中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

中国科学院大学
University of Chinese Academy of Sciences

# 极目卫星对亚秒周期震荡粒子沉降高时间分辨率观测研究


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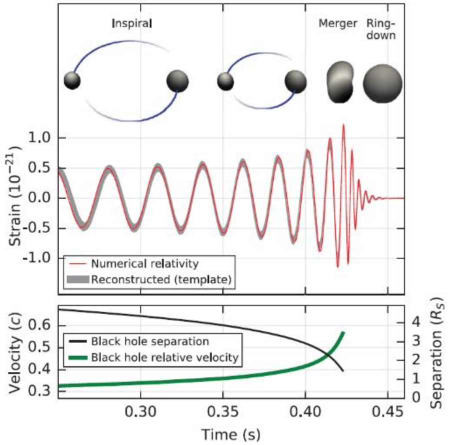
第十届青年地学论坛

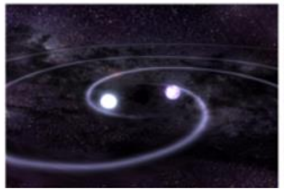
2025-05-11

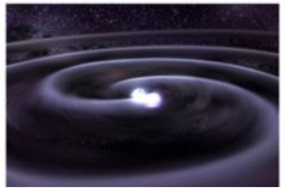
中国科学院粒子天体物理重点实验室
KEY LABORATORY OF PARTICLE ASTROPHYSICS, CAS

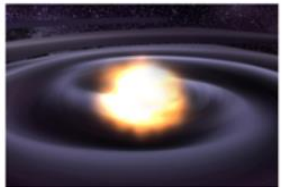
# GECAM项目简介

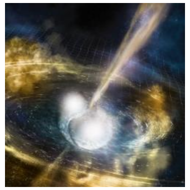


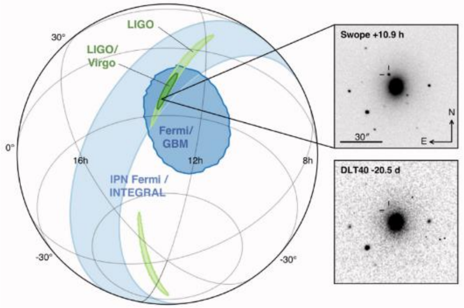

第一例引力波观测GW150914

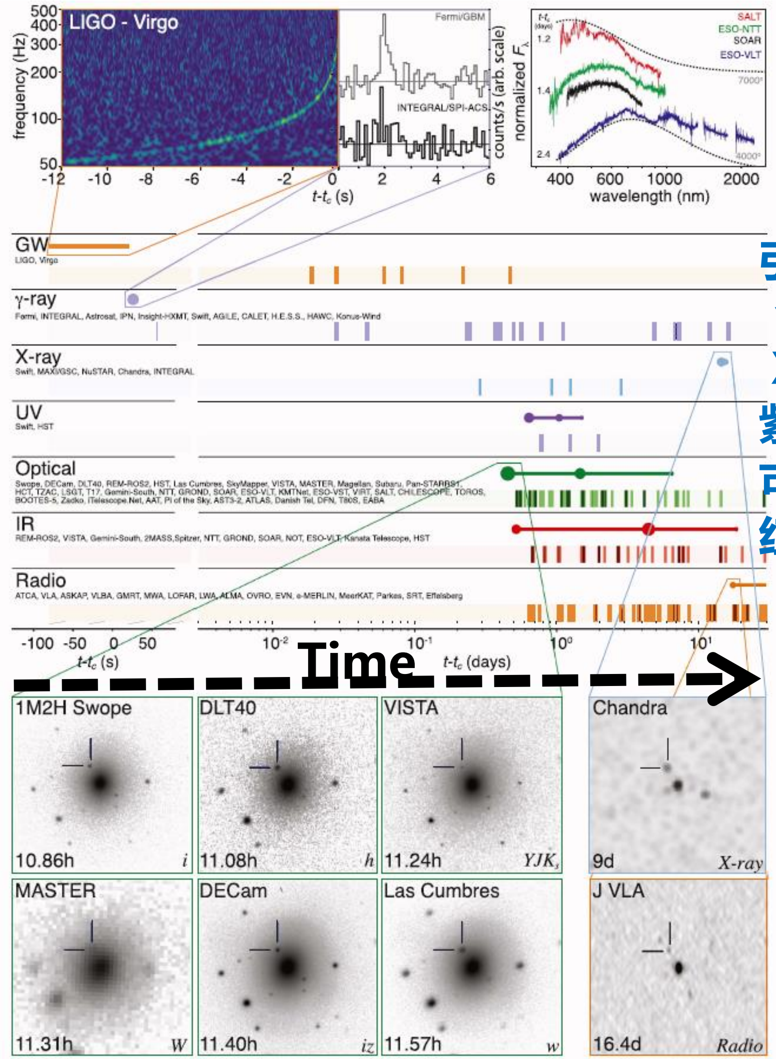








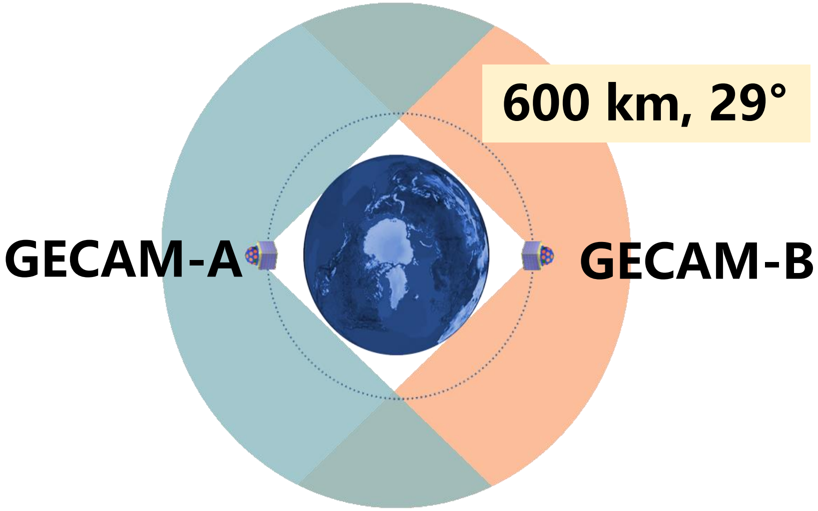

引力波
γ射线
X射线
紫外线
可见光
红外线
射电

第一例引力波电磁对应体 GW170817/GRB170817A

# 极目卫星——GECAM-A/B

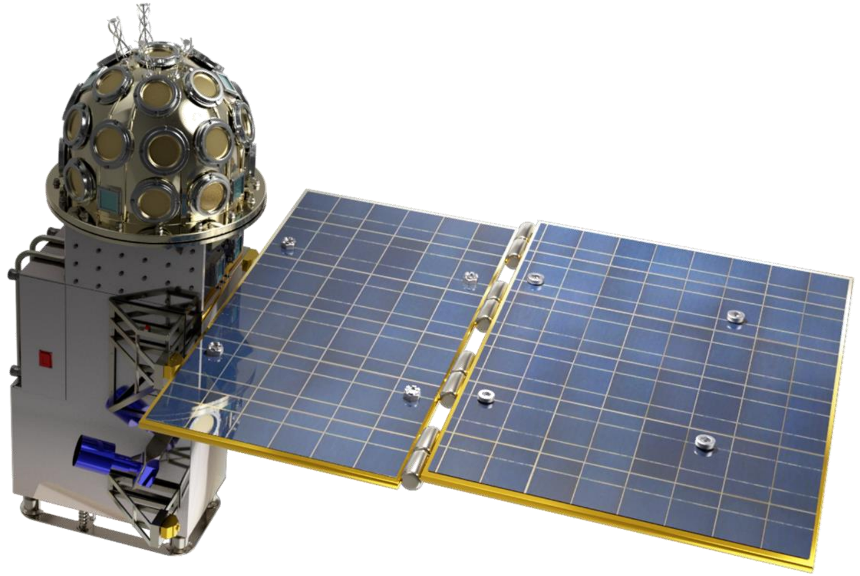
## 引力波暴高能电磁对应体全天监测器
## Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor

| 性能 | GECAM-A/B |
|---|---|
| 能量范围 | 6 keV ~ 5 MeV |
| 有效面积（单探头） | > 40 cm$^2$ |
| 时间分辨率 | 0.1 μs |
| 能量分辨率 | < 16%@59.5 keV |




**GECAM配备：**

- 25个伽马射线探测器 (GRD, 圆形)——X/γ射线灵敏
- 8个荷电粒子探测器 (CPD, 方形)——带电粒子(e, p)灵敏



**GECAM在空间环境探测方面具有巨大优势：**

1. 多星快速重访
2. 宽能段、高时间分辨率（0.1μs）
3. 大视场、多指向

# GECAM科学目标

**高能天体物理**

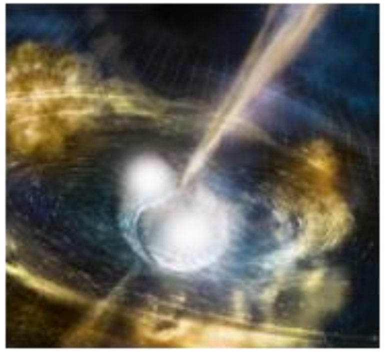
- 引力波/快速射电暴/高能中微子的高能电磁对应体
- 伽马射线暴
- 磁星
- X射线双星
- 黑洞潮汐瓦解事件

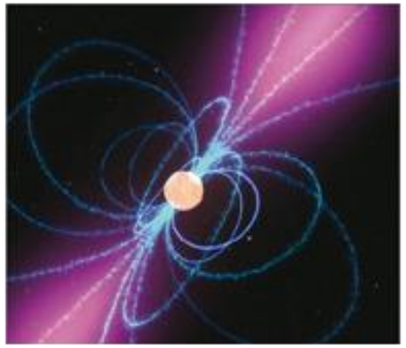
**太阳物理**

- 太阳耀斑

**高能大气物理**

- 地球伽马闪
- 地球电子束

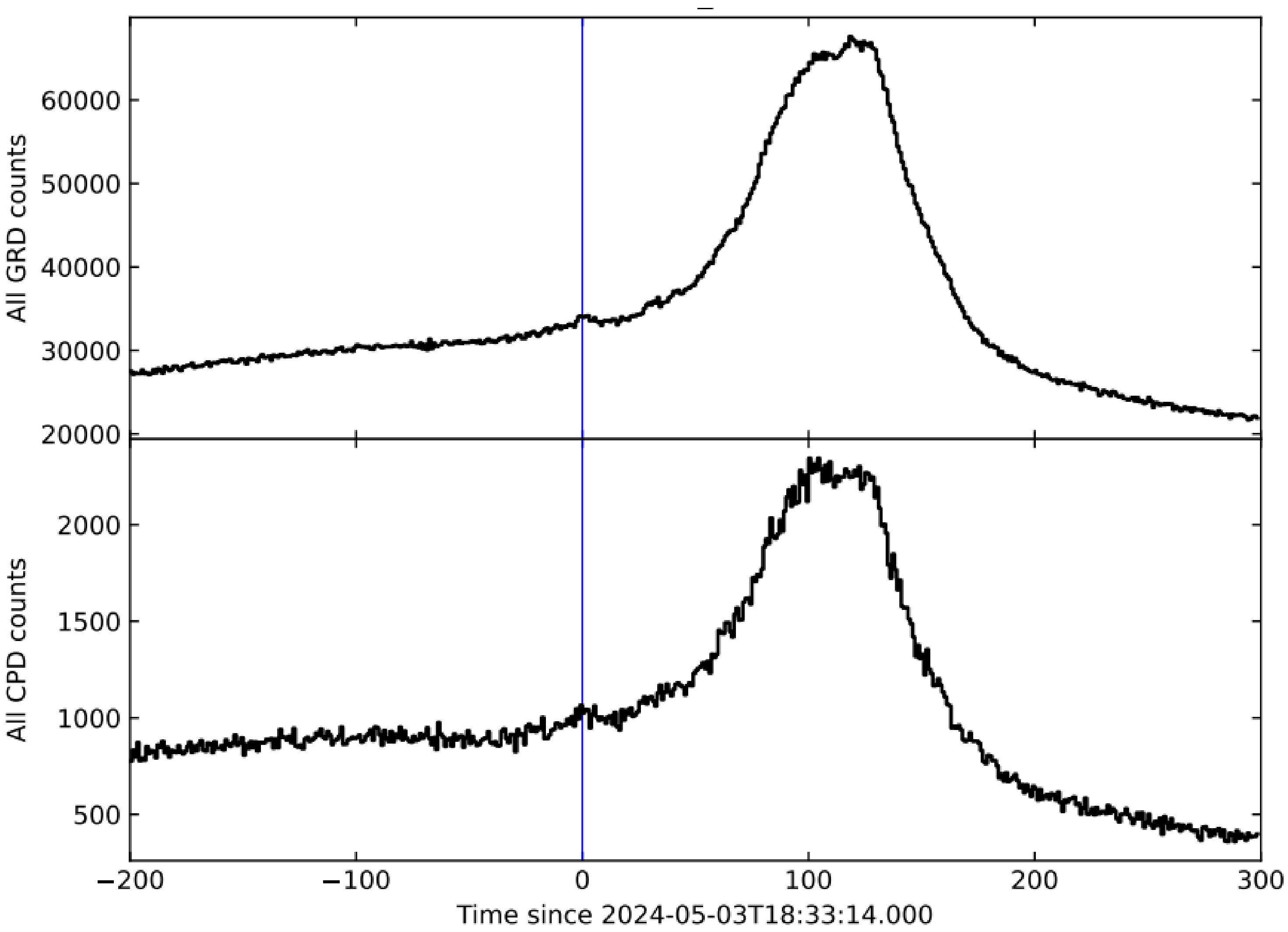




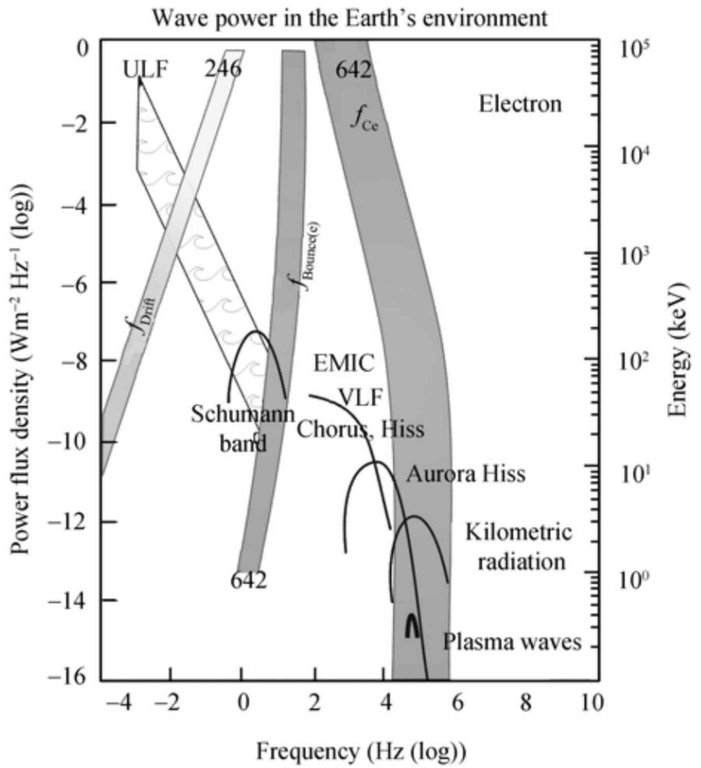




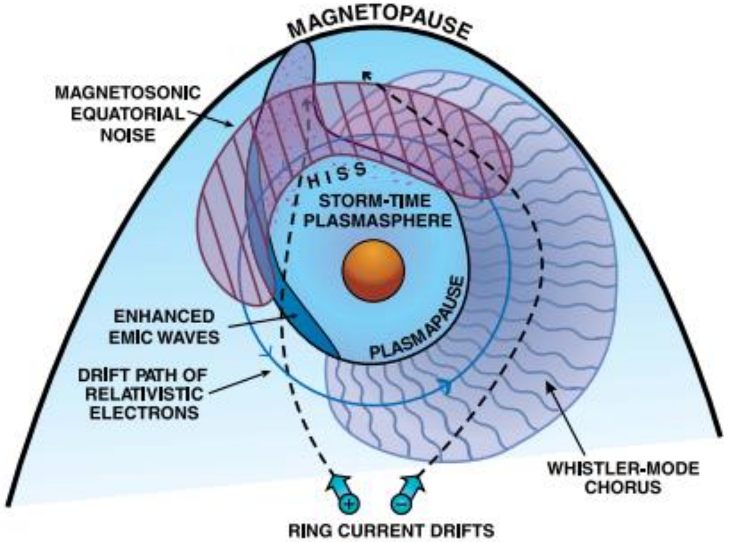
# 粒子沉降事件




粒子沉降通常表现为光滑的缓变鼓包状

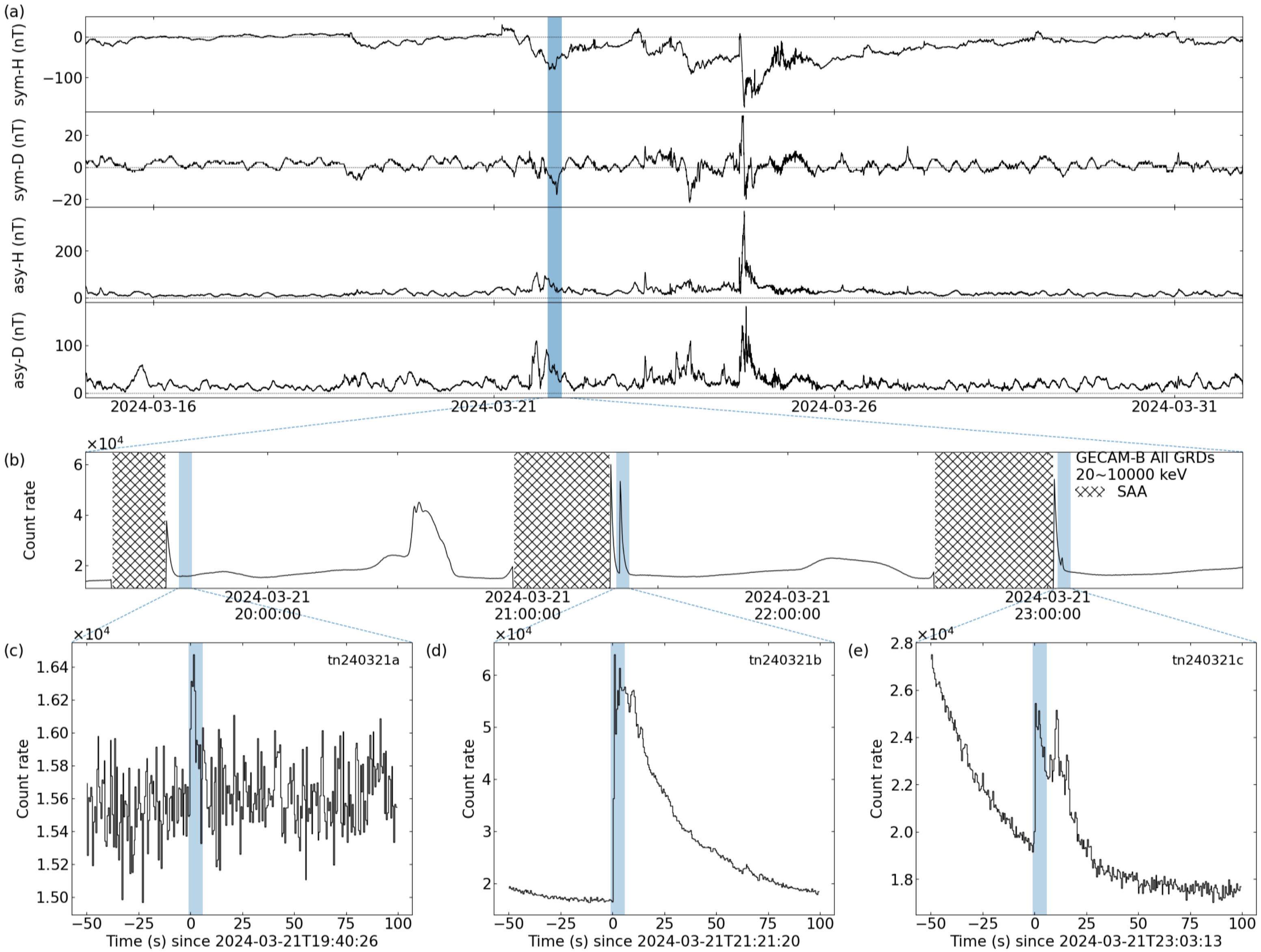



Zong et al., 2008



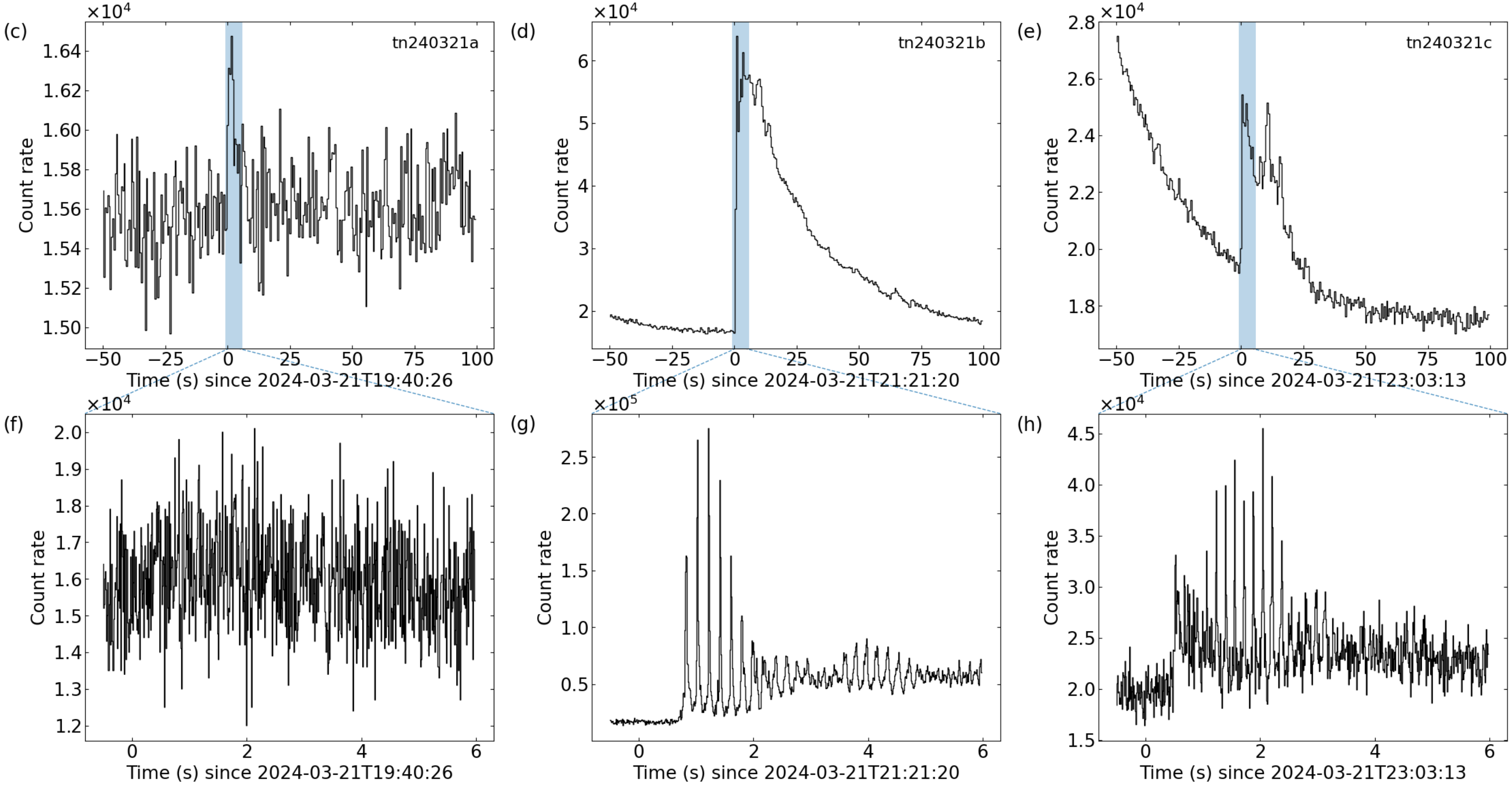

Thorne et al., 2010

# 亚秒周期震荡粒子沉降事件



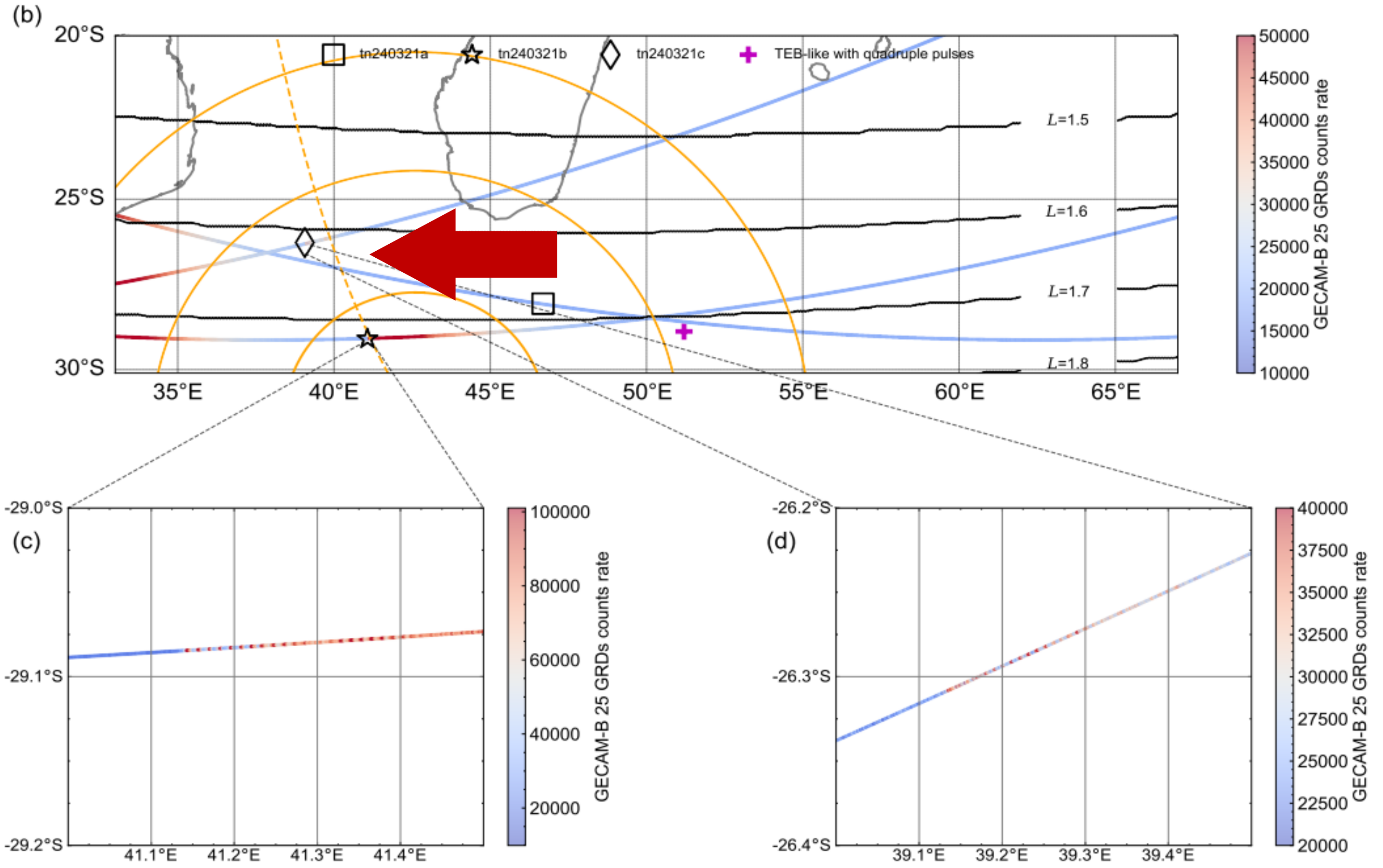

**在地磁暴期间连续三轨探测到具有快速上升的粒子沉降事件**

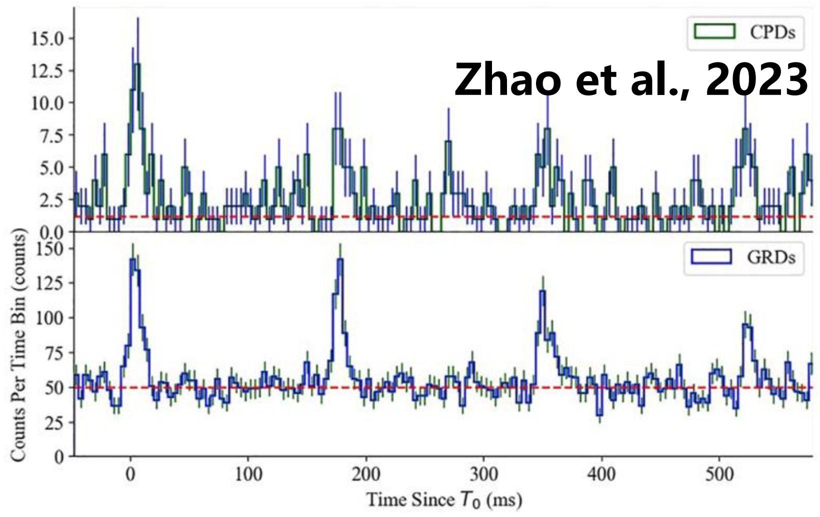
# 亚秒周期震荡粒子沉降事件




**高分辨率数据显示具有精细震荡结构**

# 亚秒周期震荡粒子沉降事件

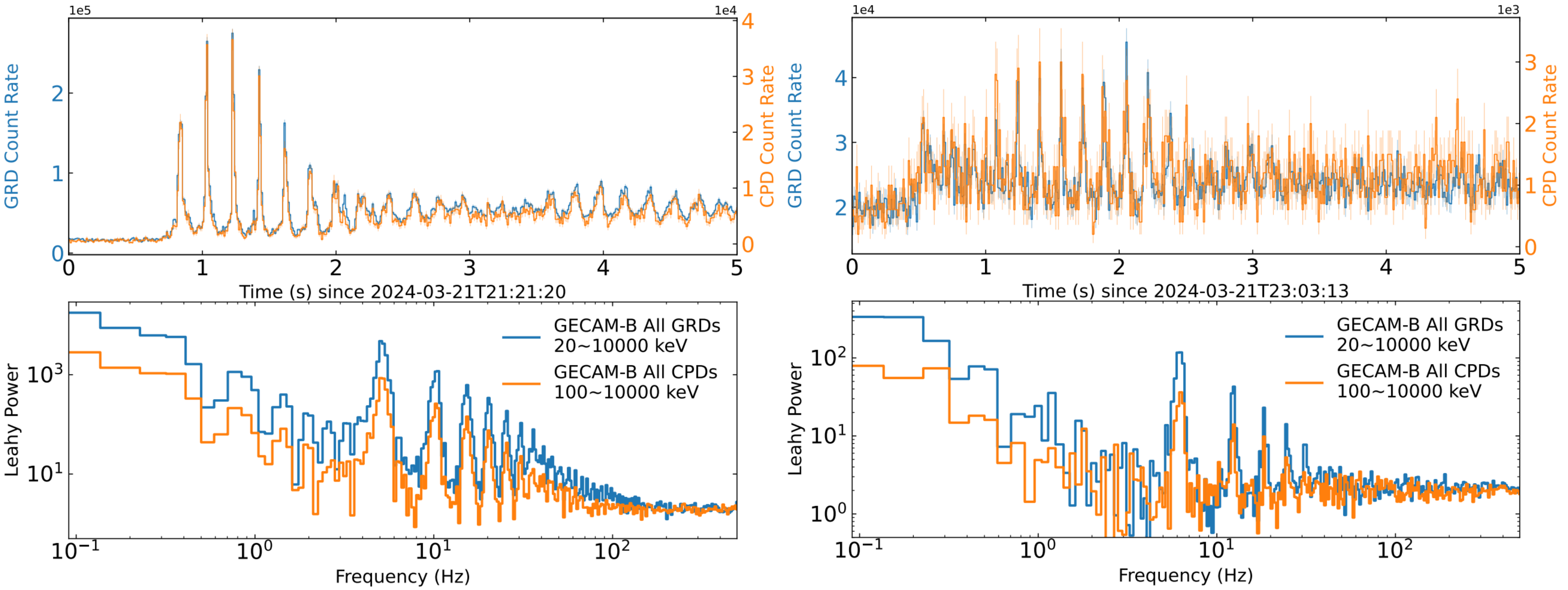



(c) TEB-like event UT 2021-09-11T18:34:40.552

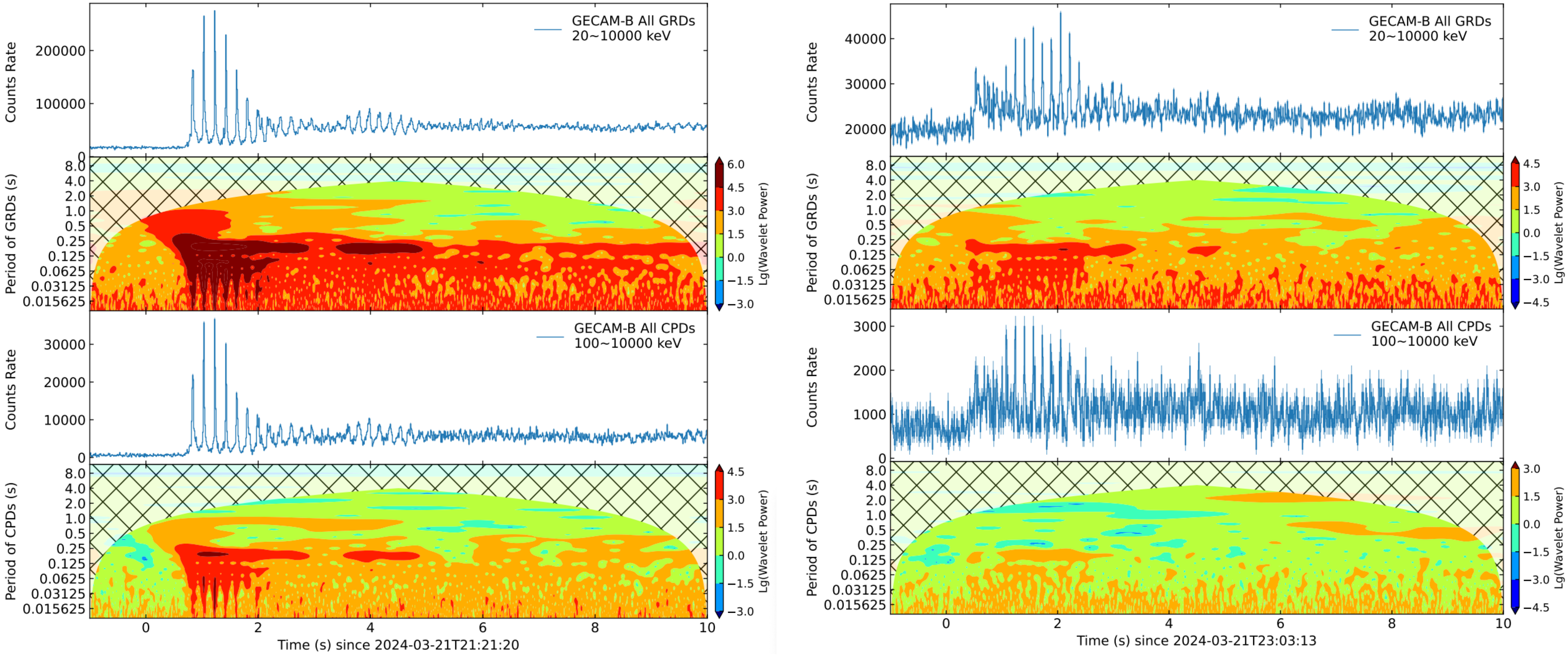
| | | | | Nadir of GECAM-B | | | Southern magnetic footprint[1] | | Northern magnetic footprint[1] | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | Trigger UTC Time | LST (hh:mm:ss) | SYM-H (nT) | Longitude (Deg) | Latitude (Deg) | Altitude (km) | Longitude (Deg) | Latitude (Deg) | Longitude (Deg) | Latitude (Deg) |
| tn240321a | 2024-03-21T19:40:26 | 22:40:26 | -78 | 46.66 | -28.09 | 597 | 48.52 | -30.49 | 42.05 | 43.26 |
| tn240321b | 2024-03-21T21:21:20 | 00:21:20 | -74 | 41.09 | -29.09 | 594 | 42.59 | -31.37 | 35.99 | 44.17 |
| tn240321c | 2024-03-21T23:03:13 | 02:03:13 | -53 | 39.10 | -26.32 | 597 | 40.42 | -28.74 | 35.34 | 42.06 |

# 亚秒周期震荡粒子沉降事件



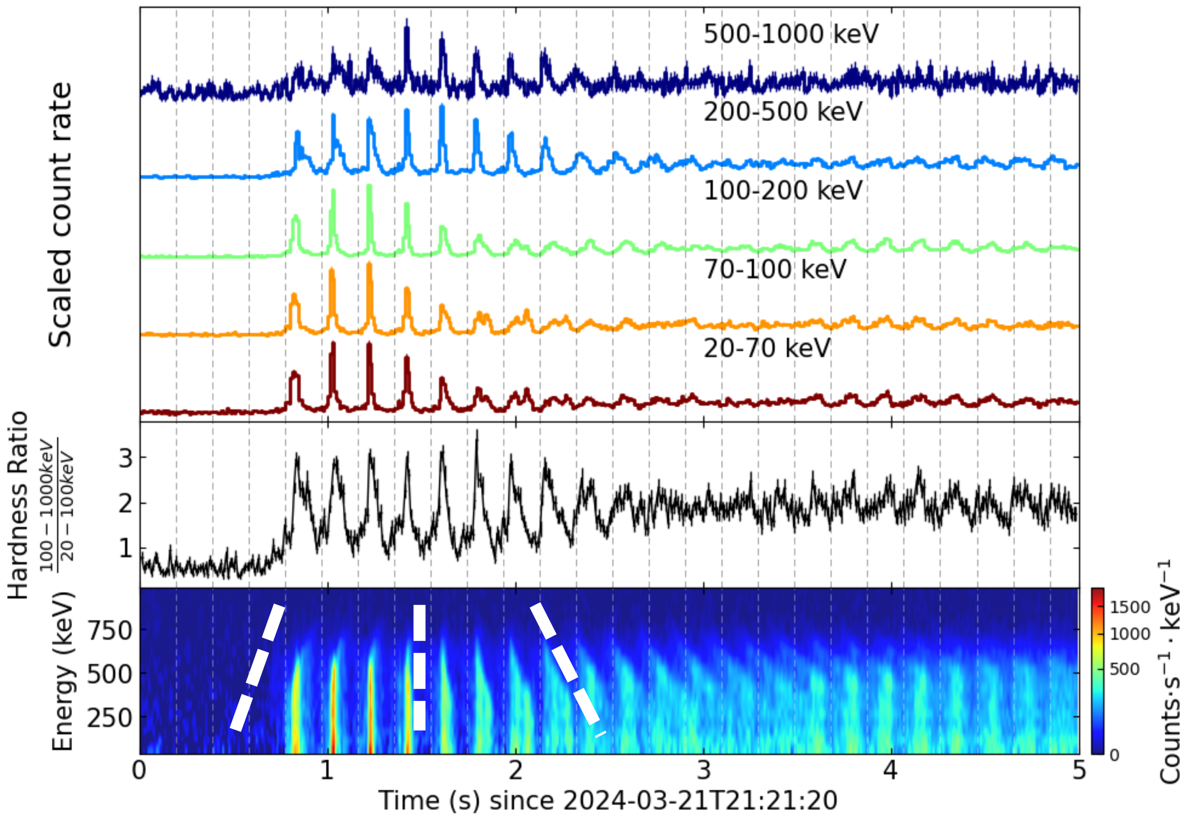

- 存在显著周期性且频率不同

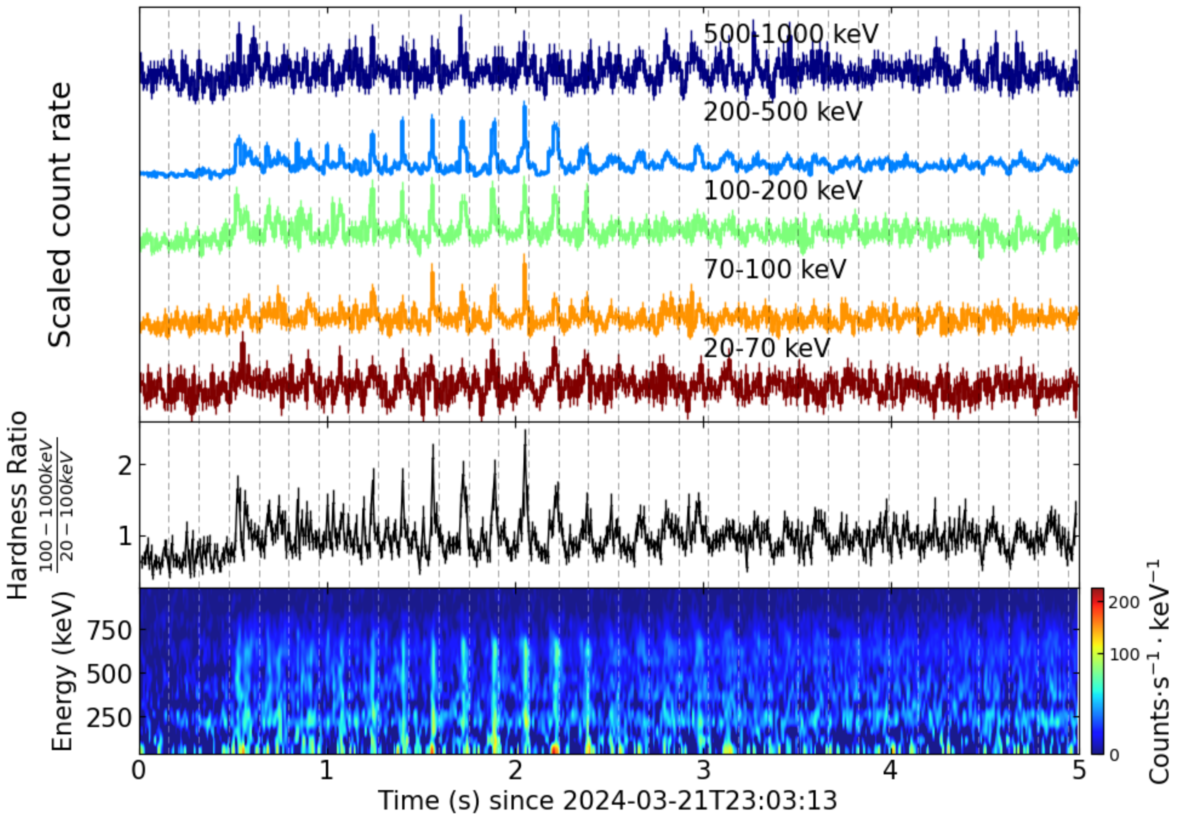
# 亚秒周期震荡粒子沉降事件




- 频率几乎不随强度演化

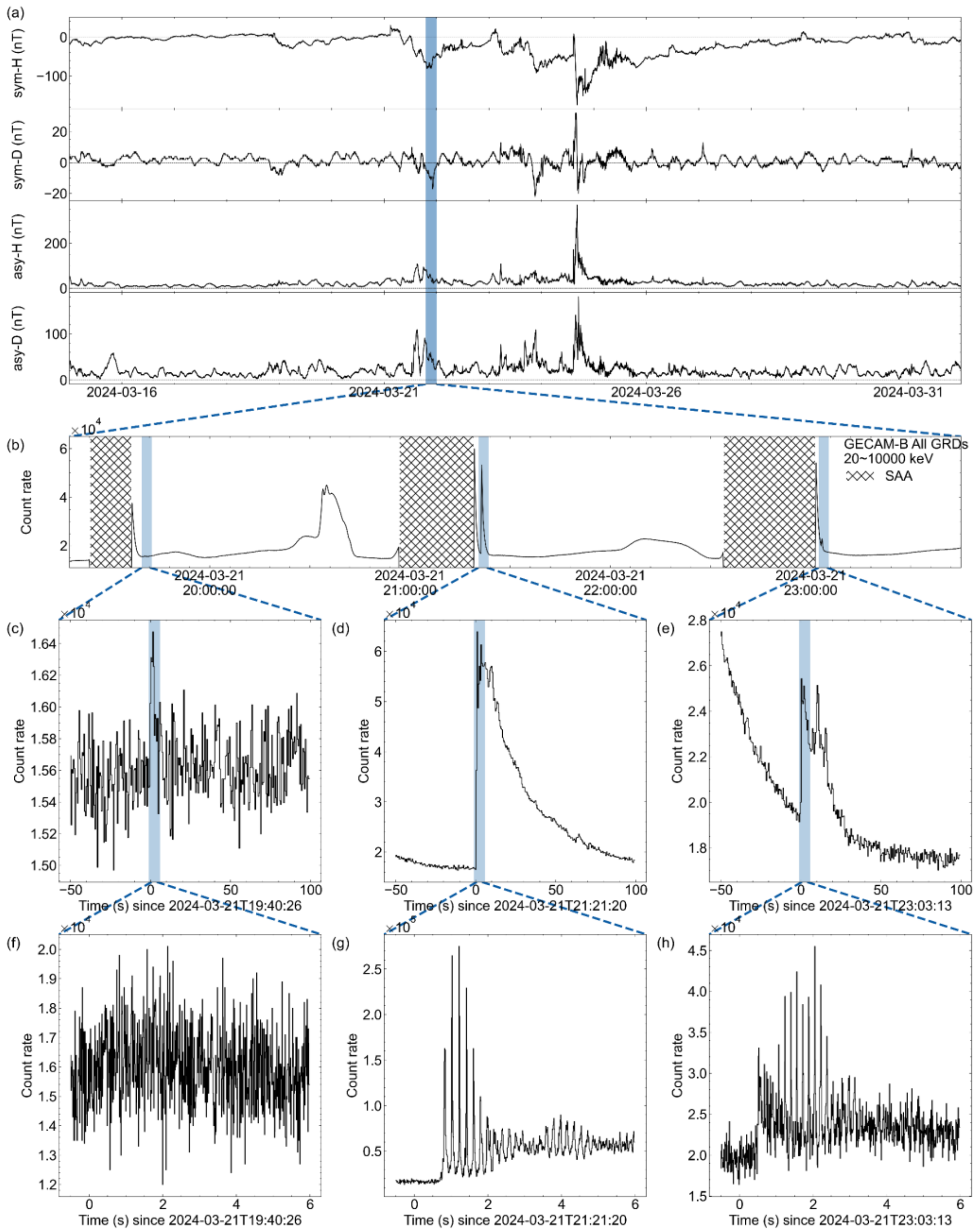
# 亚秒周期震荡粒子沉降事件




- 包络线整体有能量依赖
- 每个脉冲都有能量演化
- 高能低能粒子到达顺序翻转

# 亚秒周期震荡粒子沉降事件




观测特征：

1. 发生在地磁扰动期间，当地太阳时为晚上

   地磁暴/地磁亚暴

2. 整体向西漂移

   非VLF基站引起的人工电子带（如NWC电子带）

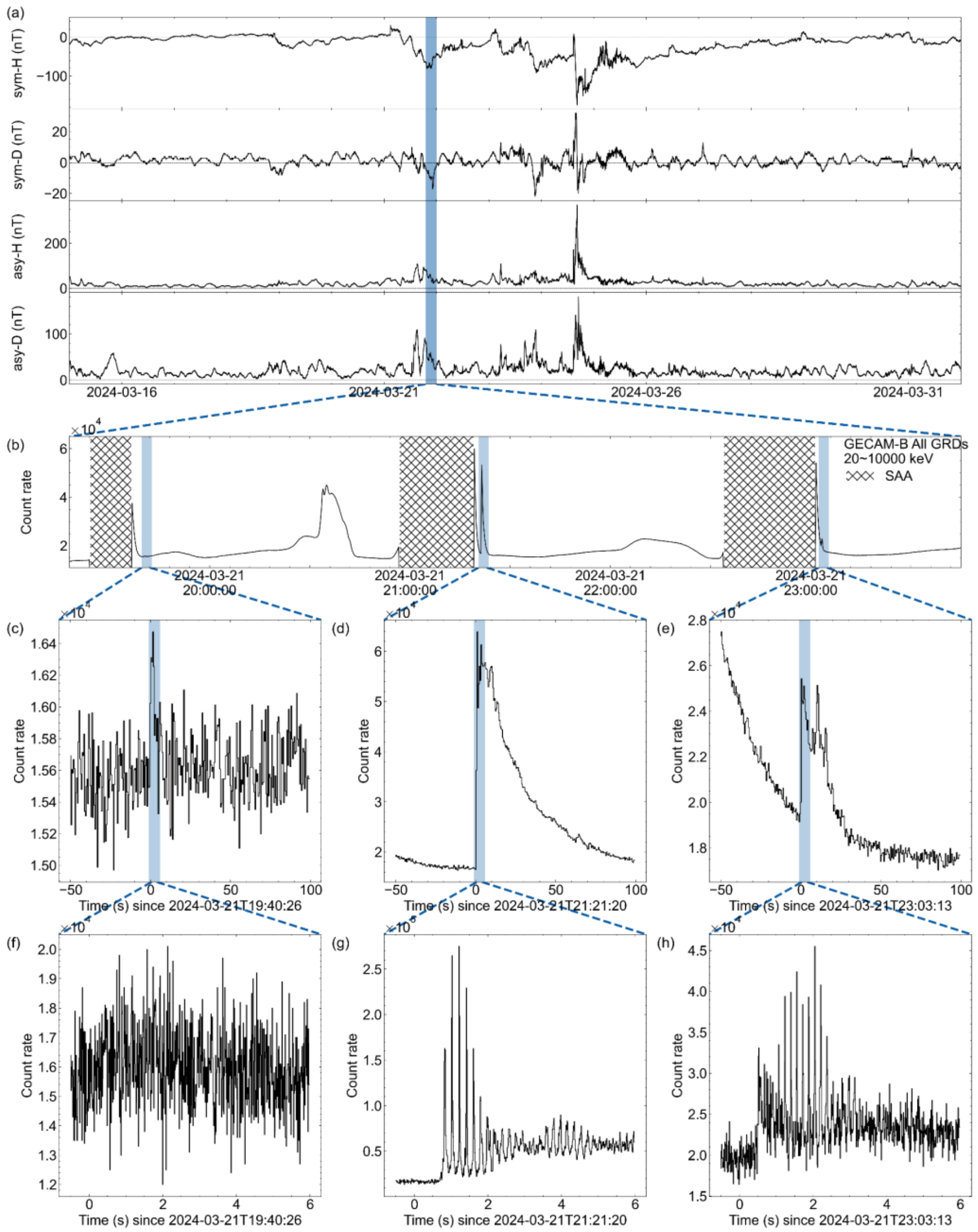
3. L<1.8，远离极光卵

   非microburst

4. 显著周期性，脉冲之间等间隔

5. 高能低能粒子到达顺序翻转

# 亚秒周期震荡粒子沉降事件

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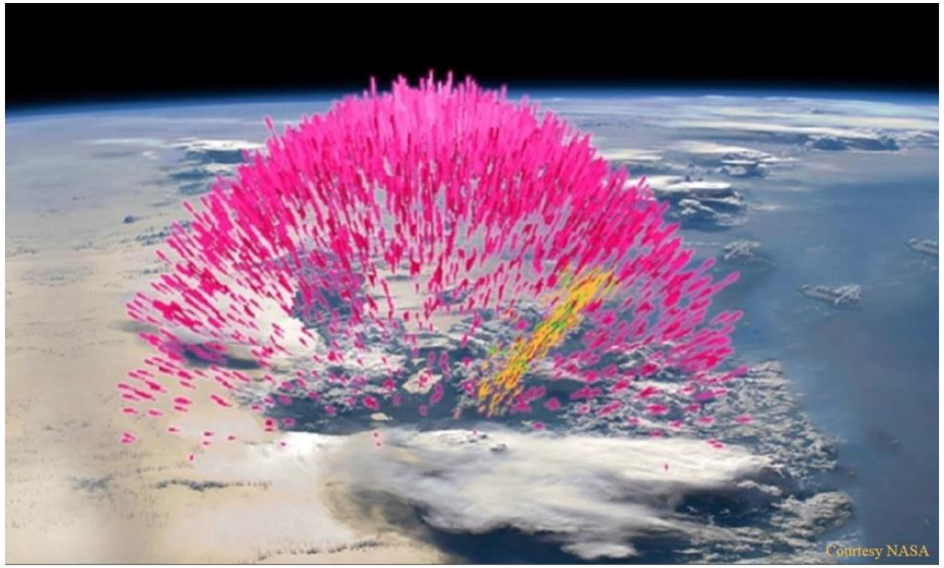
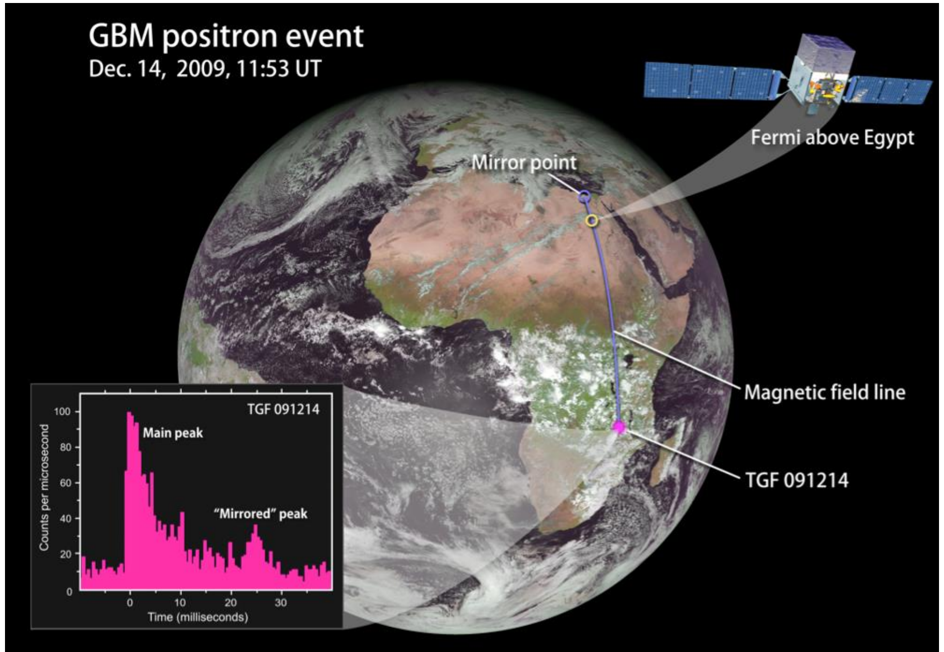
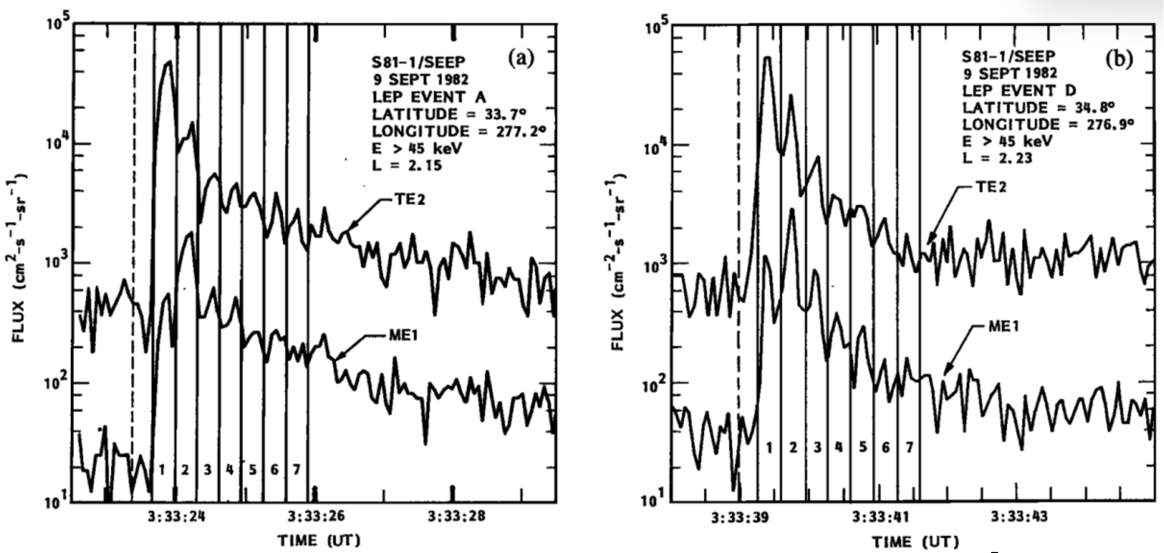
5. 高能低能粒子到达顺序翻转

时间调制? 空间调制?

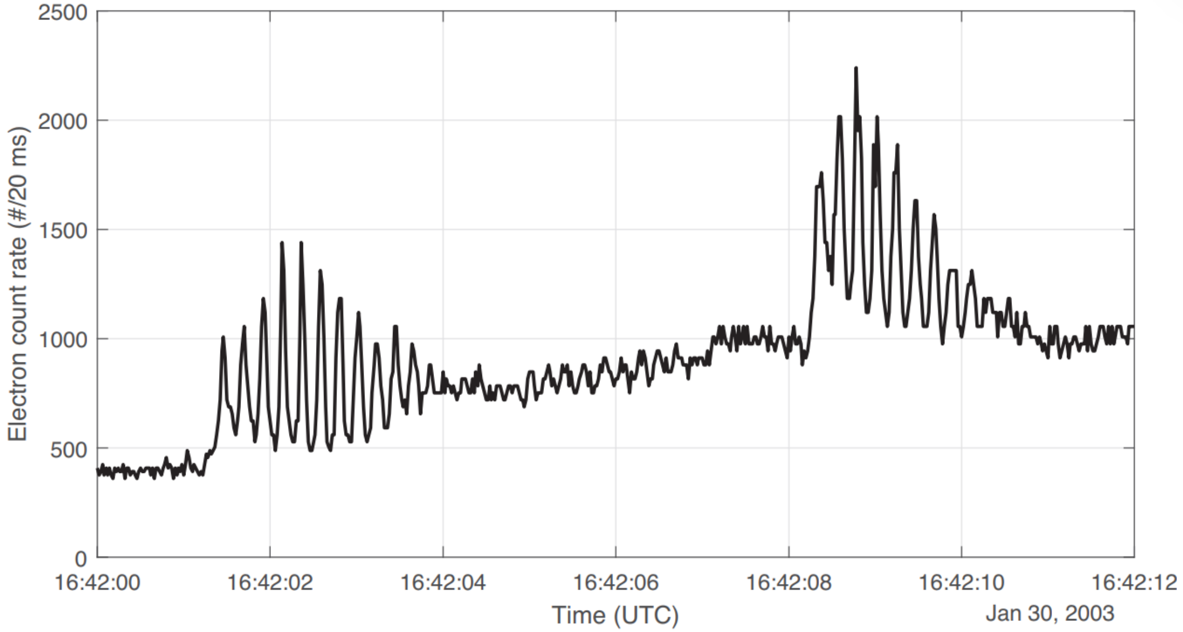
# TEB与LEP



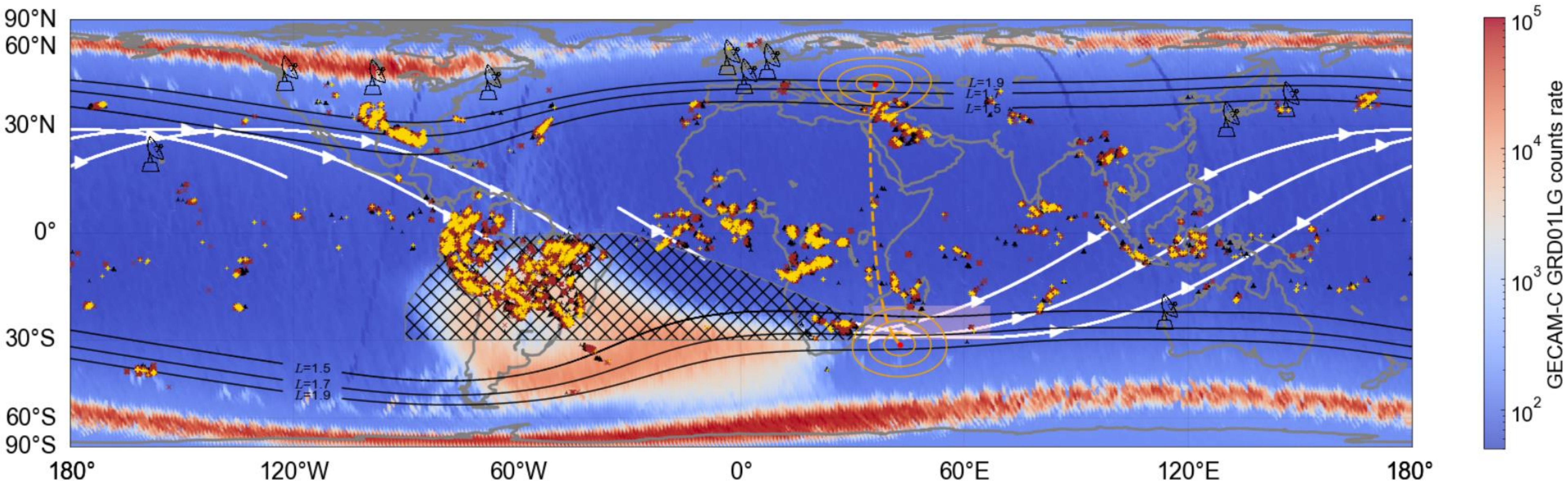




Voss et al., 1998



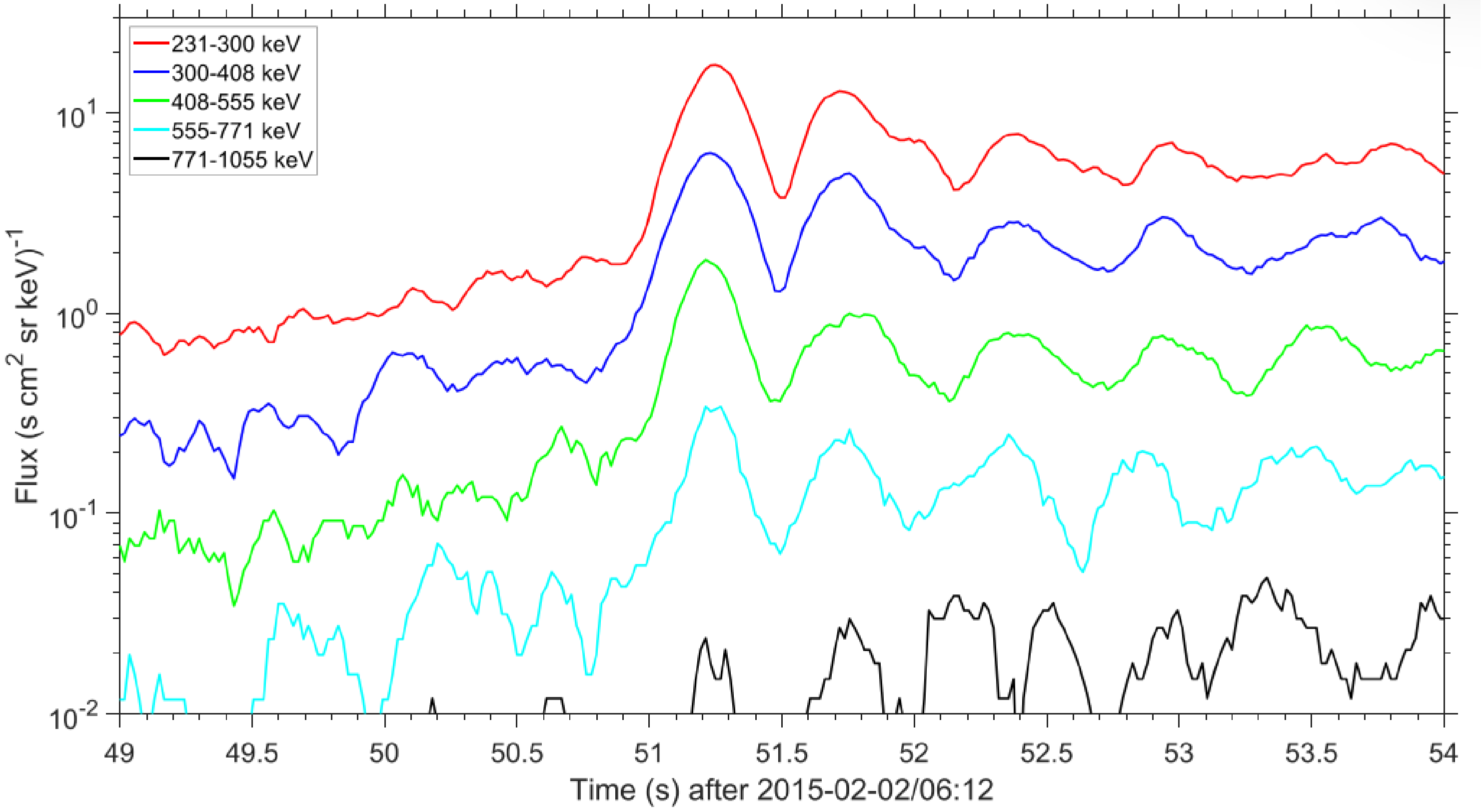

Feinland et al., 2024

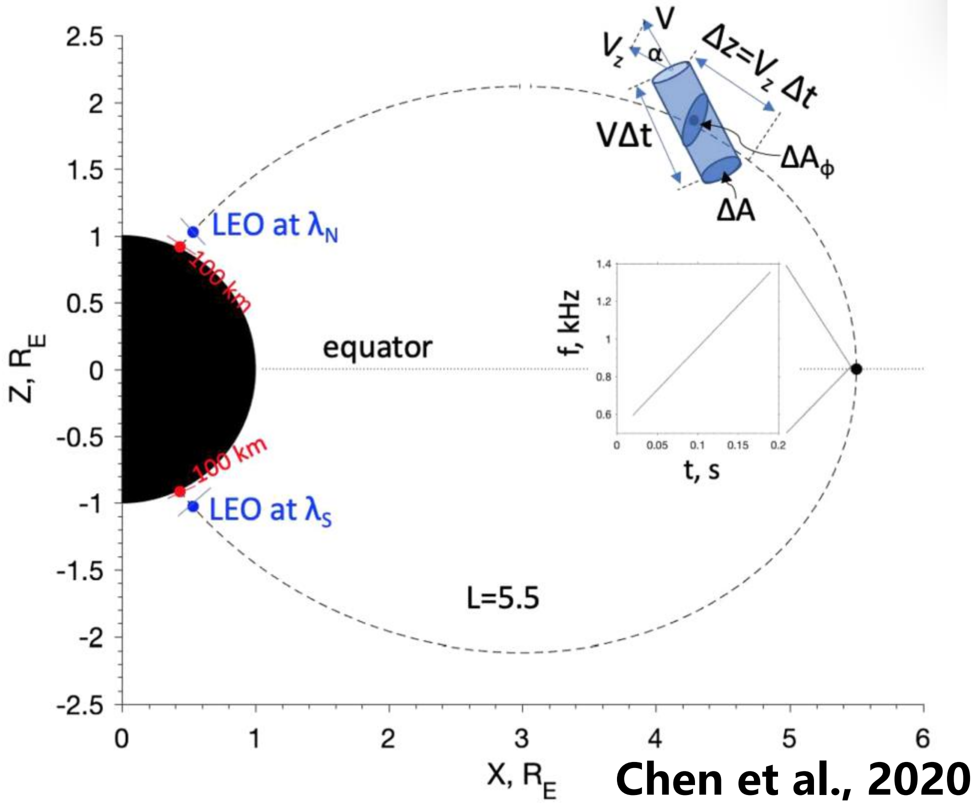
# 闪电关联?




**WWLLN数据显示没有关联闪电活动的强证据**

# 时间调制——窄视场下的电子弹跳

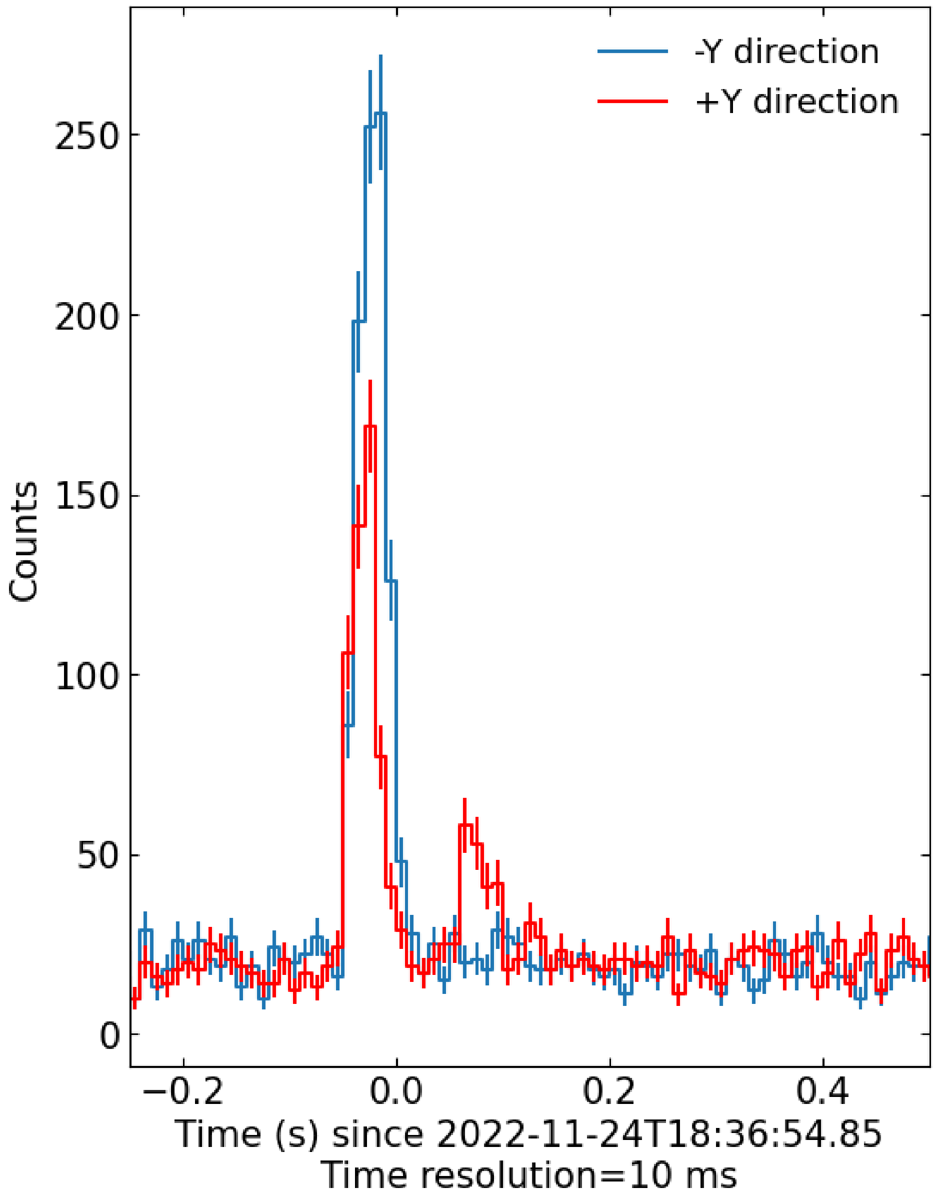


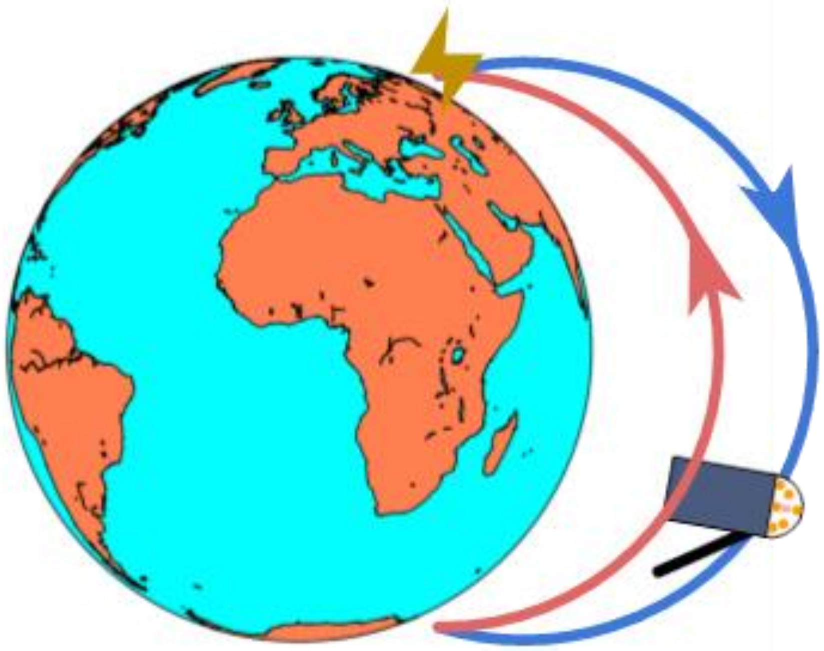



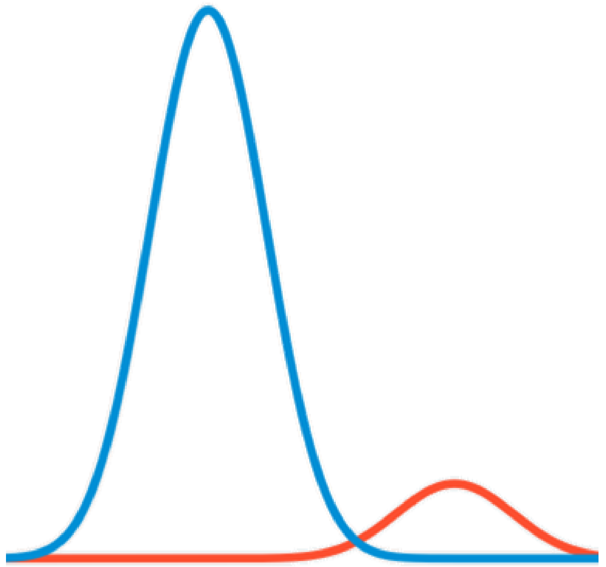

Chen et al., 2020

**对于窄视场探测器**
**电子弹跳预期可以产生单调递减的准周期信号**

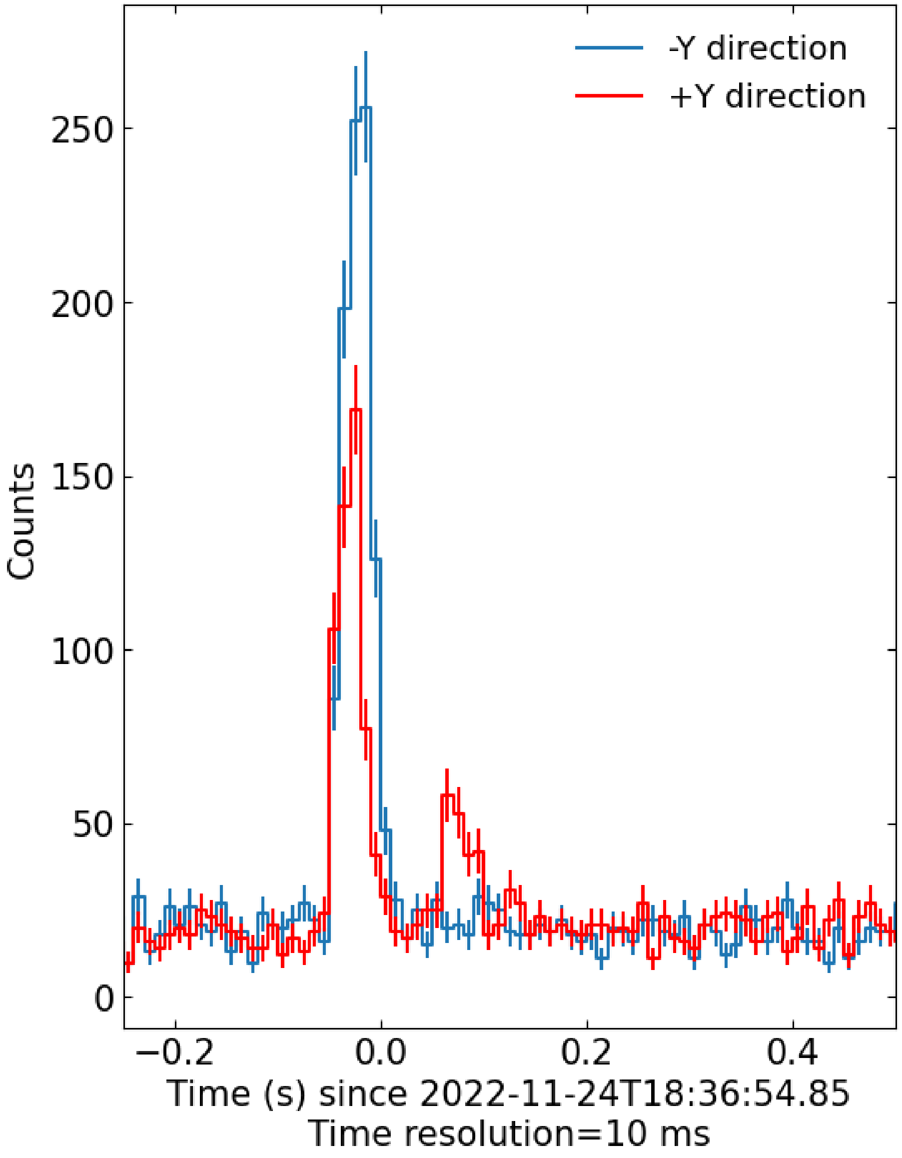
# 宽视场下的电子弹跳——以TEB为例

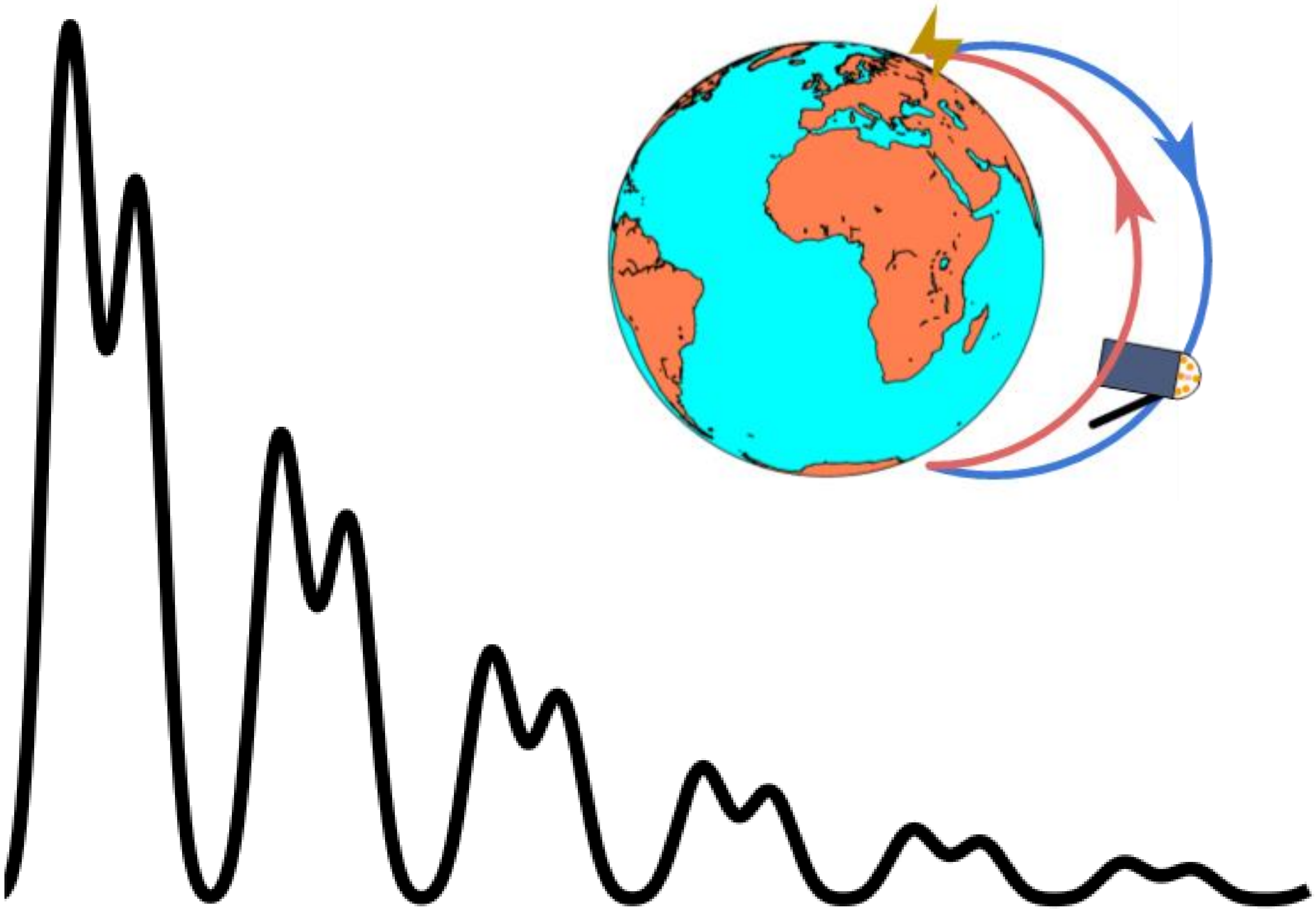




# 时间调制——电子弹跳

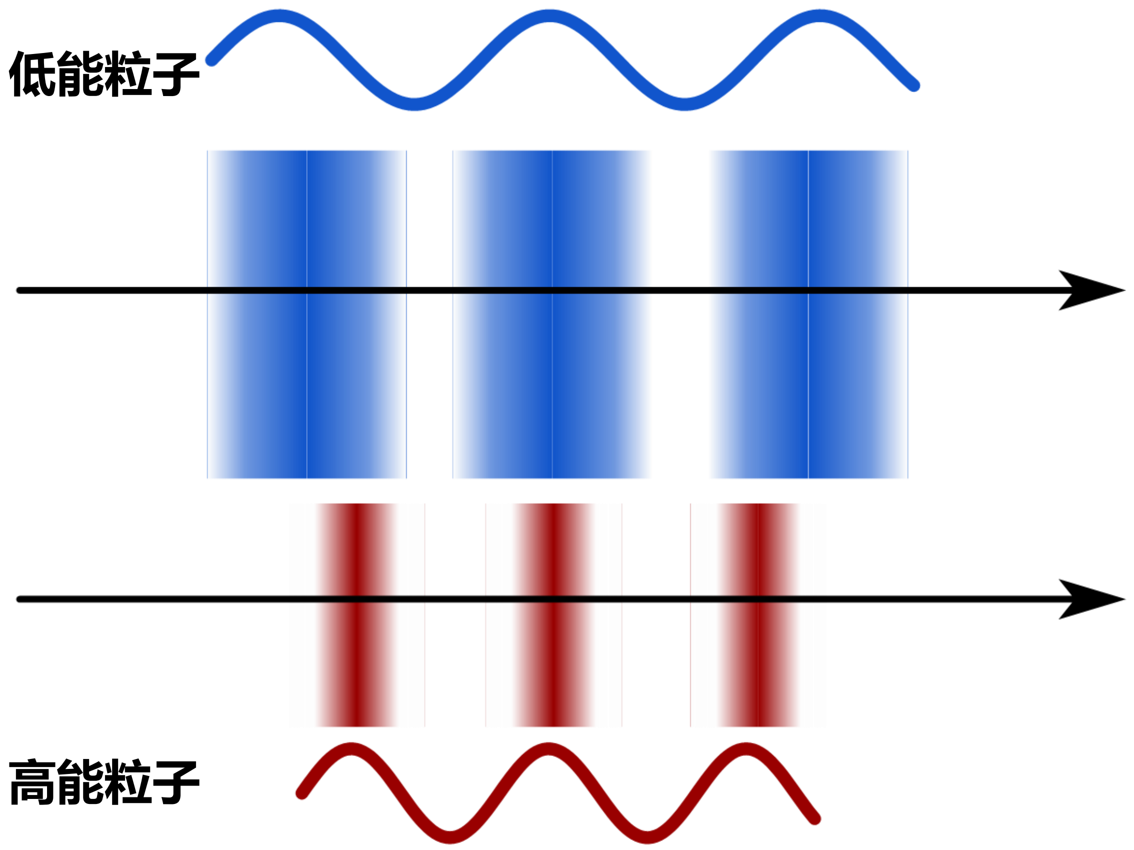


**对于宽视场探测器**

**电子弹跳预期应该产生成对单调递减的准周期信号**

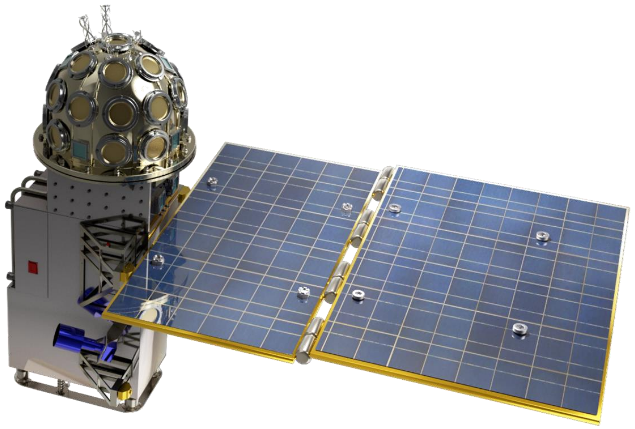
# 空间调制

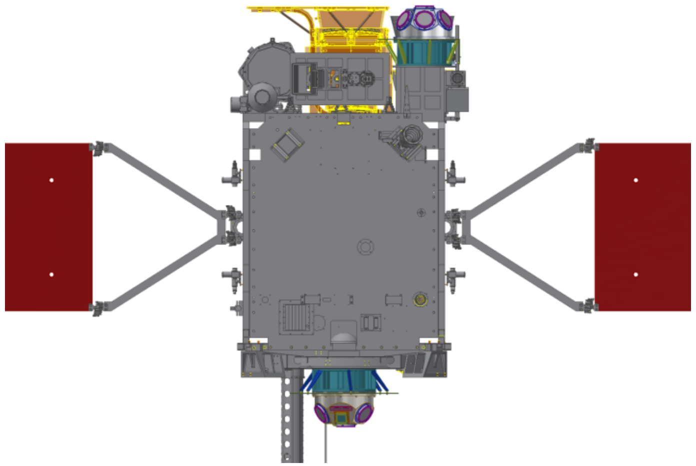


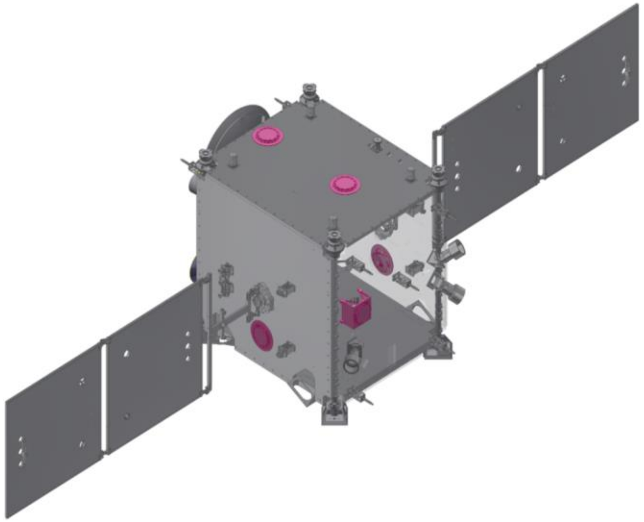

- 可以自然地解释时间-能量演化
- 但如何产生这样的空间调制还有待研究

# GECAM星座

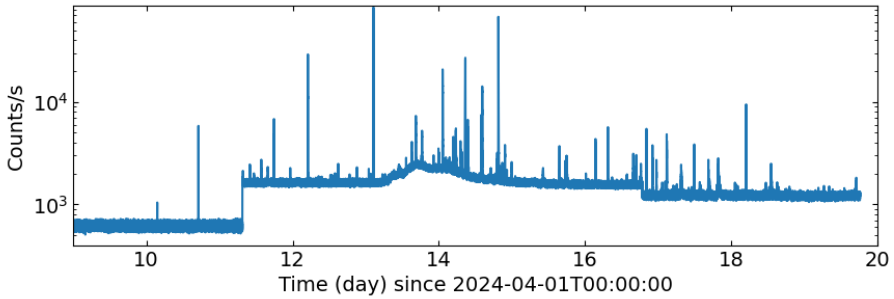
| 成员 | 发射日期 | 轨道 | 探测能段 （设计） | 运行状态 |
|---|---|---|---|---|
| GECAM-A | 2020-12-10 | LEO<br>(600 km, 29°) | 8-5000 keV | 常规运行 |
| GECAM-B | | | 8-5000 keV | 常规运行 |
| GECAM-C<br>(SATech-01/HEBS) | 2022-07-27 | SSO<br>(500 km, 97.4°) | 6-5000 keV | 2025-02-13<br>结束运行 |
| GECAM-D<br>(DRO-A/GTM) | 2024-03-13 | DRO<br>(31,0000-45,0000km) | 10-1000 keV | 调试阶段 |

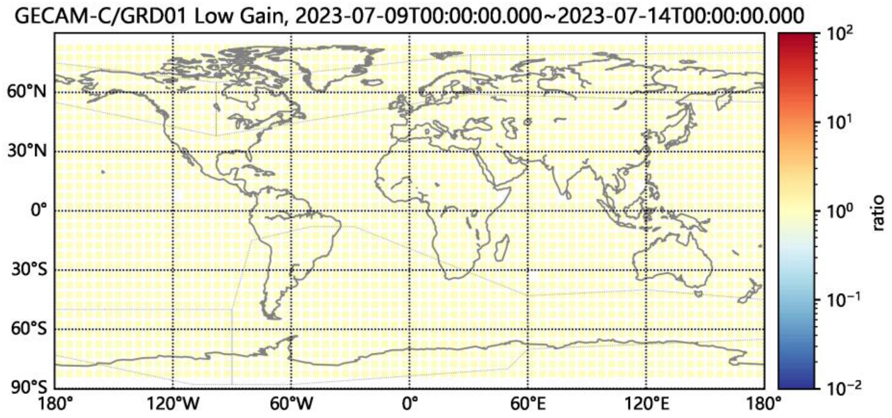


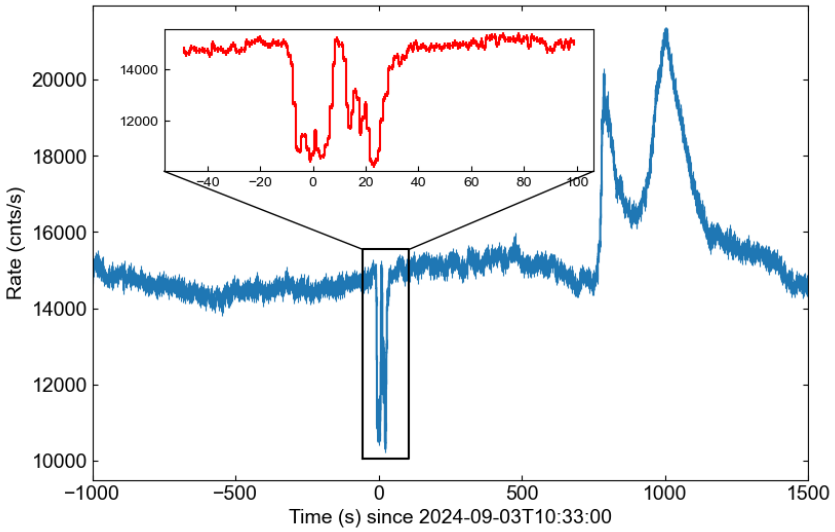




# 利用GECAM开展空间环境研究




- **利用GECAM-D的无遮挡优势**
  **可以实现对太阳硬X射线耀斑的持续监测**
  **刻画太阳质子事件在DRO轨道的演化**

- **基于GECAM-C构建了空间环境数据库**
  **观测到太阳质子事件/地磁暴期间**
  **南北极粒子通量的升高**
  **以及内辐射带中粒子通量的异常降低**

- **在DRO轨道上探测到了粒子通量的“dip”结构**

**GECAM既探测到大量新型粒子事件**
**同时也有能力对特殊粒子事件提供高精度观测**

## 总结

- GECAM独立~~（首次）~~探测到的一类具有极其显著周期性的新型空间事件
- 以高精度观测到双胞胎OPP事件，并对时间-能量演化进行了精细刻画
- 为粒子沉降的周期现象起源提供了新的见解

# 欢迎意见和建议！

## 也欢迎使用GECAM数据开展空间环境研究！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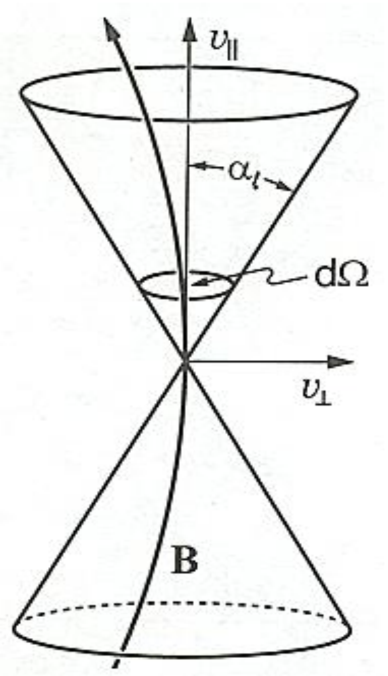
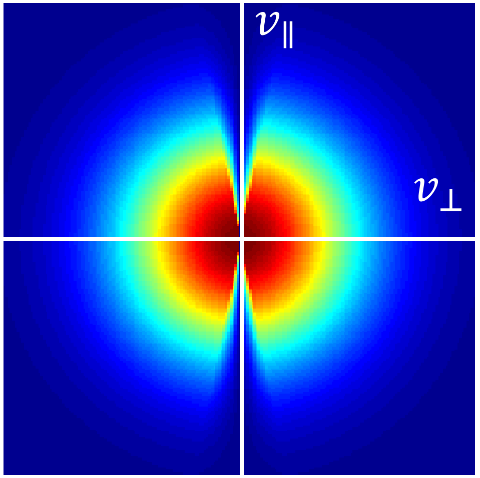
GECAM首席：熊少林研究员 xiongsl@ihep.ac.cn

合作者: 赵一（德州学院），徐未（武汉大学），陆高鹏（中国科学技术大学），周煦之（北京大学），郭孝成，李文亚（空间中心），
郭昊轩，刘佳聪，薛王陈，张艳秋 （高能所）等

# BACKUP

# 粒子沉降




- 投掷角$\alpha$：粒子运动方向与磁场的夹角

  是空间物理最重要的参数之一

  通常需要准直器结构

- 损失锥：投掷角小于一定值的粒子无法反弹

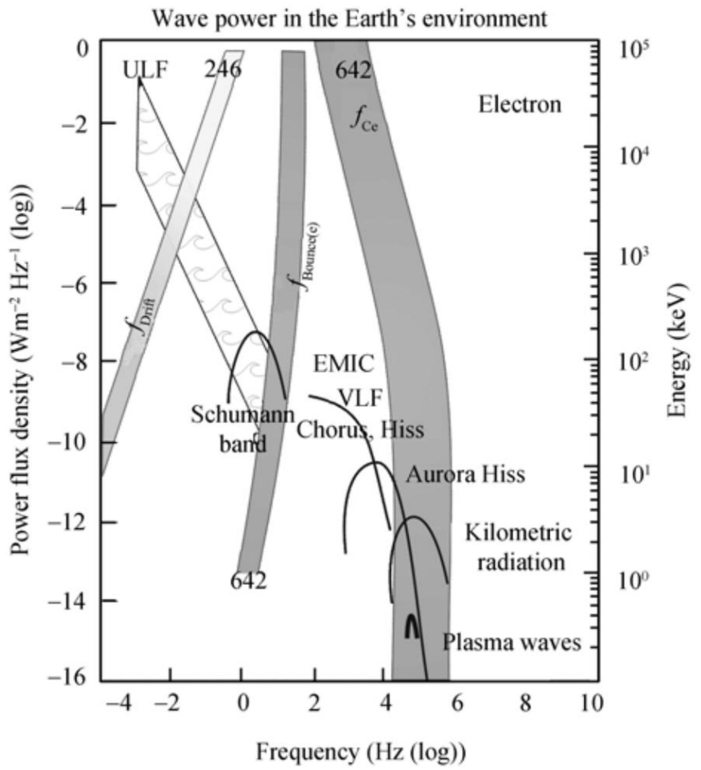
  这部分粒子会进入大气层，即粒子沉降

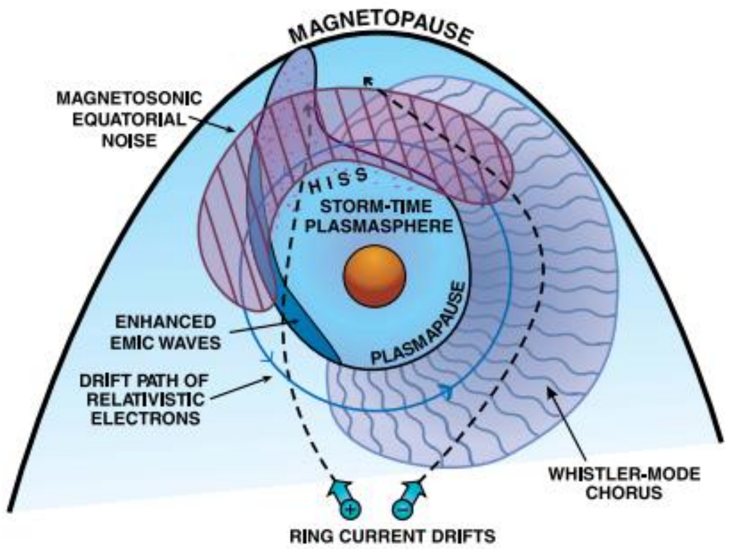
- 通过散射、加速可以使粒子的投掷角改变

  并进入损失锥

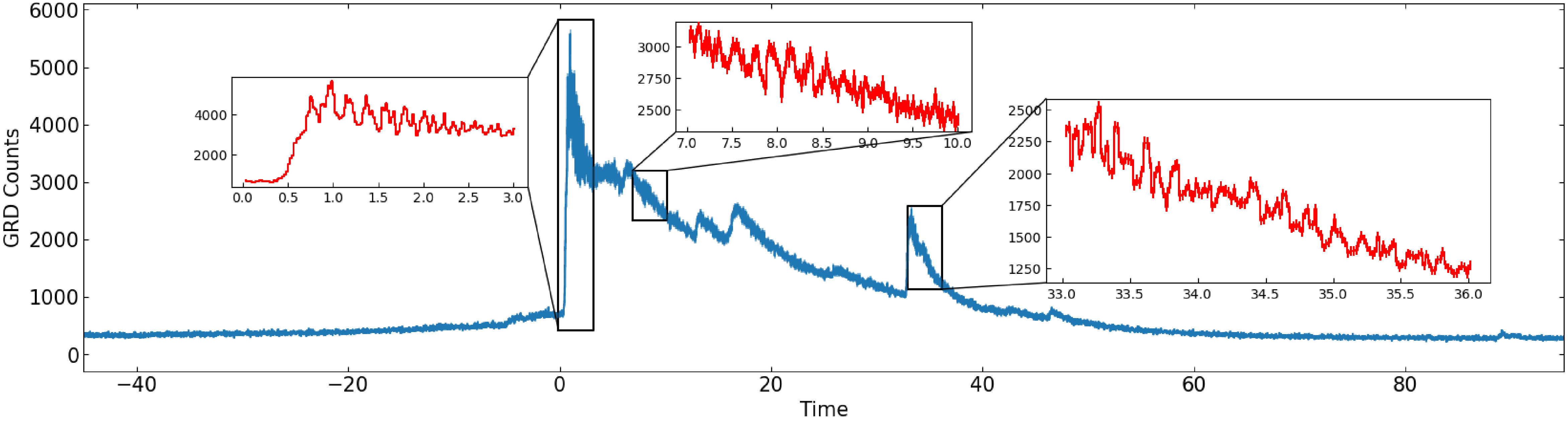
- 产生来源包括不同频率的波动与带电粒子的

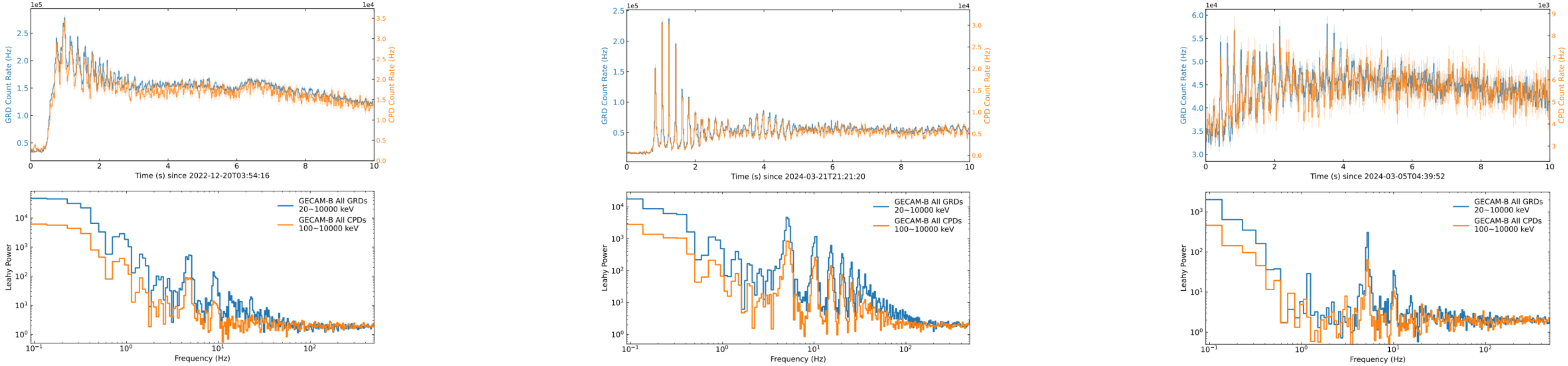
  回旋、弹跳、漂移发生共振



# Oscillating Particle Precipitation（OPP）




**GECAM独立~~(首次)~~探测到的一类具有极其显著周期性的新型空间事件！**

# Oscillating Particle Precipitation（OPP）

Article https://doi.org/10.1038/s41467-024-53036-4

## Lightning-induced relativistic electron precipitation from the inner radiation belt

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Check for updates

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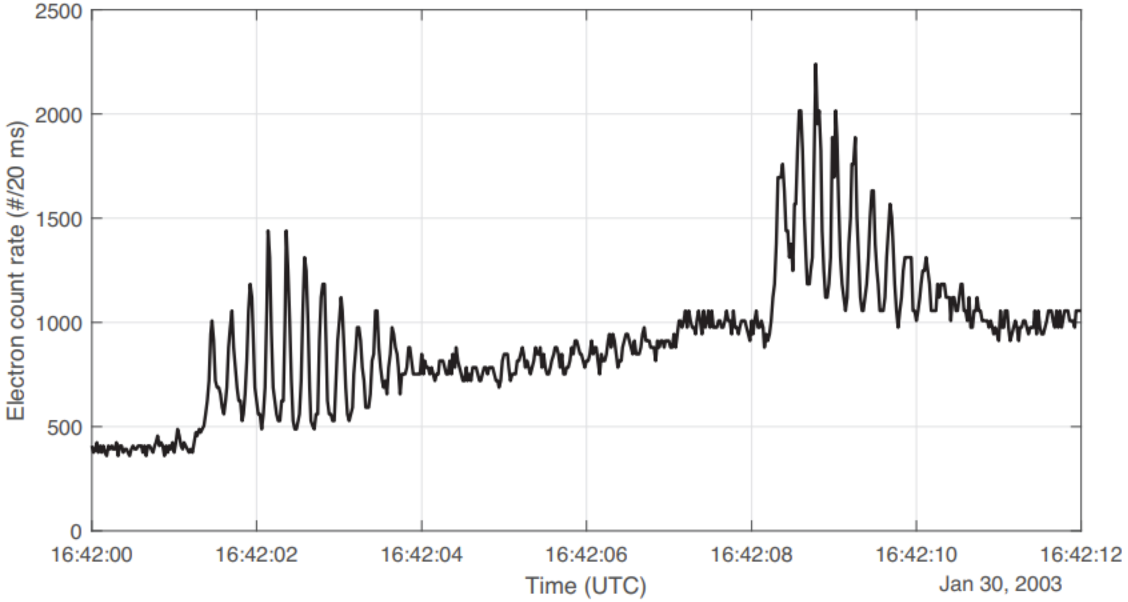
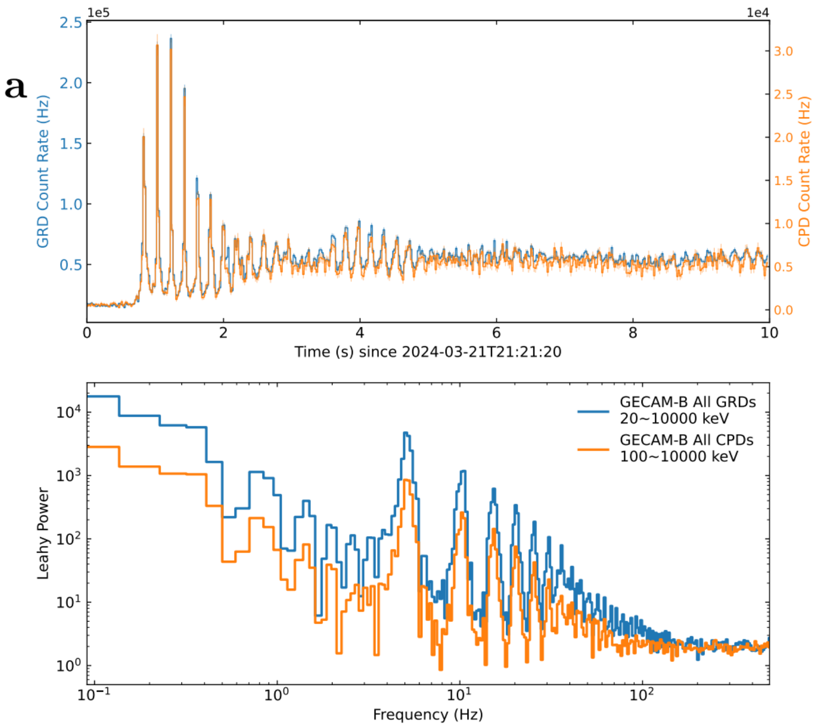
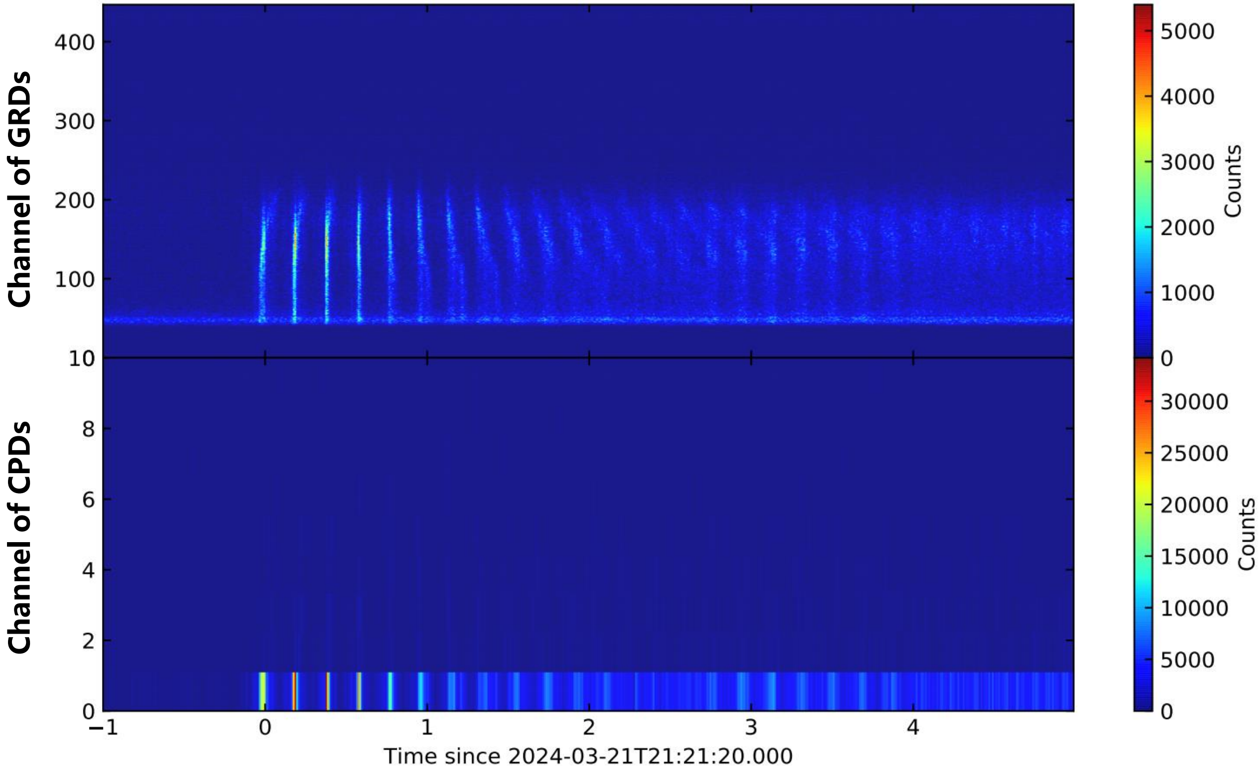
The Earth's radiation belts are maintained by a number of acceleration, loss and transport mechanisms, and the electron fluxes at any given time are highly variable. Microbursts, which are rapid (sub-second) bursts of energetic electrons entering the atmosphere from the magnetosphere, are one of the key loss mechanisms controlling radiation belt fluxes. Such rapid bursts are typically observed from the outer radiation belt and driven by interactions with whistler mode chorus waves, but they can also occur in the inner belt and slot region, driven by lightning-generated whistlers. This lightning-induced electron precipitation is typically observed at 10s–100s keV, but here we present direct observations of this phenomenon at MeV energies. This unveils a coupling between near-Earth processes, such as lightning, and radiation belt processes, such as relativistic electron microbursts, bridging the gap between Earth weather and space weather.

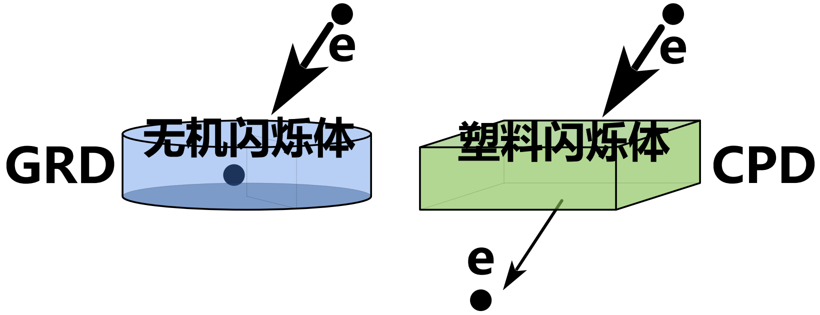



**GECAM也可以在空间物理方面发挥重要作用！**

# 针对GECAM的电子、质子鉴别



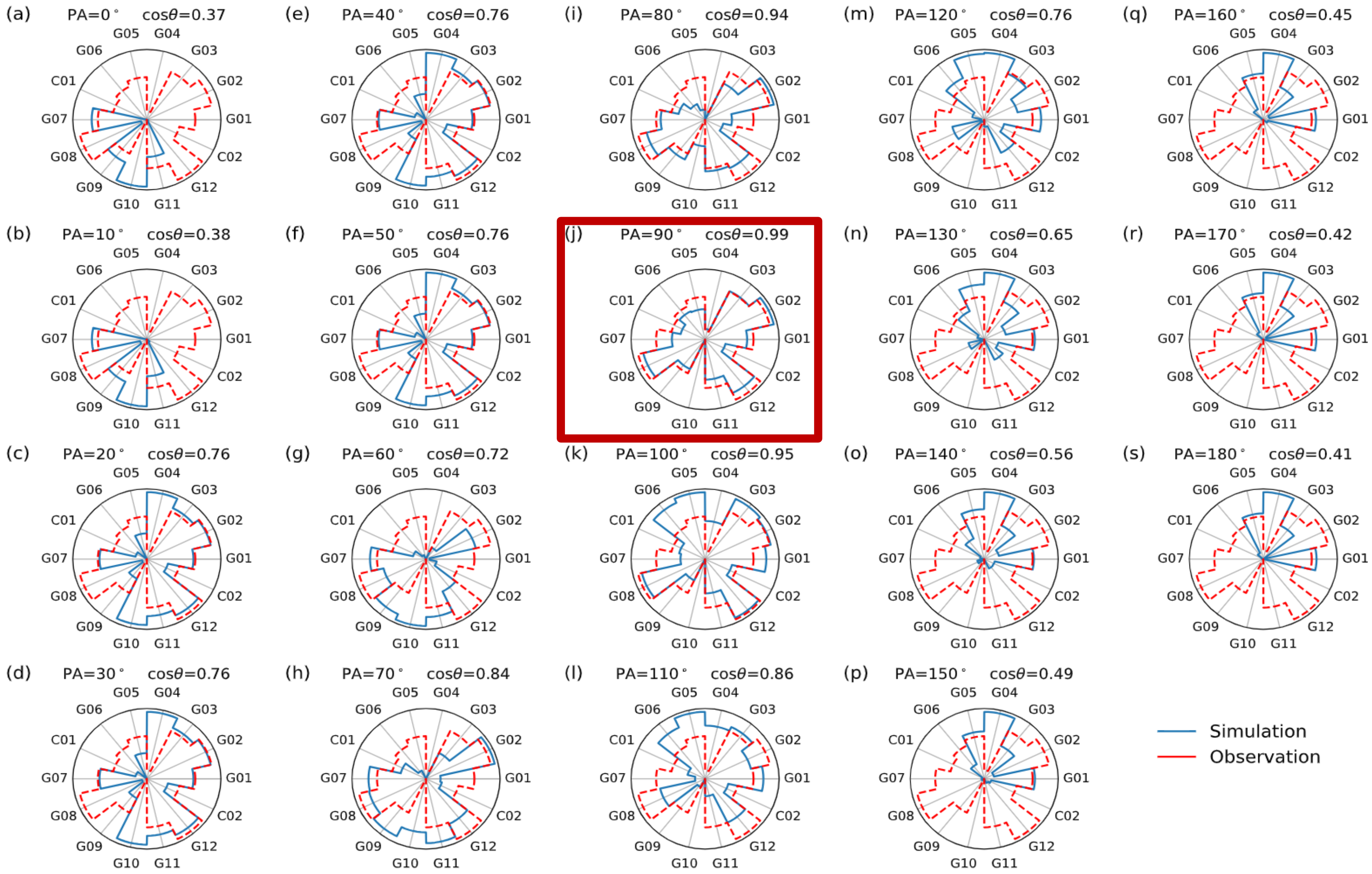



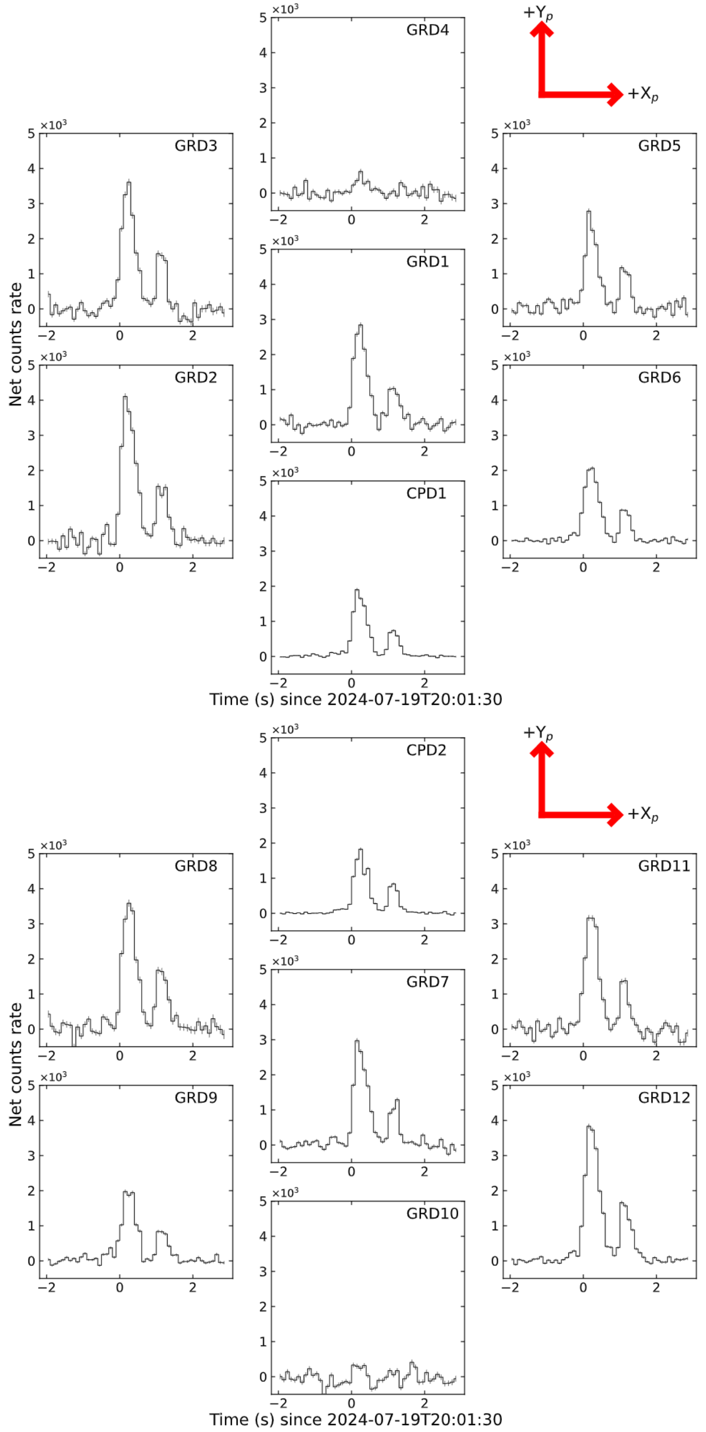




| GRD | CPD | 粒子种类 |
|---|---|---|
| 不穿透 | 不穿透 | 靠沉积能量差异进一步判断 |
| 不穿透 | 穿透 | 电子 |
| 穿透 | 穿透 | 无法鉴别 |

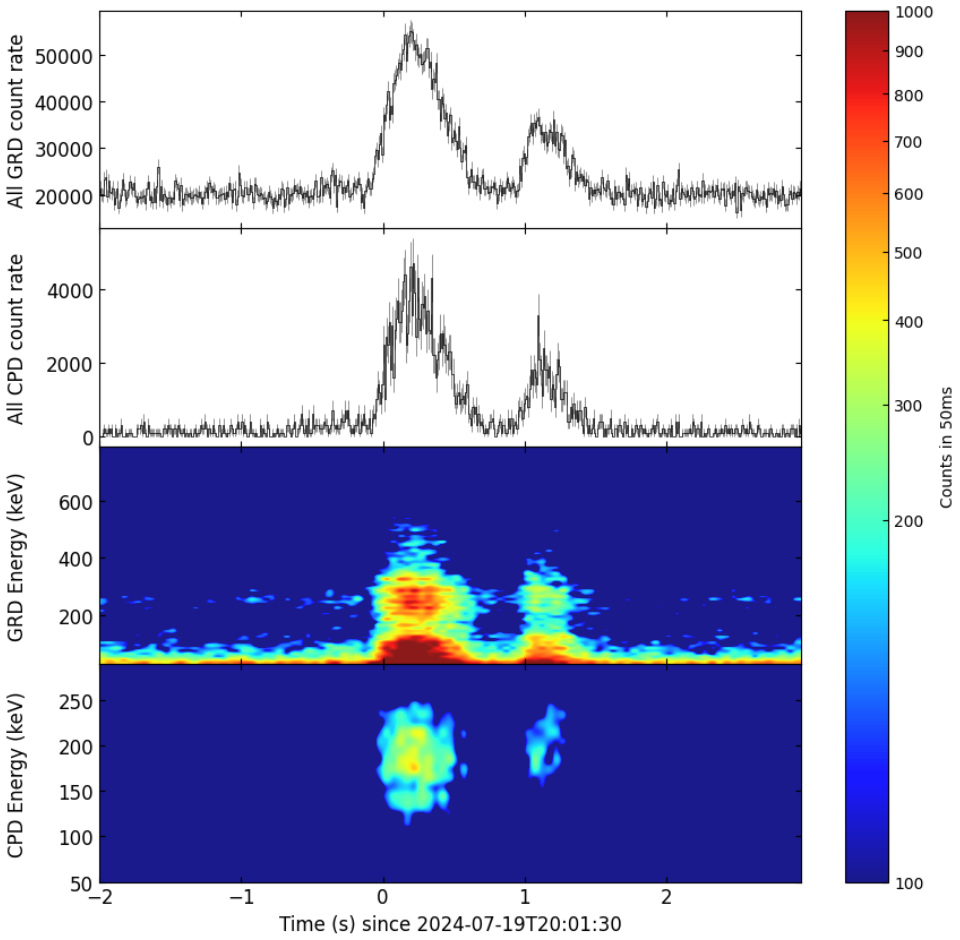
**首次利用GECAM实现了电子质子的鉴别！**

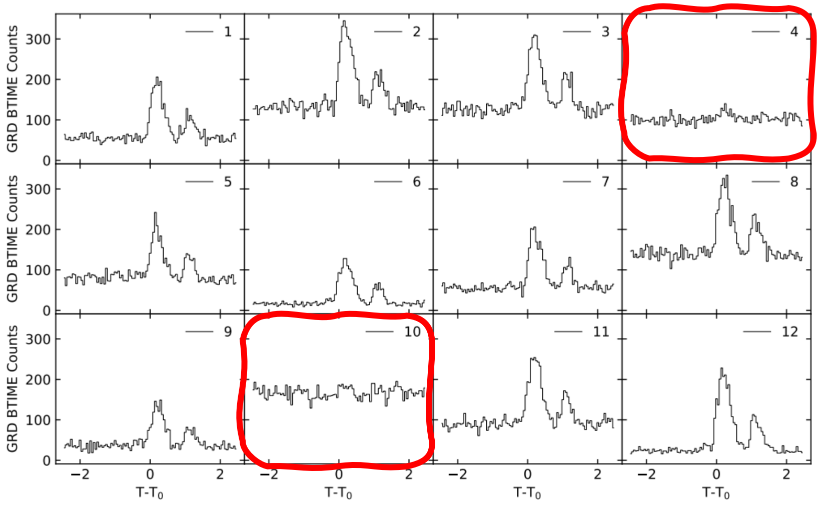
# 针对GECAM的投掷角测量

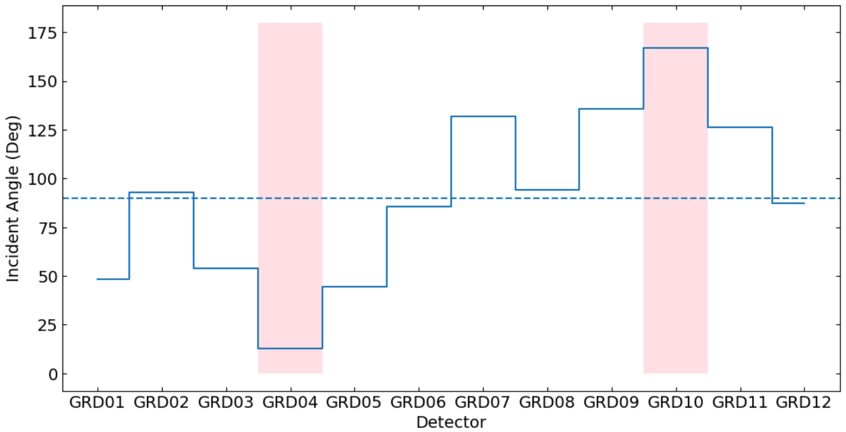


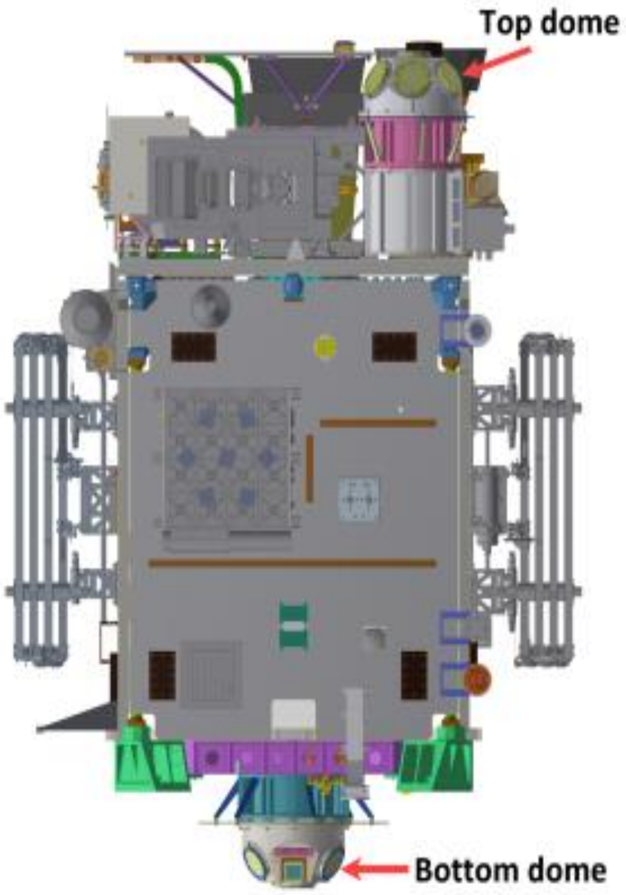



# 针对GECAM的投掷角测量



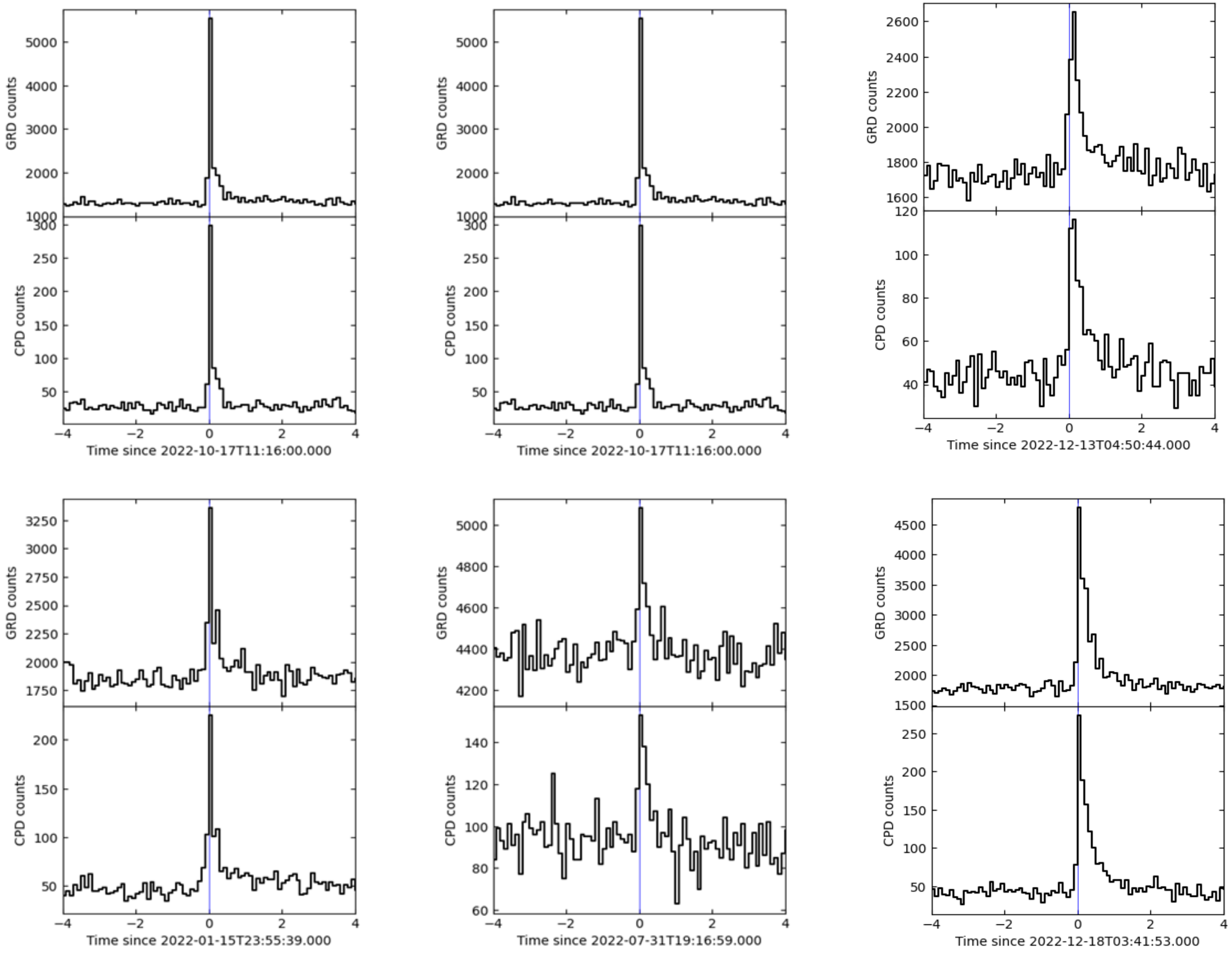



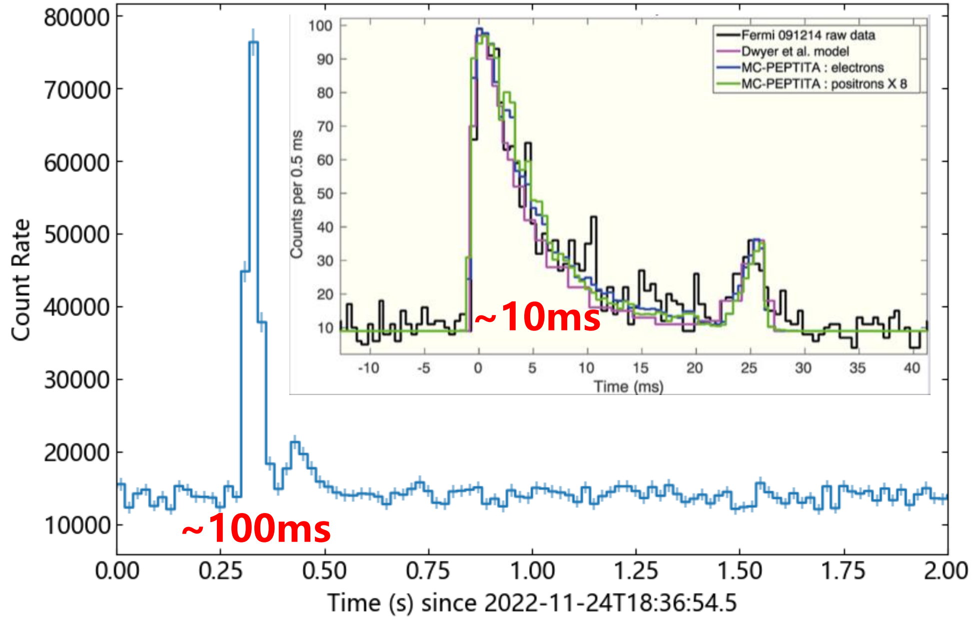



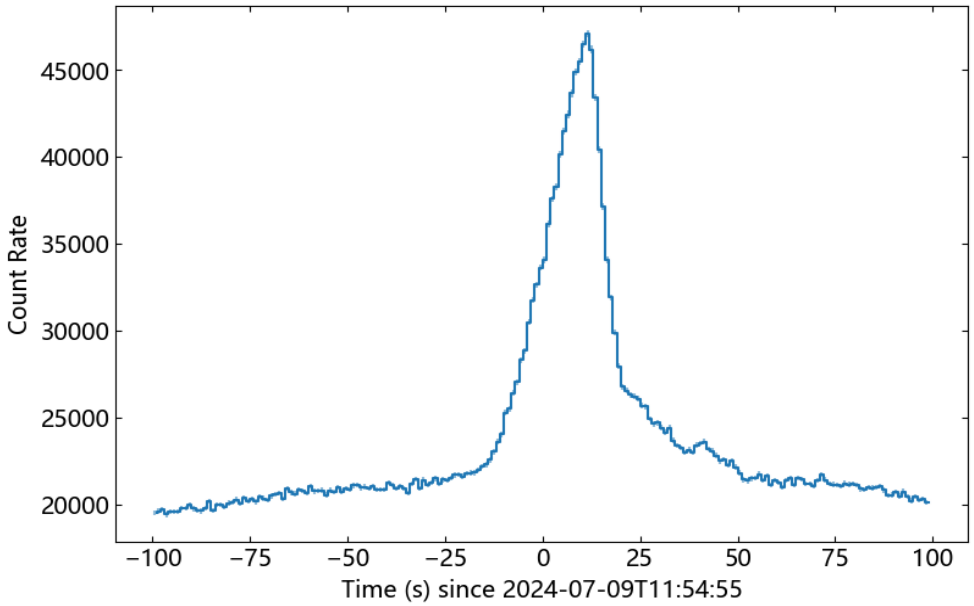




**发展了一套利用GECAM对带电粒子进行投掷角测量的方法**

# 短时标空间粒子暴

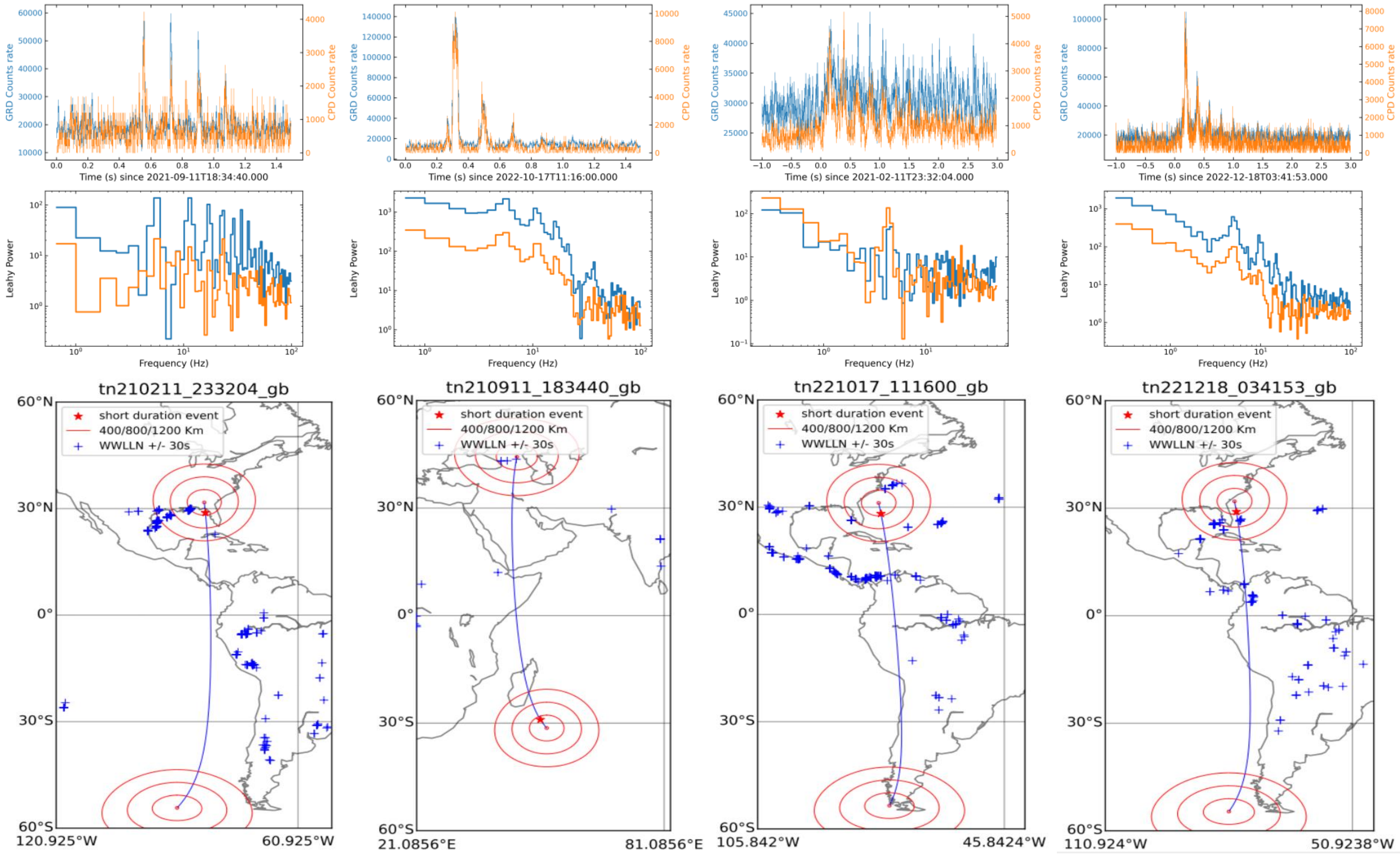


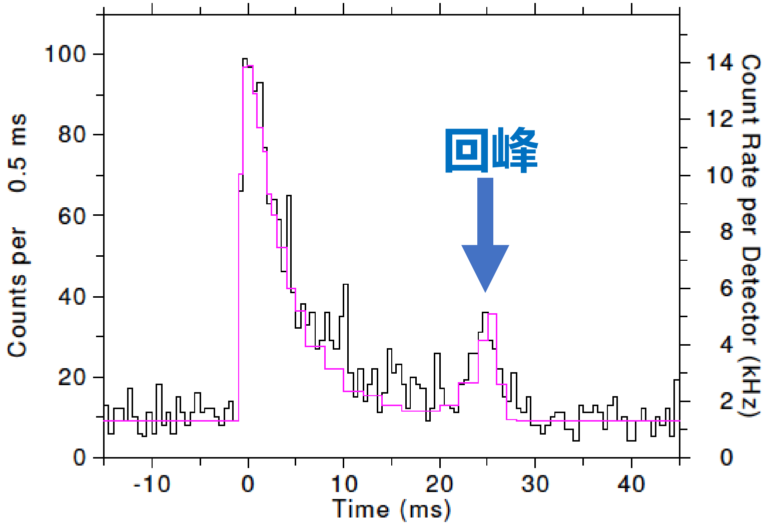



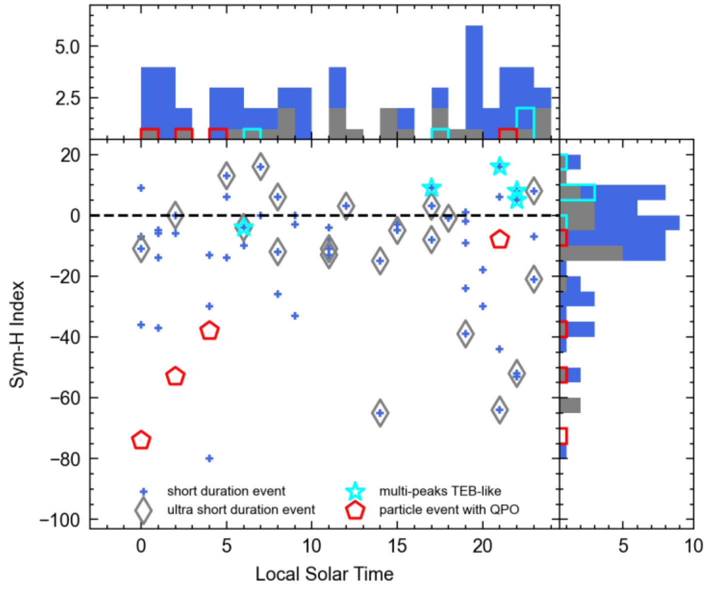




**持续时间远大于TEB，但又远小于一般粒子沉降事件**

# 短时标空间粒子暴与多峰TEB-like

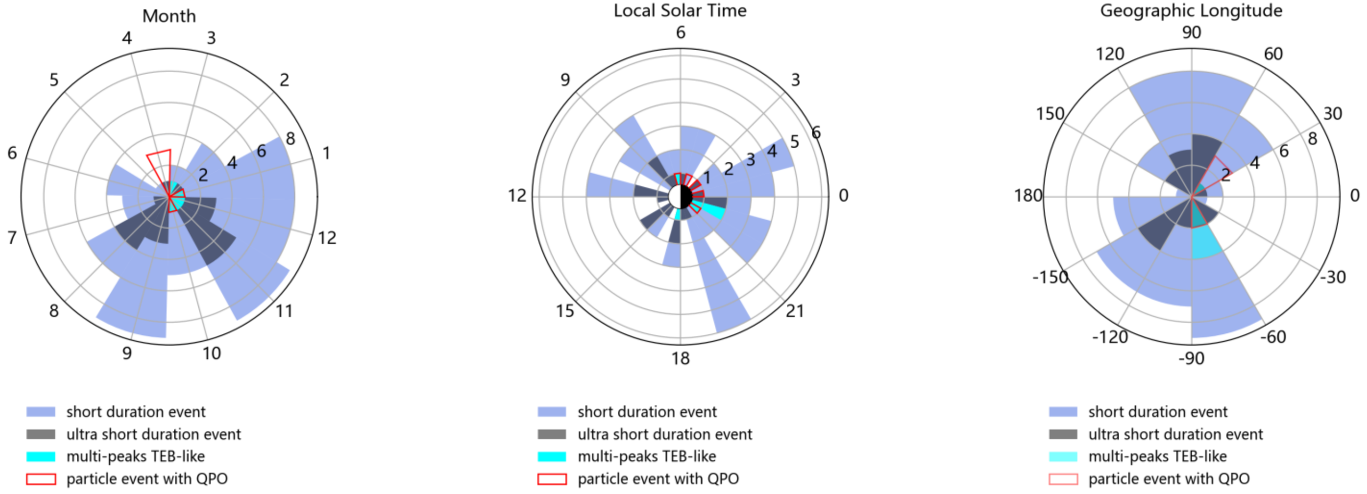


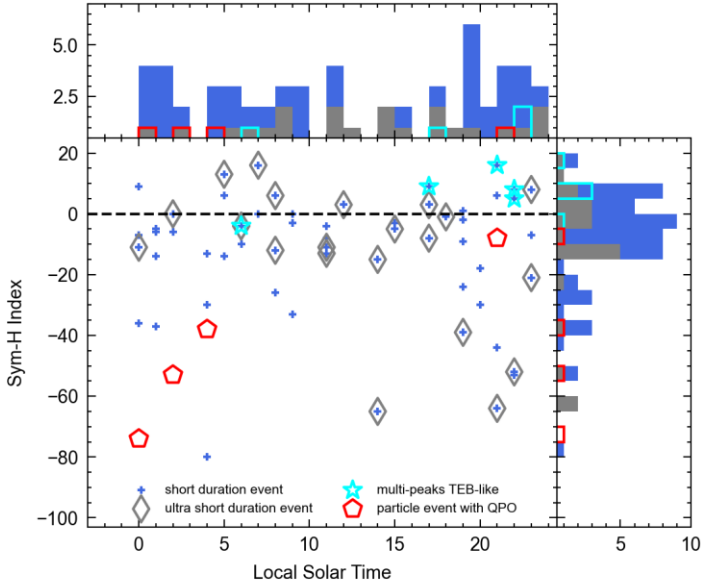



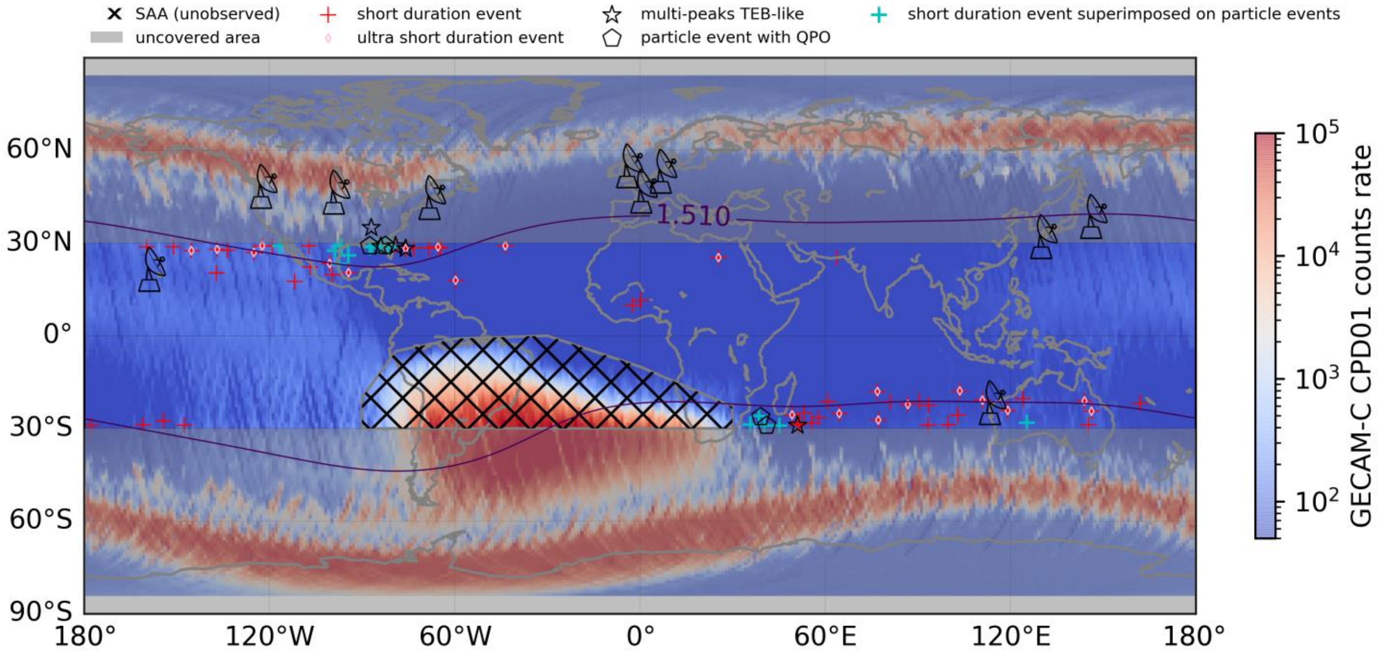



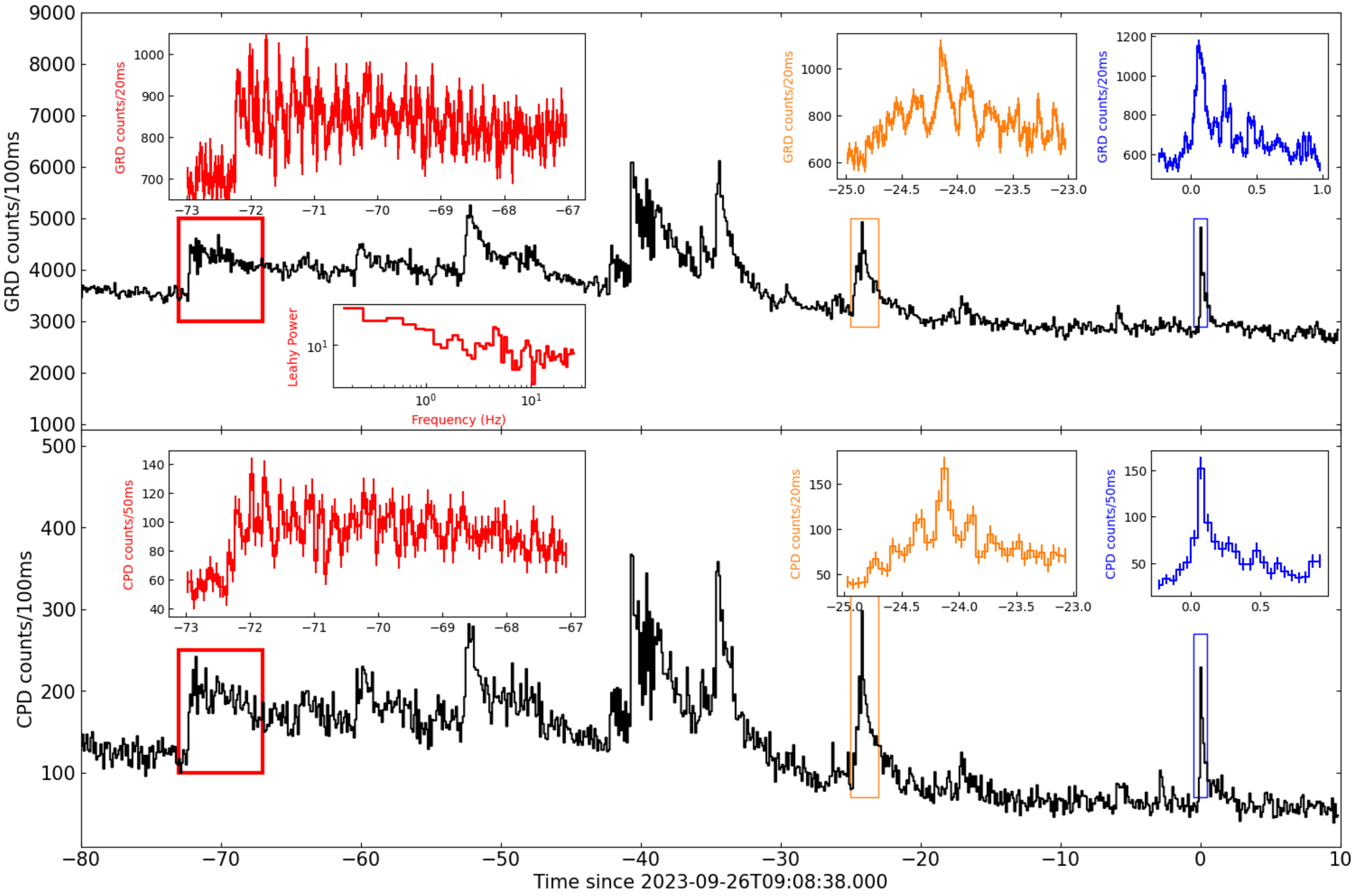

从统计上揭示了多峰TEB-like与闪电、地磁暴的关联性

# OPP与多峰TEB-like





GRD counts/100ms
CPD counts/100ms
Time since 2023-09-26T09:08:38.000
GRD counts/20ms
CPD counts/50ms
CPD counts/20ms
Leahy Power
Frequency (Hz)