Study of Earth's Stratospheric γ-Ray Emission in Geographical Coordinates with *Fermi* LAT

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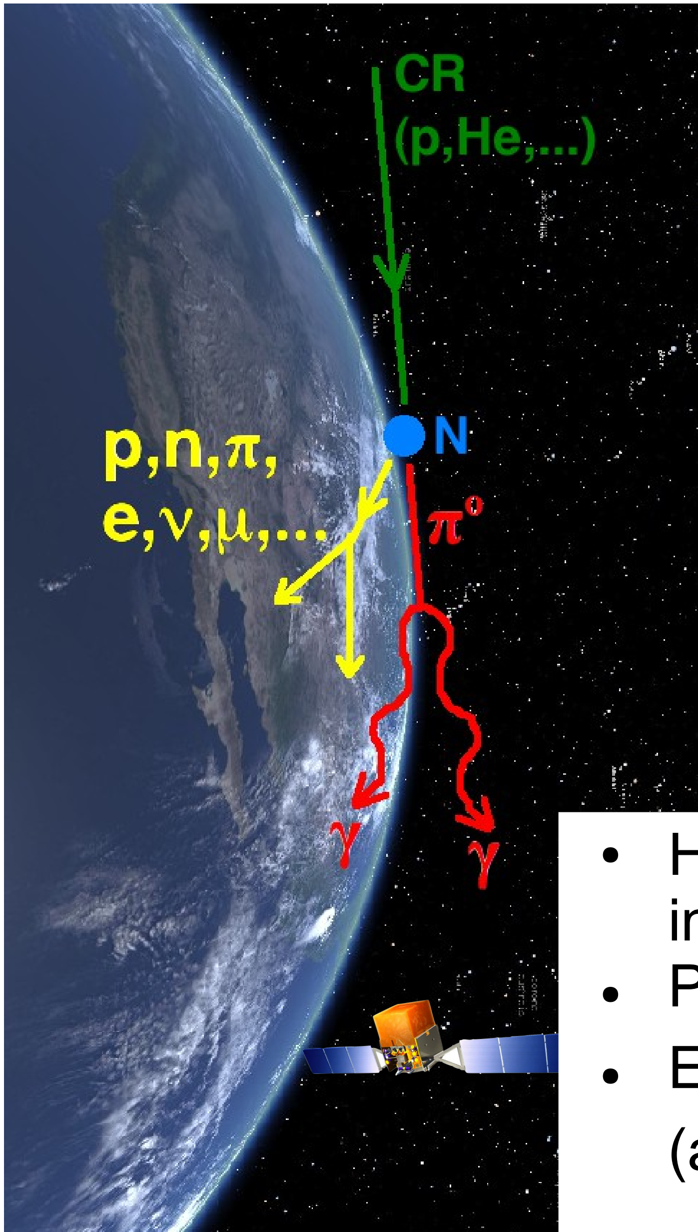
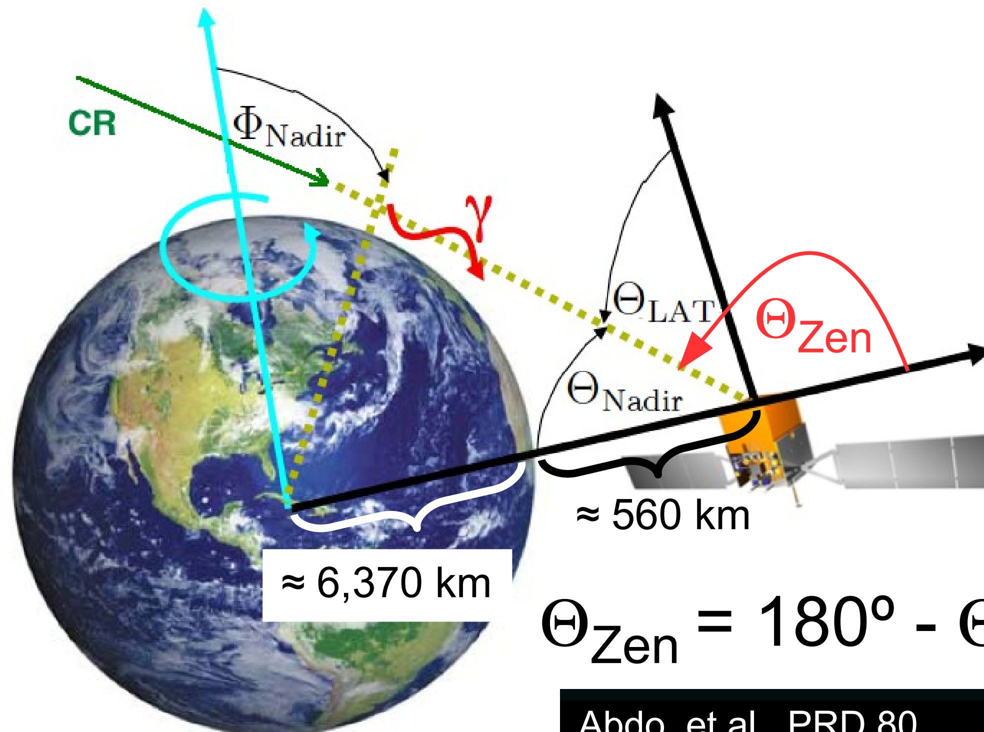
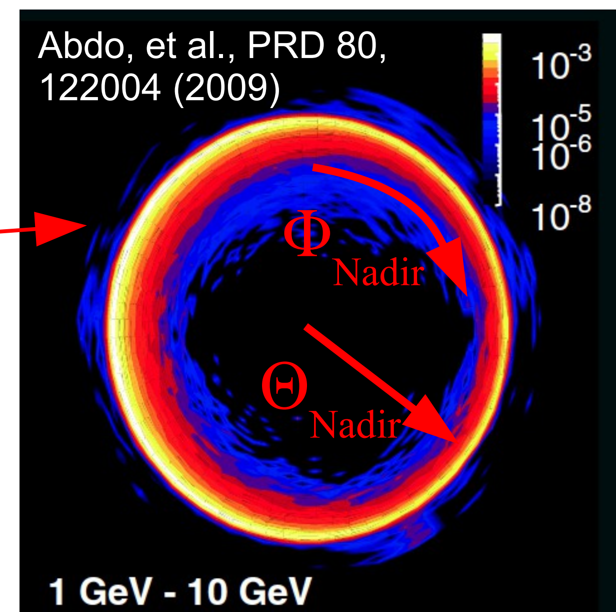
Cosmic-Ray (CR)-Induced γ-Ray Emission of Earth



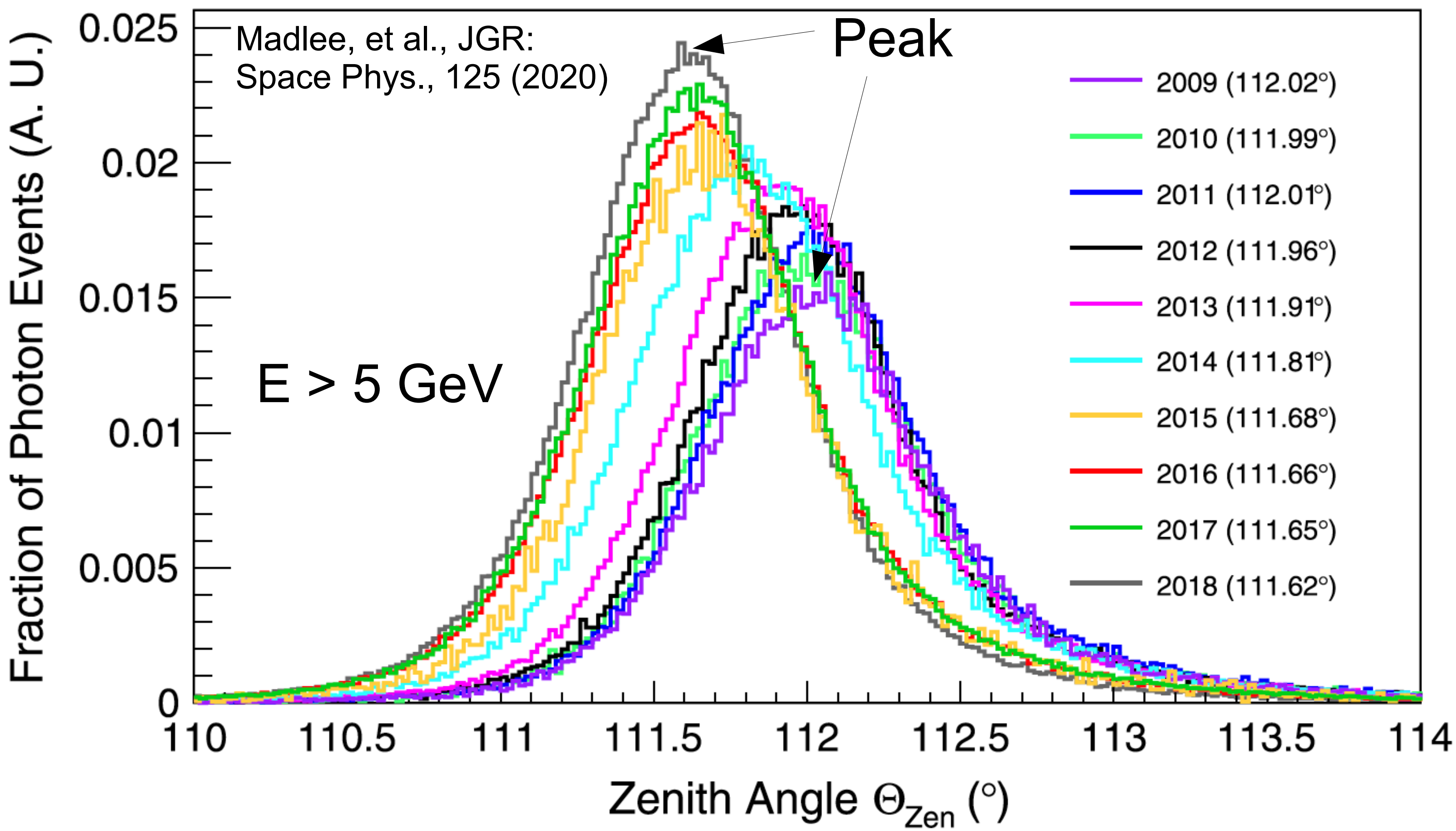


$$\Theta_{Zen} = 180^{o} - \Theta_{Nadir}$$

- How Earth appears in γ ray for LAT
- Physical limb: $\Theta_{Zen} \approx 113°$
- Emission peak: $\Theta_{Zen} \approx 112°$ (altitude ≈ 50 km)

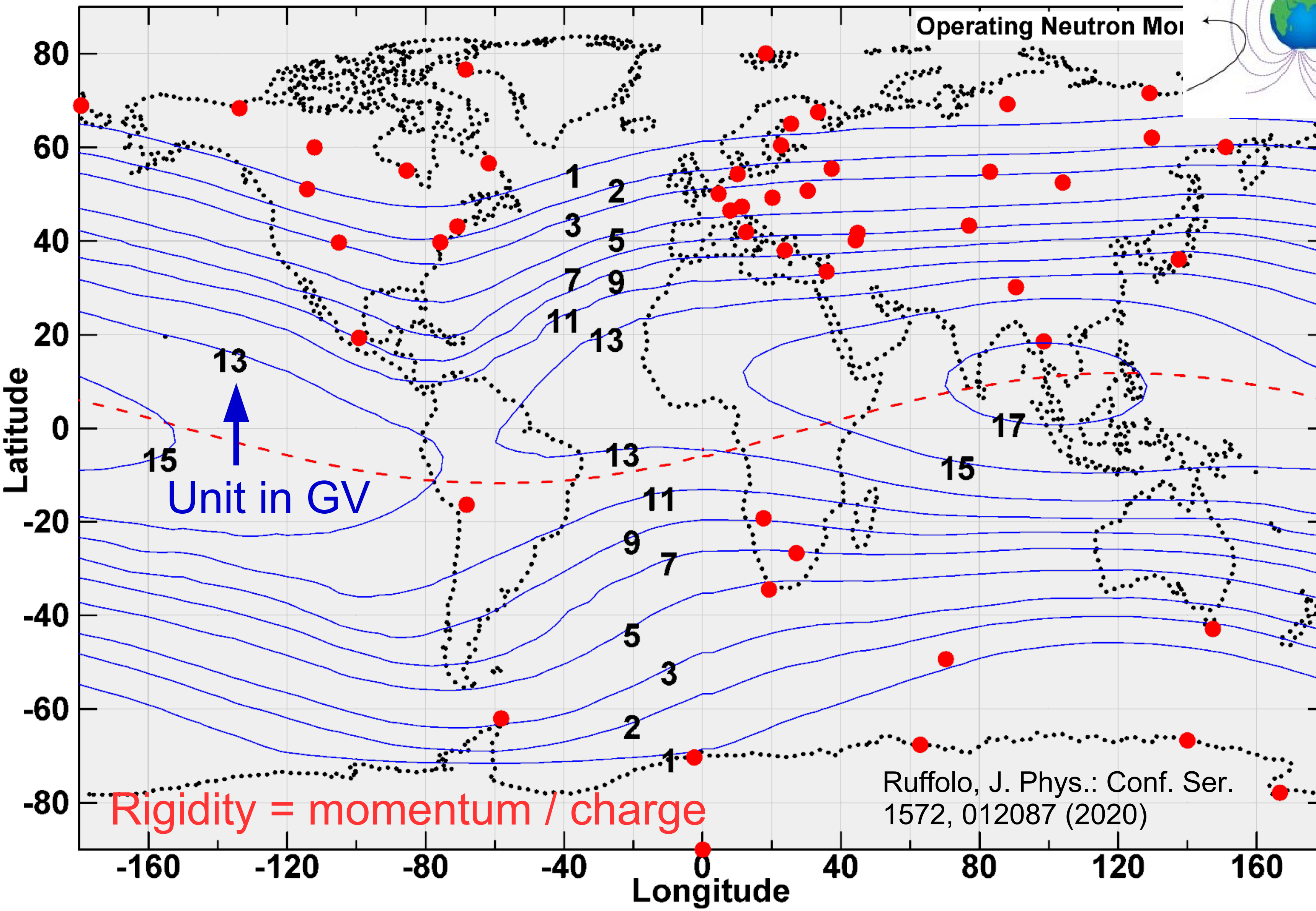


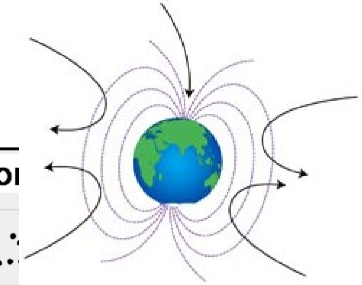
Earth's γ-Ray Zenith Profile



- Peak of profile moved over time due to LAT orbital decay
- Use data from Peak < Θ_{Zen} < Peak + 2.0° because we can assume that these γ rays were produced at ~50-km altitude (top of stratosphere)
- γ rays with Θ_{Zen} < peak were produced at unknown altitude

Vertical Geomagnetic Cutoff Rigidity

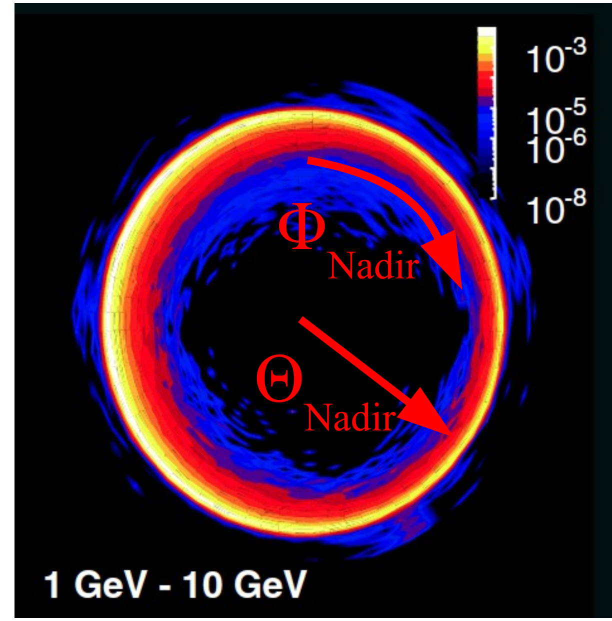


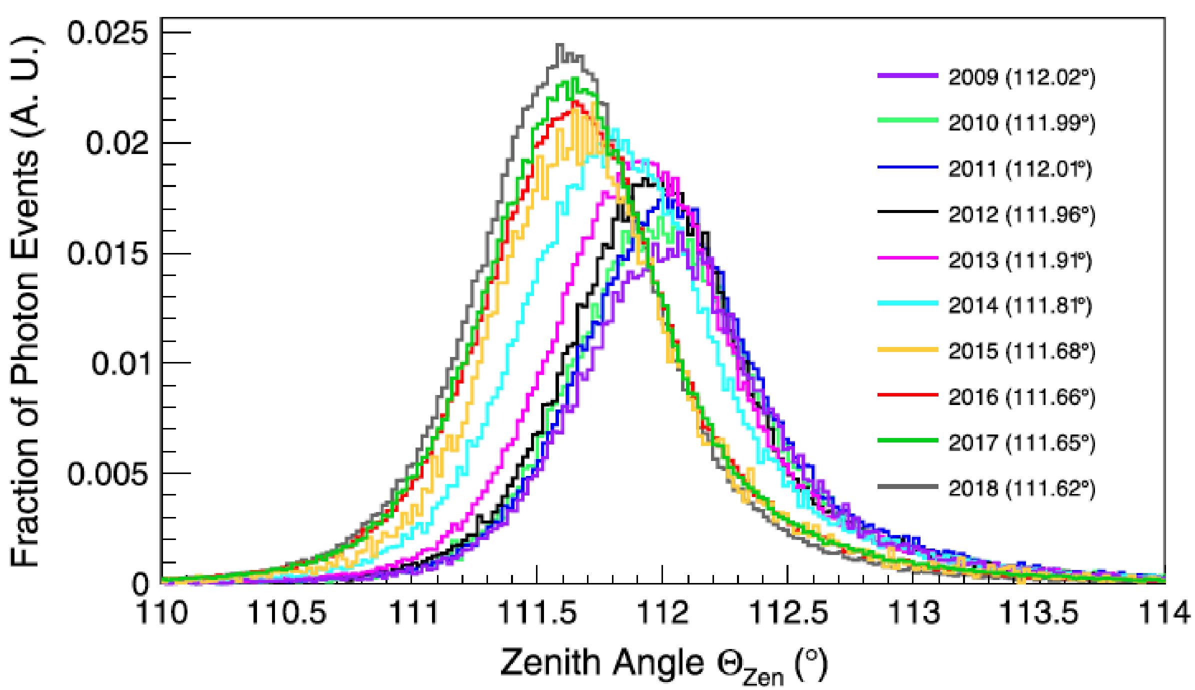


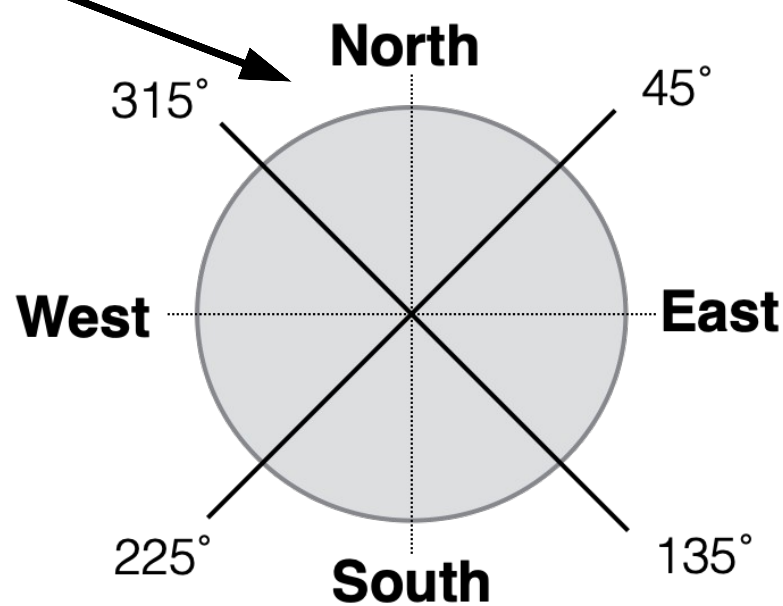
Earth's magnetic field blocks CRs below cutoff rigidities for certain locations

Data Set

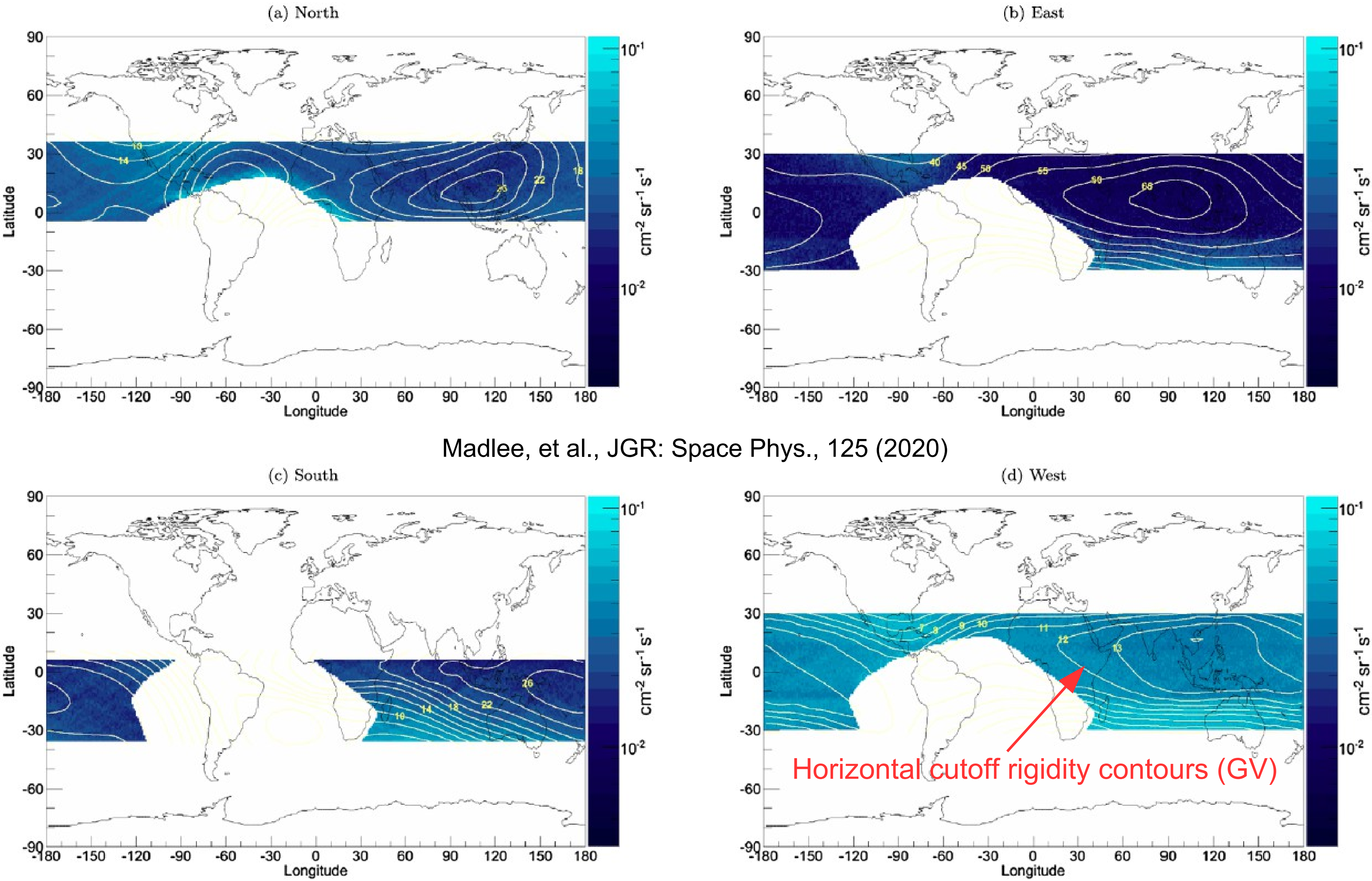
- Jan 1, 2009 to May 30, 2018
- Rocking angle > 55º
- Energy = 200 MeV – 20 GeV
- Peak < Θ_{Zen} < Peak + 2.0º
- Incident angle < 65º
- Event selection = P8R2 Source V6
- Divide Φ_{Nadir} into 4 sections: N, E, S, W





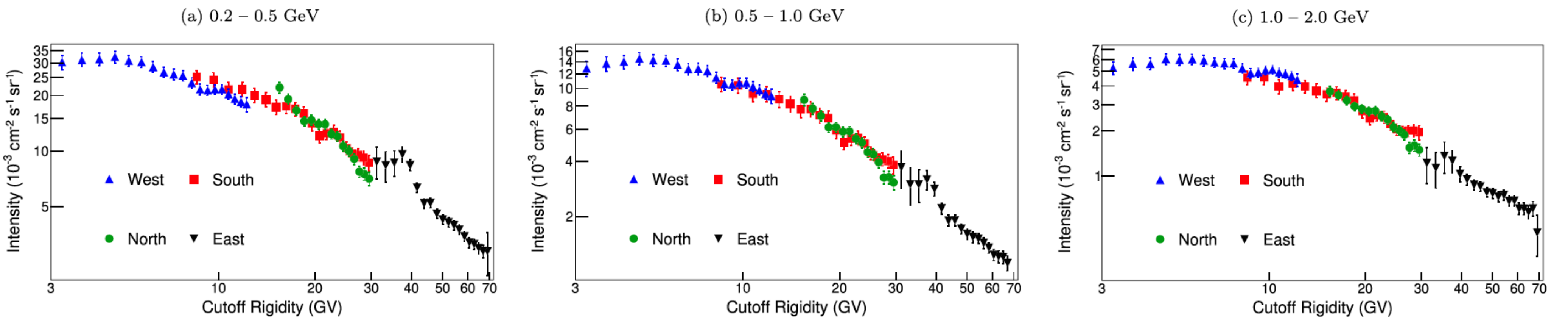


Earth's Stratospheric γ-Ray Intensity Maps

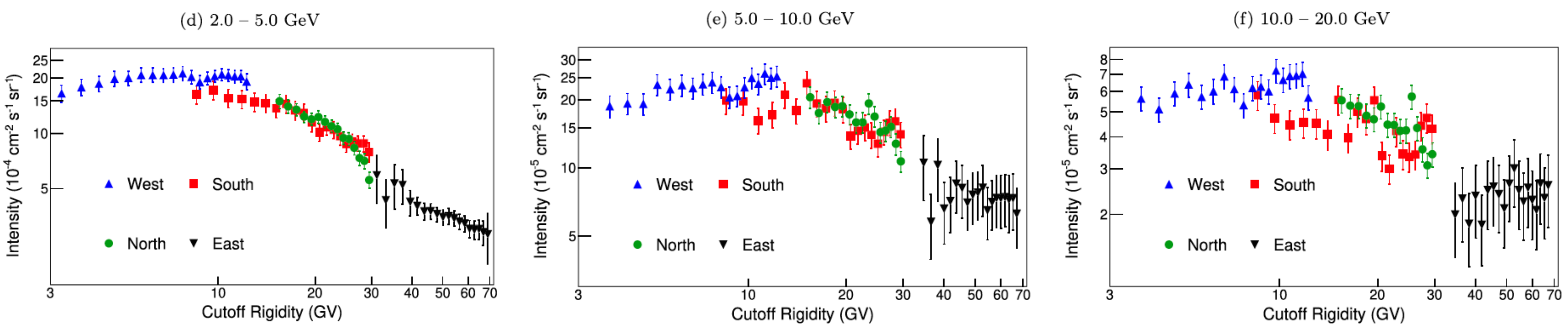


Madlee, et al., JGR: Space Phys., 125 (2020)

Earth's γ-Ray Intensity vs Cutoff Rigidity

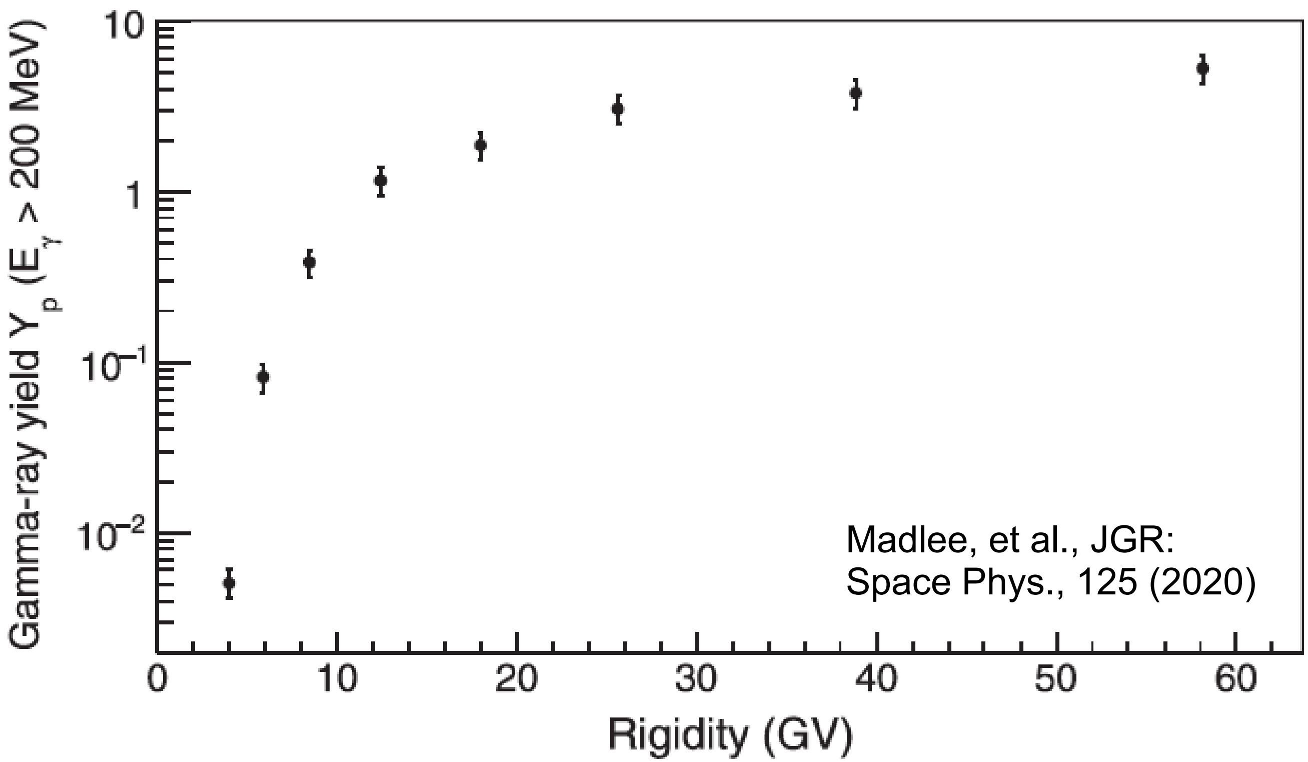


Madlee, et al., JGR: Space Phys., 125 (2020)



- Cutoff rigidity = minimum rigidity for CRs to reach the top of atmosphere at certain location (here for the horizontal direction)
- Earth's γ-ray intensity decreases for increasing cutoff rigidity because CR flux falls steeply with energy
- Minimum CR energy to produce γ rays = the lower bound of the energy bin

Earth's Stratospheric γ-Ray Yield between 0.2 – 20 GeV



γ-ray intensity above cutoff rigidity P_c observed by LAT

$$I(P_c) = \int_{P_c}^{\infty} \sum_i J_i(P) Y_i(P) \, dP$$

CR spectrum of particle i at rigidity P

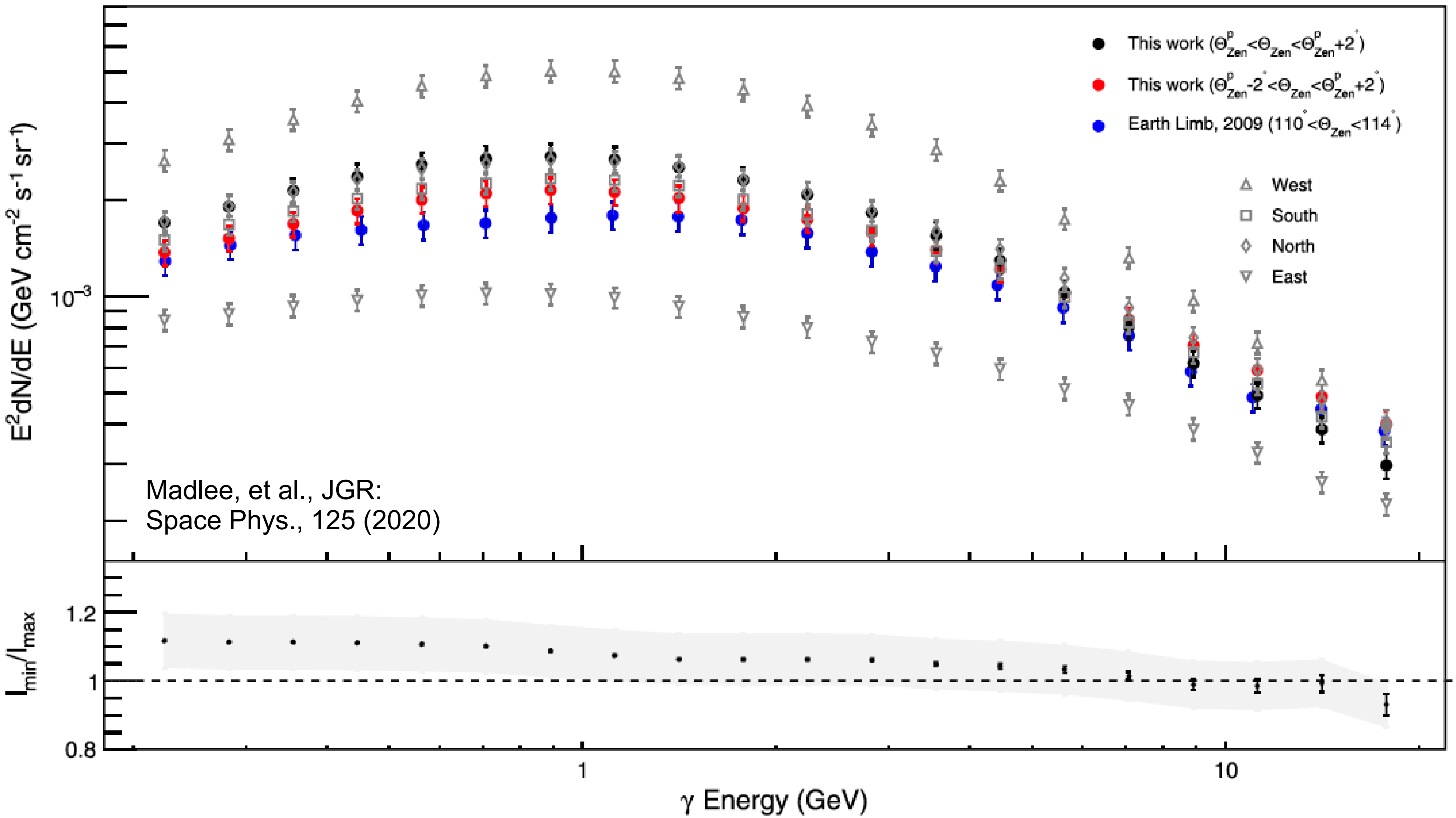
γ-ray yield function for particle i at rigidity P

- Assume only CR protons and He, and Y_{He} = 1.6Y_p,

$$Y_p(P) = -\frac{[dI/dP_c]_P}{J_p(P) + 1.6 J_{\text{He}}(P)}$$

- Interpretation: Y_p = Earth's γ-ray intensity per rigidity emitted from the stratosphere (~50 km) as observed by the LAT divided by CR proton intensity per rigidity near Earth

Earth's γ-Ray Spectrum

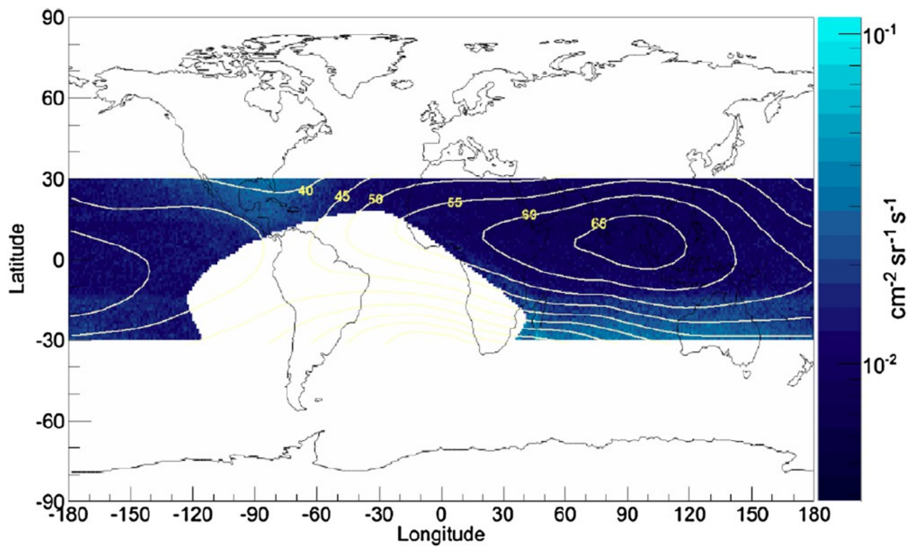


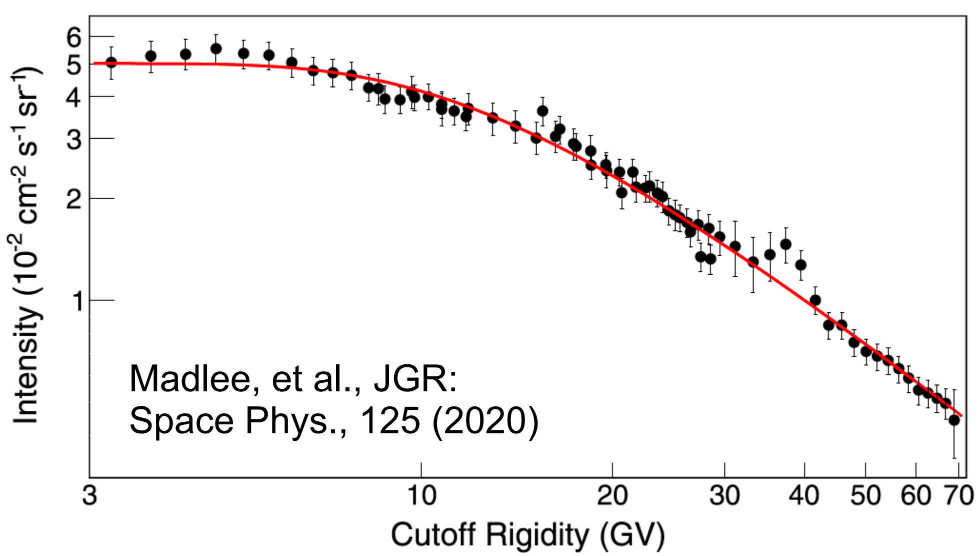
I_{max} = Intensity during solar maximum period (2012 – 2017)

I_{min} = Intensity during solar minimum period (2009 – 2011 and 2017 – 2018)

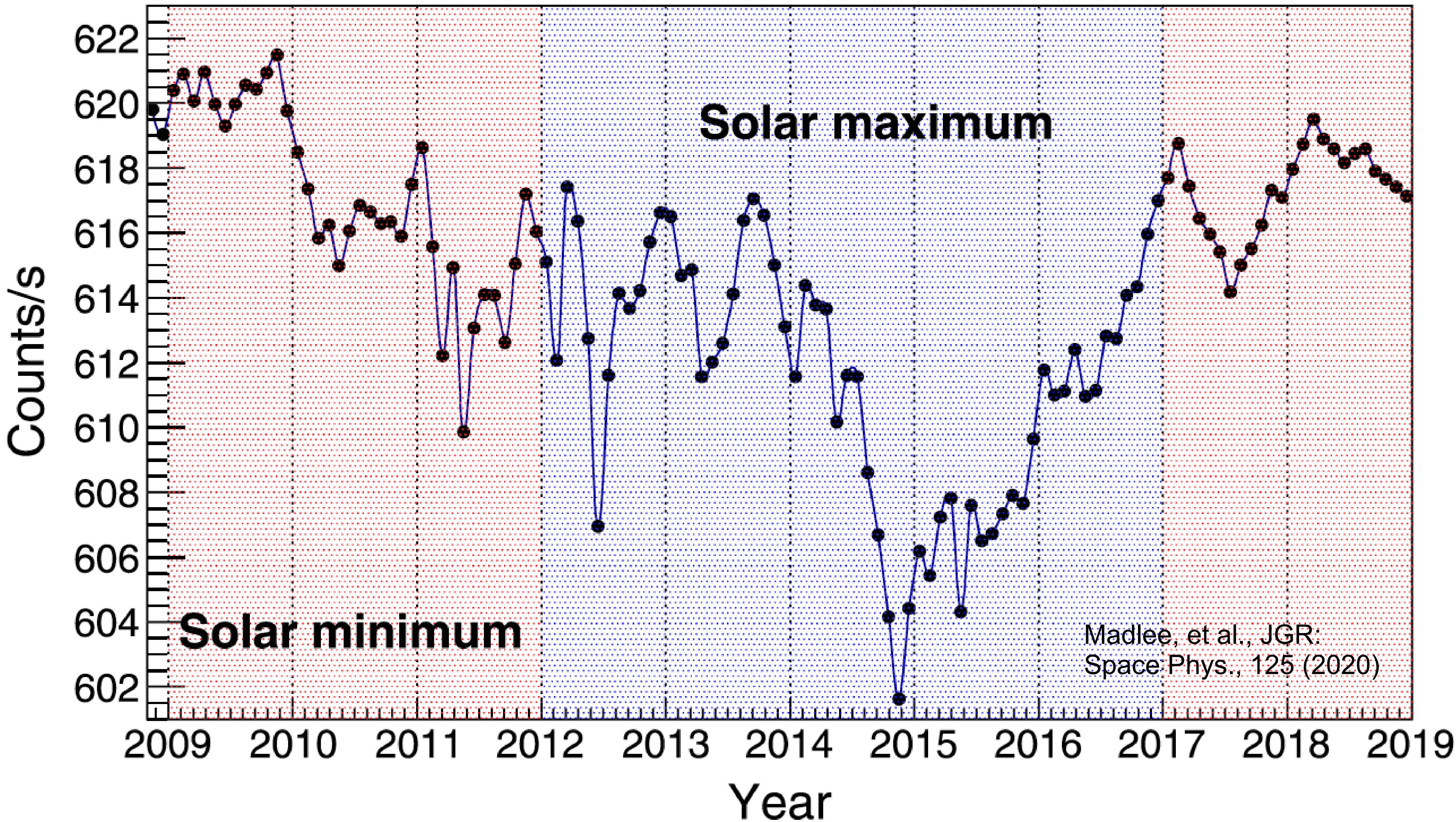
Summary

- Using *Fermi* LAT data, we obtain the first geographical maps of the Earth's stratospheric γ-ray emission from CR air showers
- We study associations between γ-ray emission intensity and the geomagnetic cutoffs for CRs
- We calculate the stratospheric γ-ray yield function between 0.2 – 20 GeV due to CR protons
- This work presents unique data on CR interactions with the heliosphere, the geomagnetic field, and the atmosphere





Back Up 1: High-Cutoff Neutron Monitor Count Rate



Back Up 2: Atmospheric Column Density