

Studies of cosmic-ray solar modulation with the PAMELA experiment

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on behalf of the PAMELA collaboration

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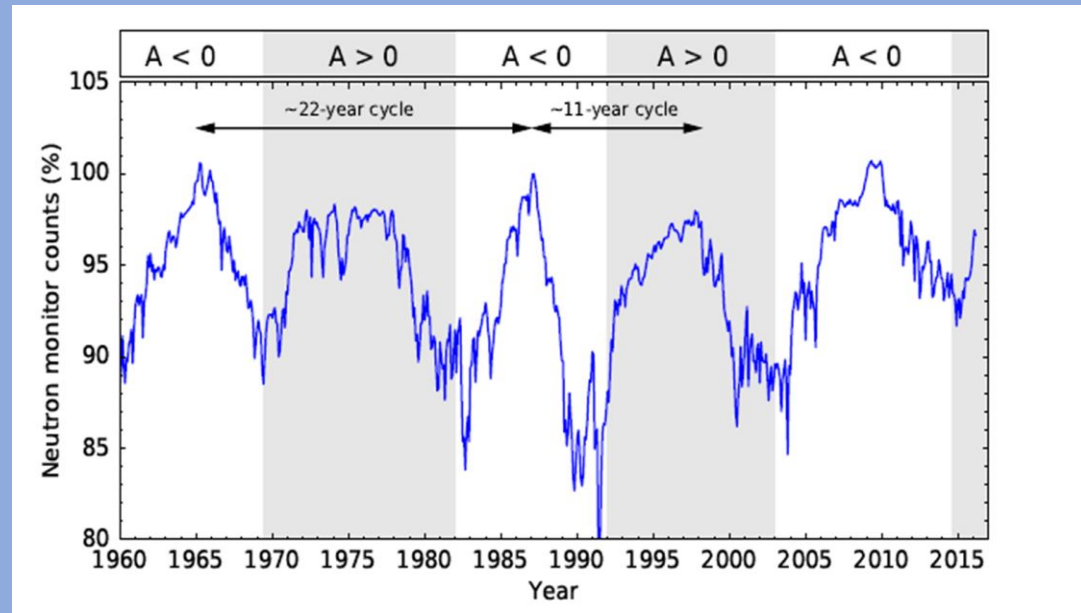
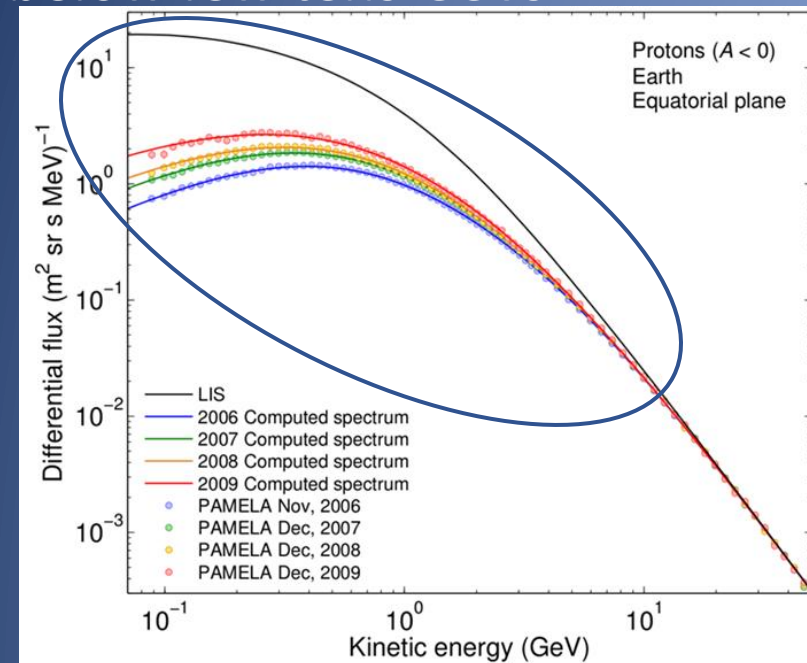
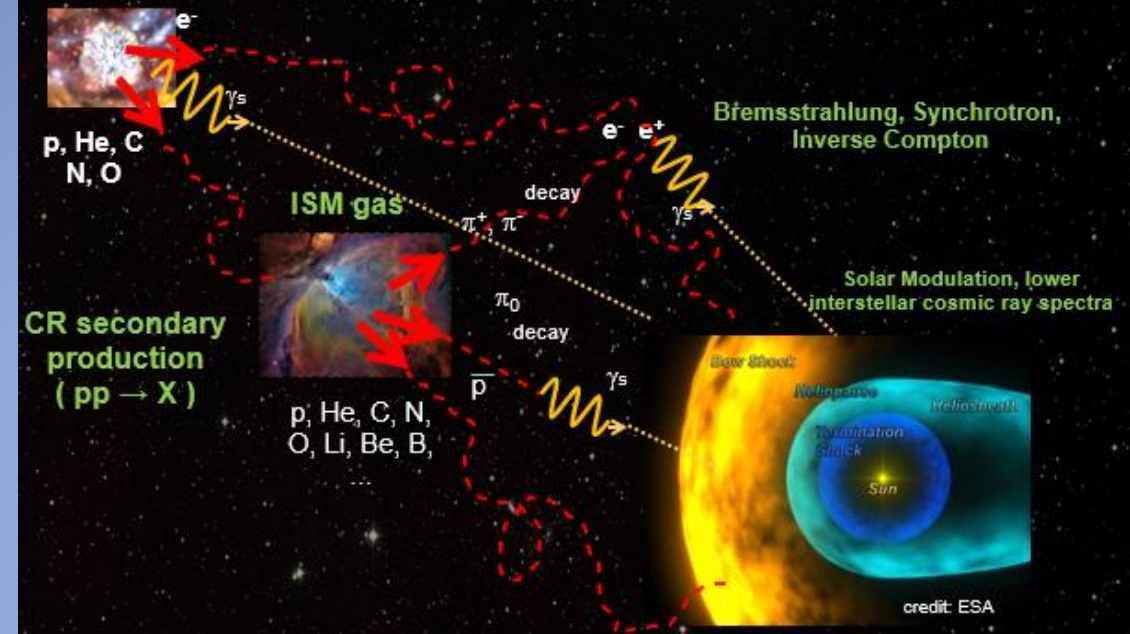
Solar Modulation of Cosmic Rays

Interaction of Cosmic Rays with Heliospheric Magnetic Field frozen into the Solar Wind

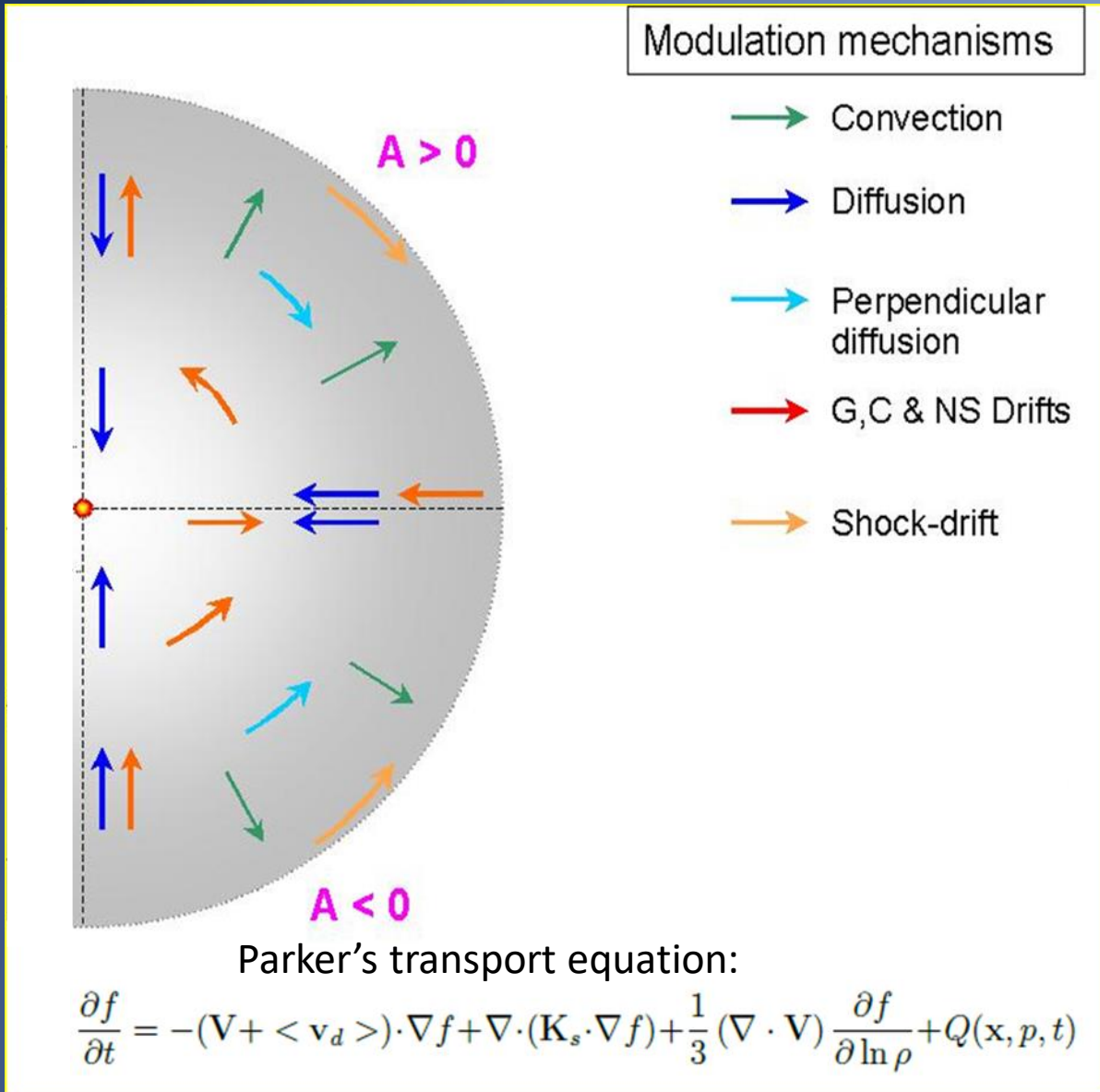
Solar Modulation

Decrease of energy spectrum below few tens GeVs

Time dependence of the fluxes as a function of the solar activity phase



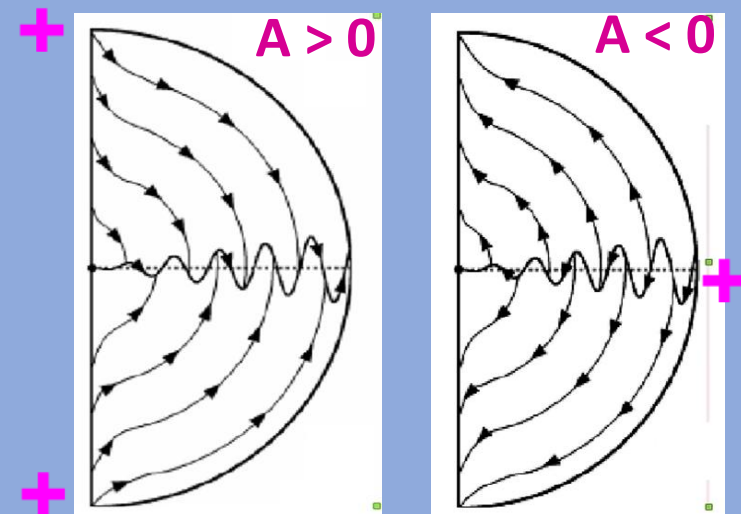
Mechanisms of solar modulation effect on Cosmic Rays



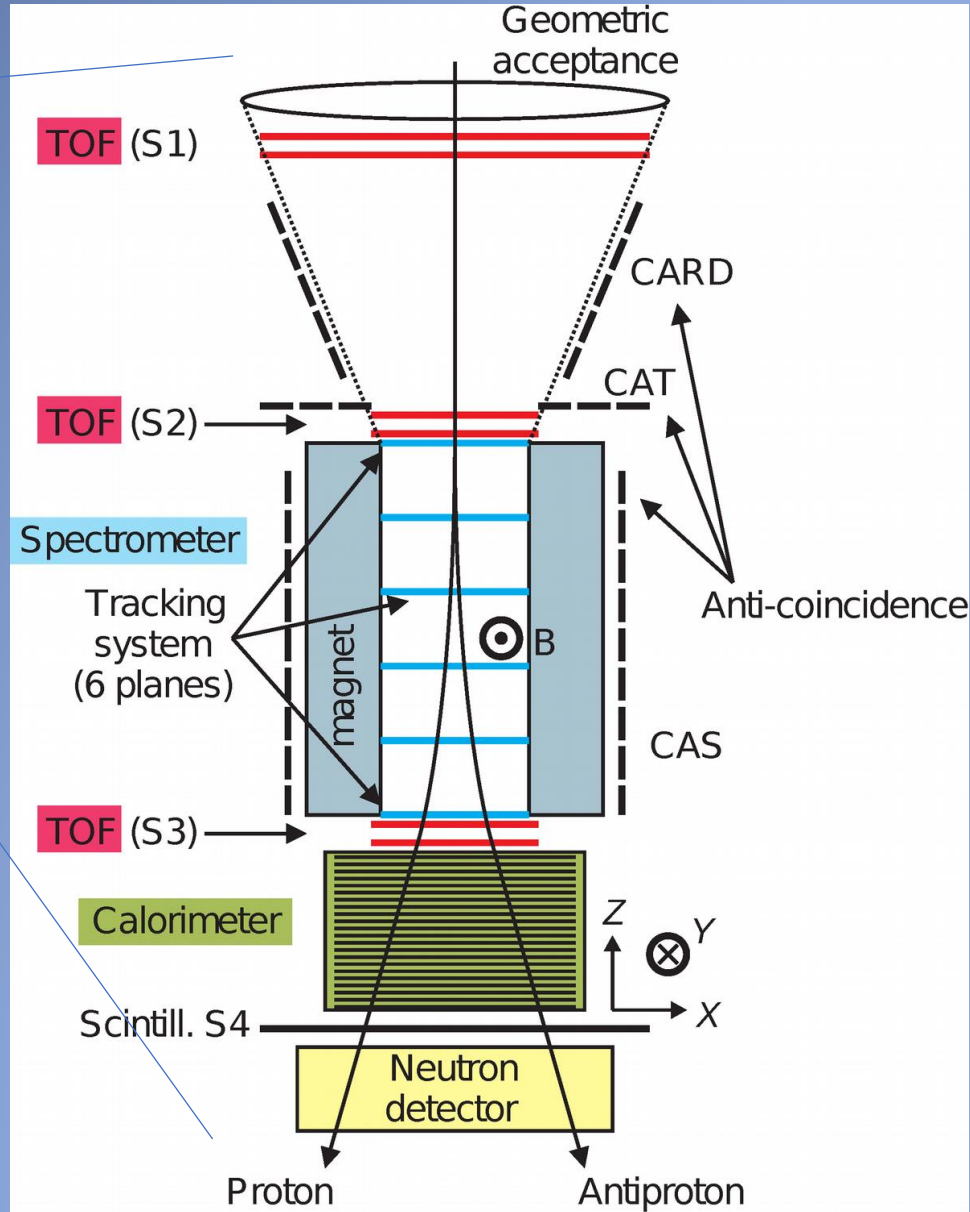
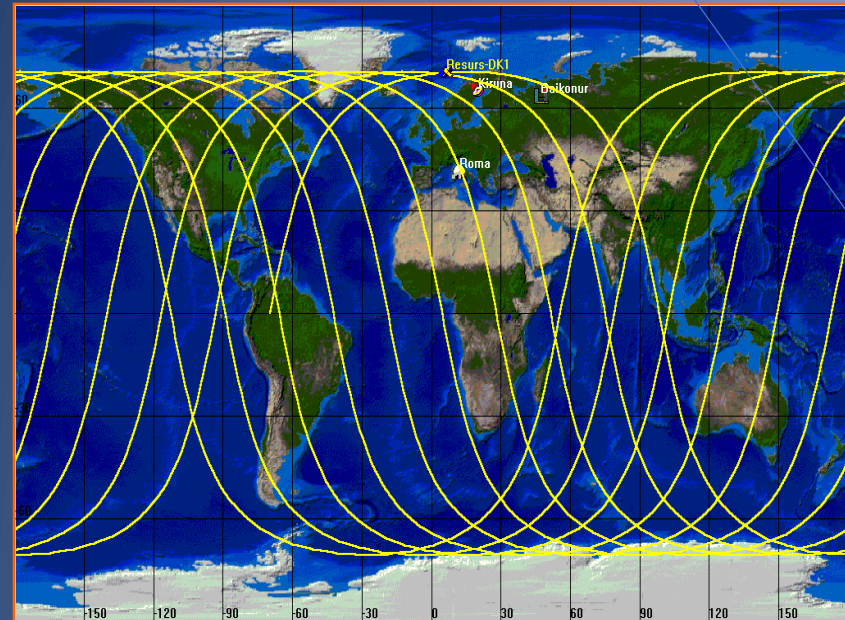
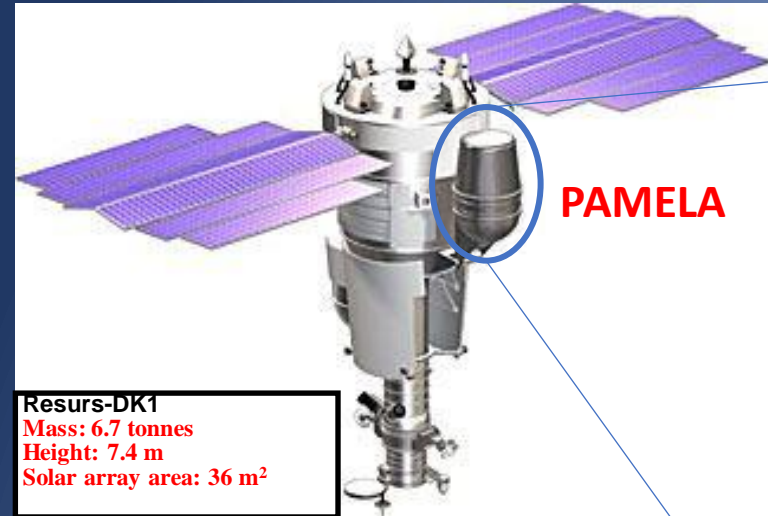
Numerical models can model the Local Interstellar Spectrum (LIS) assumed for any Galactic Cosmic Ray species



Take into account the charge sign effect resulting from drift motions shown, here for positively charged particles



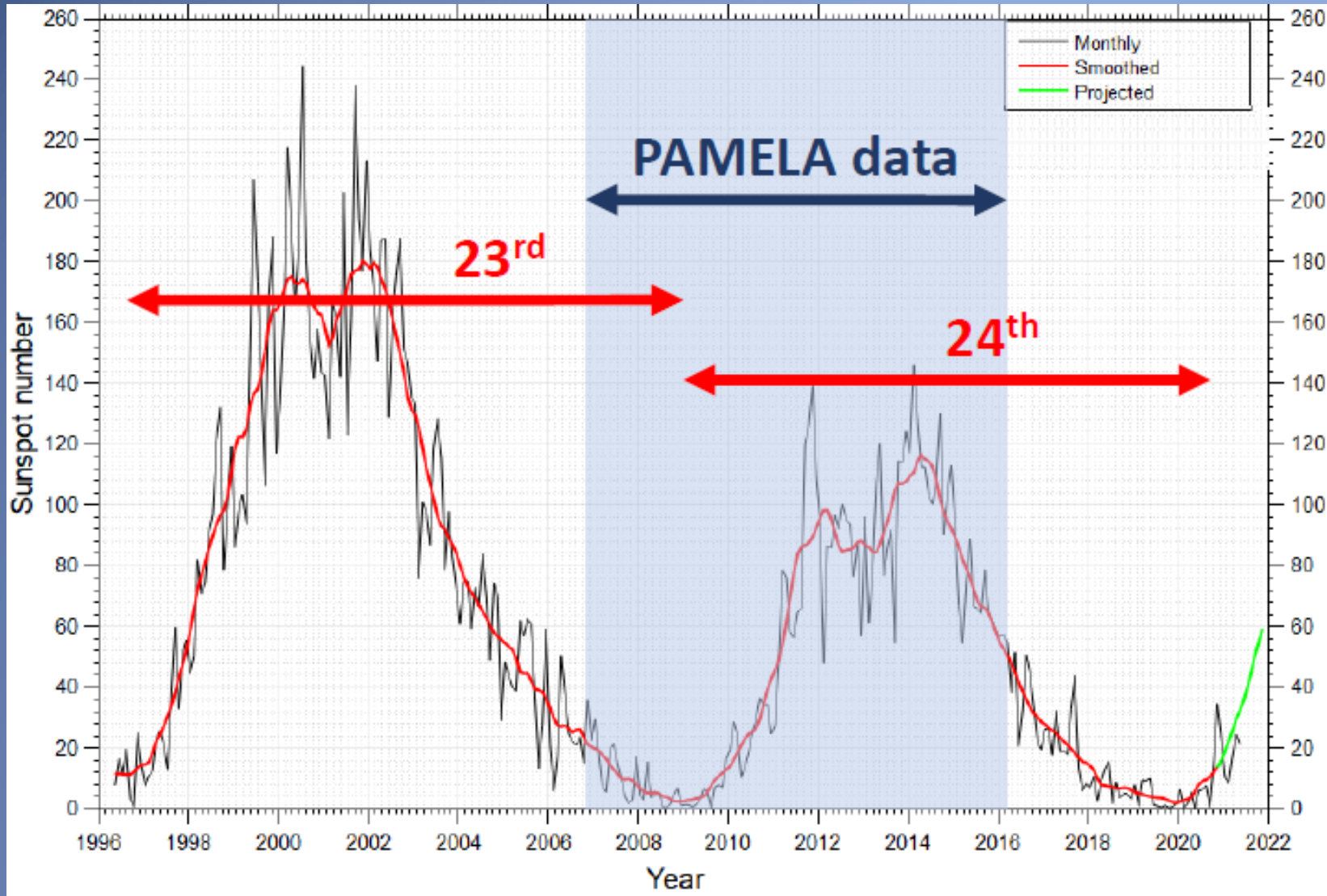
The PAMELA experiment



PAMELA strengths:

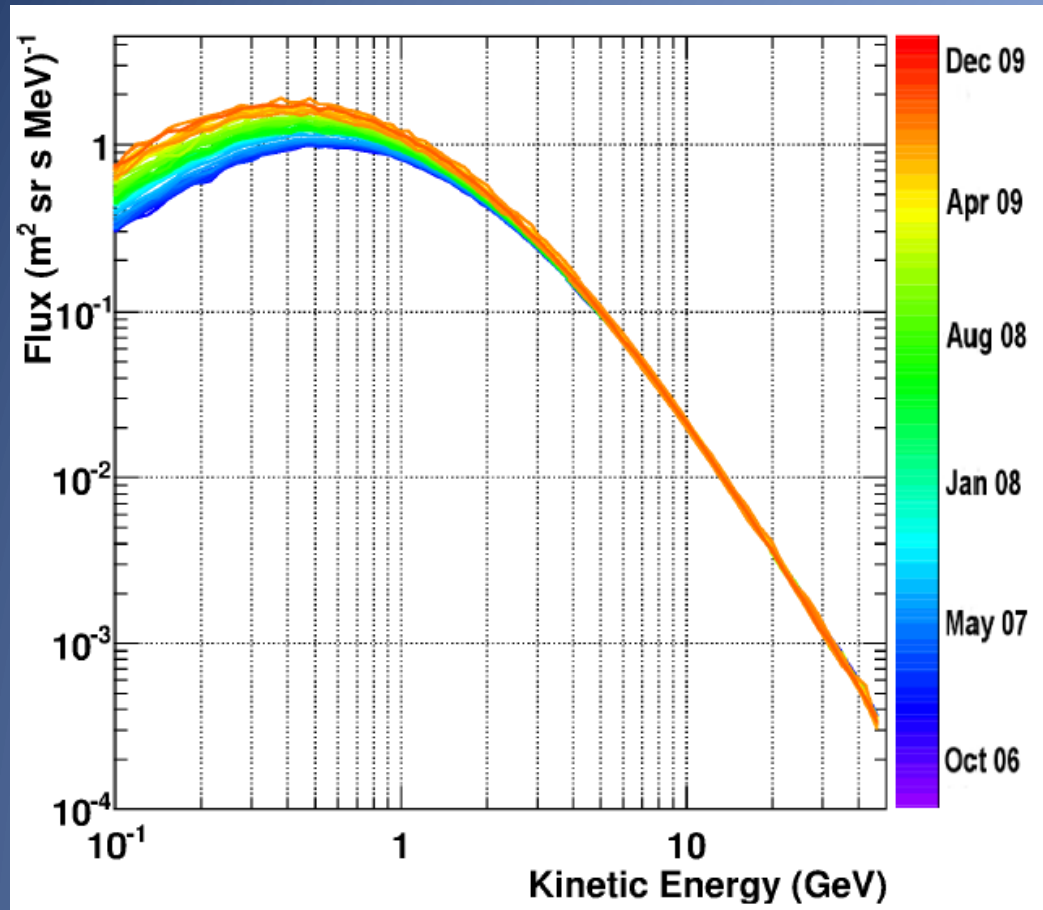
- **Semi-polar orbit** allowed to measure cosmic rays where the Störmer cut-off is lower.
- **Magnetic spectrometer** and ToF system measured particle rigidity and velocity. These allowed to establish the charge sign of the particles.
- **Electromagnetic calorimeter** was used to discriminate protons from electrons.
- **About 10 years of data taking** allowed to study Cosmic Rays fluxes during an almost whole solar cycle.

The solar activity during the PAMELA operation



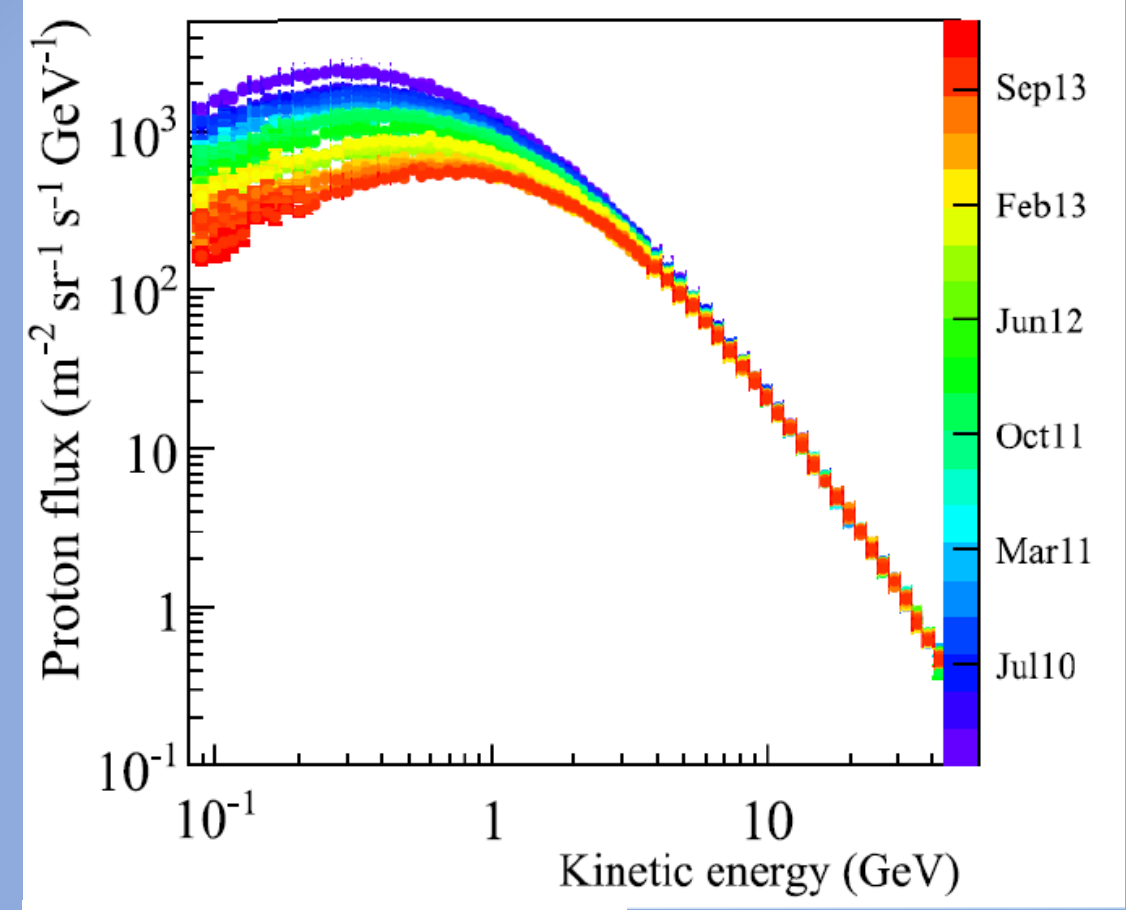
PAMELA results about the solar modulation effects

Hydrogen differential spectra
from July 2006 to December 2009



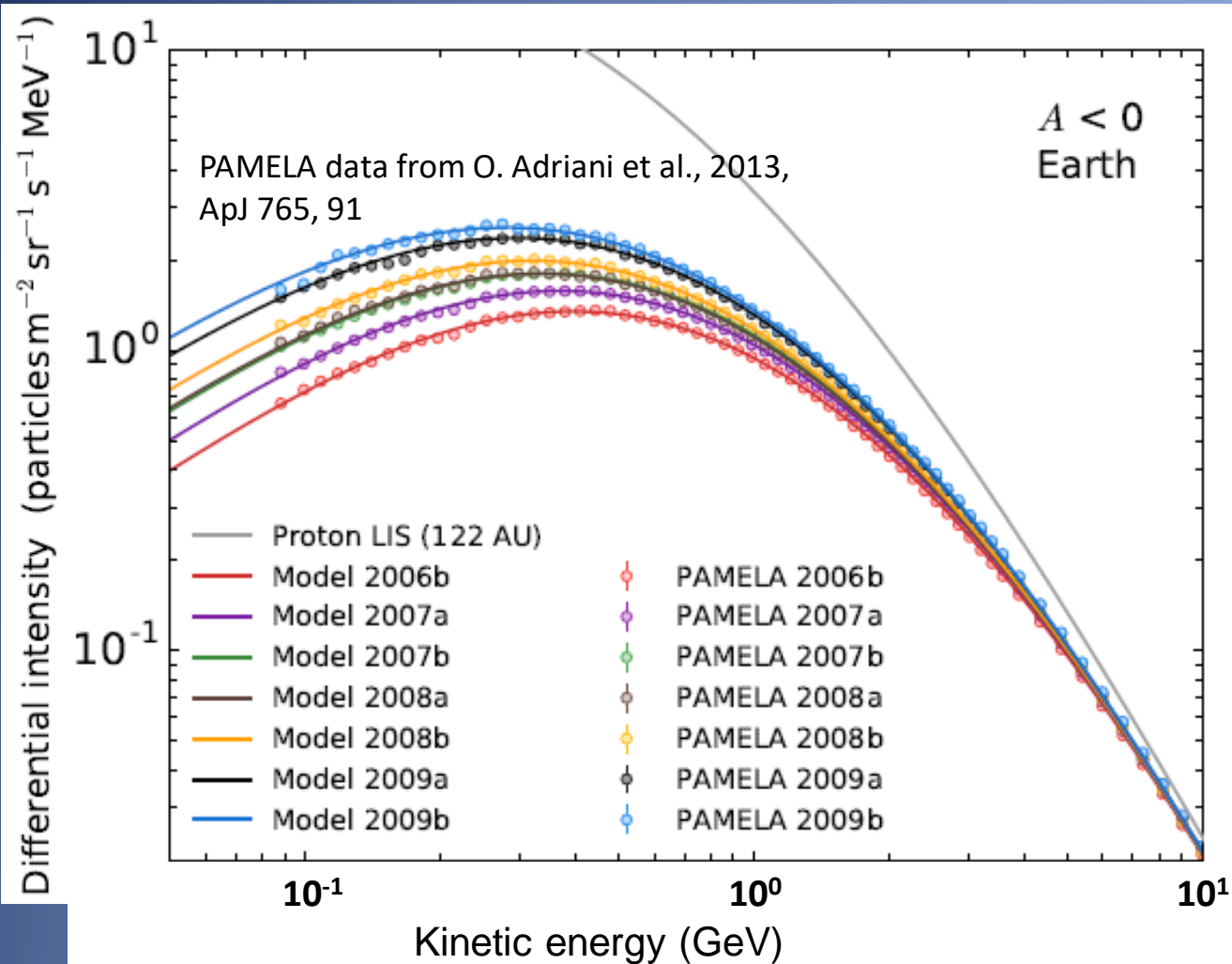
O. Adriani *et al* 2013 *ApJ* 765, 91

Hydrogen differential spectra from
January 2010 to February 2014



Martucci *et al* 2018 *ApJL* 854, L2

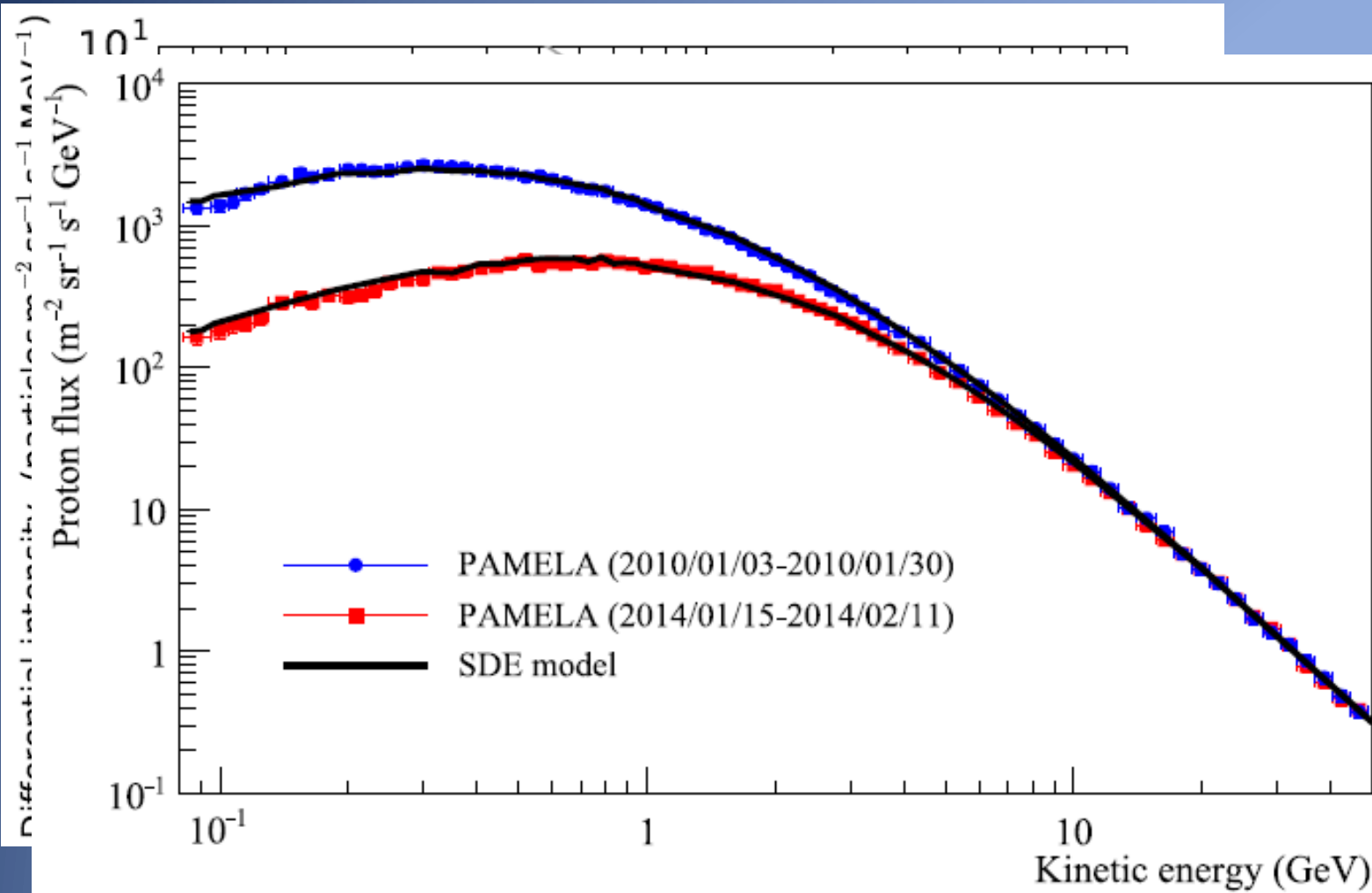
PAMELA results about the solar modulation effects



M.S. Potgieter and E. E. Vos, 2017 A&A 601, A23.

PAMELA hydrogen fluxes during solar minimum were used to calibrate a 3D numerical model of propagation in the Heliosphere.

PAMELA results about the solar modulation effects

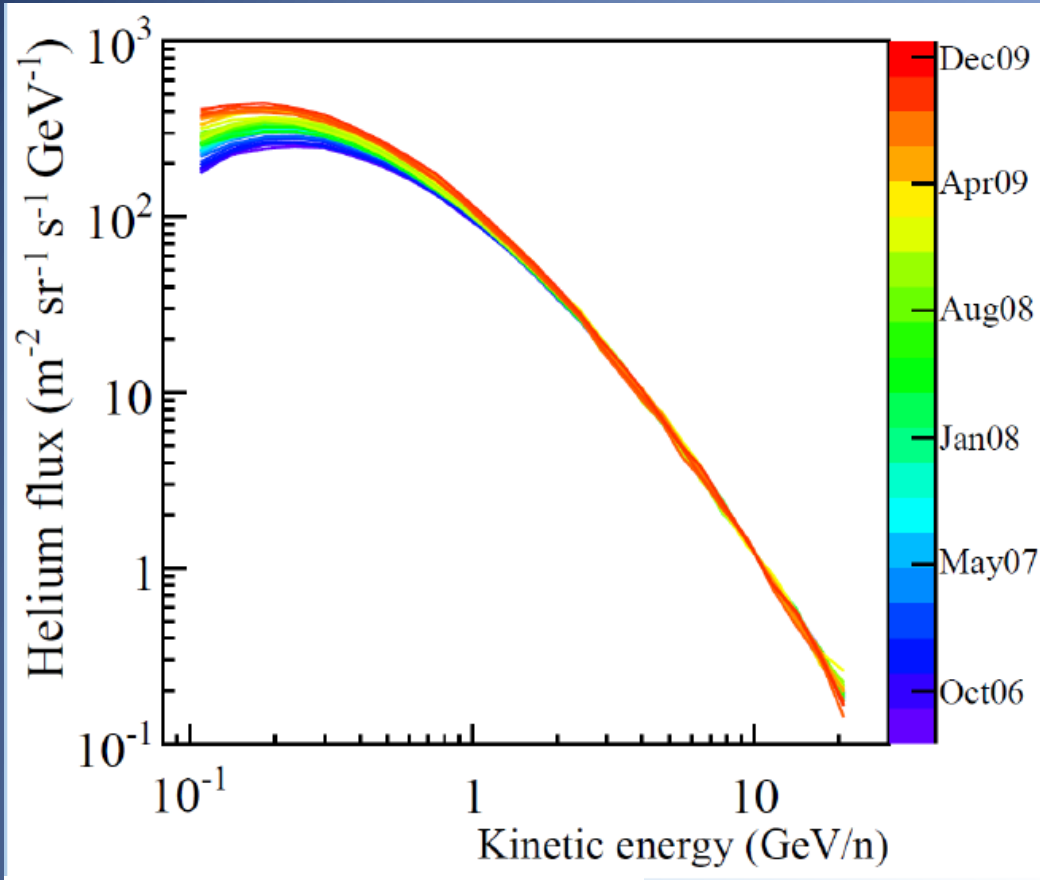


Martucci et al 2018 *ApJL* 854, L2

PAMELA hydrogen fluxes during solar maximum are also used to calibrate the 3D numerical model of propagation in the Heliosphere.

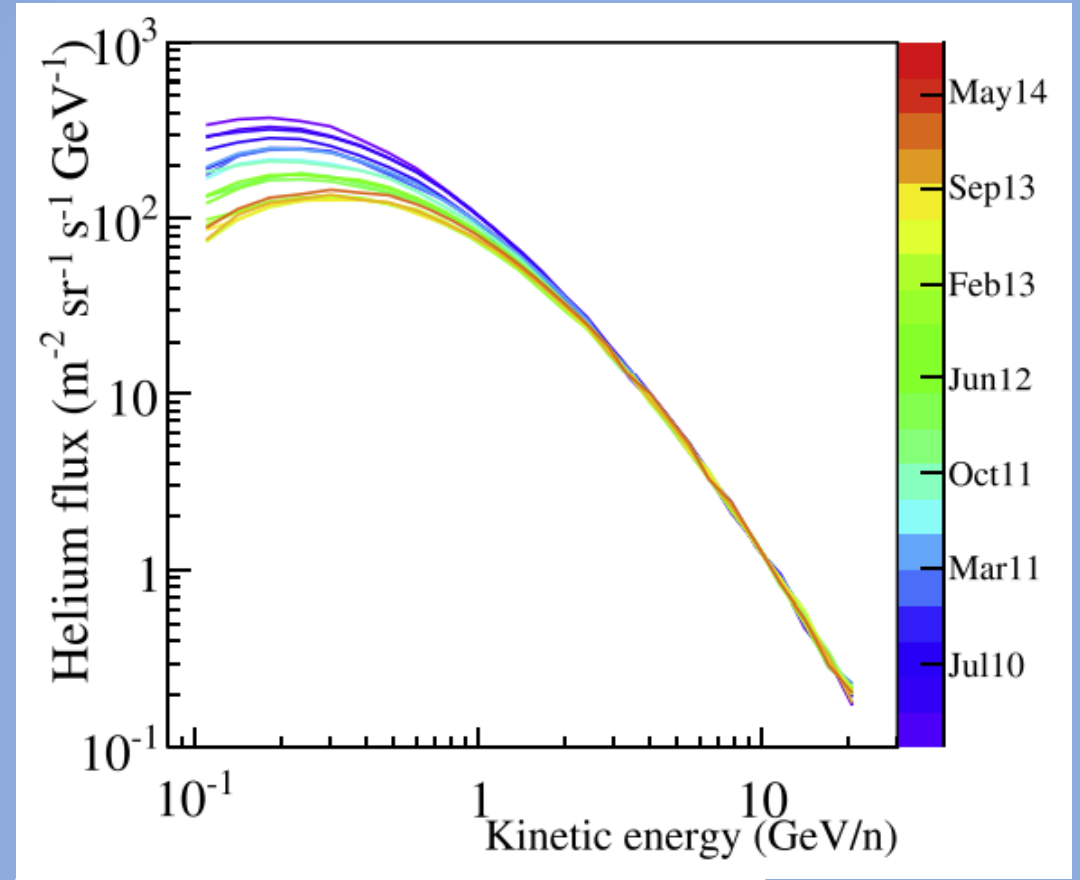
PAMELA results about the solar modulation effects

Helium differential spectra from July 2006 to December 2009



N. Marcelli *et al* 2020 *ApJ* 893, 145

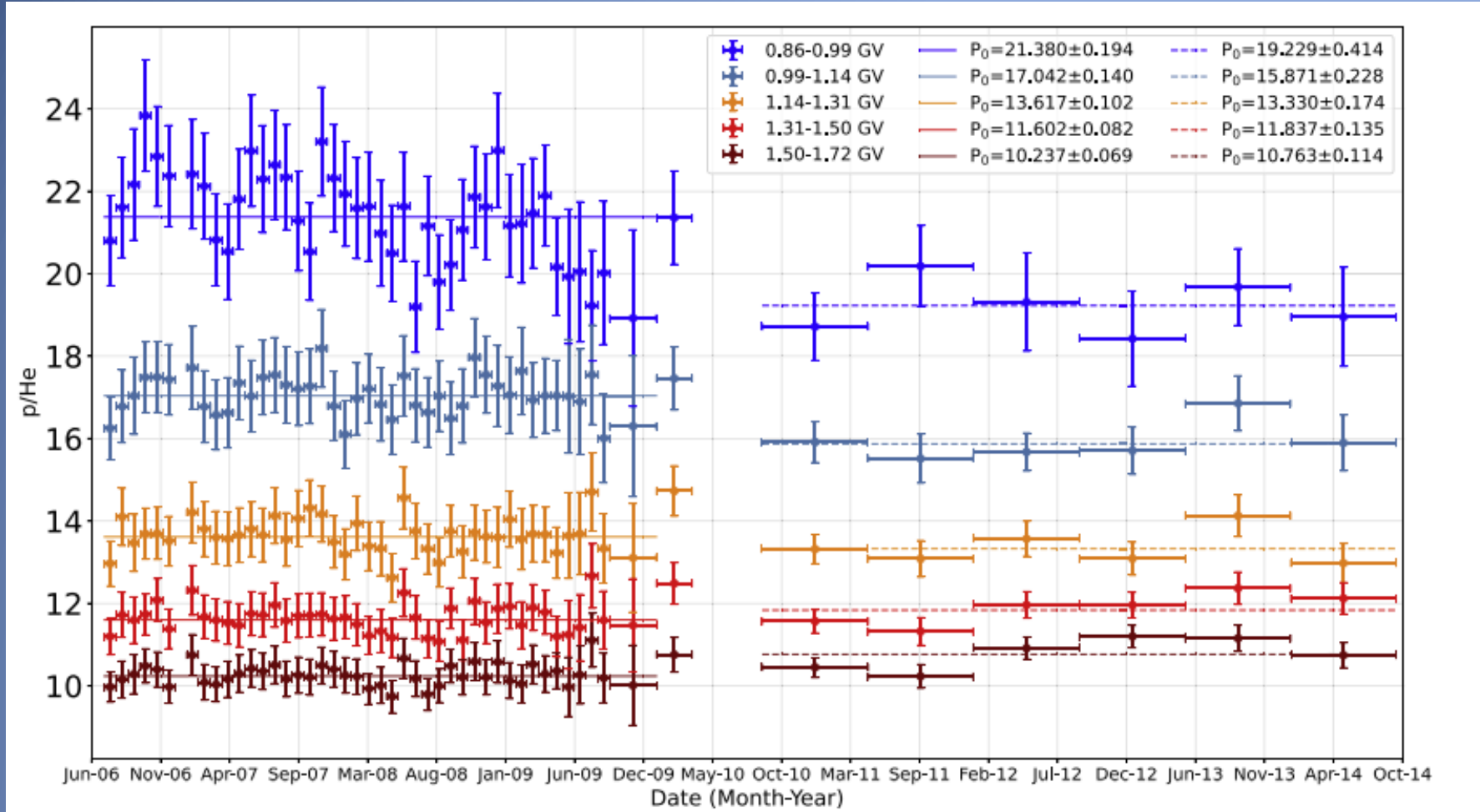
Helium differential spectra from January 2010 to September 2014



N. Marcelli *et al* 2022 *ApJL* 925:L24

PAMELA results about the solar modulation effects

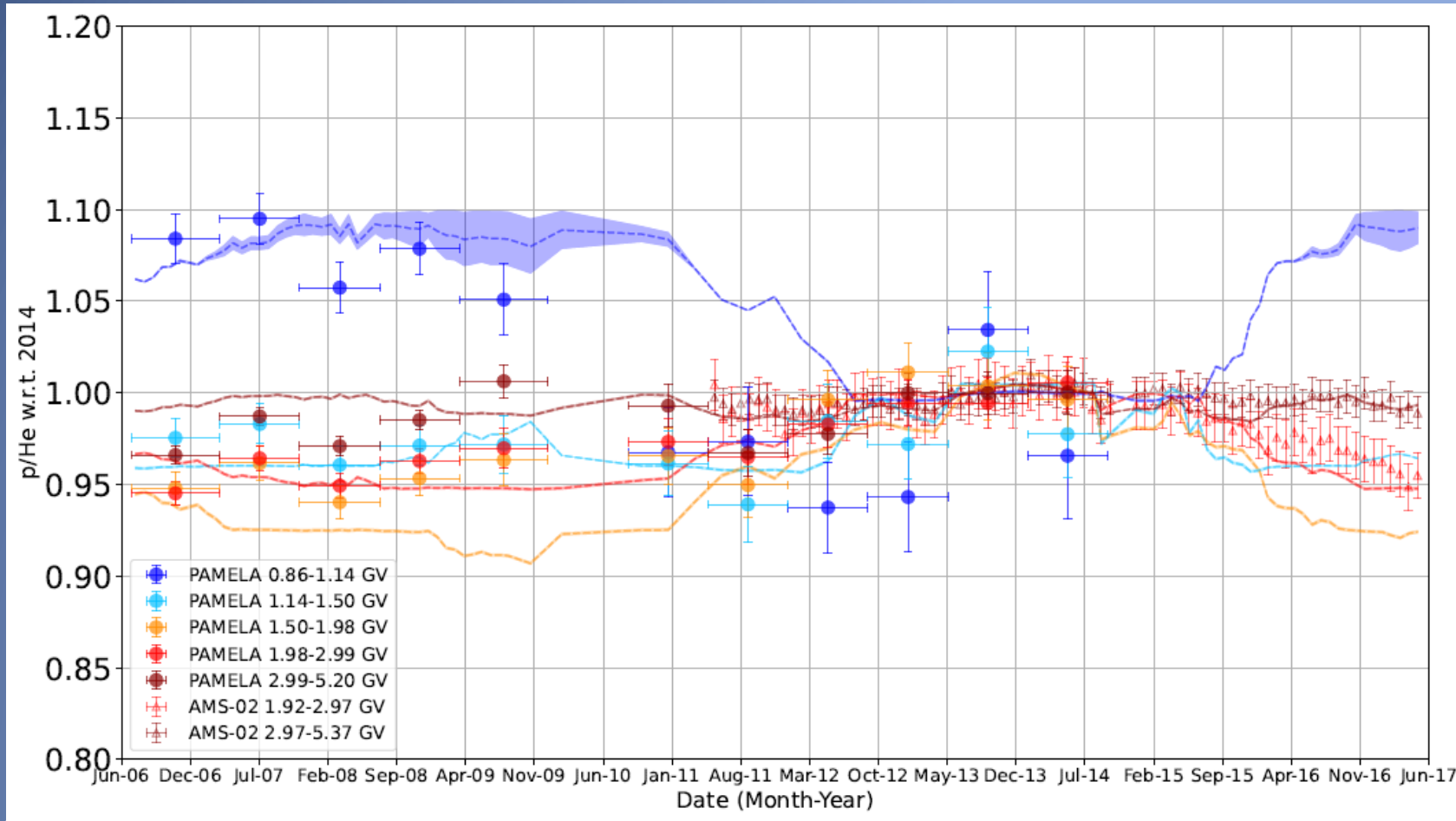
Time profiles of the hydrogen-to-helium flux-ratio for different rigidity ranges.



N. Marcelli et al 2022 ApJL 925:L24

PAMELA results about the solar modulation effects

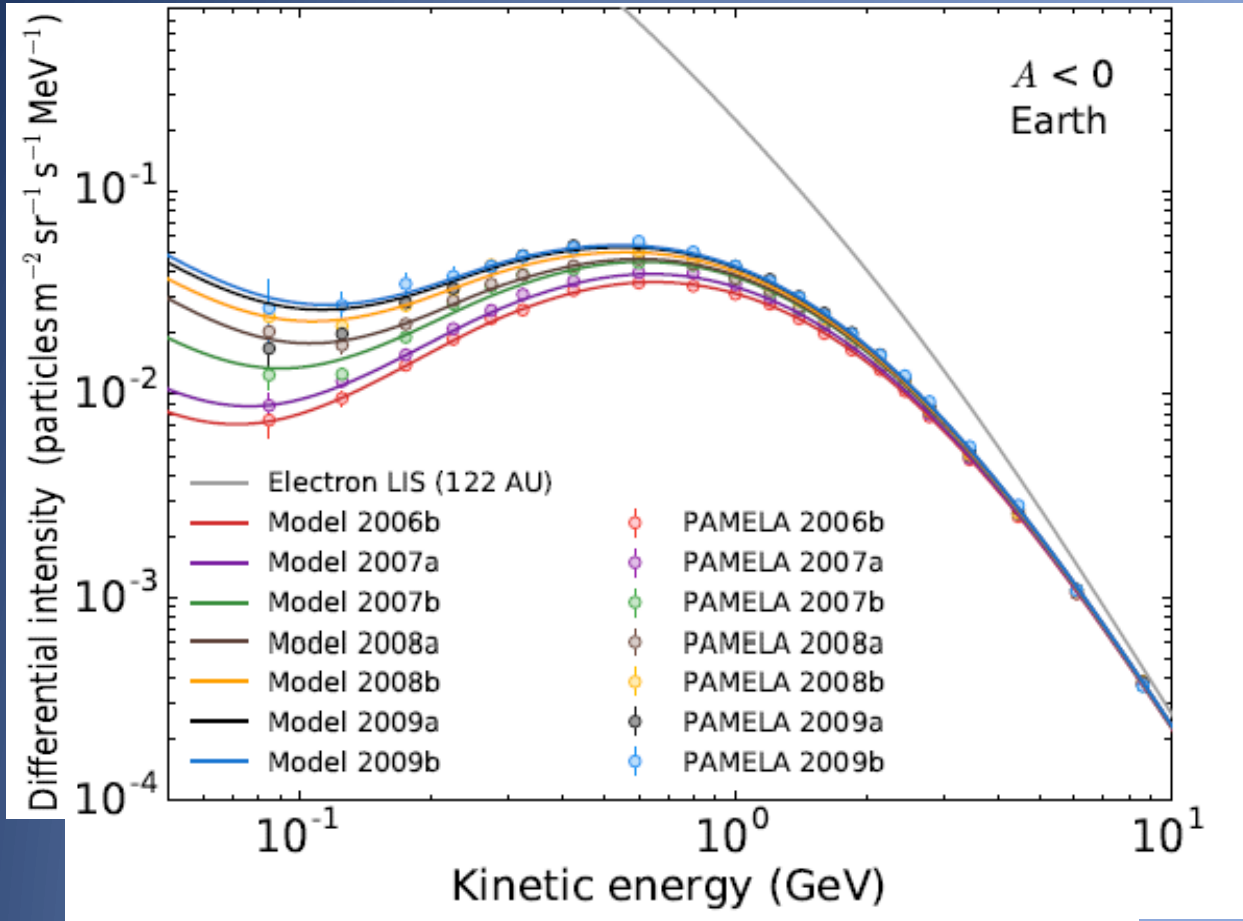
Hydrogen-to-Helium flux-ratio time profiles studied with the expectations coming from the Force-Field approximation of Solar Modulation



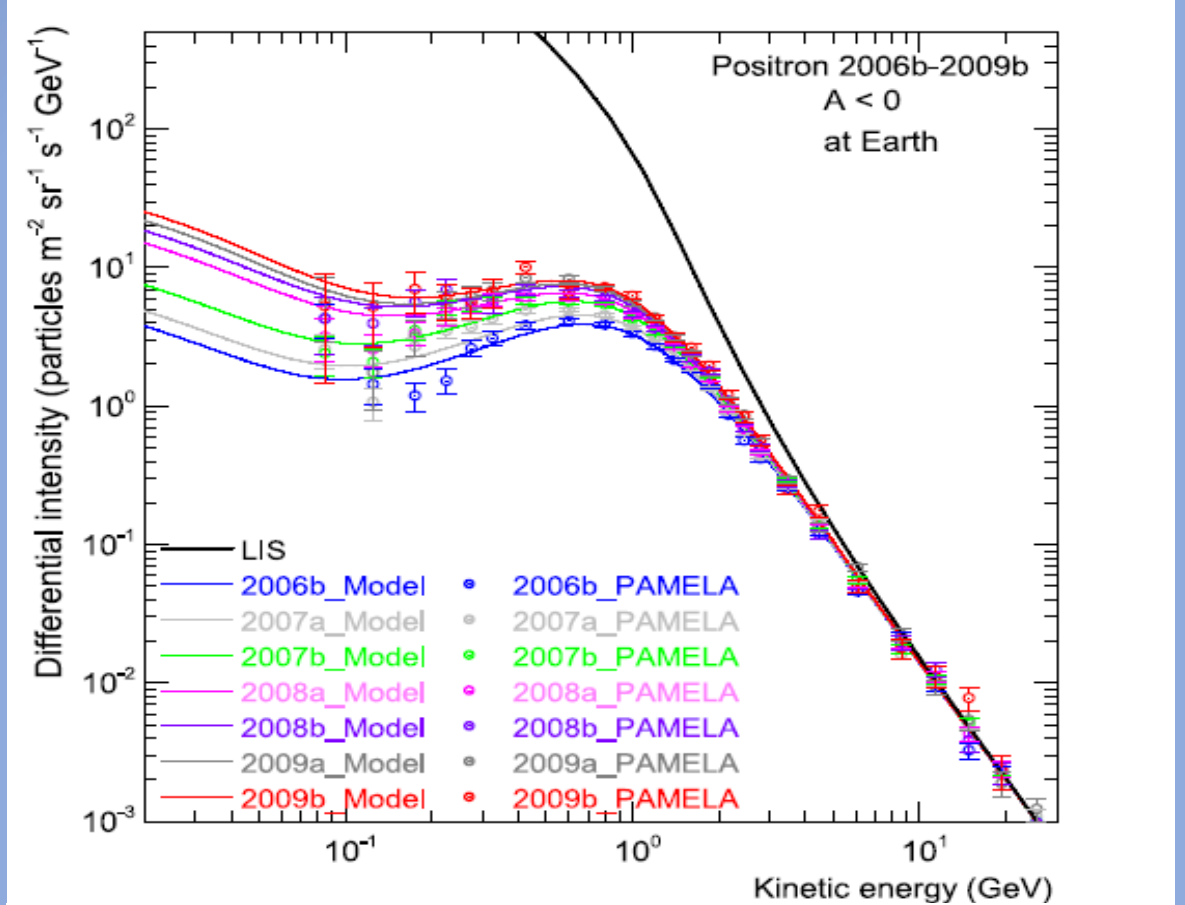
N. Marcelli et al 2022 ApJL 925:L24

PAMELA results about the solar modulation effects

PAMELA electron and positron fluxes are also used to calibrate a 3D numerical model of propagation in the Heliosphere



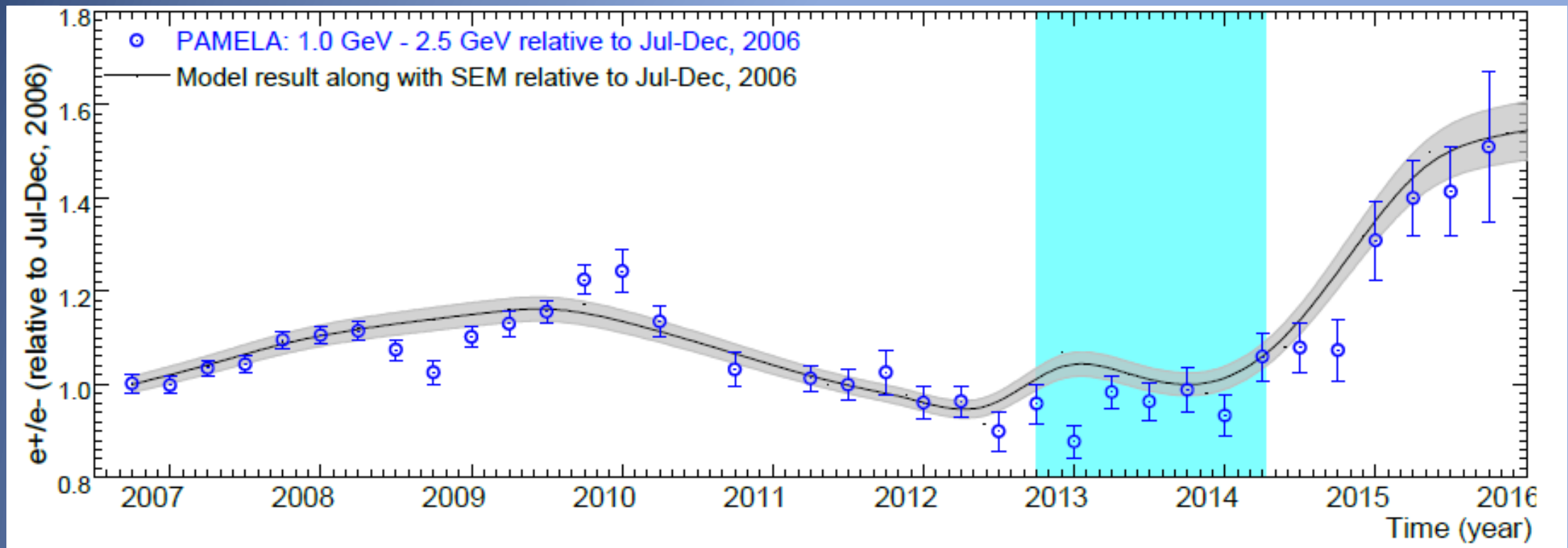
M.S. Potgieter and E. E. Vos, 2017 *A&A* 601, A23.
PAMELA data from O. Adriani et al, 2015, *ApJ* 810:142



O.P.M. Aslam et al, 2019 *ApJ* 873, 70
PAMELA data from R. Munini, PhD thesis, University of Trieste, Italy, 2013

PAMELA results about the solar modulation effects

PAMELA positron-to-electron flux ratios have been well reproduced by the 3D numerical model of propagation in the Heliosphere

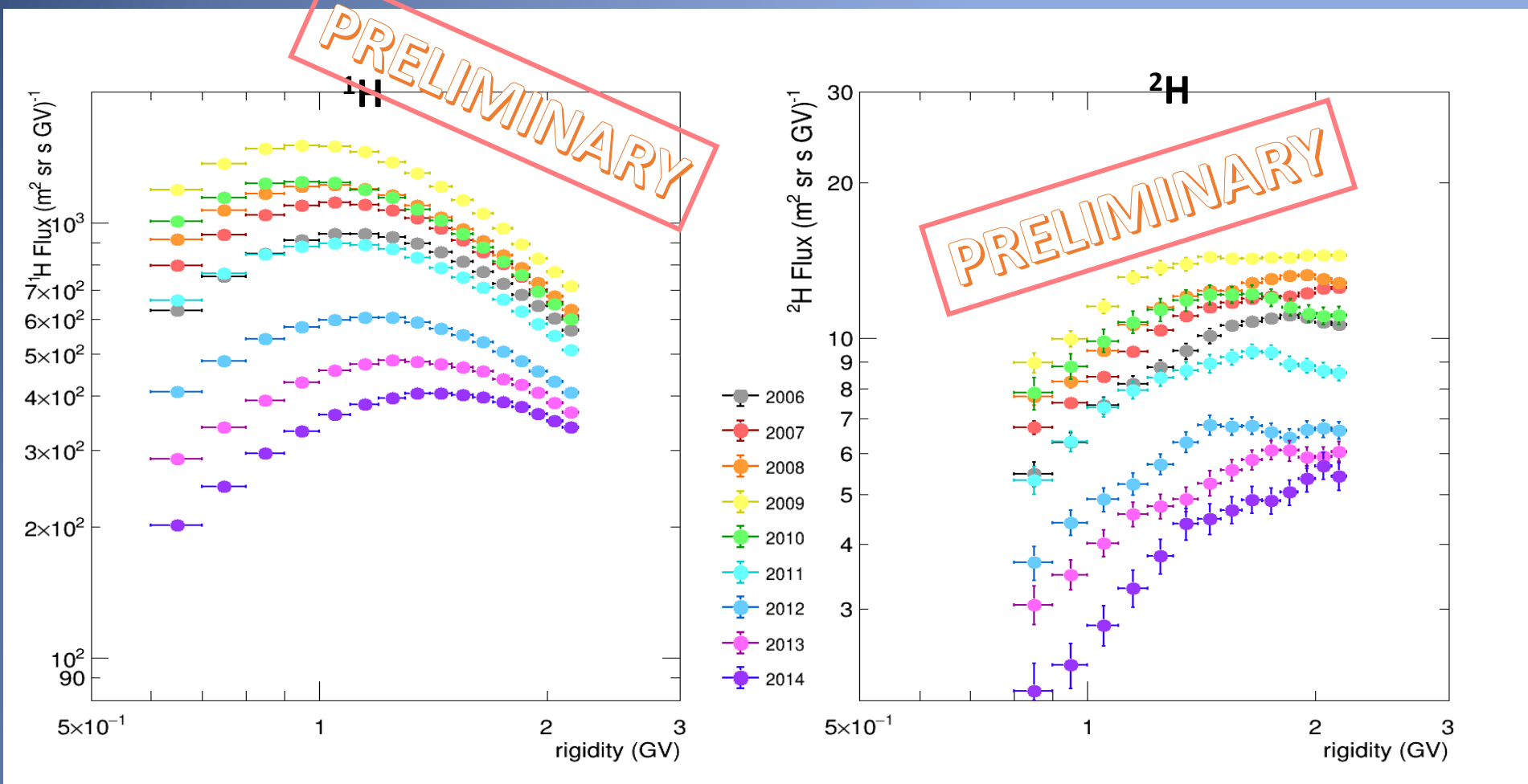


O.P.M. Aslam *et al* 2021 *ApJ* 909, 215

PAMELA data from O. Adriani *et al.*, 2016, *PhRvL*, 116, 241105

PAMELA results about the solar modulation effects

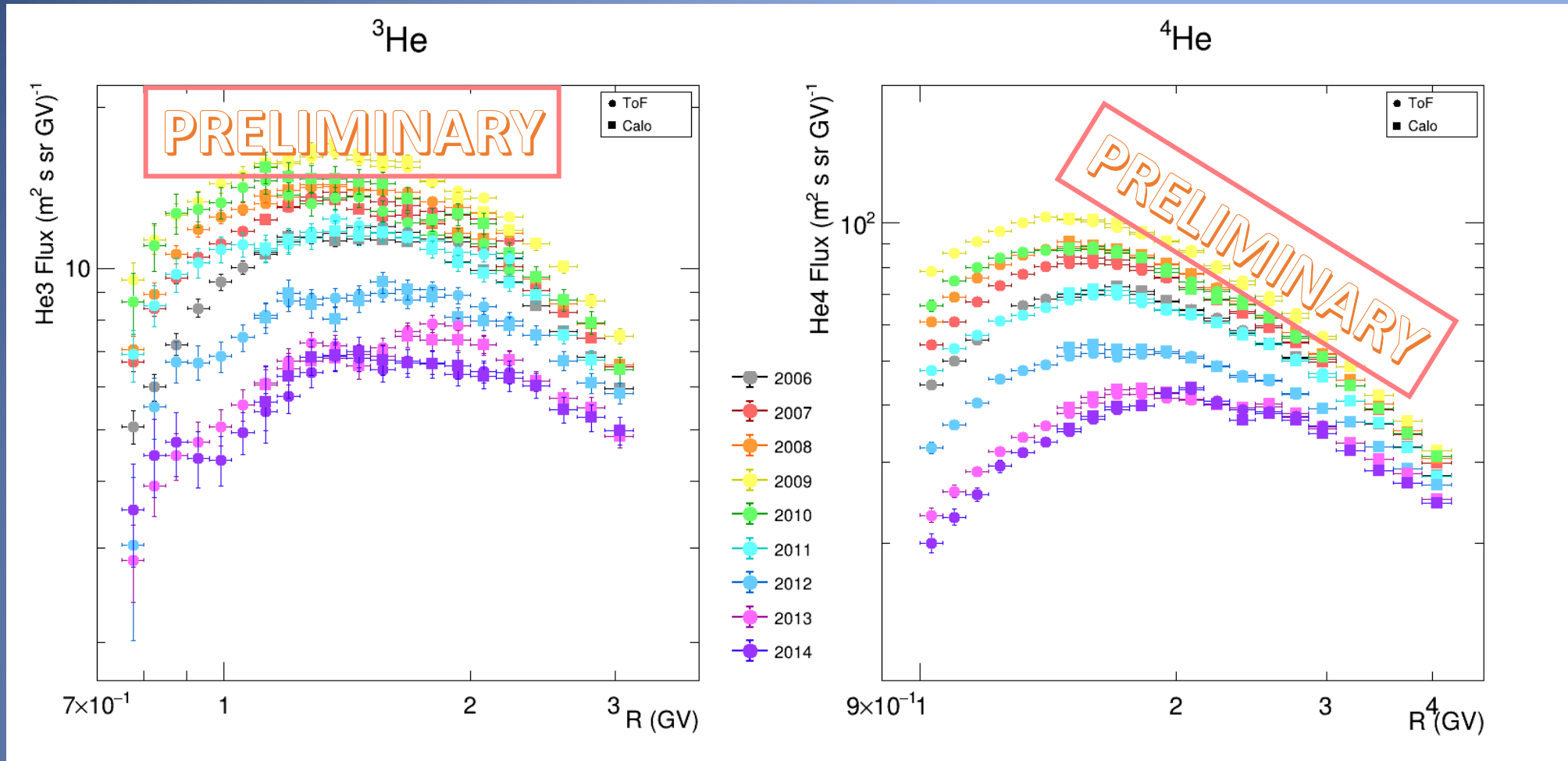
Preliminary results about proton and deuteron yearly fluxes:



A. Lenni, PhD thesis, University of Trieste, Italy, 2022

PAMELA results about the solar modulation effects

Preliminary results about helium-3 and helium-4 yearly fluxes:



A. Lenzi et al., PoS ICRC 2021, 1310

Conclusions

- The PAMELA experiment provided essential measurements of cosmic-ray fluxes for studies of solar modulation over an almost whole solar cycle with a change of solar magnetic polarity.
- Measured energy spectra of cosmic-ray hydrogens and helium nuclei, electrons and positrons over time were provided and used to calibrate a state-of-the-art 3D numerical model of cosmic-ray propagation in the Heliosphere.
- The time profile of the measured positron-to-electron flux ratio at low energies has allowed to study more deeply with the 3D-model the relevance of the charge-sign effect introduced by drift motions in Heliosphere.
- The time profiles of the proton-to-helium flux ratio was measured at different rigidities to study the solar modulation effects resulting from their different charge-to-mass ratio and the difference in the shape of their respective LIS.
- An analogous study of these effects will also be performed by studying deeply the fluxes of the major isotopic components, i.e. protons, deuterons, helium-3 and helium-4 nuclei, whose preliminary results have been presented, and the relative time profiles of their flux ratios for low rigidity ranges.