



# Simulation of Cosmic-ray Sun's Shadow with CMEs

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芜湖 2026-4-22

# Outline

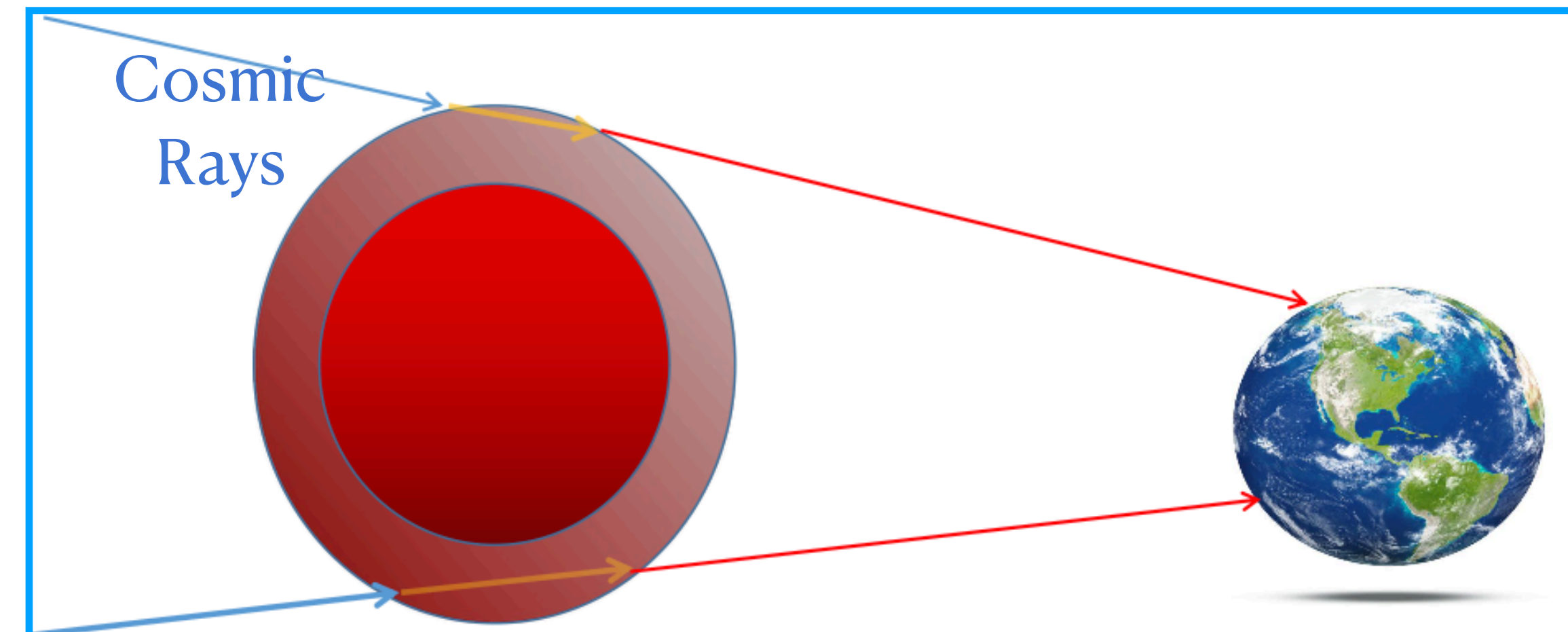
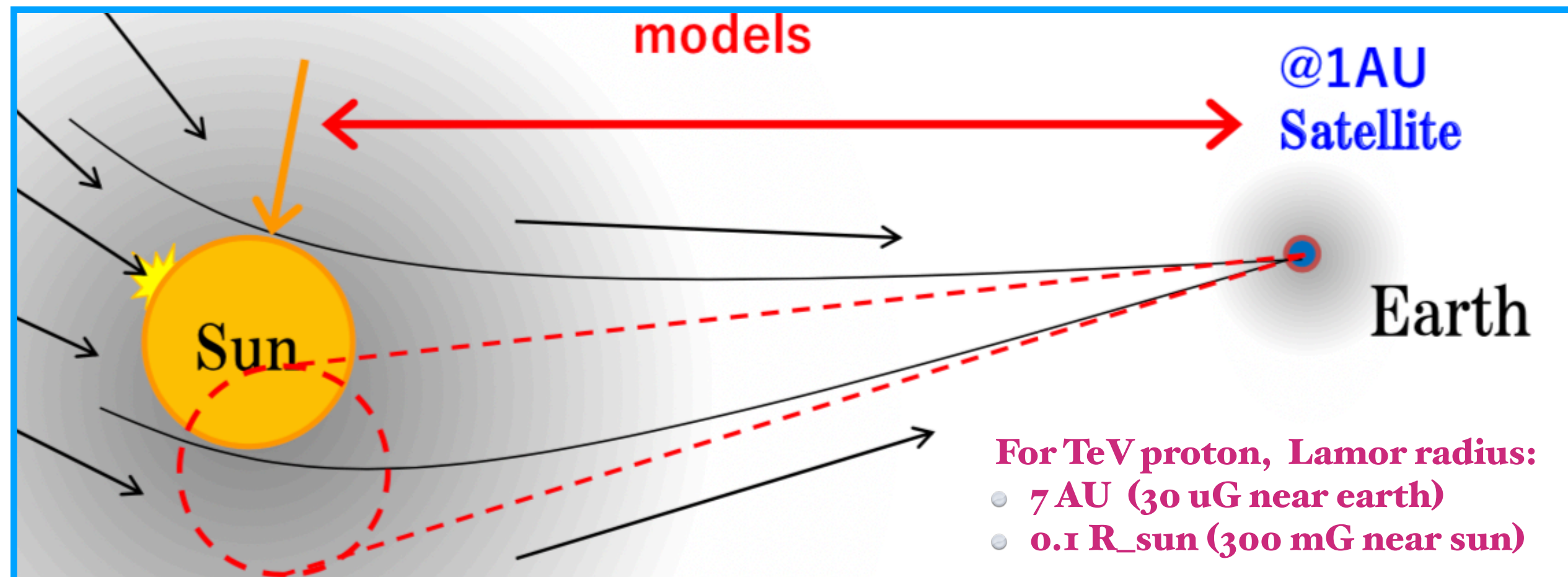
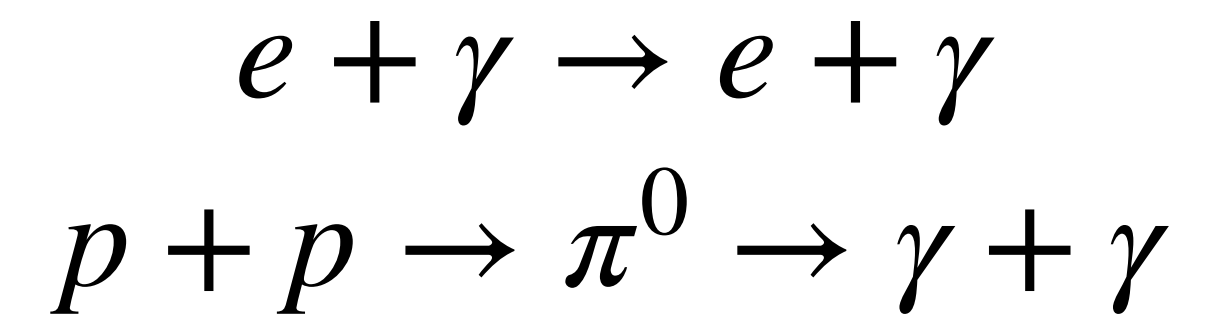
1. Introduction
2. Simulation without CMEs
3. Simulation with CMEs
4. Summary

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1. **Introduction**
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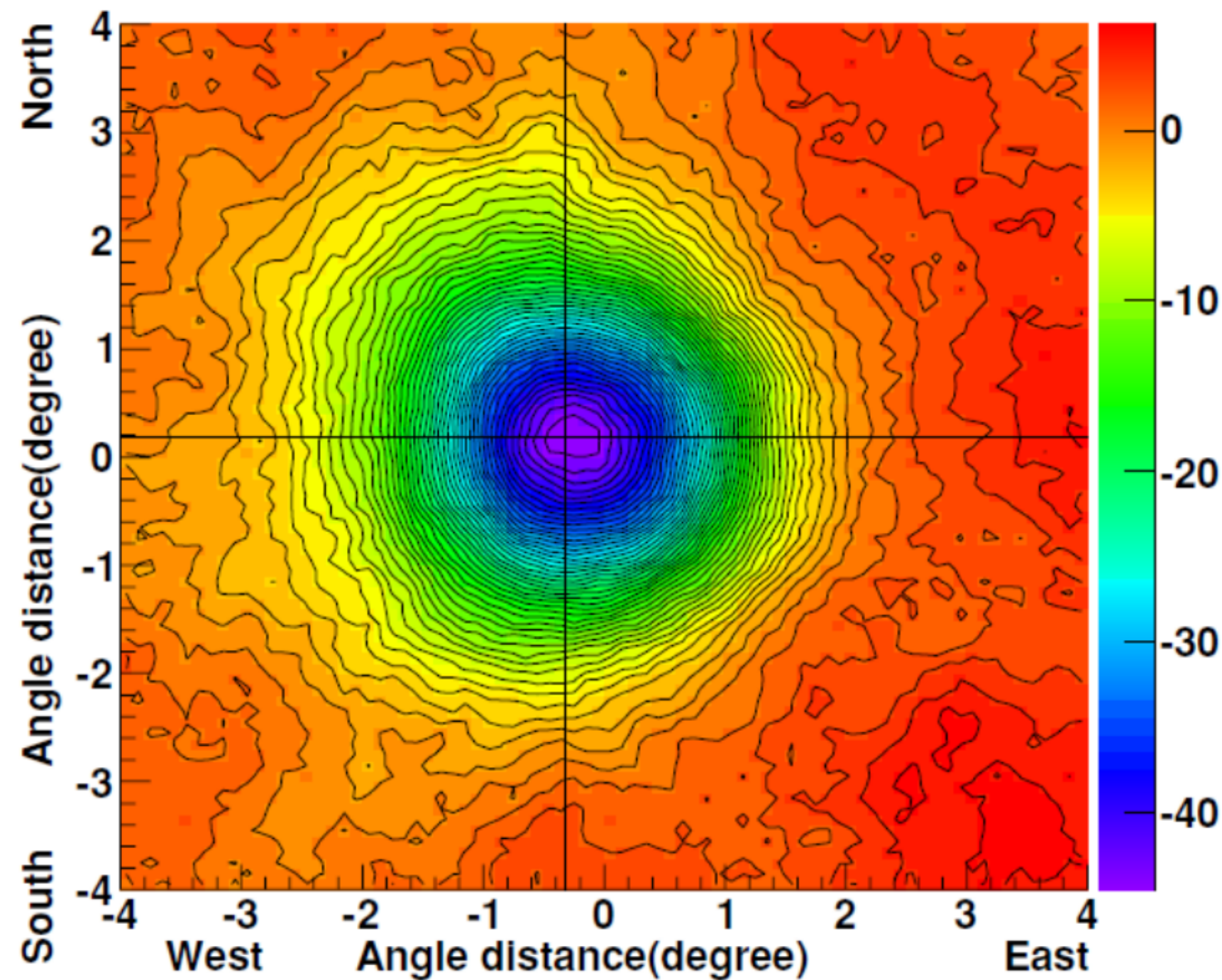
# Cosmic-ray Sun Shadow & Solar Gamma Rays

combined processes

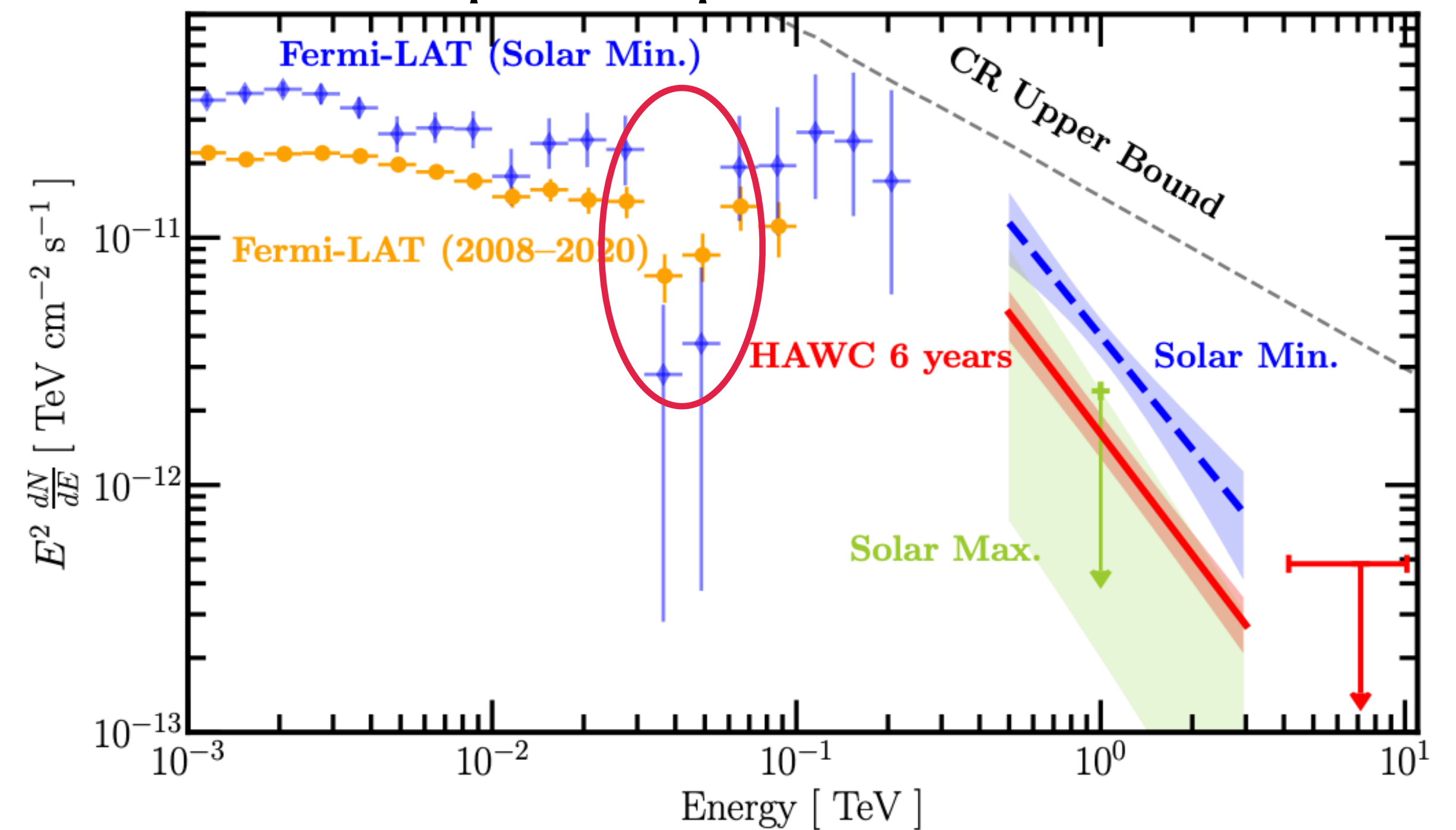


# Cosmic-ray Sun Shadow & Solar Gamma Rays

Cosmic Ray Sun Shadow of ARGO-YBJ



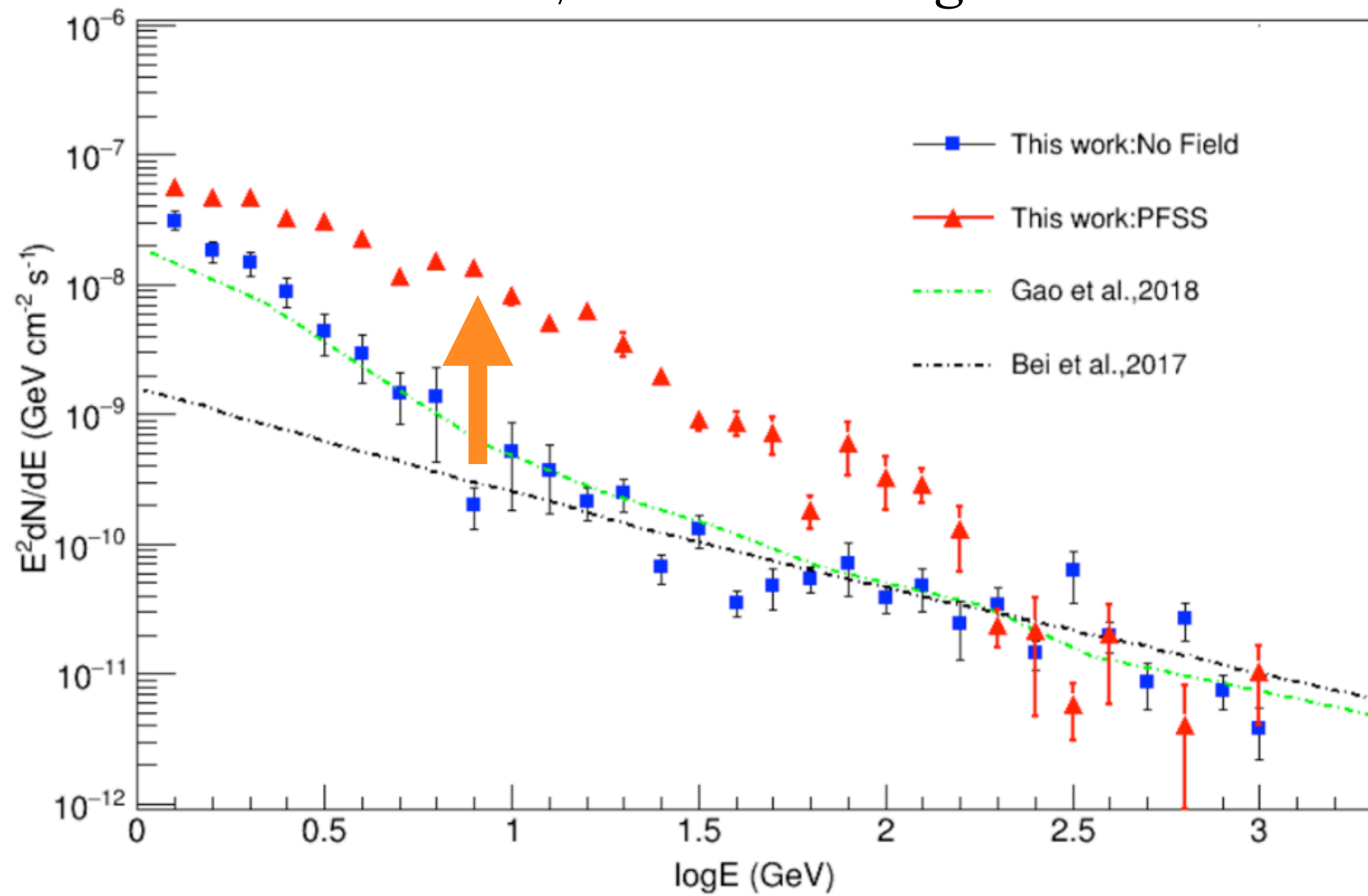
Solar Gamma-ray Spectrum:  
unexpected dip & lower simulation flux



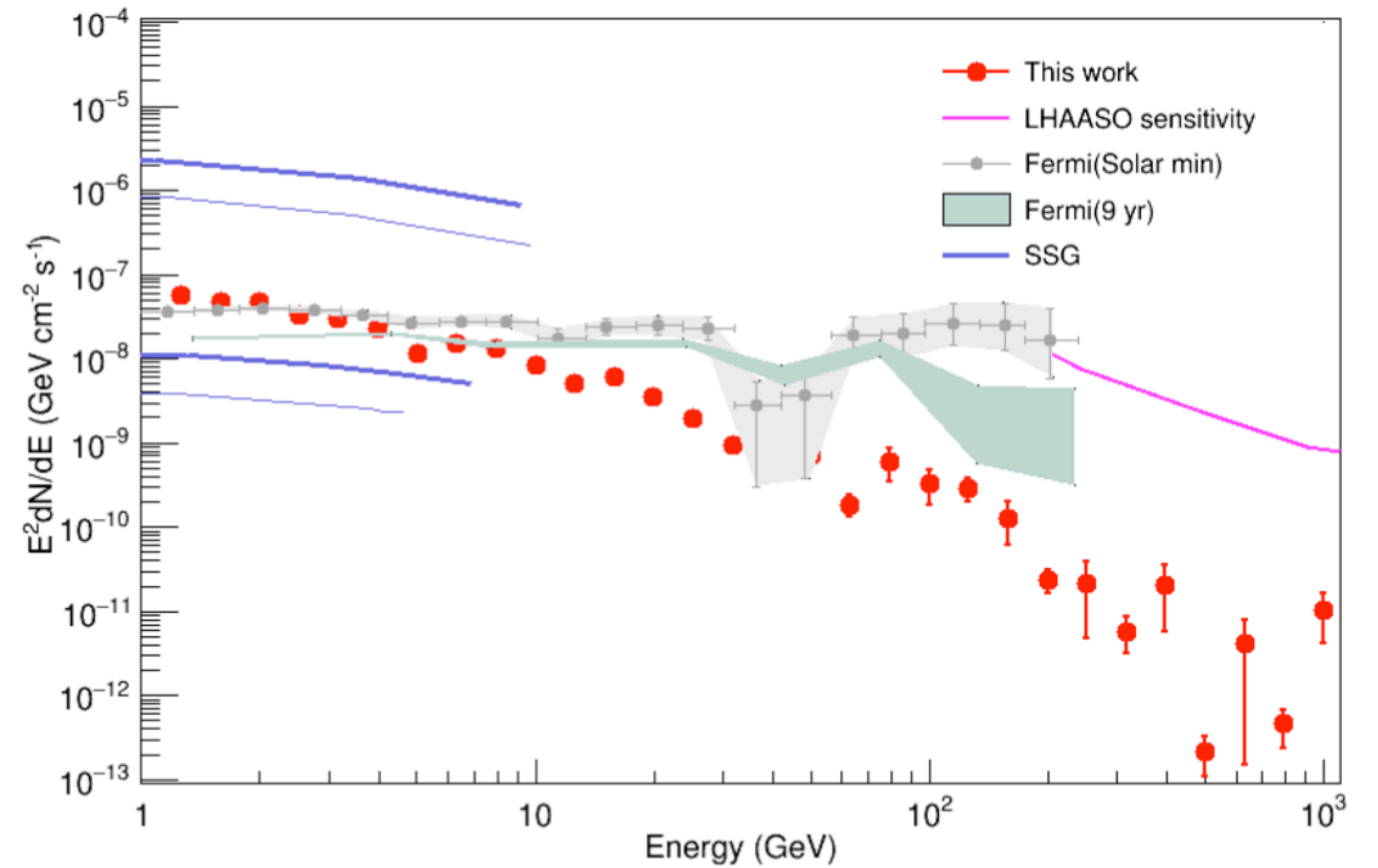
arXiv:2212.00815

# Solar Gamma-ray Spectrum

Simulation w/wo coronal magnetic field



Simulation & Observation



Zhe Li et al. PoS (ICRC2019) 1182

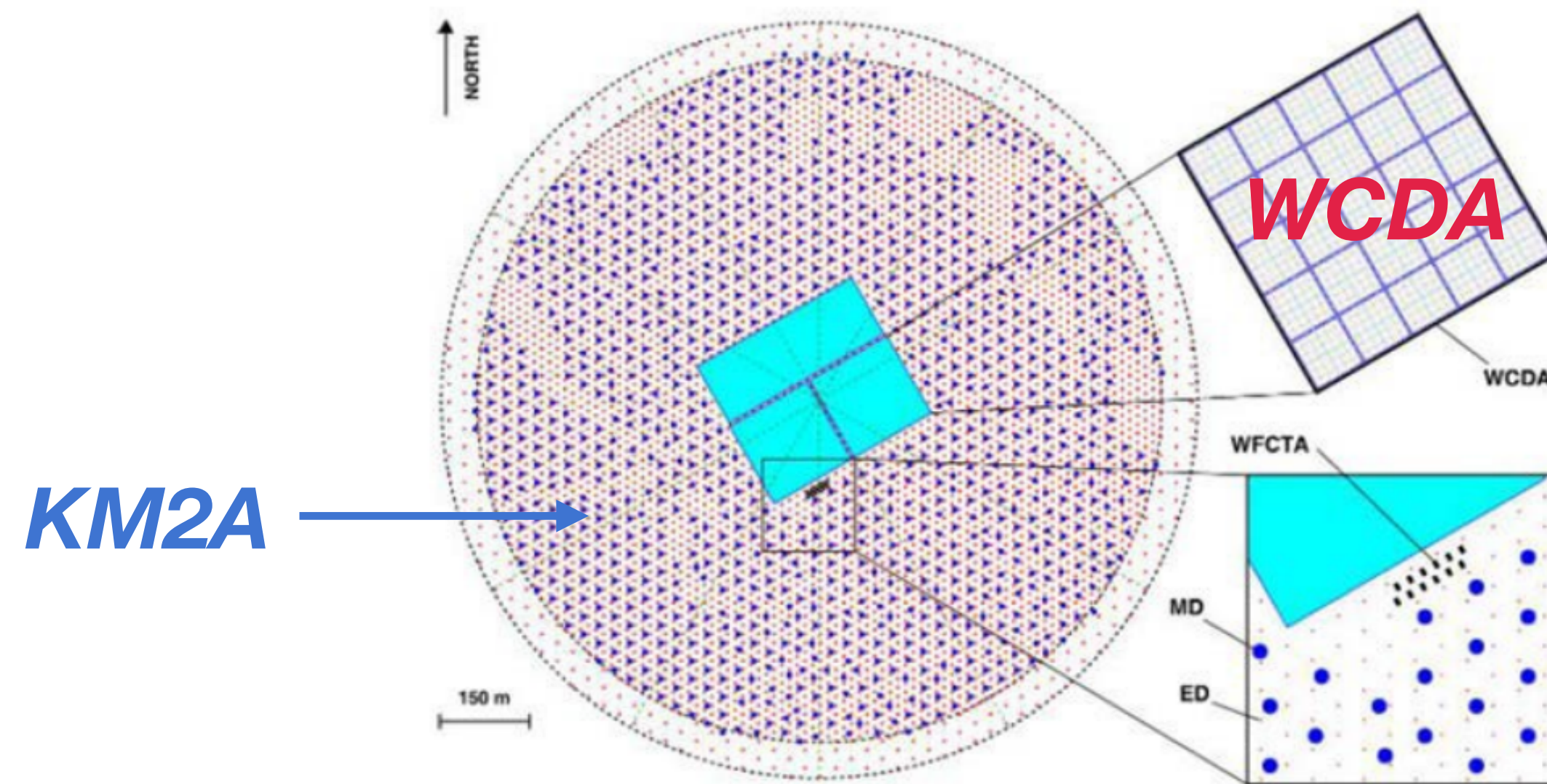
# LHAASO Array

## Full Array:

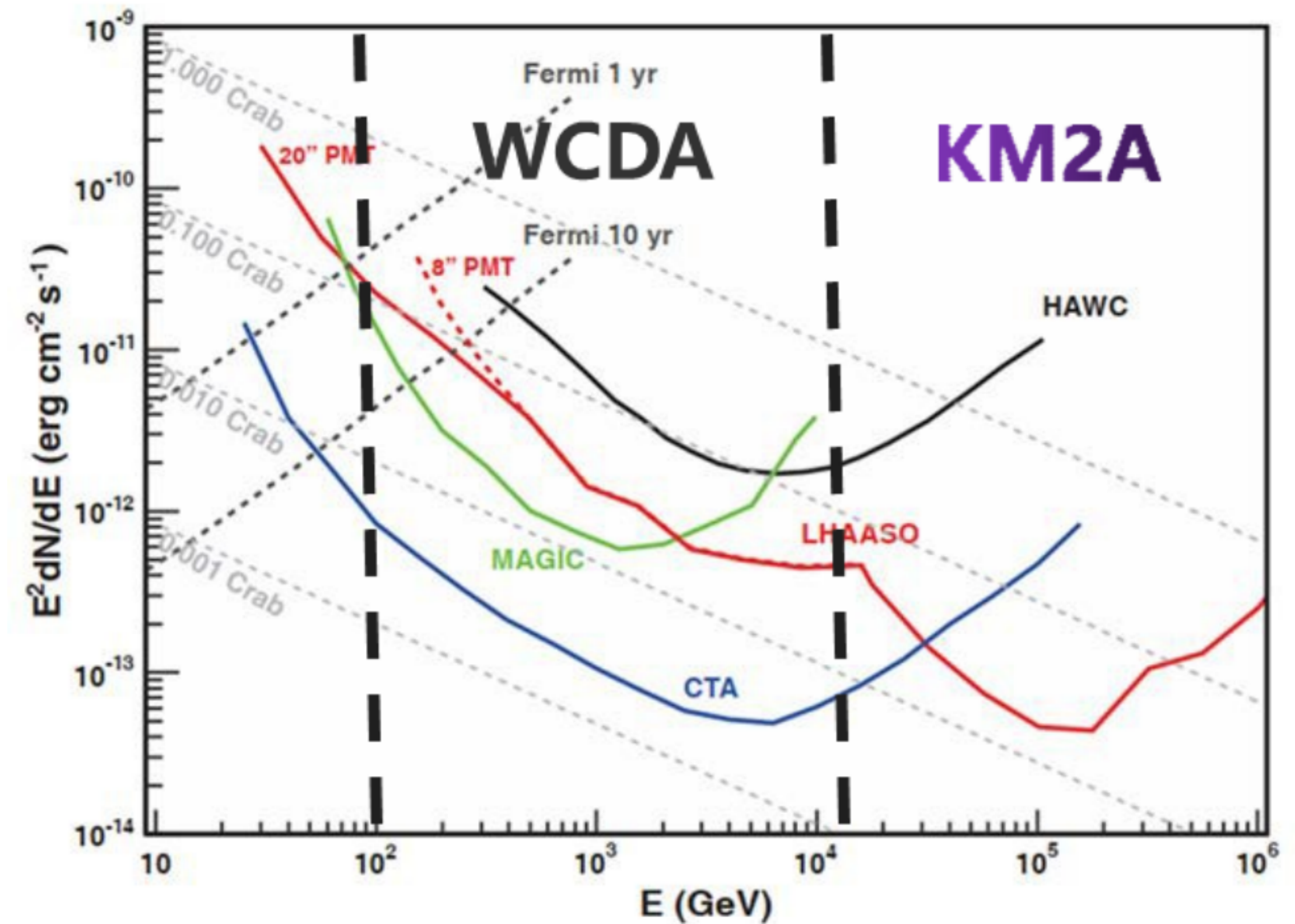
*KM2A: 5195 EDs +1188 MDs ~ 40 TeV*

*WCDA: 3120 water Cherenkov detectors ~ 4 TeV*

*WFCTA: 18 wide field of view Cherenkov telescopes*

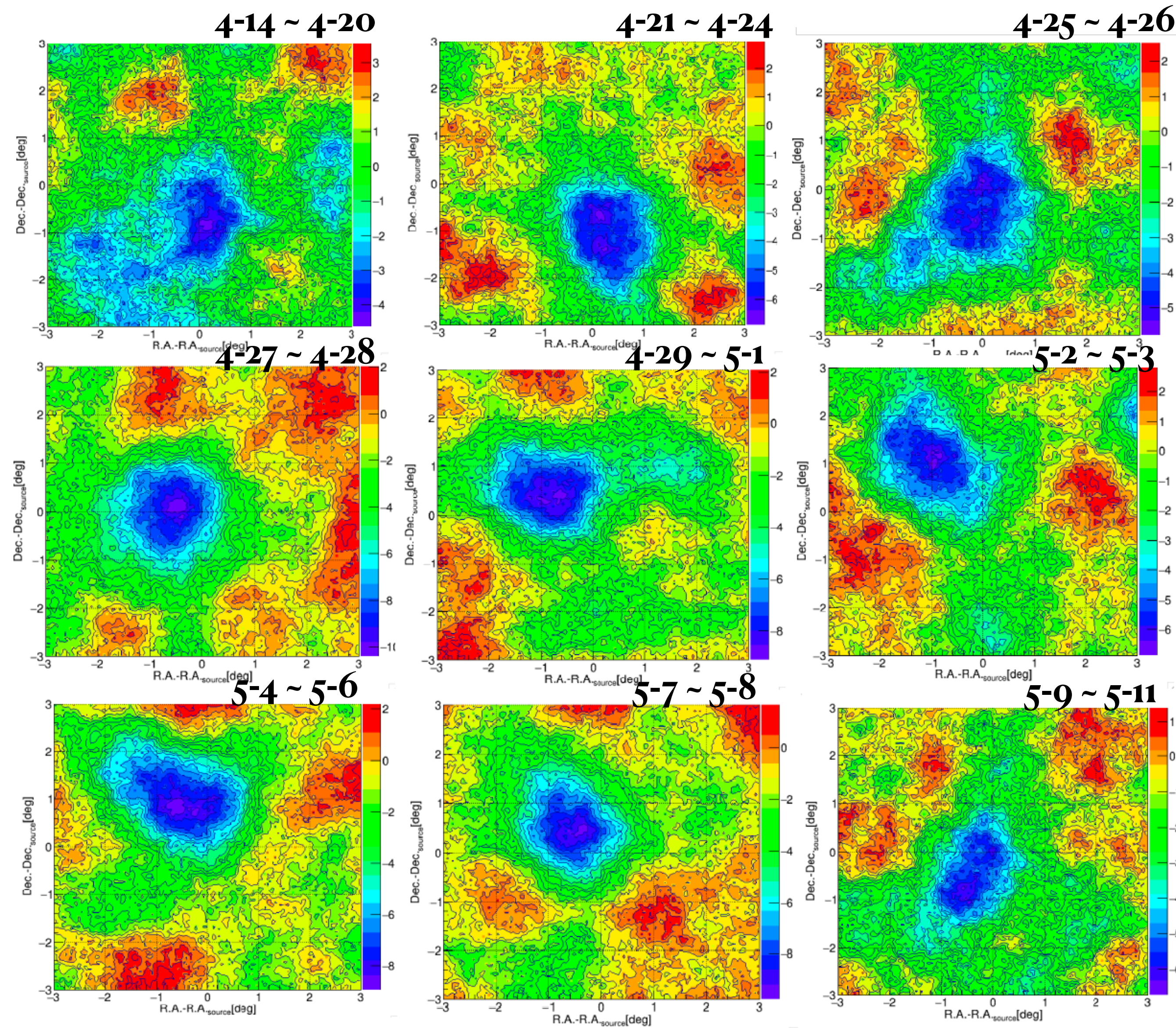


## Sensitivity



# LHAASO Observation of Sun Shadow

**Carrington  
Rotation 2243:**  
Apr. 14, 2021  
~  
May 11, 2021



The LHAASO could enable us to reduce **time window** of the Sun shadow observation to an unprecedented level ~ several days

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# Coronal Magnetic field Model for Quiet Sun

Without Coronal Mass Ejection etc.

Potential Field Source Surface Model (PFSS)

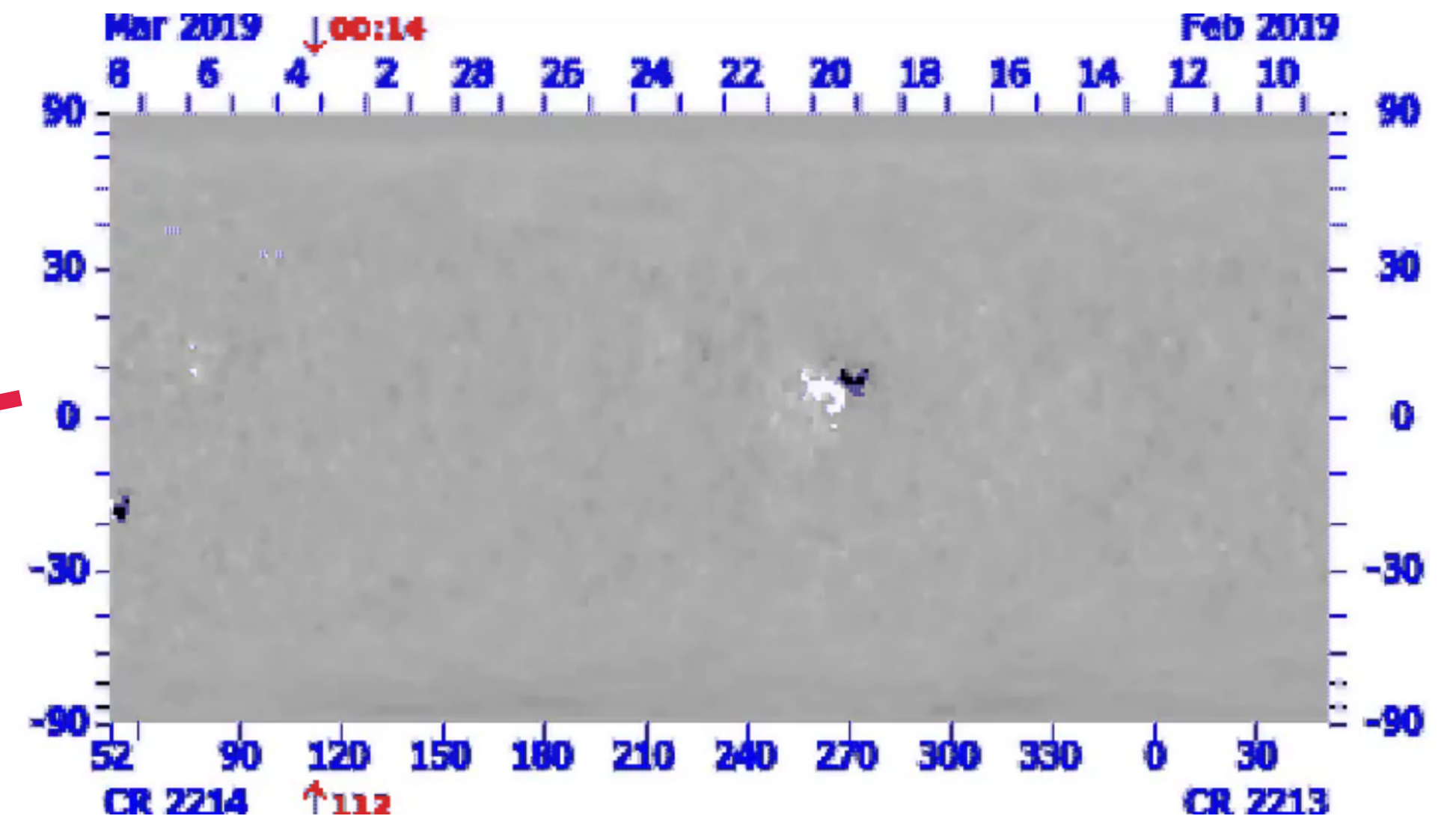
$$\left. \begin{aligned} \nabla \times B &= 0 \\ \nabla \cdot B &= 0 \end{aligned} \right\} \nabla^2 \Phi_B = 0$$

Boundary conditions:

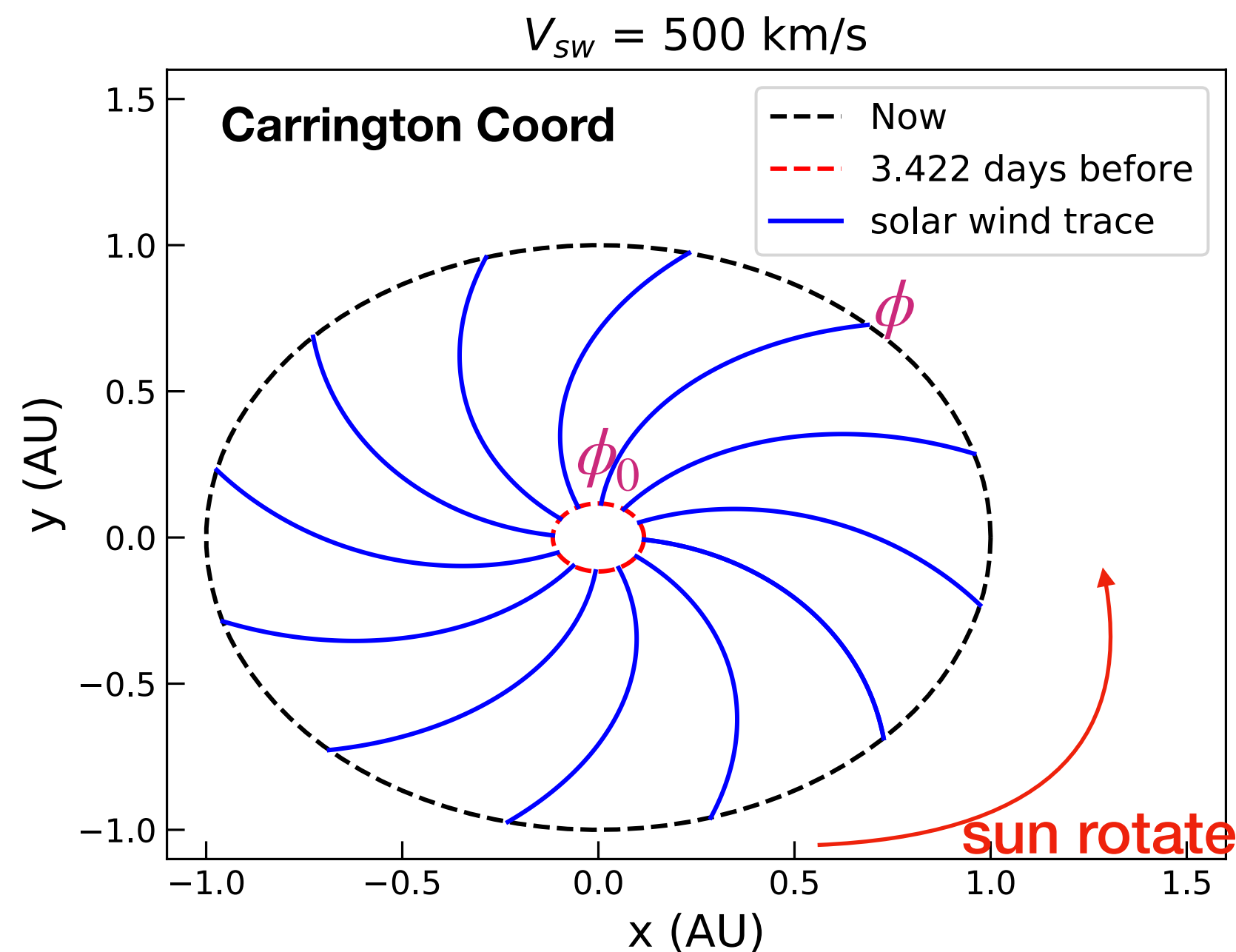
$$\begin{aligned} B_r(\theta, \phi) &= g(\theta, \phi) & r &= 1 \\ B_\theta &= B_\phi = 0 & r &= R_{ss} \end{aligned}$$

Magnetogram from HMI

(maps of magnetic field at the **photosphere**)



# Parker theory of Interplanetary Magnetic Field



## Parker spiral

$$\phi = \phi_0 - \frac{R_{ss} * \Omega_{Sun}}{V_{sw}} \left( \frac{r}{R_{ss}} - 1 - \ln\left(\frac{r}{R_{ss}}\right) \right)$$

$$R_{ss} = 2.5R_{Sun}$$

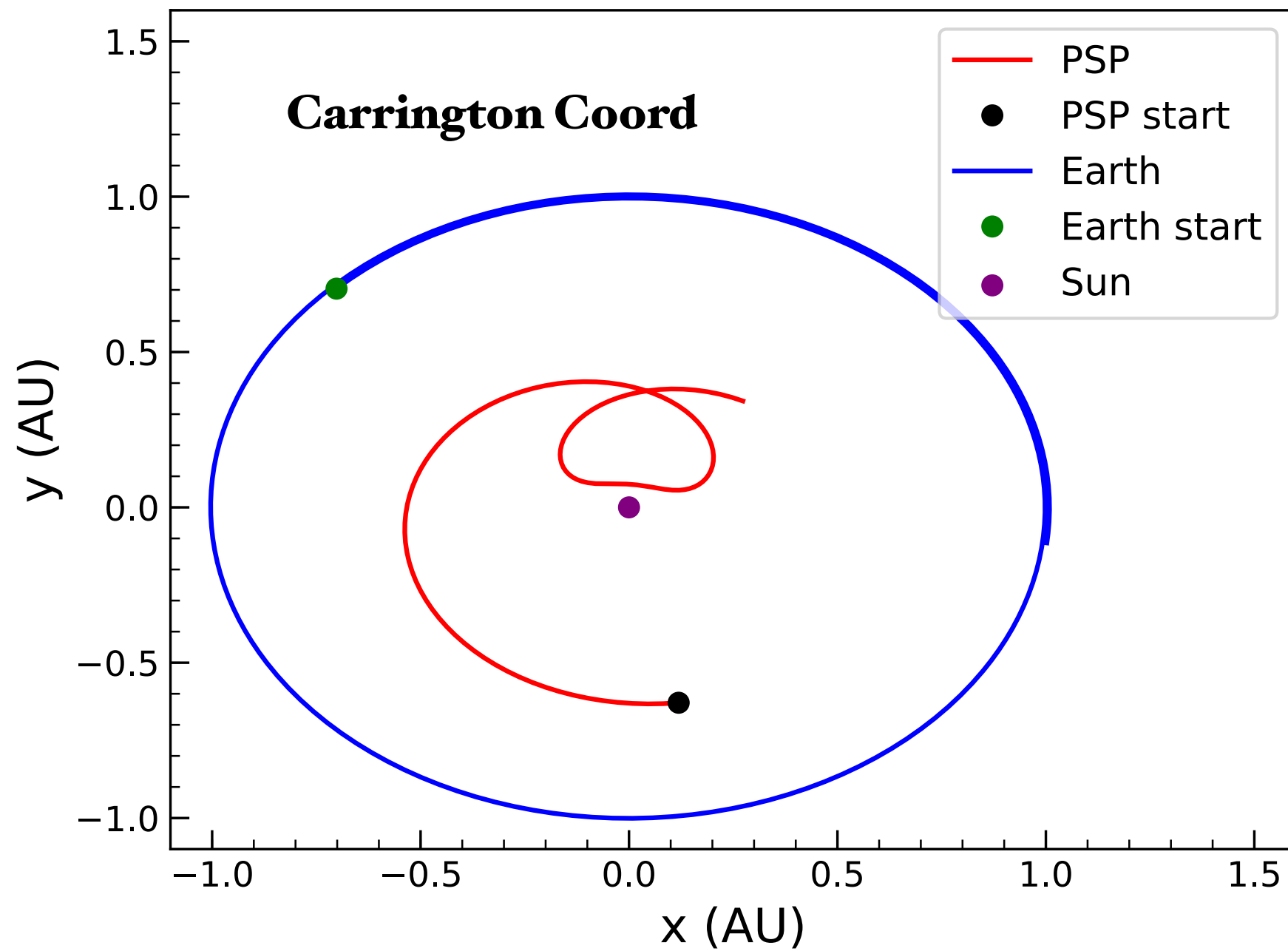
$$B_r(r, \theta, \phi) = B_r(R_{ss}, \theta, \phi_0) \left( \frac{R_{ss}}{r} \right)^2$$

$$B_\theta(r, \theta, \phi) = 0$$

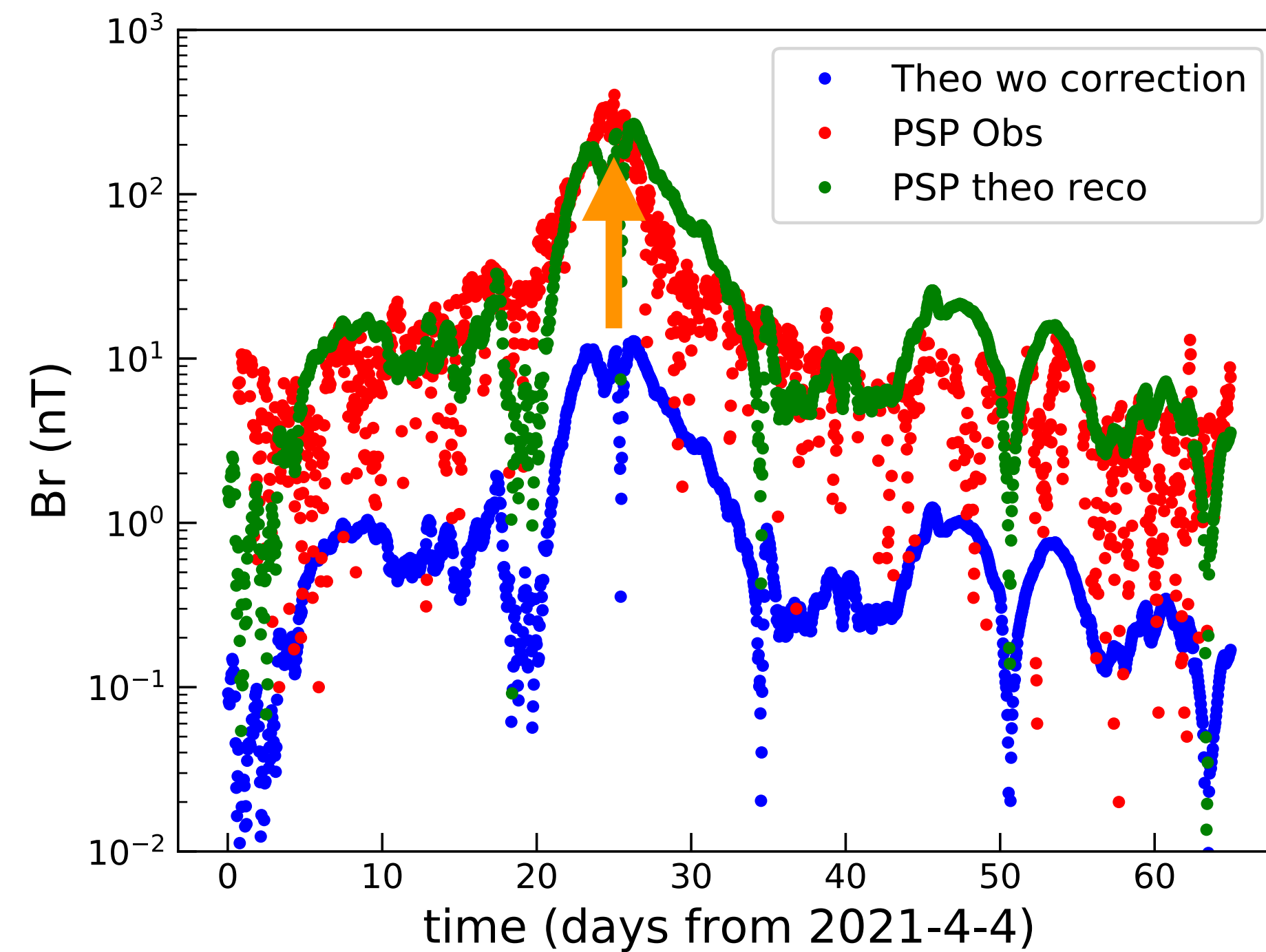
$$B_\phi(r, \theta, \phi) = -B_r(r, \theta, \phi) \left( \frac{\Omega_{Sun}}{V_{sw}} \right) (r - R_{ss}) \sin\theta$$

# Correction by the PSP observation

2021-4-4 ~ 2021-5-11 by PSP



Magnetic map tends to **underestimate MF**



# Simulation of Sun Shadow

- Back tracing method
- To construct self-consistent & time-dependent magnetic field to calculate Sun's shadow
- Without air shower simulation, using PSF instead

**Antiproton**

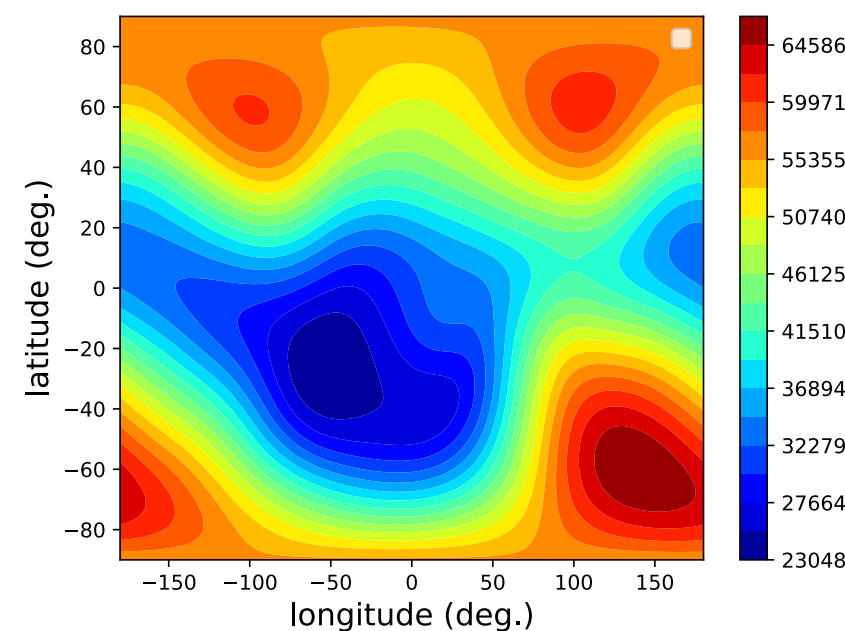


Interplanetary Magnetic Field: Parker Model

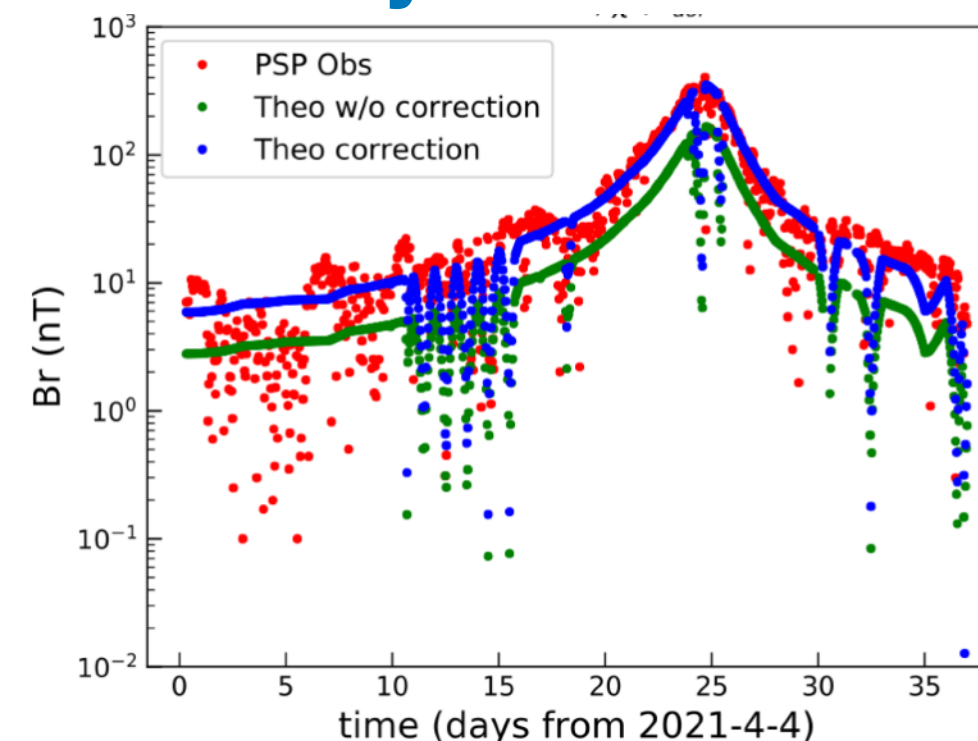
Coronal Magnetic Field: PFSS/CSSS



**Geomagnetic Field: IGRF 13**



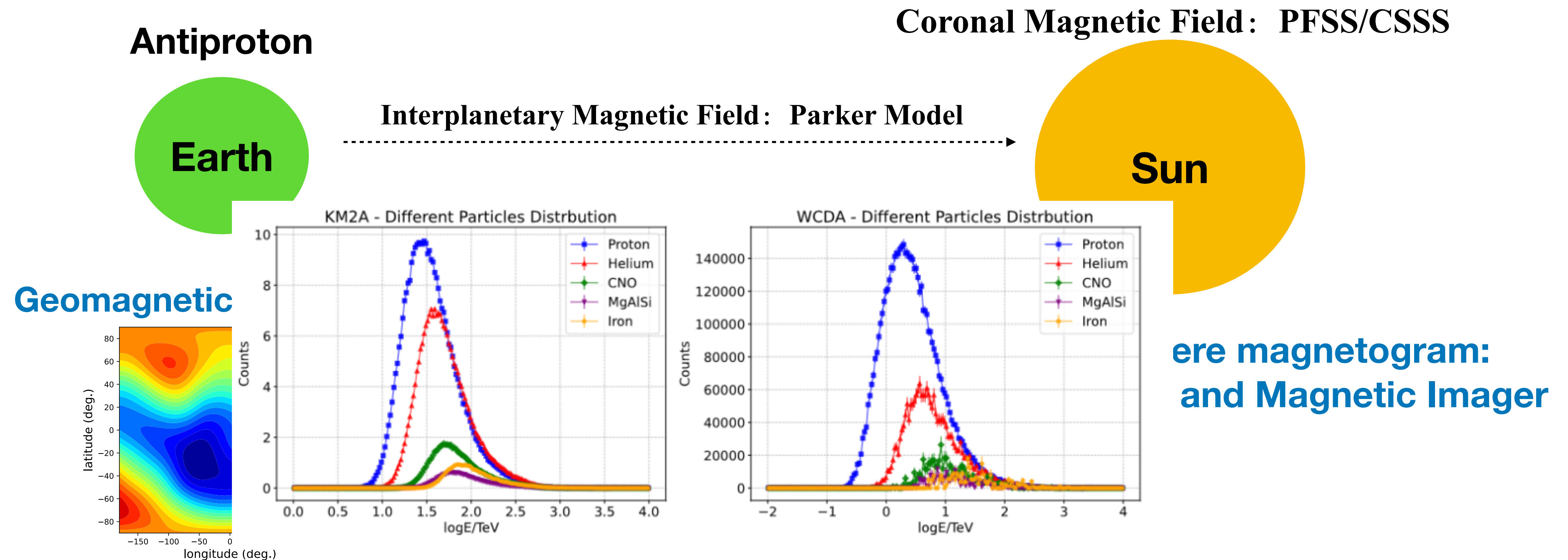
**Corrected by Parker Solar Probe**



**photosphere magnetogram:  
Helioseismic and Magnetic Imager**

# Simulation of Sun Shadow

- Back tracing method
- To construct self-consistent & time-dependent magnetic field to calculate Sun's shadow
- Without air shower simulation, using PSF instead



# Data Analysis of Experimental Cosmic Ray Data

- **Data Set**

WCDA/KM2A : 2021.3.5~2023.12.31 (1032 days)

$$5^\circ < zenith < 45^\circ$$

- **Background Estimation**

- **Significance calculation**

Li-Ma formula

The Equal Zenith Angle Method

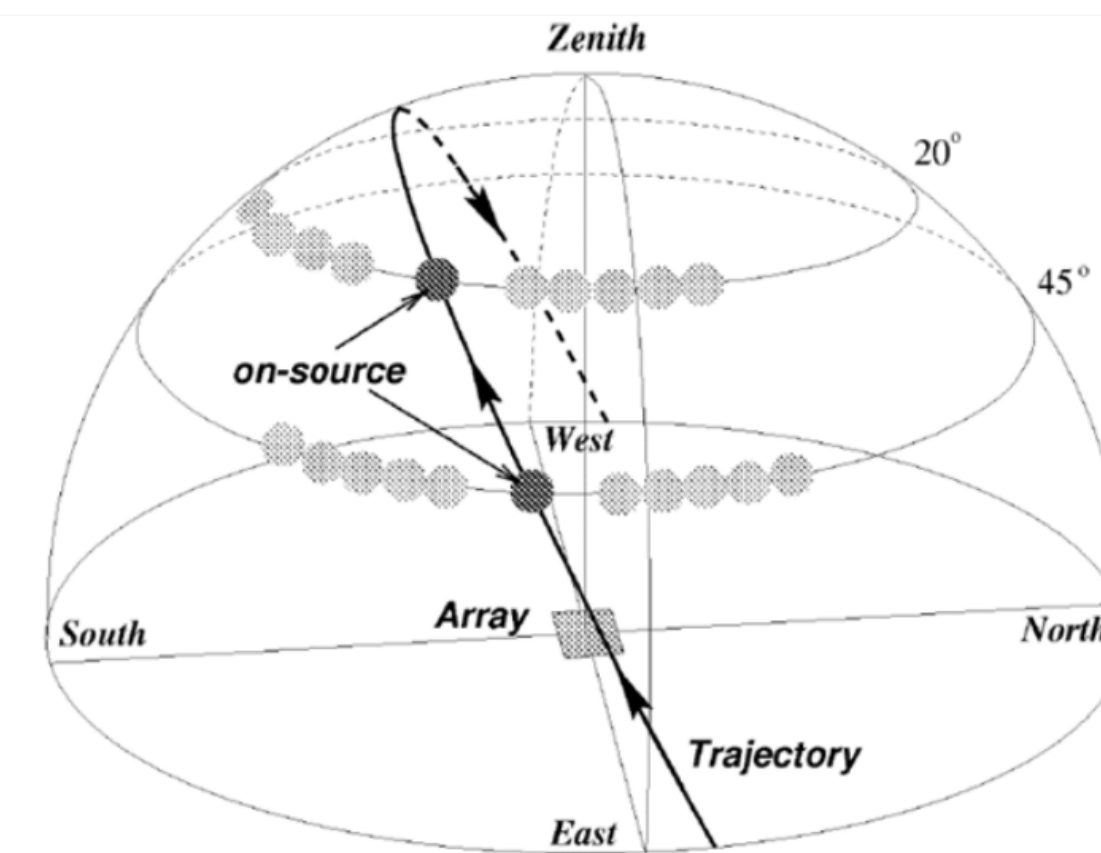
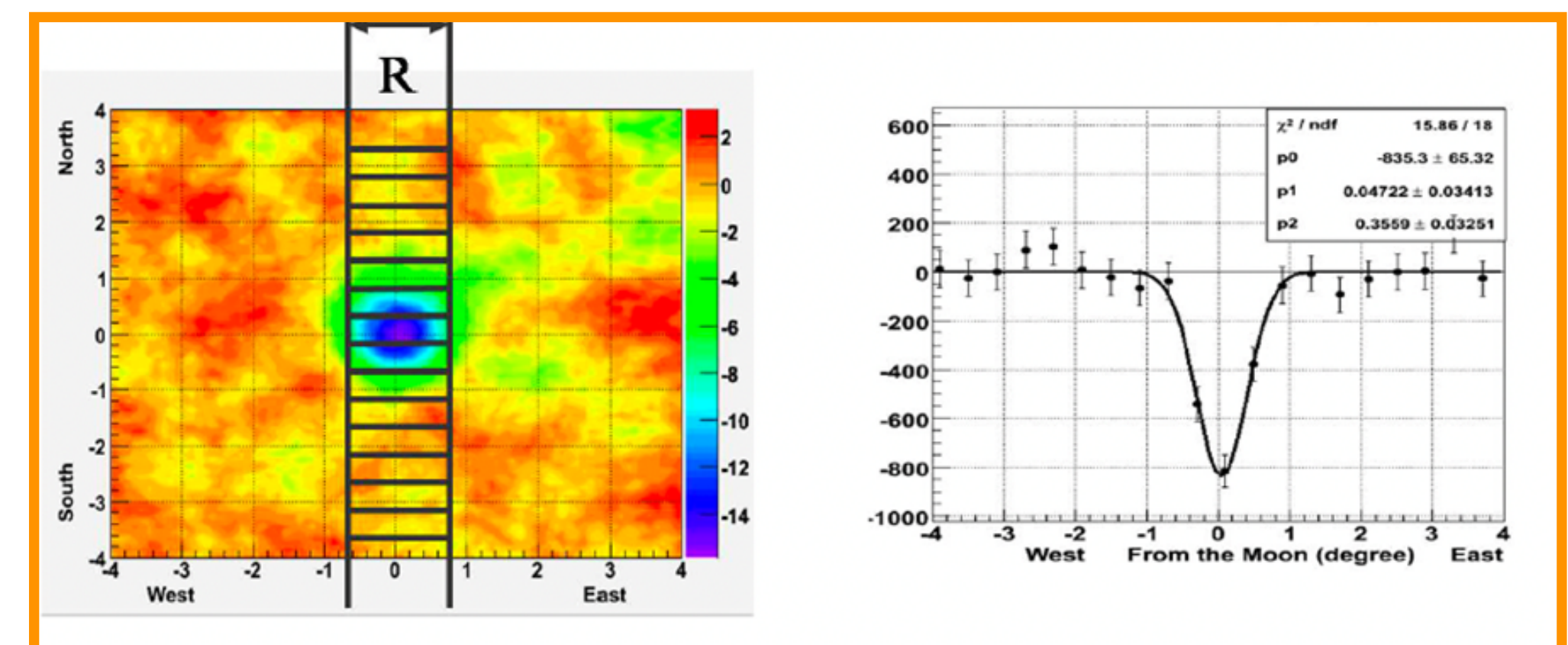


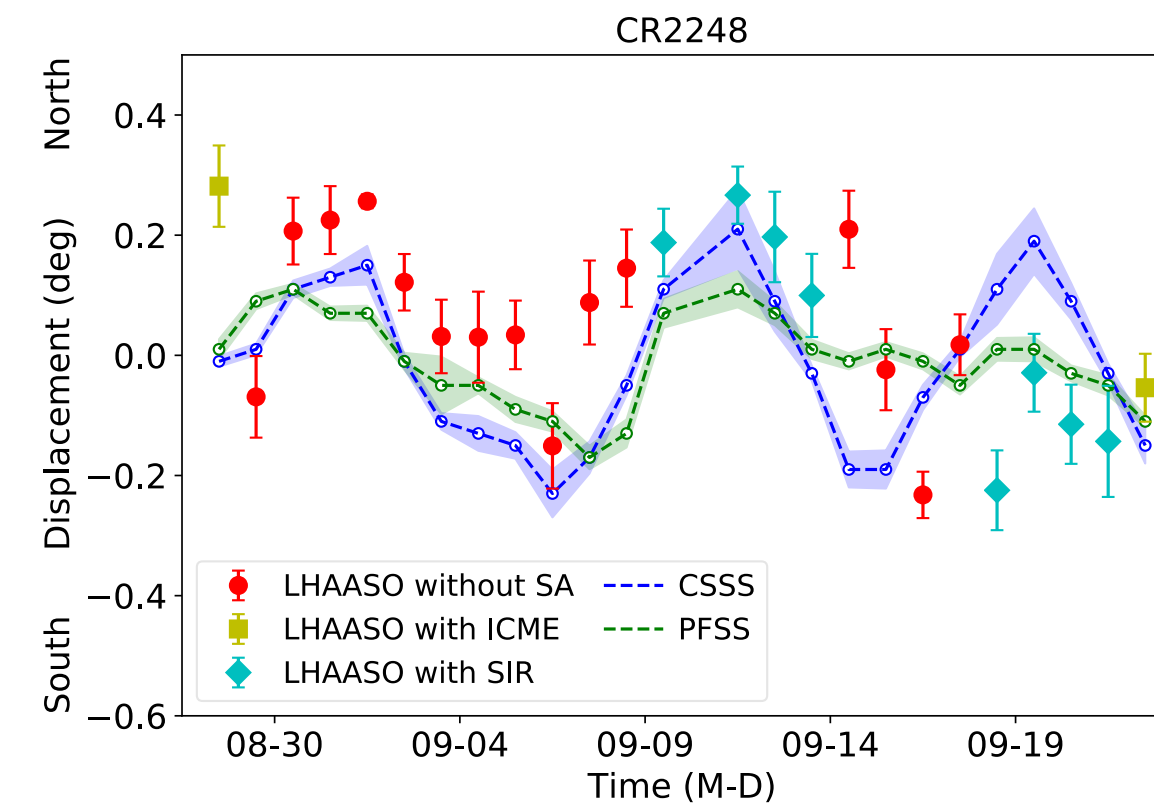
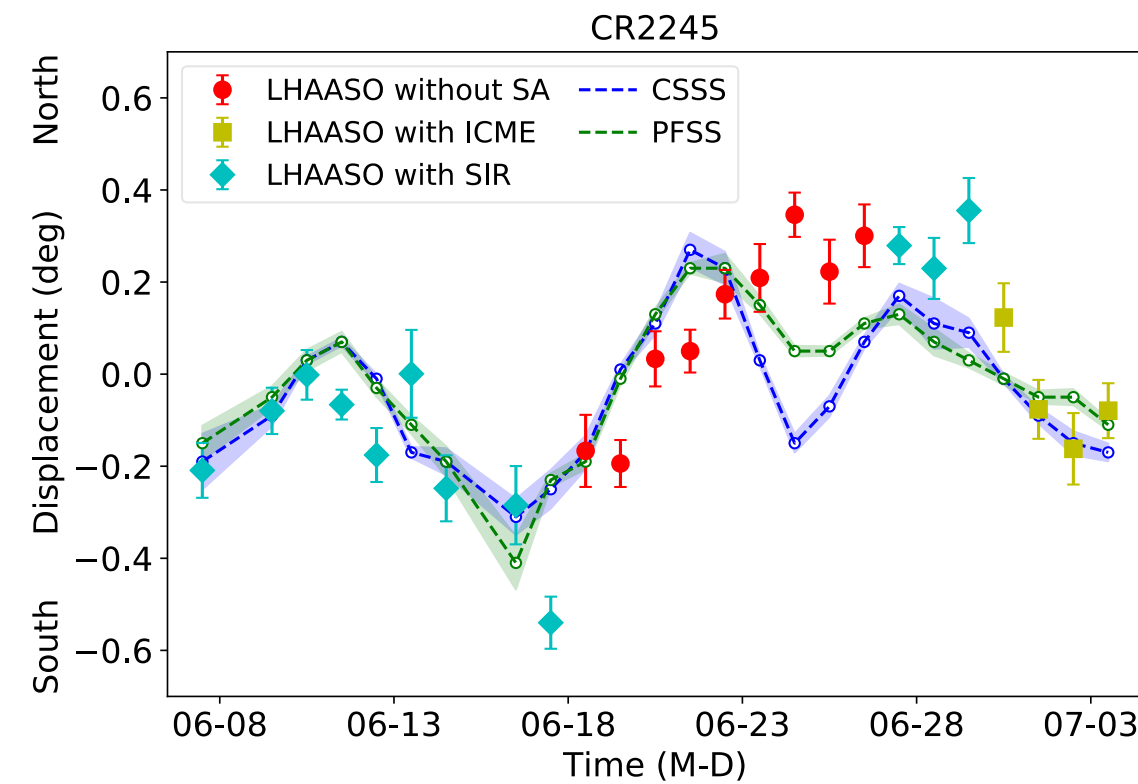
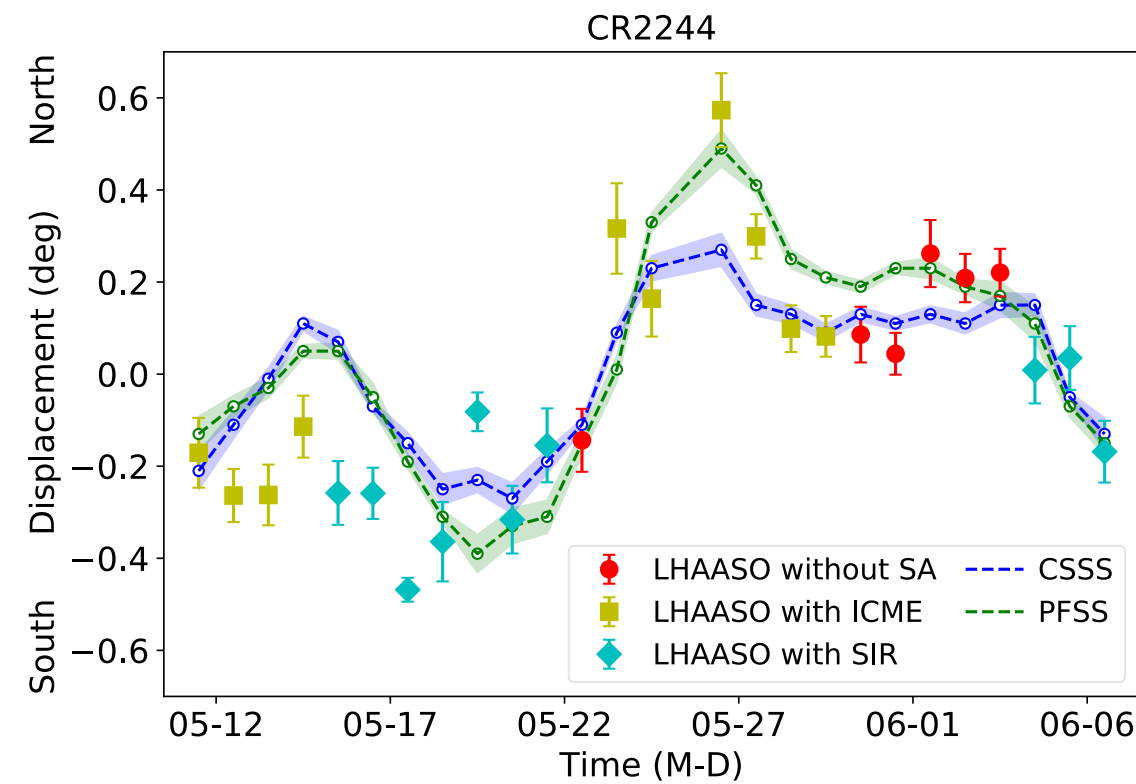
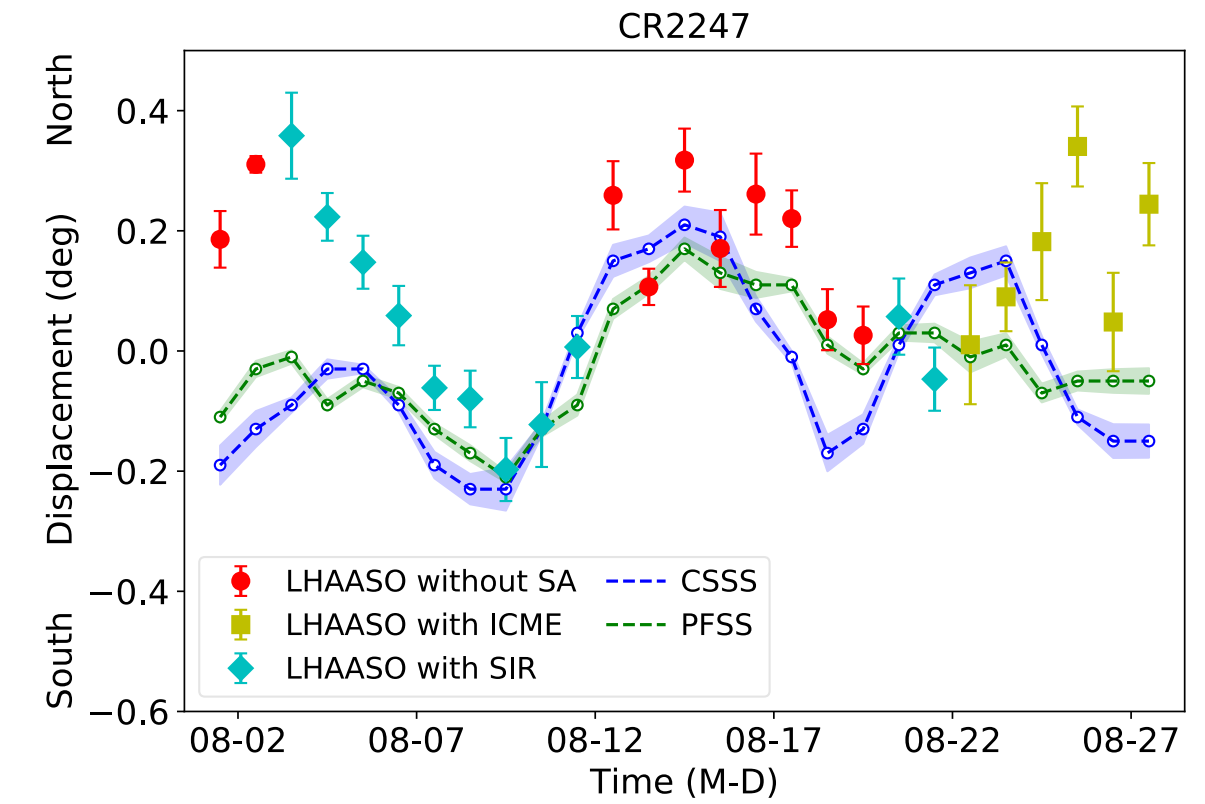
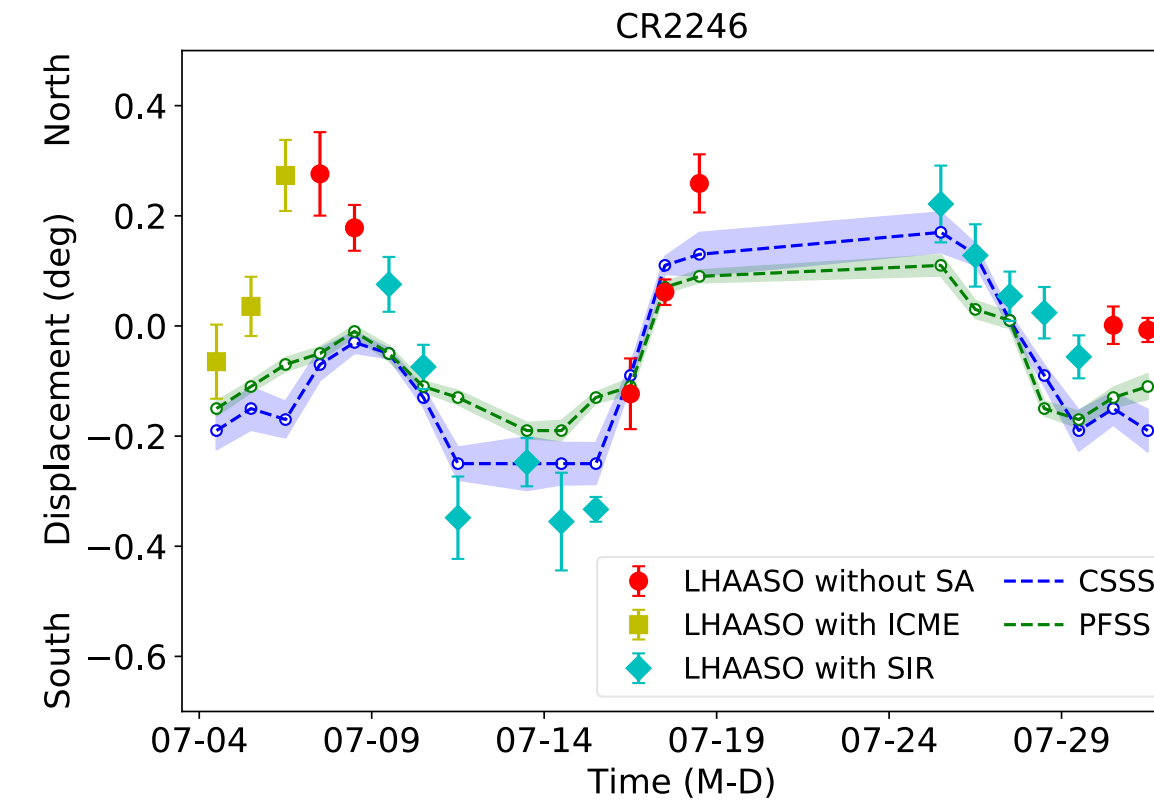
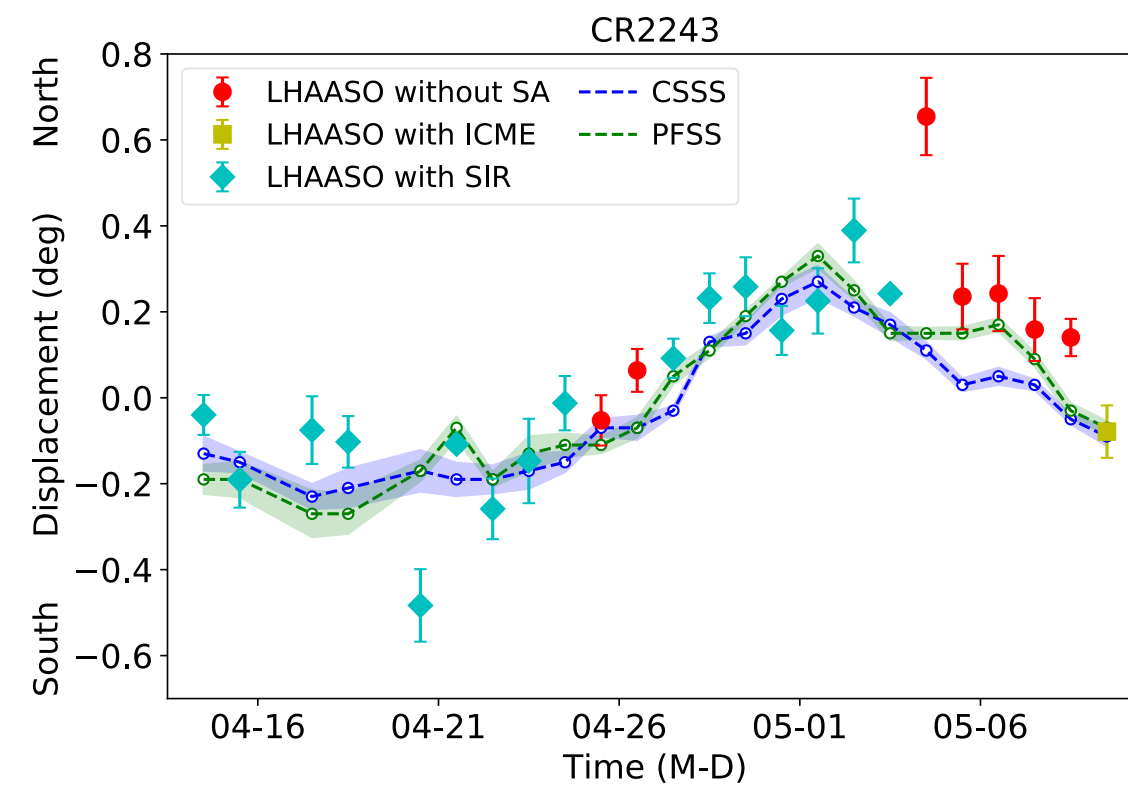
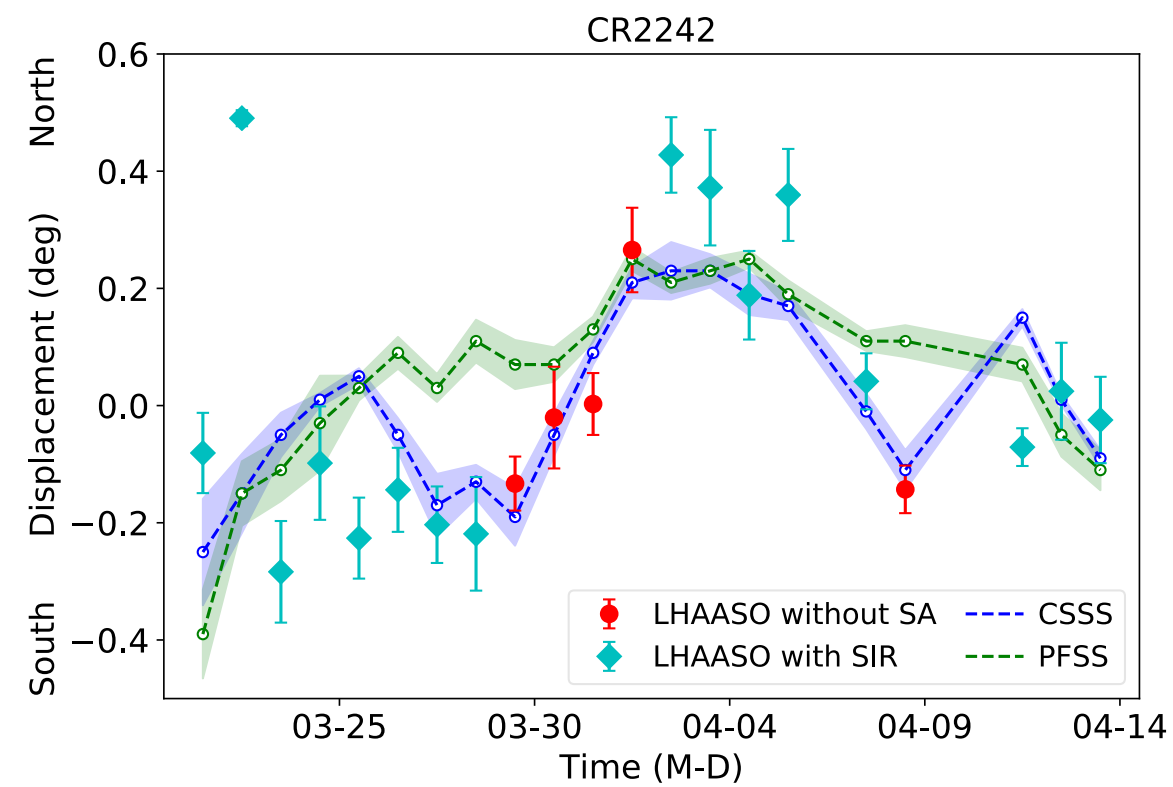
图 4.2 等天顶角法示意图

## Displacement of Sun's shadow



# North-South Displacement of Sun Shadow

Year: 2021



$$\chi^2 = \sum \frac{(D_{obs} - D_{MC})^2}{(\sigma_{obs})^2 + (\sigma_{MC})^2 + (\sigma_{sys})^2}$$

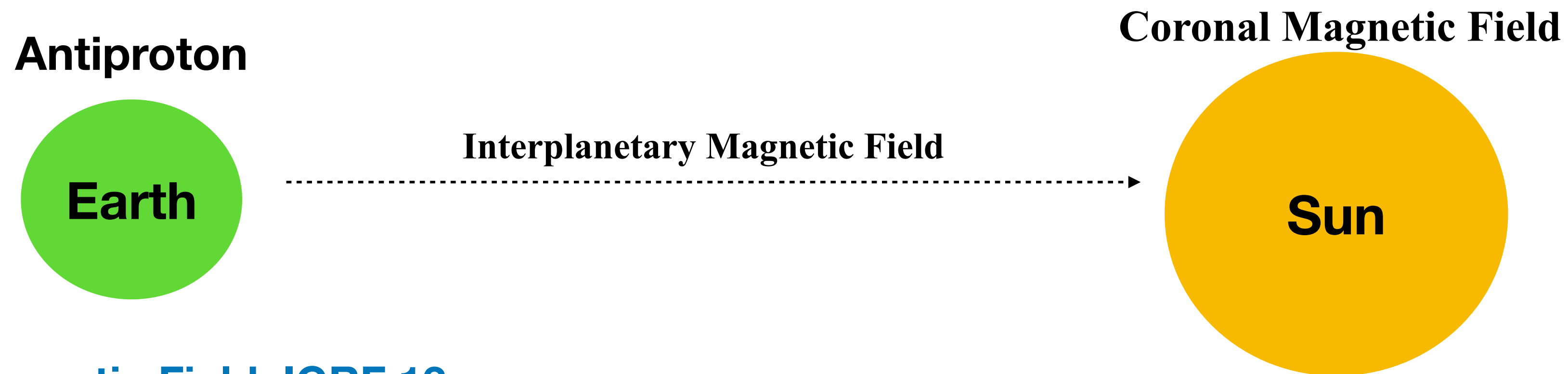
$\chi^2$  : CSSS < PFSS

# Outline

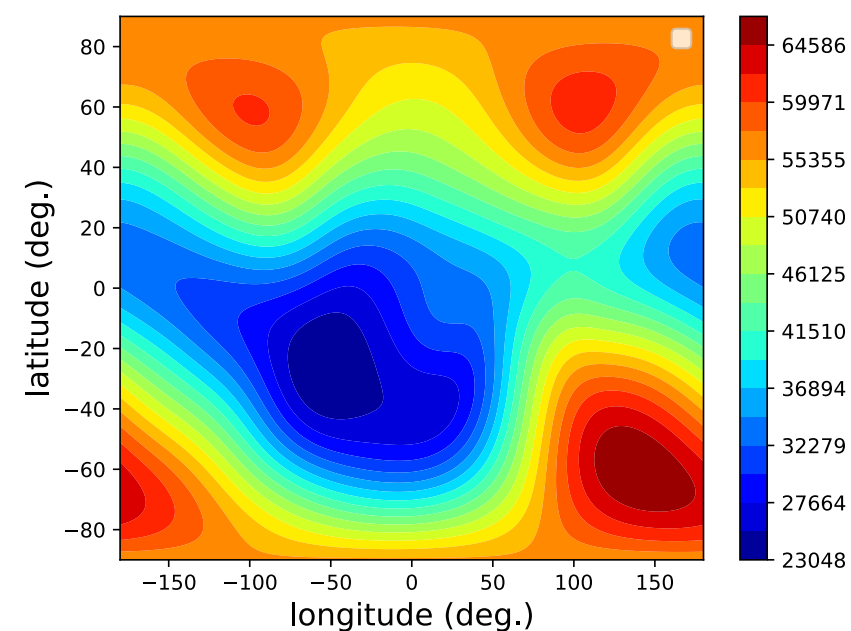
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# Simulation of Sun Shadow

- Back tracing method
- CMF & IMF: MHD simulation (with / wo CMEs)
- Without air shower simulation, using PSF instead



**Geomagnetic Field: IGRF 13**

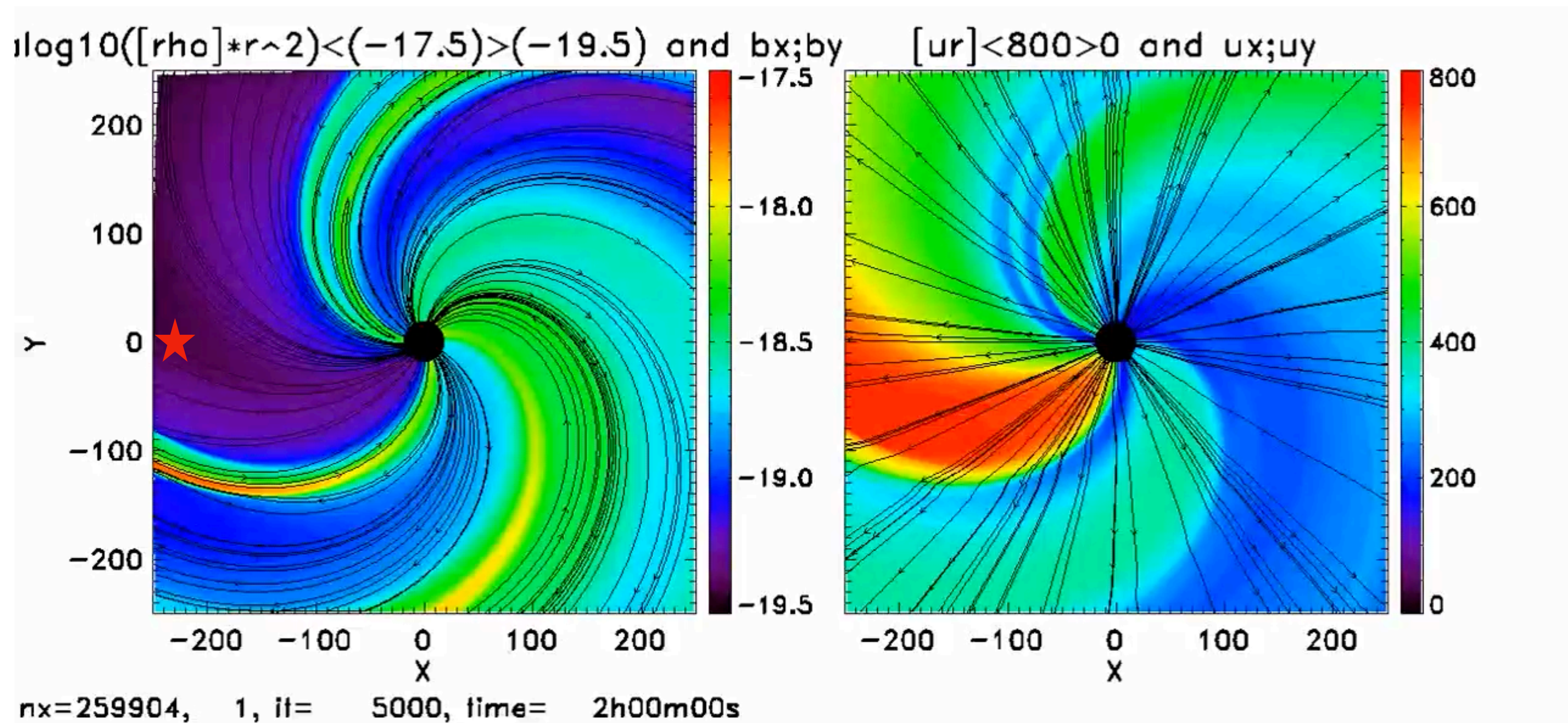


**MHD simulation (with / wo CMEs)**

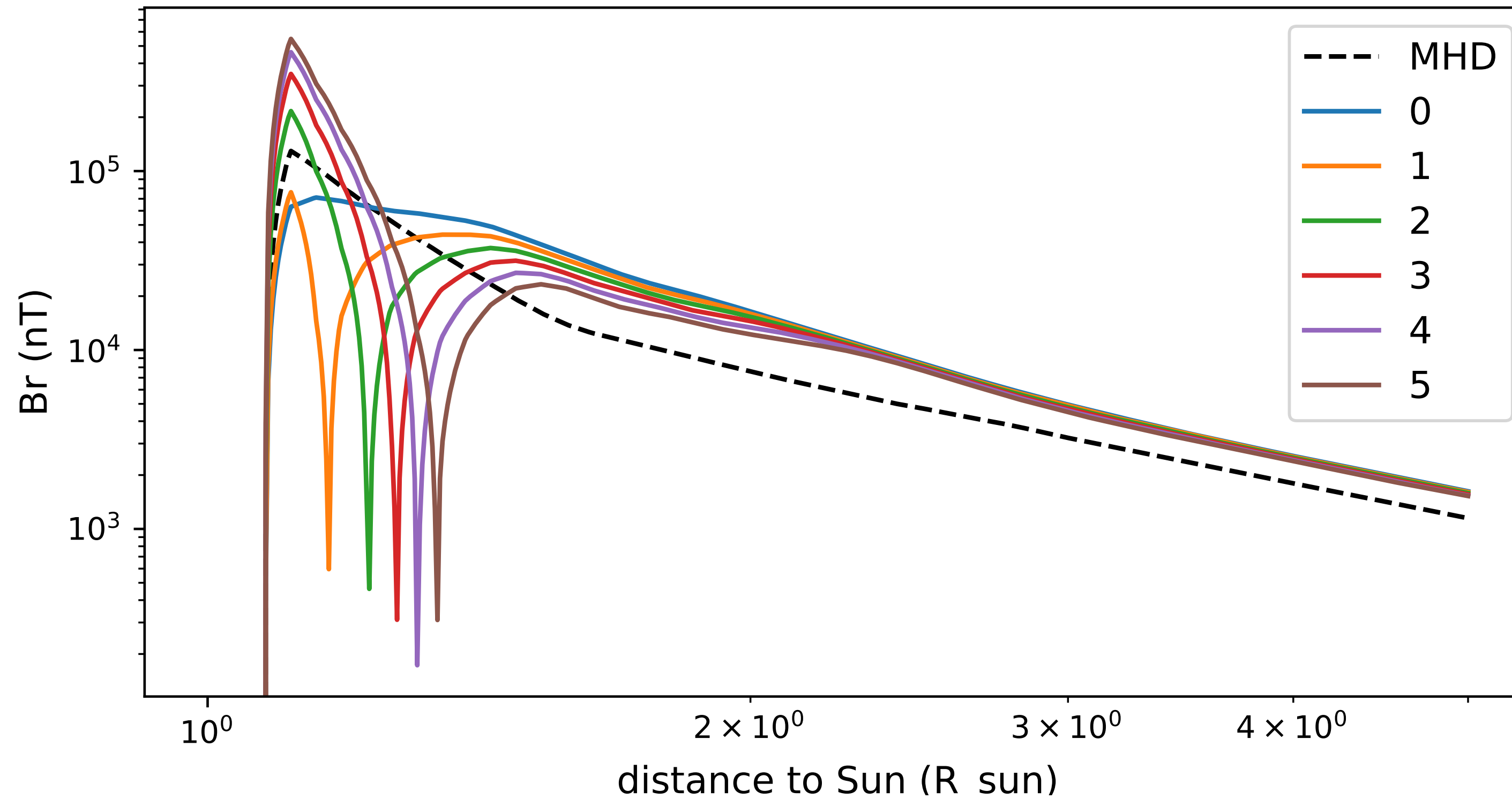
# CMEs in CR2277

CR2277: 2023-10-29 ~ 2023-11-24

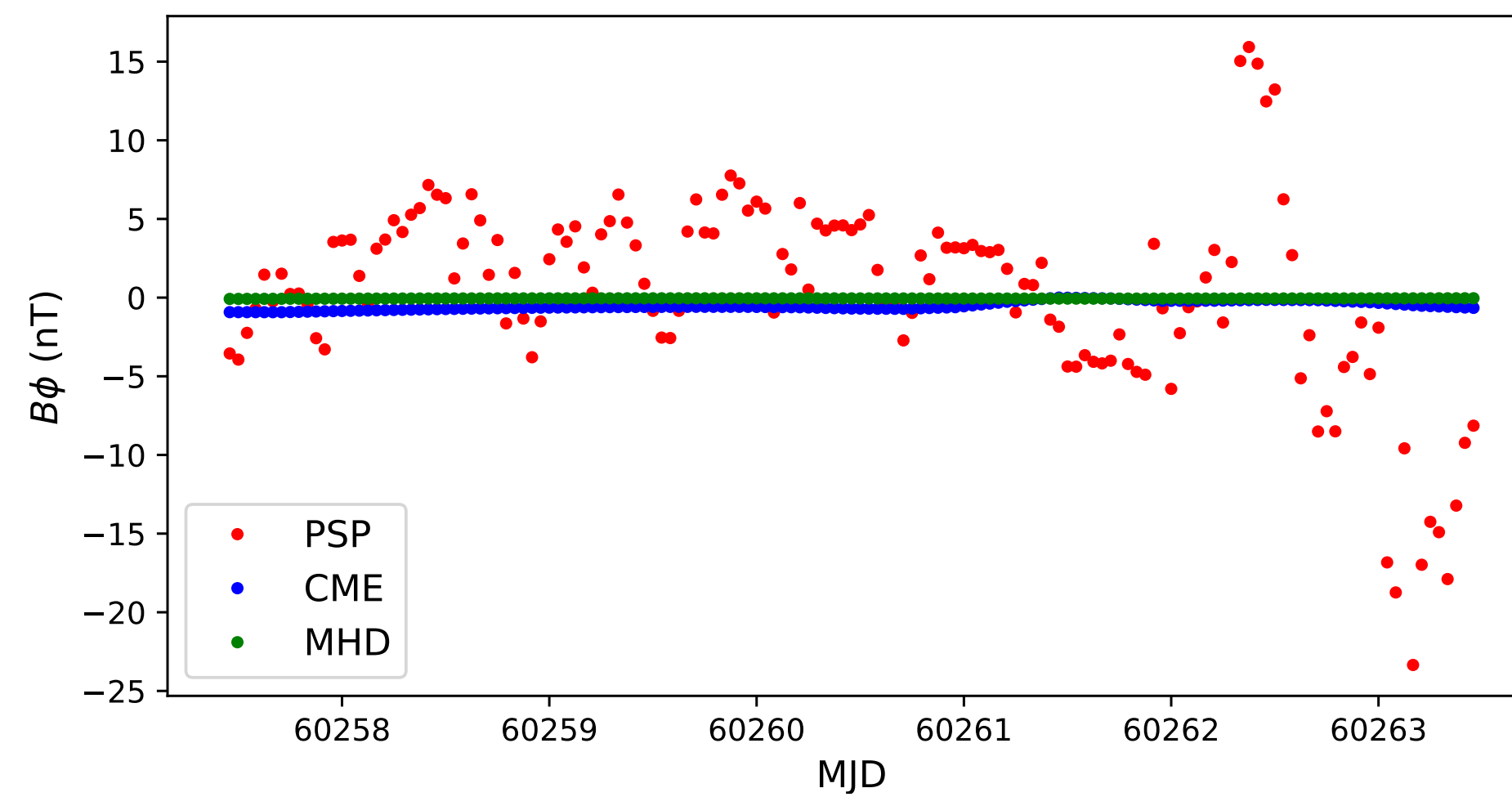
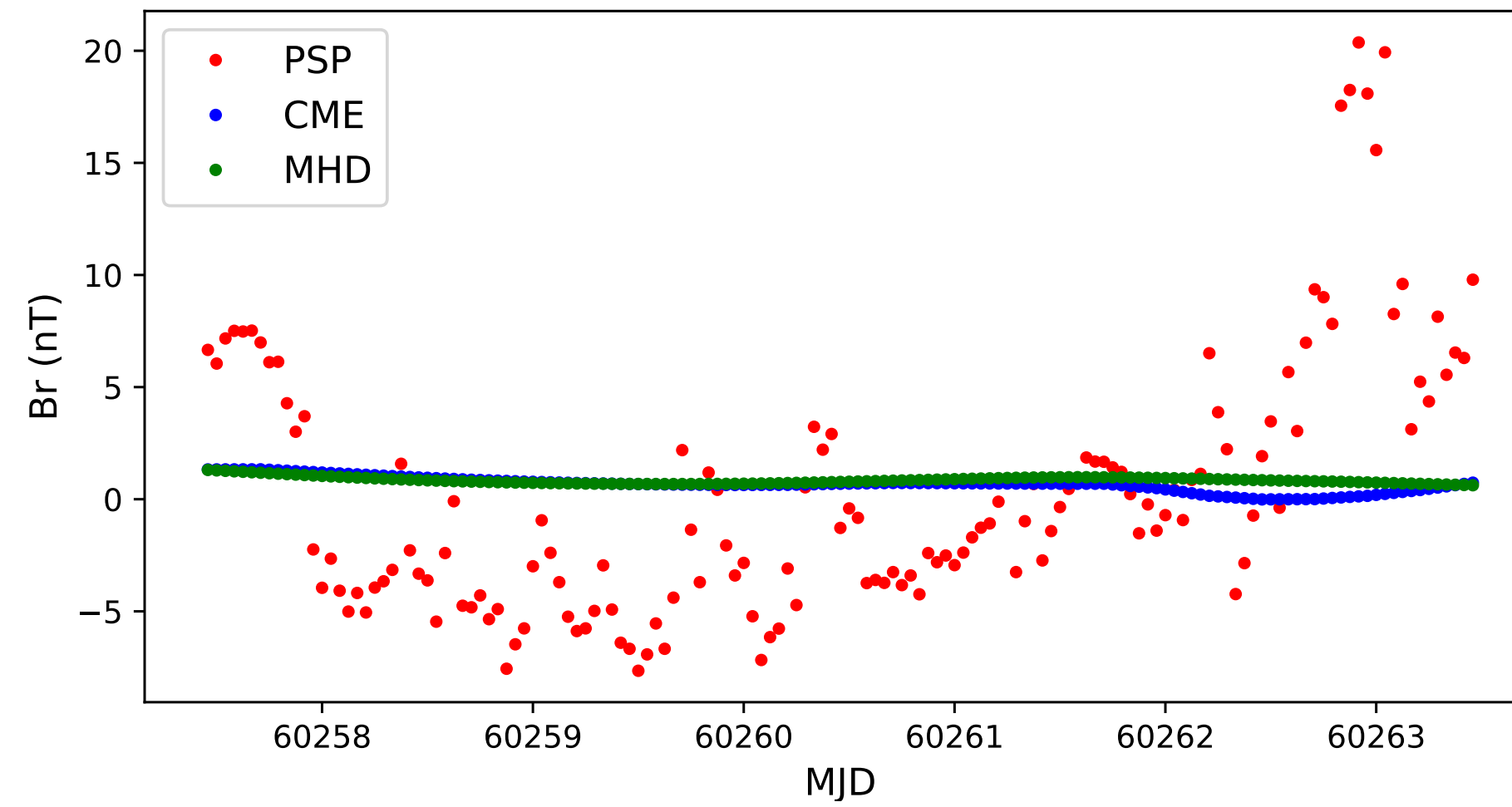
CMEs: 2023-11-09T11:00:00 ~ 2023-11-15T11:00:00



# Time variation of Br in Earth-Sun line

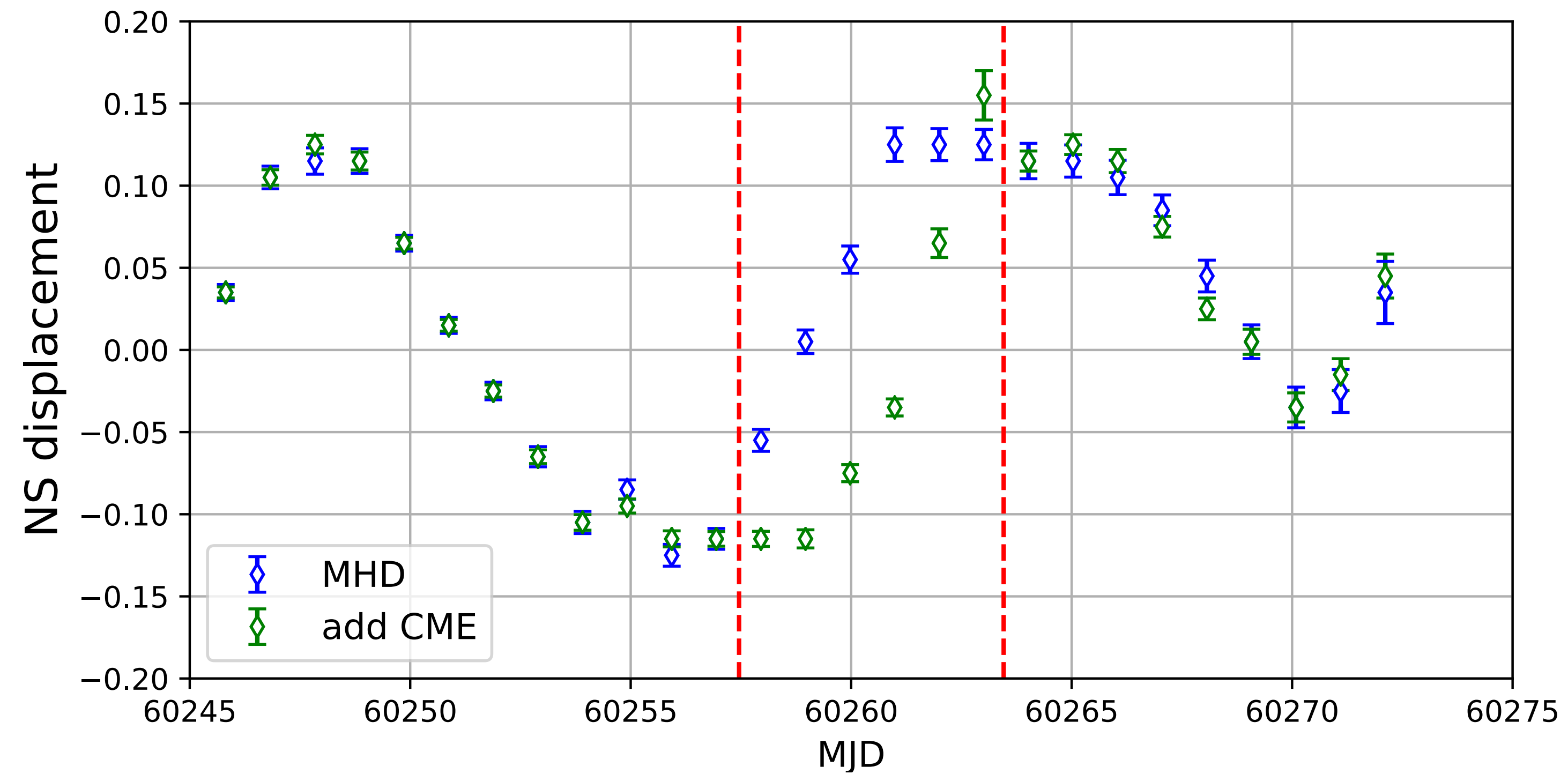


# Comparison with PSP



# Result with CMEs

CR2277: 27 days, 27 bins



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# Summary & Outlook

- Research of cosmic-ray Sun shadow and solar gamma rays is deeply connected
- LHAASO observation of cosmic-ray Sun shadow can be used to study solar magnetic field
- LHAASO observation can be used to study CMEs magnetic field in the future

**Backup**

# Coronal Magnetic field – Quiet Sun

Potential Field Source Surface Model (PFSS)

$$\left. \begin{aligned} \nabla \times \mathbf{B} &= 0 \\ \nabla \cdot \mathbf{B} &= 0 \end{aligned} \right\} \nabla^2 \Phi_B = 0 \quad (\text{A finite-difference method})$$

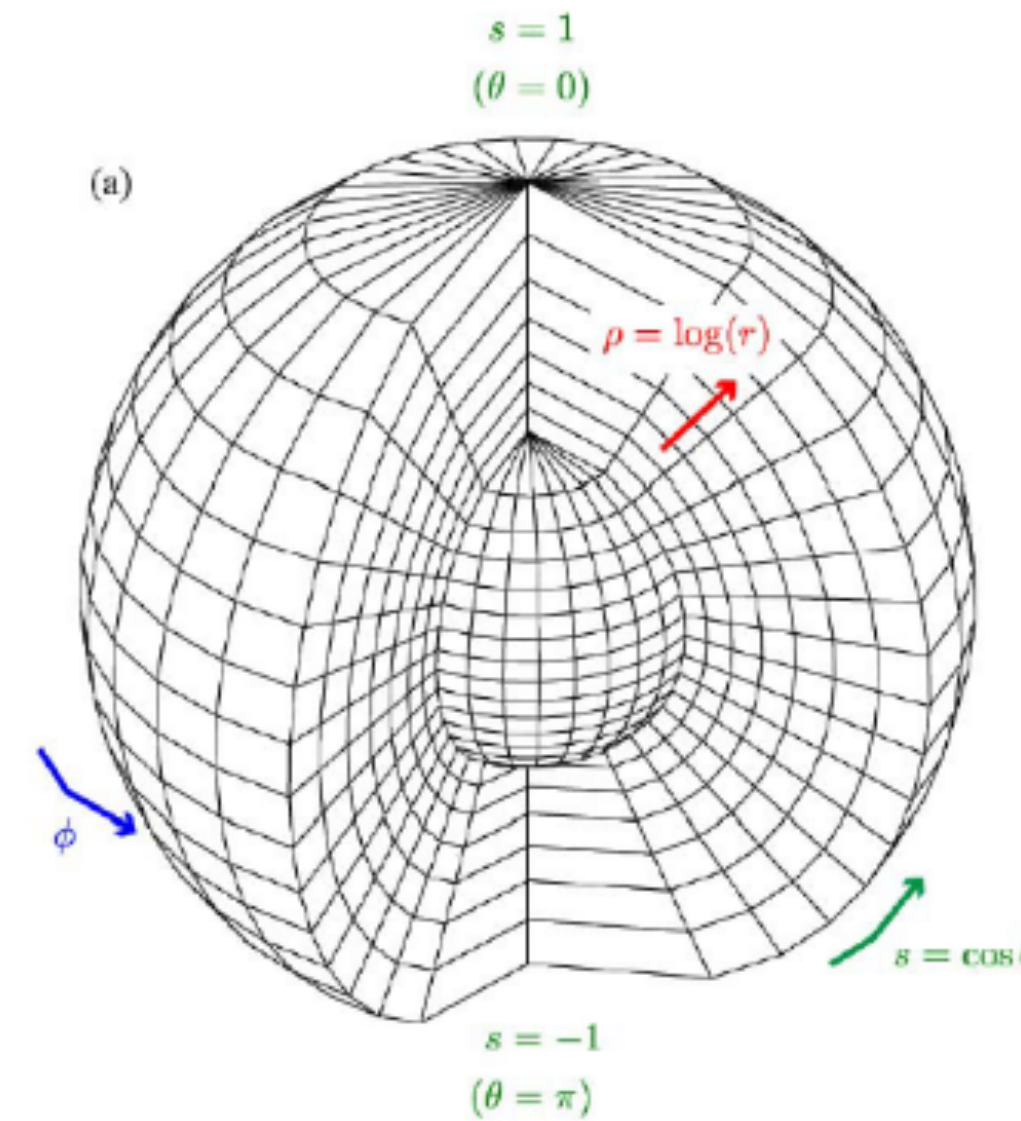
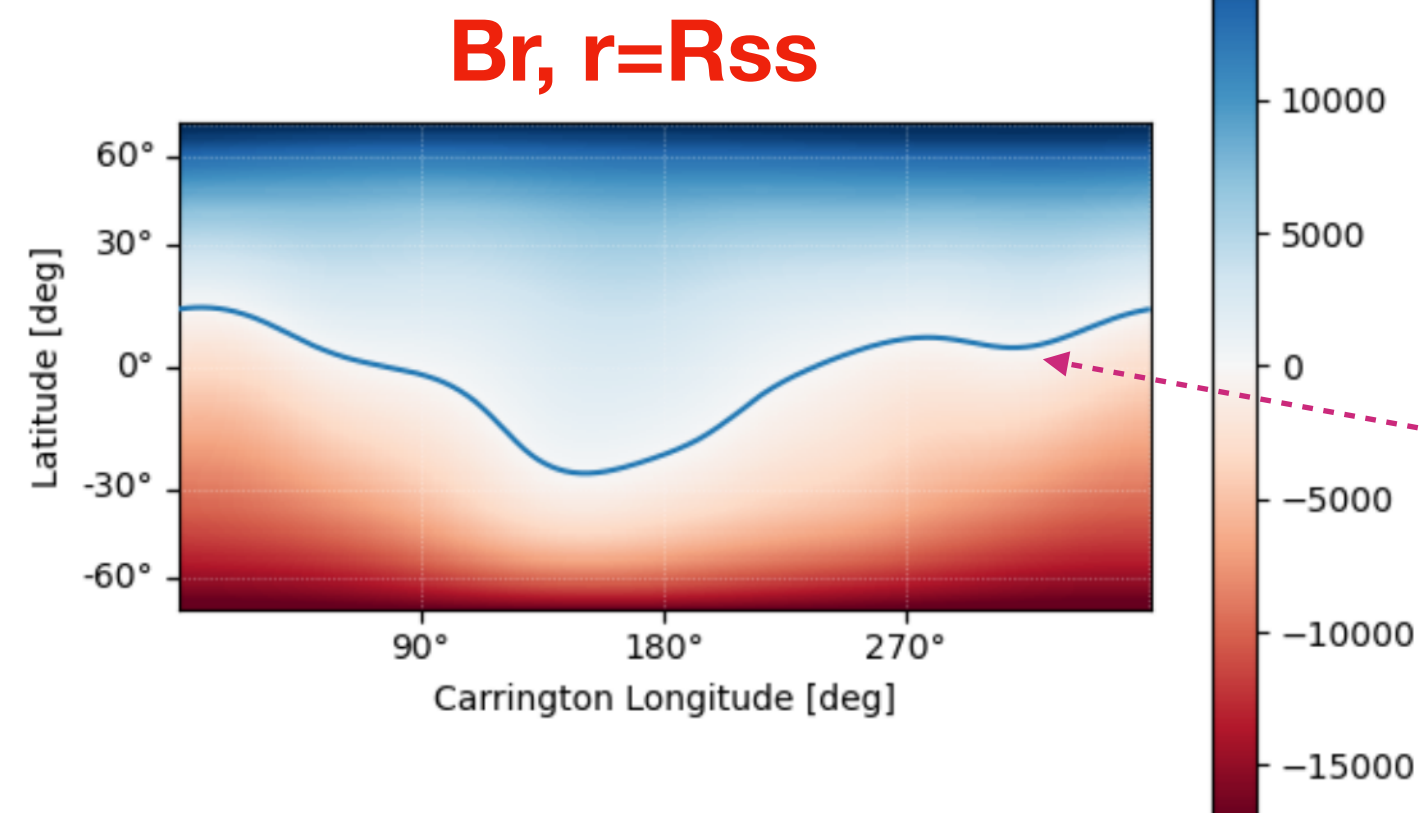
Boundary conditions:

**magnetogram**

$$\begin{aligned} B_r(\theta, \phi) &= g(\theta, \phi) & r = 1 \\ B_\theta = B_\phi &= 0 & r = R_{ss} \end{aligned}$$

Helioseismic and Magnetic Imager (HMI) synoptic map

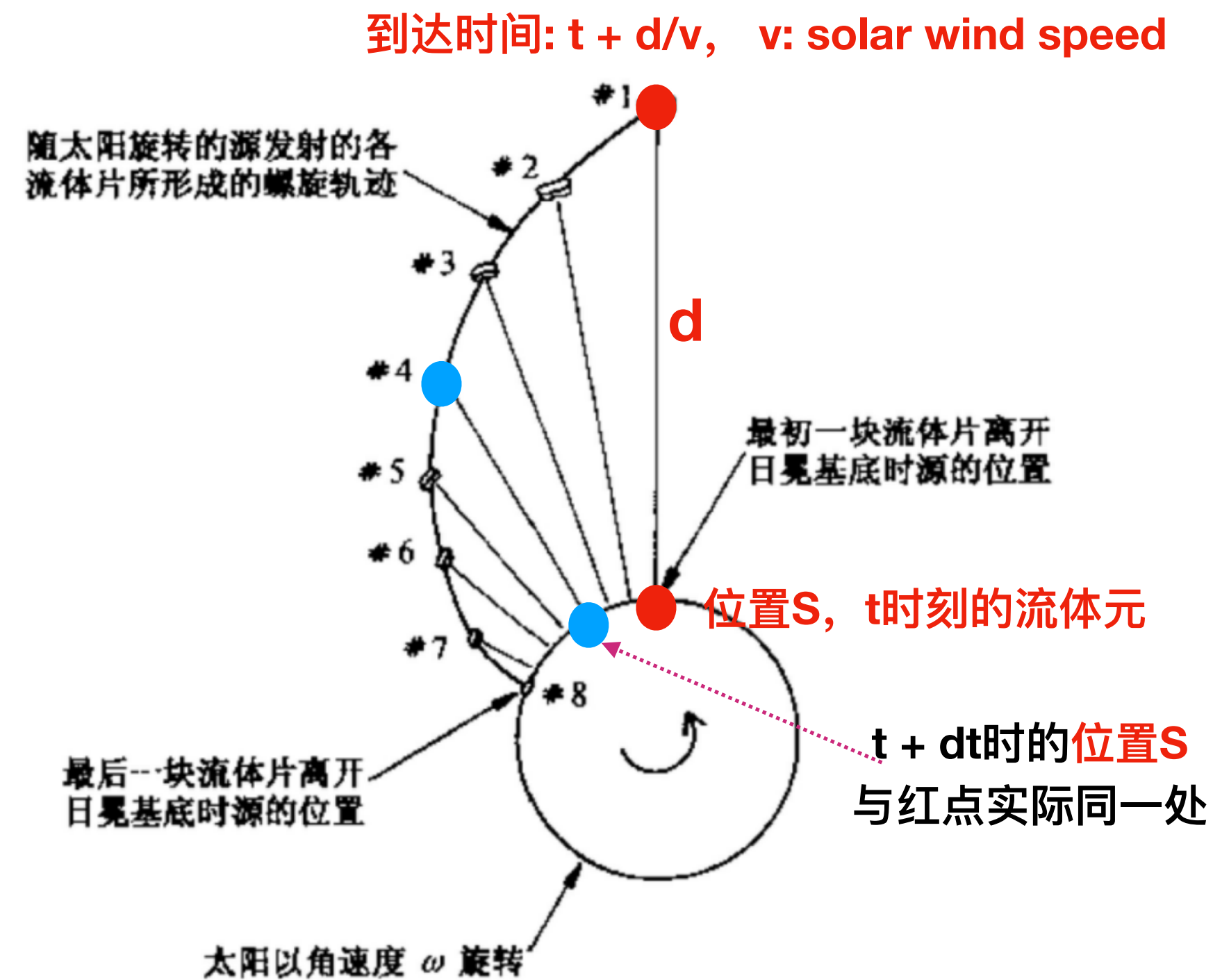
$R_{ss} = 2.5$     $n_r = 150$     $n_{ph} = 360$     $n_{th} = 180$



**$B_r = 0$  near equator**

# Parker theory of IMF

Main point: Solar wind “Carries” magnetic field (IMF) with it

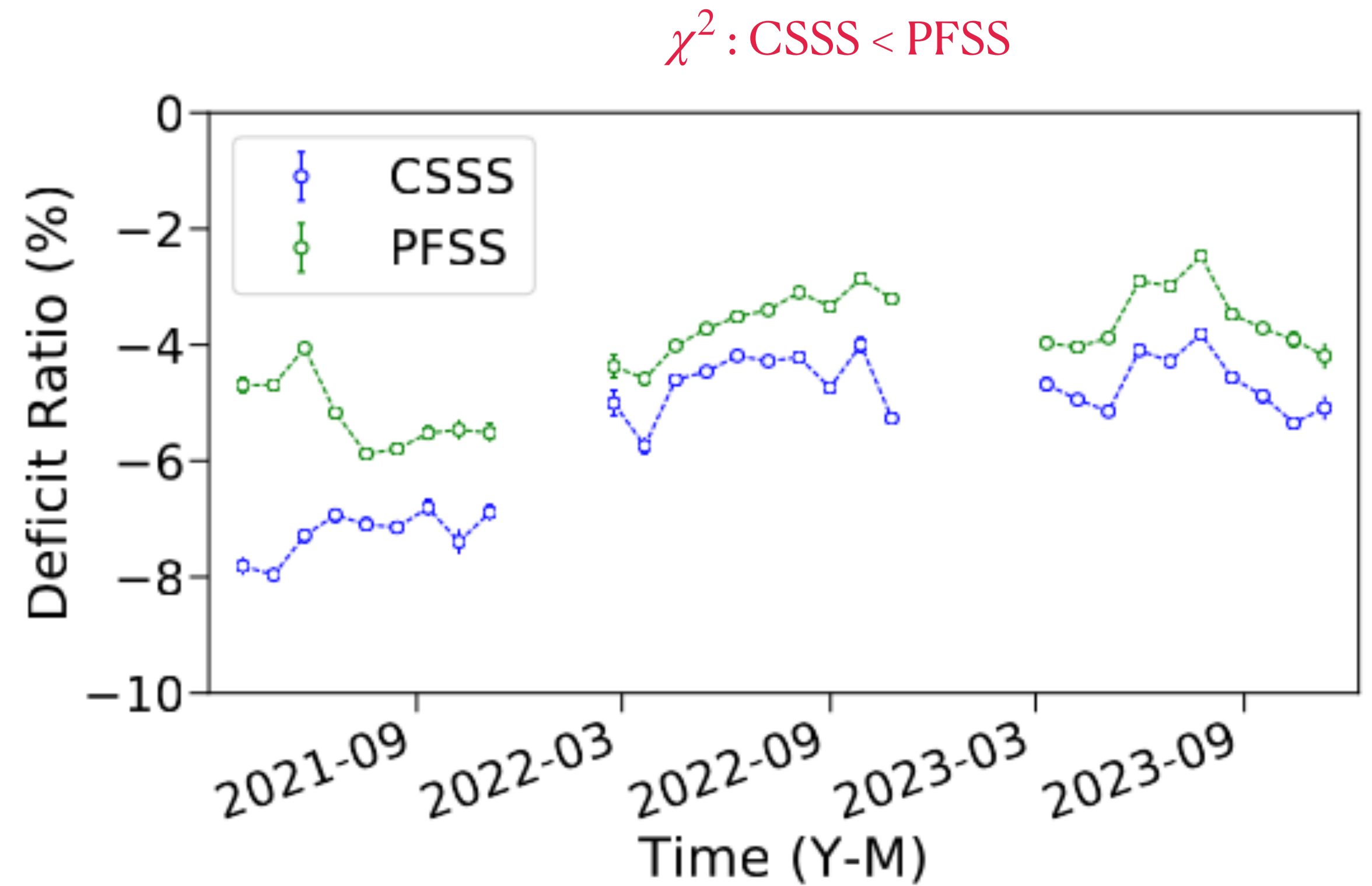
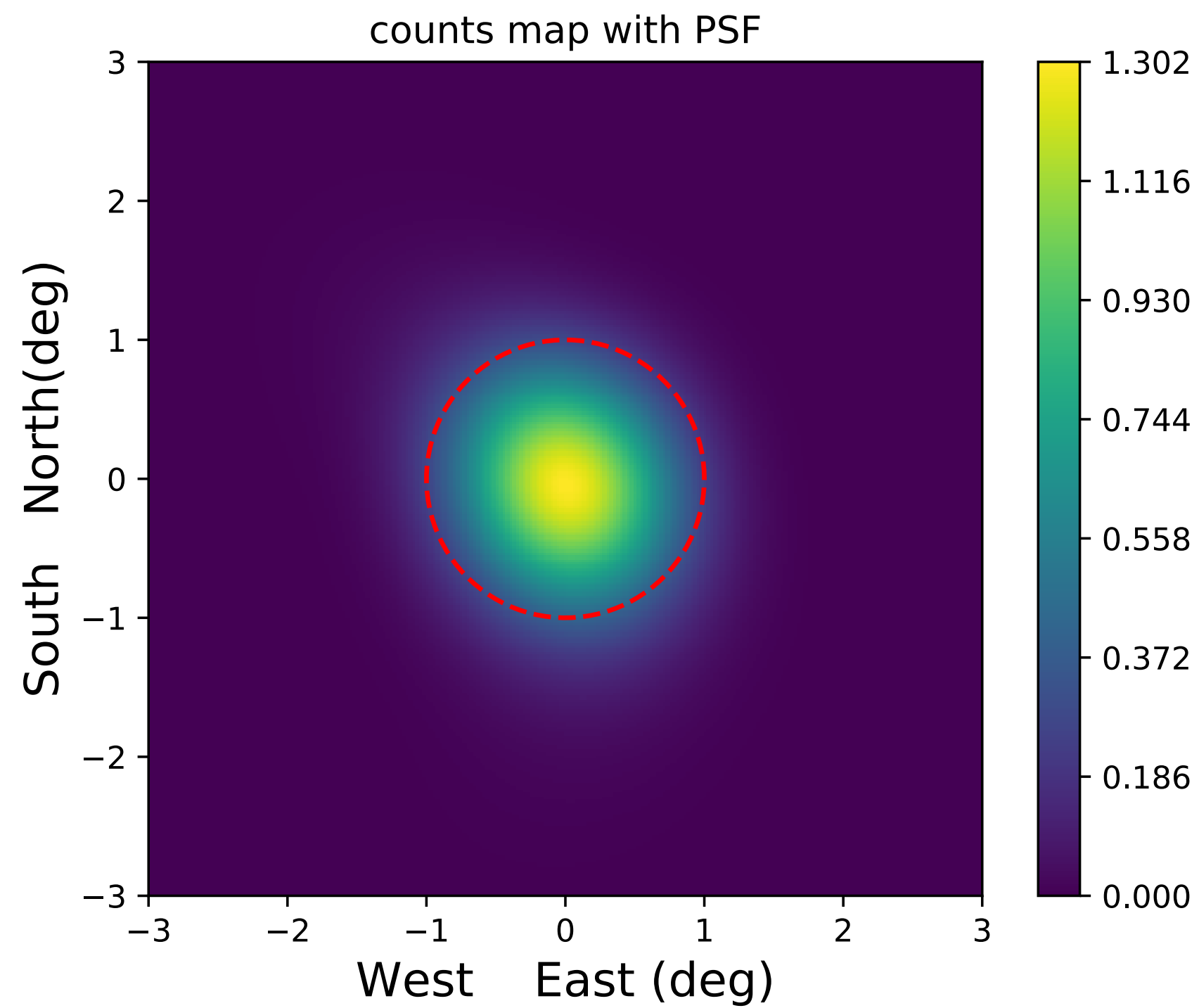


Lawn sprinkler



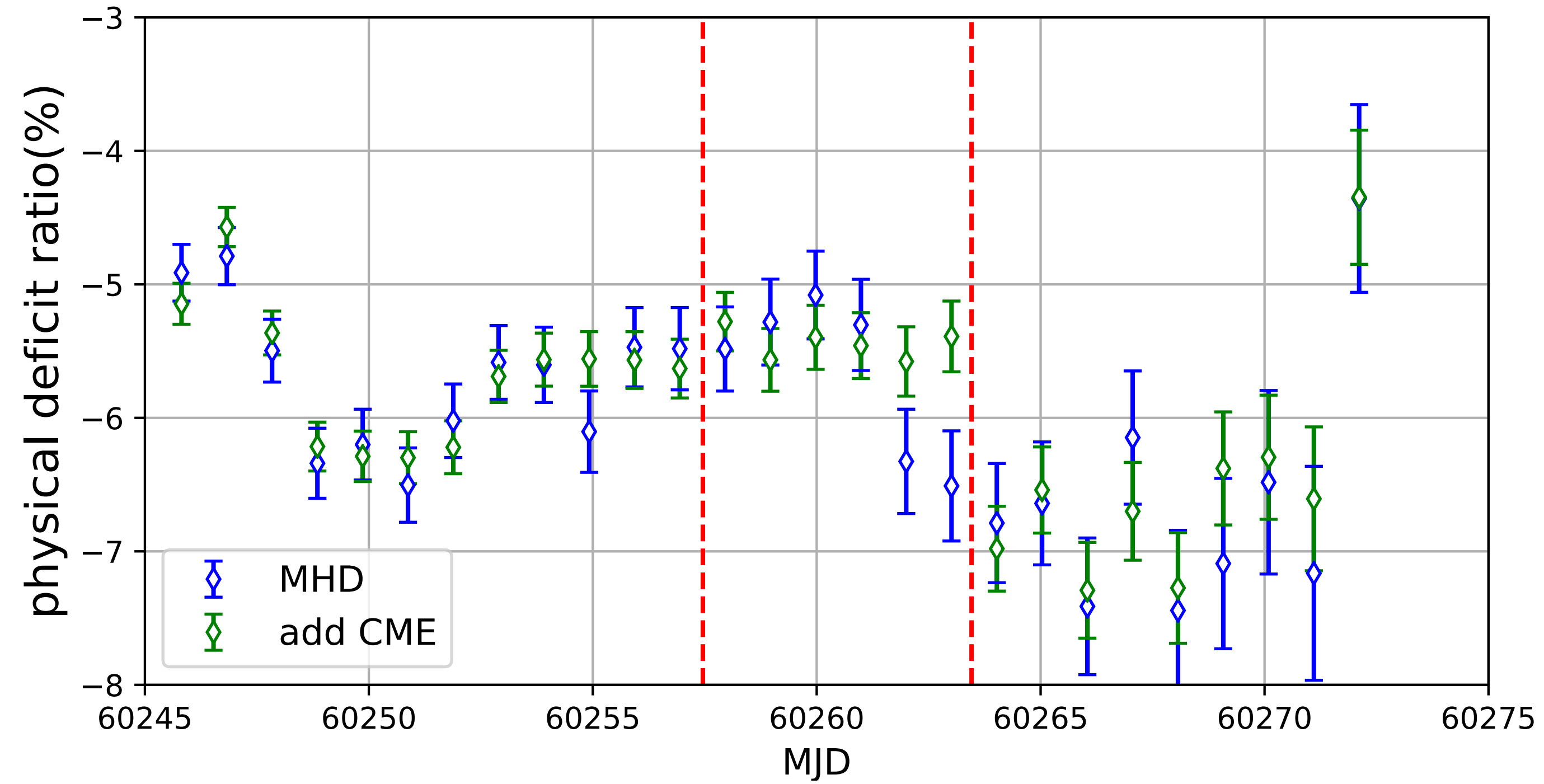
# Deficit Ratio of Sun Shadow

$$\text{deficit ratio} = \frac{N_{\text{hit with } B}}{N_{\text{all}}}, 1^\circ$$



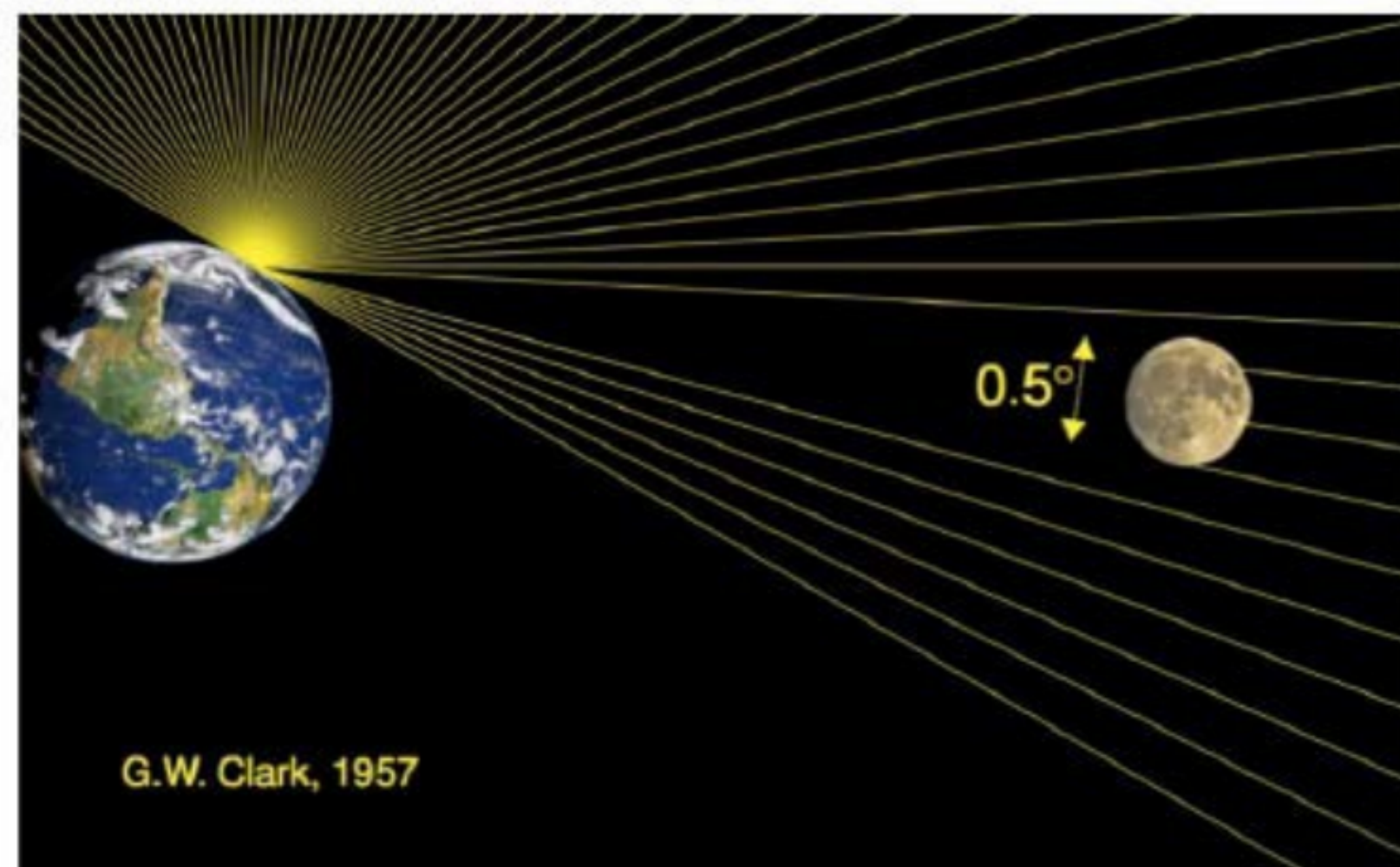
# Result with CMEs

CR2277: 27 days, 27 bins

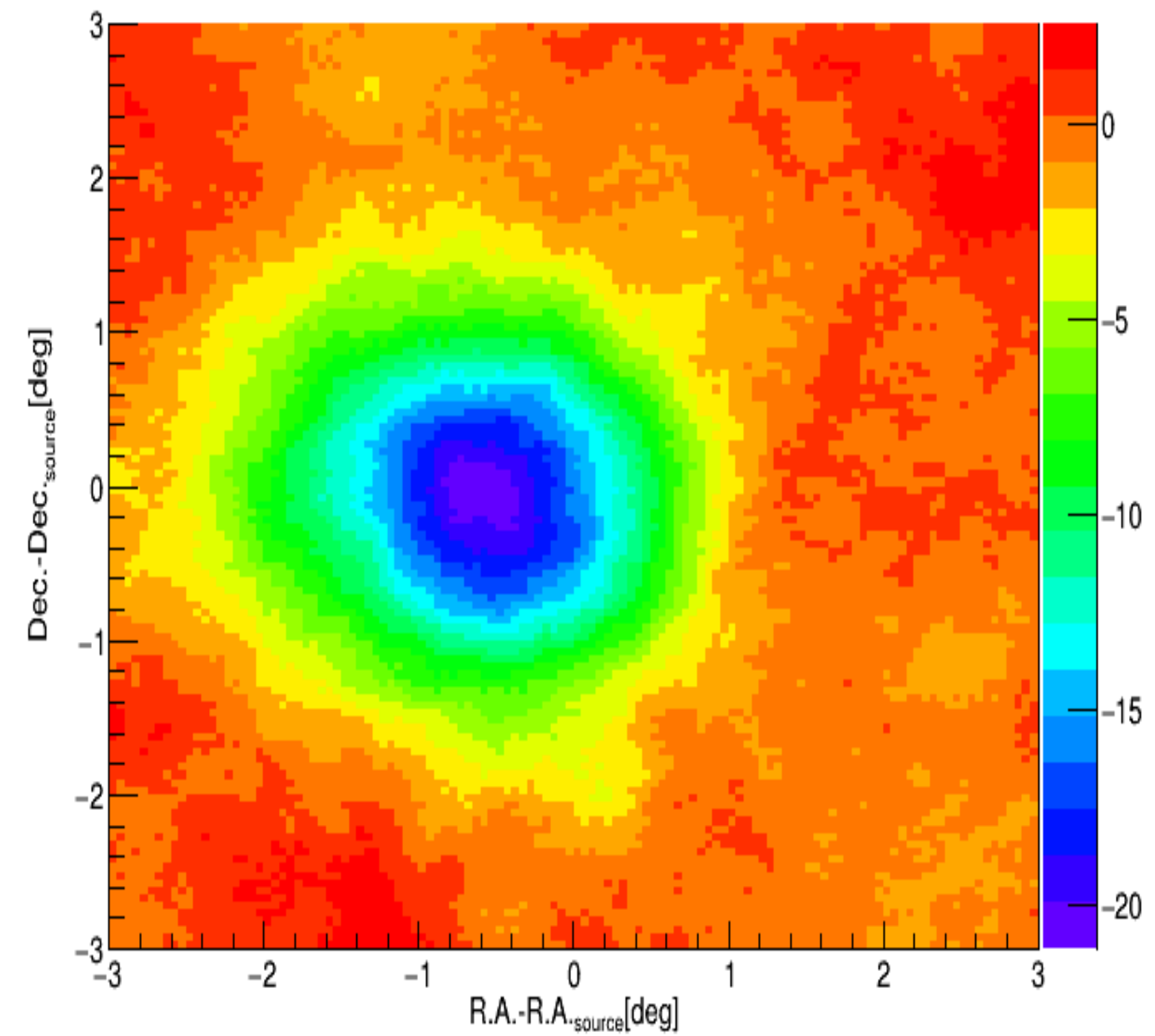


# Moon's Shadow

The interception of the cosmic ray by the Moon will lead to event deficit from the direction of the Moon.



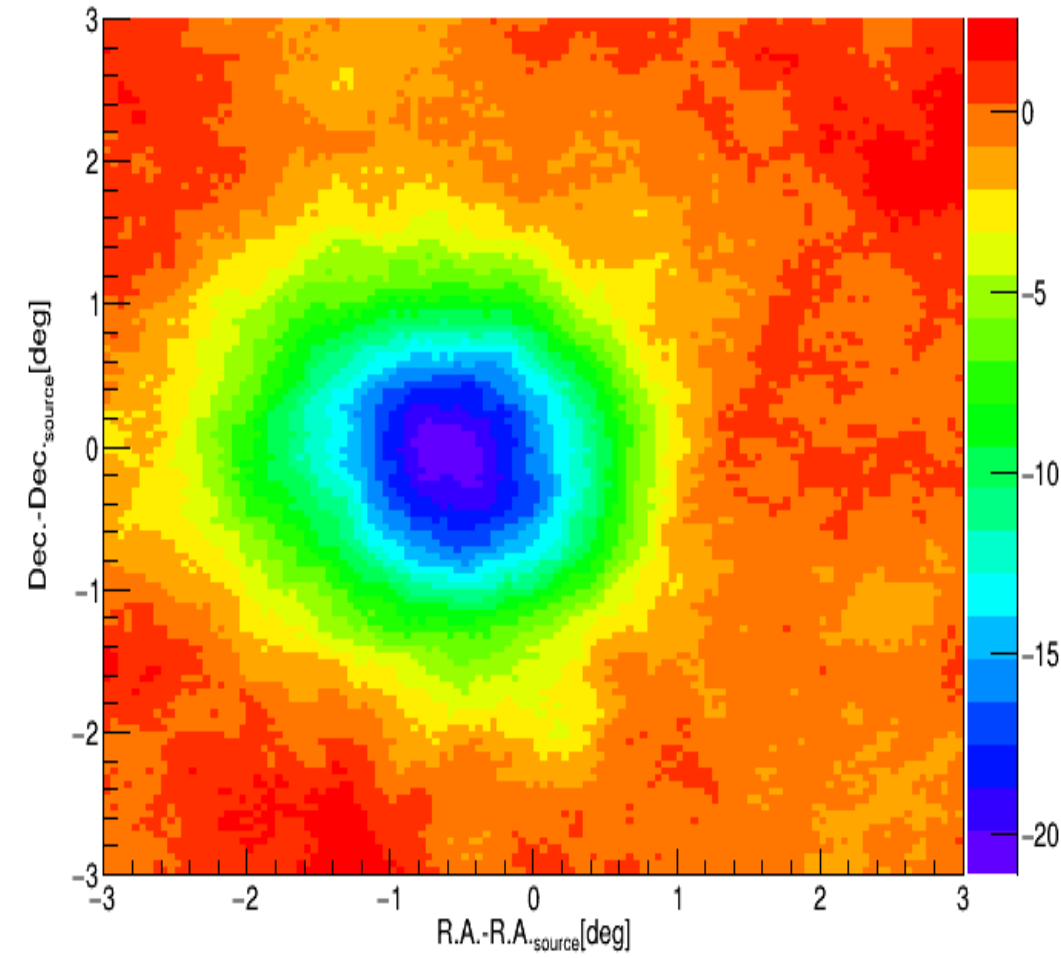
From David Boersma



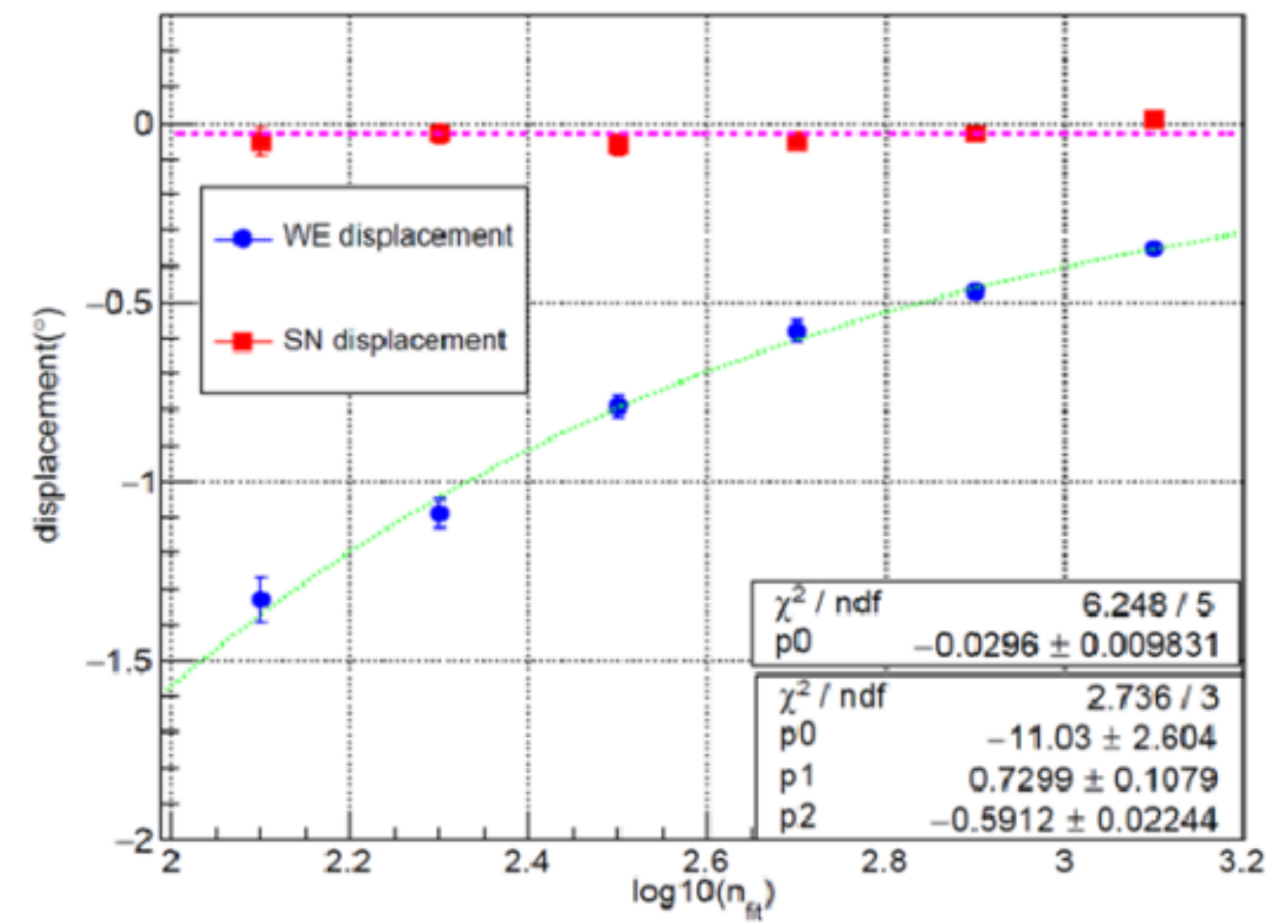
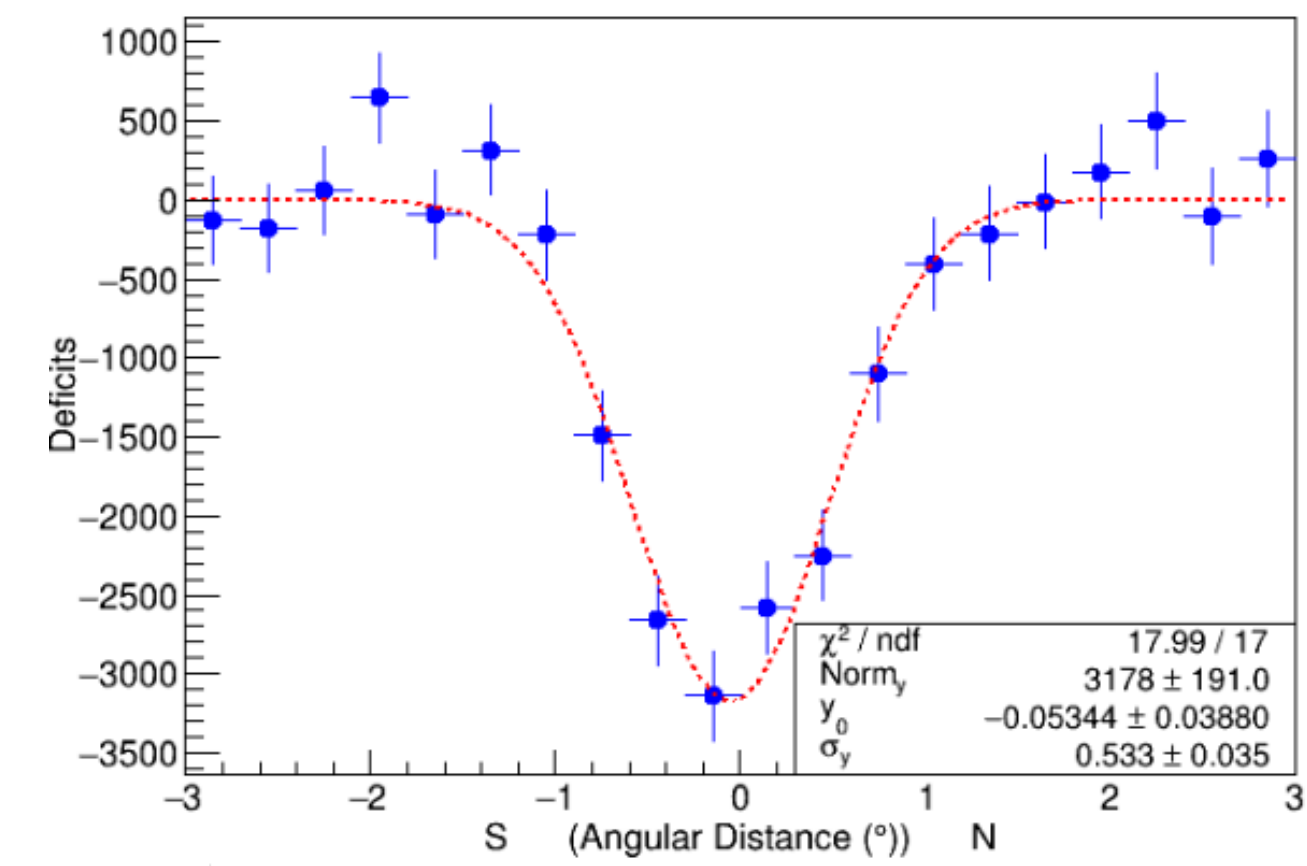
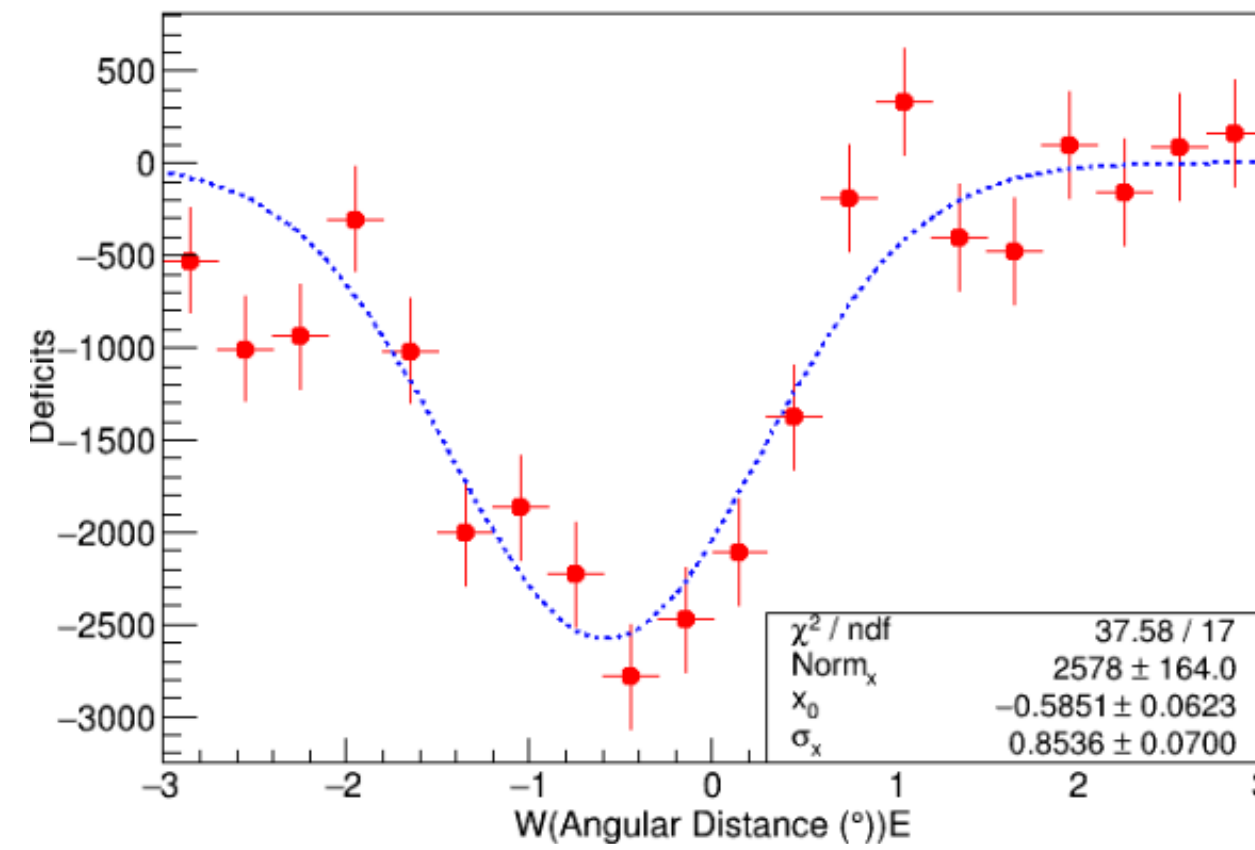
LHAASO observation  
2021.4

# Observation of Moon's Shadow

Significance Map



2021-4



# Observation of Sun Shadow

## Significance Map of CR2243 (27 days)

