

太陽X線光子計測データの解析

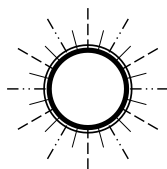


成影 典之（国立天文台）

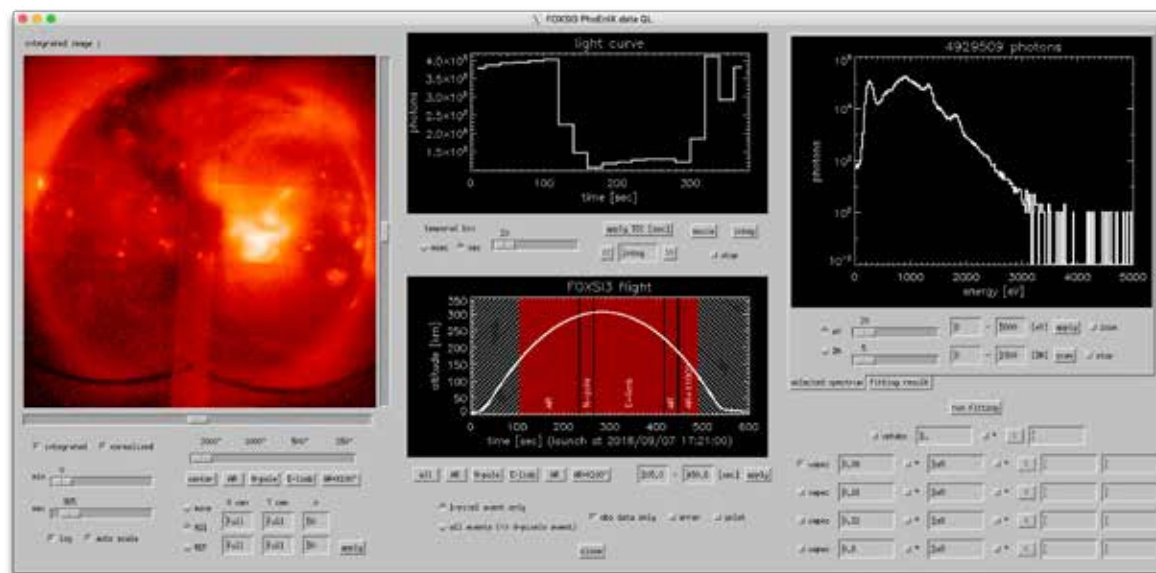
長澤 俊作（東京大学カブリIPMU）、川手 朋子（核融合科学研究所）、
萩野 浩一（東京理科大学）、三石 郁之（名古屋大学）、
渡辺 伸、坂尾太郎、松崎 恵一（ISAS/JAXA）、
高橋 忠幸（東京大学カブリIPMU）、石川 真之介（立教大学）



本日の講演内容



- 太陽コロナの紹介
- 太陽コロナ（フレア）観測の現状と進展
- 世界初の太陽X線光子計測データの紹介
- 太陽X線光子計測データの解析ツール開発
- 今後の展開



Significance of solar corona study

[Plasma physics]

Natural laboratory of plasma

- Magnetic reconnection
- Particle acceleration

[Unique observation target]

The closest star

- Solar phenomenon can be observed with wide field of view and with spatial and temporal resolutions

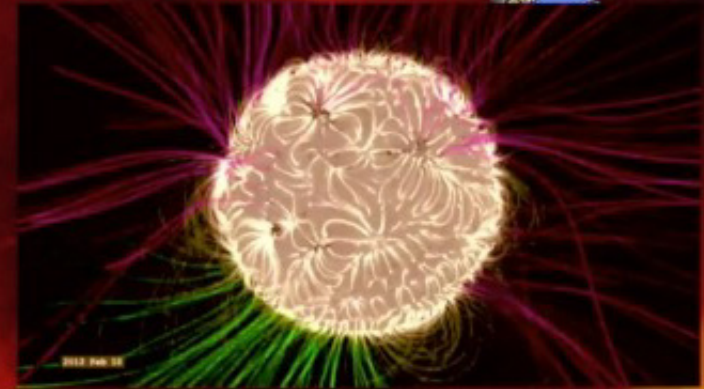
[Impacts on Earth and social environments]

The mother of the Earth

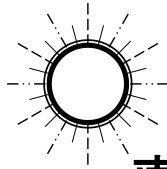
- Evolution of life (cosmic rays)
- Space weather

[As a star]

- Reference of other astrophysical objects



太陽コロナ（フレア）を どうやって計測する？

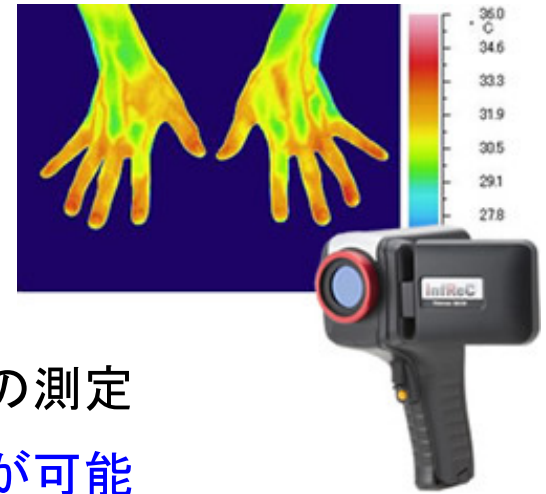


直接計測

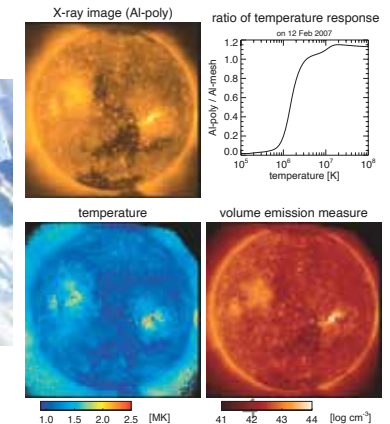
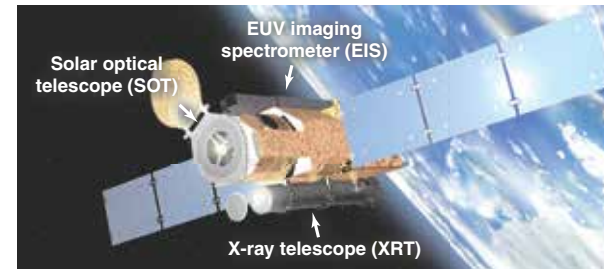


- 精確な測定が可能
- 観測装置を測定点に持っていく必要がある
- 測定点が限られる

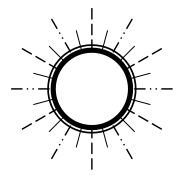
リモート計測



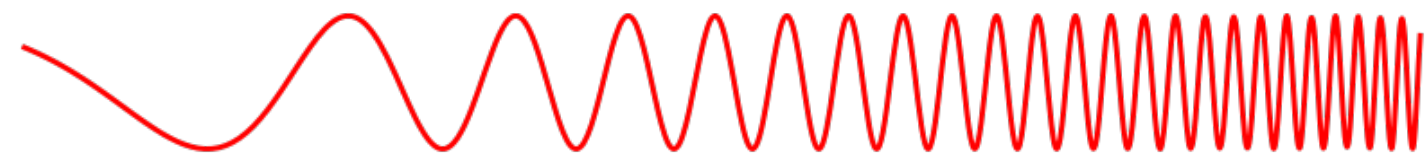
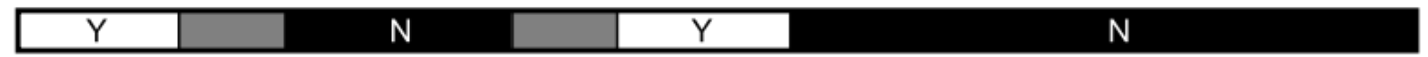
- そこそこの精度の測定
- 遠方からの測定が可能
- 広範囲を測定することが可能



太陽コロナ（フレア）のリモート観測： X線を計測する



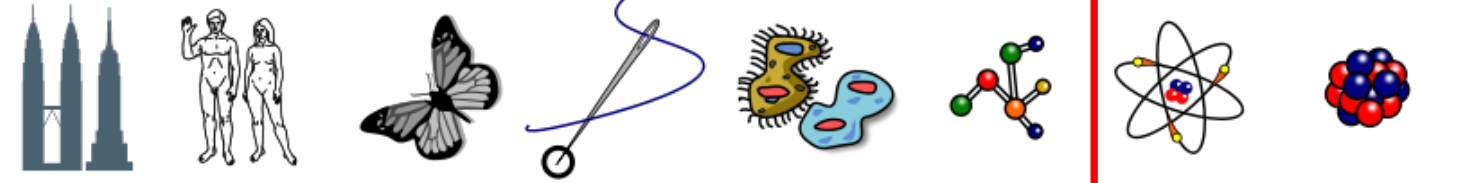
Penetrates Earth's Atmosphere?



Radiation Type
Wavelength (m)

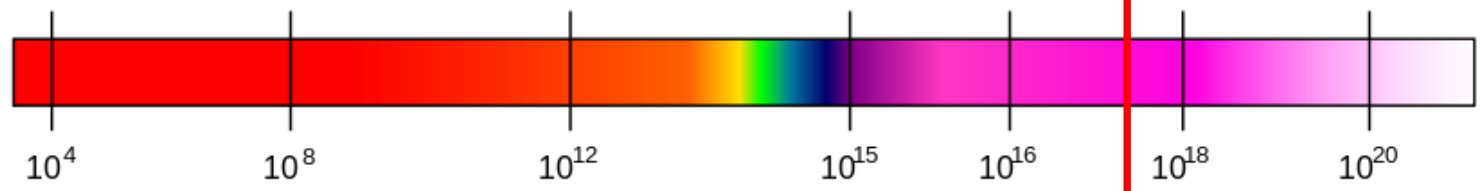
Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma ray
10^3	10^{-2}	10^{-5}	0.5×10^{-6}	10^{-8}	10^{-10}	10^{-12}

Approximate Scale of Wavelength

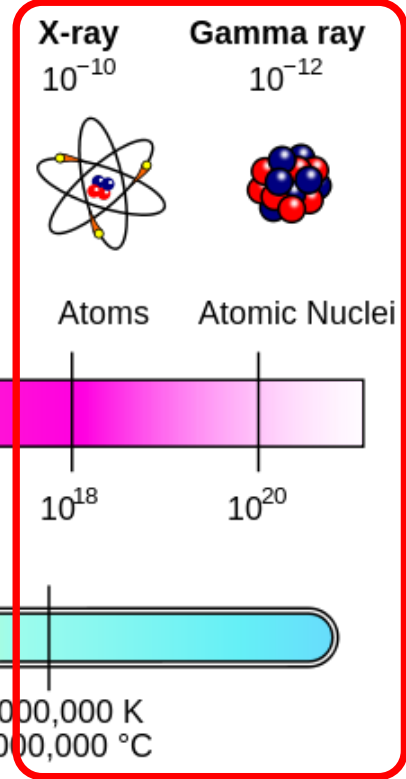
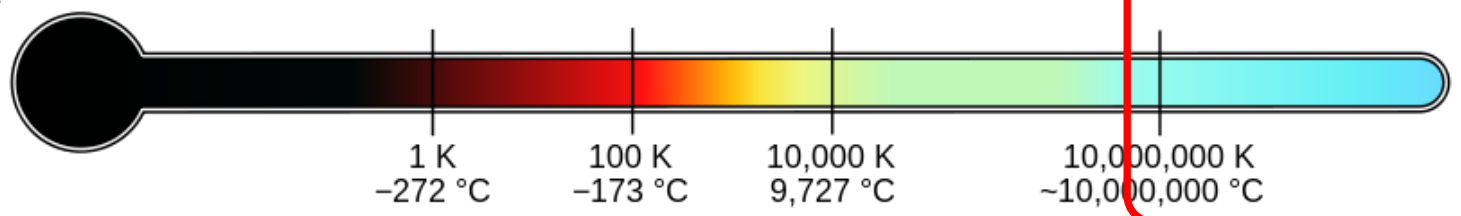


Buildings Humans Butterflies Needle Point Protozoans Molecules Atoms Atomic Nuclei

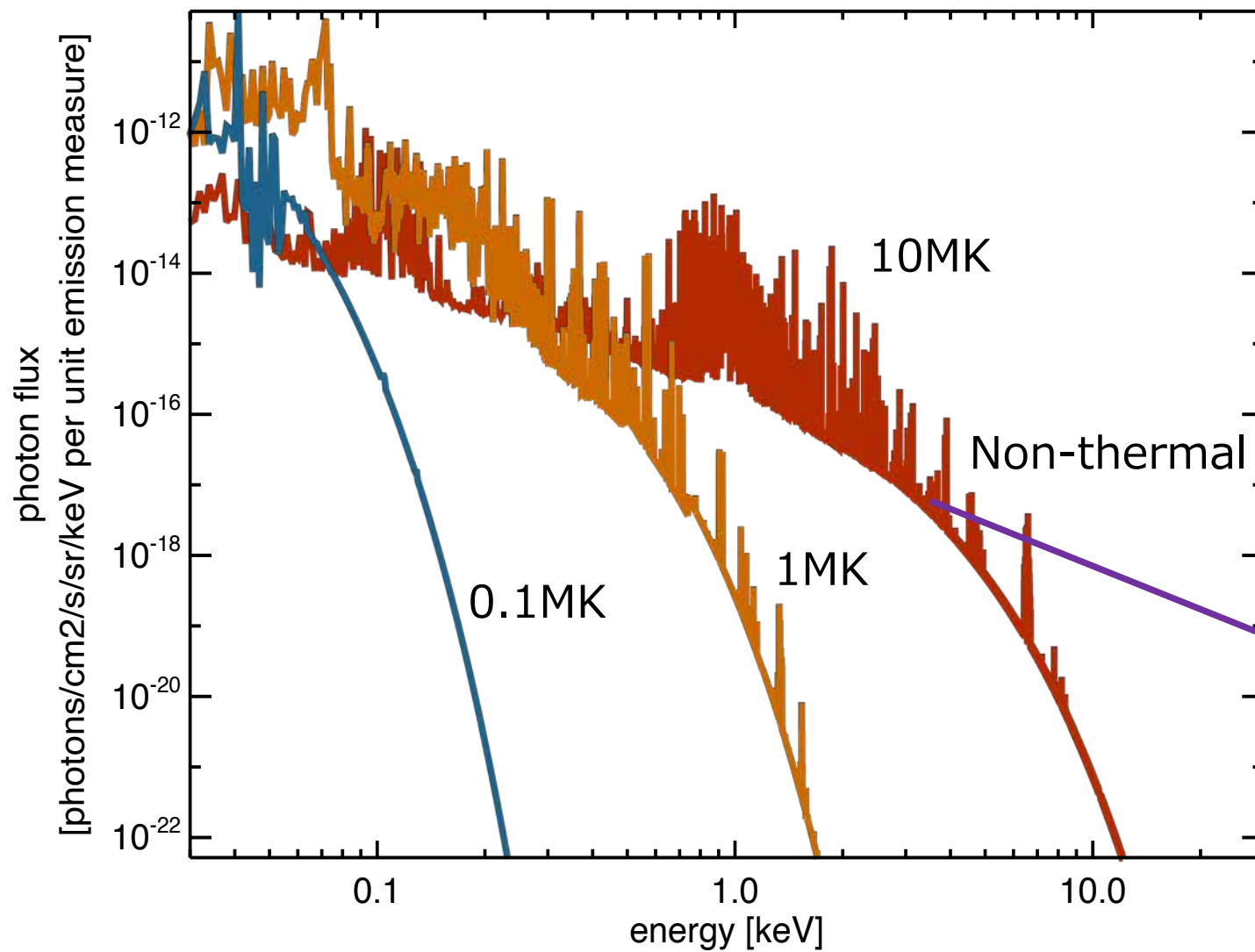
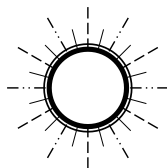
Frequency (Hz)



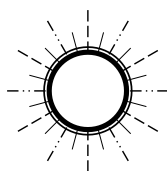
Temperature of objects at which this radiation is the most intense wavelength emitted



太陽コロナ（フレア）のリモート観測： X線を計測する



理想の太陽コロナ（フレア）観測

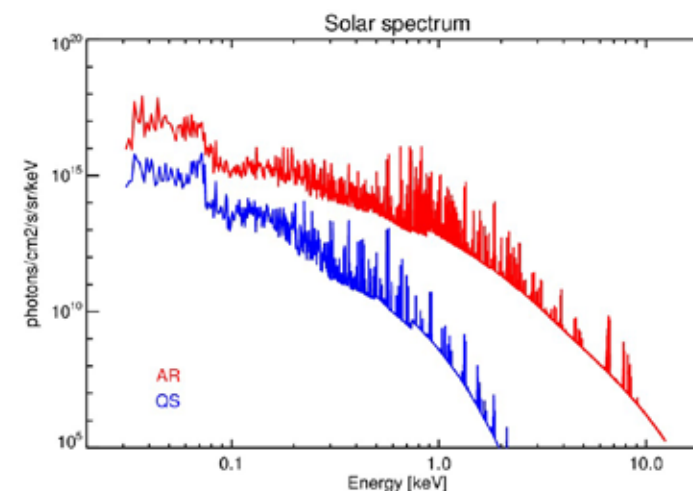
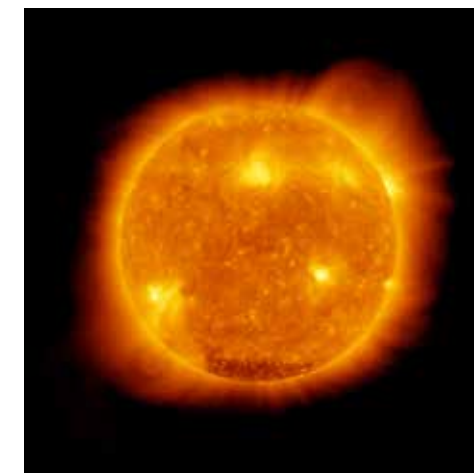


観測に対する要求

- 高温および非熱的プラズマを検出可能なこと
- プラズマの物理量を空間・時間分解して取得できること

観測方法

- **X線用ミラーと高速度カメラを用いた
光子計測型・集光撮像分光観測**
 - **X線帯域**: 高温および非熱的プラズマに対する高い感度
 - **連続光成分**: 急激な温度変化に対する素早い反応
 - **輝線**: プラズマに対する豊富な情報を含む
 - **ミラーを用いた集光撮像**:
高いダイナミックレンジと空間分解能を確保するため
 - **高速度カメラ**: 時間分解能を確保するため
 - **分光**: 物理量を取得するため



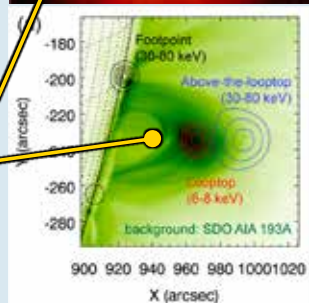
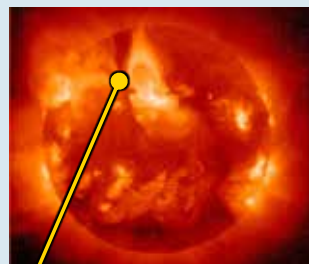
空間・時間・エネルギーの情報を同時に得る!!

太陽コロナ（フレア）のX線観測

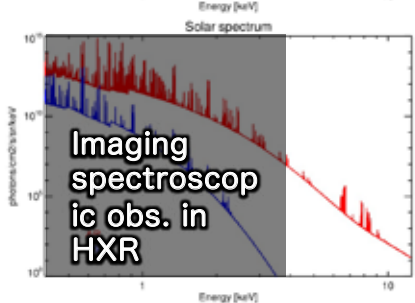
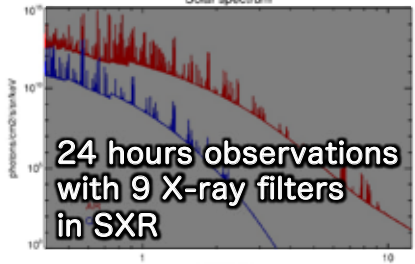
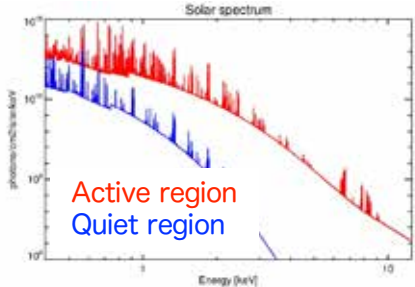
Soft X-rays
Yohkoh / SXT
Hinode / XRT
(1991 ~ present)



Hard X-rays
Yohkoh / HXT
RHESSI
(1991 ~ 2018)

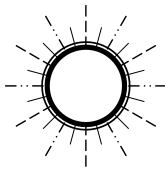


flare

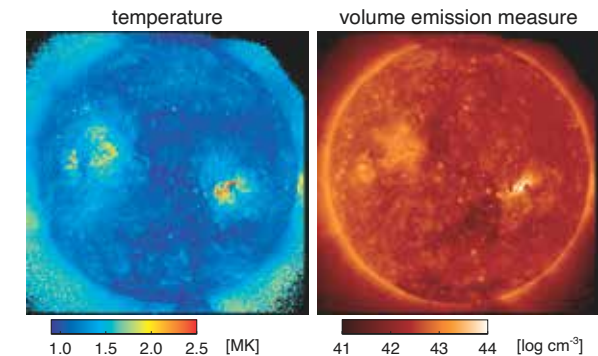
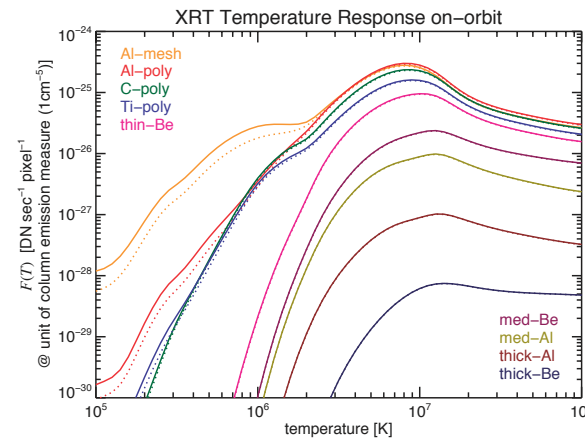
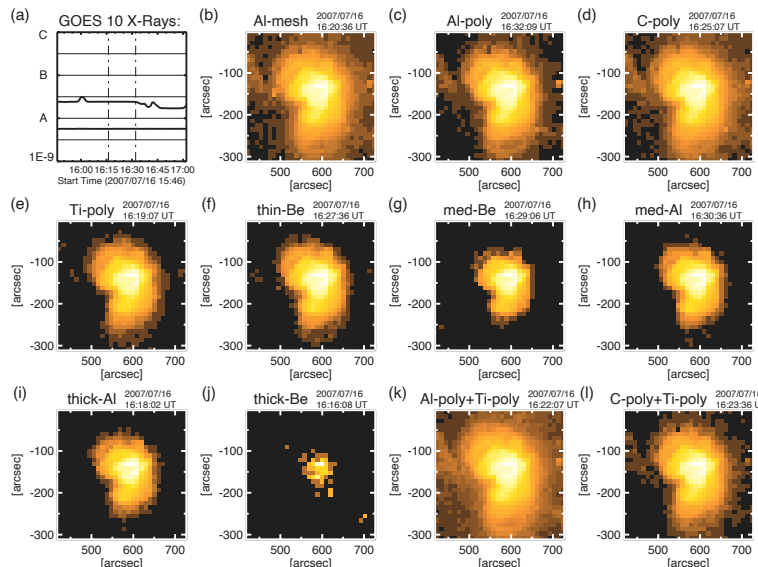
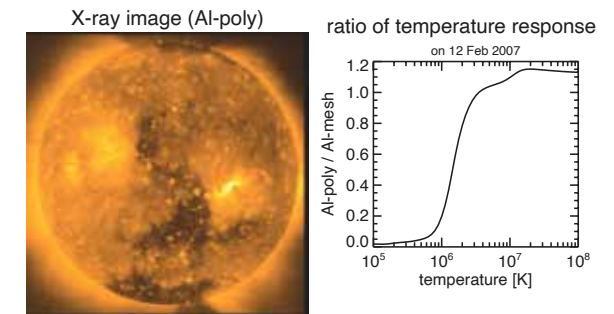
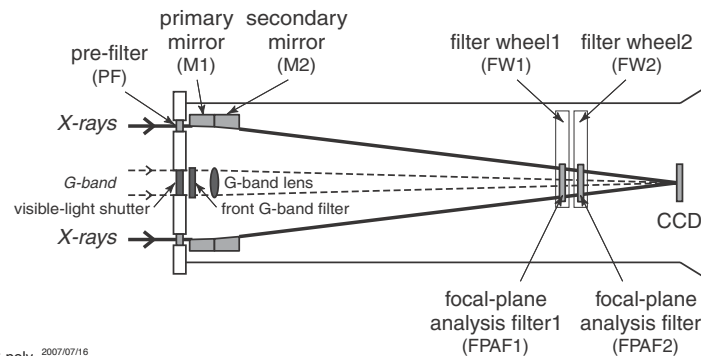
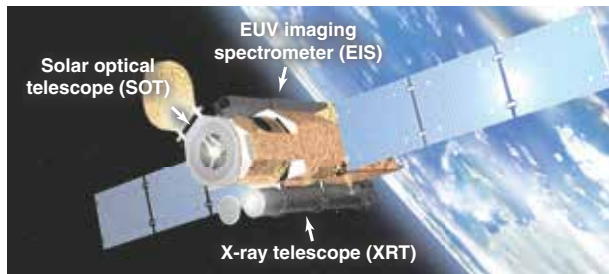




Existing soft X-ray focusing imaging observation grazing incidence mirror + X-ray filters



Hinode / X-ray telescope (XRT)

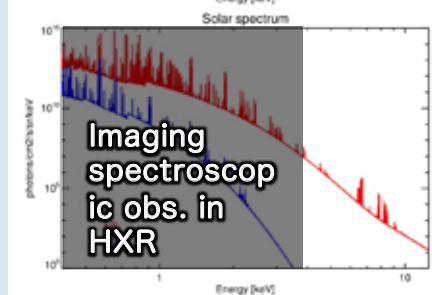
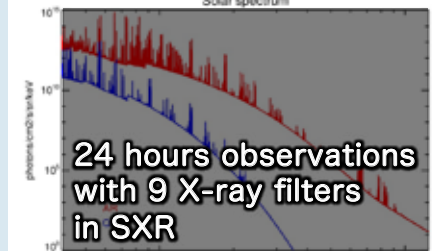
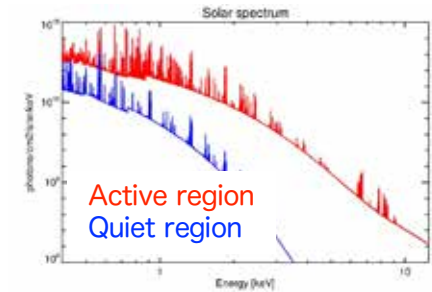
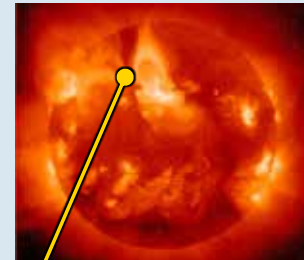


With good dynamic range, spatial- and temporal- resolutions.
But, no energy resolution.

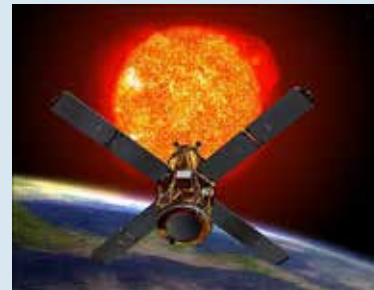
Using 9 X-ray filters, the index of coronal temperature (filter-ratio temperature) can be derived.

太陽コロナ（フレア）のX線観測

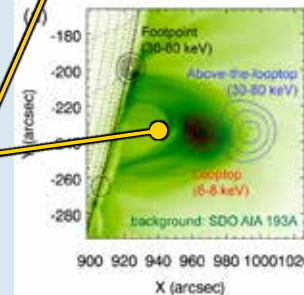
Soft X-rays
Yohkoh / SXT
Hinode / XRT
(1991 ~ present)



Hard X-rays
Yohkoh / HXT
RHESSI
(1991 ~ 2018)

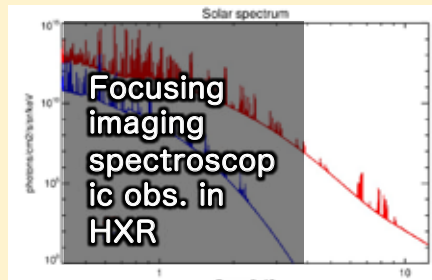
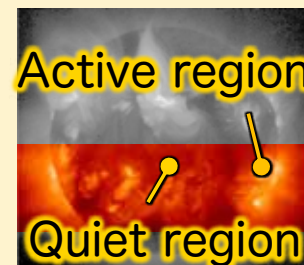


flare

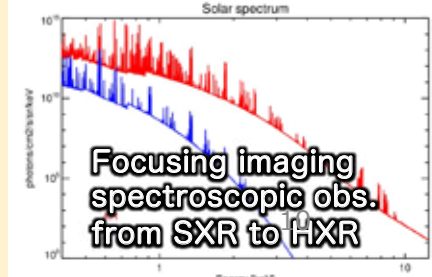
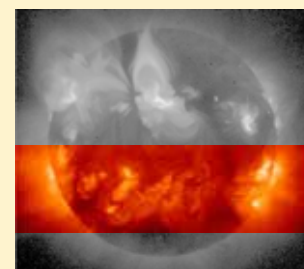


↓ **Next: spatial-, temporal- & energy-resolutions and high dynamic range**

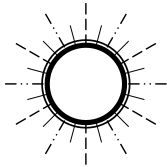
Sounding rocket
FOXSI-1, 2
(2012, 2014)



Sounding rocket
FOXSI-3
(Sep 7th 2018)



軟X線用高速度カメラ（裏面照射型CMOSセンサー）



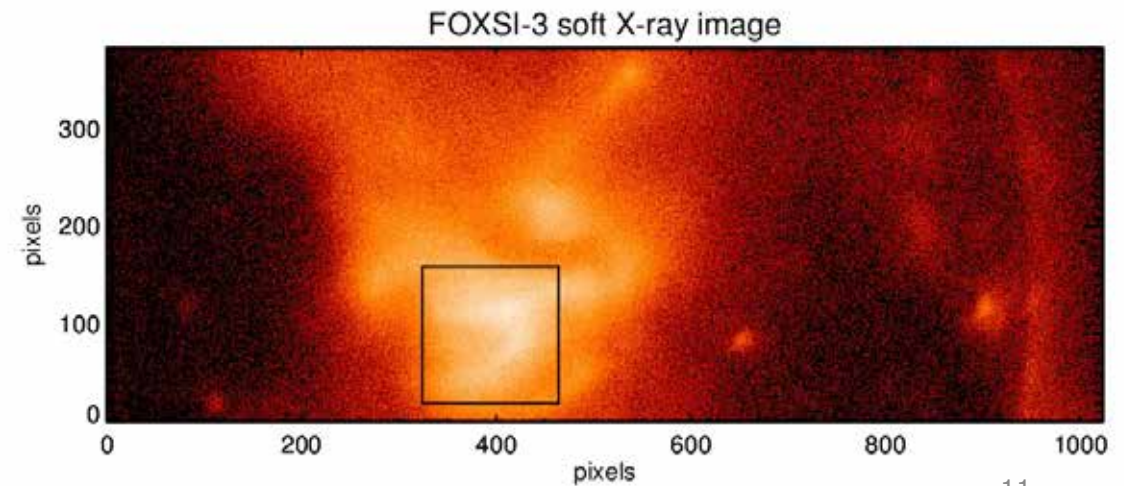
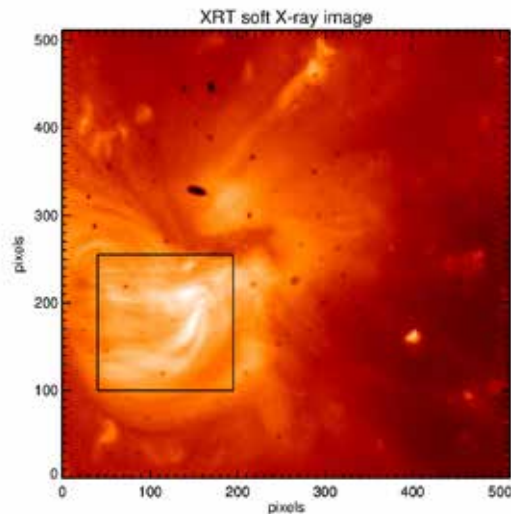
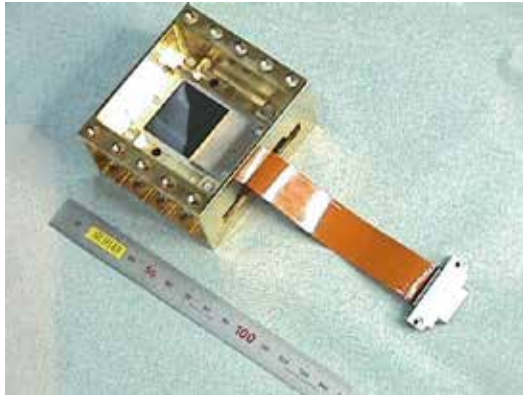
Existing instruments (Yohkoh, Hinode)

New instruments (FOXSI)

X-ray mirror + CCD



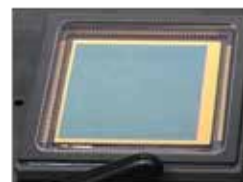
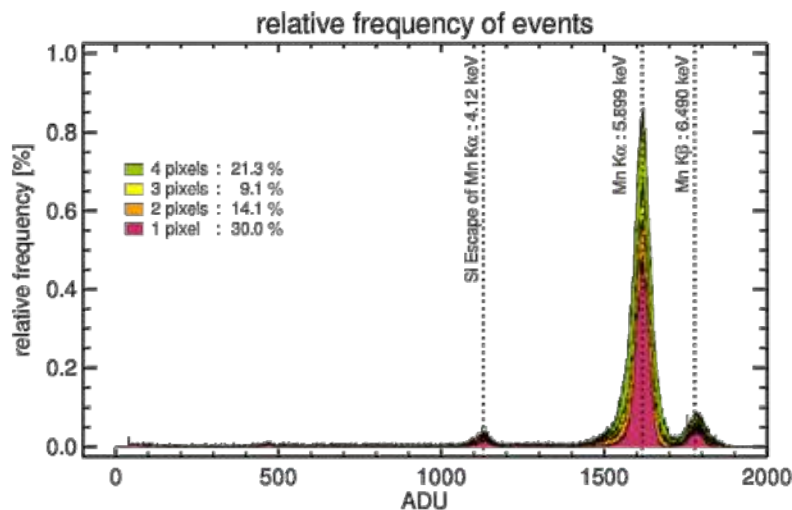
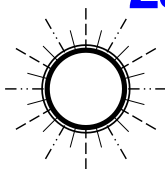
X-ray mirror + CMOS





裏面照射型CMOSセンサーの性能 (Narukage et al. 2020)

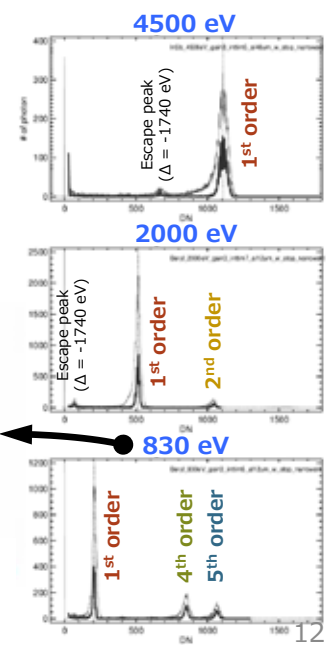
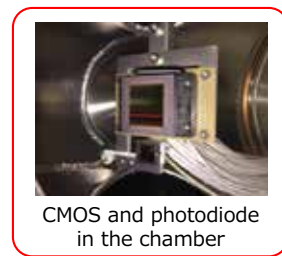
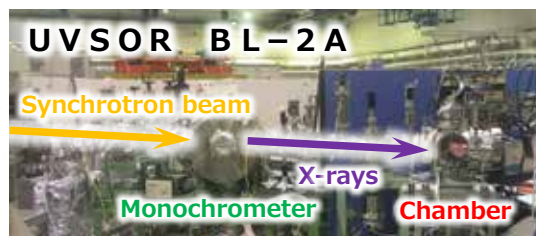
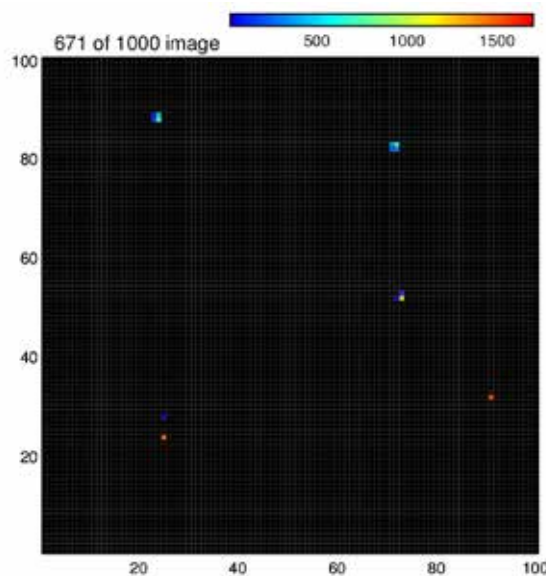
250 FPS for 384 x 1024 pixels (160 MB / sec) (Ishikawa et al., 2018)



Soft X-ray CMOS sensor

1 pixel event rate	: 30.0 %
valid split event rate	: 44.5 %
valid event rate	: 74.5 %
FWHM of 1 pixel event	: 168 [eV]
FWHM of valid split event	: 319 [eV]
FWHM of valid event	: 227 [eV]

Spectrum of ⁵⁵Fe source



Example of imaging spectroscopy with photon-counting

Imaging obs. = imaging spectroscopy

All order beams are mixed. 1st order (830 eV) 4th order (3,320 eV) 5th order (4,150 eV)



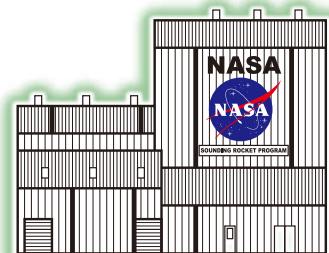
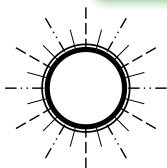
t = 65.0 sec
Payload Separation

t = 43.5 sec
Black Brant Burnout

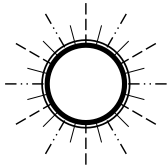
t = 16.0 sec
Black Brant Mod 2 Ignition

t = 6.2 sec
Terrier Burnout

t = 0.0 sec
Launch



FOXSI-3 (the 3rd flight of Focusing Optics X-ray Solar Imager)



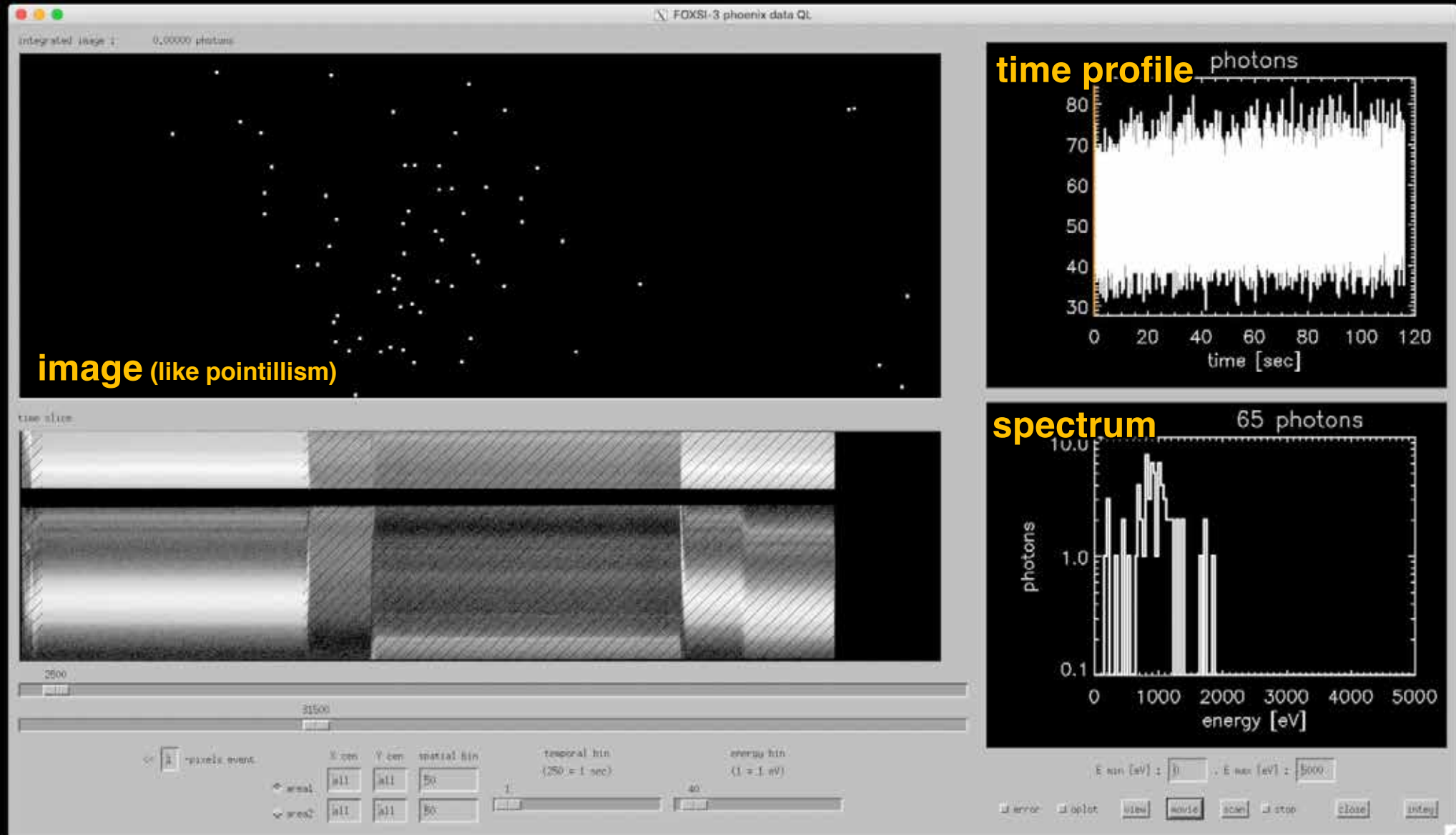
- US-Japan collaborative sounding rocket experiment.
→ **FOXSI-3 was successfully launched on September 7th, 2018.**
- Objectives:
 1. Study small scale energy release in the solar corona
 2. Demonstrate the new technology for X-ray imaging spectroscopy
- Method:
 1. Hard X-ray imaging spectroscopy
 2. **Soft X-ray imaging spectroscopy (for the first time in the world) with a high-speed X-ray camera**

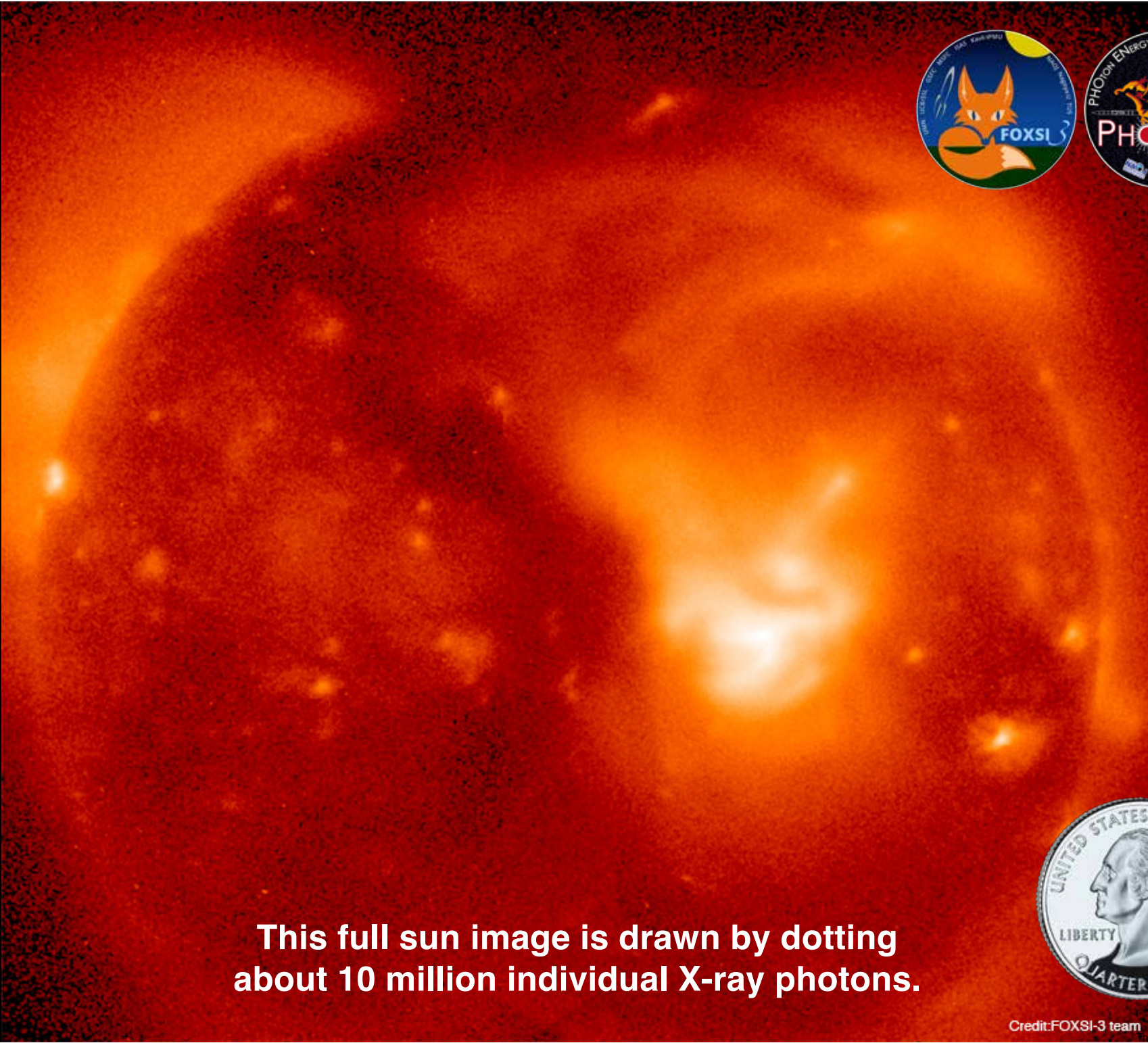


See
<http://foxsi.umn.edu/>
and
<https://hinode.nao.ac.jp/en/news/topics/foxsi-3-180907/>

FOXSI-3 Soft X-ray data

250 FPS data (4 ms continuous exposure)





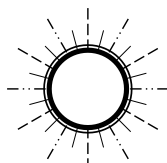
This full sun image is drawn by dotting about 10 million individual X-ray photons.



FOXSI-3 によりもたらされたもの

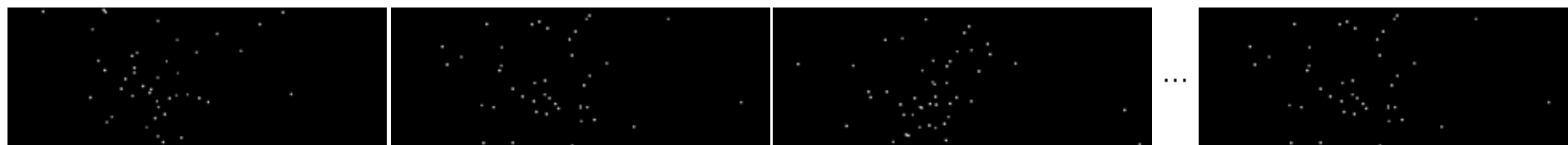
1千万個の軟X線光子1個1個の

位置・時間・エネルギー情報（世界初のデータ）

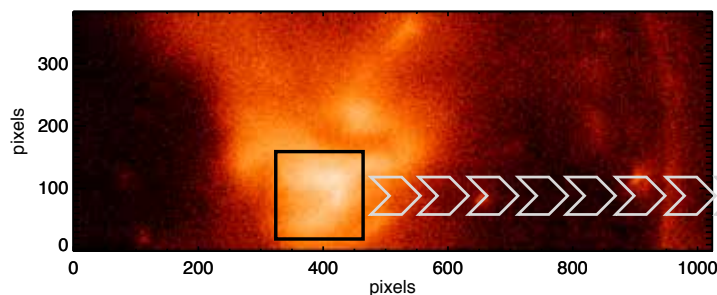


(a) Observational data

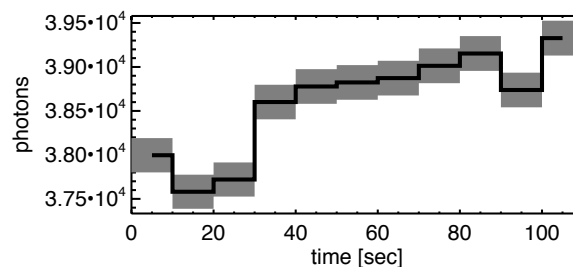
Flow of time (high-speed continuous exposure with 250 frames per second)



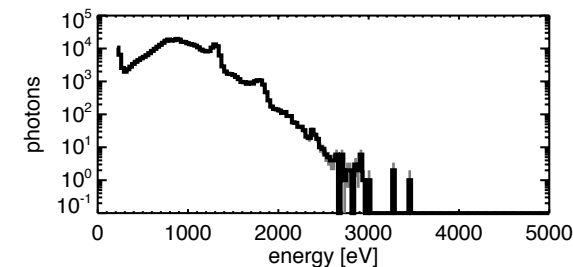
(b) Solar Image with integrated X-ray photons



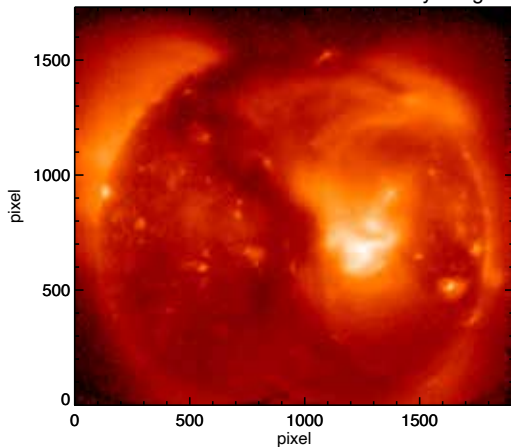
(c) Time variation of X-ray photon number in an active region



(d) X-ray spectrum of an active region



FOXSI-3 PhoEnIX full Sun soft X-ray image



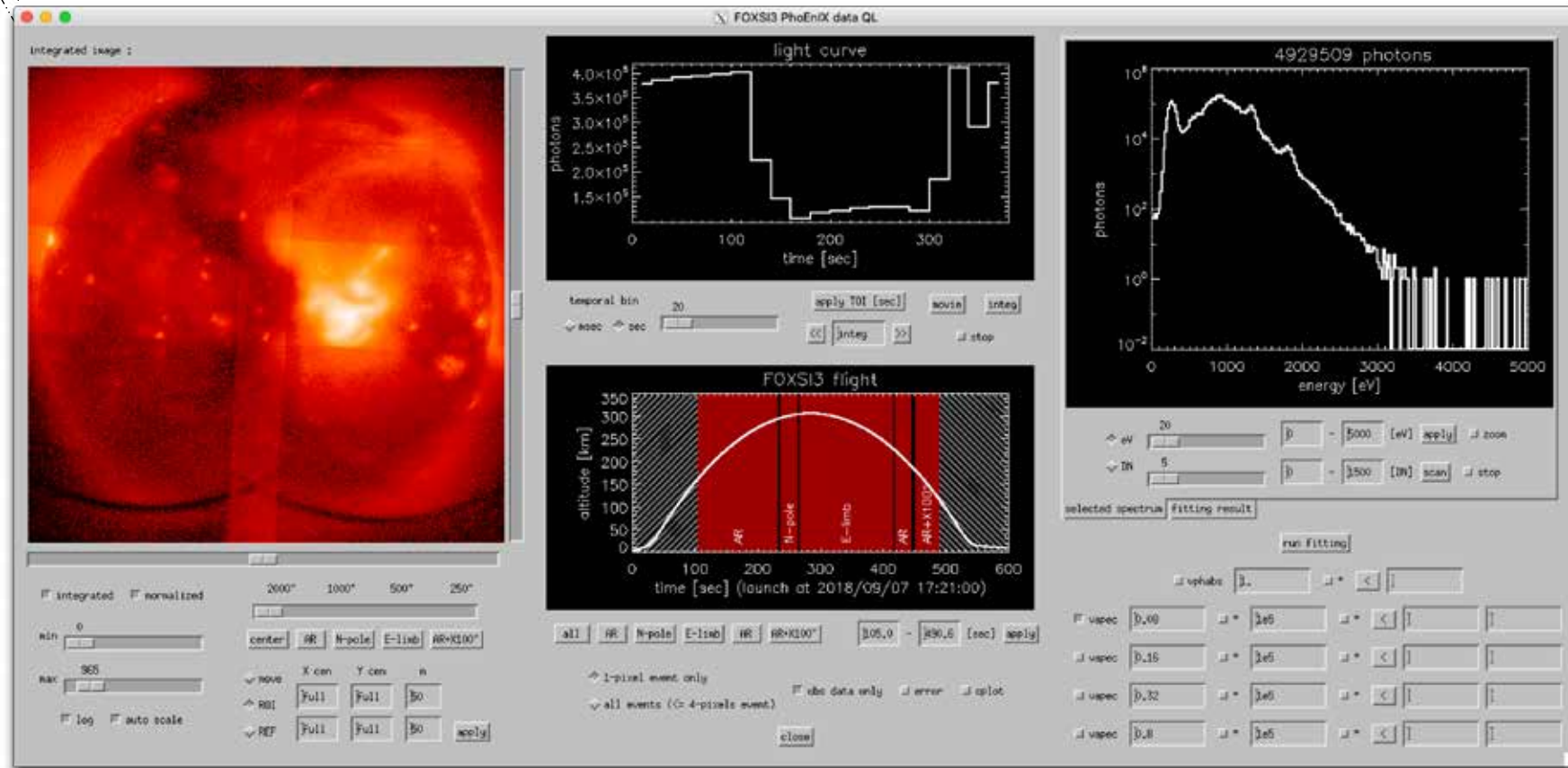
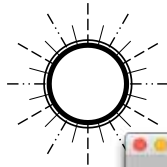
取得したデータ

- 空間サンプリング：1秒角
- 時間サンプリング：4ミリ秒
- エネルギーサンプリング：約4eV

太陽コロナの特徴的なスケール

- 空間スケール：数秒角
- 時間スケール：数秒～数分
- 温度：多温度＋非熱的成分

1千万個の光子情報を どの様に扱い、 どの様にサイエンスを引き出す？



FOXSI-3 のデータ解析用 GUI ツール

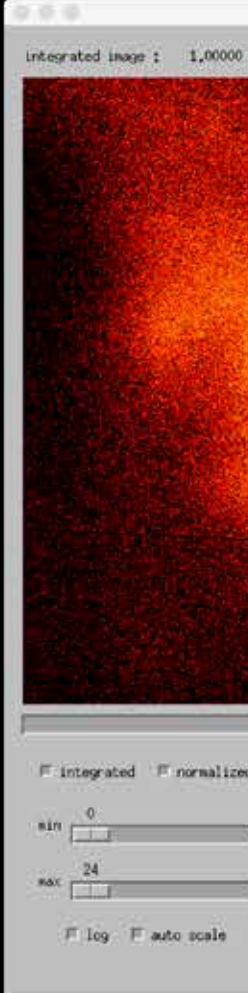
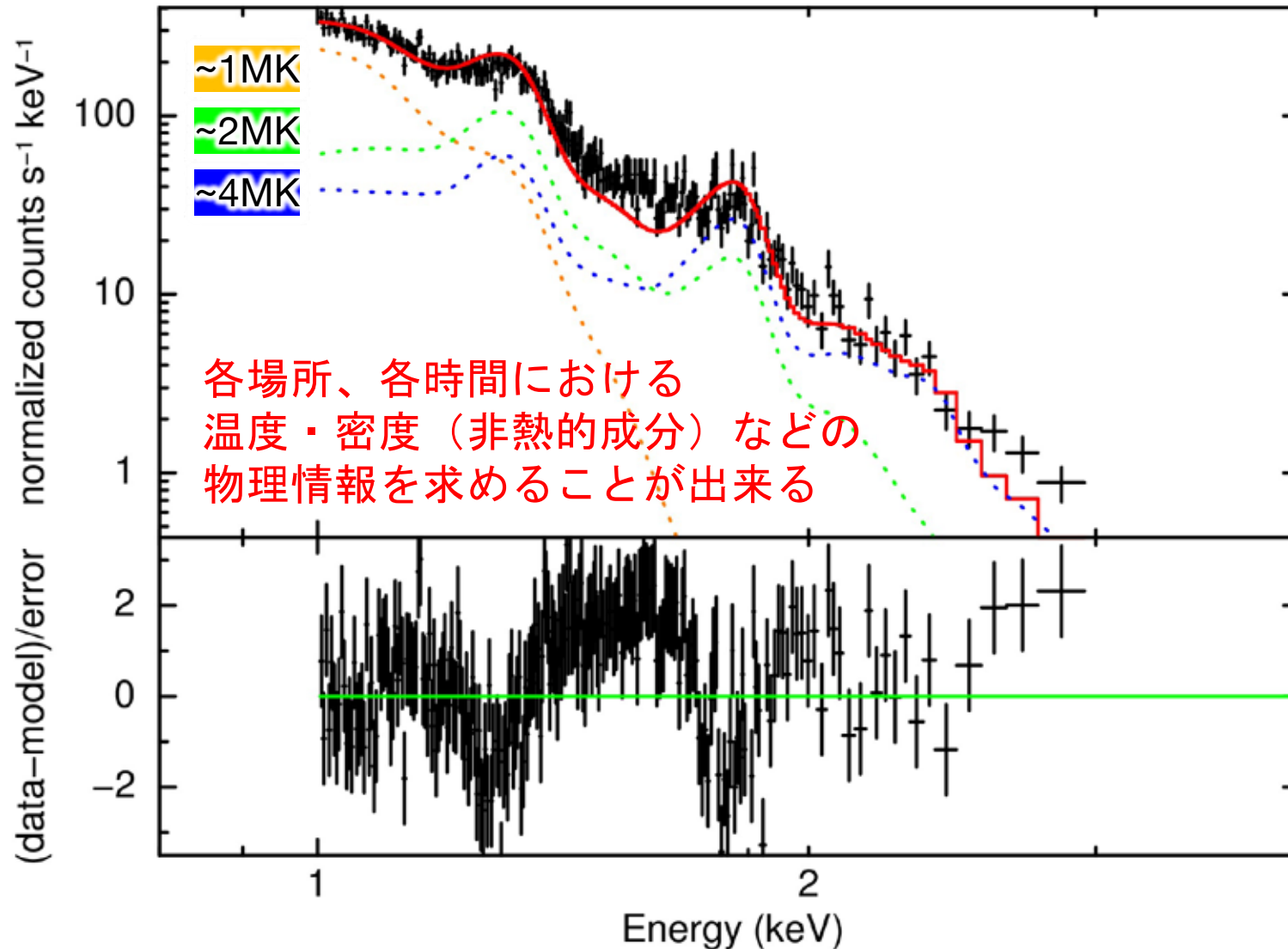
1. 解析したい領域・時間・エネルギー帯域の選択
2. 空間・時間・エネルギー binning の調整
3. スペクトルフィッティング (*Xspec* を使用) が GUI で視覚的に行える。

現在は、
太陽の解析で広く使われている
IDLをベースに開発

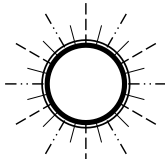
FOXSI3 PhoEnIX

More adjustment is required:

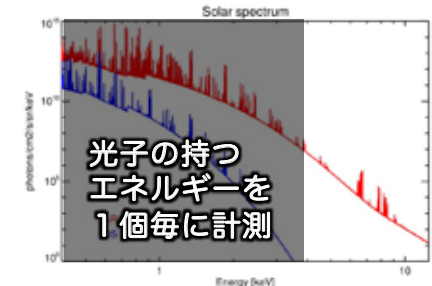
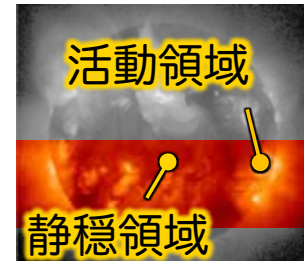
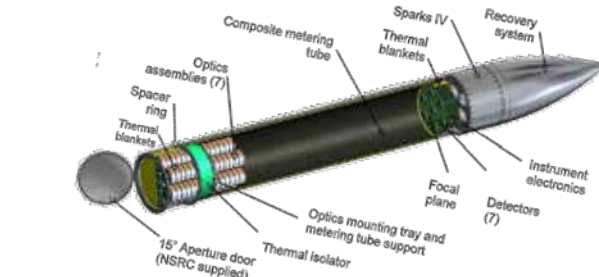
- More temperature components
- Abundance
- Calibration



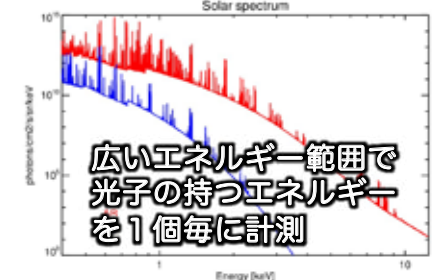
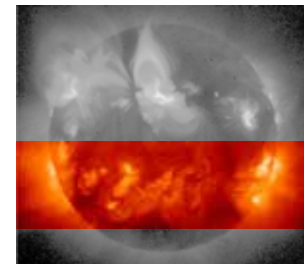
今後の太陽X線観測の展開



ロケット実験
FOXSI-1, 2
(2012年, 2014年)

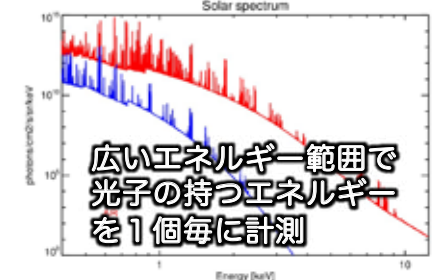
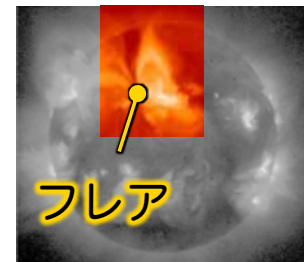
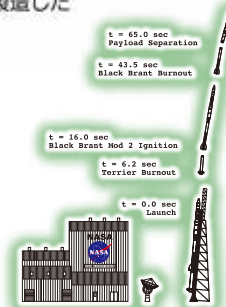


ロケット実験
FOXSI-3
(2018年)

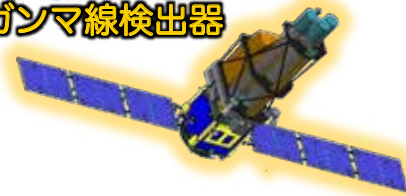


ロケット実験
FOXSI-4
(2024年春)

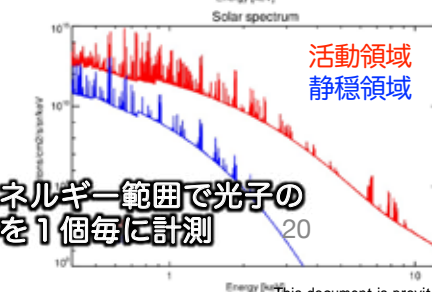
世界初の太陽フレア
X線集光撮像分光観測



軟X線望遠鏡
硬X線望遠鏡
軟ガンマ線検出器



「PhoENiX」衛星
(2030年代はじめ)





FOXSI-4: 2024年春 いよいよ太陽フレア観測に挑む!!

<https://rscience.gsfc.nasa.gov/keydocs/SolarFlareCampaign.pdf>

Glesener, Lindsay 19-HFORT19-0016

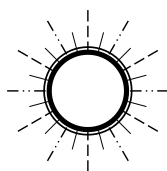
OVERALL GRADE (mark panel overall score with "X")

	Excellent	E/V G	Very Good	VG/ G	Good	G/F	Fair	F/P	Poor
'X': Overall grade.	X								



	July, 2020	2021	2022	2023	2024
Schedule	Proposal was accepted by NASA	Design & Development	Fabrication & Test	Integration & Test	Launch!!

観測ロケット実験 FOXSI-4 の科学目的



観測ロケットを用いた**世界初の**
太陽フレア観測キャンペーン

• Science objectives:

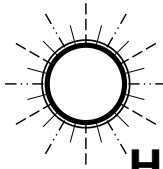
1. Determine how much particle acceleration occurs in the gradual phase of a flare
2. Produce images and spectra of flare footpoints from thermal to non-thermal energies
3. Determine where non-thermal sources and heated plasma are located in a given coronal configuration
4. Measure the spatial distribution of superhot sources in a flare
5. Identify locations of energetic electrons in an erupting CME



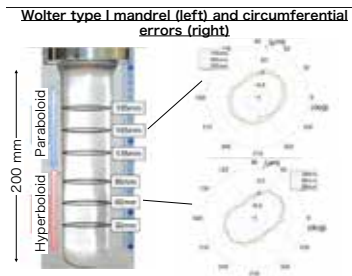
観測方法: **X線集光撮像分光観測**
(FOXSI-3 のアップデート)



FOXSI-4 によりもたらされるの 新機軸の太陽フレア高エネルギープラズマ観測

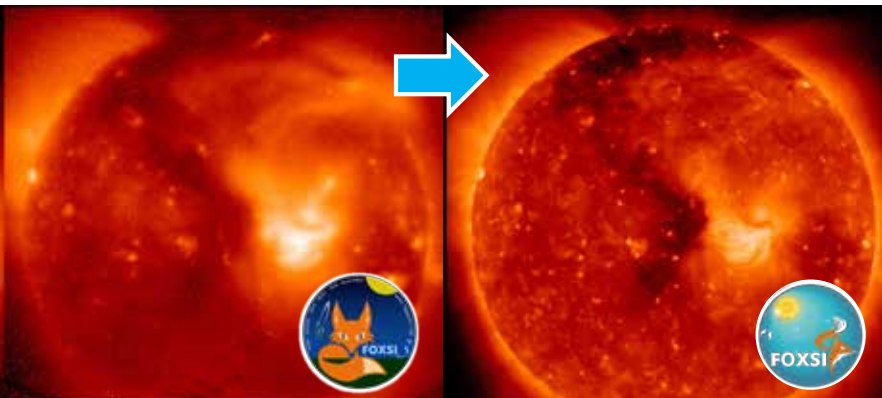
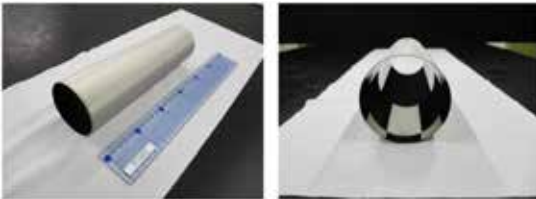


High-precision electroformed X-ray mirror



Goal (cf. FOXSI-3)

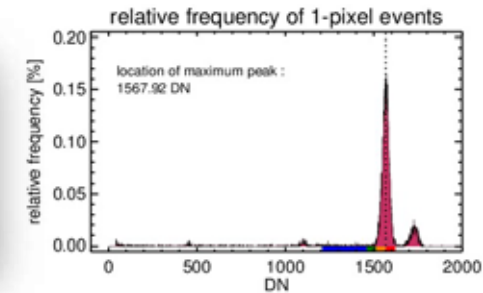
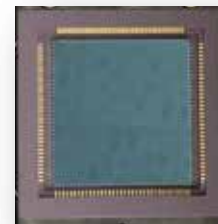
- $<10''$ HPD ($\leftarrow 30''$ HPD)
- $<4''$ FWHM ($\leftarrow 5''$ FWHM)



Updated CMOS (for soft X-rays) & CdTe (for hard X-rays) detectors

CMOS detector (cf. FOXSI-3)

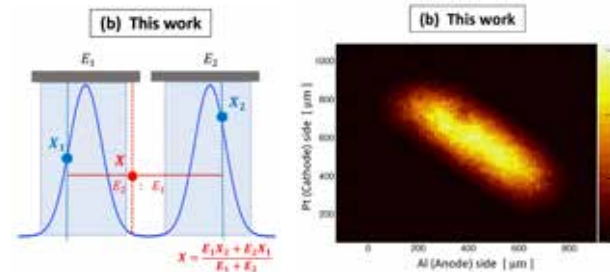
- 25 μm depletion layer thickness ($\leftarrow 4 \mu\text{m}$) for
- Higher sensitivity to high-energy X-rays
- Higher robustness against X-rays



CMOS の
光子計測能力
(^{55}Fe 線源)

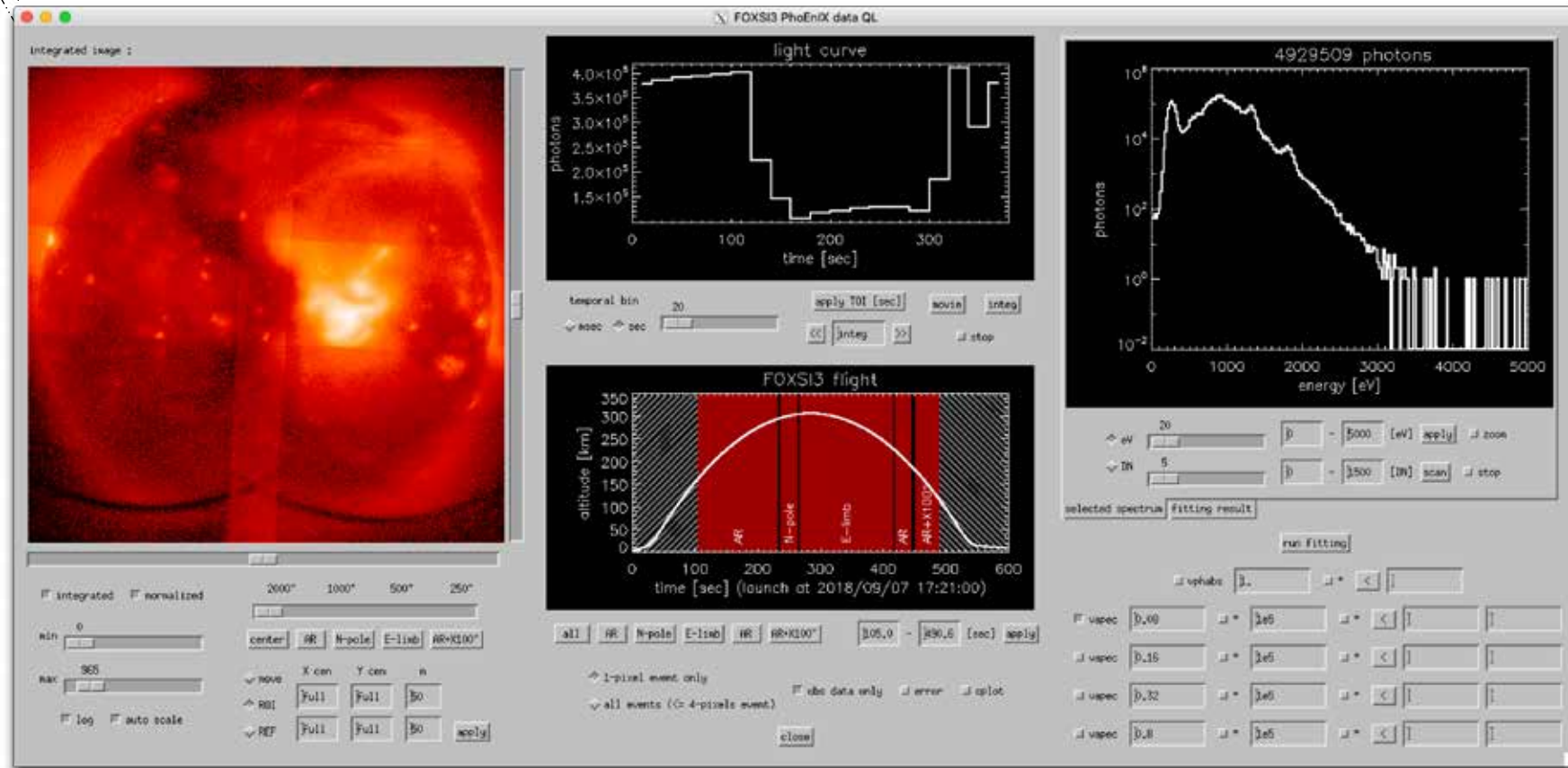
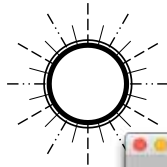
CdTe detector (cf. FOXSI-3)

- Position resolution ($\sim 30 \mu\text{m}$ $\leftarrow 60 \mu\text{m}$)
- High Count Rate ($\sim 5 \text{ k events / s / detector}$
 $\leftarrow 500 \text{ events / s / detector}$)



サブストリップ・レベルでの位置決定精度の達成 (Furukawa et al., 2020)

1千万個の光子情報を どの様に扱い、 どの様にサイエンスを引き出す？



FOXSI-3 のデータ解析用 GUI ツール

1. 解析したい領域・時間・エネルギー帯域の選択
2. 空間・時間・エネルギー binning の調整
3. スペクトルフィッティング (*Xspec* を使用) が GUI で視覚的に行える。

現在は、
太陽の解析で広く使われている
IDLをベースに開発