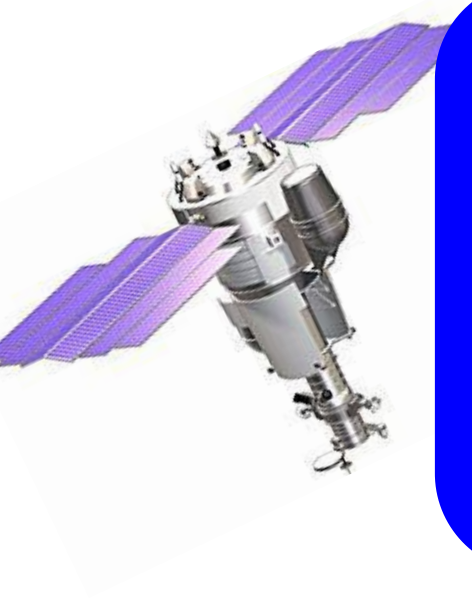
Вариации потоков космических лучей по данным прецизионных измерений магнитными спектрометрами PAMELA и AMS-02

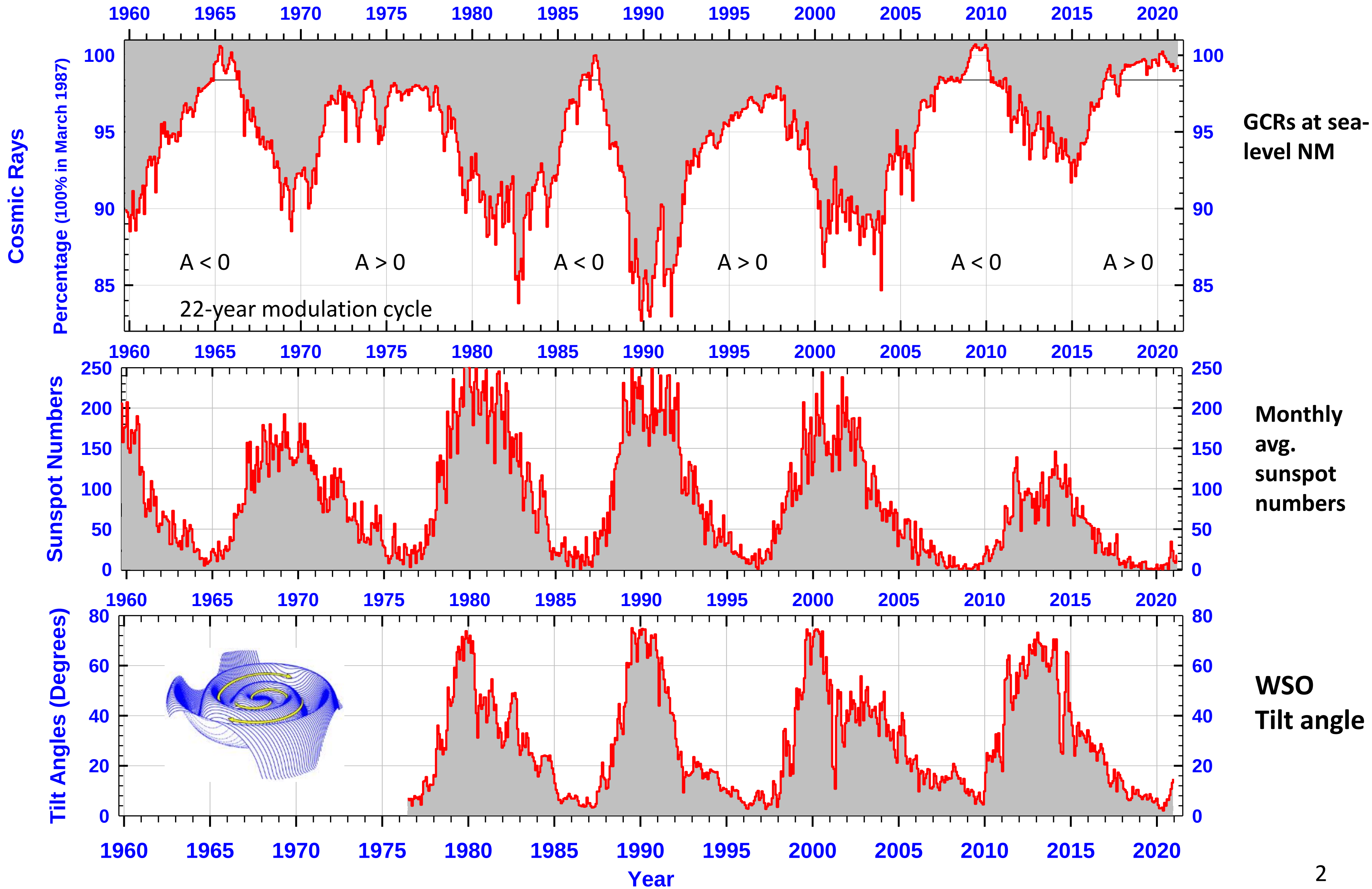
Владимир Михайлов
МИФИ

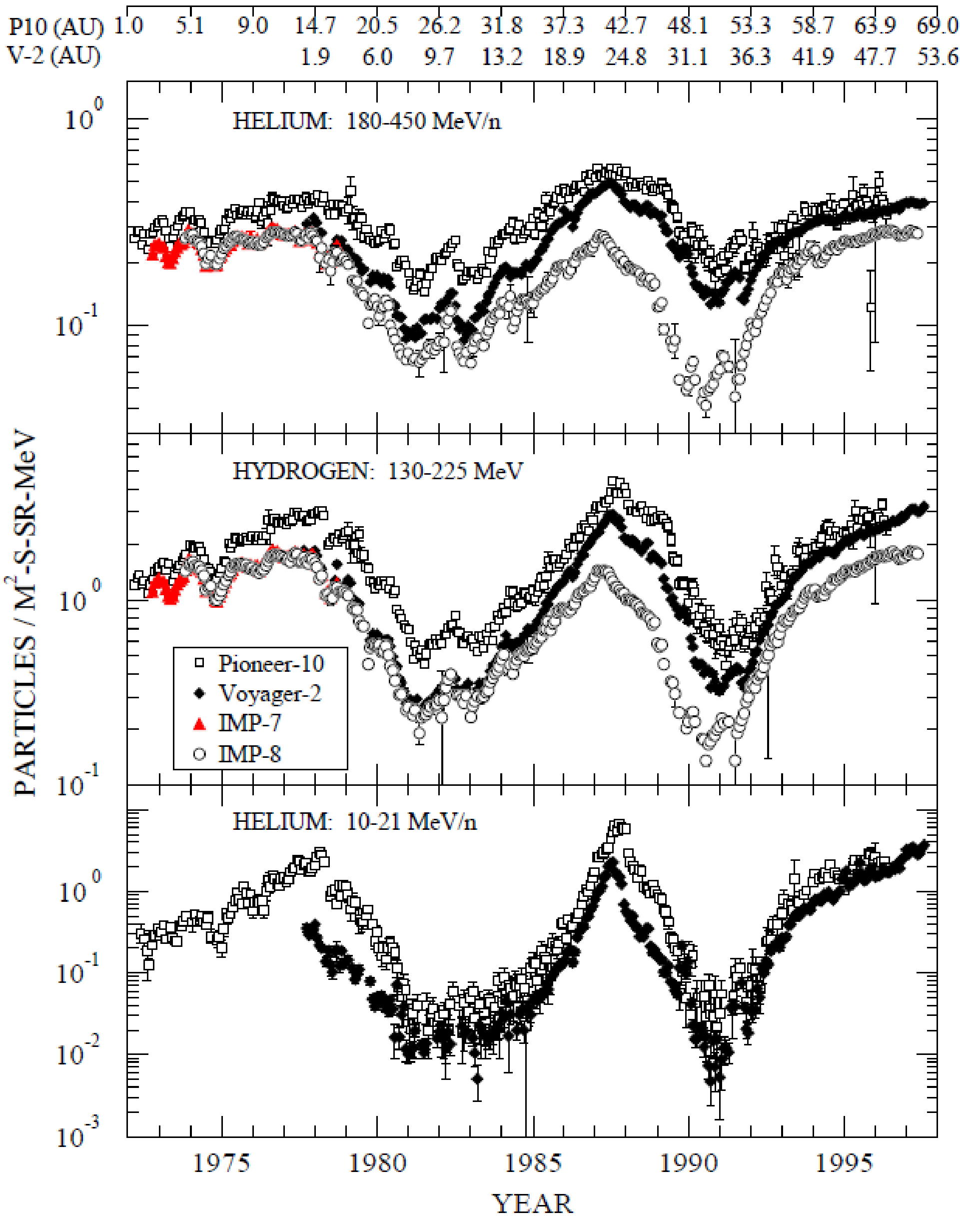


- **Введение. Модели модуляции.**
- **Магнитные спектрометры PAMELA & AMS-02**
- **Результаты 2020-2022:**

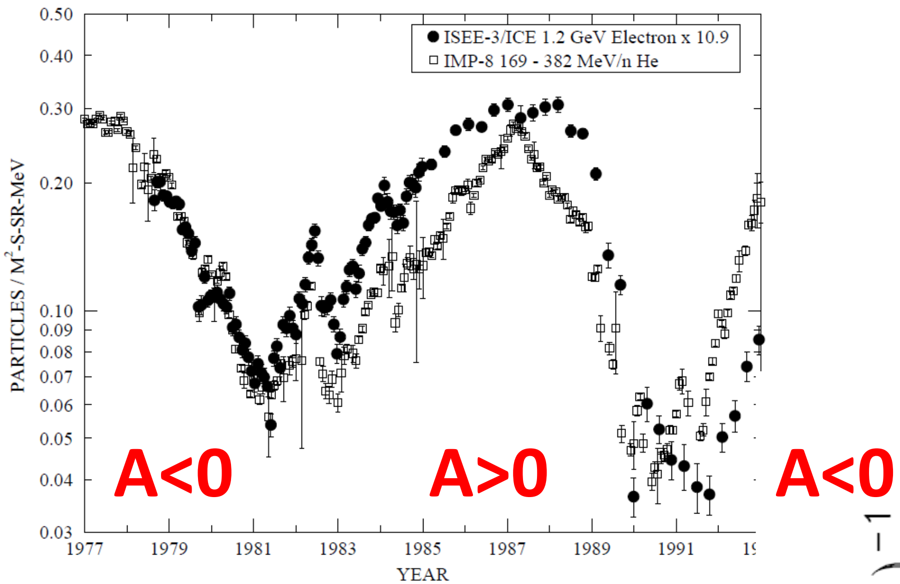
- **зависимость от знака заряда**
- **локальные межзвездные спектры,**
- **27 –дневные вариацие p и He**
- **зависимость модуляции от скорости** β

Modulation of Galactic Cosmic Rays observed at sea-level NM compared to two solar activity proxies

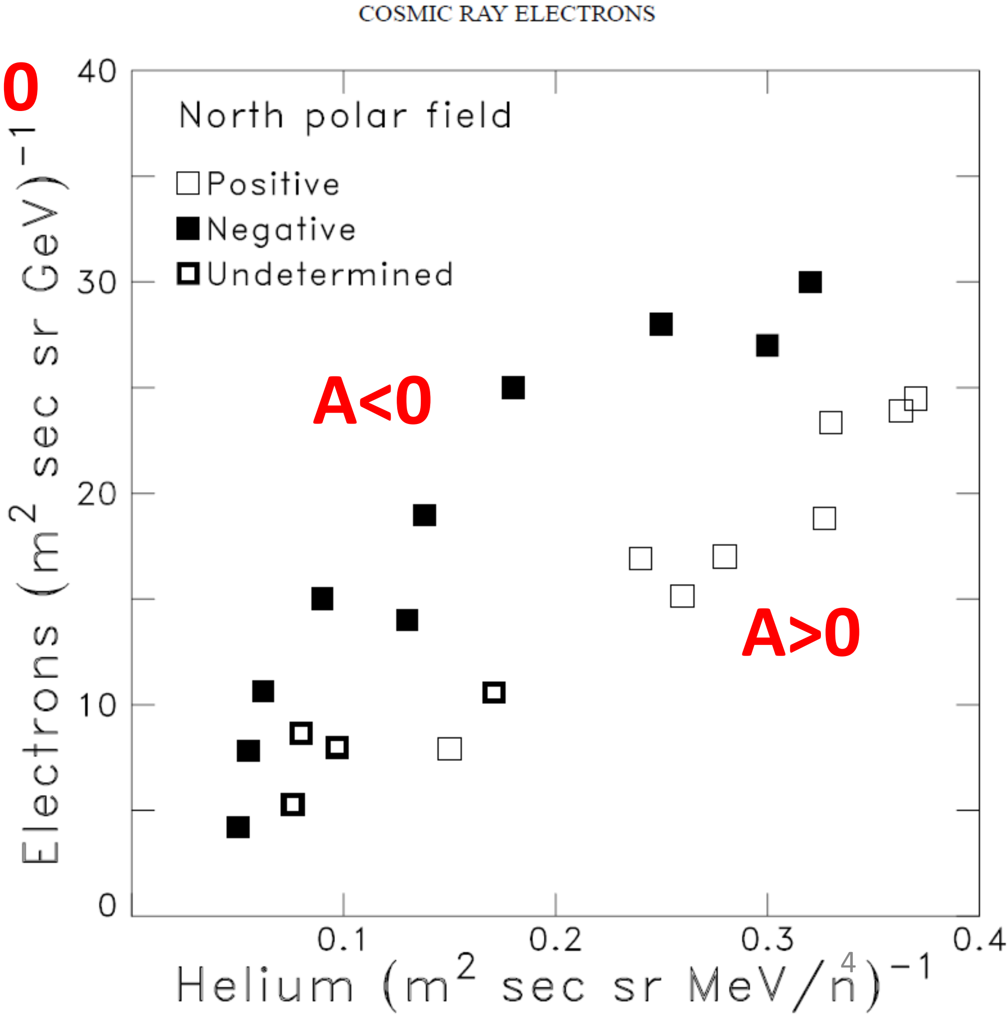




Time histories of the galactic cosmic ray (26 day averages) of H, He and 10–22 MeV/n anomalous helium from **IMPs 6, 7 and 8** at 1 AU and **V2 and P10** at larger heliocentric distances.



Time history of 1.2 GeV electrons (Clem *et al.*, 1996) and 169–382 MeV/n He from 1977–1993.0. The electron data was multiplied by a normalizing factor of 10.9.



Regression plot of electron and helium fluxes from 1965 to 1990. The 1.3 GeV electrons, and 190 MeV/n helium plotted here have similar rigidity. (Garcia-Munoz *et al.*, 1991)

Space Science Reviews **83:** 63–73, 1998

Parker's Transport Equation in the Heliosphere

$$\frac{\partial f}{\partial t} = \underbrace{-\vec{V}_{SW}\cdot\vec{\nabla} f}_{\text{Solar wind convection}} \underbrace{-\vec{V}_{D}\cdot\vec{\nabla} f}_{\text{Particle drifts}} + \underbrace{\vec{\nabla}\cdot(K\cdot\vec{\nabla} f)}_{\text{Particle diffusion}} + \underbrace{\frac{1}{3}\vec{\nabla}\cdot\vec{V}_{SW}\frac{\partial f}{\partial \ln R}}_{\text{Adiabatic energy changes}}$$

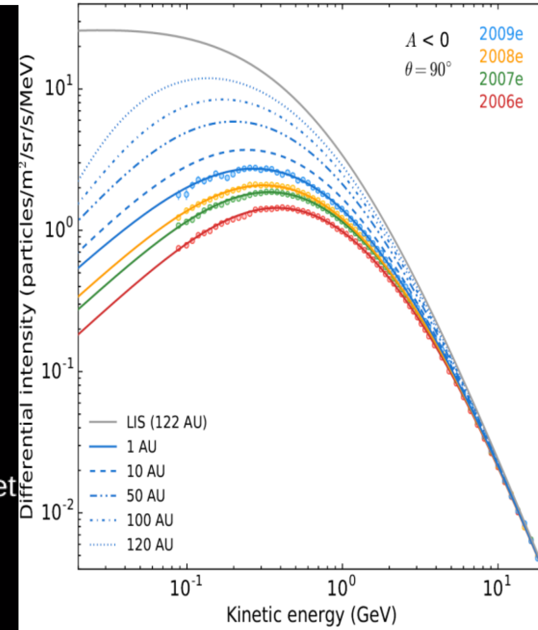
Particle convection with the solar wind.

Particle drifts due to heliospheric magnetic field gradients, curvatures and heliospheric current sheet

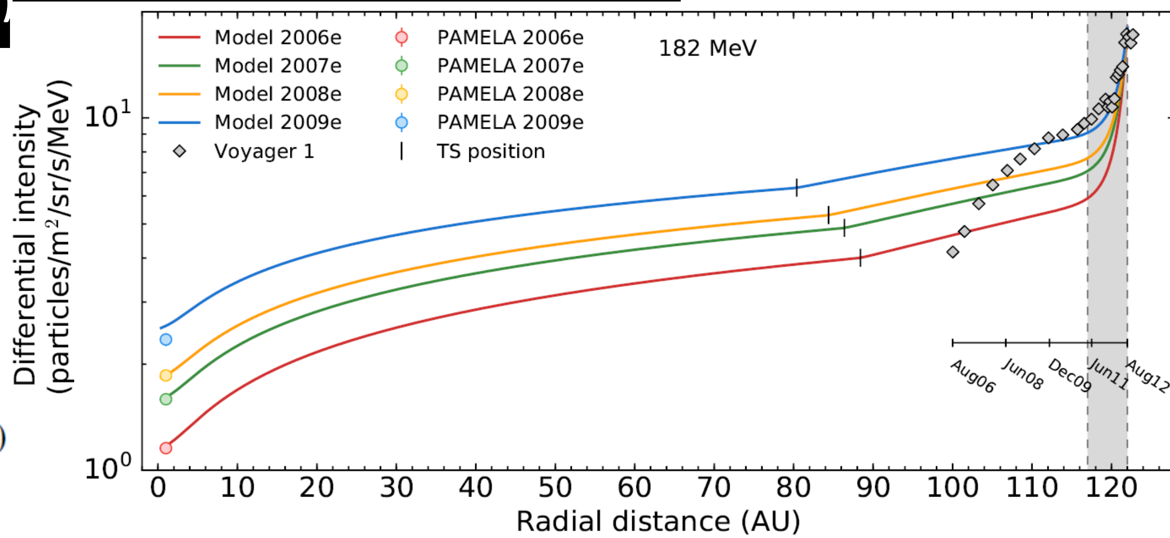
Particle diffusion due to scattering on magnetic field irregularities.

Adiabatic energy losses (or gains) due to expansion (or compression) of the solar wind.

Parker (Planet. Space Science, 13, 9,1965)



Potgieter, Vos 2016



Potgieter, 2021, ISCRA

<u>Модель силового поля</u>

$$J(r, E, t) = \frac{E^2 - E_0^2}{(E+\Phi)^2 - E_0^2} J(\infty, E+\Phi(t))$$

Φ - потенциал модуляции

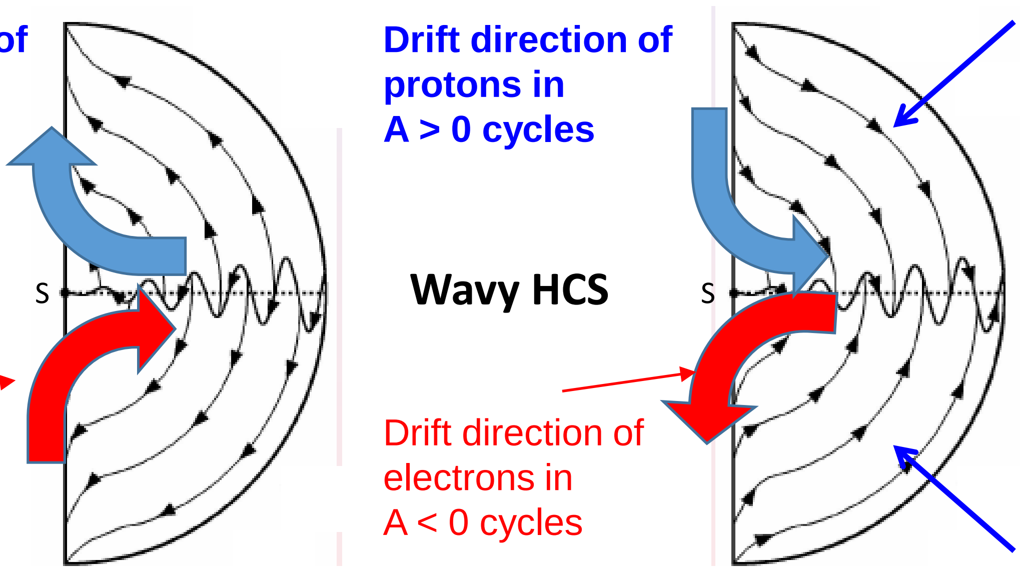
J (∞, E) - локальный межзвездный спектр (LIS)

Направления дрейфа противоположно заряженных частиц

Drift direction of protons in A < 0 cycles

Drift direction of protons in A > 0 cycles

HMF averaged direction; *B*



Drift direction of electrons in A > 0 cycles

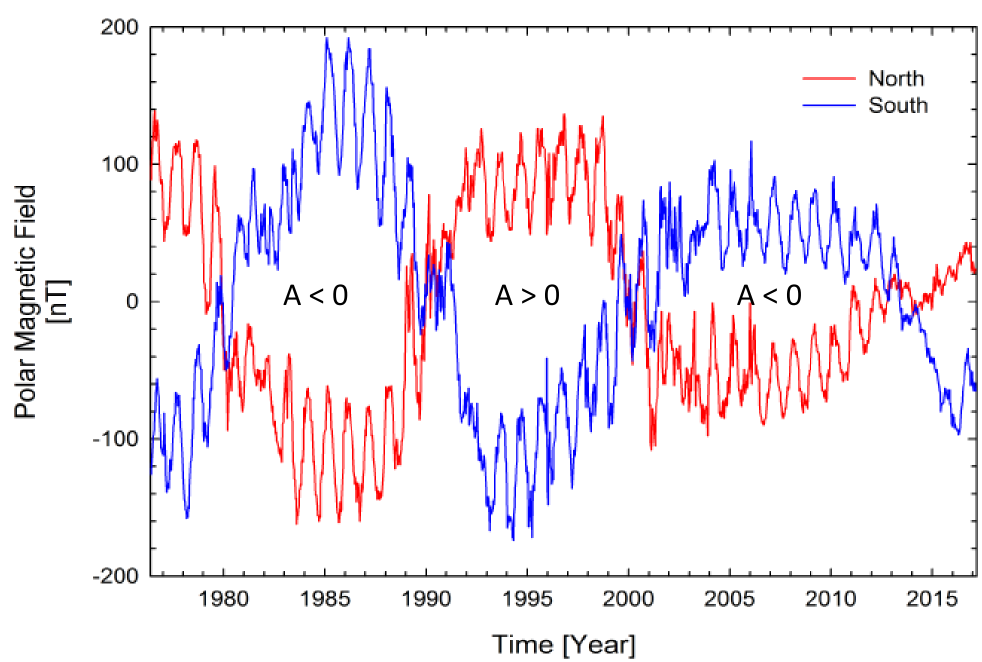
Drift direction of electrons in A < 0 cycles

Jokipii & Thomas (1981)

During A < 0 'polarity' cycles, protons drift inwards mainly along the HCS and get therefore modulated according to the till angle but less so during A > 0 cycles. This gives a 22-year modulation cycle…!

Reversal of HMF's 'polarity'

HMF switches its direction about every 11 years around maximum solar activity…! …a clear 22-year cycle.



From Potgieter, 2021, ISCRA

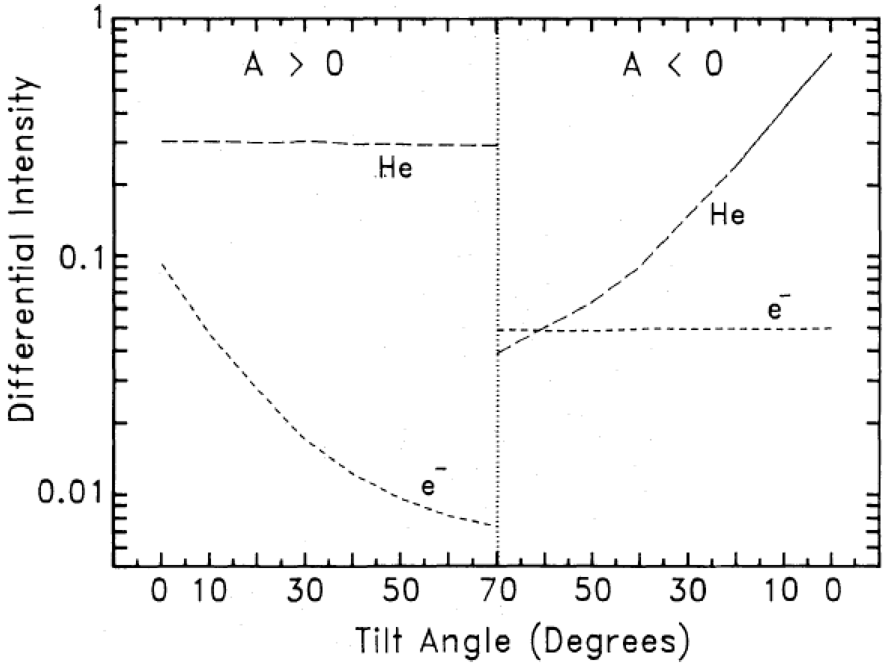
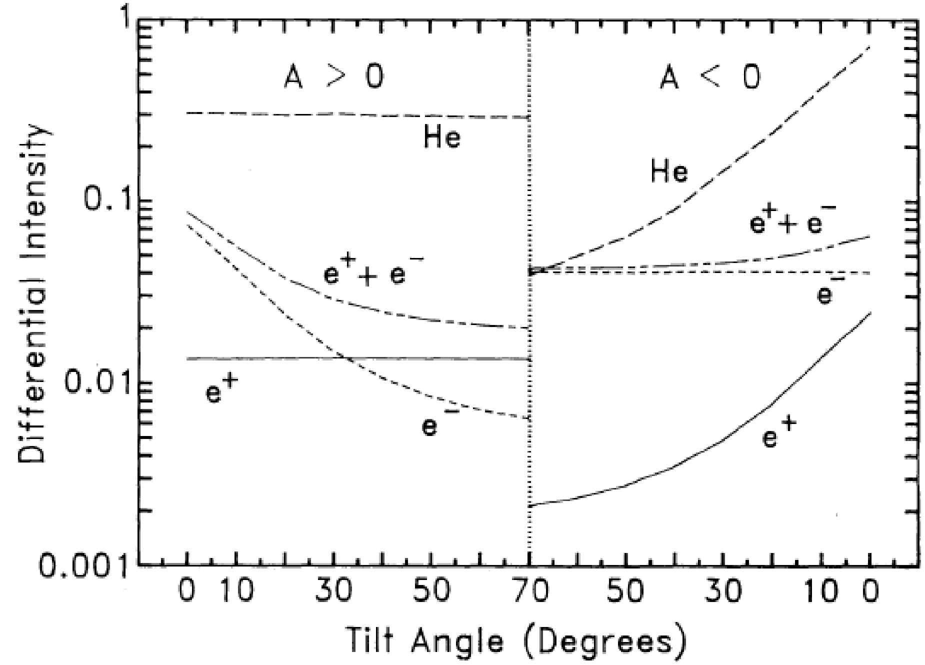


Fig. 2. The predicted differential intensity (particles $m^{-2}\,s^{-1}\,sr^{-1}\,MeV^{-1}$) for electrons ($e^-$) and helium (He) for 800 MV at Earth as a function of neutral sheet tilt angle, α. The period $A>0$ is represented by $\alpha=0°-70°$, and $A<0$ by $\alpha=70°-0°$. The change in the polarity of the IMF (e.g., 1980) is depicted by the central, vertical dotted line

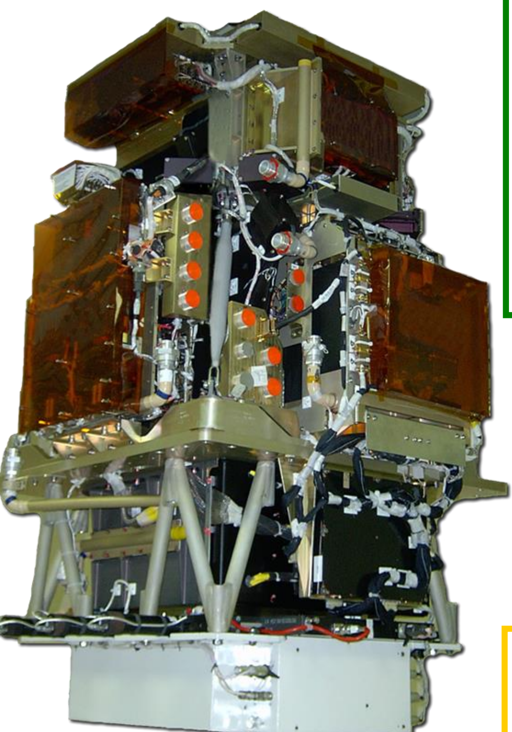


С учетом 25% вклада позитронов

Potgieter, Burger, A&A 233, 598, 1990

PAMELA detectors

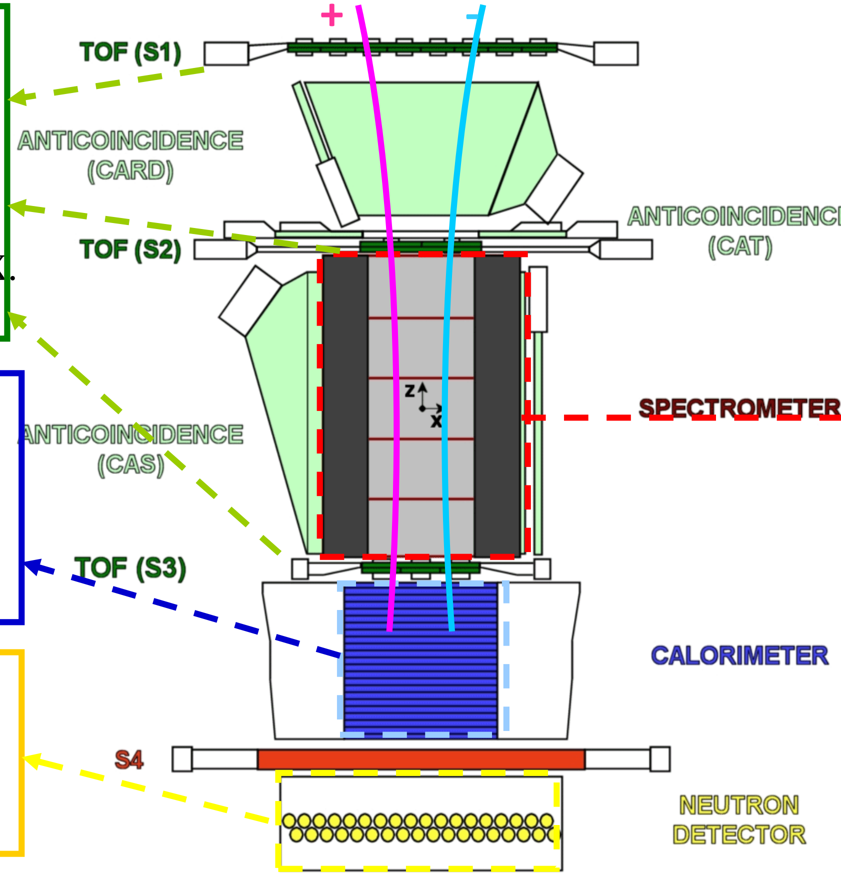
Main requirements → high-sensitivity antiparticle identification and precise momentum measure



Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Electromagnetic calorimeter
W/Si sampling (16.3 X_0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

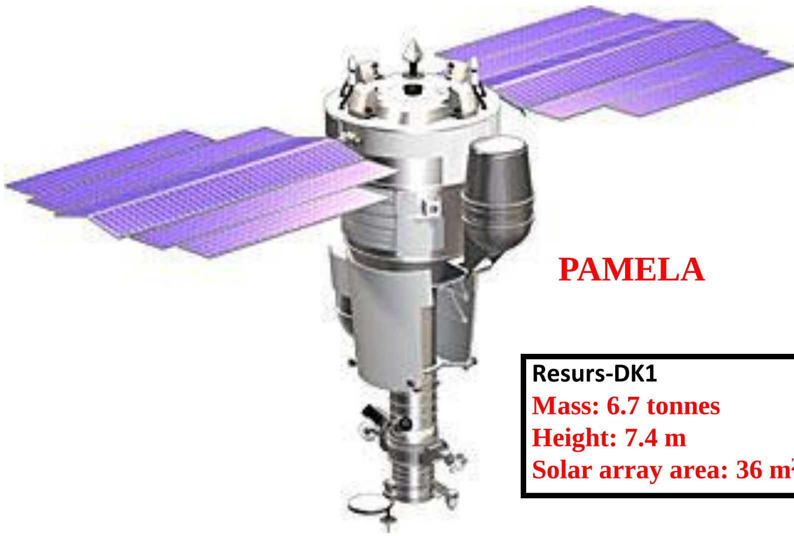
Neutron detector
^{3}He tubes + polyethylene moderator:
- High-energy e/h discrimination



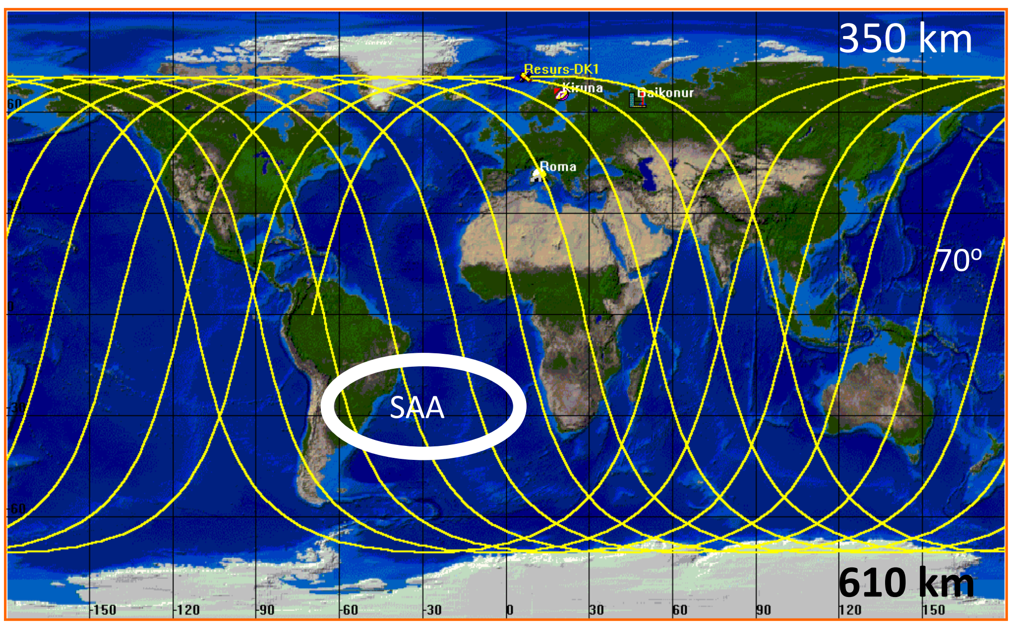
GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

Resurs-DK1 satellite



Resurs-DK1
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2



~90 mins

- Resurs-DK1: multi-spectral imaging of earth's surface
- PAMELA mounted inside a pressurized container
- Launched on 15th June 2006 PAMELA in continuous data-taking mode since then.
- Quasi-polar and elliptical orbit (70.0°, 350 km - 600 km) – from 2010 circular orbit (70.0°, ~600 km)
- Traverses the South Atlantic Anomaly
- Data transmission to the Earth terminated on 23 January 2016

Since June 2006 till January 2016:

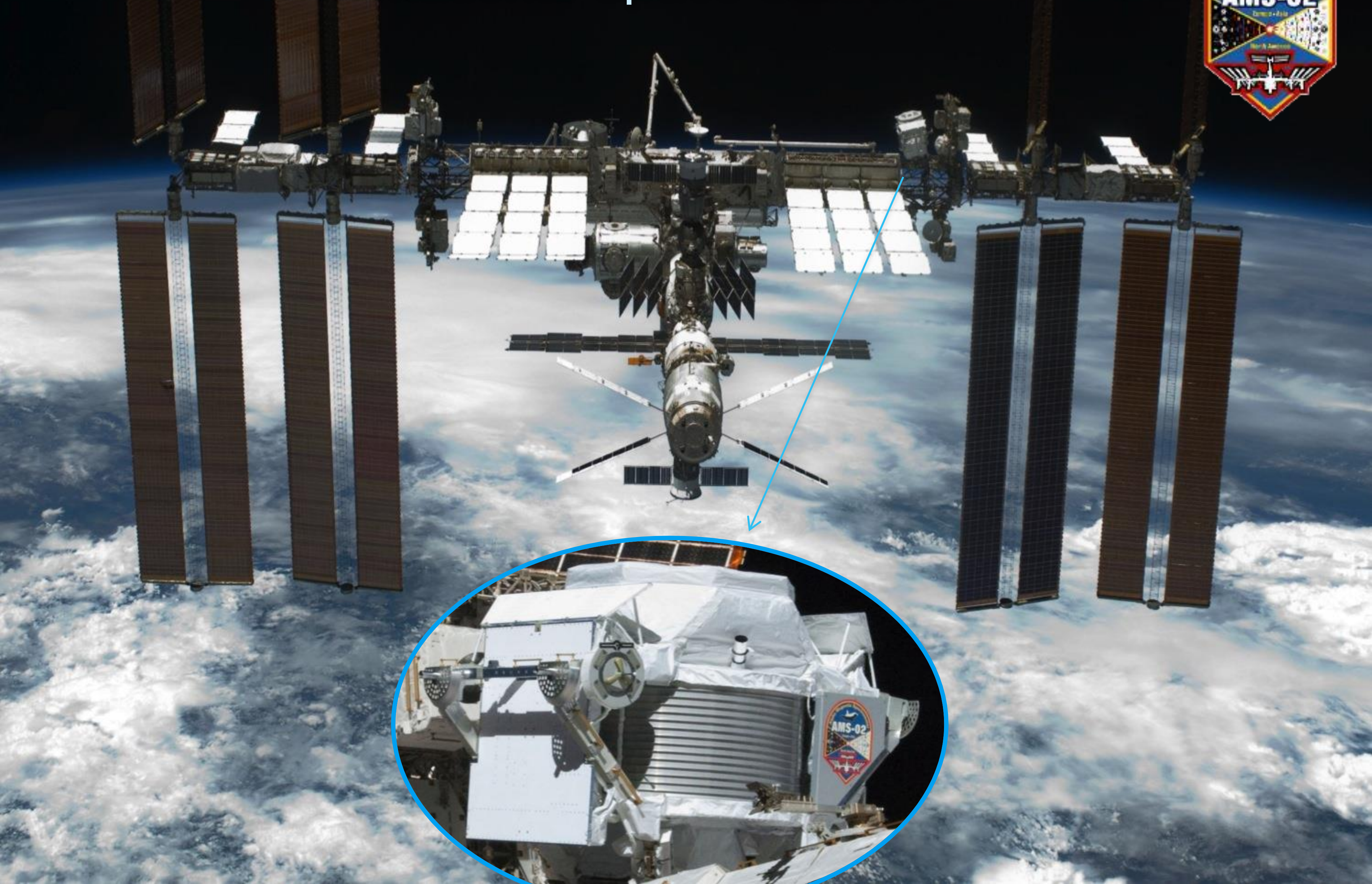
~3700 days of data taking (~80%)

~55 TByte of raw data downlinked

~9·10^9 triggers recorded and analyzed

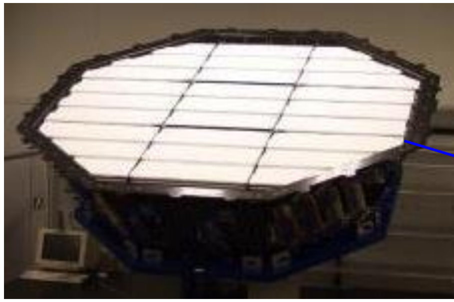
ARINA spectrometer (MEPHI)

The Alpha Magnetic Spectrometer (AMS) on the International Space Station

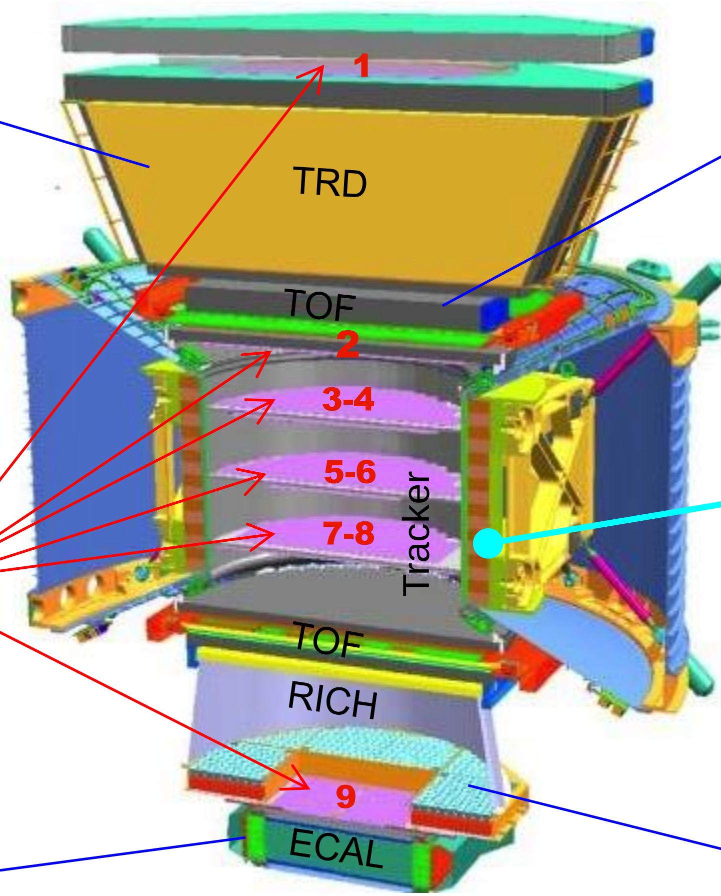


AMS : A TeV precision, multipurpose spectrometer

Transition Radiation Detector
Identify electrons



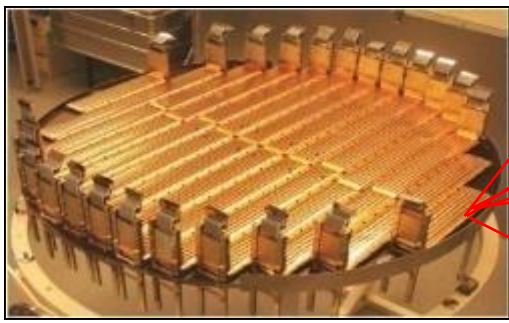
Particles are defined by their charge (Z) and energy (E) or momentum (P)



Time of Flight
Z, E

Magnet
±Z

Silicon Tracker
Z, P

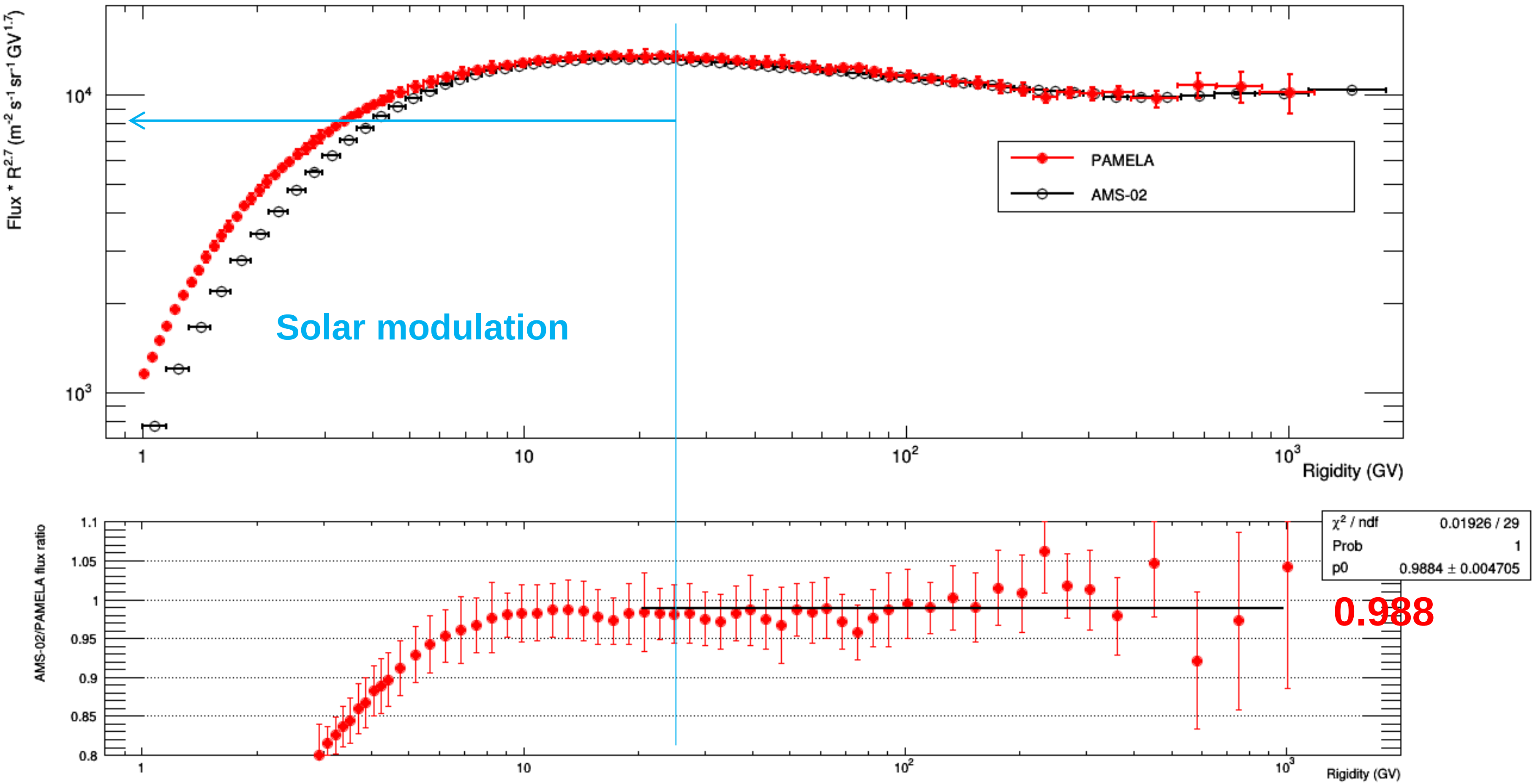


Ring Imaging Cherenkov
Z, E

Electromagnetic Calorimeter
E of electrons

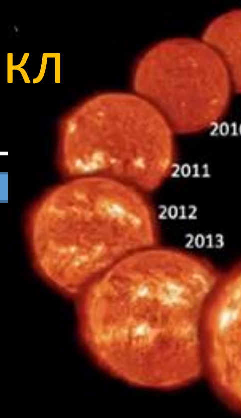
The Charge and Energy (momentum) are measured independently by many detectors

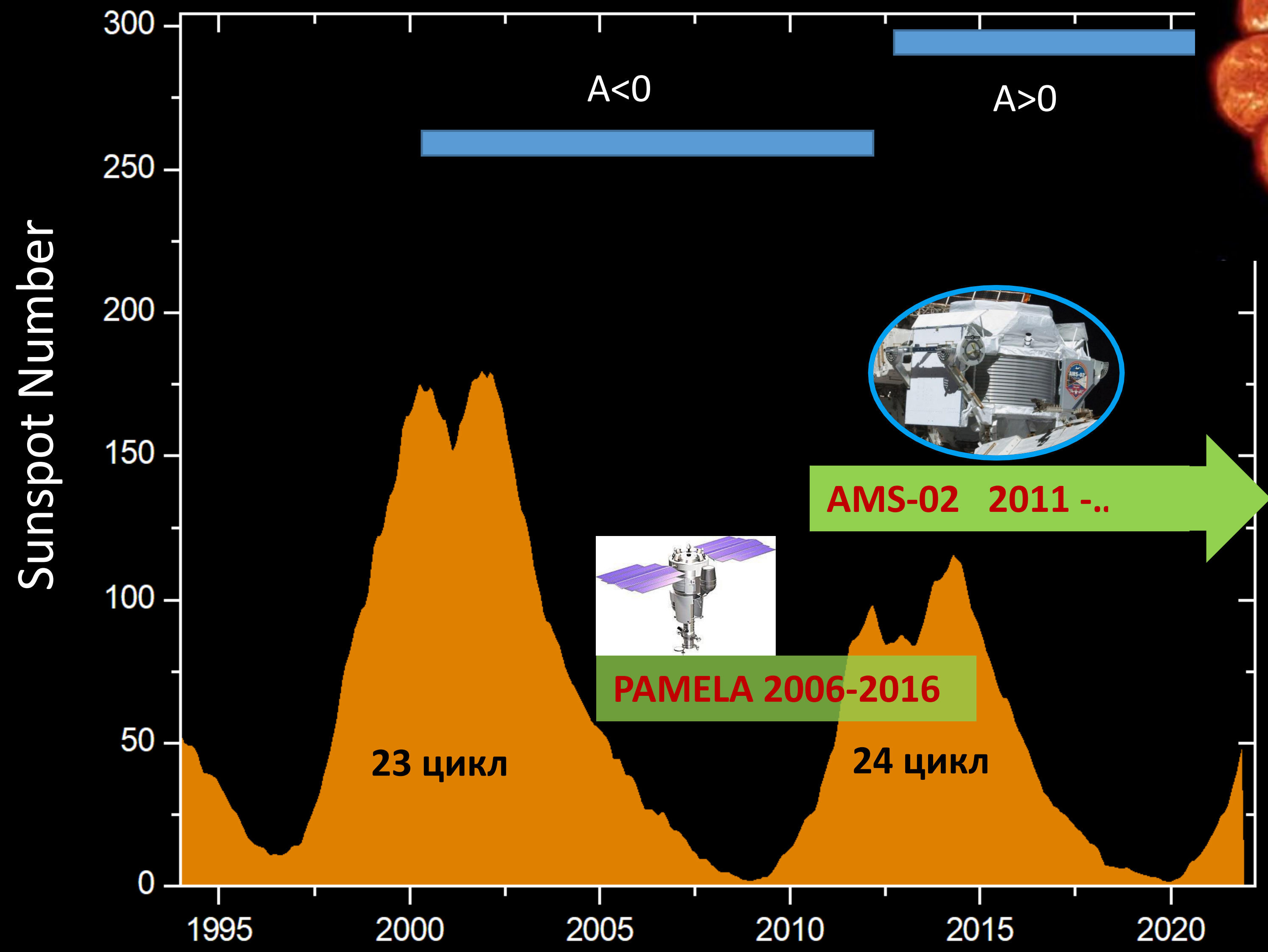
PAMELA vs AMS-02 : спектр протонов



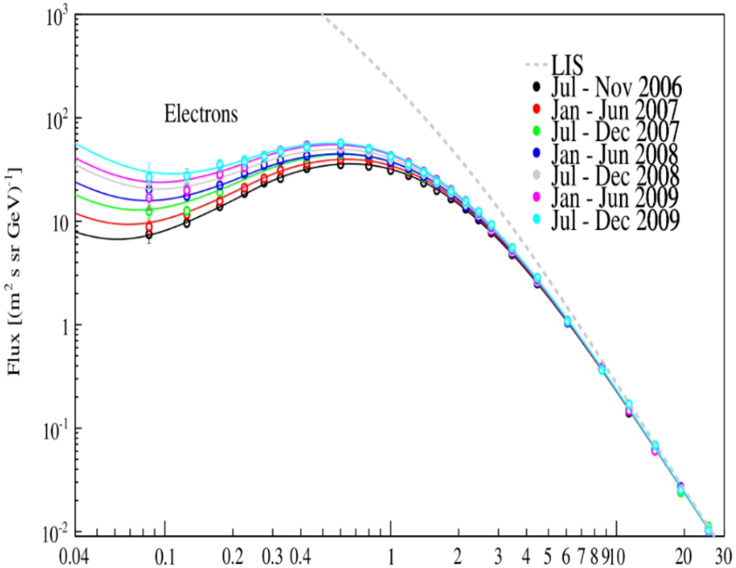
O. Adriani et al, Phys. Rep. (2014)

Долговременные вариации : Солнечный цикл

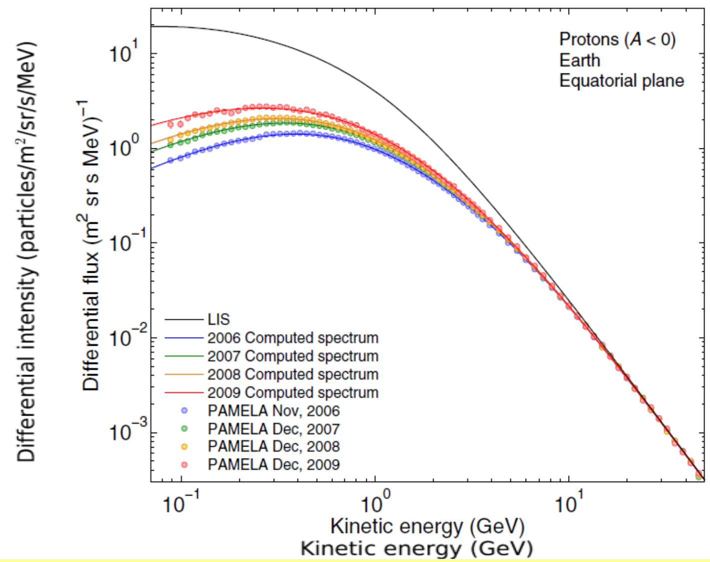




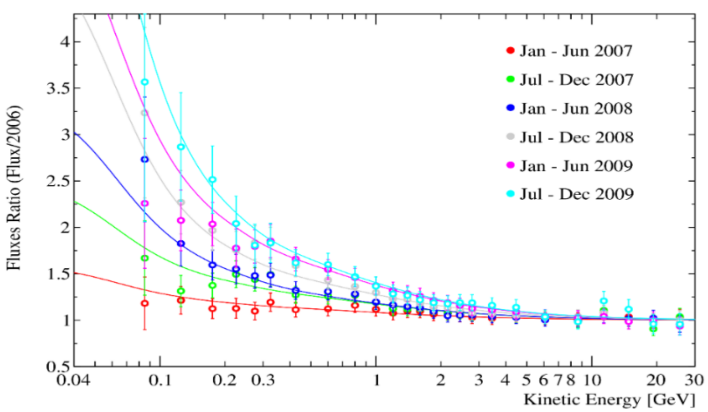
Time dependence of spectra



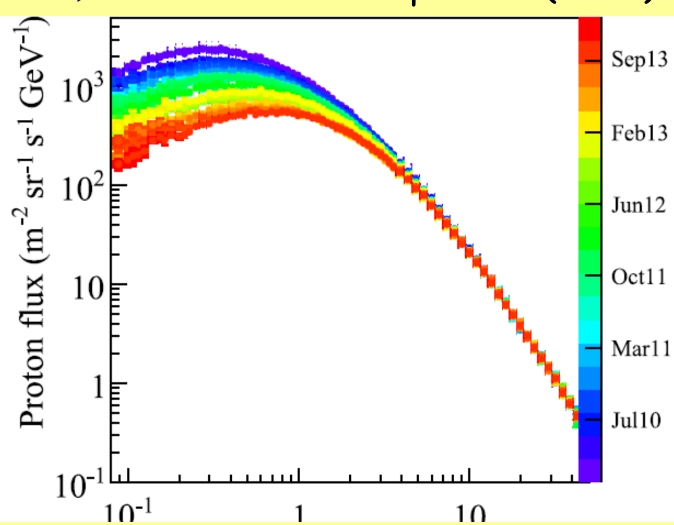
The measured fluxes for the period from July 2006 to December 2009



Evolution of the proton energy spectrum from July 2006 to December 2009, O. Adriani et al. ApJ 765 (2013) 91



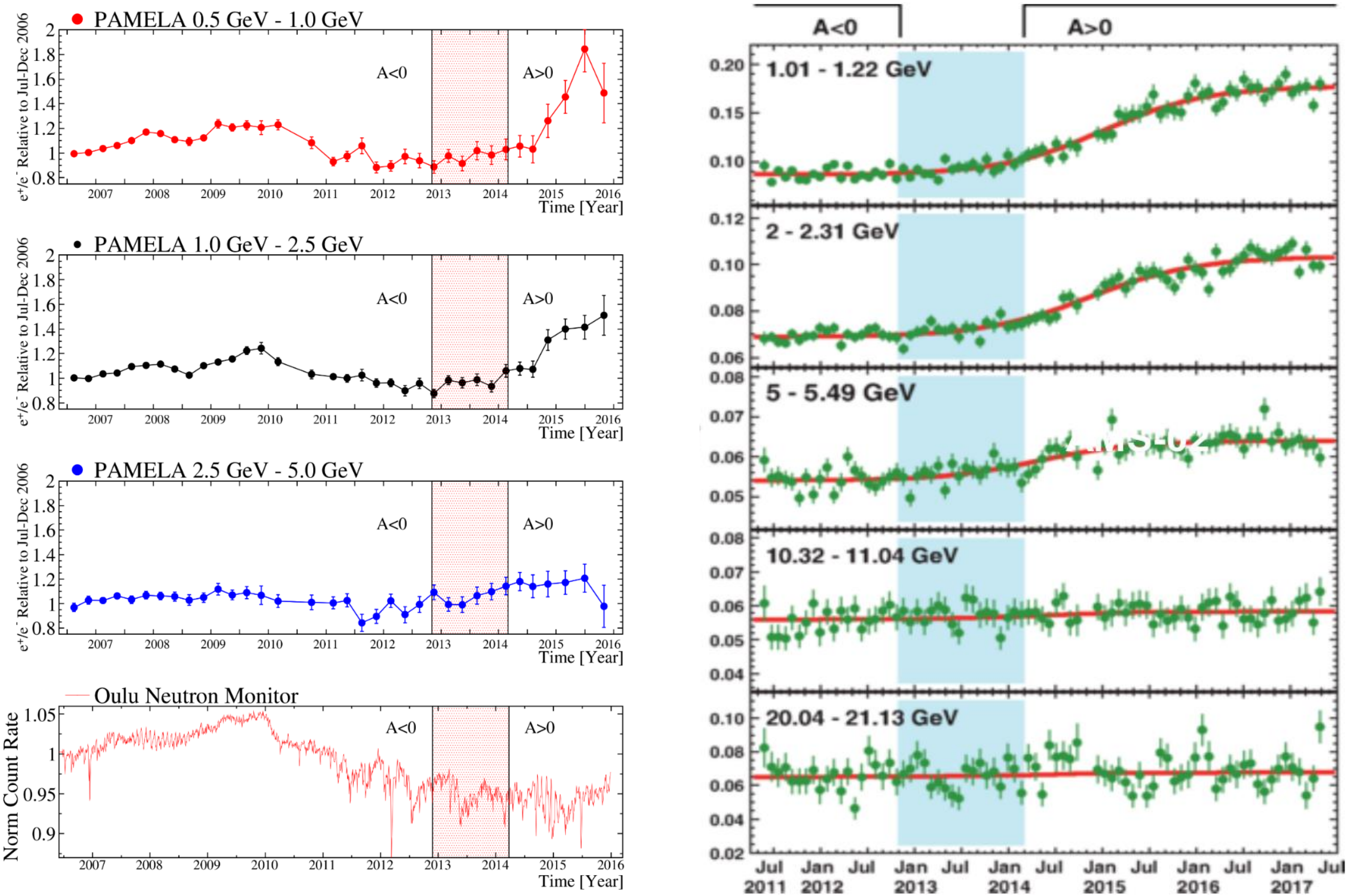
Evolution of the, electron (e^-) energy spectrum from July 2006 to December 2009,
O. Adriani et al. ApJ 810 (2015) 2, 142



Evolution of the proton energy spectrum from Jan 2010 to Sept 2014, ApJ Letters, 854(2018) L2

Зависимость модуляции от знака заряда

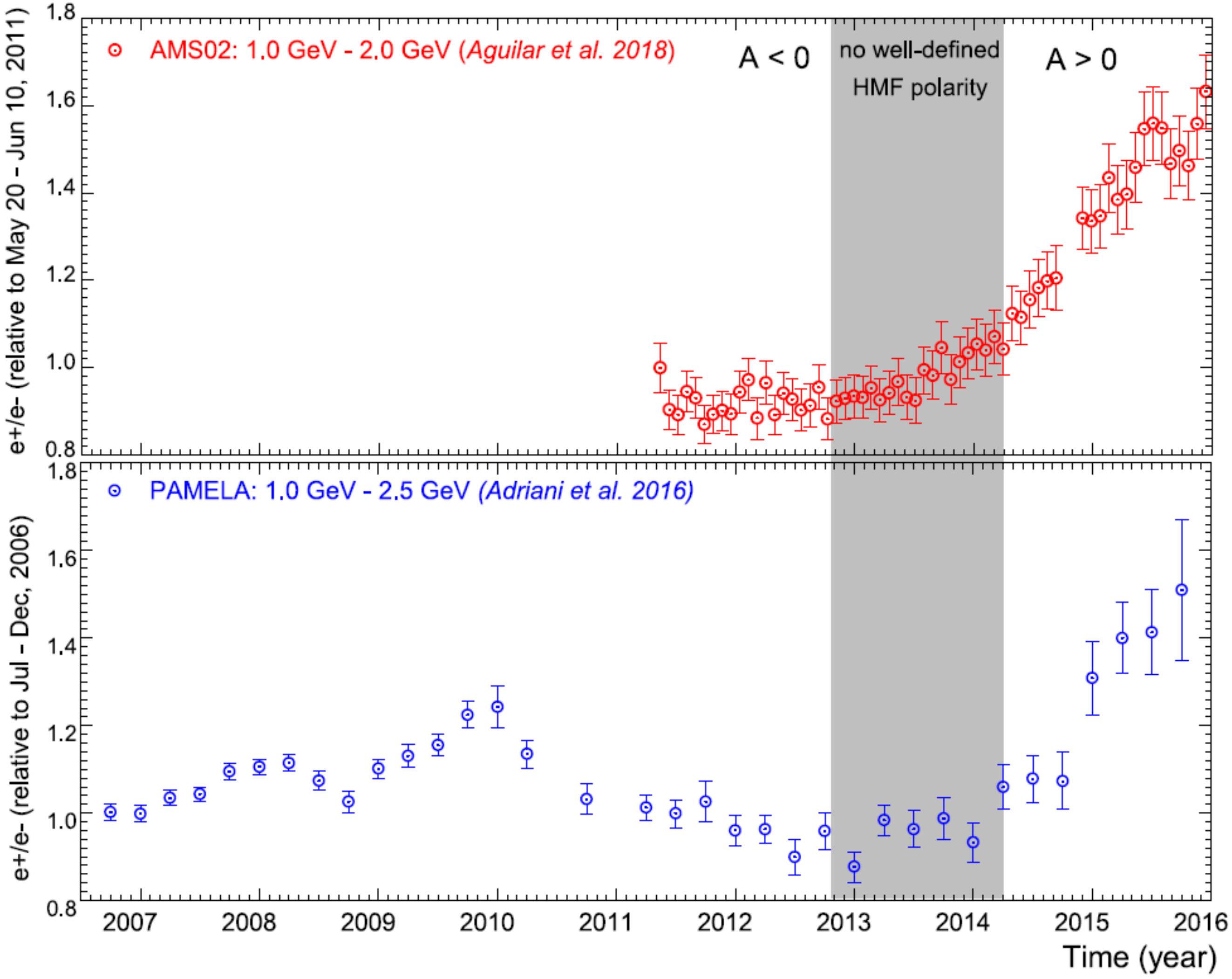
Time dependence of the e+/e- ratio



PAMELA, PRL 116 (2016)

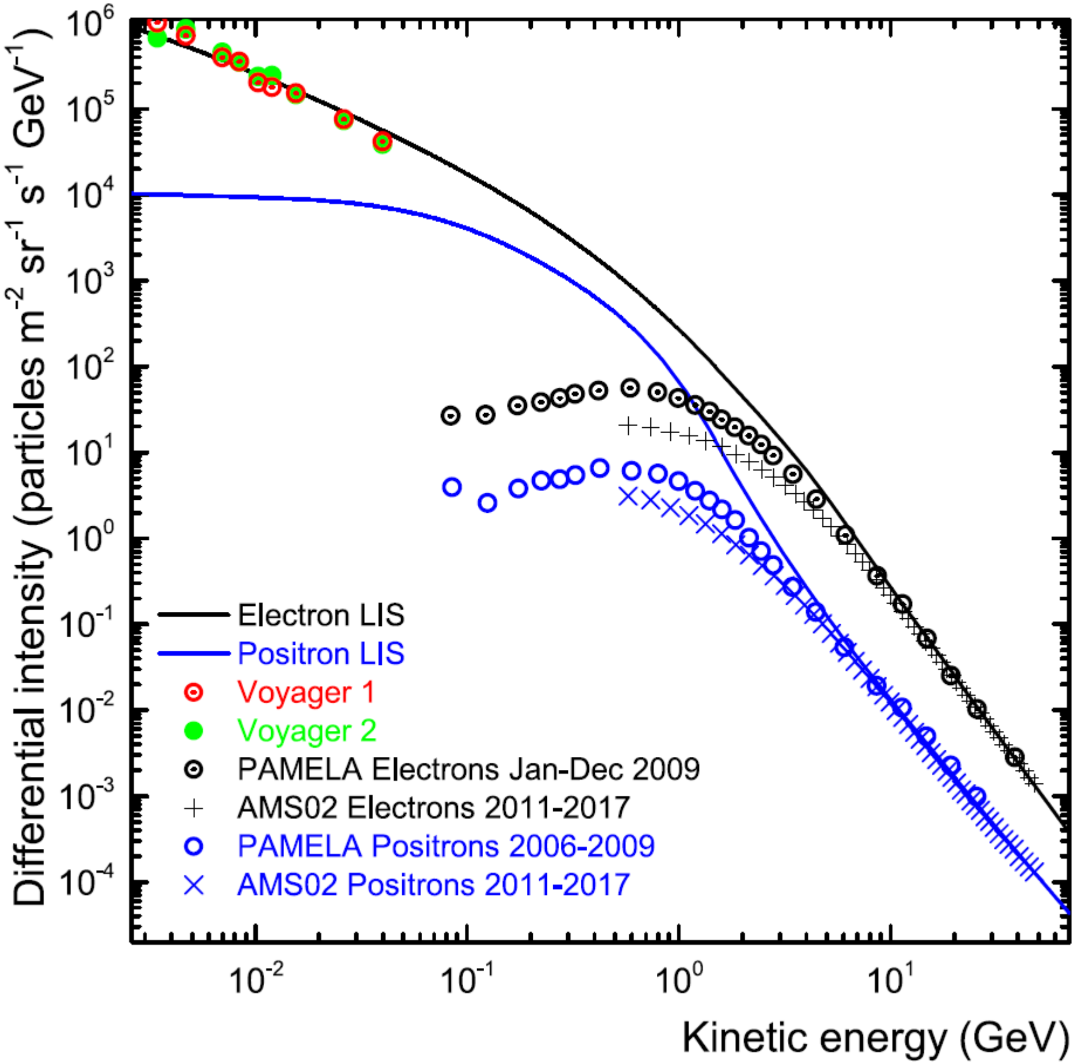
AMS-02, PRL 122 (2019) 101101

Относительные изменение отношения e^+/e^- со временем по измерениям AMS02 и PAMELA



O.Aslam+ ApJ, 909:215, 2021

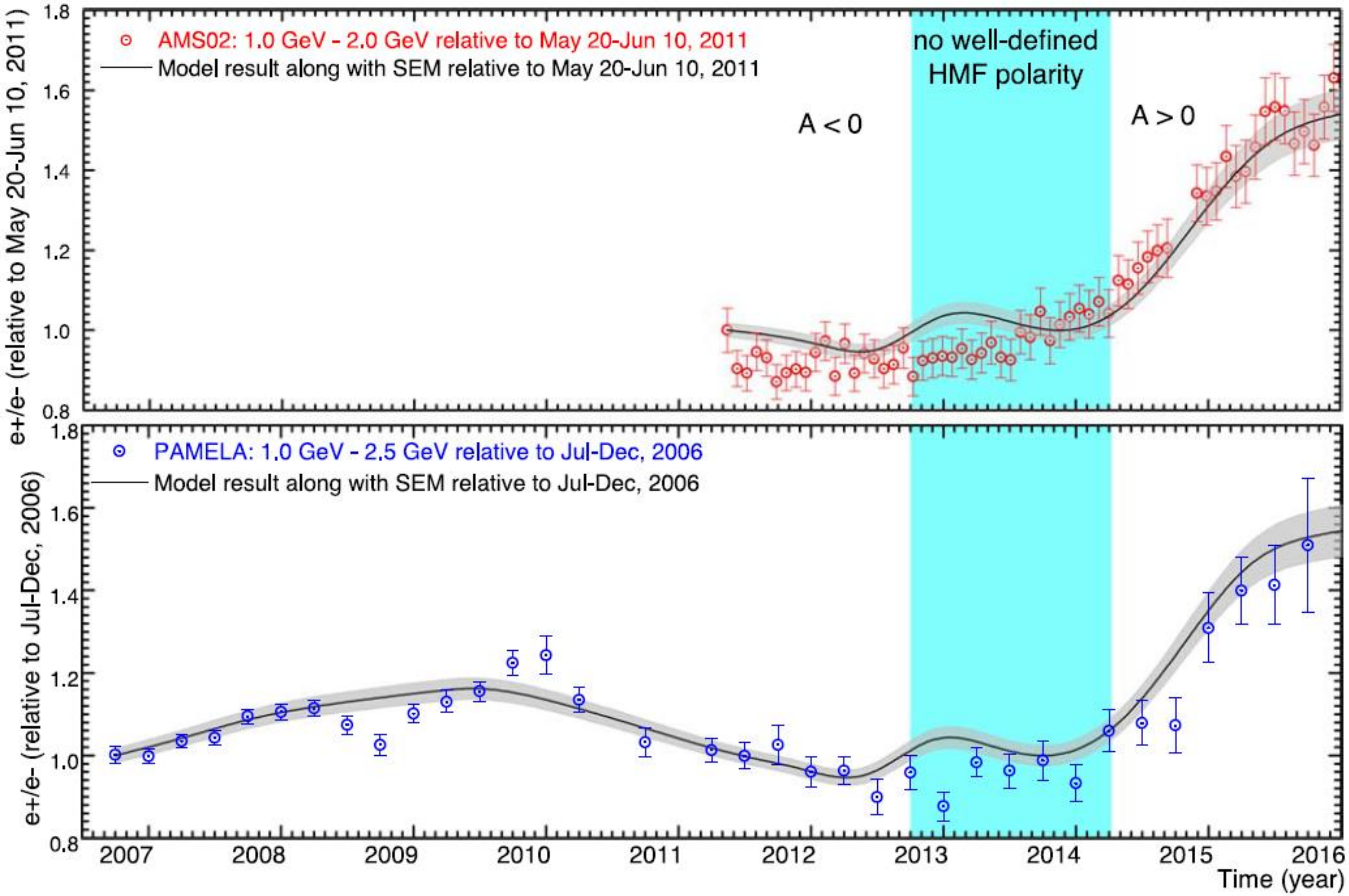
Локальный спектр **e**⁻ и e⁺



The black solid line depicts the LISs for GCR electrons as computed with GALPROP and “tuned” to Voyager 1 (Cummings et al. 2016) and Voyager 2 observations (Stone et al. 2019) at low KEs and PAMELA (Adriani et al. 2015) and AMS02 observations (Aguilar et al. 2018b) at high KEs

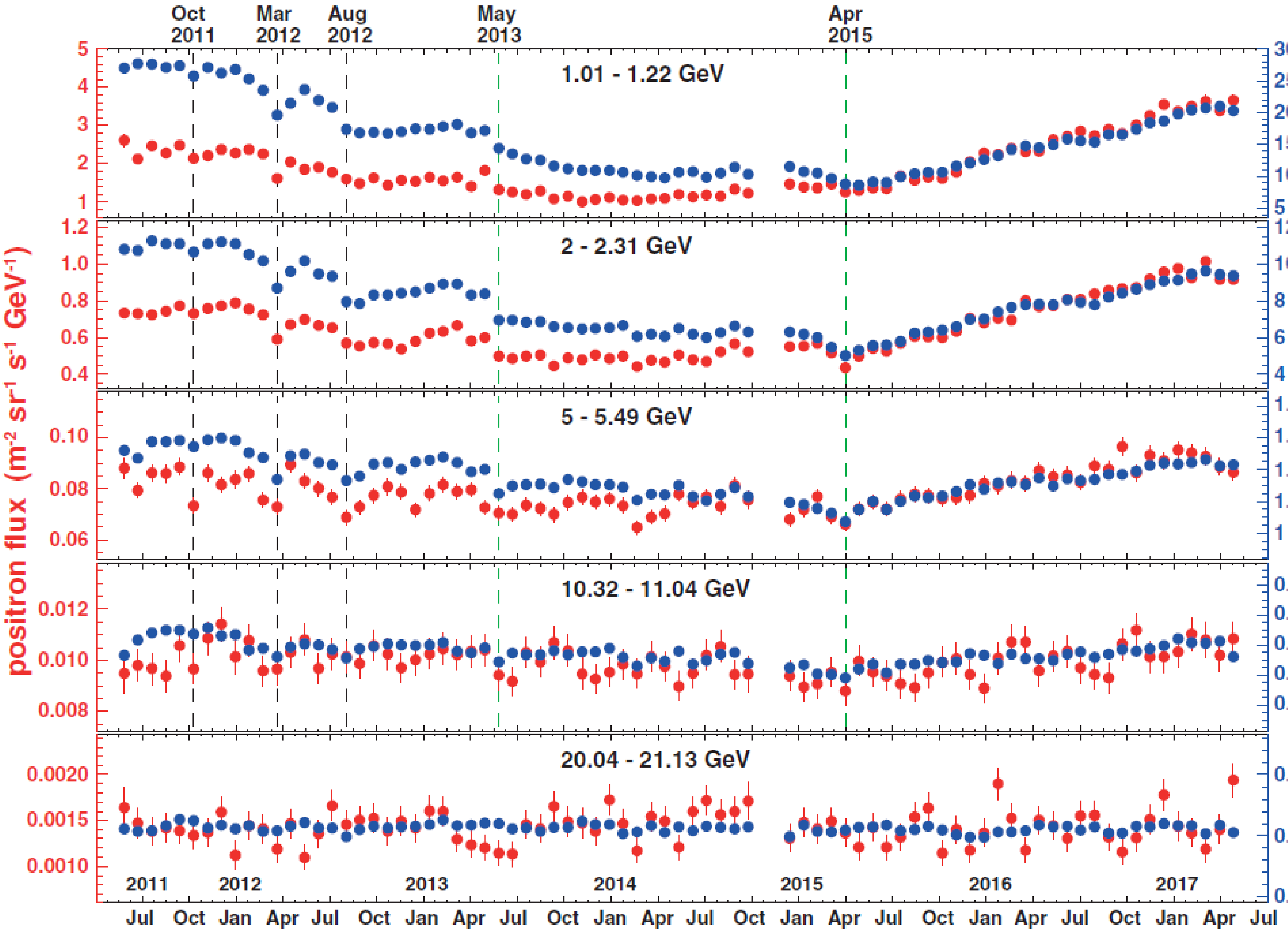
ApJ, 909:215, 2021

Моделирование временных зависимостей



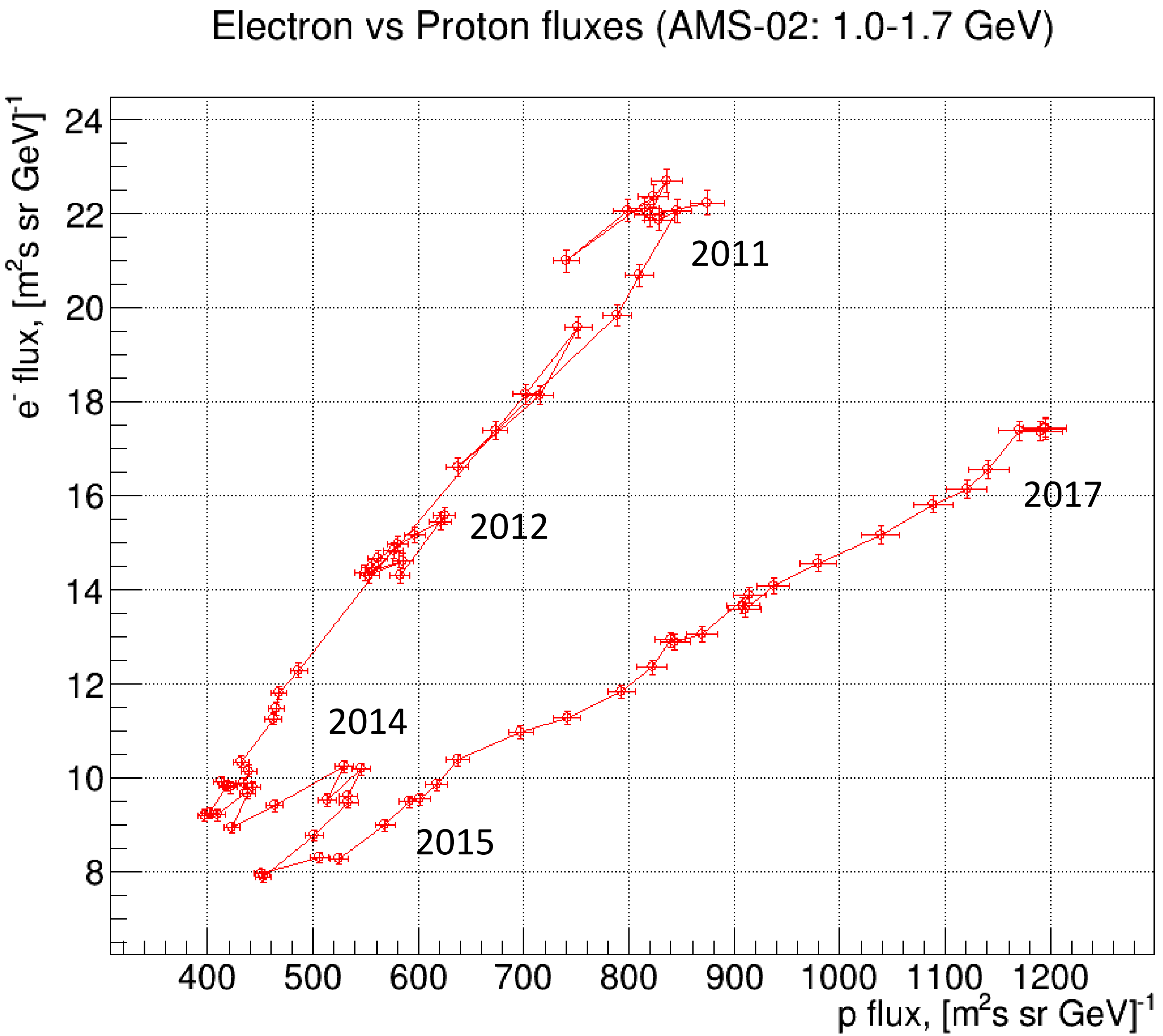
- The tilt angle α of the HCS and the magnitude B of the observed HMF at Earth are considered to be good proxies for solar activity in the numerical modeling of GCR modulation
- However, in order to reproduce the observed PAMELA and AMS02 spectra after 2009, we had to change the diffusion coefficients, as well as the drift coefficient,

ApJ, 909:215, 2021

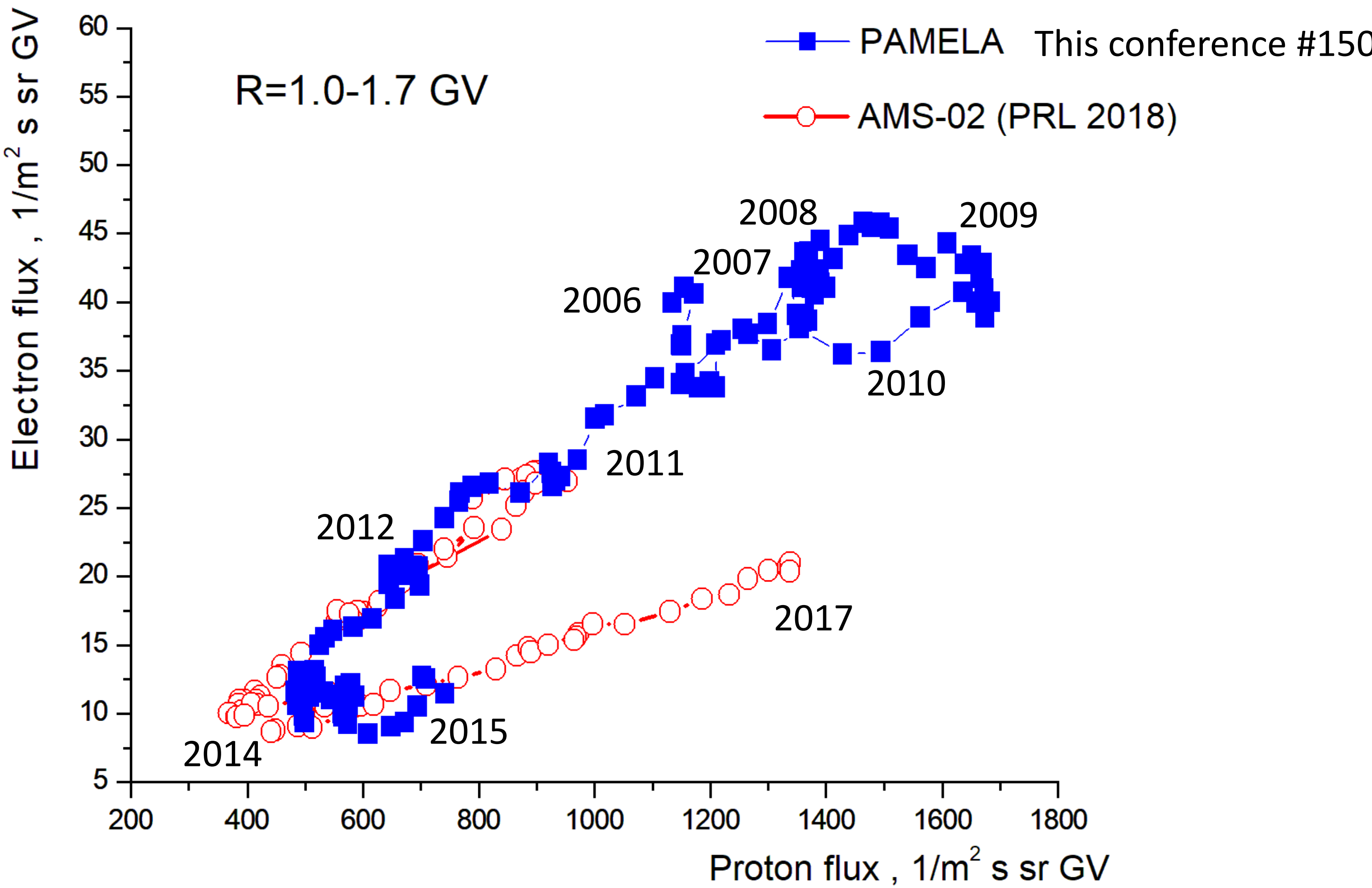


PHYSICAL REVIEW LETTERS 121, 051102 (2018)

Зависимость потоков электронов от потоков протонов в 24 цикле СА



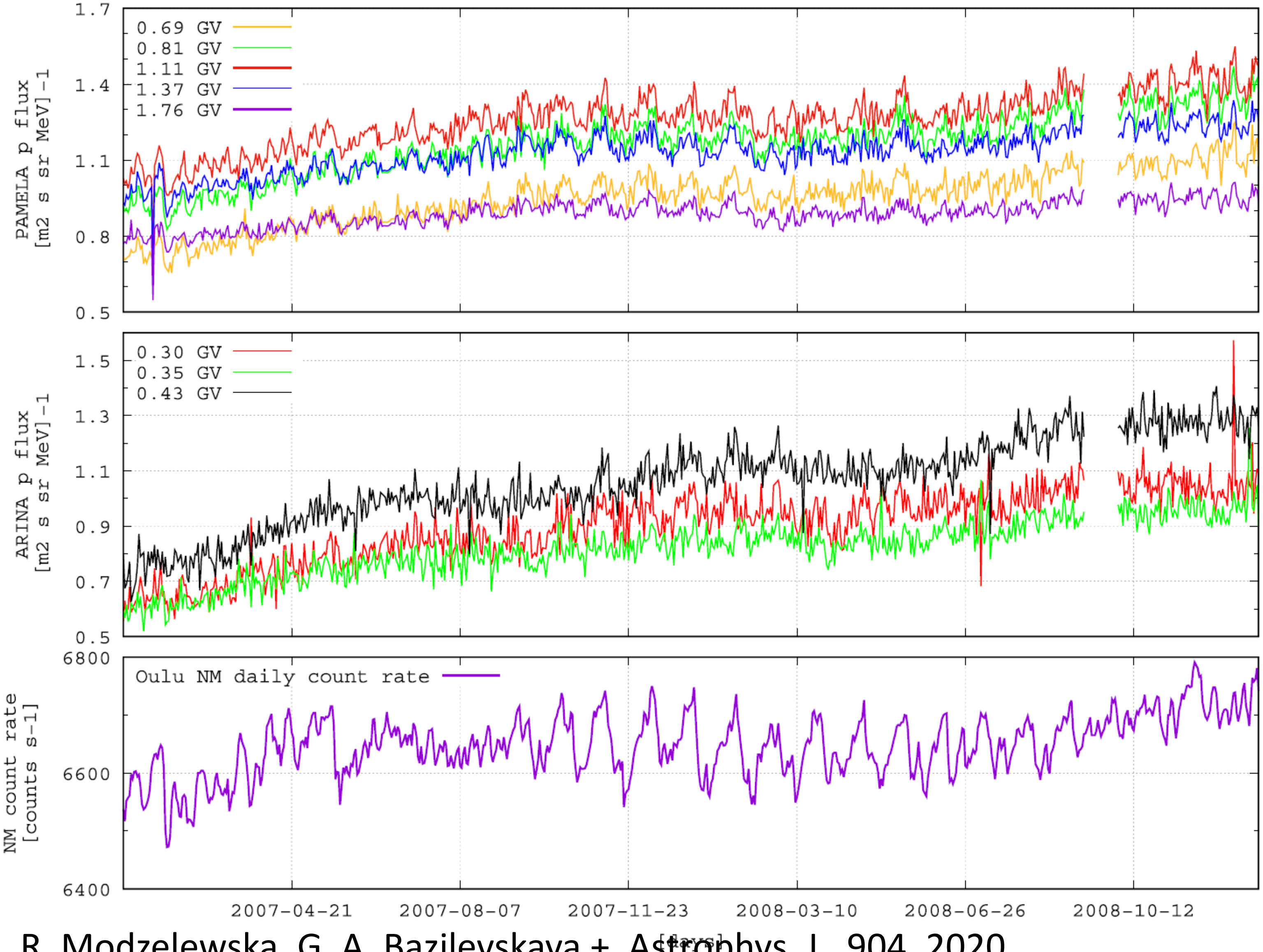
Зависимость потоков электронов от потоков протонов в 23-24 циклах



29 июня, MOD #150 Мухин и др. Зависимость модуляции космических лучей от знака заряда по данным эксперимента PAMELA

Коротко-периодические вариации

Суточные потоки протонов в 2007-2008



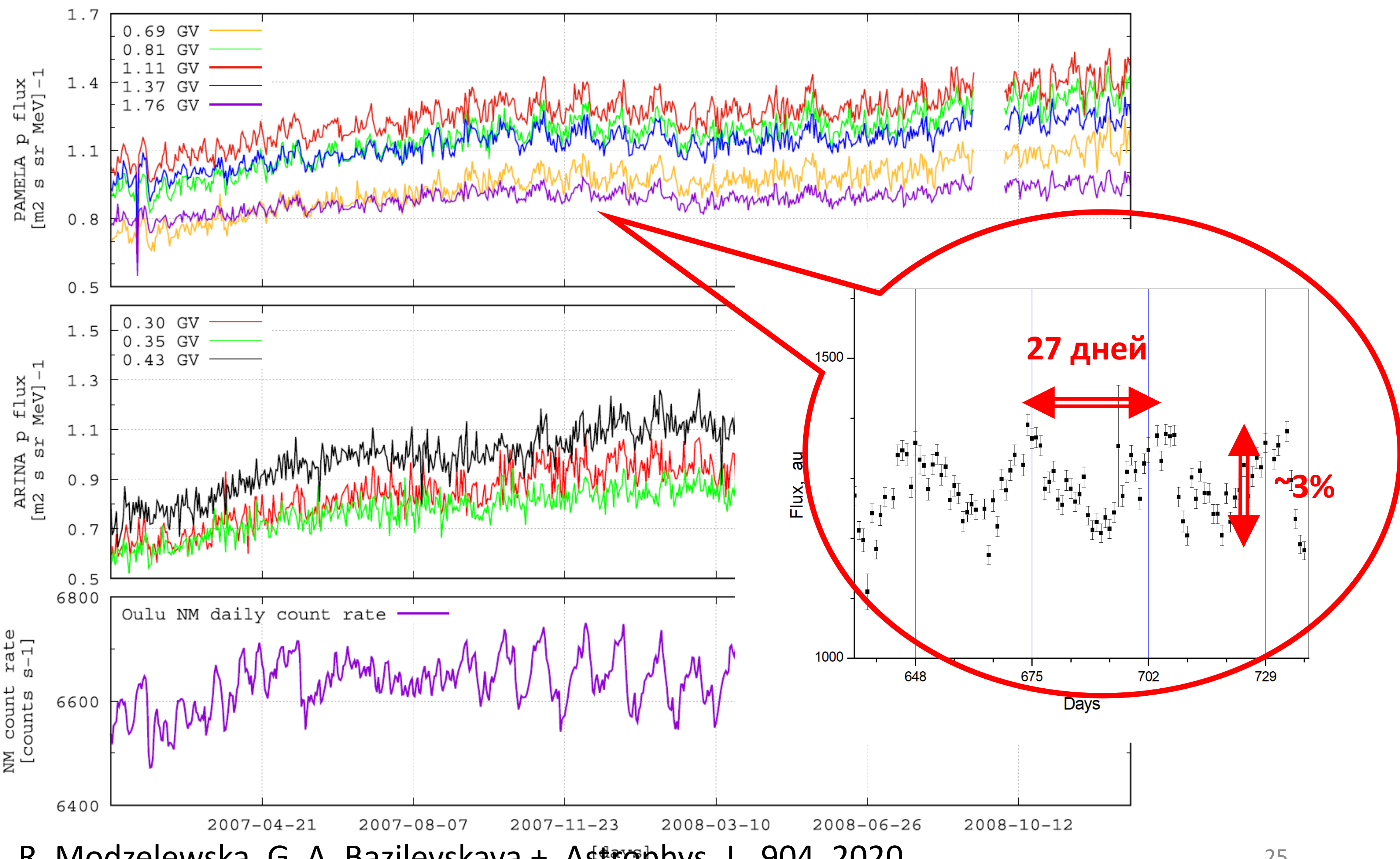
PAMELA

ARINA

Oulu NM (cutoff rigidity 0.8 GV)

R. Modzelewska, G. A. Bazilevskaya + Astrophys. J., 904, 2020

Суточные потоки протонов в 2007-2008

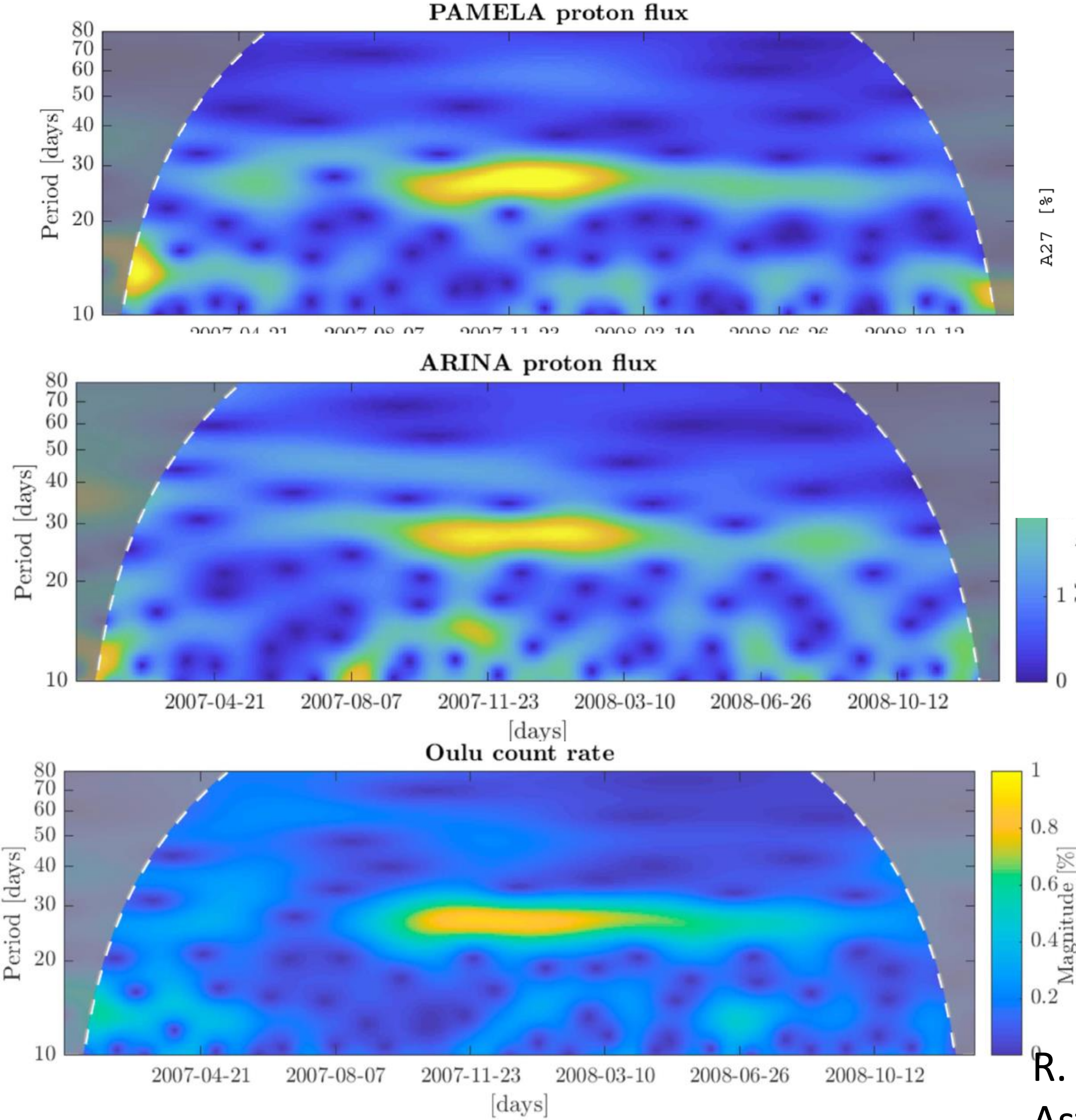


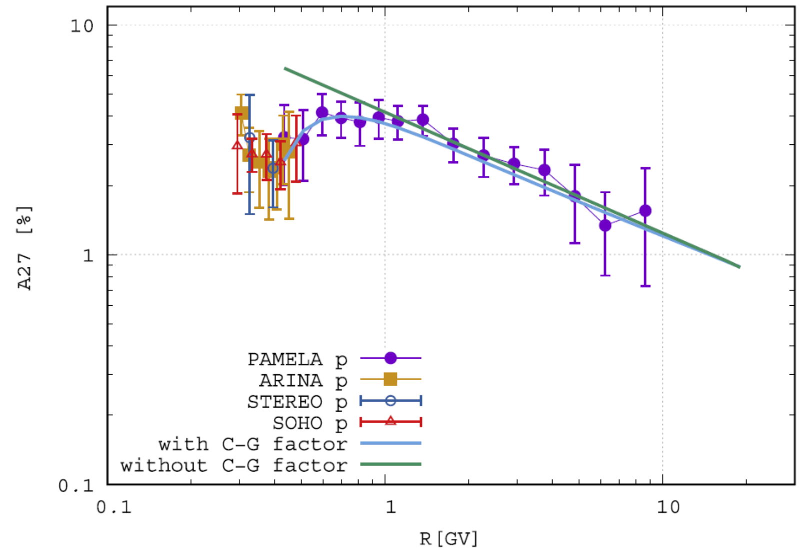
R. Modzelewska, G. A. Bazilevskaya + Astrophys. J., 904, 2020

Рекурентные вариации космических лучей:
связаны с вращением Солнца
: 27 days

2016-03-22 2016-03-24 2016-03-26

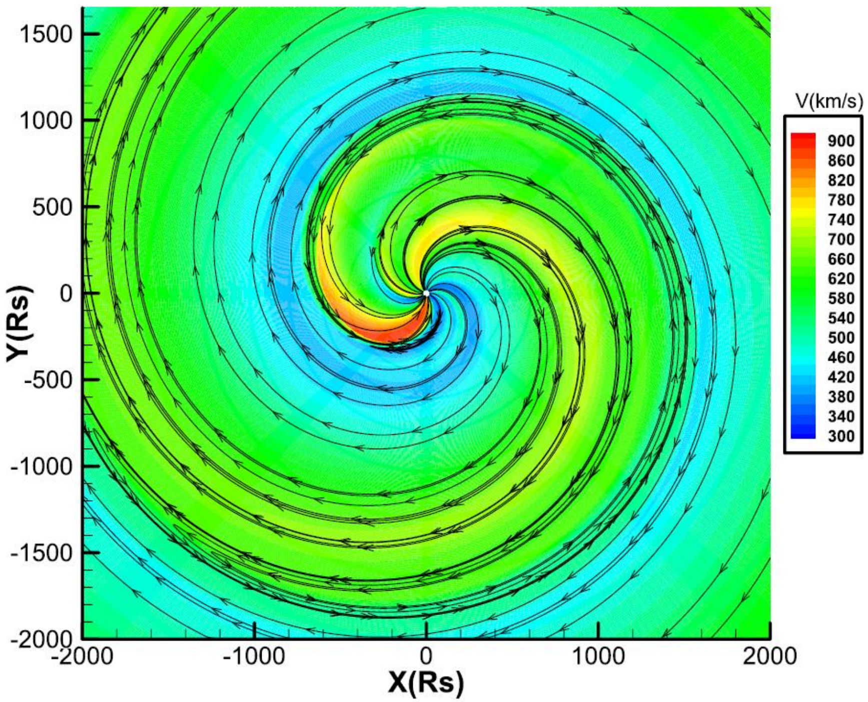
Вращение корональной дыры – источника высокоскоростного солнечного ветра



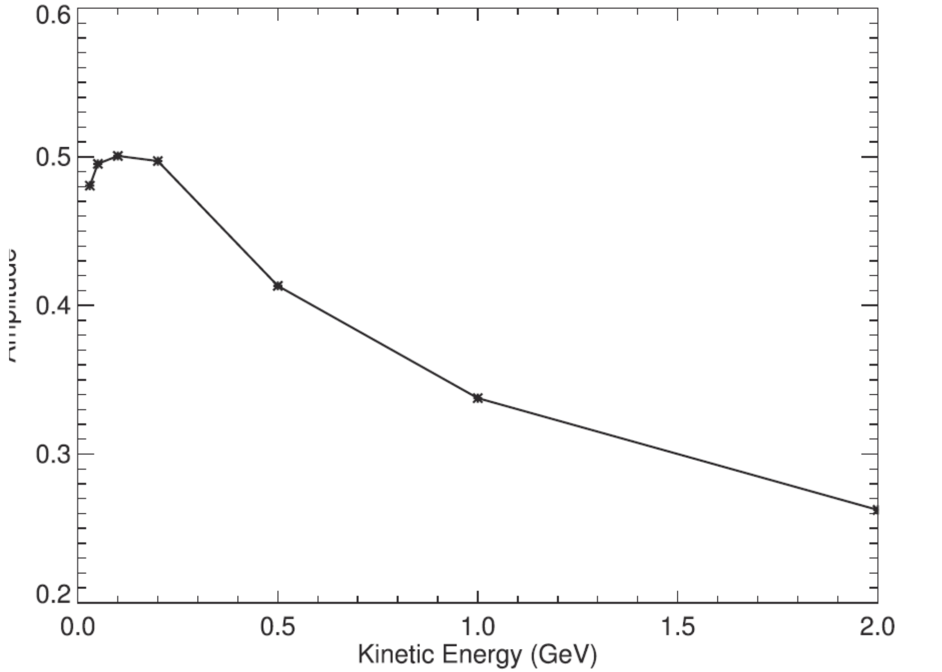


The A27 for PAMELA, ARINA, SOHO, and STEREO proton fluxes as a function of rigidity R in 2007–2008.

R. Modzelewska, G. A. Bazilevskaya + Astrophys. J., 904, 2020



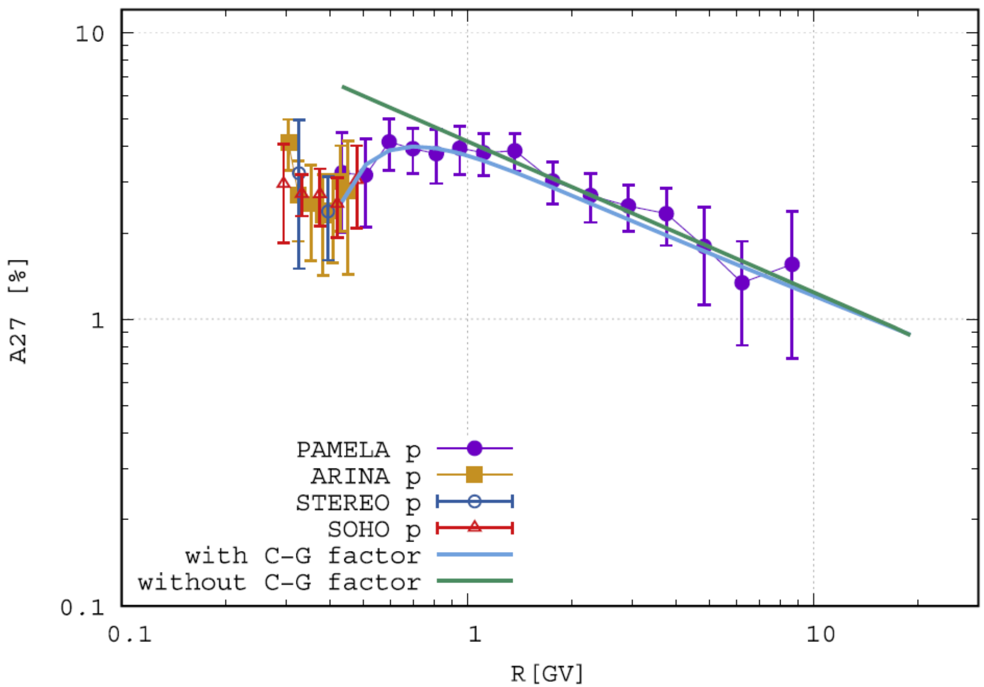
The MHD-simulated solar wind plasma speed in the heliospheric equatorial plane (X–Y plane) following the color-coded values exhibited on the right side.
The IMF line topology is also shown. The axis scale is in solar radius



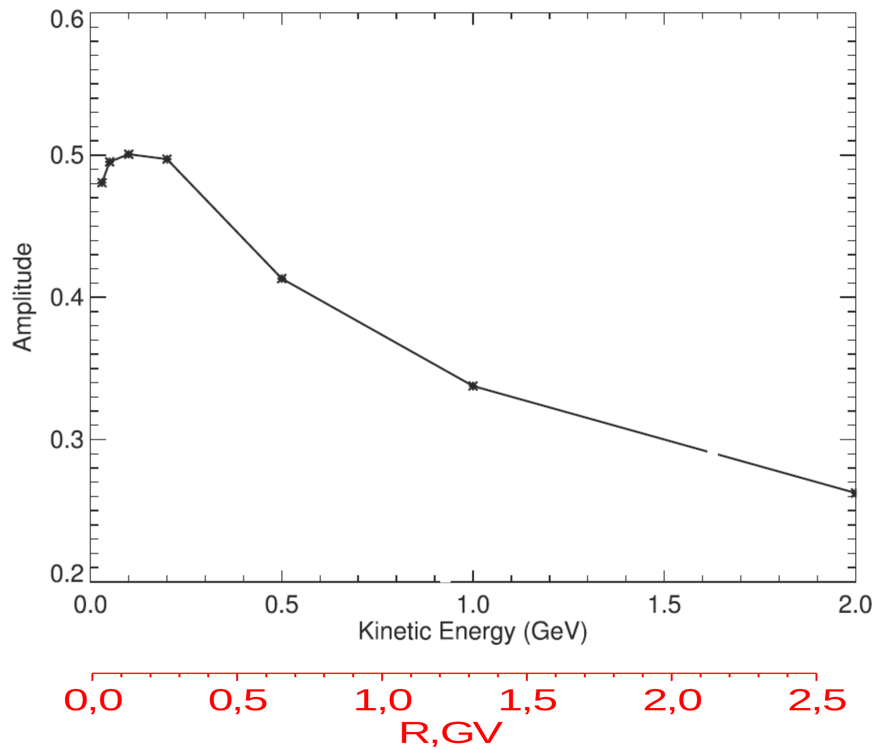
Amplitude of the CIR-introduced GCR proton intensity variation as a function of their kinetic energy at a radial distance of 3.01 au

Xi Luo + , The Astrophysical Journal, 899:90, 2020

Зависимость амплитуды A27 от жесткости R (энергии)



The A27 for PAMELA, ARINA, SOHO, and STEREO proton fluxes as a function of rigidity R in 2007–2008..

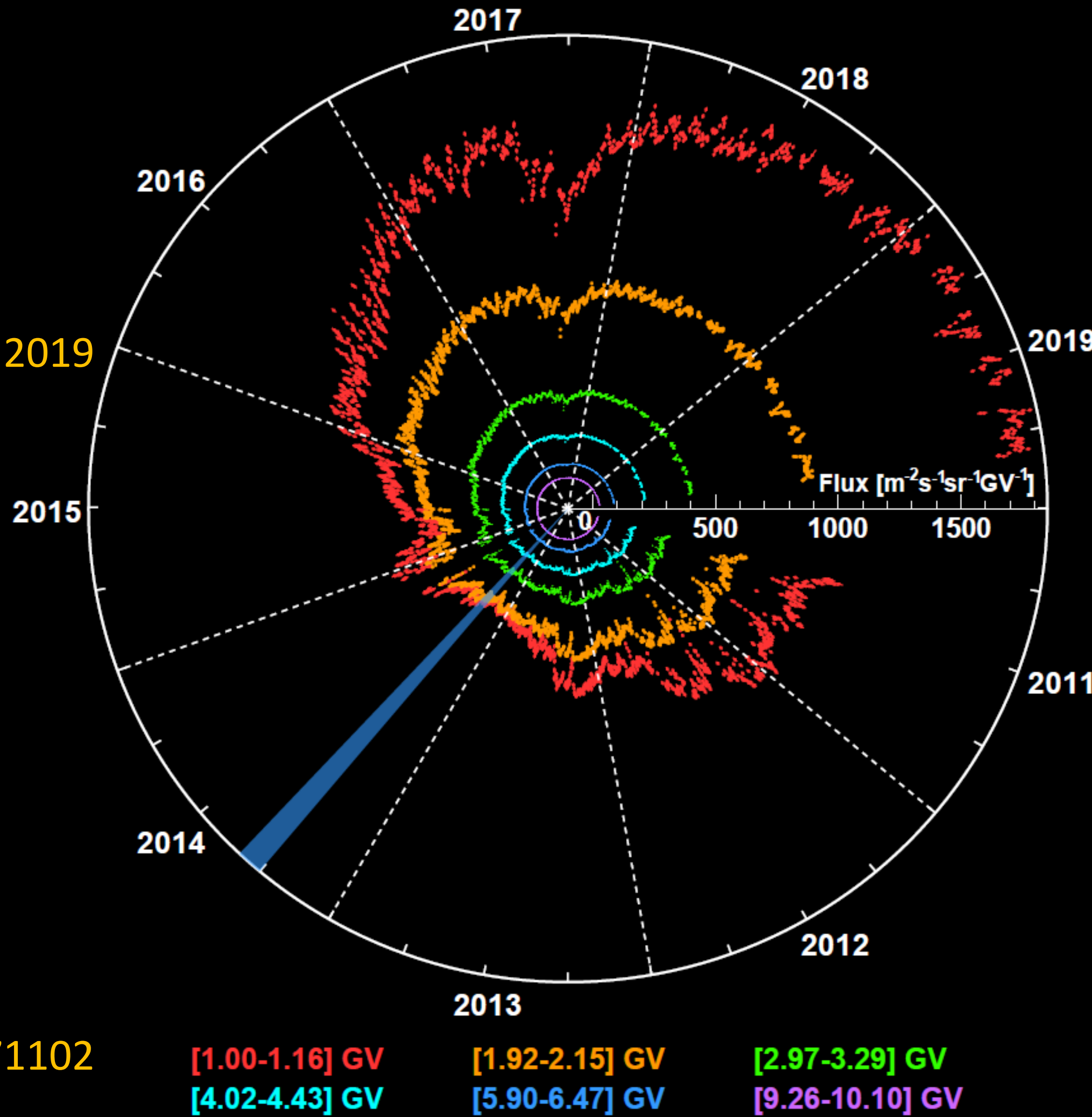


Amplitude of the CIR-introduced GCR proton intensity variation as a function of their kinetic energy at a radial distance of 3.01 au

Xi Luo + , The Astrophysical Journal, 899:90, 2020

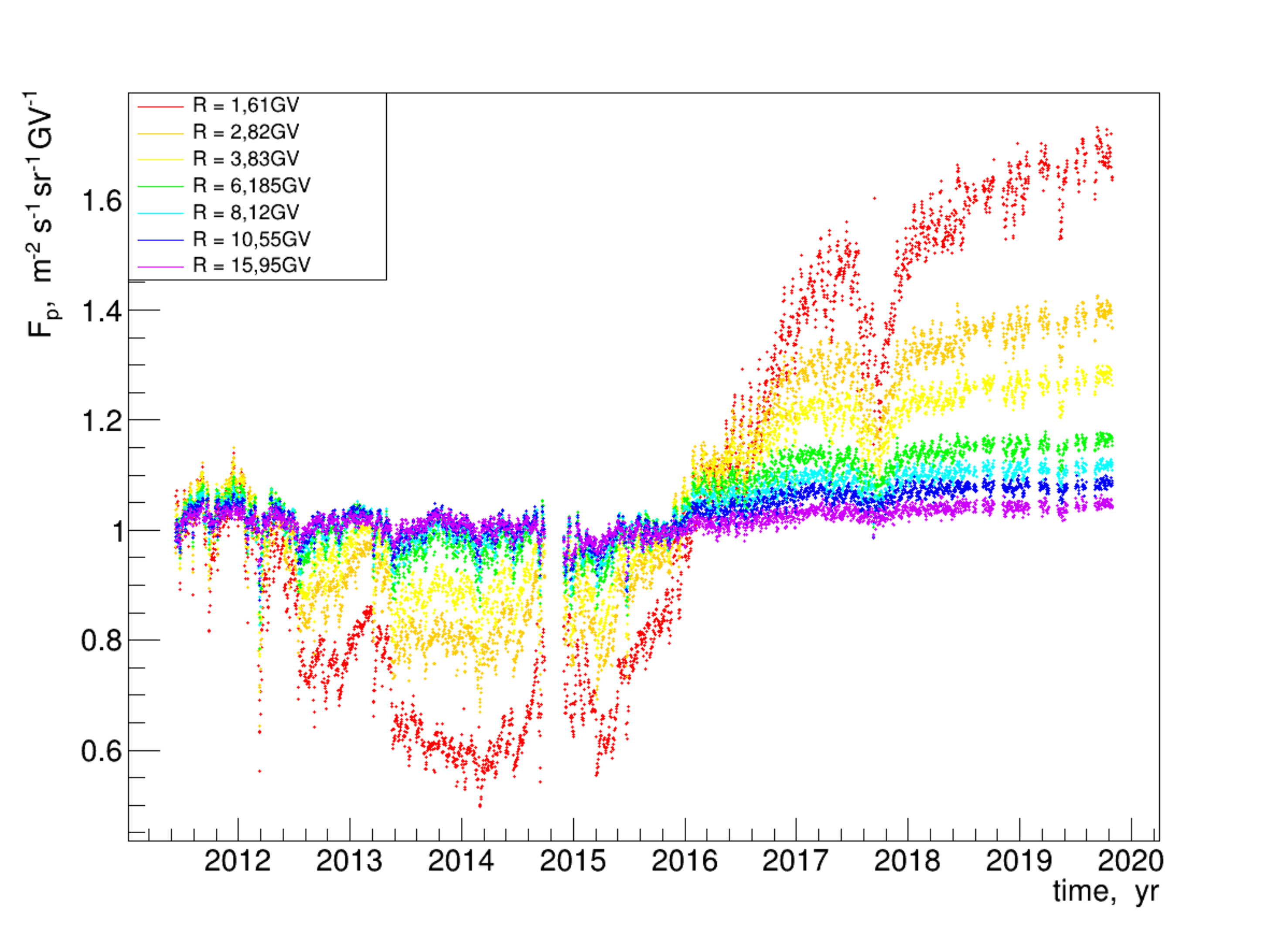
Суточные потоки протонов AMS -02

.5×10^9 протонов
арегистрировано
20 мая 2011 по 29 октября 2019



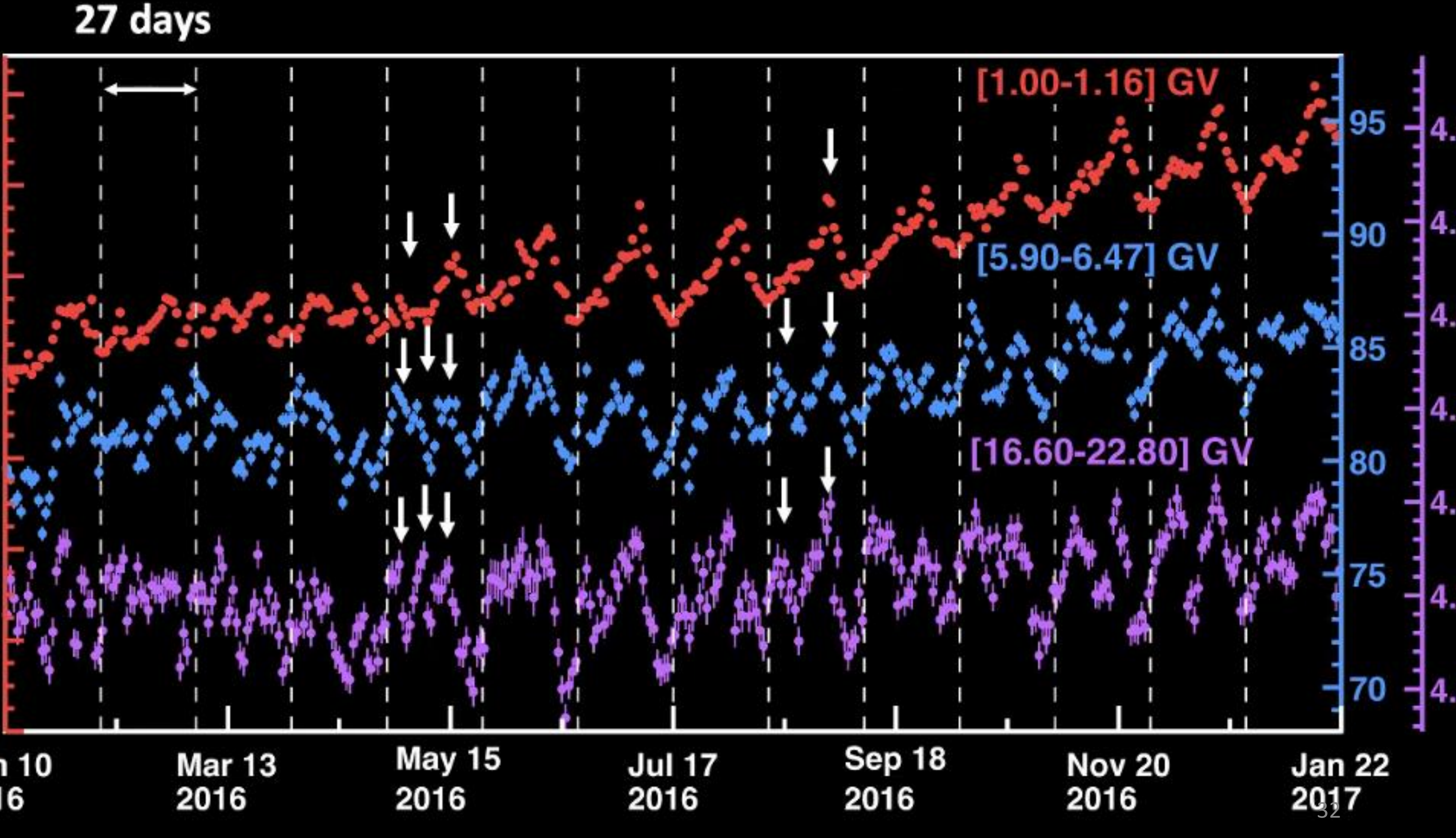
AMS Collaboration
Phys. Rev. Lett., 2021,127, 271102

Относительные вариации потоков протонов в AMS-02 (2011-2019)



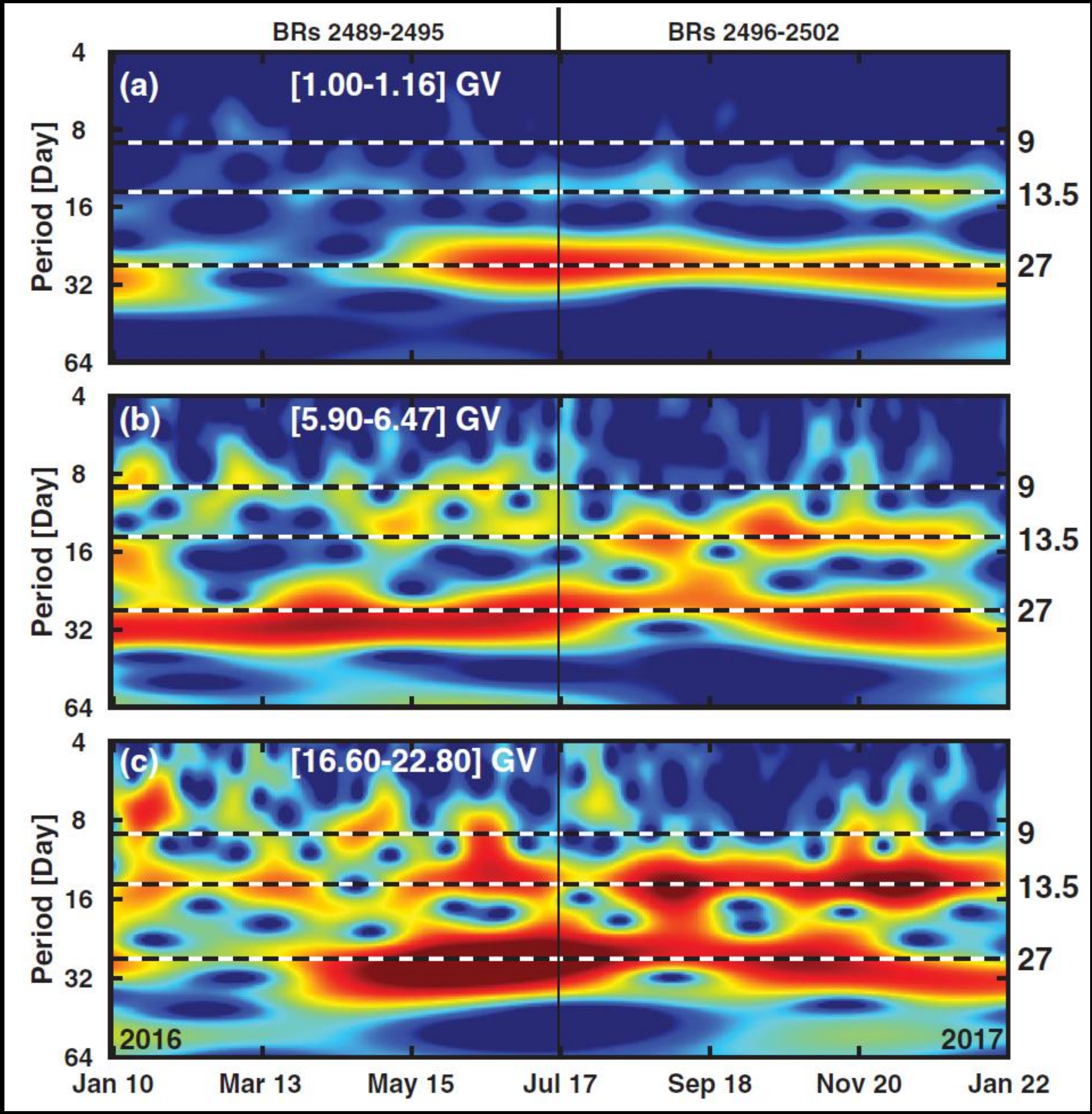
По данным Phys. Rev. Lett., 127,2021

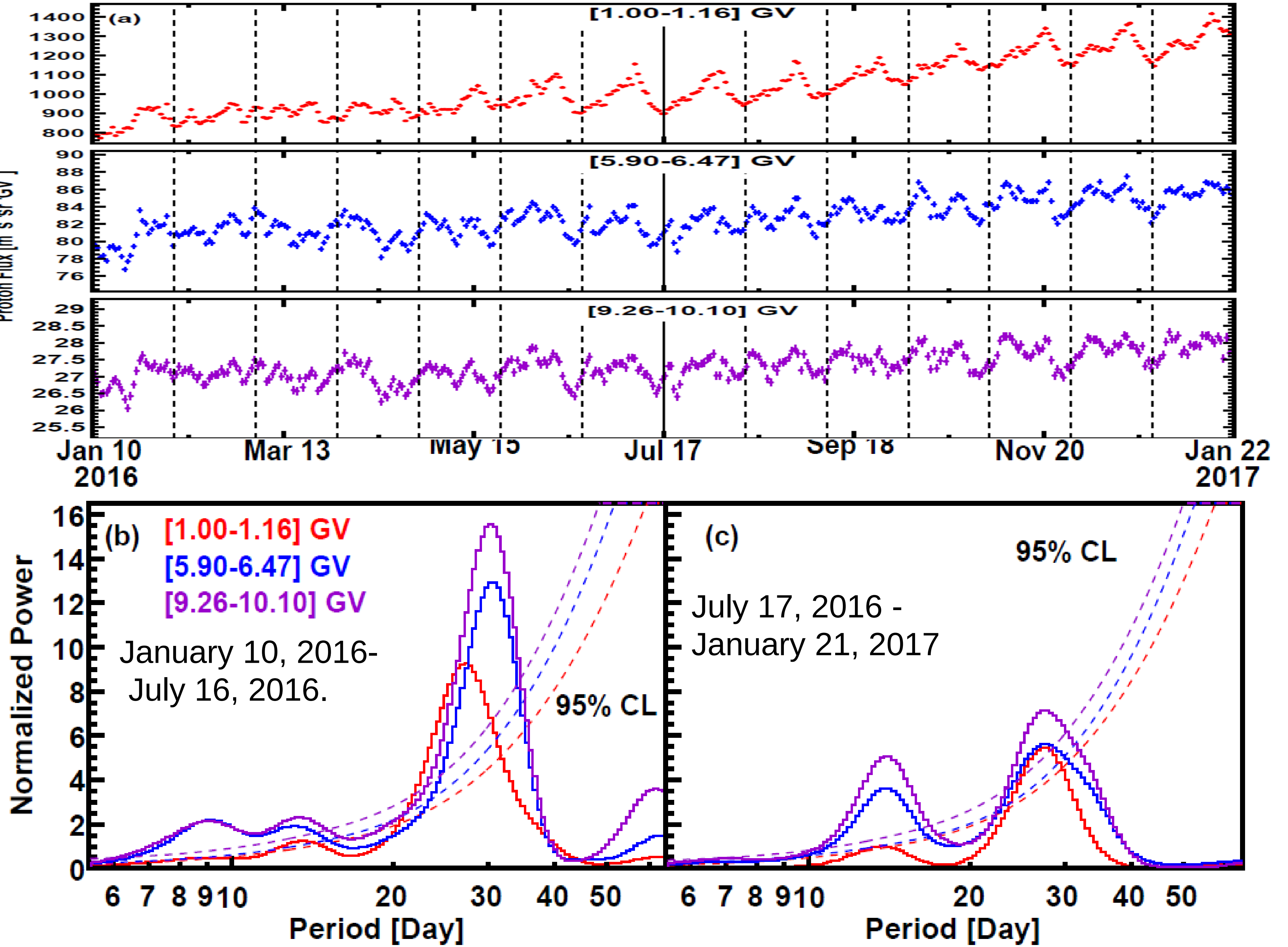
Рекуррентные вариации потоков протонов с периодами 9, 13 и 27 дней в 2016



Вейвлет спектр потока протонов в 2016

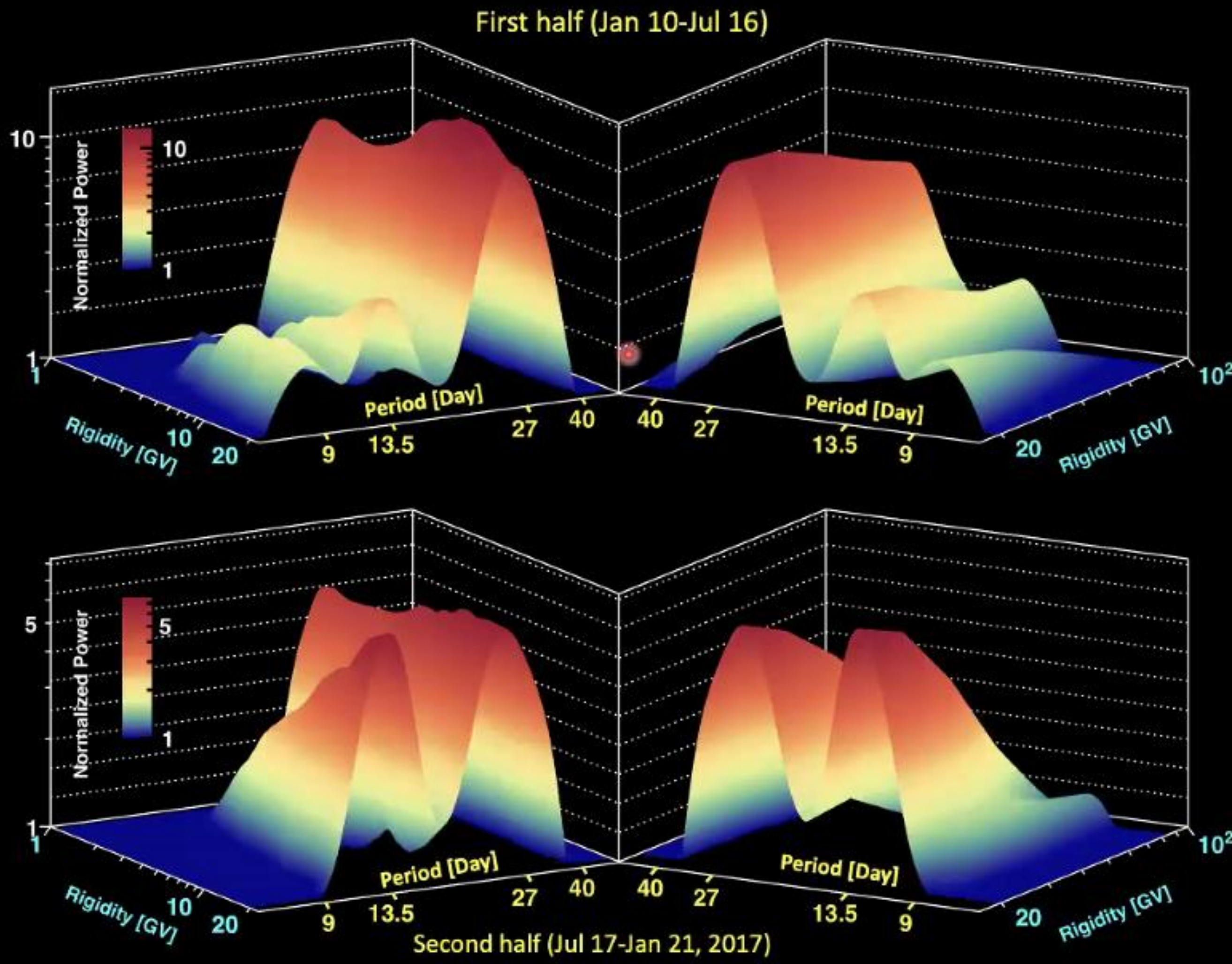
- Нормированная спектральная плотность p/σ^2
- Периоды 27, 13.5 и 9 дней
- Вариации различны в трех диапазонах жесткости R





(a)
[1.00-1.16] GV
1400
1300
1200
1100
1000
900
800
[5.90-6.47] GV
90
88
86
84
82
80
78
76
[9.26-10.10] GV
29
28.5
28
27.5
27
26.5
26
25.5
Jan 10 2016
Mar 13
May 15
Jul 17
Sep 18
Nov 20
Jan 22 2017
(b)
[1.00-1.16] GV
[5.90-6.47] GV
[9.26-10.10] GV
January 10, 2016- July 16, 2016.
95% CL
Normalized Power
16
14
12
10
8
6
4
2
0
6 7 8 9 10 20 30 40 50
Period [Day]
(c)
95% CL
July 17, 2016 - January 21, 2017
6 7 8 9 10 20 30 40 50
Period [Day]

Periodicities of Daily Proton Fluxes in 2016

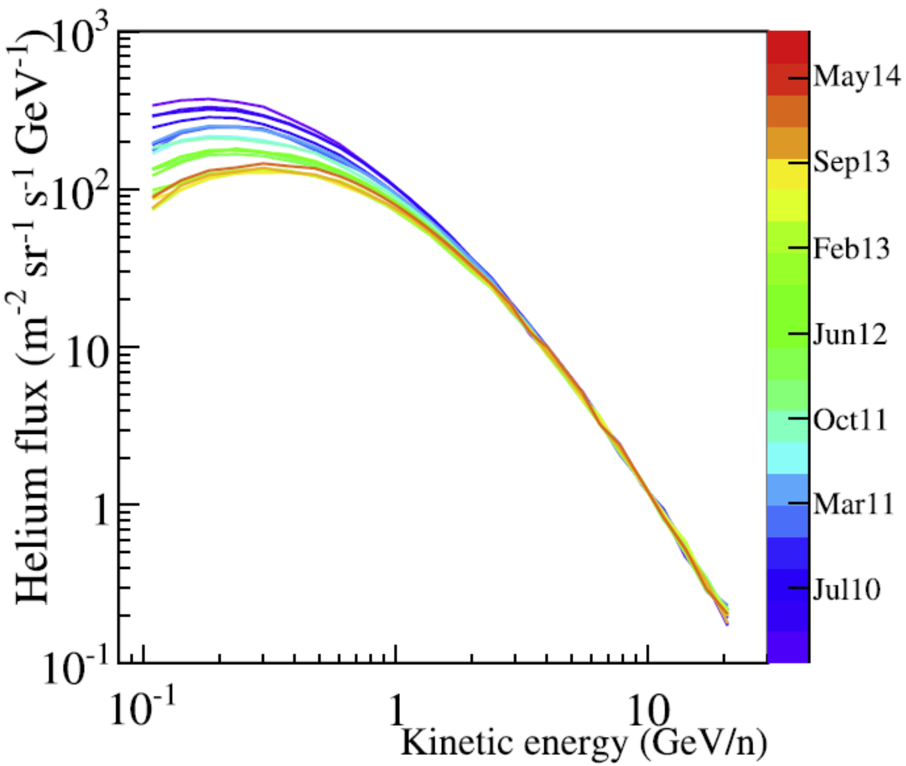


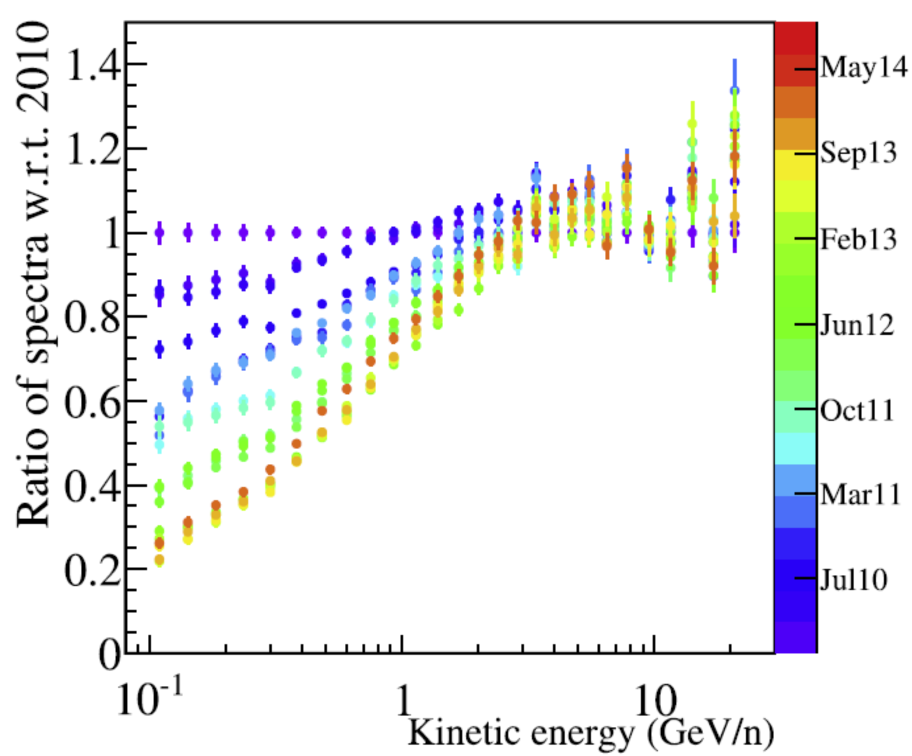
The strength of **9-day and 13.5-day periodicities** increases with increasing rigidity up to **~20 GV**, and then decreases with increasing rigidity up to **100 GV.**

Phys. Rev. Lett. 127, 271102 (2021)

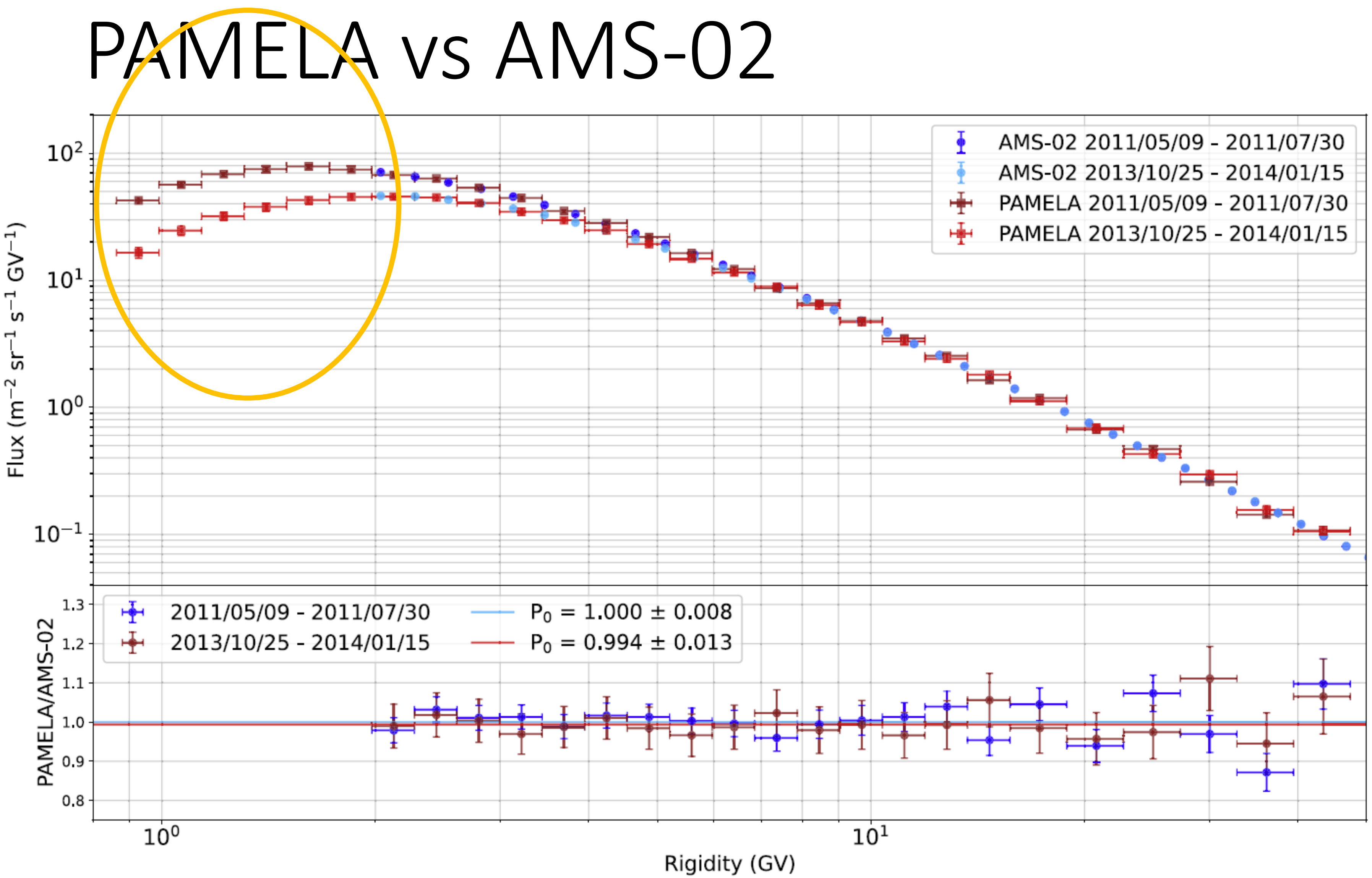
Time dependence of He spectra after 23-th cycle Solar Minimum (2010-2014)

- N. Marcelli+ (PAMELA Collaboration) The Astrophysical Journal Letters, 925:L24 , 2022

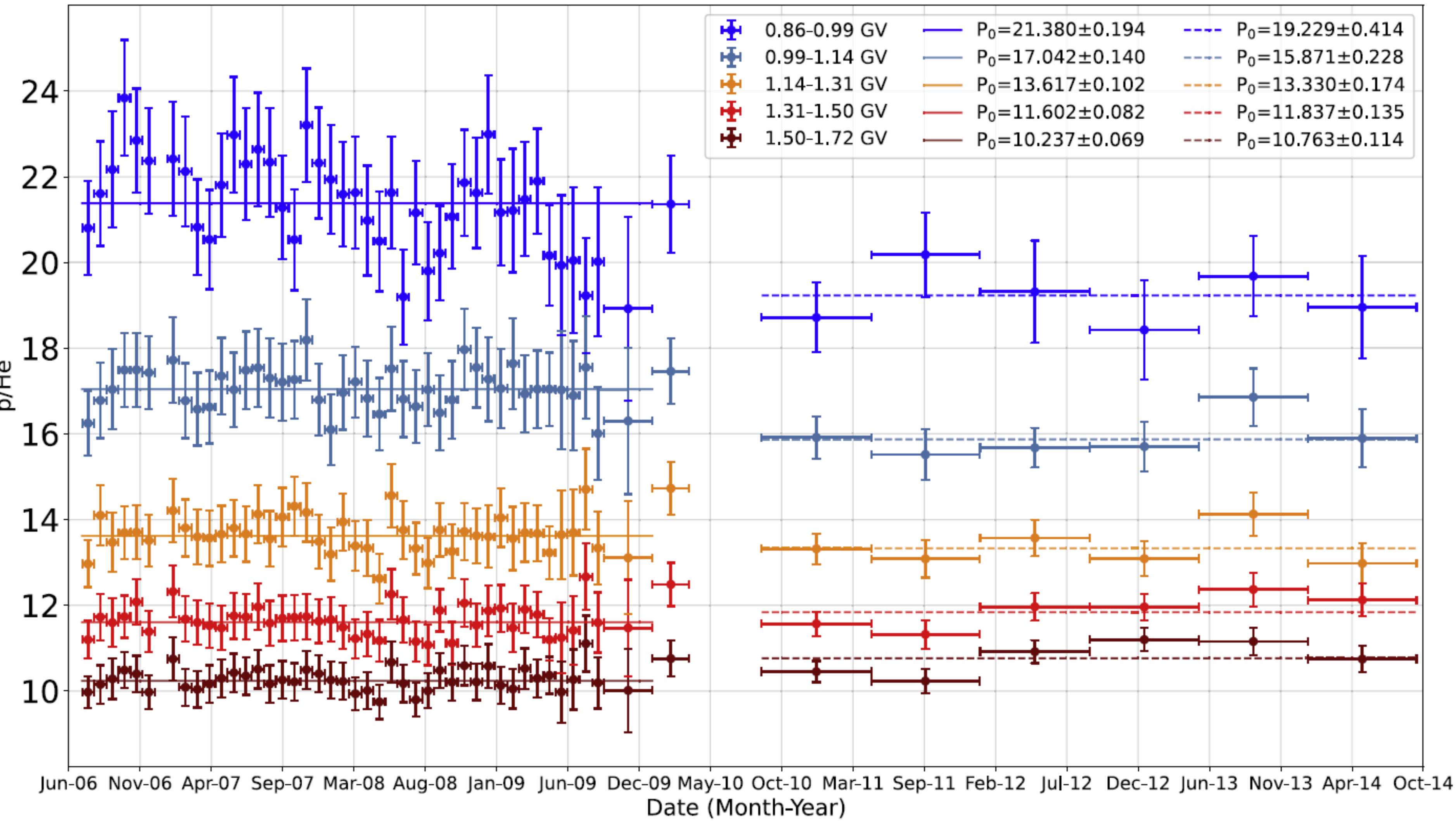




PAMELA vs AMS-02



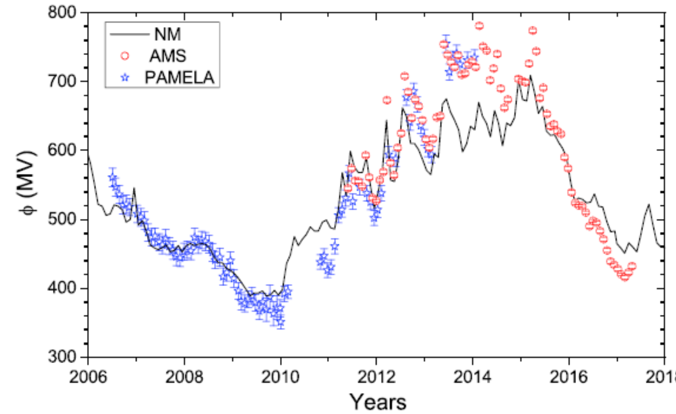
N. Marcelli+ (PAMELA Collaboration), 2022



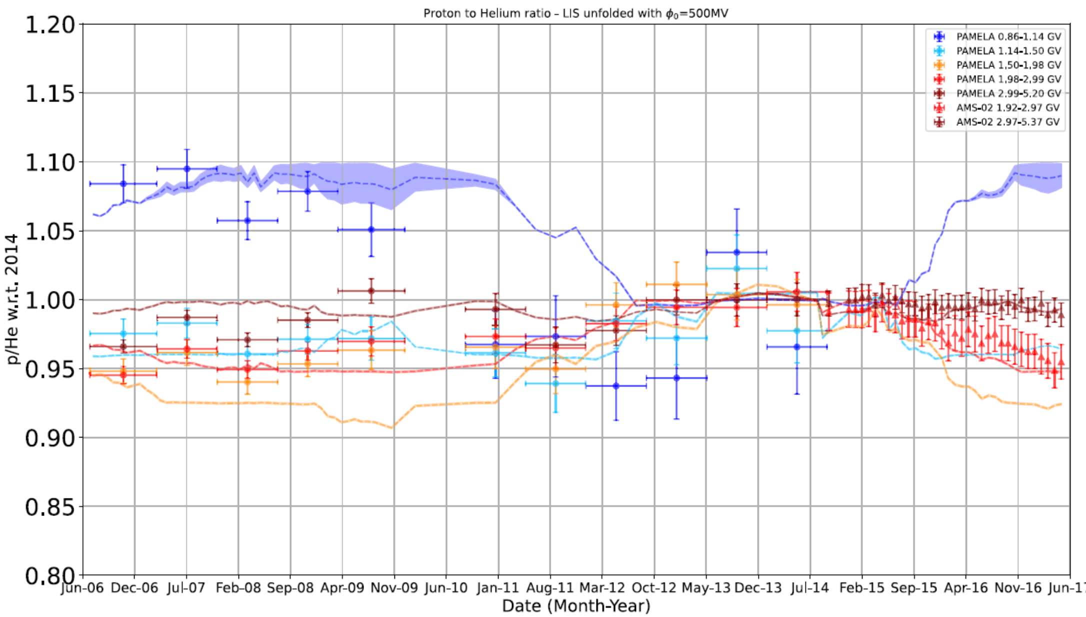
Time profiles of proton-to-helium ratio for the five rigidity intervals.

Koldobskiy, S. A., + *Journal of Geophysical Research: Space Physics*, *124*, 2367, 2019

Отношение He/p зависит от LIS



Расчет LIS для параметра модуляции Φ=500 МВ



Since the force-field approximation assumes the same modulation parameter for different particle species …
the observed time variation of the proton-to-helium flux ratios are dominated by the shapes of the proton and helium nuclei LIS,

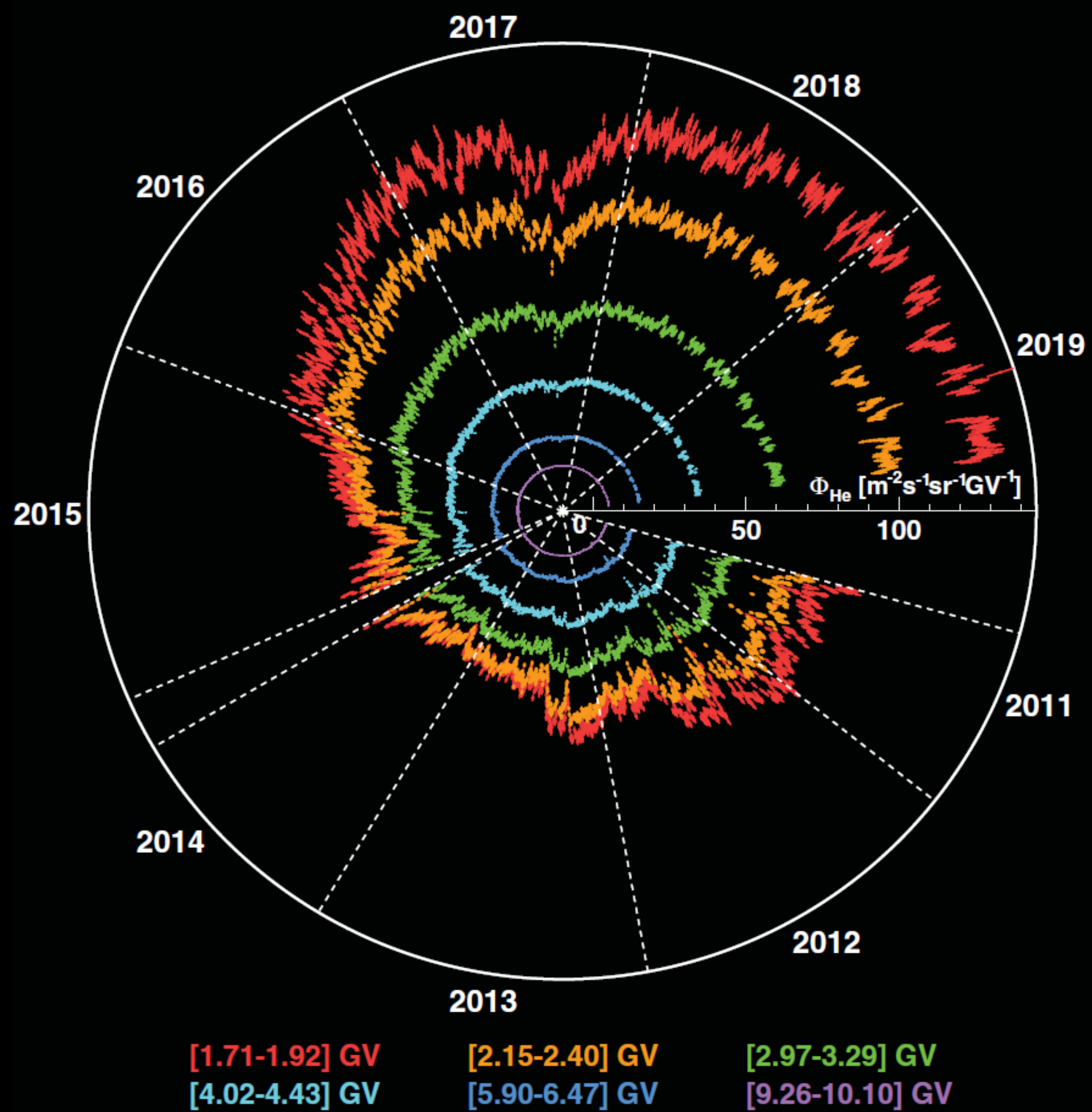
$$J(r, E, t) = \frac{E^2 - E_0^2}{(E + \Phi)^2 - E_0^2} J(\infty, E + \Phi(t))$$

Различие в LIS?

N. Marcelli+ (PAMELA Collaboration) ApJL, 925(2022)L24

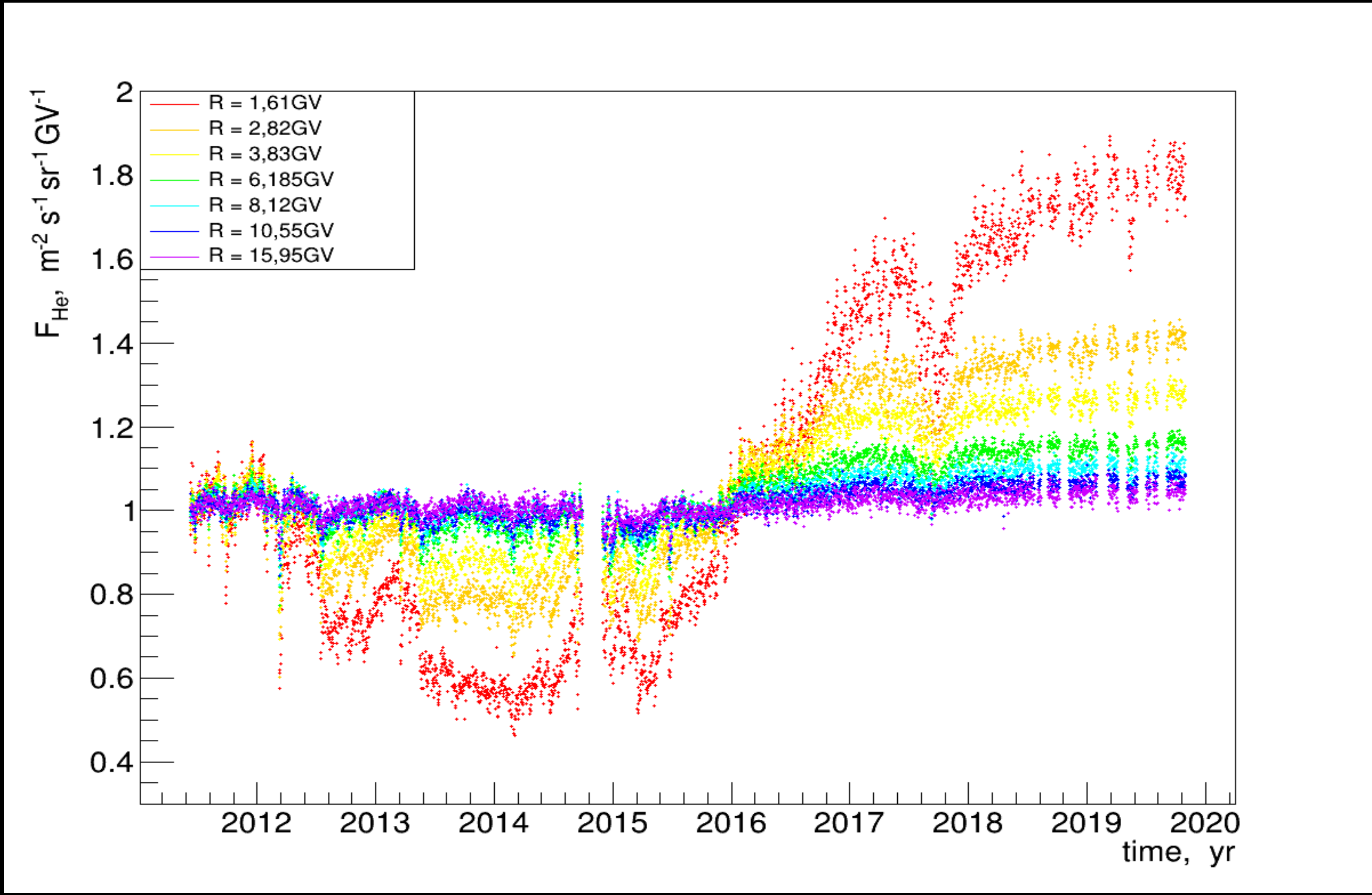
Суточные потоки ядер He по данным AMS -02

.6×10⁸ ядер He
арегистрировано
 20 мая 2011 по 29 октября 2019
диапазоне R 1.7-100 GV

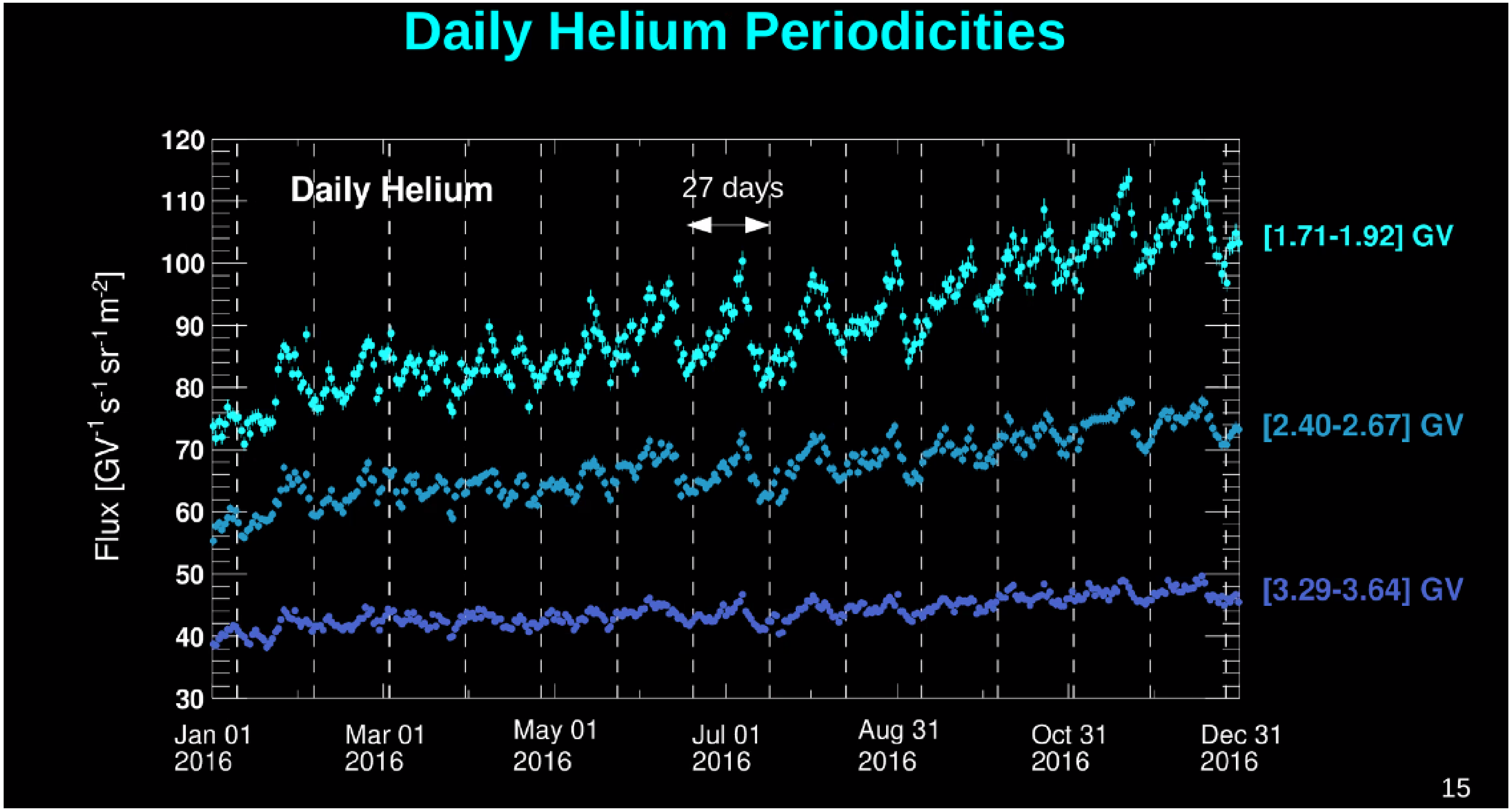


AMS Collaboration
Phys. Rev. Lett., 2022,128, 231102

Относительные вариации потоков ядер He по данным AMS-02 (2011-2019)

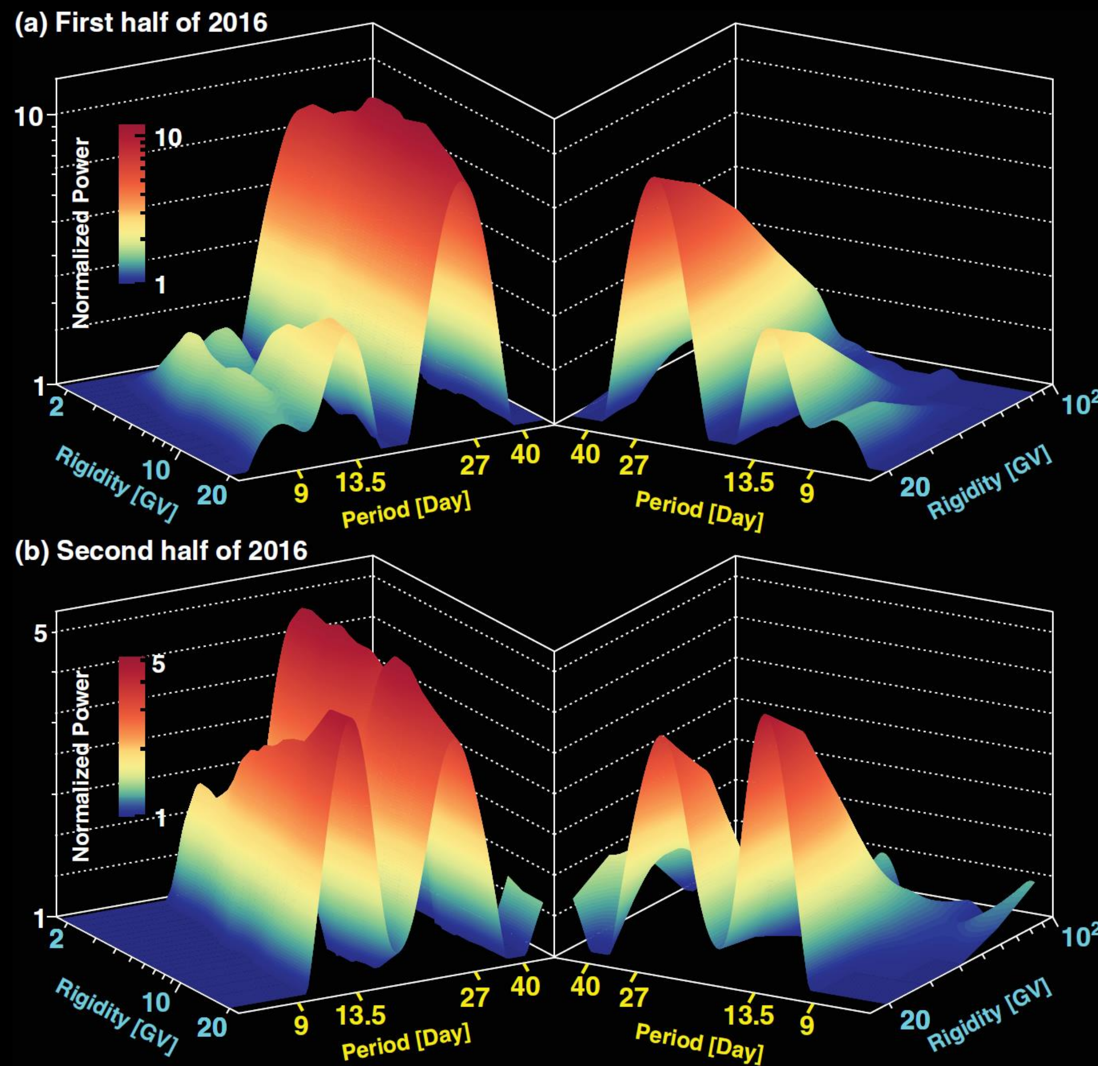


По данным Phys. Rev. Lett. 128,2022

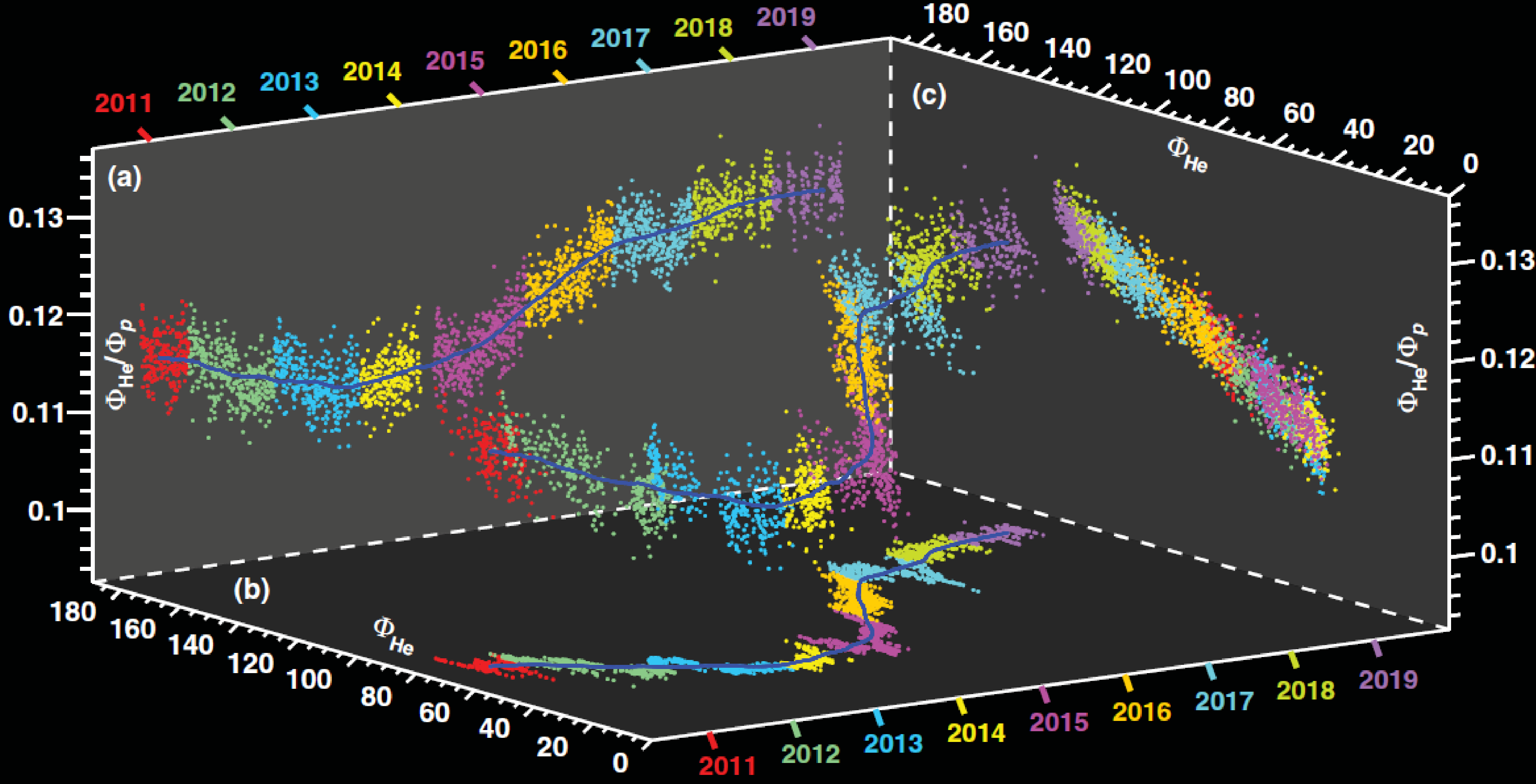


Daily Helium Periodicities
Daily Helium
27 days
Flux [GV^{-1} s^{-1} sr^{-1} m^{-2}]
120
110
100
90
80
70
60
50
40
30
[1.71-1.92] GV
[2.40-2.67] GV
[3.29-3.64] GV
Jan 01 2016
Mar 01 2016
May 01 2016
Jul 01 2016
Aug 31 2016
Oct 31 2016
Dec 31 2016
15

Periodicities in He fluxes in 2016

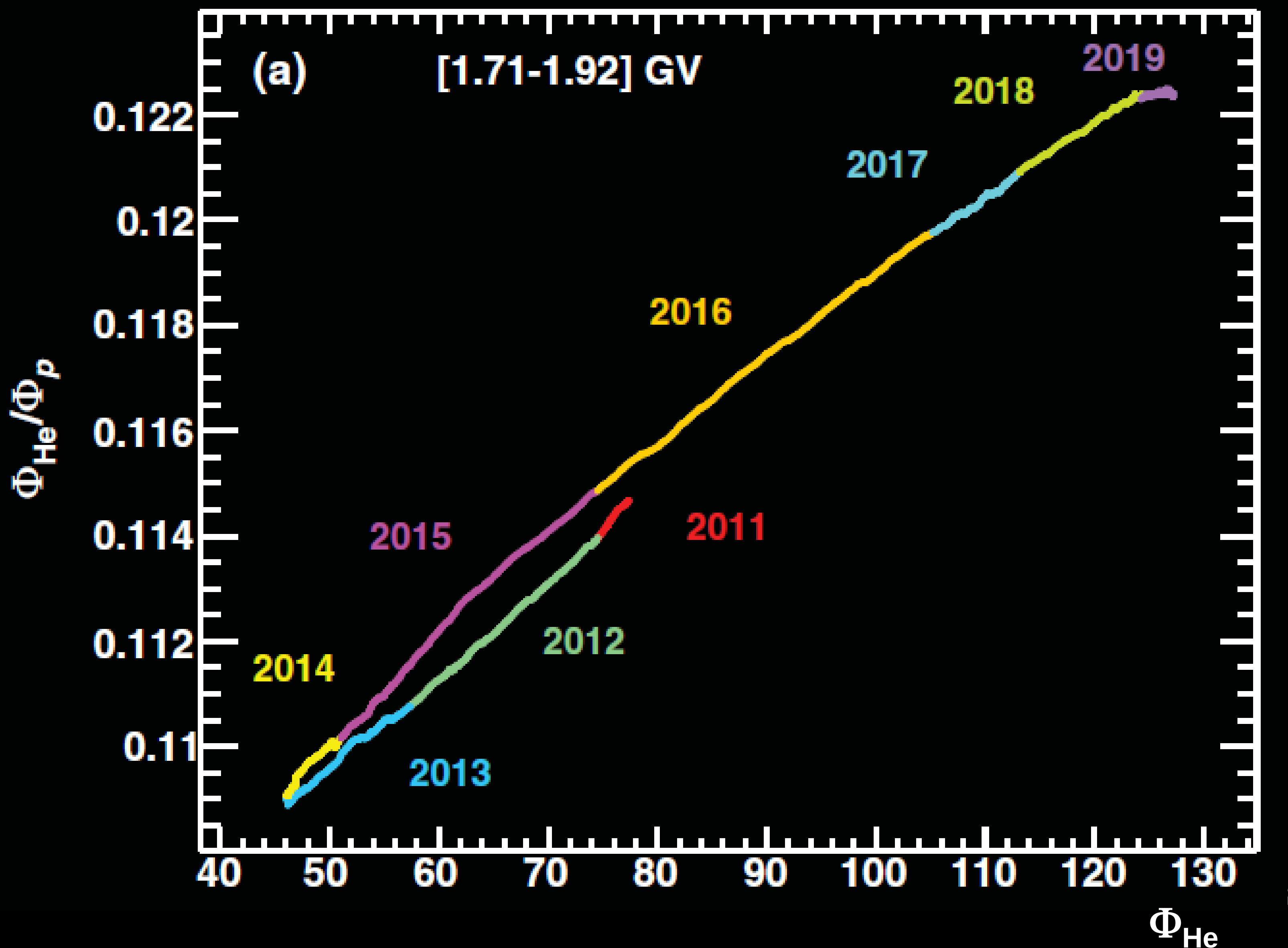


Сравнение потоков протонов и ядер гелия



Phys. Rev. Lett. 128,2022,231102

Зависит ли He/p от полярности HMF?


(a)
[1.71-1.92] GV
ΦHe/Φp
ΦHe
0.122
0.12
0.118
0.116
0.114
0.112
0.11
40
50
60
70
80
90
100
110
120
130
2011
2012
2013
2014
2015
2016
2017
2018
2019

Спасибо за внимание !