LHAASO重点研发项目年度进展会

Estimation of solar disk gamma-ray emission based on Geant4

Zhe Li

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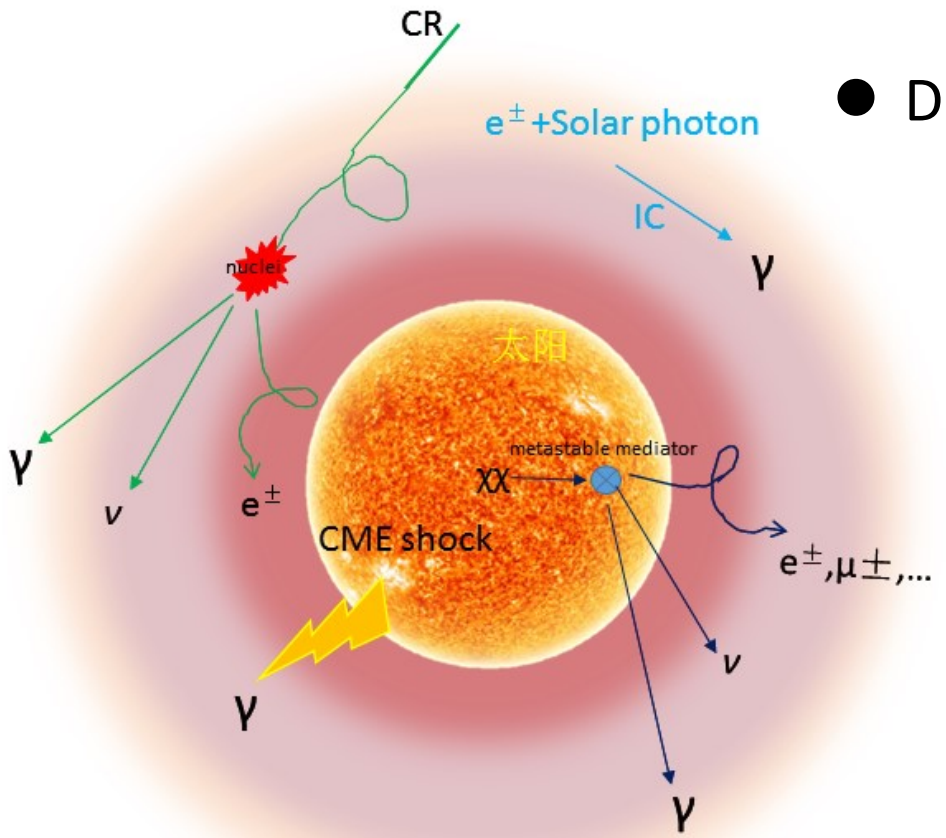
Outline

1. Solar gamma-ray radiation introduction
2. G4SOLAR program
3. Solar disk simulation result

1.1 Gamma-ray emission from the Sun

- The highest-energy gamma-ray observed from a flare is ＜10GeV



- Dark matter annihilation (no observation result)

- **High energy gamma-rays from the solar region are produced mainly by two distinct process:**

  ✓ One is produced by IC of cosmic-ray electrons on solar photons, denoted as “**IC component**”

  ✓ The other is from the hadronic interaction of cosmic rays with solar atmosphere (photosphere and chromosphere) ,denoted as “**Solar disk component**”

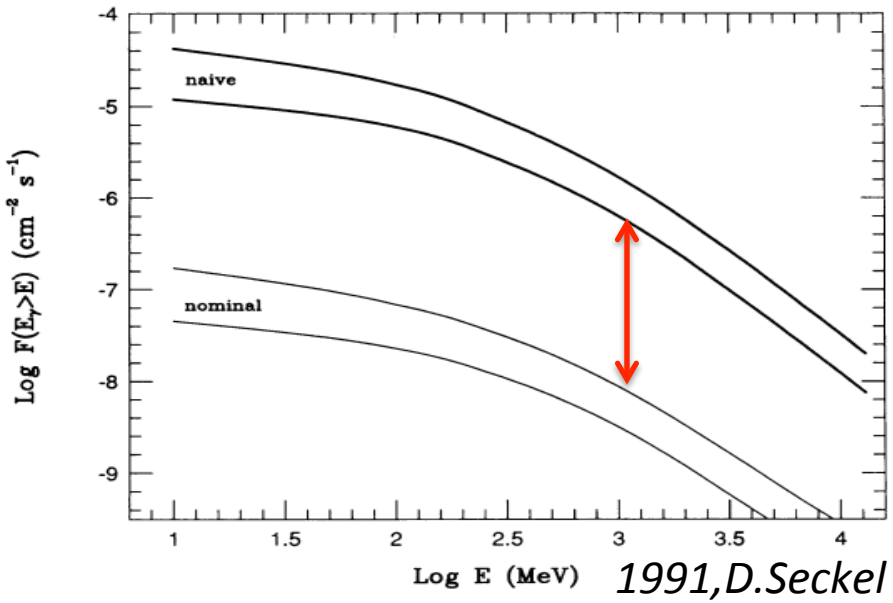
  features: Point like; steady γ-ray source; can be detected on the earth

1.2 Significance of Observation Solar γ-rays

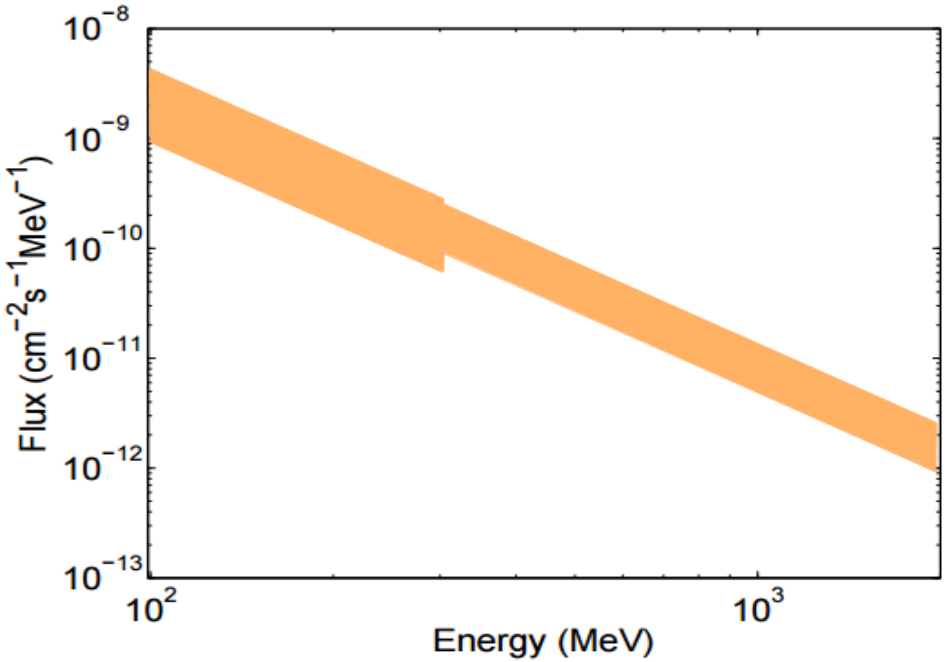
New probe to study

- ✧ proton spectrum
- ✧ dark matter physics
- ✧ electron spectrum
- ✧ solar physics
- ✧ new physics …

1.3 Some results of solar disk gamma-ray



1991,D.Seckel



2008，Orlando,et al.

Theoretical result (10MeV-10GeV)

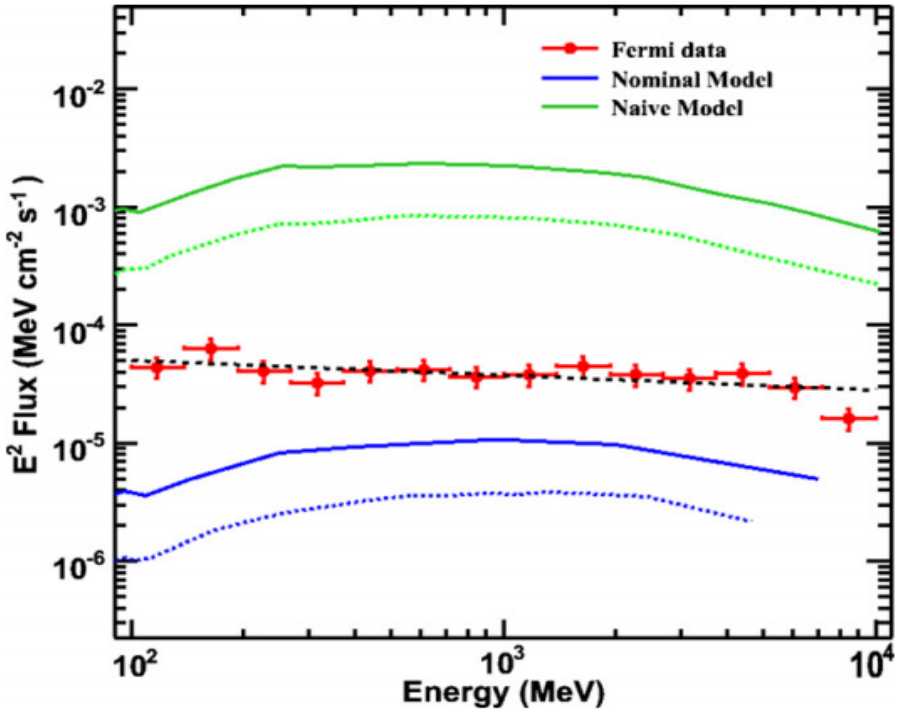
- So far the first detailed theoretical study of γ -ray emission from interactions of CR protons in the solar atmosphere;

EGRET results (100-300MeV,>300MeV)

Source	100-300 MeV	>300MeV
Extended	2.1±1.3	1.7±0.9
Model extended	1.3	0.9
Disk	1.4±0.9	0.4±0.2
Seckel's disk model	0-1.1	0.1-0.5

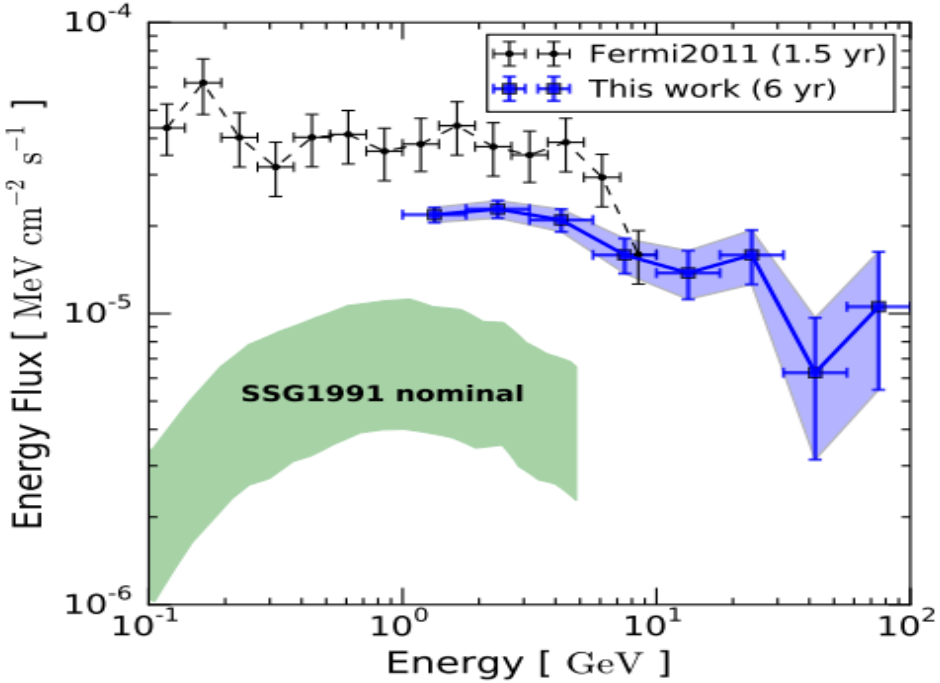
1.3 Some results of solar disk gamma-ray

Fermi results (0.1-10GeV & 1-100GeV)



2011, Abdo et al. Fermi

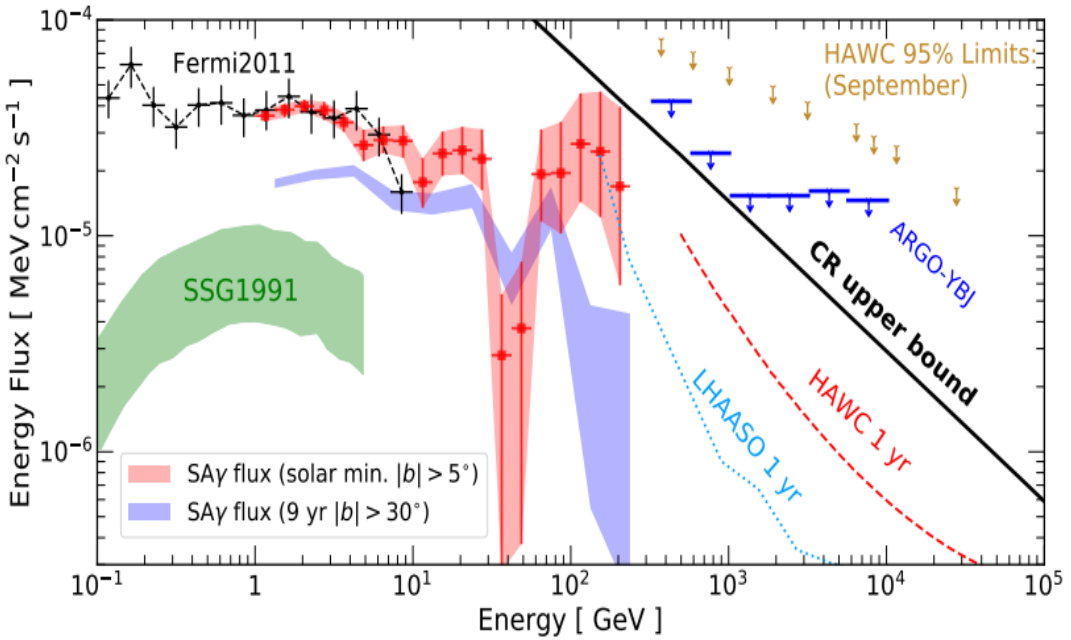
- 1.5y data collection
- Energy : 0.1-10 GeV
- Spectral index:≈**2.11±0.73 (power law)**



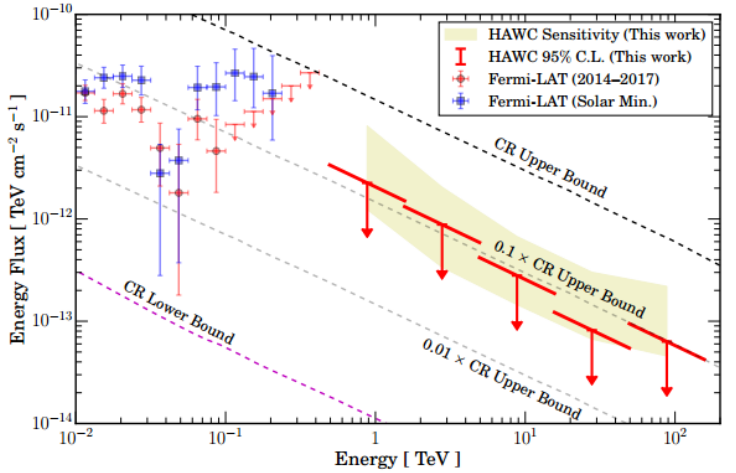
2016,Ng et al.

- 6y data collection
- Energy : 1-100 GeV
- Spectral index:≈**2.3 (power law)**

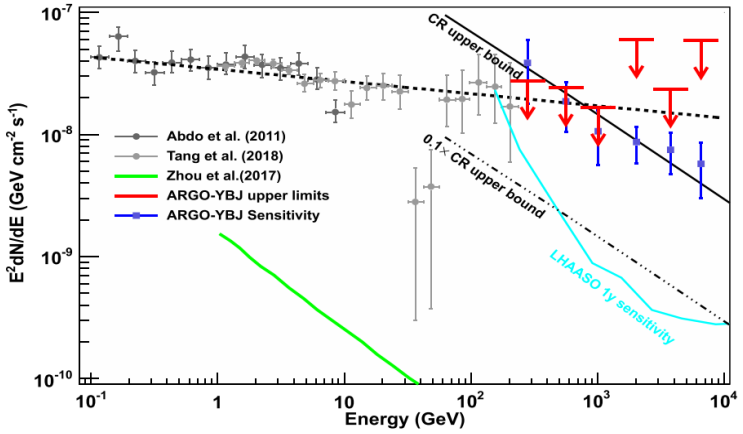
1.3 Some results of solar disk gamma-ray



Tang, et al.,2018



HAWC, 2018



ARGO-YBJ, 2019

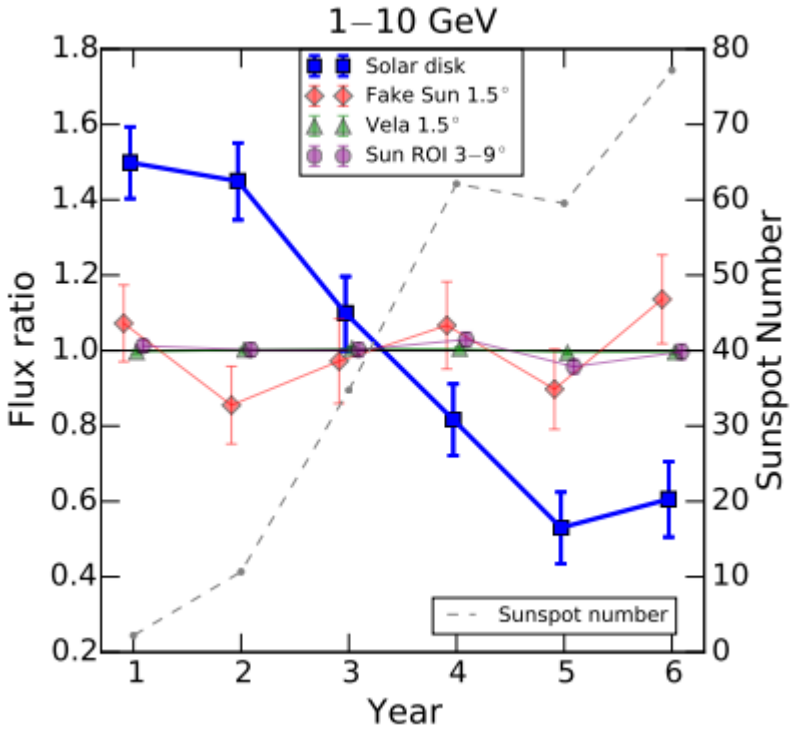
- The nine-year observation of Fermi is different with the trend that during solar minimum period;

- HAWC 95% upper limits from 3 years of data, from November 2014 to December 2017. (activity period)

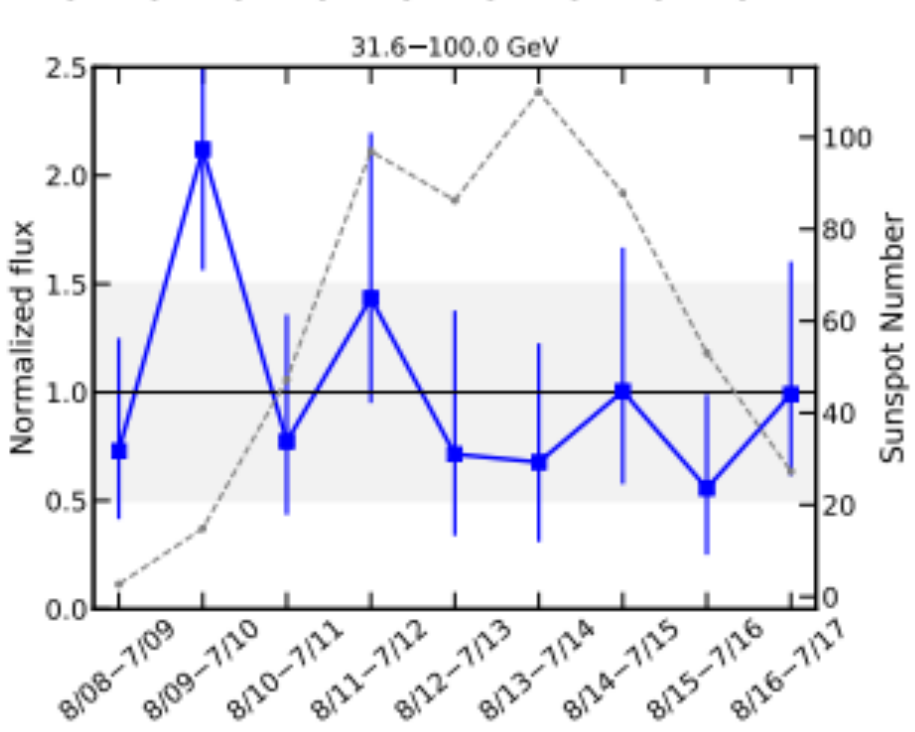
- ARGO-YBJ 95% upper limits, from 2008 January to 2010 December. (quiet period)

1.3 Some results of solar disk gamma-ray

- **The flux of solar high energy γ-ray is related to solar activity**



Kenny,2015

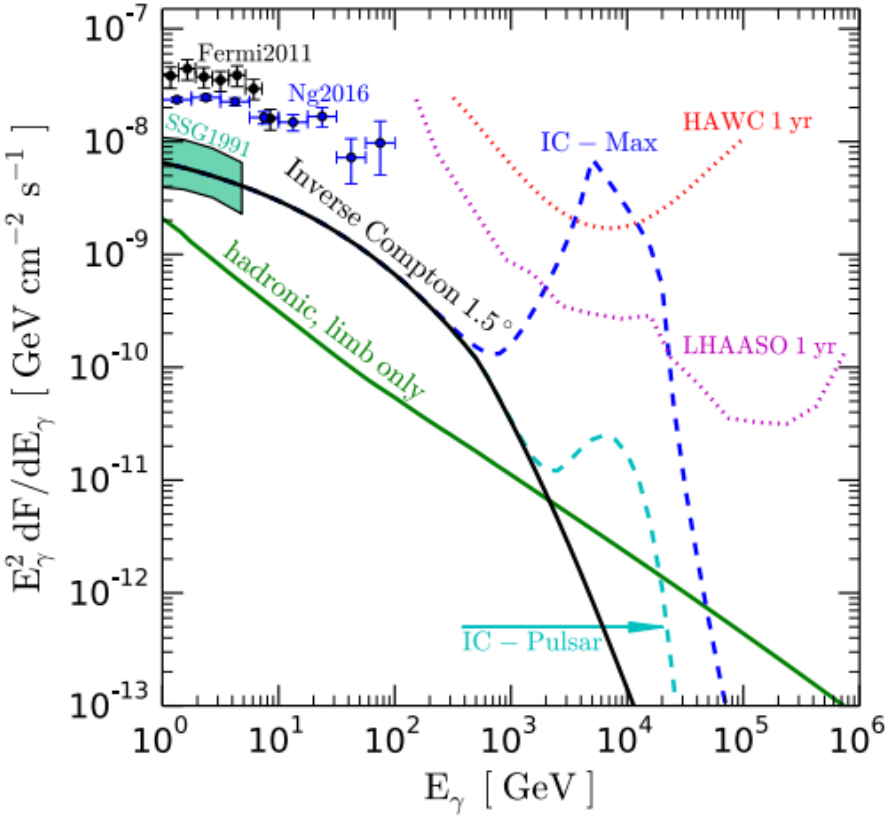


Tang,2018

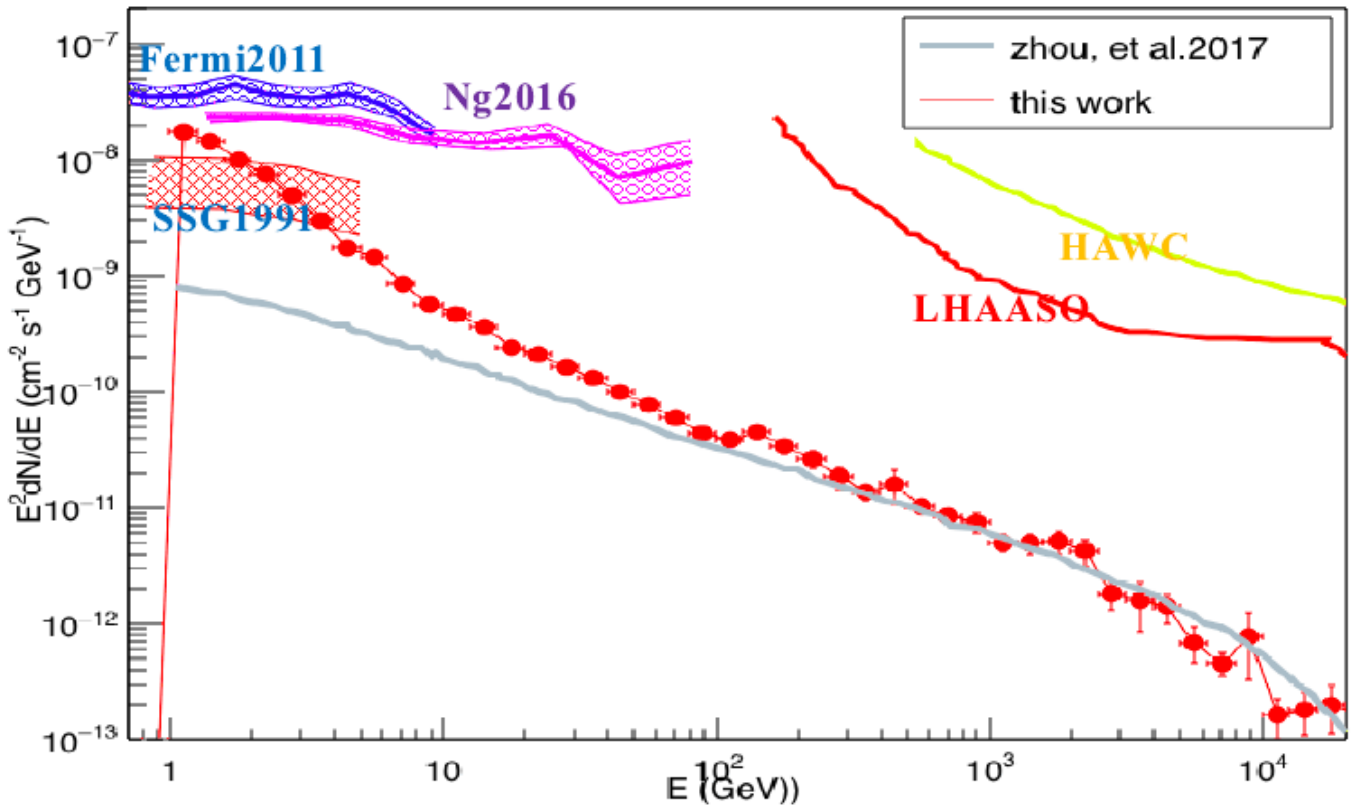
Implied that the effects of the sun's magnetic field is unneglectable!

1.3 Some results of solar disk gamma-ray

- **Simulation result without solar magnetic field is far from Fermi observation**



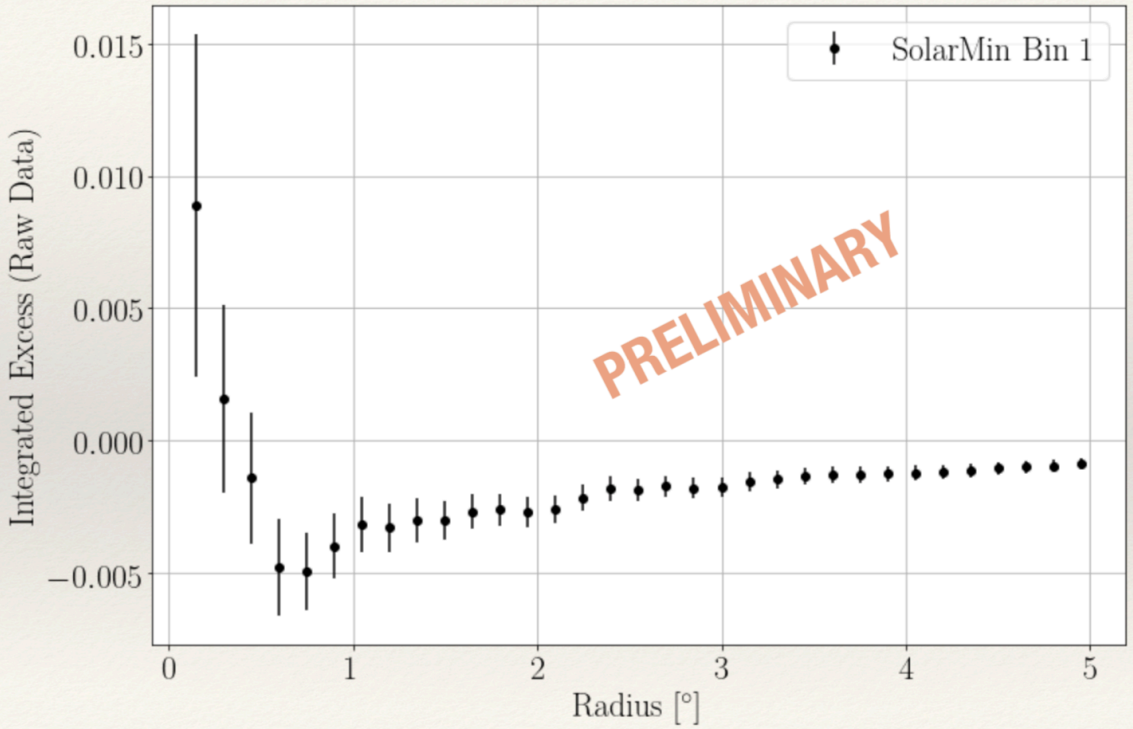
Zhou et al.,2017



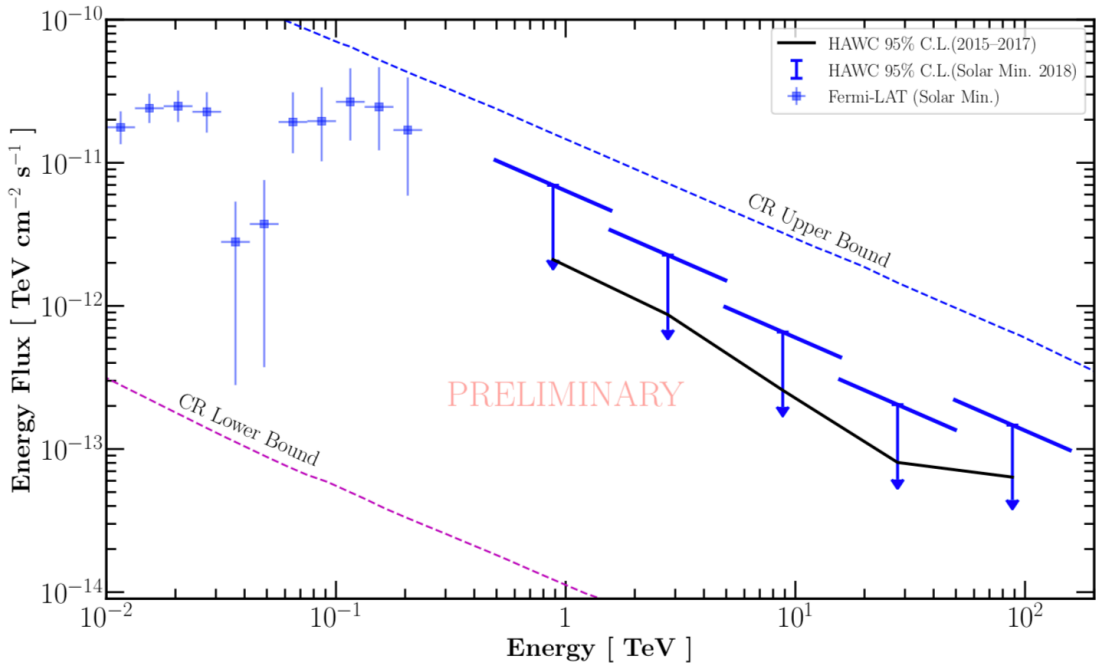
Gao et al.,2018

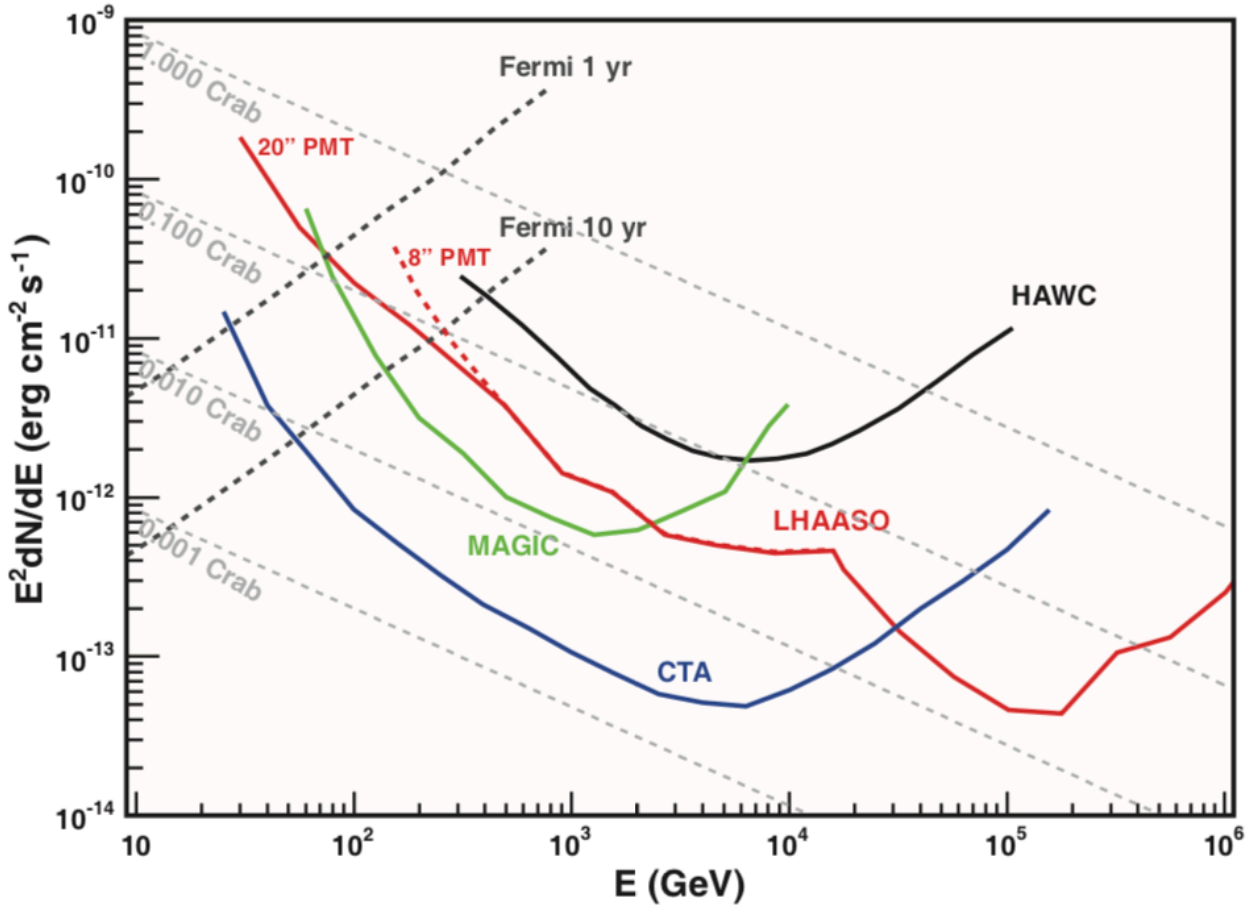
HAWC在ICRC2019上报道的最新结果

2018 Data: Enter Solar Minimum

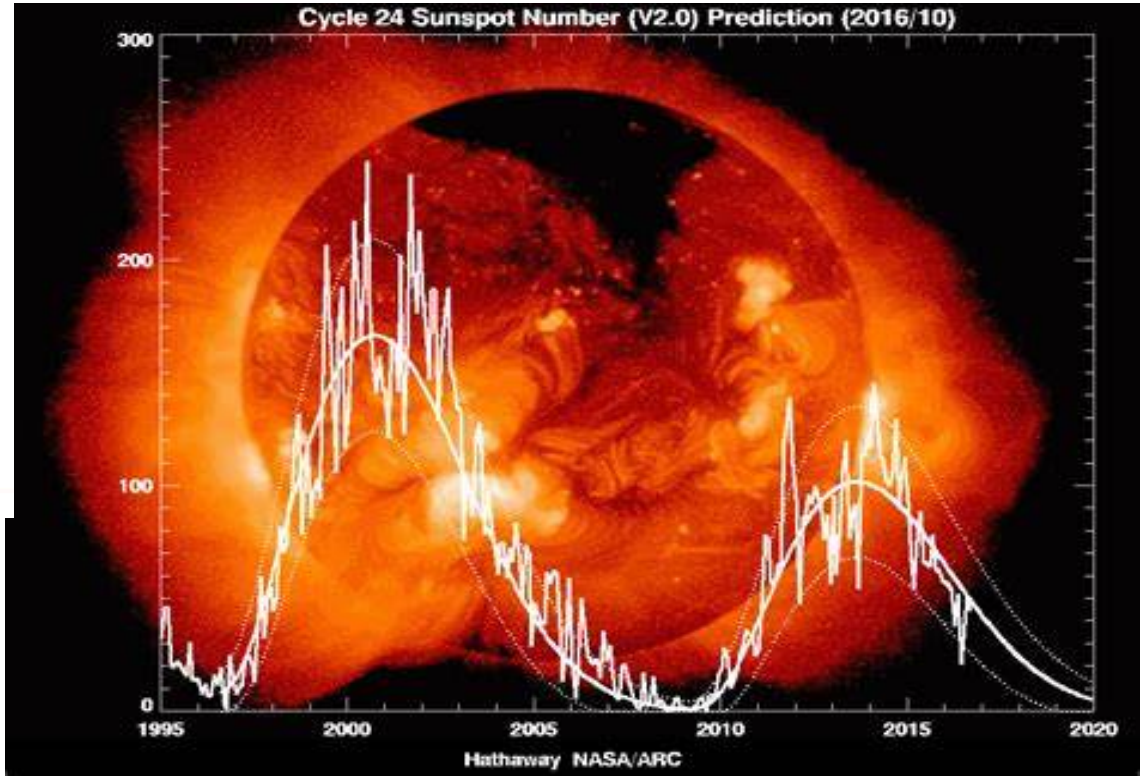


Upper Limits





- LHAASO的灵敏度和能量覆盖范围都优于HAWC；
- ¼ WCDA阵列自2019年4月份开始运行，刚好处于太阳活动极小期，可以开展太阳伽马辐射的观测研究；



2. G4SOLAR program

G4SOLAR program is developed based on Geant4, it contains:

(1) Solar atmosphere structure;

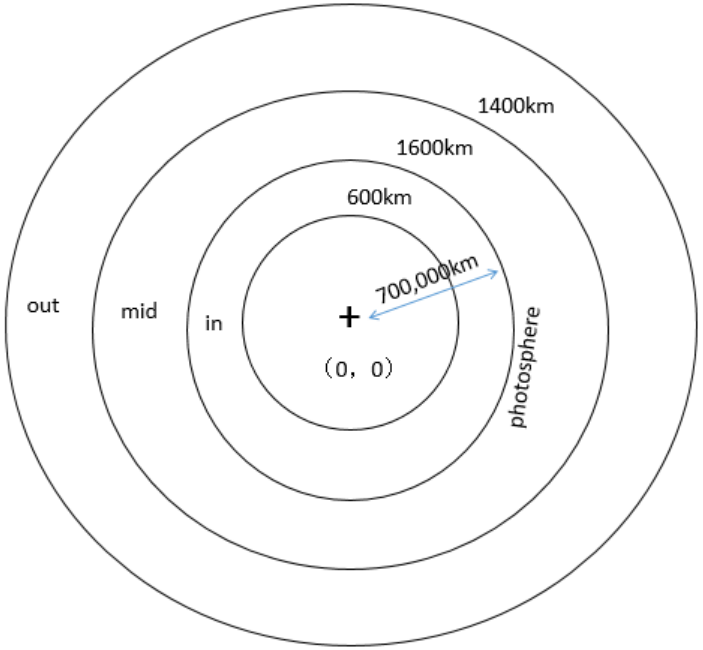
(2) Corona magnetic field;

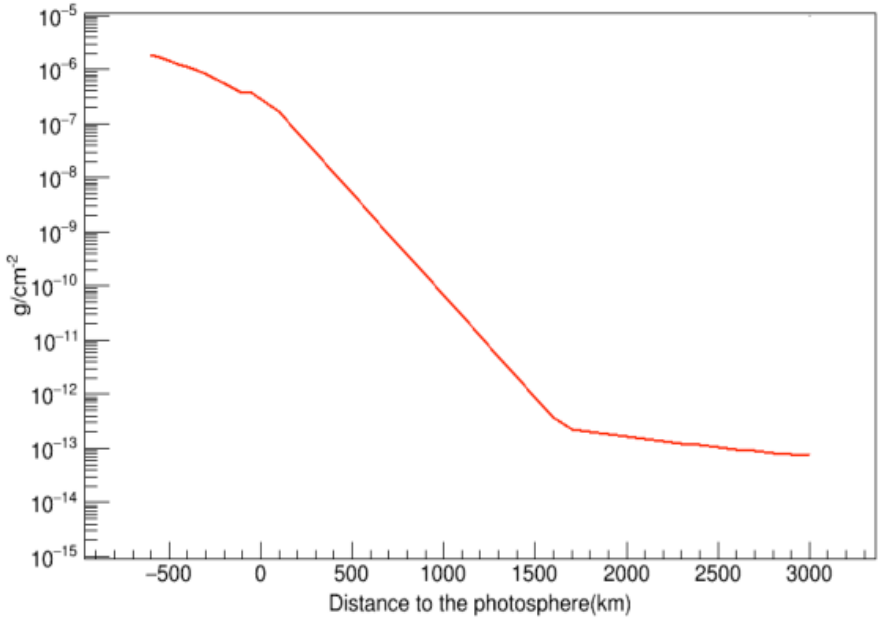
(3) Primary cosmic ray sampling (position, direction and energy);

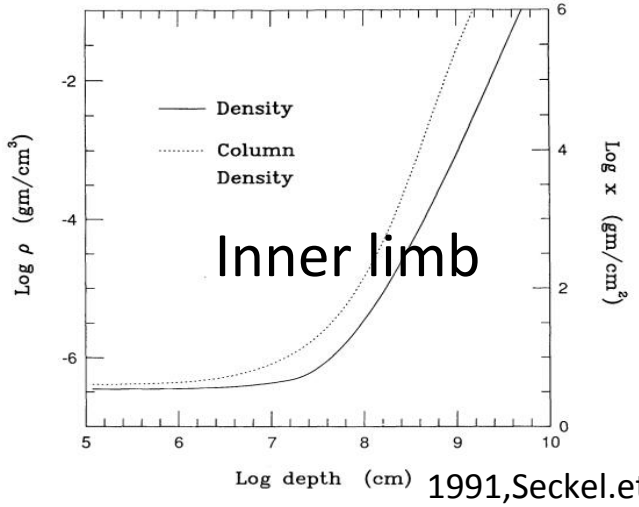
- The FTFP_BERT physics interaction lib was employed in the G4SOLAR program. This lib contains all standard electromagnetic process, and the Bertini cascade is used for hadron <5GeV, Fritiof model for hadron >4GeV ;
- Only the γ-ray, produced during the cascade, going out of the outside layer with energy greater than 100MeV can be recorded by G4SOLAR;

2. G4SOLAR program

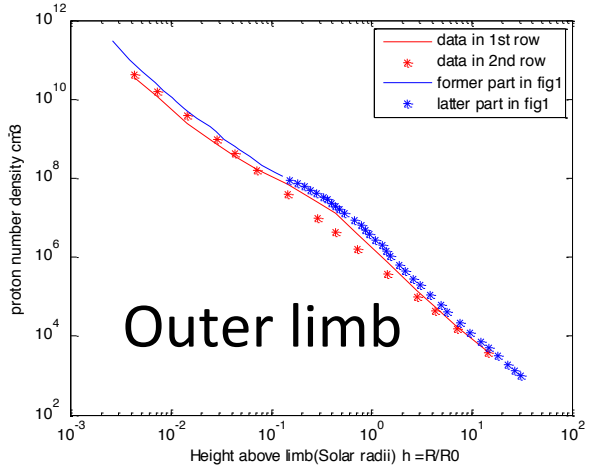
➢ Solar atmosphere structure







1991,Seckel.etal



1966,Marvin L. White.

- ➢ 3600 layers in total, 1km thickness for each layer;
- ✓ Choose the depth when proton column density is **50g/cm²** (about **521.5km** to solar limb edge), and **600 km within limb edge** was chosen in G4SOLAR;
- ✓ The proton within the sphere **3000 km** is under consideration;

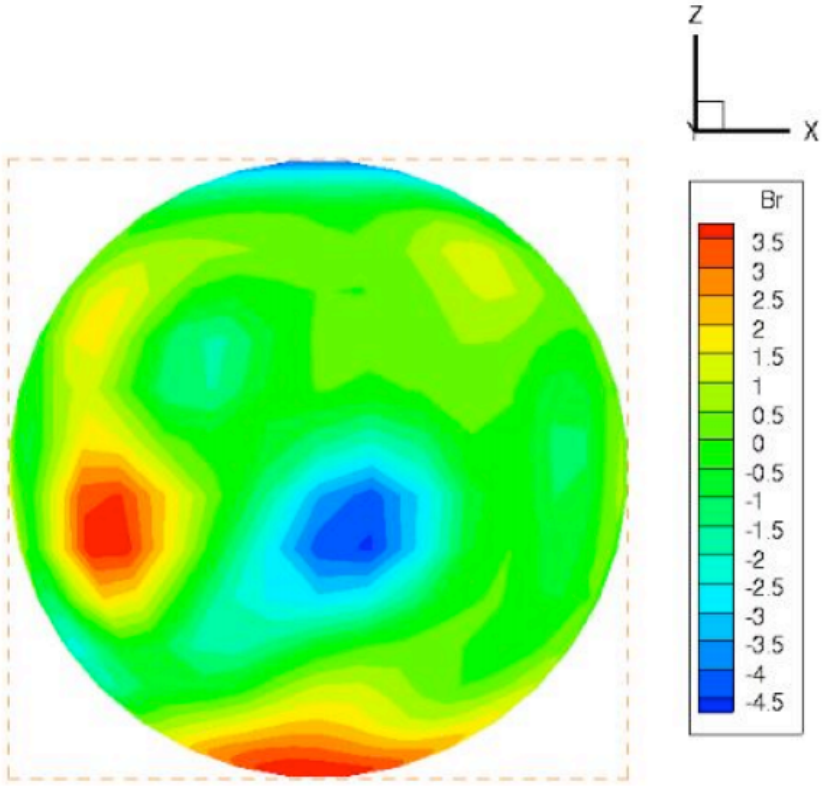
2. G4SOLAR program

➢ Corona magnetic field

1. The potential-field source-surface (PFSS) model for “quiet” Sun was adopted in G4SOLAR;

2. the magnetic field construction was resolved by the interpolation of observed corona magnetic field structure during 2008y;

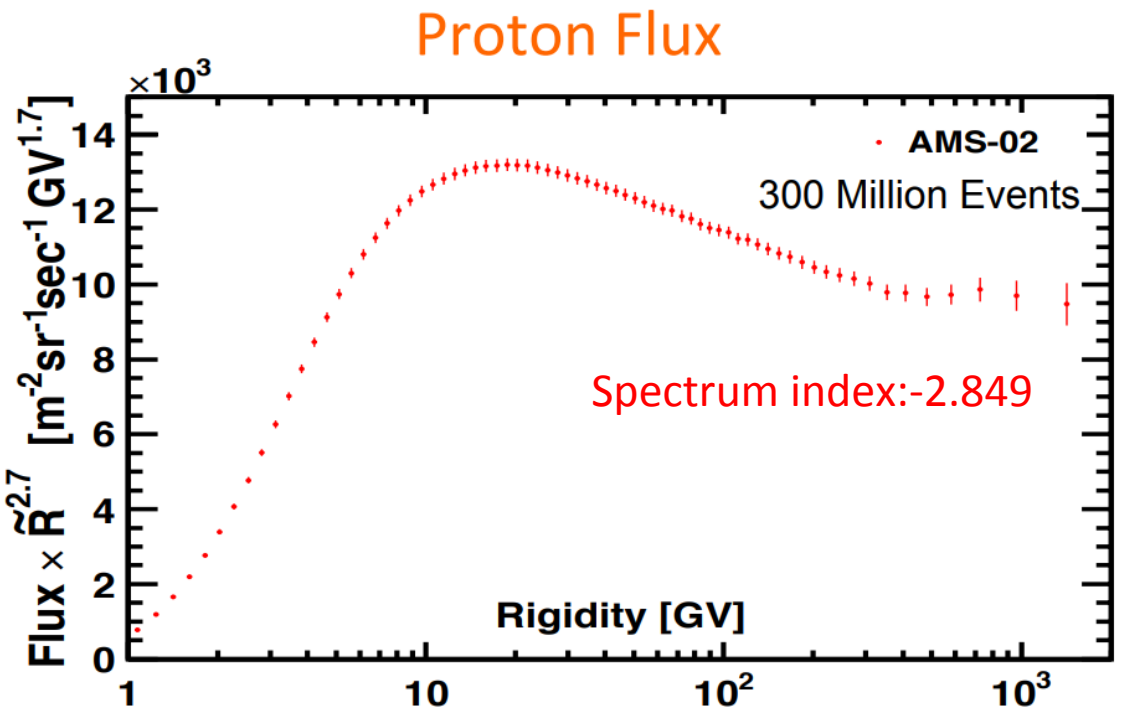
3. The important features of this model is shown in the right figure. Average field strengths are on the order of a few gauss;



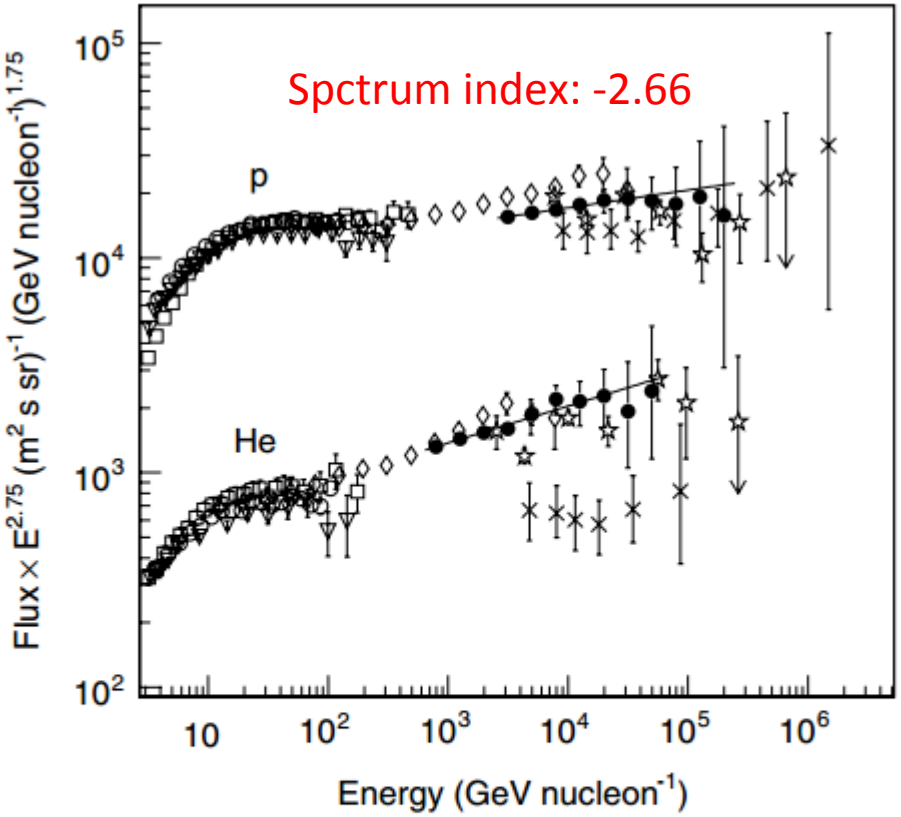
PFSS model for “quiet” Sun

2. G4SOLAR program

➢ Primary Proton spectrum



AMS,2015



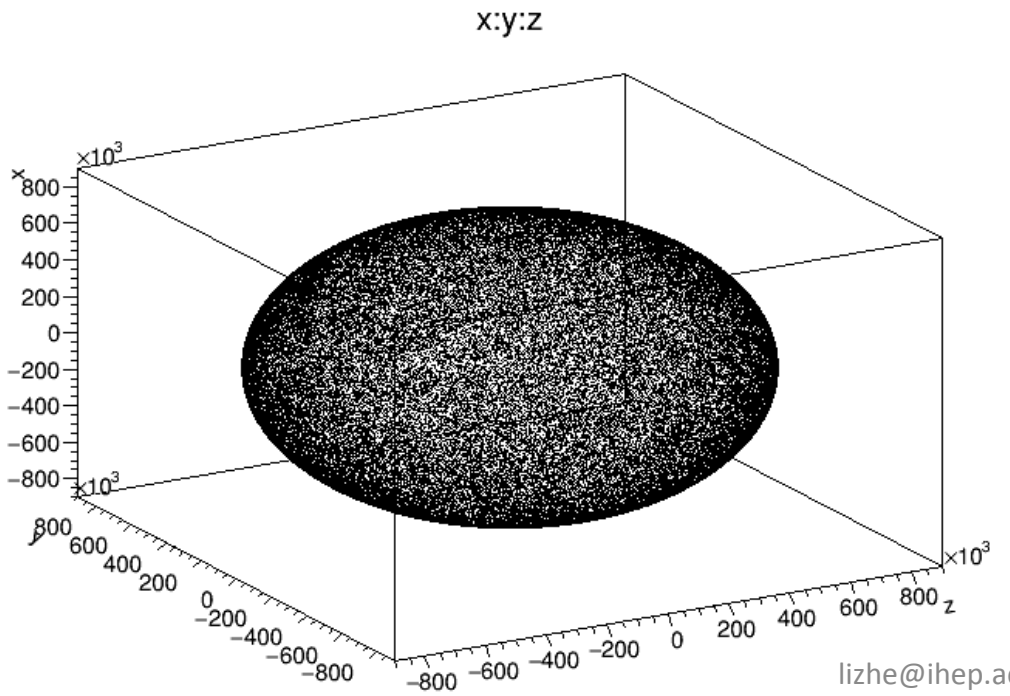
CREAM,2011

2. G4SOLAR program

➢ Primary cosmic ray sampling

Proton energy range: 100MeV – 100 TeV, divided into six energy intervals;

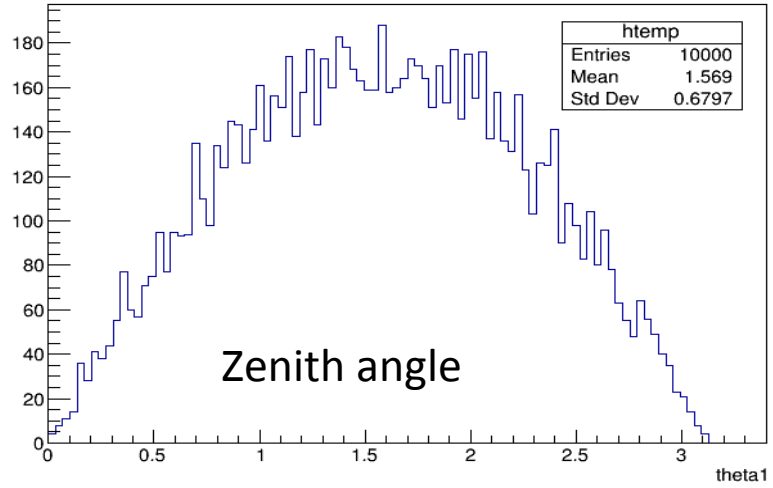
Number of sampling: 1,000,000 for each energy intervals

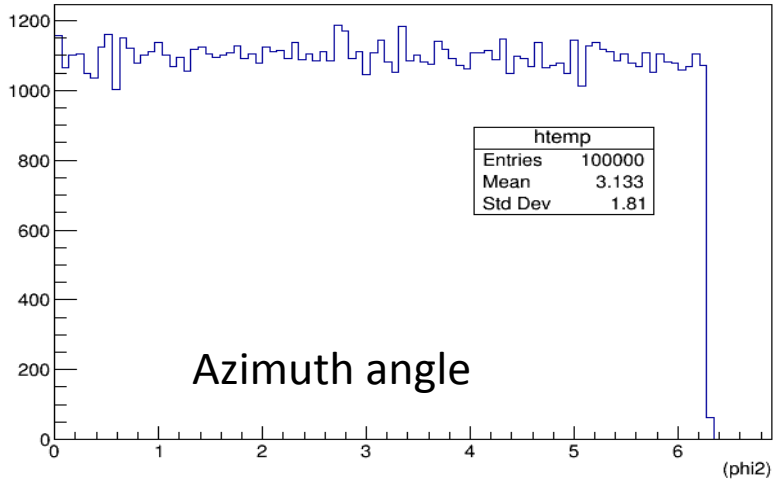


Position sampling:
distributed on the sphere surface homogeneously

2. G4SOLAR program

➢ Primary cosmic ray (proton) sampling

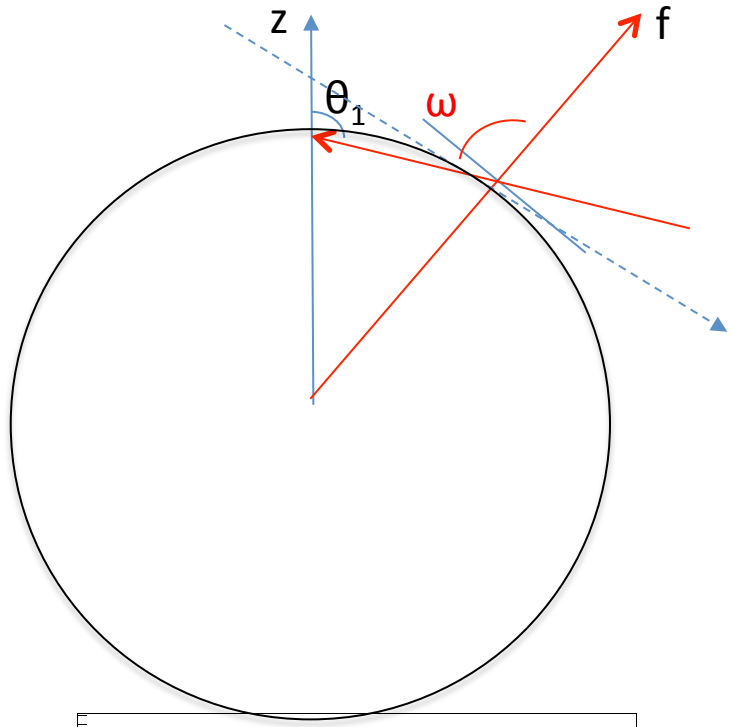


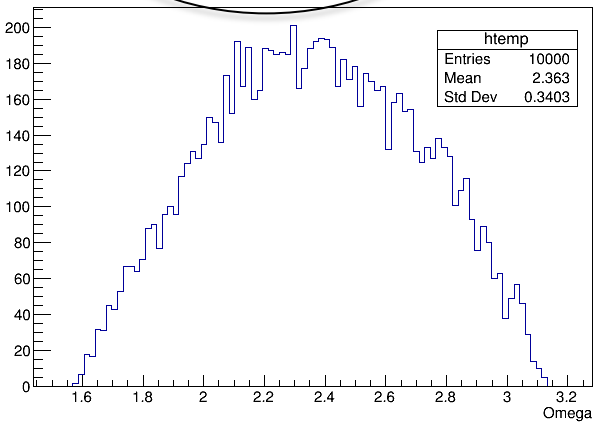


Primary direction:
zenith angle (0,2π)
Azimuth angle (0,2π)

The angle (ω) between normal direction and incident direction is used to estimate particles that can be penetrate into the solar atmosphere or not:

$\omega : (\pi/2, \pi)$





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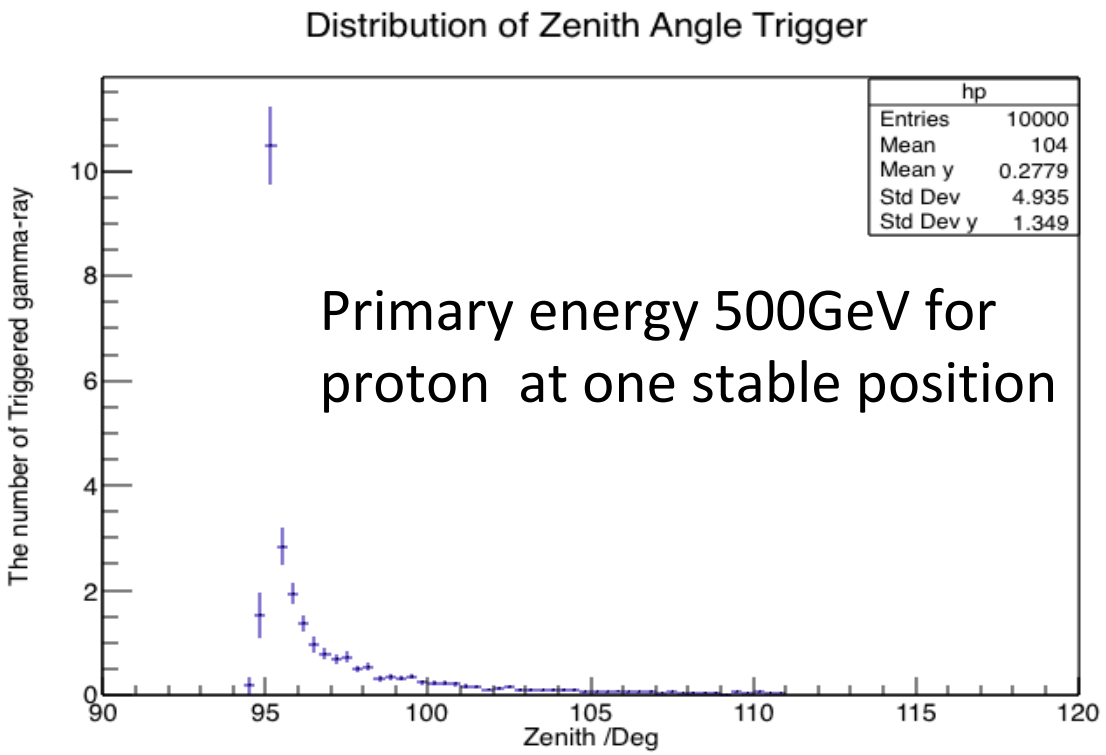
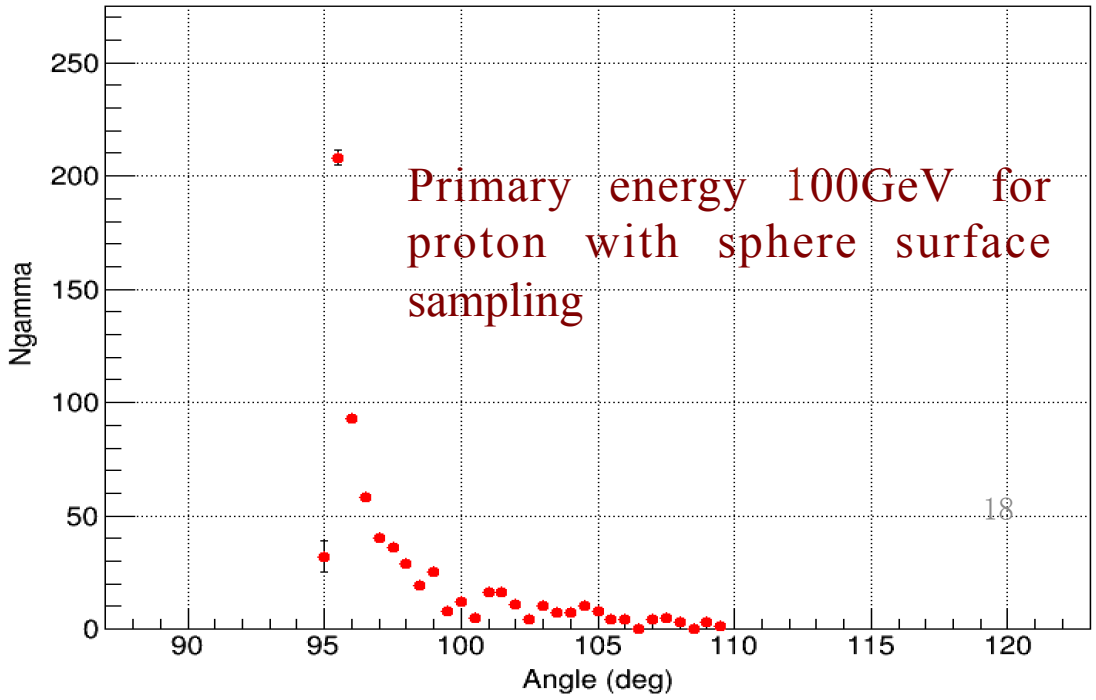
2. G4SOLAR program

Recorded gamma-ray number VS. incident direction (right: ω)

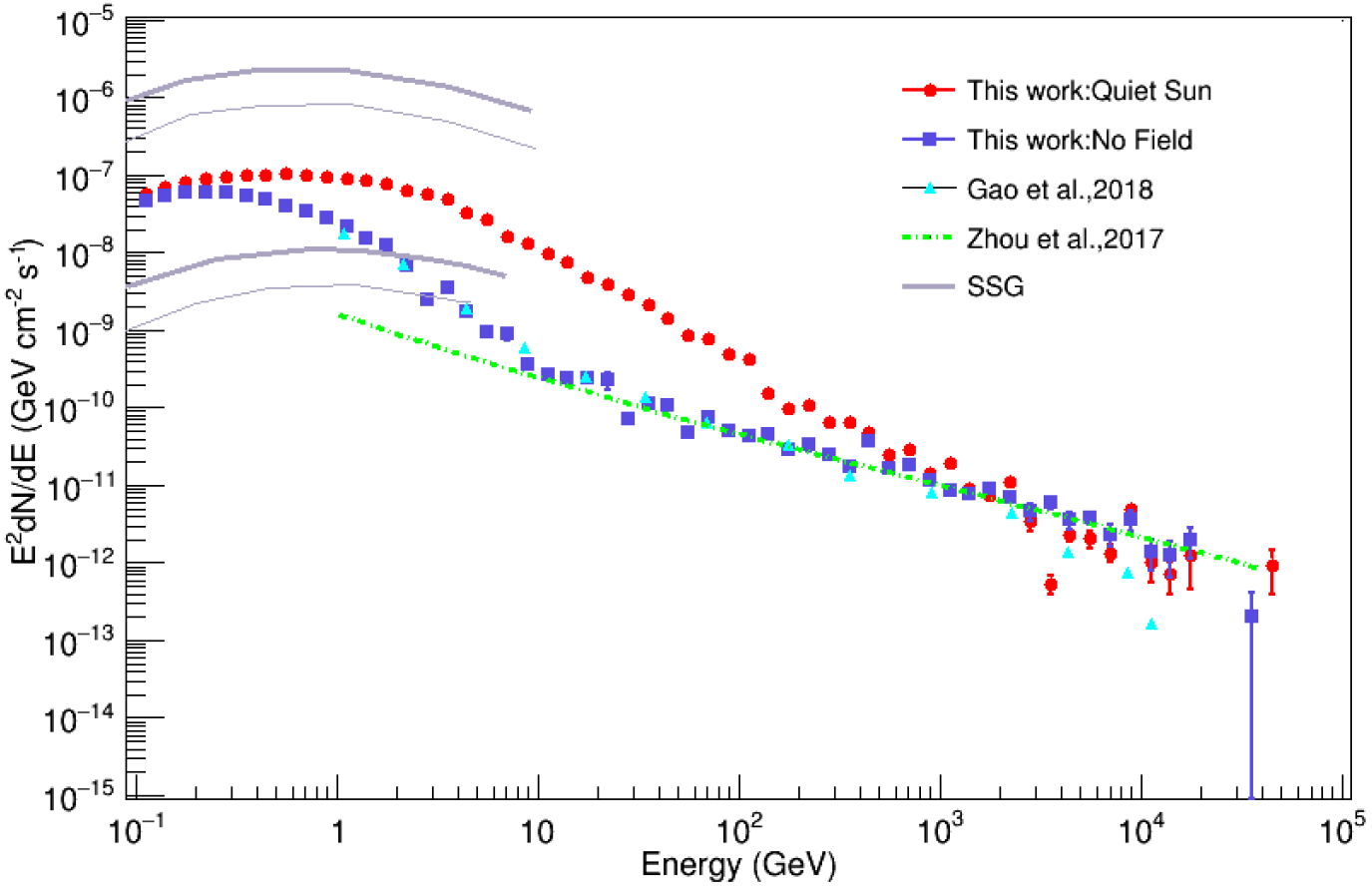


Gao, et al., 2018



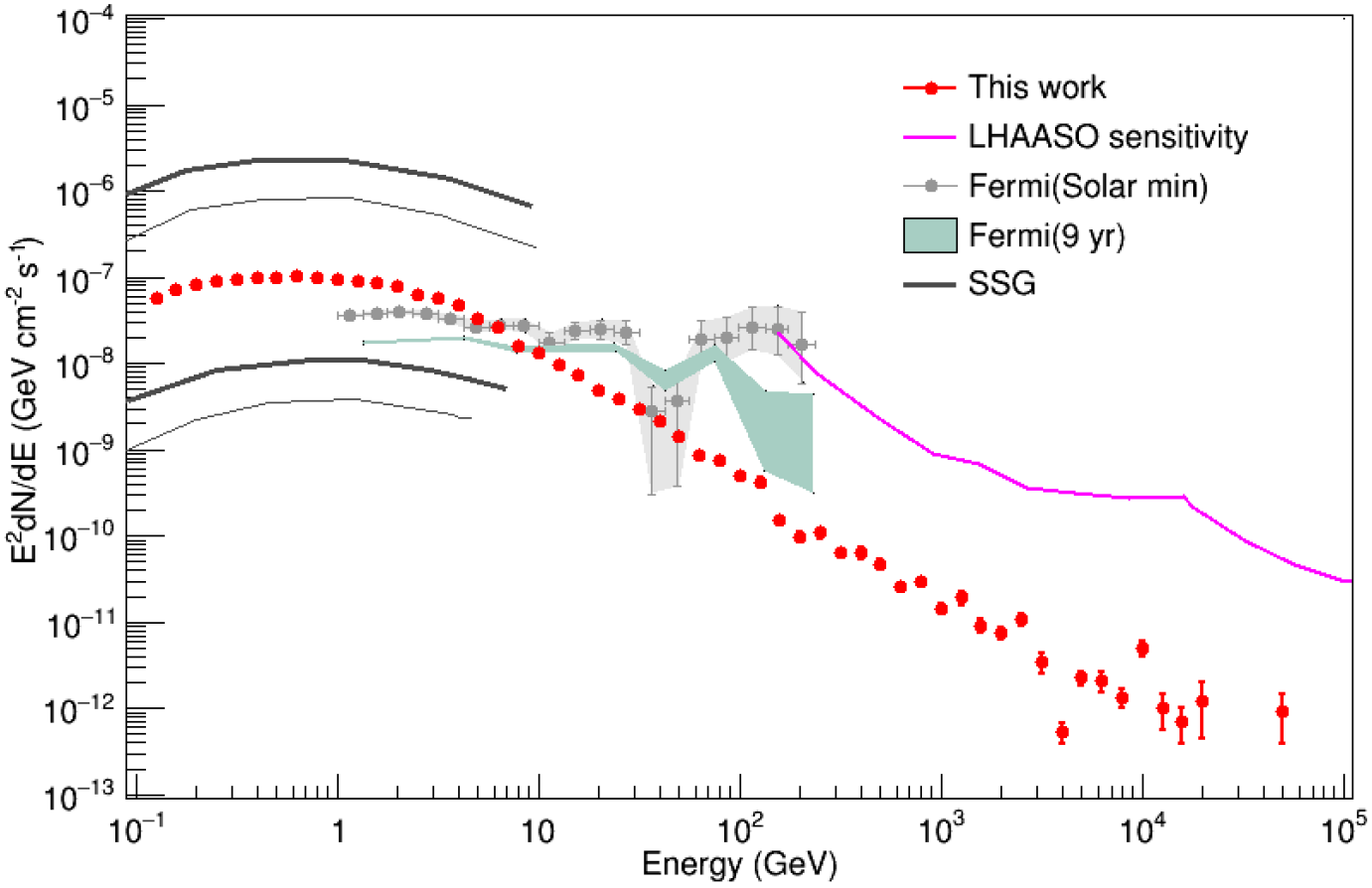
This work

3. Solar disk simulation result



- The gamma-ray flux with no magnetic is higher than other results;
- The gamma-ray flux with "quiet" Sun magnetic field simulation increased obviously for gamma rays with energy <100 GeV;
- there is no increasing flux for gamma-ray >150 GeV, which implied that the corona magnetic field make little effect.

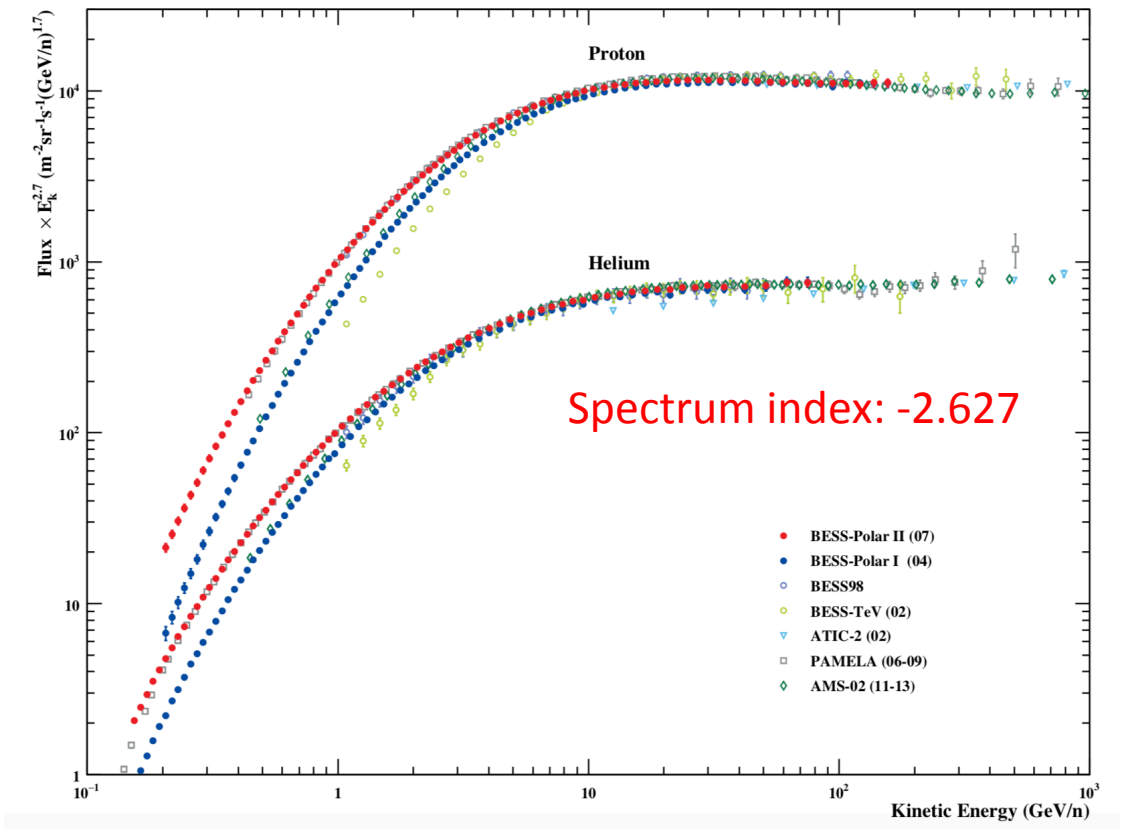
3. Solar disk simulation result



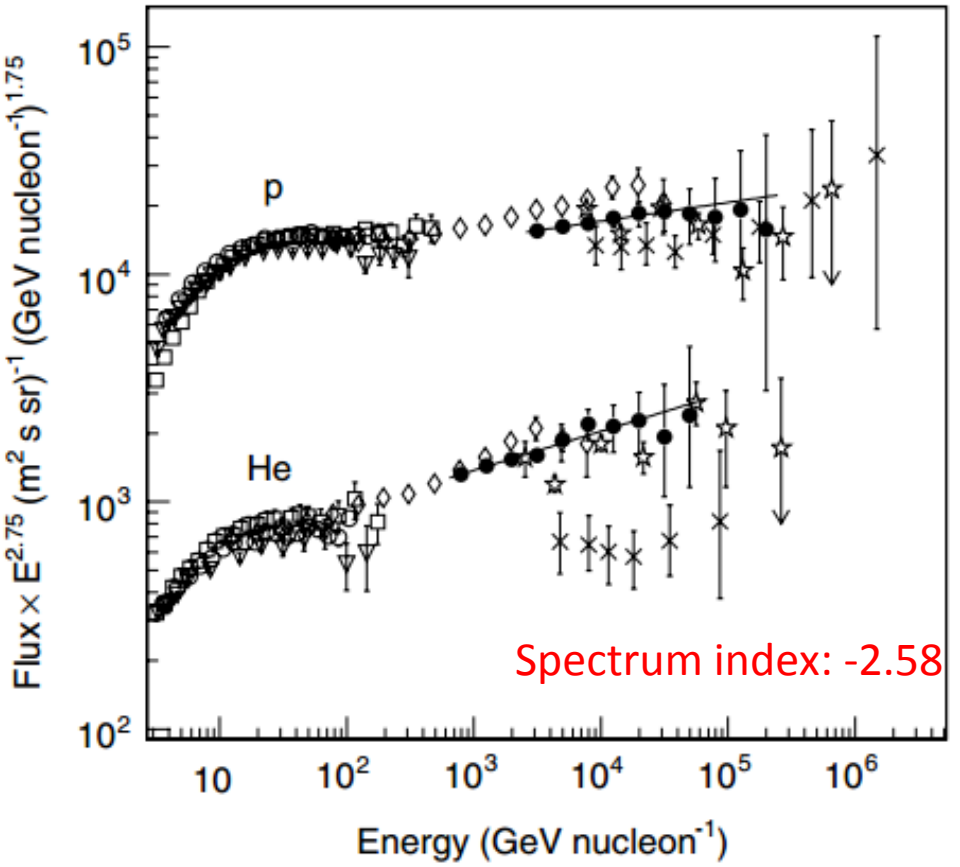
- For solar disk gamma-ray <5GeV, the spectrum is little higher than *Fermi* data ;
- For solar disk gamma-ray >5GeV and <10GeV, the spectrum is in agreement with *Fermi* data ;
- For gamma-ray >10GeV, the simulated spectrum became much softer than *Fermi* data.

3. Solar disk simulation result

- Primary helium spectrum

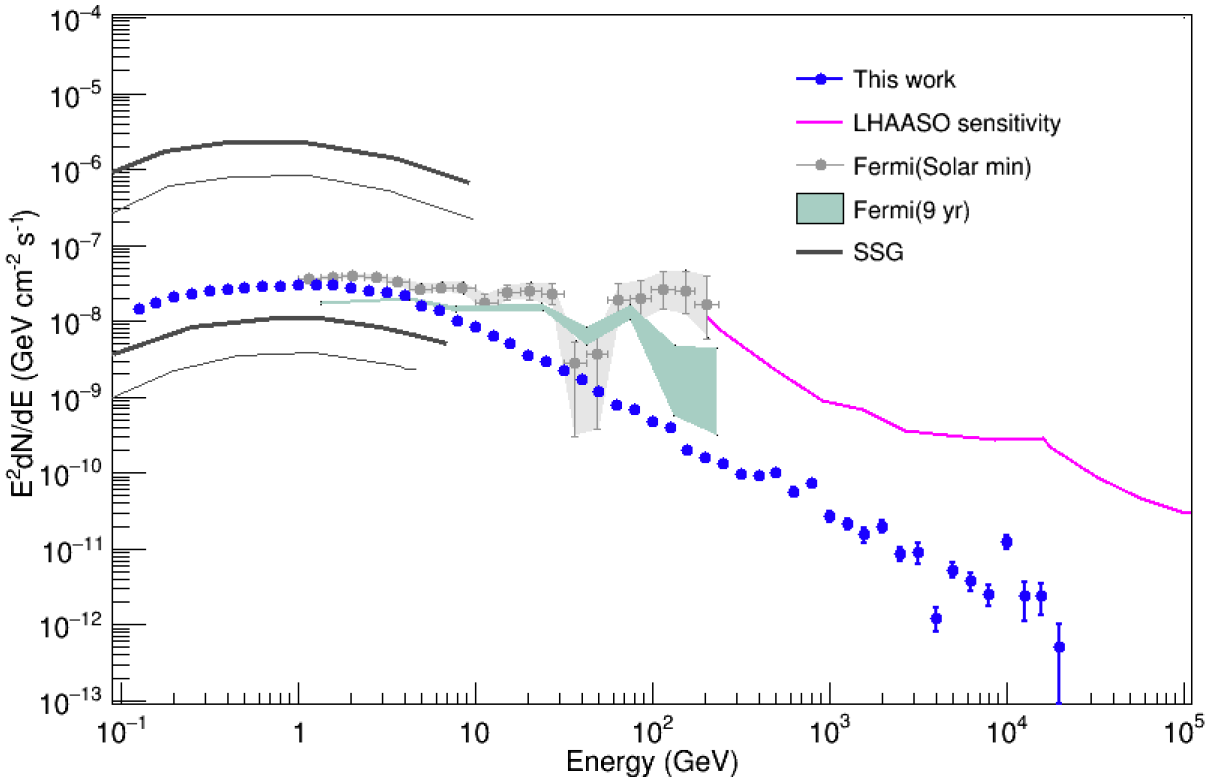


2016,BESS

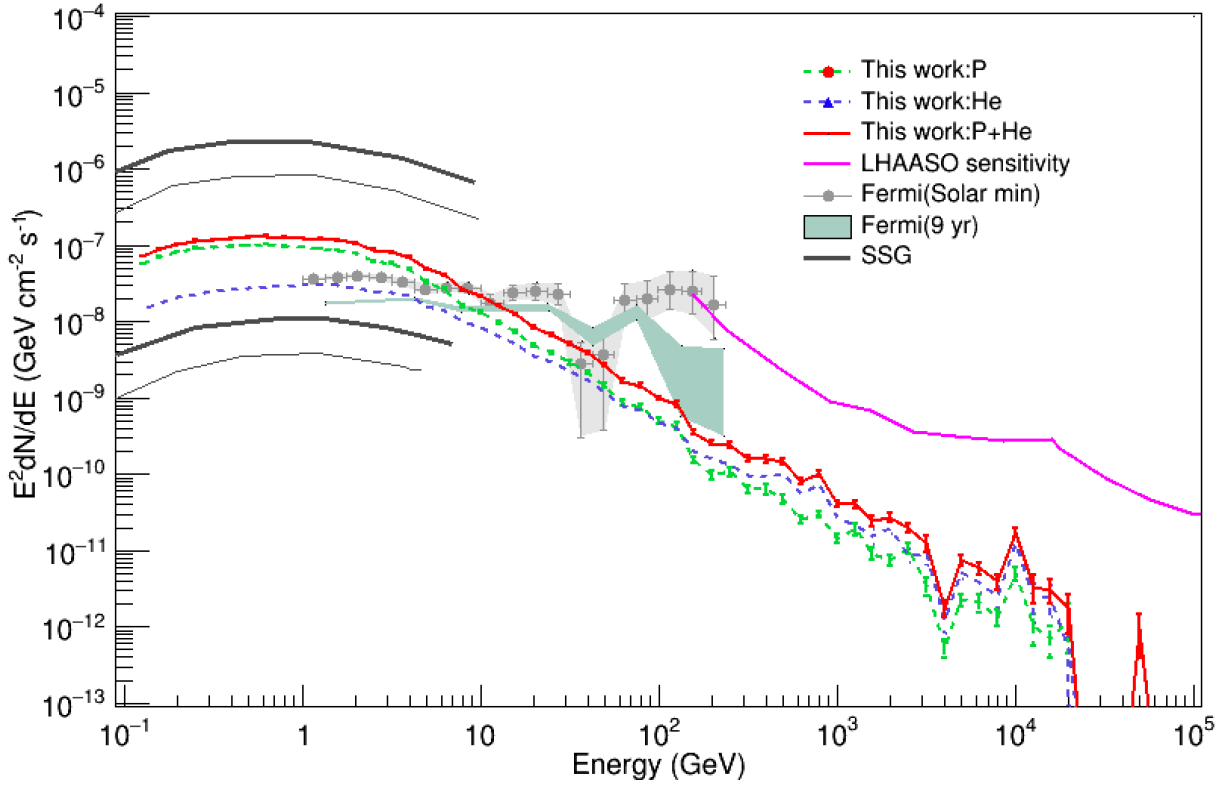


CREAM,2011

3. Solar disk simulation result



Gamma-ray flux produced by Helium primary particle.



Primary particle: P + He

Summary

- The **G4SOLAR** program was developed to simulated the interaction between cosmic rays and solar based on Geant4;
- **More complex sampling procedure** of primary cosmic ray (proton) was investigated and checked;
- The **PFSS model for "quiet" Sun** was employed in G4SOLAR program to describe the magnetic field structure of corona;
- Solar disk gamma-ray is much **softer than *Fermi*** observation.

Thanks for your attention!