_{inc,i}}{E_{\gamma,i}} \Delta(E_{inc,i}) \right] \left[ f_{pp} \frac{dN_H}{dE_{inc,i}} \left\{ 1 + \frac{\sigma_{HeN}}{\sigma_{pN}} \left( \frac{dN_H}{dR} \right)^{-1} \frac{dN_{He}}{dR} \frac{dR_{He}}{dR_H} \right\} \right] \quad (3)$$

- Red color terms is using for **incident proton spectrum**
- Use **helium spectrum from AMS-02 measurement (2015)**
- $f_{pp} \equiv E_{\gamma}(d\sigma^{pp \rightarrow \gamma}/dE_{\gamma})$  is a table in K&O model which behave like a scattering amplitude that depend on the energy of incident particle
- Crosssection  $\sigma_{HeN}/\sigma_{pN}$  at high energy ( $> 10\text{GeV}$ ) is almost remain constant ( $\approx 1.6$ )

# Poisson likelihood function

On the previous slide, we want to find the incident proton.  
Let define some loss function to compare model and measurement

$$\mathcal{L} = \prod_{i=1}^N P_{\text{pois}}(n_{i,\text{model}}, n_{i,\text{measurement}}) \quad (4)$$

For numerically convenient, redefined into logarithmic form

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

This part is the hard work of computer to find best incident cosmic ray proton that match the spectrum from measurement.

# Algorithm

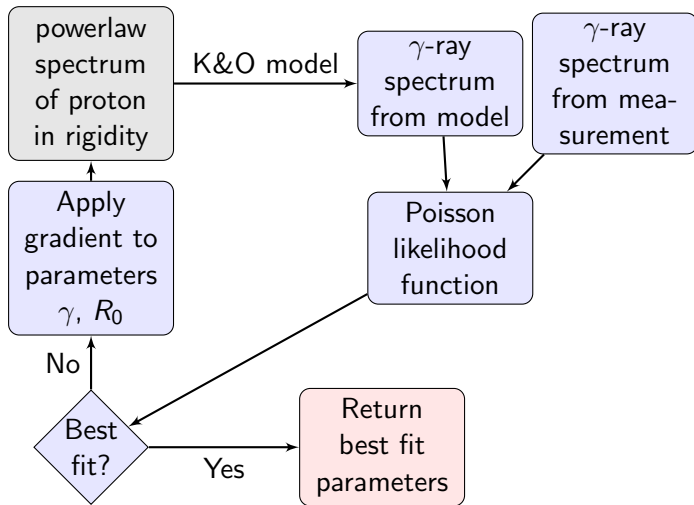


Figure: Flow chart of optimization process

# Results

Best fits	$\gamma_1$	$\gamma_2$	$E_{\text{Break}}$ (GeV)
SPL	$2.68 \pm 0.01(0.03)$	-	-
BPL	$2.84 \pm 0.04(0.06)$	$2.64 \pm 0.04(0.17)$	$328 \pm 151(267)$

Table: Optimization results

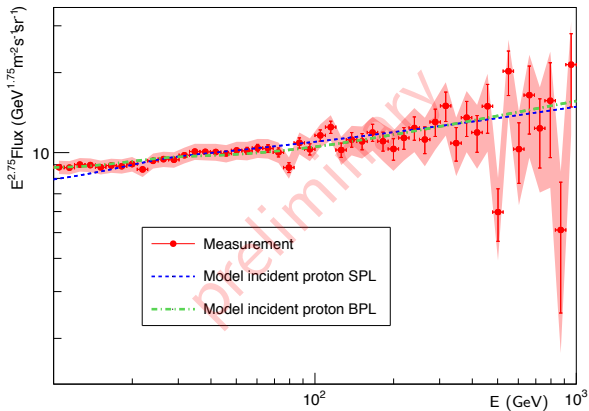
- Likelihood Ratio Test (LRT)  $\Rightarrow$  BPL better than SPL with a significant level of  $3.3\sigma$

Where  $1\sigma$  of systematic error and total error (take into account instrumental error) was shown in the table consequently.

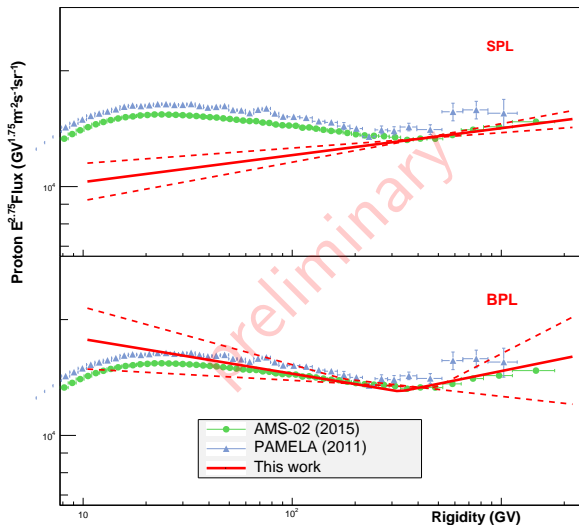
Notice that error of parameters came from [Monte Carlo Simulation](#)

# $\gamma$ -ray spectrum

## Model vs Measurement



# Proton spectrum





# Conclusion

- We found an energy break point around 328 GeV with a significant level of  $3.3\sigma$  which agree with other measurement
- Put weight on the previous study [M. Ackermann et al. (2014)] that we could take a benefit of brightness  $\gamma$ -ray from Earth's high atmosphere to indirectly observe cosmic ray spectrum which cause it's luminosity

# References

- [1] O. Adriani et al., Science 332, 69 (2011) [2] M. Ackermann et al. (Fermi LAT Collaboration), Phys. Rev. Lett. 112, 151103
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- [4] M. Aguilar et al. (AMS Collaboration), Phys. Rev. Lett. 115, 211101
- [5] M. Aguilar et al. (AMS Collaboration), Phys. Rev. Lett. 114, 171103
- [6] L. Lyons, Statistics for nuclear and particle physicists

# Acknowledgement

- Dr. Warit Mitthumsiri  
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# Backup slide

# Power law in energy

In our case, we use power in energy then we need to convert by relativistic energy-mass relation

## Single power law (SPL)

$$\frac{dN}{dE} = N_0 [E_k (E_k + 2m_p)]^{-\gamma/2} \left( \frac{E_k + m_p}{\sqrt{E_k (E_k + 2m_p)}} \right) \quad (6)$$

## Broken power law (BPL)

$$\frac{dN}{dE} = \begin{cases} N_0 [E_k (E_k + 2m_p)]^{-\gamma_1/2} \left( \frac{E_k + m_p}{\sqrt{E_k (E_k + 2m_p)}} \right) & : E < E_{\text{Break}} \\ N_0 [E_b (E_b + 2m_p)]^{(\gamma_2 - \gamma_1)/2} [E_k (E_k + 2m_p)]^{-\gamma_2/2} \left( \frac{E_k + m_p}{\sqrt{E_k (E_k + 2m_p)}} \right) & : E \geq E_{\text{Break}} \end{cases} \quad (7)$$

# Error determination

## Statistical error (Random error)

- ① Get back to raw count and **random new count in each energy bin by Poisson random function**
- ② Recalculate proton spectrum
- ③ Optimize it and store the parameter that we got
- ④ do it over thousands of times and fill in histogram to interpret error by saying sigma of gaussian function

## Total error (take into account instrument)

- ① Get back to raw count and **random new count in each energy bin by Poisson random function**
- ② **Random value we got again by systematic error (Apparatus)**
- ③ Recalculate proton spectrum
- ④ Optimize it and store the parameter that we got
- ⑤ do it over thousands of times and fill in histogram to interpret error by saying sigma of gaussian function

# Monte Carlo Simulation

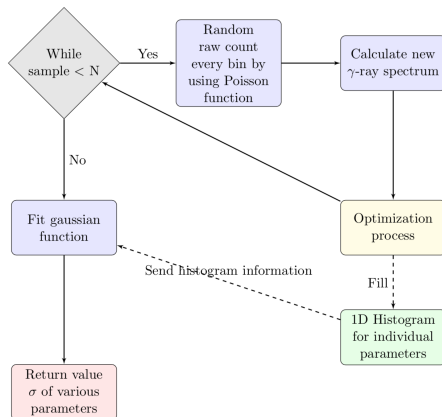


Figure: Statistical error determination

# Monte Carlo Simulation

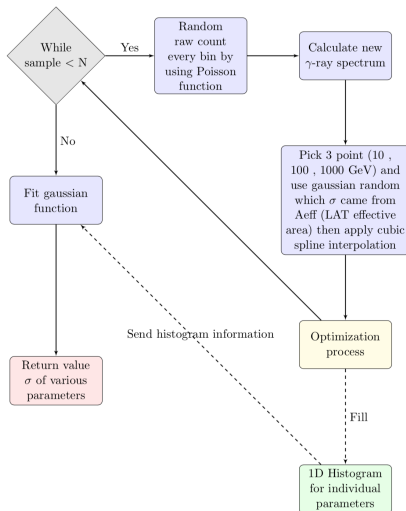
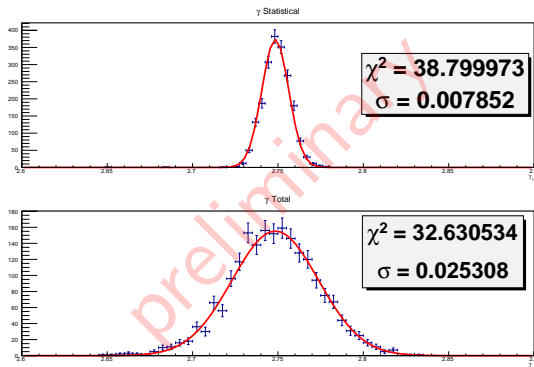


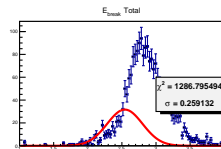
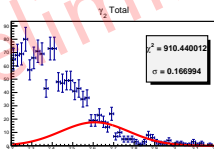
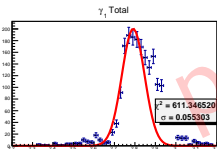
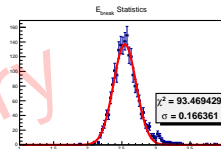
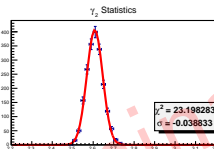
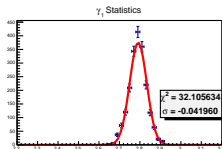
Figure: Total error determination



# Single power law (SPL)

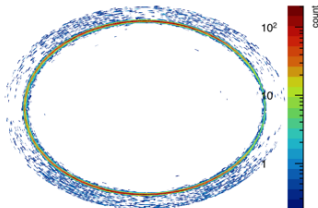


# Broken power law (BPL)

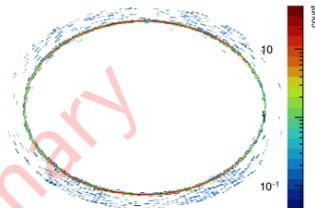


# Count map

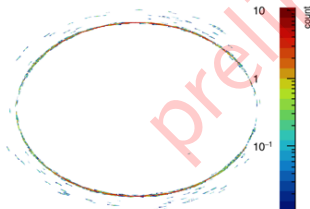
Count map 10.000-10.965 GeV



Count map 30.200-33.113 GeV



Count map 91.201-100.000 GeV

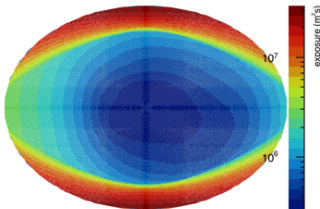


Count map 912.011-1000.000 GeV

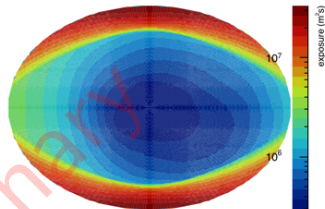


# Exposure map

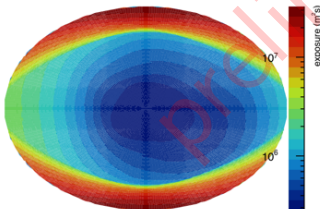
Exposure map 10.000-10.965 GeV



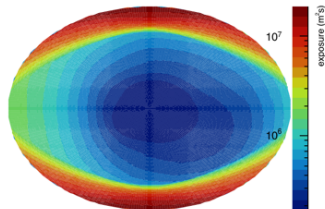
Exposure map 30.200-33.113 GeV



Exposure map 91.201-100.000 GeV

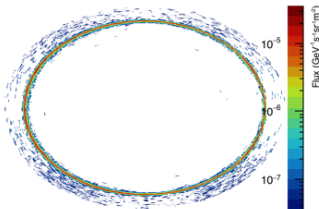


Exposure map 912.011-1000.000 GeV

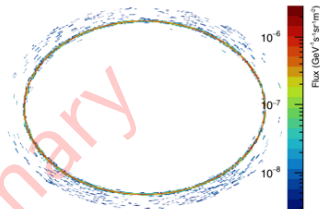


# Flux map

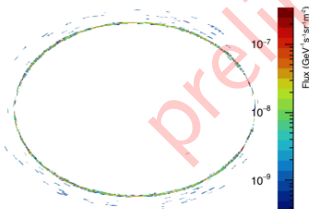
Flux map 10.000-10.965 GeV



Flux map 30.200-33.113 GeV



Flux map 91.201-100.000 GeV



Flux map 912.011-1000.000 GeV

