

# CALETによる10年間の太陽変調観測と ドリフトモデルによる再現

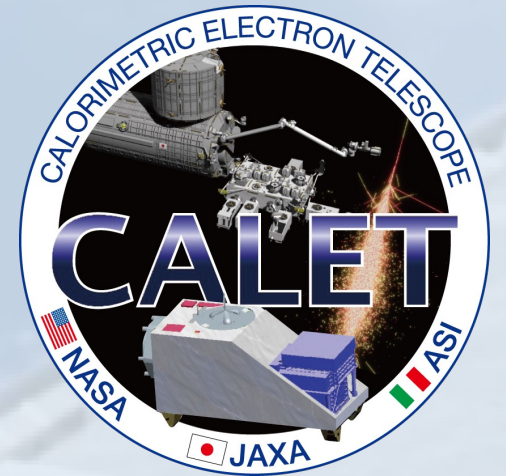
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三宅 晶子, 宗像一起<sup>A</sup>, 赤池陽水<sup>B</sup>,

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他 CALETチーム



# Measurements of Low-Energy CRs by the CALET

## Low-energy $e^-$ shower trigger mode (LEE Trigger):

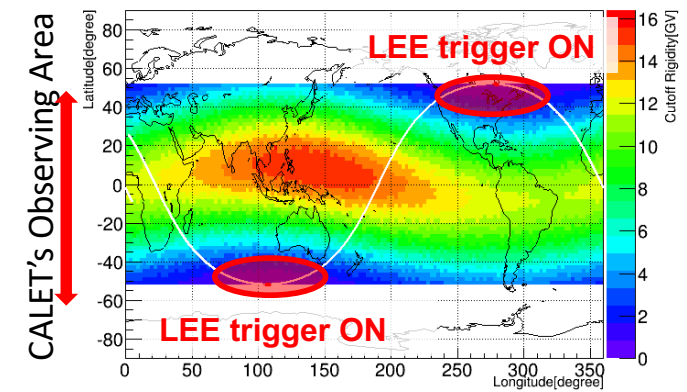
- Trigger threshold: shower energy  $> 1$  GeV
- The LEE trigger is enabled only in high-latitude regions (geomagnetic cutoff rigidity  $< \sim 5.0$  GV)
  - The LEE trigger is activated for 90 sec. twice per ISS orbit.

**Oct. 13, 2015 ~ Dec. 31, 2025**

Total Live Time:  $\sim 1465$  [hours]

Total events :  $\sim 1.6 \times 10^8$  [events]

Cutoff rigidity map and ISS orbit



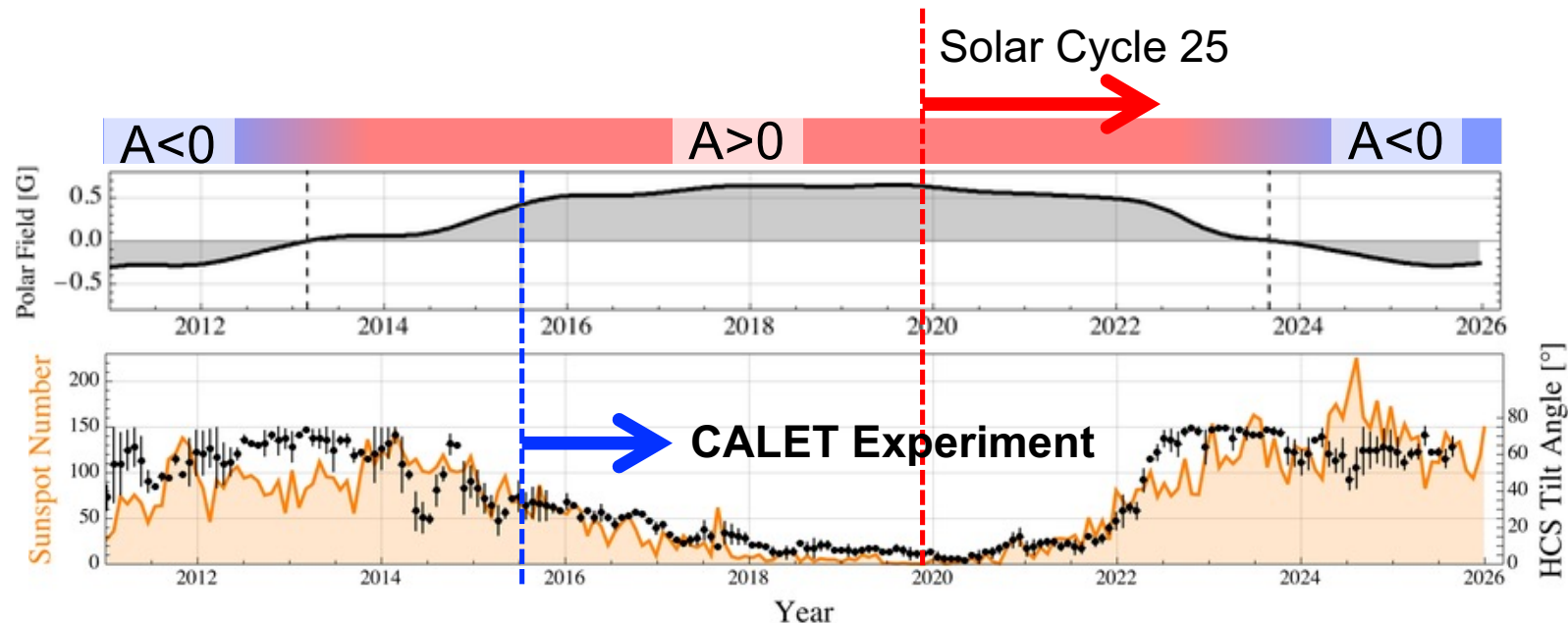
<http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html>

## Analyses of LEE-trigger data

- All-electron ( $e^-+e^+$ ) flux for each Carrington rotation
- Electron and proton count rates at  $\sim 3.8$  GV for investigating charge-sign dependence
- Daily count rates ( $\sim 3.8$ GV) for Forbush decrease studies
- \* *The electron count rate was derived by assuming that the positron contamination followed the proton contamination and was normalized to a 7% positron fraction in November 2015 (CR 2170), based on the AMS-02 measurement.*

# Recent Solar Cycle

## Time profile of the polar field, sunspot number, and HCS tilt angle

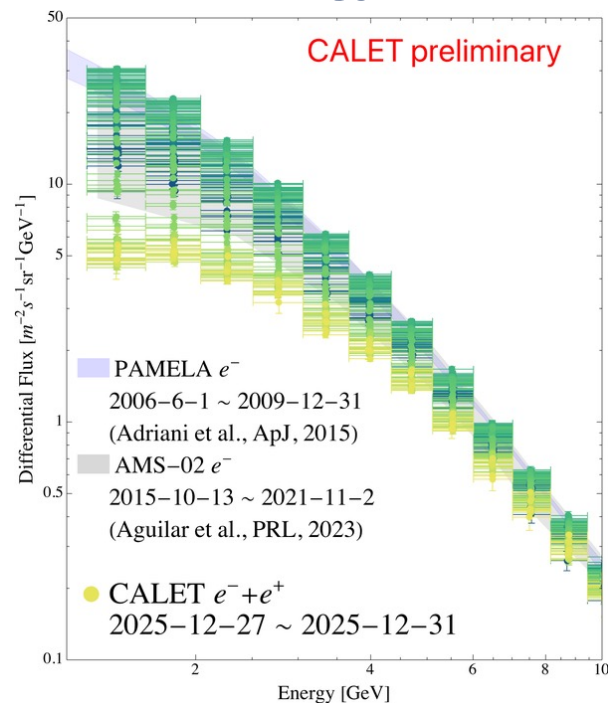


- Solar Cycle 25 began in December 2019, following the solar minimum.
- Solar activity has rapidly increased since 2022, and the Sun's polar magnetic field has reversed from positive to negative.  
→ The global solar magnetic polarity appears to have changed from  $A>0$  to  $A<0$ .

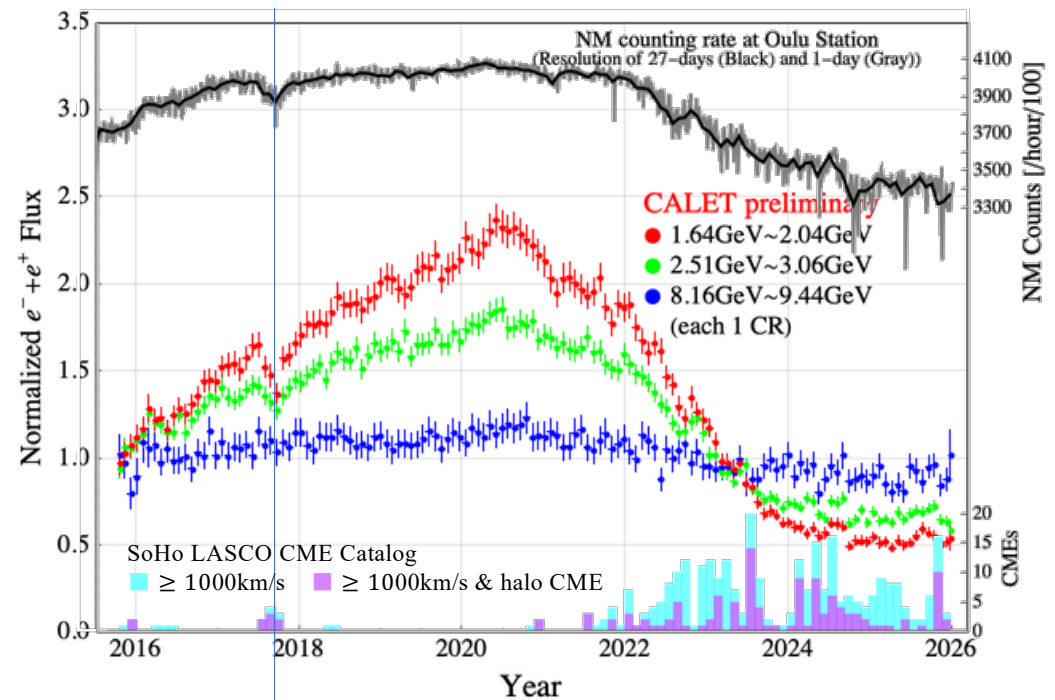
# Long-Term Variation of the CR $e^- + e^+$ Flux

- The 1–10 GeV  $e^- + e^+$  flux began to decrease about six months after the beginning of Solar Cycle 25 (Dec. 2019) and eventually reached its lowest level during the observation period.
- The  $e^- + e^+$  flux has remained low even after the magnetic polarity reversal, and no clear effect of the polarity reversal has been observed so far.

## CR $e^- + e^+$ energy spectrum



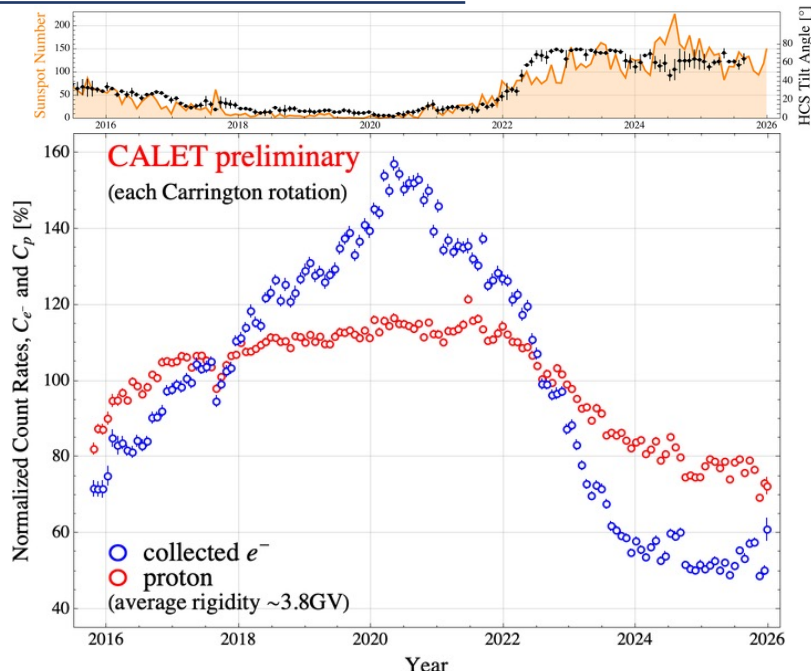
## Time profile of the CR $e^- + e^+$ flux



# Charge-Sign Dependence of Solar Modulation

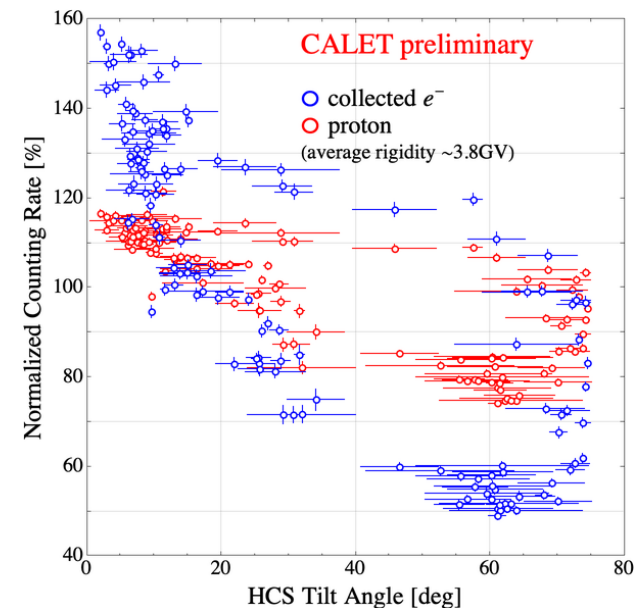
- The proton count rate also reached its lowest level since the beginning of the CALET observations.
- CALET observed a clear hysteresis loop between the CR intensity and the HCS tilt angle over the solar cycle.

## Time profile of the CR proton and electron count rates



(Average value for the entire period is normalized to 100%)

## Correlation between the CR proton/electron count rates and HCS tilt angle

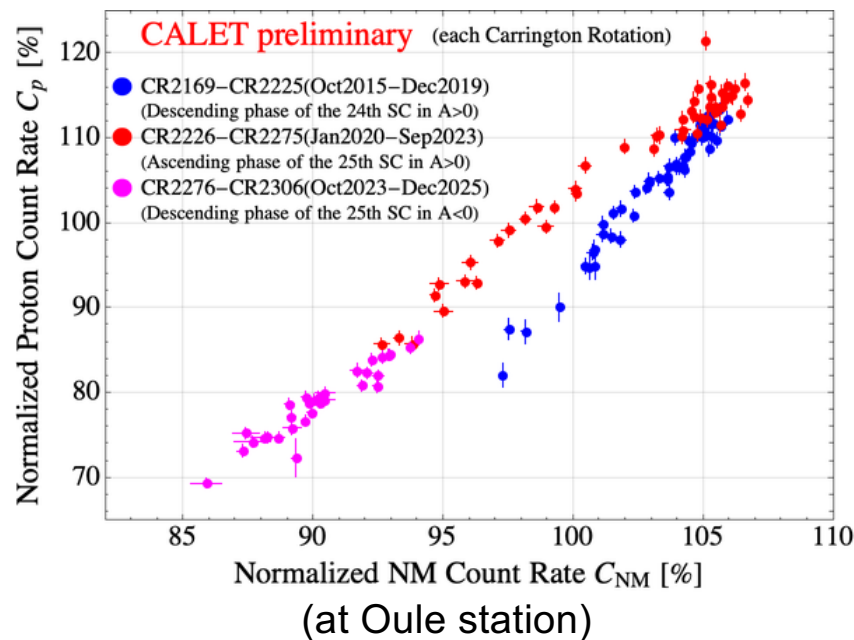


(This figure shows the results up to Sep. 2025 (CR2302), for which WSO's HCS tilt angle data is publicly available.)

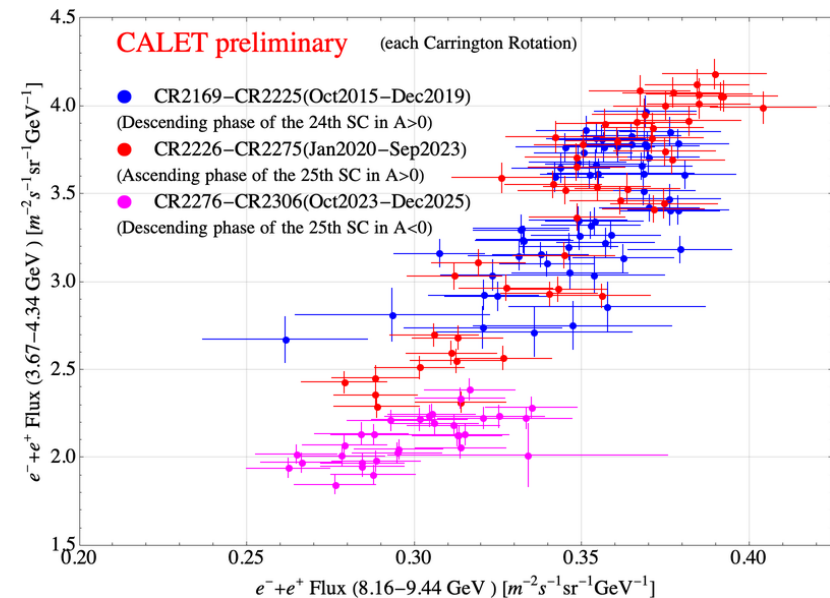
# Rigidity Dependence

The proton rigidity dependence differs between the descending and ascending phases of the solar cycle. However, the post-reversal descending phase still follows the ascending-phase relationship, whereas no comparable difference is observed for electrons.

## Correlation between count rates of $\sim 3.8$ GV protons and NM count rate



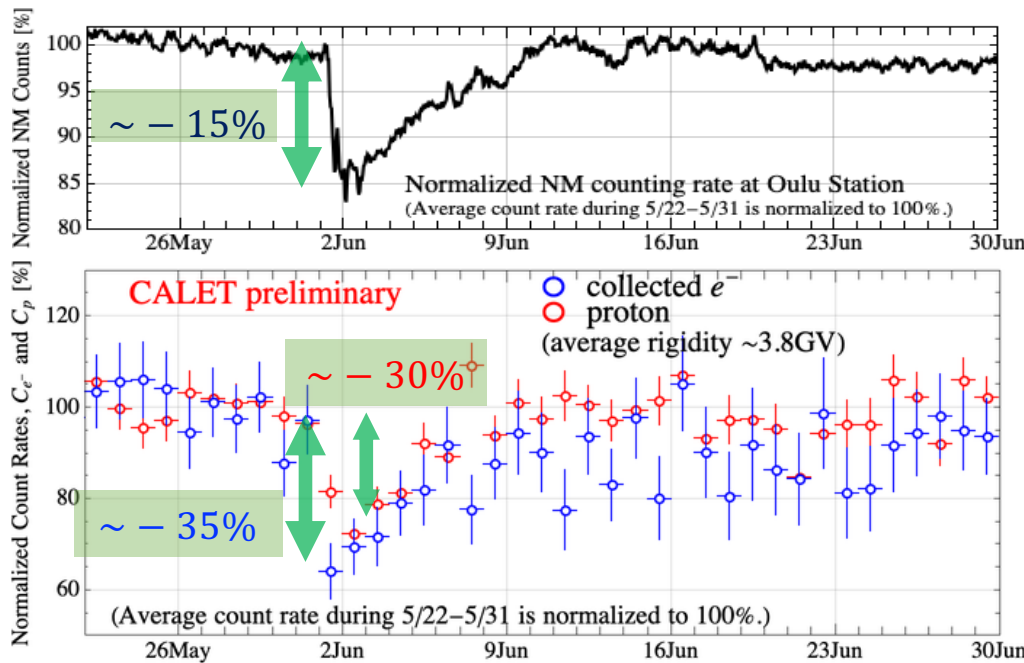
## Correlation between $\sim 4.0$ GeV $e^-+e^+$ flux and $\sim 8.8$ GeV $e^-+e^+$ flux



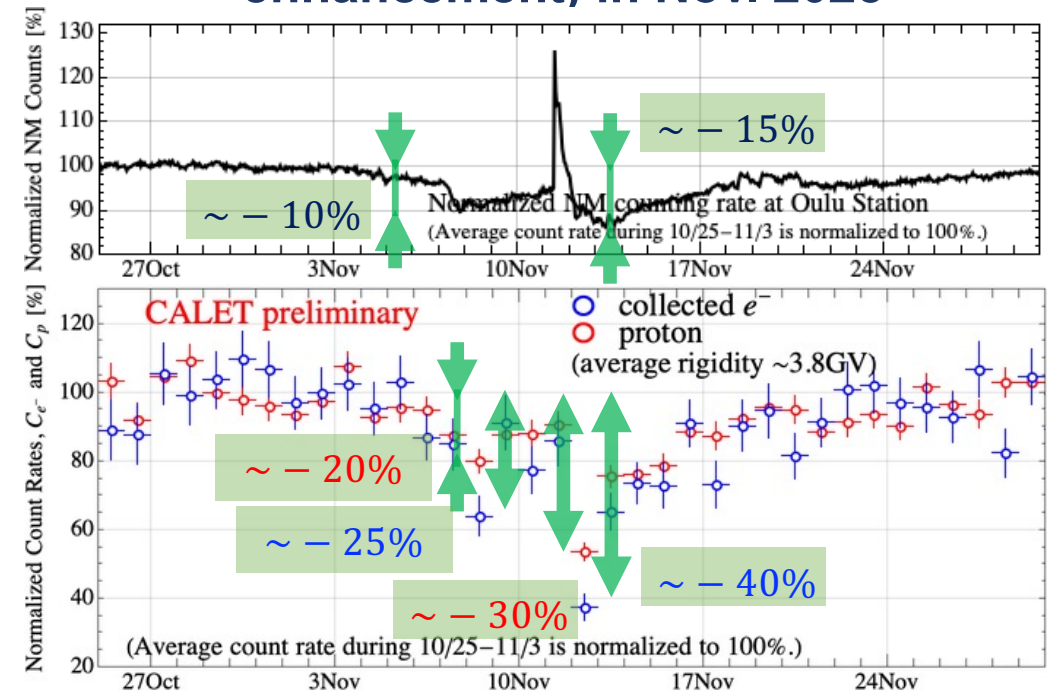
# Forbush Decreases (FDs) of CR Protons and Electrons

- The June and November 2025 events also suggest electron–proton differences in amplitude and/or timing.
- These preliminary results indicate event-to-event diversity in the electron and proton responses to FDs.

## FD caused by an ICME accompanied by $>1000$ km/sec $V_{sw}$ in June 2025



## FD with a strong GLE (ground level enhancement) in Nov. 2025

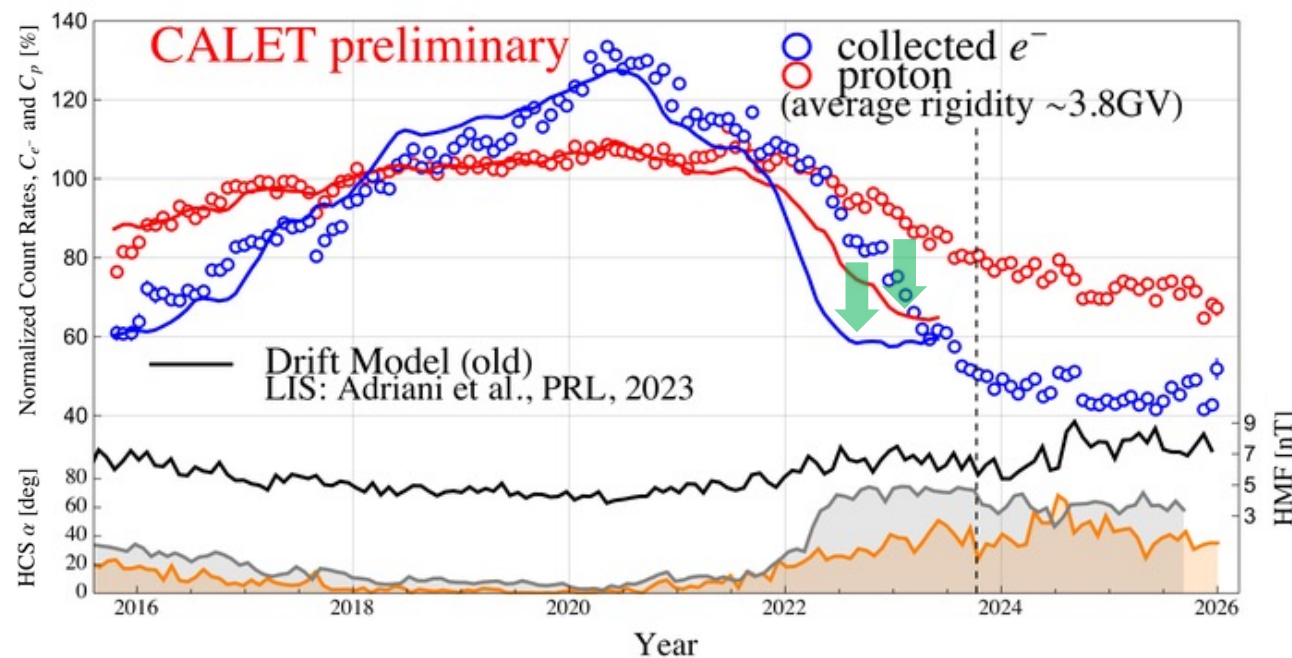


( **Note:** Error bars show statistical uncertainties only; systematic uncertainties are under evaluation.)

# Previous Drift Model Validation with CALET observations

- We succeeded to reproduce the observed charge-sign dependence for the descending phase of the solar cycle (Adriani et al., PRL, 2023).
- However, this model fails to reproduce that for the ascending phase of the solar cycle (presented at the JPS fall meeting in 2023).

## Time profile of the CR proton and electron count rates



# Previous Drift Model: GCR Transport

## Stochastic differential equation (SDE)

$$\begin{cases} d\vec{r} = (\nabla \cdot \hat{k} + \vec{V}_{sw} + \vec{V}_{drift})dt + \sum_s \alpha_s dW_s(t) \\ dp = -\frac{1}{3}p(\nabla \cdot \vec{V}_{sw})dt \end{cases}$$

## Diffusion coefficient

$$\begin{cases} \kappa_{\parallel} = 1 \times 10^{22} \left( \frac{p}{1 \text{ GeV}/c} \right) \left( \frac{B_{1\text{AU}}}{B} \right) [\text{cm}^2/\text{s}] \\ \kappa_{\perp\theta} = 1 \times 10^{20} \left( \frac{p}{1 \text{ GeV}/c} \right) \left( \frac{B_{1\text{AU}}}{B} \right)^{1.4-0.6 \sin^2 \theta} [\text{cm}^2/\text{s}] \\ \kappa_{\perp 2} = 2 \times 10^{20} \left( \frac{p}{1 \text{ GeV}/c} \right) \left( \frac{B_{1\text{AU}}}{B} \right) [\text{cm}^2/\text{s}] \end{cases}$$

## Drift motion

$$\langle v_D \rangle = \nabla \times \left( \kappa_A \frac{\vec{B}}{|B|} \right), \quad \kappa_A = \frac{v R_L}{3}$$

HCS drift velocity:

- approximation function based on distance from the HCS (Burger and Potgieter, 1989)
- If the distance between the sheets becomes less than the gyro-radius of pseudo particle, the HCS drift velocity is reduced accordingly.

# New Drift Model: GCR Transport

## Stochastic differential equation (SDE)

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## Diffusion coefficient

$$\begin{cases} \kappa_{\parallel} = 1 \times 10^{22} \left( \frac{p}{1 \text{ GeV}/c} \right) \left( \frac{5 \text{ nT}}{B} \right)^{1.2} [\text{cm}^2/\text{s}] \\ \kappa_{\perp\theta} = 1 \times 10^{20} \left( \frac{p}{1 \text{ GeV}/c} \right) \left( \frac{5 \text{ nT}}{B} \right)^{1.6-0.8 \sin^2 \theta} [\text{cm}^2/\text{s}] \\ \kappa_{\perp 2} = 2 \times 10^{20} \left( \frac{p}{1 \text{ GeV}/c} \right) \left( \frac{5 \text{ nT}}{B} \right)^{1.2} [\text{cm}^2/\text{s}] \end{cases}$$

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# New Drift Model: Heliosphere

## Solar wind and magnetic field

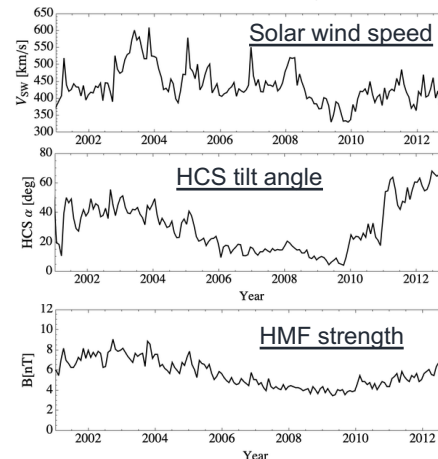
- Isotropic solar wind speed.
- Standard Parker spiral heliospheric magnetic field (HMF).
- Variations of the observed solar-wind speed and HMF (referring to NASA/Goddard Space Flight Center, OMNIweb).
- Radial dependent tilt angle of the heliospheric current sheet (HCS).

## Heliosphere and heliosheath

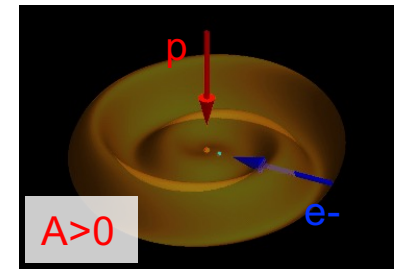
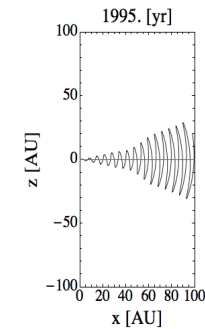
- Bubble-like structures of the heliosphere (85 AU) and heliosheath (120AU).
- In the heliosheath, the solar wind speed (the magnetic strength) is reduced to 1/2.6 (increased to 2.5 times) of that in the heliosphere (Burlaga et al., ApJ, 2009).

### Solar wind and HMF near the Earth

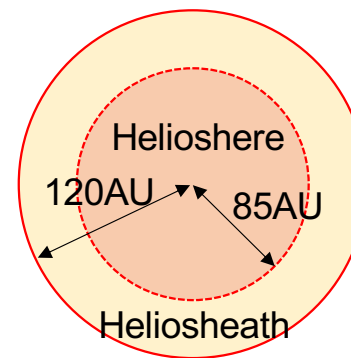
(OMNI Web, WSO)



### Heliospheric Current Sheet (HCS)

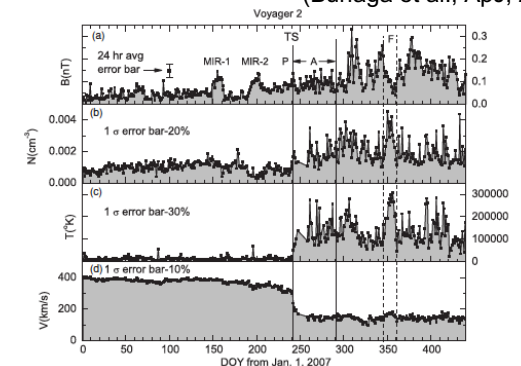


### Global Heliosphere



### Solar wind and HMF in the near the HTS

(Burlaga et al., ApJ, 2009)



# New Drift Model: Heliosphere

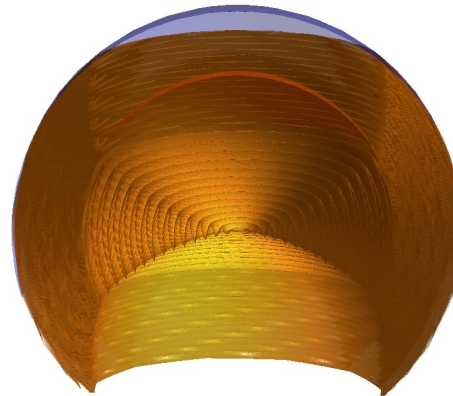
## Solar wind and magnetic field

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- Variations of the observed solar-wind speed and HMF (referring to NASA/Goddard Space Flight Center, OMNIweb).
- Radial dependent tilt angle of the heliospheric current sheet (HCS).

## Heliosphere and heliosheath

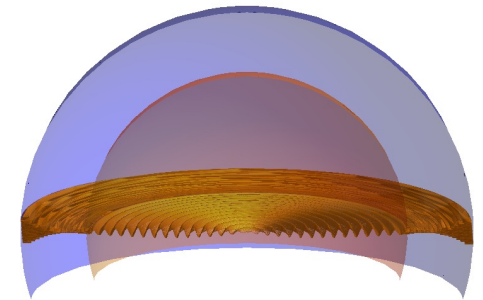
- Bubble-like structures of the heliosphere (85 AU) and heliosheath (120AU).
- In the heliosheath, the solar wind speed (the magnetic strength) is reduced to  $1/2.6$  (increased to 2.5 times) of that in the heliosphere (Burlaga et al., ApJ, 2009).

HCS for descending phase

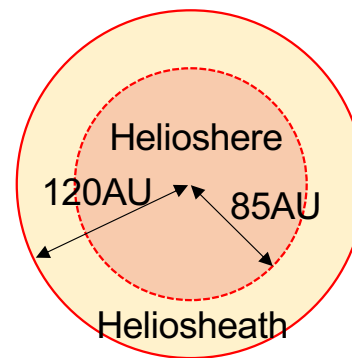


(HCS tilt angle at 1 AU is assumed to be 10 degrees.)

HCS for ascending phase

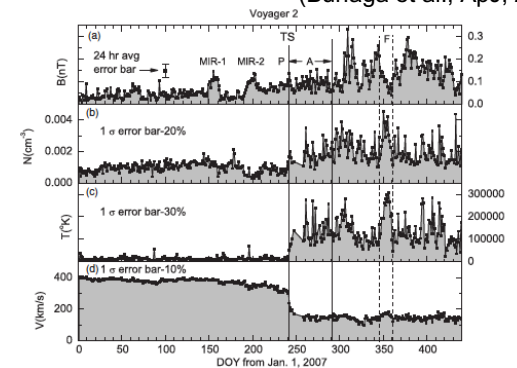


Global Heliosphere



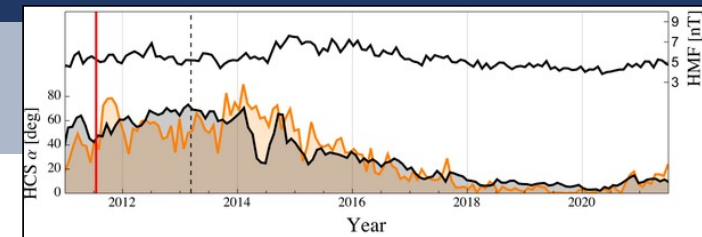
Solar wind and HMF in the near the HTS

(Burlaga et al., ApJ, 2009)



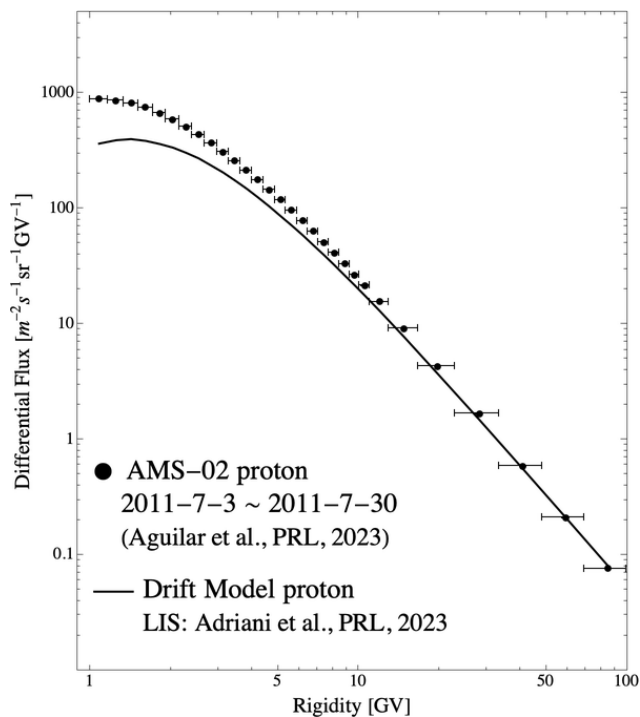
# Model Refinement : Proton Spectrum

## Comparison with proton spectra observed by AMS-02

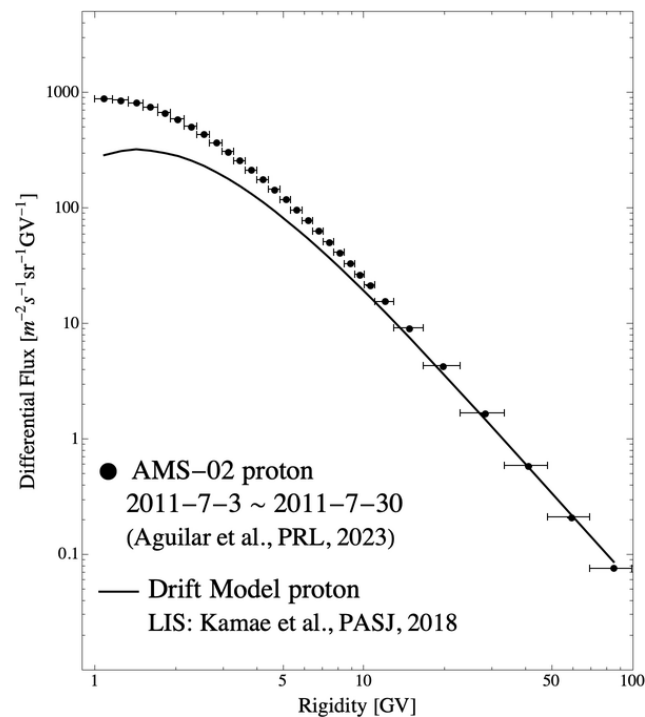


Previous model

$\left[ \begin{array}{l} \text{w/o heliosheath} \\ \kappa_{\parallel} \propto B^{-1} \end{array} \right]$

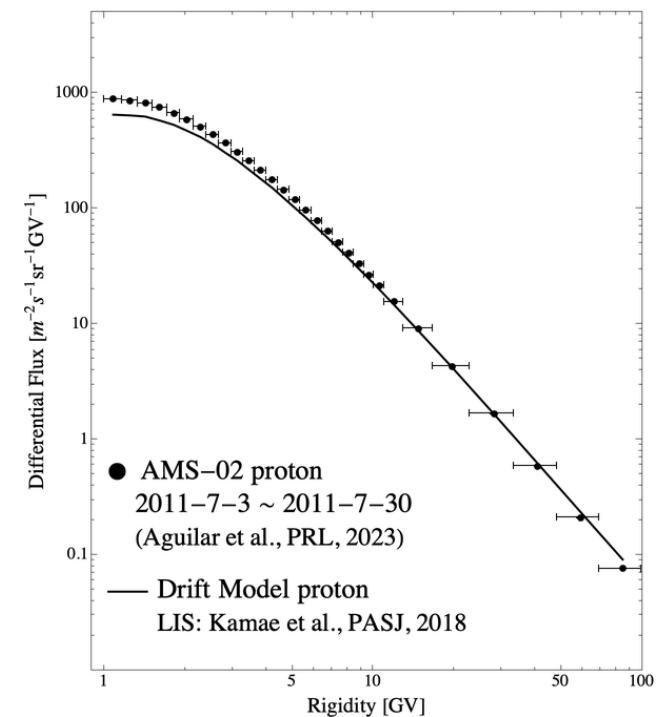


with Heliosheath  
(+ LIS refinement)



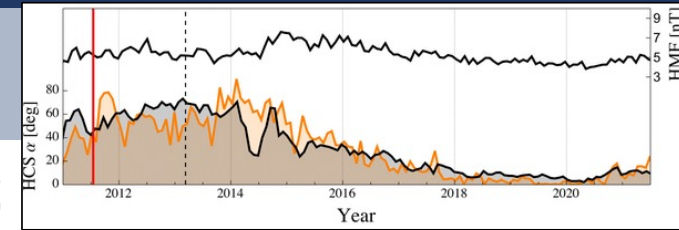
New model

$\left[ \begin{array}{l} \text{w/ heliosheath} \\ \kappa_{\parallel} \propto B^{-1.2} \end{array} \right]$

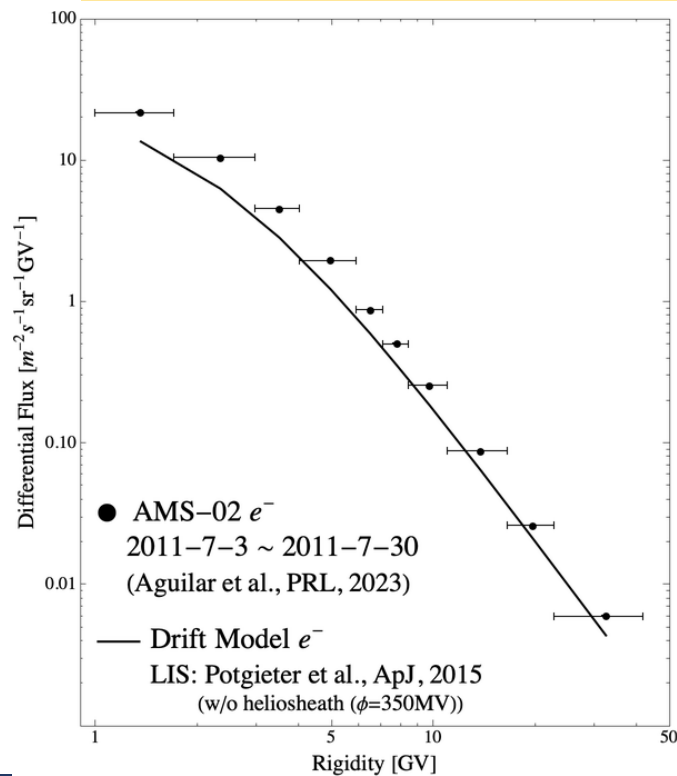


# Model Refinement : Electron Spectrum

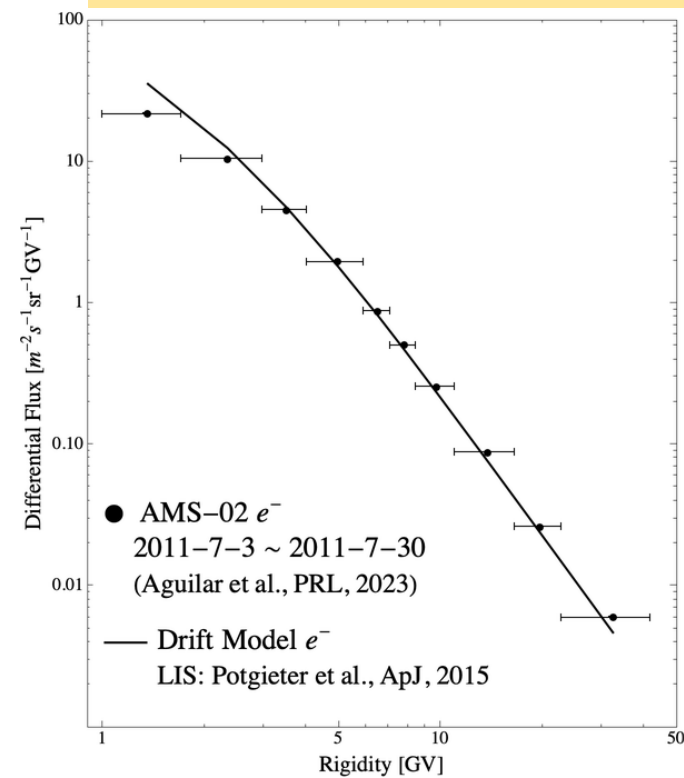
## Comparison with electron spectra observed by AMS-02



Previous model  
[ w/o heliosheath,  $\kappa_{\parallel} \propto B^{-1}$  ]



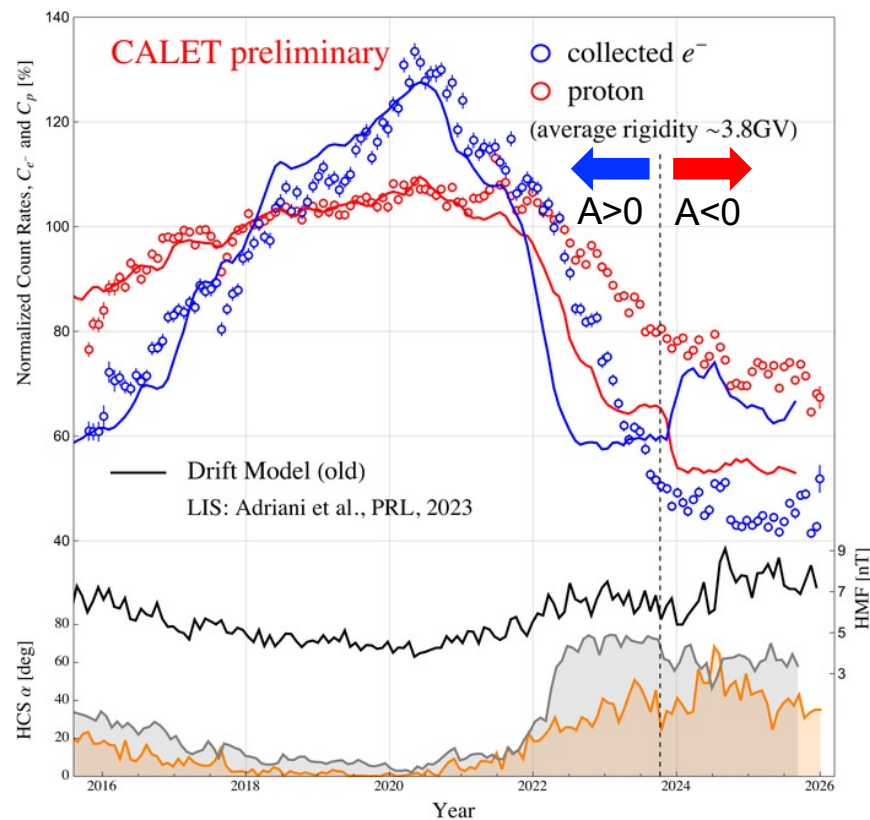
New model  
[ w/ heliosheath,  $\kappa_{\parallel} \propto B^{-1.2}$  ]



# Time profile of the CR proton and electron count rates

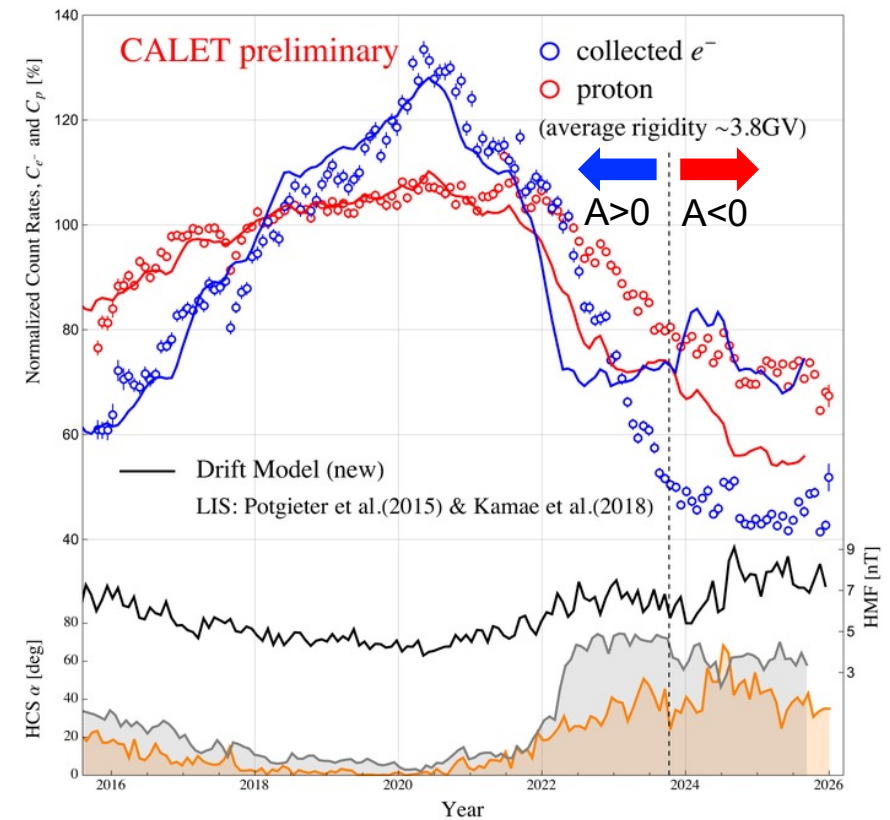
## Previous model

[ w/o heliosheath,  $\kappa_{\parallel} \propto B^{-1}$  ]



## New model

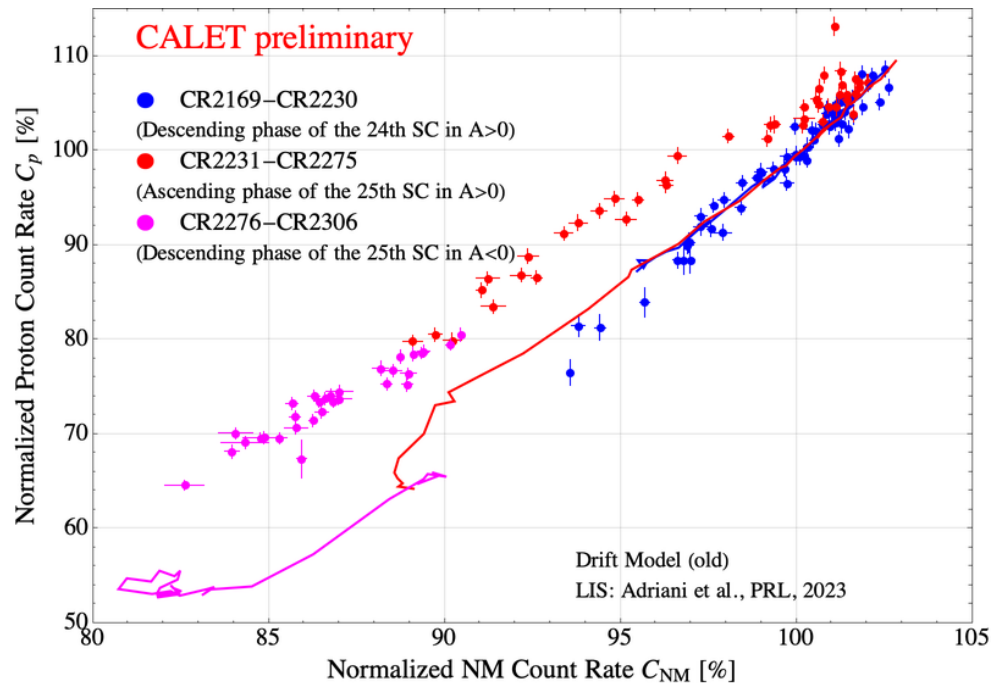
[ w/ heliosheath,  $\kappa_{\parallel} \propto B^{-1.2}$  ]



# Rigidity Dependence of the GCR Proton modulation

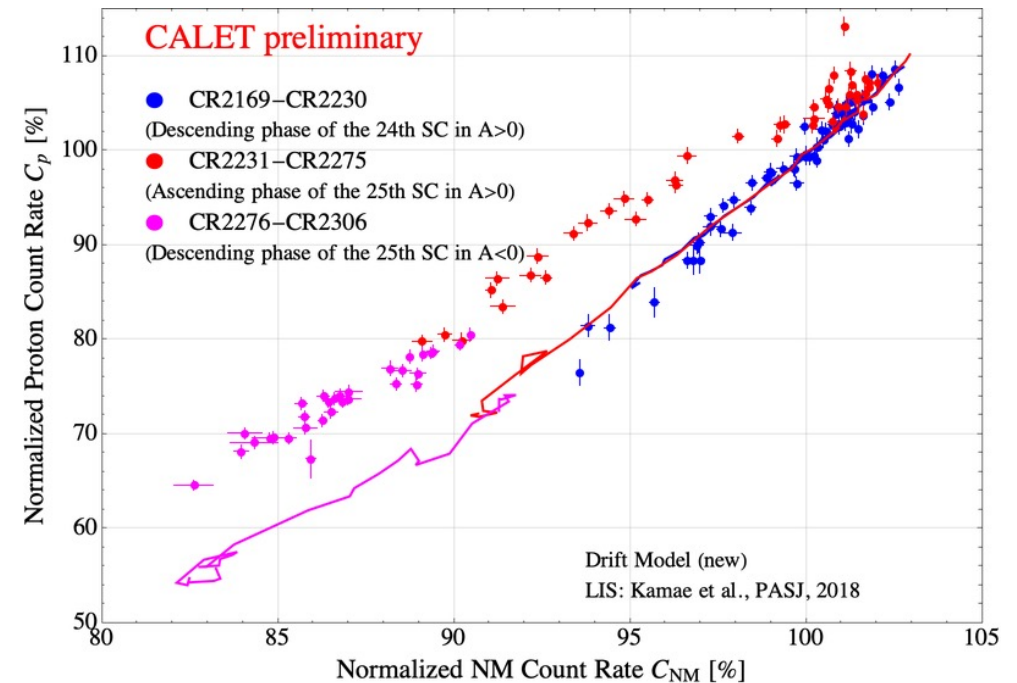
## Previous model

[ w/o heliosheath,  $\kappa_{\parallel} \propto B^{-1}$  ]



## New model

[ w/ heliosheath,  $\kappa_{\parallel} \propto B^{-1.2}$  ]



# Summary

## Results of the CALET observation

- CALET has continuously observed galactic cosmic rays over one solar cycle, covering the solar minimum, maximum, and magnetic polarity reversal.
- The 1–10 GeV all-electron flux continuously decreased after the beginning of Solar Cycle 25, reaching the lowest level observed by CALET, with no clear signature of the magnetic polarity reversal so far.
- Charge-sign-dependent modulation is clearly observed, including hysteresis with the HCS tilt angle.
- The proton rigidity dependence differs between the descending and ascending phases of the solar cycle. At present, however, the post-reversal descending phase still follows the ascending-phase relationship, whereas no comparable difference is observed for electrons.
- CALET detected a variety of Forbush-decrease profiles, with preliminary indications of event-dependent differences between electron and proton responses.

## Results of the drift model validation

- We updated the drift model by considering the HMF dependence on the diffusion coefficient and a modulation in the heliosheath. However, the model still fails to reproduce the modulation during the ascending phase of the solar cycle and the rigidity dependence of proton modulation.
- Long-term CALET observations are valuable for constraining numerical models of solar modulation.