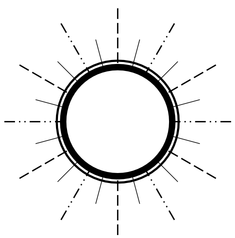
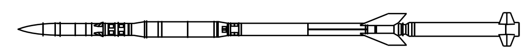
NAOJ Future Symposium: Science Roadmap of NAOJ
December 5, 2024

Solar flare X-ray focusing imaging spectroscopy

state-of-the-art solar flare observations with spatial, temporal and energy resolutions in X-rays





Noriyuki Narukage (NAOJ)
FOXSI sounding rocket team members
PhoENiX satellite WG members

2. Science Goals

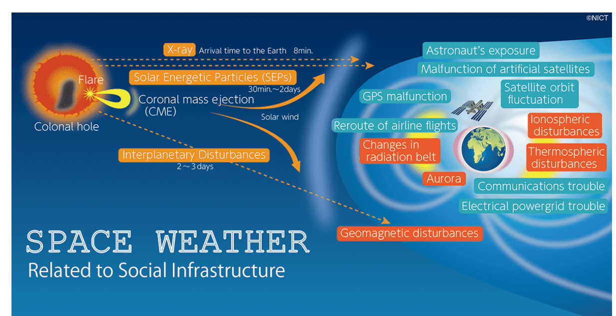
of solar flare X-ray focusing imaging spectroscopy

- The overarching goal is
  <u>to understand the universality of plasma acceleration to high-energies and how such phenomena on the Sun and stars can impact planetary environments and habitability</u>.

- Scientific Key Words

  <u>As the Plasma Universe</u>
  - **Magnetic Reconnection**
  - **Plasma Heating**
  - **Particle Acceleration**

  <u>Impacts to Environments</u>
  - **Space Weather**
  - **Habitability**



ひので XRT

Why Solar Flare Observation
– Significance of solar flare 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**

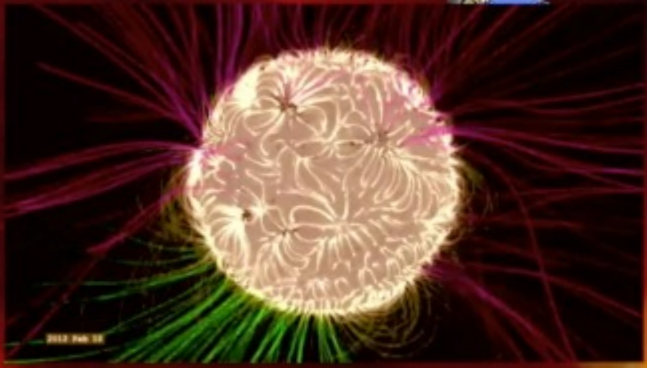
[Impacts on the Earth and social environments]

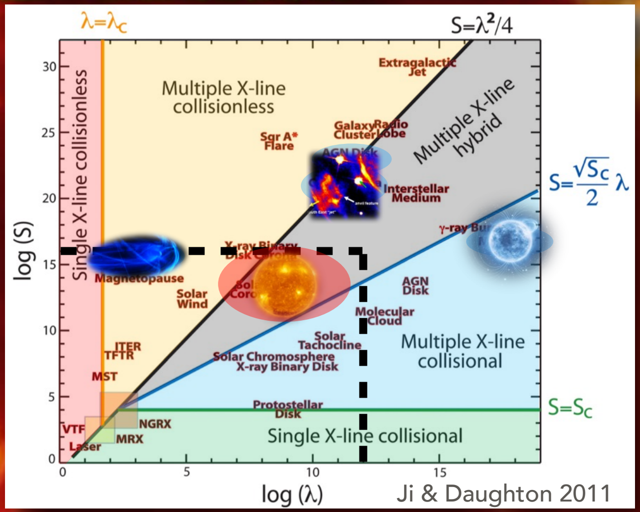
The mother of the Earth

- **Evolution of life (cosmic rays)**
- **Space weather**

[As a star]

- **Reference of other astrophysical objects**





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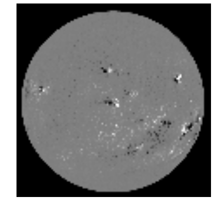
Unsolved problems in solar physics

The X-ray Focusing Imaging Spectroscopy can tackle it.

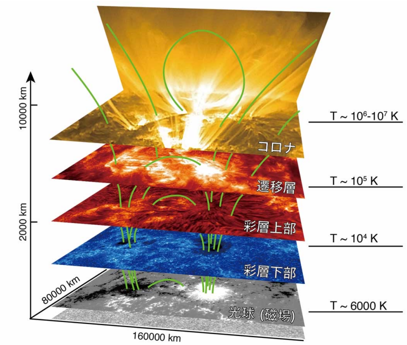
- How are the magnetic fields of the sun created?



➔ **Solar Dynamo Problem**

How is the solar corona formed (heated)?

➔ **Solar Coronal Heating Problem**



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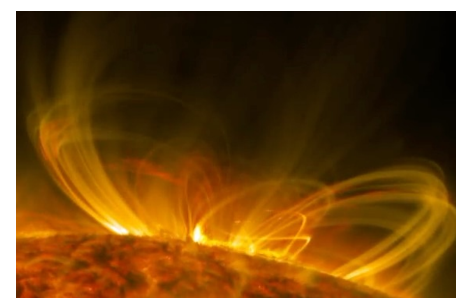
How do explosive phenomena occur in the solar atmosphere?

➔ **Solar Flare Problem**

How are particles accelerated by solar flares?



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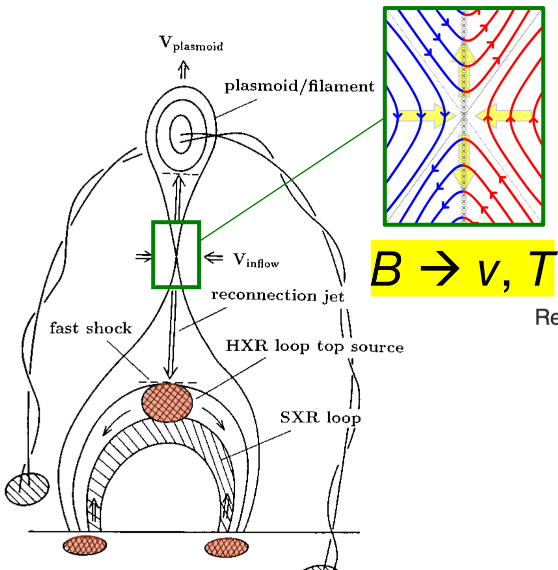
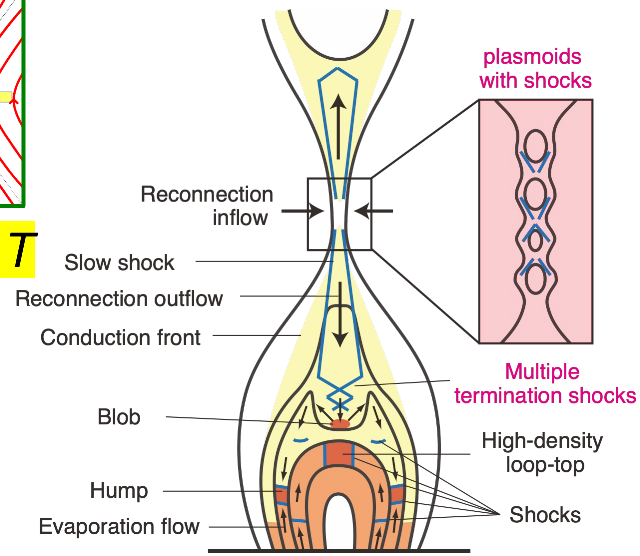
➔ **Solar Particle Acceleration Problem**

Solar Flare (Magnetic Reconnection)



Shibata et al. 1995



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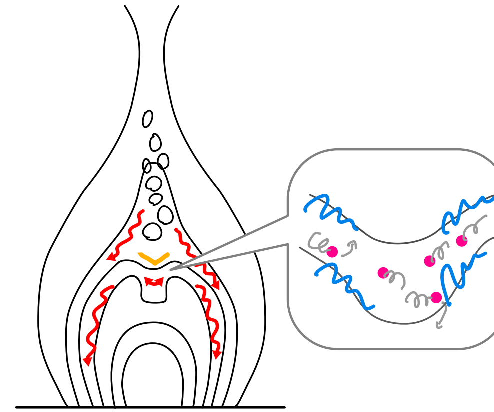


Level 1 — global scale

Level 2 — macro scale

Level 3 — meso/collision scale

Level 4 — micro/kinetic scale

MHD simulation / scale free

PIC simulation

10^8 m, 10^7 m, 10^6 m, 10^5 m, 10^3 m, 1m

6″ 4″ 2″ 1.2″

footpoint, looptop, above-the-looptop

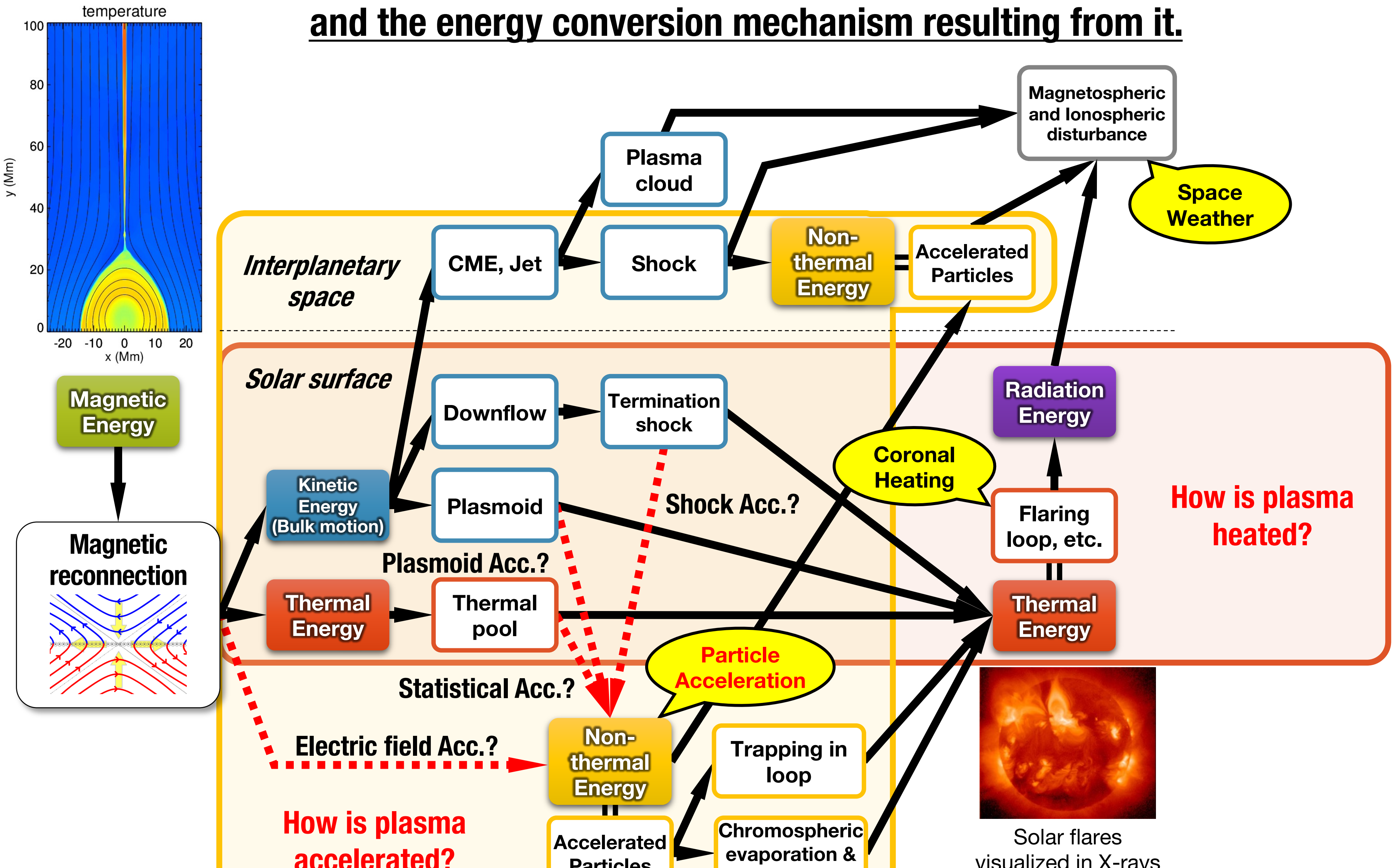
shock, jets, reconnection, plasmoids, etc.

collision, thermalization, ionization equilibrium,

inertia length, gyro-radius, curvature drift, etc.

Energy Flow Chart of Solar Flare (Magnetic Reconnection)

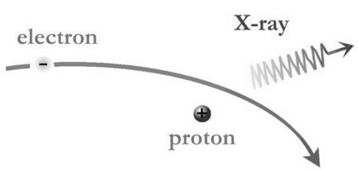
3. Science Objectives **Investigation of the energy release caused by magnetic reconnection and the energy conversion mechanism resulting from it.**



4. Science Investigations

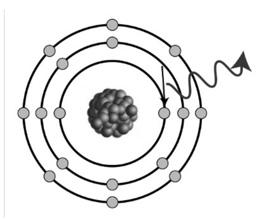
X-ray Focusing Imaging Spectroscopy

Bremsstrahlung (continuum)



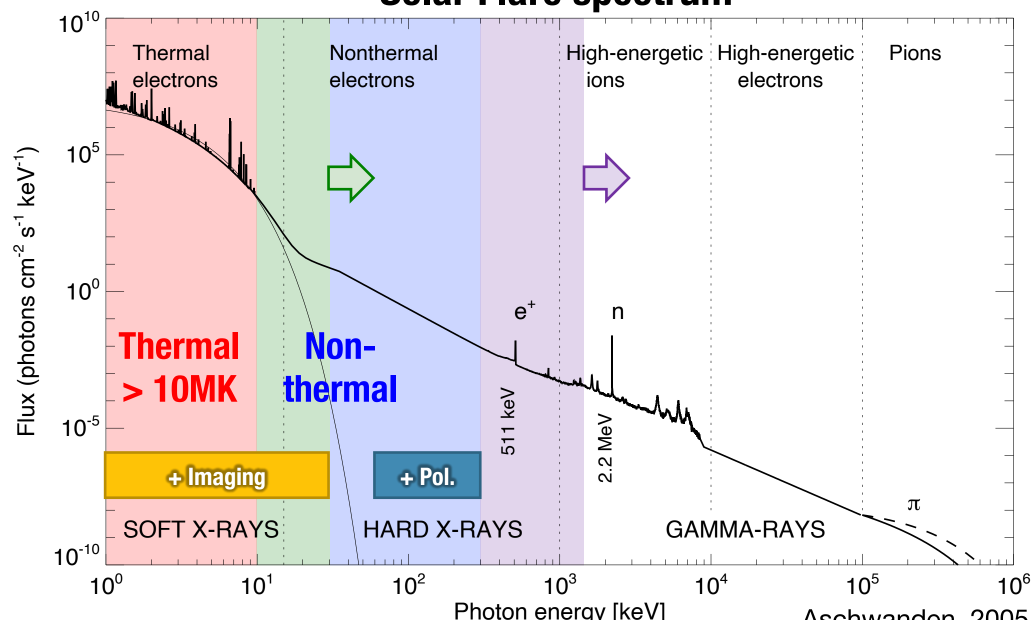
Responds to rapid temperature changes

Emission lines



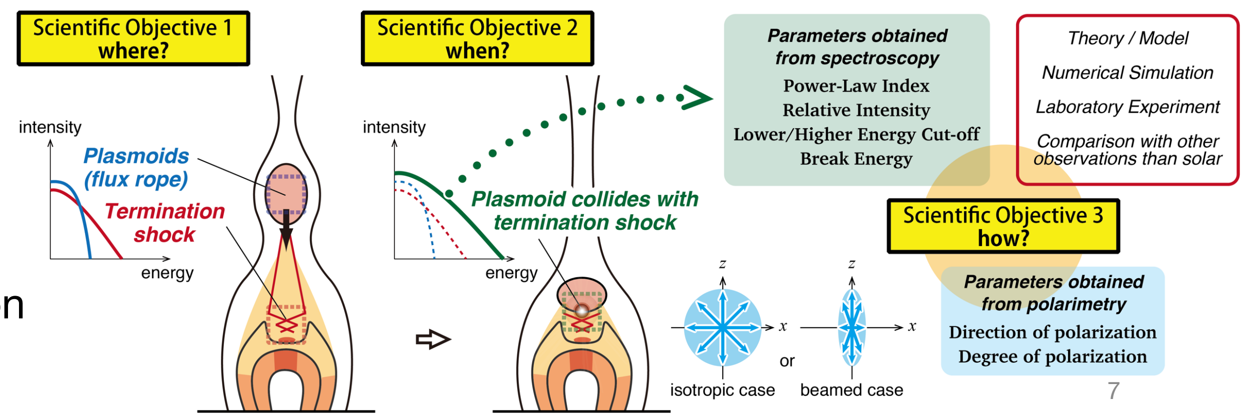
Information on abundance etc.

Solar Flare spectrum



Aschwanden, 2005

To achieve the science objectives, X-ray focusing imaging spectroscopy is the key observation, since it can **track the evolution of spatially and temporary resolved X-ray spectrum** which contains rich information on the high energy plasma generated by solar flares.

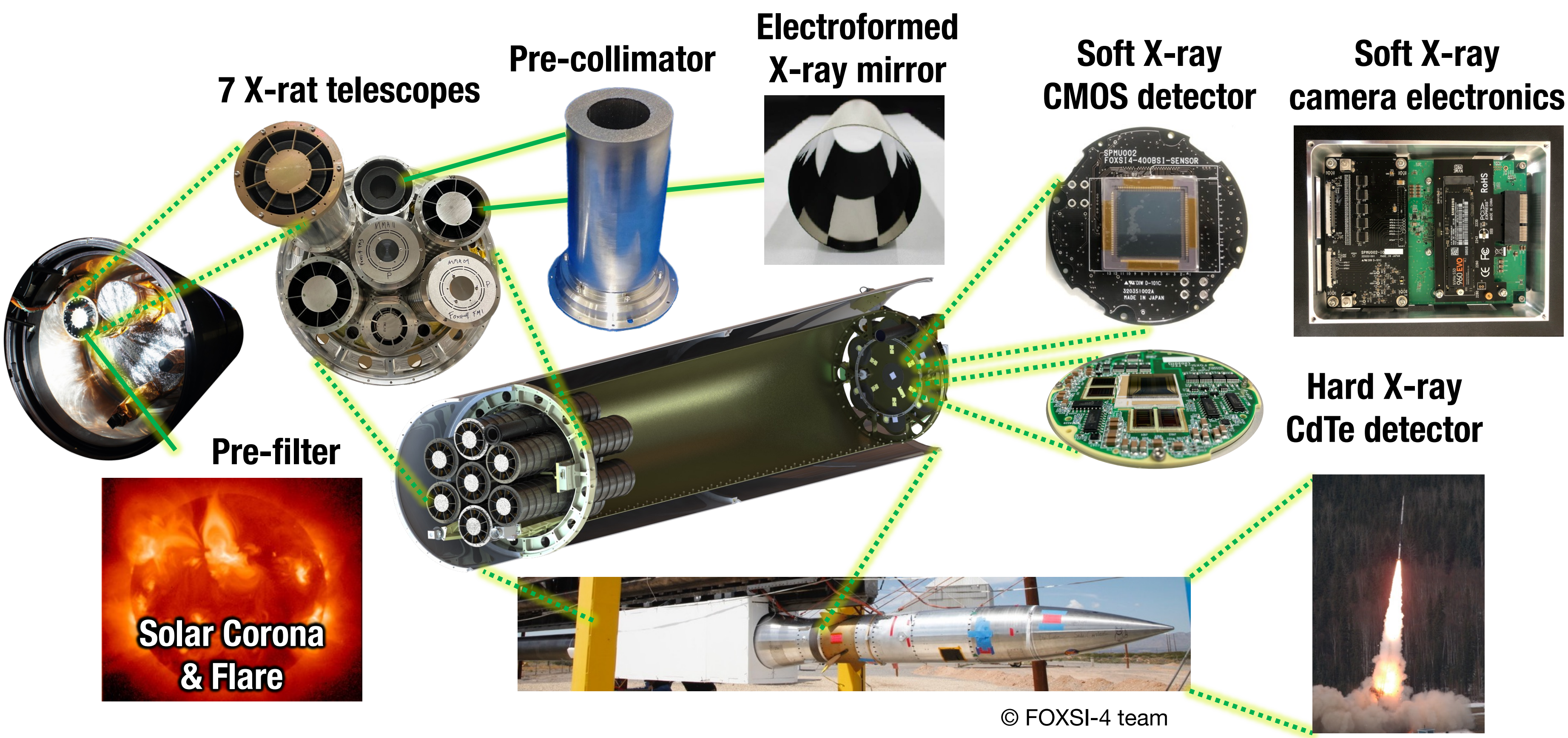


5. Instruments and data to be returned

Required technologies

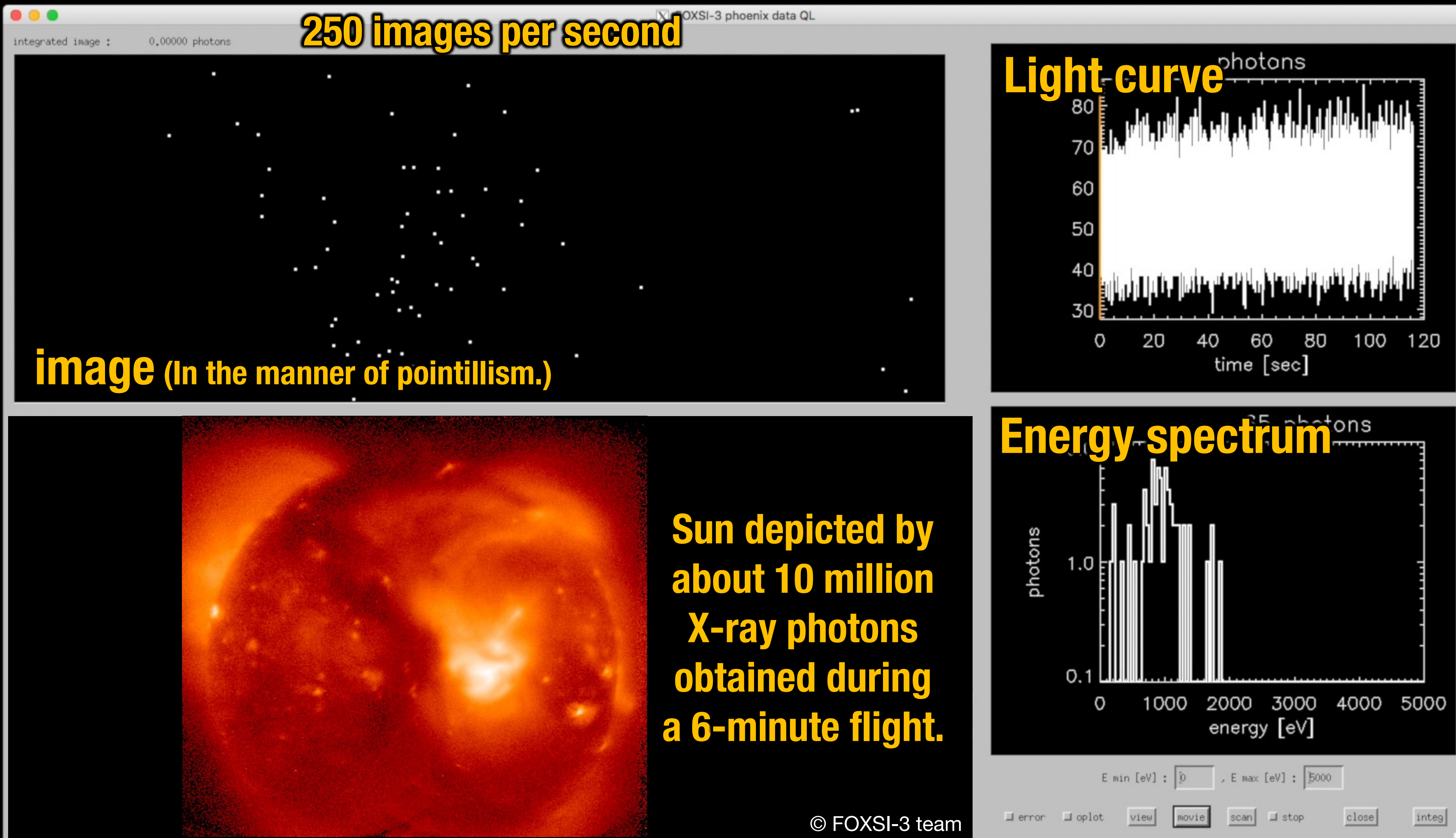
for solar flare X-ray focusing imaging spectroscopy

FOXSI-4 was successfully launched on 17th April 2024.



Soft X-ray data acquired by FOXSI-3 (launched in 2018)

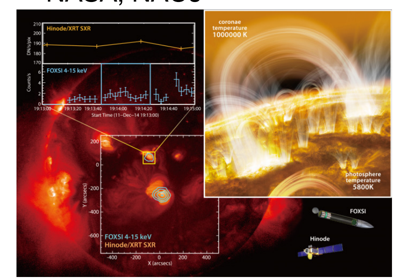
High-speed continuous imaging at 250 images per second (4 ms exposure)



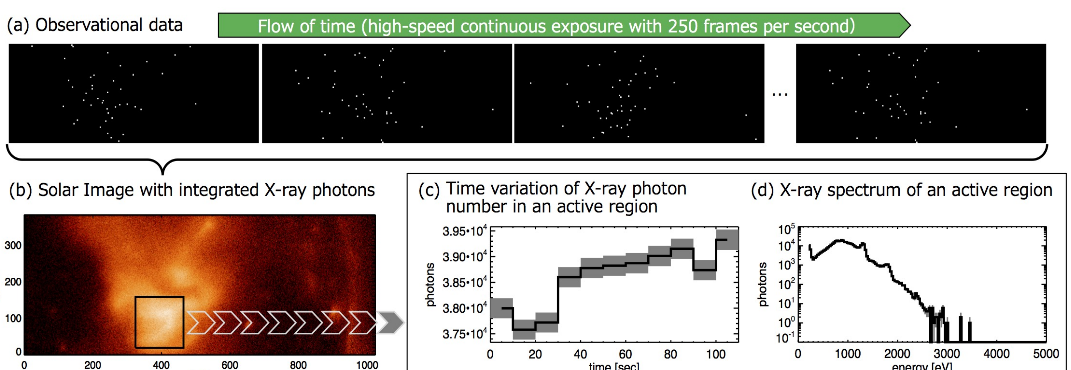
6. Originality and international competitiveness
7. Current Status

Achievements
of solar flare X-ray focusing imaging spectroscopy

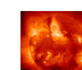
- Successful FOXSI sounding rocket series, which are the US-Japan collaborative projects using NASA rockets
  - First focusing imaging spectroscopy for the solar corona **<u>in hard X-rays</u>** (FOXSI-1 and -2)
  - First focusing imaging spectroscopy for the solar corona **<u>in soft X-rays</u>** (FOXSI-3)
  - In 2024, first focusing imaging spectroscopy for **<u>a solar flare</u>** in X-rays (FOXSI-4)



<u>FOXSI-2 result</u>
Published in nature astronomy

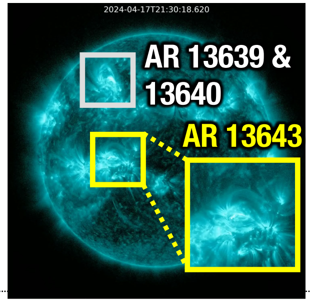


<u>FOXSI-3 result</u>
First imaging-spectroscopy in soft X-rays



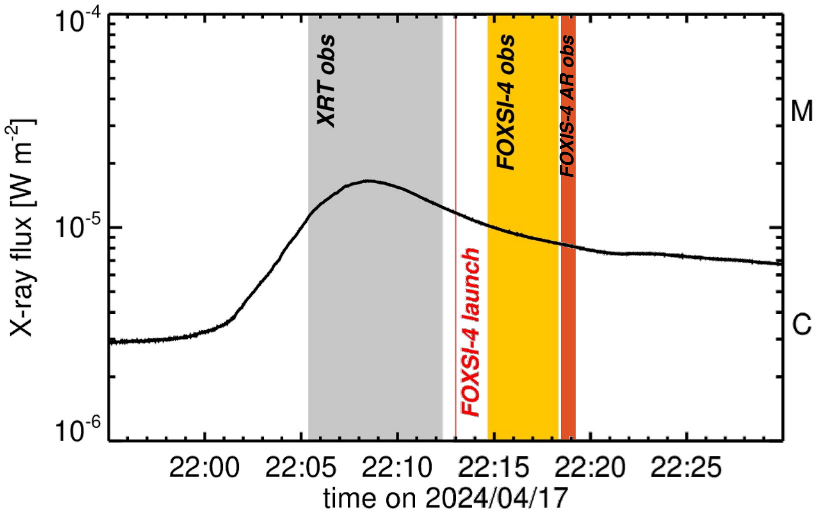
<u>FOXSI-4</u>
Flare campaign in 2024

Summary of FOXSI-4 observation

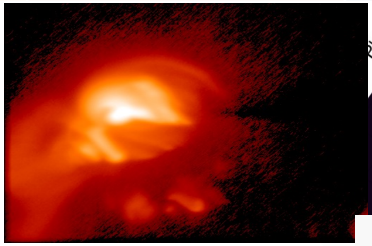


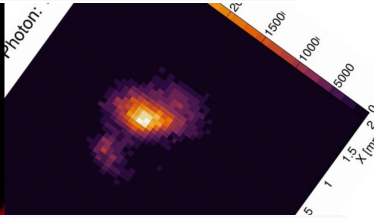
- Observations
  - Flare in decay phase (~3.5 min)
    - Flaring loop
    - Onset of blighting
    - Eruption
  - Non-flaring AR (~1 min)

	Soft X-ray telescope	Hard X-ray telescope
Detected photons	> 10 M photons	> 20 k photons
Spatial sampling	1.1 arcsec	8.8 arcsec (ave.) 3 arcsec (best)
Temporal sampling	~ 4 msec	~ 170 usec
Energy range	~ 1 keV – ~ 10 keV	~ 4 keV – ~ 20 keV
Energy resolution	~ 0.3 keV @ 6 keV	~ 0.8 keV @ 14 keV
Spectrum	Continuum + several lines	Continuum + Fe line

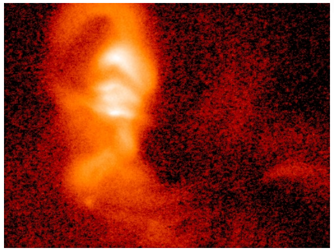


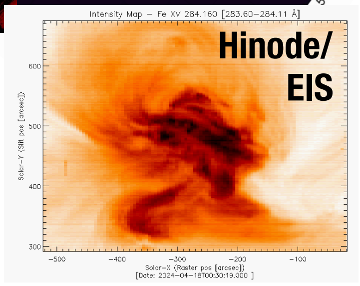
Flaring AR 13643





Non-flaring AR 13639 & 13640



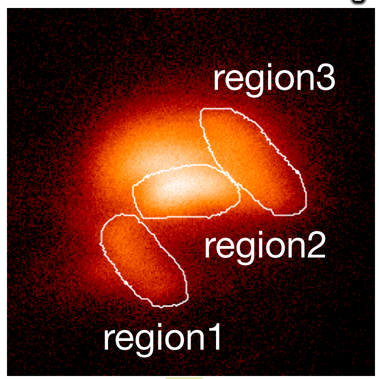


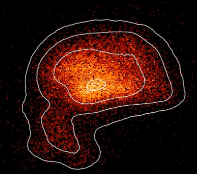
Remarkable Features of FOXSI-4 data

Soft X-ray data (up to ~10 keV) with ~ 1.5 M photons detected by CMOS2

Scientists can flexibly assign individual X-ray photons for analysis.

CMOS2 data (Small effective area optics)

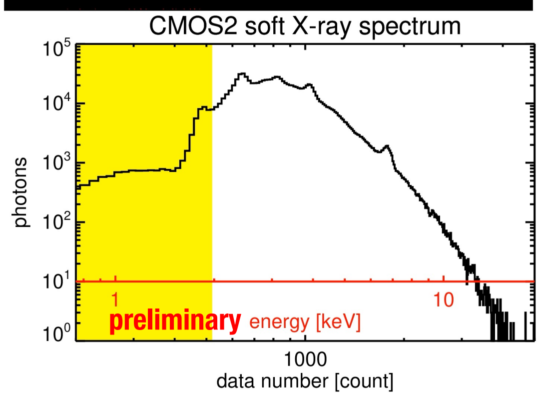


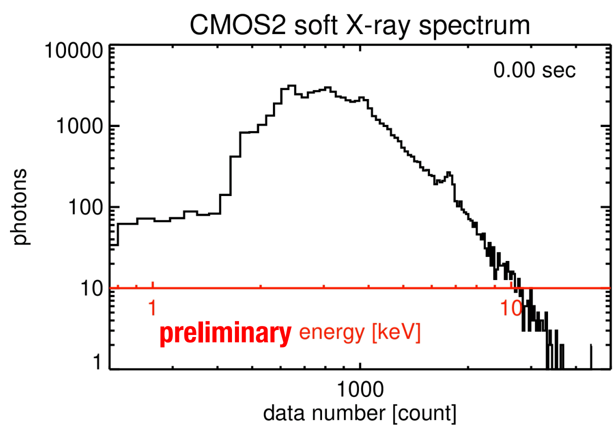


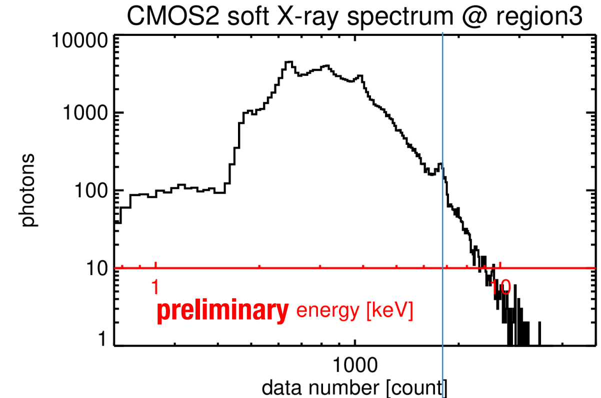
Example1: Investigate the spatial distribution of high-energy plasmas

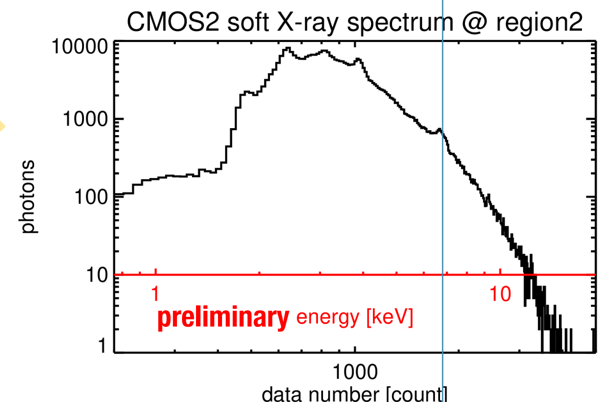
Example3: Examine the energy spectra of each structure

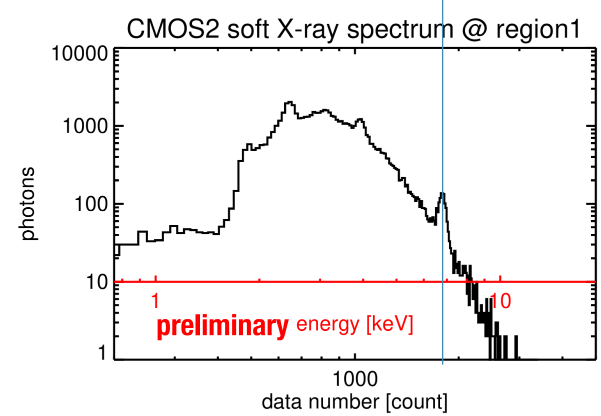
Example2: Investigate the temporal evolution of the entire flaring region spectrum with 10 sec cadence

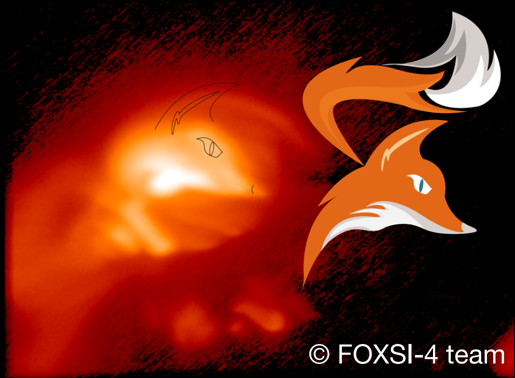


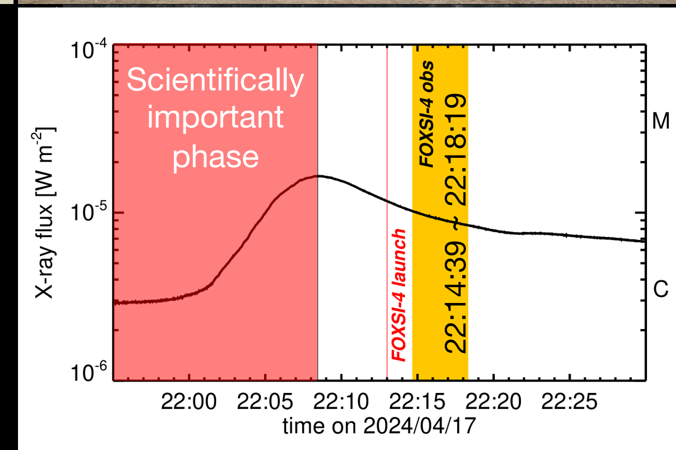












- FOXSI-4 was launched on April 17, 2024, and successfully completed the world's first solar flare X-ray focusing imaging-spectroscopic observation.
- Data calibration and scientific analysis are ongoing.

And on to the next FOXSI

FOXSI-5 has been selected by NASA with the highest rating of Excellent.

FOXSI

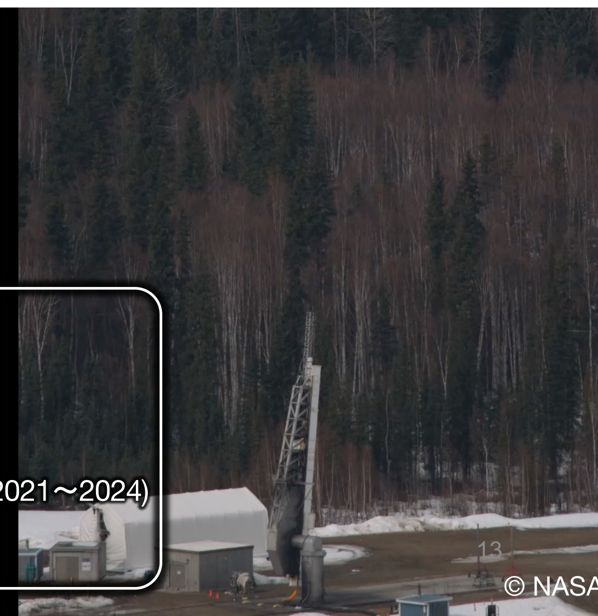
小規模計画 ISAS/JAXA

科研費 KAKENHI

日米共同・太陽フレアX線集光撮像分光観測ロケット実験 FOXSI-4,
PI: 成影 (FY2021～2025)

- 基盤研究(A) 22H00134, PI: 成影 (FY2022～2024)
- 国際共同研究加速基金(国際共同研究強化(B)) 21KK0052, PI: 成影 (FY2021～2024)
- 基盤研究(A) 21H04486, PI: 渡辺 (FY2021～2024)

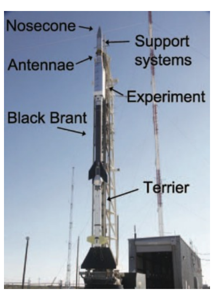
ほか（上記は現在実施中のもののみ記載；採択順）



Future Plans (including 8. Cost assessments, budget line and status)

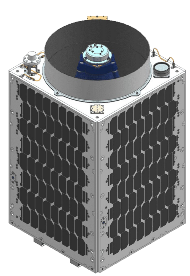
Utilizing three types of opportunities in different scales, we will create scientific results speedily and ceaselessly.

Category	Spatial resolution	Energy range	Observable flaring phase	Mission lifetime	Cost	Preparatory period	Example	Opportunity
Sounding rocket	~ 1 arcsec sampling	0.8 – 20 keV	from the peak of a flare	~5 minutes	< 5M	2-3 years	• ***FOXSI-5*** (2025; TBD)	NASA H-LCAS (Heliophysics Low Cost Access to Space)
SmallSat (90kg class)	~ 3 arcsec sampling	0.8 – 10 keV	before the occurrence of flares	~ 2 years	~ 10M	2-3 years	Using microsatellite bus of Canon Electronics (in the 2020s)	NASA H-FORT (Heliophysics Flight Opportunities for Research and Technology)
Full size satellite	~ 0.75 arcsec sampling	0.8 – 30 keV	before the occurrence of flares	> 2 years	> ~200M	10 years	• ***PhoENiX*** (in the 2030s)	• ISAS/JAXA competitive M-class mission concept A/O • NASA MIDEX



Sounding rocket
(NASA)
- 2m long instrument
- Recoverable

© FOXSI team



SmallSat
(Canon Electronics)
- ~0.6m long instrument
- ~90kg (total mass)

© CANON ELECTRONICS INC.

Full size satellite
(ISAS/JAXA)
- ~3m long instrument
- ~600kg (total mass)

© PhoENiX WG

Schedule

第五期中期計画期間 (2028-2033)

Annual Plan	2024 (R6)	2025 (R7)	2026 (R8)	2027 (R9)	2028 (R10)	2029 (R11)	2030 (R12)	2031 (R13)	2032 (R14)	2033 (R15)	2034 (R16)	2035 (R17)	2036 (R18)	2037 (R19)
Sounding rocket FOXSI-5	Launch preparations		Launch											
SmallSat (90kg class)	Conceptual study / Basic development	Proposal / Review		Fabrication/Test		Launch / Operation		Post-mission operation						
Full size satellite (In the case of ISAS/JAXA opportunity)	Conceptual study / Basic development			Proposal / Review		Reviews / Design / Fabrication / Test							Launch / Operation	

The following items will be carried out throughout the entire period
- Analysis of observation data obtained from the FOXSI series
- Numerical calculations and theoretical studies on magnetic recombination, including particle acceleration

Hinode (will be terminated in FY2033) in VL, EUV and X-rays

SOLAR-C (plan to be launched in FY2028) in EUV

9. Project Organization

Solar Physics	High Energy Astrophysics	Space Plasma Physics	Laboratory or Fusion Plasma Physics	Engineering, etc. (other than those listed on the left)

PI/Co-I Name	Affiliation	Major responsibilities	
		in Pre-phase A1a	in Pre-phase A1b and A2
Noriyuki Narukage	NAOJ	Project lead	Principal Investigator (PI)
Mitsuo Oka	UCB	Mission science study	Project Scientist (PS)
Yasushi Fukazawa	Hiroshima U.	SGSP science study	Project Scientist (PS)
Shin Watanabe	ISAS/JAXA	System study	Mission system lead
Keiichi Matsuzaki	ISAS/JAXA	System study, SXIS design study	Mission system lead
Taro Sakao	ISAS/JAXA	SXIS science & design study, System study	SXIS lead, mirror study
Lindsay Glesener	U. Minnesota	HXIS US contribution study	HXIS U-lead, mirror study
Kouichi Hagino	U. Tokyo	HXIS science study	HXIS J-lead, camera study
Tsunefumi Mizuno	Hiroshima U.	SGSP science study	SGSP lead, detector study
Kazuto Yamauchi	Osaka U.	SXIS mirror study	SXIS mirror study
Satoshi Matsuyama	Nagoya U.	SXIS mirror study	SXIS mirror study
Masayuki Ohta	ISAS/JAXA	SXIS/SGSP detector study	SXIS/SGSP detector study
Ikuyuki Mitsuishi	Nagoya U.	Pre-filter and HXIS mirror study	Pre-filter and HXIS mirror study
Säm Krucker	UCB/FHNW	SXIS/HXIS US+Swiss contribution study, HXIS design study	SXIS/HXIS US+Swiss contribution study, SXIS/HXIS design & science study
Tom Woods	LASP, Colorado U.	SXIS/HXIS US contribution study	SXIS/HXIS US contribution study, SXIS/HXIS design & science study
Amir Caspi	SwRI	SXIS science study	SXIS design & science study
Steven Christe	NASA/GSFC	HXIS design study	HXIS design & science study
Amy Winebarger	NASA/MSFC	SXIS/HXIS US contribution study	SXIS/HXIS US contribution study & science study
Patrick Champey	NASA/MSFC	HXIS mirror study	HXIS mirror study
Wayne Baumgartner	NASA/MSFC	HXIS mirror study	HXIS mirror study
Bin Chen	NJIT	SXIS/HXIS science study, Radio observation study	SXIS/HXIS science study, Radio observation study
Alexander Warmuth	AIP	SXIS/HXIS science study, DLR contribution study	SXIS/HXIS science study, DLR contribution study
Tomoko Kawate	NIFS	Science study	SXIS/HXIS/SGSP science study
Masumi Shimojo	NAOJ	SXIS science study	SXIS science study
Takafumi Kaneko	Niigata U.	SXIS/HXIS science study with simulations	SXIS/HXIS science study with simulations
Natasha Jeffrey	Northumbria U.	SGSP science study	SGSP science study
Satoshi Masuda	Nagoya U.	Science study	Science study
Shinsuke Takasao	Osaka U.	Science study	Science study
Iain Hannah	U. Glasgow	Science study	Science study
Seiji Zenitani	IWF/ ÖAW	Science study	Science study
Hiroshi Tanabe	U. Tokyo	Laboratory-based science study	Laboratory-based science study
Munetaka Ueno	JAXA	N/A	System advisory
Takeshi Takashima	ISAS/JAXA	System study	Science advisory
Iku Shinohara	ISAS/JAXA	Science advisory	Science advisory
Hiroyasu Tajima	Nagoya U.	Science advisory	Science advisory
Tadayuki Takahashi	Kavli IMPU	Science advisory	Science advisory

10. Why NAOJ ?

- In Japan, the NAOJ has played a central role in solar satellite projects in cooperation with ISAS/JAXA.
  - Such as **Yohkoh**, **Hinode**, and **SOLAR-C** satellites.
- In addition, the Solar Group of the NAOJ has been developing new observation technologies in between these large satellite projects, and has been successful in small-scale projects such as sounding rocket experiments (**CLASP**, **FOXSI**) and balloon experiment (**SUNRISE**), continuing to produce world-first scientific results.

➔ Our project is based on this trend and heritage.

- This has great significance not only from a scientific perspective, but also from the perspective of human resource development and the succession of development know-how and technology for space missions at NAOJ.