Cosmic Ray Elemental Spectra and Atmospheric Neutrino Fluxes

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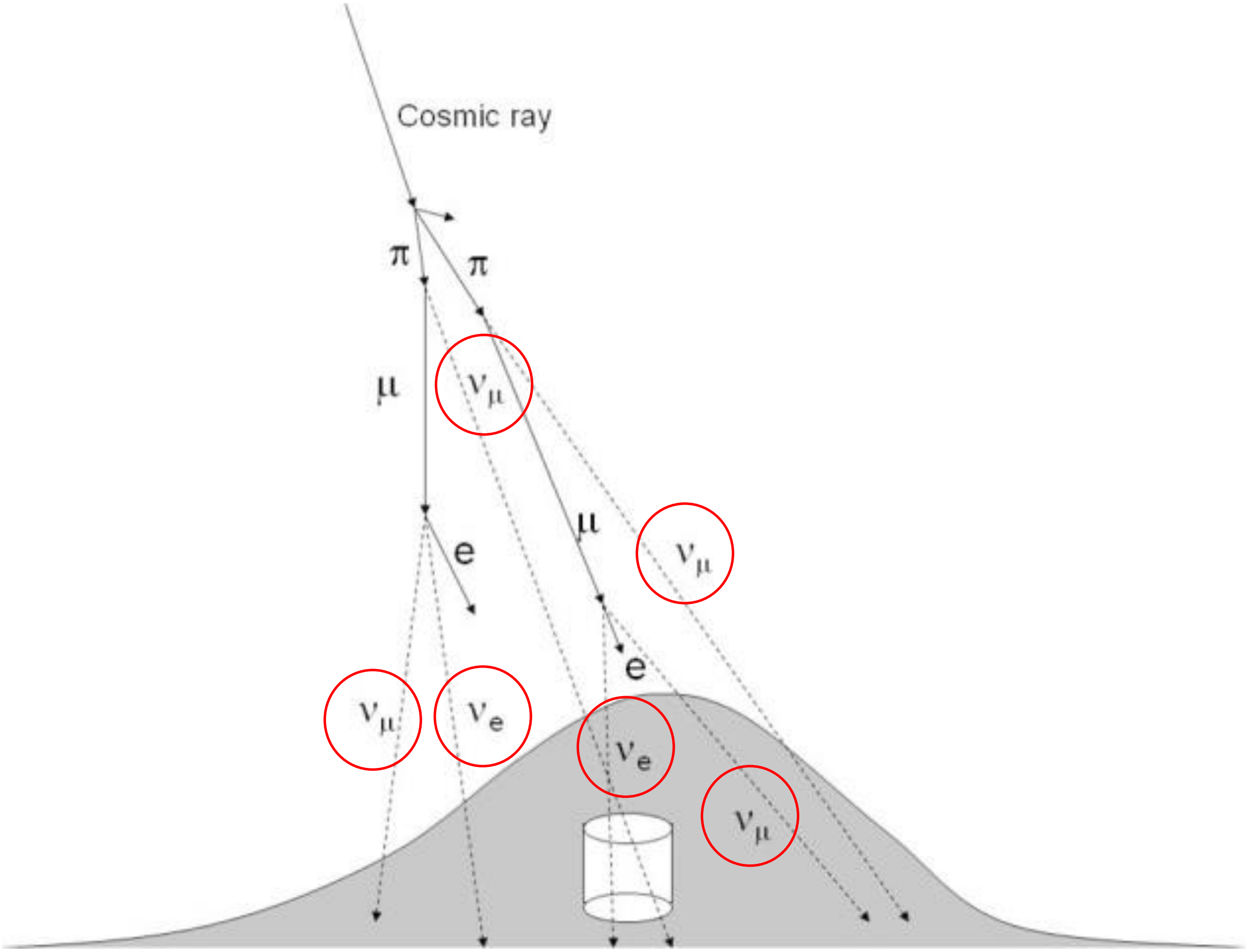
Credit: IceCube/Nasa

Background: Atmospheric Neutrinos

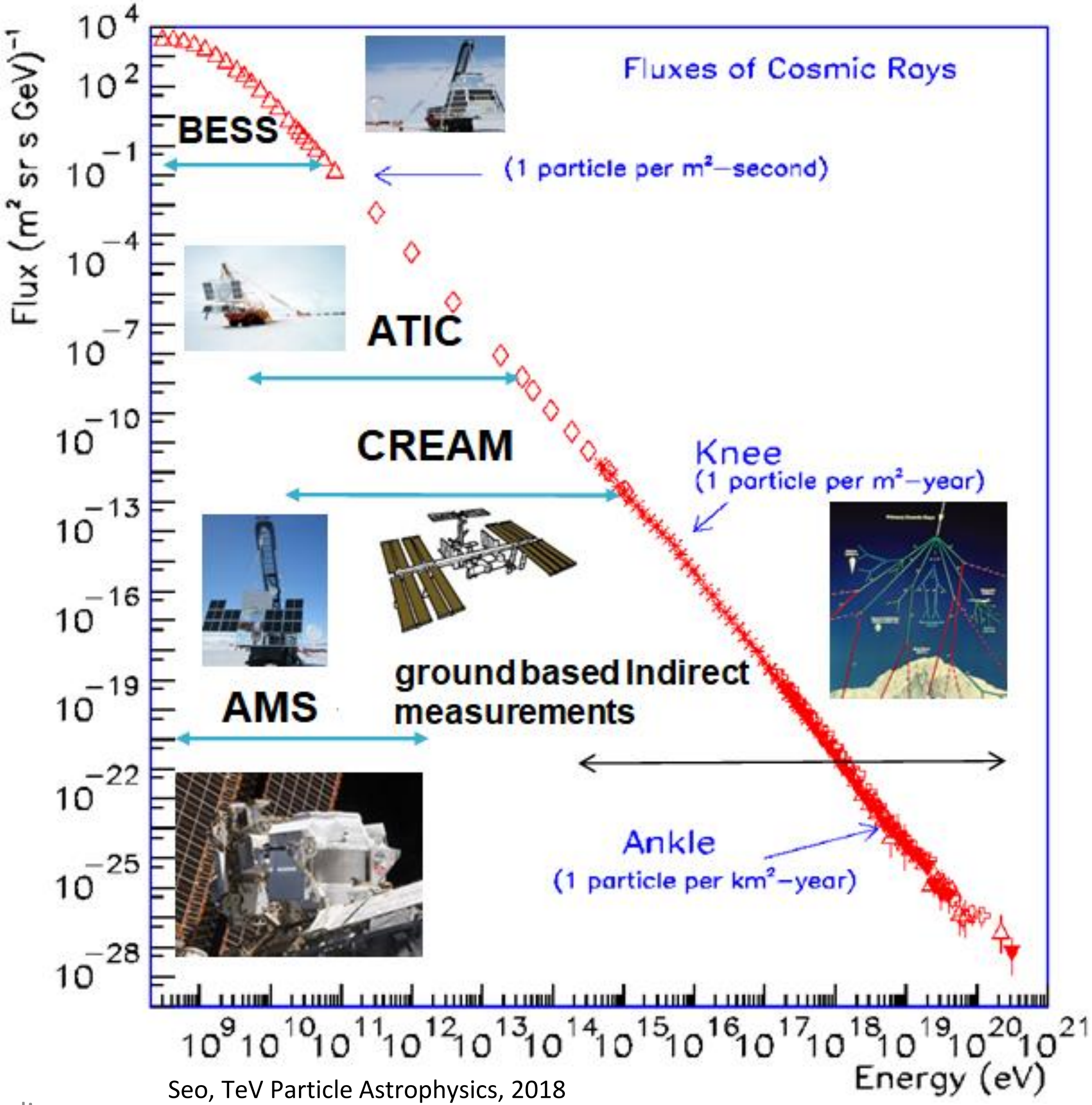


Kajita, Atmospheric neutrinos and discovery of neutrino oscillations, 2010

- Produced when cosmic rays interact with Earth's atmosphere
- Atmospheric neutrinos dominate spectra until ~100 TeV, above which astrophysical signal begins to appear

Background: Cosmic Rays

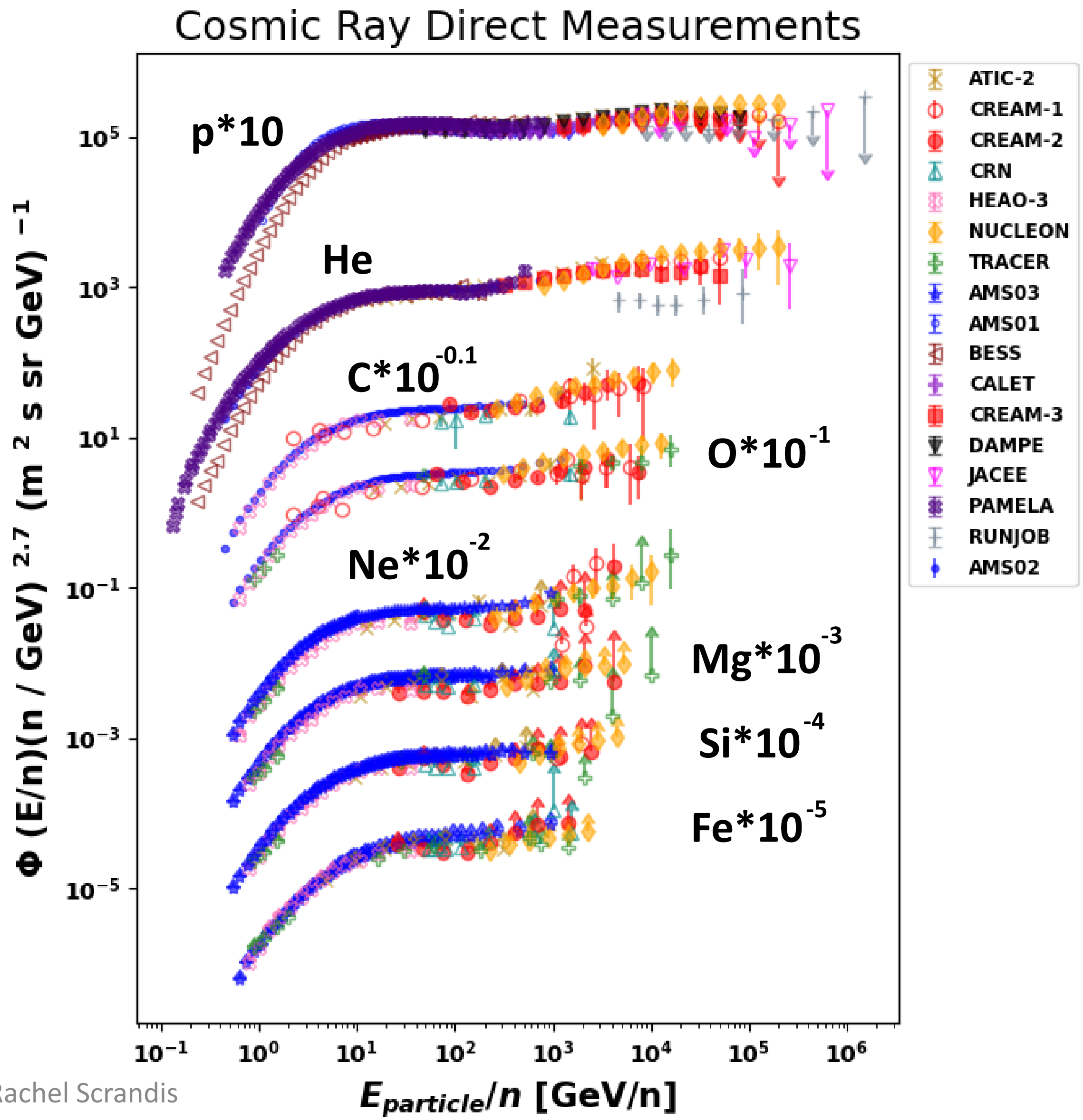
- Generally protons + heavier elements
- All-particle presents a ‘knee’ around 3 PeV
- It is expected to arise from change in underlying population
- Knee energies in cosmic rays translate to transitional energy regime in neutrinos



Seo, TeV Particle Astrophysics, 2018

Direct Measurement Data

- Extends from ~0.1 GeV/n to 10^6 GeV/n
- All elements present spectral hardening ~200 GV
- Assume an acceleration population w/ rigidity dependent cutoff
(Peters, Il Nuovo Cim. 22, 800-819, 1961)



4 Population Model

$$F_i = \underbrace{a_{i,0}E^{\gamma_{i,0}} * \exp\left(\frac{-E}{Z_i R_{cut0}}\right)}_{\text{Population 0}} + \underbrace{a_{i,1}E^{\gamma_{i,1}} * \exp\left(\frac{-E}{Z_i R_{cut1}}\right)}_{\text{Population 1}} + \underbrace{a_{i,2}E^{\gamma_{i,2}} * \exp\left(\frac{-E}{Z_i R_{cut2}}\right)}_{\text{Population 2}} + \underbrace{a_{i,3}E^{\gamma_{i,3}} * \exp\left(\frac{-E}{Z_i R_{cut3}}\right)}_{\text{Population 3}}$$

•Each element will have the same rigidity cut off (Rcut), but different coefficients (a) and indices (γ) (Gaisser, Stanev, & Tilav. Frontiers of Physics. 8, 6, 2013)

•Element Grouping (M. Aguilar et al., Phys. Rev. Lett., 126, 4, 2021):

- <u>Proton Group:</u> p; <u>Helium Group:</u> He, C, O, Fe; <u>Neon Group:</u> Ne, Mg, Si

4 Population Model

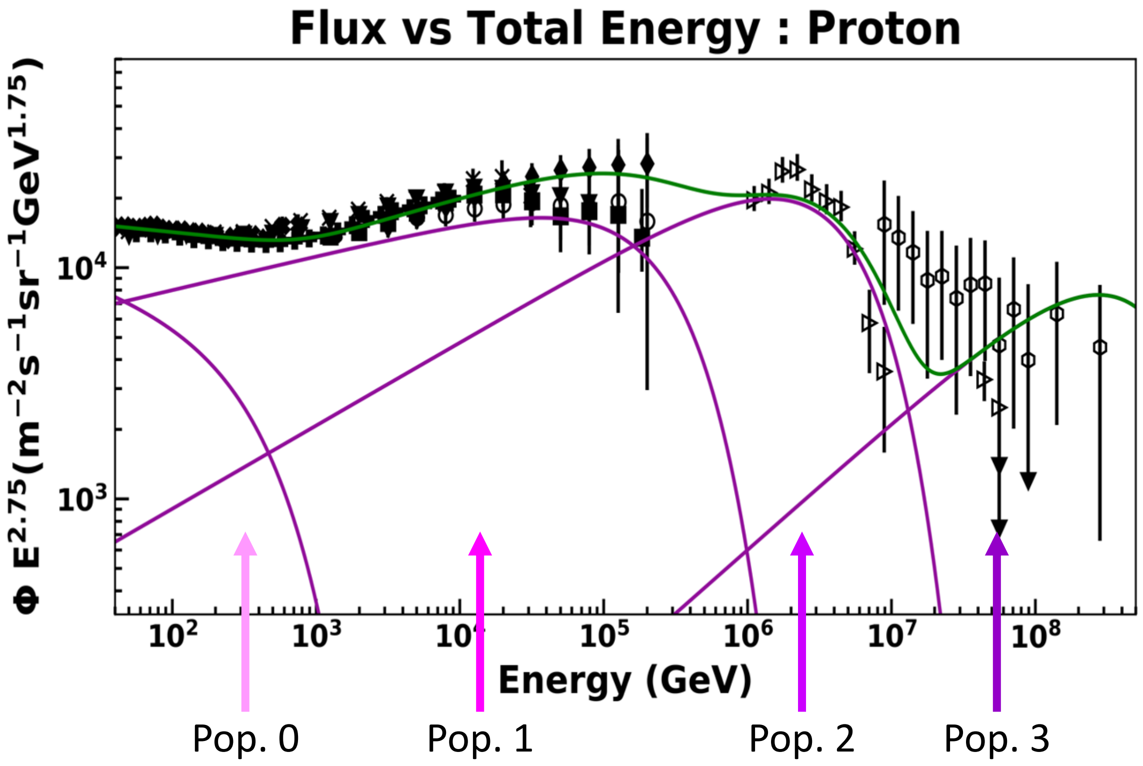
$$F_i = a_{i,0}E^{\gamma_{i,0}} * \exp\left(\frac{-E}{Z_i R_{cut0}}\right) + a_{i,1}E^{\gamma_{i,1}} * \exp\left(\frac{-E}{Z_i R_{cut1}}\right) + a_{i,2}E^{\gamma_{i,2}} * \exp\left(\frac{-E}{Z_i R_{cut2}}\right) + a_{i,3}E^{\gamma_{i,3}} * \exp\left(\frac{-E}{Z_i R_{cut3}}\right)$$

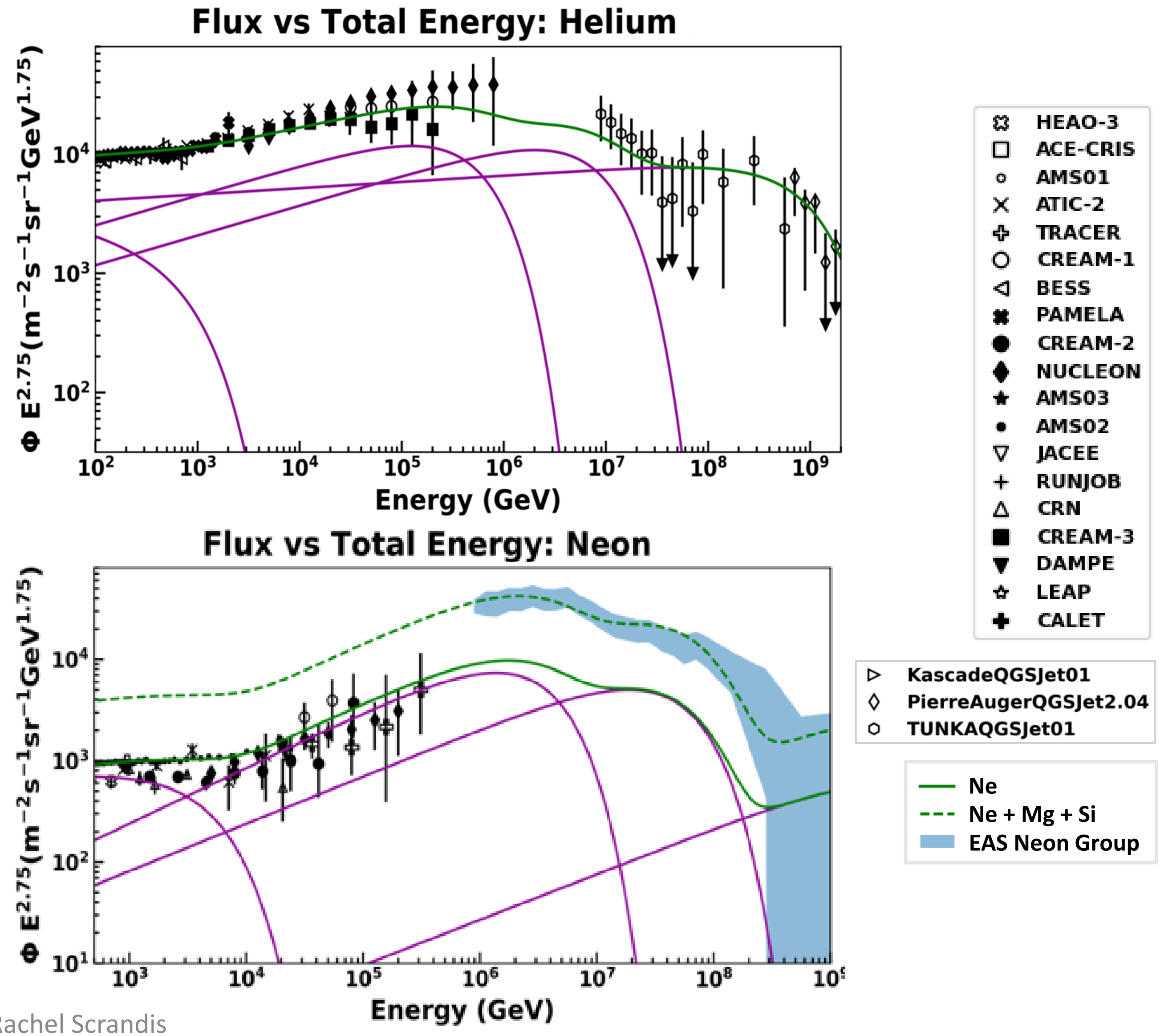
Population 0 | Population 1 | Population 2 | Population 3

Case / Model	Pop 0 RCutoff	Pop 1 RCutoff	Pop 2 RCutoff	Pop 3 RCutoff	Pop 4 RCutoff
Gaisser et al ‘H3a’	-	4 PV	30 PV	2 EV	60 EV
Case I	400 GV	50 TV	4 PV	500 PV	-
Case II	400 GV	250 TV	4 PV	500 PV	-
Case III	400 GV	800 TV	4 PV	500 PV	-

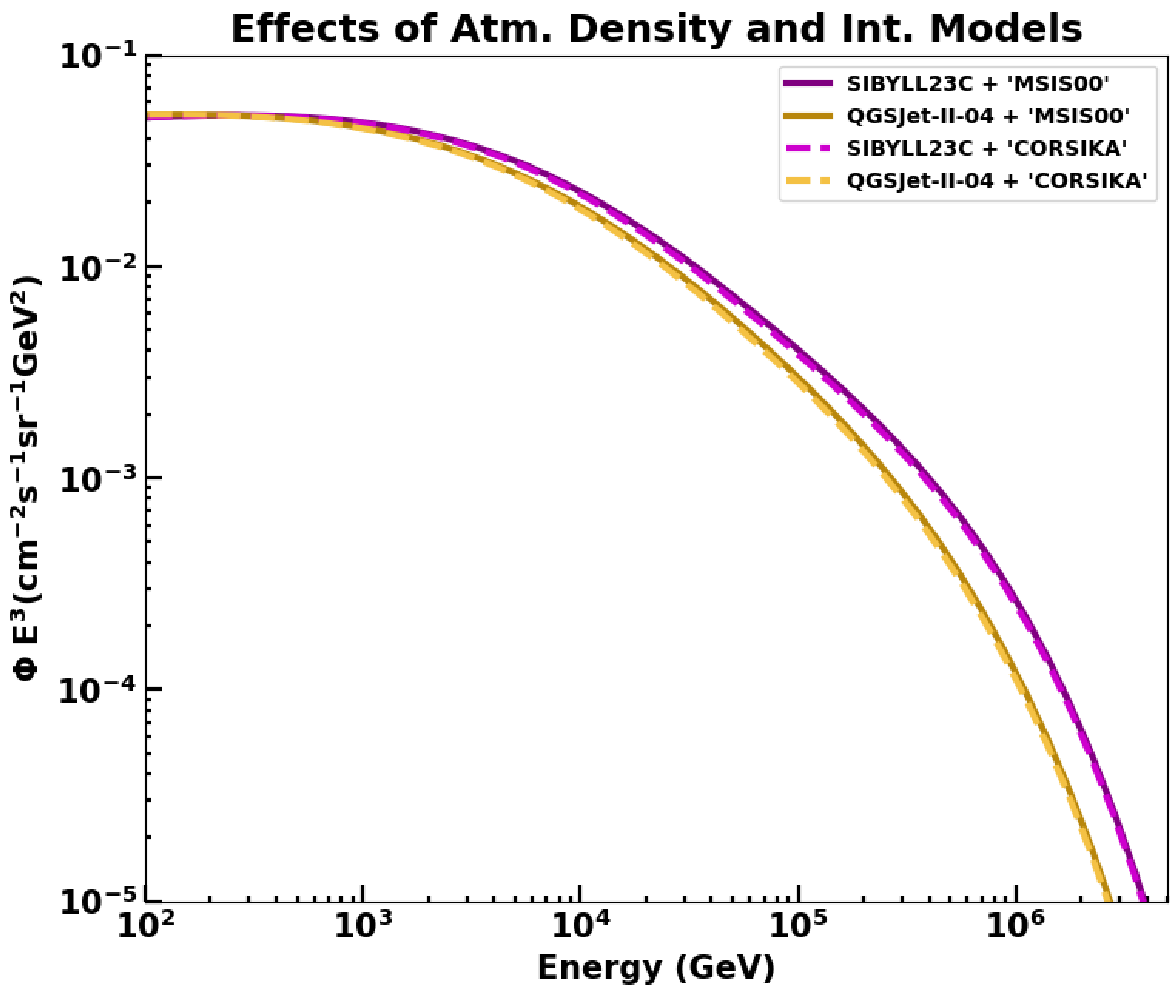
(Gaisser, Stanev, & Tilav. Frontiers of Physics. 8, 6, 2013)

Fitting Results: Case II (250 TV)



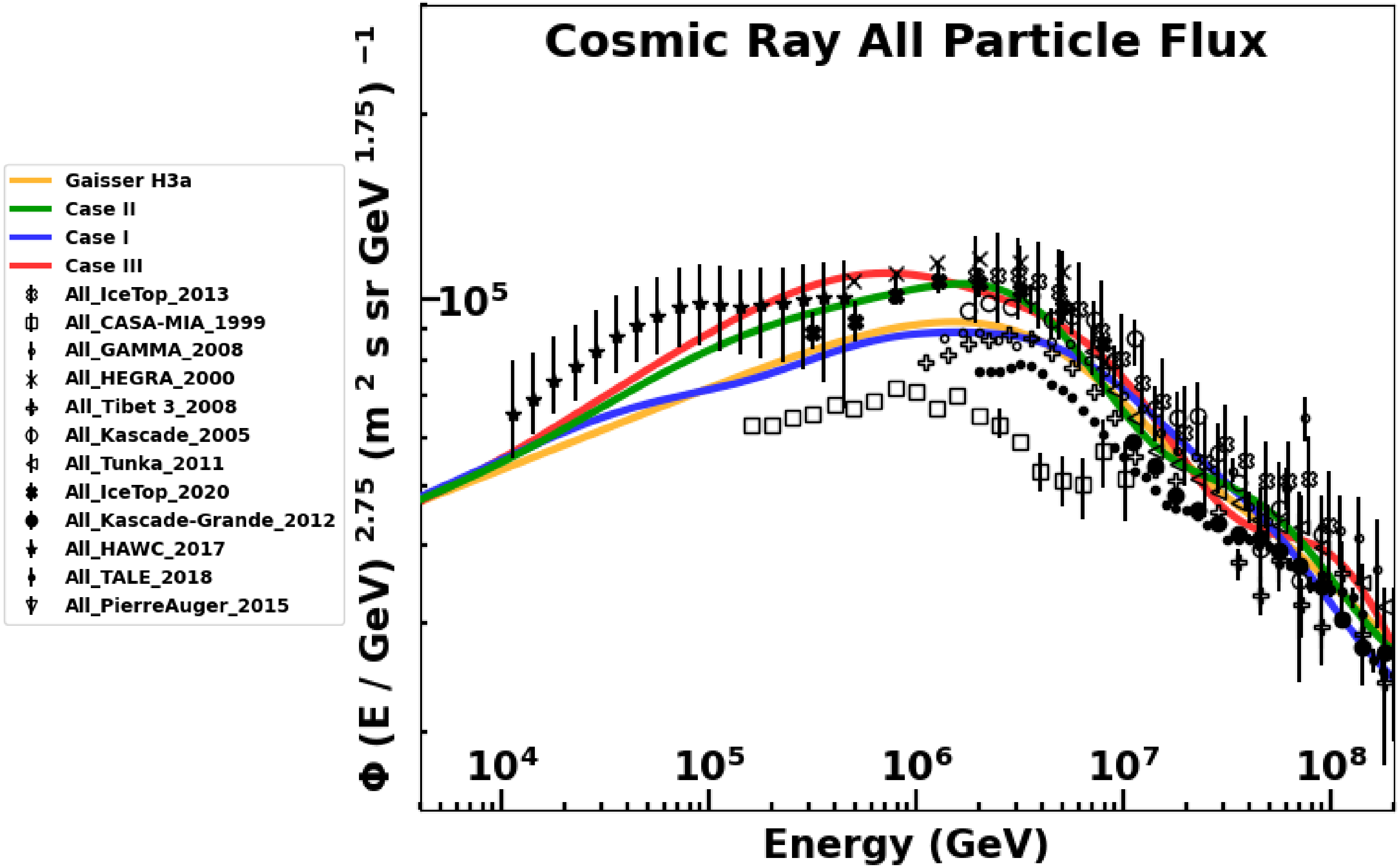


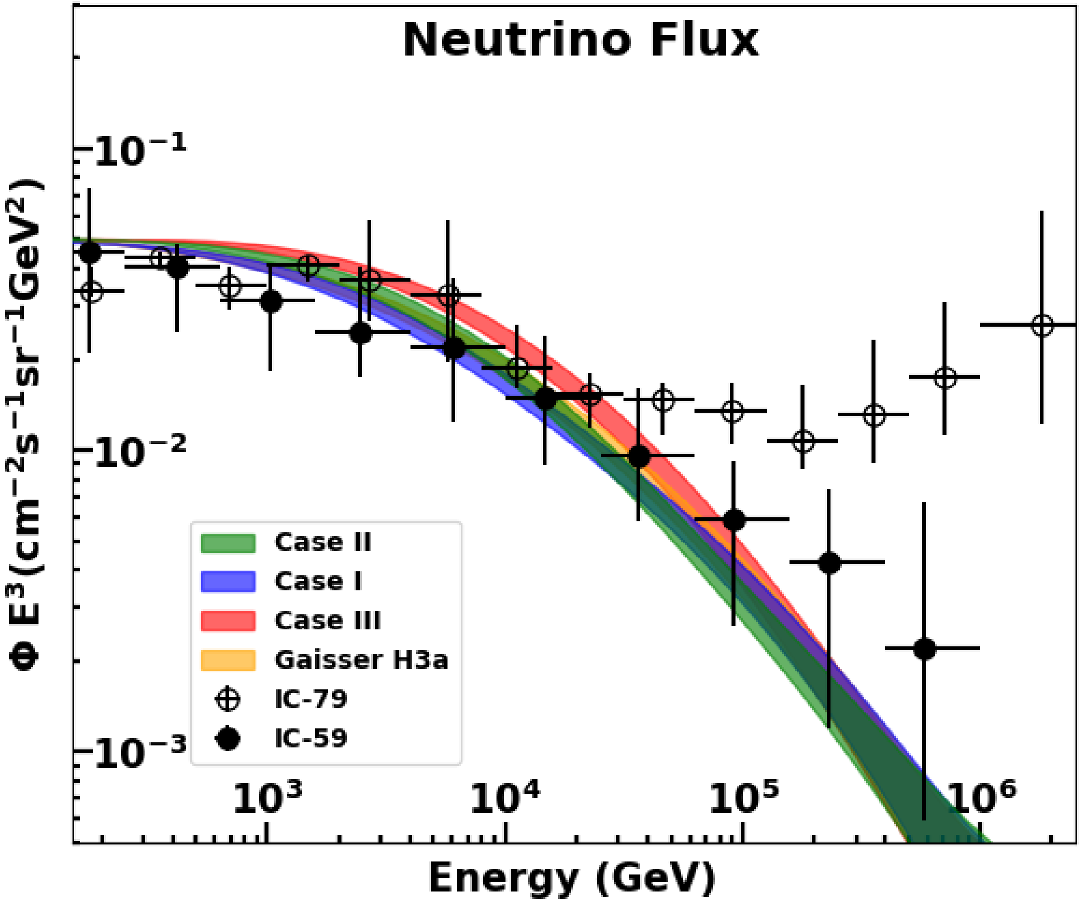
Atmospheric Neutrino Conversion



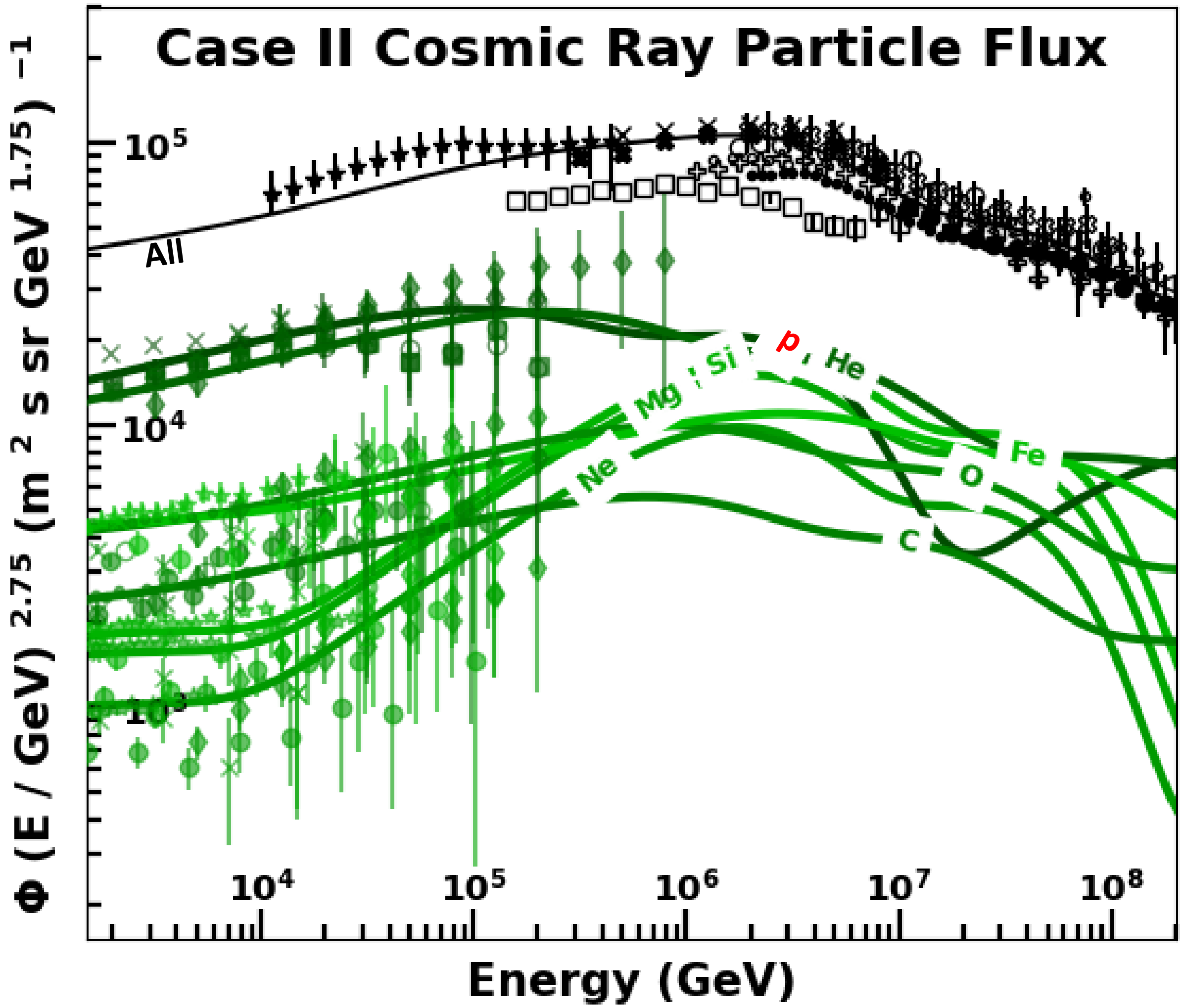
- Utilizing MCEq (A. Fedynitch et al, EPJ Web Conf. 99, 2015)
- MSIS00 atmospheric profile chosen (J.M. Picone et al, J. Geophys. Res. 107, 2002)
- SIBYLL2.3c (F. Riehn et al, PoS ICRC. 301, 2017) and QGSJet-II-04 (Sergey Ostapchenko, Phys.Rev. D83, 2011) interaction models chosen
- Simulation location was chosen to be South Pole
- Flux is averaged over zenith angle and season

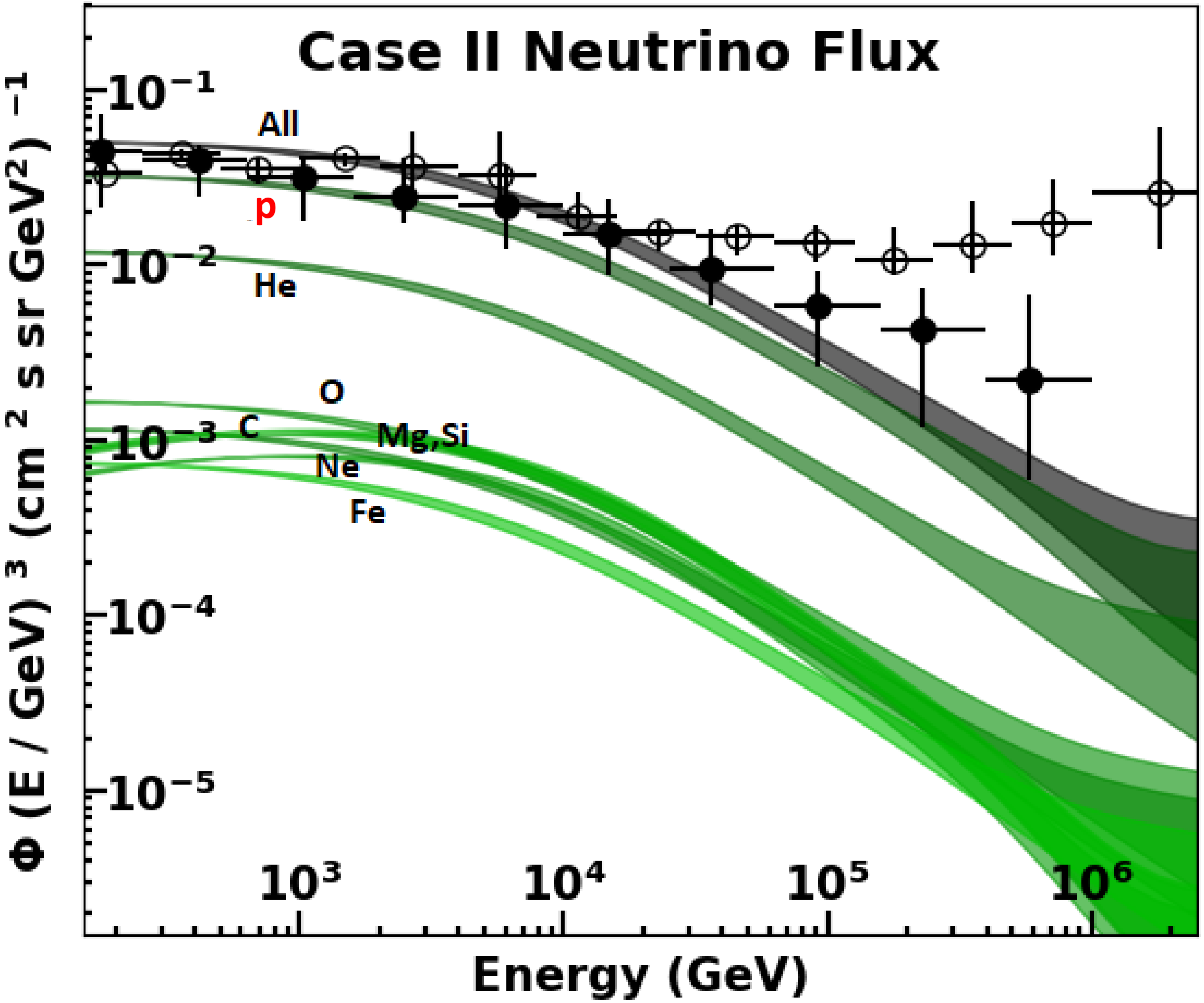
Results: All Particle and Atm. Neutrino Fluxes





Results: Proton Contribution





Results: Minor Tension