AMS1 Secondary Proton Analysis and its Contribution to the ISS Dosimetric Validation

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Three Definitions of Particles at LEO

- **Primary** GCR particles
- **Secondary downward** particles at LEO
- **Secondary upward** particles at LEO

- **Primary** GCR particles are familiar to all of you. There exist at least 10 GCR models of varying complexity and computational efficiency, and I will very briefly discuss three of them

- **Secondary downward** particles at LEO, are generated by the collision of primary GCR and upper earth atmosphere

- **Secondary upward** particles at LEO, are generated by the collision of primary GCR and secondary downward particles with the upper Earth atmosphere

Motivation and Outline

- To **enhance** the physics represented in the existing environmental models at **LEO**

- Very brief introduction to existing LEO environmental models
- Explain the **AMS1** proton measurement
- Correlate AMS1 proton measurement with the **PAMELA** proton data
- Develop a parametric model for the downward and upward secondary proton spectra at LEO
- **Quantify** the parametric model improvements for the ISS validation work
- Brief Summary

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[#] →

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

→ Inversion of $\Phi_i(R,t) \rightarrow \Phi_i(E,t)$

DLR[*] →

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

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

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

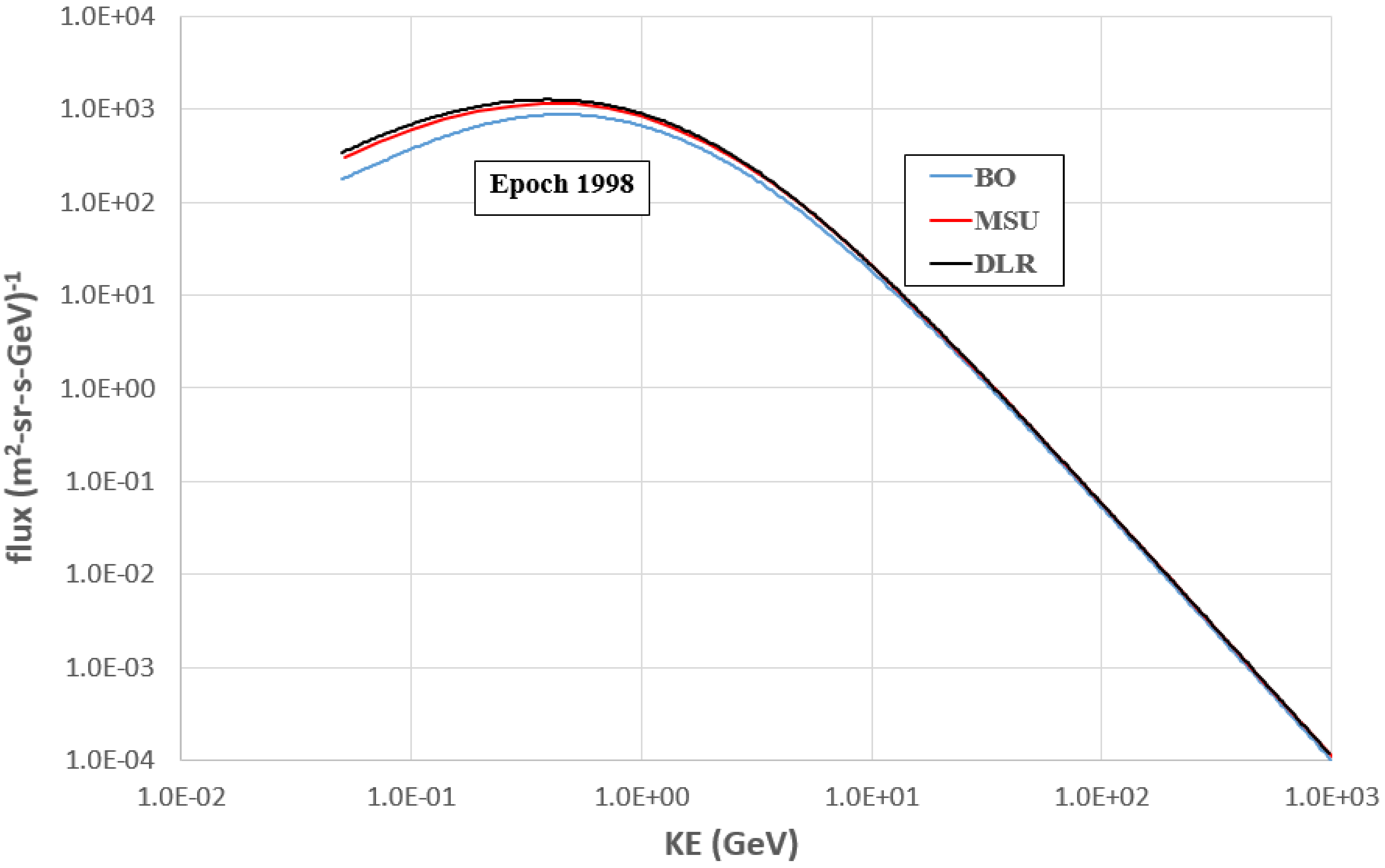
All 3 models are valid at 1 AU outside the Earth geomagnetic field

[%] Badhwar, G.D., et al. (1994), Long term modulation of galactic cosmic radiation and its model for space exploration, *Adv. in Space Res.*, v. 14, pp. 749-757

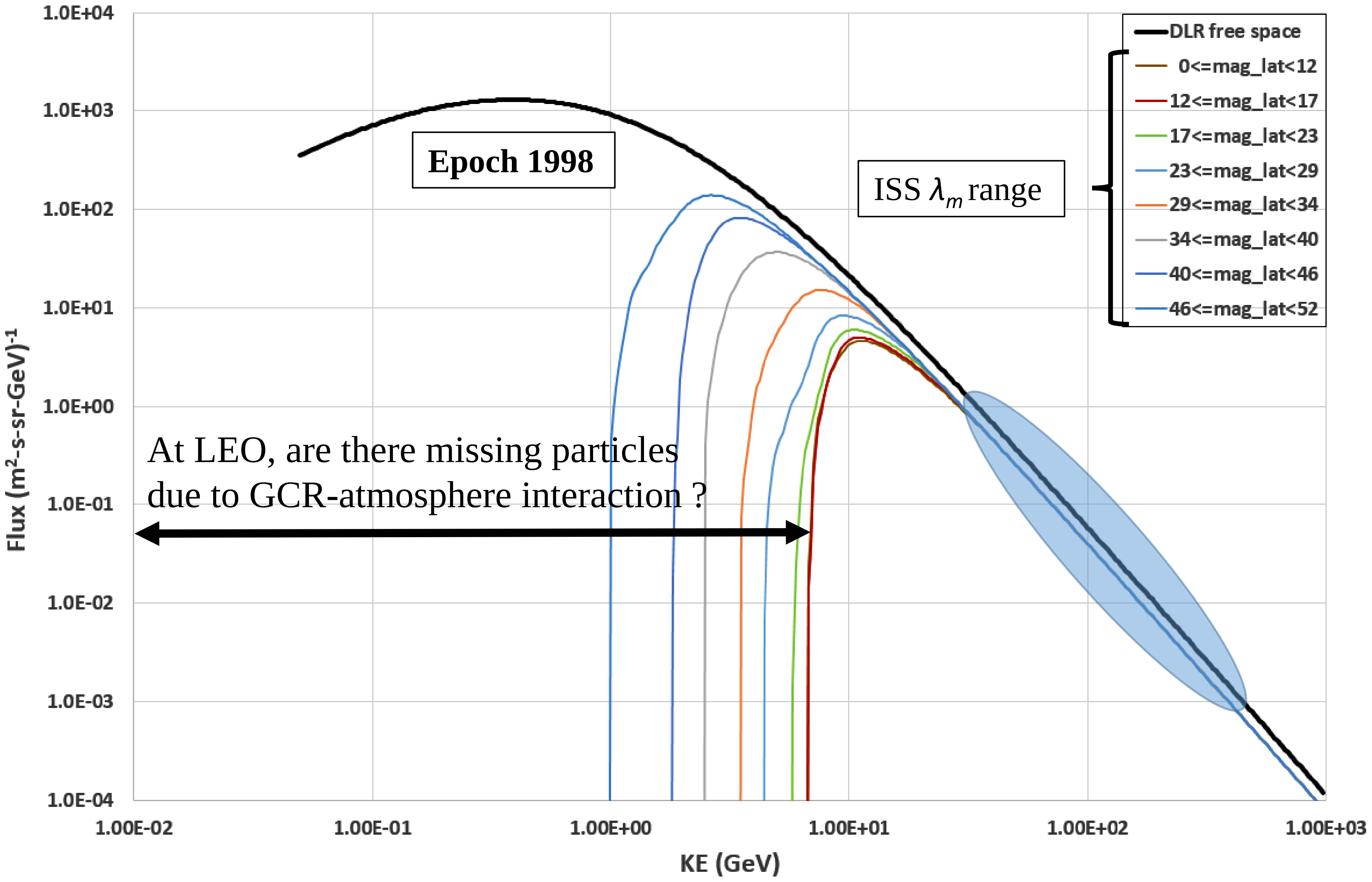
[#] Nymmik, R., et al. (1994), An analytical model, describing dynamics of galactic cosmic ray heavy particles, *Adv. in Space Res.*, v. 14, pp. 759-763

[*] 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



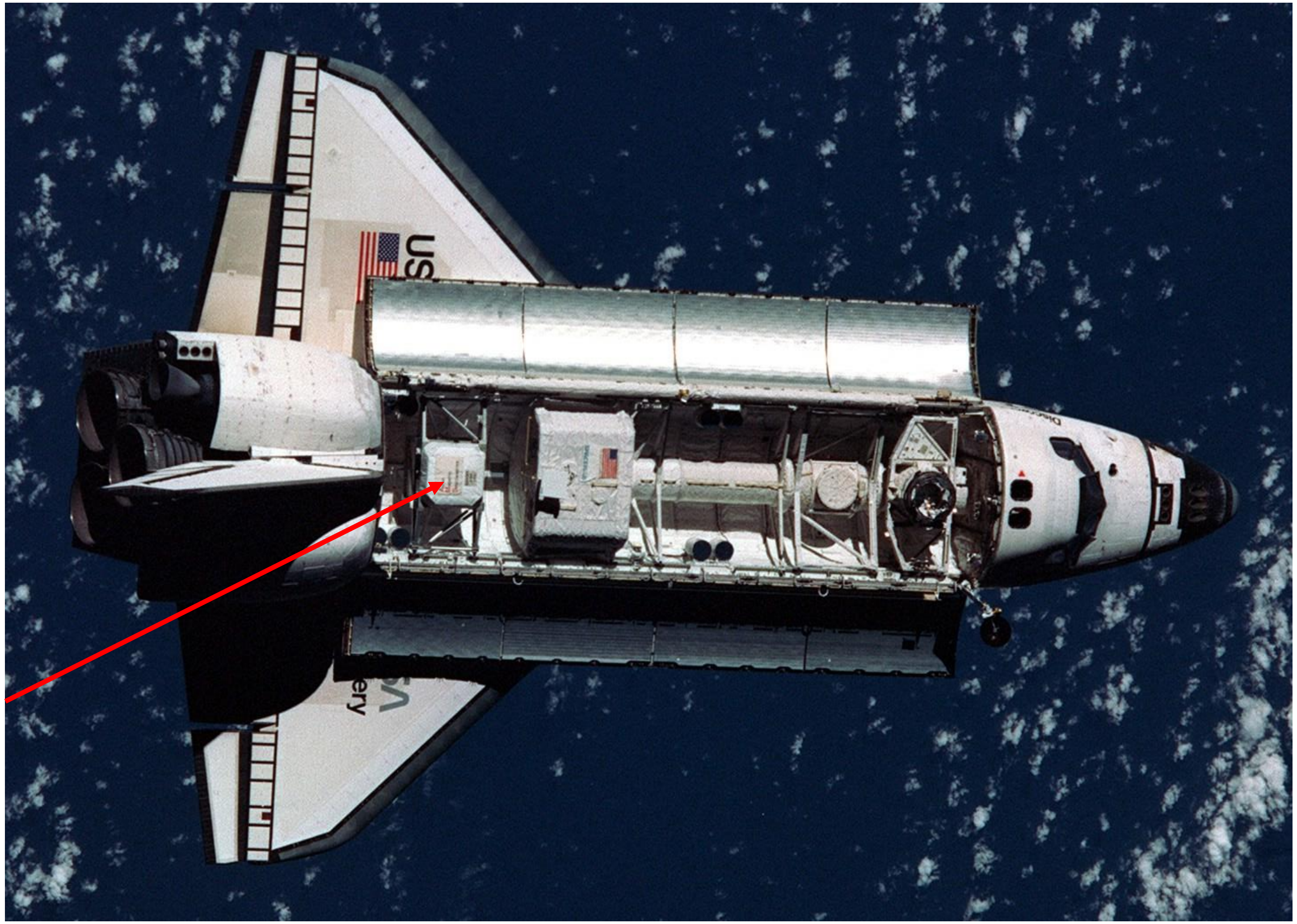
DLR GCR Proton Spectra at Free Space and LEO



AMS1 Detector

AMS1 payload

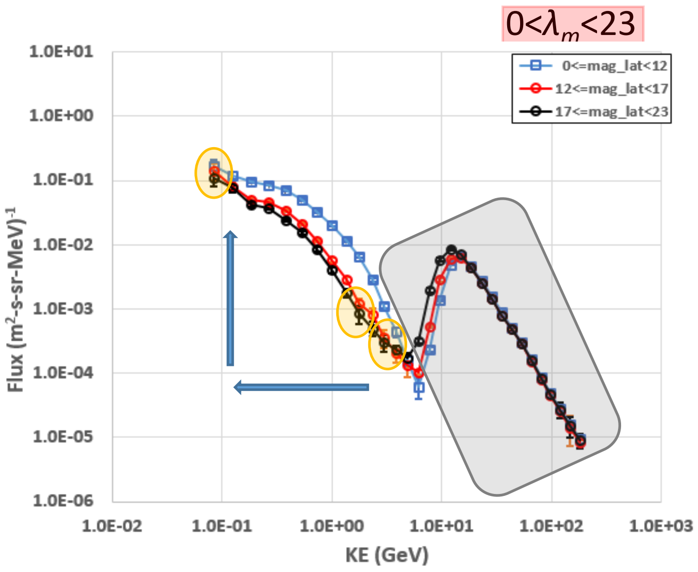
STS 91 (last STS flight to Mir)
June 2 - 12, 1998 (10 days)
Perigee/Apogee: 350 - 390 km.
Inclination: 51.7°
Orbital period: 92 min.
FOV=64° (-32° ~ +32°) wrt. Z axis
Z axis offset accuracy=1°
Proton E_K range of 0.1 - 200 GeV
SAA data are excluded

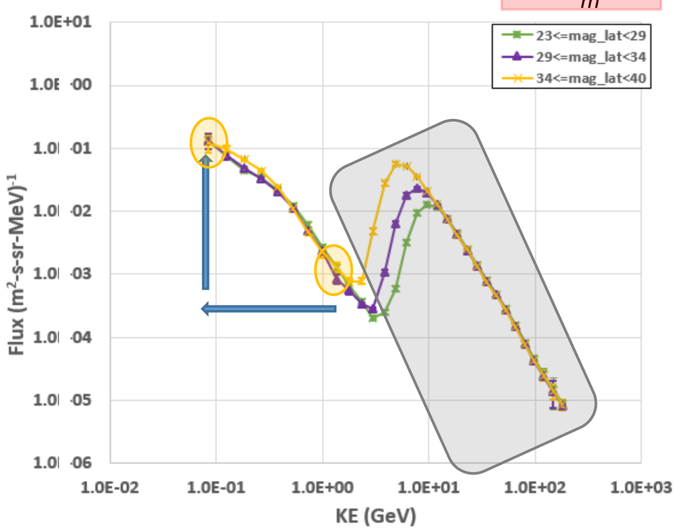


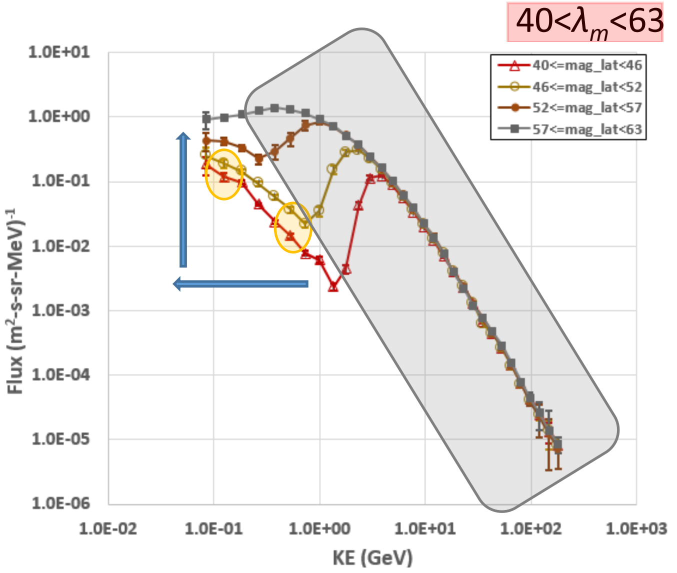
AMS1

AMS1 Downward/Upward Proton Data - I

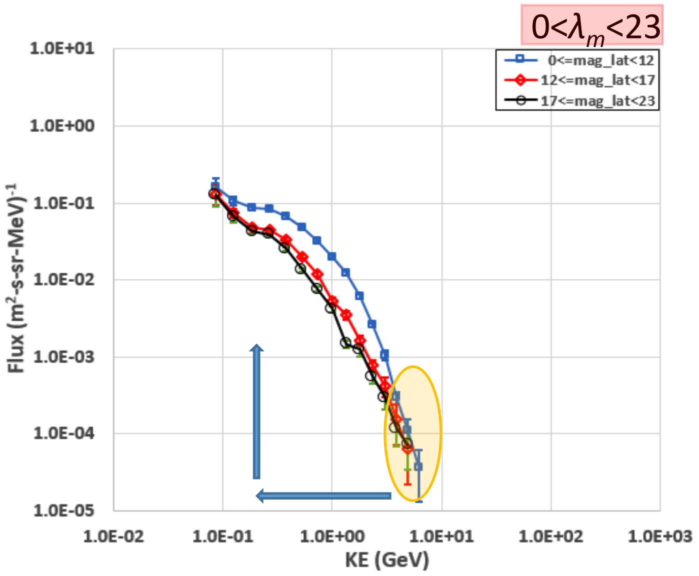
Downward

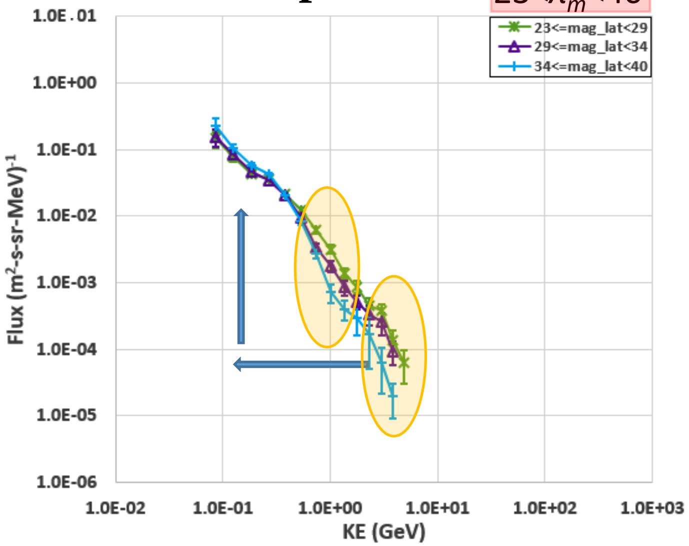


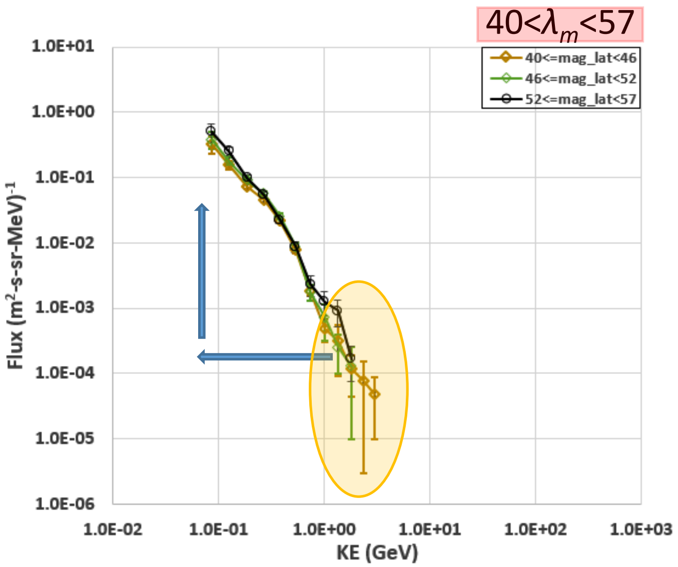




Upward

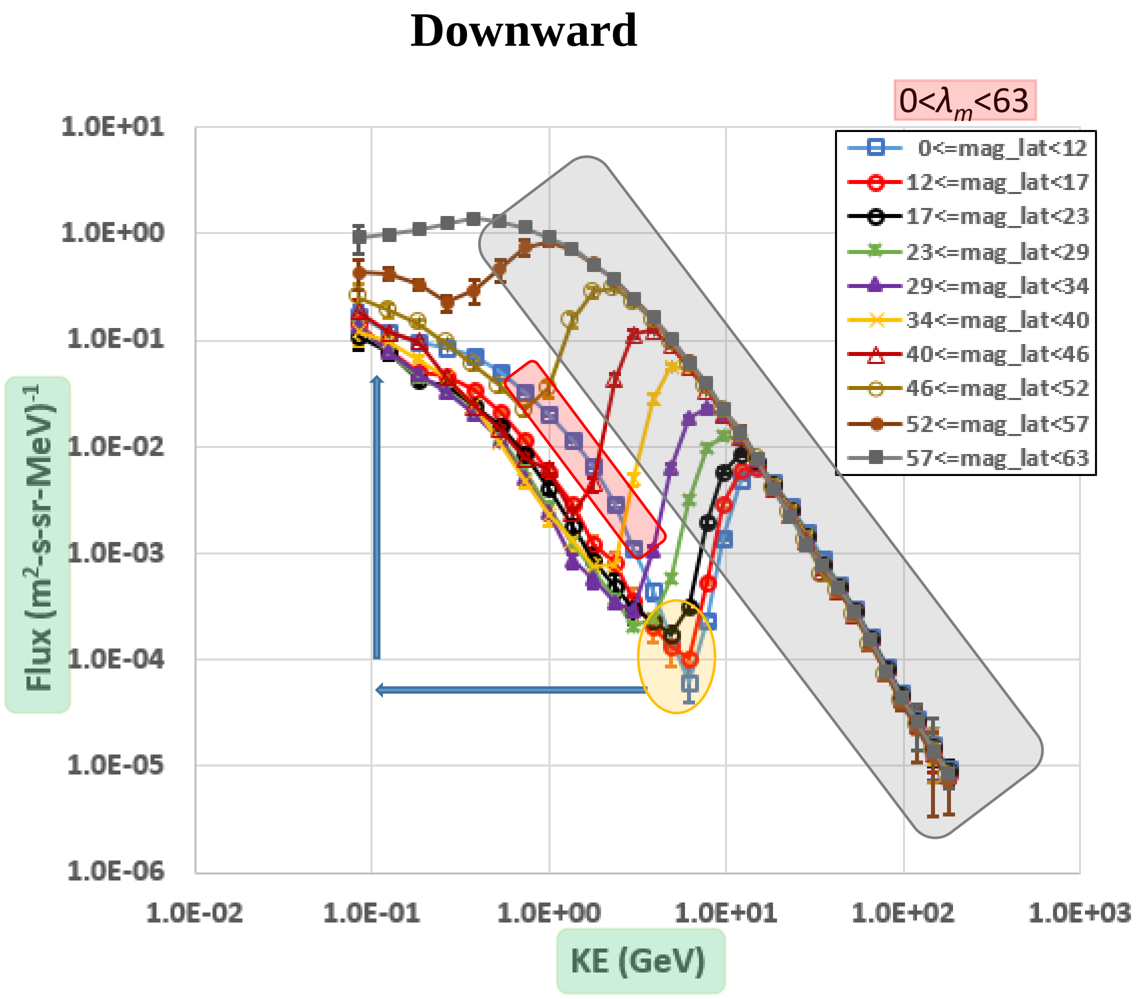


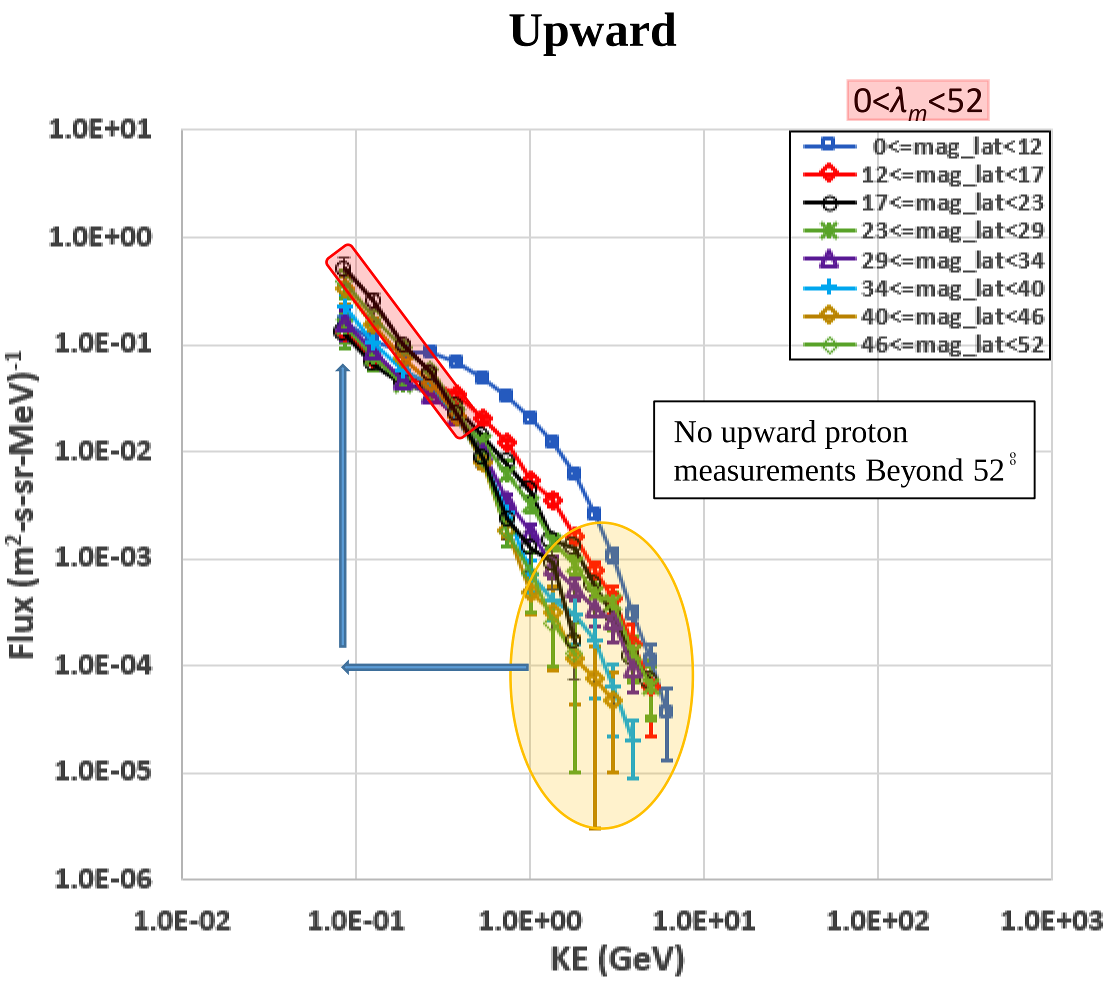




Alcaraz, J., et al. (2000), Protons in near earth orbit, *Physics Letter B*, v. 472, pp. 215-226

AMS1 Downward/Upward Proton Data - II





Alcaraz, J., et al. (2000), Protons in near earth orbit, *Physics Letter B*, v. 472, pp. 215-226

Two Questions about AMS1 Proton Measurements

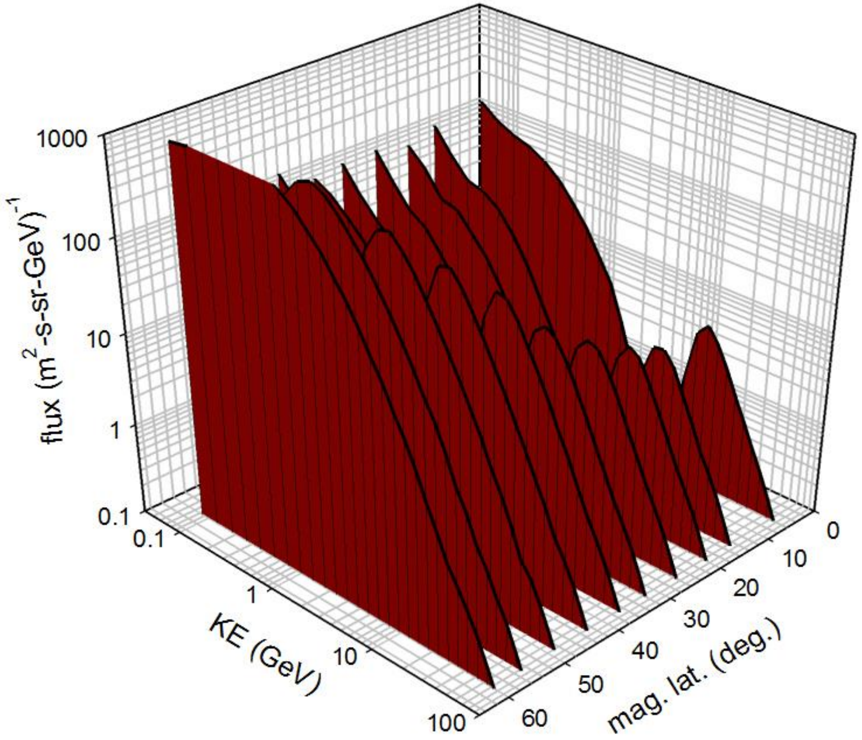
Based on AMS1 downward/upward proton measurements, two questions immediately come up:

- Q1: AMS1 was a "**proof of concept**" simple detector, and acted as a precursor to the far more expensive and much larger AMS2 detector. So, how do you know that AMS1 was **functioning properly**?

- Q2: Are there any **correlation** between secondary downward and secondary upward AMS1 proton measurements?

Is the AMS1 Downward Proton Spectra Profile Correct?

AMS1*

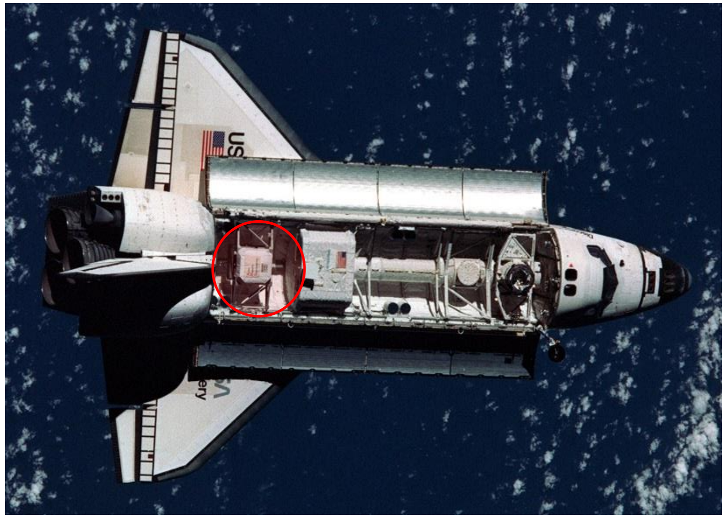


June 2 - 12, 1998 (10 days), SAA data are excluded

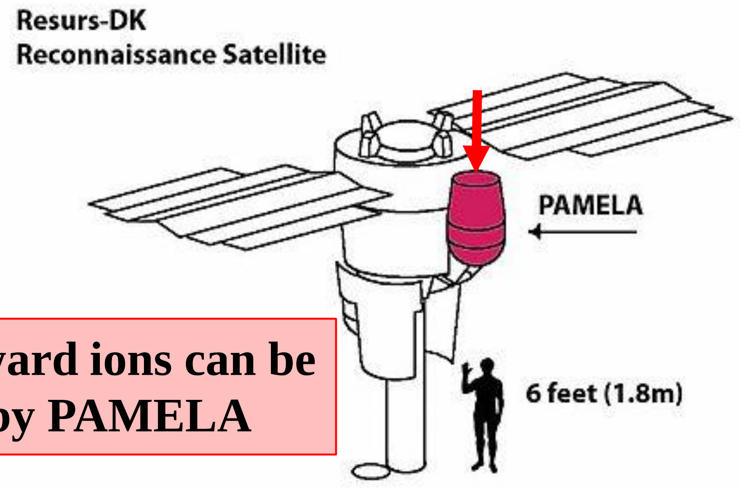
*Alcaraz, J., et al. (2000), Protons in near earth orbit, *Physics Letter B*, v. 472, pp. 215-226

AMS1 vs. PAMELA Detector Specification

AMS1 **(Alpha Magnetic Spectrometer 1)**
STS 91
June 2 - 12, 1998 (10 days)
Data collection June 2 - 12, 1998 (10 days)
Perigee/Apogee: 350 - 390 km.
Inclination: 51.7°
Period: 92 min.
FOV=64° (wrt. Z axis) with accuracy of 1°
Proton E_K range: 0.1 - 200 GeV
SAA data are excluded

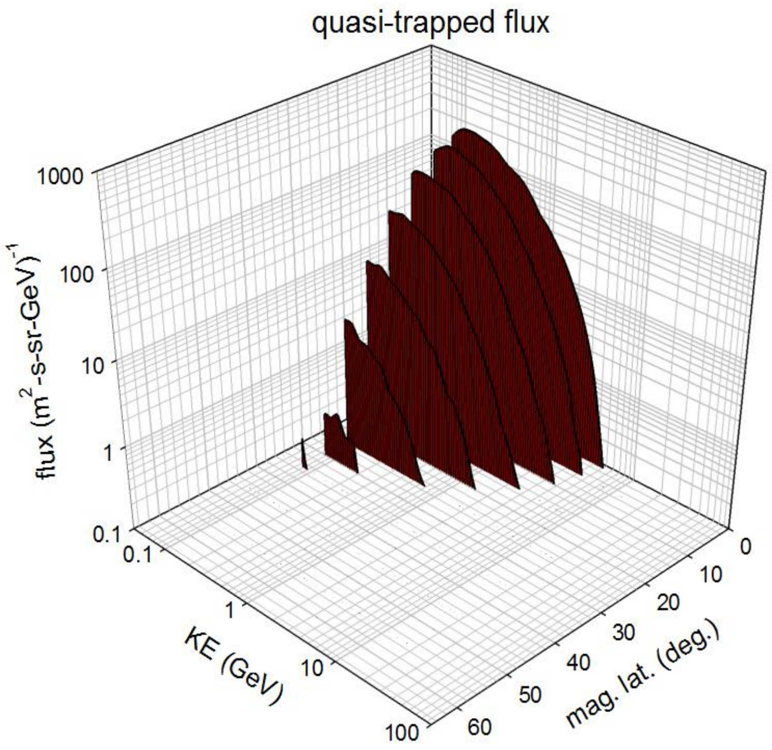


PAMELA **(Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics)**
Host Satellite, Resurs DK1 (Soyuz-FG)
June 15, 2006 - present
Data collection July 2006 - September 2009 (~800 days)
Perigee/Apogee: 360 - 604 km. (~600 km. circular since 2010)
Inclination: 70°
Period : 94 min.
FOV~60°
Proton E_K range: 0.1 - 70 GeV
SAA/SEP data are excluded

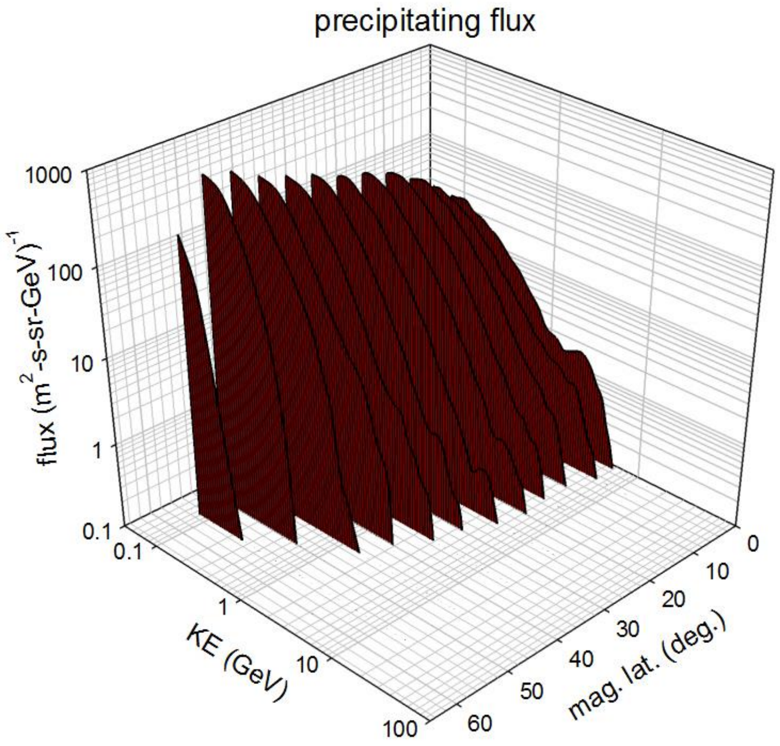


***Only downward ions can be collected by PAMELA**

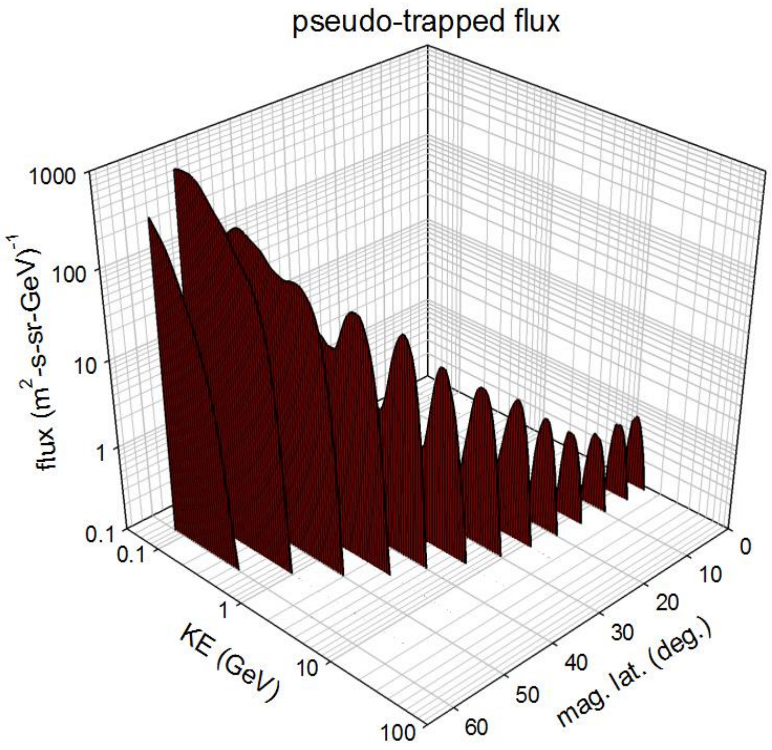
PAMELA Secondary Downward Proton Spectra Components



Equatorial region



Short lived



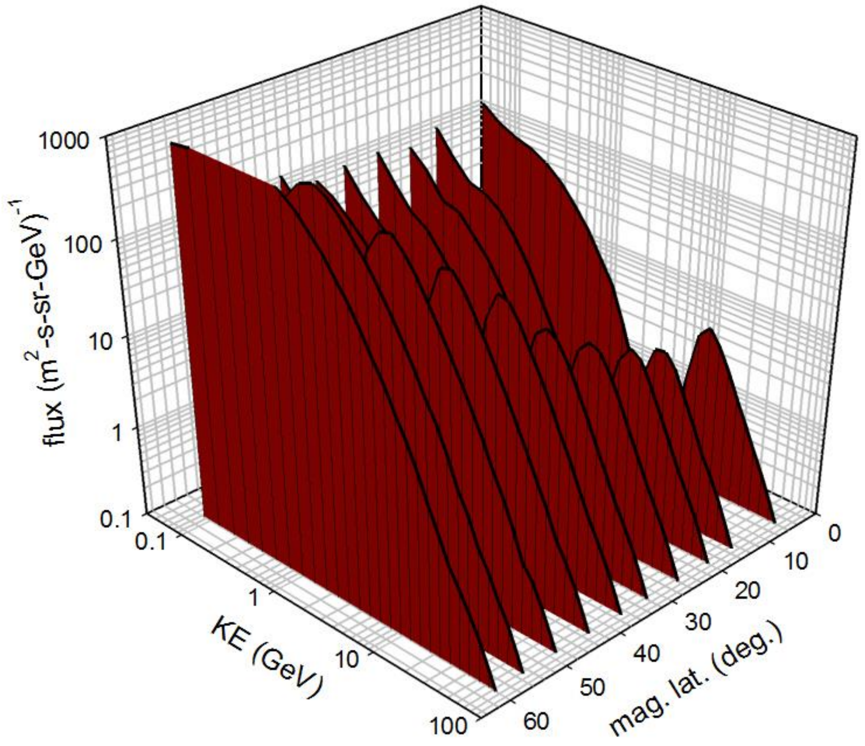
Long lived

July 2006 - September 2009 (~800 days)
Downward proton, SAA/SEP data are excluded

Adriani, O., et al. (2015), Reentrant albedo proton fluxes measured by the PAMELA experiment, *Journal of Geophysical Research: Space Physics*, 0.1102/2015JA021019

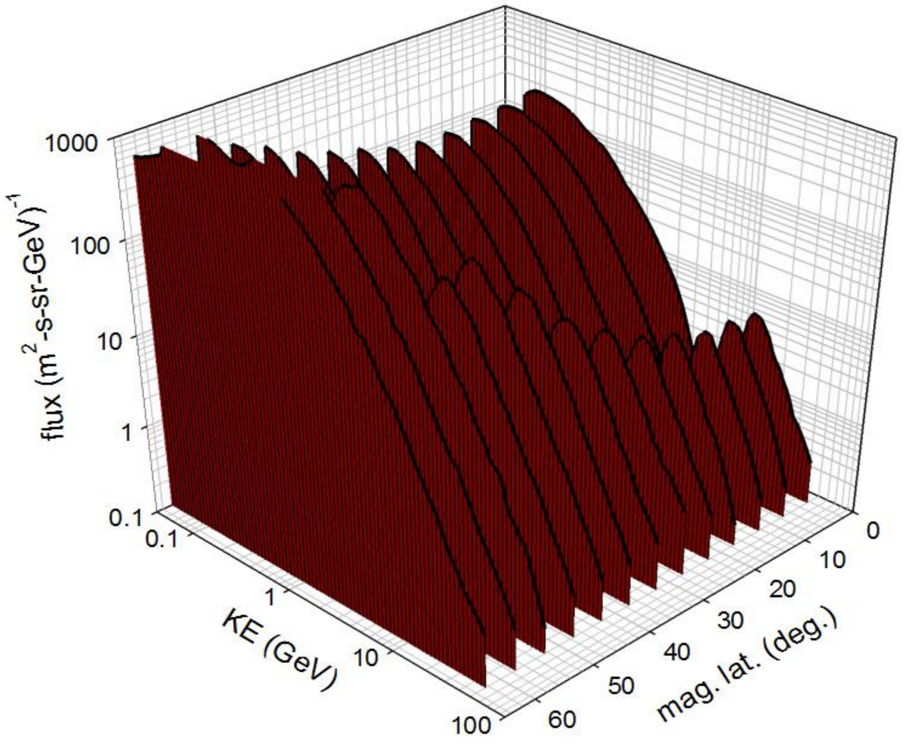
AMS1 Downward Proton vs. PAMELA Proton Spectrum

AMS1*



June 2 - 12, 1998 (10 days)
Downward proton, SAA data are excluded

PAMELA#

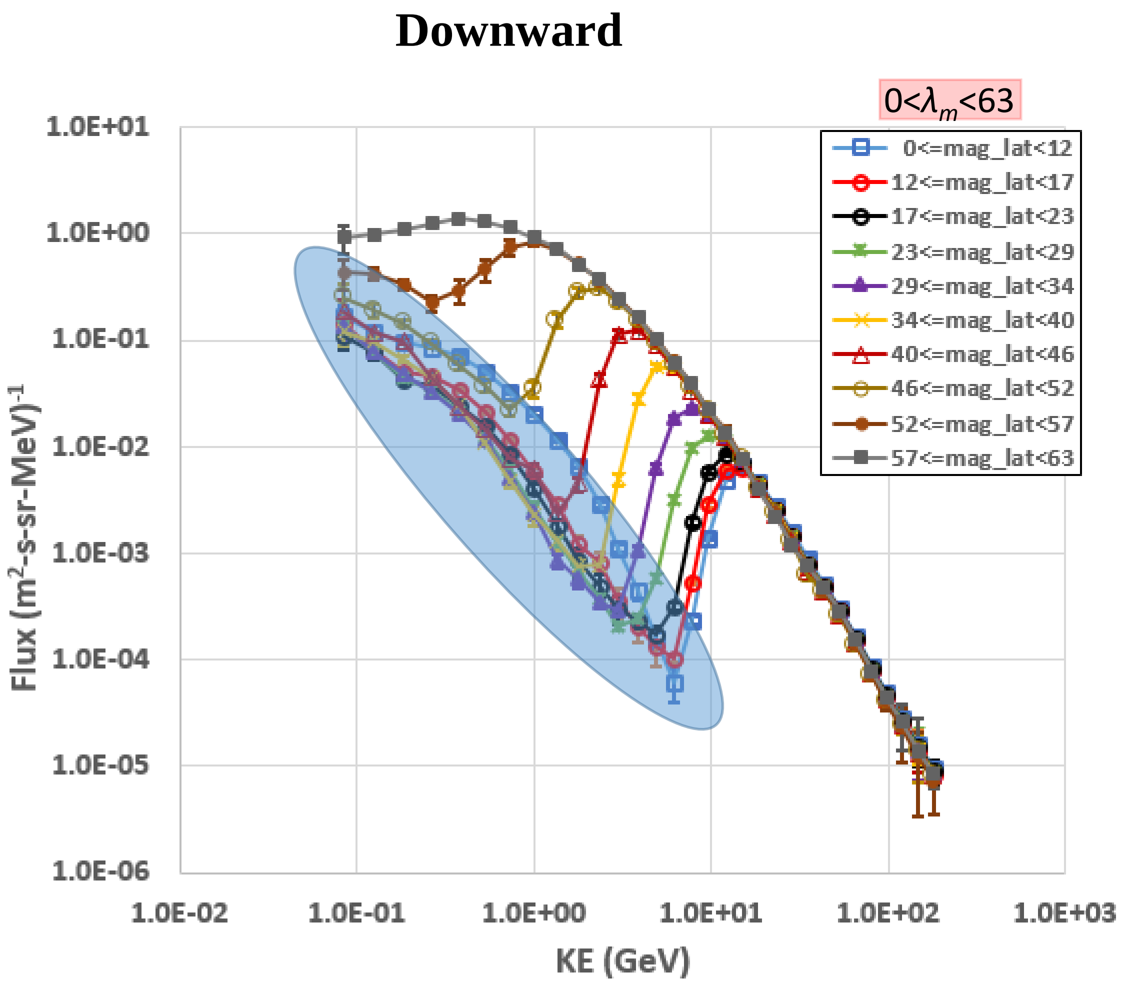


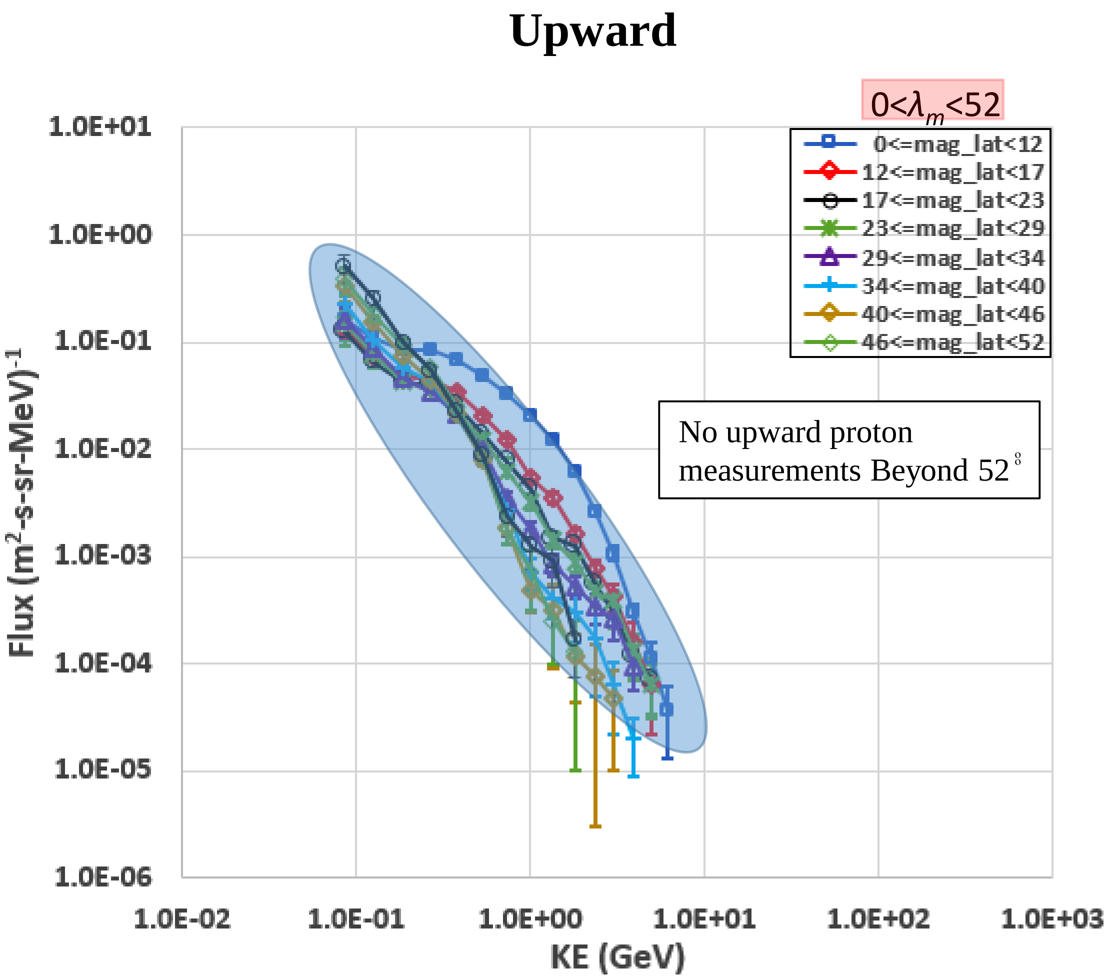
July 2006 - September 2009 (~800 days)
Downward proton, SEP/SAA data are excluded

*Alcaraz, J., et al. (2000), Protons in near earth orbit, *Physics Letter B*, v. 472, pp. 215-226

#Adriani, O., et al. (2015), Reentrant albedo proton fluxes measured by the PAMELA experiment, *Journal of Geophysical Research: Space Physics*, 0.1102/2015JA021019

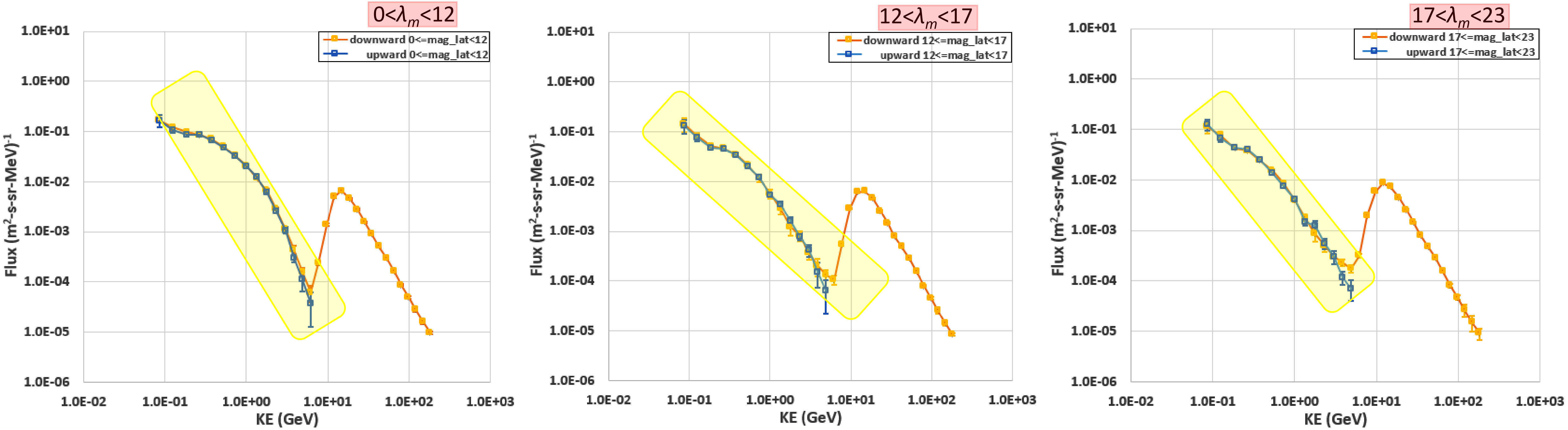
AMS1 Downward/Upward Proton Data Correlation





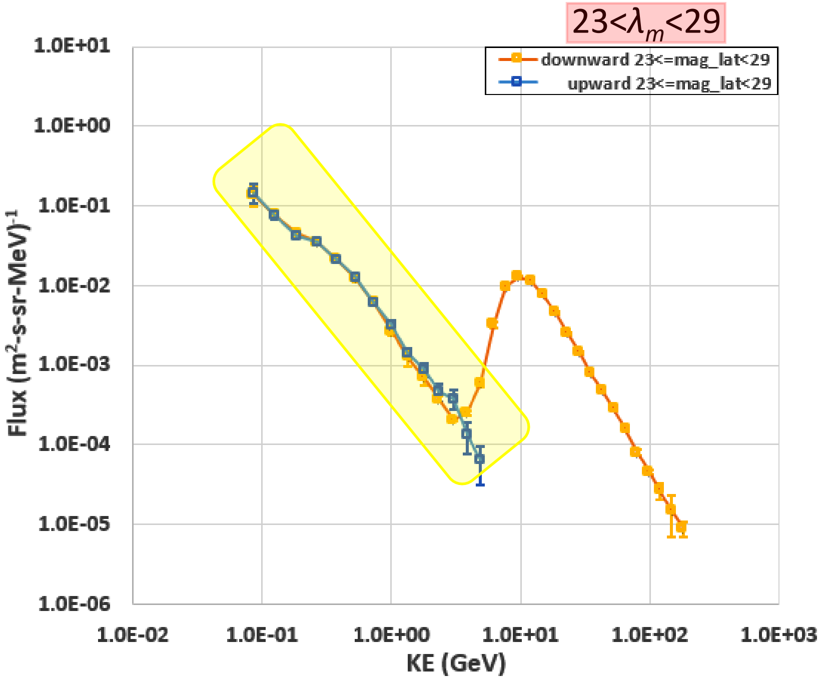
Alcaraz, J., et al. (2000), Protons in near earth orbit, *Physics Letter B*, v. 472, pp. 215-226

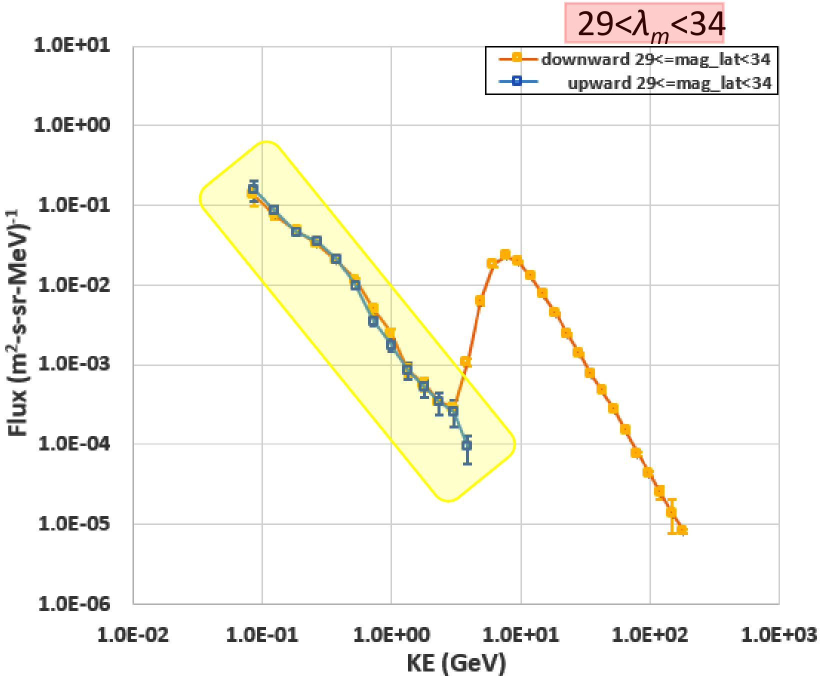
AMS1 Downward/Upward Proton Data Correlation - I

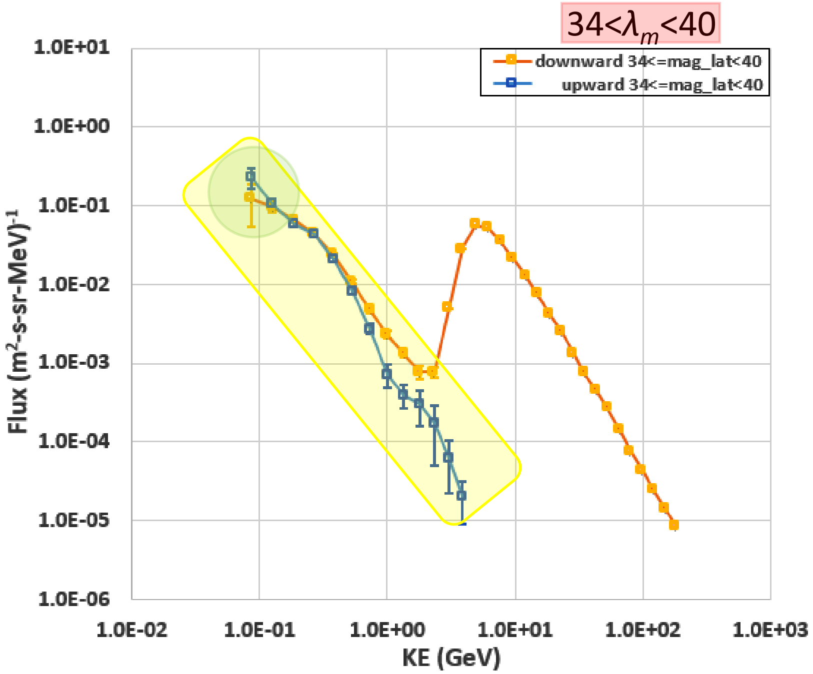


Alcaraz, J., et al. (2000), Protons in near earth orbit, *Physics Letter B*, v. 472, pp. 215-226

AMS1 Downward/Upward Proton Data Correlation - II

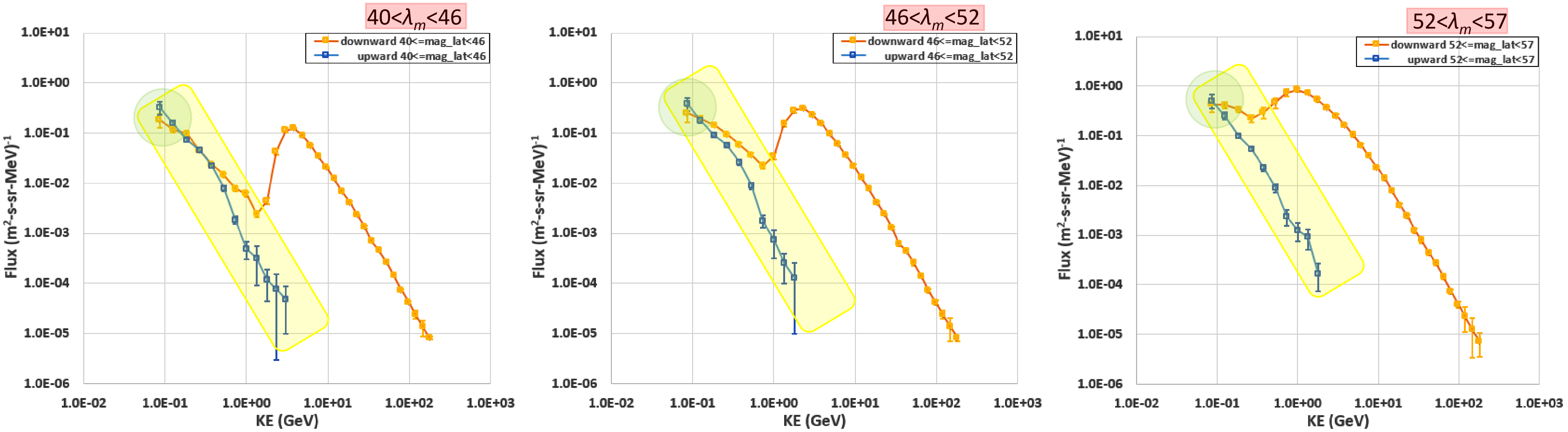






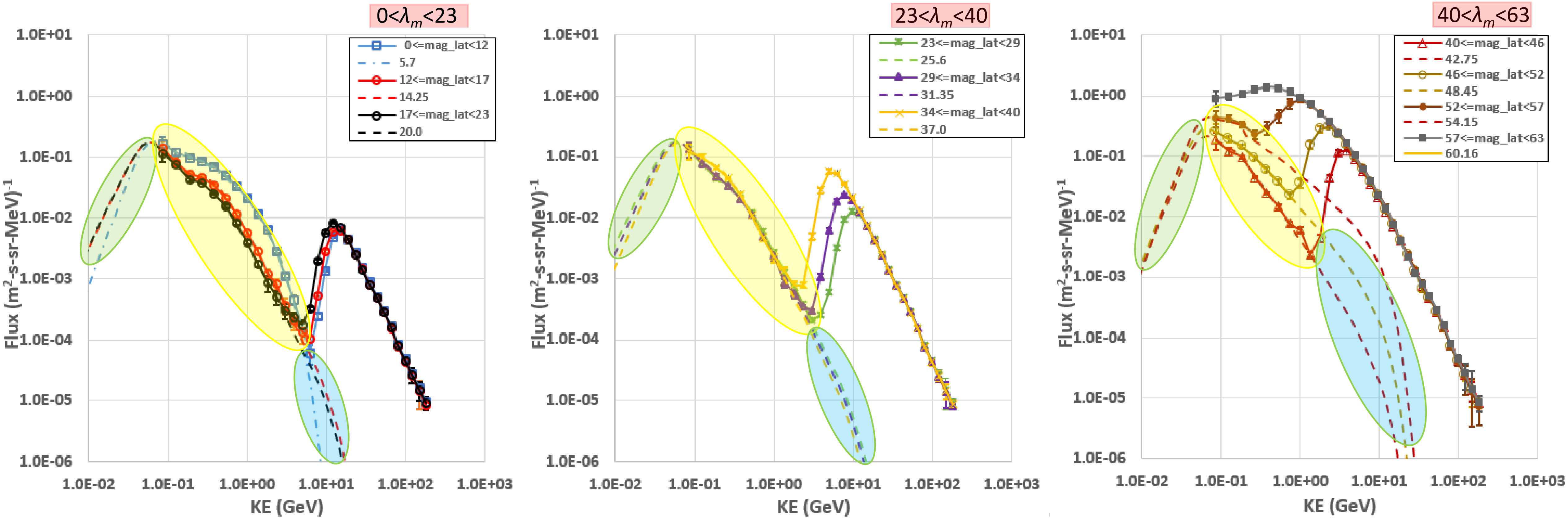
Alcaraz, J., et al. (2000), Protons in near earth orbit, *Physics Letter B*, v. 472, pp. 215-226

AMS1 Downward/Upward Proton Data Correlation - III

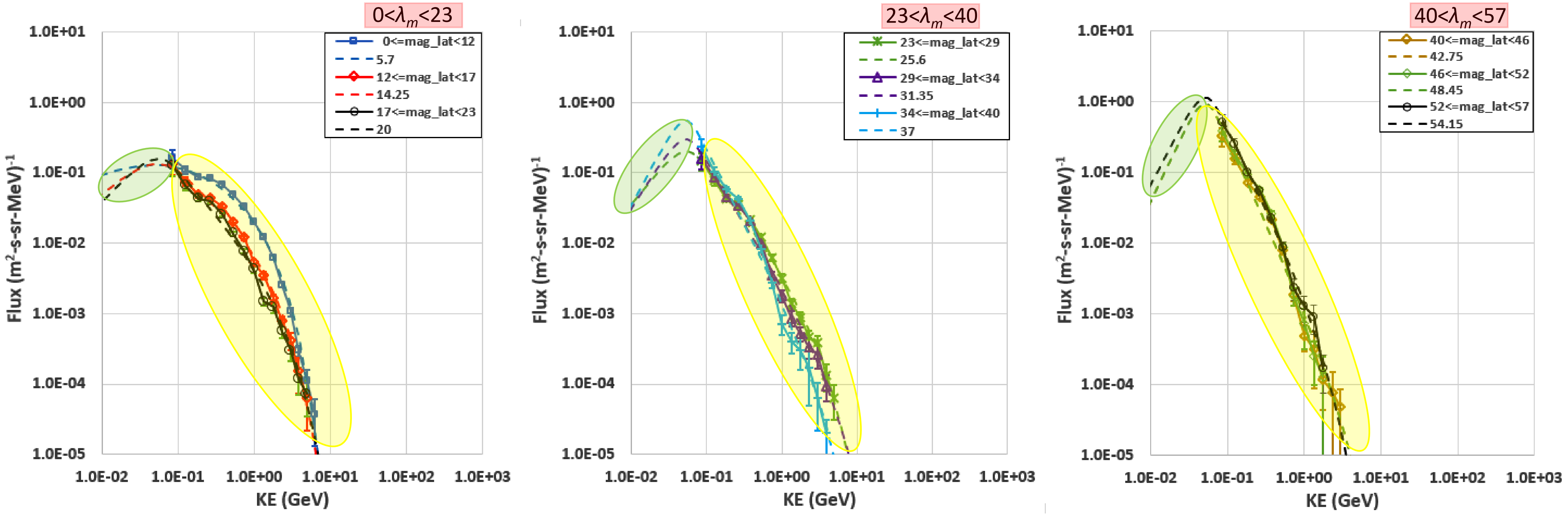


Alcaraz, J., et al. (2000), Protons in near earth orbit, *Physics Letter B*, v. 472, pp. 215-226

Criteria for Parameterization of AMS1 Downward Protons

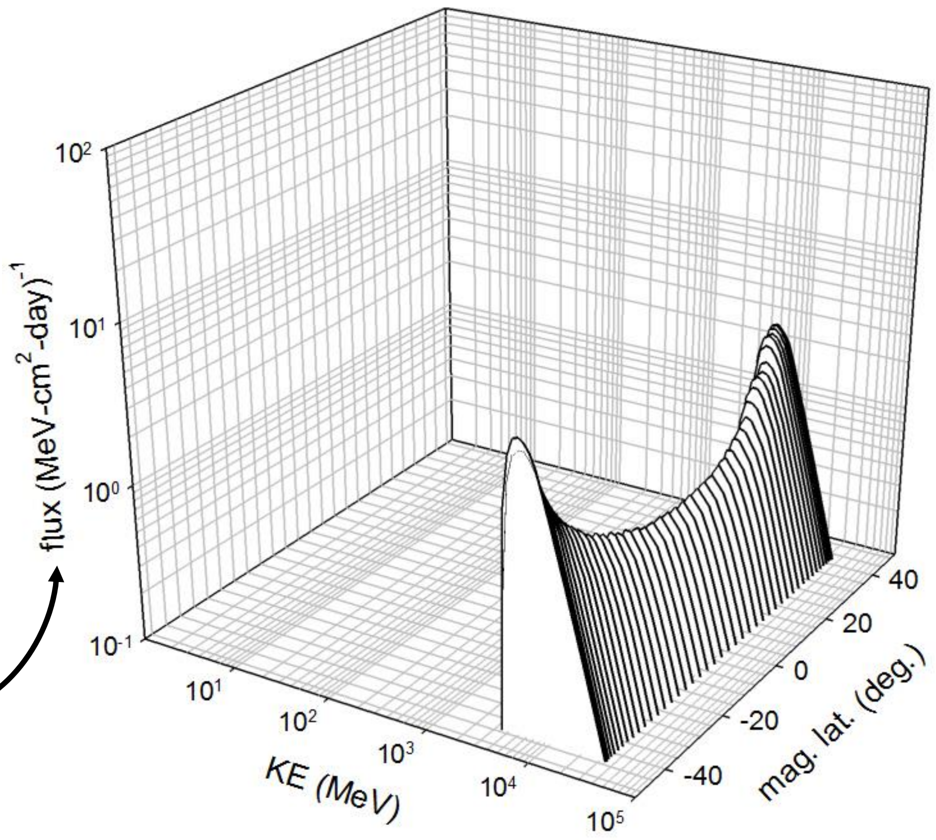


Criteria for Parameterization of AMS1 Upward Protons



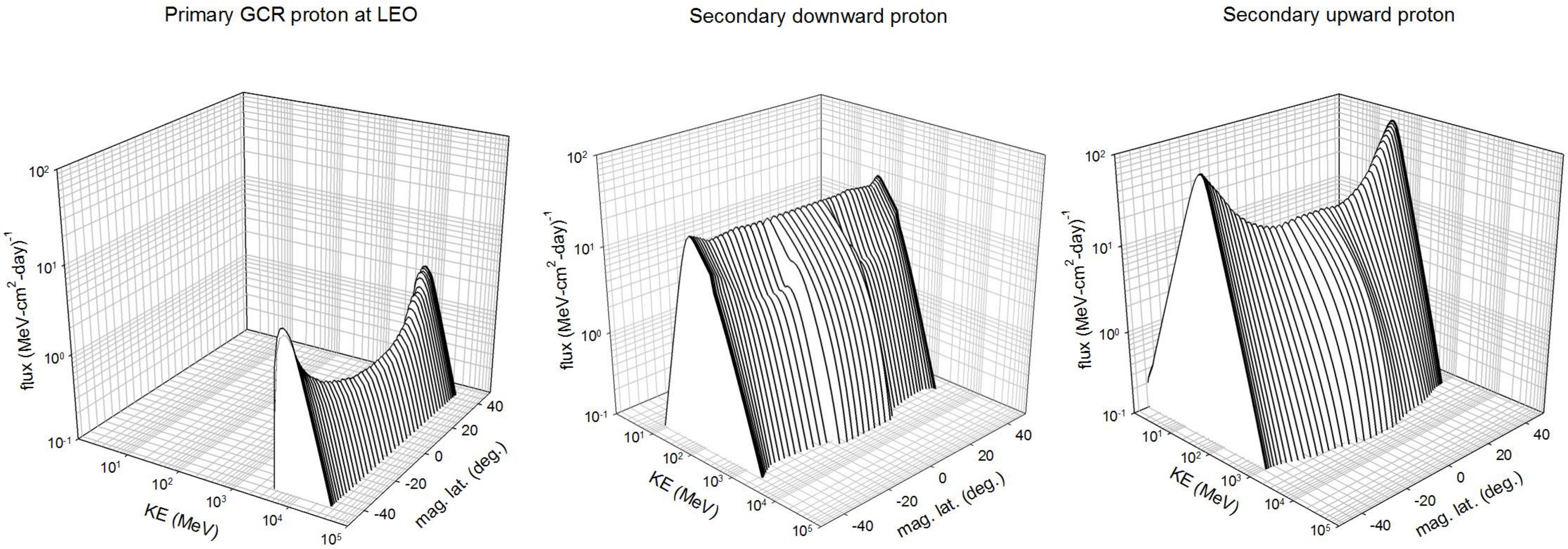
Primary GCR Proton at LEO vs. Magnetic Latitude

DLR model was used to generate the GCR spectra



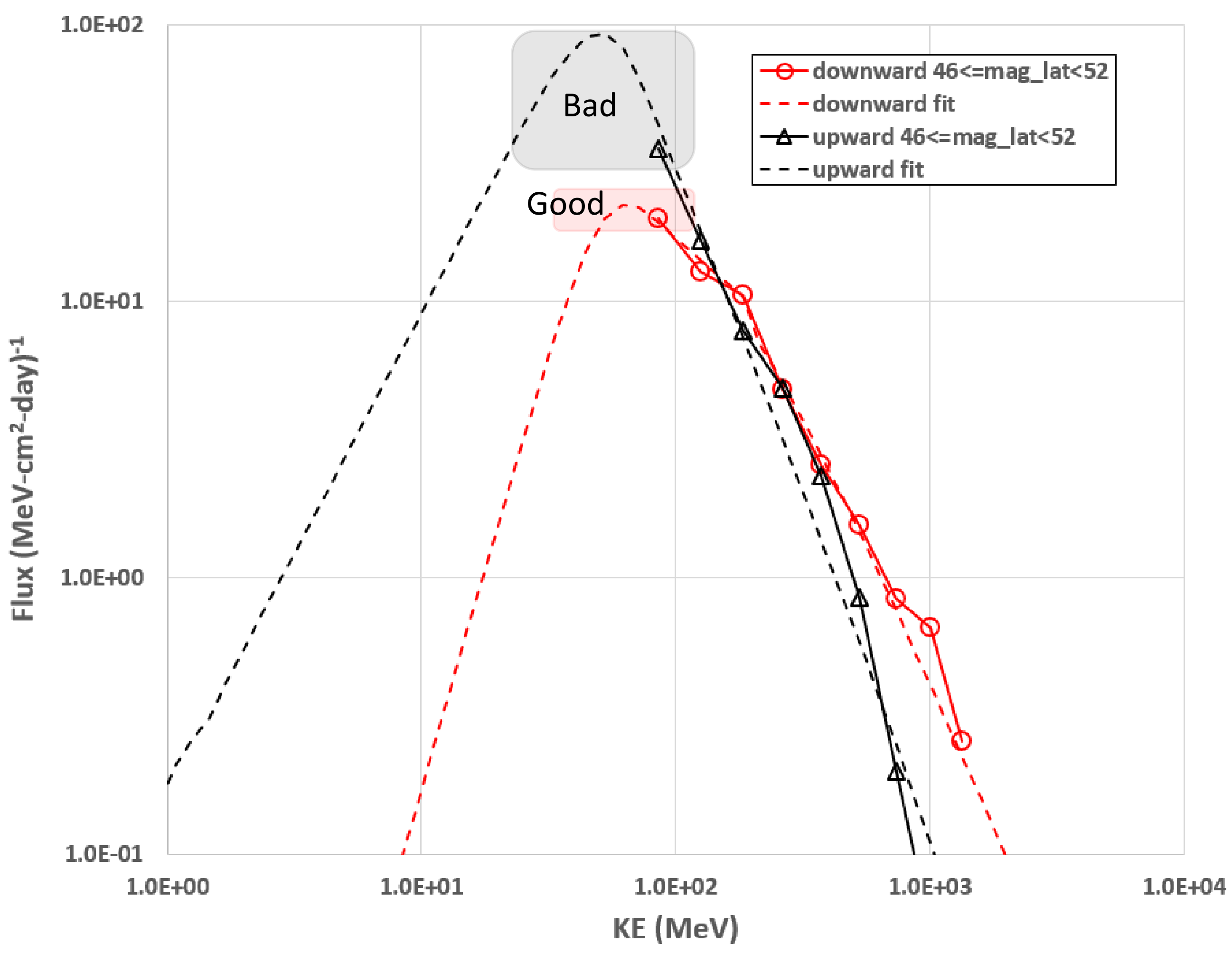
Flux is converted from #/(MeV-m^2-s-sr.) to #/(MeV-cm^2-day)

Primary/Secondary Proton at LEO vs. Magnetic Latitude - I

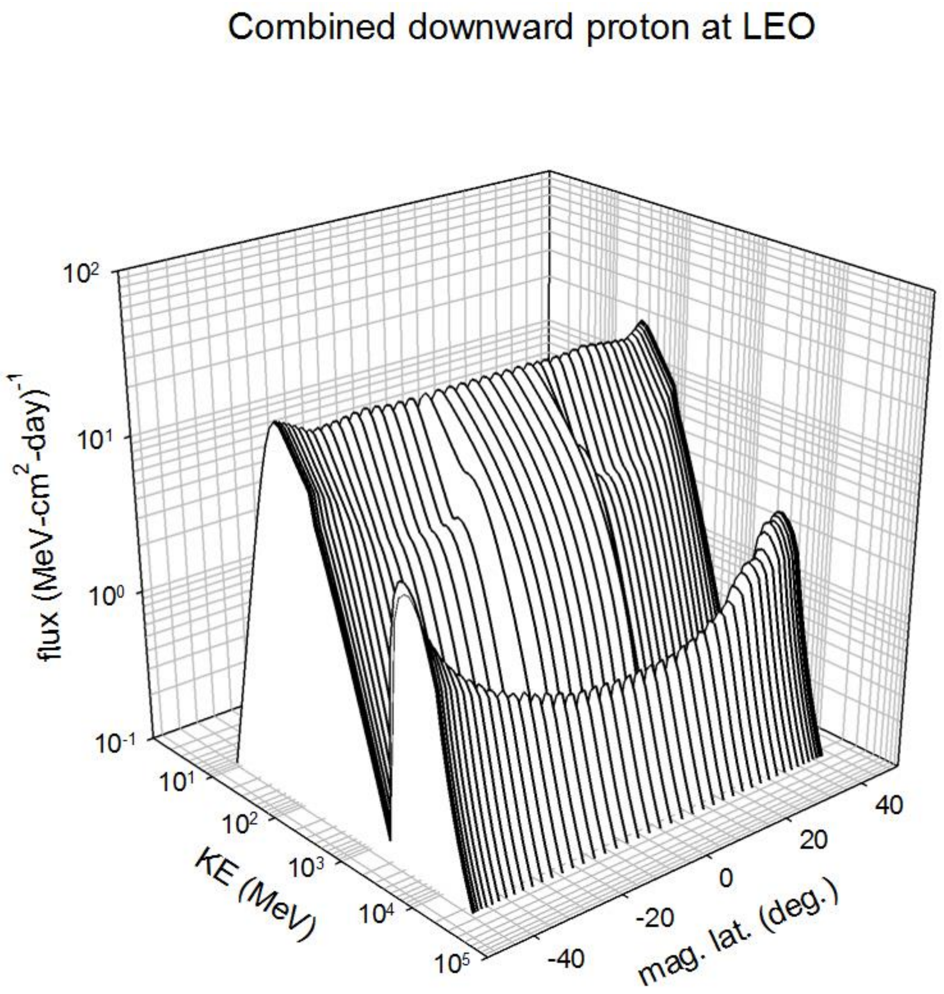


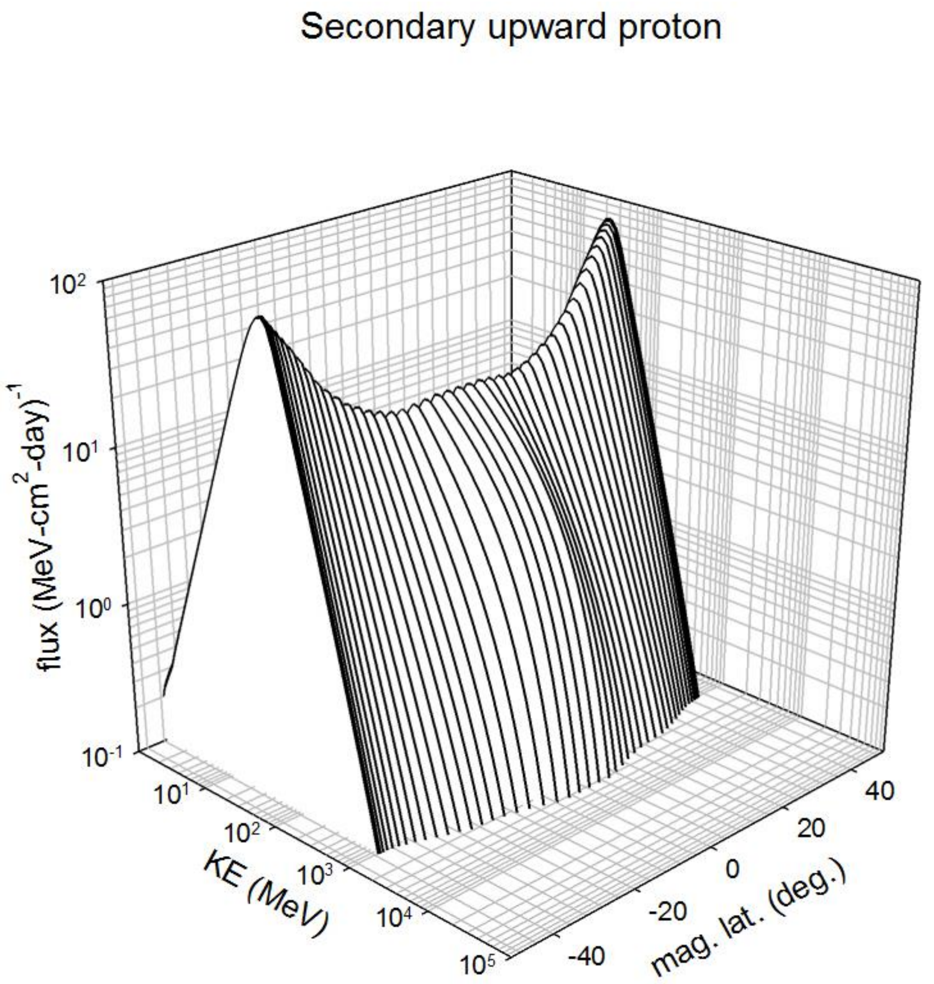
Flux is converted from #/(MeV-m^2-s-sr.) to #/(MeV-cm^2-day)

Parameterization Issues



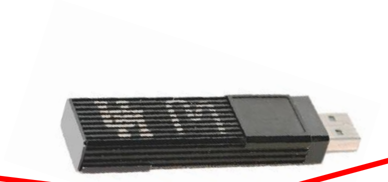
Primary/Secondary Proton at LEO vs. Magnetic Latitude - II

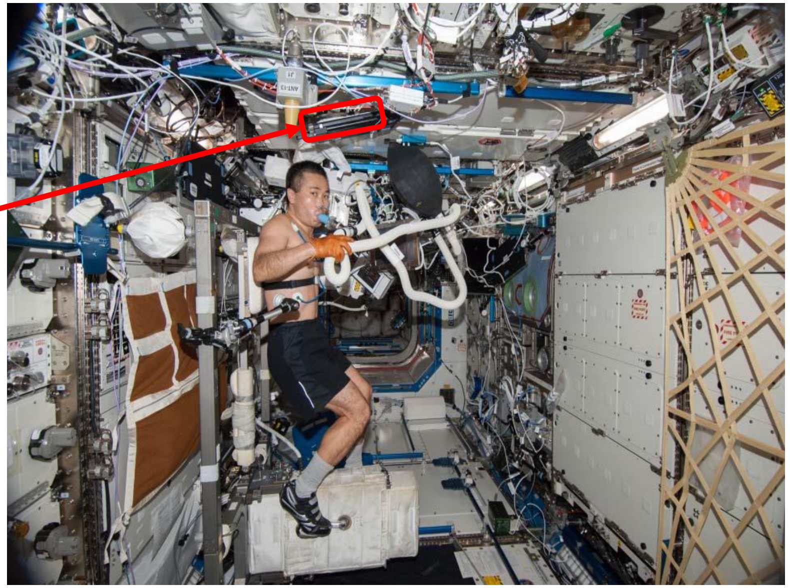


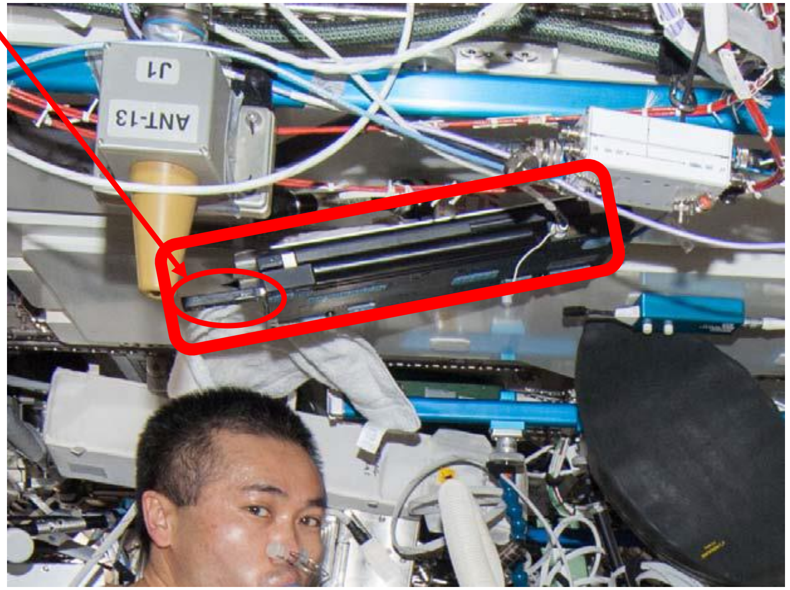


Flux is converted from #/(MeV-m^2-s-sr.) to #/(MeV-cm^2-day)

US Lab REM Detector Location



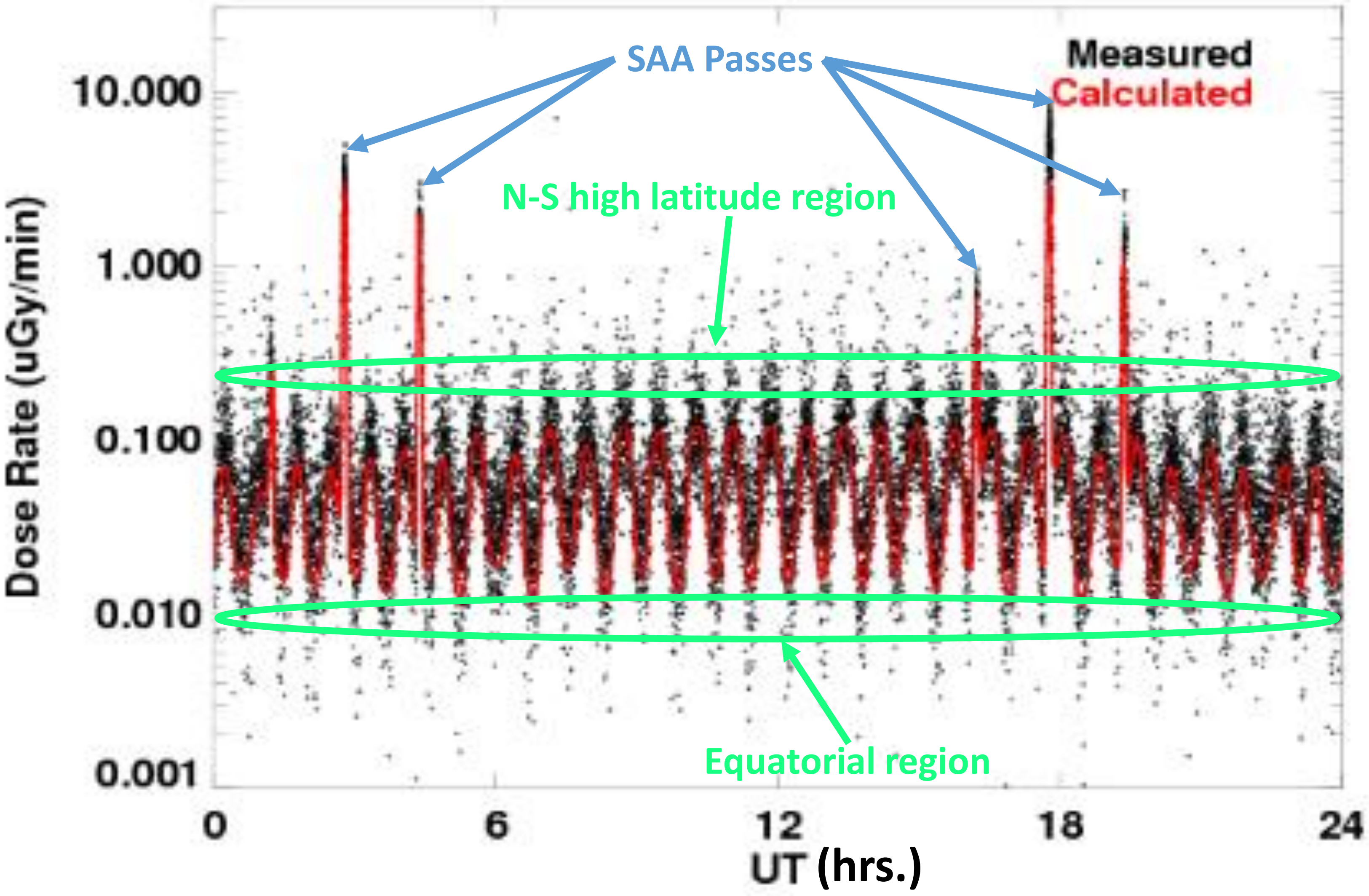




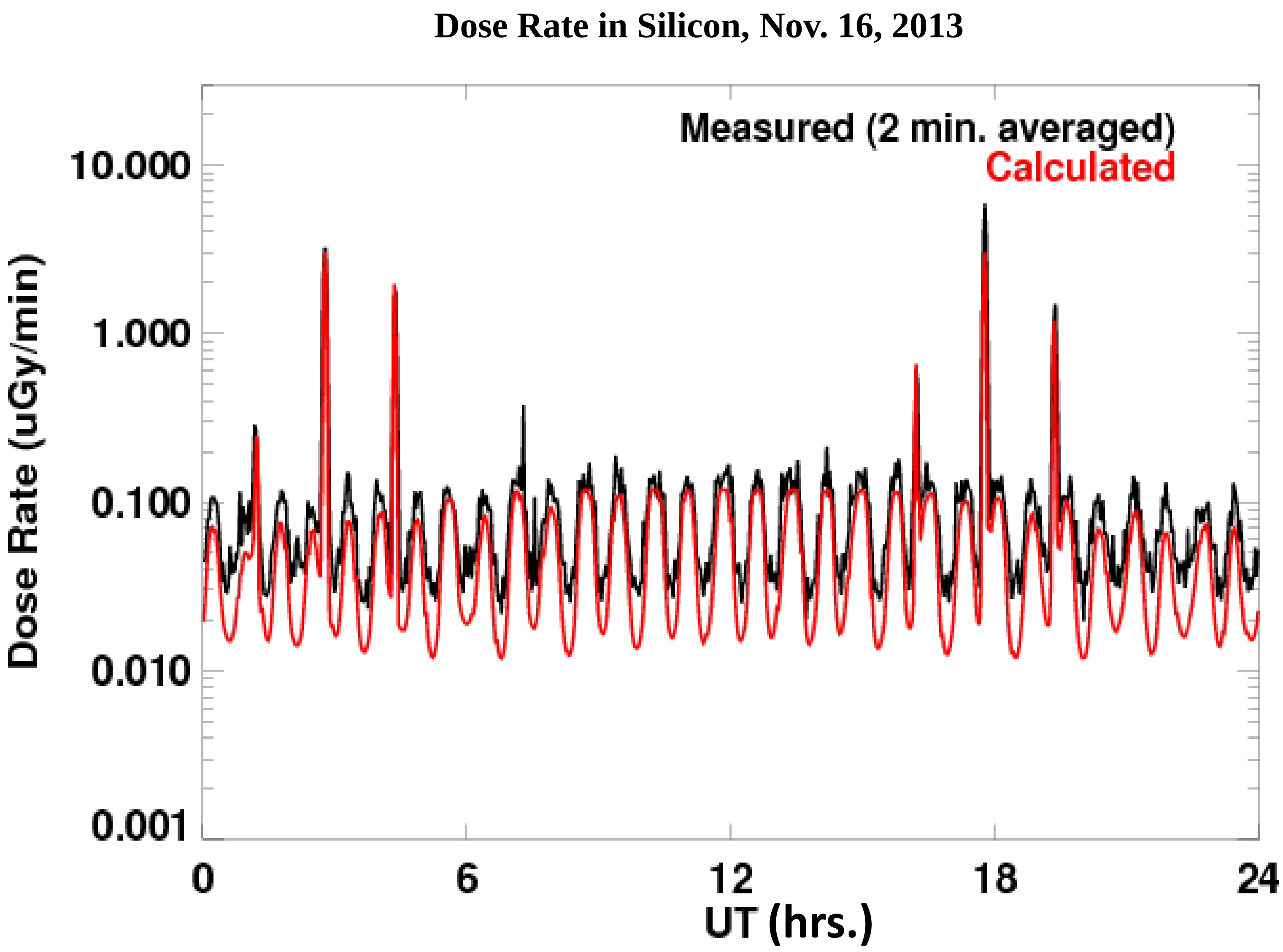
- Update CAD model
- Find detector location within CAD model
- Ray-trace ISS at detector location to extract shielding thickness around detector

Calculation Results – US Lab Dose Rate

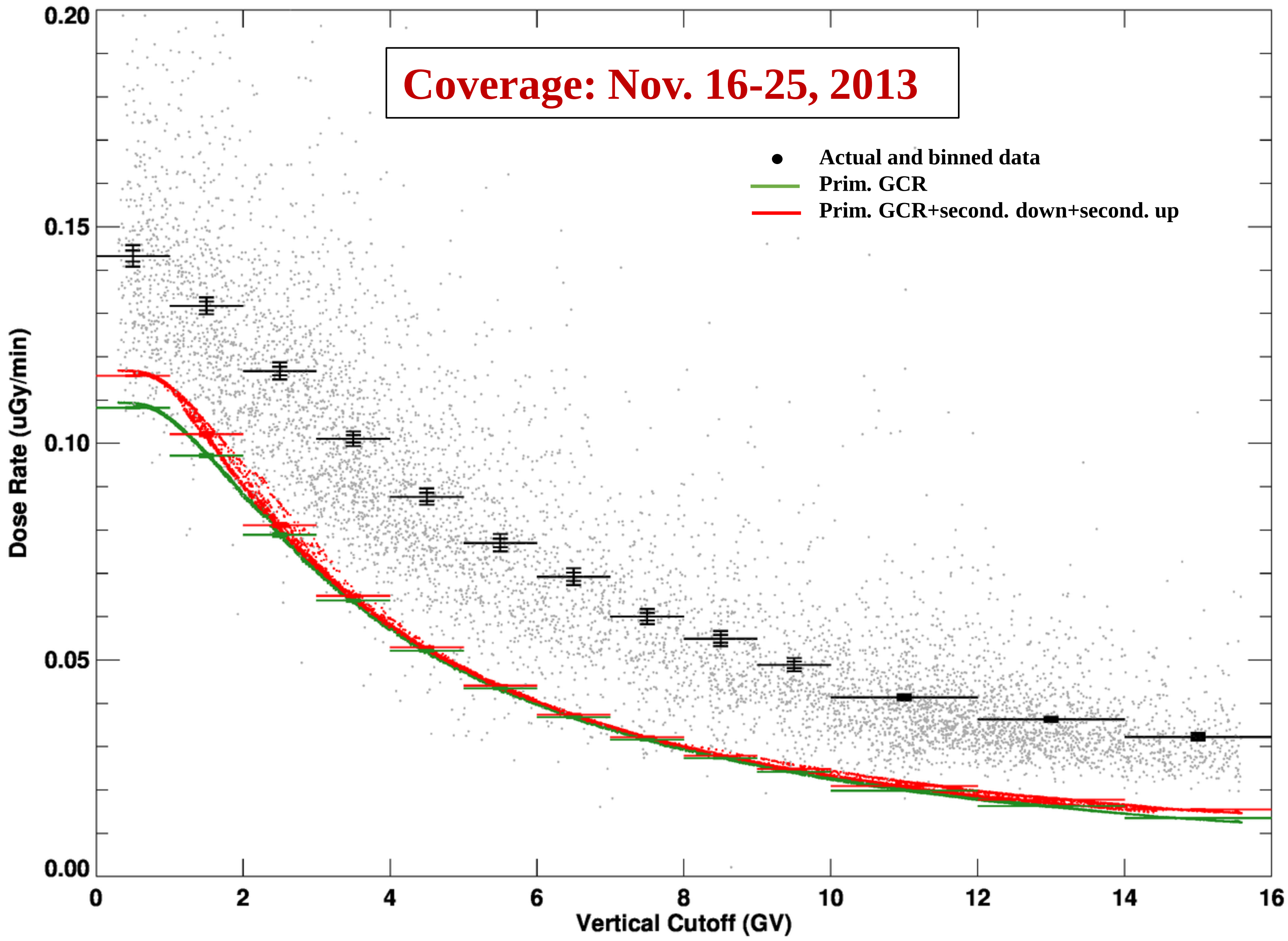
Dose Rate in Silicon, Nov. 16, 2013



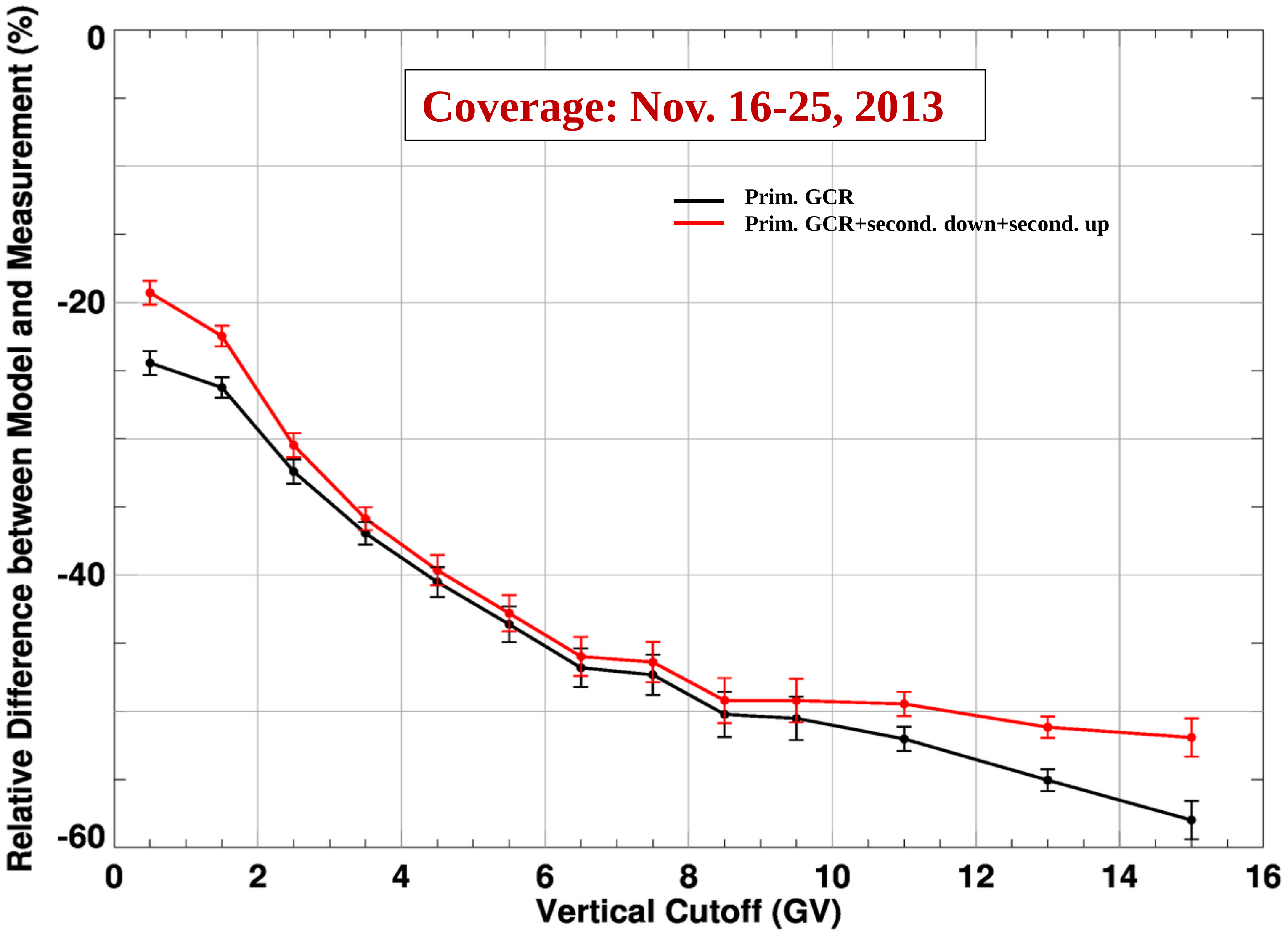
Average Dose Rate (2 minute bins)



US Lab REM Dose Rate Data vs. Model



US Lab REM Validation Improvement



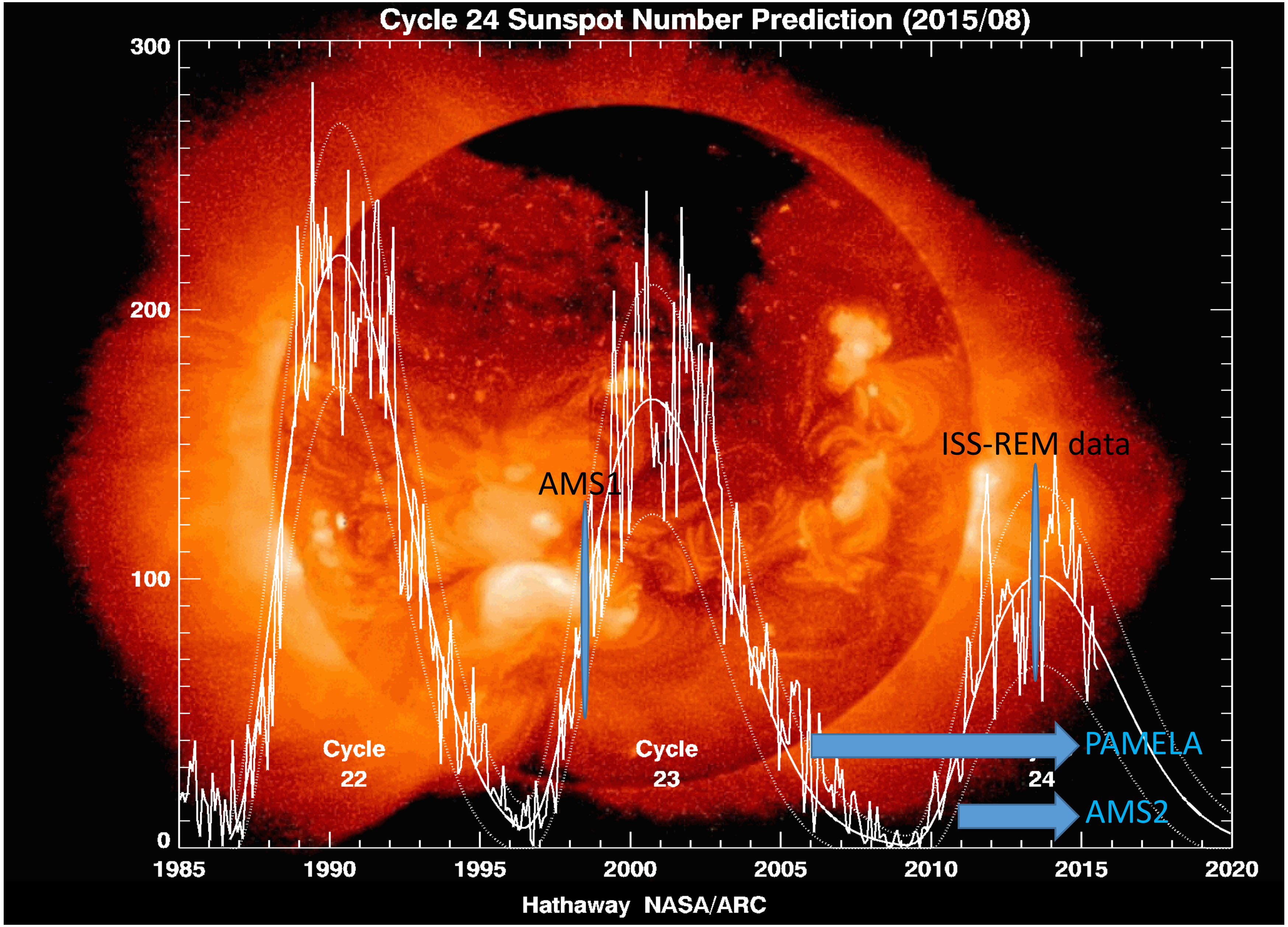
Issue to consider:

We mixed/matched 1998/2013 epochs.

Parameterization was from 1998 (AMS1)

ISS data was from 2013

Epoch Correlation between AMS1 and ISS Measurement



Hathaway, 2015, ARC, NASA
Science News, 2014-2015

Summary and Future Work

- Used **AMS1** downward/upward and **PAMELA** data to show the existence of a low energy secondary particle component at LEO due to GCR-atmosphere interactions (only protons were discussed)

- From AMS1 data, provided a parametric model to account for the downward/upward production of secondary protons at LEO

- **Quantified** how the parametric model improved the ISS validation work

- Over all, we improved ISS validation by <10%

- To improve the ISS validation further, we must consider incorporating time dependency (i.e. accessing PAMELA, AMS2 data)

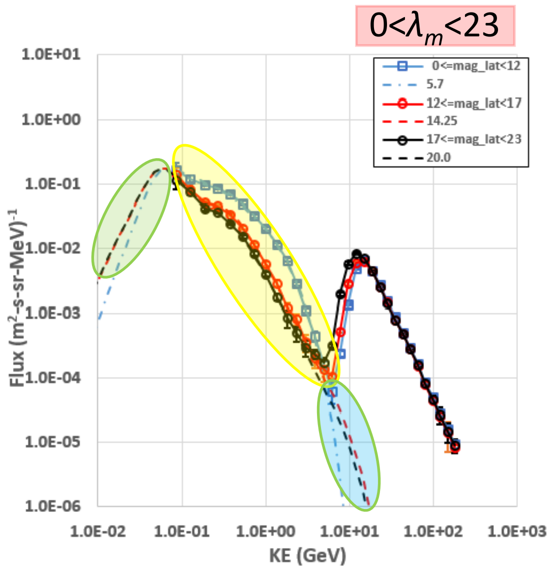
Back up

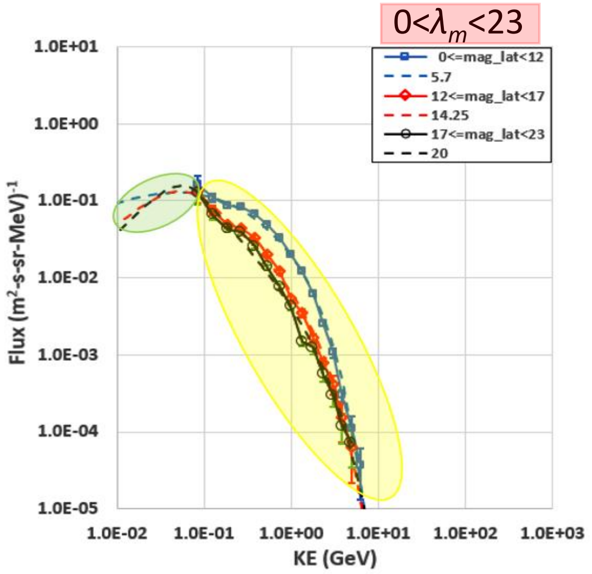
Criteria for Parameterization of AMS1 Data

- Accurate parameterization of the upward/downward AMS1 data, accounting for all magnetic latitudes (λ_m) and energies (yellow ovals)

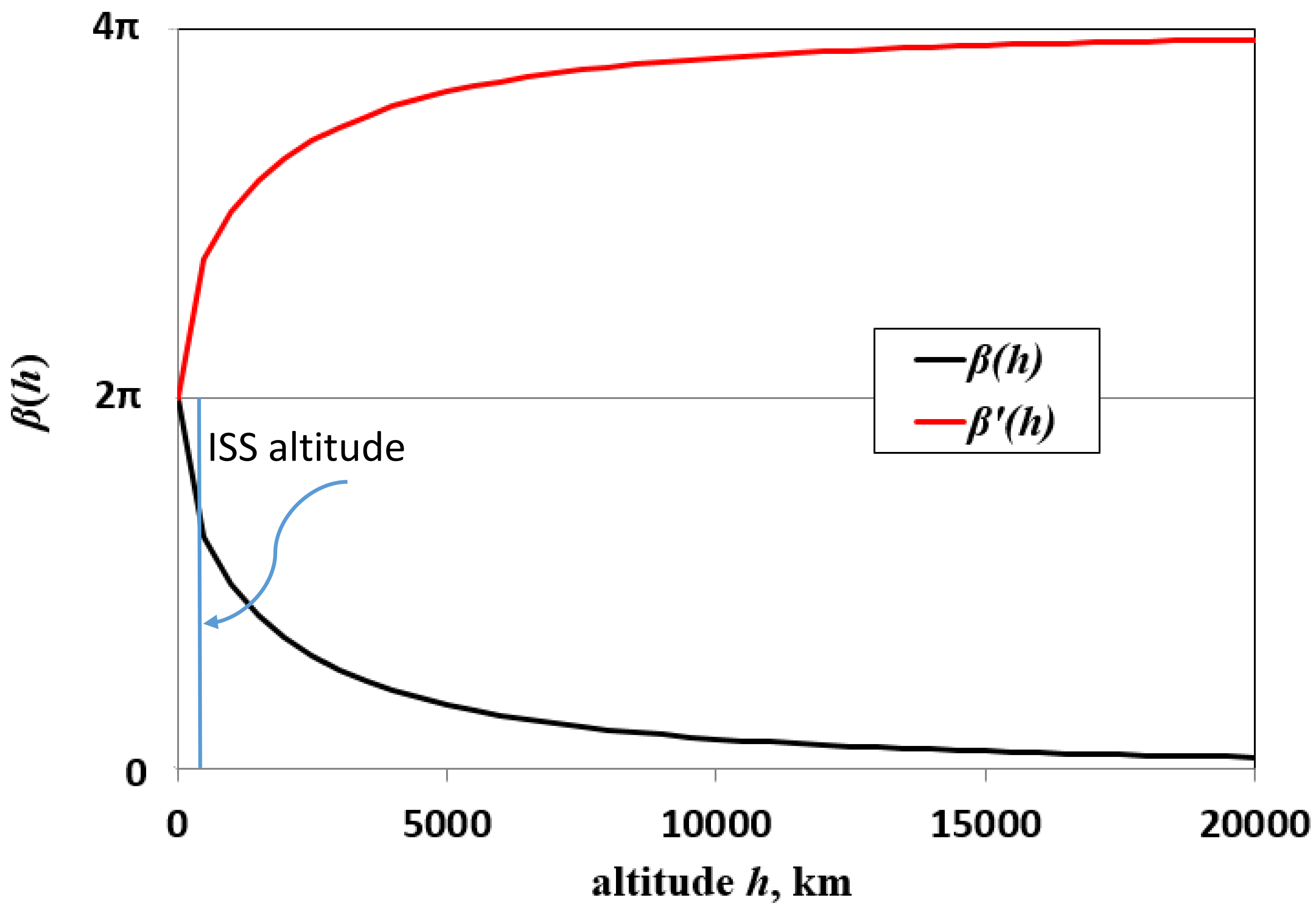
- Meaningful representation of high energy roll off (blue ovals)

- A "good guess" representation of low energy roll off (green ovals). Note, while low energy roll off functional form is rather arbitrary, it can not behave like a neutron spectrum





GCR Blockage due to Earth Shadow



Parameterization of Downward Proton

AMS1 data

- ($\lambda_m <= 12°$) → $F(E) = E^{-a} e^{b-cE}$
- ($\lambda_m > 12°$)
  - ($E < 185$ MeV) → $F(E) = e^{[a + b(\log E)]}$
  - ($E >= 185$ MeV) → $F(E) = e^{[a + b(\log E) + c(\log E)/\log(\log(E)]}$

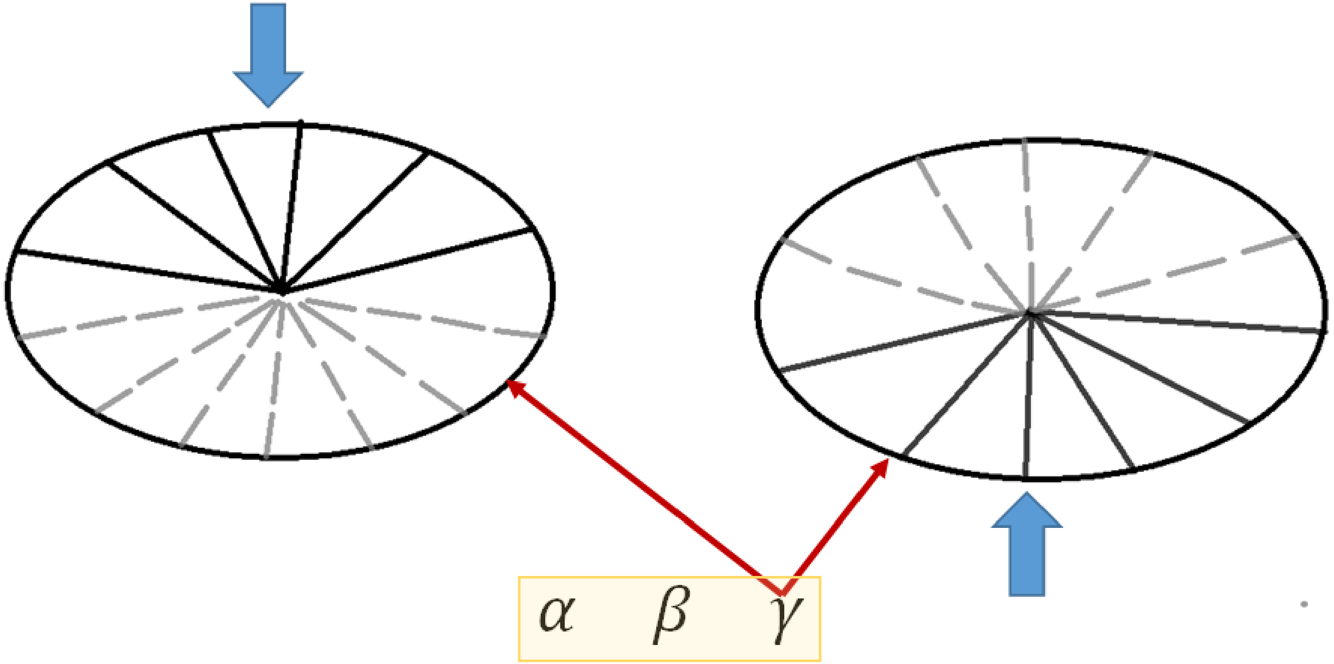
Low E (MeV) roll off → $F(E) = 1 - e^{-(E/50)^4}$

High E (MeV) roll off → $F(E) = e^{-(E/10000)^2}$

HZETRN Transport Procedure

BC_1 = LEO primary GCR + Downward

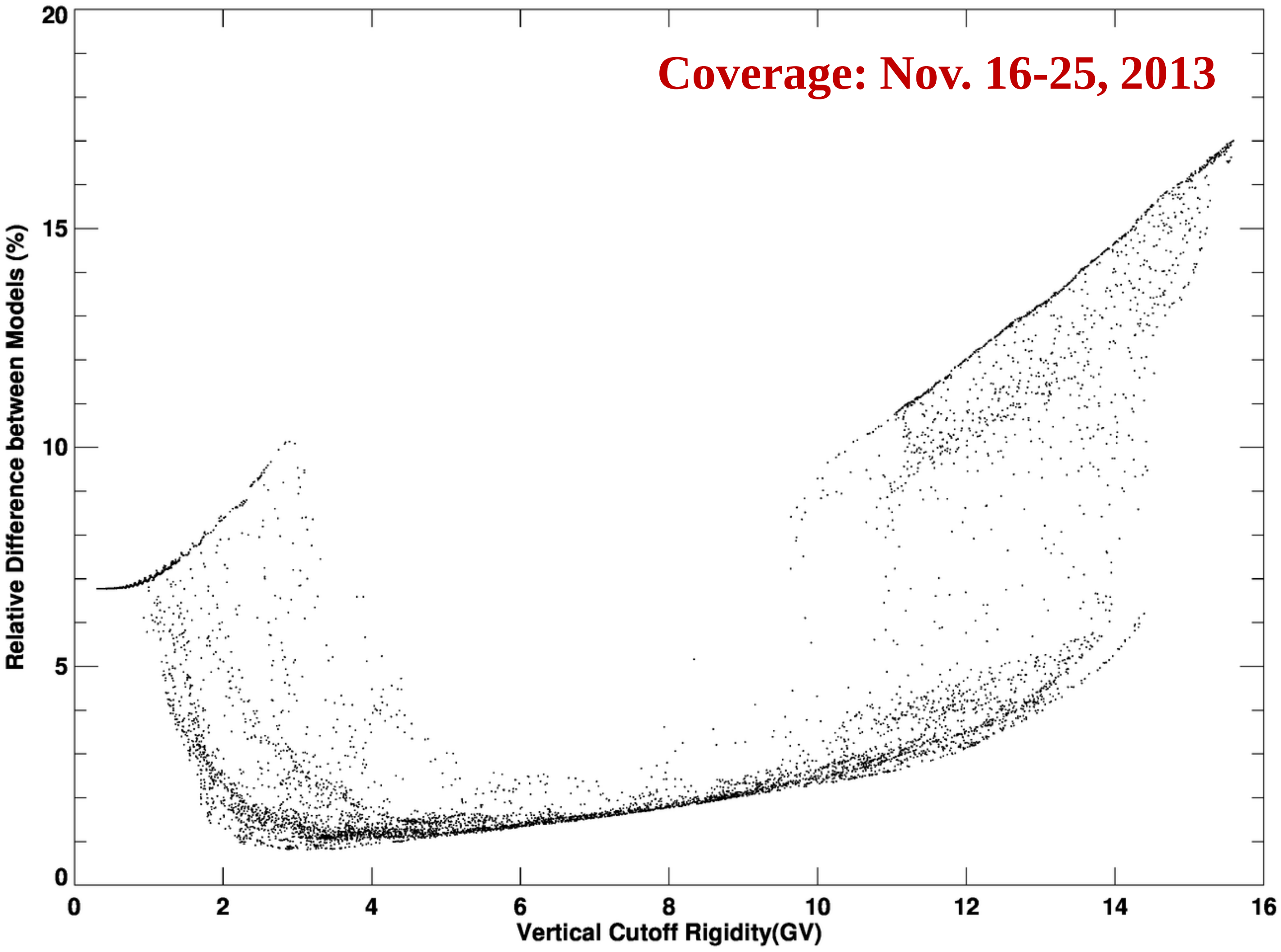
BC_2 = Upward (splash)



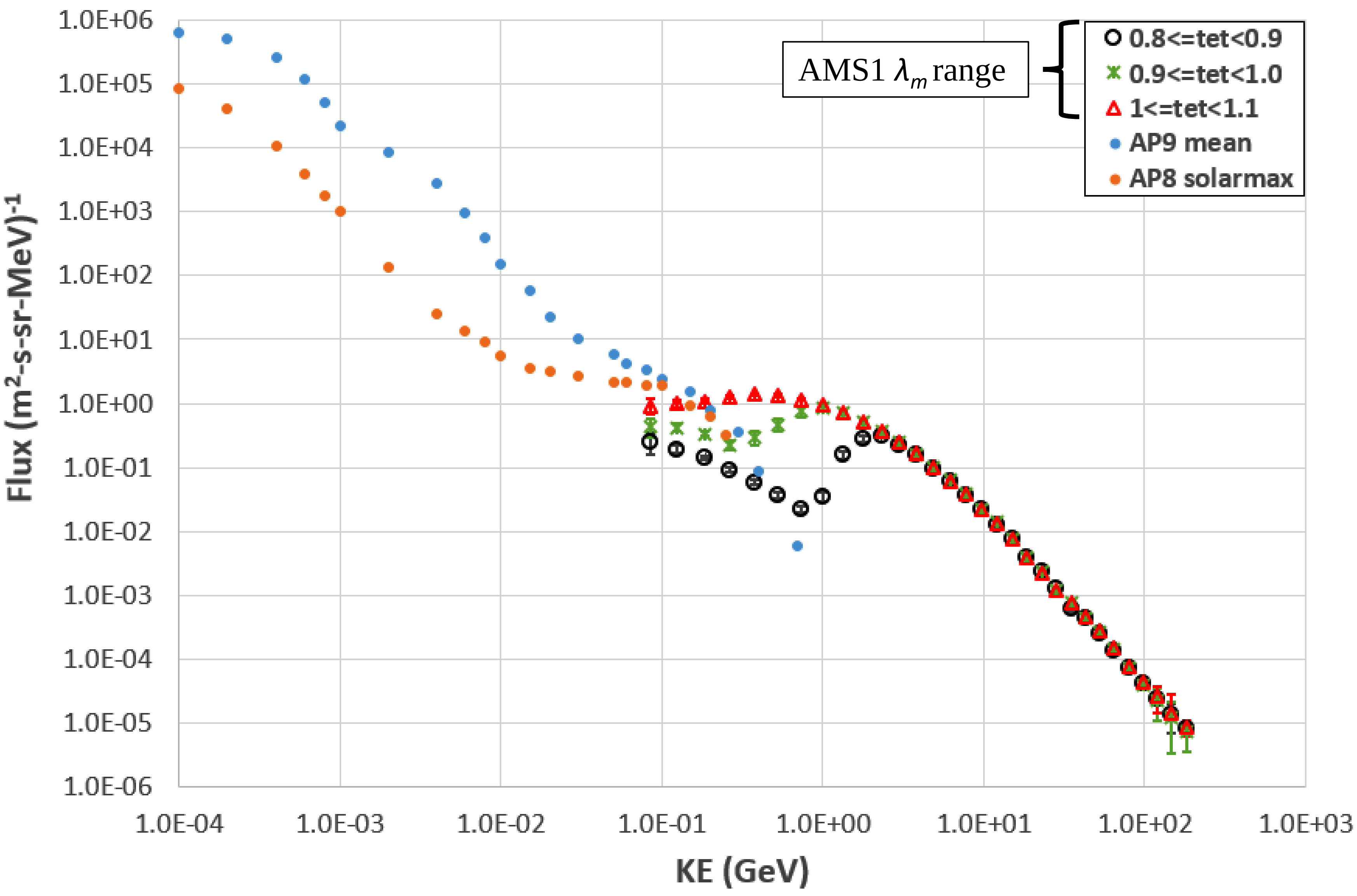
BC_1 → HZETRN → $Dose_1$

BC_2 → HZETRN → $Dose_2$

Model Comparison of US Lab REM Dose Rates (New vs. Old)



What About Trapped Protons ?



PAMELA Definitions

- Events with trajectories similar to those of stably trapped protons, but originated and reabsorbed by the atmosphere during a time shorter than a few drift periods, were identified as quasi-trapped (QT)

- Precipitating protons (UT_S) with lifetimes shorter than a bounce period. Corresponding ω_{bounce} values are similar to those of quasi-trapped protons, while ω_{gyro} distribution is much broader outside the SAA, extending to much lower values

- Pseudotrapped protons (UT_L) with relatively long lifetimes. They are characterized by large gyroradii and ω_{drift}, and by small ω_{gyro} and ω_{bounce} values, resulting in unstable trajectories due to resonances occurring between component frequencies. They can perform several drift cycles (up to a few hundreds) reaching large distances from the Earth's surface, sometimes forming intermediate loops, before they are reabsorbed by the atmosphere