Results from the AMS experiment on low-energy cosmic rays

Time-dependence of cosmic-ray fluxes
Implications for solar modulation studies

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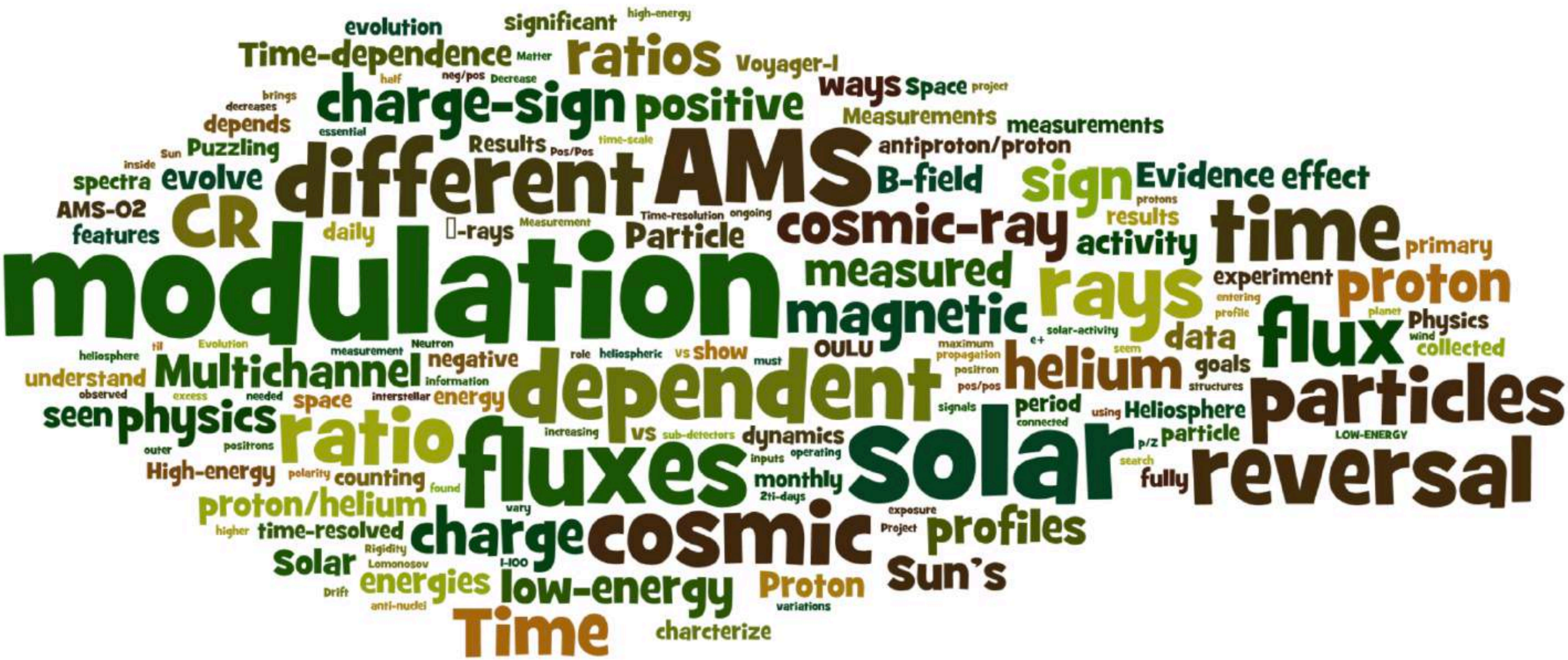
24-30 August 2017 – Moscow, Russia

Wordcloud



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Time-dependence
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Project
profiles
Rigidity
Solar
Lomonosov
I-100
Sun's
energies
Drift
low-energy
Proton
variations
anti-nuclei
Time
charcterize

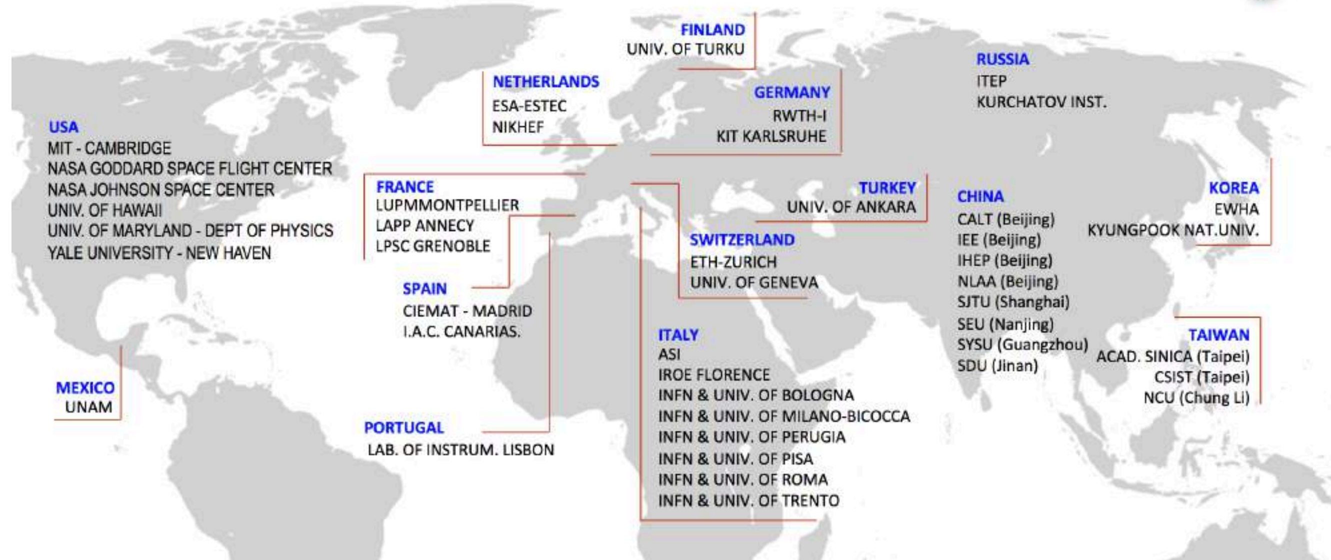
Outline

- The AMS project and physics goals
- Low-energy cosmic rays and solar physics
- Time-dependence of proton and helium fluxes
- Time-dependence of electron and positron fluxes
- Solar modulation of cosmic rays in the Heliosphere

The AMS Project

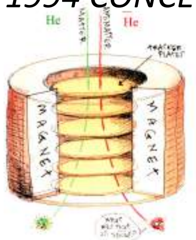
AMS Collaboration

- *16 countries*
- *60 institutes*
- *500+ physicists*
- *20 years*



Project timeline

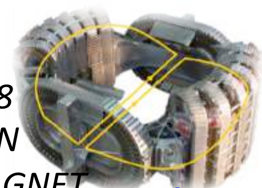
1994 CONCEPT



1997 AMS-01 PROTOTYPE

1998: STS-91

2000 @CERN AMS-02 CONSTRUCTION



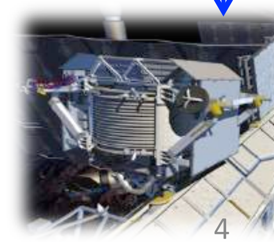
2008 @CERN SC MAGNET BEAM TEST

2010 TVT @ ESA (NL)

2010 @CERN SC -> PM NEW BEAM TEST

2011 @KSC INTEGRATION & CR-μ RUN

MAY 2011 STS-134 FLIGHT



ON THE ISS

→ Steadily taking data on the ISS since May 19th 2011

The AMS Project

Particle physics experiment operating in the International Space Station
Precision measurement of primary cosmic rays at TeV energies

Physics goals

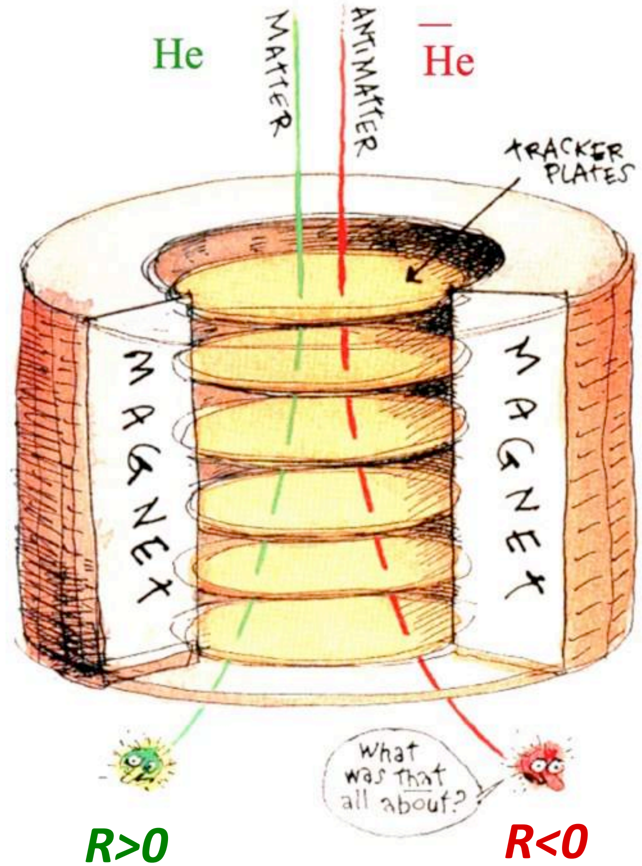
- ✓ **Antimatter search (|Z|>1 anti-nuclei)**
- ✓ **Dark Matter (light anti-matter & γ-rays)**
- ✓ **Exotic signals?**
- ✓ **GCR & γ-rays astrophysics**
- ✓ **Solar Physics (solar modulation & SEP)**
- ✓ **Magnetospheric physics**

How it will fulfill these goals?

- **Large collaboration: 16 Countries, 60 Institutes and ~500+ Physicists**
- **Same concept (precision & capability) as the large state-of-the-art HEP detectors**
  [but: fitting into the space shuttle & no human intervention after installation]
- **Operation in space, ISS, at 400km, no backgrounds from atmospheric interactions**
  [extensive multi-step space qualification tests]
- **Collection power: geometrical factor (≈ 0.5 m2sr) X exposure time (= ISS lifetime)**
  [extensive calibration campaigns on ground]

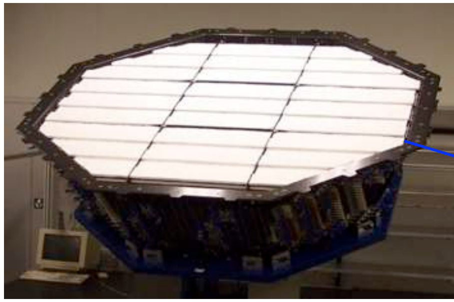
Measurement concept

The eventual discrimination between matter and antimatter is provided by the measurement of their charge-sign

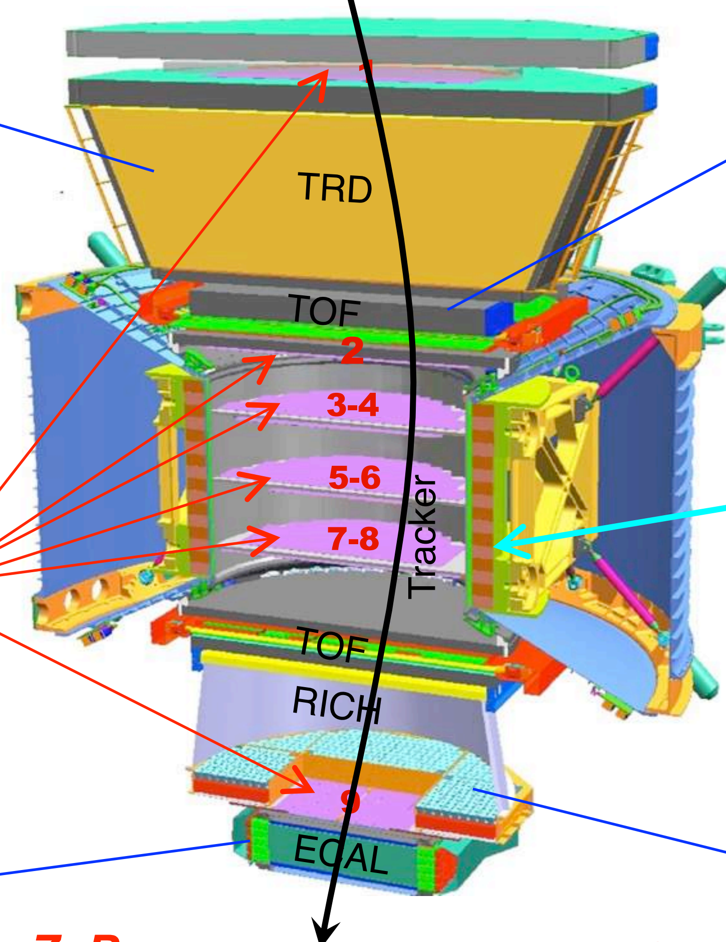


The AMS-02 sub-detectors

TRD
Identify e+, e-

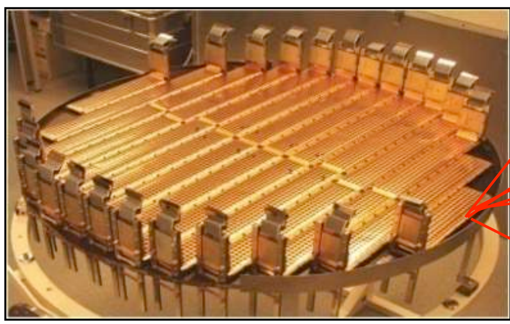


Particles and nuclei are defined by their charge (**Z**) and energy (**E ~ P**)

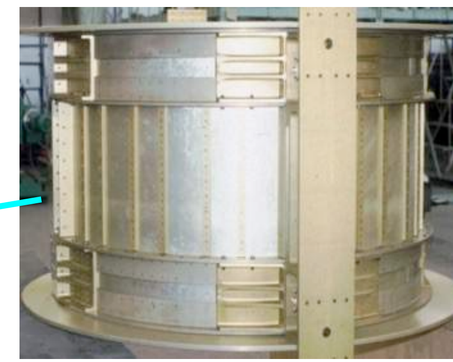


TOF
Z, E

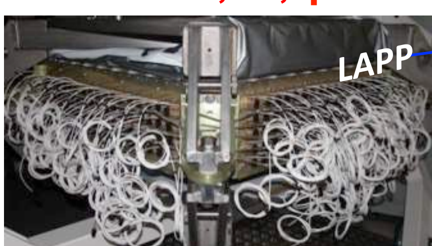
Silicon Tracker
Z, P



Magnet
±Z



ECAL
E of e+, e-, γ



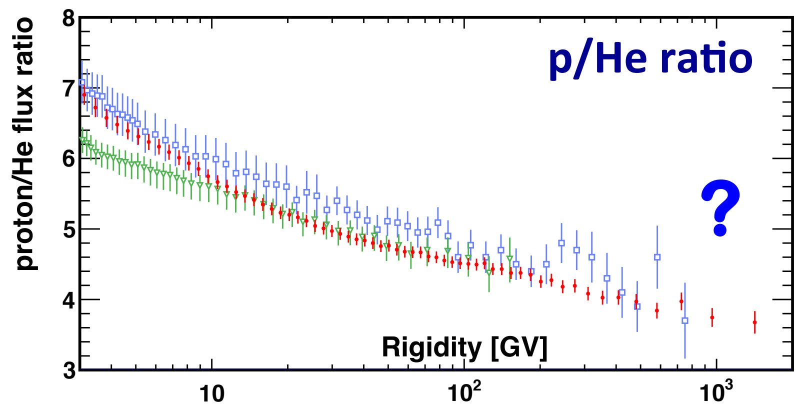
RICH
Z, E

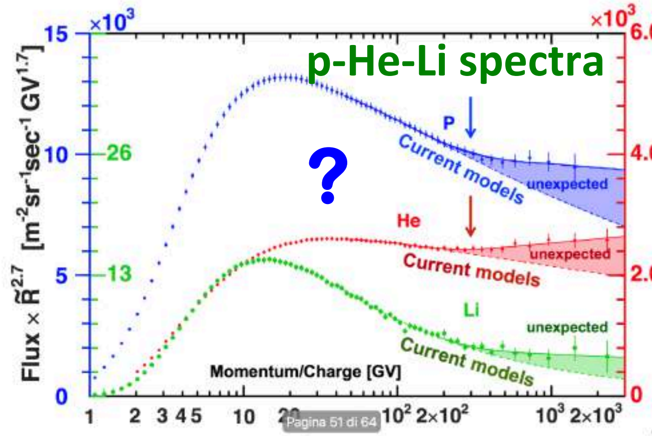
Z, P are measured independently from Tracker, RICH, TOF and ECAL

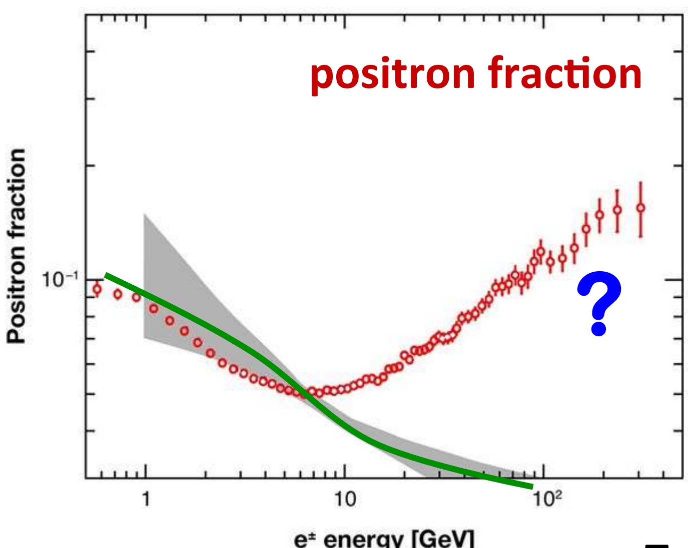
Talk by V. Choutko

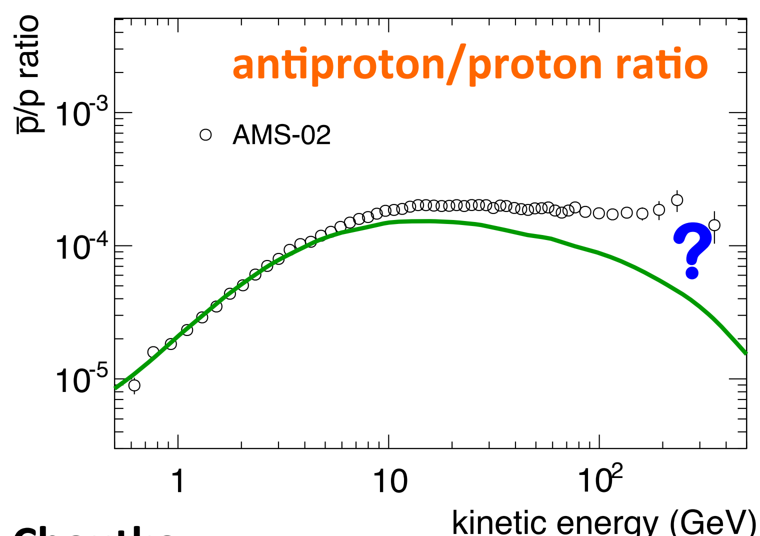
High-energy measurements: puzzling results

- Decrease of proton/helium ratio
- High-energy hardening of all nuclei
- Puzzling excess of high-energy positrons
- Unexpectedly flat antiproton/proton ratio









Talk by V. Choutko

Why low-energy, why solar modulation

Measurements of CR spectra brings valuable information on the origin and propagation of these particles, along with the nature of dark matter

When entering the Heliophere, primary cosmic rays encounter the magnetized solar wind, which *modulates* their flux low energy

Solar modulation provokes significant modifications in the shapes of cosmic-ray spectra up to the energies of several tenths of GeV/n. This effect is:

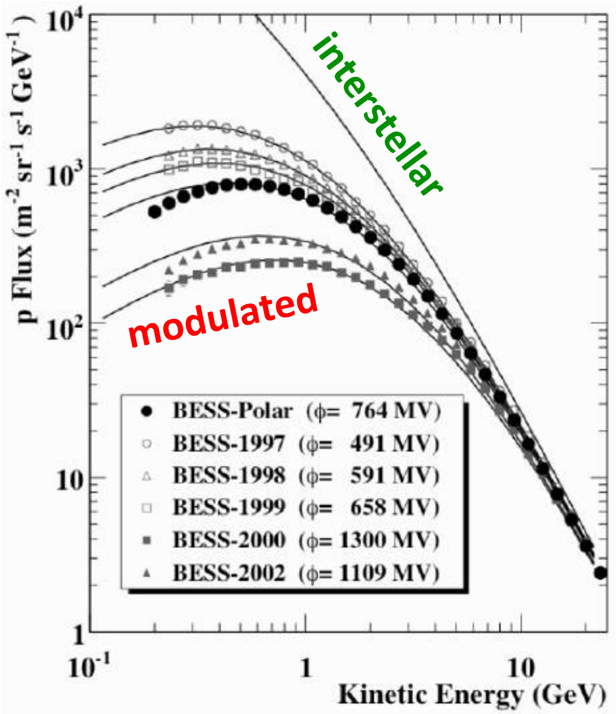
- ✓ **Time dependent**
- ✓ **Energy dependent**
- ✓ **Space dependent**
- ✓ **Particle dependent**

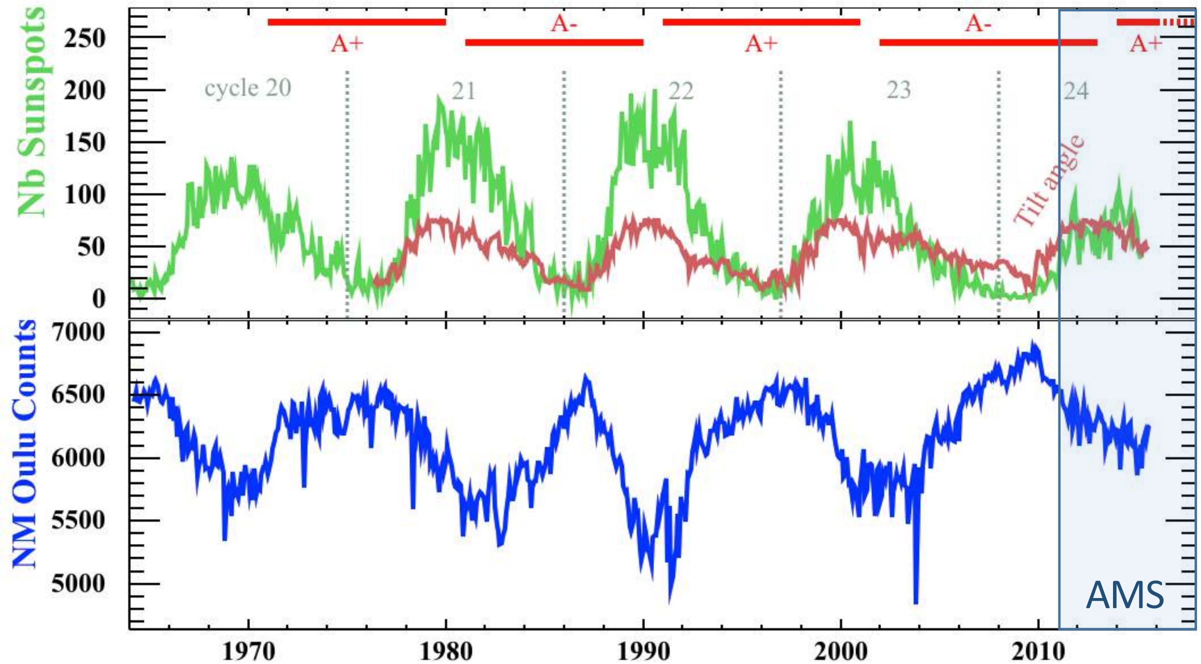
A comprehensive description of the cosmic radiation must account for the transport of these particles in the heliosphere

Measurement requirements:

- **LOW-ENERGY, because the modulation effect decreases with increasing energy**
- **TIME-REOLVED, because the effect depends upon the evolving solar activity**
- **MULTI-CHANNEL, because solar modulation depends on charge-sign dependent processes**

Why low-energy, why time-resolved

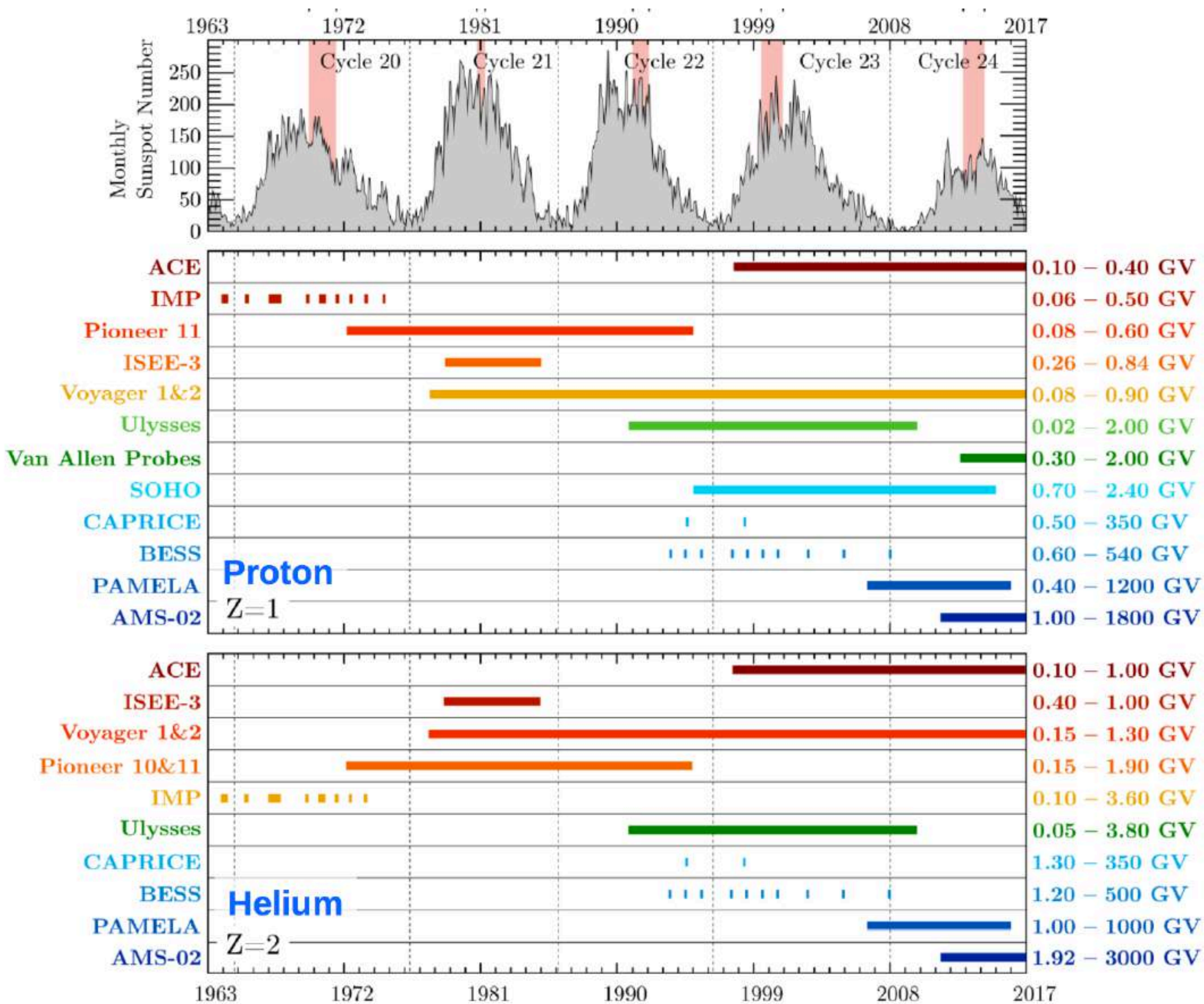




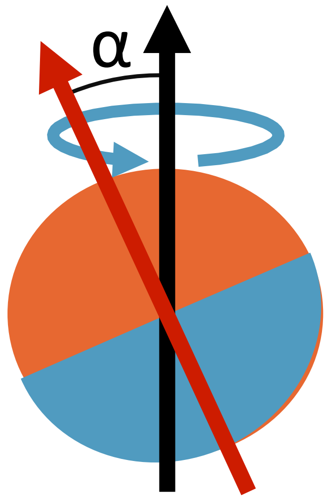
When the Sun activity is higher, the heliospheric B-field provides stronger shielding against cosmic rays coming from outer space, before they reach our planet.

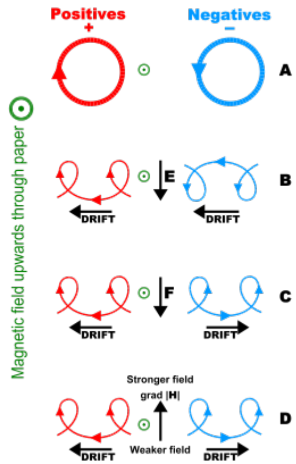
To study solar modulation, data on time-dependence of the cosmic-ray flux at monthly timescale are needed

Measurements of CR modulation in space

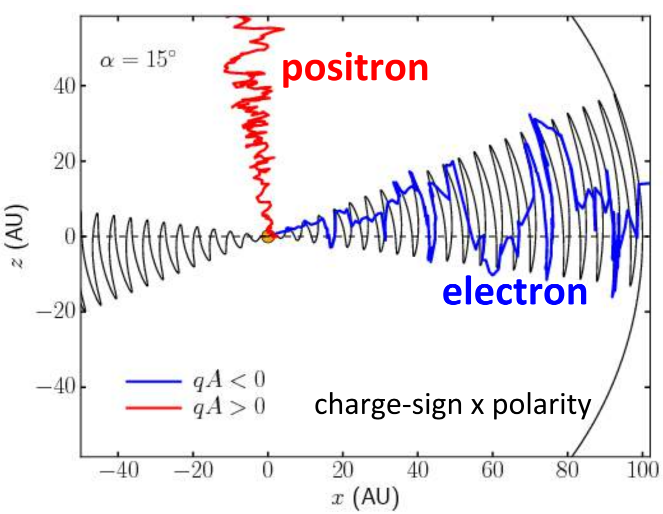


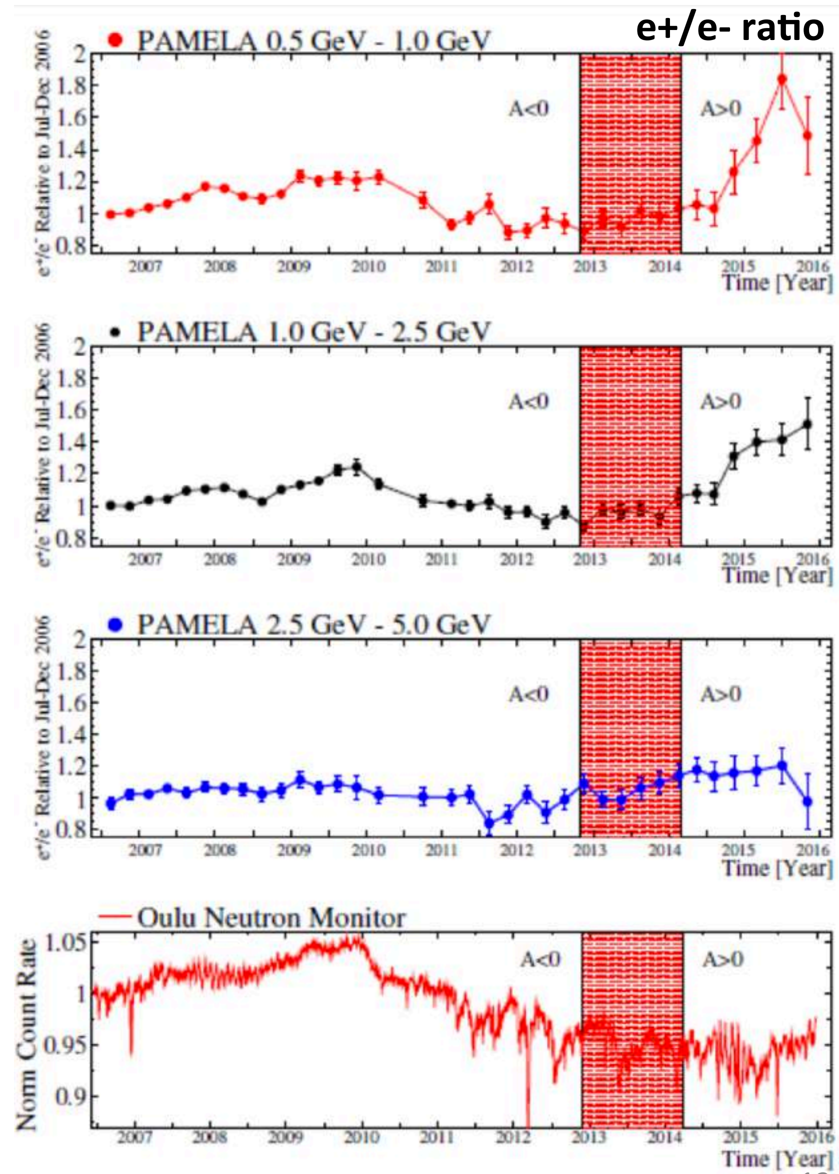
Solar modulation: charge-sign dependence





- ✓ **Drift motion across the regular B-field**
- ✓ **Different trajectories for particles & antiparticles**
- ✓ **Interchanged role with B-field reversal (T=11-yrs)**



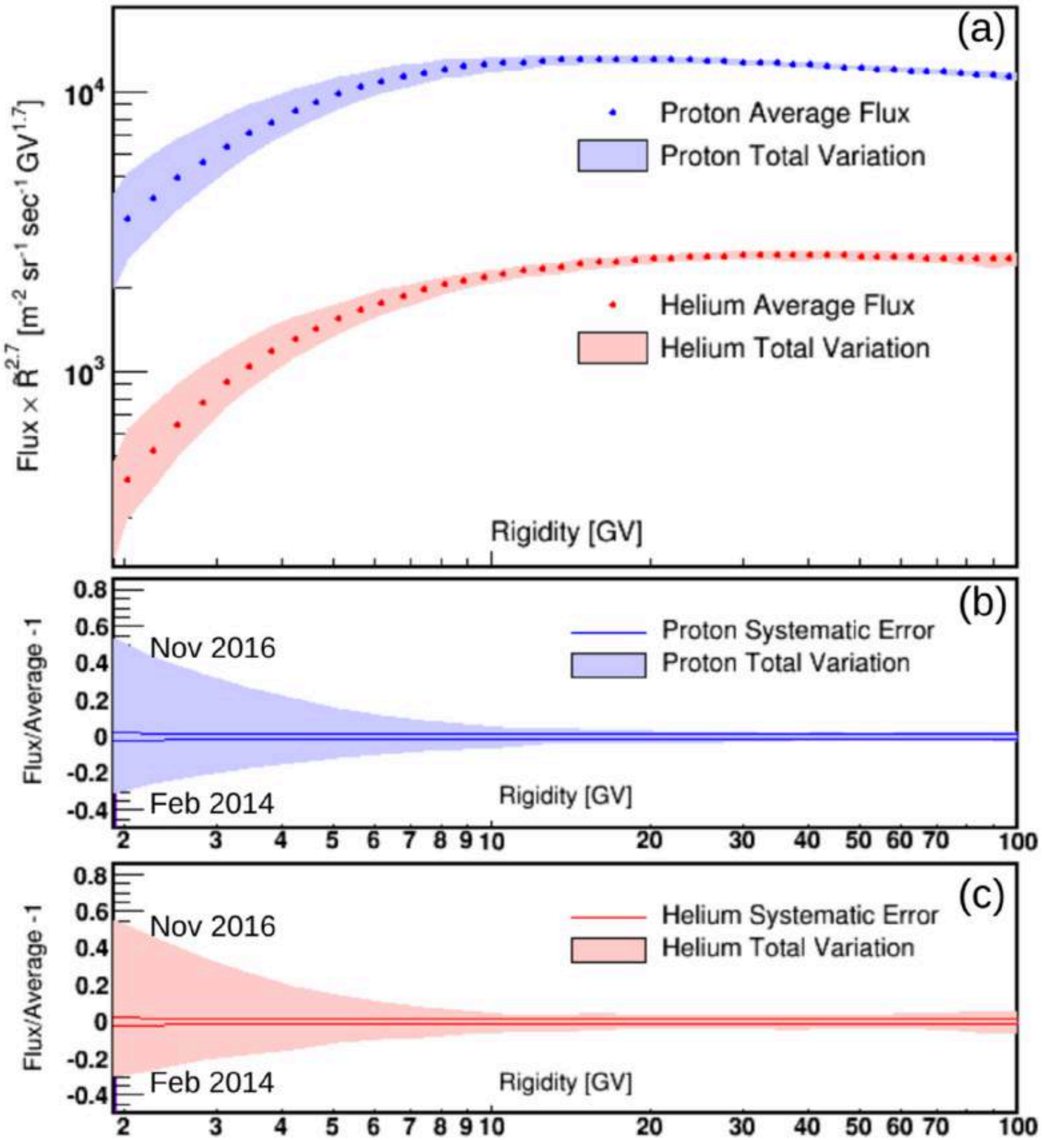


AMS Results: proton & Helium in 5.5 years

Proton and helium fluxes

Rigidity range: R=1-100 GV
Total exposure time: 5.5 yr
Period: May 2011 – Nov2016
Time-resolution: 27-days

The flux of CR protons and helium measured over half a solar cycle show significant variations



Rigidity R=p/Z [GV]

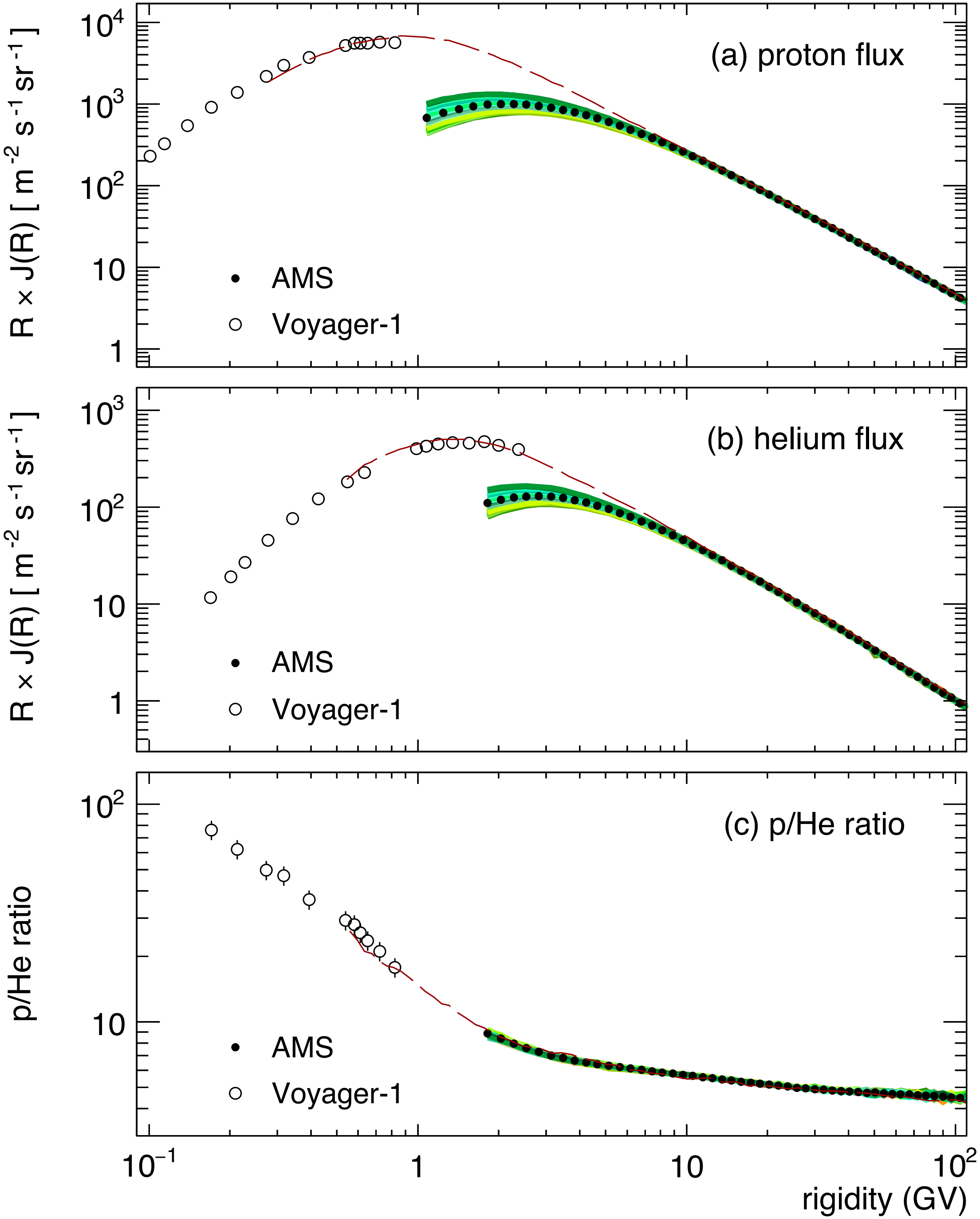
AMS results
Proton and helium fluxes in cosmic rays

AMS + Voyager-1 data comparison

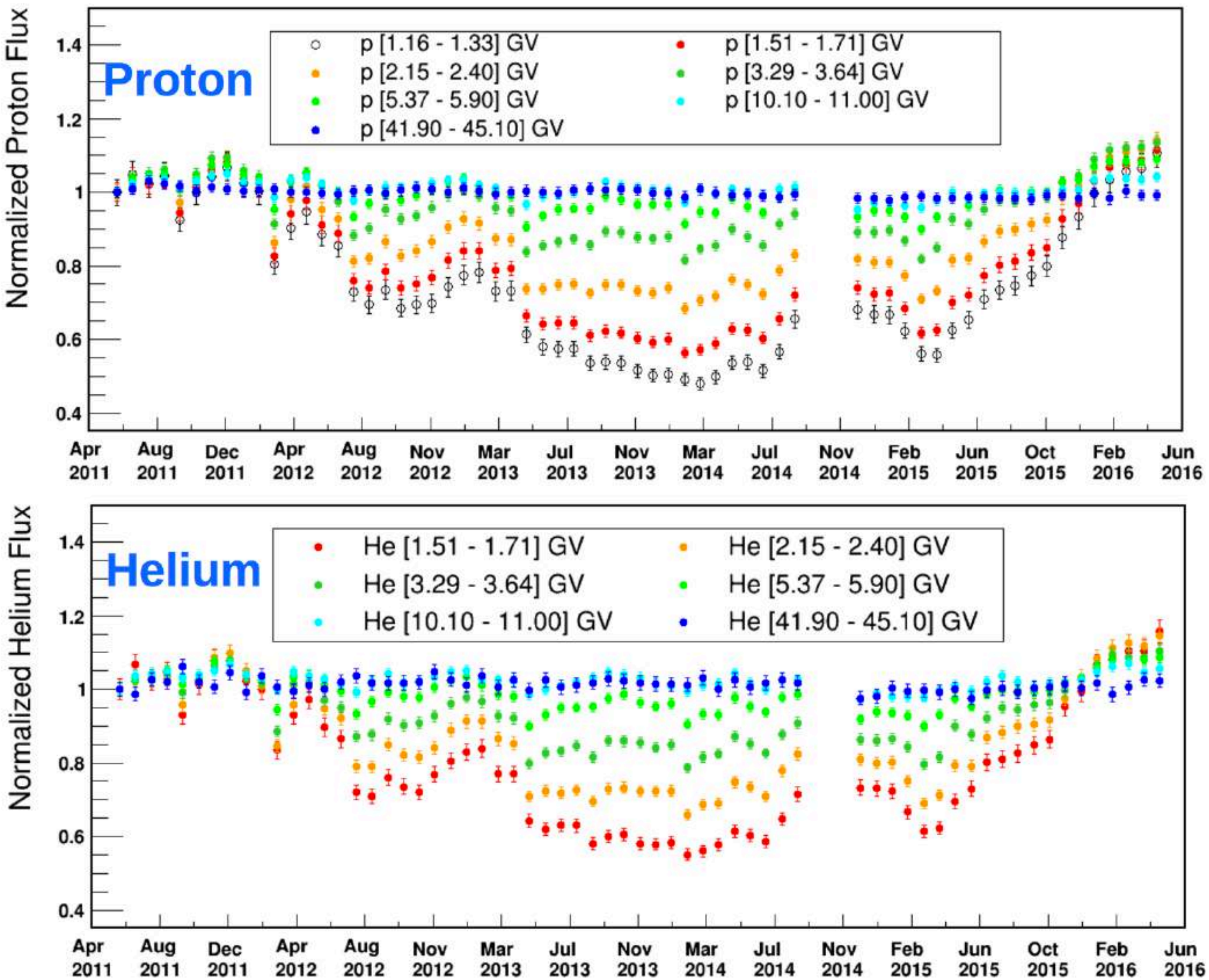
AMS has measured the proton/helium ratio as function of rigidity R=p/Z.

The AMS p/He ratio, measured inside the Heliosphere around the solar maximum, is found **not to vary** with time.

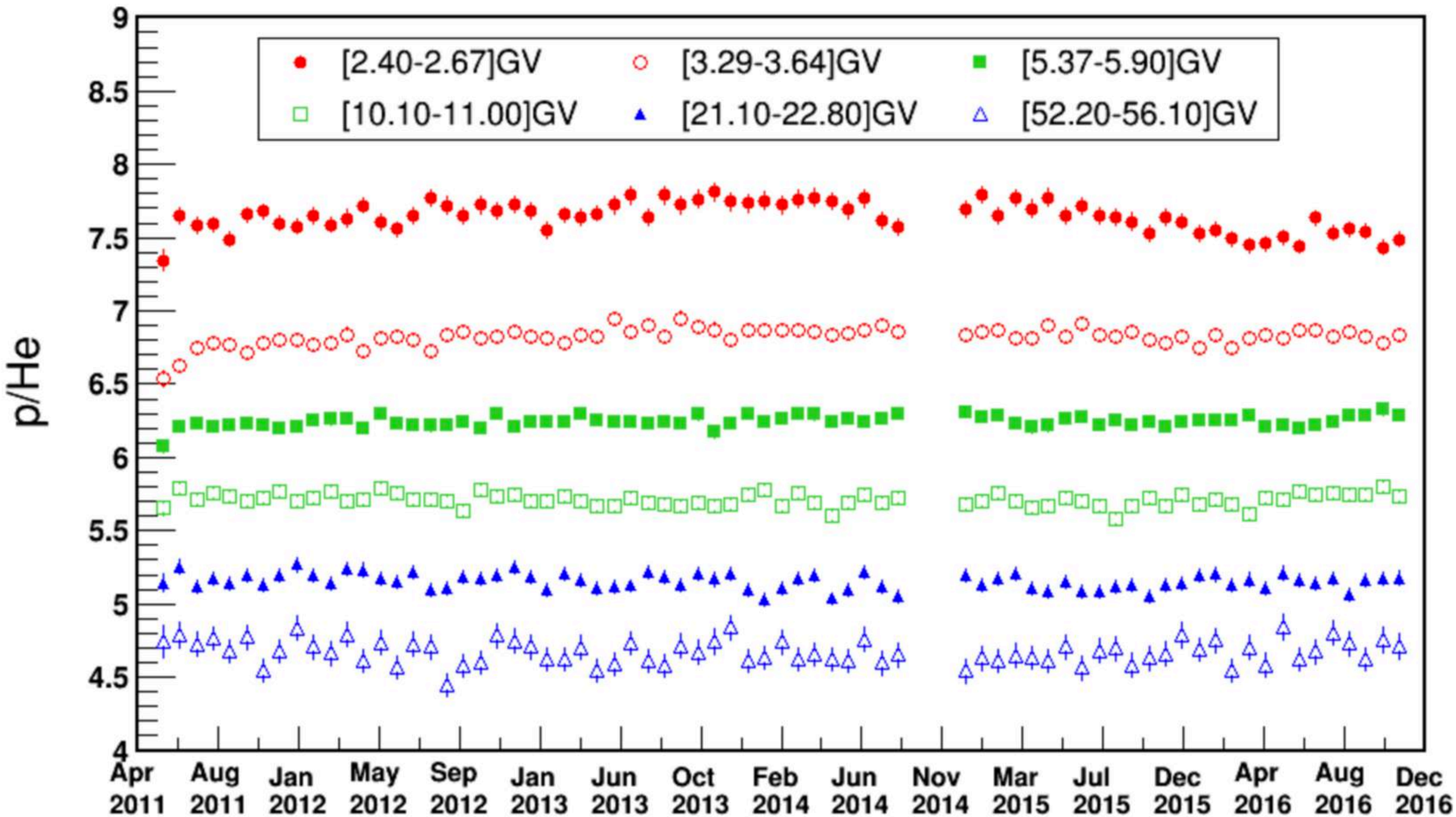
Apparently, this ratio is representative of its **interstellar** value (measured by Voyager-1).



Time profiles of proton and helium fluxes

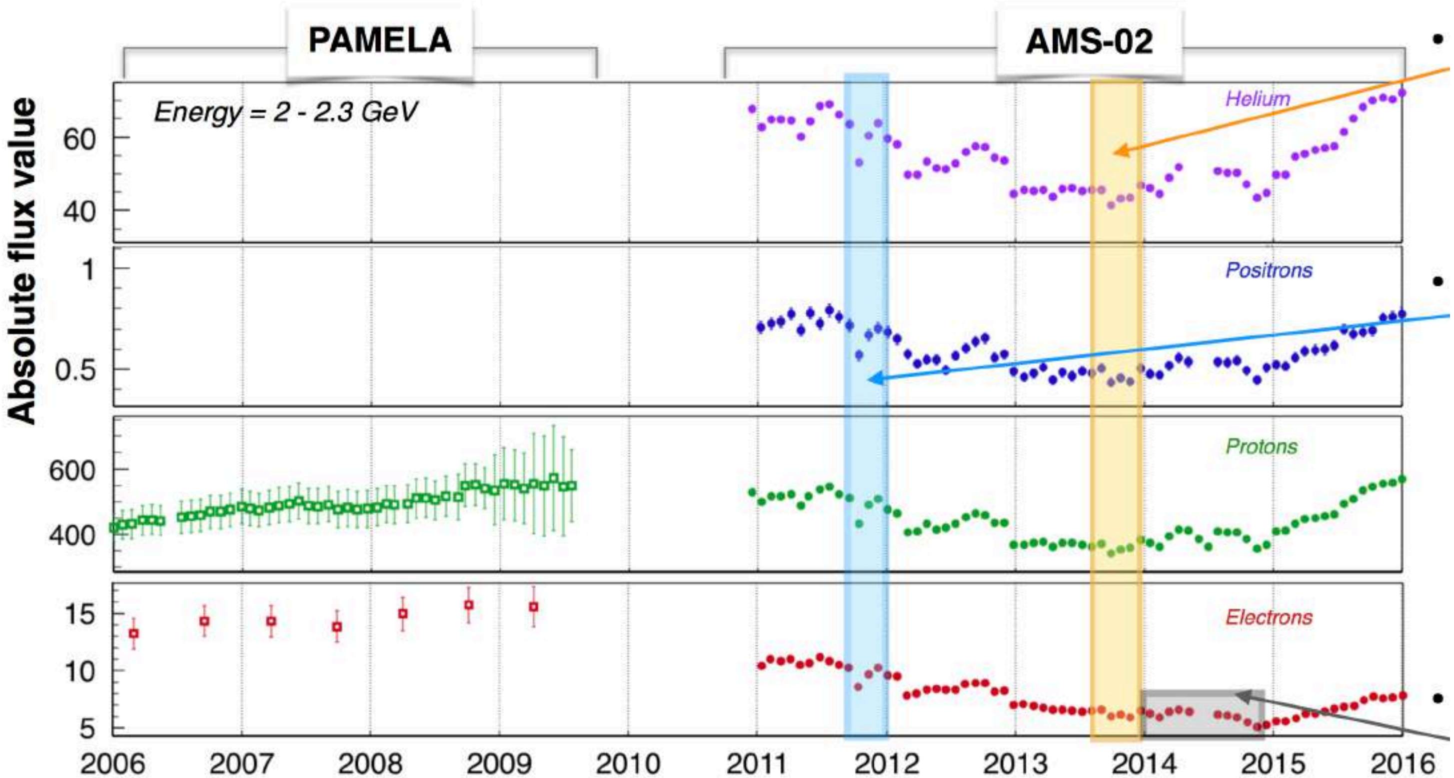


Time profile of the proton/helium ratio



Multichannel time profiles: p, He, e+, e-

All species show similar time profiles, with peculiar structures and small differences



- Flux minimum (activity maxium)
- Short time structures (SEP)
- Electron flux still decreasing after proton minimum

A better inspection can be done using positive/negative and positive/positive ratios

Time profiles of pos/pos and neg/pos ratios

Neutron monitor rates

Monthly and daily counting rates from neutron monitor detectors at ground level.

Proton flux VS time

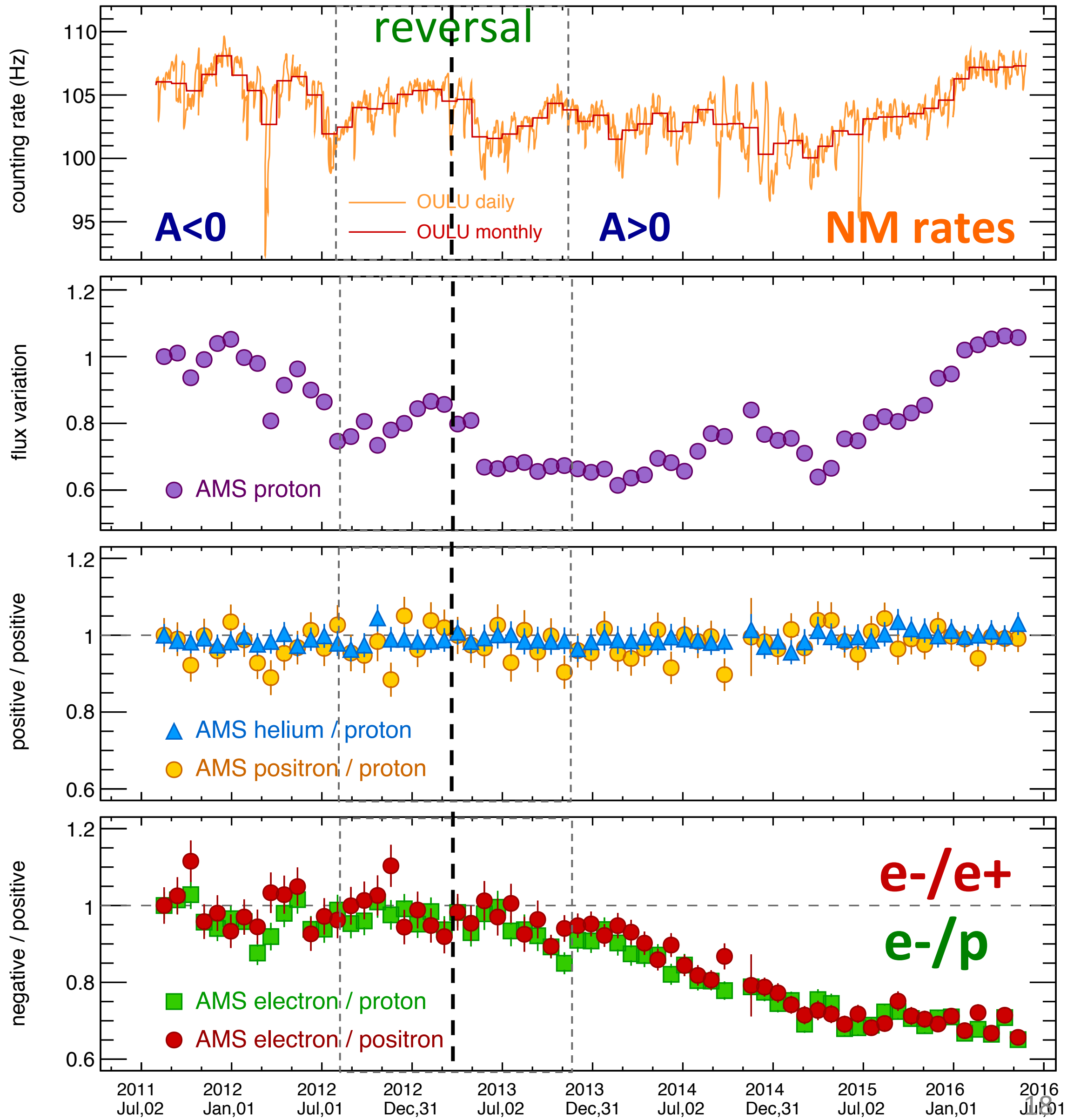
Evolution of the proton flux between 2011 and 2017 at different energies.

Pos/Pos ratios vs time

Time evolution of particle ratios with same charge sign. No particular features.

Neg/Pos ratios vs time

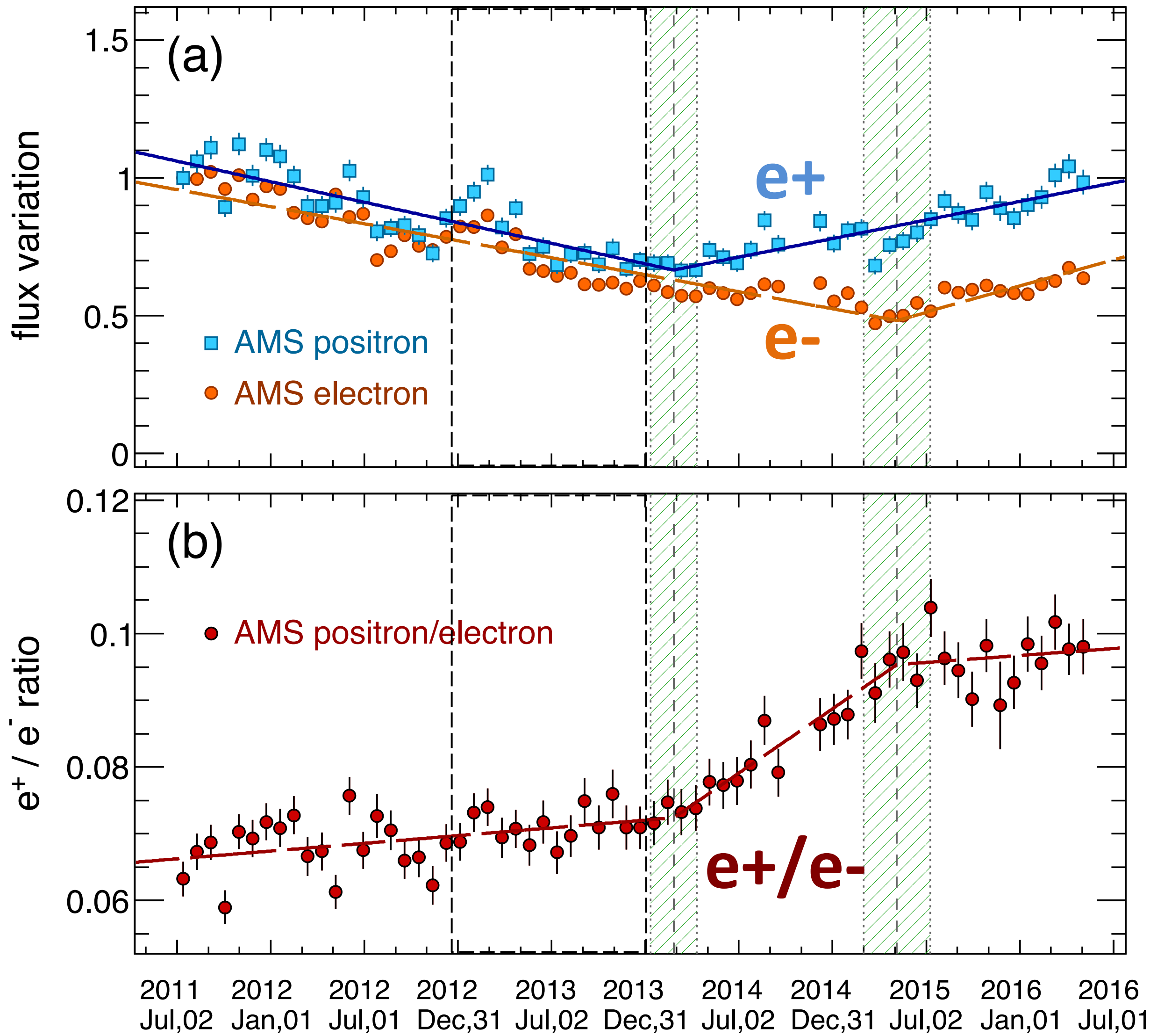
Time evolution of particle ratios with oppsite charge sign. Puzzling features have been observed. They seem to be connected with the reversal of the Sun's B field.



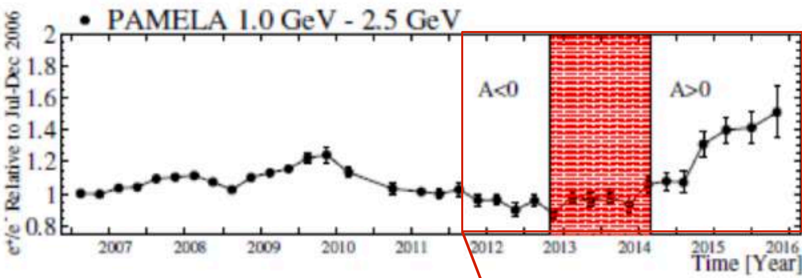
Multichannel investigation of solar modulation with AMS

The fluxes of CR particles with different charge sign are seen to evolve in different ways during the Sun's magnetic reversal.

The response of positive and negative particles to change in solar activity (and polarity) may have different timescales.



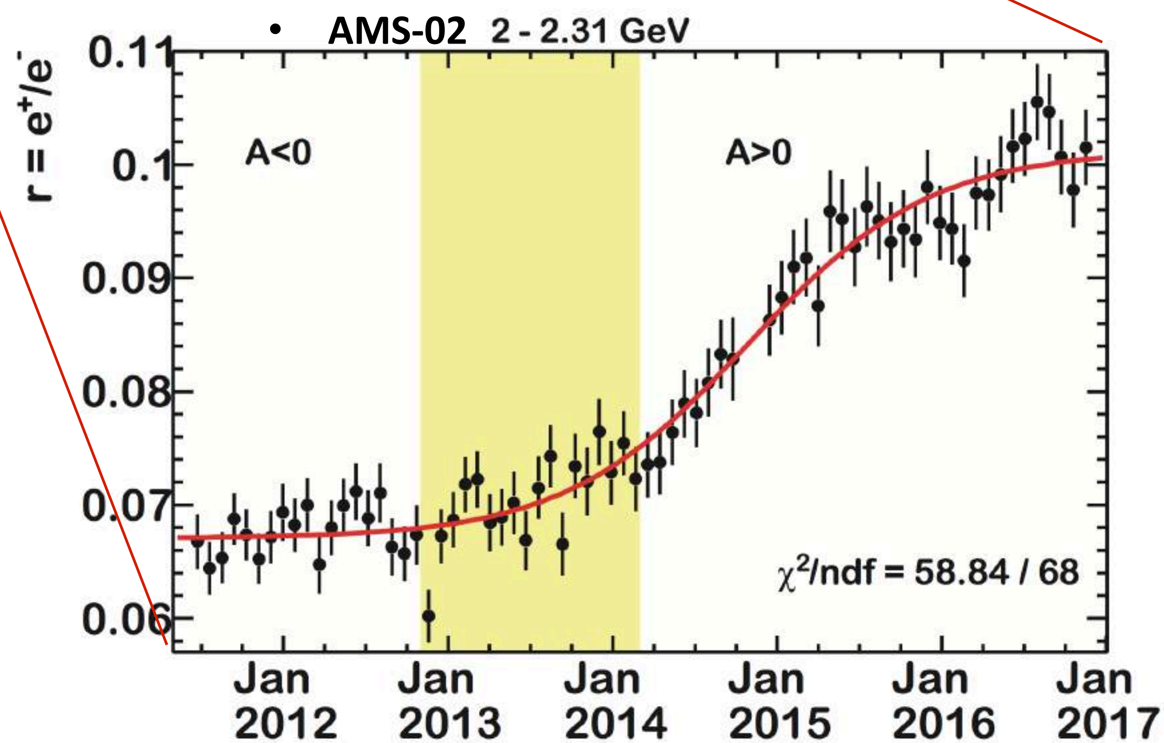
Evidence for charge-sign dependent modulation



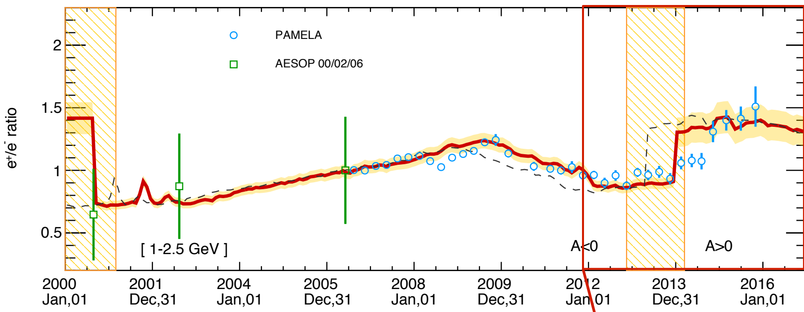
Adriani et al. PRL 2016

The fluxes of CR particles with different charge sign are seen to evolve in different ways during the Sun's magnetic reversal.

Multichannel cosmic-ray collected during this period are essential to understand and fully charcterize the dynamics of magnetic reversal.



Evidence for charge-sign dependent modulation



NT+ arXiv:1707.06916

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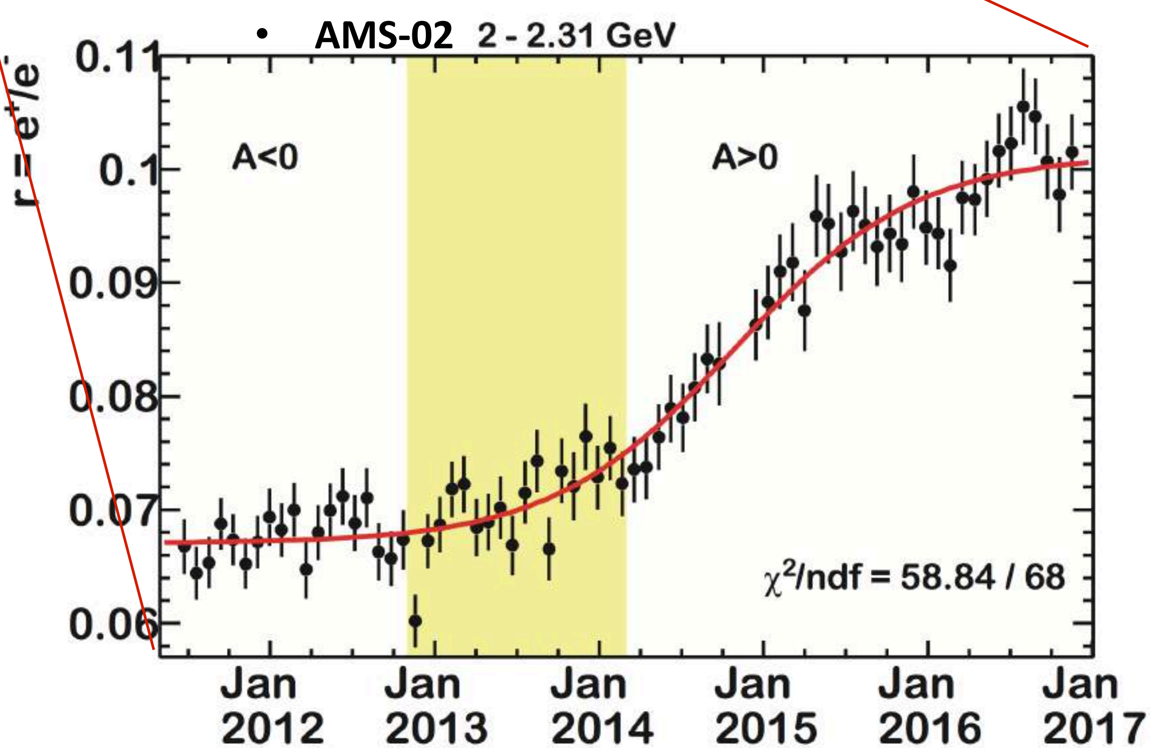
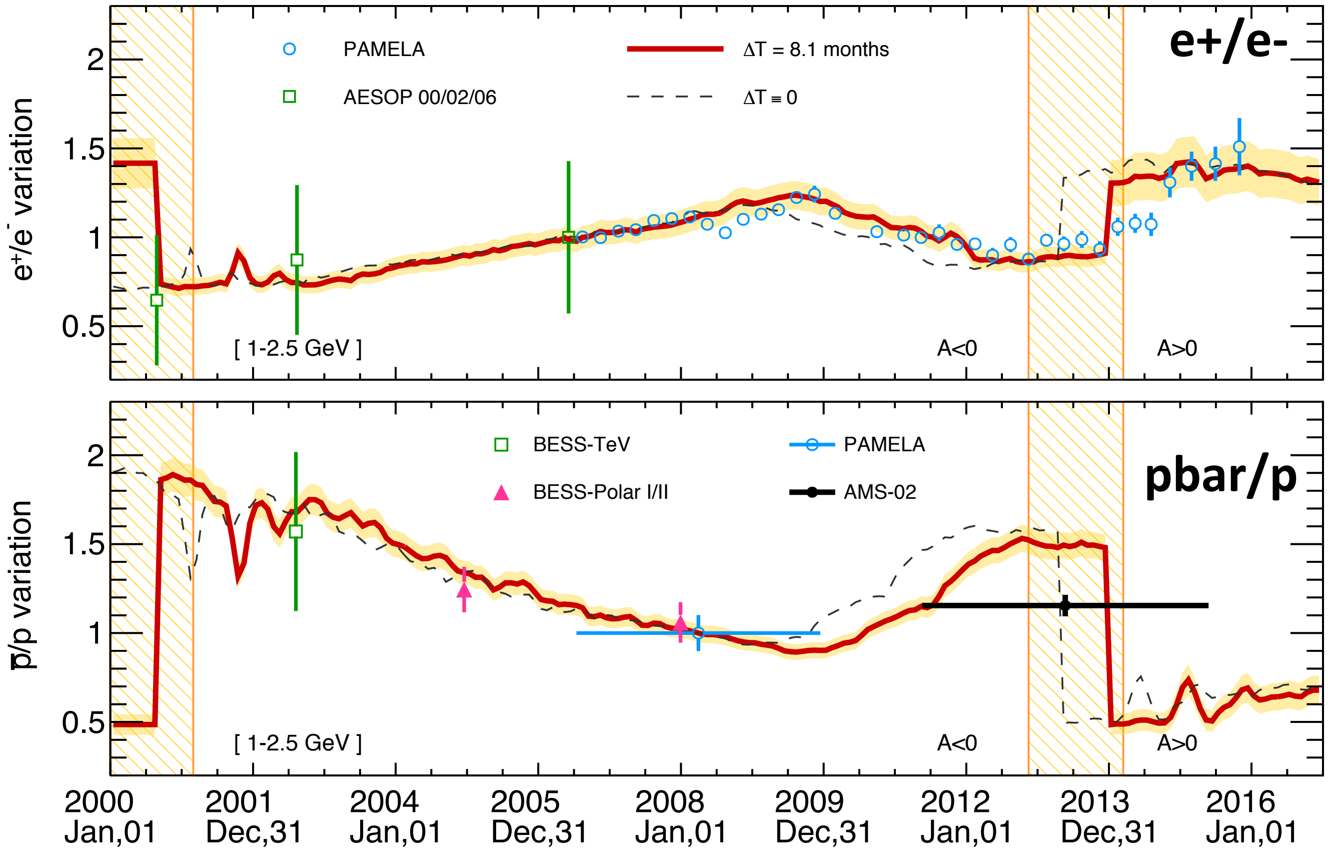


Evidence for charge-sign dependent modulation

Data-driven model prediction
using solar-activity data as inputs

polar B-field reversal

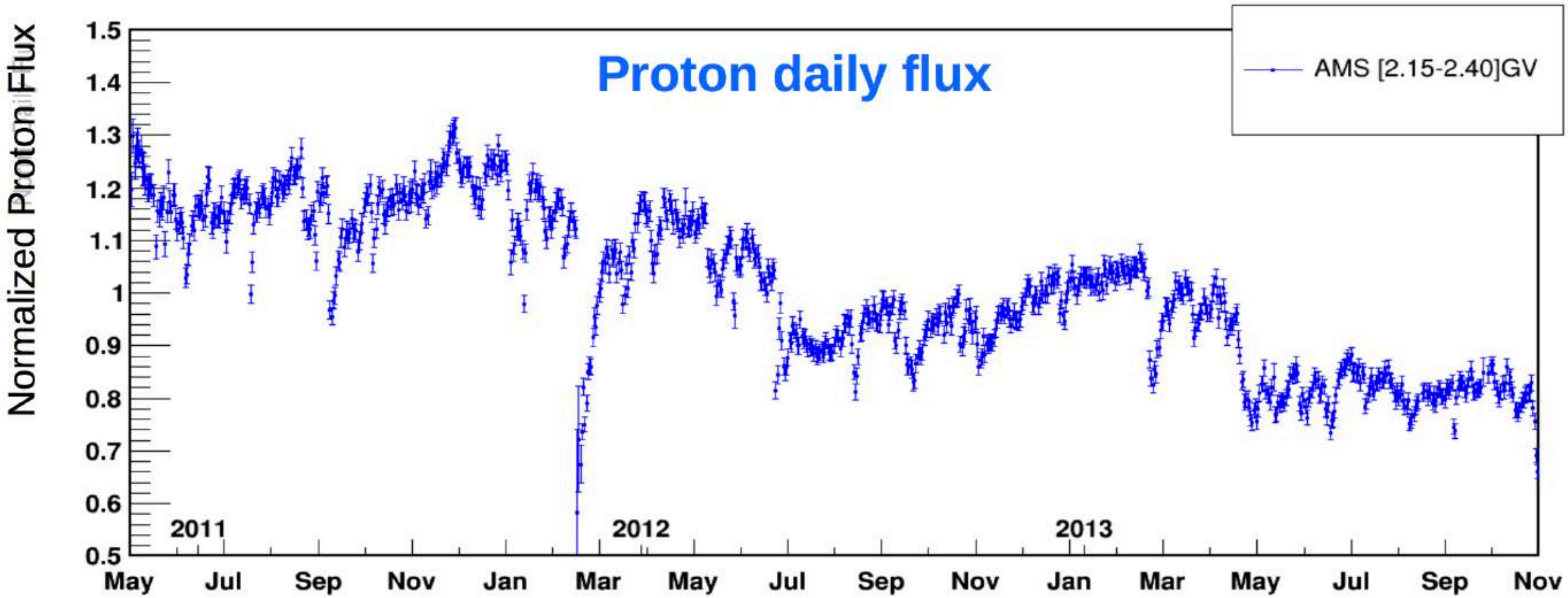


AMS-02 measurements of the antiproton/proton ratio are ongoing...

- Increase of the positron / electron ratio
- Decrease of antiproton/proton ratio
- Time-lag of ~8.1 month w.r.t. solar-activity data

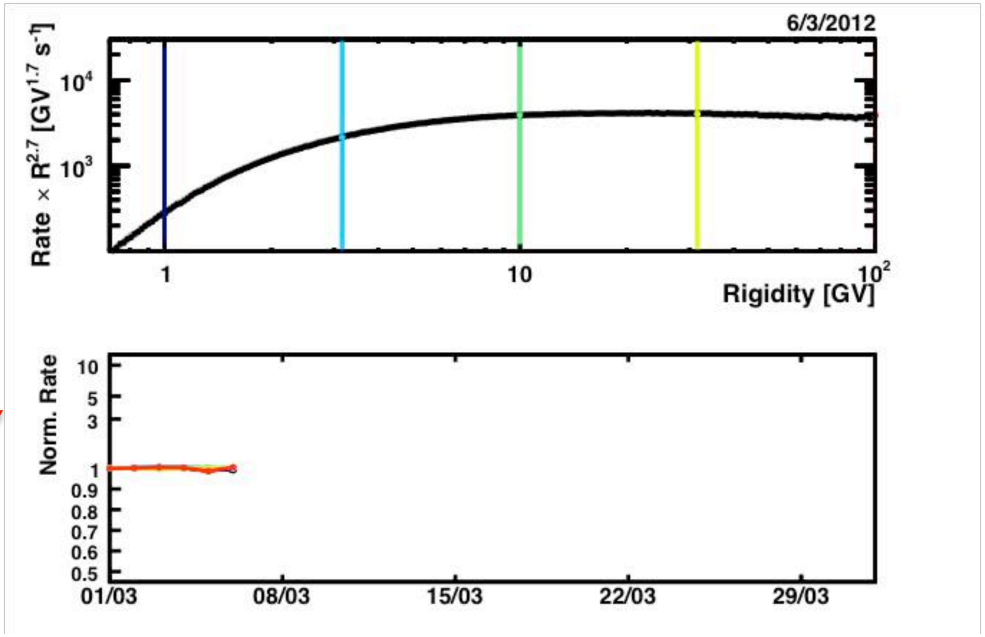
Daily flux of cosmic-ray proton

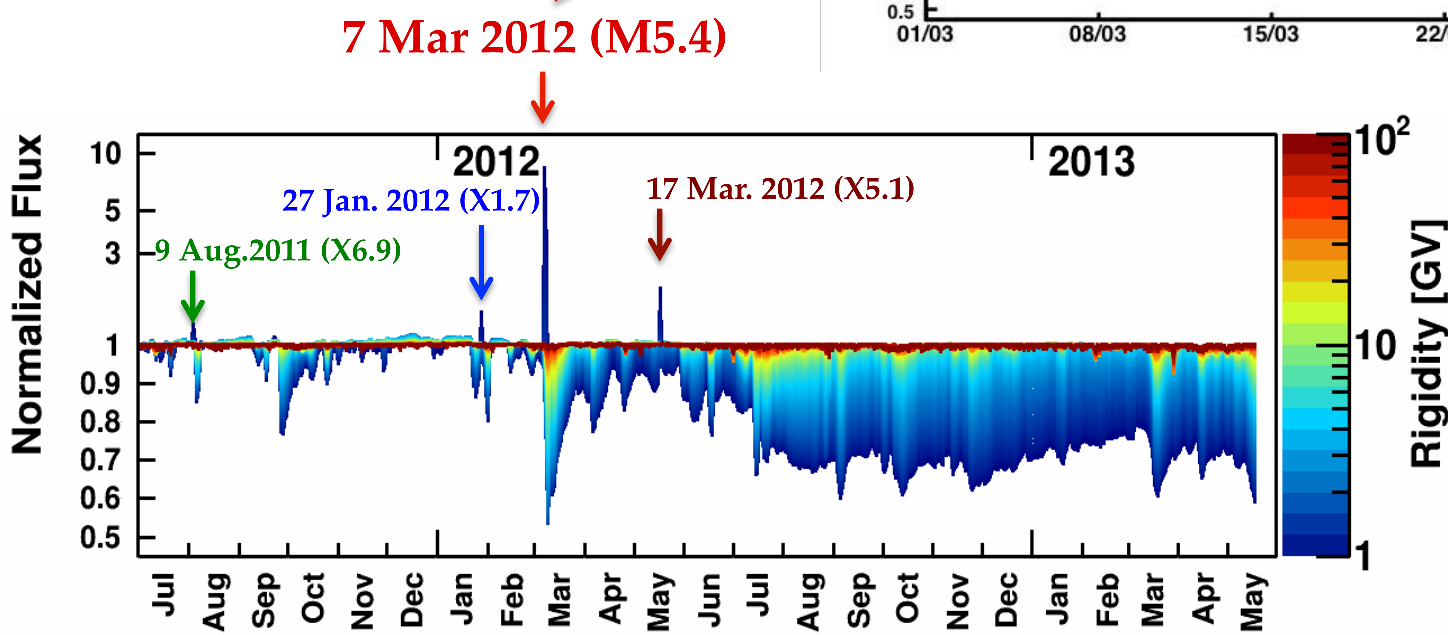
A detailed study of the fluxes evolution with time is needed in order to develop and test



Solar modulation study at small time-scale

- *AMS gives us the opportunity to monitor the solar modulation effect over an entire solar cycle and more.*
- *The time variation of the proton spectrum is currently studied on daily basis.*
- *Solar energetic particle events can be detected and studied (flux intensity, spectral shape, composition)*





animated slide
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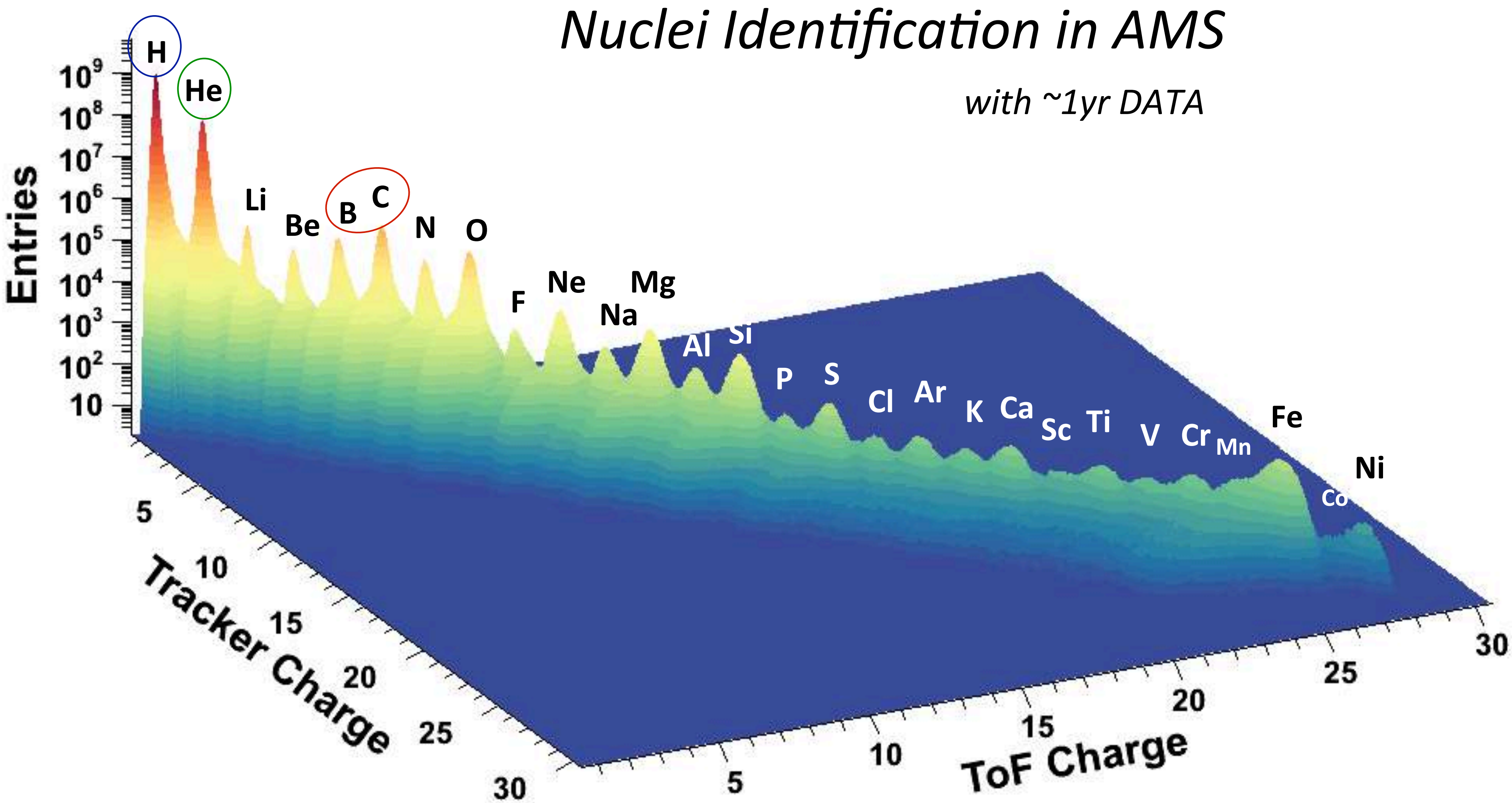
Thank you

Спасибо за внимание

Identification of nuclei with AMS



Modeling cosmic-ray transport in Helisophere

$$\underbrace{\frac{\partial f}{\partial t}}_{\text{Flux}} = \underbrace{\nabla \cdot [\mathbf{K} \cdot \nabla f]}_{\text{Diffusion}} - \underbrace{\boldsymbol{V} \cdot \nabla f}_{\text{Convection}} - \underbrace{\langle \boldsymbol{v}_D \rangle \cdot \nabla f}_{\text{Particle drift}} + \underbrace{\frac{1}{3}(\nabla \cdot \boldsymbol{V}) \frac{\partial f}{\partial \ln p}}_{\text{Adiabatic losses}} + \underbrace{Q(r,p,t)}_{\text{Source / LIS}}$$

Krymsky – Parker Equation, 1964

Modeling cosmic-ray transport in Helisophere

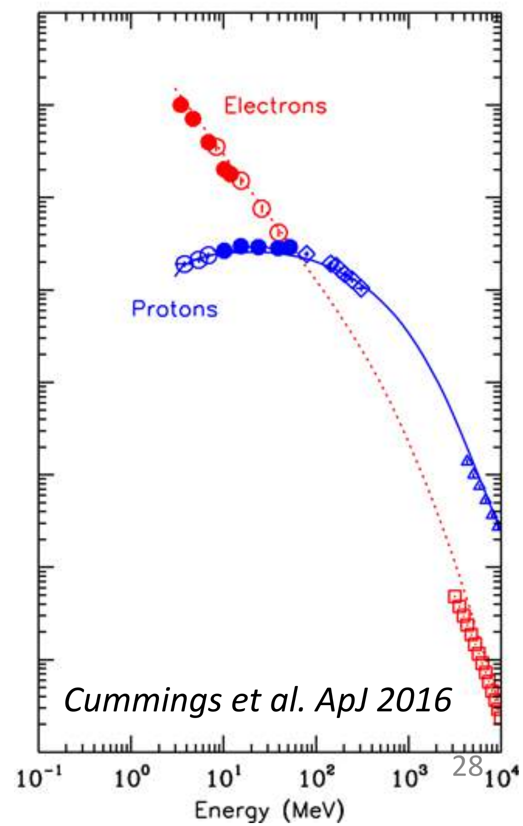
$$\underbrace{\frac{\partial f}{\partial t}}_{\text{Flux}} = \underbrace{\nabla\cdot\left[\mathbf{K}\cdot\nabla f\right]}_{\text{Diffusion}} - \underbrace{\boldsymbol{V}\cdot\nabla f}_{\text{Convection}} - \underbrace{\langle \boldsymbol{v}_D \rangle \cdot \nabla f}_{\text{Particle drift}} + \underbrace{\frac{1}{3}(\nabla\cdot\boldsymbol{V})\frac{\partial f}{\partial \ln p}}_{\text{Adiabatic losses}} + \underbrace{Q(r,p,t)}_{\text{Source / LIS}}$$

Essential input: Local interstellar spectra

- Low-energy (E<GeV): Strong constraints from Voyager-1, which is now sampling the interstellar space.
- High-energy (E>20 GeV) constraints from AMS-02

Protons and electrons: direct constraints from Voyager-1 (*Cummings et al. 2016*) + AMS (*Aguilar et al. 2014 & 2015*)

Antiprotons and positrons: from calculations of secondary CR production in the interstellar medium (NT PRD 2015)



In practice, the LIS input states the boundary conditions of the problem

Modeling cosmic-ray transport in Helisophere

$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K} \cdot \nabla f] - \mathbf{V} \cdot \nabla f - \langle \mathbf{v}_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln p} + Q(r,p,t)$$

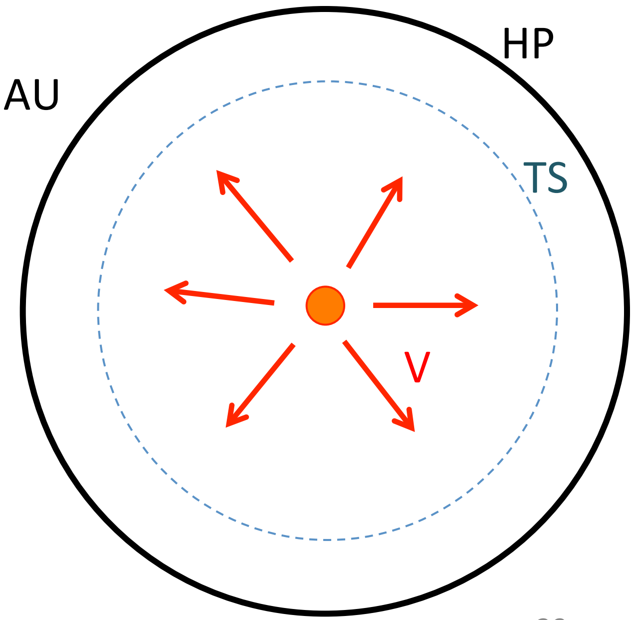
Flux — **Diffusion** — **Convection** — **Particle drift** — **Adiabatic losses** — **Source / LIS**

Convection and energy losses due to Solar Wind

Radially outflowing from the Sun with speed V= 400 km/s

Change to subsonic speed beyond termination shock @ r=85 AU

Vanishing at the Heliopause boundary @ r=122 AU

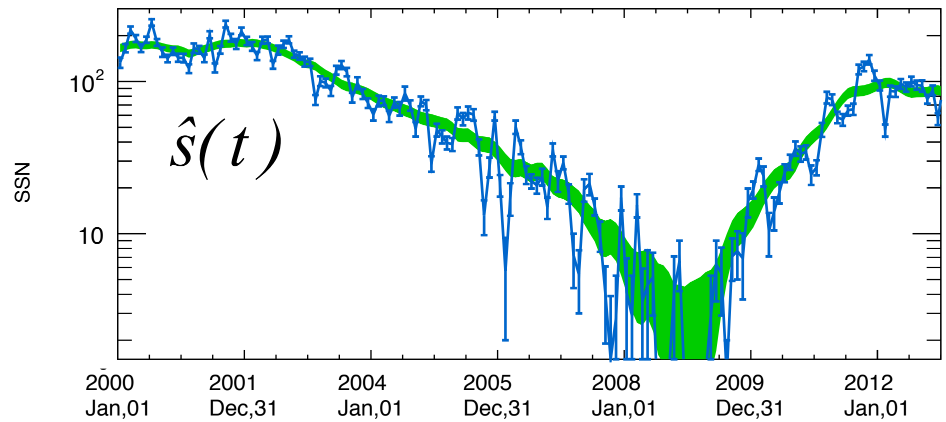


Modeling cosmic-ray transport in Helisophere

$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K} \cdot \nabla f] - \boldsymbol{V} \cdot \nabla f - \langle \boldsymbol{v}_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla \cdot \boldsymbol{V}) \frac{\partial f}{\partial \ln p} + Q(r,p,t)$$

Flux | **Diffusion** | **Convection** | **Particle drift** | **Adiabatic losses** | **Source / LIS**

$$\begin{cases} K_{\perp} = 0.02 \cdot K_{//} \\ K_{//} = k^0(t) \dfrac{10^{22} \cdot \beta p / GeV}{3B/B_0} \end{cases}$$



- ✓ **Adimensional normalization factor**
- ✓ **Time-dependent & related to solar activity**

$$\kappa^0(s) = a \cdot log_{10}(s) + b$$

S = measured sunspot number

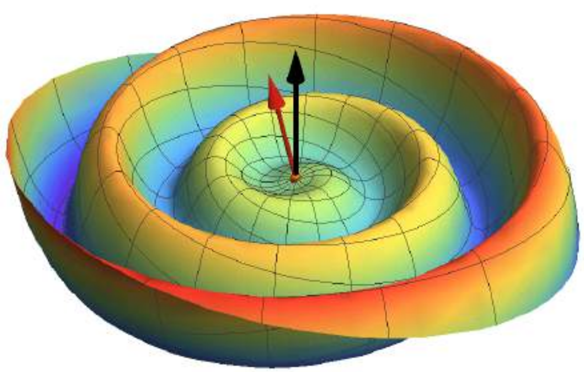
Modeling cosmic-ray transport in Helisophere

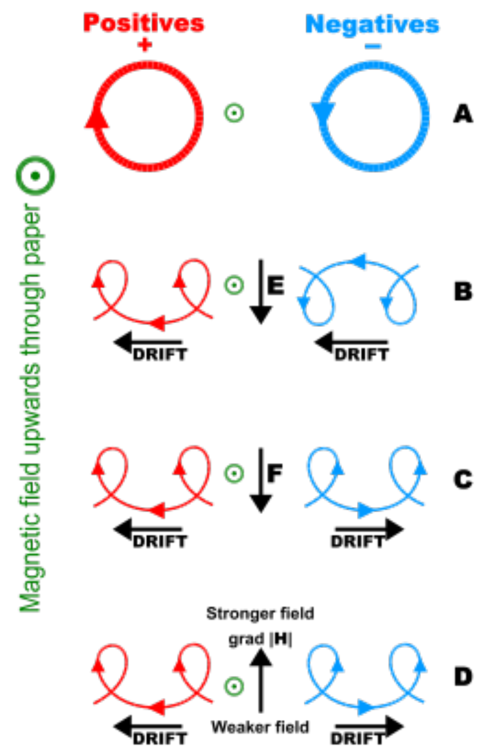
$$\underbrace{\frac{\partial f}{\partial t}}_{\text{Flux}} = \underbrace{\nabla \cdot [\mathbf{K} \cdot \nabla f]}_{\text{Diffusion}} - \underbrace{\boldsymbol{V} \cdot \nabla f}_{\text{Convection}} - \underbrace{\langle \boldsymbol{v}_D \rangle \cdot \nabla f}_{\text{Particle drift}} + \underbrace{\frac{1}{3}(\nabla \cdot \boldsymbol{V}) \frac{\partial f}{\partial \ln p}}_{\text{Adiabatic losses}} + \underbrace{Q(r,p,t)}_{\text{Source / LIS}}$$

Drift motion along the B-field spiral

$$\langle \mathbf{v}_{\mathrm{dr}} \rangle = \frac{\beta\, P}{3} \nabla \times \frac{\mathbf{B}}{B^2}$$

- ✓ **Charge-sign dependent effect.**
- ✓ **Important in the Heliospheric Current Sheet**





- ✓ **The HCS "*waviness*" depends on *tilt-angle* α**

Modeling cosmic-ray transport in Helisophere

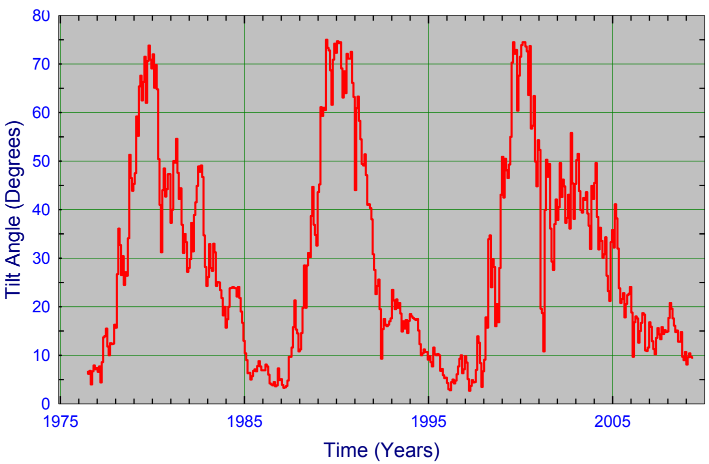
$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K} \cdot \nabla f] - V \cdot \nabla f - \langle v_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla \cdot V)\frac{\partial f}{\partial \ln p} + Q(r,p,t)$$

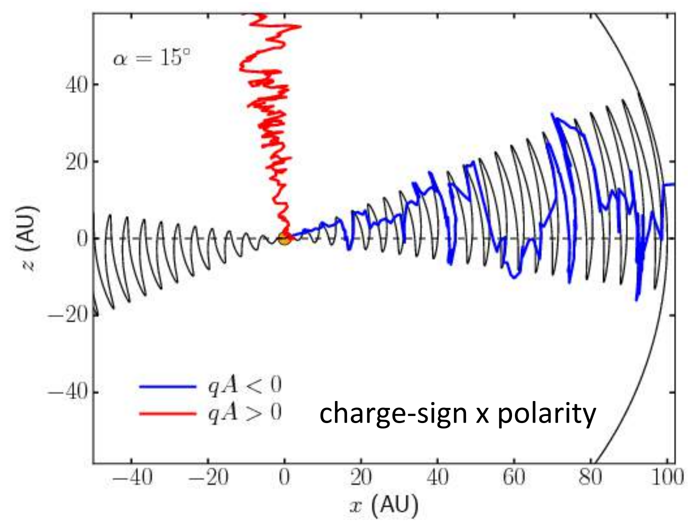
Flux | Diffusion | Convection | Particle drift | Adiabatic losses | Source / LIS

Drift motion along the B-field spiral

- ✓ **Charge-sign dependent effect.**
- ✓ **Important in the Heliospheric Current Sheet**
- ✓ **Different trajectories for particles & antiparticles**
- ✓ **Interchanged role with B-field reversal (T=11-yrs)**

Tilt angle reconstruction from WSO





To investigate the effects, time-resolved flux data on particles and antiparticles are needed