# Precision Measurement of the Monthly Cosmic Ray Fluxes with the Alpha Magnetic Spectrometer on the International Space Station

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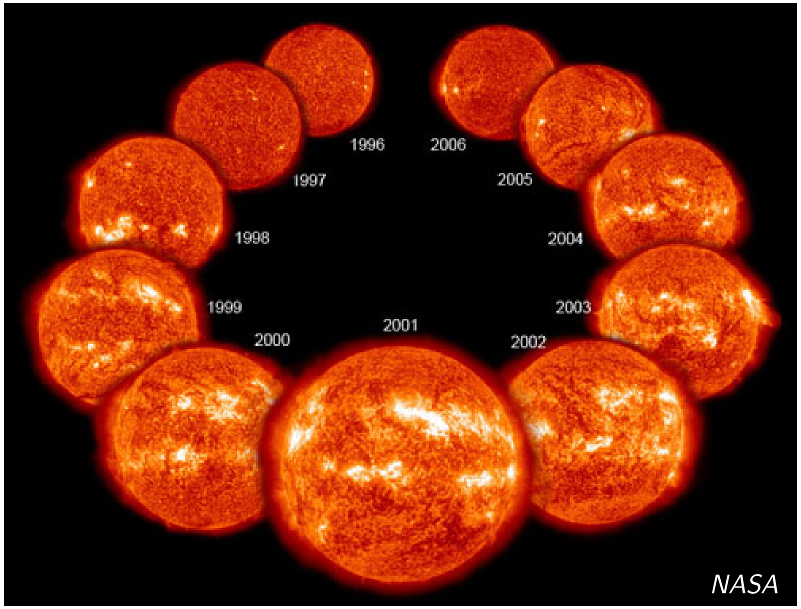
*Figures: IBEX Team/Adler Planetarium, NASA*

# Outline

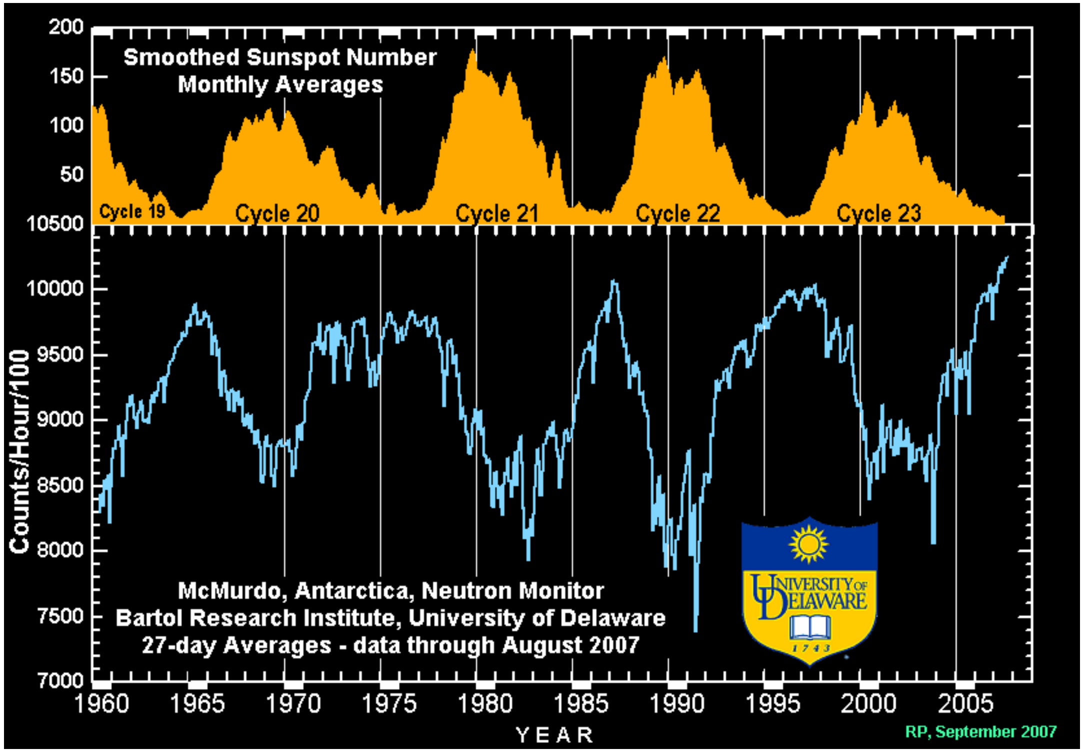
- The Sun and the heliosphere
- Solar modulation of cosmic rays
- AMS-02 on the ISS
- Monthly cosmic ray fluxes measurement
- Theoretical interpretation

# Solar activity and cosmic rays




The Sun goes through an 11-years period of activity, which can be measured from Earth by counting the number of sunspots on the surface of the Sun.

The number of galactic cosmic rays (GCRs) reaching the Earth is anti-correlated with the intensity of the solar activity and shows a 22-years periodicity, in addition to the 11-years cycle.



# Solar wind

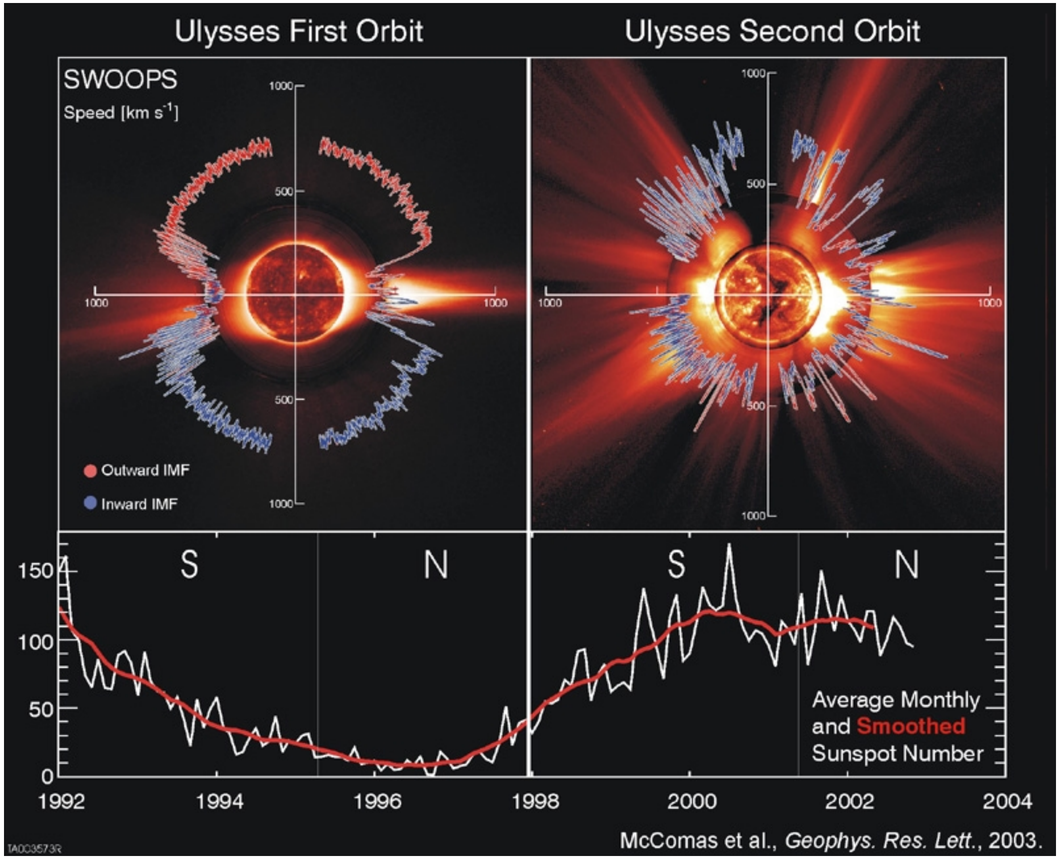

Biermann (1951): why do comet tails always point away from the Sun? Maybe the Sun emits a constant stream of particles!

Parker (1958): the corona is so hot that cannot be in static equilibrium, so it expands: let's call it solar wind!

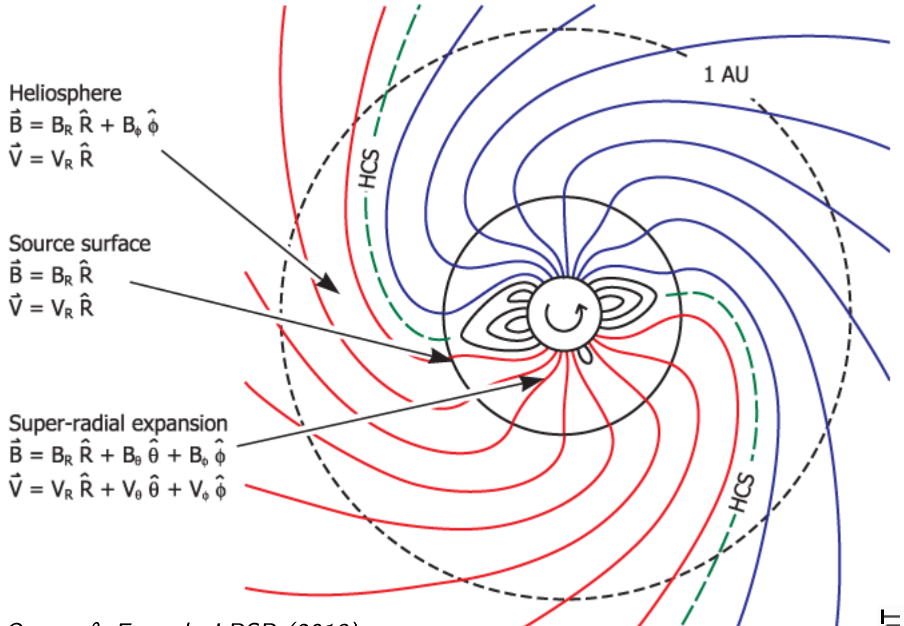
Ulysses (1990-2009): three orbits around the Sun with 80° inclination.

Observation of two components of solar wind:

- Slow: 400 km/s, 1.5x$10^6$ K; highly variable; from coronal streamers at the equator
- Fast: 800 km/s, 8x$10^5$ K; less variable; from coronal holes at the poles



# Heliospheric magnetic field

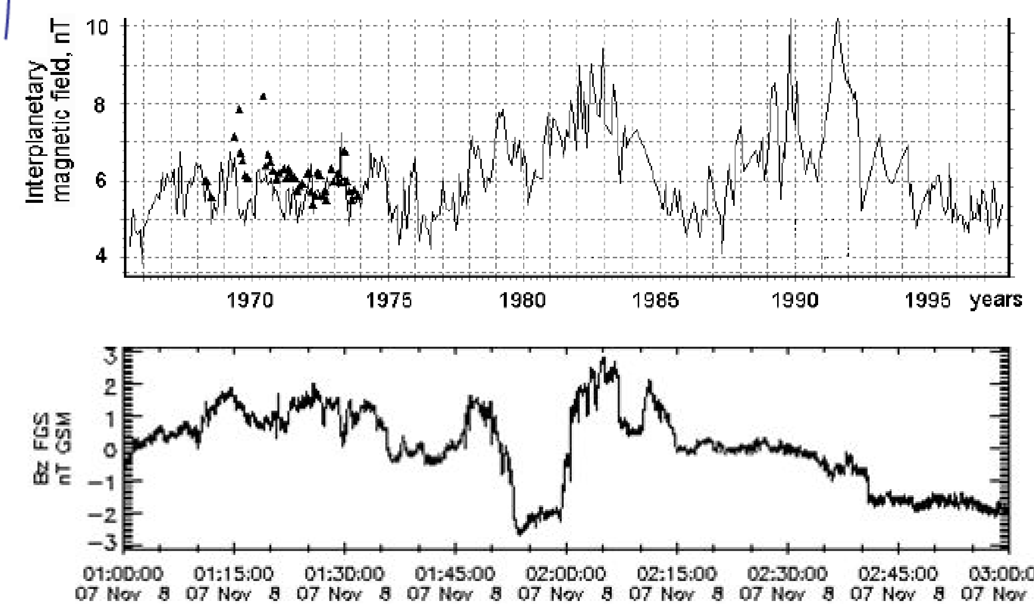



*Owens & Forsyth, LRSP (2013)*

The coronal magnetic field is embedded in the solar wind plasma and it expands with it, becoming the heliospheric magnetic field (HMF).

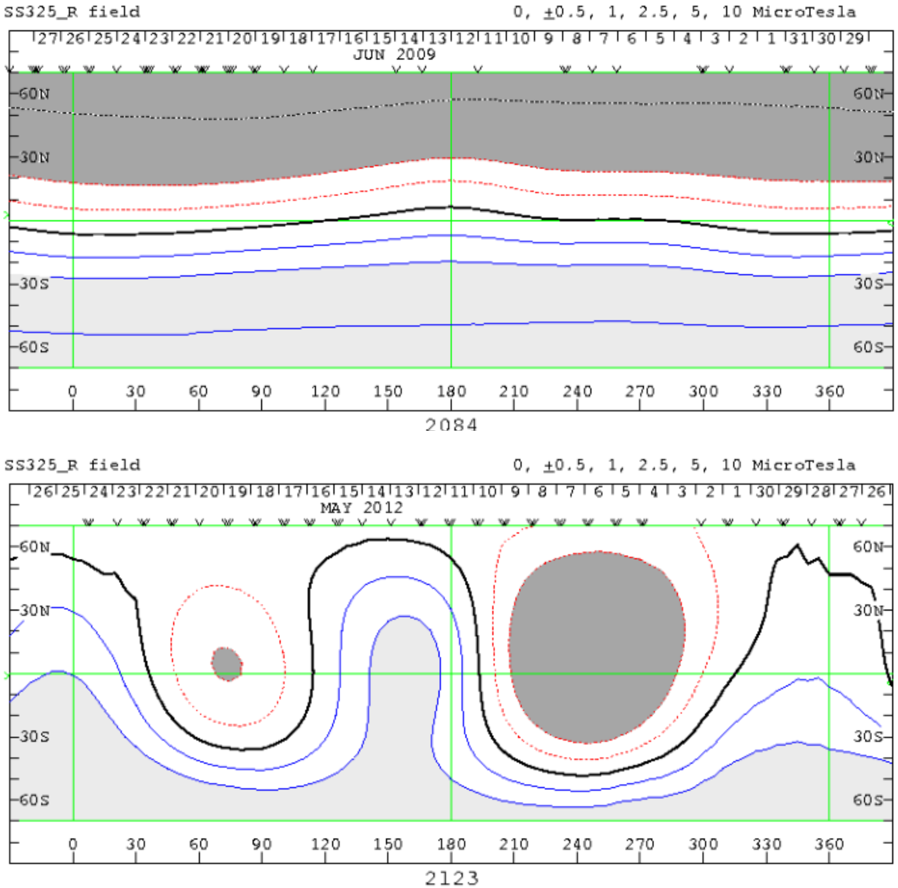
The footpoints of the magnetic field lines co-rotate with the Sun, so the HMF is bent into a spiral shape, called Parker's spiral.

Daily and sub-daily variability is high, but on average the field is well described by the Parker model in all the heliosphere, as observed by Pioneer, Voyager and Ulysses.




*Belov, SSRv (2000)*

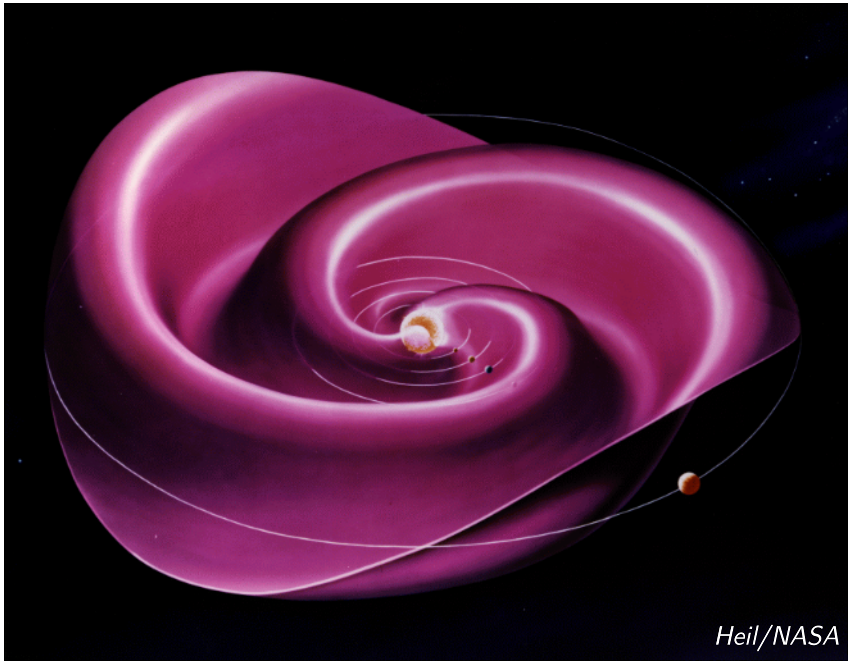
# Heliocurrent sheet



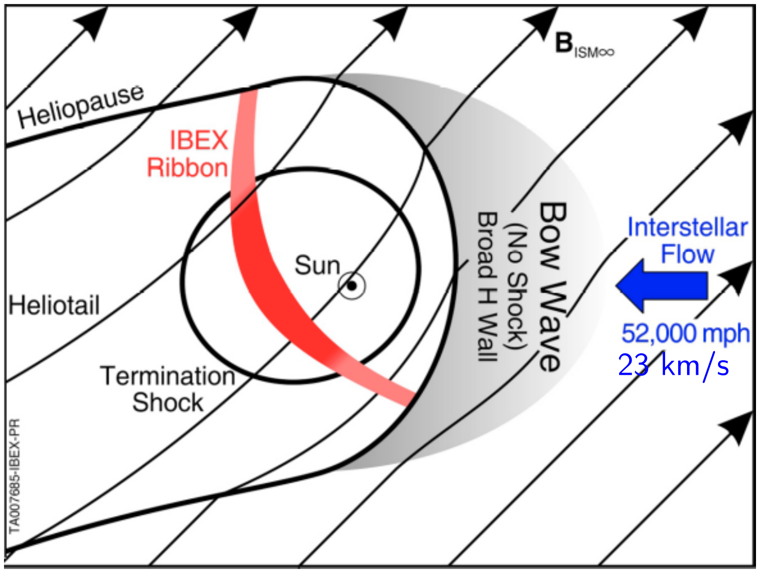

*http://wso.stanford.edu/synsourcel.html*

Coronal field model computed at Wilcox Solar Observatory (Stanford) used to get the inclination of the magnetic equator. During the maximum, the equator is ill-defined.

The magnetic equator expands becoming a neutral surface: the heliocurrent sheet (HCS).



# Heliosphere structure




*McComas et al., Sci (2012)*

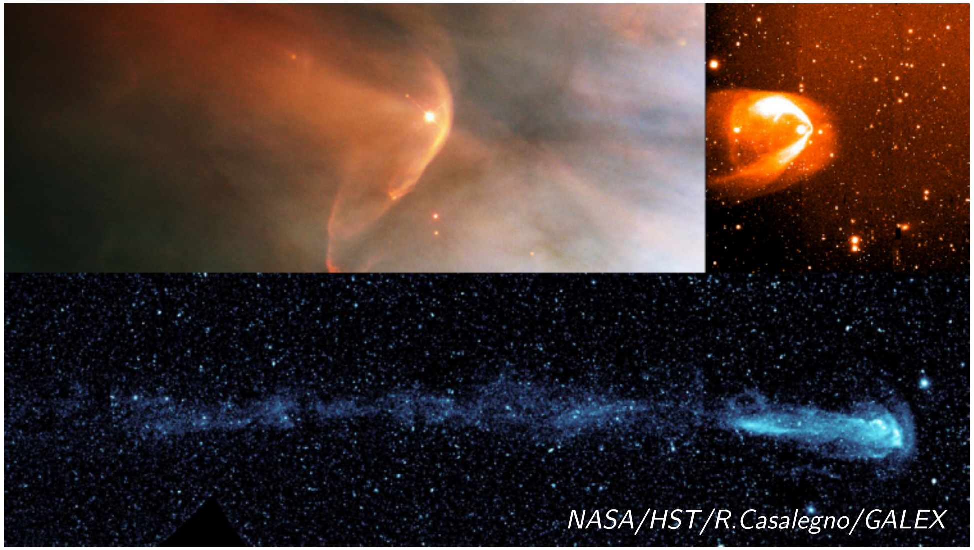
The heliosphere is a bubble of plasma and magnetic field surrounding the solar system, created by the solar wind.

At the termination shock (TS), the solar wind transitions from super-sonic to sub-sonic.

At the heliopause (HP), the solar wind pressure equals the interstellar medium (ISM) pressure.

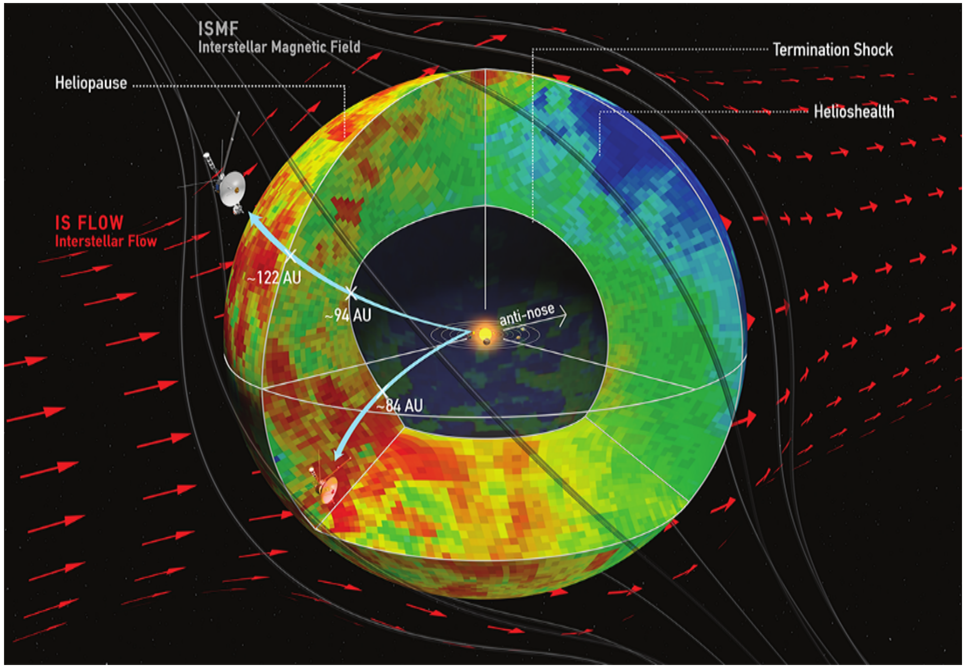
The heliotail is the wake wave created by the motion of the Sun in the ISM.

Observations of astropheres seems to confirm the existence of a comet-like tail.

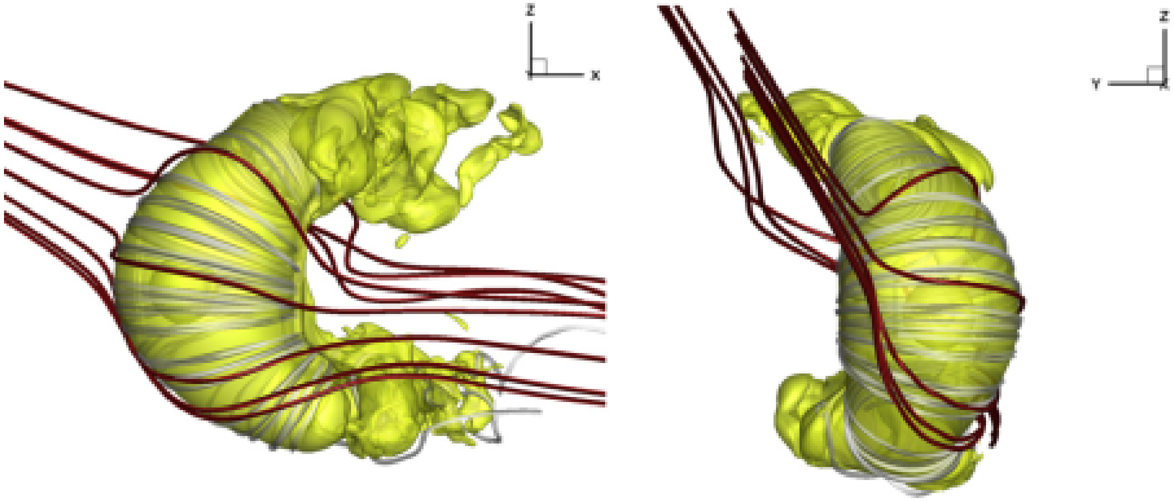


# Heliosphere structure: latest news

Comparing data from Cassini, Voyager and IBEX shows that the tail and the nose react with similar time scales to the changing solar activity.
The heliosphere might be more bubble-like than expected!



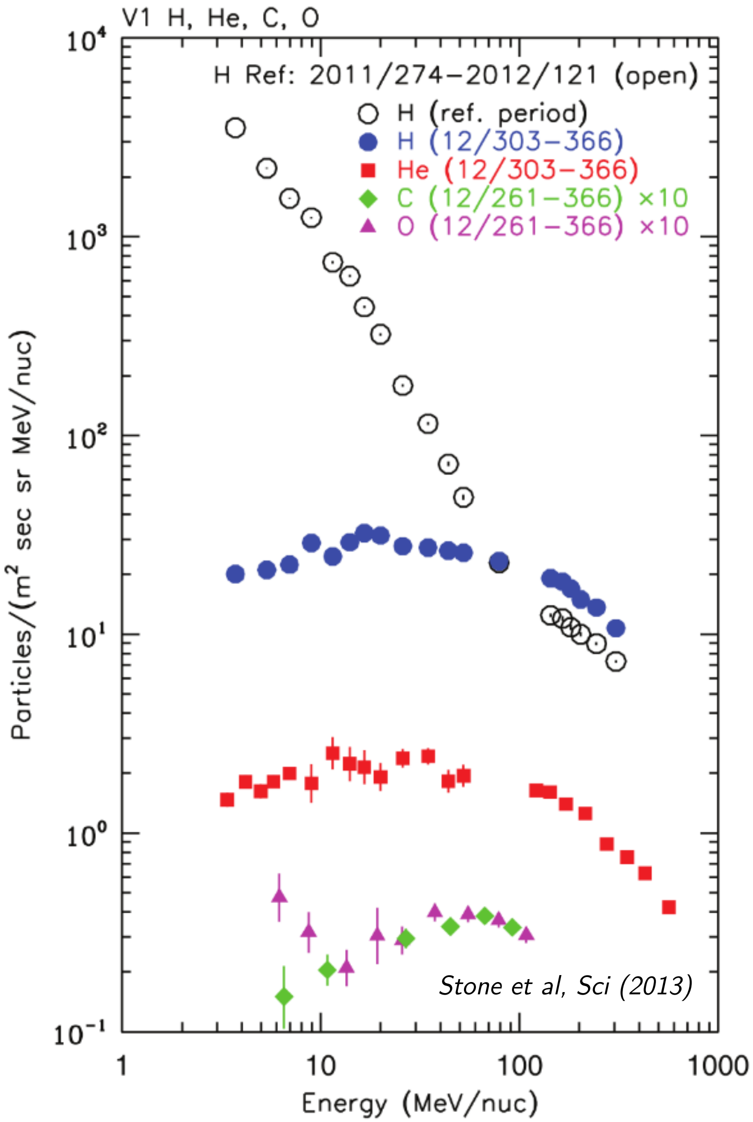

*Dialynas et al., NatAs (2017)*



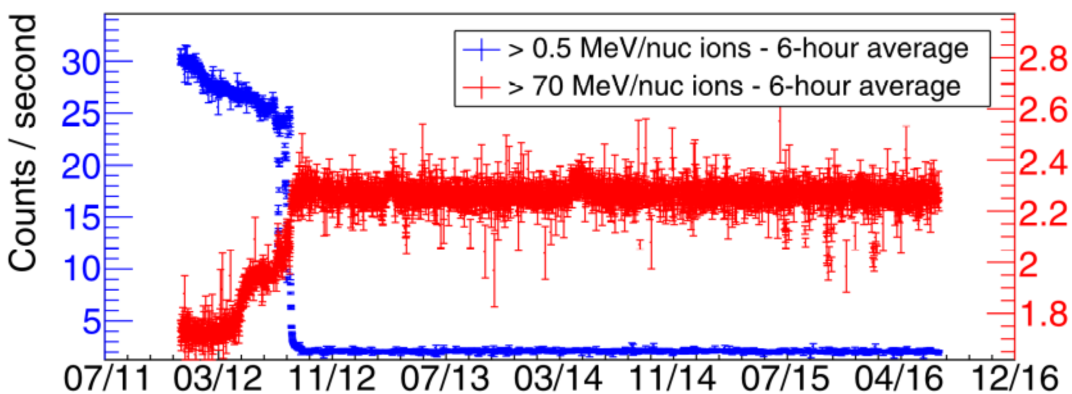

*Opher et al., ApJ (2015)*

Some models even predict a croissant-like shape, consistent with data.

# Voyager 1 in the interstellar medium




- 25 August 2012: Voyager 1 reaches the heliopause
- Fluxes stable since then: best candidate for low energy range of the local interstellar spectrum (LIS)




*https://voyager.gsfc.nasa.gov/flux.html*

# Voyager 1 & 2 status

Jet Propulsion Laboratory
California Institute of Technology

NEWS | OCTOBER 5, 2018

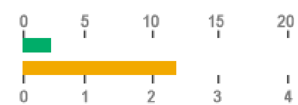
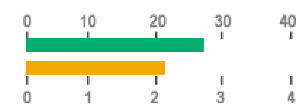
## NASA Voyager 2 Could Be Nearing Interstellar Space

*"Since late August, the Cosmic Ray Subsystem instrument on Voyager 2 has measured about a 5 percent increase in the rate of cosmic rays hitting the spacecraft compared to early August. The probe's Low-Energy Charged Particle instrument has detected a similar increase in higher-energy cosmic rays.*

*[...]*

*In May 2012, Voyager 1 experienced an increase in the rate of cosmic rays similar to what Voyager 2 is now detecting. That was about three months before Voyager 1 crossed the heliopause and entered interstellar space."*

*https://www.jpl.nasa.gov/news/news.php?feature=7252*

| | Voyager 1 | Voyager 2 |
|---|---|---|
| **Launch Date** | Mon, 05 Sept 1977 12:56:00 UTC | Sat, 20 Aug 1977 14:29:00 UTC |
| **Mission Elapsed Time** | 41 : 01 : 04 : 08 : 11 : 07 (YRS MOS DAYS HRS MINS SECS) | 41 : 01 : 19 : 06 : 38 : 08 (YRS MOS DAYS HRS MINS SECS) |
| **Distance from Earth** | 21,536,766,901 km | 17,762,142,137 km |
| | 143.96439469 AU | 118.73258659 AU |
| **Distance from Sun** | 21,475,734,986 km | 17,770,948,708 km |
| | 143.55642153 AU | 118.79145489 AU |
| **Velocity with respect to the Sun (estimated)** | 16.9995 kps | 15.3741 kps |
| **One-Way Light Time** | 19:57:18 (hh:mm:ss) | 16:27:28 (hh:mm:ss) |
| **Cosmic Ray Data** |  |  |

*https://voyager.jpl.nasa.gov/mission/status/#where_are_they_now*

# Transport equation of GCRs

GCR propagation in the heliosphere described by the Parker equation:

$$\frac{\partial f}{\partial t} = \underbrace{-\vec{V}_{SW} \cdot \vec{\nabla} f}_{\text{Solar wind plasma convection}} \underbrace{-\vec{V}_D \cdot \vec{\nabla} f}_{\text{Particle drift}} + \underbrace{\vec{\nabla} \cdot (K \cdot \vec{\nabla} f)}_{\text{Particle diffusion}} + \underbrace{\frac{1}{3} \vec{\nabla} \cdot \vec{V}_{SW} \frac{\partial f}{\partial \ln R}}_{\text{Energy changes}} + \underbrace{Q}_{\text{Sources/sinks}}$$

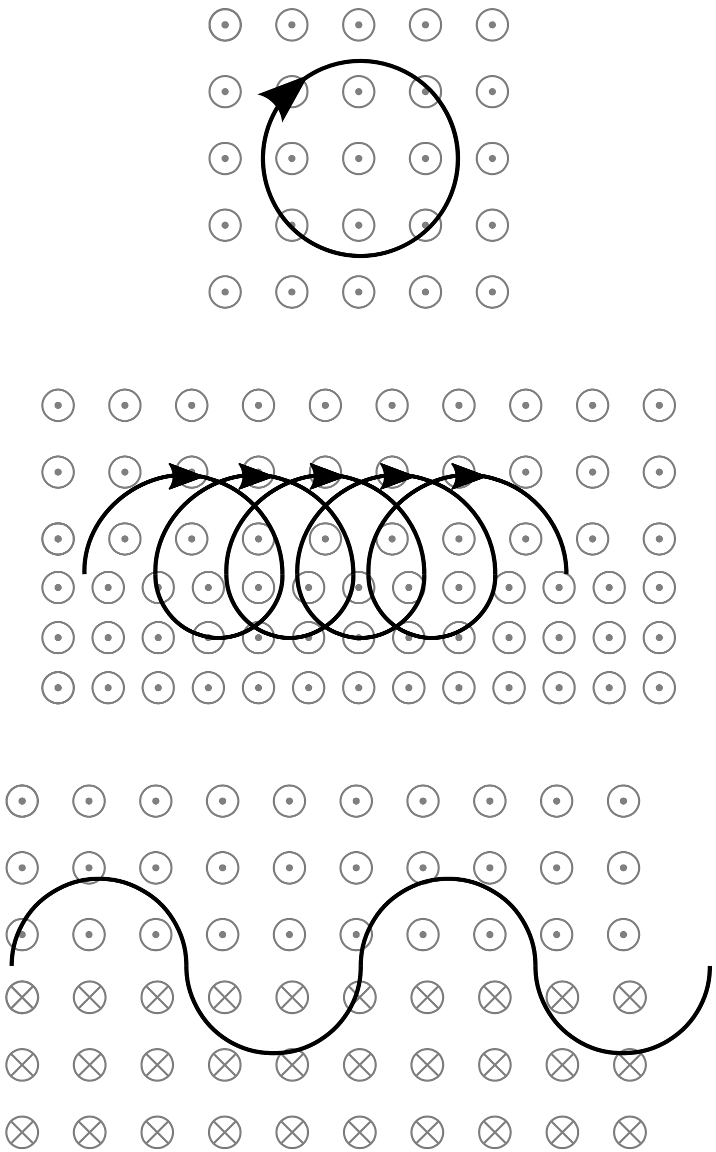
$f$ = omnidirectional distribution function of GCRs

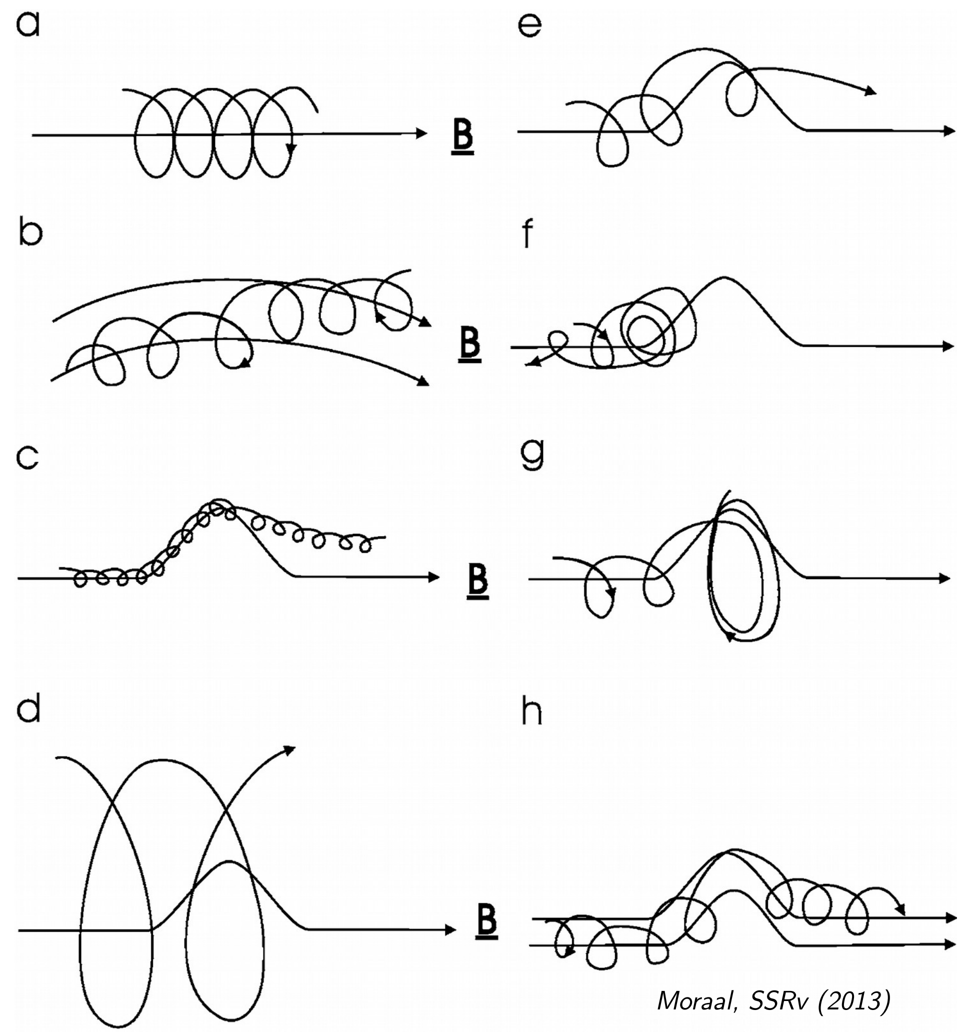
$K$ = diffusion tensor: scattering on magnetic field irregularities

Particle drifts due to heliospheric magnetic field gradients and heliospheric current sheet.

Adiabatic energy losses/gains due to expansion/compression of solar wind velocity.

# Charged particles in magnetic field

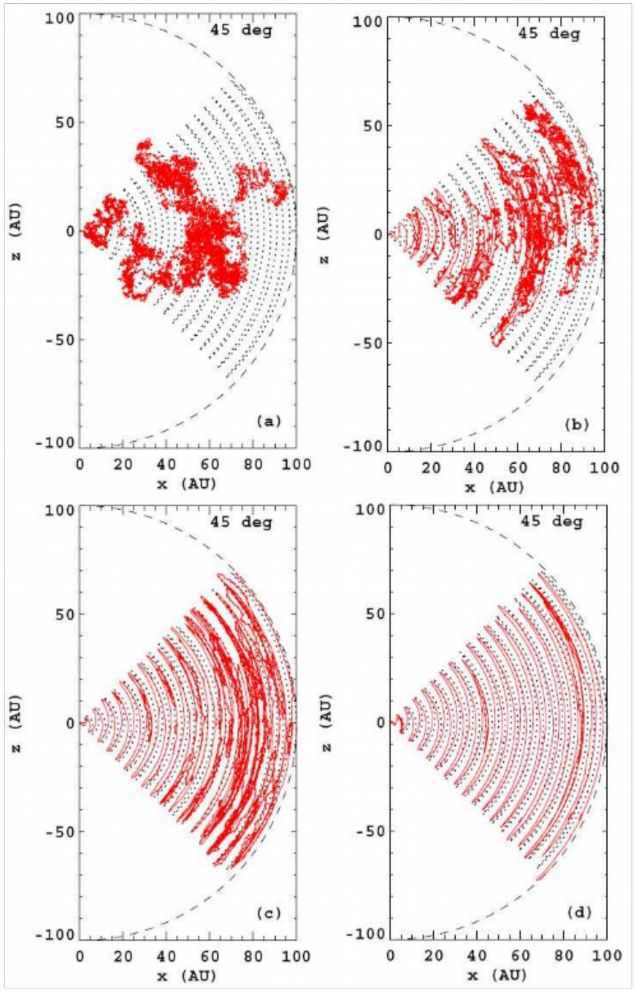




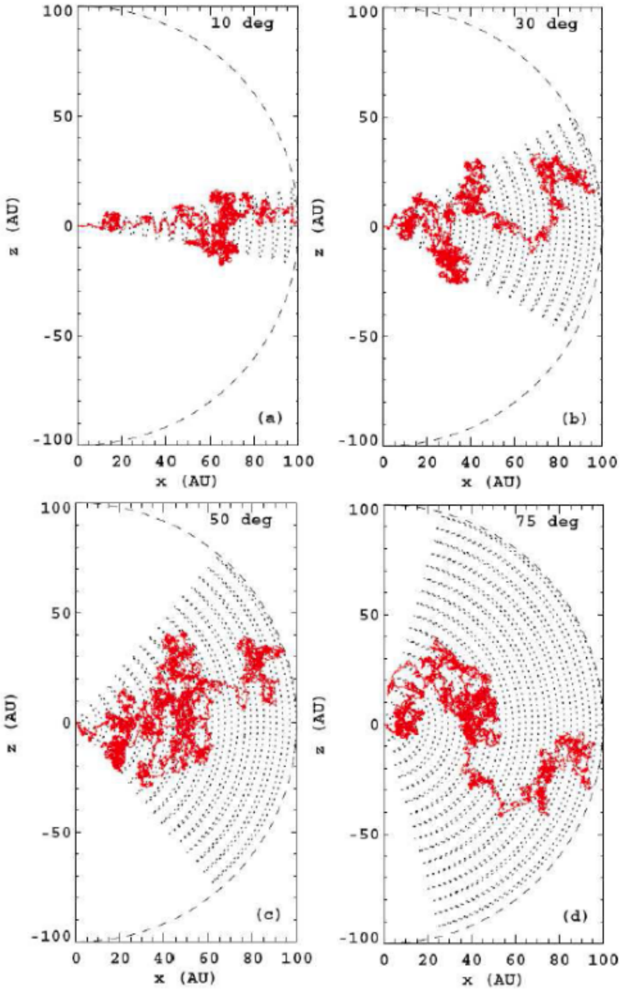

*Moraal, SSRv (2013)*

# GCR trajectories – Monte Carlo simulation

Decreasing diffusion




Increasing HCS tilt angle

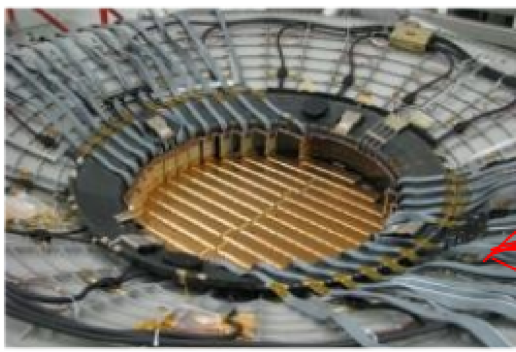



*Strauss et al., Ap&SS (2012)*

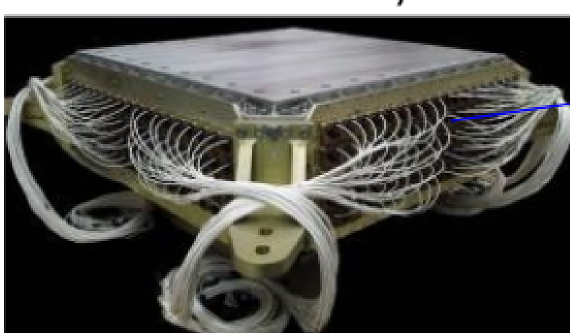
# AMS: a TeV precision spectrometer

**TRD:** Identify e+, e-, Z

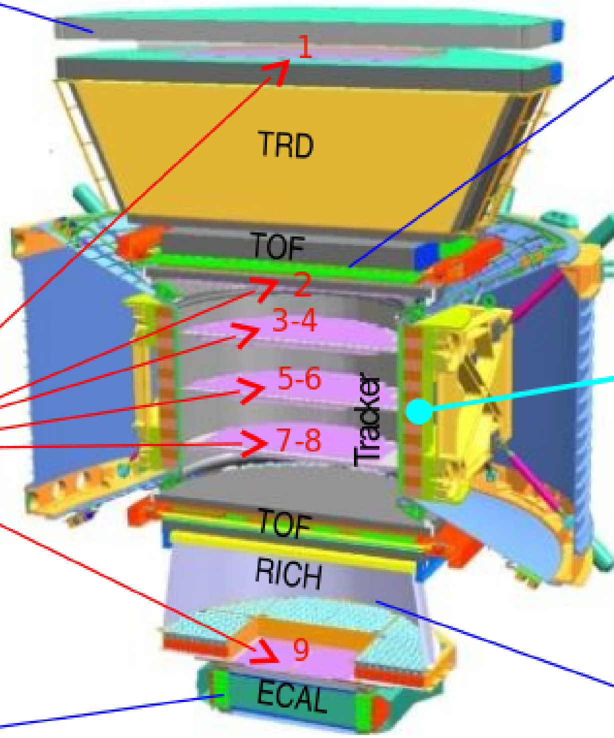
**Silicon Tracker:** Z, P



**ECAL:** E of e+, e-



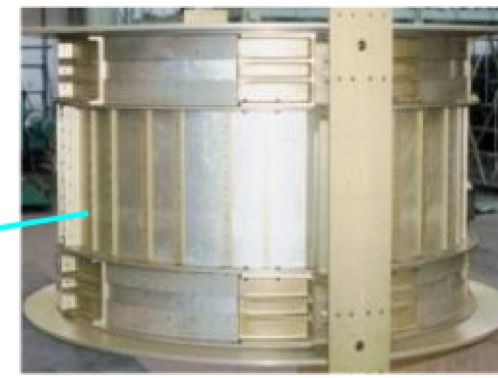
**Particles and nuclei are defined by their charge (Z) and energy (E) or momentum (P). Rigidity R = P/Z**




**Z and P**
**are measured independently by the Tracker, RICH, TOF and ECAL**

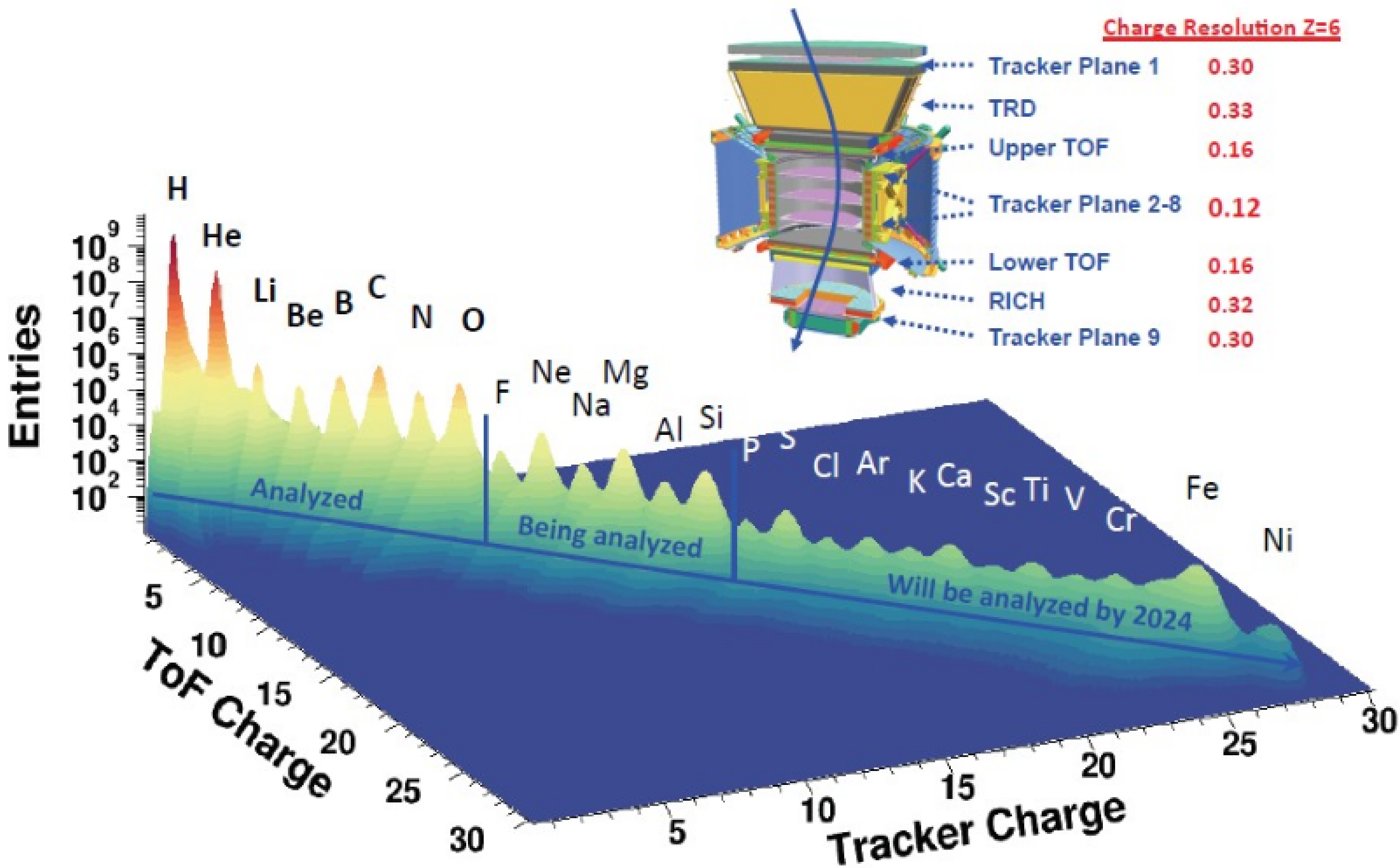
**TOF:** Z, E

**Magnet:** ±Z



**RICH:** Z, E

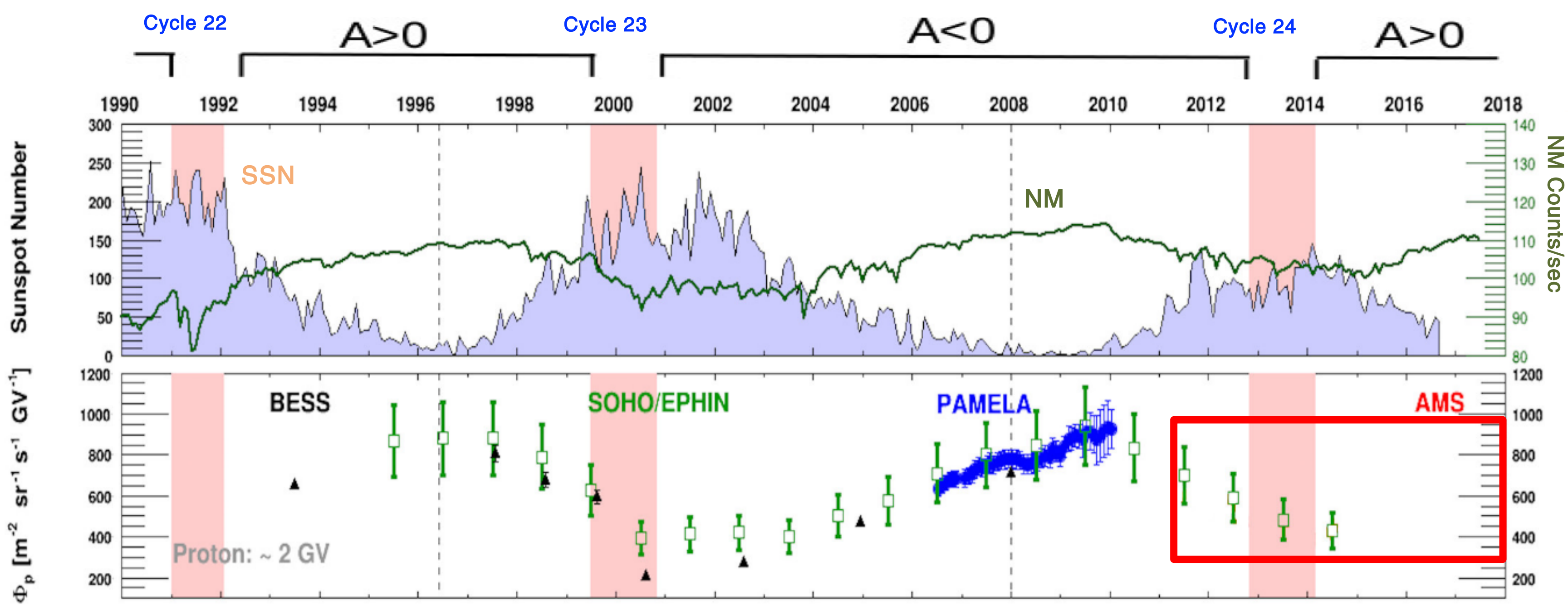
# Precision measurement of GCRs



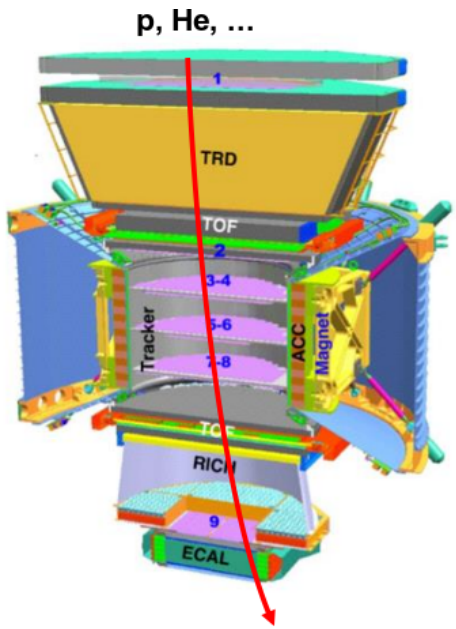

**AMS has 7 instruments which independently measure Cosmic Nuclei**

# GCR data from space

- Scarcity of data from space above GV
- AMS taking data during ascending phase of solar cycle 24, solar maximum and descending phase of solar cycle.
- AMS will keep measuring GCRs until ISS end-of-life (2024?), analyzing the maximum of the next solar cycle



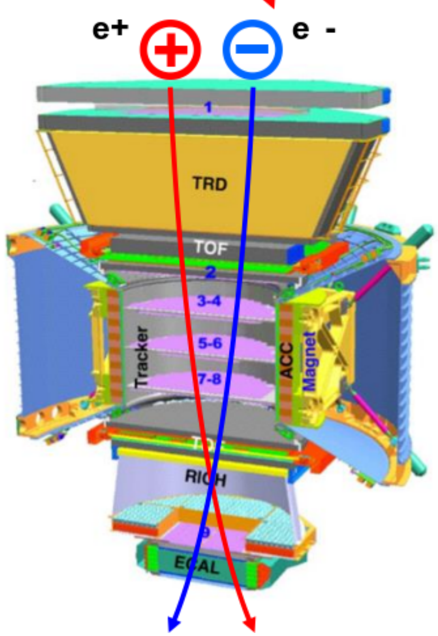
# Analysis workflow




### Time-of-Flight
- Trigger
- Particle direction & velocity
- Charge

### Silicon tracker + Magnet
- Rigidity
- Charge & Sign

### Montecarlo vs Data
- Tracker resolution
- Cross-sections
- Efficiencies




### Time-of-Flight
- Trigger
- Particle direction & velocity
- Charge

### Silicon tracker + Magnet
- Rigidity
- Charge & Sign

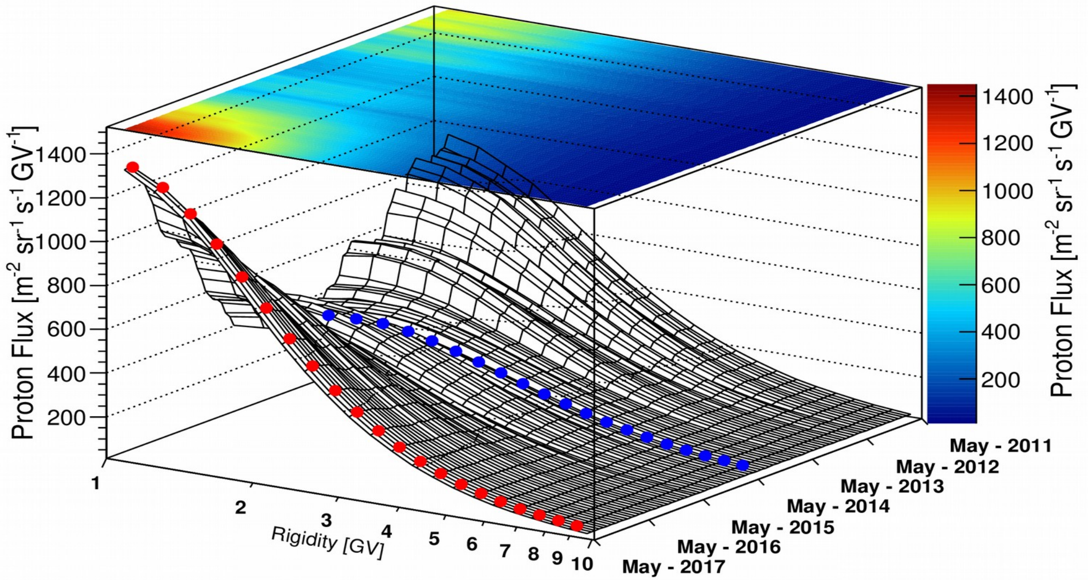
### TRD
- $e^+$ and $e^-$ identification

### ECAL
- $e^+$ and $e^-$ identification
- Energy

### ECAL vs Tracker
- Energy scale stability

### Montecarlo vs Data
- Charge-confusion
- Efficiencies

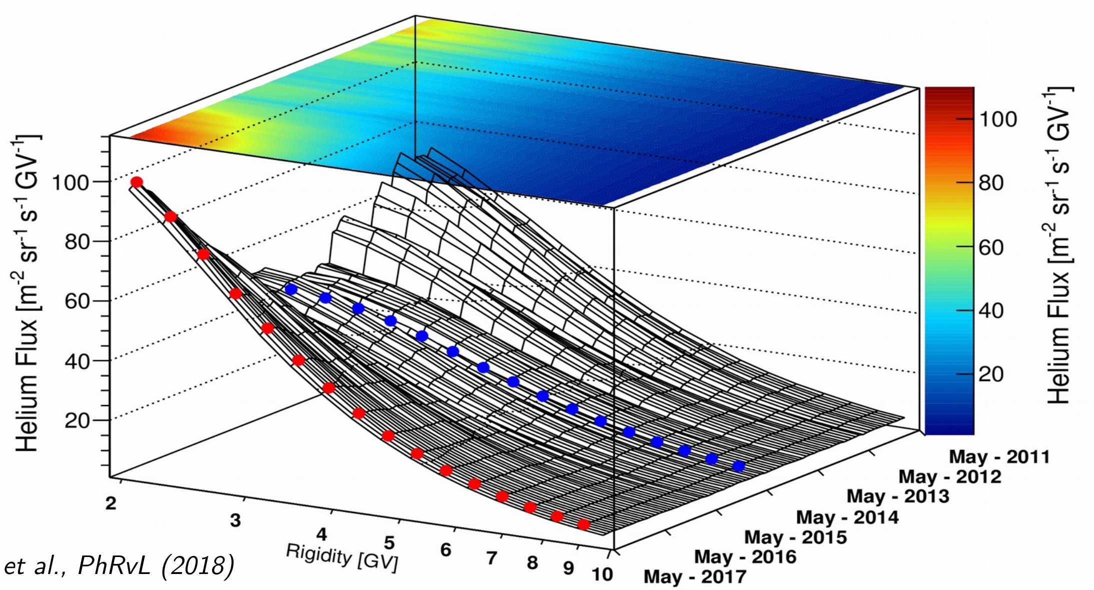
# AMS p & He fluxes vs time & rigidity




**Protons**

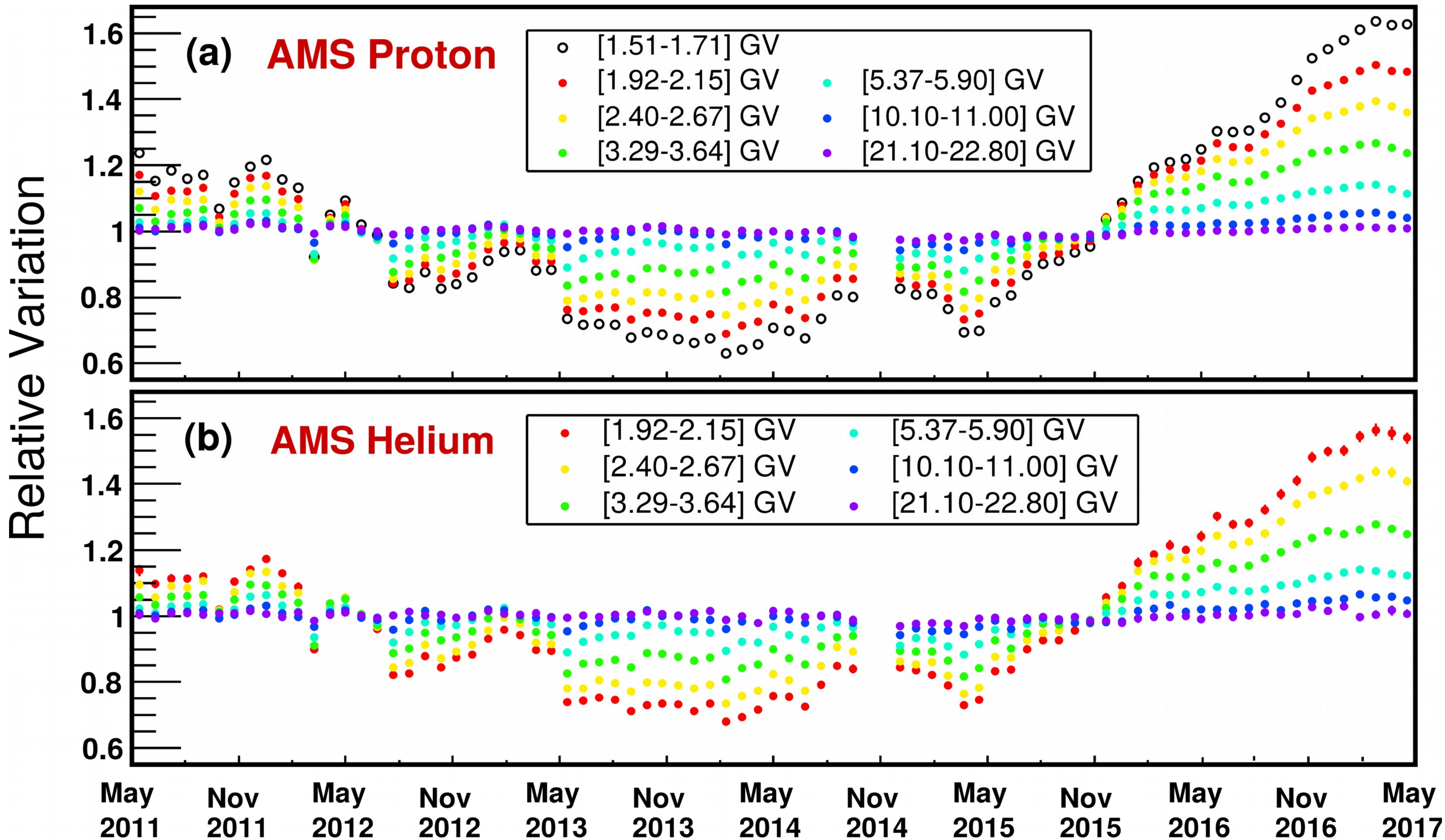
- May 2011 – May 2017
- 79 Bartels rotations
  1 BR = 27 days

**Helium**



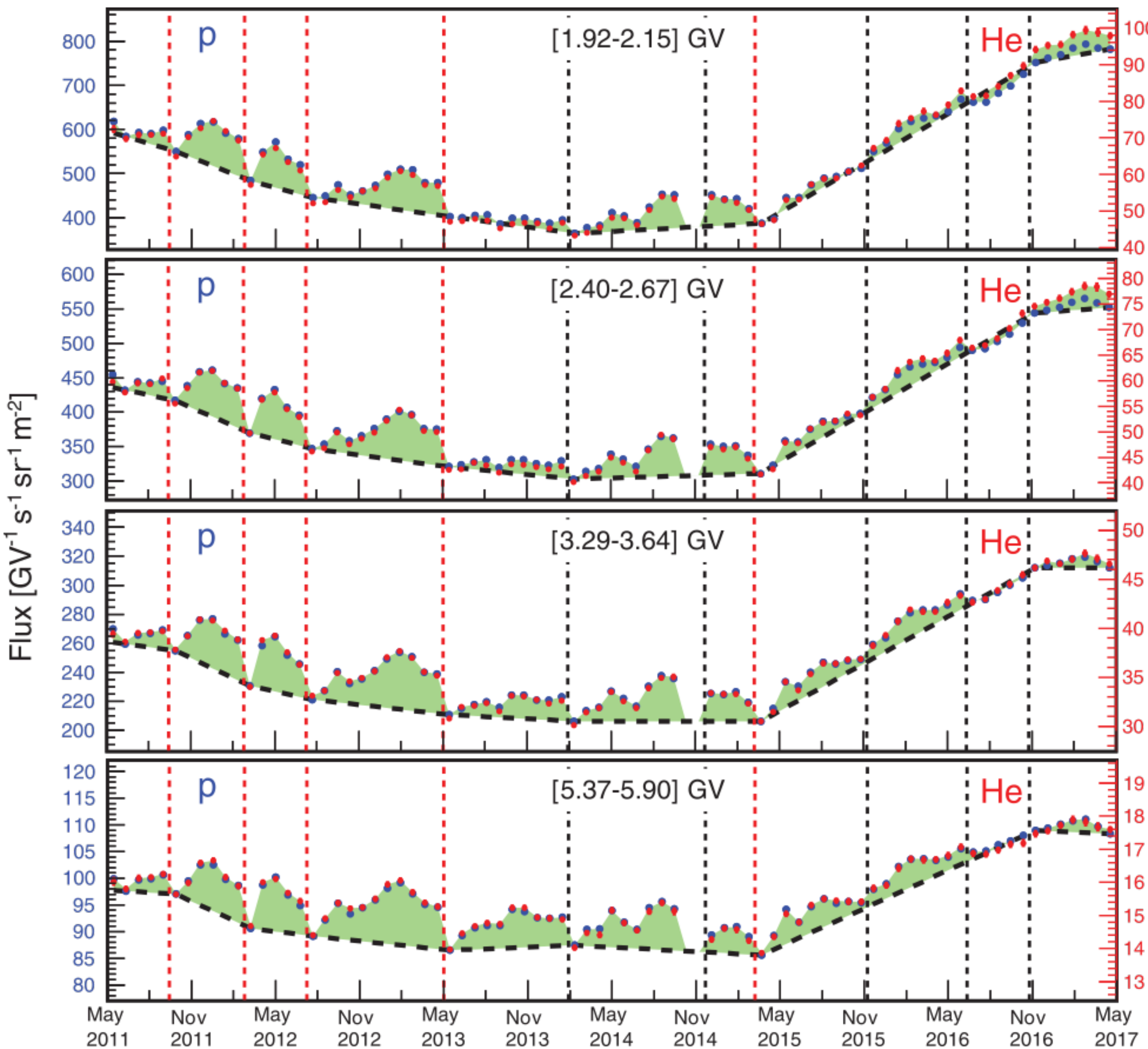

*Aguilar et al., PhRvL (2018)*

# AMS p & He fluxes relative variation



# AMS p & He low energy structures

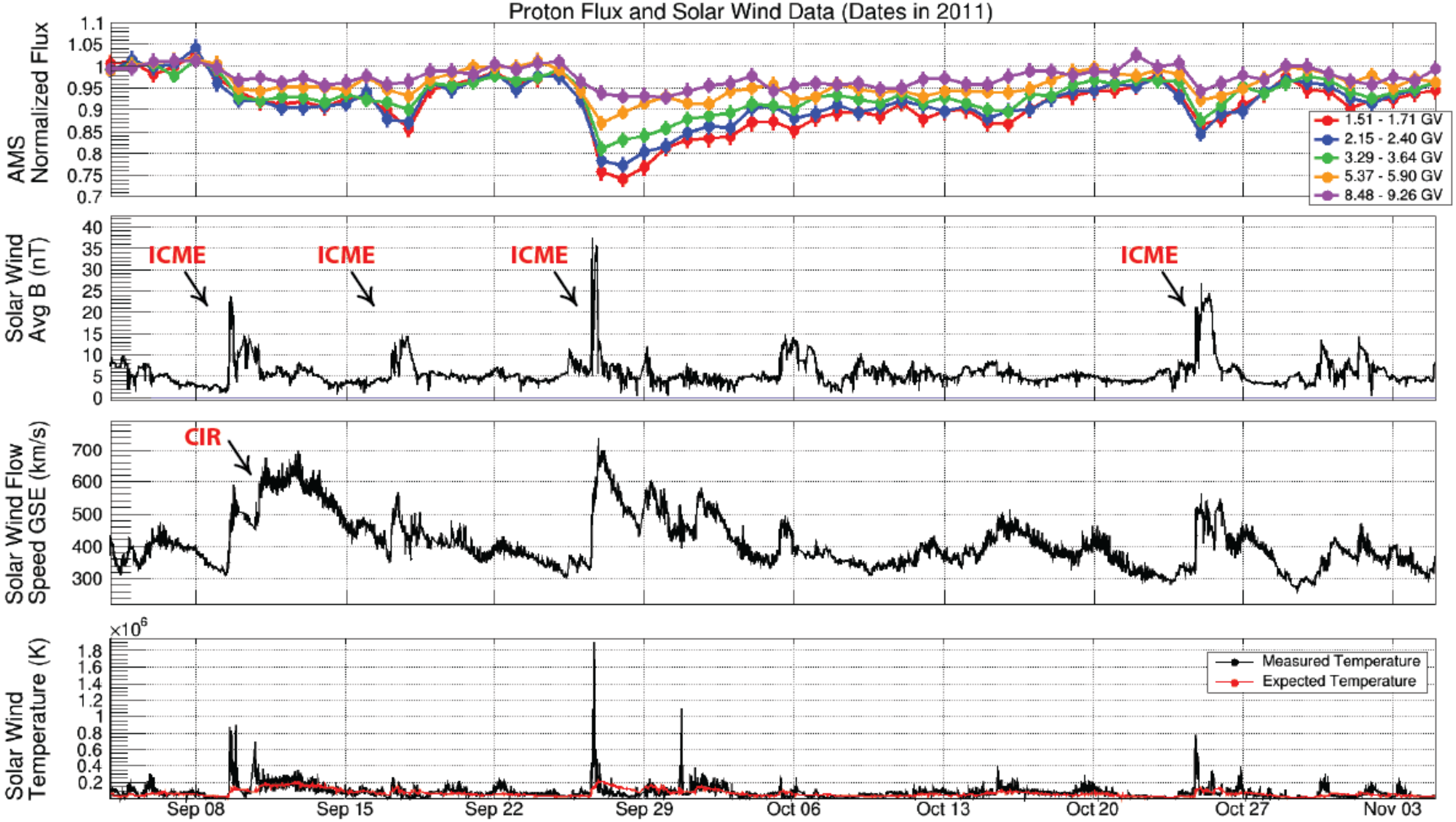
- Structures coincident in both amplitude and time for p and He
- Short-term solar activity and global heliospheric perturbances



*Aguilar et al., PhRvL (2018)*

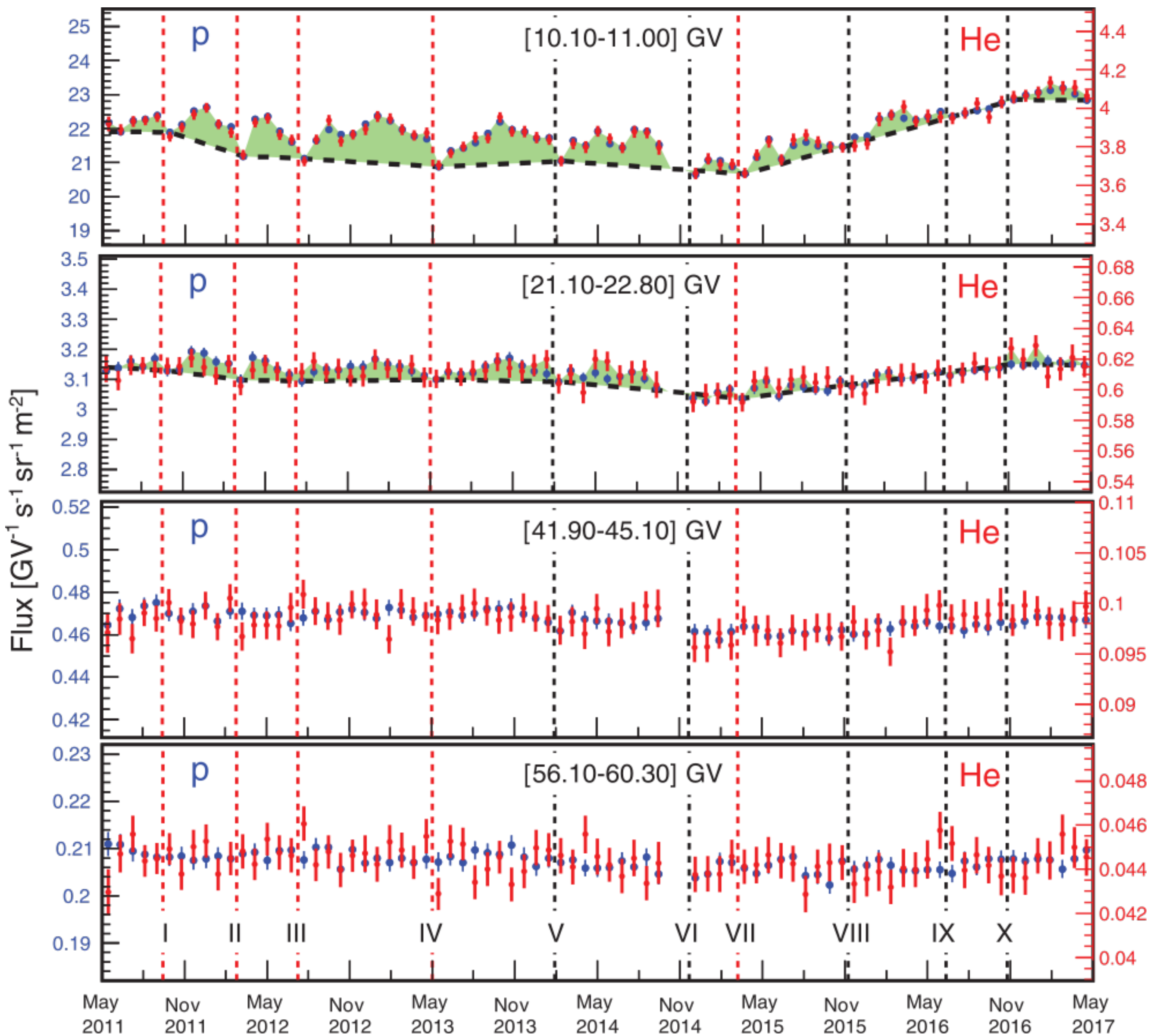
# AMS short-term solar activity studies

- Daily flux analysis: work in progress at UHM (Cristina Consolandi)
- Correlation of AMS flux variations with solar wind structures (Chris Light)



# AMS p & He low energy structures

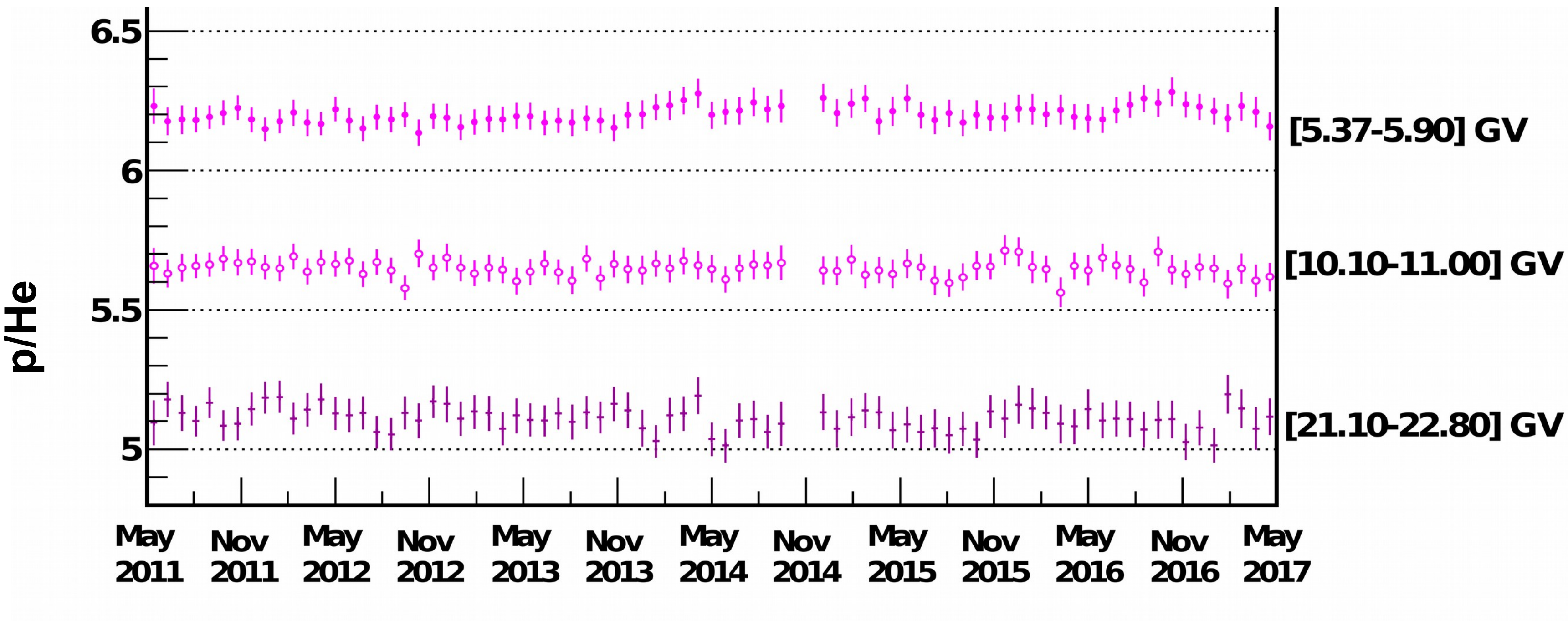
- Amplitude of structures decreases with increasing rigidity
- Above 40 GV, variations are consistent with statistical fluctuations




*Aguilar et al., PhRvL (2018)*

# AMS monthly p/He flux ratio

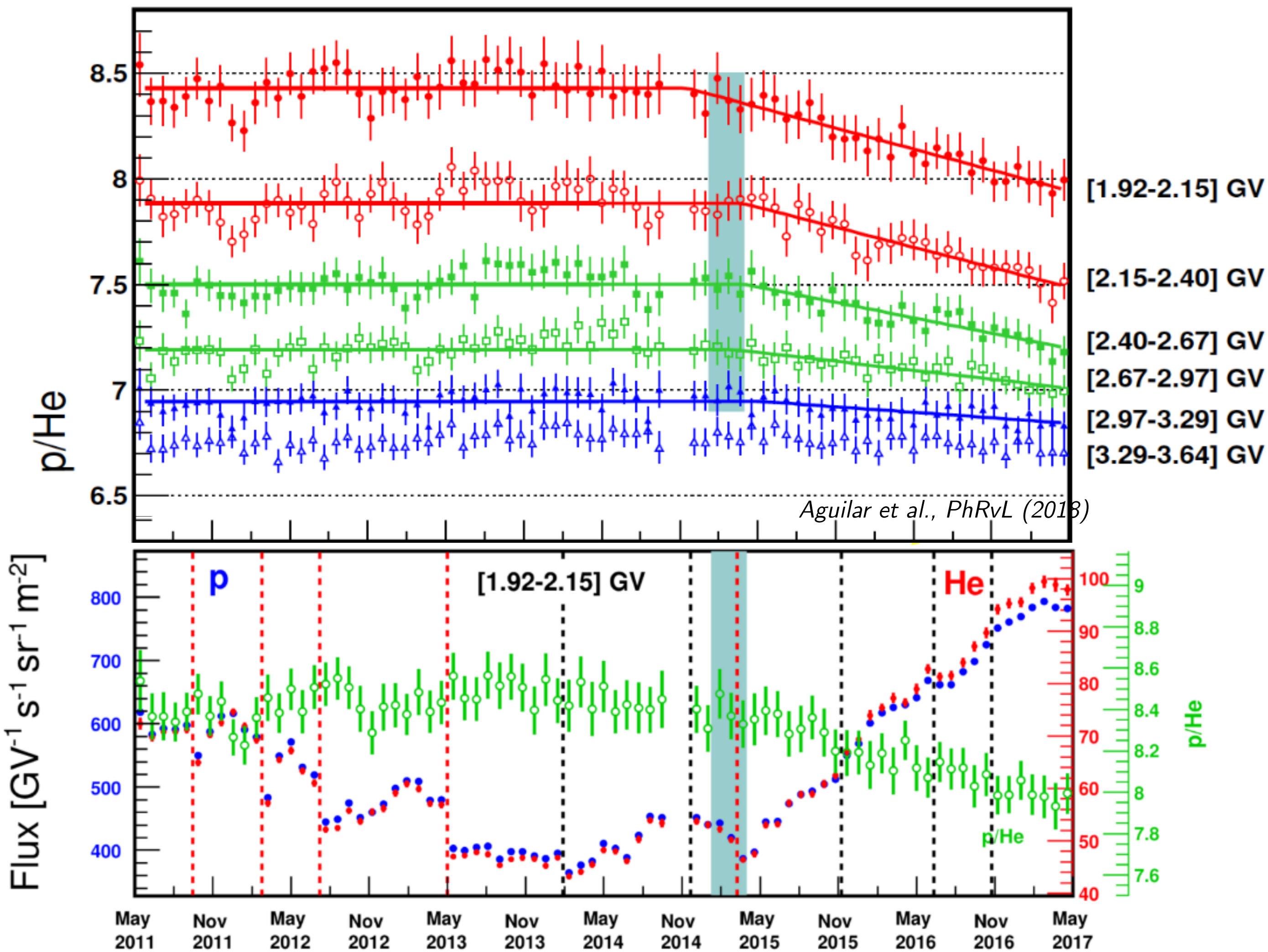
p/He flux ratio stable in time above 3 GV: all variations consistent with statistical fluctuations



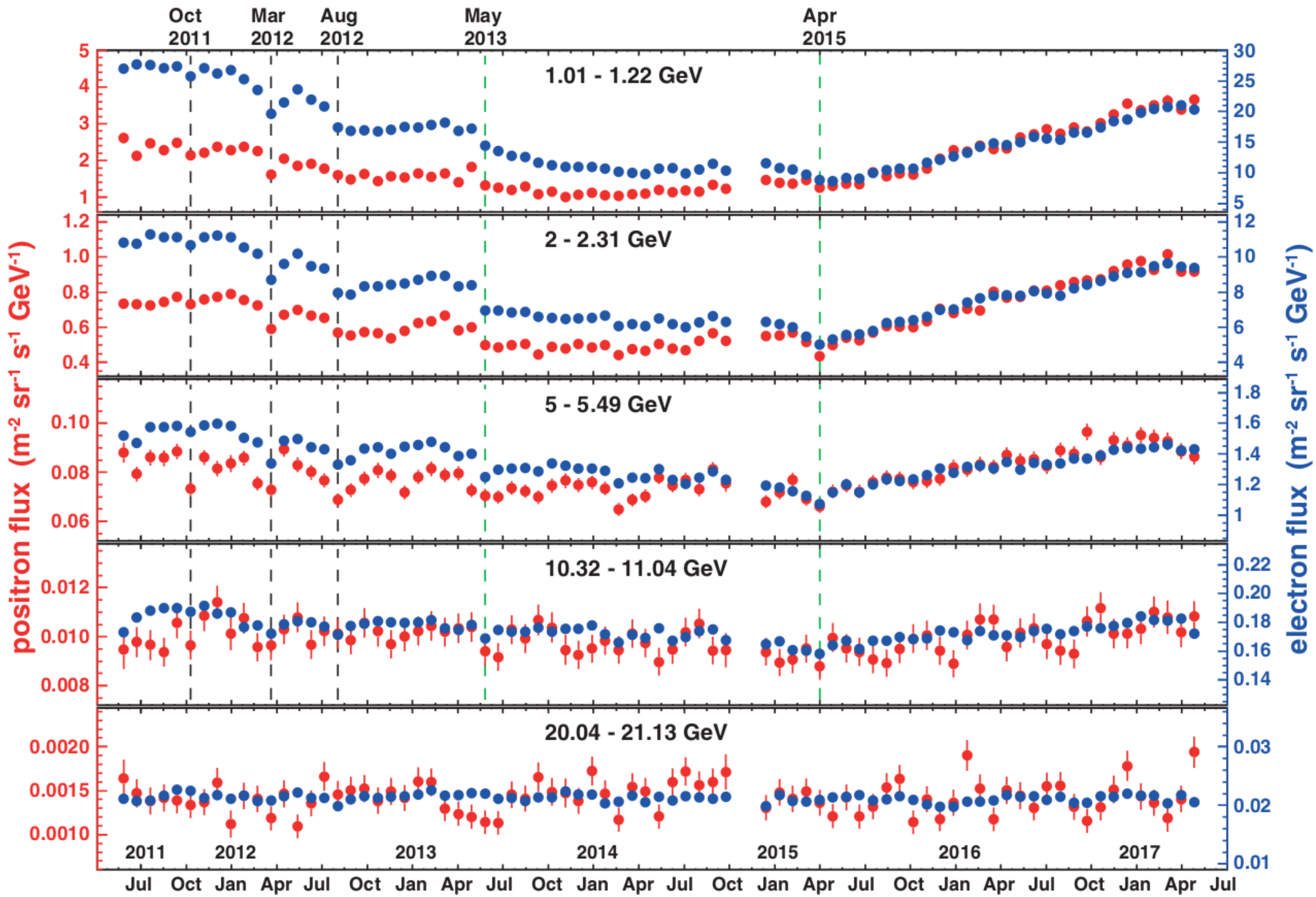

*Aguilar et al., PhRvL (2018)*

# AMS monthly p/He flux ratio

- Long-term time dependence of p/He flux ratio below 3 GV
- p/He decrease coincident in time with flux recovery phase



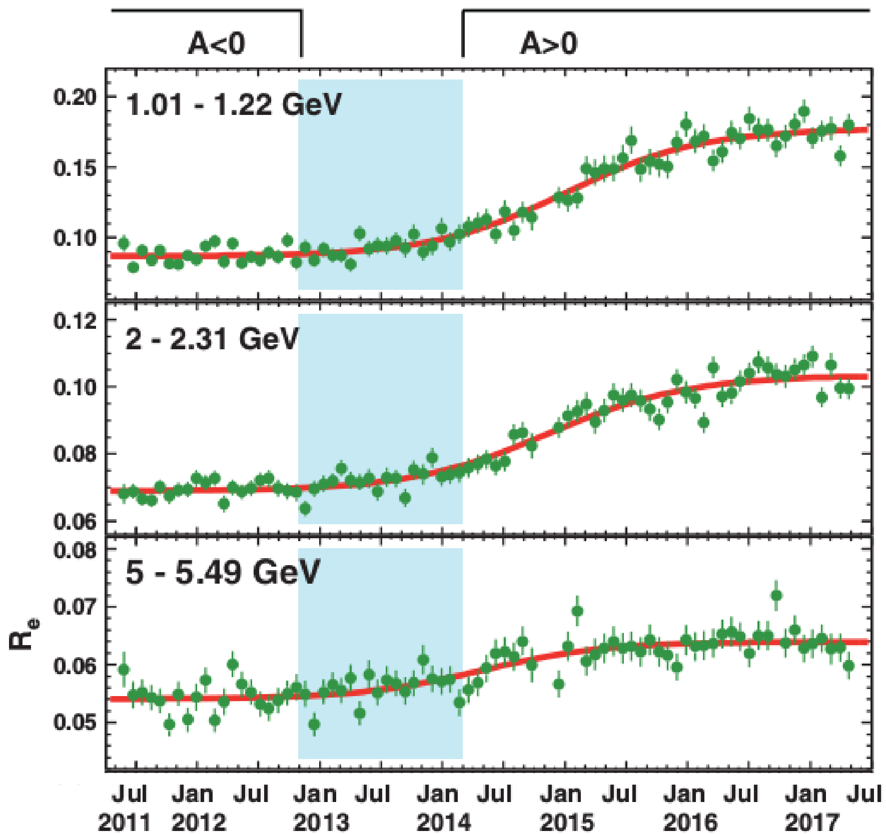
# AMS monthly $e^+$ and $e^-$ fluxes

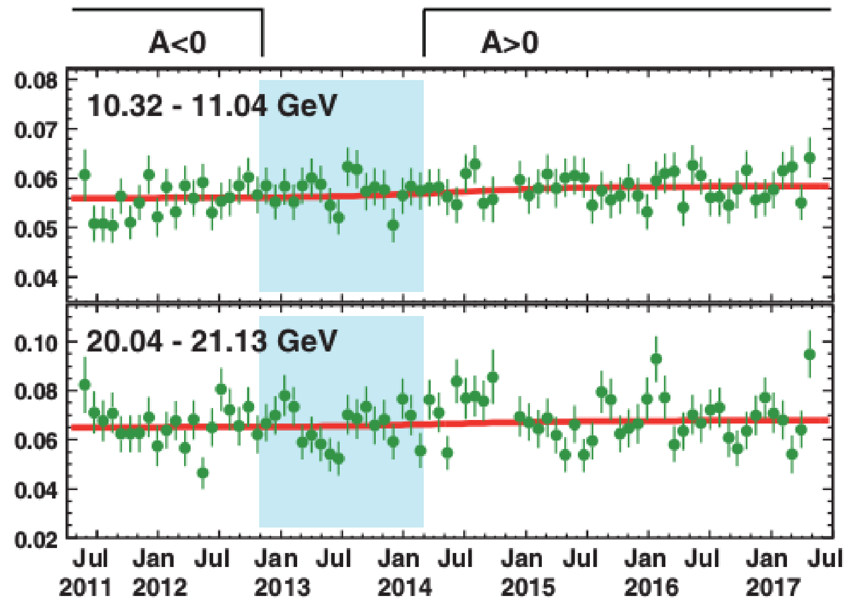



*Aguilar et al., PhRvL (2018)*

# AMS monthly $e^+/e^-$ flux ratio

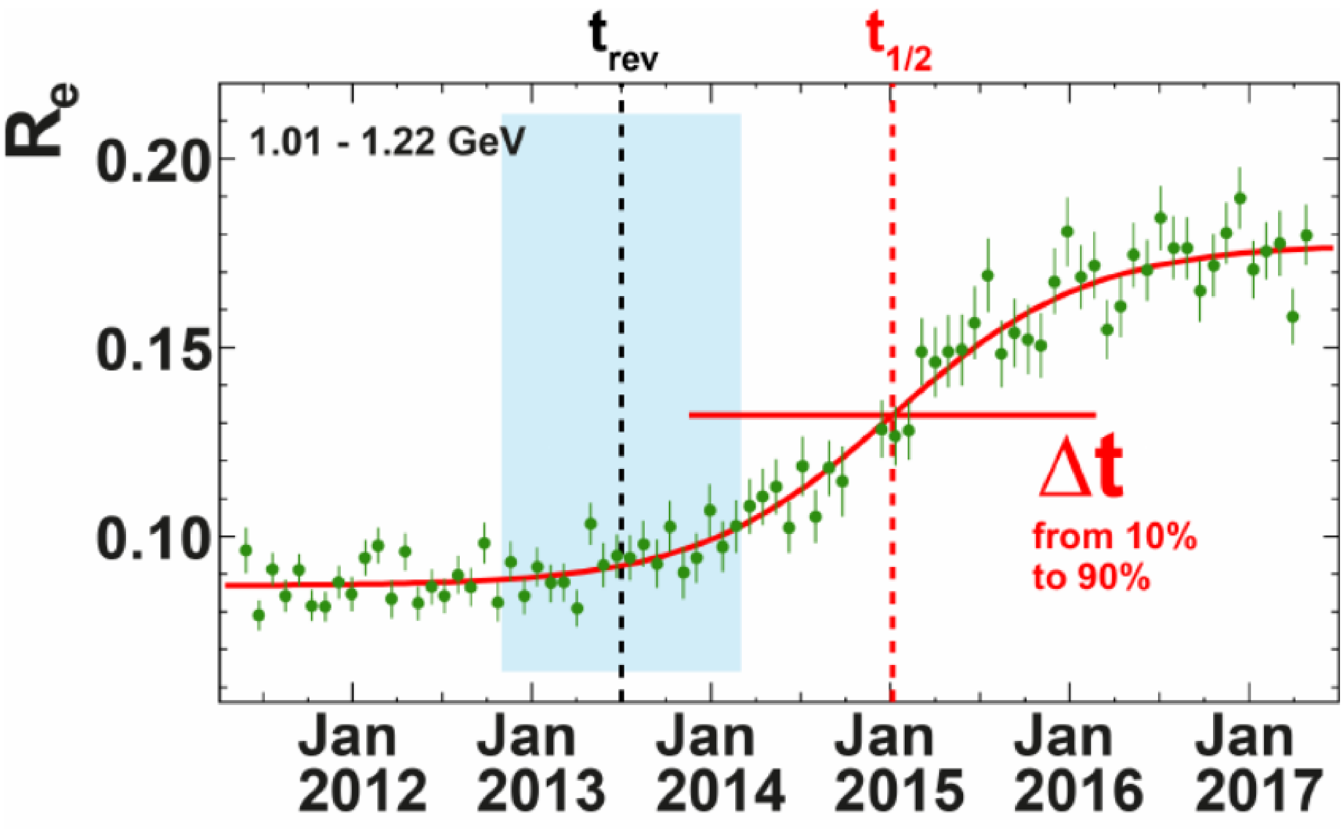
- Short-term variations in the fluxes largely cancel
- Smooth transition from one value to another during the period of the solar magnetic field polarity reversal




*Aguilar et al., PhRvL (2018)*

# AMS $e^+/e^-$ transition parametrization




**relative amplitude of transition**

$$R_e(t,E) = R_0(E)\left[1 + \frac{C(E)}{\exp\left(-\frac{t-t_{1/2}(E)}{\Delta t(E)/\Delta_{80}}\right)+1}\right]$$

**duration of transition** **midpoint of transition**

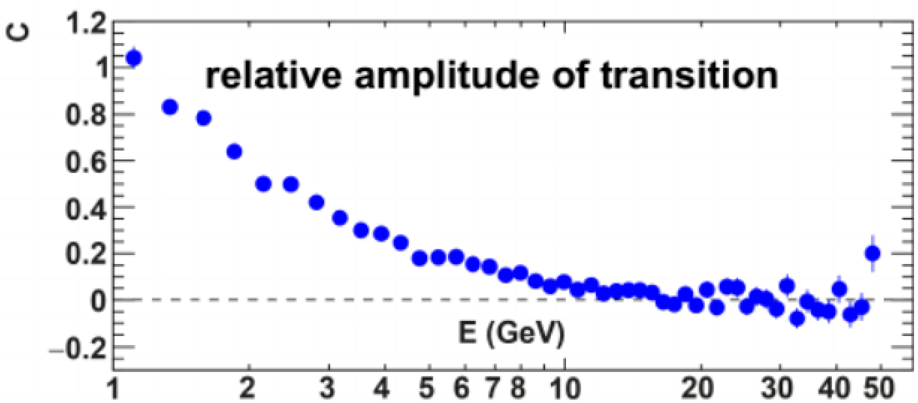
# AMS $e^+/e^-$ transition parametrization

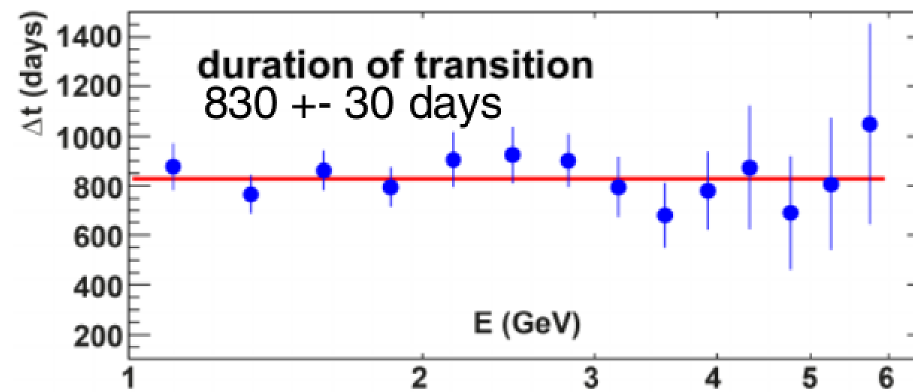
relative amplitude of transition

$$R_e(t,E) = R_0(E)\left[1 + \frac{C(E)}{\exp\left(-\frac{t - t_{1/2}(E)}{\Delta t(E)/\Delta_{80}}\right) + 1}\right]$$

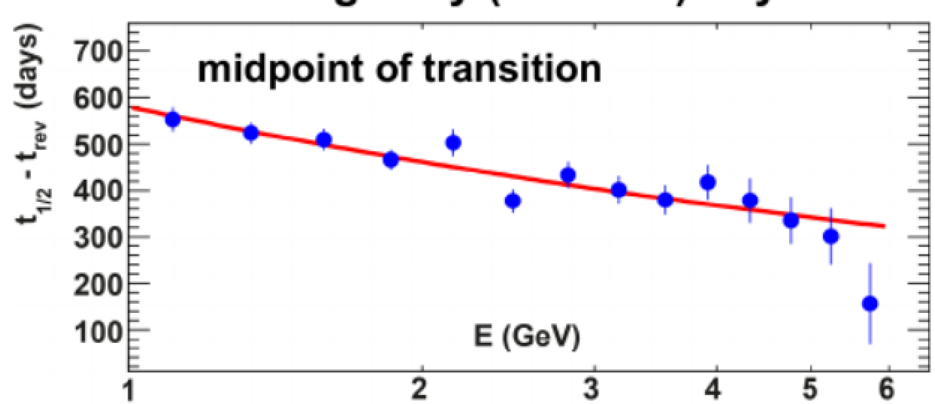
duration of transition

midpoint of transition



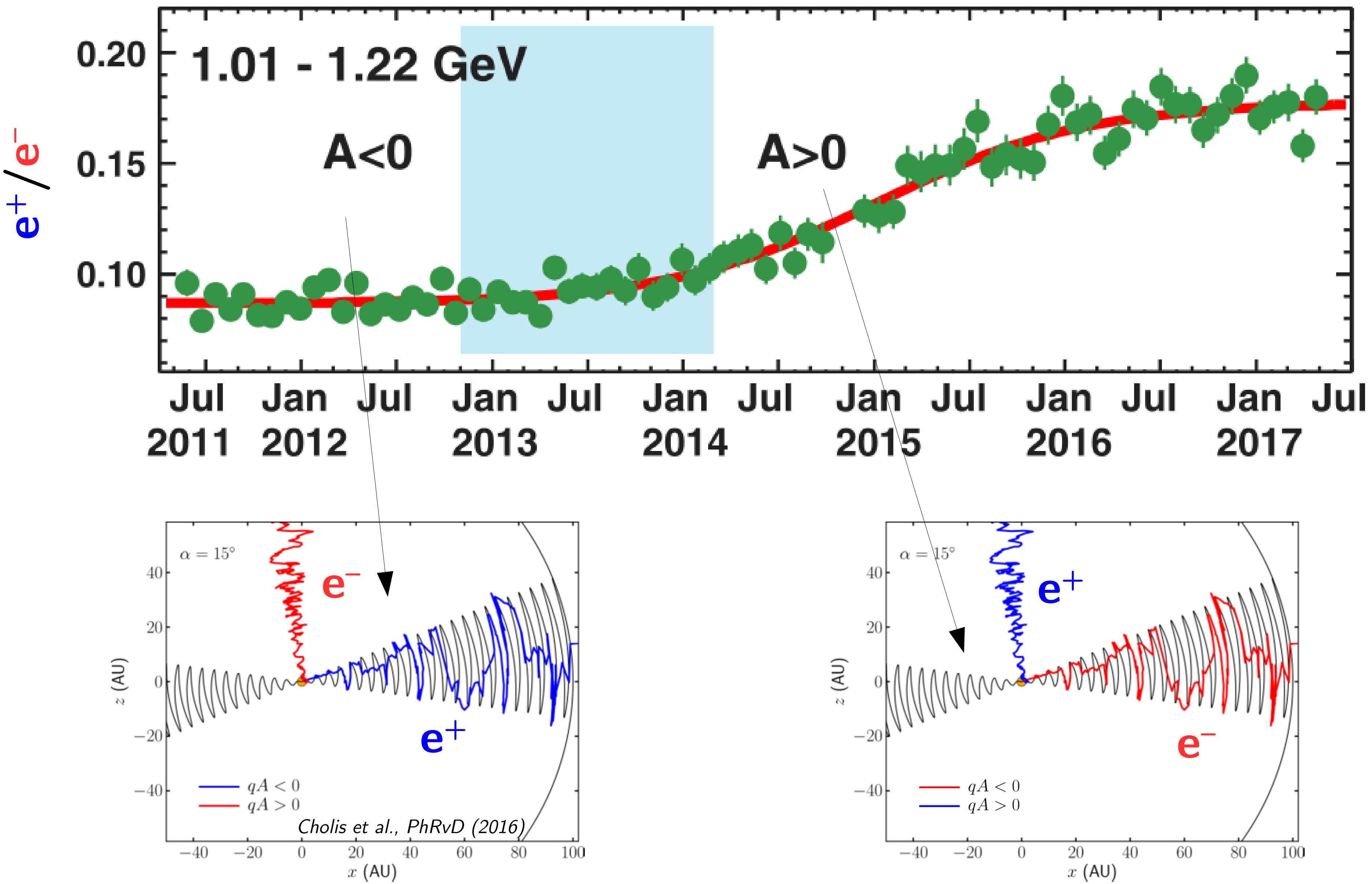




**Midpoint of transition changes by (260 ± 30) days from 1 to 6 GeV.**



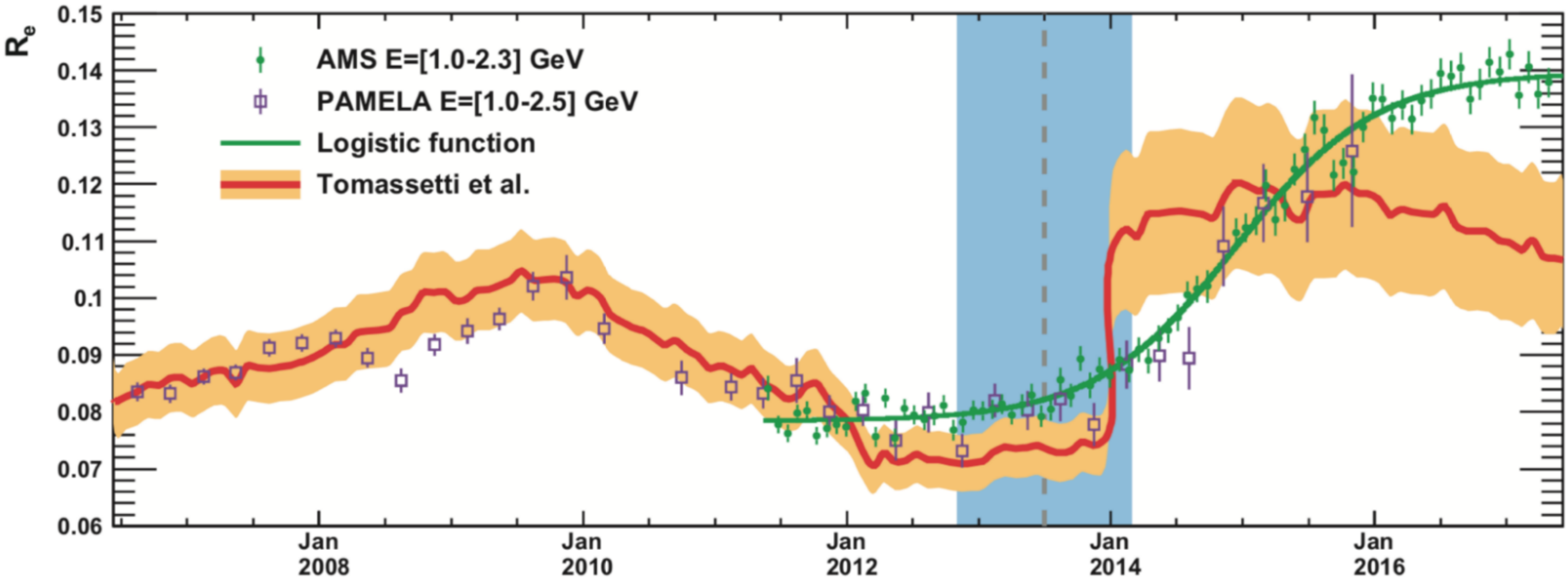

*Aguilar et al., PhRvL (2018)*

# Charge-sign dependent modulation



# Charge-sign dependent modulation

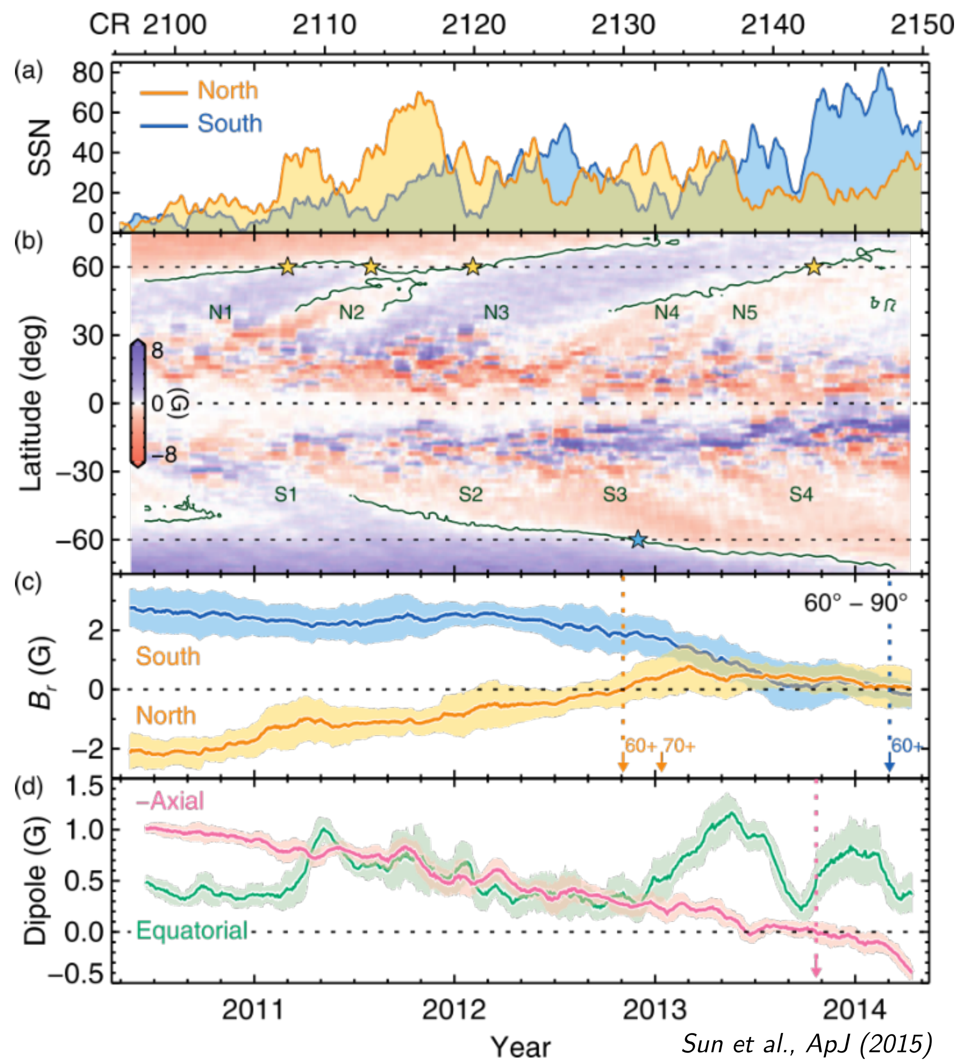
- Behavior during polarity reversal difficult to model
- Easiest thing to do: flip polarity in a given date => wrong!




*Tomassetti et al., ApJL (2017)*

# Solar magnetic field polarity reversal

- Polarity reversal process is complex and asymmetric between North and South hemispheres




*Sun et al., ApJ (2015)*

# Origin of p/He time dependence

Below 3 GV, p/He at a given rigidity is not flat with time, but the mean free paths of p, $^3$He and $^4$He are assumed to be exactly the same in rigidity.

Where is the time dependence coming from?

$$\frac{\partial f}{\partial t} + \underbrace{\vec{V}_{SW} \cdot \vec{\nabla} f}_{\text{Solar wind convection}} - \underbrace{\vec{\nabla} \cdot (K \cdot \vec{\nabla} f)}_{\text{Diffusion and drifts}} - \underbrace{\frac{1}{3} \vec{\nabla} \cdot \vec{V}_{SW} \frac{\partial f}{\partial \ln R}}_{\text{Adiabatic energy losses and gains}} = 0$$

Two hypothesis:

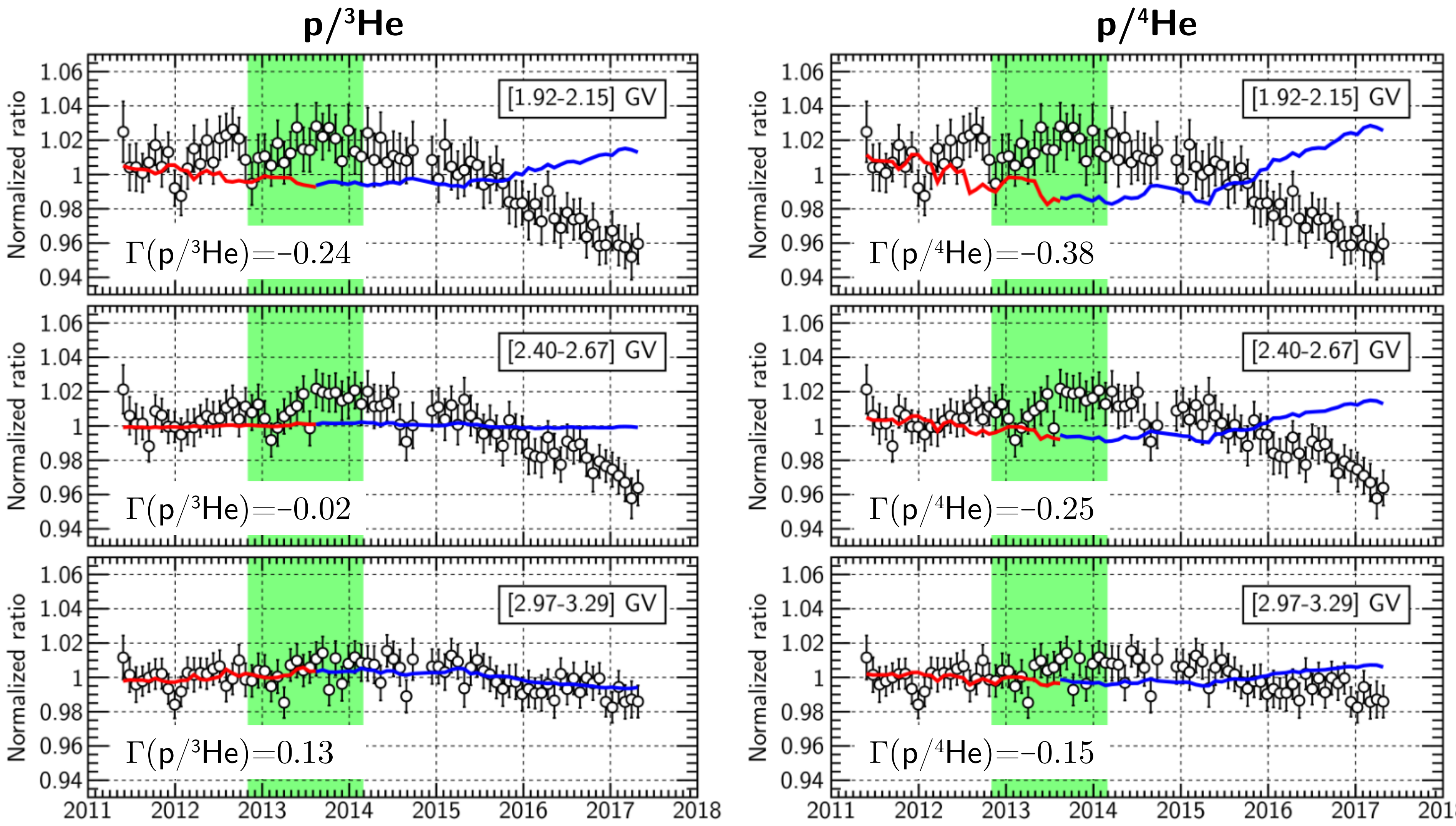
1) Velocity dependence of the diffusion coefficient: $k(r, R) = \beta k_1(r) k_2(R)$
Even if $k_2$ is the same for all nuclei, the beta multiplying it will change the divergence of the diffusive flux term in the Parker equation for nuclei with different A/Z.

2) Difference in the LIS shape: the adiabatic energy change term in the Parker equation depends on the spectral index, so if two nuclei have the same A/Z, but different spectral index, the last term will be different.

Both effects are physically present, but which one is most important?

# LIS shape dependence

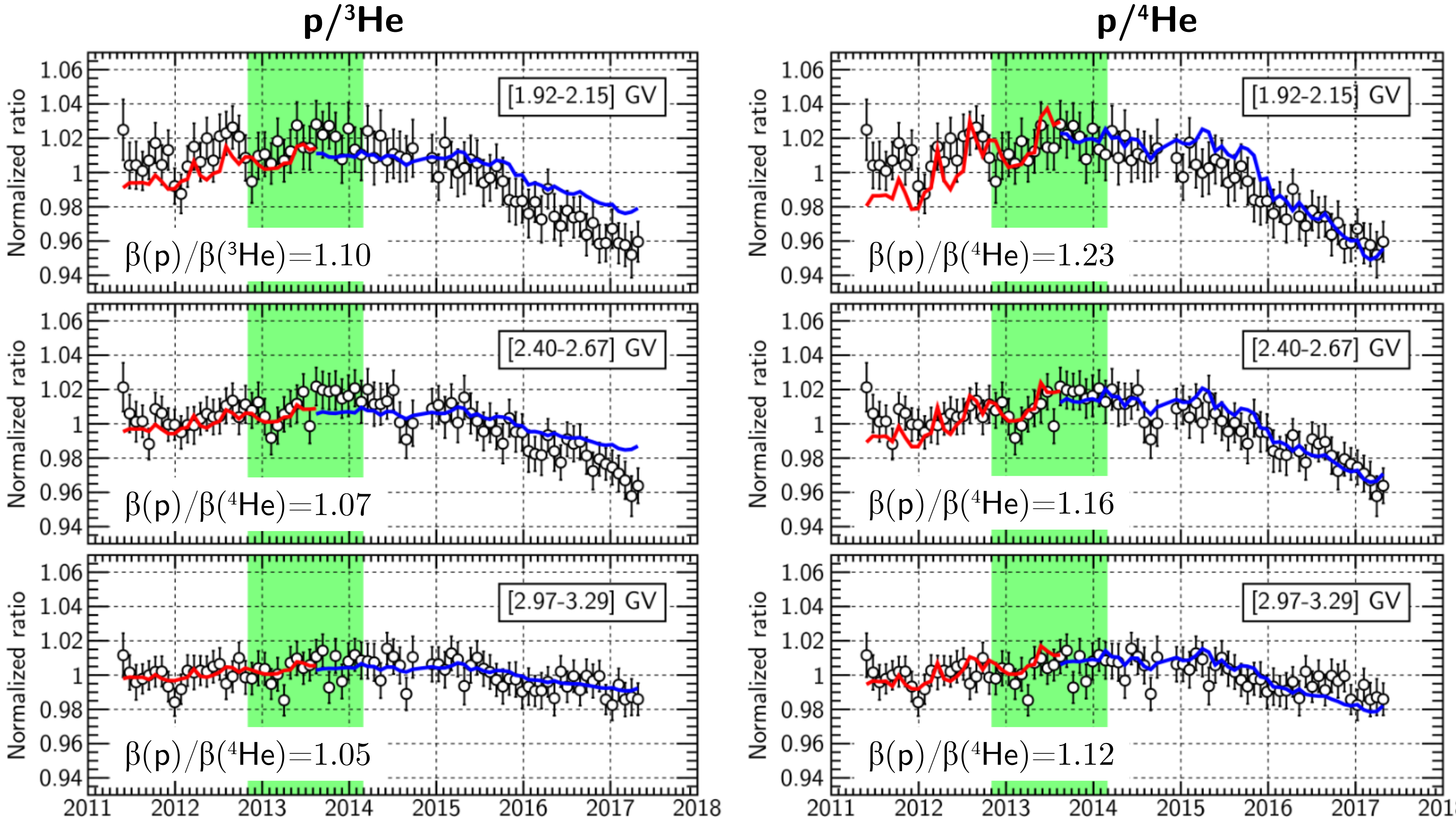
**Same A/Z=1 for all particles**; p LIS; $^{3}$He LIS; $^{4}$He LIS.




*Corti et al., Submitted to ApJ (2018)*

# A/Z dependence

**Same LIS for all particles**; A/Z(p) = 1; A/Z($^3$He) = 3/2; A/Z($^4$He) = 2.




*Corti et al., Submitted to ApJ (2018)*

# Conclusions

- AMS measured p, He, $e^+$, $e^-$ monthly fluxes during the ascending phase of solar cycle 24, through its maximum and toward its minimum.
- The high performances of AMS allow to study the long-term time variations as well short-term solar activity.
- Above 3 GV the AMS p/He flux ratio is time independent, while below 3 GV the p/He flux ratio has a long-term decrease.
- AMS $e^+/e^-$ ratio clearly shows the charge-sign dependence of solar modulation: for the first time, the charge-sign dependent modulation during solar maximum has been investigated in detail by leptons alone.
- Time behavior of $e^+/e^-$ ratio understood from theory, but detailed description requires advances in numerical models.
- Time behavior of p/He ratio reproduced from numerical models, due to A/Z dependence of diffusion coefficient.