X射线数据处理的基本原理和方法

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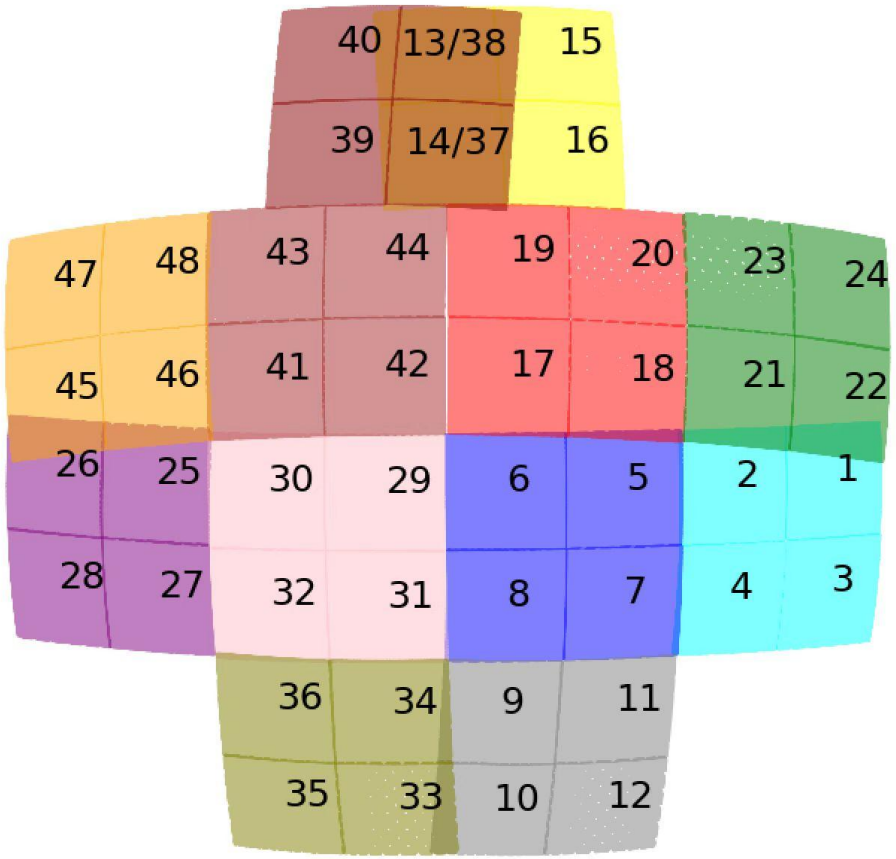
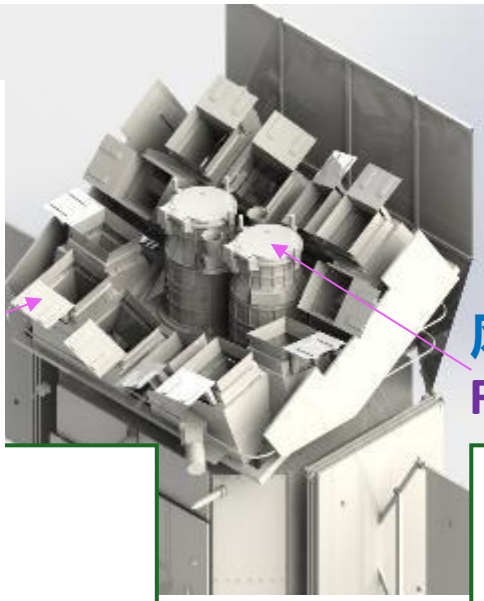
天关卫星（Einstein Probe）

A space mission for all-sky monitoring to discover & study high-energy transients and variability in X-rays





Autonomous slew & follow-up within ~ 3min

Fast alert data downlink and uplink (ToO)

风行天

FXT(2 modules)

Wolter-1 type + CCD

FoV: 38’

band: 0.3-10keV

eff. area: 2x 300cm² @1keV

angular FWHM: 30”

positioning accuracy: <10”

@ 1 ks

逐光子事例数据

- WXT采用CMOS（48片4k x 4k）；读出一帧50 ms
- 光学CMOS：光子数多，只记录每个读出周期内每个像素上的光子个数（计数矩阵）
- X射线CMOS：光子数少，记录每个读出周期内每个光子的位置、时间和能量（事例列表）

Select All Invert	TIME 1D s Modify	RAWX 1I pixel Modify	RAWY 1I pixel Modify	Amp 1B Modify	PHA 1J chan Modify	STATUS 16X Modify	DETX 1I Modify	DETY 1I Modify	X 1I Modify	Y 1I Modify	GRADE 1I Modify	PI 1J chan Modify
1	1.551116734500E+008	2004	2090	1	339	0	1933	2134	5007	5143	4	226
2	1.551116734500E+008	2316	2084	1	57	0	2245	2128	5176	4880	0	38
3	1.551116734500E+008	2304	2095	1	372	0	2233	2139	5178	4896	0	249
4	1.551116734500E+008	4022	2951	1	844	0	3957	2998	6850	3941	2	565
5	1.551116735000E+008	2277	1994	1	191	0	2206	2038	5079	4862	0	127
6	1.551116735000E+008	2174	2083	1	106	0	2103	2126	5095	4997	0	71
7	1.551116736000E+008	3048	1449	1	124	0	2977	1499	5060	3922	3	83
8	1.551116736000E+008	2262	2230	1	455	0	2191	2273	5266	5006	3	304
9	1.551116736000E+008	257	3684	1	807	0	188	3735	5368	7484	0	540
10	1.551116736999E+008	2220	1778	1	122	0	2149	1821	4867	4789	2	81
11	1.551116736999E+008	2253	2686	1	122	0	2182	2730	5641	5267	0	82
12	1.551116737499E+008	3979	2106	1	119	0	3911	2157	6126	3512	0	79
13	1.551116737499E+008	2447	2085	1	163	0	2375	2129	5249	4773	1	109

WXT data flow

- Raw data: Satellite→Ground station→Ground support system
- Raw data → Level 0 data
- Level 0 data → Level 1 data (Level 1 data generation software)
- Level 1 data → Level 2&3 data (Data analysis software)
- Based on heasoft-6.25 (C, perl, python)

Level 1 data

root	1st subdirectory	2nd subdirectory	file name	description
[obsID]	auxil	——	ep[obsID].orb	orbit file
			ep[obsID].att	attitude file
			ep[obsID].mkf	make filter file
	wxt	event	ep[obsID]wxt[number][pp]_uf.evt	event file

[obsID]	an 11 digits number to identify the observation
[number]	the number of CMOS, from 1 to 48
[pp]	satellite status: po — pointing settled sl — during a slew
[level]	level of event file: Level 1: uf — unfiltered event file Level 2: cl — cleaned event file

Level 2&3 data

ep[obsID]wxt[number][pp]_cl.evt	event file
ep[obsID]wxt[number].mkf	make filter file
ep[obsID]wxt[number].img	image
ep[obsID]wxt[number].exp	exposure map
ep[obsID]wxt[number].cat	source catalog
ep[obsID]wxt[number]s[sourceID].lc	source light curve
ep[obsID]wxt[number]s[sourceID]bk.lc	background light curve
ep[obsID]wxt[number]s[sourceID].pha	source spectrum
ep[obsID]wxt[number]s[sourceID]bk.pha	background spectrum
ep[obsID]wxt[number]s[sourceID].arf	ancillary response file
ep[obsID]wxt[number].rmf	response matrix

如何从1级数据产生2级和3级数据？

- **产生一次观测所有CMOS数据产品**

  wxtpipeline indir=/NFS/wxtdata/11900000001 outdir=./output

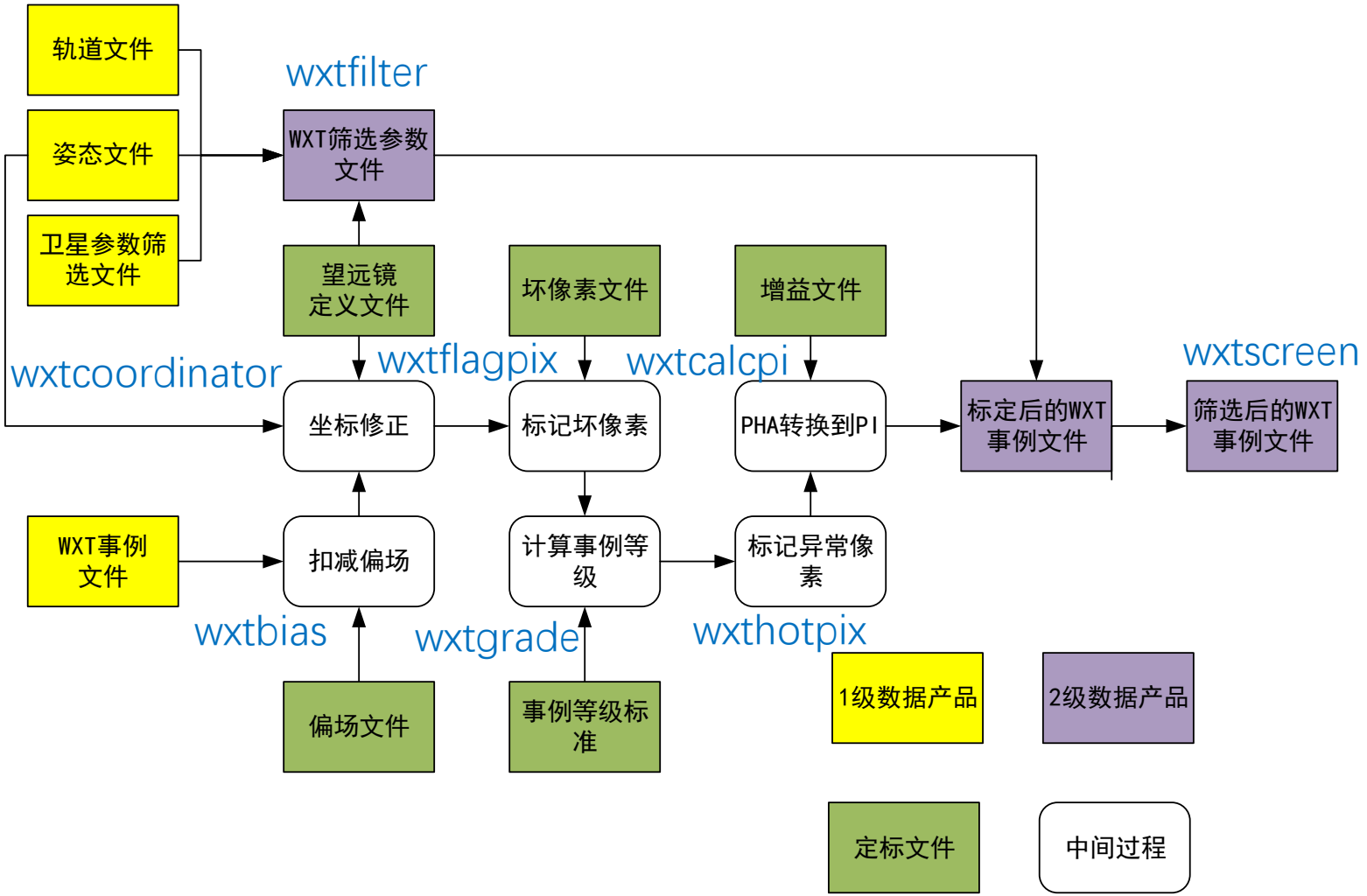
- **产生一次观测单个CMOS数据产品**

  wxtpipeline indir= outdir= stemcmosid=36

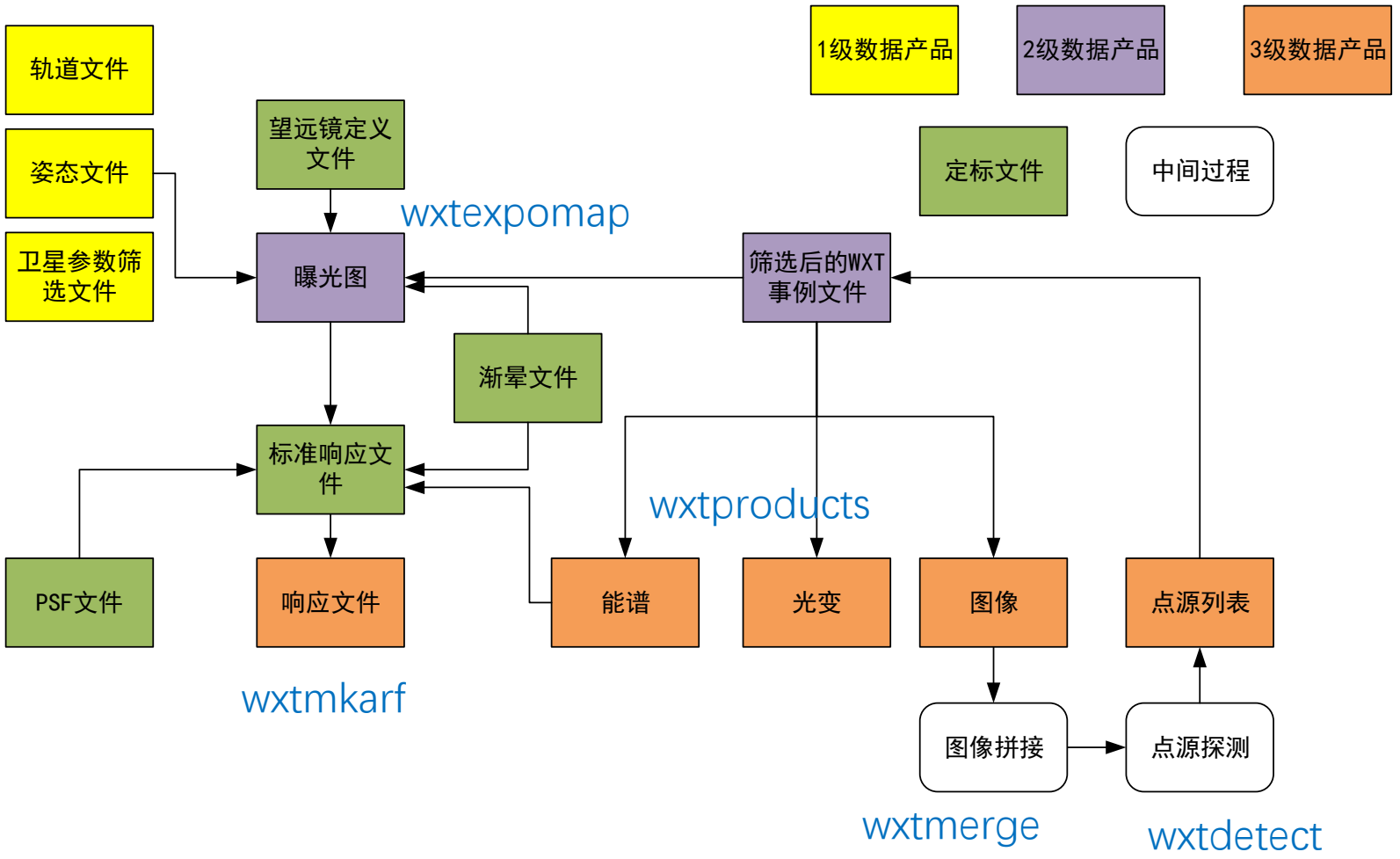
- **需要覆盖已有产品**

  wxtpipeline indir= outdir= stemcmosid= clobber=yes

标准数据产品生成流程（定标、筛选）

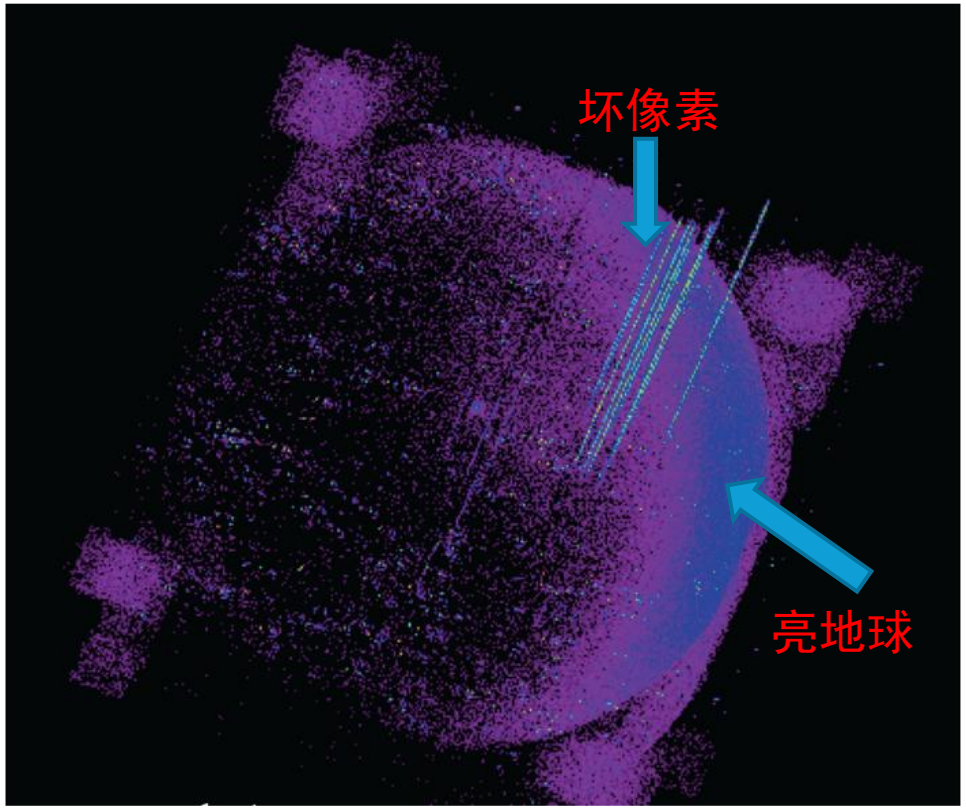


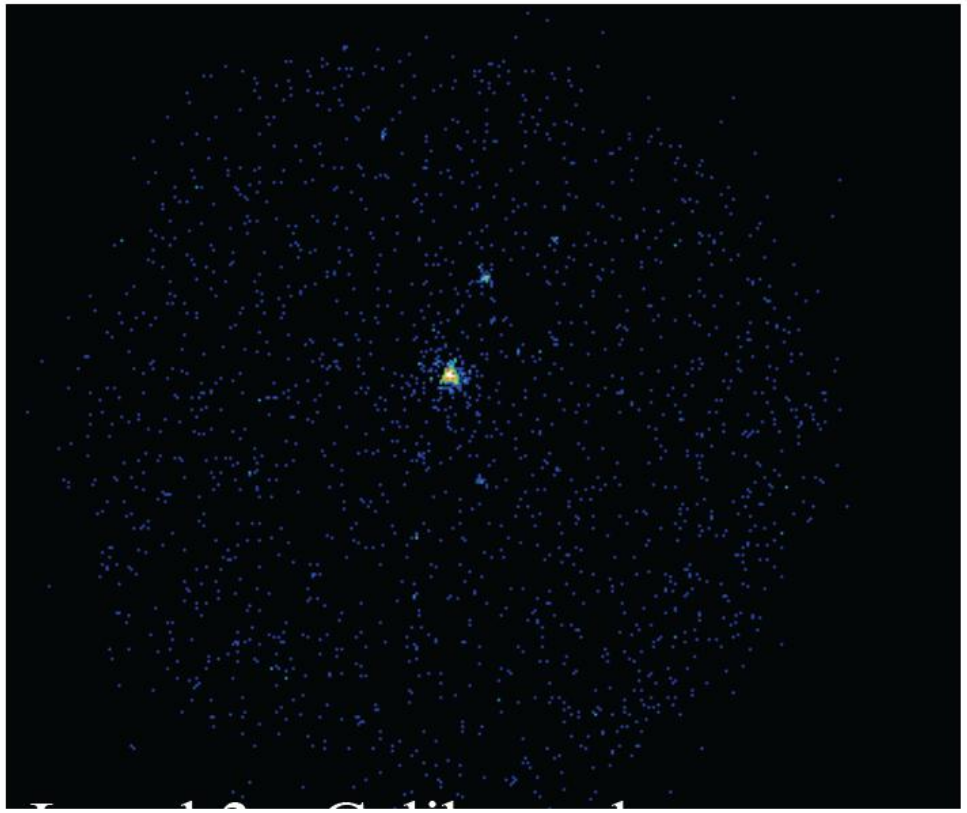
标准数据产品生成流程（产品提取）



第1阶段—定标

如何去掉各种污染事例和修正物理量



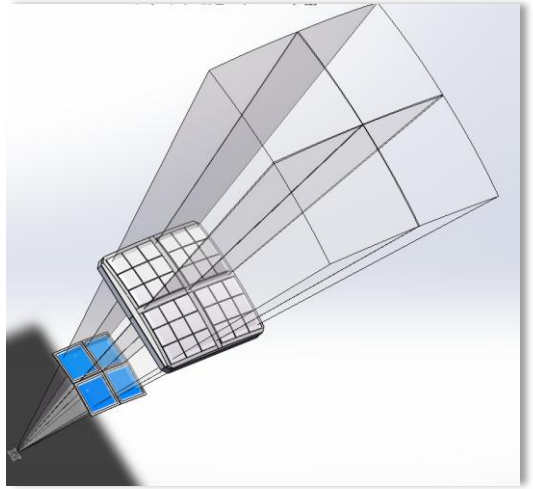


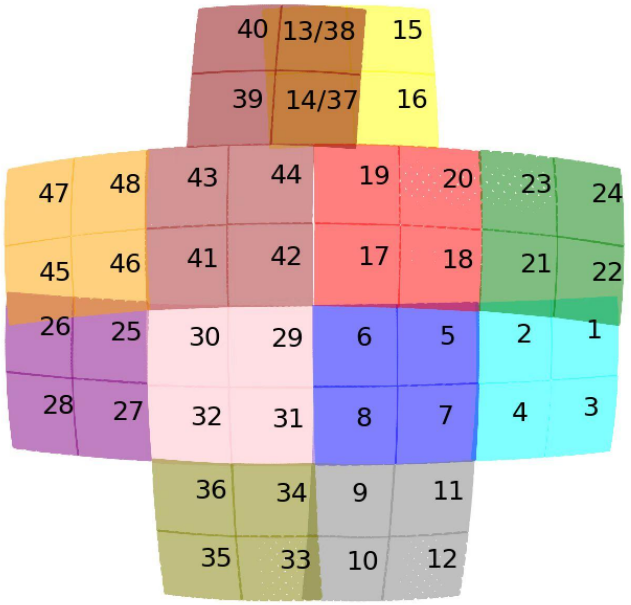
扣减偏场 wxtbias

- 输入：事例文件（1级）、偏场文件
- 输出：事例文件
- 任务：从每个事例的PHA值中减去电子学基线。基线值由偏场文件给出，与探测器位置相关（理论上每个像素都不同）

坐标修正 wxtcoordinator

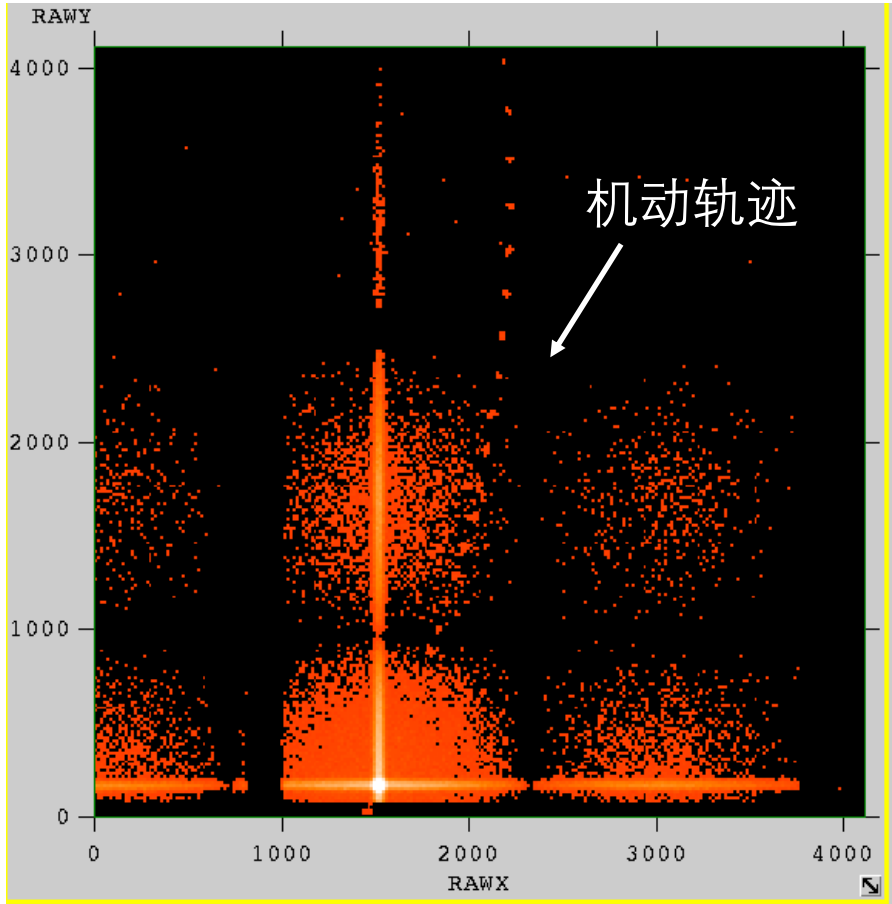
- 输入：事例文件、姿态文件、望远镜定义文件
- 输出：事例文件
- 任务：将原始探测器坐标修正为天球坐标。



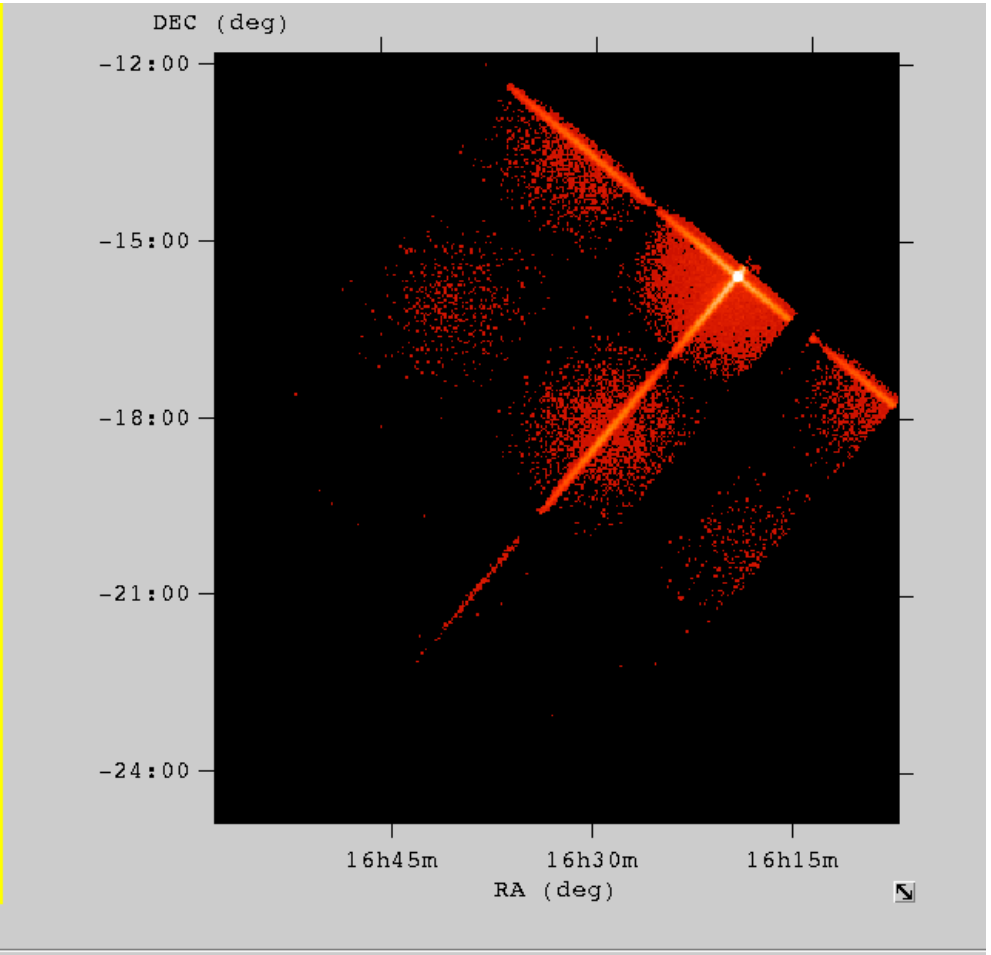


坐标转换

探测器坐标图像



天球坐标图像



OBJECT, RA_OBJ, DEC_OBJ, RA_NOM, DEC_NOM 来自观测计划，不同CMOS共用
RA_PNT, DEC_PNT, PA_PNT 由wxtcoordinator计算，不同CMOS不同

标记坏像素 wxtflagpix

- 输入：事例文件、坏像素文件
- 输出：事例文件
- 任务：读取坏像素列表，将位于这些像素上事例的STATUS改为对应的值，供后续筛选使用。

计算事例等级 wxtgrade

- 输入：事例文件、事例等级标准
- 输出：事例文件
- 任务：通过每个事例周围3x3像素上的信号（PHAS）判断其是否为X射线的事例，或者为带电粒子产生的信号。 X射线的事例多数只在一个像素上产生过阈信号；而带电粒子容易在多个相邻像素上产生过阈信号。

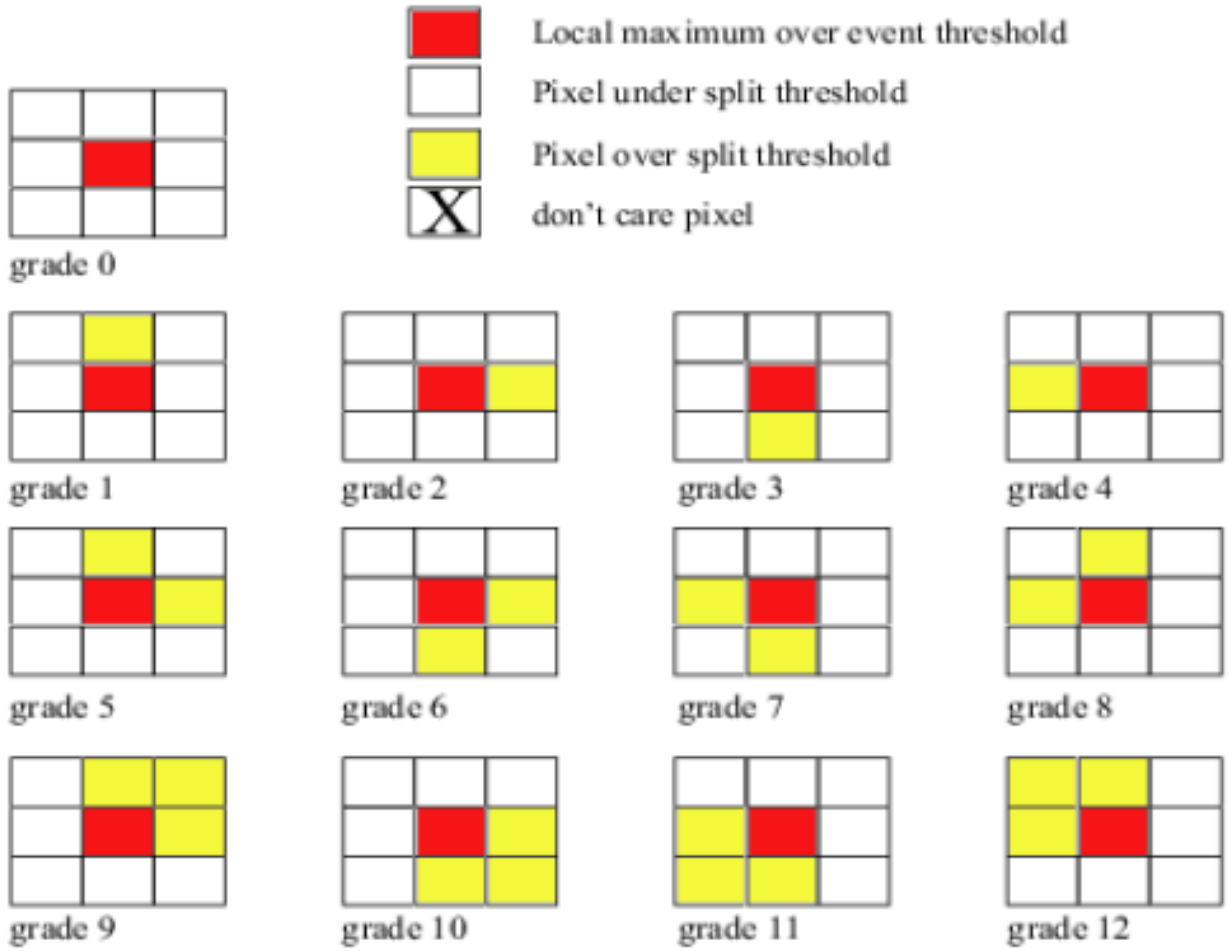
事例的Grade

Single pixel events

Double pixel events

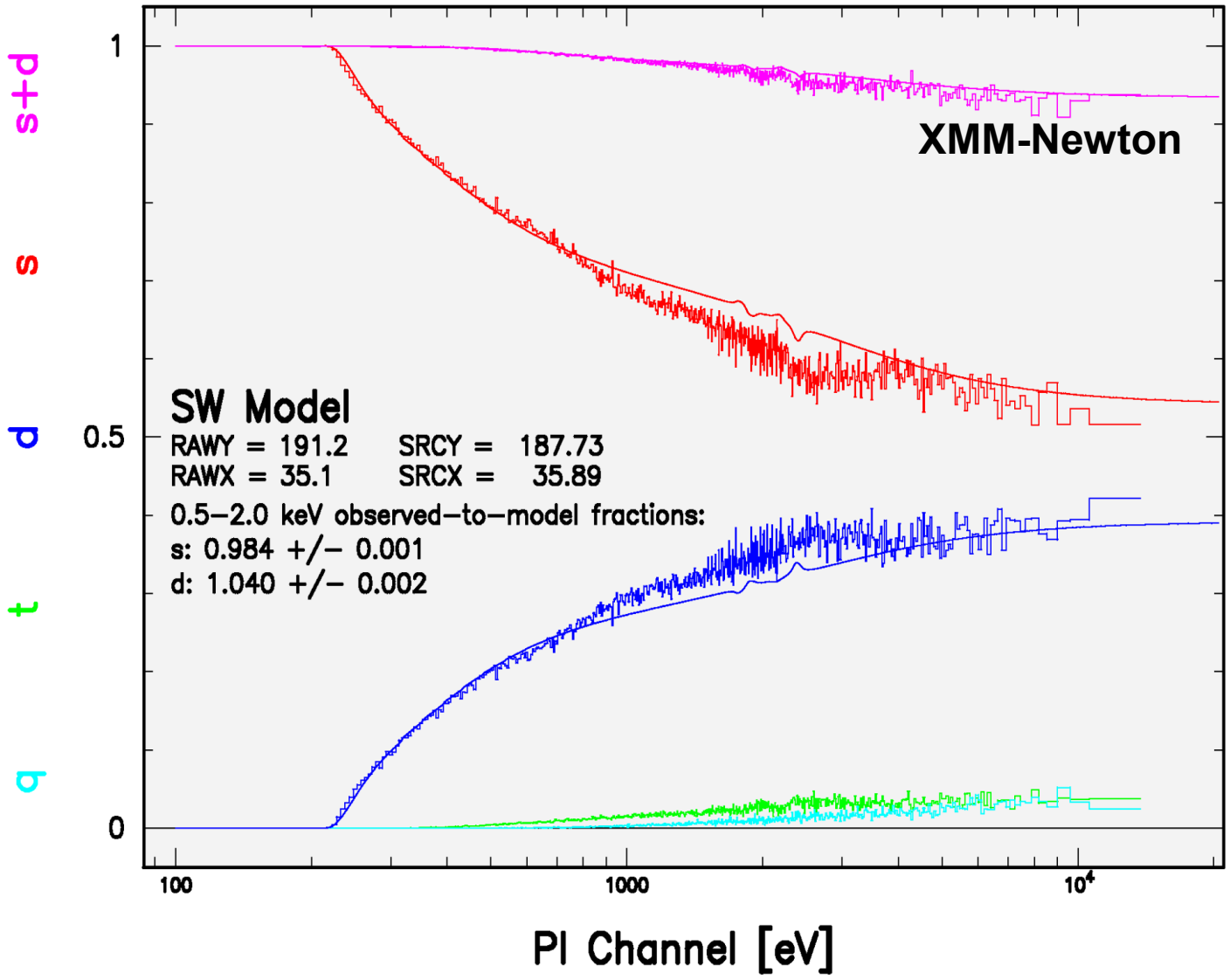
Triple events

Quadruple events



光子堆叠（pile-up）效应

在某一个读出周期（帧）内，多个光子打在相同（相邻）像素上，被记录成一个光子



标记异常像素 wxthotpix

- 输入：事例文件
- 输出：事例文件
- 任务：寻找已知坏像素列表中未标注的异常像素。使用事例列表生成一幅图像，先计算单个像素相对于整个探测器平均计数水平的超出概率，找出异常像素的候选体；再比较其周围像素的计数的分布是否符合PSF的形状。

PHA转换到PI wxtcalcpi

- 输入：事例文件、增益文件

- 输出：标定后的事例文件（2级）

- 任务：PHA为电子学记录的信号幅度，其与真实能量通过增益联系。增益与温度和探测器位置有关，且会随时间缓慢变化。需要查找增益文件中与当前状态相近的数据，然后进行插值得出合适的增益值。

- PI对能量进行线性化表述，不随时间变化

  PI = PHA * Gain / Nom_Gain

1024 Chan 4096 Chan

10.0 eV/Chan 2.5 eV/Chan

生成筛选参数文件 wxtfilter

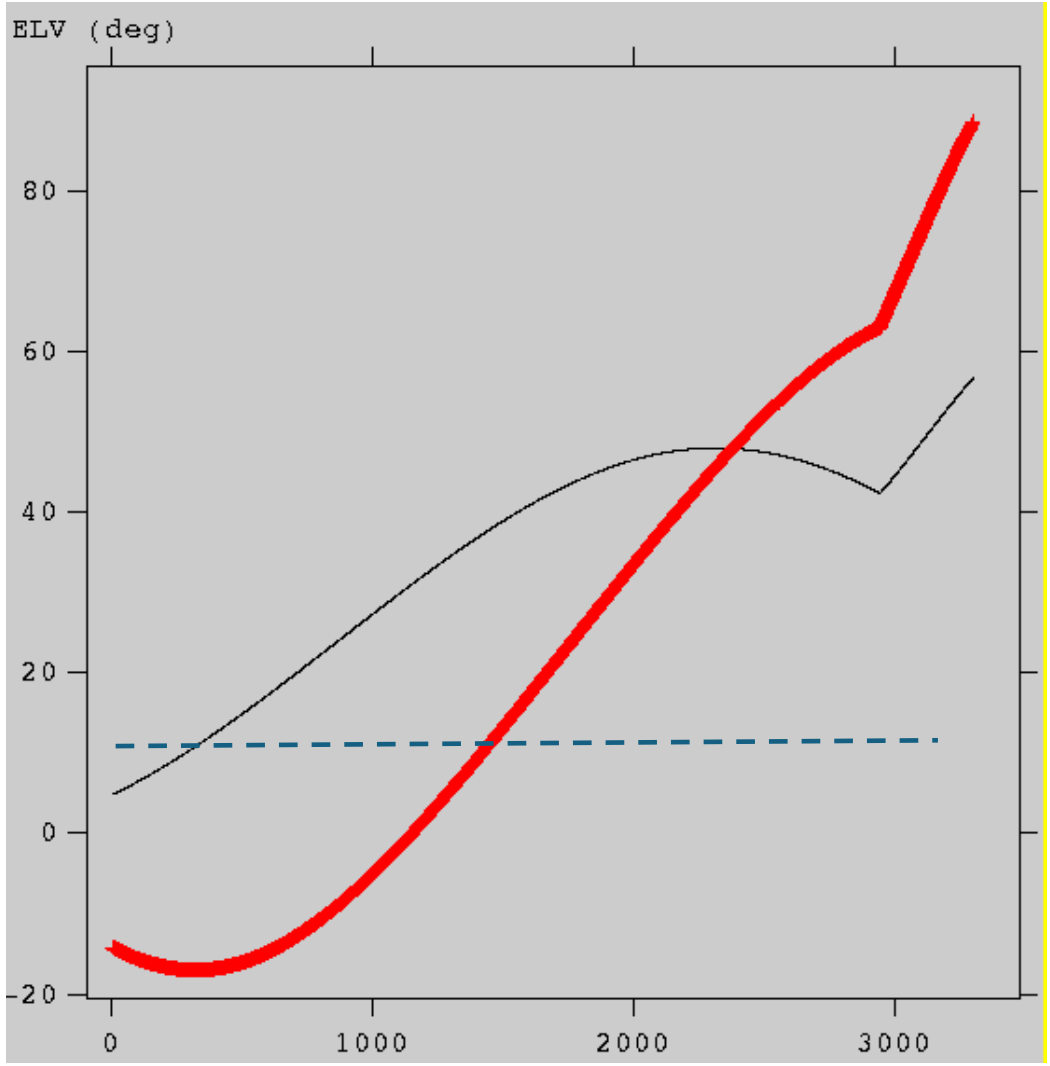
- 输入：轨道文件，姿态文件，卫星参数筛选文件
- 输出：WXT筛选参数文件（2级）
- 任务：根据轨道和姿态文件计算视场和地球夹角、太阳夹角等物理量，并与工程参数文件中温度、电压等参数合并形成筛选参数文件，用于确定GTI给后续事例筛选使用。

TIME	SAT_ALT	SAT_LAT	SAT_LON	RA	DEC	ROLL	ELV	BR_EARTH	FOV_FLAG	SUNSHINE	SUN_ANGLE	MOON_ANGLE	RAM_ANGLE	ANG_DIST	COR_SAX	MCILWAIN_L	SAA	SAFEHOLD	SETTLED
1D	1E	1E	1E	1E	1E	1E	1E	1E	1I	1I	1E	1E	1E	1E	1E	1E	1I	1B	1J
s	km	deg	deg	deg	deg	deg	deg	deg			deg	deg	deg	deg	GeV/c				
Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1.709931867999E+008	6.939145E+003	-3.473939E+00(	6.392447E+001	3.381824E+002	-3.727231E+00:	1.646941E+002	7.857980E+001	8.087708E+001	0	1	1.045314E+002	1.558219E+002	8.022302E+001	6.225435E+001	1.419046E+001	1.068463E+000	0	0	3
1.709931877999E+008	6.939148E+003	-3.504201E+00(	6.397528E+001	3.381826E+002	-3.727219E+00:	1.646941E+002	7.859872E+001	8.089146E+001	0	1	1.045313E+002	1.558219E+002	8.025493E+001	6.225441E+001	1.418532E+001	1.068656E+000	0	0	3
1.709931878810E+008	6.939148E+003	-3.504201E+00(	6.397528E+001	3.381826E+002	-3.727219E+00:	1.646941E+002	7.859872E+001	8.089146E+001	0	1	1.045313E+002	1.558219E+002	8.025493E+001	6.225441E+001	1.418532E+001	1.068656E+000	0	0	0
1.709931887999E+008	6.939151E+003	-3.534455E+00(	6.402608E+001	3.381870E+002	-3.727135E+00:	1.646909E+002	7.861909E+001	8.090616E+001	0	1	1.045277E+002	1.558218E+002	8.033101E+001	6.225373E+001	1.418017E+001	1.068850E+000	0	0	0
1.709931897999E+008	6.939153E+003	-3.564718E+00(	6.407691E+001	3.381910E+002	-3.727119E+00:	1.646885E+002	7.863863E+001	8.092012E+001	0	1	1.045246E+002	1.558211E+002	8.039551E+001	6.225257E+001	1.417500E+001	1.069045E+000	0	0	0
1.709931907999E+008	6.939156E+003	-3.594949E+00(	6.412770E+001	3.381949E+002	-3.727301E+00:	1.646860E+002	7.865615E+001	8.093207E+001	0	1	1.045222E+002	1.558185E+002	8.041985E+001	6.224965E+001	1.416980E+001	1.069241E+000	0	0	0
1.709931917999E+008	6.939160E+003	-3.625175E+00(	6.417848E+001	3.382007E+002	-3.727753E+00:	1.646831E+002	7.867140E+001	8.094114E+001	0	1	1.045191E+002	1.558129E+002	8.044942E+001	6.224363E+001	1.416458E+001	1.069438E+000	0	0	0
1.709931927999E+008	6.939164E+003	-3.655393E+00(	6.422926E+001	3.382077E+002	-3.728590E+00:	1.646801E+002	7.868309E+001	8.094622E+001	0	1	1.045162E+002	1.558034E+002	8.050189E+001	6.223372E+001	1.415934E+001	1.069636E+000	0	0	0
1.709931937999E+008	6.939167E+003	-3.685619E+00(	6.428007E+001	3.382191E+002	-3.729918E+00:	1.646750E+002	7.869089E+001	8.094607E+001	0	1	1.045115E+002	1.557882E+002	8.055080E+001	6.221788E+001	1.415407E+001	1.069835E+000	0	0	0

第2阶段—筛选事例（wxtscreen）

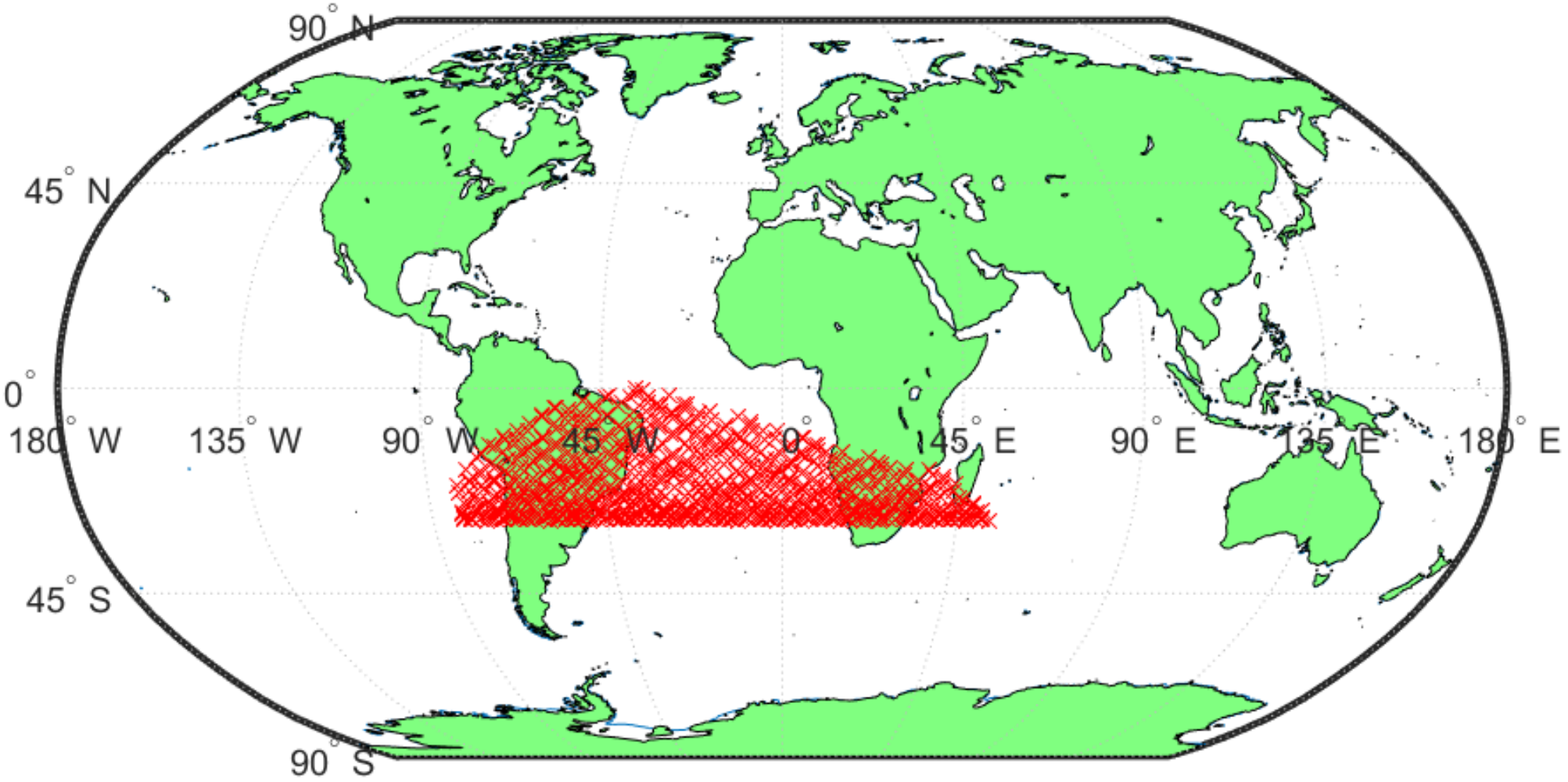
- 输入：标定后的事例文件，筛选参数文件
- 输出：筛选后的事例文件
- 任务：根据事例文件中的值（能量、位置、等级、时间）、筛选参数文件（温度、ELV、SAA等）将事例文件中符合要求的事例挑选出来
- ELV>=10&&SAA==0&&ANG_DIST<0.01&&SETTLED==1
- STATUS==b0
- exprgrade=“0-12”
- COR 和 BR_EARTH 备选

和地球边缘的夹角



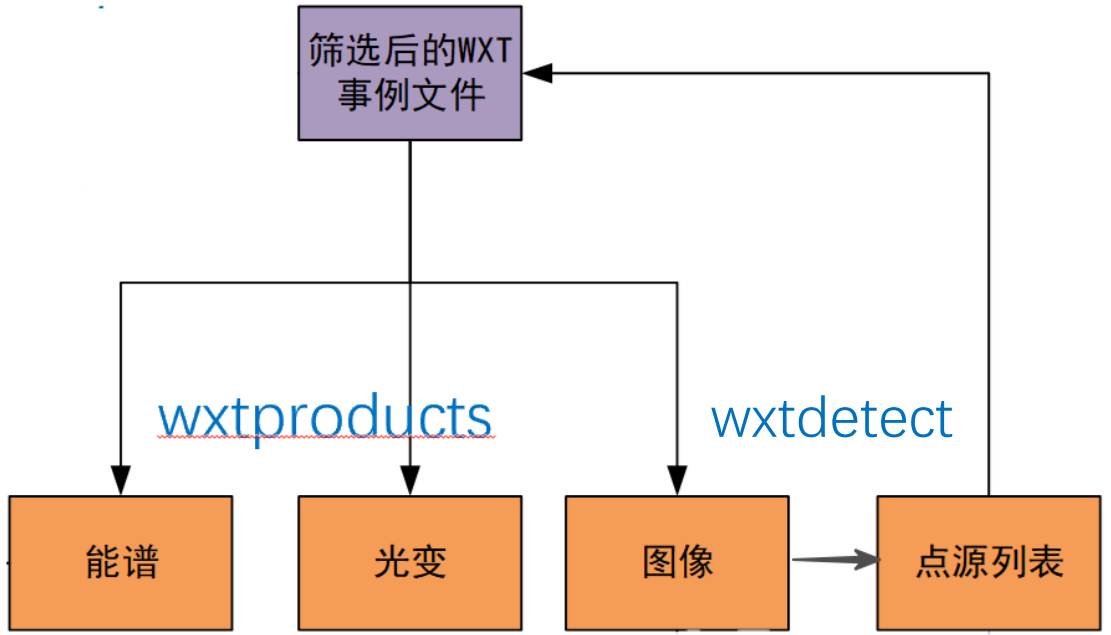
不同CMOS的可用时间差别明显

EP轨道穿过的SAA



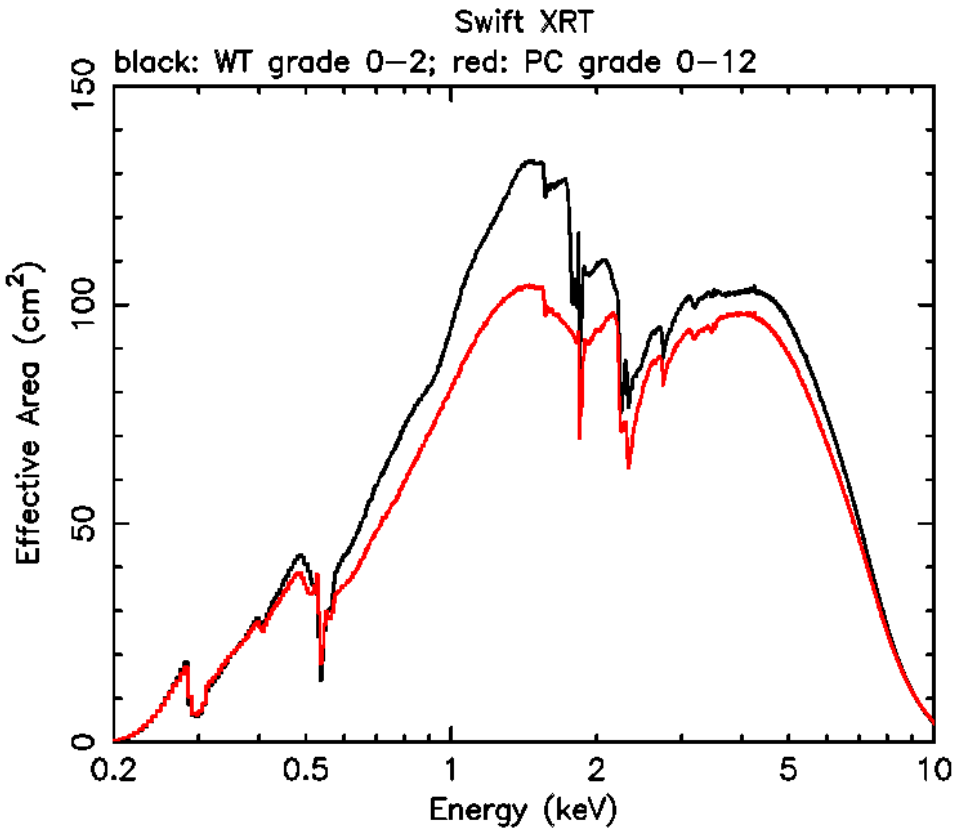
第3阶段—生成源表，光变，能谱，图像（wxtdetect+wxtproducts）

- 输入：筛选后的事例文件
- 输出：图像，源表，光变，能谱，响应
- 任务：根据事例文件中的值（能量、位置、等级、时间）将事例统计成高级产品
- filter grade region time pha
- extract curve spectrum image

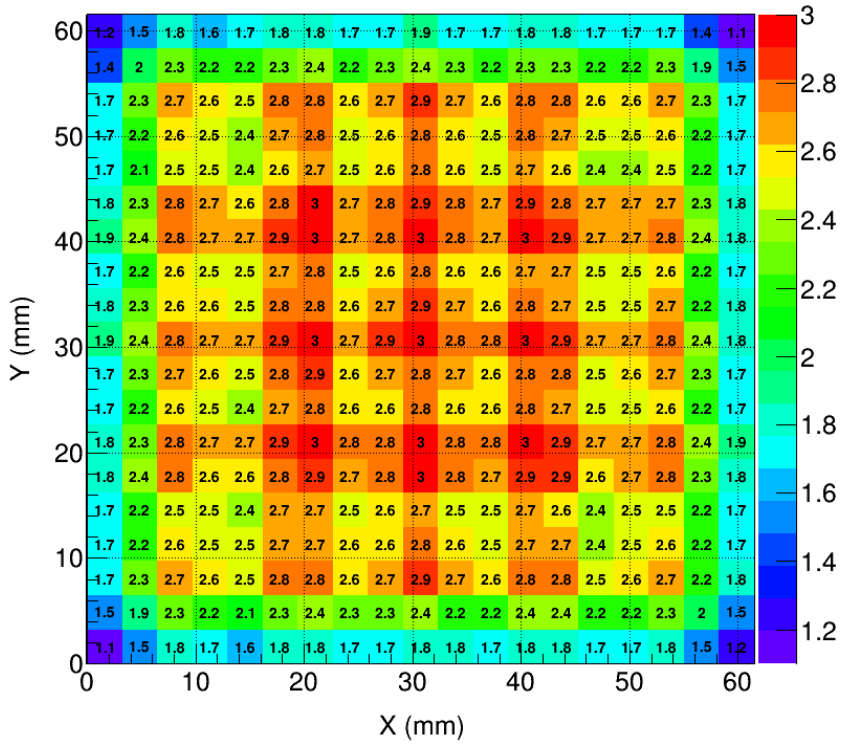


生成响应和有效面积 wxtmkarf

有效面积（arf）：给定工作模式和grade下对不同入射能量的面积



WXT单体视场内有效面积的变化@1 keV



生成响应和有效面积 wxtmkarf

响应文件 (rmf) :给定工作模式和grade下对不同入射能量的出射谱矩阵

Select All / Invert	ENERG_LO E keV Modify	ENERG_HI E keV Modify	N_GRP I Modify	F_CHAN I Modify	N_CHAN I Modify	MATRIX 1024E Modify	
1	1.000000E-001	1.050000E-001	1	0	1024	Plot	
2	1.050000E-001	1.100000E-001	1	0	1024	Plot	
3	1.100000E-001	1.150000E-001	1	0	1024	Plot	
4	1.150000E-001	1.200000E-001	1	0	1024	Plot	
5	1.200000E-001	1.250000E-001	1	0	1024	Plot	
6	1.250000E-001	1.300000E-001	1	0	1024	Plot	
7	1.300000E-001	1.350000E-001	1	0	1024	Plot	
8	1.350000E-001	1.400000E-001	1	0	1024	Plot	
9	1.400000E-001	1.450000E-001	1	0	1024	Plot	
10	1.450000E-001	1.500000E-001	1	0	1024	Plot	
11	1.500000E-001	1.550000E-001	1	0	1024	Plot	
12	1.550000E-001	1.600000E-001	1	0	1024	Plot	
13	1.600000E-001	1.650000E-001	1	0	1024	Plot	
14	1.650000E-001	1.700000E-001	1	0	1024	Plot	
15	1.700000E-001	1.750000E-001	1	0	1024	Plot	
16	1.750000E-001	1.800000E-001	1	0	1024	Plot	
17	1.800000E-001	1.850000E-001	1	0	1024	Plot	
18	1.850000E-001	1.900000E-001	1	0	1024	Plot	
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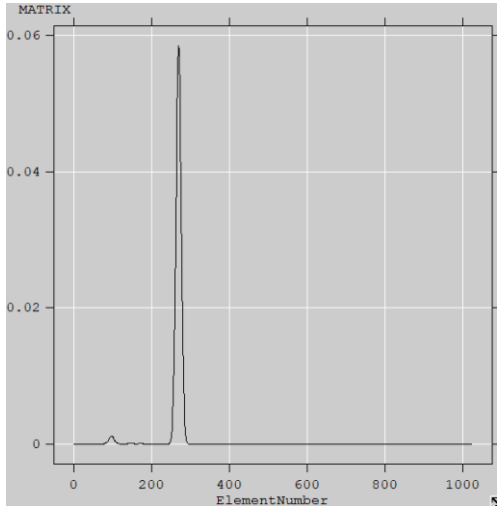
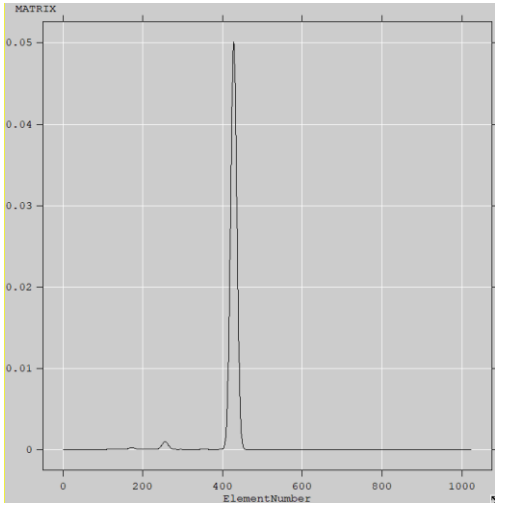
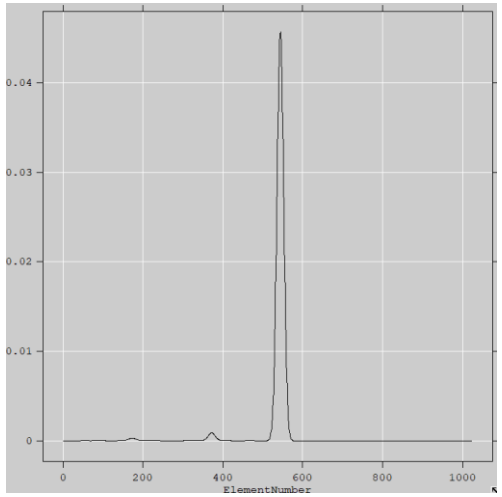
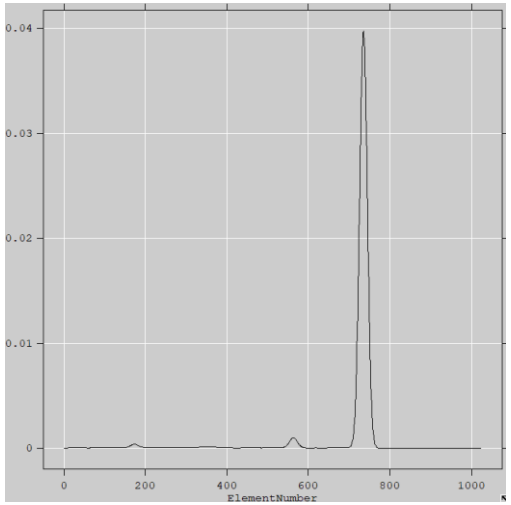
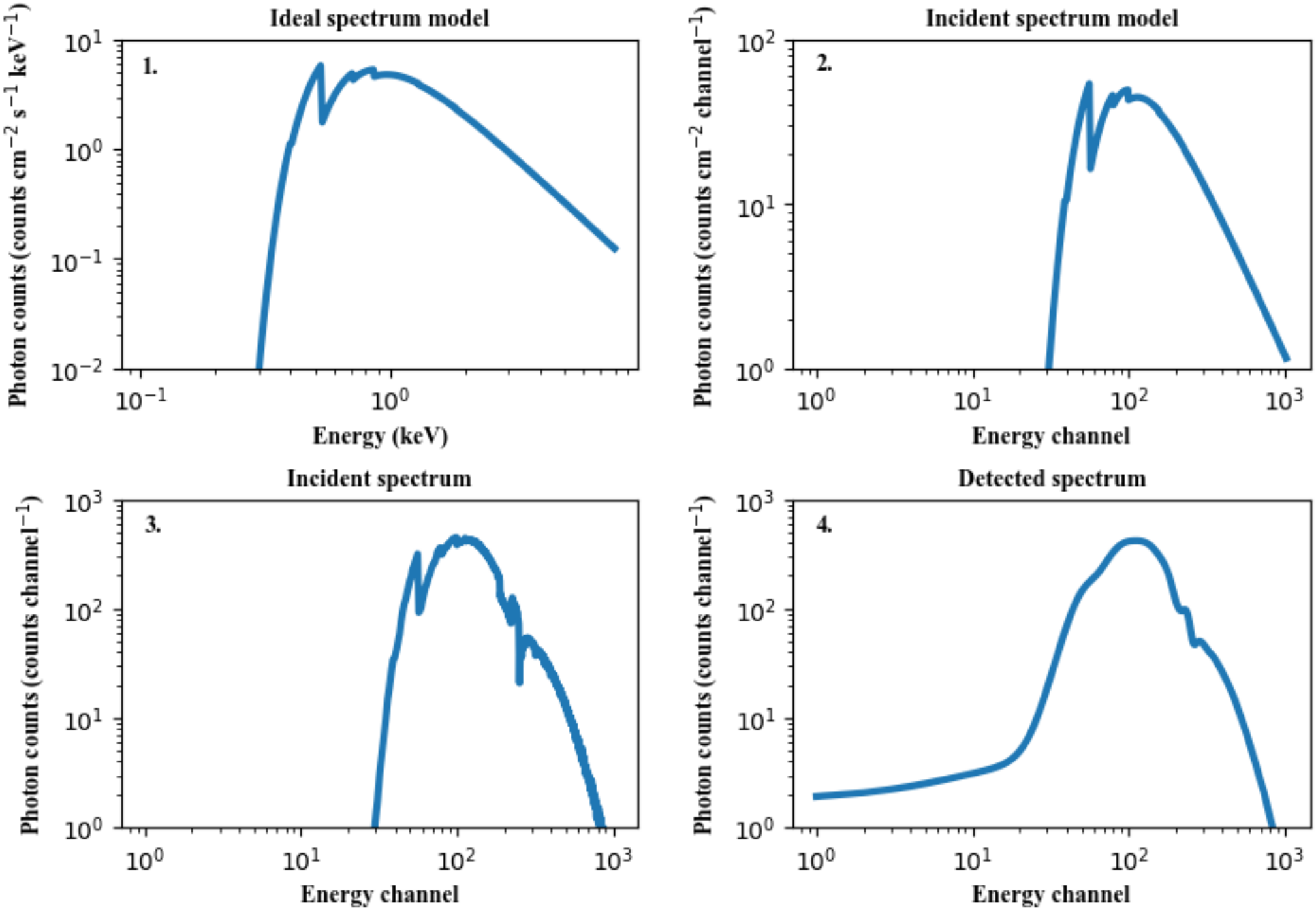
20	1.950000E-001	2.000000E-001	1	0	1024	Plot	










Ideal spectrum model
1.
Photon counts (counts cm^{-2} s^{-1} keV^{-1})
Energy (keV)
Incident spectrum model
2.
Photon counts (counts cm^{-2} channel^{-1})
Energy channel
Incident spectrum
3.
Photon counts (counts channel^{-1})
Energy channel
Detected spectrum
4.
Photon counts (counts channel^{-1})
Energy channel

小结

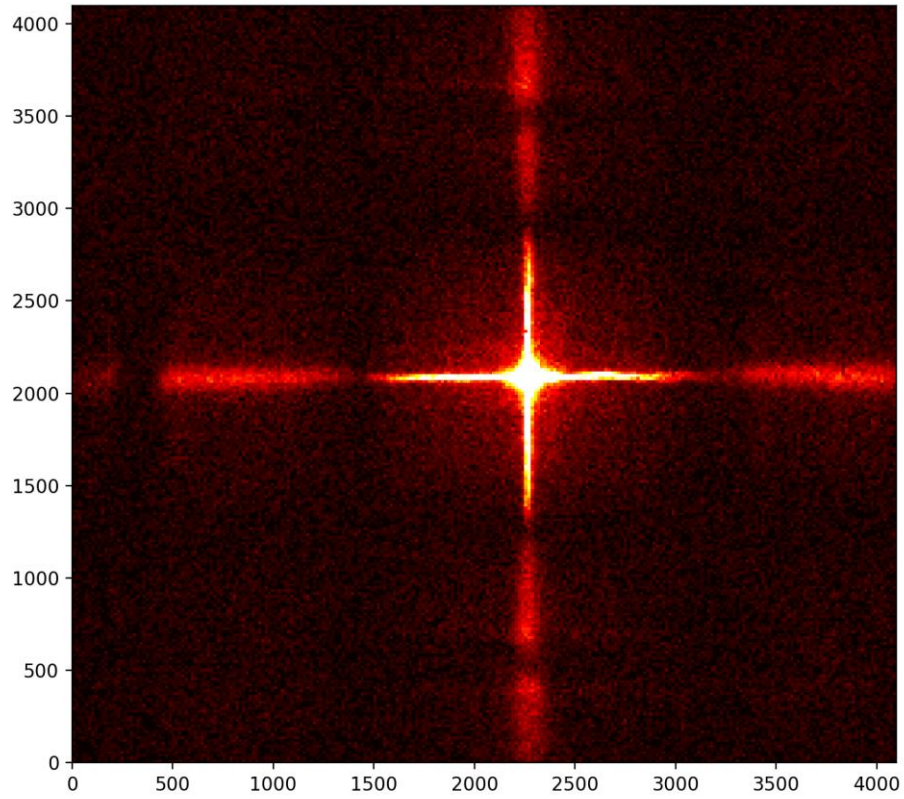
- **第1阶段—定标：** 扣减偏场、坐标转换、标记坏像素、计算事例等级、标记异常像素、PHA转换PI、生成筛选参数文件
- **第2阶段—筛选事例：** 地球角度、SAA区、指向稳定性、亮地球……
- **第3阶段—生成高级数据产品：** 源表，光变，能谱，图像

高级数据产品提取：图像、光变、能谱

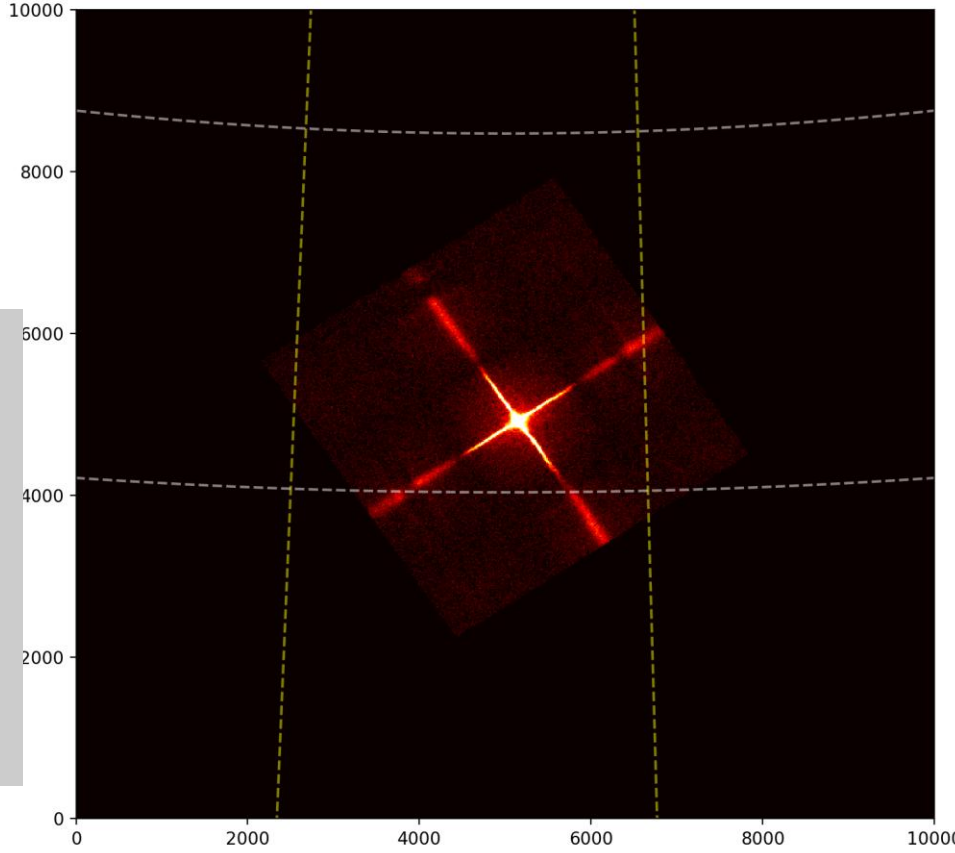
Select All Invert	TIME 1D s Modify	RAWX 1I pixel Modify	RAWY 1I pixel Modify	Amp 1B Modify	PHA 1J chan Modify	STATUS 16X Modify	DETX 1I Modify	DETY 1I Modify	X 1I Modify	Y 1I Modify	GRADE 1I Modify	PI 1J chan Modify
1	1.551116734500E+008	2004	2090	1	339	0	1933	2134	5007	5143	4	226
2	1.551116734500E+008	2316	2084	1	57	0	2245	2128	5176	4880	0	38
3	1.551116734500E+008	2304	2095	1	372	0	2233	2139	5178	4896	0	249
4	1.551116734500E+008	4022	2951	1	844	0	3957	2998	6850	3941	2	565
5	1.551116735000E+008	2277	1994	1	191	0	2206	2038	5079	4862	0	127
6	1.551116735000E+008	2174	2083	1	106	0	2103	2126	5095	4997	0	71
7	1.551116736000E+008	3048	1449	1	124	0	2977	1499	5060	3922	3	83
8	1.551116736000E+008	2262	2230	1	455	0	2191	2273	5266	5006	3	304
9	1.551116736000E+008	257	3684	1	807	0	188	3735	5368	7484	0	540
10	1.551116736999E+008	2220	1778	1	122	0	2149	1821	4867	4789	2	81
11	1.551116736999E+008	2253	2686	1	122	0	2182	2730	5641	5267	0	82
12	1.551116737499E+008	3979	2106	1	119	0	3911	2157	6126	3512	0	79
13	1.551116737499E+008	2447	2085	1	163	0	2375	2129	5249	4773	1	109

图像

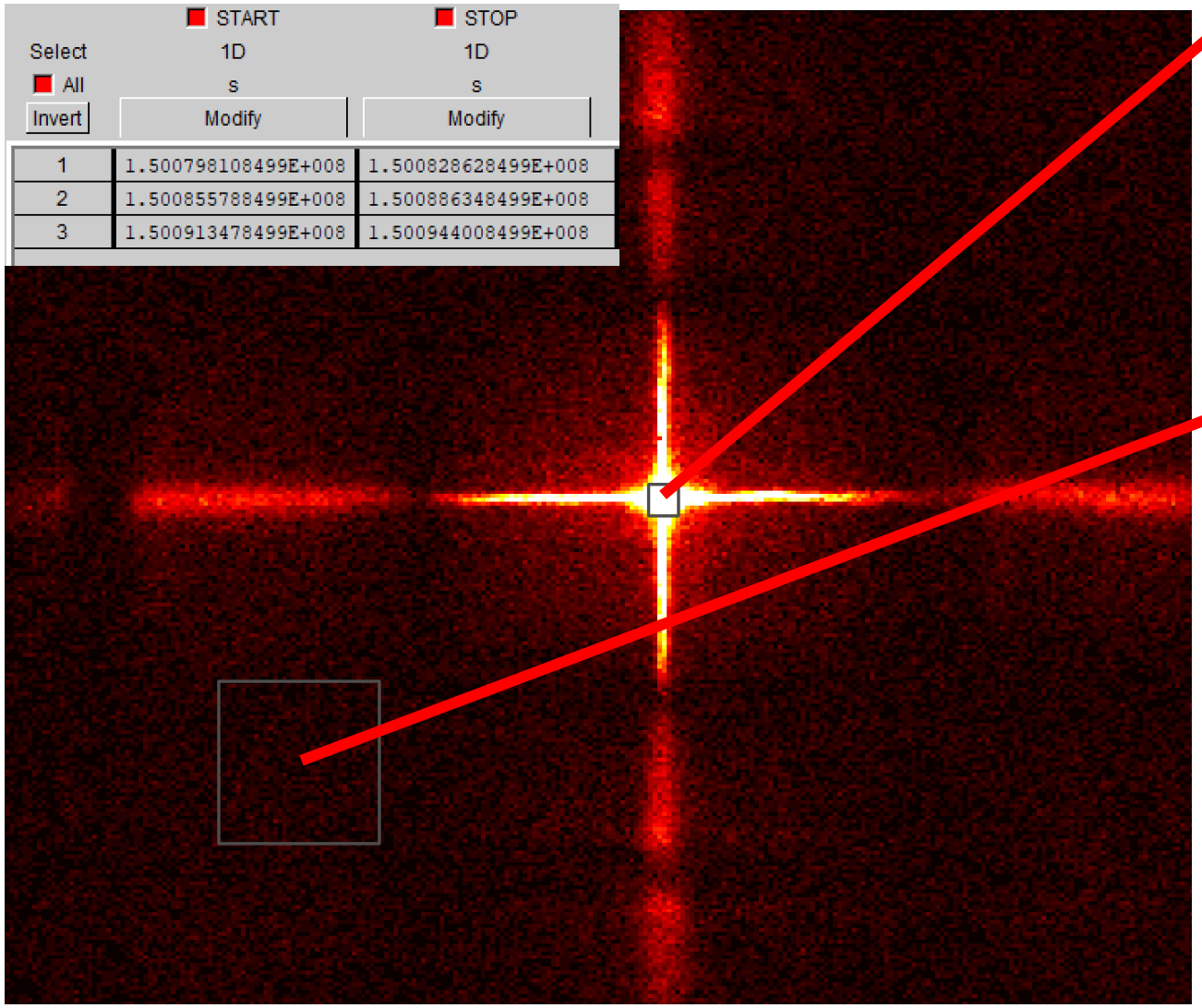
- 原始坐标
- 探测器坐标
- 天球坐标

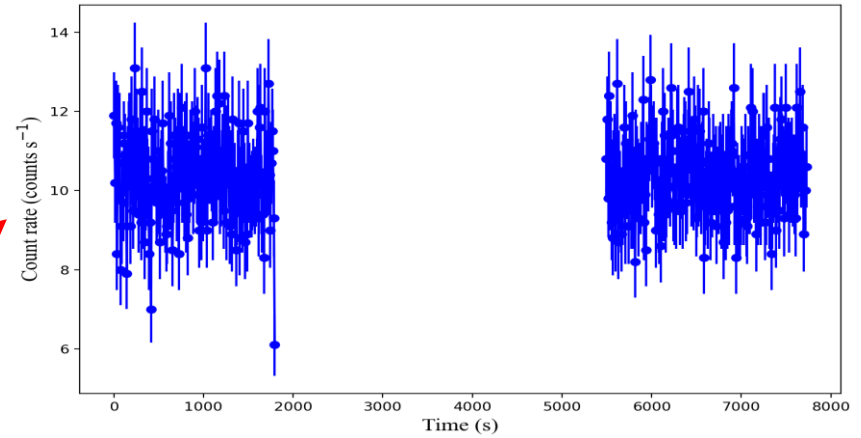


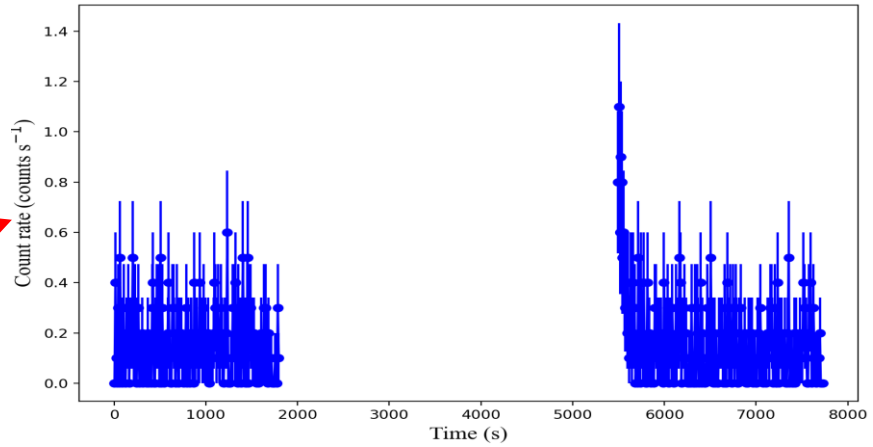

```
TLMIN9  =                    1 / Minimum value for X column
TLMAX9  =                10000 / Maximum value for X column
TCRPX9  =  5.0005000000000E+03 / X image reference pixel
TCRVL9  =  8.4000360000000E+01 / X image reference pixel coordinate (deg)
TCDLT9  = -2.2649350000000E-03 / X image scale (deg/pixel)
TCTYP9  = 'RA---TAN'           / X coordinate type
TCUNI9  = 'deg     '           / X units
TNULL9  =                   -1 / Added by wxtpipeline_0.1.0
TLMIN10 =                    1 / Minimum value for Y column
TLMAX10 =                10000 / Maximum value for Y column
TCRPX10 =  5.0005000000000E+03 / Y image reference pixel
TCRVL10 =  2.2183970000000E+01 / Y image reference pixel coordinate (deg)
TCDLT10 =  2.2649350000000E-03 / Y image scale (deg/pixel)
TCTYP10 = 'DEC--TAN'           / Y coordinate type
TCUNI10 = 'deg     '           / Y units
TNULL10 =                   -1 / Added by wxtpipeline_0.1.0
```

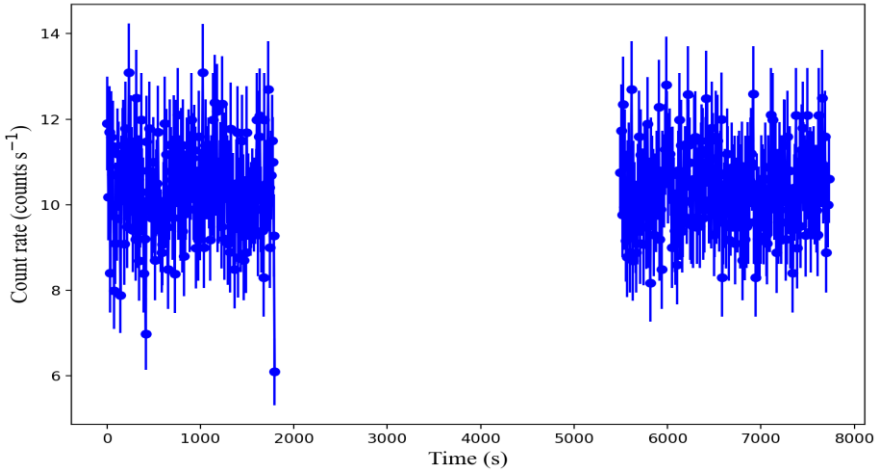


光变：光子到达时间


START
STOP
Select
1D
1D
All
s
s
Invert
Modify
Modify
1 1.500798108499E+008 1.500828628499E+008
2 1.500855788499E+008 1.500886348499E+008
3 1.500913478499E+008 1.500944008499E+008


Count rate (counts s^{-1})
Time (s)


Count rate (counts s^{-1})
Time (s)


Count rate (counts s^{-1})
Time (s)

能谱：光子能量

- **能道-能量对应关系**

0	Primary	Image	0	Header Image Table
1	MATRIX	Binary	6 cols X 1980 rows	Header Hist Plot All Select
2	EBOUNDS	Binary	3 cols X 1024 rows	Header Hist Plot All Select

Select All Invert	CHANNEL I Modify	E_MIN E keV Modify	E_MAX E keV Modify
1	0	0.000000E+000	1.000000E-002
2	1	1.000000E-002	2.000000E-002
3	2	2.000000E-002	3.000000E-002
4	3	3.000000E-002	4.000000E-002
5	4	4.000000E-002	5.000000E-002
6	5	5.000000E-002	6.000000E-002
7	6	6.000000E-002	7.000000E-002
8	7	7.000000E-002	8.000000E-002
9	8	8.000000E-002	9.000000E-002
10	9	9.000000E-002	1.000000E-001
11	10	1.000000E-001	1.100000E-001
12	11	1.100000E-001	1.200000E-001
13	12	1.200000E-001	1.300000E-001
14	13	1.300000E-001	1.400000E-001
15	14	1.400000E-001	1.500000E-001
16	15	1.500000E-001	1.600000E-001
17	16	1.600000E-001	1.700000E-001
18	17	1.700000E-001	1.800000E-001
19	18	1.800000E-001	1.900000E-001
20	19	1.900000E-001	2.000000E-001