



Transient Large-Scale Anisotropy in TeV Cosmic Rays due to an Interplanetary Coronal Mass

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[\[arxiv:2601.02801\]](https://arxiv.org/abs/2601.02801)

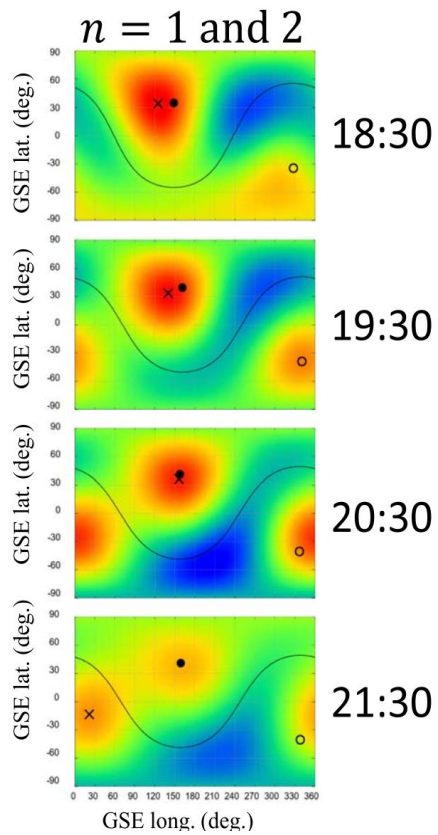
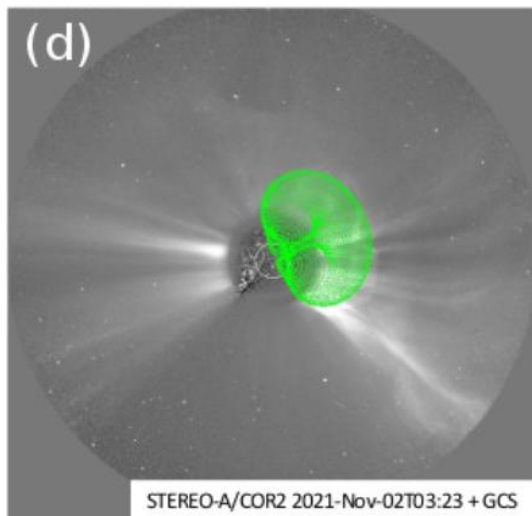
Motivation



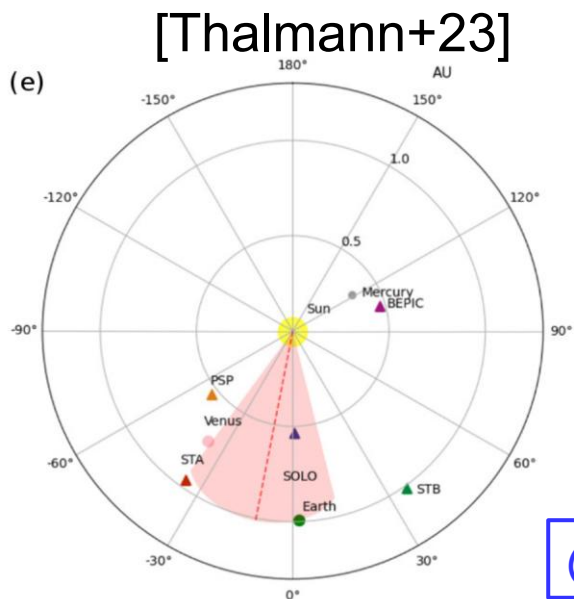
- **Forbush decreases (FD)** in GCR flux has been observed using an underground muon detector at Sakashita (median rigidity **331 GV**; Sakakibara et al. 1979)
- **Precursory anisotropy** before arrival of an interplanetary shock & FD in Misato underground muon detector (median rigidity **145 GV**; Munakata et al. 2000):
 - ✓ Pitch-angle distribution due to loss cone effect (Ruffolo 1999), prospect for advance warning of space weather effects
- **Solar cycle variation** of diurnal anisotropy was reported in underground muon data up to median energy **~600 GeV** (Munakata et al. 2010)

Transient effects on large-scale cosmic ray anisotropy have never been observed above **~150 GeV**

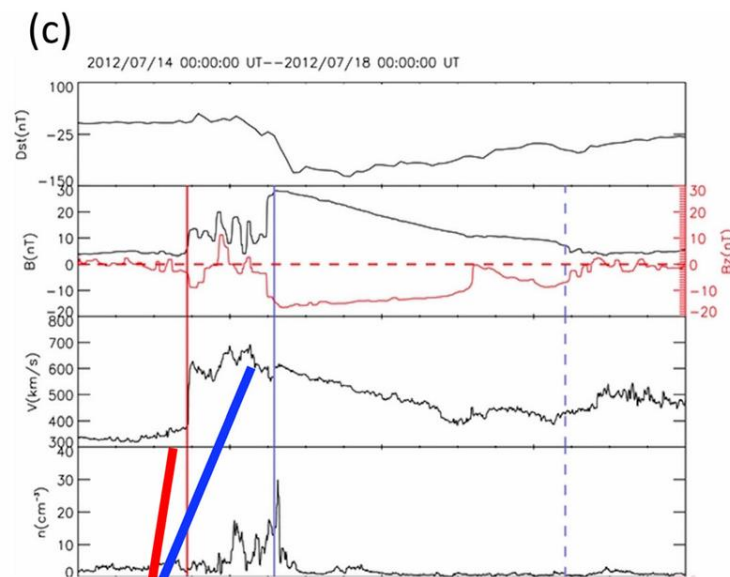
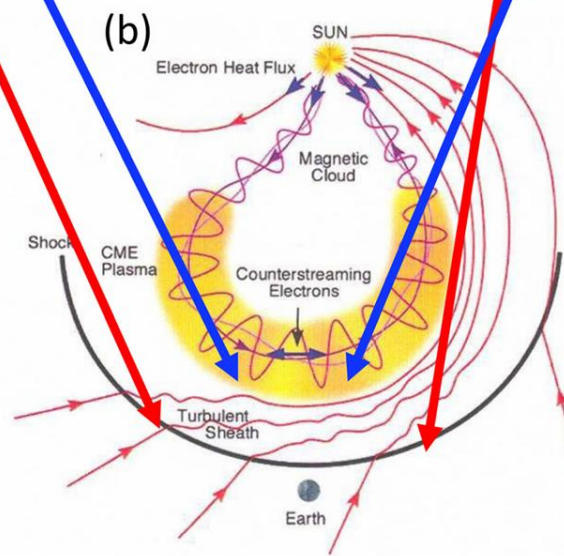
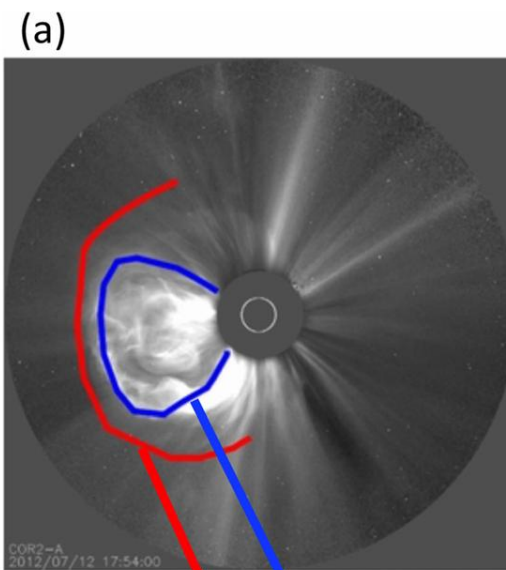
Motivation



[Munakata+22]

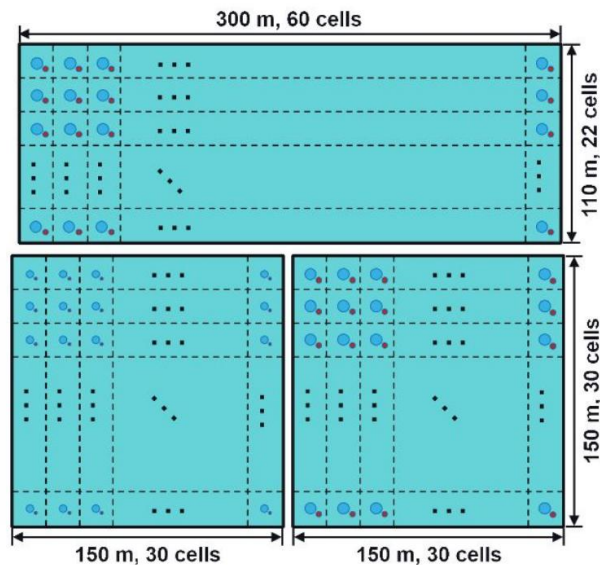
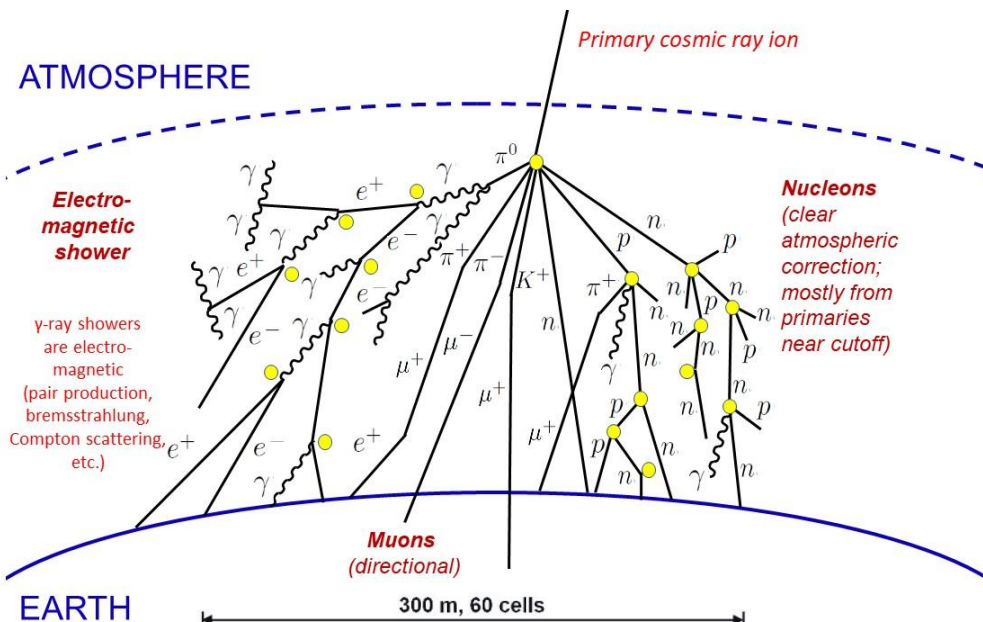
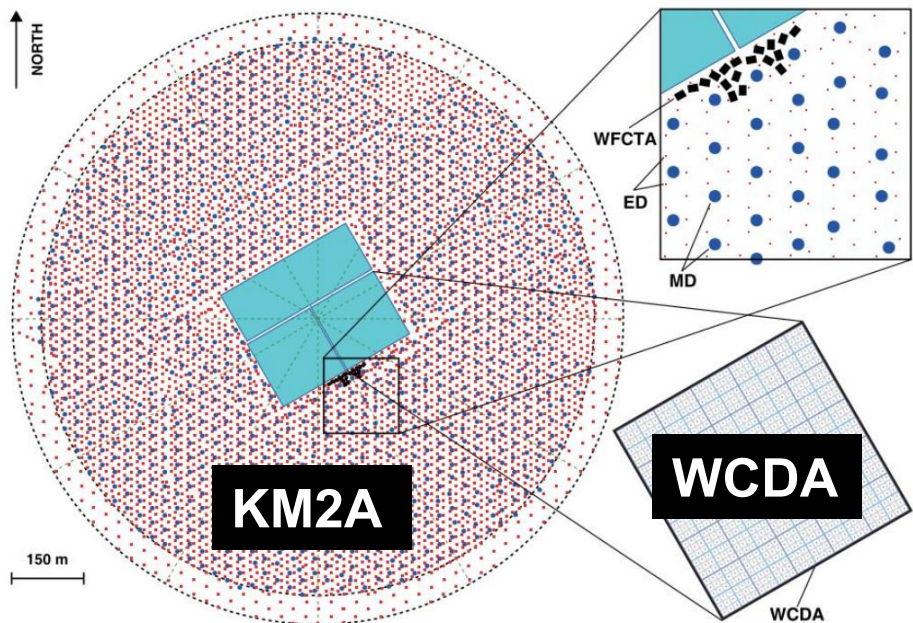


@ 15 GV, 2021 Nov 4



Zhang et al. Progress in Earth and Planetary Science, 2021

Data

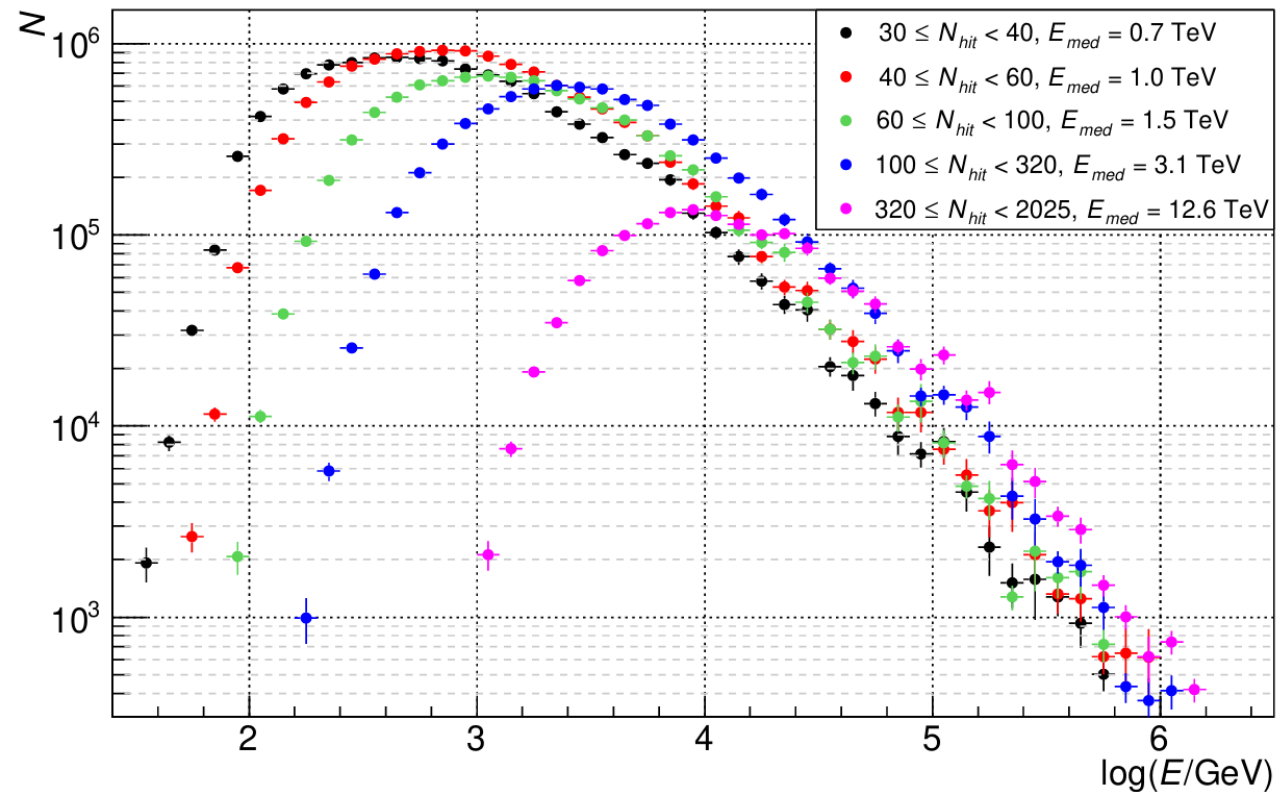


利用LHAASO-WCDA数据，探测TeV宇宙射线。

Data



- 排除事例数目异常的小时（每小时 $1e8$ 到 $1.2e8$ 个事例）。
- 天顶角 $< 45^\circ$ ，LHAASO-WCDA中5个能段：
 - $30 < n_{hit} < 40$ ：中值能量 0.7TeV 。
 - $40 < n_{hit} < 60$ ：中值能量 1.0TeV 。
 - $60 < n_{hit} < 100$ ：中值能量 1.5TeV 。
 - $100 < n_{hit} < 320$ ：中值能量 3.1TeV 。
 - $320 < n_{hit} < 2025$ ：中值能量 12.6TeV 。



Method



- 将每小时的强度天图以相同立体角进行划分。

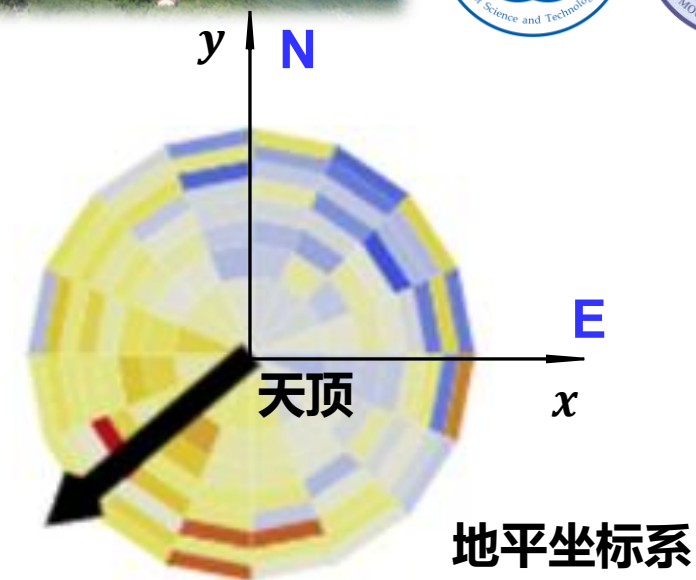
day:	1	2	3	4	5
	off	off	on	off	off

- $I_{t,\theta,\varphi} = \frac{N_{t,\theta,\varphi}^{on}}{\frac{1}{4} \sum_{day \neq 3} N_{t,\theta,\varphi}^{off}}$: 初始的每小时天图值。

- $I_{t,\theta,\varphi}^{Final} = \frac{I_{t,\theta,\varphi}}{\sum_{\varphi} I_{t,\theta,\varphi}}$: 对天顶角环带做归一化

- 定义梯度值 g : 指向相对强度更大的方向 (黑色箭头)

$$\begin{cases} x_i = \sin\theta_i \cos\varphi_i \\ y_i = \sin\theta_i \sin\varphi_i \end{cases} \quad \begin{aligned} &\text{目标函数: } f = 1 + g_x x_i + g_y y_i \\ &\text{最小化: } \chi^2 = \sum_{i=1}^n \frac{[I_i - (1 + g_x x_i + g_y y_i)]^2}{\sigma^2(I_i)} \end{aligned}$$



t : hour

θ : zenith angle

φ : azimuth angle

x : eastward

y : northward

Method



- 定义显著性 S .

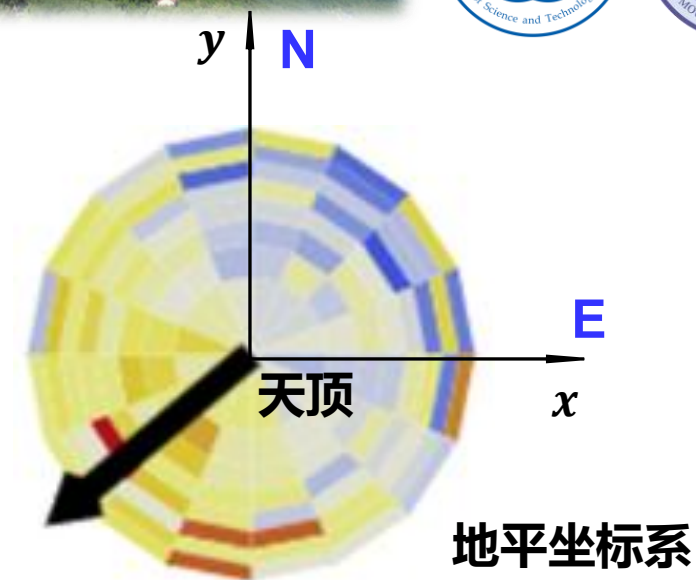
g_x, g_y : Gaus distribution $\rightarrow S_{g_x} = \frac{g_x}{\sigma_{g_x}}, S_{g_y} = \frac{g_y}{\sigma_{g_y}}$

$$g = \sqrt{g_x^2 + g_y^2}$$

g : Rayleigh distribution

$$P(g) = \frac{g}{\sigma_g^2} e^{-g^2/(2\sigma_g^2)}$$

$\rightarrow S_g$ 为标准正态分布中的显著性值，它与梯度值 g 在瑞利分布下的显著性等价，即两者具有相同的 p 值。



t : hour

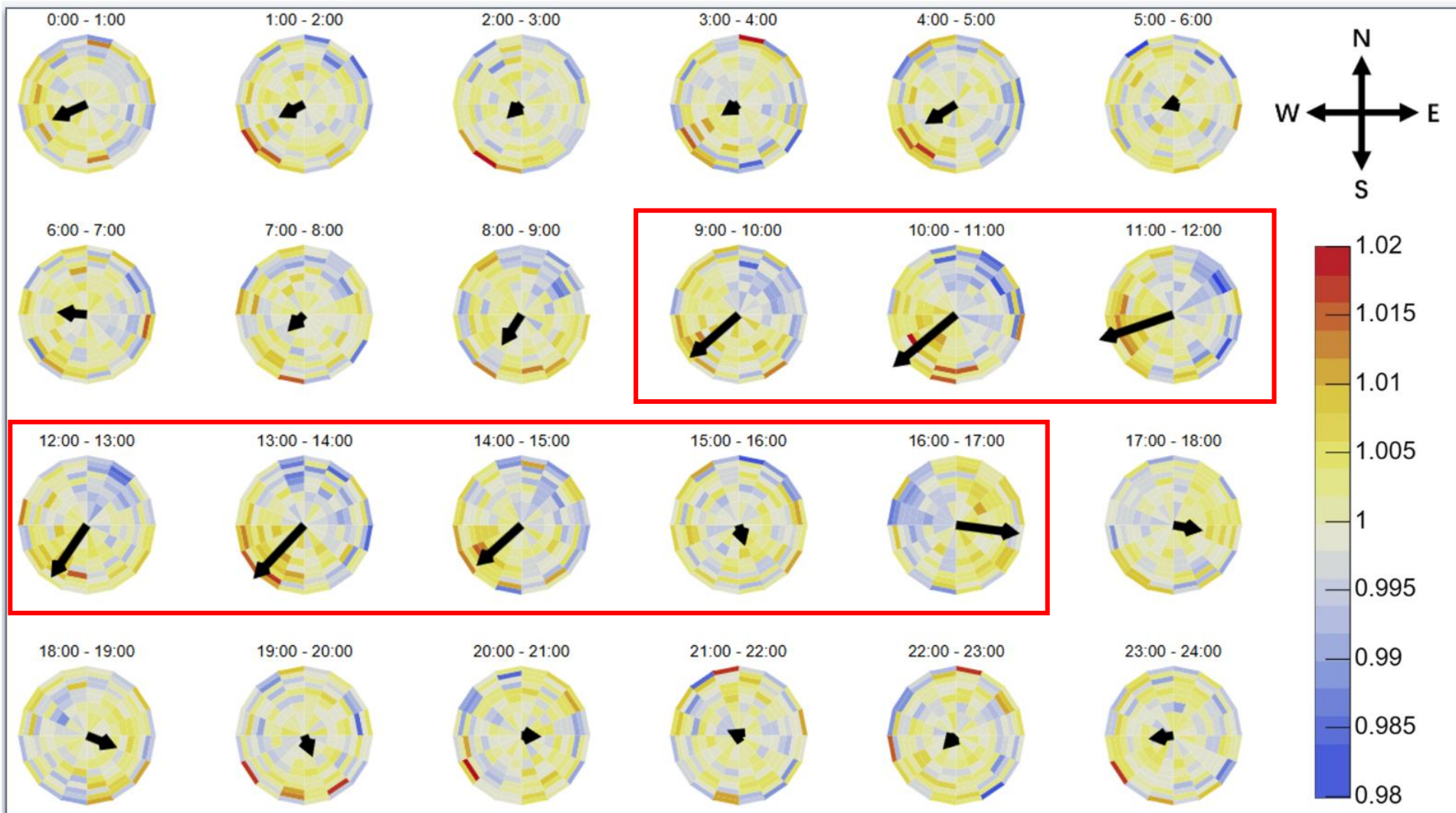
θ : zenith angle

φ : azimuth angle

x : eastward

y : northward

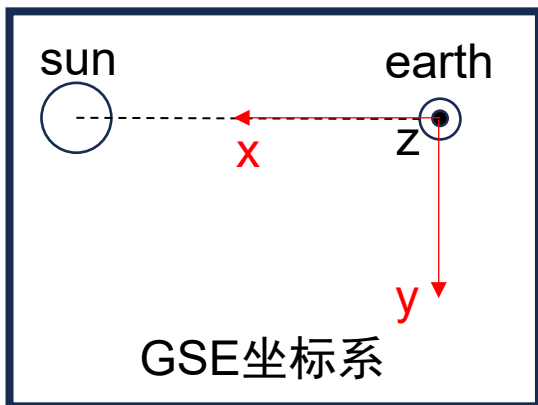
ICME 20211104 事件分析



在2021.11.4的ICME发生期间，梯度值有明显的变化，WCDA看到了明显的各向异性。

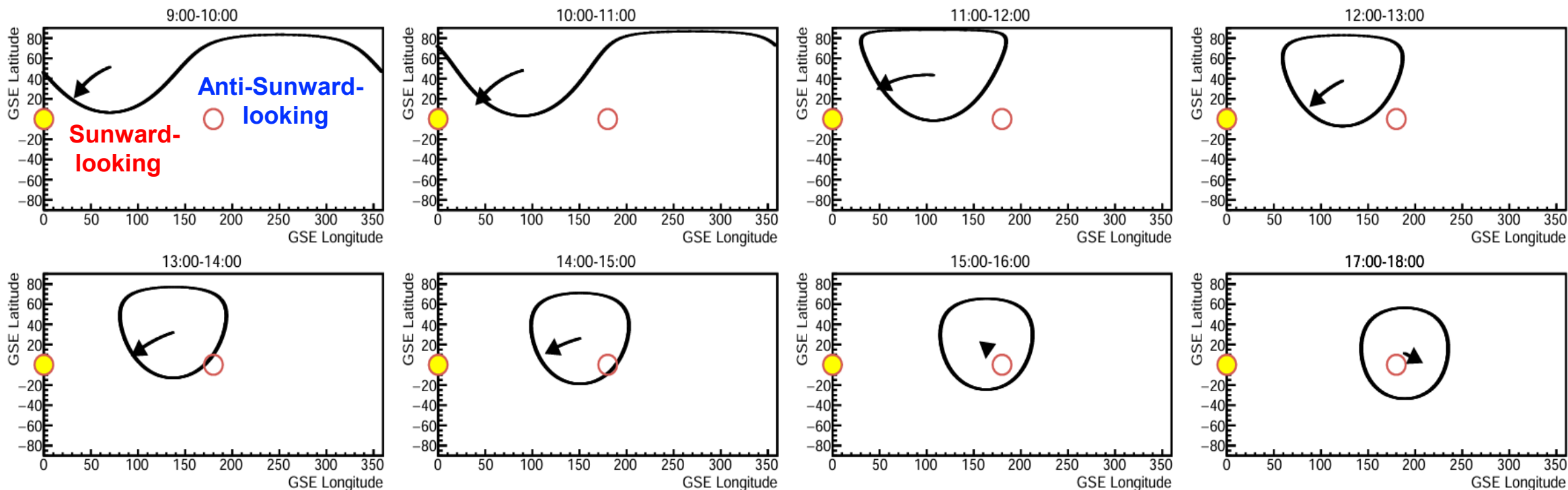
$30 < N_{hit} < 40$, 中值能量0.7TeV

ICME 20211104 事件分析



GSE坐标系下的梯度显示，在行星际激波到达后，在更接近朝向太阳的观测方向上，宇宙射线的通量更高。

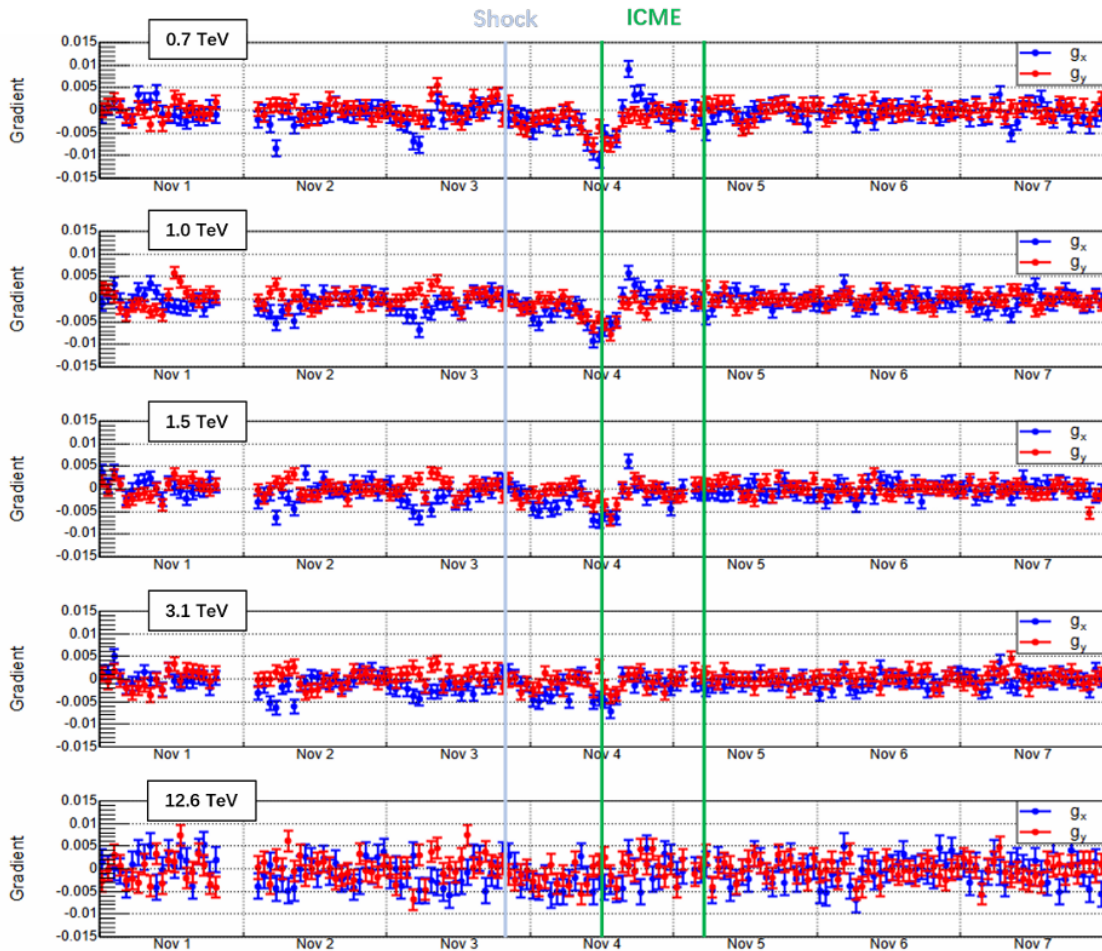
30<Nhit<40, 中值能量0.7TeV



ICME 20211104 事件分析

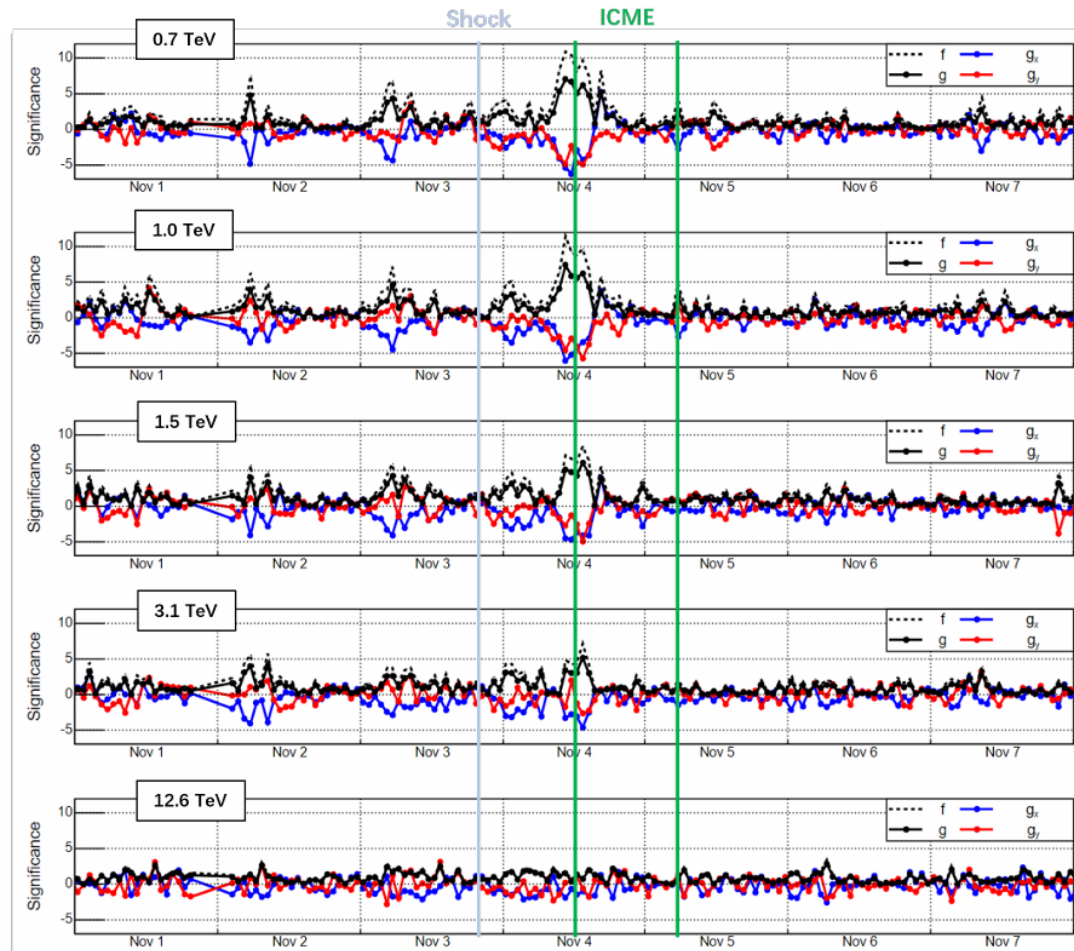


Gradient



g_x -> Eastward
 g_y -> Northward
 g -> Magnitude

Significance



f is obtained by a formal fitting uncertainty σ_f
 g is obtained by an empirical uncertainty σ_g .

有四个能段超过 5σ

幂律拟合



- 显著性最大的小时10:00 – 11:00
作幂律拟合 αE^γ
- $\alpha = 0.010 \pm 0.001$
- $\gamma = -0.526 \pm 0.125$

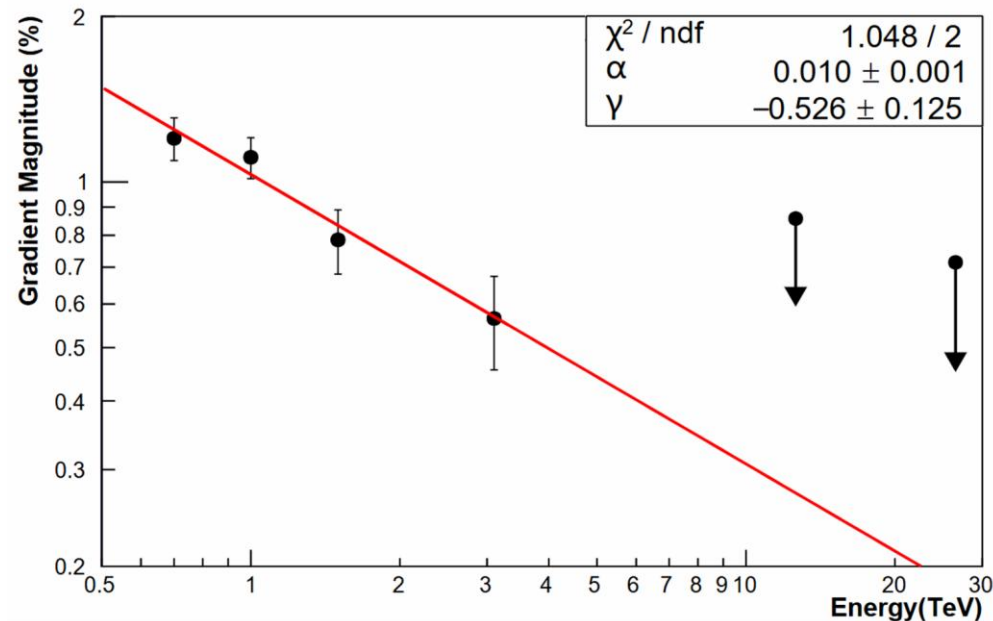


TABLE I. Detection of transient large-scale CR anisotropy on November 4, 2021.

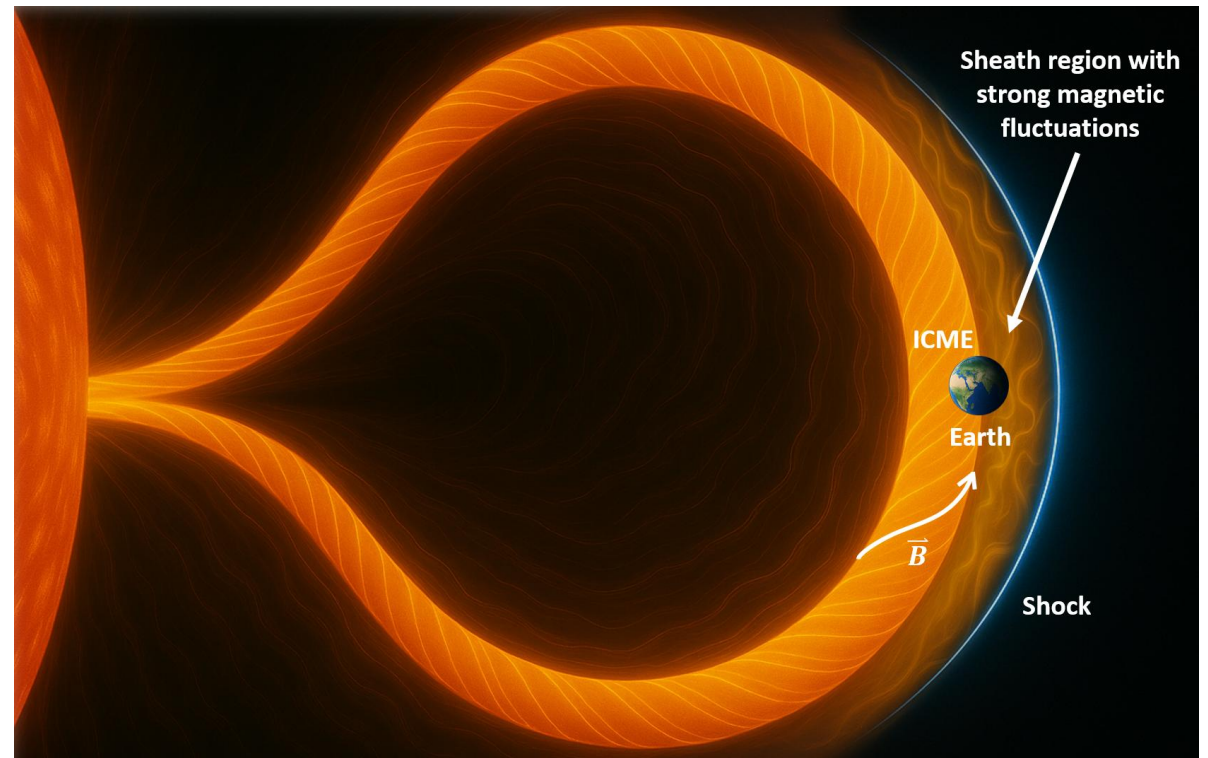
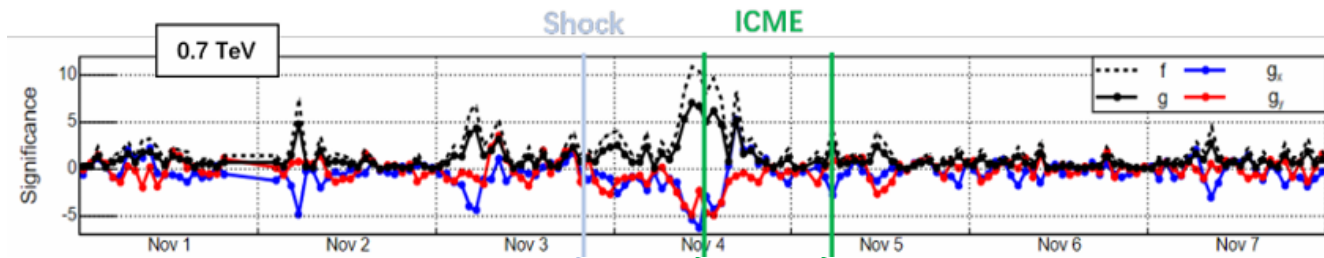
Detector	N_{hit} or N_{fitE} range	Median primary CR energy (TeV)	Time (UT)	Gradient magnitude, g (%)	Formal significance (σ)	Normalized significance (σ)	Chance probability, p	Time of max. significance?
WCDA	[30, 40)	0.7	<u>10:00 - 11:00</u>	1.20	10.98	7.06	1.67e-12	✓
	[40, 60)	1.0	<u>10:00 - 11:00</u>	1.11	11.46	7.42	1.17e-13	✓
	[60, 100)	1.5	<u>10:00 - 11:00</u>	0.78	7.17	5.11	3.22e-07	
	[60, 100)	1.5	13:00 - 14:00	0.92	8.48	6.08	1.20e-09	✓
	[100, 320)	3.1	<u>10:00 - 11:00</u>	0.56	4.80	3.41	6.50e-04	
	[100, 320)	3.1	13:00 - 14:00	0.81	7.11	5.14	2.75e-07	✓
	[320, 2025)	12.6	<u>10:00 - 11:00</u>	0.52	1.84	1.53	1.26e-01	
	[320, 2025)	12.6	14:00 - 15:00	0.63	2.35	1.98	4.77e-02	✓
KM2A	(10, +∞)	26.5	<u>10:00 - 11:00</u>	0.51	3.44	2.55	1.08e-02	
	(10, +∞)	26.5	14:00 - 15:00	0.65	4.56	3.42	6.26e-04	✓

Discussion

- Liouville 定理：静态、光滑的磁场不能产生或增强宇宙线各向异性 (<1%)。
- 运动中的 ICME 磁场会产生运动电场，对宇宙线做功，从而产生微弱的偶极各向异性 (<0.3%)。
- 各向异性的增强可能源于 ICME 鞘层中较强的湍动磁场，使来自部分方向的 TeV 宇宙线受到更强散射，从而增强瞬态各向异性。



Significance



Summary



- 我们首次呈现了 **TeV** 能段中**瞬时大尺度各向异性变化**的证据，该现象出现在 **2021 年 11 月 4 日**一次 **ICME**（行星际日冕物质抛射）经过期间。
- 在 LHAASO-WCDA 的四个能段（中位能量分别为 **0.7、1.0、1.5 和 3.1 TeV**）中，我们在距离天顶 **45°** 范围内发现了具有显著性 (**$>5\sigma$**) 的瞬时天区梯度。
- 该天图梯度的振幅（若解释为偶极各向异性）大约对应于 **$(1\%)*(E/\text{TeV})^{(-0.53)}$** 。
- 观测到的结果显示：**来自太阳方向的宇宙线增多**（可能与鞘层法线方向一致）。
- 全球其它的广延空气簇射阵列在同一时刻观测天空的不同区域，若将各方数据结合，我们可以构建出**全球性的瞬时各向异性图像**。



Thanks !

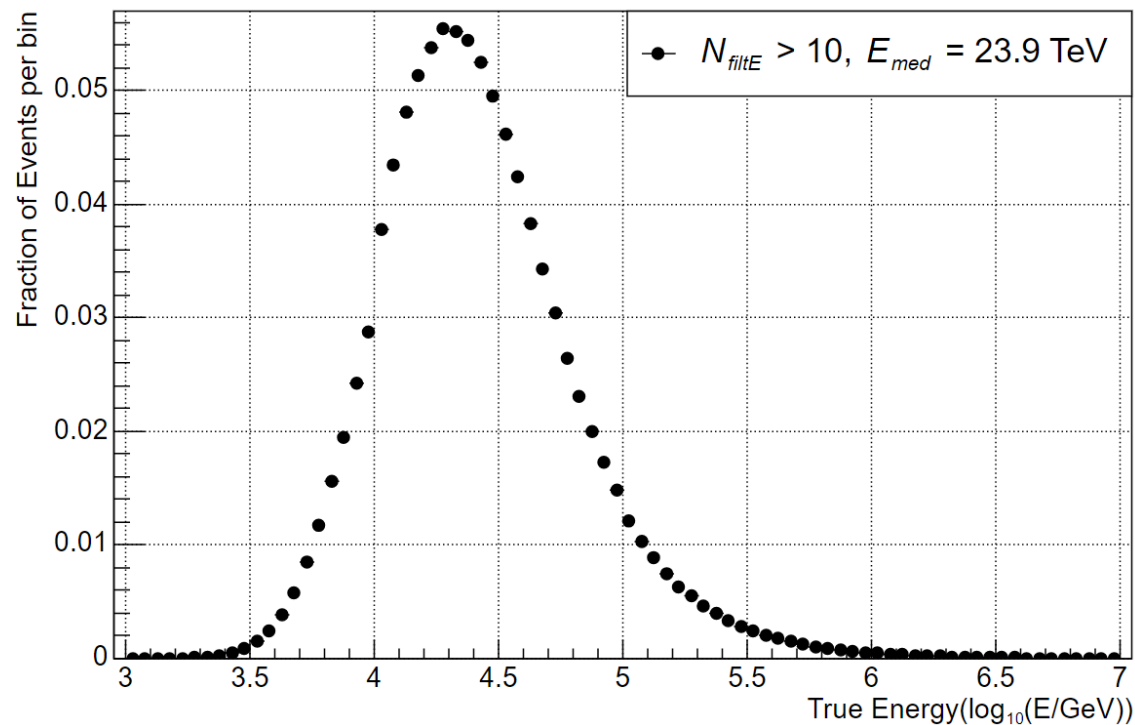


backup

KM2A: weak significance

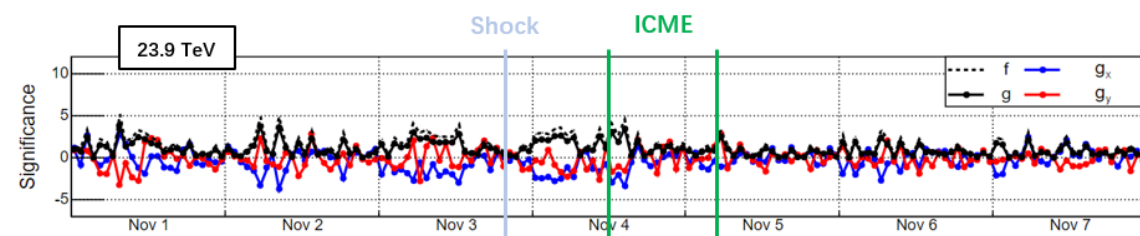
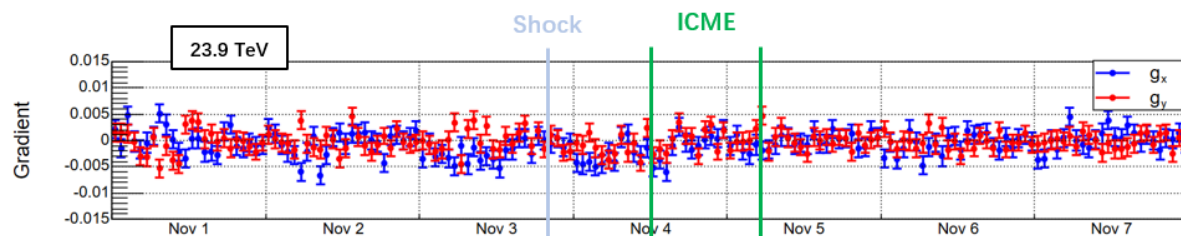


- 天顶角 $< 45^\circ$, KM2A中1个能段。



Blue: g_x Red: g_y

Significance of blue: g_x red: g_y black: g

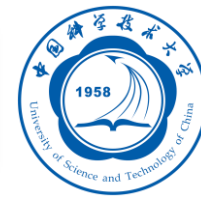


有关的ICME事件



Datatype	Disturbance Y/M/D (UT)	ICME Plasma/Field Start Y/M/D (UT)	ICME Plasma/Field End Y/M/D (UT)	Name	mjd	hour(0-23)	Maximum significance	Ebin	Angle_g&B	Angle_g&V
Mk	2021/11/03 1942	2021/11/04 0700	2021/11/05 0500	20211104	59522	10	6.8	0	95.9346	157.1885
	2022/02/09 2100	2022/02/10 1300	2022/02/11 1800	20220211	59621	13	6.2	3	79.5361	178.498
	2023/01/03 2100	2023/01/04 0200	2023/01/05 2200	20230104	59948	15	5.6	0	98.4931	117.0532
	2023/07/07 1200	2023/07/07 1200	2023/07/08 1500	20230707	60132	11	11.4	0	109.9195	36.9255
	2023/07/25 2233	2023/07/26 1700	2023/07/28 1100	20230726	60151	13	12.7	0	88.8103	158.4142
	2023/09/18 1331	2023/09/19 0800	2023/09/21 1000	20230920	60207	9	7.8	0	154.8394	151.7718
Cod	2024/10/08 0000	2024/10/08 0000	2024/10/08 1100	20241008	60591	6	6.68	0	0.2014	82.9257
	2024/10/10 1514	2024/10/10 2200	2024/10/12 0300	20241011	60594	9	5.8	2	16.9503	146.8833
	2024/10/12 0900	2024/10/12 1200	2024/10/14 1800	20241014	60597	10	5.4	1	114.8111	90.7721

How to calculate the upper limit ?



[O. HELENE. 1981]

$$\int_0^{g_{0.95}} G(g) dg = 0.95$$

$$G(g) = \prod_i \text{Poisson}(N_{on,i} | N_{s,i} + N_{off,i}) = \prod_i \frac{(N_{s,i} + N_{off,i})^{N_{on,i}}}{N_{on,i}!} e^{-(N_{s,i} + N_{off,i})}$$

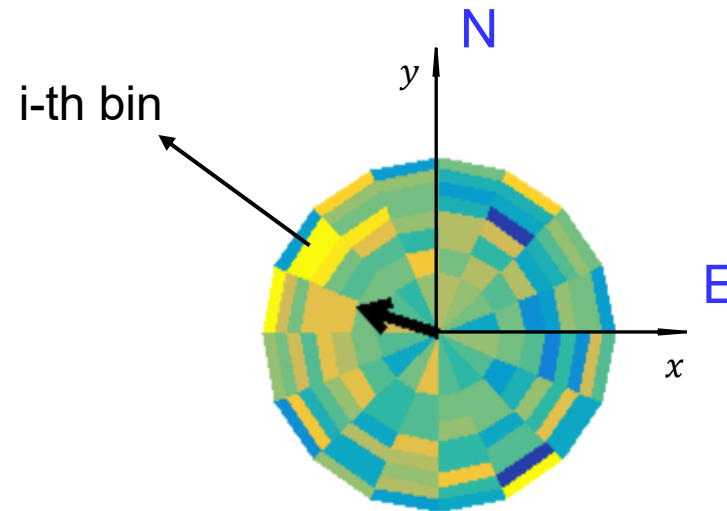
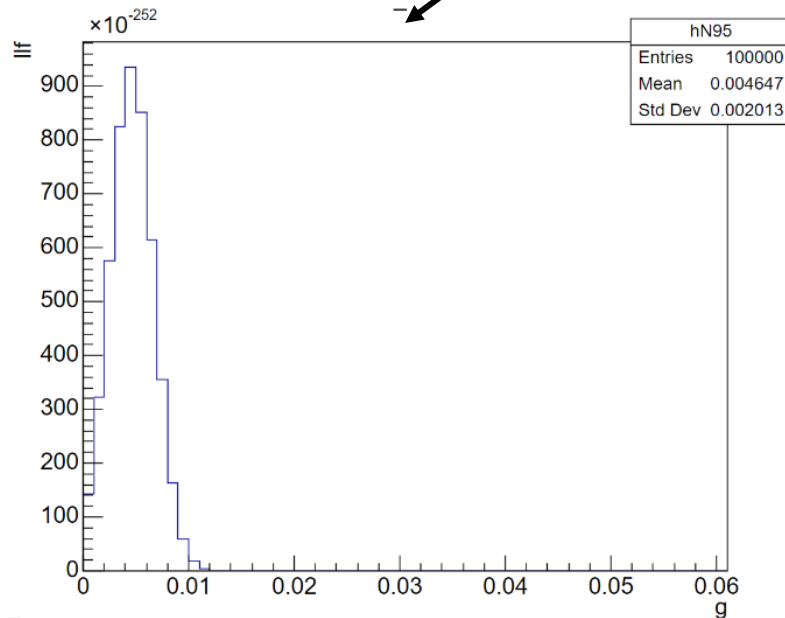
$$N_{s,i} = N_{s,i}(g)$$

We assume that the direction of signal is the result we obtained through fitting ($\phi = \arctan(\frac{g_y}{g_x})$)

We change the value of g to get the expected skymap (i.e. to get $N_{s,i}$).

So we can get the distribution of g vs $G(g)$

The position at the 0.95 quantile is $g_{0.95}$ (the uplimit)



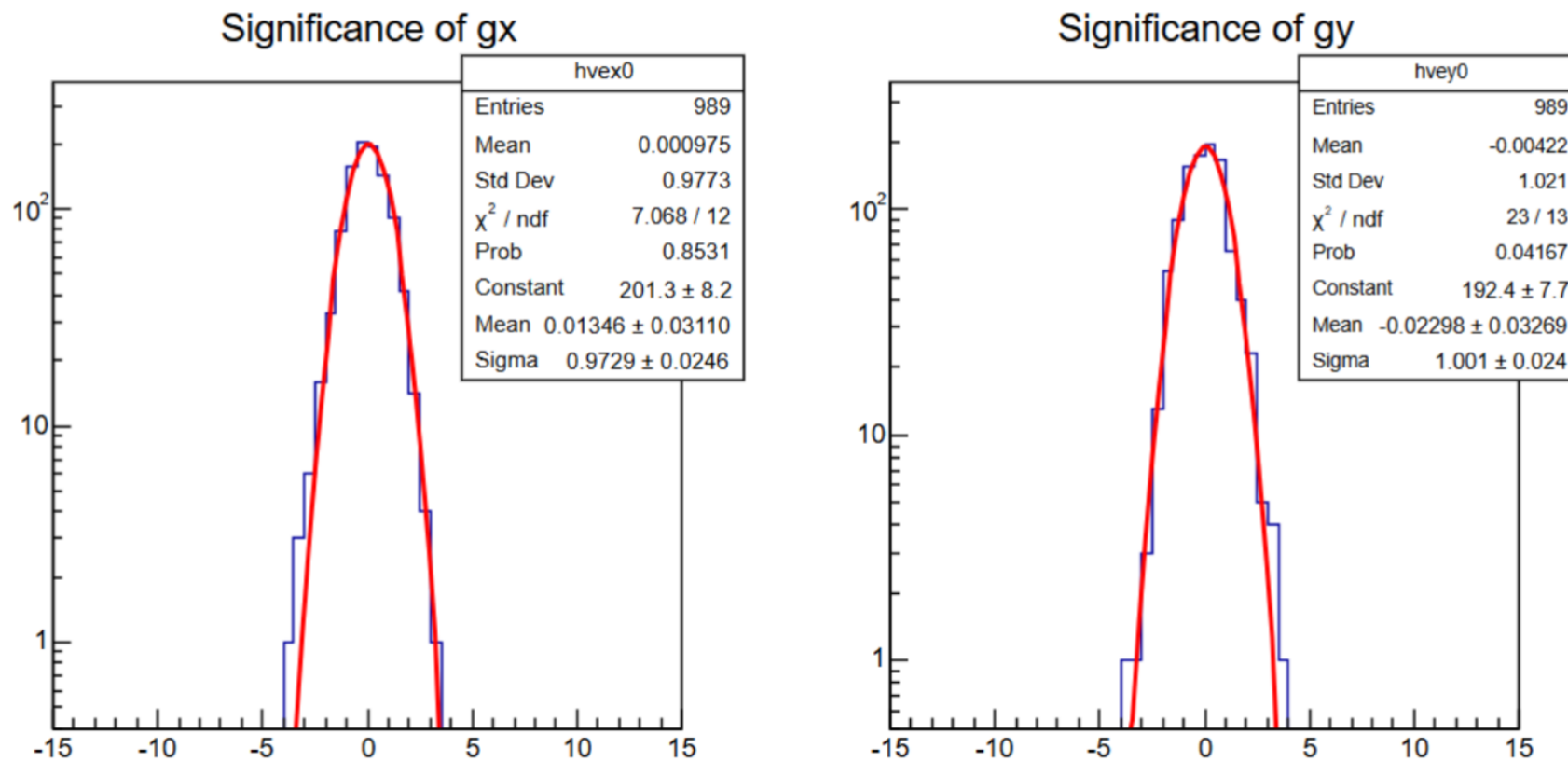


FIG. S3. Distributions of $S_x = g_x/\sigma_g$ and $S_y = g_y/\sigma_g$ for 45 days of quiet-time data, for WCDA data with $30 \leq N_{hit} < 40$, compared with Gaussian fits.

运动磁场产生各向异性



偶极各向异性幅度估算为：

$$\delta \sim \gamma \frac{qVBL}{E}$$

其中：

- γ : 谱指数
- q : 粒子电荷
- V : ICME 速度
- B : 磁场强度
- L : 磁场区域尺度
- E : 宇宙线能量

- $V \approx$ ICME 速度 (几百 km/s)
- $B \approx$ 磁场强度 (观测值)
- $L = 0.5$ AU (非常宽松的假设)
- 粒子: 1 TeV 质子 ($E = 10^{12}$ eV)

$$\delta < 0.3\%$$

湍流磁场偏转宇宙线



1. 提出机制

- 我们假设：ICME 鞘层中的小尺度湍流磁场会导致宇宙线的随机散射。
- 湍流幅度：约 **1 nT**
- 相干时间：约 **10 分钟**

2. 单步偏转角

- 在一个相干尺度内，宇宙线的偏转角约为：

$$\Delta\theta \approx 0.67 \text{ mrad} = 0.038^\circ$$

3. 累积随机游走

- 总持续时间：**14 小时**
- 相干块数： $\frac{14 \text{ h}}{10 \text{ min}} \approx 84$
- 随机游走放大因子： $\sqrt{84} \approx 9$
- 总偏转角：

$$\theta_{\text{rms}} \approx 9 \times 0.67 \text{ mrad} \approx 0.006 \text{ rad}$$

4. 各向异性估算

- 如果不同方向的散射强度在约 **0.6 rad** 的天空范围内有差异，
- 则可能产生约 **1% 量级的瞬态各向异性**。

How to calculate significance ?



For a specified hour bin t , in the case there is no real anisotropy, then the statistical fluctuations of g_x and g_y generally follow **Gaussian distributions** with a mean of 0 and statistical uncertainty σ_x .

The **significance** of g_x and g_y is defined as follows:

$$S_{g_x} = \frac{g_x}{\sigma_g},$$
$$S_{g_y} = \frac{g_y}{\sigma_g}.$$

Given that g_x and g_y can be expressed as

$$g_x = g \sin \phi,$$
$$g_y = g \cos \phi,$$

the probability density function (PDF) of the gradient magnitude for a given hour t is derived as:

$$P(g) = \frac{g}{\sigma_g^2} e^{-g^2/(2\sigma_g^2)}.$$

Using this Rayleigh distribution, the p – *value*, i.e., the chance probability of obtaining this gradient magnitude g , can be calculated given the statistical uncertainty σ_g .

We then calculate the significance value S_g that corresponds to a two-sided chance probability equal to p – *value* for a Gaussian distribution.