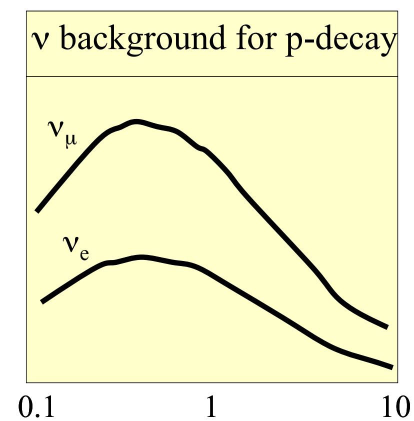
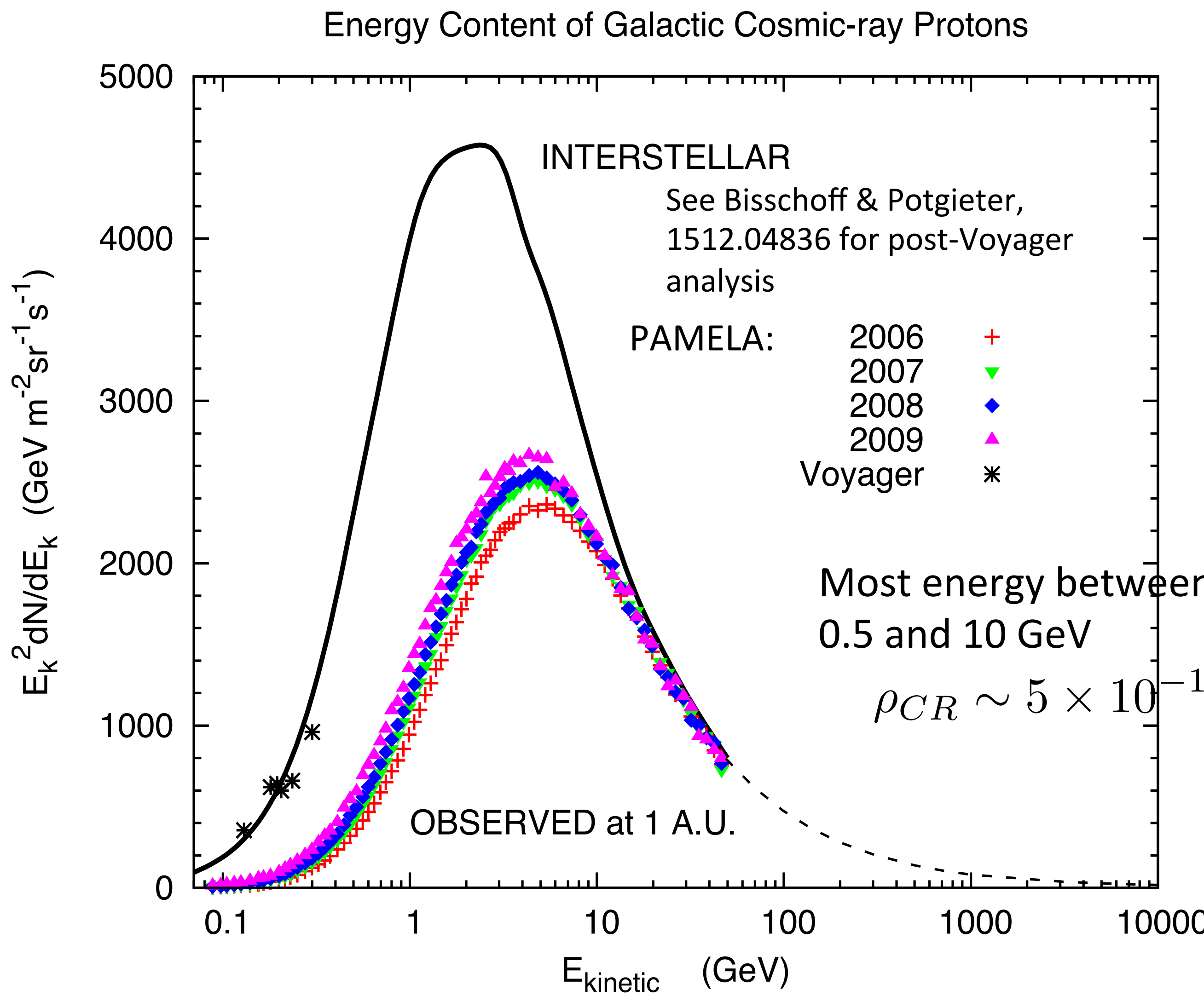
Cosmic-ray fluxes relevant for Atmospheric Neutrinos

I. $\leq$ TeV

II. TeV ~ PeV



From the local ISM to 1 AU



Most energy between 0.5 and 10 GeV

$$\rho_{CR} \sim 5 \times 10^{-13}\ erg/cm^3$$

Solar modulation

BESS, AMS, 1997 - 2000 Cycle 22, A > 0
Fig. from TG & Honda, 2002

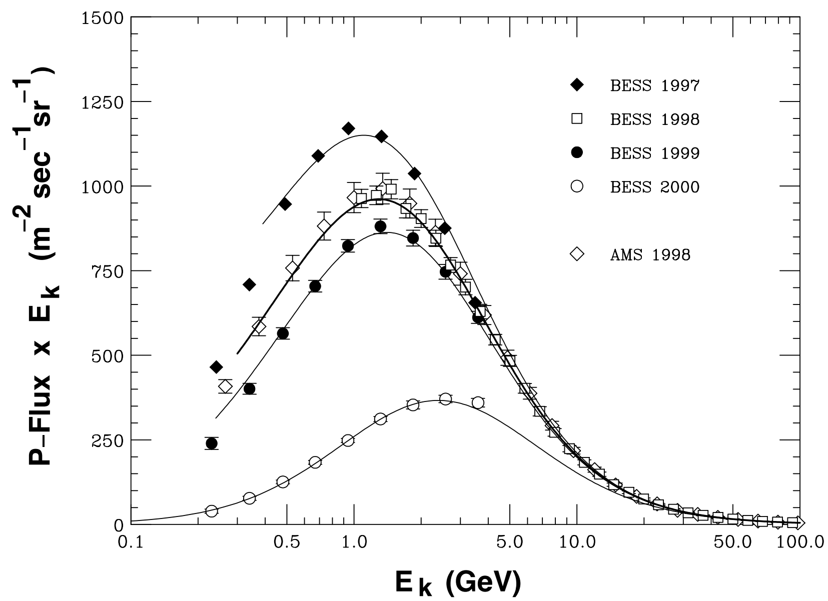
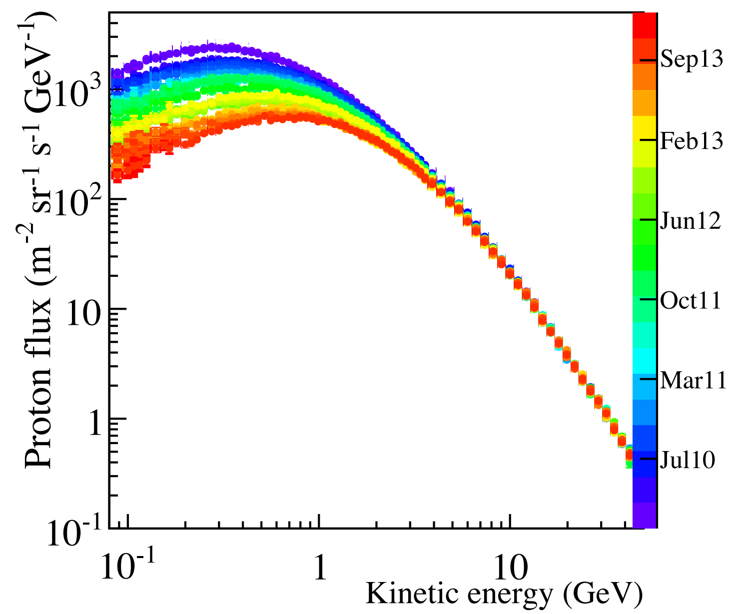


Figure 9 Proton spectra measured by BESS in 1997, 1998, 1999, and 2000 (70). Curves are explained in the text.

PAMELA, 2010 – 2013
Martucci et al., 1801.07112



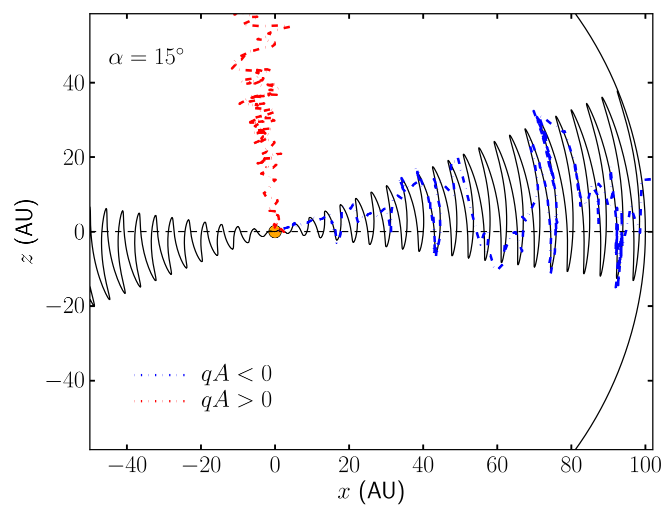
See Cholis, Hooper & Linden, PR D 93 (2016) 043016 a full, physically motivated parameterization of charge-sign-dependent solar modulation

Charge-sign-dependent solar modulation

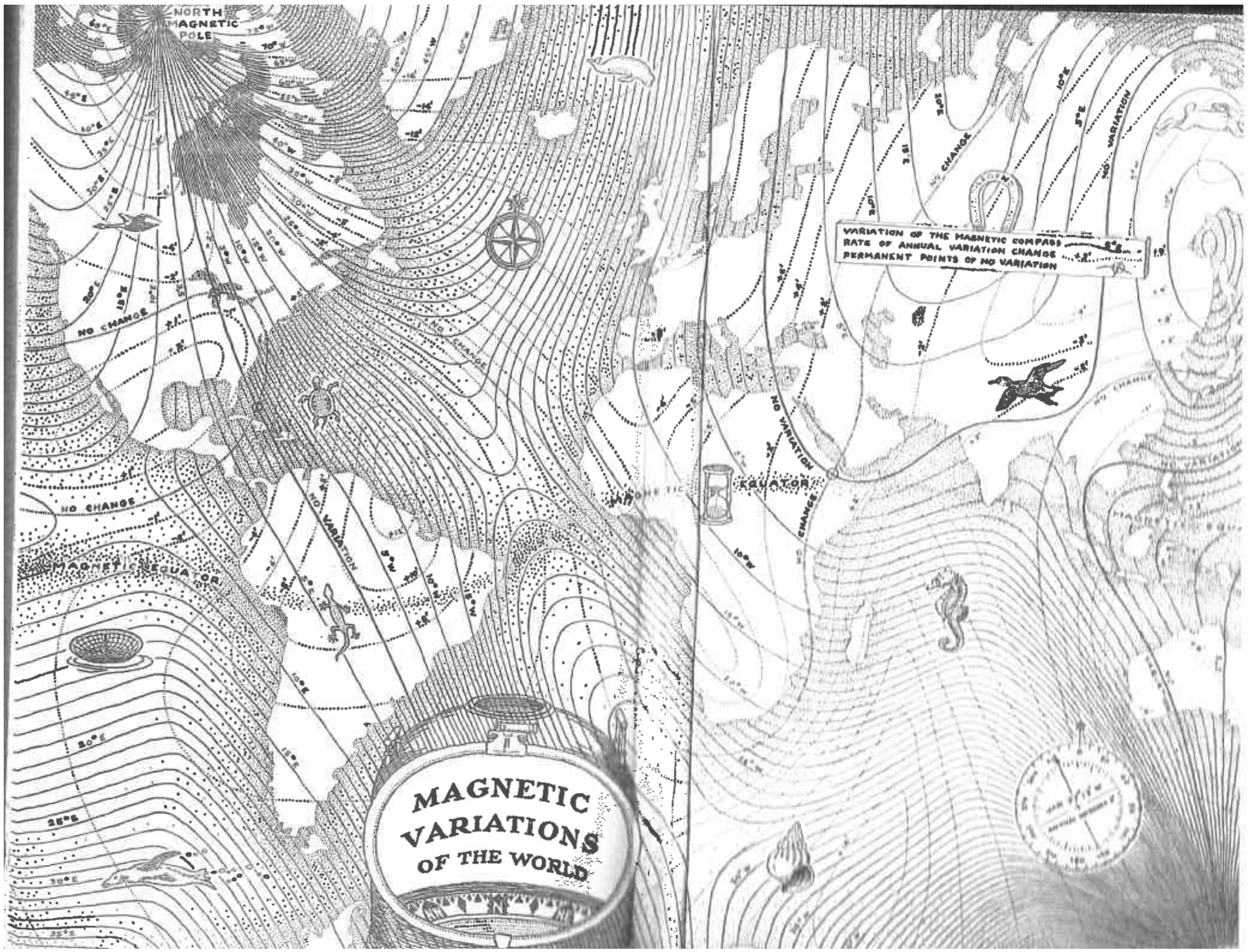
- A = polarity of the solar magnetic field
- Changes sign around solar max
- Modulation depends on qA
  - Protons, anti-protons are modulated differently
  - Cholis, Hooper, Linden, PR D93 (2016) 043016

*Gives a detailed parameterization of the force-field parameter as a function of date that accounts for the physical effects of drift and diffusion in the heliospheric magnetic field

PHYSICAL REVIEW D **93,** 043016 (2016)

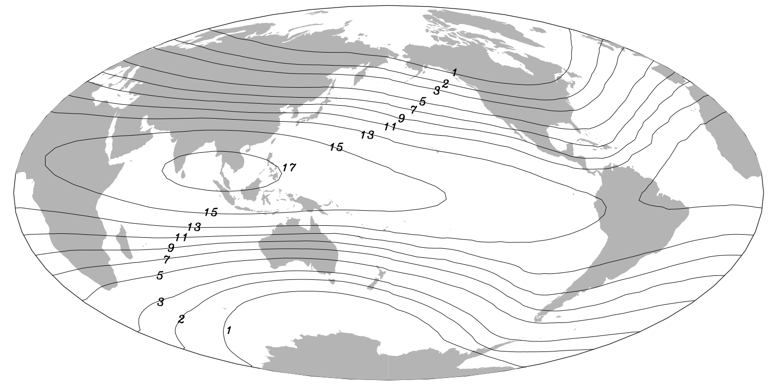


Next step:
getting through the geomagnetic field



Guy Murchie, 1954

Geomagnetic cutoffs



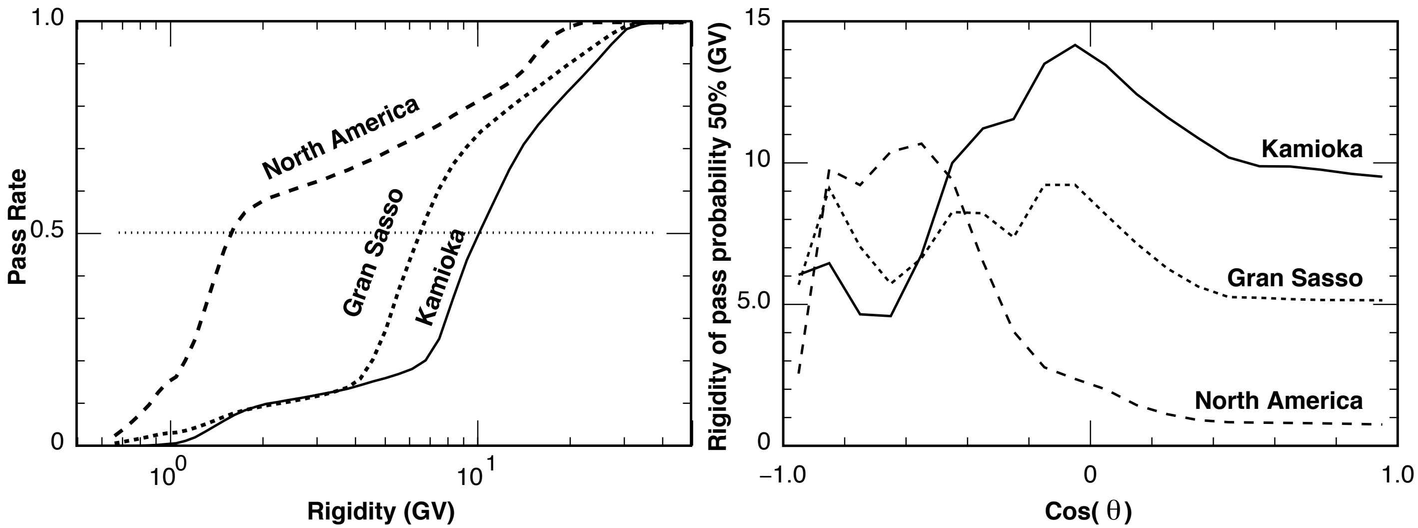
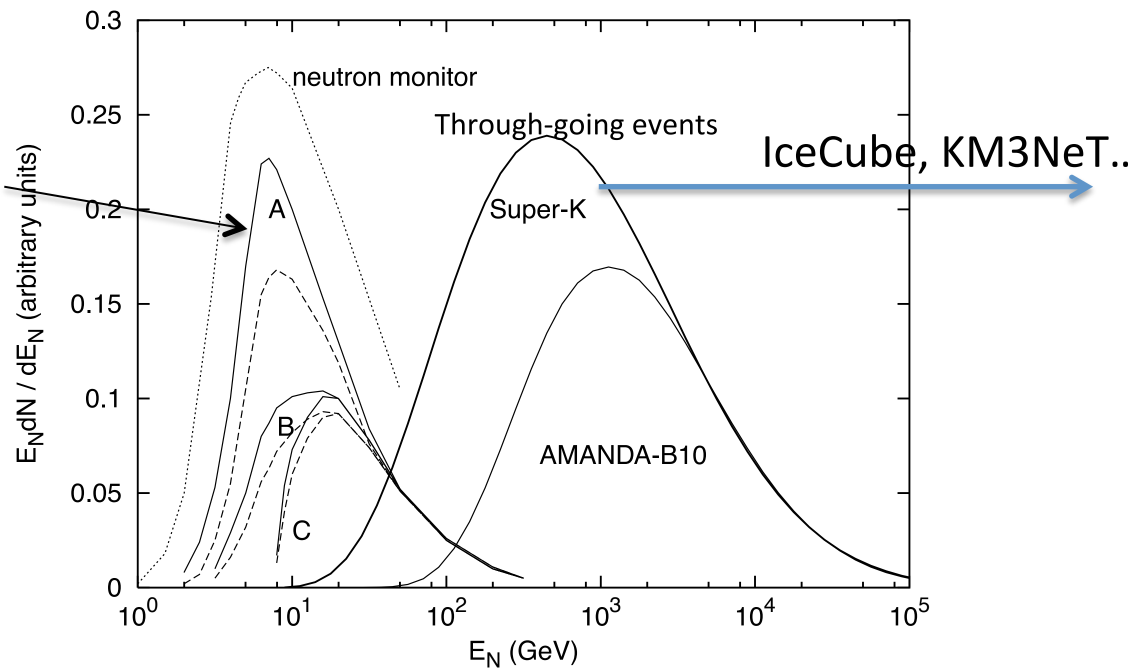


Figure 11 Cutoffs at three locations: north-central North America (Soudan, Sudbury); Gran Sasso; Kamioka. The left panel shows the passing rate as a function of rigidity integrated over all directions. The right panel shows the rigidity above which half the particles in the azimuthal band at each zenith angle reach the atmosphere. (Positive $\cos\theta$ refers to downward-moving particles.) TG & Honda, 2002

What primary energies are relevant?

Sub-GeV events at Super-K

A) Without cutoffs
B) Upgoing events
C) Downgoing events



TG, Honda, Ann.Revs. 52 (2002)

Strong East-West effect at Super-K

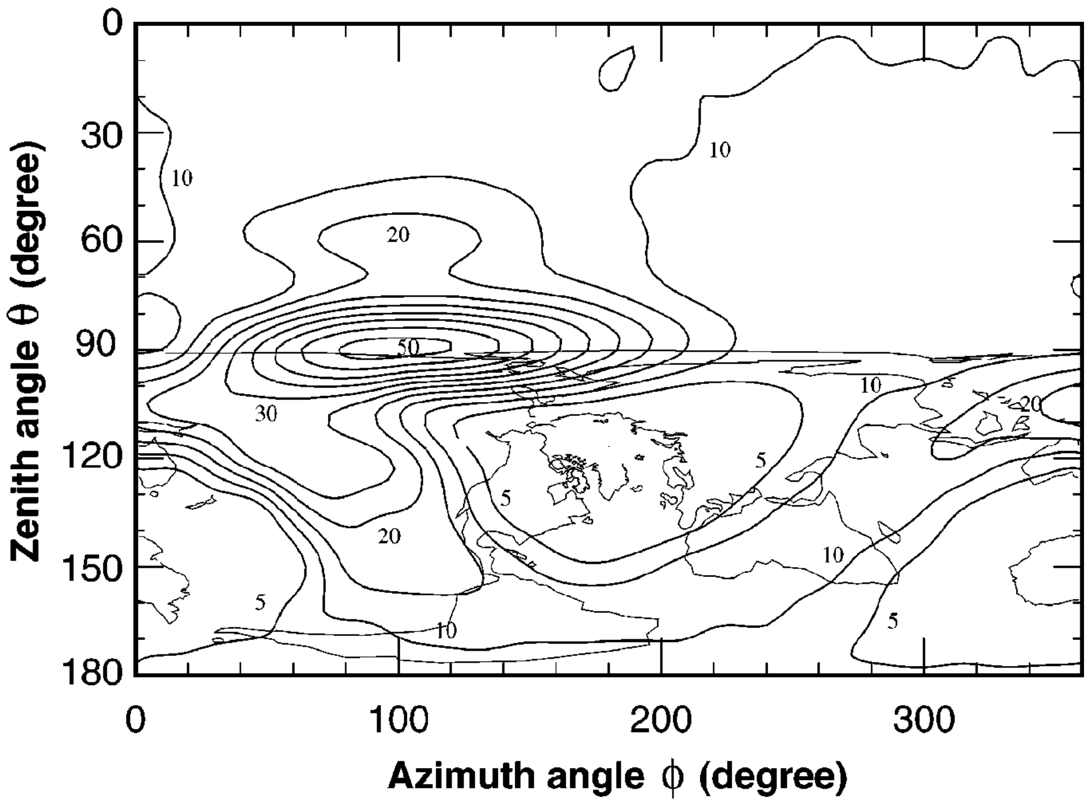
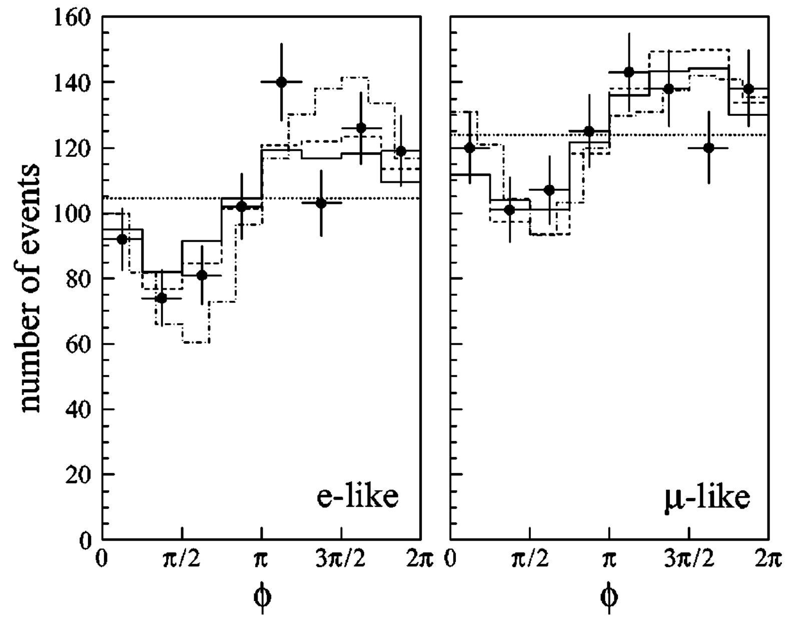


Figure 10 Contour map of the rigidity cutoff as seen from the Kamioka site. Rigidity cutoffs are shown as a function of arrival direction of the neutrino. (Zenith angle >90° is for upward-moving particles.) An outline map of the continents is superimposed on the lower hemisphere.

East-West effect on neutrinos



HKKM
Honda et al., PRD52 (1995)

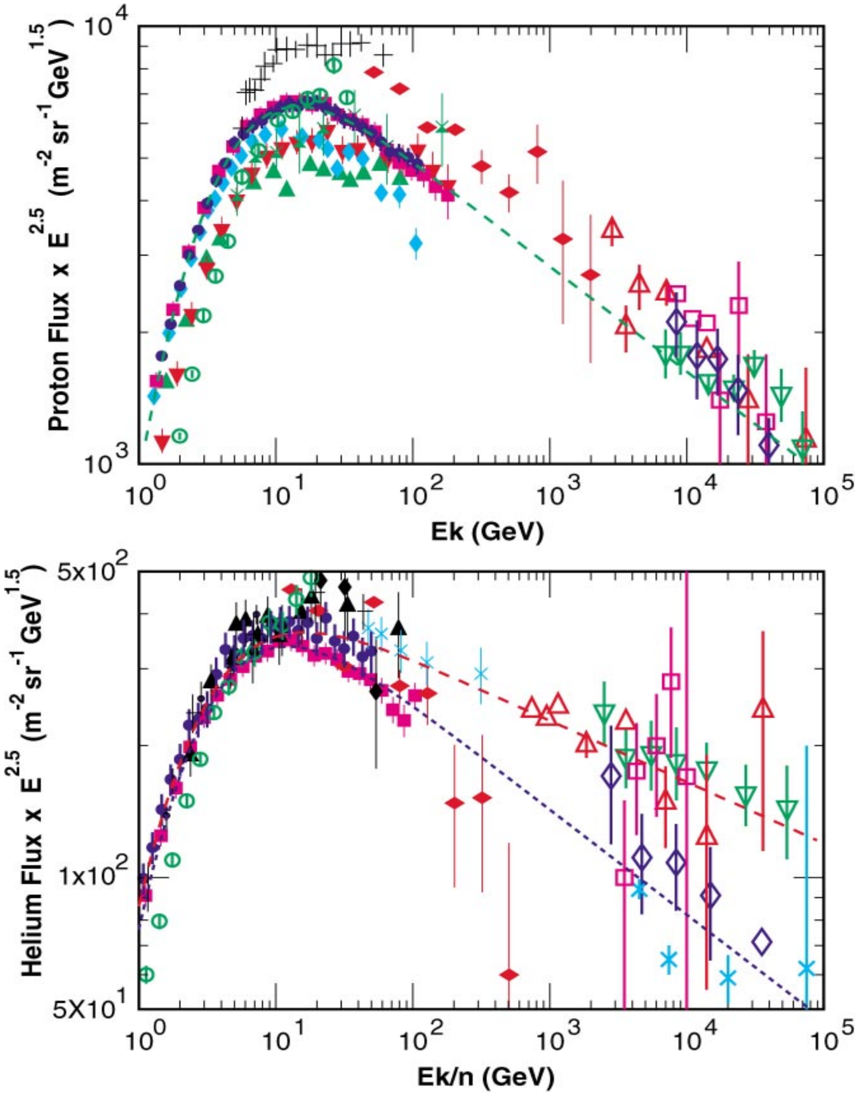
Lipari, Stanev, TG, PRD58 (1998)

Lipari,
Astropart. Phys. 14 (2000) 171

Data from Super-K* in fixed zenith band compared to calculations.
Complemented observation of zenith dependence from oscillations.

*Super-K, (Futagami et al., P.R.L. 82 (1999) 5192

Spectrum circa 2002



Nucleons per GeV/nucleon

Figure 6 Observed flux of cosmic-ray protons and helium. The dashed lines show the fits described in the text. The data are: Webber (48), crosses; LEAP (49), upward solid triangles; MASS1 (50), open circles; CAPRICE (52), vertical solid diamonds; IMAX (53), downward solid triangles; BESS98 (54), solid circles; AMS (55, 56), solid squares; Ryan (57), horizontal solid diamonds; JACEE (58), downward open triangles; Ivanenko (59), upward open triangles; Runjob (60), open diamonds; Kawamura (61), open squares.

TG & Honda, 2002

Flux parameterizations

$$\phi(E_k) = K \times \left(E_k + b \exp\left[-c\sqrt{E_k}\right]\right)^{-\alpha}$$

TG, Honda, Lipari, Stanev ICRC 27 (Hamburg) 2001 5(1643)

E in GeV, the b and c factors account for modulation at solar min

TABLE 2 Parameters for all five components in the fit of Equation 10

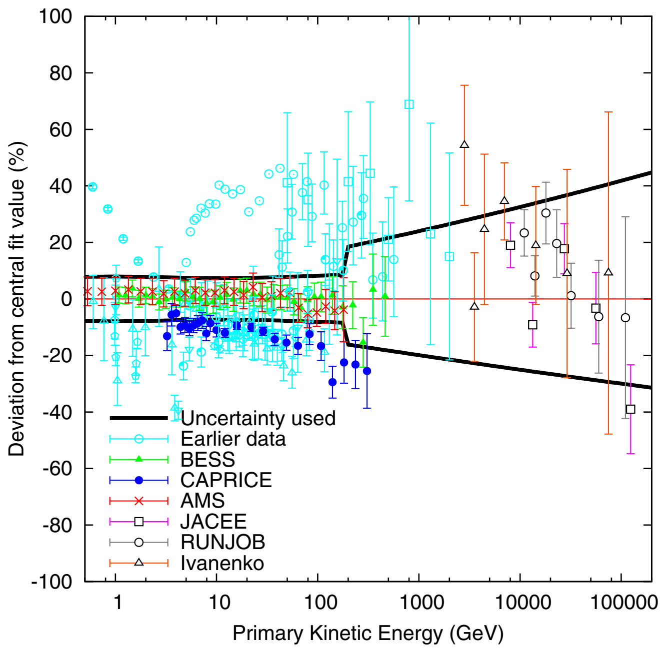
Parameter/component	α	$\boldsymbol{K}$	$\boldsymbol{b}$	$\boldsymbol{c}$
Hydrogen ($A = 1$)	2.74 ± 0.01	14900 ± 600	2.15	0.21
He ($A = 4$, high)	2.64 ± 0.01	600 ± 30	1.25	0.14
He ($A = 4$, low)	2.74 ± 0.03	750 ± 100	1.50	0.30
CNO ($A = 14$)	2.60 ± 0.07	33.2 ± 5	0.97	0.01
Mg-Si ($A = 25$)	2.79 ± 0.08	34.2 ± 6	2.14	0.01
Fe ($A = 56$)	2.68 ± 0.01	4.45 ± 0.50	3.07	0.41

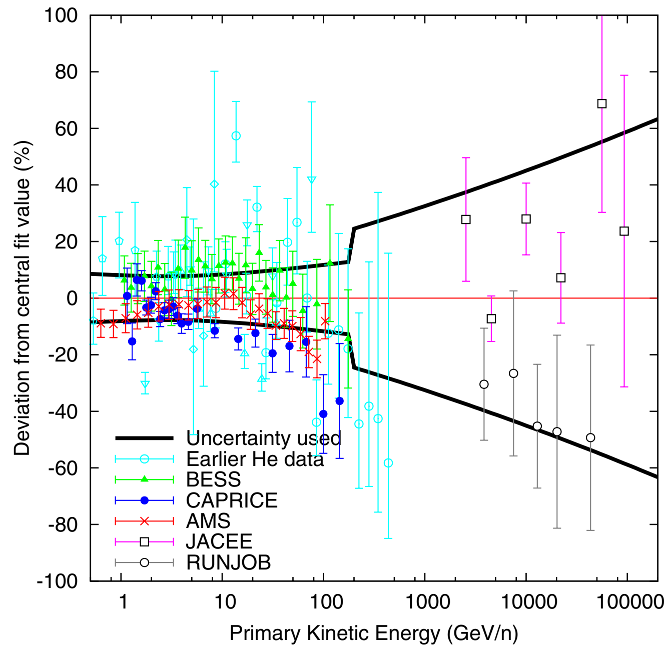
Parameter values from TG, Honda (Ann.Revs.Nucl. Part. Sci. 52, 2002).

In view of more recent data, it is good that we favored the "high" He !

Data, 2005

Low energy measurements with spectrometers, higher energy with calorimeters



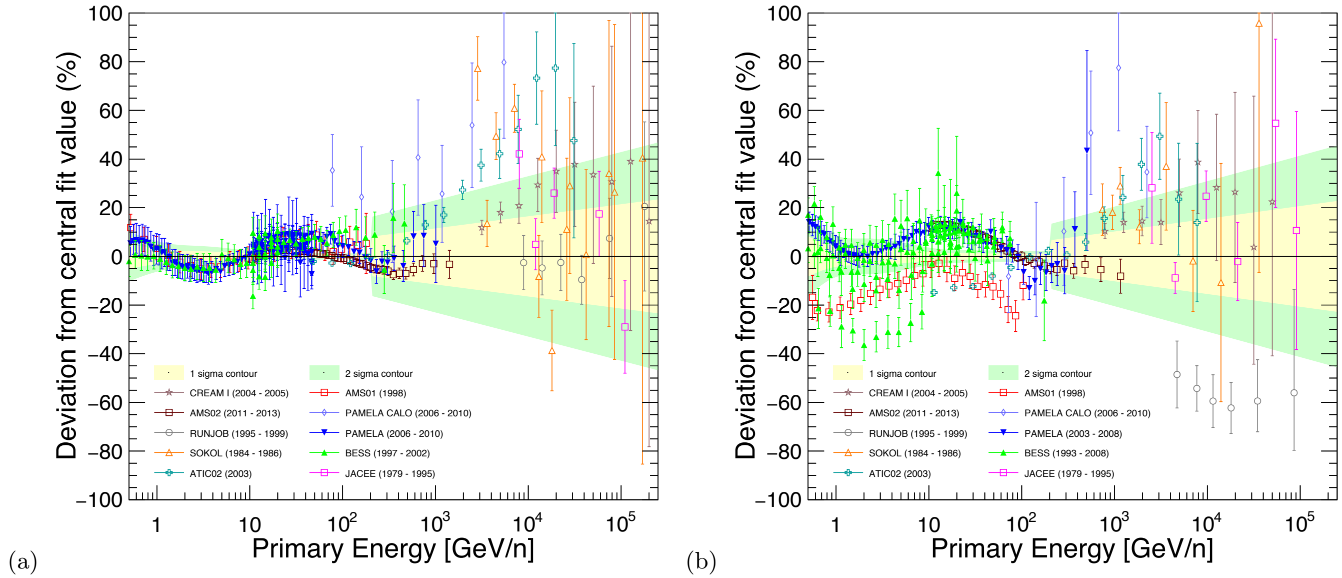


Ratio of data to parameterization for protons and helium from uncertainties paper Barr et al., PR D74 (2006) 094009

Updated fits include new data:

Evans et al., PR D95 (2017) 023012 (1612.03219)

Protons Helium



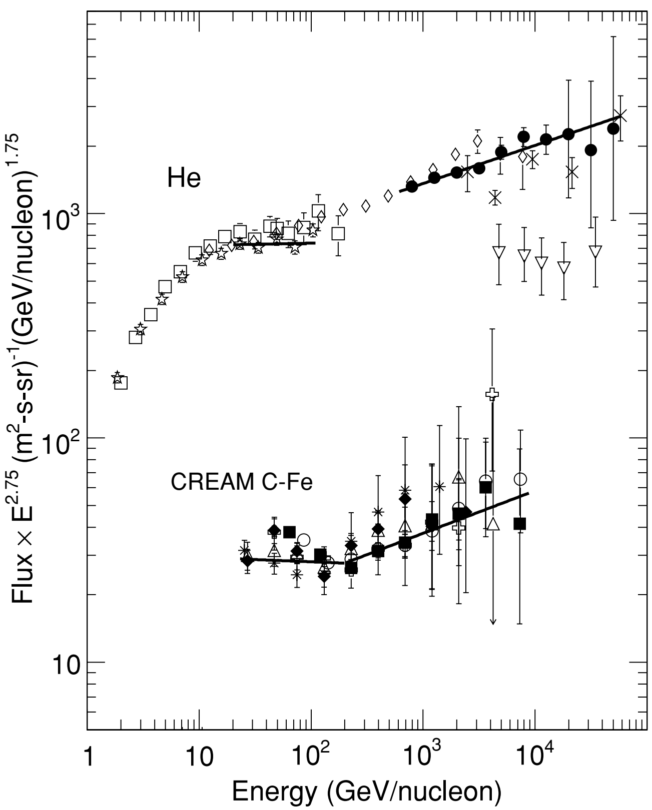
Main new data sets: PAMELA, AMS02, CREAM

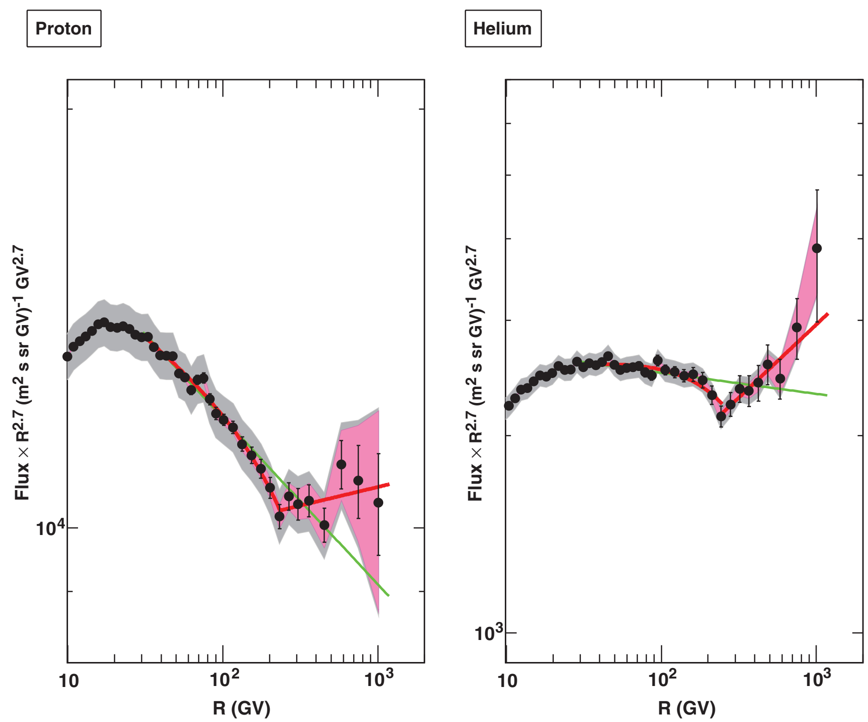
Plots show ratio of data to fits to the GHLS form with new parameter values.

Uncertainty band is reduced.

However: Note systematic difference in shape

New observation: Spectral hardening

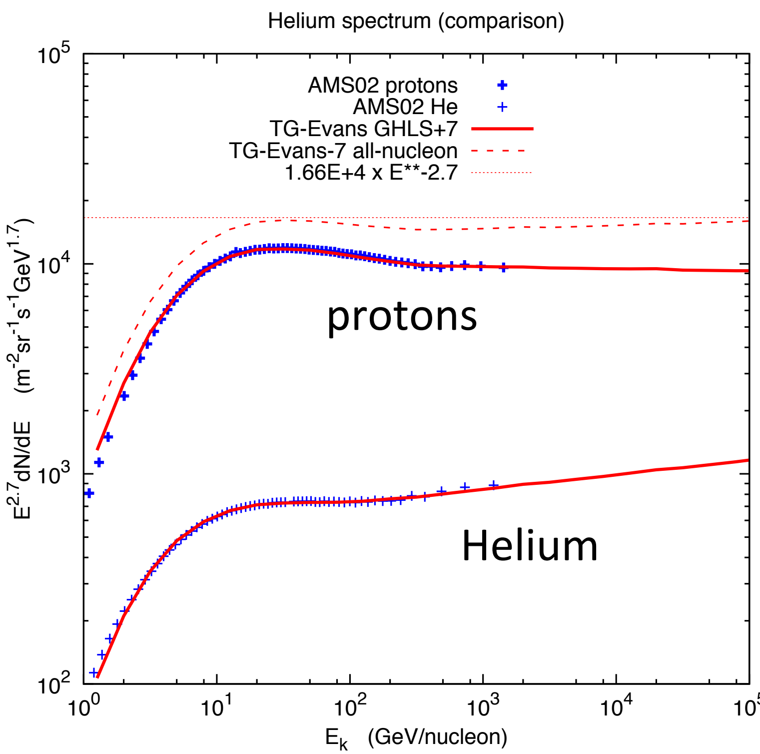




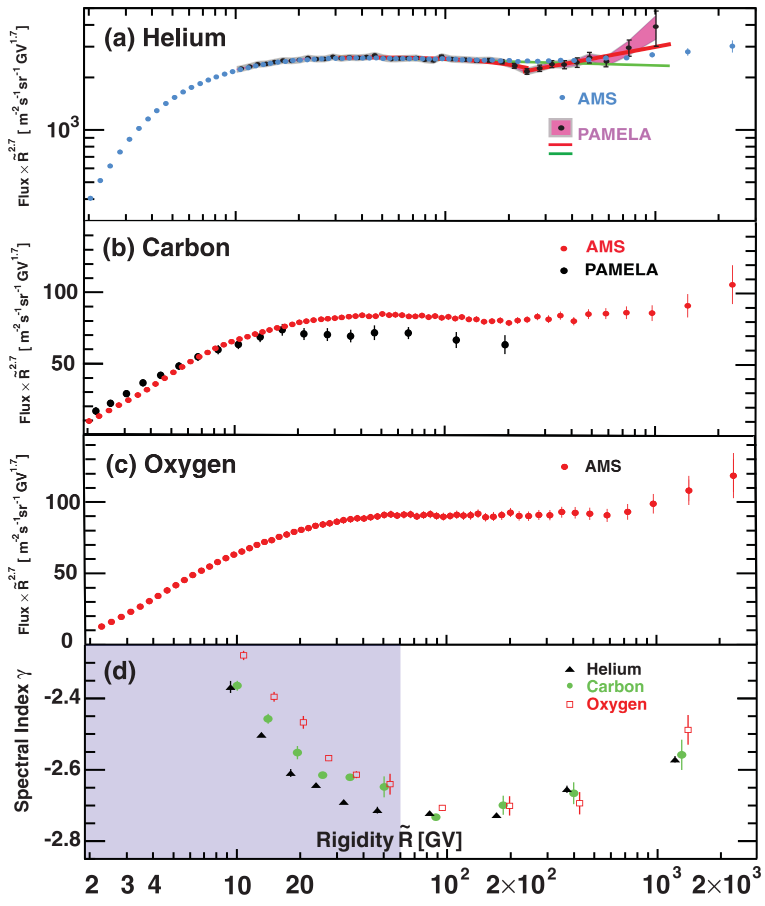
PAMELA, Science 332 (2011) 69

“Discrepant hardening”
CREAM, Ap.J. Letters 714 (2010) L89

AMS 02



Rigidity dependent hardening



AMS02, PRL 119 (2017) 251101

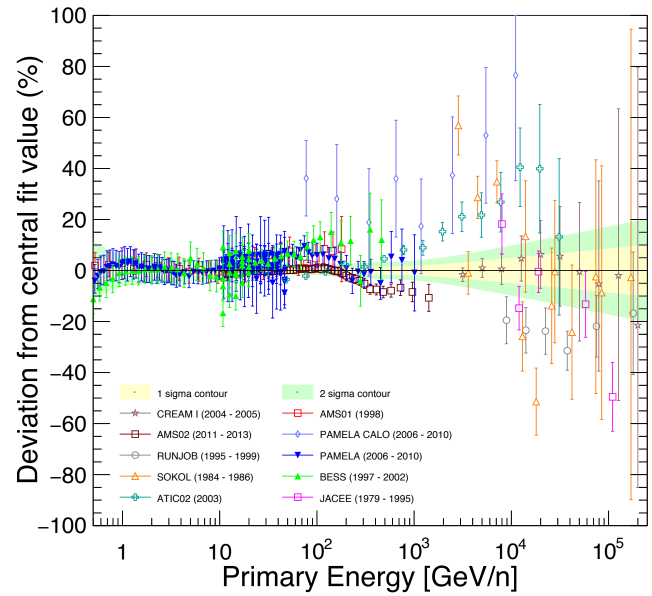
Evans et al. 7 parameter fit addresses the hardening for protons

$$\phi(E_p) = K \times \left(E_p + b\exp\left[-c\sqrt{E_p}\right]\right)^{-\alpha} \times \left[1 + \left(\frac{E_p}{k}\right)^s\right]^{\frac{\alpha-\alpha'}{s}}$$

3 new parameters:

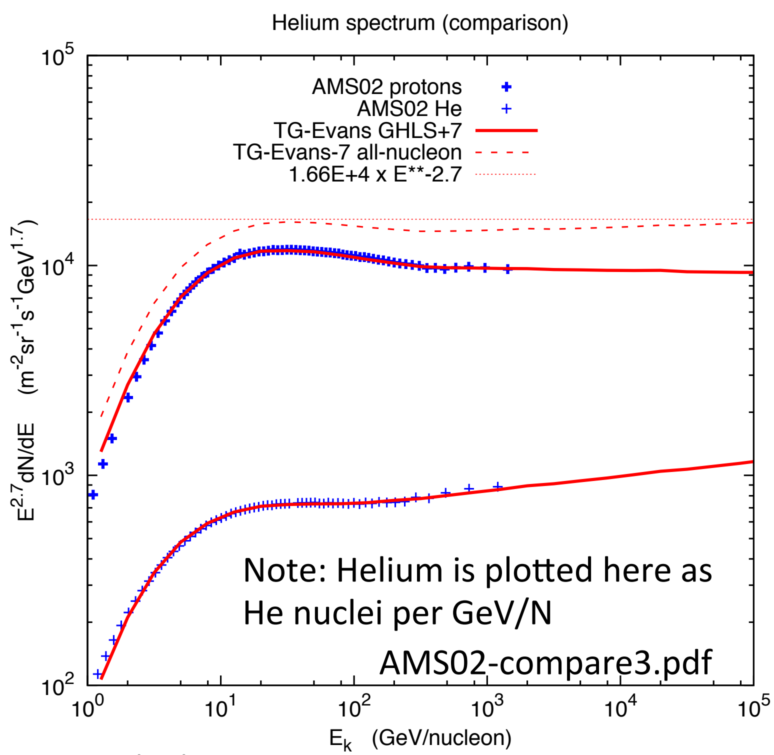
- k ≈ 150 GeV,
- s = sharpness,
- α' < α = high energy spectral index

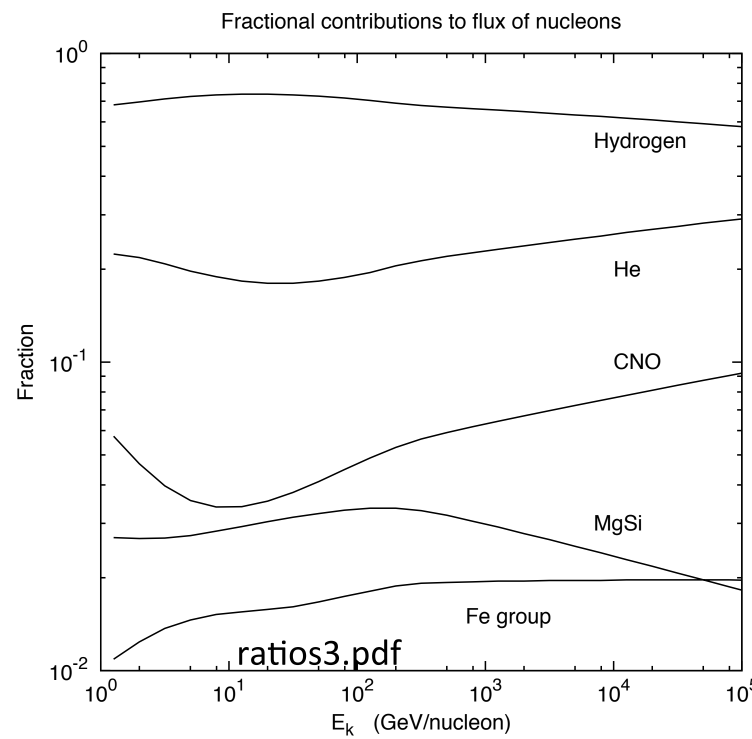
The steepening factor form is from
Ter-Antonyan & Haroyan, hep-ex:0003006
(see also Lipari, Astropart. Phys. 97 (2018) 197



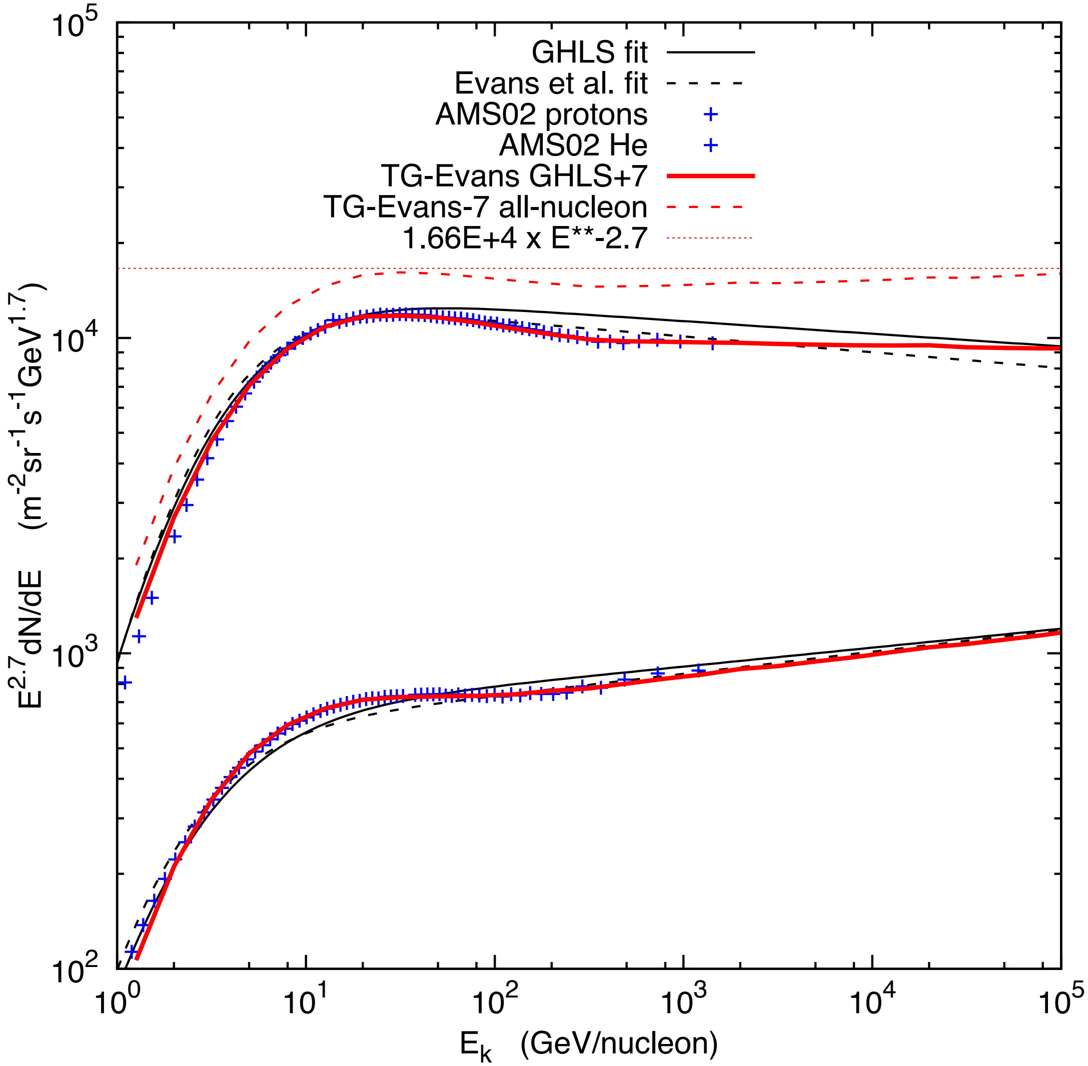
Modified versions of Evans et al.

Since I want to use these parameterizations specifically for AMS02 antiprotons, I adjusted the fits to give better agreement with AMS02 H and He data. I used the seven-parameter form for He as well as for H. (Evans used it only for H.)
Work is in ~/atmosnu/Giles2016/bartol/primary/gbthesisdata/tkg2016/ (11-12 Feb 2017)
Note: AMS02 data are converted from GV to kinetic energy per nucleon in gnuplot files.



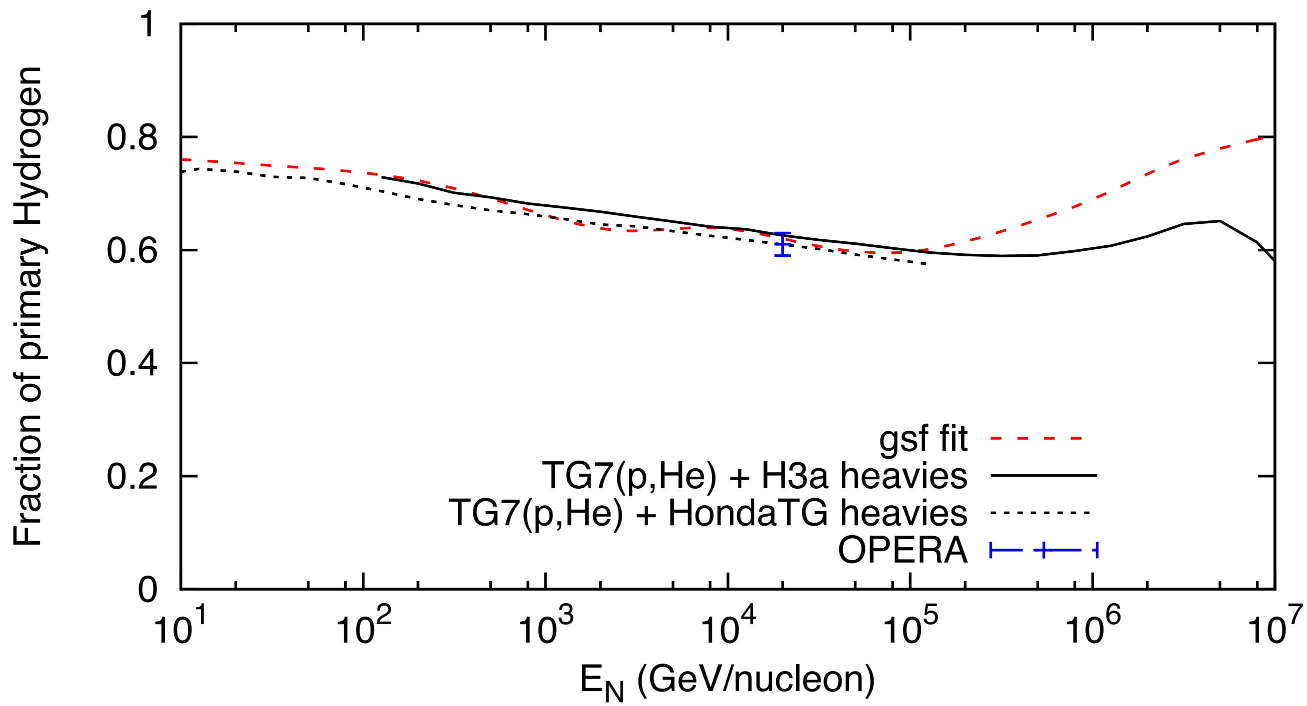


Compare fits to AMS02



Hydrogen fraction and ν/ν̄ ratio

To first order depends on $\delta_0 = \frac{p-n}{p+n} \approx \frac{H}{N}$



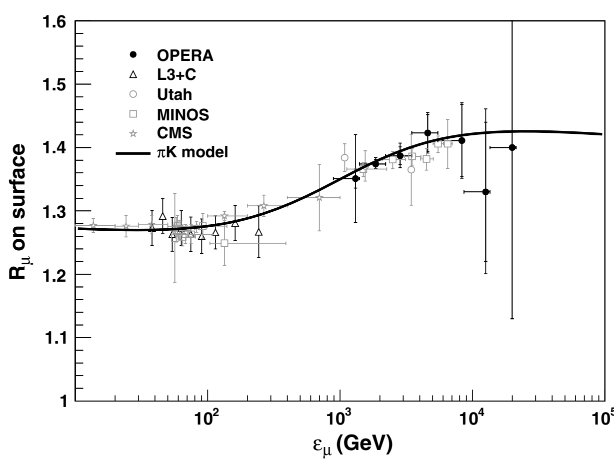
Relation to atmospheric muons

Pions only (Frazer et al., PR D 5 (1972) 1653

$$\frac{\mu^+}{\mu^-} \approx \frac{1+\beta\delta_0\alpha_\pi}{1-\beta\delta_0\alpha_\pi} = \frac{f_{\pi^+}}{1-f_{\pi^+}},$$

$$\beta = \frac{1-Z_{pp}-Z_{pn}}{1-Z_{pp}+Z_{pn}} \approx 0.909;$$

$$\alpha_\pi = \frac{Z_{p\pi^+}-Z_{p\pi^-}}{Z_{p\pi^+}+Z_{p\pi^-}} \approx 0.165$$



Include K → $\mu + \nu_\mu$

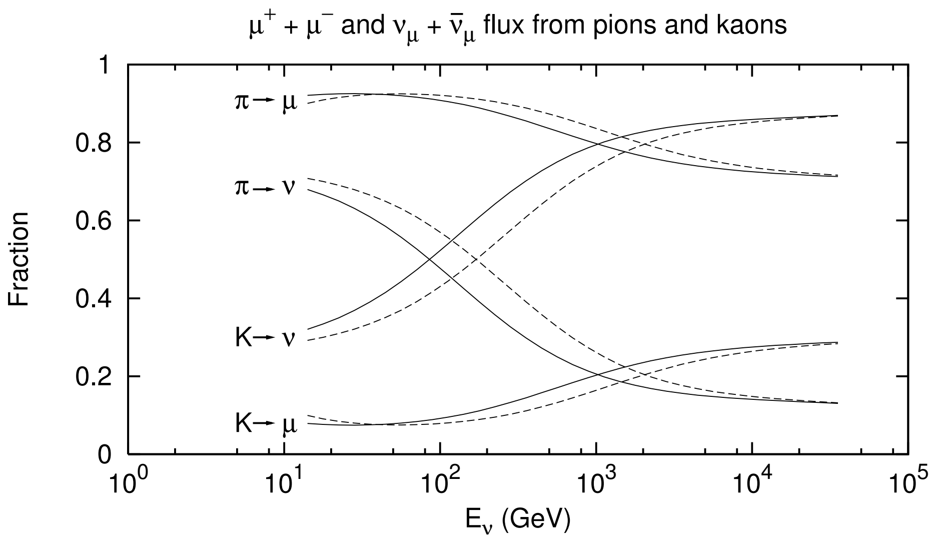
TG Astropart. Phys. 35(2012) 801

$$\frac{\mu^+}{\mu^-} = \left[\frac{f_{\pi^+}}{1+B_{\pi\mu}\cos(\theta)E_\mu/\epsilon_\pi} + \frac{\frac{1}{2}(1+\alpha_K\beta\delta_0)A_{K\mu}/A_{\pi\mu}}{1+B^+_{K\mu}\cos(\theta)E_\mu/\epsilon_K}\right] \times \left[\frac{(1-f_{\pi^+})}{1+B_{\pi\mu}\cos(\theta)E_\mu/\epsilon_\pi} + \frac{(Z_{NK^-}/Z_{NK})A_{K\mu}/A_{\pi\mu}}{1+B_{K\mu}\cos(\theta)E_\mu/\epsilon_K}\right]^-$$

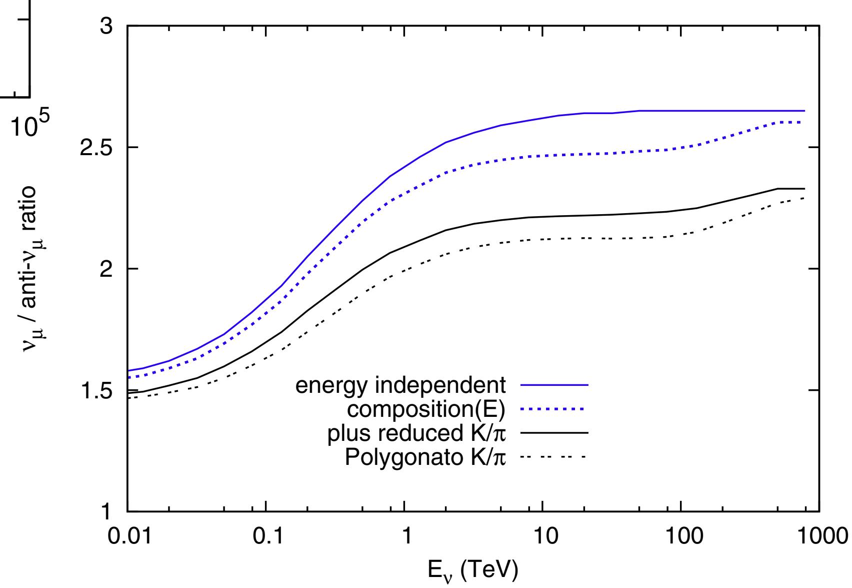
$$\alpha_K = \frac{Z_{pK^+}-Z_{pK^-}}{Z_{pK^+}+Z_{pK^-}}$$

Rise in muon charge ratio reflects higher asymmetry in the charged kaon channel, which becomes more important when $E_\mu > \varepsilon_K \approx 850$ GeV.
The key parameter is α_K

The effect is more important for ν_μ



2-body decay kinematics favors
K over π for neutrinos

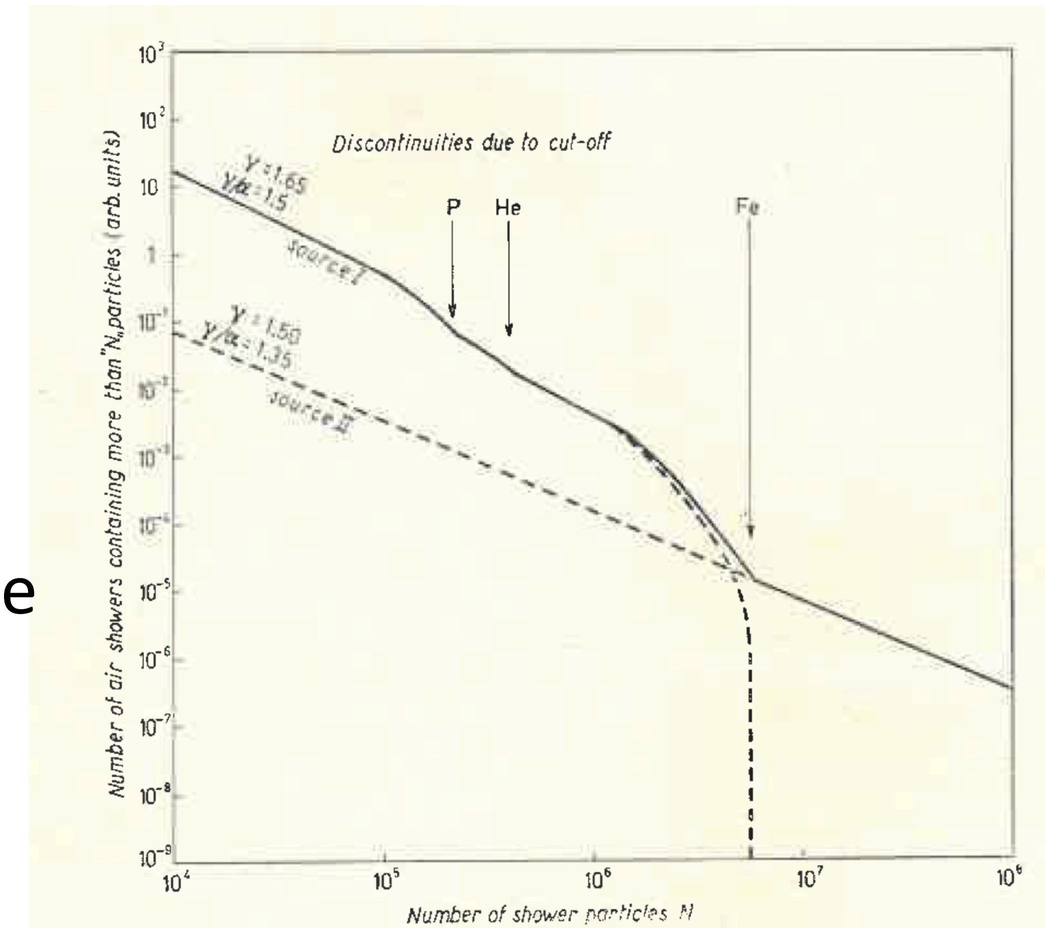


E >> 100 TeV

- Flux too low for direct measurements
- Ground-base EAS experiments
  - Large aperture x exposure provides data to >> EeV
  - All-particle spectrum depends on E per nucleus
  - Composition measurements at best resolve groups of nuclei, e.g. (p, He, CNO, Mg-Si, Fe)
- We need the spectrum of nucleons (in E per nucleon) to calculate fluxes of leptons
- Physics-based models give useful guidance

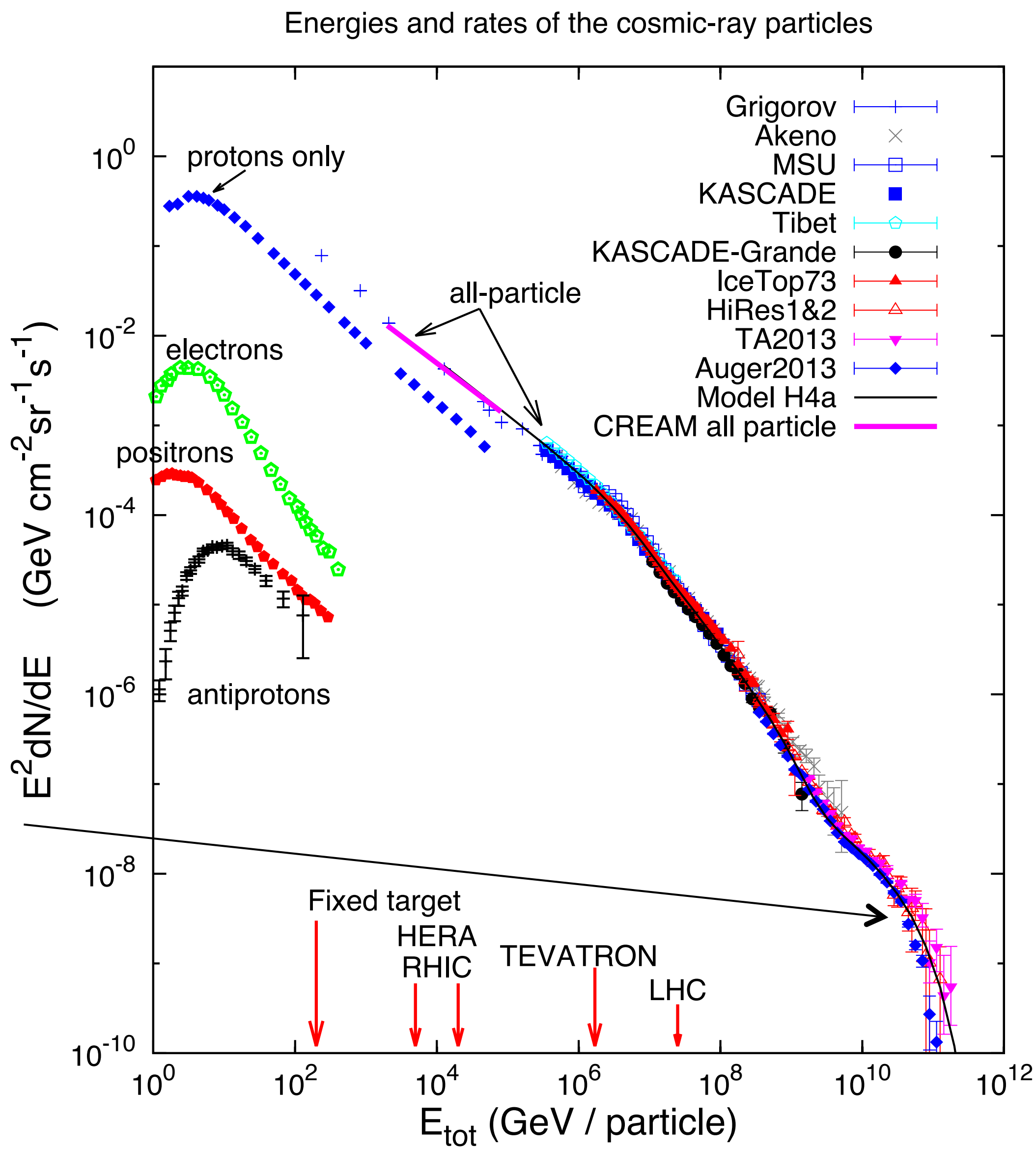
Peters cycles and particle populations

- Rigidity dependence
  - $R = P_{tot}\, c / Z e$
  - Implies sequence: p, He, C, … Fe
- Spectral hardening
  - Suggests new particle population
- Galactic and extra-galactic populations



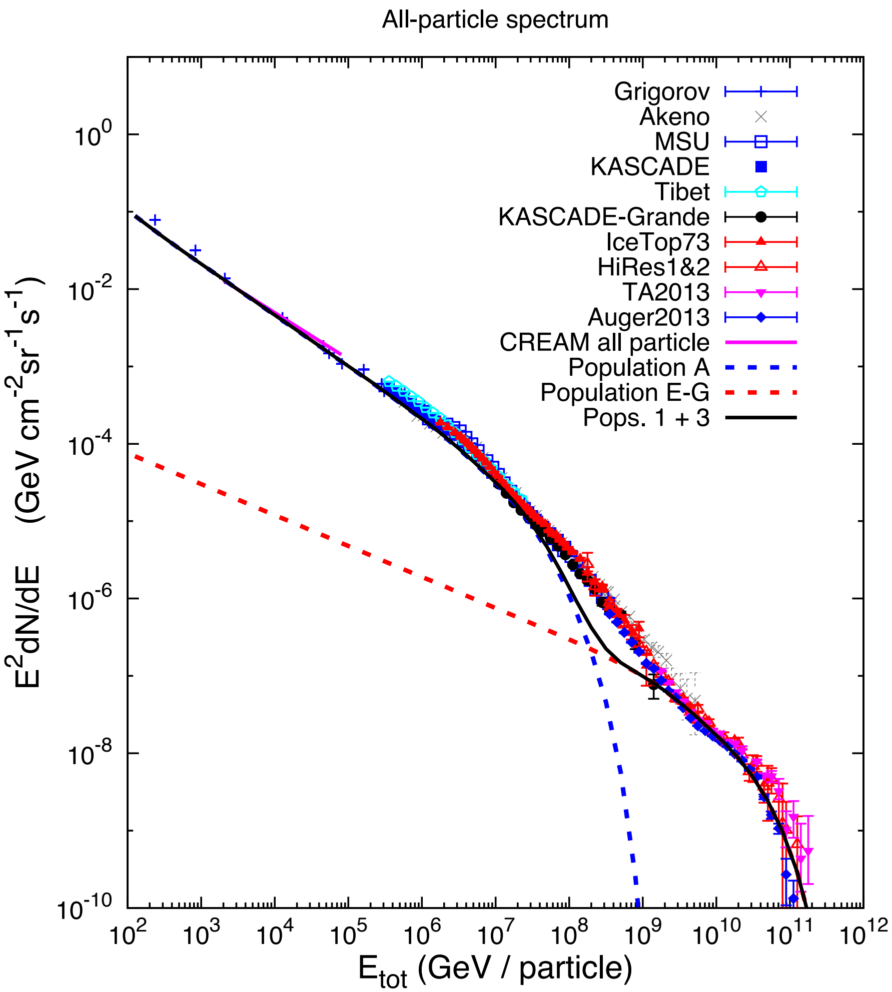
B. Peters, Il Nuovo Cimento 22 (1961) 800

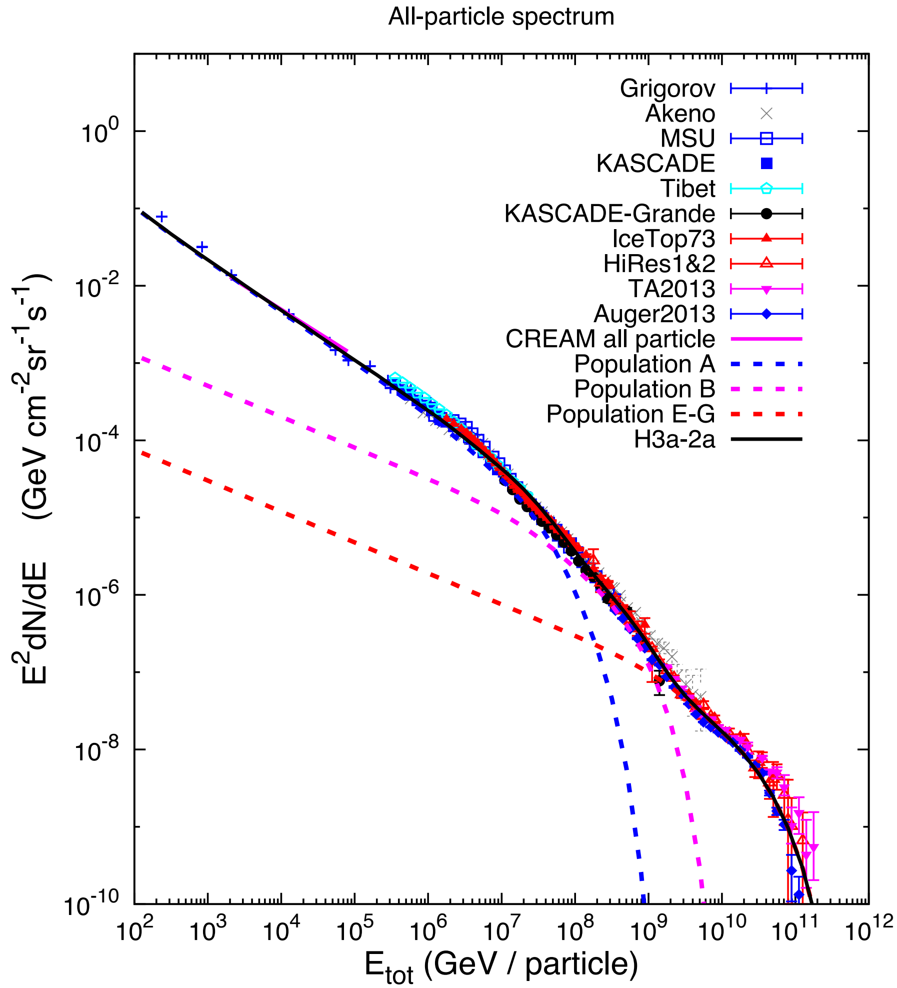
Spectrum
-- a global view



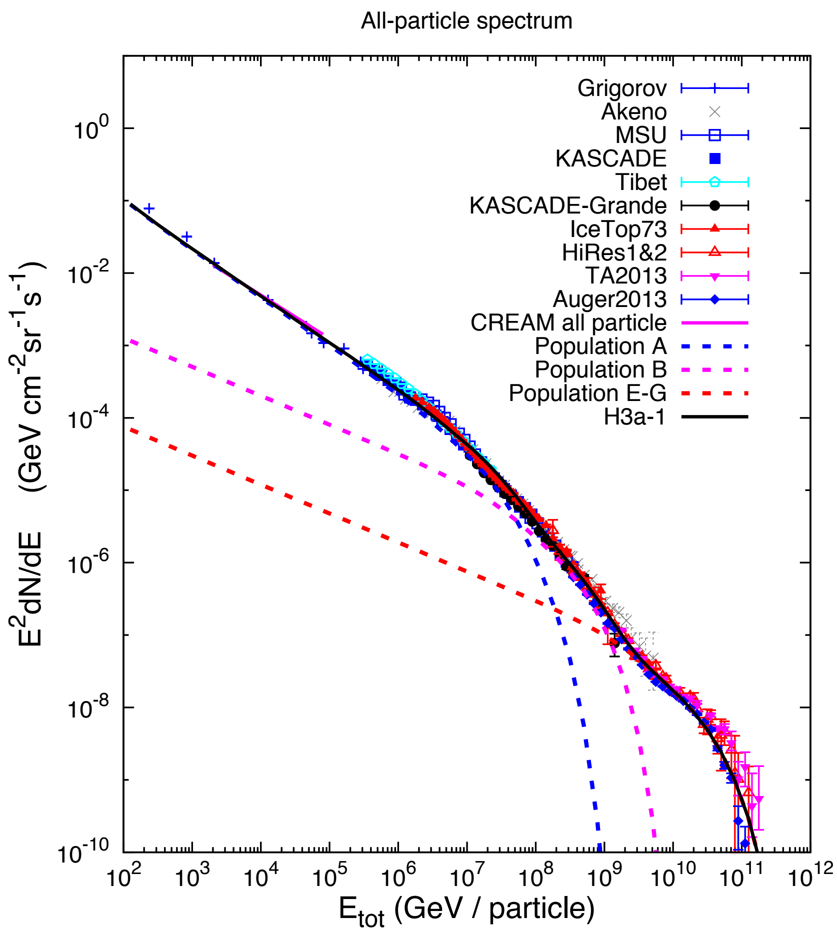
Cutoff ? …. or Maximum energy of acceleration?

2 components is not enough





3 population model



Pop. 1: Galactic I

- Assume power-law extrapolation of each group from direct measurements
- Assume rigidity-dependent cutoff at the knee

Pop. 2: Galactic II

Needed to fill in before extra-galactic component

Assume rigidity-dependent cutoff

Pop. 3: Extragalactic

Hillas' Galactic population B

Review: Diffusive shock acceleration in supernova remnants R101

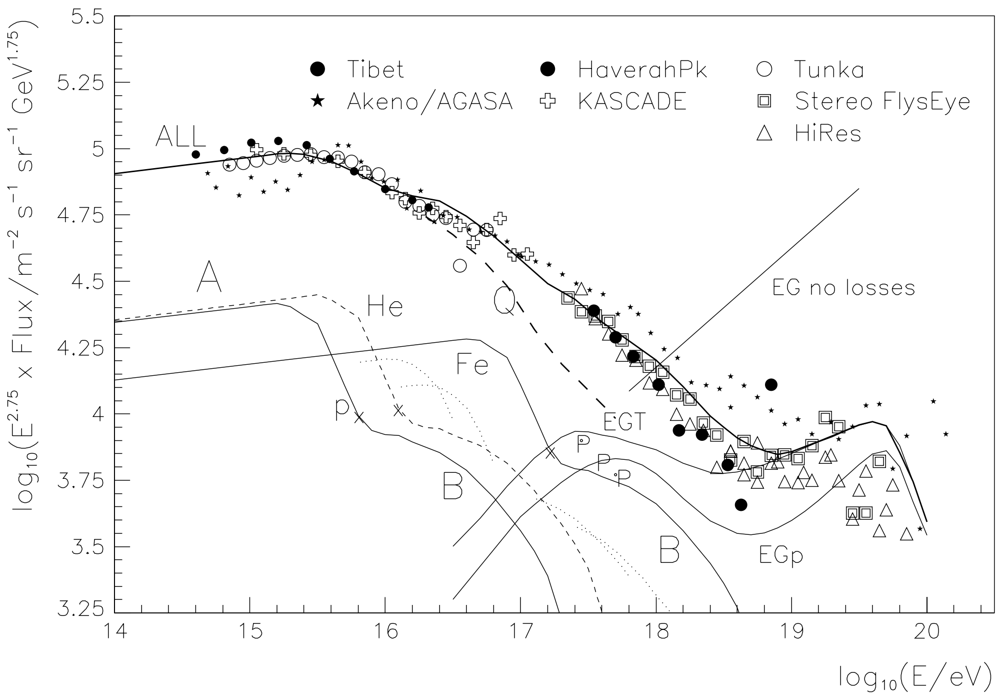
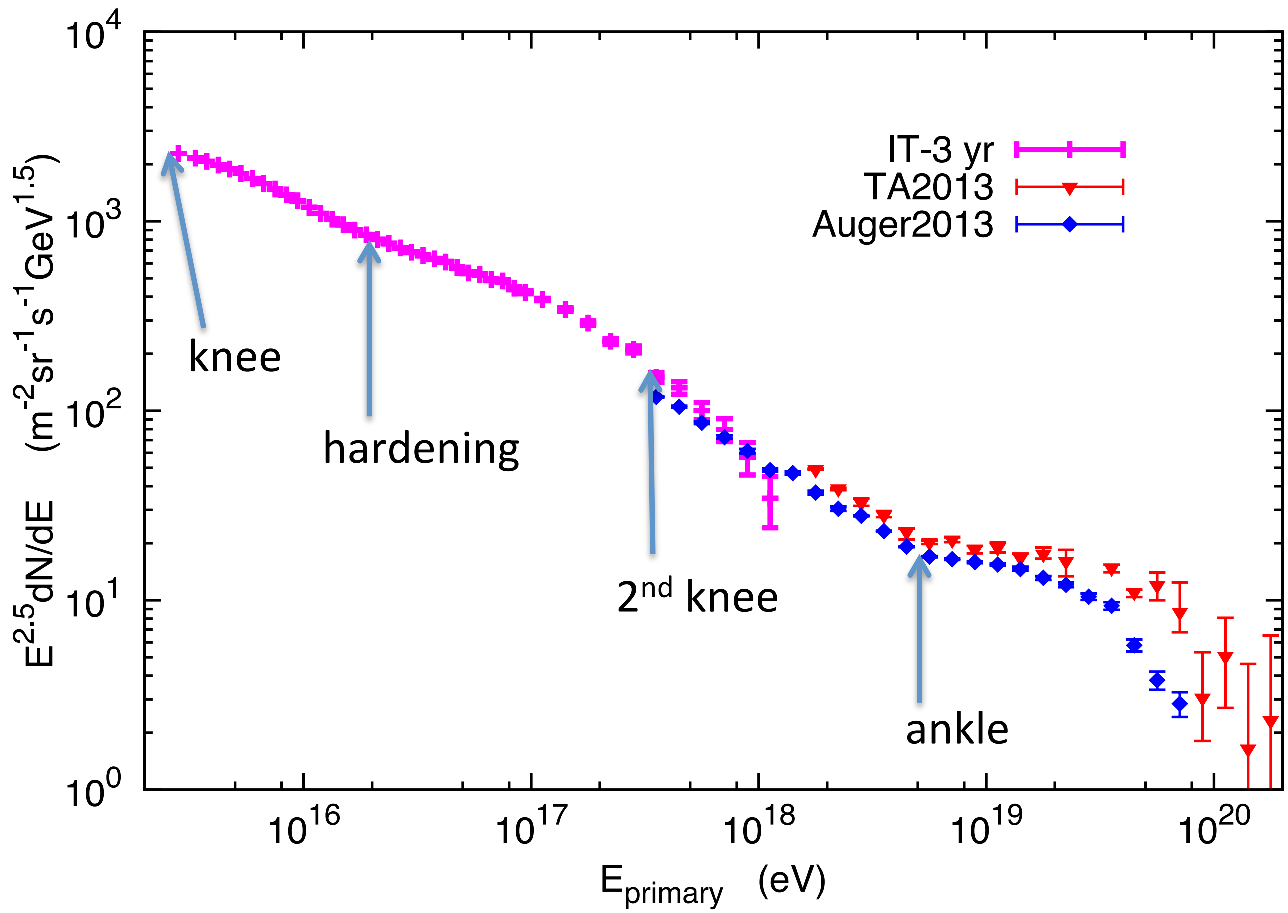


Figure 2. The cosmic ray spectrum as the sum of galactic H, He, CNO, Ne–S and Fe components with the same rigidity dependence, and extragalactic H + He (total EGT) having a spectrum $\propto E^{-2.3}$ before suffering losses by CMBR and starlight interactions. The galactic components were given a turn-down shape based on KAS CADE knee shape as far as the point marked *x*. The dashed line Q is the total if the extended tail B of the galactic flux is omitted.

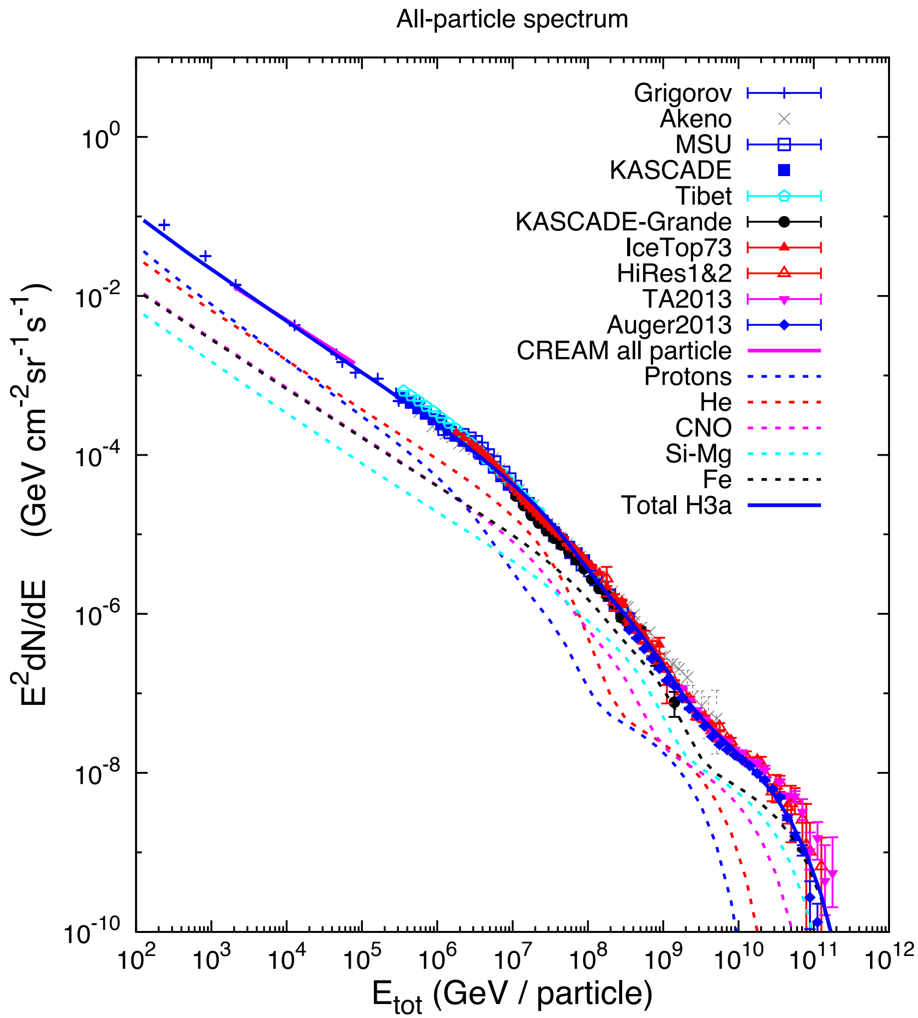
A.M. Hillas, J. Phys. G: Nucl. Part. Phys. **31** (2005) R95–R131

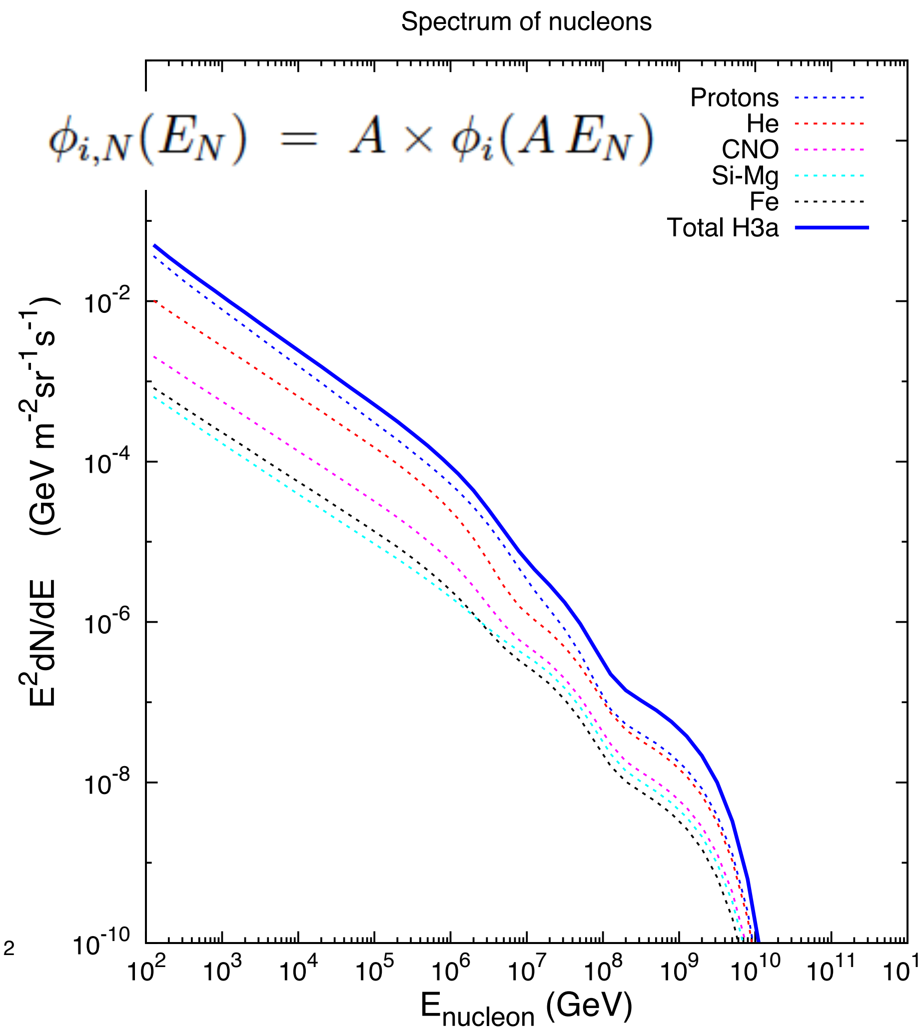
Features in all-particle spectrum



All-particle spectrum to nucleon spectrum

$$\phi_i(E) \equiv E\frac{\mathrm{d}N_i}{\mathrm{d}E} = \Sigma_{j=1}^{3} a_{i,j} E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$





Three-population models

		p	He	CNO	Mg-Si	Fe
Galactic A	Pop. 1:	7860	3550	2200	1430	2120
	$R_c = 4$ PV	1.66 1	1.58	1.63	1.67	1.63
Galactic B	Pop. 2:	20	20	13.4	13.4	13.4
	$R_c = 30$ PV	1.4	1.4	1.4	1.4	1.4
Extragalactic: H3a →	Pop. 3:	1.7	1.7	1.14	1.14	1.14
	$R_c = 2$ EV	1.4	1.4	1.4	1.4	1.4
Extragalactic: H4a →	Pop. 3(*):	200	0.0	0.0	0.0	0.0
	$R_c = 60$ EV	1.6				

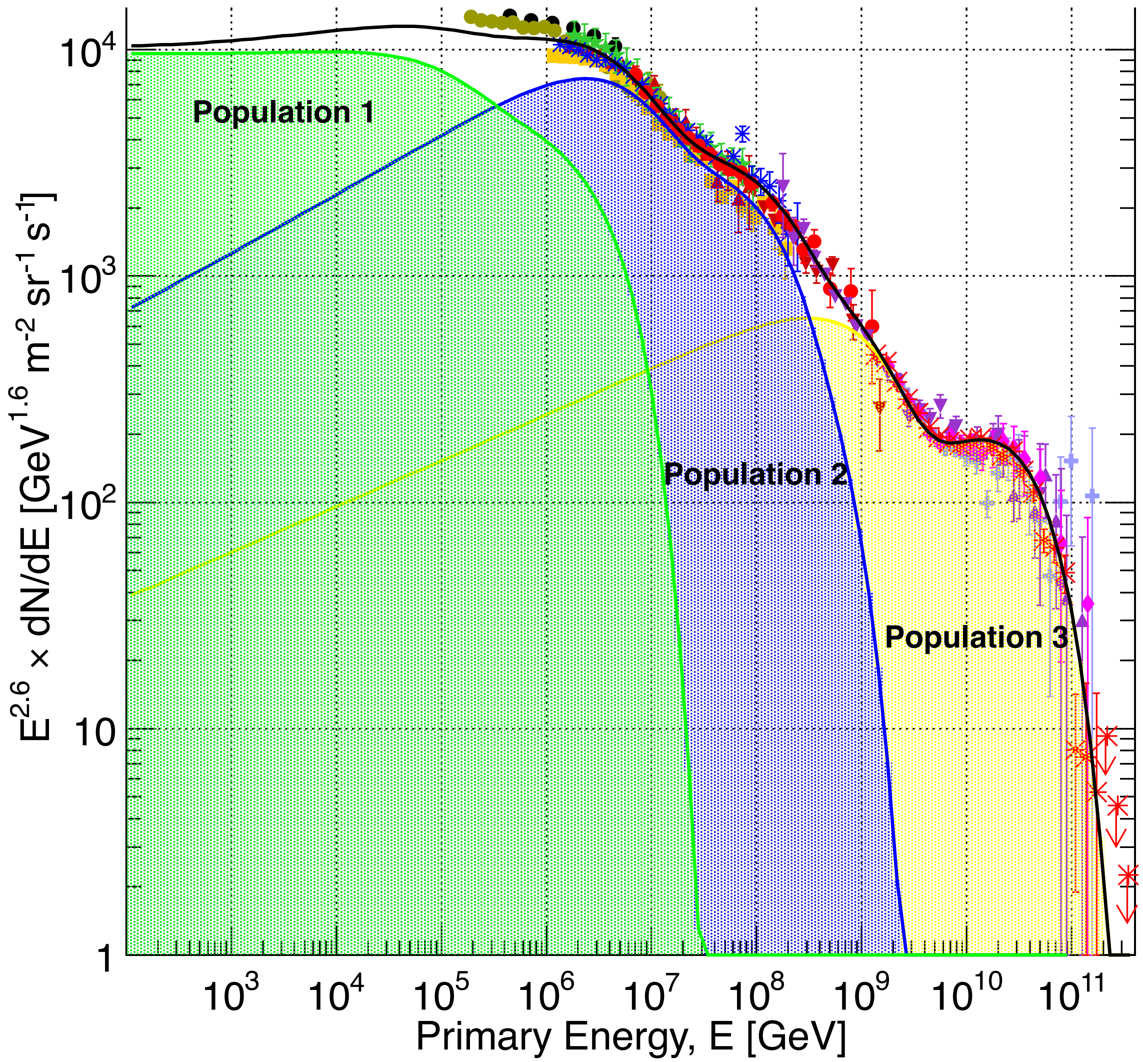
TG Astropart. Phys. 35 (2012) 801

GST

	p	He	C	O	Fe	$50 < Z < 56$	$78 < Z < 82$
Pop. 1:	7000	3200	100	130	60		
$R_c = 120$ TV	1.66 1	1.58	1.4	1.4	1.3		
Pop. 2:	150	65	6	7	2.3	0.1	0.4
$R_c = 4$ PV	1.4	1.3	1.3	1.3	1.2	1.2	1.2
Pop. 3:	14				0.025		
$R_c = 1.3$ EV	1.4				1.2		

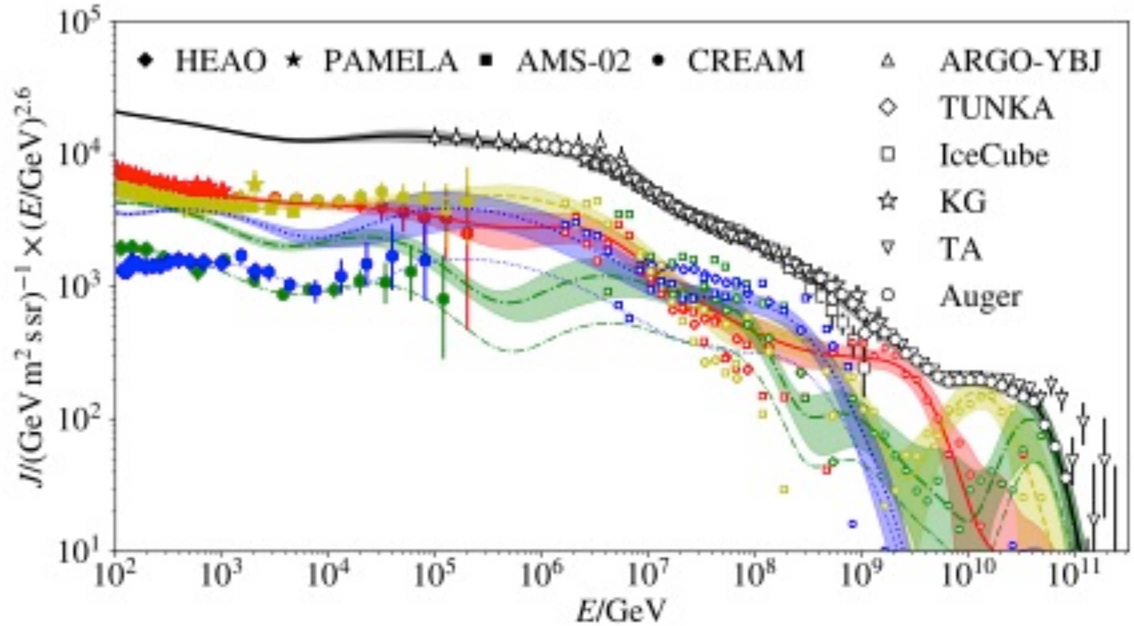
TG, Stanev, Tilav, Front. Phys. (Beijing) 8 (2013) 748 (arXiv:1303.3565

GST 3 population model

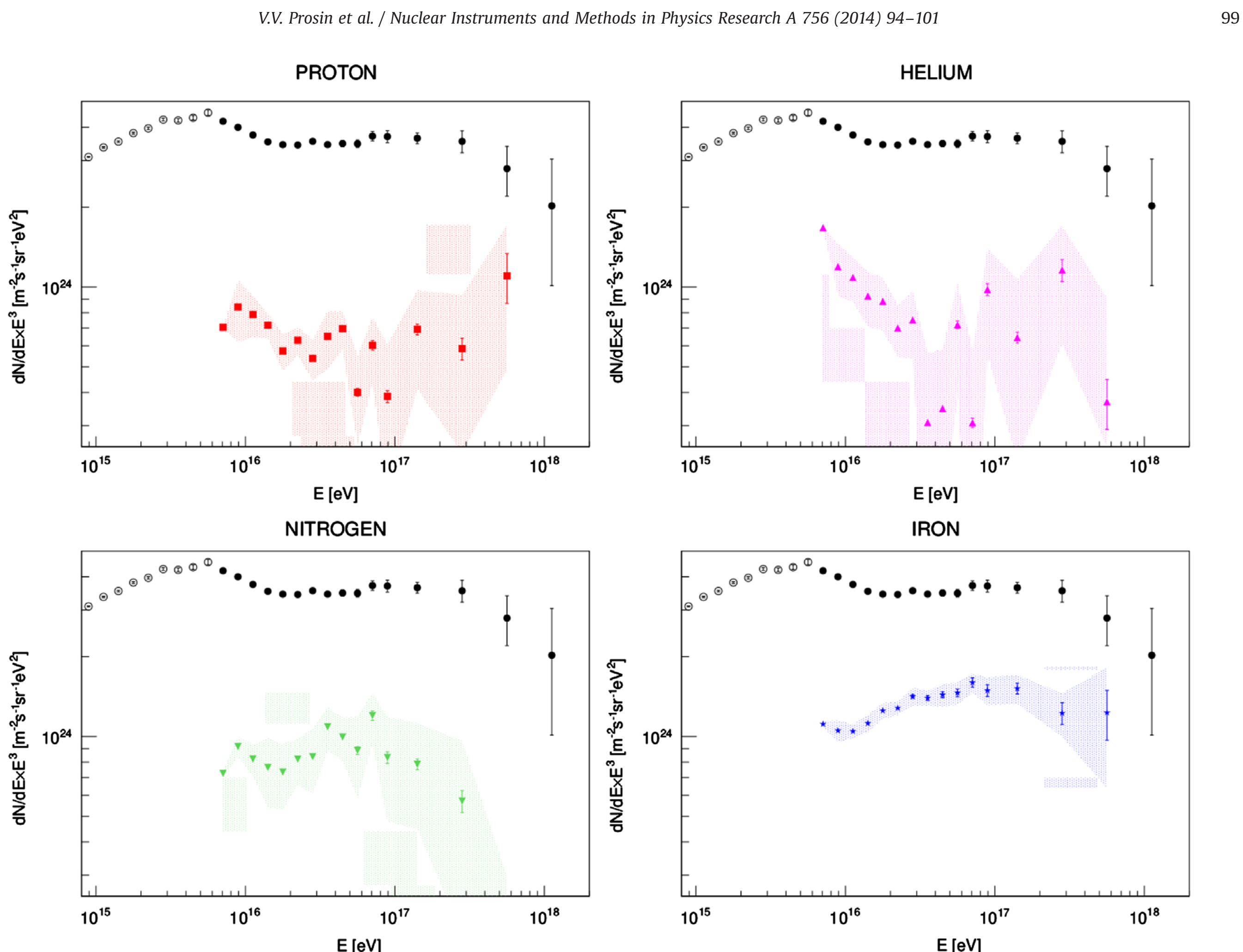


GSF (Global Spline Fit)

"Data-driven", no input model (H. Dembinski et al., 1711.11432)

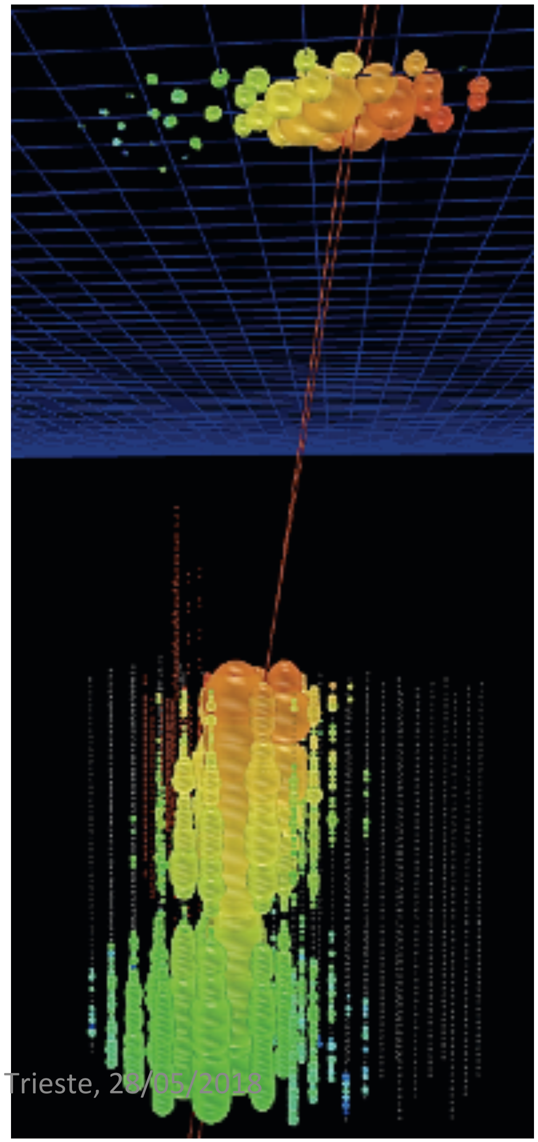


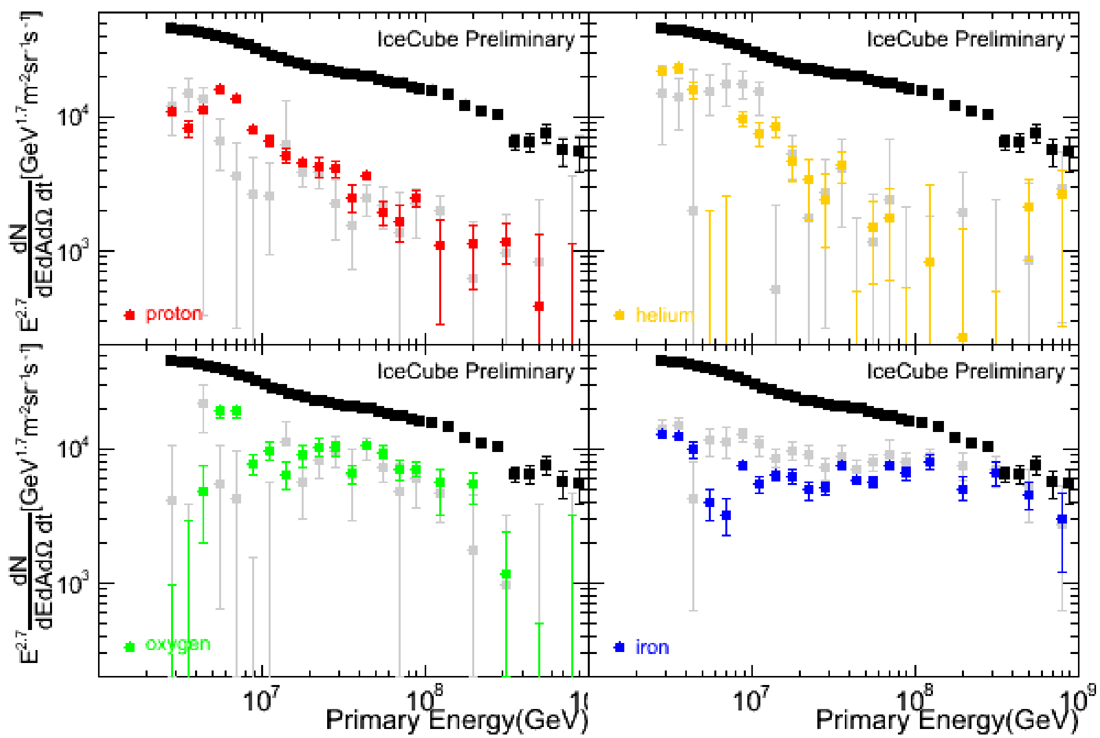
TUNKA



V.V. Prosin et al. / Nuclear Instruments and Methods in Physics Research A 756 (2014) 94–101
99
PROTON
HELIUM
NITROGEN
IRON
dN/dE×E^3 [m^{-2}s^{-1}sr^{-1}eV^2]
10^{24}
10^{15}
10^{16}
10^{17}
10^{18}
E [eV]

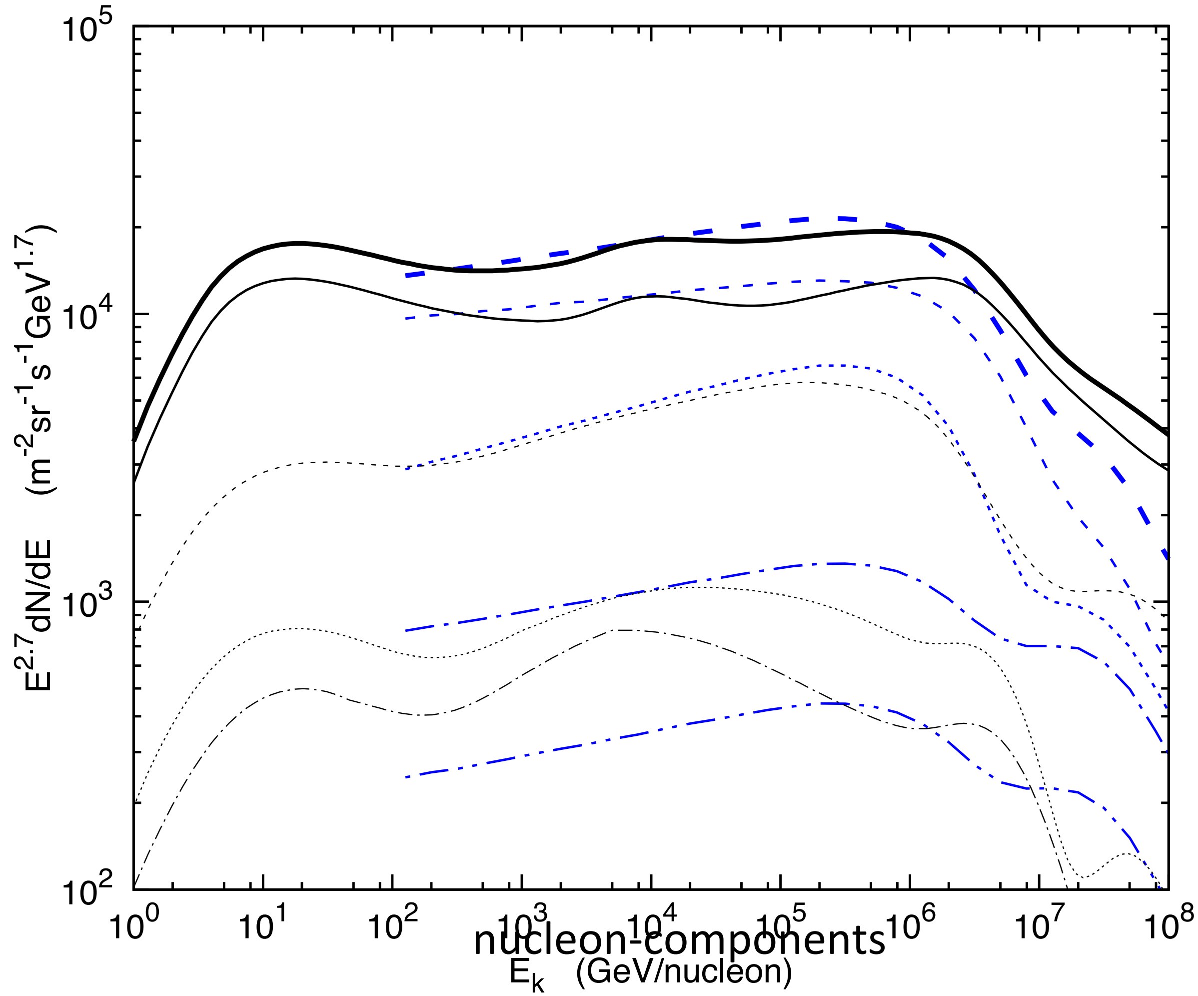
IceCube/IceTop coincident events



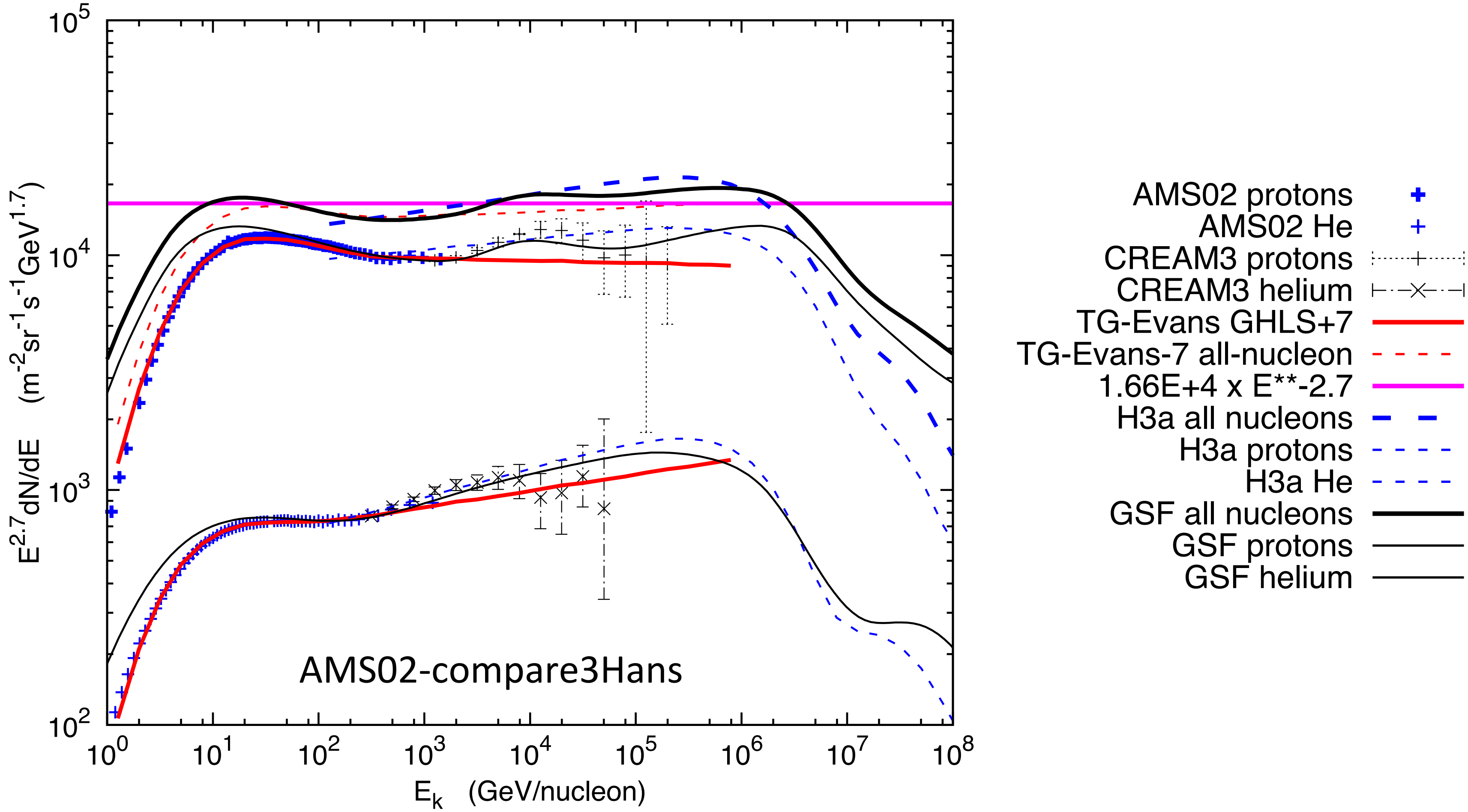


IceCube, ICRC 2015, arXiv:1510.05225

Nucleon spectra: compare H3a, GSF



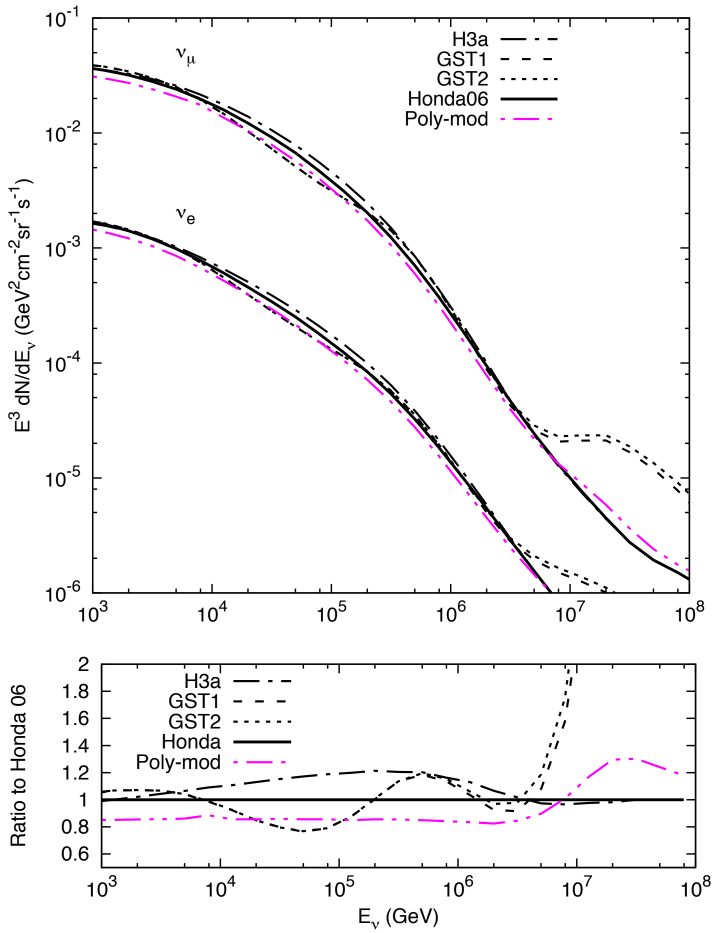
Compare p and He (incl. data)



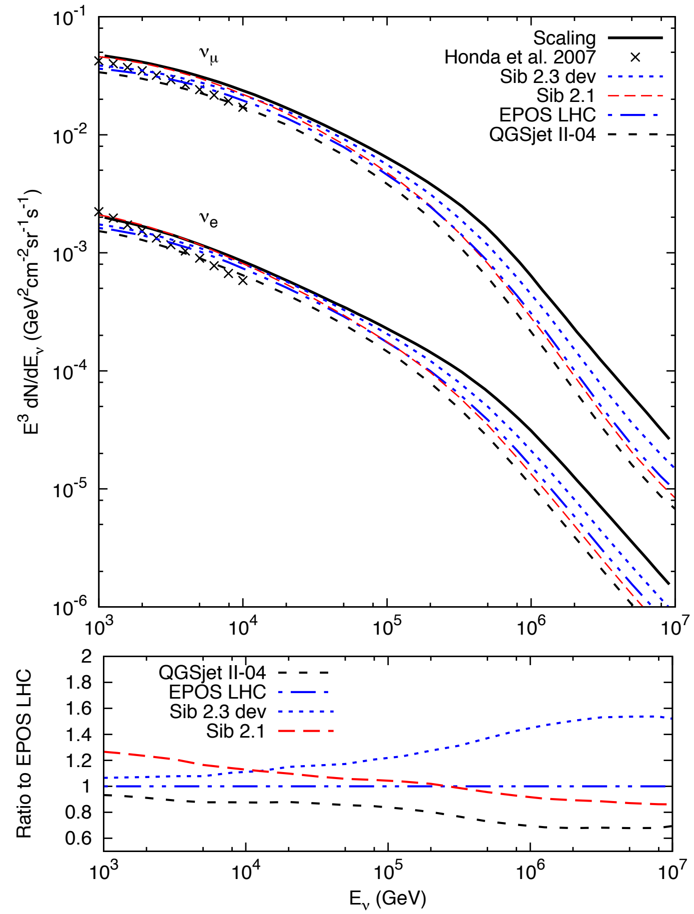
Uncertainties in conventional ν fluxes:

TG: 1605.03073

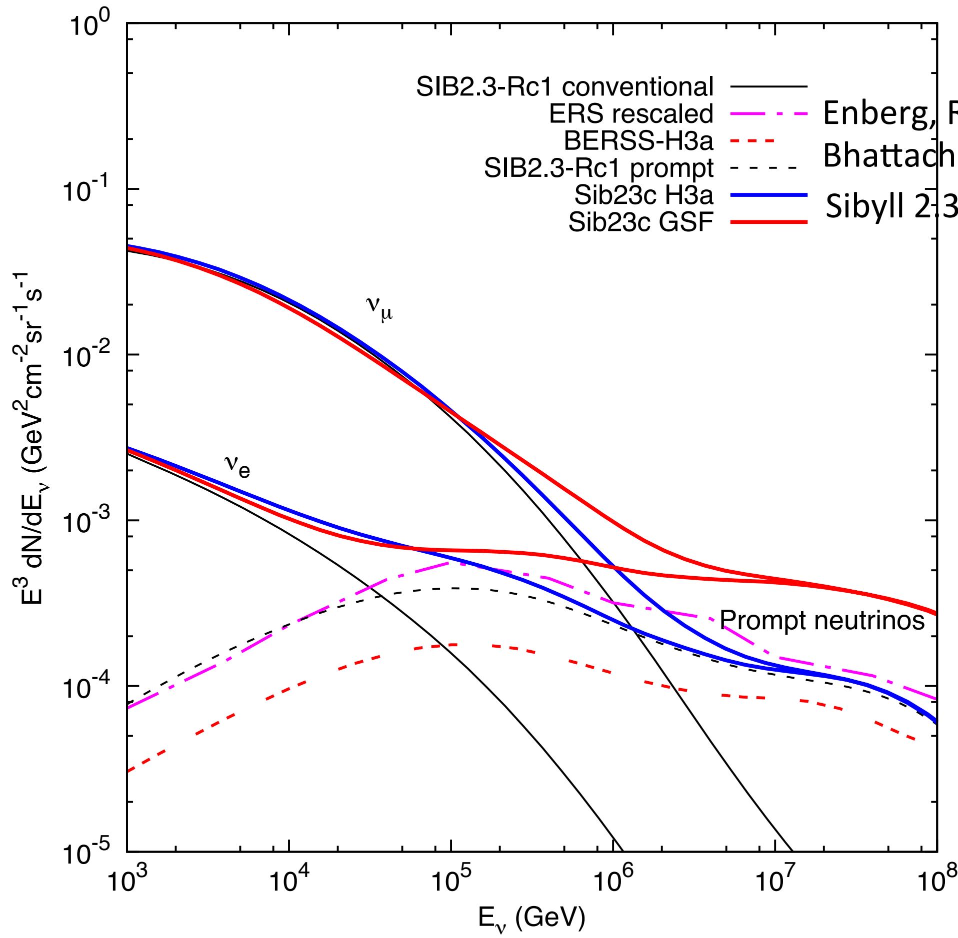
Different primary spectra



Different hadronic interaction models



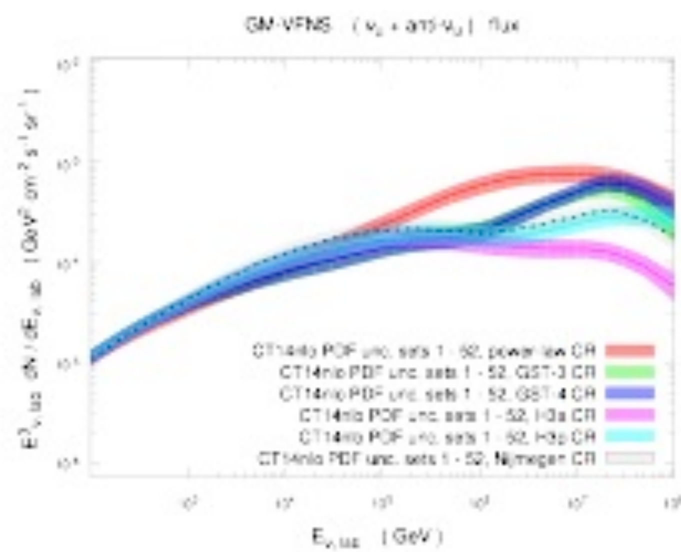
Uncertainties in prompt ν



Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Bhattacharya, Enberg, Reno, Sarcevic, Stasto, JHEP 06 (2015) 110

Sibyll 2.3: F. Riehn et al., ICRC 2017



Note lower crossover for electron neutrinos

Benzke Garzelli, et al., arXiv: 1705.10386