

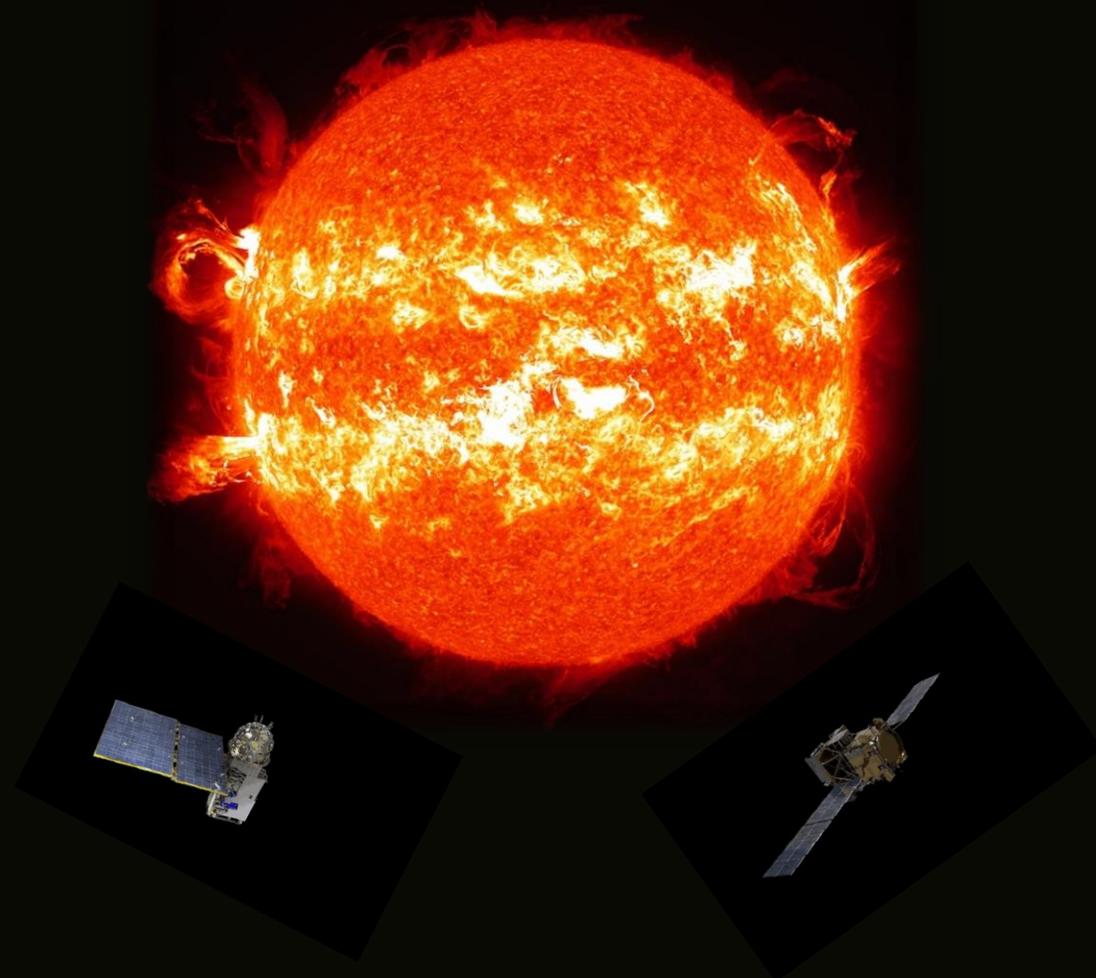
# GECAM 太阳数据处理和研究

苏杨

中国科学院紫金山天文台

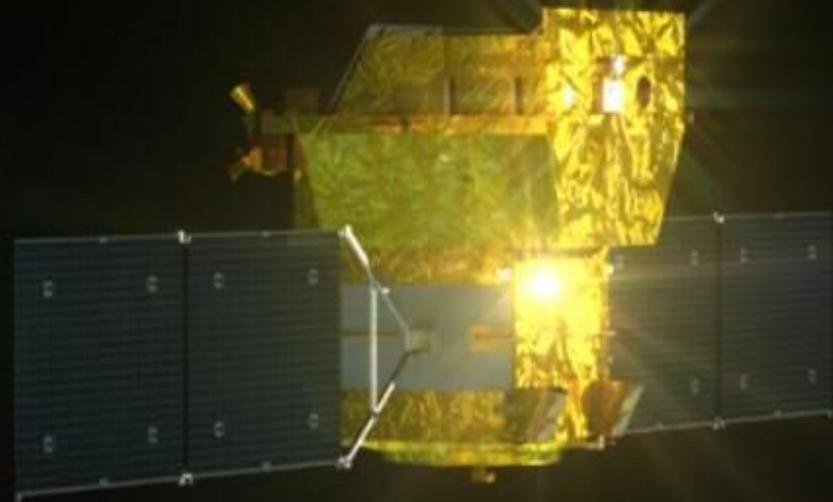
[yang.su@pmo.ac.cn](mailto:yang.su@pmo.ac.cn)

2020.10



# 目录

- 太阳高能活动和观测
- GECAM太阳数据
- GECAM Solar 软件进展



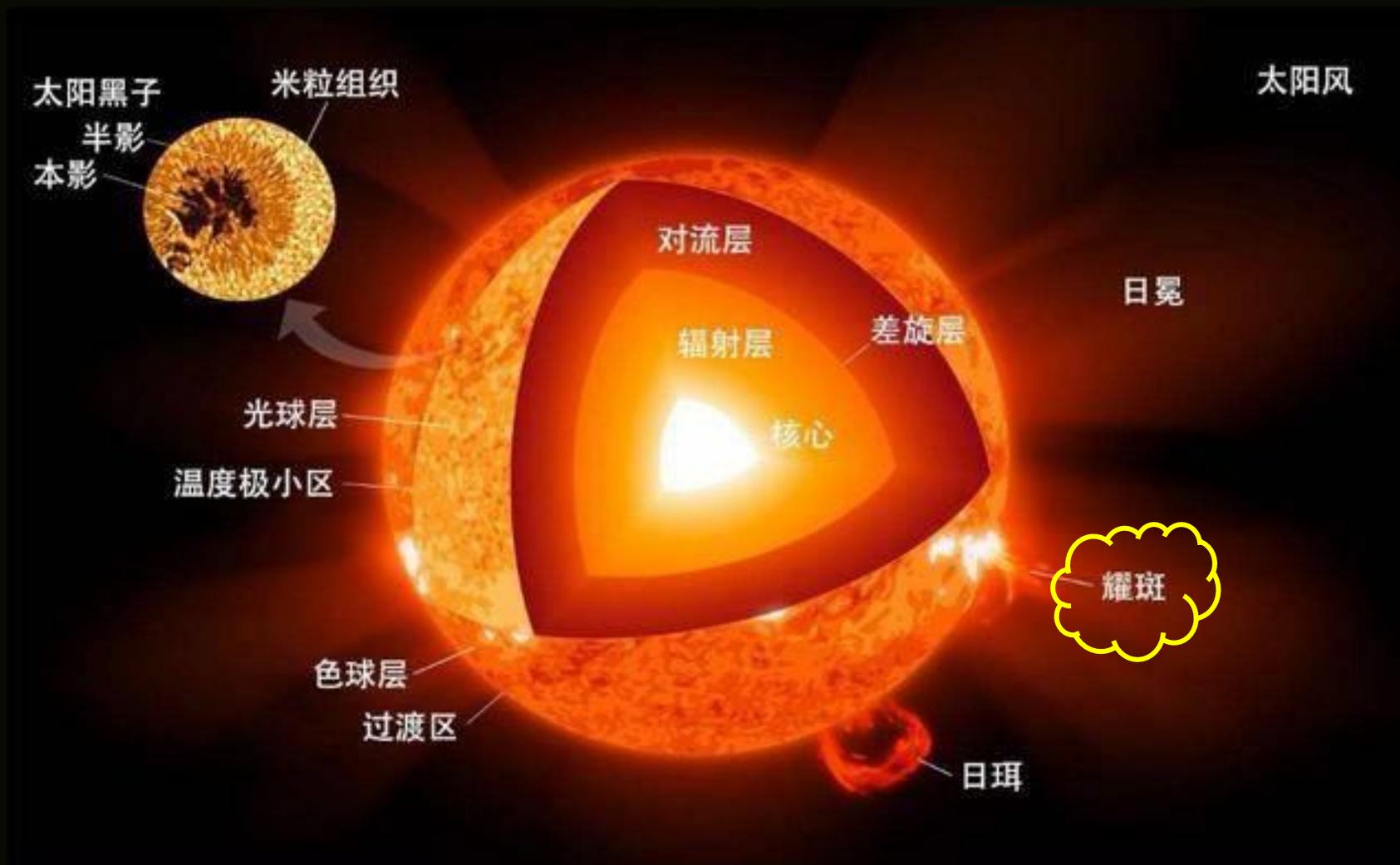
## 极其普通

一颗普通的主序星  
单是银河系内就有上千亿颗恒星

## 极其特殊

唯一与人和地球密切相关的恒星  
唯一可以详细观察的恒星  
提供了我们所需的几乎所有能量  
一个天然实验室

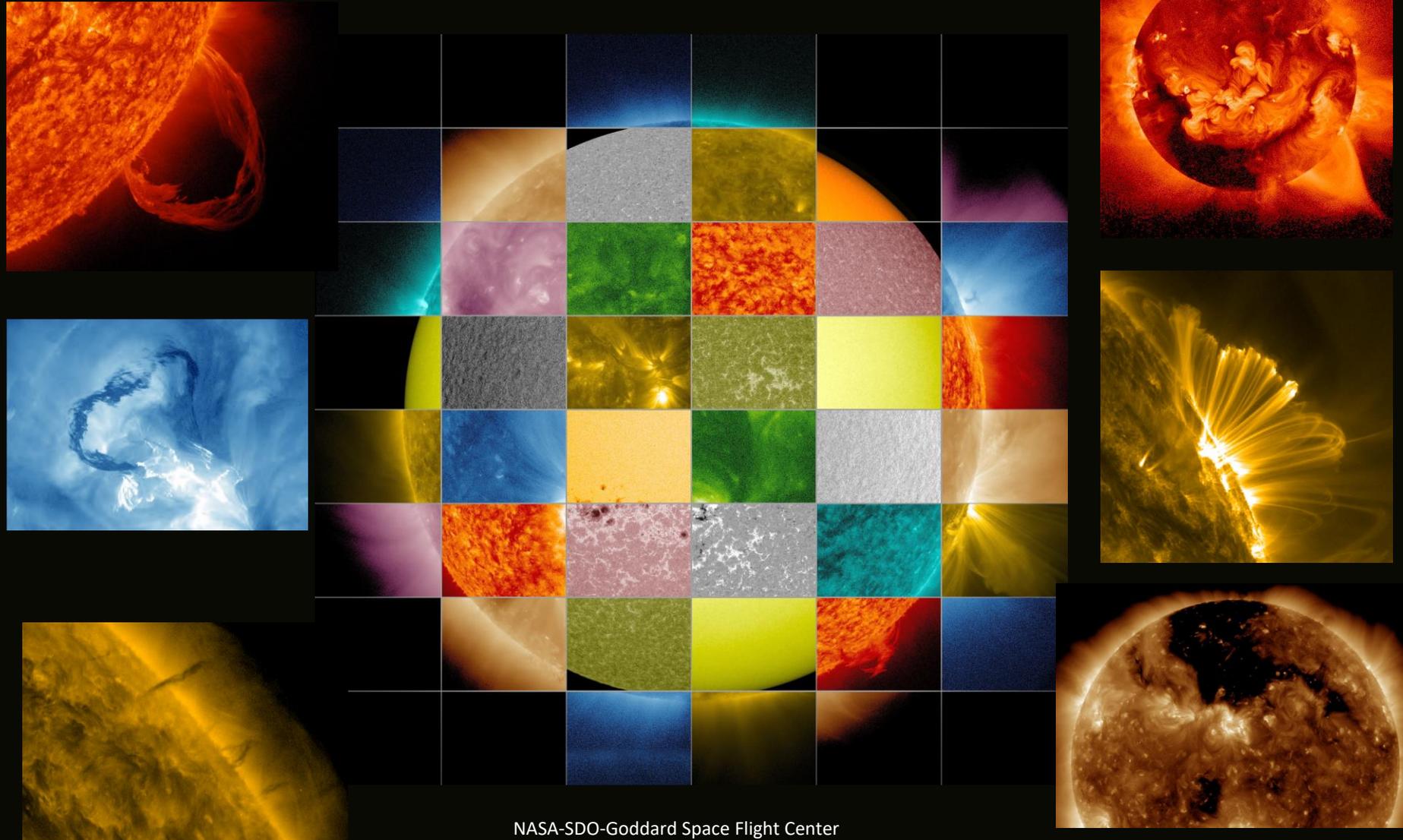




BOREXINO Collaboration, Nature 2014对太阳pp中微子的直接测量, 证实了太阳物理学家的标准太阳模型

# 太阳高能活动

## 多波段中丰富的太阳活动现象



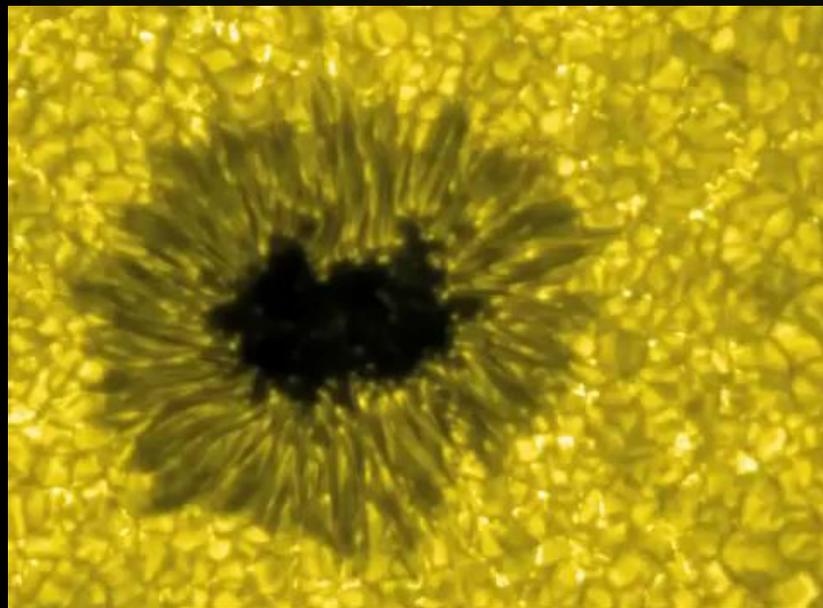
NASA-SDO-Goddard Space Flight Center

YOHKOH

- ◎ 中国古代有最早最详细的黑子记录
- ◎ 黑子、活动区、耀斑 密切相关

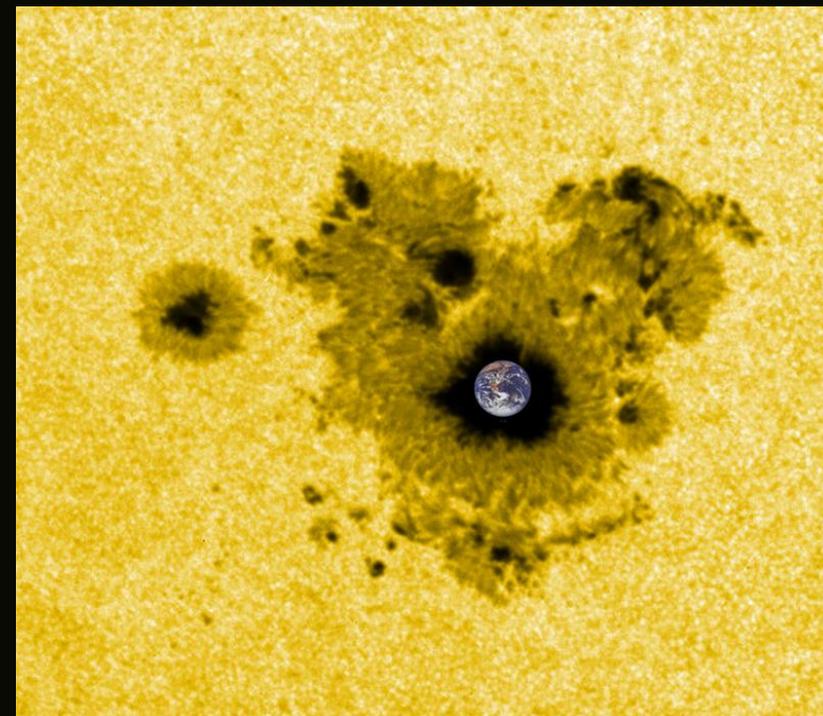


苏杨/南京/FZ1000

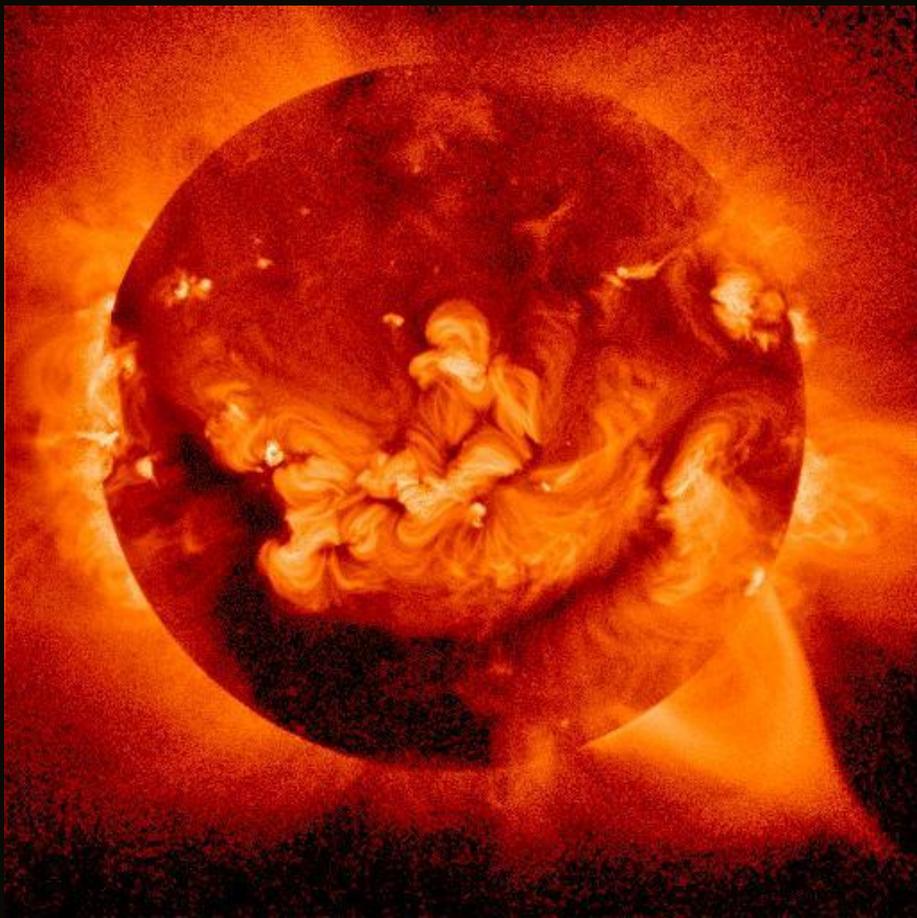


黑子和米粒组织

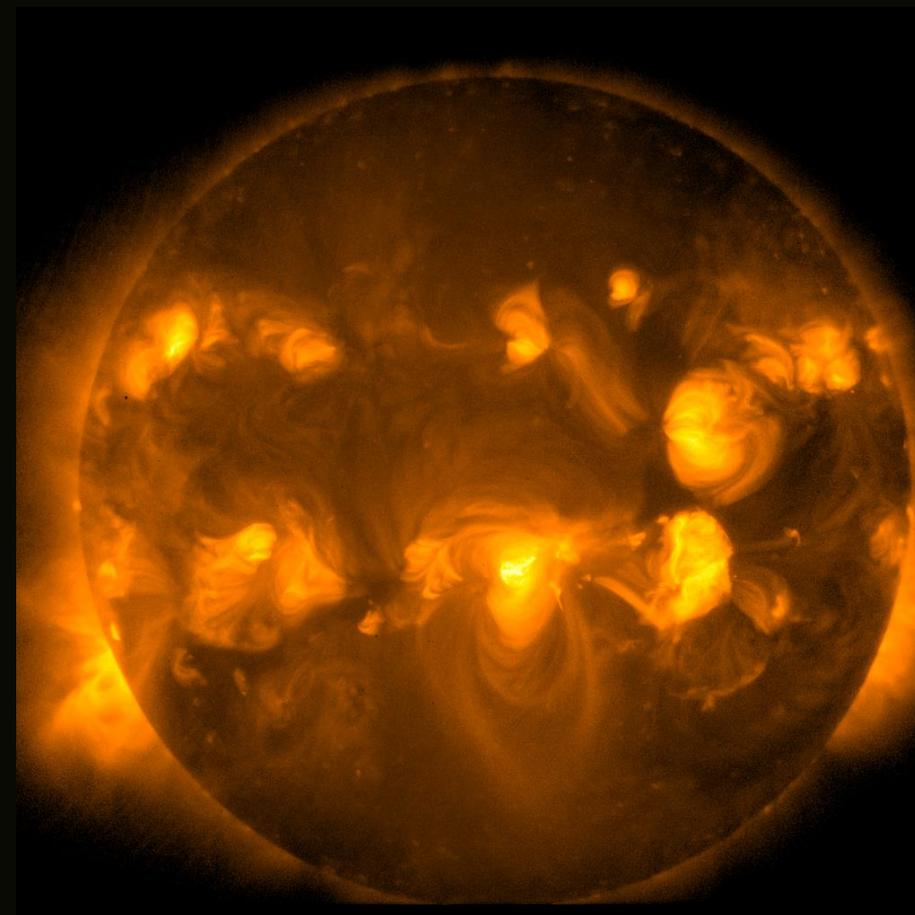
(G-band movie, 28 Aug 2007, Hinode/SOT)



黑子群 (TRACE, Apollo 17)



Yohkoh

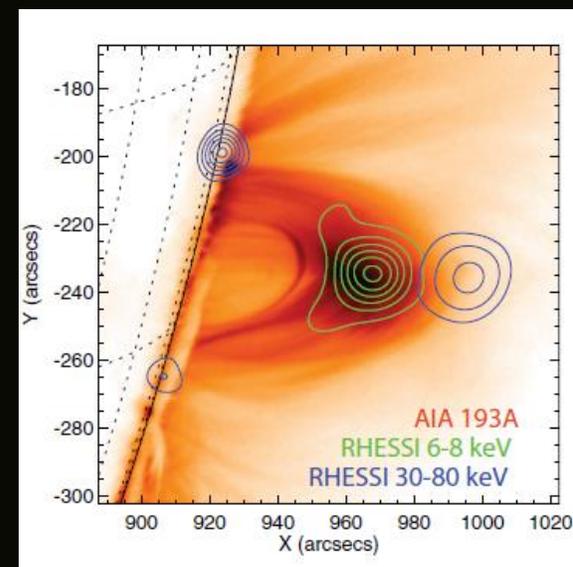
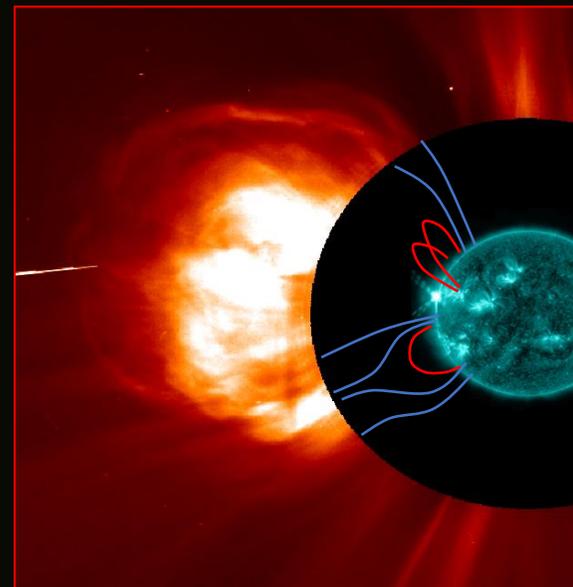


Hinode/XRT



### 高能辐射是能量释放和粒子加速的直接产物

- 研究太阳X射线，伽马射线，极紫外辐射（和射电辐射），及背后的物理过程
- 主要观测对象是太阳活动和爆发现象
  - 太阳耀斑 (flares)
  - 日冕物质抛射 (CME)
  - 太阳高能粒子事件 (SEP)
  - 活动区和日冕加热
  - 磁重联过程
  - 粒子加速，等离子体加热
  - 耀斑触发过程
  - ...



X射线成像和像谱, Krucker and Battaglia, 2014

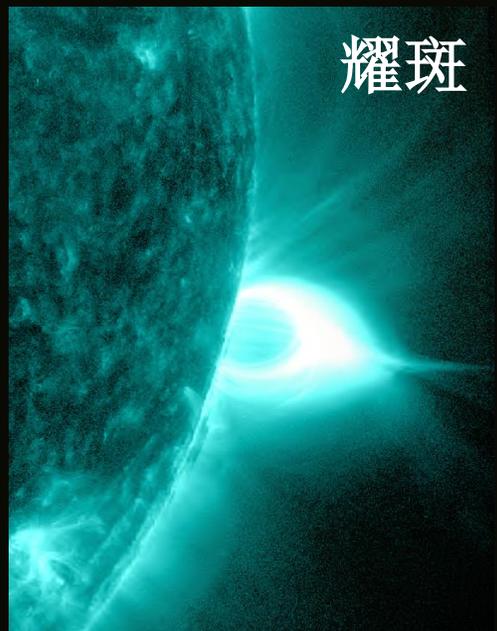
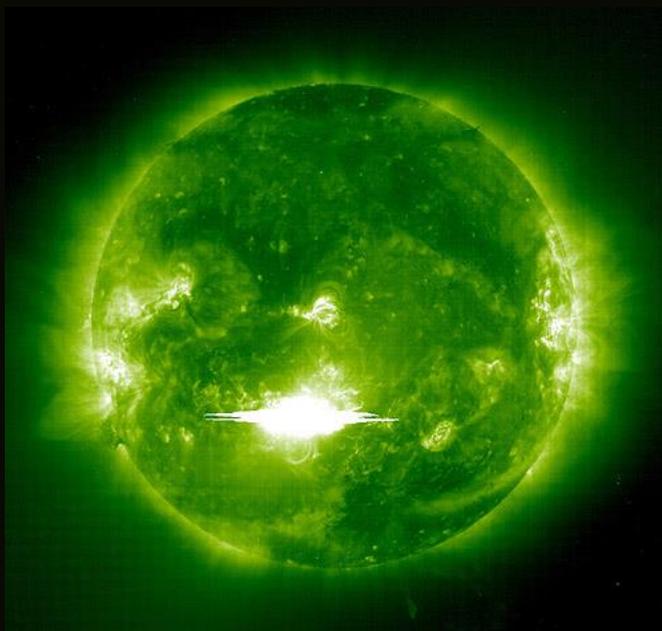
# 太阳高能活动

## 太阳爆发活动

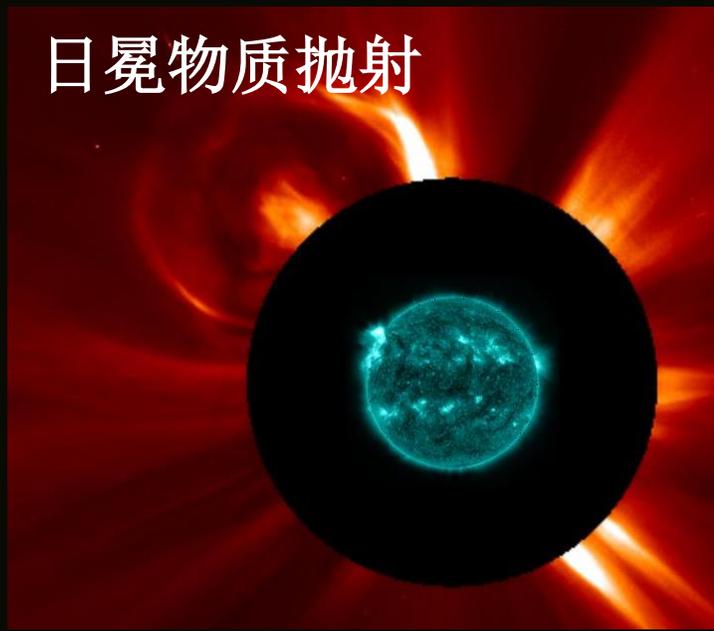
- 耀斑(flares), 日冕物质抛射 (CME) -> 太阳高能粒子事件 (SEP)
- 太阳系内最强烈的能量释放, 灾害性空间天气的主要源头

能量可达上百亿颗氢弹  
温度可达几千万度

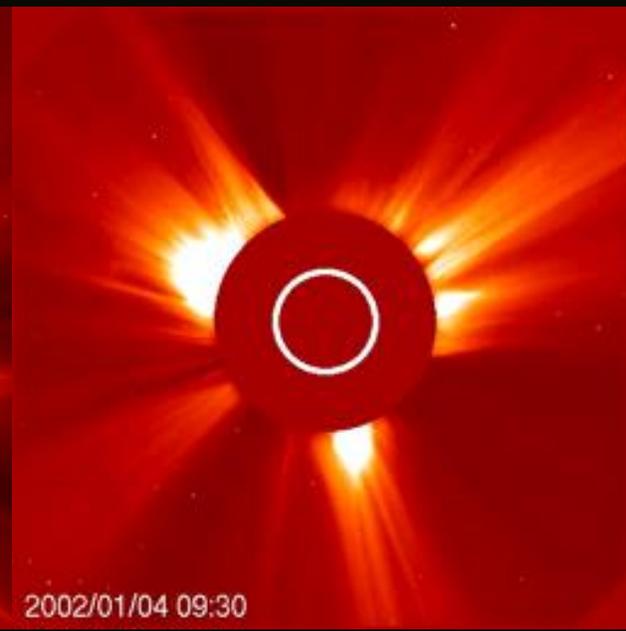
速度可超过3000 公里每秒  
质量可达上百亿吨

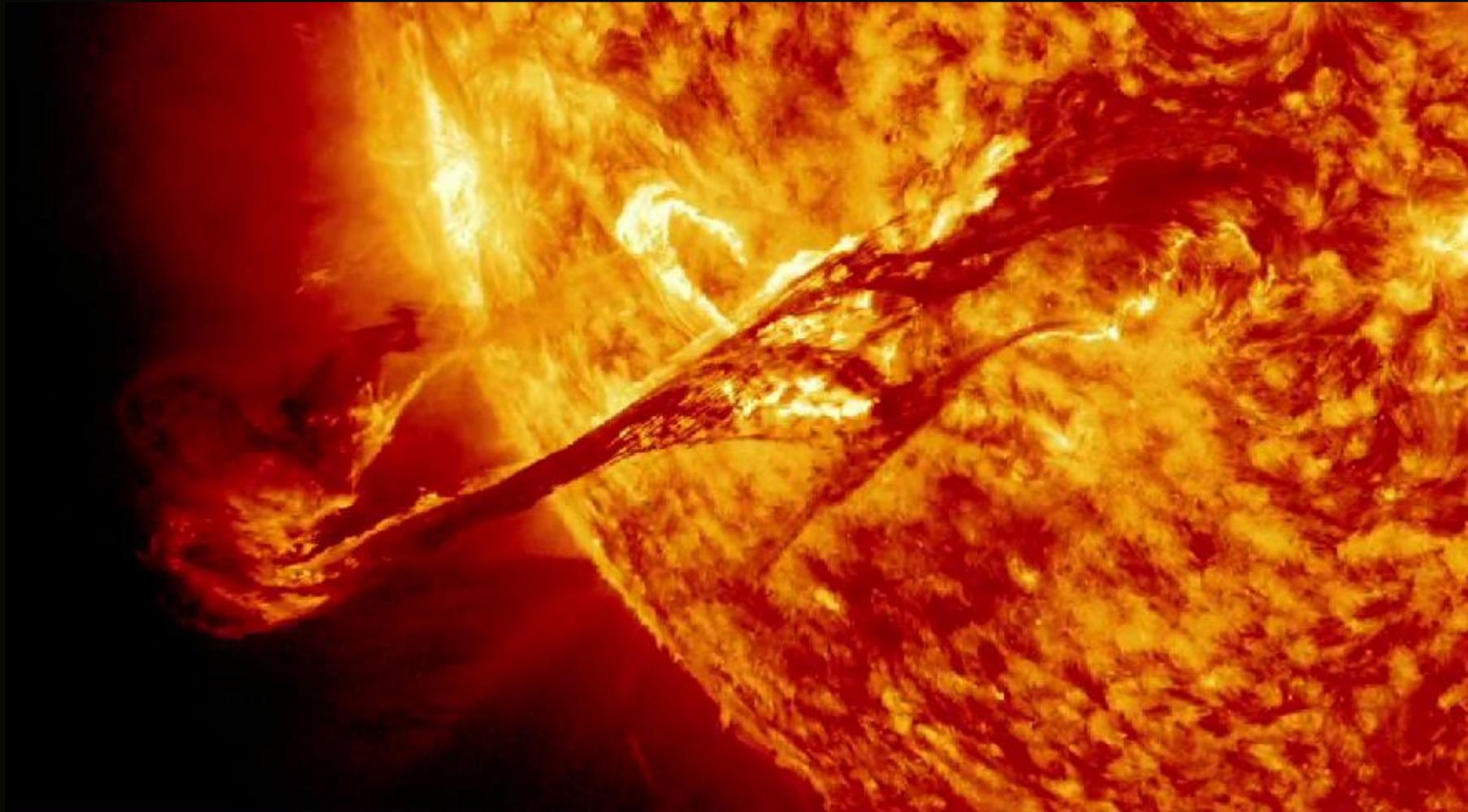


耀斑



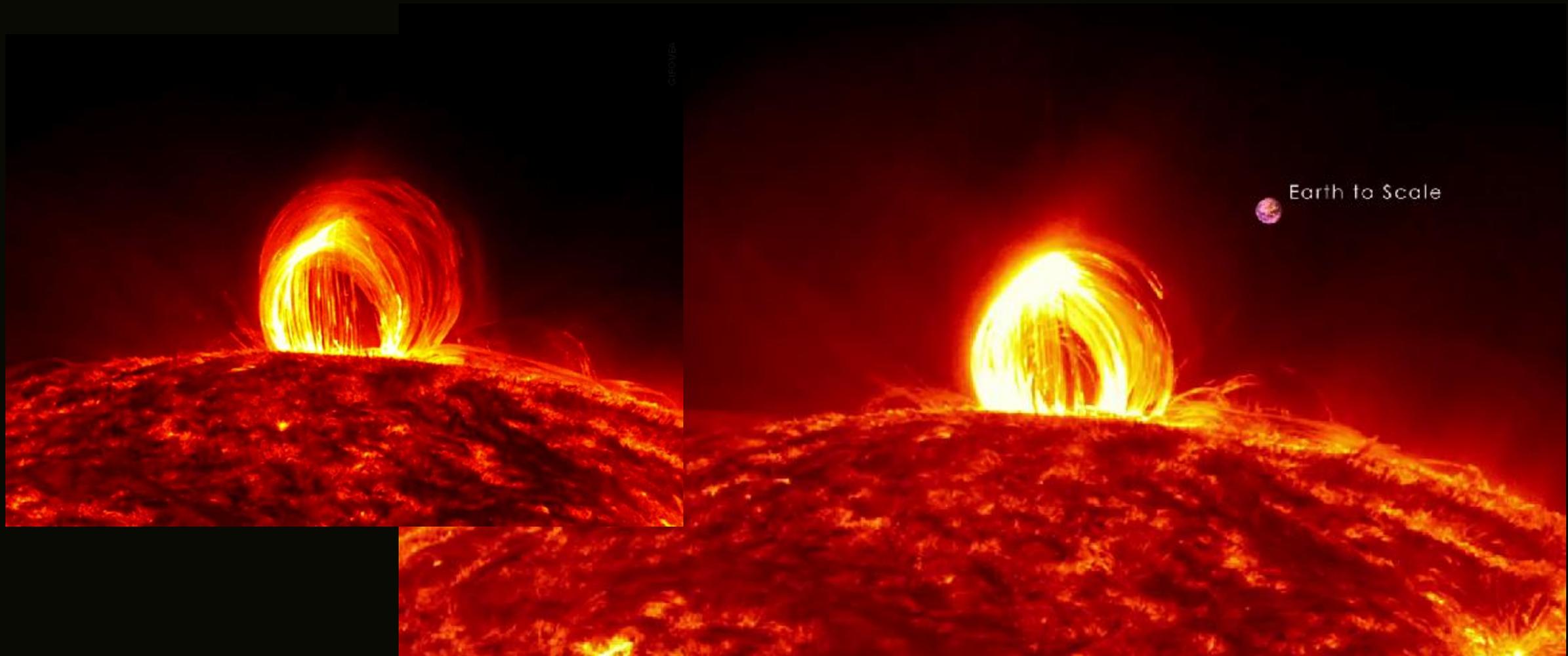
日冕物质抛射





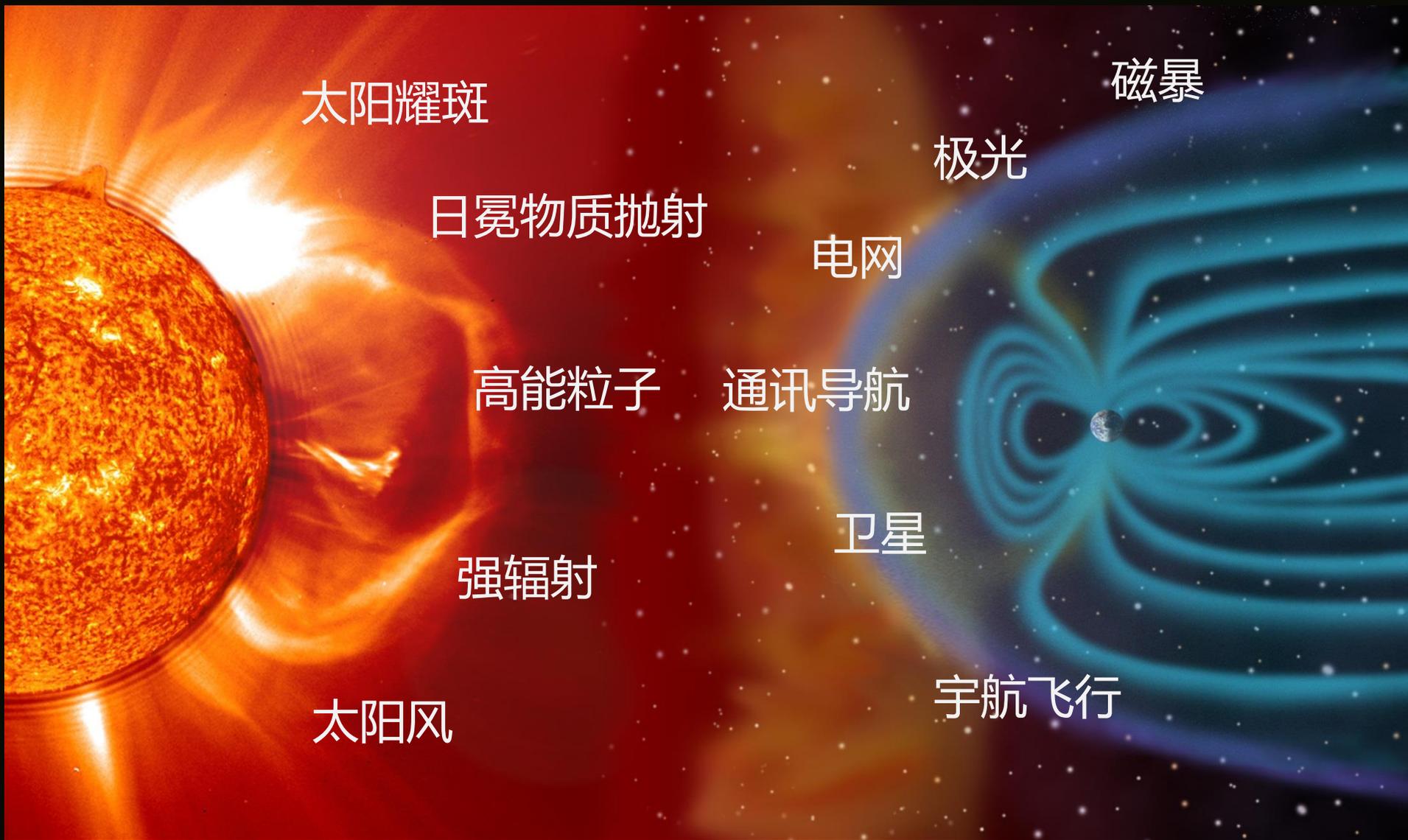
暗条爆发形成CME (August 31, 2012, NASA/GSFC, SDO)  
流浪地球 电影开篇同款爆发

耀斑环和冕雨 (NASA, SDO)



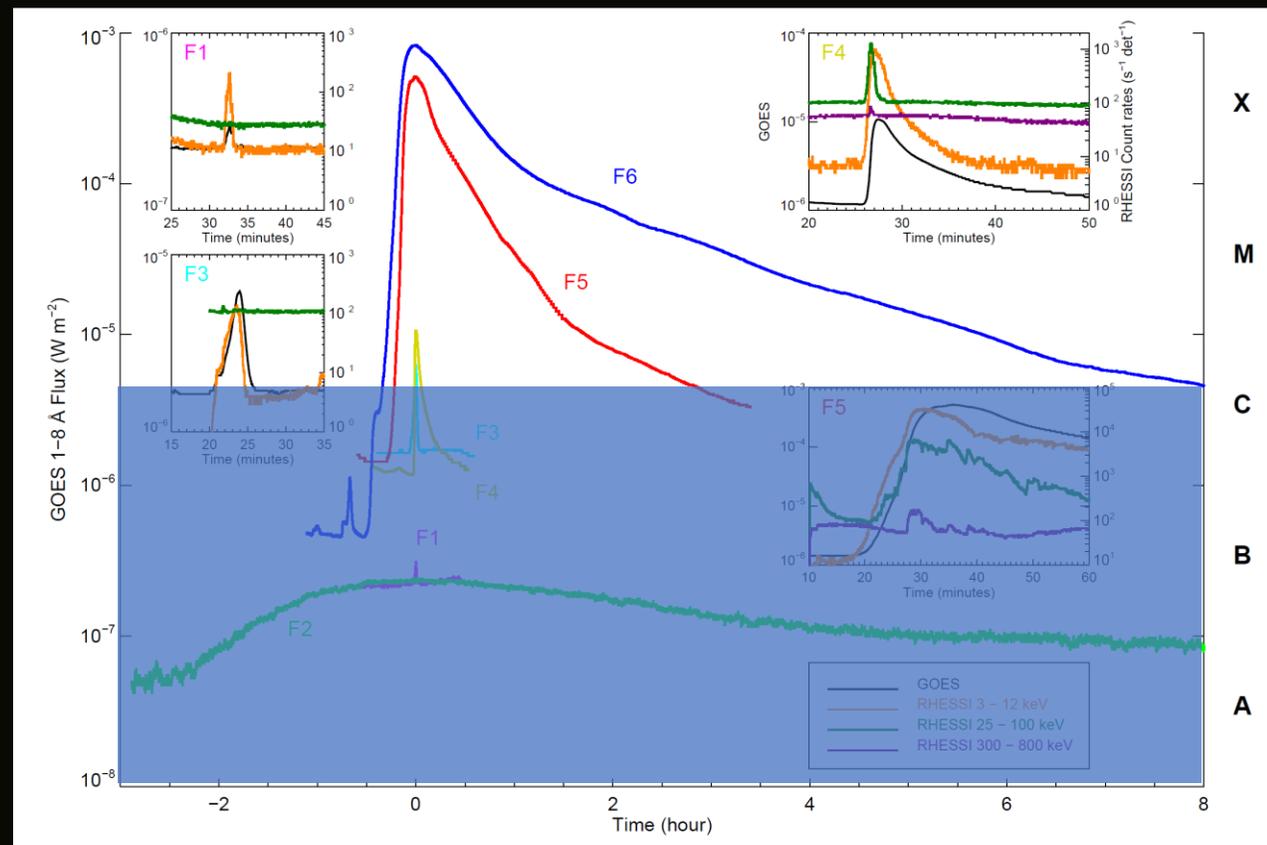
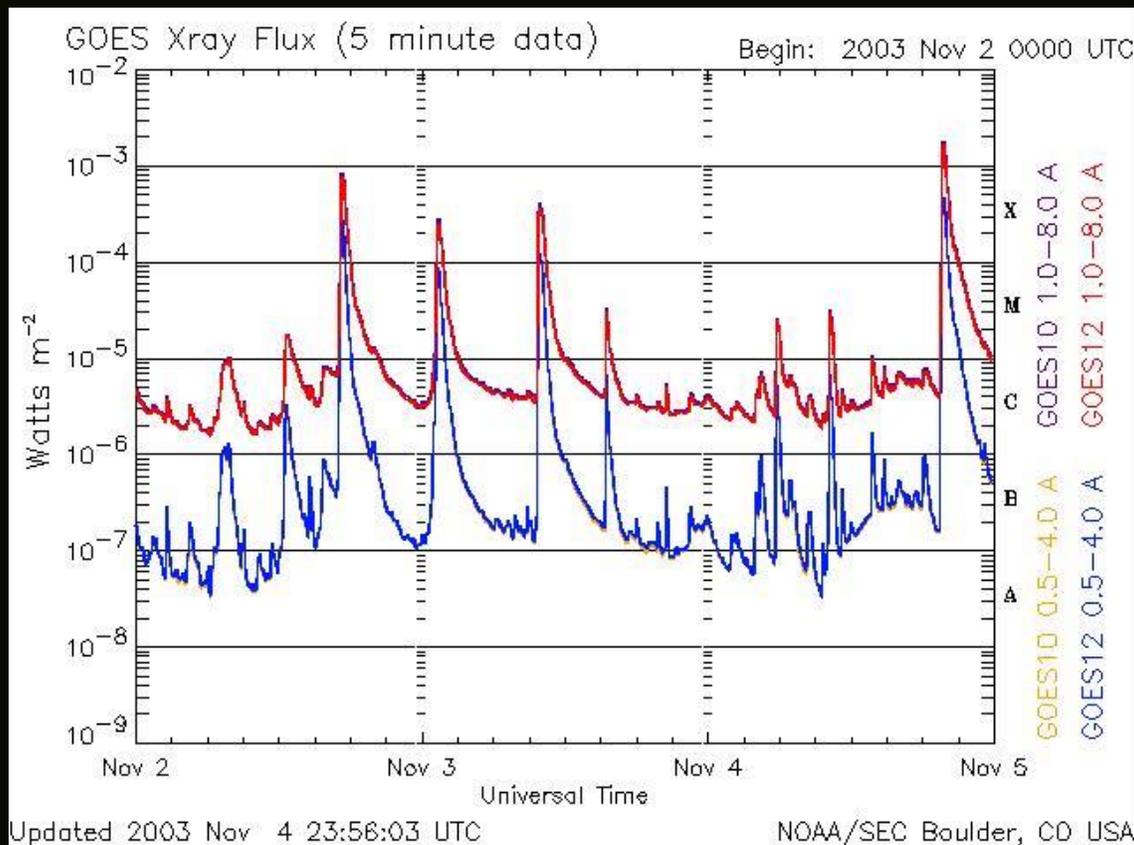
# 太阳高能活动

## 太阳爆发和空间天气



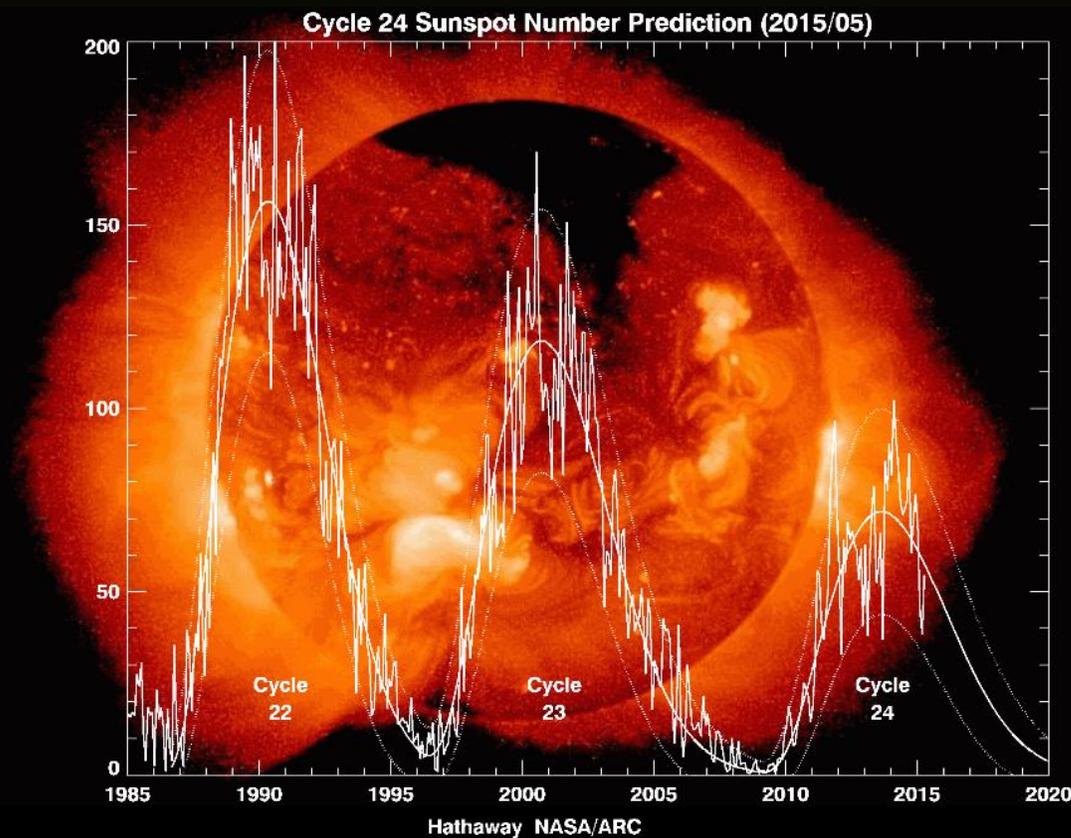
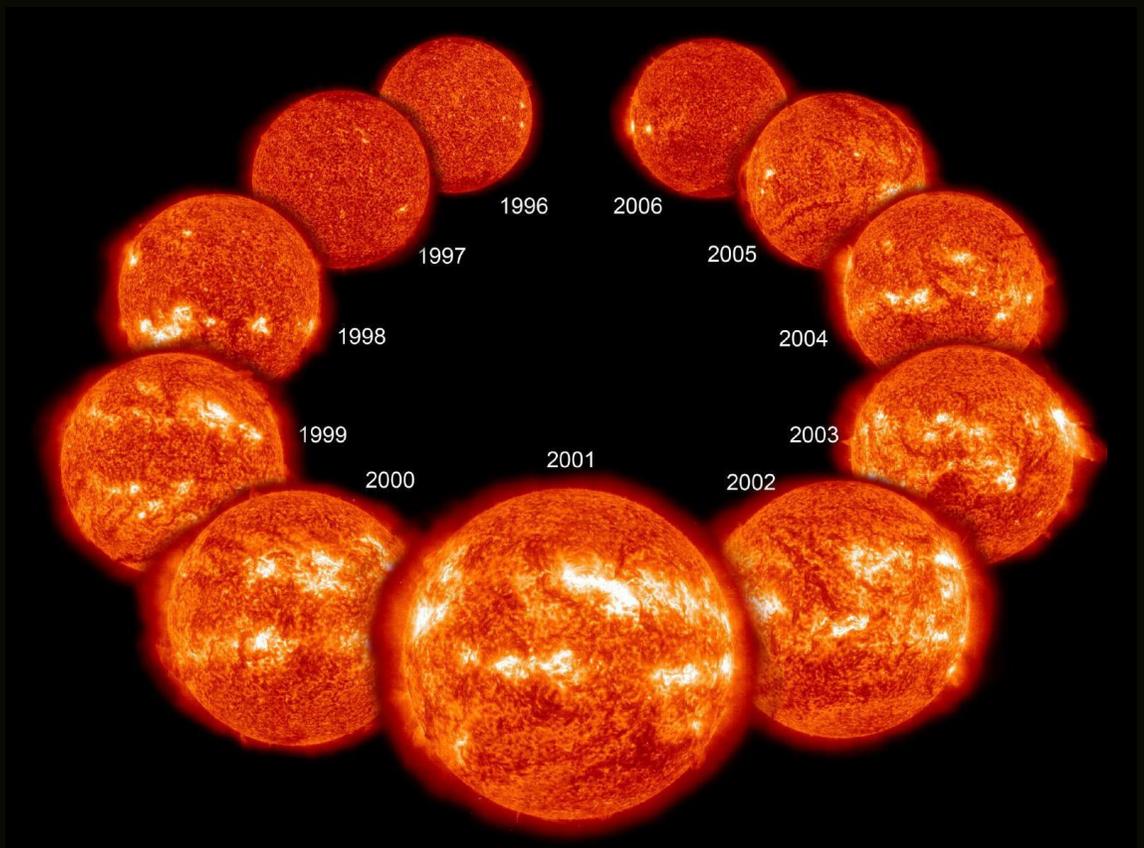
- 典型耀斑:  $10^{27}$  ergs/s, 大耀斑可释放  $10^{32}$  ergs
- 耀斑级别: GOES 1-8 Å 流量: A, B, C, **M**, **X**

## 耀斑的多样性



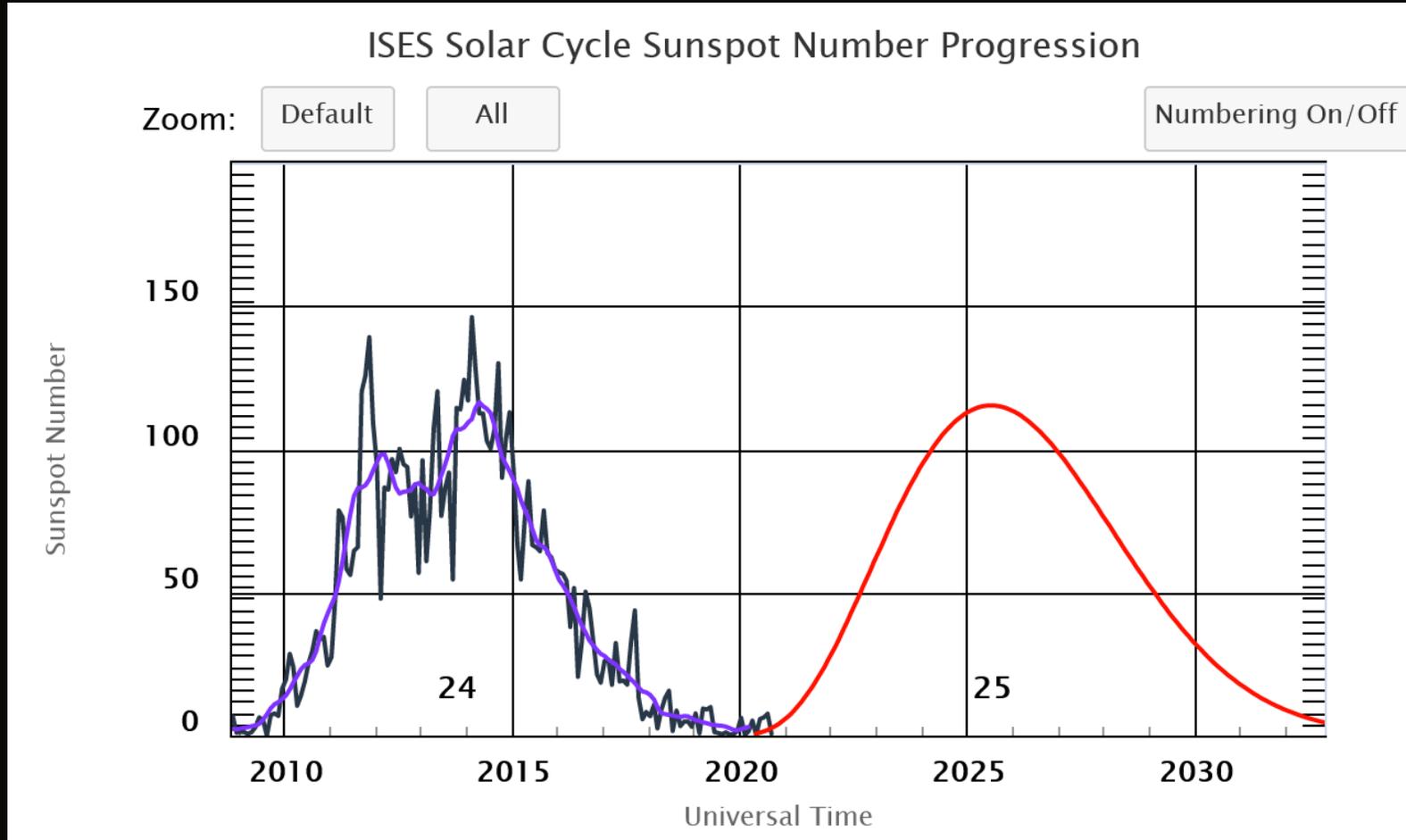
苏杨, 等 (2020, 中国科学)

~11年的太阳活动周期

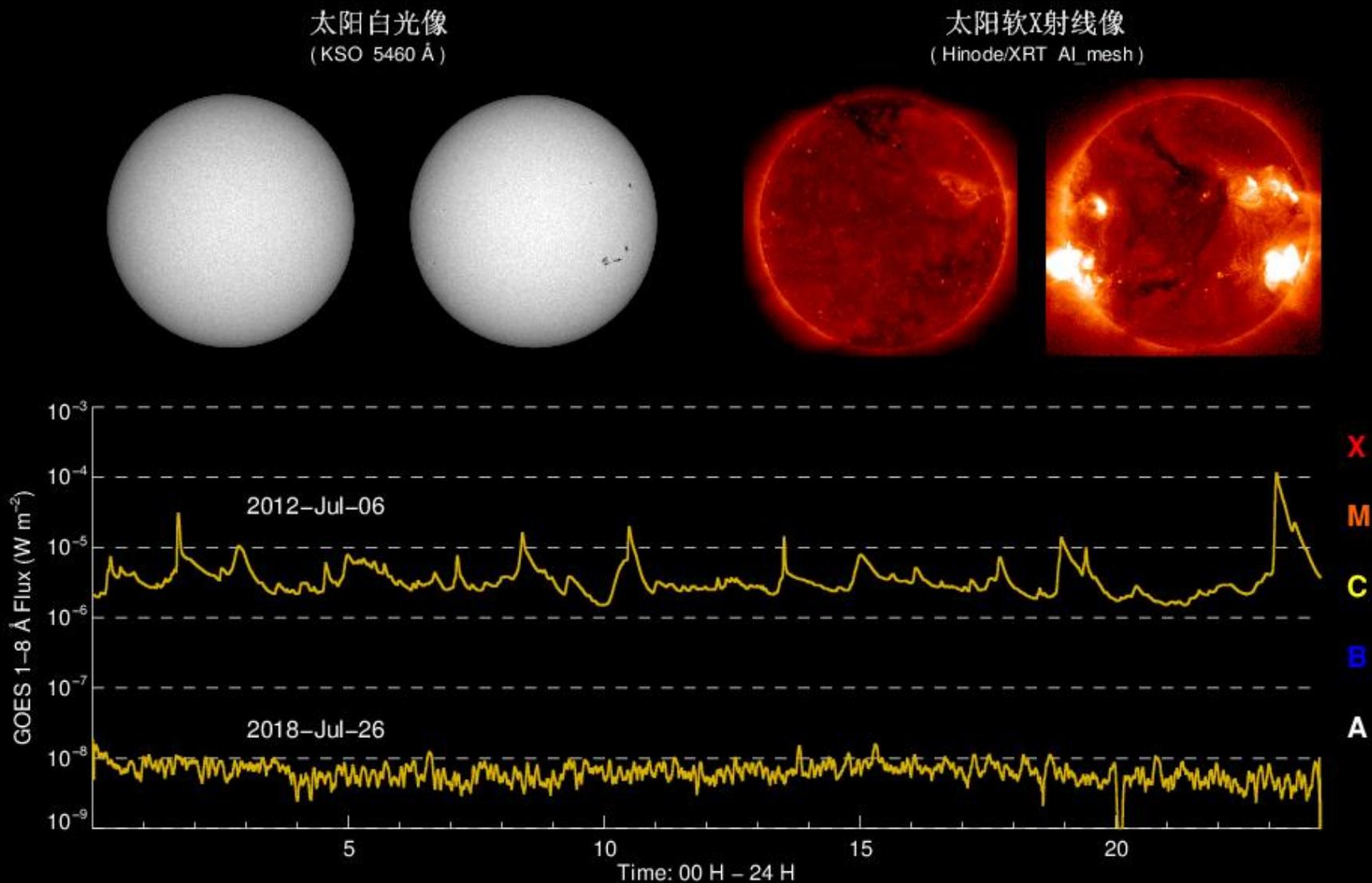


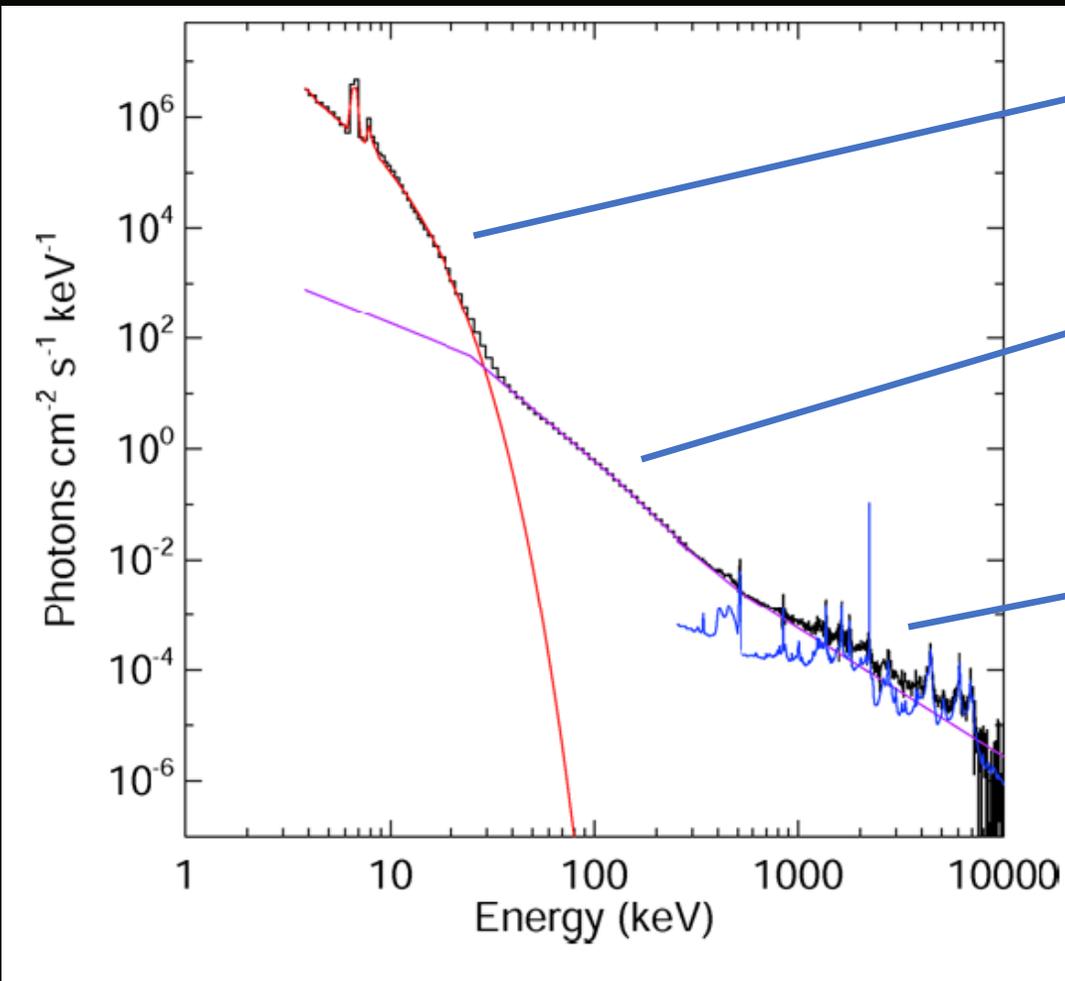
2012-2018 RHESSI 共记录 >12万个X射线事件 (偏多)

2009-2019 GOES 共记录 >13800个耀斑 (偏少)



太阳活动宁静期和活跃期的比较, 苏杨, 等 (2020, 中国科学, GECAM专辑)





**热轫致辐射和谱线:**

~6百万到几千万度的等离子体

**非热轫致辐射:**

加速的高能电子

**伽马射线连续谱和谱线:**

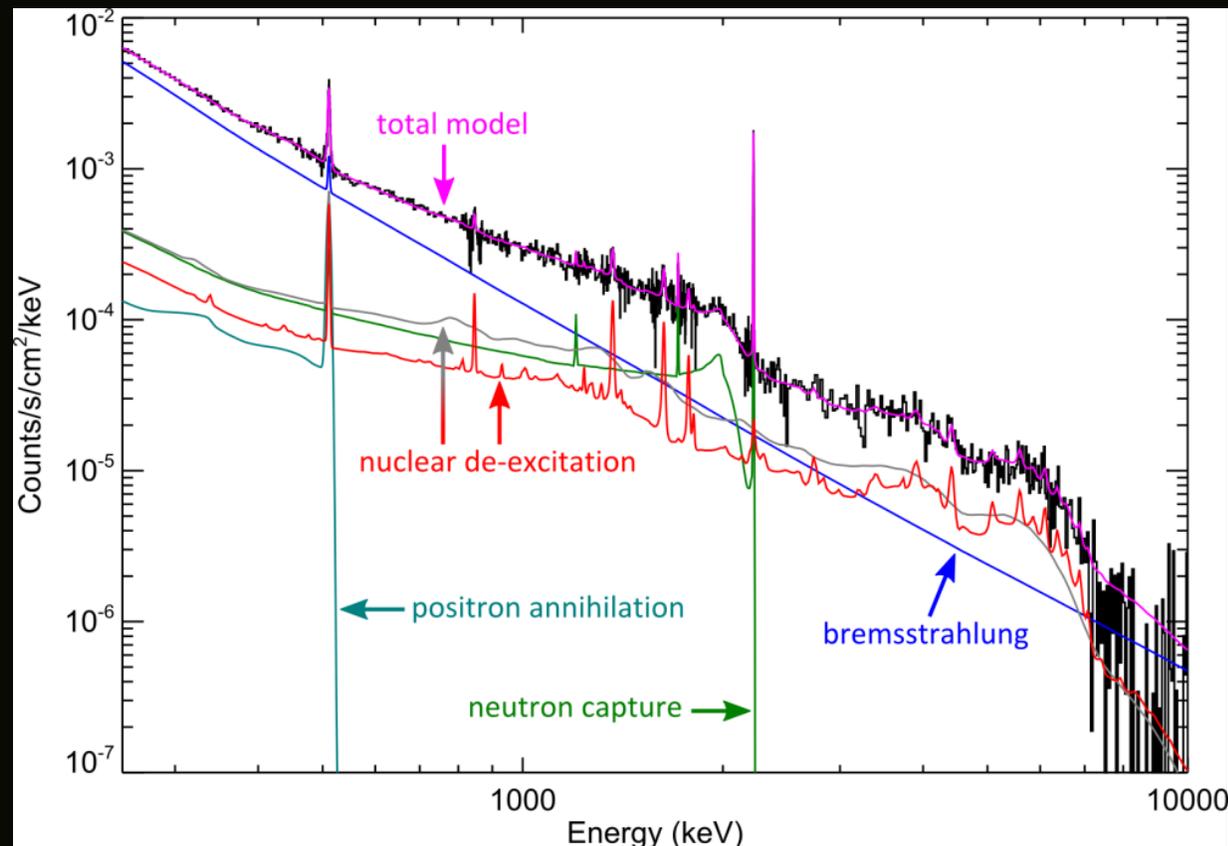
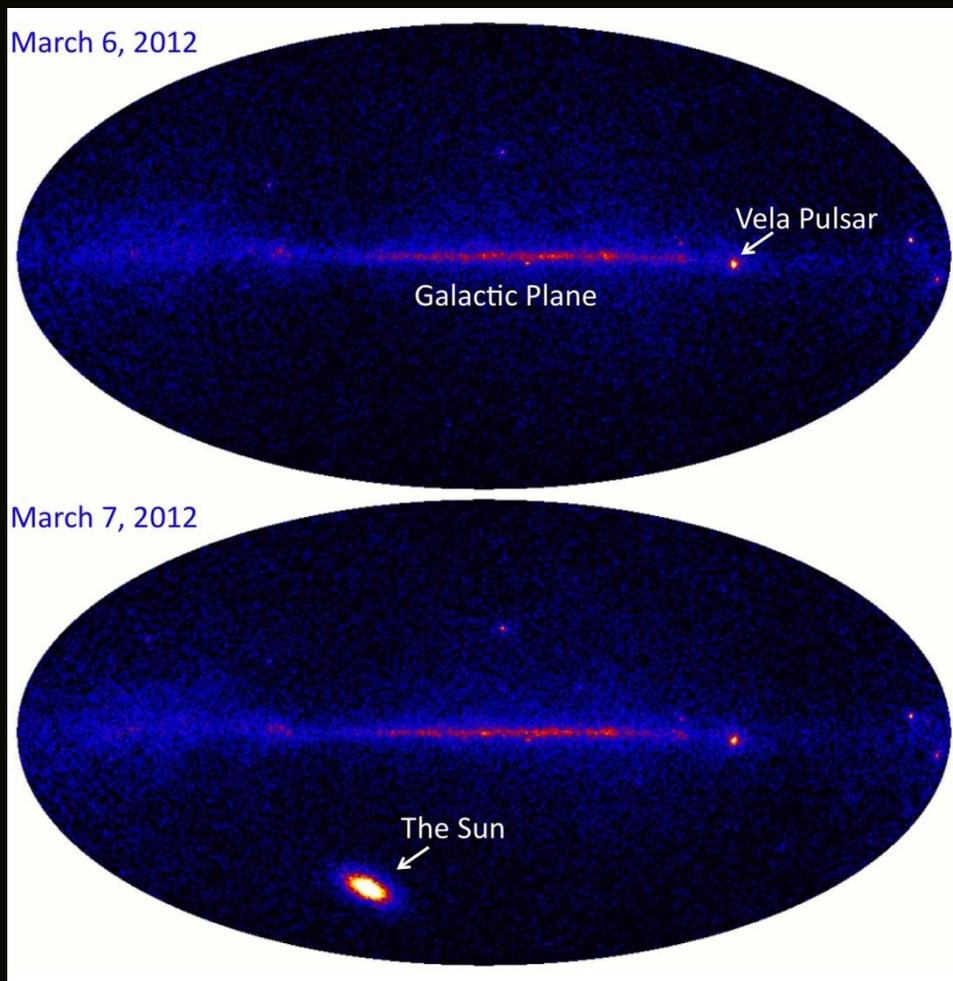
加速的高能电子和离子

John C. Raymond et al. 2012, Lin 2011

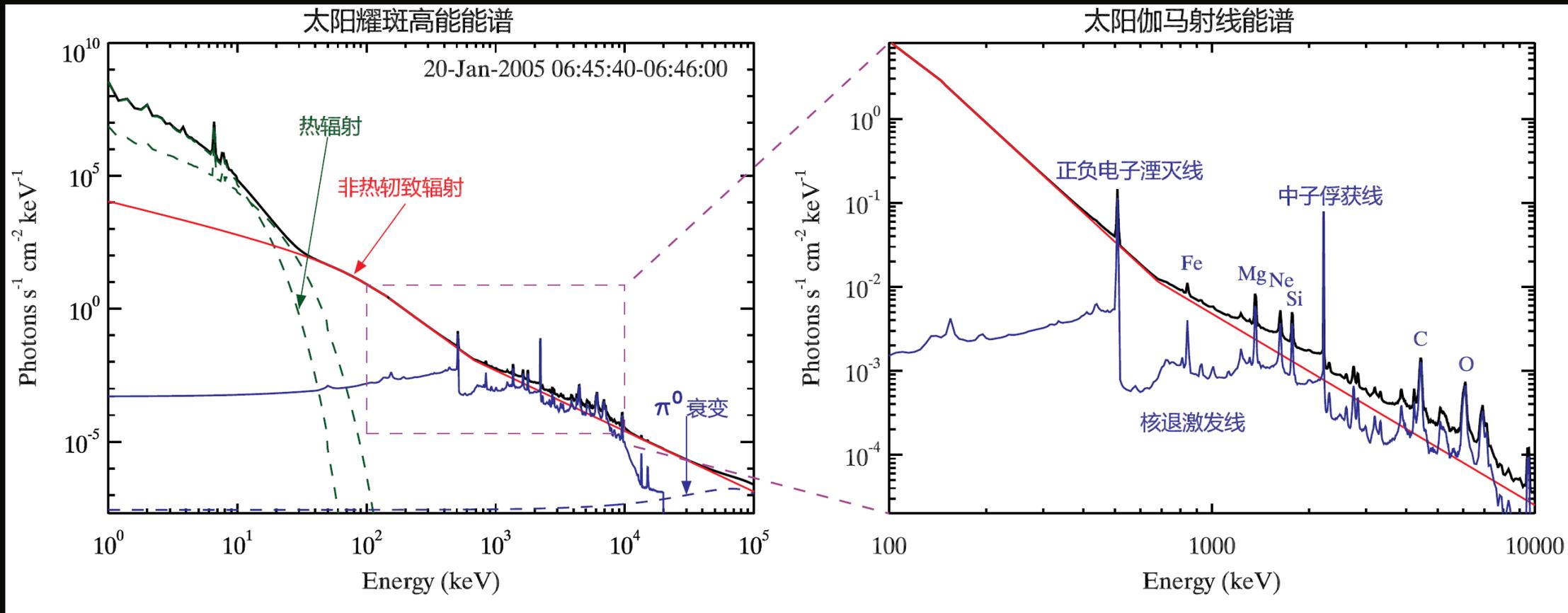
- 伽马耀斑期间，太阳是最亮的Gamma射线天体（近）

## RHESSI著名成果之一

- Highest Resolution Gamma-Ray Spectrum
- (Smith et al. 2003, *Astrophysical Journal*, 595, L81)

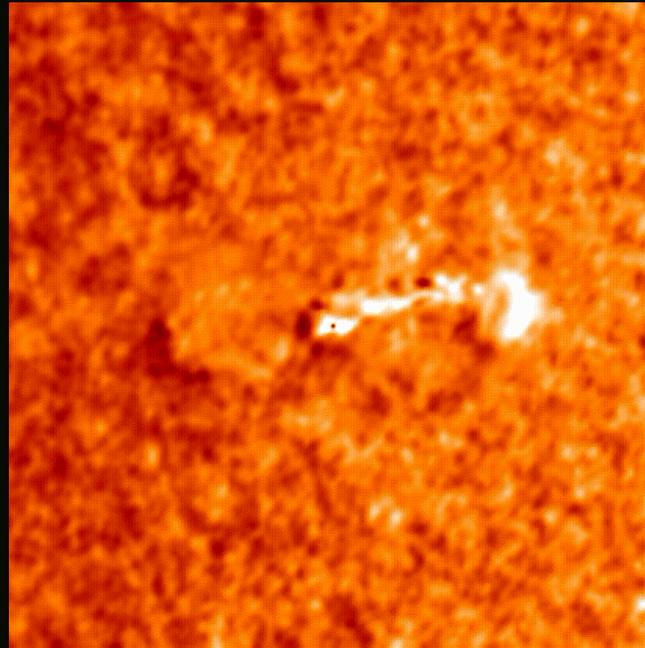


## 太阳耀斑高能能谱 (苏杨, 陈维, 等, 2020 中国科学)

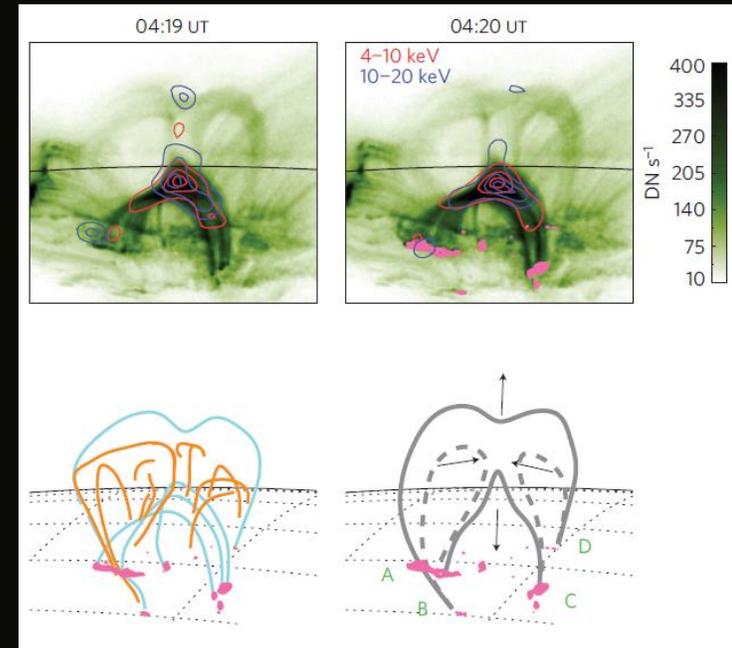


- 磁重联中的系列问题
- 粒子加速系列问题
- 日冕加热
- QPP振荡, 毫秒级尖峰结构
- 日震, 白光耀斑, 太阳射电暴
- 行星际激波, 质子加速, SEP
- 伽马射线辐射系列问题
- 太阳极高能事件 (超级耀斑) 的可能性

耀斑 造成 日震 (SOHO卫星)  
Kosovichev et al. Nature 1998



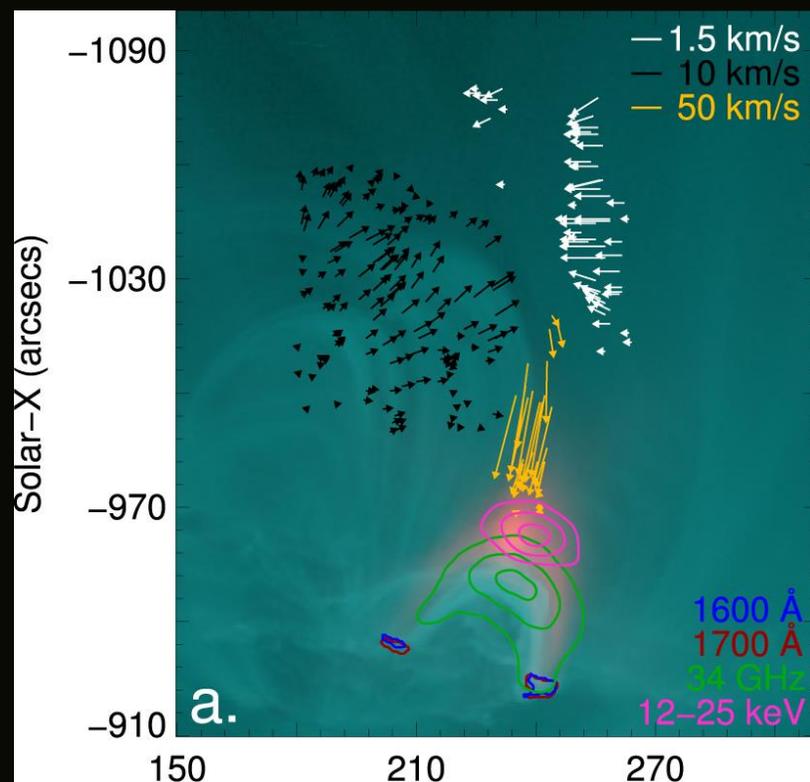
首次系统性证实耀斑磁重联过程  
Su et al. 2013, Nature Physics



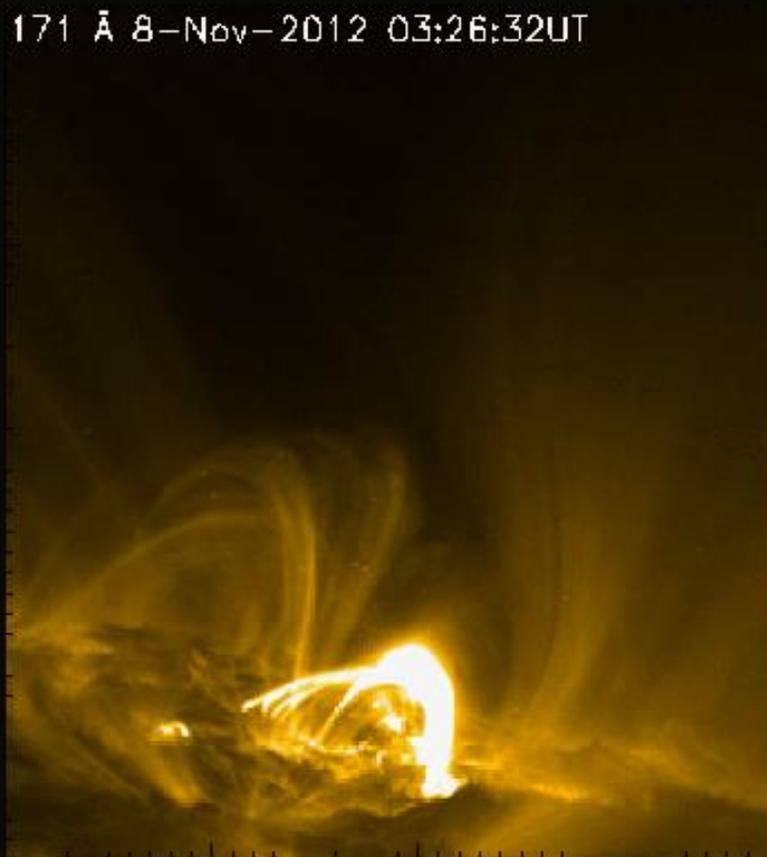
磁重联的例子, Sun et al. 2016

1-2 MK

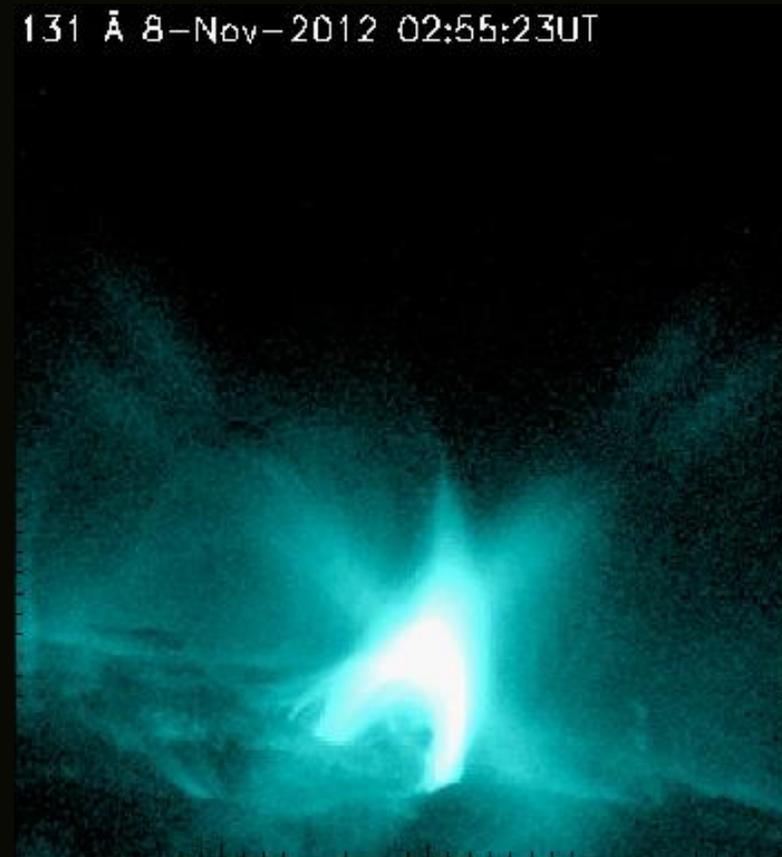
~11 MK



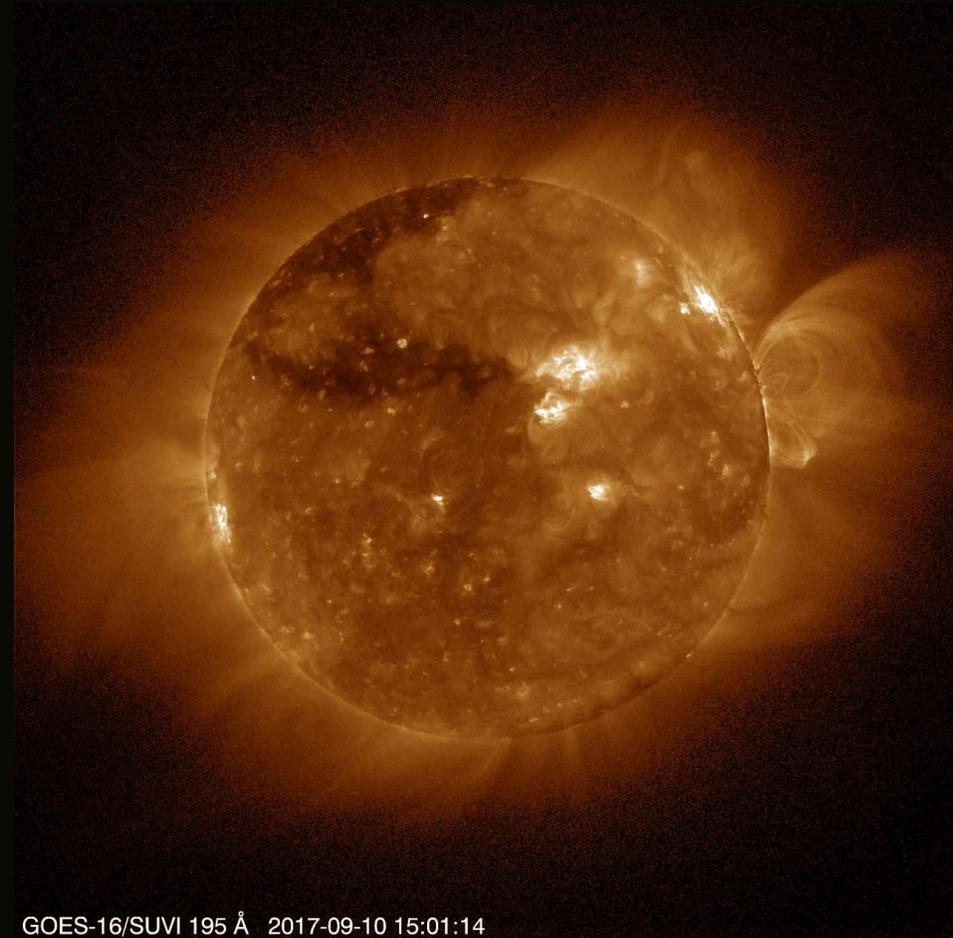
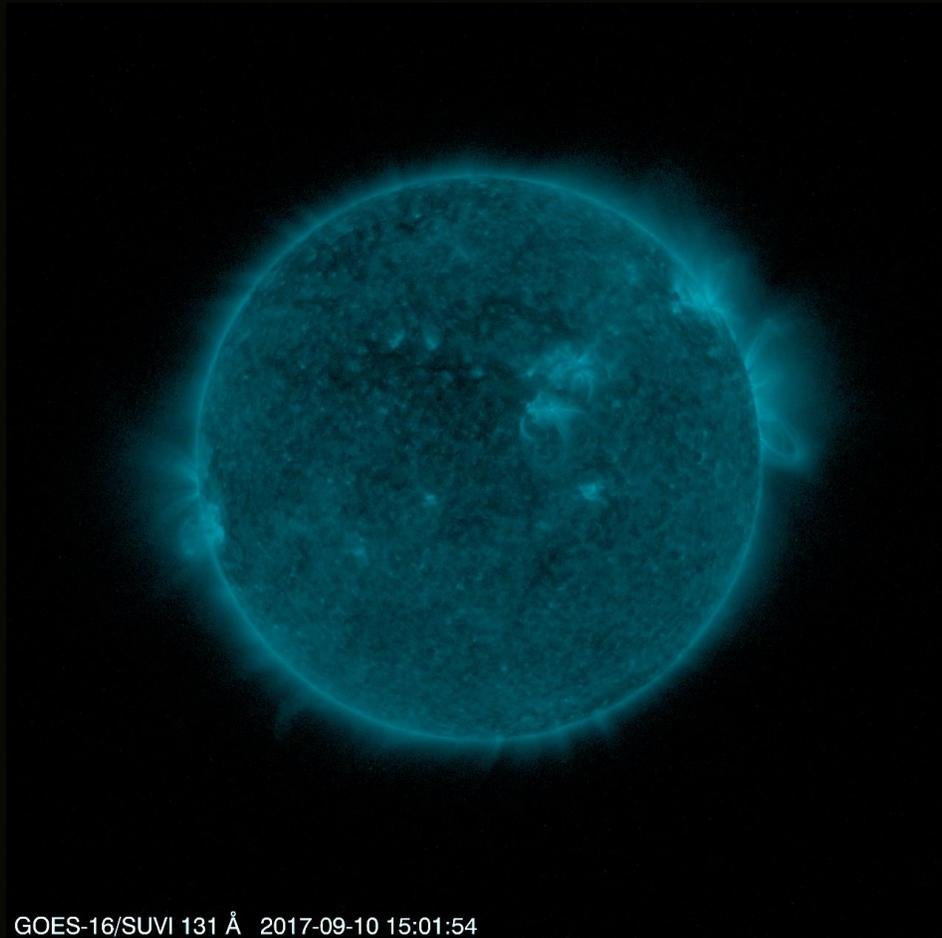
171 Å 8-Nov-2012 03:26:32UT



131 Å 8-Nov-2012 02:55:23UT



- Seaton and Darnel 2018, 著名的2017年9月10号耀斑



GOES/SUVI

一批重量级设备：Solar Orbiter, PSP, NSF Daniel K. Inouye Solar Telescope (4米), SDO, ...

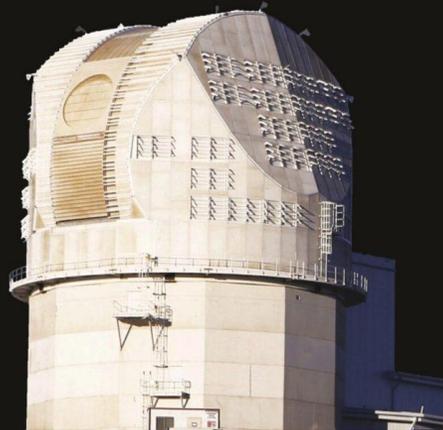
## 2020: A NEW ERA OF SOLAR ASTRONOMY

Working together  
to study the Sun

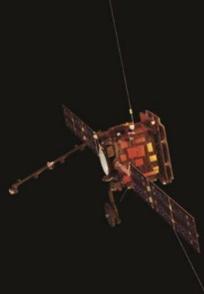
A new era for solar astronomy is dawning, specifically because of three separate observation initiatives. Each is equipped with the necessary tools and located where they can best achieve those goals. Ultimately, because of their different, yet complementary approaches to studying the sun, these efforts led by the National Science Foundation, NASA and the European Space Agency, will augment what each can do, making robust scientific endeavors even better. Together, they create a comprehensive understanding of our sun.

	NSF's Daniel K. Inouye Solar Telescope	ESA/NASA Solar Orbiter	NASA Parker Solar Probe
<b>Mission</b>	Ground-based remote observation and mapping	Space-based measurements	Space-based measurements
<b>Research goals</b>	Map Sun's surface & its atmospheric magnetic fields, especially the inner corona, where solar storms begin	Make detailed measurements of the solar wind, which is responsible for sending problematic radiation towards Earth	Probing the Sun's outer corona (part of its atmosphere) to understand origins of the solar wind
<b>Closeness to Sun</b>	91 million miles (Earth)	35 million miles (similar to distance of Mercury)	4 million miles (nearest to Sun)
<b>Length of Mission</b>	44 years	7 years	7 years
<b>Telescope Size</b>	4m	12.5cm (equivalent to 50cm telescope on Earth)	No telescope observing Sun's surface
<b>Image resolution</b>	Can clearly resolve solar features the size of 330 football fields	Can clearly resolve solar features the size of 2,200 football fields	n/a

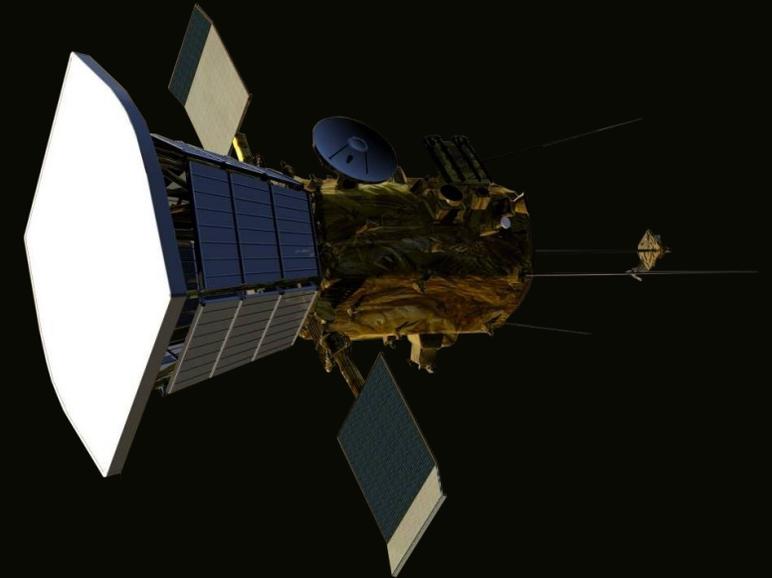
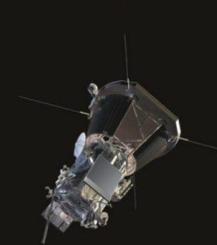
NSF's Daniel K. Inouye Solar Telescope



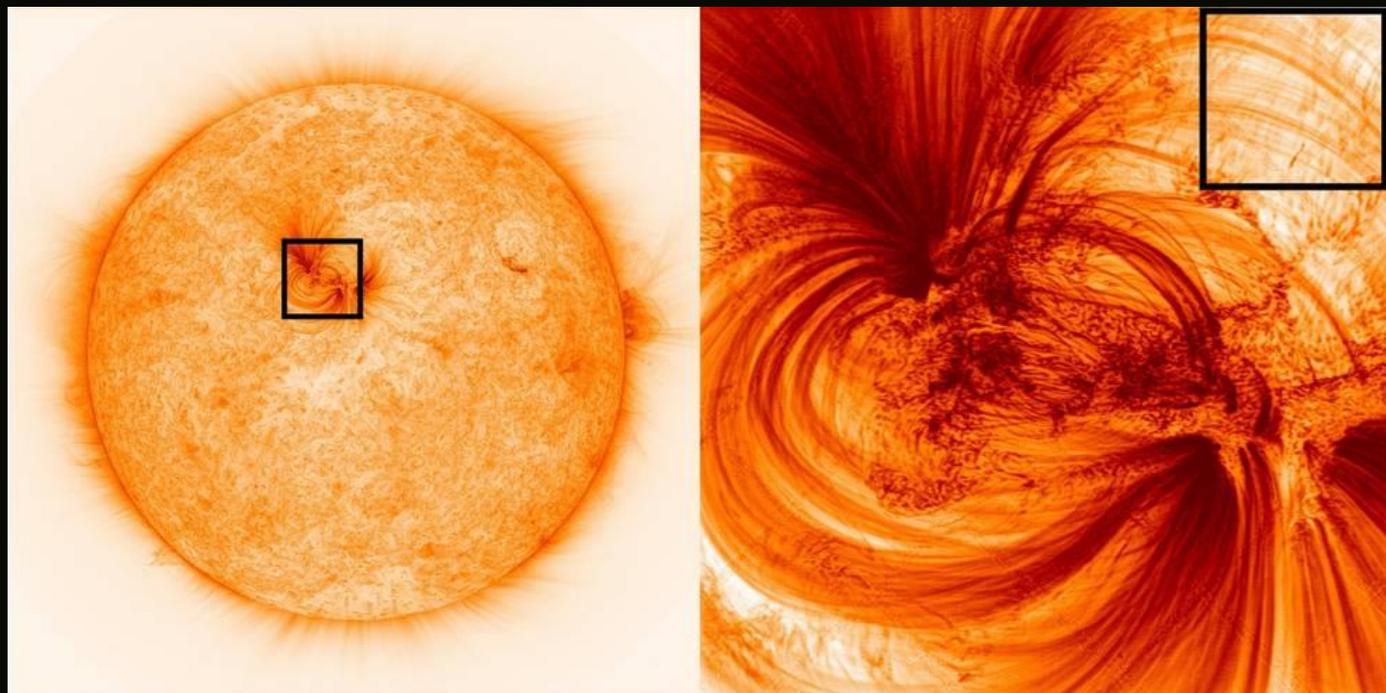
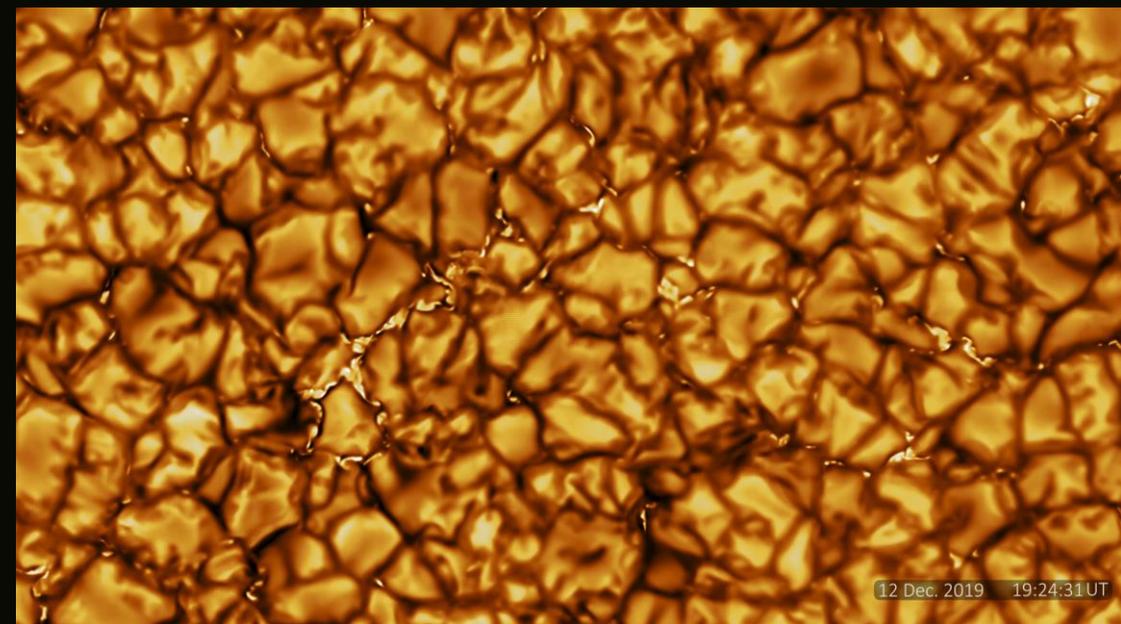
ESA/NASA Solar Orbiter



NASA Parker Solar Probe



- 地面观测最高分辨率图像：（4米）  
27 x 15 arcsec  
Credit: NSO/NSF/AURA
- 紫外空间观测最高分辨率：日冕环精细结构（ $<0.25$ 角秒）
- Hi-C telescope, 探空火箭2018  
Credits: NASA/University of Central Lancashire, Williams et al. 2020



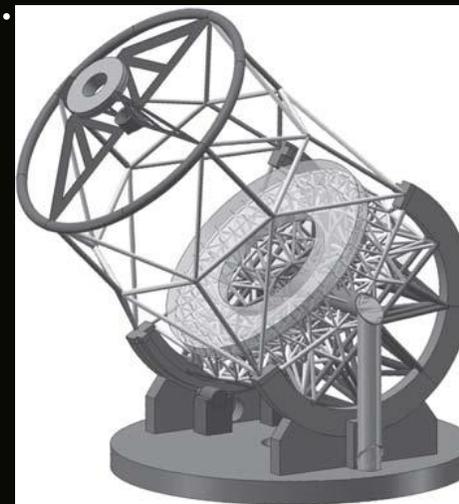
国内：ASO-S, CHASE, NVST, ASO-G, 怀柔, 2米环...



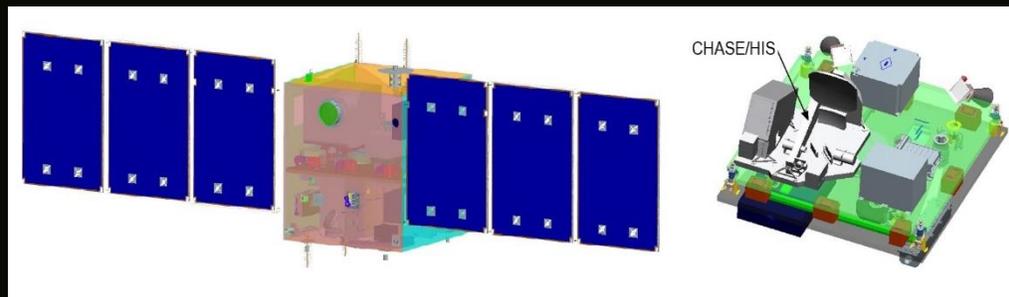
**ASO-S**  
先进天基太阳天文台  
中科院紫金山天文台等



**NVST**  
1米新真空太阳望远镜  
云南天文台抚仙湖



**CGST (ASO-G)**  
8米中国巨型太阳望远镜  
现行方案  
刘忠, 等, 2019



**CHASE**  
太阳H $\alpha$ 波段光谱成像  
航天八院、南京大学

1960s

1970s

1980s

1990s

2000s

2010s

2020s

2030s

## 国外部分卫星/仪器

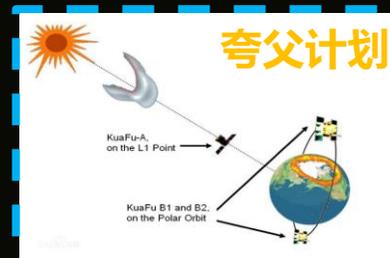


**FIERCE, FOXSI**



## 国内太阳观测卫星

天文卫星1号  
空间太阳望远镜  
(SST)  
SMESE



下一代  
预研中

- 高能辐射来自太阳爆发能量释放的直接产物，非常有效的诊断工具
  - 高温等离子体，高能粒子
- 向来是空间观测任务的重点之一

YOHKOH  
(1991)



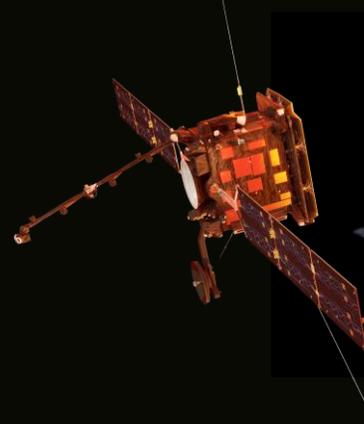
RHESSI  
(2002)



Hinode  
(2006)

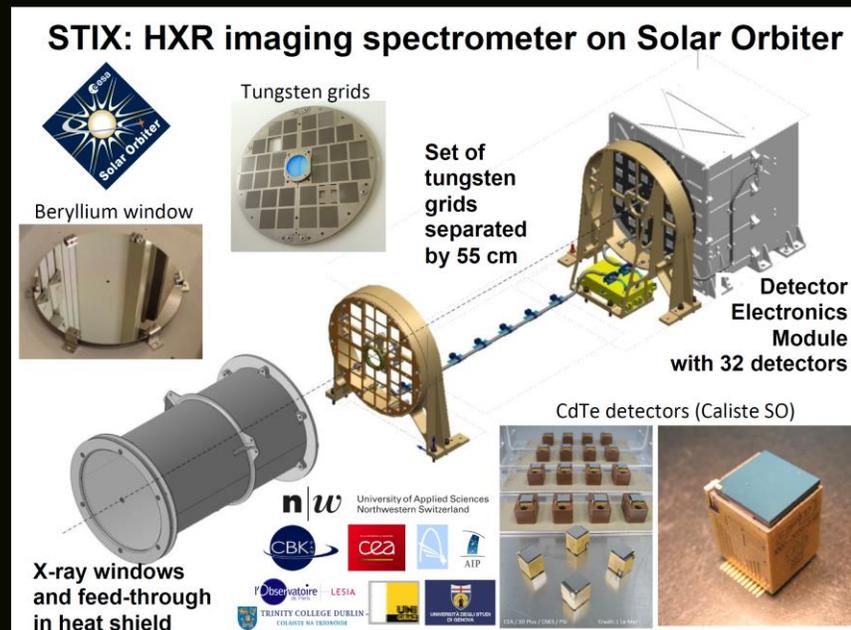
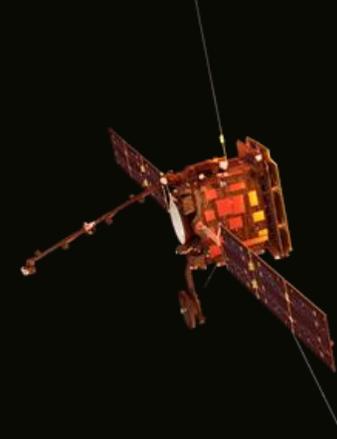
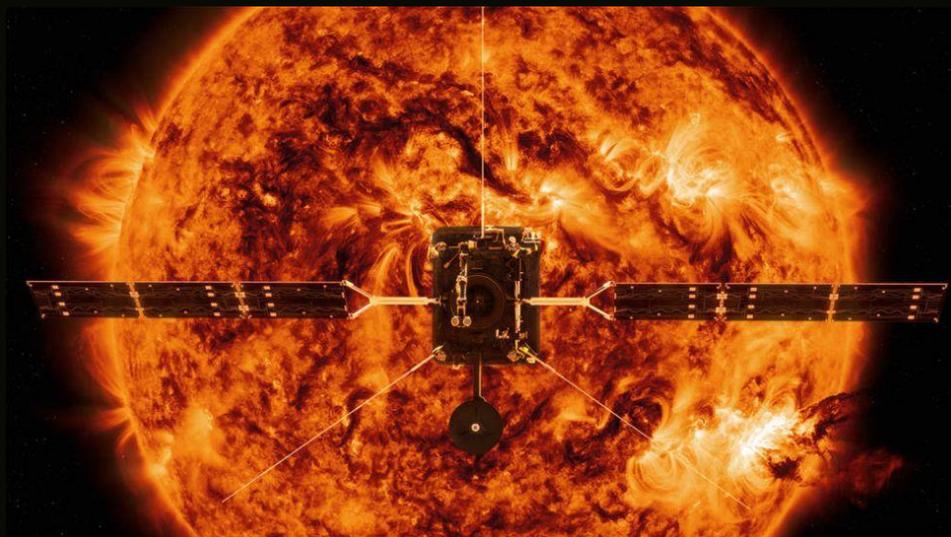


Solar Orbiter  
(2020)



ASO-S  
(~2022)



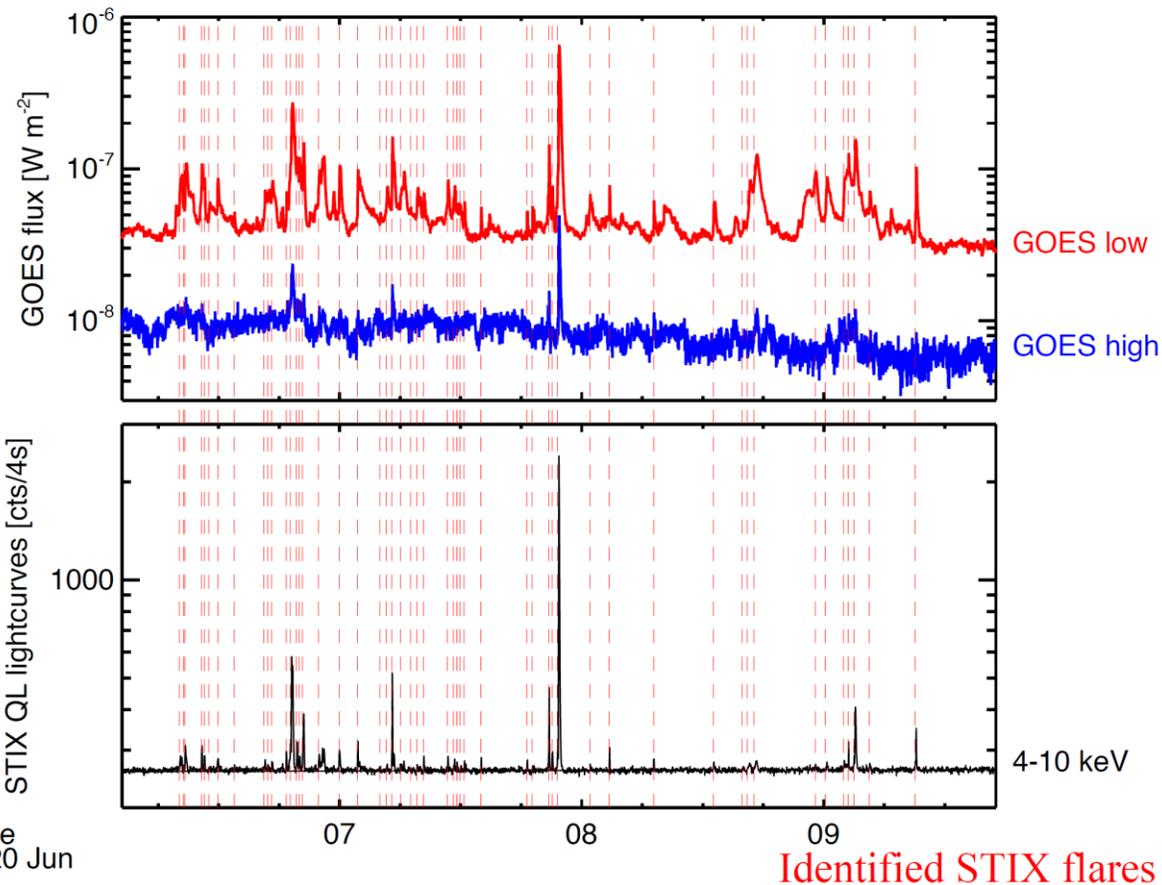


## STIX

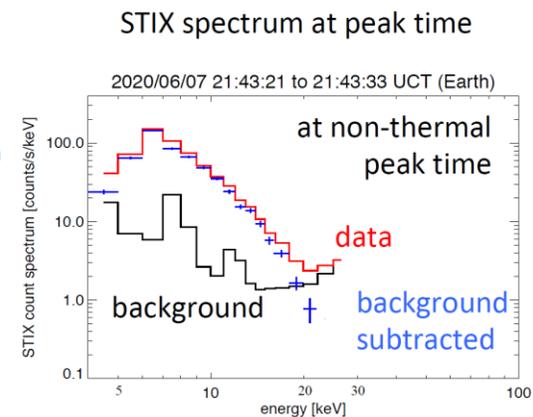
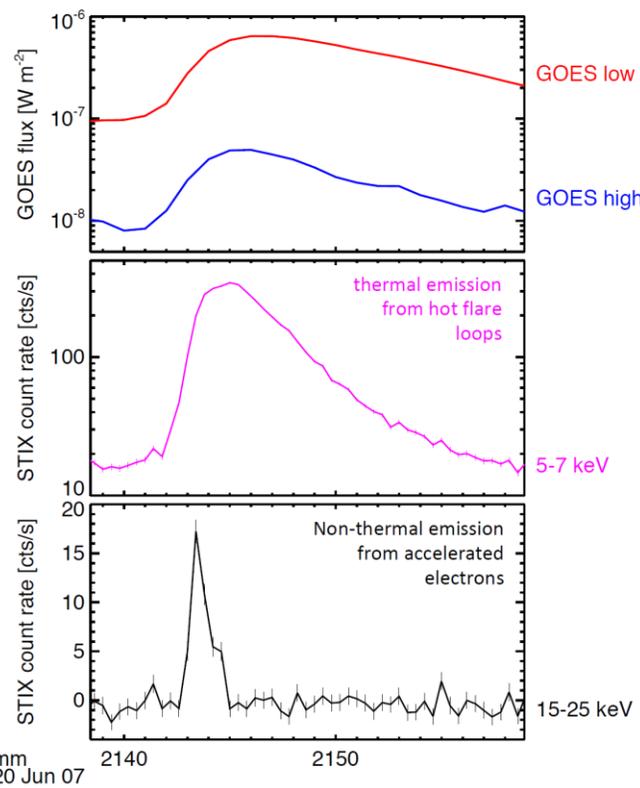
- 4-150 keV
- 69 flares observed
- 2 occulted M class flares
- 67 microflares, largest at GOES B6 level

- Nominal science phase starts in November 2021
- STIX workshop planned for 2021

如使用STIX数据, 请务必联系STIX团队

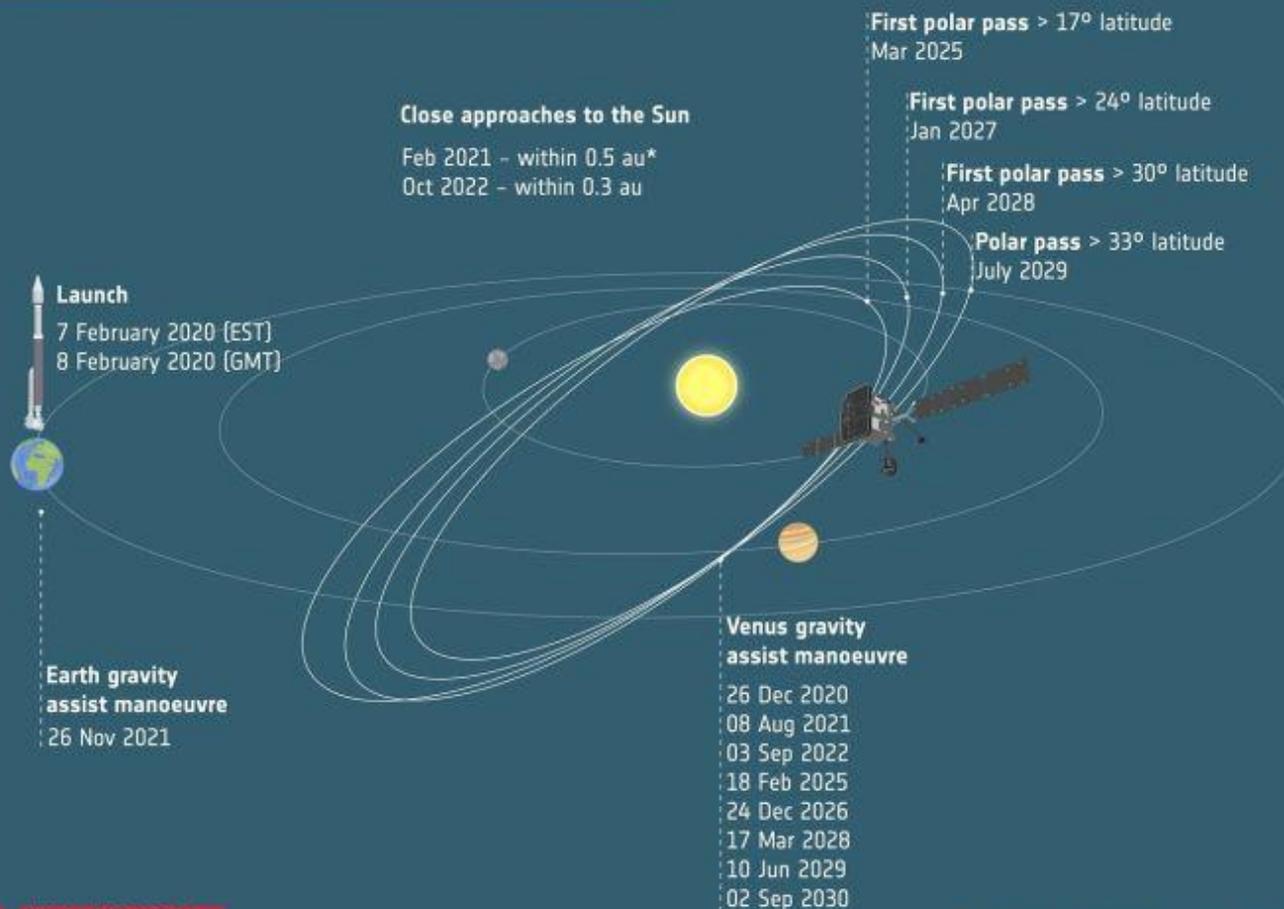


## B6 flare on June 7th



Light travel time difference has been adjusted

## SOLAR ORBITER JOURNEY AROUND THE SUN



#SolarOrbiter #WeAreAllSolarOrbiters

\*1 au = average distance between Sun and Earth (149 597 870 700 m)

**300 million km**

Maximum distance between Earth and Solar Orbiter

**16.5 min**

Maximum time for a radio signal to travel one way between Earth and Solar Orbiter

**22 orbits**

around the Sun

**Nov 2021**

Start of main mission

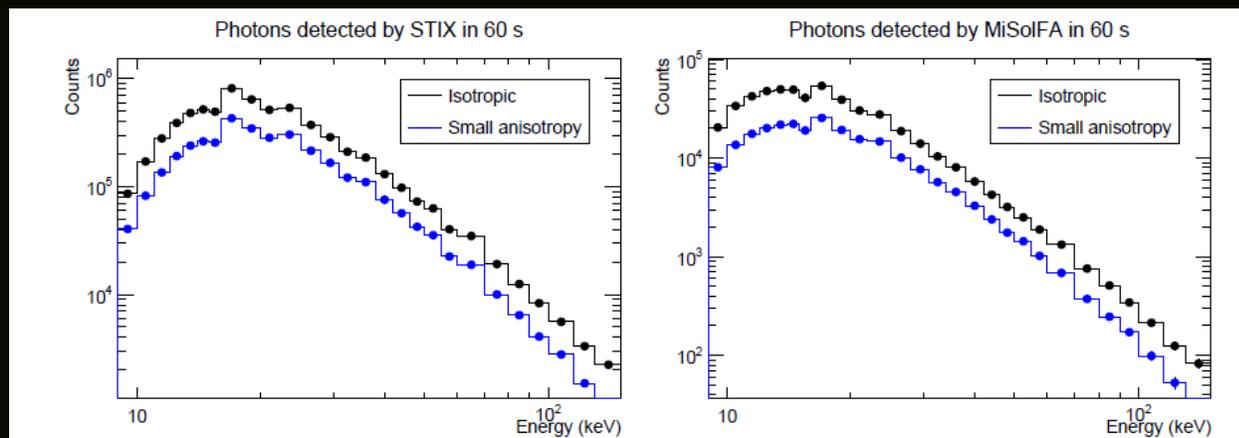
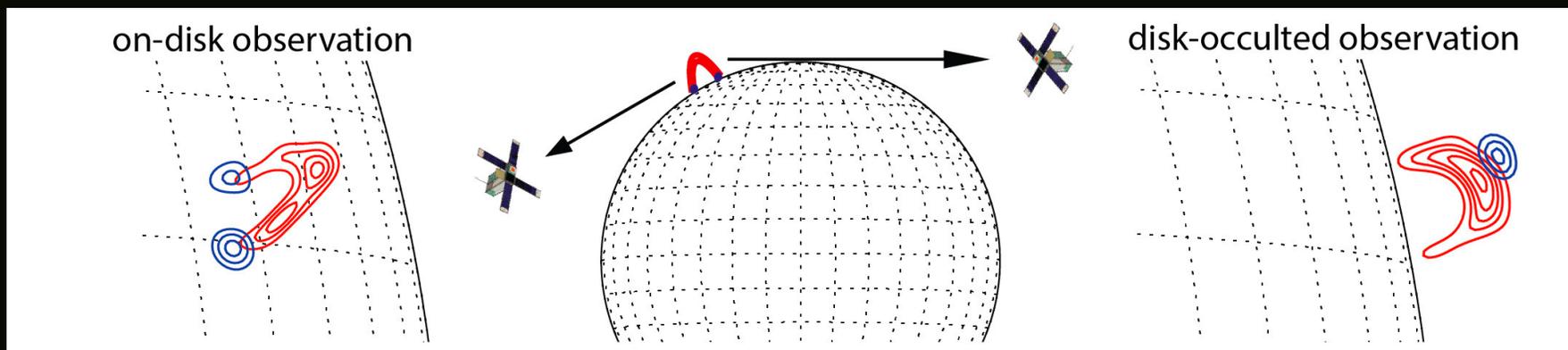
**Dec 2026**

Expected start of extended mission



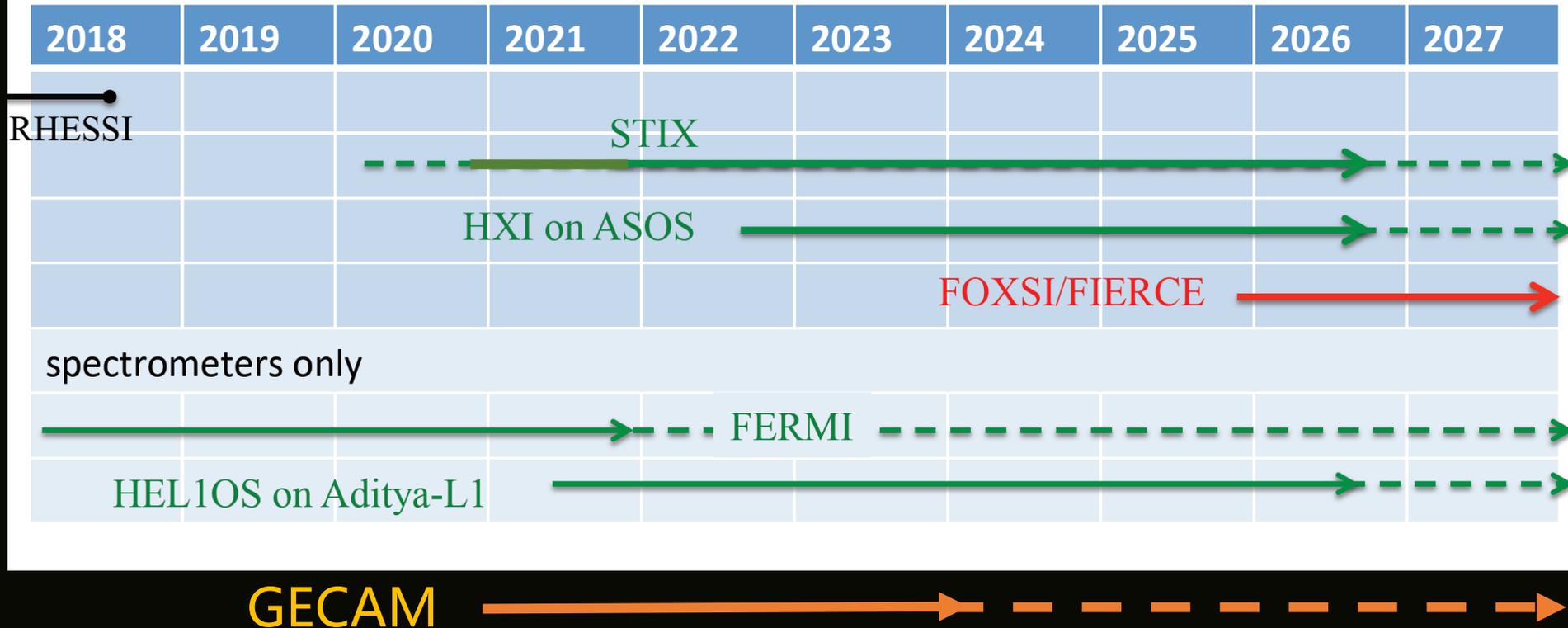
立体观测, 未来太阳观测重点发展方向之一, 对高能辐射研究非常重要

- SO/STIX, ASO-S/HXI 首次实现X射线多视角成像
- SO/STIX, GECAM, ASO-S/HXI, MiSolFA, 等可首次进行多视角能谱测量
- Krucker et al. 2019 (ASO-S RAA 专辑)



Casadei et al. 2017

## Outlook for solar HXR imaging spectroscopy



来自Säm Krucker 报告





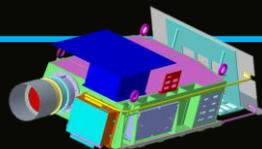
## 先进天基太阳天文台

- 我国首颗太阳综合观测卫星：**一磁两暴**，三载荷
- 中科院先导二期
- 紫台等单位研制，首席科学家：甘为群
- 目前正在转入正样
- 2021年底具备发射状态
- <http://aso-s.pmo.ac.cn/index.php>



### ➤ 全日面矢量磁像仪——FMG

主要观测太阳全日面光球矢量磁场



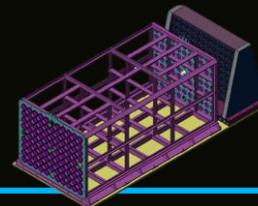
### ➤ 莱曼阿尔法太阳望远镜——LST

在莱曼 $\alpha$ 和白光波段获取太阳内冕高时间分辨率图像和太阳高时空分辨率全日面图像。



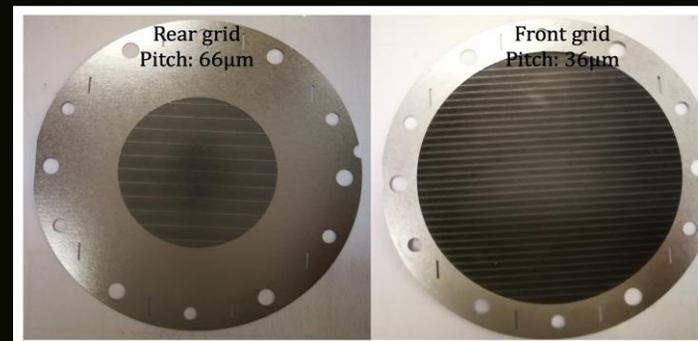
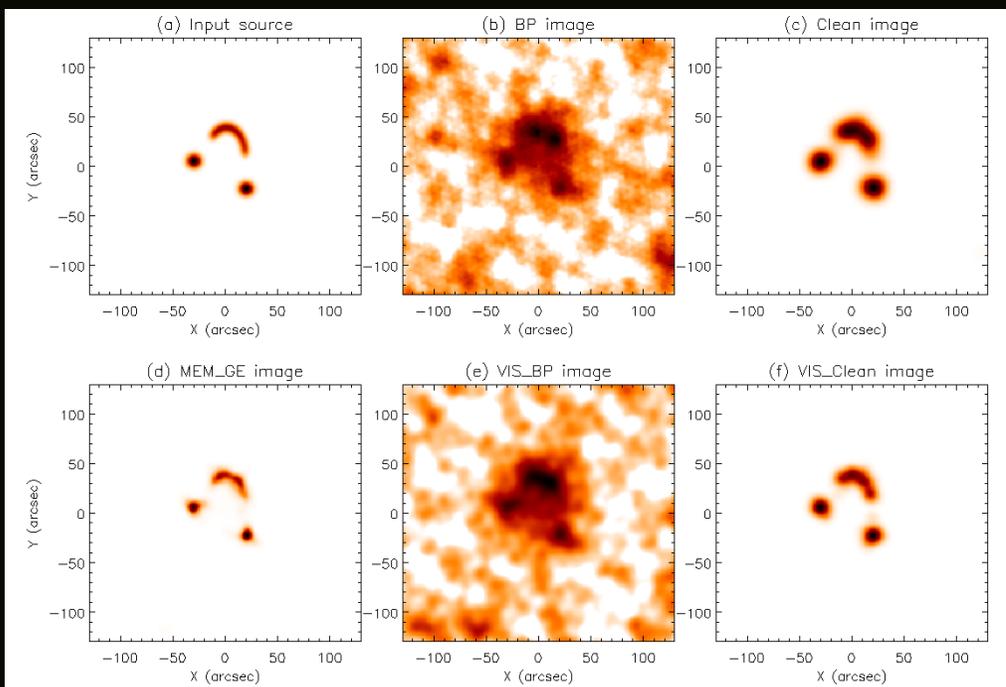
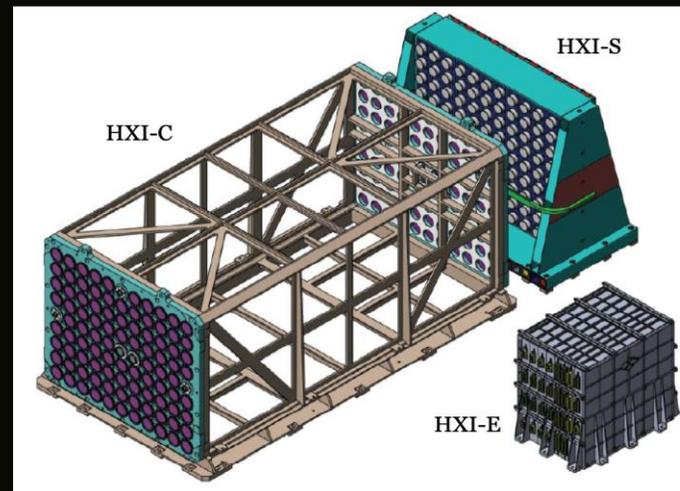
### ➤ 硬X射线成像仪——HXI

对30keV至200keV的高能辐射进行成像和能谱观测



- 原理：空间调制傅里叶变换成像
- 目标：研究耀斑非热辐射和高能电子
- 观测能段：~30 - 200 keV
- 记录能量：10-400 keV
- 空间分辨率：~3角秒
- 探测器：99个，其中背景5个，总流量3个

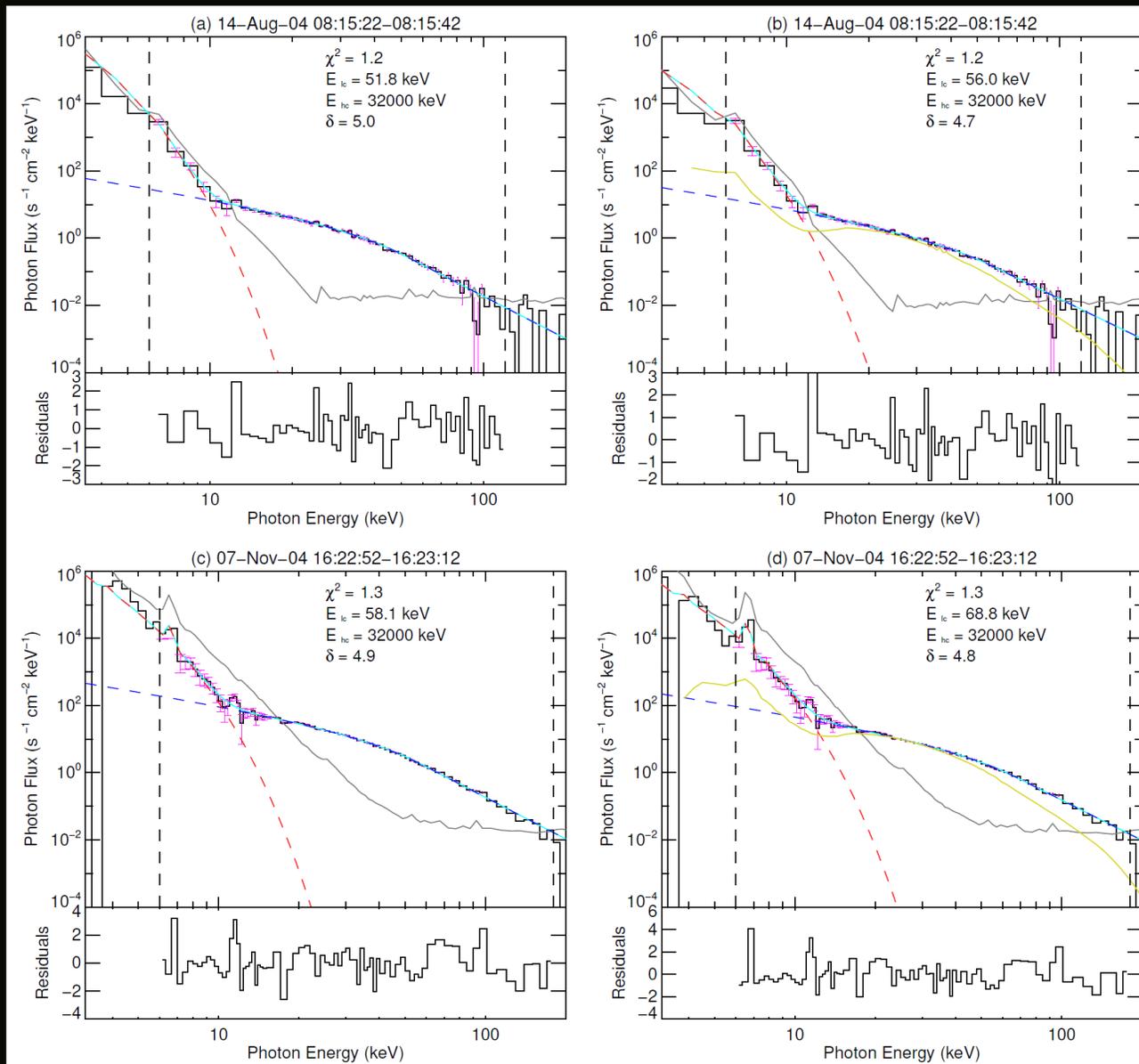
HXI准直器，量能器，电控箱



36微米节距光栅

## 高能电子的低能截止

Xia et al. 2020 in revision



# GECAM

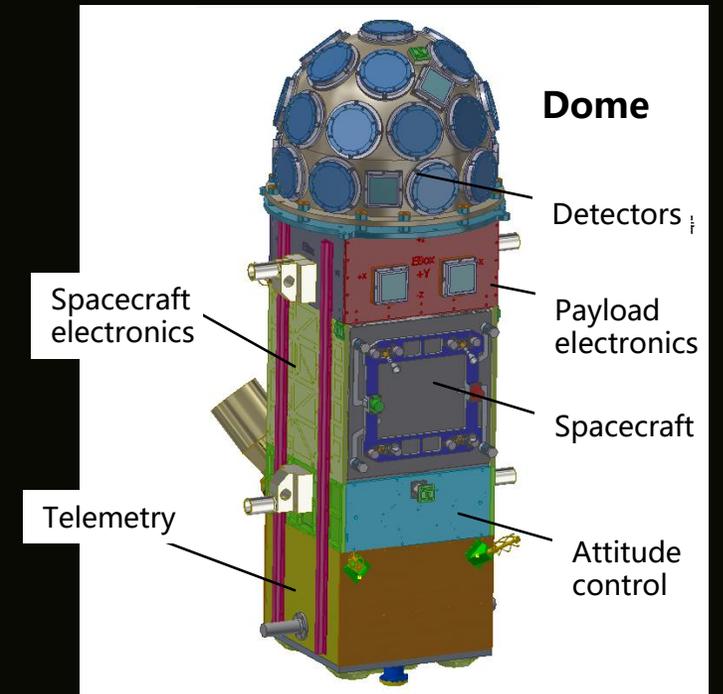
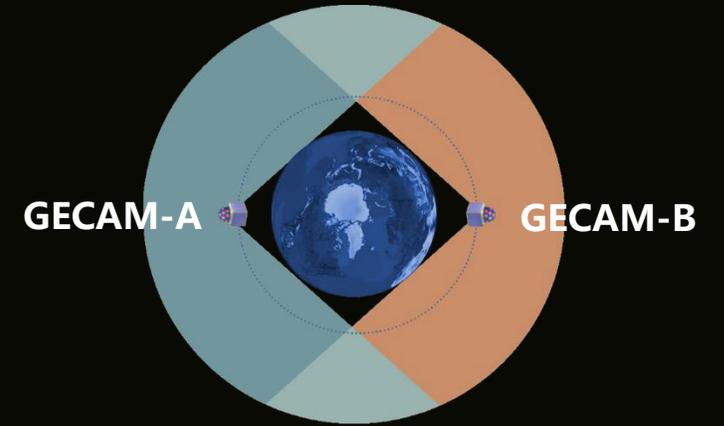
双星共轨、单星25个探测器的配置非常  
有利于完整记录太阳耀斑的高能辐射

- **Characteristics**

- **FOV:** ~100% all-sky
- **Energy band:** 6 keV – 5 MeV (LaBr<sub>3</sub>)
- **Sensitivity:** ~2E-8 erg/cm<sup>2</sup>/s
- **Localization:** ~1 deg (1-σ stat., 1E-5 erg/cm<sup>2</sup>)

- 紫台HXI科学团队将负责处理GECAM solar data (类似 Fermi Solar)

- Su et al. 2020, SCIENCE CHINA Physics, Mechanics & Astronomy
- <http://engine.scichina.com/doi/10.1360/SSPMA-2020-0012>

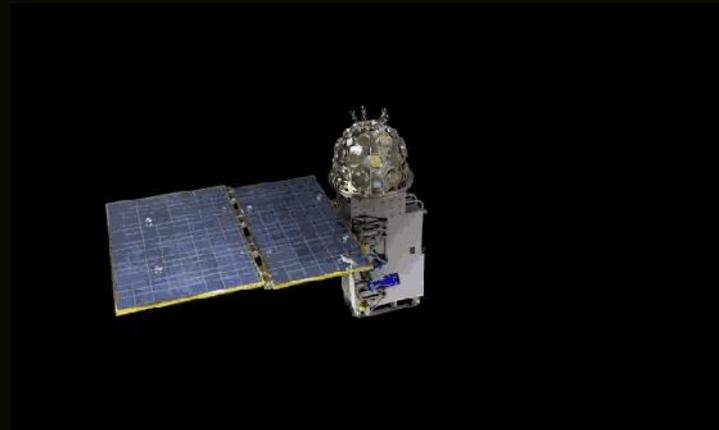


GECAM satellite

# GECAM Solar



- ASO-S (先进天基太阳天文台)
- 载荷之一HXI (硬X射线成像仪)
- 观测耀斑硬X射线暴：能谱，成像，像谱
- 能段：~30 - 200 keV
- 空间分辨率：~3角秒
- 成像原理：空间调制傅里叶变换成像
- 量能器：溴化镧晶体



- GECAM (引力波暴高能电磁对应体全天监测器)
- 观测X射线暴和伽马射线暴：能谱
- 能段：6 keV - 5 MeV
- 量能器：溴化镧晶体

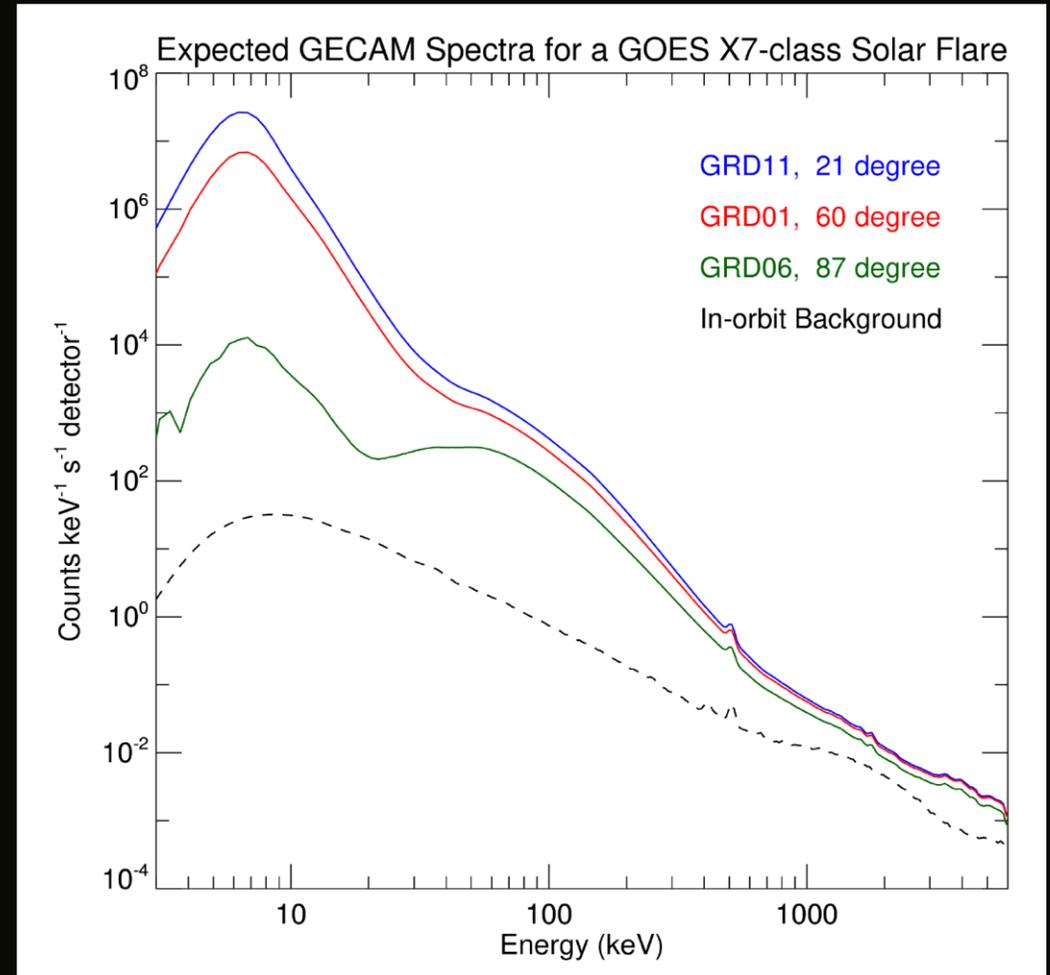
# GECAM Solar

## GECAM对耀斑研究的优势:

- 高灵敏度, 利于探测小耀斑
- 不同朝向的多探测器 (有利于探测强耀斑)
- 几乎完整的监测记录
- 高时间分辨率 (毫秒级的尖峰结构)
- 伽马射线唯一 (+Fermi)

## 可能的问题:

- 大耀斑流量很高, 会有较强的pile-up效应
- 无论是大耀斑还是小耀斑, 都可能会影响GRB等探测 (可通过定位, 但无法完全去除)



# GECAM Solar 软件

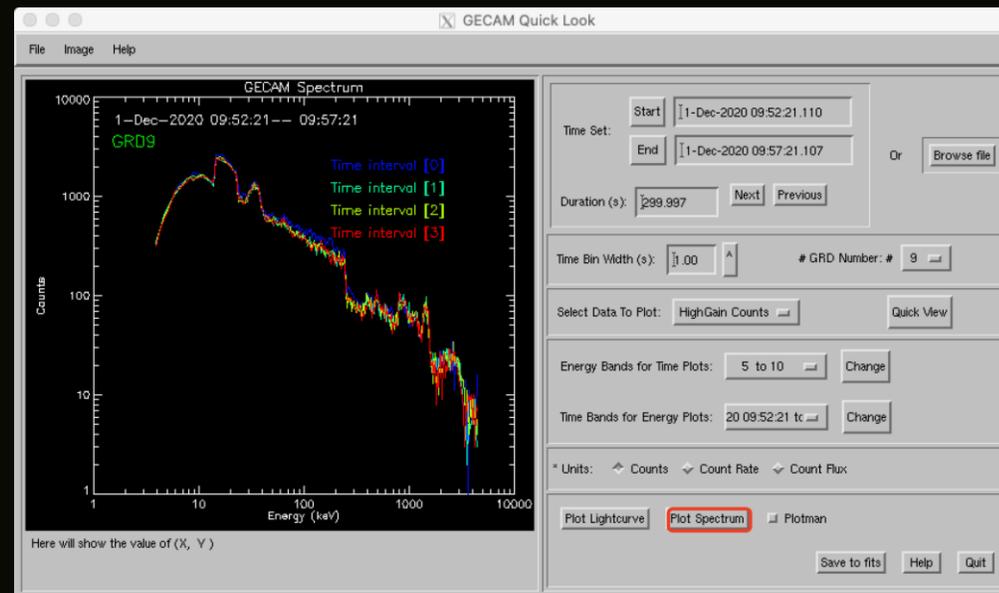
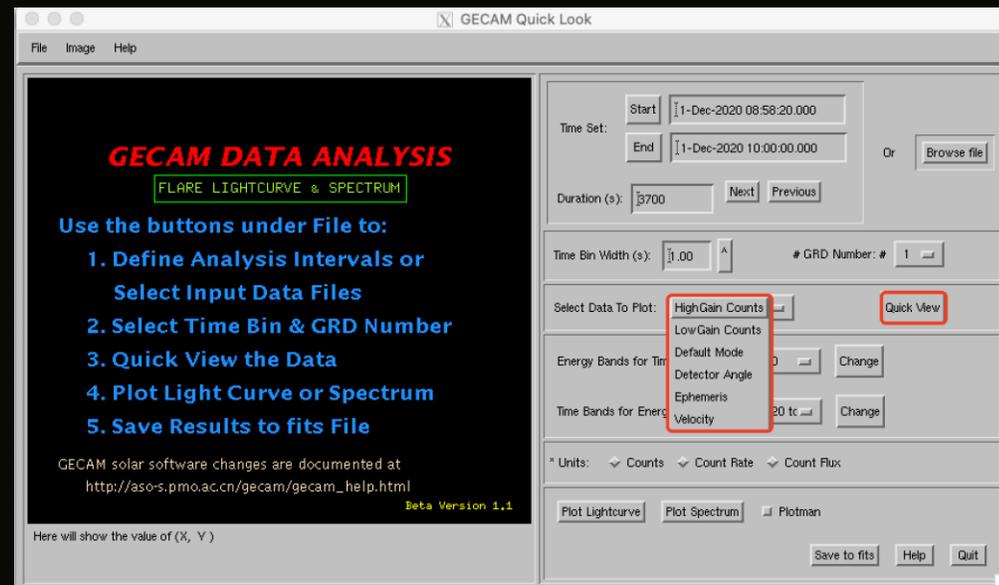
当前版本的产品主要包括：

- **软件 (beta版)** ，需运行于IDL和SSW (Solar Software太阳物理软件包) 环境：
  - 快视软件包 (GUI界面) (陈维, 等)
  - 耀斑自动识别记录软件 (苏杨, 等)
- **文档：**
  - 《GECAM Solar快视软件使用说明》
  - 《GECAM Solar能谱处理说明文档》
  - 《GECAM Solar耀斑识别说明文档》

# GECAM Solar 软件

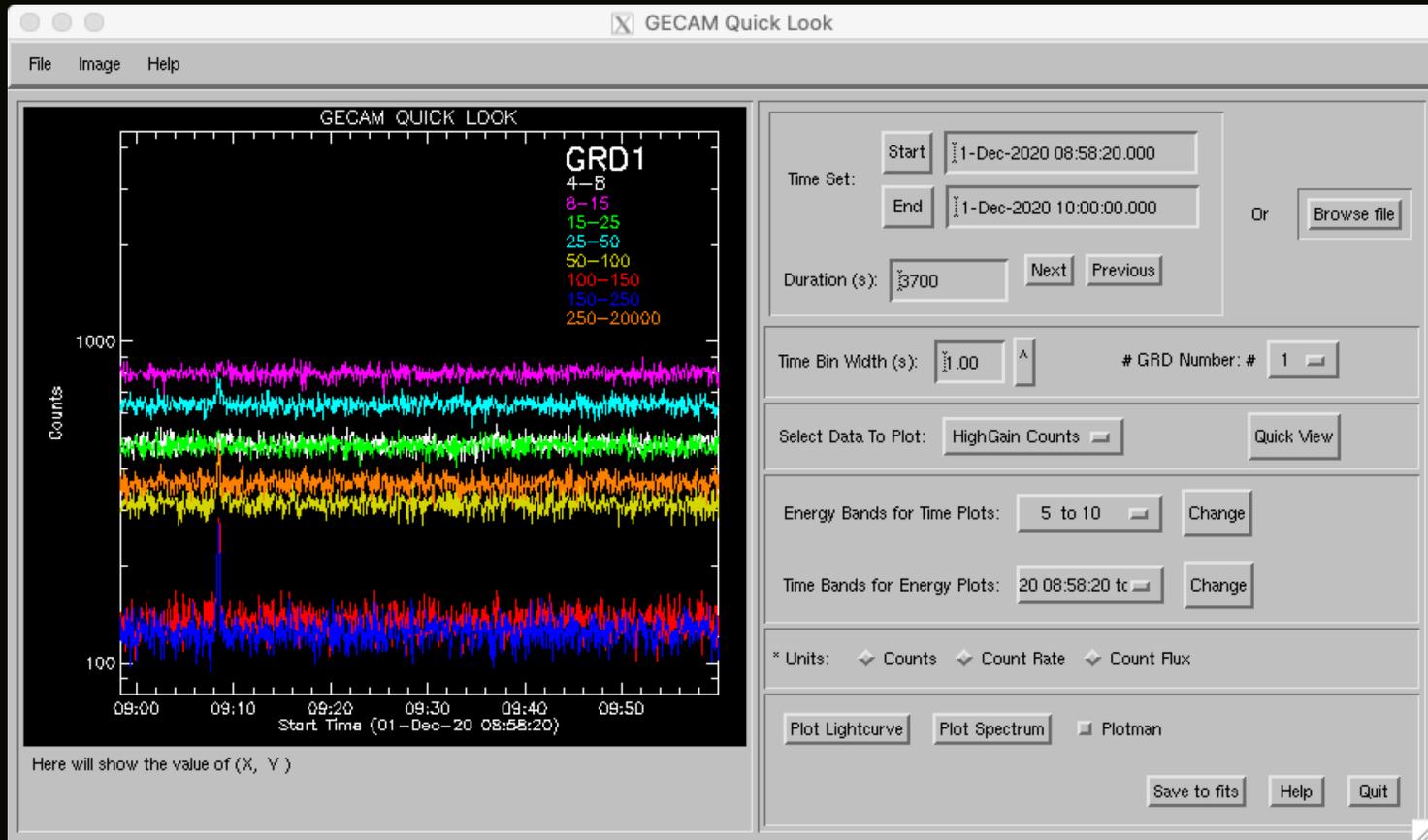
主要功能（将随模拟数据的更新不断完善）：

1. 数据处理功能：
2. 快视数据GUI查看功能
3. 能谱数据输出功能：
4. 能谱分析功能：借助OSPEX软件
5. 耀斑识别功能：自动识别并记录太阳耀斑事件，产生事件列表。

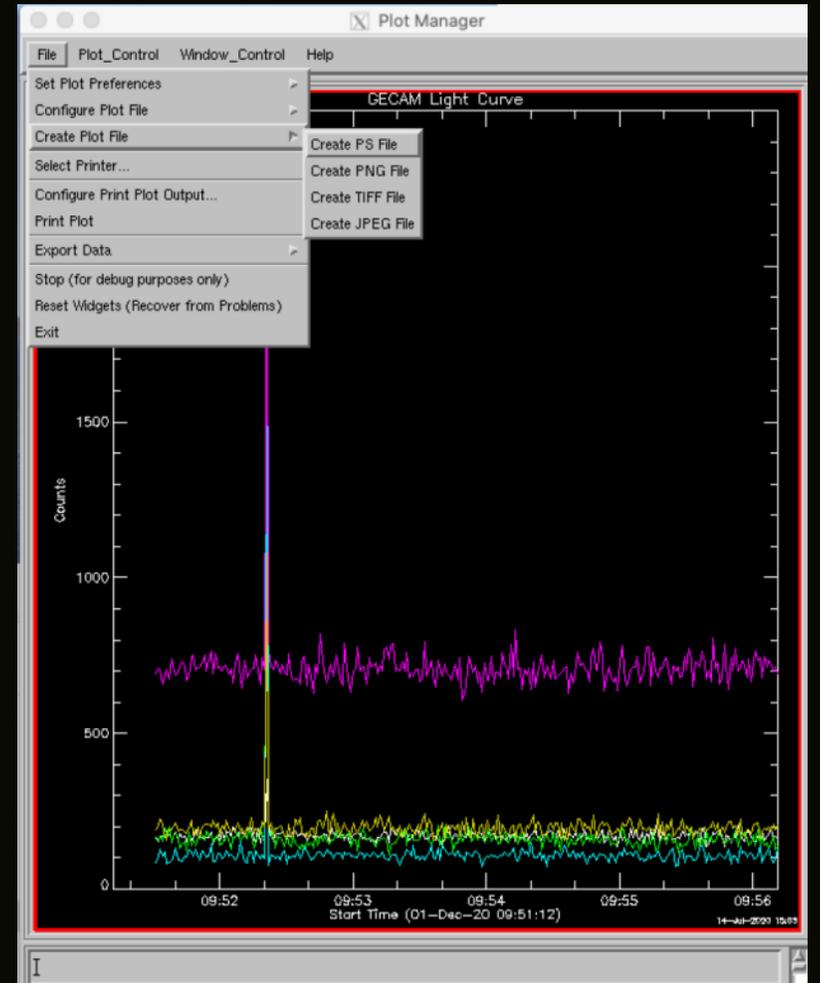


# GECAM Solar 软件

两种输入和显示模式:

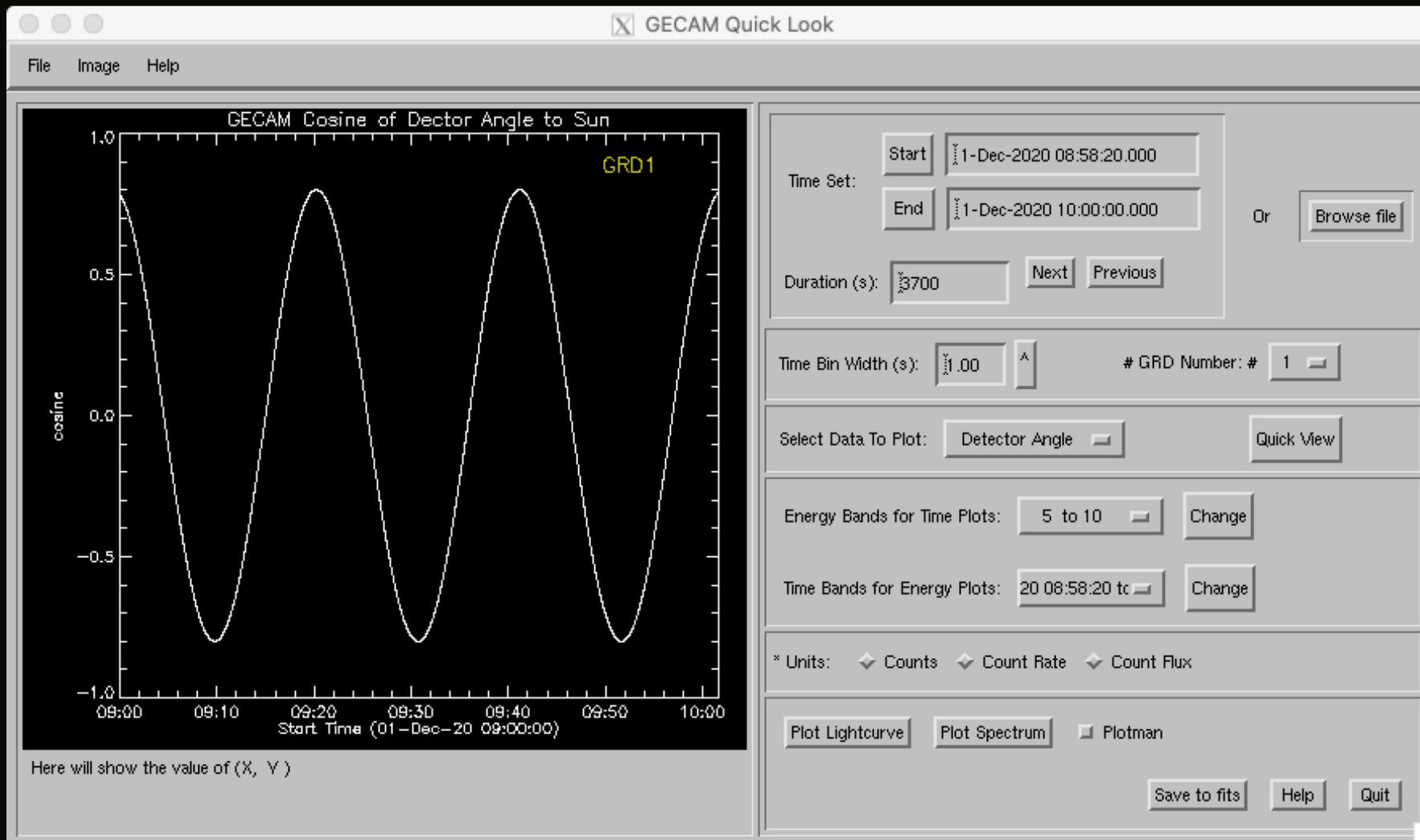


Plotman,可进行各种互动操作



# GECAM Solar 软件

预览太阳夹角，轨道，粒子等参数（将包括在耀斑快视数据中）



# GECAM Solar 软件

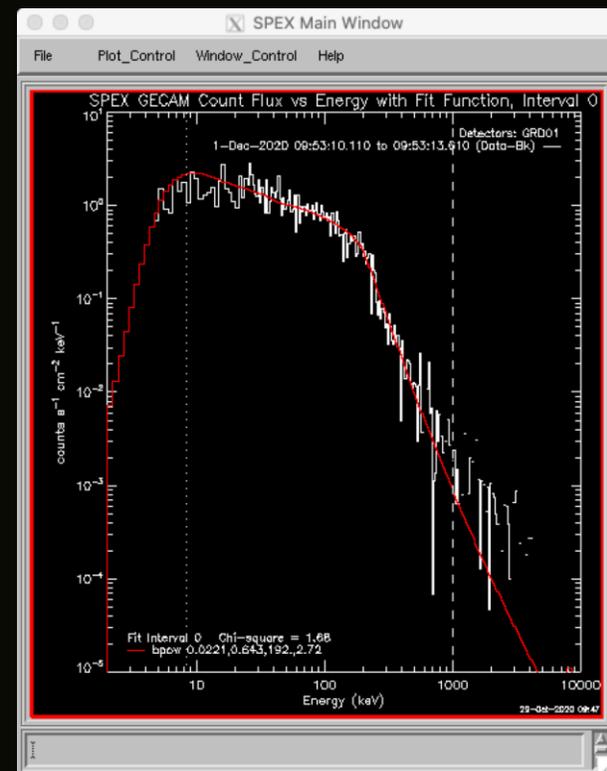
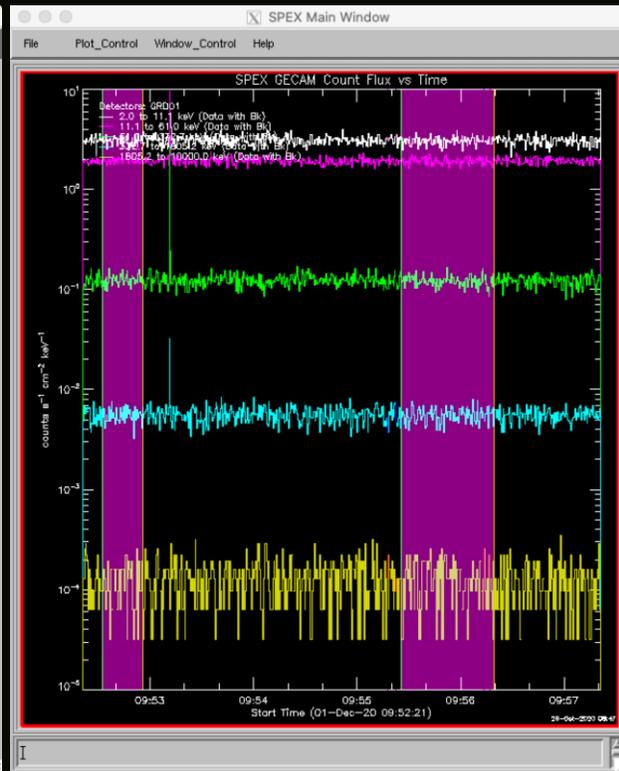
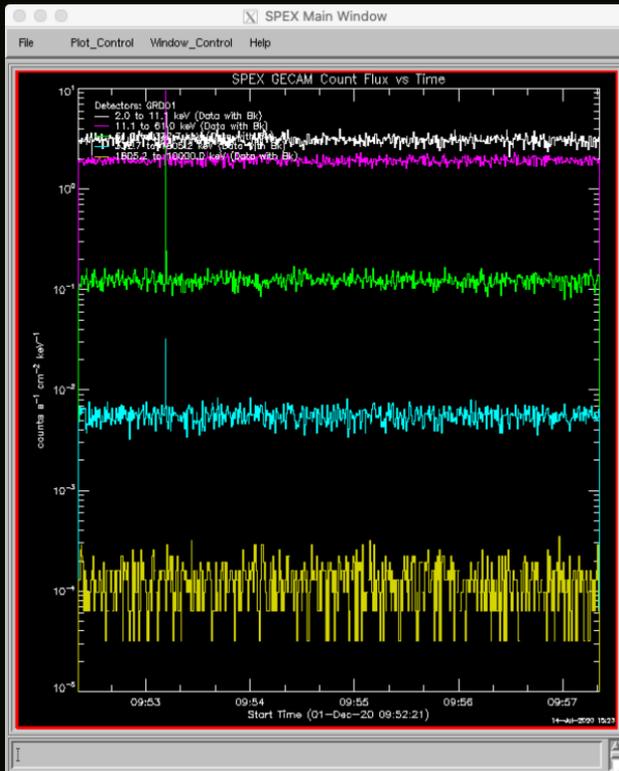
## OSPEX 能谱分析

### 1. 输入和显示

### 选择背景

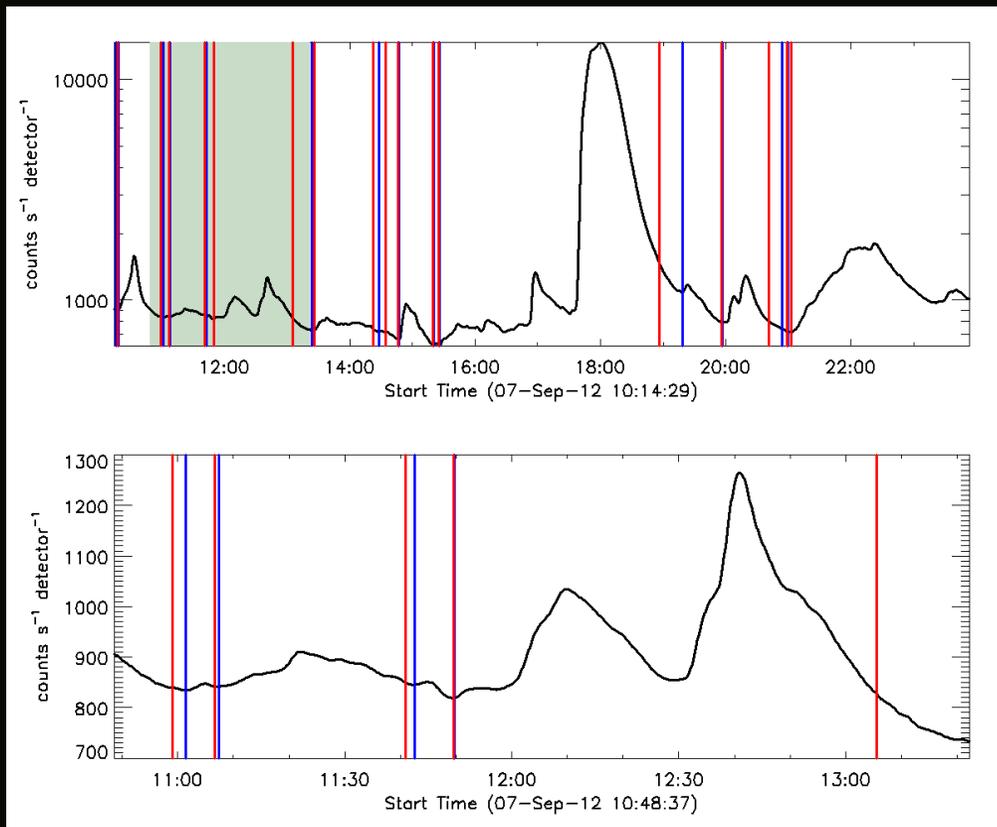
### 能谱

### 能谱拟合



# GECAM Solar 软件

## GECAM 耀斑自动识别 (基于GOES 1-8 Å 数据测试, 接近GECAM低能段)



GECAM\_20120908\_flarelist.txt - 记事本

文件(F) 编辑(E) 格式(O) 查看(V) 帮助(H)

```
# N: flare number
# DATE: day of observation
# START: start time of flare
# Peak: time of peak intensity
# END: end time of flare
# DUR: duration of event in unit of minute
# Eband: energy band used for detection
# Emax: maximum energy detected
# Peak cts: peak count rate in cts/s
# BG cts: background count rate in cts/s
# Total counts: total counts
```

N	DATE	START	PEAK	END	DUR(m)	Eband	Emax	Peak cts	BG cts	Total counts
1	20120908	10:16:00.039	10:17:01.478	10:17:21.957	0.1	5-10 keV	-- keV	910.1	907.0	81741.34
2	20120908	10:18:13.157	10:33:24.502	10:59:00.477	4.0	5-10 keV	-- keV	1604.8	908.0	2557566.50
3	20120908	11:01:23.834	11:04:38.391	11:06:41.269	0.5	5-10 keV	-- keV	850.8	834.6	269265.91
4	20120908	11:07:22.229	11:22:13.094	11:40:49.235	3.3	5-10 keV	-- keV	914.3	841.4	1727408.88
5	20120908	11:42:31.634	11:45:05.231	11:49:31.466	0.7	5-10 keV	-- keV	855.5	846.1	352175.22
6	20120908	11:49:41.706	12:40:53.649	13:05:28.184	7.4	5-10 keV	-- keV	1272.6	818.8	4270854.50
7	20120908	13:23:33.605	13:24:24.804	13:25:56.962	0.2	5-10 keV	-- keV	739.6	730.7	110041.66
8	20120908	13:26:07.202	13:37:33.270	14:22:16.104	5.5	5-10 keV	-- keV	835.1	733.3	2583226.50
9	20120908	14:27:43.778	14:31:18.814	14:34:02.652	0.6	5-10 keV	-- keV	725.9	716.0	273421.72
10	20120908	14:34:12.891	14:35:45.050	14:46:30.158	1.2	5-10 keV	-- keV	719.1	708.6	505663.38
11	20120908	14:47:00.878	14:53:19.751	15:19:46.923	3.2	5-10 keV	-- keV	968.3	660.4	1512656.63
12	20120908	15:19:57.163	15:22:41.000	15:25:24.837	0.5	5-10 keV	-- keV	639.4	618.4	208100.39
13	20120908	15:25:35.077	17:59:51.875	18:56:31.500	20.6	5-10 keV	-- keV	14760.4	620.0	40786828.00
14	20120908	19:18:42.679	19:23:39.634	19:56:05.206	3.7	5-10 keV	-- keV	1185.0	1083.2	2154028.75
15	20120908	19:56:46.166	20:18:57.347	20:41:08.529	4.3	5-10 keV	-- keV	1297.8	791.0	2578852.75
16	20120908	20:54:06.759	20:54:06.759	20:58:53.475	0.5	5-10 keV	-- keV	740.6	734.3	211827.13
17	20120908	20:59:34.435	21:00:46.114	21:02:38.752	0.3	5-10 keV	-- keV	722.8	716.5	136346.31

第 12 行, 第 1 列    70%    Windows (CRLF)    UTF-8

N	DATE	START	PEAK	END	DUR(m)	Eband	Emax	Peak cts	BG cts	Total counts
1	20120908	10:16:00.039	10:17:01.478	10:17:21.957	0.1	5-10 keV	-- keV	910.1	907.0	81741.34
2	20120908	10:18:13.157	10:33:24.502	10:59:00.477	4.0	5-10 keV	-- keV	1604.8	908.0	2557566.50
3	20120908	11:01:23.834	11:04:38.391	11:06:41.269	0.5	5-10 keV	-- keV	850.8	834.6	269265.91
4	20120908	11:07:22.229	11:22:13.094	11:40:49.235	3.3	5-10 keV	-- keV	914.3	841.4	1727408.88
5	20120908	11:42:31.634	11:45:05.231	11:49:31.466	0.7	5-10 keV	-- keV	855.5	846.1	352175.22

谢 谢 ！

