Evaluation of Galactic Cosmic Rays Models Using AMS2 and PAMELA Measurements

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New Opportunities in the AMS2 Era #2, Arlington Virginia

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Motivation and Outline

Motivation:

- Use **AMS2/PAMELA** Galactic Cosmic Rays (**GCR**) proton measurements, to **highlight** differences among 3 existing GCR models at < 3 GeV, and > 3 GeV ranges

Outline:

- Brief description of the **BO/MSU/DLR** GCR models
- Review of historical GCR measurements
- Explain **AMS2/PAMELA** proton measurements
- Correlate **AMS2/PAMELA** measurements with the **BO/MSU/DLR** models
- **Highlight** regions of exposure importance to astronauts
- Summary/conclusion

Brief Introduction of the BO/MSU/DLR GCR Models

BO% →

$$\begin{cases} \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 V_s \Phi_i(E,t)\right] - \frac{1}{3}\left[\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 V_s)\right]\left[\frac{\partial}{\partial E}\left(\frac{E+2E_0}{E+E_0}\right)E\Phi_i(E,t)\right] - \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 \kappa(r,E,t)\frac{\partial}{\partial r}\Phi_i(E,t)\right] = 0 \\ \kappa(r,E,t) = \frac{\kappa_0 \beta R(E)}{V_s \phi(t)}\left[1+\left(\frac{r}{r_0}\right)^2\right] \end{cases}$$

MSU# →

$$\Phi_i(R,t) = \frac{C_i \beta^{\alpha_i}}{R^{\gamma_i}}\left[\frac{R}{R+R_0(R,t)}\right]^{\Delta_i(R,t)}$$

DLR* →

$$\Phi_i(R,t) = \frac{C_i \beta^{\alpha_i}}{R^{\gamma_i}}\left[\frac{R}{R+R_0(R,t)}\right]^{\Delta_i(R,t)}$$

Transformation $\Phi_i(R,t) \rightarrow \Phi_i(E,t)$

$$\Delta(t) = c + bW(t)$$

$$W_{oulu} = -0.093 NM_{oulu} + 638.7$$

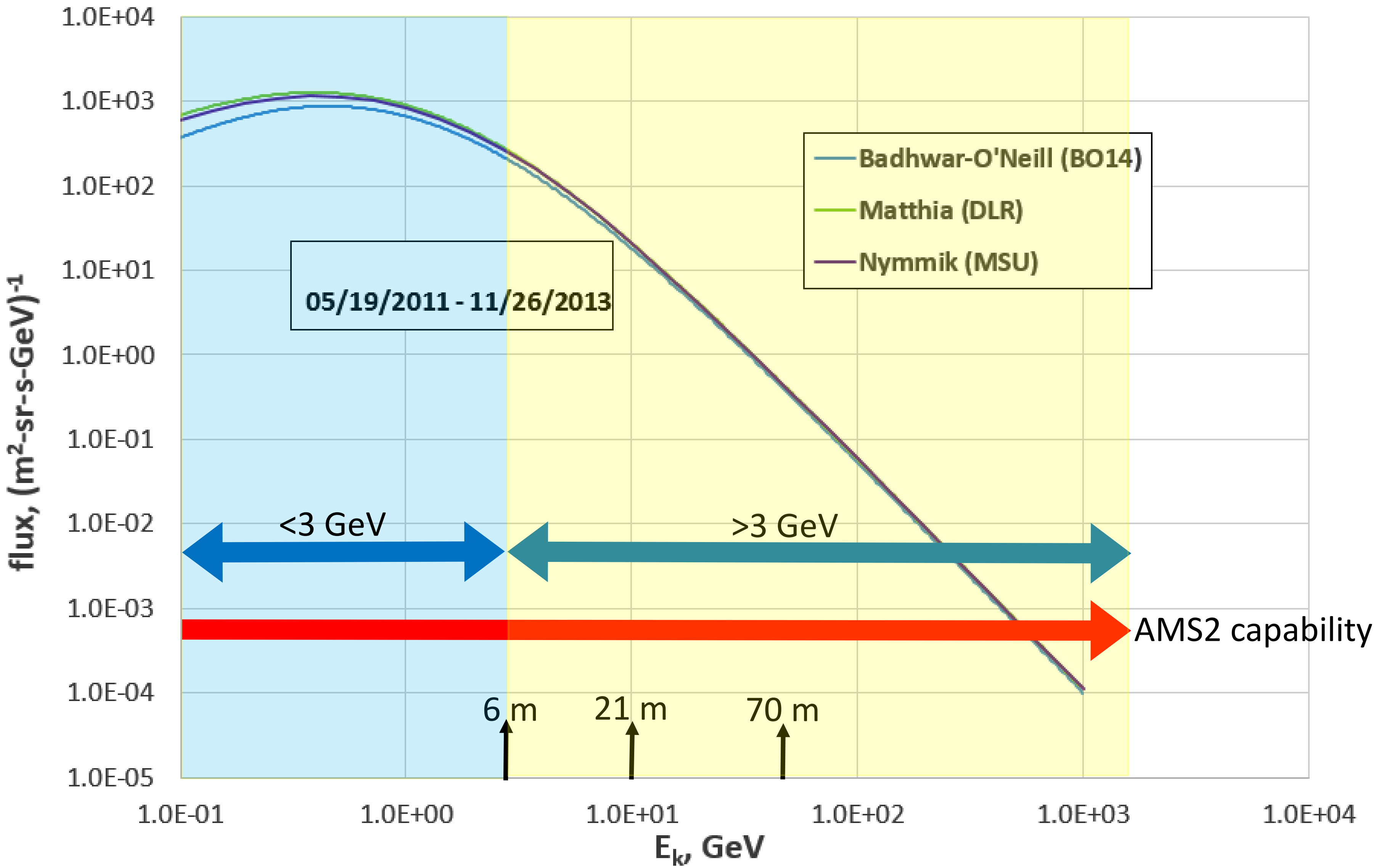
All 3 models are valid at 1 AU outside the Earth geomagnetic field

%Badhwar, G.D., O'Neill, P.M. (1994), Long term modulation of galactic cosmic radiation and its model for space exploration, *Adv. in Space Res.*, v. 14, pp. 749-757

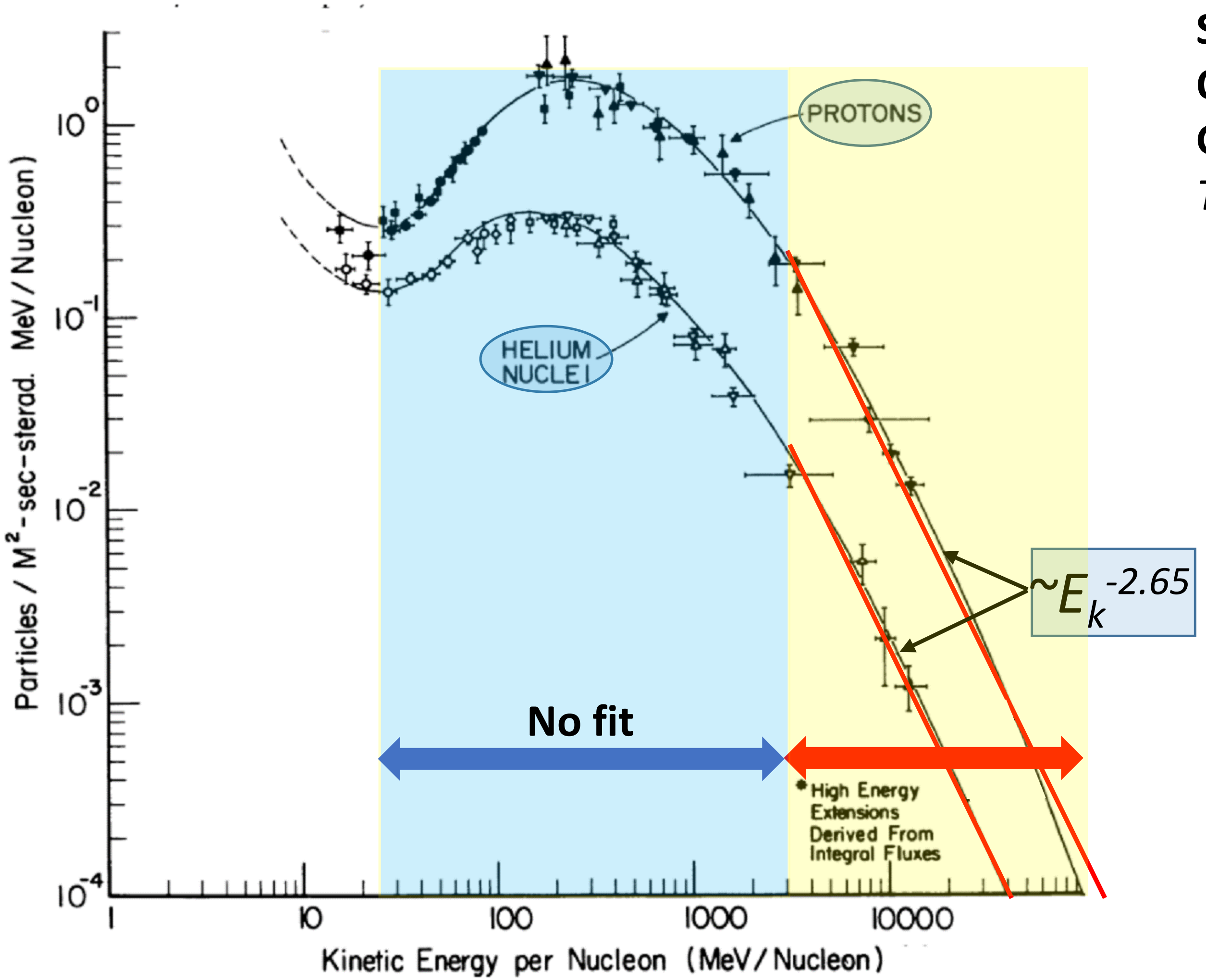
#Nymmik, R., et al. (1994), An analytical model, describing dynamics of galactic cosmic ray heavy particles, *Adv. in Space Res.*, v. 14, pp. 759-763

*Matthia, D., et al. (2013), A ready-to-use galactic cosmic ray model, *Adv. in Space Res.*, v. 51, pp. 329–338

BO/MSU/DLR GCR Proton Spectra at Free Space



Historical GCR measurements - I

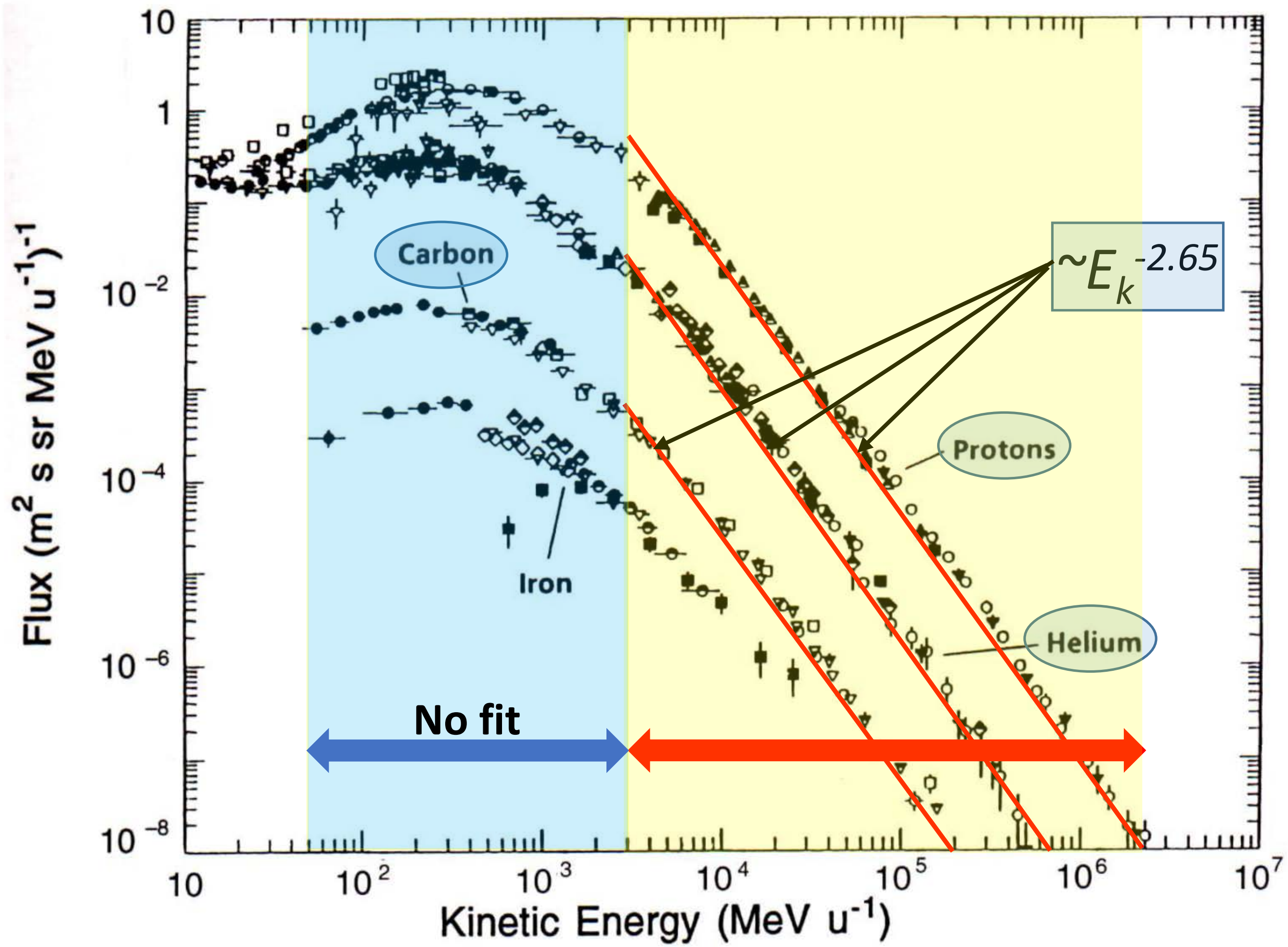


SOLAR MODULATION AND ENERGY DENSITY OF GALACTIC COSMIC RAYS

G. Gloeckler and J.R. Jokipii

The astrophysical journal, Vol. 148, April 1967

Historical GCR Measurements - II



ELEMENTAL AND ISOTOPIC COMPOSITION OF THE GALACTIC COSMIC RAYS

J. A. Simpson

Ann. Rev. Nucl. Part. Sci. 1983.33:323-81, 1983

P.R.L. Paper on AMS2/PAMELA (May 2015)

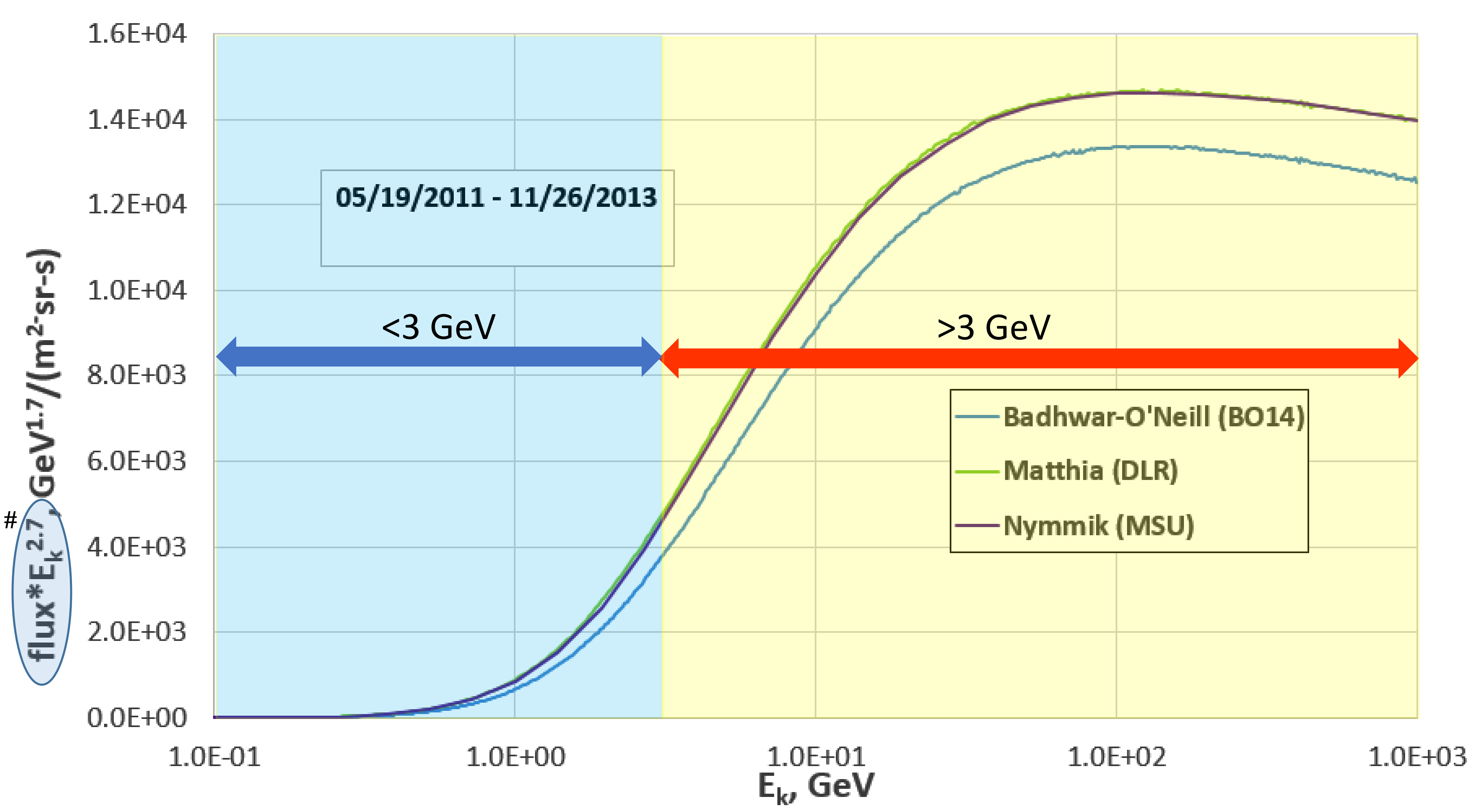
PRL **114,** 171103 (2015) PHYSICAL REVIEW LETTERS week ending 1 MAY 2015

Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station

(0.43 GeV – 1.80 TeV)

M. Aguilar,[26] D. Aisa,[33,34] B. Alpat,[33] A. Alvino,[33] G. Ambrosi,[33] K. Andeen,[22] L. Arruda,[24] N. Attig,[21] P. Azzarello,[33,16] A. Bachlechner,[1] F. Barao,[24] A. Barrau,[17] L. Barrin,[15] A. Bartoloni,[38] L. Basara,[3,37] M. Battarbee,[45] R. Battiston,[37,a] J. Bazo,[33] U. Becker,[9] M. Behlmann,[9] B. Beischer,[1] J. Berdugo,[26] B. Bertucci,[33,34] G. Bigongiari,[35,36] V. Bindi,[19] S. Bizzaglia,[33] M. Bizzarri,[33,34] G. Boella,[28,29] W. de Boer,[22] K. Bollweg,[20] V. Bonnivard,[17] B. Borgia,[38,39] S. Borsini,[33] M. J. Boschini,[28] M. Bourquin,[16] J. Burger,[9] F. Cadoux,[16] X. D. Cai,[9] M. Capell,[9] S. Caroff,[3] J. Casaus,[26] V. Cascioli,[33] G. Castellini,[14] I. Cernuda,[26] D. Cerreta,[33,34] F. Cervelli,[35] M. J. Chae,[41] Y. H. Chang,[10] A. I. Chen,[9] H. Chen,[9] G. M. Cheng,[6] H. S. Chen,[6] L. Cheng,[42] H. Y. Chou,[10] E. Choumilov,[9] V. Choutko,[9] C. H. Chung,[1] C. Clark,[20] R. Clavero,[23] G. Coignet,[3] C. Consolandi,[19] A. Contin,[7,8] C. Corti,[19] E. Cortina Gil,[16,b] B. Coste,[37,15] W. Creus,[10] M. Crispoltoni,[33,34] Z. Cui,[42] Y. M. Dai,[5] C. Delgado,[26] S. Della Torre,[28] M. B. Demirköz,[2] L. Derome,[17] S. Di Falco,[35] L. Di Masso,[33,34] F. Dimiccoli,[37] C. Díaz,[26] P. von Doetinchem,[19] F. Donnini,[33,34] W. J. Du,[42] M. Duranti,[33,34] D. D'Urso,[33] A. Eline,[9] F. J. Eppling,[9] T. Eronen,[45] Y. Y. Fan,[44,c] L. Farnesini,[33] J. Feng,[3,d] E. Fiandrini,[33,34] A. Fiasson,[3] E. Finch,[32] P. Fisher,[9] Y. Galaktionov,[9] G. Gallucci,[35] B. García,[26] R. García-López,[23] C. Gargiulo,[15] H. Gast,[1] I. Gebauer,[22] M. Gervasi,[28,29] A. Ghelfi,[17] W. Gillard,[10] F. Giovacchini,[26] P. Goglov,[9] J. Gong,[31] C. Goy,[3] V. Grabski,[27] D. Grandi,[28] M. Graziani,[33,34] C. Guandalini,[7,8] I. Guerri,[35,36] K. H. Guo,[18] D. Haas,[16,e] M. Habiby,[16] S. Haino,[10,44] K. C. Han,[25] Z. H. He,[18] M. Heil,[9] J. Hoffman,[10] T. H. Hsieh,[9] Z. C. Huang,[18] C. Huh,[13] M. Incagli,[35] M. Ionica,[33,34] W. Y. Jang,[13] H. Jinchi,[25] K. Kanishev,[37,15] G. N. Kim,[13] K. S. Kim,[13] Th. Kirn,[1] R. Kossakowski,[3] O. Kounina,[9] A. Kounine,[9] V. Koutsenko,[9] M. S. Krafczyk,[9] G. La Vacca,[28] E. Laudi,[33,34,f] G. Laurenti,[7,8] I. Lazzizzera,[37] A. Lebedev,[9] H. T. Lee,[44] S. C. Lee,[44] C. Leluc,[16] G. Levi,[7,8] H. L. Li,[44,g] J. Q. Li,[31] Q. Li,[31] Q. Li,[9,h] T. X. Li,[18] W. Li,[4] Y. Li,[16,d] Z. H. Li,[6] Z. Y. Li,[44,d] S. Lim,[13] C. H. Lin,[44] P. Lipari,[38] T. Lippert,[21] D. Liu,[44] H. Liu,[31] M. Lolli,[7,8] T. Lomtadze,[35] M. J. Lu,[37,i] S. Q. Lu,[44,d] Y. S. Lu,[6] K. Luebelsmeyer,[1] J. Z. Luo,[31] S. S. Lv,[18] R. Majka,[32] C. Mañá,[26] J. Marín,[26] T. Martin,[20] G. Martínez,[26] N. Masi,[7,8] D. Maurin,[17] A. Menchaca-Rocha,[27] Q. Meng,[31] D. C. Mo,[18] L. Morescalchi,[35,j] P. Mott,[20] M. Müller,[1] J. Q. Ni,[18] N. Nikonov,[22] F. Nozzoli,[33] P. Nunes,[24] A. Obermeier,[1] A. Oliva,[26] M. Orcinha,[24] F. Palmonari,[7,8] C. Palomares,[26] M. Paniccia,[16] A. Papi,[33] M. Pauluzzi,[33,34] E. Pedreschi,[35] S. Pensotti,[28,29] R. Pereira,[19] N. Picot-Clemente,[12] F. Pilo,[35] A. Piluso,[33,34] C. Pizzolotto,[33] V. Plyaskin,[9] M. Pohl,[16] V. Poireau,[3] E. Postaci,[2] A. Putze,[3,k] L. Quadrani,[7,8] X. M. Qi,[18] X. Qin,[33,g] Z. Y. Qu,[44,l] T. Räihä,[1] P. G. Rancoita,[28] D. Rapin,[16] J. S. Ricol,[17] I. Rodríguez,[26] S. Rosier-Lees,[3] A. Rozhkov,[9] D. Rozza,[28] R. Sagdeev,[11] J. Sandweiss,[32] P. Saouter,[16] C. Sbarra,[7,8] S. Schael,[1] S. M. Schmidt,[21] A. Schulz von Dratzig,[1] G. Schwering,[1] G. Scolieri,[33] E. S. Seo,[12] B. S. Shan,[4] Y. H. Shan,[4] J. Y. Shi,[31] X. Y. Shi,[9,m] Y. M. Shi,[43] T. Siedenburg,[1] D. Son,[13] F. Spada,[38] F. Spinella,[35] W. Sun,[9] W. H. Sun,[9,n] M. Tacconi,[28,29,15] C. P. Tang,[18] X. W. Tang,[6] Z. C. Tang,[6] L. Tao,[3] D. Tescaro,[23] Samuel C. C. Ting,[9] S. M. Ting,[9] N. Tomassetti,[17] J. Torsti,[45] C. Türkoğlu,[2] T. Urban,[20] V. Vagelli,[22] E. Valente,[38,39] C. Vannini,[35] E. Valtonen,[45] S. Vaurynovich,[9] M. Vecchi,[40] M. Velasco,[26] J. P. Vialle,[3] V. Vitale,[33] S. Vitillo,[16] L. Q. Wang,[42] N. H. Wang,[42] Q. L. Wang,[5] R. S. Wang,[43] X. Wang,[9] Z. X. Wang,[18] Z. L. Weng,[9] K. Whitman,[19] J. Wienkenhöver,[1] H. Wu,[31] X. Wu,[16] X. Xia,[26,g] M. Xie,[9,h] S. Xie,[43] R. Q. Xiong,[31] G. M. Xin,[42] N. S. Xu,[18] W. Xu,[6,9] Q. Yan,[9] J. Yang,[41] M. Yang,[6] Q. H. Ye,[43] H. Yi,[31] Y. J. Yu,[5] Z. Q. Yu,[6] S. Zeissler,[22] J. H. Zhang,[31] M. T. Zhang,[18] X. B. Zhang,[18] Z. Zhang,[18] Z. M. Zheng,[4] H. L. Zhuang,[6] V. Zhukov,[1] A. Zichichi,[7,8] N. Zimmermann,[1] P. Zuccon,[9] and C. Zurbach[30]

Modified BO/MSU/DLR Proton Spectra



#Aguilar, M., et al. (2015), Precision measurement of the proton flux in primary cosmic rays from rigidity of 1 GV to 1.8 TV with the alpha magnetic spectrometer on the international space station, *Phys. Rev. Letters*, *114-171103*, May 2015

AMS2/PAMELA Specifications

AMS2 **(Alpha Magnetic Spectrometer 2)**

STS 134

May 19, 2011 – present

Data coverage: May 2011 - November 2013 (~922 days)

Perigee/Apogee: 341 - 353 km.

Inclination: 51.6°

Period: 91 min.

Proton E_K range: 0.43 - 1800 GeV (1.0 - 1800 GV)

SAA data are excluded

PAMELA **(Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics)**

Host Satellite, Resurs DK1 (Soyuz-FG)

June 15, 2006 - present

Data coverage: May 2011 - November 2013 (~922 days)

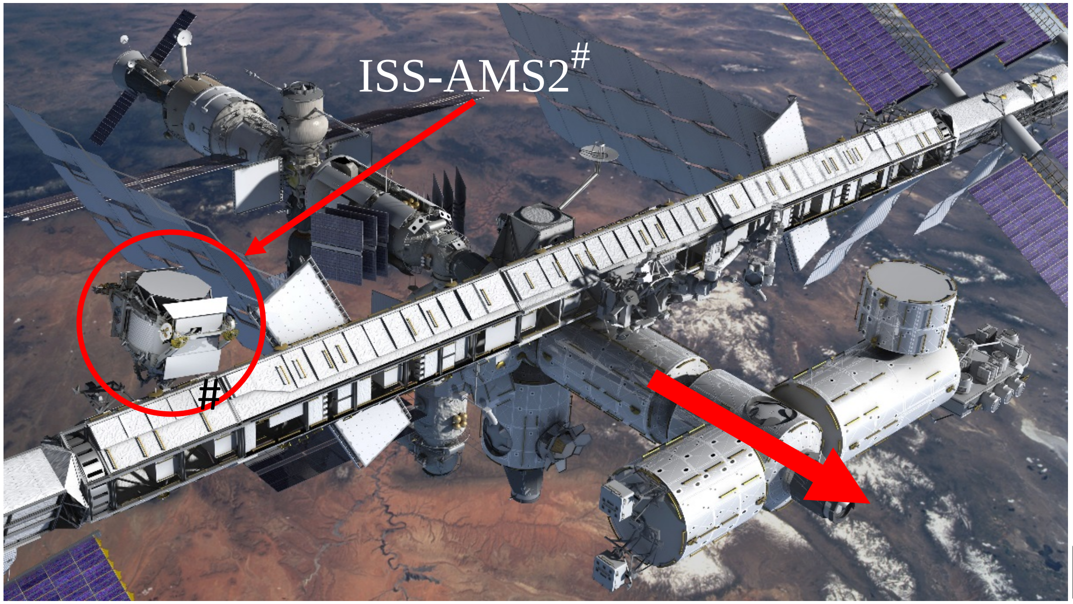
Perigee/Apogee: 360 - 604 km. (~600 km. circular since 2010)

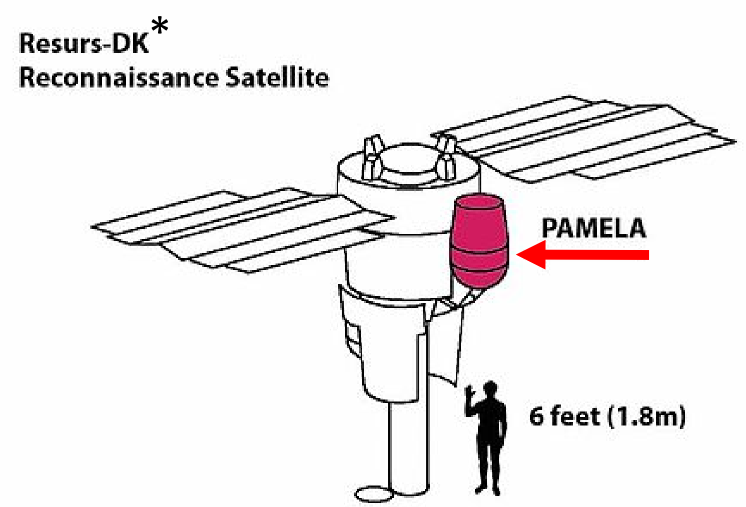
Inclination: 70°

Period : 94 min.

Proton E_K range: 0.1 - 1000 GeV (0.6 - 1000 GV)

SEP/SAA data are excluded

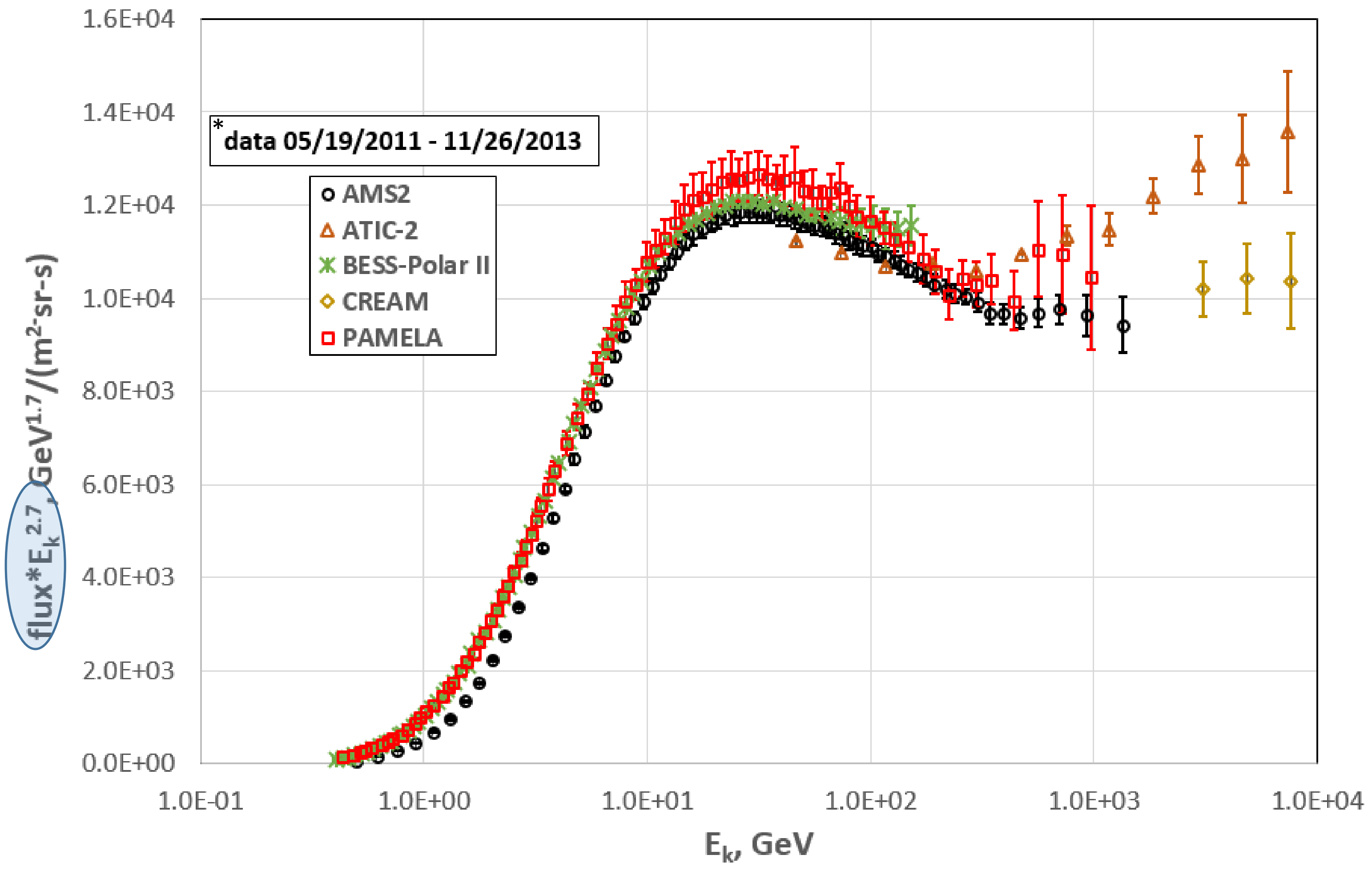




#STS-134/ULF6-AMS, https://ams.nasa.gov, May, 2011

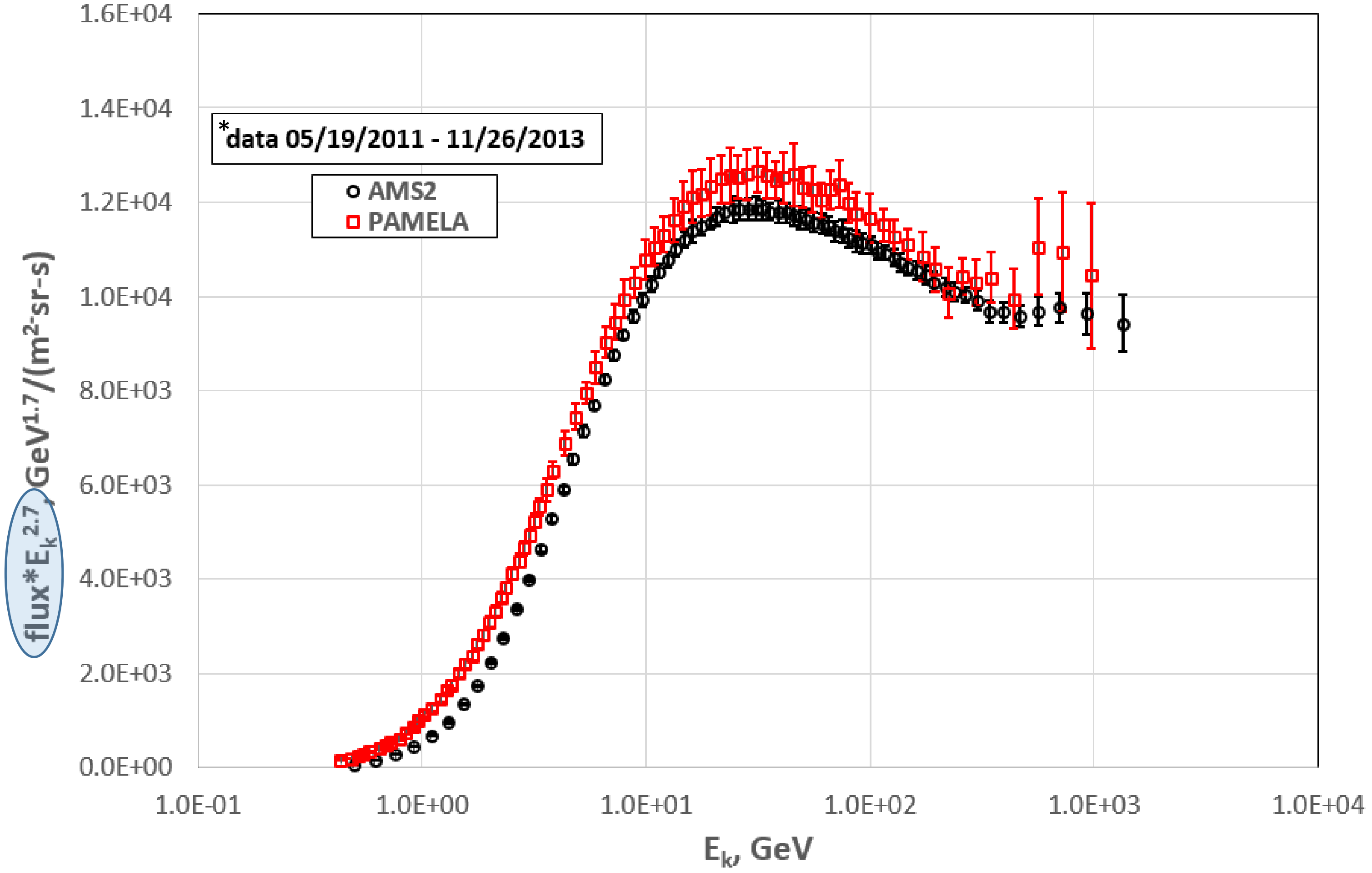
*Adriani, O., et al. (2011), PAMELA measurements of cosmic-ray proton and helium spectra, *Science*, *332*, p: 69-72, Apr. 2011

Modified AMS2/PAMELA/ATIC-2/BESS-Polar II/CREAM Proton Spectra



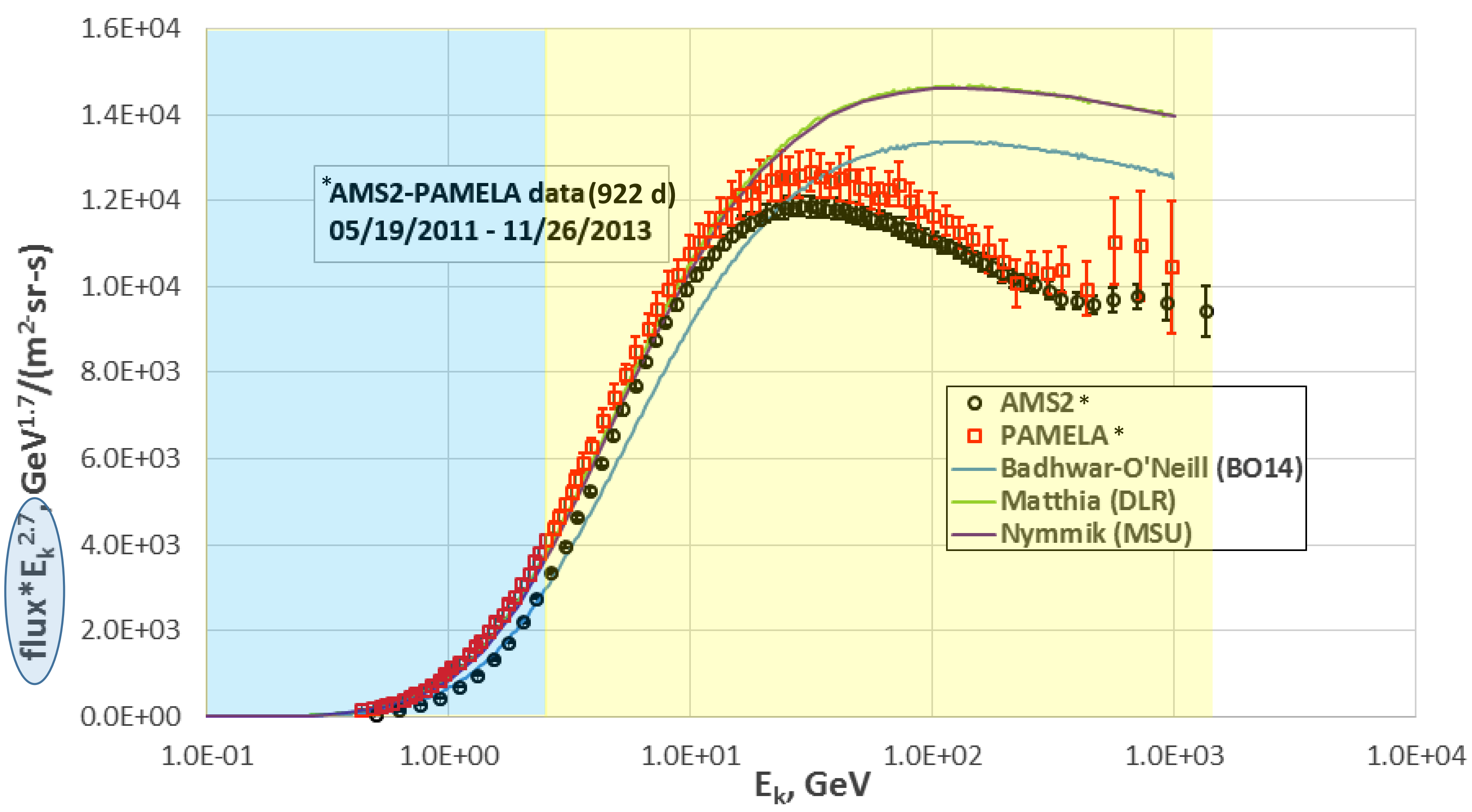
*Aguilar, M., et al. (2015), Precision measurement of the proton flux in primary cosmic rays from rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station, *Physical Review Letters*, *114*, 171,103

Modified AMS2/PAMELA Proton Spectra



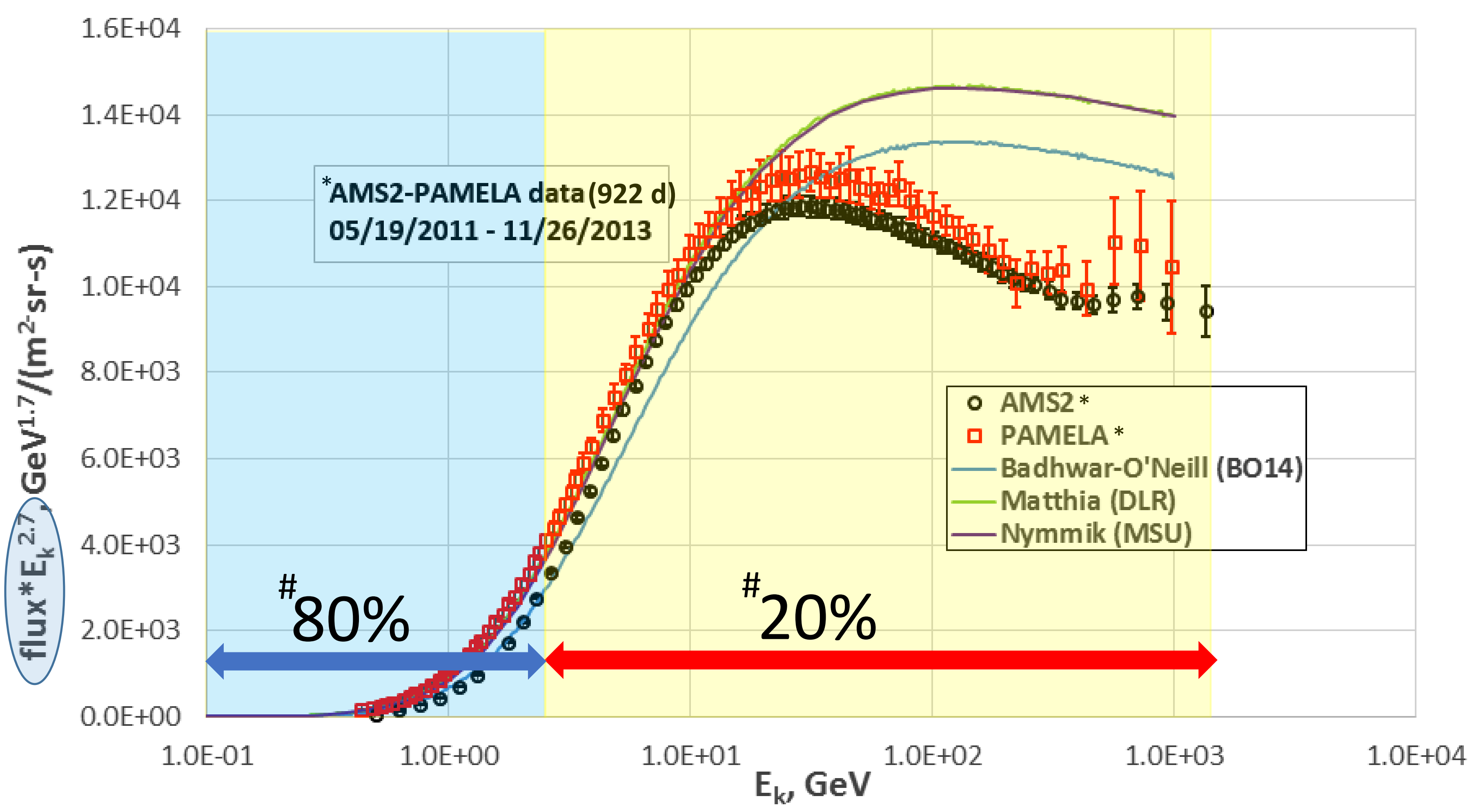
*Aguilar, M., et al. (2015), Precision measurement of the proton flux in primary cosmic rays from rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station, *Physical Review Letters*, *114*, 171,103

AMS2/PAMELA Proton Spectra Measurement vs. GCR Models



*Aguilar, M., et al. (2015), Precision measurement of the proton flux in primary cosmic rays from rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station, *Physical Review Letters*, *114*, 171,103

Significance of GCR Radiation Exposure (E) in Each Energy Region



*Aguilar, M., et al. (2015), Precision measurement of the proton flux in primary cosmic rays from rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station, *Physical Review Letters*, *114*, 171,103

#Slaba, T. C., Blattnig, S. R. (2014), GCR environmental models I: Sensitivity analysis for GCR environments, AGU pubs., *Space Weather*, *12*, 217-224

#70-80% of the astronaut effective dose resulting from GCR protons comes from protons with energy < 3 GeV

Summary/Conclusion

- Briefly reviewed 3 GCR models and discussed the differences among them
- Compared GCR model predictions to published AMS2/PAMELA proton measurements
- Showed that the **BO** model is closest to the AMS2 measurements in the region of greatest importance for astronaut exposure (< 3GeV), while the **MSU**/**DLR** models are closest to the PAMELA measurements in this region
- Showed that the **BO** model under-predicts the AMS2/PAMELA measurements at higher energies