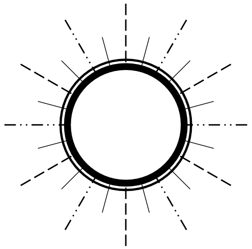
PhoENiX

Physics of Energetic and Non-thermal plasmas in the X (= magnetic reconnection) region



Noriyuki Narukage (NAOJ)
and PhoENiX WG member

Science Goal

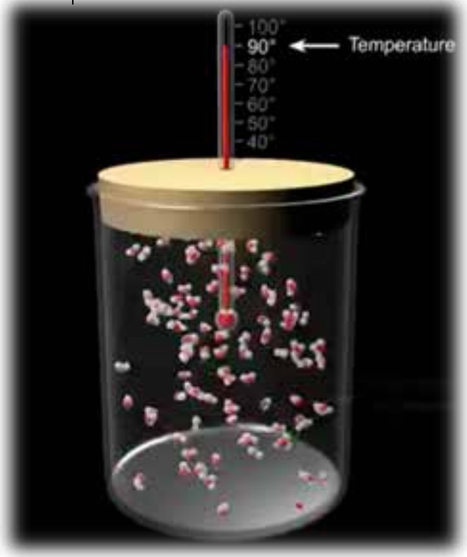
Understanding of particle acceleration during magnetic reconnection

- **Science Objectives**

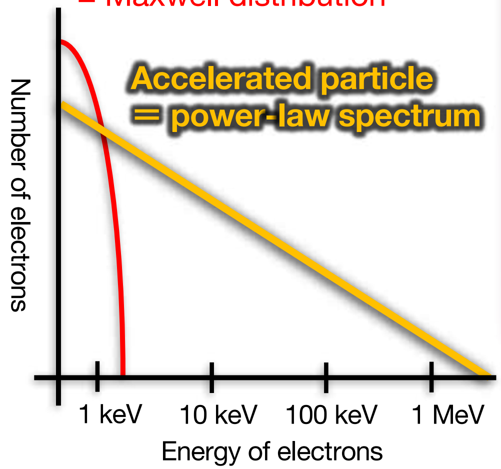
1. To identify
   particle acceleration sites
   in reconnection-associated structures in solar flares
2. To investigate
   the timing of particle acceleration
   during reconnection-associated phenomena in solar flares
3. To characterize
   the properties of accelerated particle populations in solar flares

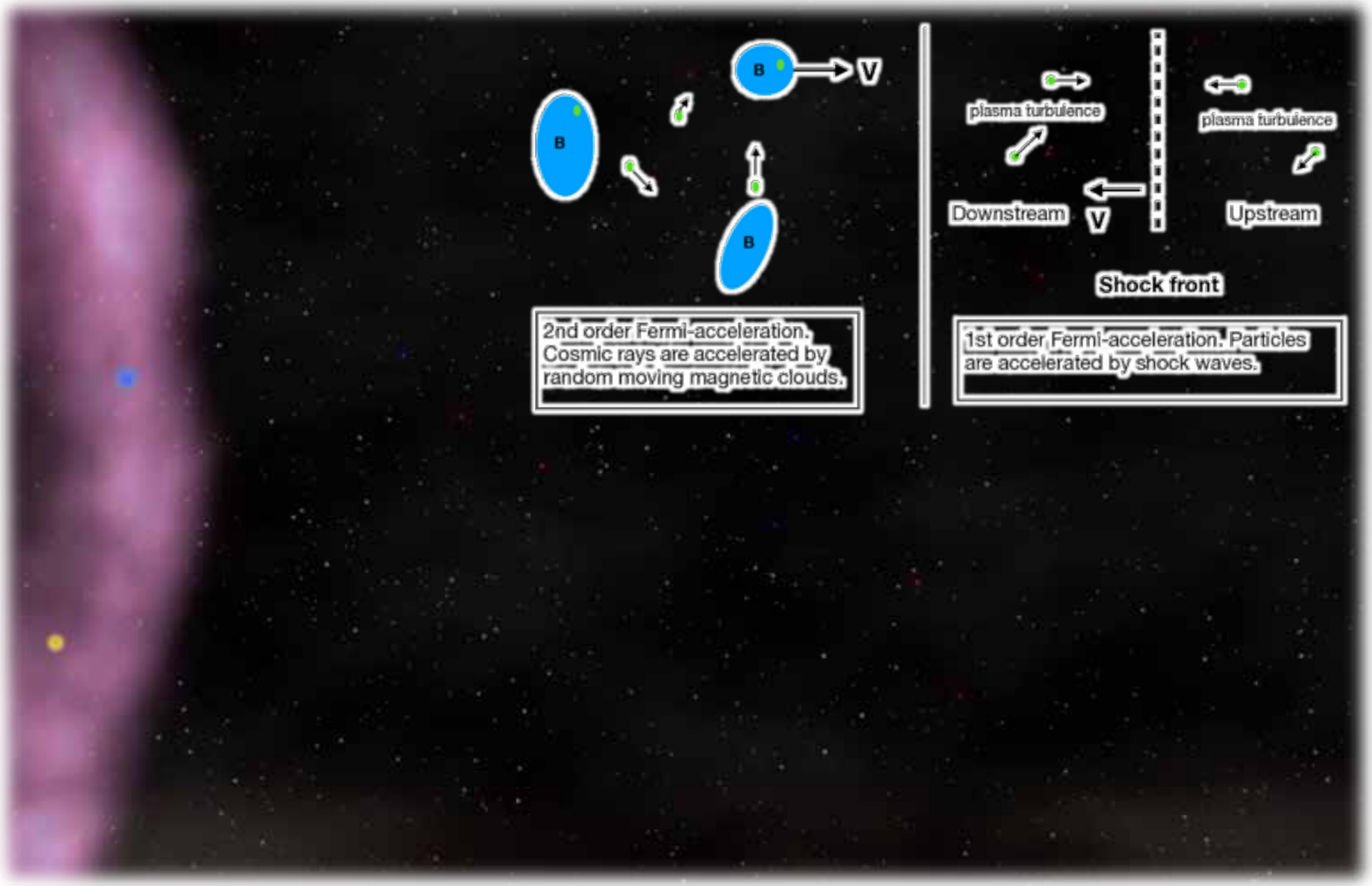
Particle acceleration

Accelerated particles are deviated from equilibrium.



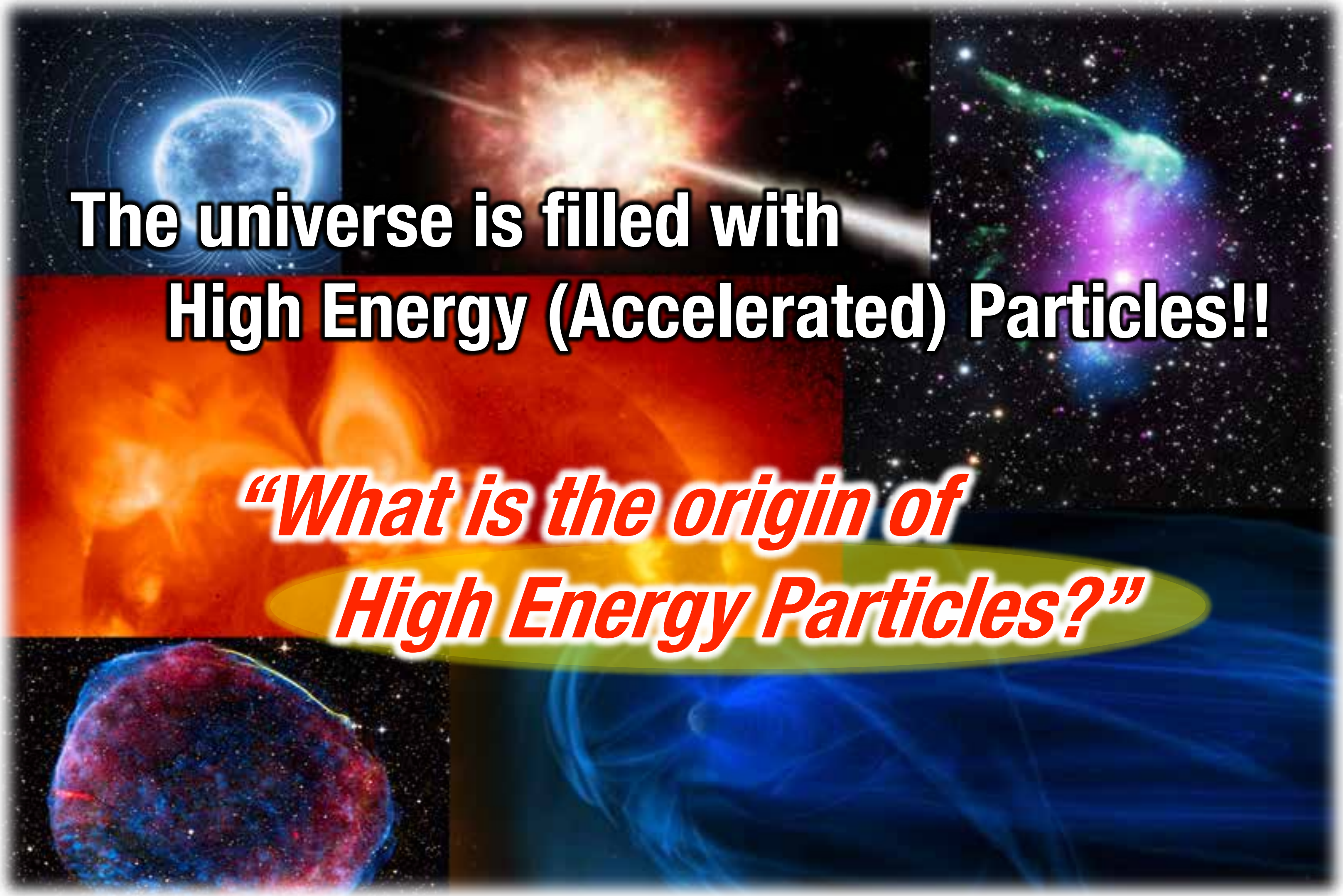
Thermal equilibrium
= Maxwell distribution





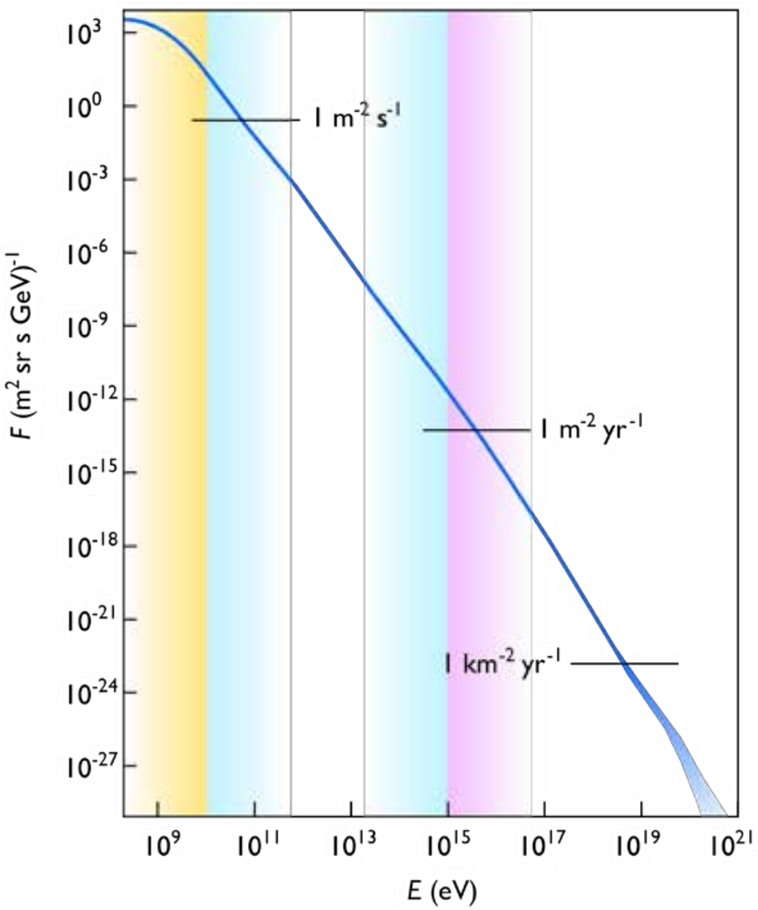
Particle acceleration

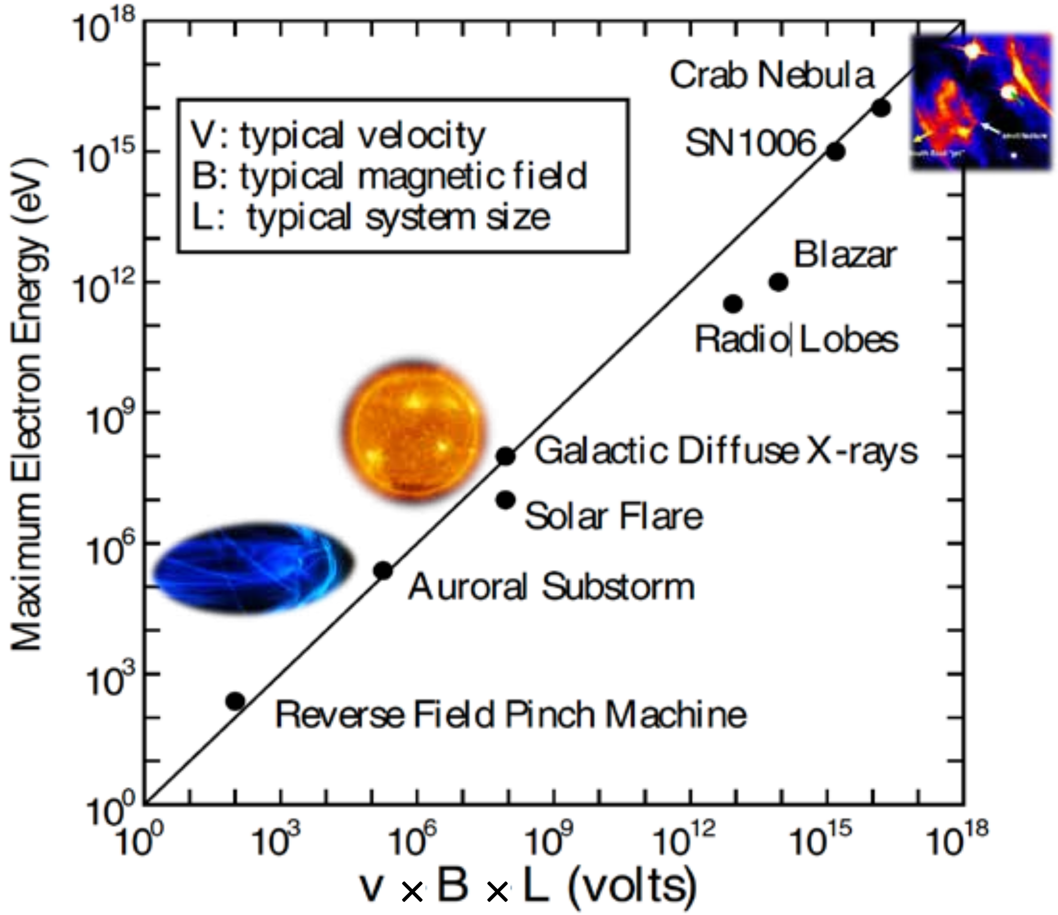
Accelerated particles are ubiquitously detected in the universe.



Particle acceleration

The energy of accelerated particles achieves up to 10^{20} eV.
Accelerated particles are ubiquitously detected in the universe.



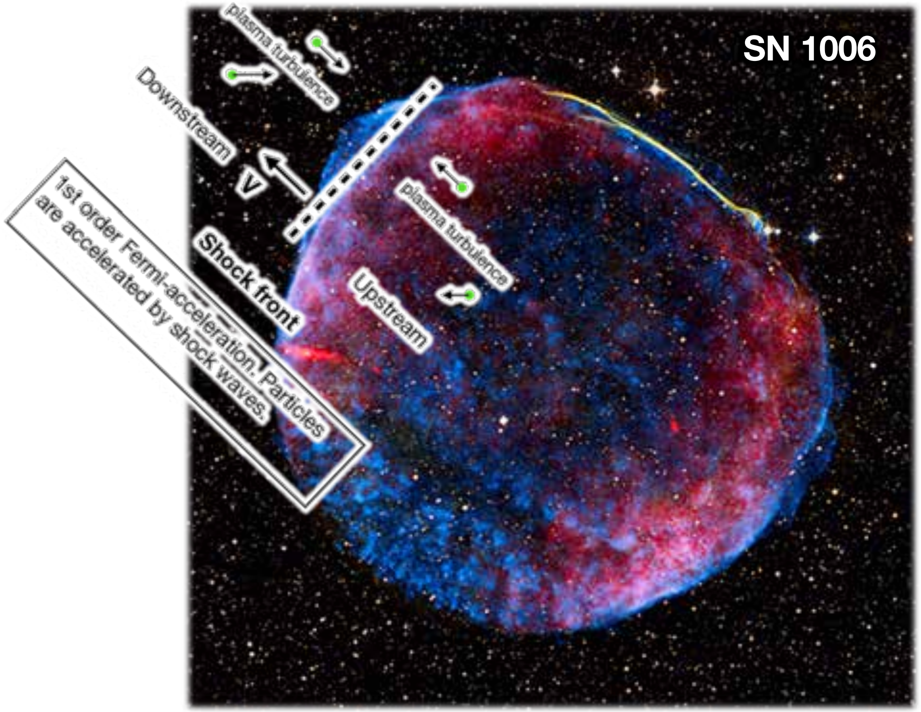


Makishima (1999)

Particle acceleration

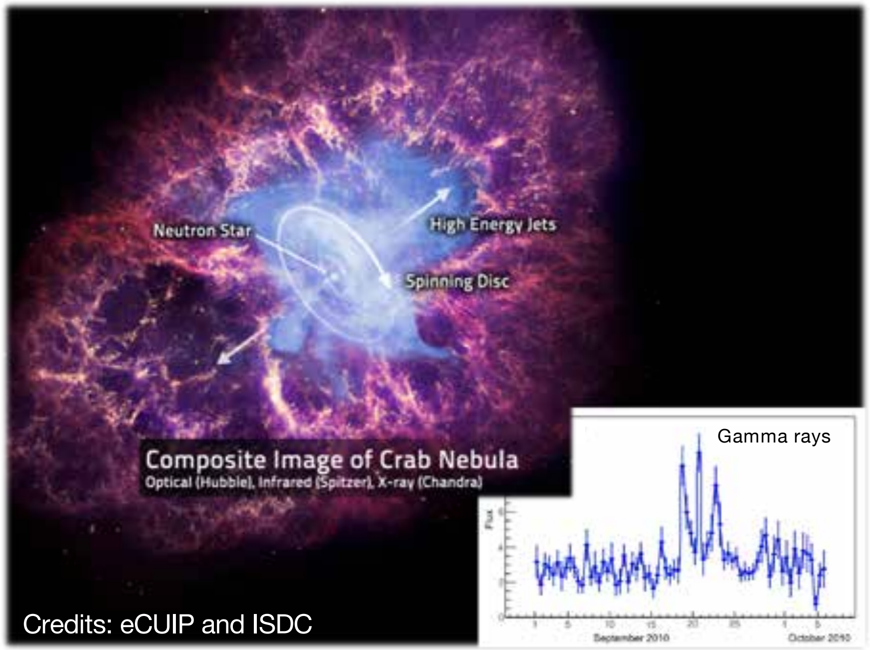
How are particles accelerated? It is not fully understood.

Super Nova Remnant
(long time acceleration)



1st order Fermi-acceleration
Statistical acceleration

Gamma-ray Burst
(short time acceleration)

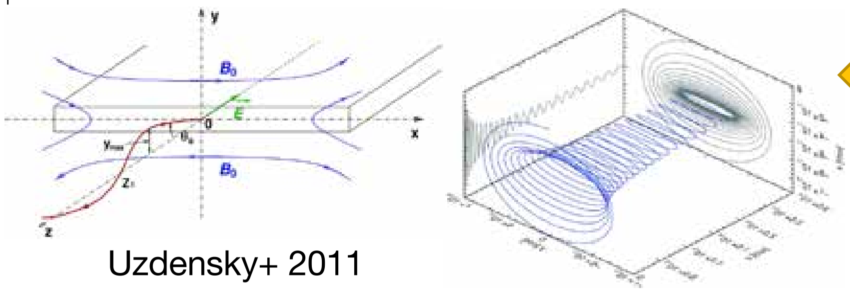


Balbo+ 2011

How are particles accelerated in very short time?

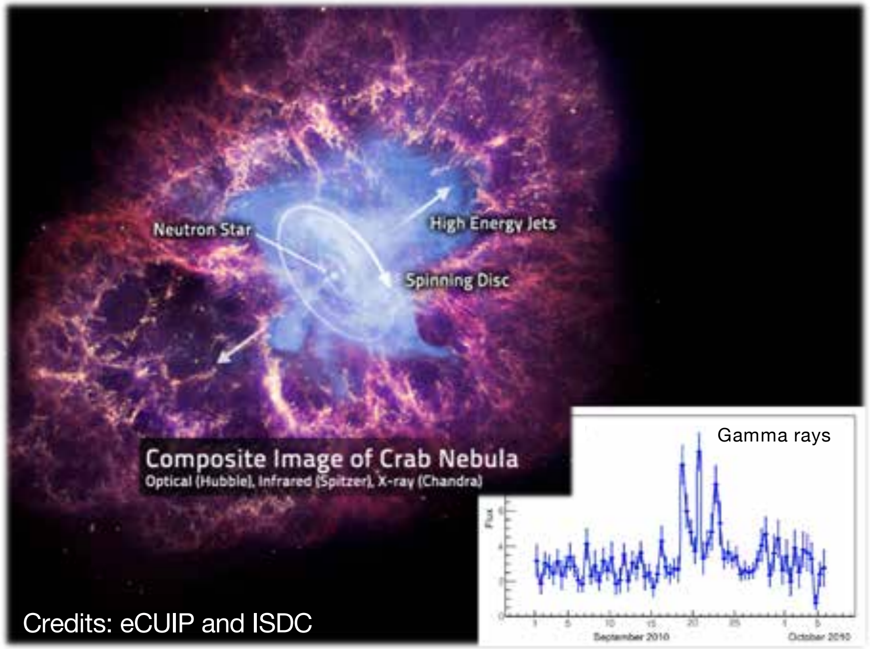
Particle acceleration

Magnetic reconnection is a key.

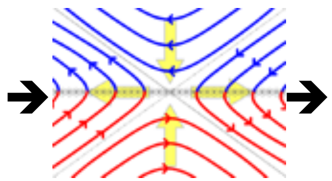


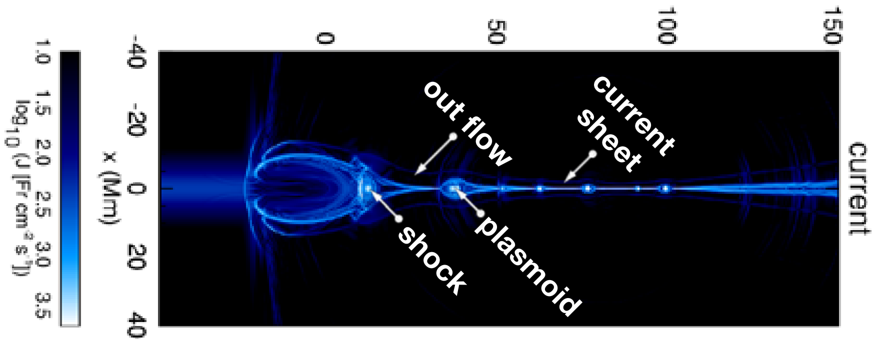
Uzdensky+ 2011

Gamma-ray Burst
(short time acceleration)



Balbo+ 2011





Courtesy of Dr. Kaneko

How are particles accelerated
in very short time?

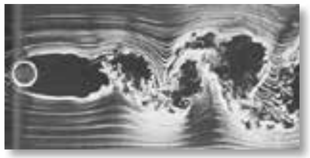
Magnetic Reconnection

MR is fundamental plasma process and ubiquitously occurs in the universe.

Lundquist number

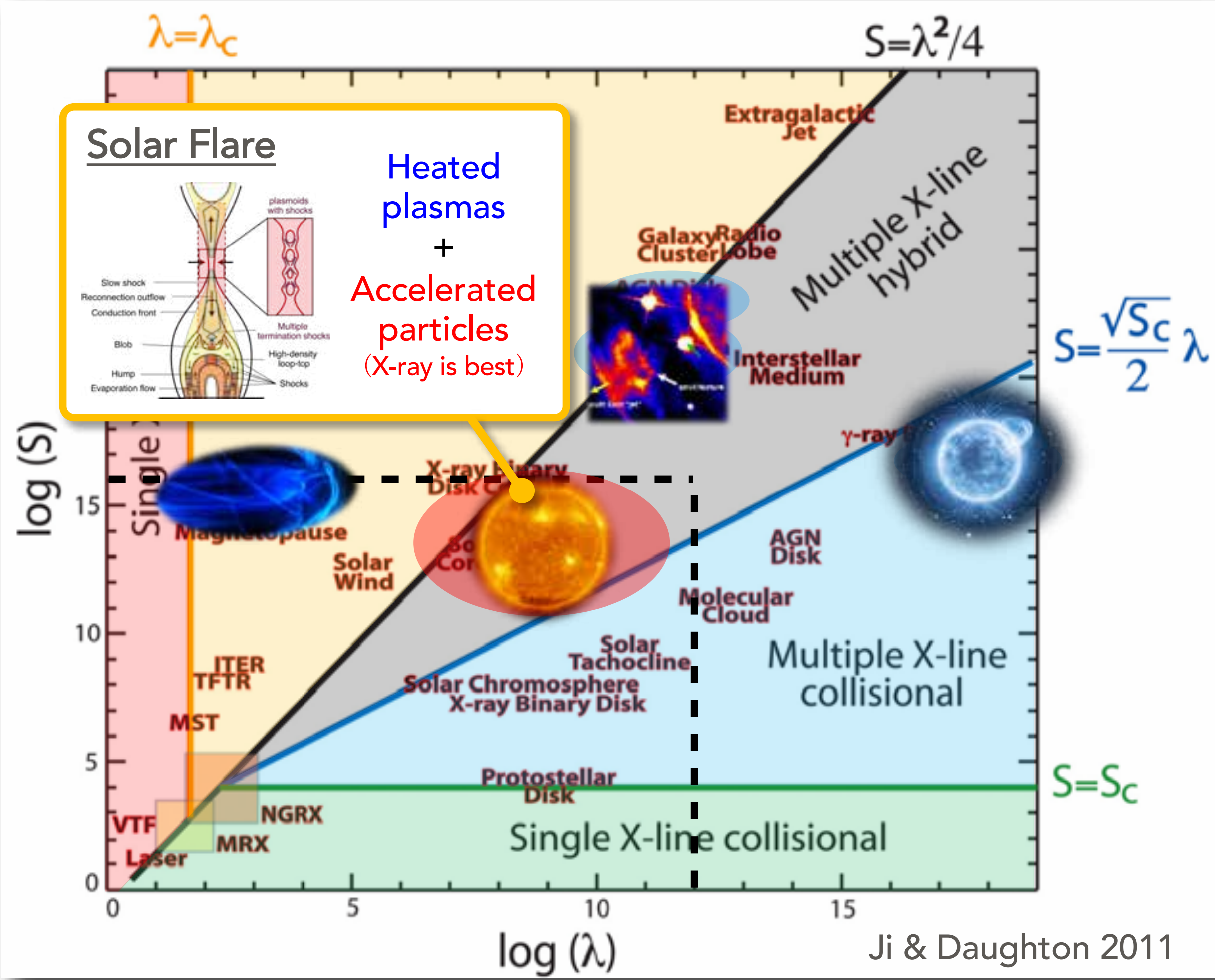
$$S \equiv \frac{\mu_0 V_A L_{CS}}{\eta}$$

Cf. Reynolds number



$R_e = 10^4$

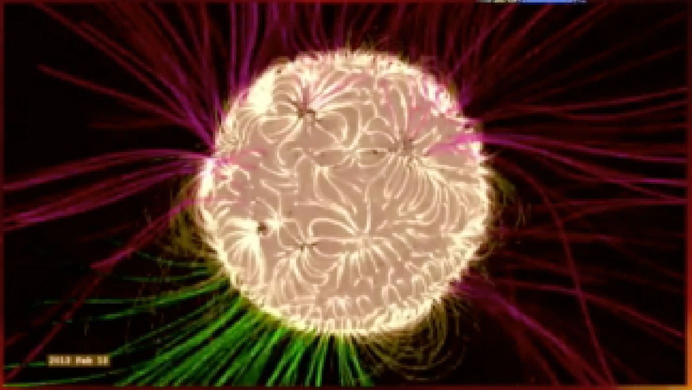
$R_e = 1.54$



Effective plasma size $\lambda \equiv \frac{L}{d_i}$

ひので XRT

Significance of solar flare study



[Plasma physics]

Natural laboratory of plasma

- **Magnetic reconnection**
- **Particle acceleration**

[Unique observation target]

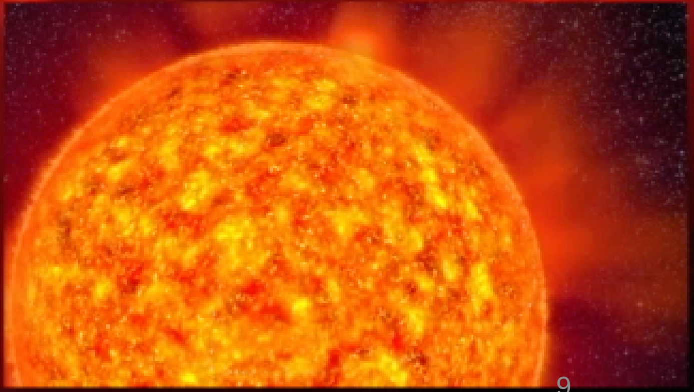
The closest star

- **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**



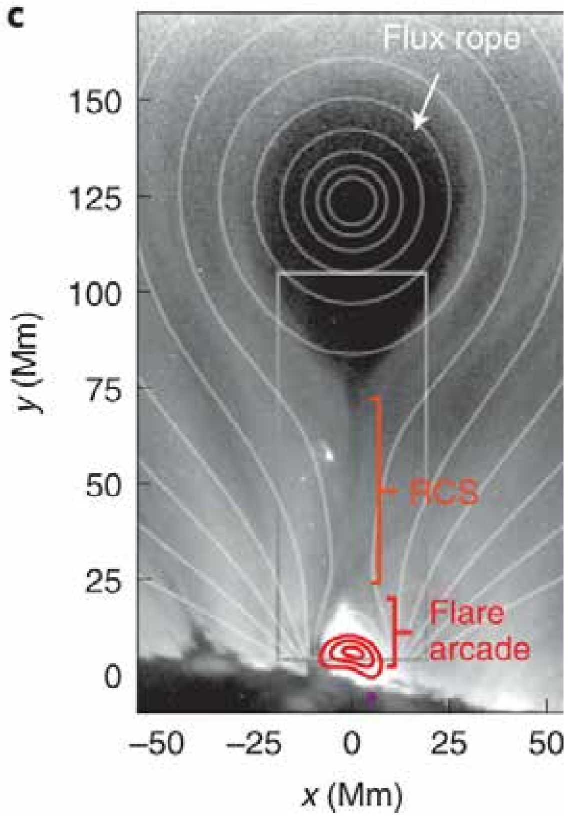
[As a star]

- **Reference of other astrophysical objects**

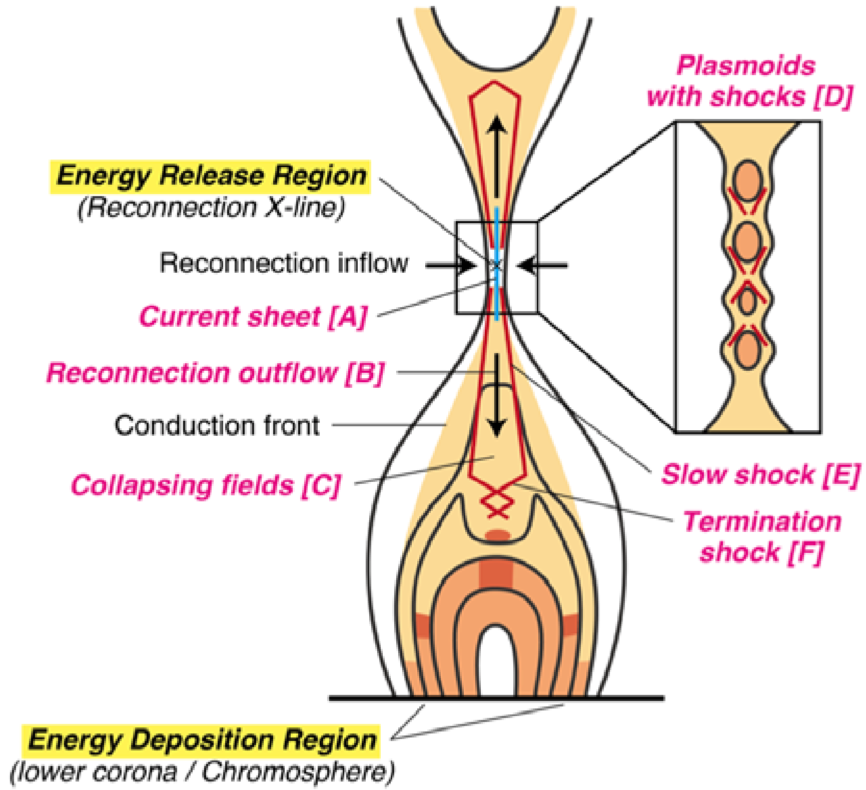
2011-09-12 05:34:16 UT

Magnetic Reconnection in Solar Flare

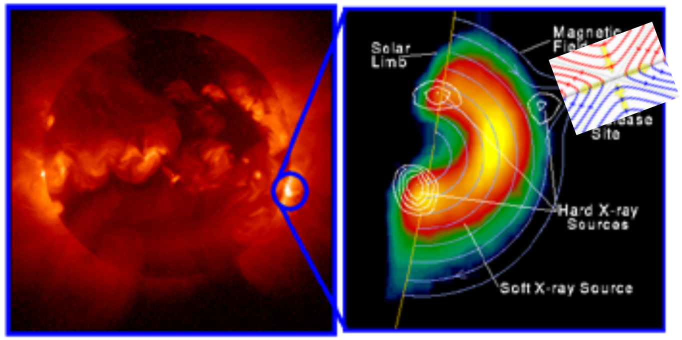
Observation



Model



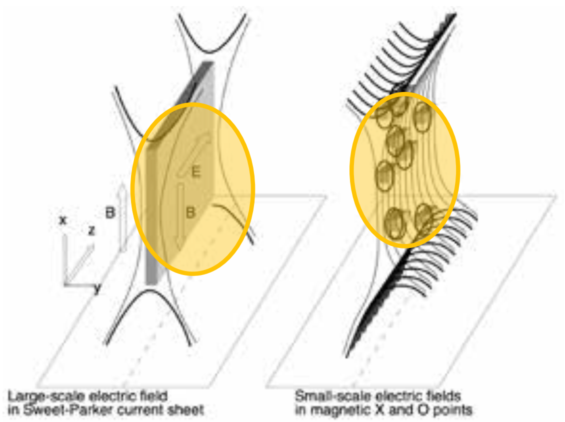
Particle Acceleration is one of the major puzzles in solar physics



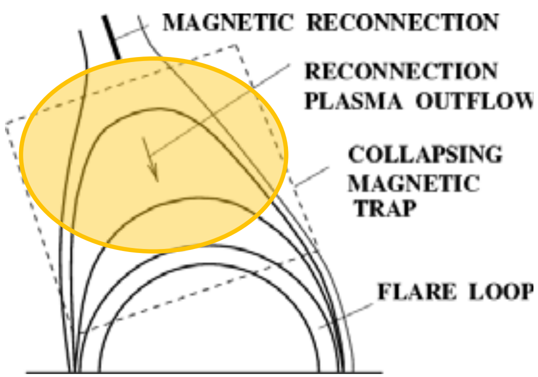
By hard X–ray observations, it is known that the particles are accelerated by solar flares.
But particle acceleration site is still puzzle.

This is caused by poor observations of energy release regions in X-rays.

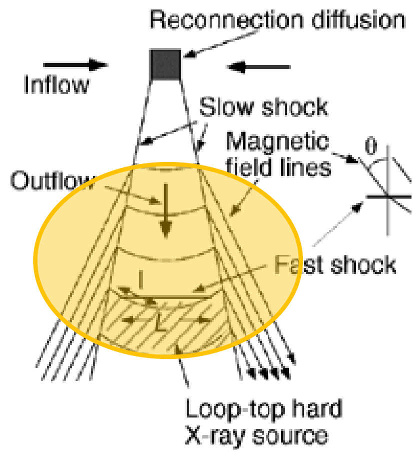
DC acceleration? | Collapsing magnetic traps? | Shocks? | Turbulence?



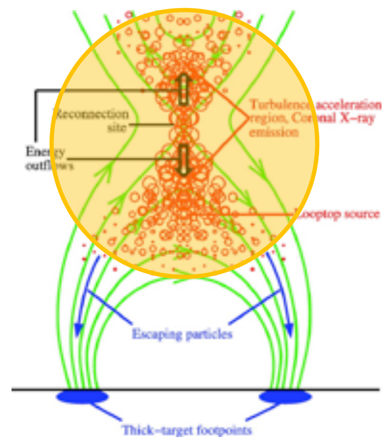
Aschwanden (2002)



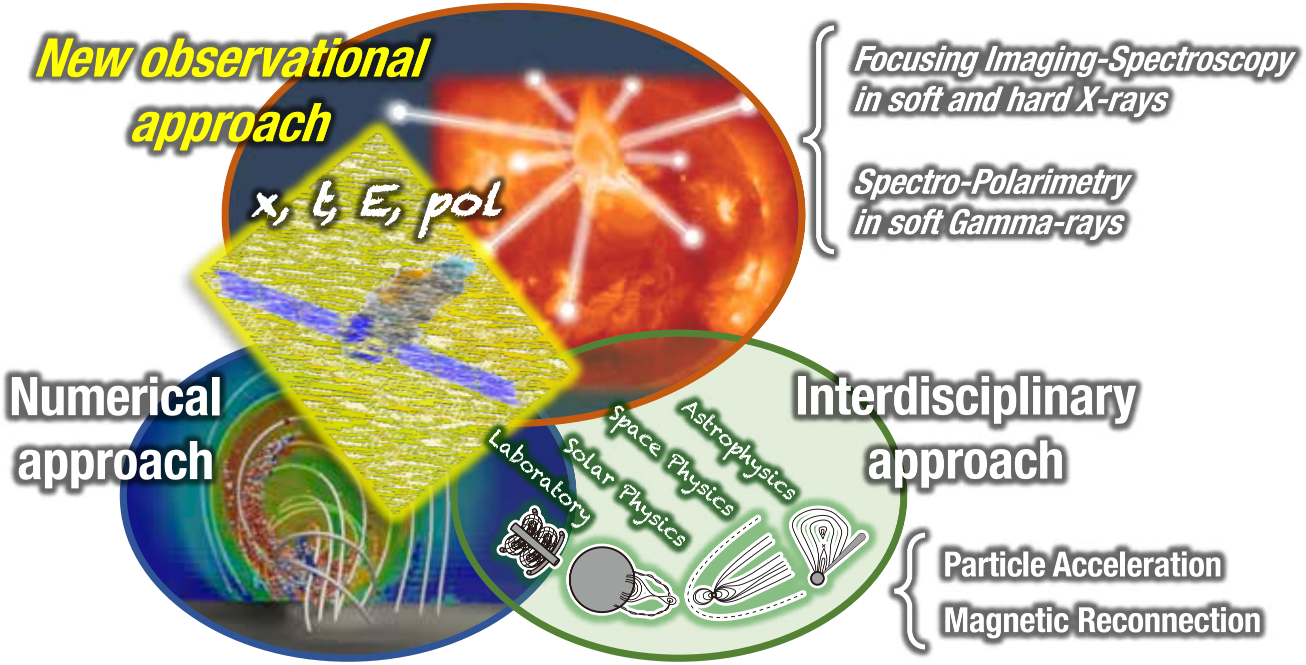
Karlicky & Kosugi (2004)



Tsuneta & Naito (1998)



Liu et al. (2008), Petrosian, (2012)



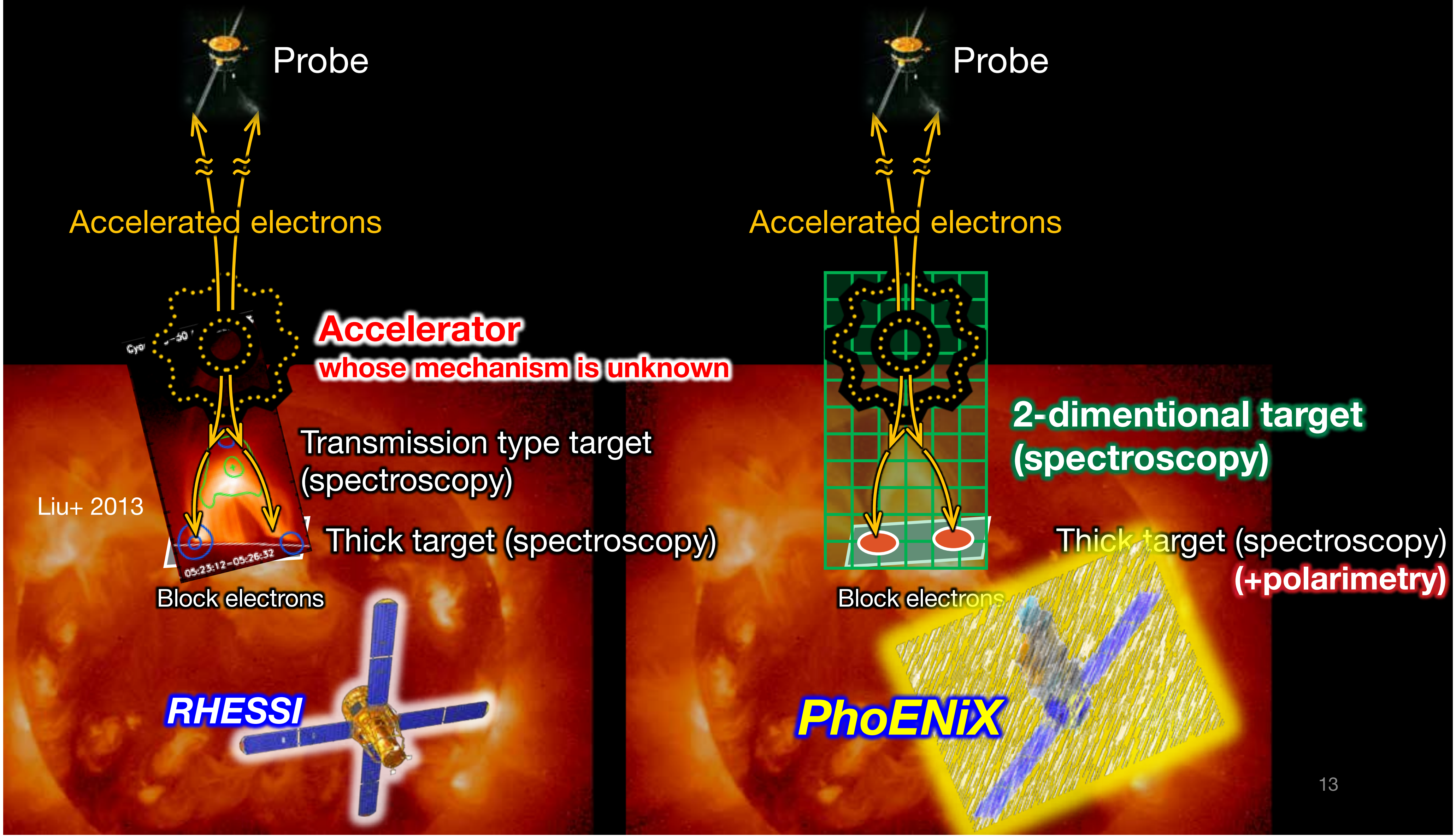
Science Objectives of *PhoENiX* mission

1. Identify particle acceleration sites in solar flares [where]
2. Investigate temporal evolution of particle acceleration [when]
3. Characterize properties of accelerated particles [how]

planned to be realized in Solar Cycle 26 (2030')

Experiment to investigate the mechanism of accelerator

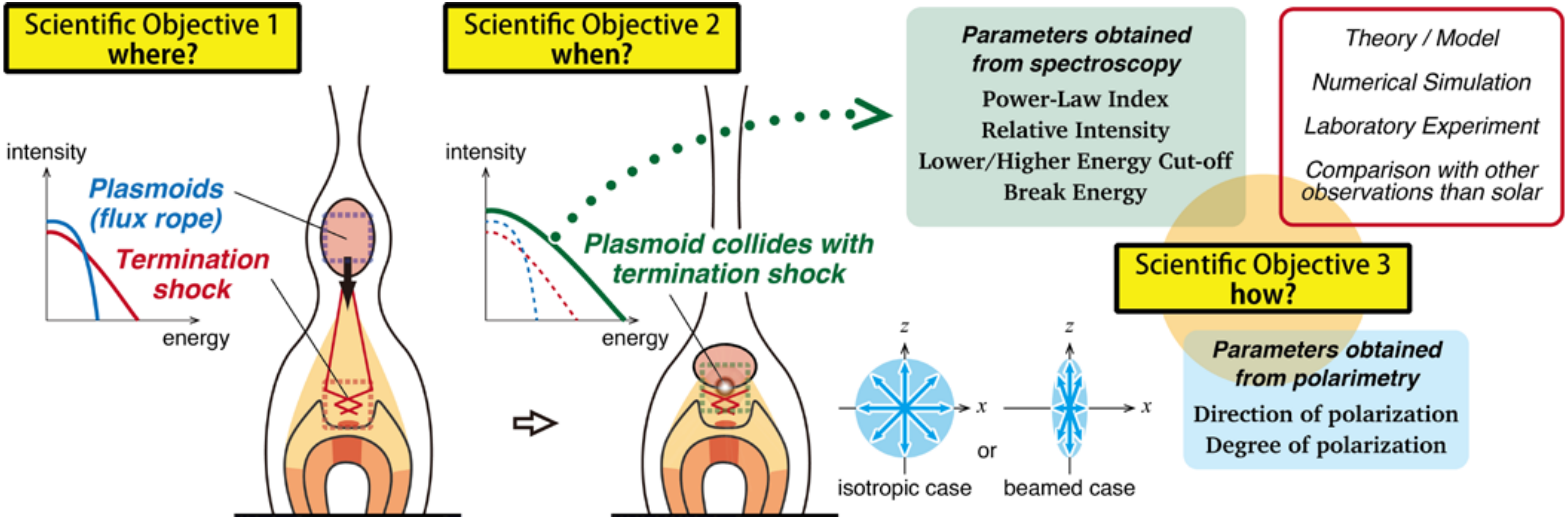
A certain experimental equipment | **A preferable experimental equipment**



<u>Observational Approach</u> for Scientific Objectives

- **Science Objectives**

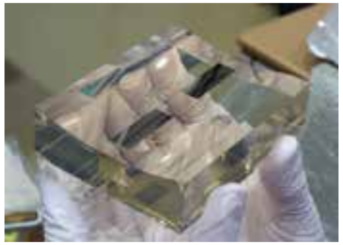
1. To identify ***particle acceleration sites*** <u>in reconnection-associated structures</u> in solar flares
2. To investigate ***the timing of particle acceleration*** <u>during reconnection-associated phenomena</u> in solar flares
3. To characterize ***the properties of accelerated particle populations*** in solar flares



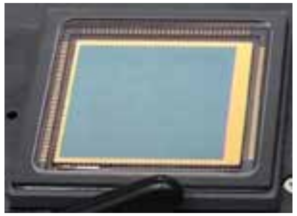
Instruments and Key technologies of PhoENiX

The basic developments of these technologies have been completed.

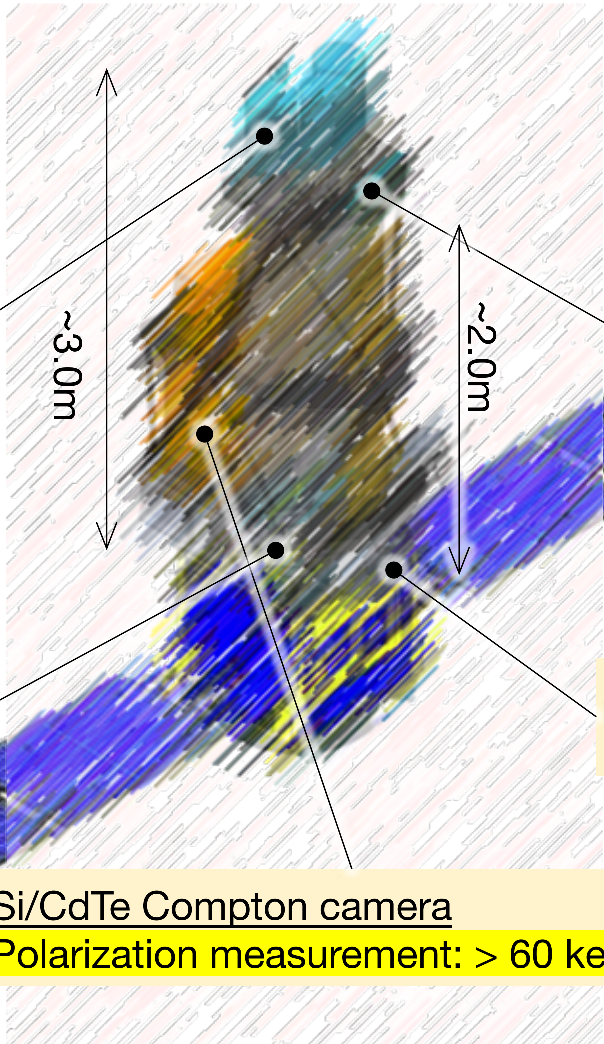
Soft X-ray Imaging Spectrometer (0.5 keV ~ 10 keV)



High-precision X-ray mirror
Resolution: < 2 arcsec
Low scatter: 10^{-4} @ 20 arcsec

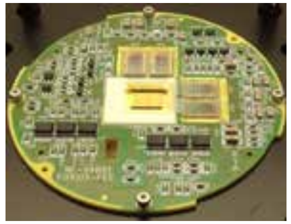


High-speed soft X-ray camera
Back-illuminated CMOS sensor



Hard X-ray Imaging Spectrometer (5 keV ~ 30 keV)

Large effective area X-ray mirror
Resolution: < 8 arcsec (FWHM)



High-sensitivity hard X-ray camera
Fine-pitch CdTe detector

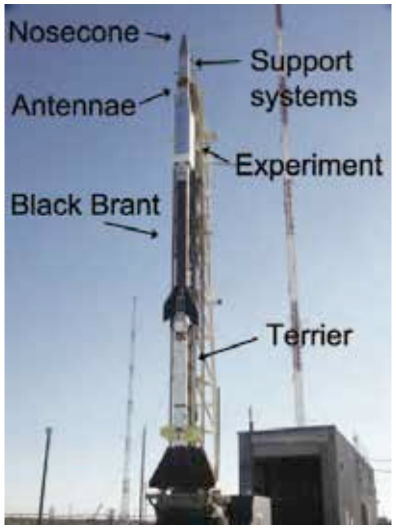
Soft Gamma-ray SpectroPolarimeter
(20 keV ~ > 600 keV)

Si/CdTe Compton camera
Polarization measurement: > 60 keV

Demonstration of Observational Approach
= FOXSI (Focusing Optics X-ray Solar Imager) sounding rocket

- US-Japan collaborative sounding rocket experiment.
- Objectives:
  - Study small scale energy release in the solar corona
  - Demonstrate the new technology for X-ray imaging spectroscopy
- Method: X-ray focusing imaging spectroscopy
- Observation time : about 6 min / flight

2012 **2014** **2018**



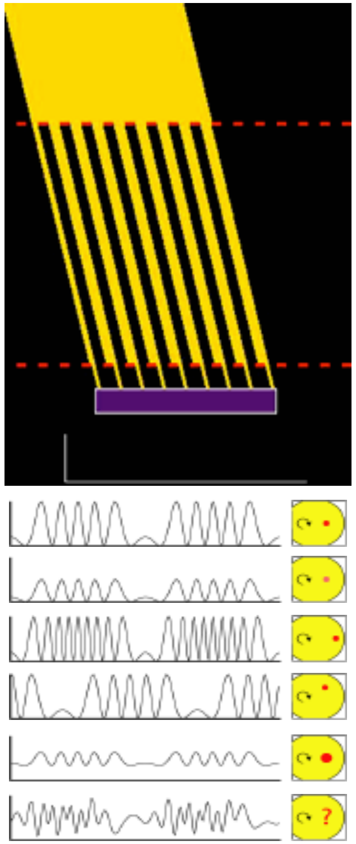
FOXSI 2nd launch
White Sands Missile Range
New Mexico - USA
Dec 11, 2014

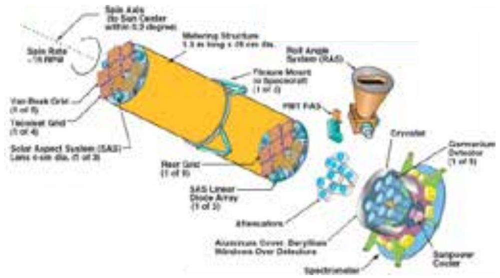
HXR focusing imaging spectrograph of FOXSI

This is planned to be used as PhoENiX HXR instrument.

Existing instruments (RHESSI etc.)

Modulation collimator + detector

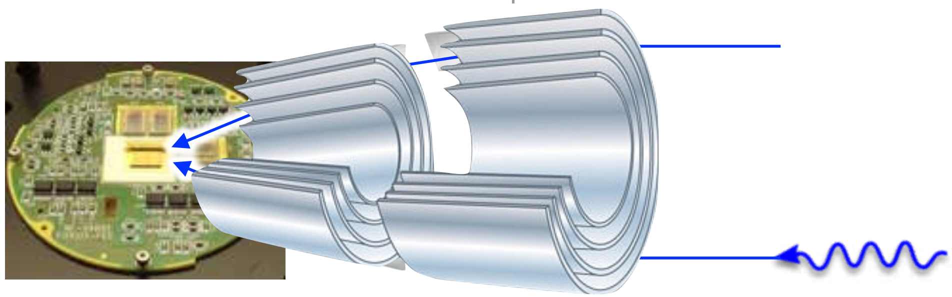




New instruments（FOXSI）

Grazing incidence mirror + CdTe detector

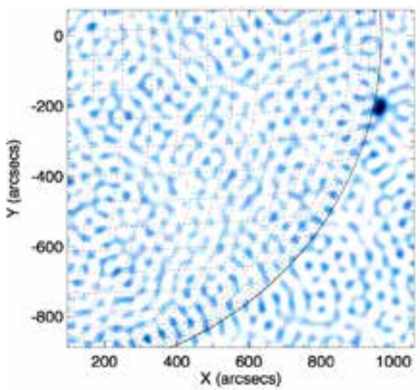
Credit: Chandra telescope



CdTe detector
Furukawa et al. 2019

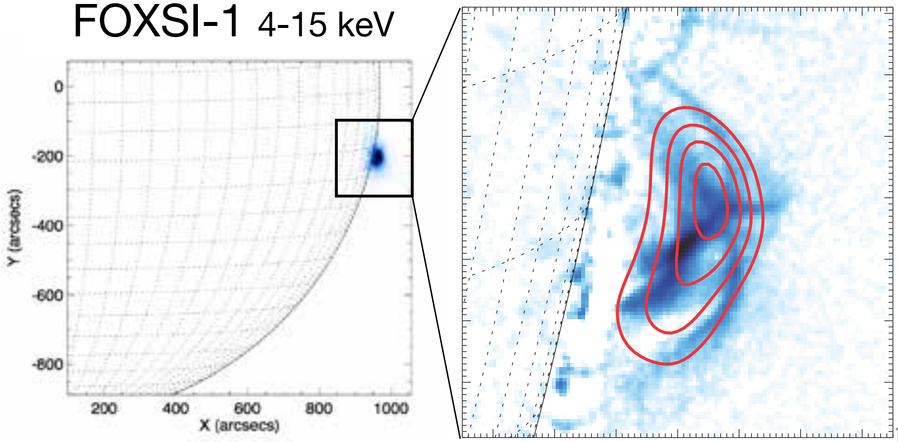
Wolter-I geometry

RHESSI 4-15 keV

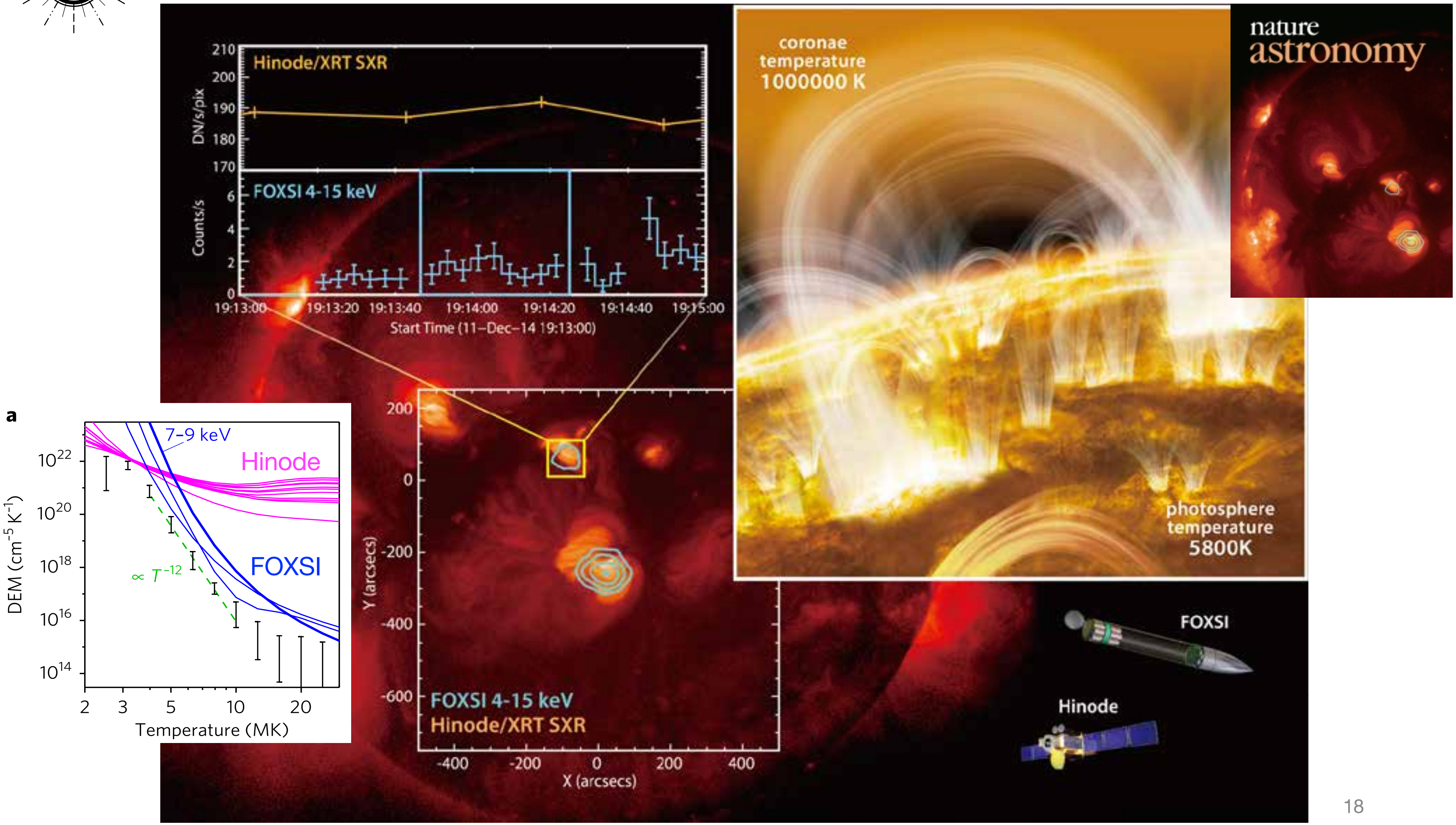


FOXSI-1 4-15 keV

FOXSI-1 4-12 keV



FOXSI-2 result was published from Nature Astronomy （Ishikawa et al. 2017）



SXR focusing imaging spectrograph of FOXSI-3

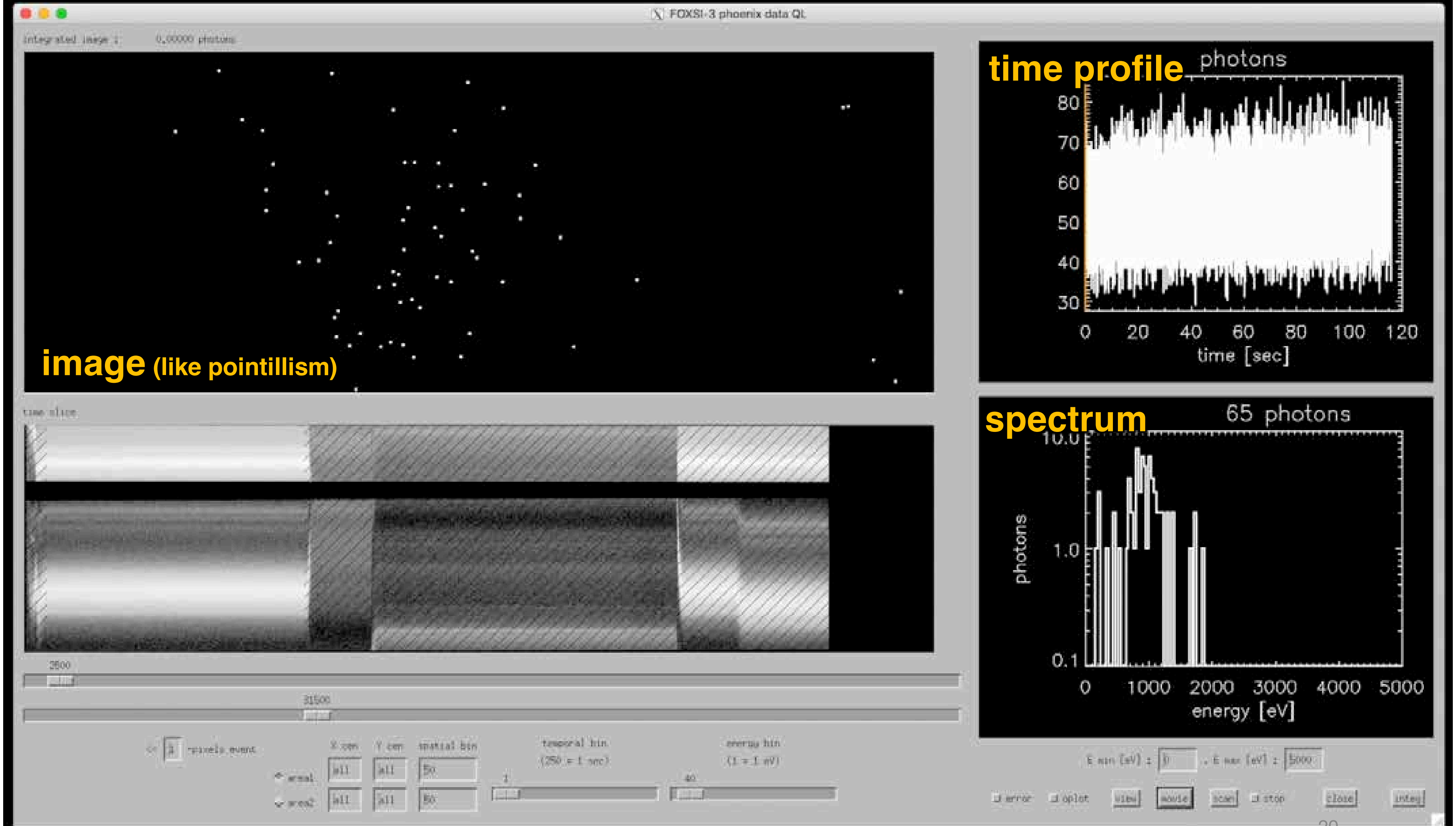
This is planned to be used as PhoENiX SXR instrument.

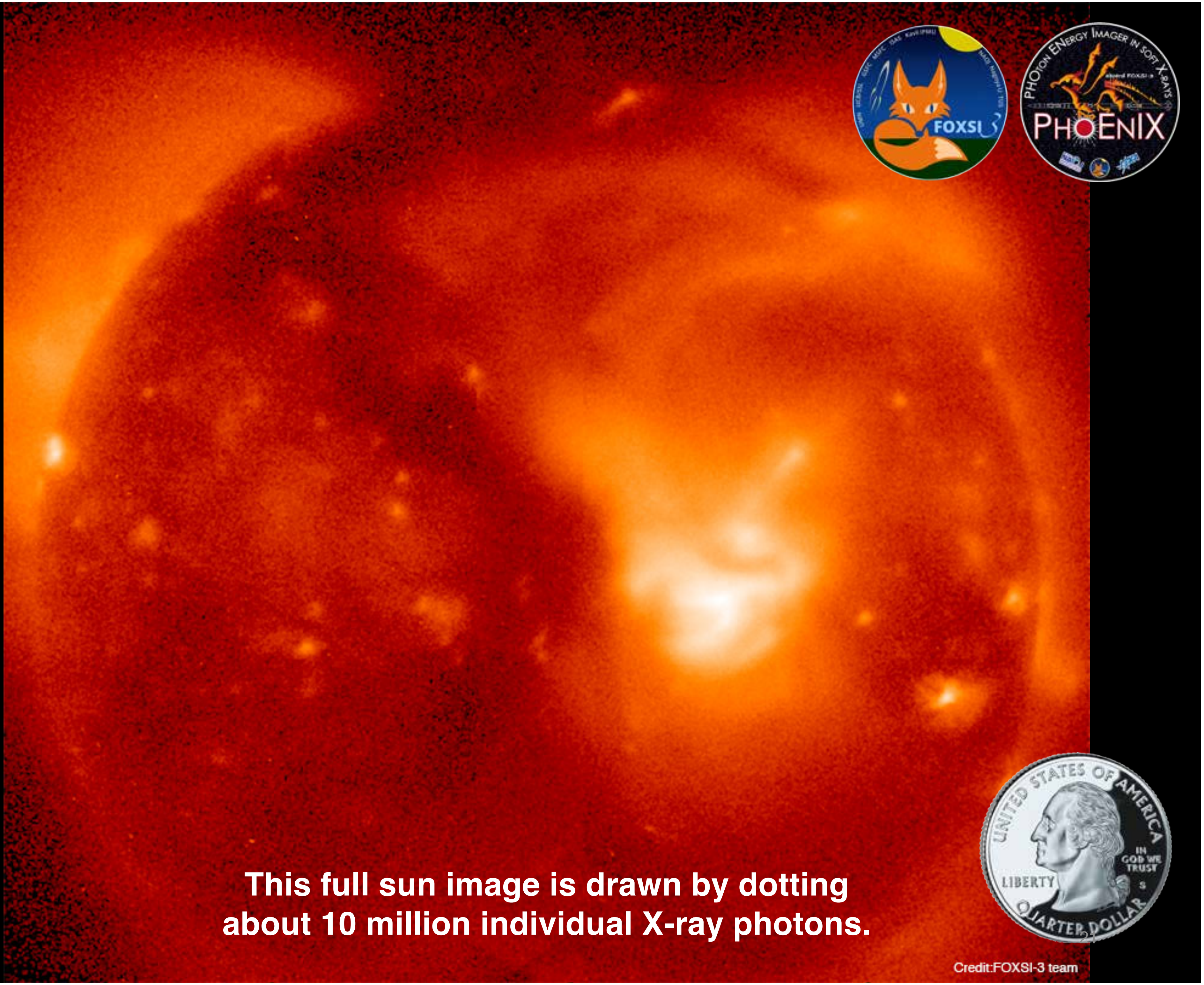
- US-Japan collaborative sounding rocket experiment.
  ➔ **FOXSI-3 was successfully launched on September 7th, 2018.**
- Objectives:
  1. Study small scale energy release in the solar corona
  2. Demonstrate the new technology for X-ray imaging spectroscopy
- Method:
  1. Hard X-ray imaging spectroscopy
  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

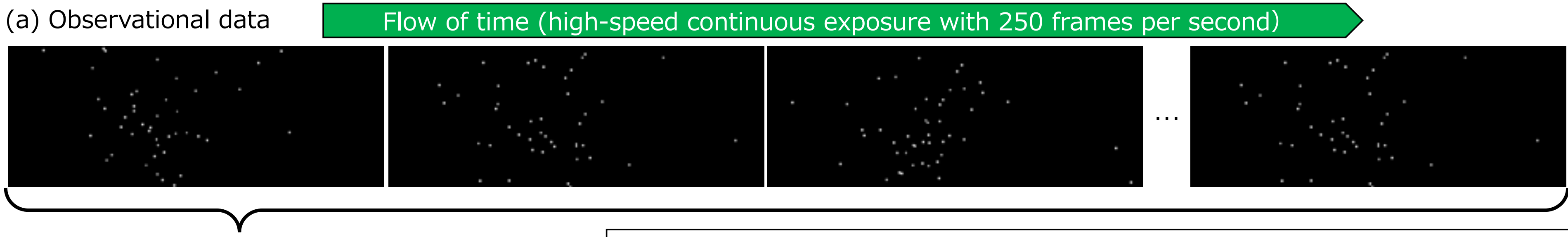
250 FPS data (4 ms continuous exposure)



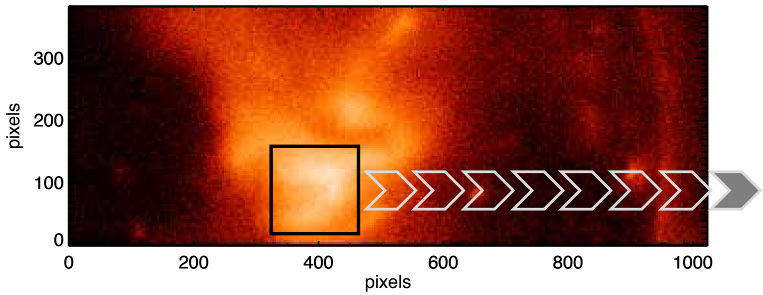

FOXSI 3
PHOton ENergy IMAGER IN SOFT X-RAYS
PhoENIX
UNITED STATES OF AMERICA
LIBERTY
IN GOD WE TRUST
QUARTER DOLLAR
This full sun image is drawn by dotting
about 10 million individual X-ray photons.
Credit:FOXSI-3 team

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

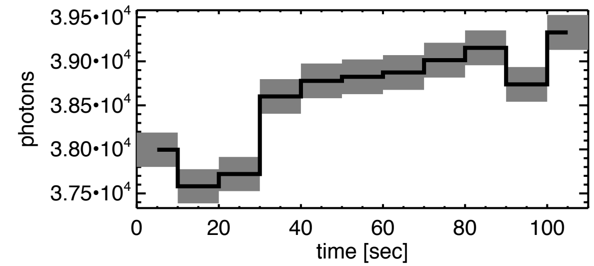
(a) Observational data



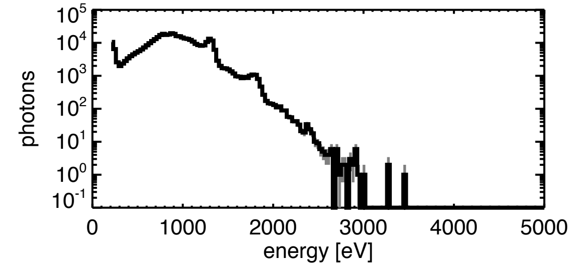
(b) Solar Image with integrated X-ray photons



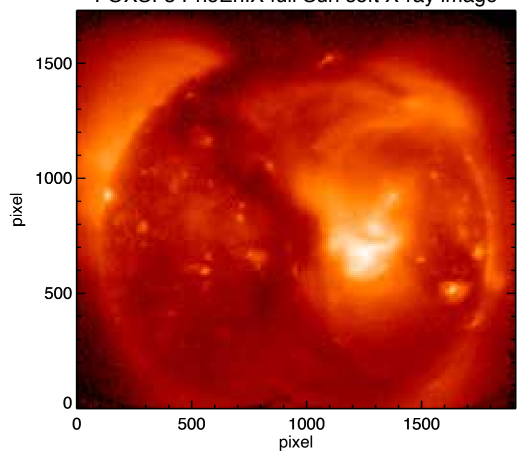
(c) Time variation of X-ray photon number in an active region



(d) X-ray spectrum of an active region

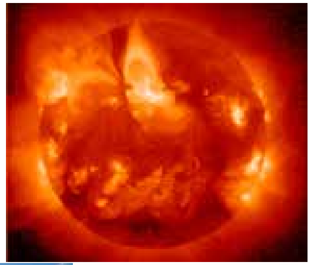


FOXSI-3 PhoEnIX full Sun soft X-ray image



- **FOXSI-3 successfully performed the focusing imaging spectroscopic observation of the solar corona in soft X-rays (from 0.5 keV) for the first time in the world!!**

FOXSI-4 sounding rocket project :
It's time to observe a flare!!

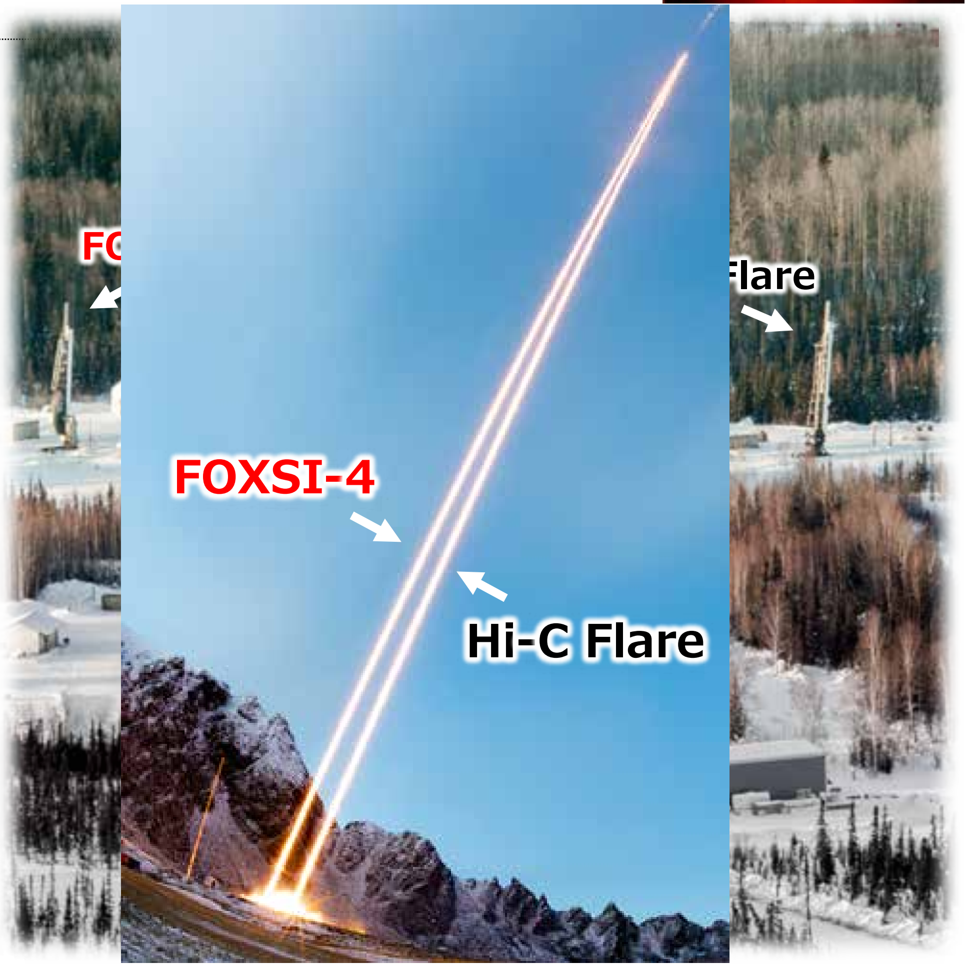


First sounding rocket to observe a solar flare

- 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**

- Method: **Focusing imaging spectroscopy in X-rays (update of FOXSI-3 observation)**



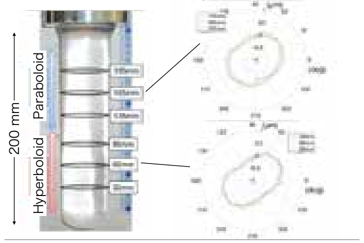
Solar Flare Campaign White Paper:
https://rscience.gsfc.nasa.gov/keydocs/SolarFlareCampaign.pdf

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

FOXSI-4 sounding rocket project

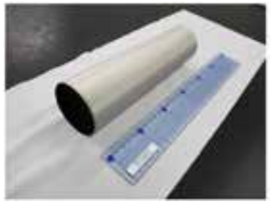
High-precision electroformed X-ray mirror

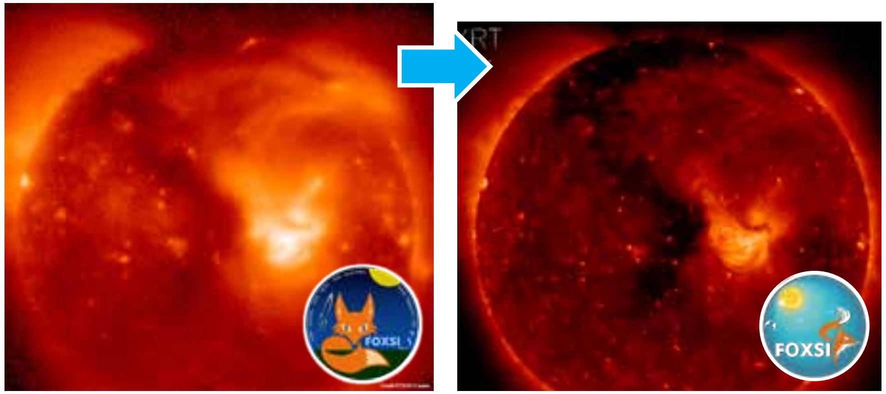
Wolter type I mandrel (left) and circumferential errors (right)



Goal (cf. FOXSI-3)

- <10” HPD (🡐 30” HPD)
- <4” FWHM (🡐 5” FWHM)



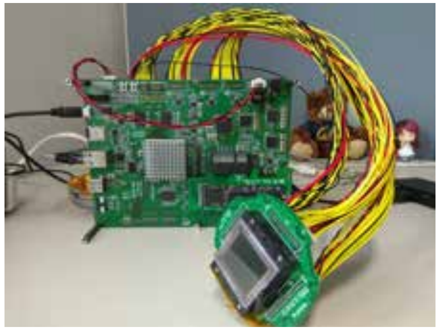


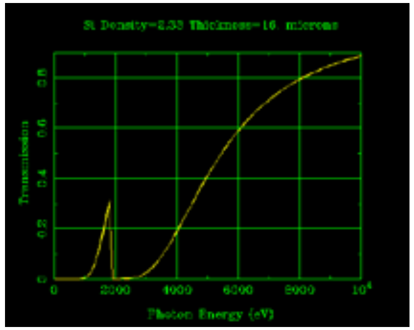
Updated CMOS (for soft X-rays) & CdTe (for hard X-rays) detectors

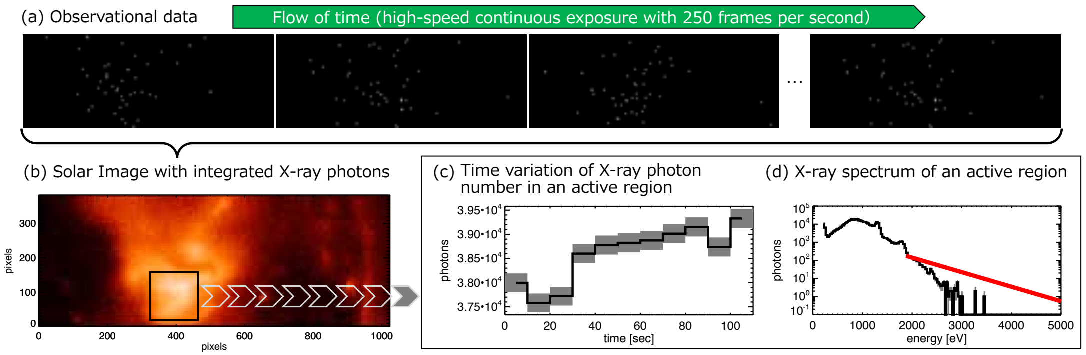
CMOS detector (cf. FOXSI-3)

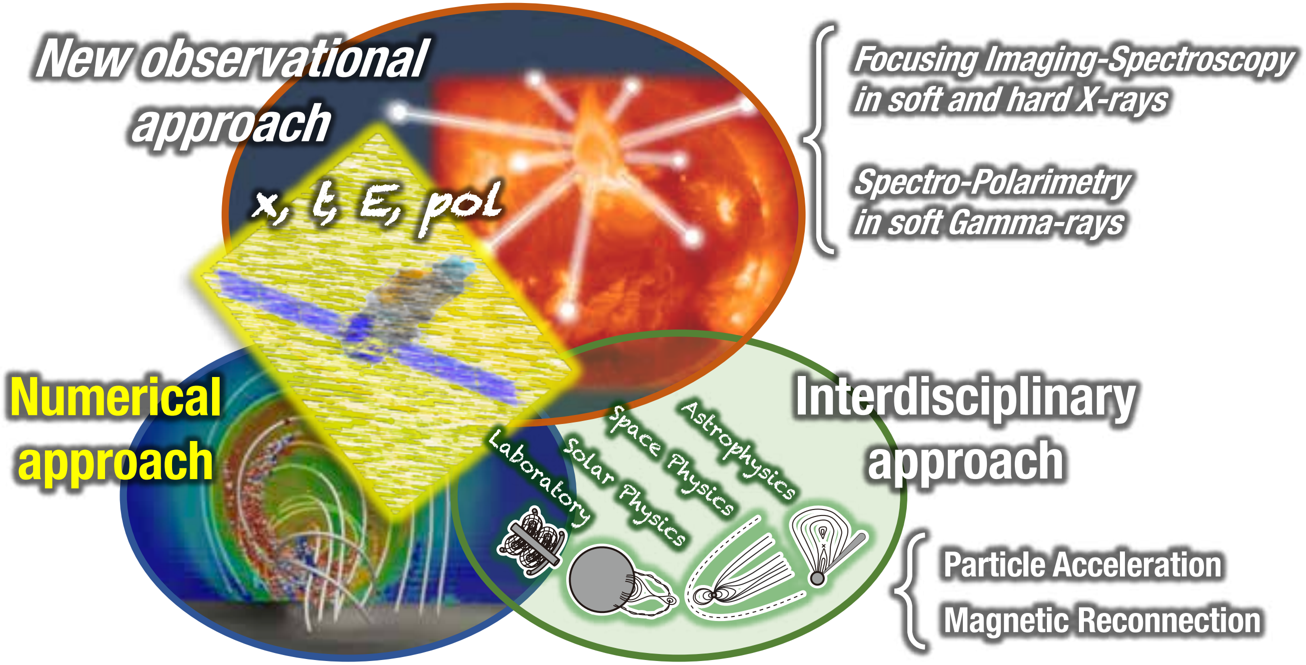
25 um depletion layer thickness (🡐 4 um) for

- Higher sensitivity to high-energy X-rays
- Higher robustness against X-rays







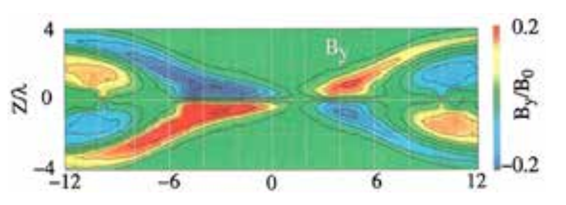


Science Objectives of *PhoENiX* mission

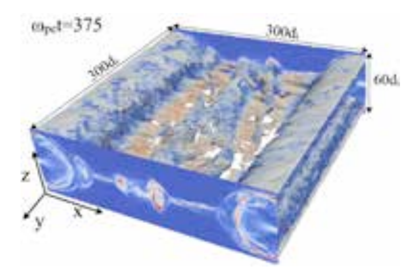
1. Identify particle acceleration sites in solar flares [where]
2. Investigate temporal evolution of particle acceleration [when]
3. Characterize properties of accelerated particles [how]

planned to be realized
in Solar Cycle 26 (2030')

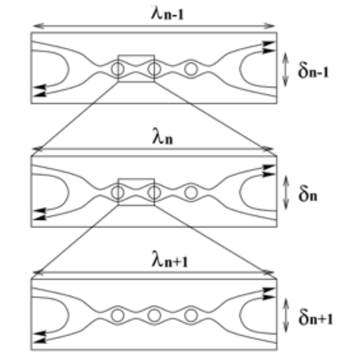
Numerical



$\lambda \sim 10$ (Hoshino et al. 2001)



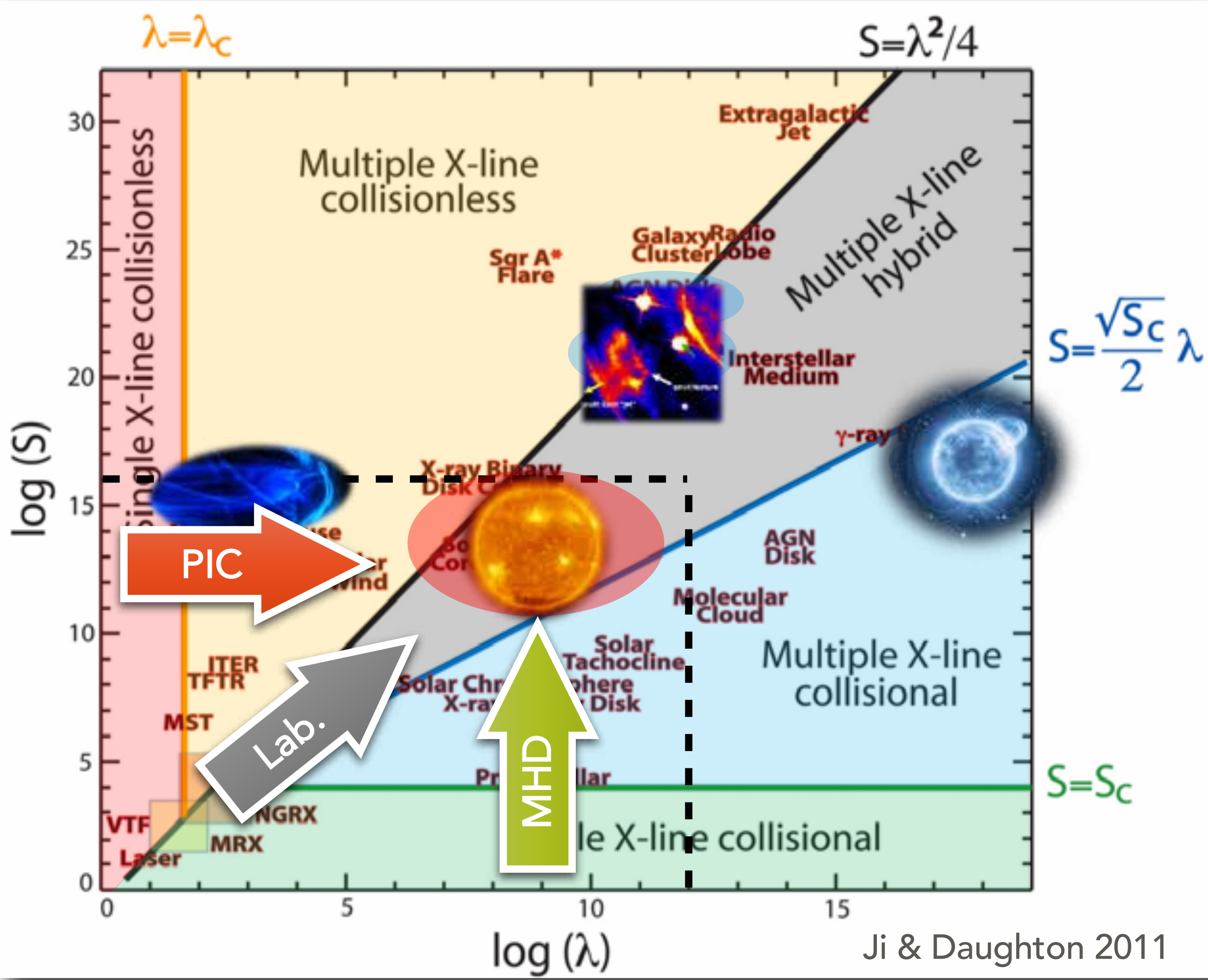
$\lambda \sim 100$ (Guo et al. 2015)

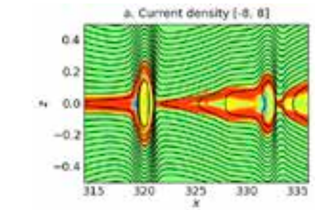


Model of Shibata & Tanuma 2001

Lundquist number

$$S \equiv \frac{\mu_0 V_A L_{CS}}{\eta}$$



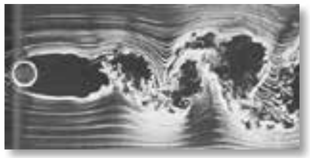


Dynamical Petschek
$S < 10^6$
(Shibayama et al. 2015)

Plasmoid chain MR
$10^4 < S < 10^6$

Sweet-Parker model
$S < 10^4$

Cf. Reynolds number



$R_e = 10^4$

$R_e = 1.54$

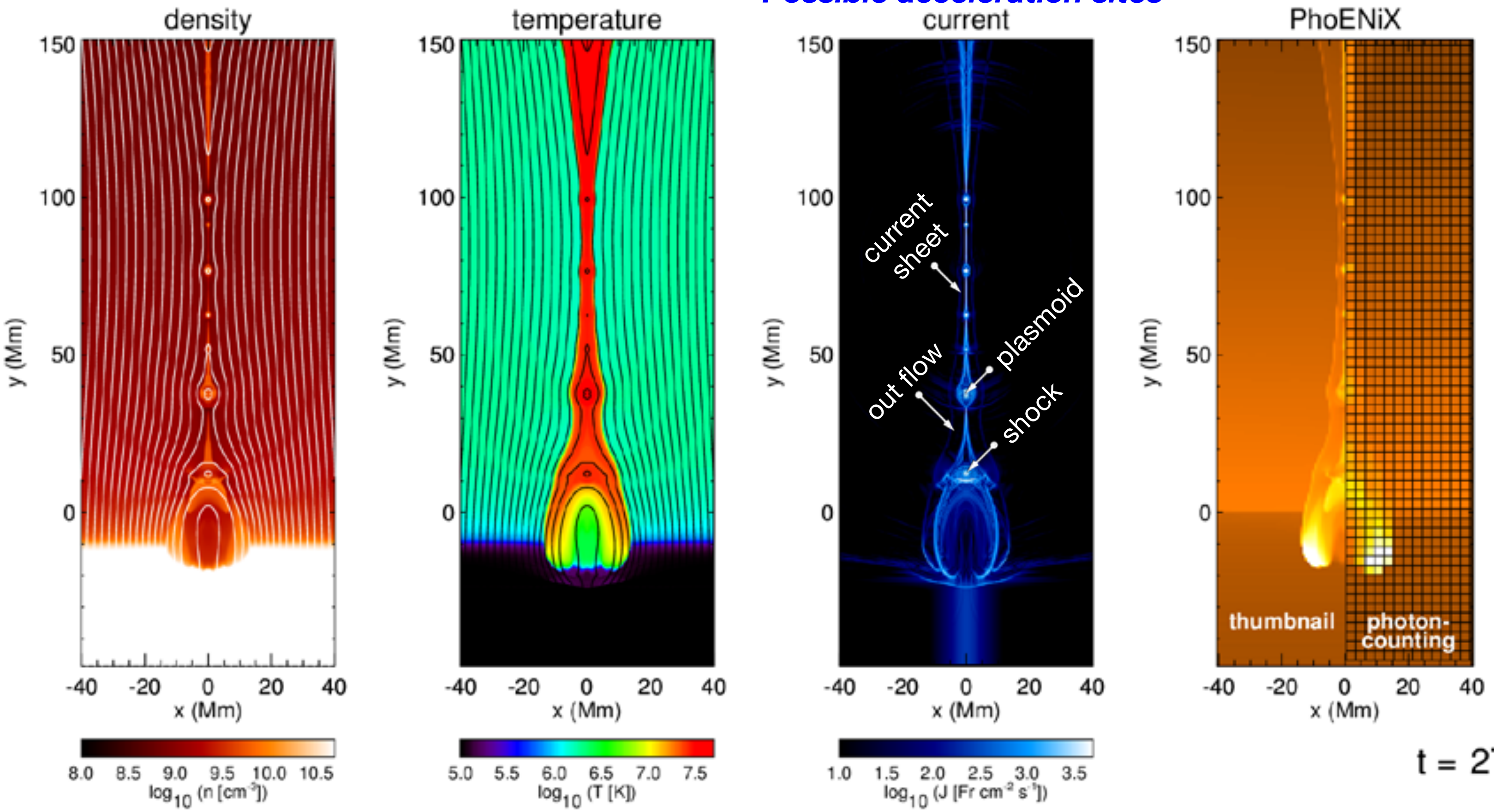
Effective plasma size $\lambda \equiv \frac{L}{d_i}$

Numerical Approach
MHD for understanding of ambient plasma

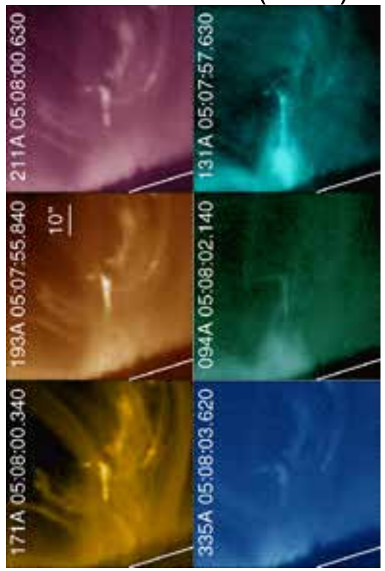
MHD simulation of a solar flare (magnetic reconnection)

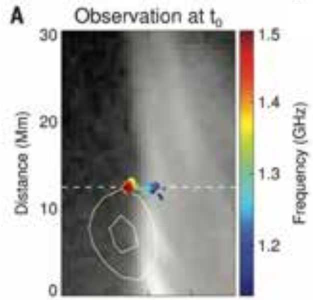
calculated by Kaneko

Possible acceleration sites



Takasao et al. (2012)





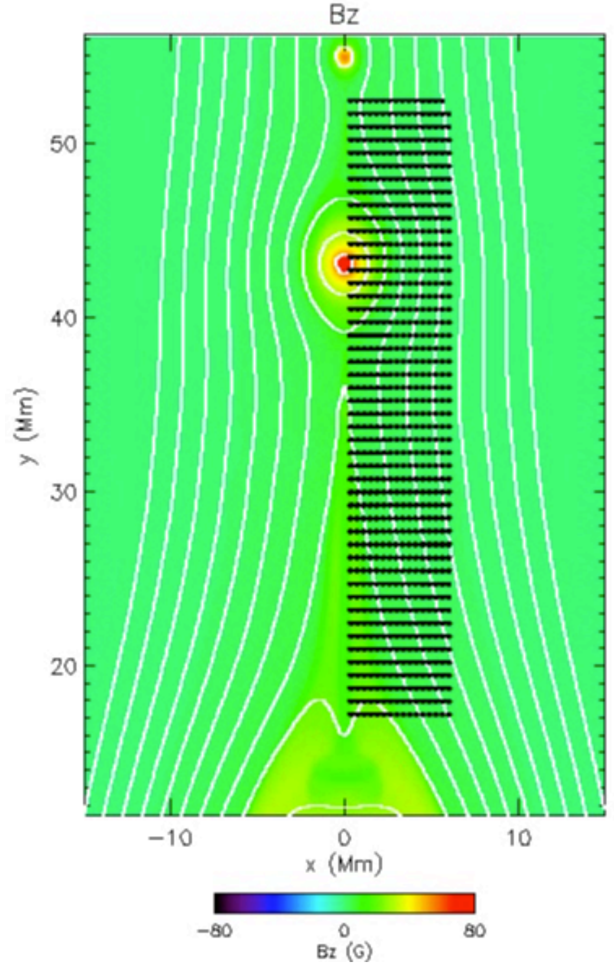
Chen et al. (2015)

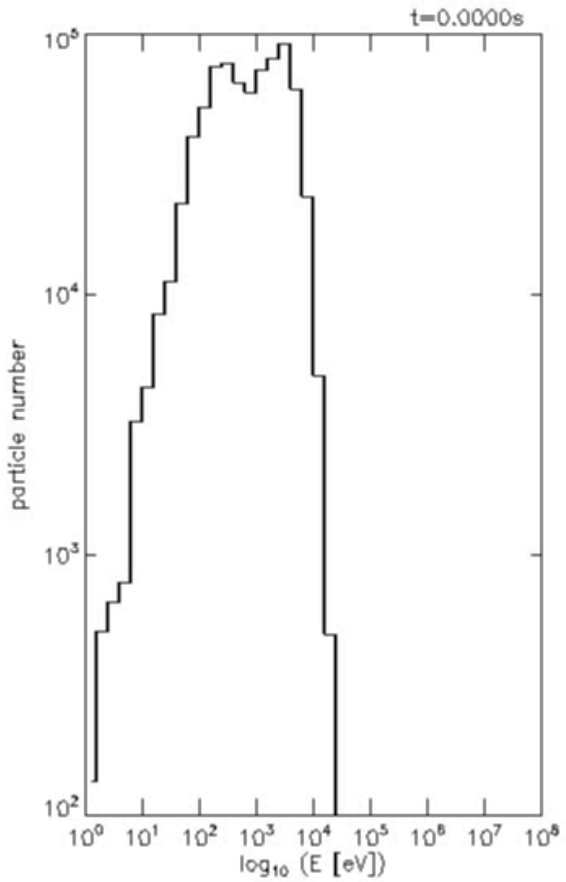
t = 270.0 sec

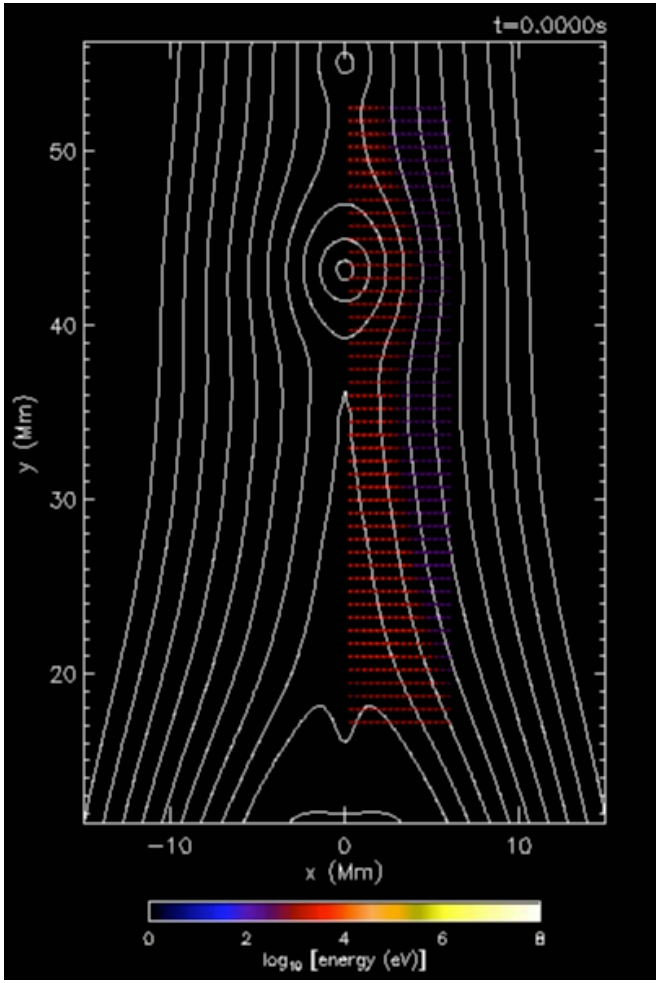
Numerical Approach

MHD + GCA for understanding of particle acceleration

calculated by Kaneko



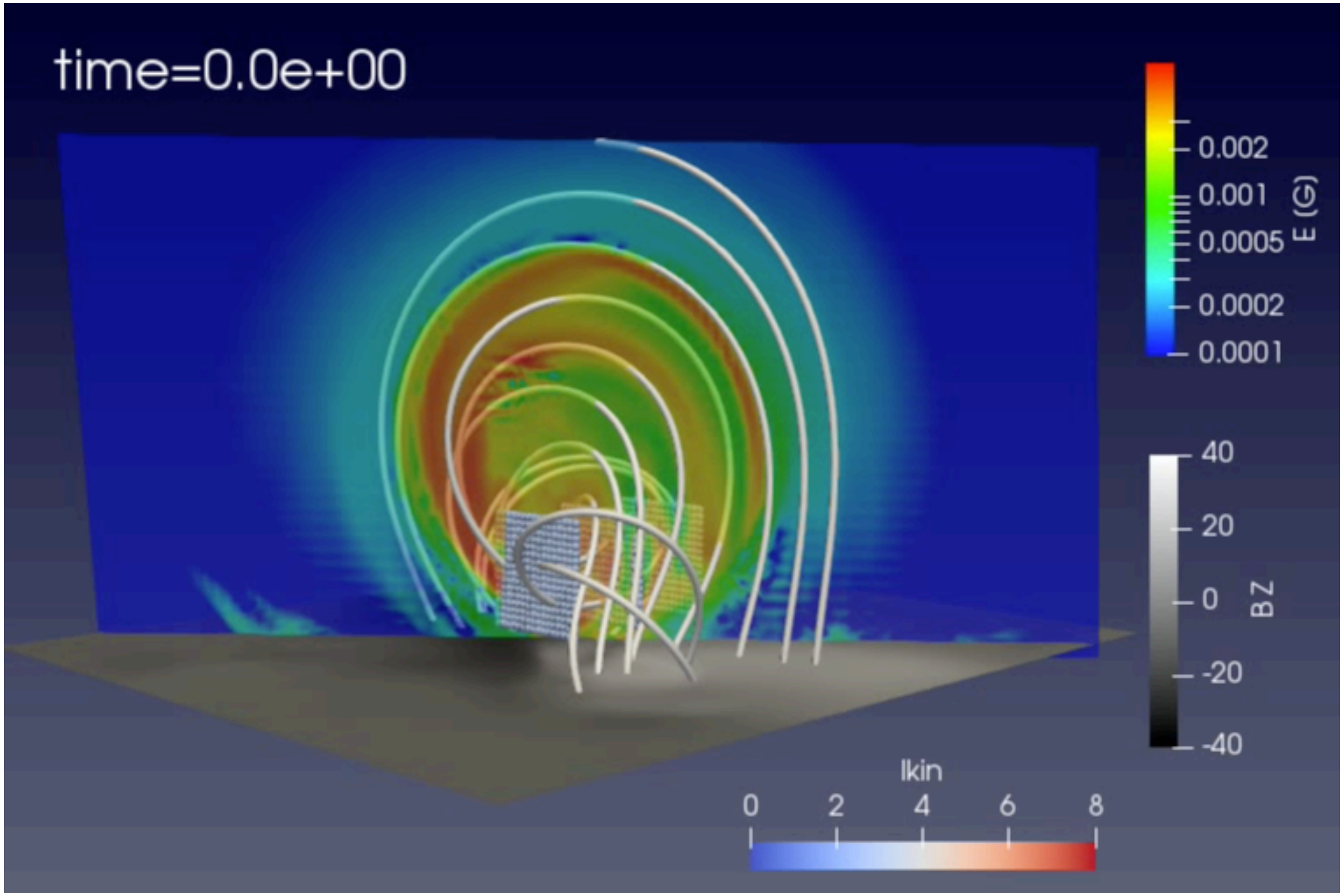




Numerical Approach

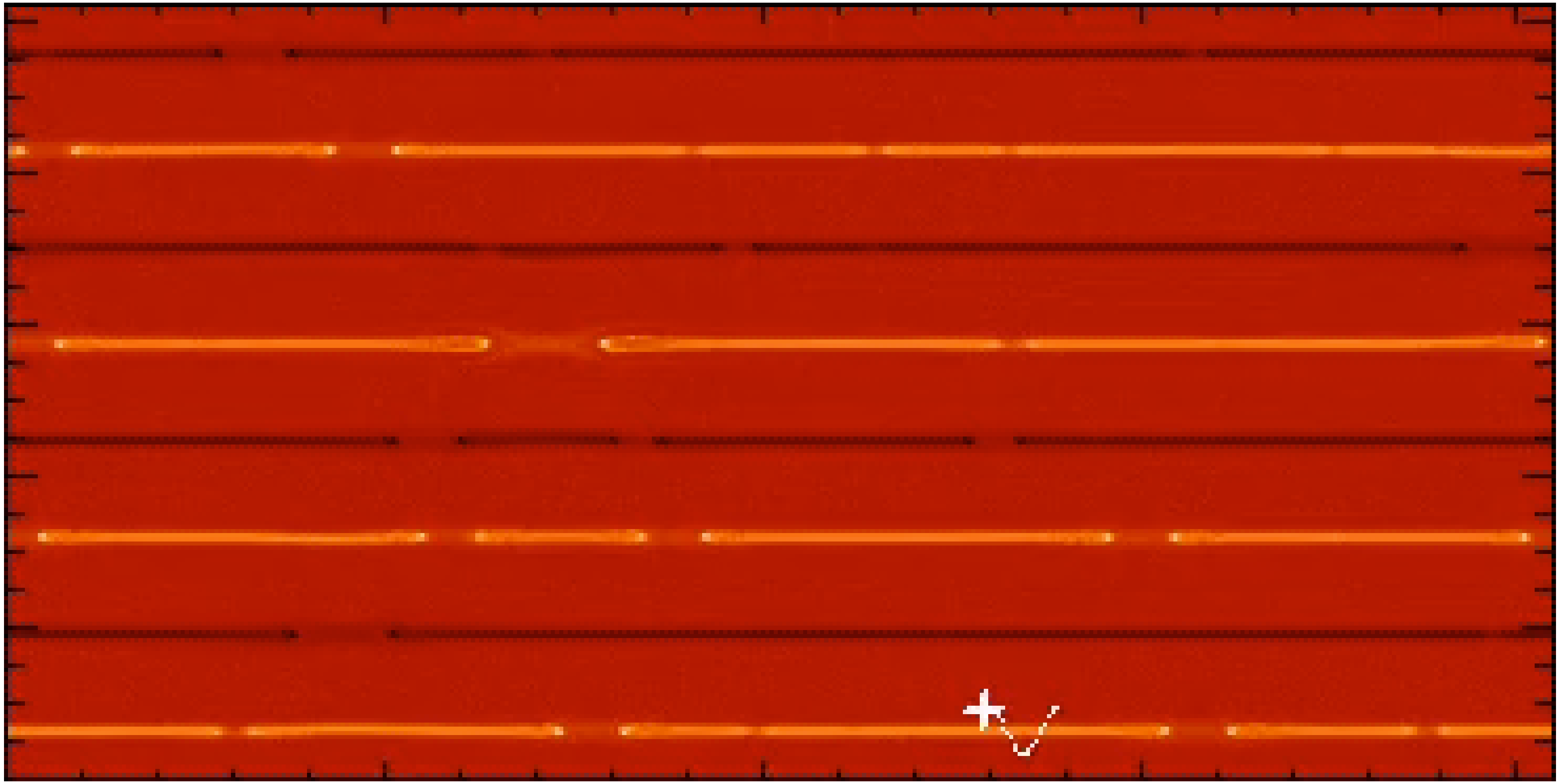
MHD + GCA for understanding of particle acceleration

calculated by Kaneko



Numerical Approach

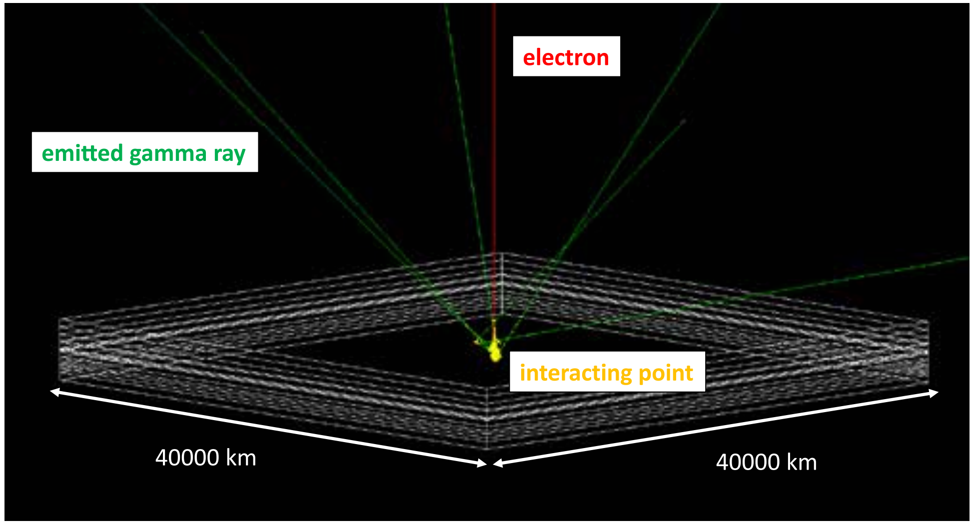
PIC for understanding of particle acceleration



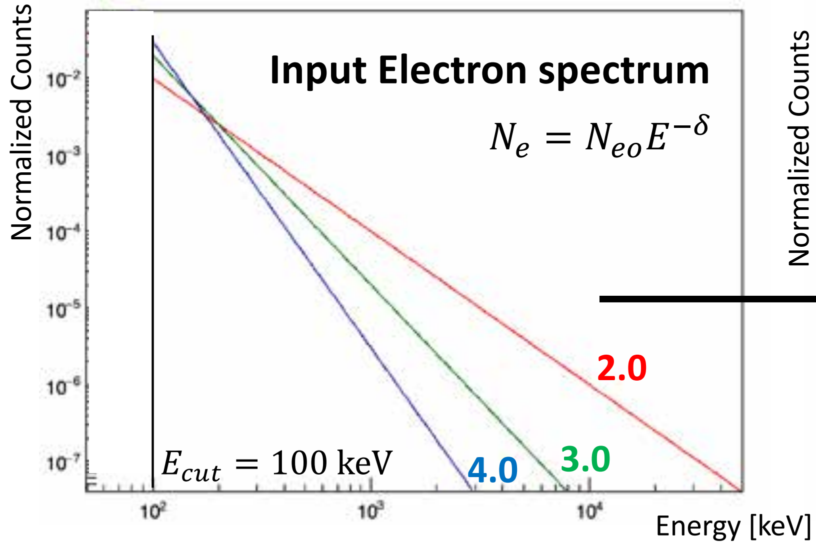
Numerical Approach

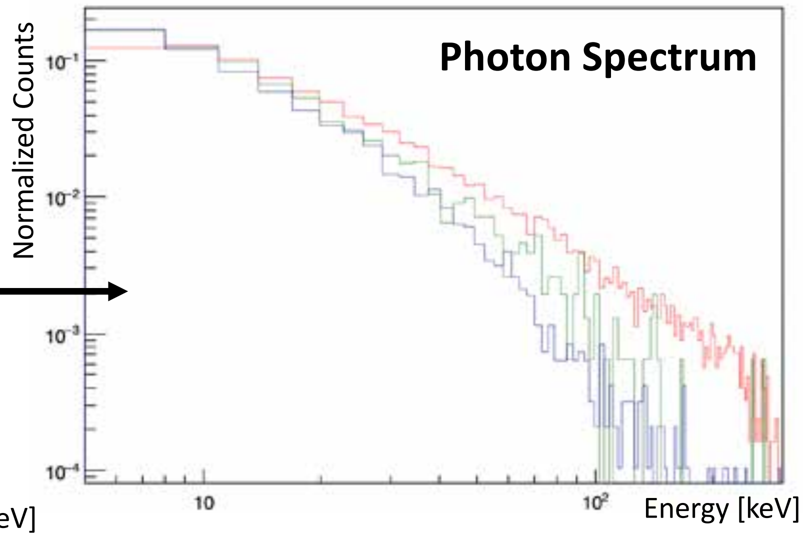
Emission model for comparison between observation and numerical simulation

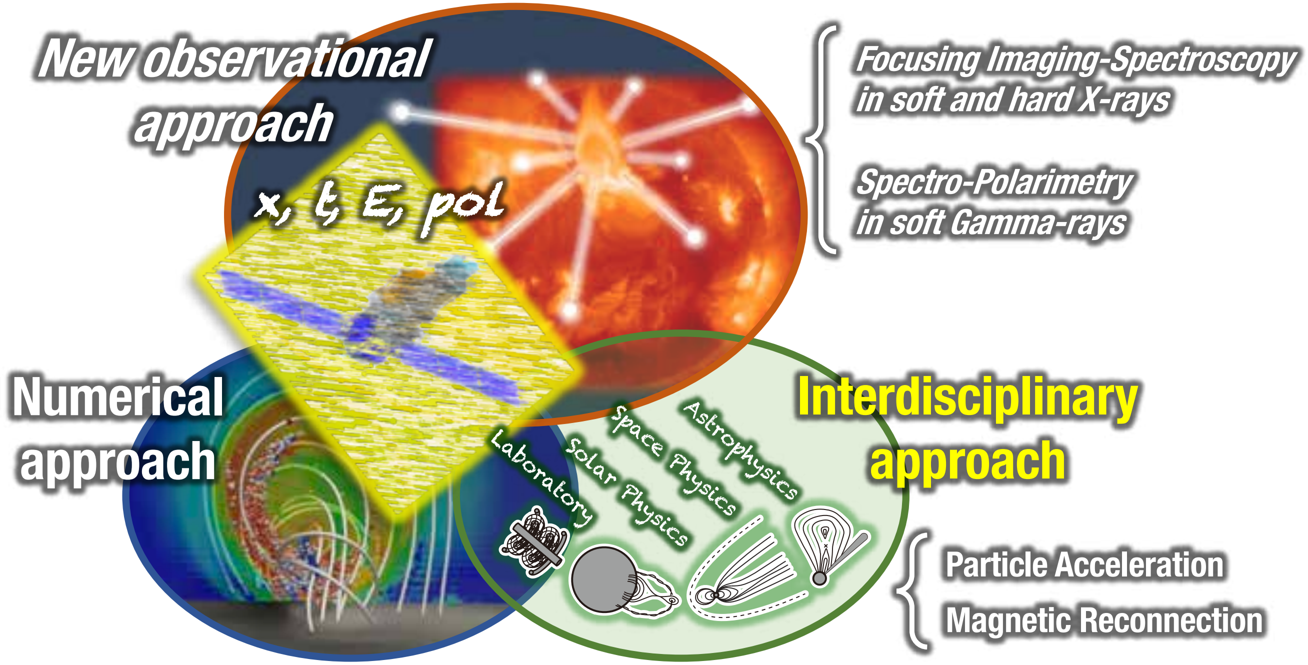
calculated by Nagasawa



Solar corona model in ComptonSoft







Science Objectives of *PhoENiX* mission

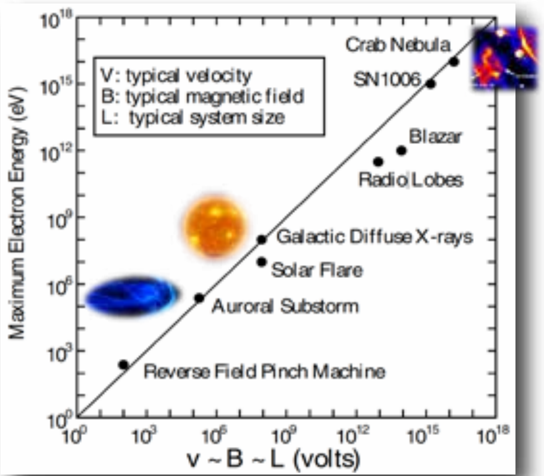
1. Identify particle acceleration sites in solar flares [where]
2. Investigate temporal evolution of particle acceleration [when]
3. Characterize properties of accelerated particles [how]

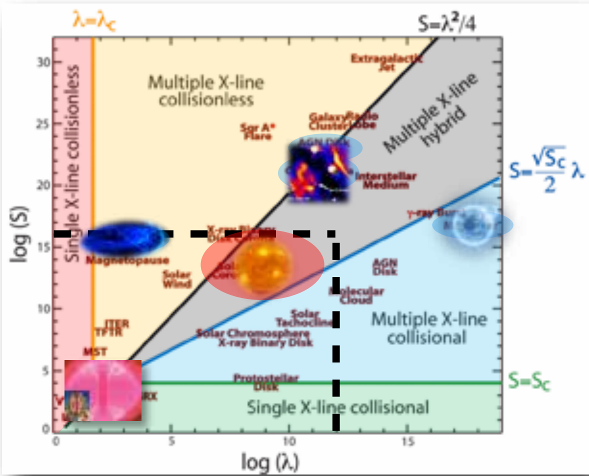
planned to be realized in Solar Cycle 26 (2030')

Interdisciplinary approach

with strength and heritage of each research field

- **Space Physics**
  - Observation in interplanetary space (trace of plasmas from the sun)
  - PIC simulation





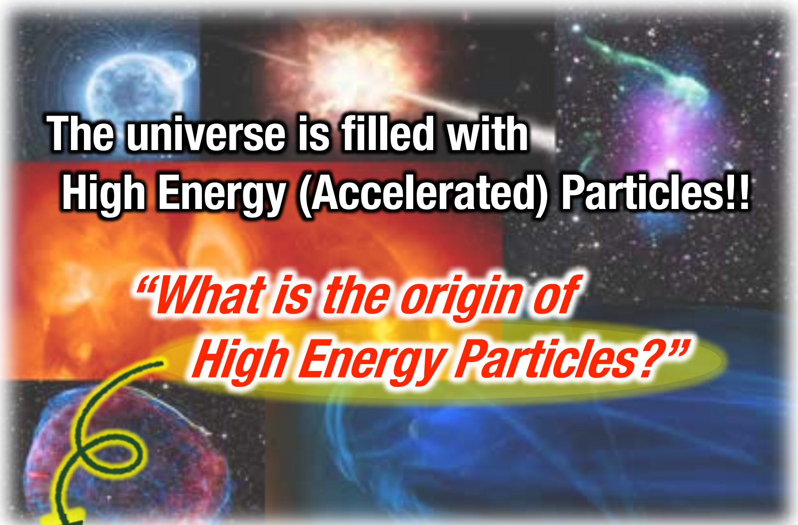
- **Laboratory plasma physics**
  - Laboratory experiment of MR

- **Astrophysics**
  - X-ray & gamma-ray observations
  - X-Ray Spectral Fitting Package (Xspec)
  - X-ray emission model
  - Key technologies

Common Physics

- ***Particle Acceleration***
- ***Magnetic Reconnection***

- **Solar Physics**
  - Solar observations
  - MHD simulation
  - Key technologies



Science Objectives of *PhoENiX* mission

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PHYSICS OF ENERGETIC AND NON-THERMAL PLASMAS IN THE X-REGION
PhoENiX

planned to be realized in Solar Cycle 26 (2030')

- ✓ Energization of space plasmas
- ✓ Formation and evolution of life
- ✓ Influence on planetary environments

The sun is unique in that:

- ✓ A natural laboratory of high energy plasmas
- ✓ Mother of life
- ✓ Impact on earth and social environments

Sounding Rocket *FOXSI* series

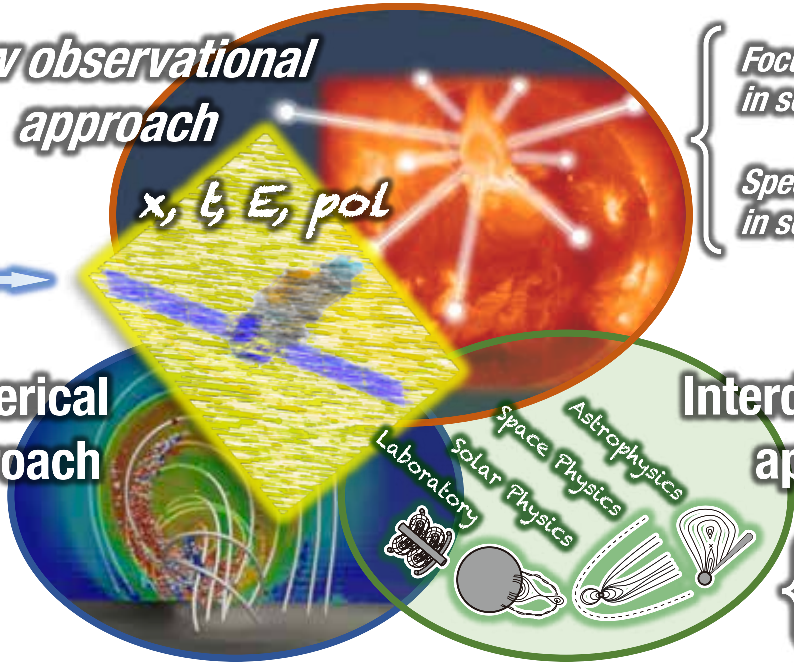
2012 2014 2018

FOXSI

2024 Flare campaign

NASA DRIVE Science Center

SolFER
Solar Flare Energy Release
https://solfer.umd.edu/



Focusing Imaging-Spectroscopy in soft and hard X-rays

Spectro-Polarimetry in soft Gamma-rays

Particle Acceleration

Magnetic Reconnection