利用数值方法研究宇宙线在不同时间尺度上的太阳调制

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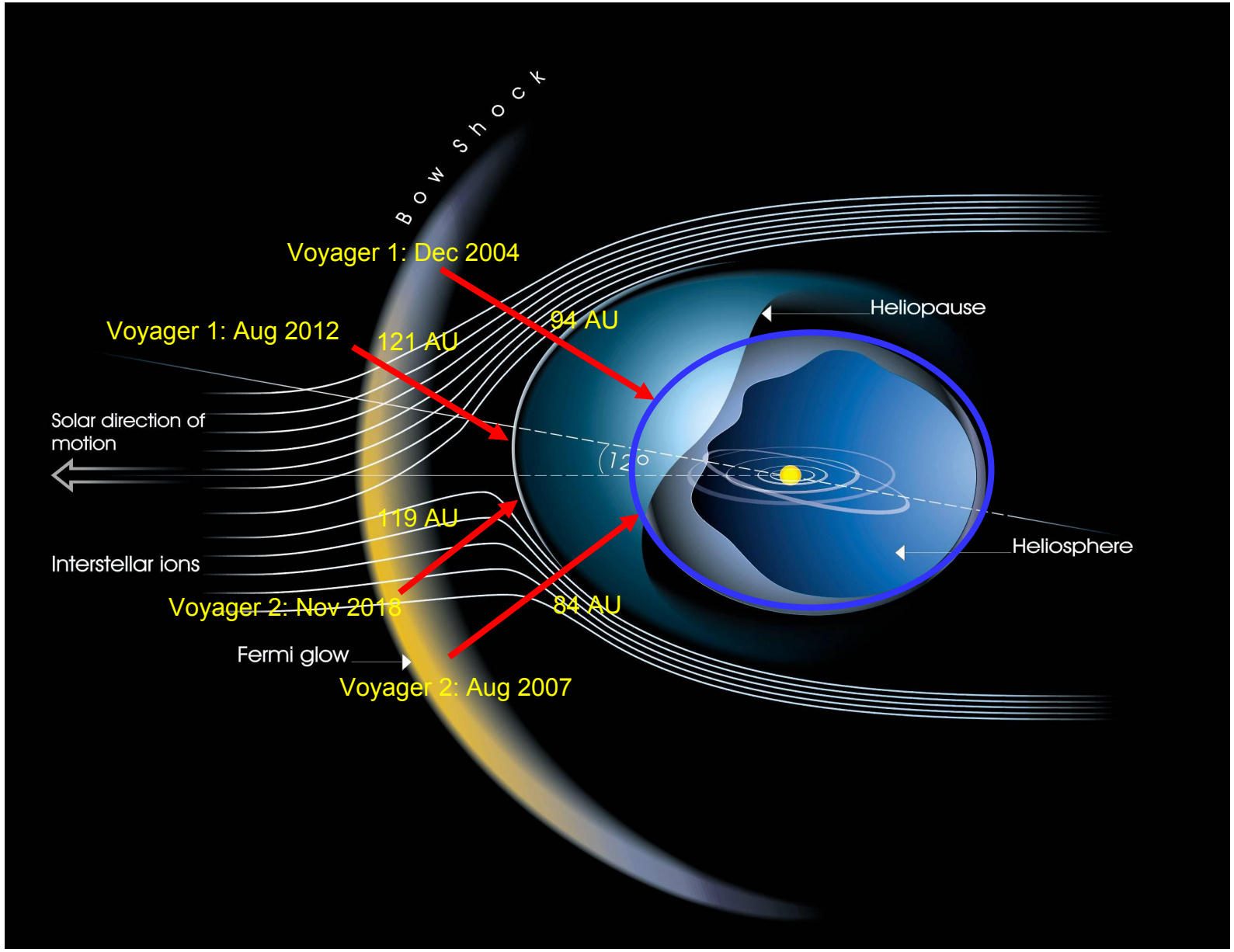
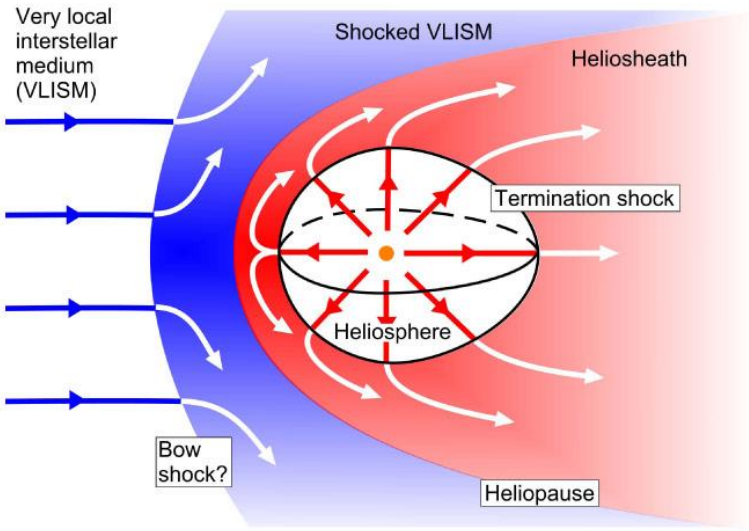
Outline

- **The Solar Wind, Heliosphere**
- **Modulation Theory, Numerical Model**
- **Long-term Modulation**
- **Short-term Modulation**

Heliosphere

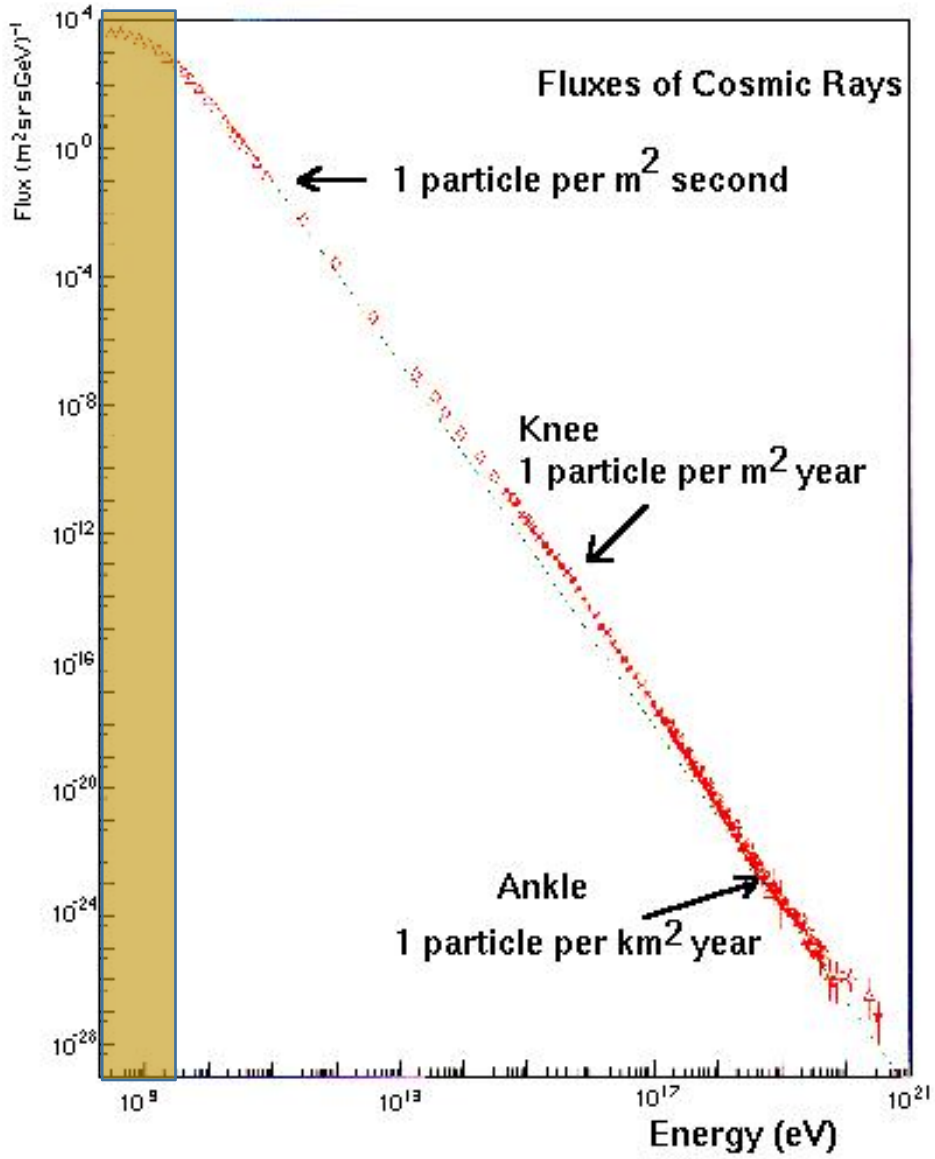


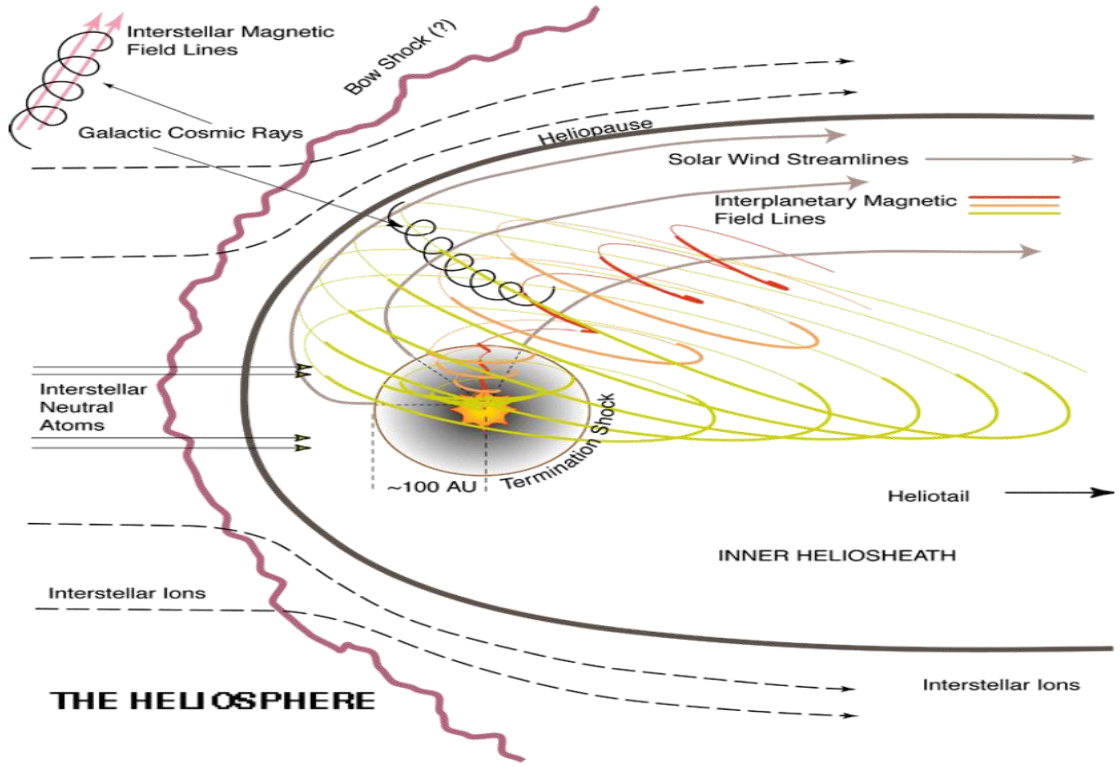


Owens and Forsyth. Living Rev. 2013

1 au Solar Wind:
400 km/s
mainly protons and electrons
~6 cm^{-3}
10^5 K

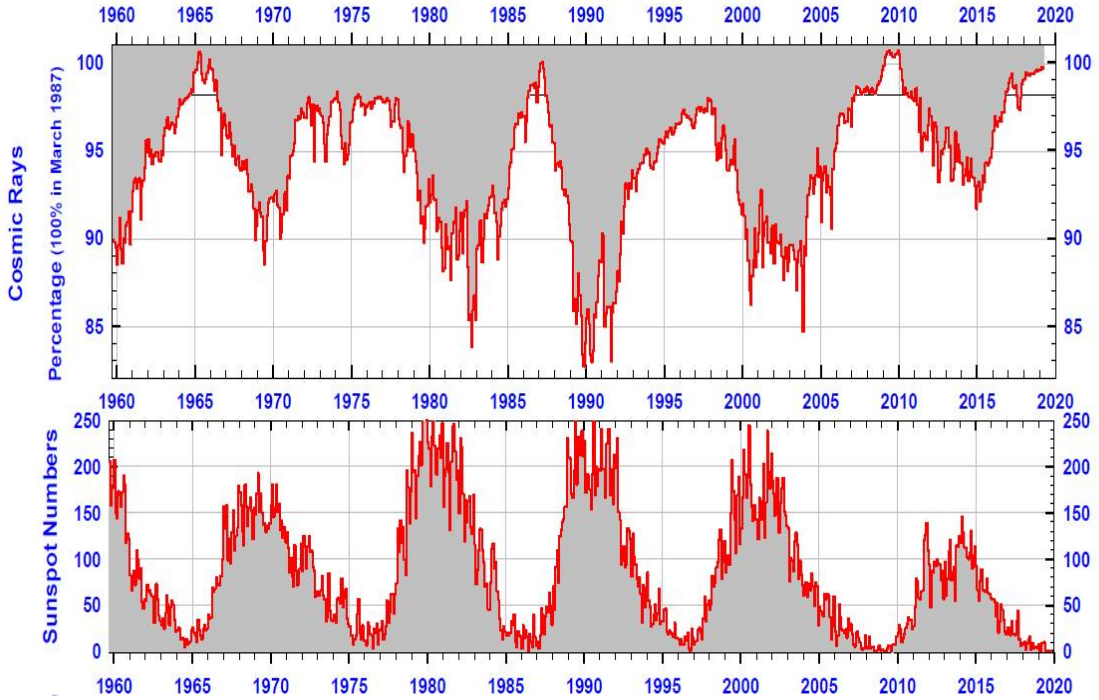
Galactic Cosmic Ray Spectrum for Solar Modulation





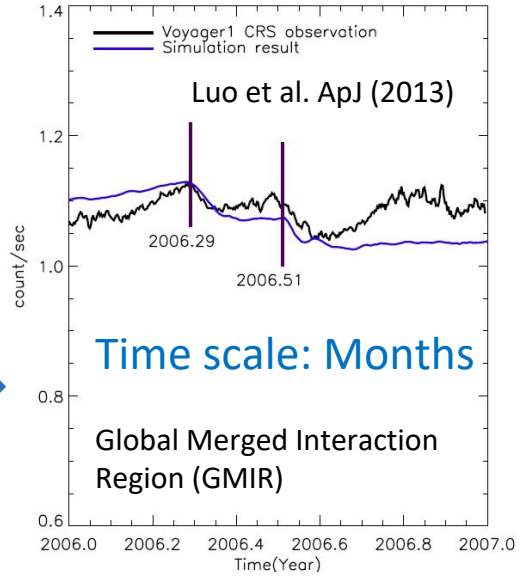
Cosmic ray Protons with energy below about ~30 GeV are subject to solar modulation

GCR Solar Modulation



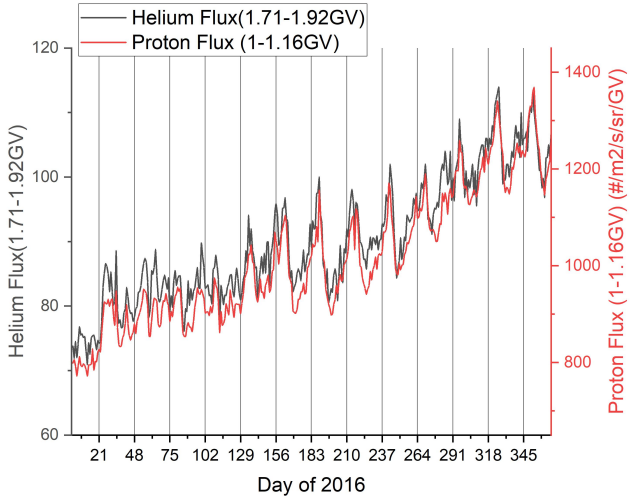
Time scale: Years

Potgieter, LRSP(2013)

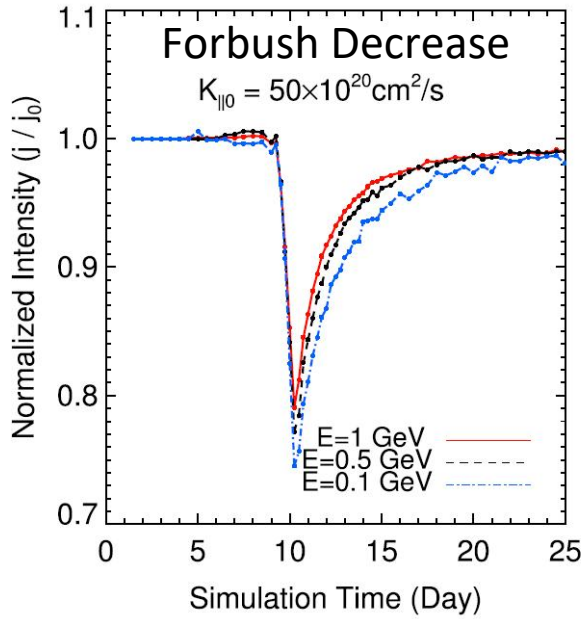


Time scale: Months

Global Merged Interaction Region (GMIR)



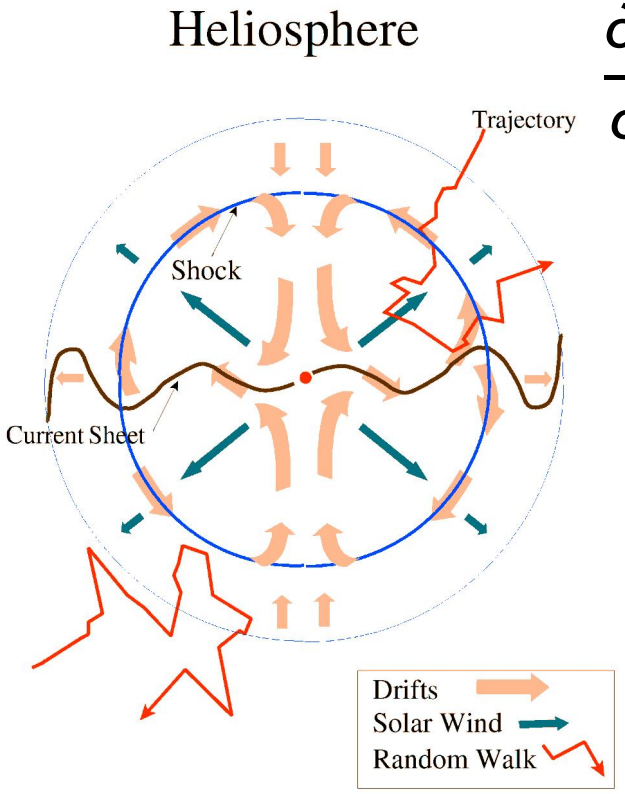
Luo et al. ApJ (2017)



Time scale: Days

Galactic Cosmic Rays (GCR) is modulated by the Sun at different time scales, which are related to different solar activities and solar wind structures.

GCR Transport Theory



Convection Drift | Diffusion | Adiabatic Energy Change

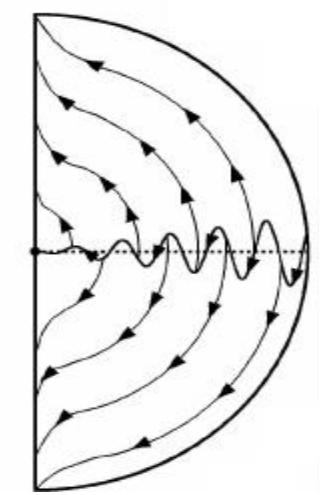
$$\frac{\partial f}{\partial t} = -\left(V_{sw} + \langle V_d \rangle\right) \cdot \nabla f + \nabla \cdot \left(K_s \cdot \nabla f\right) + \frac{1}{3}\left(\nabla \cdot V_{sw}\right)\frac{\partial f}{\partial \ln p}$$ *(E. N. Parker 1965)*

$$j(r, E, t) = p^2 f(r, p, t)$$

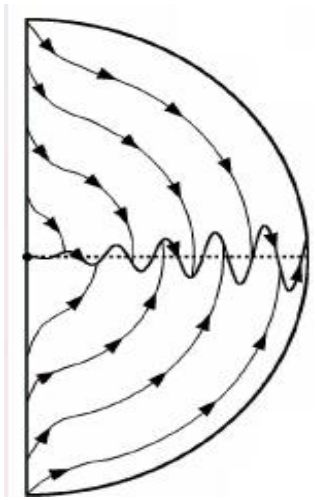
1. Convection: The outwards moving solar wind advects the magnetic field and cosmic rays.
2. Diffusion: Scattering by the irregularity of the magnetic field cause the cosmic ray diffuse.
3. drift : Large scale spatial variation of the average magnetic field cause coherent guiding-center drifts (gradient, curvature and current sheet).
4. adiabatic energy change : the expansion and compression of solar wind $\nabla \cdot V$ causes the cosmic ray particles lose or gain energy.

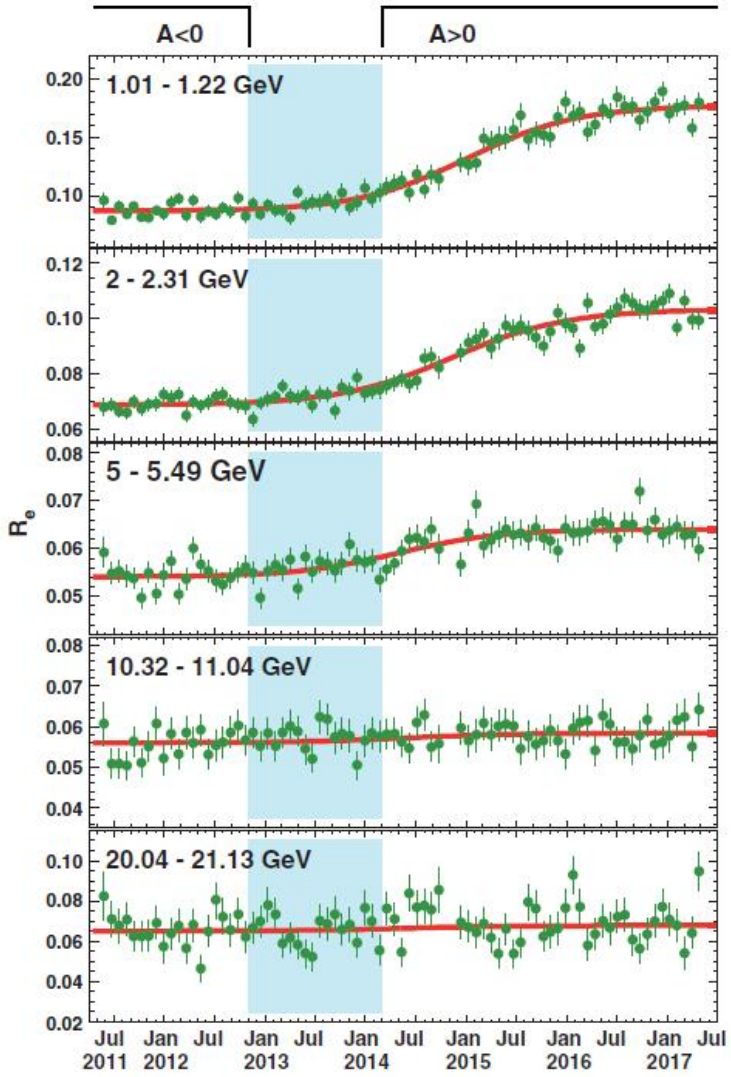
The Drift Effect: Charge–Sign Dependent Modulation

Drift direction of electrons in A > 0 cycle



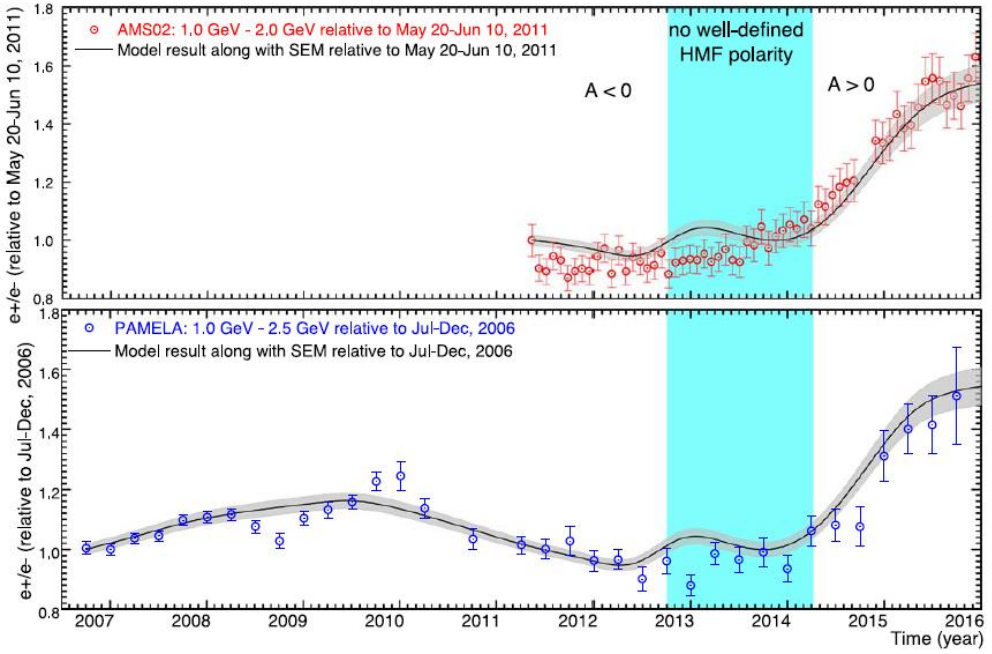
Drift direction of electrons in A < 0 cycle



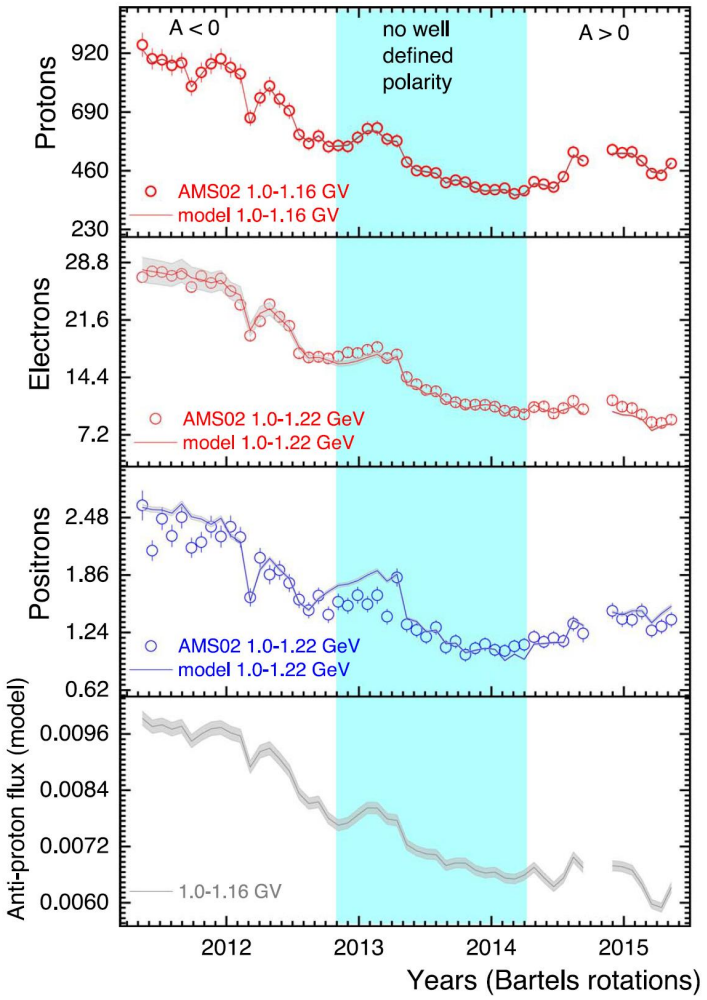


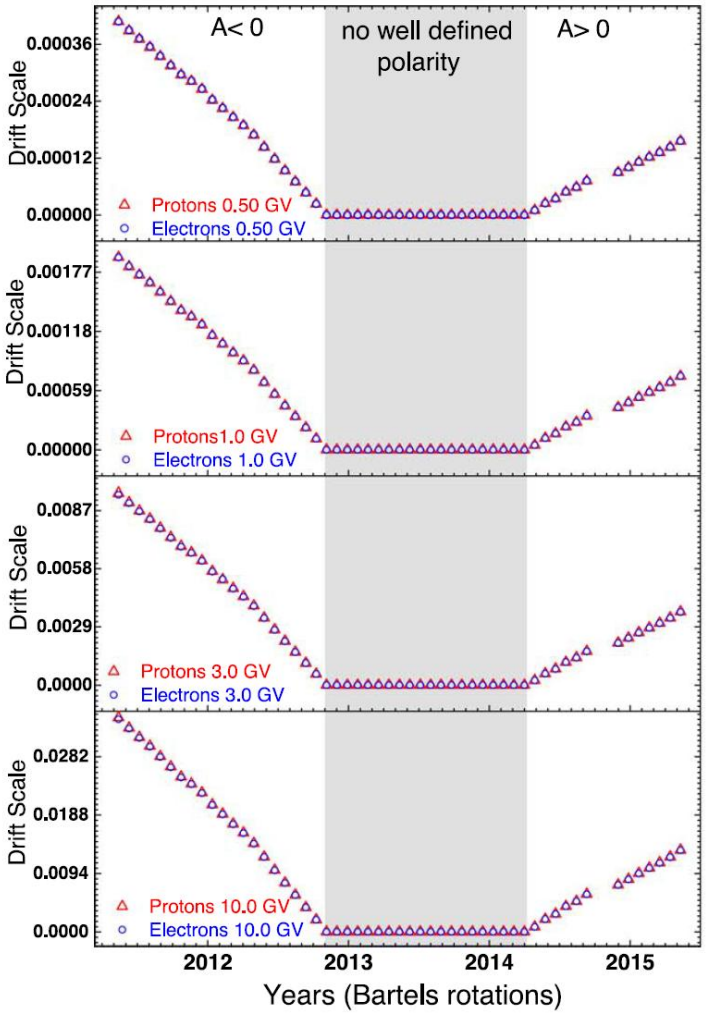
Aguilar M. et al. PRL 2018

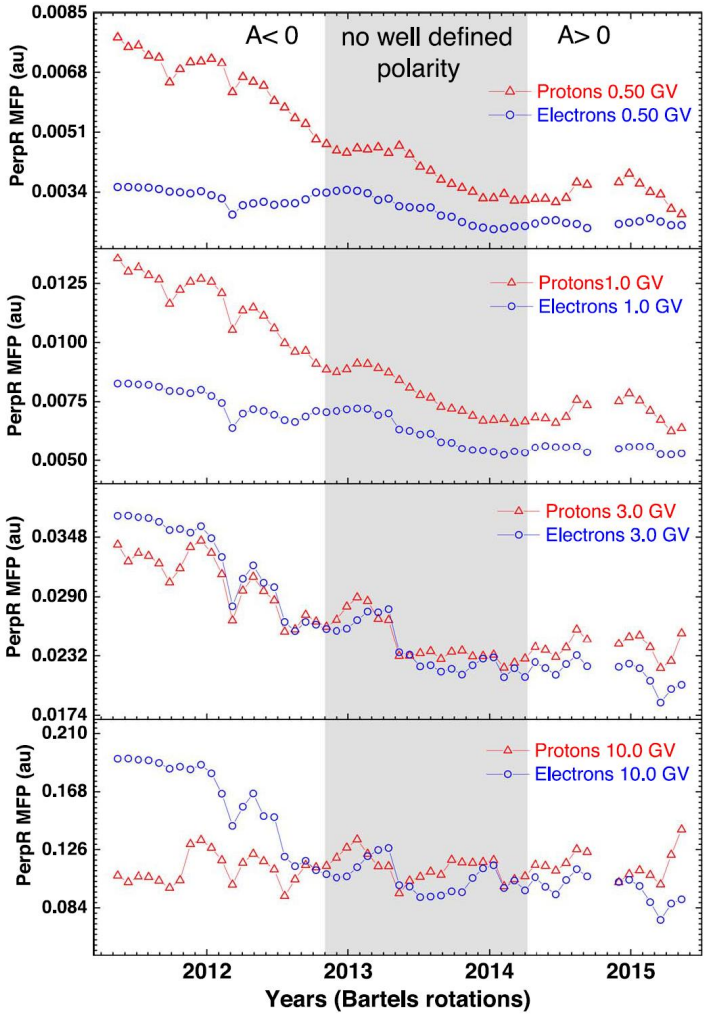
The positron to electron ratio rises after the Solar Magnetic Field polarity reverse from A<0 to A>0.



Solar Modulation During Solar Magnetic Polarity Reversal

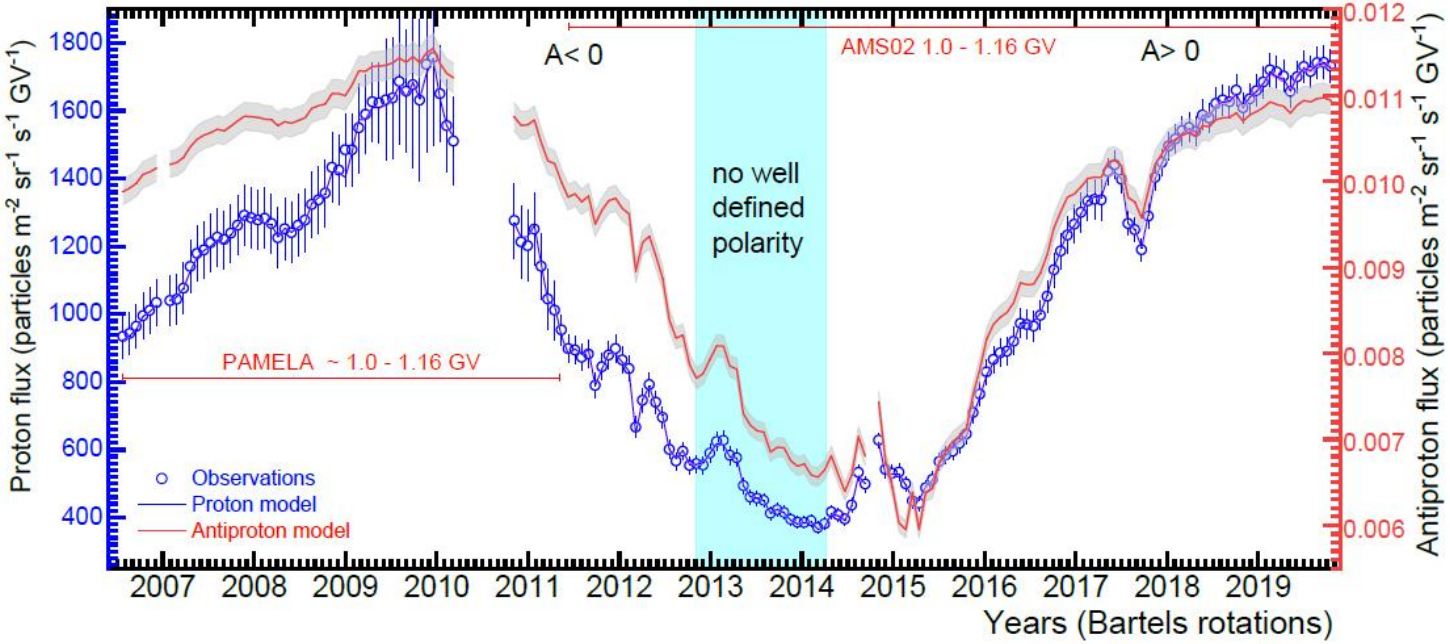


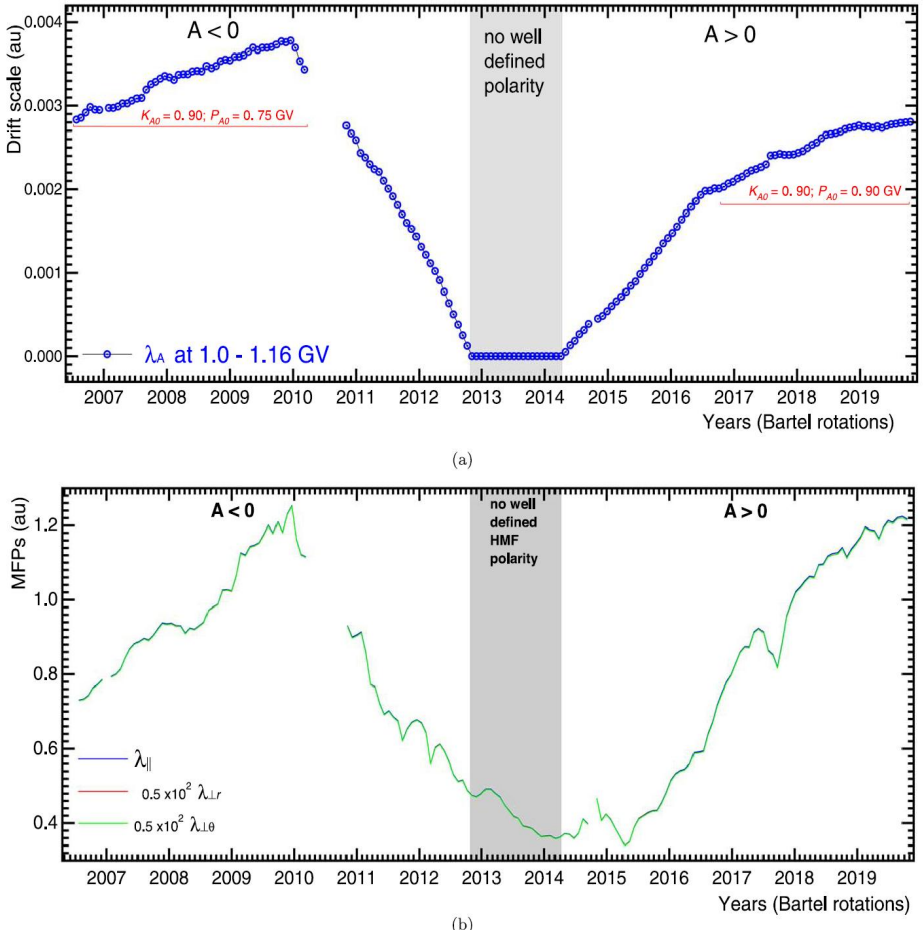


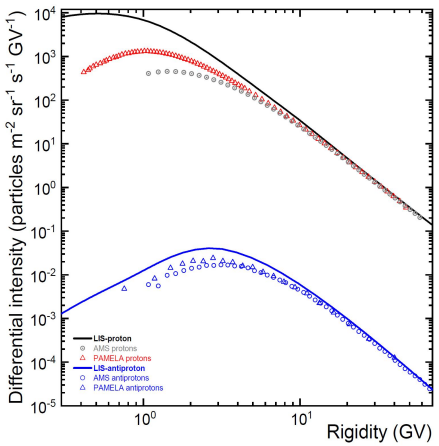


Aslam et al., ApJ, 2023, 947,72

Solar Modulation During Solar Magnetic Polarity Reversal

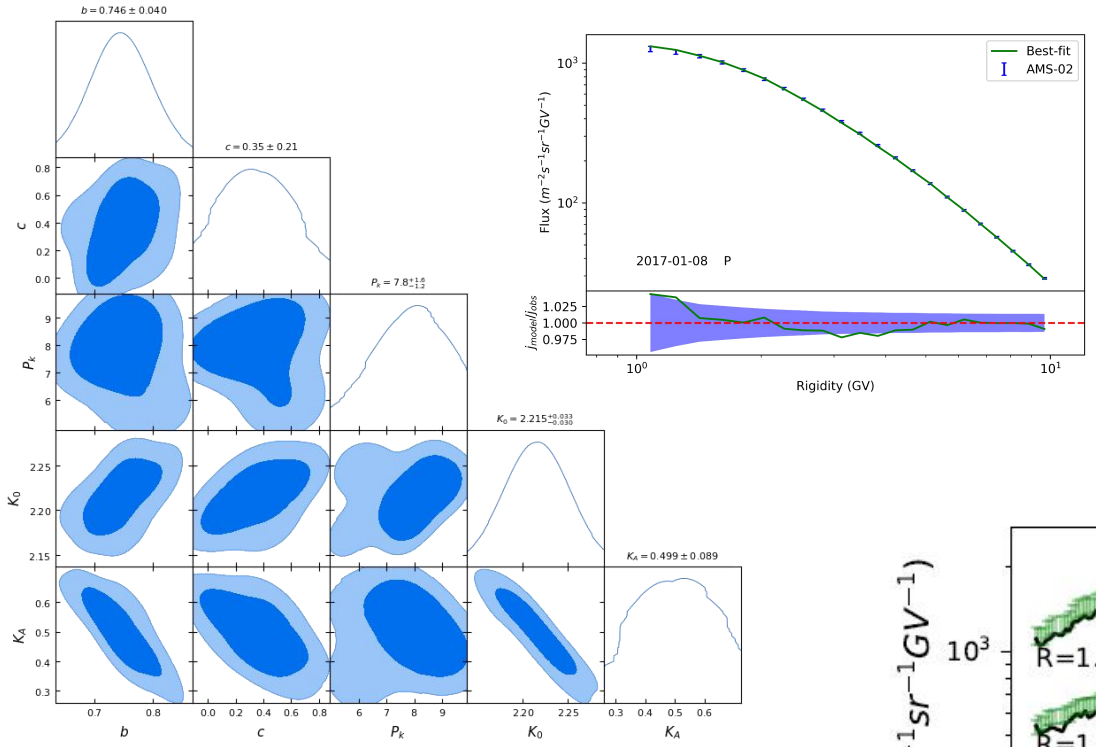






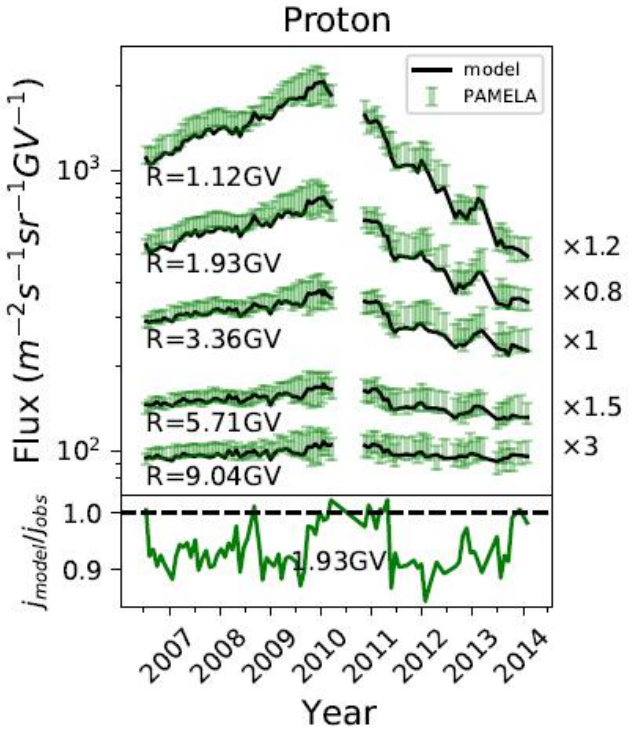
Aslam et al., ApJ, 2023, 953,101

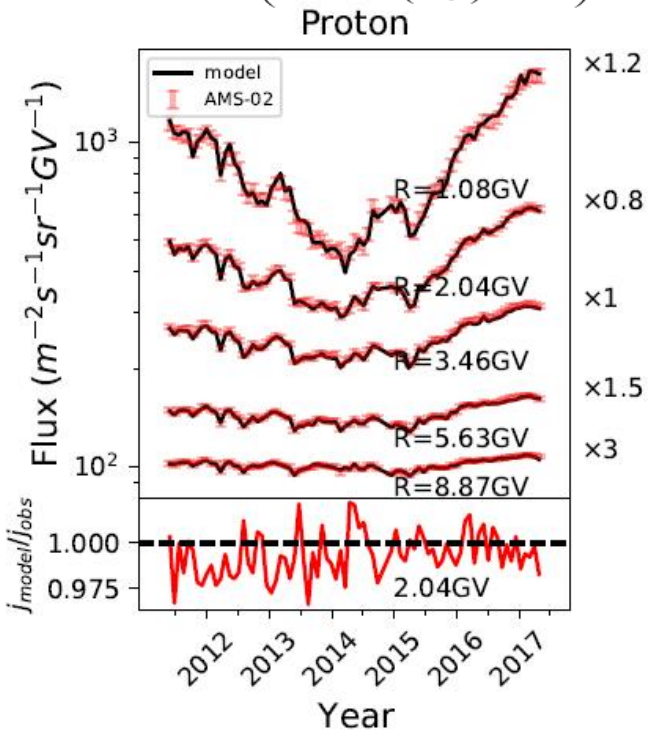
GCR 11 Year Long-term Solar Modulation: Reproduce AMS Proton Observation



$$v_d = \nabla \times \left(K_A \frac{qP\beta}{3B} \frac{(P/P_0)^2}{1+(P/P_0)^2} \frac{\vec{B}}{B} \right)$$

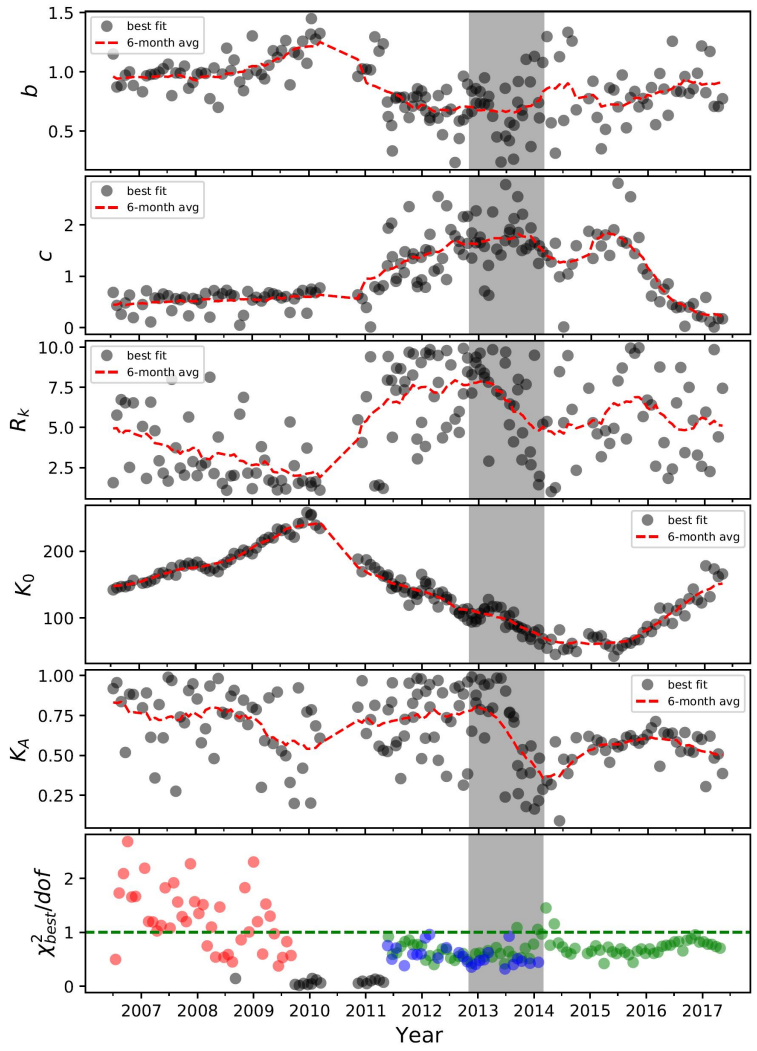
$$K_{\parallel} = K_0 \left(\frac{B_{eq}}{B} \right) \left(\frac{P}{P_0} \right)^b \left(\frac{\left(\frac{P}{P_0}\right)^d + \left(\frac{P_k}{P_0}\right)^d}{1+\left(\frac{P_k}{P_0}\right)^d} \right)^{\frac{c-b}{d}}$$



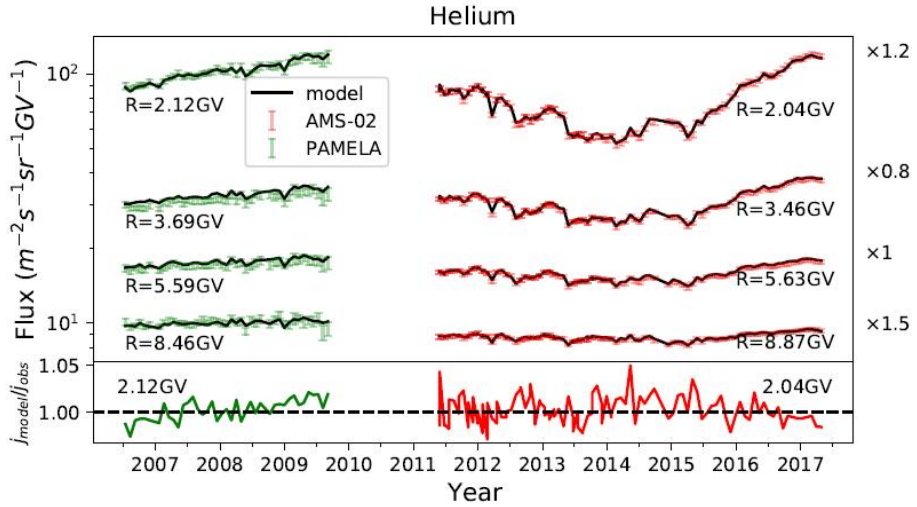


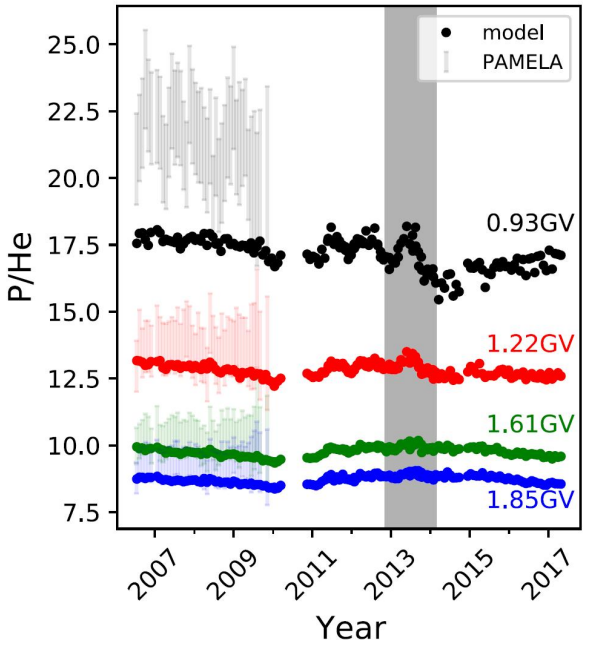
Song, Luo+, 2021, ApJS

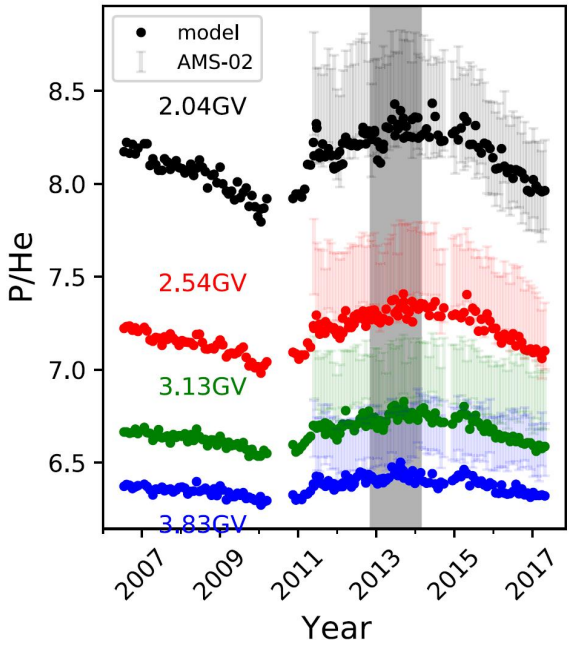
Reproduce AMS Helium Observation



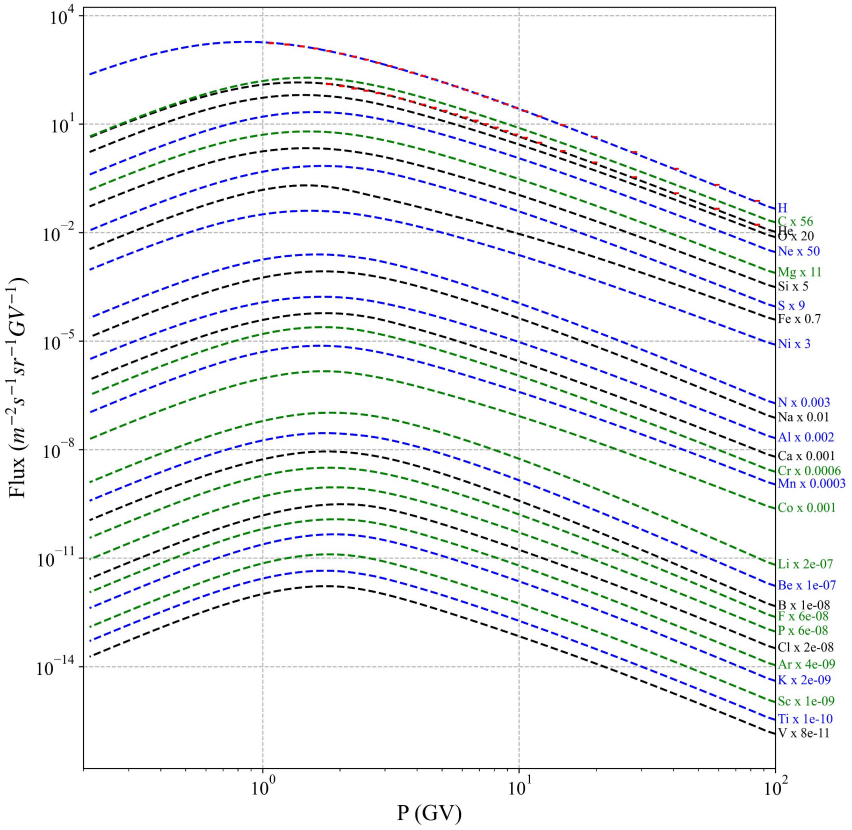
The same set of modulation parameters are utilized to reproduce Helium flux variation.

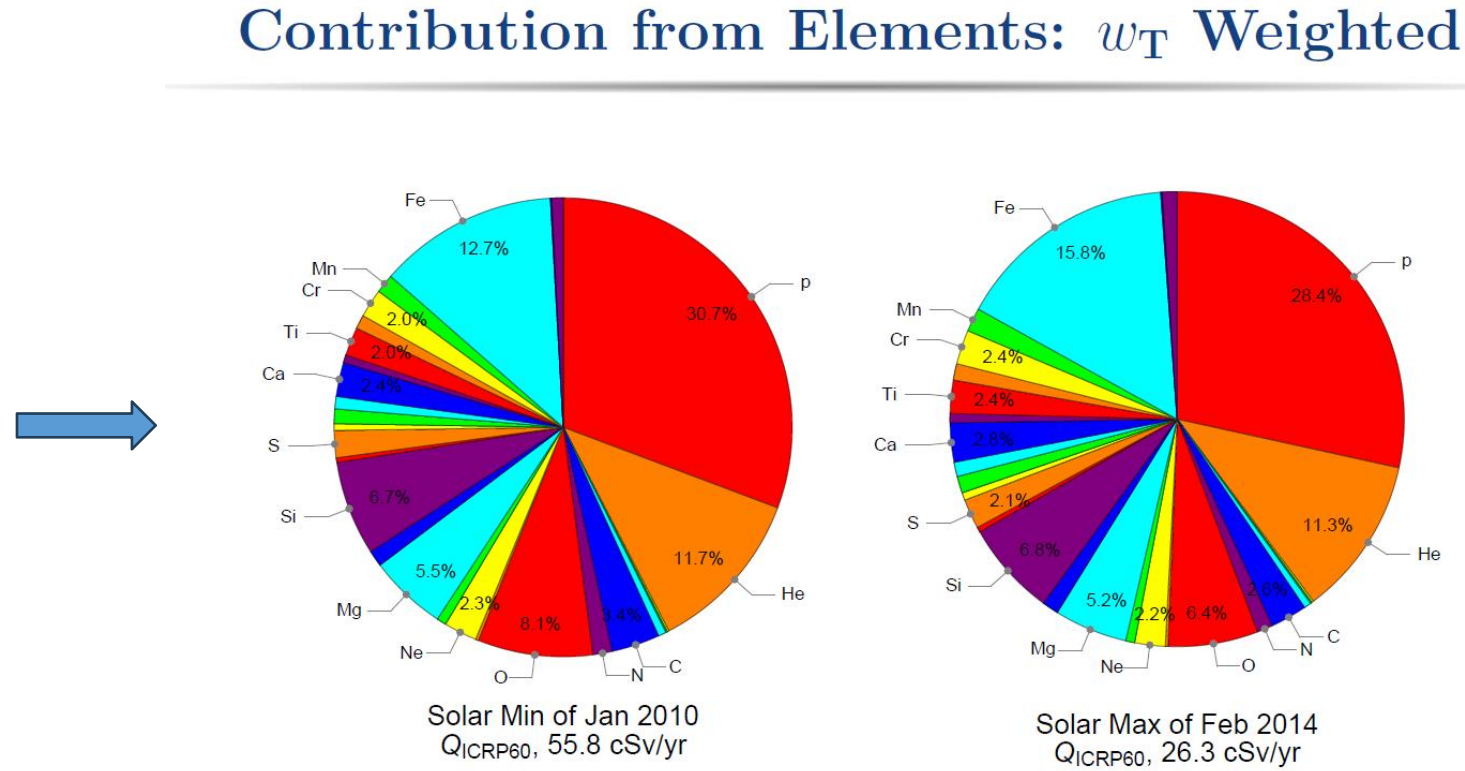






Convert GCR Spectra to Radiaiton Dose





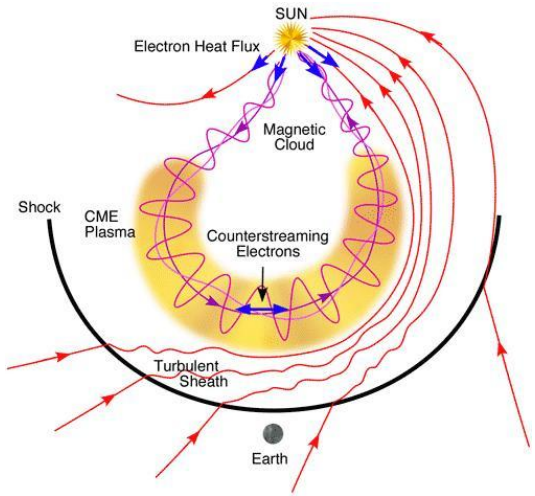
Chen, X., Xu, S., Song, X., Huo, R., & Luo, X. (2023). *Space Weather*, *21*

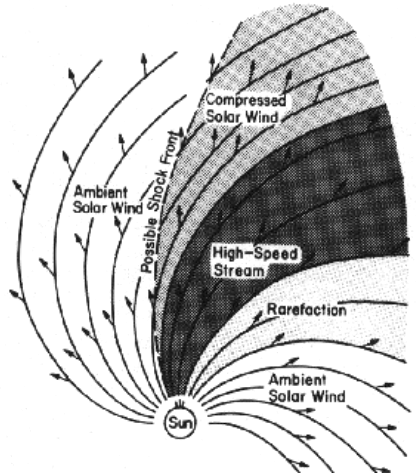
The same set of modulation parameters are utilized to reproduce GCR spectra (From Z=1 to Z=26).

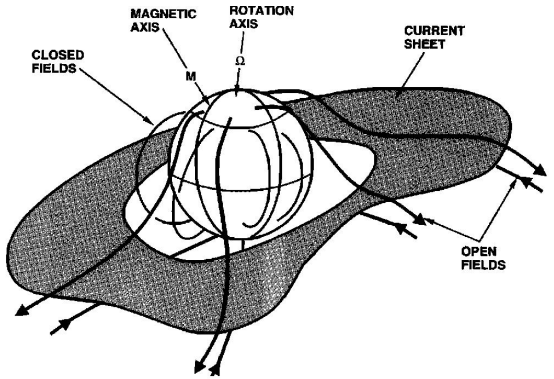
$$H_T = \sum_R \int dE \; 4\pi J_R(E) \; (D_{T,R}/\Phi)(E) Q$$

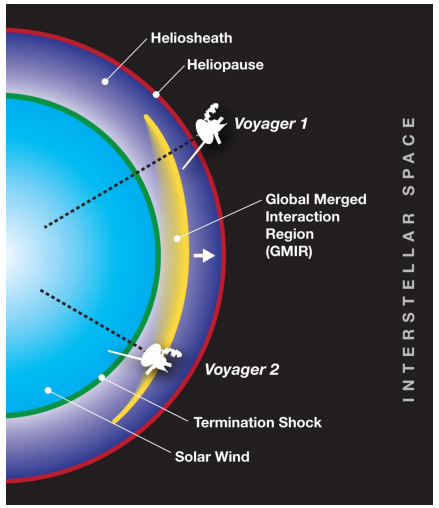
GCR Short–term Solar Modulation

Various Solar Wind Plasma Structures

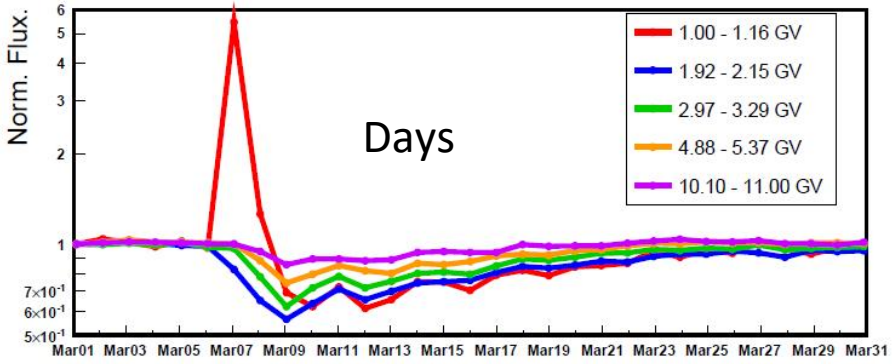




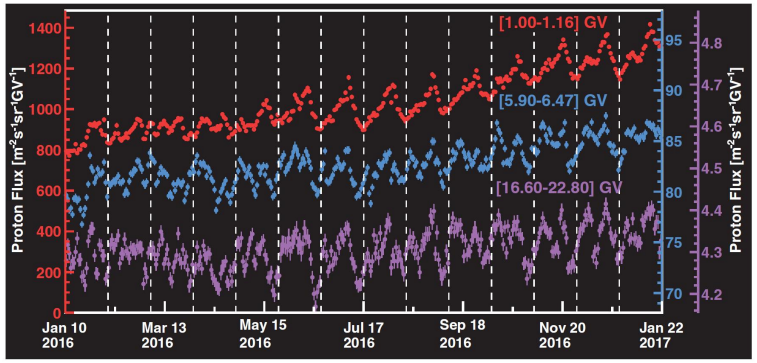




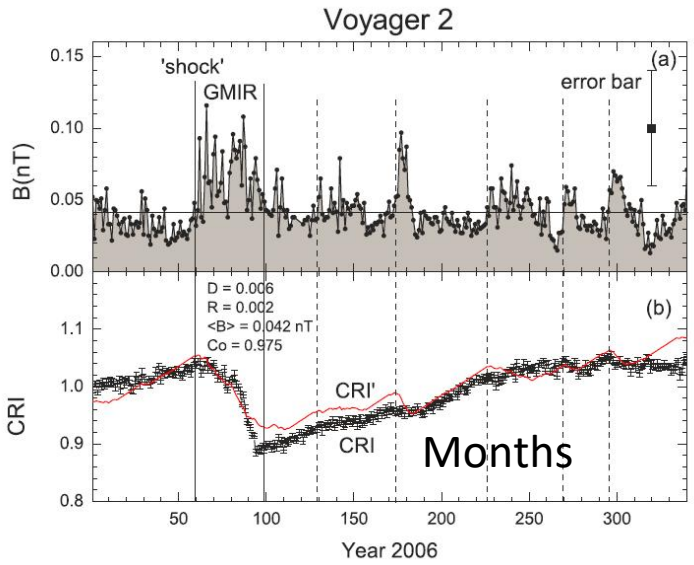
Weeks



Consolandi et al., 2015

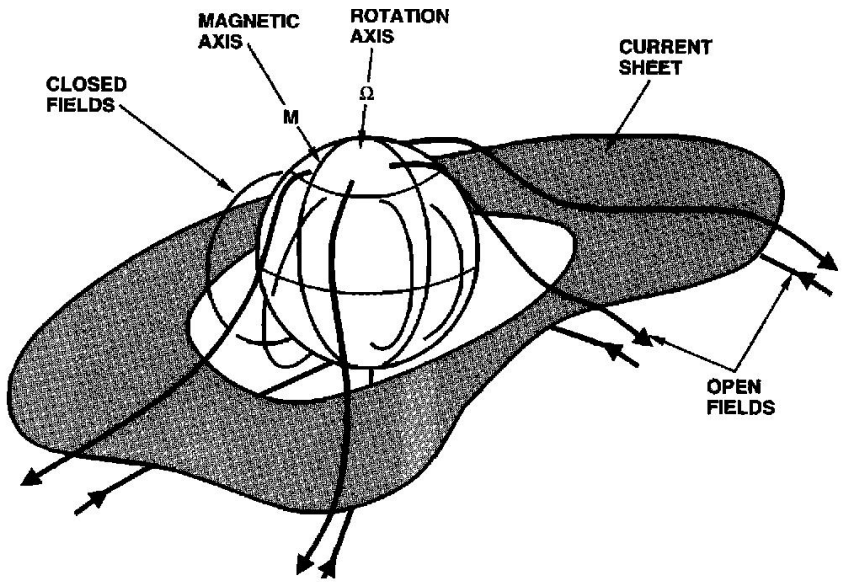


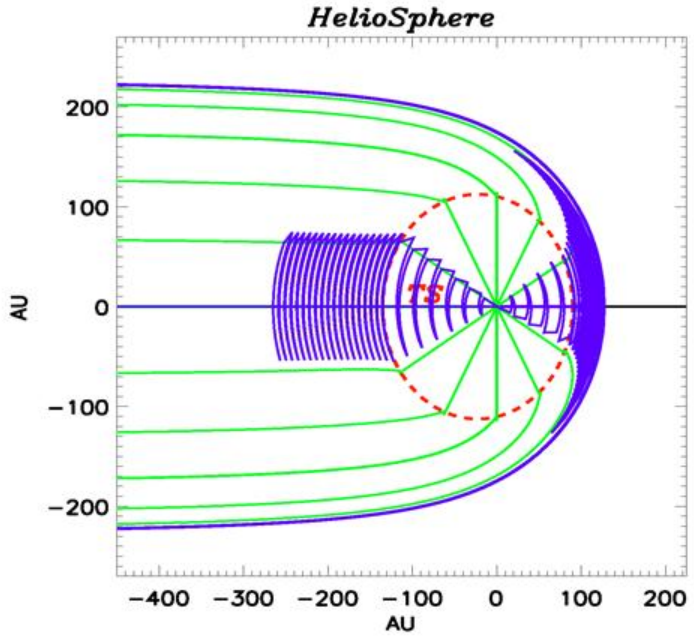
Aguiliar M. et al. 2021

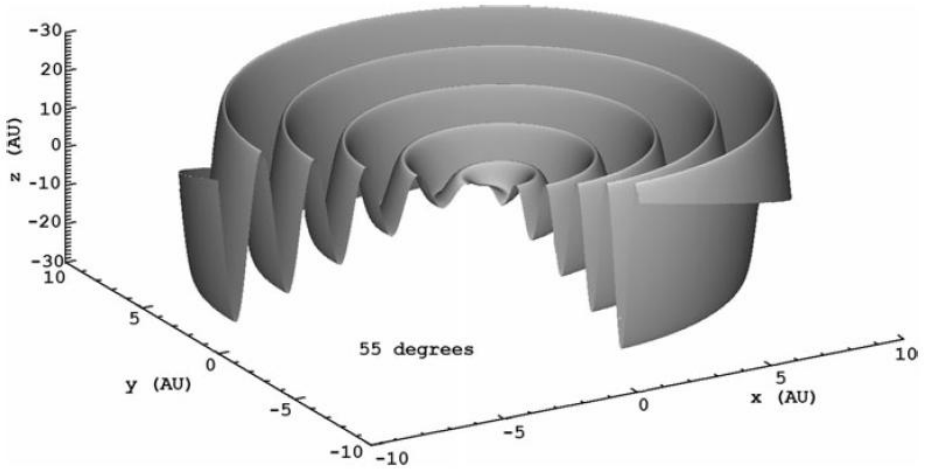


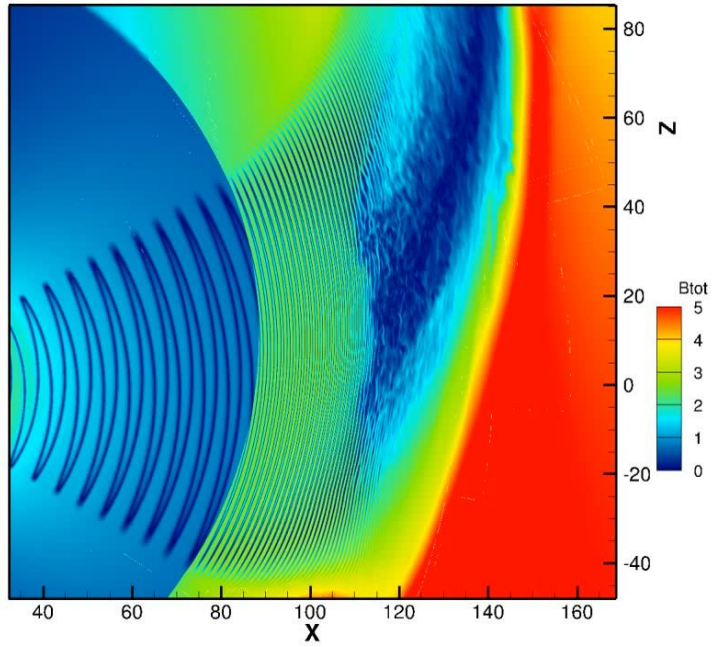
Burlaga et al. 2013

Heliosphere Current Sheet

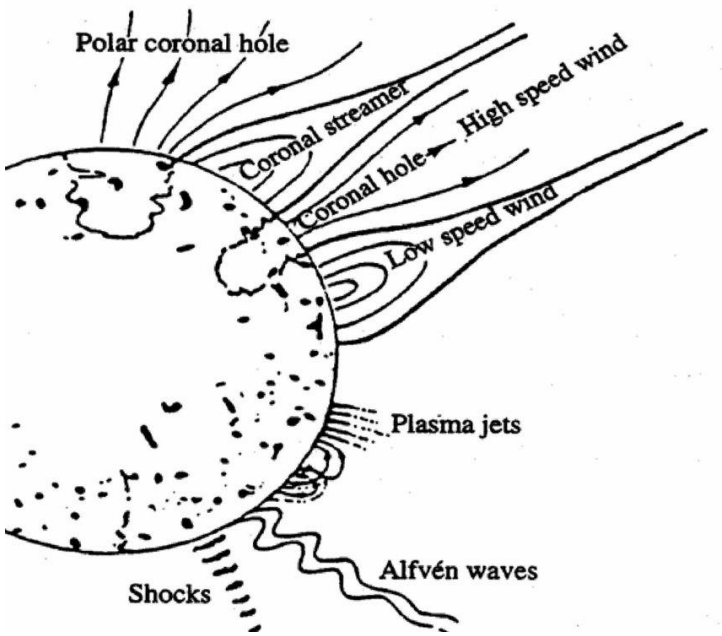




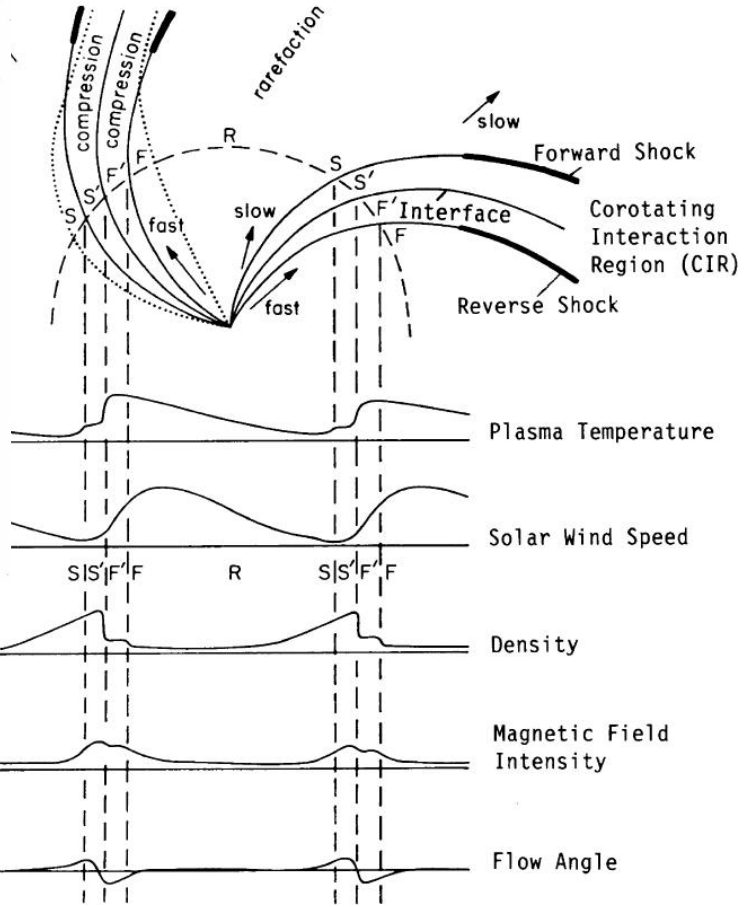




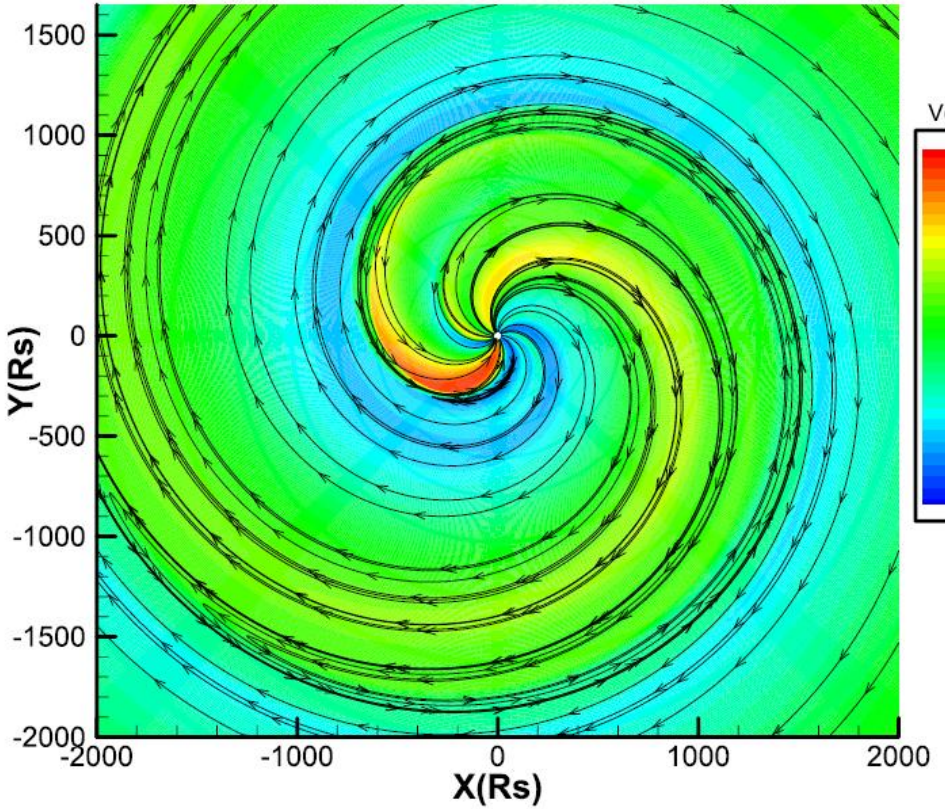
Corotating Interaction Region



Dryer et al.
(1987)



$$\psi = \arctan(r\Omega / V)$$

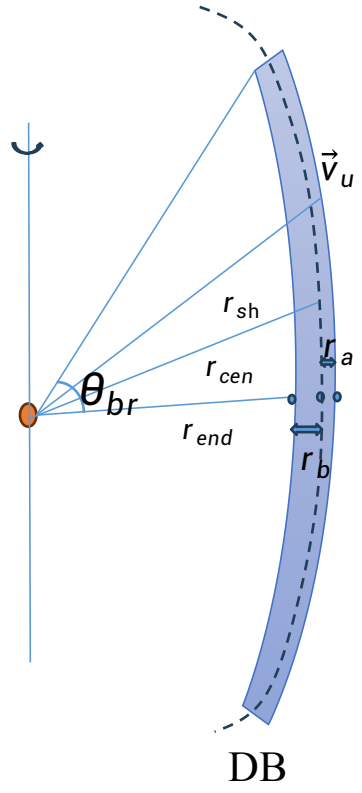


According to the Parker theory, The fast solar wind stream gets less twisted.

Belcher and Davis (1971)

Luo et al. (2020)

GCR Short–term Solar Modulation: Forbush Decrease Events

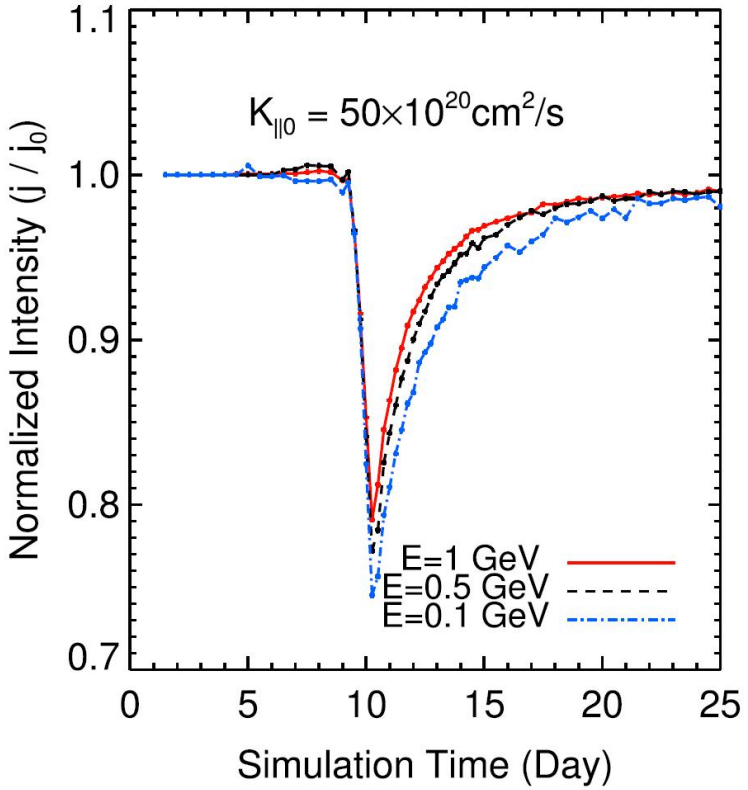


Diffusion Barrier Scenario

DB

$$\frac{\rho_2}{\rho_1} = 1 + \rho f(r)\mathrm{h}(\theta)g(\phi)$$

$$\kappa'_{\parallel,\perp} = \frac{\kappa_{\parallel,\perp}}{1 + \rho f(r)\mathrm{h}(\theta)g(\phi)}$$



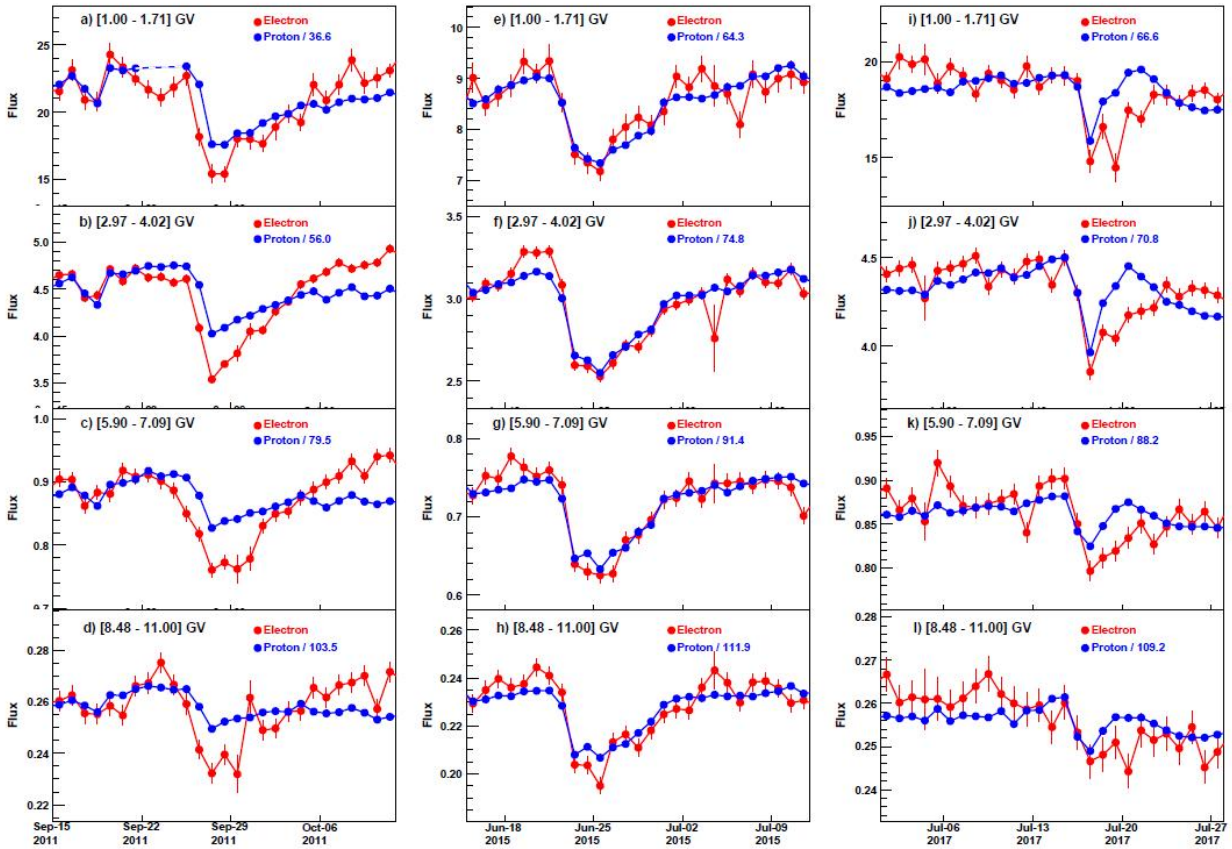
The energy dependence.

DAMPE 实验数据

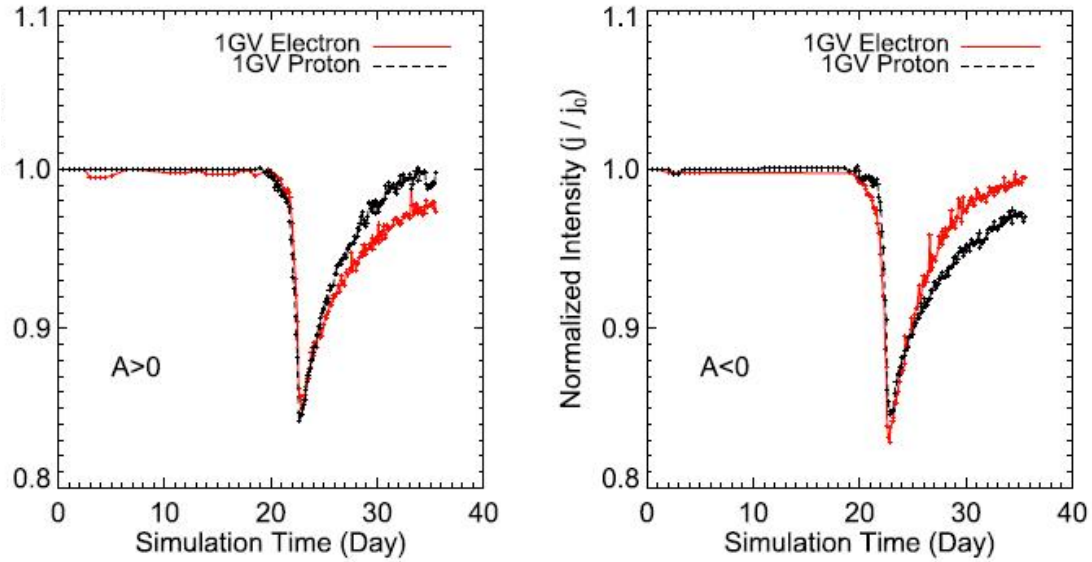
Recovery time energy dependence

Luo+, et al., ApJ, 2017

GCR Short–term Solar Modulation: Forbush Decrease Events

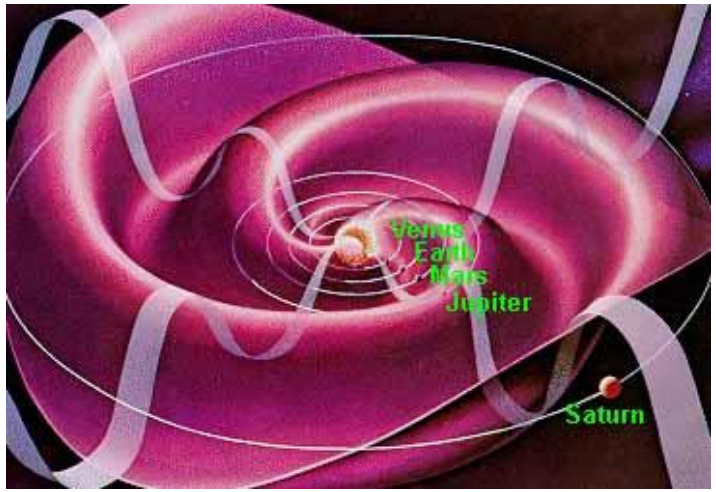


The charge-sign dependence.



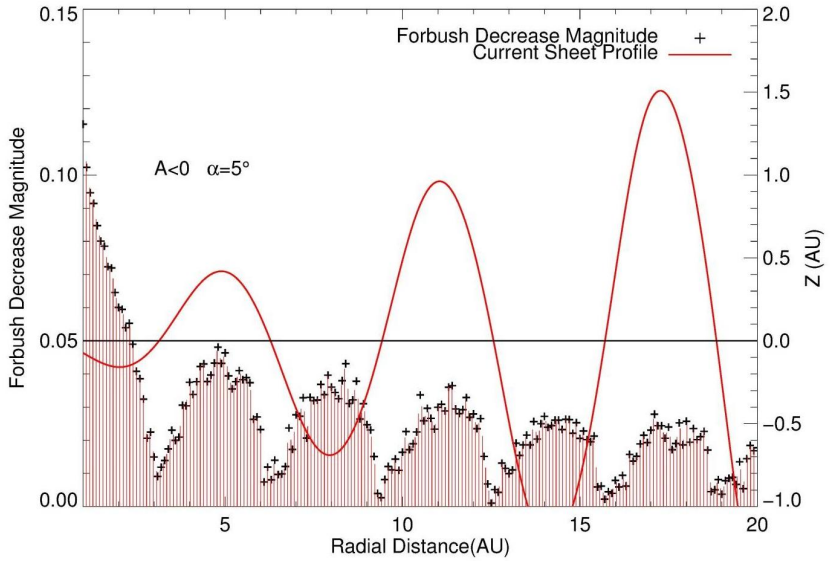
Luo+, et al., ApJ, 2018

GCR Short–term Solar Modulation: Forbush Decrease Events



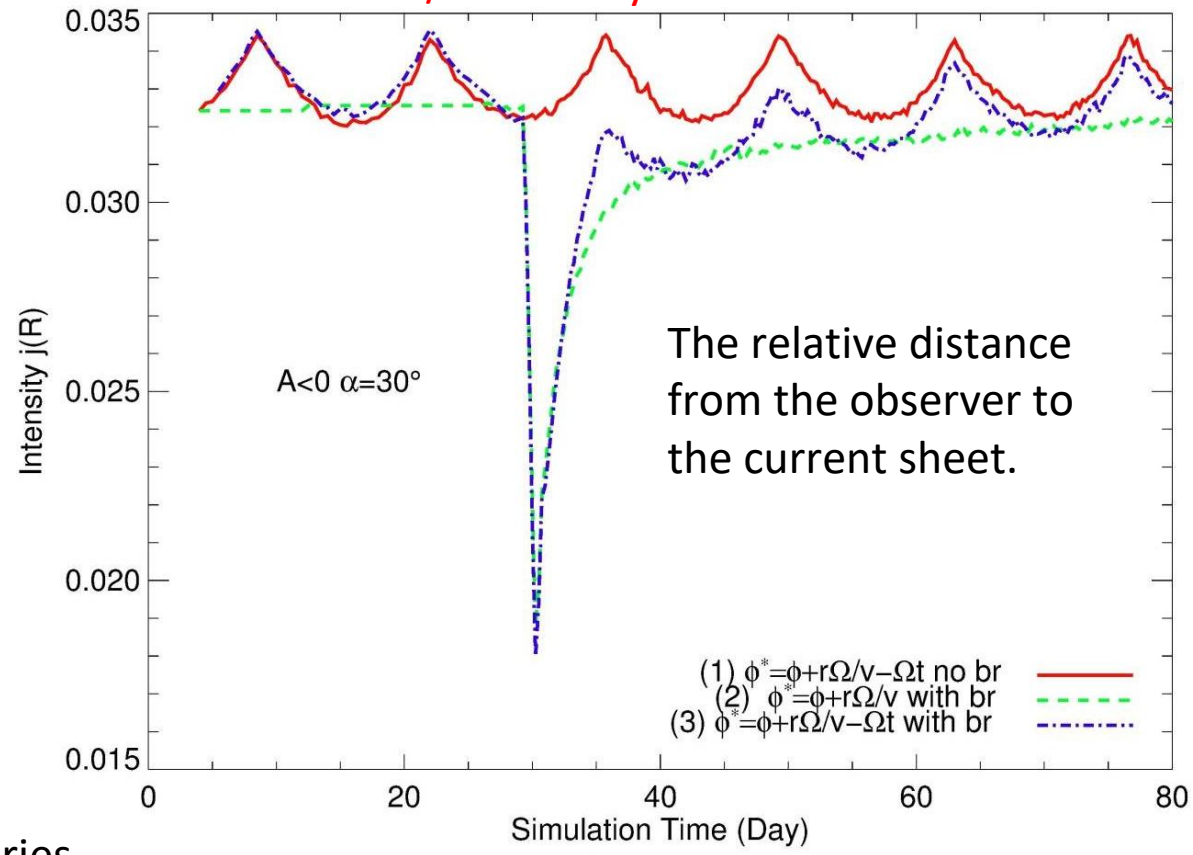
$$-\cot(\theta_{cs}) = \tan a \sin(\phi^*)$$

$$\phi^* = \phi + \frac{r\Omega}{V_{sw}} - \Omega t$$



Fd magnitude varies with distance.

T=T/2=13.5days



The relative distance from the observer to the current sheet.

Luo, Xi, et al., ApJ, 2017

GCR Short–term Solar Modulation: Corotating Interaction Region

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0$$

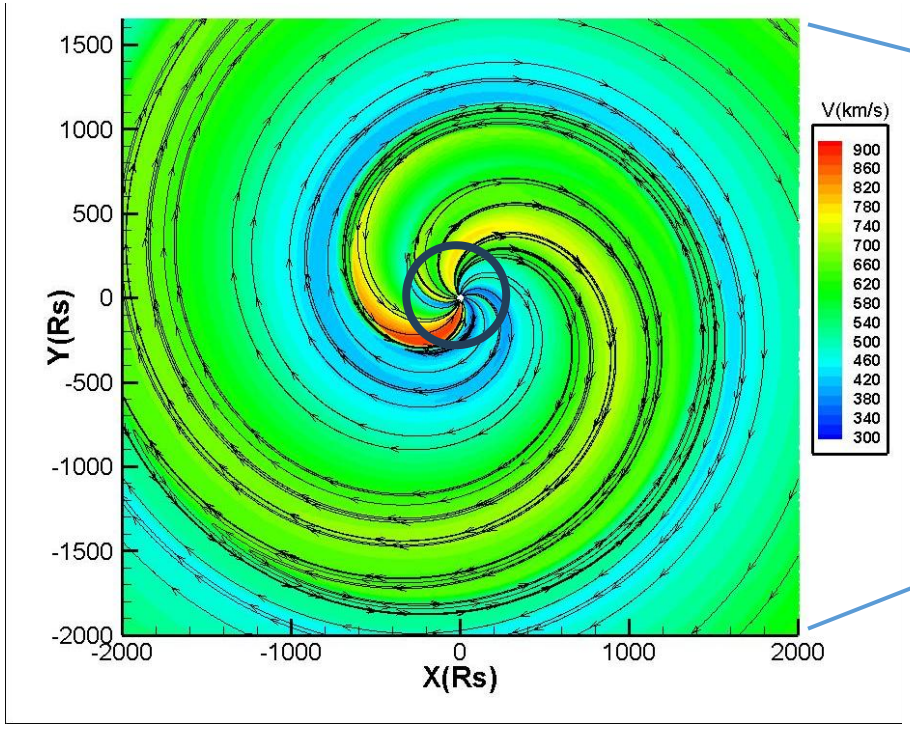
$$\frac{\partial \rho \boldsymbol{V}}{\partial t} + \nabla \cdot \left[\left(P + \frac{B^2}{2\mu_0} \right) \boldsymbol{I} + \rho \boldsymbol{V}\boldsymbol{V} - \frac{\boldsymbol{B}\boldsymbol{B}}{\mu_0} \right] = -\frac{\rho G M_s}{r^2} \frac{\boldsymbol{r}}{r} + \boldsymbol{V} \cdot \boldsymbol{f}$$

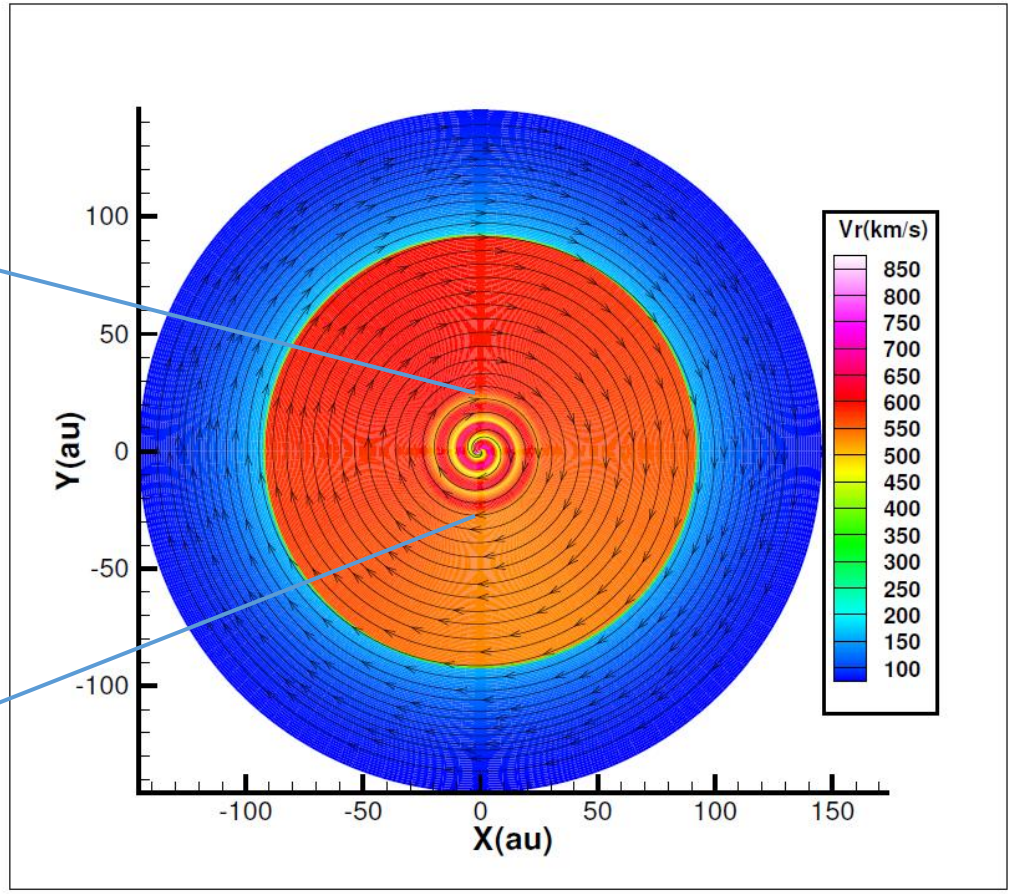
$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{V}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{V}) = 0$$

$$\frac{\partial P}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = -(\gamma - 1) P \nabla \cdot \boldsymbol{V}$$

Expressed in the solar co-rotating frame.

$$((V_r, V_\theta, V_\phi), (B_r, B_\theta, B_\phi), N, P)$$





GCR Short–term Solar Modulation: Corotating Interaction Region

$\vec{B}$ $\vec{V}_{sw}$ **The MHD simulation**

Diffusion Tensor

$$\vec{\vec{\kappa}} = \kappa_{\perp}\vec{\vec{I}} + (\kappa_{\parallel} - \kappa_{\perp})\hat{b}\hat{b}$$

$$K_{\parallel} = K_0 \beta \left(\frac{B_{eq}}{B}\right)\left(\frac{R}{R_0}\right)^{a}\left(\frac{\left(\frac{R}{R_0}\right)^{c} + \left(\frac{R_k}{R_0}\right)^{c}}{1 + \left(\frac{R_k}{R_0}\right)^{c}}\right)^{\frac{b-a}{c}}$$

$$K_{\perp,r,\theta} = 0.02 K_{\parallel}$$

Drift Speed

$$\langle \vec{v_D} \rangle = (K_d)_0 \frac{pv}{3q} \nabla \times \left(\frac{\vec{B}}{B^2}\right)$$

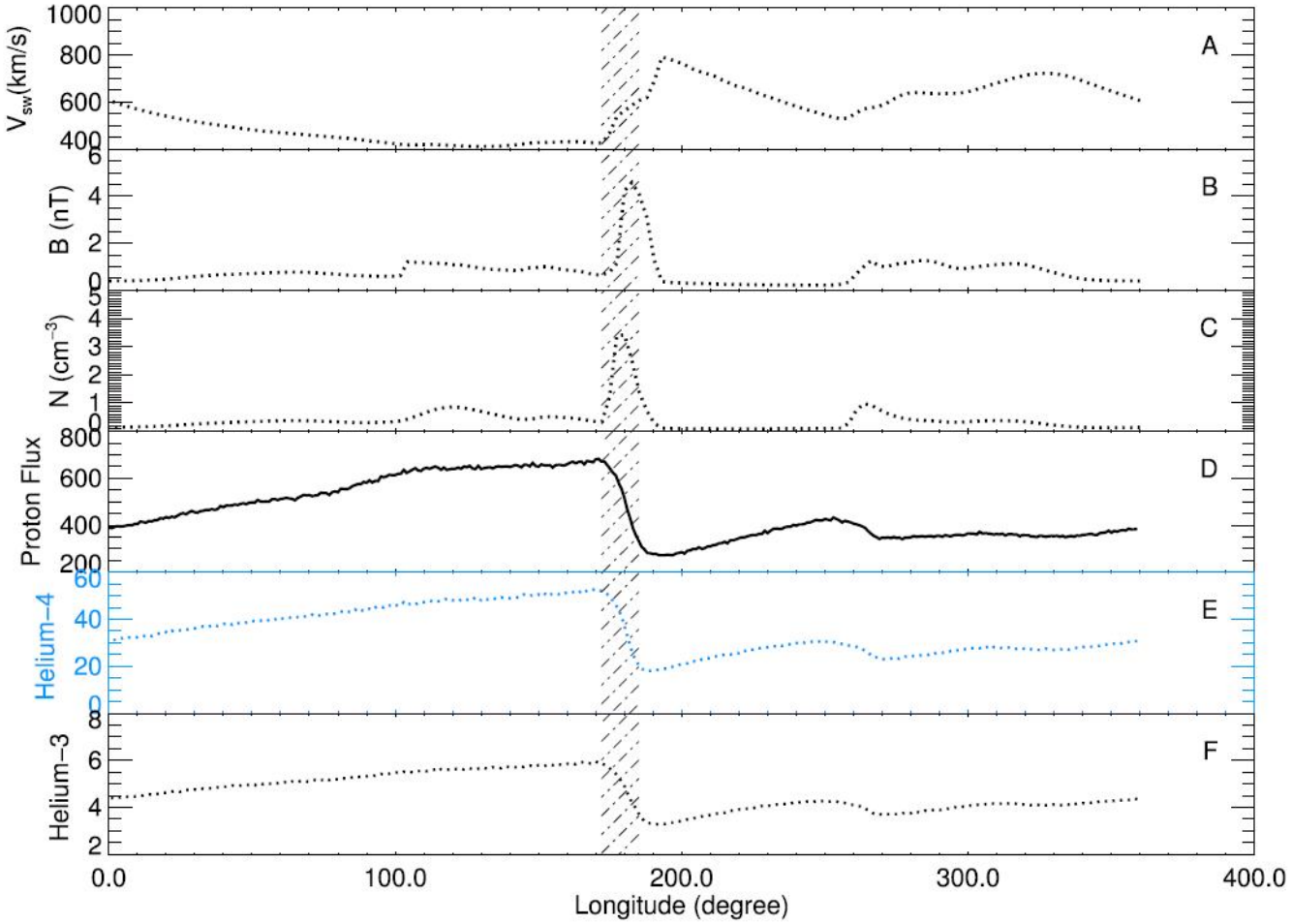
Solar Wind Speed

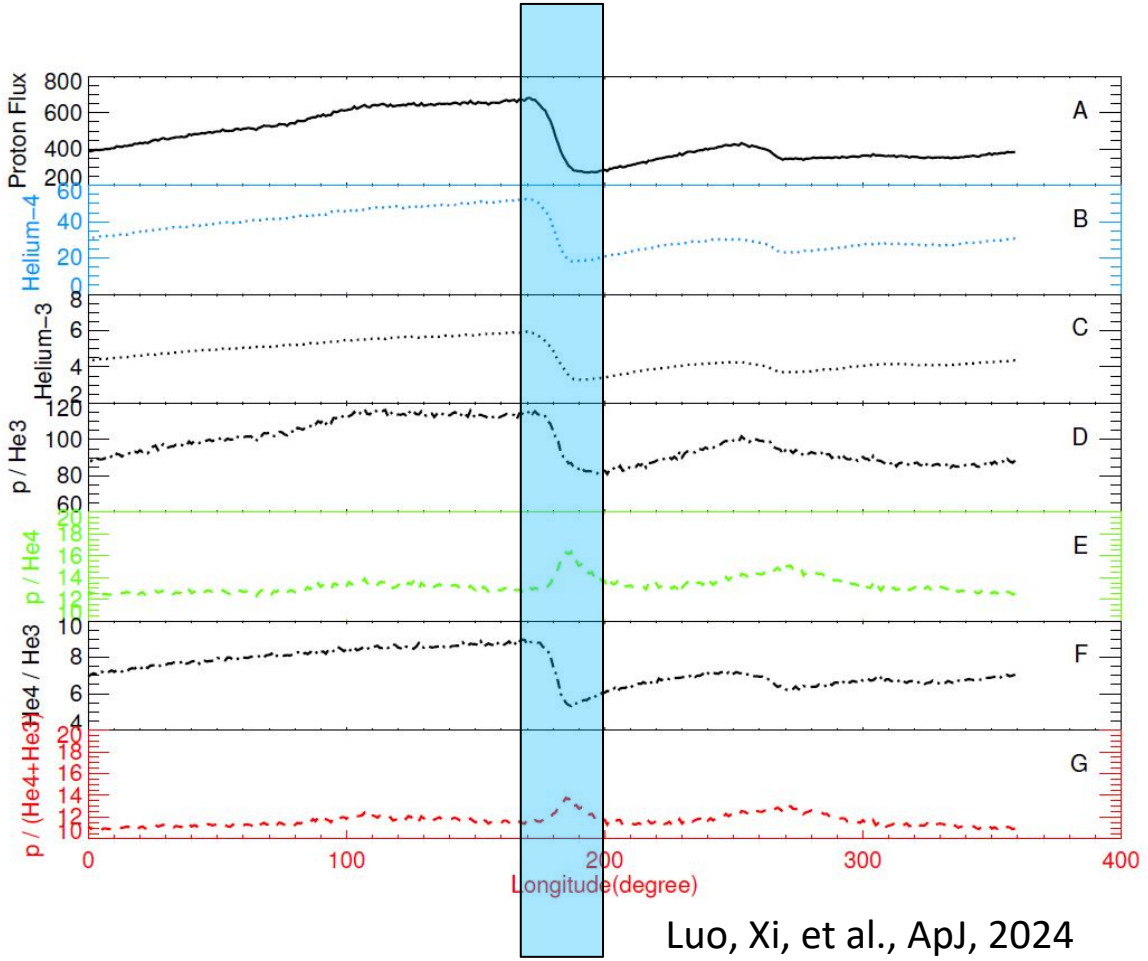
$\vec{V}_{sw}$

$$d\vec{\mathbf{x}} = \sqrt{2\vec{\kappa}} \cdot d\vec{\mathbf{w}}(s) + (\nabla \cdot \vec{\vec{\kappa}} - \vec{\mathbf{V}}_{sw} - \vec{\mathbf{V}}_d)ds$$

$$dp = \frac{1}{3}\nabla \cdot \vec{\mathbf{V}}_{sw}\, p ds$$

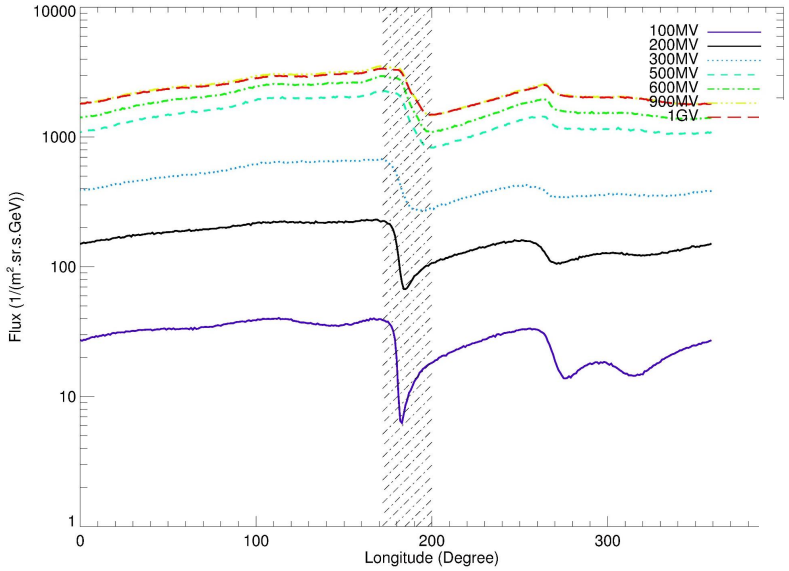
GCR Short-term Solar Modulation: Corotating Interaction Region

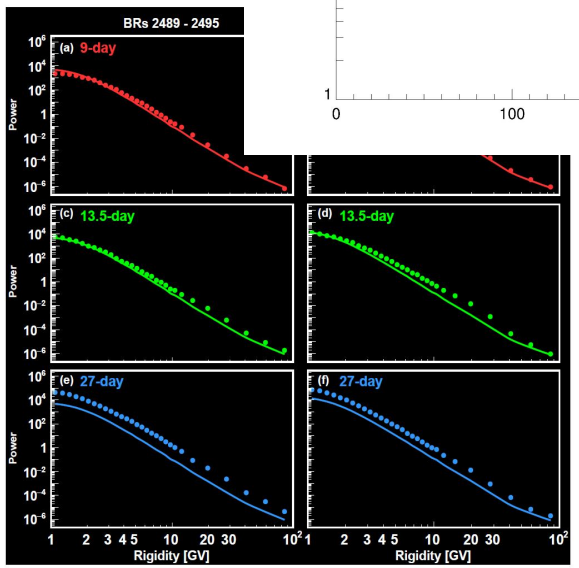




Luo, Xi, et al., ApJ, 2024

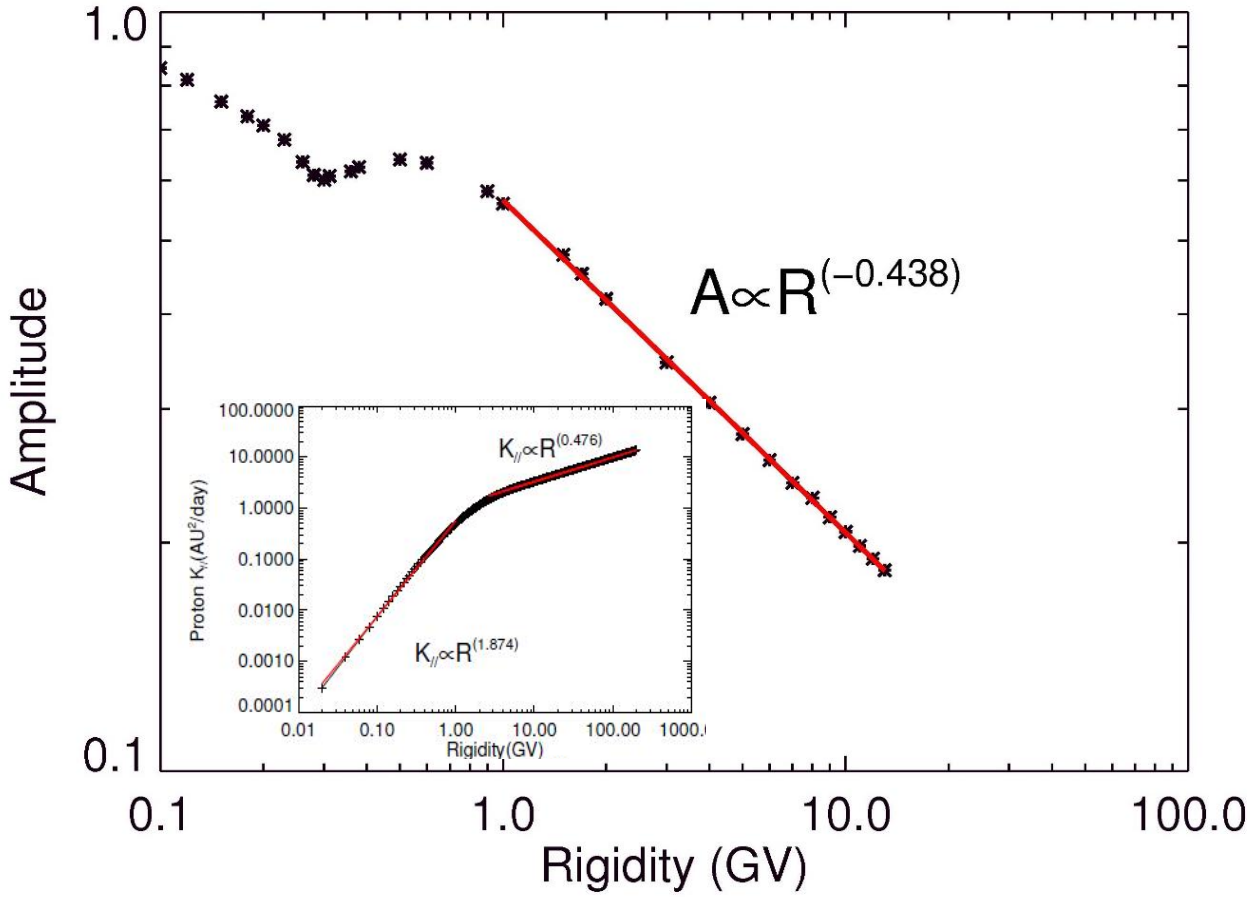
GCR Short-term Solar Modulation: Corotating Interaction Region





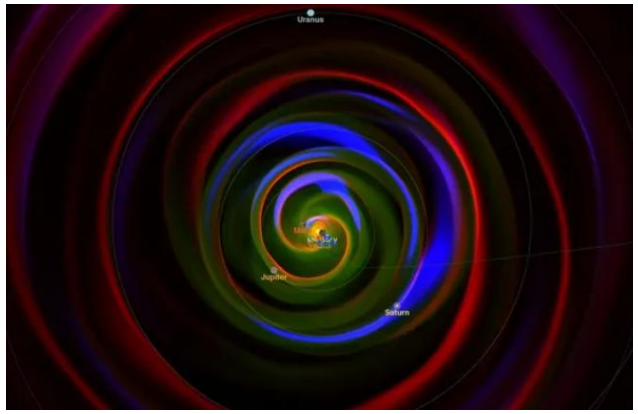
AMS observation Physical Review Letters 127, 271102 (2021)

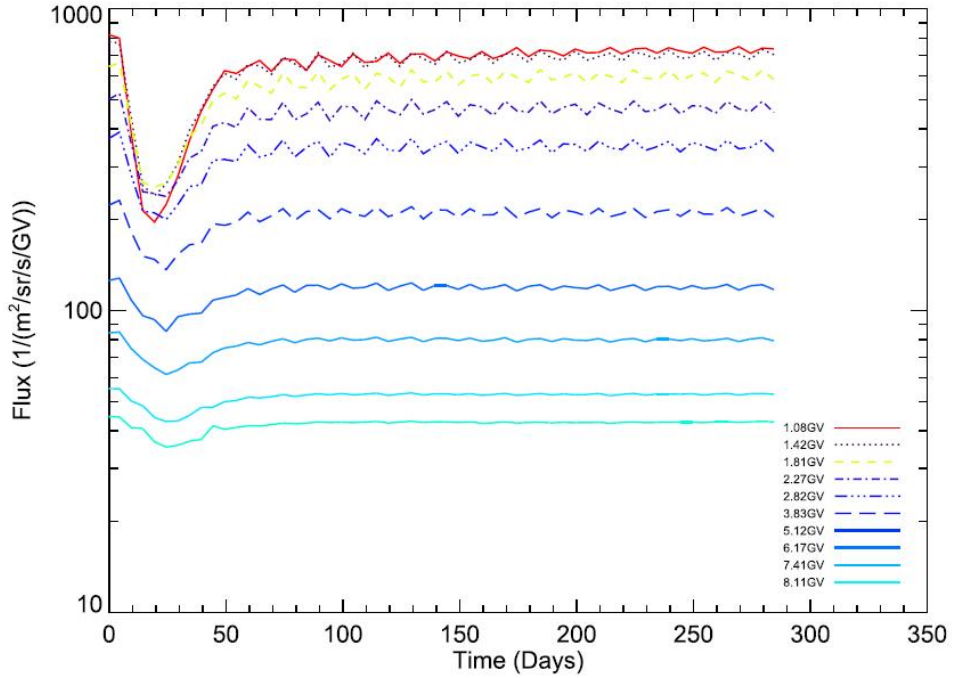
The effect of CIR on GCR proton exhibits rigidity dependence.

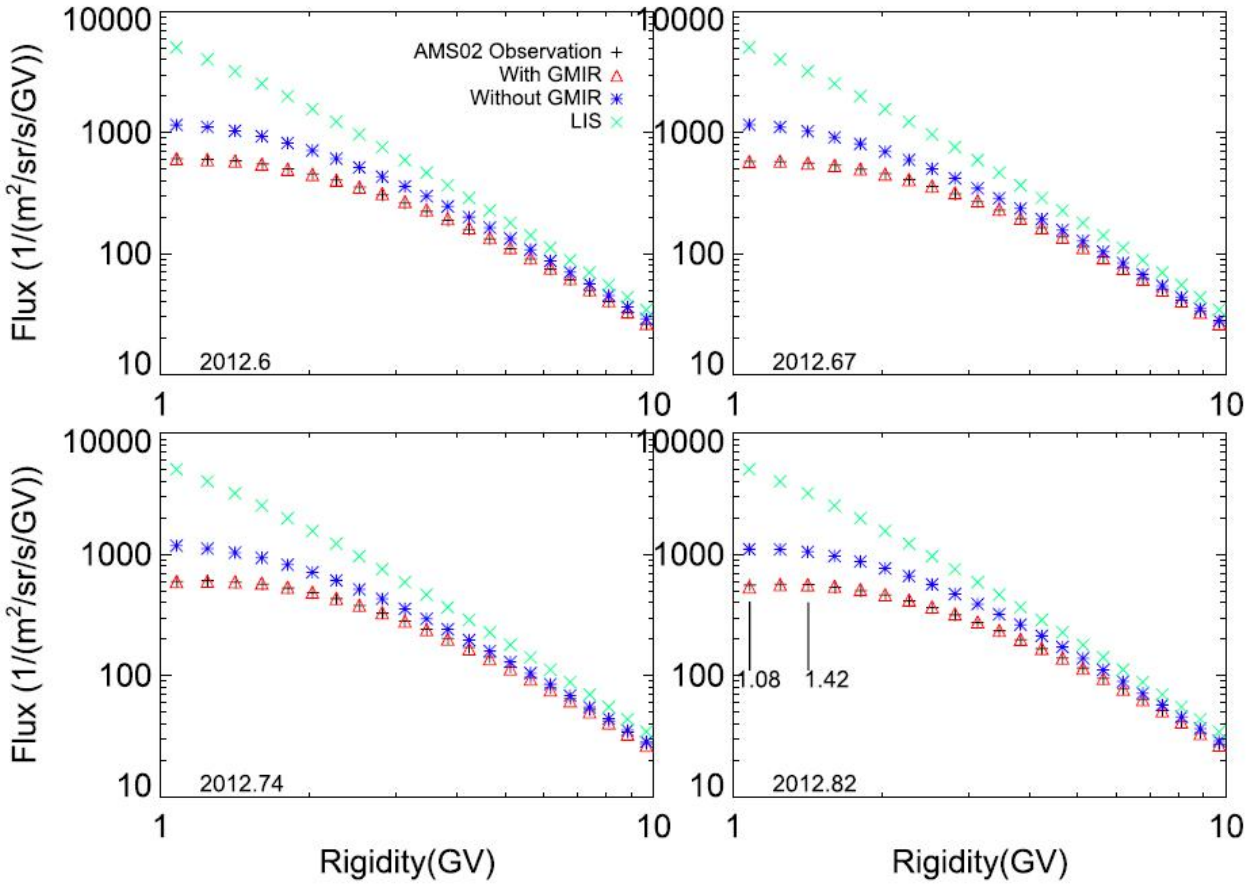


Luo, Xi, et al., ApJ, 2024

GCR Short-term Solar Modulation: Global Merged Interaction Region



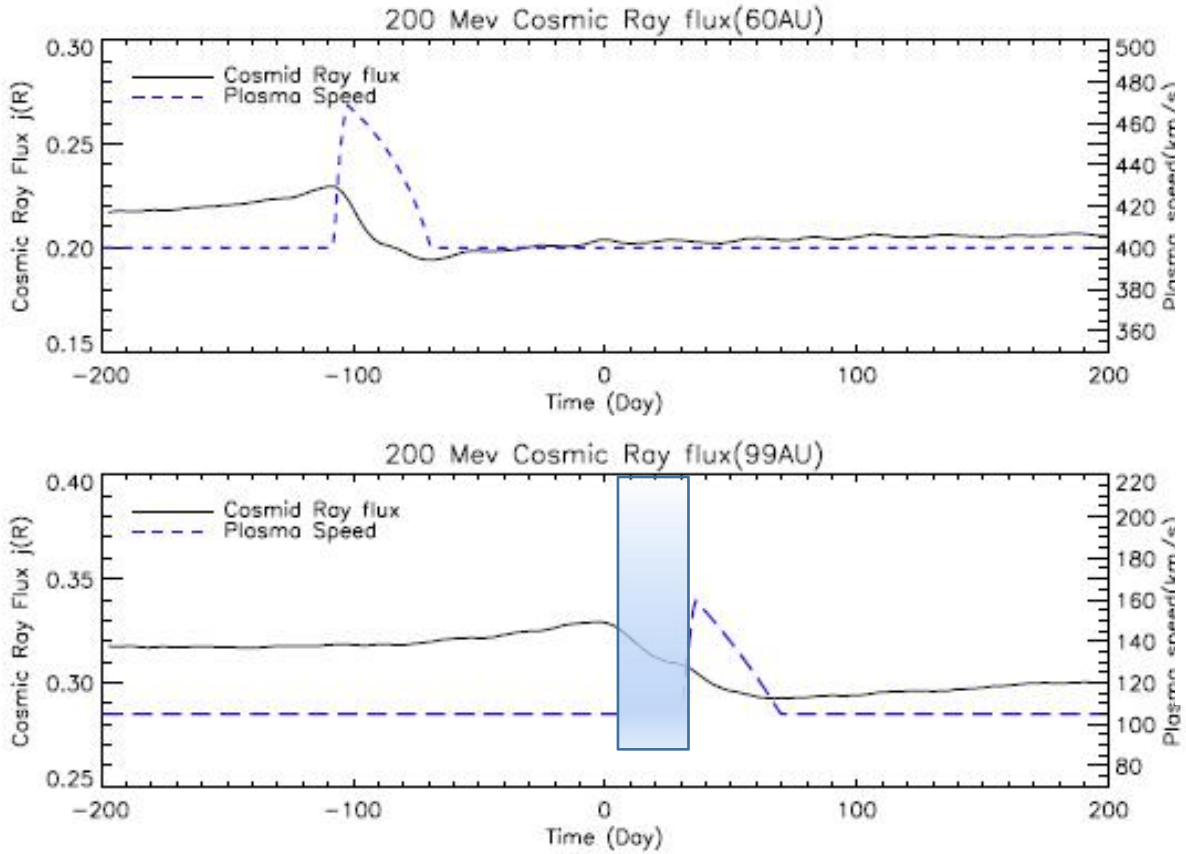




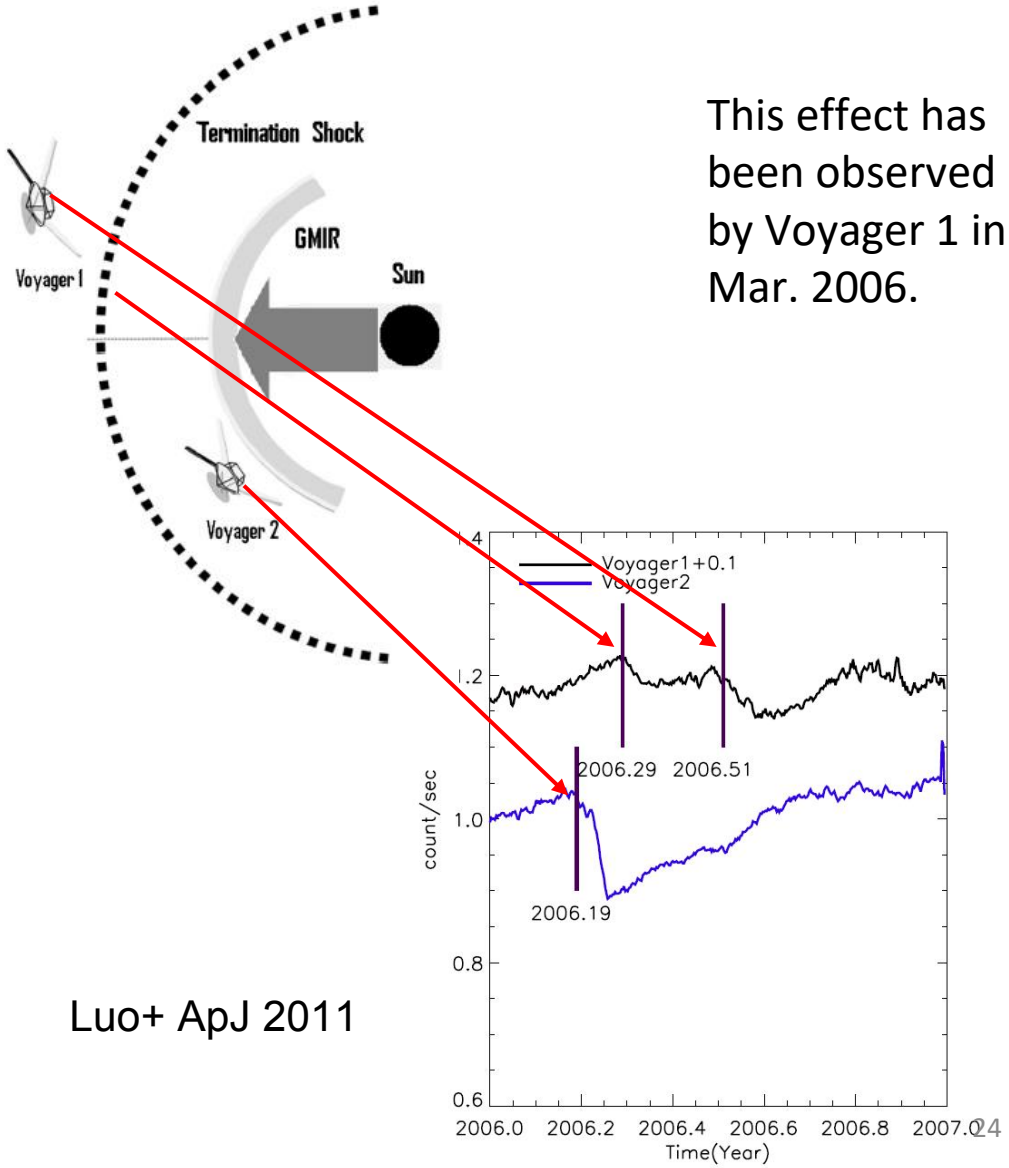
GMIR event at 1 au. (2012 July)

Luo+ ApJ 2019

GCR Short-term Solar Modulation: Global Merged Interaction Region



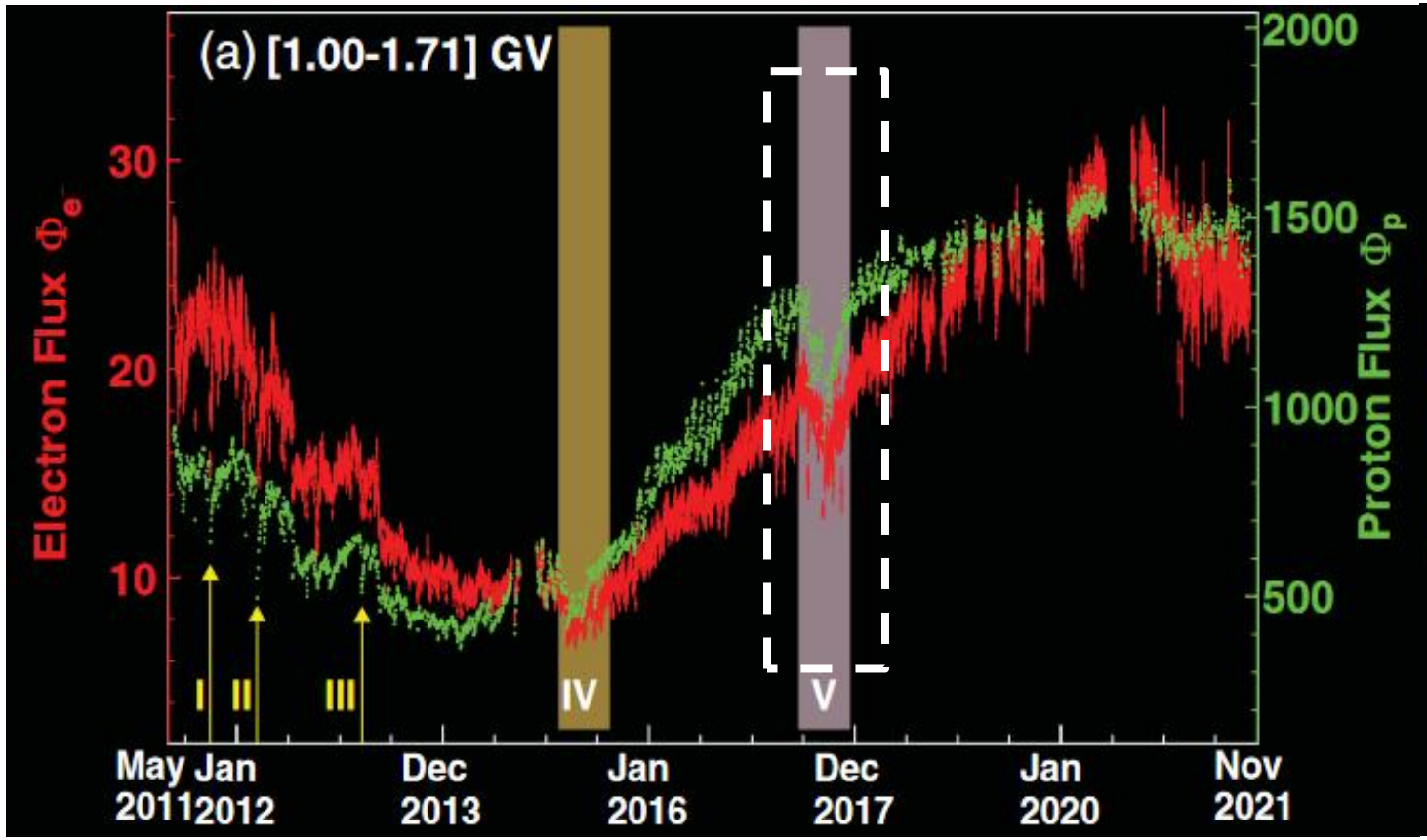
The GCR "remote sense"the interaction between the GMIR and Terminaiton Shock.

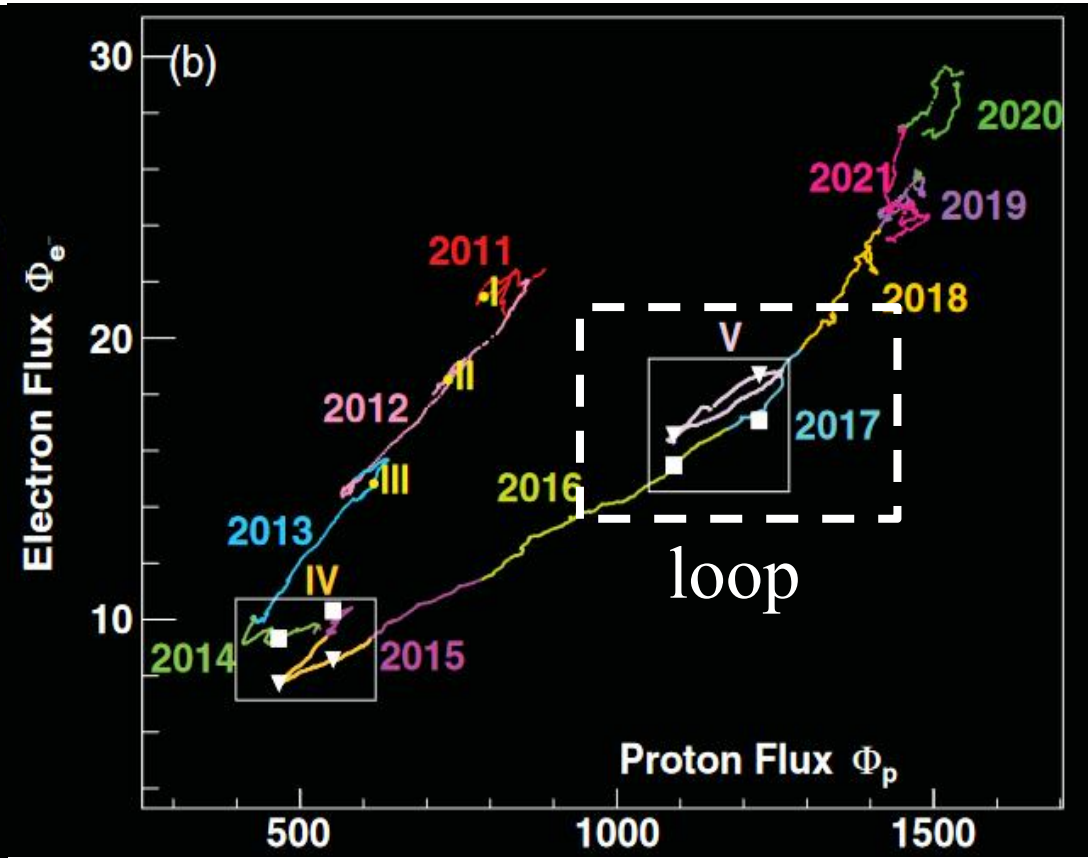


Luo+ ApJ 2011

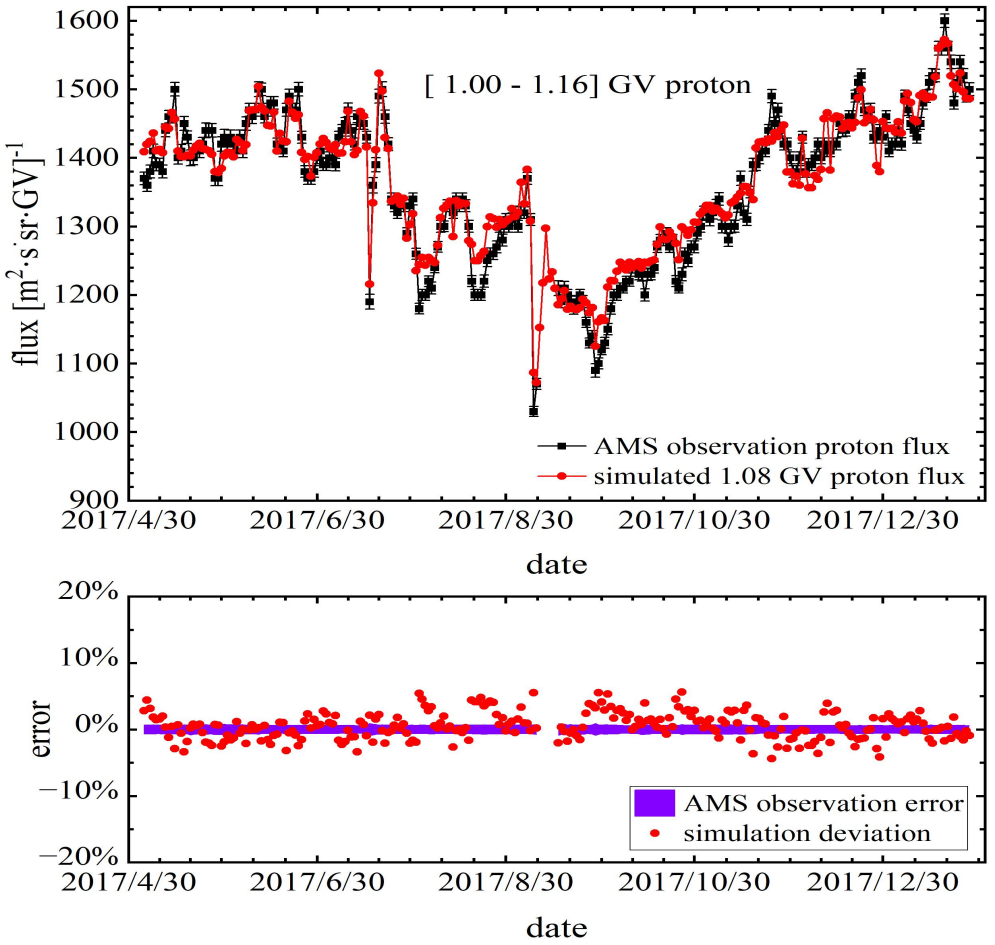
This effect has been observed by Voyager 1 in Mar. 2006.

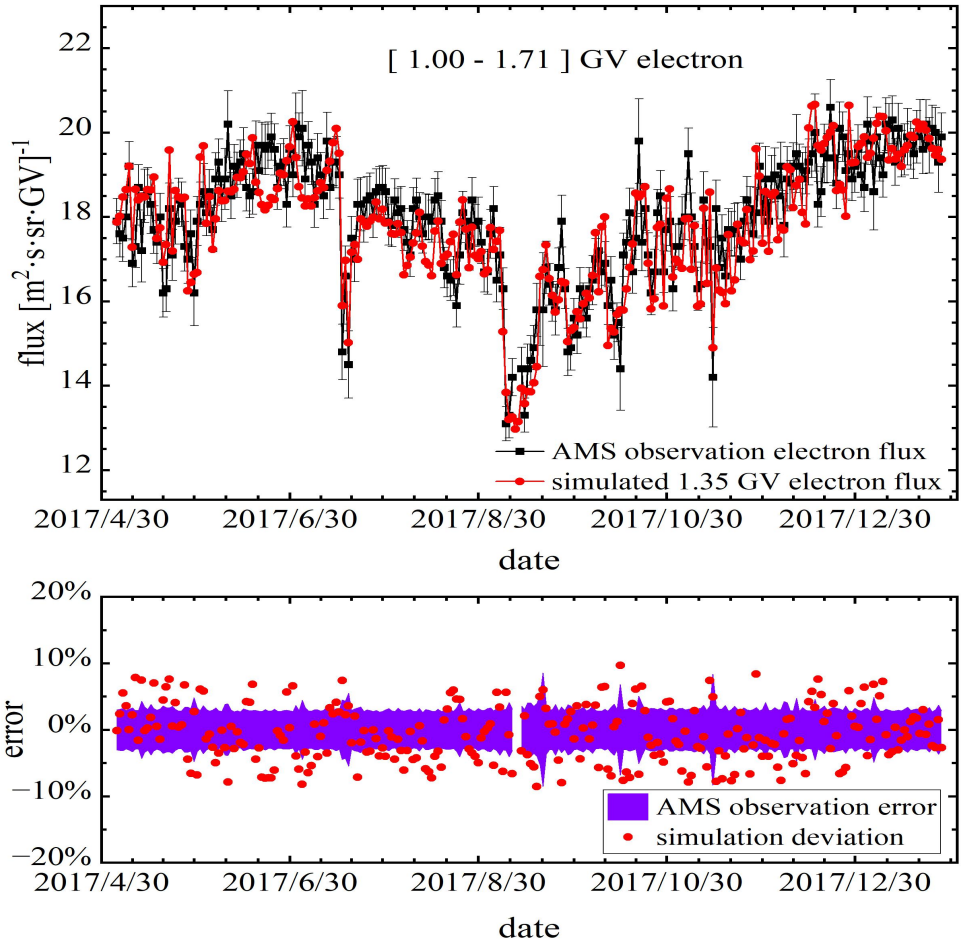
Global Merged Interaction Region





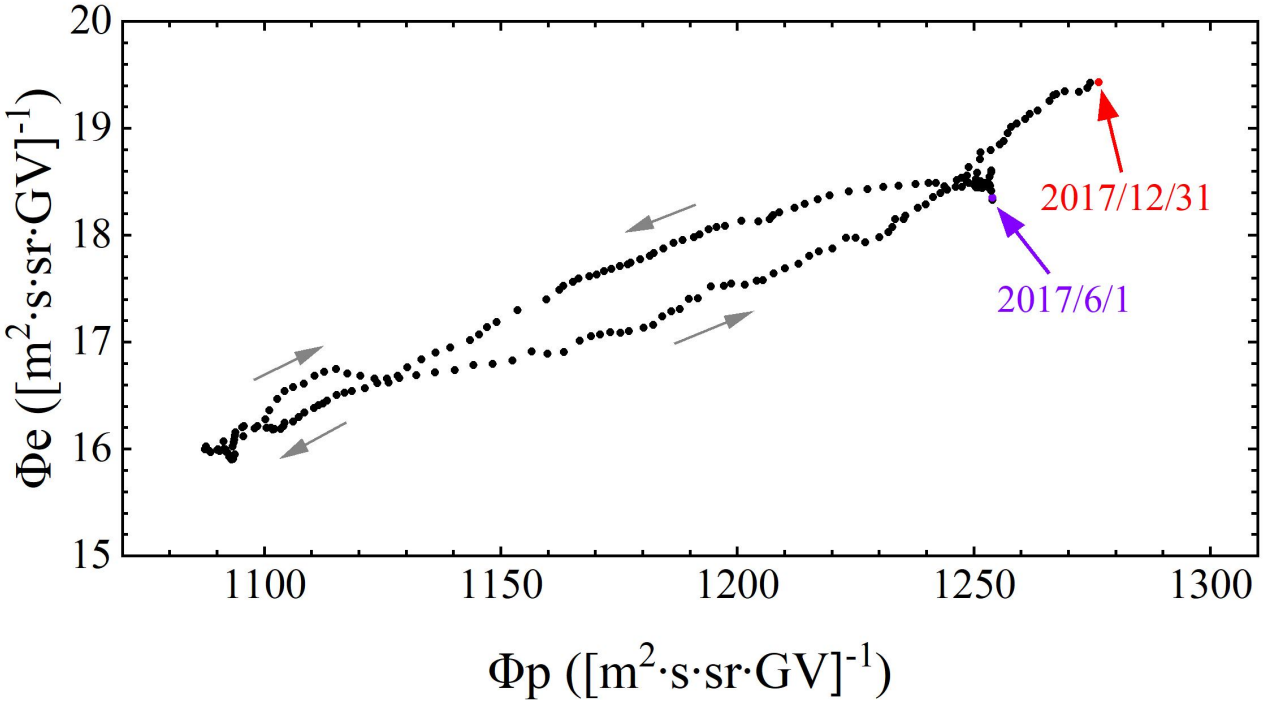
Simulation For 2017 Decrease Event





Simulation For 2017 Decrease Event

Yang, Luo* et al. A&A 2025



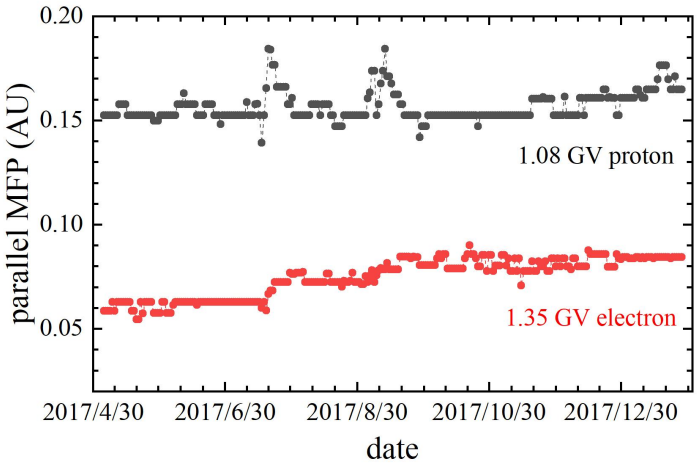
The grey arrows point in the direction of time increase.

[1.00 – 1.71] GV

J_p: average of simulation results at 1.08 GV, 1.24 GV, 1.42 GV, 1.61 GV

J_e: simulation results at 1.35 GV

Φ_p and Φ_e : moving average of 2 BRs' (54 days) J_p and J_e with a step of 1 day



Summary

1. Based on Parker transport theory, state of art cosmic ray transport model has been developed, cosmic ray short-term solar modulation has been studied.

2. AMS GCR observation can be reproduced by the numerical model, the GCR observation during the solar magnetic field reversal period has also been reproduced.

3. Recent AMS observation provides much challenge for the current cosmic ray transport theory and numerical models.

Thanks!